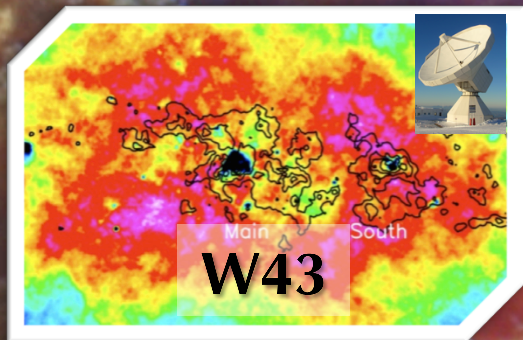
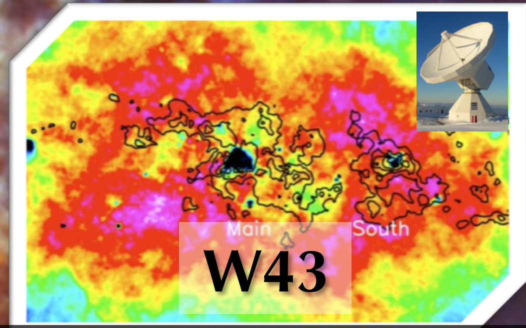
HOBYS and W43, two more steps towards a Galaxy-wide understanding of high-mass star formation

Frédérique Motte (AIM Paris-Saclay)

With the consortia of
- the HOBYS Herschel Key Program « the Herschel imaging survey of OB Young Stellar objects »
- the W43 IRAM & ATLASGAL Large program « Origin of molecular cloud and star formation in W43 »



Linking cloud structure/kinematics & star formation activity



The 9 closest cloud complexes forming high-mass stars.

- 50-100 pc at d = 0.7-3 kpc
- $M_{cloud} = 2\ 10^5 – 1\ 10^6\ M_\odot$
- Forming up to 20 $M_\odot$ stars
- Herschel 70-500 μm

The nearest cloud complex at the tip of the Galactic bar.

- 140 pc at d = 6 kpc
- $M_{cloud} = 7\ 10^6\ M_\odot$
- Forming up to 50-100 $M_\odot$ stars
- HI, CO, SiO, ATLASGAL, Spitzer, …

Main open questions:

1) Origin of molecular cloud complexes and their high-density structures.

2) Link of the star formation efficiency to the cloud concentration and dynamics.

Cloud structure and OB star formation as seen by HOBYS, the *Herschel* imaging survey of OB Young Stellar objects

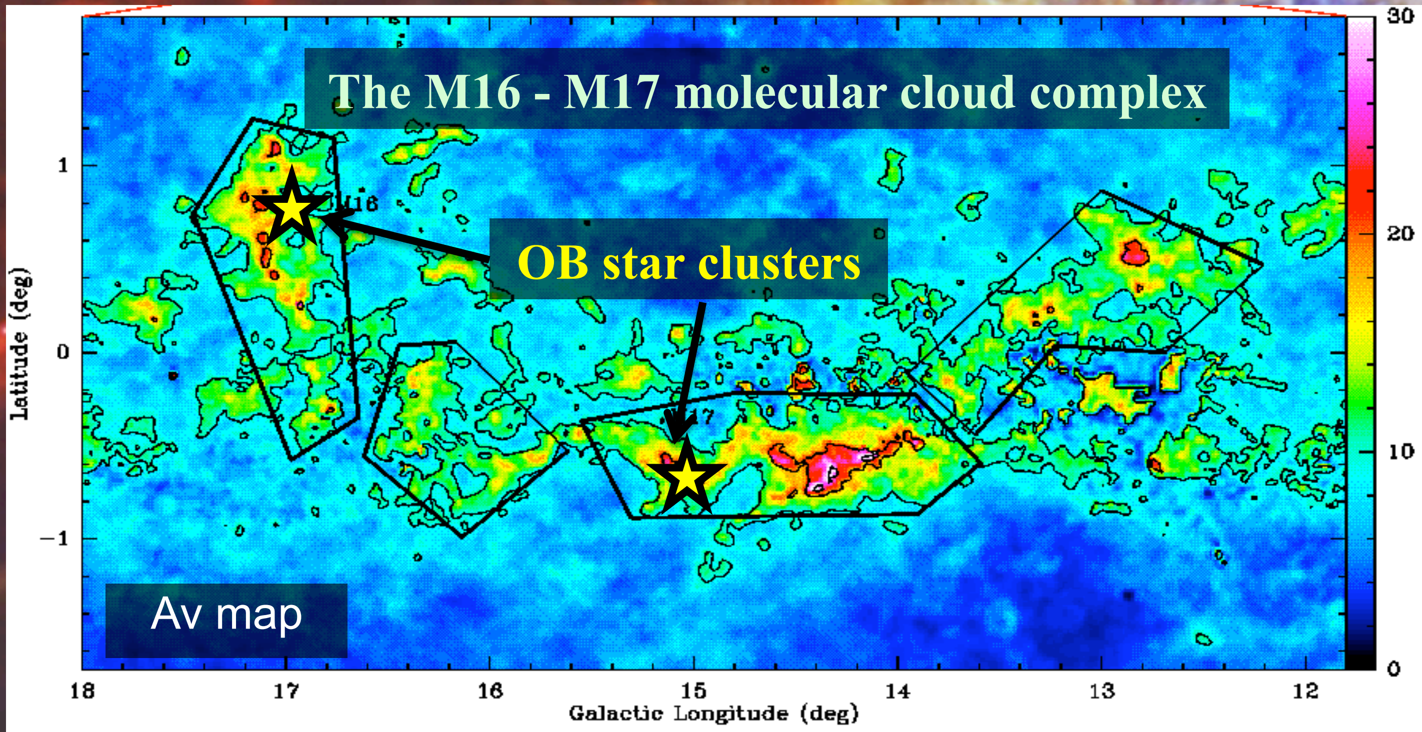
http://hobys-herschel.cea.fr

Frédérique Motte, Annie Zavagno, Sylvain Bontemps,

P. Didelon, M. Hennemann, T. Hill, V. Minier, Q. Nguyen-Luong, N. Schneider, F. Louvet, Ph. André, T. Csengeri, A. Men'shchikov, N. Peretto (AIM, Paris Saclay)

A. Abergel, L. D. Anderson, D. Arzoumanian, M. Attard, M. Benedettini, Z. Balog, J.-P. Baluteau, J.-Ph. Bernard, P. Cox, L. Deharveng, D. Elia, C. Fallscheer, J. Di Francesco, A.-M. di Giorgio, M. Griffin, P. Hargrave, M. Huang, J. Kirk, V. Könyves, S. Leeks, J. Z. Li, A. Marston, P. Martin, S. Molinari, G. Olofsson, P. Palmeirim, P. Persi, M. Pestalozzi, S. Pezzuto, D. Polychroni, M. Reid, A. Rivera, H. Roussel, D. Russeil, K. Rygl, S. Sadavoy, P. Saraceno, M. Sauvage, T. Sousbie, E. Schisano, B. Sibthorpe, L. Spinoglio, S. Stickler, L. Testi, D. Teyssier, R. Vavrek, D. Ward-Thompson, G. White, C. D. Wilson, A.Woodcraft

A complete imaging survey of cloud complexes forming OB stars at <3kpc



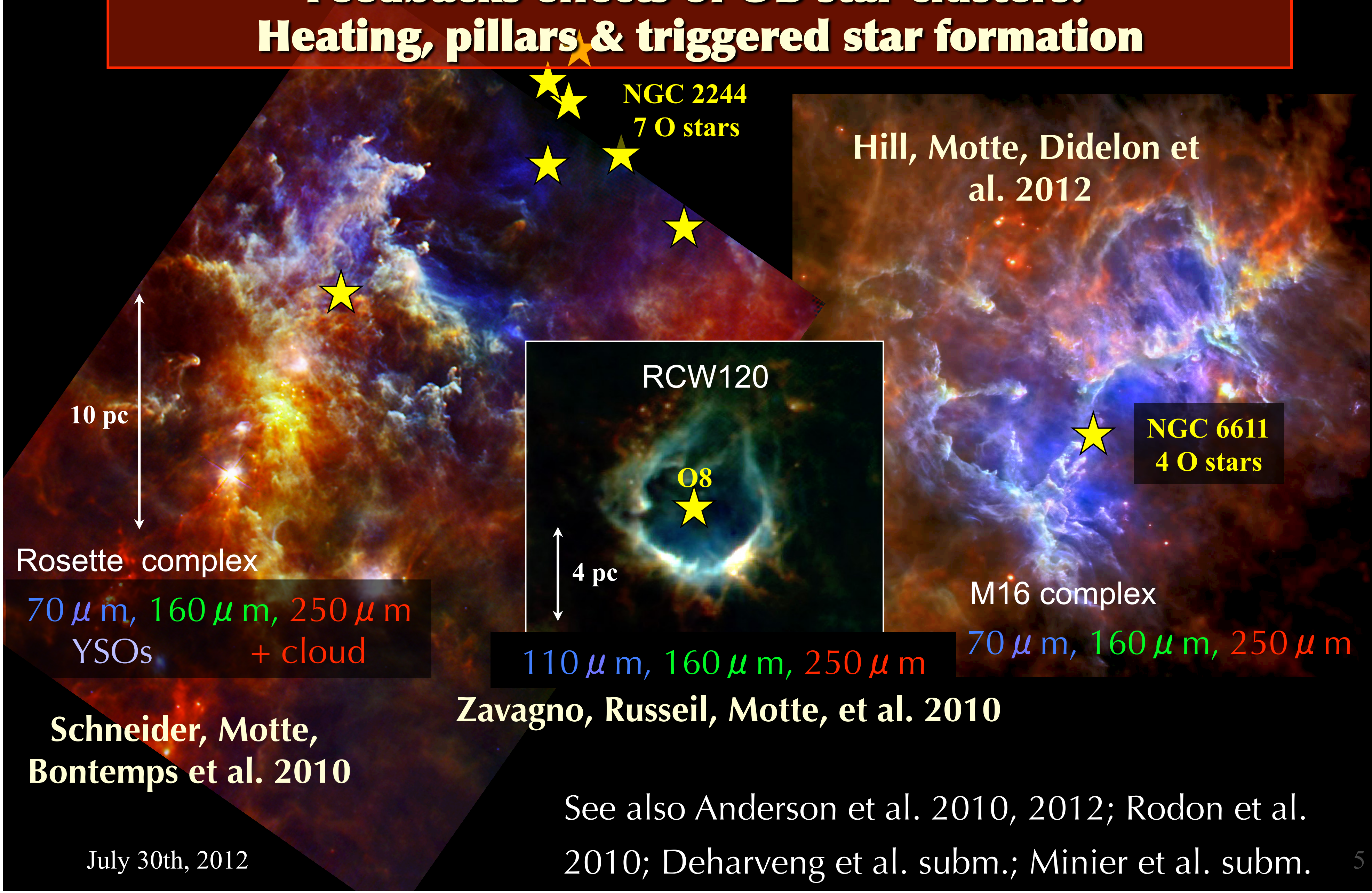
9 complexes:
10^5 - 10^6 $M_\odot$
50 - 100 pc
at <3 kpc

Associated with OB clusters.

⇒ enough statistics (~250 high-mass protostars expected) to study the precursors of stars up to 20 $M_\odot$.

⇒ Ideal to study feedback/triggering (cloud under the influence of OB star clusters).

Feedbacks effects of OB star clusters: Heating, pillars & triggered star formation

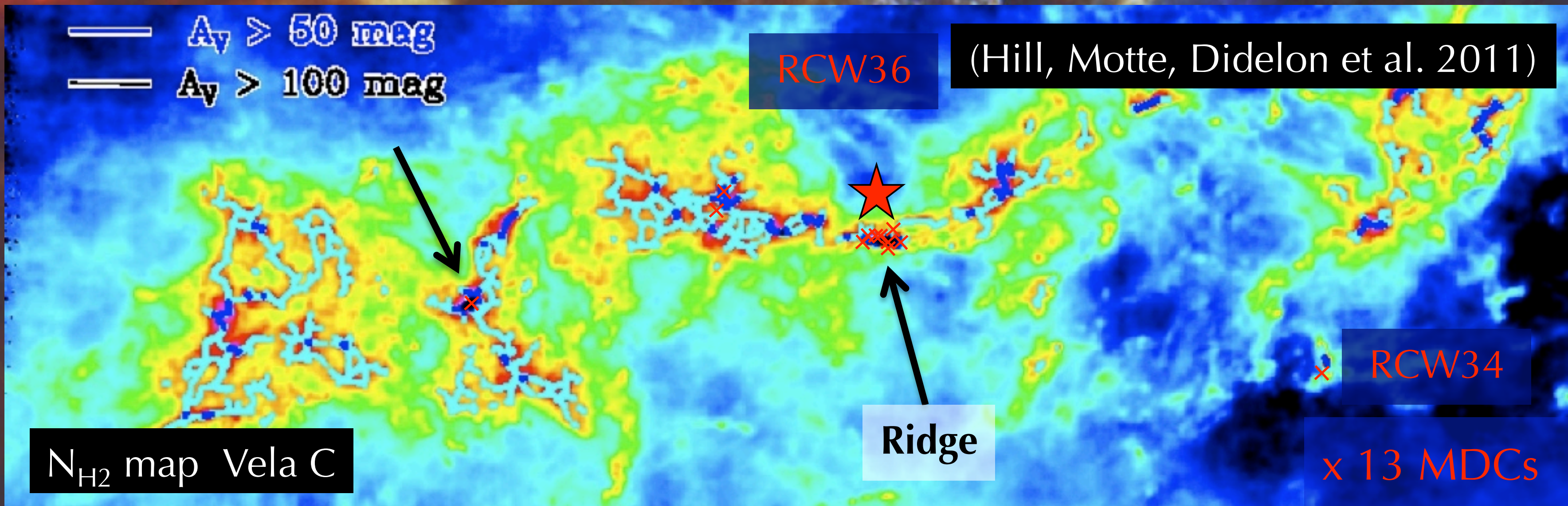


See also Anderson et al. 2010, 2012; Rodon et al. 2010; Deharveng et al. subm.; Minier et al. subm.

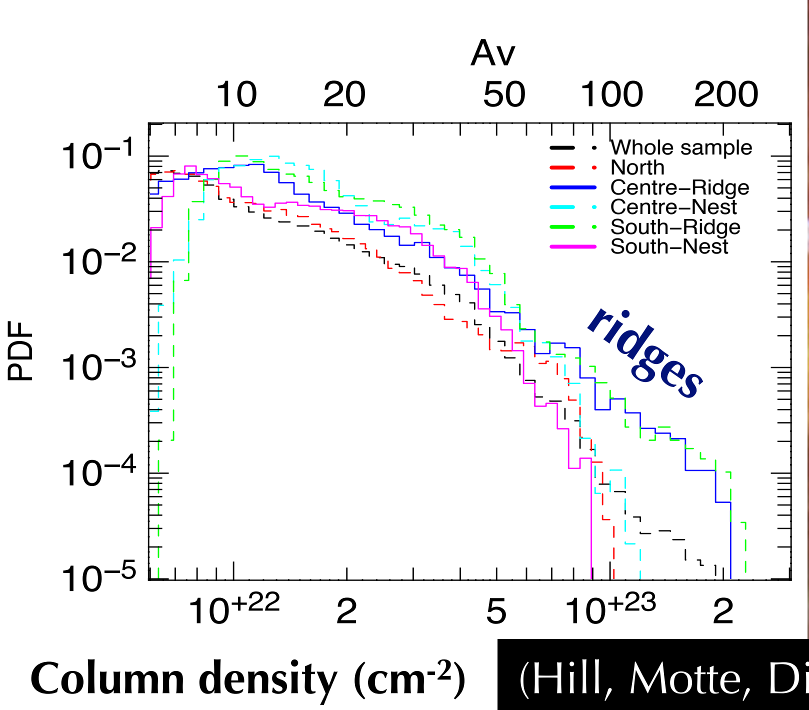
Cloud structure: disorganized networks of filaments versus single dominating ridges

- Dust temperature & column density images from Graybody fits (36″ resolution)
- Census of filaments with DisPerSE (Sousbie 2011) and MDCs (massive dense cores) with Getsources (Men'shchikov et al. 2012)

⇒ High-mass stars form preferentially in ridges, high-column density (Av > 100 mag), elongated cloud structures dominating their surrounding.



Distribution of mass in regions harboring ridges



(Hill, Motte, Didelon et al. 2011)

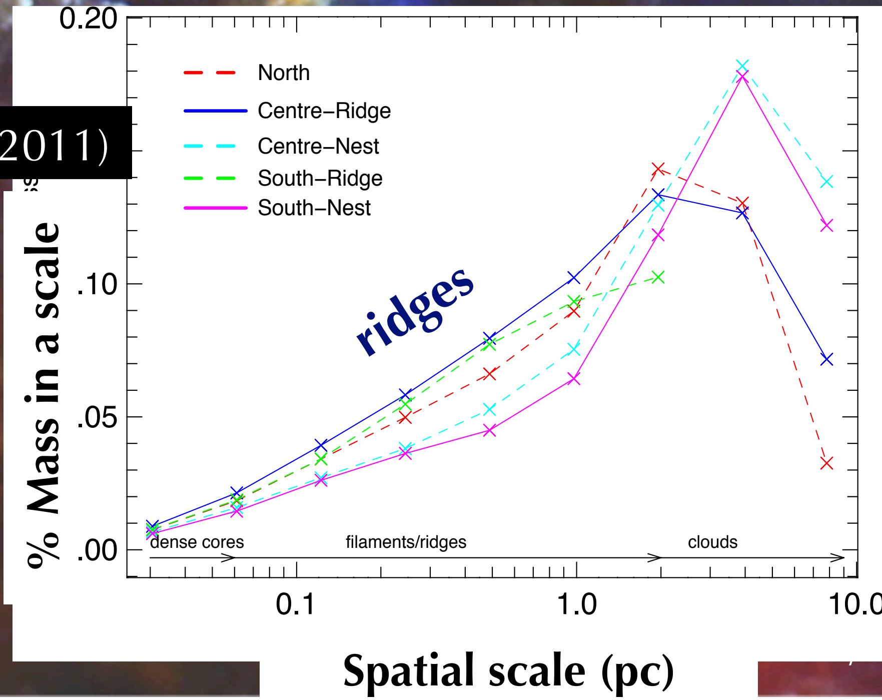
At high column density, Center-Ridge has a flatter PDF slope than South-Nest.

⇒ *may* suggest that gravity rather than turbulence is shaping its cloud (e.g. Klessen 2000)

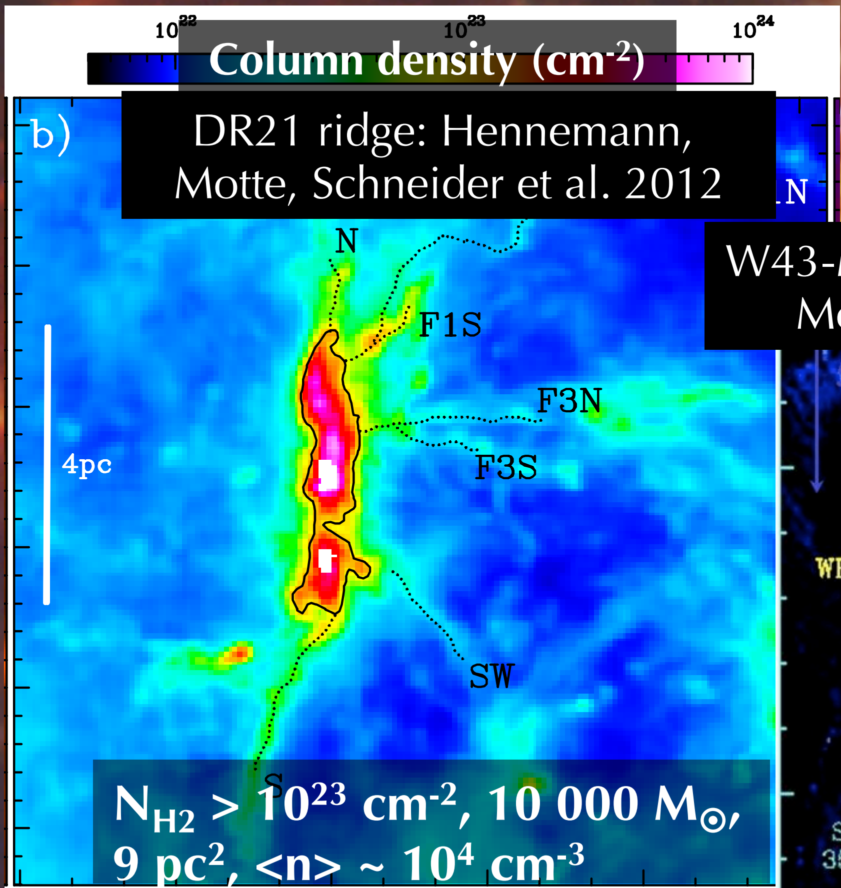
Like coherent structures created via constructive large-scale flows (Federrath et al. 2010).

More mass is concentrated in single ridges than in the lower-A_v filaments of nests.

⇒ The potential well of ridges is shaping their surrounding regions and/or vice-versa…

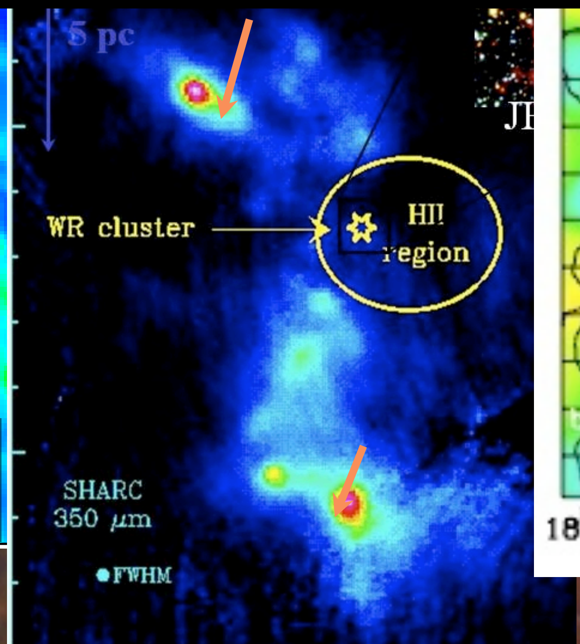


Ridges (5-10 pc², >100 A_v) are extreme IRDCs formed by dynamical scenarios such as filament merging or global infall

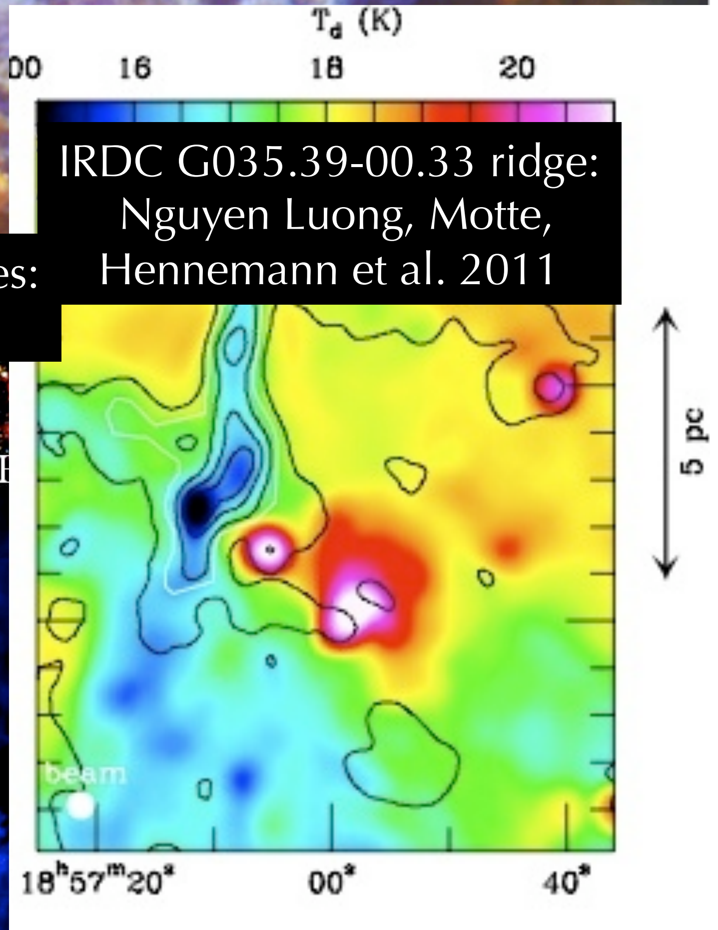


DR21 ridge: Hennemann, Motte, Schneider et al. 2012

$N_{H2} > 10^{23}$ cm^{-2}, 10 000 $M_\odot$, 9 pc², <n> ~ 10^4 cm^{-3}



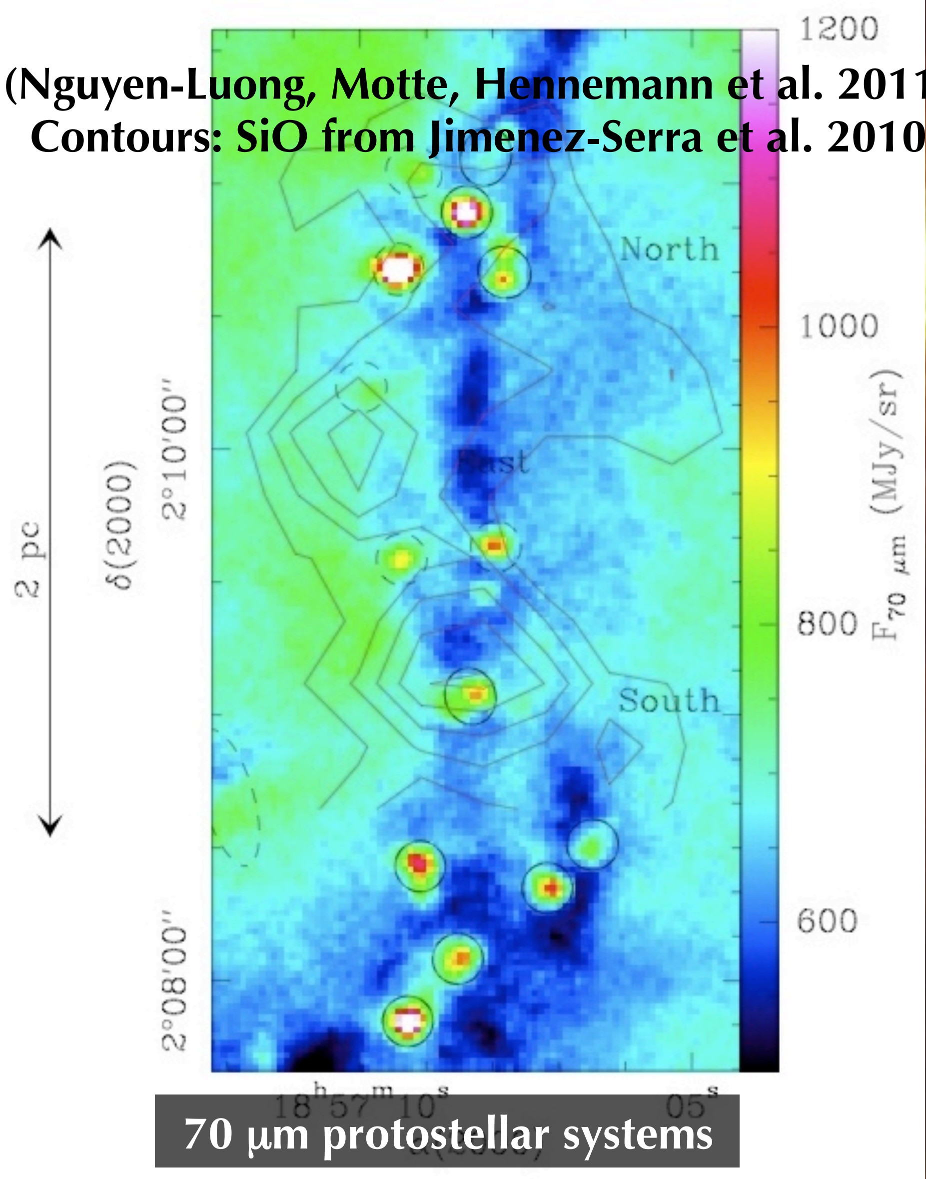
W43-MM1, MM2-MM3 ridges: Motte, Schilke, Lis 2003



IRDC G035.39-00.33 ridge: Nguyen Luong, Motte, Hennemann et al. 2011

See also Schneider et al. 2012; Nguyen et al in prep.

Mini-starburst cluster in the G035.39-00.33 ridge



- Herschel census of protostellar dense cores (Getsources extraction , SED fitting by graybody models):

⇒ 5 high-mass class 0 protostars or 20 protostars with 2 $M_\odot$ on the MS.

- Assumptions:

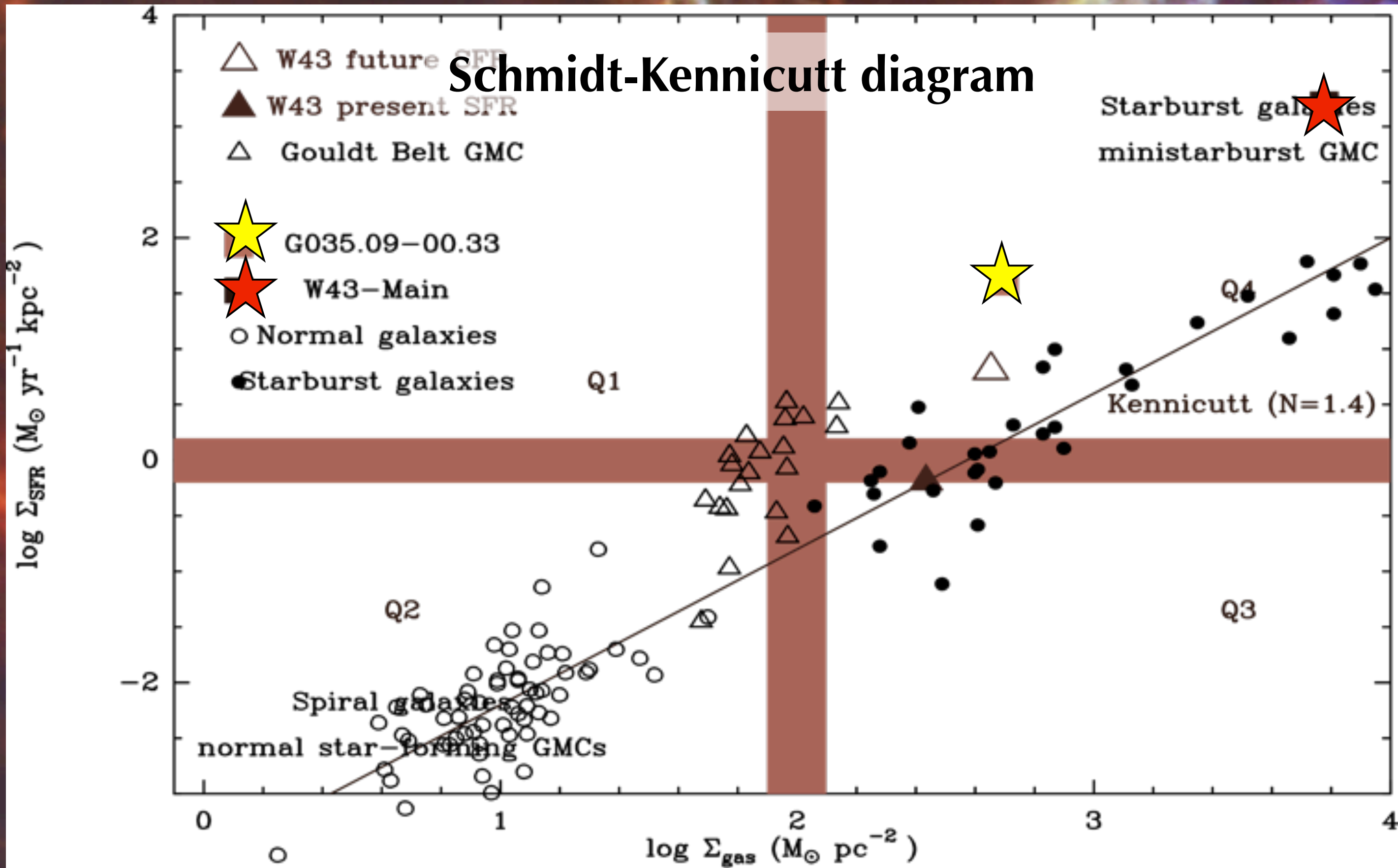
✓ **<u>Core-to-star mass efficiency</u>: 20-40% in 0.1 pc 10^6 cm^{-3} dense cores**

✓ **<u>Protostellar lifetime</u>: 10^5 yr of IR-quiet/Class0-like massive protostars**

✓ <u>Fast episode of cloud formation</u>: 1-3 **10^6 yr**

⇒ A mini-burst of SF (SFE ~20%, SFR~300 $M_\odot$/Myr, 40 $M_\odot$/yr/kpc^2 within 8 pc^2)

Definition of Galactic mini-starburst regions/ridges



Starburst quadrant:

$\Sigma_{SFR} > 1\ M_\odot/yr/kpc^2$

$\Sigma_{gas} > 100\ M_\odot/pc^2$

A mini-starburst region: a large amount of dense gas in a pc² area which is forming a cluster of high-mass stars.

(Motte et al. 2003; Nguyen Luong, Motte, Hennemann et al. 2011)

The first *Herschel* images of HOBYS revealed...

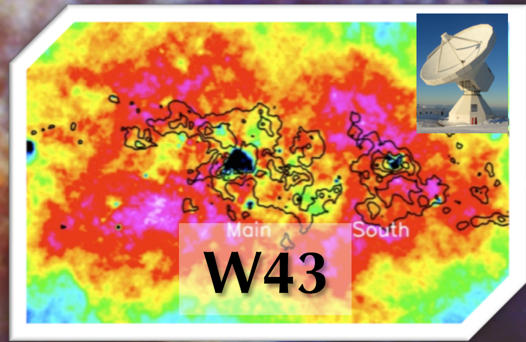
1. Feedback effects of OB star clusters on molecular clouds such as heating, pillars and triggered star formation.

2. Networks of filaments among which the "ridges" (well-ordered, high-N_{H2}, dominating filaments) are forming high-mass stars/mini-starburst.

3. Precursors of high-mass stars : protoOB-stars, massive starless cores and their associated ministarburst clusters. ***see Martin Hennemann's talk!***

(Motte et al. 2010; Hennemann et al. 2010, in prep.; Giannini et al. 2011; Zavagno et al. 2010 ; Nguyen Luong et al. 2011)

Linking the formation of molecular clouds and high-mass stars: the W43 case study



Frédérique Motte & Quang Nguyen Luong
(AIM, Paris Saclay) (CITA, Toronto)
With: P. Schilke, P. Carlhoff, F. Louvet, S. Bontemps

And observers from the W43/ATLASGAL consortium:
F. Schuller, N. Schneider, H. Beuther, T. Csengeri, K. Menten, R. Simon, C. Kramer, F. Wyrowski, Th. Henning, L. Bronfman, M. Walmsley, A. Zavagno, …

With modelers of molecular cloud formation:
F. Heitsch, P. Hennebelle, E. Vazquez-Semadeni, R. Banerjee, …

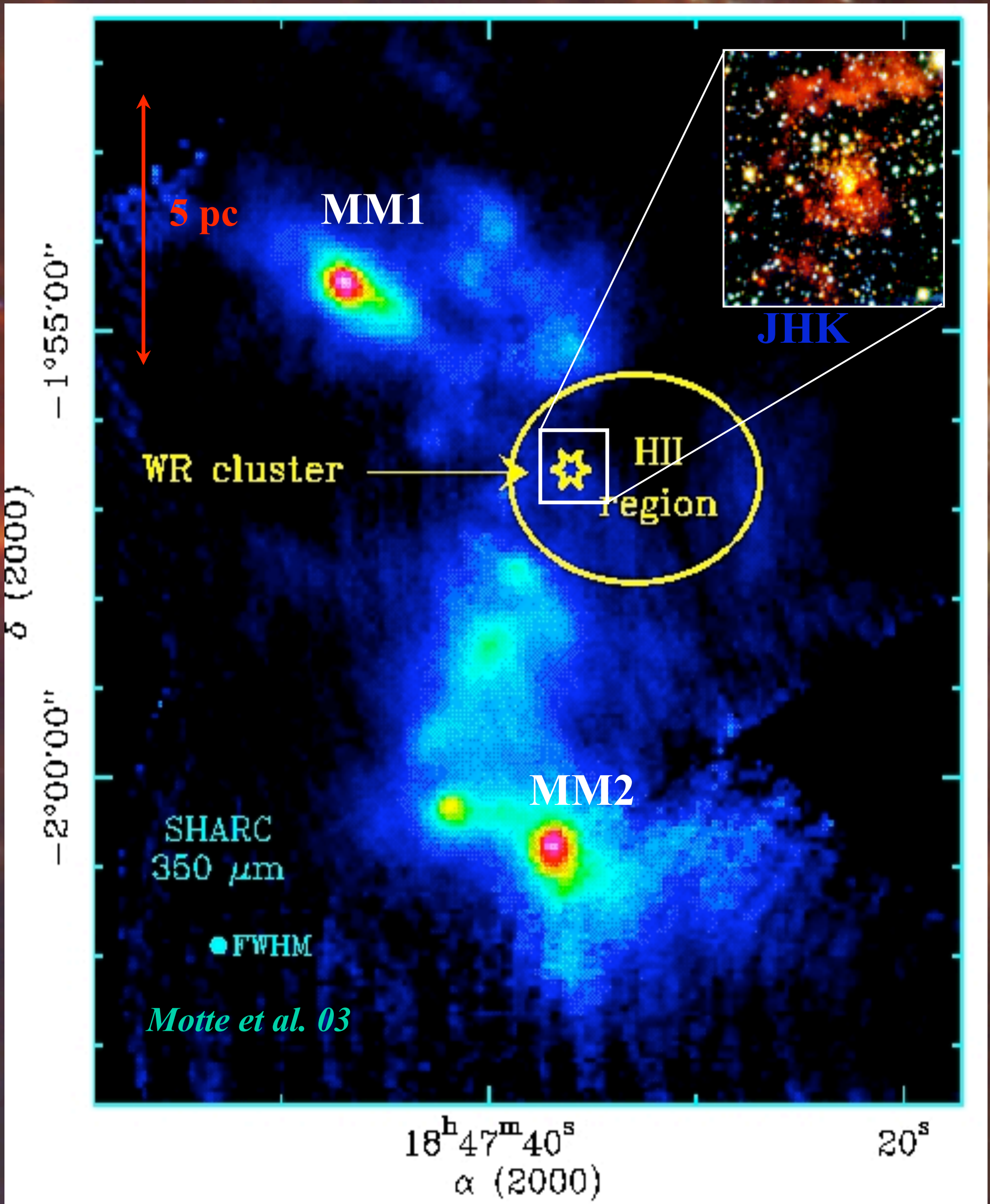
Linking the formation of molecular clouds and high-mass stars: the W43 case study

1. Definition of a new molecular cloud and star-forming complex: W43 (around the W43-Main, clouds with a velocity coherence over 140 pc)

2. Extreme characteristics (total mass, velocity dispersion, mass concentration, SFR, …) of W43 and its location at the tip of the Galactic bar

3. Imprints in W43 of molecular cloud formation from HI gas and first signatures for converging flows (atomic envelope, global collapse, low-velocity shocks, …)

The mini-starburst cloud region W43-main



Two episodes of efficient star formation

1. A OB/WR stellar cluster powering a giant H II region:

3 10^6 $L_\odot$, 10^{51} photon/s

5 pc, A_v = 30 mag *(Blum et al. 1999)*

2. An active star-forming cloud:

- 20 pc, 10^6 $M_\odot$
- more than 50 high-mass protostars

⇒ SFE ~ 25% /10^6 yr

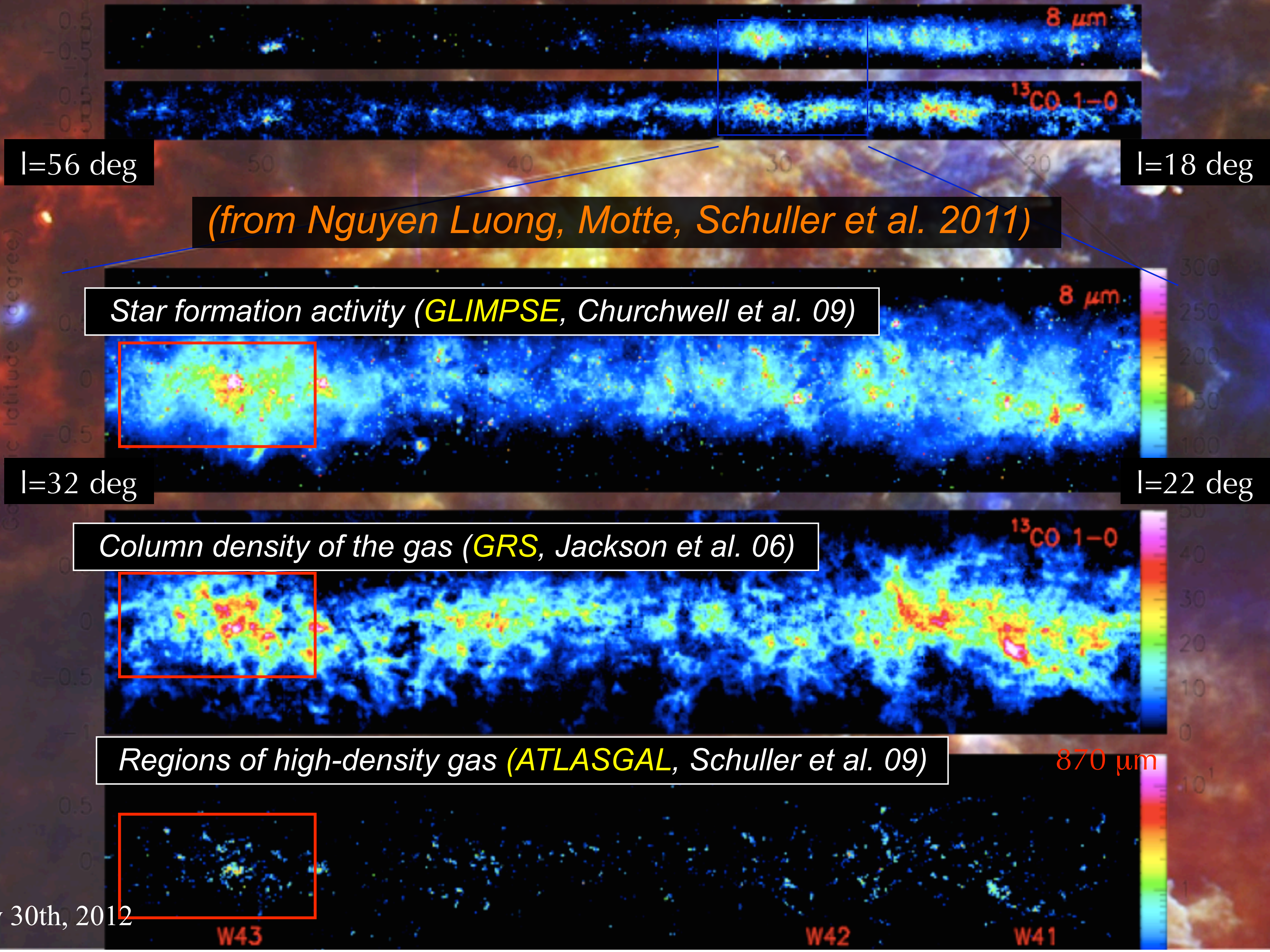
⇒ SFR ~1500 $M_\odot$ Myr^{-1} over 60 pc^2

SFR density ~25 $M_\odot$ yr^{-1} pc^{-2}

(Motte, Schilke, Lis 2003)

- global collapse of the MM1 and MM2 ridges *(Motte et al. 2005)*

W43, an extreme molecular complex of the Milky Way

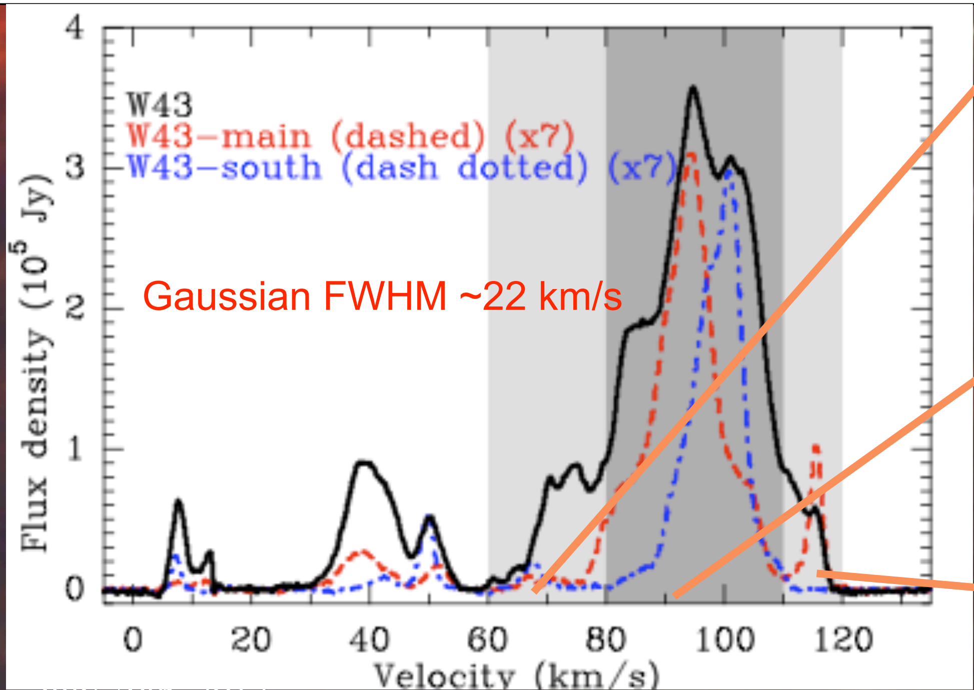


W43, a coherent molecular complex in space/vel

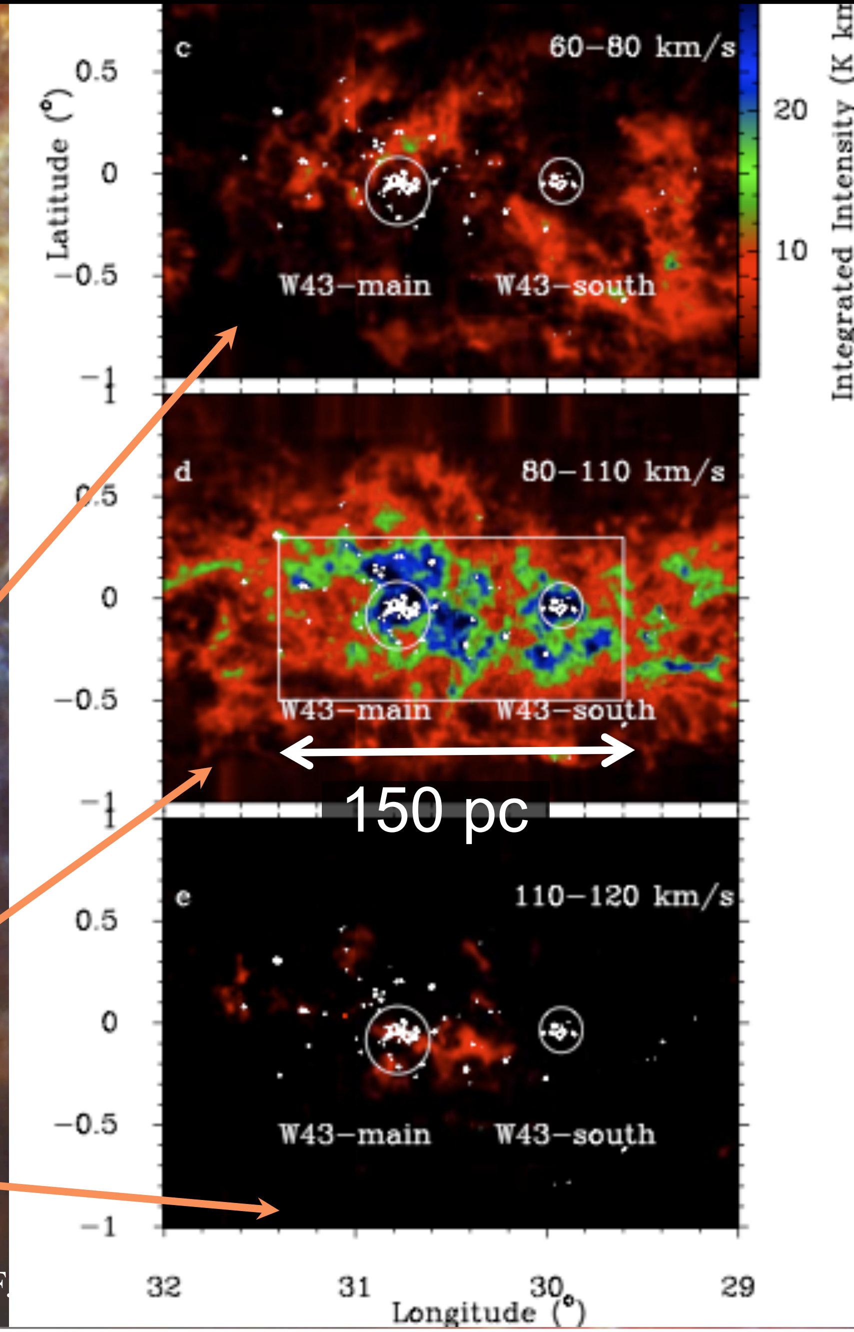
- Main velocity range: 80-110 km/s
- Line wings: 60-80 km/s (partly associated) and 110-120 km/s (most probably associated

(Nguyen Luong et al. 2011)

^{13}CO 1-0 line averaged over the complete W43 complex



^{13}CO 1-0 image integrated over 3 velocity ranges



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Comparison with other molecular and star-forming clouds/complexes

With its size (~140 pc), mass (7.1 x 10^6 $M_\odot$), and velocity dispersion (*FWHM* ~ 22.3 km/s), W43 defines as a GMC Association (GMA quoted in extragalactic studies) or molecular complex.

Large amount of gas: at least 1 order of magnitude larger than nearby Gould belt molecular complexes

Its concentration of cloud material in dense structures and its star formation rate are exceptional for such large amount of gas. *(Nguyen-Luong et al. 2011)*

	Distance (kpc)	Diameter (pc) from ^{13}CO	Gas mass ($M_\odot$) From ^{12}CO	Concentration of mass into cold dense <5 pc clumps	SFR present-future ($M_\odot$ yr^{-1})
W43	6	140	7 x 10^6	12%	0.01-0.1
Cygnus X	1.7	160	5 x 10^6	1%	0.003-0.07
CMZ	8.5	350	3 x 10^8	1%	
Orion	0.5	50	5 x 10^5		0.0004-0.001

Star formation activity in W43

- Past Star Formation Rate (SFR):

from the 8 μm image (GLIMPSE, Churchwell et al. 2009) with SFR equations generally used for extragalactic studies

$$\Rightarrow SFR_{8\,\mu m} = \frac{\nu L_\nu[8\mu m]}{1.57 \times 10^9\, L_\odot} \sim 0.01\, M_\odot\, yr^{-1} \times \left(\frac{d}{6\,kpc}\right)^2$$

(Wu et al. 2005, Kennicutt 1998)

x10

- Future SFR:

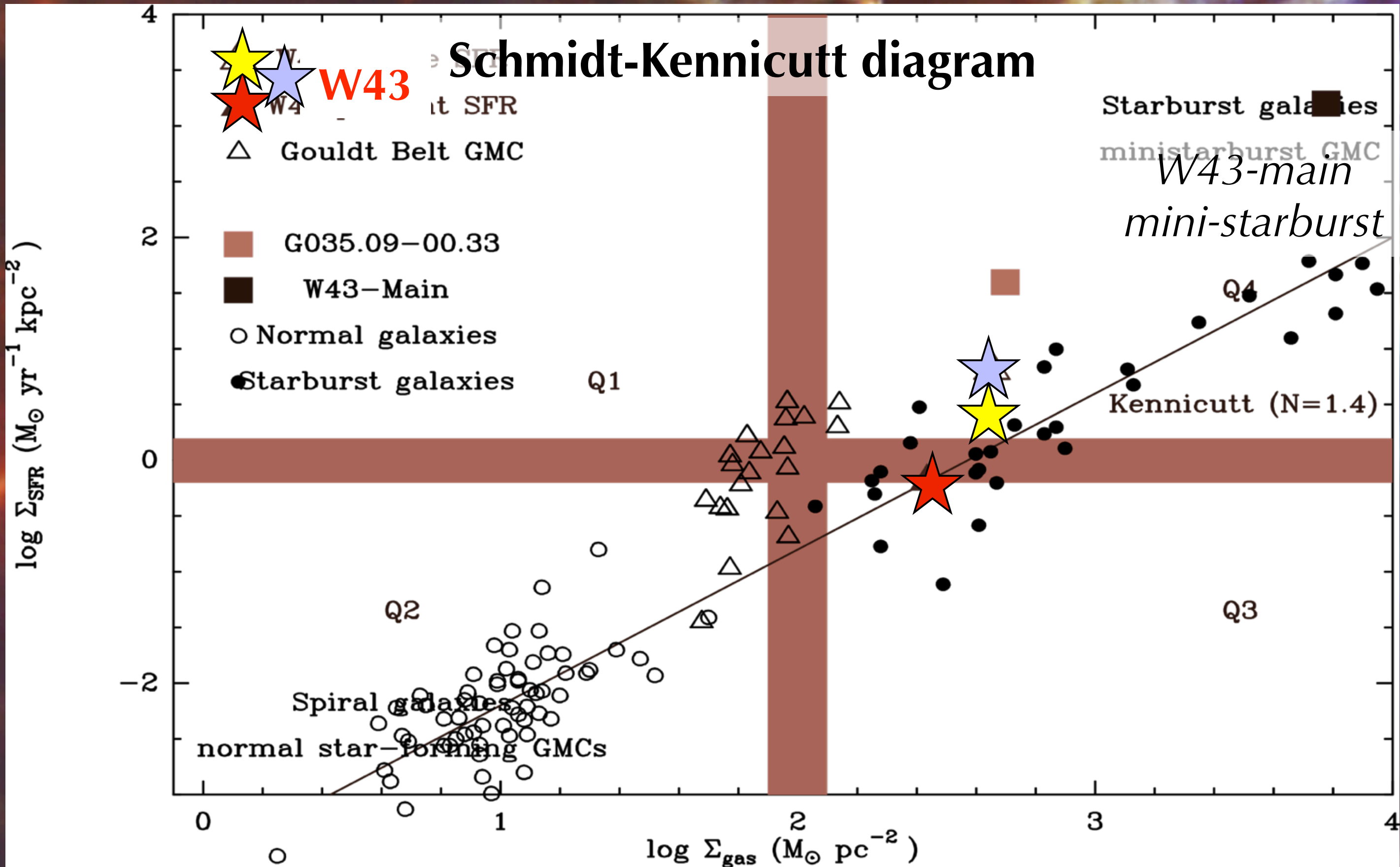
from the total molecular mass of the W43 cloud and assuming typical star formation efficiency and cloud lifetimes (1-3 x 10^6 yr)

$$\Rightarrow SFR_{CO} = 0.05 - 0.14\, M_\odot\, yr^{-1} \times \left(\frac{M_{total}}{7.1 \times 10^6\, M_\odot}\right) \times \left(\frac{SFE}{2\%}\right)$$

Are we witnessing the formation of new starburst cluster? *(Nguyen Luong et al. 2011)*

- Past and Future SFRs can be compared with the Present SFR derived from the YSOs population found with *Herschel (Nguyen Luong et al. in prep.)*

History of the star formation (SFR) in W43



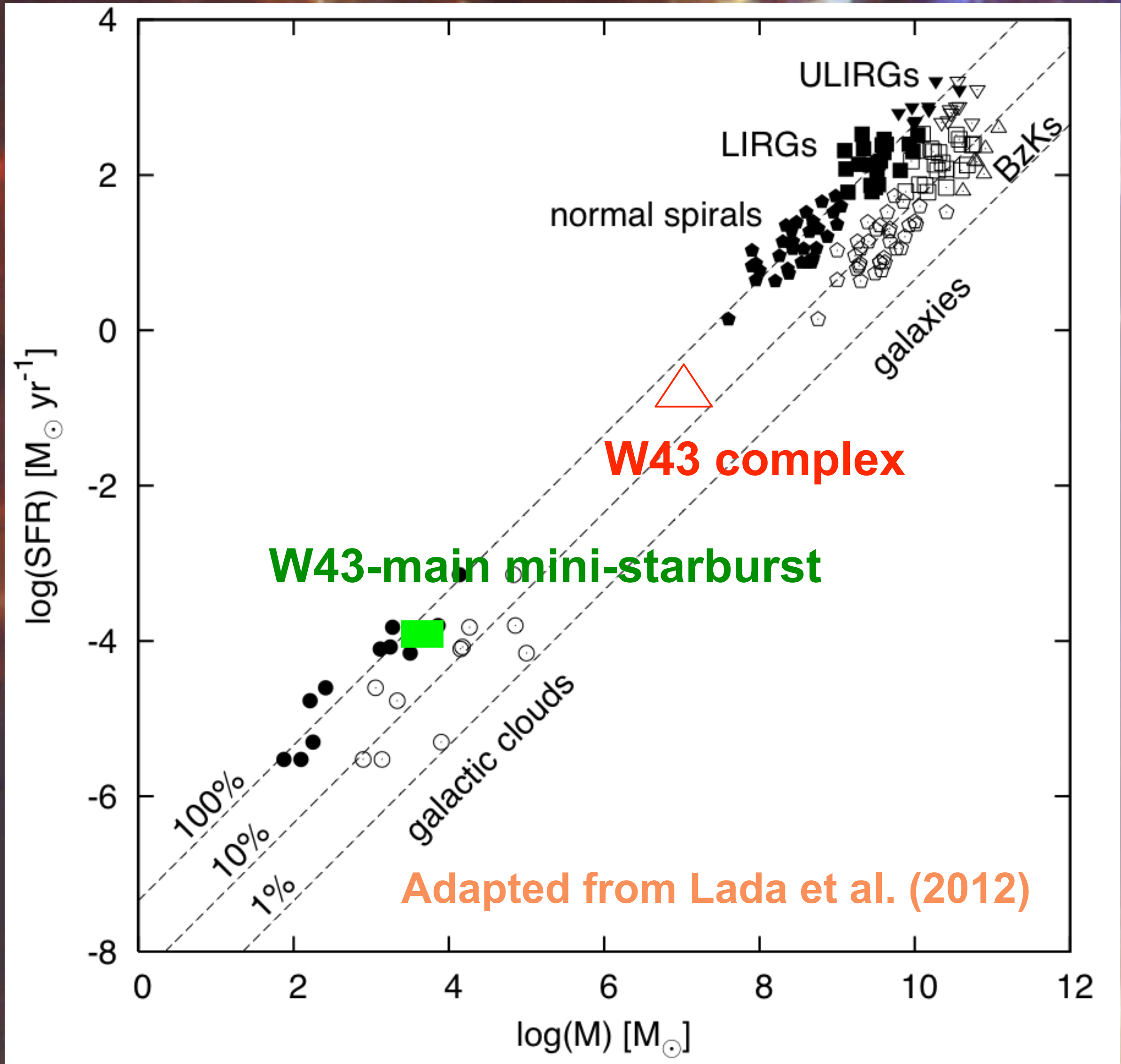
Spitzer mid-IR flux
→ Past SFR ★

Herschel (Hi-GAL) sample of protostars
→ Present SFR ★

Total mass of the gas
→ Future SFR ★

Figure adapted from Nguyen Luong, Motte, Schuller et al. (2011b), Nguyen Luong et al. in (prep.). **But huge uncertainties for all these SFRs! crude asumptions, rough extrapolations, often indirect measurements…**

W43, bridging galaxies to Gould Belt clouds



W43 distance and location in our Galaxy

Kinematic distance of W43:

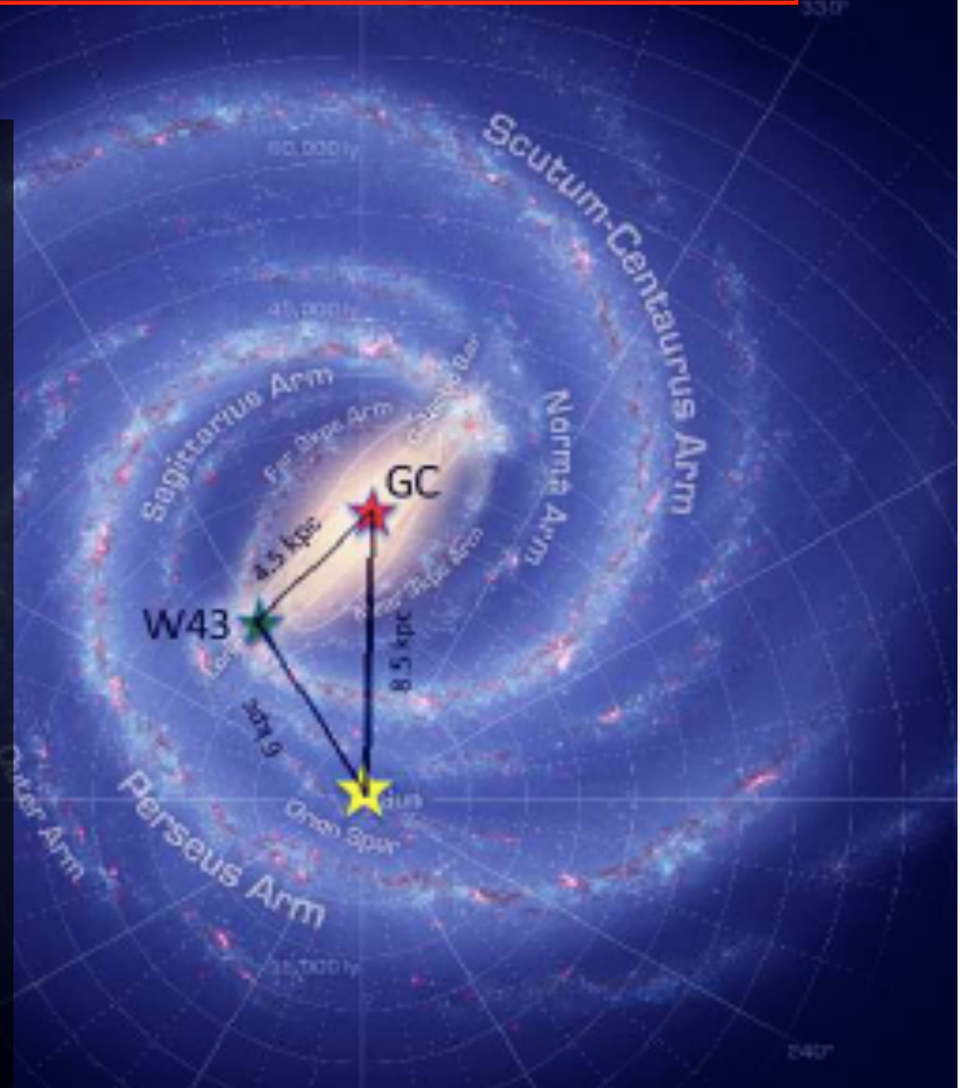
$<V_{LSR}> = 95.9$ km/s @ $l = 30.5^{o}$

=> $d_{near} = 5.9$ kpc, $d_{far} = 8.7$ kpc

Given its peculiar characteristics

(large mass, exceptionnal concentration, large velocity dispersion, high star formation rate),

W43 is most probably at the meeting point of the Scutum-Centaurus arm and the Bar and thus at the tip of the Bar ~6 kpc from our Sun. *(Nguyen-Luong et al. 2011)*



Adapted from Churchwell et al. (2009)

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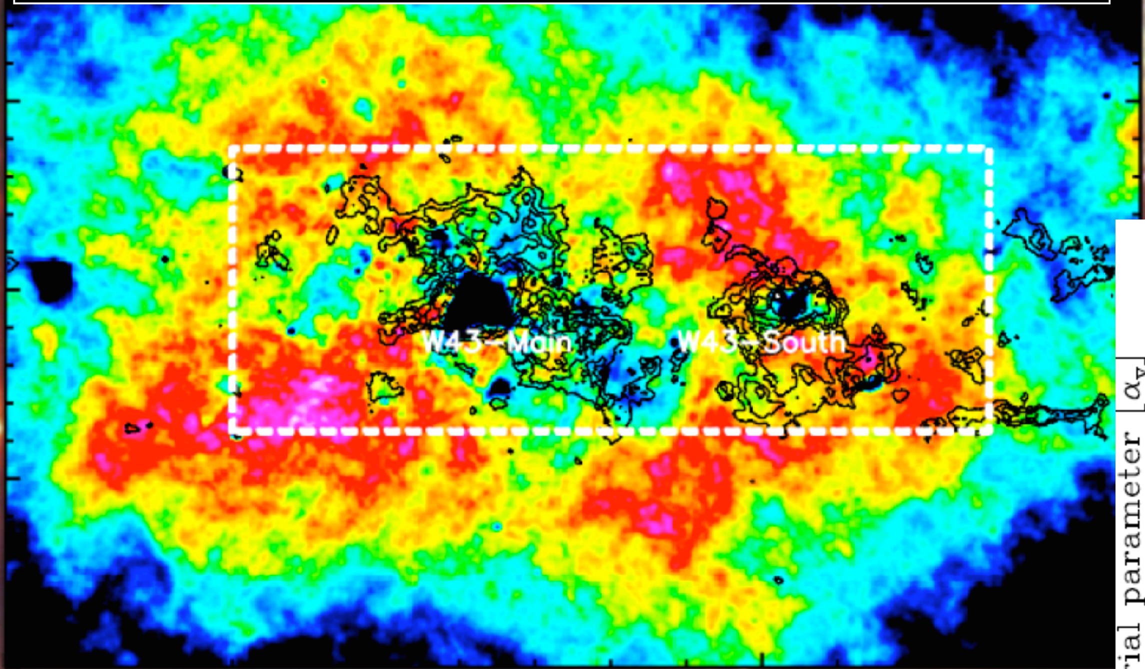
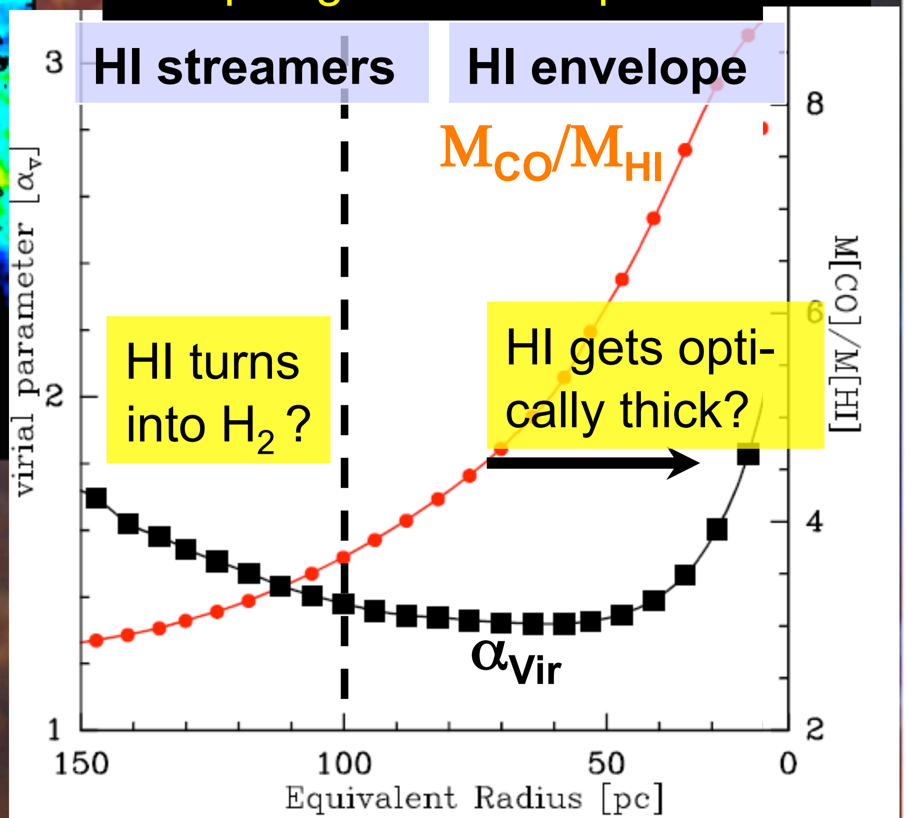
The W43 complex formed out of HI gas

W43: HI from VPS (color) & ^{13}CO 1-0 from GRS (contours)



Preliminary analysis: HI gas is turned into H_2 gas @ 150-70 pc. The molecular cloud complex is close to Virial equilibrium or collapsing on 20-200 pc scales.



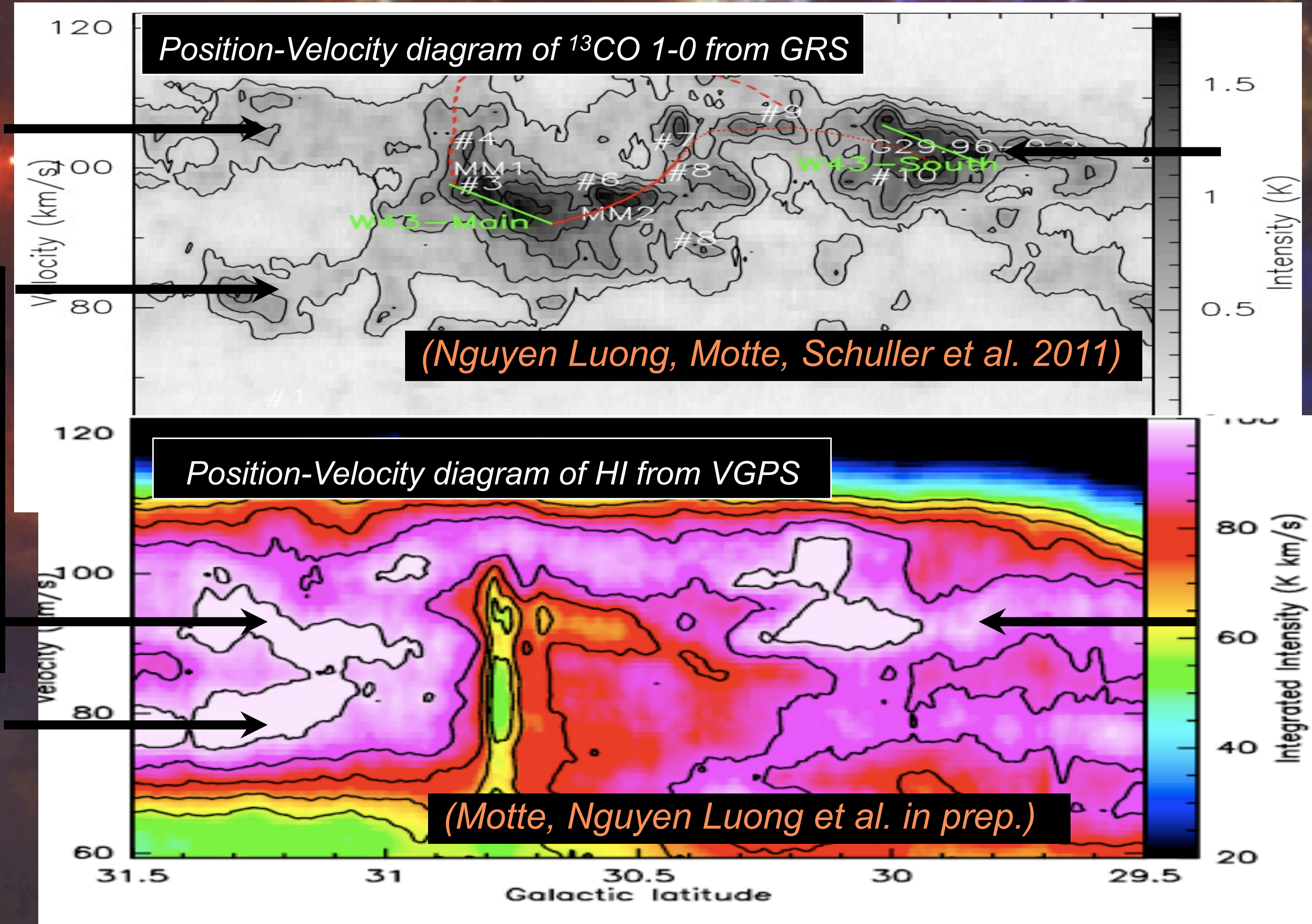
An HI envelope (200 pc) surrounds the molecular complex (150 pc).

(Nguyen Luong, Motte, Schuller et al. 2011)

(Motte, Nguyen Luong et al. in prep.)

Identifying HI flows around W43

Do HI flows forming CO reflect initial colliding flows?



Origin of molecular clouds and star formation in W43 - a large IRAM program

by F. Motte, P. Schilke, Q. Nguyen Luong P. Carlhoff, et al.
152 hours with HERA/EMIR at the IRAM 30m

Target: W43 is the closest molecular complex of the Galactic Bar.

Goal: Build up a complete database for W43 to test the numerical simulations of converging flows (e.g. Heitsch & Hartmann 2008; Banerjee et al. 2009; Vazquez-Semadeni et al. 2011).

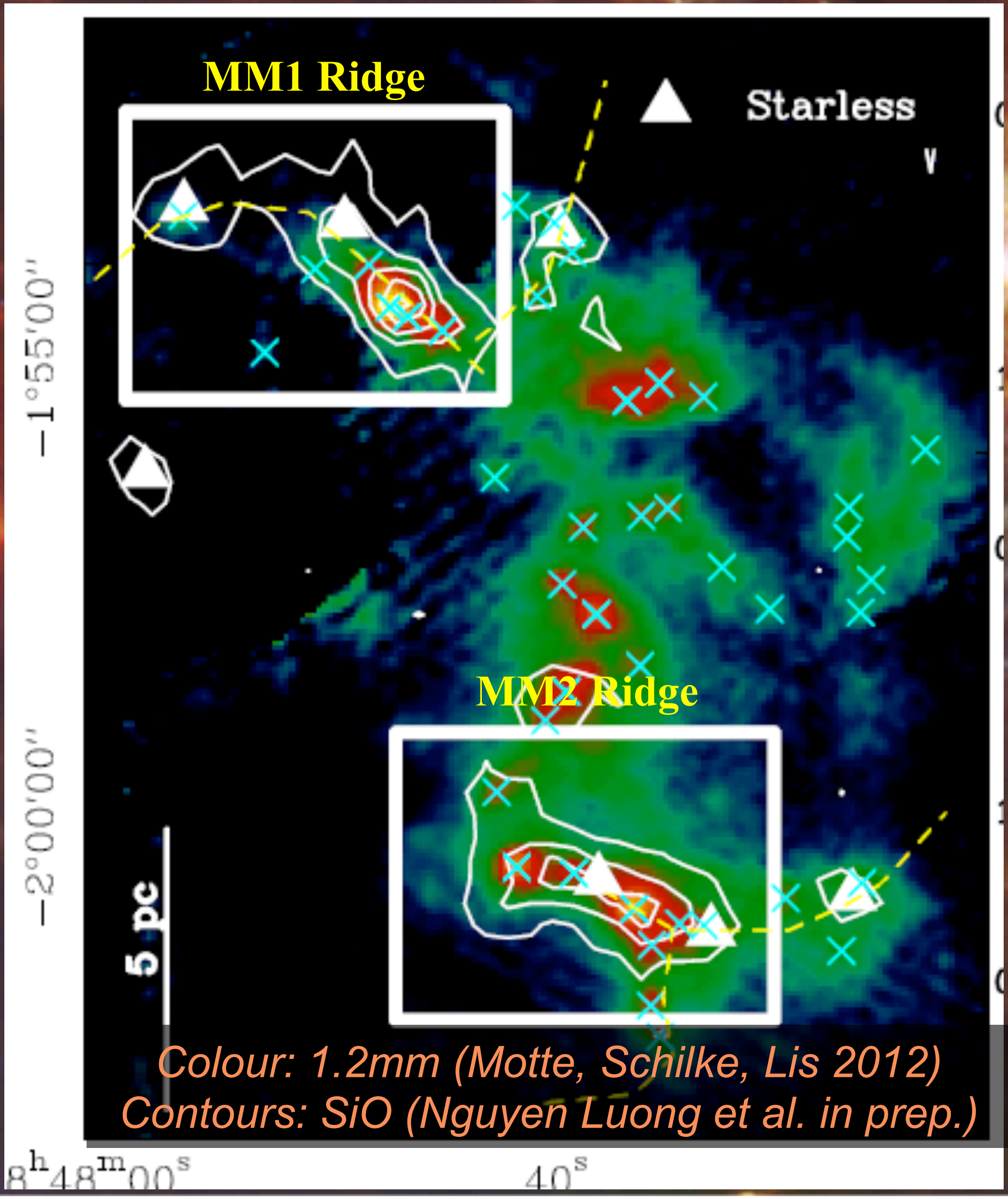
Imagings: *(Carlhoff et al. in prep.; Nguyen Luong et al. in prep.)*

- of the entire complex with HERA in ^{13}CO 2-1 & $C^{18}O$ 2-1

- of dense regions with EMIR in HCO^{+} 3-2 & $H^{13}CO^{+}$ 2-1, SiO 2-1...

First results: the densest filaments/ridges are undergoing supersonic global infall (~2 km s^{-1} over 5 pc) and display low-velocity SiO shocks.

Extended SiO emission not associated with protostars



Colour: 1.2mm (Motte, Schilke, Lis 2012)
Contours: SiO (Nguyen Luong et al. in prep.)

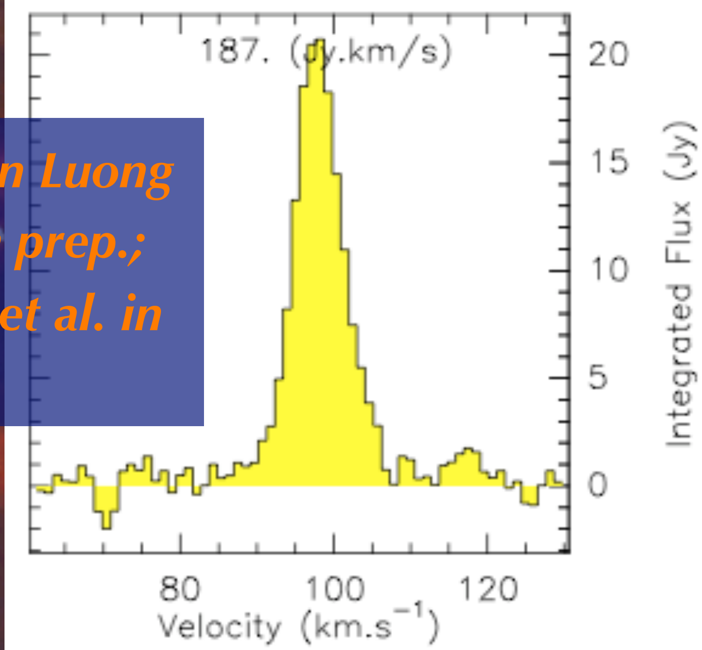
5 pc

Colour: 70 μm (Beuther et al. 2012)
Contours: SiO (Nguyen Luong et al. in prep.)

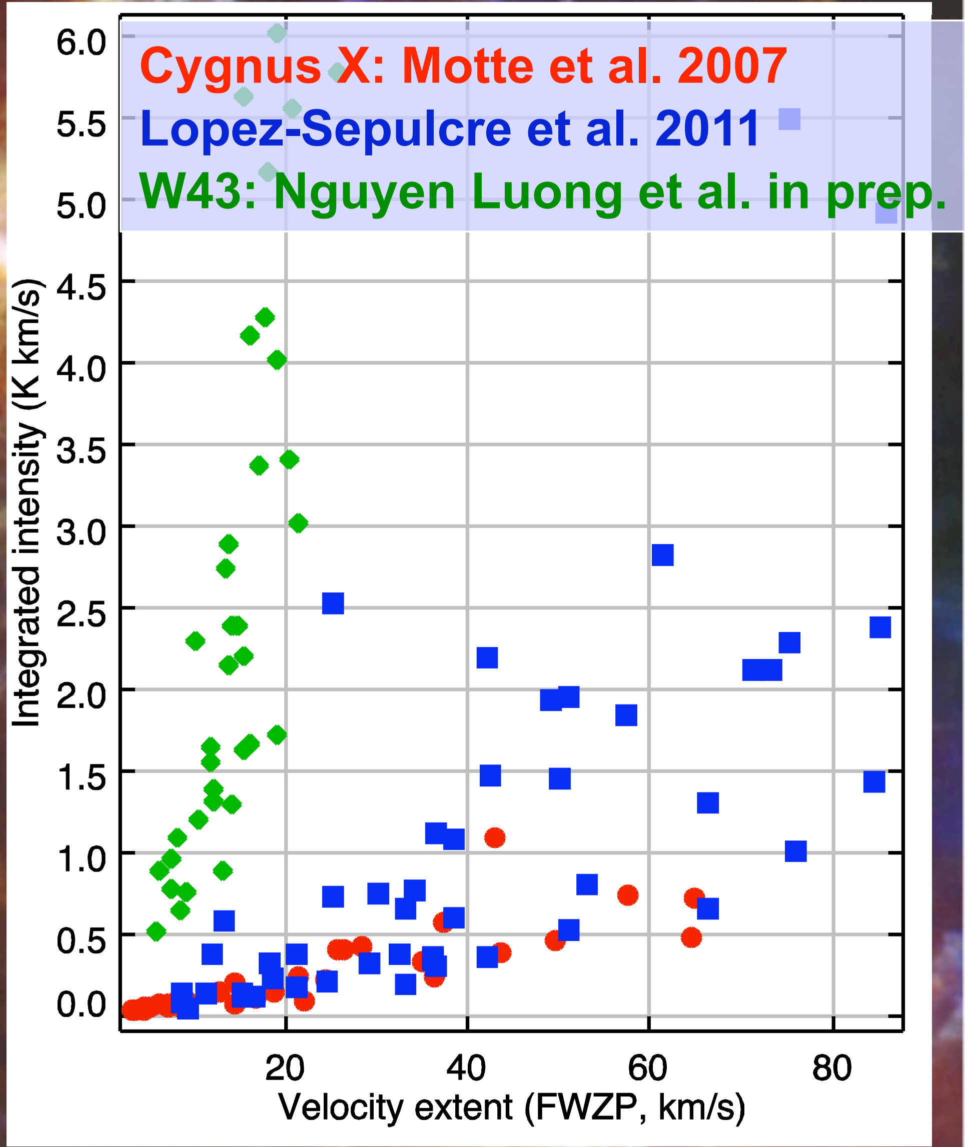
SiO 2-1: bright line and emission extended over ~5 pc dominating filaments /ridges.

Clearly detected at position far from protostars: 70 μm from. EPOS KP or 3mm IRAM PdBI cores

SiO, a signature of low-velocity shock flow?



(Nguyen Luong et al. in prep.; Louvet et al. in prep.)



In W43, SiO lines are at rest, with no clear outflow wings => shocks from streamers/converging flows shears?

Their integrated intensity are among the largest (See also Motte et al. 2007; Jimenez-Serra et al. 2010)

Summary

With HOBYS, we have: (see also Martin Hennemann's talk)

1. Shown feedback effects of OB star clusters on the clouds.
2. Discovered ridges: dominating filaments inside which high-mass stars preferentially form.
3. Measured SF rates and shown they are high in ridges/mini-starbursts.

In the W43 case-study, we have:

1. Defined of a new molecular cloud and star-forming complex.
2. Interpreted its extreme characteristics as due to its location at the tip of the Galactic bar.
3. Revealed first imprints of molecular cloud formation from HI gas through converging flows.

The HOBYS and W43 surveys are two more steps towards understanding Galactic-scale star formation. Their results points towards linking highly-dynamical molecular cloud formation to intense star formation activity.