From filamentary clouds to fibers feeding individual cores: how do filaments impact cloud and star formation?

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With inputs from the *Herschel*/HOBYS and *Herschel*/HGBS consortia, the W43-HERO consortium, and the Planck collaboration.

Special thanks to Ph. André, P. Didelon, M. Hennemann, T. Hill, F. Louvet, T. Csengeri, N. Peretto, D. Arzoumanian, Q. Nguyen Luong, N. Schneider, S. Bontemps, P. Hennebelle.

Outline on our current understanding of filamentology

1. A hierarchy of filaments from 0.1 to 100 pc, at least.
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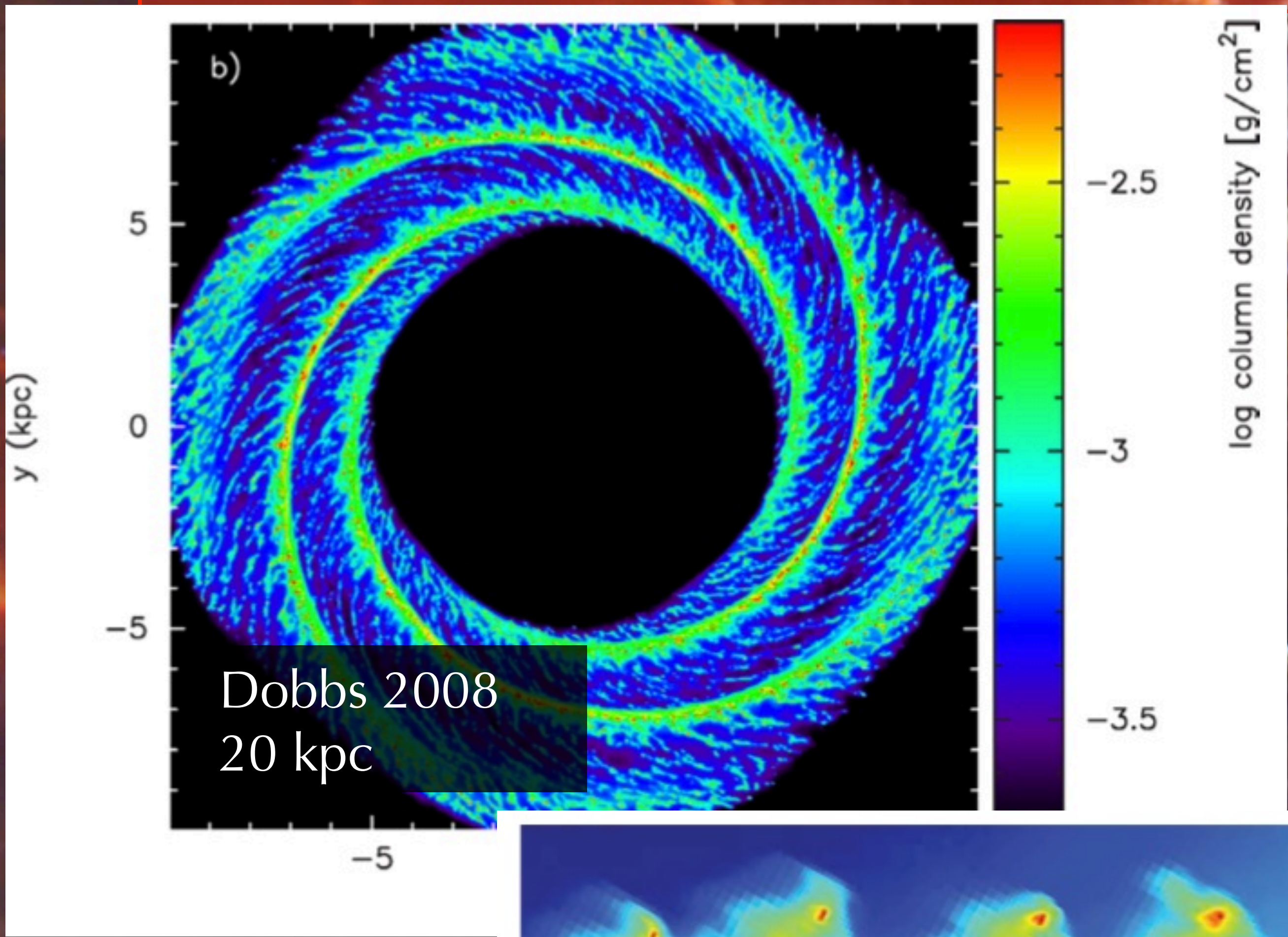
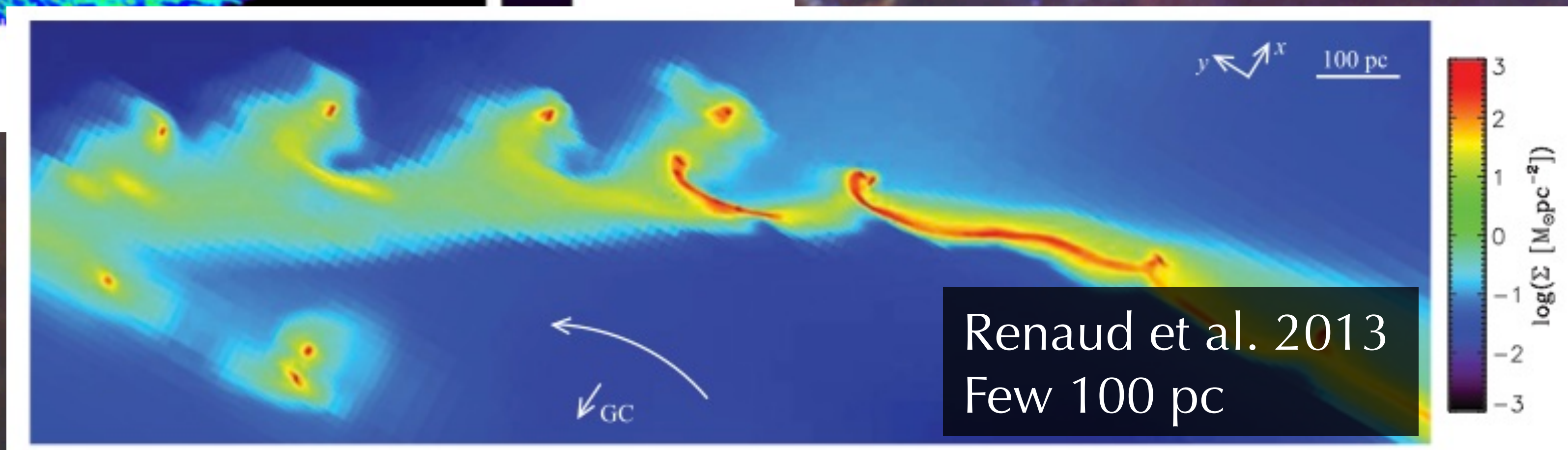
Numerical simulations on Galactic scales

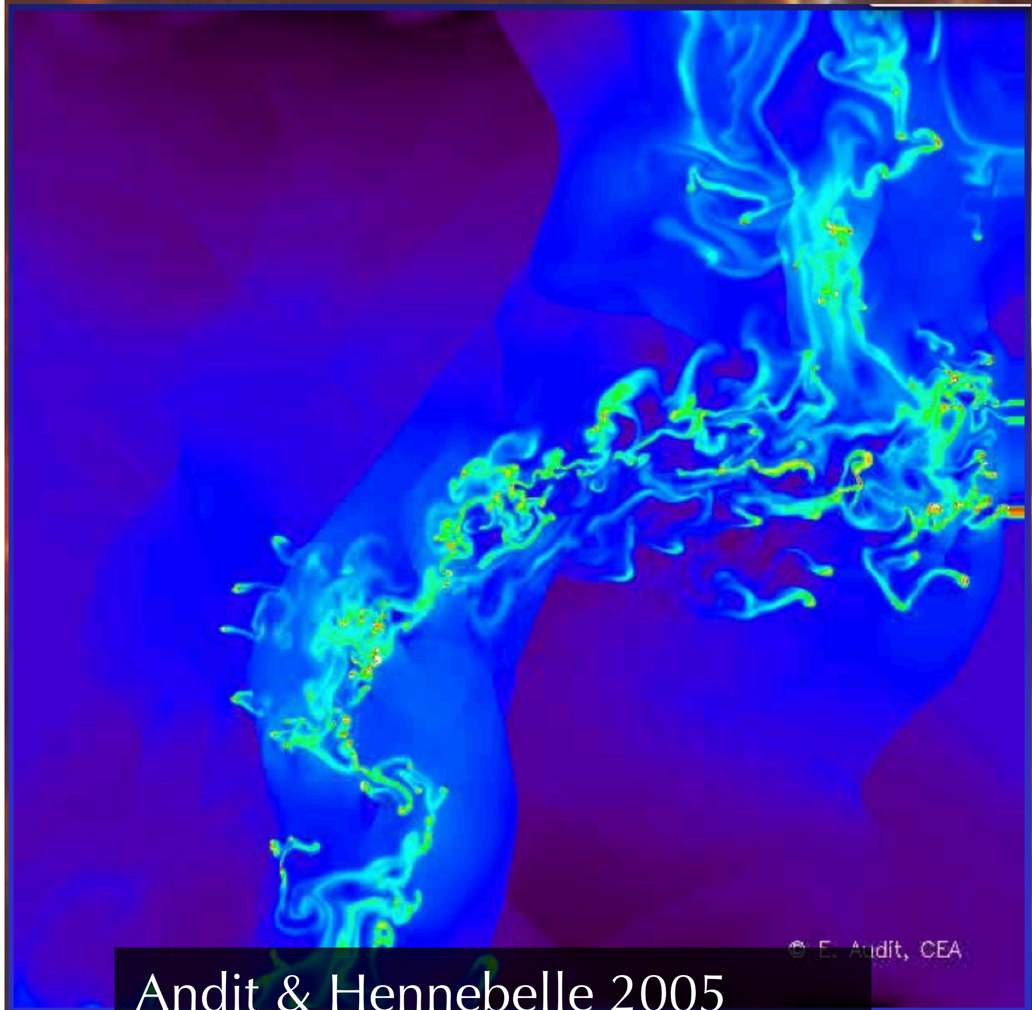


- Arms are created by a spiral potential

⇒ 100 pc GMC along arms or spurs have filamentary shapes.



Numerical simulations on GMC scales



Andit & Hennebelle 2005
10 pc box

- Cloud structured by supersonic turbulence

e.g. Padoan & Nordlund 1999; Klessen & Burkert 2000; Smith+ 2011…

- Cloud formed through colliding flows of turbulent HI gas

e.g. Audit & Hennebelle 2005; Vasquez-Semademi+ 2006; Heitsch+ 2006; Clark+ 2012…

- Larger simulations of pieces of a galaxy

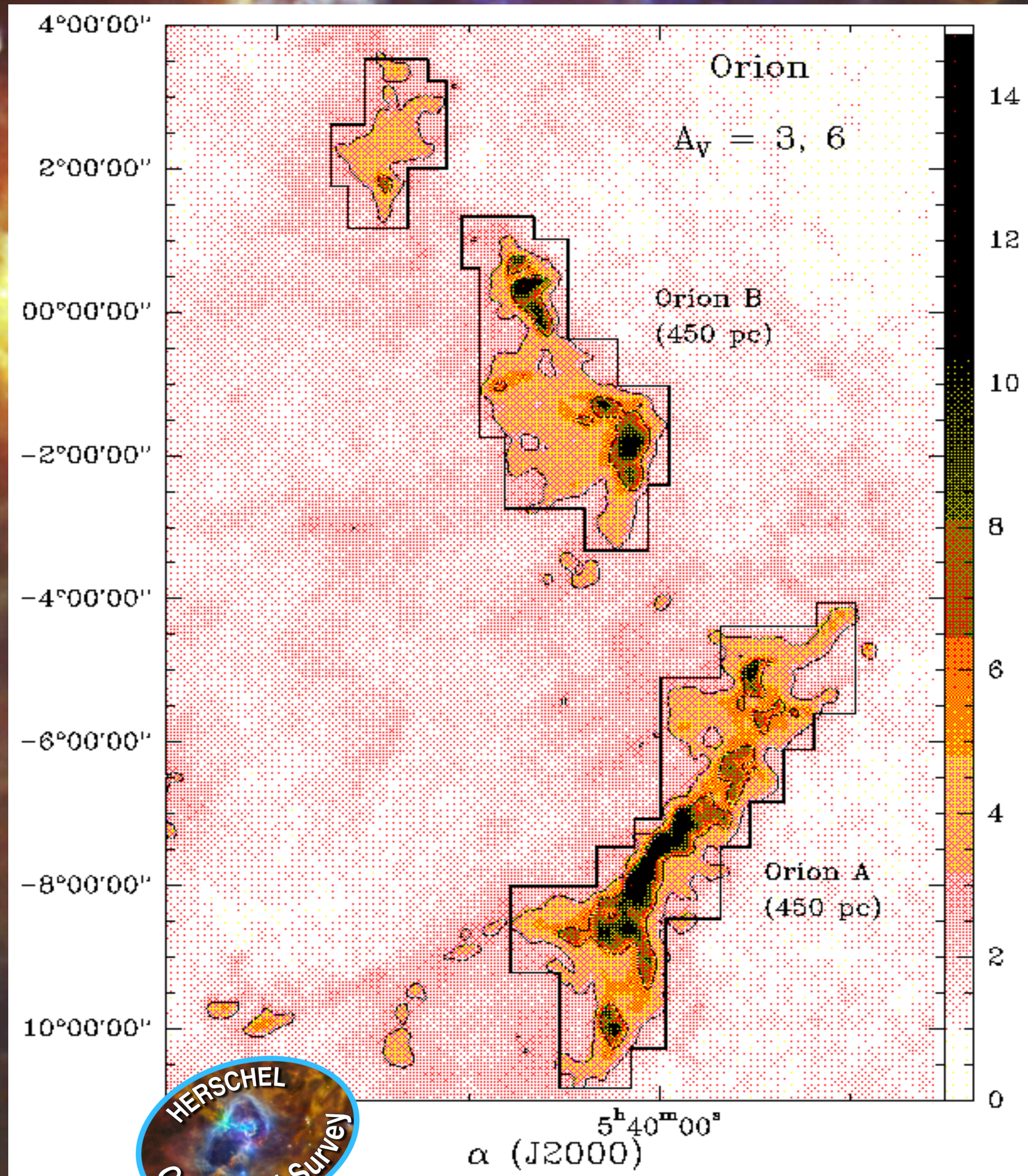
Talks by Paolo Padoan and Rowan Smith

⇒ A hierarchy of 0.01-10 pc core/clumps/ clouds with filamentary shape.

10-100 pc clouds are often filamentary

- On 10 pc sizes, clouds are often filamentary: Schneider & Elmegreen 1979; Heyer+ 1987,…
- 50-100 pc molecular cloud complexes and giant molecular filaments also: Bally+ 1987; Cambrésy+ 1999; Schneider+ 2011; Ragan+ 2014

⇒ A hierarchy of filaments



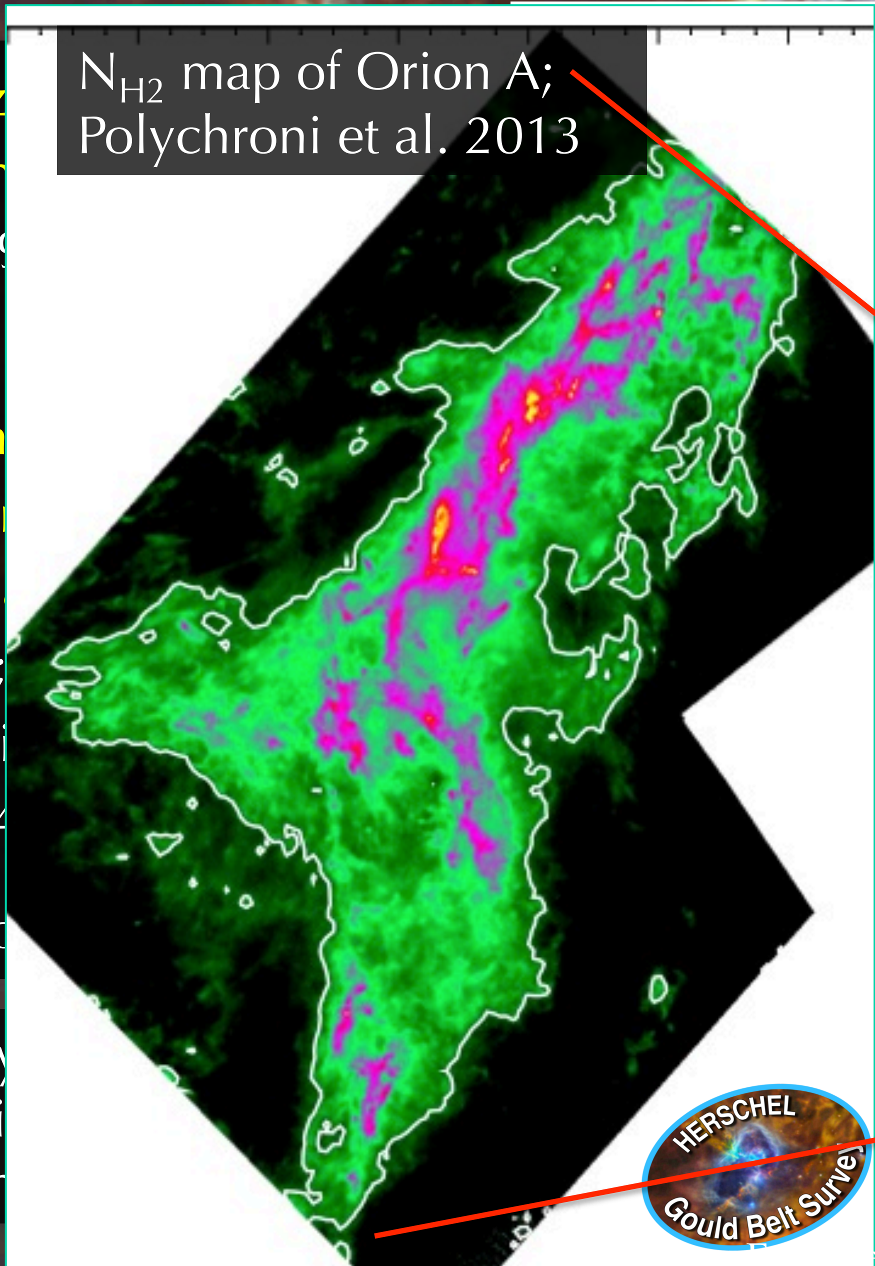
Courtesy: S. Bontemps
NIR extinction map of the Orion molecular complex

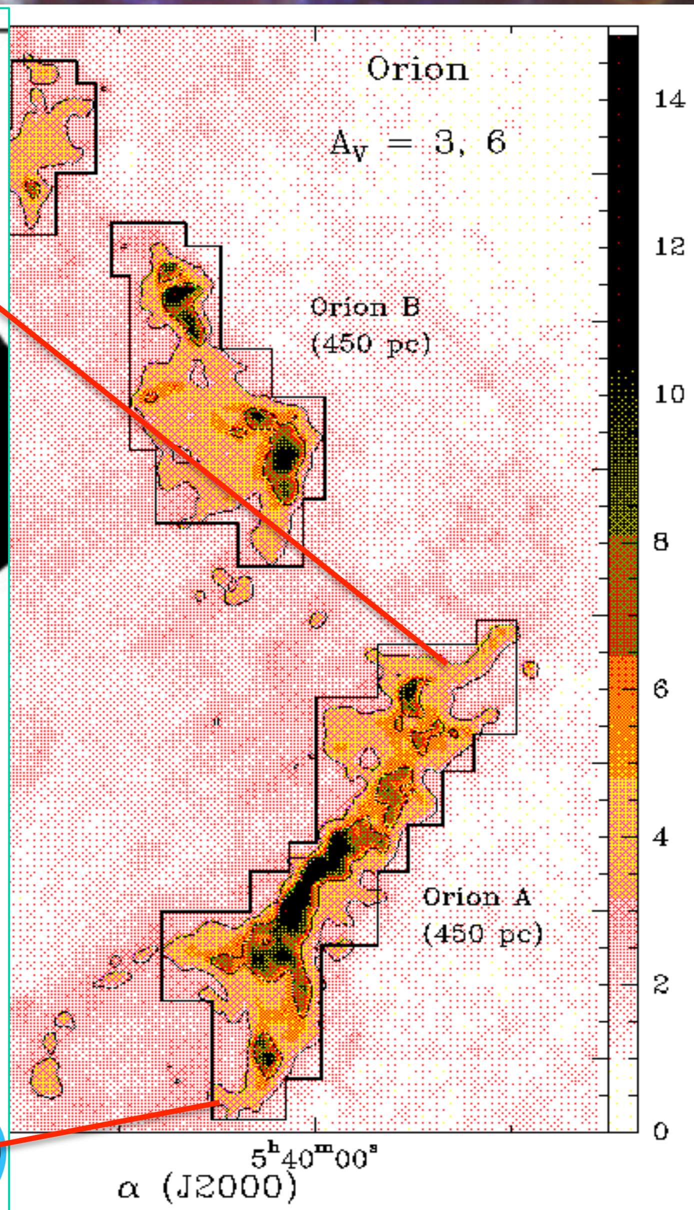
10-100 pc clouds are often filamentary

- On 10 pc siz… often filamen… Elmegreen 1… 1987,…
- 50-100 pc m… complexes a… molecular fil… Bally+ 1987;… 1999; Schnei… Ragan+ 2014

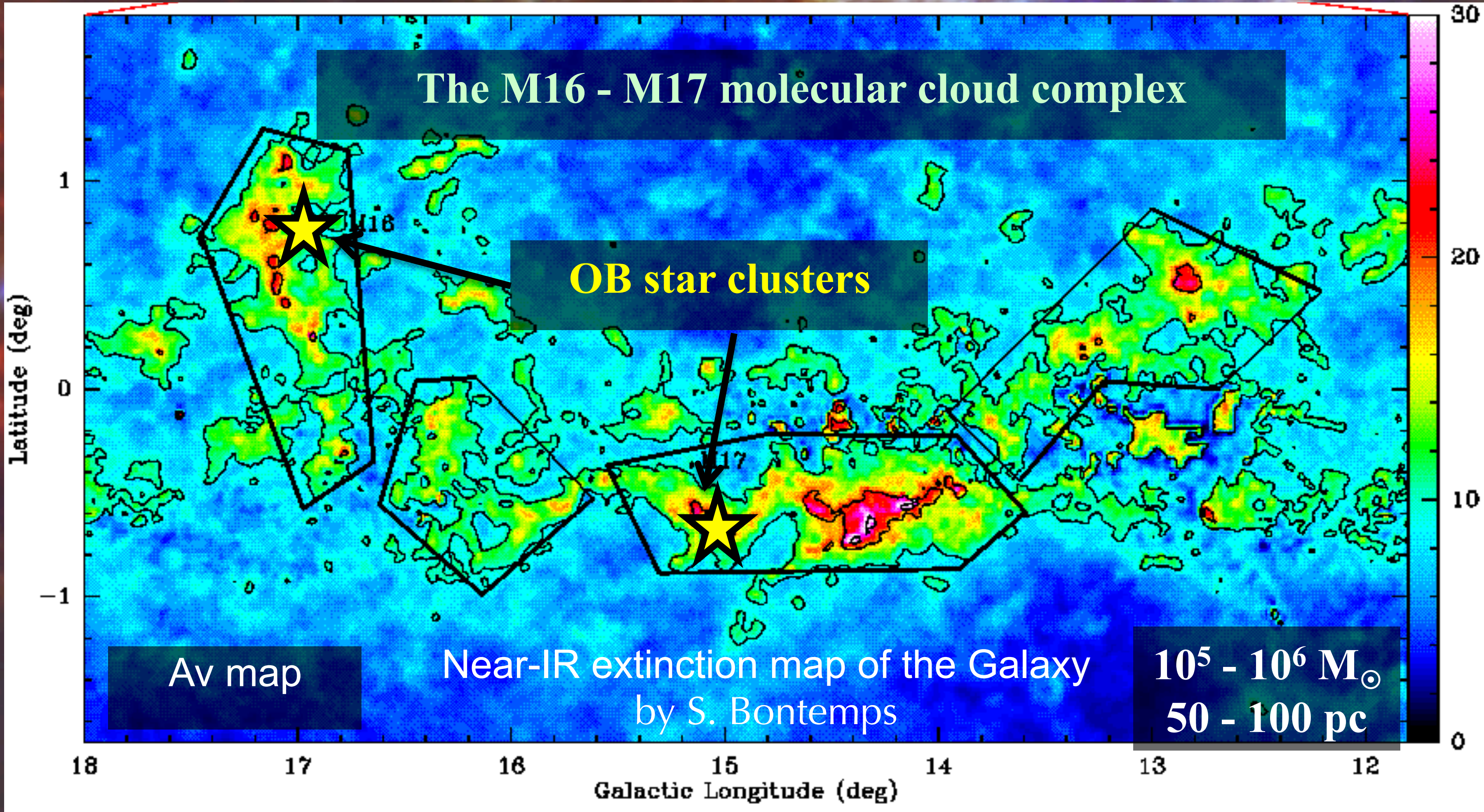
⇒ A hierarchy c…

Courtesy… NIR exti… Orion m…



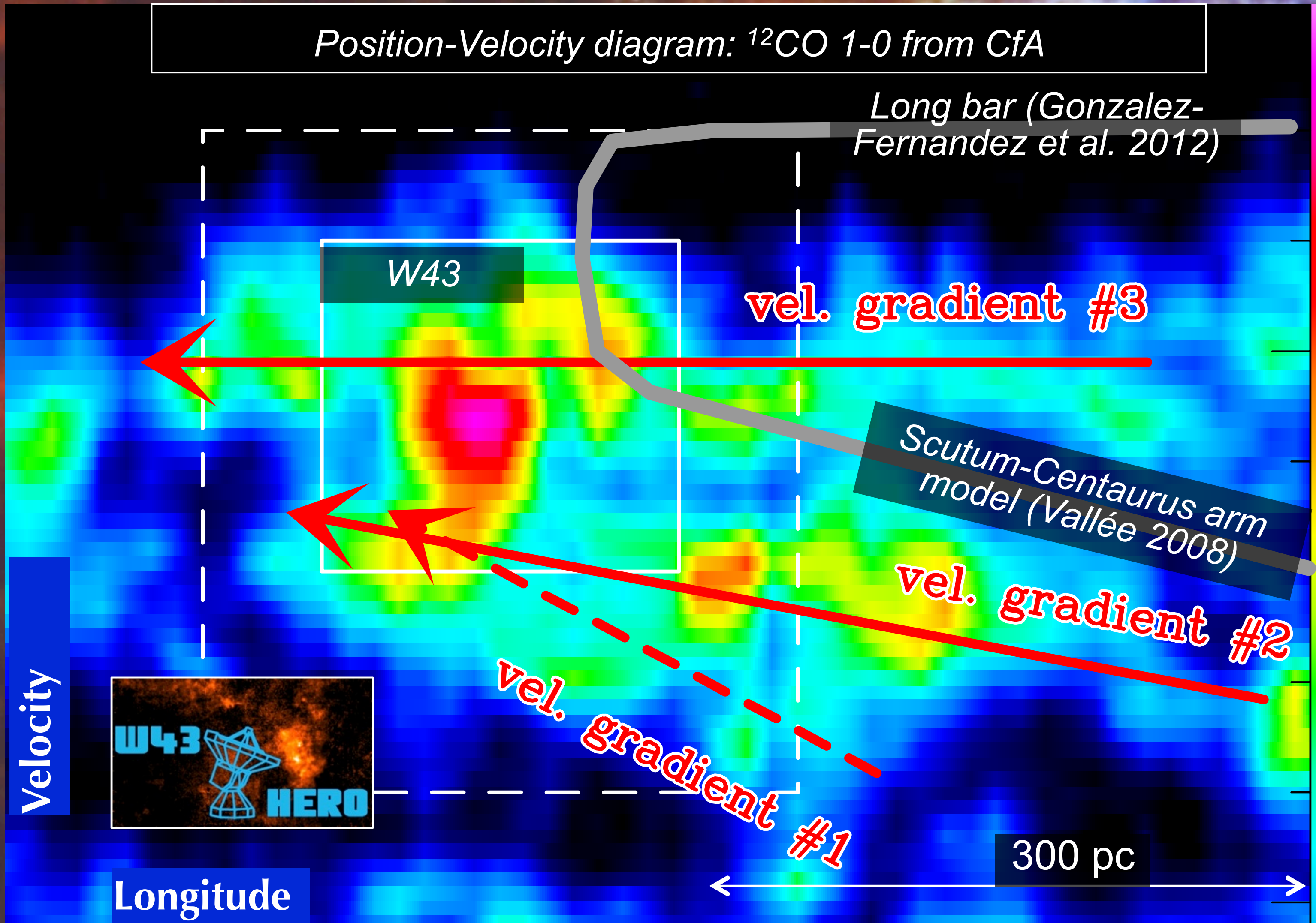


Massive molecular cloud complexes are pieces of the nearest Galactic arms (HOBYS sample)



⇒ Cloud agglomeration along the Galactic arm is probably setting the privileged elongation, as suggested by simulations.

Two cloud ensembles developing along the longitude and joining W43



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

W43:
140 pc, 10^7 $M_\odot$
In front of the long bar.

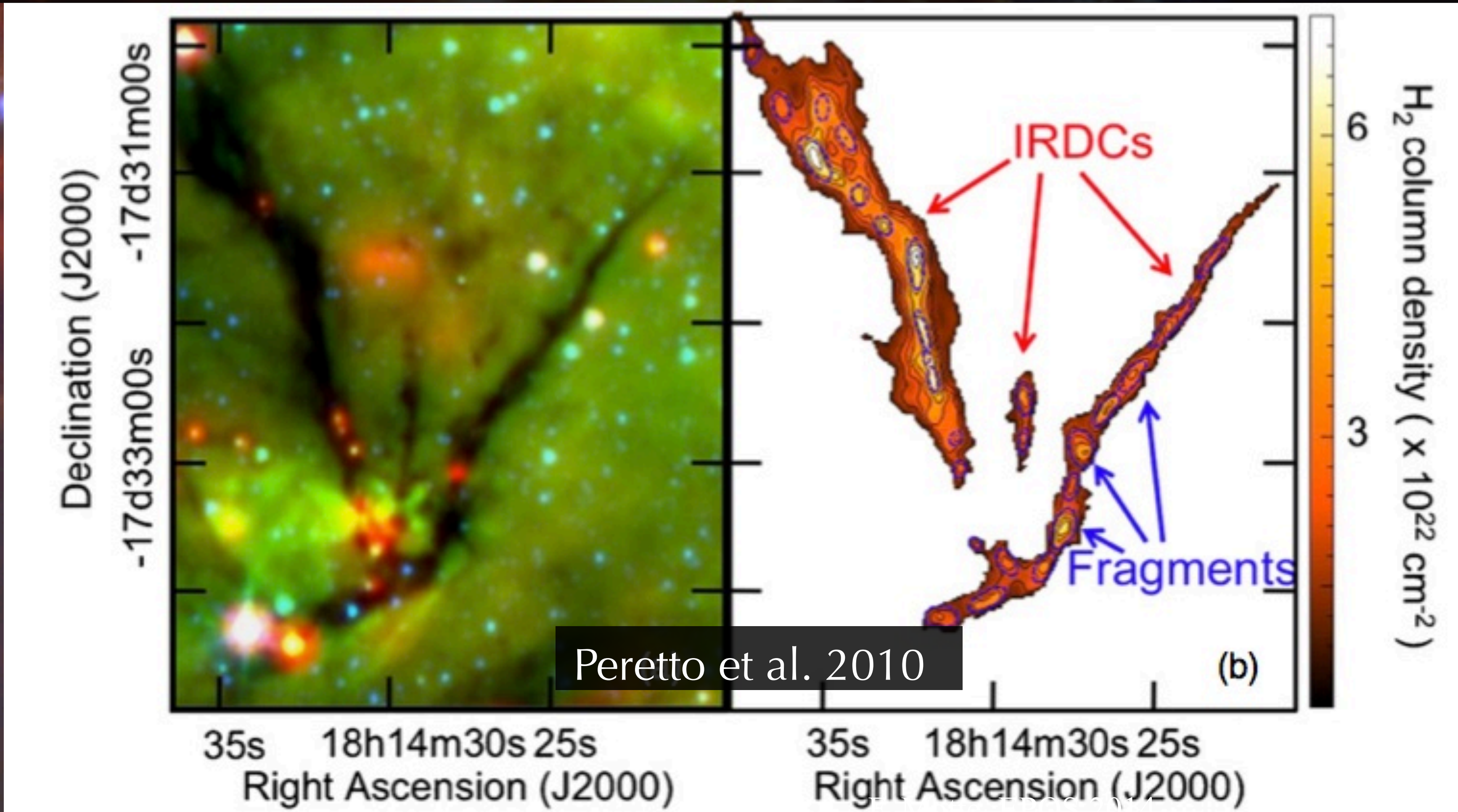
^{12}CO gas is flowing along the Galactic arm toward W43.

Galactic models predict accumulation of gas in front of the bar (Wozniak et al. 2007).

Pc-scales filaments studies to be generalized…

IRDCs forming massive stars have filamentary shapes on pc scales: Pérault et al. 1996; Rathborne et al. 2006; Simon et al. 2006; Peretto et al. 2009…

Diffuse filaments called striations too: Goldsmith et al. 2008; …



Peretto et al. 2010

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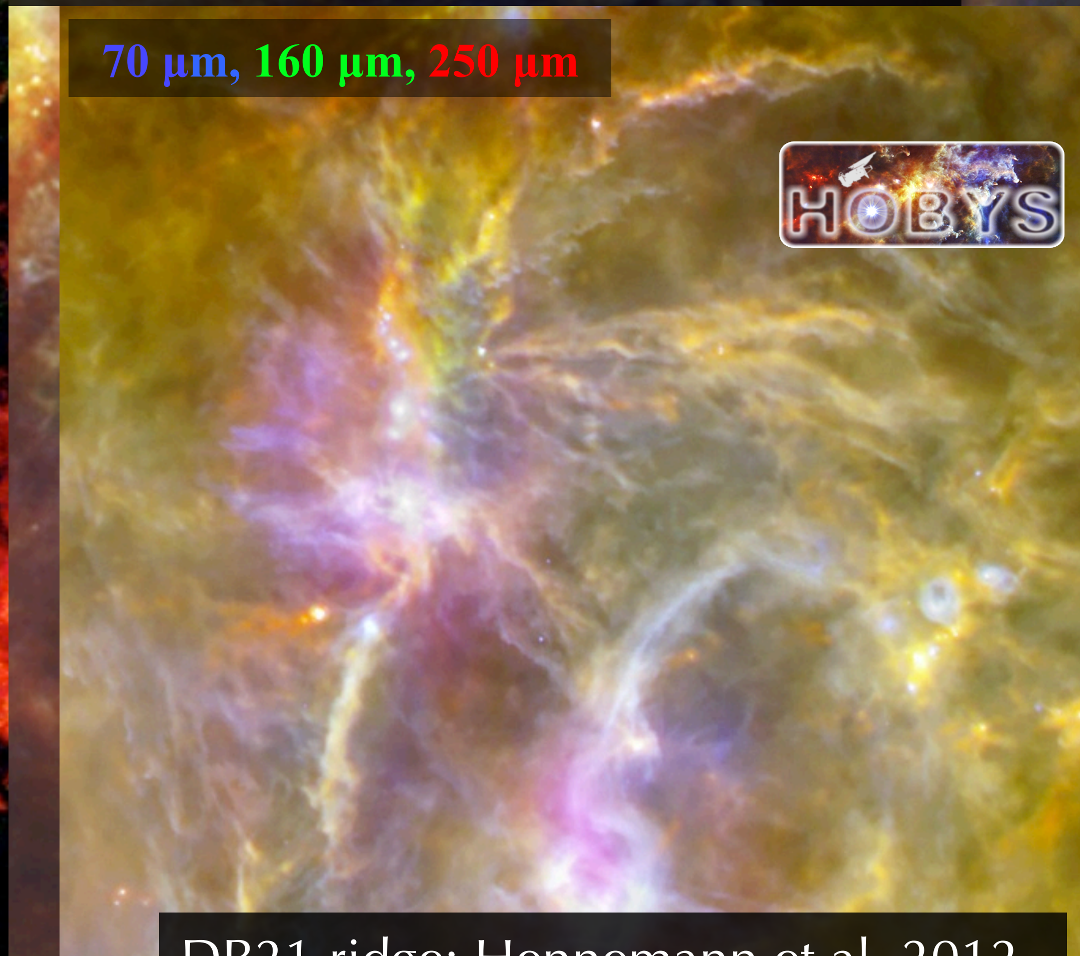
Herschel imaging and the ubiquity of filaments

From non-star forming regions to clouds forming clusters of massive stars.

Key programs: HGBS, HOBYS, Hi-Gal, EPOS,… see also Planck images

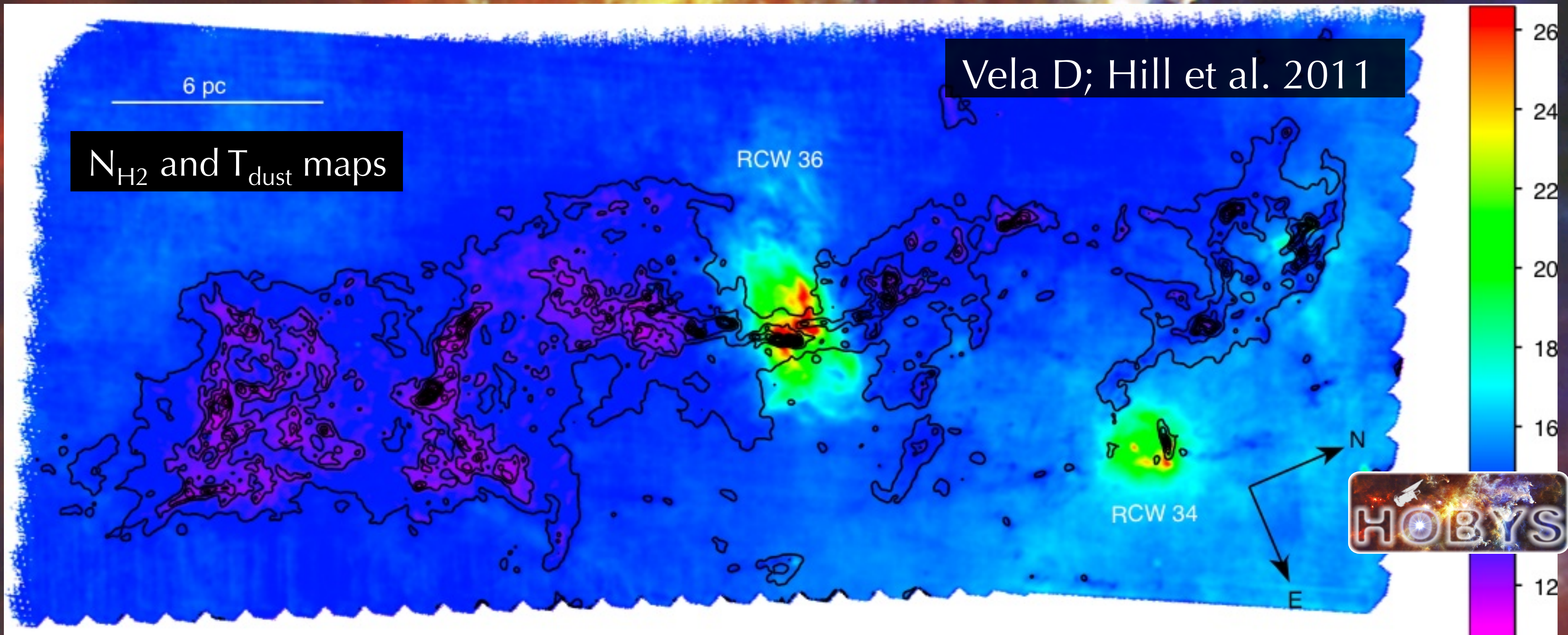
Polaris cloud; Mensh'chikov et al. 2010; Mivilles-Déchênes et al. 2010



DR21 ridge; Hennemann et al. 2012

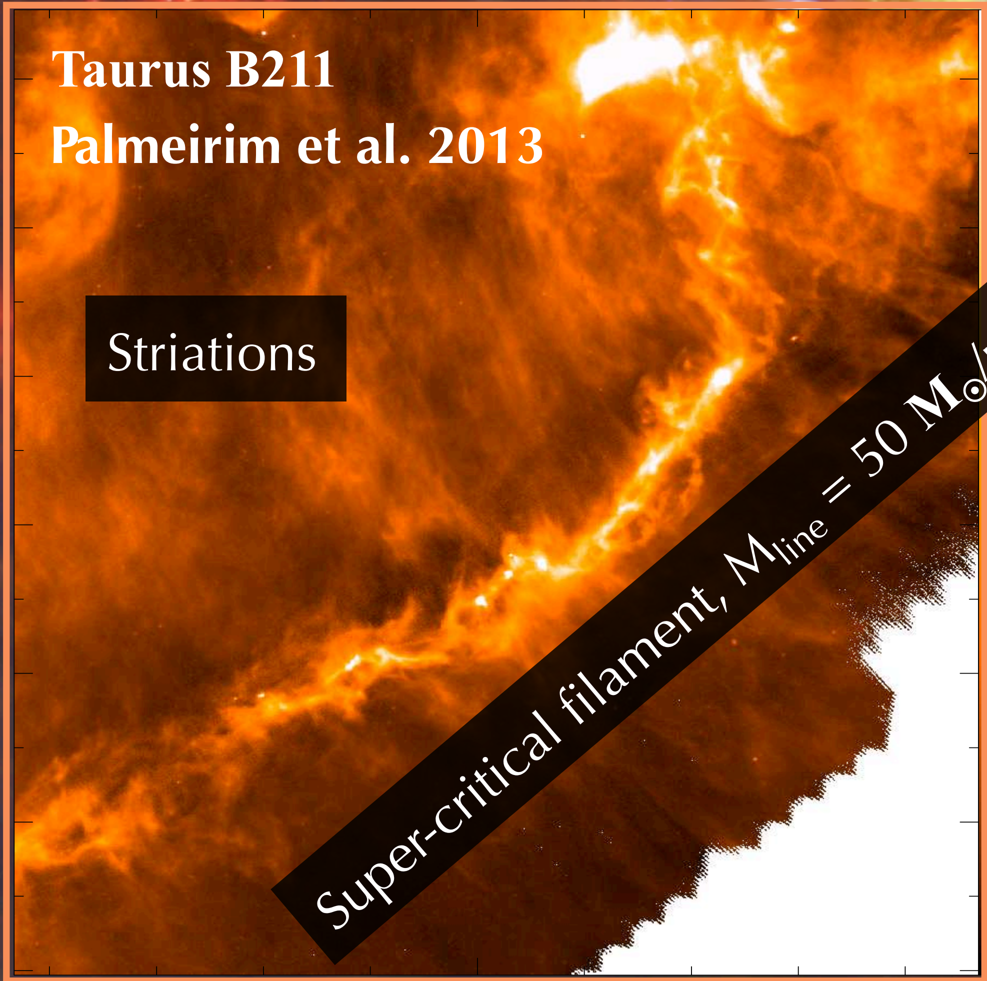
Filaments basic characterization

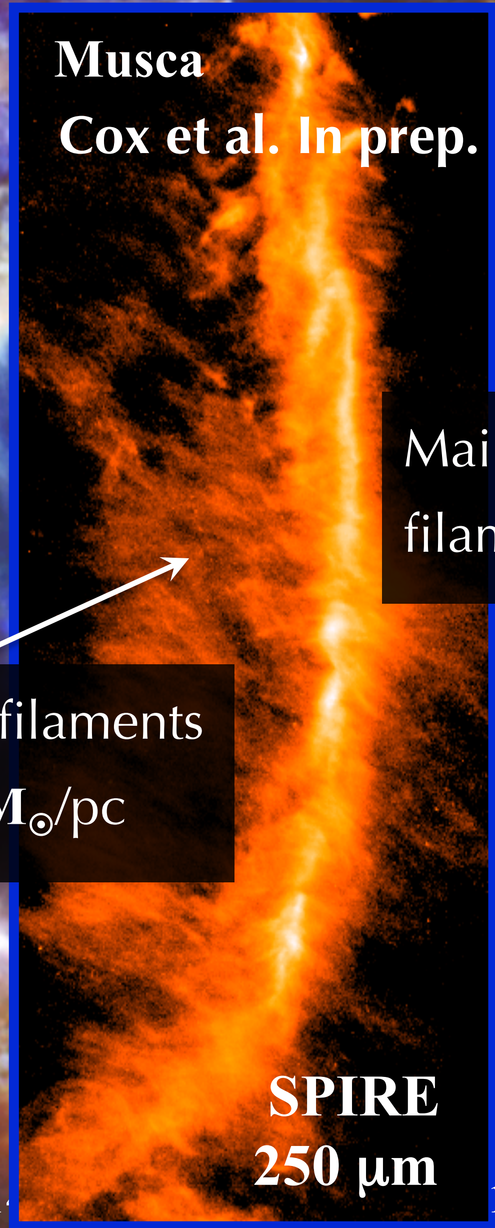
- Column density and dust temperature images created from Bayesian fitting of SEDs by modified blackbody models and high-resolution techniques (36″-18″ resolution; Hill et al. 2011, 2012; Palmeirim et al. 2013) .



Striations vs. star-forming filaments

Linear mass, M/L, compared to the thermally critical value at T_{dust}, $M_{crit} = 2\ c_s^2/G = 15\ M_\odot/pc$ (Ostriker et al. 1964).



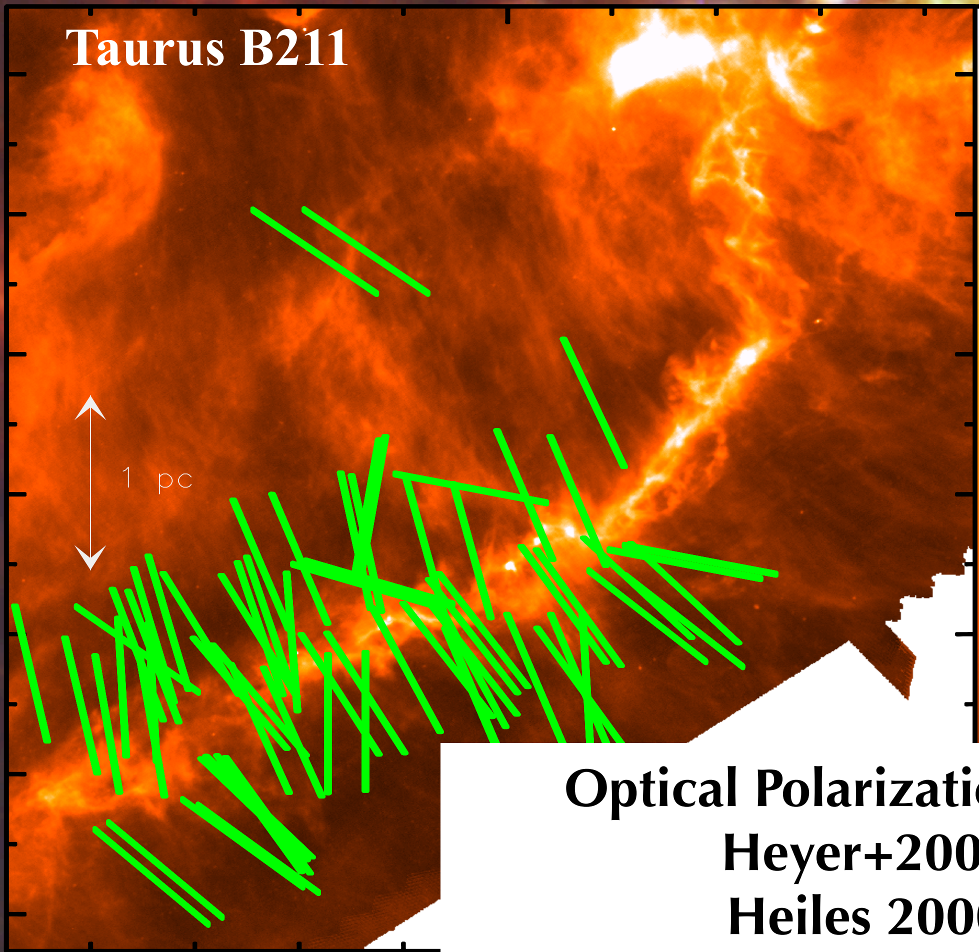


Sub-critical filaments
$M_{line} < 15\ M_\odot/pc$

Striations aligned with B field

B field direction traced by optical, NIR starlight or dust polarization.

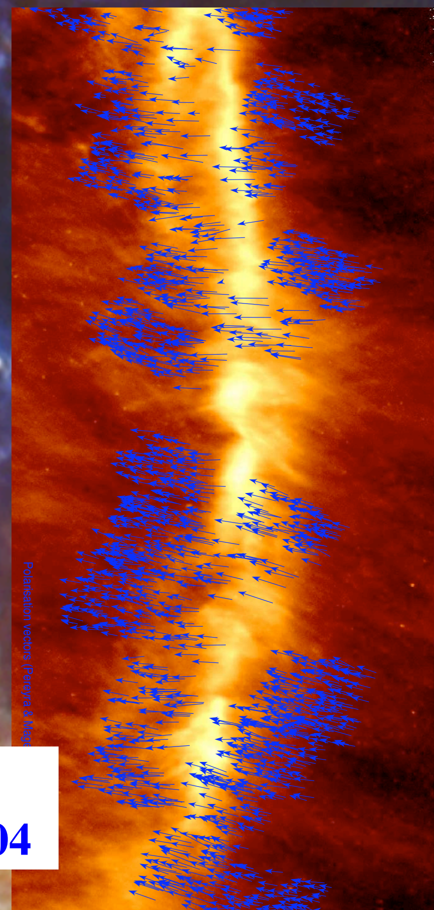
Striations suggestive of slow drifts/accretion of gas.



Optical Polarization
Heyer+2008
Heiles 2000

(see also results from the Planck collaboration)

Musca **B field**



Pereyra & Magelhaes 2004

250 µm

Magnetic field structure of super-critical filaments

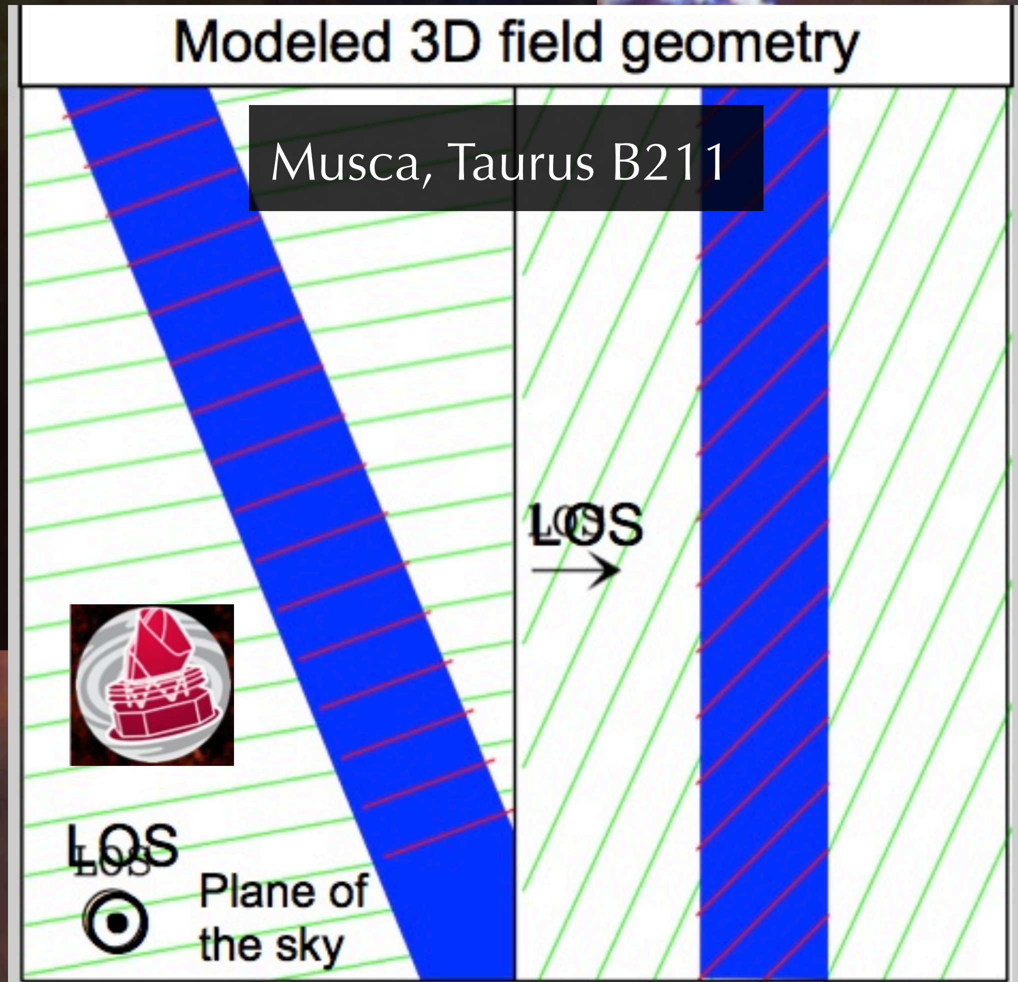
Orientation of the B field and polarization fraction are different

- in the background + striations
- within super-critical filaments:

rotation of the B-field angle

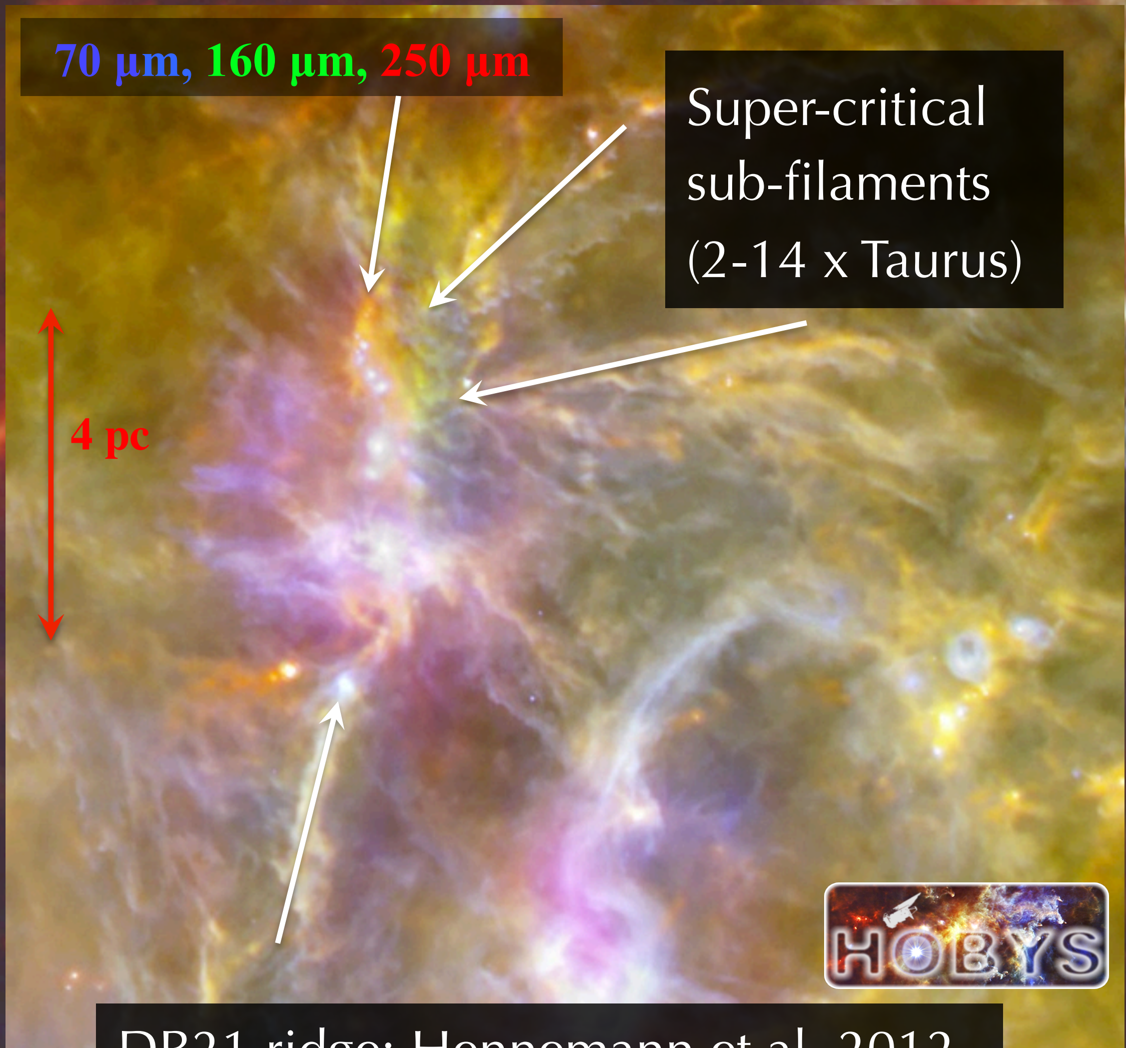
decrease of the polarization fraction

⇒ Evolution (twist?) of the B-field structure during the formation of supercritical filaments?



(Courtesy D. Arzoumanian Planck collaboration)

More spherical networks of sub-filaments toward very dense regions (ridges/hubs)



DR21 ridge; Hennemann et al. 2012

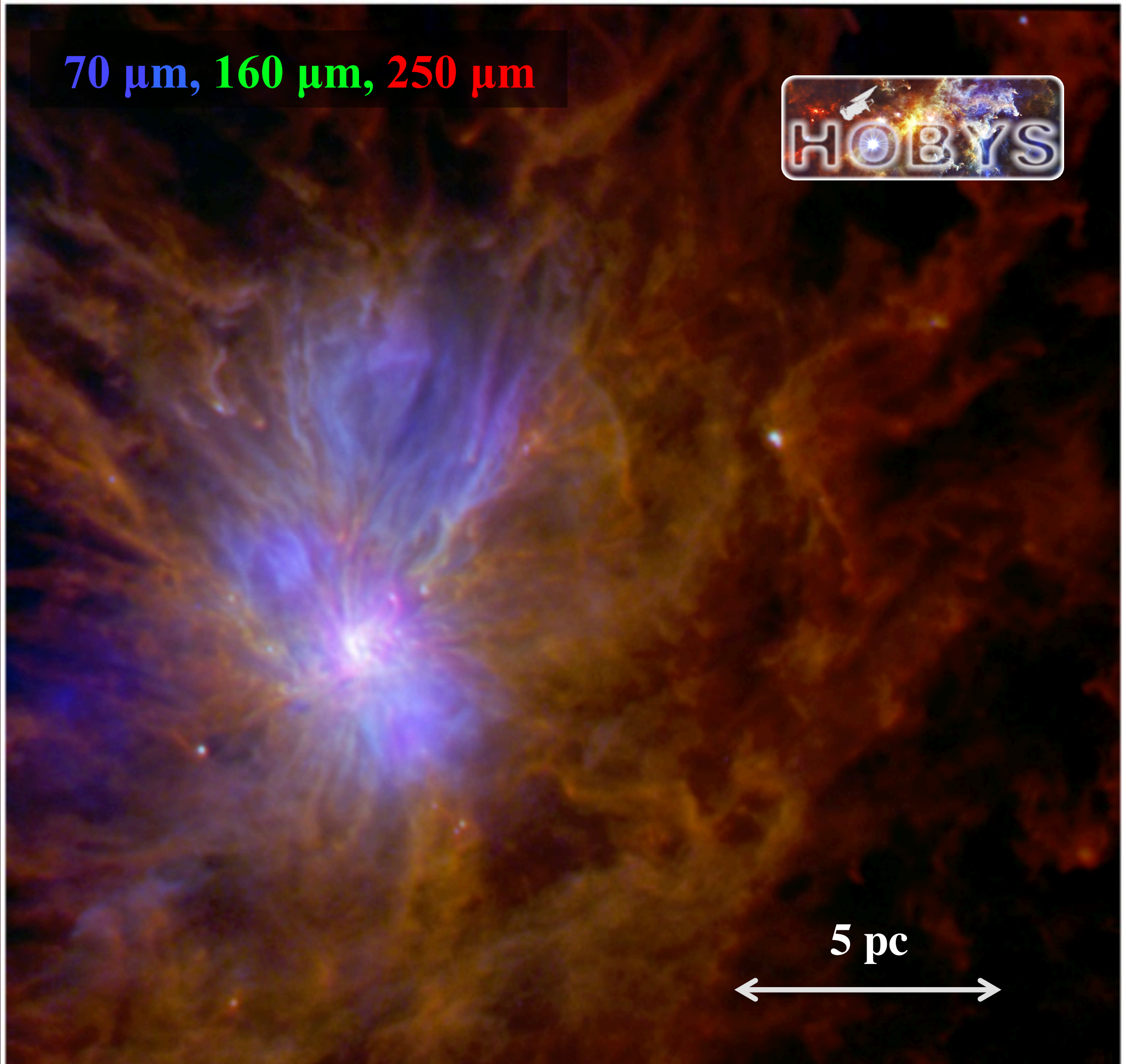
DR21 ridge, a very dense filamentary cloud with

M_{line} ~ 4 000 $\mathbf{M}_{\odot}$/pc (80 x Taurus) or 15 000 $\mathbf{M}_{\odot}$ within 5 pc^3

Ridges are high-column density (Av > 100 mag), elongated cloud structures forming high-mass star clusters (e.g. Hill et al. 2011; Motte et al. 2012).

Sub-filaments suggestive of accretion flows driven by the global infall observed (e.g. Schneider et al. 2010).

More spherical networks of sub-filaments toward very dense regions (ridges/hubs)



MonR2 hub; Didelon et al. 2014; Rayner et al. 2014

MonR2 hub, a very concentrated cloud with

5000 $M_\odot$ within r < 1 pc (~as dense as the DR21 ridge).

Density structure in $\rho(r) \sim r^{-2.5}$ (Didelon et al. 2014), suggesting the effect of a forced infall.

Cloud globally infalling has to be confirmed (Loren 1977)…

Another hub (Peretto+ 2014)

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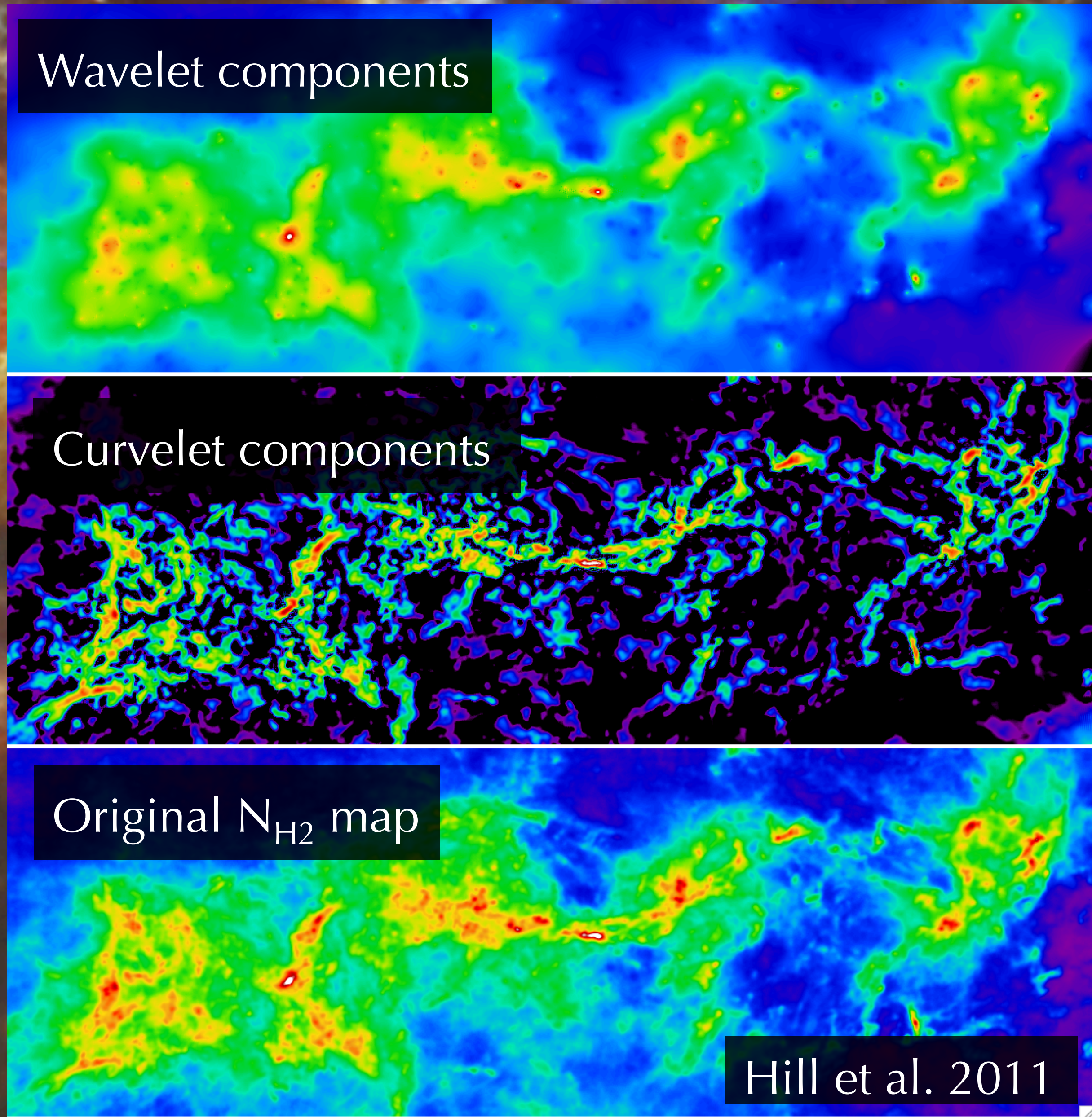
Quantification of the importance of filaments

Filaments modeled as prolate spheroids (Kainulainen+ 2014), crest of > 0.5 pc size (Arzoumanian+ 2011), cylinders (Mensh'chikov 2012; Schizano+ 2014), …

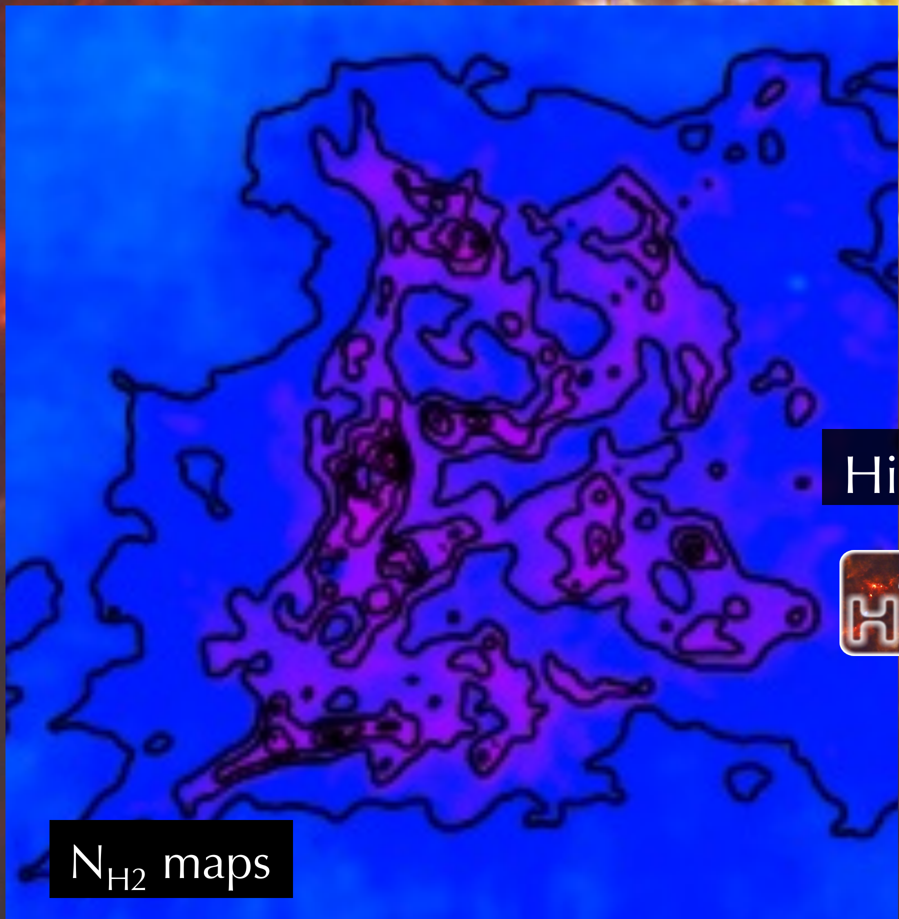
Using multi-resolution decomposition tools such as MCA (Stark et al. 2003, 2004), 10-20% of the gas resides in filamentary structures.

This ratio rises to ~50% in ridges and drops to a few % in hubs.

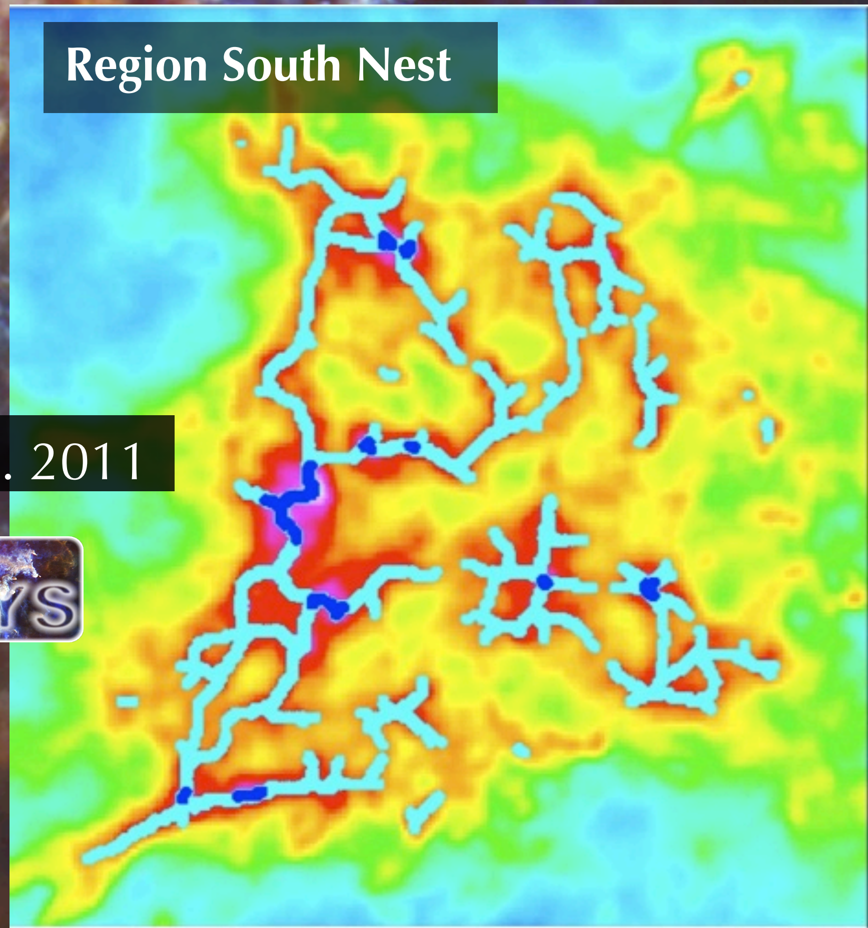


Tools to trace network of filaments

Census of filaments with e.g. DisPerSE (Sousbie 2011), a topological tool (used for the cosmic web) based on the theory of persistence and discrete Morse theory.

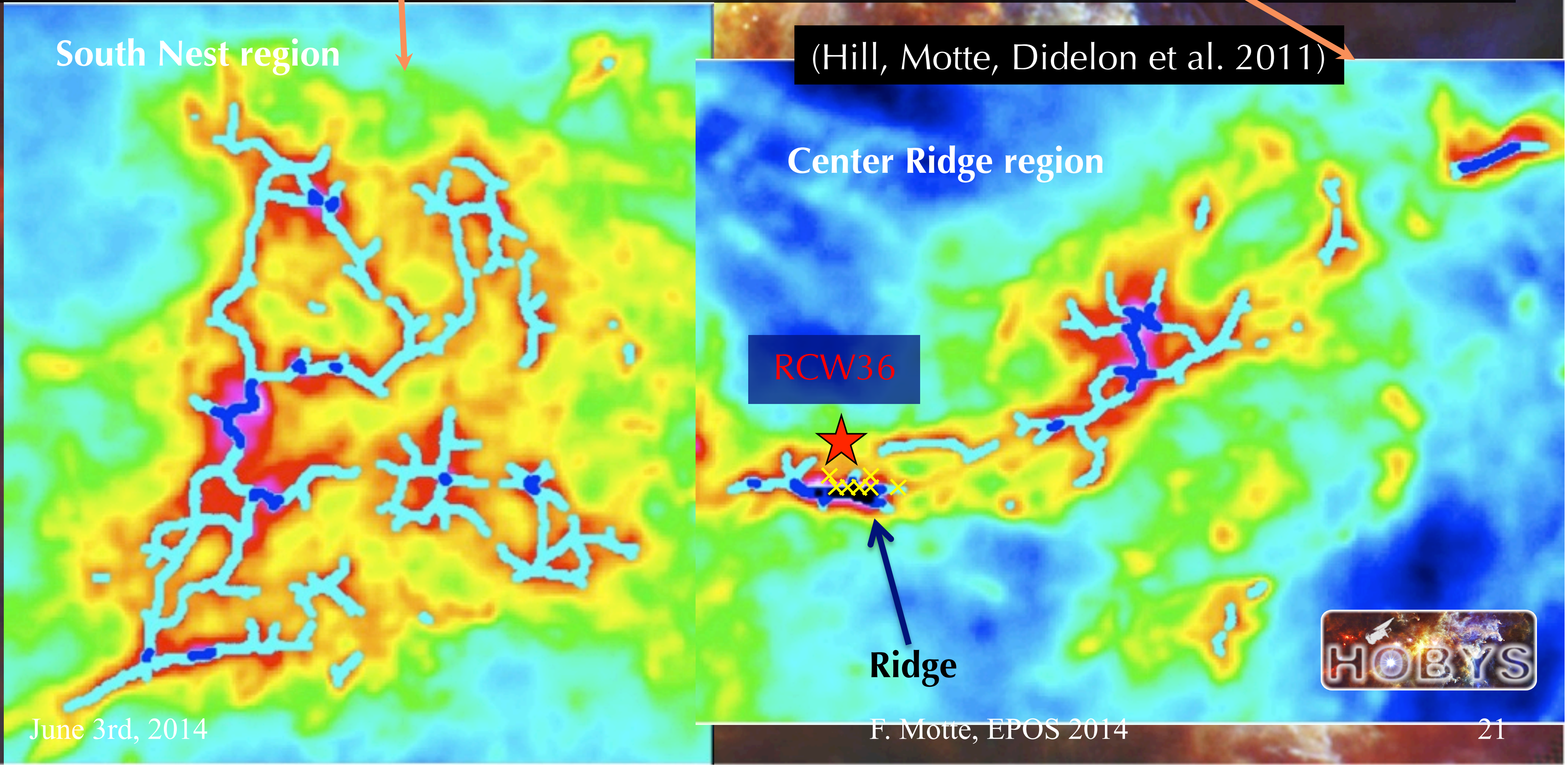


Hill et al. 2011

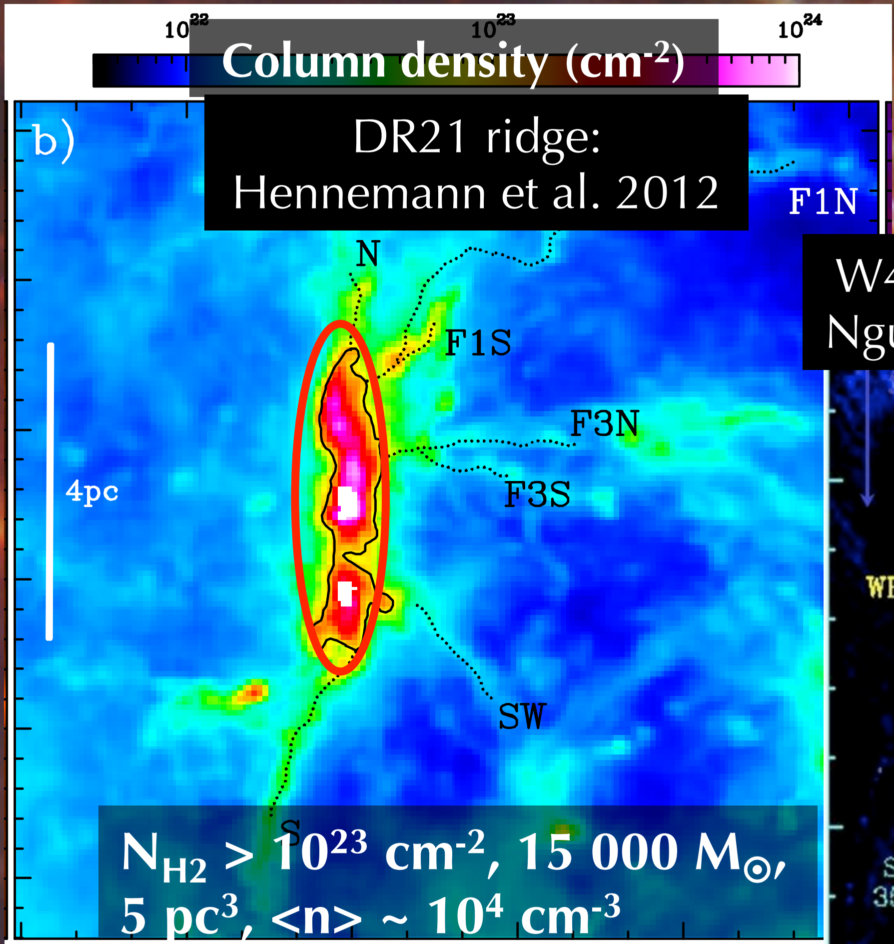


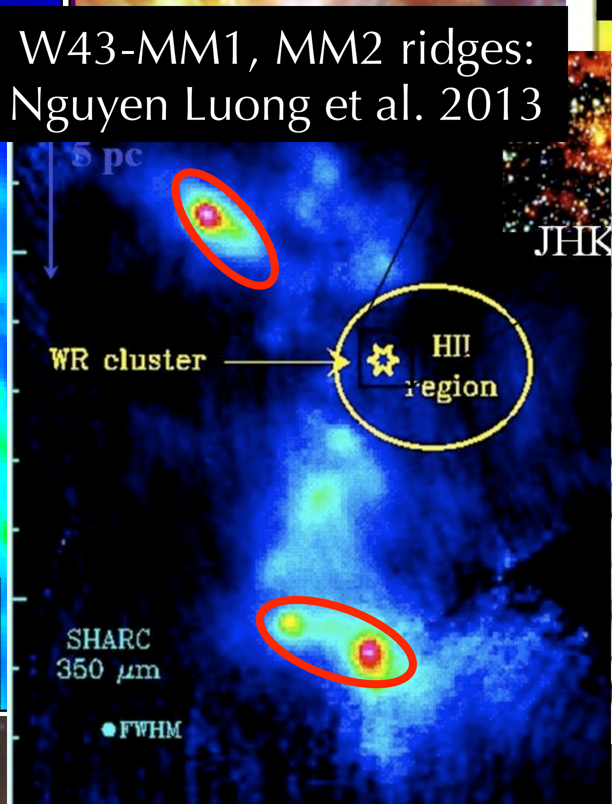
Comparing cloud structure in sub-regions

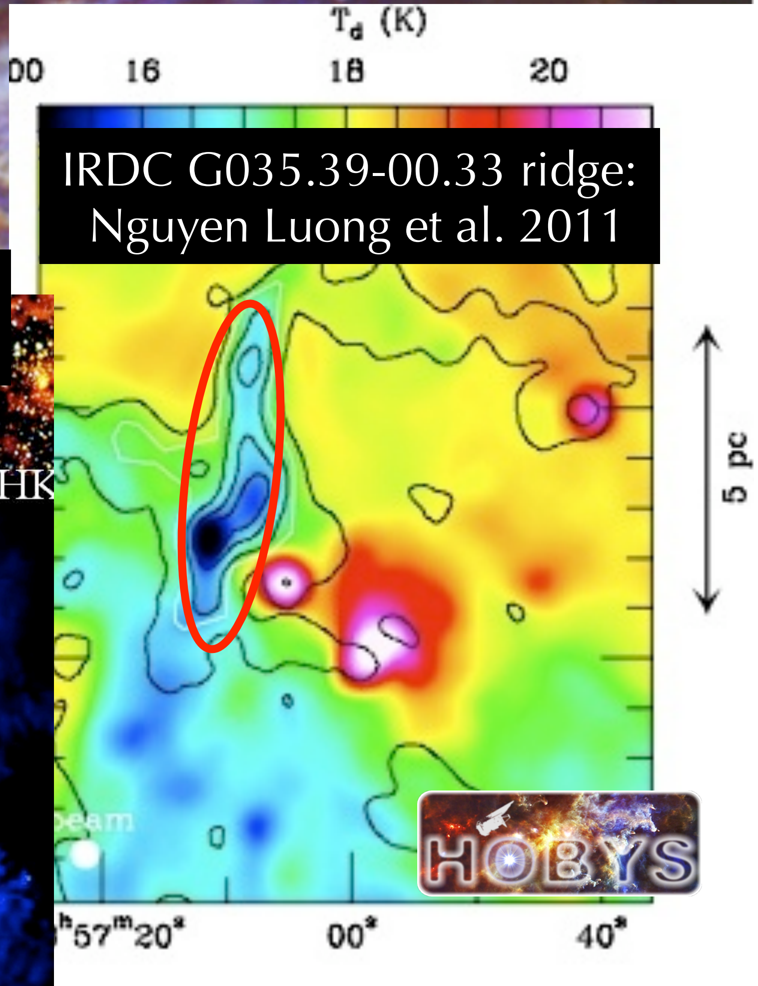
- Disorganized network of filaments versus single dominating ridges
- High-mass stars form preferentially in ridges, high-column density (Av > 100 mag), elongated cloud structures dominating their surrounding.



Ridges (5-10 pc², ~10⁴ cm⁻³) are extreme IRDCs/clumps





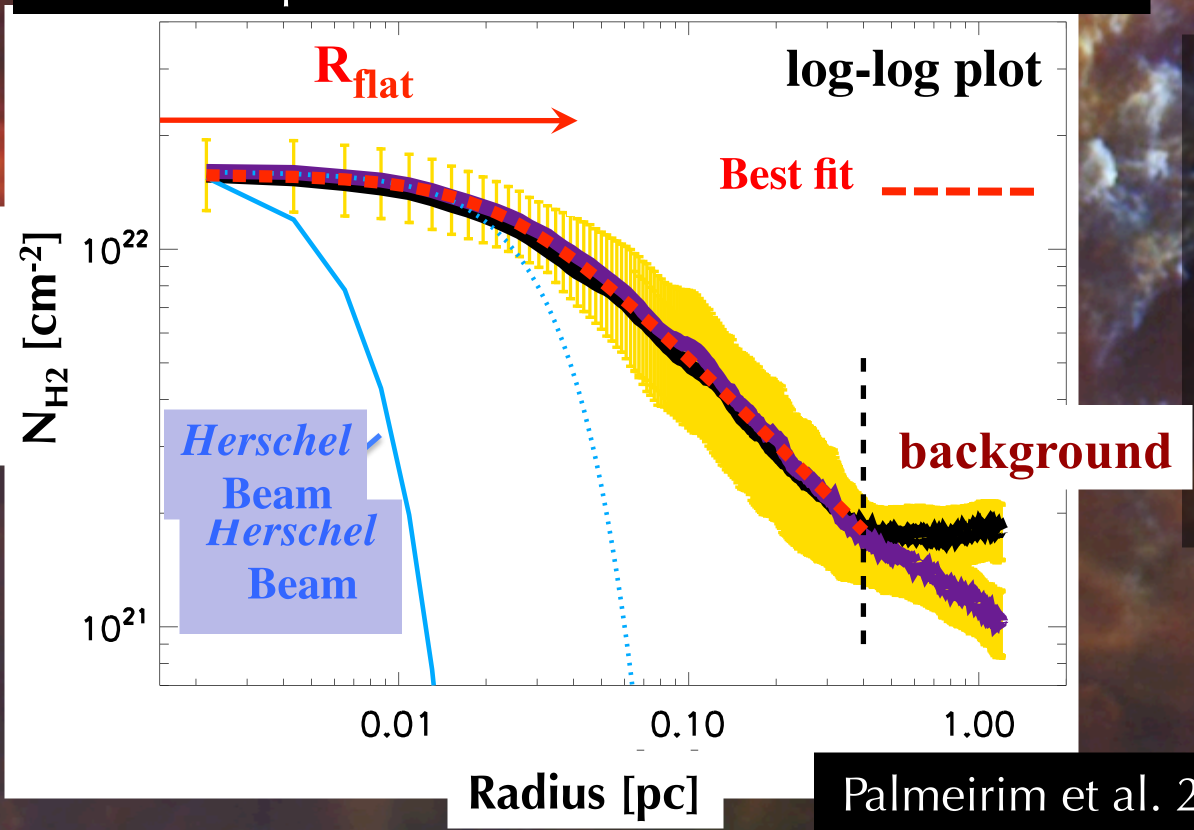


See also Schneider et al. 2010; Motte et al. 2012

Density structure perpendicular to filaments

Herschel resolves filaments with Plummer-like profiles and 0.1 pc inner width (Arzoumanian+ 2011; Palmeirim+ 2013; Peretto+ 2012) in agreement with Nutter+ (2008). See however Juvela+ 2012; Hennemann+ 2012…

Transverse profile of the Taurus B213 main filament



Palmeirim et al. 2013

Plummer-like model:

$$\rho(r) = \rho_c / [1 + (r/R_{flat})^2]$$

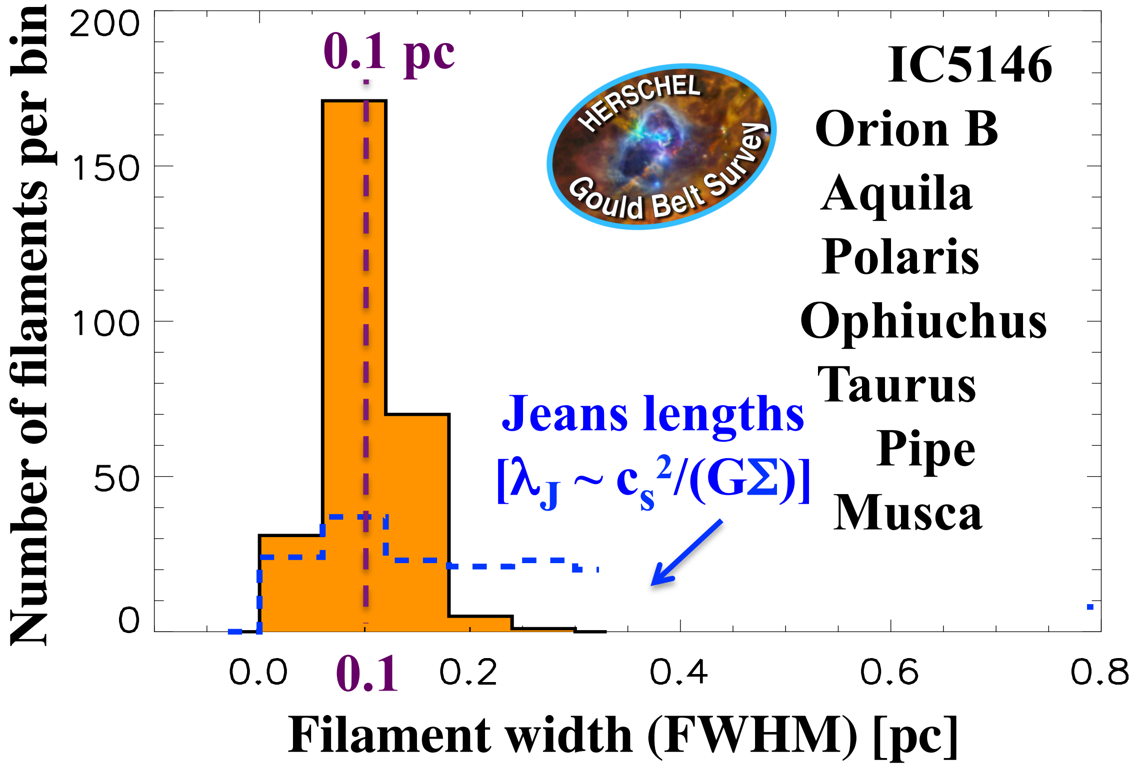
Flat inner plateau: $2R_{flat} \sim 0.1$ pc

⇒ Filaments form from the dissipation of turbulence, 0.1 pc is the sonic scale.

Arzoumanian et al. 2011

Filaments have a characteristic width of 0.1 pc

Statistical distribution of widths for > 270 filaments



Arzoumanian et al. 2011

Self-gravitating contracting filaments can maintain 0.1 pc if they are accreting (Inutsuka & Miyama 1997)

New paradigm of SF (André et al. 2010, 2012 PPVI):

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

⇒ Filaments are the link between clouds and prestellar cores that form within their 0.1 pc width.

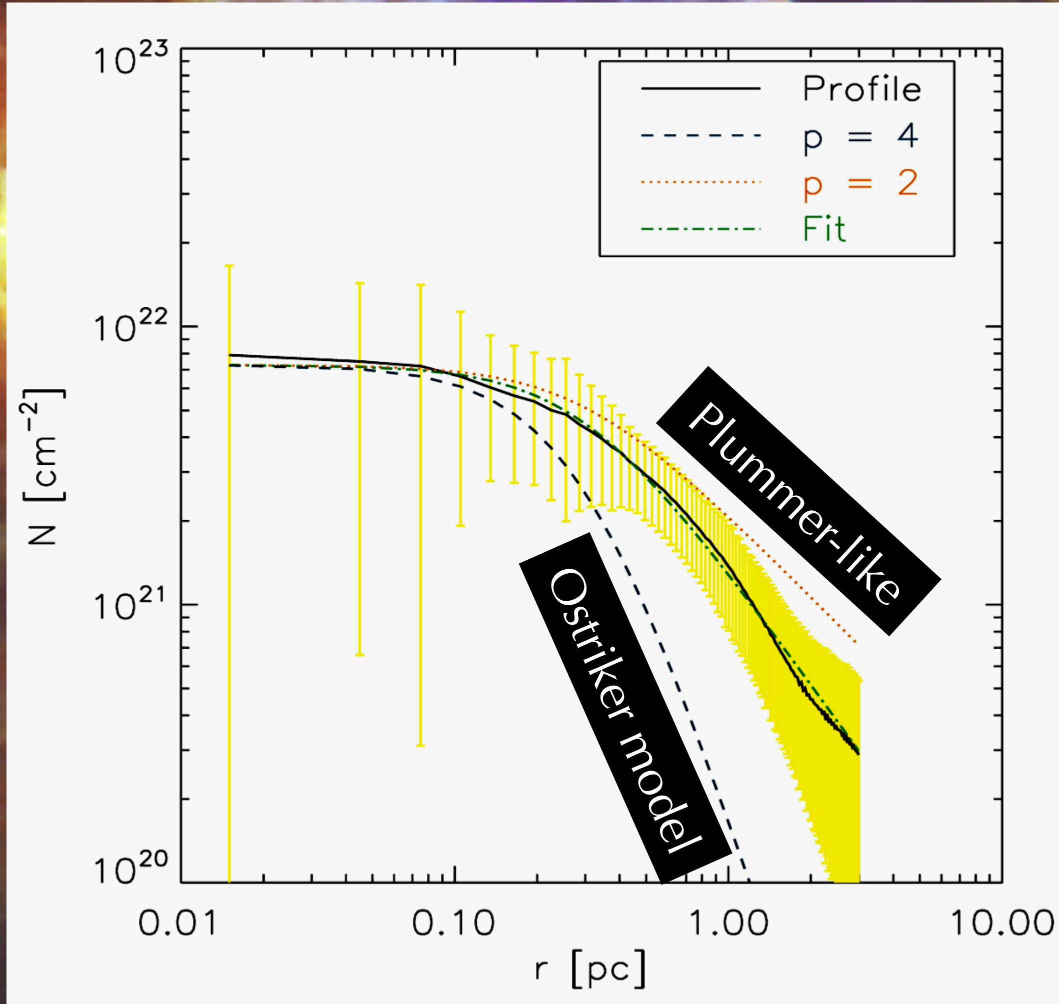
⇒ The threshold of instability equals the SF threshold (Av > 8 mag or 150 $M_\odot$/pc²).

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.

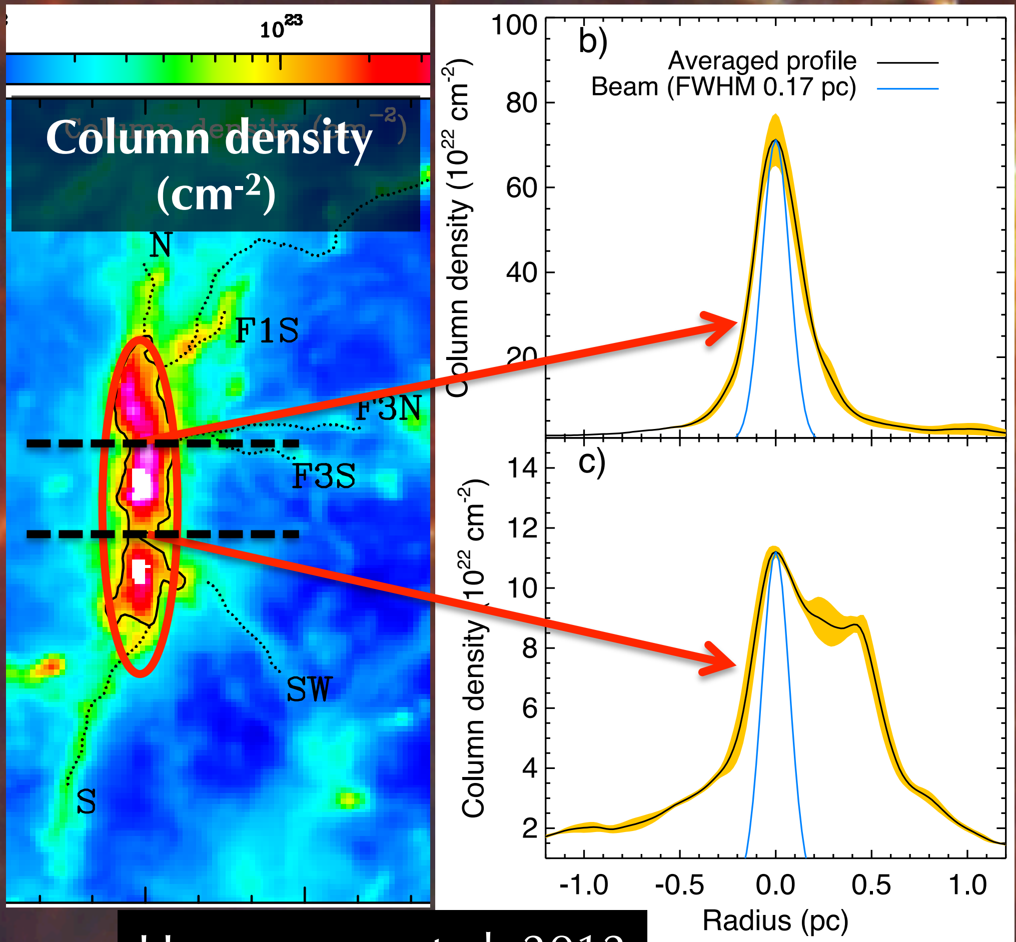
Hennebelle & André 2013:
Self-gravitating accreting filaments have a dissipation scale of 0.1 pc if it arises from ion-neutral friction.

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



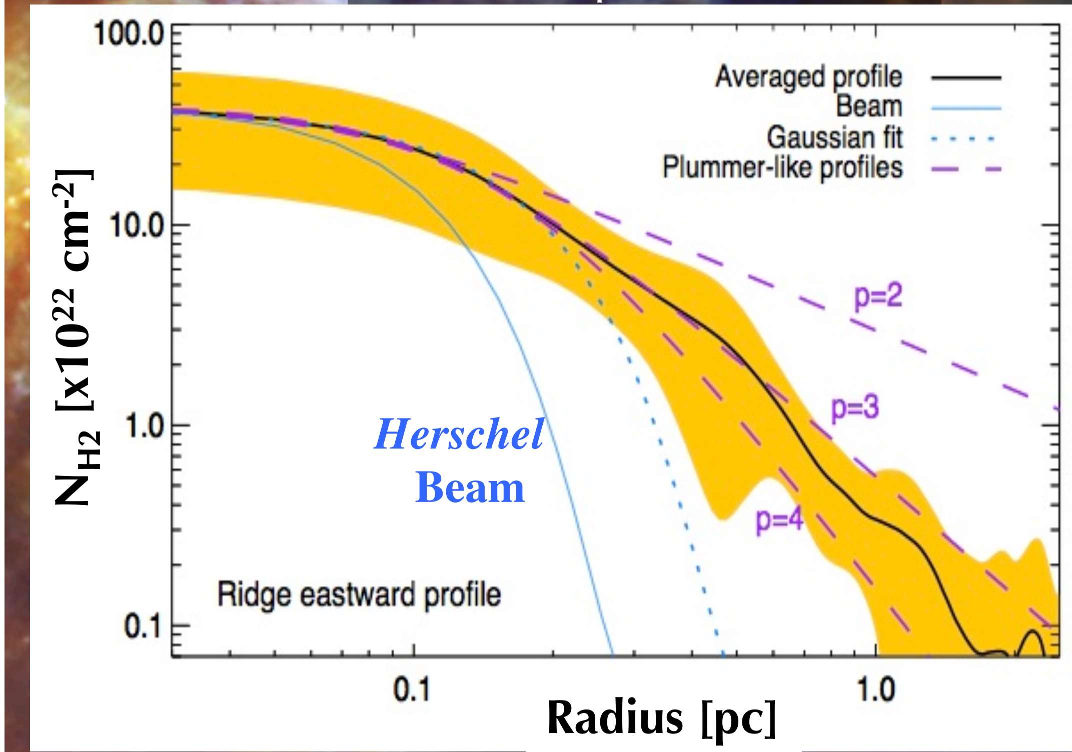
Gomez & Vazquez-Semademi 2014

Ridge are substructured and compressed clumps



Hennemann et al. 2012

Transverse profile of DR21



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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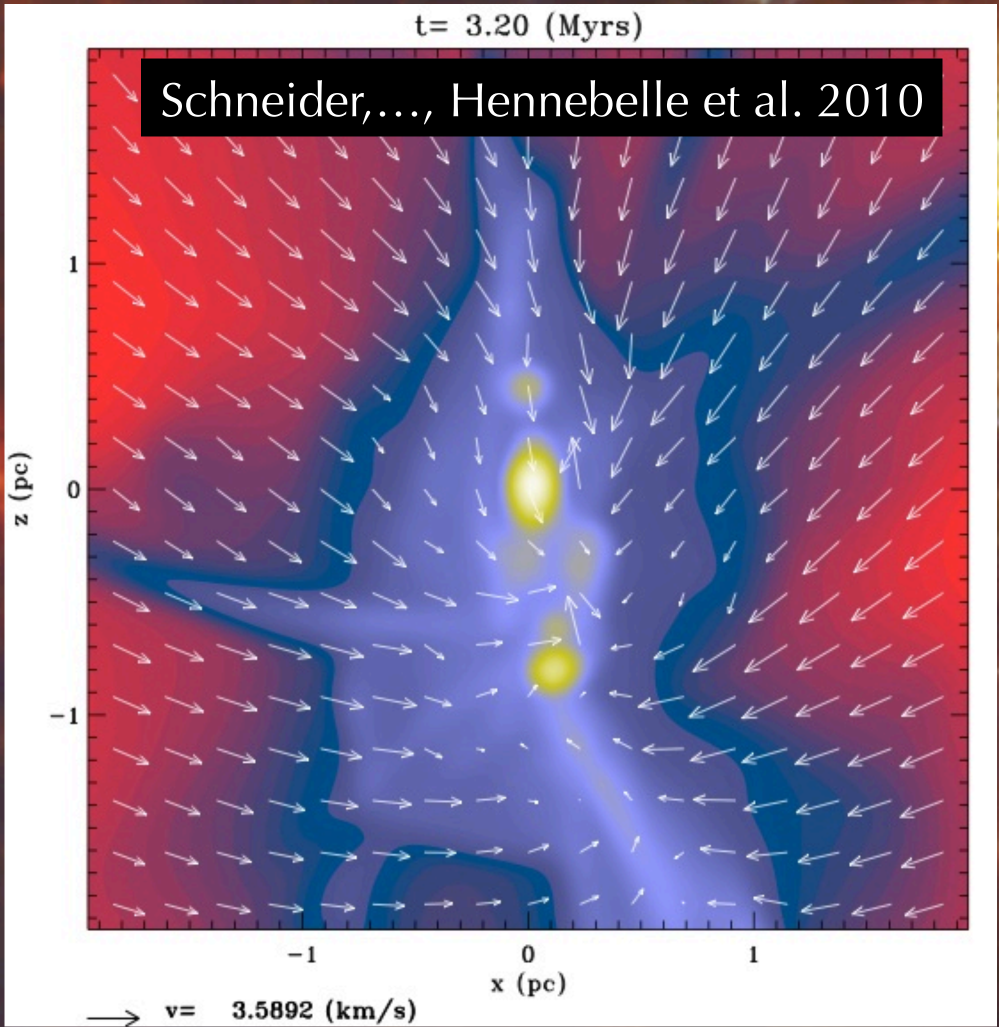
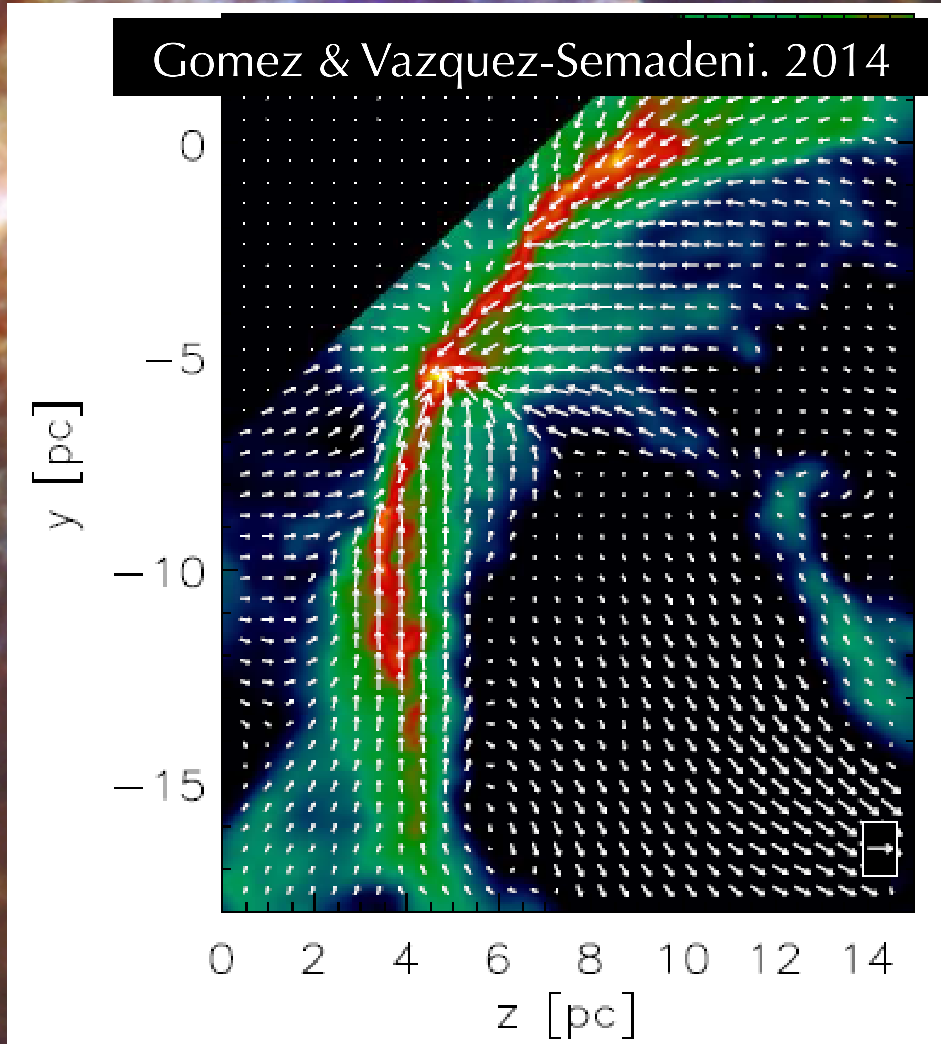
Globally collapsing filaments: cloud gas is accreted onto filaments and in turn onto SF seeds

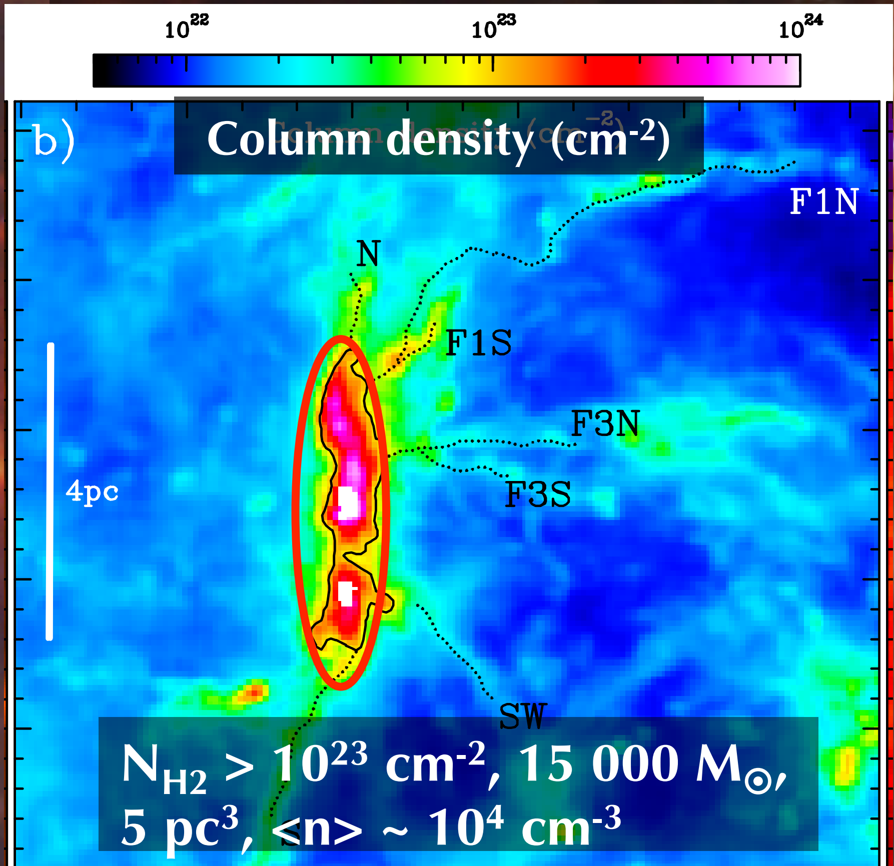




See also numerical simulations by F. Heitsch, and R. Smith on smaller scales…

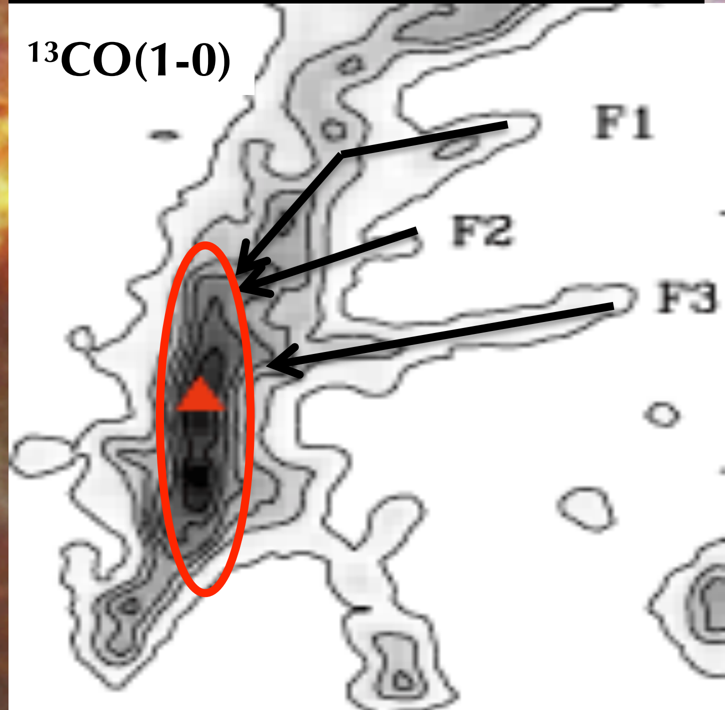
Most ridges should form by cloud global collapse

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



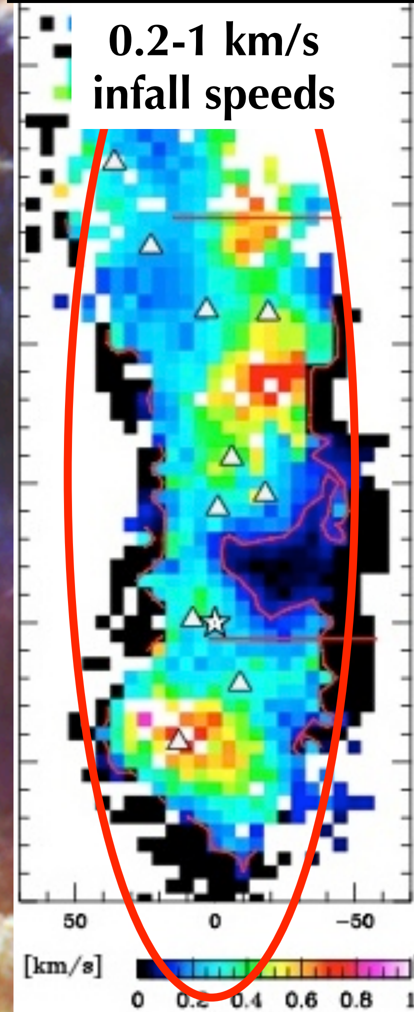
Hennemann, Motte, Schneider et al. 2012

Gas flows along sub-filaments



Schneider, Csengeri, Bontemps et al. 2010

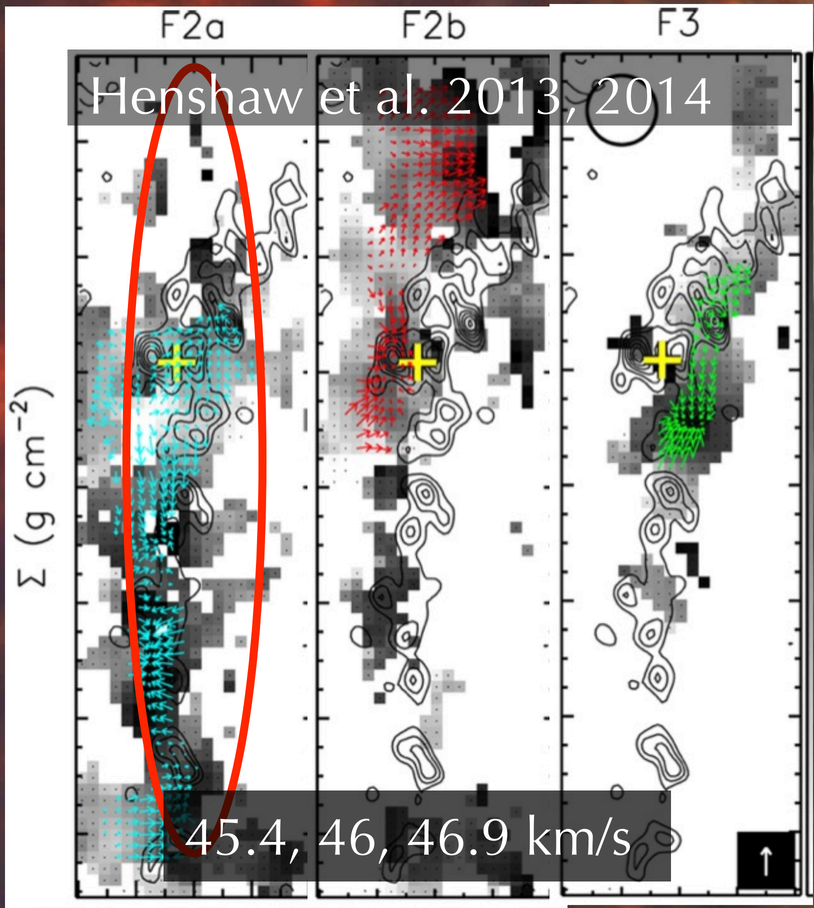
Global infall



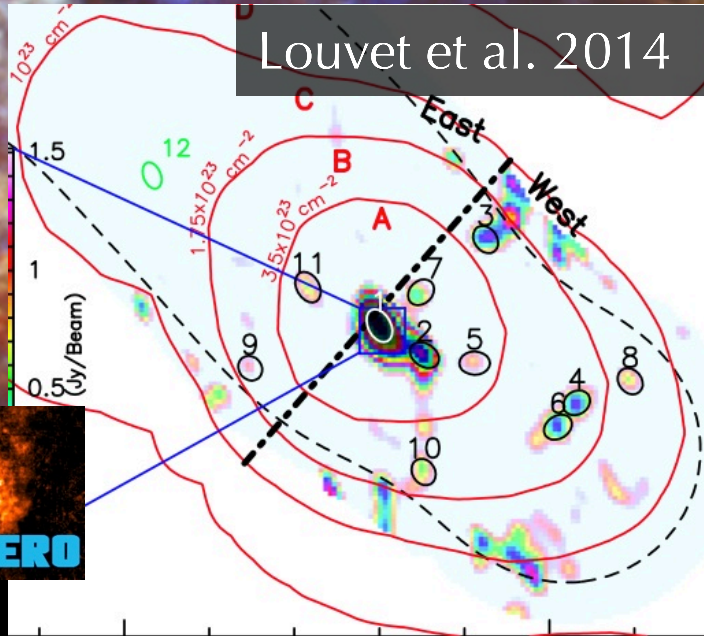
- Similar kinematics found for other ridges/hubs (Peretto et al. 2008, 2014; Kirk et al. 2013; Motte et al. in prep.; …)

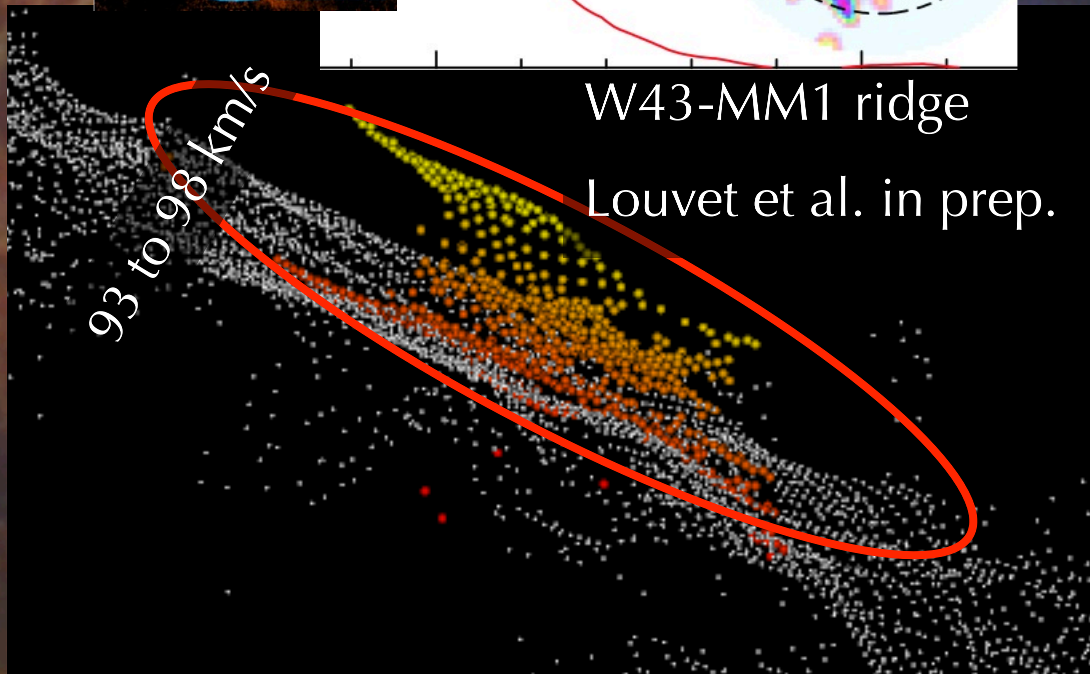
Ridges are braids of star-forming filaments/layers

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



see also Tackenberg+ 2014



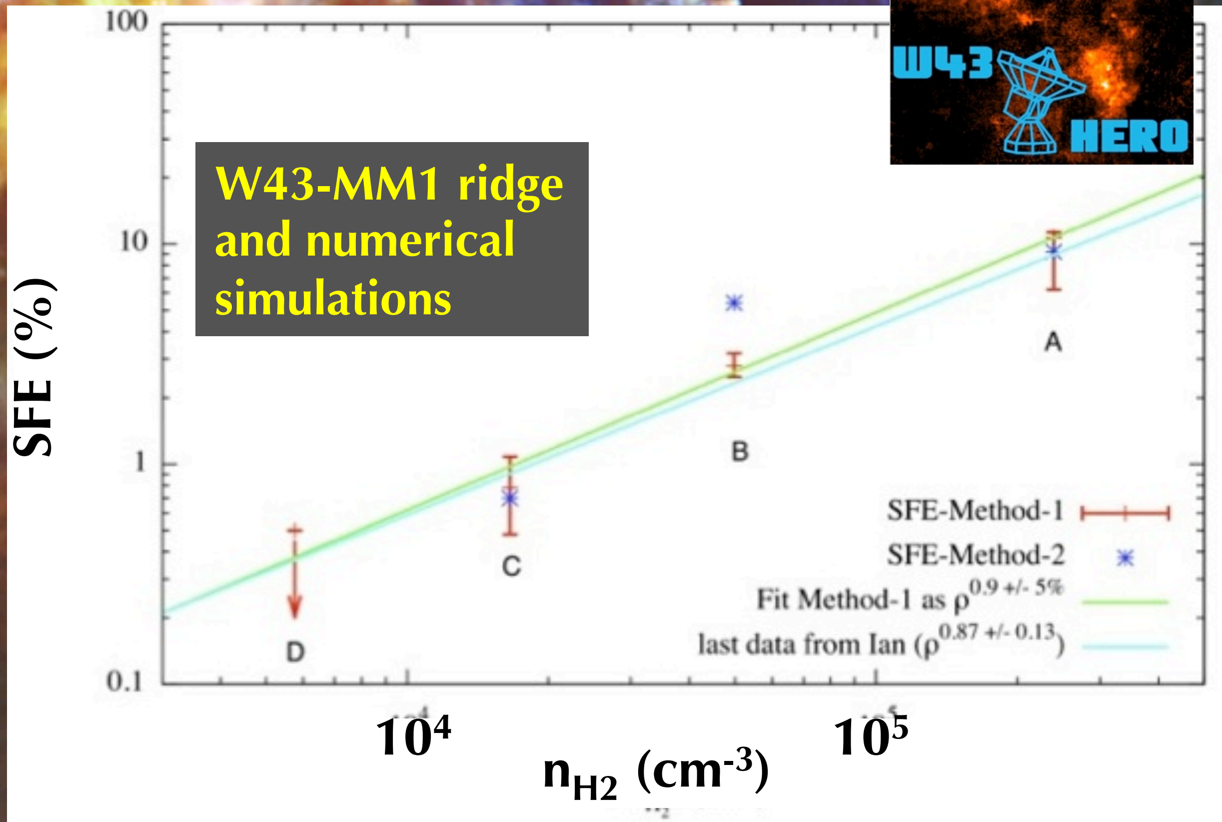


Is a constant CFE a good approximation?

An IRAM Plateau de Bure census of protostars in the W43-MM1 ridge provides an estimate of the clump to core formation efficiency (CFE, Louvet et al. 2014).

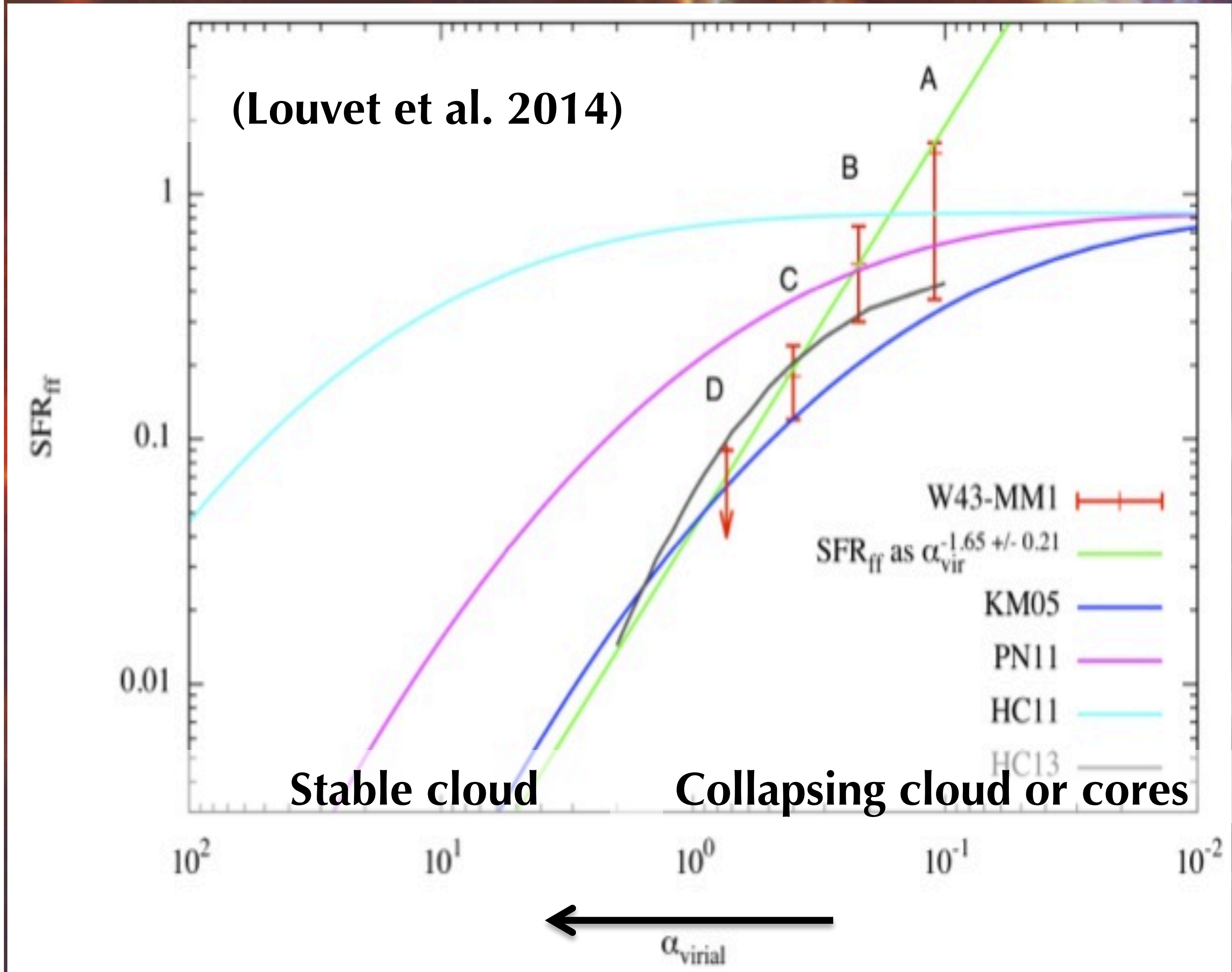
Lada et al.(2012) relation between SFR and cloud mass implicitely assumes a constant CFE in regions above the SF threshold (Av> 8 mag).

SFE measured within the W43-MM1 ridge and in numerical simulations increases with volumetric density (Louvet, Motte, Hennebelle et al. 2014)



(Louvet, Motte, Hennebelle et al. 2014)

Constraining statistical theories of SFR on W43-MM1…



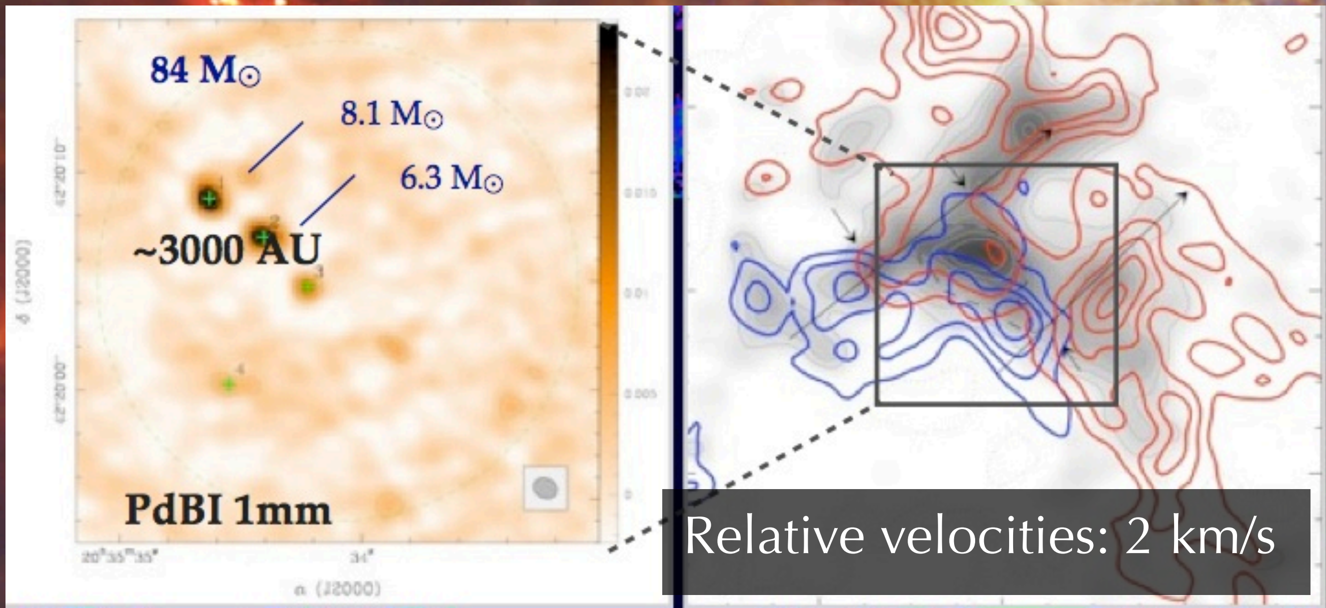
- Statistical models of SFR suggests saturation at low virial numbers (Krumholz & McKee 2005; Padoan & Nordlund 2011; Hennebelle & Chabrier 2011, 2013; Federrath et al. 2012).

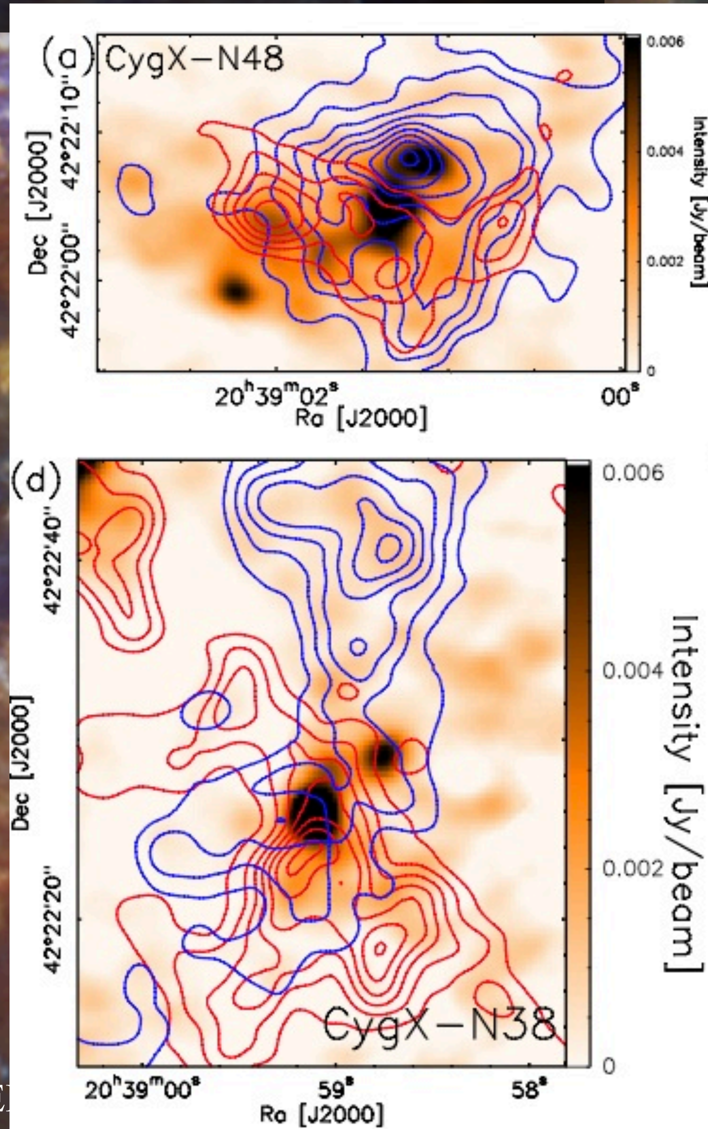
- Inconsistent with observations in W43.

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

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).

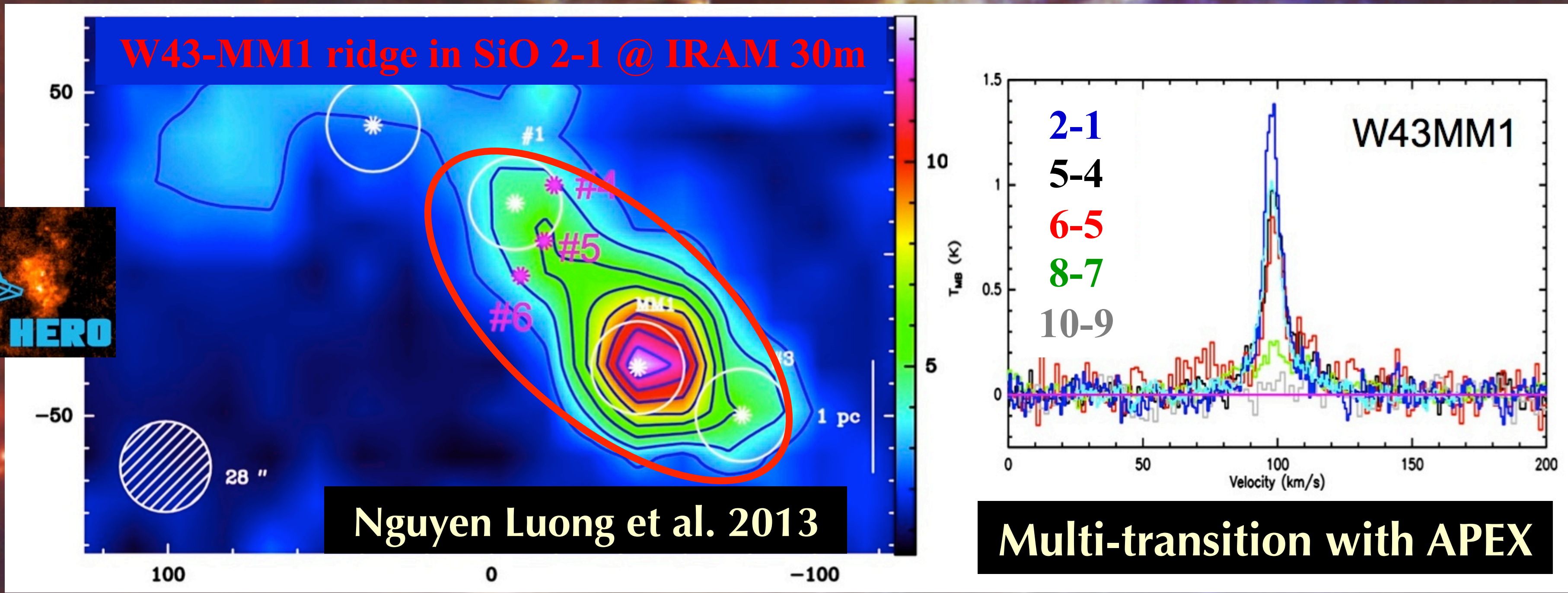




See also Henshaw et al. 2014

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

Bright & extended SiO emission along W43 ridges



SiO classically associated with protostellar outflows. In W43-MM1, >70% is associated to 5-10 km/s shocks (Louvet et al. 2014)

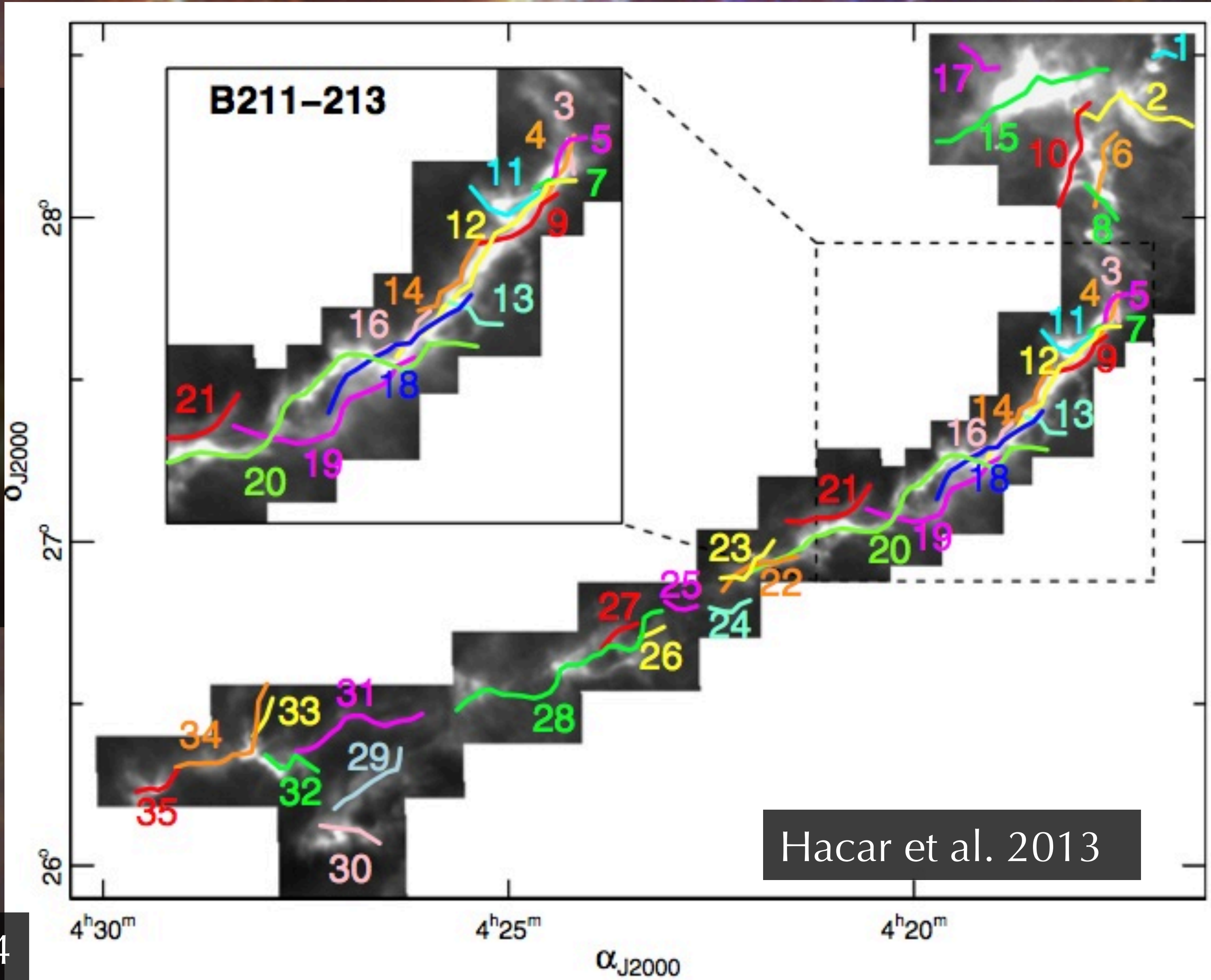
Observations compared with shock models with Si in gas or SiO in grain mantles to constrain the filament merging (Gusdorf et al. in prep.).

See also Jiménez-Serra et al. 2011; Sanhueza et al. 2013; …

Braids/bundles of filaments are not specific to ridges

Velocity-coherent filaments/fibers detected in $C^{18}O$. spreading 3.5 km/s

⇒ Supercritical filaments also form through filament merging.



Hacar et al. 2013, 2014

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1. A hierarchy of filaments from 0.1 to 100 pc, at least.

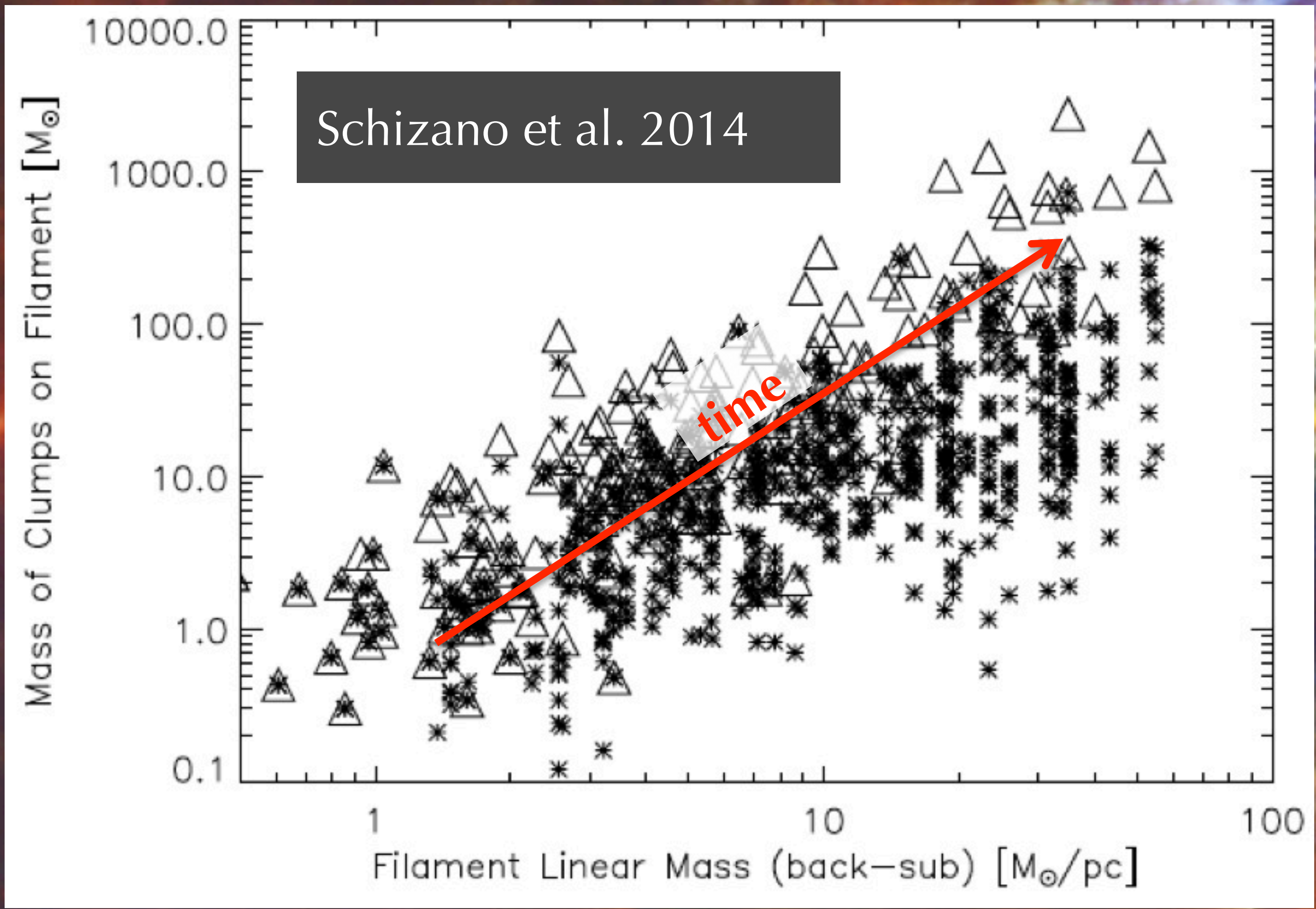
2. Geometrical considerations on pc-scale filaments make the distinction between striations, supercritical filaments, and ridges.

3. Among the *Herschel* legacies will be precise constraints on filaments structure.

4. Studies of filament kinematics suggest that they are unhomogeneous and dynamical systems.

5. Should filaments bother those studying individual cores and protostars?

Link between filaments and dense cores

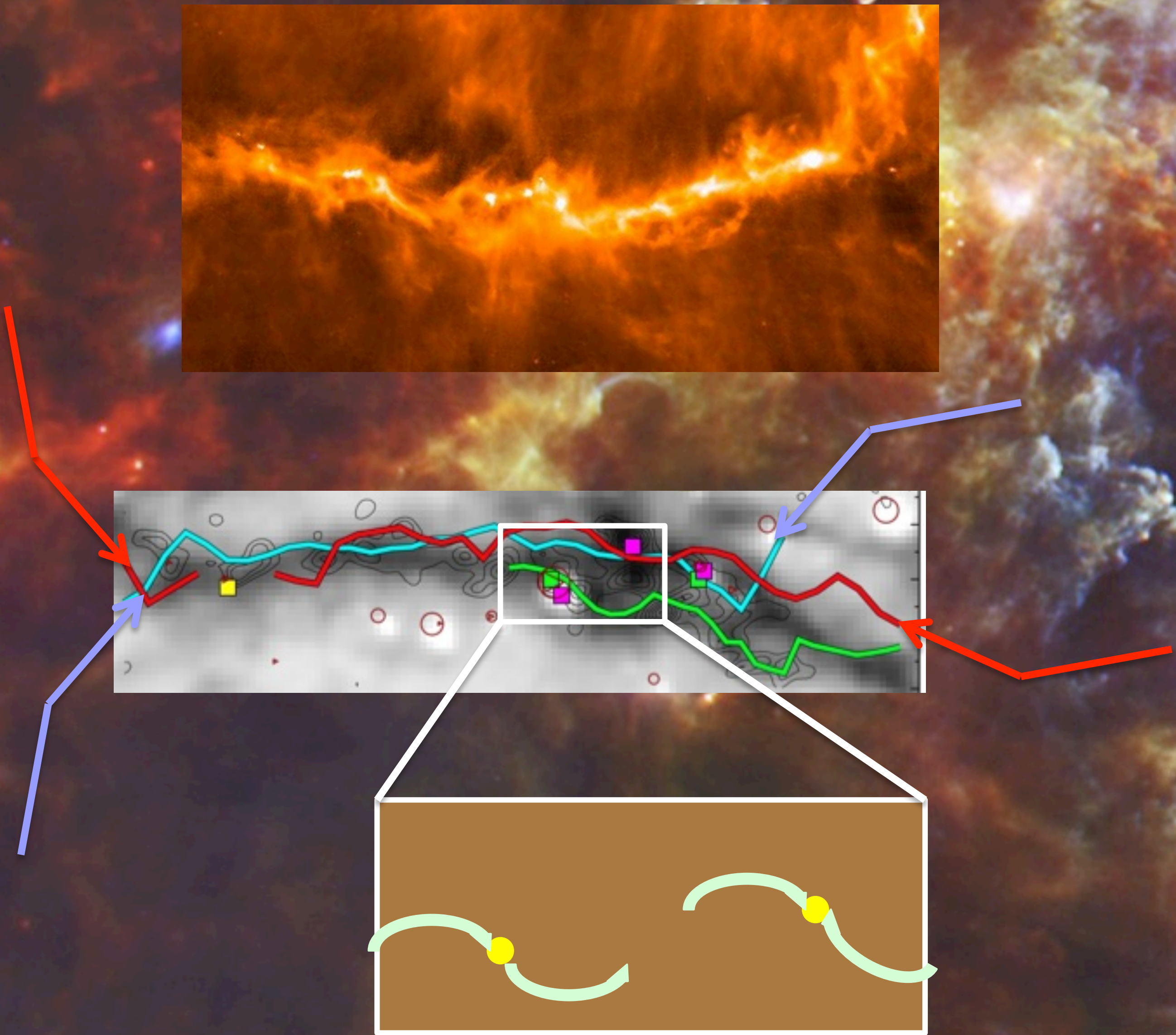


In HGBS fields, 75% of prestellar cores are within super-critical filaments.

In HOBYS fields, massive protostars are found within ridges or hubs.

In Hi-GAL fields, filaments get denser and clumps grow in mass as the SF develops.

Is the concept of prestellar dense cores meaningful in ridges?



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. Protostar accretion is non-local & anisotropic.

⇒ Prestellar cores may not exist in such dynamical environments.

Conclusion AND questions on filamentology

- A hierarchy of coherent filaments from 100 pc to 0.1 - 0.01 pc. What is their origin? spiral shock? thermal instability? supersonic turbulence? gravity?
- Striations are feeding supercritical filaments along B-field. At what pace? And does it increase the mass of protostellar cores?
- Supercritical filaments have 0.1 pc inner width that corresponds to the sonic scale. How could this width be conserved while the filament is contracting? Are supercritical filaments homogeneous quasi-static structures?
- Ridges are braids of supercritical filaments, are globally contracting, and continuously fed by sub-filaments. Are they stagnation points? or the result of forced infall?
- Stars are forming within supercritical filaments, clusters of massive stars within ridges or hubs. Do prestellar cores and protostars accrete mass from their parental filament/ridge/hub?