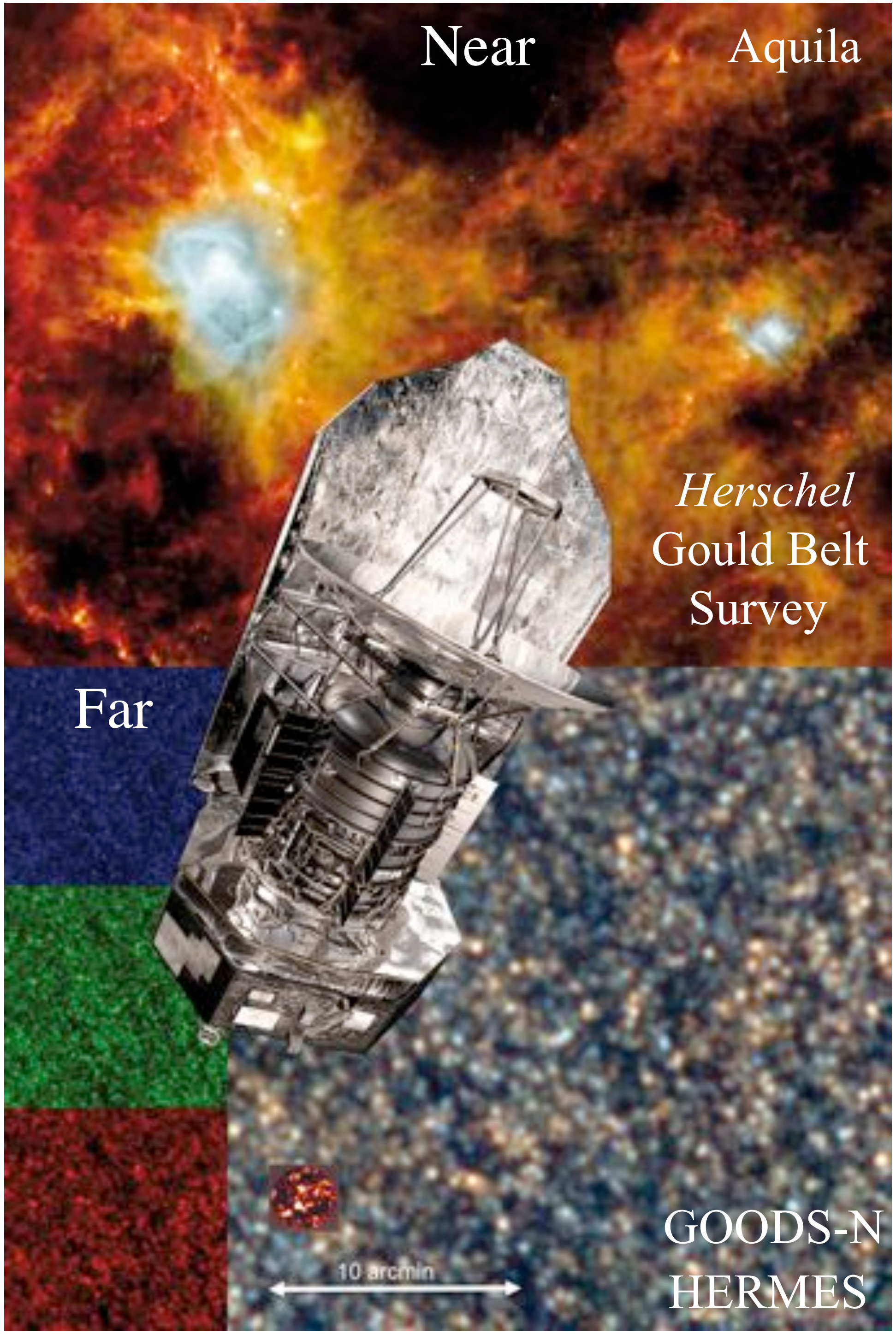
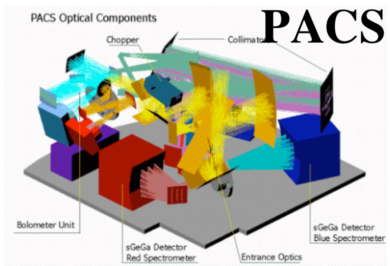


Characterization of cloud structure: From *Herschel* to CCAT

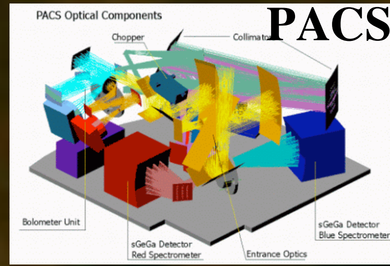
Philippe André
CEA
Laboratoire AIM Paris-Saclay



Formation and Development of Molecular Clouds
CCAT Meeting – Cologne – 06/10/2011

Outline:

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



- Results from the *Herschel* Gould Belt survey on the structure of molecular clouds

- The role of filaments in the core/star formation process

- Speculations: A universal scenario for star formation ?

- Areas where CCAT will contribute

Herschel GB survey IC5146 Arzoumanian et al. 2011

With: A. Menshchikov, V. Könyves, N. Schneider, D. Arzoumanian, S. Bontemps, F. Motte, P.Didelon, N. Peretto, D. Ward-Thompson, J. Kirk, M. Hennemann, J. Di Francesco, P. Martin, S. Molinari, P. Palmeirim, J.Ph. Bernard & the *Herschel* Gould Belt KP Consortium

Herschel shows a wealth of filamentary structure in every interstellar cloud

Aquila: Actively star forming | **Polaris: Non star forming**

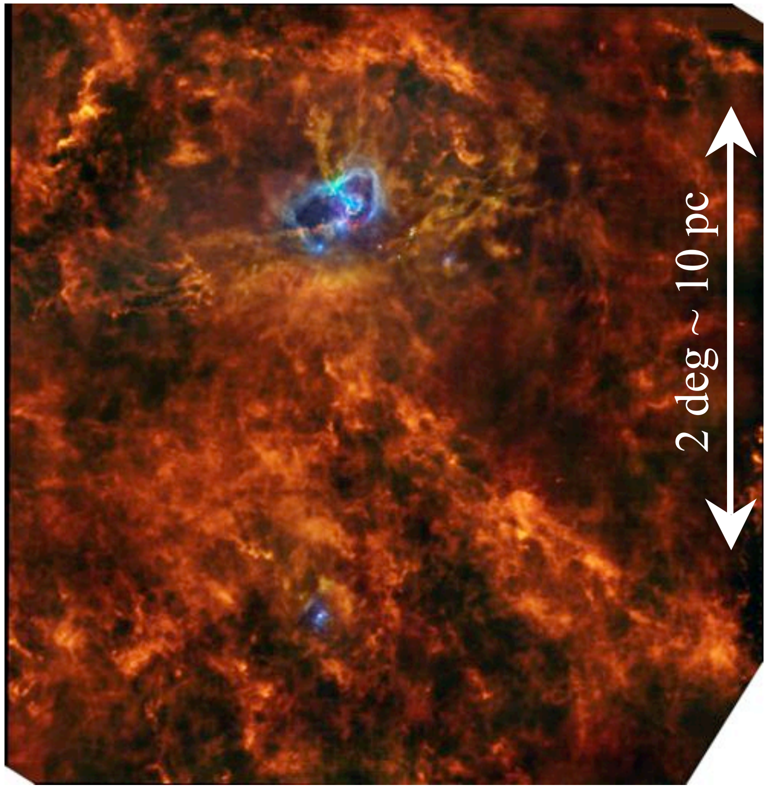
d ~ 260 pc

SPIRE 500 μm + PACS 160/70 μm

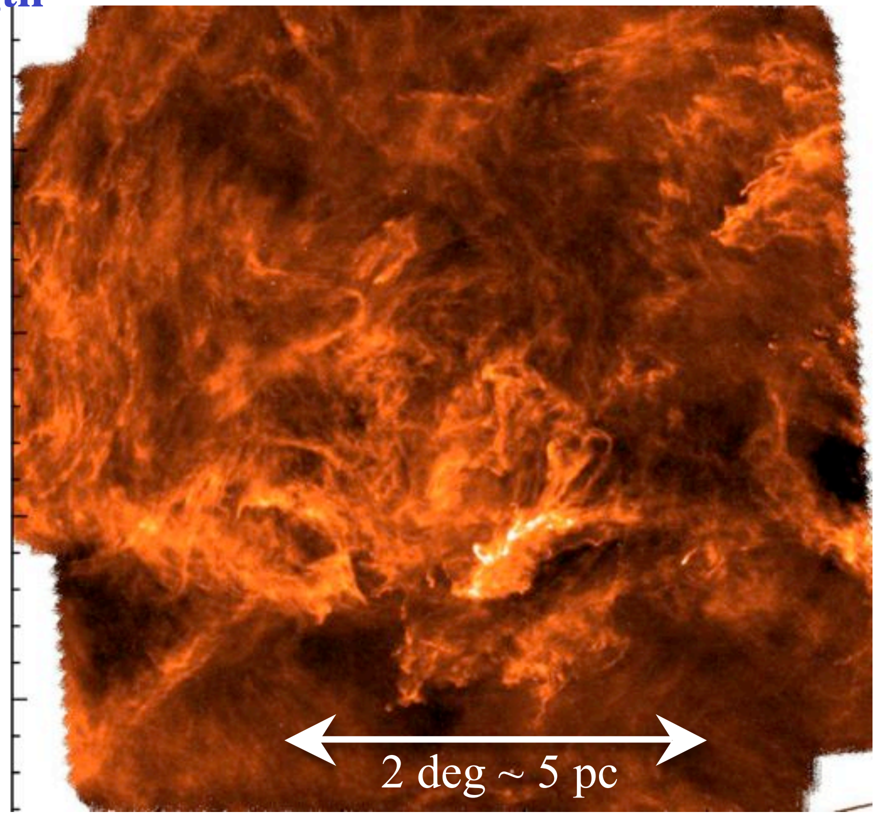
~ 15'' ~ 0.02 pc @ d = 300 pc
< Jeans length

SPIRE 250 μm

d ~ 150 pc



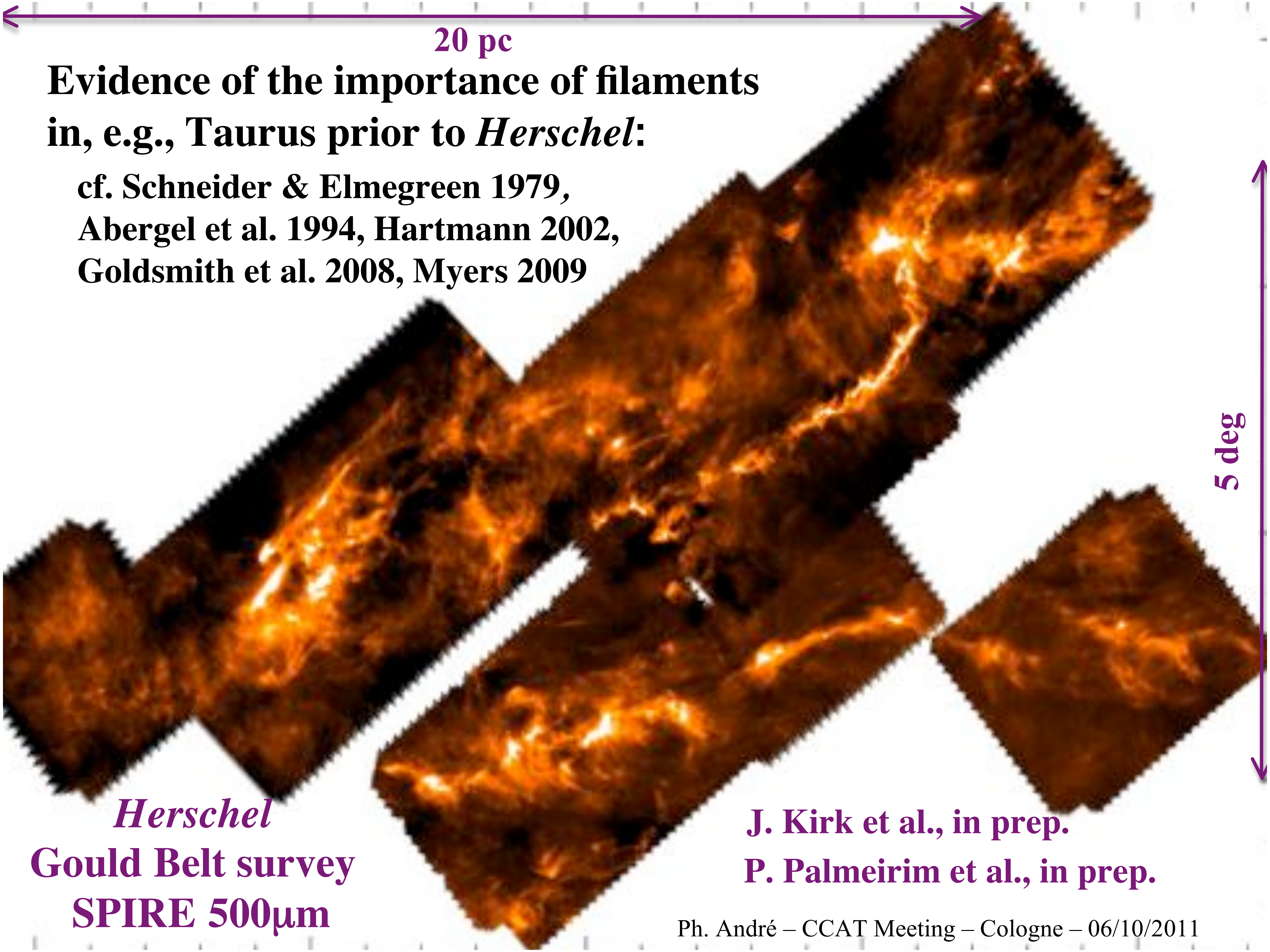
Aquila Rift - *Herschel* Gould Belt survey
André et al. 2010, Bontemps et al. 2010, Könyves et al. 2010



Polaris Flare - Gould Belt survey
Men'shchikov et al. 2010, Miville-Deschênes ea. 2010, Ward-Thompson et al. 2010

Evidence of the importance of filaments in, e.g., Taurus prior to *Herschel*:

cf. Schneider & Elmegreen 1979*,* Abergel et al. 1994, Hartmann 2002, Goldsmith et al. 2008, Myers 2009



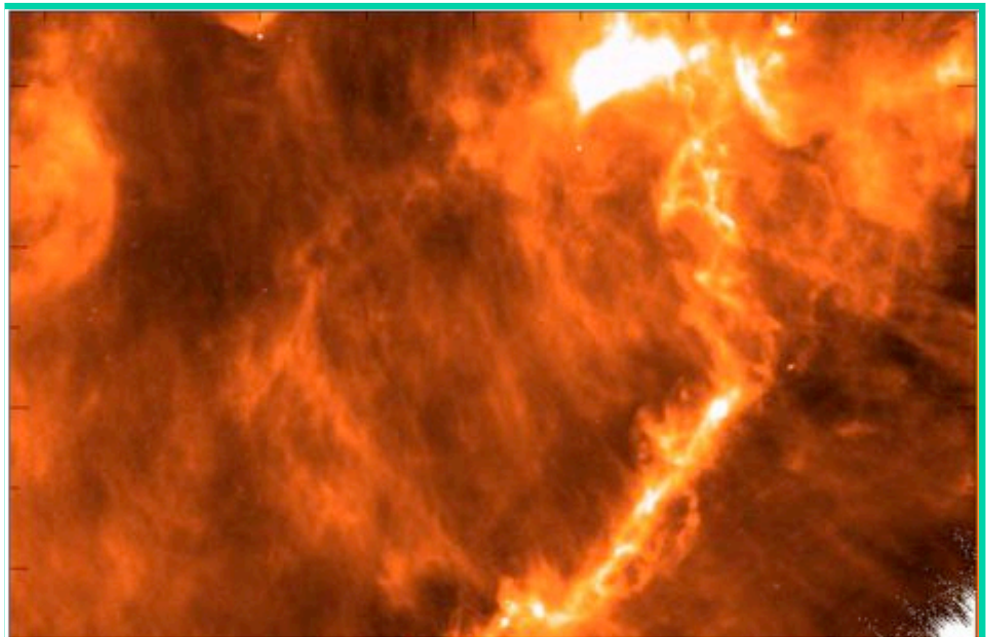
Herschel
Gould Belt survey
SPIRE 500μm

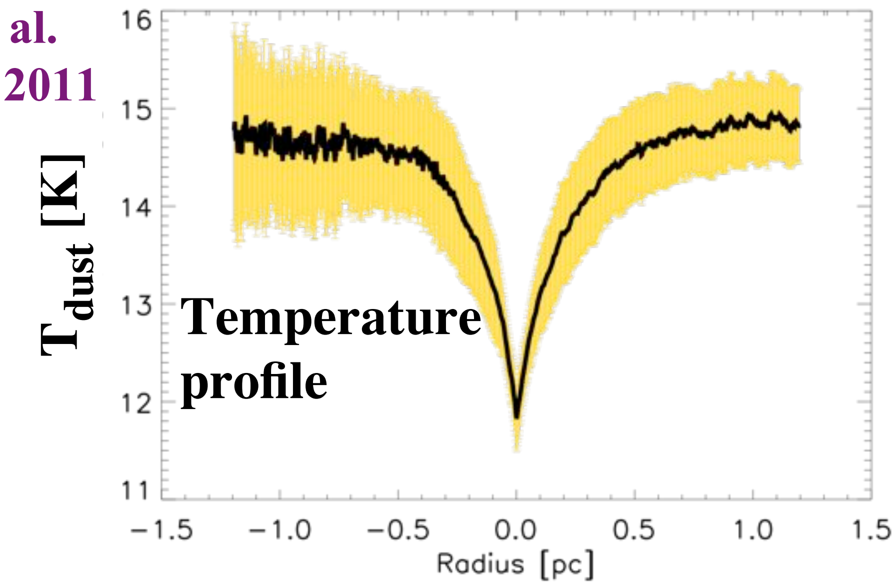
J. Kirk et al., in prep.
P. Palmeirim et al., in prep.

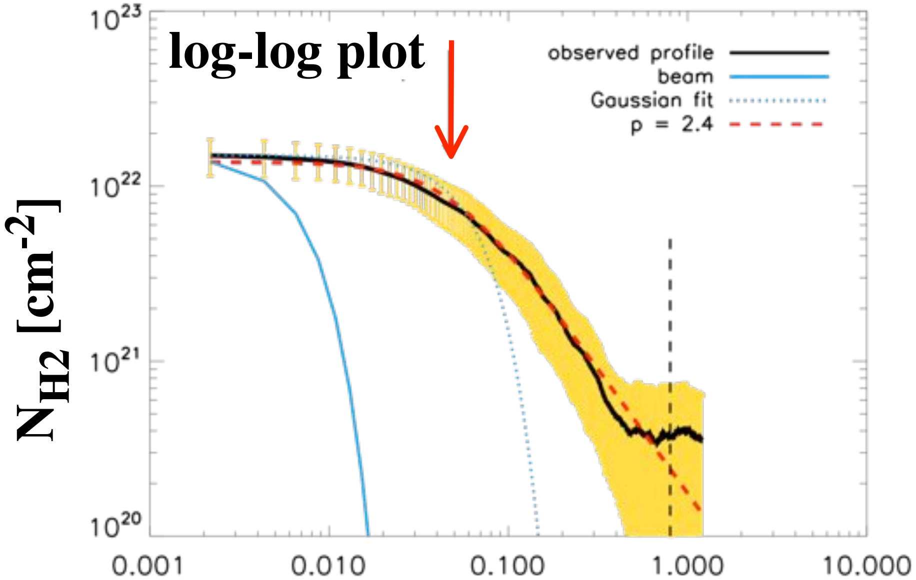
Characterizing the structure of filaments with *Herschel*

Taurus B213 filament
SPIRE 250μm

Arzoumanian et al.
Palmeirim et al. 2011







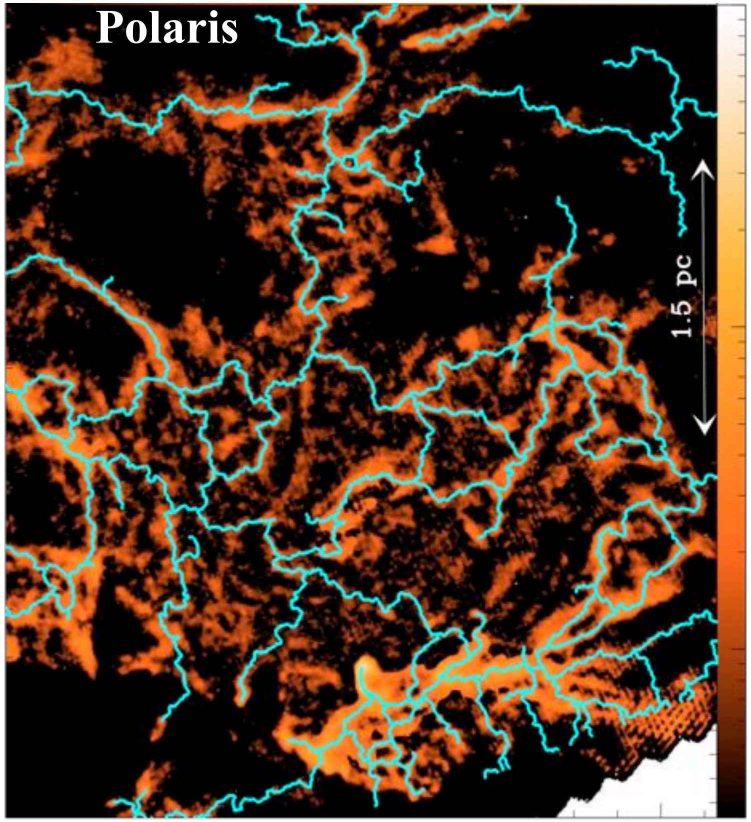
Plummer-like density profile:

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

with $R_{flat} \sim 0.05$ pc

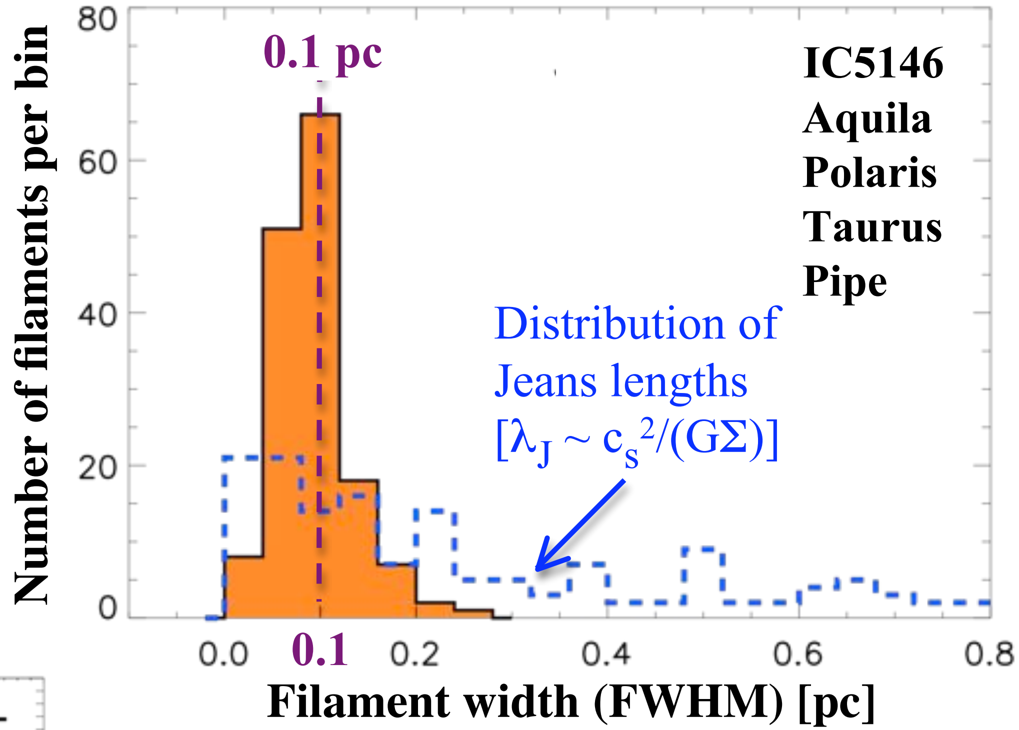
Diameter of flat inner plateau ~ 0.1 pc

Filaments have a characteristic width ~ 0.1 pc

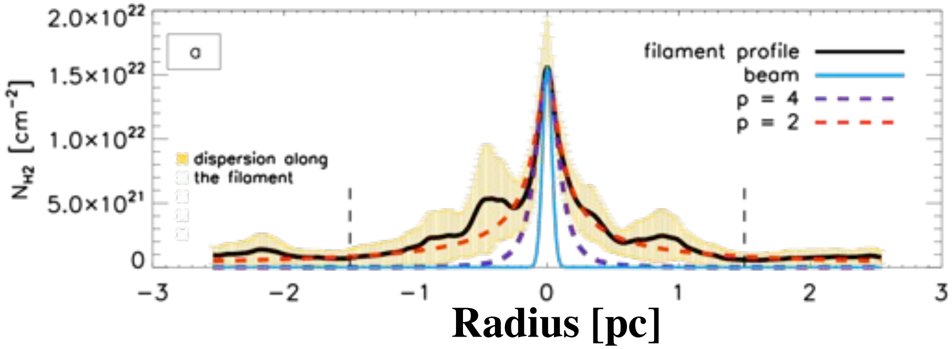


D. Arzoumanian et al. 2011, A&A, 529, L6

Statistical distribution of widths for 150 filaments



Example of a filament radial profile



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

Dense cores form primarily in filaments

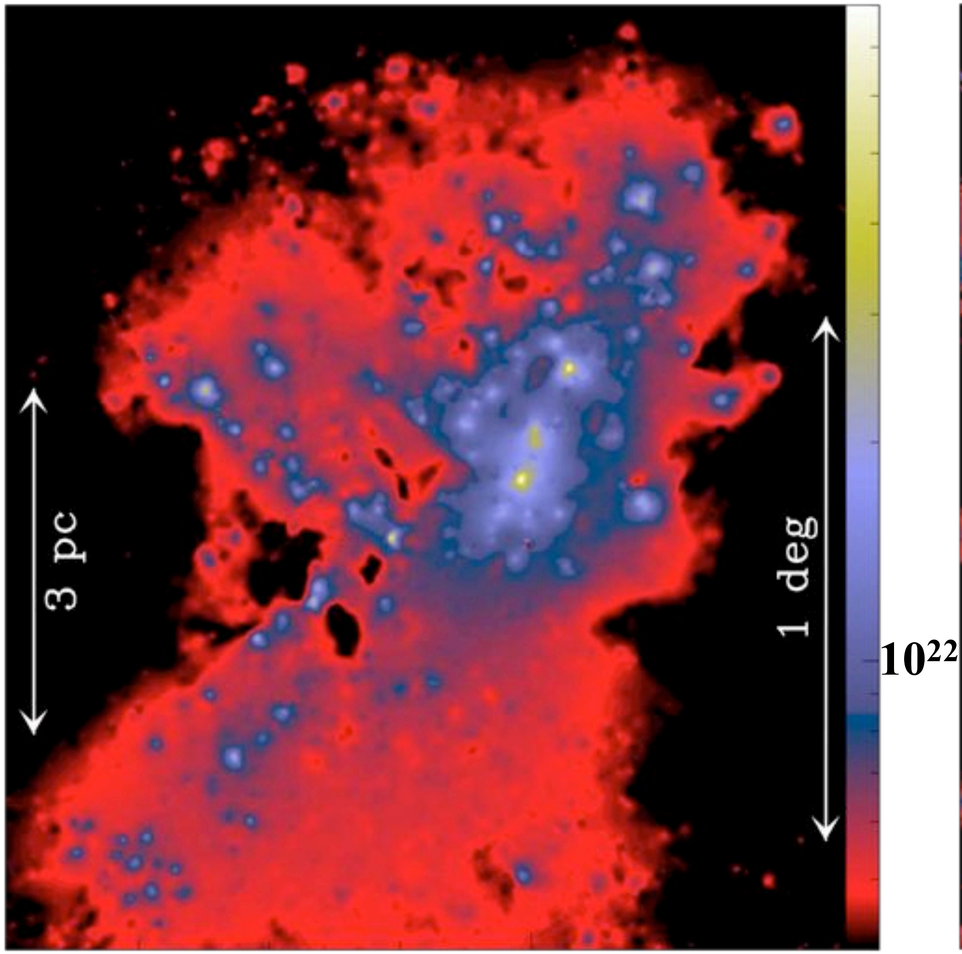
Morphological Component Analysis:

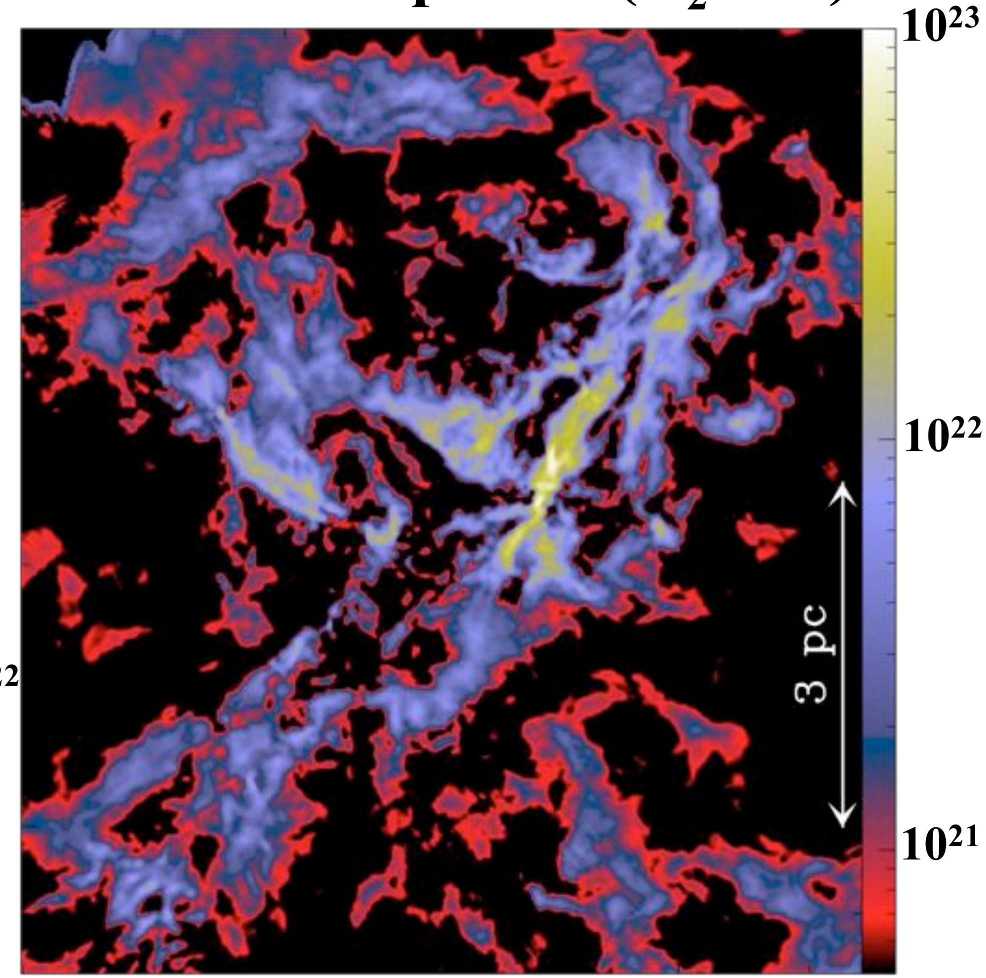
(P. Didelon based on Starck et al. 2003)

***Herschel* Column density map**

=

Cores		Filaments
Wavelet component (H_2/cm^2)	**+**	**Curvelet component (H_2/cm^2)**





Core extraction using "getsources"

(A. Men'shchikov et al. 2010, 2011)

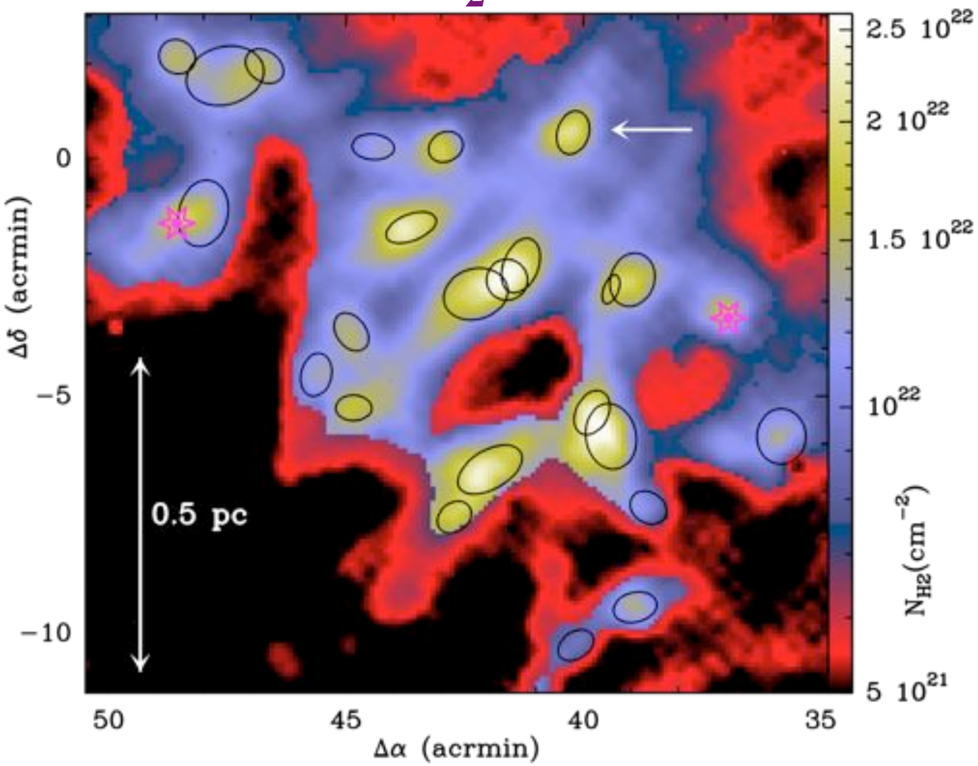
- **Core = single star-forming entity**

  (Need to resolve ~ 0.01-0.1 pc)

- **Prestellar = bound & starless**

Examples of starless cores in Aquila

***Herschel* N_{H_2} map (cm^{-2})**



Könyves et al. 2010, A&A special issue

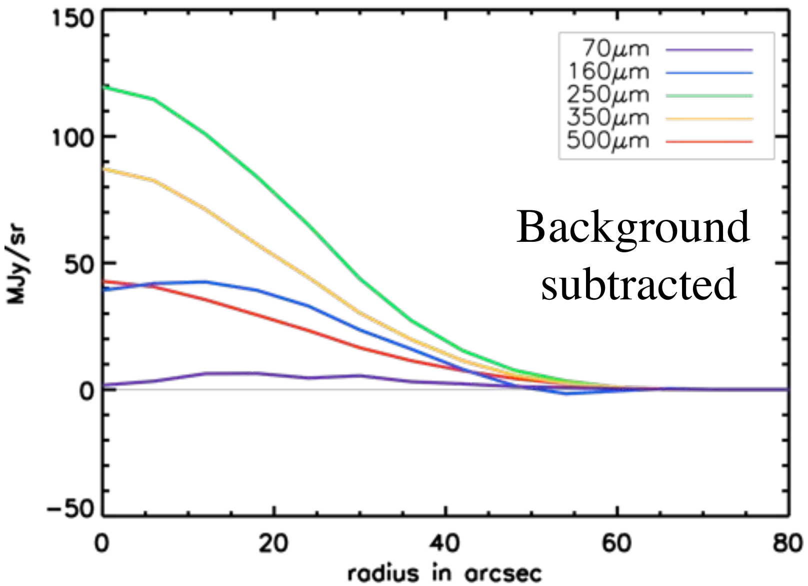
541 starless cores (no PACS 70 μm), including 341 prestellar cores

+

201 YSOs (with PACS 70μm)

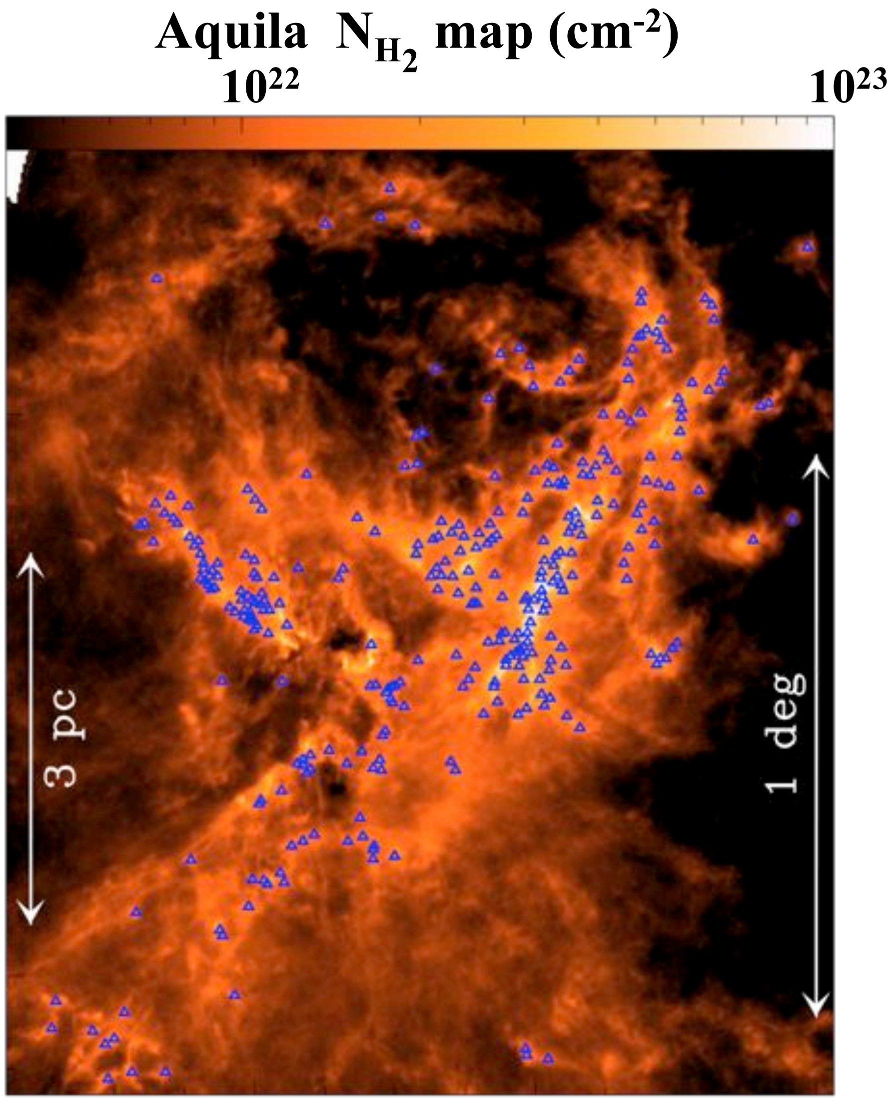
identified with *getsources* in Aquila

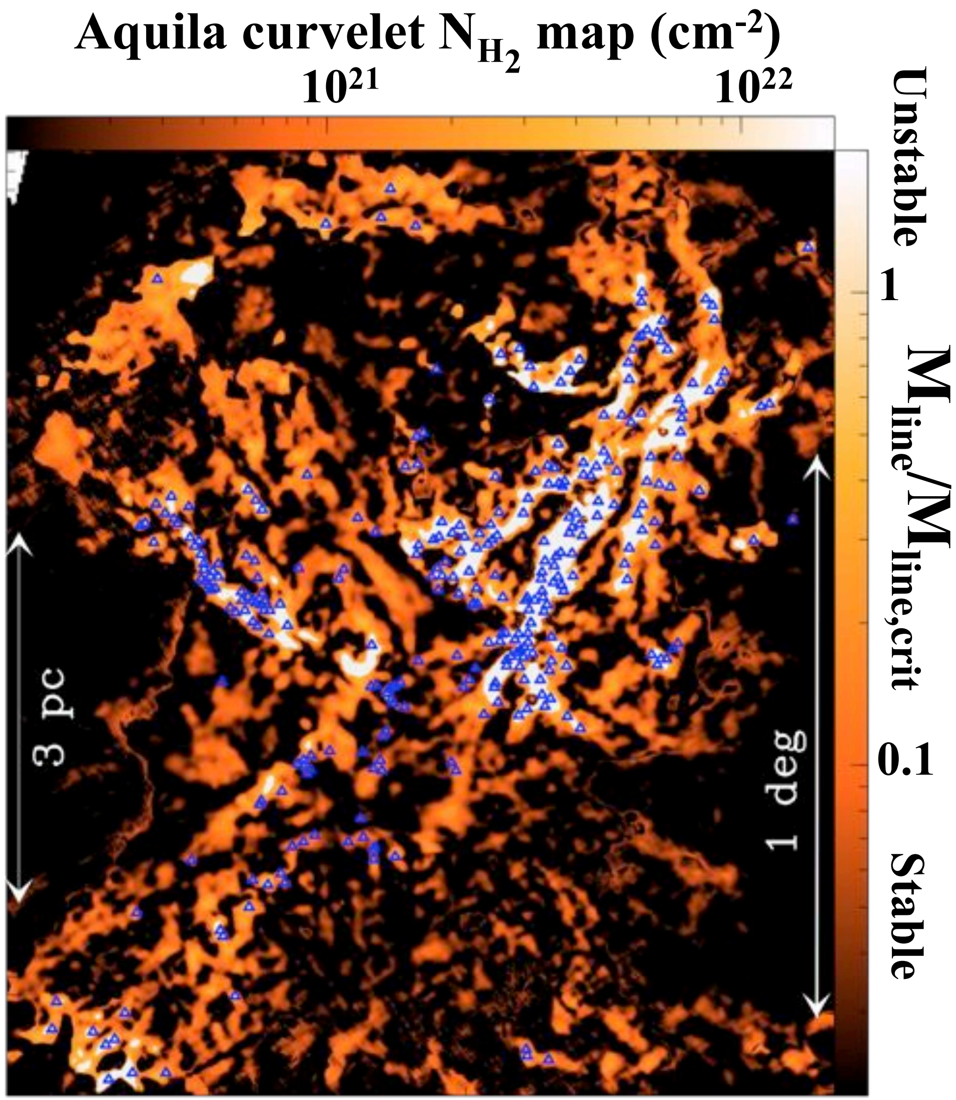
Radial intensity profiles



Prestellar cores are preferentially found within the densest filaments

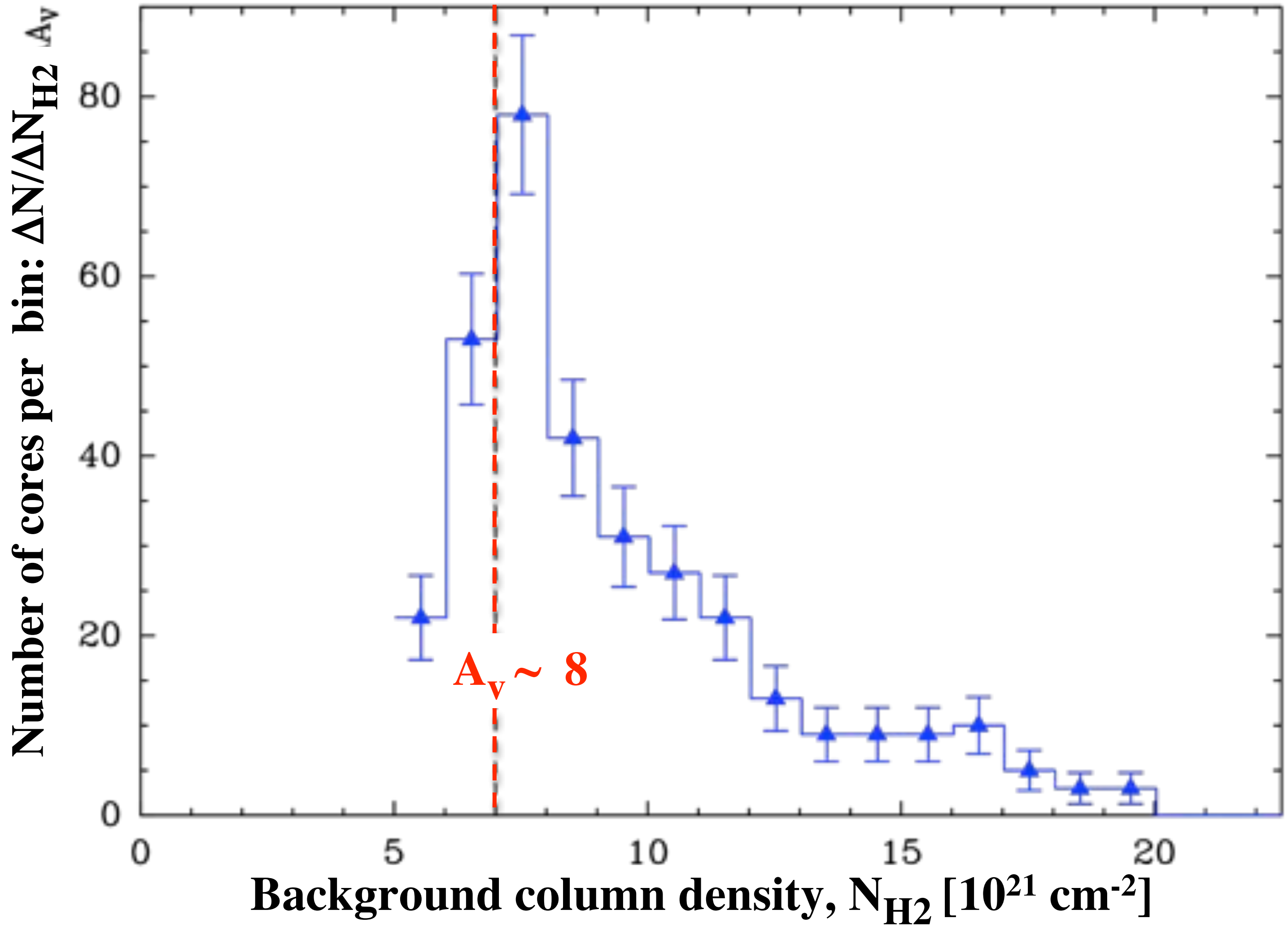
△ : Prestellar cores - 90% found at N_{H_2}> 7x10^{21} cm^{-2} <=> A_v(back) > 8





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 $A_v \sim 8$ ⇔ $\Sigma \sim 130\ M_\odot\ pc^{-2}$

cf. Onishi et al. 1998
Johnstone et al. 2004

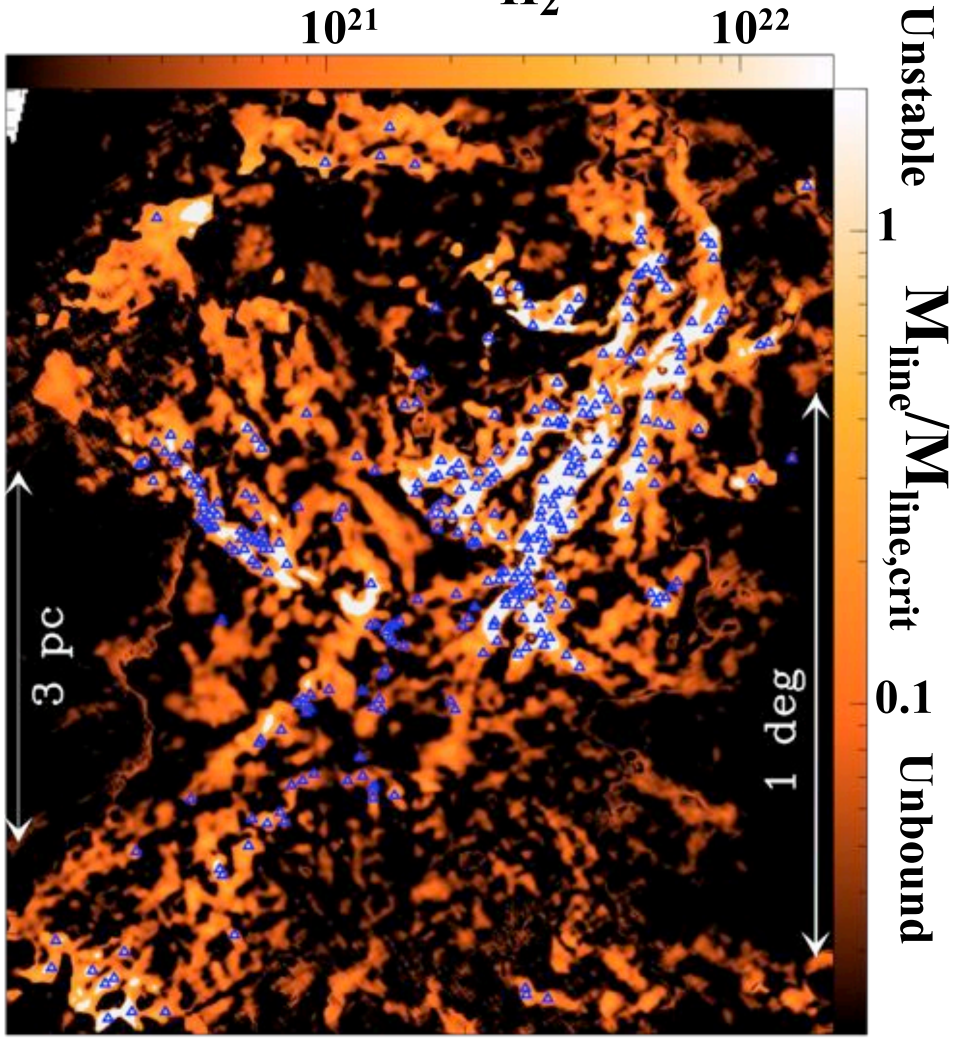
See also (for YSOs):
Goldsmith ea. 2008
Heiderman, Evans et al. 2010
Lada, Lombardi, Alves 2010

André et al. IAU270, Könyves et al. in prep

Interpretation of the star formation threshold

△ : Prestellar cores

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



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 $M_{line} < M_{line,\ crit}$**
- **$M_{line,\ crit} = 2\ c_s^2/G \sim 15\ M_\odot/pc$**

for T ~ 10K ⇔ Σ threshold $\sim 150\ M_\odot/pc^2$

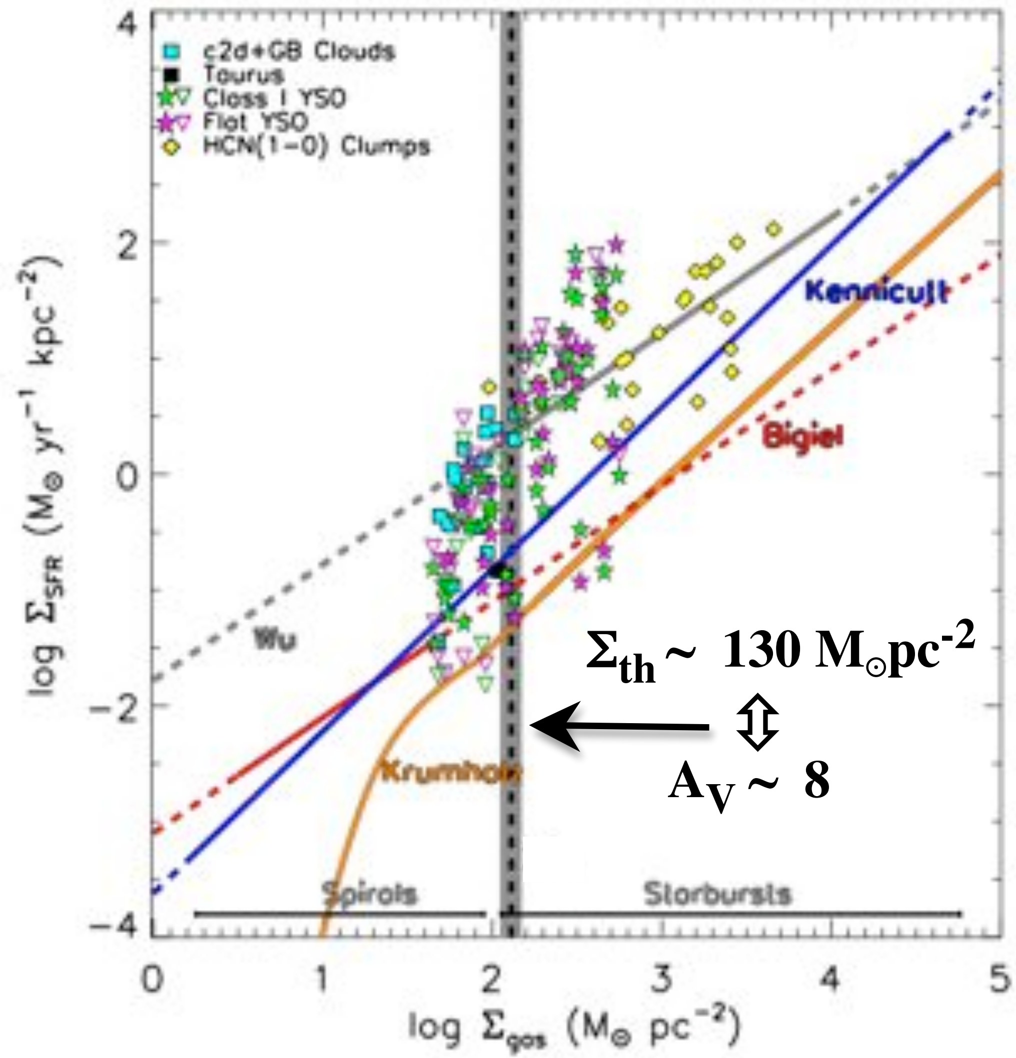
➢ **Simple estimate:**

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

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

Importance of the star formation threshold on (extra)galactic scales

Star formation rate vs. Gas surface density



Heiderman, Evans et al. 2010

$\Sigma_{SFR} \propto \Sigma_{gas}$

for

$\Sigma_{gas} > \Sigma_{threshold}$

Heiderman et al. 2010

Lada et al. 2010

See

Gao & Solomon 2004

for external galaxies

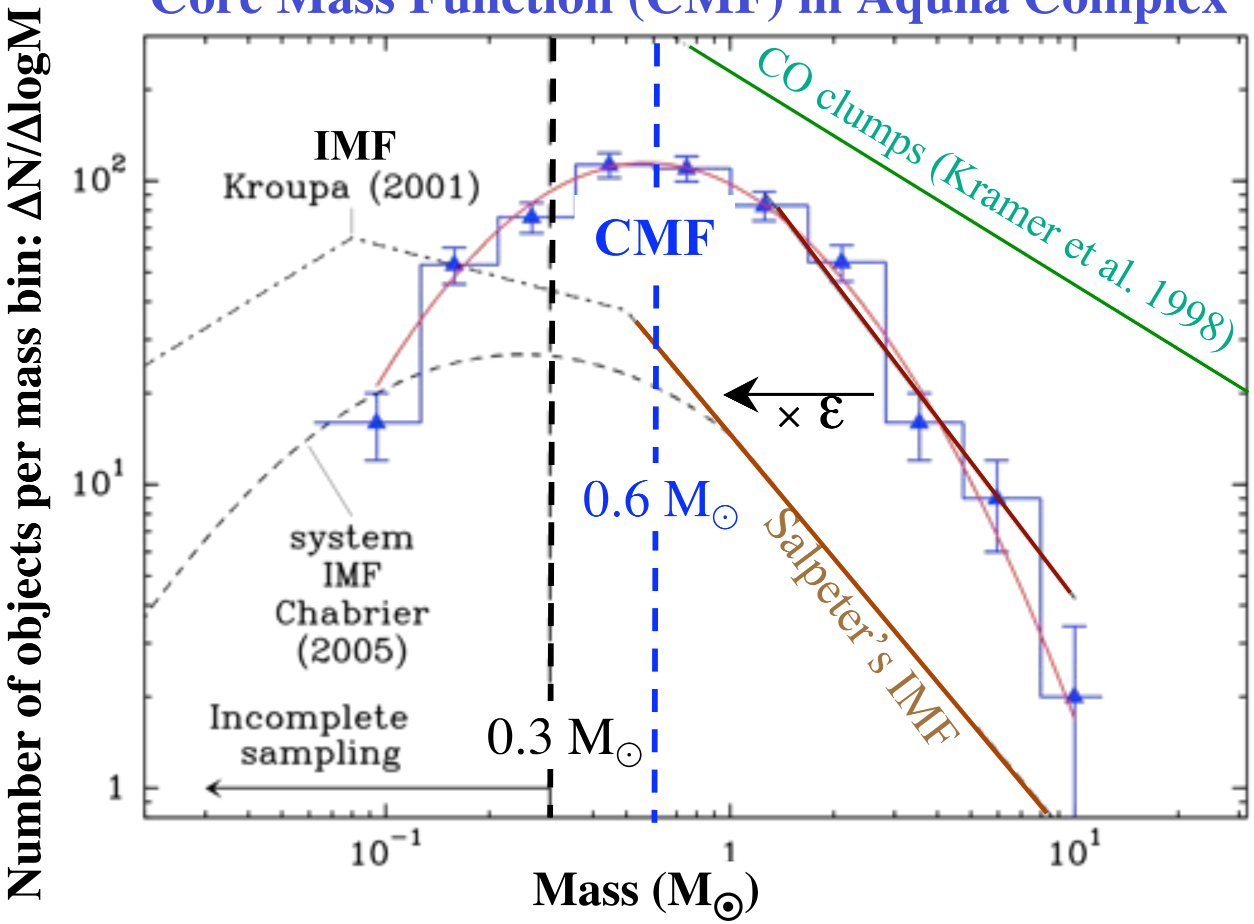
Confirming the link between the prestellar CMF & the IMF

André et al. 2010
Könyves et al. 2010
A&A vol. 518

341-541 prestellar cores in Aquila

Factor ~ 2-9 better statistics than earlier CMF studies

Core Mass Function (CMF) in Aquila Complex



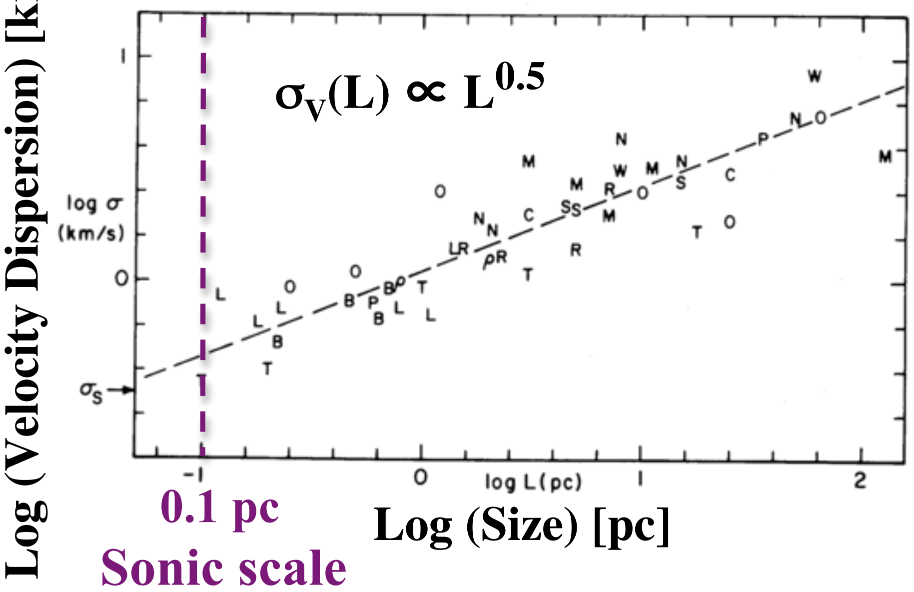
- Good (~ one-to-one) mapping between core mass and stellar system mass: $M_* = \varepsilon\, M_{core}$ with ε ~ 0.2-0.4 in Aquila
- CMF peaks at ~ 0.6 $M_\odot$ ≈ Jeans mass in marginally critical filaments

Are interstellar filaments formed by large-scale turbulent compression ?

Filament width ~ 0.1 pc ~ sonic scale of ISM turbulence

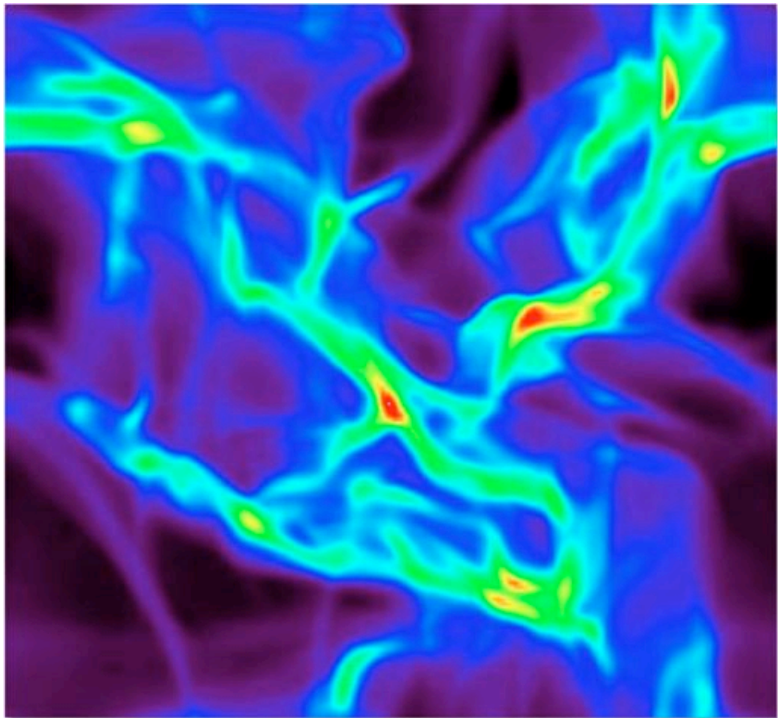
Linewidth-Size relation in clouds

(e.g. Larson 1981, Heyer et al. 2009)



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

Simulations of turbulent fragmentation

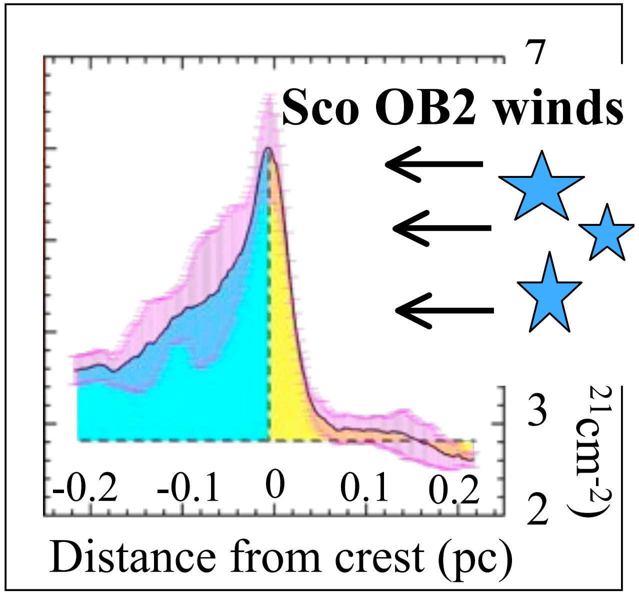


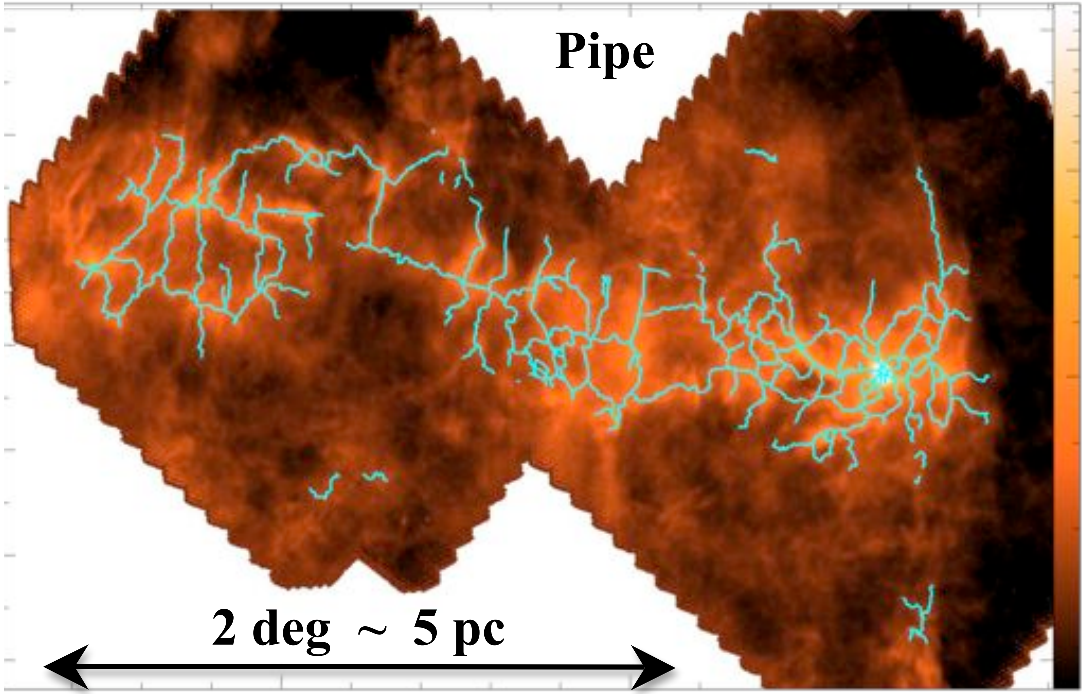
Padoan, Juvela et al. 2001

$$\lambda \sim L/\underbrace{\mathcal{M}(L)^2}_{\text{compression ratio (HD shock)}} \sim 0.1 \text{ pc}$$

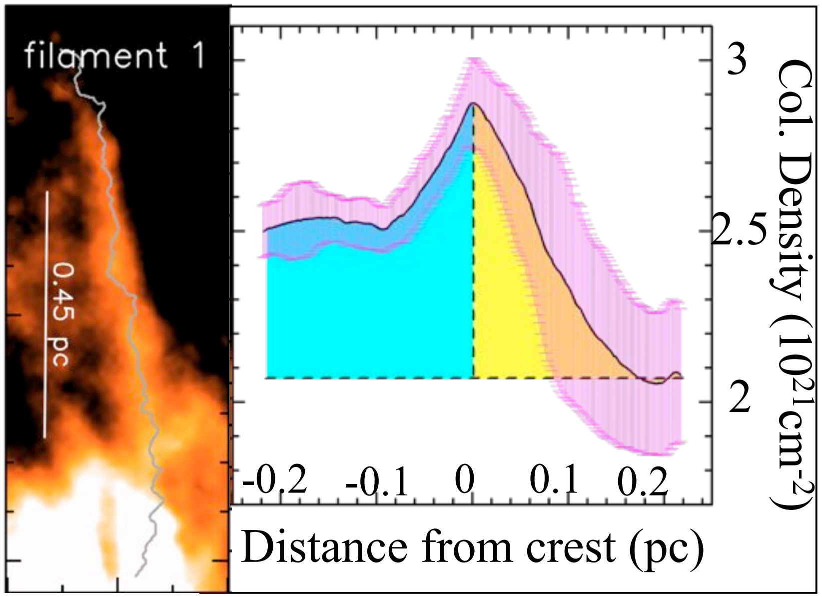
Evidence of the formation of filamentary structures by large-scale compression in the Pipe Nebula

- **In the Pipe several filaments have asymmetric column density profiles, most likely due to compression by the winds of Sco OB2 (Peretto et al., in prep)**





Column density map (Peretto et al.)
Herschel **Gould Belt survey**



Toward a universal scenario for star formation ?

- *Herschel* results suggest **core formation occurs in 2 main steps**:
  1) Filaments form first in the cold ISM, probably as a result of the dissipation of **MHD turbulence** (cf. Padoan et al. 2001);
  2) The densest filaments then fragment into prestellar cores via **gravitational instability** (cf. Inutsuka & Miyama 1997) above a critical threshold $\Sigma_{th} \sim 150\ M_{\odot}\ pc^{-2} \Leftrightarrow A_V \sim 8$

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

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

Many remaining open issues: Areas where CCAT will contribute

- **Does the scenario emerging from *Herschel* observations of nearby (low-mass SF) regions also hold in high-mass SF regions ?**

  ➢ **CCAT can resolve individual prestellar cores up to ~ 3 kpc**

- **Signatures of the low-velocity interstellar shocks responsible for the <u>formation of filaments</u> in the turbulent picture ?**

  ➢ **Good diagnostic with CCAT: [CI] (492 GHz) / CO ratio**

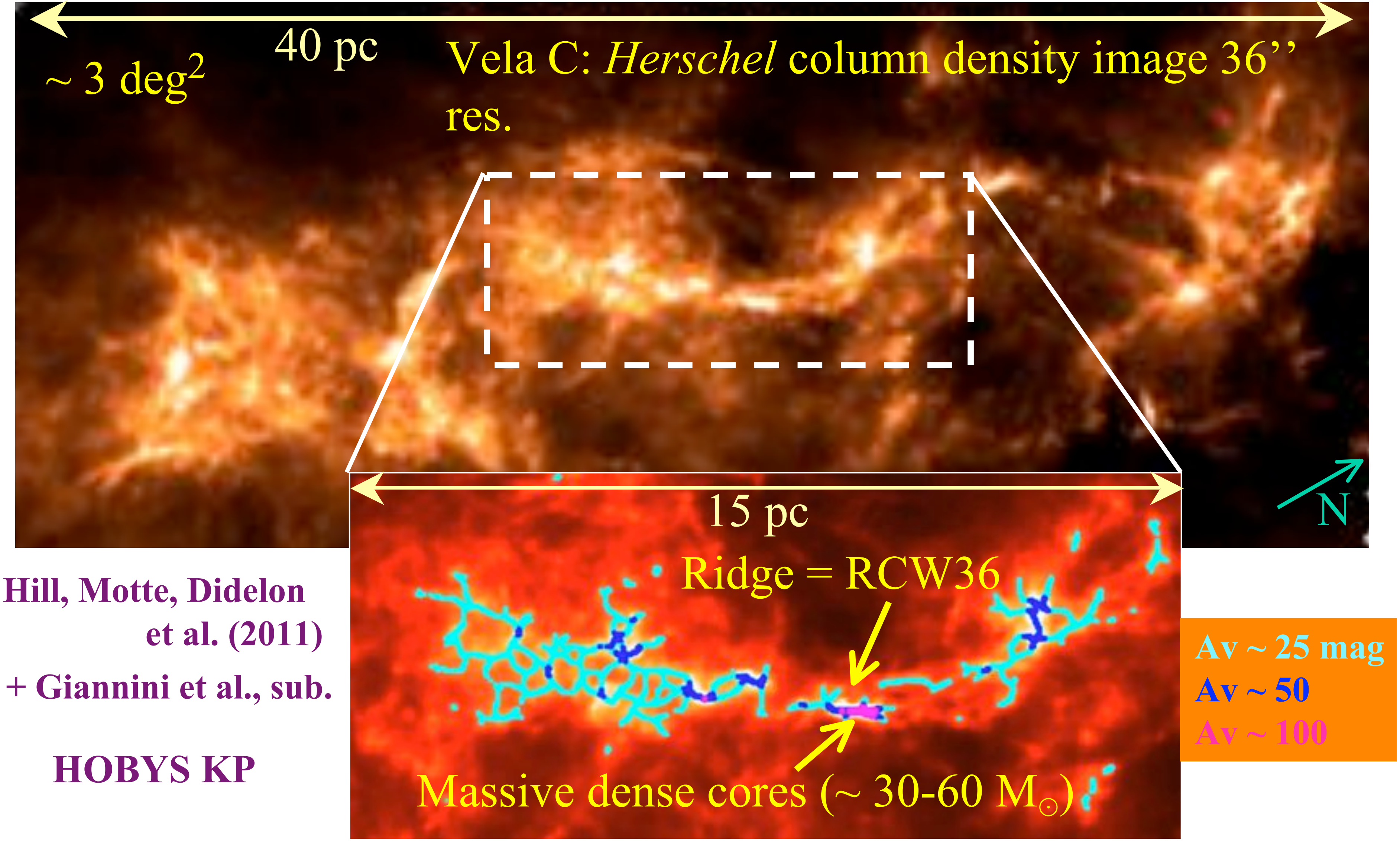
- **<u>Evolution of filaments:</u>**

  - **Do subcritical filaments disperse without gaining mass ?**

  - **Do supercritical filaments accrete mass while collapsing ?**

  ➢ **Extensive high-resolution line mapping and comparison with numerical simulations + radiative transfer**

Massive star formation also occurs along filaments



Hill, Motte, Didelon et al. (2011)
+ Giannini et al., sub.

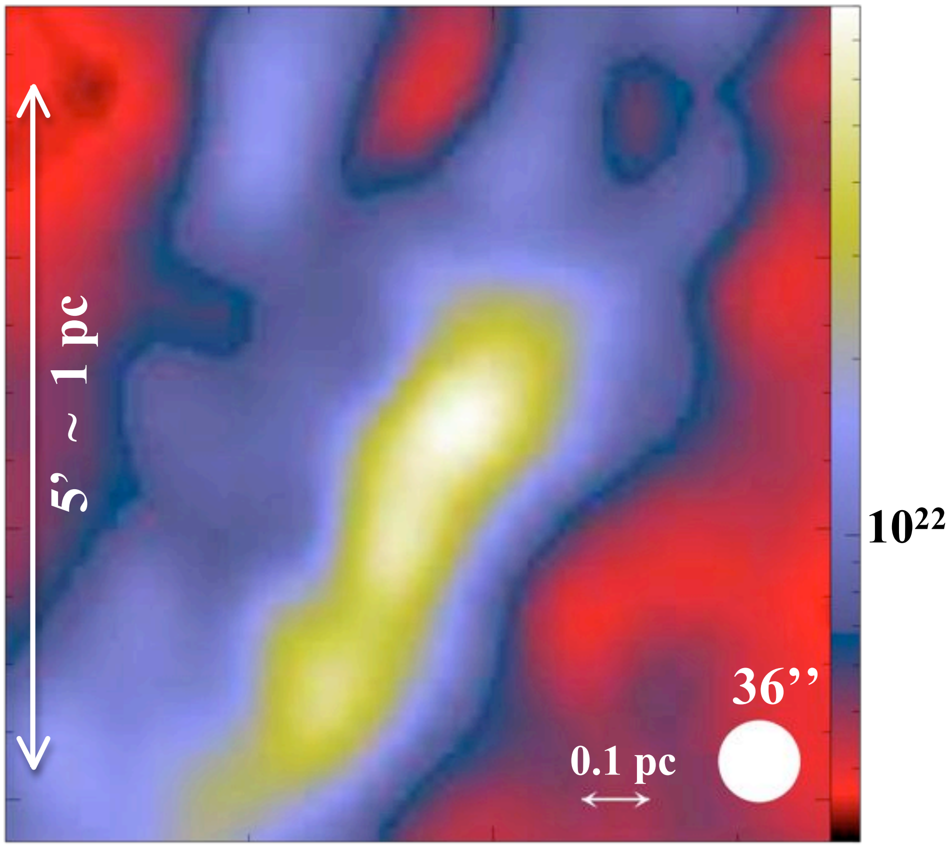
HOBYS KP

➢ **The Vela C centre ridge is an extreme version of the supercritical filaments seen in the Gould Belt survey (~ Serp-South in Aquila)**

Crucial need for high-resolution ground-based imaging when studying massive star formation

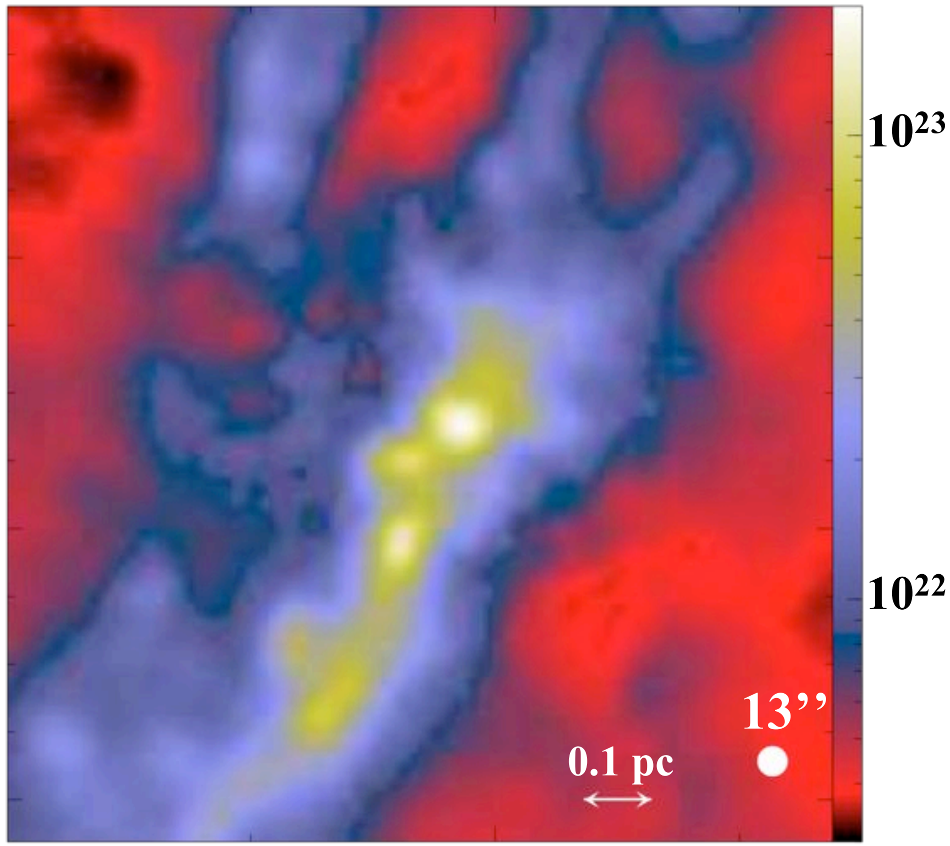
Example: RCW36 in Vela-C (d ~ 700 pc)

***Herschel* (500 µm res.: ~ 36'')**
Column density map (H_2/cm^2)



Minier et al., in prep.

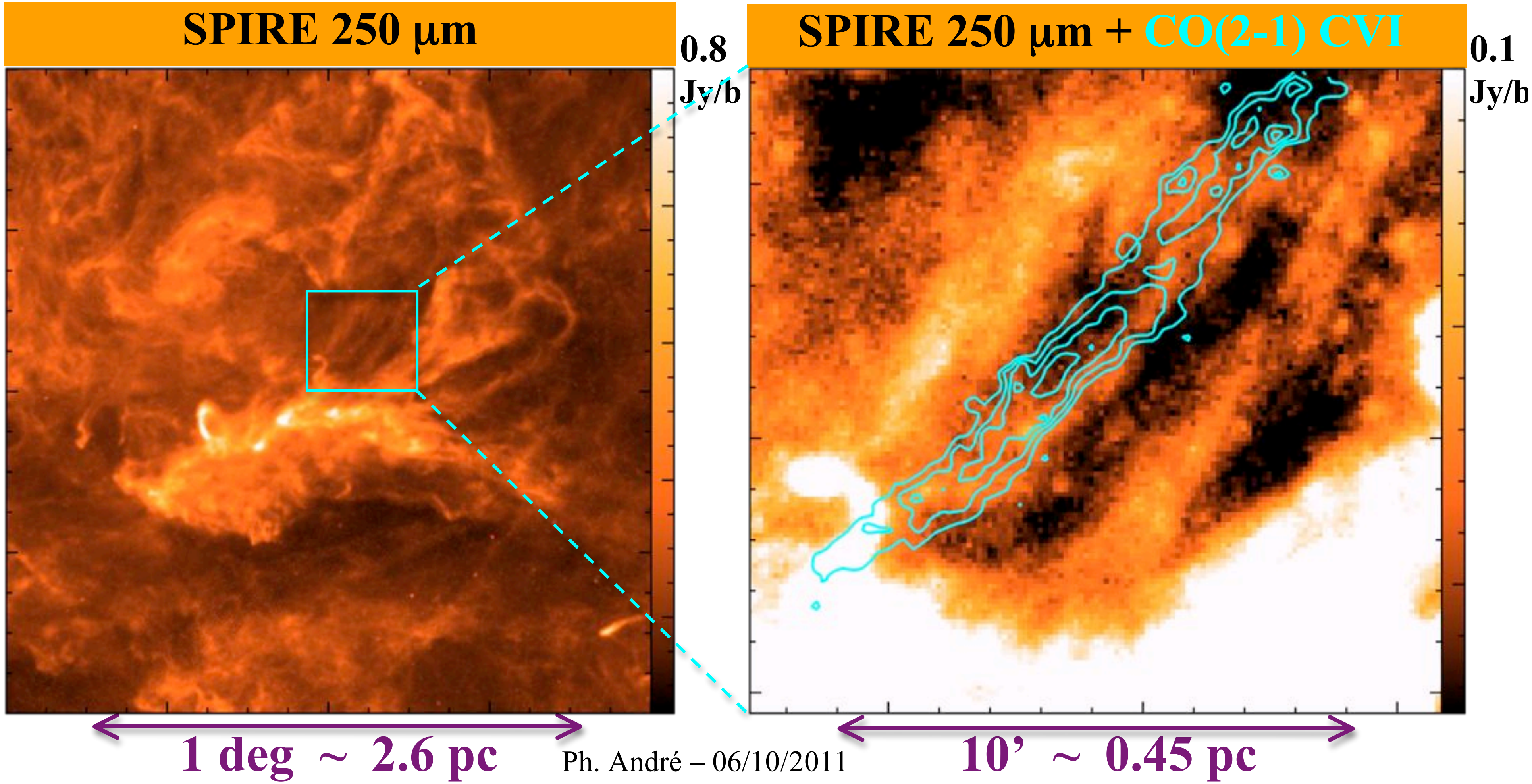
***Herschel* + P-ArTéMiS (450 µm res.: ~ 10'')**
Column density map (H_2/cm^2)



APEX/P-ArTéMiS obs. (see André et al. 2008)

Signatures of filament formation by turbulence dissipation (e.g. low-velocity shocks)?

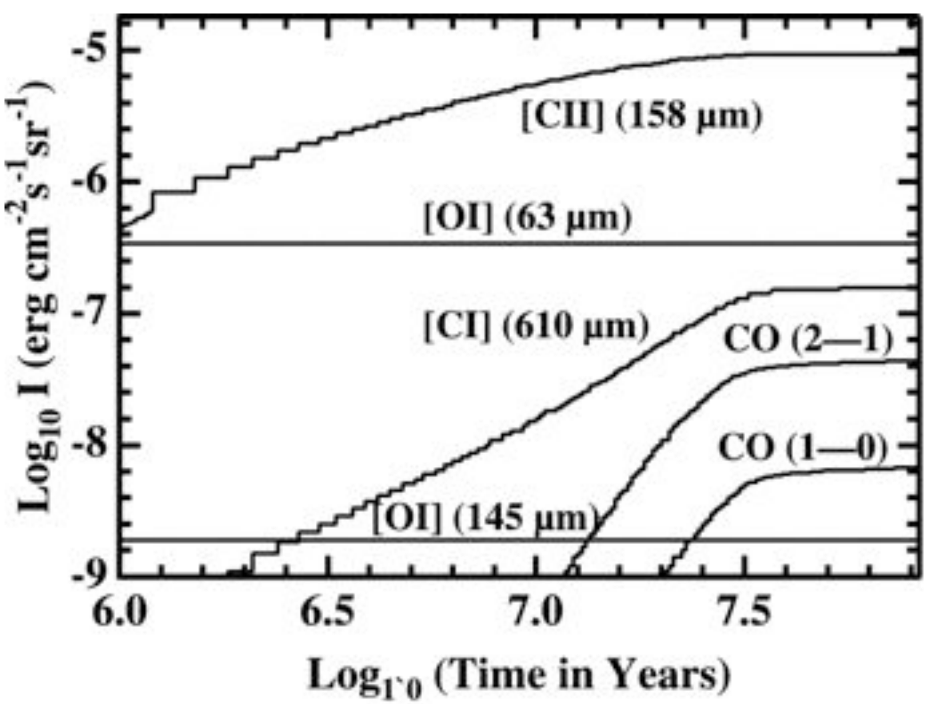
➢ In Polaris, one of the most tenuous filaments detected by SPIRE coincides with a CO(2-1) structure of intense velocity shear (~ 40 km/s/pc) found at IRAM 30m (Hily-Blant & Falgarone 2009)



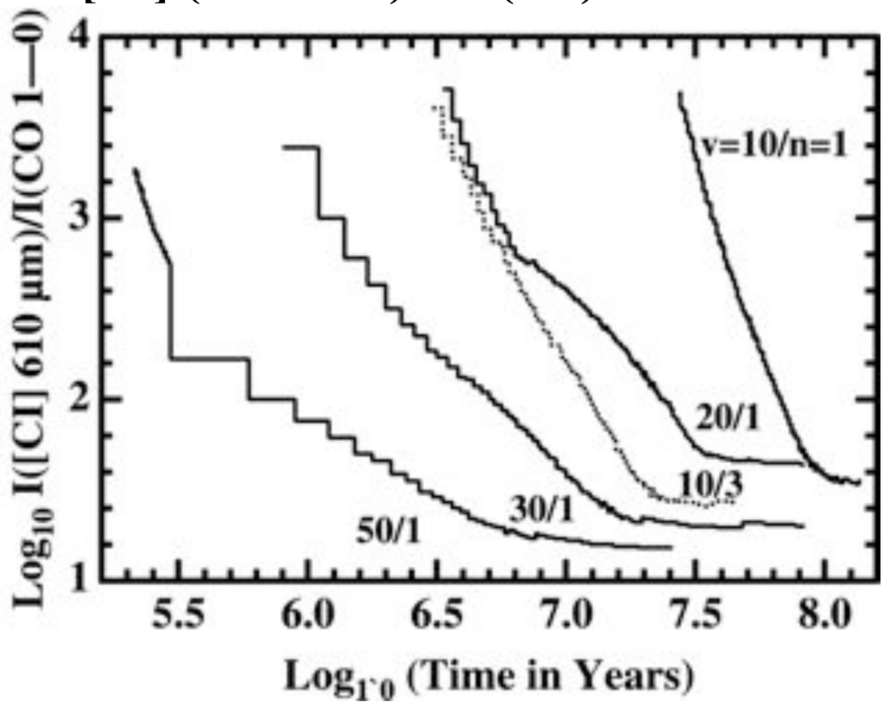
A diagnostic of filament formation behind low-velocity interstellar shocks: the [CI]/CO ratio

Models of molecular cloud formation behind shocks in atomic gas (Bergin et al. 2004)

Predicted line intensities vs. time



[CI] (492 GHz)/CO(1-0) ratio vs. time



- **Need to detect (and map) weak [CI] (492 GHz) emission ~ 0.1 K km/s**
- **Need high spatial resolution to resolve filamentary structure**

Conclusions: Example areas where CCAT will contribute

• **Does the scenario emerging from *Herschel* observations of nearby (low-mass SF) regions also hold in high-mass SF regions ?**

➢ **CCAT can resolve individual prestellar cores up to ~ 3 kpc**

• **Signatures of the low-velocity interstellar shocks responsible for the formation of filaments in the turbulent picture ?**

➢ **Good diagnostic with CCAT: [CI] (492 GHz) / CO ratio**

• **Direct spectroscopic evidence that massive supercritical filaments accrete mass while collapsing/contracting ?**

➢ **Extensive high-resolution line mapping and comparison with numerical simulations + radiative transfer**