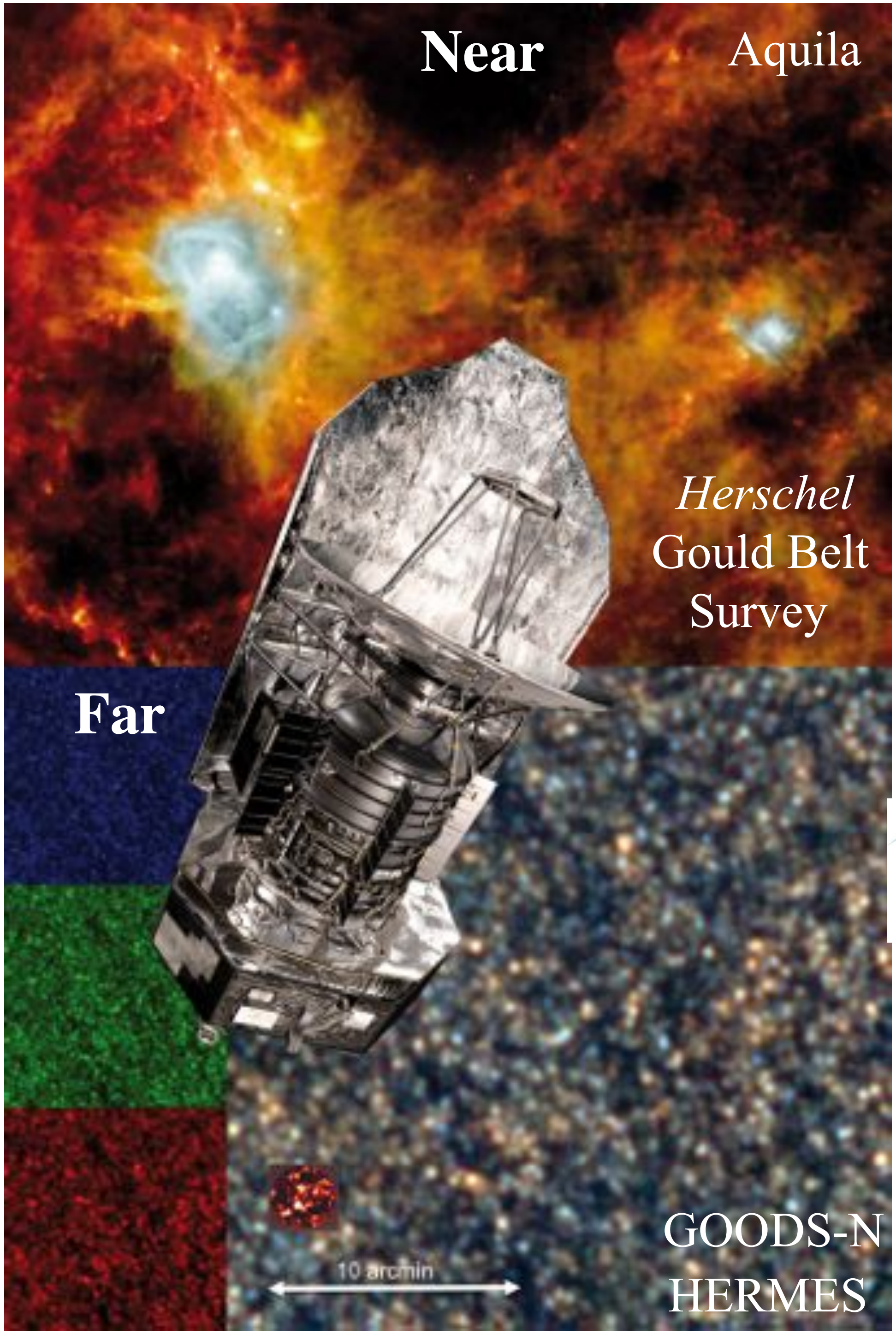


Results from the *Herschel* Gould Belt survey: Toward a New Paradigm for Star Formation on GMC scales ?

Philippe André
CEA
Laboratoire AIM Paris-Saclay

SPIRE
SAG 3

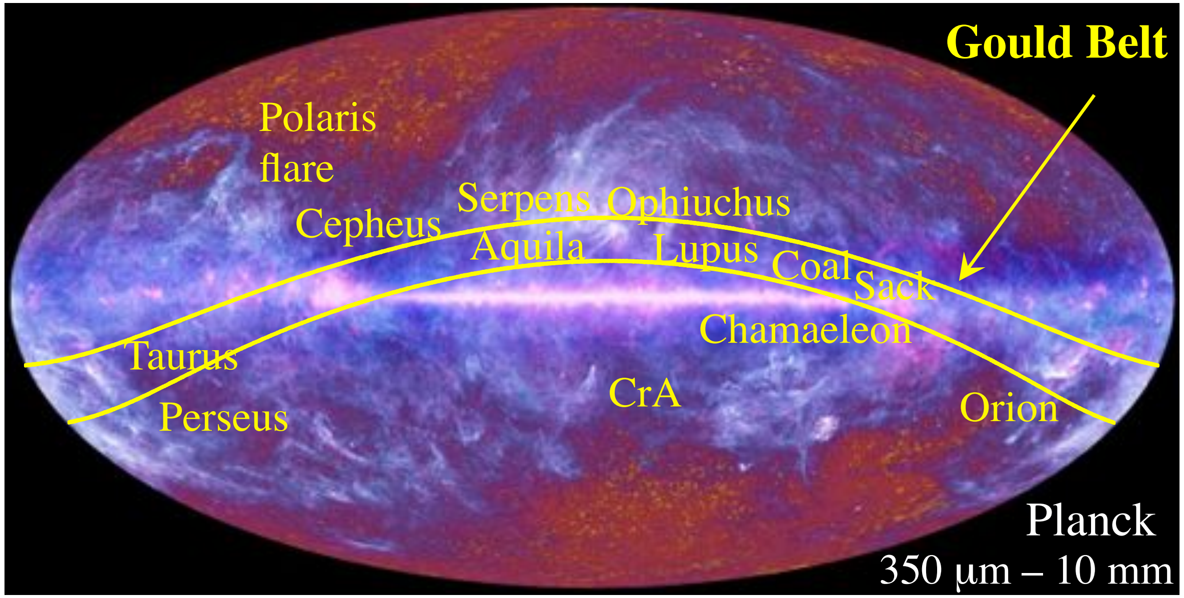
PACS

Journées ASA – Grenoble – 12 Nov 2013

The *Herschel* Gould Belt Survey

SPIRE/PACS 70-500 μm imaging of the bulk of nearby (d < 0.5 kpc) molecular clouds (~ 250 deg^2), mostly located in Gould's Belt.

- ➢ Complete census of prestellar cores and Class 0 protostars.



http://gouldbelt-herschel.cea.fr/

~ 15" resolution at λ ~ 200 μm

←→

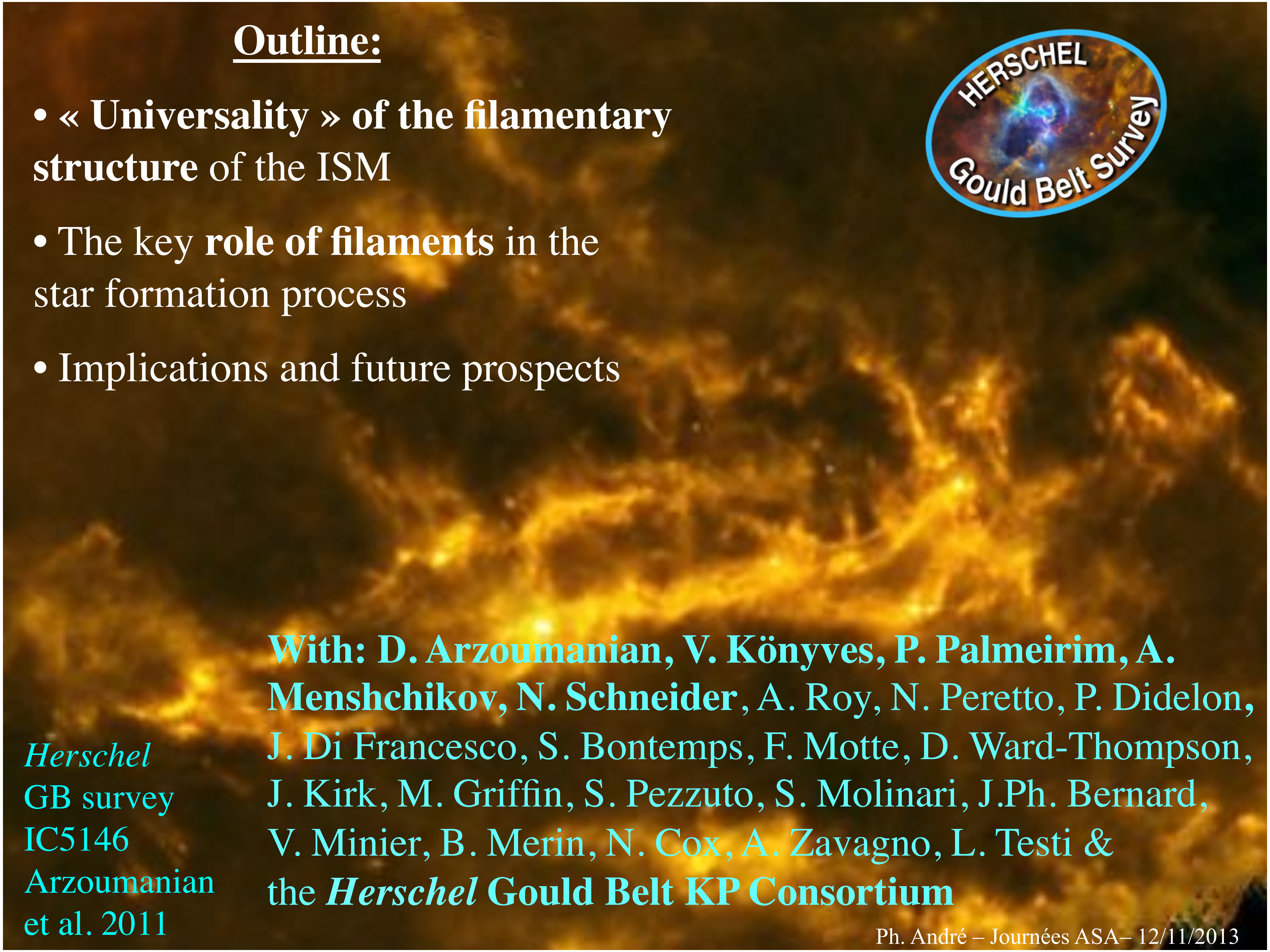
~ 0.02 pc < Jeans length @ d = 300 pc

Motivation: Key issues on the early stages of star formation

- What generates prestellar cores & drives their evolution to protostars ?
- Nature of relationship between the prestellar CMF & the IMF ?

Outline:

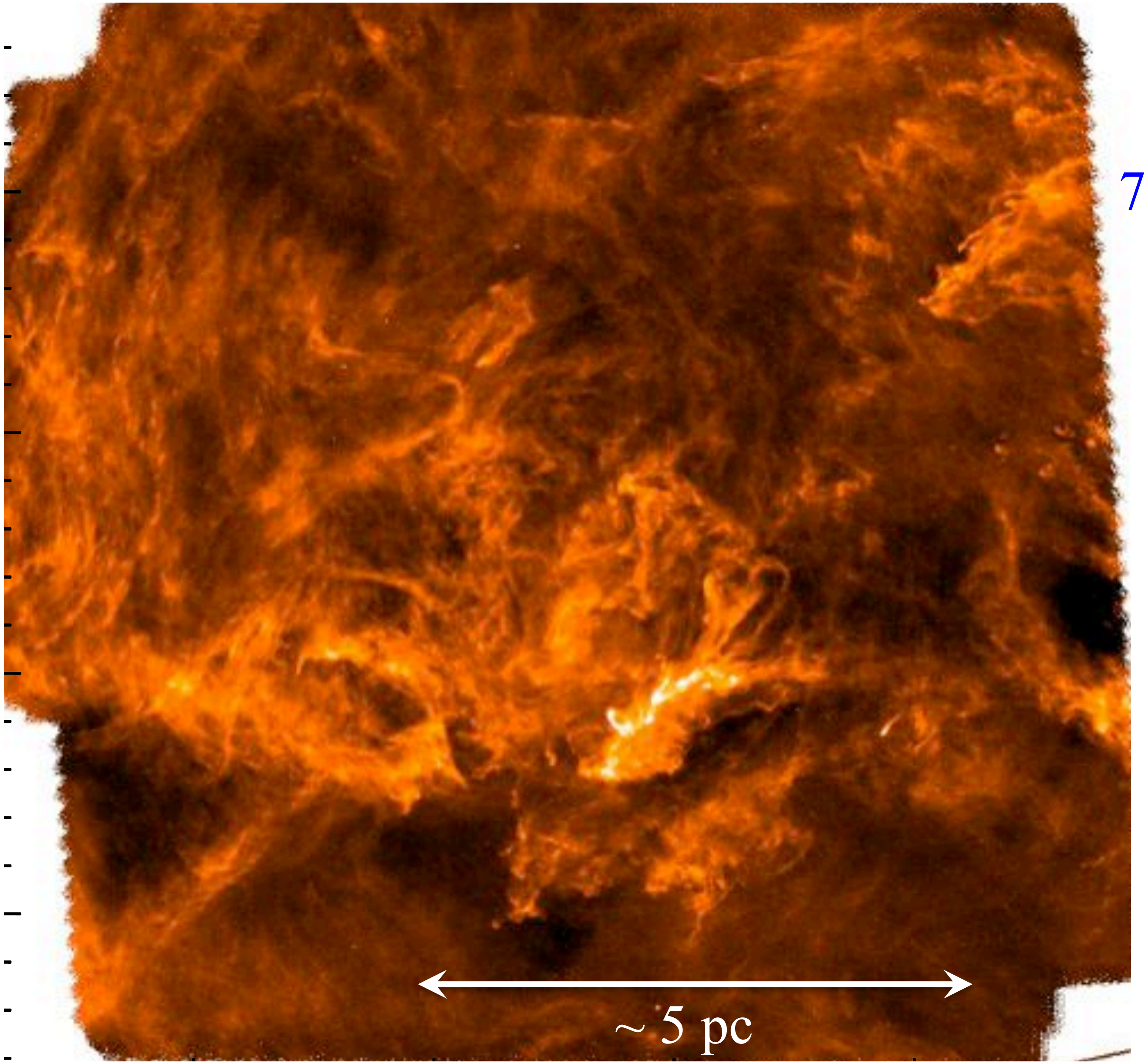
- « **Universality** » **of the filamentary structure** of the ISM
- The key **role of filaments** in the star formation process
- Implications and future prospects



Herschel GB survey IC5146 Arzoumanian et al. 2011

With: D. Arzoumanian, V. Könyves, P. Palmeirim, A. Menshchikov, N. Schneider, A. Roy, N. Peretto, P. Didelon, J. Di Francesco, S. Bontemps, F. Motte, D. Ward-Thompson, J. Kirk, M. Griffin, S. Pezzuto, S. Molinari, J.Ph. Bernard, V. Minier, B. Merin, N. Cox, A. Zavagno, L. Testi & the ***Herschel*** **Gould Belt KP Consortium**

Filamentary structure of the cold ISM prior to SF



SPIRE 250 μm image

Gould Belt Survey
Herschel // mode
70/160/250/350/500 μm

Polaris flare translucent cloud
(d ~ 150 pc)

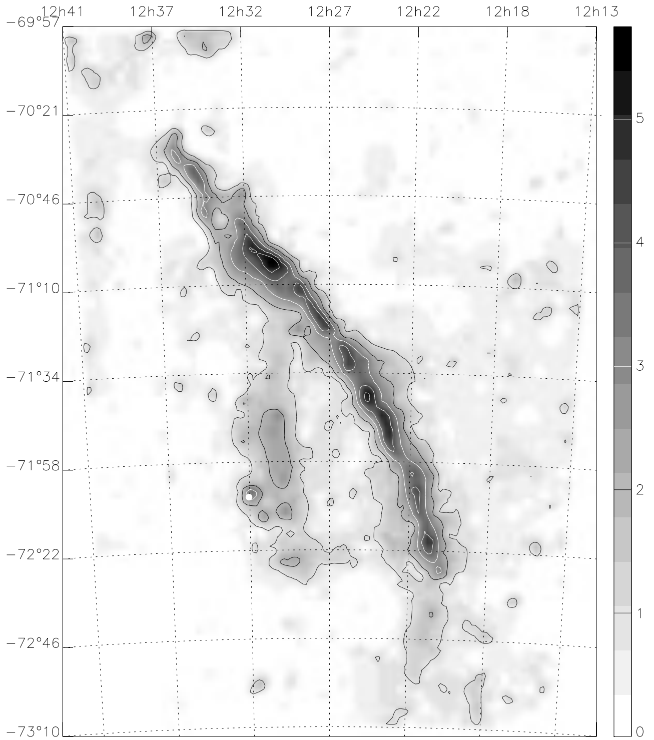
~ 5500 $M_\odot$ (CO+HI)
Heithausen & Thaddeus '90

~ 13 deg^2 field

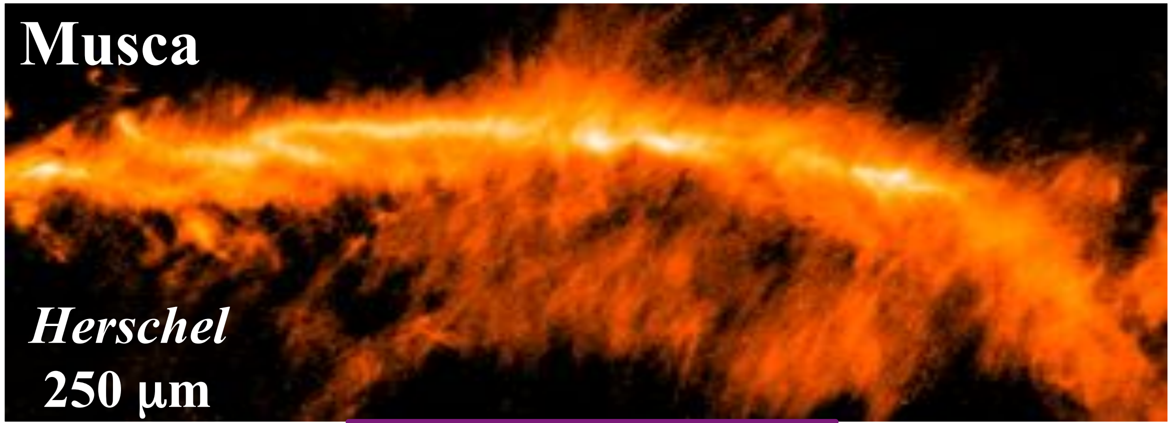
Miville-Deschênes et al. 2010
Ward-Thompson et al. 2010
Men'shchikov et al. 2010
André et al. 2010
A&A vol. 518

Evidence of the importance of filaments prior to *Herschel* but … much fainter filaments + universality with *Herschel*

Extinction map of Musca

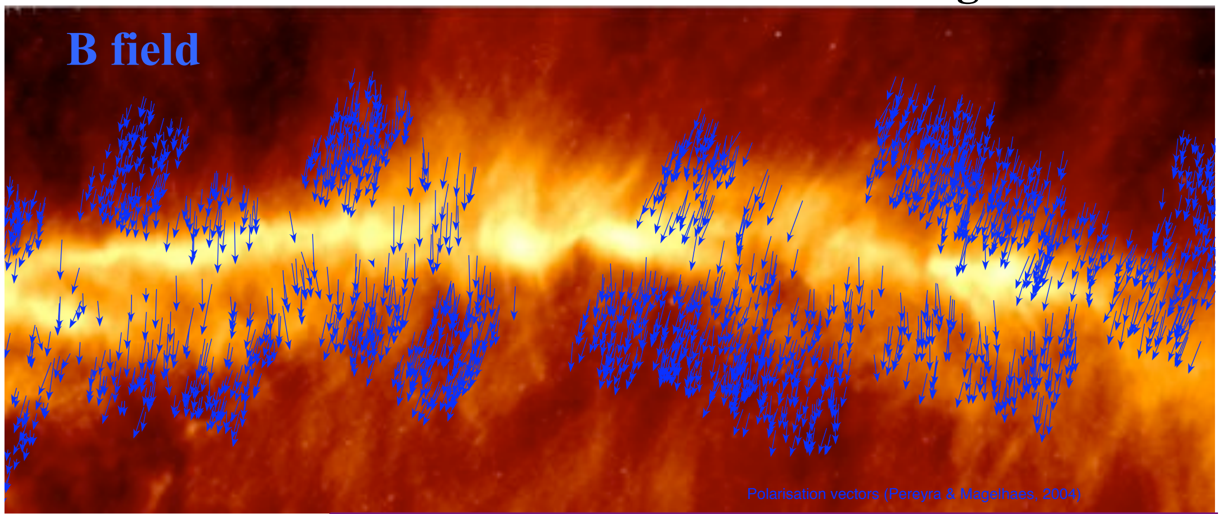


Cambrésy 1999



N. Cox et al., in prep.

Polarization vectors overlaid on *Herschel* image of Musca



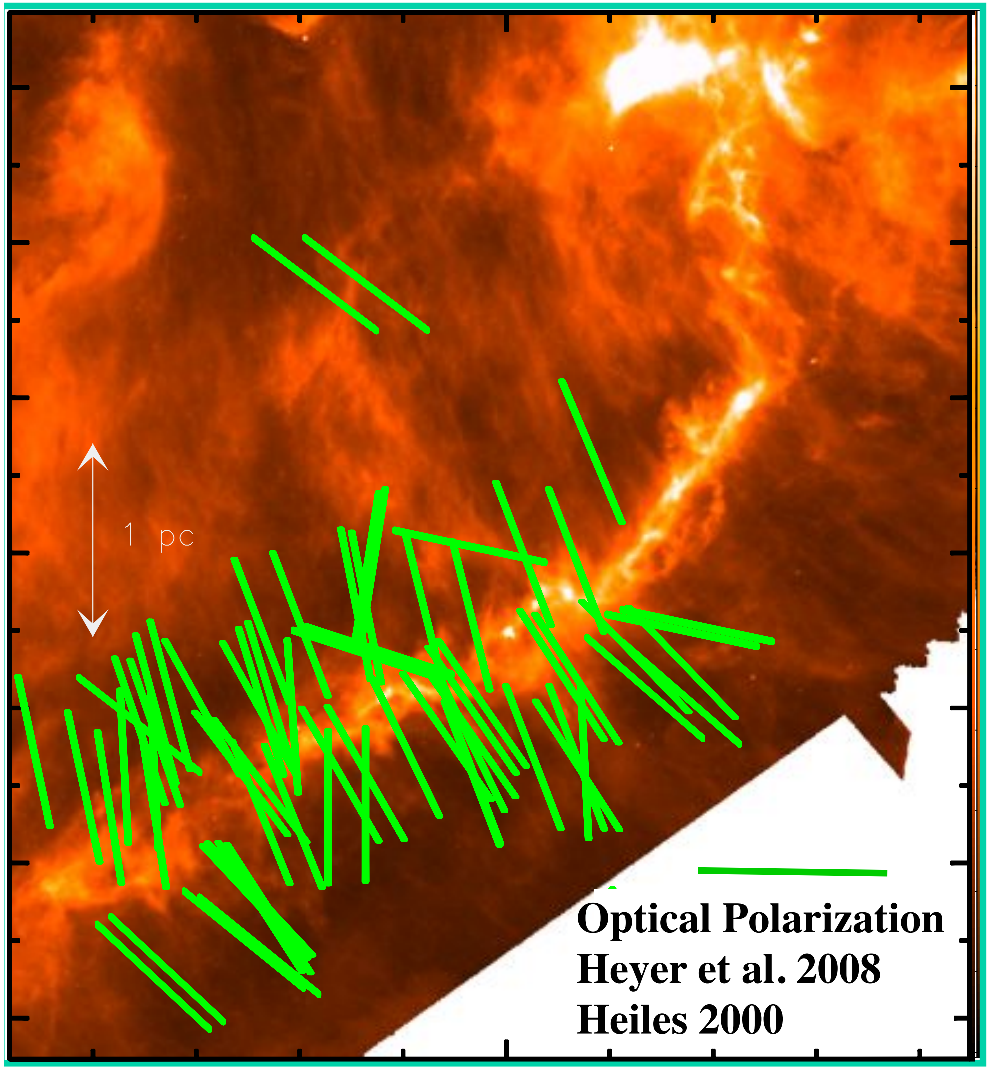
N. Cox et al. + Pereyra & Magelhaes 2004

See also:
Schneider & Elmegreen 1979;
Abergel et al. 1994; Johnstone & Bally 1999;
Hatchell+2005; Hily-Blant & Falgarone 2007; Myers 2009 …
+ Many numerical simulations

Very common pattern: main filament + network of perpendicular striations or "sub-filaments"

Taurus B211/3 filament: M/L ~ 50 $M_\odot$/pc

P. Palmeirim et al. 2013

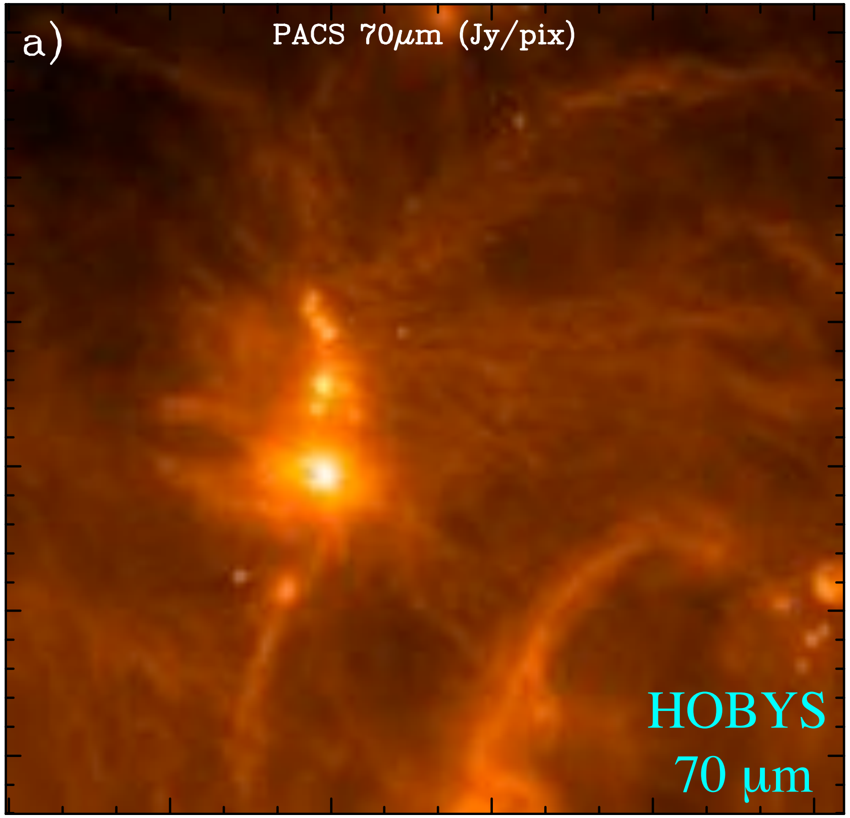


➢ **Suggestive of accretion flows into the main filaments**

DR21 in Cygnus X:
M/L ~ 4000 $M_\odot$/pc

M. Hennemann, F. Motte et al. 2012

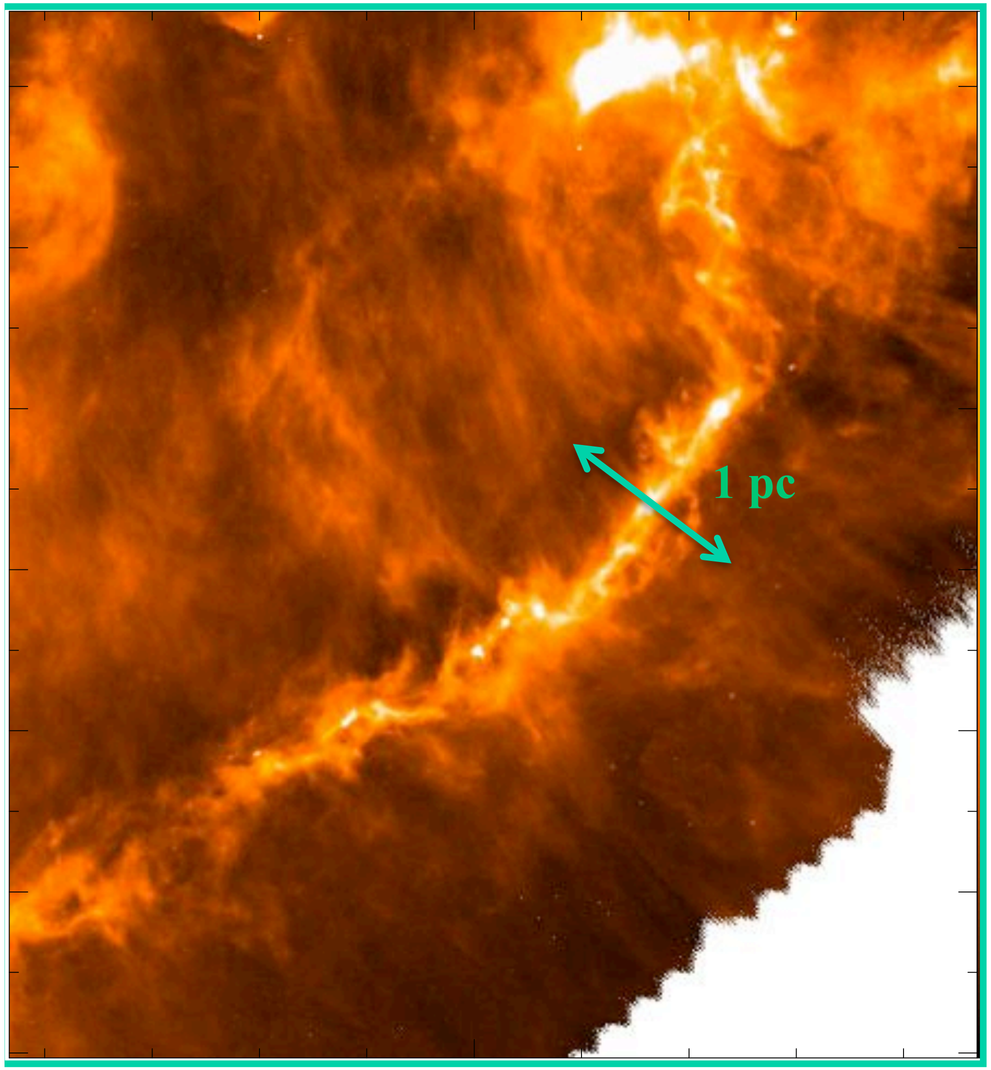
Also Schneider ea. 2010, Csengeri ea. 2011

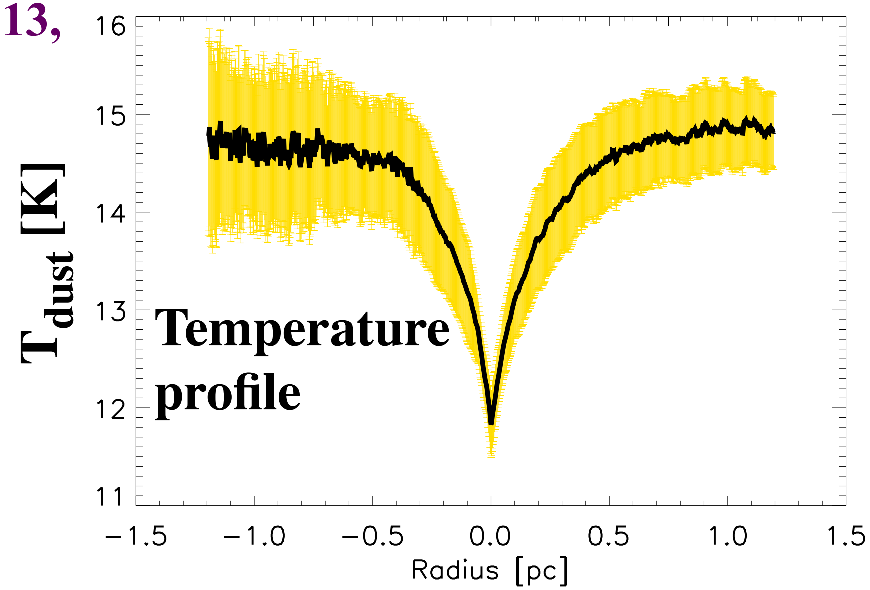


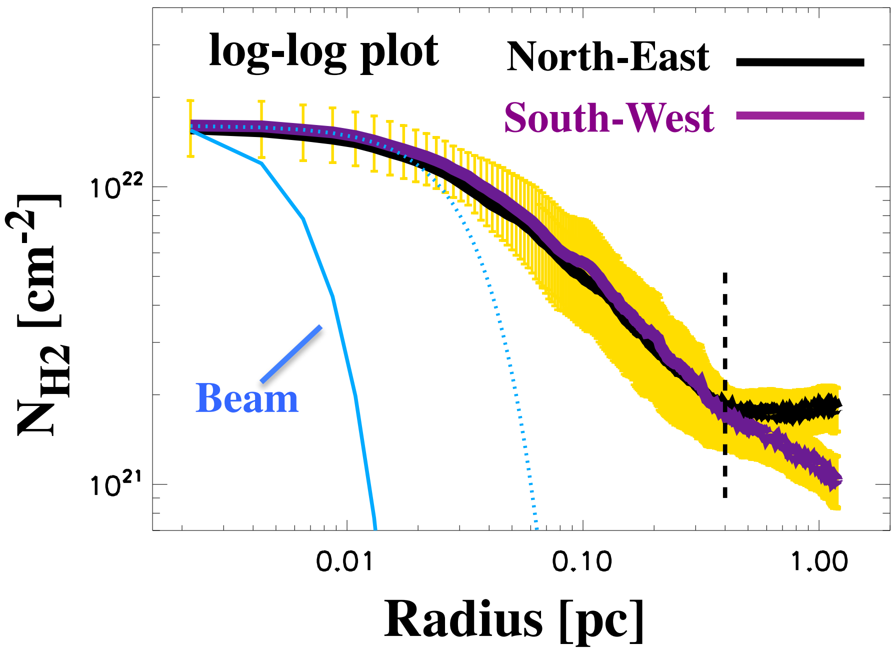
Characterizing the structure of filaments with *Herschel*

Taurus B211/3 filament
SPIRE 250μm

Palmeirim et al. 2013, A&A, 550, A38

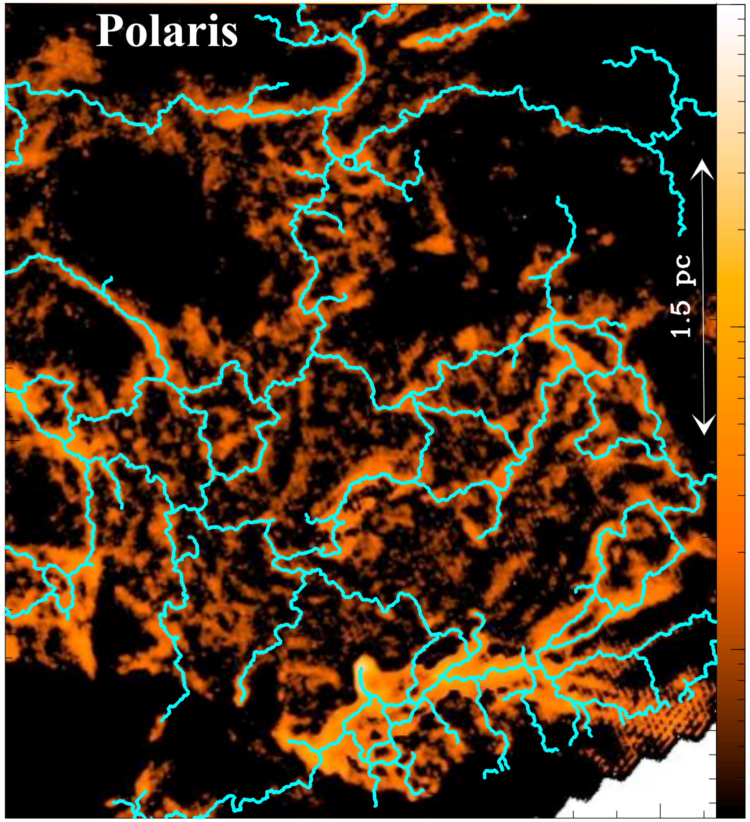






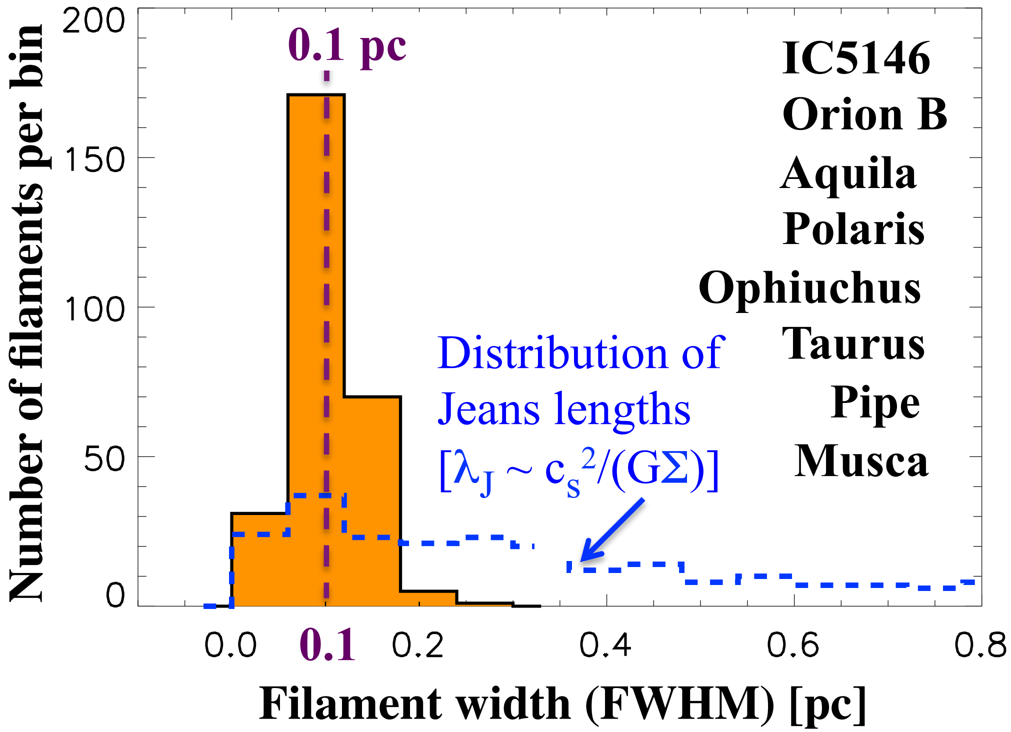
Filaments have a characteristic inner width ~ 0.1 pc

Arzoumanian et al. 2011, A&A, 529, L6
D. Arzoumanian's PhD thesis



Using the DisPerSE algorithm (Sousbie 2011) to trace the crest of each filament

Statistical distribution of widths for > 270 filaments



➢ Strong constraint on the formation and evolution of filaments

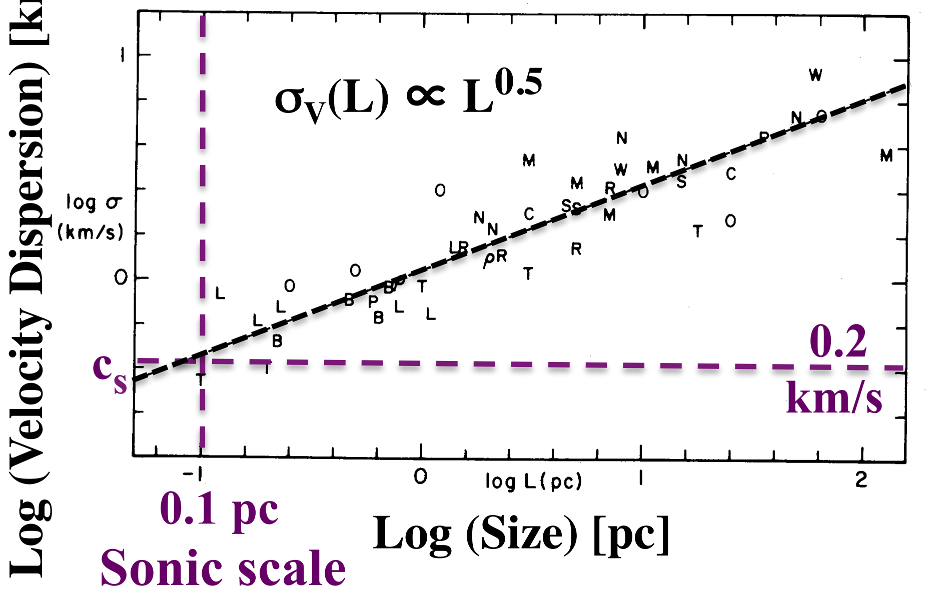
Filament width ~ 0.1 pc ~ sonic scale of ISM turbulence

↓

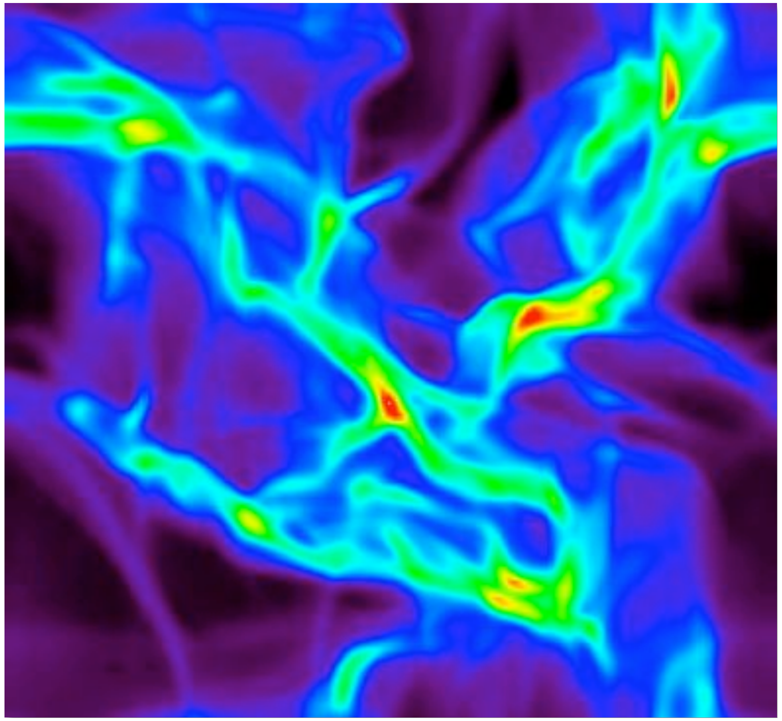
Filaments due to dissipation of large-scale turbulence ?

Linewidth-Size relation in clouds

(Larson 1981, MNRAS, 194, 809)



Simulations of turbulent fragmentation

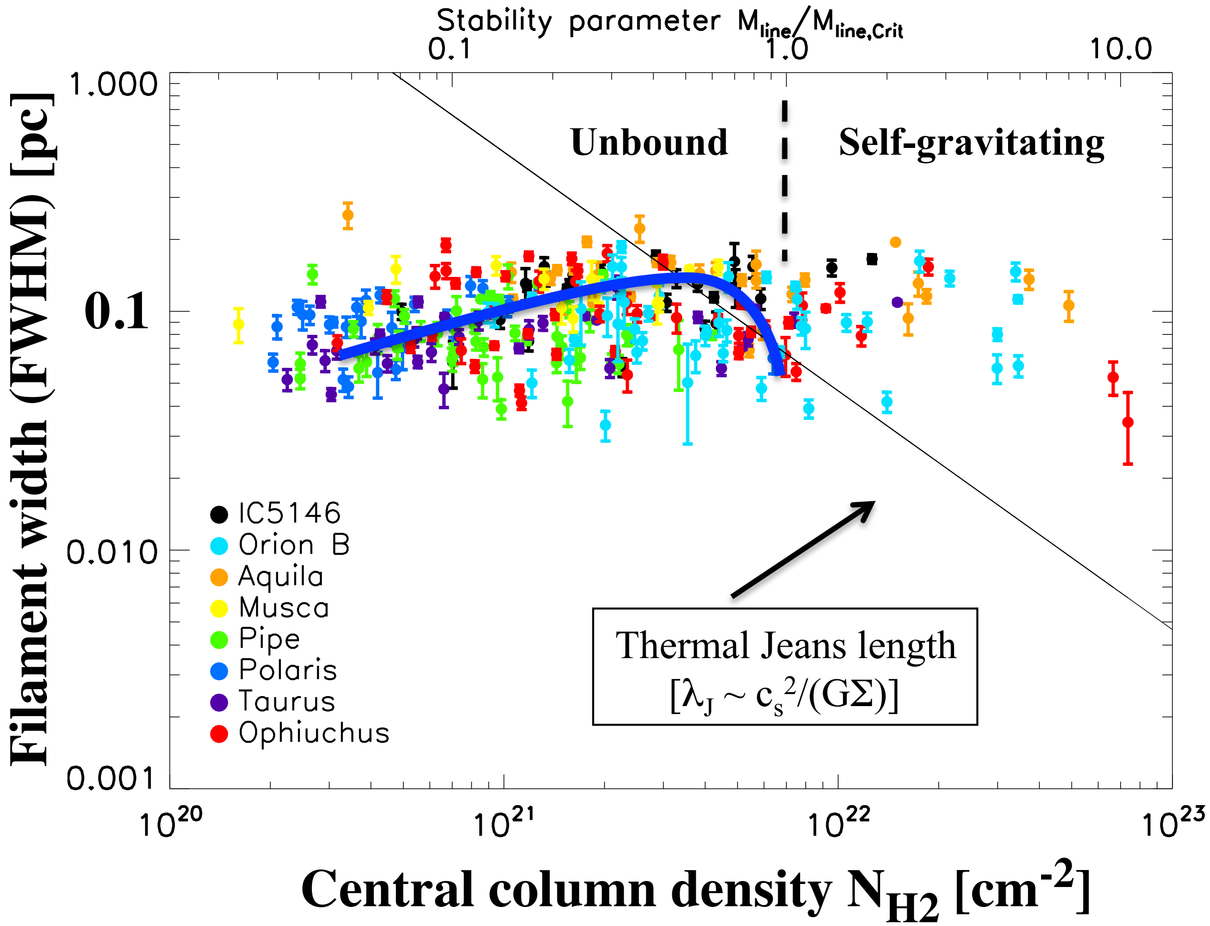


Padoan, Juvela et al. 2001, ApJ, 553, 227

➢ **Corresponds to the typical thickness of shock-compressed structures in the turbulent fragmentation scenario**

➢ **Filaments from a combination of MHD turbulent compression *and* shear; (Hennebelle 2013, A&A, 556, A153)**

Filament width vs. Column density



Arzoumanian et al. 2011, A&A, 529, L6
D. Arzoumanian's PhD thesis

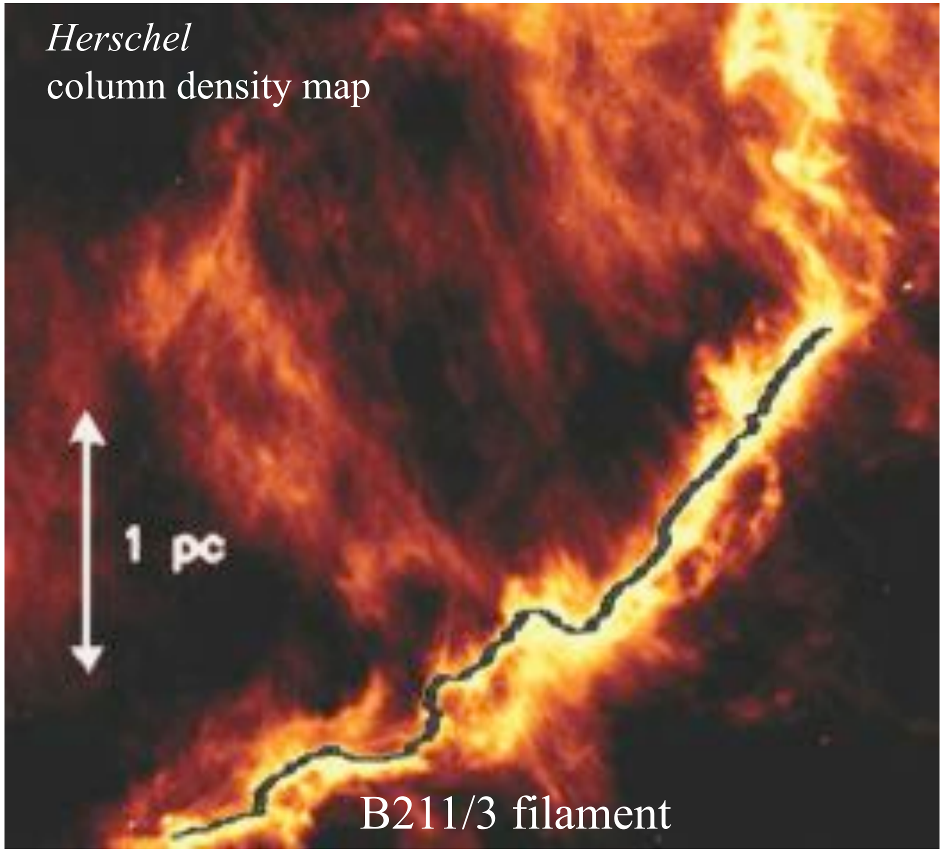
At low densities, consistent with model of polytropic filaments ($P \sim \rho^{\gamma}$ with $\gamma \sim 0.8$) in pressure equilibrium with a typical ISM pressure $P_{ext}/k_B \sim 5 \times 10^4$ K cm^{-3} (Inutsuka, in prep.)

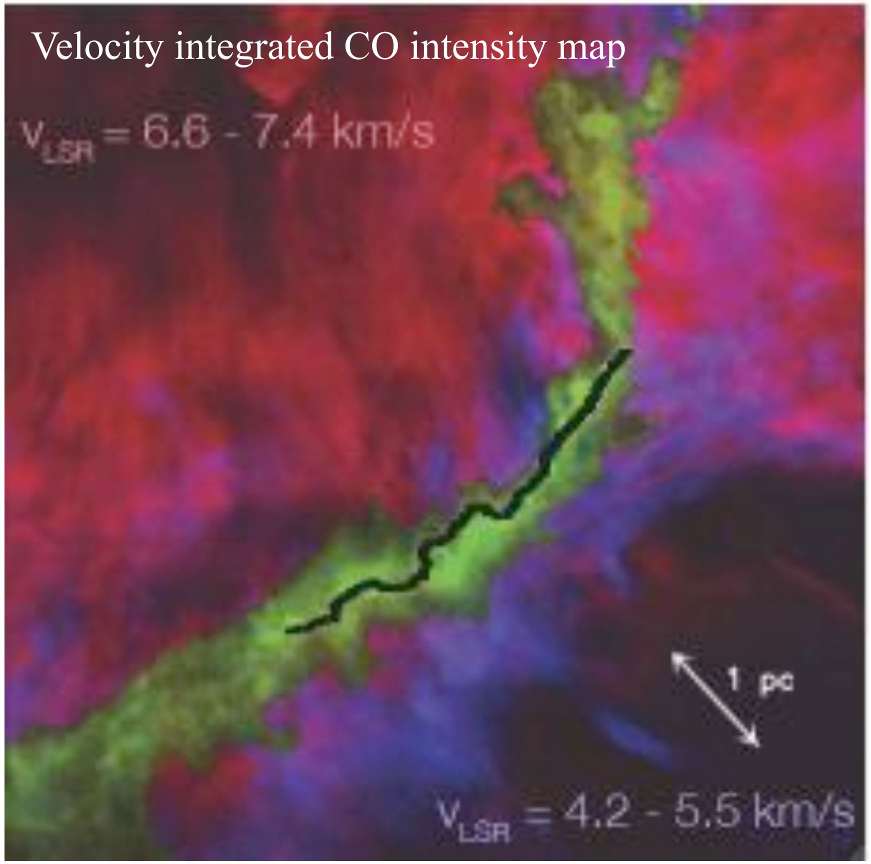
See also Fischera & Martin 2012, A&A, 542, A77 for a similar model for isothermal filaments

Evidence of accretion of background material (striations) onto self-gravitating filaments

Example of the B211/3 filament in the Taurus cloud ($M_{line} \sim$ 54 $M_{\odot}$/pc)

Palmeirim et al. 2013



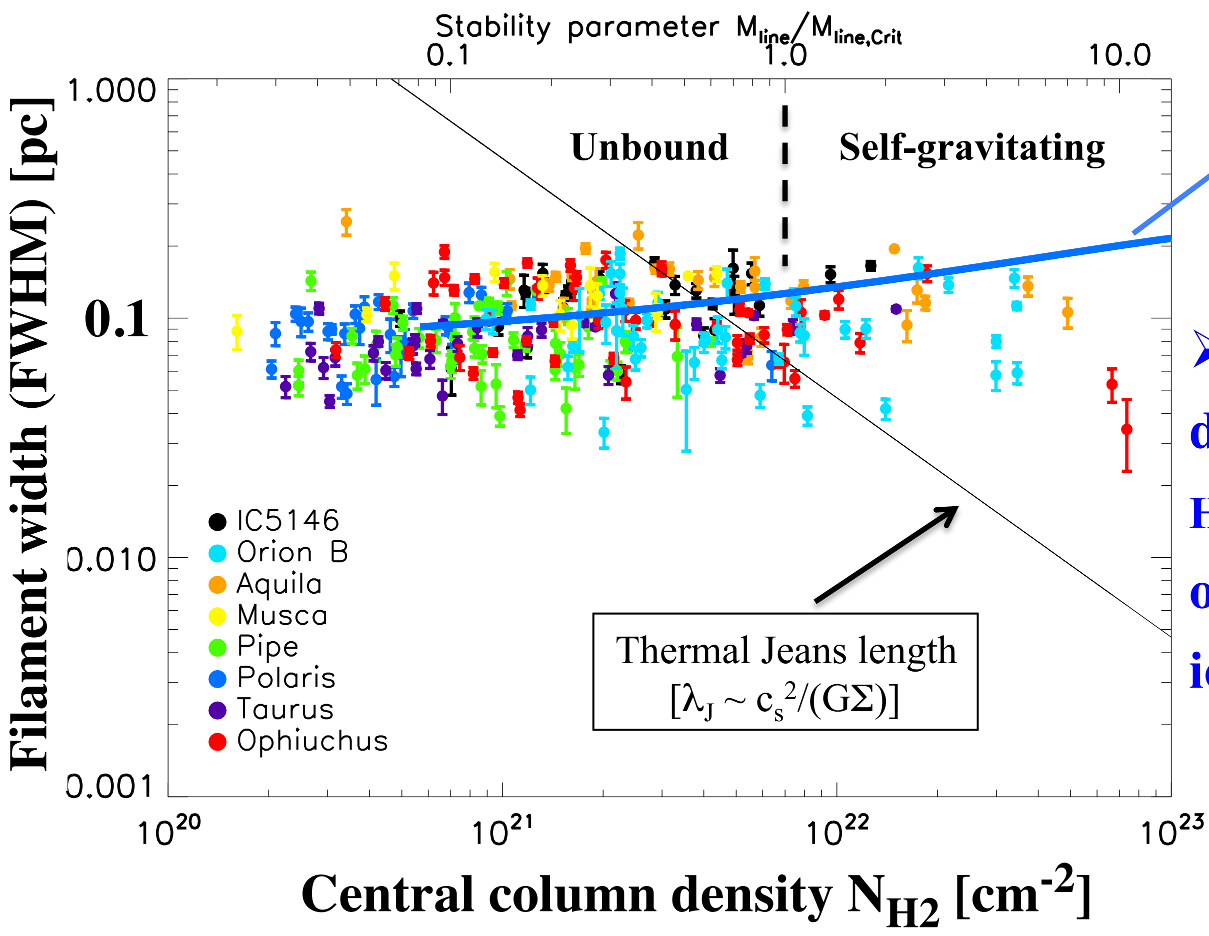


Estimate of the mass accretion rate:

$\dot{M}_{line} \sim$ 25-50 $M_{\odot}$/pc/Myr

CO observations from Goldsmith et al. 2008

Filament width vs. Column density



At high densities, consistent with a model of accreting filaments

(Hennebelle & André 2013, A&A)

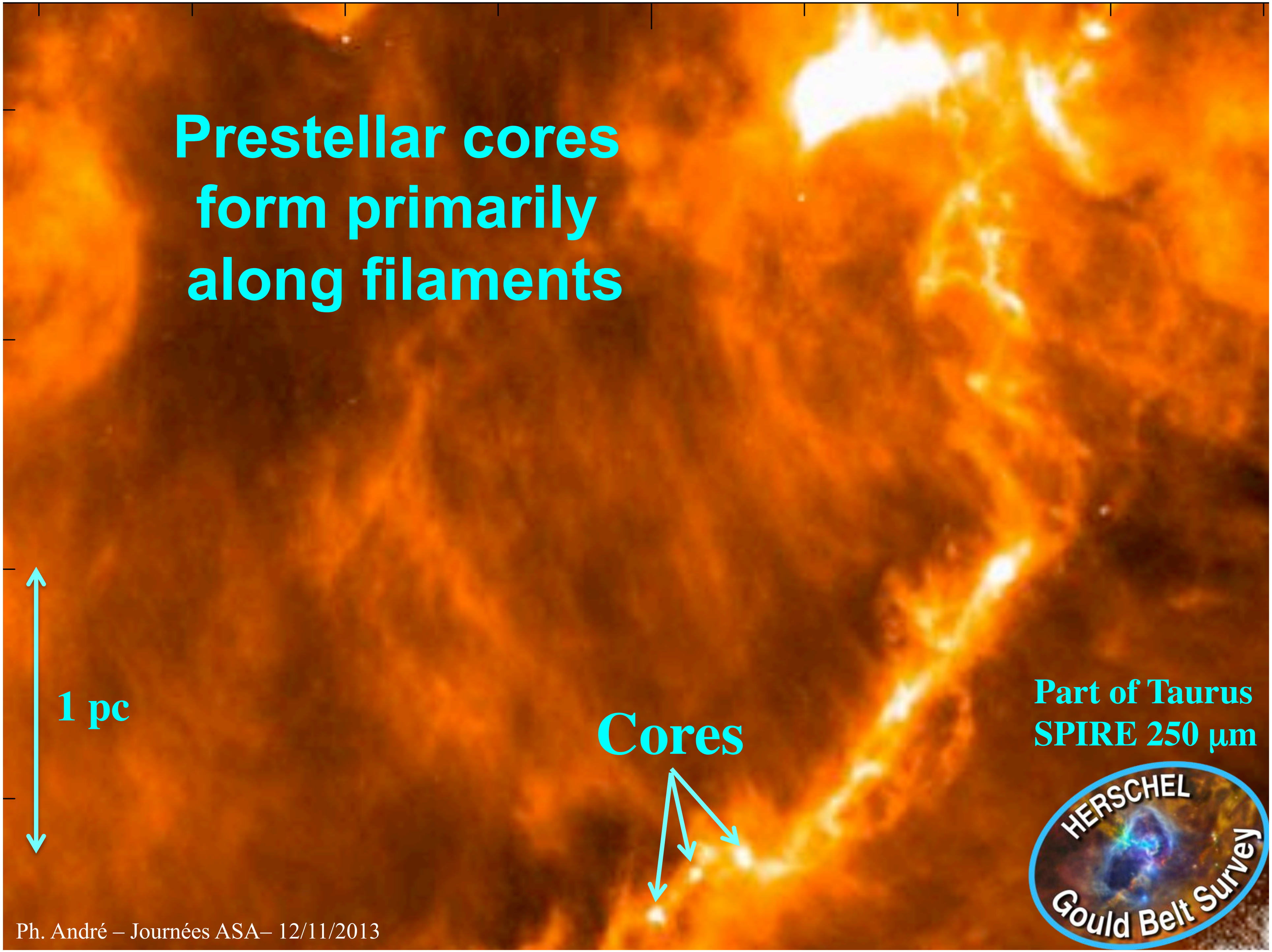
- **Balance between 'accretion-driven turbulence' (Klessen & Hennebelle '10) and dissipation of MHD turbulence due to ion-neutral friction**

↓

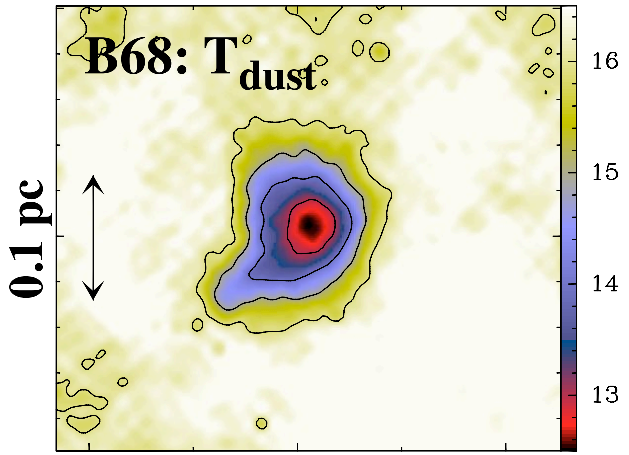
« Dynamical » equilibrium with <width> ~ 0.1 pc

See also Heitsch 2013a,b

Arzoumanian et al. 2011
D. Arzoumanian's PhD thesis

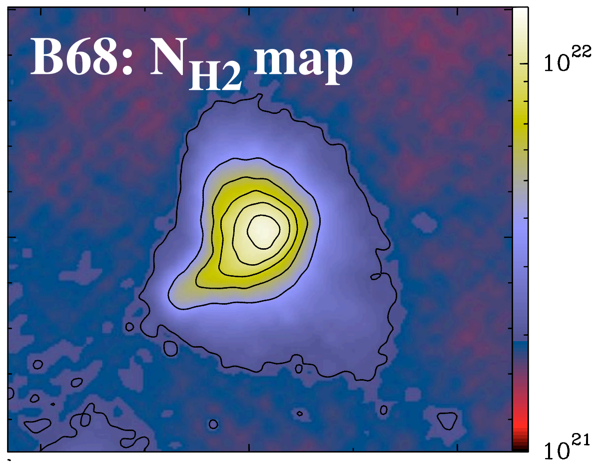

Prestellar cores
form primarily
along filaments
1 pc
Cores
Part of Taurus
SPIRE 250 μm
HERSCHEL
Gould Belt Survey

Cores: temperature and density structure derived from *Herschel* data

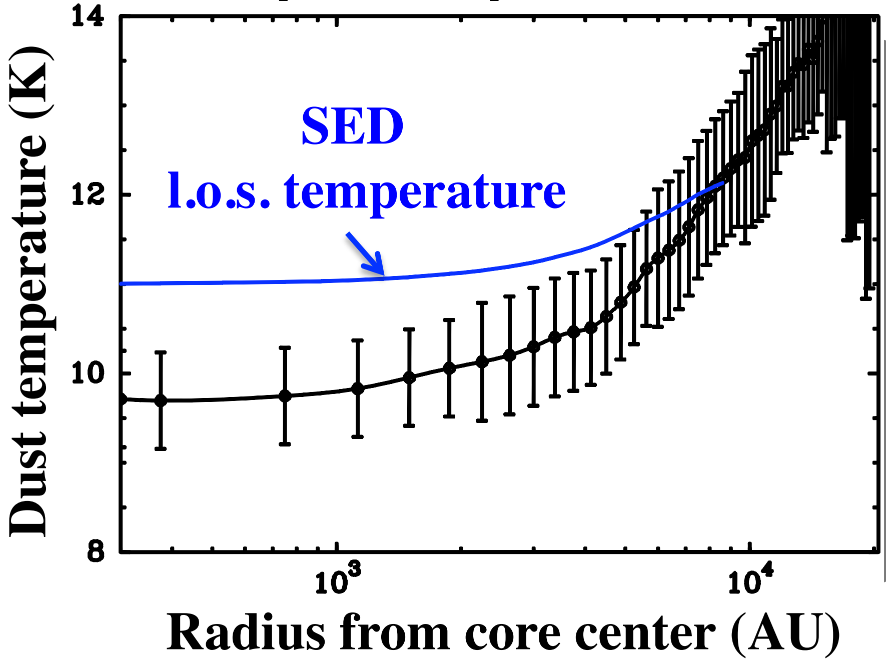


Roy et al. 2013
HGBS Program
(Abel inversion)

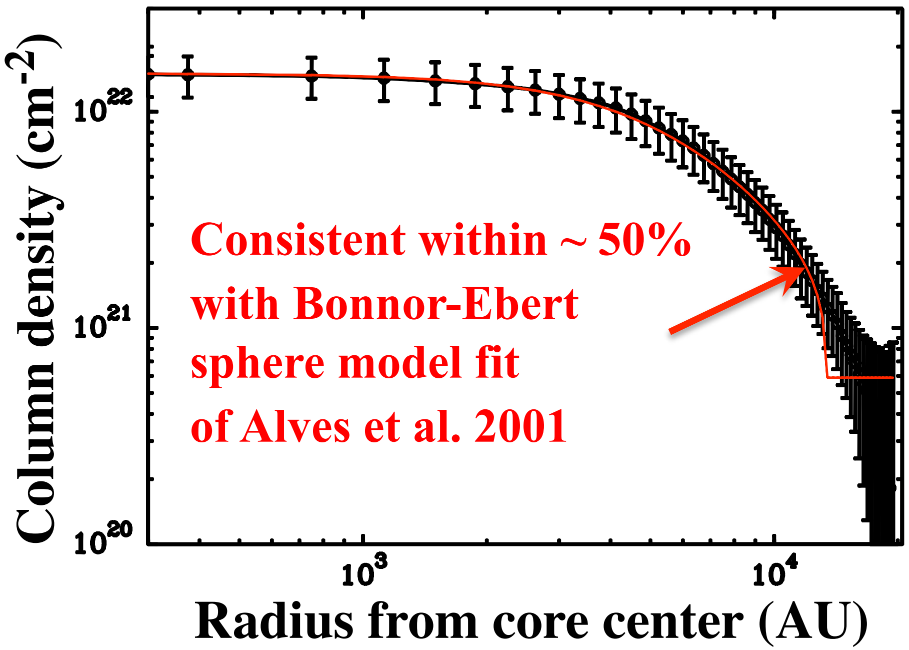
Nielbock et al. 2012
EPoS Program
(2D ray-tracing)



Temperature profile of B68



Column density profile of B68

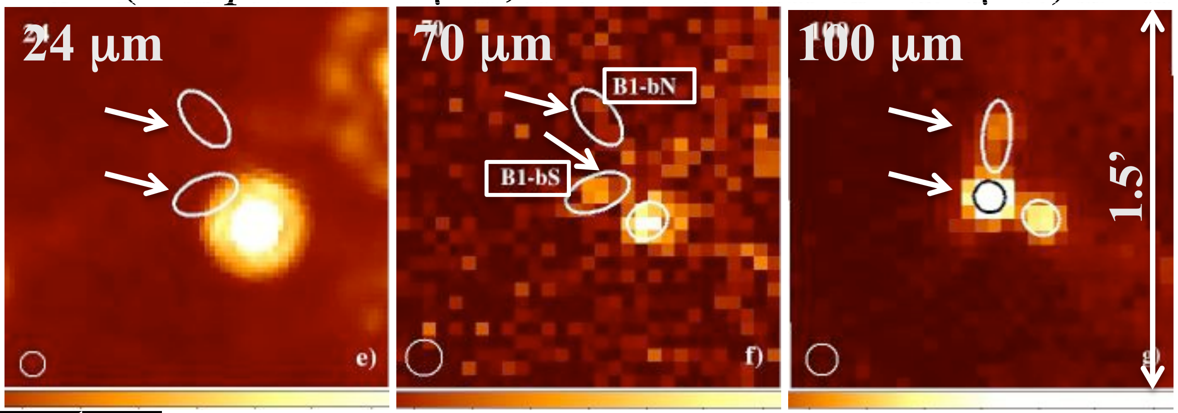


Identification of new, extreme Class 0 objects: Prime targets for follow-up studies with ALMA, PdB

→ Candidate « first protostellar cores » (FPCs) (cf. Larson 1969)

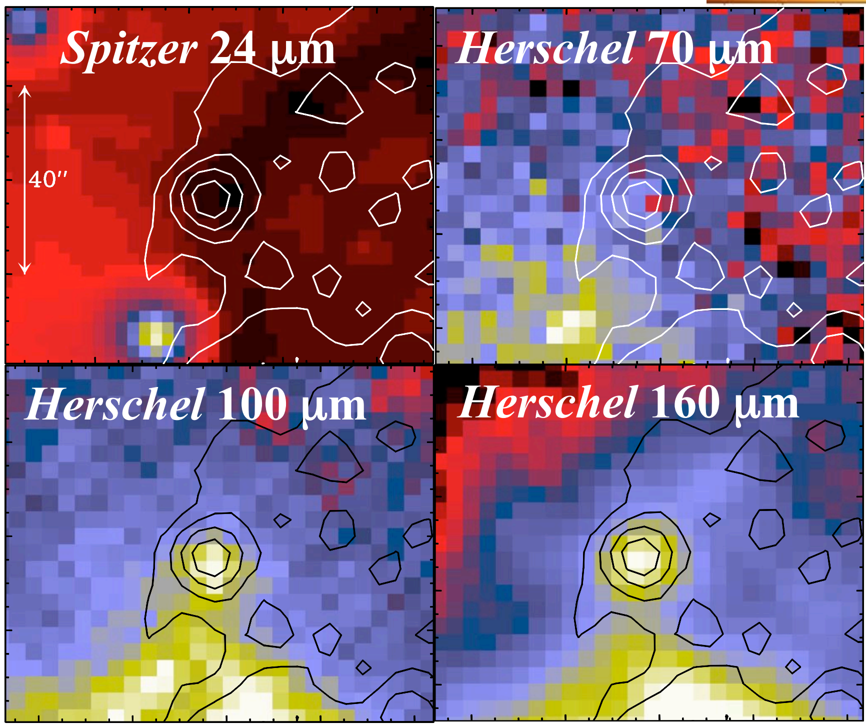
→ SEDs consistent with FPCs (cf. Commerçon+2012)

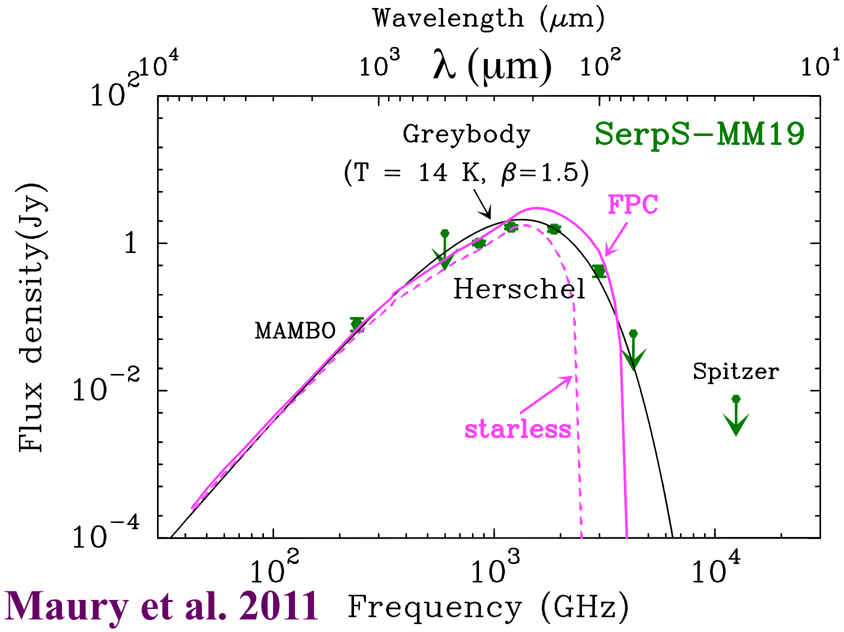
Two candidate FPCs in Perseus B1-bS and B1-bN
(no *Spitzer* 24 µm, but *Herschel* 70/100 µm)



Pezzuto et al. 2012, A&A, 547, A54

SerpS-MM19 (Maury et al. 2011)





Maury et al. 2011

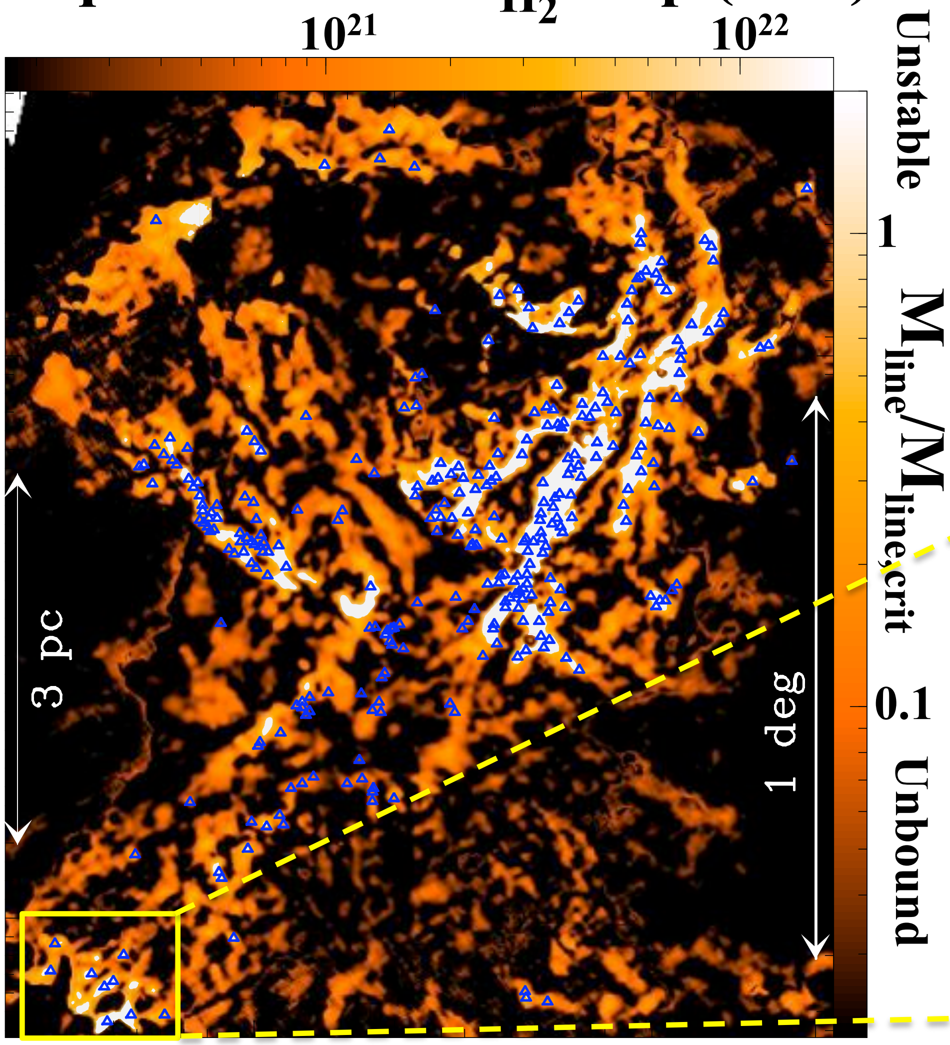
~ 75 % of prestellar cores form in filaments, above a column density threshold $N_{H_2} \gtrsim 7\times10^{21}$ cm^{-2}

<=>

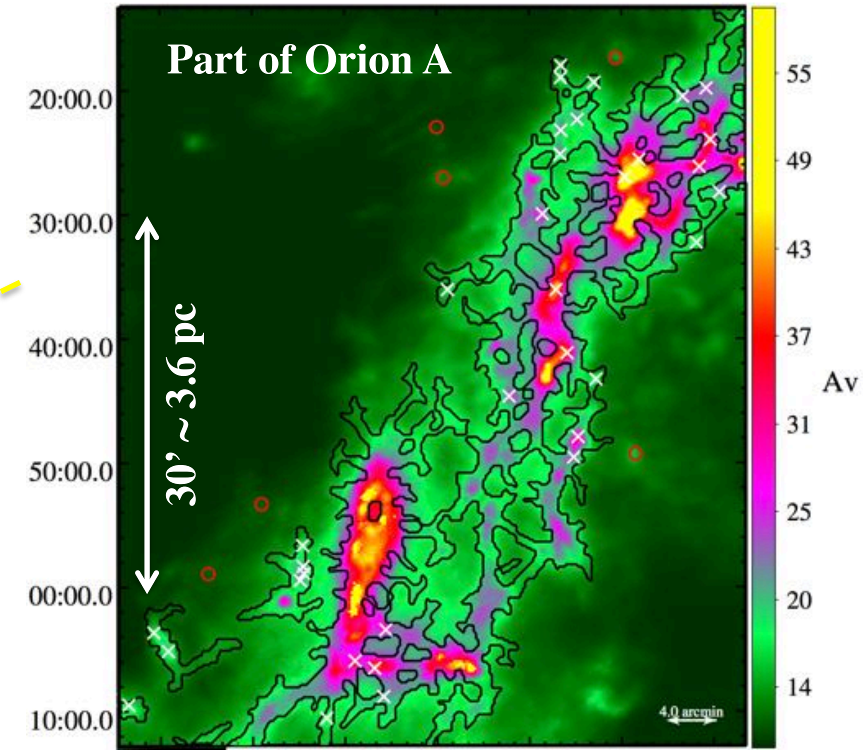
$A_V \gtrsim 8$

$\Sigma_{threshold} \sim 130\ M_\odot/pc^2$

Aquila curvelet N_{H_2} map (cm^{-2})



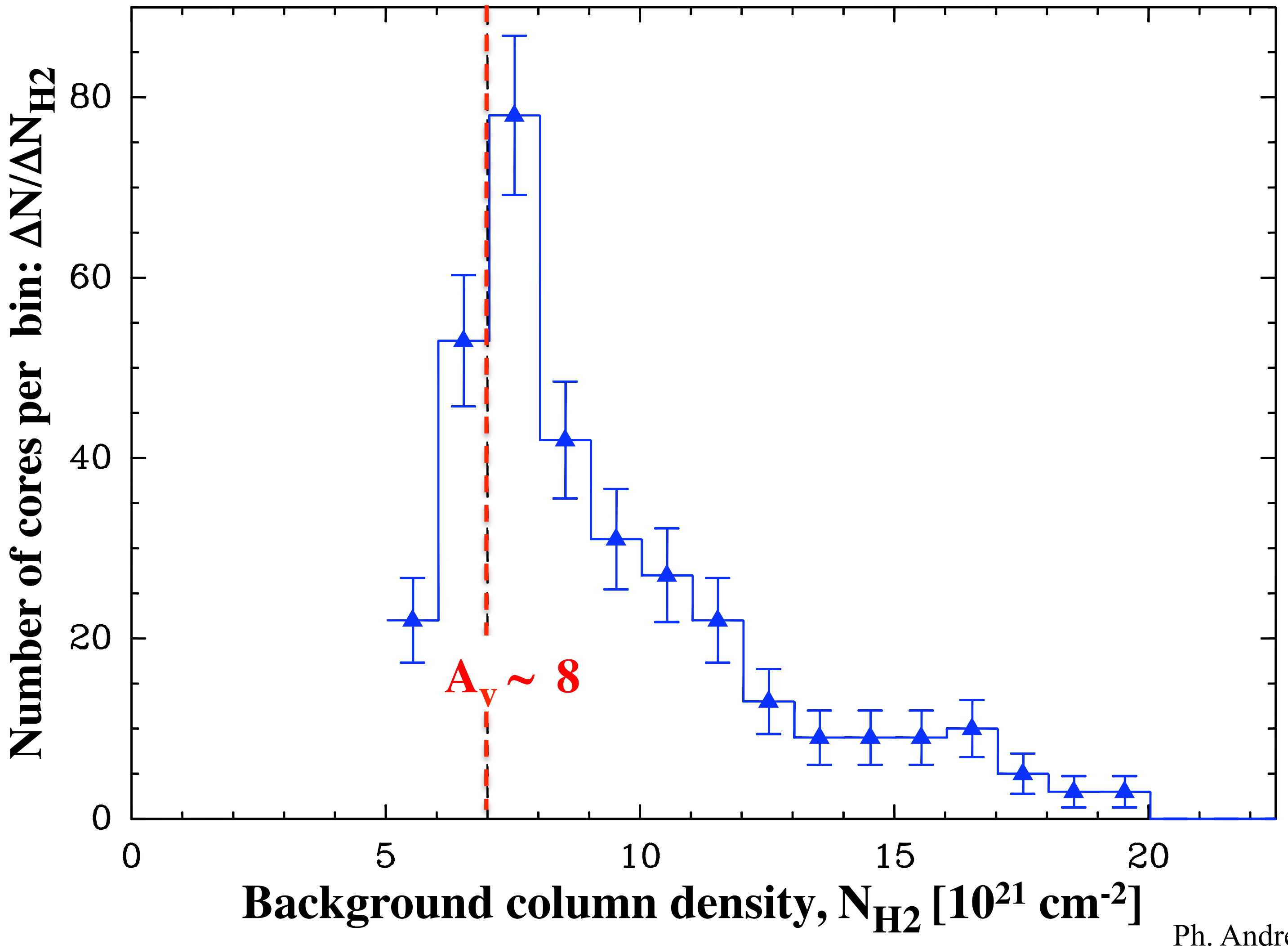
André et al. 2010 + Könyves et al. 2010, A&A, 518



Polychroni al. 2013, ApJL, in press

Strong evidence of a column density "threshold" for the formation of prestellar cores

Distribution of background column densities for the Aquila prestellar cores



In Aquila, ~90% of the prestellar cores identified with *Herschel* are found above $A_v \sim 8 \Leftrightarrow \Sigma \sim 130\ M_\odot\ pc^{-2}$

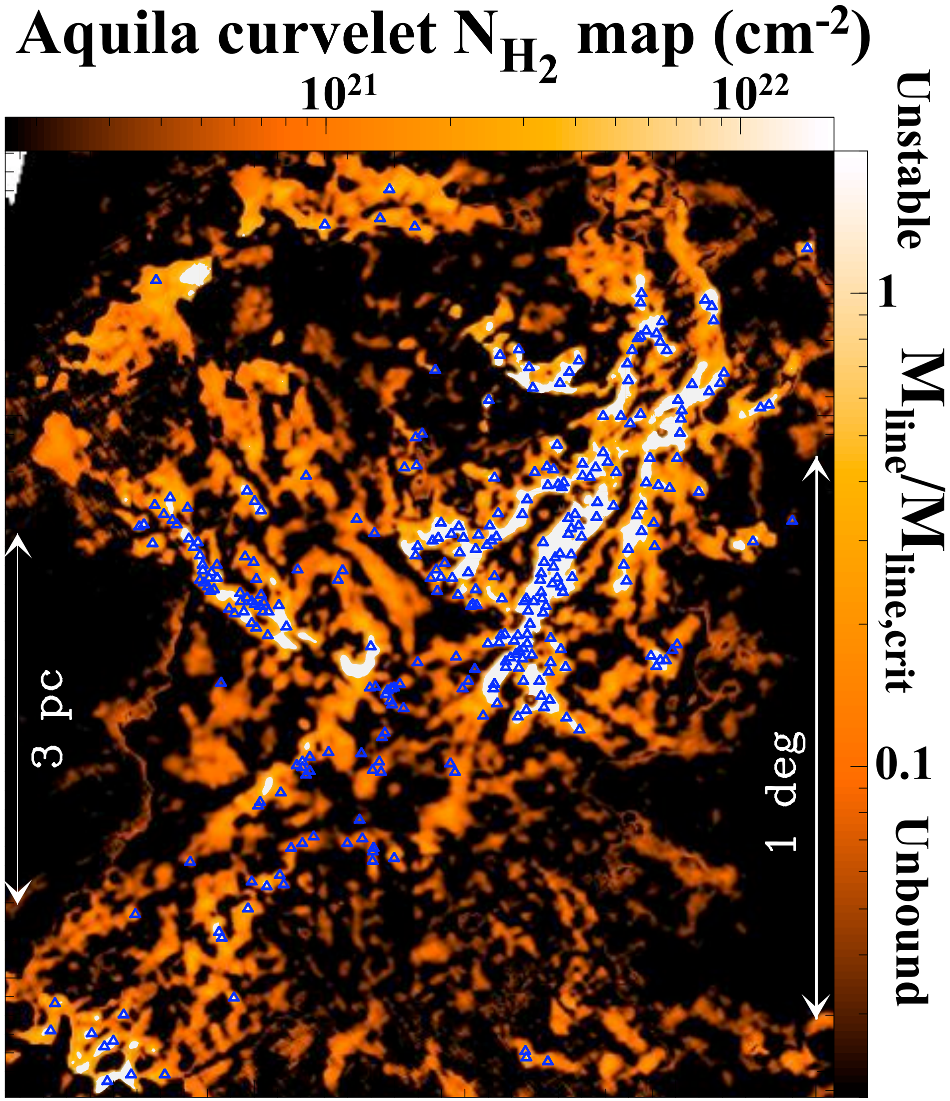
Könyves etal. in prep

André et al. IAU270

See also (for YSOs):
Heiderman ea. 2010
Lada et al. 2010

Interpretation of the threshold: Σ or M/L above which interstellar filaments are gravitationally unstable

△ : Prestellar cores



André et al. 2010, A&A Vol. 518

➢ The gravitational instability of filaments is controlled by the mass per unit length M_{line} (cf. Ostriker 1964, Inutsuka & Miyama 1997):

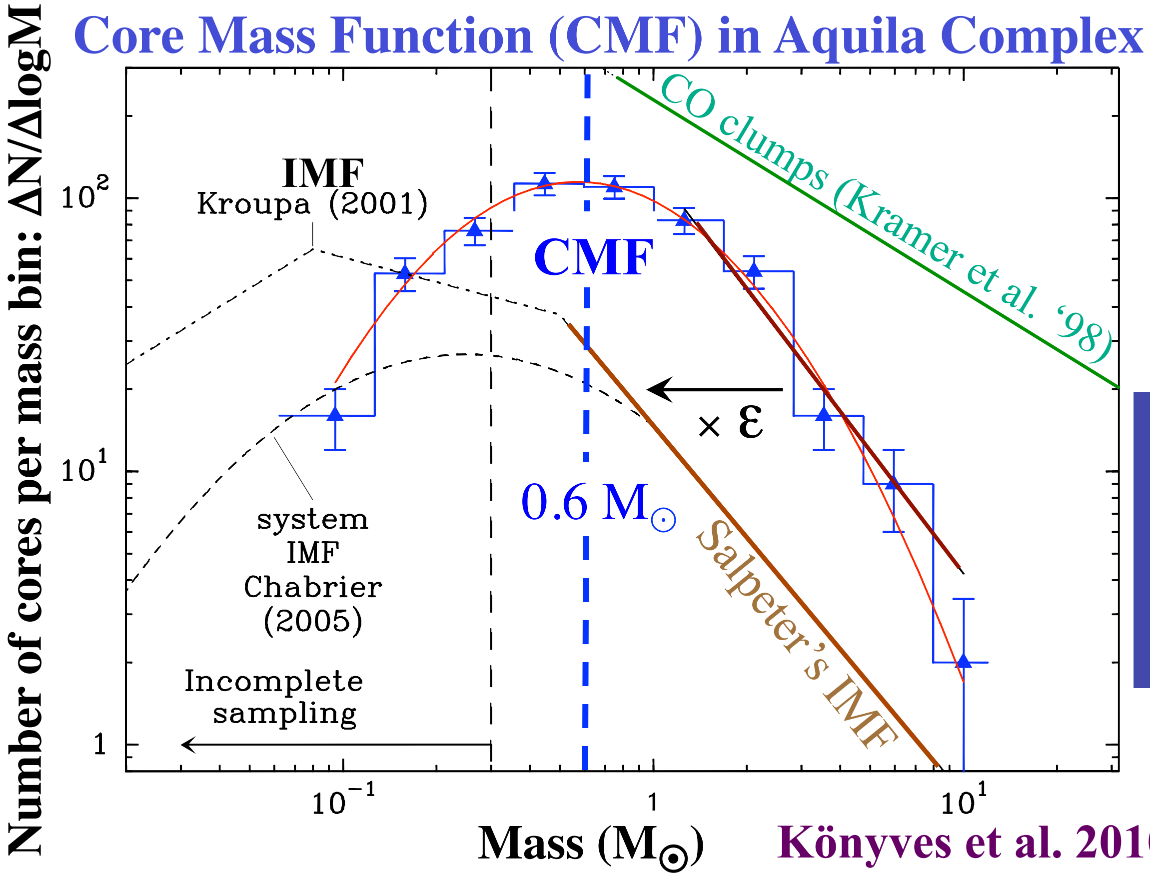
- unstable if $M_{line} > M_{line,\,crit}$
- unbound if $M_{line} < M_{line,\,crit}$
- $M_{line,\,crit} = 2\, c_s^2/G \sim 16\ M_\odot/pc$ for T ~ 10K ⇔ Σ threshold ~ 160 $M_\odot/pc^2$

➢ Simple estimate:

$M_{line} \propto N_{H2}$ x Width (~ 0.1 pc)

Unstable filaments highlighted in white in the N_{H2} map

Filament fragmentation may account for the peak of the prestellar CMF and the “base” of the IMF



Könyves et al. 2010, André et al. 2010

> 400 prestellar cores in Aquila (cf. Könyves et al. 2010 + in prep.)

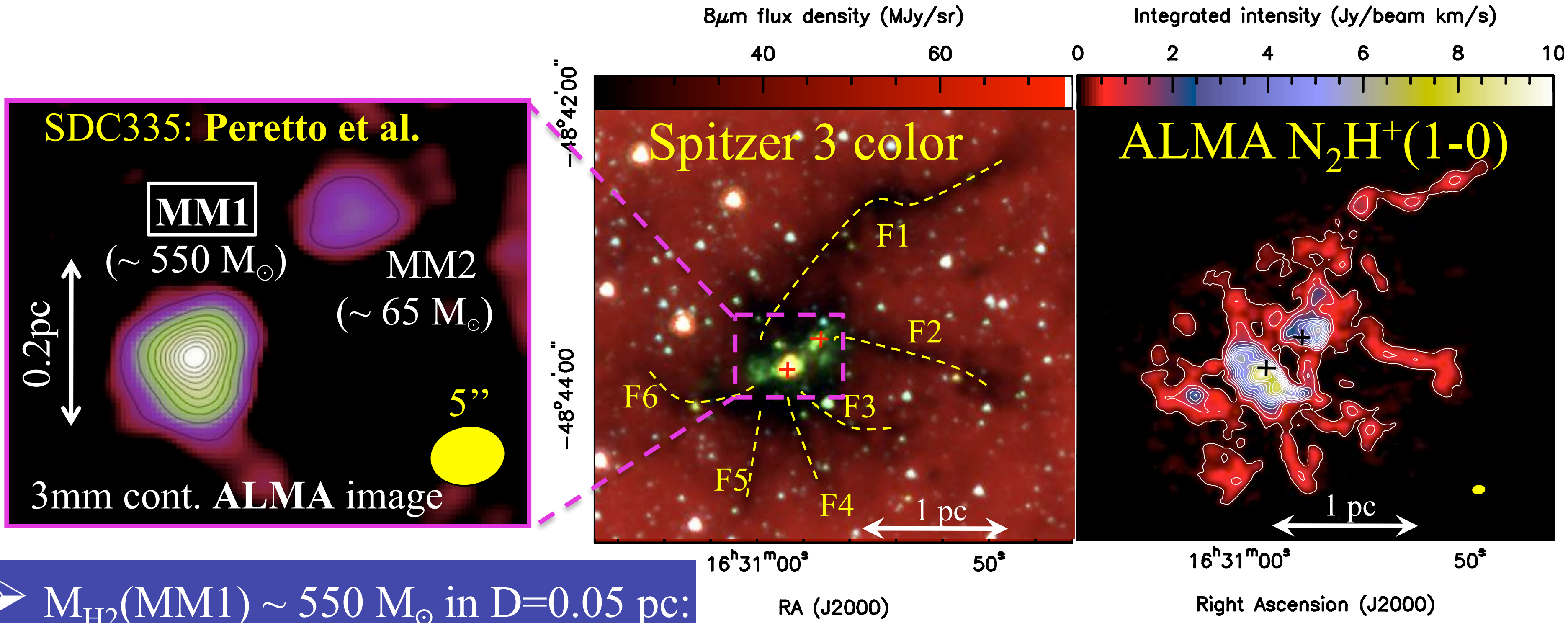
Jeans mass:

$$M_{Jeans} \sim 0.5\, M_{\odot} \times (T/10\,K)^2 \times (\Sigma_{crit}/160\, M_{\odot}pc^{-2})^{-1}$$

- ➢ Good mapping between core mass and stellar system mass: $M_* = 0.3 \times M_{core}$
- ➢ **CMF peaks at ~ 0.6 $M_{\odot}$ ≈ Jeans mass in marginally critical filaments**
- ➢ **Suggests prestellar cores at the peak of the CMF result from gravitational fragmentation of filaments**

Role of filaments in massive star formation ?

ALMA identification of a massive protostellar core at the center of a converging network of filaments



- M_{H2}(MM1) ~ 550 $M_\odot$ in D=0.05 pc: Most massive protostellar core ever observed?

Peretto, Fuller et al. 2013, A&A, 555, A112

See also *Herschel*/HOBYS results (PI: F. Motte) : massive star formation found in “ridges” at the junction of (supercritical) filaments (Schneider+ 2012)

Toward a new paradigm for star formation ?

- *Herschel* results suggest **star formation occurs in 2 main steps**:
  1) Filaments form first in the cold ISM, probably as a result of the dissipation of **large-scale MHD turbulence**;
  2) The densest filaments then fragment into prestellar cores via **gravitational instability** above a critical (column) density threshold $\Sigma_{th} \sim 150\ M_{\odot}\ pc^{-2}$ ⇔ $A_V \sim 8$ ⇔ $n_{H2} \sim 2 \times 10^4\ cm^{-3}$

- Filament fragmentation appears to produce the peak of the prestellar CMF and likely accounts for the « base » of the IMF

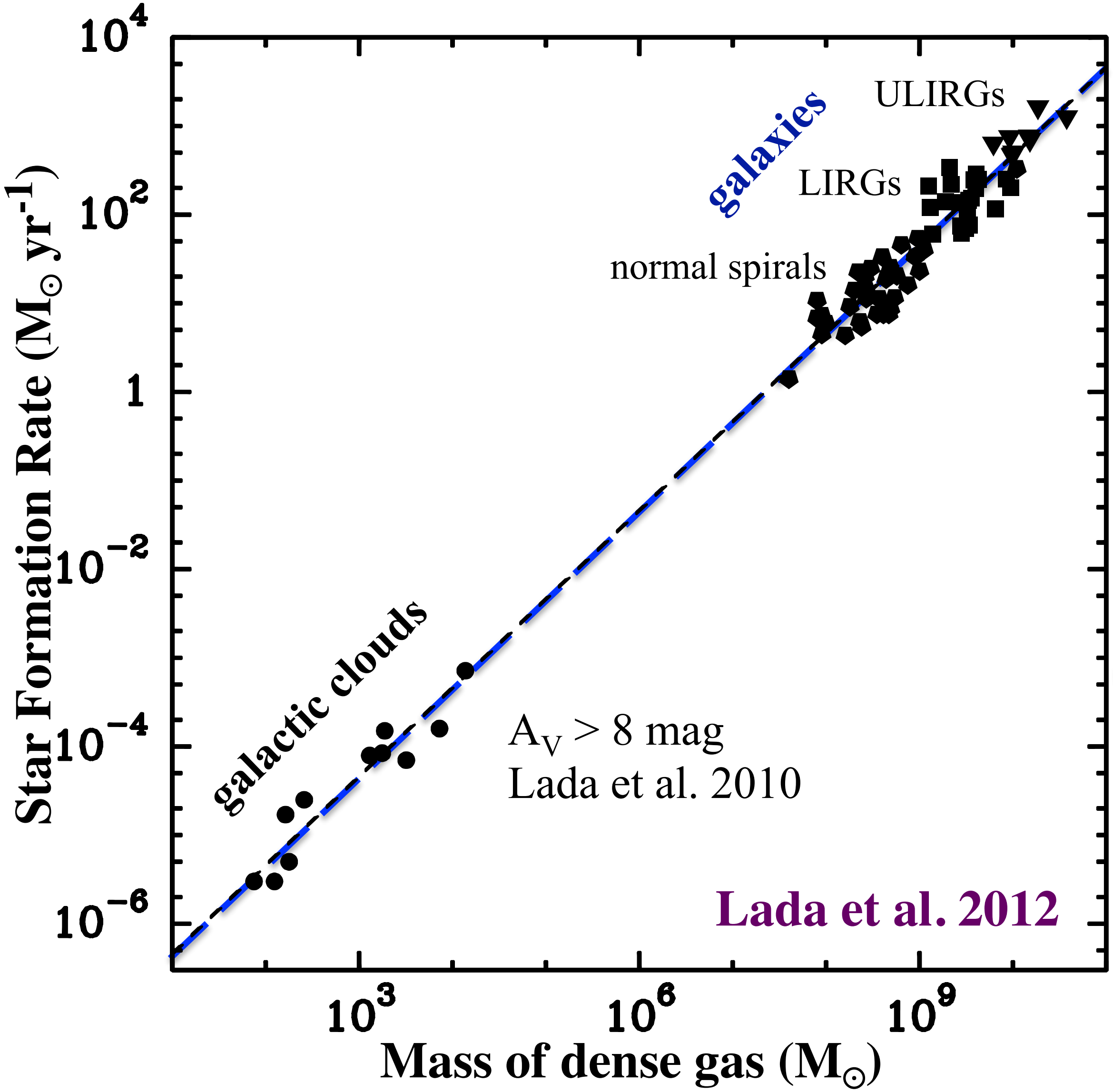
- Massive star formation tends to occur in « ridges » ($A_V > 100$) at the junctions of supercritical filaments

- This scenario may possibly account for the global rate of star formation on galactic scales

See related chapter for « Protostars & Planets VI »
by André, Di Francesco, Ward-Thompson, Inutsuka, Pudritz, Pineda

(See also astro-ph/1309.7762)

A universal star formation law above the threshold ?



■ HCN Gao & Solomon 2004

$$\mathbf{SFR}\ (M_\odot/\mathrm{yr}) \simeq 4.5 \times 10^{-8} \times M_{dense}(M_\odot)$$

$$= \varepsilon_{core} \times f_{pre} \times M_{dense} / t_{pre}$$

$$\simeq 0.3 \times 0.15 \times M_{dense}(M_\odot) / 10^6$$

***Herschel* results on Aquila prestellar cores**

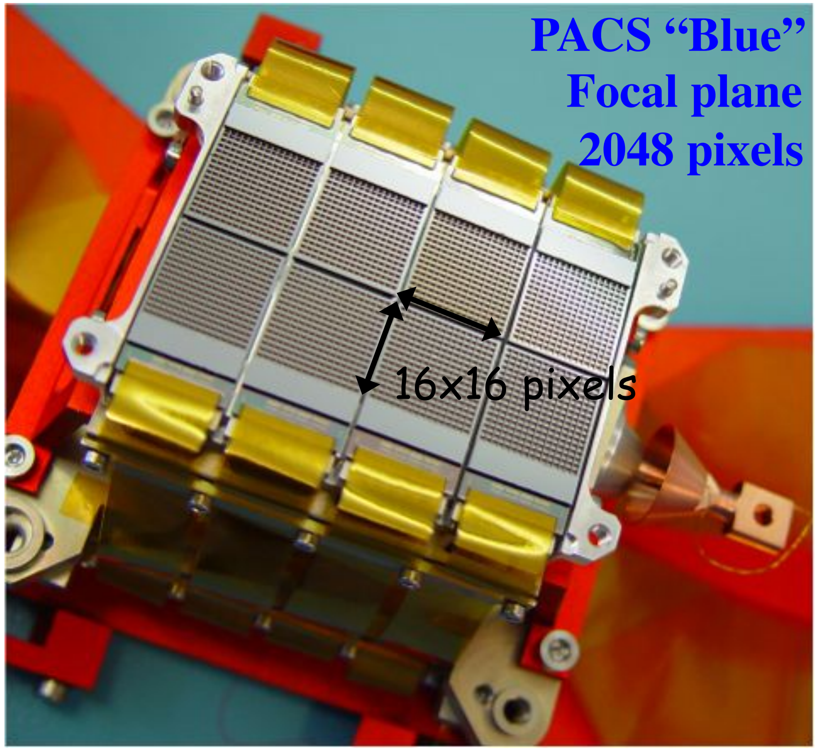
M_{dense} = Mass of dense gas above the threshold ($A_V > 8$ or $n_{H2} > 2.5 \times 10^4\ cm^{-3}$)

André et al. 2011 (astro-ph/1309.7762)

ArTéMiS : A powerful tool to study massive star-forming « ridges » beyond the Gould Belt

×3.4 higher resolution than SPIRE

×3-(10) faster than SABOCA



ArTéMiS : 2304 pixels @ 450 μm;
2304 pixels @ 350 μm; 1152 pixels @ 200 μm

First 350 μm observations with ArTéMiS at APEX in July/Sep 2013 : NGC 6334 (d ~ 1.7 kpc)