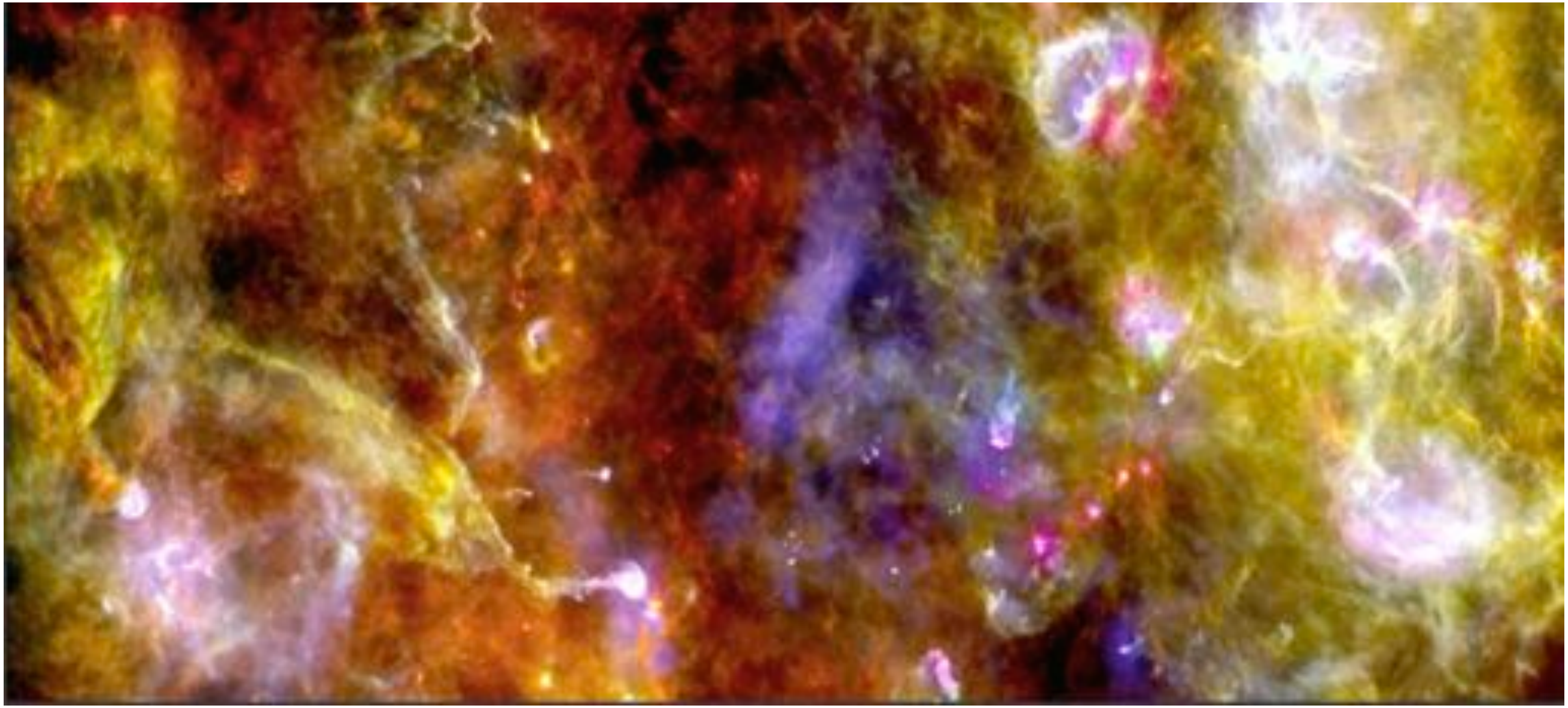
Results from *Herschel* on the structure of the cold ISM: Toward a new paradigm for star formation on GMC scales?

Philippe André

CEA - Lab. AIM Paris-Saclay

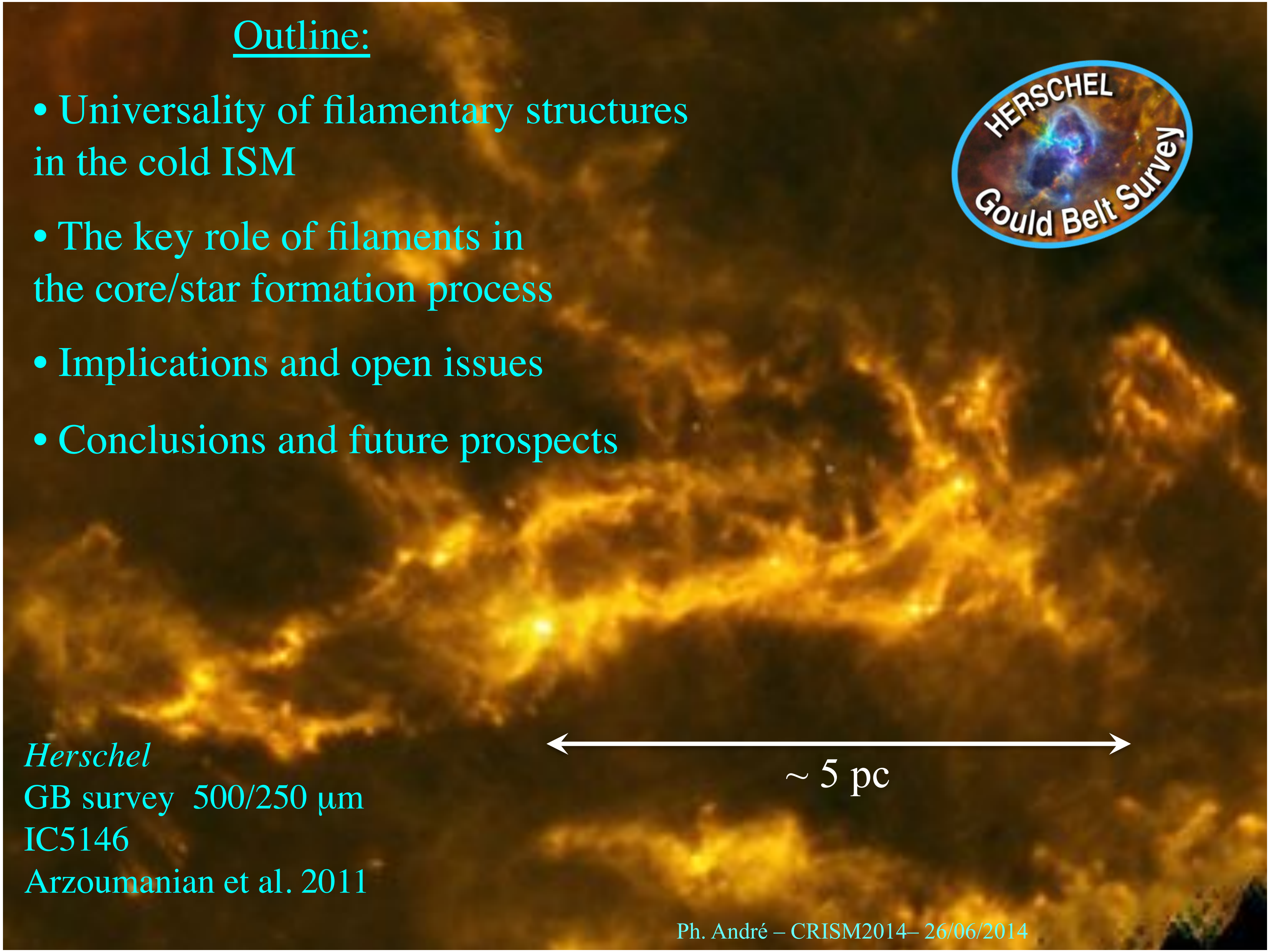
Herschel HOBYS - Cygnus X (Hennemann, Motte et al. 2012)

CRISM2014 - 26/06/2014



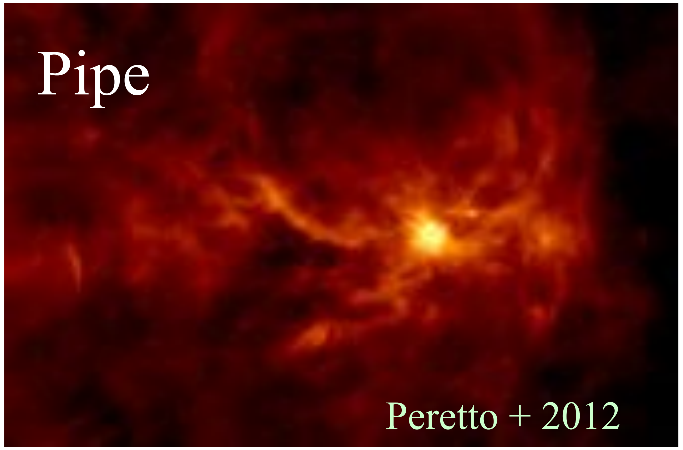
Outline:

- Universality of filamentary structures in the cold ISM
- The key role of filaments in the core/star formation process
- Implications and open issues
- Conclusions and future prospects



Herschel
GB survey 500/250 μm
IC5146
Arzoumanian et al. 2011

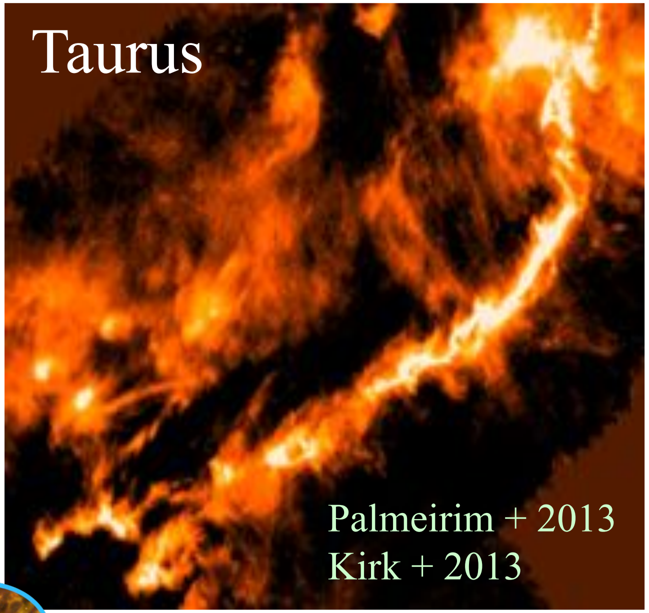
Herschel has revealed a “universal” filamentary structure in the cold ISM


Pipe

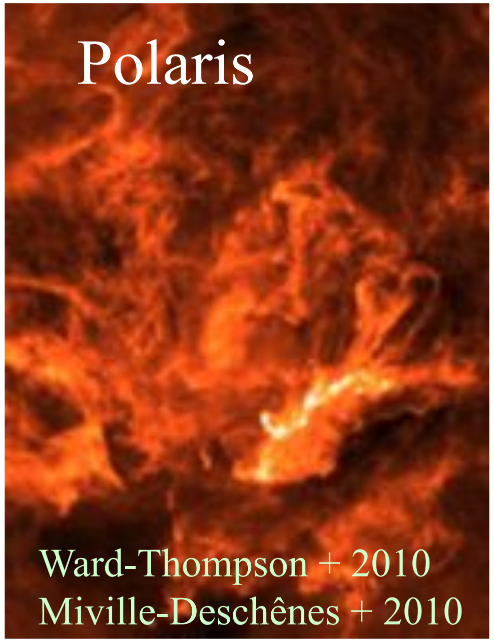
Peretto + 2012


IC5146

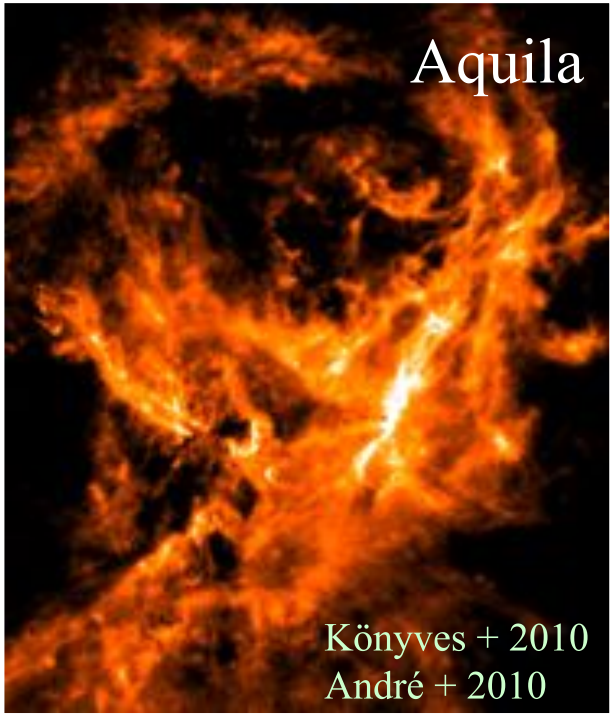
Arzoumanian + 2011


Taurus

Palmeirim + 2013
Kirk + 2013

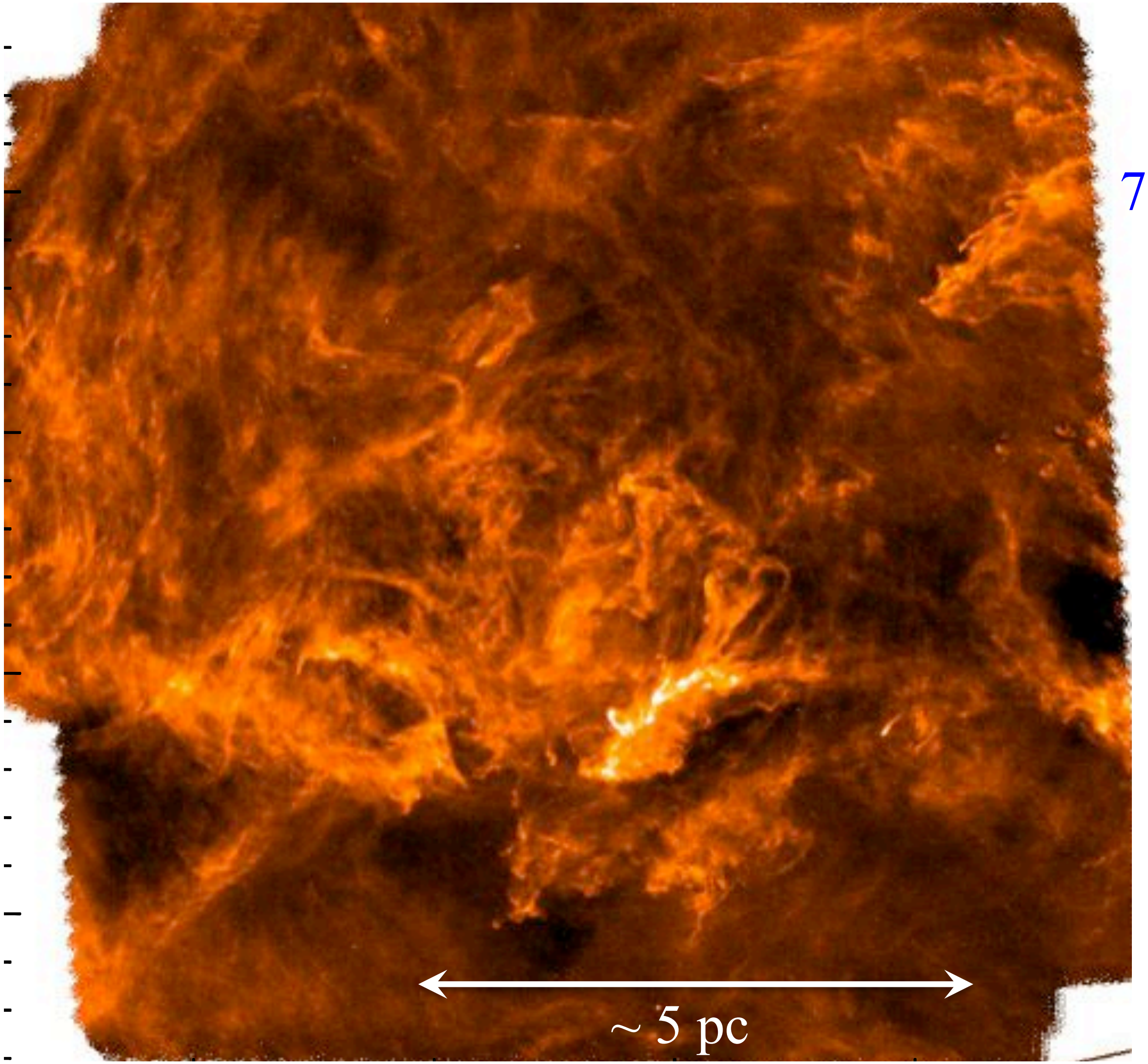

Polaris

Ward-Thompson + 2010
Miville-Deschênes + 2010


Aquila

Könyves + 2010
André + 2010

Structure of the cold ISM prior to star formation



Herschel/SPIRE 250 μm image

Gould Belt Survey
PACS/SPIRE // mode
70/160/250/350/500 μm

Polaris flare
translucent cloud:
non star forming

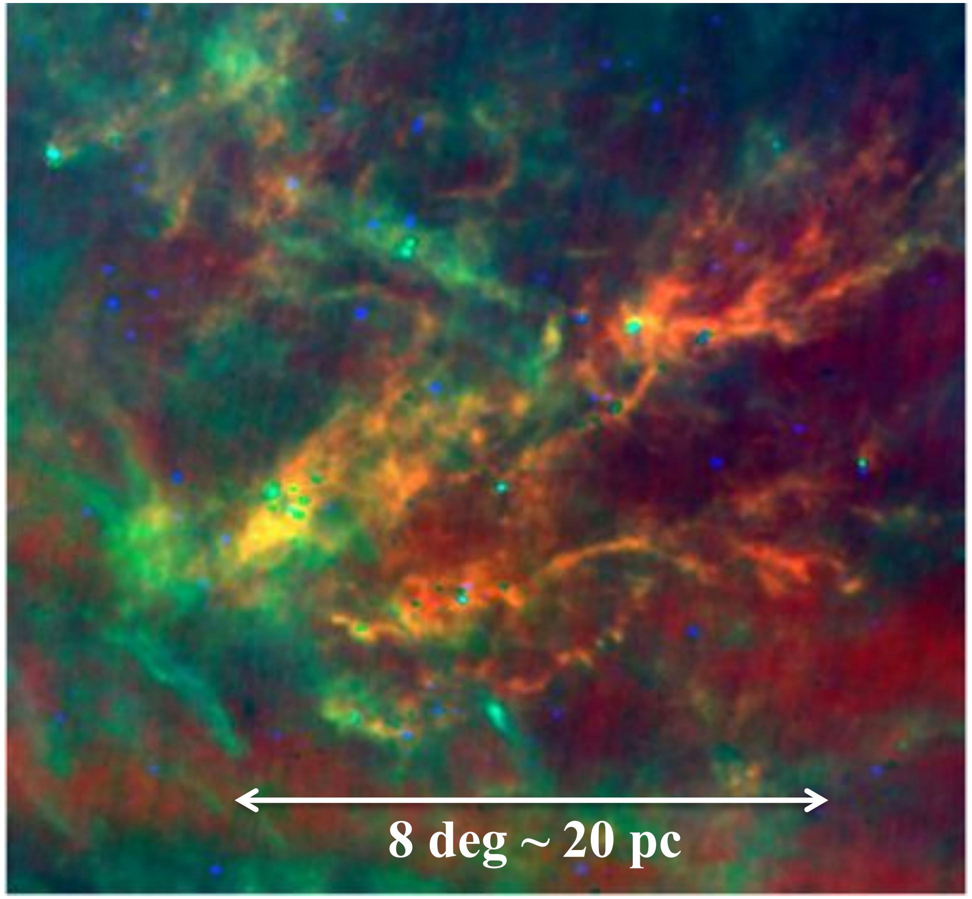
~ 5500 $M_\odot$ (CO+HI)
Heithausen & Thaddeus '90

~ 13 deg^2 field

Miville-Deschênes et al. 2010
Ward-Thompson et al. 2010
Men'shchikov et al. 2010
André et al. 2010

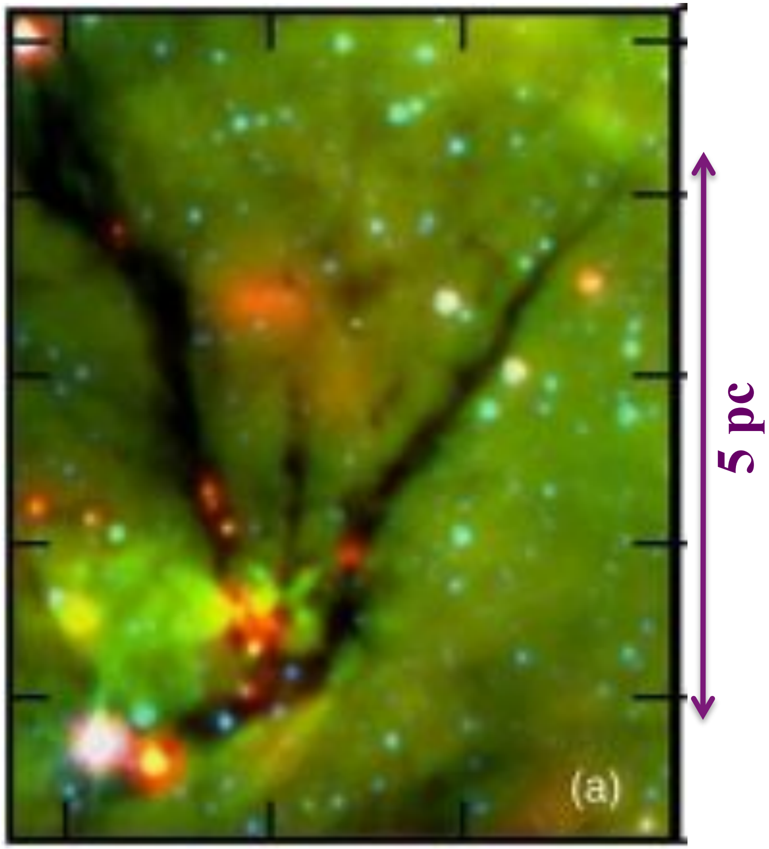
Evidence of the importance of filaments prior to *Herschel*

Taurus
***IRAS* (100-60/100/12 μm) composite**



Abergel, Boulanger et al. 1994, ApJ, 423, L59

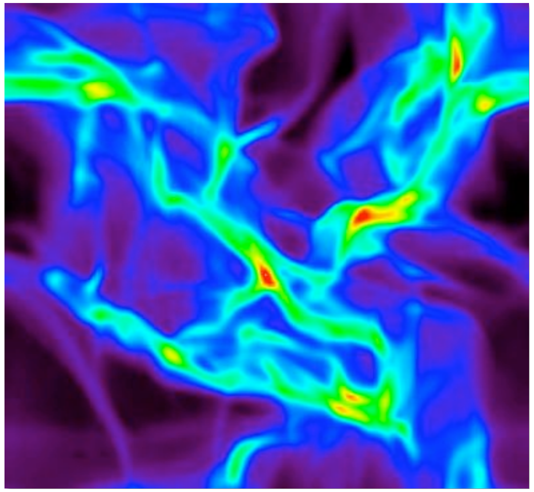
Infrared Dark Clouds
***Spitzer* (3.6/8/24 μm) composite**



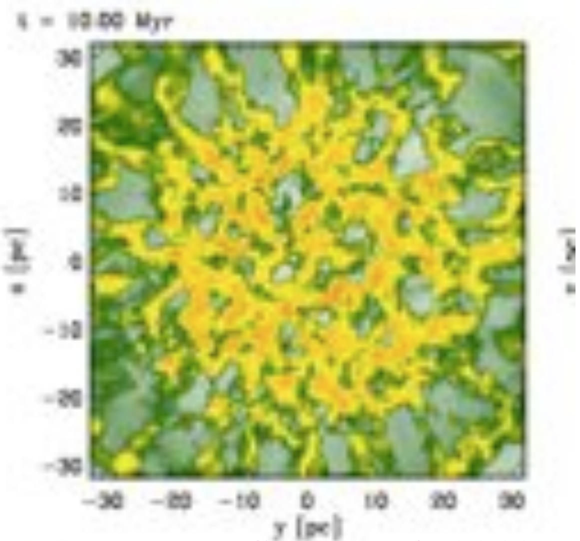
Peretto & Fuller 2009/10, ApJ, 723, 555

See also: Schneider & Elmegreen 1979, ApJS; Johnstone & Bally 1999, ApJ;
Hartmann 2002, ApJ; Hatchell et al. 2005, A&A; Goldsmith et al. 2008, ApJ; Myers 2009, ApJ …

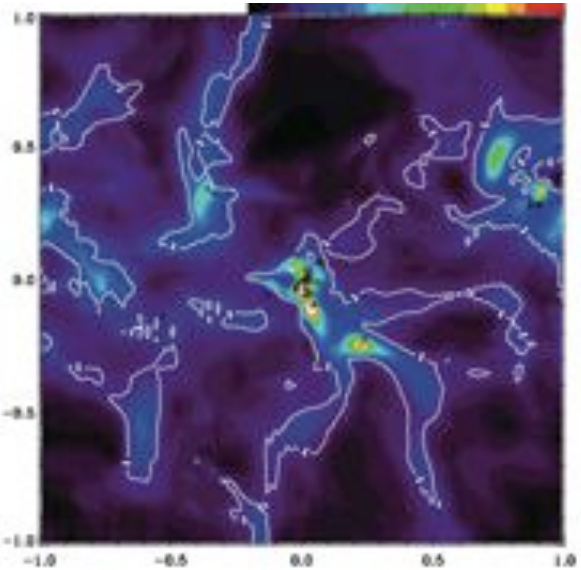
The observed filaments are reminiscent of those found in cloud simulations with large-scale turbulence



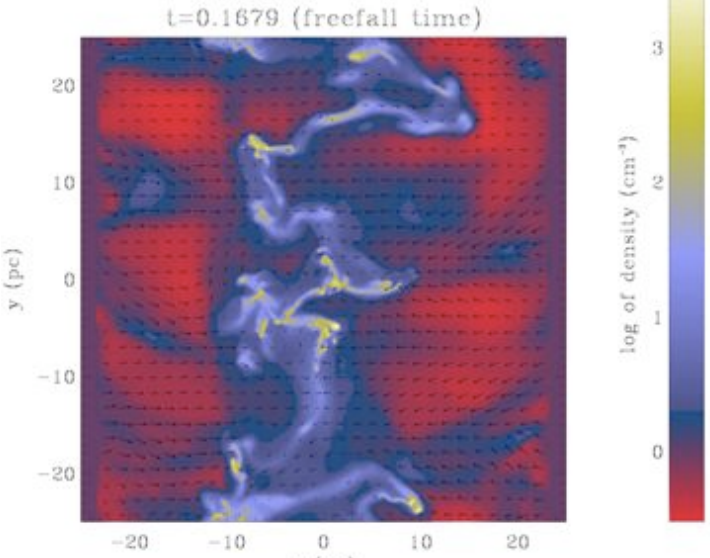
Padoan et al. 2001, ApJ, 553, 227



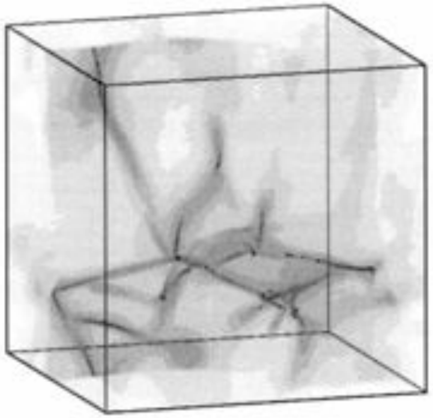
Vazquez-Semadeni+2011, MNRAS, 414, 2511



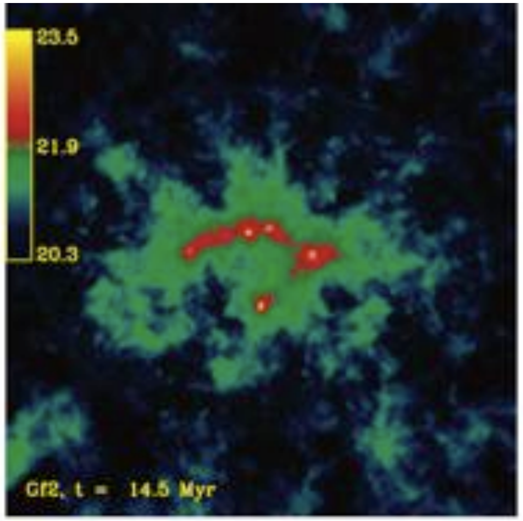
Nakamura & Li 2008, ApJ, 687, 354



Hennebelle et al. 2008, A&A, 486, L43



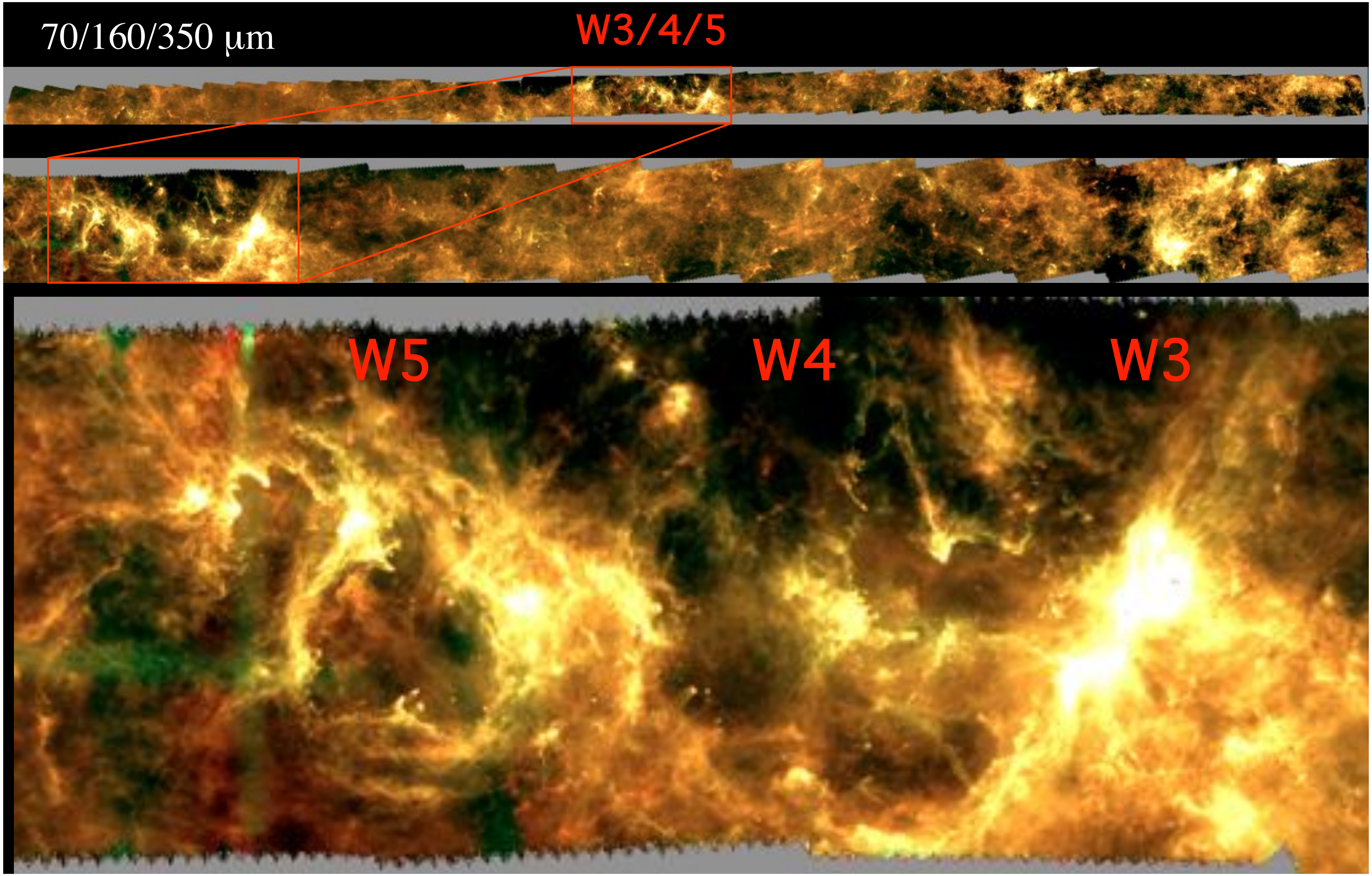
Klessen & Burkert 2000, ApJS, 128, 287



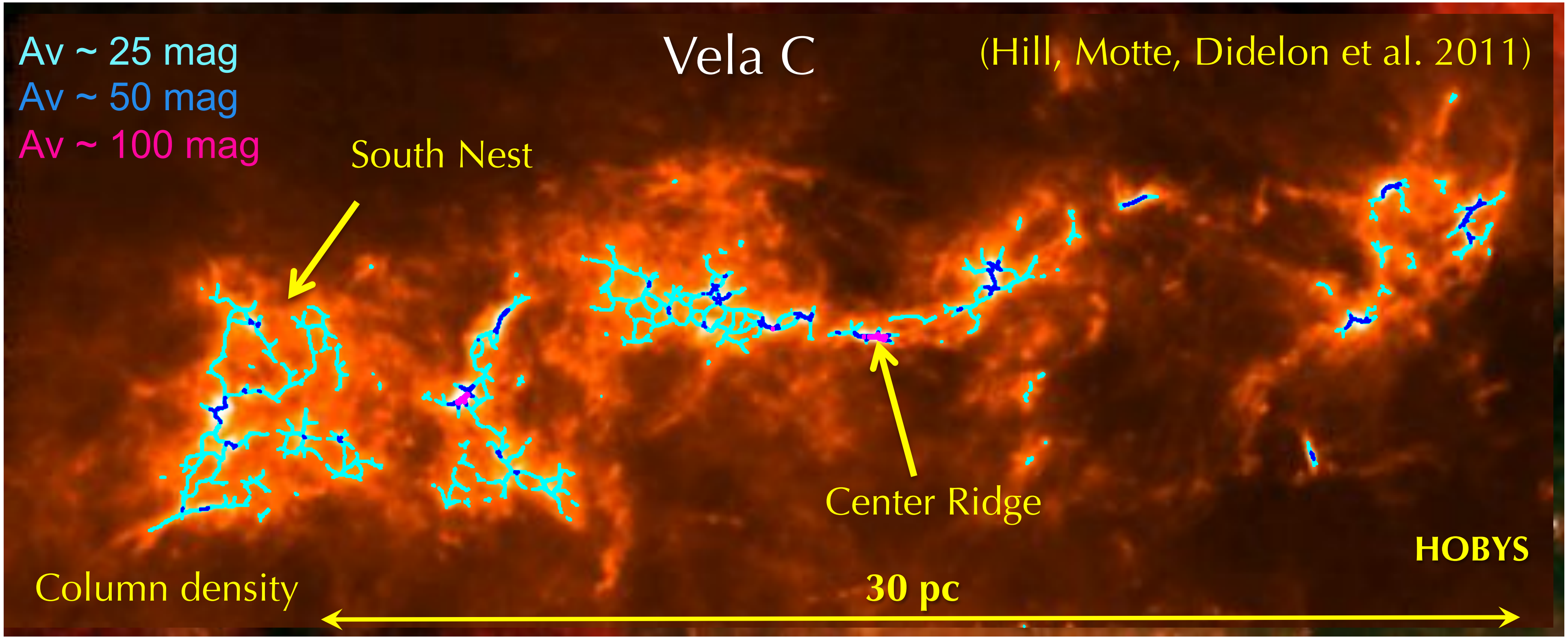
Heitsch et al. 2008, ApJ, 674, 316

Filaments are seen throughout the Galactic Plane

Herschel/HI-GAL image of part of the Milky Way (e.g. Molinari+2010, Schisano+2014)



Filamentary Networks: Organization



Tracing filamentary networks with the DisPerSE algorithm (Sousbie 2011, MNRAS, 414, 350)

Hill et al. 2011, A&A, 533, A94; Minier et al. 2013, A&A, 550, A50

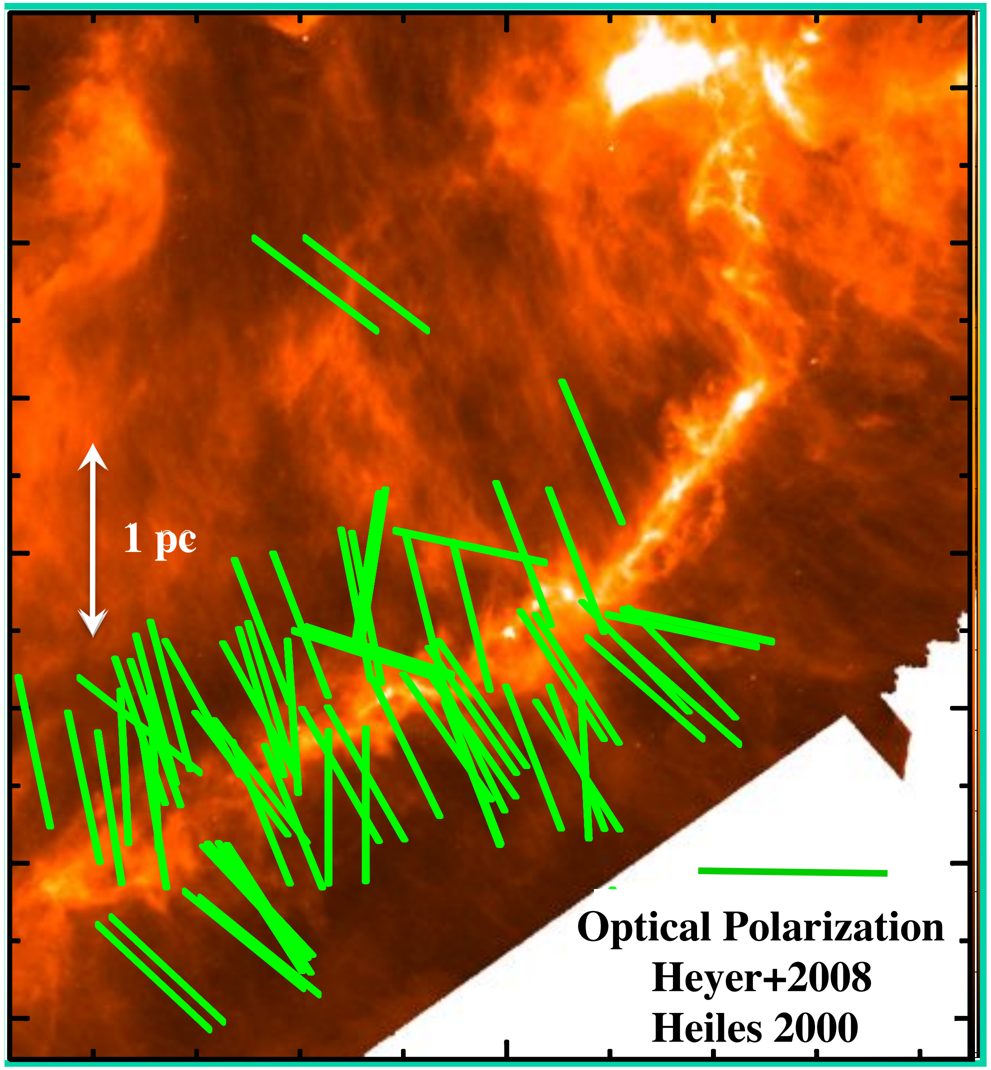
Disorganized networks ('nests') and dominating 'ridges'

- **Showing relative importance of turbulence vs. gravity (?)**

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

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

P. Palmeirim et al. 2013



Optical Polarization
Heyer+2008
Heiles 2000

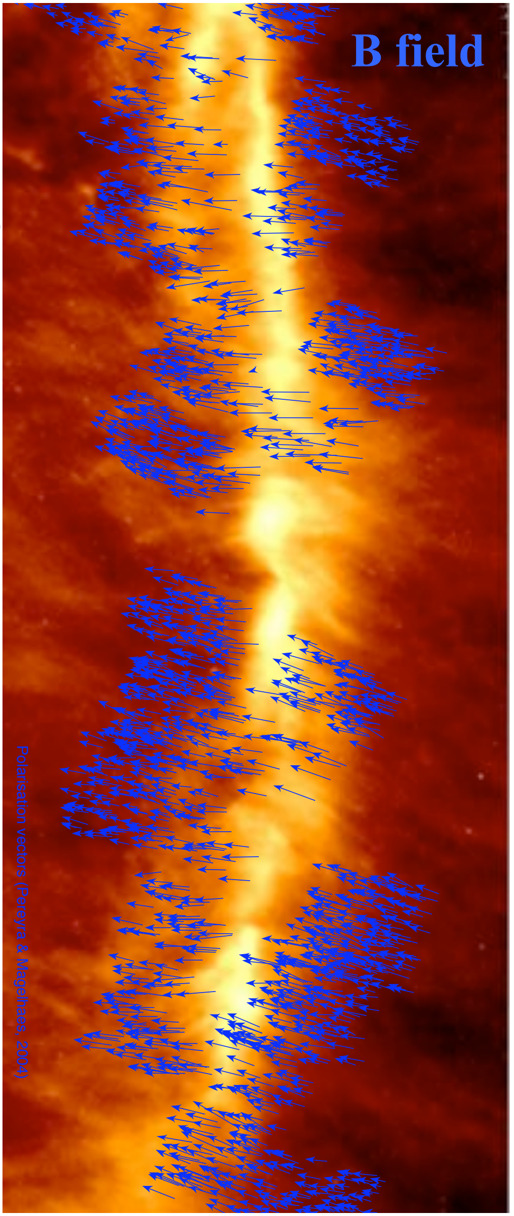
Musca filament:
M/L ~ 30 $M_\odot$/pc

N. Cox et al. in prep

HERSCHEL Gould Belt Survey

Optical polarization vectors overlaid on *Herschel* images

Pereyra & Magelhaes 2004



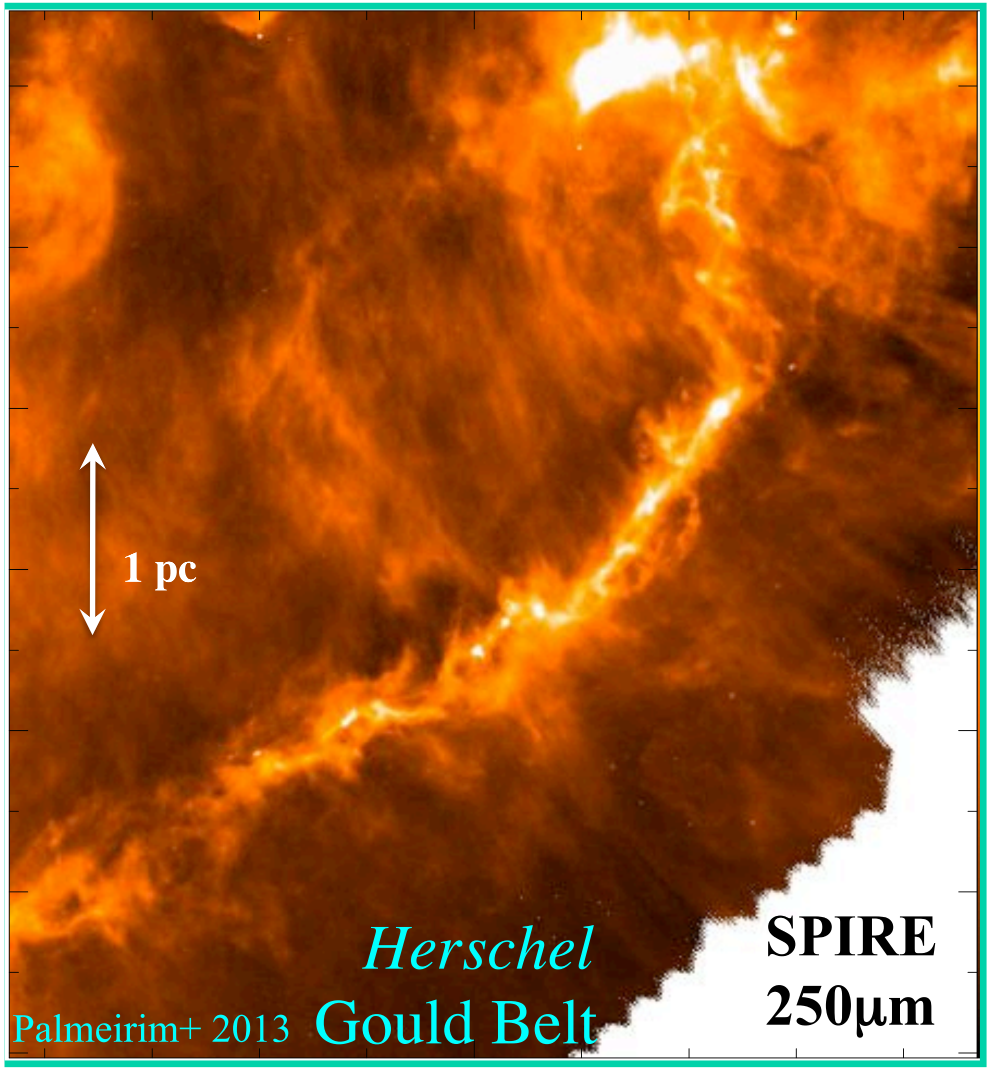
Very common pattern: main filament or “ridge” + network of perpendicular striations or “sub-filaments”

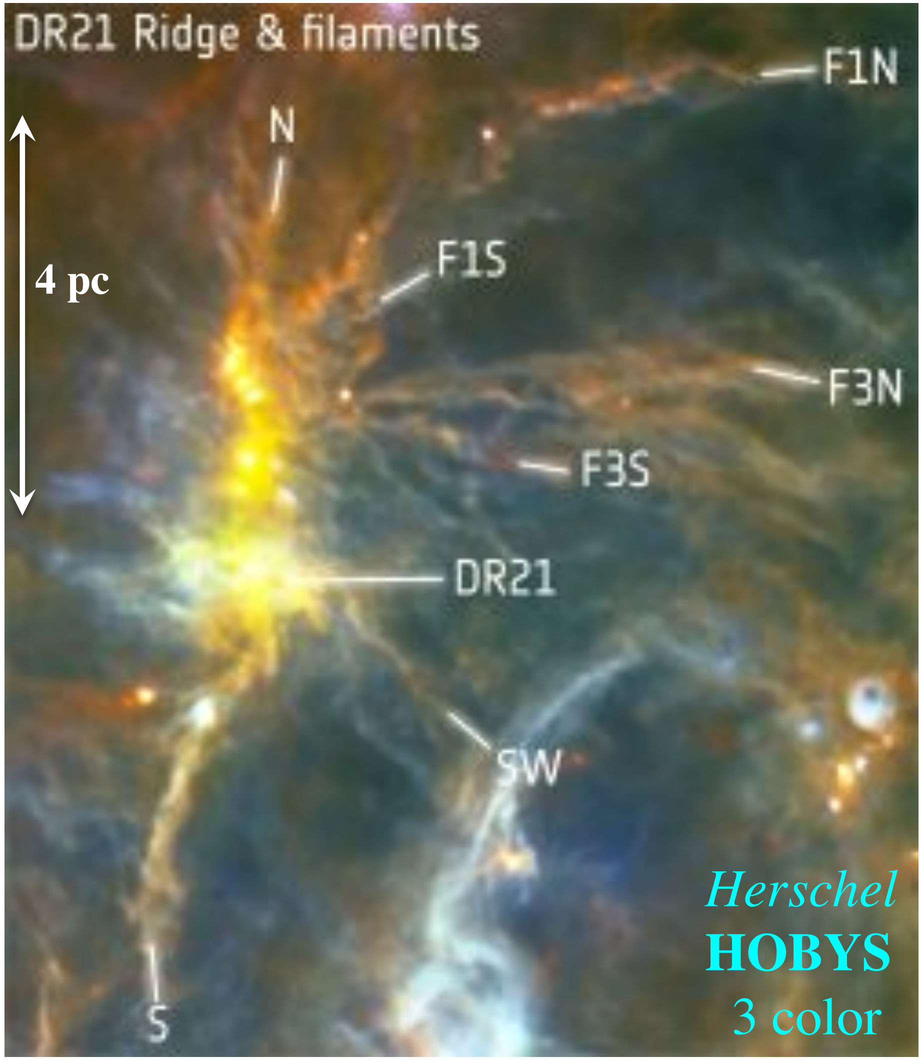
Taurus B211/3 filament:
M/L ~ 50 $M_\odot$/pc

- ➢ Suggestive of accretion flows into the main filaments

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

Hennemann, Motte et al. 2012

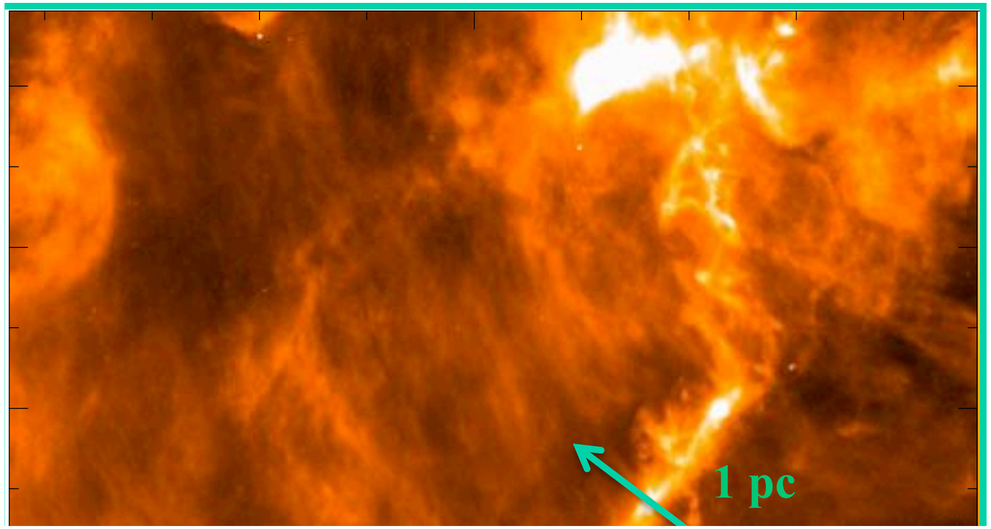


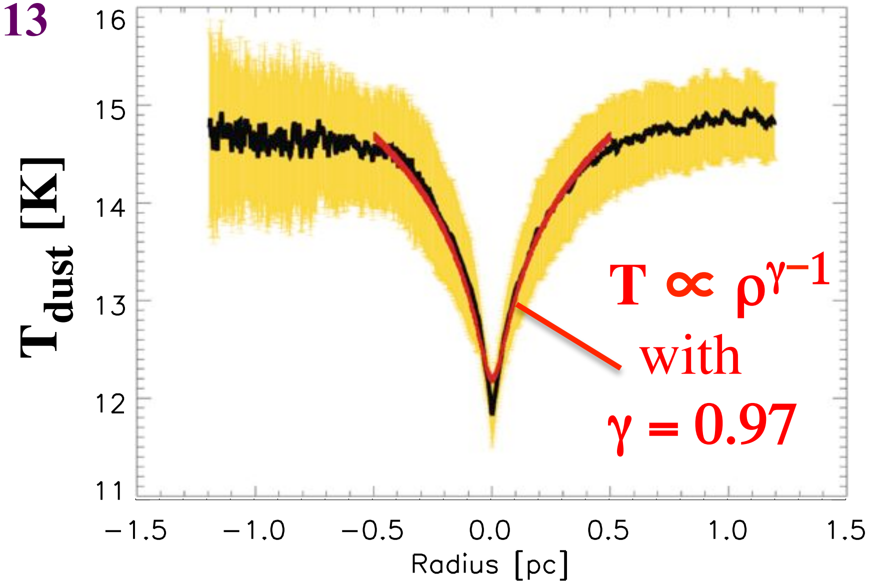


Characterizing the structure of filaments with *Herschel*

Palmeirim et al. 2013

Taurus B211/3 filament
SPIRE 250µm



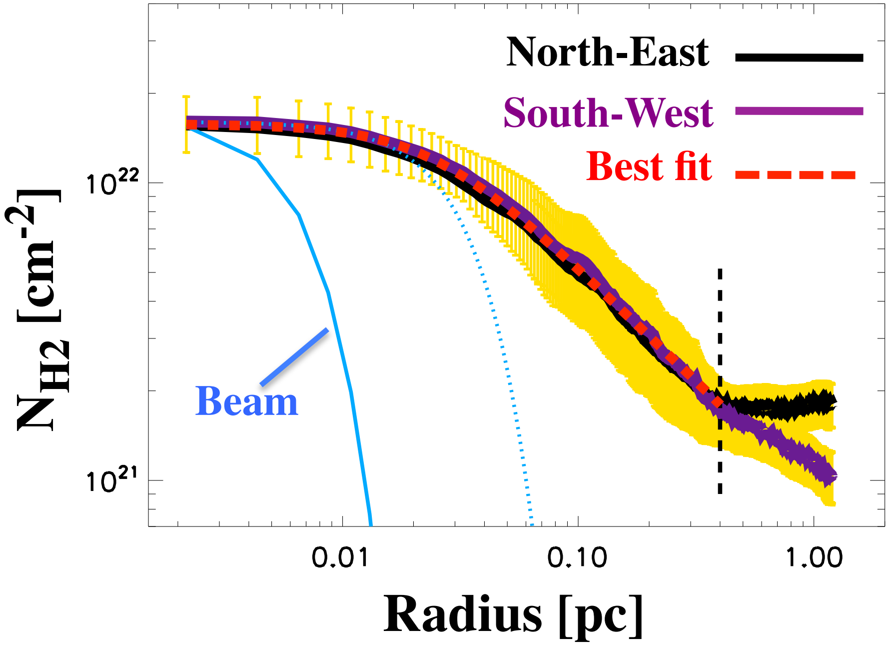


Plummer-like density profile:

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

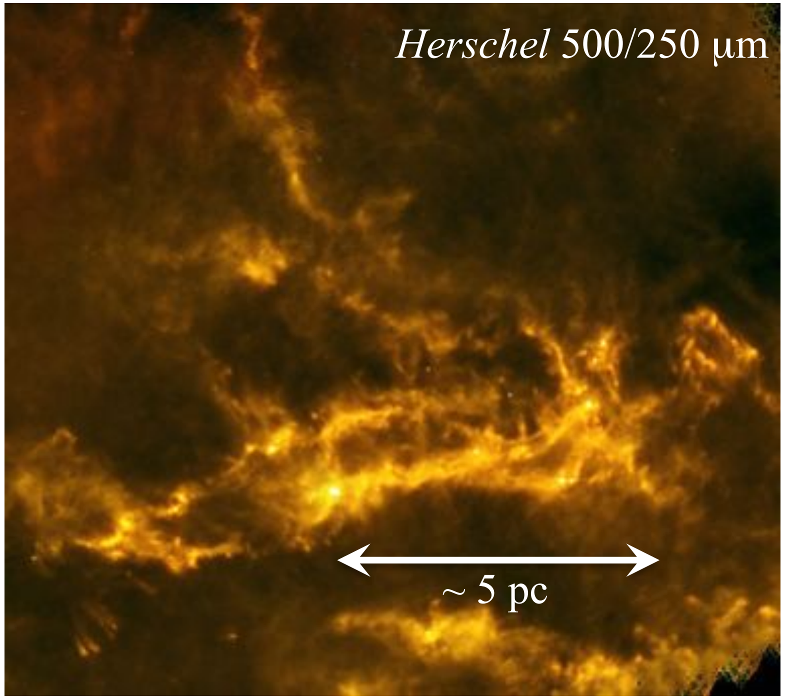
with $R_{flat} \sim 0.05$ pc

Diameter of flat inner plateau ~ 0.1 pc

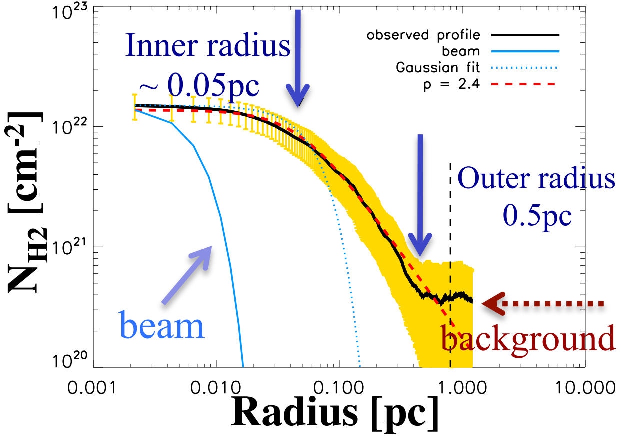


Filaments have a characteristic inner width ~ 0.1 pc

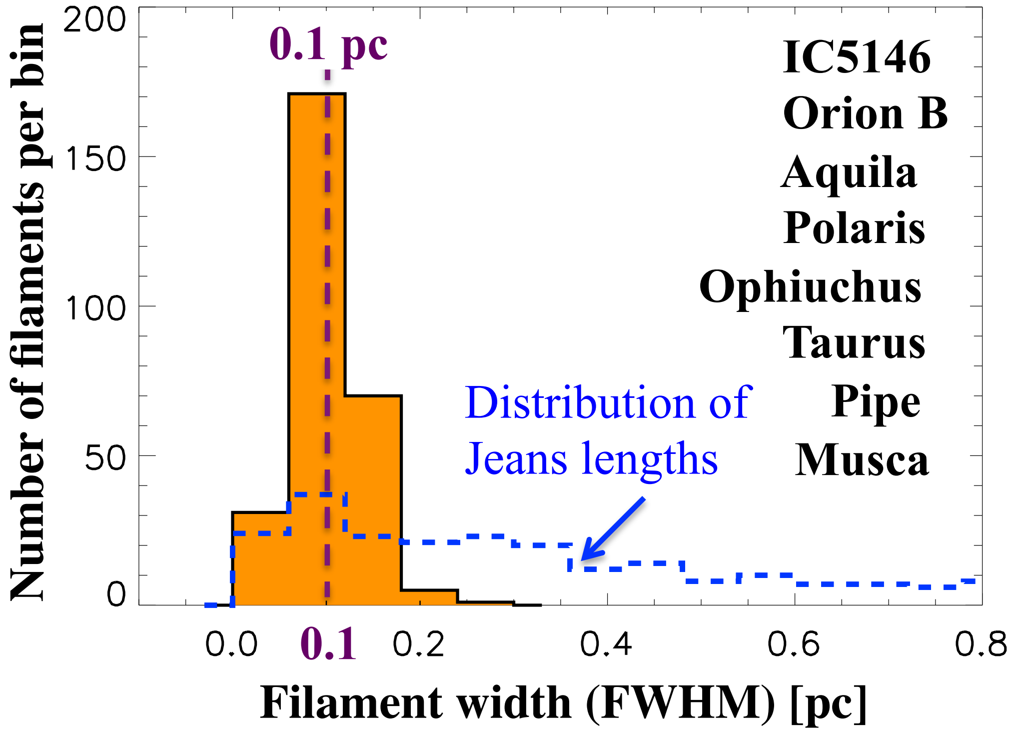
Network of filaments in IC5146



Example of a filament radial profile



Statistical distribution of widths for > 270 nearby filaments (d< 450 pc)



D. Arzoumanian et al. 2011 + PhD thesis

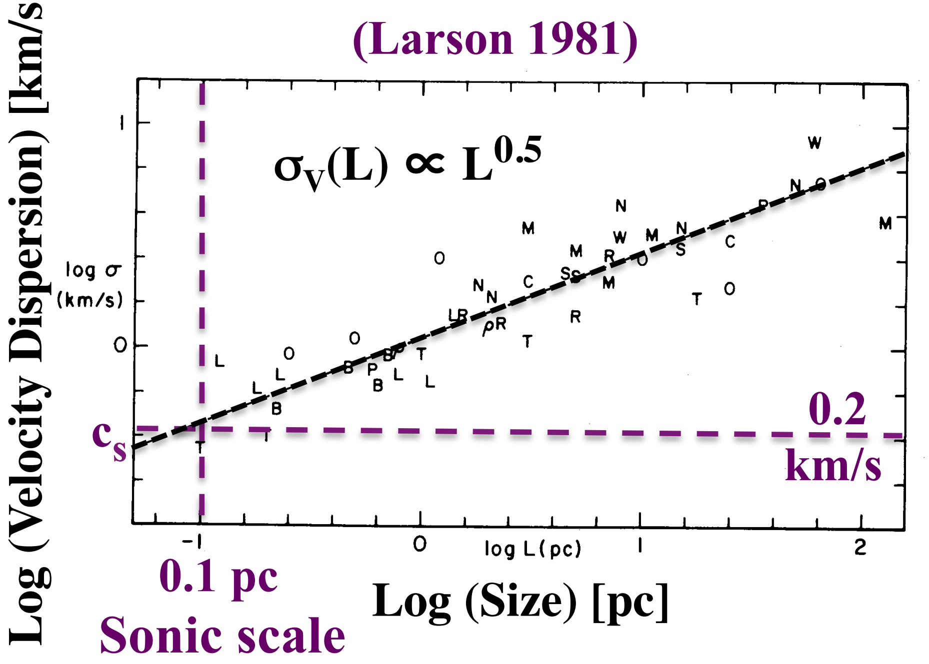
- **Strong constraint on the formation and evolution of filaments**

Filaments due to large-scale supersonic turbulence ?

Filament width ~ 0.1 pc: ~ sonic scale of interstellar turbulence ?

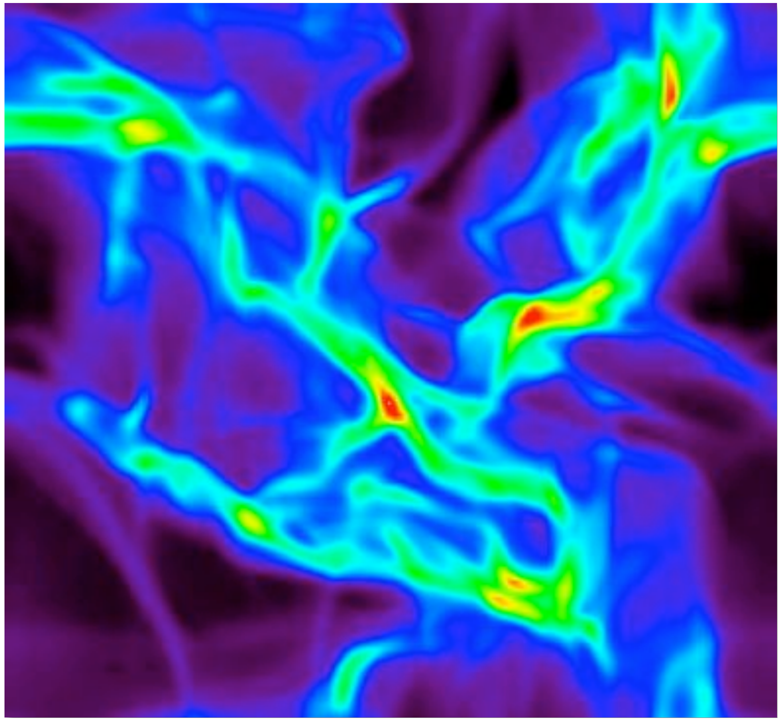
Linewidth-Size relation in clouds

(Larson 1981)



- **Corresponds to the typical thickness expected for shock-compressed layers in HD**

Simulations of turbulent fragmentation

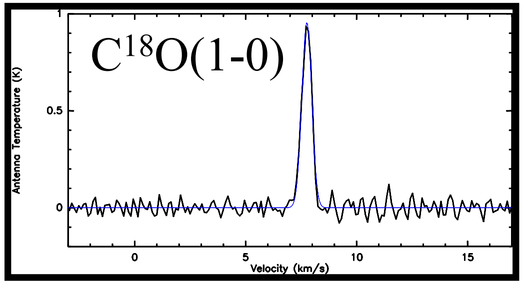


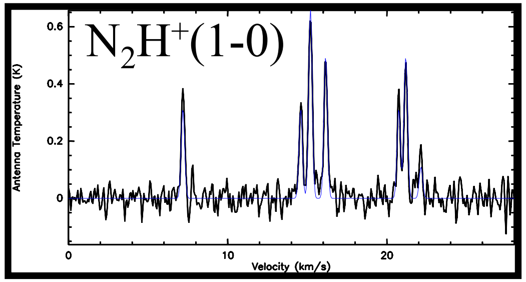
Padoan, Juvela et al. 2001

- **Filaments from a combination of MHD turbulent compression *and* shear; width set by the dissipation scale of MHD waves ? (Hennebelle 2013)**

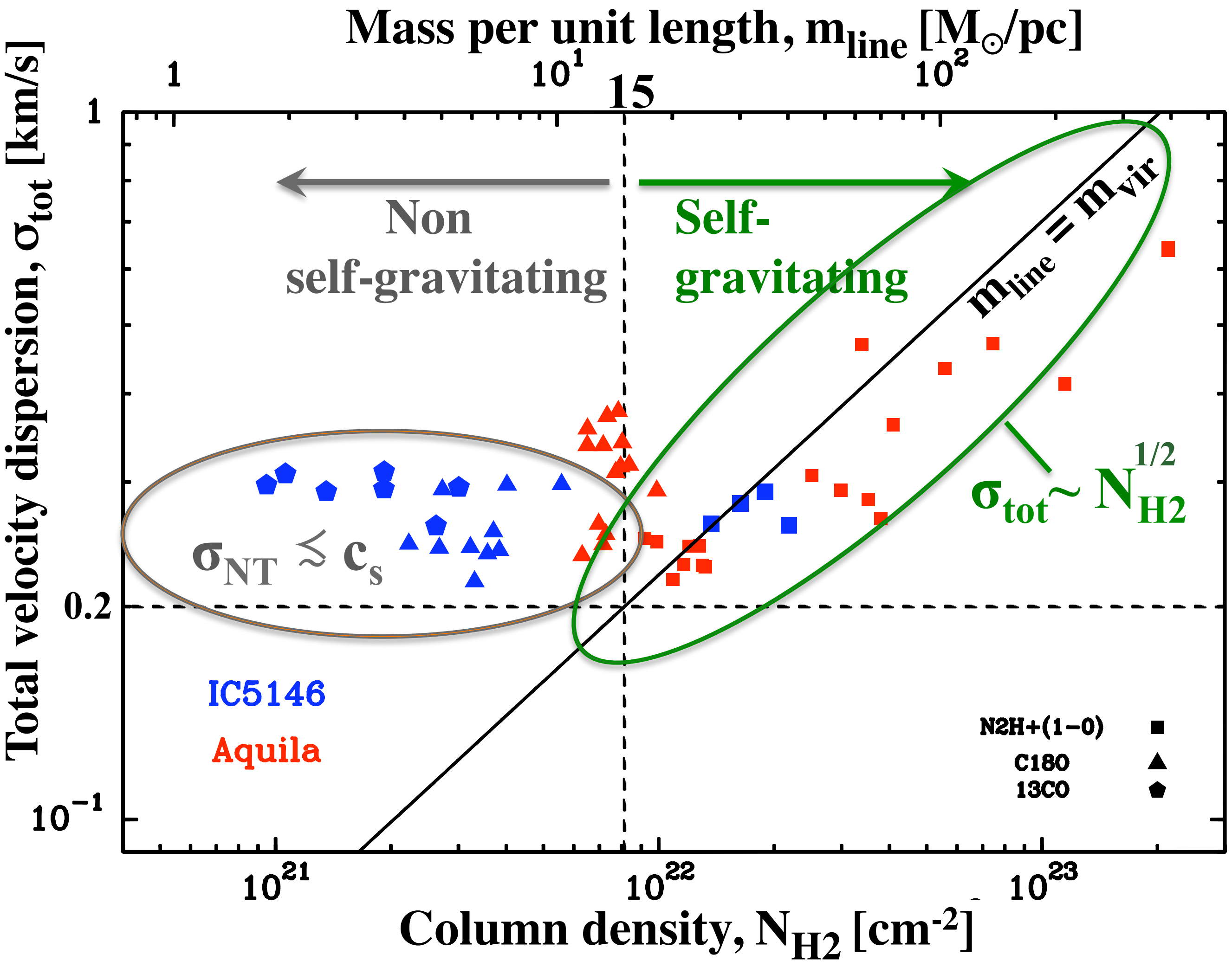
Velocity dispersion of filaments vs. column density

IRAM 30m $C^{18}O$, N_2H^+ observations





Arzoumanian et al. 2013



Low-density filaments have subsonic levels of internal turbulence: $\sigma_{turb} < c_s$ (Hacar & Tafalla 2011; Arzoumanian et al. 2013)

Dense cores form primarily in filaments

Morphological Component Analysis:

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

***Herschel* Column density map**

=

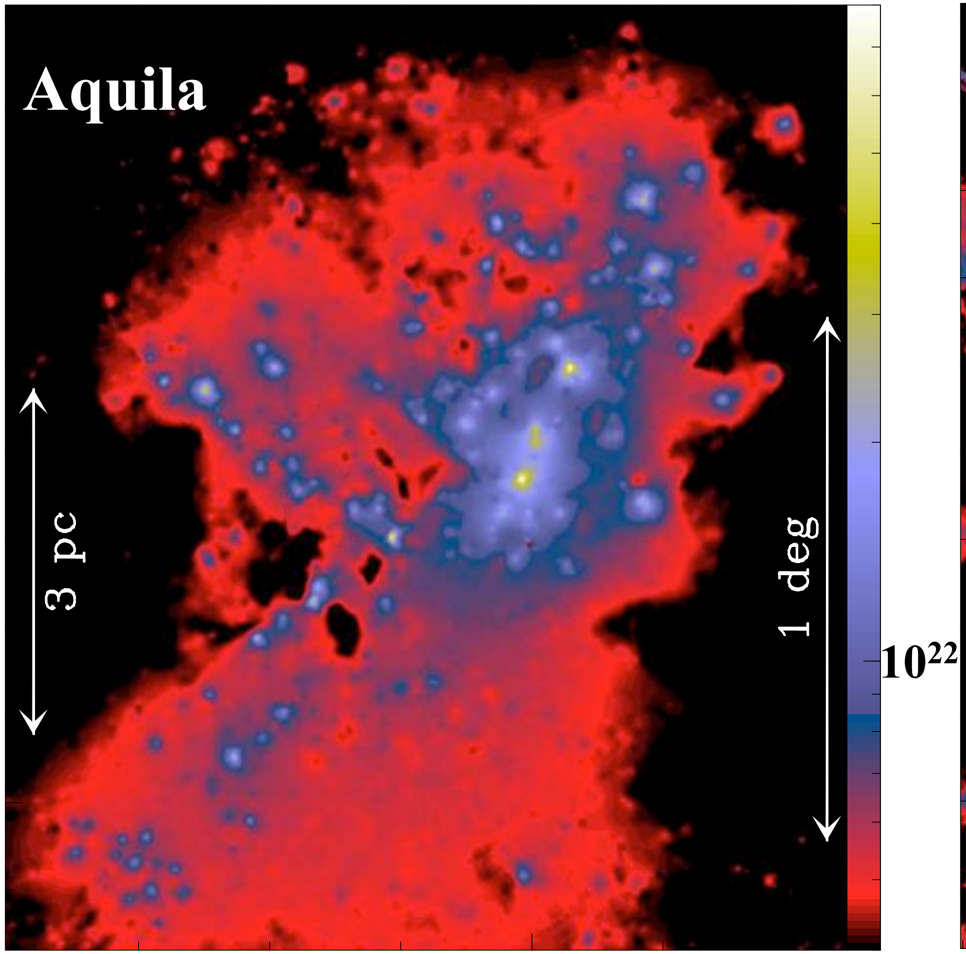
Cores

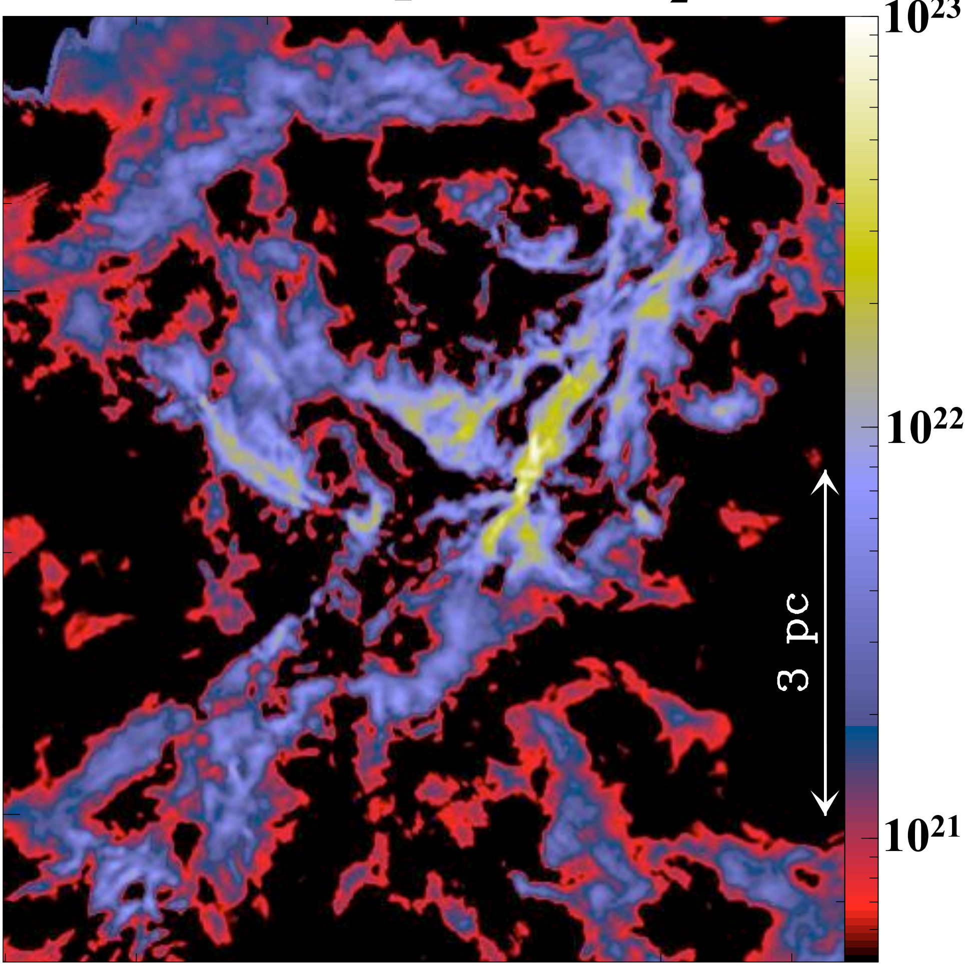
Wavelet component (H_2/cm^2)

+

Filaments

Curvelet component (H_2/cm^2)



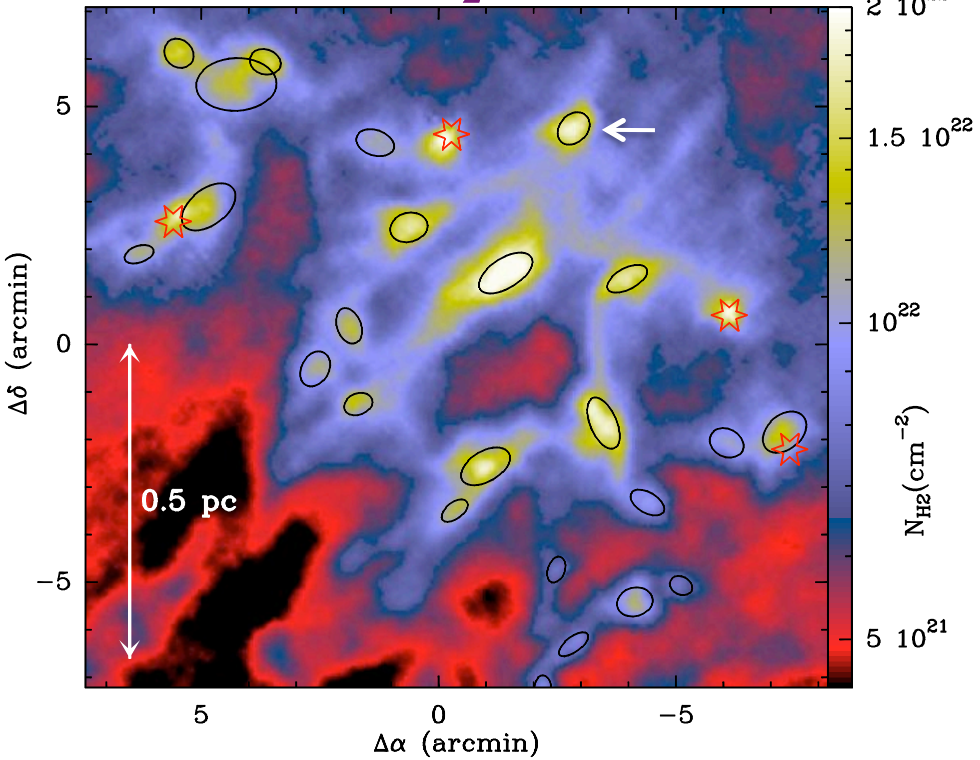


Examples of *Herschel* prestellar cores in Aquila

- **Core = single star-forming entity**
  (Need to resolve ~ 0.01-0.1 pc)
- **Starless = no central proto★**
- **Prestellar = bound & starless**

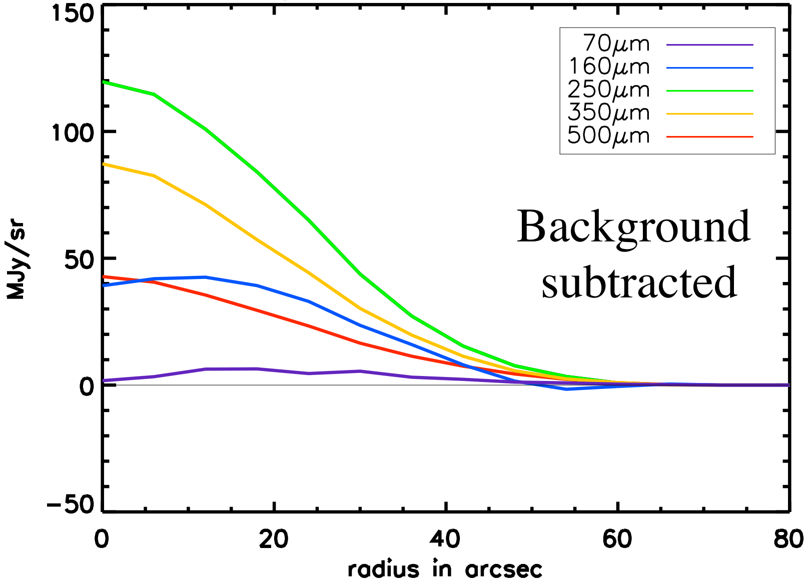
[For definitions, see:
Di Francesco et al. 2007, PPV
Ward-Thompson et al. 2007, PPV
André+2000, Williams+ 2000, PPIV]

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



Könyves et al. 2010

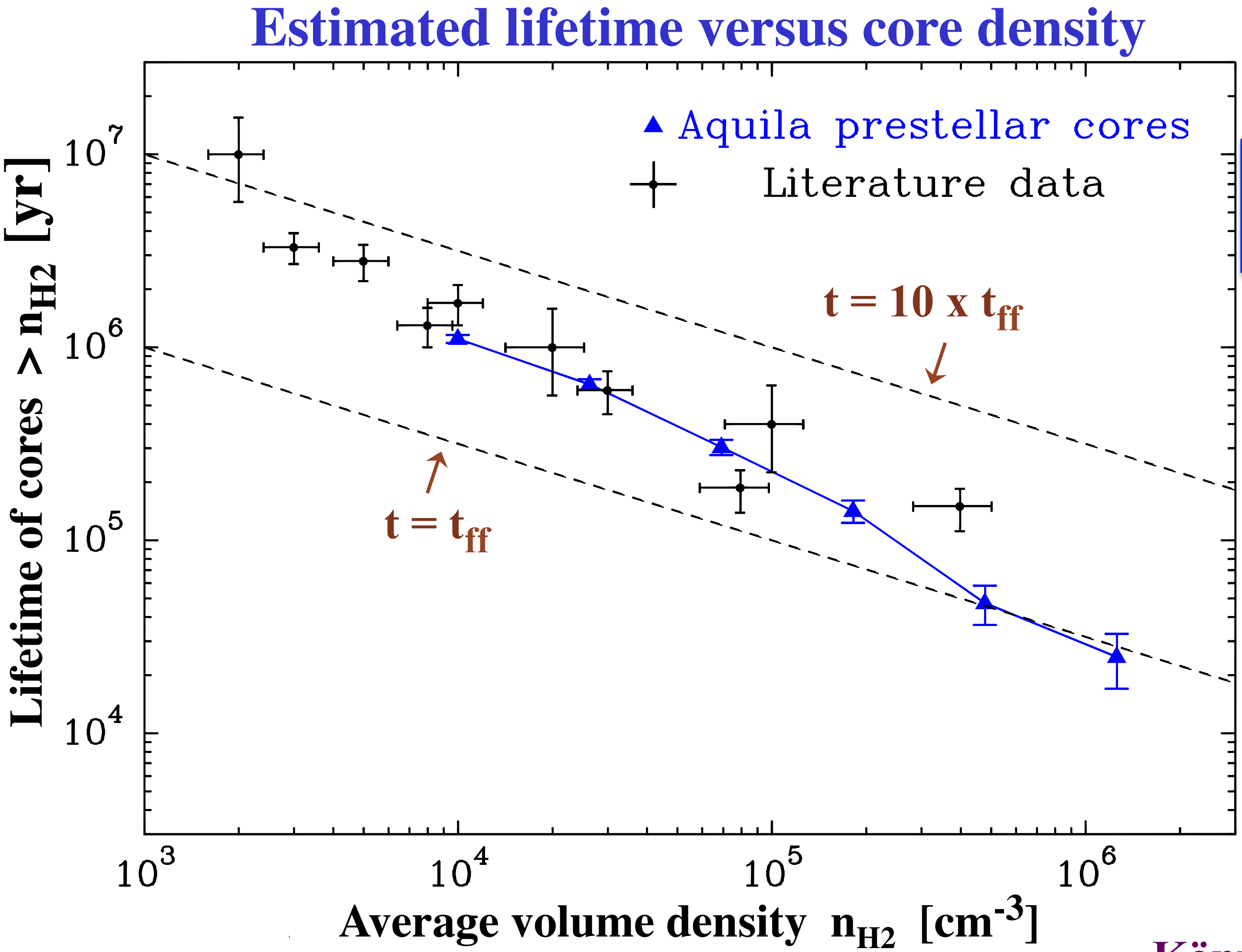
Radial intensity profiles



Background subtracted

Ellipses: FWHM sizes of cores extracted with getsources (Men'shchikov et al. 2012)

Estimates of prestellar core lifetimes in Aquila



~ 450 *Herschel* prestellar cores

t_{pre}= 1+-0.3 Myr
~ 3-4 t_{ff}

~ 200 *Herschel* Class0/ClassI protostars
(t ~ 0.5 Myr)

~ 800 *Spitzer* ClassII YSOs
[Dunham+2013]
(t ~ 2 Myr)

Könyves et al. in prep.

cf. Lee & Myers 1999
Ward-Thompson et al. 2007 PPV (literature data)

The prestellar CMF is very similar in shape to the IMF

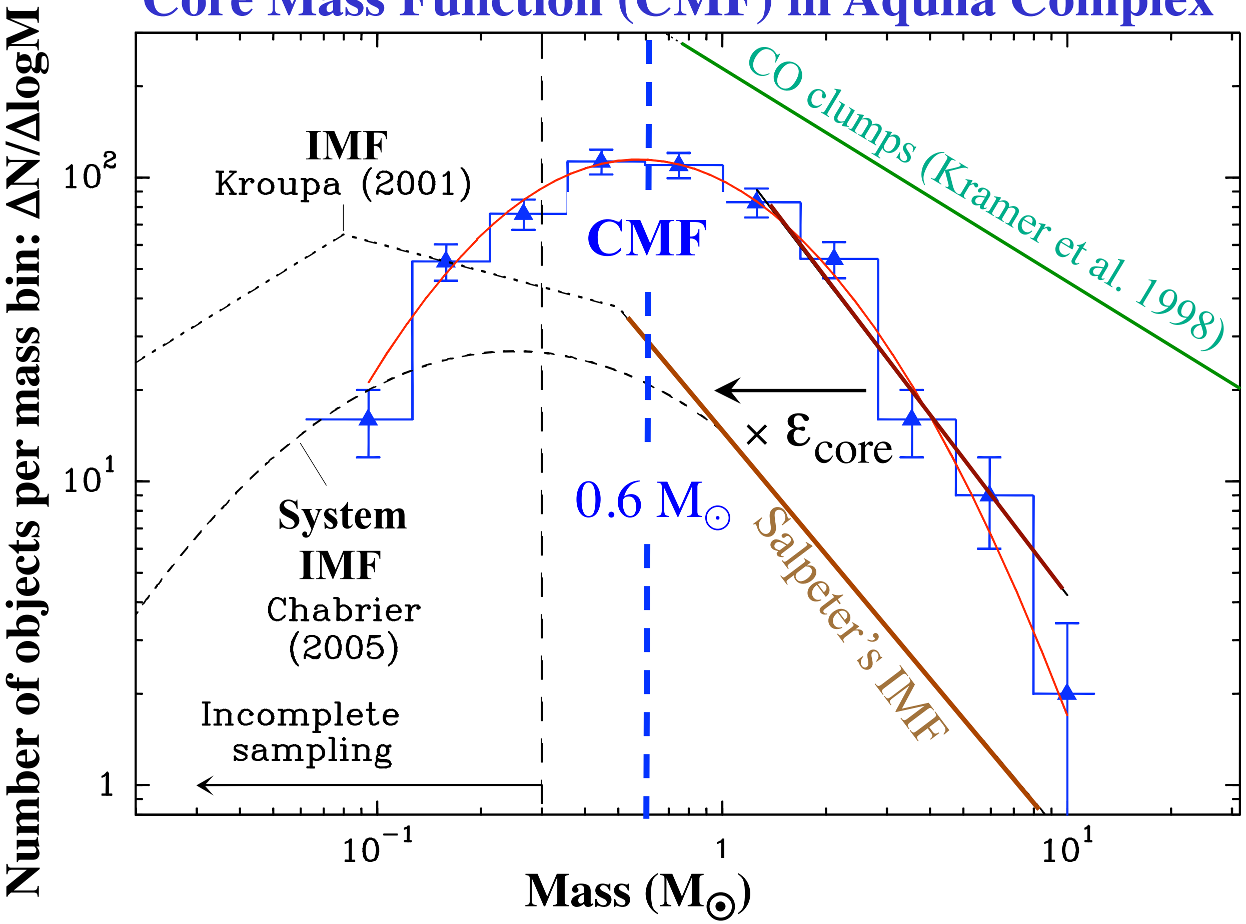
Könyves et al. 2010
André et al. 2010

~ 450 prestellar cores in Aquila

Factor ~ 2-9 better statistics than earlier CMF studies

(e.g Motte et al. 1998; Alves et al. 2007)

Core Mass Function (CMF) in Aquila Complex



- **Good (~ one-to-one) mapping between core mass and stellar system mass: $M_* = \varepsilon_{core} M_{core}$ with $\varepsilon_{core} \sim 0.3$ in Aquila**
- **Supports cloud fragmentation models of the IMF**

(cf. Padoan & Nordlund 2002; Hennebelle & Chabrier 2008)

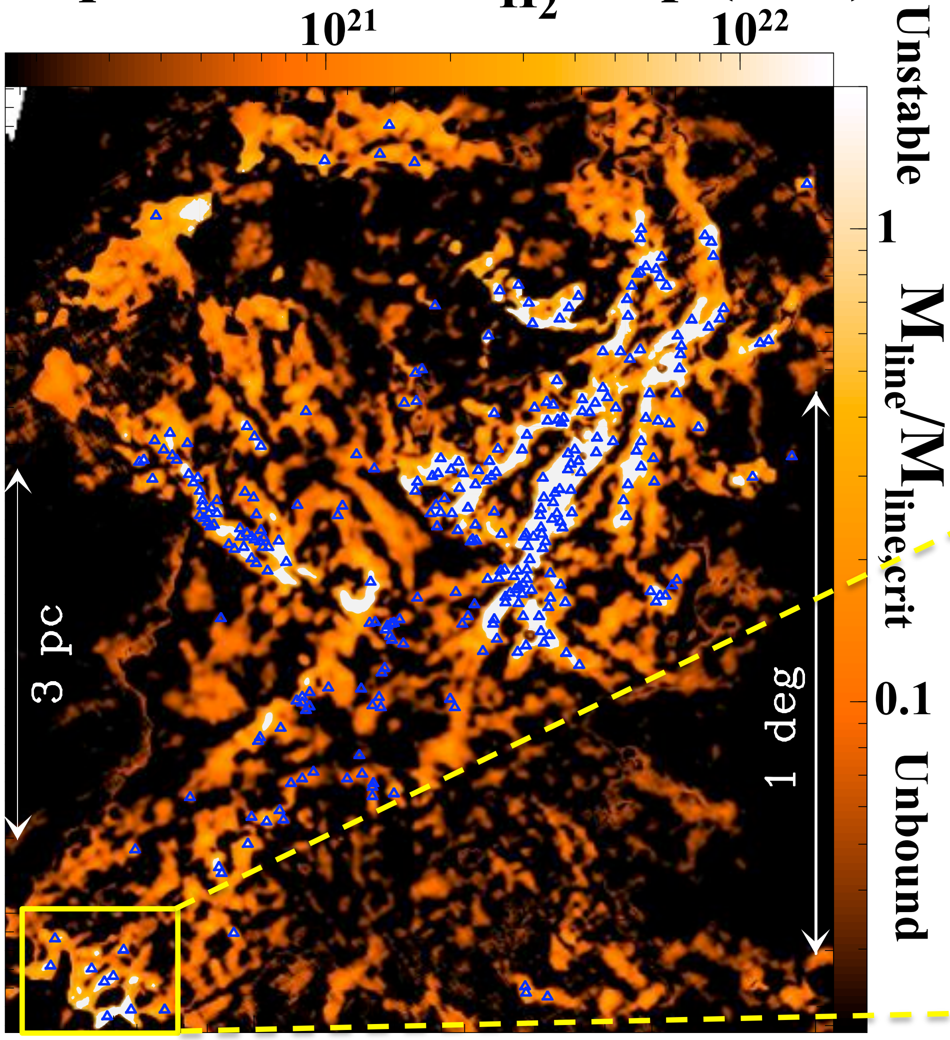
~ 75^{+15}_{-5} % of prestellar cores form in filaments, above a column density threshold $N_{H_2} \gtrsim 7\mathrm{x}10^{21}$ cm^{-2}

<=>

$A_V \gtrsim 7$

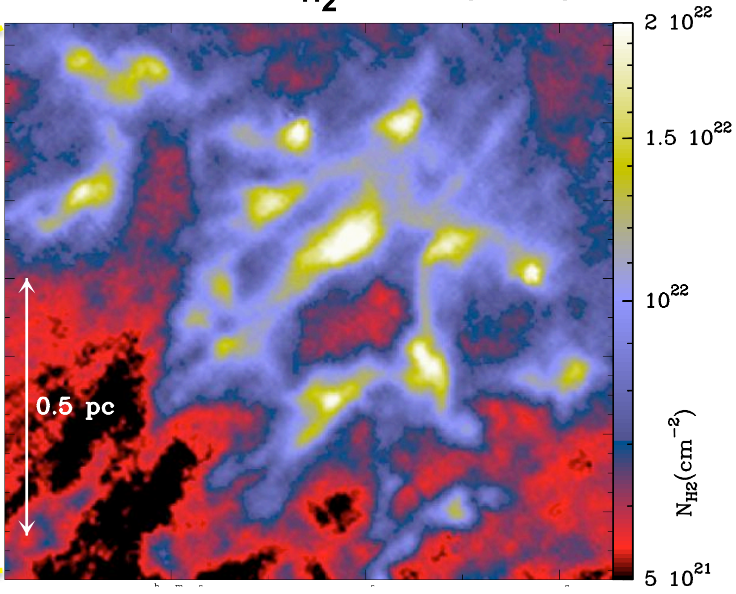
$\Sigma_{\rm threshold} \sim 150\ M_{\odot}/\mathrm{pc}^2$

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



Examples of *Herschel* prestellar cores (△)

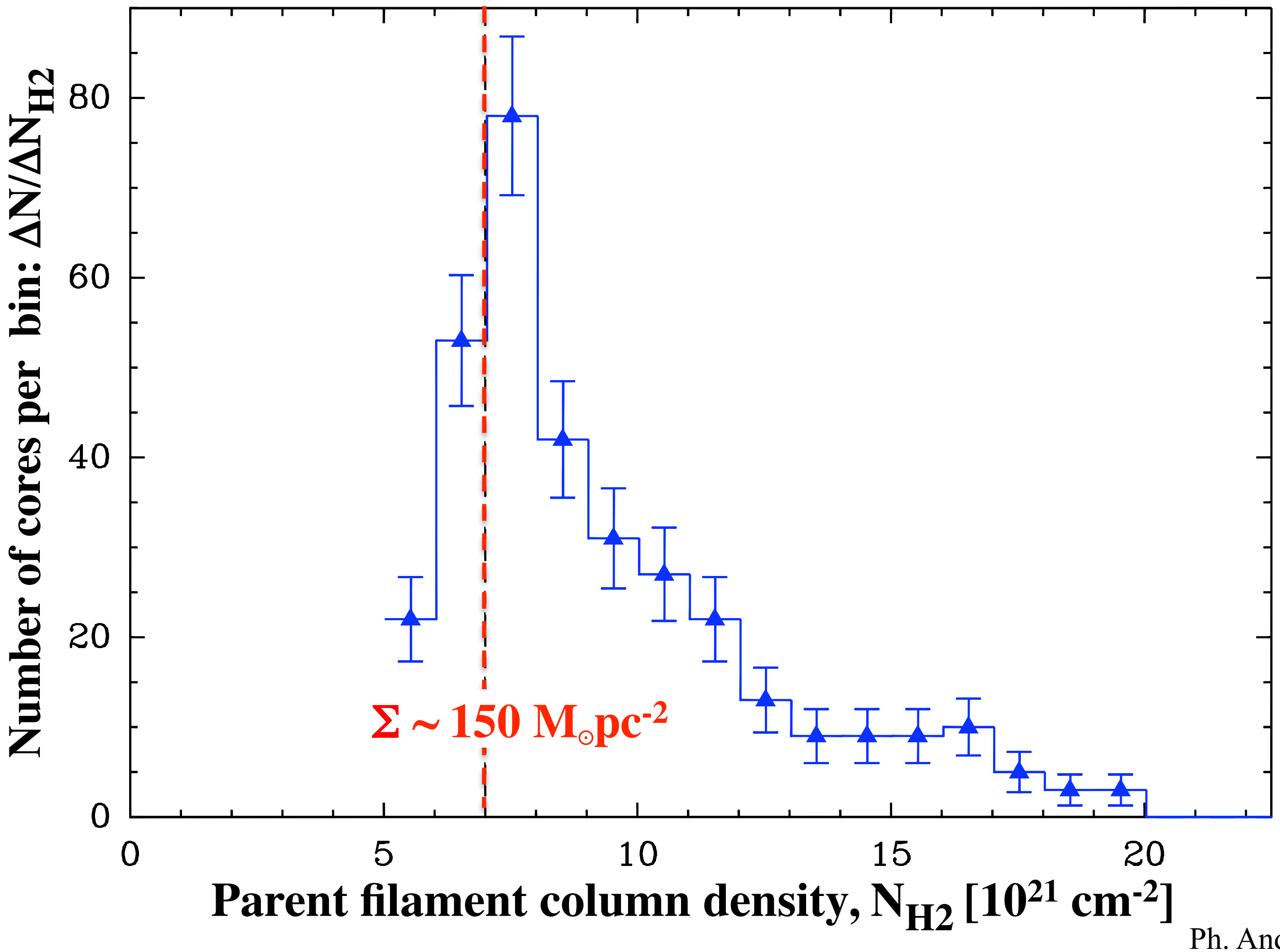
Blow-up N_{H_2} map (cm^{-2})



André et al. 2010, Könyves et al. 2010 + in prep

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 $A_v \sim 7$ ⇔ $\Sigma \sim 150\ M_{\odot}\ pc^{-2}$

Könyves etal. in prep

André+2014 PPVI

See also:

Onishi+1998

Johnstone+2004

Gravitational instability of ~ isothermal filaments

- ➢ **Controlled by the mass per unit length $M_{line} = M/L$**

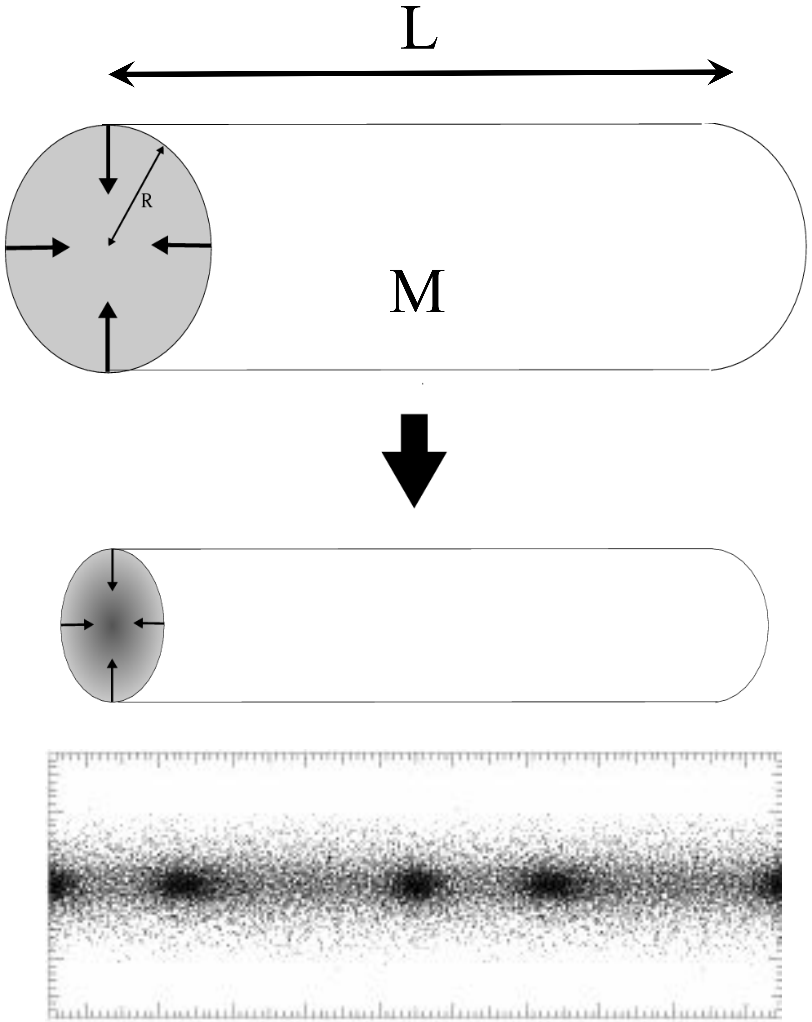
- ➢ **Filaments are expected to be:**

- **gravitationally unstable** (radial collapse + fragmentation) if $\boxed{M_{line} > M_{line,\,crit}}$ (Inutsuka & Miyama 1992-97)

- **unbound** (→ expansion or pressure confinement) if $\boxed{M_{line} < M_{line,\,crit}}$ (Fischera & Martin 2012)

- **hydrostatic equilibrium for** $M_{line,\,crit} = 2\, c_s^2/G \sim 16\ M_\odot/\mathrm{pc}$ at $T \sim 10$ K (Ostriker 1964)

Cylindrical approximation

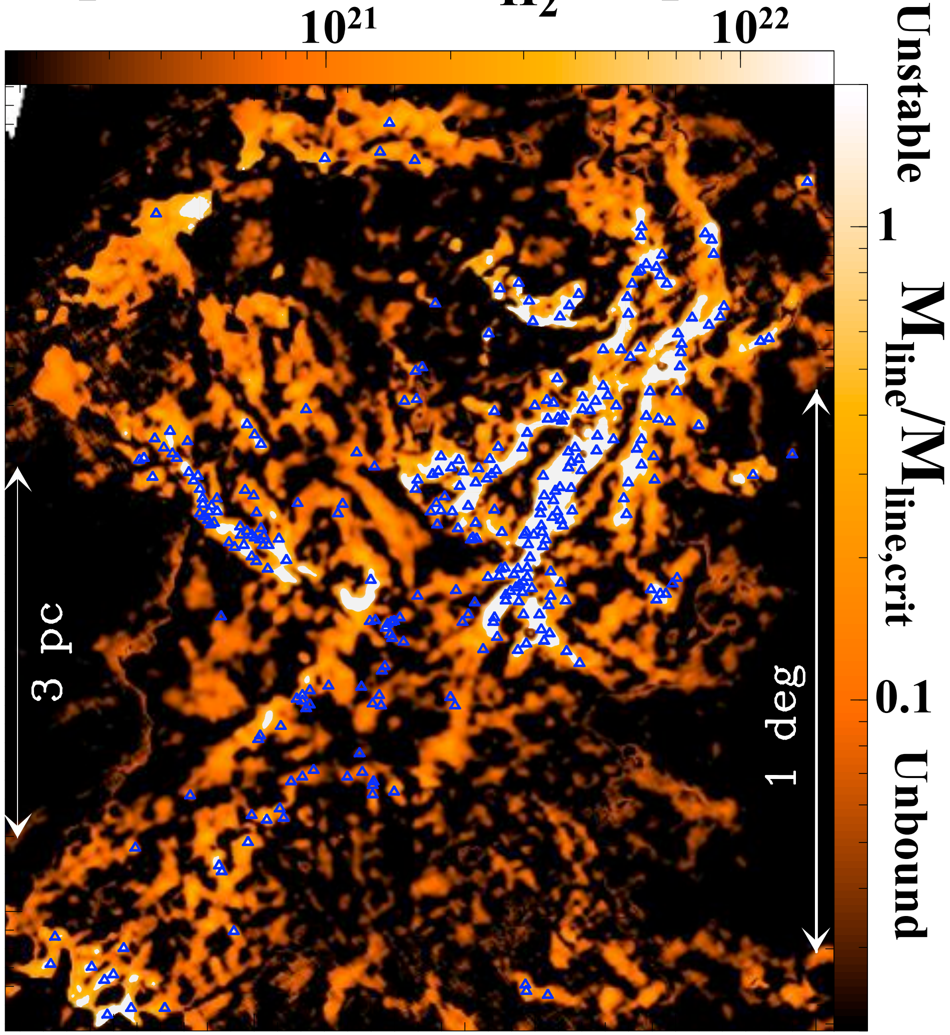


Inutsuka & Miyama 1992/97

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

△ : Prestellar cores

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



André et al. 2010, A&A, 518, L102

➢ Filaments are expected to be:

- gravitationally 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 $M_\odot/pc^2$

⇔ ρ threshold ~ 1600 $M_\odot/pc^3$

➢ Simple estimate:

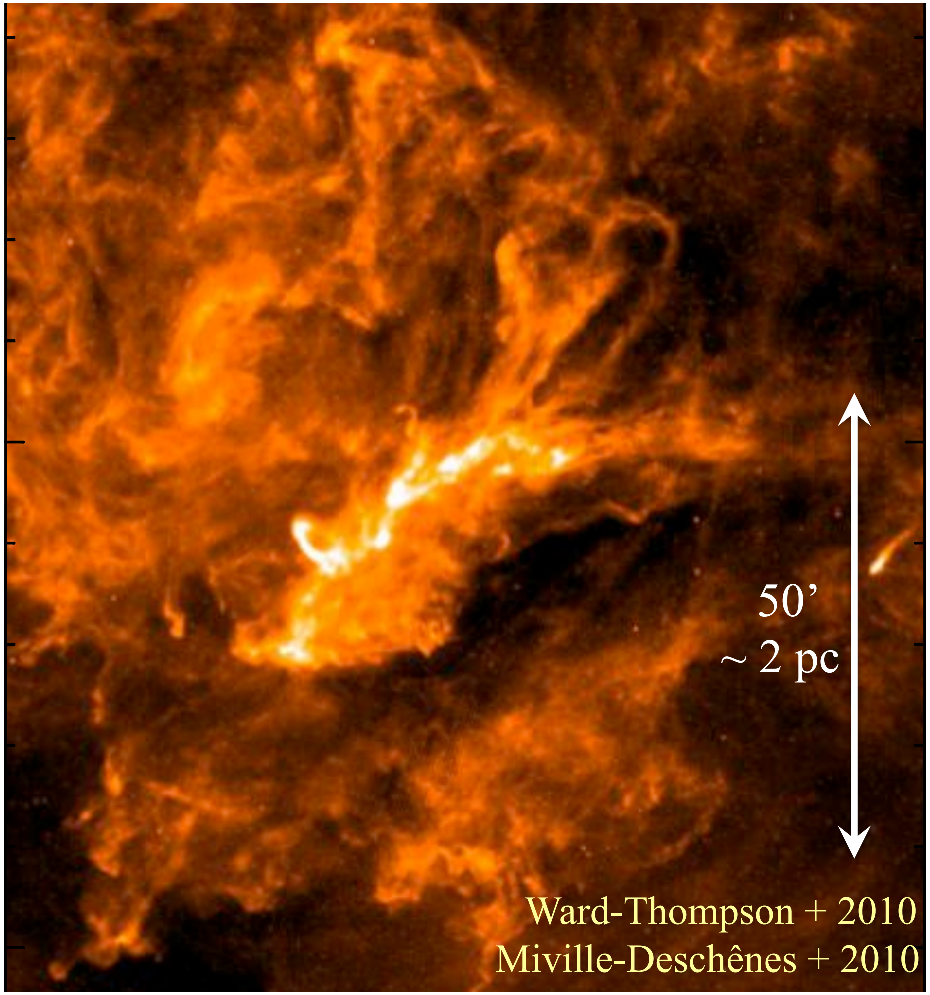
$M_{line} \propto N_{H2}$ x Width (~ 0.1 pc)

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

Toward a new paradigm for ~ $M_\odot$ star formation ?

See Protostars & Planets VI chapter (André, DiFrancesco, Ward-Thompson, Inutsuka, Pudritz+2014 - astro-ph/1312.6232)

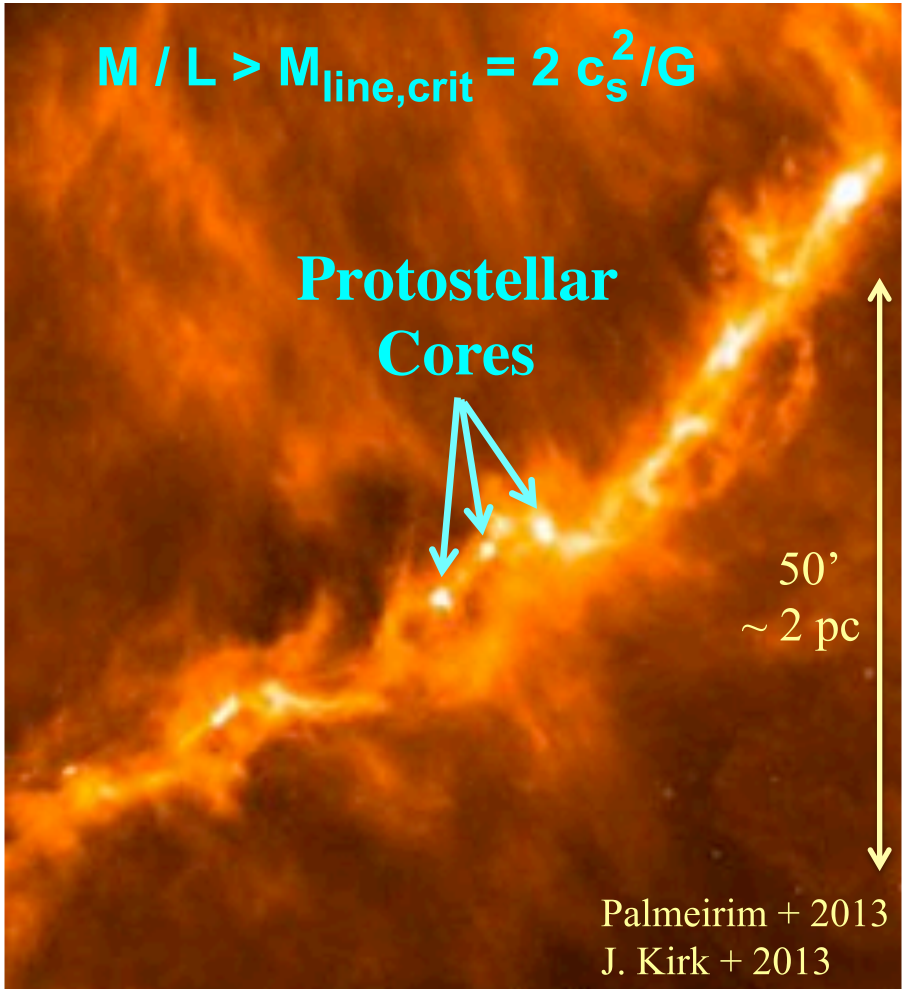
1) Large-scale MHD supersonic 'turbulence' generates filaments



Ward-Thompson + 2010
Miville-Deschênes + 2010

Polaris – *Herschel*/SPIRE 250 μm

2) Gravity fragments the densest filaments into prestellar cores

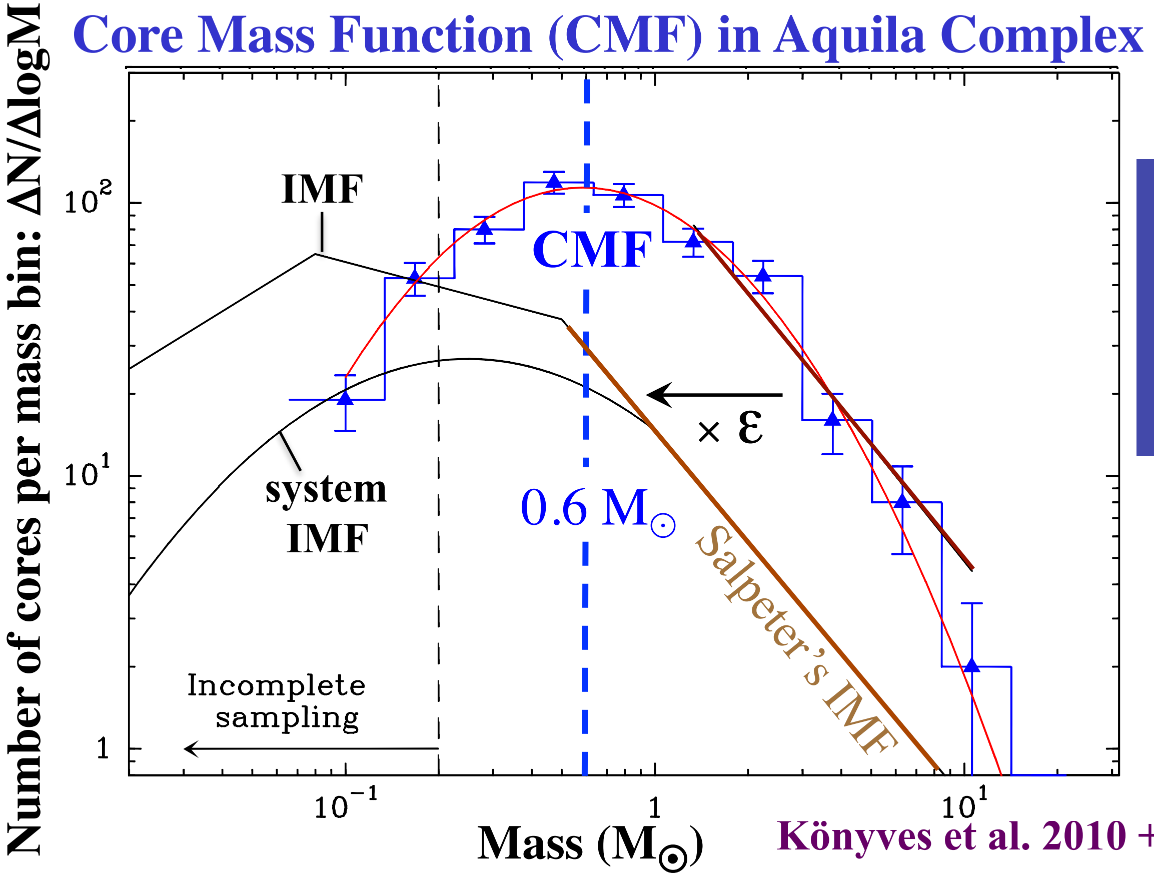

$M / L > M_{line,crit} = 2\, c_s^2 / G$

Protostellar Cores

Palmeirim + 2013
J. Kirk + 2013

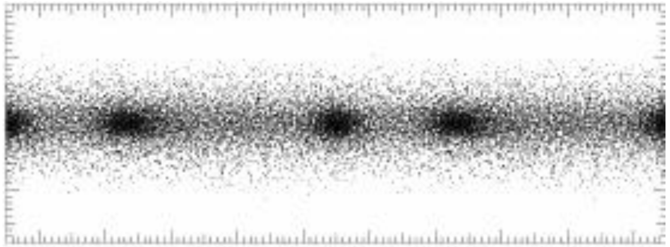
Taurus B211/3 – *Herschel* 250 μm

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



Jeans mass:

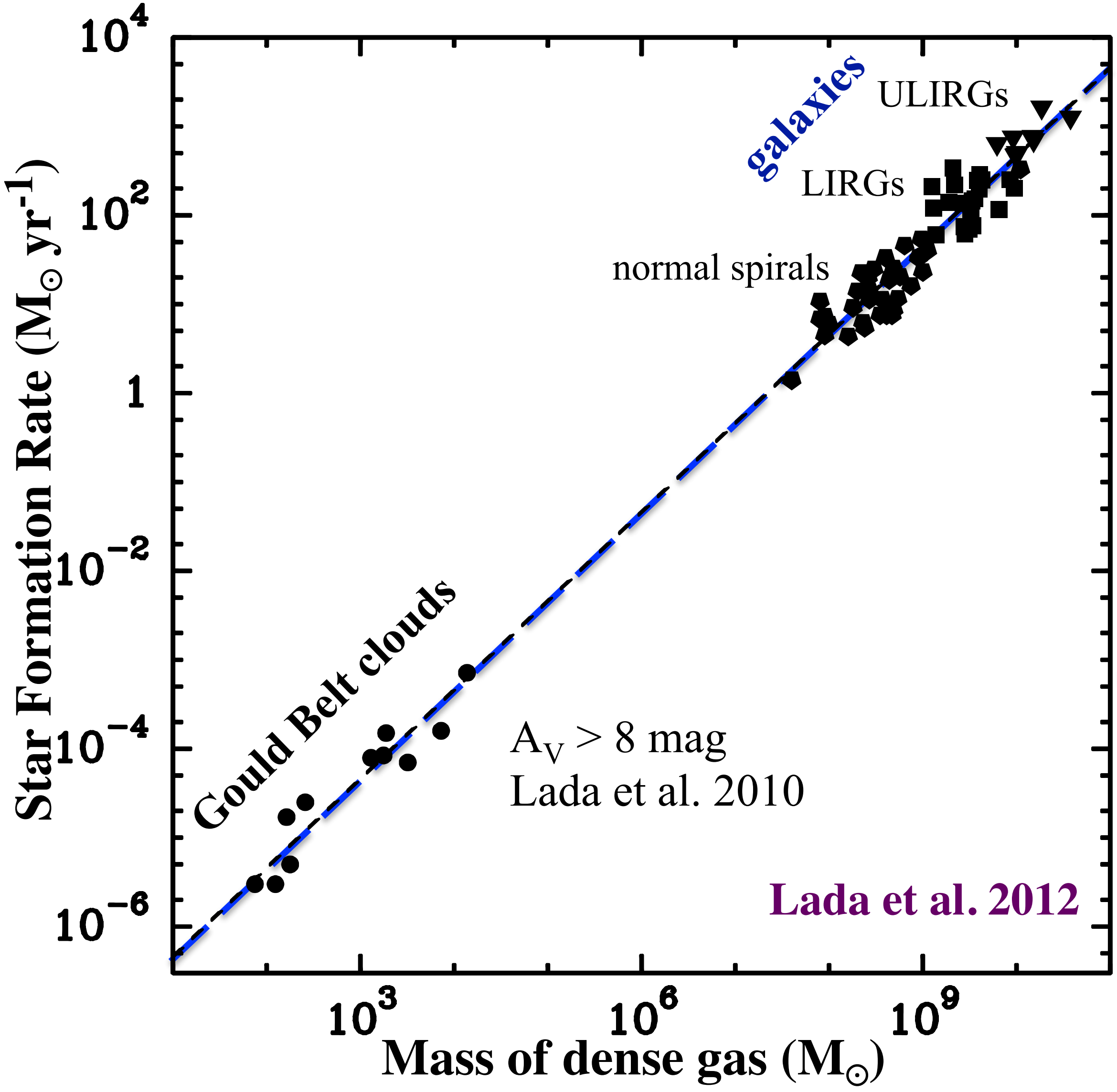
$$M_{Jeans} \sim 0.5\,M_\odot \times (T/10\,K)^2 \times (\Sigma_{crit}/160\,M_\odot pc^{-2})^{-1}$$



Könyves et al. 2010 + in prep. ; André+2014 PPVI

- CMF peaks at ~ 0.6 $M_\odot$ ≈ Jeans mass in marginally critical filaments
- Close link of the prestellar CMF with the stellar IMF: $M_\bigstar \sim 0.3 \times M_{core}$
- Characteristic stellar mass may result from filament fragmentation

A universal star formation law above the threshold ?



■ HCN Gao & Solomon 2004

SFR ($M_\odot$/yr)

$$\simeq$$

$$4.5 \times 10^{-8} \times M_{dense}(M_\odot)$$

$$=$$

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

$$\simeq$$

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

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

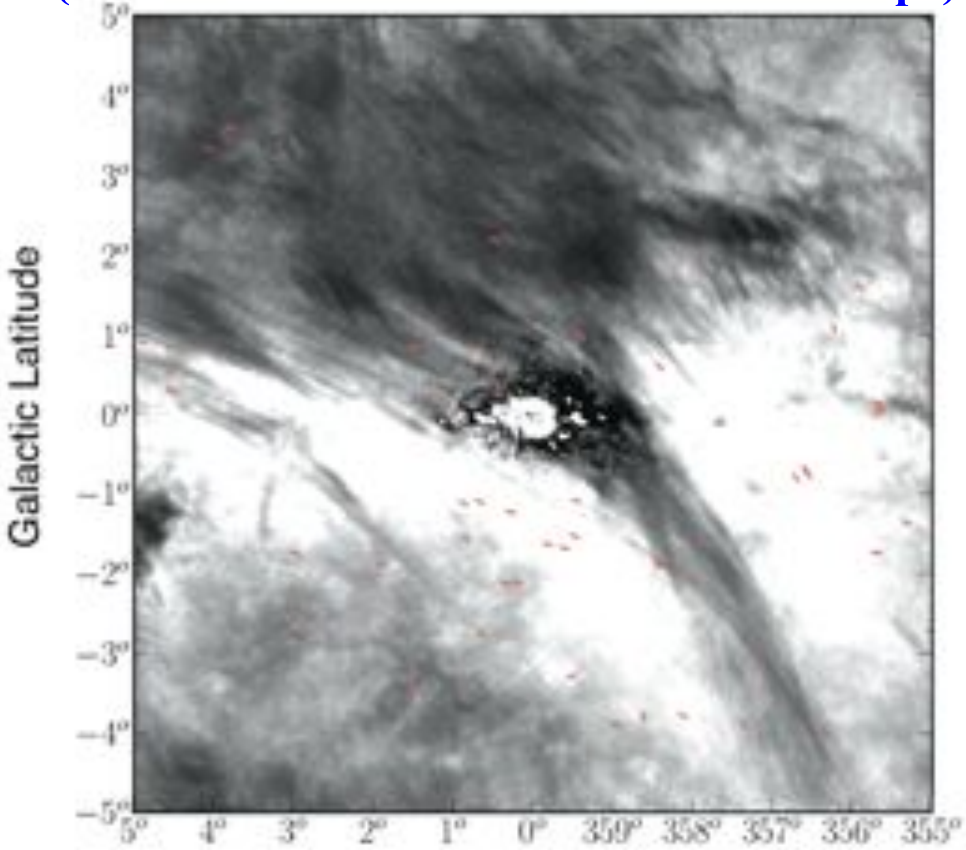
M_{dense} = Mass of dense gas above the threshold ($A_V > 8$ or $n_{H2} > 2.5 \times 10^4$ cm^{-3})

André+2014 PPVI; Könyves+, in prep

Formation of filament structures in the cold ISM ?

Hint: Prominent filaments are also seen in HI absorption (CNM)

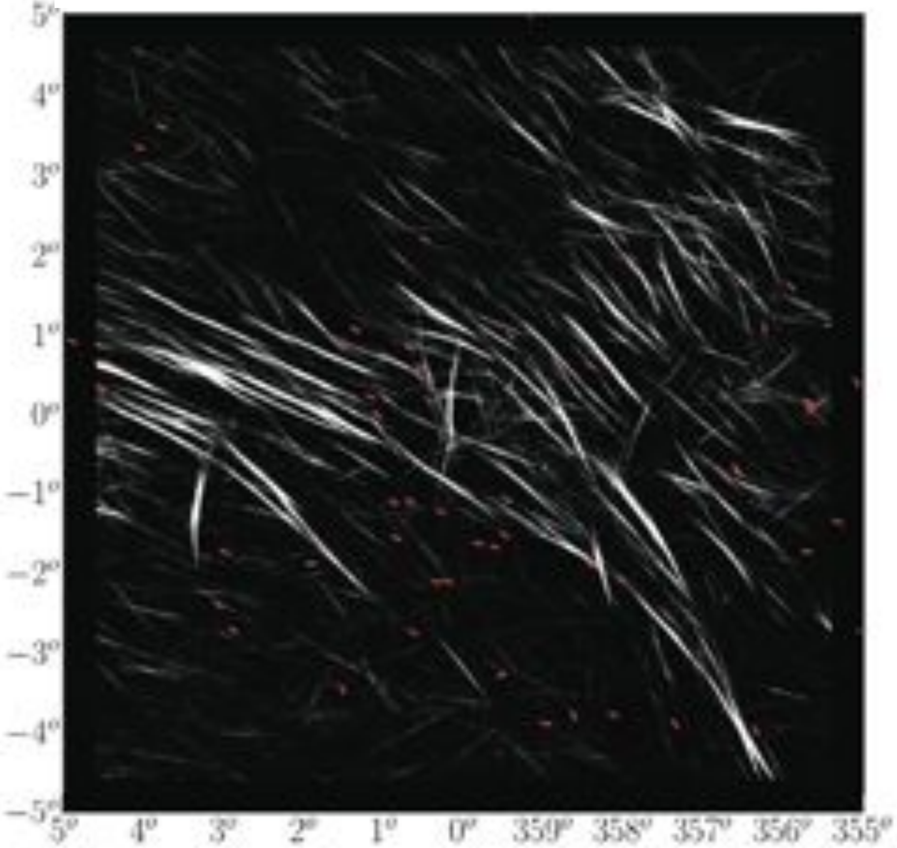
The Riegel-Crutcher cloud in HI asborption (ATCA+ Parkes – Resolution: 100" ~ 0.1 pc)



McClure-Griffiths et al. 2006

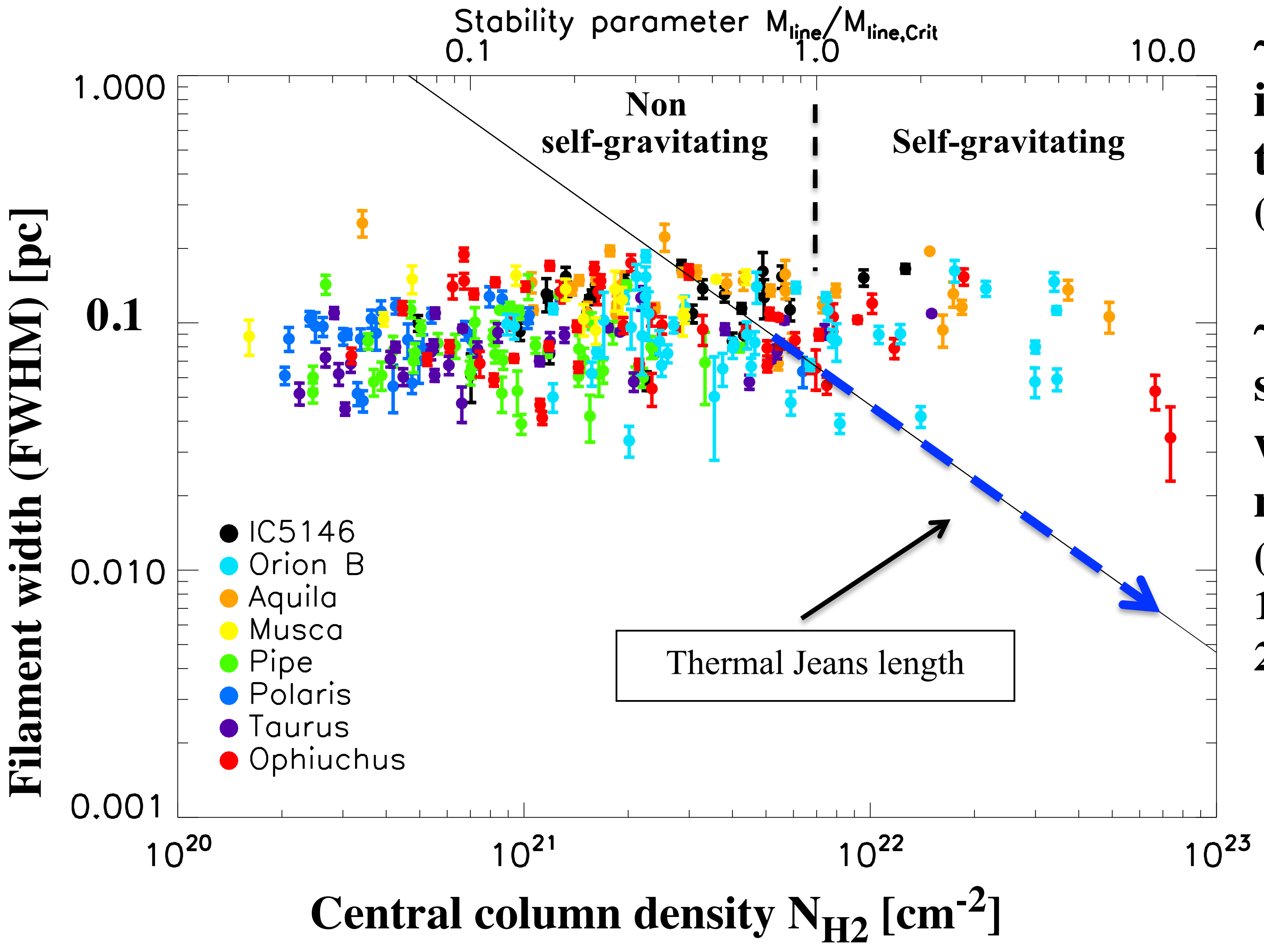
Galactic Longitude

HI filaments traced with the "Rolling Hough Transform"



Clark et al. 2014

Origin of the characteristic width of filaments ?



~ sonic scale of interstellar turbulence ?
(cf. Padoan+2001)

~ dissipation scale of MHD waves in molecular gas ?
(eg. Mouschovias 1991; Hennebelle 2013)

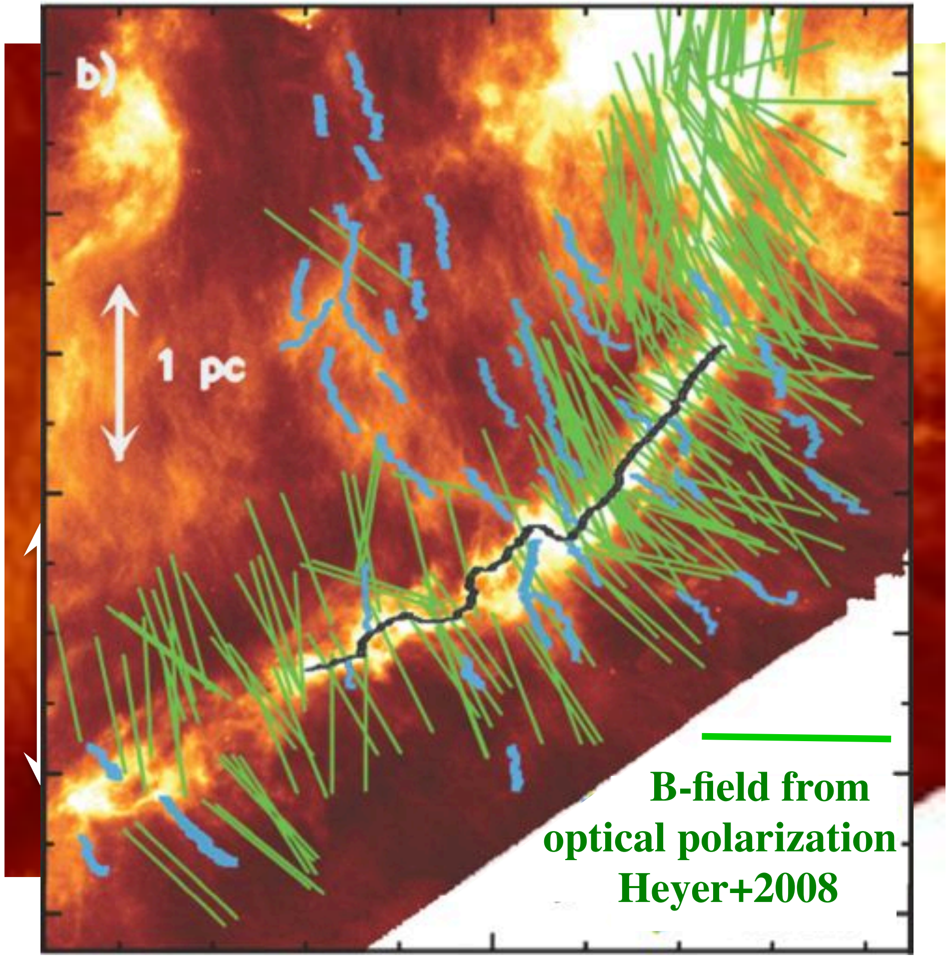
Paradox:
Dense filaments should radially contract !

D. Arzoumanian et al. 2011 + PhD thesis

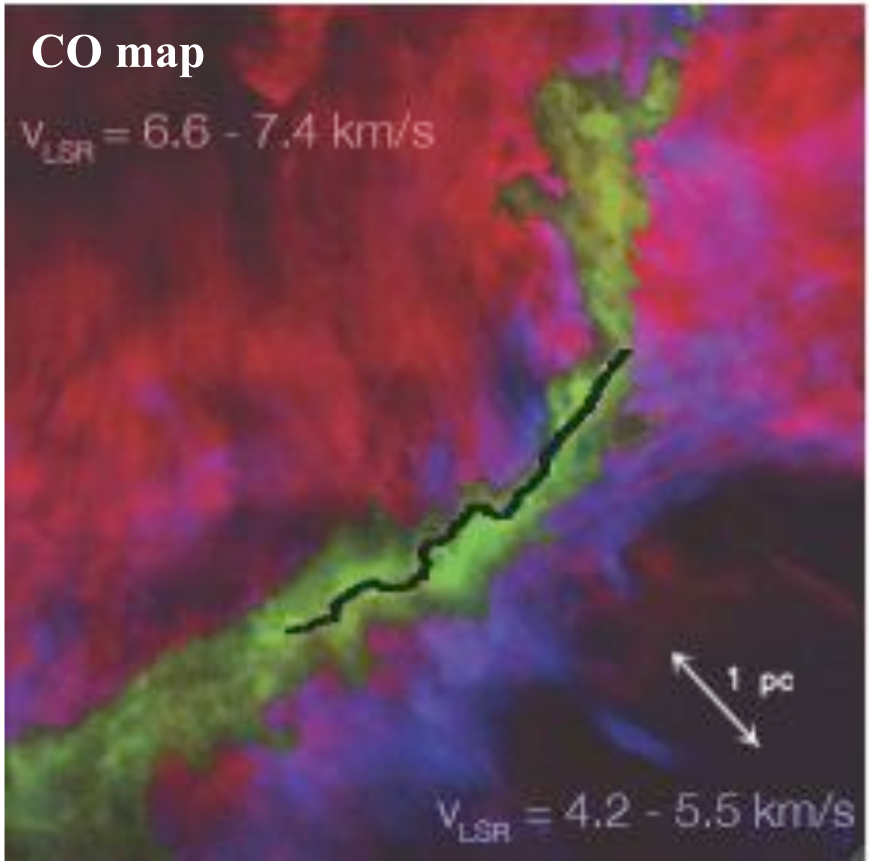
Key: Evidence of accretion of background material (striations) along field lines onto self-gravitating filaments

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

Palmeirim et al. 2013 (see also H. Kirk+2013 for another example: Serpens-South)



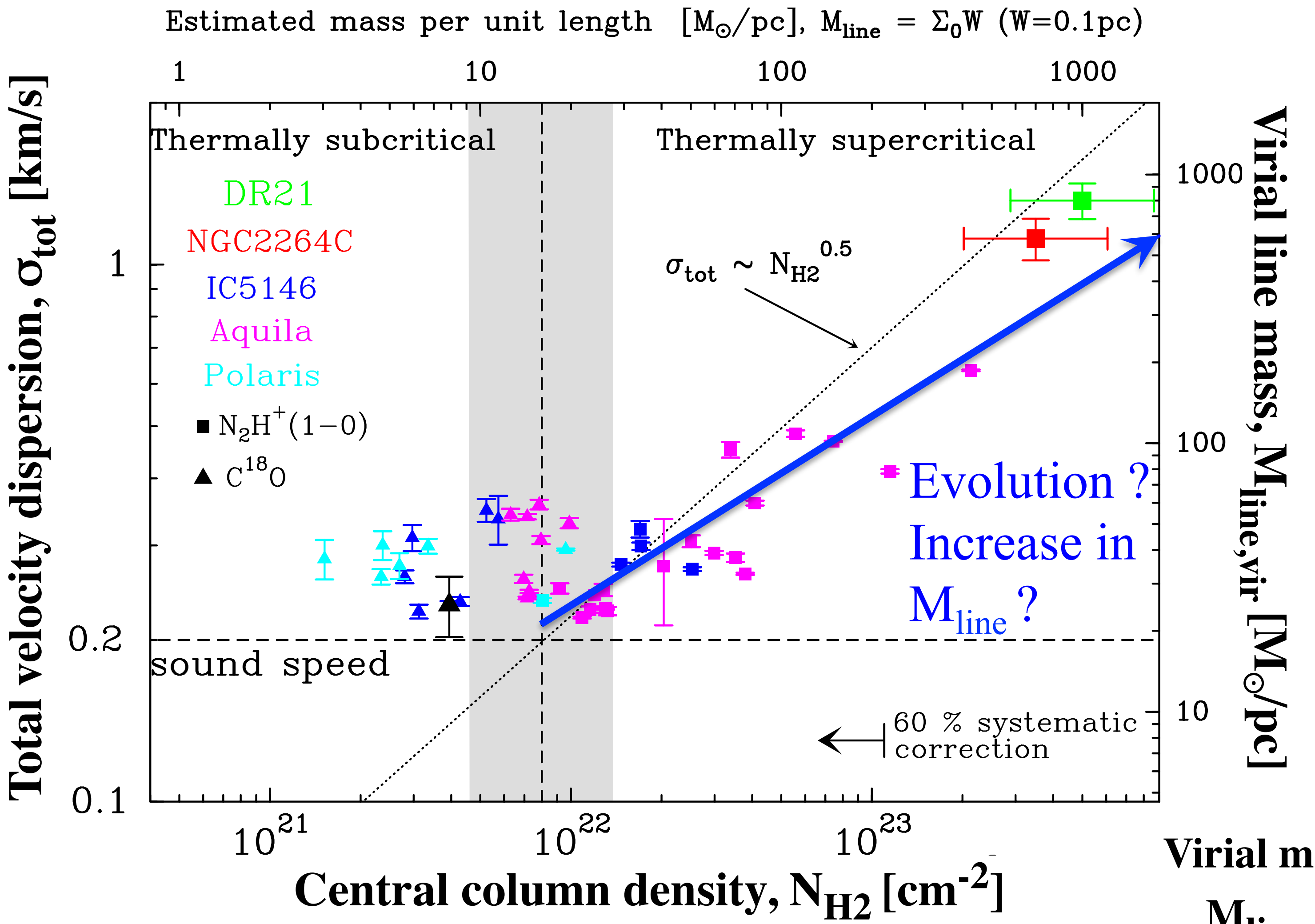
B-field from optical polarization Heyer+2008



CO observations from Goldsmith et al. 2008

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

Growth of self-gravitating filaments by accretion ?



Evolution ?
Increase in
M_{line} ?

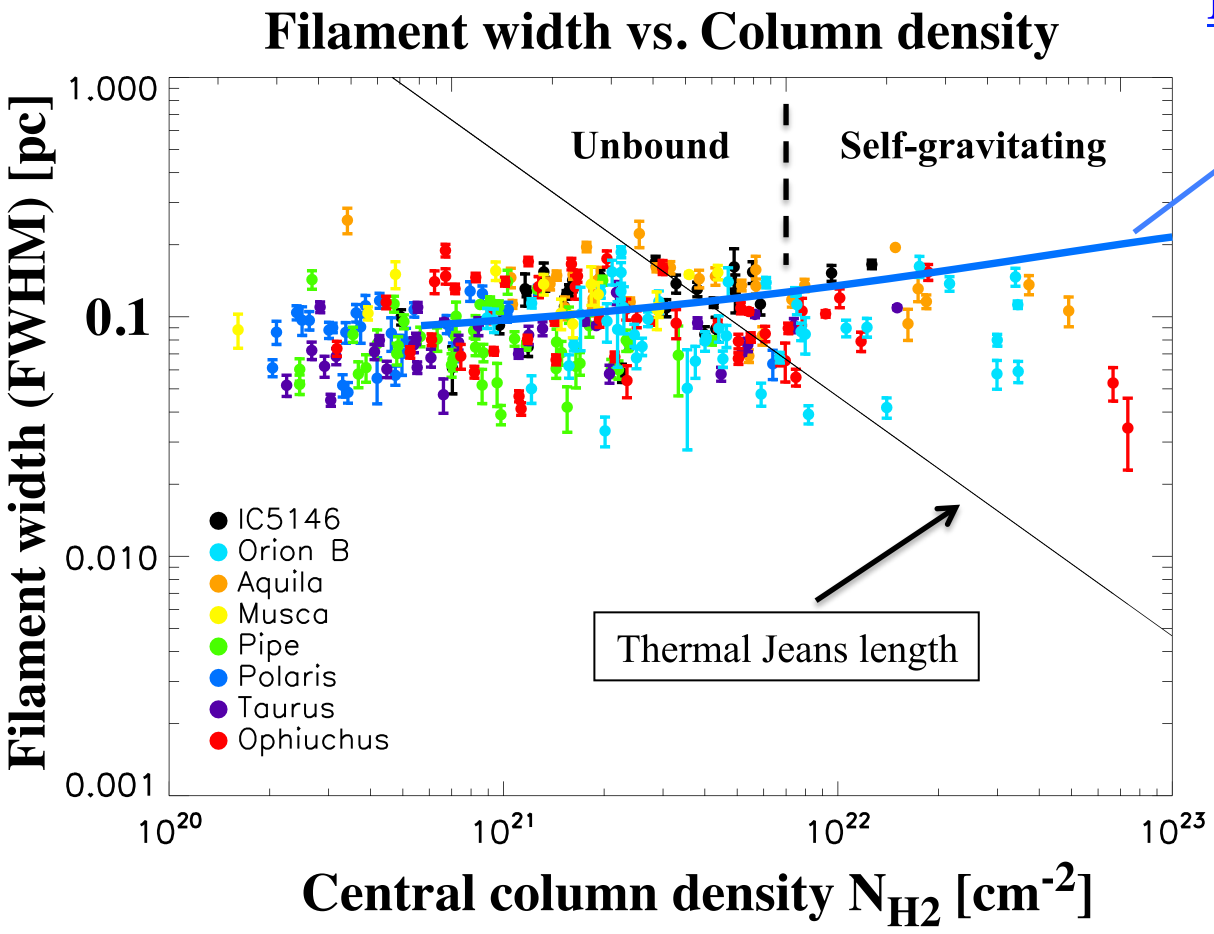
IRAM 30m observations
Arzoumanian et al. 2013

Virial mass unit length:

$$M_{line,vir} = 2\,\sigma_{tot}^2/G$$

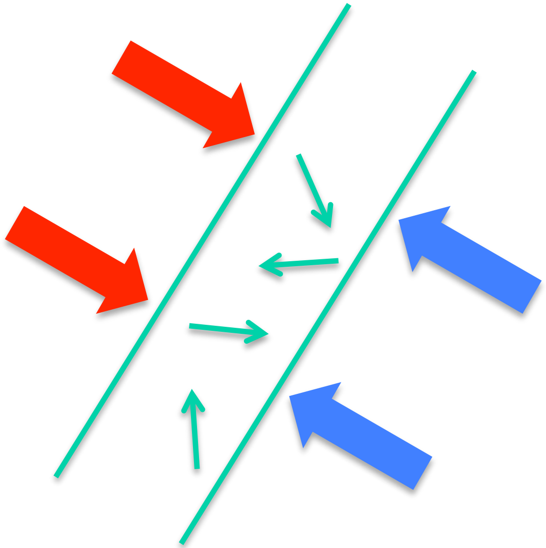
(Fiege & Pudritz 2000)

Accretion-driven MHD turbulence can prevent the radial contraction of dense filaments



D. Arzoumanian et al. 2011 + PhD thesis
+ Hennebelle & André 2013

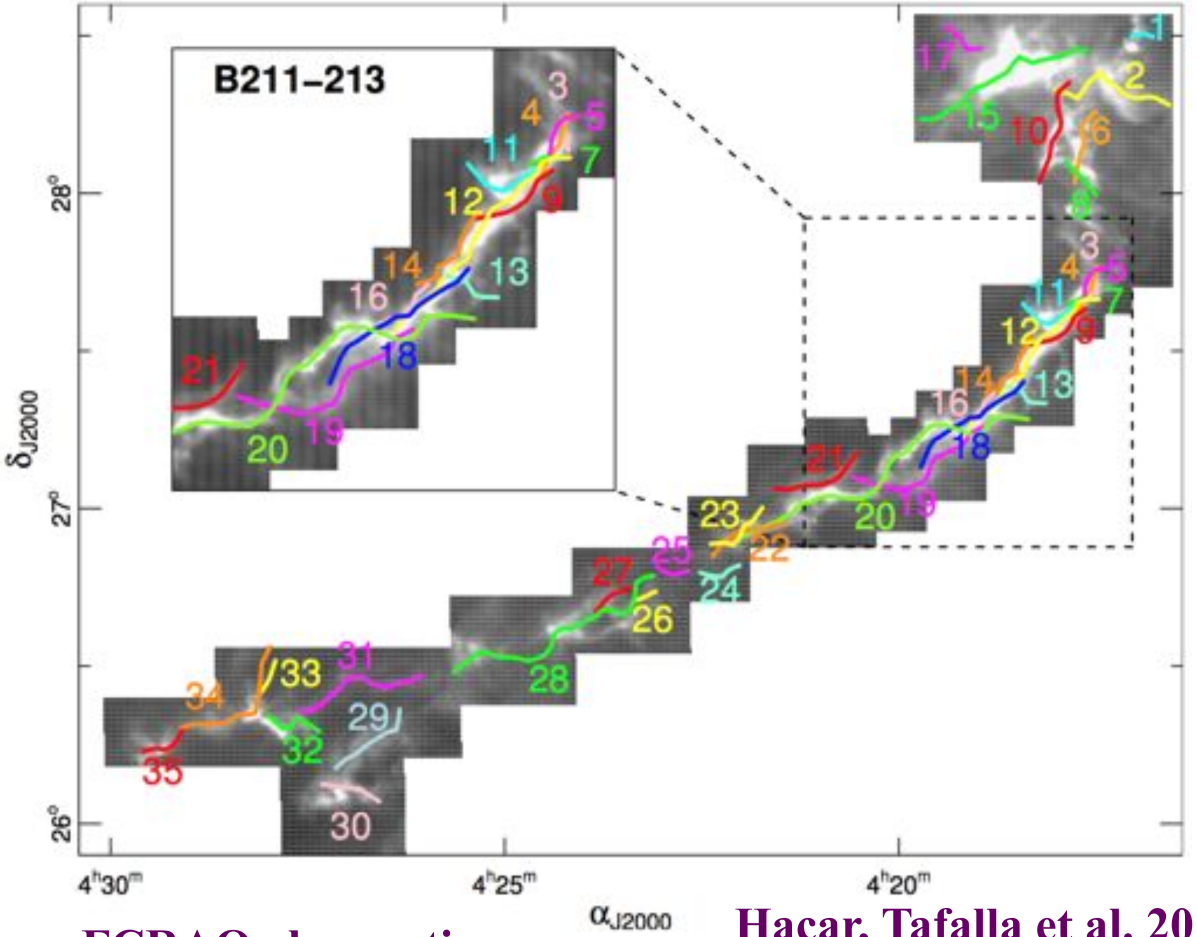
Model of accreting filaments



Balance between accretion-driven turbulence (Klessen & Hennebelle 2010) and dissipation of MHD turbulence due to ion-neutral friction

« Dynamical » equilibrium with <width> ~ 0.1 pc

Evidence of velocity-coherent substructures or "fibers" in the Taurus B211/B213 filament



FCRAO observations

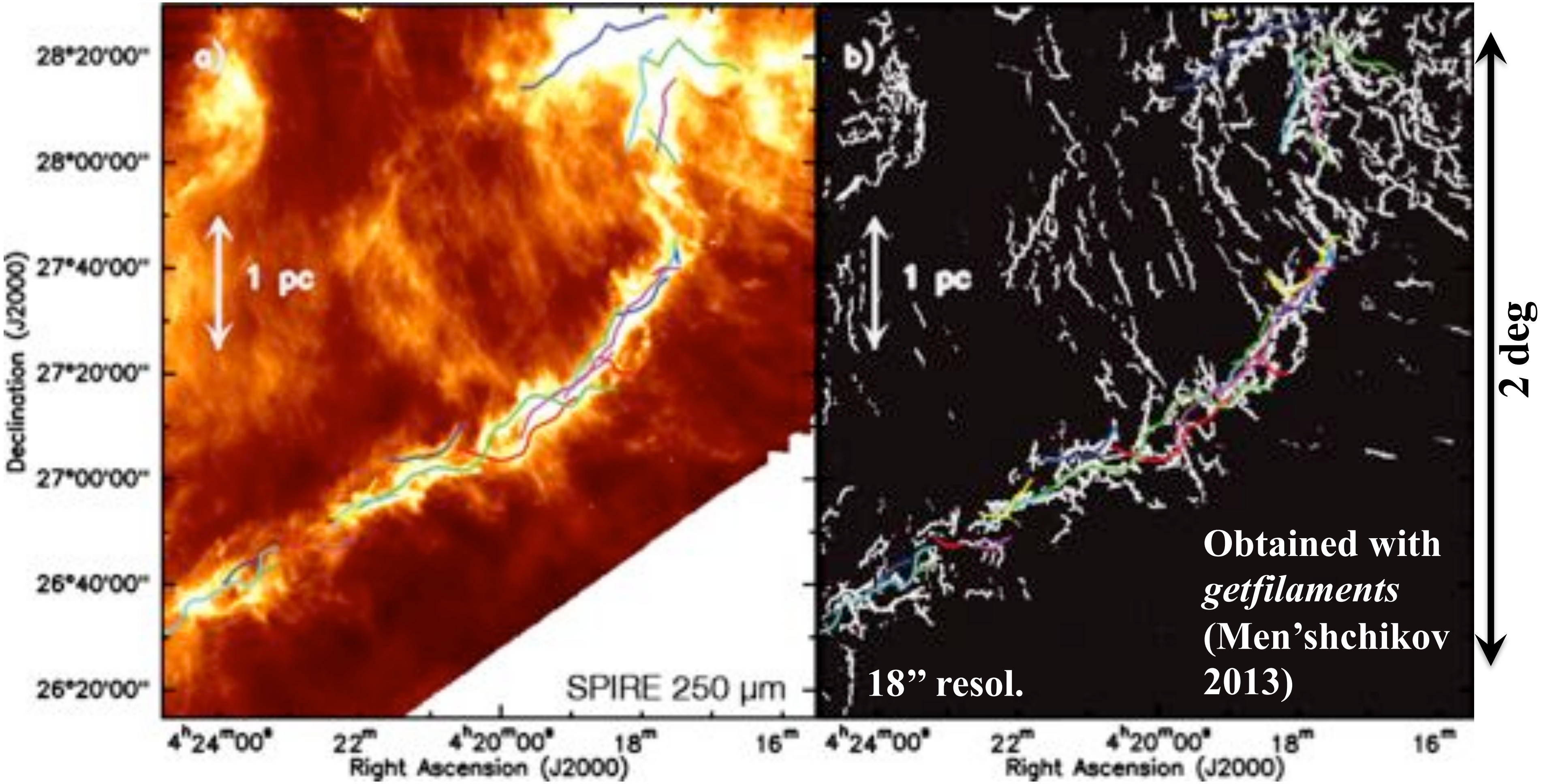
Hacar, Tafalla et al. 2013, A&A, 554, A55

- **Bundle of 35 velocity-coherent « fibers » (~ 0.5 pc long) detected in $C^{18}O$ and making up the main filament**

The *Herschel* filaments are not perfect cylinders …

Hacar et al. (2013)'s $C^{18}O$ « fibers » overlaid on *Herschel* 250 µm image (Palmeirim et al. 2013)

Filtered 250 µm image showing the fine structure of the Taurus B211/3 filament



18" resol.

Obtained with *getfilaments* (Men'shchikov 2013)

➢ **The B211/3 « fibers » may possibly be the manifestation of accretion-driven turbulence in the main filament (?)**

Conclusions: Toward a universal scenario for star formation on global (GMC) scales ?

- *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 large-scale **MHD turbulence**;
  2) The densest filaments then fragment into prestellar cores via **gravitational instability** above a critical density threshold
  $\Sigma_{th} \sim 150\ M_{\odot}\ pc^{-2} \Leftrightarrow A_V \sim 8 \Leftrightarrow n_{H2} \sim 2 \times 10^4\ cm^{-3}$

- 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 as a function of dense molecular gas on galactic scales