Growth of Structure and Star Formation in the Interstellar Medium: Observations

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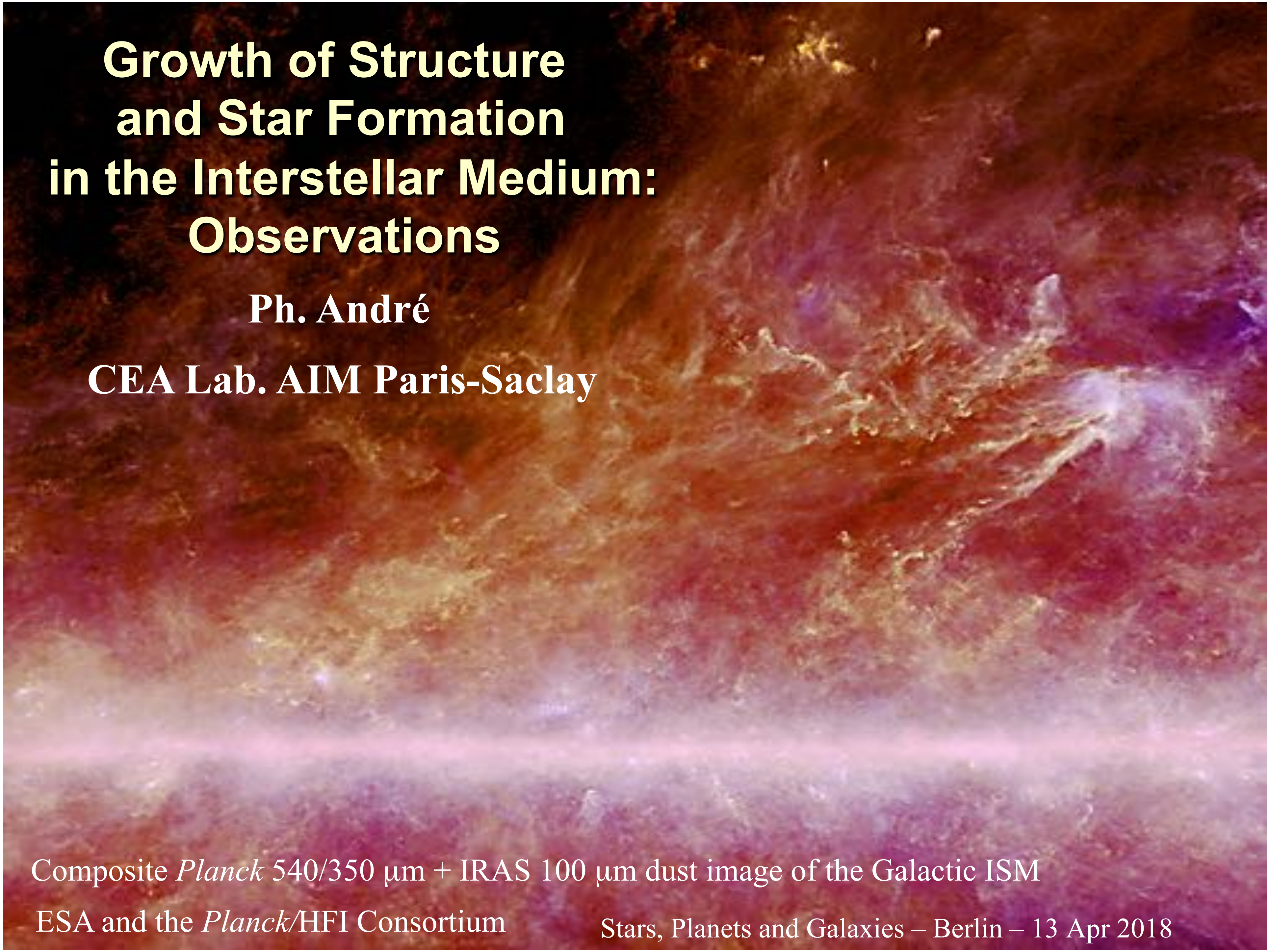
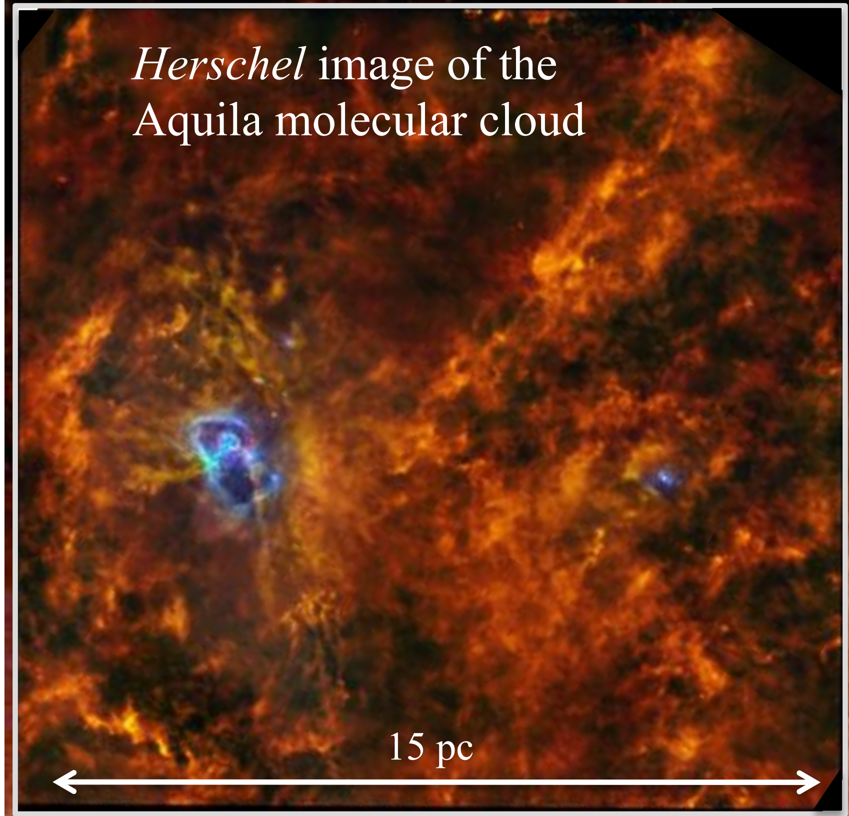


Composite *Planck* 540/350 μm + IRAS 100 μm dust image of the Galactic ISM

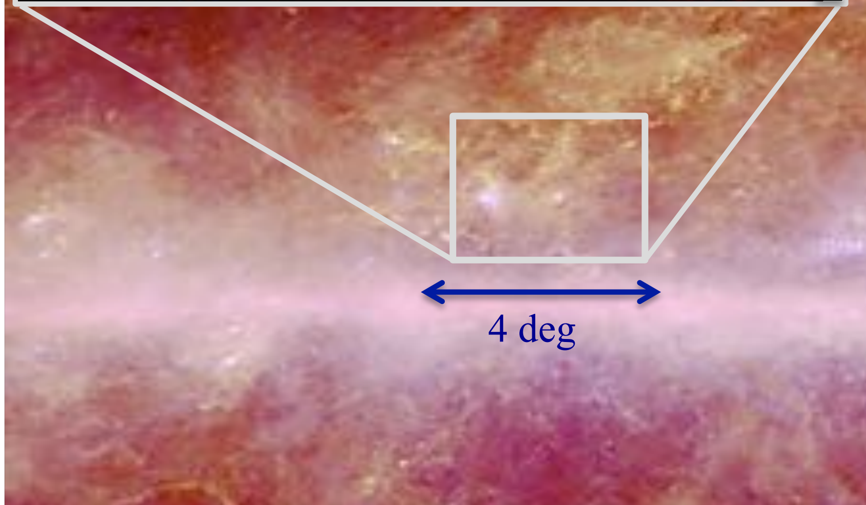
ESA and the *Planck*/HFI Consortium

Stars, Planets and Galaxies – Berlin – 13 Apr 2018



Outline

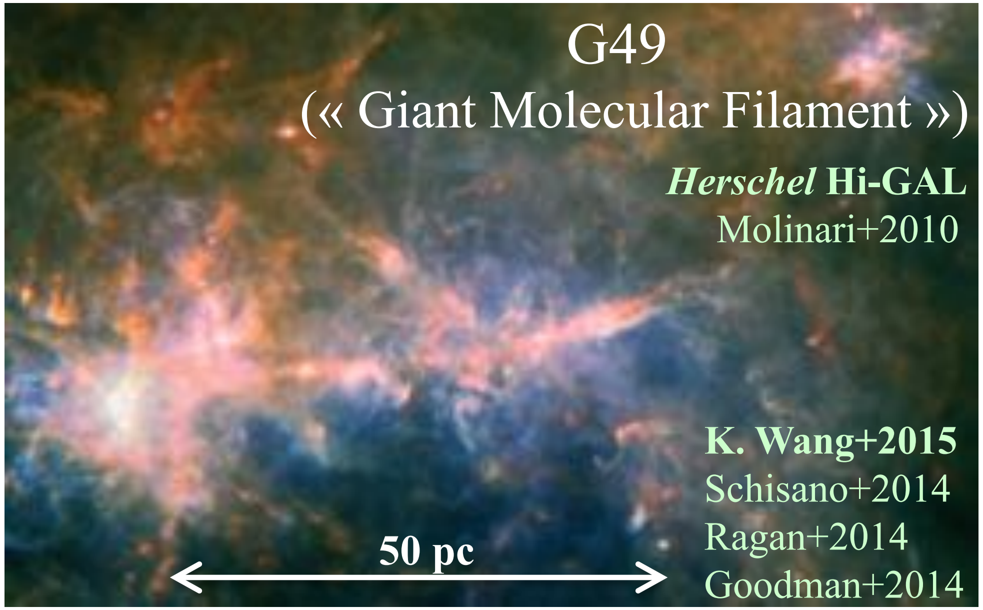
- Introduction: Omnipresence and 'universality' of filamentary structures in the cold ISM
- Results supporting a filamentary paradigm of star formation
- Observational constraints on the formation and evolution of ISM filaments
- Conclusions

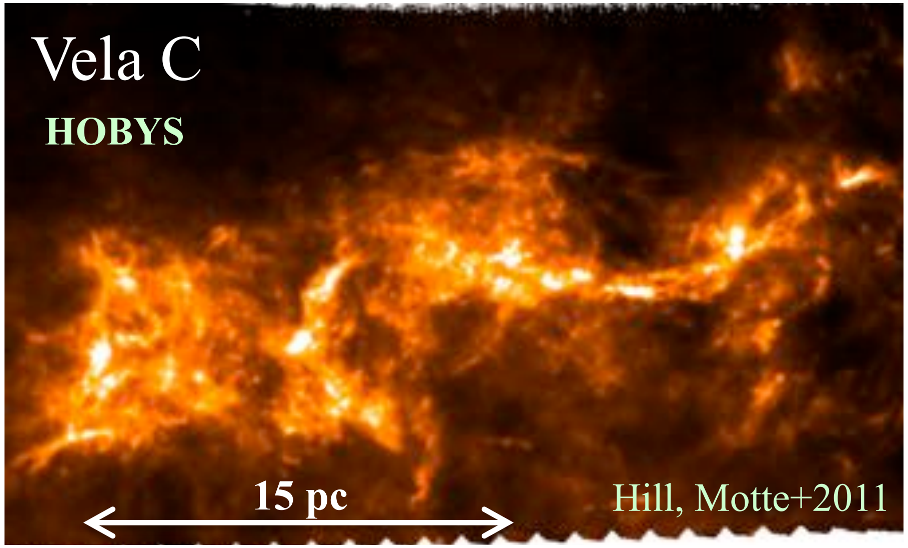


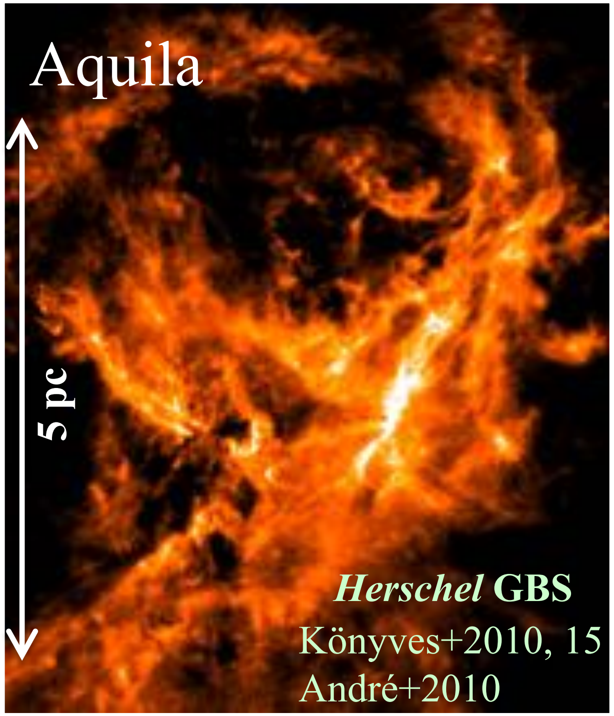
Planck image of the Galactic ISM

Thanks to: D. Arzoumanian, V. Könyves, Y. Shimajiri, A. Roy, P. Palmeirim, A. Bracco, E.Ntormousi

Herschel has revealed a "universal" filamentary structure in the cold ISM



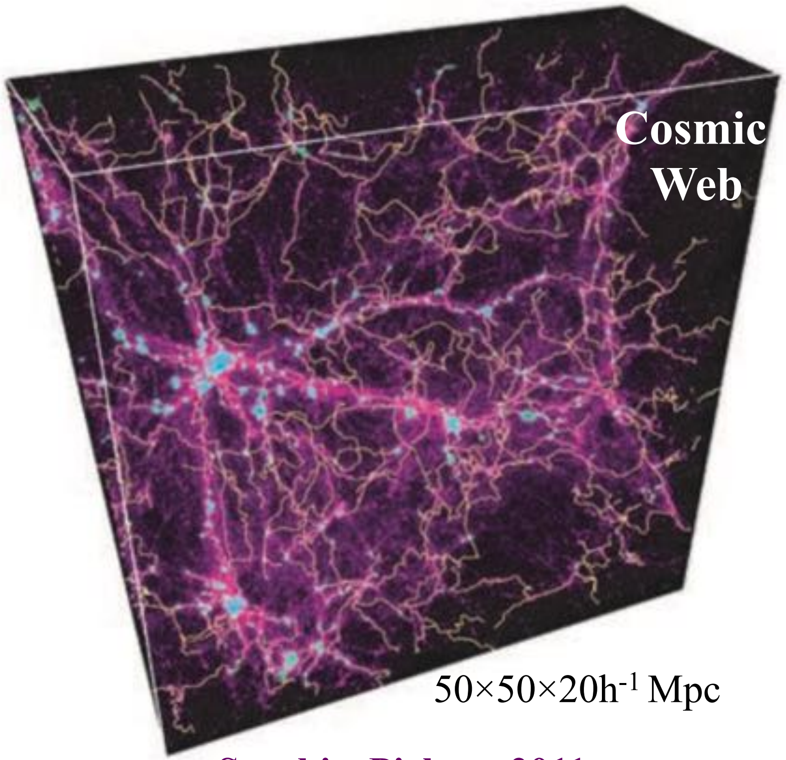




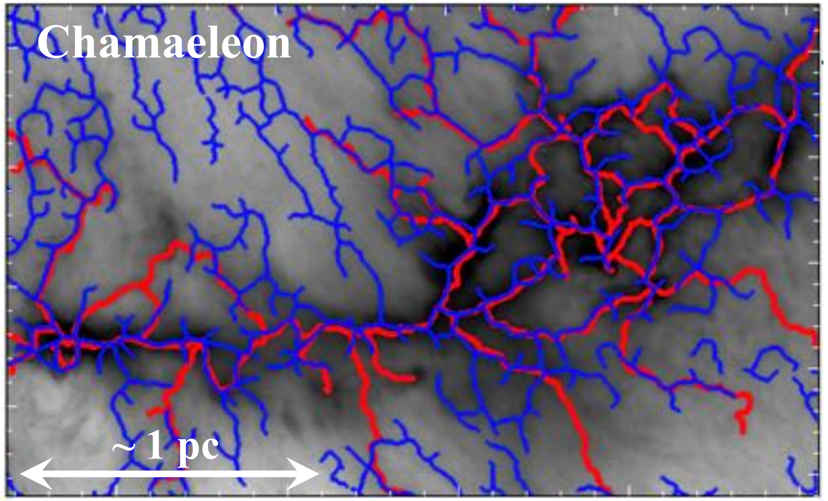
Tracing filamentary networks

Different techniques: Projection on curvelets (Starck+2003), **DisPerSE (Sousbie2011),** ***getfilaments* (Men'shchikov+2013), *FilFinder* (Koch & Rosolowsky 2015),** Hessian matrix (Schisano+2014, Planck XXXII 2016), Rolling Hough Transform RHT (Clark+2014), Template Matching TM (Juvela 2016)

DisPerSE

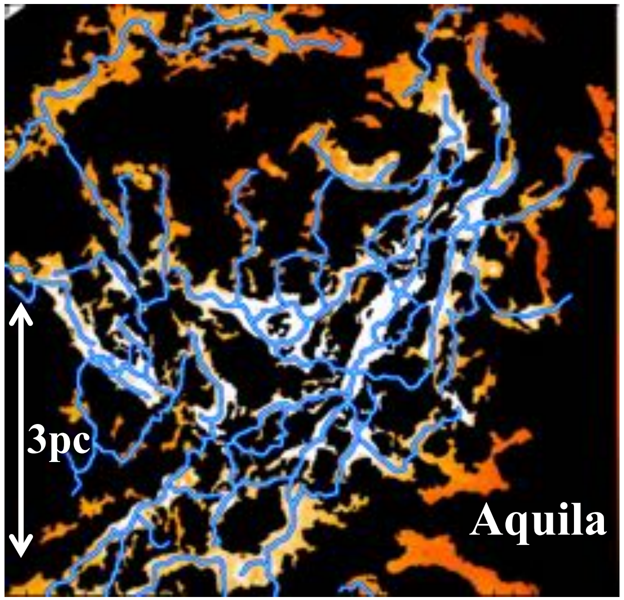


Sousbie, Pichon+2011



***FilFinder* & DisPerSE**

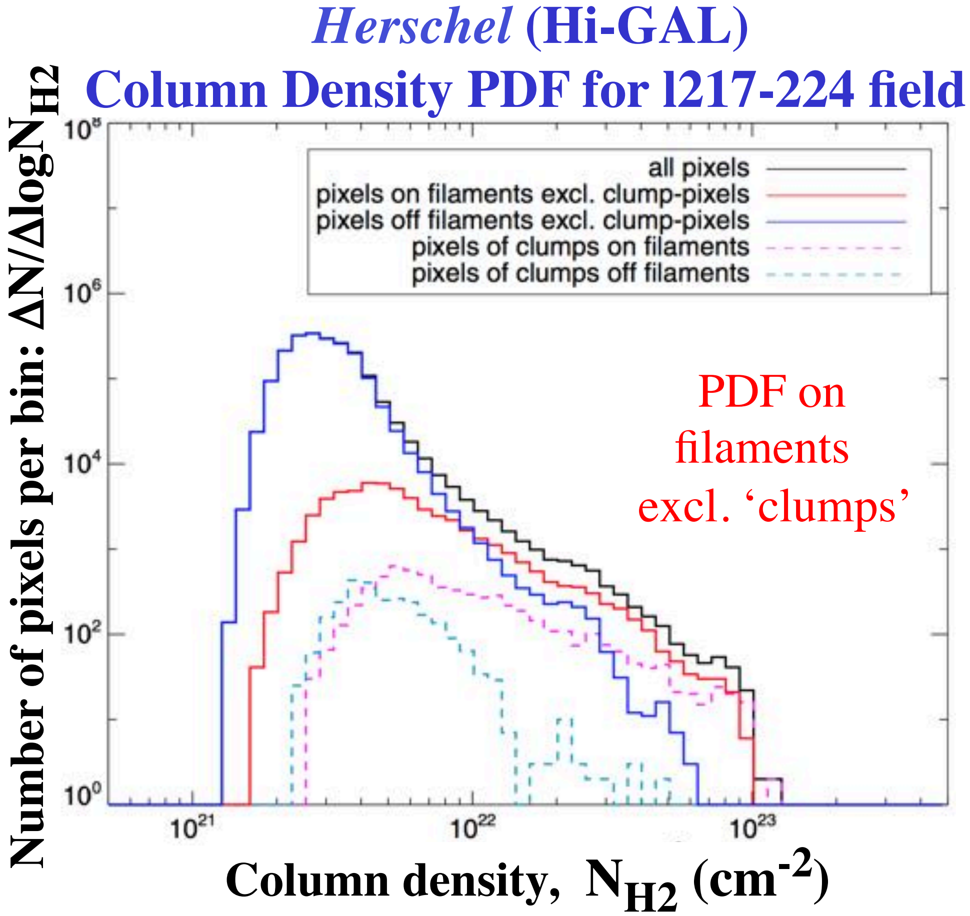
Koch & Rosolowsky 2015



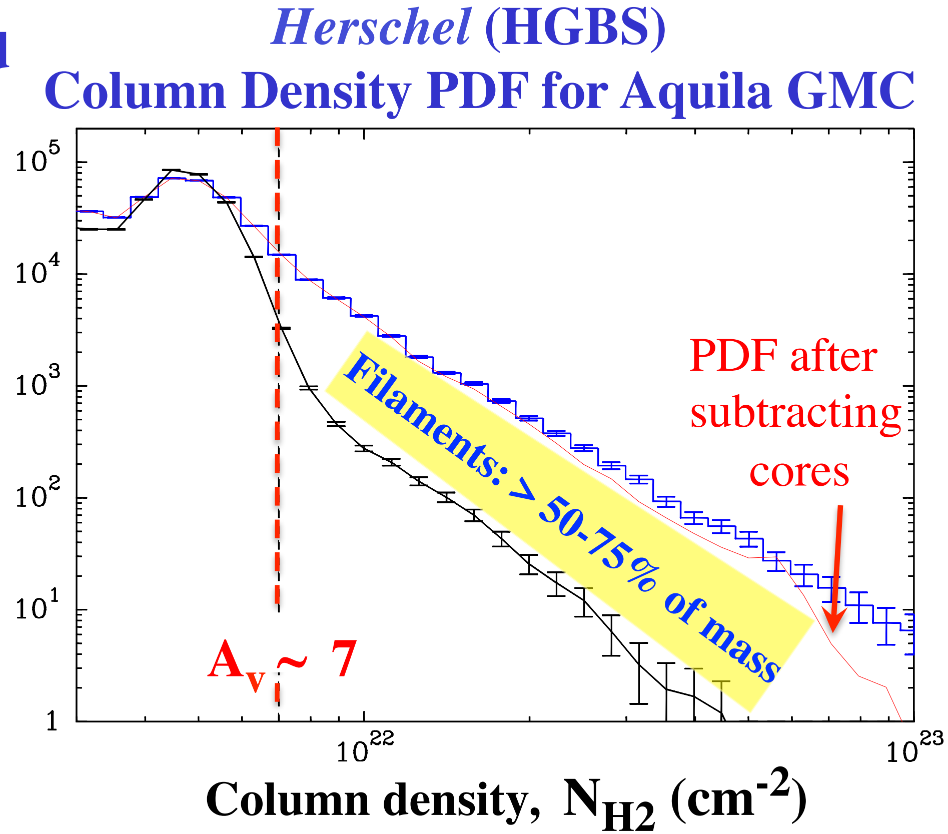
***getfilaments* & DisPerSE**

Menshchikov 2013
Könyves+2015

Filaments dominate the mass budget of GMCs at high densities



Schisano et al. 2014

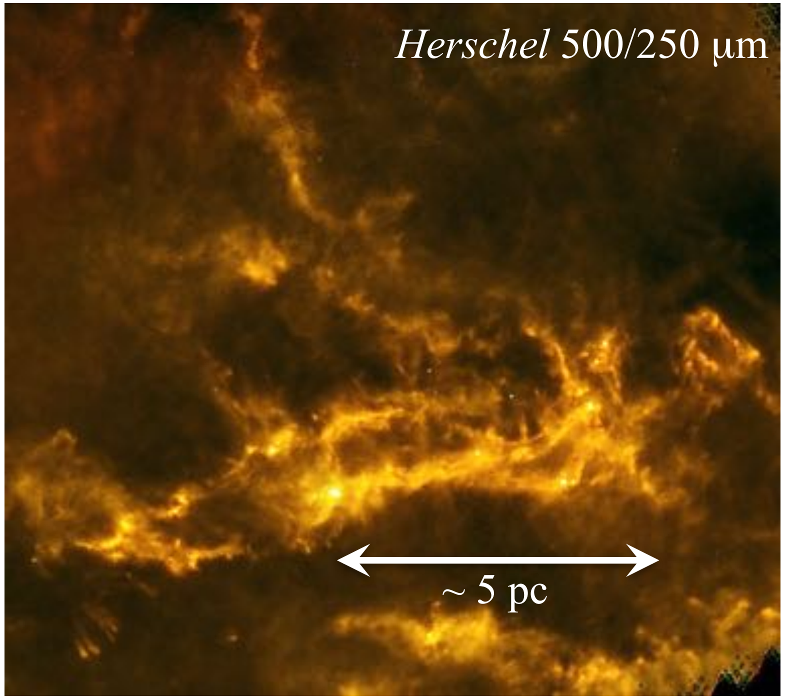


Könyves et al. 2015

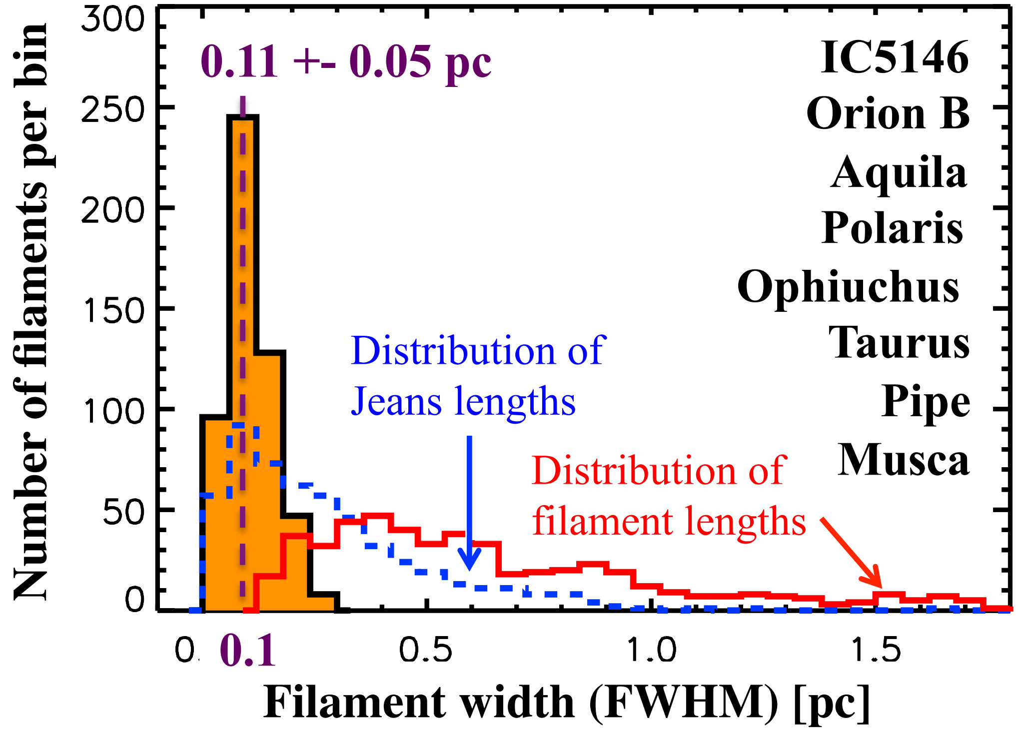
- Below $A_V \sim 7$: ~ 10-20 % of the mass in the form of filaments
- **Above $A_V \sim 7$: > 50-75 % of the mass in the form of filaments**

Nearby filaments have a common inner width ~ 0.1 pc

Network of filaments in IC5146

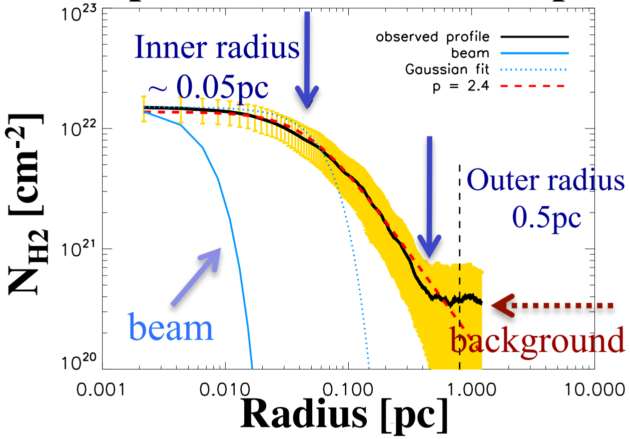


Distribution of inner widths for 500+ nearby (d < 450pc) filaments



D. Arzoumanian+2011 & 2018

Example of a filament radial profile

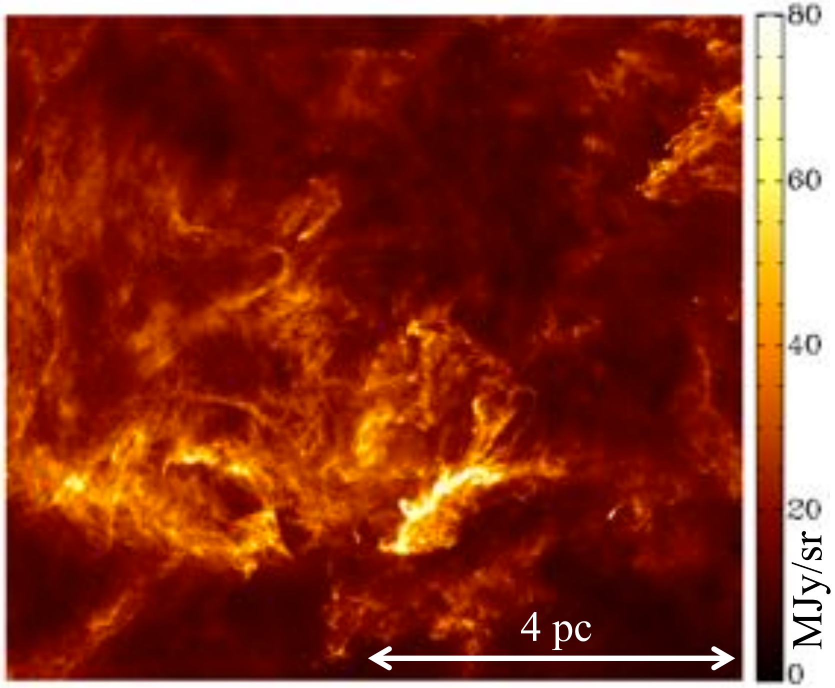


Possibly linked to sonic scale of turbulence?
(cf. Padoan+2001; Federrath 2016)

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

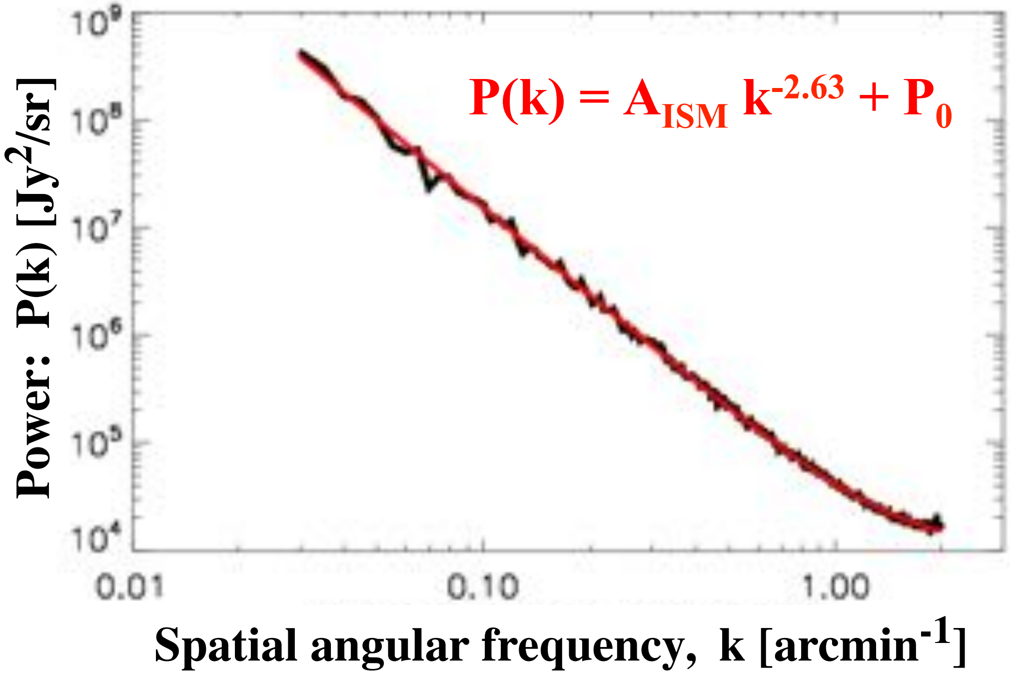


Miville-Deschênes et al. 2010

Tension with scale-free power spectrum

Panopoulou+2017

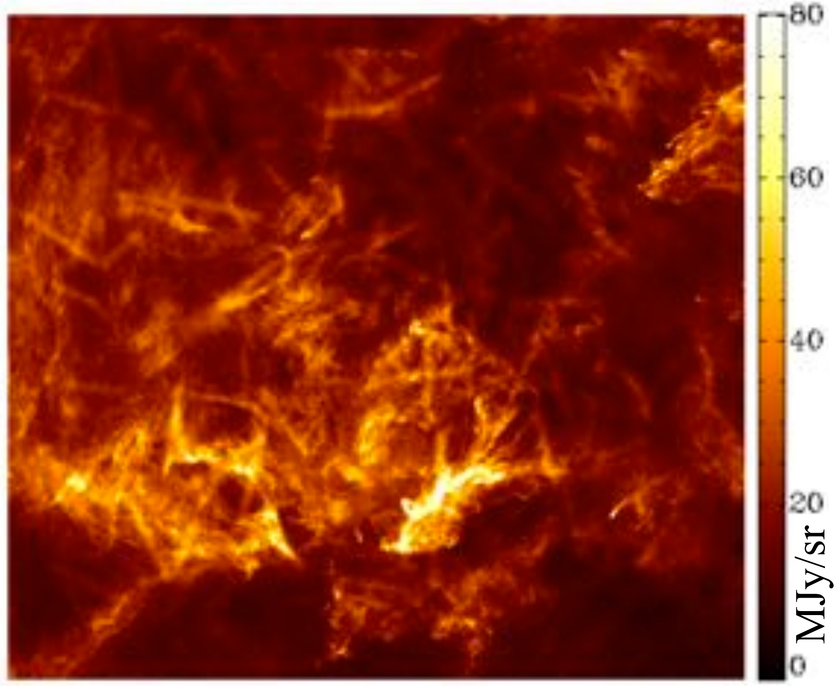
Noise-subtracted, deconvolved power spectrum of Polaris image



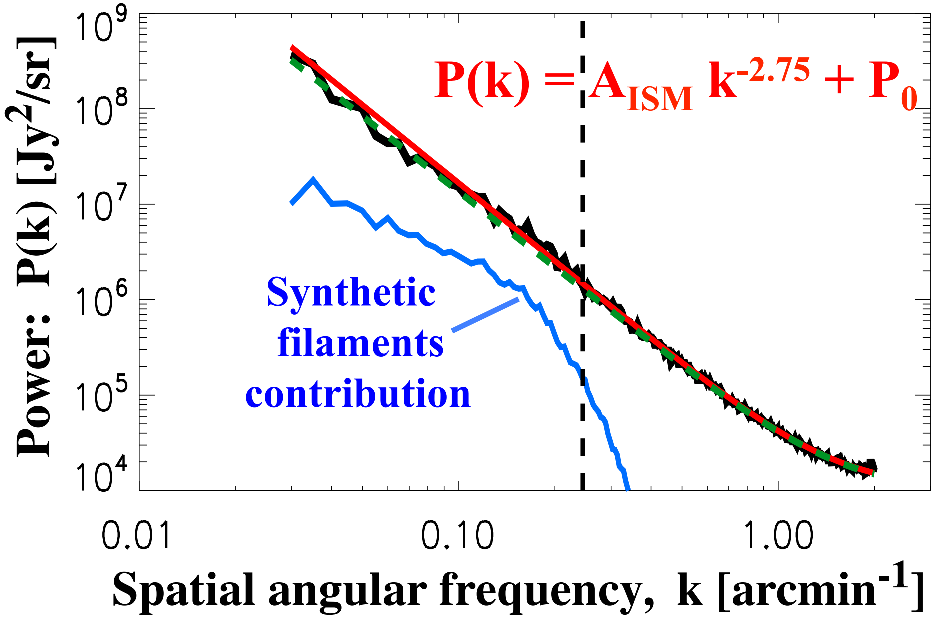
A simple experiment

A. Roy et al. 2018

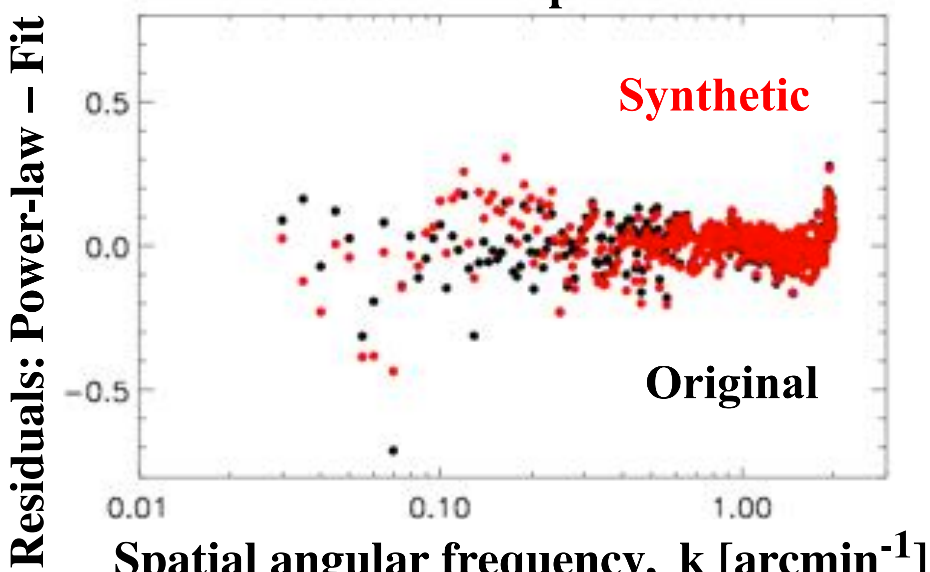
Injecting a population of synthetic
0.1 pc filaments with contrast ~ 50%
in SPIRE 250 µm image of Polaris
translucent cloud



Power spectrum of image
with synthetic 0.1 pc filaments



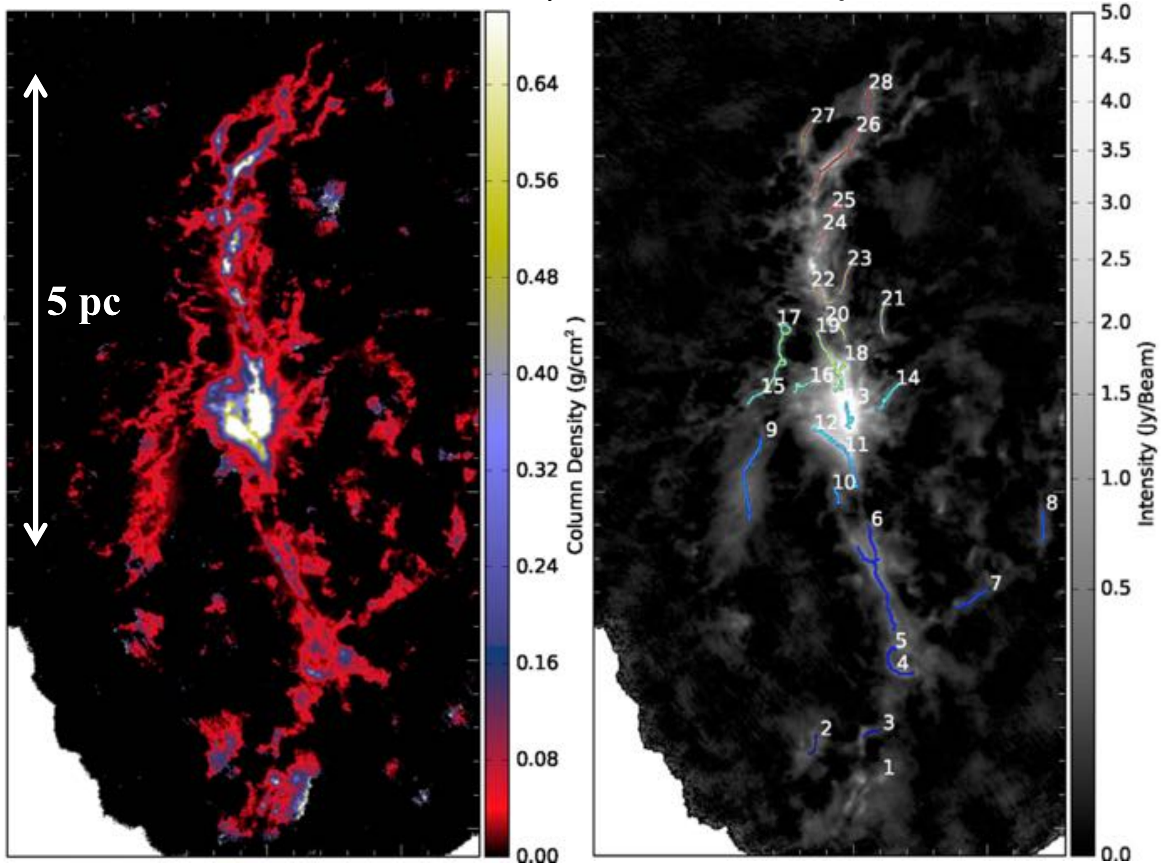
Difference from power-law fit



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

Independent measurements of filament widths

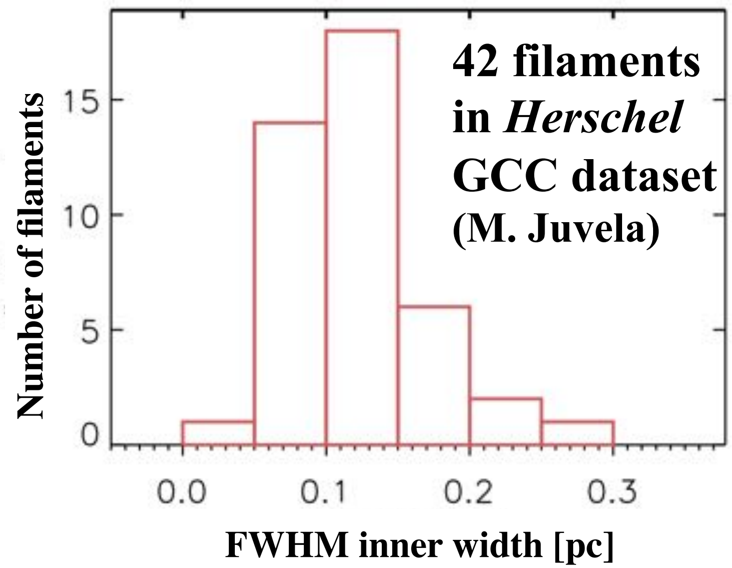
JCMT/SCUBA2 (850/450µm) GBS study of Orion A-N



Salji, Richer, Buckle+2015: FWHM = $0.08^{+0.07}_{-0.03}$ pc
(28 filaments in Orion A)

- ➢ **Generally ~ consistent when performed in the submm dust continuum**

Independent analysis of GB filaments:
<FWHM> = 0.09+-0.05 pc
Koch & Rosolowsky 2015



Median inner FWHM = 0.13+-0.05 pc
Rivera-Ingraham+2016

- ➢ **Less consistent in molecular lines (N_2H^+,^{13}CO)**

(FWHM ~ 0.03 to ~ 0.4 pc – e.g. Lee+2014, Panopoulou+2014)

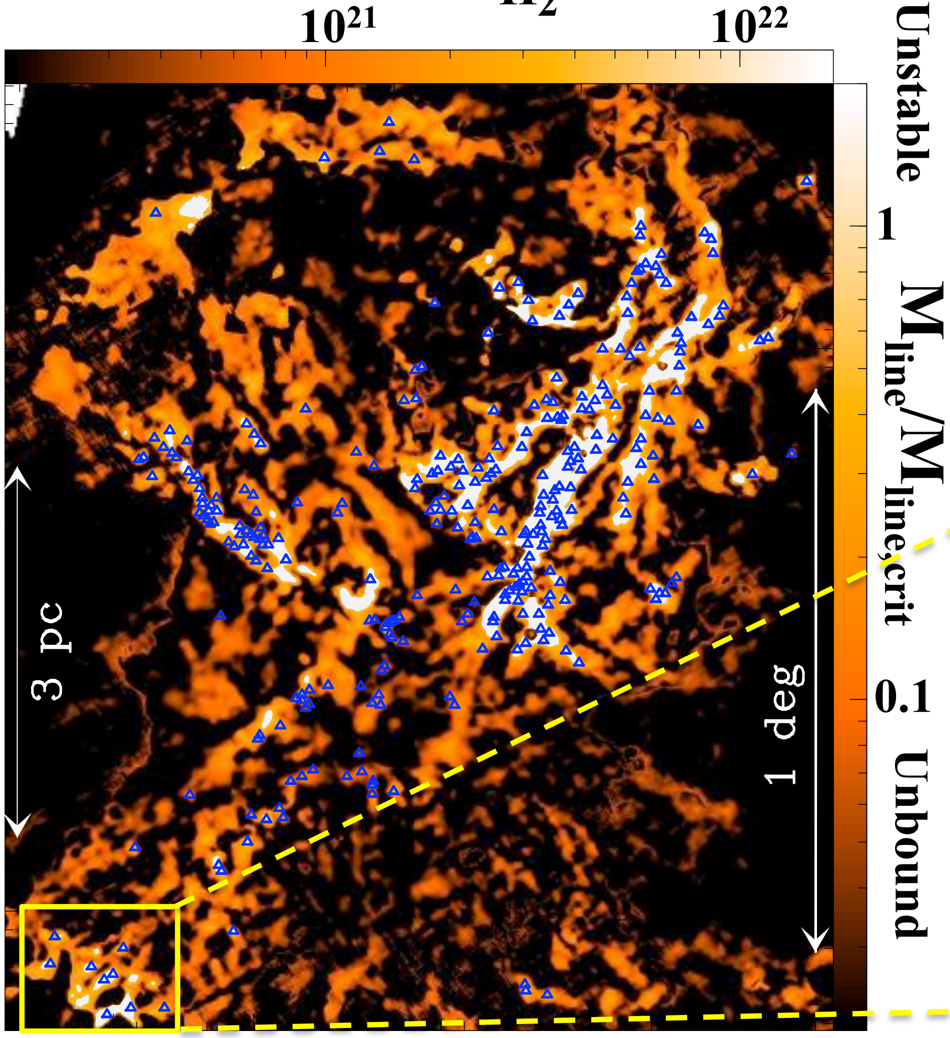
~ 75^{+15}_{-5} % of prestellar cores form in filaments, above a column density threshold $N_{H_2} \gtrsim 7\times10^{21}$ cm^{-2}

<=>

$A_V \gtrsim 7$

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

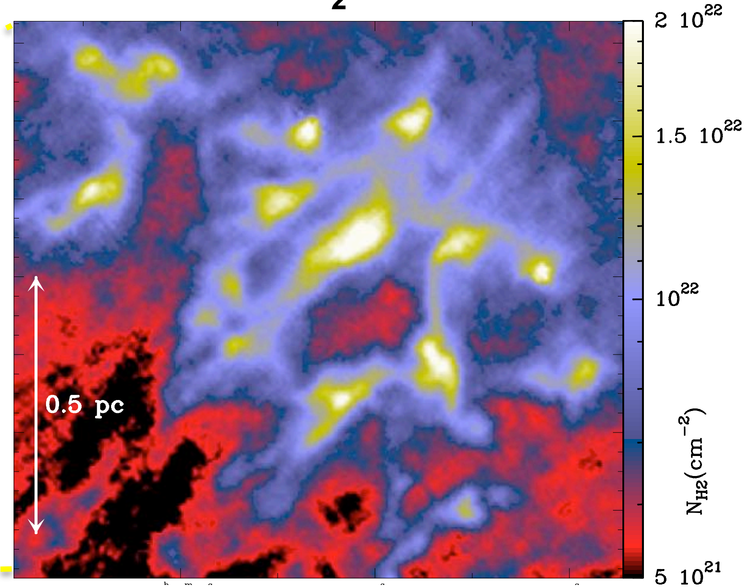
Aquila curvelet N_{H_2} map (cm^{-2})



André et al. 2010, Könyves et al. 2015

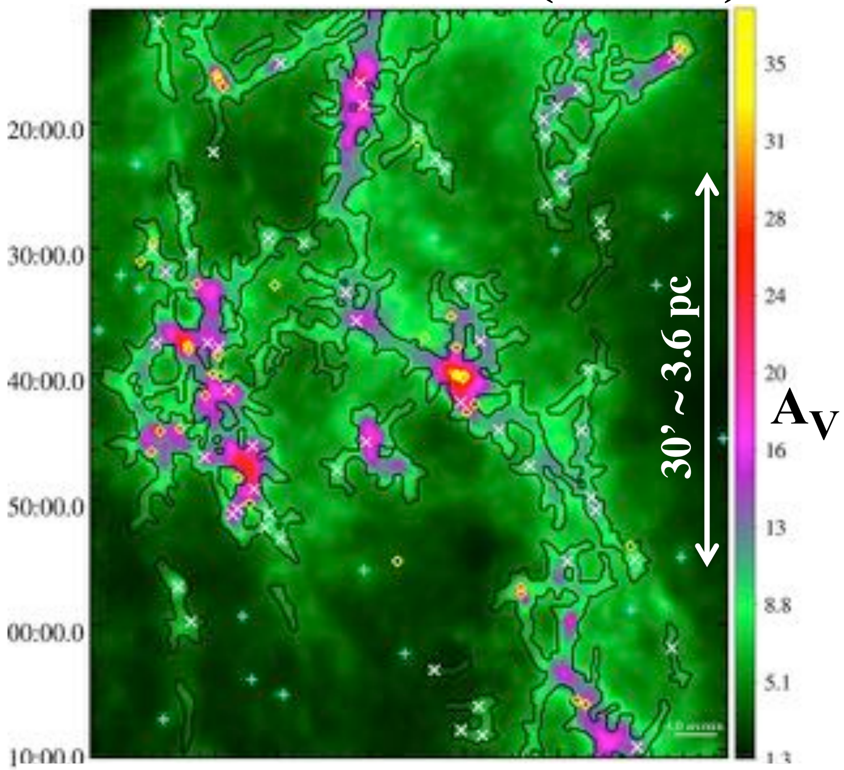
Examples of *Herschel* prestellar cores (△)

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



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

Part of Orion A (L1641)



Polychroni al. 2013, ApJL

Also:

Bresnahan+2018 (CrA)

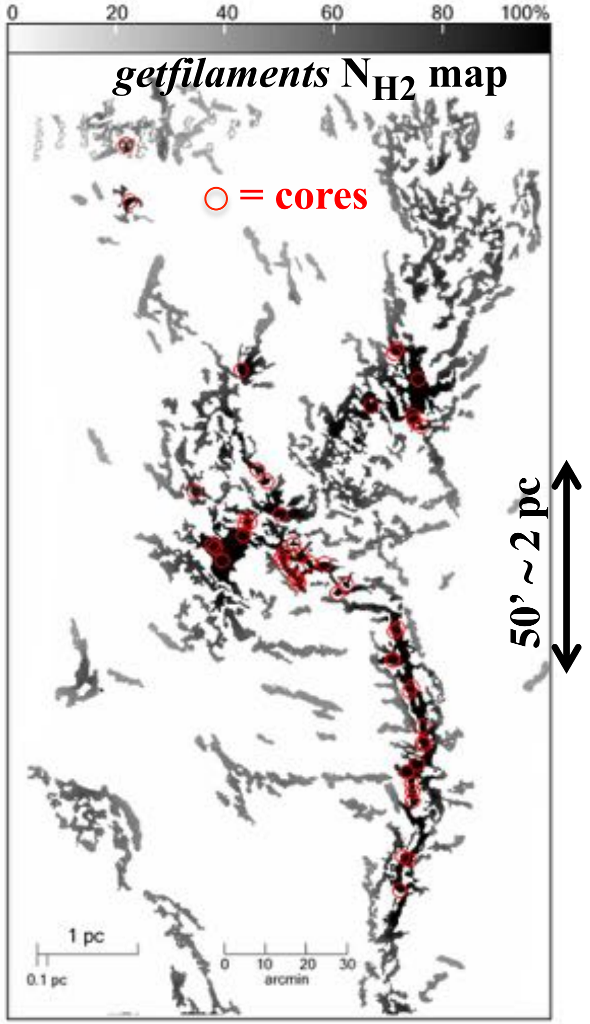
Ladjelate+2018 (Oph)

Könyves+2018 (Orion B)

Benedettini+2018 (Lupus)

…

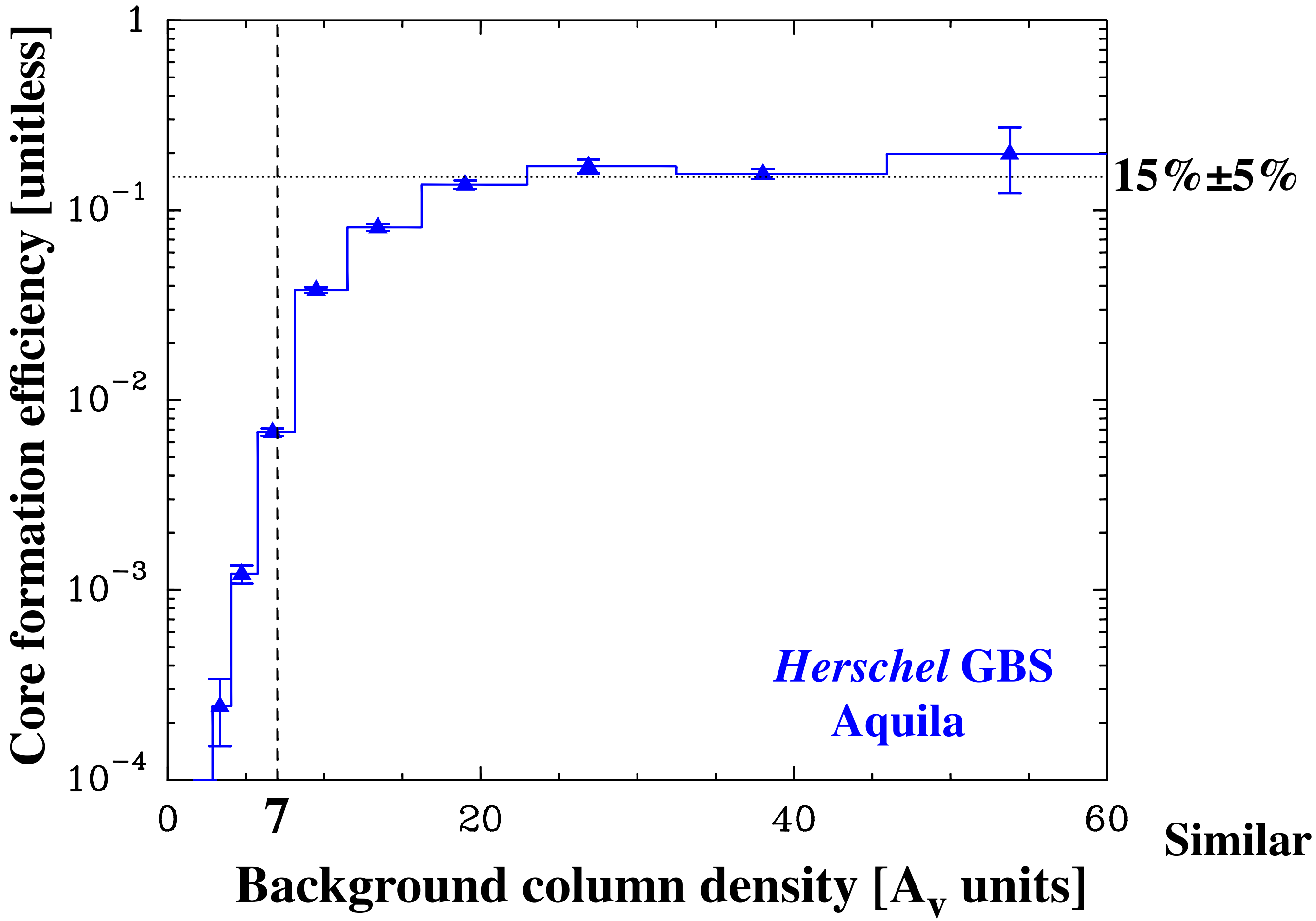
Taurus B211/3+ L1495



Marsh al. 2016, MNRAS

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

Prestellar CFE as a function of background A_V



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

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

André+2010

Könyves+2015

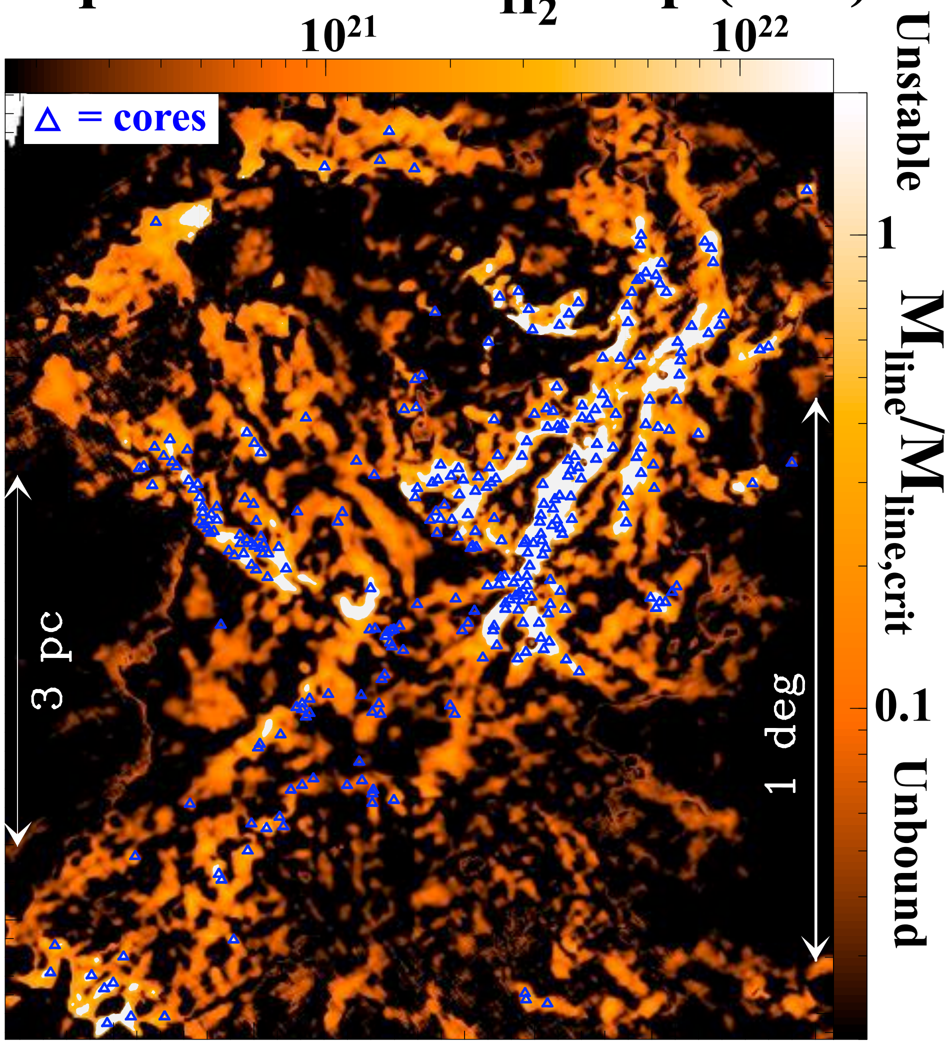
Similar to threshold for YSOs (*Spitzer*):

Heiderman+2010; Lada+2010; Evans+2014

Interpretation: M/L threshold above which interstellar filaments are gravitationally unstable

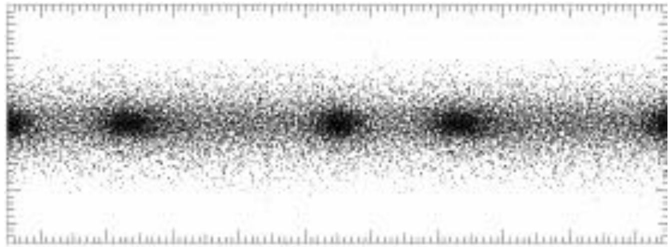
△ : Prestellar cores

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



André+2010; Könyves+2015

- The gravitational instability of filaments is controlled by the mass per unit length $M_{line} = M/L$:
  - unstable (to fragmentation & radial collapse) if $M_{line} \gtrsim M_{line,\,crit}$



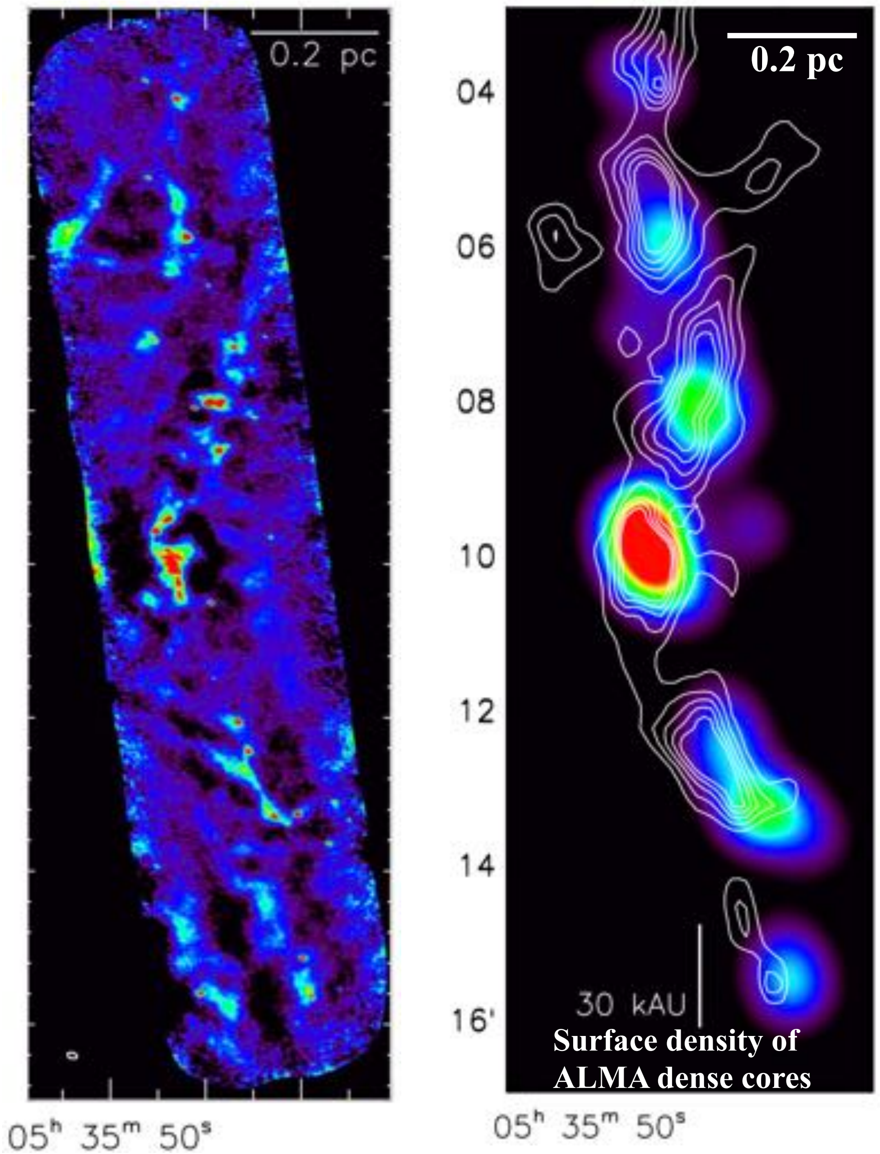
Inutsuka & Miyama 1992/97

$M_{line,\,crit} = 2\,c_s^2/G \sim 16\ M_\odot/pc$ for $T \sim 10$ K $\Leftrightarrow$ Σ threshold $\sim 160\ M_\odot/pc^2$ (for 0.1 pc filaments)

Unstable filaments in white

Fragmentation of filaments – Core spacing

ALMA 3mm mosaic of the Orion A ISF



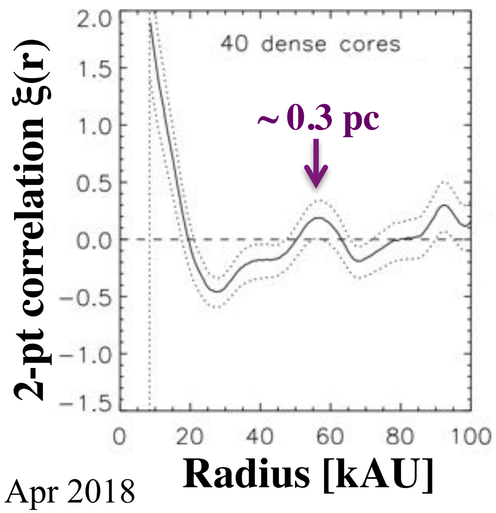
Kainulainen+2017

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



Modification of standard cylinder fragmentation theory:

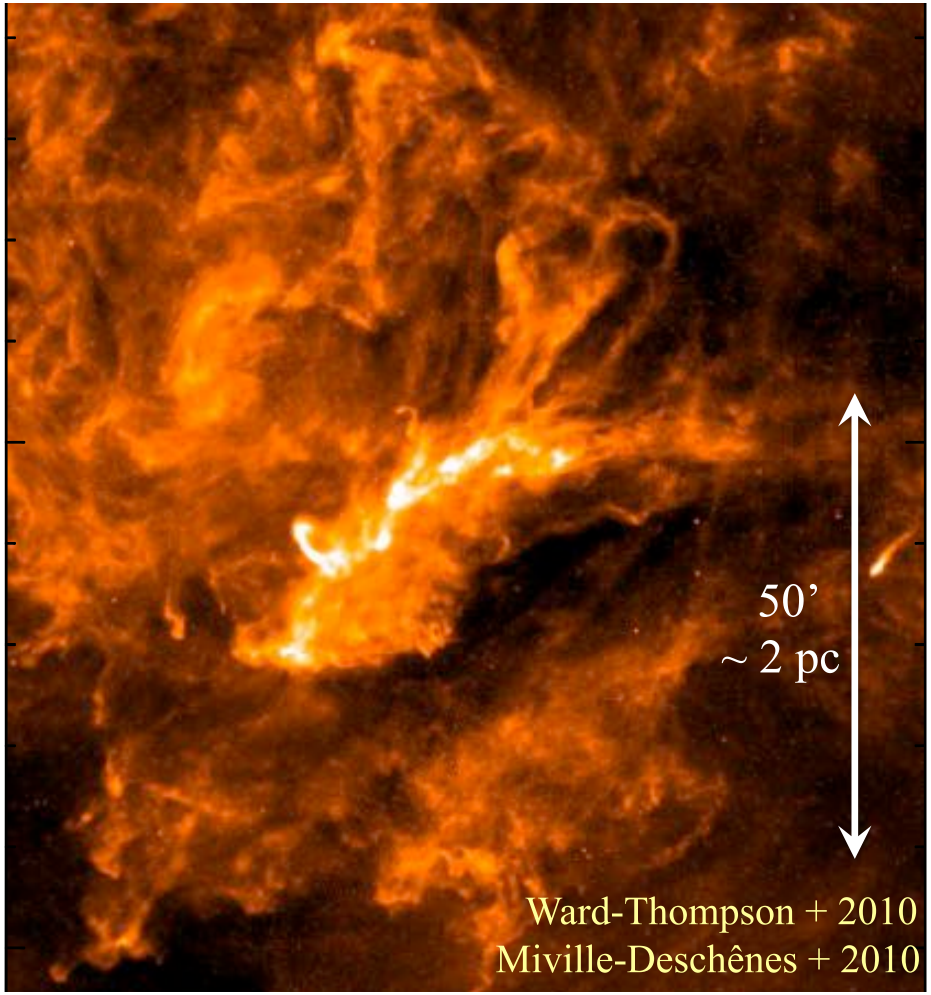
Clarke, Whitworth+'16
Gritschneder+2017

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

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

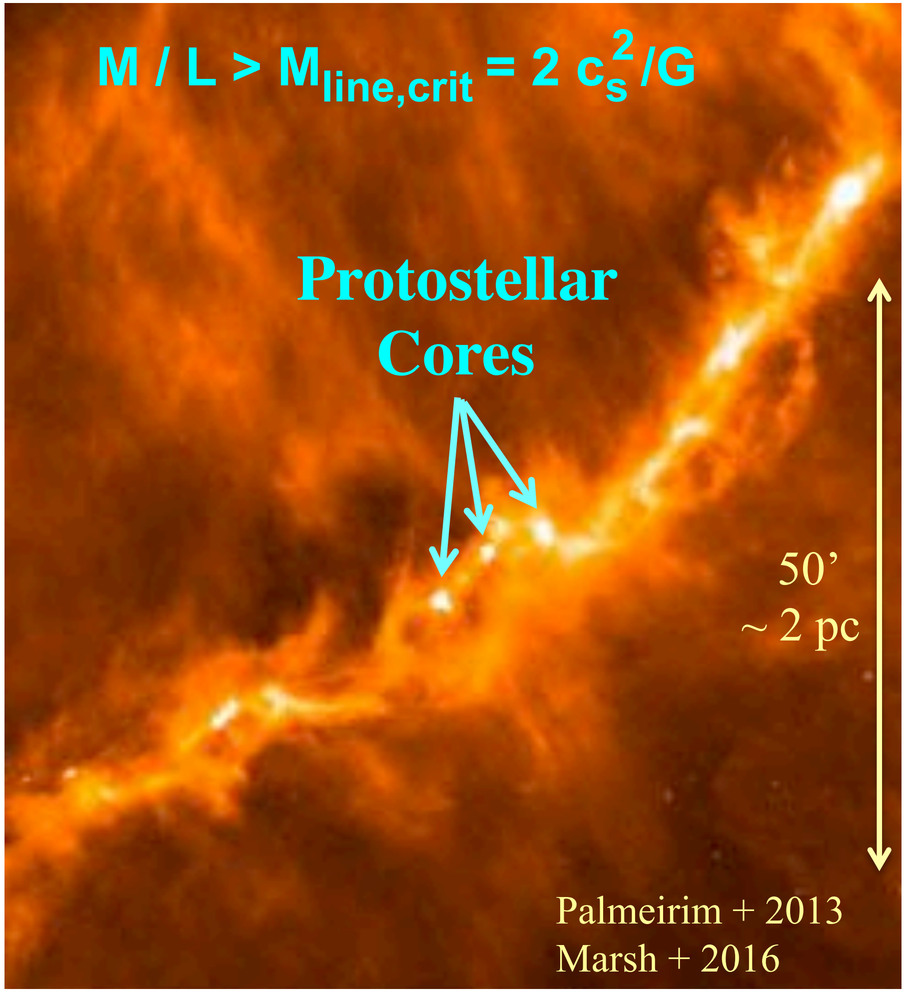
Protostars & Planets VI chapter (André, Di Francesco, Ward-Thompson, Inutsuka, Pudritz, Pineda 2014)

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



Polaris – *Herschel*/SPIRE 250 μm

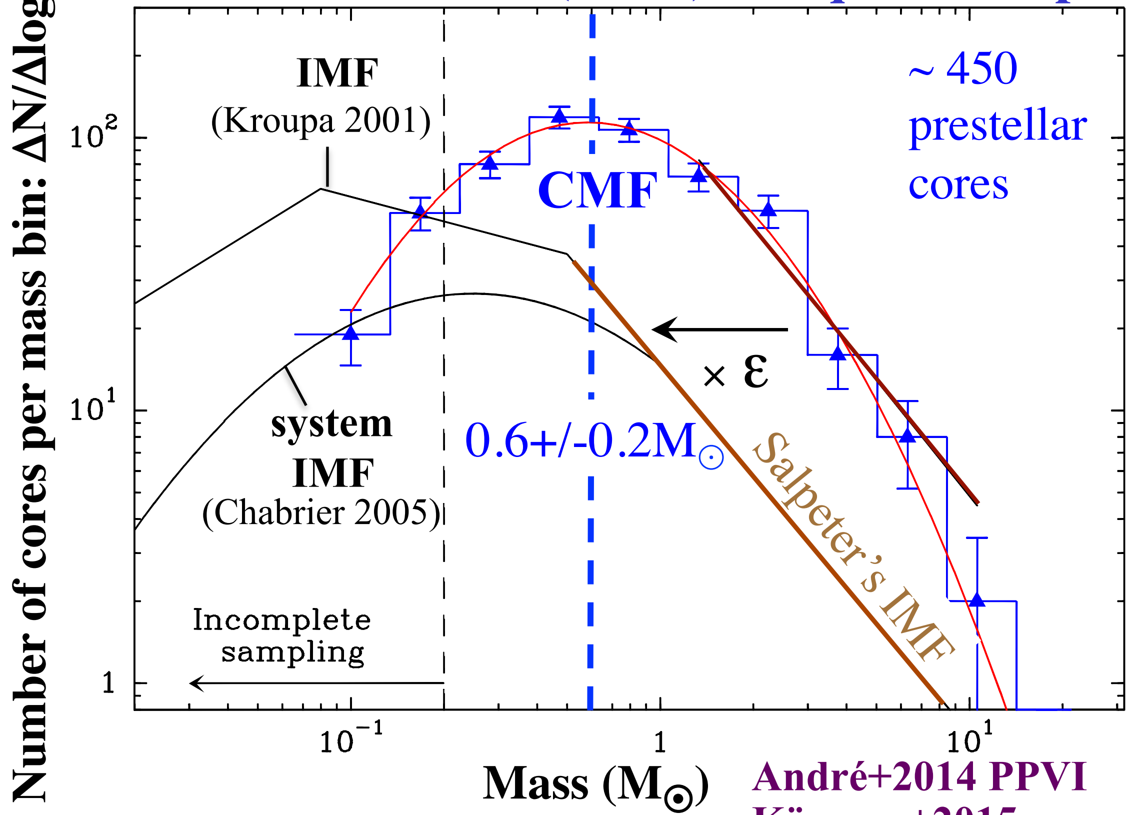
2) Gravity fragments the densest filaments into prestellar cores



Taurus B211/3 – *Herschel* 250 μm

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

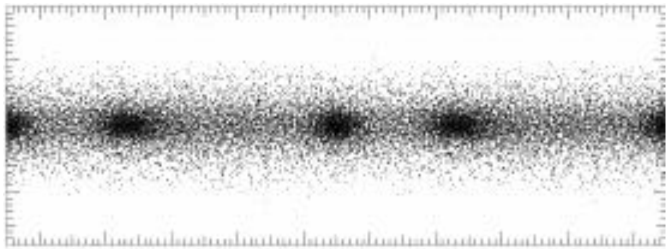
Core Mass Function (CMF) in Aquila Complex



André+2014 PPVI
Könyves+2015

Jeans mass:

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



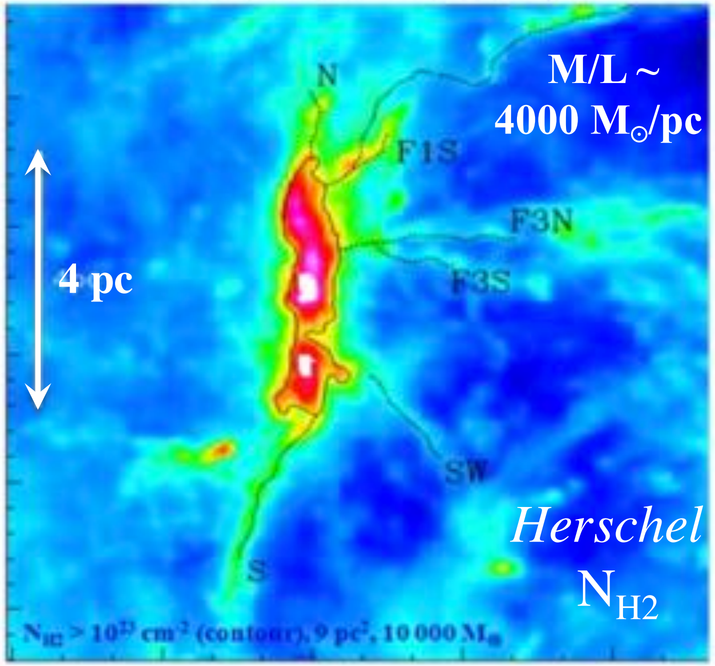
Inutsuka & Miyama 1997

- $\boxed{\text{CMF peaks at} \sim 0.6\ M_{\odot} \approx \text{Jeans mass in marginally critical filaments}}$
- 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

Filaments/'ridges' & 'hub-filament' structures play a key role in massive SF

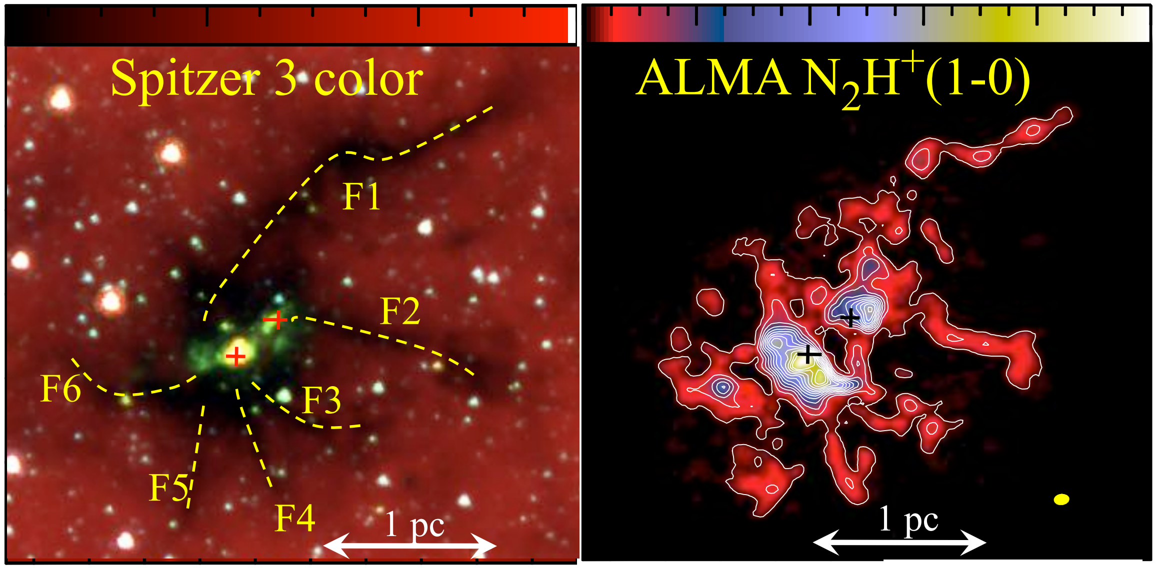
➢ **Massive prestellar cores may not exist; high-mass protostars are 'clump-fed', gathering mass from pc-scale `hub-filament' structures**

The DR21 ridge and its sub-filaments



Schneider+2010, Csengeri+2011, Henneman+2012

SDC335: ALMA identification of a massive protostellar core at the center of a converging network of filaments



Peretto+2013

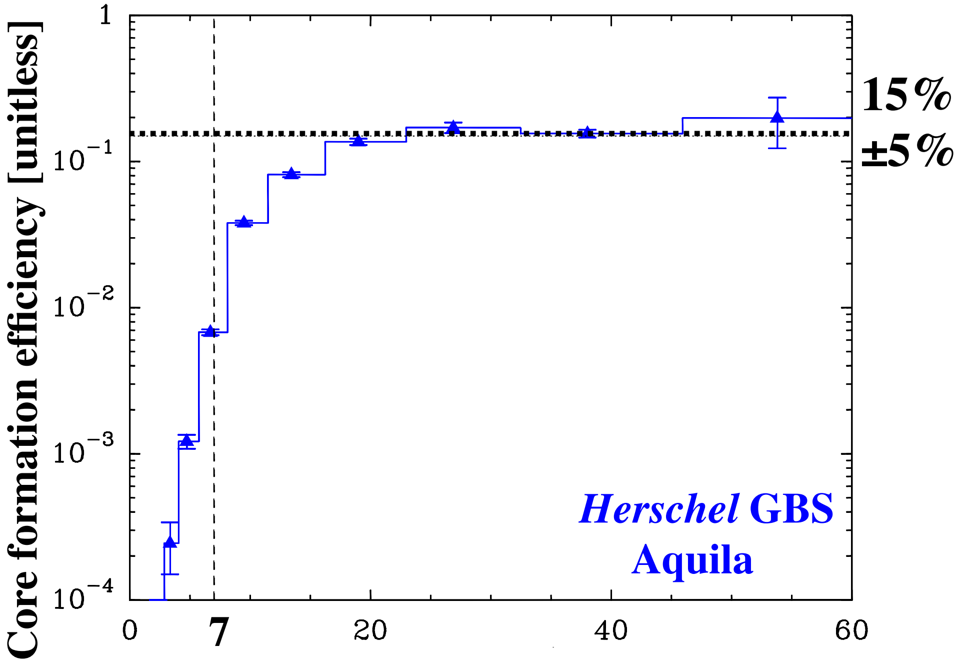
➢ **> 50% of massive star formation and star clusters occur in ultra-dense (A_V >> 100, M/L > 100×$M_{line,crit}$) 'ridges' at the junctions of (supercritical) filaments** (cf. Schneider+2012)

Motte, Bontemps, Louvet 2017 ARA&A

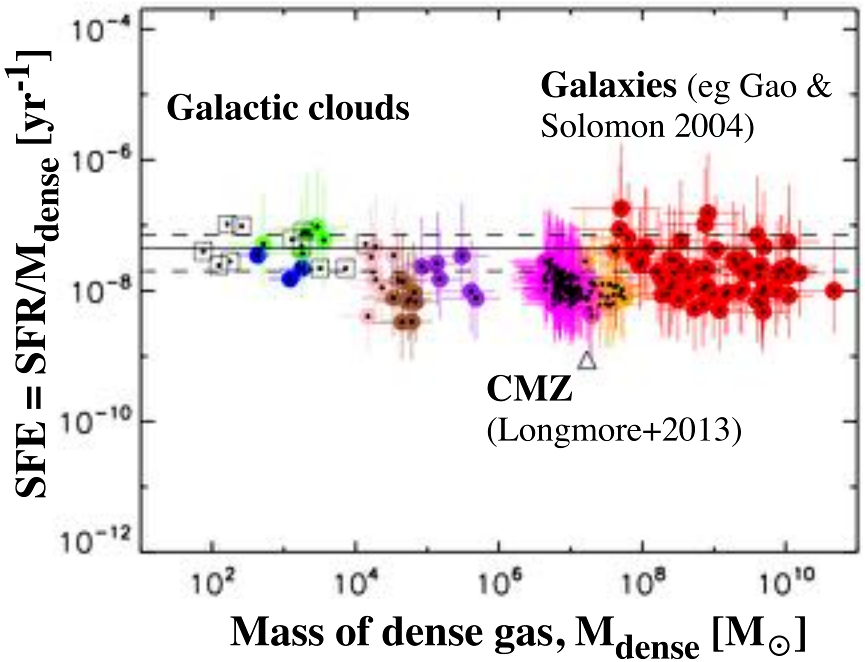
Importance of filaments in the ISM of other galaxies?

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 et al. 2015



Lada+2012 **Shimajiri+2017**

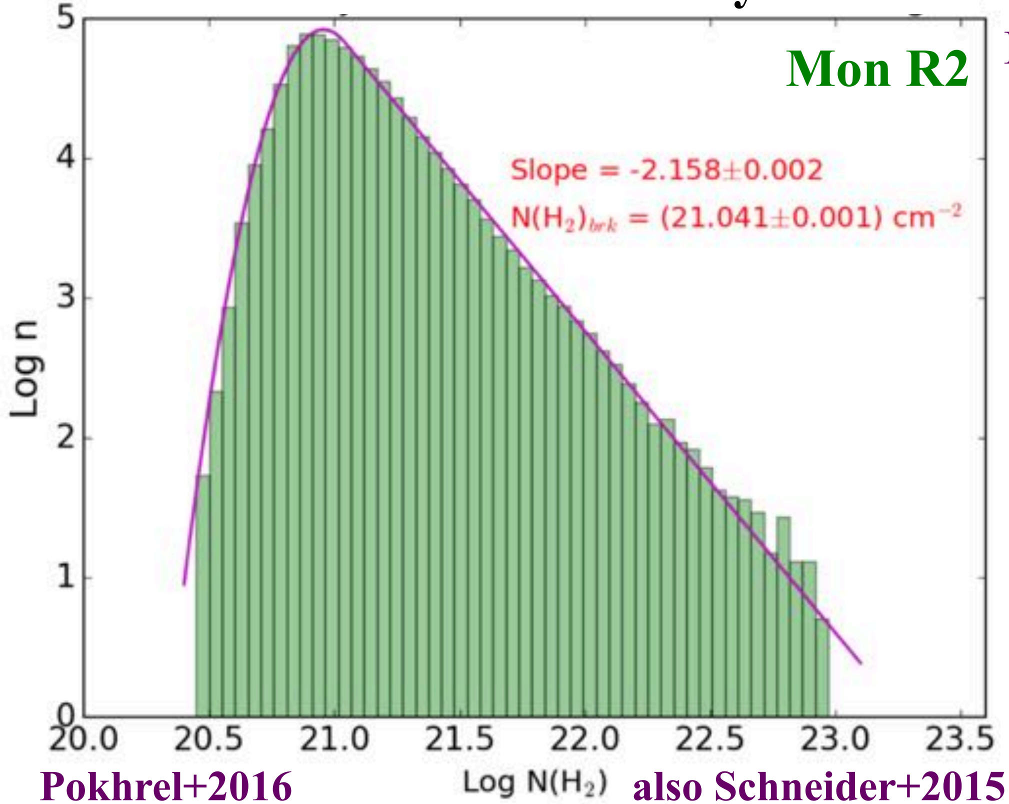
➢ **Filaments may help to regulate the star formation efficiency in the dense molecular gas of galaxies (e.g. Shimajiri+2017)**

Origin of ISM filaments - Role of gravity

“Hub-filament” systems with central cluster-forming “hub” + converging network of filaments

See Myers 2009

Power-law column density PDFs

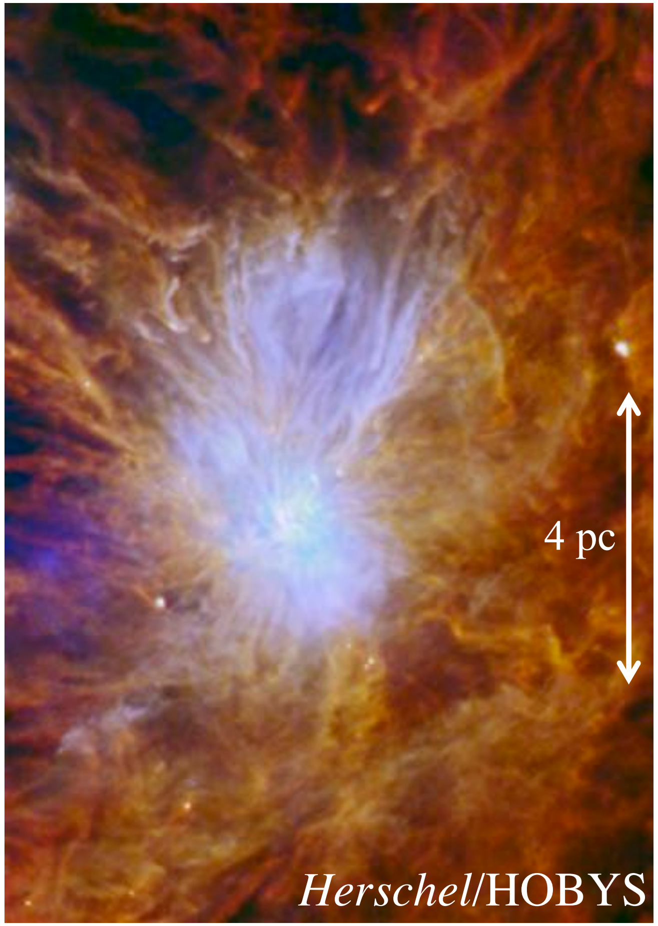


Pokhrel+2016 also Schneider+2015

Mon R2 hub:

$M \sim 1300\ M_\odot$ in central 1 pc^2

Didelon+2015, Pokhrel+2016, Rayner+2017

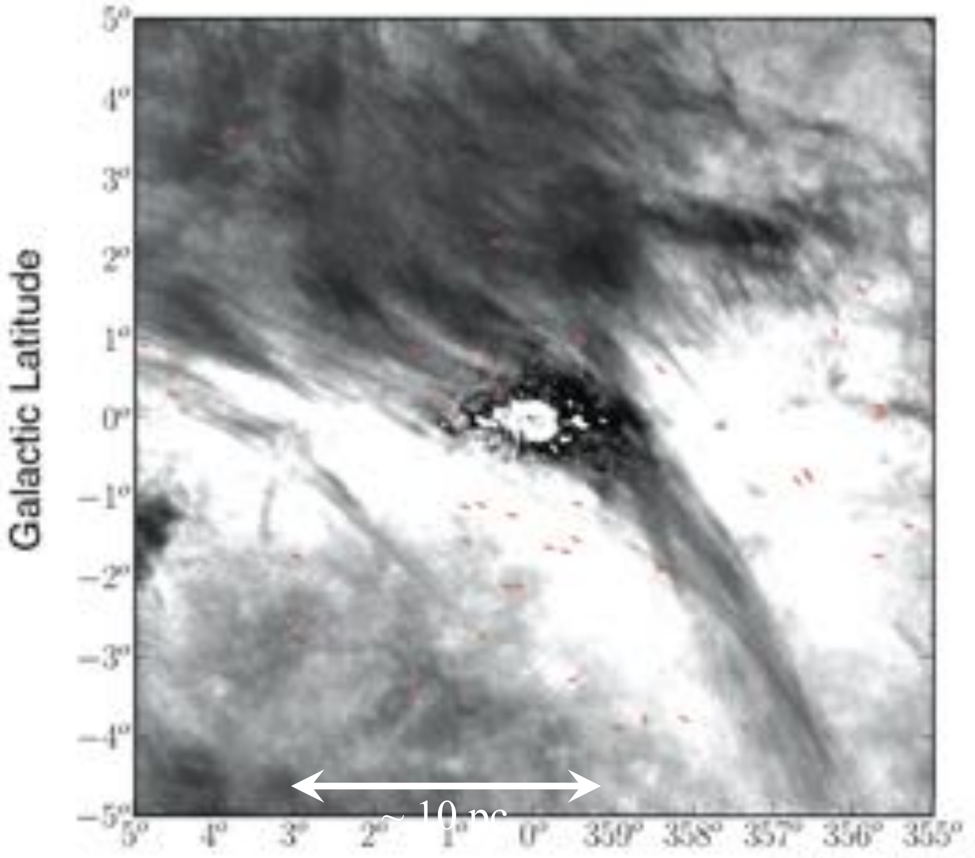


+ Kinematic signatures of large-scale collapse in some cases (e.g. SD335: Peretto+2013)

But … Filamentary structures are already widespread in non-self-gravitating interstellar clouds

Atomic (HI) clouds

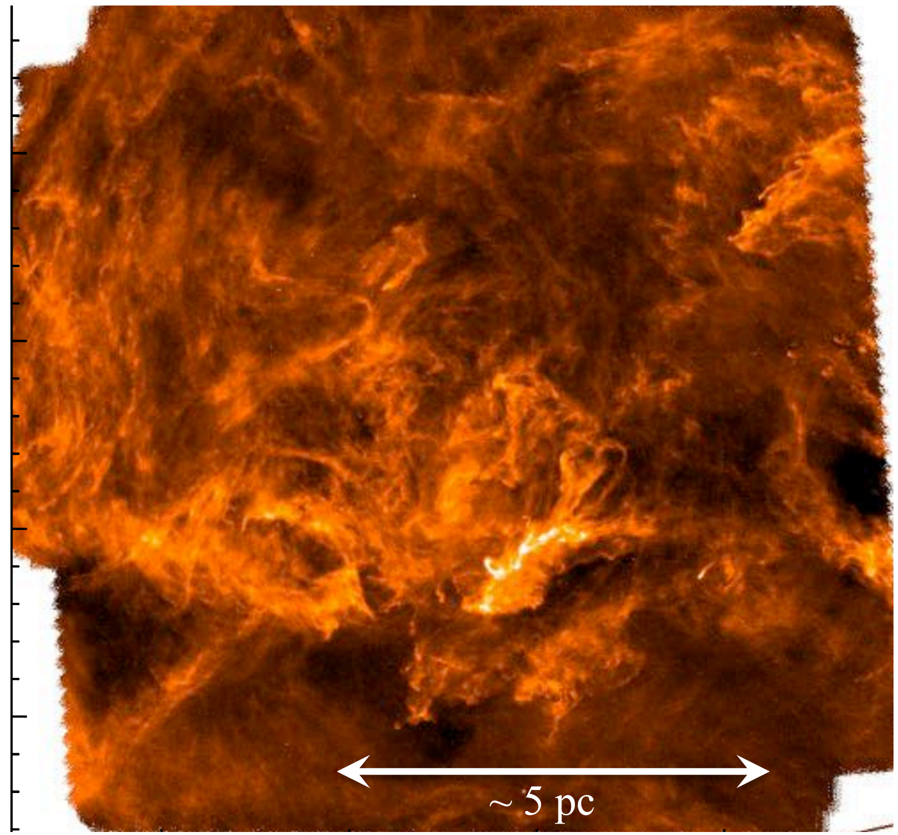
The Riegel-Crutcher cloud in HI asborption
(ATCA+ Parkes – Resolution: 100" ~ 0.1 pc)



McClure-Griffiths+2006
Clark+2014; Kalberla+2016

Translucent molecular clouds

The Polaris-flare cirrus cloud
(*Herschel*/SPIRE 250 μm– Resol.: 18")

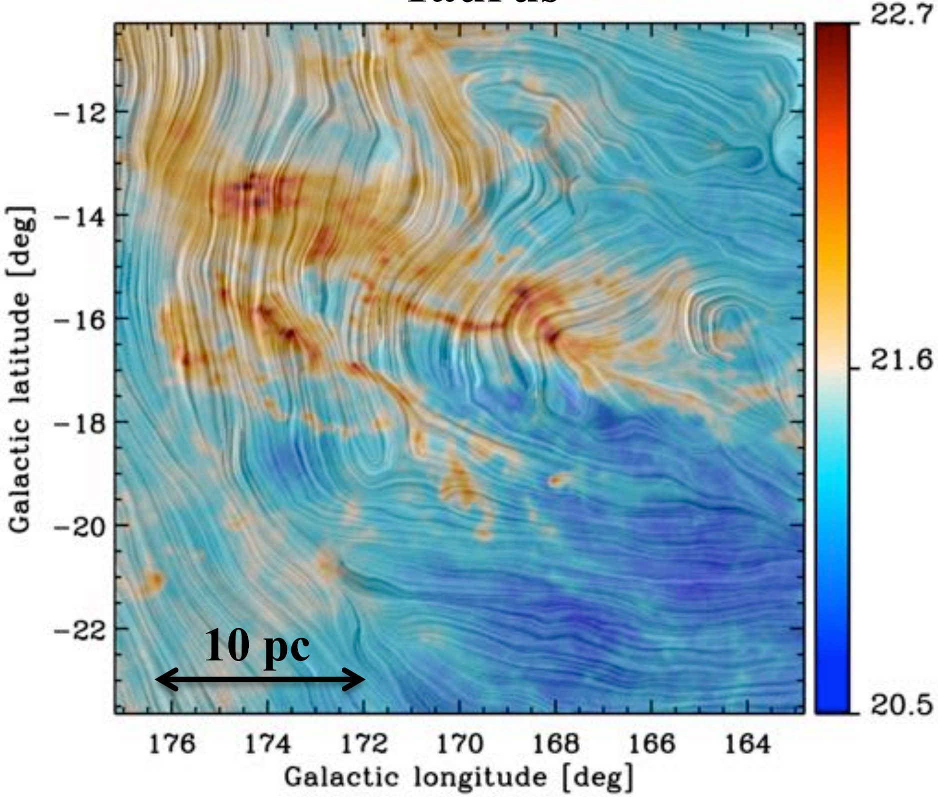


Miville-Deschênes+2010; Ward-Thompson+2010
Men'shchikov+2010

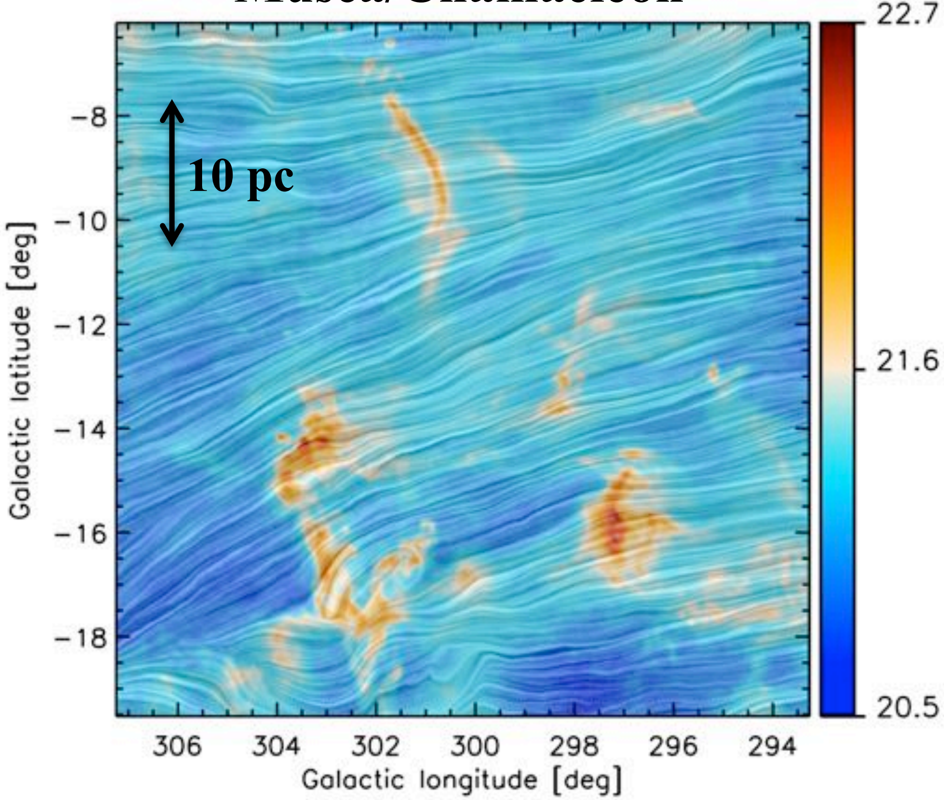
Role of magnetic fields?

- ➢ ***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)

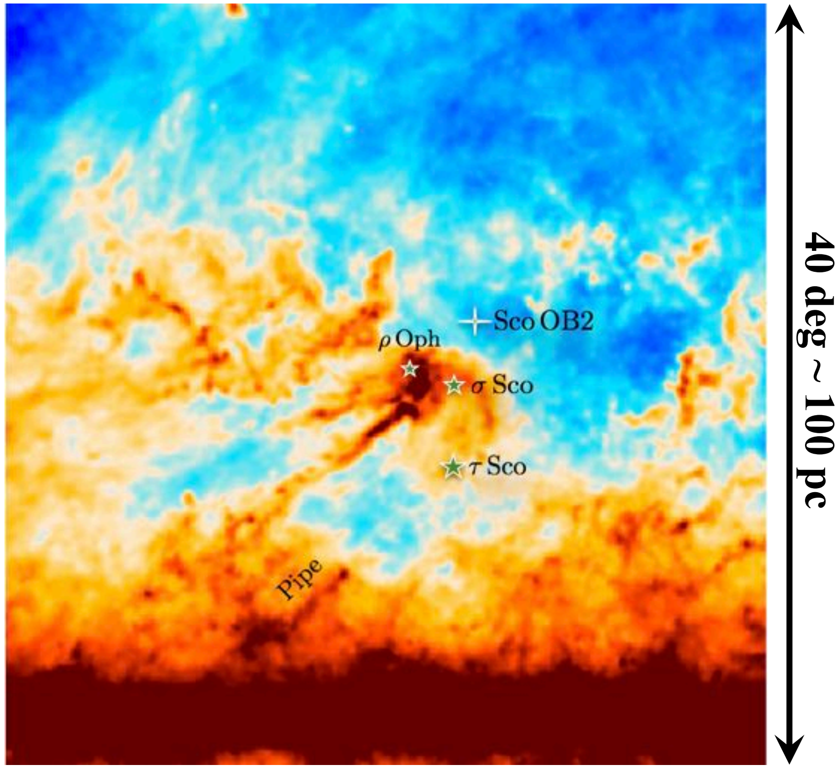
Drapery: B field lines from Q,U *Planck* 850 µm @ 10'

F. Boulanger's group

Role of large-scale flows and expanding shells

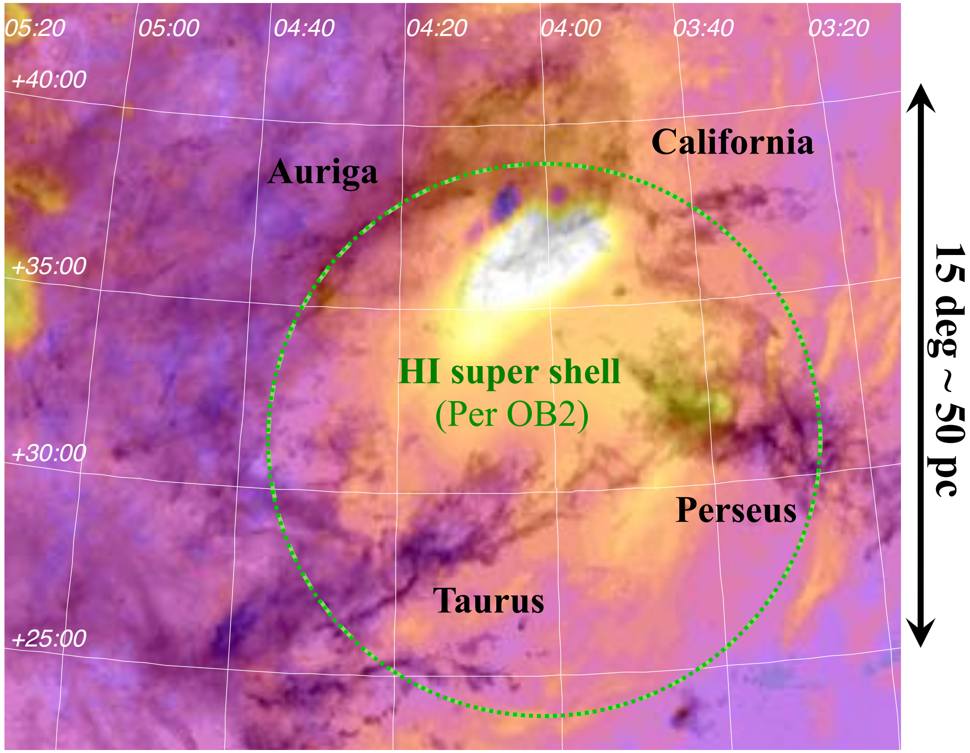
- **Many examples of clouds with cometary shapes or « head-tail » structures pointing toward OB stars/associations**
- **Suggestive of the action of stellar winds and large-scale streams/shells, not produced by gravity, sweeping up and compressing ISM material**

***Planck* 850 µm image around the Ophiuchus/Pipe clouds**



e.g. de Geus 1992; Loren & Wootten 1986; Tachihara+2002; Preibisch & Zinnecker 1999

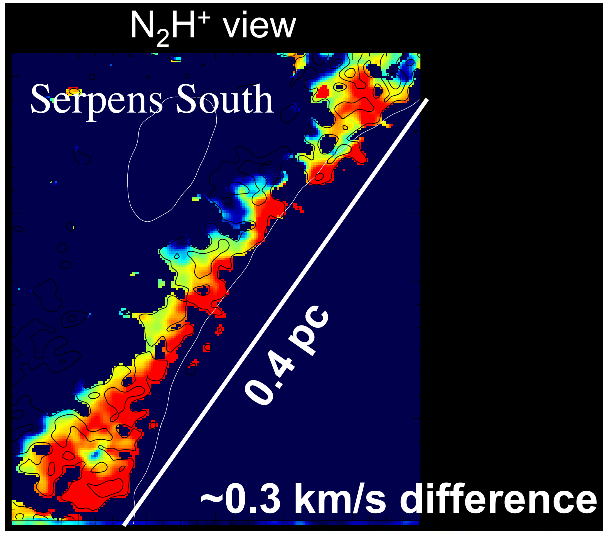
Hα color + *Planck* 350 µm (grey) image of the Taurus/Perseus/Auriga cloud complex

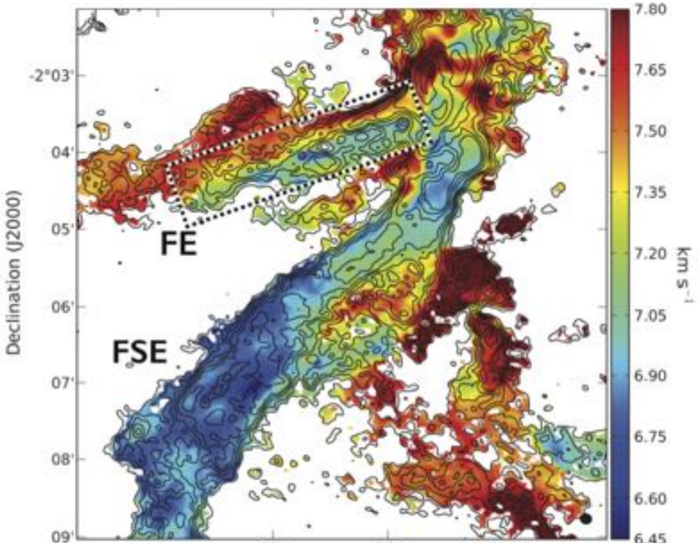


e.g. Lim+2013; Bouy & Alves 2015; Shimajiri+2018

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

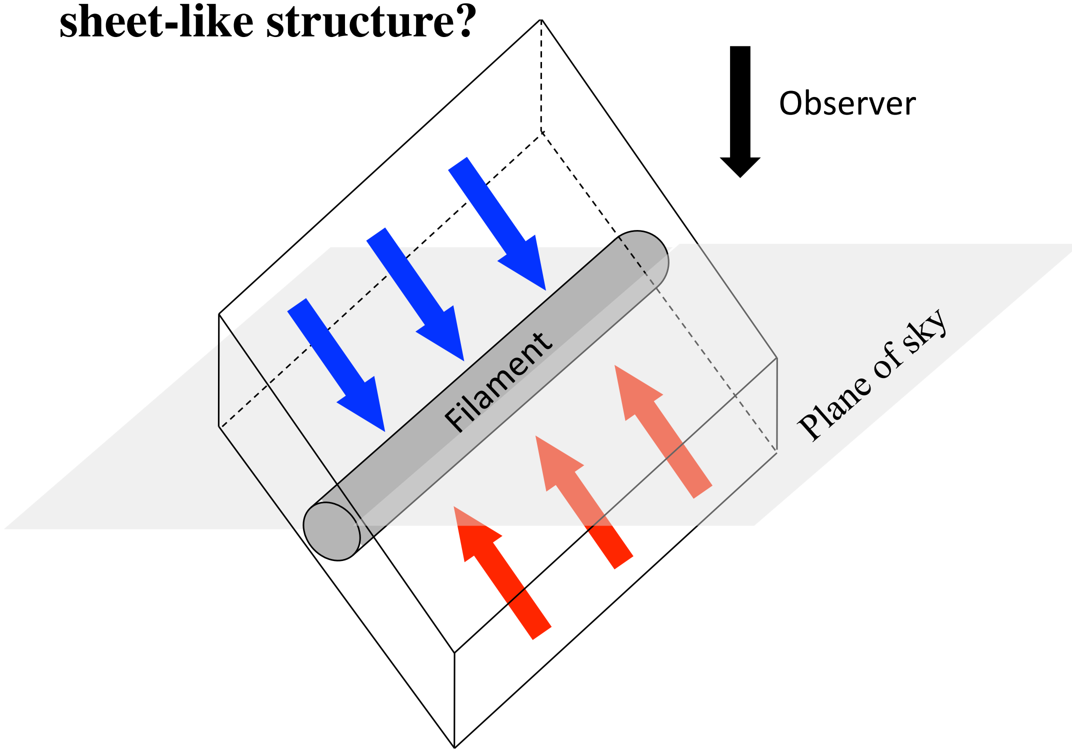
CARMA “CLASSy” SF Survey

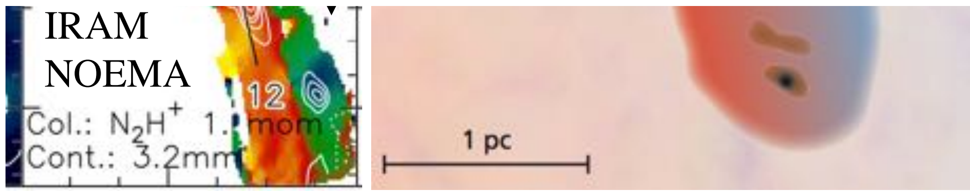




Fernandez-Lopez+2014, Mundy et al., in prep. see also H. Kirk+2013 for Serp-S

Coherent motions inside sheet-like structure?

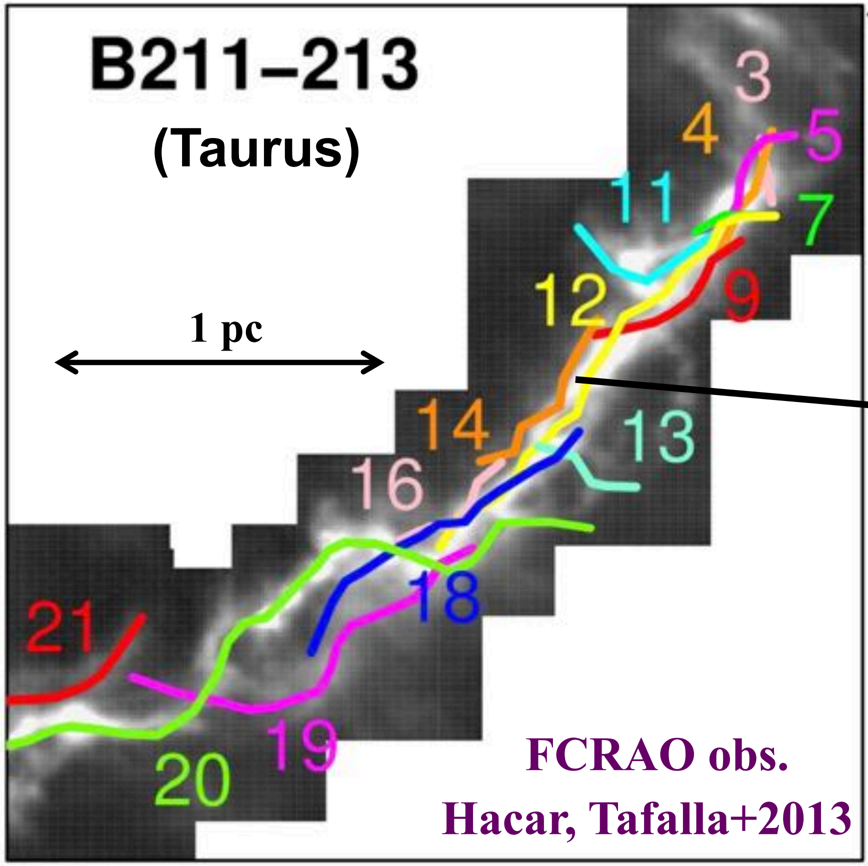




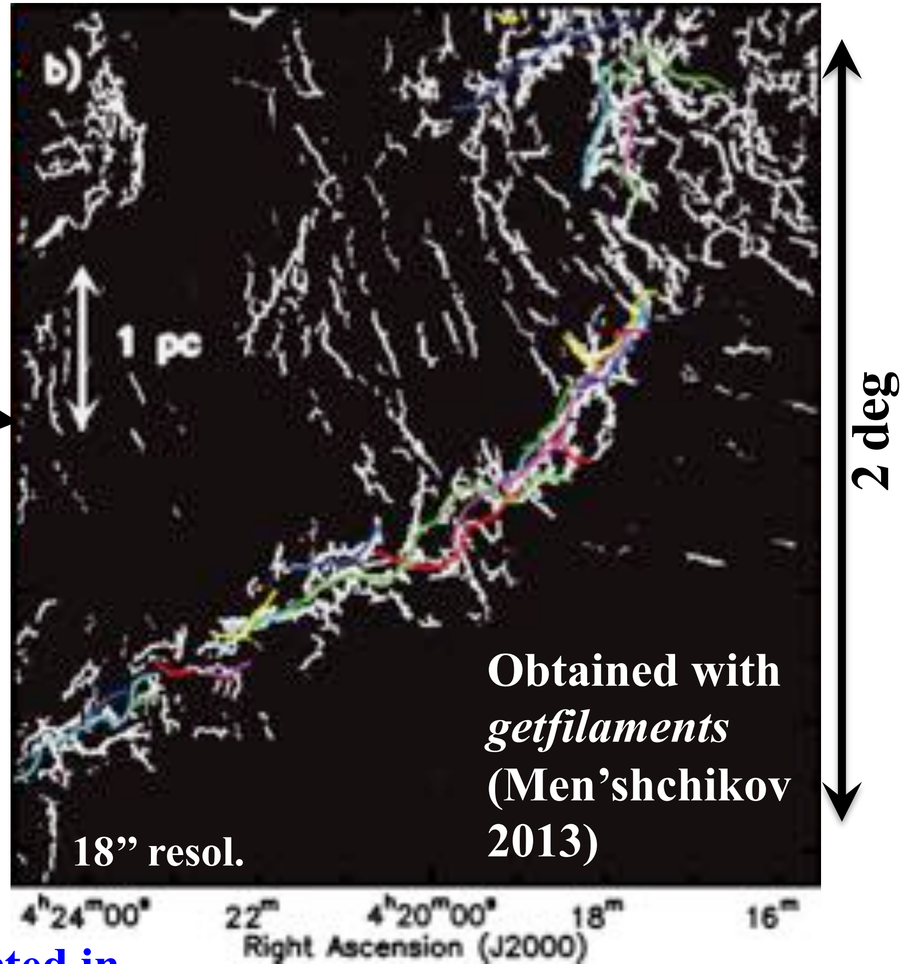
Beuther, Ragan+2015

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 $C^{18}O(2\text{-}1)$ and $N_2H^+(1\text{-}0)$ and making up the main filament**

Summary: A filamentary paradigm for star formation?

- *Herschel* results suggest $M_\odot$ **star formation occurs in 2 main steps**:
  1) ~0.1pc filaments from **large-scale compressive flows** in the ISM;
  2) Prestellar cores from **gravitational instability** of dense filaments above the critical line mass $M/L \sim 16\ M_\odot\ pc^{-1}$

- **Filament fragmentation** appears to produce the peak of the prestellar CMF and likely **accounts for the « base » of the IMF,** according to a « core-fed » picture (1 core → ~ 1 star/system)

- Massive protostars (high-mass end of IMF) may be « clump-fed » instead, gathering mass from cluster-forming 'hub-filaments'

- Evidence that dense filaments result from large-scale compressive flows and accumulation of matter ~ along B in shell-like structures

- Dense filaments appear to accrete from their parent cloud/shell and may grow in mass and complexity (fibers) with time