Observations of the filament paradigm for star formation: Where do we stand?

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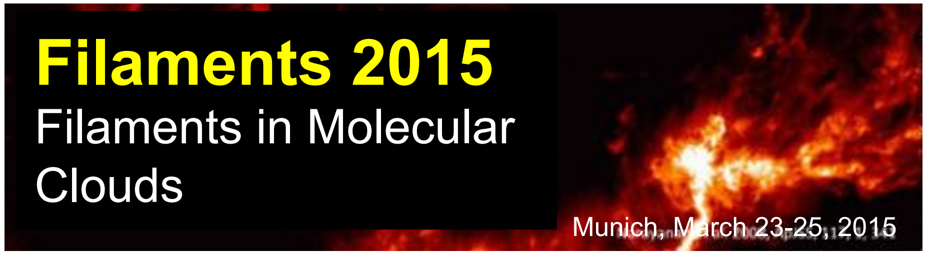
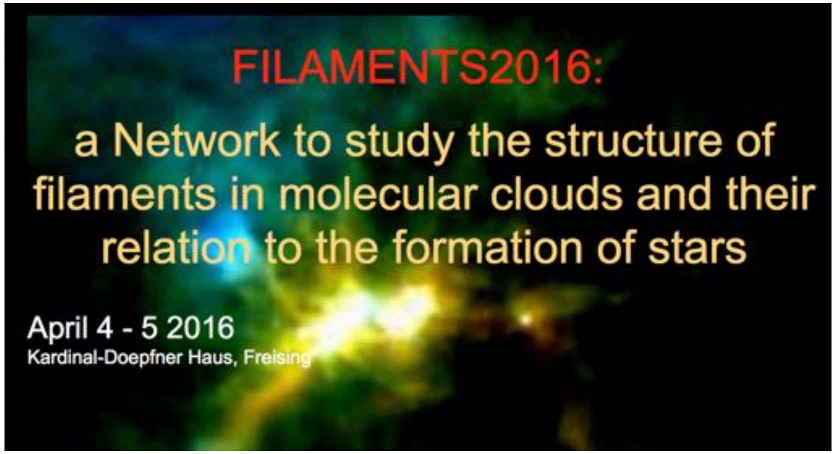




Herschel 10 years after launch : science and Celebration – ESAC Madrid – 13 May 2019

Outline

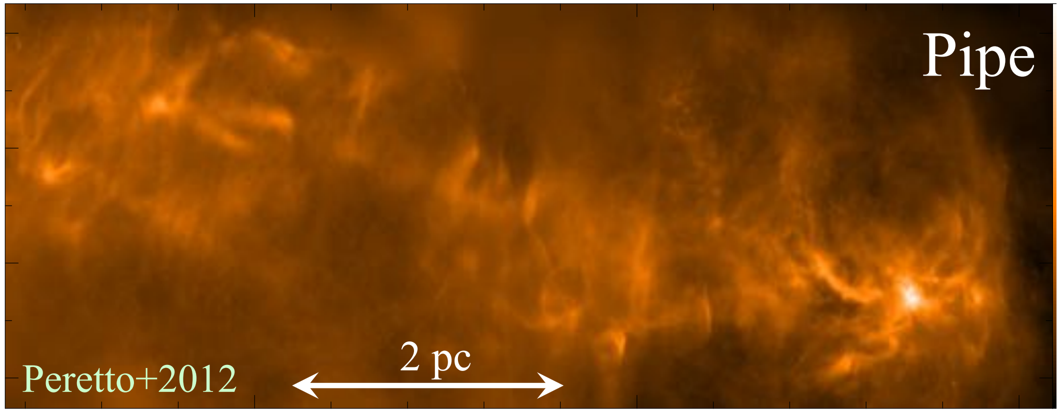
- **Introduction: Omnipresence/`Universality' of filamentary structures in the cold ISM**
- **Results supporting a filament paradigm for star formation**
- **Open issues & future prospects - Role of magnetic fields?**

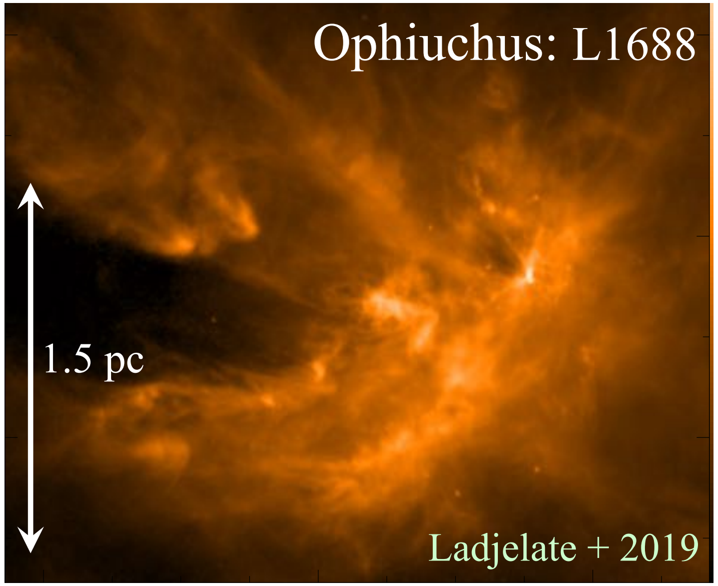
Polaris
Herschel
250/350/500 μm

With: V. Könyves, D. Arzoumanian, P. Palmeirim, J. Di Francesco, D. Ward-Thompson, S. Pezzuto, J. Kirk, A. Menshchikov, N. Schneider, A. Roy, S. Bontemps, F. Motte, M. Griffin, K. Marsh, N. Peretto, Y. Shimajiri, B. Ladjelate, A. Bracco, N. Cox, P. Didelon, & the ***Herschel* Gould Belt survey Team**

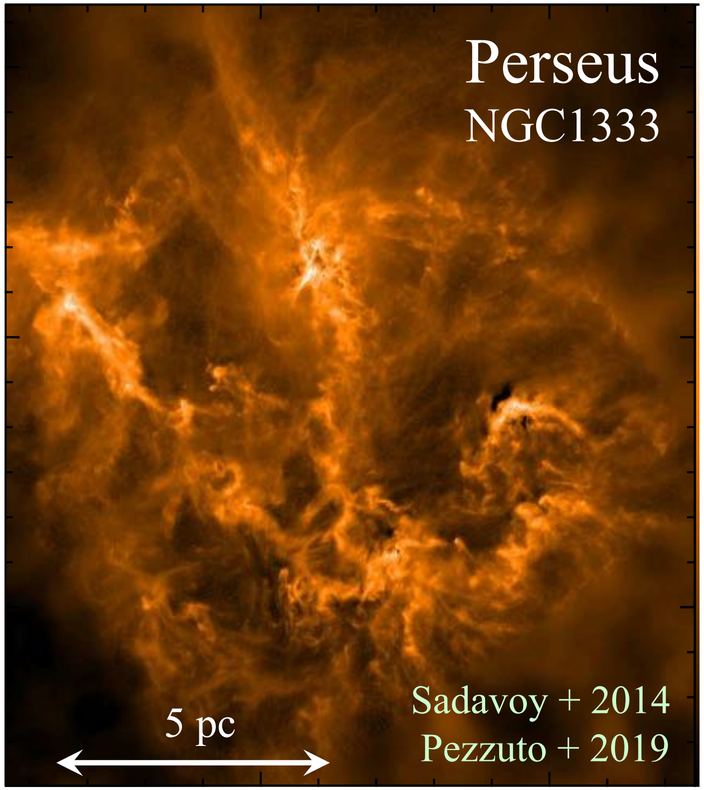
HERSCHEL Gould Belt Survey

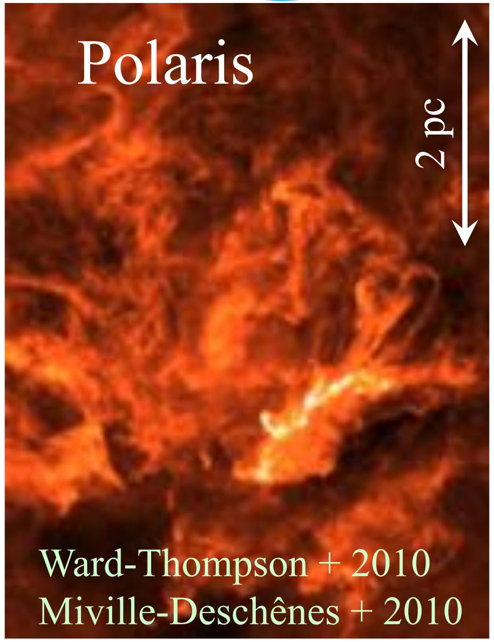
Herschel has revealed the presence of a 'universal' filamentary structure in the cold ISM

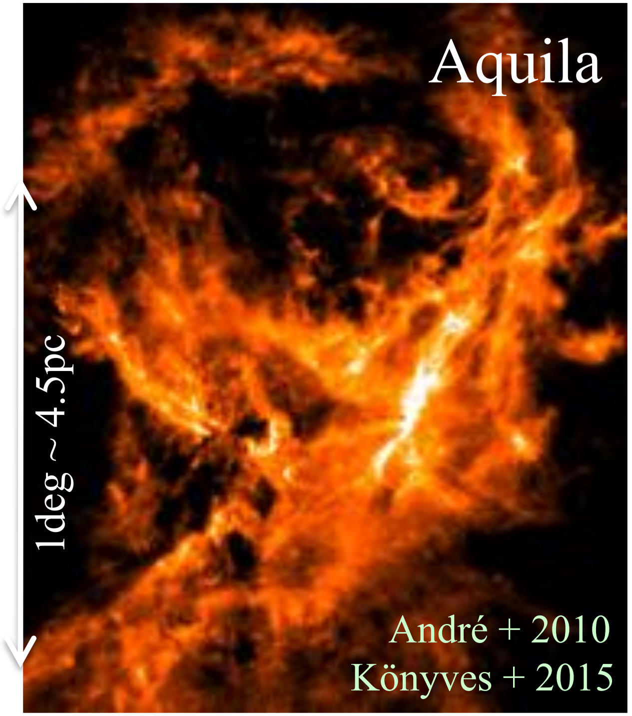




Column density maps available at http://gouldbelt-herschel.cea.fr/archives

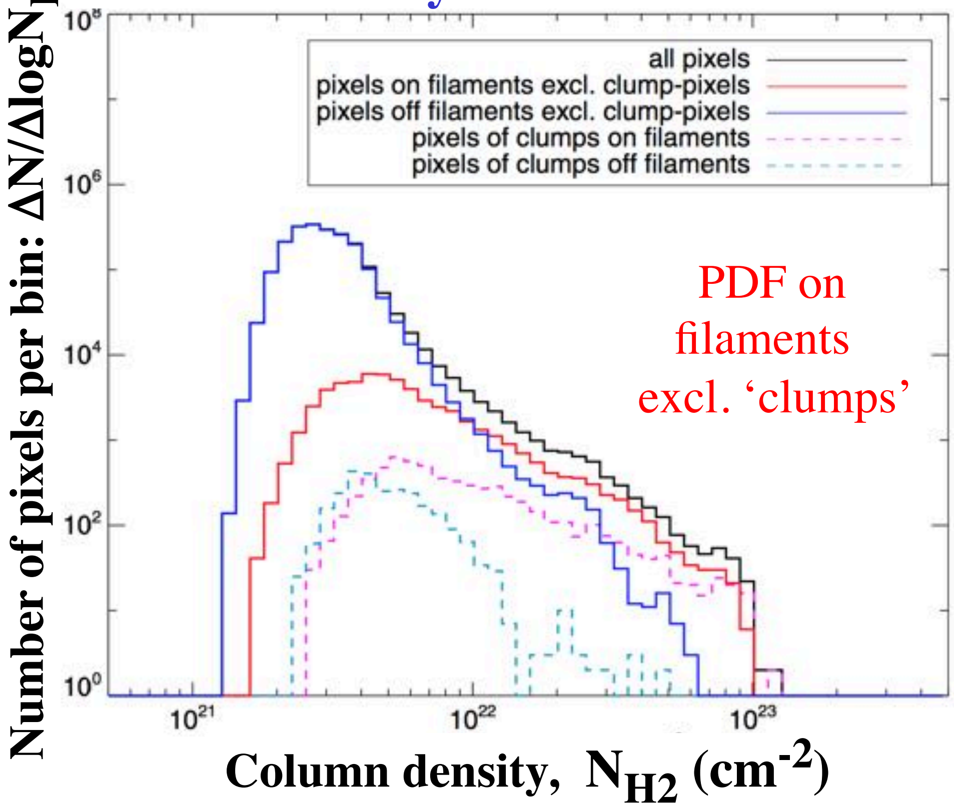






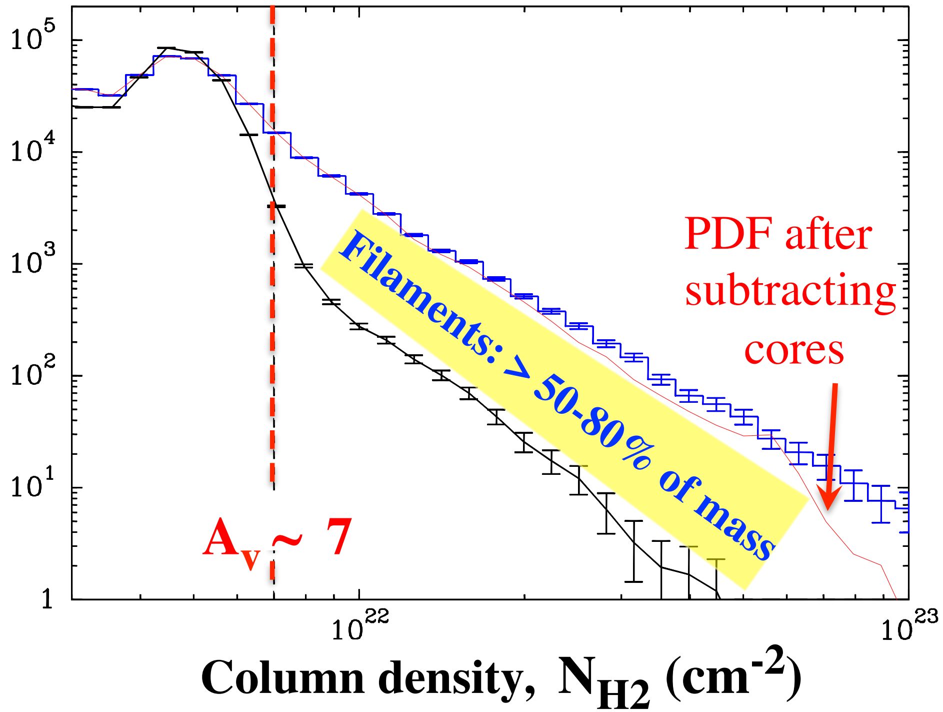
Filaments dominate the mass budget of GMCs at high densities

Herschel (Hi-GAL)
Column Density PDF for l217-224 field



Schisano et al. 2014

Herschel (HGBS)
Column Density PDF for Aquila GMC



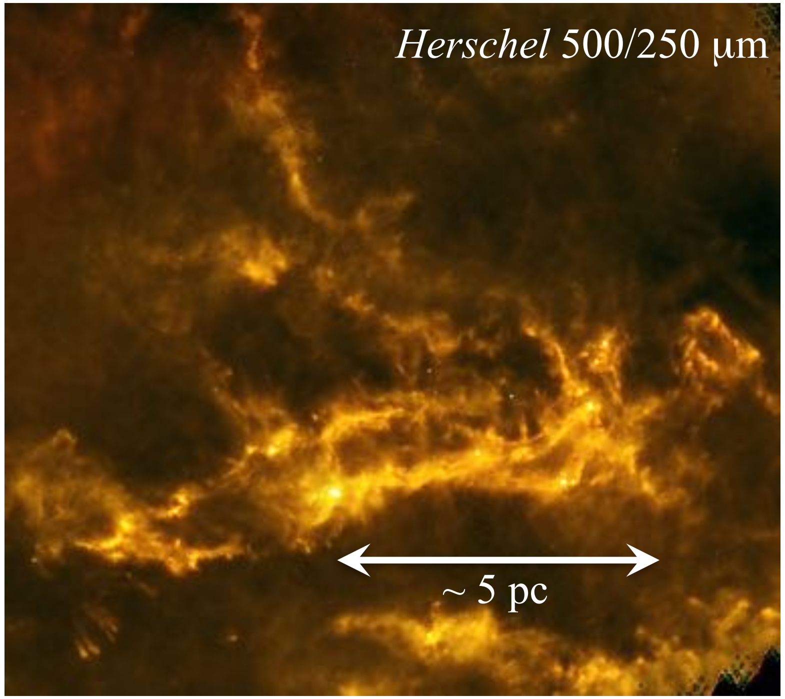
Könyves et al. 2015

Arzoumanian et al. 2019

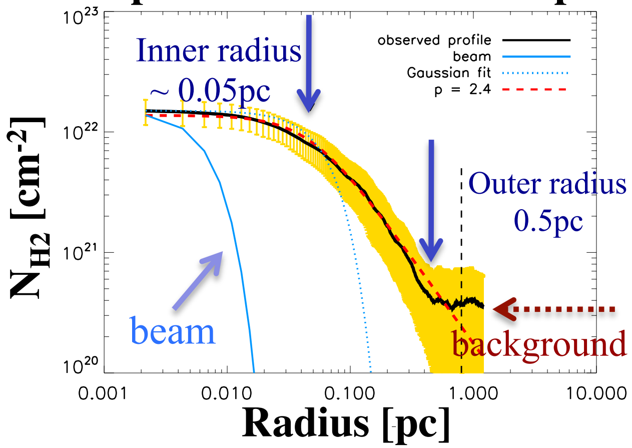
- Below $A_V \sim 7$: ~ 10-20 % of the mass in the form of filaments
- **Above $A_V \sim 7$: > 50-80 % of the mass in the form of filaments**

Nearby filaments have a common inner width ~ 0.1 pc

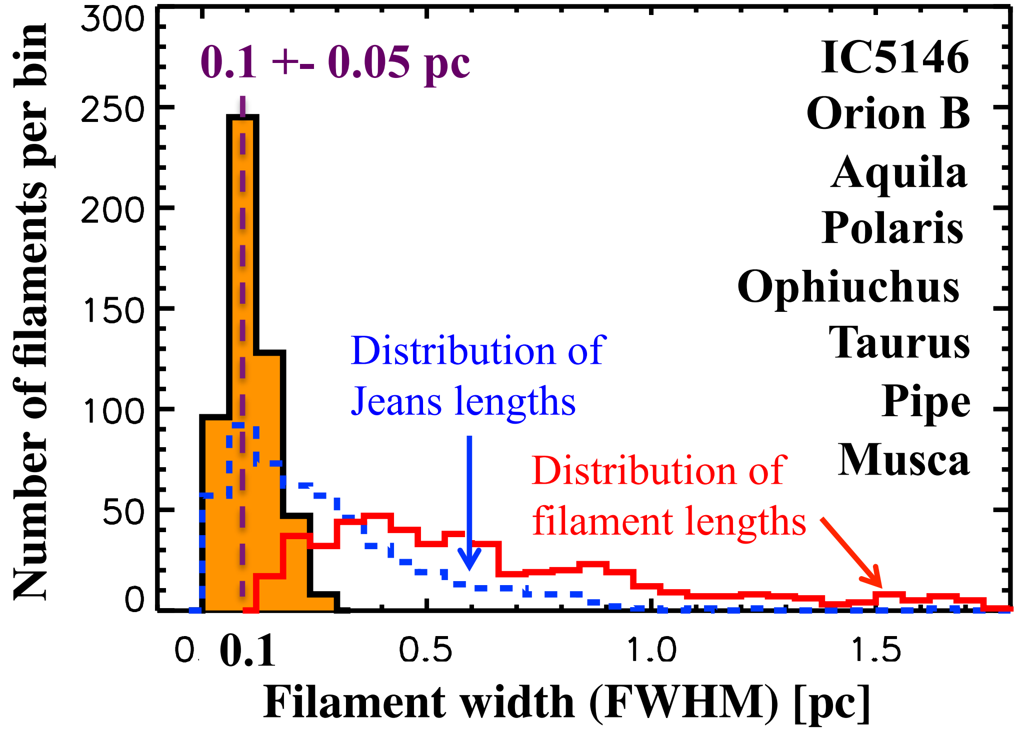
Network of filaments in IC5146



Example of a filament radial profile



Distribution of mean inner widths for ~ 600 nearby (d < 450pc) filaments



D. Arzoumanian+2011 & 2019 (A&A, 621, A42)

[but some width variations along each filament: Ysard+2013]

Possibly linked to magneto-sonic scale of turbulence?

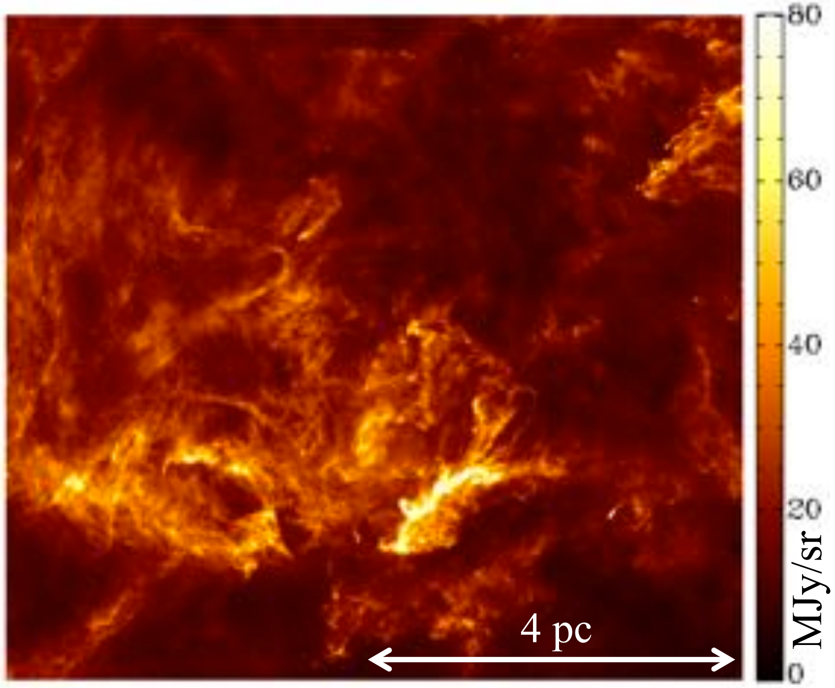
(cf. Padoan+2001; Federrath 2016)

Challenging for numerical simulations

(cf. R. Smith+2014; Ntormousi+2016)

Is a characteristic filament width consistent with the observed power spectrum of cloud images?

SPIRE 250 μm image of Polaris translucent cloud

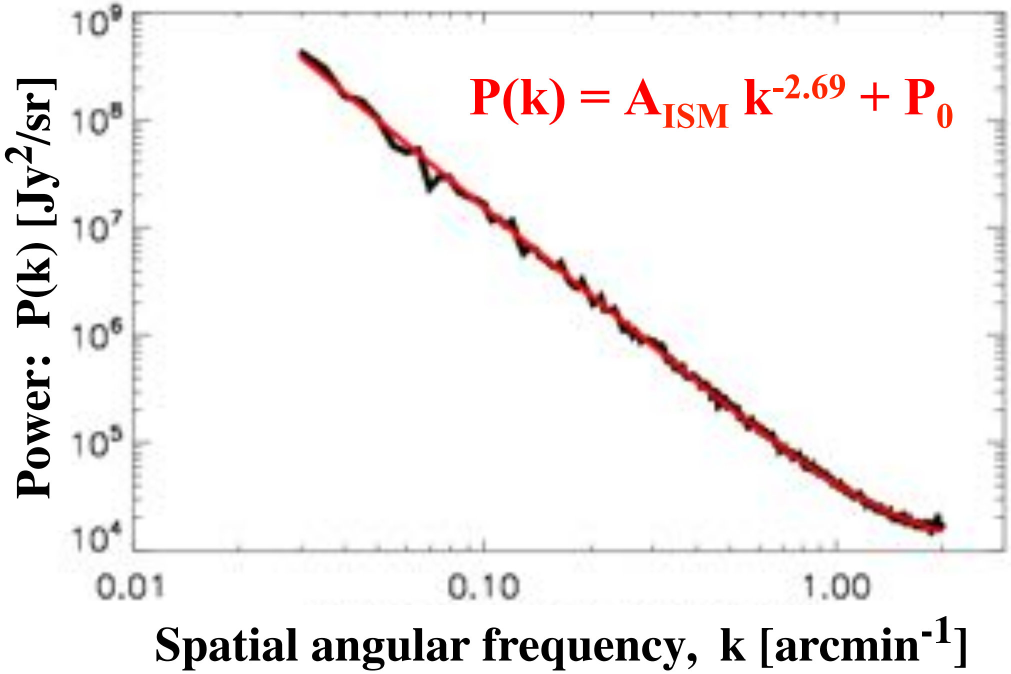


Miville-Deschênes et al. 2010

Tension with scale-free power spectrum

Panopoulou+2017

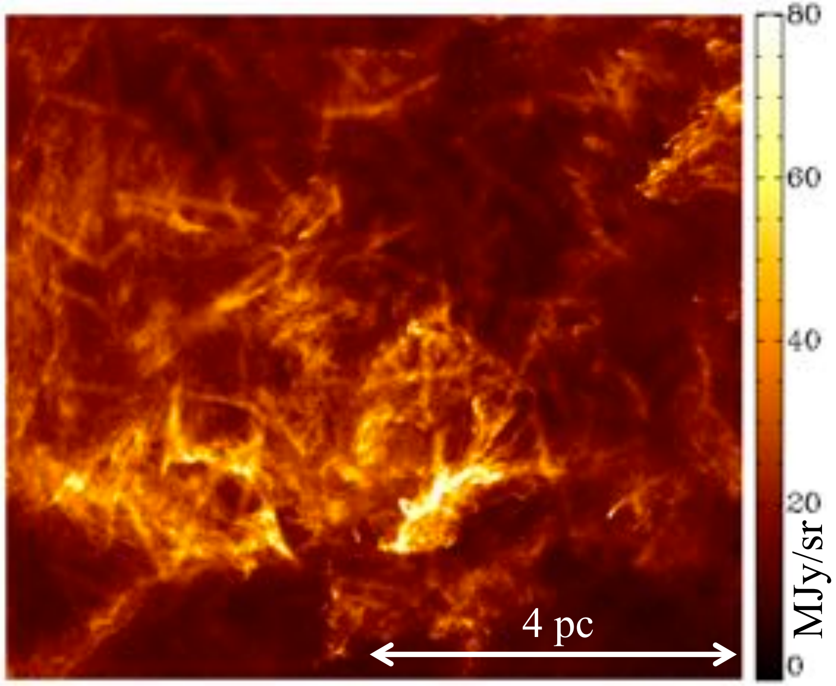
Noise-subtracted, deconvolved power spectrum of Polaris image



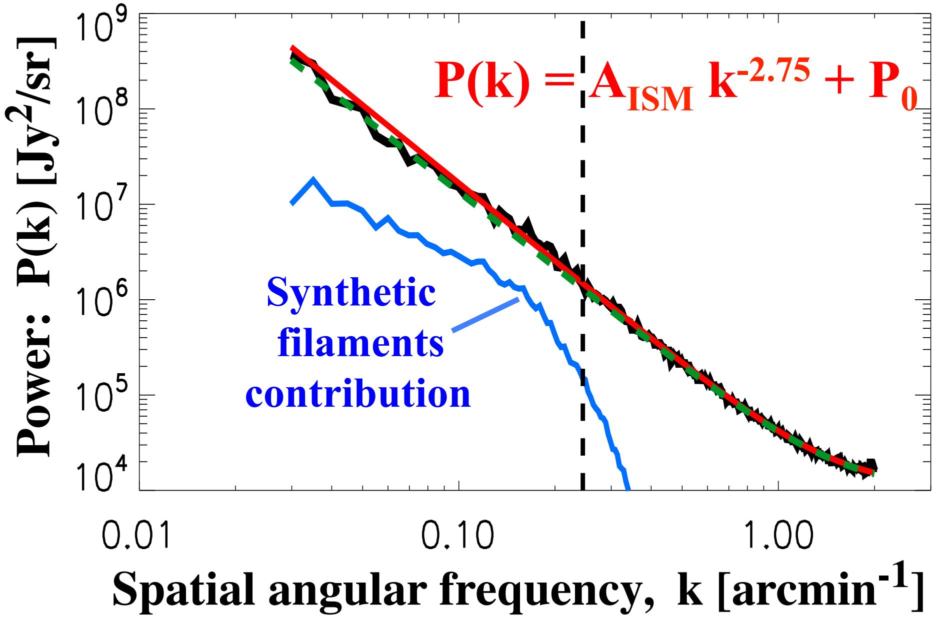
Simple tests

A. Roy et al. 2019, arXiv:1903.12608

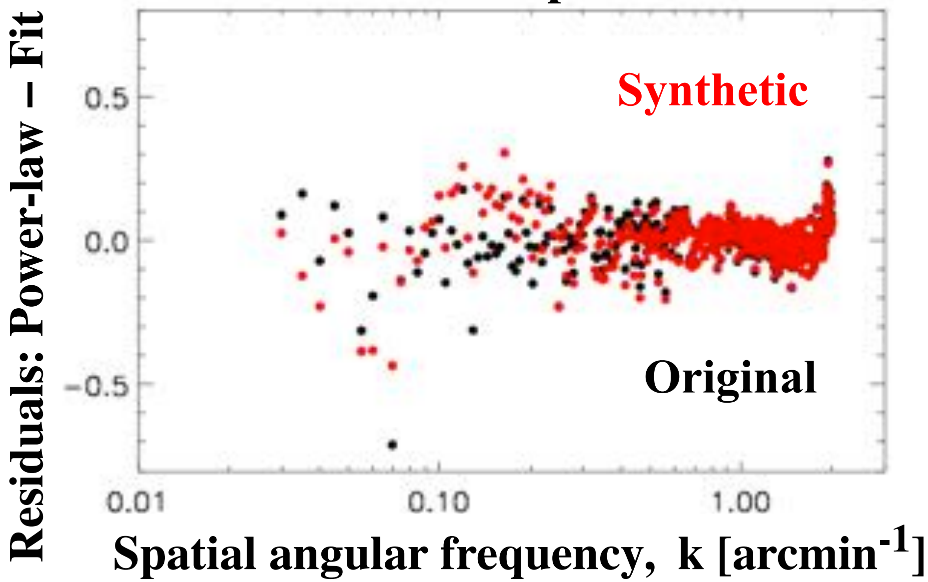
Injecting a population of synthetic 0.1 pc filaments with contrast ~ 50% in SPIRE 250 μm image of Polaris translucent cloud



Power spectrum of image with synthetic 0.1 pc filaments

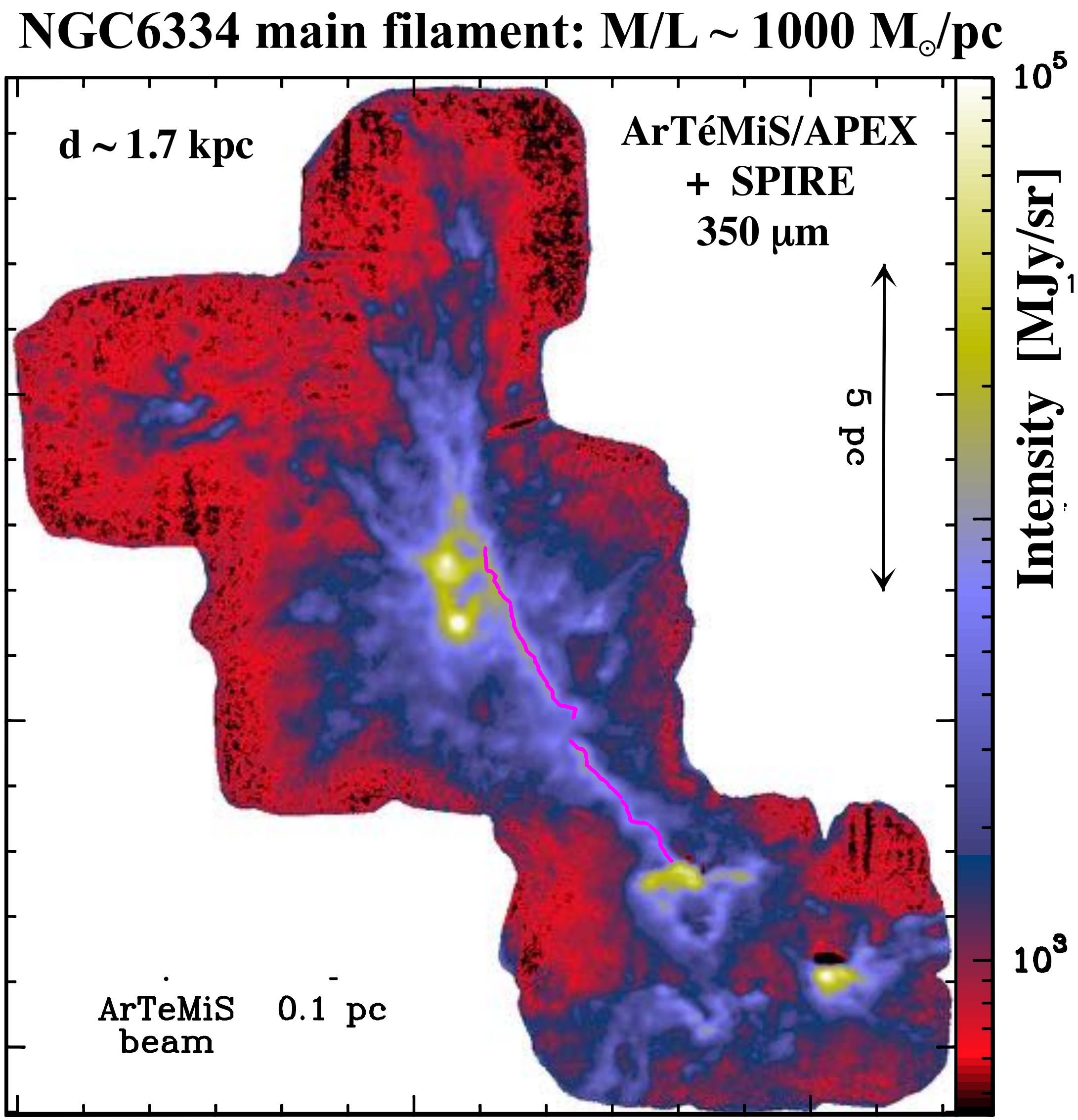


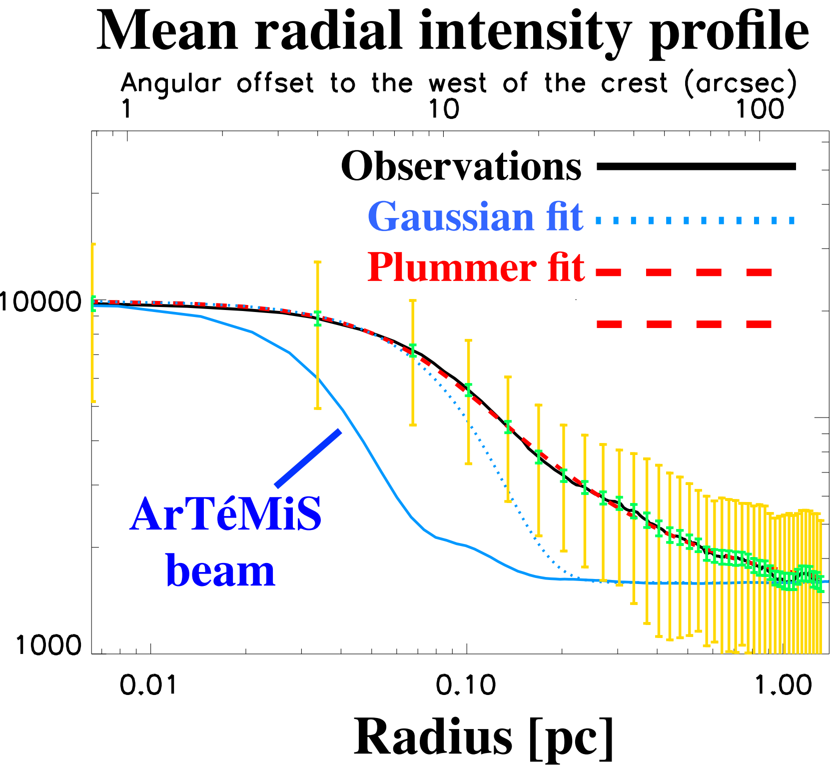
Difference from power-law fit

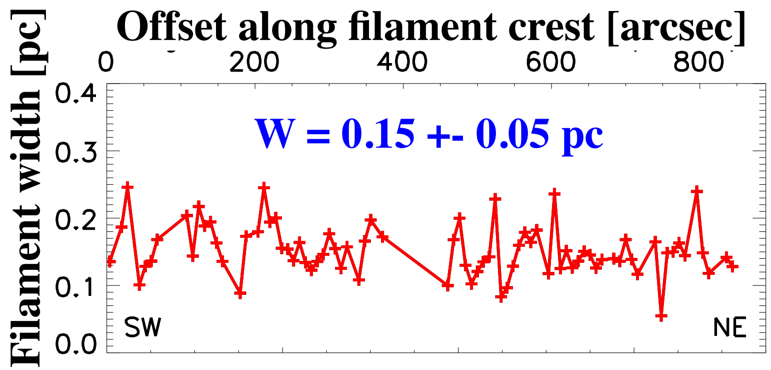


Conclusion: Observed power spectra remain consistent with a characteristic filament width ~ 0.1 pc for realistic filling factors and filament contrasts

Characteristic filament width ~ 0.1 pc not restricted to the nearby clouds of the Gould Belt



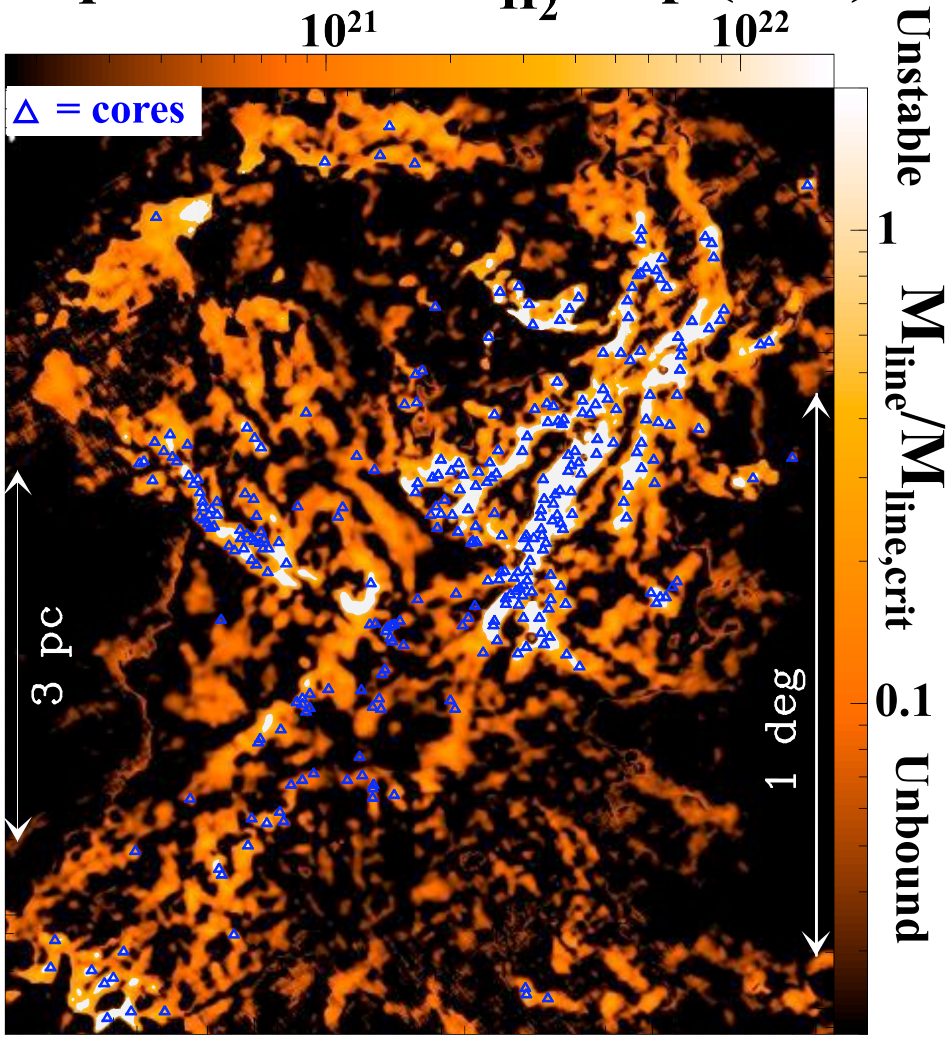




André, Revéret, Könyves+2016 - See Russeil+2013 & Tigé+2017 for *Herschel*/HOBYS results on NGC6334

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

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



André+2010; Könyves+2015

$\Sigma \gtrsim 150\ M_\odot/pc^2$

Also:

Bresnahan+2018 (CrA)

Benedettini+2018 (Lupus)

Könyves+2019 (Orion B)

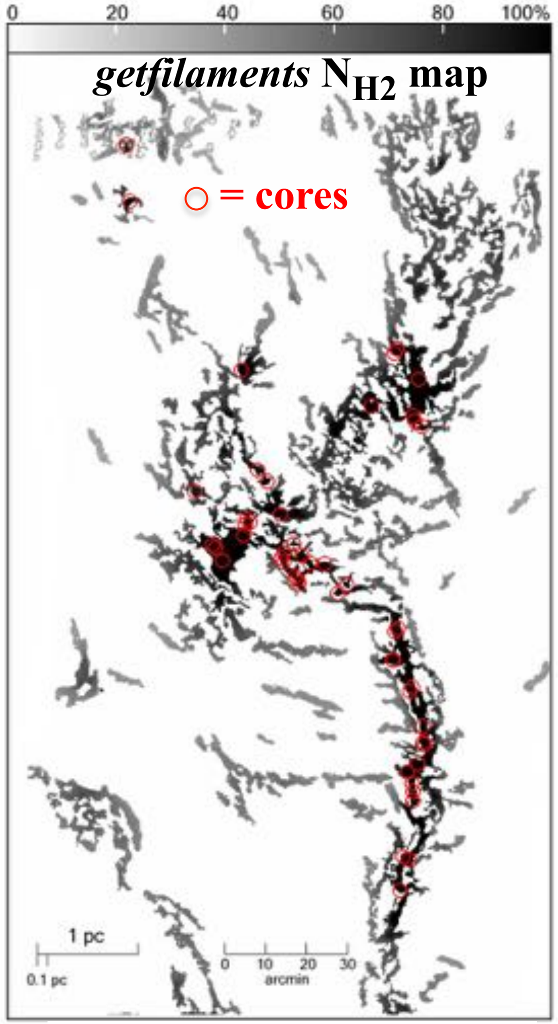
Ladjelate+2019 (Oph)

Pezzuto+2019 (Perseus)

Fiorellino+2019 (Serpens)

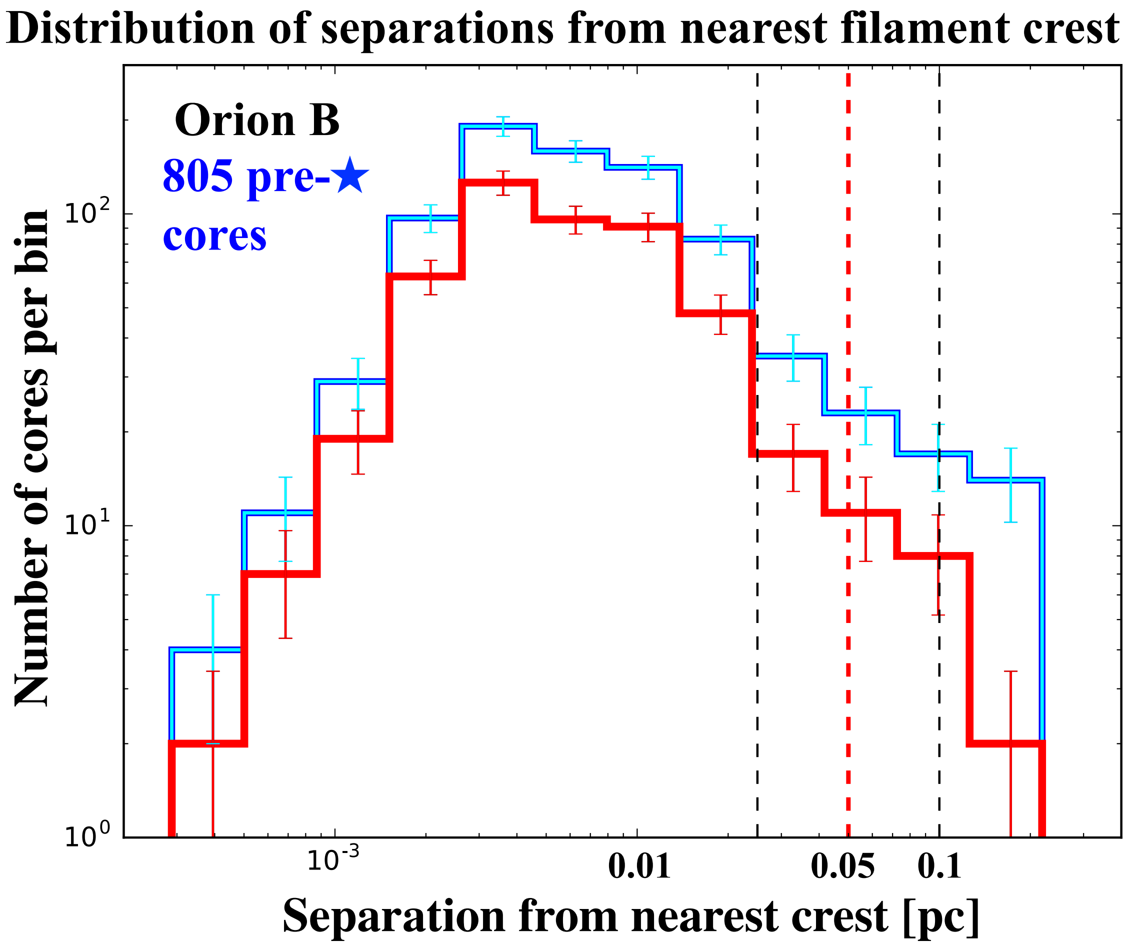
…

Taurus B211/3+L1495

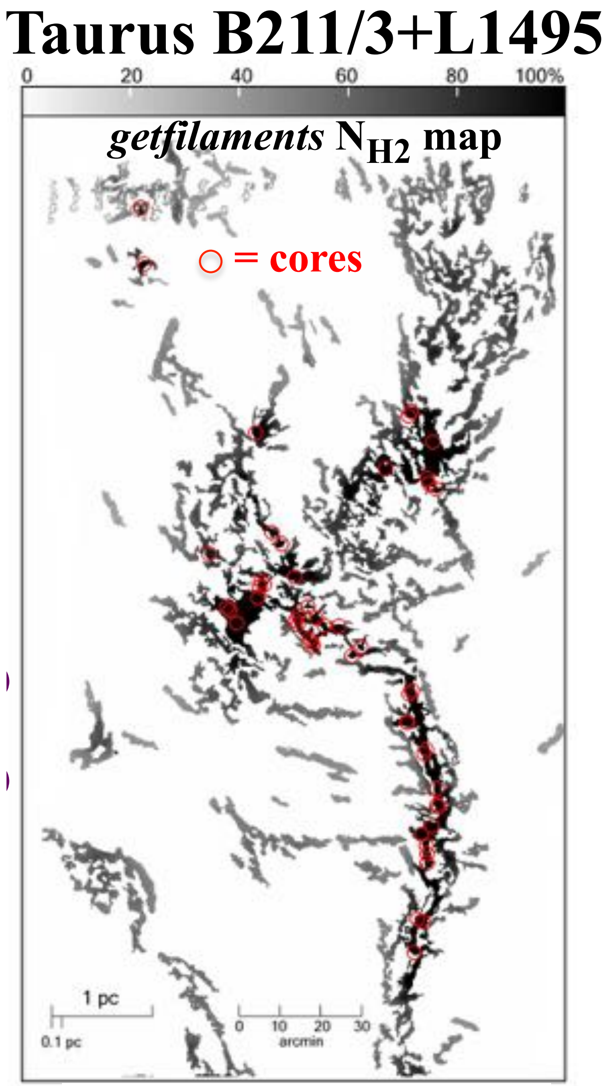


Marsh al. 2016, MNRAS

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



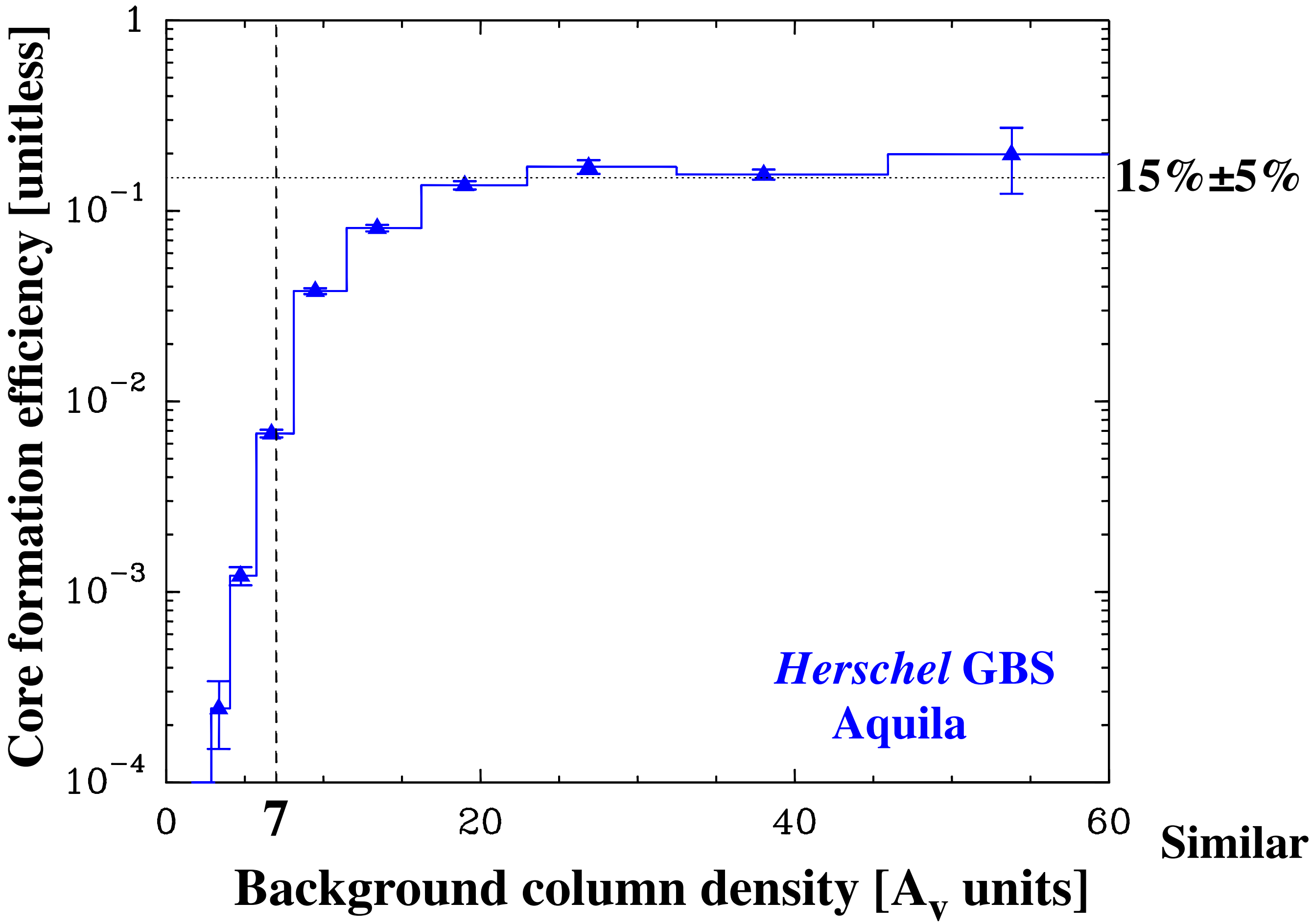
Könyves et al. 2019, A&A, submitted



Marsh al. 2016, MNRAS

Strong evidence of a column density transition/ “threshold” for the formation of prestellar cores

Prestellar CFE as a function of background A_V



$CFE(A_V) = \Delta M_{cores}(A_V) / \Delta M_{cloud}(A_V)$

In Aquila, ~90% of the prestellar cores identified with *Herschel* are found above $A_v \sim 7$ ⇔ $\Sigma \sim 150\ M_\odot\ pc^{-2}$

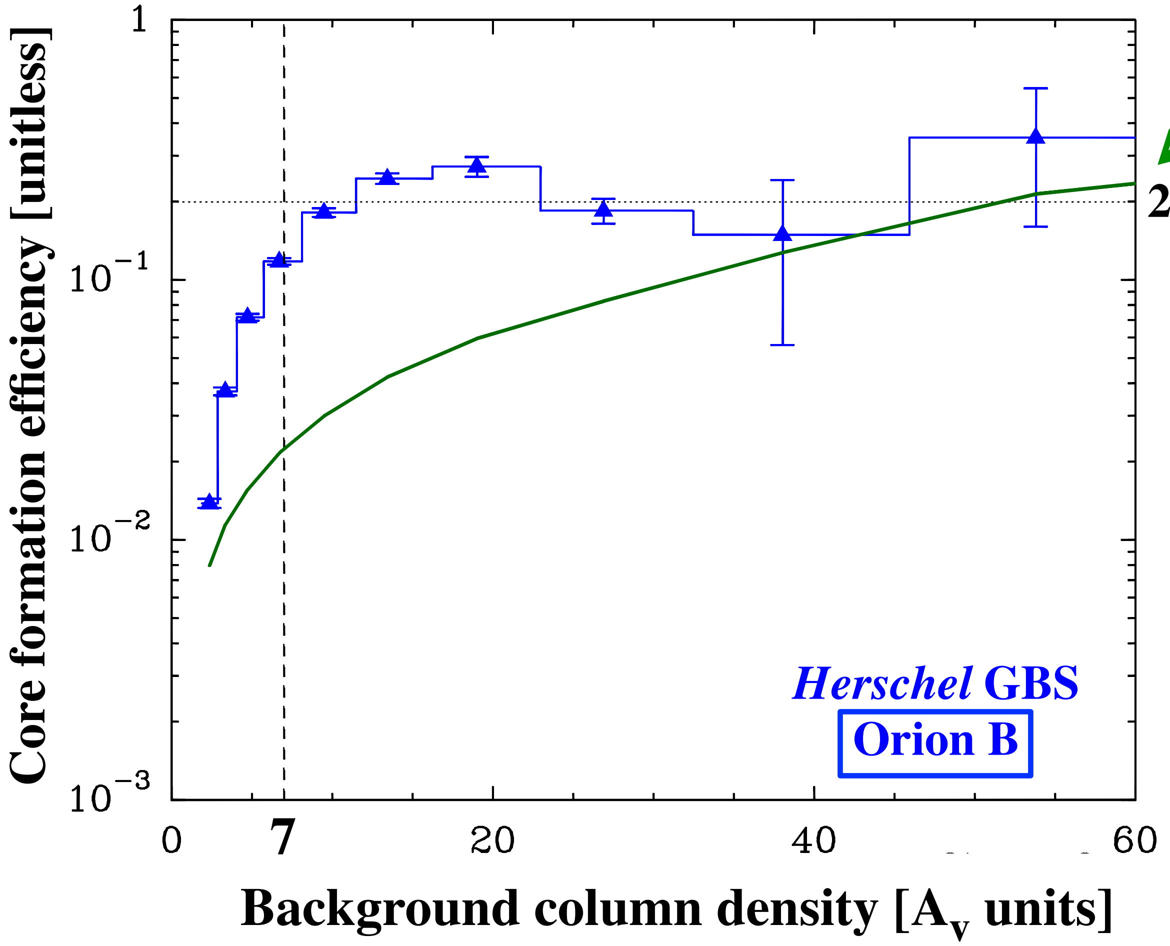
Könyves+2015, A&A

Similar to ‘threshold’ for YSOs (*Spitzer*):

Heiderman+2010; Lada+2010; Evans+2014

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

Prestellar CFE as a function of background A_V



$CFE(A_V) = \Delta M_{cores}(A_V) / \Delta M_{cloud}(A_V)$

Turbulence-regulated models of SF (ϵ_{ff} ~ 1%) cf. Krumholz+2012

Sharp transition around a fiducial value A_v ~ 7 ⇔ Σ ~ 150 $M_\odot$ pc^{-2} ⇔ M/L ~ 15 $M_\odot$/pc

André+2010; Könyves+2015

Interpretation:

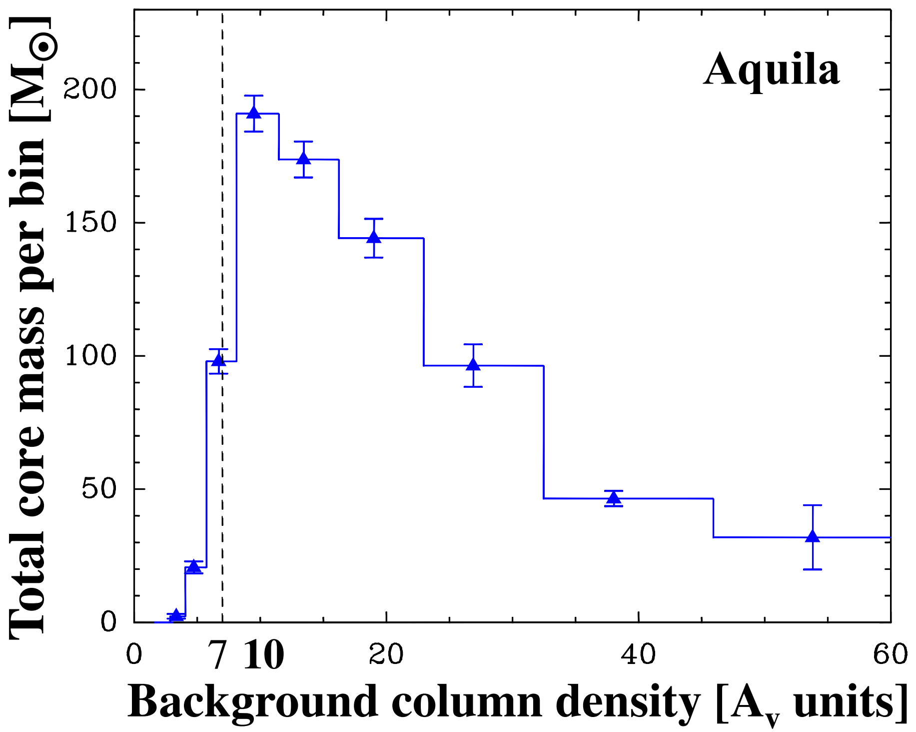
Critical M/L of nearly isothermal cylinders (Ostriker 1964; Inutsuka & Miyama 1997)

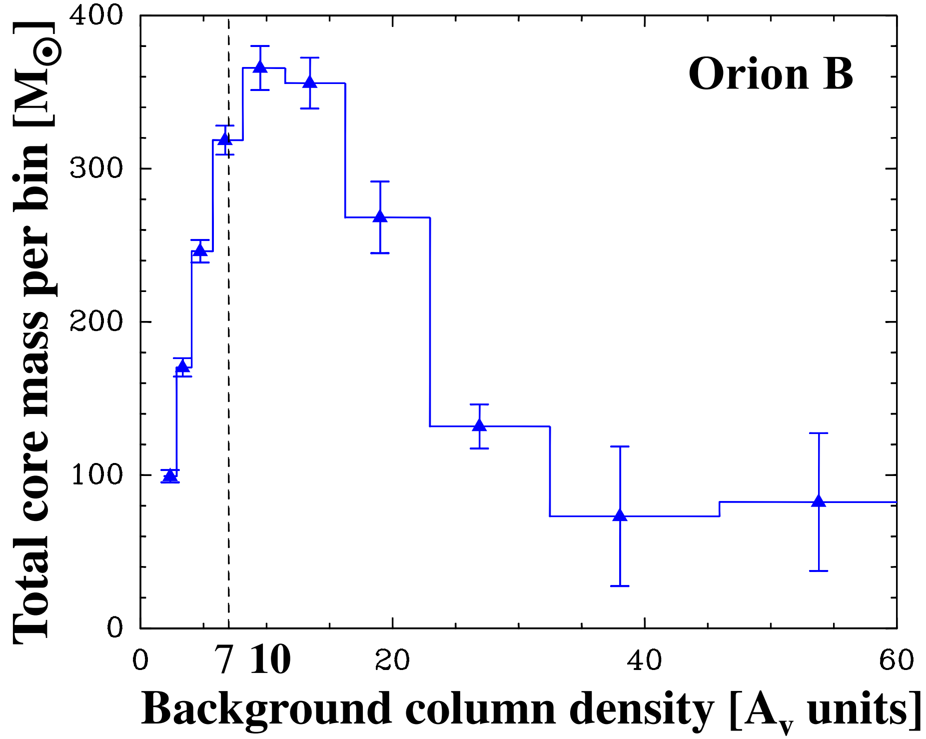
$M_{line, crit} = 2\, c_s^2/G$ ~ 16 $M_\odot$/pc for T ~ 10 K

Könyves+2019, A&A, submitted

Most prestellar cores form near the column density "threshold" (in 'transcritical' filaments)

Total prestellar core mass as a function of background A_V





Sharp transition around a fiducial value
$A_v \sim 7 \Leftrightarrow \Sigma \sim 150\ M_\odot/pc^2$
$\Leftrightarrow M/L \sim 15\ M_\odot/pc$

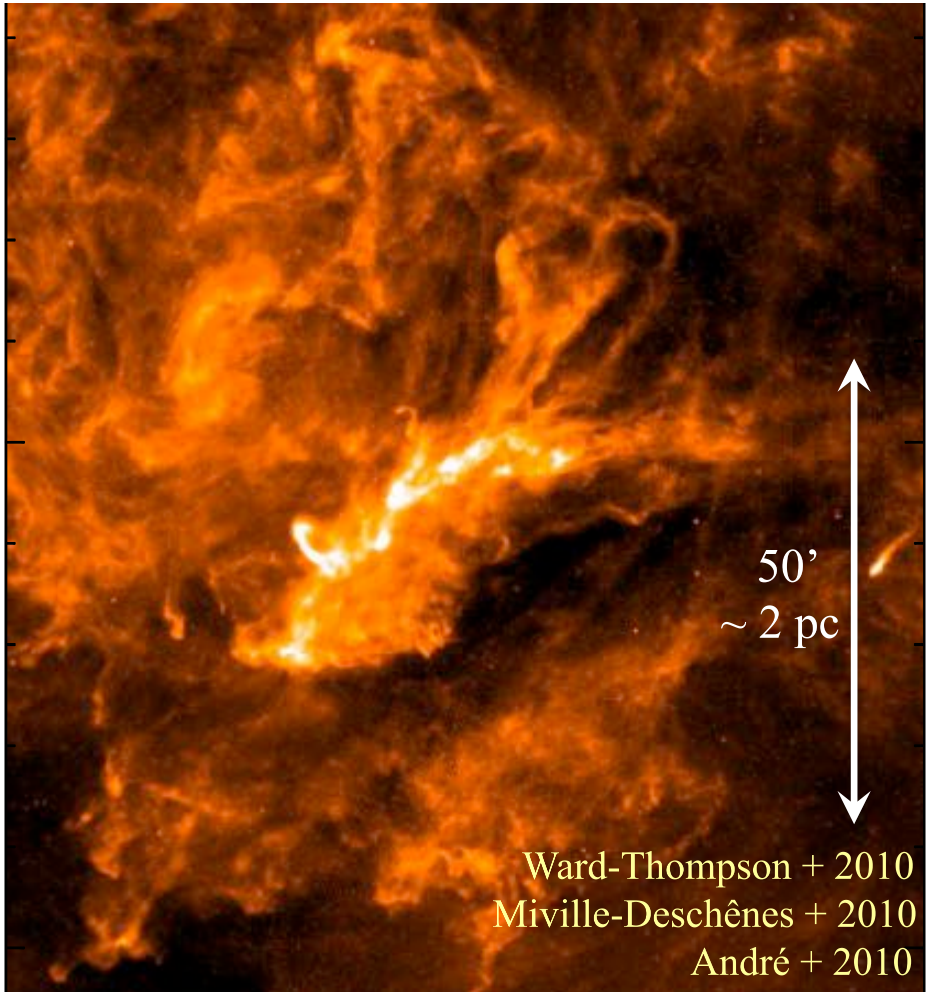
Könyves+2019, A&A, submitted

A filament paradigm for ~ $M_\odot$ star formation?

Schneider & Elmegreen 1979; Larson 1985; Nagasawa 1987; Inutsuka & Miyama 1997; Myers 2009 …

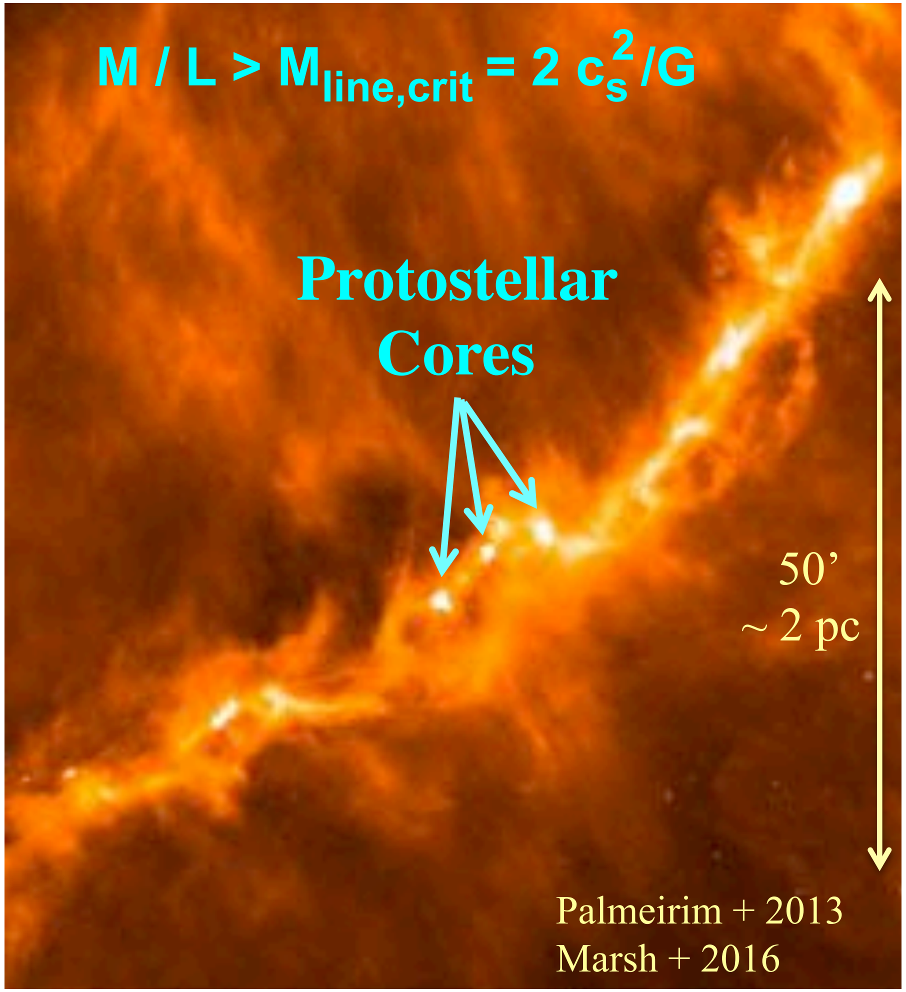
Protostars & Planets VI chapter (André, DiFrancesco, Ward-Thompson, Inutsuka, Pudritz, Pineda 2014)

1) Large-scale MHD 'turbulent' compressive flows create ~0.1 pc filaments



Polaris – *Herschel*/SPIRE 250 μm

2) Gravity fragments the densest filaments into prestellar cores

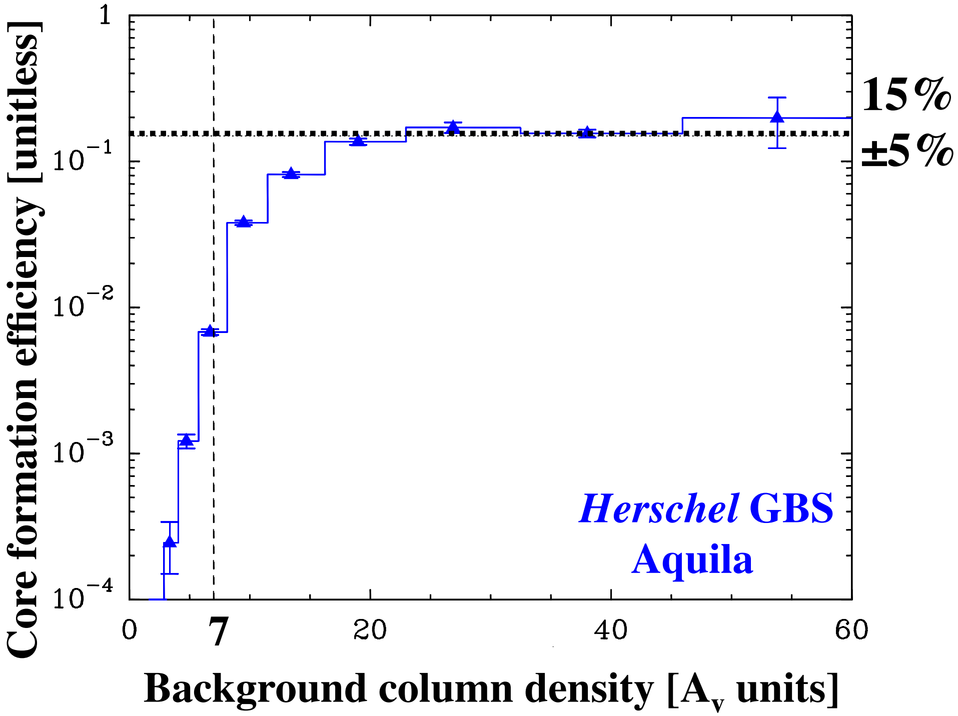


Taurus B211/3 – *Herschel* 250 μm

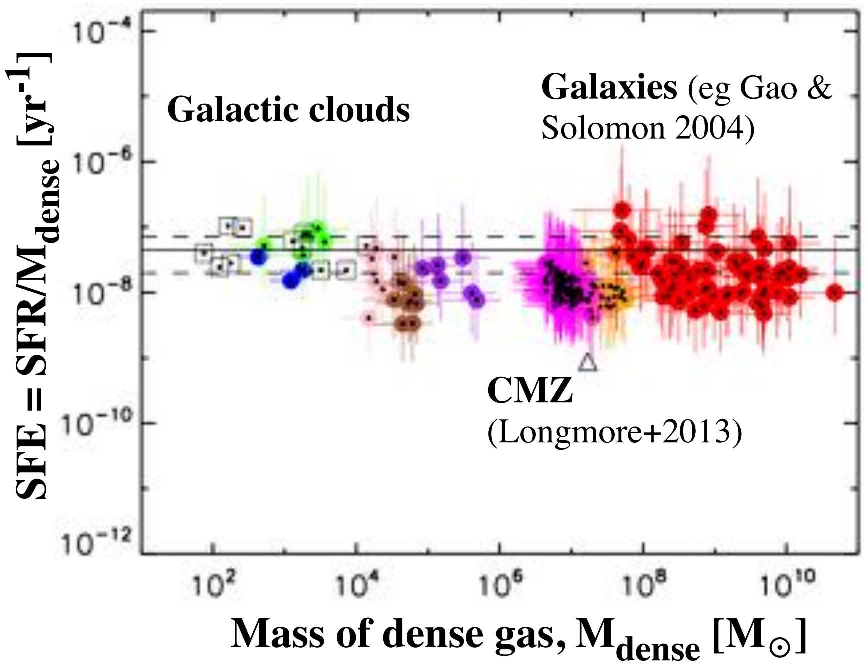
Importance of filaments in the ISM of other galaxies?

A characteristic prestellar core formation efficiency in dense gas filaments → **Responsible for a common star formation efficiency in the dense (> 10^4 cm^{-3}) molecular gas of galaxies?**

Prestellar CFE as a function of background A_V



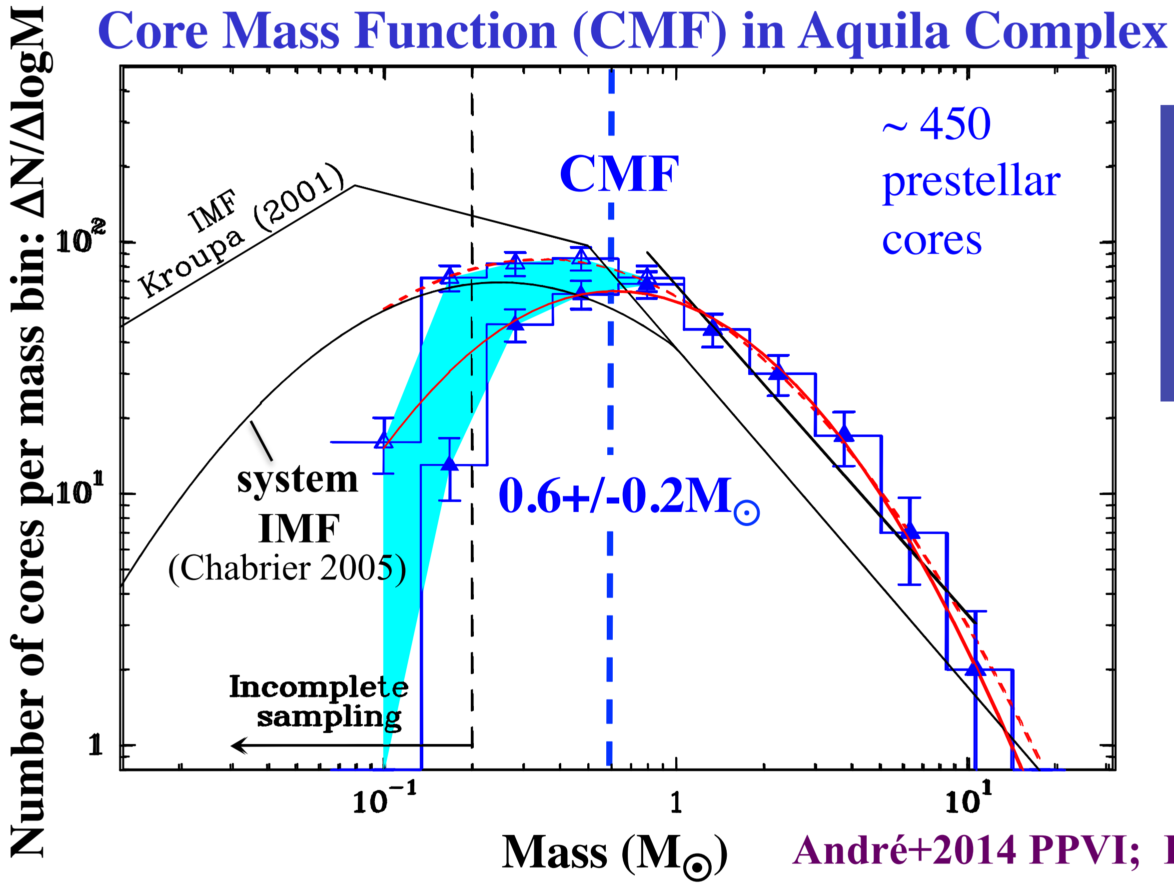
Könyves+2015



Lada+2012 Shimajiri+2017

➤ **Filaments may help to regulate the star formation efficiency in the dense molecular gas of galaxies** (e.g. Shimajiri+2017)

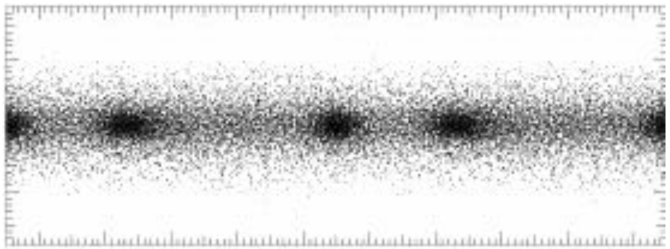
Filament fragmentation can account for the peak of the prestellar CMF and (possibly) the “base” of the IMF



André+2014 PPVI; Könyves+2015

Jeans mass:

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

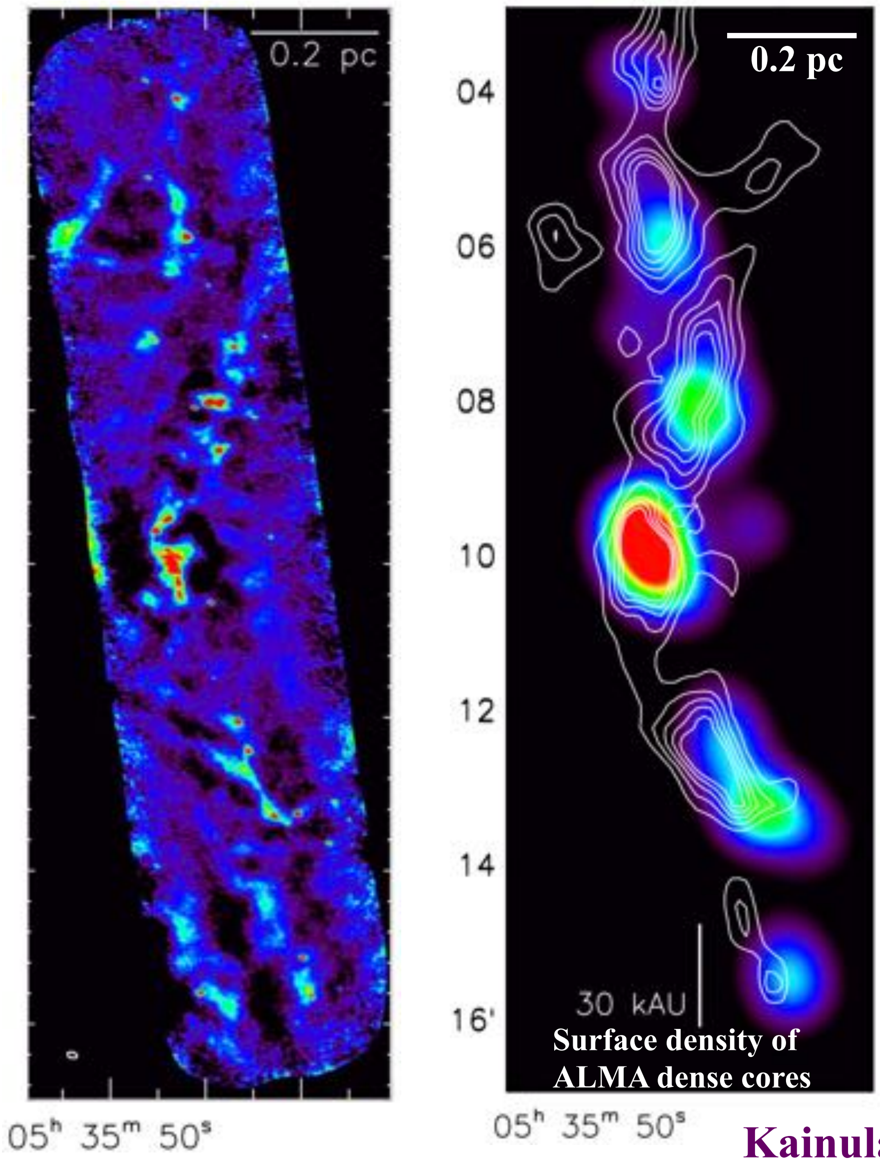


Inutsuka & Miyama 1997

- CMF peaks at ~ 0.6 $M_\odot$ ≈ Jeans mass in marginally critical filaments
- Close link of the prestellar CMF with the stellar IMF: $M_\star \sim 0.4 \times M_{core}$ (see also Motte+1998; Alves+2007)
- Characteristic (pre)stellar mass may result from filament fragmentation

Detailed fragmentation manner of filaments?

ALMA 3mm mosaic of the Orion A ISF



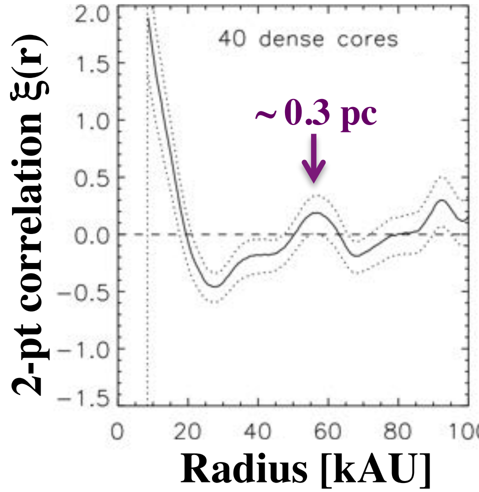
Kainulainen+2017

Some evidence of hierarchical fragmentation within filaments
(e.g. Takahashi+2013; Kainulainen+2013; Teixeira+2016)

Two fragmentation modes:

- « Cylindrical » mode ←→ groups of cores separated by ~ 0.3 pc
- « Spherical » Jeans-like mode ←→ core spacing < 0.1 pc within groups

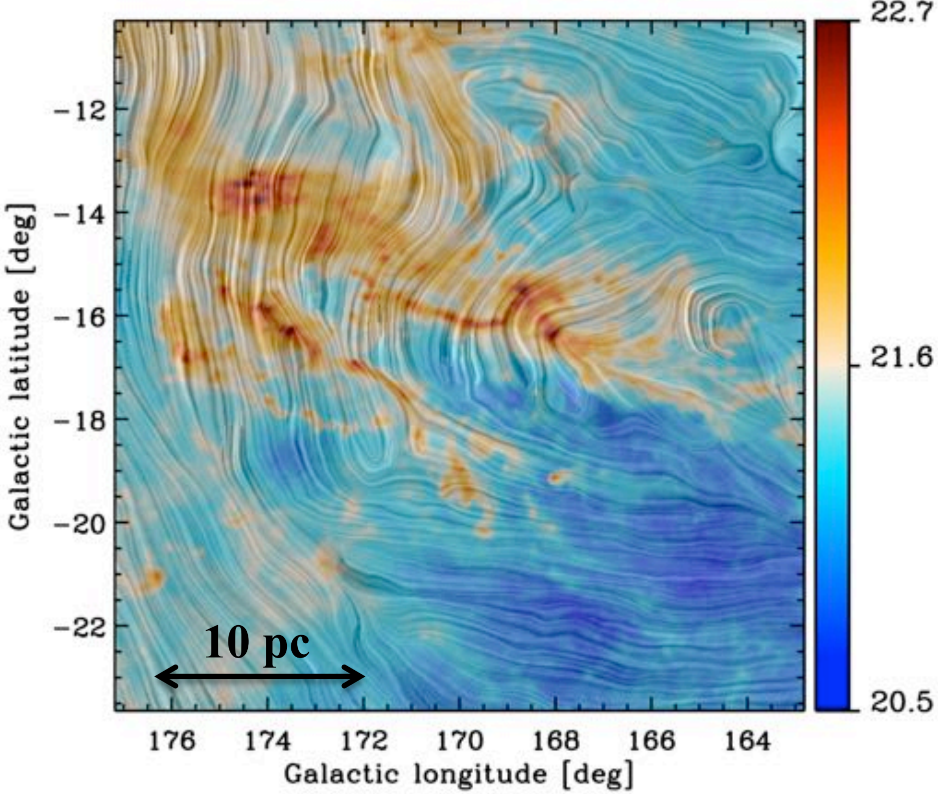
Two-point correlation function of ALMA dense cores



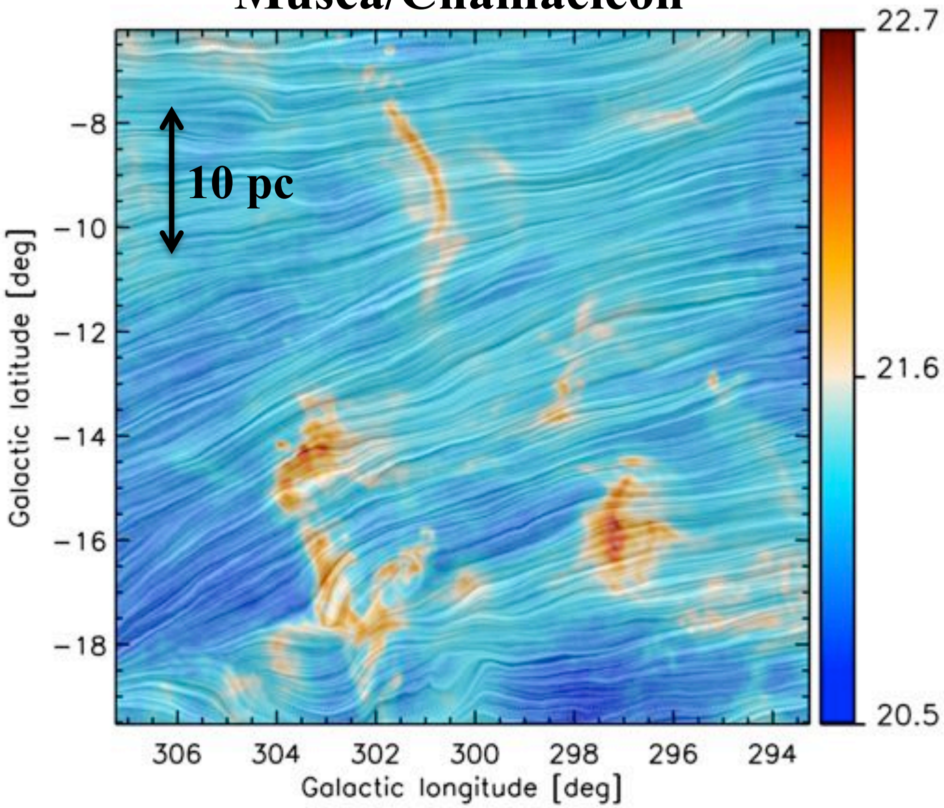
Role of magnetic fields?

- ➢ ***Planck* polarization data reveal a very organized B field on large ISM scales,**
  ~ perpendicular to dense star-forming filaments, ~ parallel to low-density filaments
- ➢ **Suggests that the B field plays a key role in the physics of ISM filaments**

Taurus



Musca/Chamaeleon



Planck intermediate results. XXXV. (2016 J. Soler)

Suggests sub-Alfvénic turbulence on cloud scales

Color: N(H) from Planck data @ 5' resol. (~ 0.2-0.3 pc)

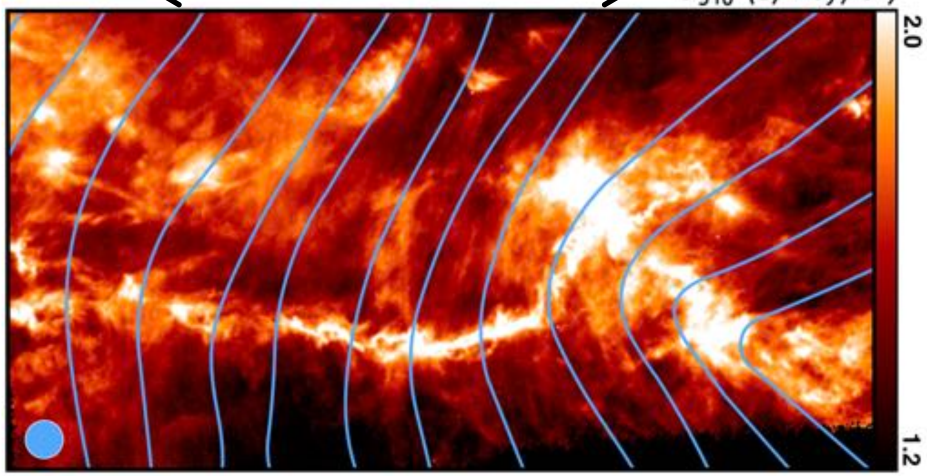
Drapery: B field lines from Q,U *Planck* 850 μm @ 10'

F. Boulanger's group

SPICA-POL (« B-BOP ») can unveil the role of magnetic fields in filament evolution and core/star formation

See SPICA-POL White Paper (arXiv:1905.03520)

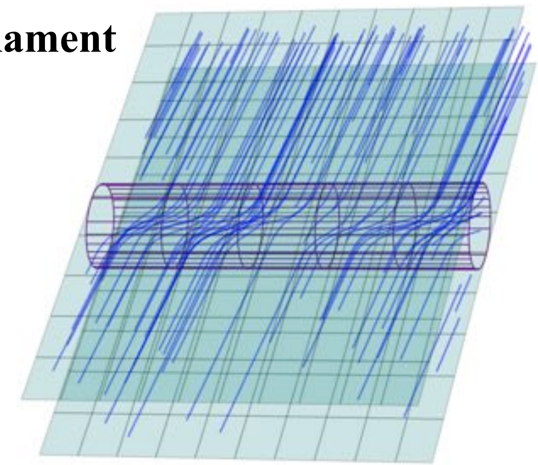
Taurus B211 filament
***Herschel* 250 µm**
+ *Planck* B lines



Palmeirim +2013
A. Bracco

- ***Planck* pol. resolution (> 10' or > 0.4 pc) insufficient to resolve the typical ~0.1 pc inner width of filaments. Can be done with SPICA**
- **SPICA will provide FIR polarized (Q, U) images with a S/N and dynamic range similar to *Herschel* images in I.**

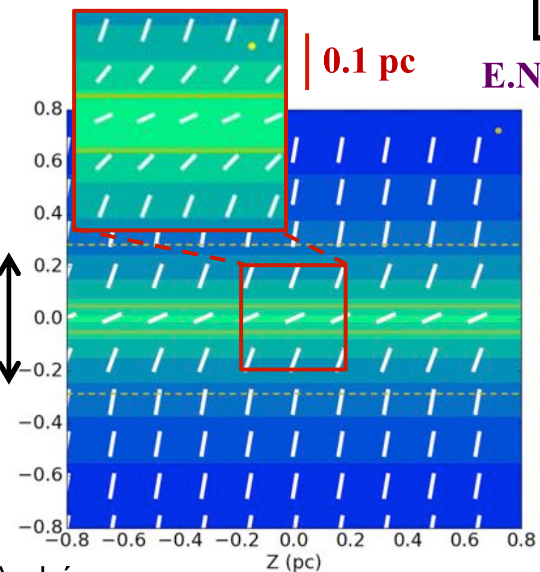
Plausible model of the B field in the central filament



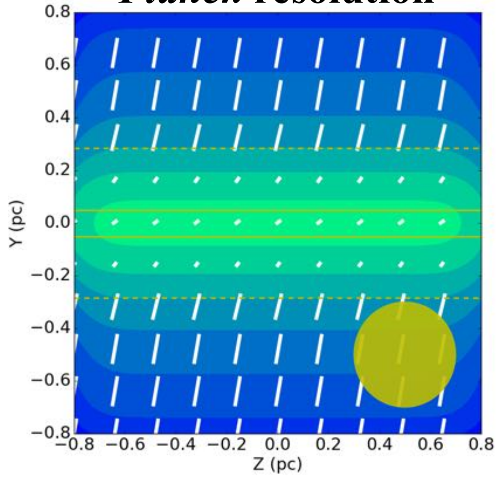
Synthetic polarization maps

E.Ntormousi

SPICA resolution

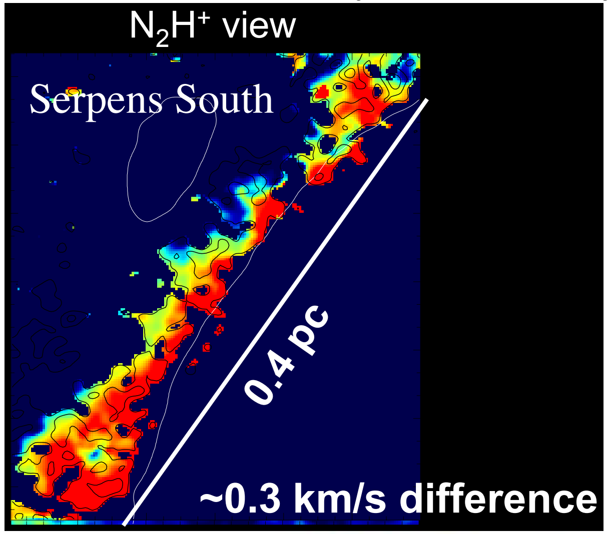


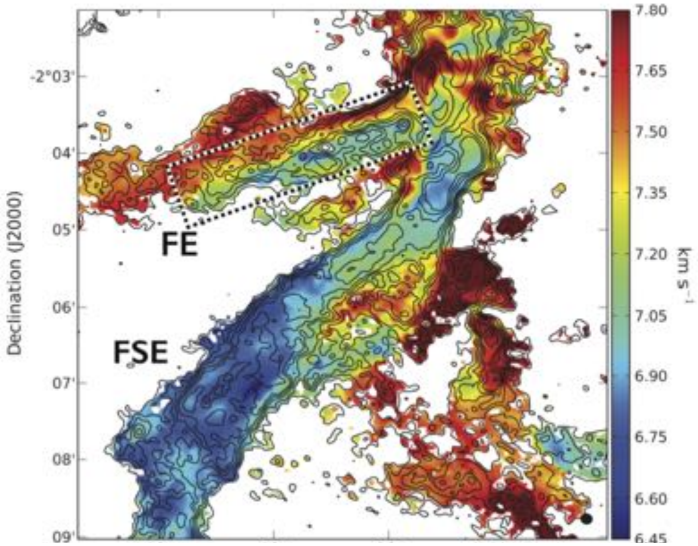
***Planck* resolution**



Detection of transverse velocity gradients across filaments: Evidence of filament formation within sheet-like structures?

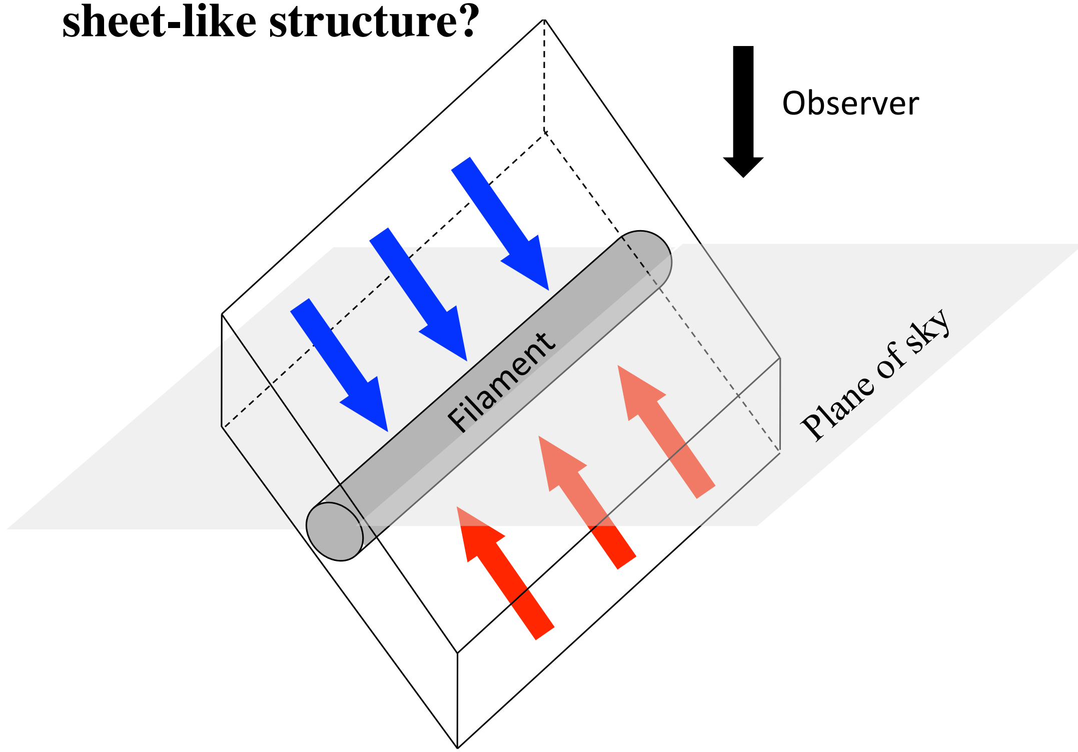
CARMA "CLASSy" SF Survey

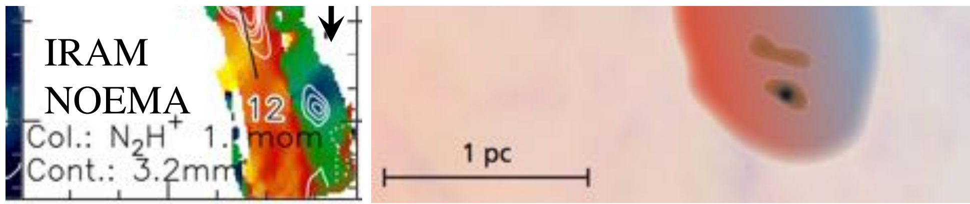




Fernandez-Lopez+2014; Dhabal, Mundy+2018
see also H. Kirk+2013 for Serp-S

Coherent motions inside sheet-like structure?

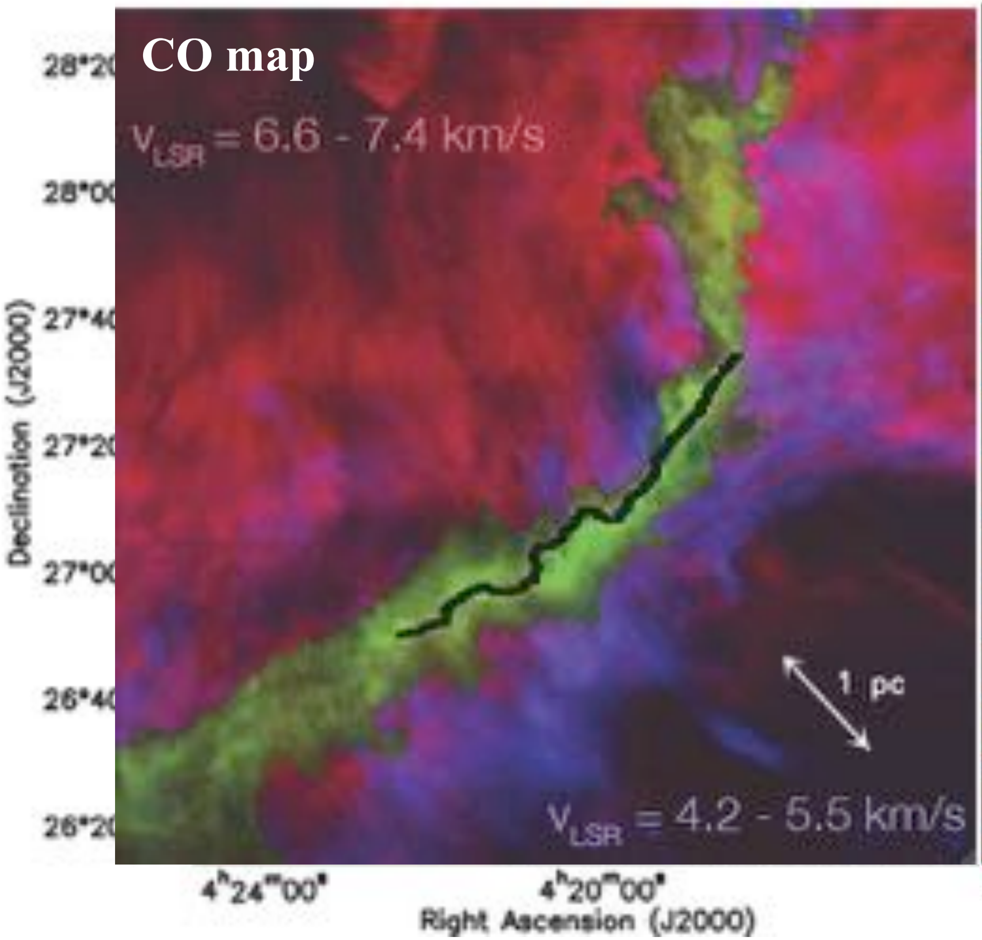




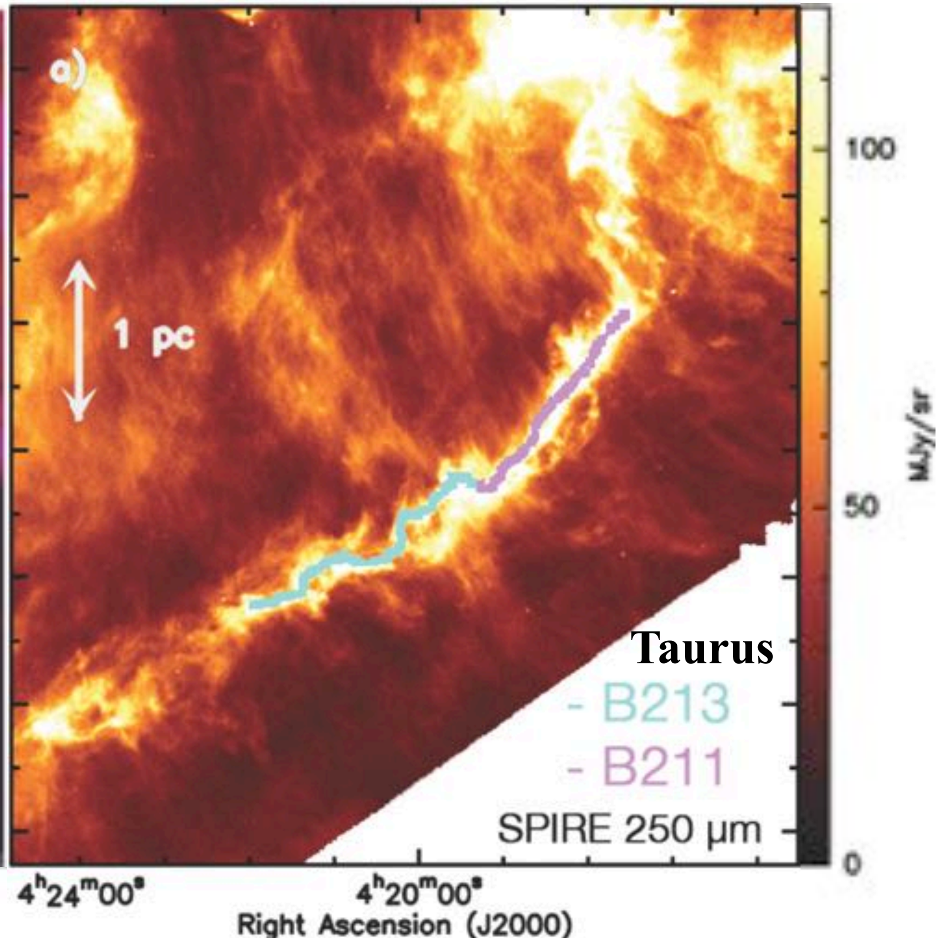
Beuther, Ragan+2015

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

➢ **Striations and sub-filaments are suggestive of accretion flows into the star-forming filaments - Tend to be // to the large-scale B field**



CO observations from Goldsmith+2008



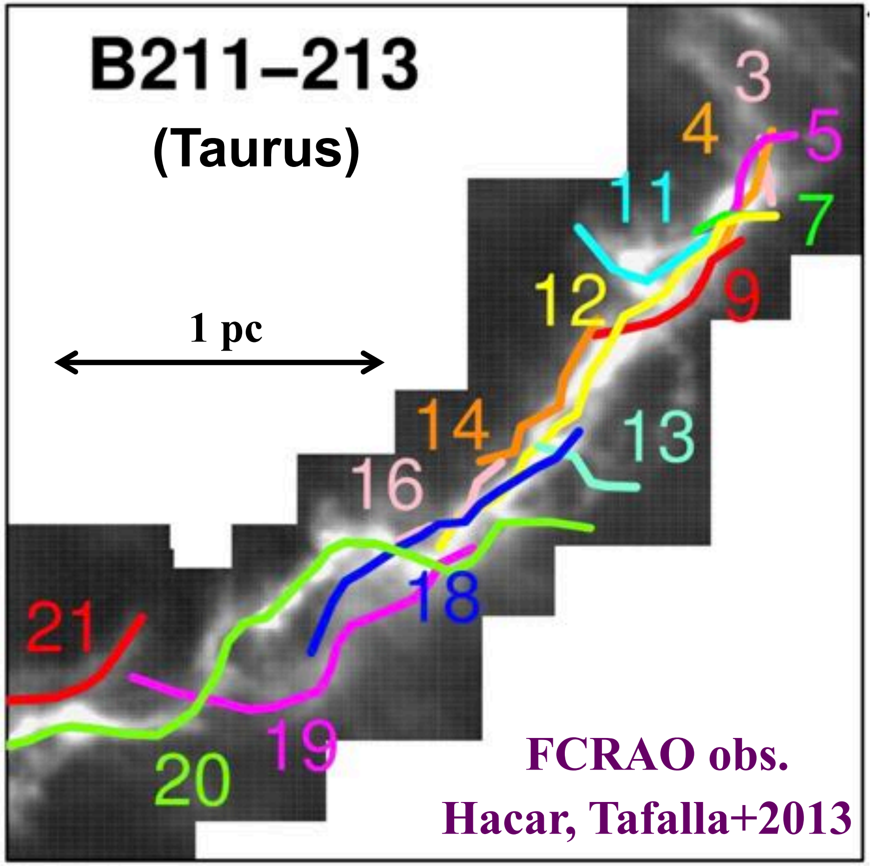
Estimated mass accretion rate:

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

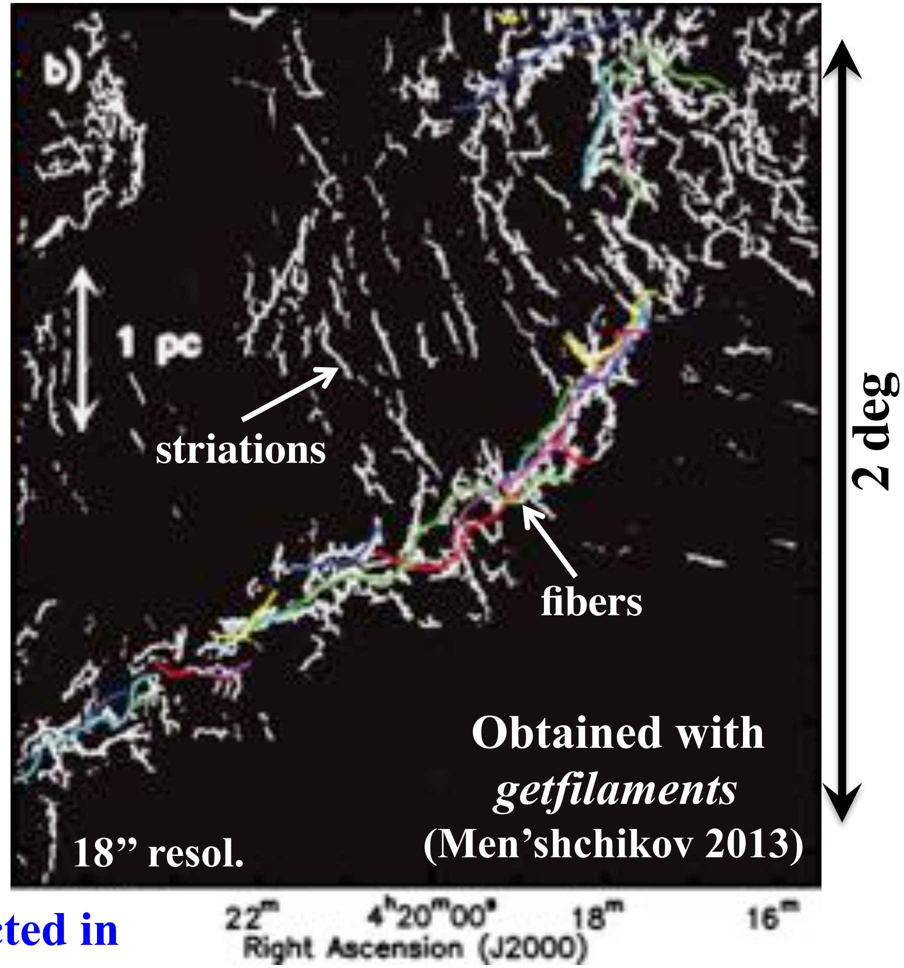
Palmeirim+2013
Shimajiri+2019a

Velocity-coherent "fibers" in dense molecular filaments: Accretion-generated substructure?

$C^{18}O$ velocity components overlaid on *Herschel* 250 µm dust continuum image



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



➢ **Bundle of 35 velocity-coherent « fibers » detected in $C^{18}O$(2-1) and N_2H^+(1-0) and making up the main filament**

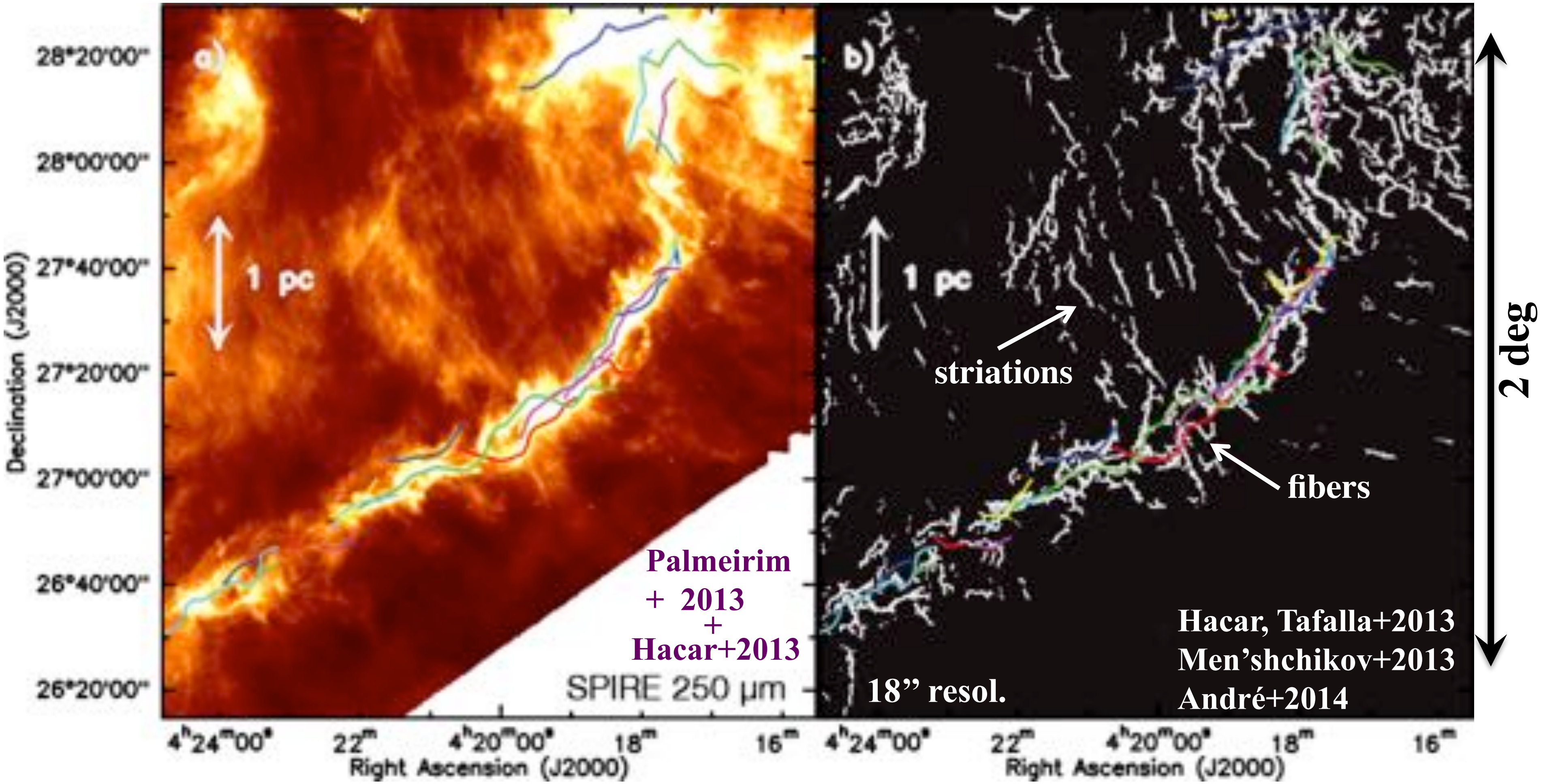
See also Hacar+2018 for Orion

Probing the magnetic link between striations and fibers

High resolution/dynamic range polarimetric imaging with B-BOP

- **Geometry of the B-field *within* the (~ 0.1 pc) system of intertwined « fibers » developing inside star-forming filaments and the connection with the striations seen on larger scales**

SPICA-POL White Paper (arXiv:1905.03520)



Summary and conclusions

- *Herschel* results support a **filamentary paradigm for star formation** but many issues remain open and/or strongly **debated**
- The properties of **molecular filaments** need to be better understood as they represent the **initial conditions of prestellar core formation**
- Evidence that dense filaments result from large-scale compressive flows and accretion of matter ~ along B within sheet-like structures.
- **Magnetic fields likely play a key role** in the formation/evolution/ fragmentation of filaments but remain poorly constrained
- **High-resolution polarimetric imaging** at far-IR/submm λs from space with **SPICA can lead to decisive progress**