Fragmentation of molecular clouds, filaments, the core mass function and the origin of the stellar initial mass function

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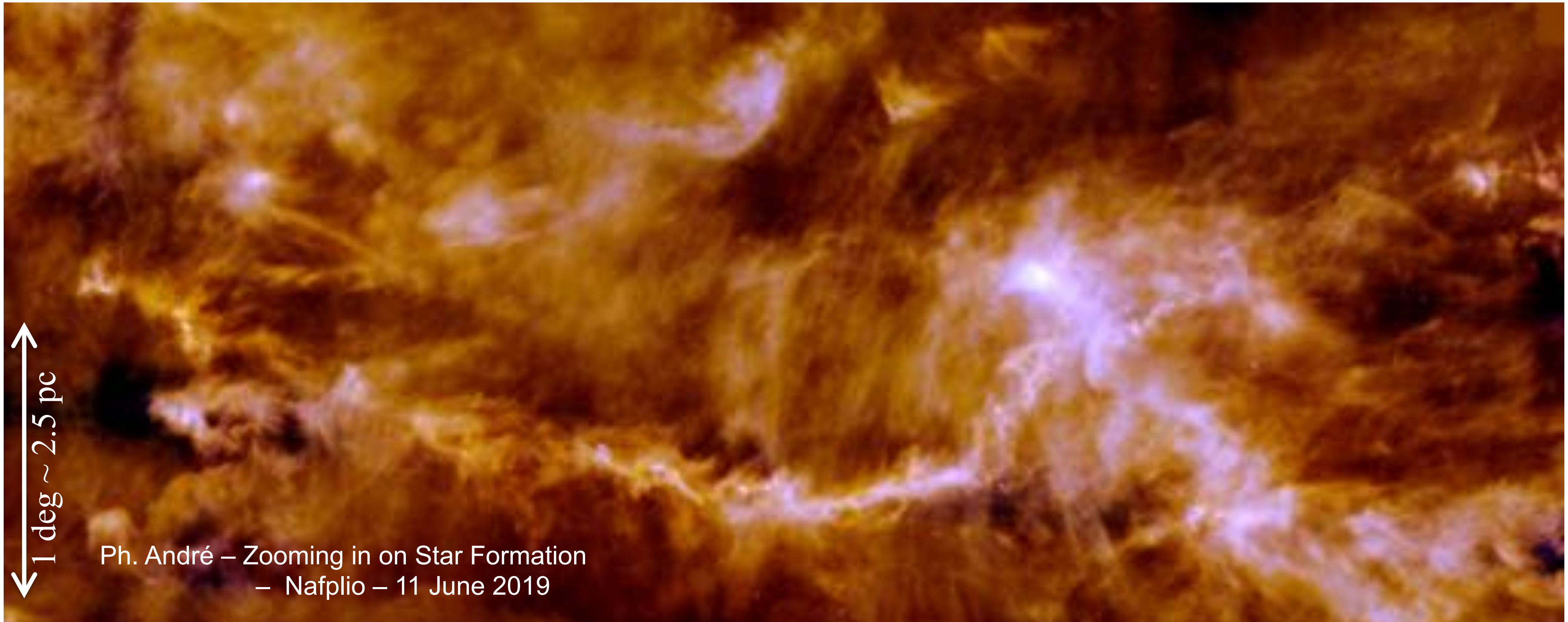
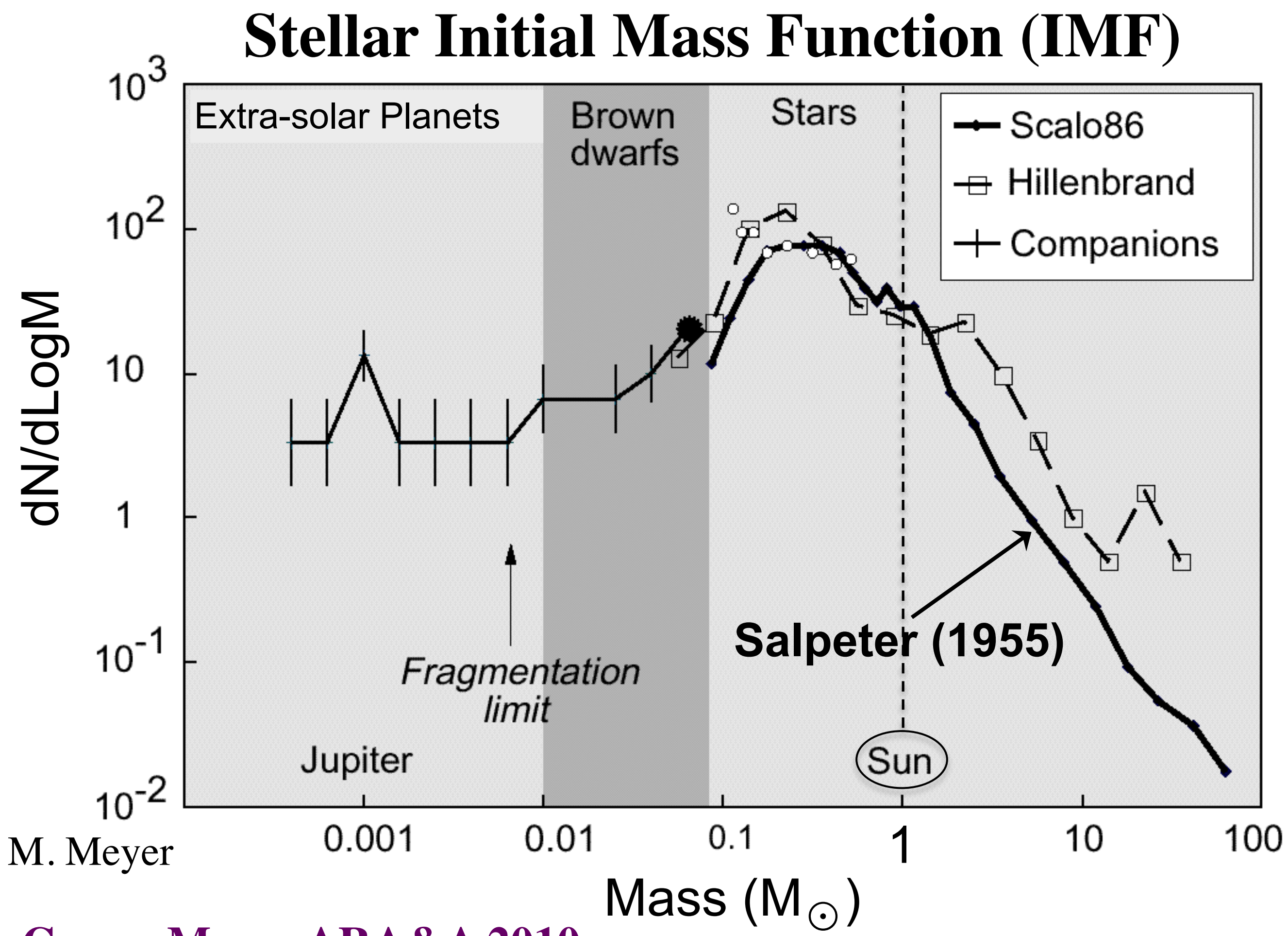
Thanks to: D. Arzoumanian, V. Könyves, Y. Shimajiri, A. Roy, P. Palmeirim, E. Ntormousi



Herschel GBS 160/250/500 μm composite image of Taurus B211/3 (Palmeirim+2013)

A "universal" star formation product: the IMF



M. Meyer

See Bastian, Covey, Meyer ARA&A 2010

Also Kroupa 2002; Chabrier 2003

Possible variations in the early Universe

e.g. Cappellari et al. 2012

Origin of the IMF: Nature or Nurture?
Two main classes of IMF models

1) **"Nature": Gravo-turbulent cloud fragmentation models**
   (e.g. Larson 1985; Padoan, Nordlund, Jones 1997; Padoan & Nordlund 2002; Klessen & Burkert 2000; Hennebelle & Chabrier 2008).
   Stellar masses largely determined at prestellar stage of star formation; stellar IMF is inherited from the prestellar CMF resulting from cloud fragmentation.

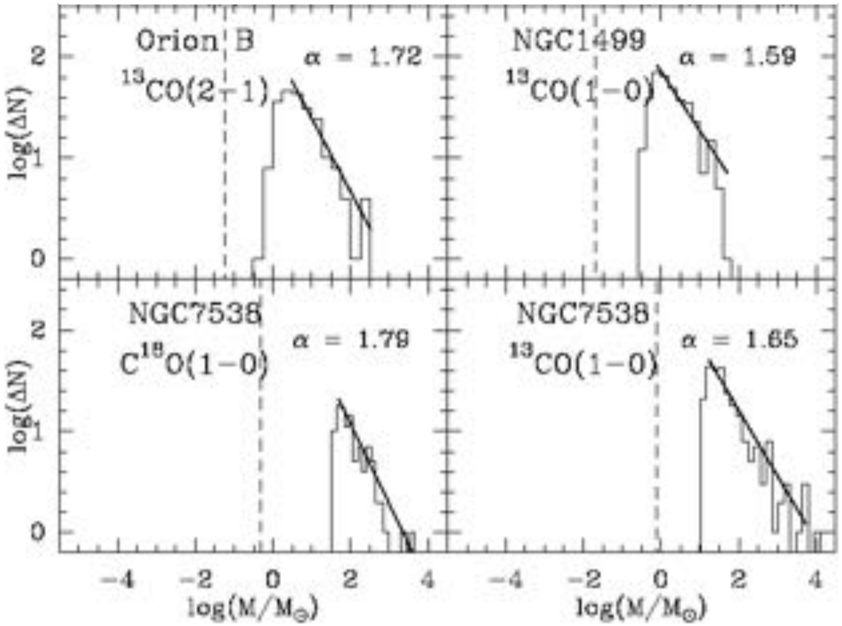
2) **"Nurture": (Competitive) Accretion between protocluster seeds at the protostellar stage of YSO evolution**
   (e.g. Zinnecker 1982; Bonnell+2001; Bate+2003).
   Final stellar masses unrelated to initial prestellar cores masses

➢ **This talk: Modification to the gravo-turbulent fragmentation picture based on *Herschel* results** on core/star formation, which **emphasize the role of filaments.**

See S. Offner et al. 2014 PPVI for a detailed review/discussion of models

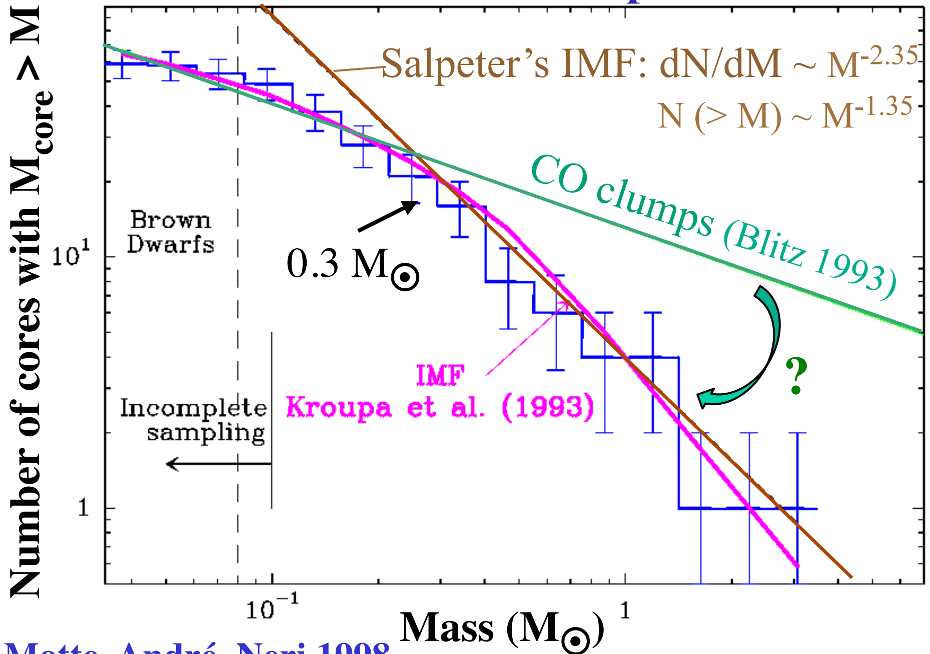
The cloud/clump mass function is shallower than the IMF but the prestellar core mass function (CMF) resembles the IMF

`Universal' cloud/clump mass spectrum:
$dN/dM \sim M^{-1.7+-0.1}$



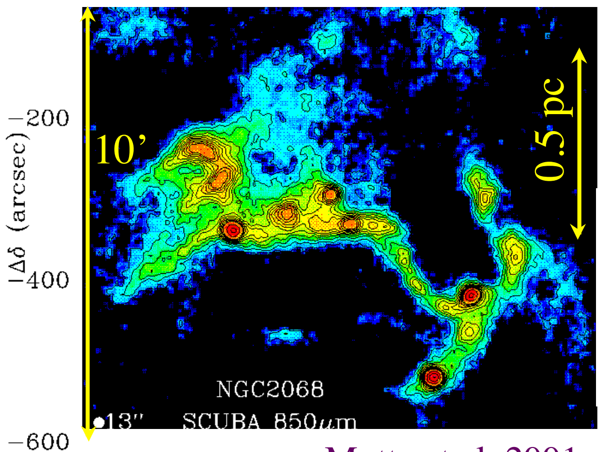
Blitz 1993; Kramer et al. 1998

Prestellar CMF in Ophiuchus



Motte, André, Neri 1998

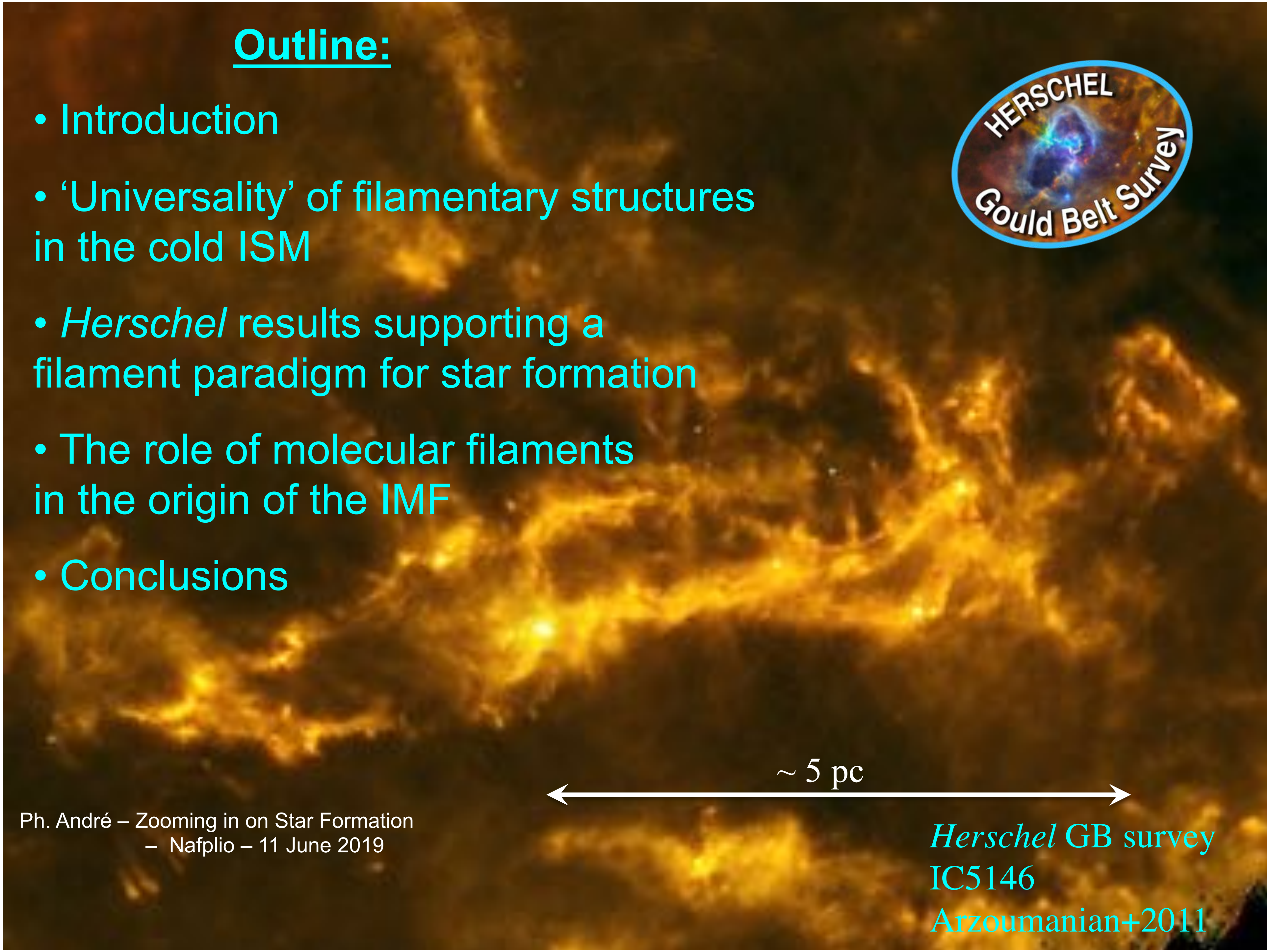
Prestellar cores in NGC2068 at 850 μm

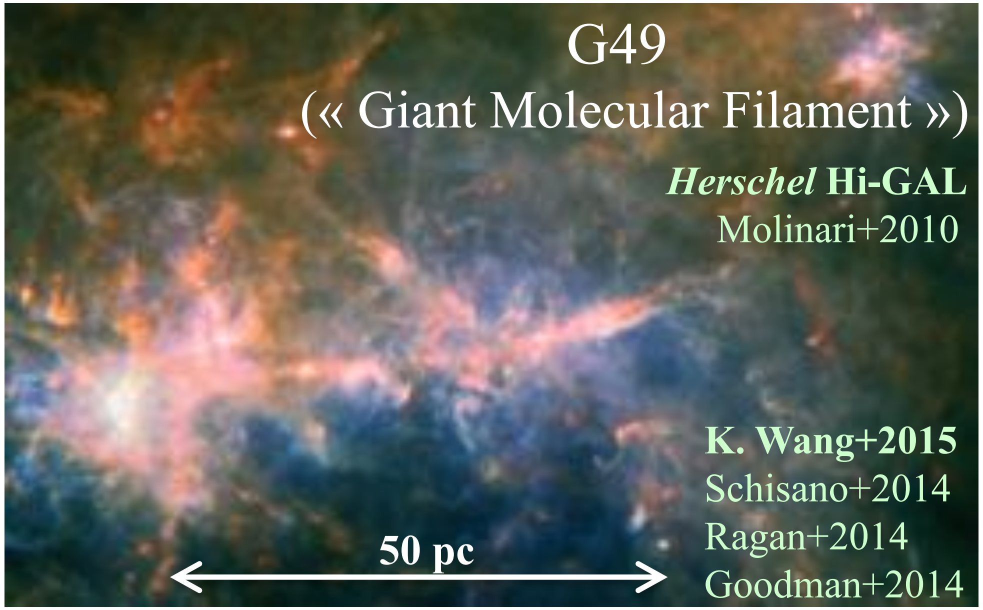


Motte et al. 2001

See also: Testi & Sargent 1998; Johnstone+2001; Stanke et al. 2006; Alves+2007 Nutter & Ward-Thompson 2007 Könyves+2015

And for massive cores: Beuther & Schilke 2004; Reid & Wilson 2006

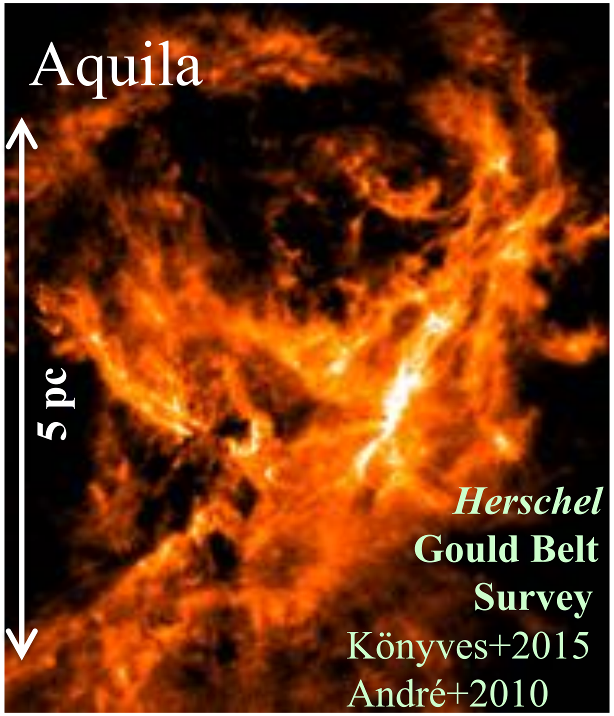

Outline:
• Introduction
• 'Universality' of filamentary structures in the cold ISM
• Herschel results supporting a filament paradigm for star formation
• The role of molecular filaments in the origin of the IMF
• Conclusions
HERSCHEL Gould Belt Survey
~ 5 pc
Herschel GB survey
IC5146
Arzoumanian+2011
Ph. André – Zooming in on Star Formation – Nafplio – 11 June 2019



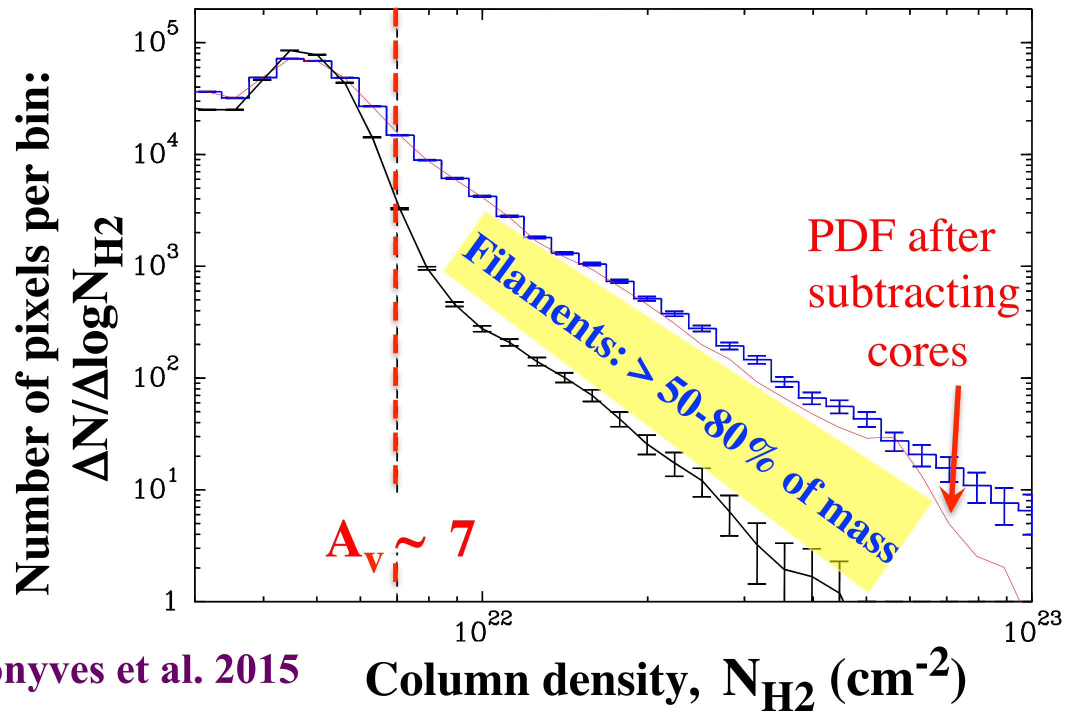
Herschel has confirmed the presence of a 'universal' filamentary structure in the cold ISM

Filaments dominate the mass budget of GMCs at high column densities

cf. Schisano+2014, Könyves+2015



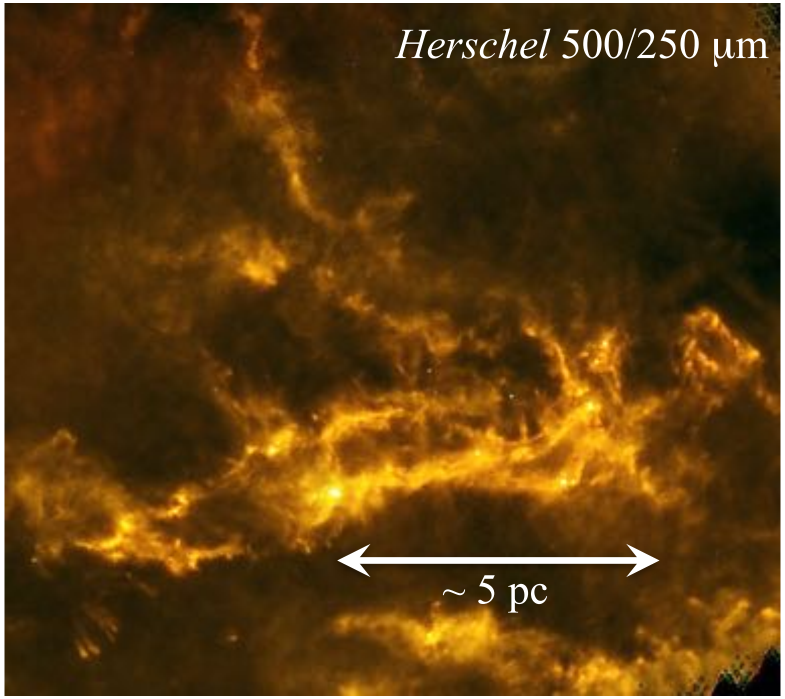
Column Density PDF for Aquila GMC



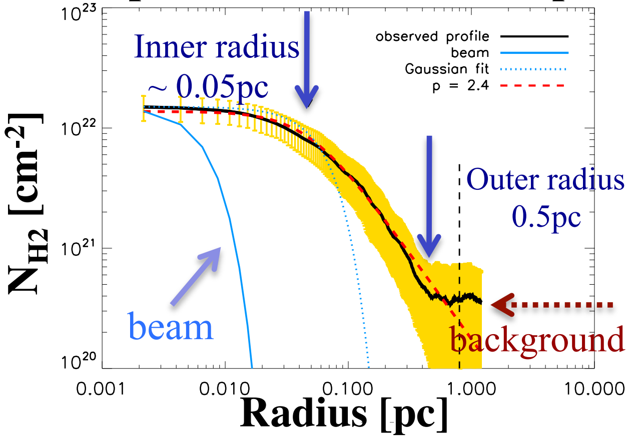
Könyves et al. 2015

Nearby filaments have a common inner width ~ 0.1 pc

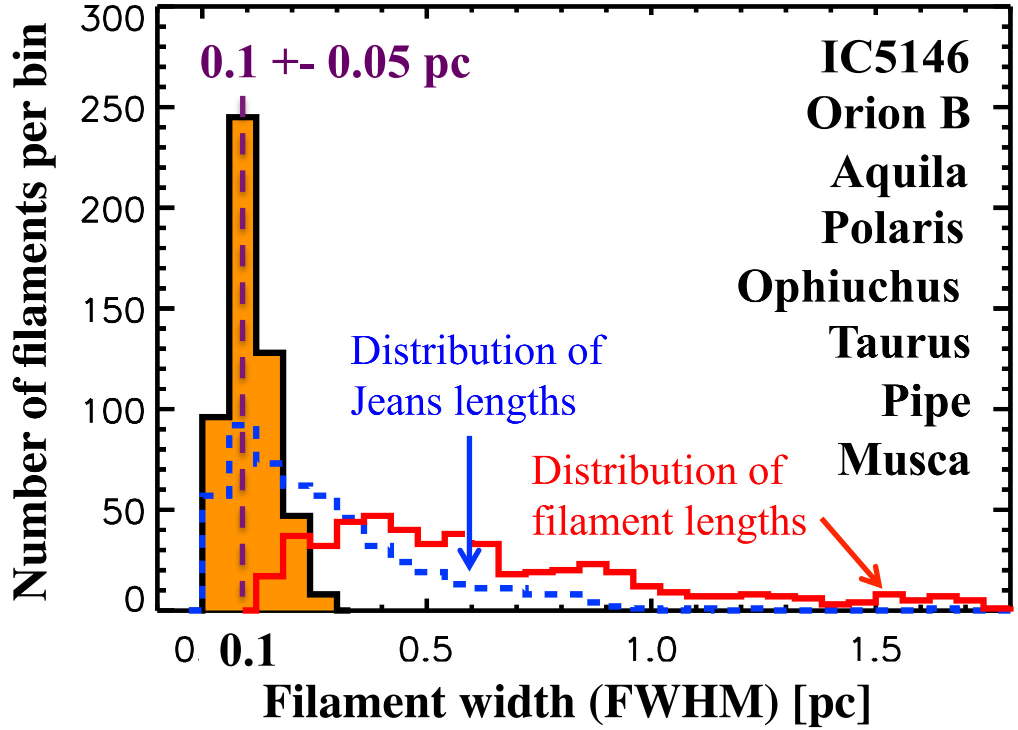
Network of filaments in IC5146



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?

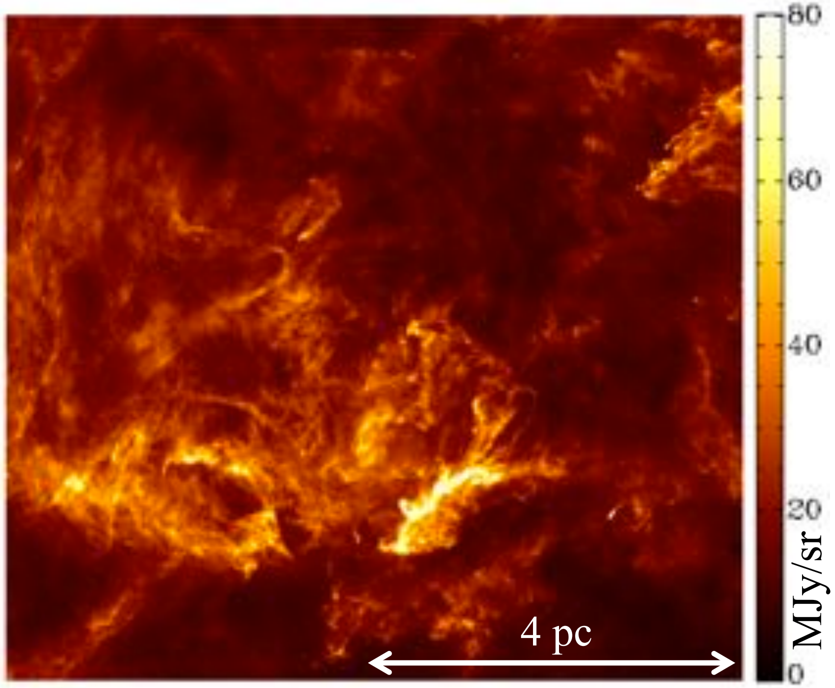
(cf. Padoan+2001; Federrath 2016)

Challenging for numerical simulations & models

(cf. R. Smith+2014; Ntormousi+2016; Auddy, Basu+2016)

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

SPIRE 250 μm image of Polaris translucent cloud

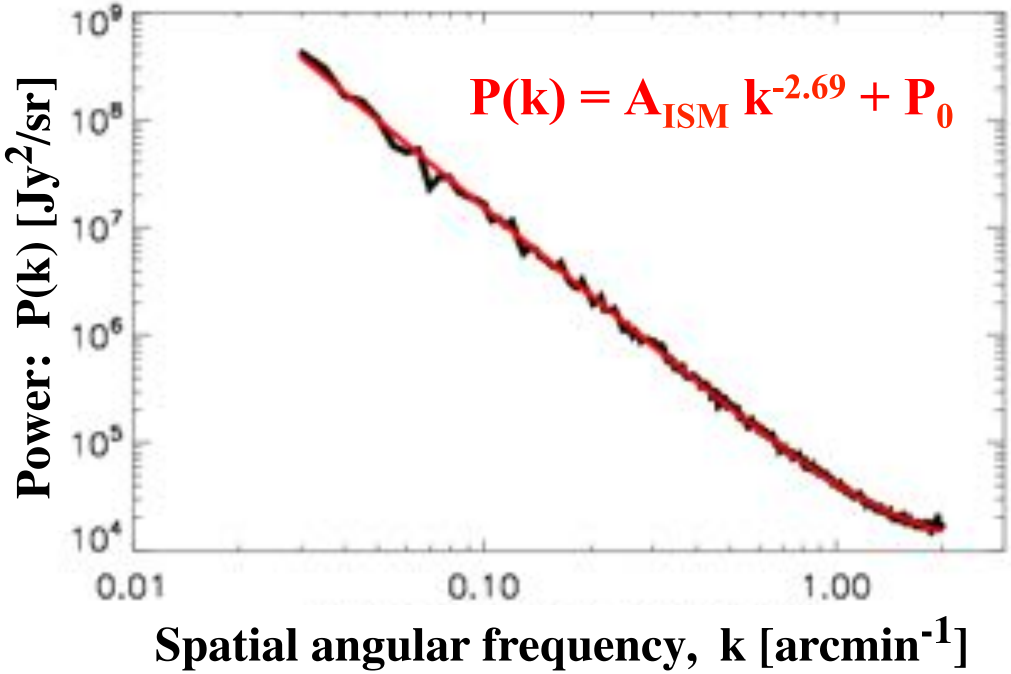


Miville-Deschênes et al. 2010

Tension with scale-free power spectrum

Panopoulou+2017

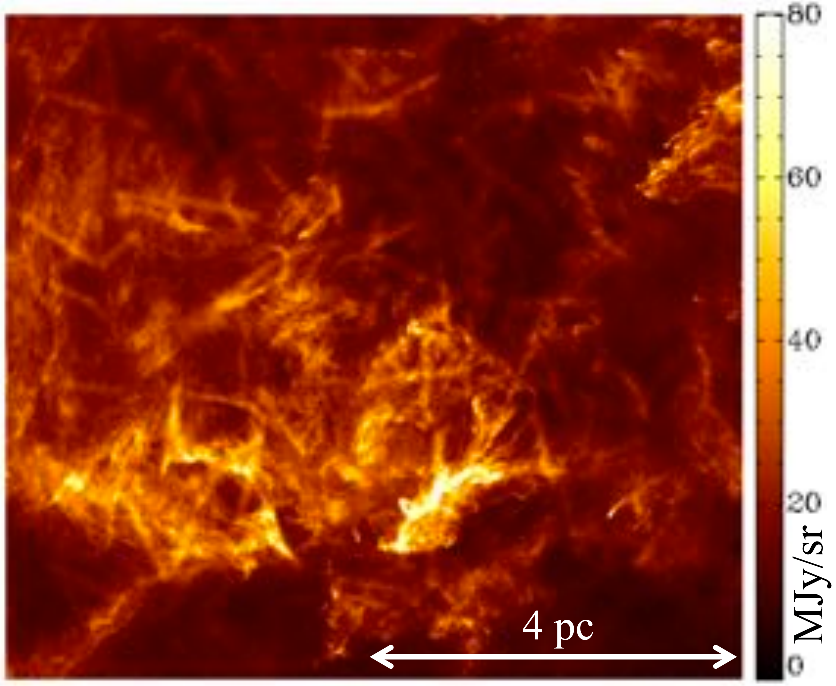
Noise-subtracted, deconvolved power spectrum of Polaris image



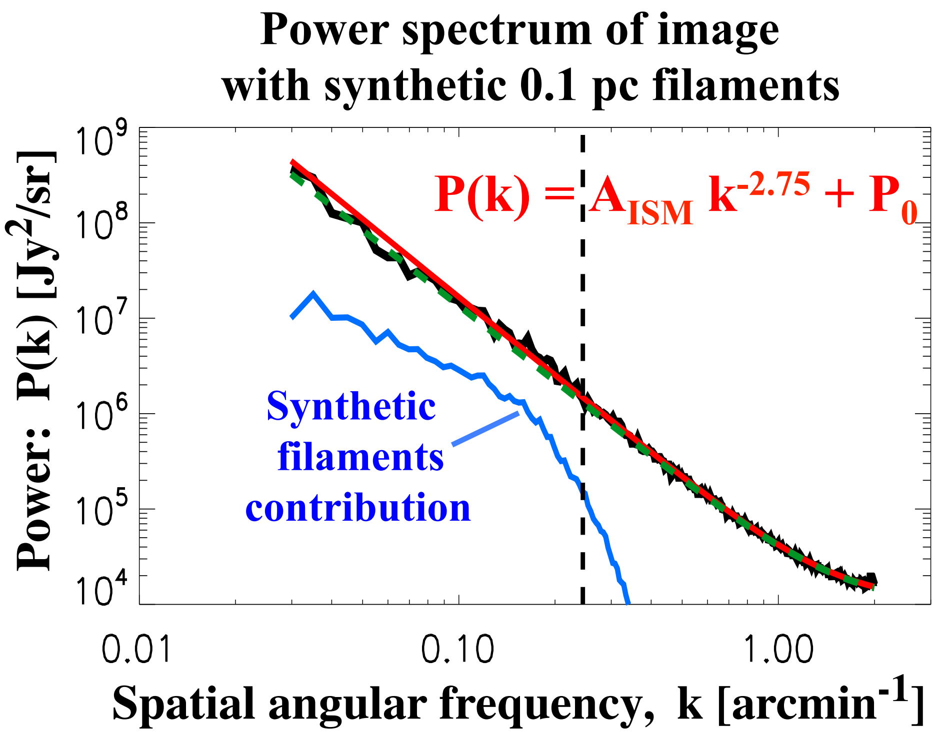
Simple tests

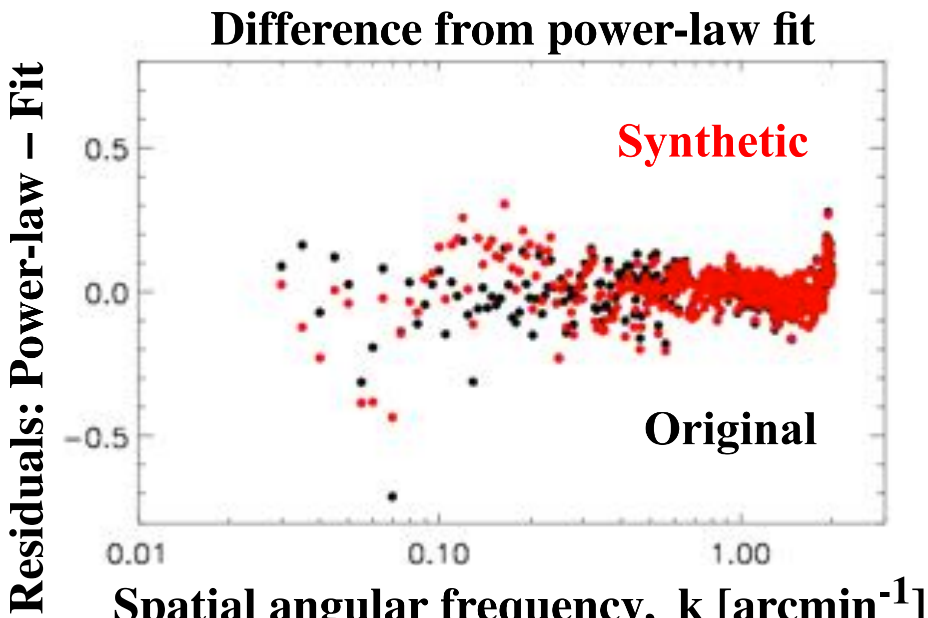
A. Roy et al. 2019, arXiv:1903.12608

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



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





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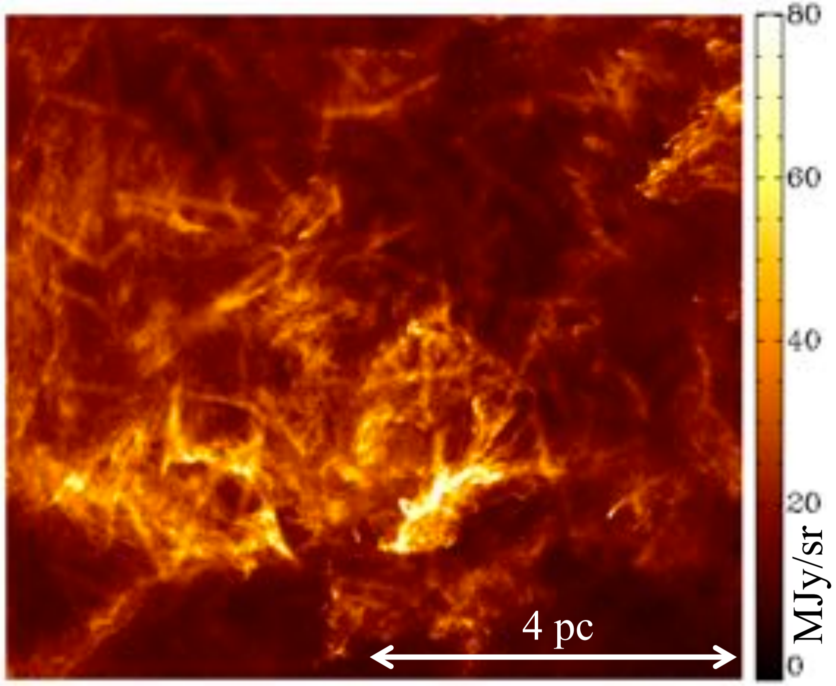
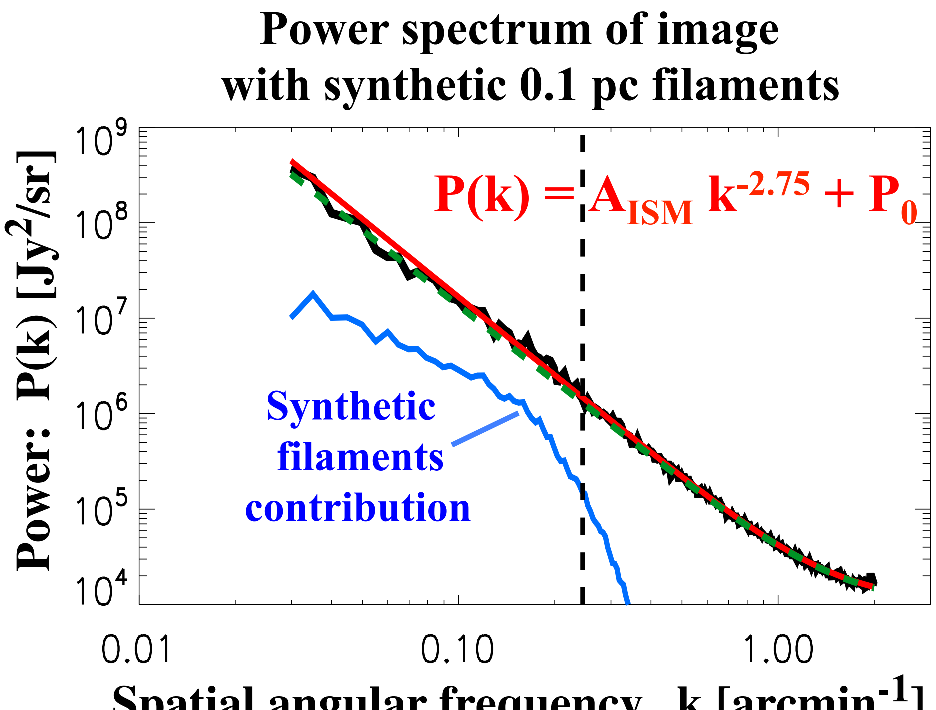
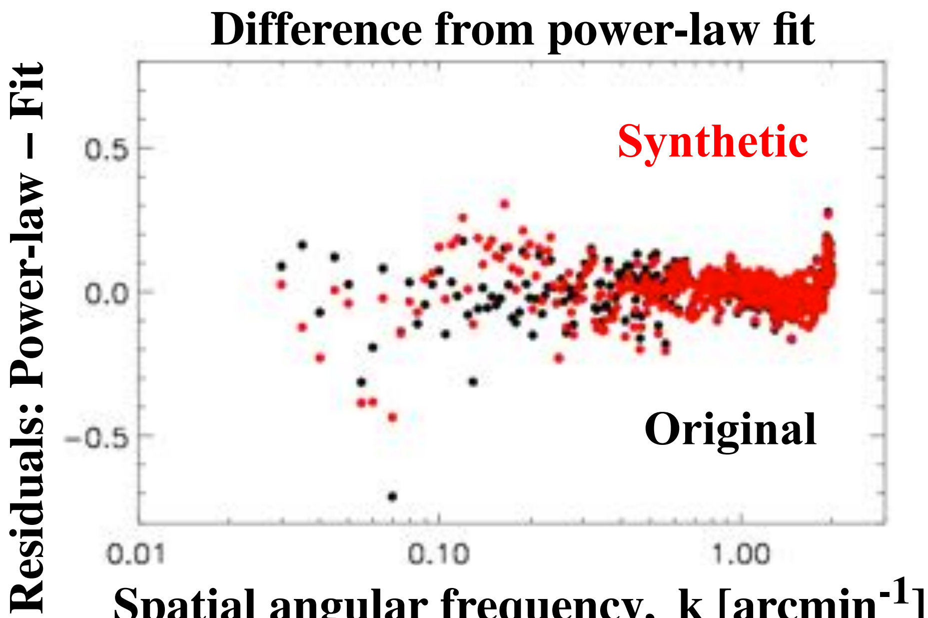




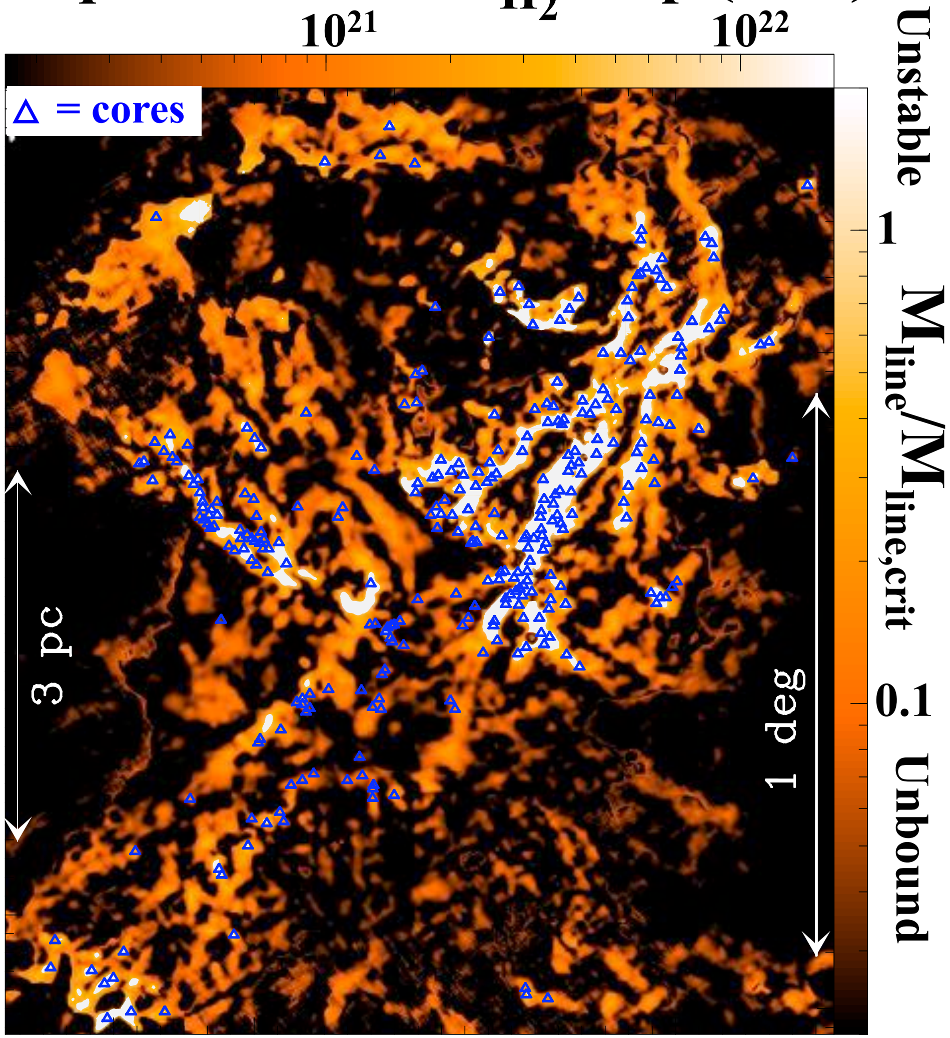


+ Extensive tests performed by Arzoumanian+2019 (A&A, 621, A42)

➢ Results of filament profile fitting are robust for high-contrast filaments

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

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

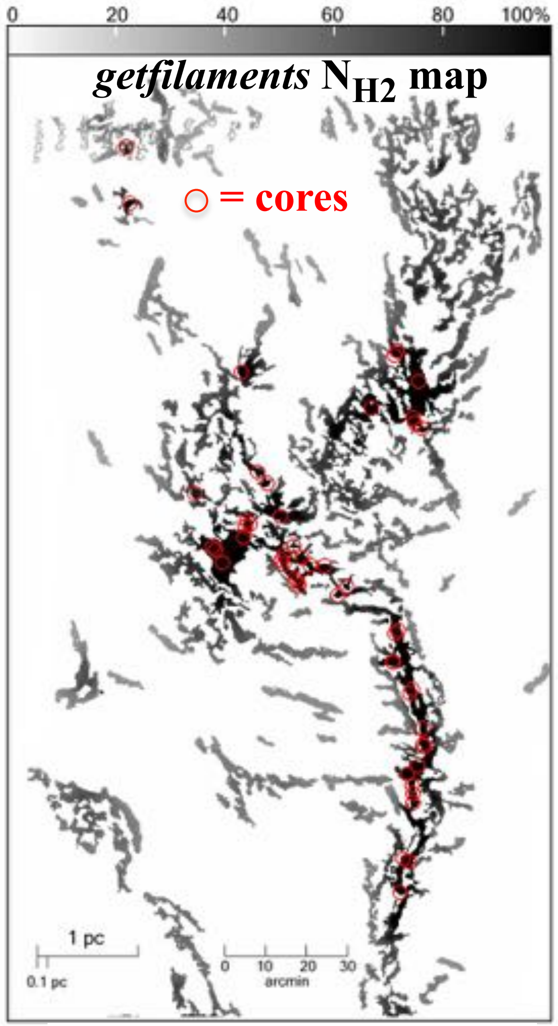


André+2010; Könyves+2015

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

Also:
Bresnahan+2018 (CrA)
Benedettini+2018 (Lupus)
Könyves+2019 (Orion B)
Ladjelate+2019 (Oph)
Pezzuto+2019 (Perseus)
Fiorellino+2019 (Serpens)
…

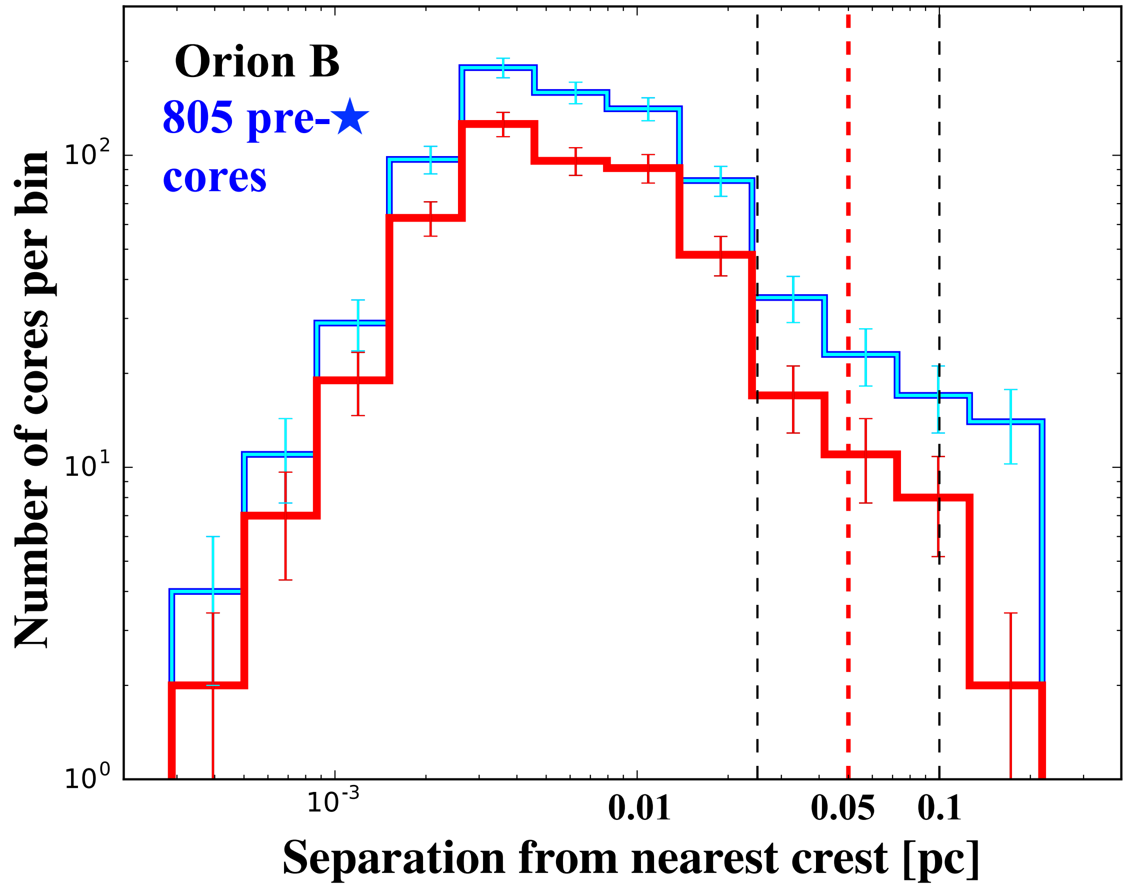
Taurus B211/3+L1495



Marsh al. 2016, MNRAS

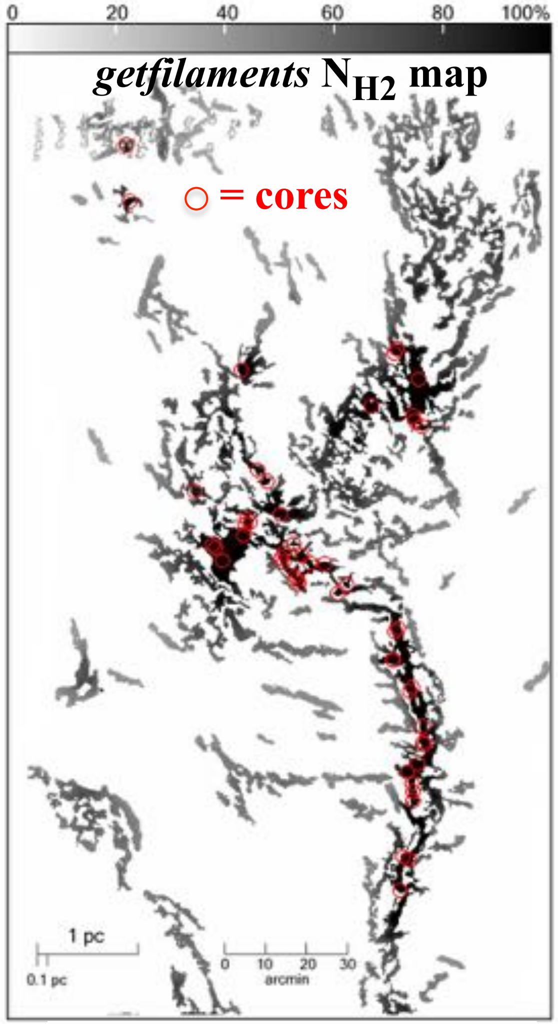
~ 75^{+15}_{-5} % of prestellar cores form in filaments, above a typical column density $N_{H_2} \gtrsim 7 \times 10^{21}$ cm^{-2}

Distribution of separations from nearest filament crest



Könyves et al. 2019, A&A, submitted

Taurus B211/3+L1495



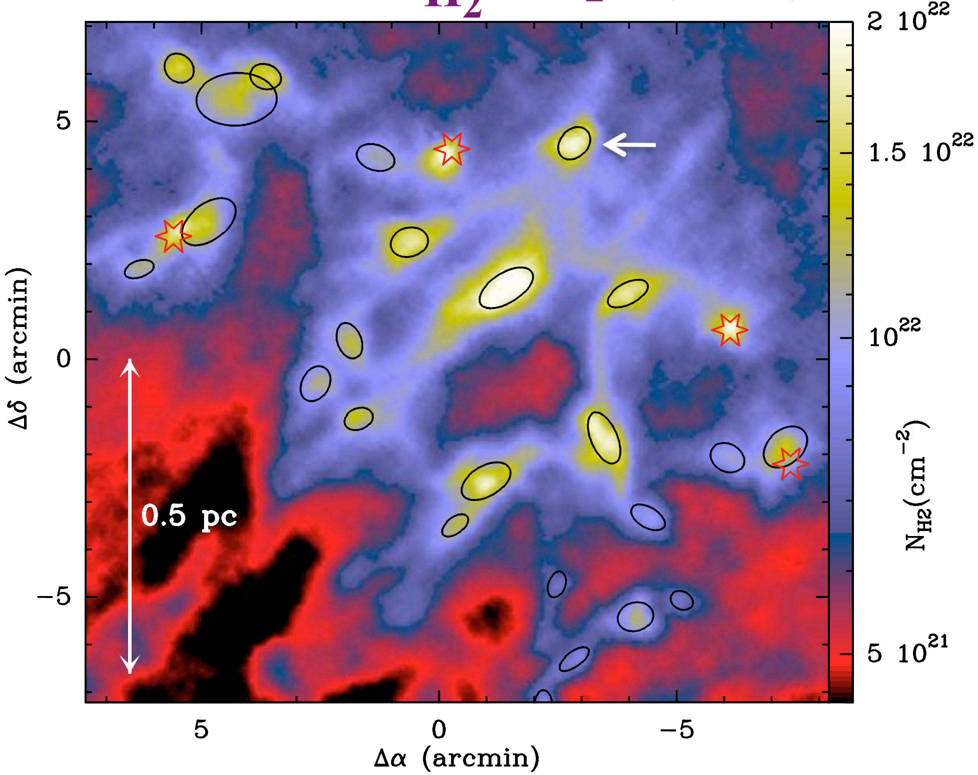
Marsh al. 2016, MNRAS

Examples of *Herschel* prestellar cores in Aquila

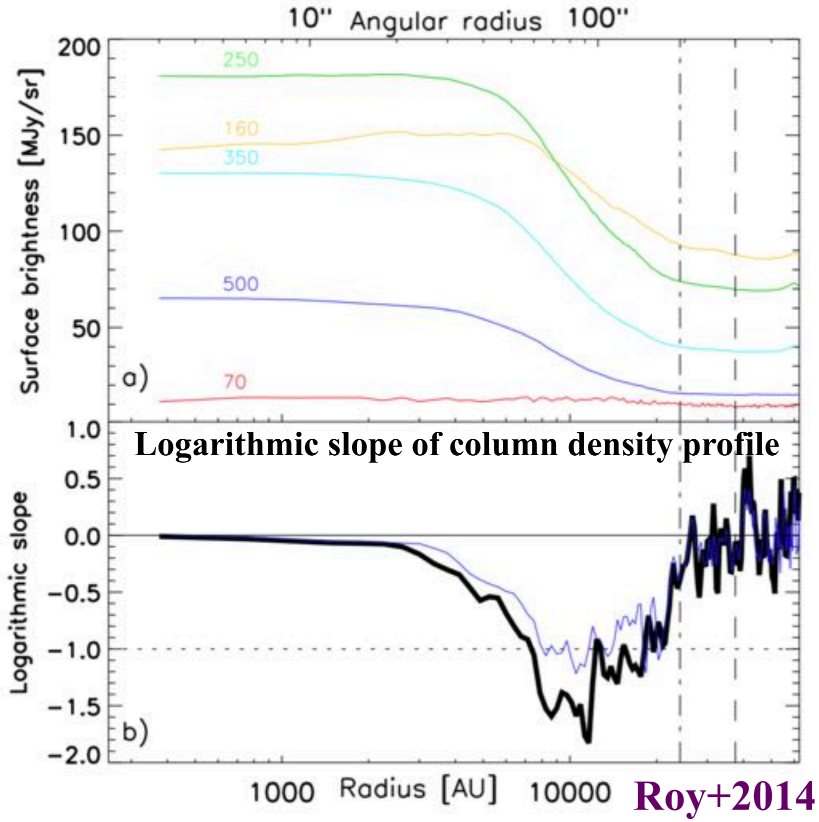
- **Core = single star-forming entity**
  (Need to resolve ~ 0.01-0.1 pc)
- **Starless = no central proto★**
- **Prestellar = bound & starless**

[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})**



Examples of radial intensity profiles



Roy+2014

Könyves+2015

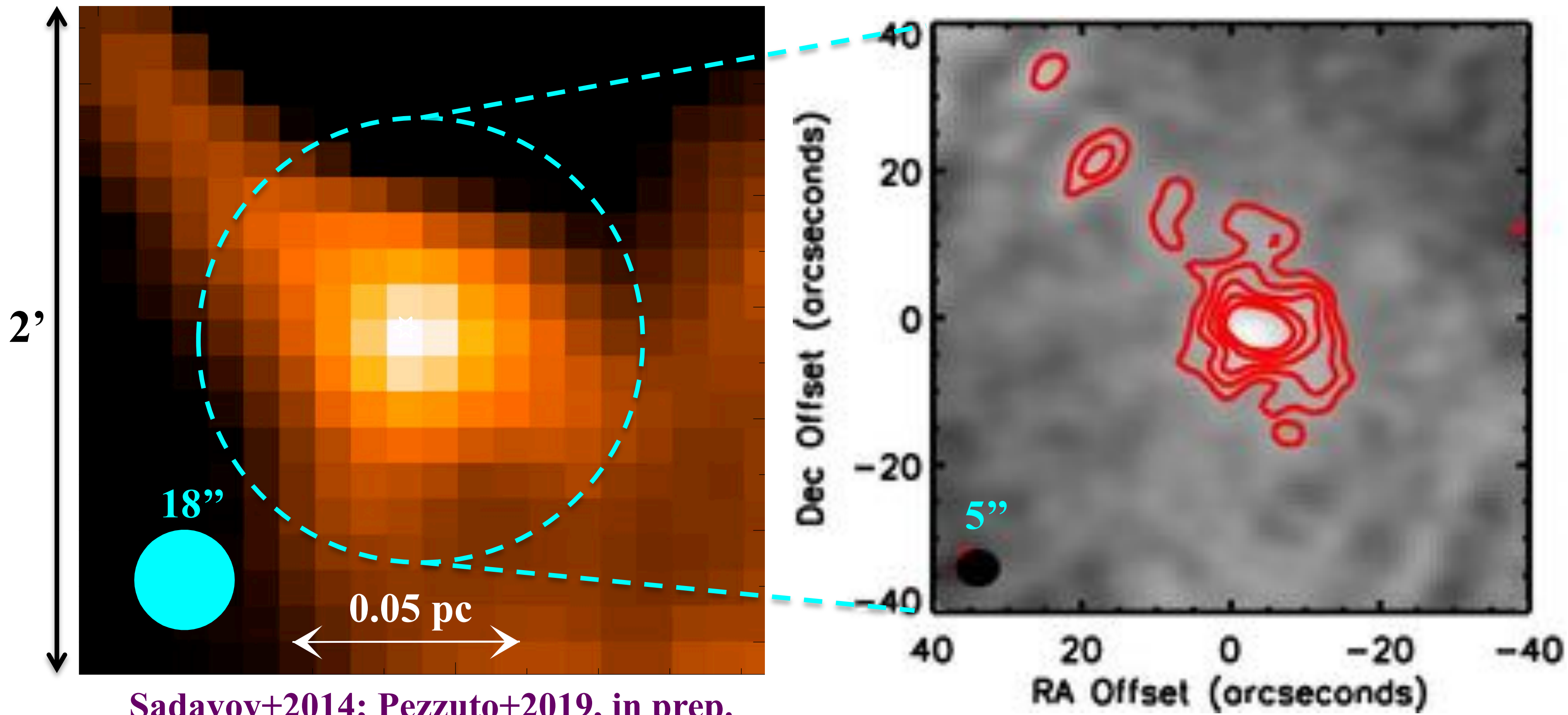
FWHM ellipses from core extraction with *getsources* (Men'shchikov+2012)

Lack of substructure within the cores identified with *Herschel* in nearby (d < 450 pc) clouds

➢ Progenitors of individual stars or binary systems, but not "clusters"

Herschel **~ 15" resolution at λ ~ 200 μm ⬄ ~ 0.02 pc < Jeans length @ d = 300 pc**

Per-Bolo 58: Herschel/SPIRE 250 μm   Perbo 58: CARMA/SZA interferometer 3mm

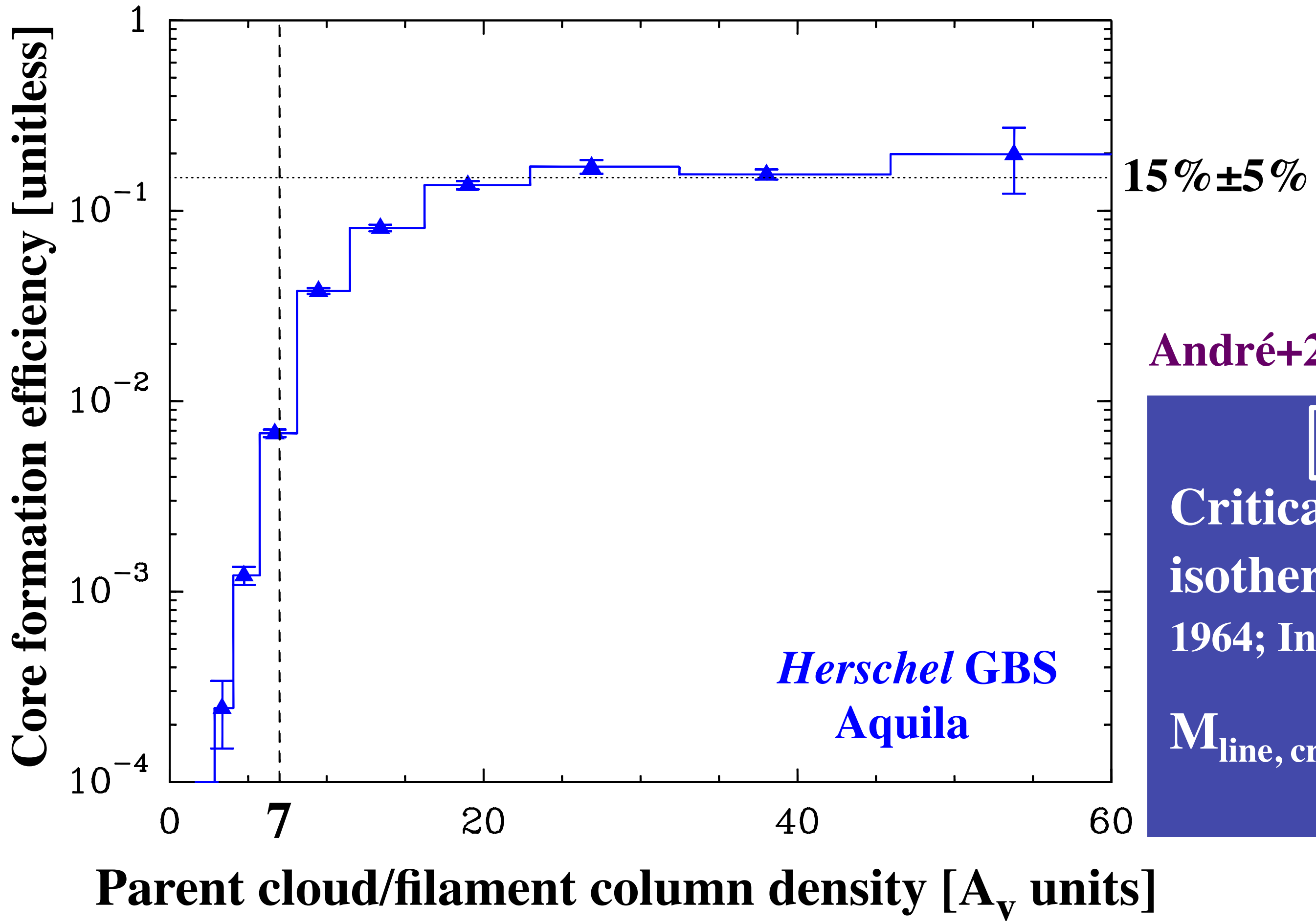


Sadavoy+2014; Pezzuto+2019, in prep.

Schnee+2010 - see also Dunham+2016; Sadavoy & Stahler 2017; Maury+2010, 2019

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

Prestellar CFE as a function of background A_V



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

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

André+2010; Könyves+2015, 2019

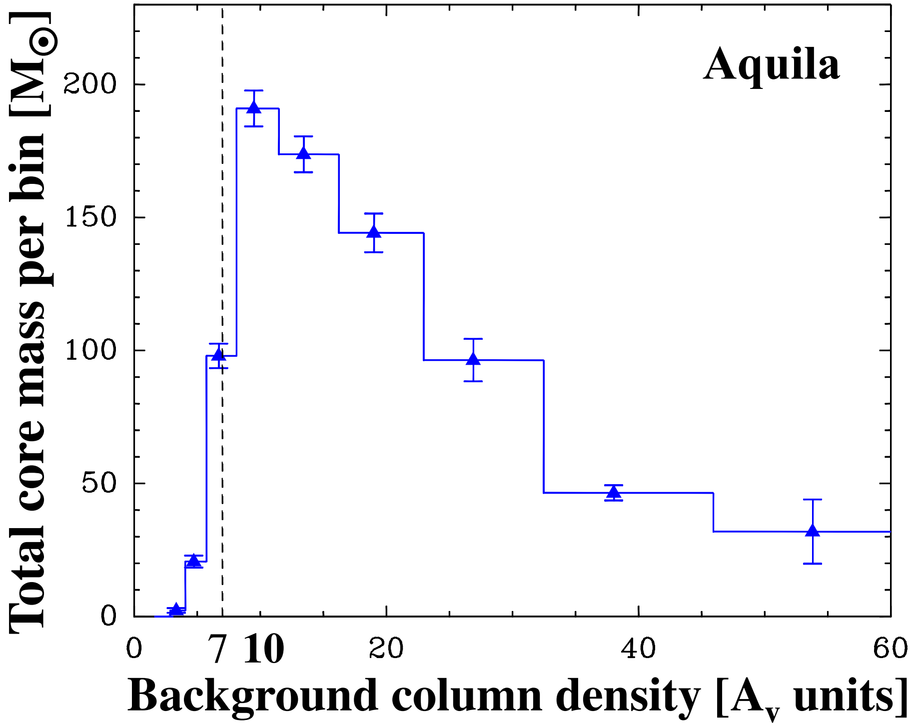
Interpretation:

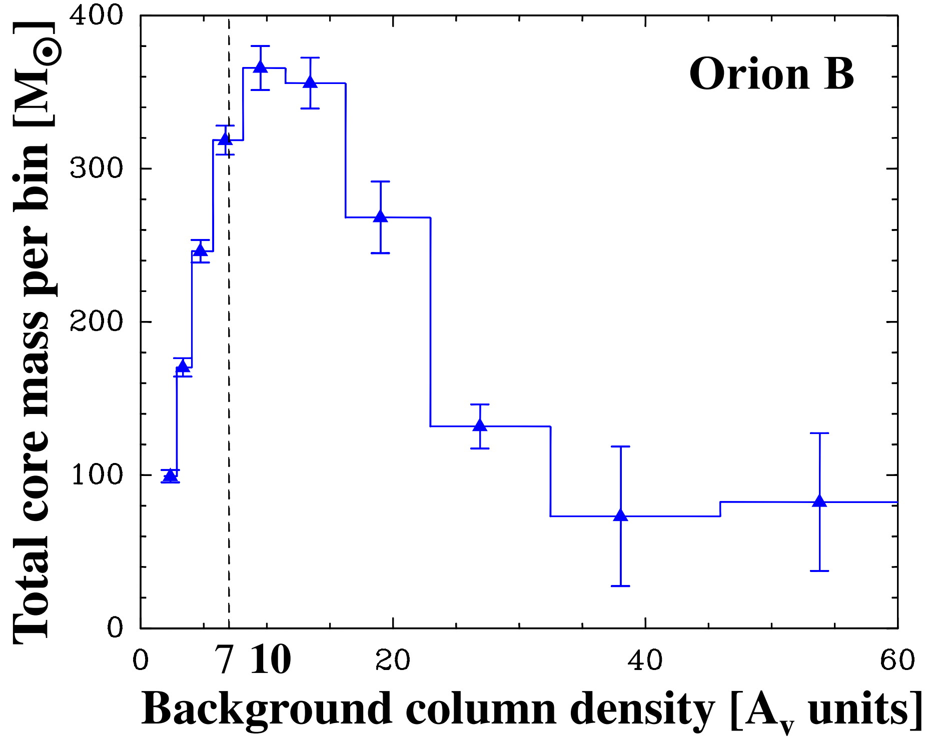
Critical M/L of nearly isothermal cylinders (Ostriker 1964; Inutsuka & Miyama 1997)

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

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

Total prestellar core mass as a function of background A_V



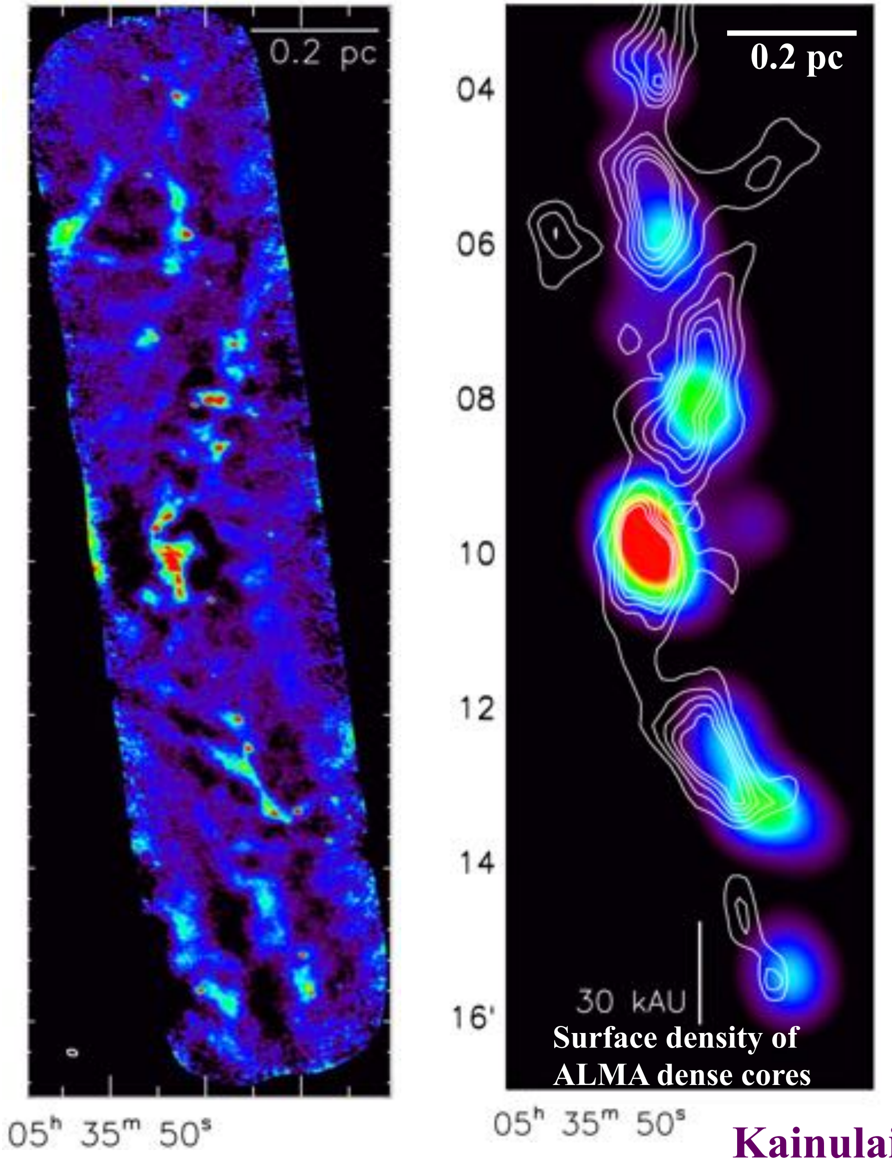


Sharp transition around a fiducial value
$A_v \sim 7 \Leftrightarrow \Sigma \sim 150\ M_\odot/pc^2$
$\Leftrightarrow M/L \sim 15\ M_\odot/pc$

Könyves+2019, A&A, submitted

Fragmentation of filaments – Core spacing

ALMA 3mm mosaic of the Orion A ISF



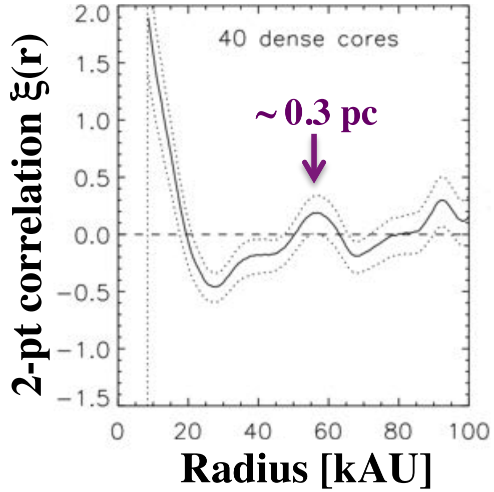
Kainulainen+2017

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

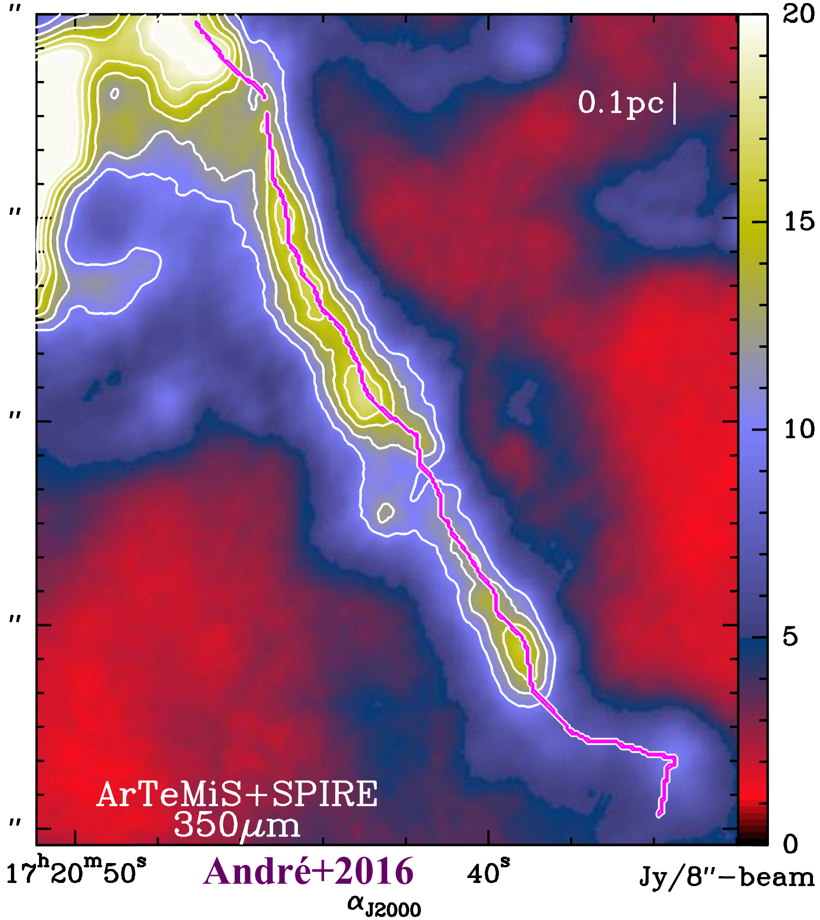
Two-point correlation function of ALMA dense cores



Evidence of two fragmentation modes in filaments:

Example of the massive filament in NGC6334 (M/L ~ 1000 $M_{\odot}$/pc; W = 0.15 +- 0.05 pc)

APEX/ArTéMiS 350 µm image of the NGC6334 filament (M/L ~ 1000 $M_{\odot}$/pc)

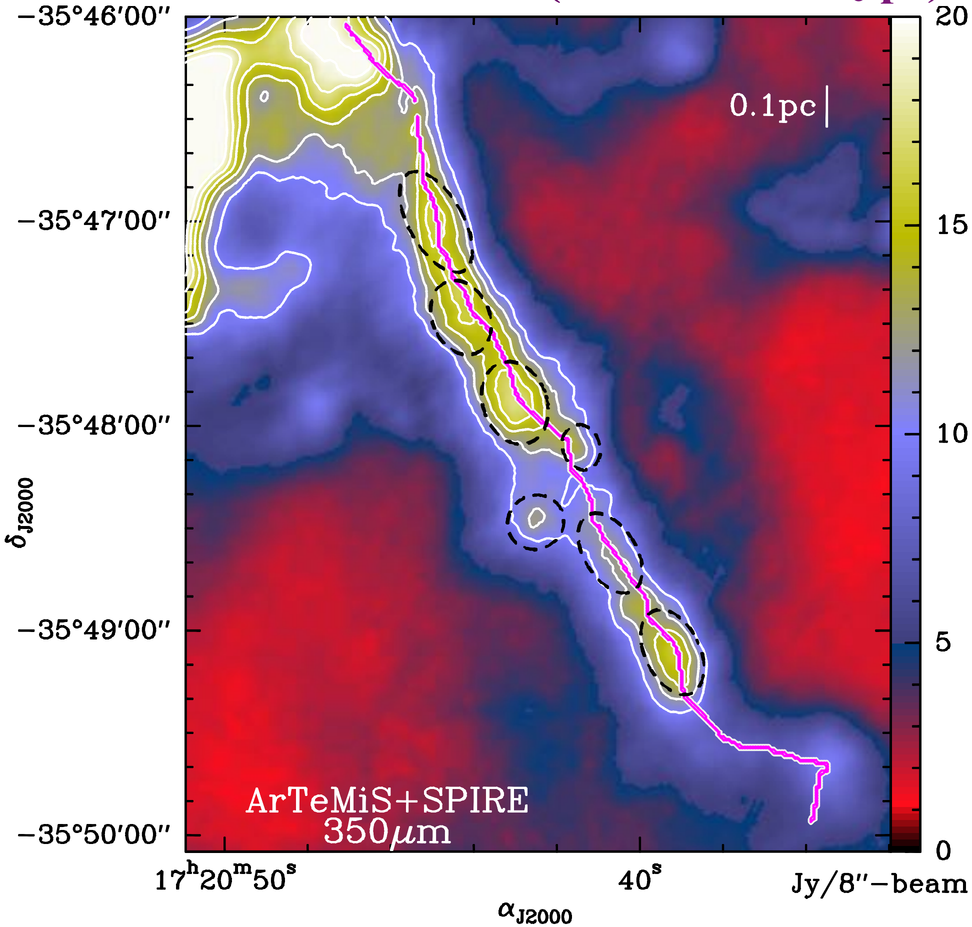


André+2016

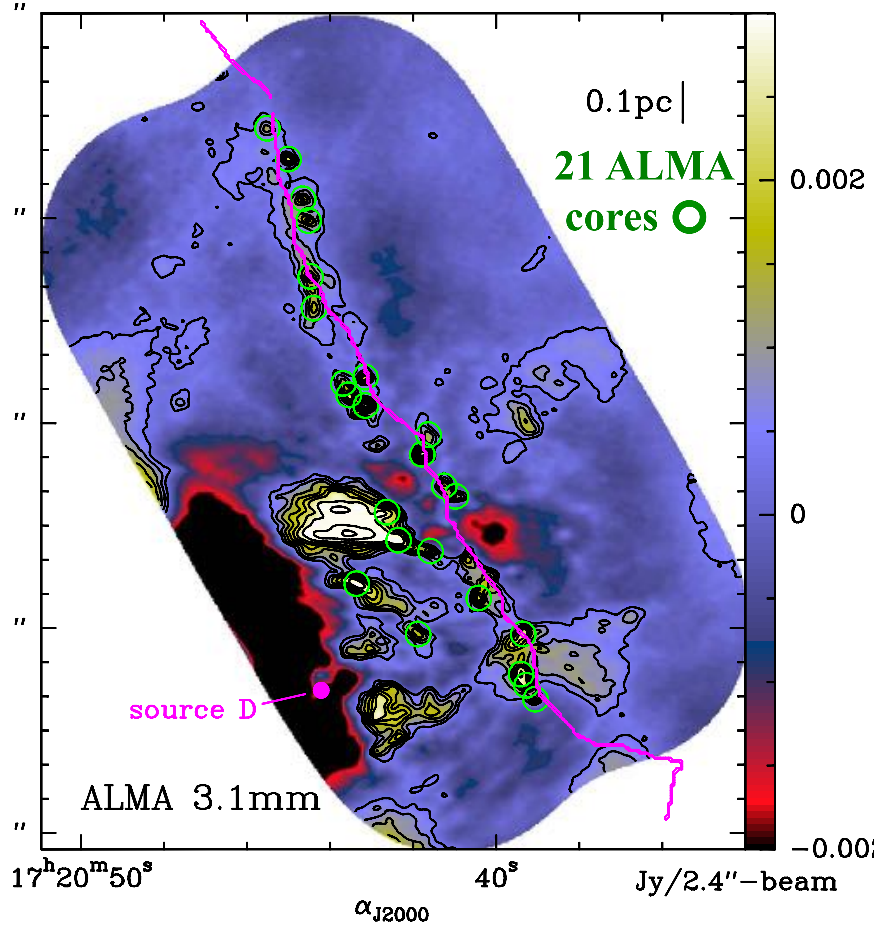
Evidence of two fragmentation modes in filaments:

Recent identification of groups of compact (< 0.03pc) ALMA 3mm/N_2H^+ cores associated with ArTéMiS clumps within the massive NGC6334 filament

APEX/ArTéMiS 350 μm image of the NGC6334 filament (M/L ~ 1000 $M_\odot$/pc)



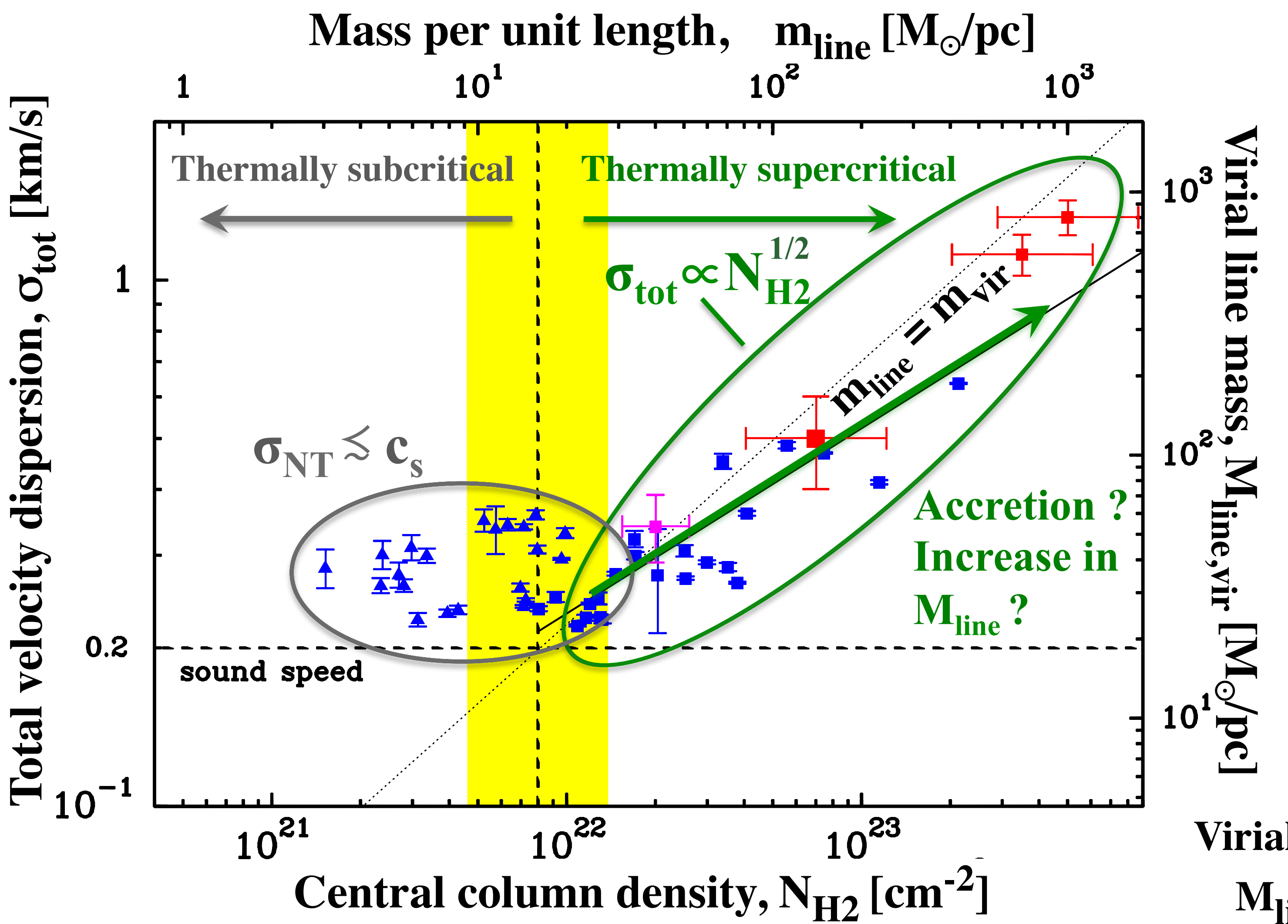
ALMA 3mm mosaic of the NGC6334 filament



- **Separation between groups: ~0.2-0.3 pc (~ ×4 fil. width?)**
- **Separation between cores: ~0.03-0.1 pc (~ Jeans)**

Shimajiri+2019, A&A, submitted

Thermally supercritical filaments are "virialized" accreting systems with $M_{line} \sim M_{line,vir}$



➔ Effective Jeans length $\lambda_{eff} \sim \sigma_{tot}^2 / (G\Sigma)$ is constant ~ 0.05-0.1 pc

➔ Effective Jeans mass $M_{BE,\,eff} \propto \sigma_{tot}^2 \propto M_{line} \propto B_{eq}$

Virial mass unit length:

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

(Fiege & Pudritz 2000)

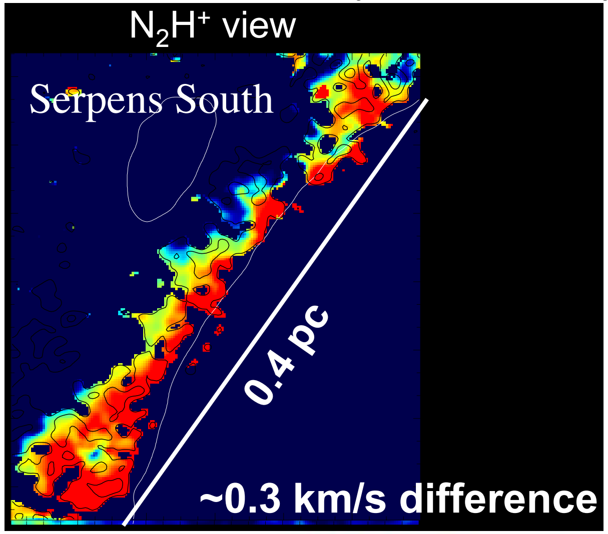
Arzoumanian+2013

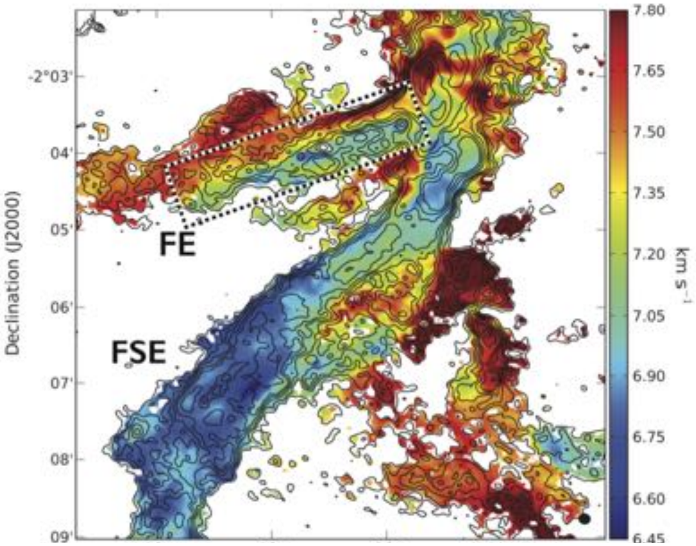
(based on IRAM 30m observations)

See also toy accretion model by Hennebelle & André 2013

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

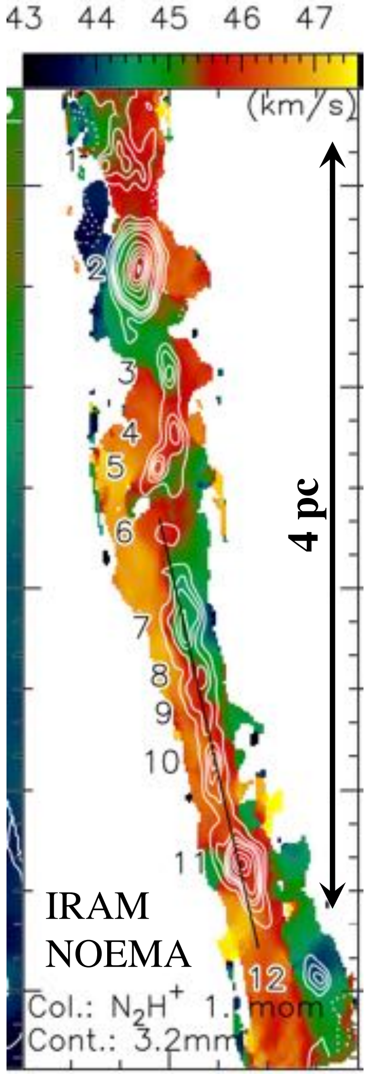
CARMA "CLASSy" SF Survey

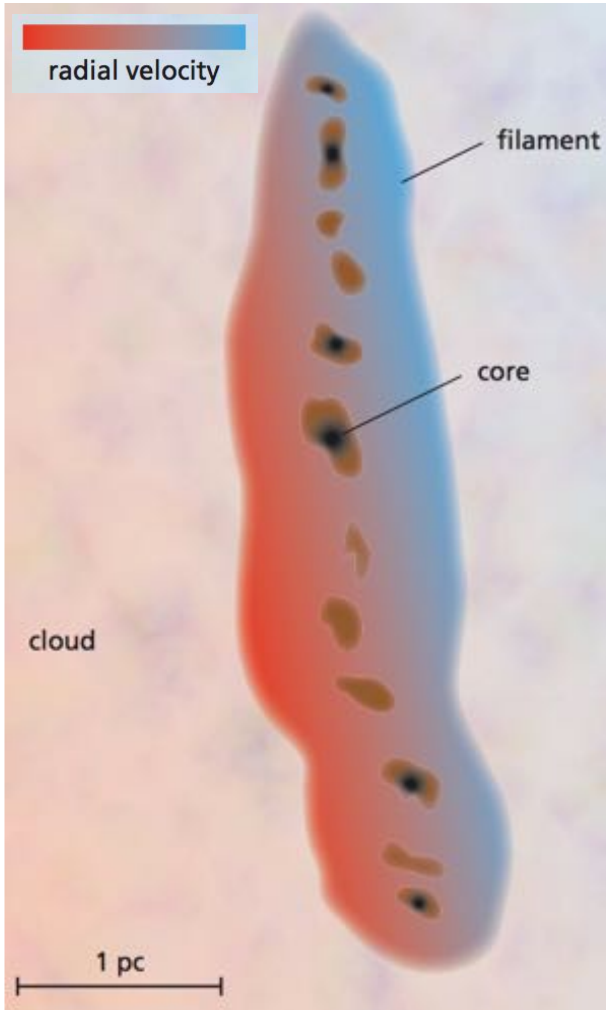




Fernandez-Lopez+2014; Dhabal, Mundy+2018
see also H. Kirk+2013 for Serp-S

Transverse N_2H^+(1-0) velocity gradient across massive IRDC 18223

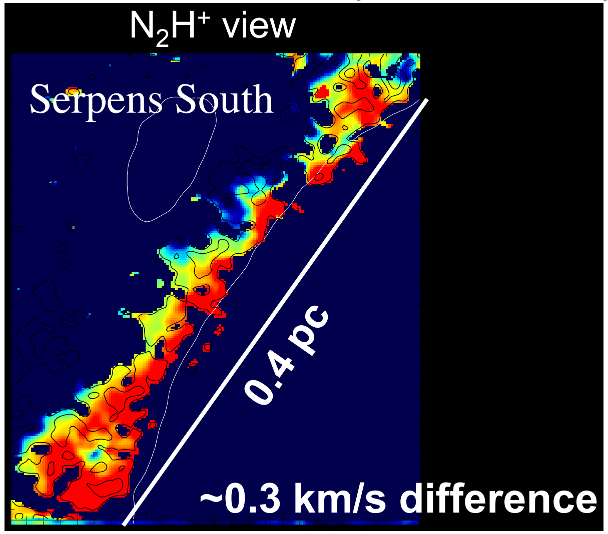


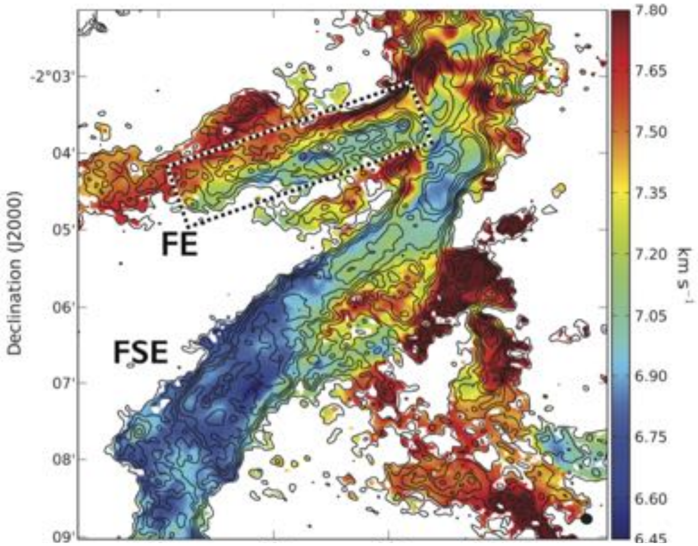


Beuther, Ragan+2015

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

CARMA "CLASSy" SF Survey

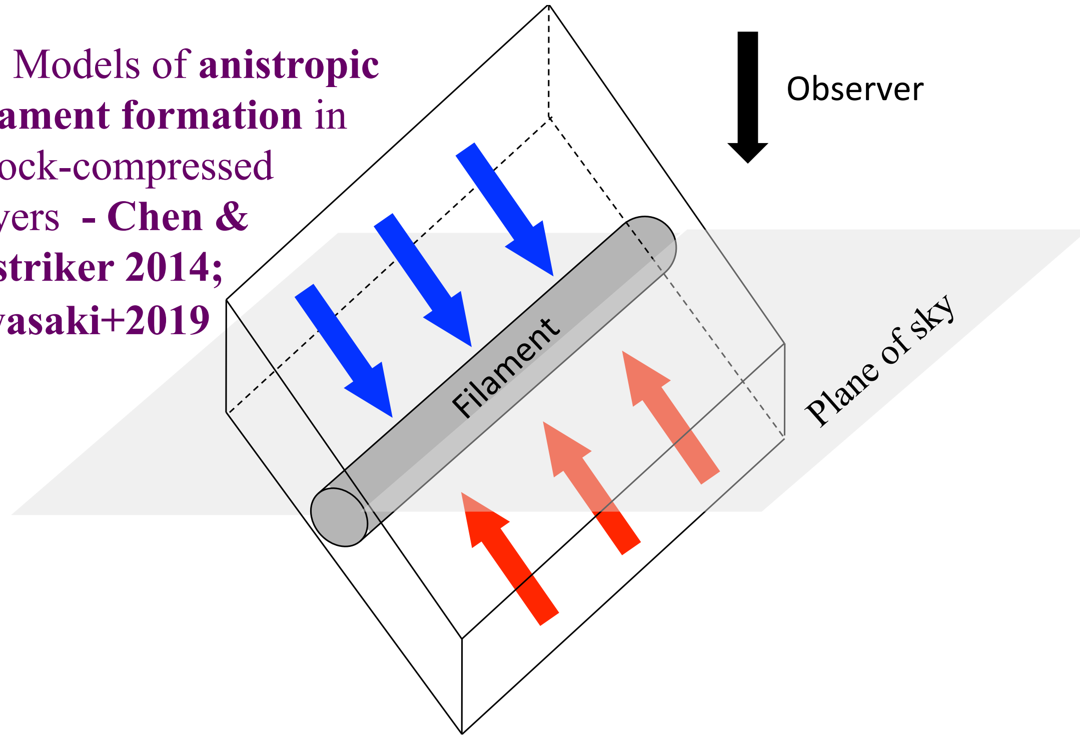


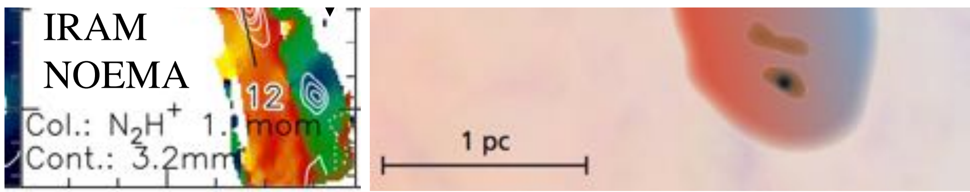


Fernandez-Lopez+2014; Dhabal, Mundy+2018
see also H. Kirk+2013 for Serp-S

Coherent motions inside sheet-like structure?

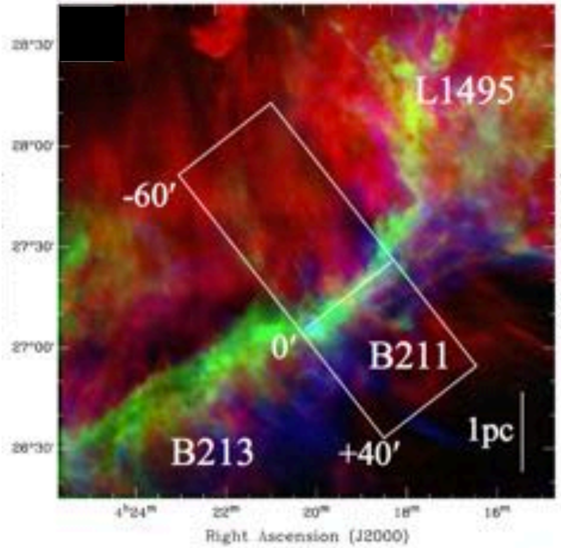
cf. Models of **anistropic filament formation** in shock-compressed layers **- Chen & Ostriker 2014; Iwasaki+2019**



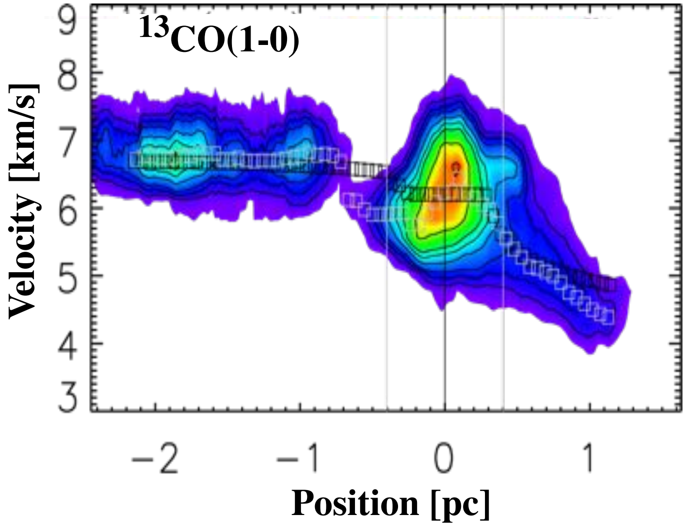


Simple modeling of the CO/*Herschel* data around the Taurus/B211 filament consistent with accretion in a sheet/shell

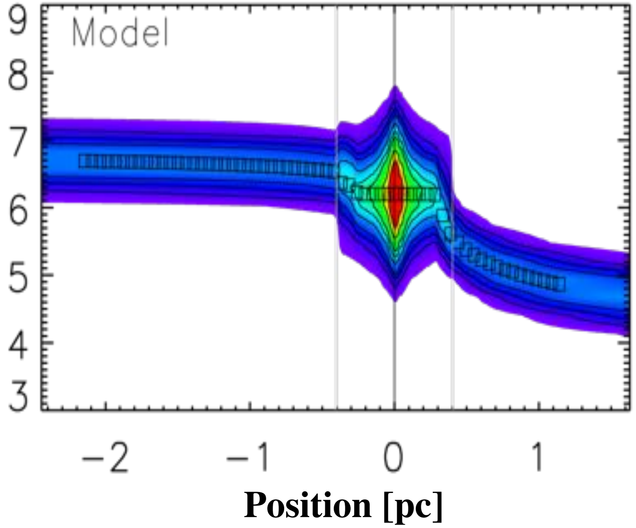
CO emission around B211

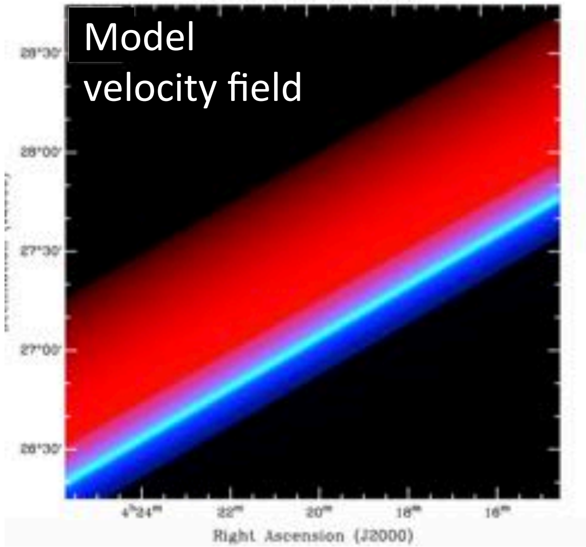


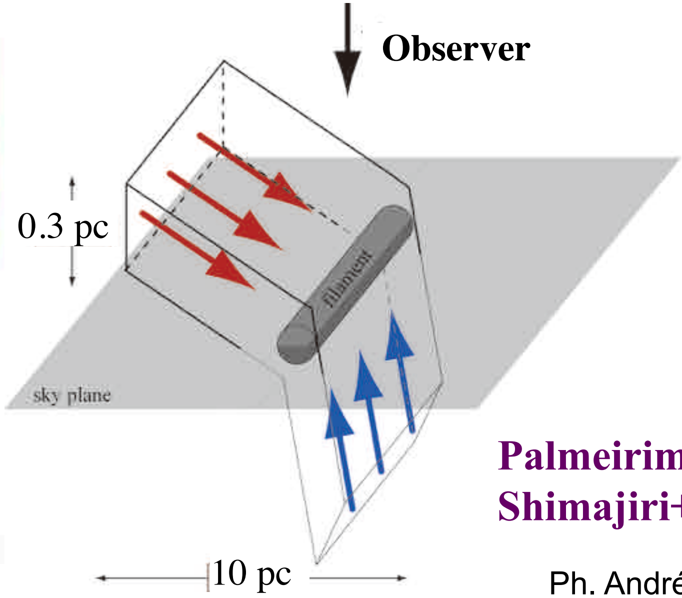
Obs. Position-Velocity diagram

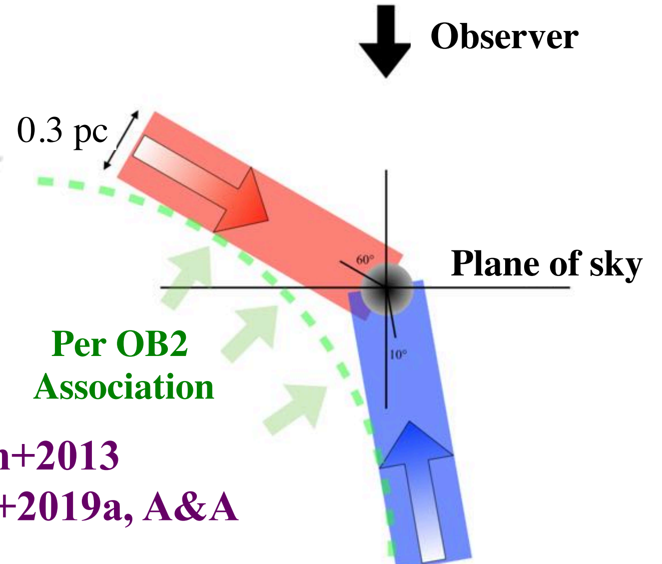


Model Pos.-Velocity diagram





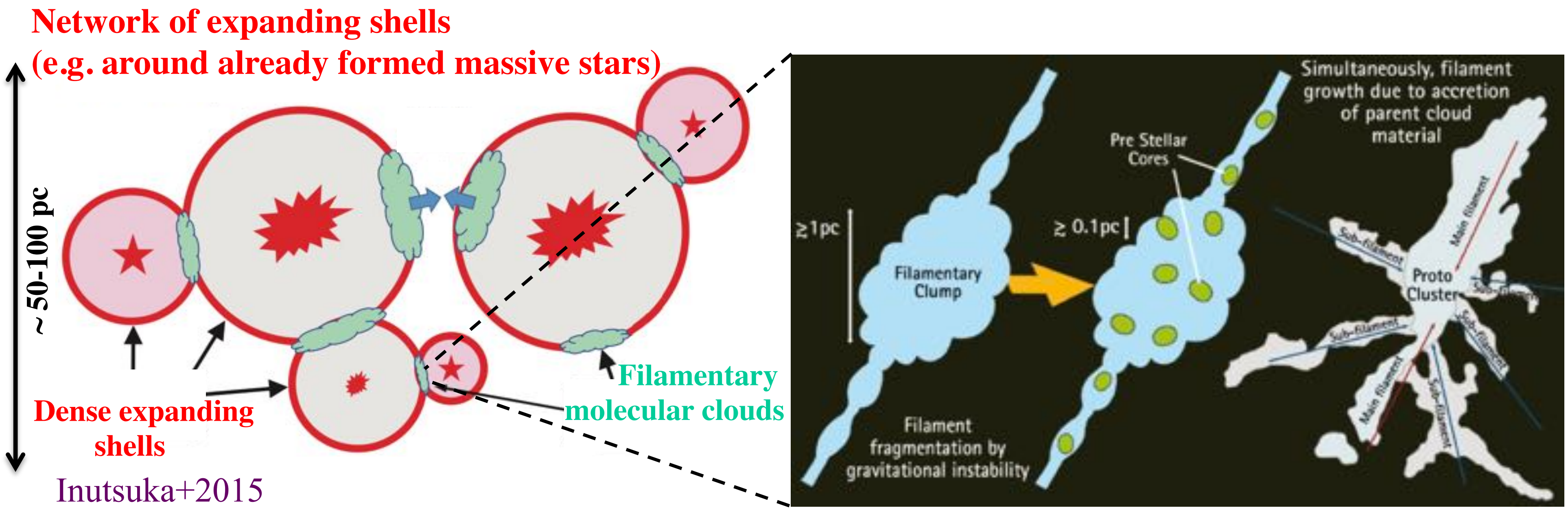




Palmeirim+2013
Shimajiri+2019a, A&A

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

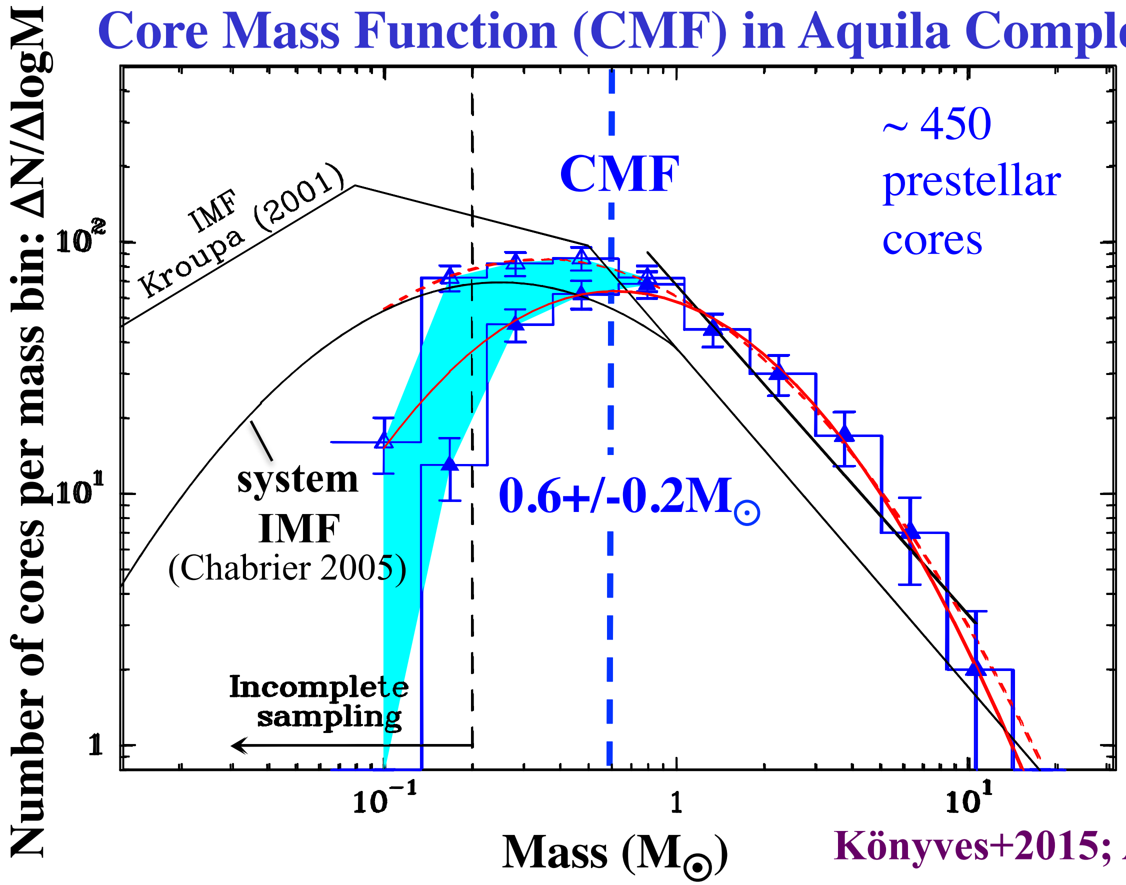
Schneider & Elmegreen 1979; Larson 1985; Nagasawa 1987; Inutsuka & Miyama 1997; Myers 2009 …
Protostars & Planets VI chapter (André, Di Francesco, Ward-Thompson, Inutsuka, Pudritz, Pineda 2014)



Inutsuka+2015

1) **Large-scale MHD compressive flows associated with multiple expanding shells create filamentary molecular clouds with ~ 0.1 pc-wide filaments**
2) **Gravity fragments the densest molecular filaments into prestellar cores close to or above** $M_{line,crit} \sim 16\ M_\odot\ pc^{-1}$
3) **Prestellar cores collapse to protostars/YSOs**

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

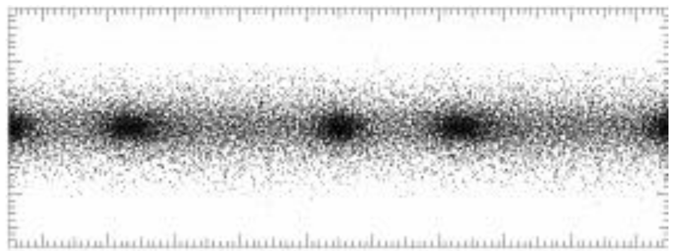


Könyves+2015; André+2014

Jeans mass:

$M_{Jeans} \sim 0.5\, M_\odot \times (T/10\, K)^2$

$\times (\Sigma_{crit}/160\, M_\odot pc^{-2})^{-1}$

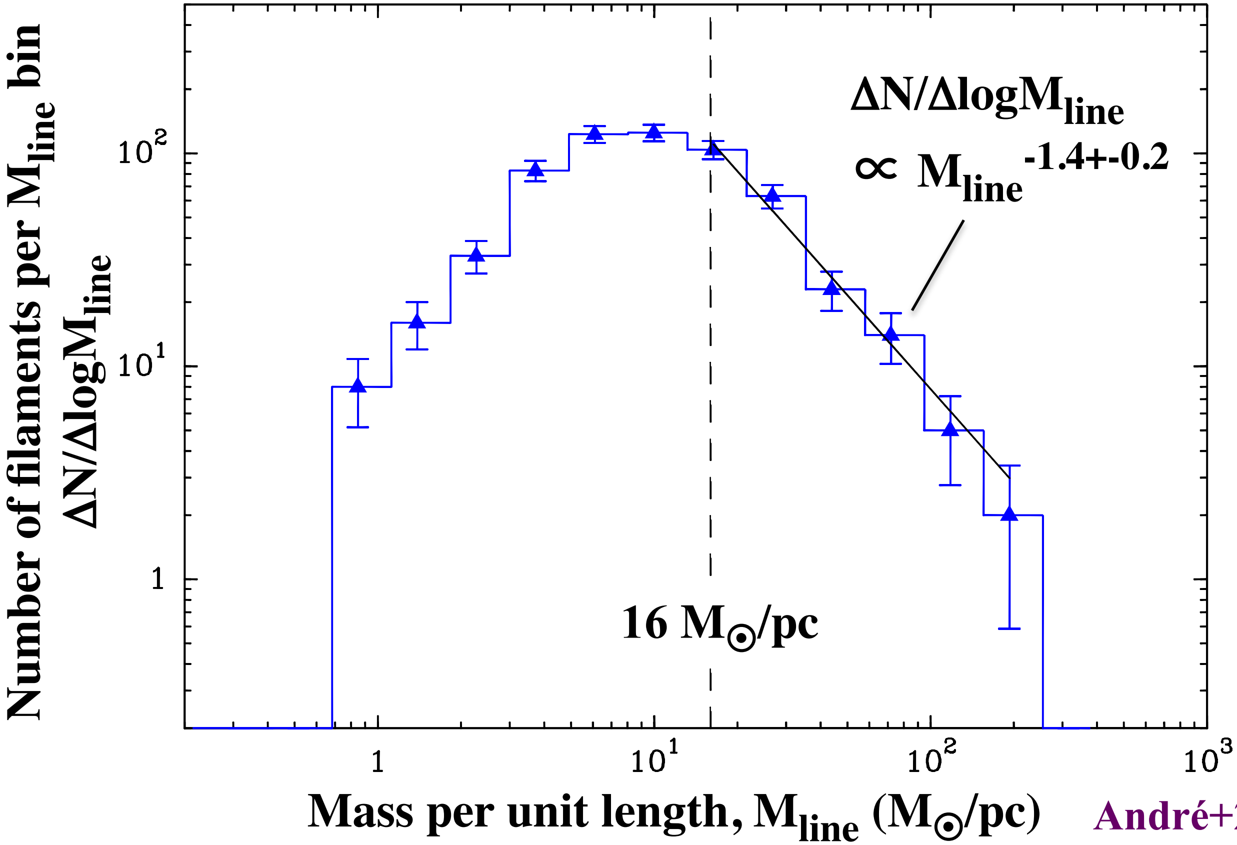


Inutsuka & Miyama 1997

- 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

Determination of the Filament Line Mass Function (FLMF)

Distribution of line masses for HGBS filaments



André+2019, A&A, submitted

Filament sample: 599 nearby filaments in IC5146, Orion B, Aquila, Polaris, Ophiuchus, Taurus, Pipe, Musca (Arzoumanian et al. 2019, A&A, 621, A42)

Complete for supercritical filaments (M_{line} > 16 $M_\odot$/pc) according to tests

Salpeter-like distribution of characteristic core masses from distribution of filament line masses

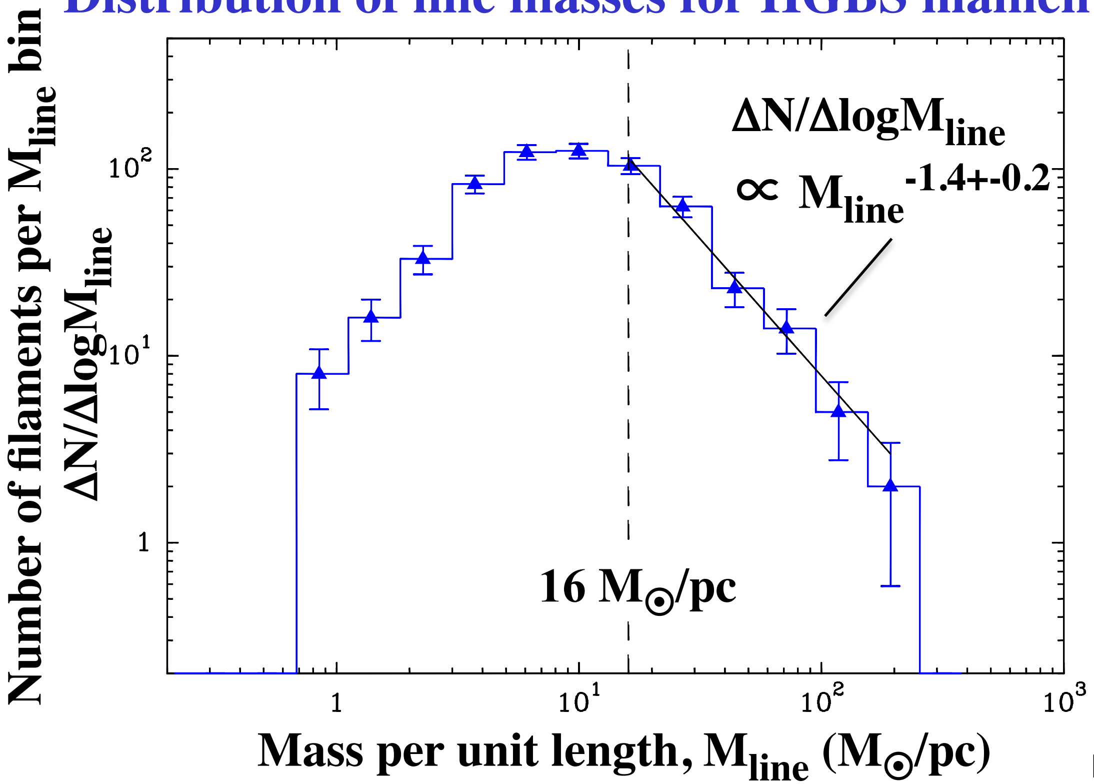
Local effective Jeans mass in a thermally supercritical filament:

Given filament properties (cf. Arzoumanian+2011, 2013, 2019):

$$M_{line} \sim \Sigma_{fil} \times W_{fil} \sim M_{line,\,vir} \equiv 2c_{s,eff}^2/G \text{ with } W_{fil} \sim 0.1 \text{ pc}$$

$$M_{Jeans} \sim M_{BE} \sim 1.3\, c_{s,eff}^4/(G^2\Sigma_{fil}) \propto \Sigma_{fil} \propto M_{line}$$

Distribution of line masses for HGBS filaments



André+2019, A&A, submitted
See also André+2014 PPVI

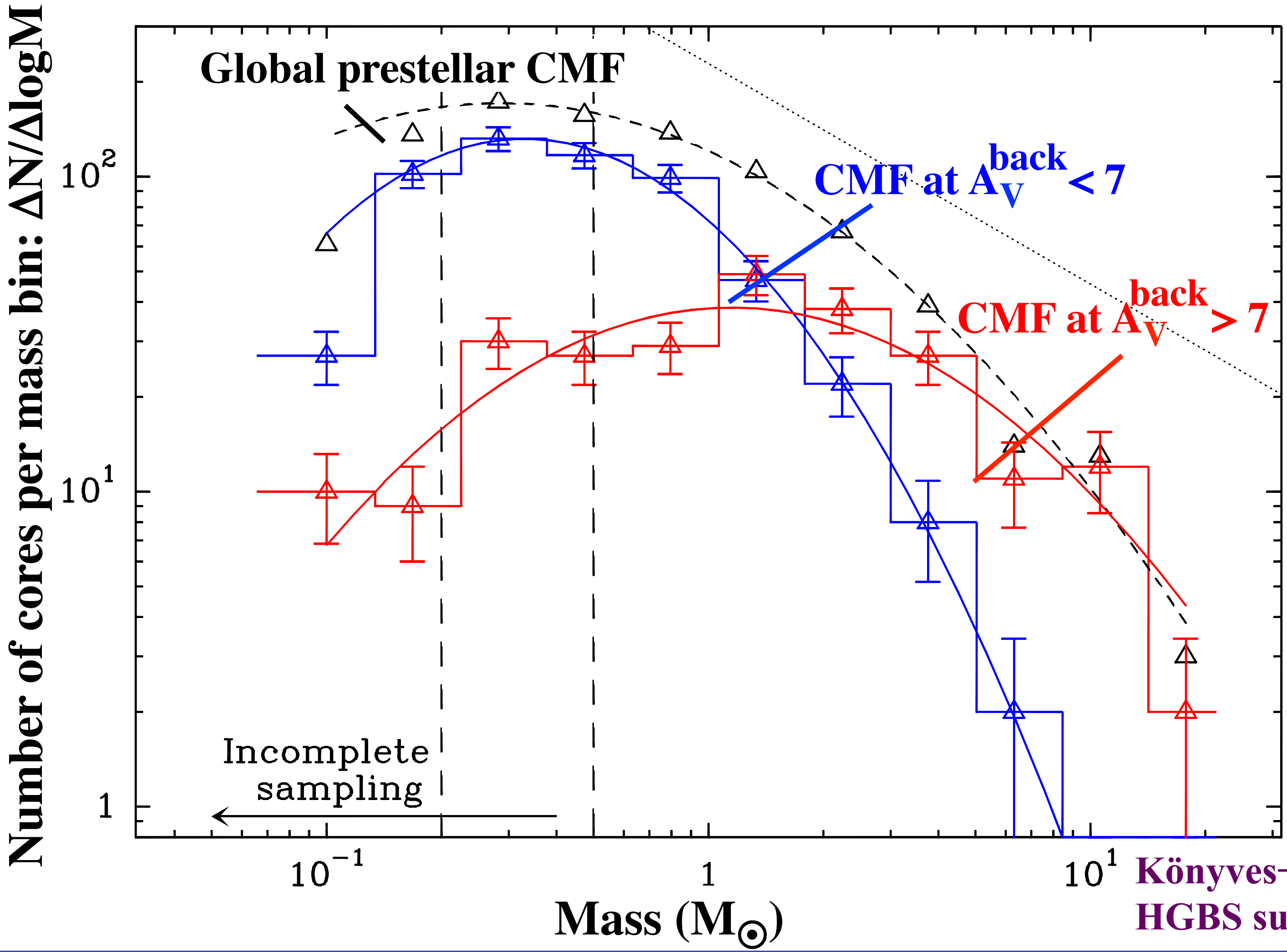
$$\Rightarrow \quad \Delta N/\Delta \log M_{BE} \propto M_{BE}^{-1.4+-0.2}$$

(Salpeter index: -1.35)

Full CMF/IMF results from the convolution of the distribution of filament line masses by the CMF in individual filaments
(Y.-N. Lee, Hennebelle, Chabrier 2017)

Dependence of the prestellar CMF on background cloud (column) density

(OrionB)



Könyves+2019
HGBS survey results

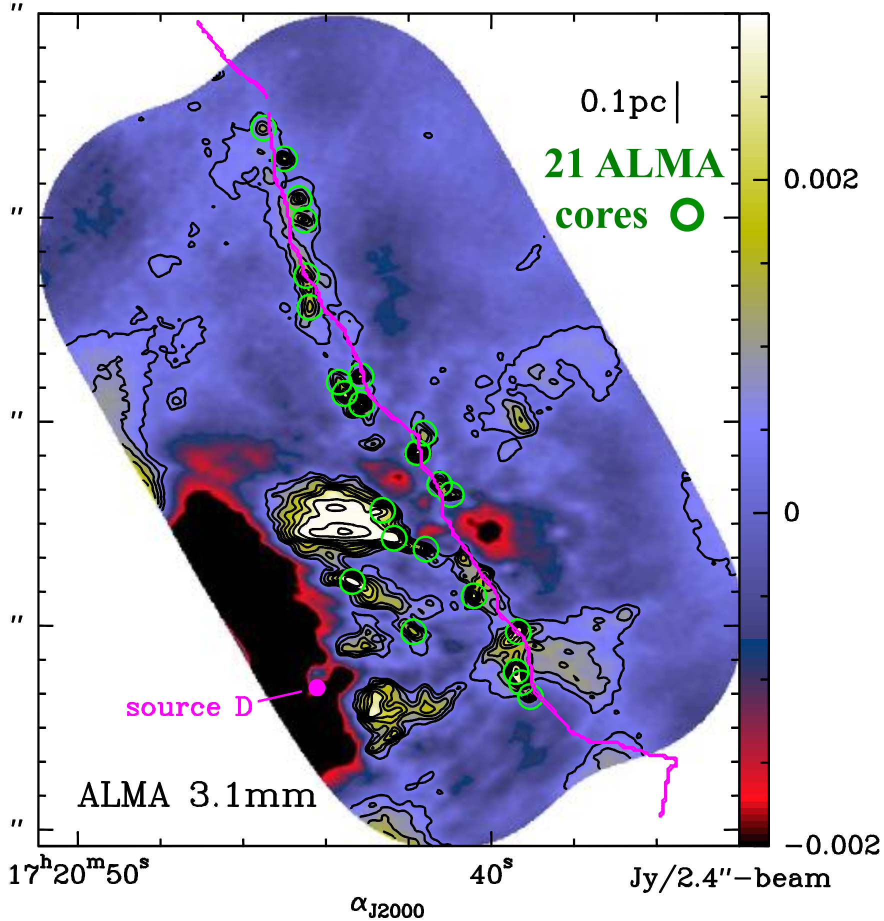
➢ **Broader CMF and more massive cores at higher background column densities, i.e. , in higher M_{line} filaments**

Tentative determination of the CMF resulting from a single (massive) filament: NGC6334 (M/L ~ 1000 $M_\odot$/pc)

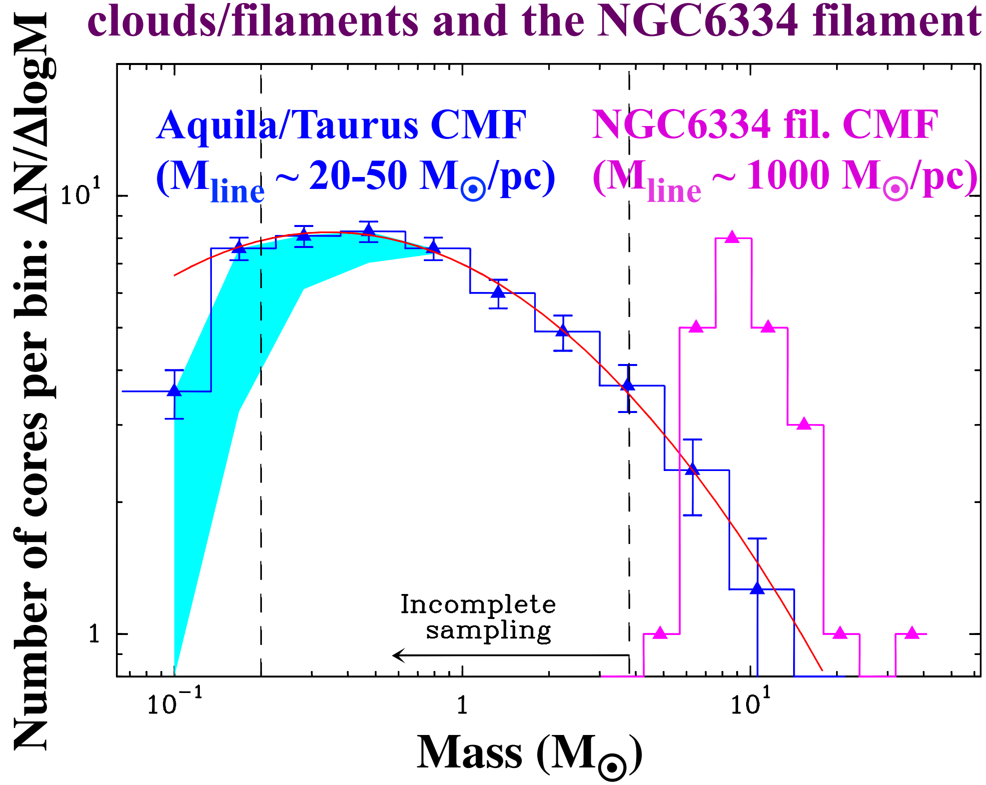
Detection of 21 compact (< 0.03pc) 3mm continuum/N_2H^+ cores with ALMA

➢ **Higher M_{line} filaments may form more massive cores**

ALMA 3mm mosaic of the NGC6334 filament (M/L ~ 1000 $M_\odot$/pc)



Comparison of the CMFs observed in nearby clouds/filaments and the NGC6334 filament



Shimajiri+2019, A&A, submitted

Summary: A filament paradigm for star formation and the IMF?

- *Herschel* results support a **filament paradigm for star formation and the IMF** although many issues remain open and/or strongly debated

- **Filament fragmentation** appears to produce the peak of the prestellar CMF and likely **accounts for the « base » of the IMF**

- **Salpeter** power law **IMF** may be **inherited from** the observed **Salpeter-like distribution of supercritical filament masses per unit length** (due to accretion ?)

High-resolution polarimetric imaging at far-IR/submm λs from space **with SPICA** can lead to **decisive progress in** our understanding of **the role of magnetic fields** **(See SPICA-POL White Paper: arXiv:1905.03520)**