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 »

Our knowledge of SF in "filaments"

Gould Belt clouds observations & simulations:

1. MHD turbulent shocks build-up filaments.
2. Gravitationally unstable filaments, for $M_{line} > 2c_s^2/G$, fragment.

⇒ Filaments are the link between clouds and prestellar cores.

⇒ Their threshold of instability equals the SF threshold of Av > 8 mag.

But…

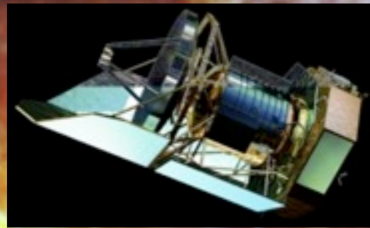
1. Cloud collision and/or global collapse create denser filaments/ridges
2. Filaments are complex bundles/braids of fibers.

⇒ Stars could be forming at the same time as filaments/clumps.

from a mass reservoir larger than pre-stellar cores.

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, A. Zavagno

W43-HERO IRAM LP, tracking the origin of molecular cloud and star formation in W43

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

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: Schuller, Csengeri et al.

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

Linking cloud structure/kinematics & star formation activity

Main open questions:

1) Origin of molecular cloud complexes and their high-density structures.
2) Link of the high-mass star formation and star formation efficiency to the cloud concentration and dynamics.

HOBYS

The 9 closest cloud complexes forming high-mass stars.

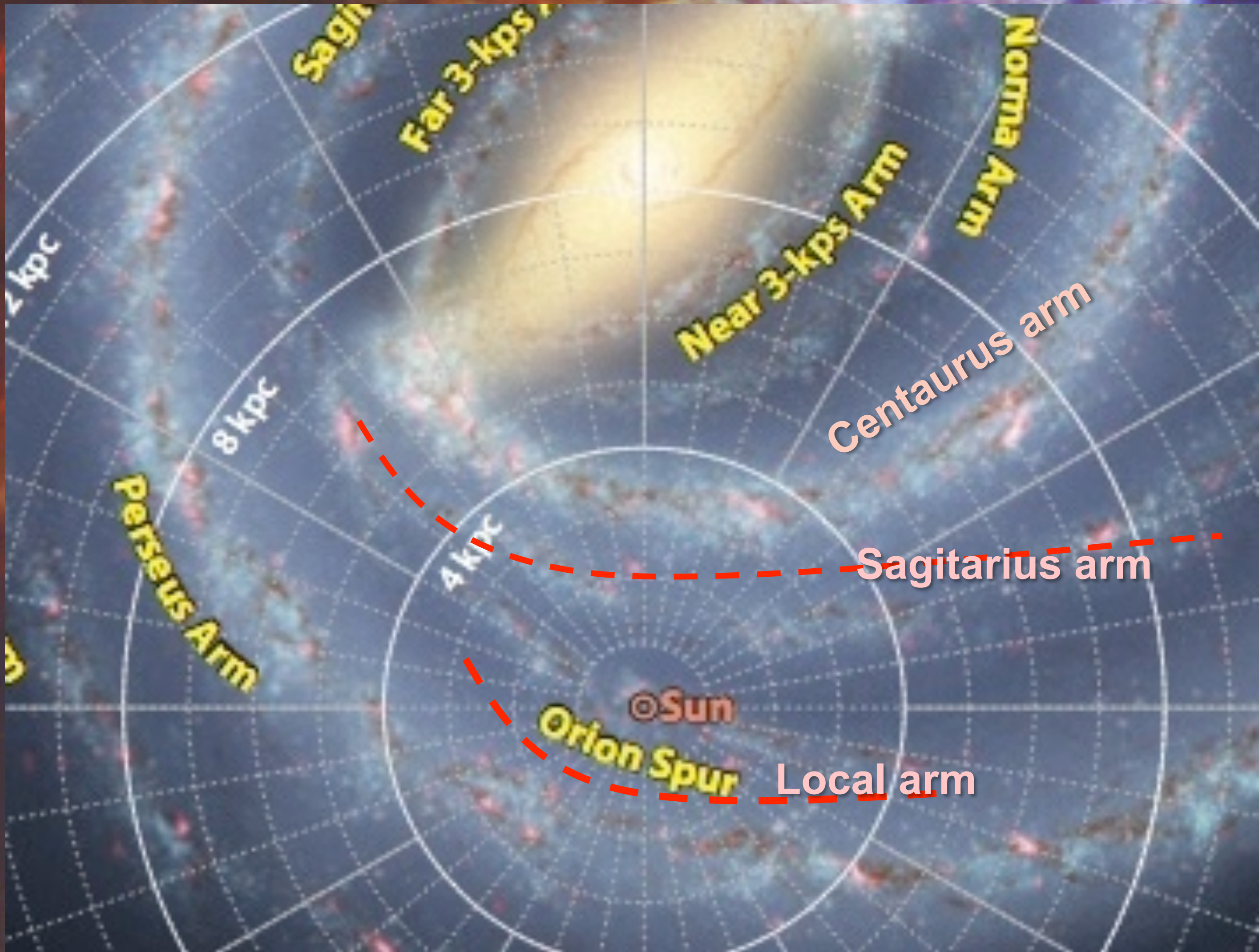
- 50-100 pc at d = 0.7-3 kpc
- $M_{cloud} = 2\ 10^5 - 1\ 10^6\ M_\odot$
- Forming up to 20 $M_\odot$ stars
- *Herschel* 70-500 μm

W43 HERO

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*, ALMA

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

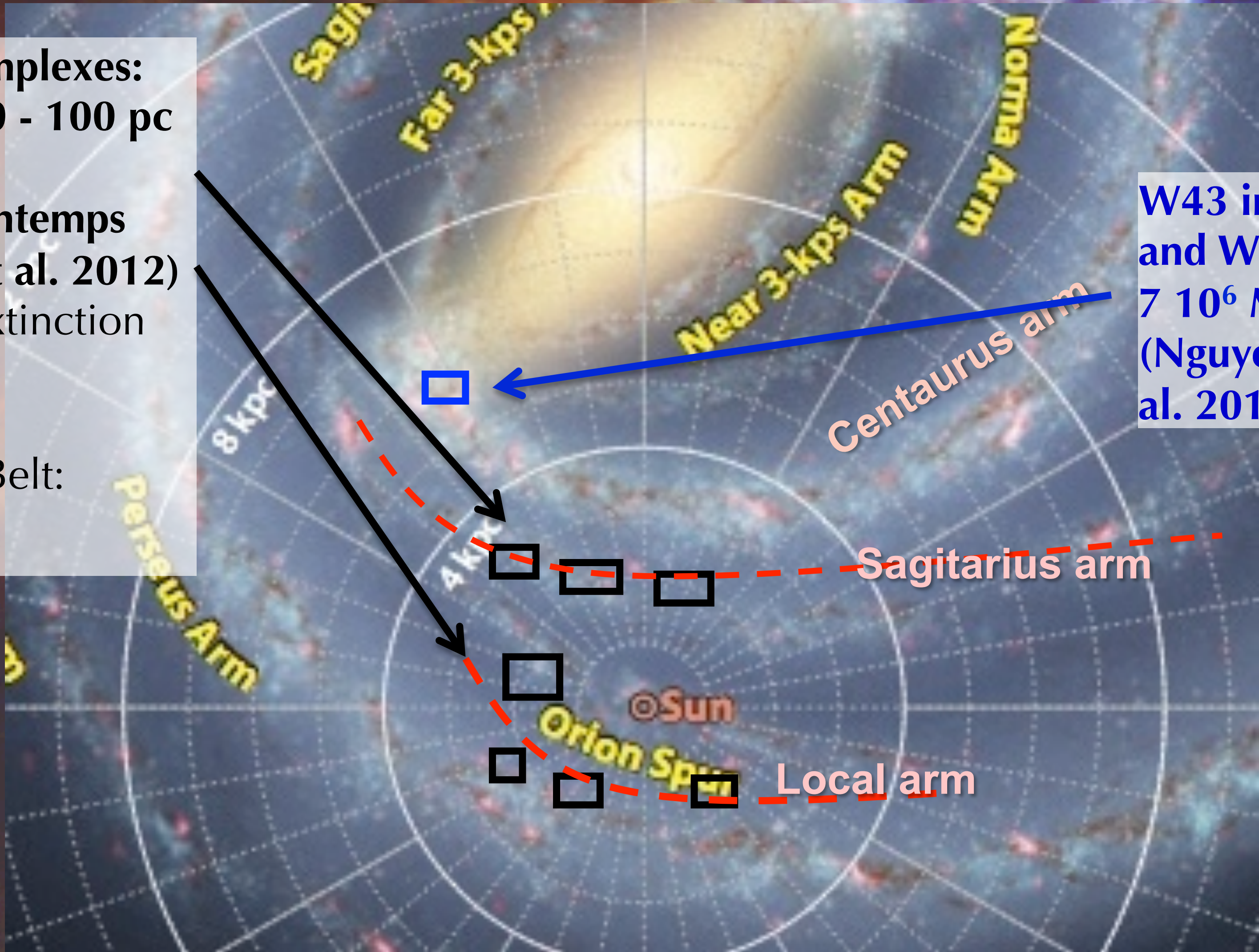


HOBYS molecular cloud complexes, pieces of the nearest spiral arms of the MW

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



W43 in Hi-GAL and W43-HERO:
7 10^6 $M_\odot$ 150 pc
(Nguyen Luong et al. 2011b)

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

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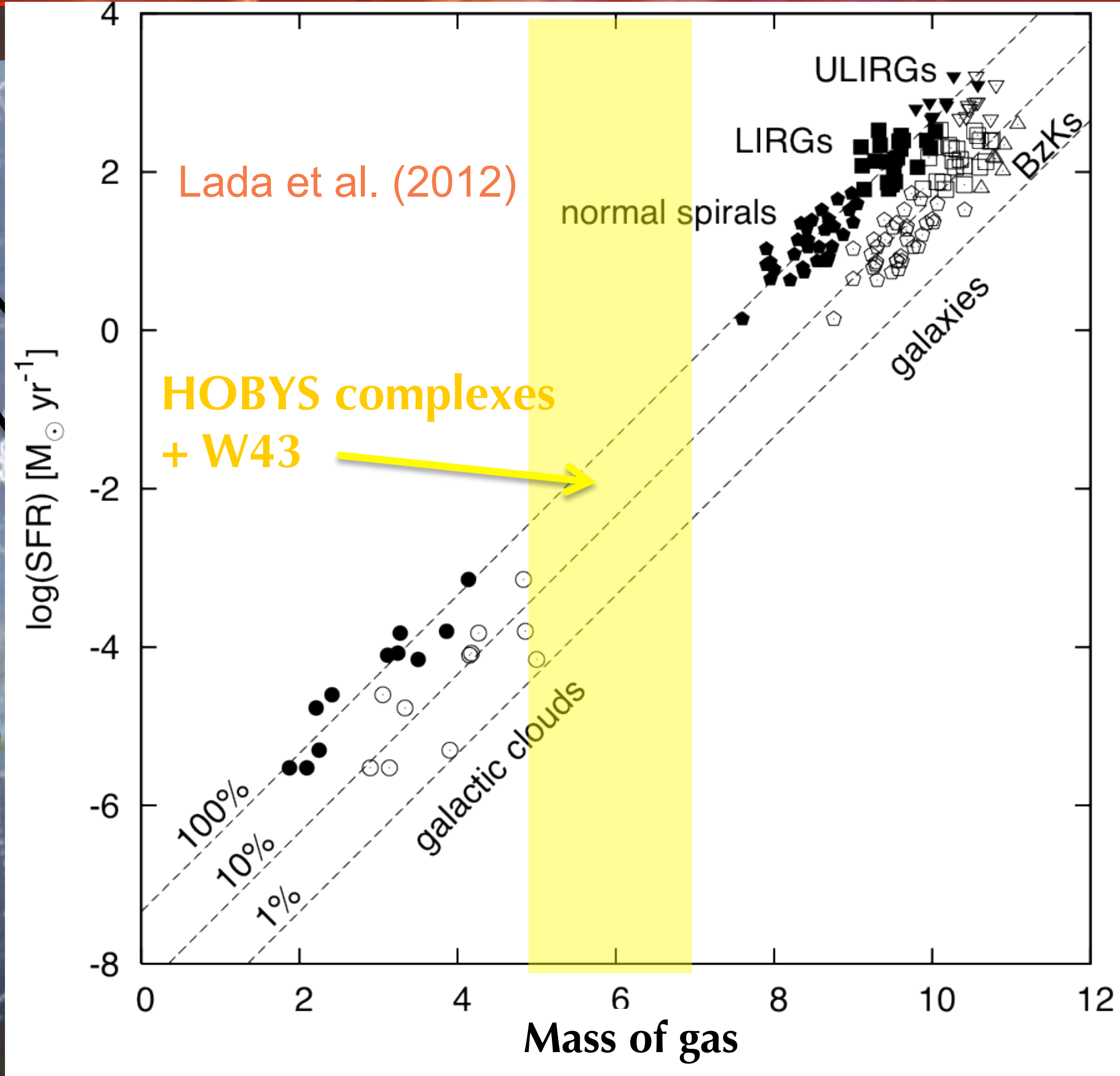

Outline: HOBYS and W43, two more steps toward a Galaxy-wide understanding of (high-mass) star formation

1. Cloud structure, kinematics, and star formation in ridges/hubs
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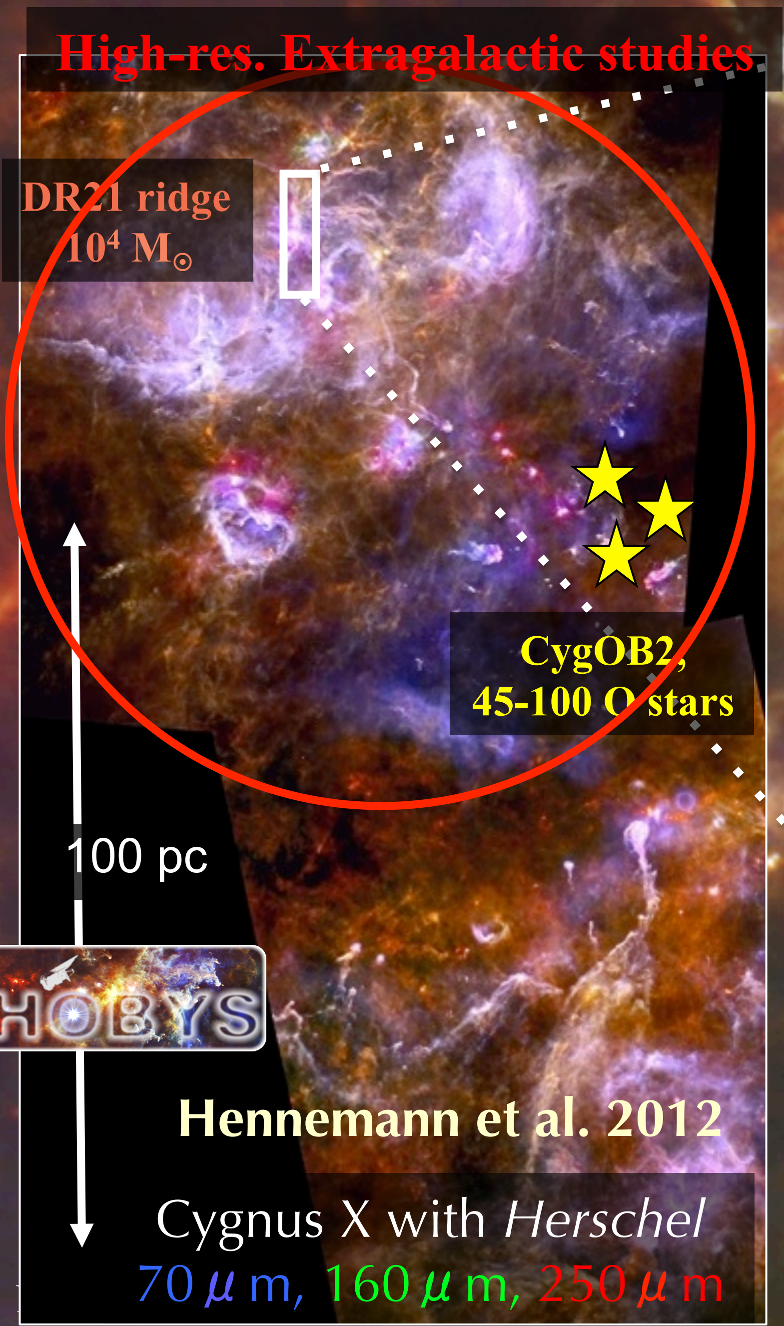
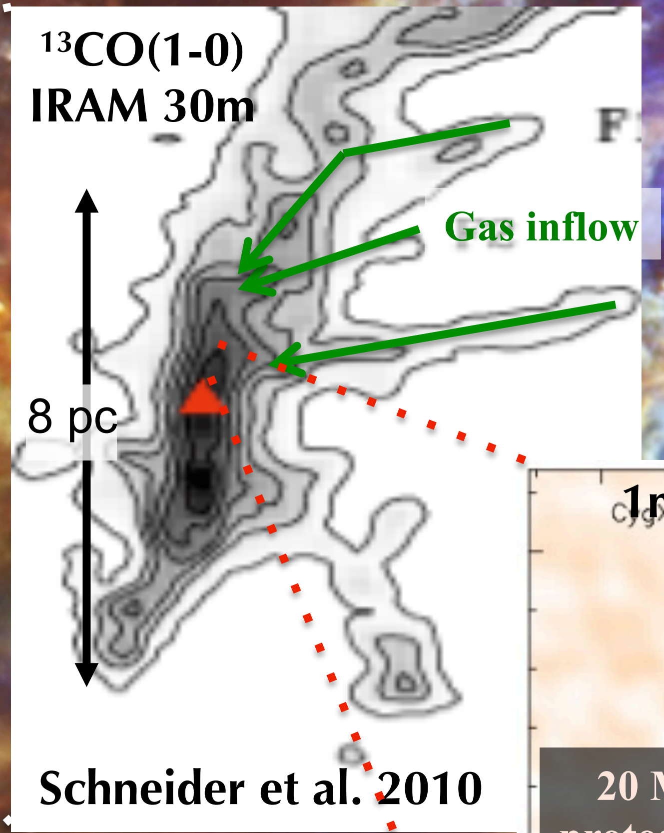
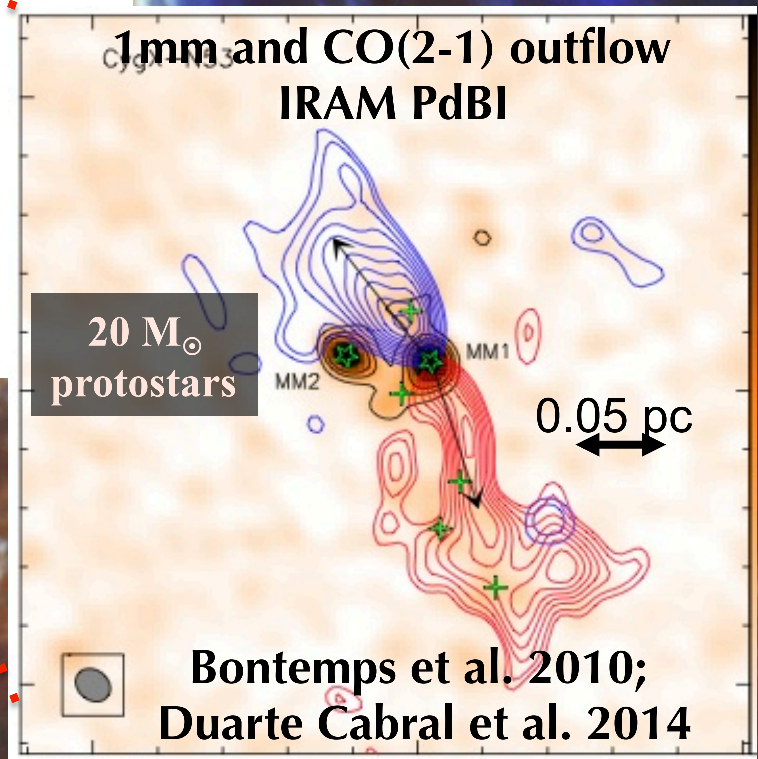
High-mass star formation: from clouds and protostars

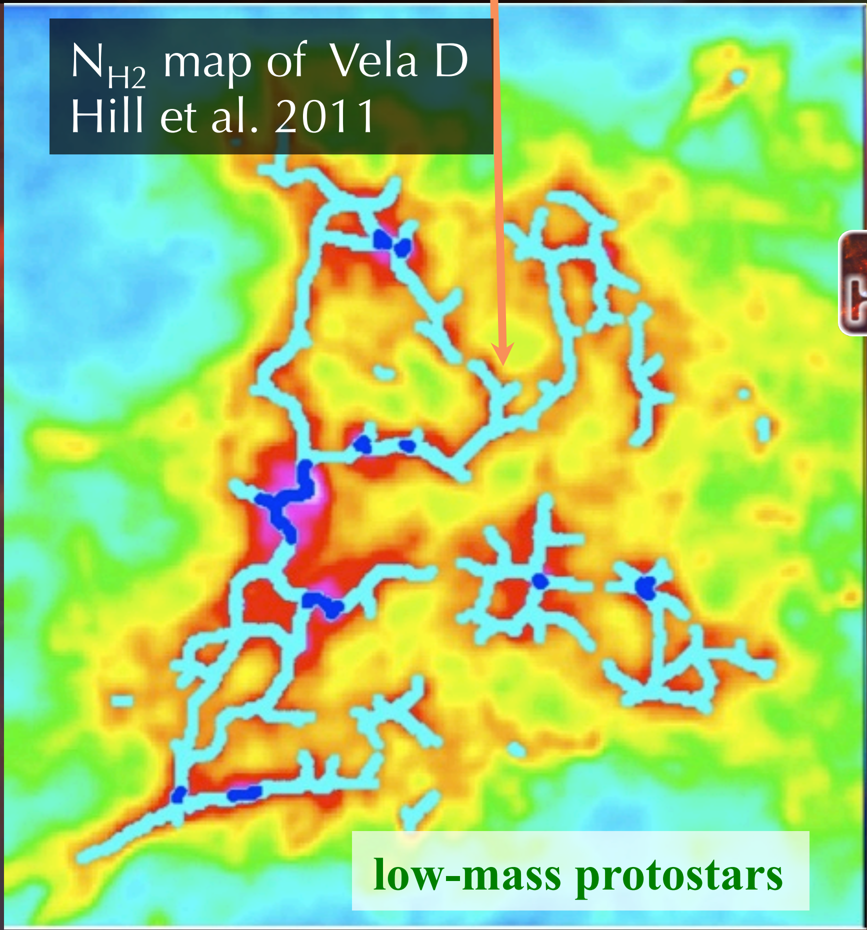


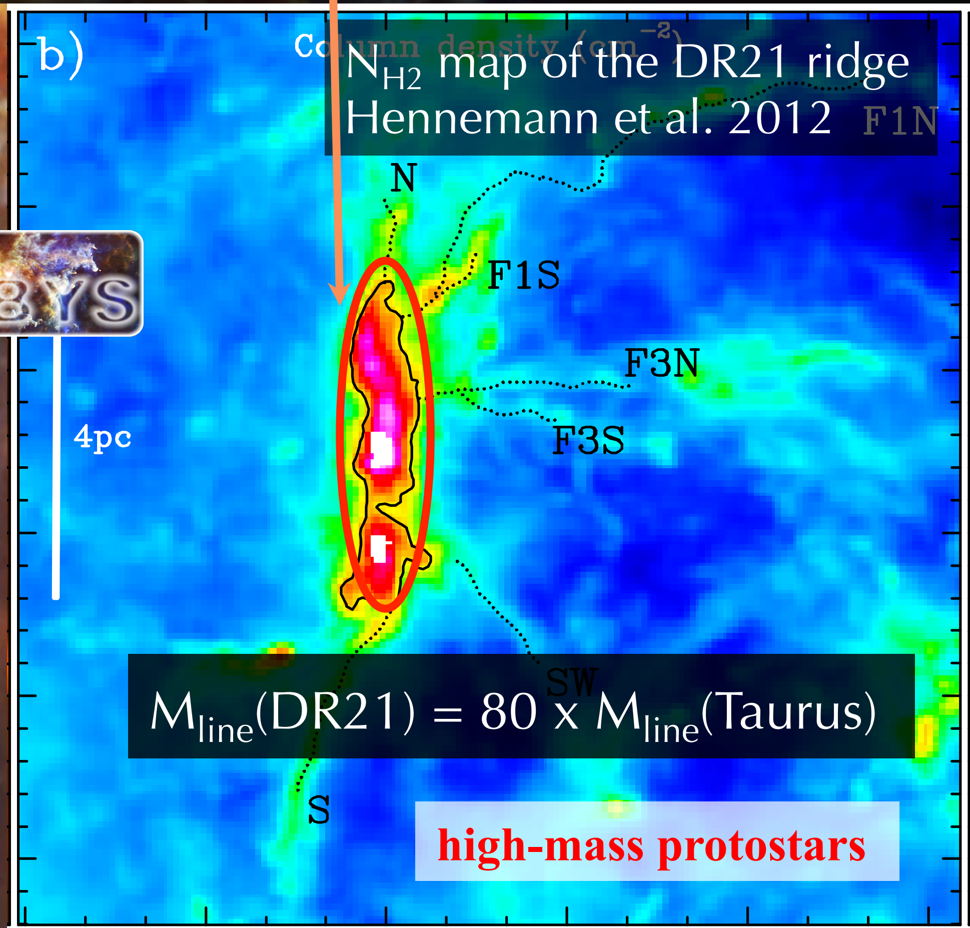




Different cloud structures form low- & high-mass stars

- Disorganized network of filaments versus single dominating ridges
- High-mass stars form preferentially in ridges, high-column density (Av > 100 mag), elongated cloud structures dominating their surrounding.





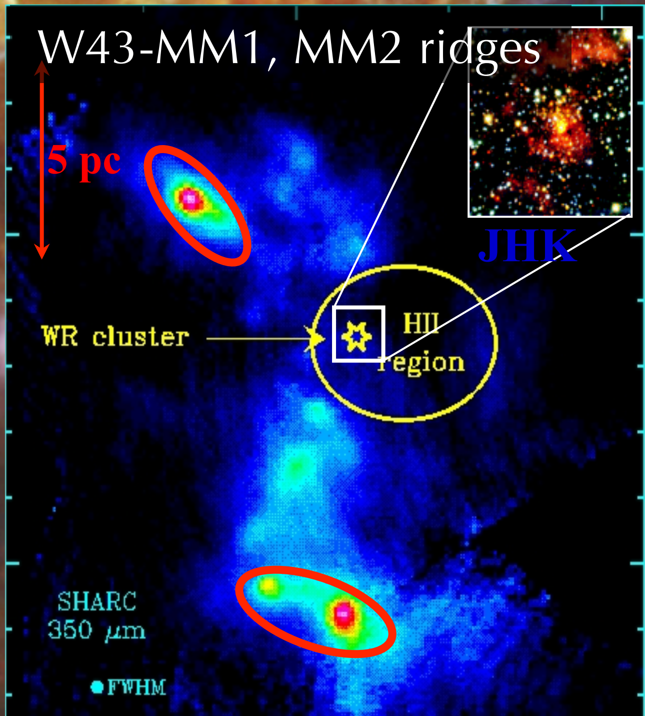
Ridges/Hubs are extreme clumps forming clusters of high-mass stars

- ~50% of the high-mass stars form in clusters within high-density elongated ridges, the other 50% form in spherical high-density hubs

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

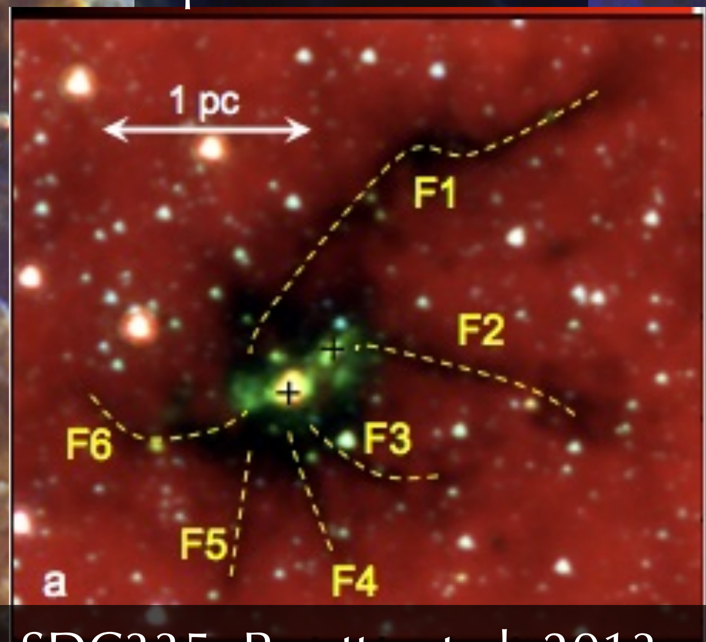
We use the 100 A_V level to identify them but it is not a physical threshold.

See also Hill+ 2011, Nguyen Luong+ 2011, Hennemann+ 2012, Didelon+ 2014, …



Nguyen Luong et al. 2013

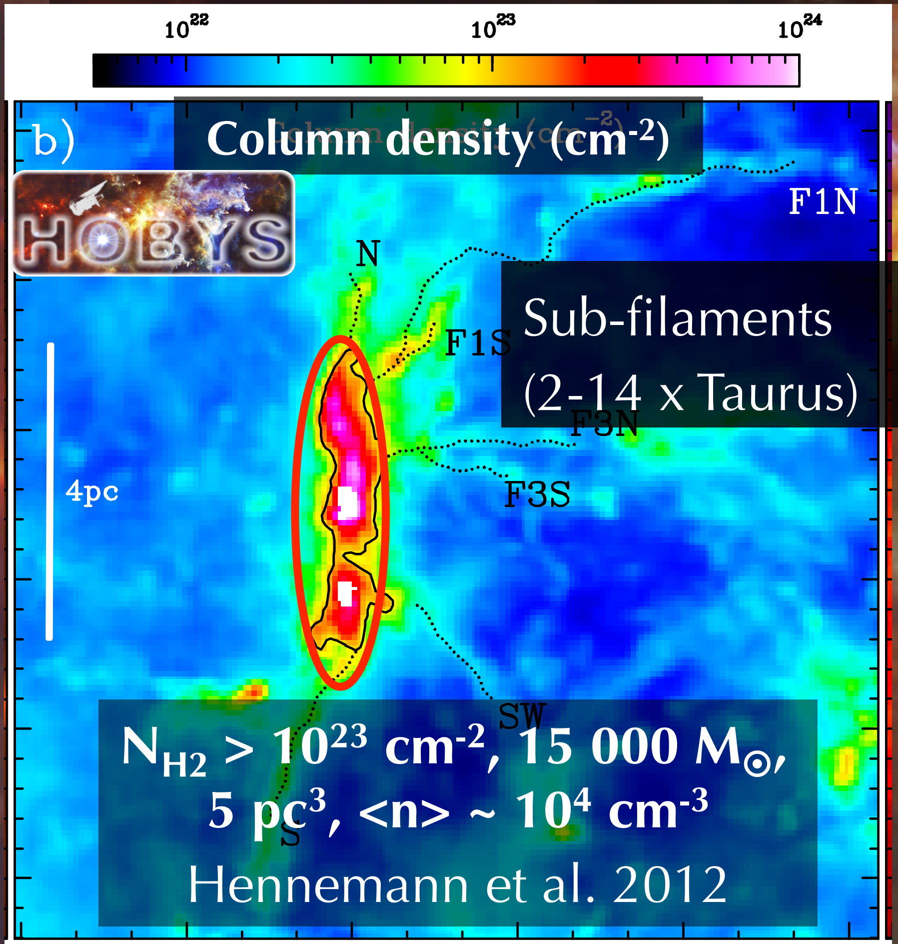
Spitzer IRDC hub

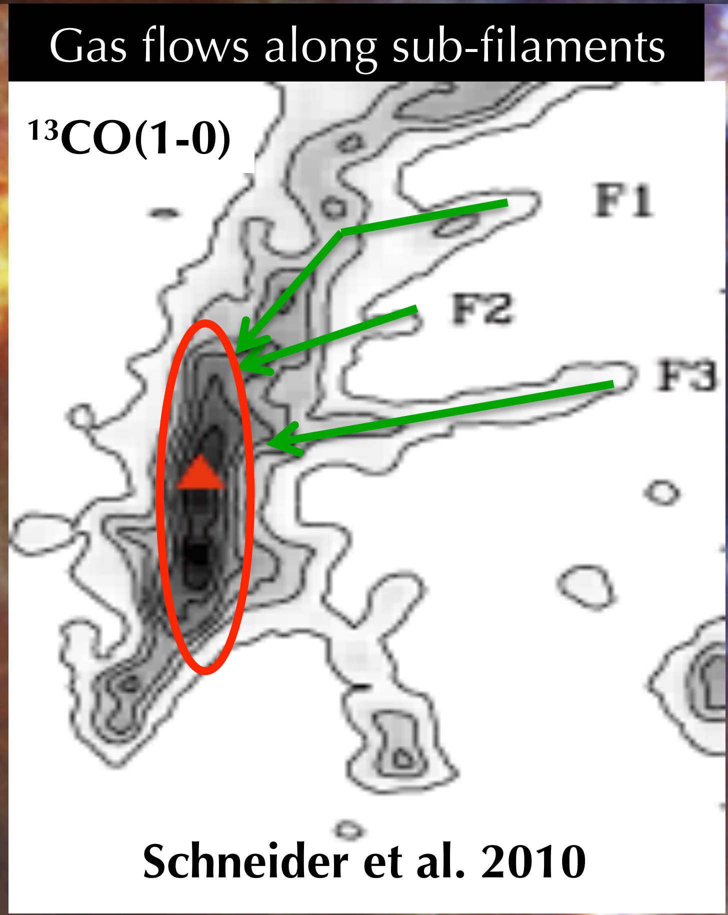


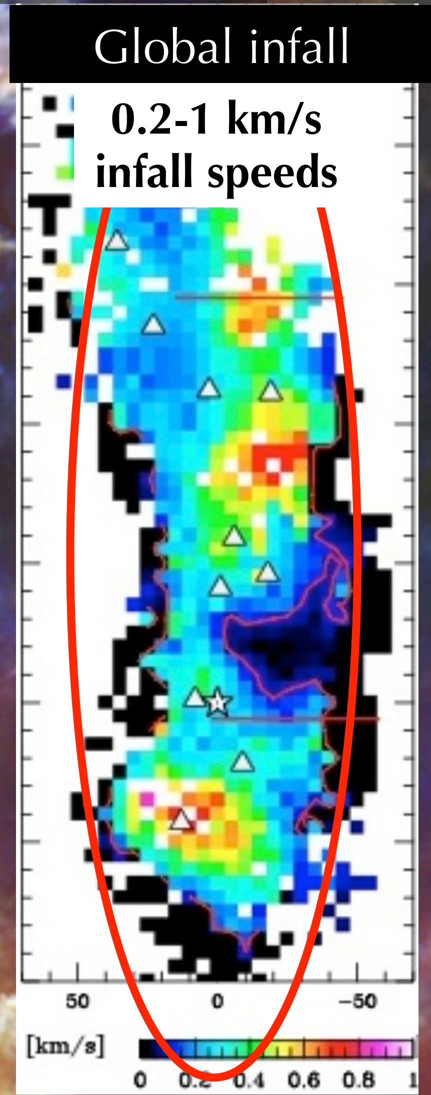
SDC335; Peretto et al. 2013

Most ridges/hubs should form by cloud global collapse

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

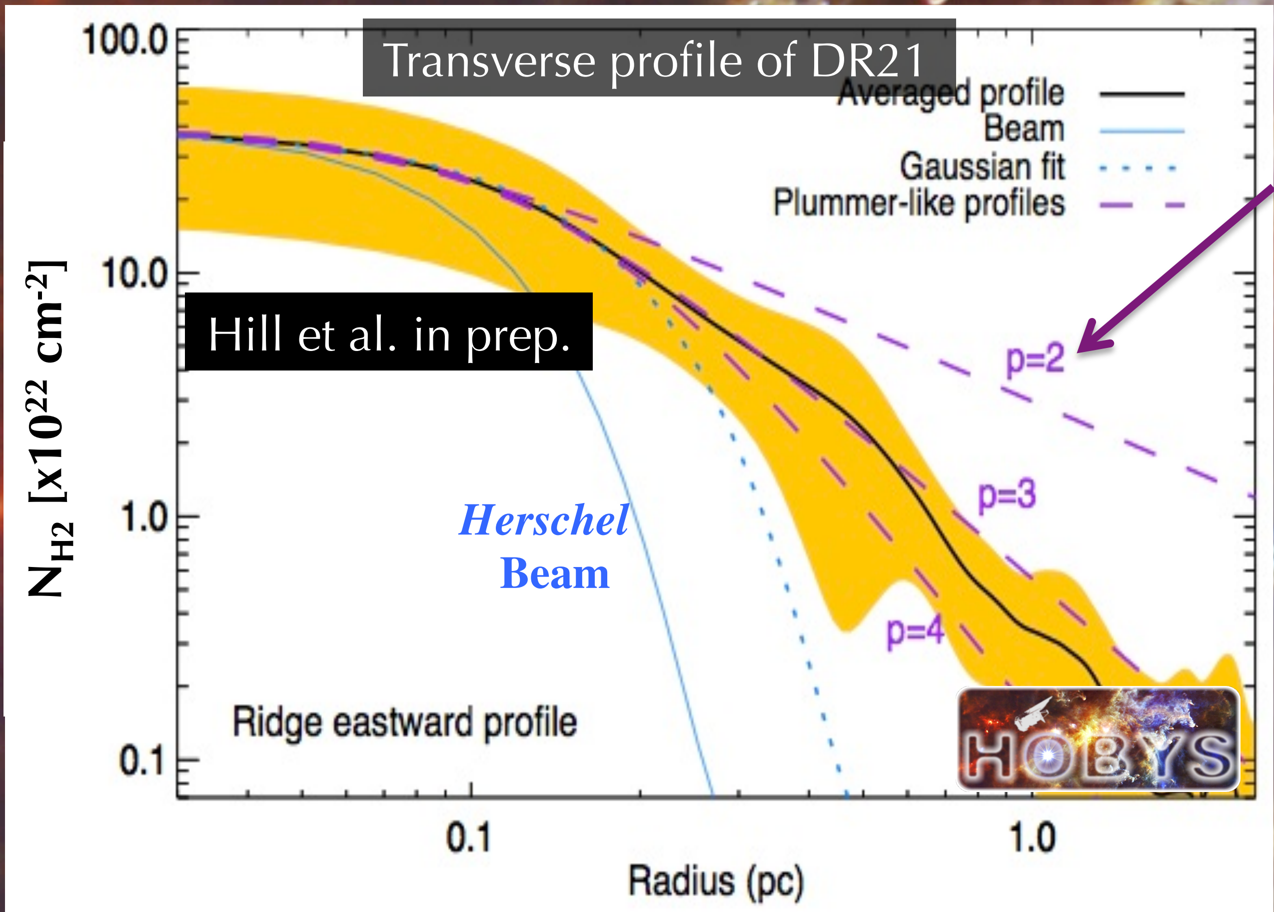






See also Peretto+ 2013, 2014; Beuther+ 2012; Nakamura+ 2014…

Ridge are substructured and compressed clumps



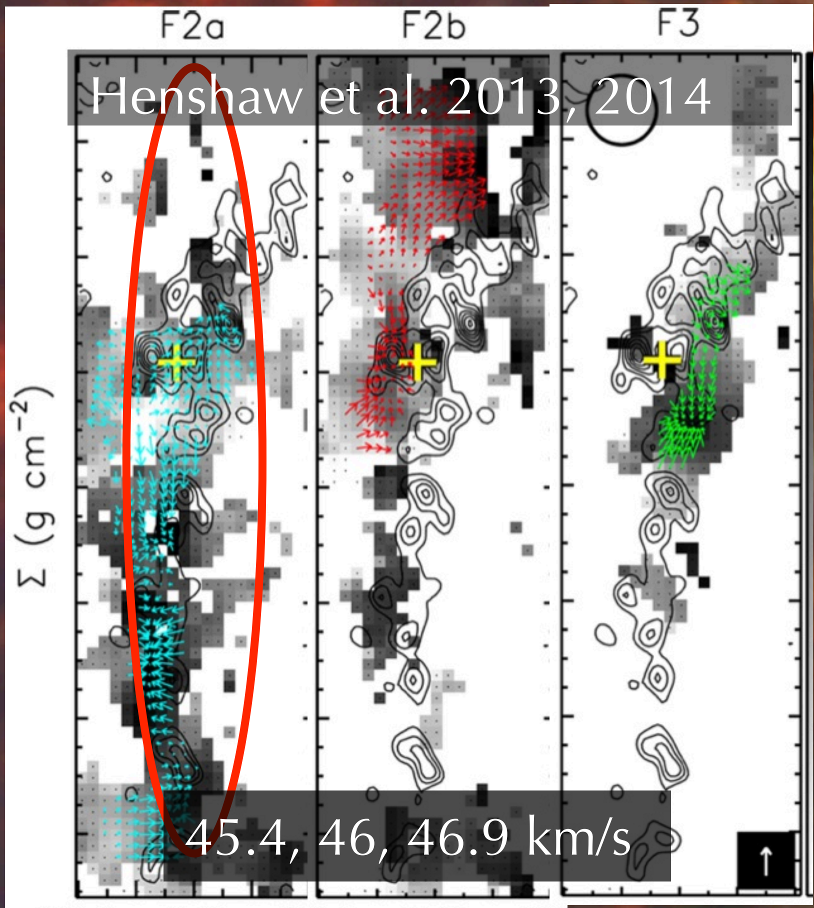
Herschel Gould Belt survey: Filaments are Plummer-like (e.g. Palmeirim et al. 2013).

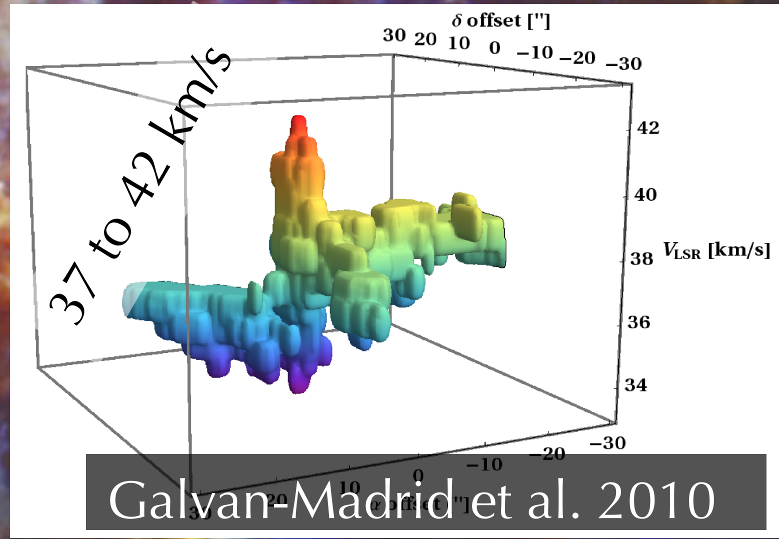
Gomez & Vazquez-Semadeni 2014; Hennebelle priv. com.: Globally collapsing filaments tend to have steeper density profiles…

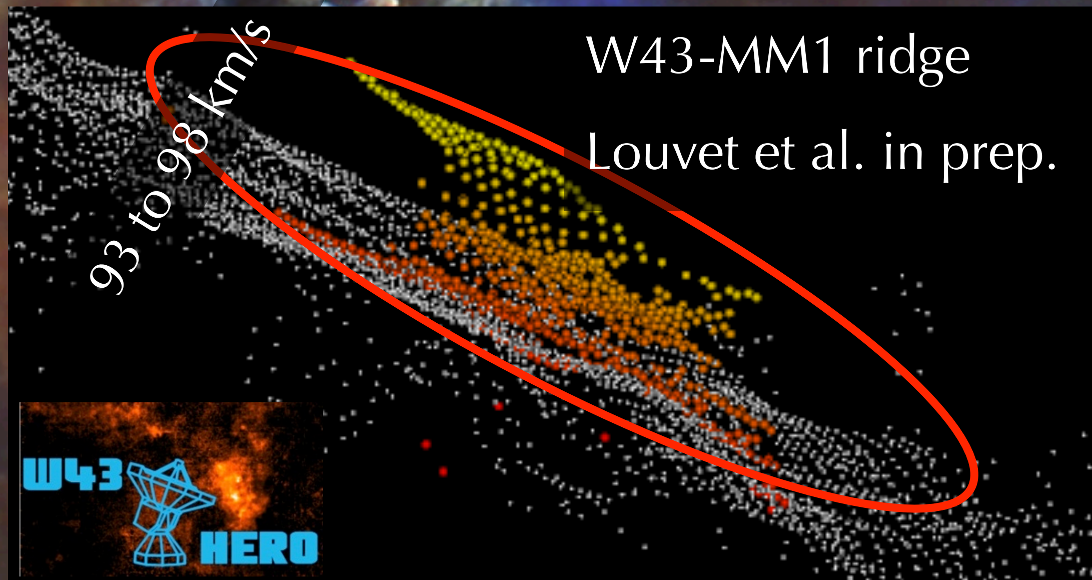
Similar density structure for the MonR2 hub (Didelon et al. 2014).
Consistent with PDF studies of Russeil et al. 2013; Rayner et al. in prep.

Ridges are bundles/braids of filaments/layers

Interferometric images in N_2H^+, NH_3 or $HN^{13}C$ display several pc filaments along ridges.



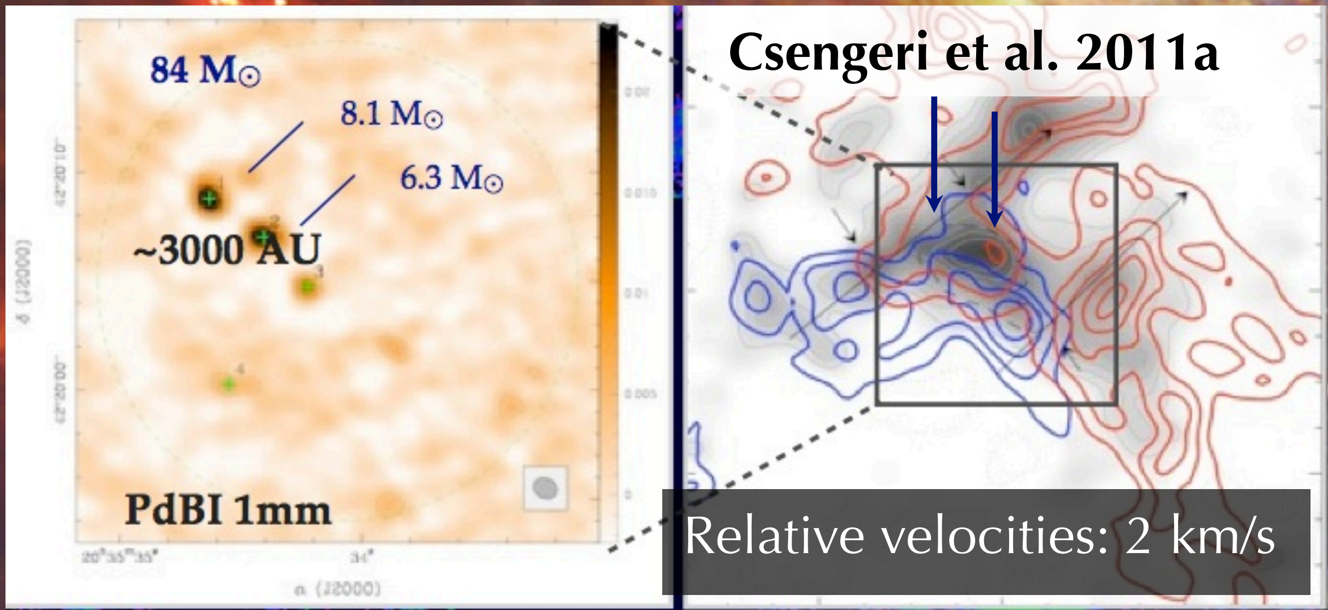


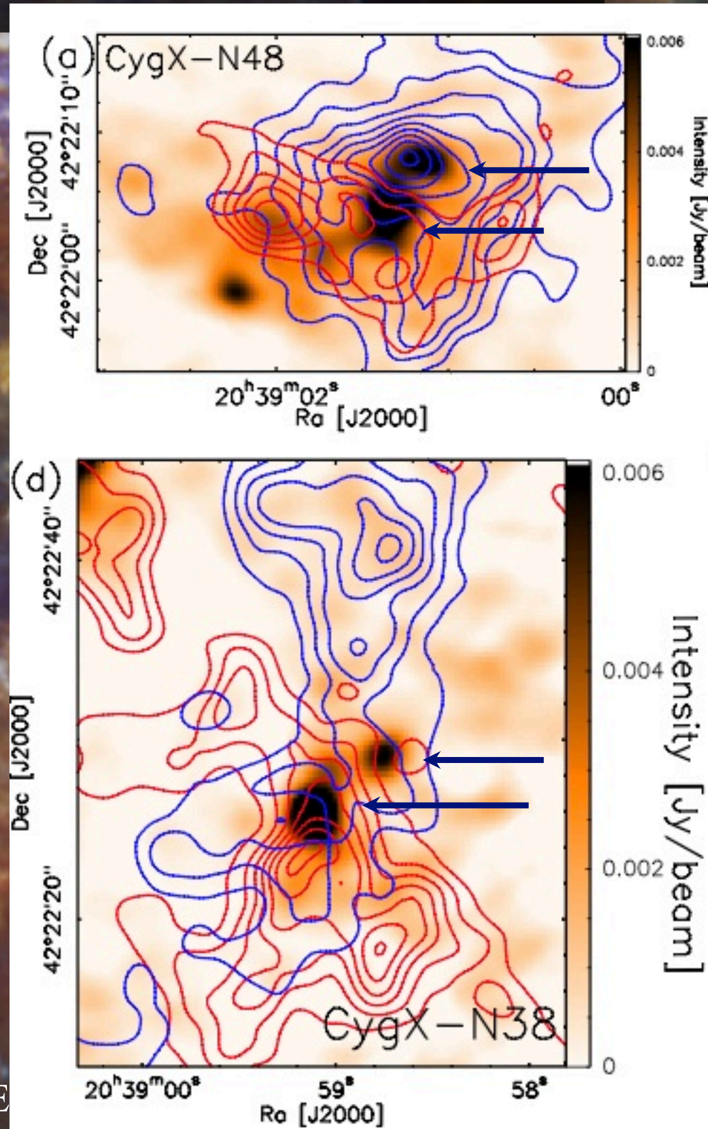


see also Tackenberg+ 2014

Velocity shears onto high-mass protostellar cores

Organized 0.05 pc flows in $H^{13}CO^+$ or N_2H^+ displaying shears at the location of high-mass protostars (Csengeri et al. 2011a, 2011b).

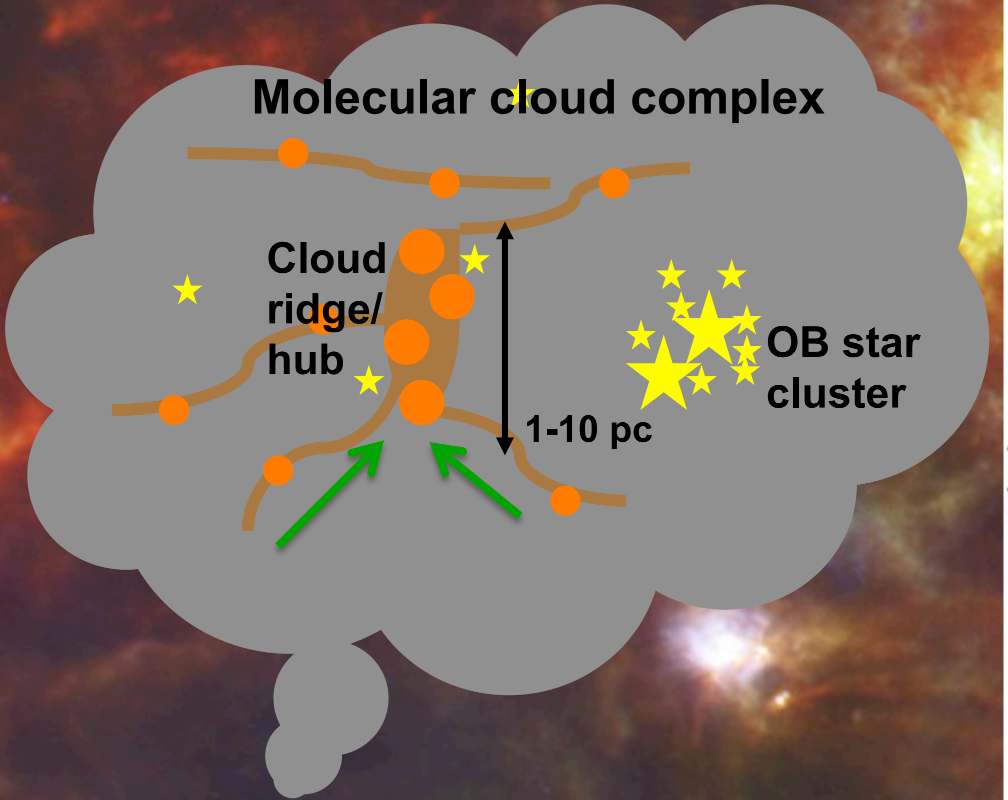


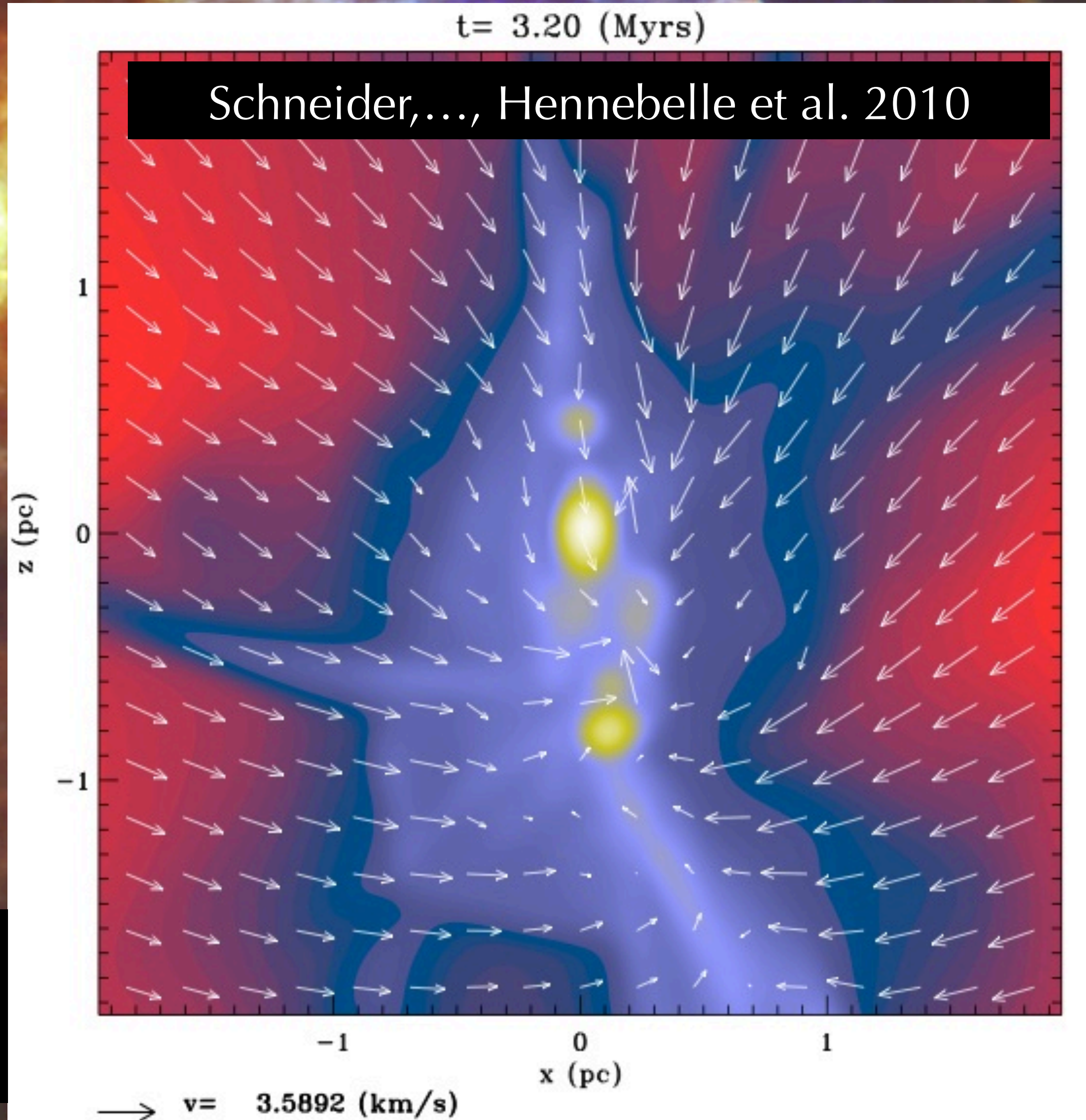


Consistent with numerical simulations by Smith et al. 2011, 2012.

Consistent with shock tracers (Csengeri et al. 2011b; Jiménez-Serra et al. 2011; Nguyen Luong et al. 2013; Sanhueza et al. 2013; …)

In ridges and hubs "gas reservoir" should replace "core": gas is accreted onto ridges/hubs and in turn onto protostars





Picture consistent witn numerical simulations by Inoue & Fukui 2013, Gomez & Vazquez-Semadeni 2014…

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Herschel/HOBYS measures "instantaneous" SFE/SFR

Making a **direct link** between protostars and their cloud, *Herschel* measures instantaneous SFE,

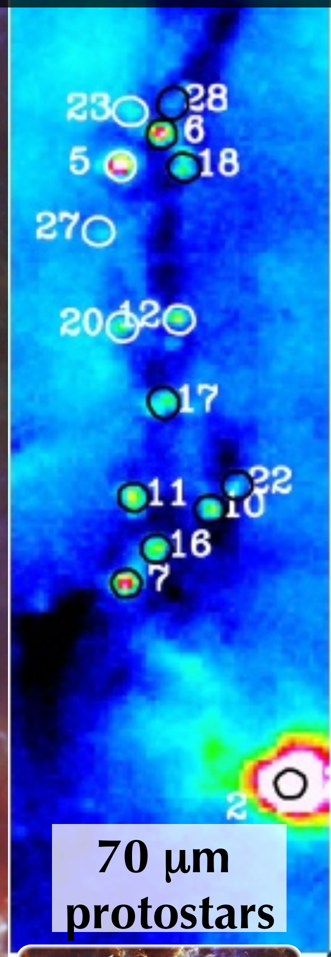
easier to compare with statistical models of SFR (e.g.Krumholz & McKee 2005; Padoan & Nordlund 2011; Hennebelle & Chabrier 2011, 2013; Federrath et al. 2012).

- *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)

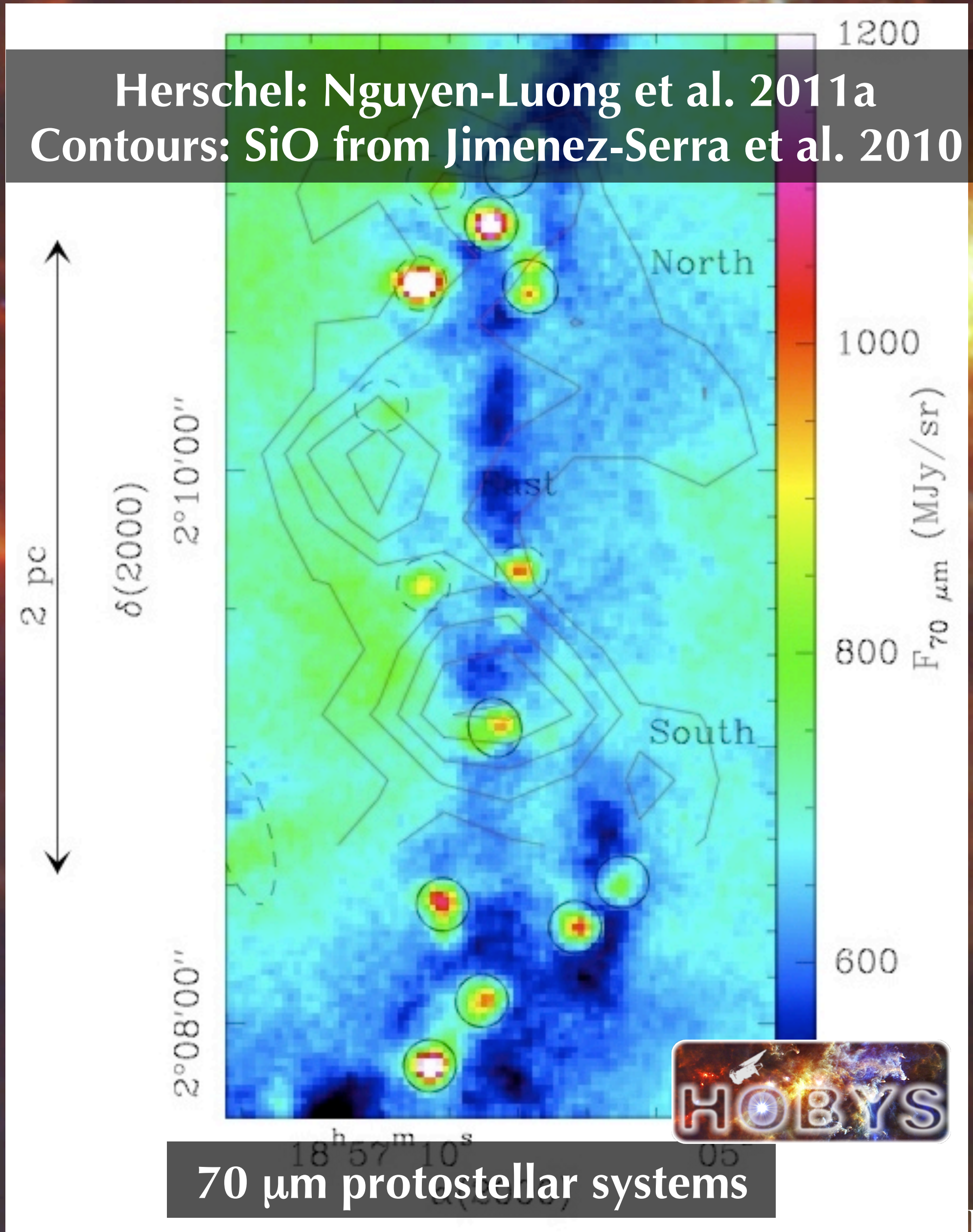
➔ "Integrated" / "Past" SFR

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

Nguyen Luong et al. 2011a



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



Herschel: Nguyen-Luong et al. 2011a
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:

✓ **<u>Core-to-star mass efficiency</u>: ε ~ 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**

✓ **<u>Kroupa IMF</u> applied to the ridge**

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

Ridges/hubs represent Galactic mini-starbursts

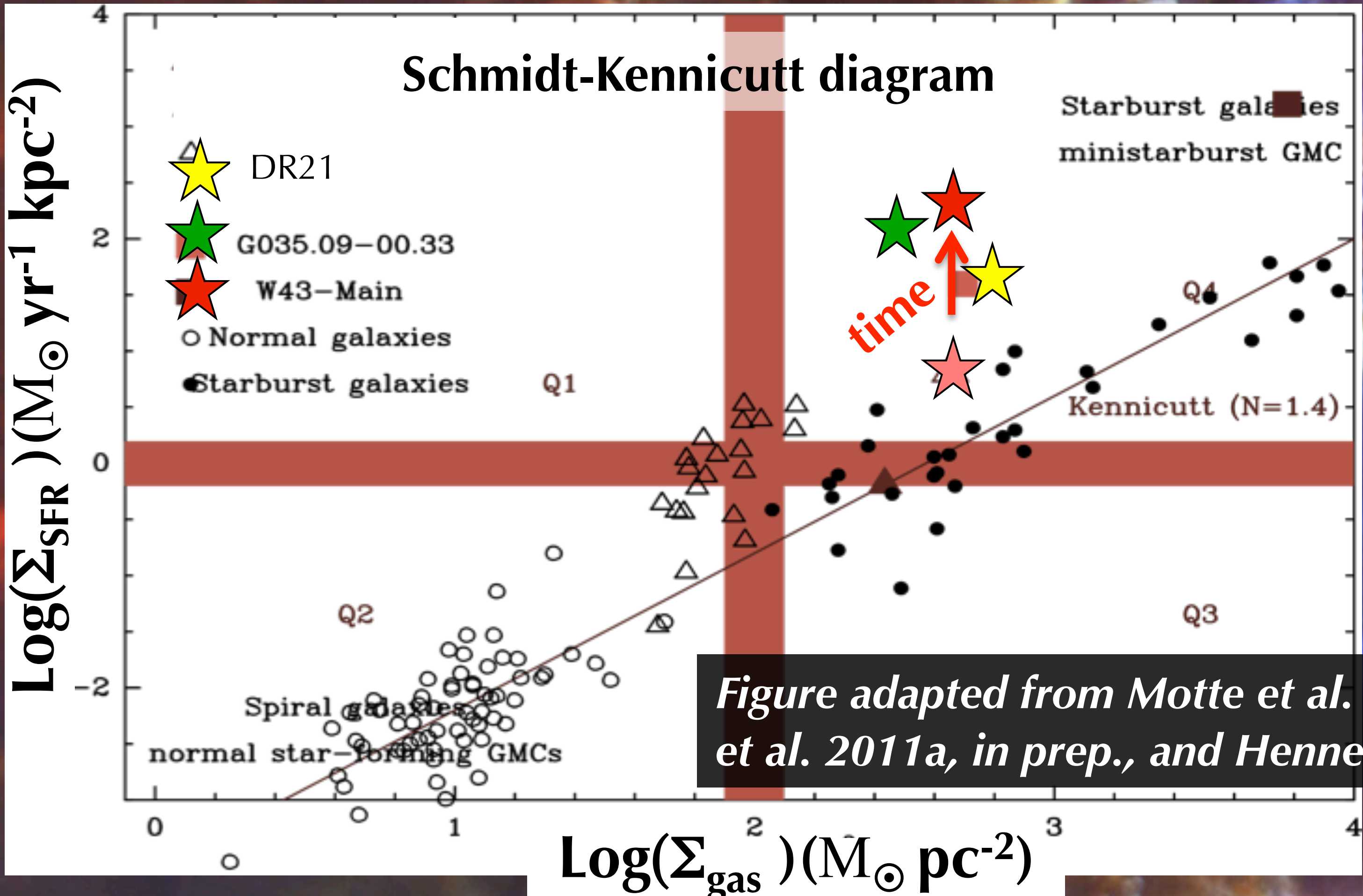


Figure adapted from Motte et al. 2003; Nguyen Luong et al. 2011a, in prep., and Hennemann et al. in prep..

Starburst quadrant:

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

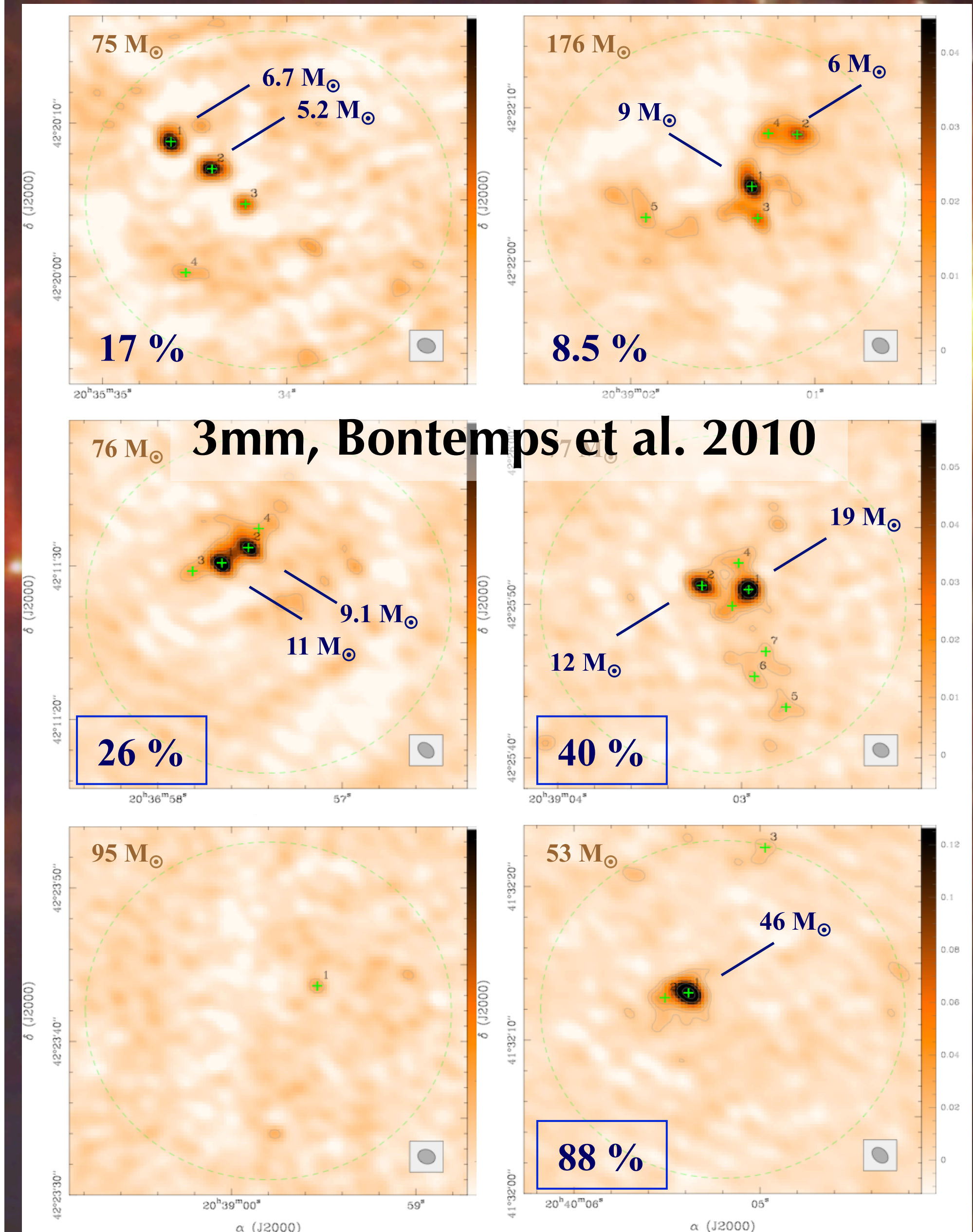
$\Sigma_{gas} > 100\ M_{\odot}/pc^2$

These pioneering studies need to be generalized…

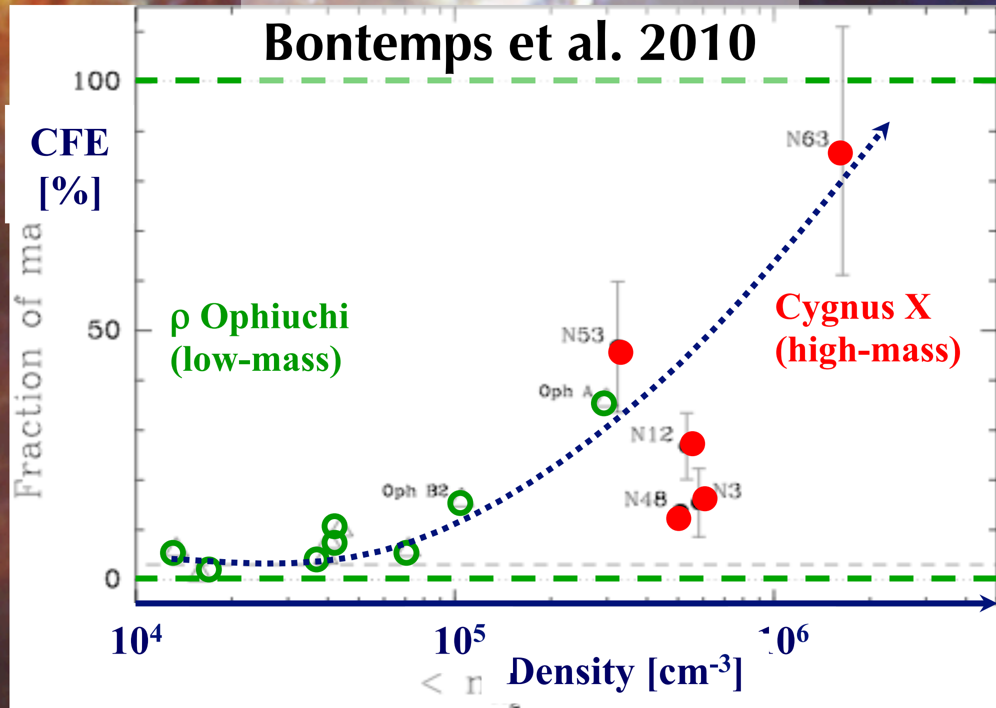
Caveats: Core-to-star formation efficiency assumed to be constant

Extrapolation of a standard IMF to mini-starburst ridges

Concentration of gas down to the "core" scales



- 0.02 pc high-mass protostellar cores
- Mass segregation
- CFE = Mass within protostellar cores / Mass of the surrounding clump



(See also Motte et al. 1998; Palau et al. 2013)

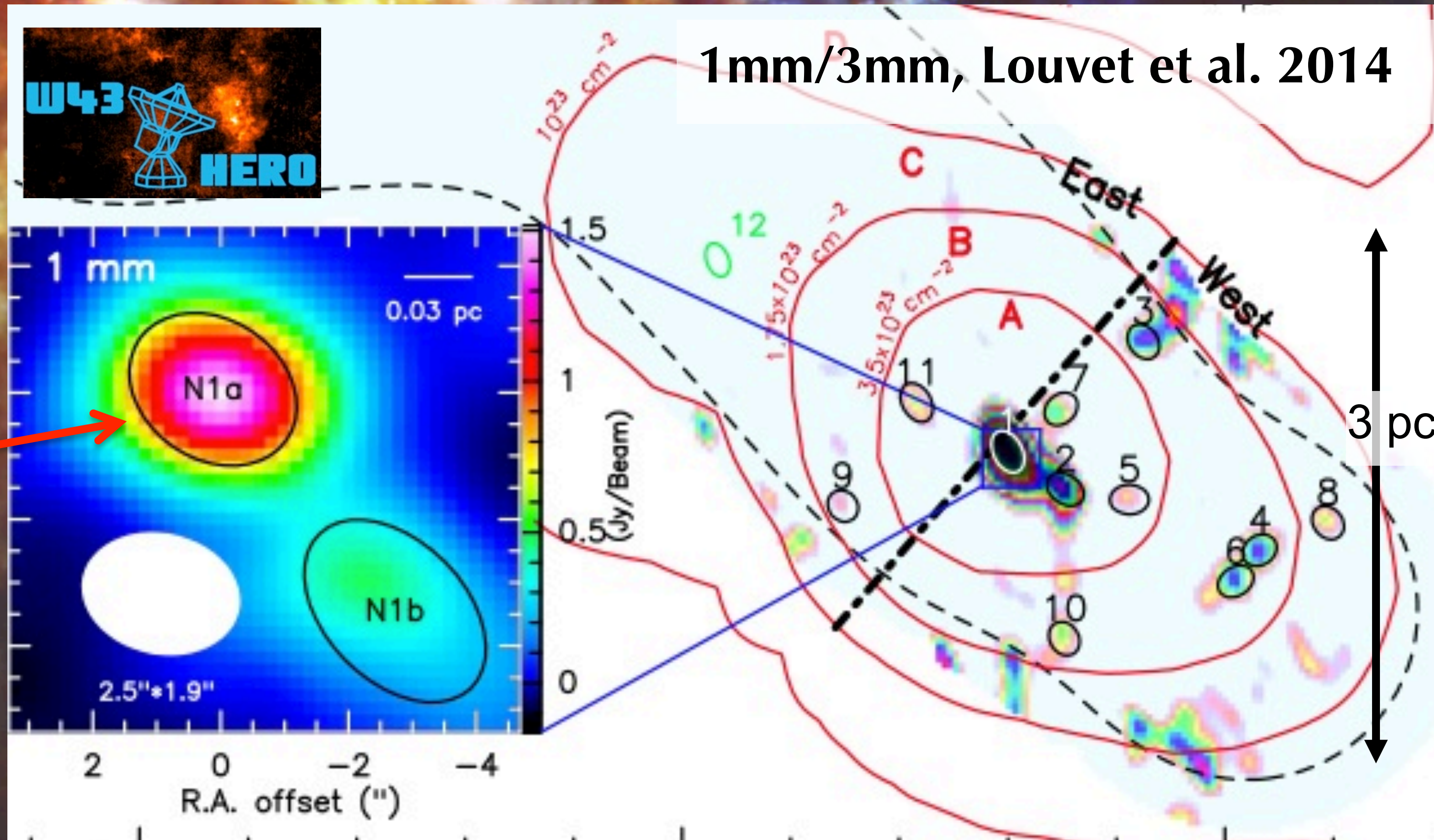
Are thresholds and constant SFE correct?

Lada et al. (2010, 2012) relation between SFR and cloud mass implicitely assumes a constant SFE in regions above the SF threshold ($n_{H2} > 1.5\ 10^4\ cm^{-3}$). See also Evans et al. 2014, André et al. 2014,… and SFR theoretical models.

IRAM Plateau de Bure census of protostars in the W43-MM1 ridge

- finds the most massive class0-like protostar: N1a: 1100 $M_{\odot}$ 0.03 pc

- investigates SFE within subregions A, B, C, D



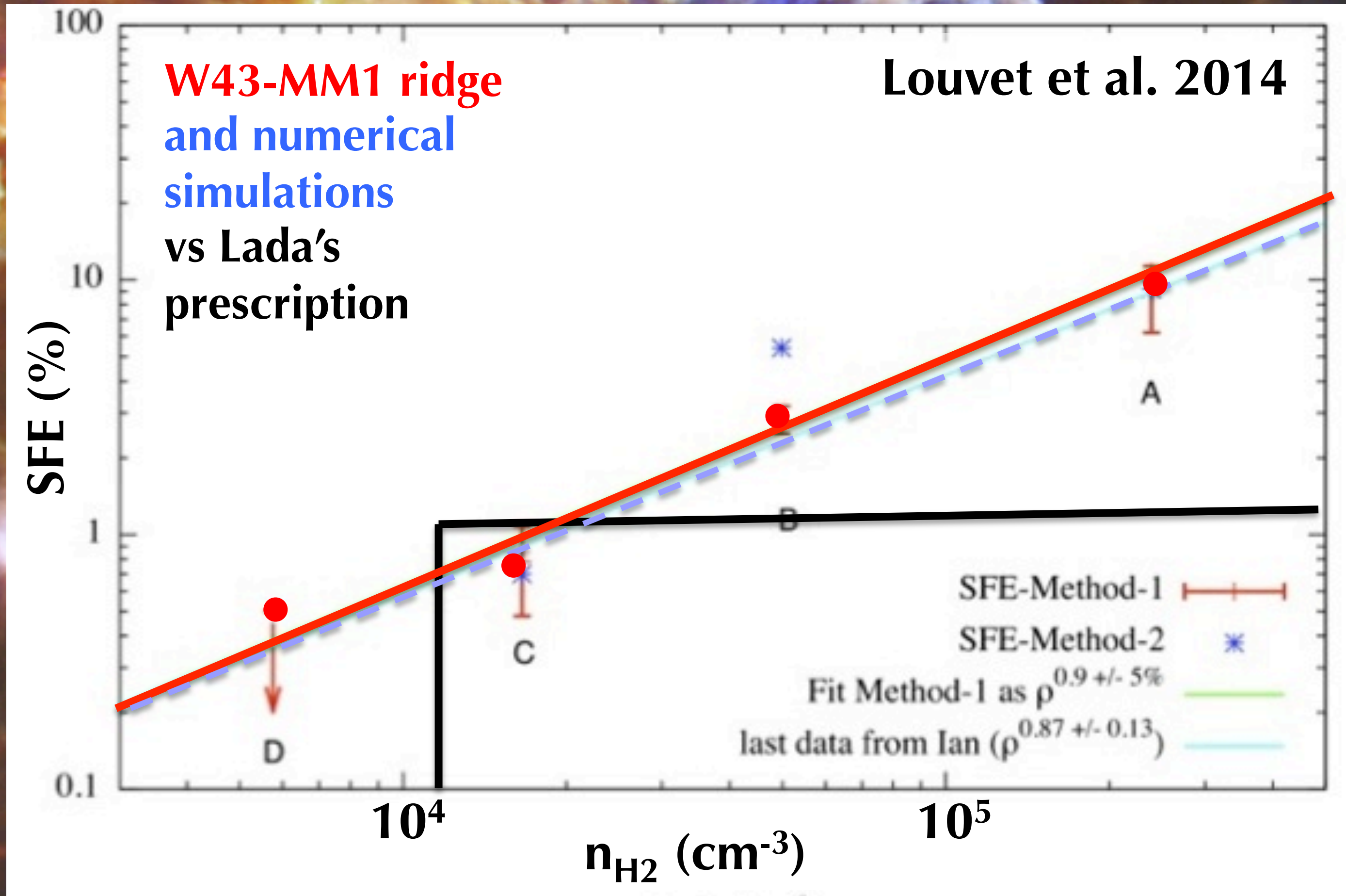
Are thresholds and constant SFE correct?

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

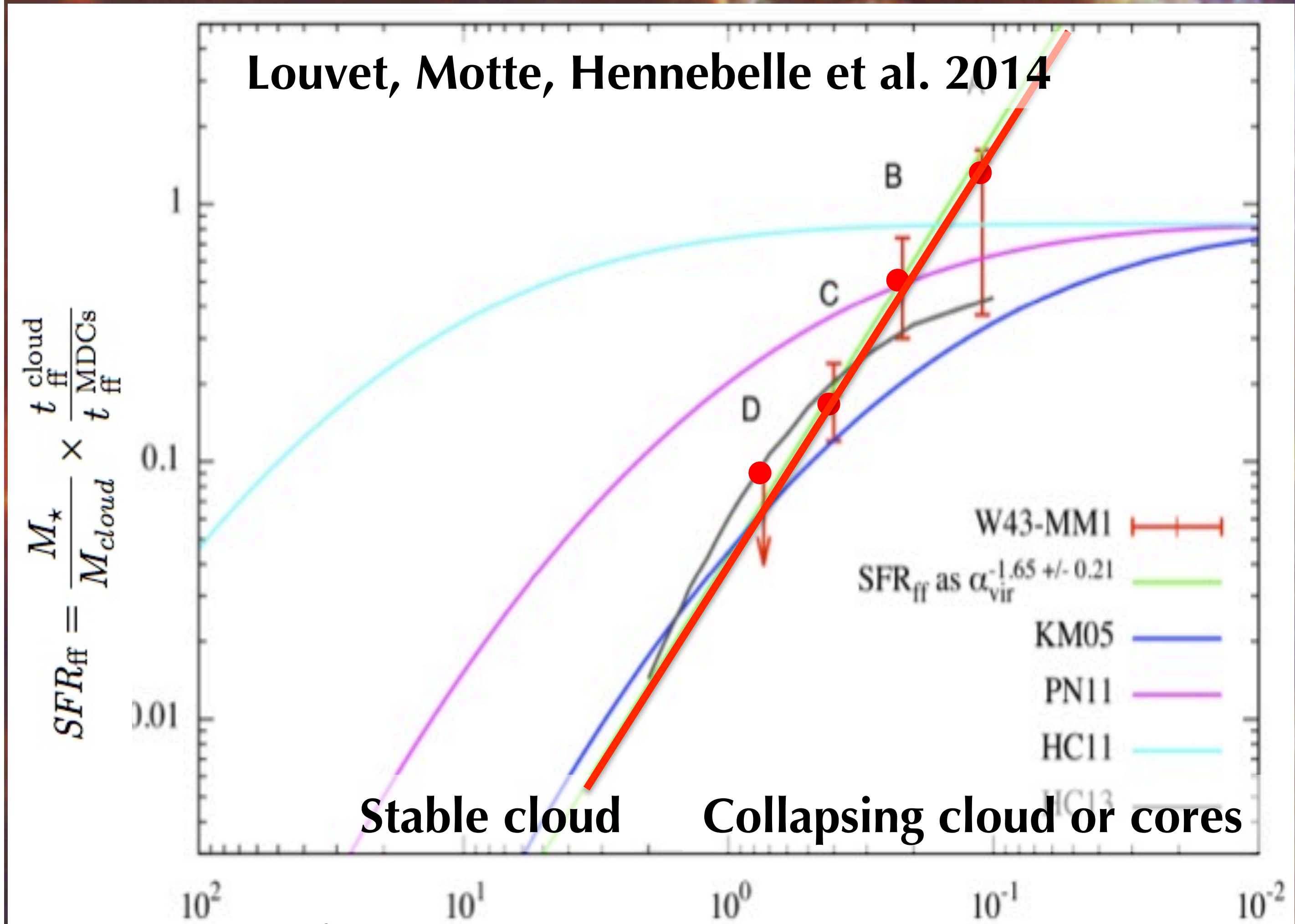
In contradiction with Lada's 2010/2012 prescription…

In agreement with previous CFE studies (Bontemps et al. 2010, Palau et al. 2013)

⇒ Cloud density sets SFE and the mass of the most massive stars that will form.



Constraining statistical theories of SFR on W43-MM1…



$$\alpha_{vir} = \sigma_s^2 \times R_{nuage} \times \frac{5}{3\,G\,M_{nuage}}$$

- 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…

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W43, a cloud agglomeration ahead of the Galactic bar

- 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)

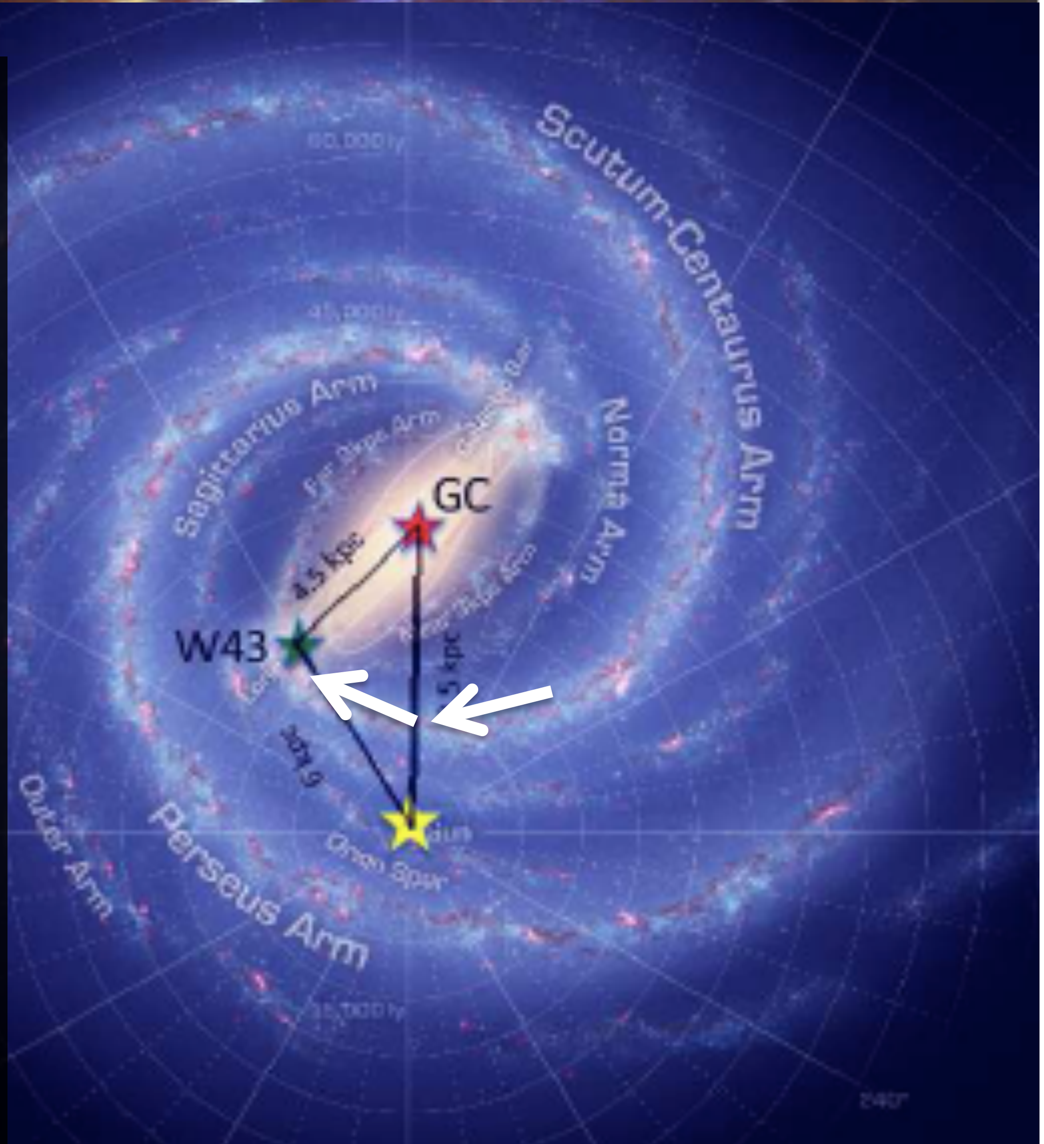
- High concentration of gas and high SFR

⇒ Located in front of the Galactic long bar *(Nguyen Luong+ 2011b)*, consistent with models of Wozniak+2007; Renaud et al. in prep.

- ^{12}CO gas is flowing along the Galactic arm toward W43

⇒ Formed by molecular cloud collision

(Motte+ 2014; Onishi+ 2015)

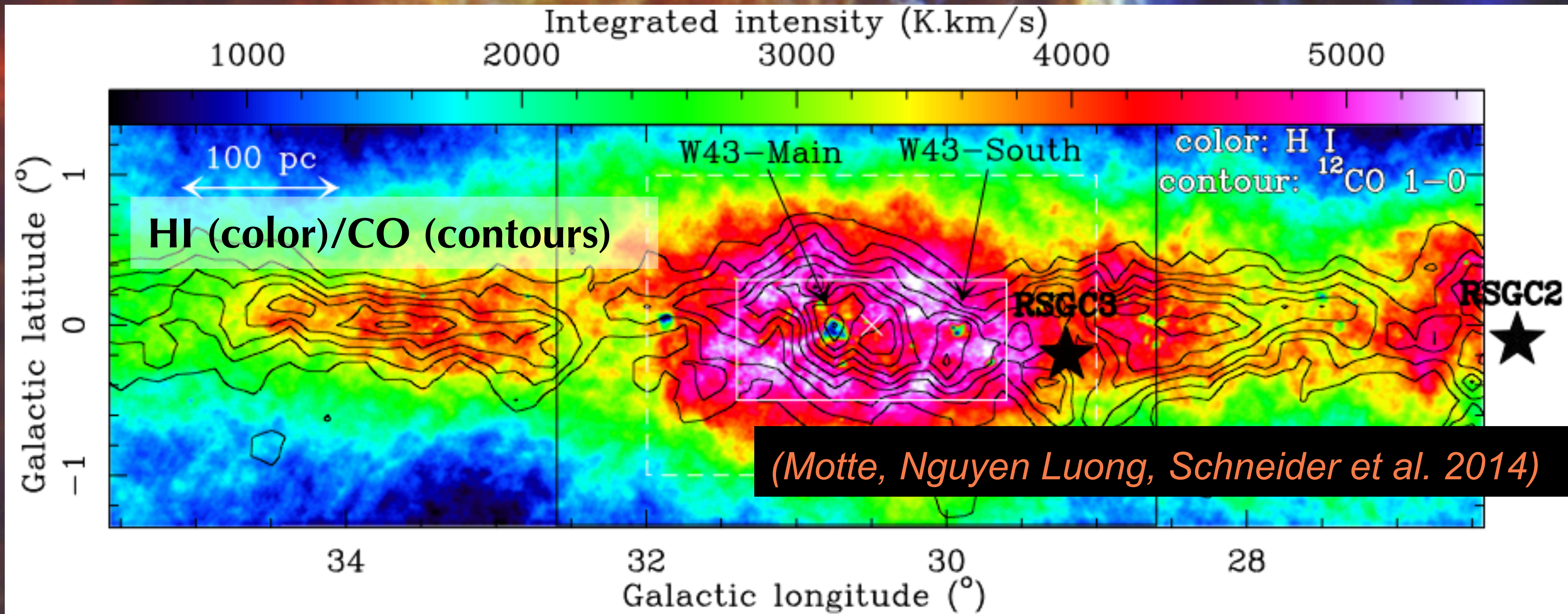


Adapted from Churchwell et al. (2009)

Searching for an HI surface density threshold

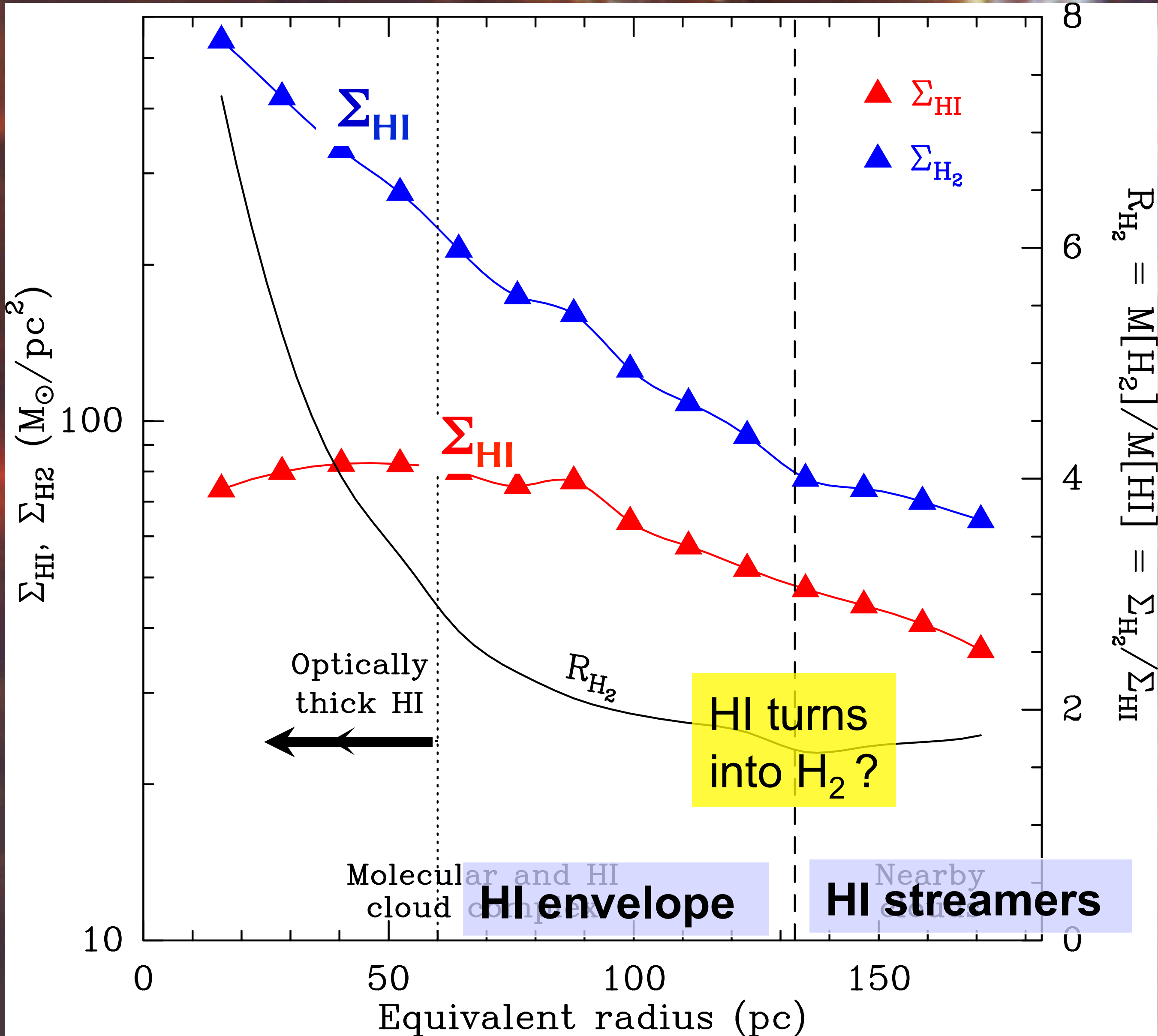
Saturation of the HI surface density generally observed (e.g. Blitz & Rosolowsky et al. 2006; Bigiel et al. 2008; Barriault et al. 2010; Lee et al. 2012) and predicted by equilibrium models (Krumhloz et al. 2009) at $\Sigma_{HI} \sim 5\text{-}15\ M_{\odot}/pc^2$

W43, with its well-defined symmetrical envelope of 270 pc 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)

Conclusions, warning, and future work

Proposed steps toward SF in ministarburst ridges/hubs

1. MHD turbulent shocks build-up filaments that gently accrete from their surrounding.
2. Gravity braids filaments in a collapsing clump attracting more filaments. Stars and filaments simultaneously form and grow. In these environments protostellar accretion is non-local & anisotropic.

⇒ HOBYS and W43-HERO results point toward linking highly-dynamical molecular cloud formation to high-density clouds and intense star formation activity.

- Warning on the definition of a molecular cloud and thus its total mass, lifetime, global SFE…
- We still lack high-angular resolution and kinematical data.
- We would need to have SF models more adequate for ministarburst ridges.