Herschel Observations of Nearby Interstellar Filaments

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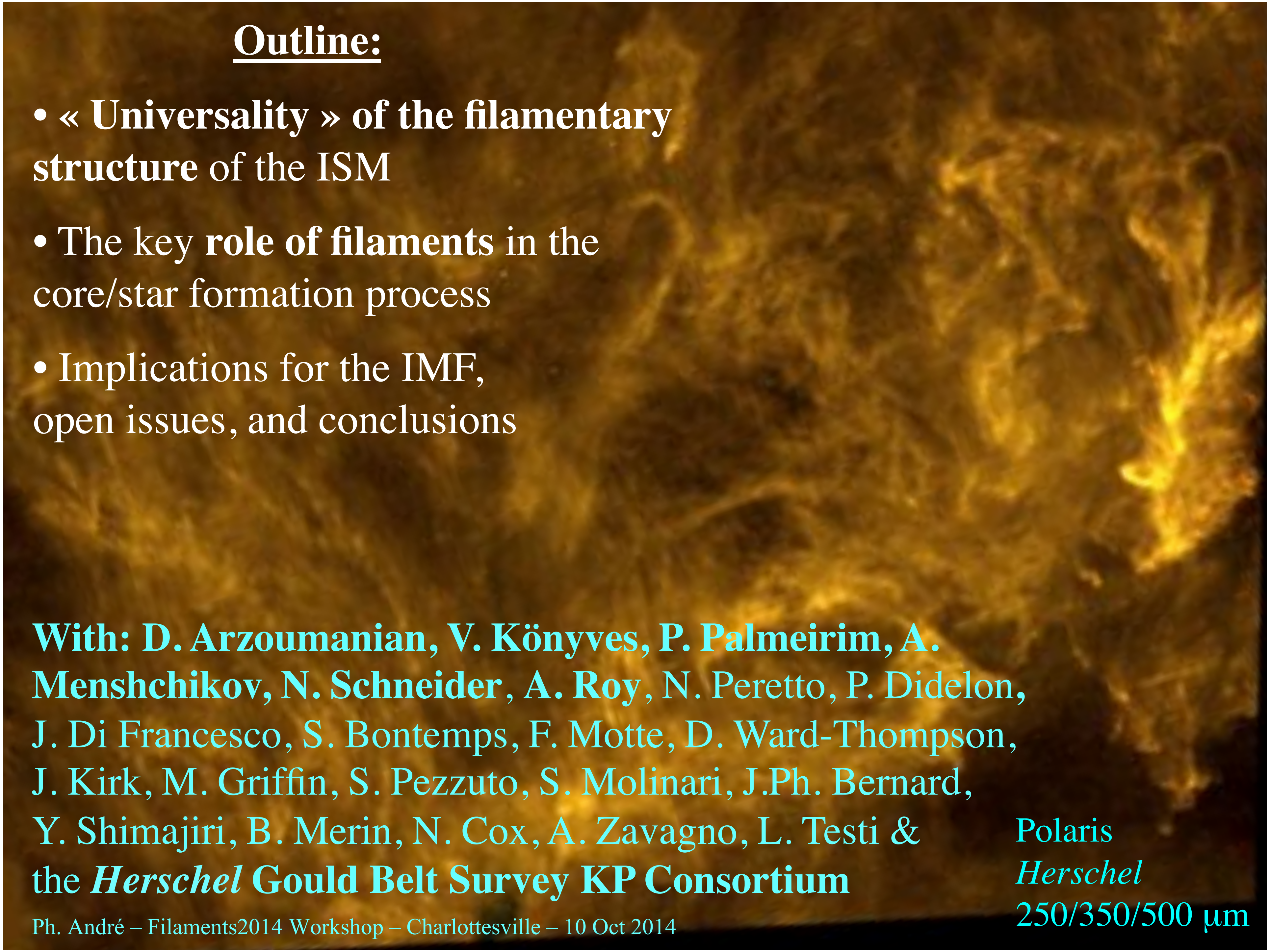
Filaments2014 Workshop – Charlottesville – 10 Oct 2014



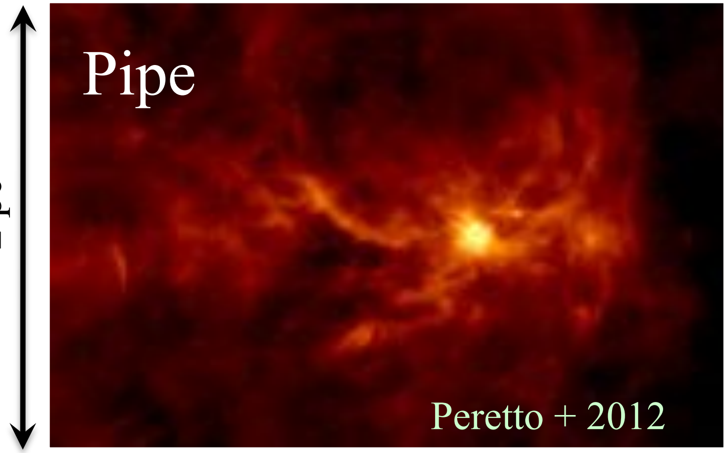
<u>Outline:</u>

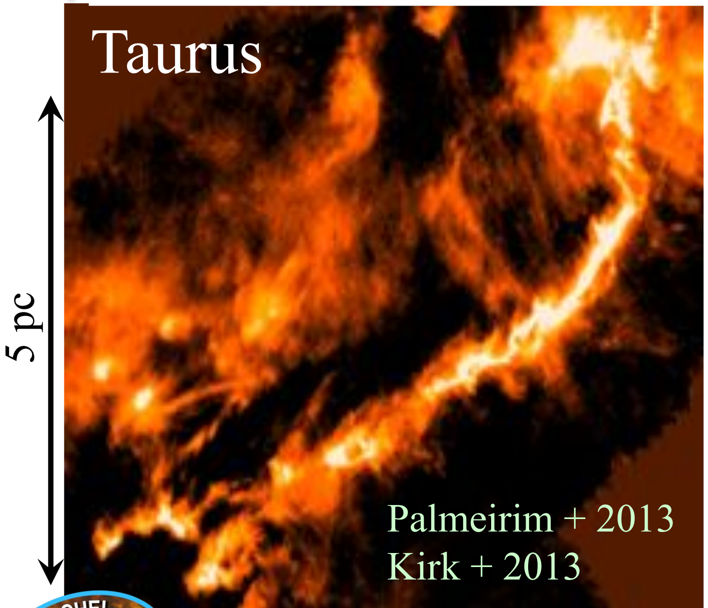
- « **Universality** » **of the filamentary structure** of the ISM
- The key **role of filaments** in the core/star formation process
- Implications for the IMF, open issues, and conclusions

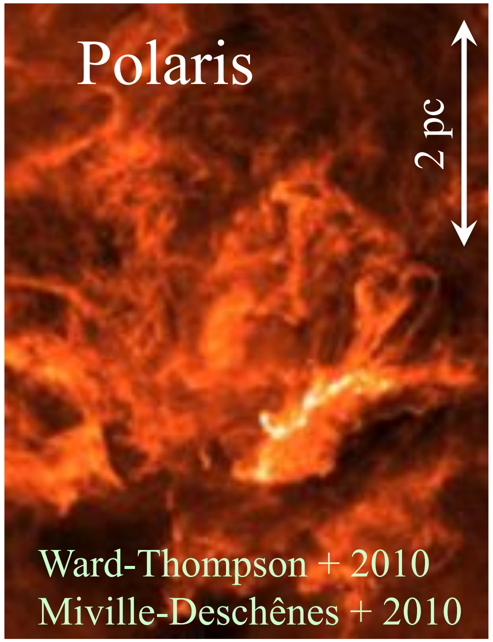
With: D. Arzoumanian, V. Könyves, P. Palmeirim, A. Menshchikov, N. Schneider, **A. Roy**, N. Peretto, P. Didelon, J. Di Francesco, S. Bontemps, F. Motte, D. Ward-Thompson, J. Kirk, M. Griffin, S. Pezzuto, S. Molinari, J.Ph. Bernard, Y. Shimajiri, B. Merin, N. Cox, A. Zavagno, L. Testi & the ***Herschel***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

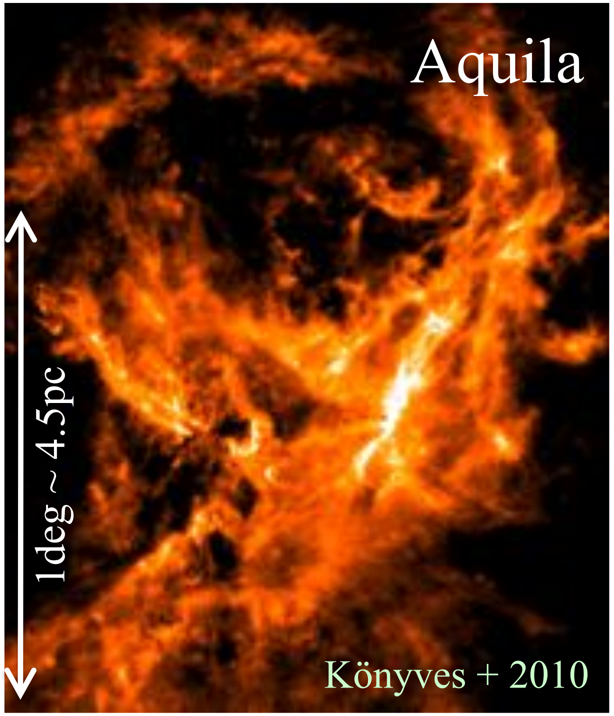
Polaris
Herschel
250/350/500 μm

Herschel has revealed a "universal" filamentary structure in nearby clouds



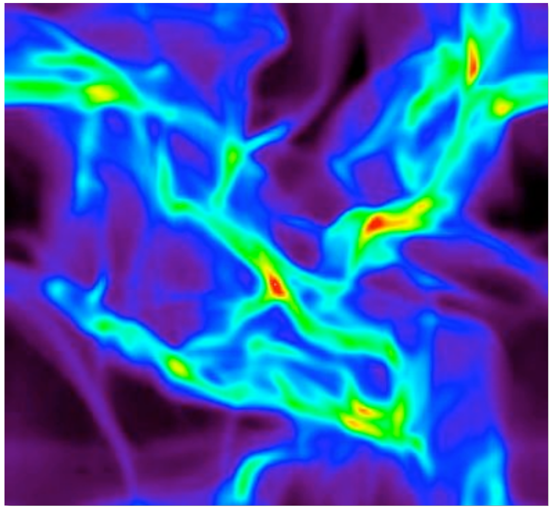






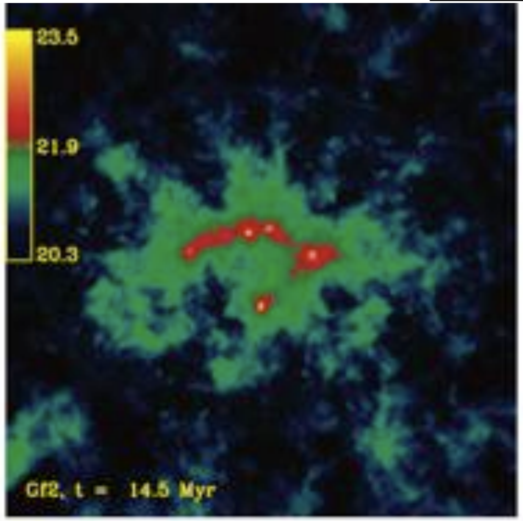
The observed filaments are reminiscent of numerical simulations of cloud evolution with large-scale flows

Turbulence

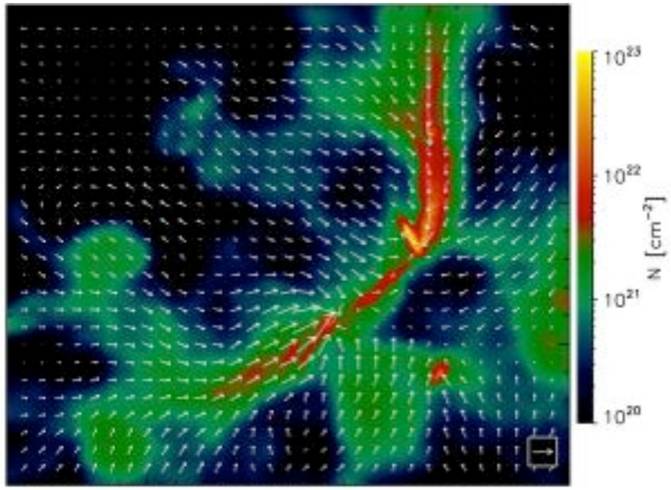


Padoan et al. 2001

Gravity

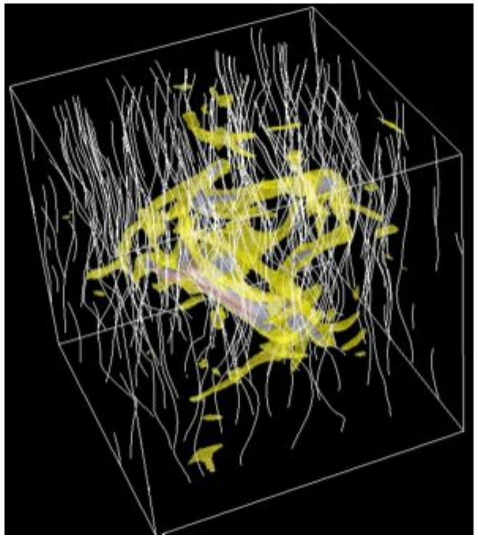


Heitsch et al. 2008

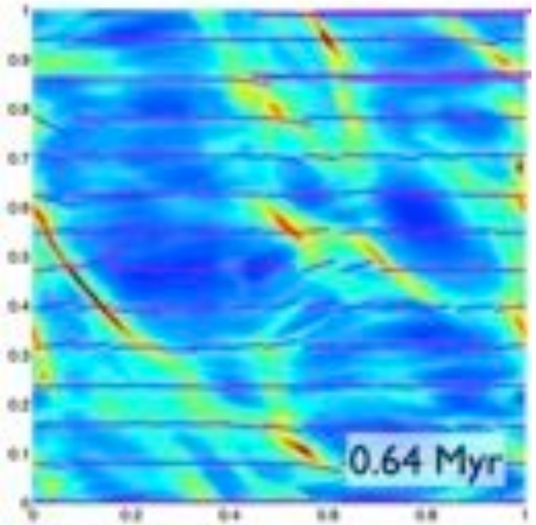


Gomez & Vazquez-Semadeni 2014

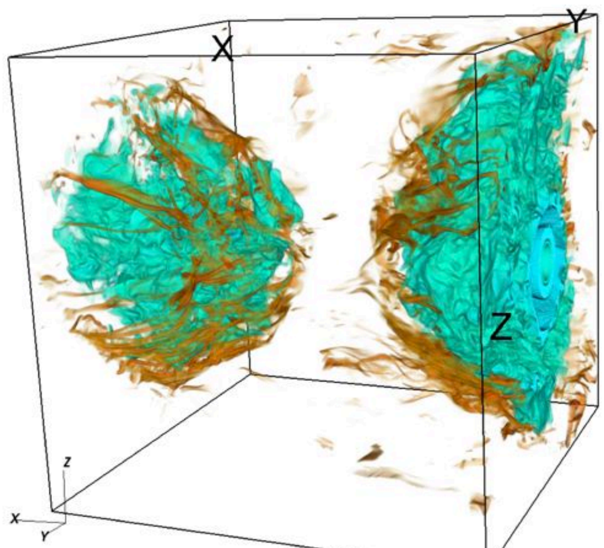
Turbulence
+
Gravity
+
B fields



Z.Y. Li et al. 2010

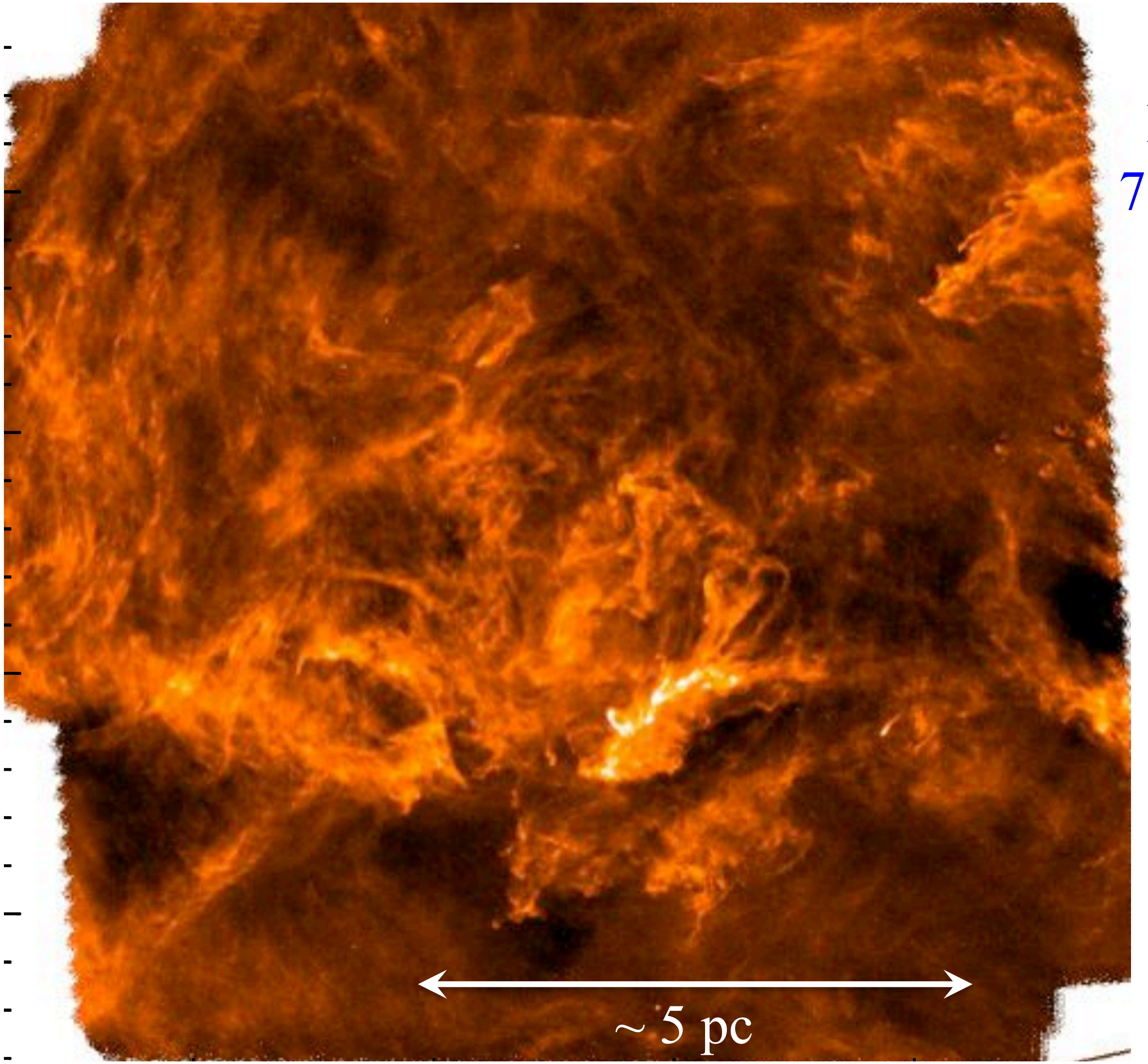


Chen & Ostriker 2014



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

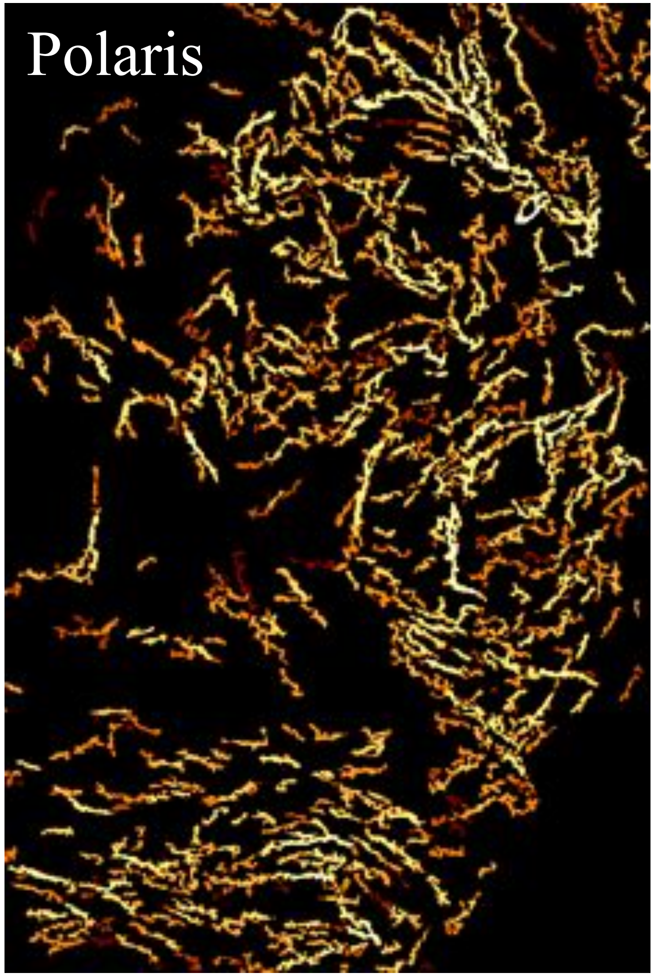
~ 13 deg^2 field

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) …

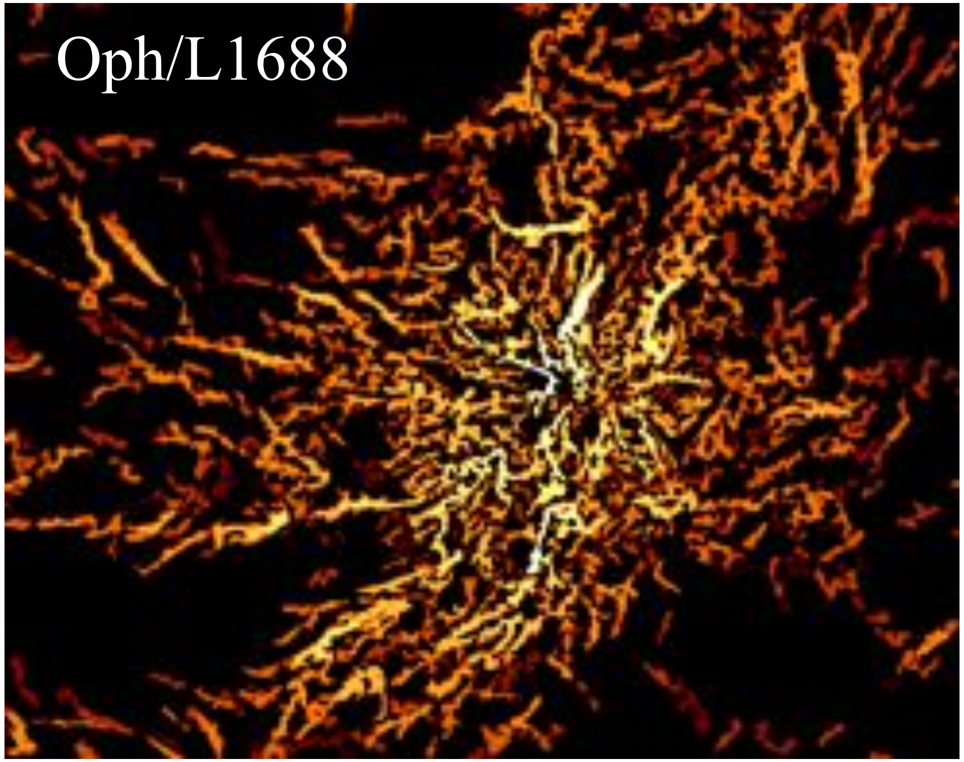
'Disorganized' network



Turbulence-dominated ?

Examples of *getfilaments* results

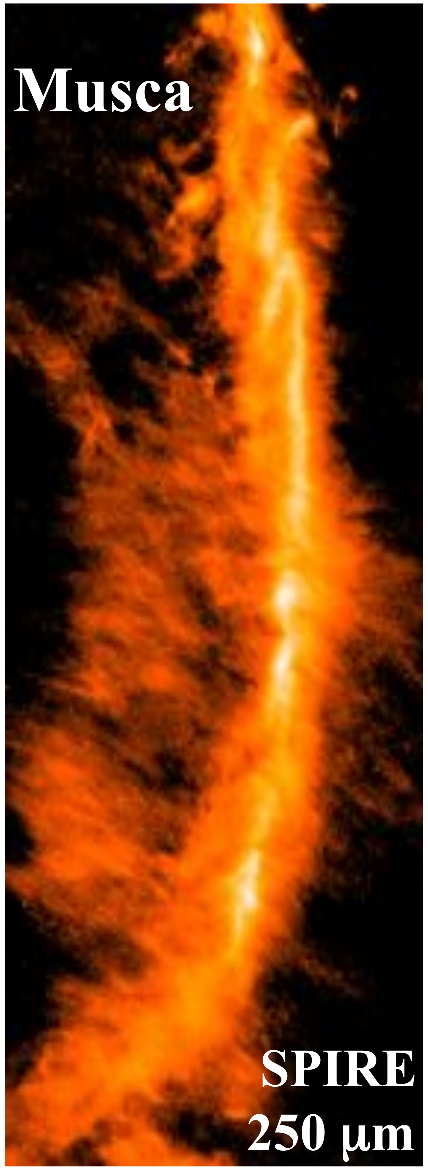
'Hub-filament' network - see Myers (2009)



Gravity-dominated ?

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

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

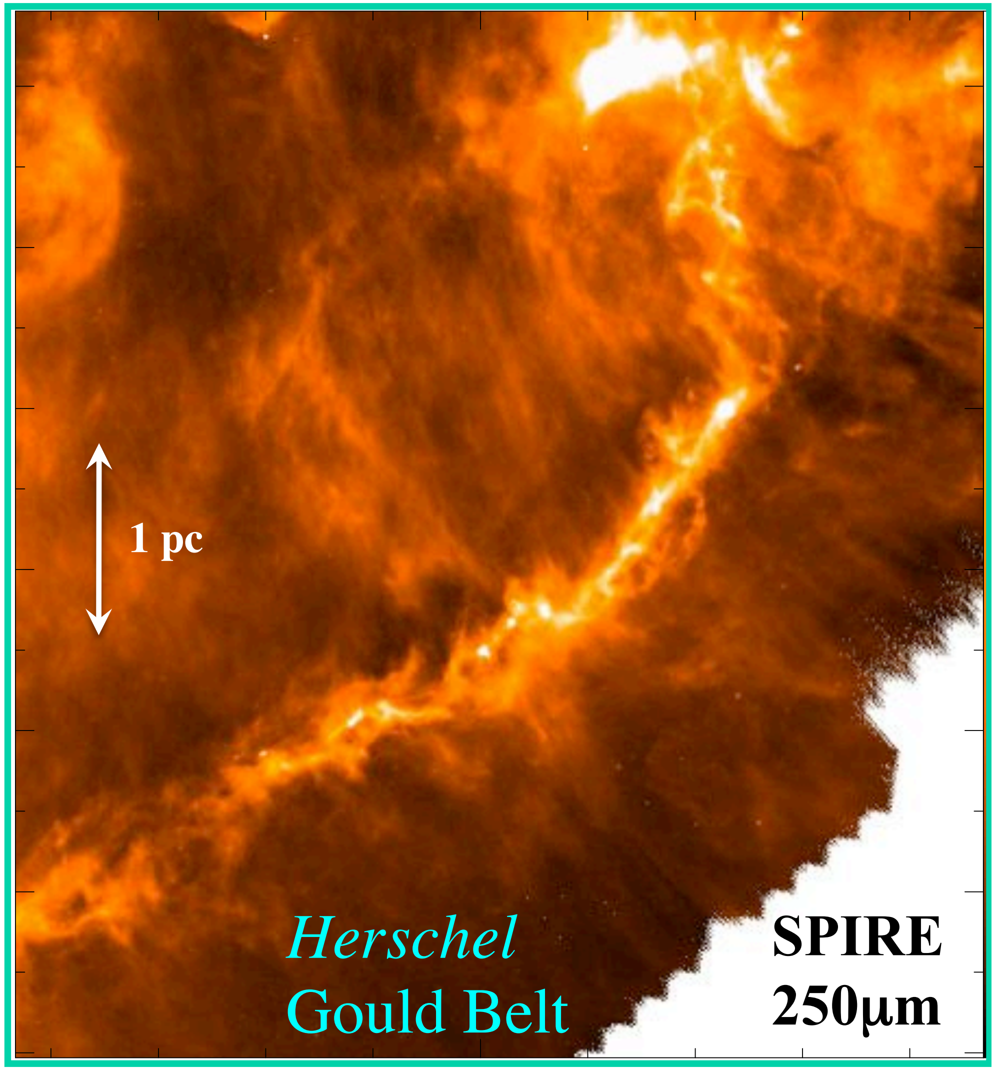


Musca filament:
M/L ~ 30 $M_{\odot}$/pc

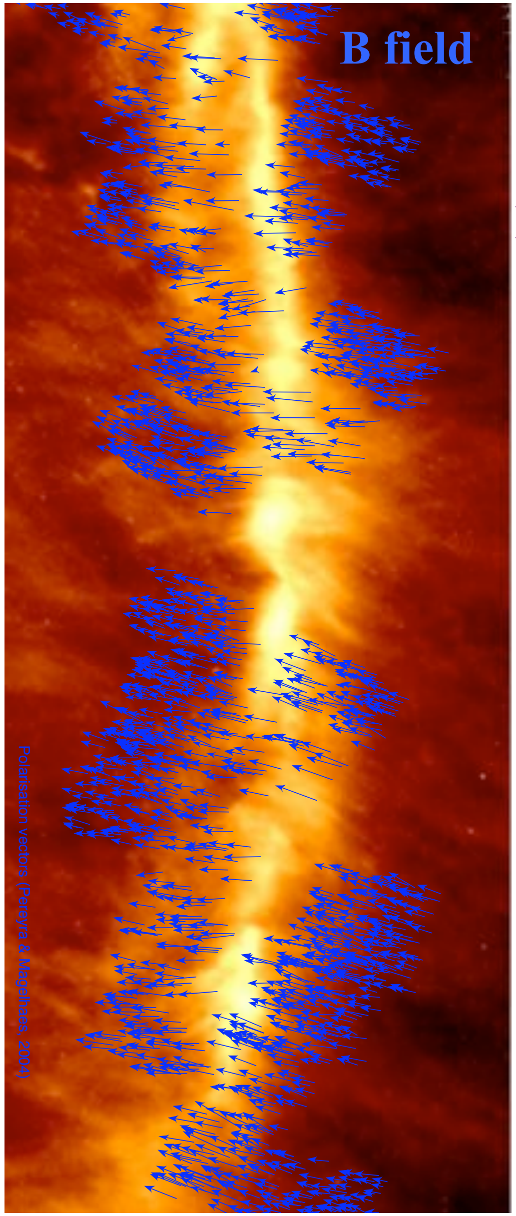
N. Cox et al in prep.

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*

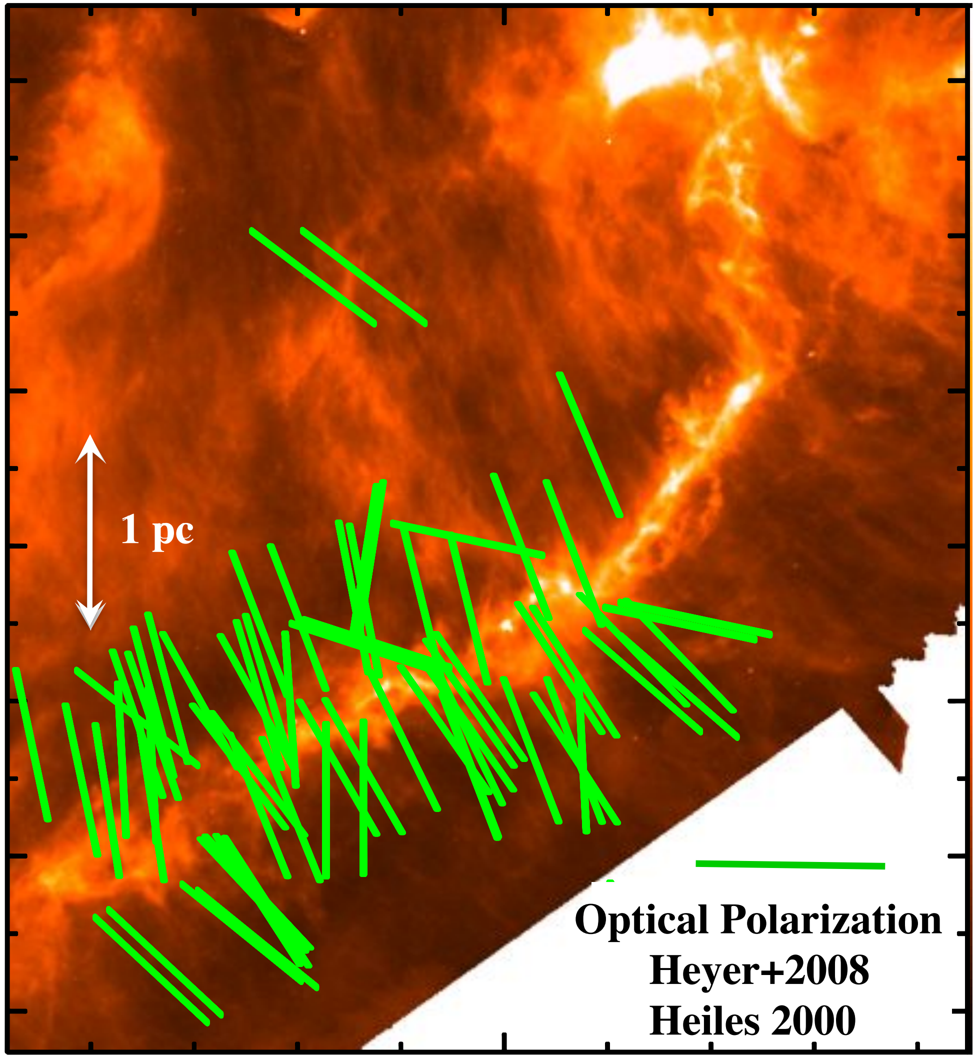


Musca filament:
M/L ~ 30 $M_\odot$/pc
N. Cox et al in prep.

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"

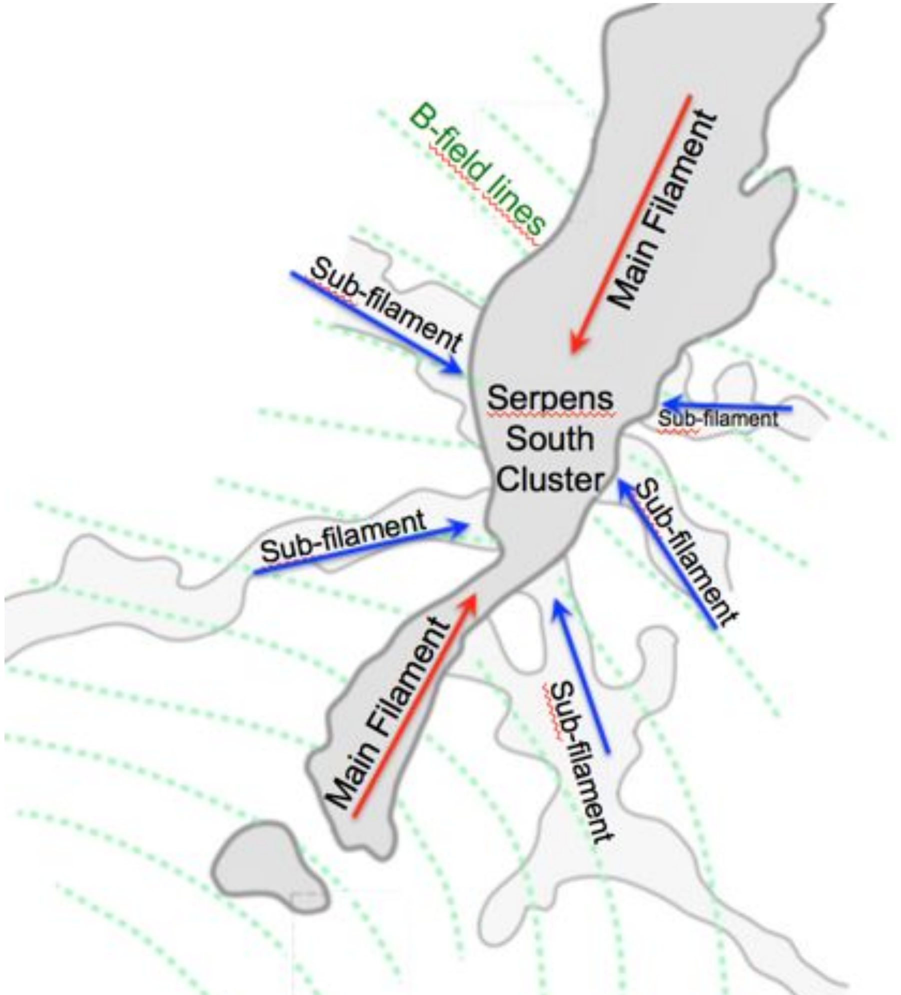
Serpens-South filament:
M/L ~ 250 $M_\odot$/pc

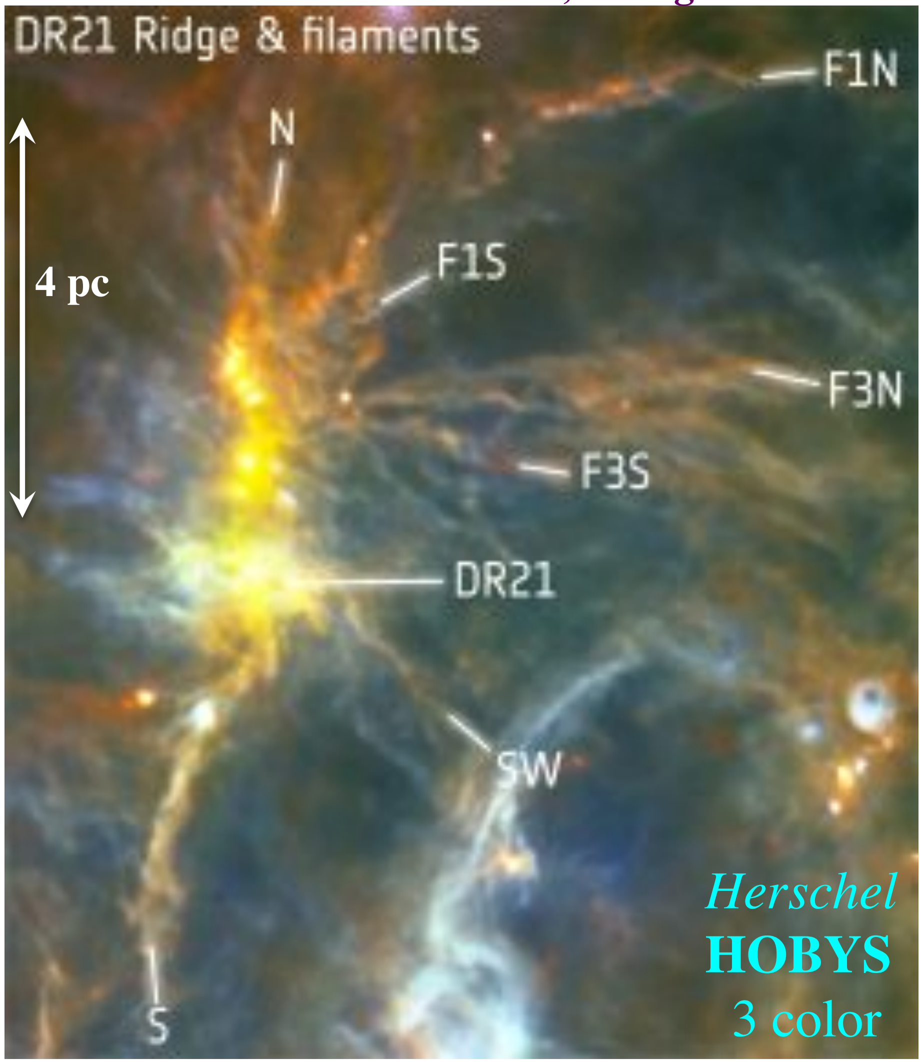
- **Suggestive of accretion flows into the main filaments**

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

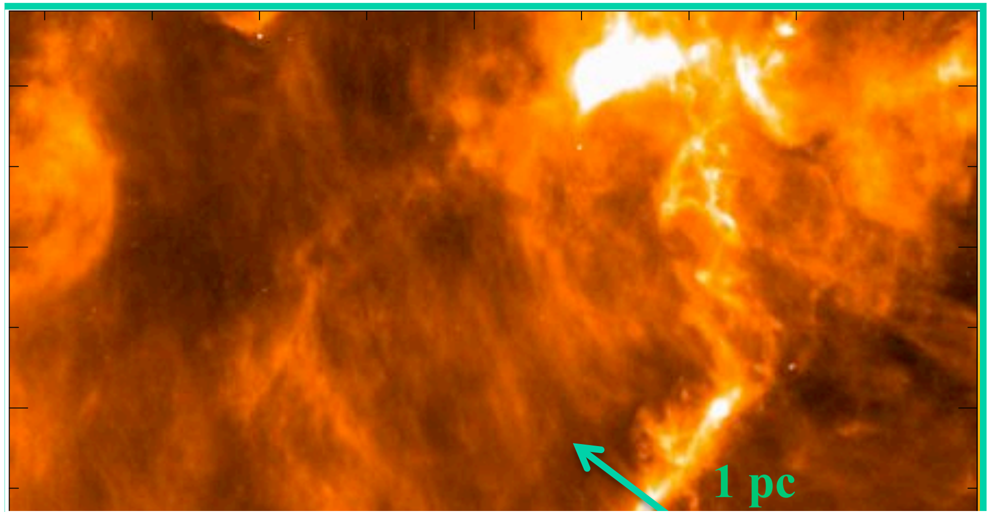


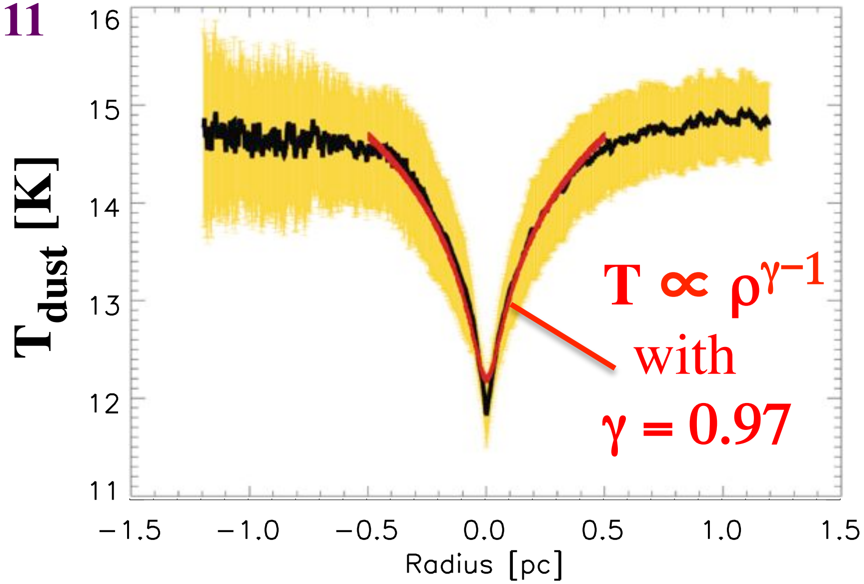


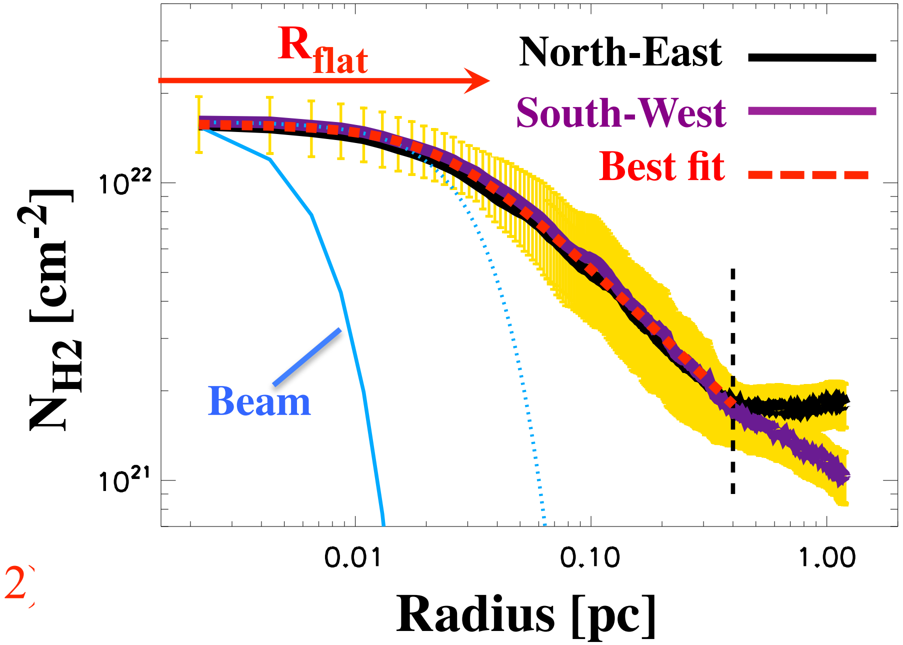
Resolving the structure of filaments with *Herschel*

Taurus B211/3 filament
SPIRE 250μm

Arzoumanian+2011
Palmeirim+2013







Plummer-like density profile (p = 2):

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

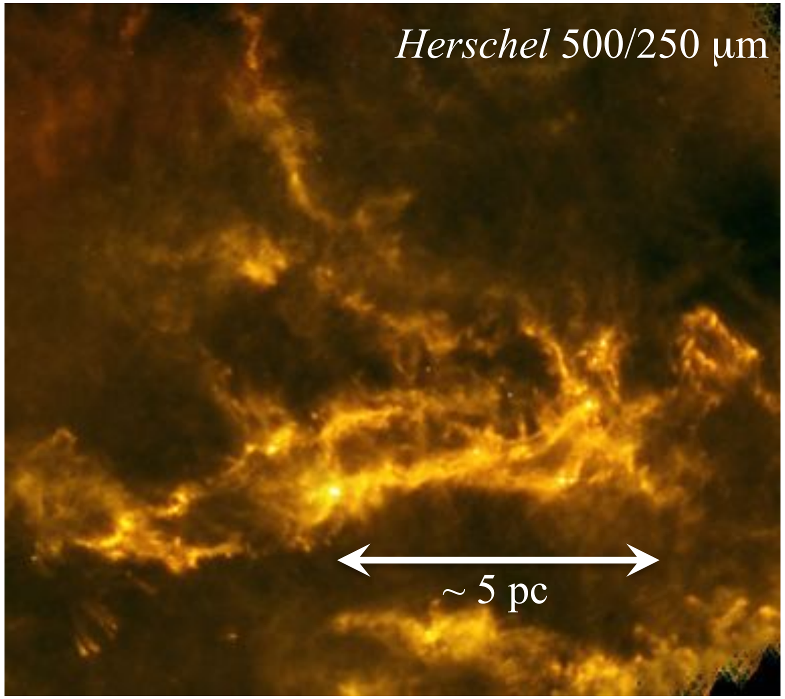
Diameter of flat inner plateau:

$2R_{flat} \sim 0.1$ pc

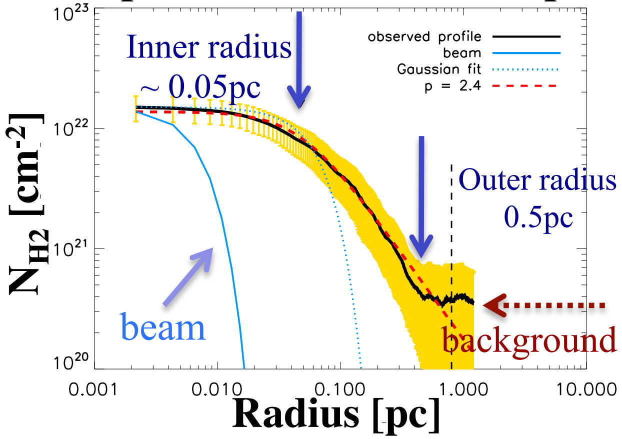
Depth along los ~ 0.1 pc (D. Li & Goldsmith '12)

Filaments have a characteristic inner width ~ 0.1 pc

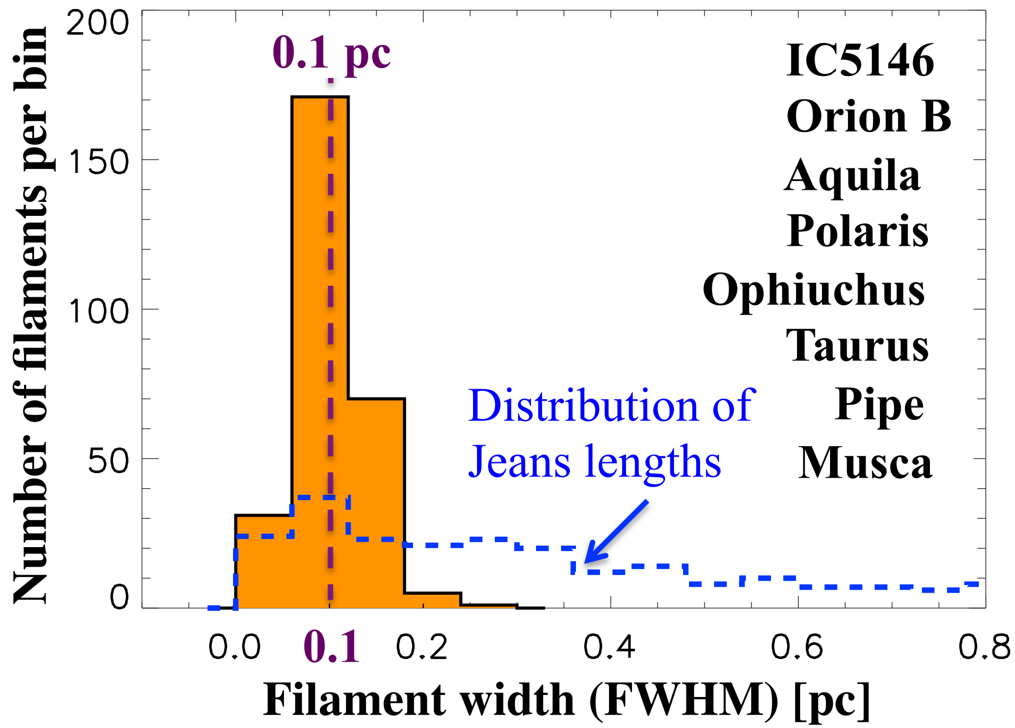
Network of filaments in IC5146



Example of a filament radial profile



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]

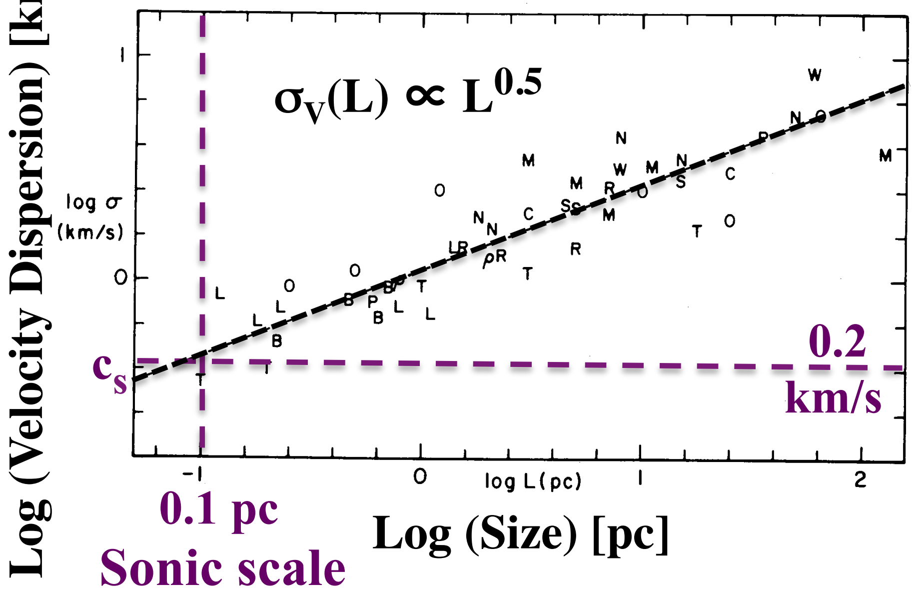
➢ **Strong constraint on the formation and evolution of filaments**

Filaments due to large-scale supersonic turbulence ?

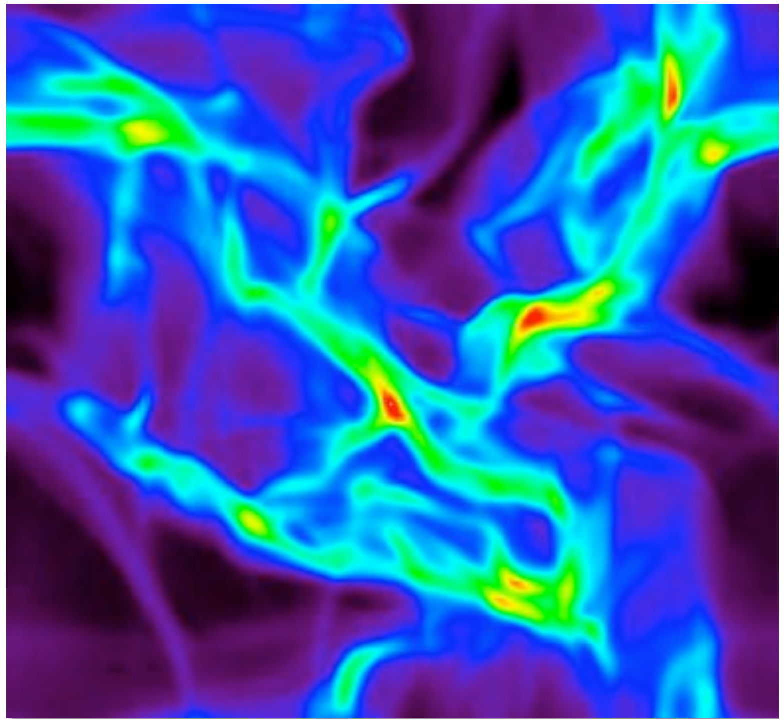
Filament width ~ 0.1 pc: ~ sonic scale of interstellar turbulence ?

Linewidth-Size relation in clouds

(Larson 1981)



Simulations of turbulent fragmentation



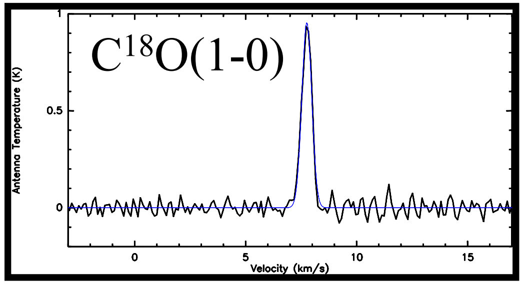
Padoan, Juvela et al. 2001

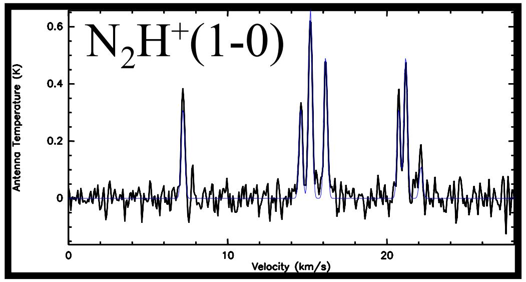
➢ **Corresponds to the typical thickness λ of shock-compressed layers in HD**

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

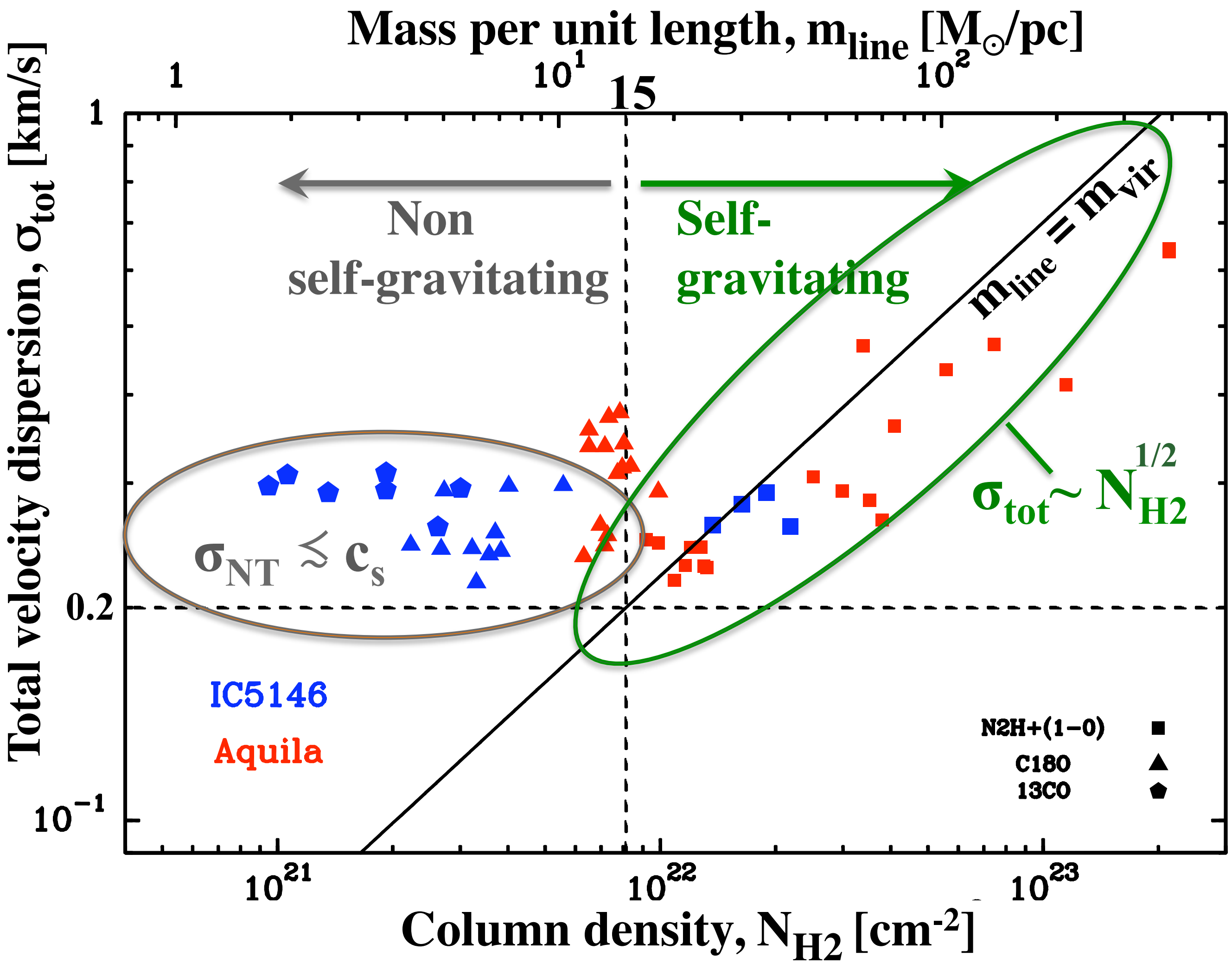
Velocity dispersion of filaments vs. column density

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)

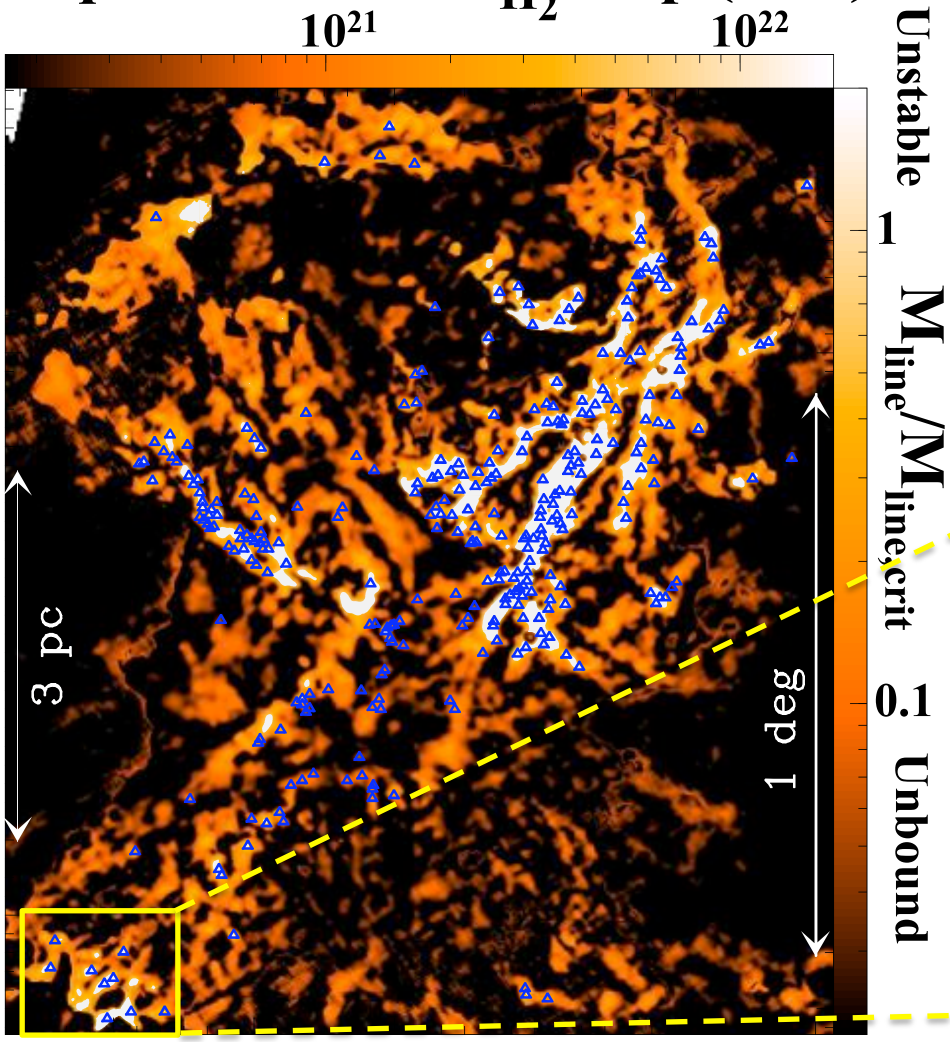
~ 75^{+15}_{-5} % of prestellar cores form in filaments, above a column density threshold $N_{H_2} \gtrsim 7\times10^{21}$ cm^{-2}

<=>

$A_V \gtrsim 7$

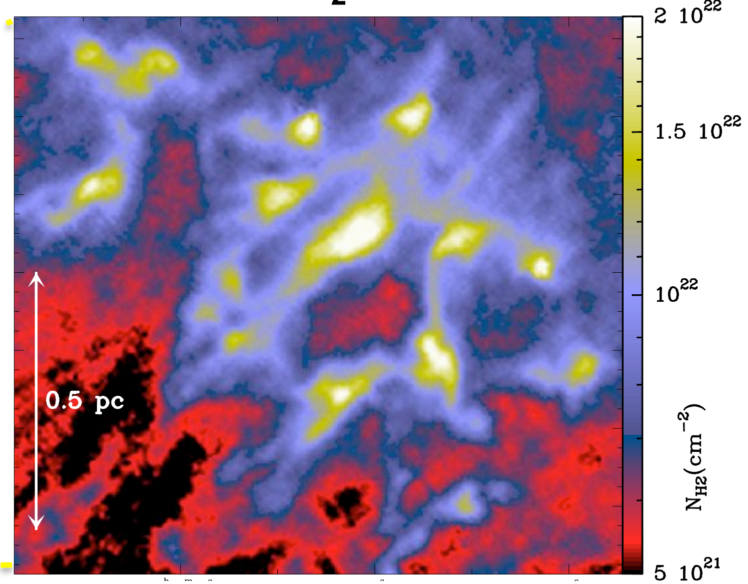
$\Sigma_{threshold} \sim 150\ M_\odot/pc^2$

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



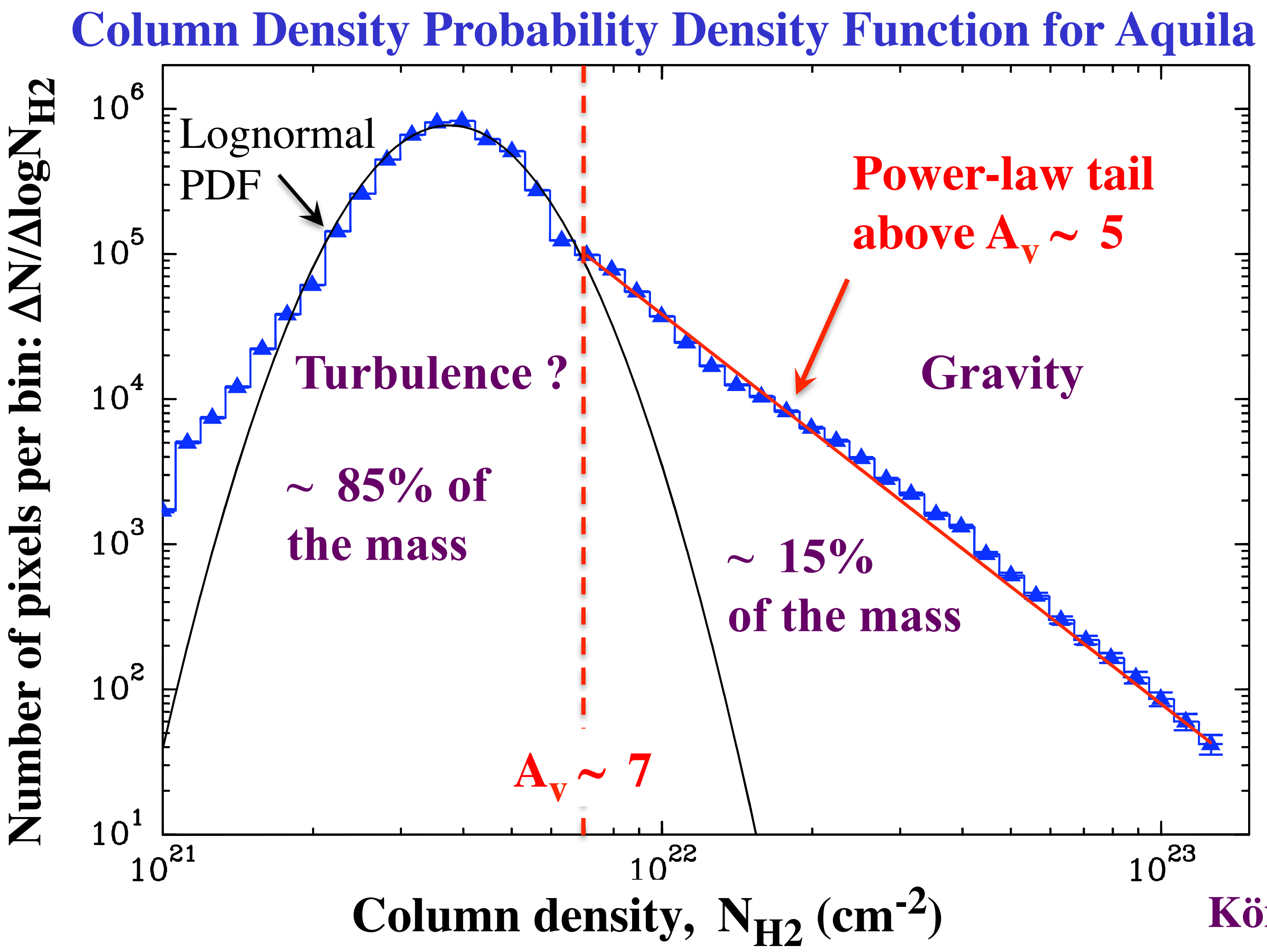
Examples of *Herschel* prestellar cores (△)

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



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

Mass budget in the Aquila cloud complex



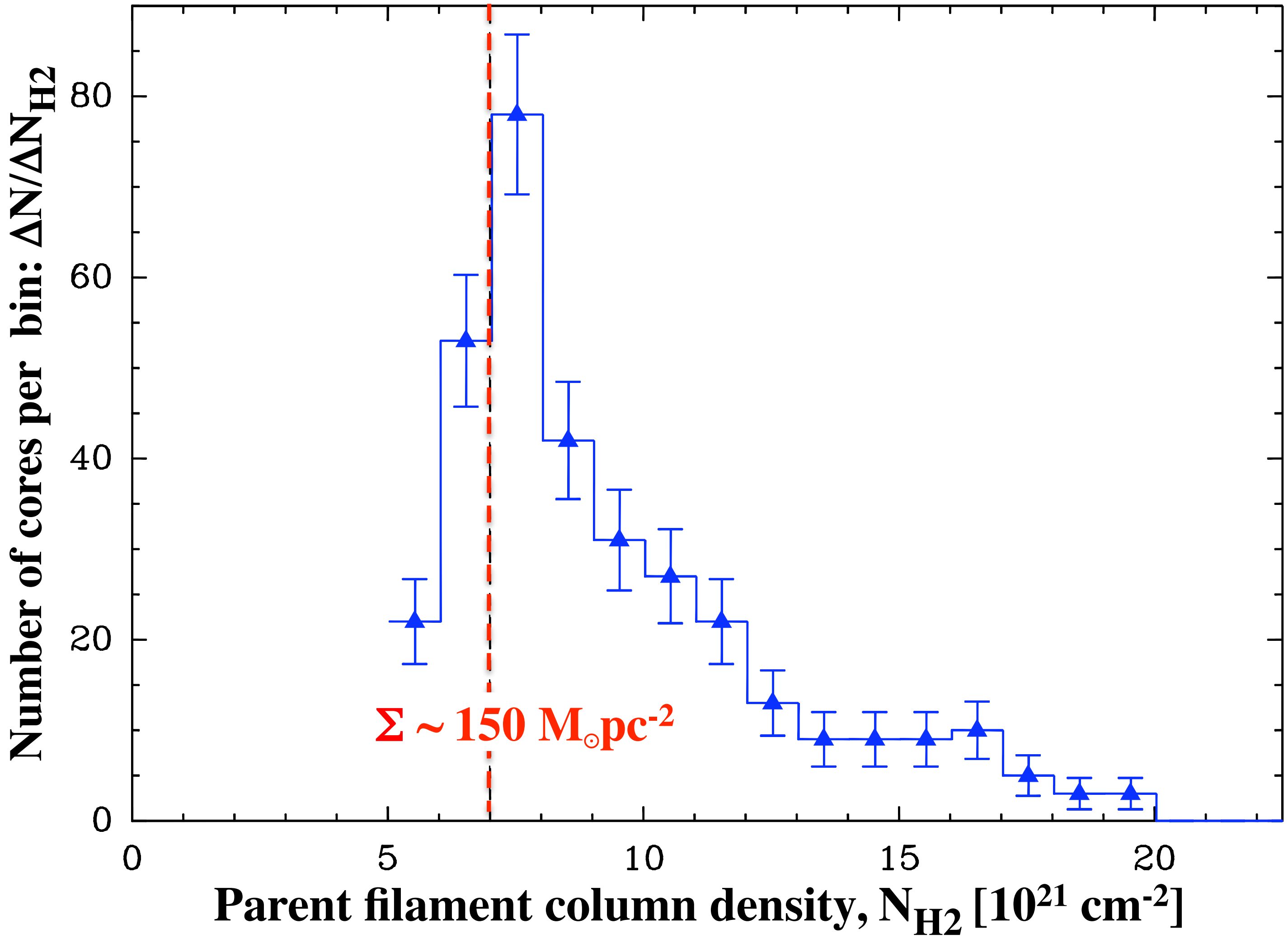
(See Schneider+2013 and Schneider+2014 for other, similar column density PDFs from *Herschel*)

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

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

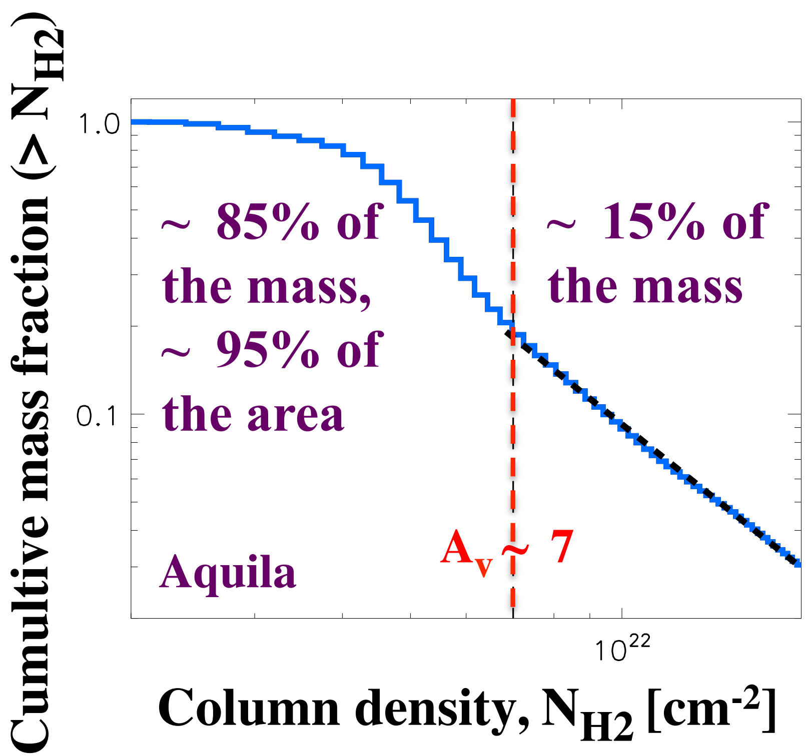
André+2014 PPVI

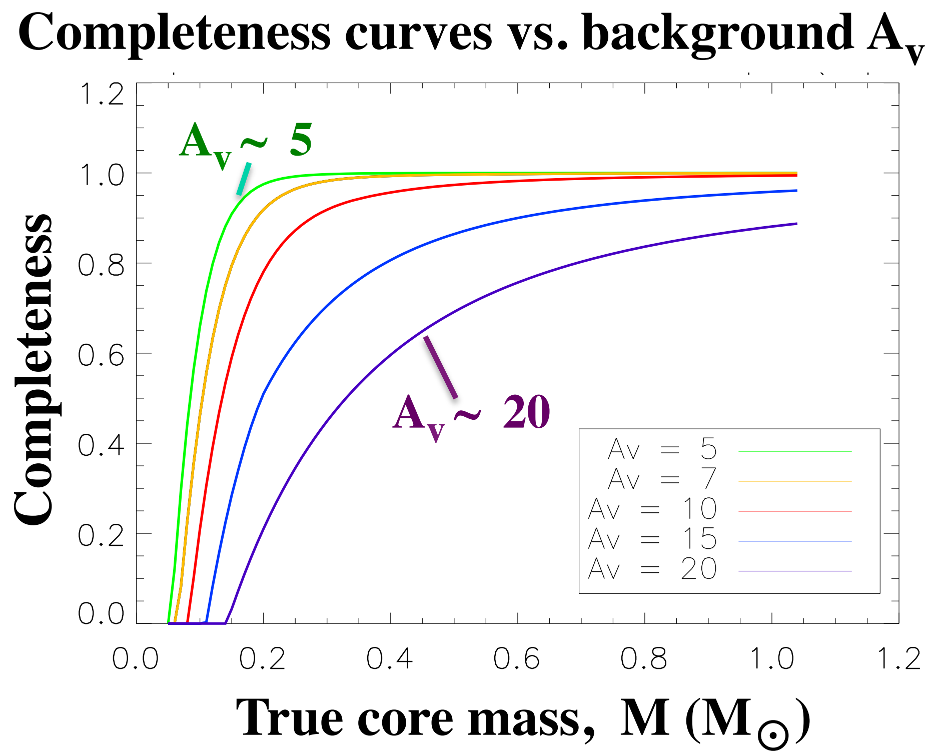
See also:

Onishi+1998

Johnstone+2004

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





Könyves et al. in prep

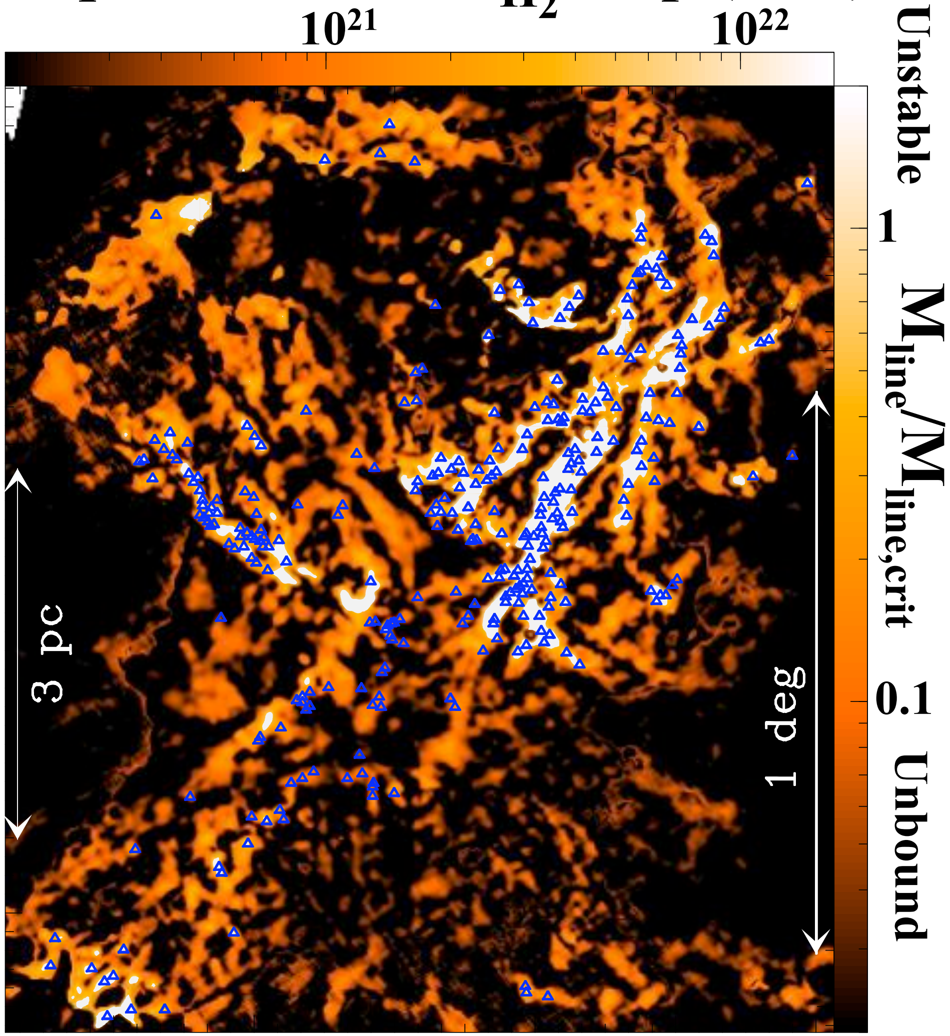
(See also Lada+2010 for similar mass fraction plots based on extinction)

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

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

- ➢ 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:

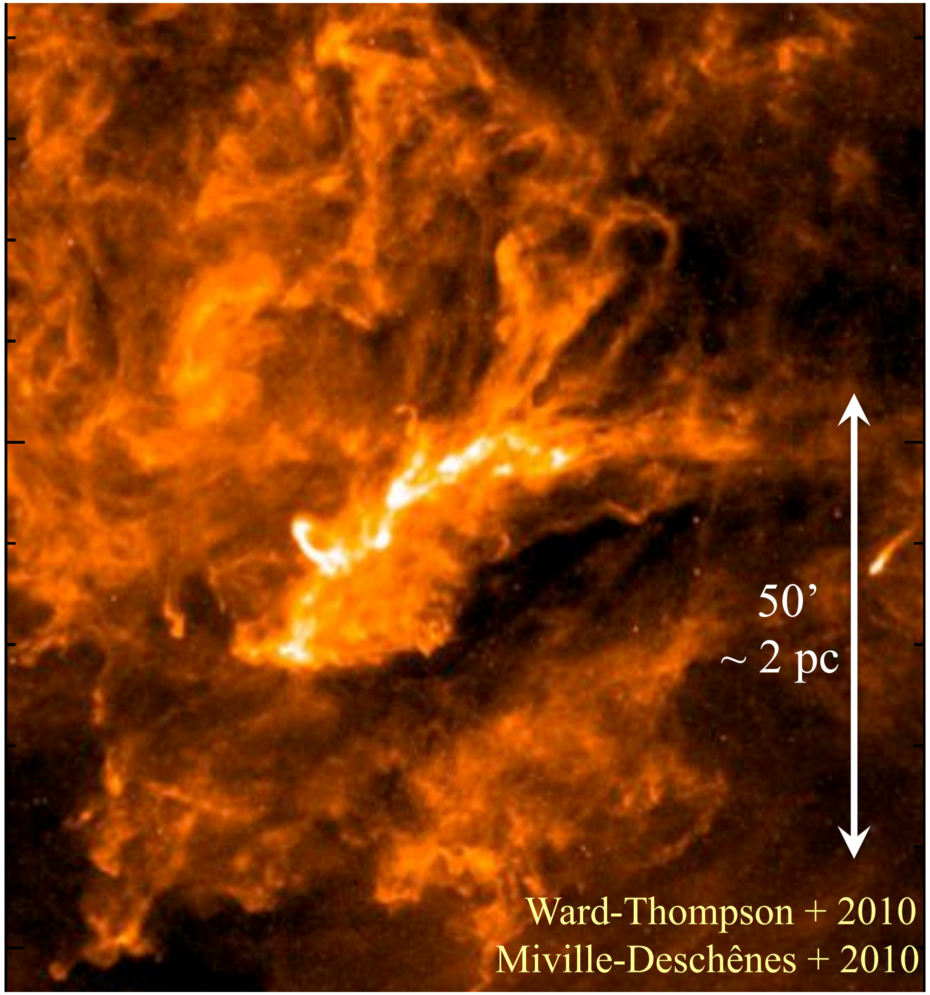
$M_{line} \propto N_{H2}$ x Width (~ 0.1 pc)

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

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

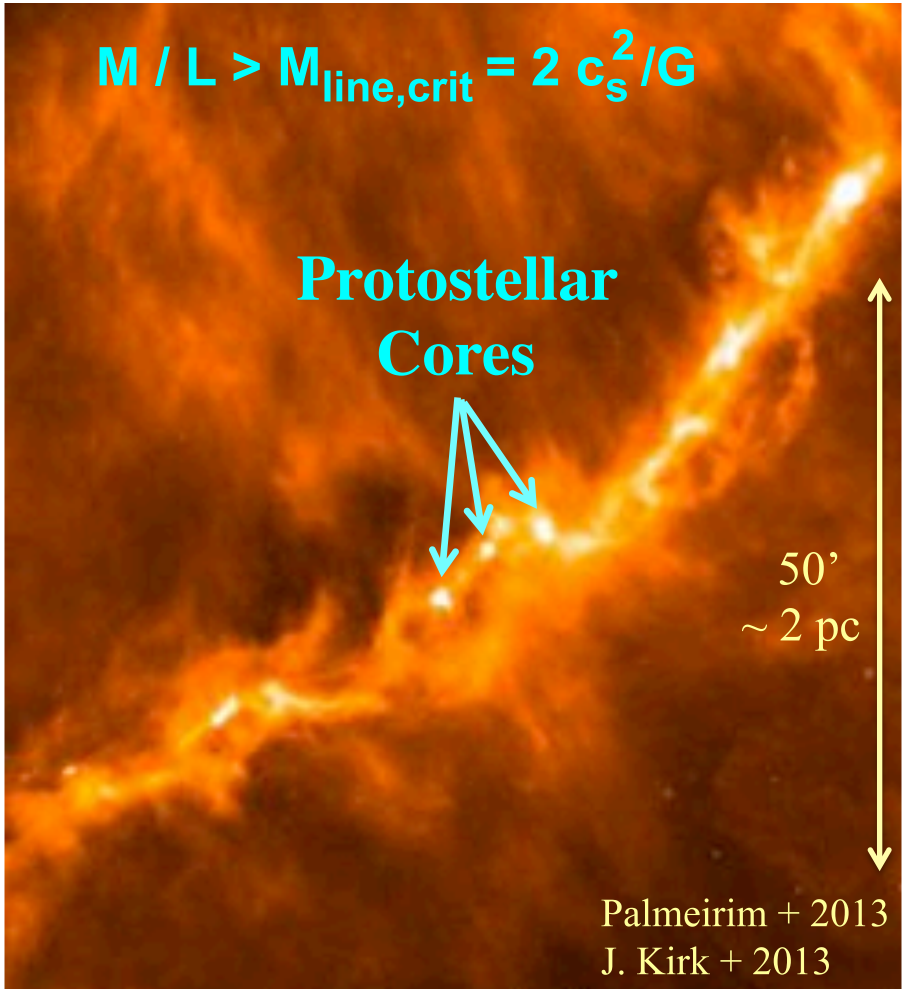
See PPVI chapter (André, Di Francesco, Ward-Thompson, Inutsuka, Pudritz, Pineda 2014 - astro-ph/1312.6232)

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



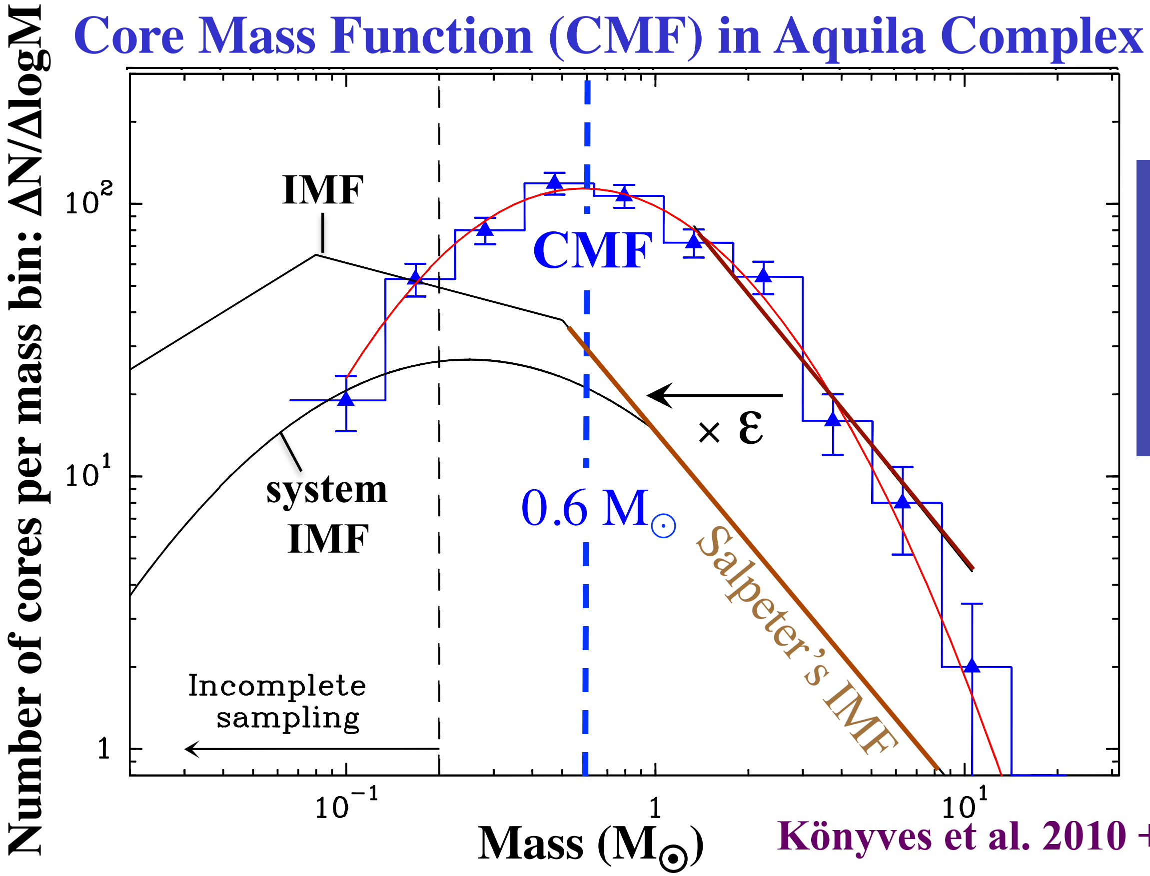
Polaris – *Herschel*/SPIRE 250 μm

2) Gravity fragments the densest filaments into prestellar cores



Taurus B211/3 – *Herschel* 250 μm

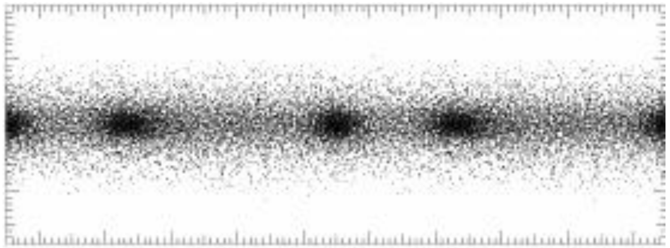
Filament fragmentation may account for the peak of the prestellar CMF and the "base" of the IMF



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

Jeans mass:

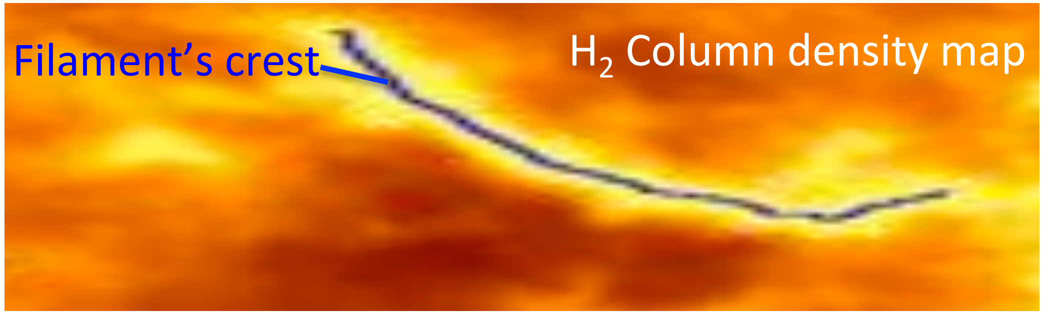
$M_{Jeans} \sim 0.5\ M_\odot \times (T/10\ K)^2 \times (\Sigma_{crit}/160\ M_\odot pc^{-2})^{-1}$



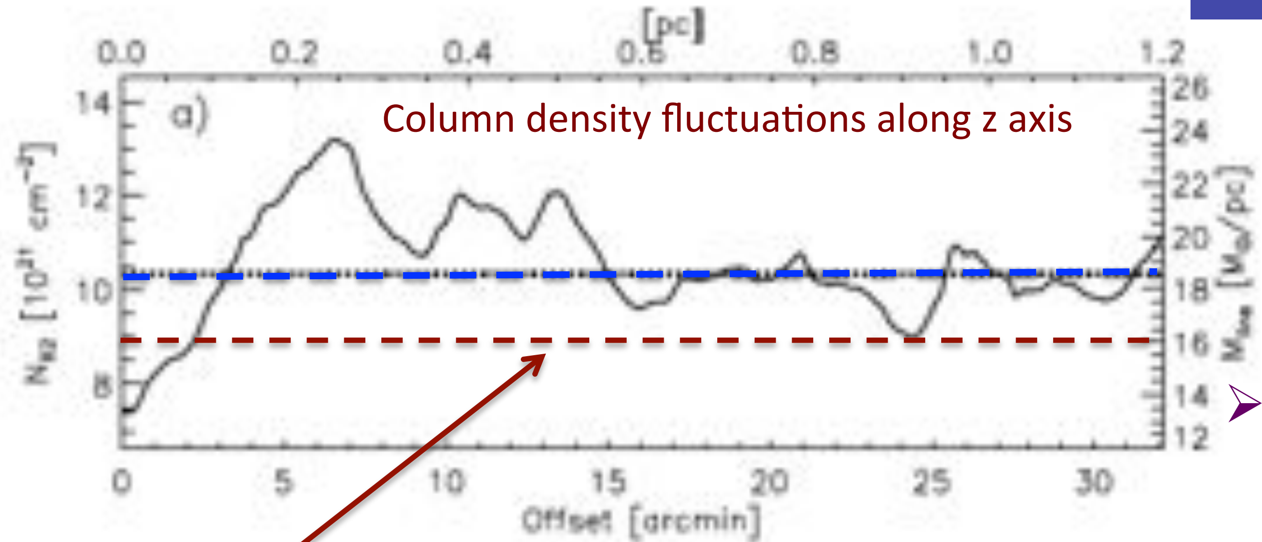
- **CMF peaks at ~ 0.6 $M_\odot$ ≈ Jeans mass in marginally critical filaments**
- **Close link of the prestellar CMF with the stellar IMF: $M_\star \sim 0.3 \times M_{core}$**
- **Characteristic stellar mass may result from filament fragmentation**

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

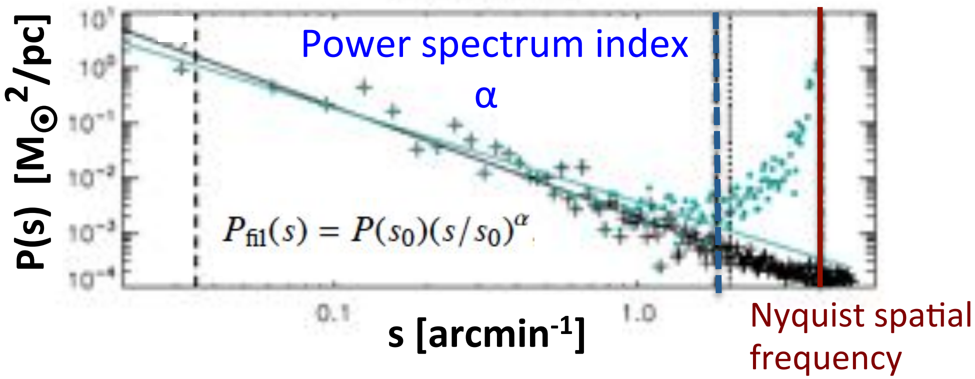
Roy et al. 2014

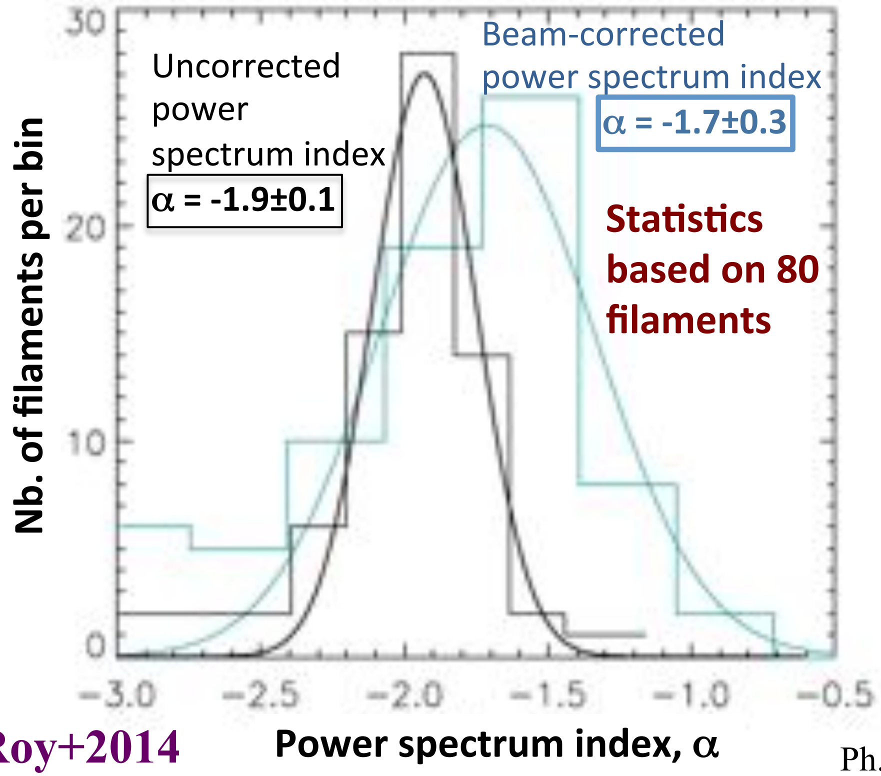
- **Statistical analysis of the line-mass fluctuations for a sample of 80 subcritical or marginally supercritical *Herschel* filaments**

Statistical properties of line-mass fluctuations

Implication

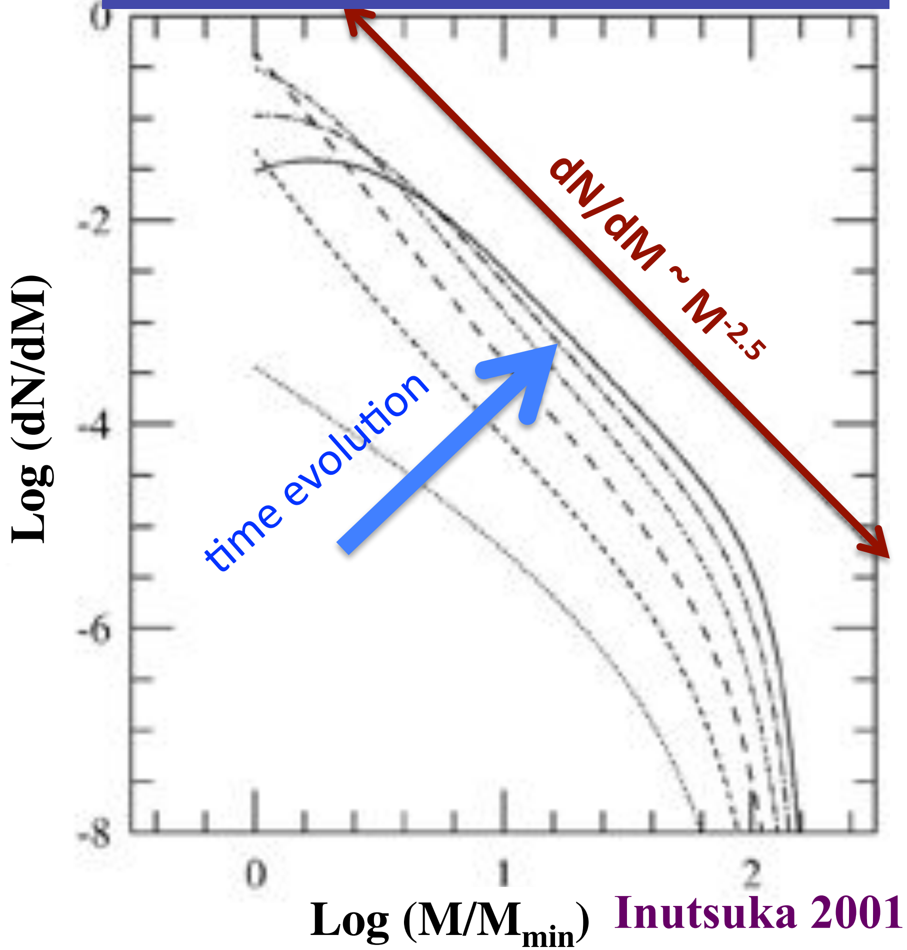
Power spectrum of line-mass fluctuations





Roy+2014

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



Inutsuka 2001

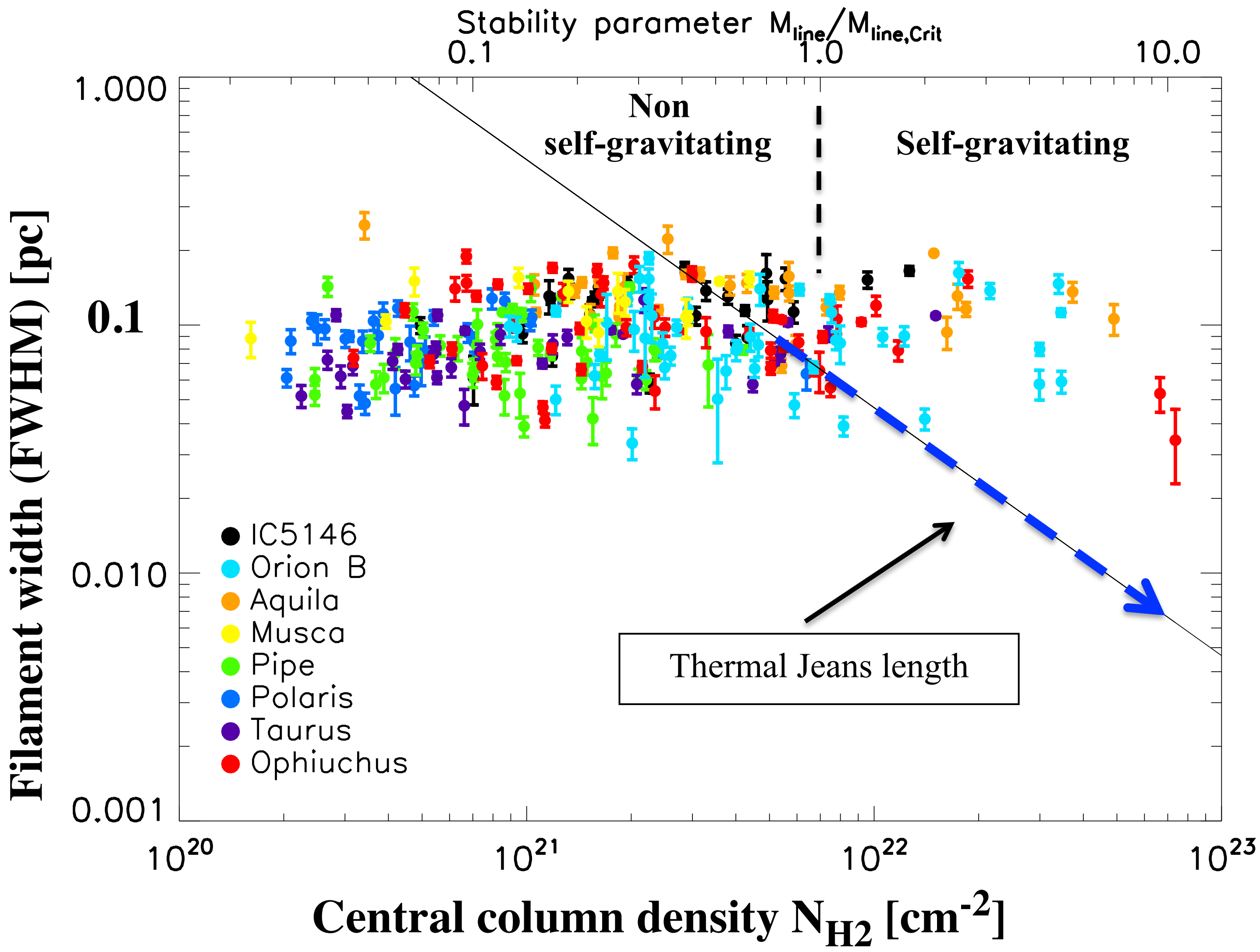
Summary: A filamentary paradigm for star formation in GMCs ?

- 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
  $\Sigma_{th} \sim 150\ M_\odot\ pc^{-2}$ ⇔ $A_V \sim 7$ ⇔ $n_{H2} \sim 2 \times 10^4\ cm^{-3}$

- 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:

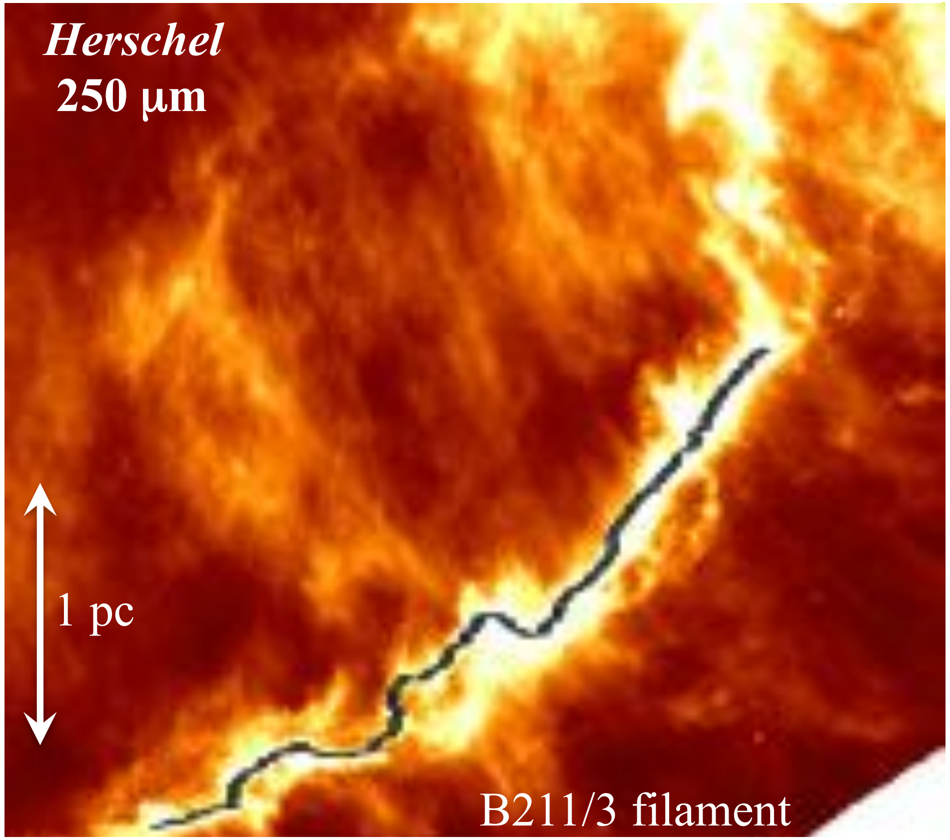
Dense filaments should radially contract !

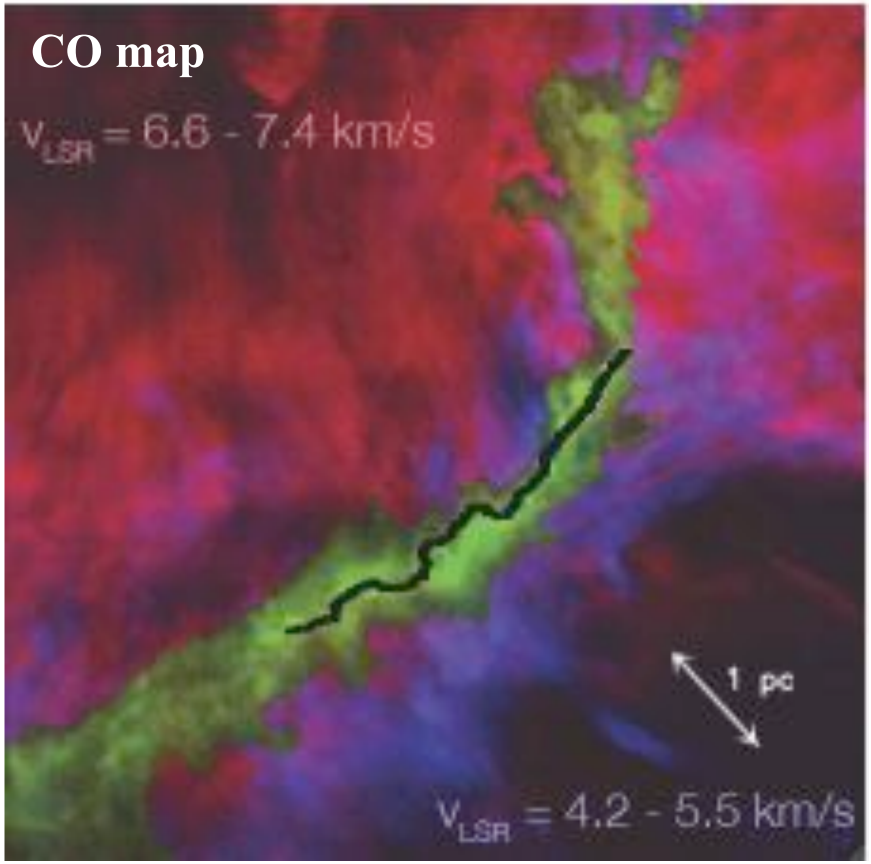
D. Arzoumanian et al. 2011 + PhD thesis

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)



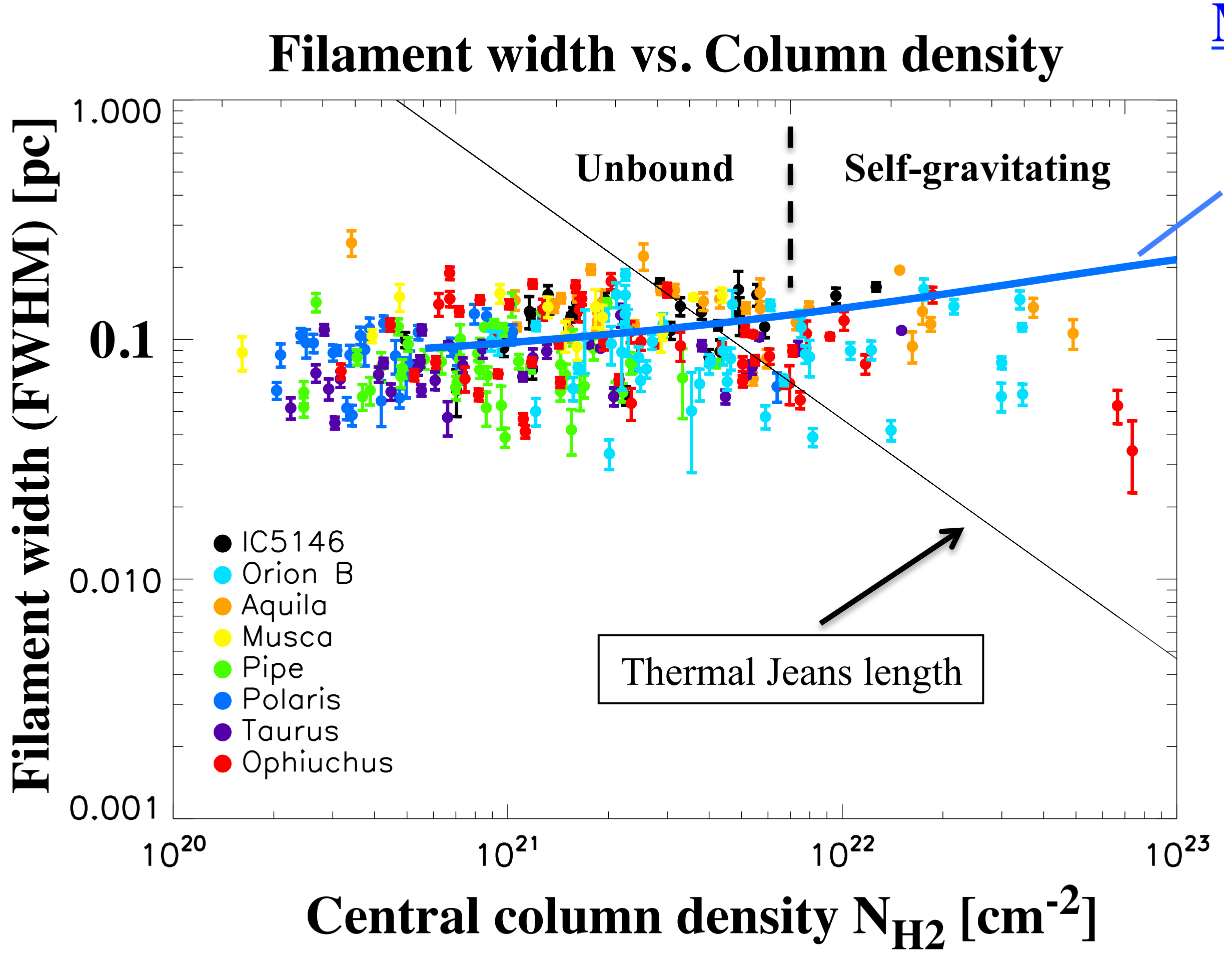


CO observations from Goldsmith et al. 2008

Estimate of the mass accretion rate:

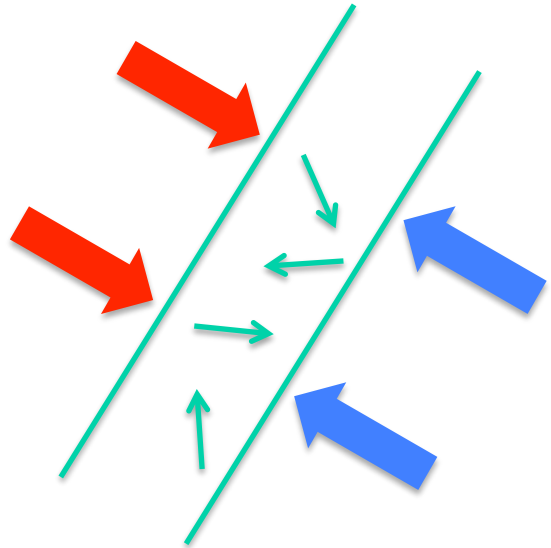
$\dot{M}_{line} \sim$ 25-50 $M_\odot$/pc/Myr

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



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

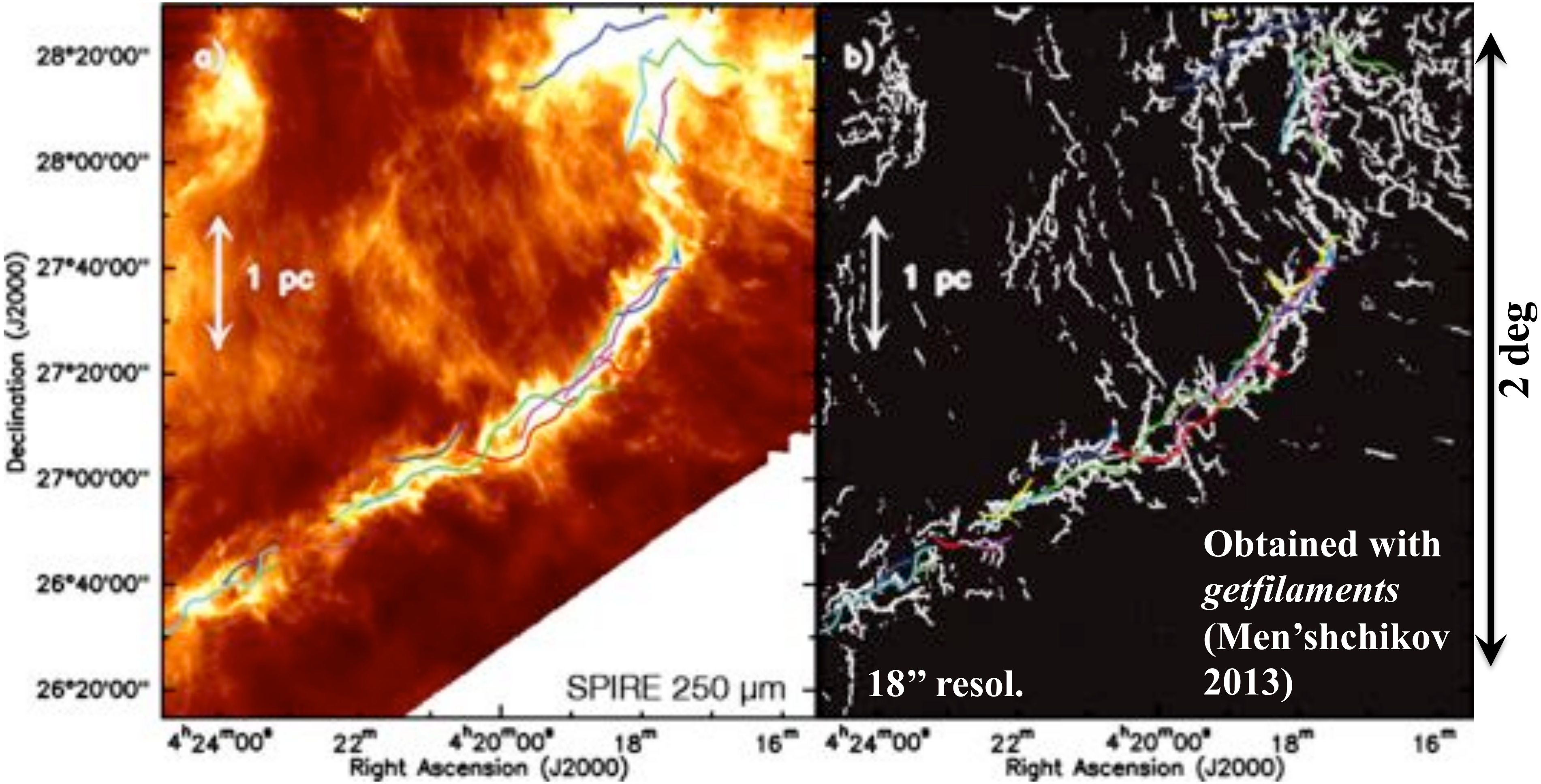
⬇

« 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

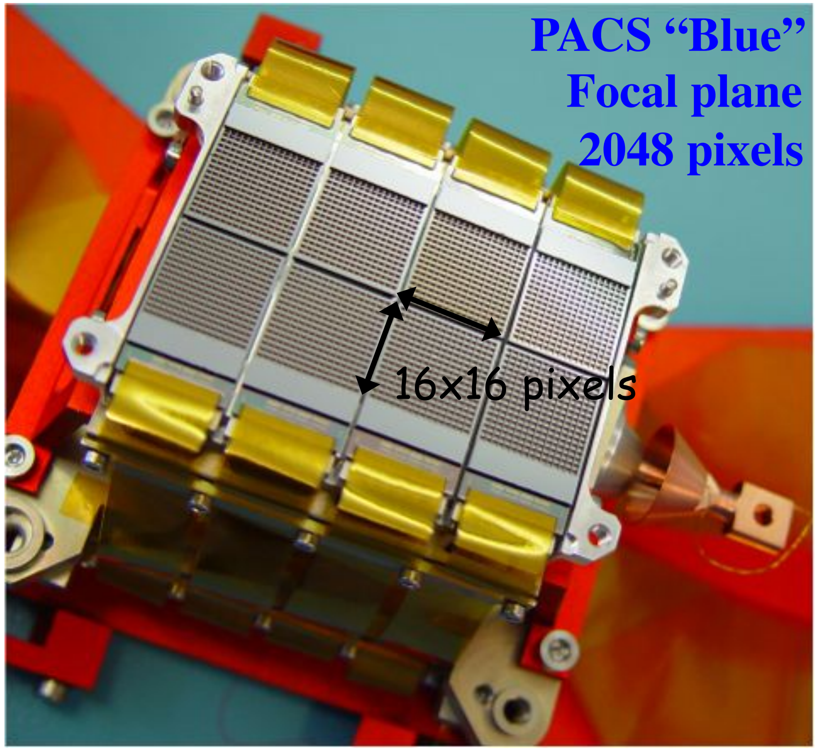


ArTéMiS : A powerful tool to study massive star-forming filaments ('ridges') beyond the Gould Belt

×3.4 higher resolution than SPIRE

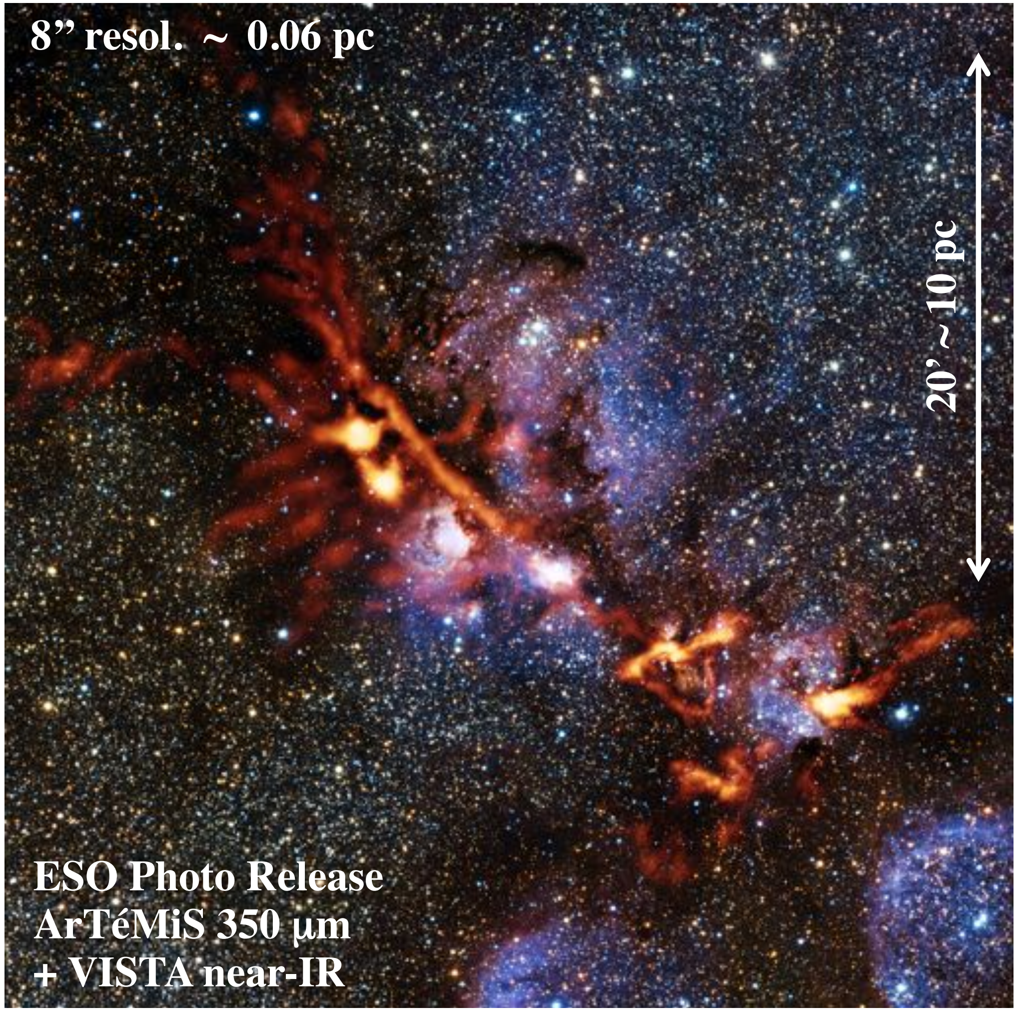
×3-(10) faster than SABOCA

OSO



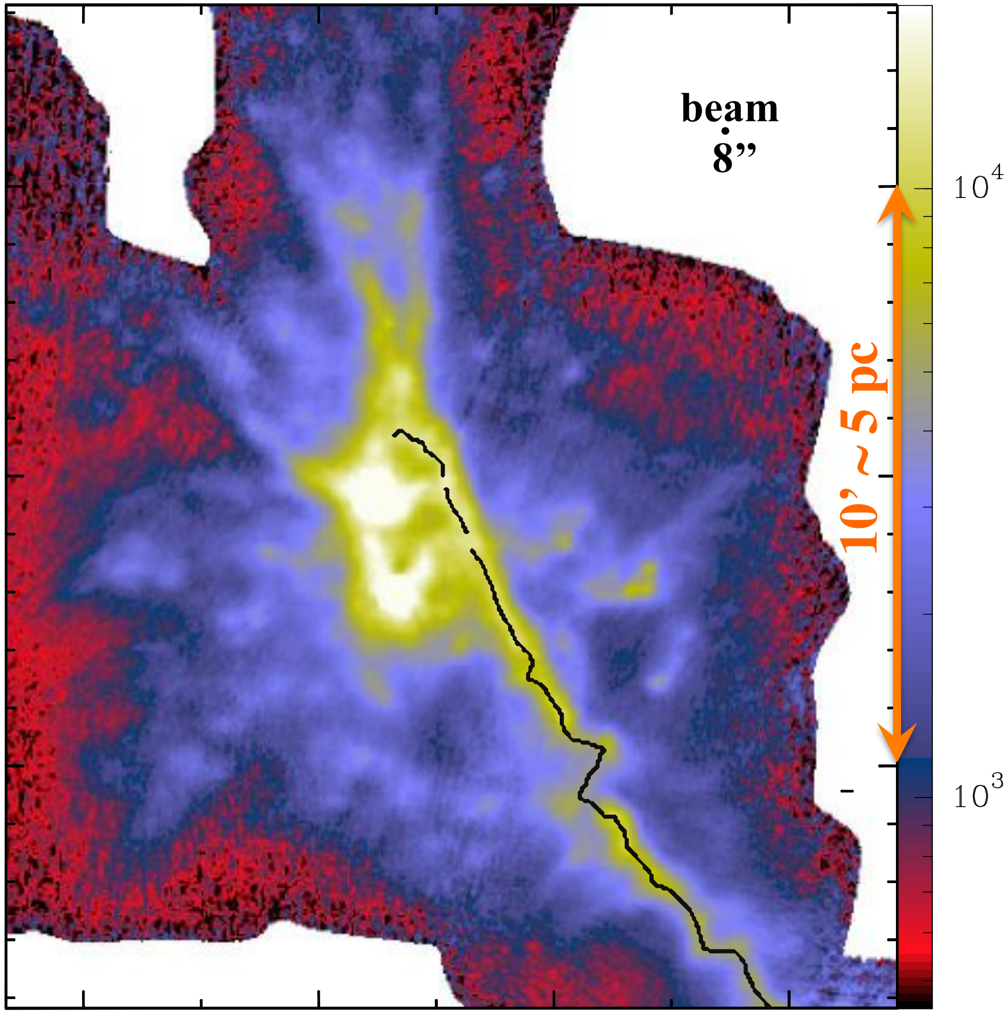
ArTéMiS : 2304 pixels @ 450 μm
2304 pixels @ 350 μm

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



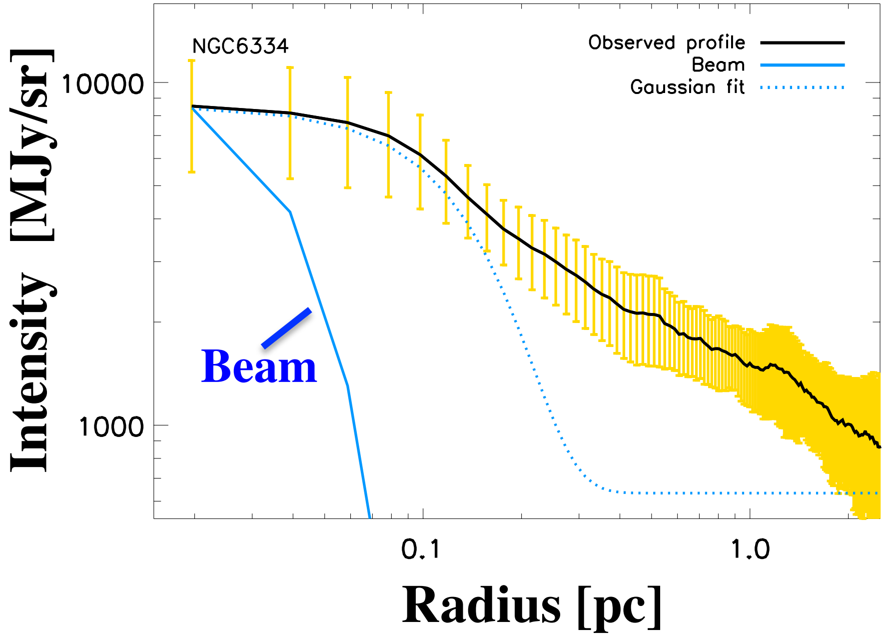
Resolving the NGC 6334 main filament (d ~1.7 kpc) with ArTéMiS + *Herschel*

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**