Herschel Observations of Nearby Interstellar Filaments

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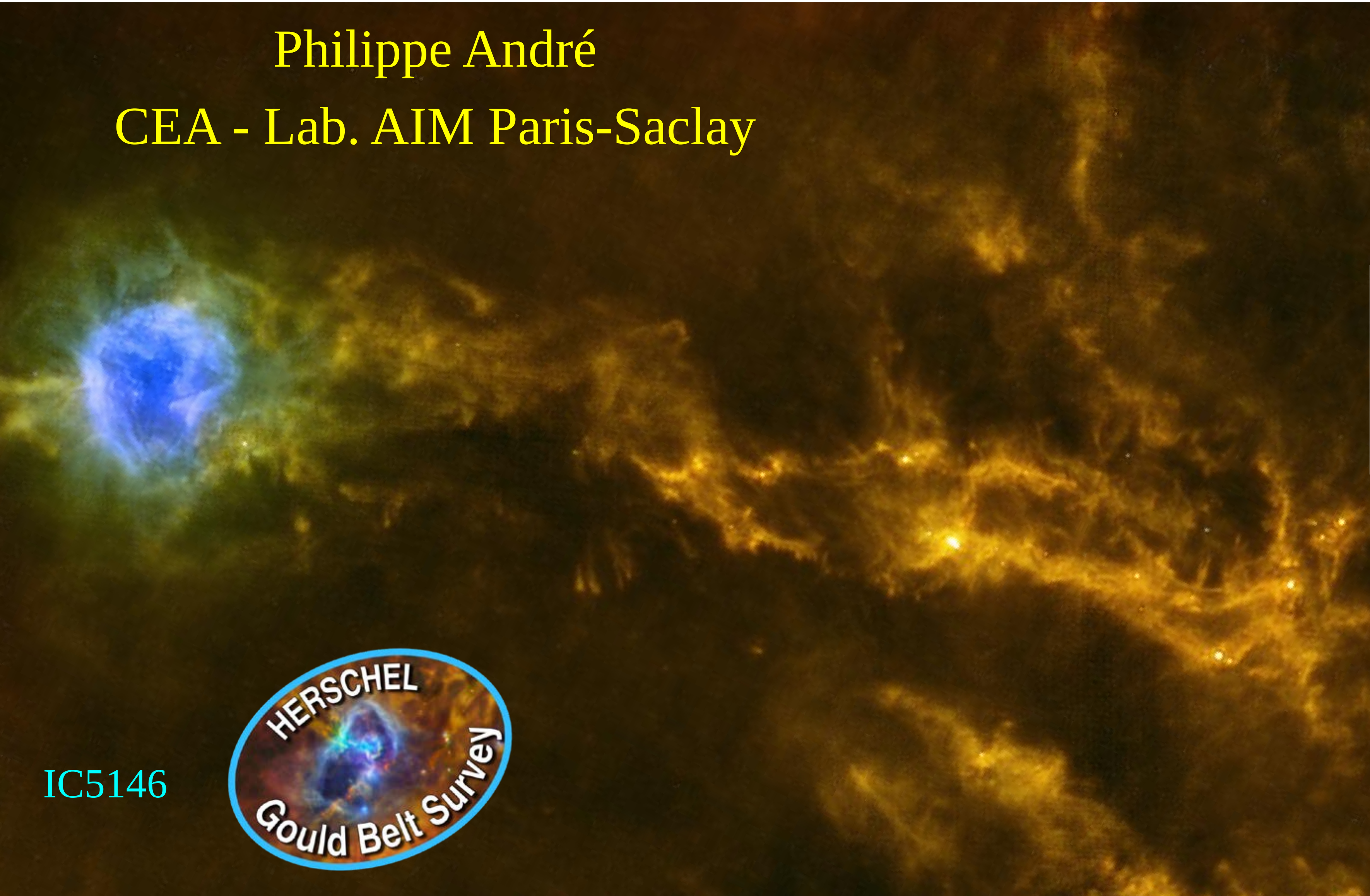
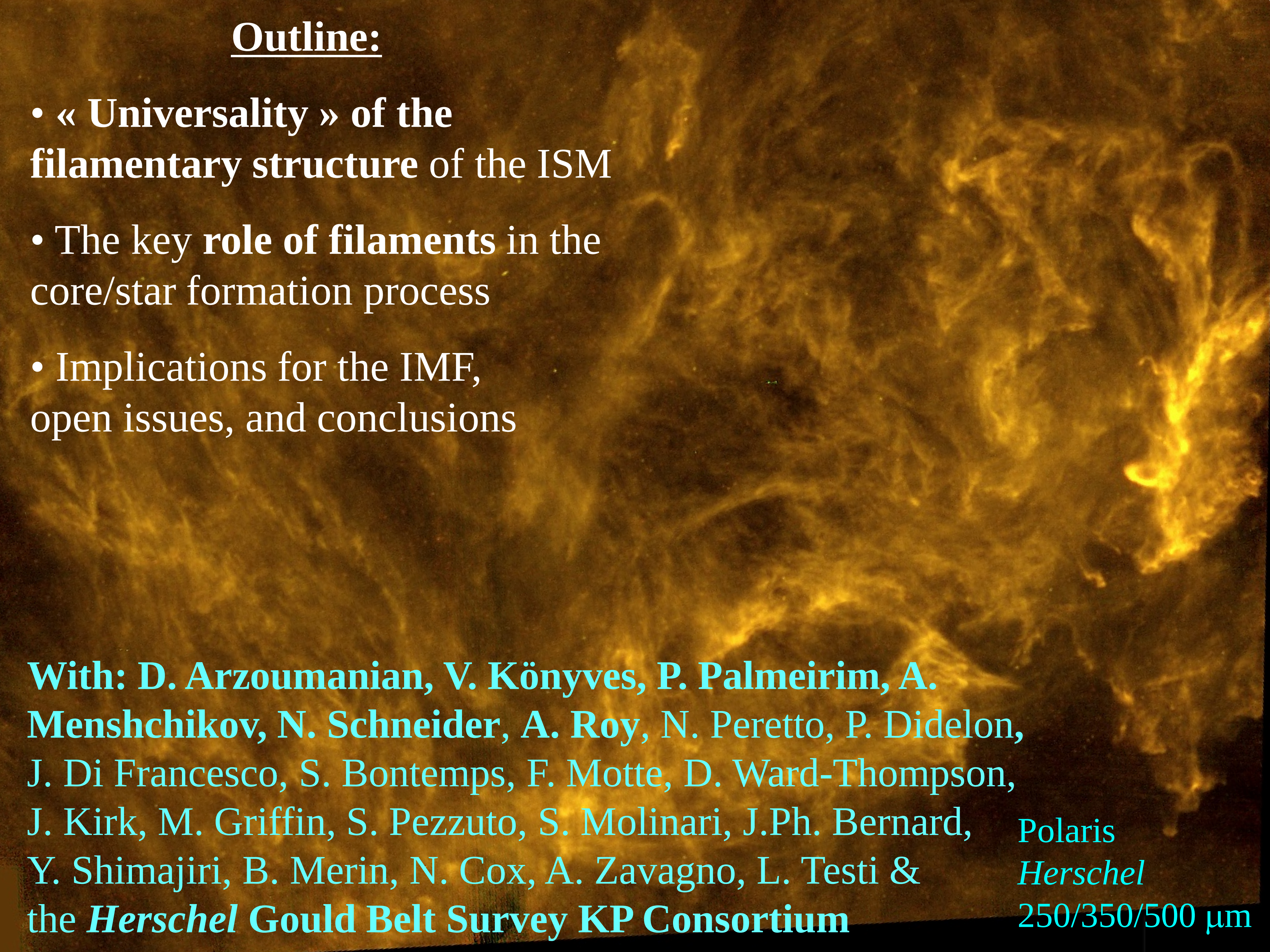

IC5146

HERSCHEL Gould Belt Survey



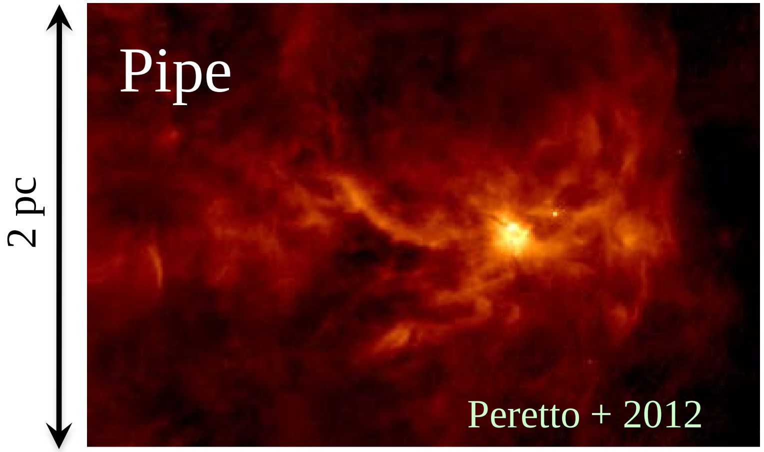
Outline:

- « **Universality** » **of the filamentary structure** of the ISM
- The key **role of filaments** in the core/star formation process
- Implications for the IMF, open issues, and conclusions

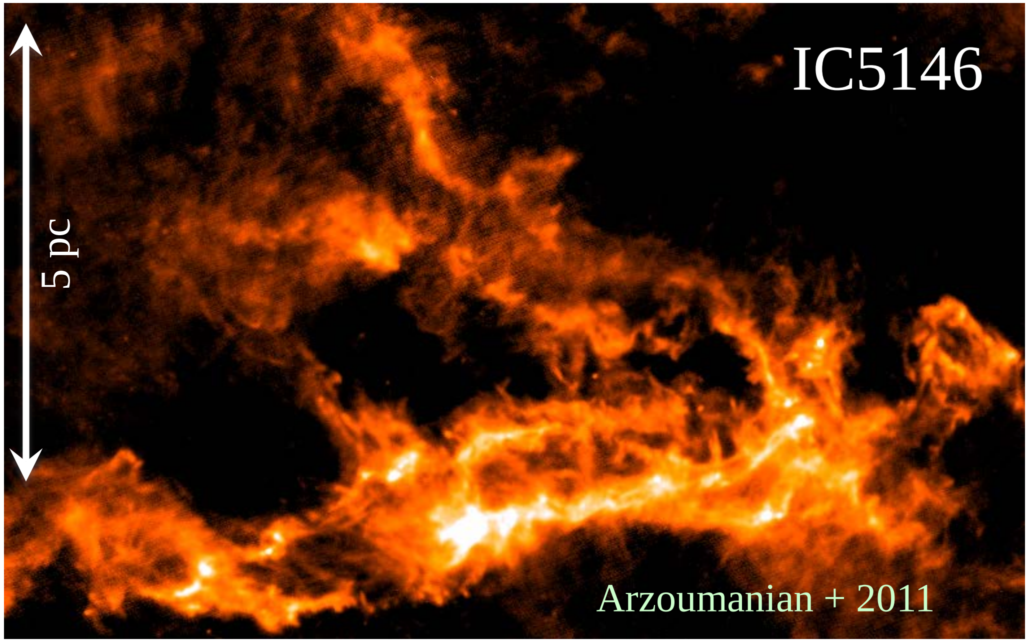
With: D. Arzoumanian, V. Könyves, P. Palmeirim, A. Menshchikov, N. Schneider, **A. Roy**, N. Peretto, P. Didelon, J. Di Francesco, S. Bontemps, F. Motte, D. Ward-Thompson, J. Kirk, M. Griffin, S. Pezzuto, S. Molinari, J.Ph. Bernard, Y. Shimajiri, B. Merin, N. Cox, A. Zavagno, L. Testi & the ***Herschel*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

Polaris
Herschel
250/350/500 µm

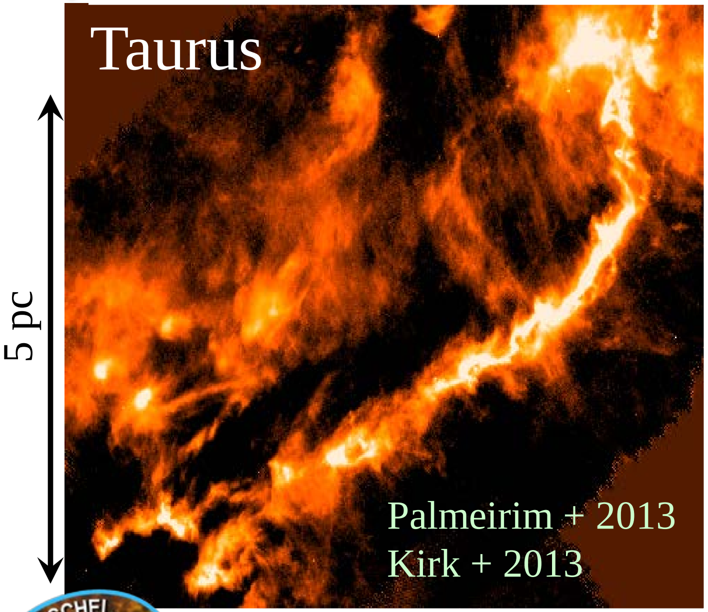
Herschel has revealed a “universal” filamentary structure in nearby clouds



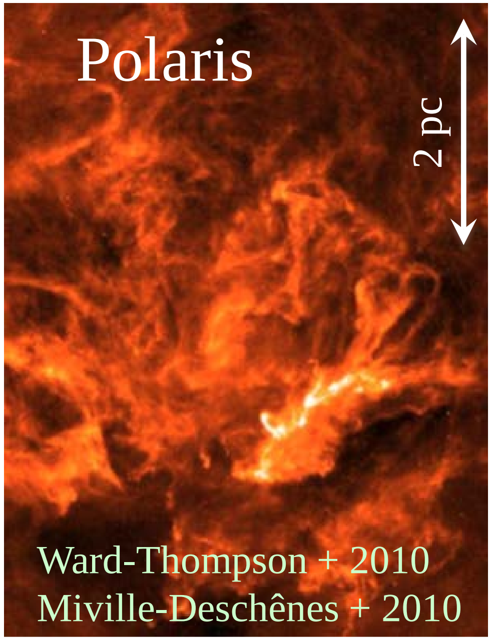
Peretto + 2012



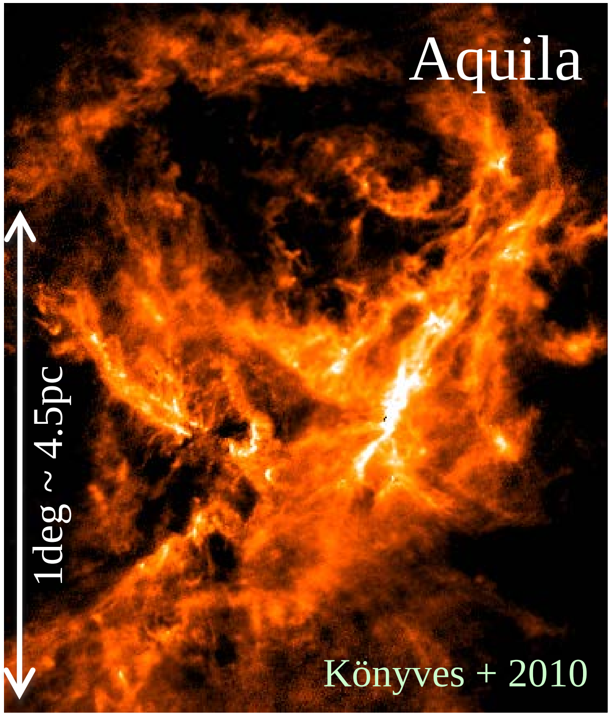
Arzoumanian + 2011



Palmeirim + 2013
Kirk + 2013



Ward-Thompson + 2010
Miville-Deschênes + 2010

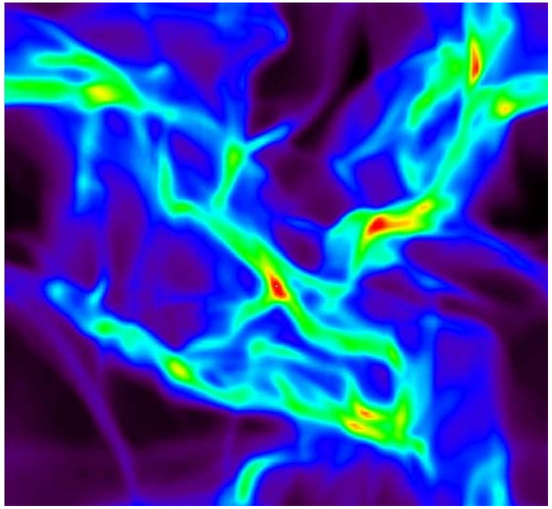


Könyves + 2010

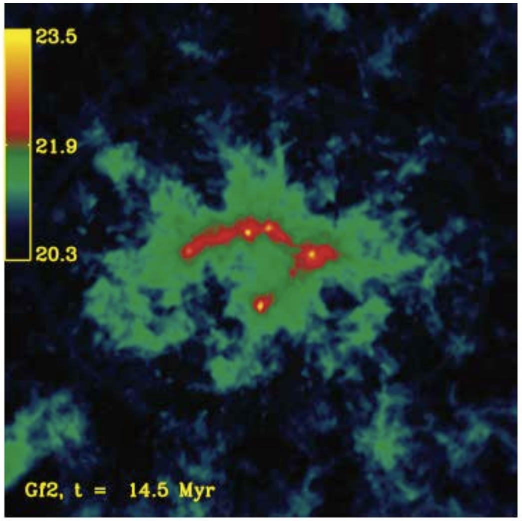
The observed filaments are reminiscent of numerical simulations of cloud evolution with large-scale flows

Turbulence

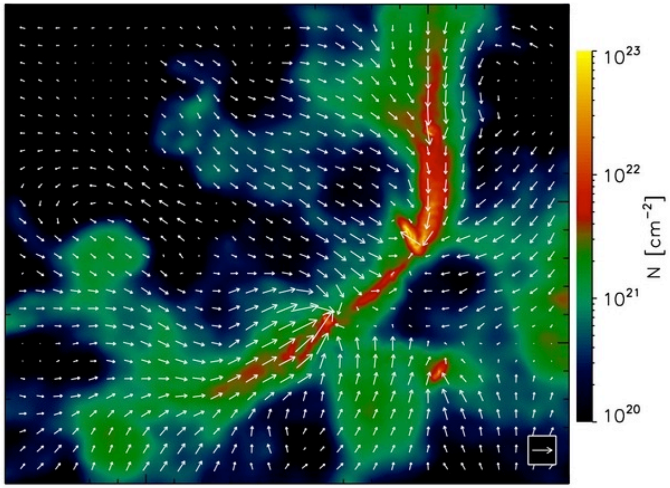
Gravity



Padoan et al. 2001

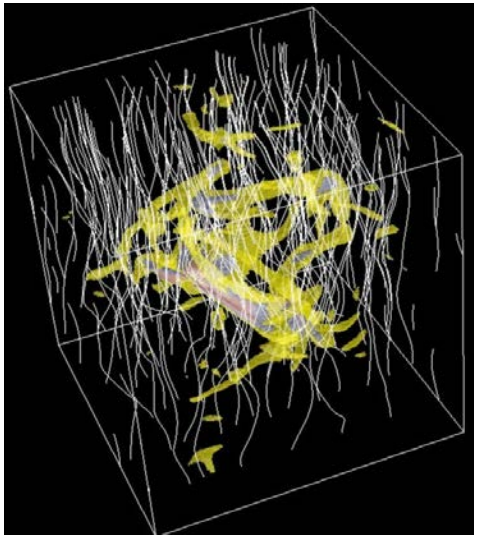


Heitsch et al. 2008

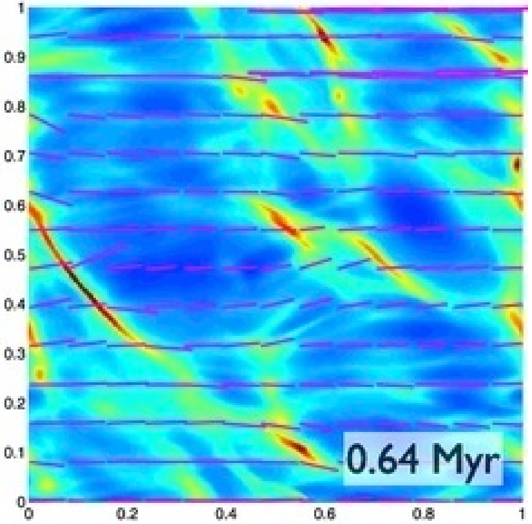


Gomez & Vazquez-Semadeni 2014

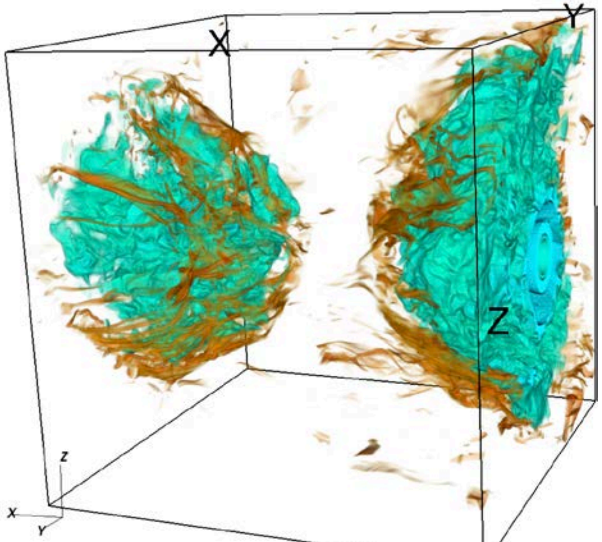
Turbulence
+
Gravity
+
B fields



Z.Y. Li et al. 2010

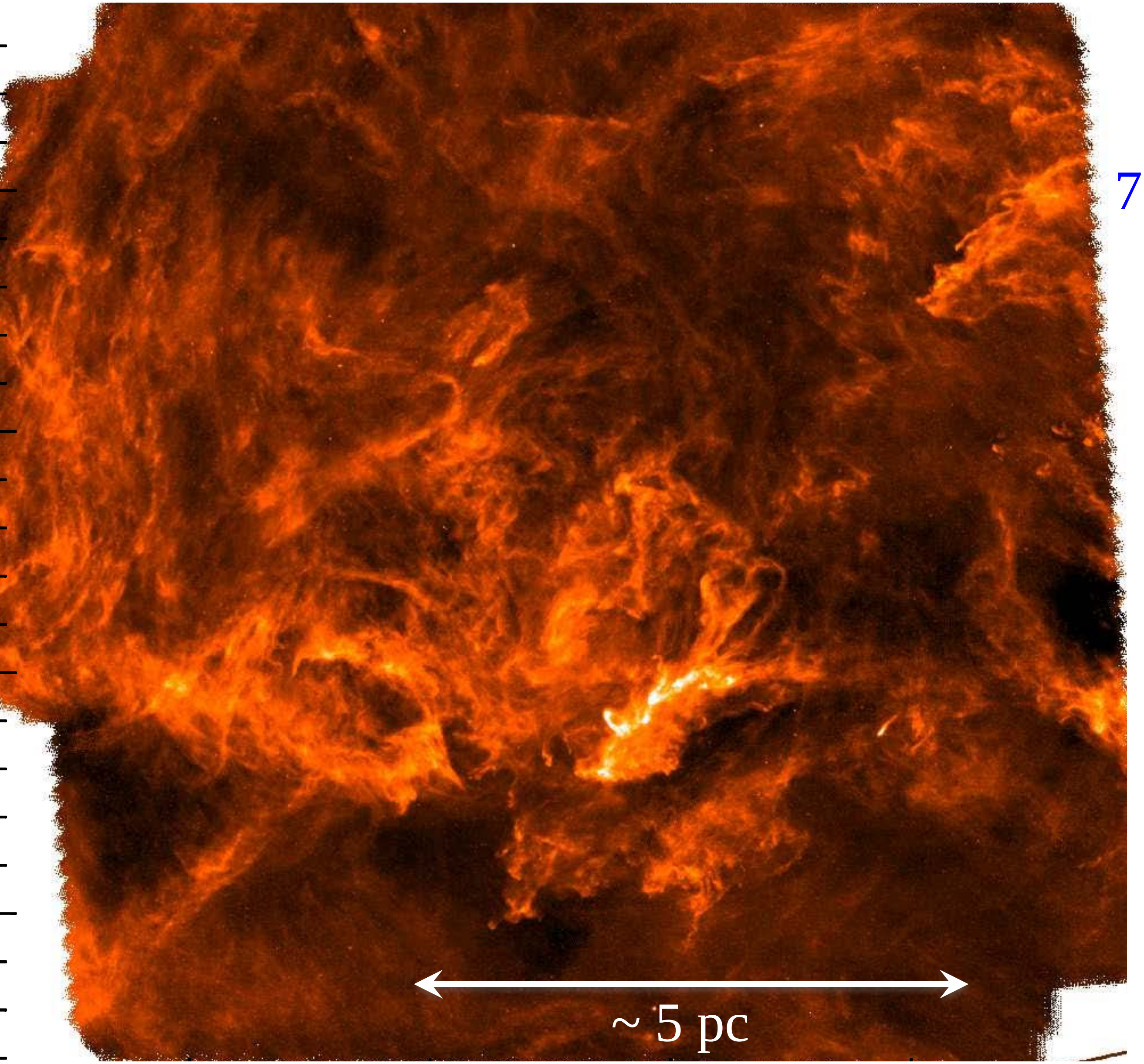


Chen & Ostriker 2014



Ntormousi et al.

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

d ~ 150 pc
~ 2200 $M_\odot$ (CO+HI)
unbound: M_{vir}/M_{tot} ~ 10
Heithausen & Thaddeus '90

~ 13 deg^2 field

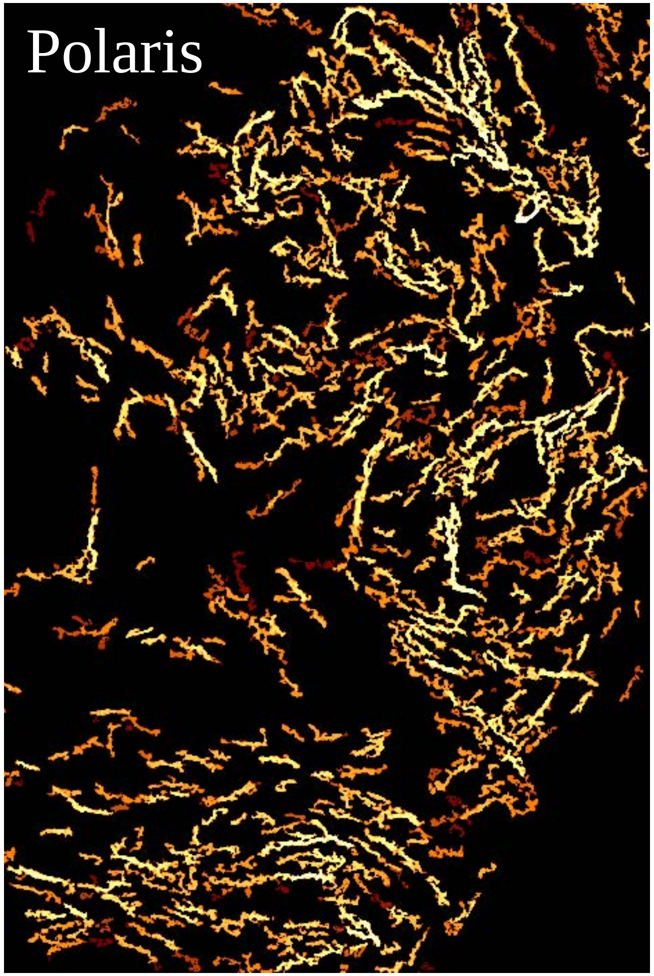
Miville-Deschênes et al. 2010
Ward-Thompson et al. 2010
Men'shchikov et al. 2010
André et al. 2010

Tracing the underlying filamentary networks

Different techniques: Projection on curvelets (Starck+2003), DisPerSE (Sousbie2011), *getfilaments* (Men’shchikov+2013) …

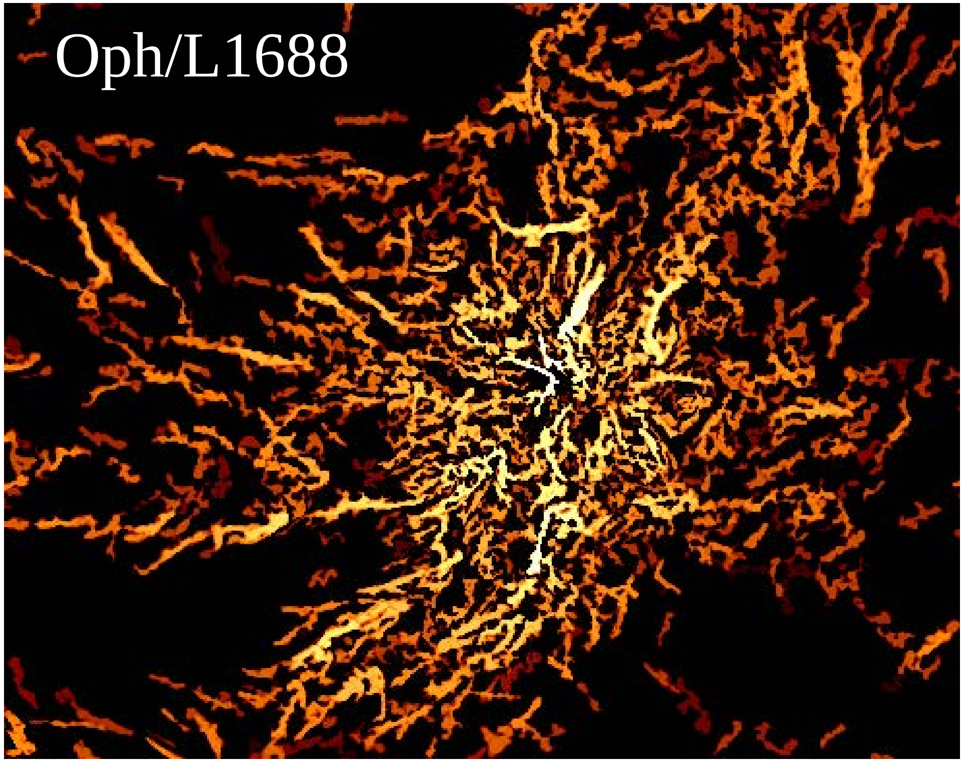
Examples of *getfilaments* results

’Disorganized’ network



Turbulence-dominated ?

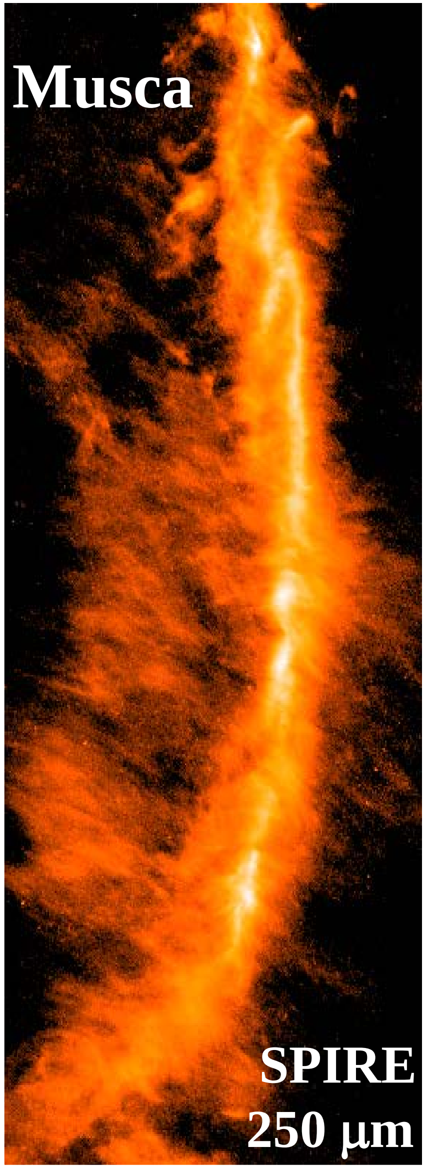
’Hub-filament’ network - see Myers (2009)



Gravity-dominated ?

See also ‘nests’ vs. ‘ridges’ (Hill+2011 – Vela C)

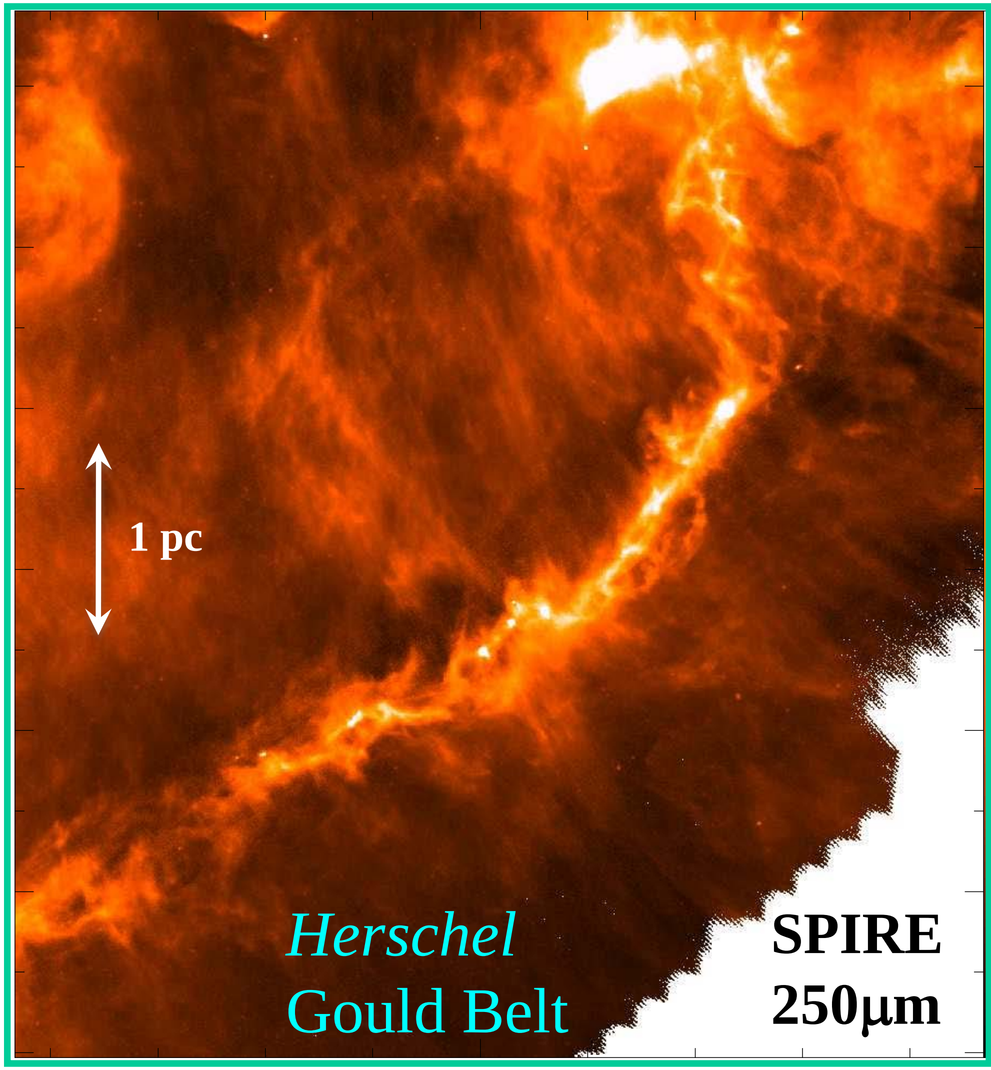
Evidence of much fainter filaments + high degree of universality with *Herschel*



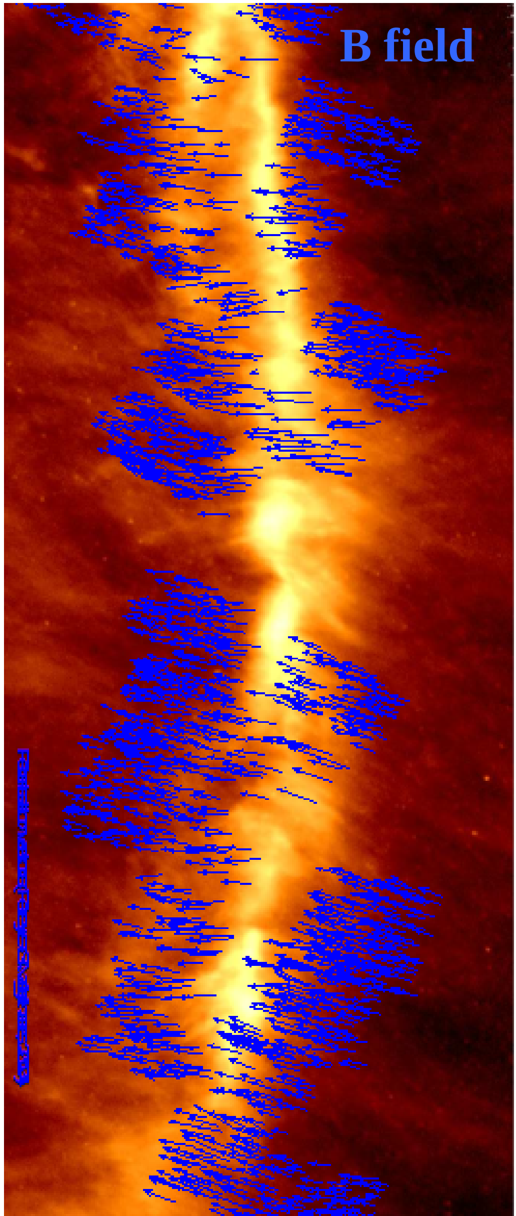
Musca filament:
M/L ~ 30 $M_\odot$/pc
N. Cox et al in prep.

HERSCHEL Gould Belt Survey

Taurus B211 filament: M/L ~ 50 $M_\odot$/pc **P. Palmeirim et al. 2013**



Evidence of much fainter filaments + high degree of universality with *Herschel*



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

N. Cox et al in prep.

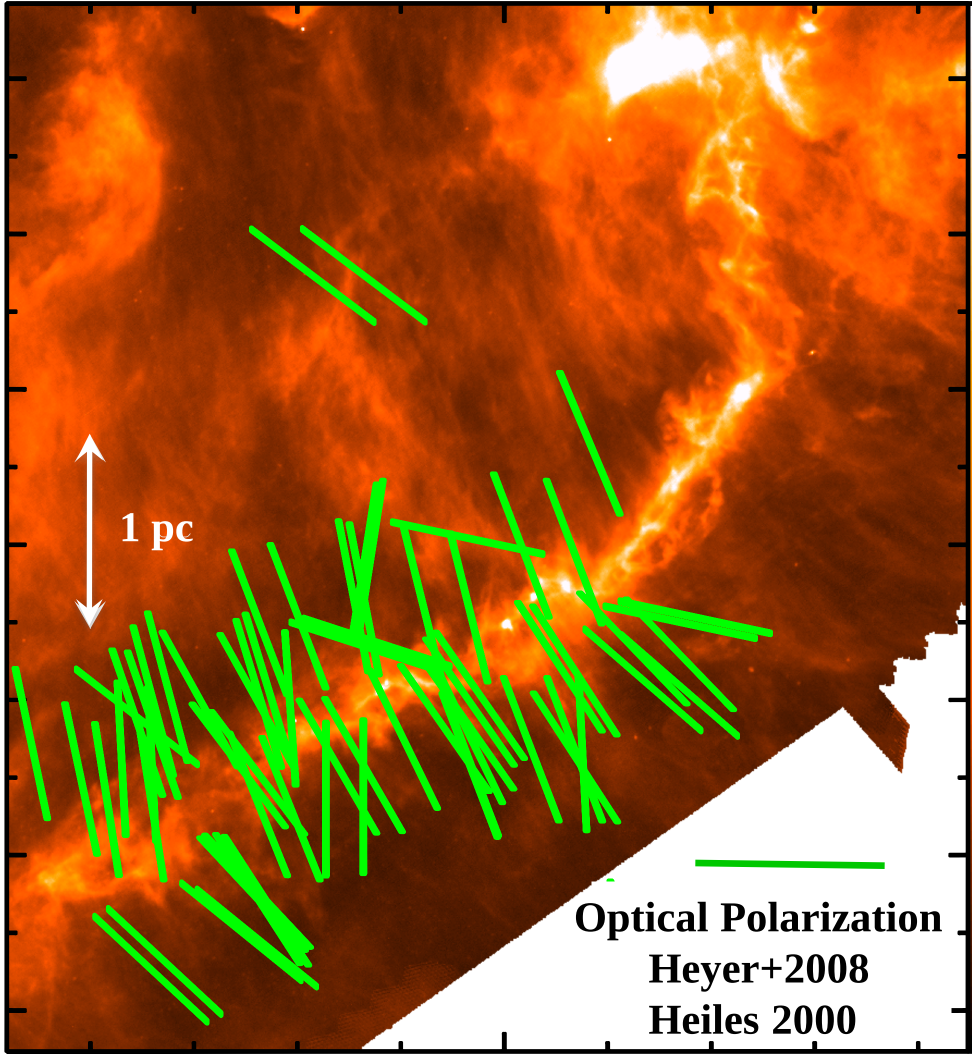
HERSCHEL
Gould Belt Survey

Polarization vectors overlaid on *Herschel* images

Pereyra & Magelhaes 2004

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

P. Palmeirim et al. 2013



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

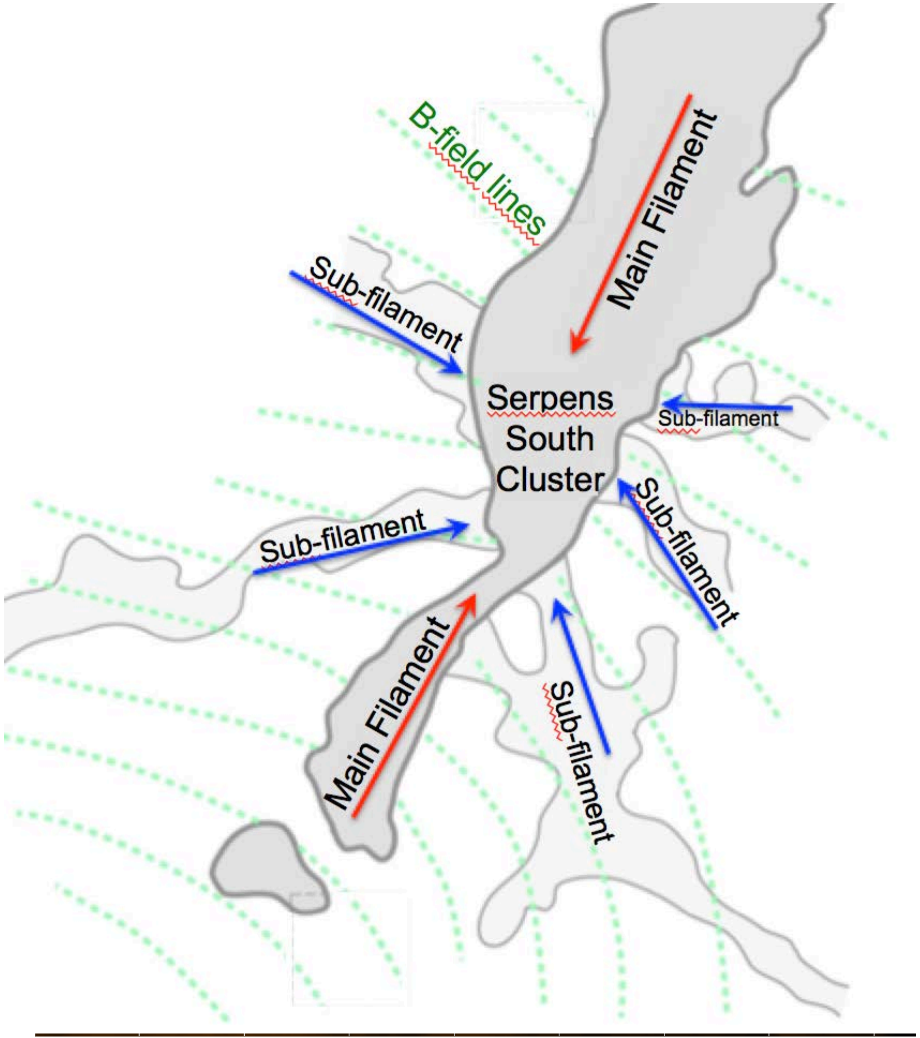
Serpens-South filament:
M/L ~ 250 $M_\odot$/pc

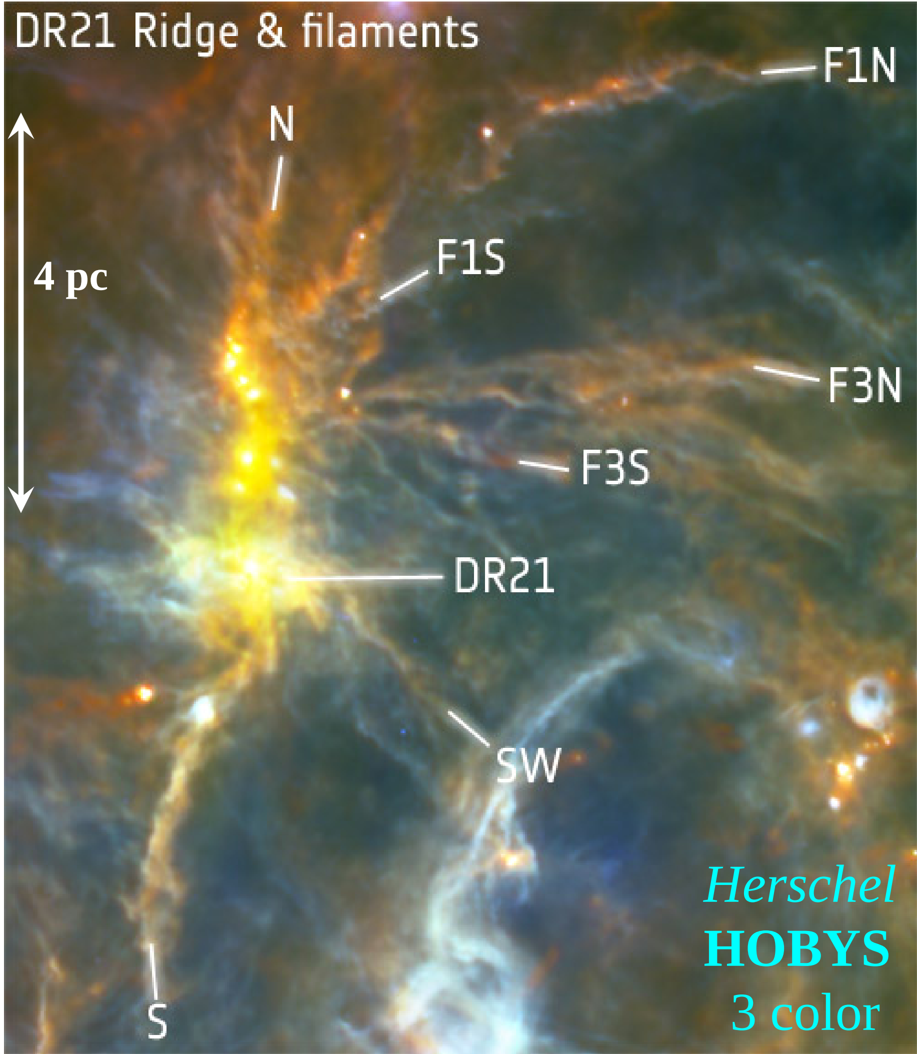
- **Suggestive of accretion flows into the main filaments**

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

Hennemann, Motte et al. 2012
Also Schneider+2010, Csengeri+2011

Sugitani+2011, H. Kirk+2013

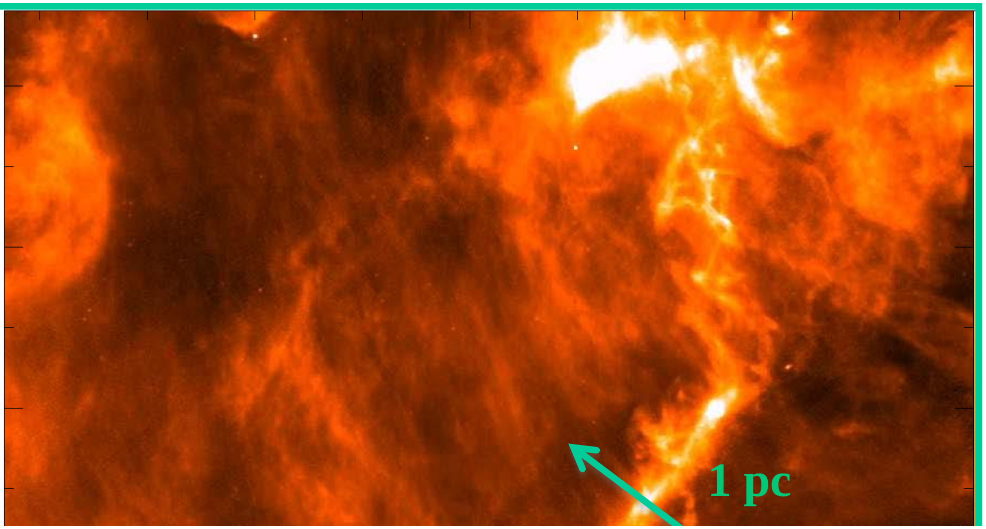


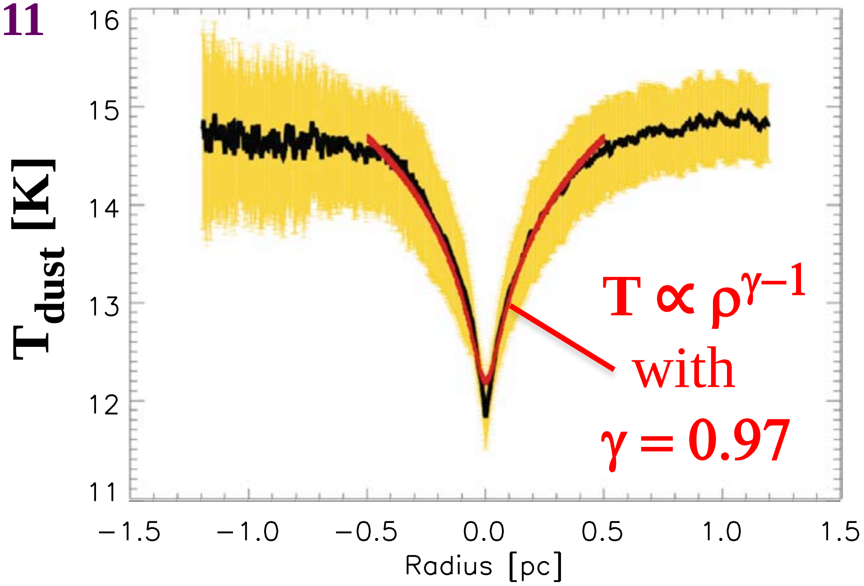


Resolving the structure of filaments with *Herschel*

Taurus B211/3 filament
SPIRE 250μm

Arzoumanian+2011
Palmeirim+2013





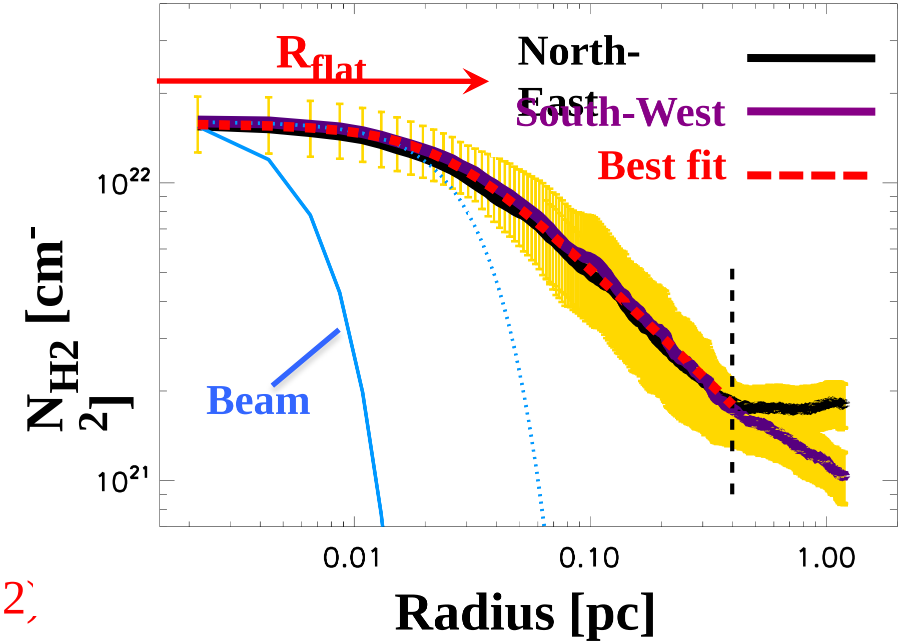
Plummer-like density profile (p = 2):

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

Diameter of flat inner plateau:

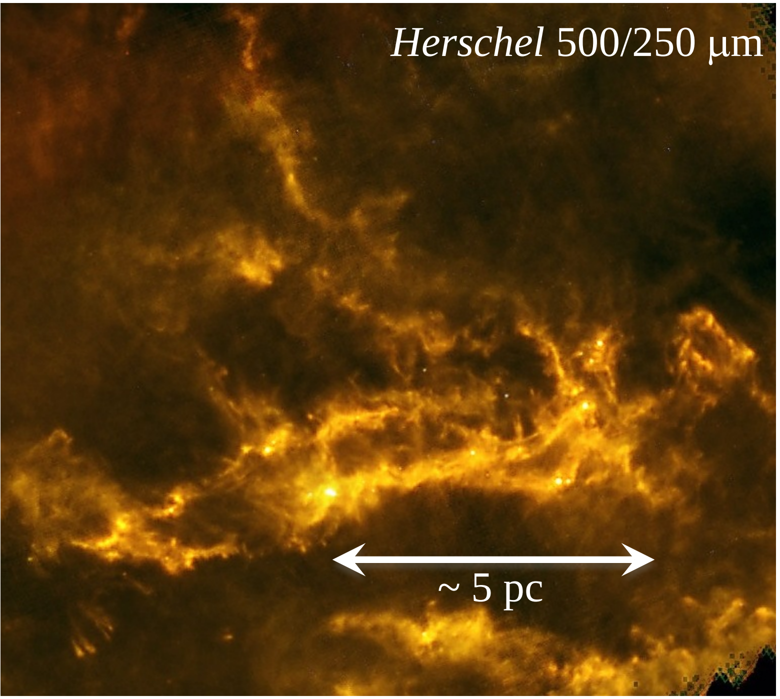
$$2R_{flat} \sim 0.1 \text{ pc}$$

Depth along los ~ 0.1 pc (D. Li & Goldsmith '12)

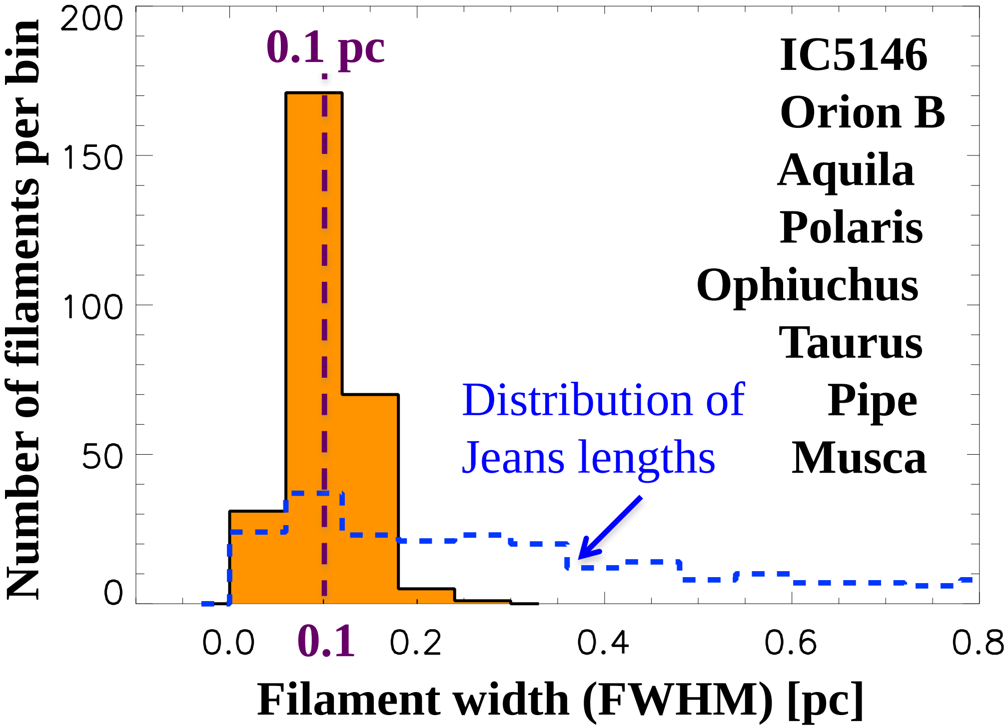


Filaments have a characteristic inner width ~ 0.1 pc

Network of filaments in IC5146



Statistical distribution of widths for > 270 nearby filaments

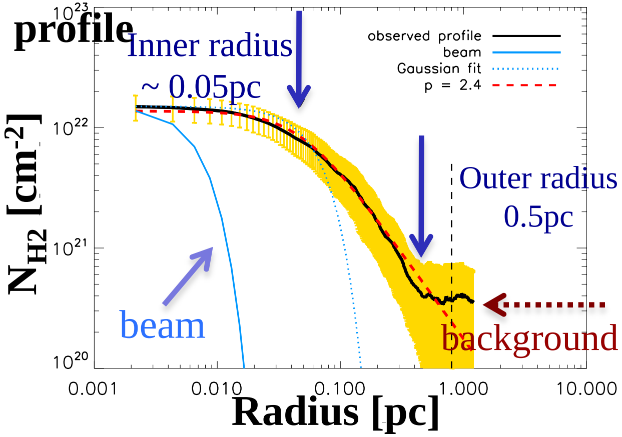


D. Arzoumanian et al. 2011 + PhD thesis

[see also Alves de Oliveira+2014 for Chamaeleon;

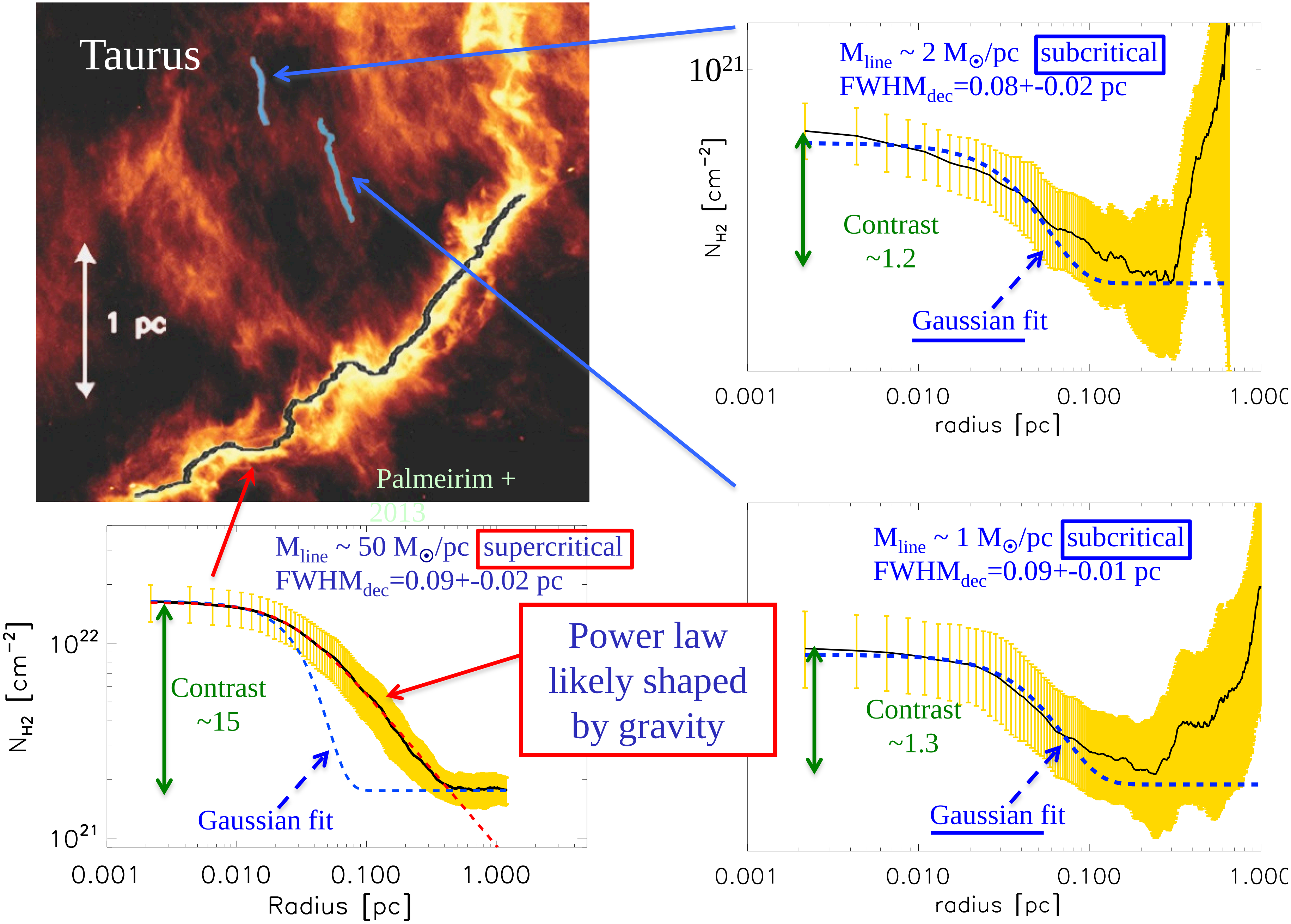
Some variations along each filament: Ysard+2014]

Example of a filament radial profile



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

Column density profiles of low- vs. high-density filaments



M_{line} ~ 2 $M_{\odot}$/pc **subcritical**
$FWHM_{dec}$=0.08+-0.02 pc

Contrast ~1.2

Gaussian fit

M_{line} ~ 50 $M_{\odot}$/pc **supercritical**
$FWHM_{dec}$=0.09+-0.02 pc

Contrast ~15

Gaussian fit

Power law likely shaped by gravity

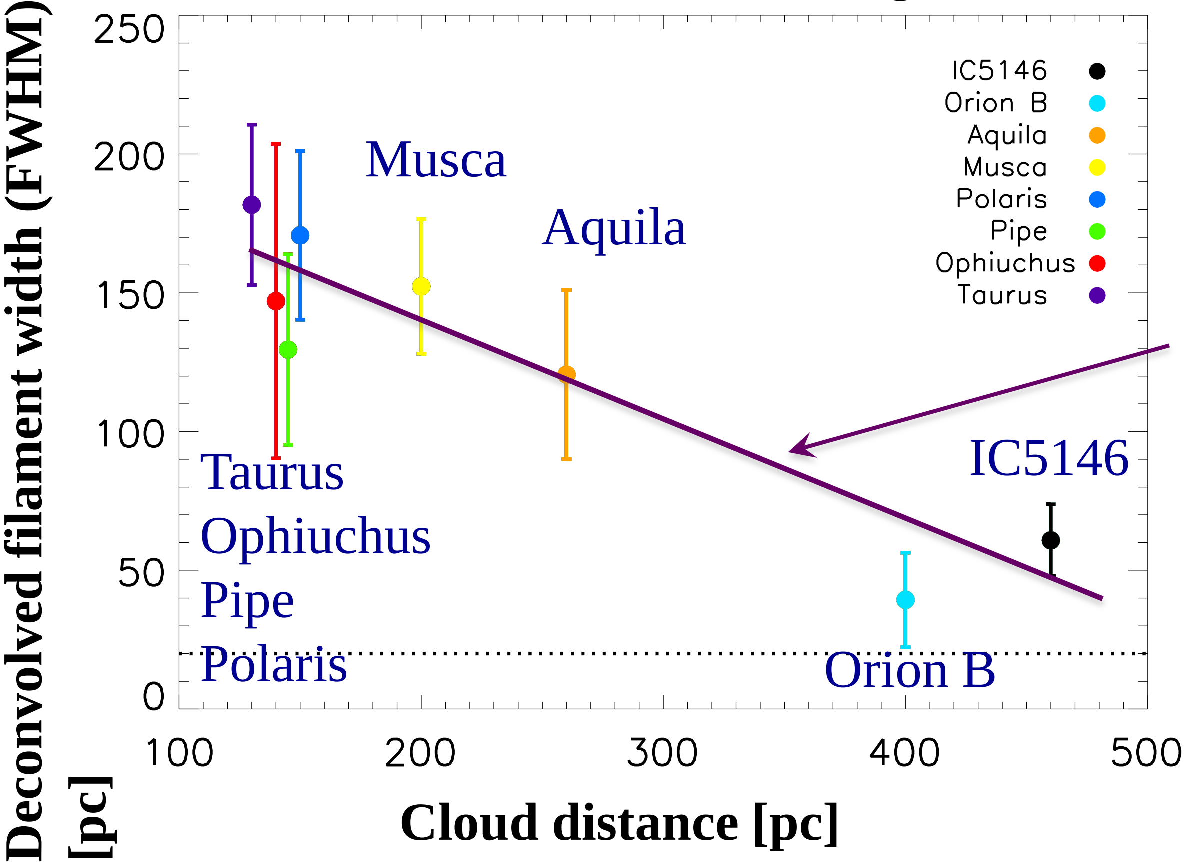
M_{line} ~ 1 $M_{\odot}$/pc **subcritical**
$FWHM_{dec}$=0.09+-0.01 pc

Contrast ~1.3

Gaussian fit

Variation of filament angular diameter with cloud distance

Median angular width of the filaments in each region



Common physical inner width ~ 0.1 pc

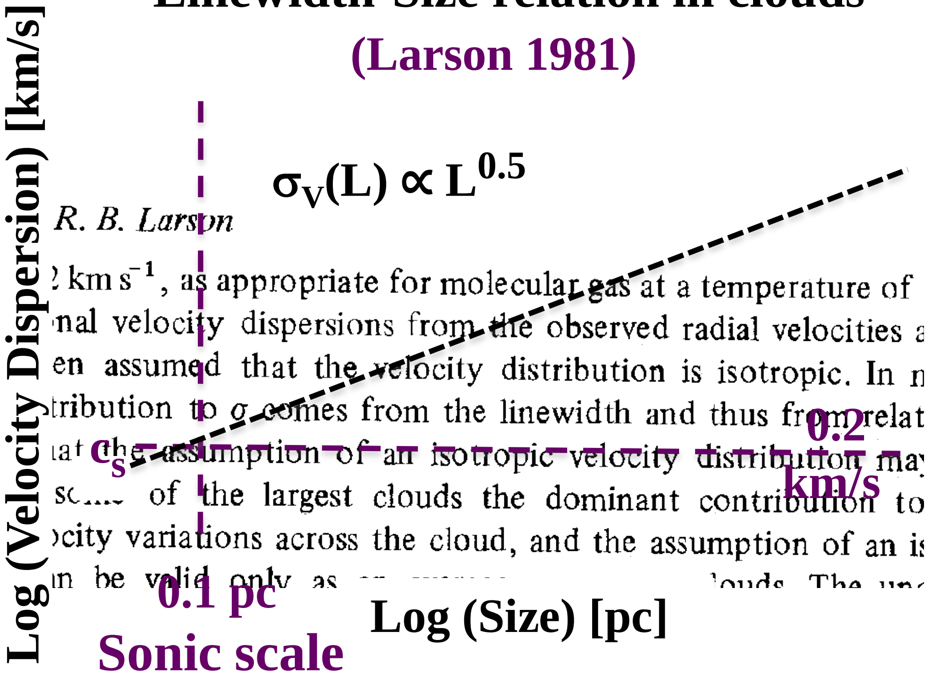
D. Arzoumanian’ s PhD thesis

Filaments due to large-scale supersonic turbulence ?

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

Linewidth-Size relation in clouds

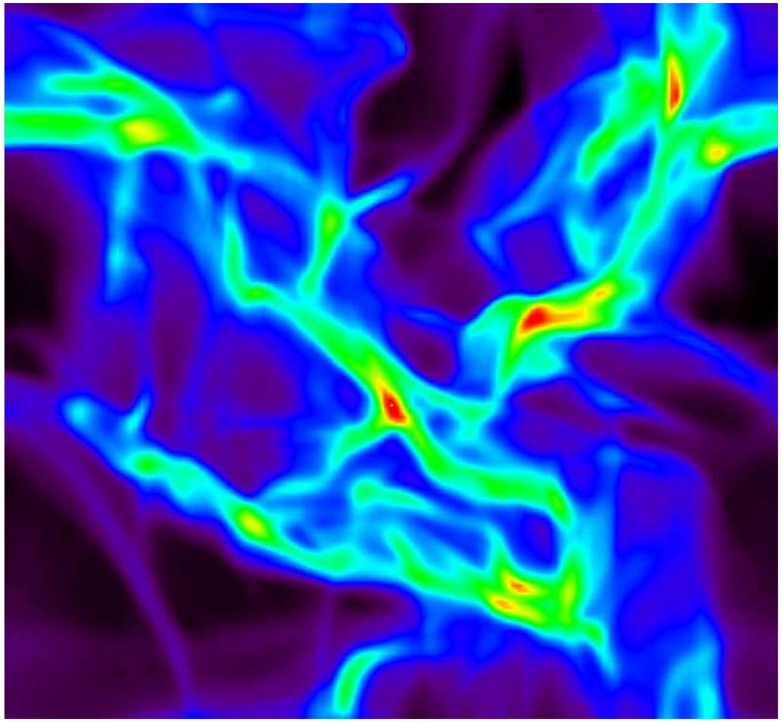
(Larson 1981)



R. B. Larson

km s^{-1}, as appropriate for molecular gas at a temperature of
nal velocity dispersions from the observed radial velocities a
en assumed that the velocity distribution is isotropic. In n
tribution to σ comes from the linewidth and thus from relat
at the assumption of an isotropic velocity distribution may
of the largest clouds the dominant contribution to
city variations across the cloud, and the assumption of an is
n be valid only as

Simulations of turbulent fragmentation



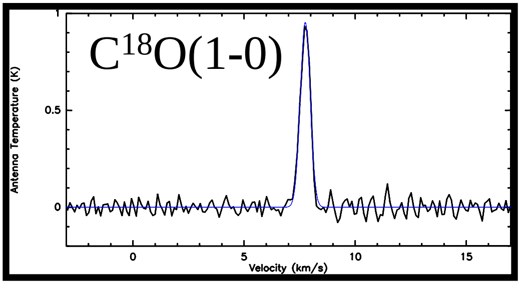
Padoan, Juvela et al. 2001

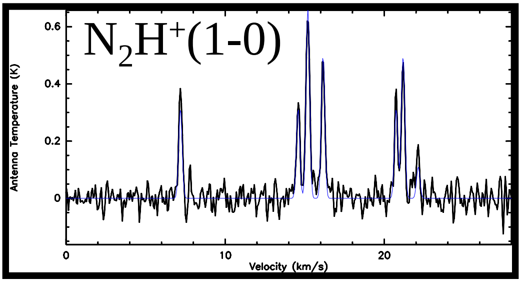
- **Corresponds to the typical thickness λ of shock-compressed layers in HD**

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

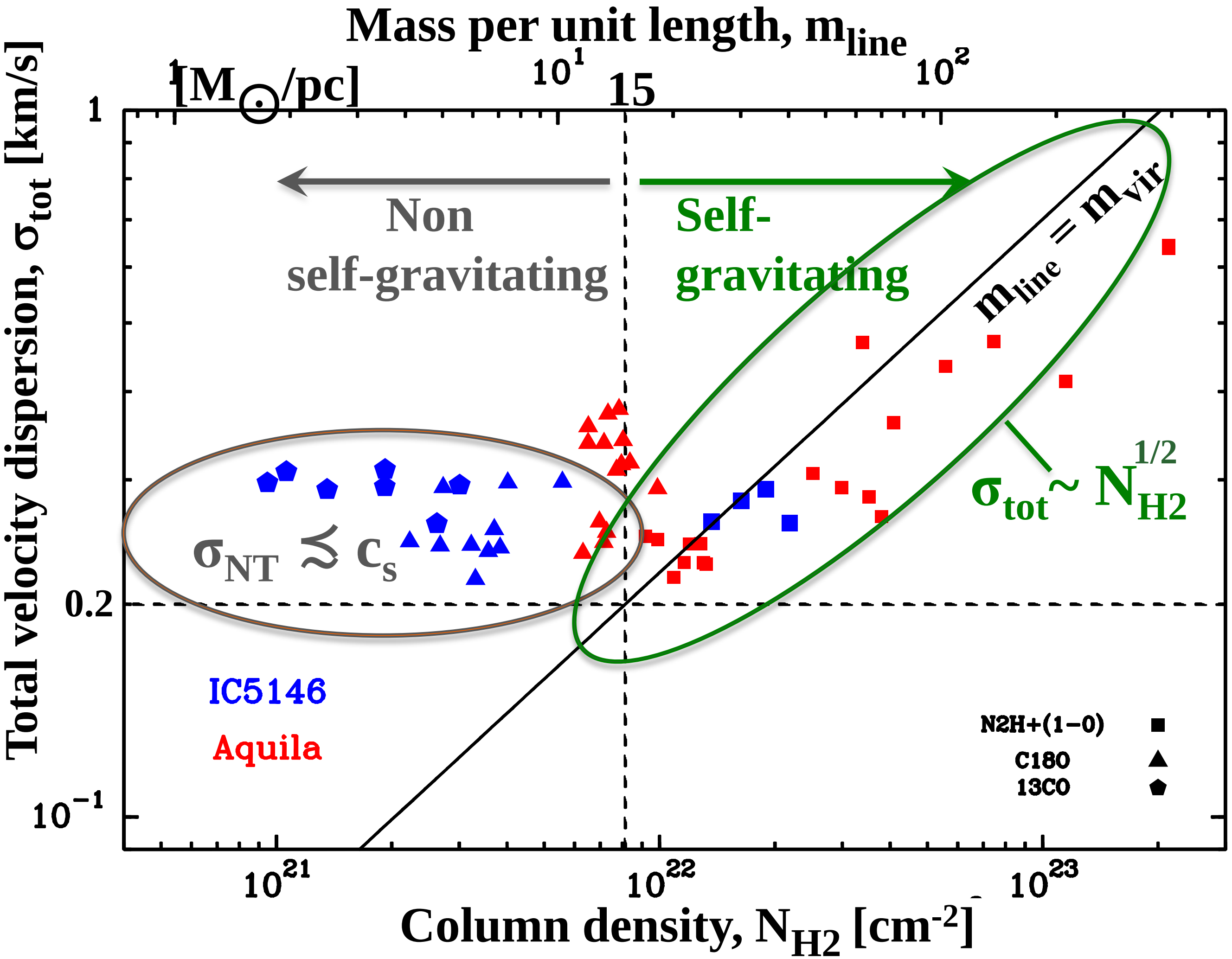
Velocity dispersion of filaments vs. column density

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)

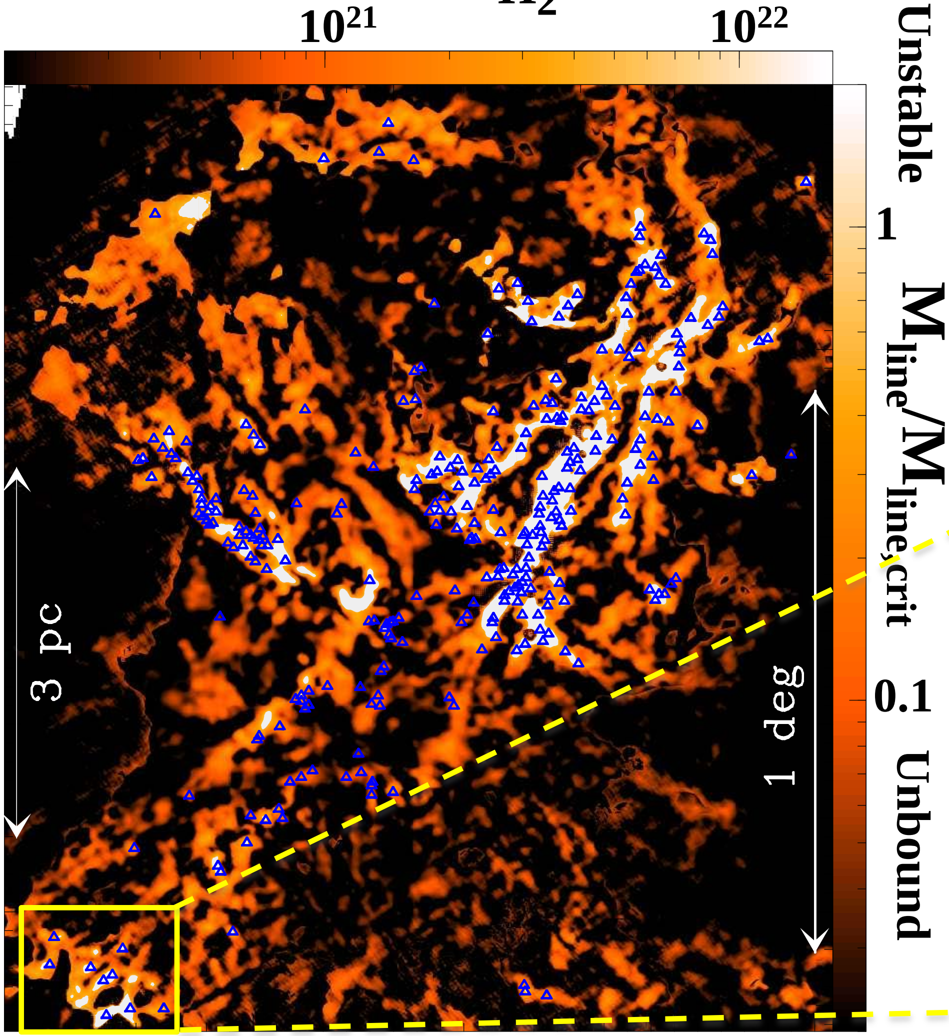
~ 75^{+15}_{-5} % of prestellar cores form in filaments, above a column density threshold $N_{H_2} \gtrsim 7\mathrm{x}10^{21}$ cm^{-2}

<=>

$A_V \gtrsim 7$

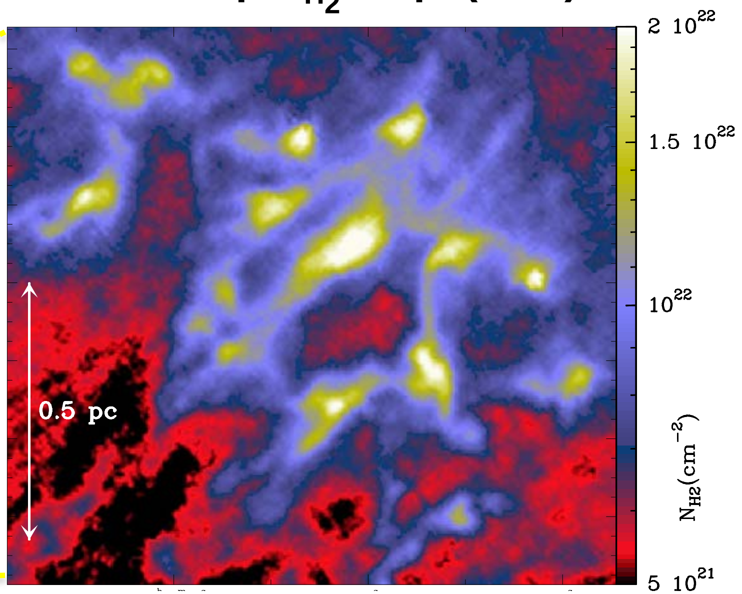
$\Sigma_{threshold} \sim 150\ M_{\odot}/\mathrm{pc}^2$

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



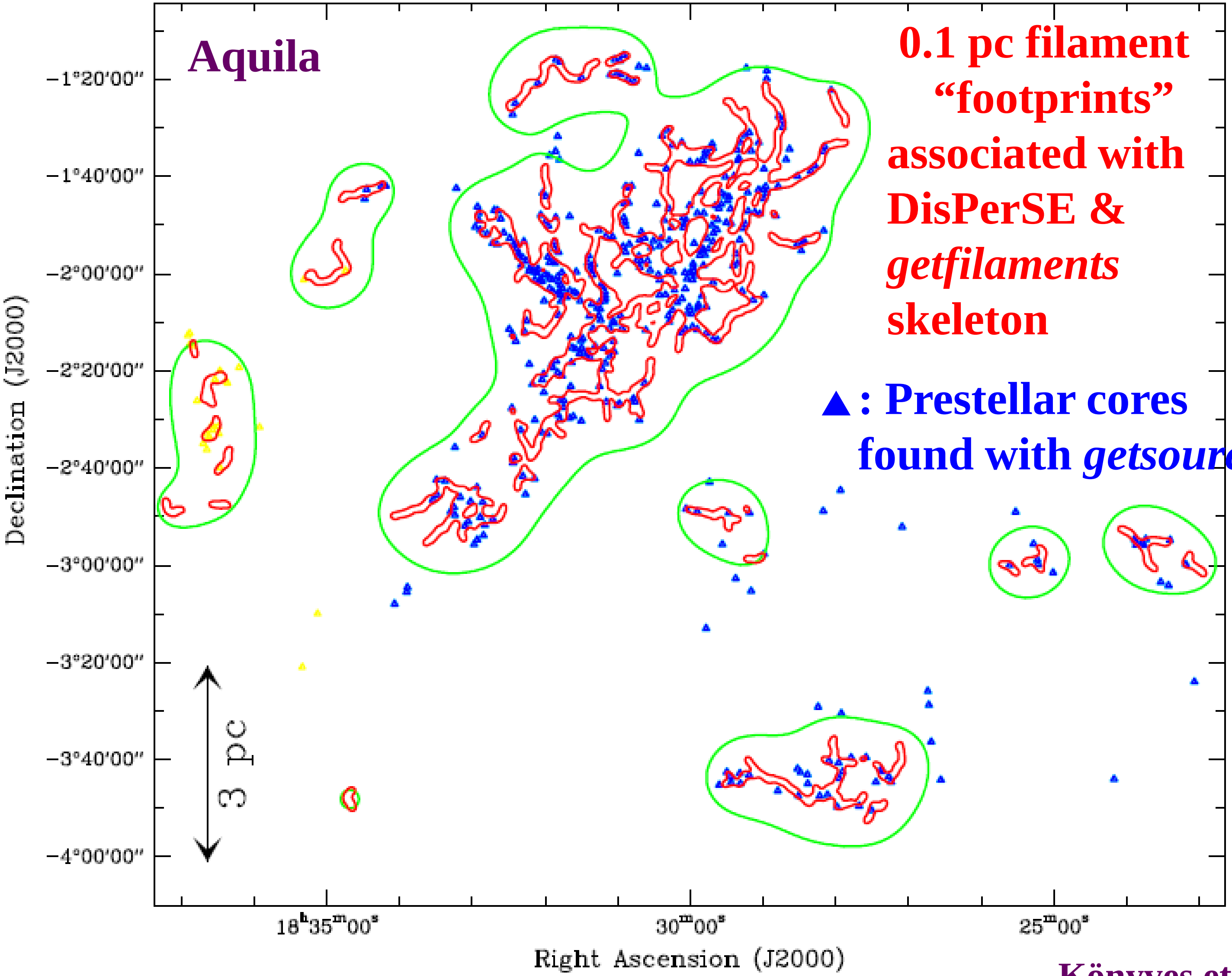
Examples of *Herschel* prestellar cores (Δ)

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



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

Quantifying the connection between filaments & cores



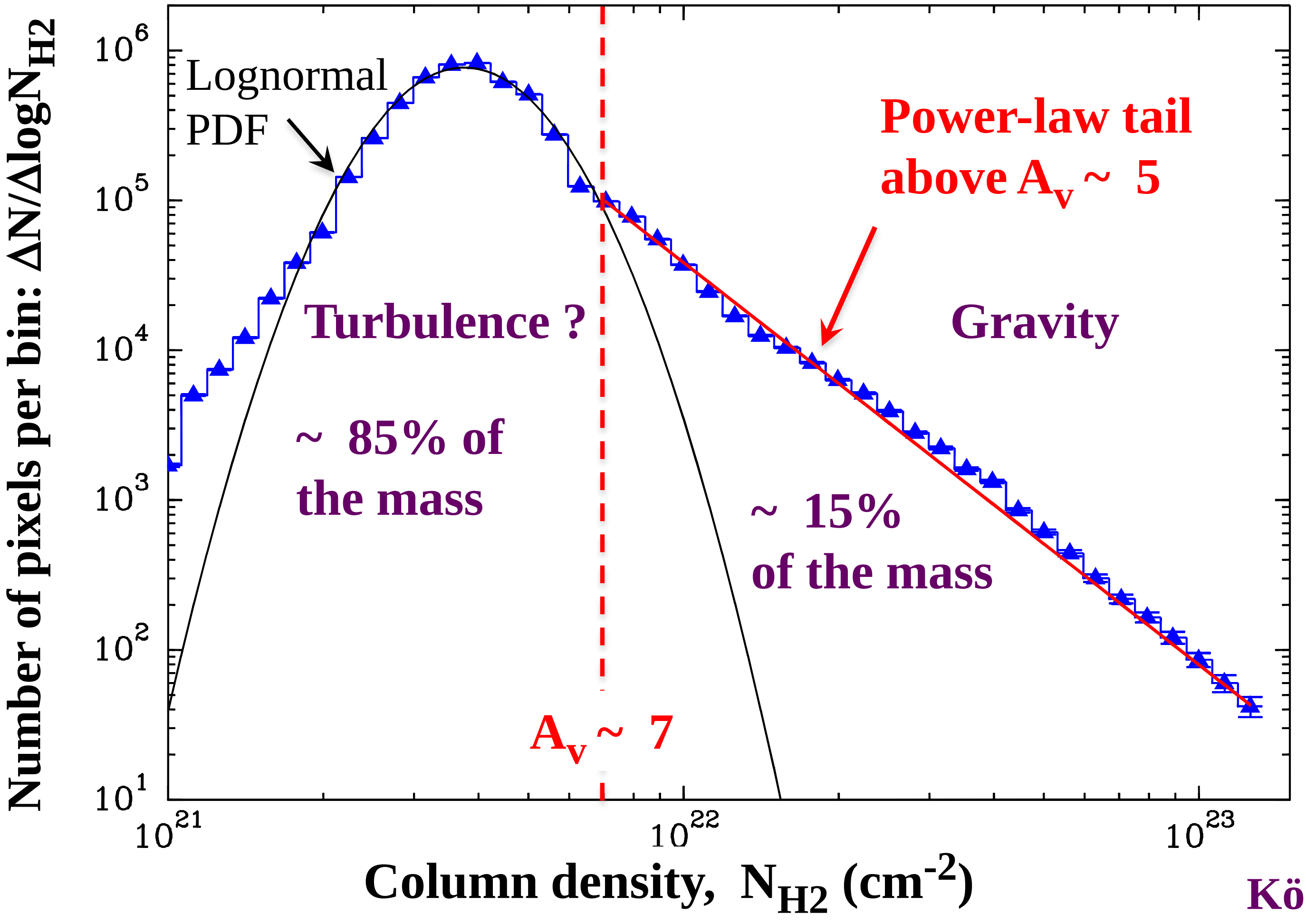
0.1 pc filament “footprints” associated with DisPerSE & *getfilaments* skeleton

▲: Prestellar cores found with *getsources*

Könyves et al., in prep.

Mass budget in the Aquila cloud complex

Column Density Probability Density Function for Aquila

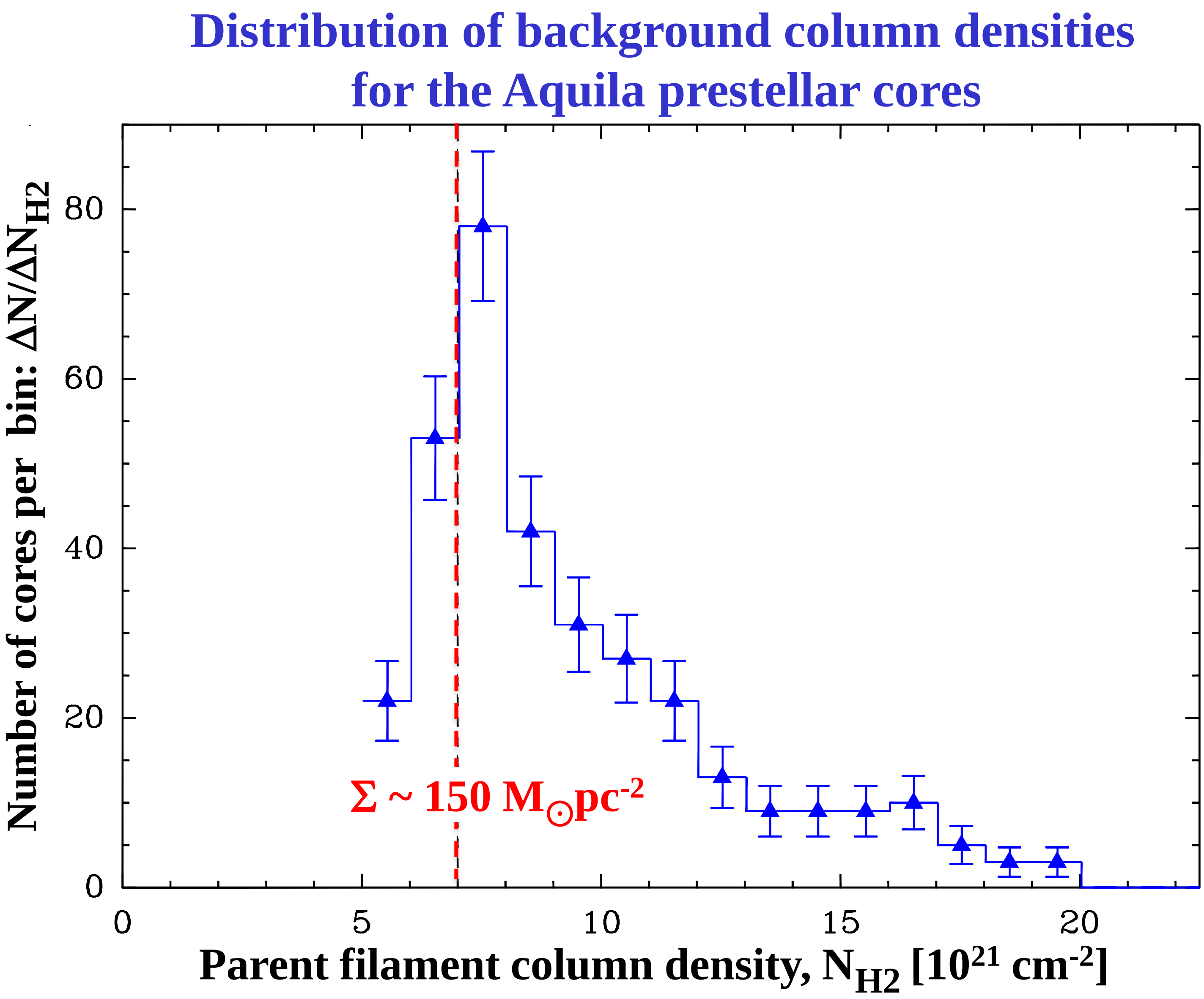


(See Schneider+2013 and Schneider+2014 for other, similar column density PDFs from *Herschel*)

Könyves et al. in prep

- **Below A_V ~ 7: ~ 20 % of the mass in the form of filaments, < 1% in prestellar cores**
- **Above A_V ~ 7: > 50 % of the mass in the form of filaments, ~ 15 % in prestellar cores**

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

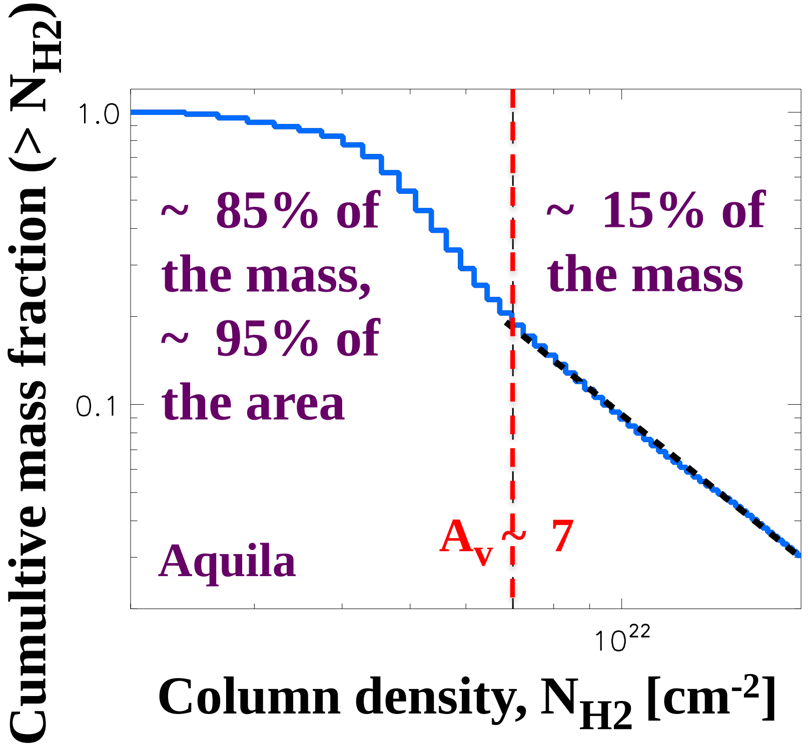
André+2014 PPVI

See also:

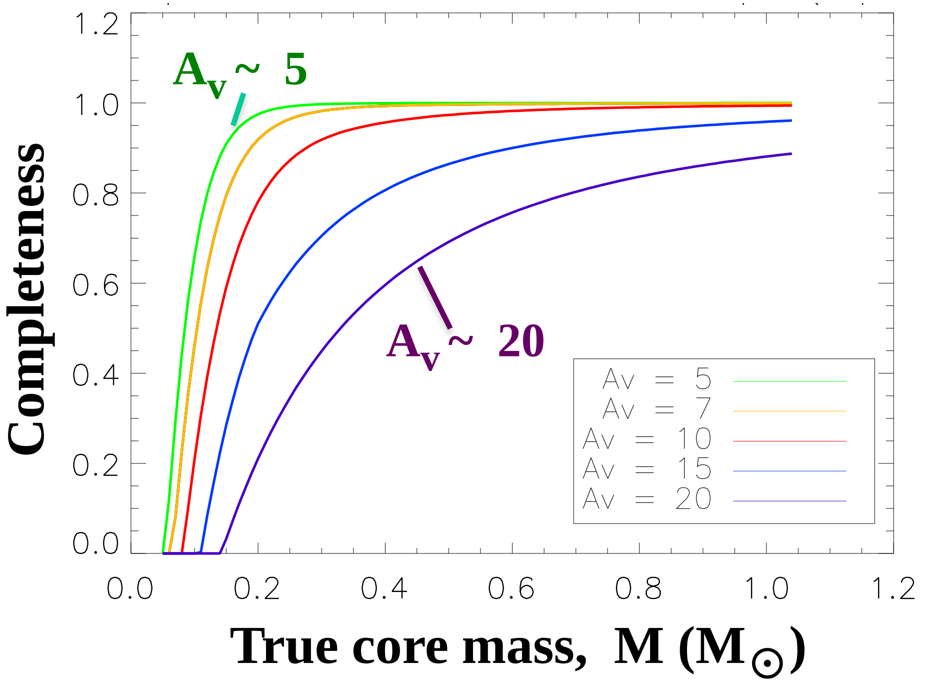
Onishi+1998

Johnstone+2004

Distribution of mass in the parent cloud and background-dependent completeness imply that this threshold is very significant !



Completeness curves vs. background A_V



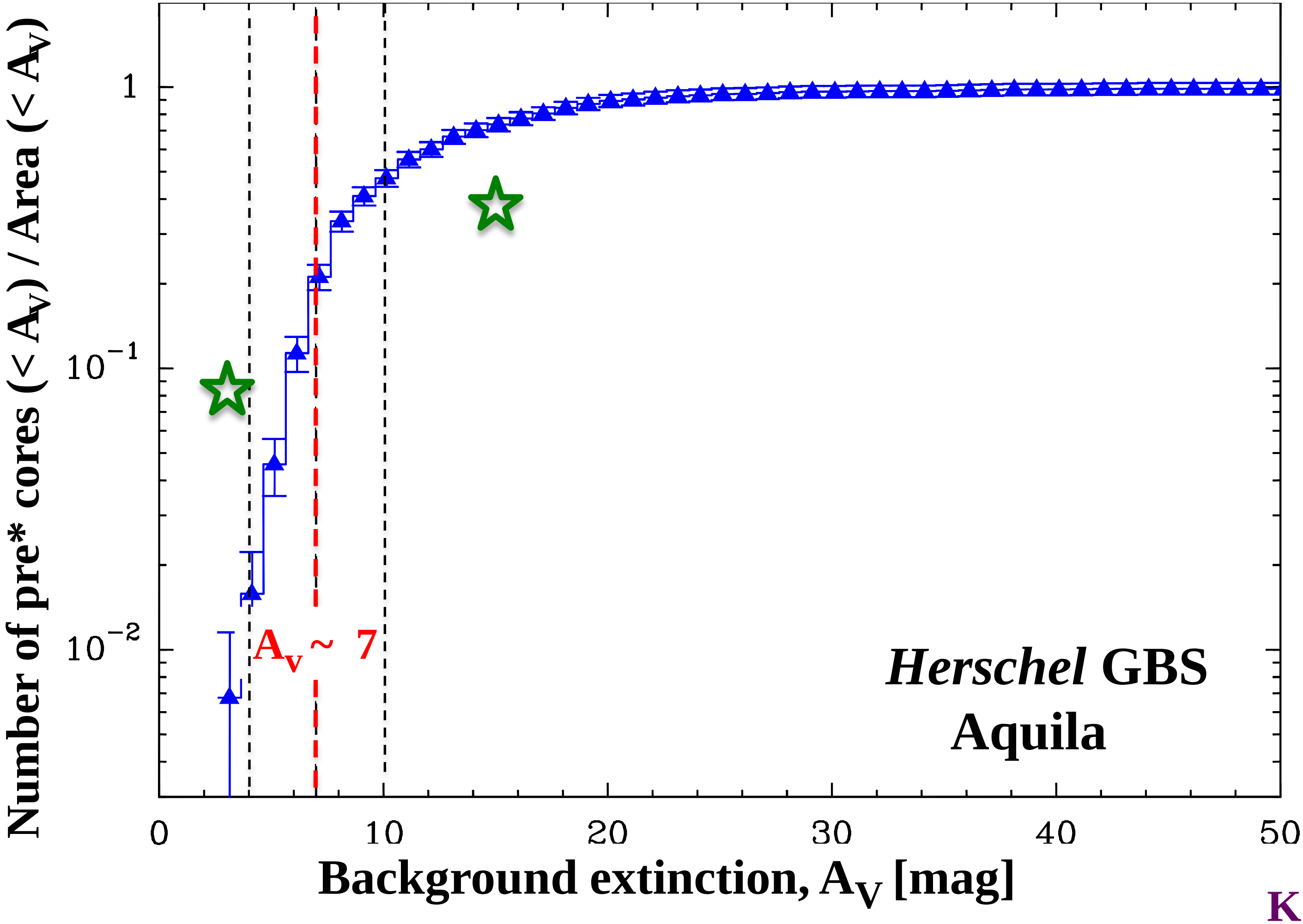
Könyves et al. in prep

(See also Lada+2010 for similar mass fraction plots based on extinction)

Completeness ↘ when A_V ↗ because “cirrus noise” fluctuations ↗ (cf. Gautier et al. 1992)

Real "threshold" or rising probability of core/star formation with increasing A_V ?

Probability of finding a prestellar core below a given extinction



Sharper transition
than

Predictions of models with no SF threshold and $\varepsilon_{ff} \sim 1\%$

Krumholz+2012

Hennebelle & Chabrier 2011

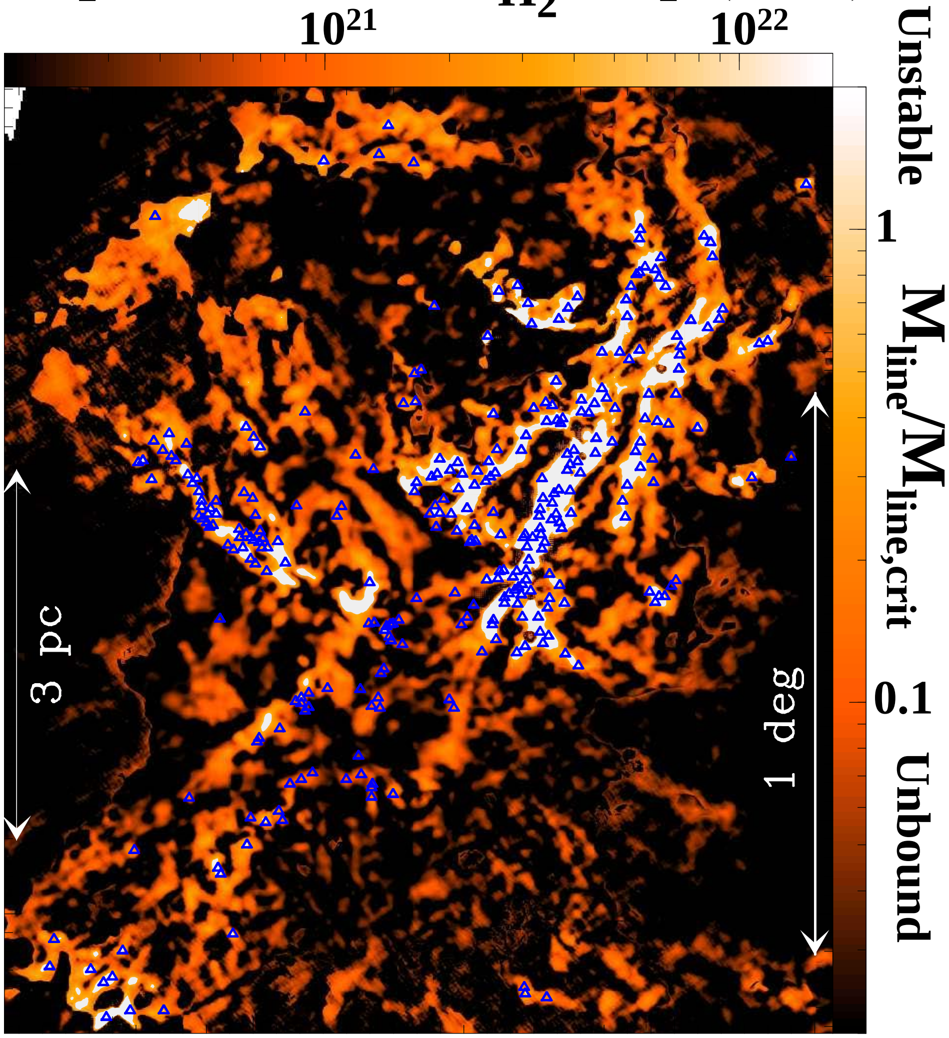
(NB: Similar conclusion by Evans+2014 using YSOs)

Könyves et al. in prep

Σ or M/L threshold above which interstellar filaments are gravitationally unstable

△ : Prestellar cores

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



André et al. 2010

- ➢ The gravitational instability of filaments is controlled by the mass per unit length M_{line} (Ostriker'64, Inutsuka & Miyama'97):

- 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 ~ 10 K ⬄ n_{H2} threshold $\sim 2 \times 10^4\, cm^{-3}$

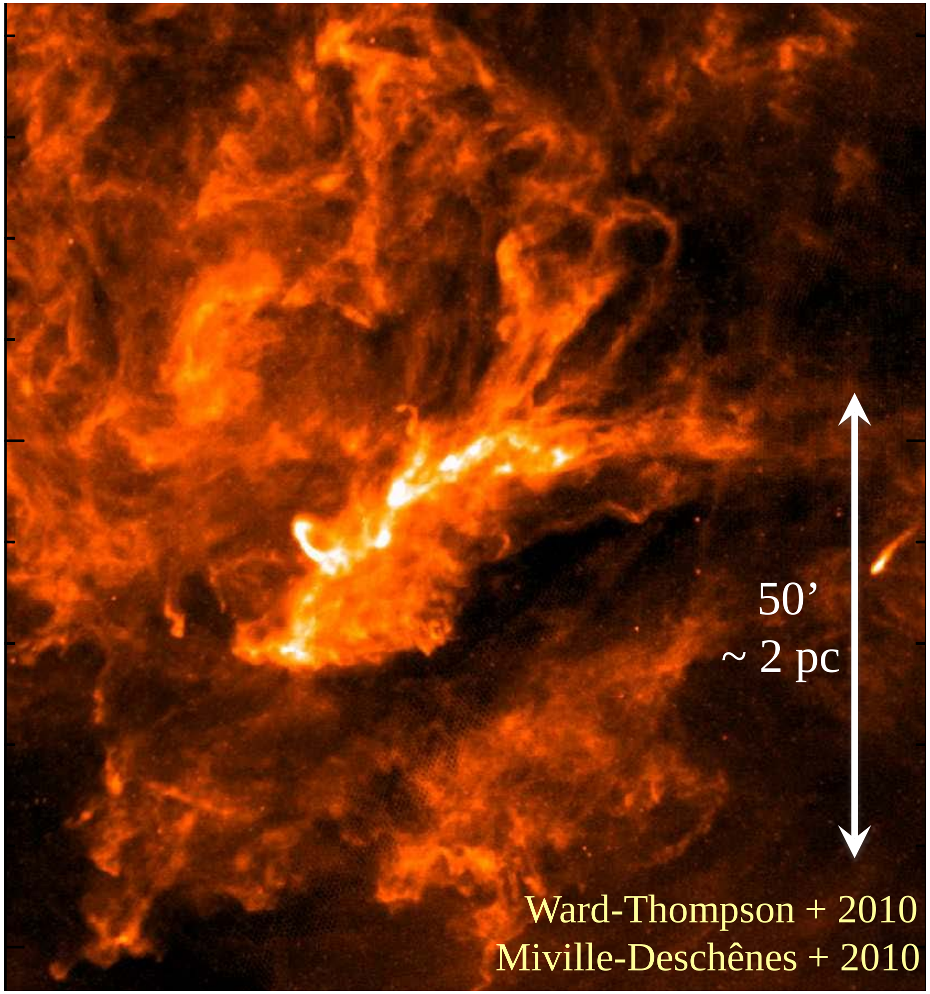
➢ Simple estimate: $M_{line} \propto N_{H2}$ x Width (~ 0.1 pc)

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

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

See PPVI chapter (André, Di Francesco, Ward-Thompson, Inutsuka, Pudritz, Pineda 2014 - astro-ph/1312.6232)

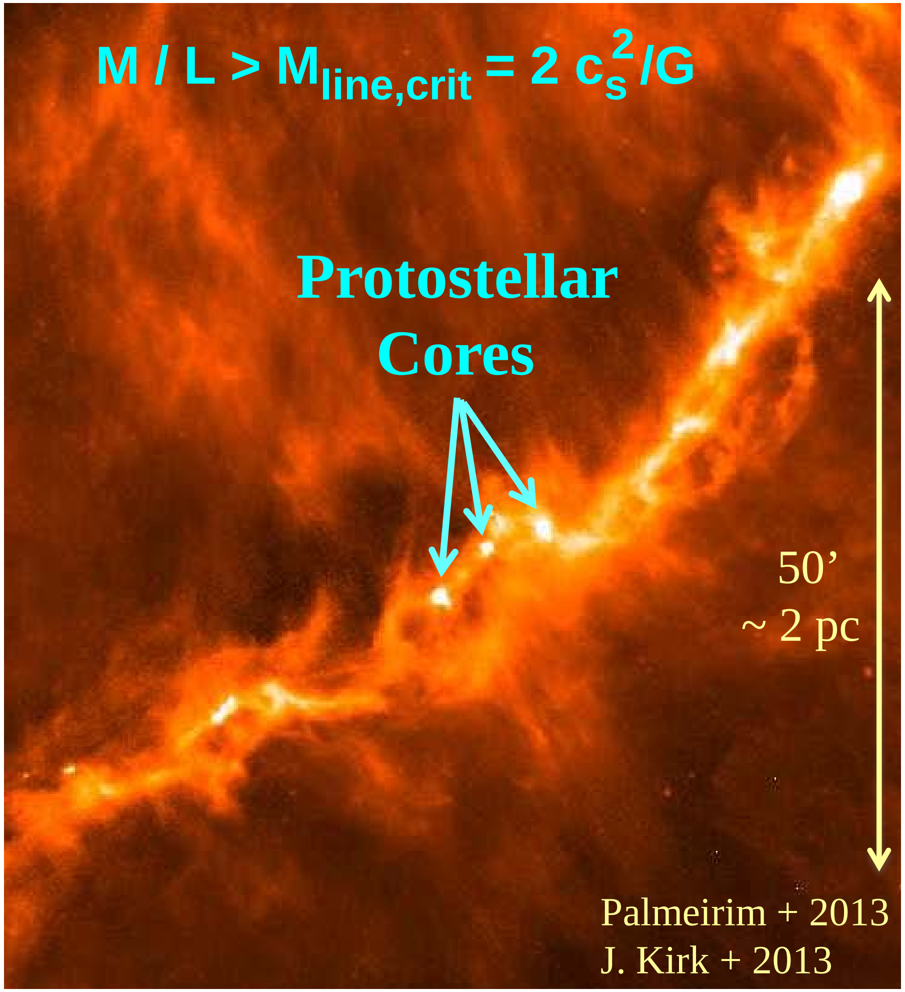
1) Large-scale MHD supersonic 'turbulence' generates filaments



Ward-Thompson + 2010
Miville-Deschênes + 2010

Polaris – *Herschel*/SPIRE 250 μm

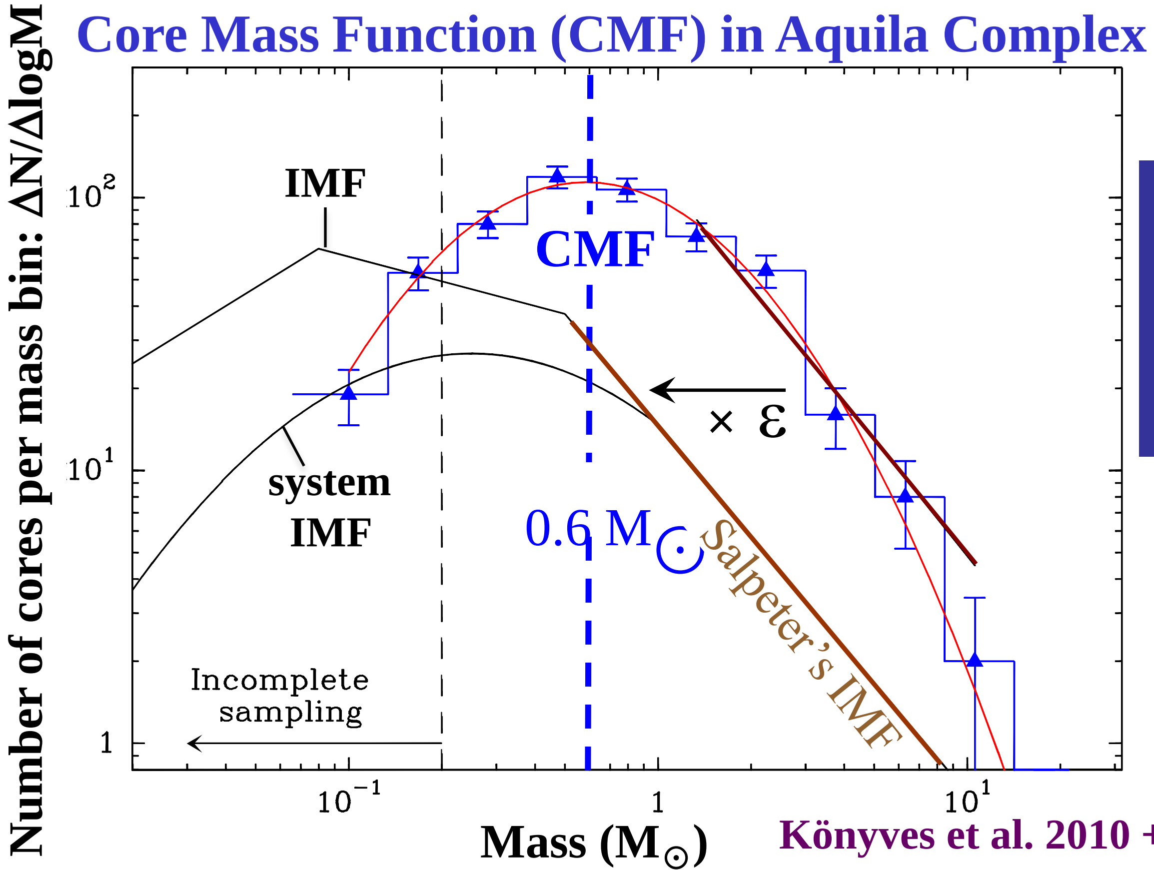
2) Gravity fragments the densest filaments into prestellar cores


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

Palmeirim + 2013
J. Kirk + 2013

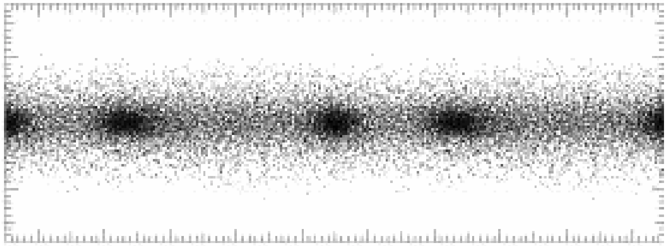
Taurus B211/3 – *Herschel* 250 μm

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


Core Mass Function (CMF) in Aquila Complex

Jeans mass:

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

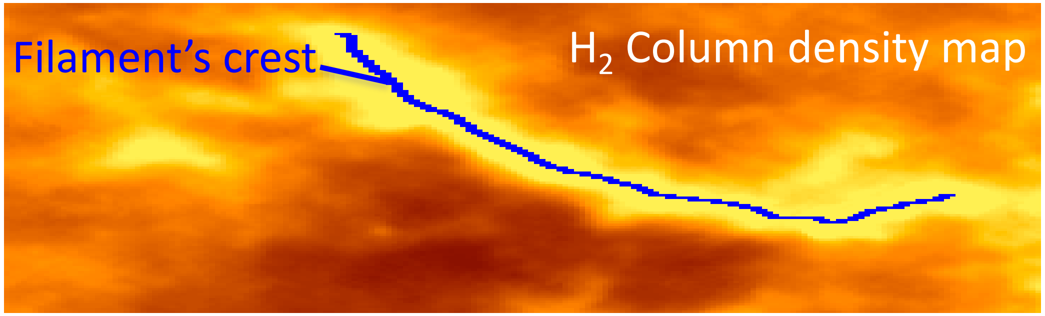


Könyves et al. 2010 + in prep.
André+2014 PPVI

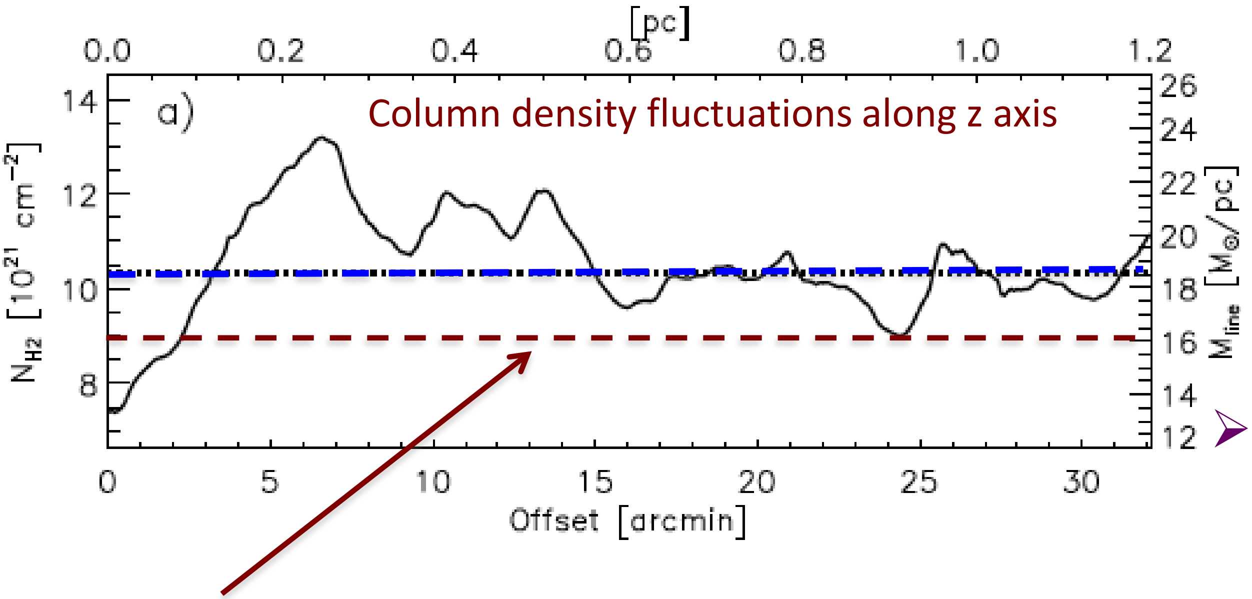
- ➢ CMF peaks at ~ 0.6 $M_\odot$ ≈ Jeans mass in marginally critical filaments
- ➢ Close link of the prestellar CMF with the stellar IMF: $M_\star \sim 0.3 \times M_{core}$
- ➢ Characteristic stellar mass may result from filament fragmentation

Can filament fragmentation account for the Salpeter power-law of the IMF ?

Example of line mass fluctuations along the long axis of a marginally critical filament



Theoretical arguments (Inutsuka 2001) suggest that this is possible provided turbulence has generated the appropriate power spectrum of initial density fluctuations



Mean line mass ≈ 18 $M_\odot$/pc

Critical line mass ~ 16 $M_\odot$/pc for an isothermal cylinder at T = 10 K

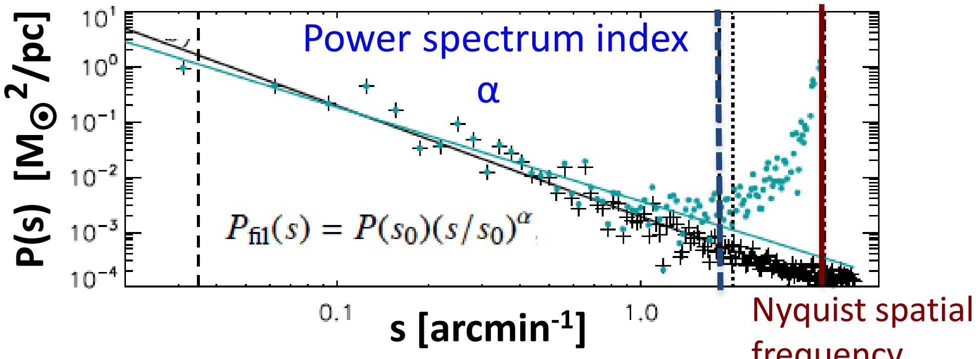
Roy et al. 2014

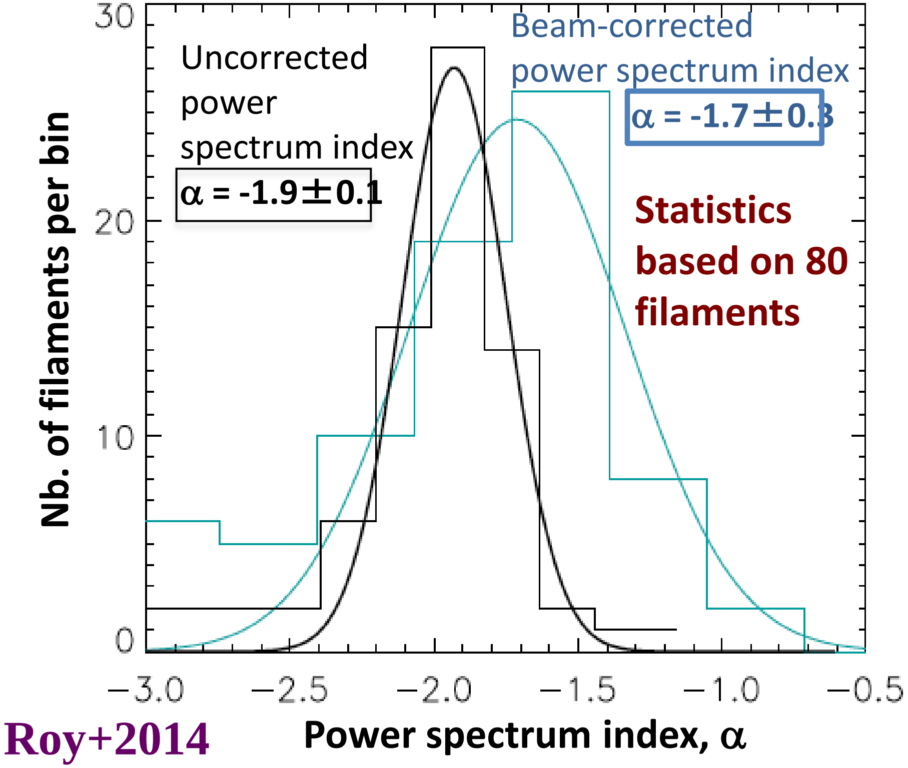
- **Statistical analysis of the line-mass fluctuations for a sample of 80 subcritical or marginally supercritical *Herschel* filaments**

Statistical properties of line-mass fluctuations

Implication

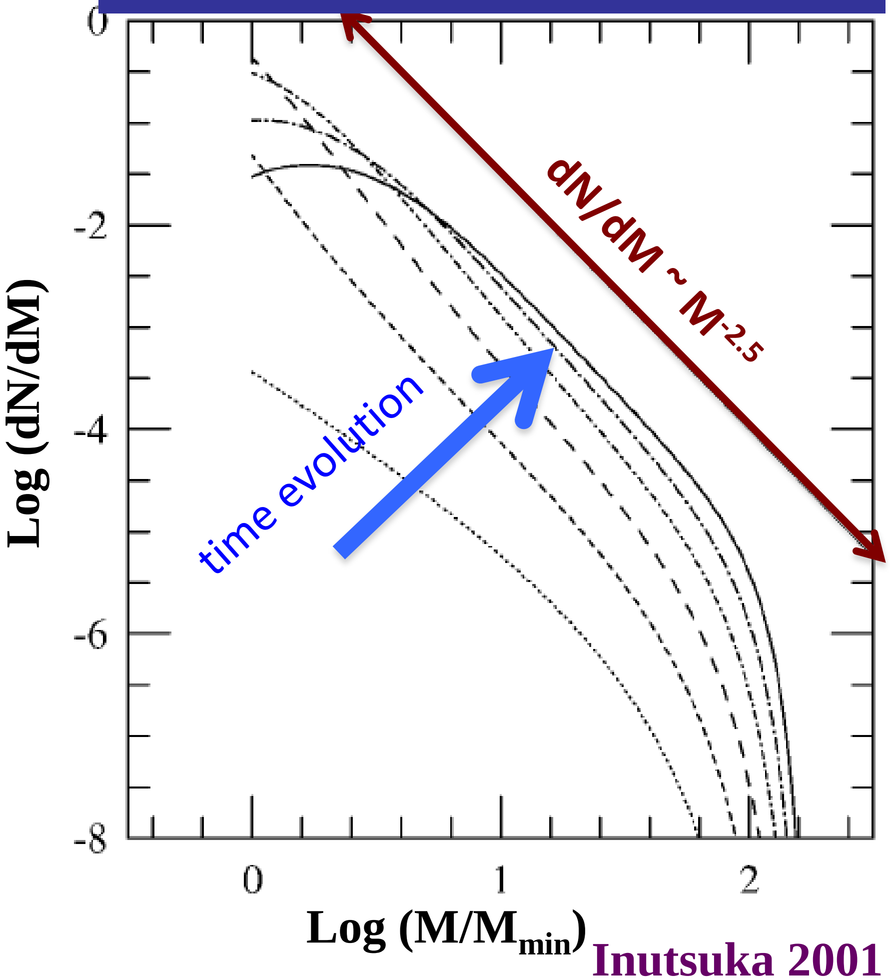
Power spectrum of line-mass fluctuations





Roy+2014

Evolution toward a Salpeter-like core mass function when initial power spectrum index α ~ -1.5



Inutsuka 2001

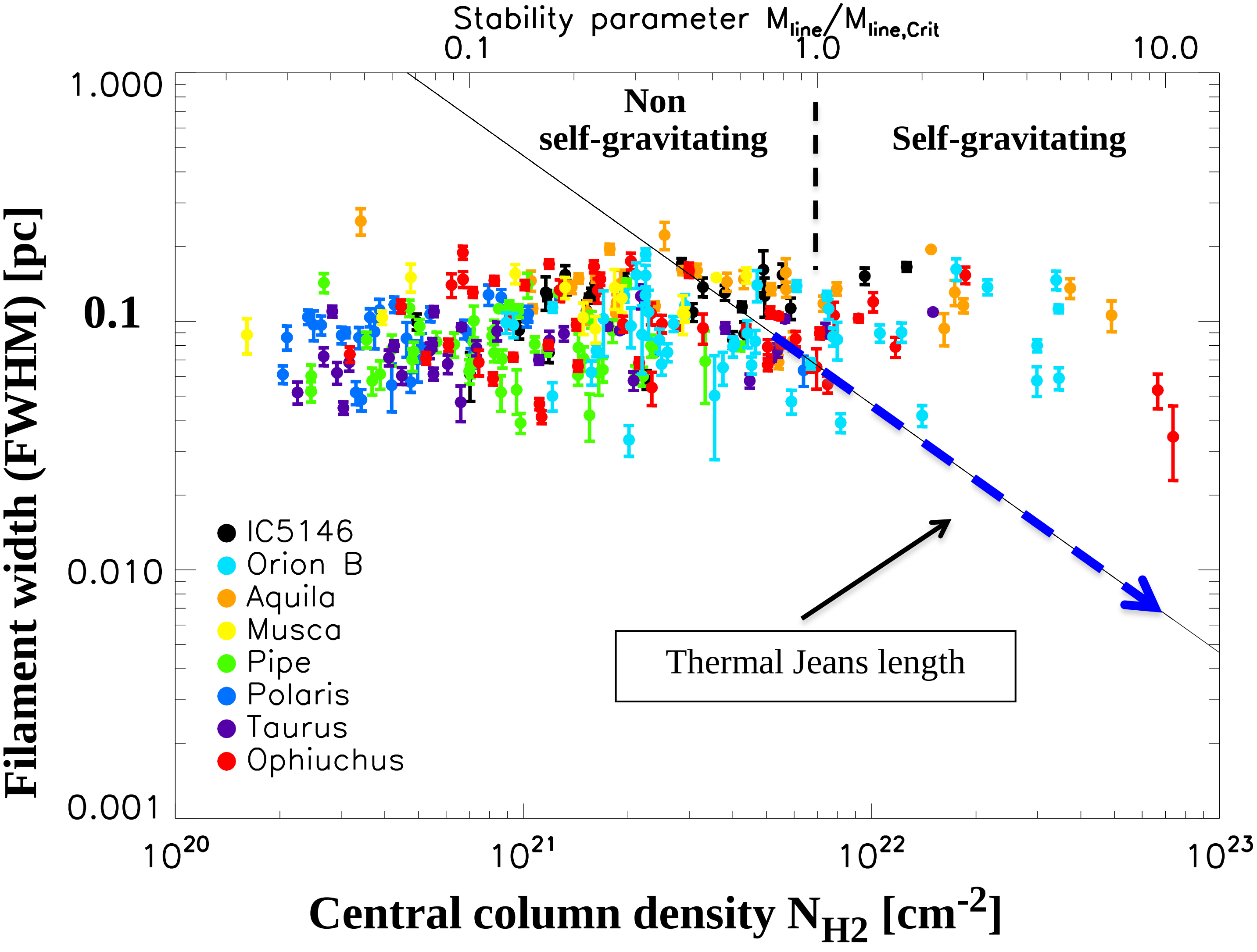
Summary: A filamentary paradigm for star formation in GMCs ?

- Observational facts: Most SF occurs in dense gas above $A_V \sim 7$;
  > 50% of this dense gas is in the form of filaments;
  > 75% of prestellar cores are within dense filaments.

- *Herschel* results suggest **star formation occurs in 2 main steps**:
  1) ~ 0.1 pc-wide filaments form first in the cold ISM, probably as a result of the dissipation of large-scale **MHD turbulence**;
  2) The densest filaments grow and fragment into prestellar cores via **gravitational instability** above a critical (column) density threshold $\Sigma_{th} \sim 150\ M_\odot\ pc^{-2} \Leftrightarrow A_V \sim 7 \Leftrightarrow n_{H2} \sim 2 \times 10^4\ cm^{-3}$

- Filament fragmentation appears to produce the peak of the prestellar CMF and may account for the « base » of the IMF, possibly more (?)

Origin of the characteristic width of filaments ?



Paradox:

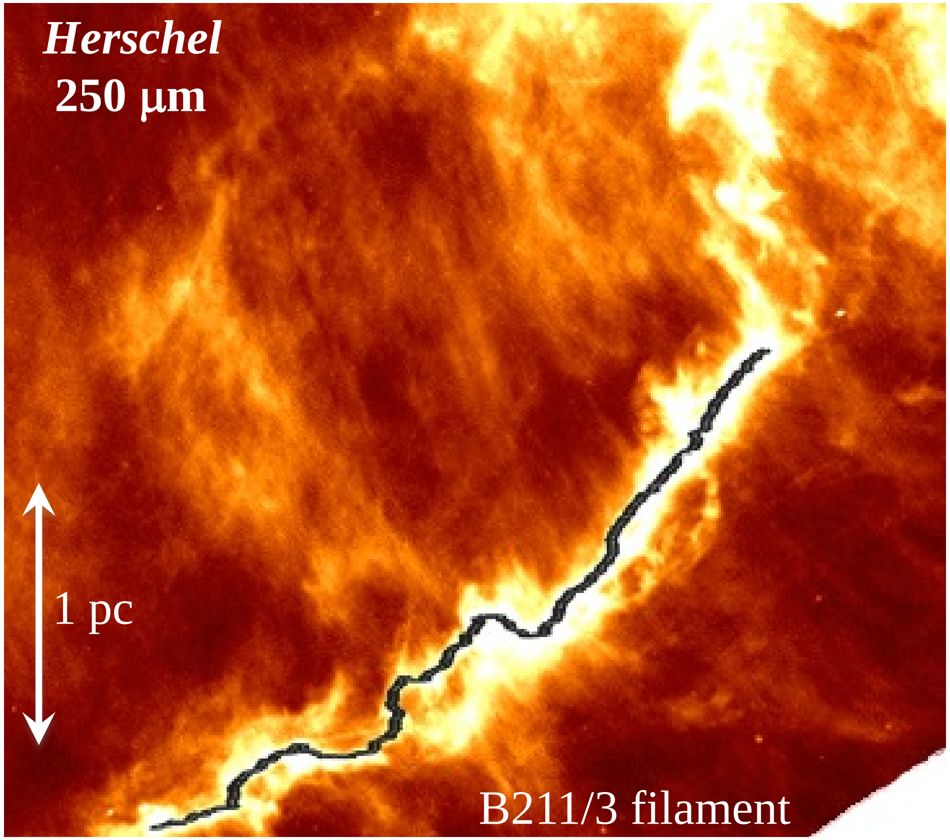
Dense filaments should radially contract !

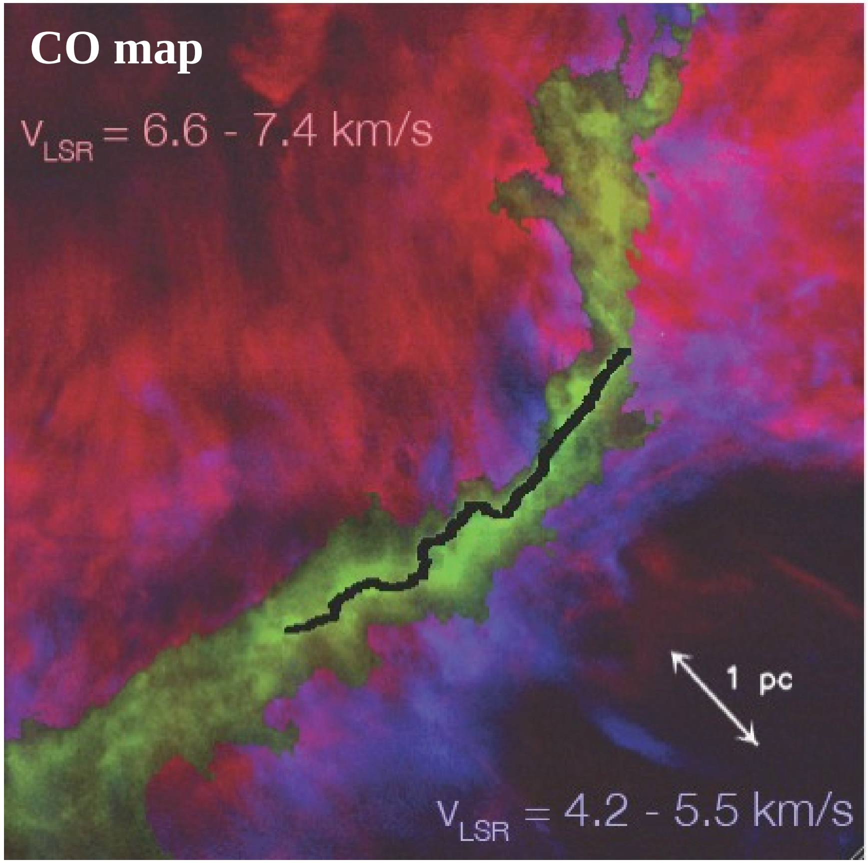
D. Arzoumanian et al. 2011 + PhD thesis

Key: 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 (see also H. Kirk, Myers ea 2013 for another example: Serpens-South)



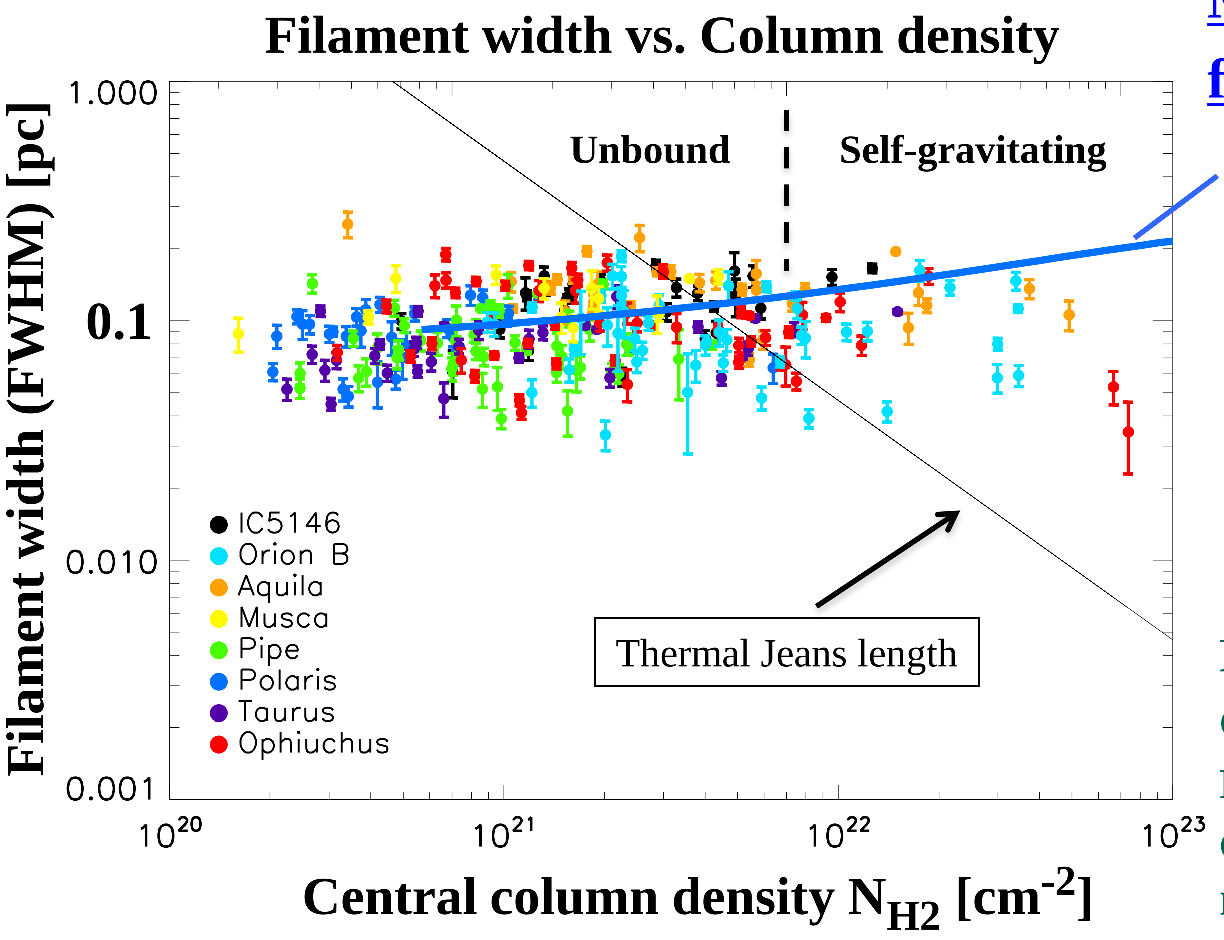


Estimate of the mass accretion rate:

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

CO observations from Goldsmith et al. 2008

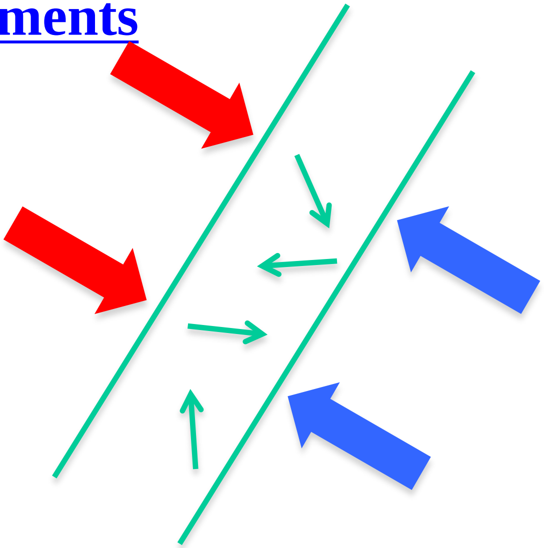
Accretion-driven MHD turbulence can prevent the radial contraction of dense filaments



Filament width vs. Column density

D. Arzoumanian et al. 2011 + PhD thesis
+ Hennebelle & André 2013 (see also Heitsch 2013)

Model of accreting filaments



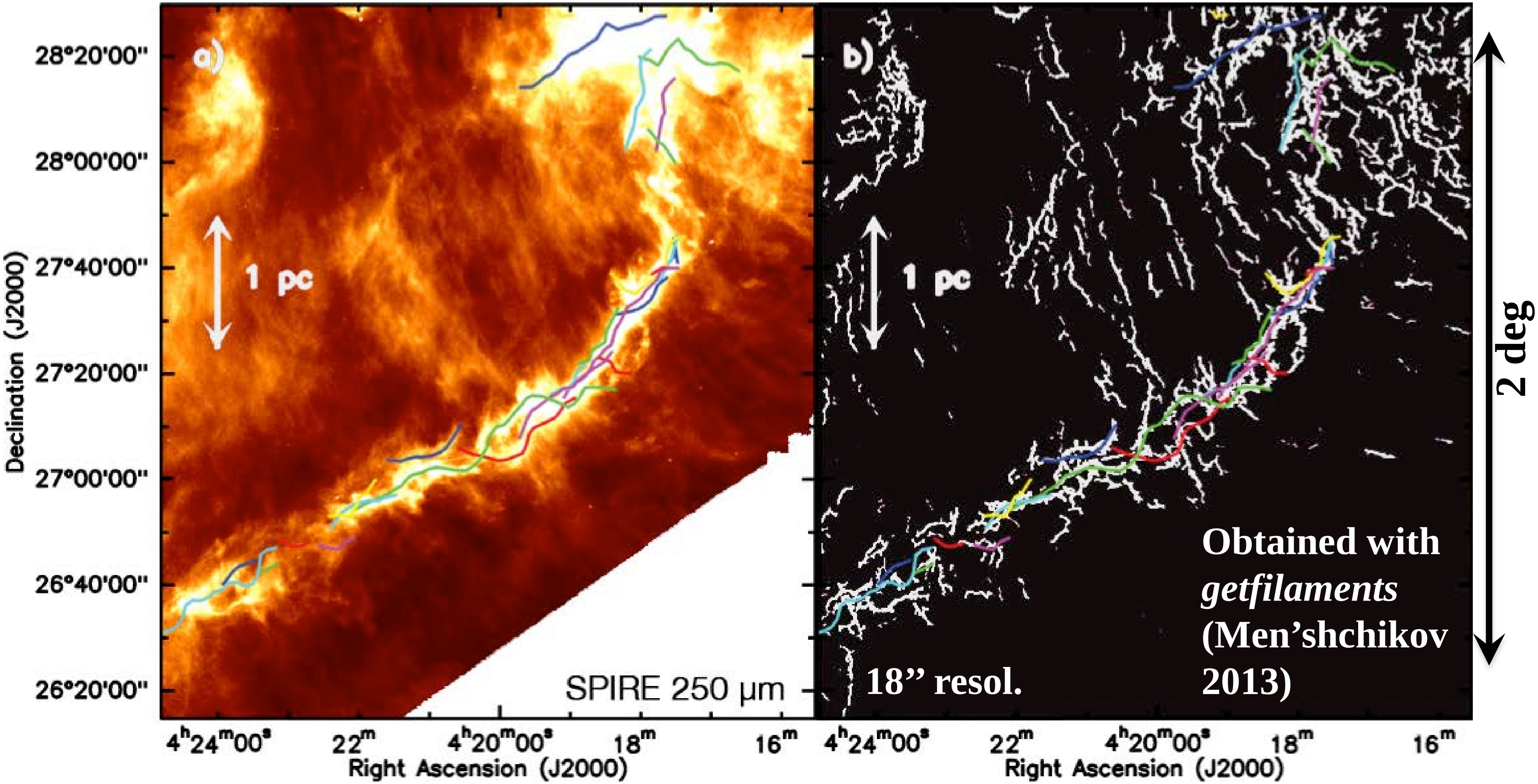
Balance between accretion-driven turbulence (Klessen & Hennebelle 2010) and dissipation of MHD turbulence due to ion-neutral friction

« Dynamical » equilibrium with <width> ~ 0.1 pc

‘Fibers’: A possible manifestation of accretion-driven turbulence ?

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.

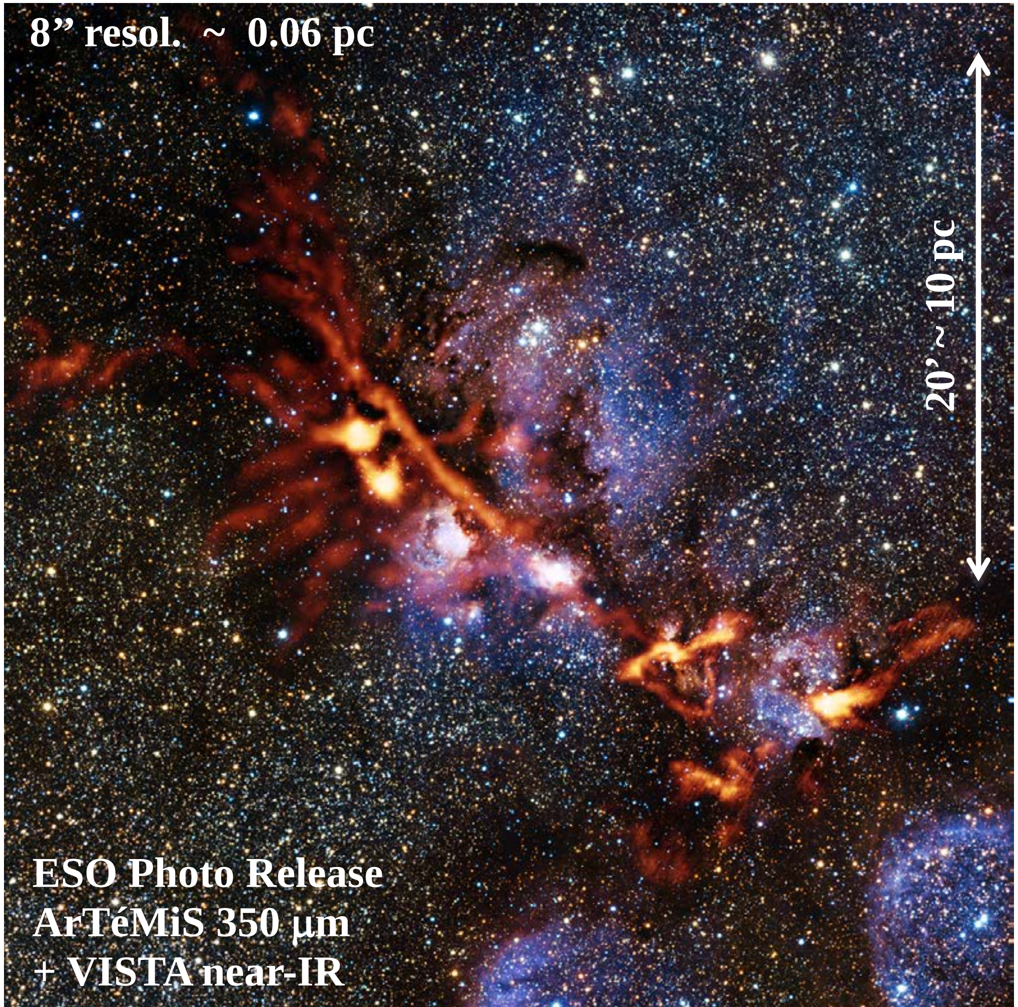
Obtained with *getfilaments* (Men’shchikov 2013)

ArTéMiS : A powerful tool to study massive star-forming filaments (‘ridges’) beyond the Gould Belt

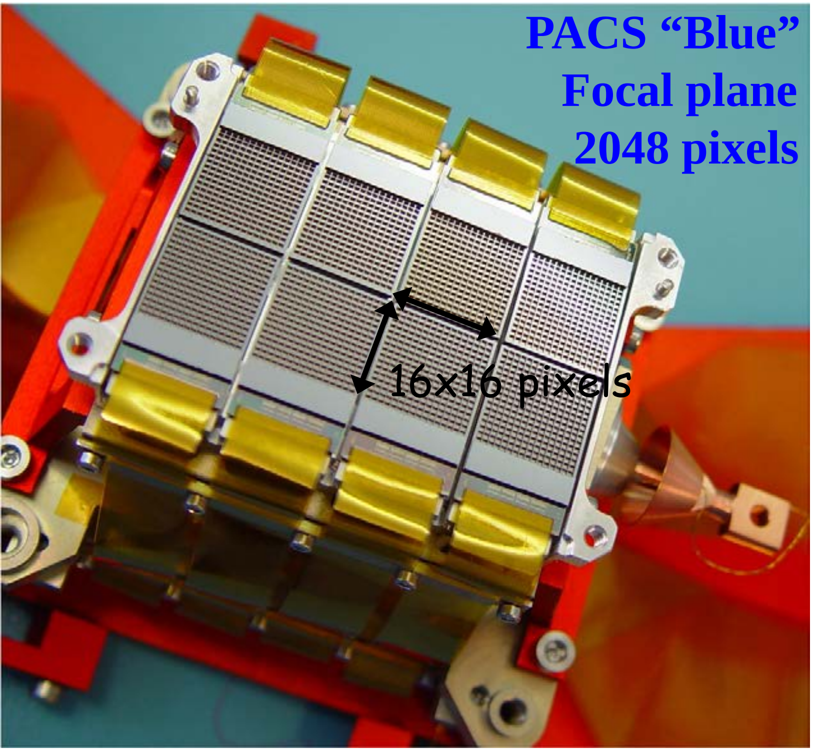
× 3.4 higher resolution than SPIRE

× 3-(10) faster than SABOCA

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



ESO Photo Release
ArTéMiS 350 μm
+ VISTA near-IR

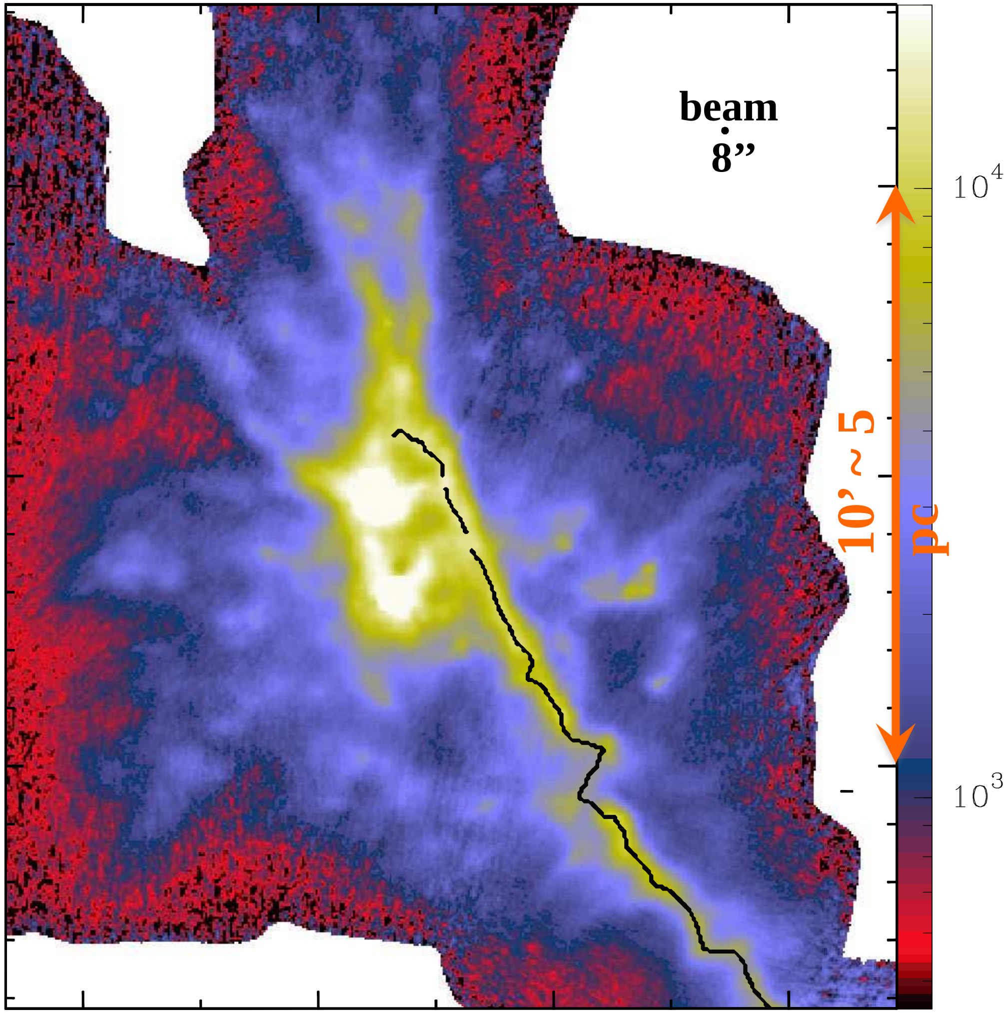


PACS “Blue”
Focal plane
2048 pixels

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

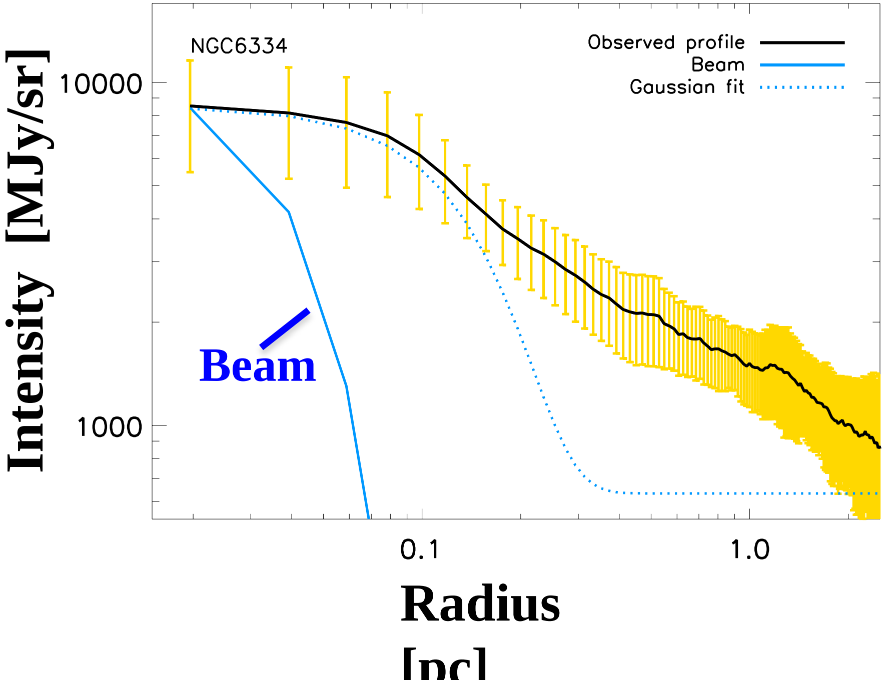
Resolving the NGC 6334 main filament (d ~1.7 kpc) with ArTéMiS + *Herschel*

ArTéMiS + SPIRE (350 μm res.: ~ 8'')



See Russeil et al. 2013, A&A, for the *Herschel*/HOBYS view of NGC6334

Radial intensity profile of NGC6334 filament



- ➢ Deconvolved FWHM width and diameter of flat inner plateau: ~ 0.1-0.2 pc
- ➢ Linear resolution: < 0.07 pc