HOBYS and W43, two more steps toward 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-HERO IRAM 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.

- 130 pc at d = 5.5 kpc
- $M_{cloud} = 8\ 10^6\ M_\odot$
- Forming up to 50-100 $M_\odot$ stars
- HI, CO, IRAM, *Herschel*, *Spitzer*, …

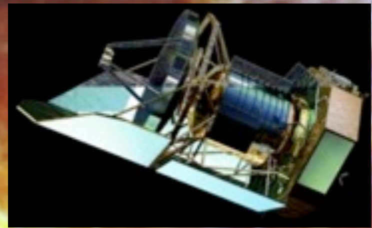
Main open questions:

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

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

Mini-starburst ridges and "instantaneous" SFR in HOBYS, the *Herschel* imaging survey of OB Young Stellar objects

http://hobys-herschel.cea.fr



SPIRE SAG3

PACS

esa

HOBYS

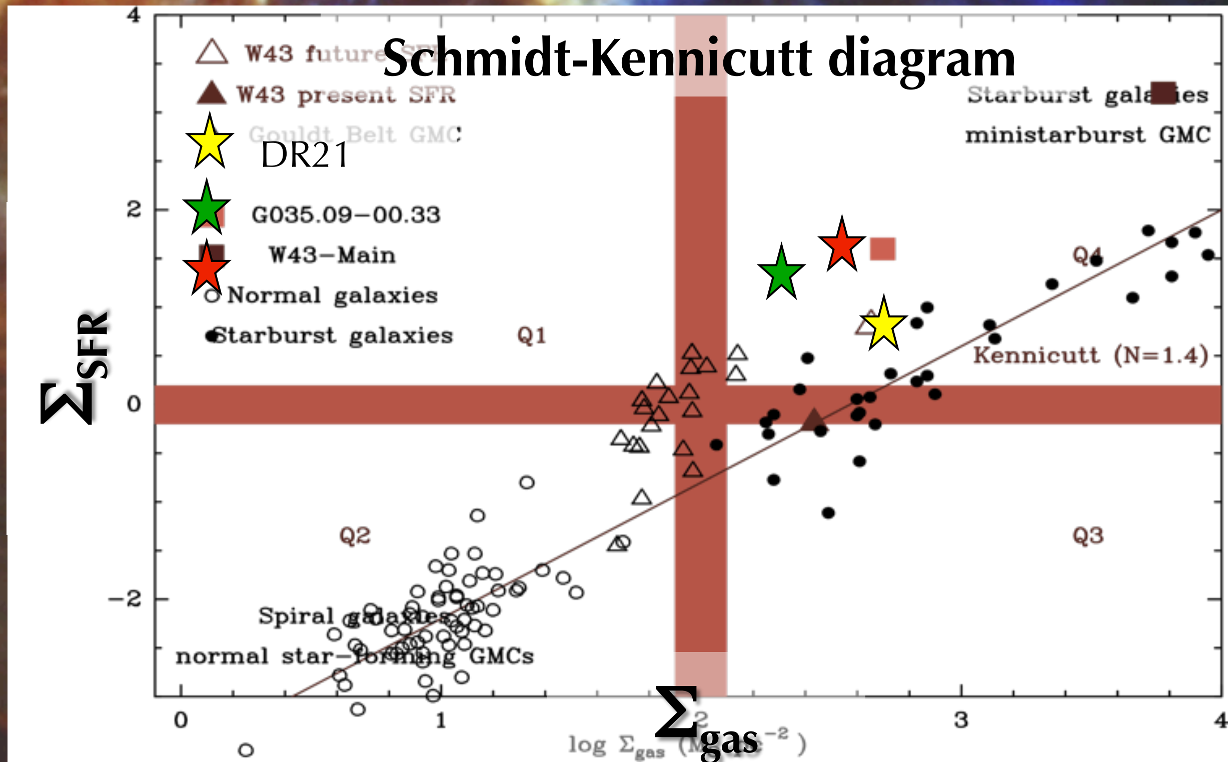
Coordinated by Frédérique Motte (AIM Paris-Saclay), Annie Zavagno, and Sylvain Bontemps

- 50 researchers from 10 institutes
- Management team: P. André, J. di Francesco, F. Motte, S. Pezzuto, D. Ward-Thompson

- Special credit to: S. Bontemps, P. Didelon, A. Gusdorf, M. Hennemann, T. Hill, F. Louvet, A. Men'shchikov, V. Minier, Q. Nguyen-Luong, N. Schneider

Mini-starburst ridges and "instantaneous" SFR in HOBYS, the *Herschel* imaging survey of OB Young Stellar objects

1. HOBYS specificity
2. Cloud structure study, ridge definition
3. Census of young stellar objects, SFR estimates
4. Future HOBYS work and perspectives

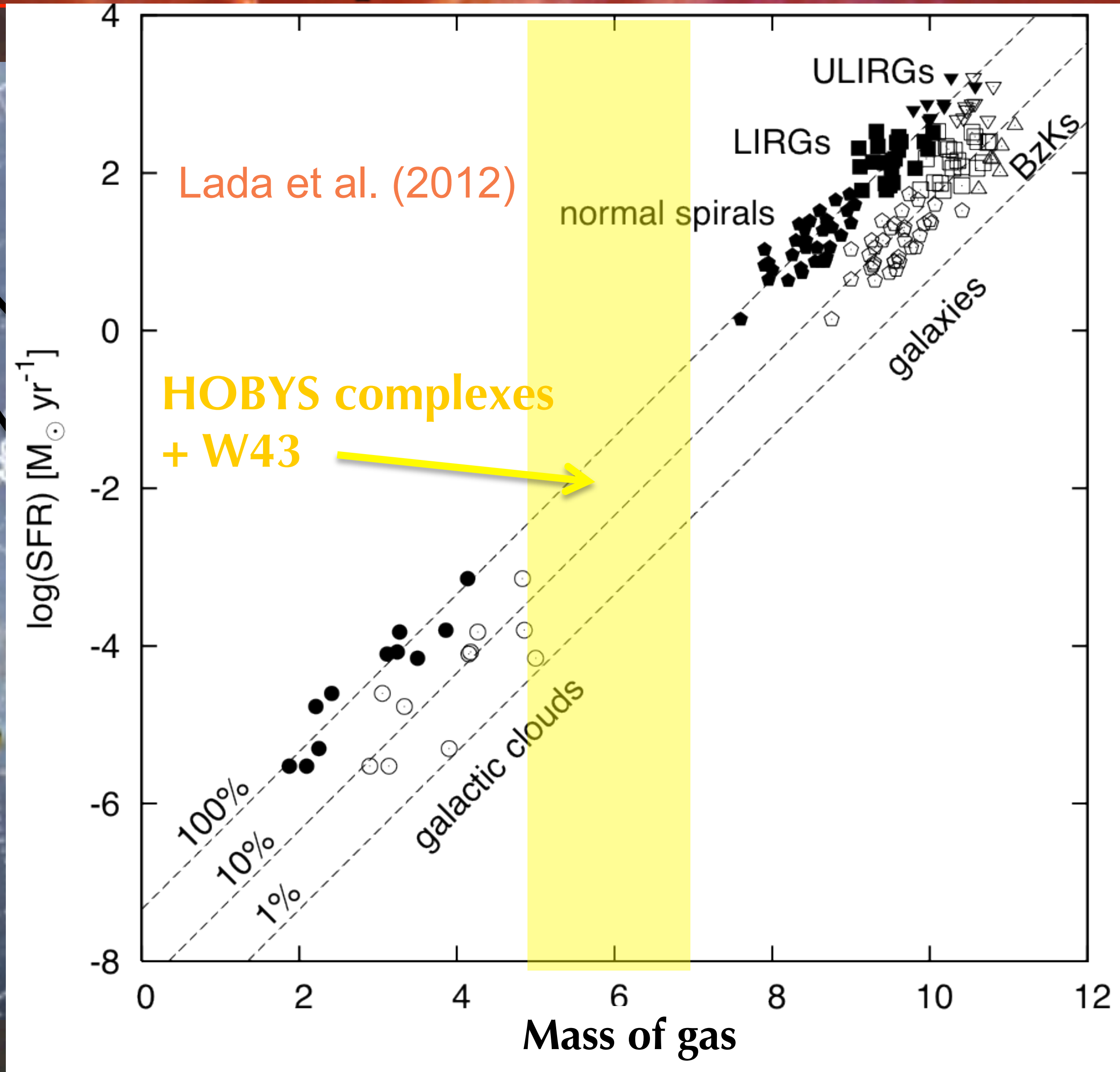


HOBYS molecular cloud complexes, pieces of the nearest spiral arms of the MW

HOBYS mol. complexes:
10^5 - 10^6 $M_\odot$ 50 - 100 pc

Catalog by S. Bontemps
(see Schneider et al. 2012)
Built from NIR extinction
and CO maps.

Orion in Gould Belt:
10^5 $M_\odot$ 50 pc



GAL
ERO:
50 pc
ong et

Herschel HOBYS suvey

- Target all molecular cloud complexes forming OB-type stars at $d_{Sun} < 3$ kpc
- Wide-field PACS/SPIRE imagings (70, 160, 250, 350, 500 μm) with 20''/sec

HPBW = 6''-36.9'' @ 0.7-3 kpc ➔ down to 0.03-0.2 pc dense cores

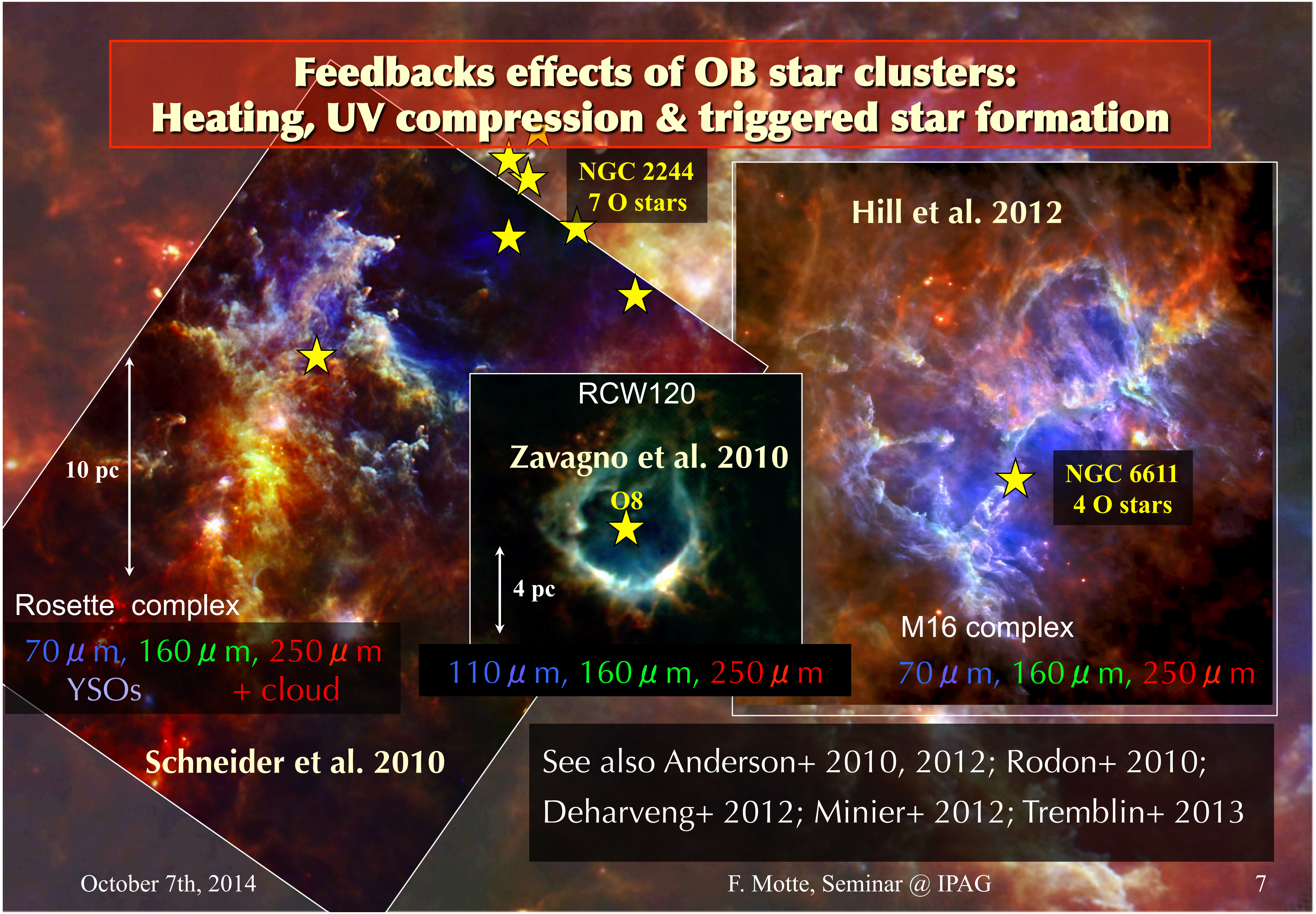
⇒ census of intermediate- to high-mass protostars

⇒ link between cloud structure and (high-mass) SF

⇒ feedback effects

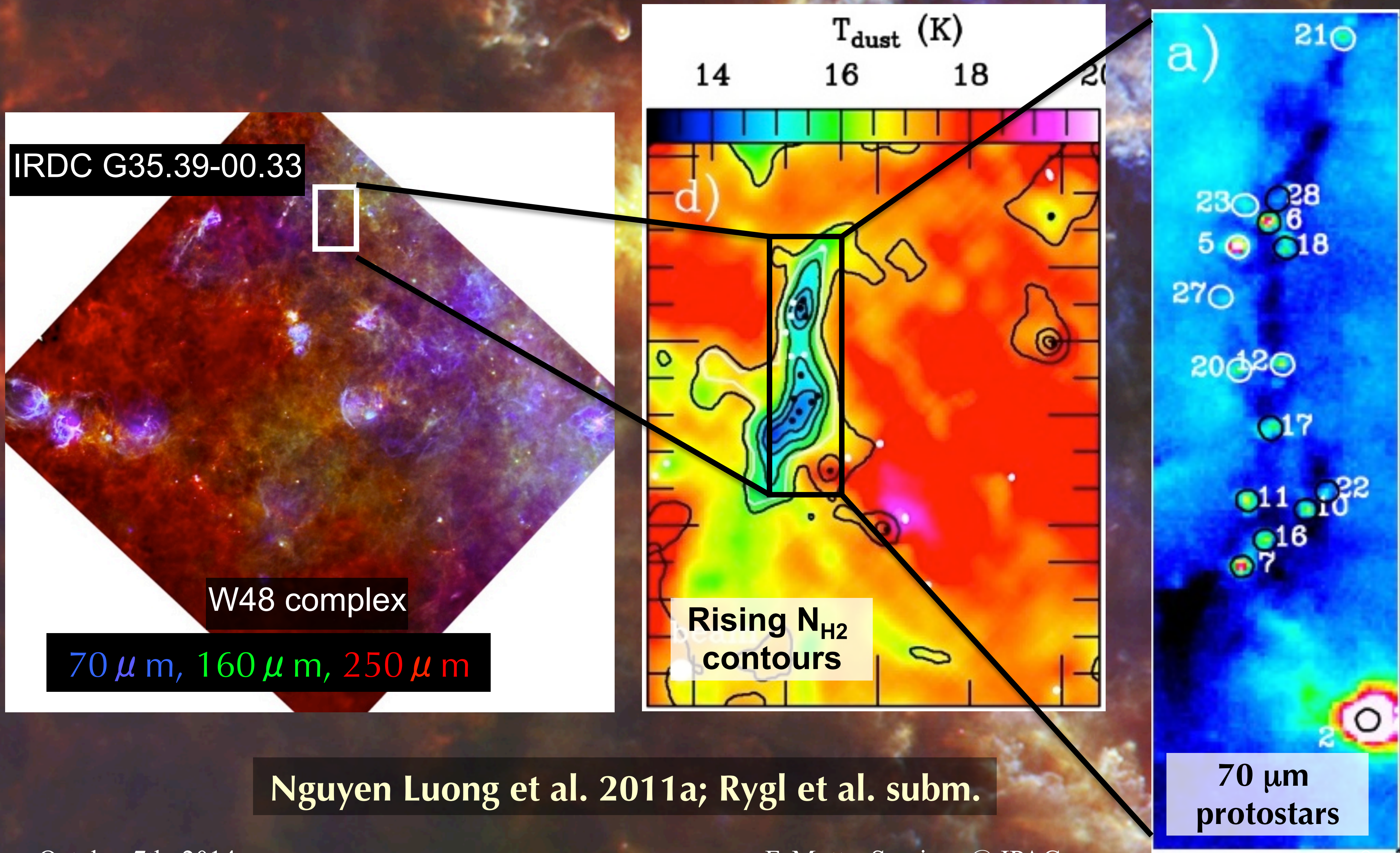
- Complementary to other *Herschel* KPs:
  - high-mass dense cores (small and isolated clouds) - EPOS (Krause et al.)
  - low-mass cores (~0.02 pc) – HGBS, Cold Cores and HOPS survey (André et al.; Juvela, Ristorcelli et al.; Megeath et al.)
  - protoclusters (~1 pc clumps) - Hi-GAL (Molinari et al.)

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



See also Anderson+ 2010, 2012; Rodon+ 2010; Deharveng+ 2012; Minier+ 2012; Tremblin+ 2013

Example cloud filament forming a stellar cluster



Nguyen Luong et al. 2011a; Rygl et al. subm.

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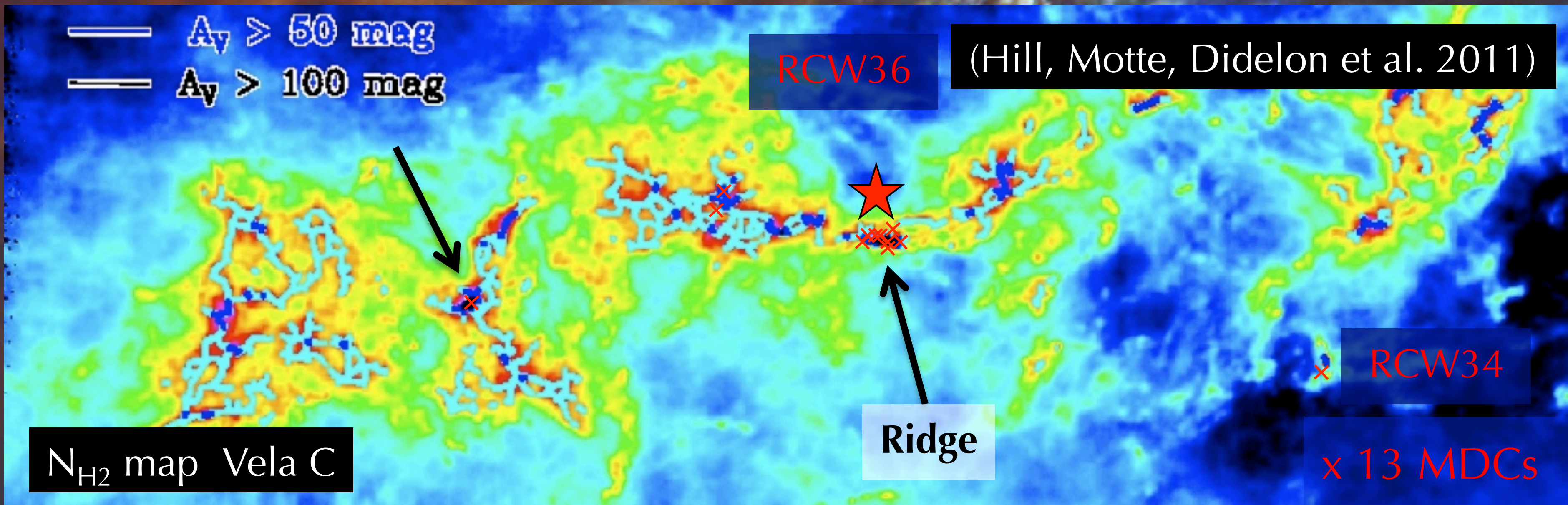
Cloud structure: disorganized networks of filaments versus single dominating ridges

- Column density images created from Bayesian fitting of SEDs by Graybody models (36″ resolution; Hill et al. 2011, 2012)
- 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.



Ridges/Hubs are extreme clumps forming clusters of high-mass stars

- ~50% of high-mass protostars are forming in clusters within high-density elongated clumps, the other 50% are forming in spherical high-density hubs

⇒ Ridge/Hub definition: 5-10 pc^3 /1 pc^3 above 10^4-10^5 cm^{-3}

(We use the 100 A_v level to identify them but it is not a physical threshold.)

- Surrounding gas concentrates toward ridges/hubs at high column-density

➢ Vela C ridge (Hill, Motte, Didelon et al. 2011)

➢ DR21 ridge in Cygnus X (Hennemann, Motte, Schneider et al. 2012)

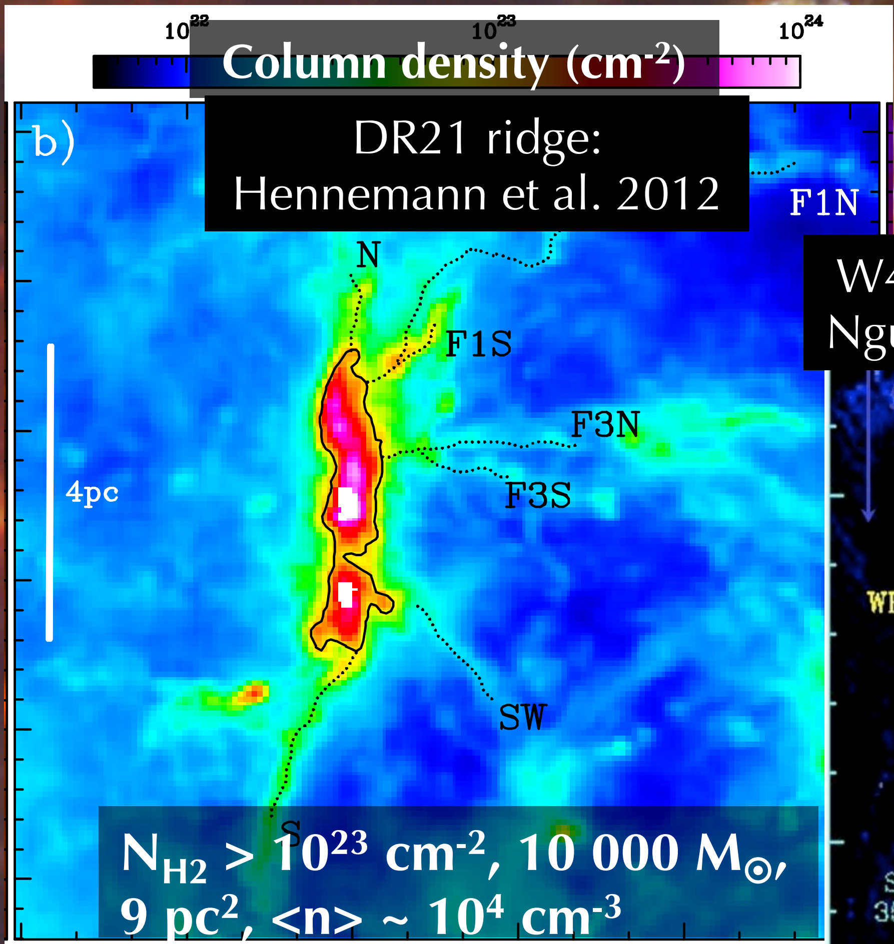
➢ IRDC G035.39-00.33 ridge (Nguyen Luong, Motte, Hennemann et al. 2011a)

➢ W43-MM1, MM2 ridges (Nguyen Luong, Motte, Carlhoff et al. 2013)

➢ MonR2 (Rayner, Griffin et al. in prep.; Didelon et al. in prep.)

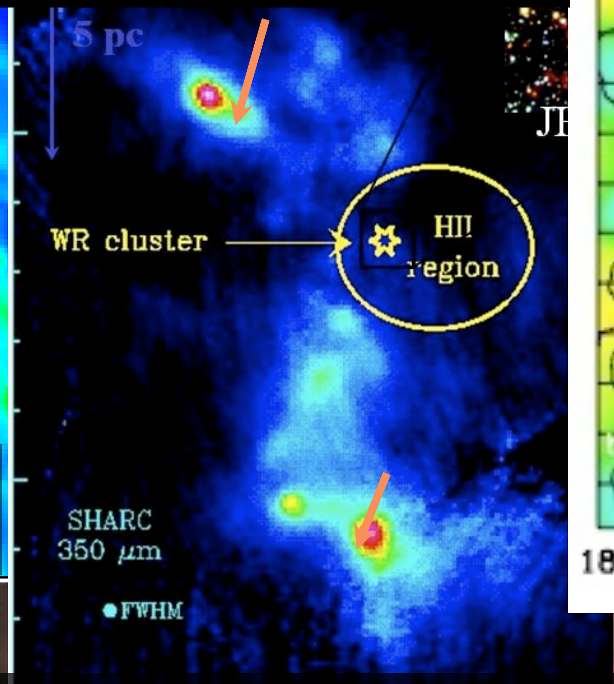
➢ Statistical characteristics of HOBYS ridges (Hill et al. in prep.)

Ridges (5-10 pc^2, >100 A_v) are extreme IRDCs formed by dynamical scenarios

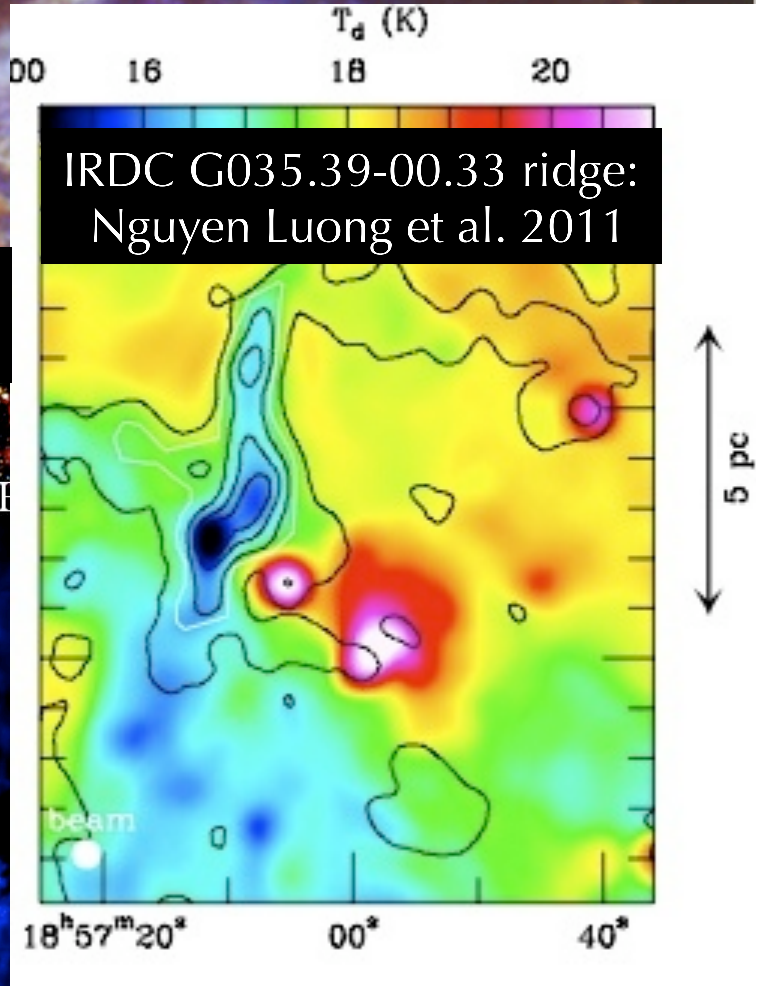


DR21 ridge:
Hennemann et al. 2012

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



W43-MM1, MM2 ridges:
Nguyen Luong et al. 2013

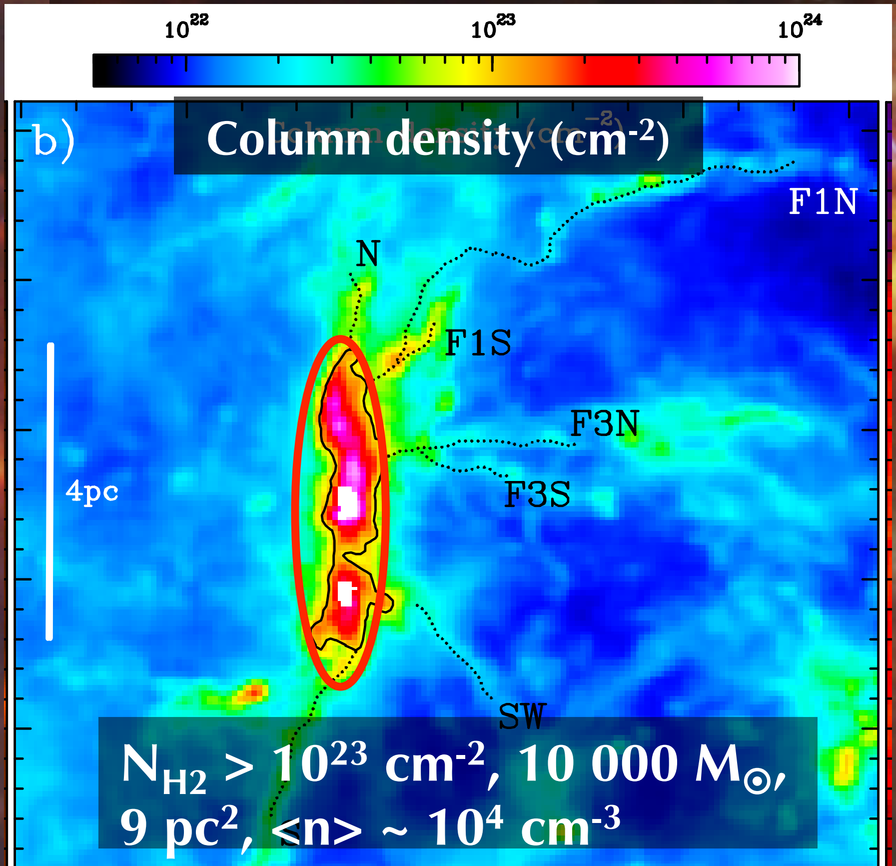


IRDC G035.39-00.33 ridge:
Nguyen Luong et al. 2011

See also Schneider et al. 2012; Louvet et al. in prep.; Rayner et al. in prep.

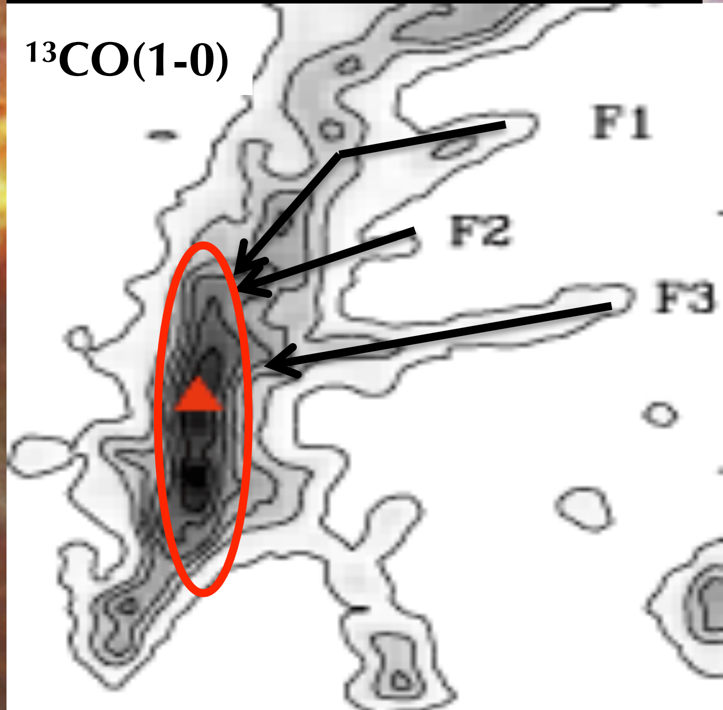
Most ridges should form by cloud global collapse

- Forced-fall (pressure-driven infall) of the DR21 ridge further fed by filaments.



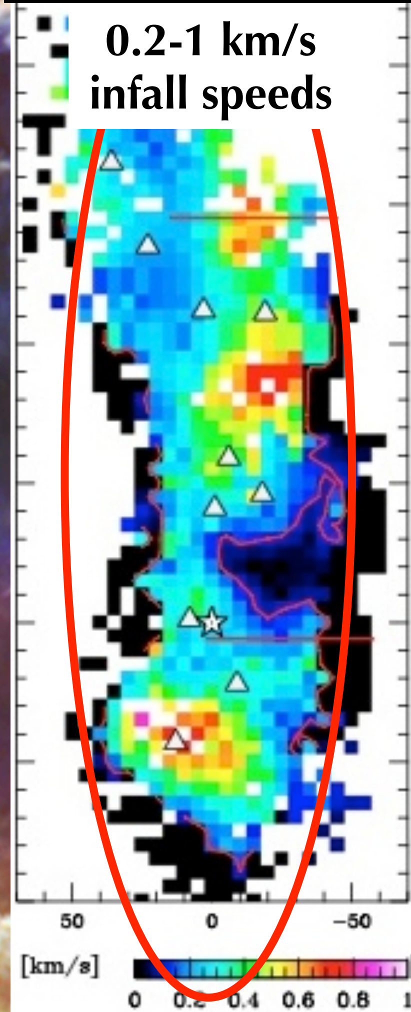
Hennemann, Motte, Schneider et al. 2012

Gas flows along sub-filaments



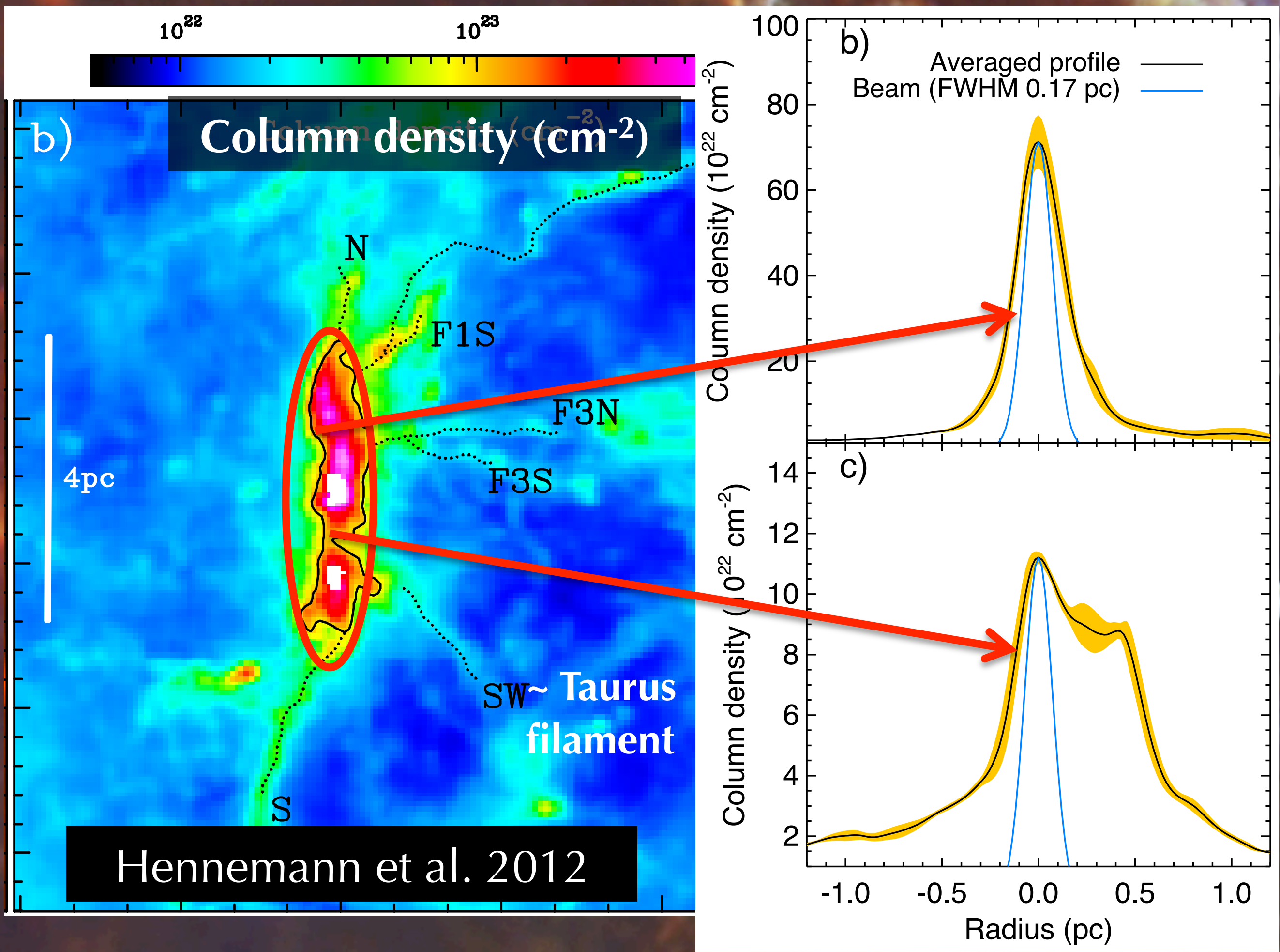
Schneider, Csengeri, Bontemps et al. 2010

Global infall



- Similar kinematics found for other ridges/hubs (Peretto et al. 2008, 2014; Louvet et al. in prep.)

The DR21 ridge, formed by merging of super-critical filaments?



Steps toward SF in ridges:

1. MHD tubulent shocks build-up filaments that gently accrete from their surrounding.
2. Gravity braids filaments in a collapsing clump attracting more filaments.
3. Stars and filaments simultaneously form. Protostar accretion is non-local & aspherical.

⇒ Prestellar cores may not exist in such environment

See Csengeri et al. 2011a-b for gas inflow shears in DR21 cores

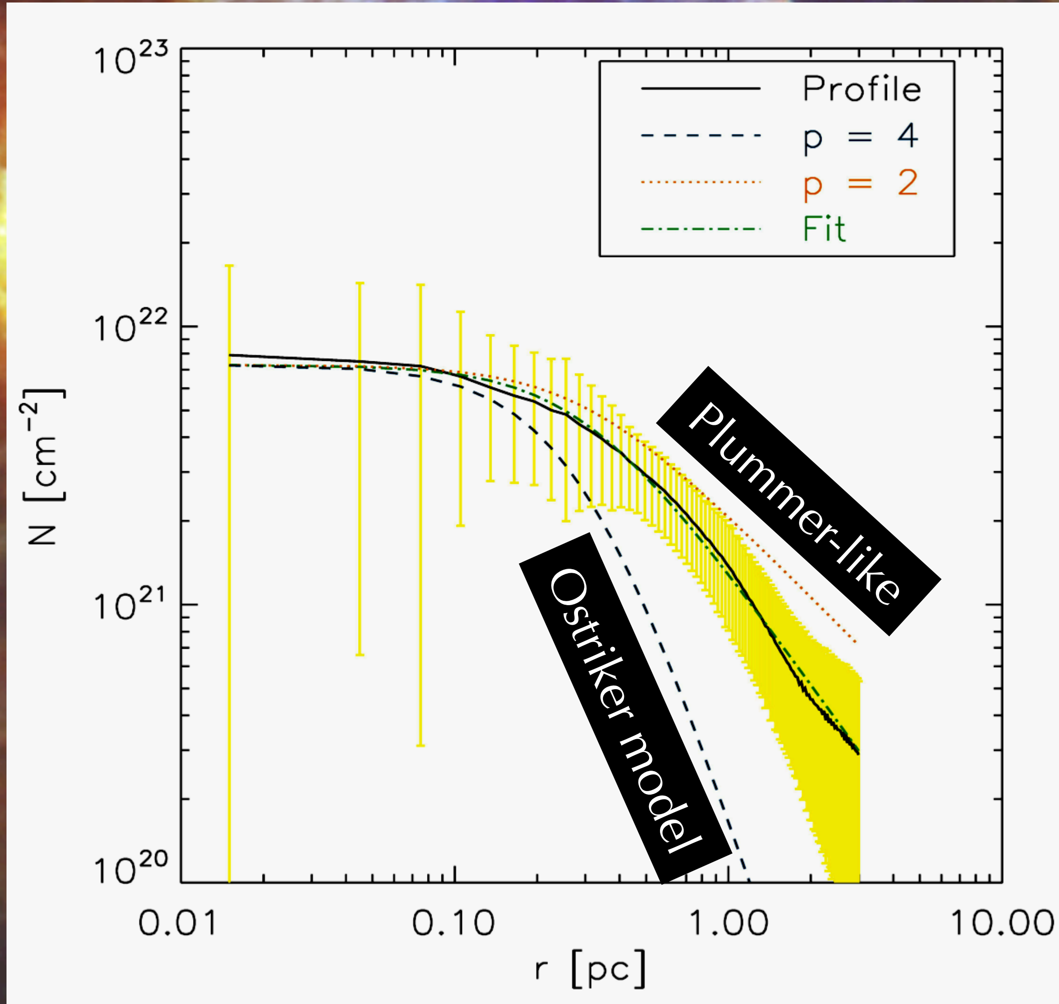
See also Henshaw et al. 2013; Louvet et al. in prep. for other ridges

HGBS results vs models of filaments

Herschel Gould Belt survey:
Filaments are Plummer-like.
0.1 pc width could be set by the sonic scale.

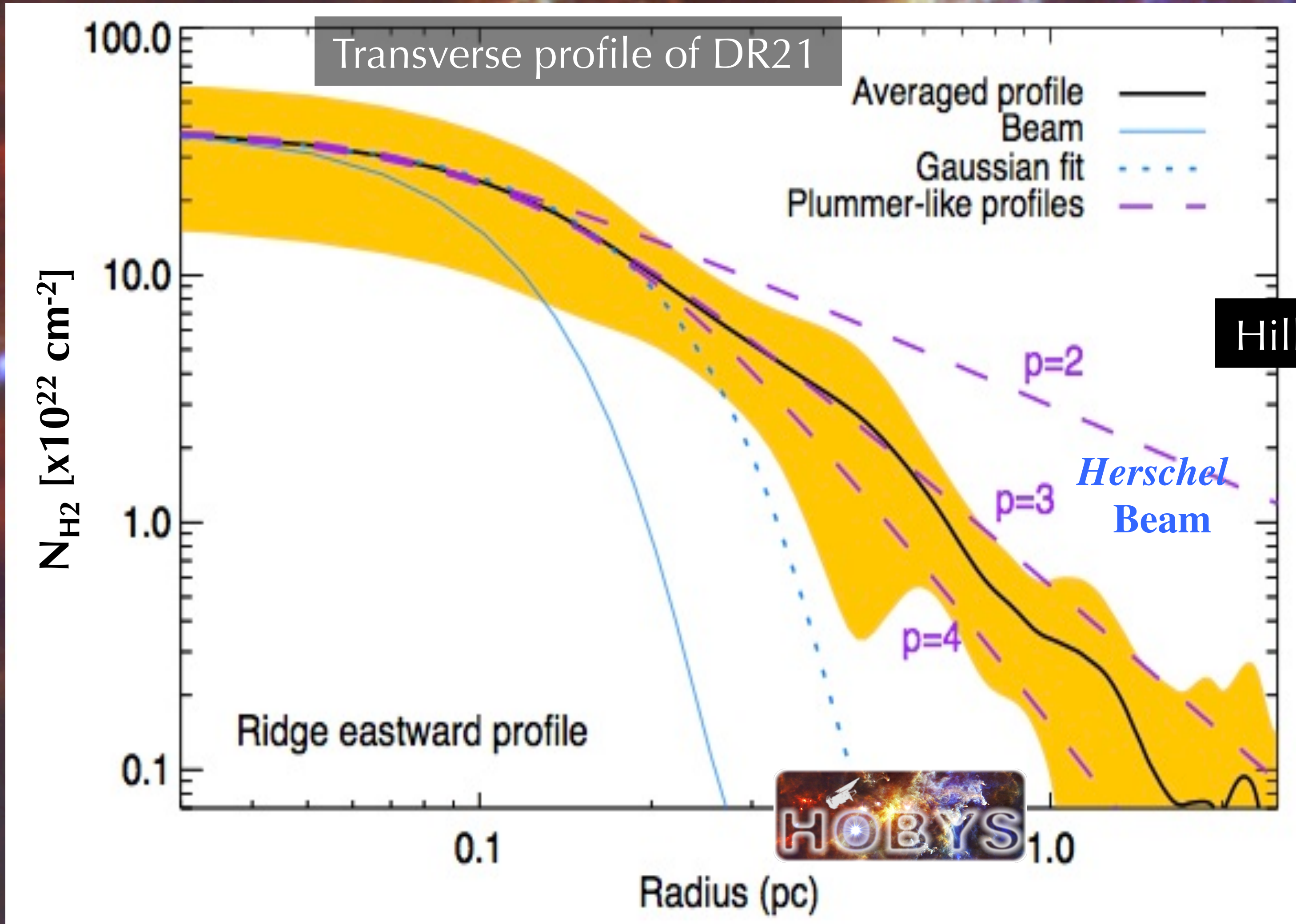
Hennebelle & André 2013:
Self-gravitating accreting filaments have a dissipation scale of 0.1 pc if it arises from ion-neutral friction.
(see also Heitsch 2013)

Gomez & Vazquez-Semadeni 2014; Hennebelle priv. com.:
Globally collapsing filaments tend to have steeper density profiles.



Gomez & Vazquez-Semademi 2014

Ridge are substructured and compressed clumps



Hill et al. in prep.

See also the density structure of the MonR2 hub (Didelon et al. 2014) and PDF studies of Schneider and col. (Russeil et al. 2013; Rayner et al. in prep.)

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HOBYS contribution to the Schmidt-Kennicutt (SFE/SFR versus M_{gas}/Σ_{gas}) relation

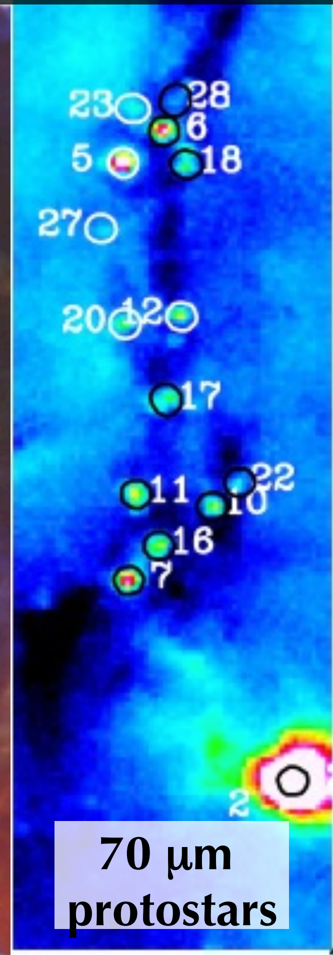
Making a **direct link** between protostars and their cloud, *Herschel* measures instantaneous SFE, easier to compare with statistical models of SFR (e.g.Krumholz & McKee 2005; Padoan & Nordlund 2011; Hennebelle & Chabrier 2011, 2013; Federrath et al. 2012).

- *Herschel* or (sub)millimeter samples of protostars (lifetime ~10^5 yr) (e.g. Motte et al. 2003; Nguyen Luong et al. 2011a; Louvet et al. 2014) ➔ "Instantaneous" / "Present-day" SFR
- *Spitzer* sample of pre-main sequence stars (lifetime ~10^6 yr) or effect of OB stars (depletion time 2 x 10^6 yr) on the cloud (e.g. Heiderman et al. 2010; Kennicutt 1998)

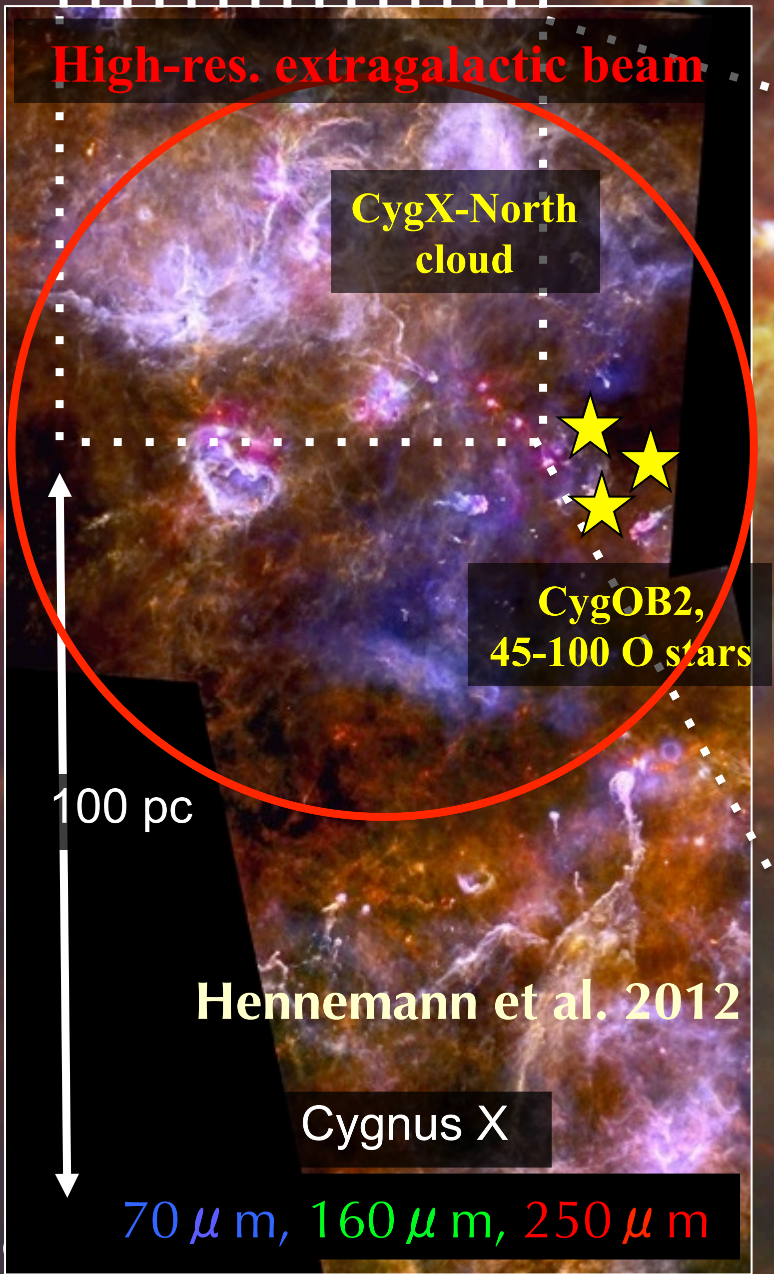
  ➔ "Integrated" / "Past" SFR

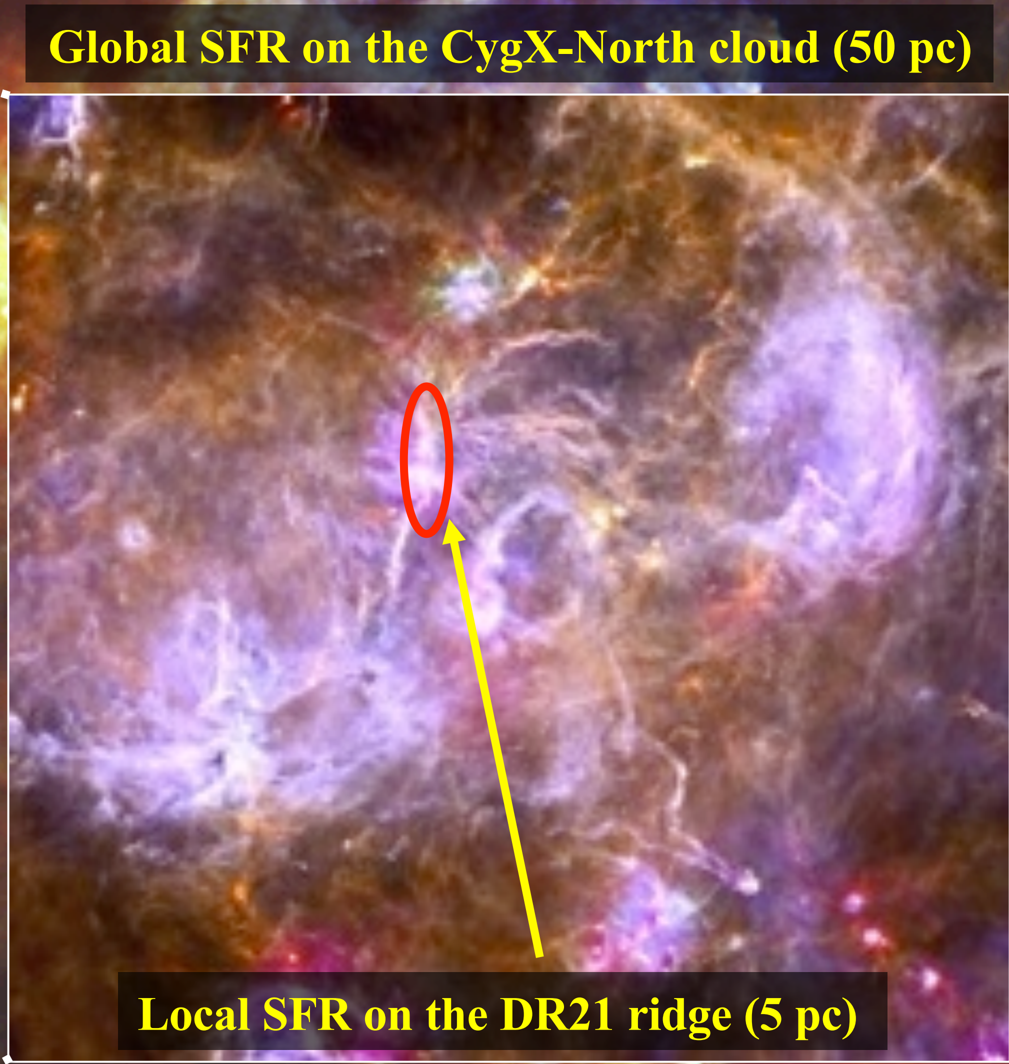
With both SFRs, one may constrain the history of star formation…

Nguyen Luong et al. 2011a



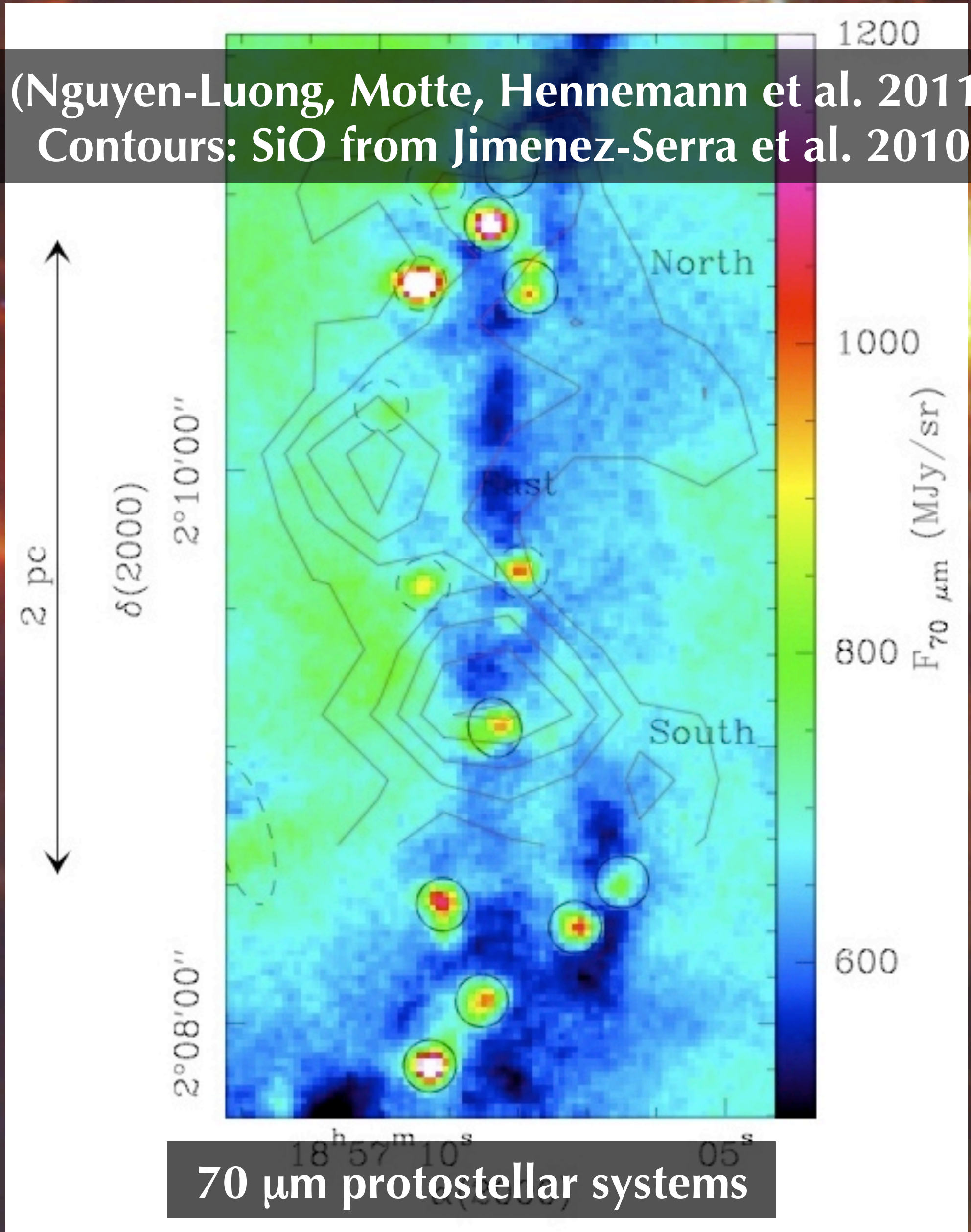
Warning: Spatial scales used for SFR/SFE estimates





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

(Nguyen-Luong, Motte, Hennemann et al. 2011)
Contours: SiO from Jimenez-Serra et al. 2010



70 µm protostellar systems

- Herschel census and SED (4µm-1mm):

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

- Assumptions:

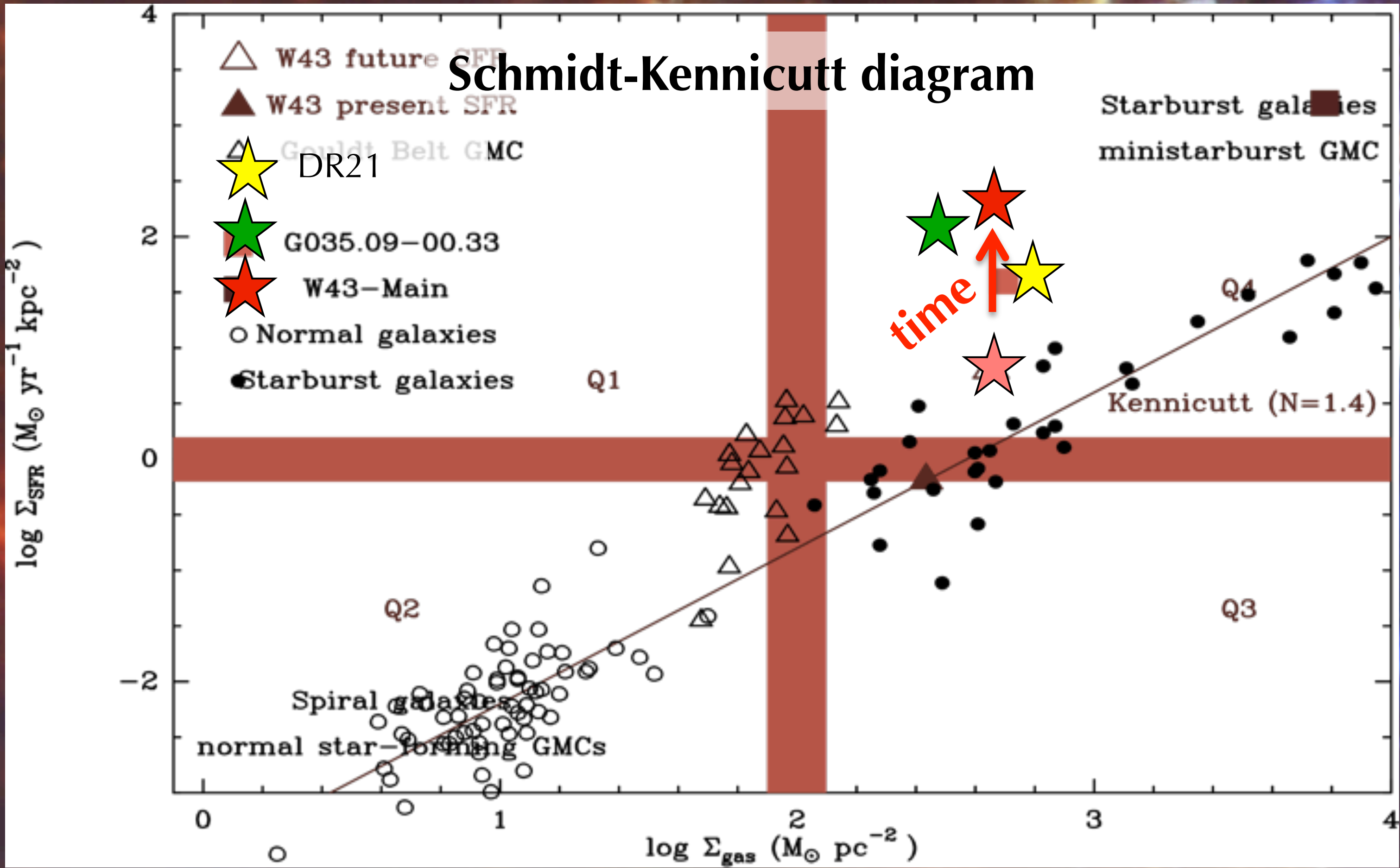
✓ **Core-to-star mass efficiency**: ε ~ **20-40% in 0.1 pc 10^6 cm^{-3} dense cores**

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

✓ Fast episode of cloud formation: 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)

Galactic mini-starburst ridges location in a SK diagram



Starburst quadrant:

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

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

All these values must be refined with new protostar catalogs. These pioneering studies need to be generalized…

Caveats: Core-to-star formation efficiency assumed to be constant

Extrapolation of a standard IMF to mini-starburst ridges

HOBYS summary and perspectives

- Summary of HOBYS findings:

Networks of filaments among which the "ridges" are globally collapsing clumps formed through filaments merging driven by cloud or ionization compression.

Ministarburst clusters containing numerous high-mass class 0-like protostars leading to high local and instantaneous SFR within ridges.

Feedback effects of OB star clusters are important for cloud and star formation.

- Future prospects:

combining Herschel Galactic-scale and ALMA studies to

- Constrain the physics at the origin of the SK relation found in x-gal studies.

- Constrain the statistical SFR theories.

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, N. Schneider

And observers from the W43/ATLASGAL consortium:

F. Schuller, 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:

P. Hennebelle, S. Glover, F. Heitsch, E. Vazquez-Semadeni, R. Banerjee, …

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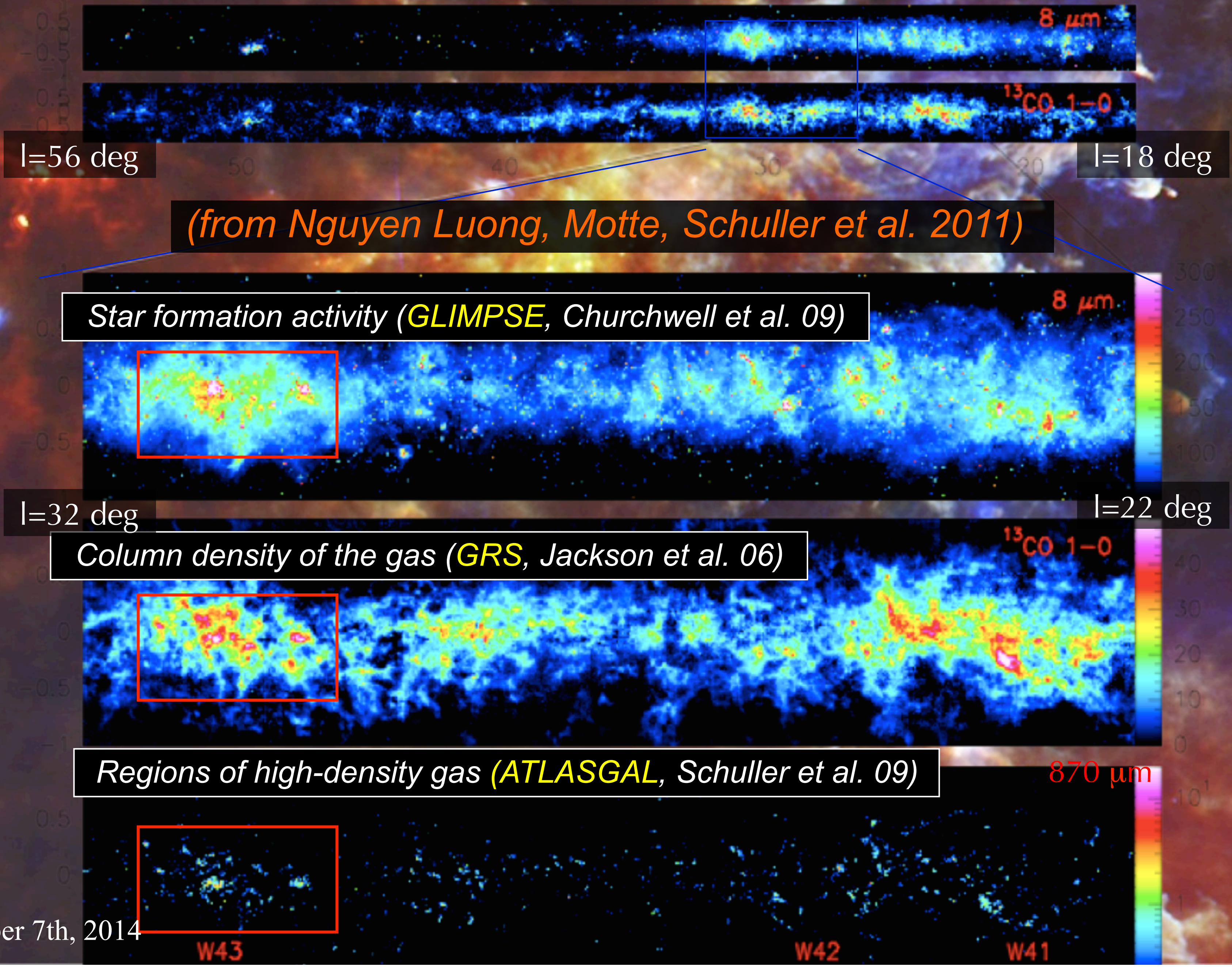
see http://www.iram-institute.org/EN/content-page-292-7-158-240-292-0.html

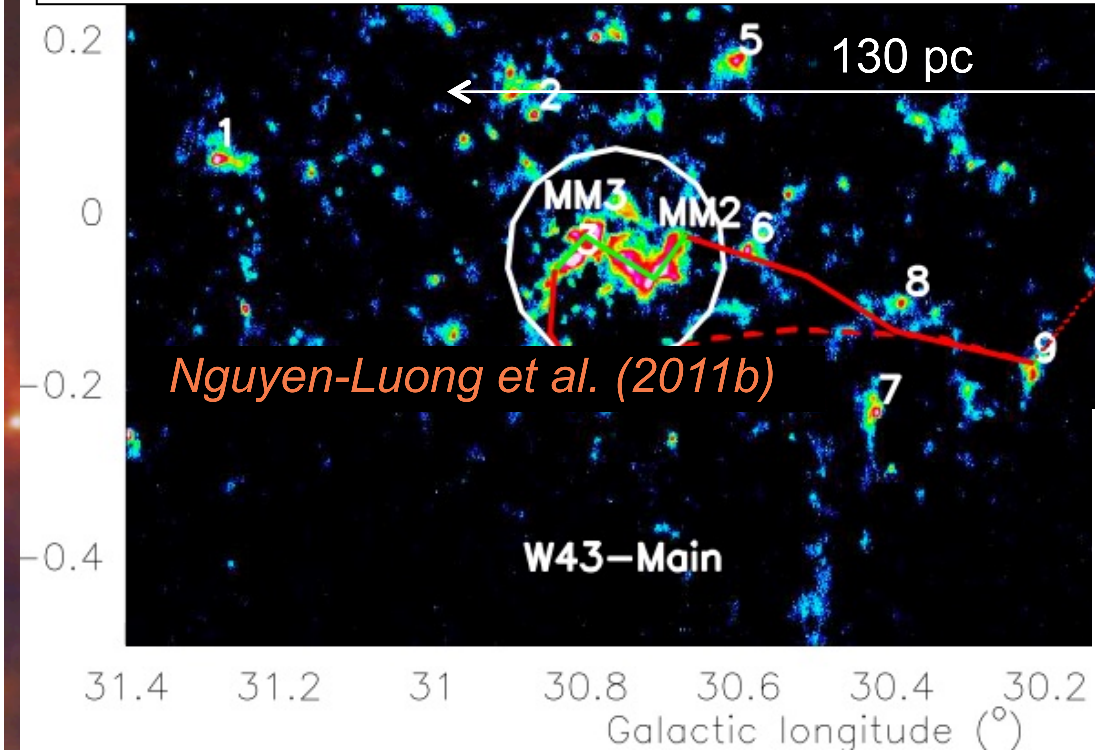
1. W43, at the leading part of the Scutum-Centaurus arm and ahead of the long bar
2. Molecular complex forming through H_2 cloud collision
3. A mini-starburst region used to constrain SFR models
4. First imprints of direct signatures for colliding flows

W43, an extreme molecular complex of the Milky Way



W43, a coherent molecular cloud structure

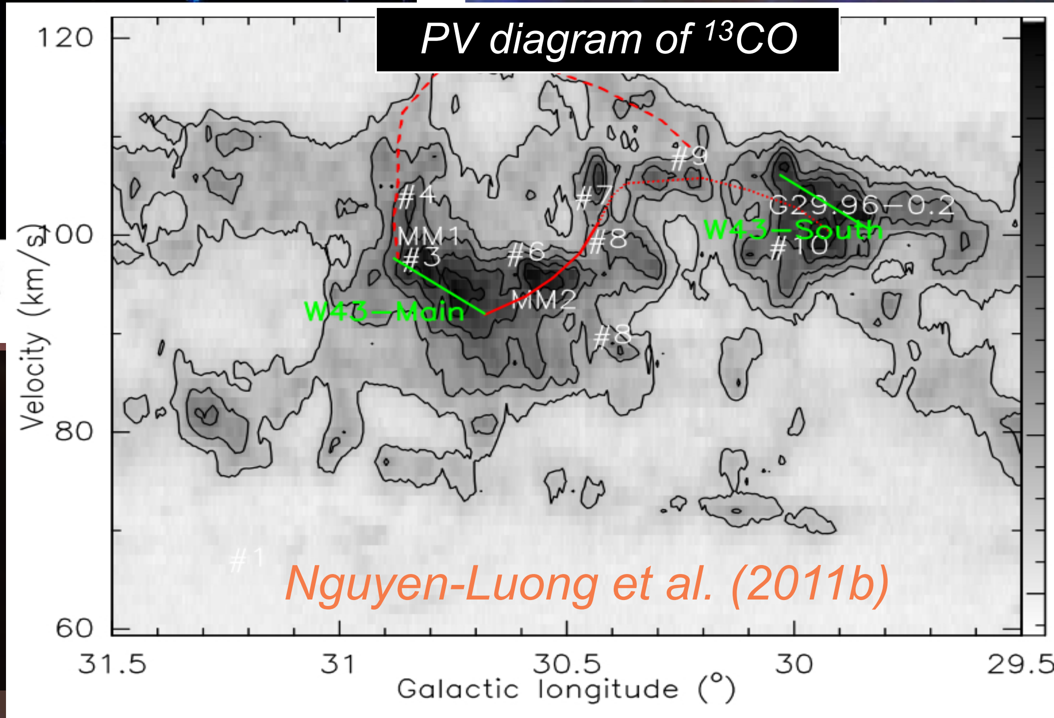
Bridges between W43-Main and W43-South using 870 μm cores (ATLASGAL, color image) and their ^{13}CO 1-0 (GRS, spectra)



Velocity gradients following filaments. Linking clouds over a 130 pc diameter

- Velocity range: (80-110 km/s) but coherent
- Large and massive: 130 pc, $8\ 10^6\ M_\odot$
- Close to Virial equ., stable against shears

(Nguyen Luong+ 2011b; Carlhoff+ 2013)



W43, a cloud agglomeration ahead of the Galactic bar

- Kinematic distance of W43:

Uncertain due to large velocity dispersion

- Complete study of the molecular cloud complex and its star formation activity:

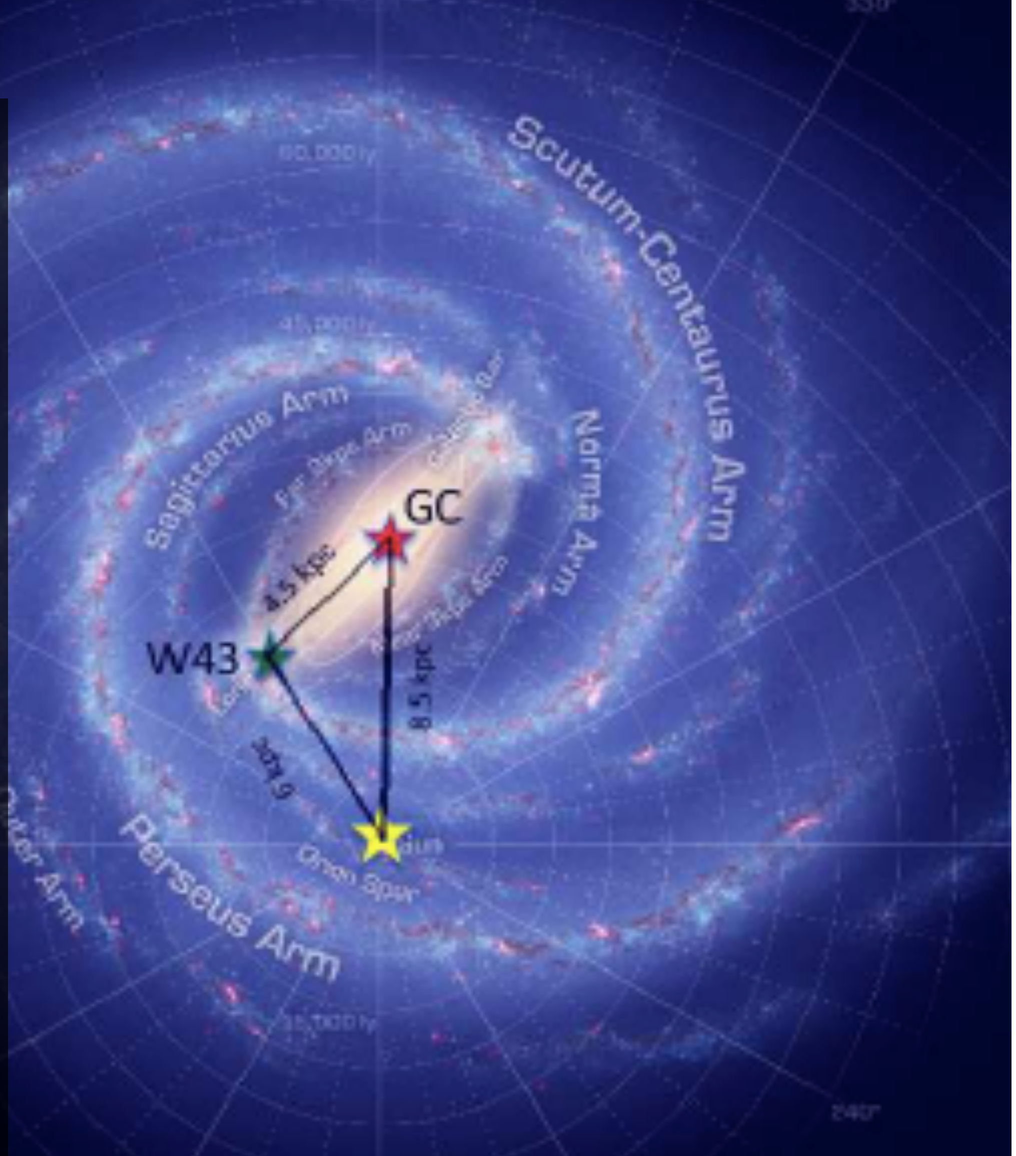
at the meeting point of the bar and the Scutum-Centaurus arm

(Nguyen-Luong et al. 2011b)

- Parallax measurements:

$\Rightarrow$ d = 5.5 kpc

(Zhang et al. 2014)



Adapted from Churchwell et al. (2009)

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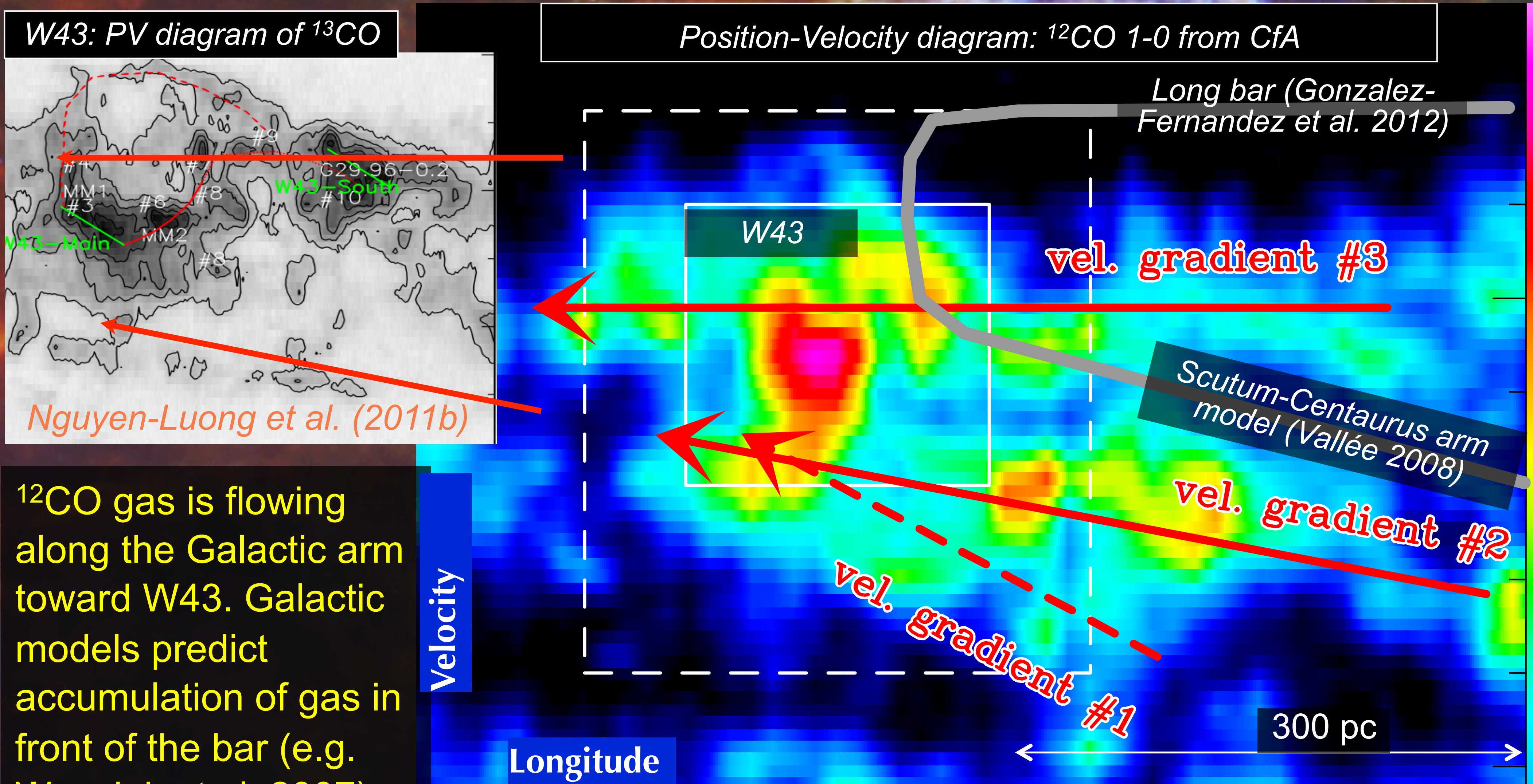
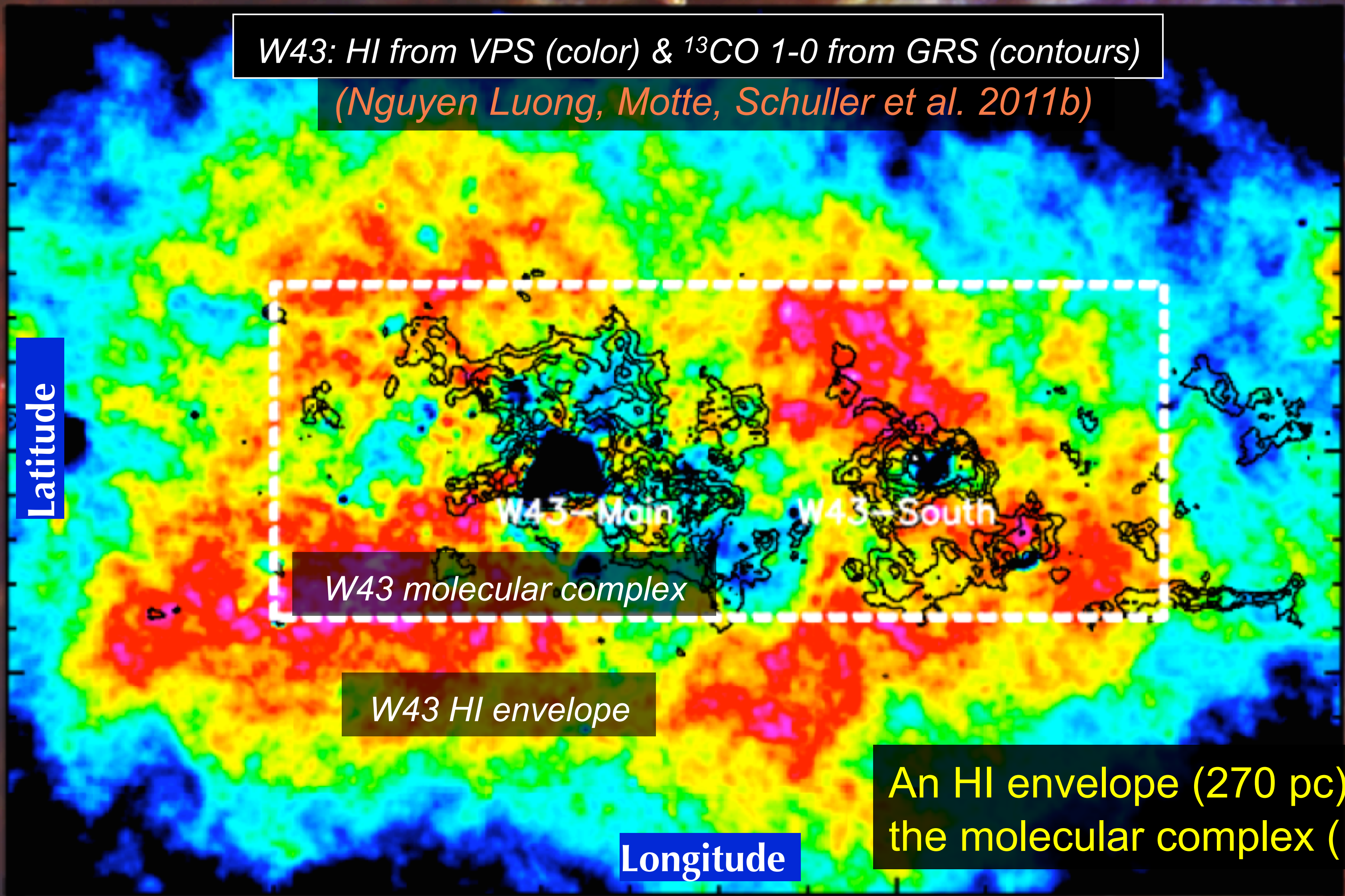
Two cloud ensembles developing along the longitude and joining W43



^{12}CO gas is flowing along the Galactic arm toward W43. Galactic models predict accumulation of gas in front of the bar (e.g. Wozniak et al. 2007).

(Motte, Nguyen Luong, Schneider et al. 2014)

An HI envelope surrounding the ^{13}CO W43 complex

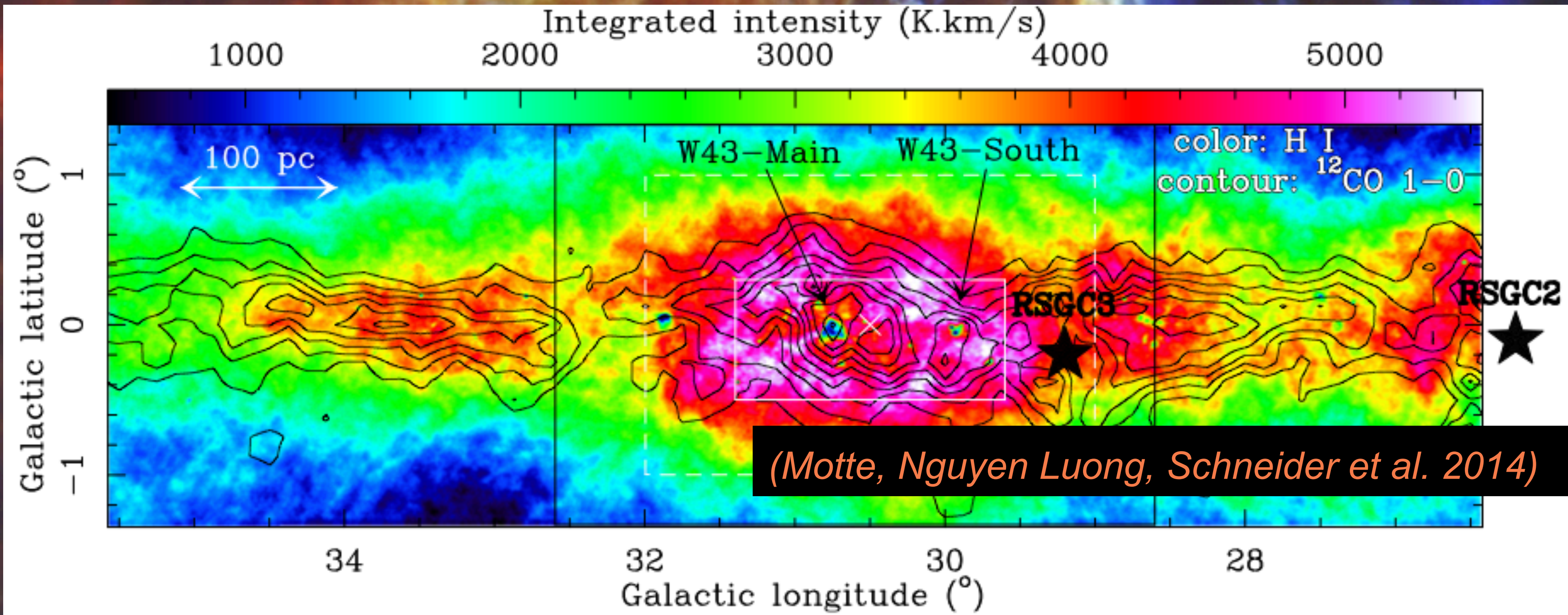


An HI envelope (270 pc) surrounds the molecular complex (130 pc).

Searching for an HI surface density threshold

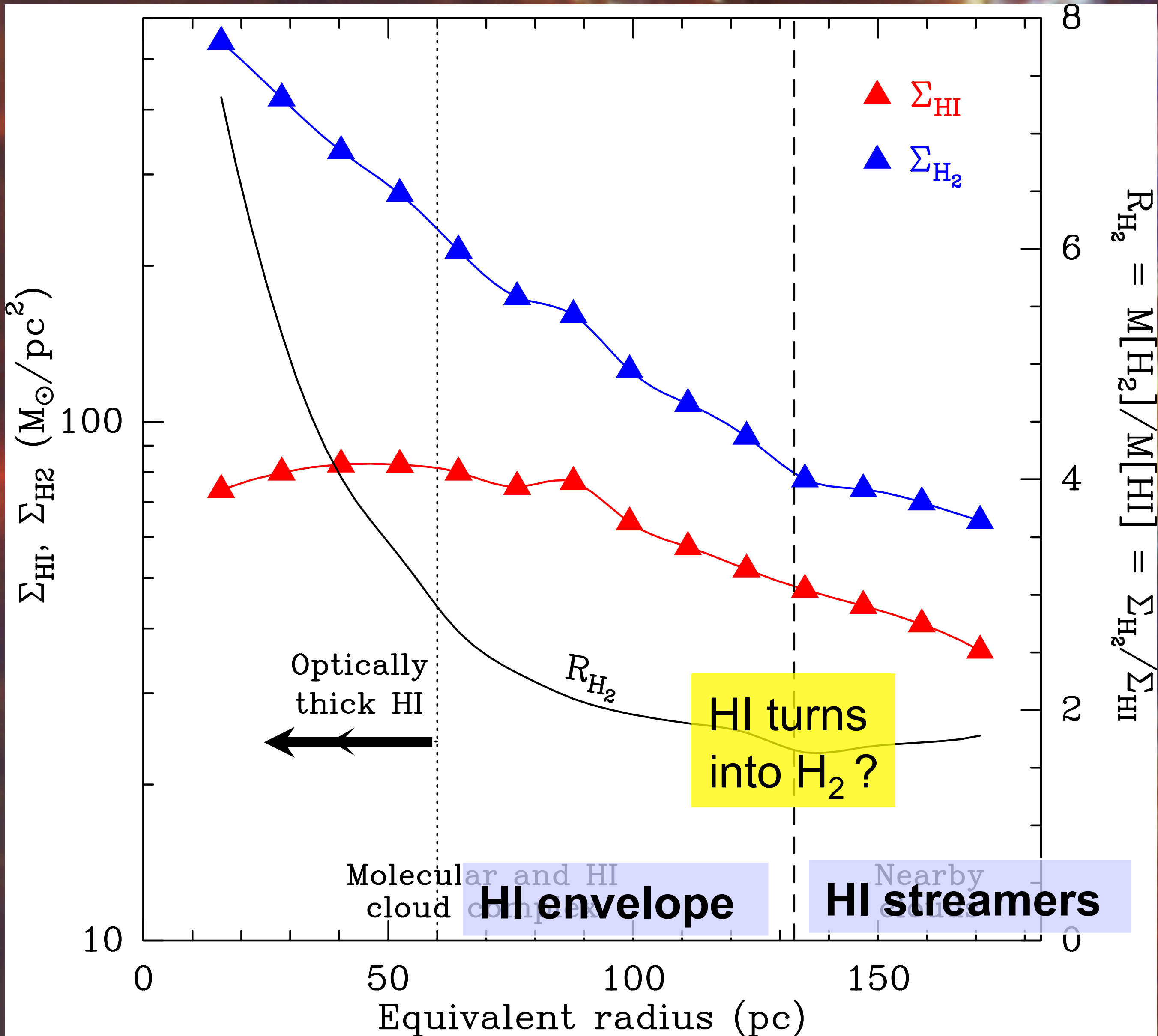
Saturation of the HI surface density generally observed (e.g. Blitz & Rosolowsky et al. 2006; Bigiel et al. 2008; Barriault et al. 2010; Lee et al. 2012) and predicted by equilibrium models (Krumhloz et al. 2009) at $\Sigma_{HI} \sim$ 5-15 $M_{\odot}/pc^2$

W43, with its well-defined symmetrical envelope could be the ideal place to investigate the atomic-to-molecular transition.



(Motte, Nguyen Luong, Schneider et al. 2014)

Radial diagram of the HI surface density



HI saturation generally found:

$\Sigma_{HI} \sim 5\text{-}15\ M_\odot/pc^2$

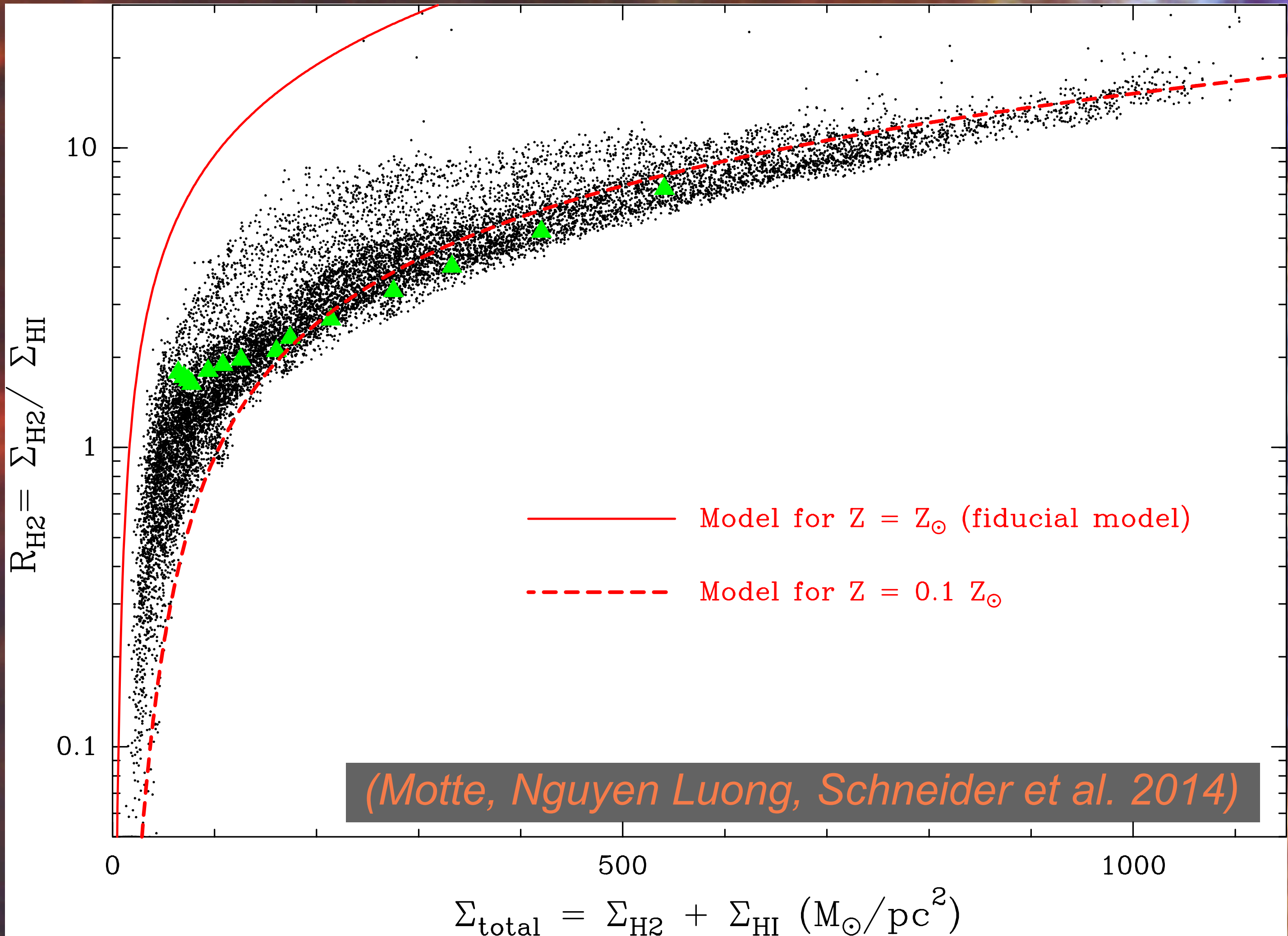
In W43:

$\Sigma_{HI} \sim 36\text{-}82\ M_\odot/pc^2$

- cloud formation is probably out of equilibrium (like in models of Glover et al. 2010)
- several layers of HI gas are turning into H_2.

(Motte, Nguyen Luong, Schneider et al. 2014)

Molecular ratio vs HI and H_2 surface density, compared to the K09 steady-state equilibrium model



Molecular ratio at the transition from HI-dominated to H2-dominated gas
- Generally taken to R_{H2} ~ 0.25-0.1
- In W43, mostly R_{H2} ~ 1-10

Clouds in W43 and its surroundings (including streaming clouds) are already molecular-dominated.

Equilibrium models in atomic-dominated regions with low radiation fields (e.g. Krumholz et al. 2009) are not appropriate.

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W43 is extreme, when compared with other molecular and star-forming clouds/complexes

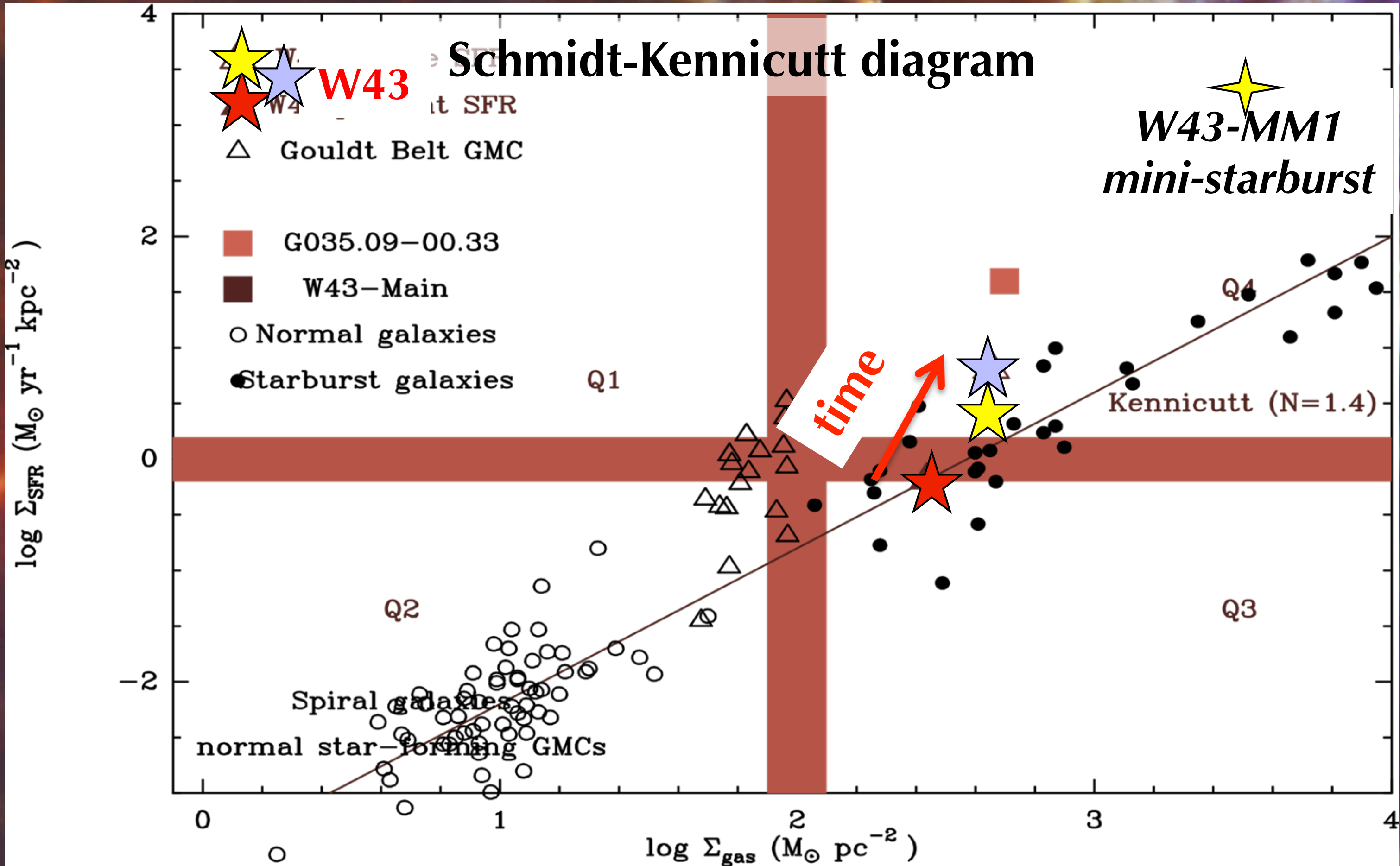
With its size (~130 pc), mass (8×10^6 $M_\odot$), and velocity dispersion (*FWHM* ~ 22.3 km/s), W43 defines as a GMC Association (GMA quoted in extragalactic studies) or molecular complex.

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. 2011b)*

	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	5.5	130	8×10^6	12%	0.01-0.1
Cygnus X	1.7	160	5×10^6	1%	0.003-0.07
CMZ	8.5	350	3×10^8	1%	low
Orion	0.5	50	5×10^5		0.0004-0.001

History of the star formation (SFR) in W43



Spitzer mid-IR flux ➔
Past/integrated SFR ★

Herschel (Hi-GAL) sample of protostars
➔ Present/ instantaneous SFR ★

Total mass of the gas
➔ Future SFR ★

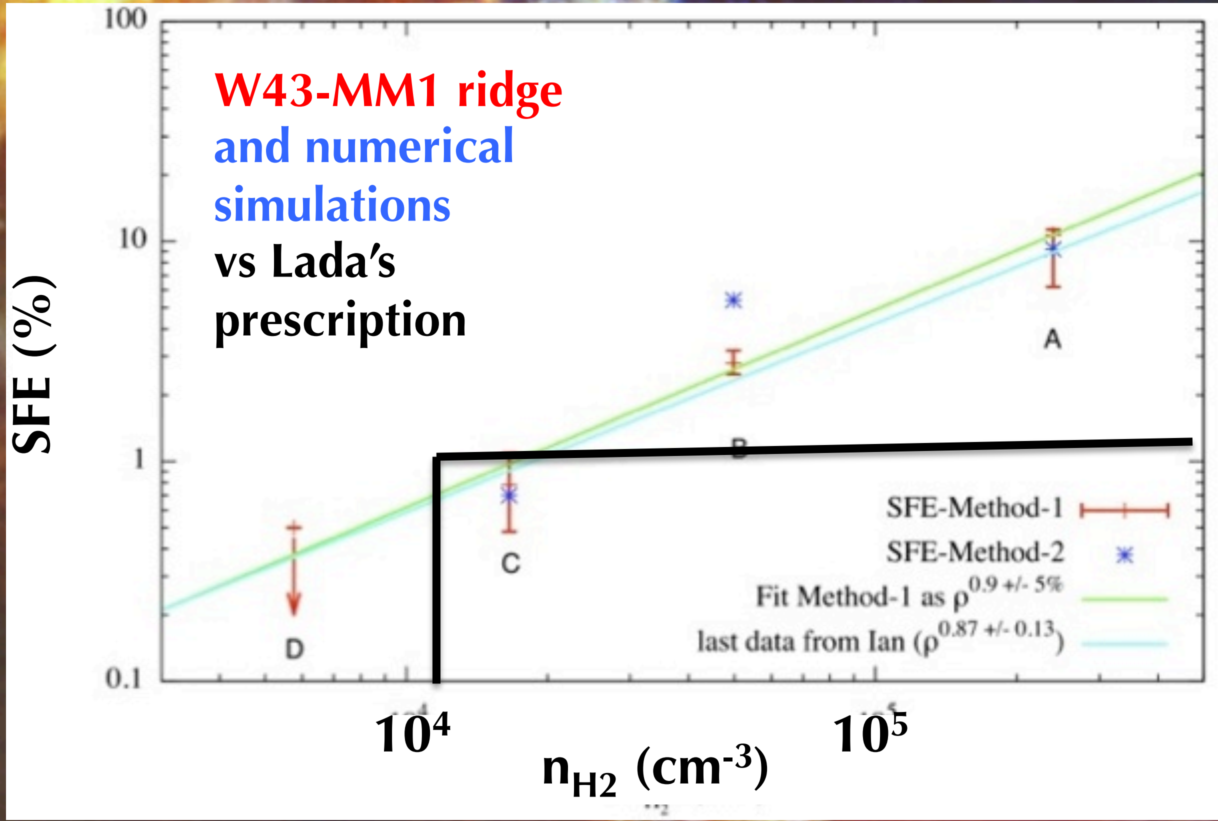
Figure adapted from Nguyen Luong, Motte, Schuller et al. (2011b, in prep.), Louvet et al. in (2014.).

Are thresholds and constant SFE correct?

Lada et al.(2012) relation between SFR and cloud mass implicitely assumes a constant SFE in regions above the SF threshold (Av> 8 mag). See also Evans et al. 2014, André et al. 2014,… and SFR theoretical models.

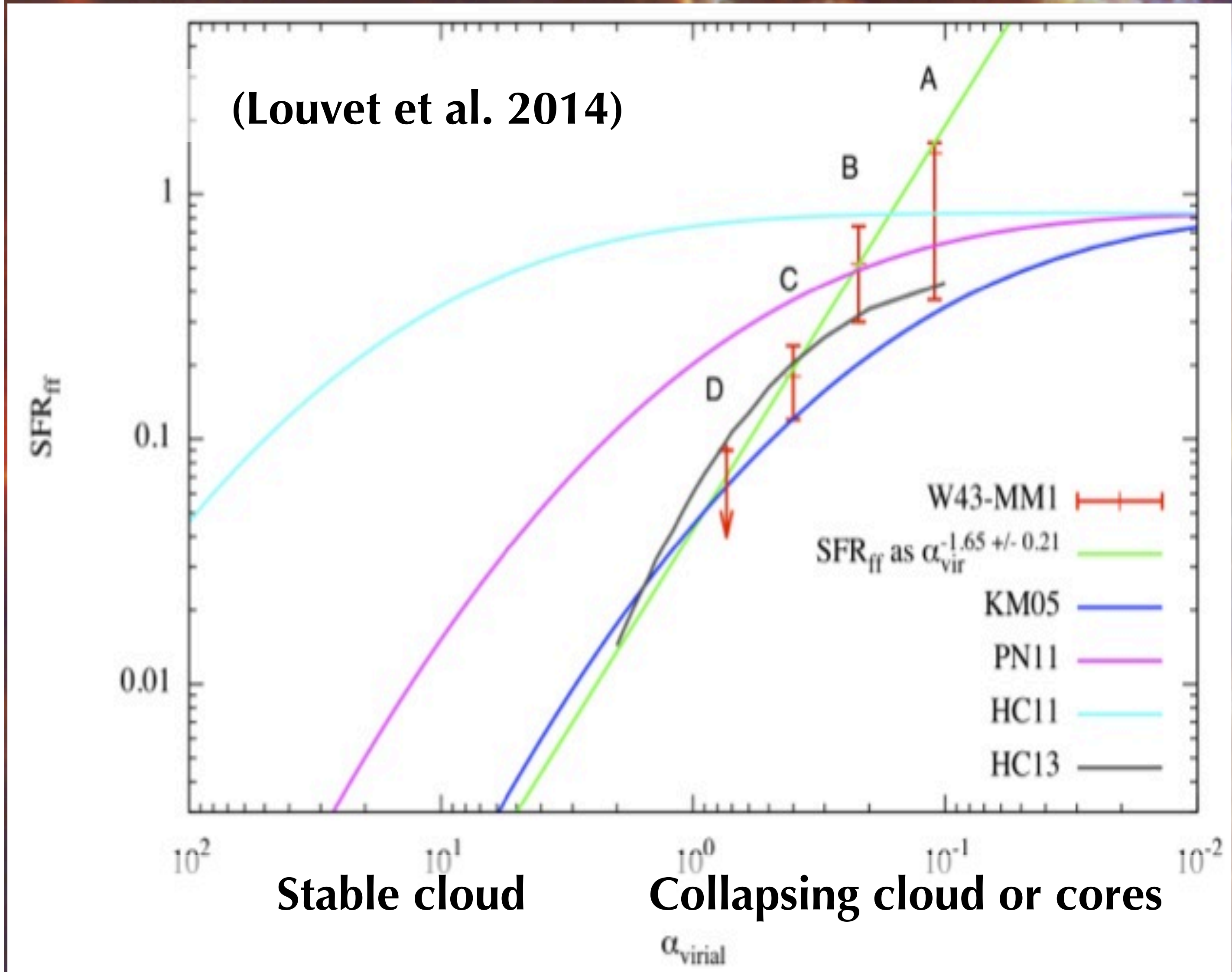
An IRAM Plateau de Bure census of protostars in the W43-MM1 ridges investigates star formation efficiency.

SFE measured within the W43-MM1 ridge and in numerical simulations increases with n_{H2} (Louvet et al. 2014)



(Louvet, Motte, Hennebelle et al. 2014)

Constraining statistical theories of SFR on W43-MM1…



- Statistical models of SFR suggests saturation at low virial numbers (Krumholz & McKee 2005; Padoan & Nordlund 2011; Hennebelle & Chabrier 2011, 2013; Federrath et al. 2012).

- Inconsistent with observations in W43.

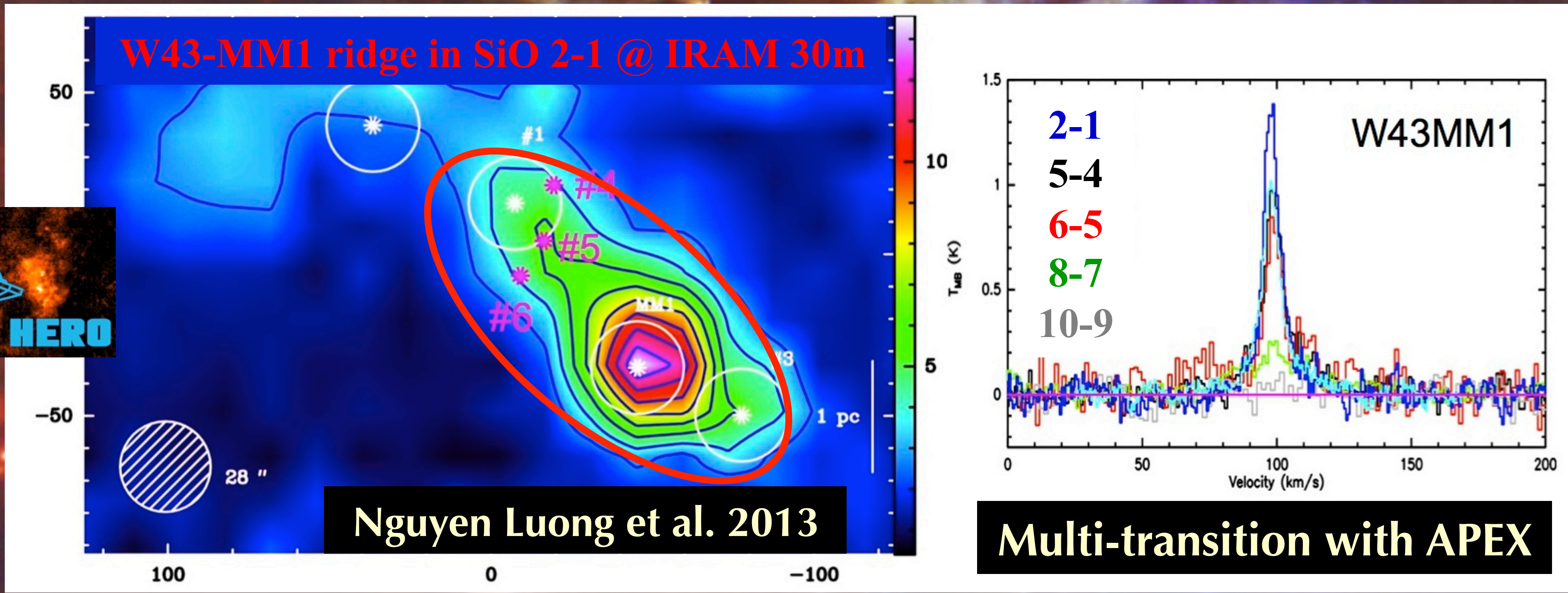
=> Multi-freefall models (Hennebelle et al. 2012; Federrath et al. 2012) with more realistic cloud structure should be more adequate…

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

see http://www.iram-institute.org/EN/content-page-292-7-158-240-292-0.html

1. W43, at the leading part of the Scutum-Centaurus arm and ahead of the long bar
2. Molecular complex forming through H_2 cloud collision
3. A mini-starburst region used to constrain SFR models
4. First imprints of direct signatures for colliding flows

Bright & extended SiO emission along W43 ridges



SiO classically associated with protostellar outflows but here most could be associated to 5-10 km/s shocks (Nguyen Luong et al. 2013)

Observations compared with shock models with Si in gas or SiO in grain mantles to constrain the filament merging (Gusdorf et al. in prep.).

See also Jiménez-Serra et al. (2011) for the IRDC G035.39-00.33

Conclusions and perspectives

- W43 is an highly-concentrated molecular complex actively forming stars.

Located at a distance of ~5.5 kpc from the Sun, it lies in front of the Galactic Bar *(Nguyen et al. 2011; Carlhoff et al. 2013; Motte et al. 2014; Louvet et al. 2014)*

- The W43 complex is one of the best examples of cloud forming from the collison of molecular cloud streaming along the Galactic arm. It displays **several signatures of colliding flows**: convergence of CO cloud ensembles, low-velocity shocks on the densest parts of the cloud, global collapse… *(Nguyen Luong et al. 2013; Motte et al. 2014; Louvet et al. in prep.)*

- W43 is one step toward understanding Galactic-scale star formation. Its muti-scale multi-tracer study is linking highly-dynamical molecular cloud formation to intense star formation activity.

- The W43 consortium is working to constrain the W43 kinematics and make precise modeling.

Summary

With HOBYS, we have:

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 at the tip of the Galactic bar.
2. Used its extreme characteristics to constrain models
3. Revealed first imprints of molecular ridge formation through colliding 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.