Clusters of high-mass protostars: From extreme clouds to minibursts of star formation

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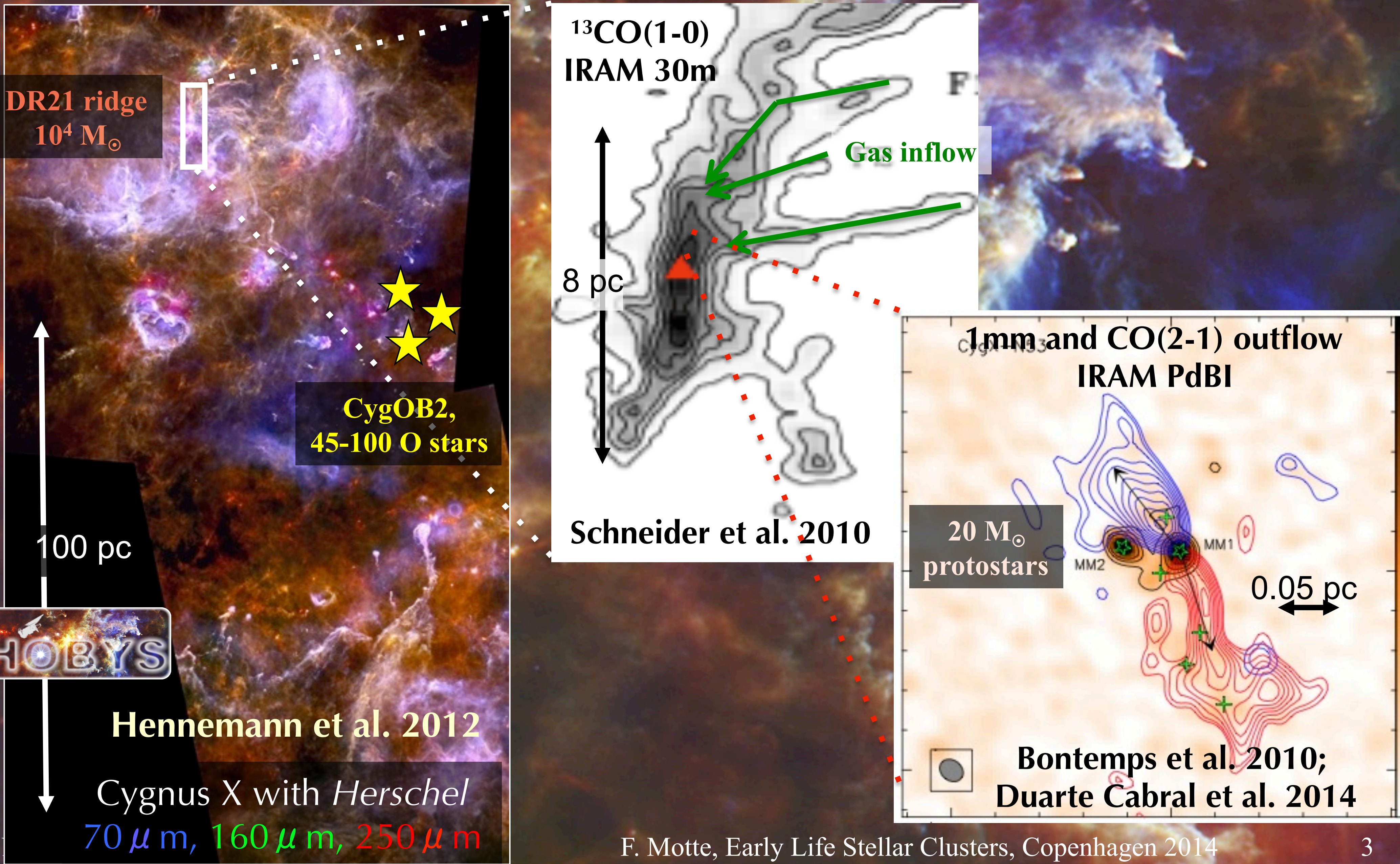
1. Short introduction

2. Cloud: Where do high-mass star clusters form?
   in dense, massive, and dynamical ridges or hubs

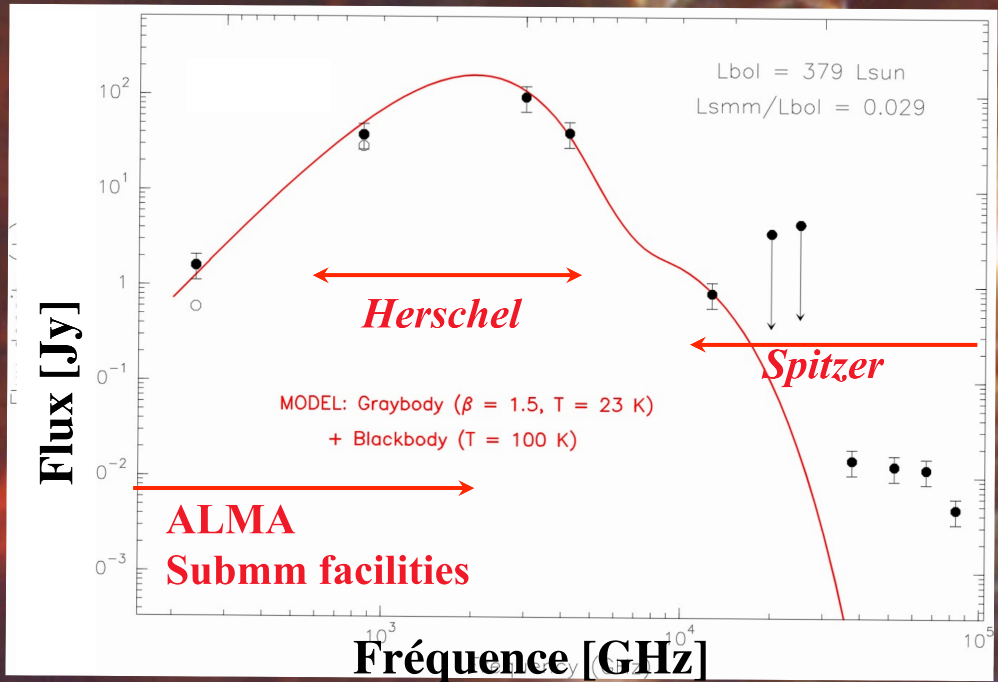
3. Clusters: Are they different when they form in ridges/hubs?
   protostars fed from large-scale
   large SFE/SFR

4. Conclusion, warnings, and future work…

Tight link between clouds and protostars



Spectral energy distribution of high-mass progenitors



- *Herschel*/PACS and SPIRE cover their SED peaks (10-50 K).
- Submm telescopes & arrays probe clouds and protostellar envelopes.
- *Spitzer* traces heated envelopes and HII regions.

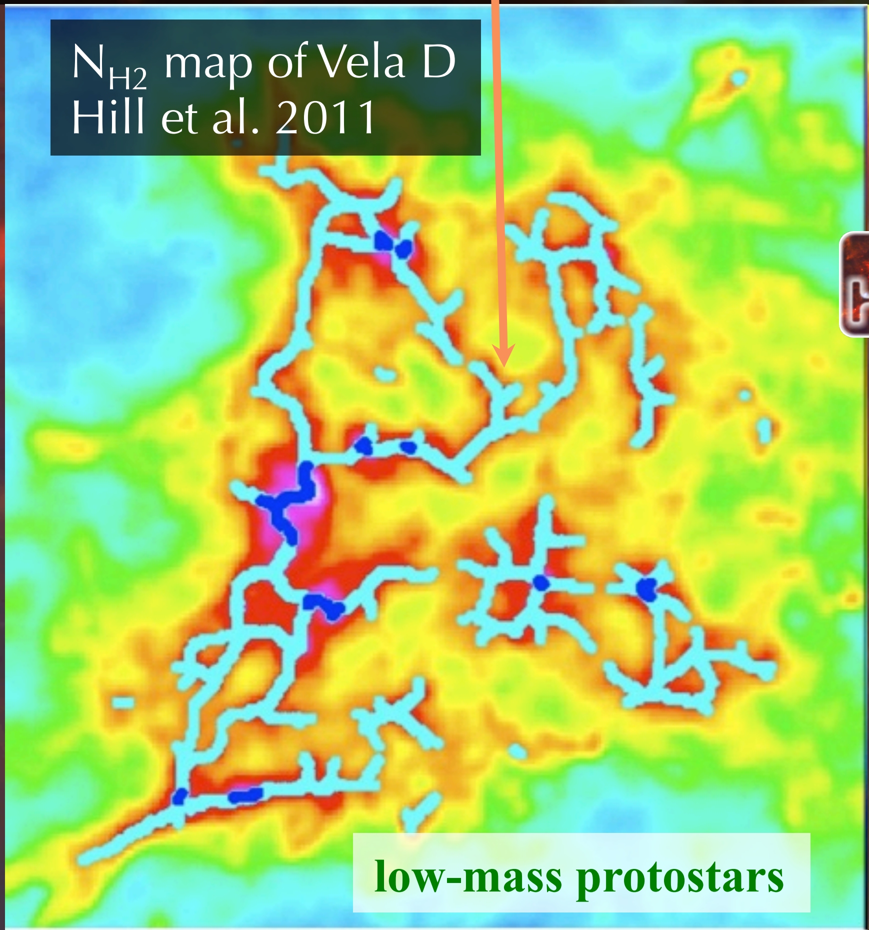
Thermal dust emission is mostly optically thin at $\lambda > 100\ \mu m$

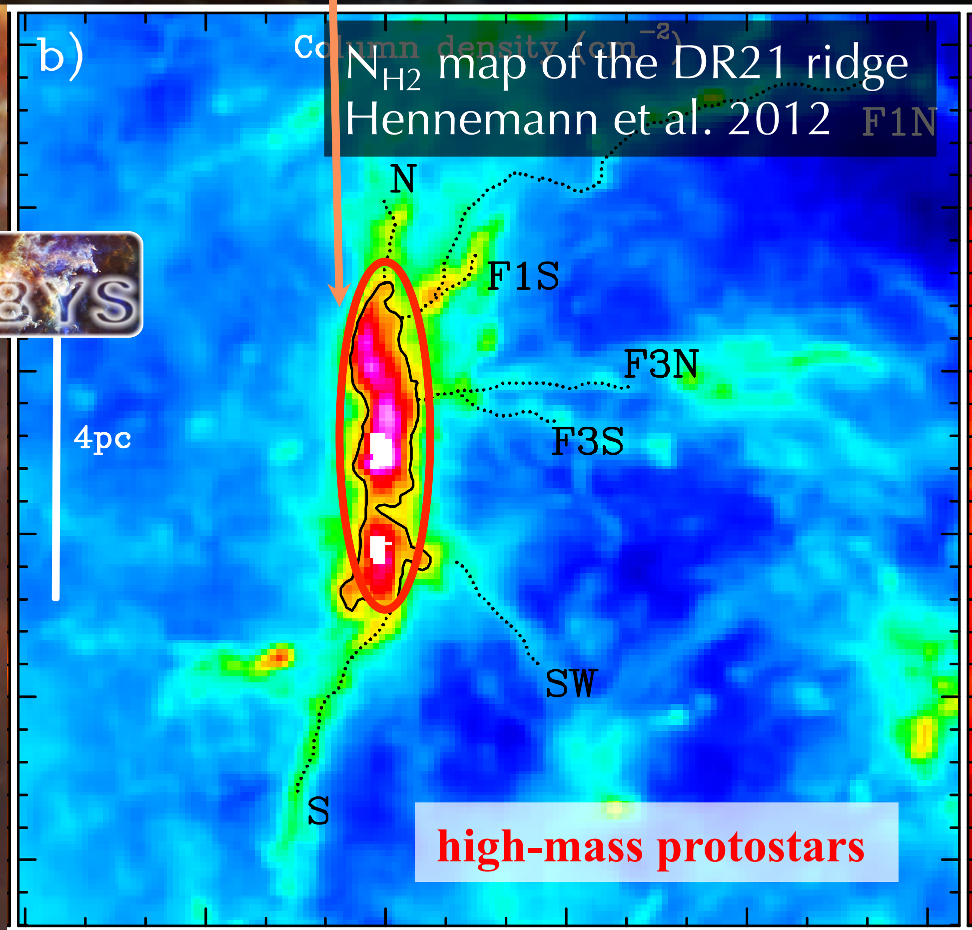
$\Rightarrow$ Accurate measurements of the gas mass reservoir associated with star formation (*Herschel* N_{H2} maps, see Hill et al. 2009, 2011)

- *Herschel*/HOBYS traces ~0.1 pc massive dense cores
- (Sub)mm interferometers trace ~0.01 pc individual 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

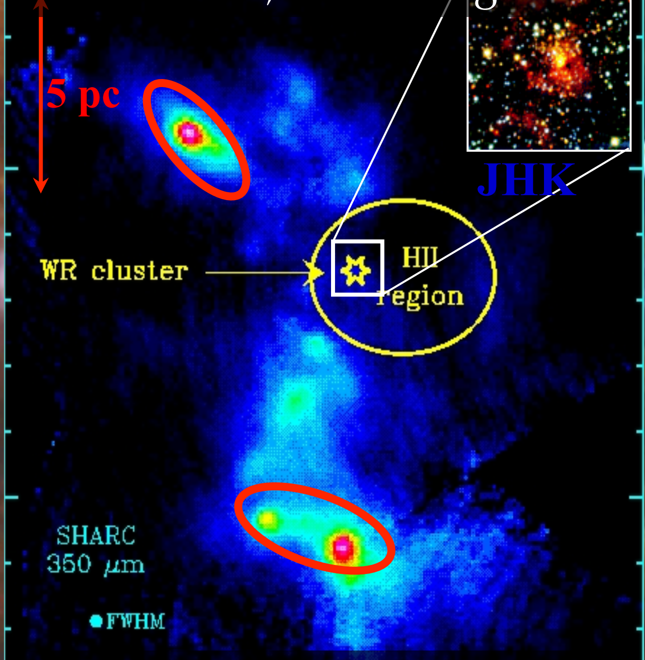
- ~50% of the high-mass stars form in clusters within high-density elongated ridges, the other 50% form in spherical high-density hubs

⇒ 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.

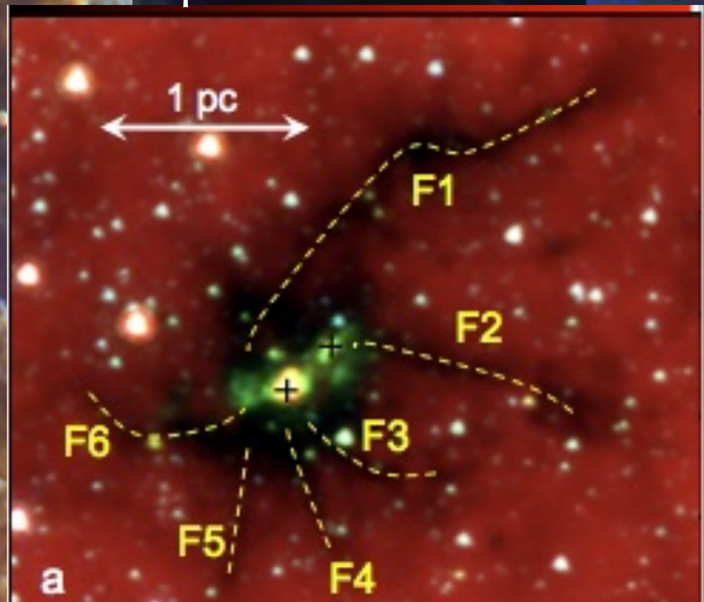
See also Hill+ 2011, Nguyen Luong+ 2011, Hennemann+ 2012, Didelon+ 2014, …

W43-MM1, MM2 ridges



Nguyen Luong et al. 2013

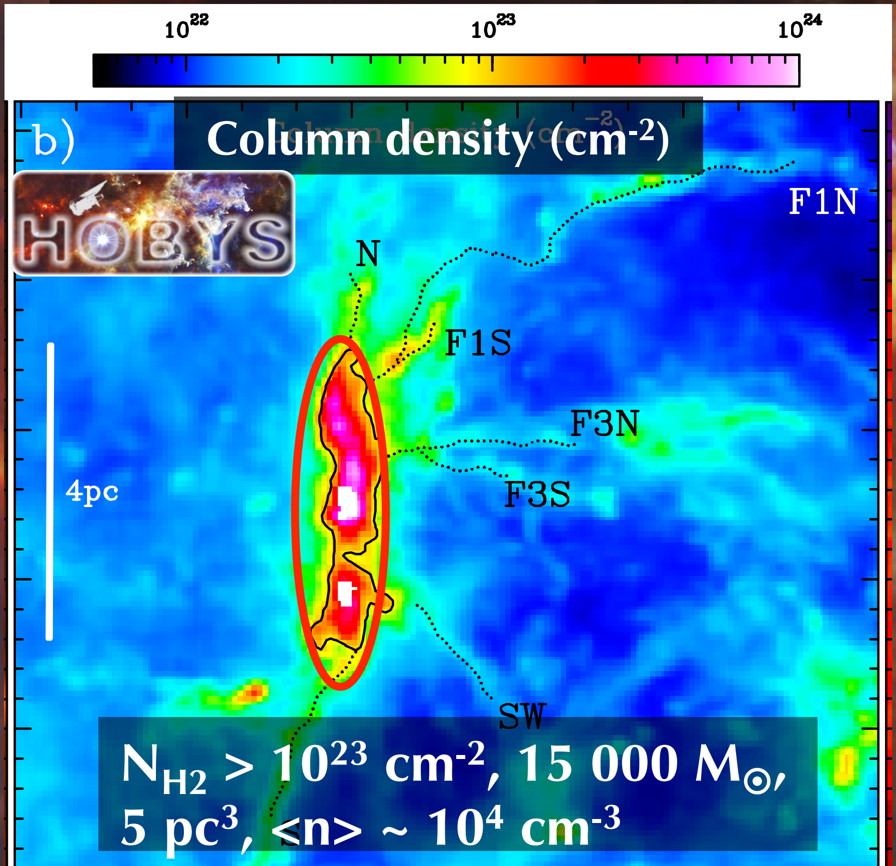
Spitzer IRDC hub



SDC335; Peretto et al. 2013

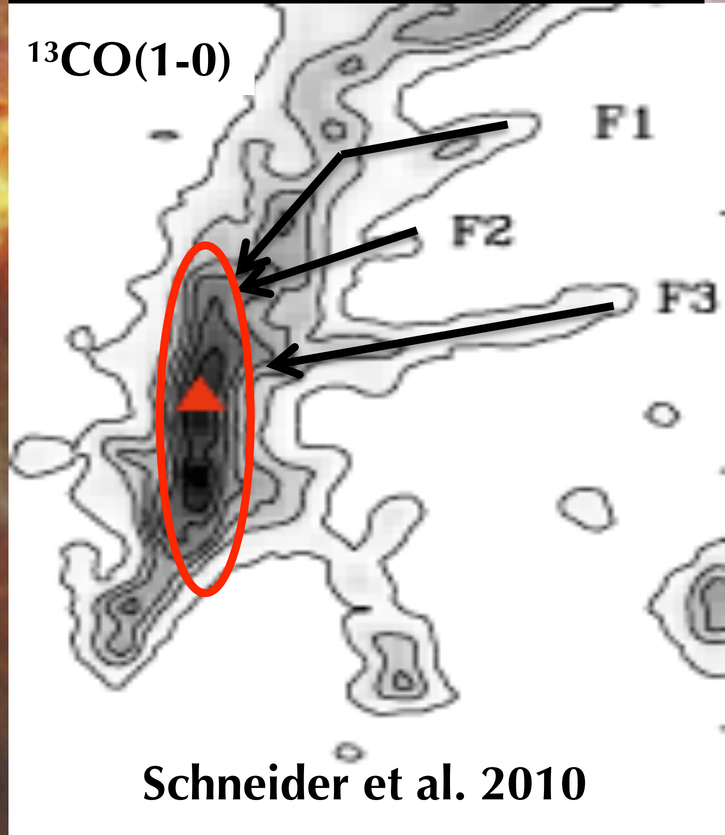
Most ridges/hubs should form by cloud global collapse

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

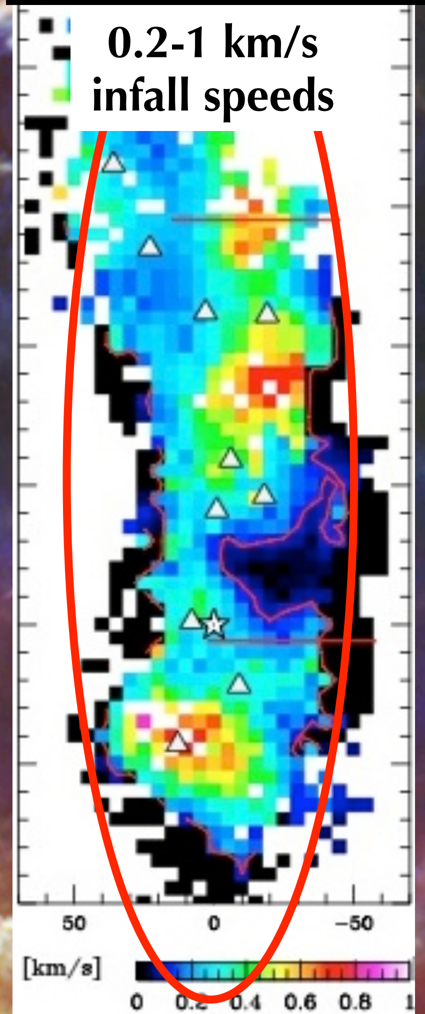


Hennemann, Motte, Schneider et al. 2012

Gas flows along sub-filaments



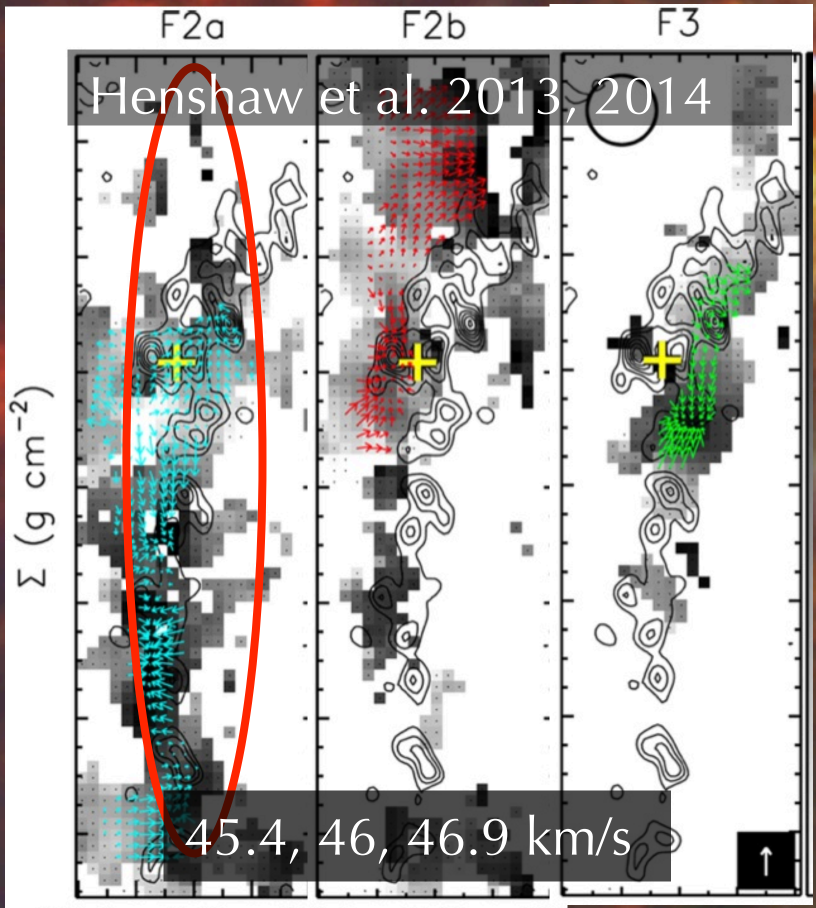
Global infall



- Similar kinematics found for other ridges/hubs (Peretto et al. 2013, 2014; Beuther 2012; Kirk et al. 2013…)

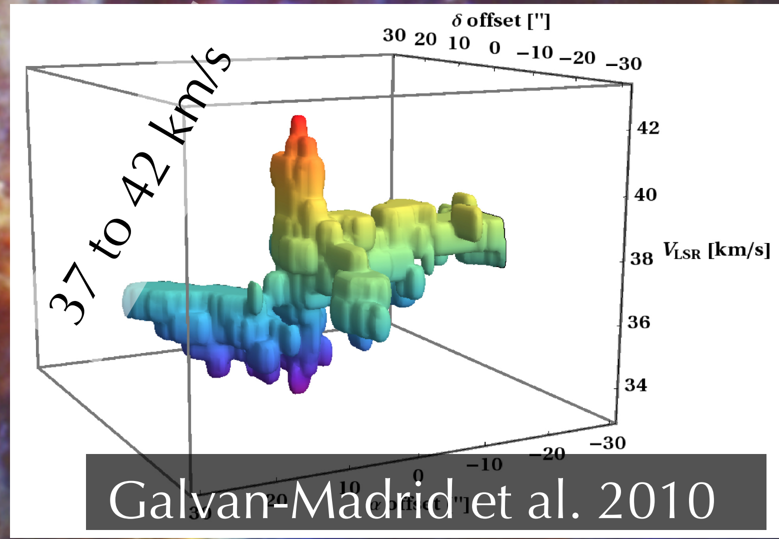
Ridges are braids of filaments/layers

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

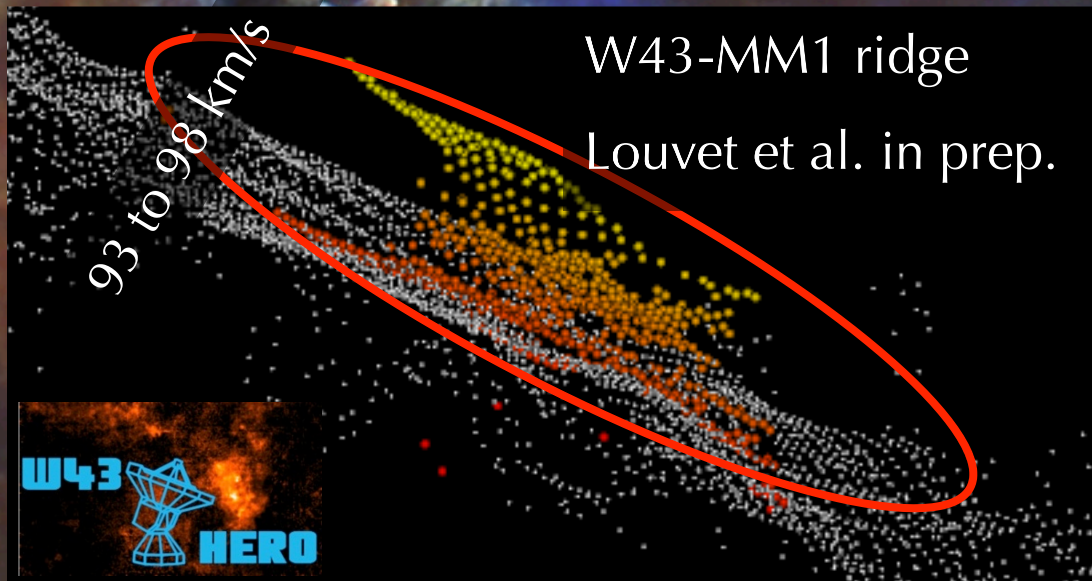


Henshaw et al. 2013, 2014

45.4, 46, 46.9 km/s



Galvan-Madrid et al. 2010



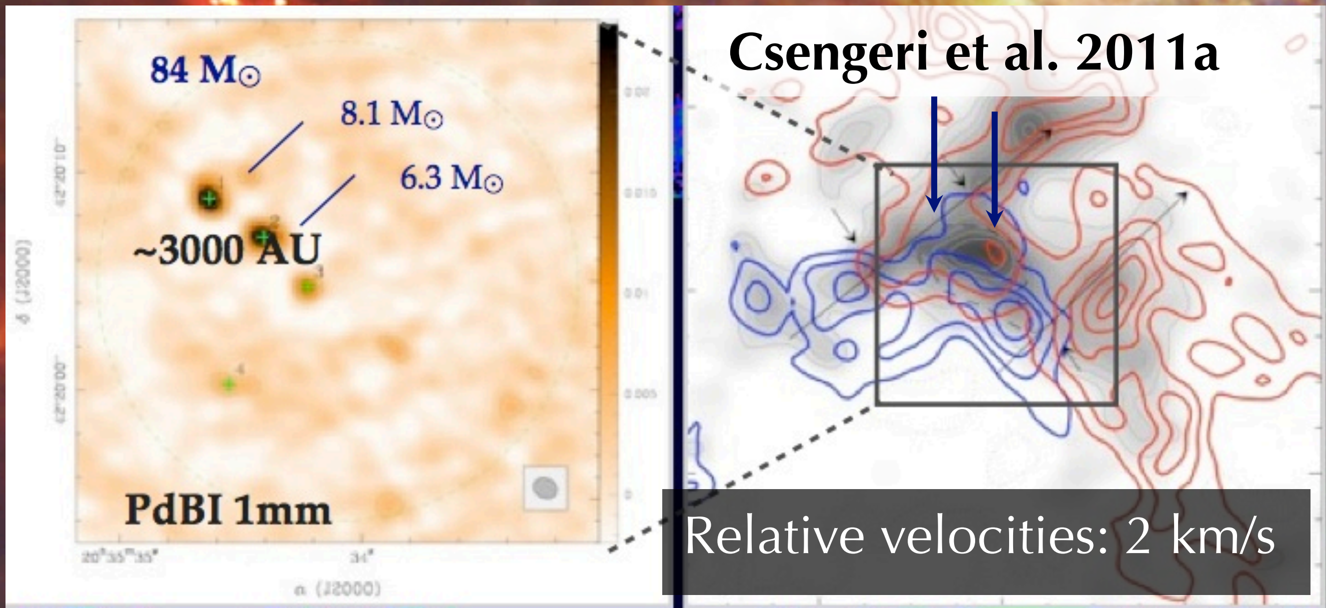
W43-MM1 ridge

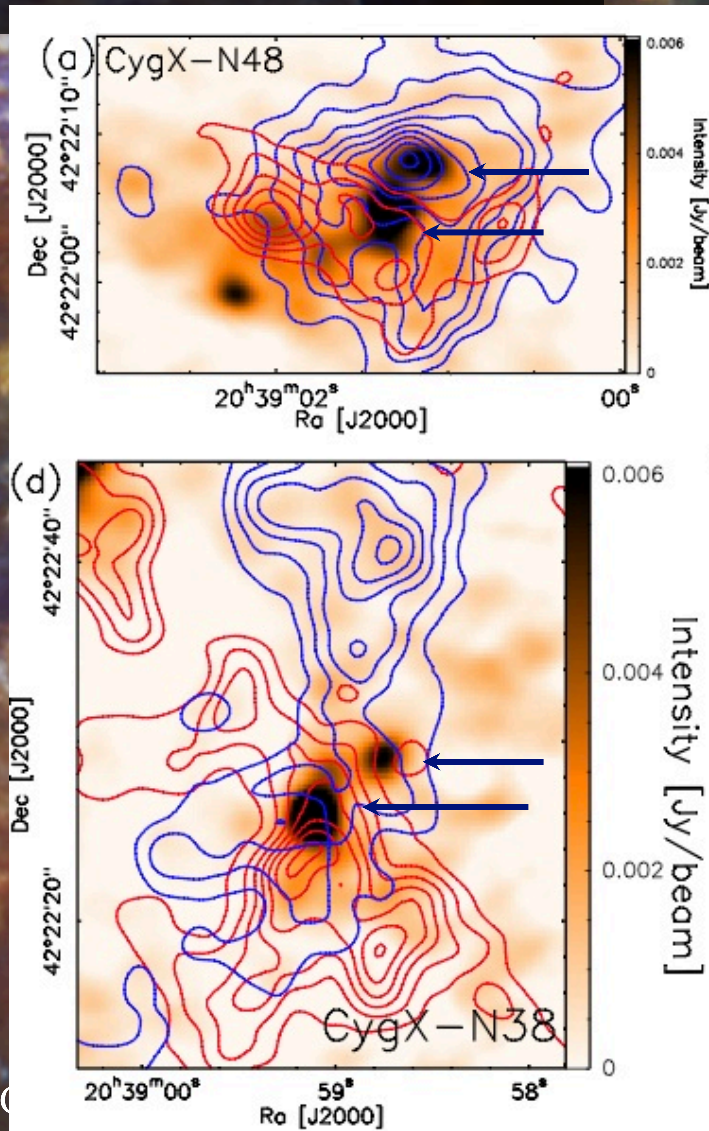
Louvet et al. in prep.

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; ...)

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Herschel/HOBYS measures "instantaneous" SFE/SFR

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

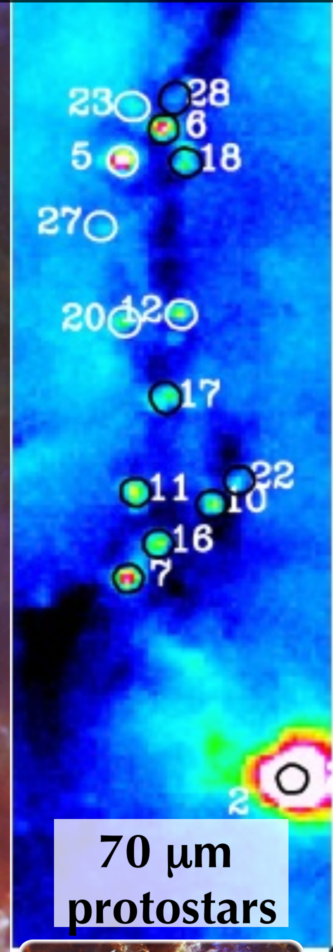
easier to compare with statistical models of SFR (e.g.Krumholz & McKee 2005; Padoan & Nordlund 2011; Hennebelle & Chabrier 2011, 2013; Federrath et al. 2012).

- *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)

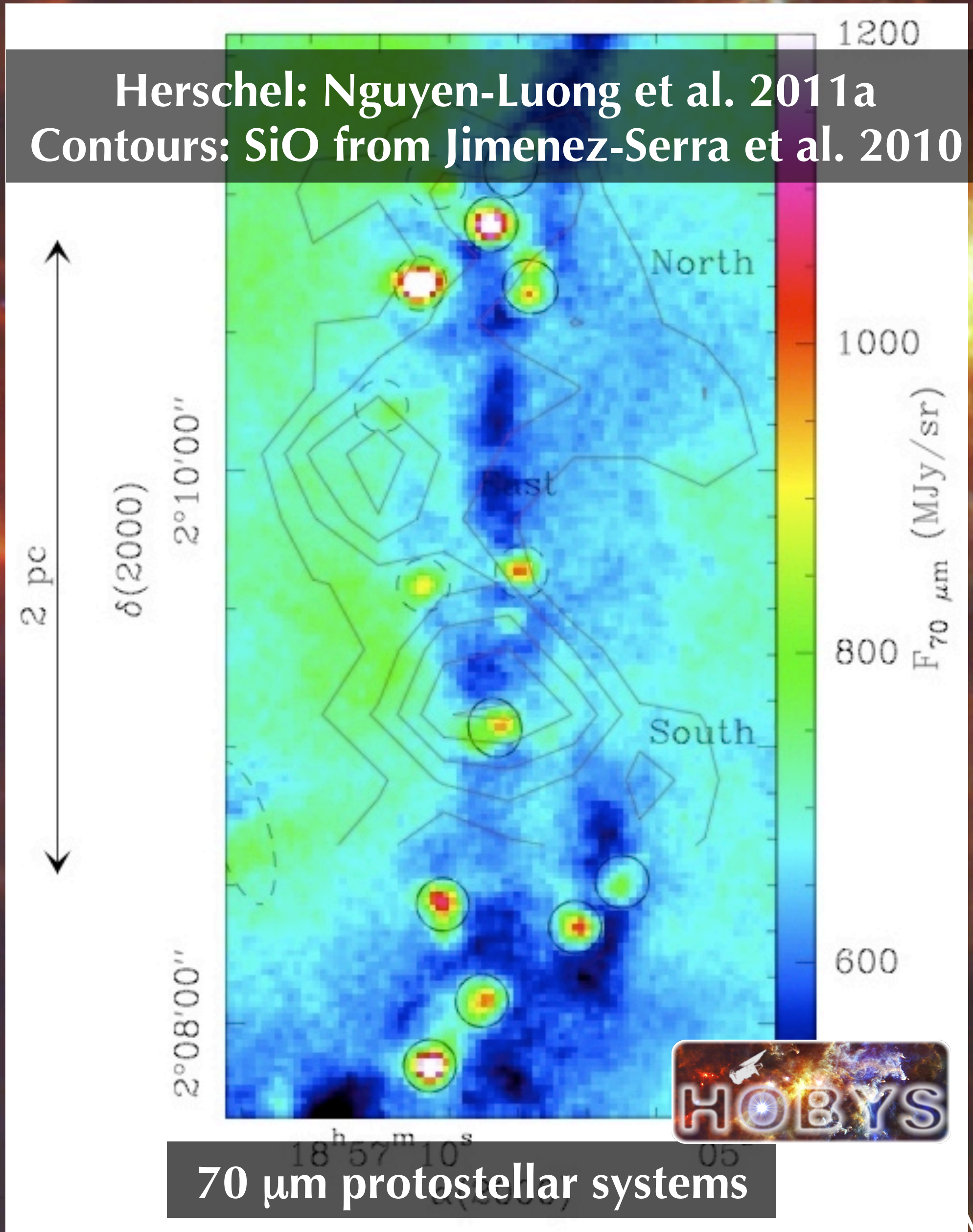
➔ "Integrated" / "Past" SFR

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

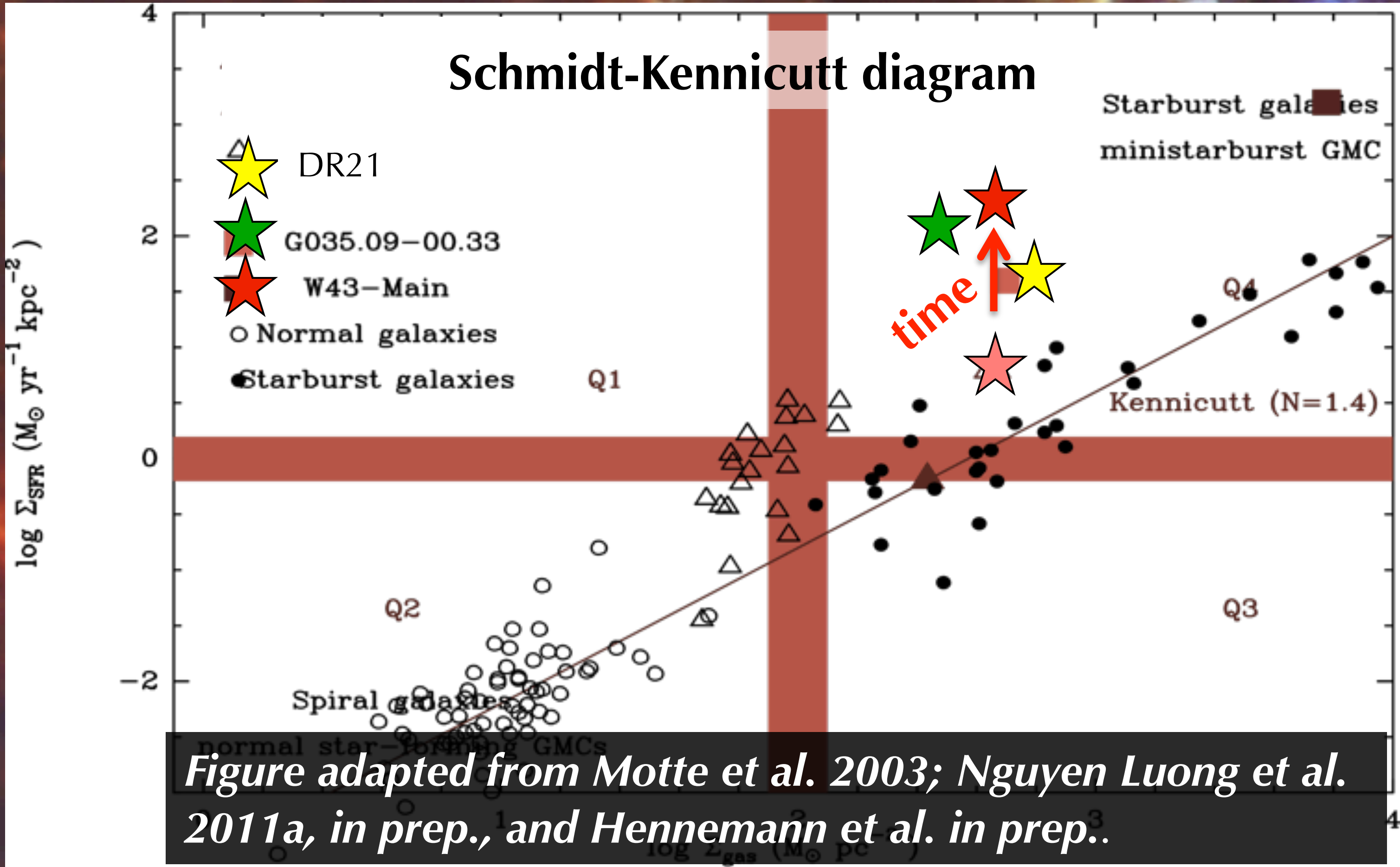


Figure adapted from Motte et al. 2003; Nguyen Luong et al. 2011a, in prep., and Hennemann et al. in prep..

Starburst quadrant:

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

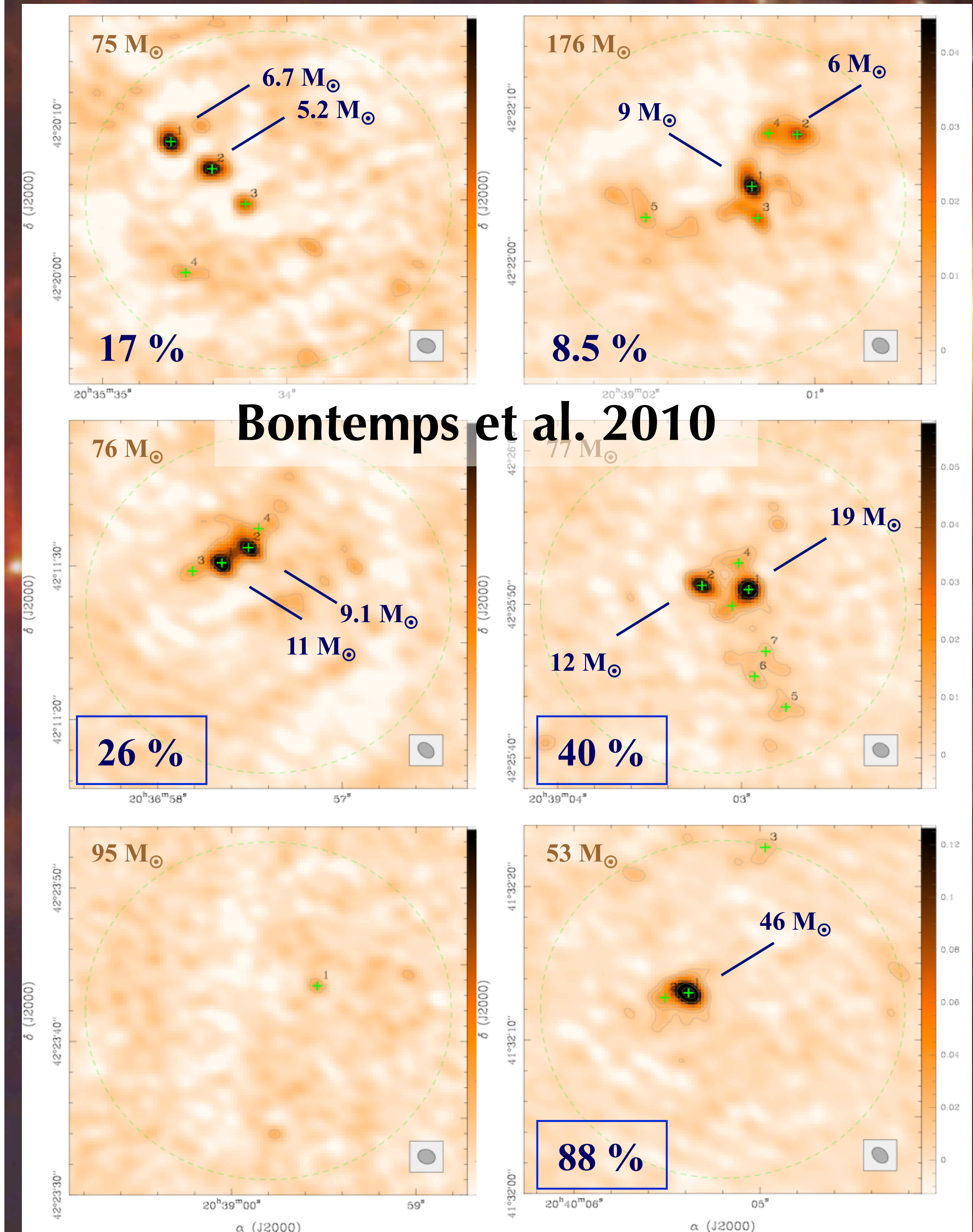
$\Sigma_{gas} > 100\ M_{\odot}/pc^2$

These pioneering studies need to be generalized…

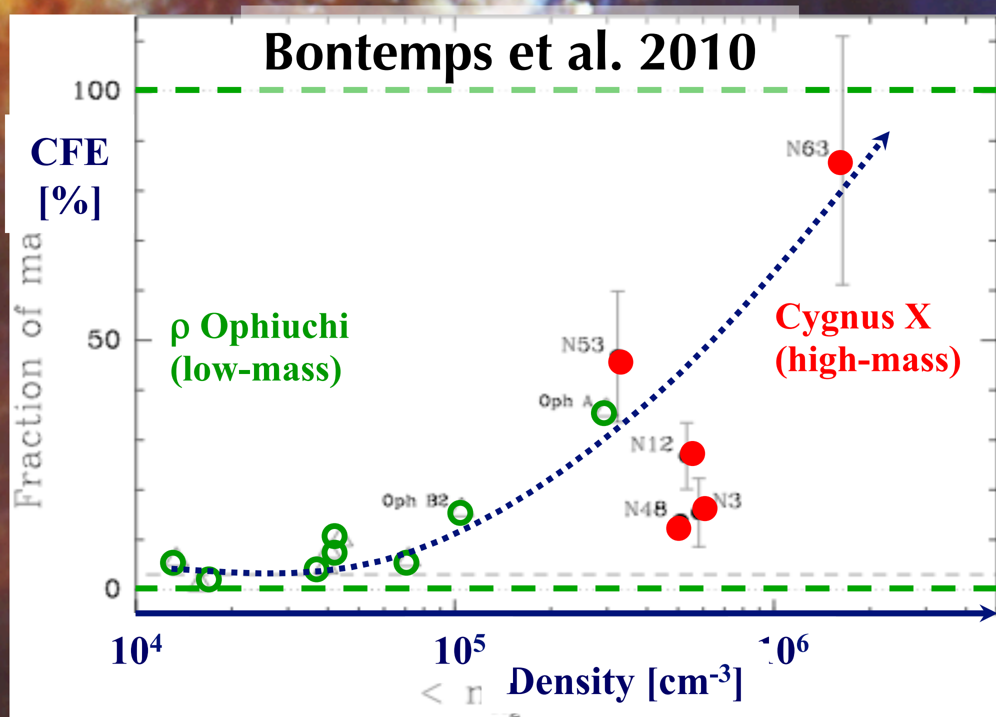
Caveats: Core-to-star formation efficiency assumed to be constant

Extrapolation of a standard IMF to mini-starburst ridges

Clusters of low- to high-mass protostars



- 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)

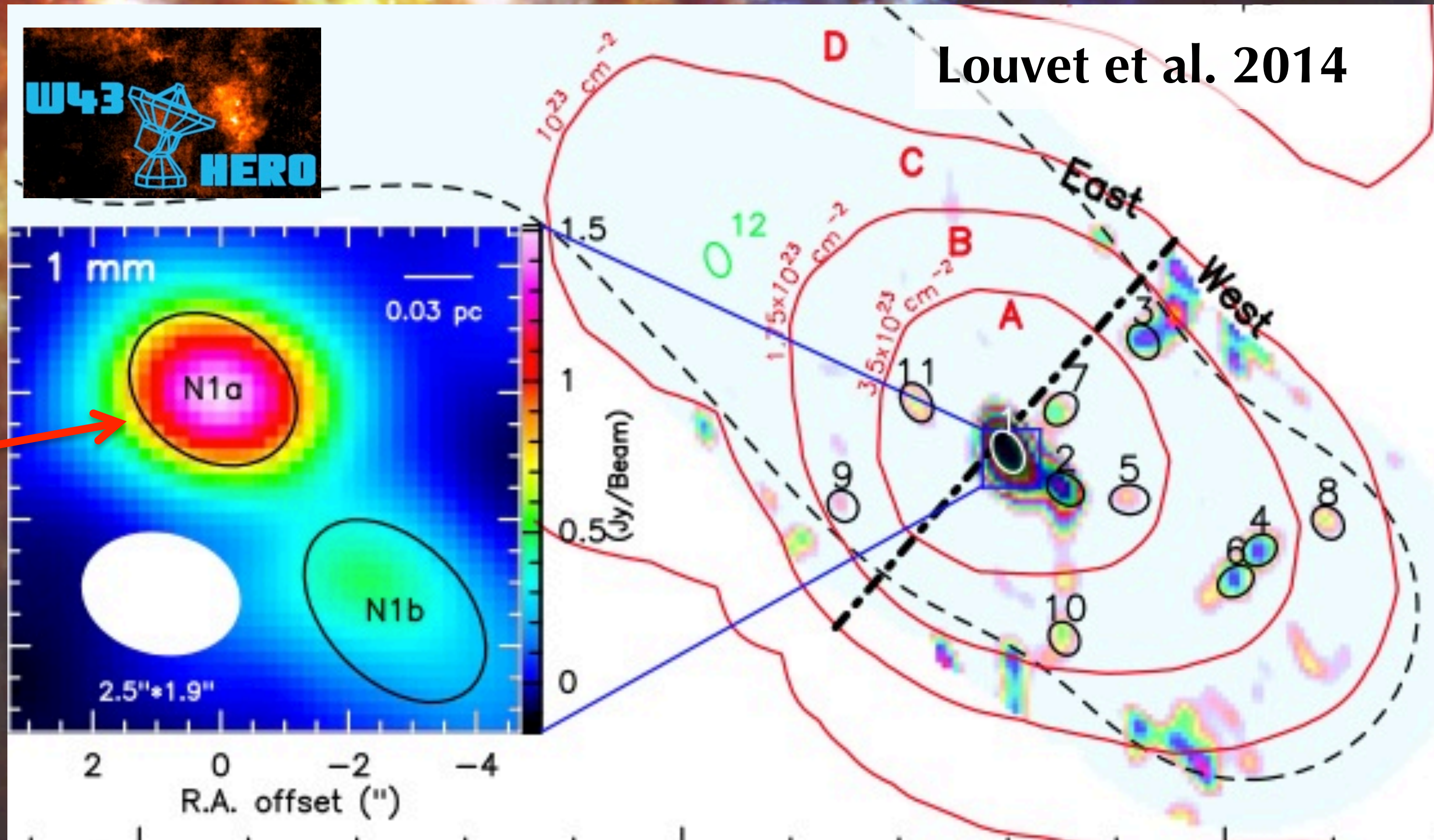
Are thresholds and constant SFE correct?

Lada et al. (2010, 2012) relation between SFR and cloud mass implicitely assumes a constant SFE in regions above the SF threshold (A_v> 8 mag). 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?

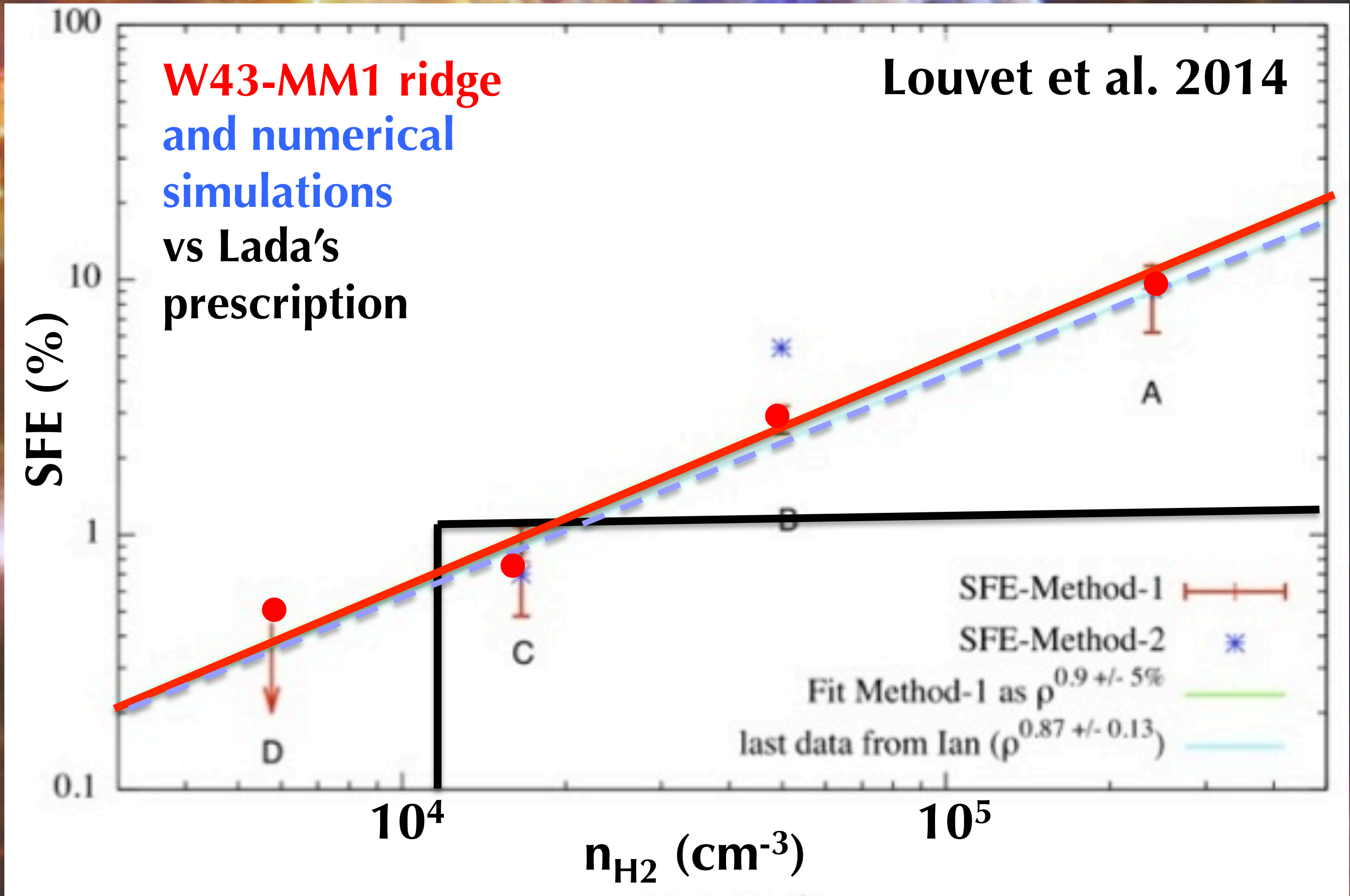
SFE measured within the W43-MM1 ridge and in numerical simulations increases with n_{H2} (Louvet et al. 2014).

In contradiction with Lada's 2010/2012 prescription…

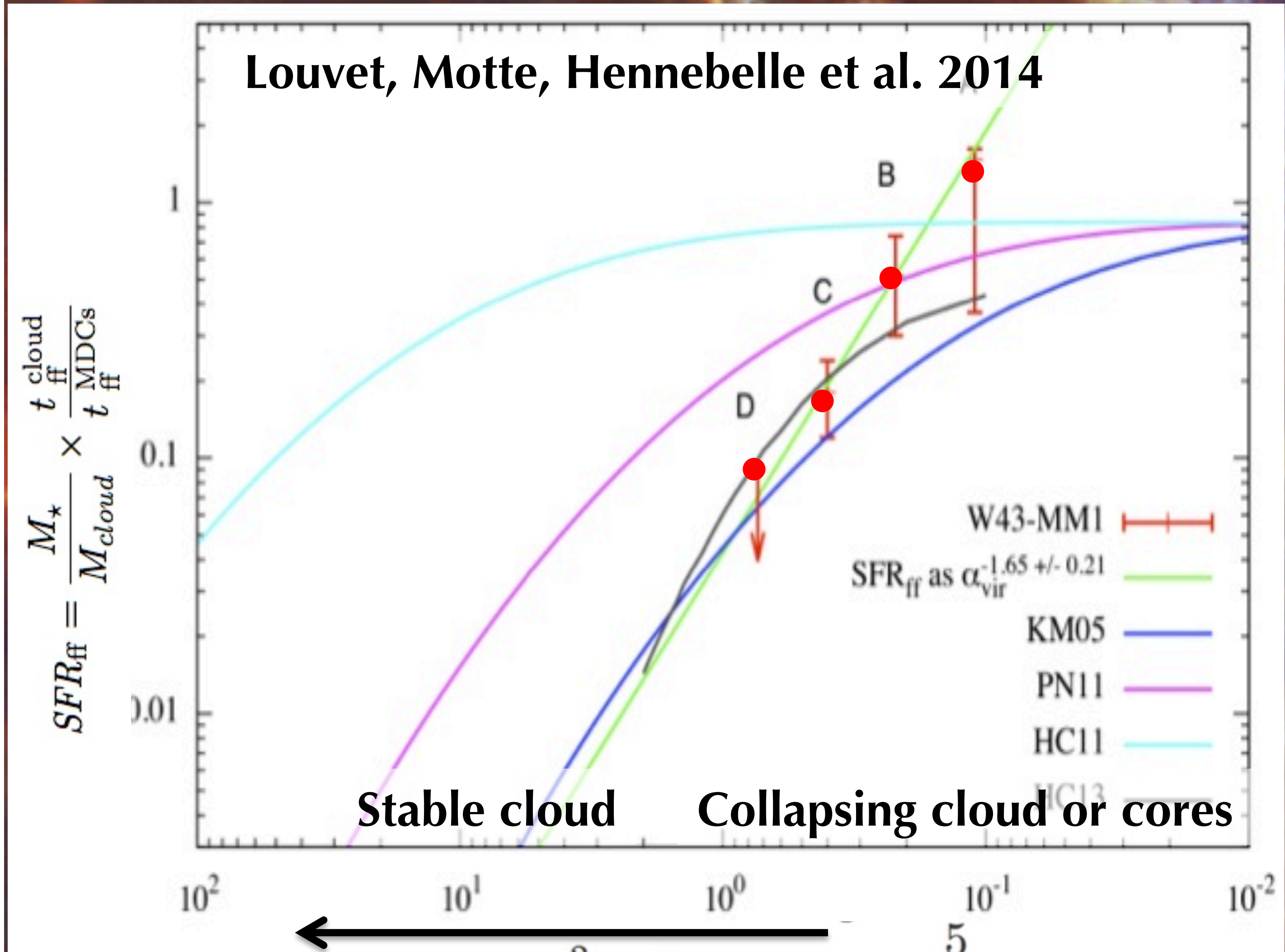
In agreement with previous CFE studies (Bontemps et al. 2010, Palau et al. 2013)

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

⇒ Environment matters!



Constraining statistical theories of SFR on W43-MM1…



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

- 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…

Conclusion, warnings, and future work

Proposed steps toward SF in 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.
3. Stars and filaments simultaneously form and grow. In these environments protostellar accretion is non-local & anisotropic.

The stellar content (higher mass star, SFE?, IMF?) of a cluster depends on the density and kinematics of its parental cloud.

⇒ The formation of mini-starburst clusters is different from that of low-mass star clusters.

But rough assumptions:

- **unknown core-to-star mass efficiency**
- IMF applied to ridges
- approximate protostellar lifetime
- …

and often lack of angular resolution and kinematical data.

Need ALMA data and SF models adequate for ridges…