Filamentary star formation and the role of magnetic fields
From *Herschel/Planck* to (SPICA &) Millimetron

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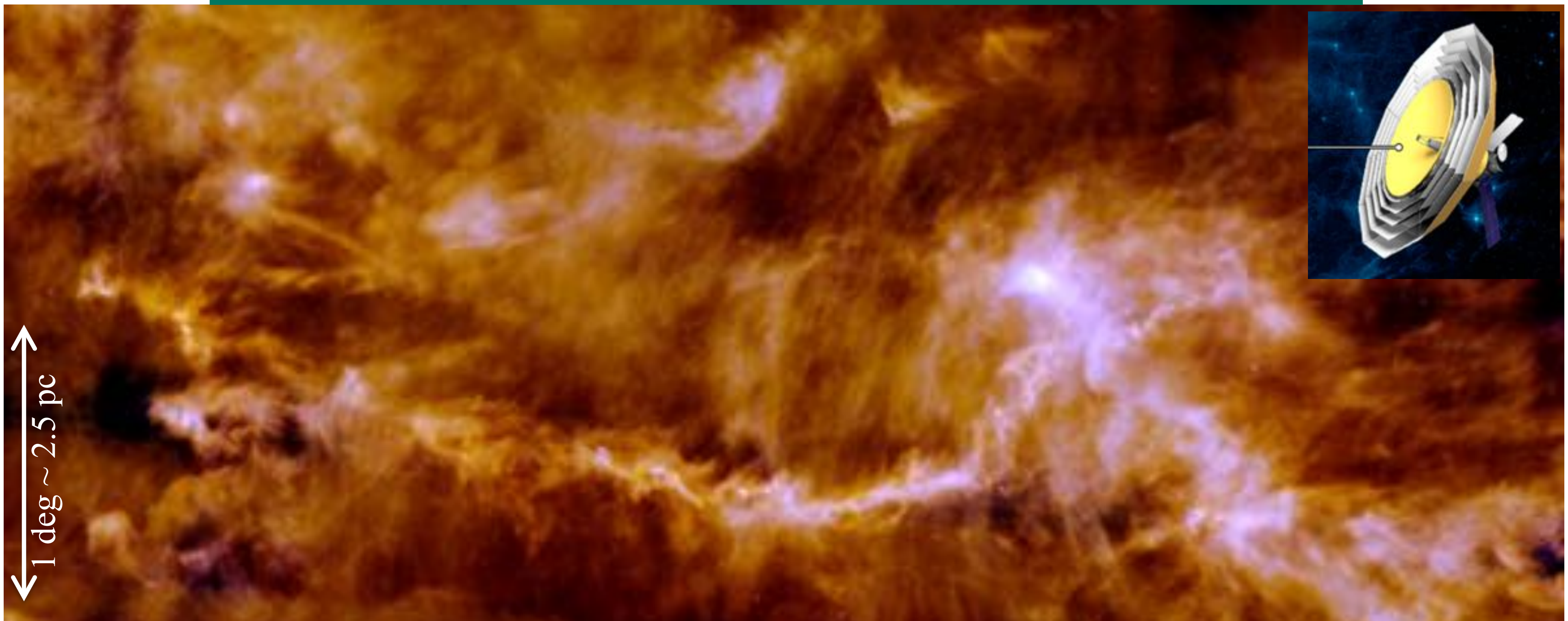


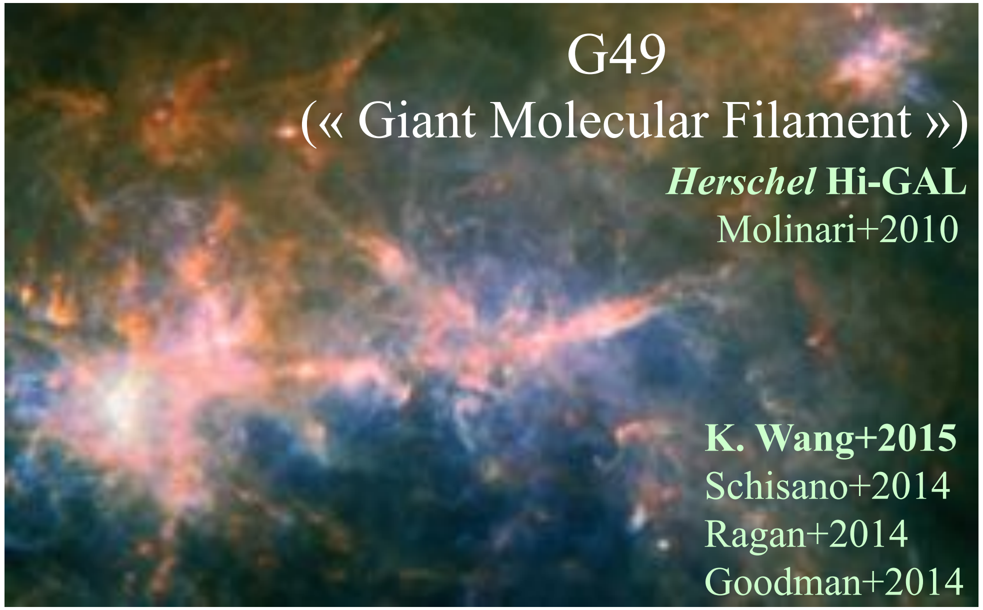
Herschel GBS 160/250/500 µm composite image of Taurus B213/B213 (Palmeirim+2013 - ESA)

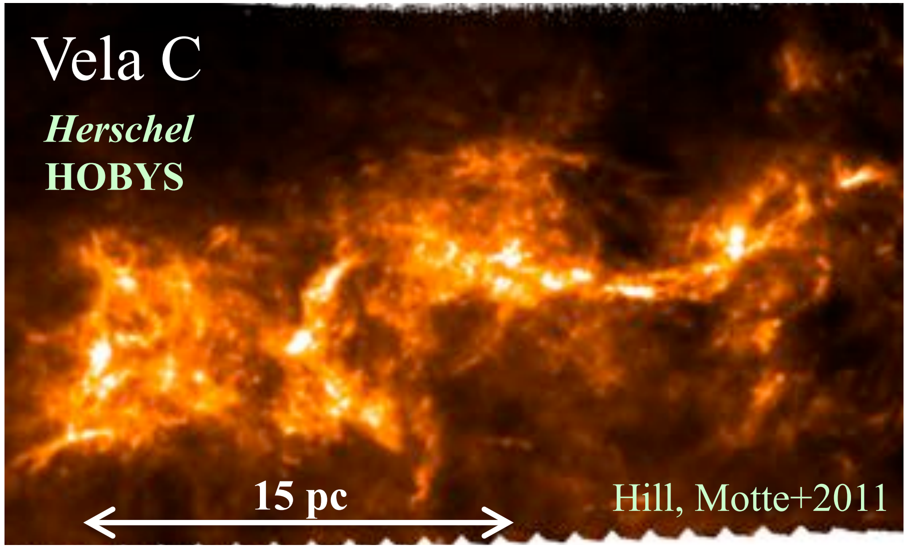
Filamentary star formation and the role of B fields

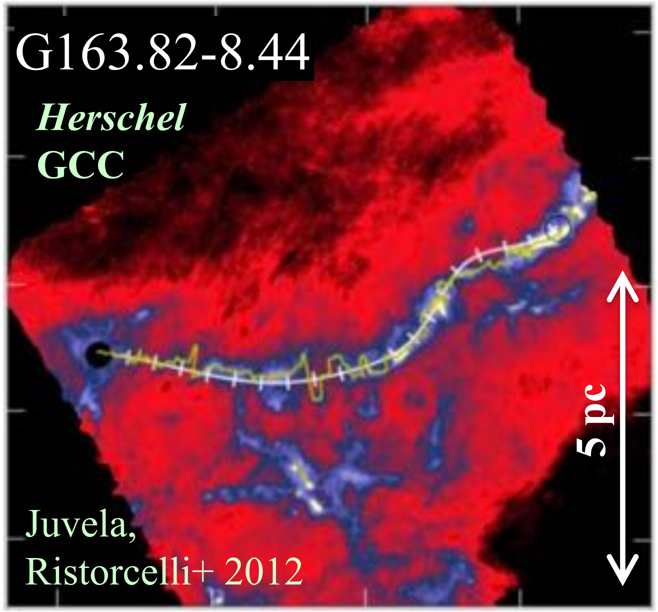
- **Fundamental Problem(s):** Initial conditions of star (& planet) formation
  (What regulates the star formation efficiency? Origin of the IMF?)

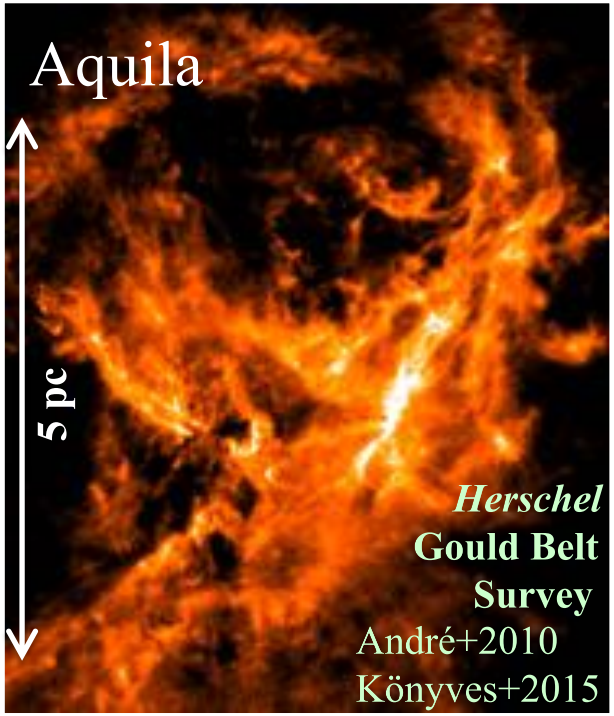
- **Outline:** • Motivation: *Herschel* and *Planck* results on ISM filaments
  → A filament paradigm for star formation
  - Role of B fields in the formation/evolution of filaments?
  - Key advantages of Millimetron for this science topic

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



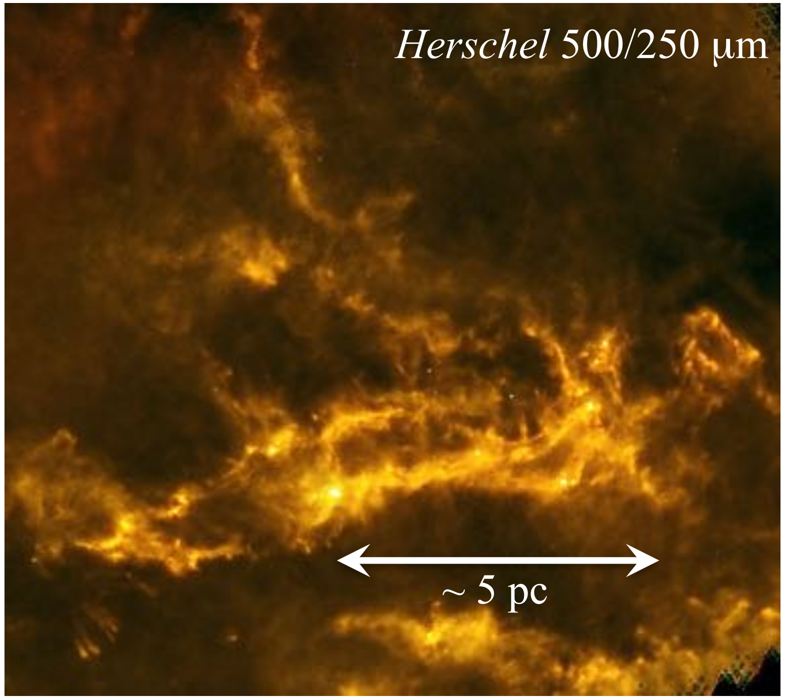




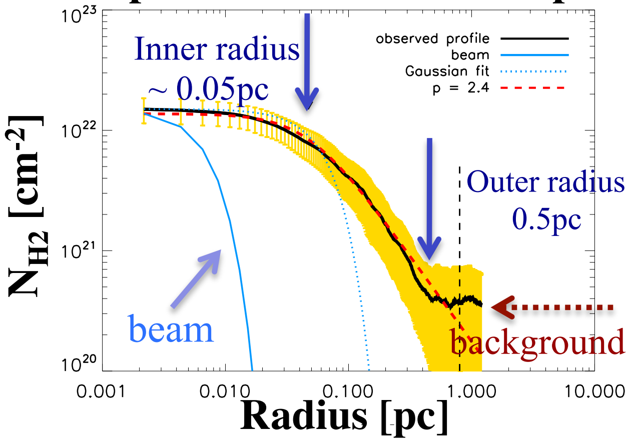


Nearby filaments have a common inner width ~ 0.1 pc

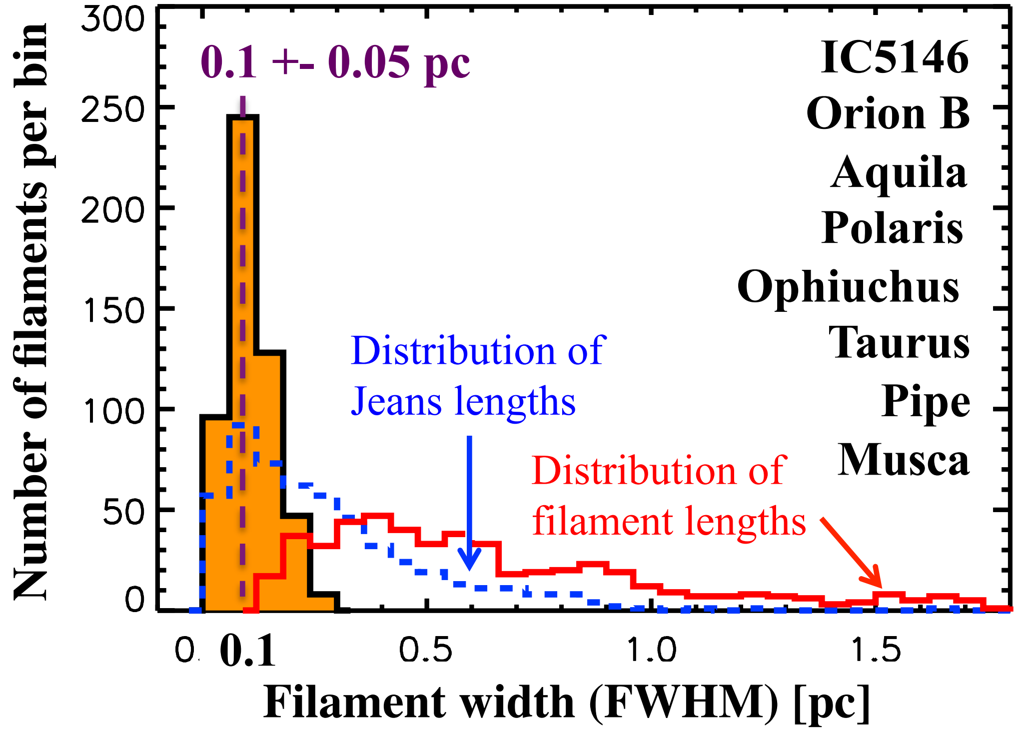
Network of filaments in IC5146



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 and caveats in Panopoulou+2017]

Possibly linked to magneto-sonic scale of turbulence?

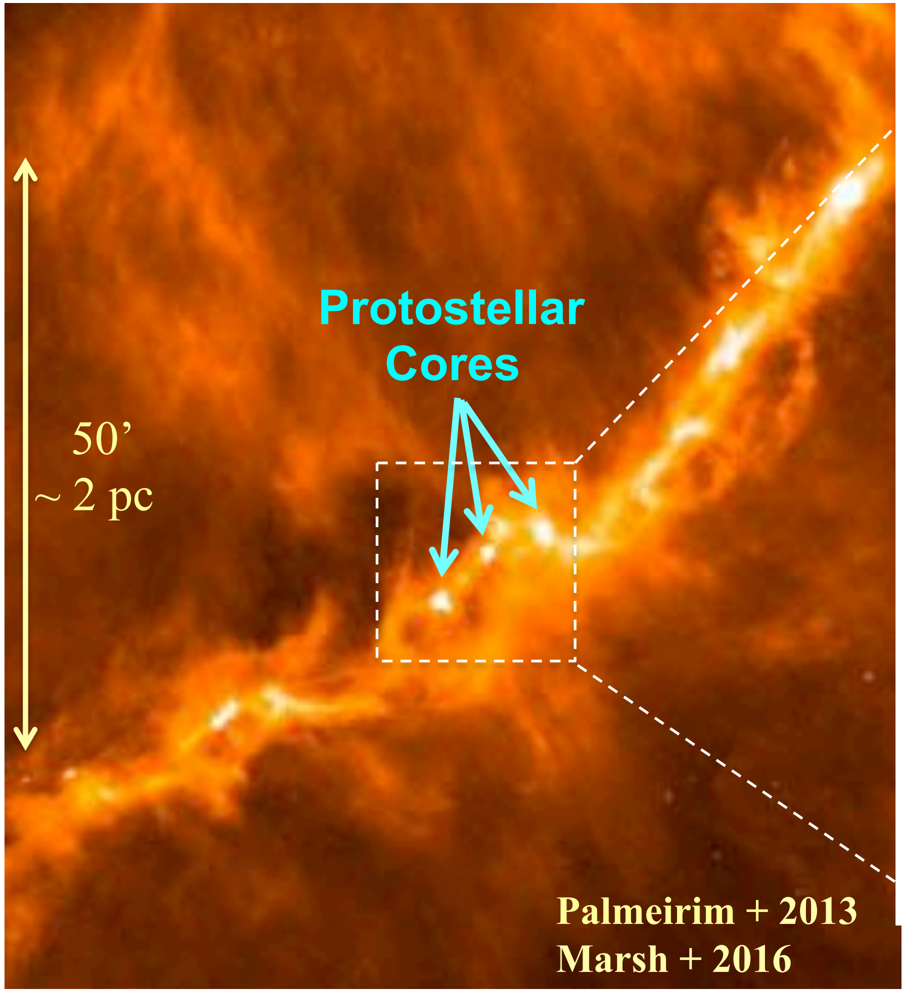
(cf. Padoan+2001; Federrath 2016)

Challenging for numerical simulations

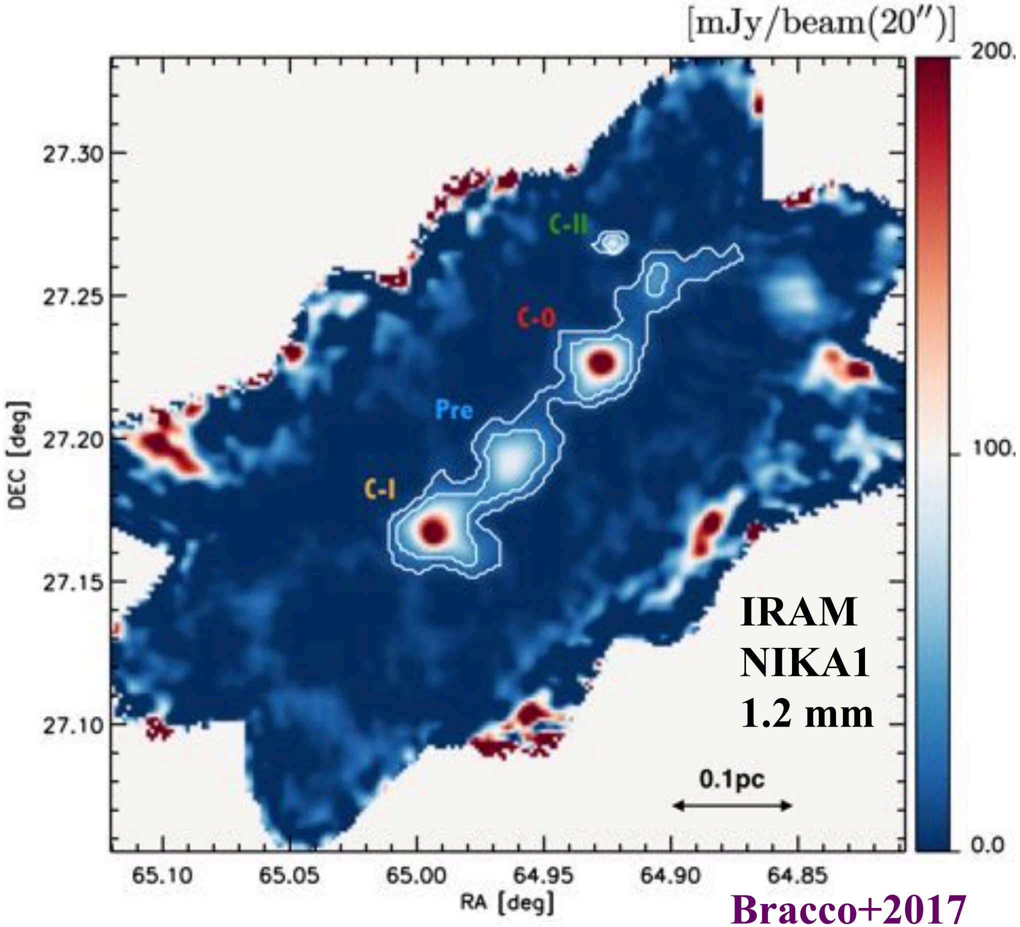
(cf. R. Smith+2014; Ntormousi+2016)

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

See Könyves+2015 (Aquila), 2019 (Orion B); Marsh+2016 (Taurus/L1495); Bresnahan+2018 (CrA), Ladjelate+2019 (Oph); Pezzuto+2019 (Perseus); Firorellino+2019 (Serpens) + Protostars & Planets VI chapter (André+2014)



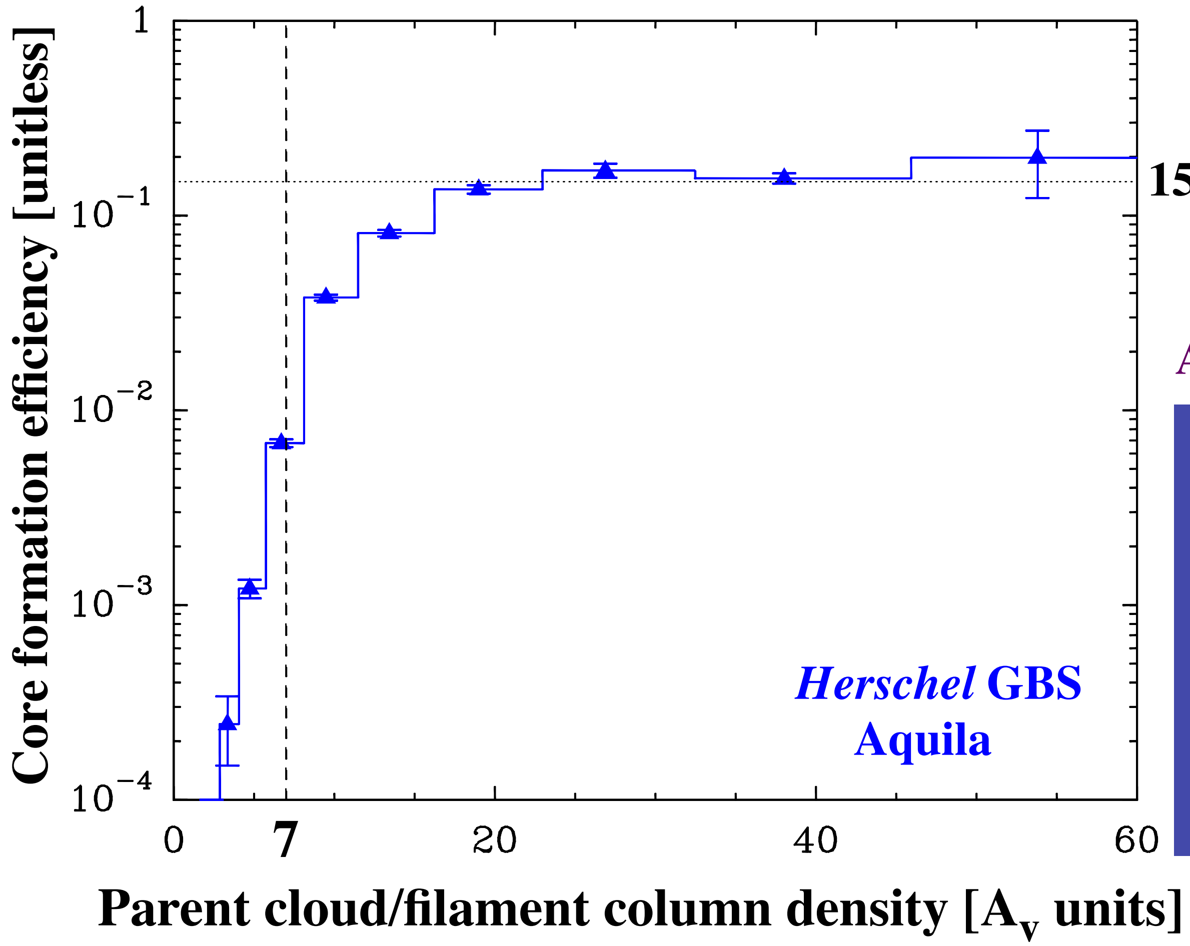
Taurus B211/3 – *Herschel* 250 µm



Bracco+2017

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

Prestellar CFE as a function of background A_V



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

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

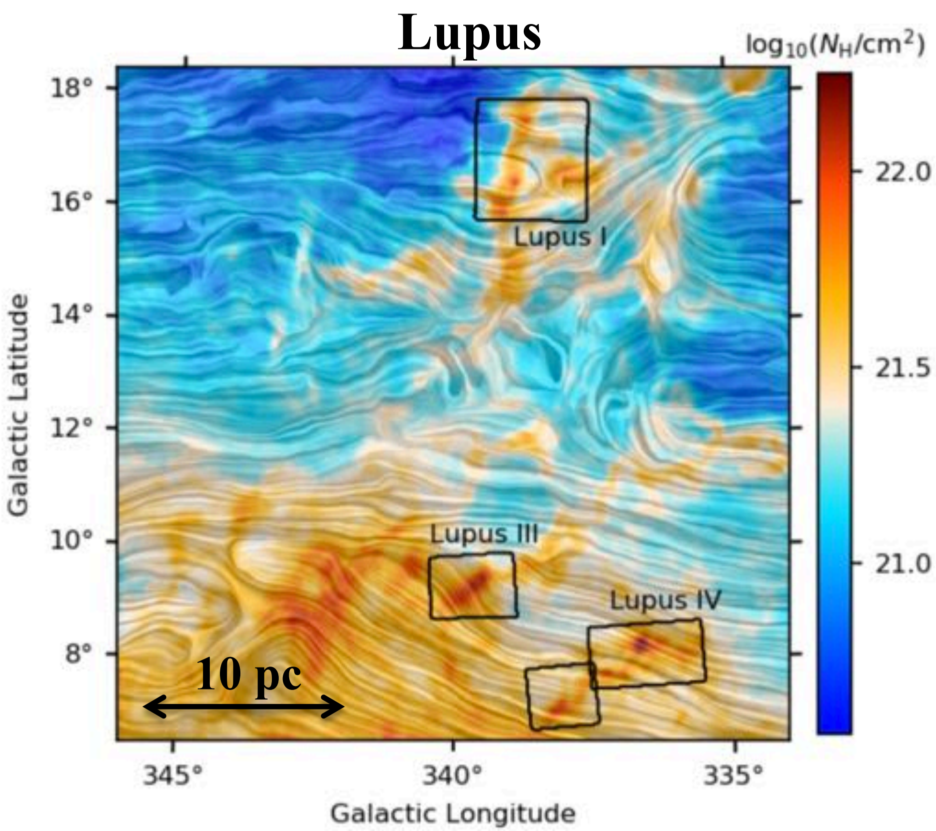
Interpretation:

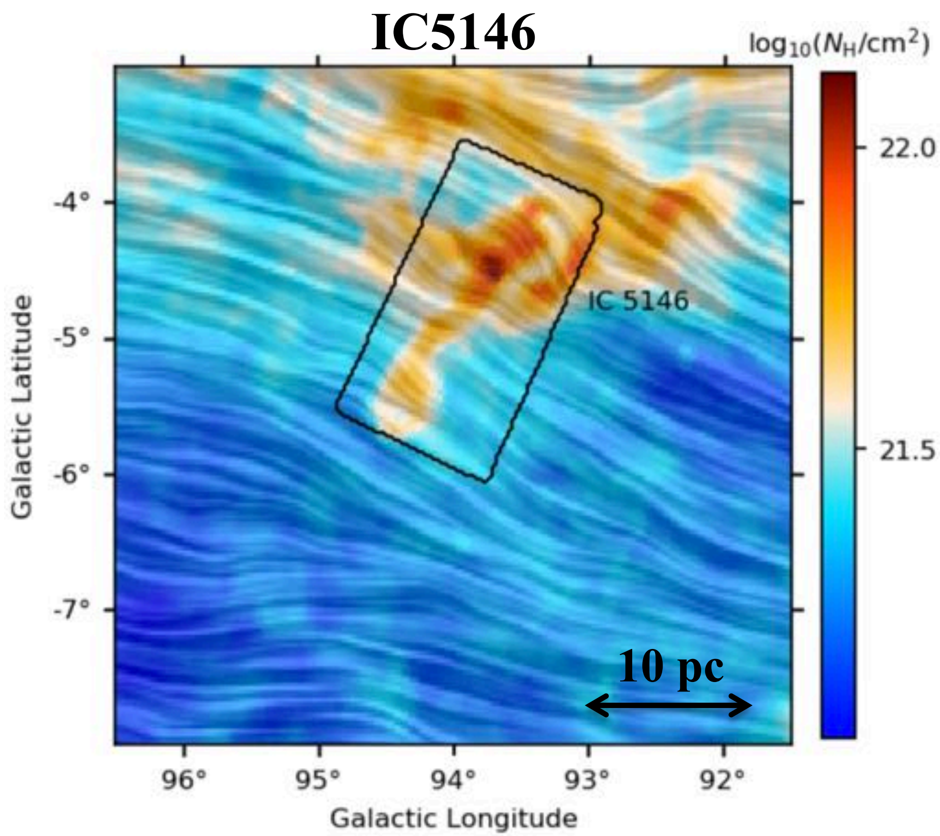
Critical M/L of nearly isothermal cylinders (Ostriker 1964; Inutsuka & Miyama 1997)

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

Planck results suggest SF filaments are magnetized

- **Highly organized B field on large scales,** ~ perpendicular to dense star-forming filaments, ~ parallel to low-density filaments
- **Suggests that the B field plays a key role in the formation process of filaments**





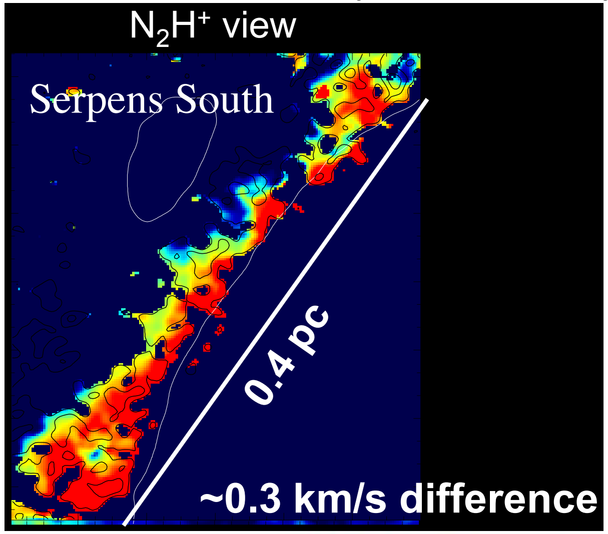
Color: N(H) from Planck data @ 5' resol. (~ 0.2-0.3 pc)

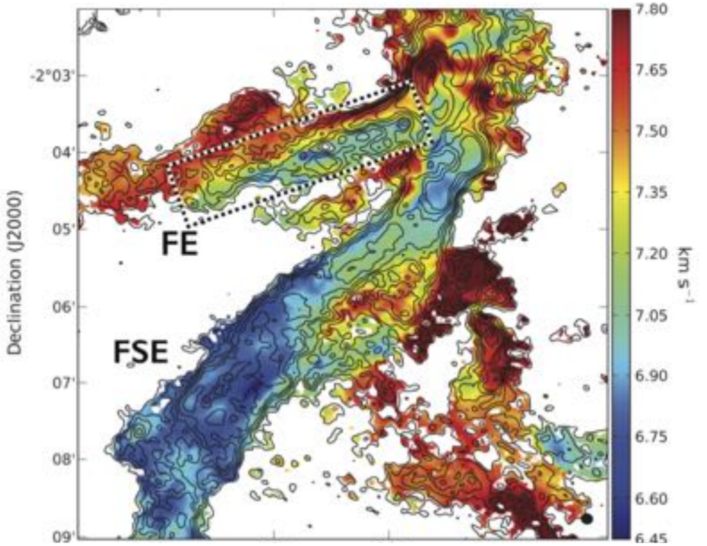
Drapery: B field lines from Q,U *Planck* 850 μm @ 10'

Planck 2015 intermediate results. XXXV.
Soler 2019

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

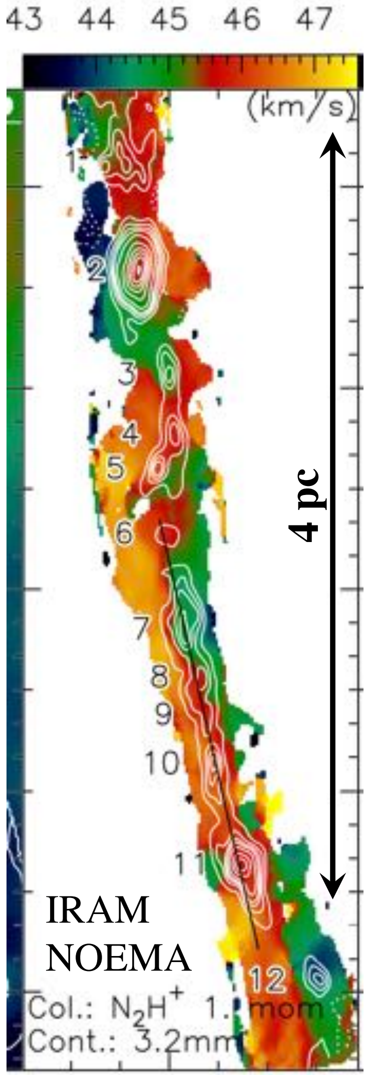
CARMA "CLASSy" SF Survey

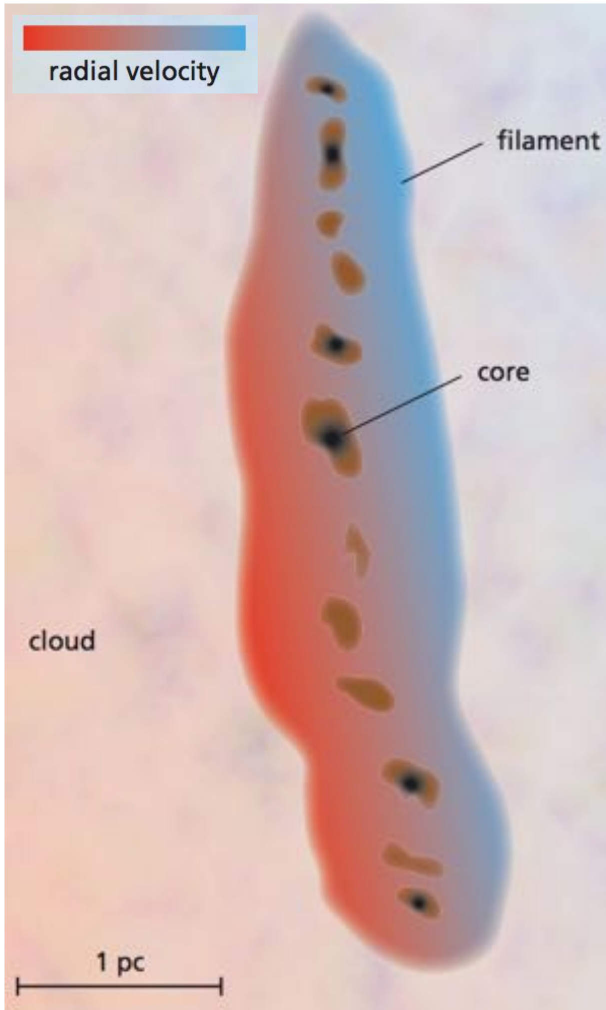




Fernandez-Lopez+2014; Dhabal, Mundy+2018
see also H. Kirk+2013 for Serp-S

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

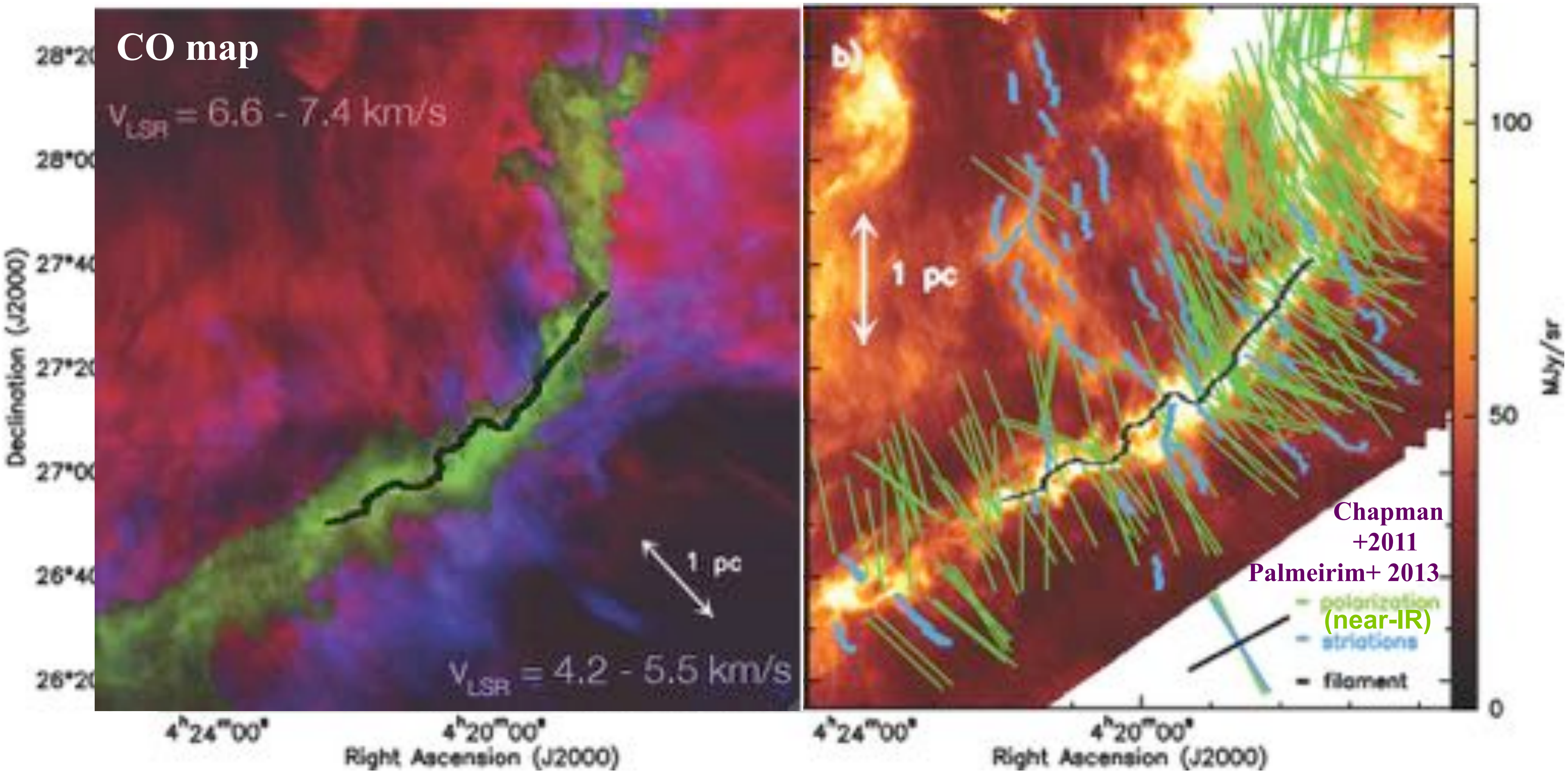




Beuther, Ragan+2015

Evidence of accretion of ambient 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

Taurus B211/3: $M_{line} \sim$ 50 $M_{\odot}$/pc

Estimated mass accretion rate:

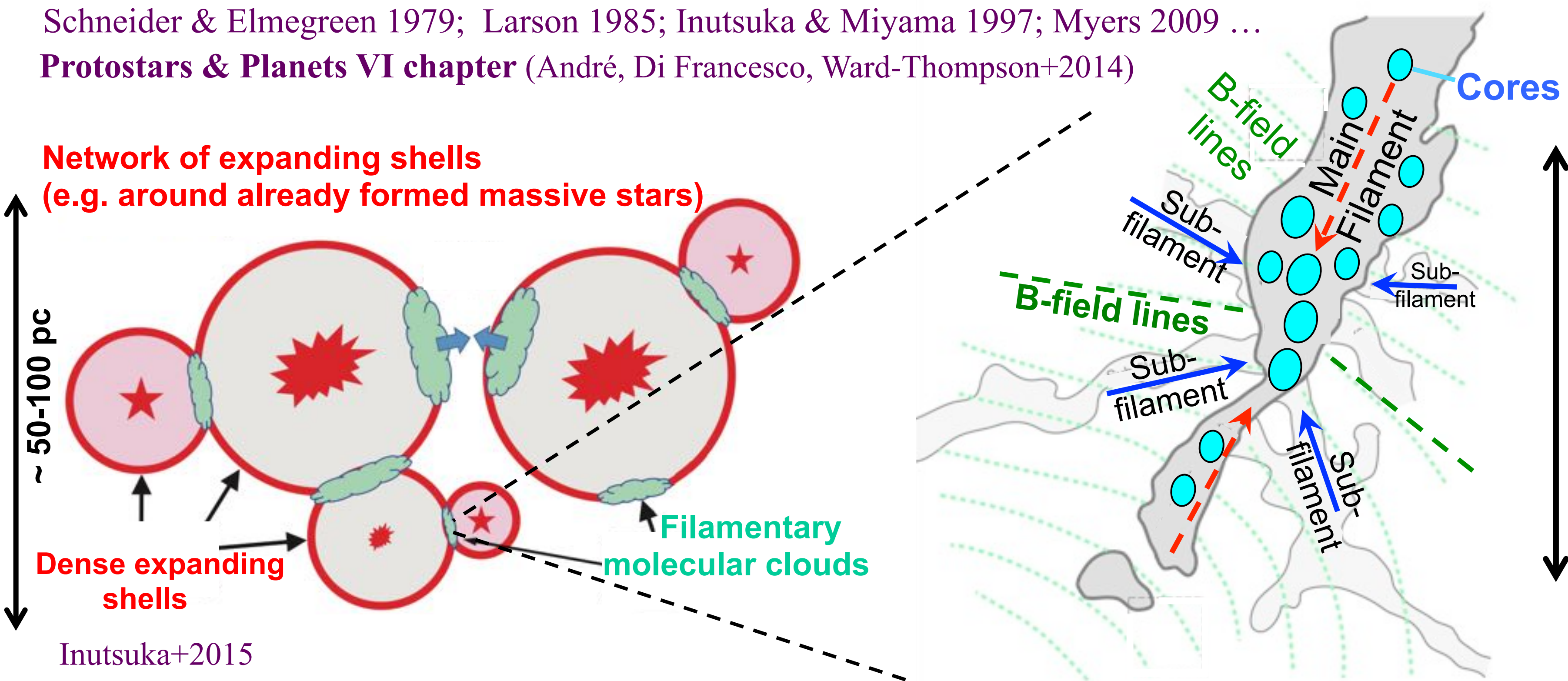
$\dot{M}_{line} \sim$ 50 $M_{\odot}$/pc/Myr

Palmeirim+2013
Shimajiri+2019a

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

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

Protostars & Planets VI chapter (André, Di Francesco, Ward-Thompson+2014)



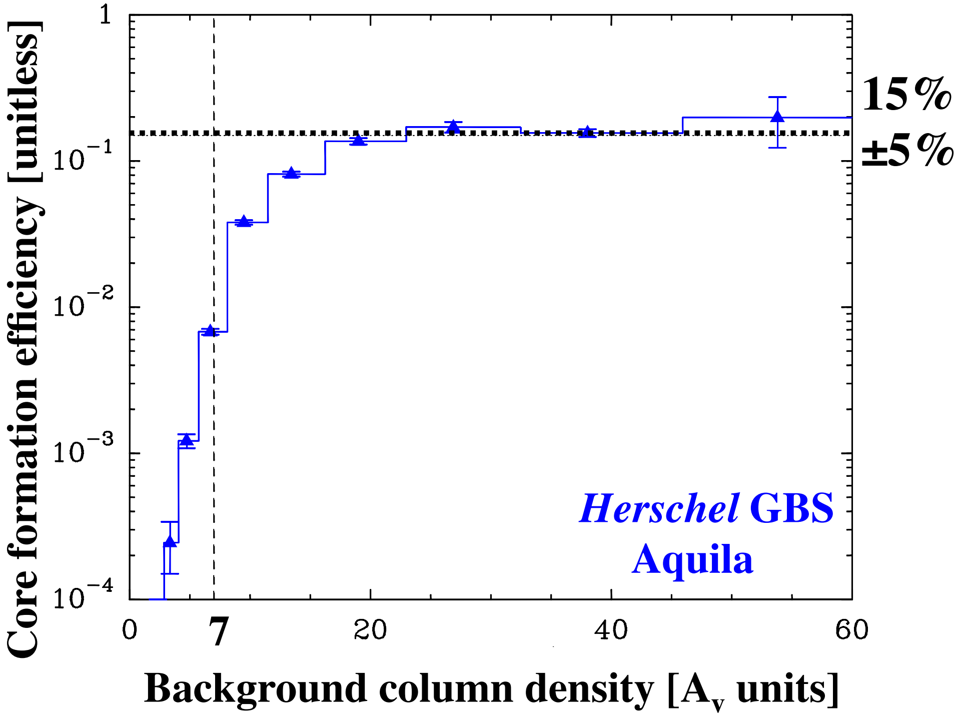
Inutsuka+2015

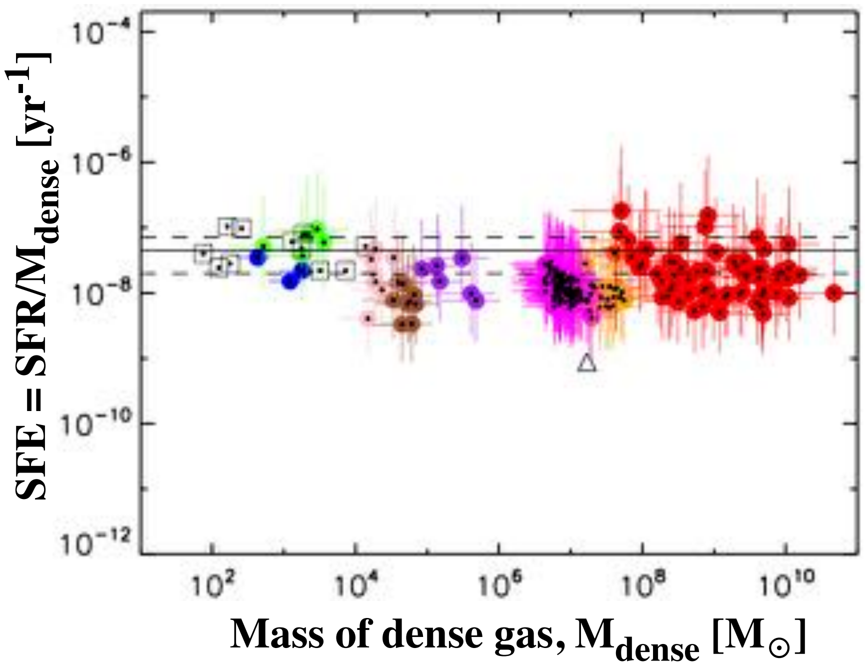
1) **Large-scale MHD compressive flows associated with multiple expanding shells create filamentary molecular clouds with ~ 0.1 pc-wide filaments**
2) **Gravity fragments the densest magnetized molecular filaments into prestellar cores close to or above** $M_{line,crit} \sim 16\ M_\odot\ pc^{-1}$
3)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

Importance of ISM filaments on galaxy-wide scales?

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



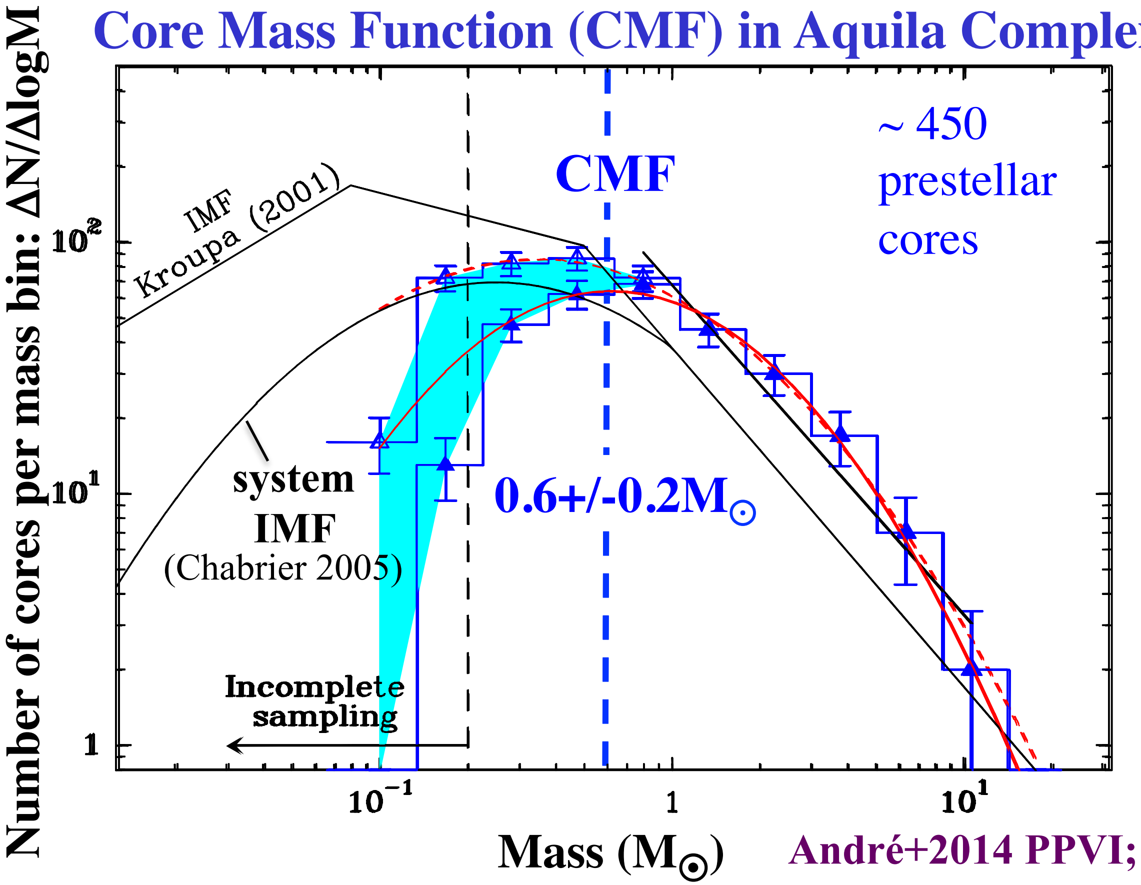


Lada+2012 Shimajiri+2017

Könyves+2015

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

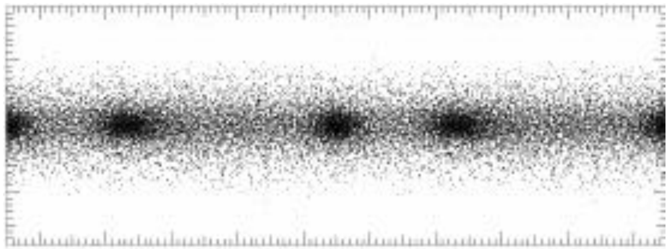
Filament fragmentation can account for the peak of the prestellar CMF and (possibly) the "base" of the IMF



André+2014 PPVI; Könyves+2015

Jeans mass:

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

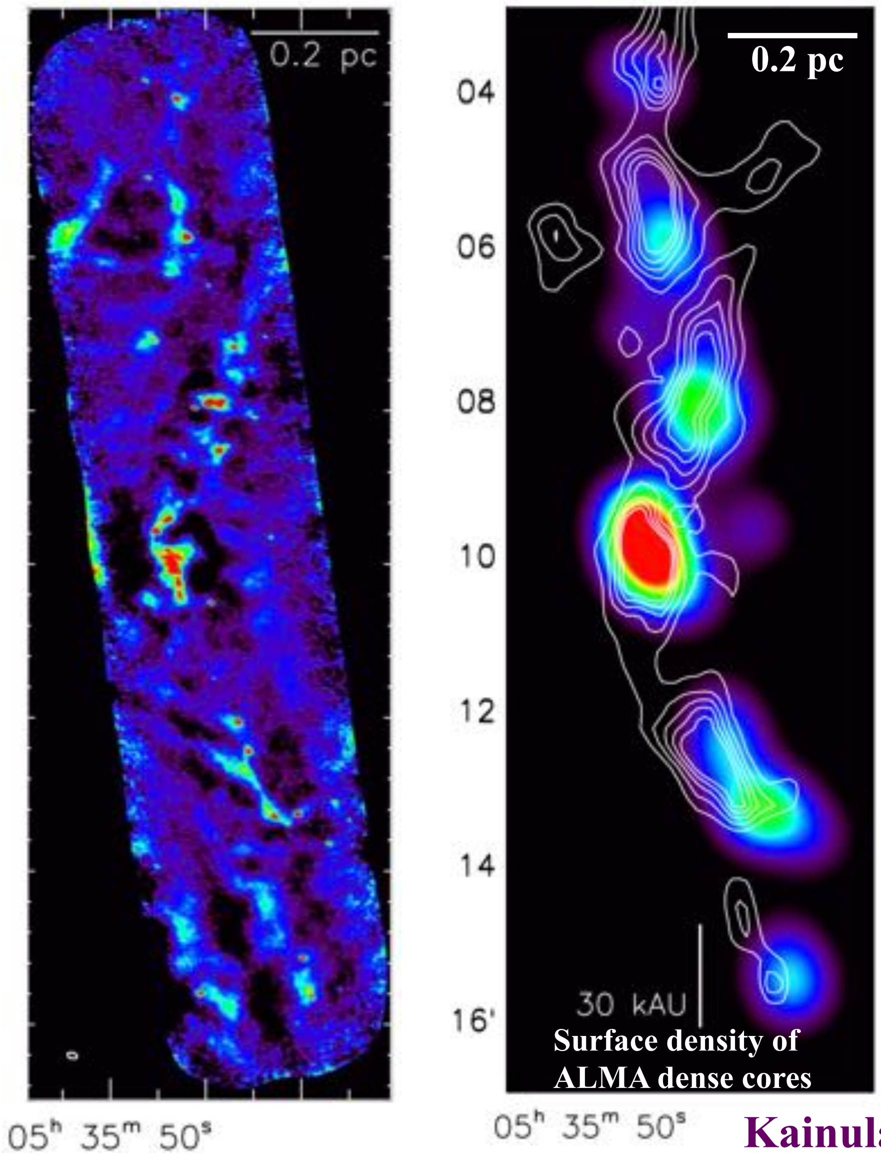


Inutsuka & Miyama 1997

- **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



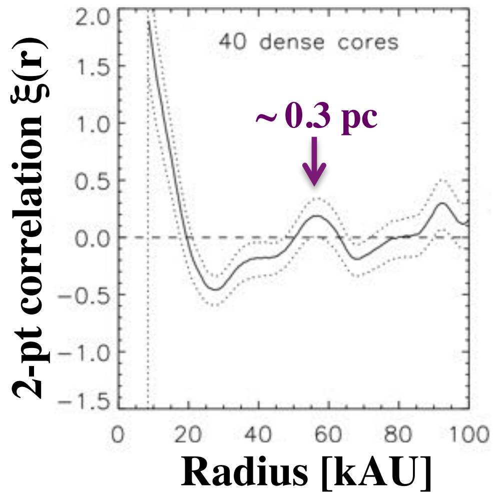
Kainulainen+2017

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

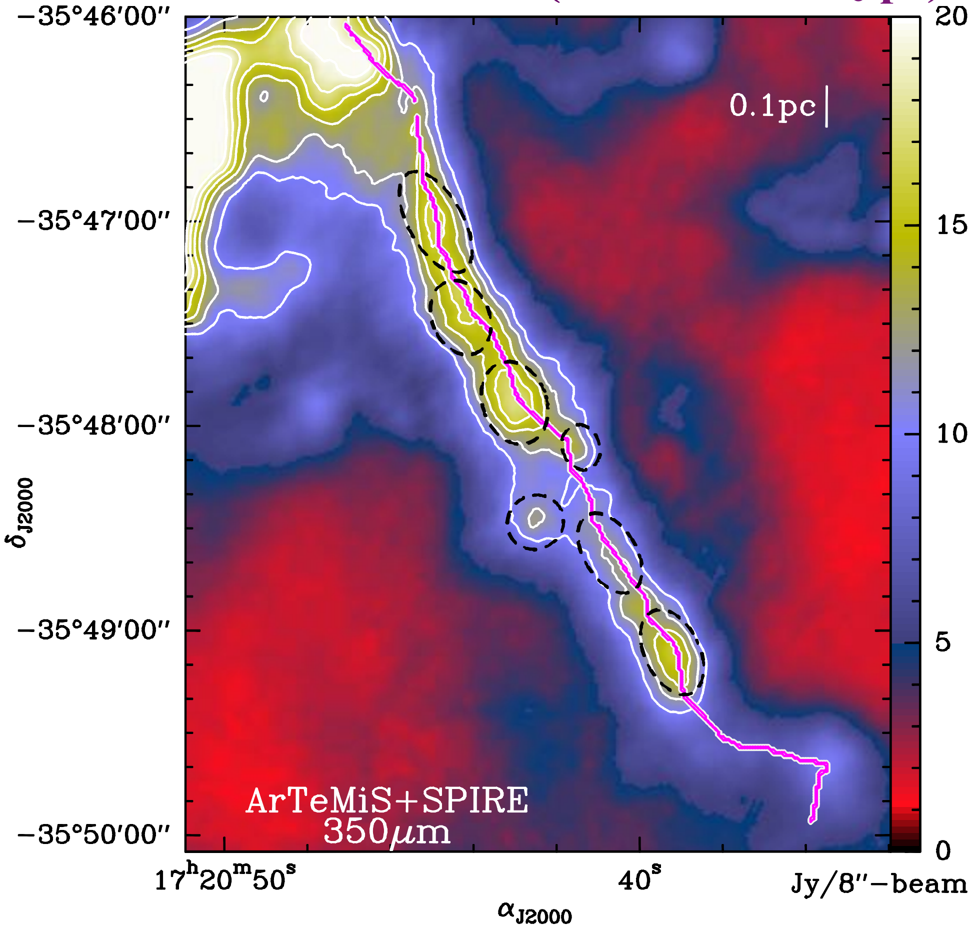
Two-point correlation function of ALMA dense cores



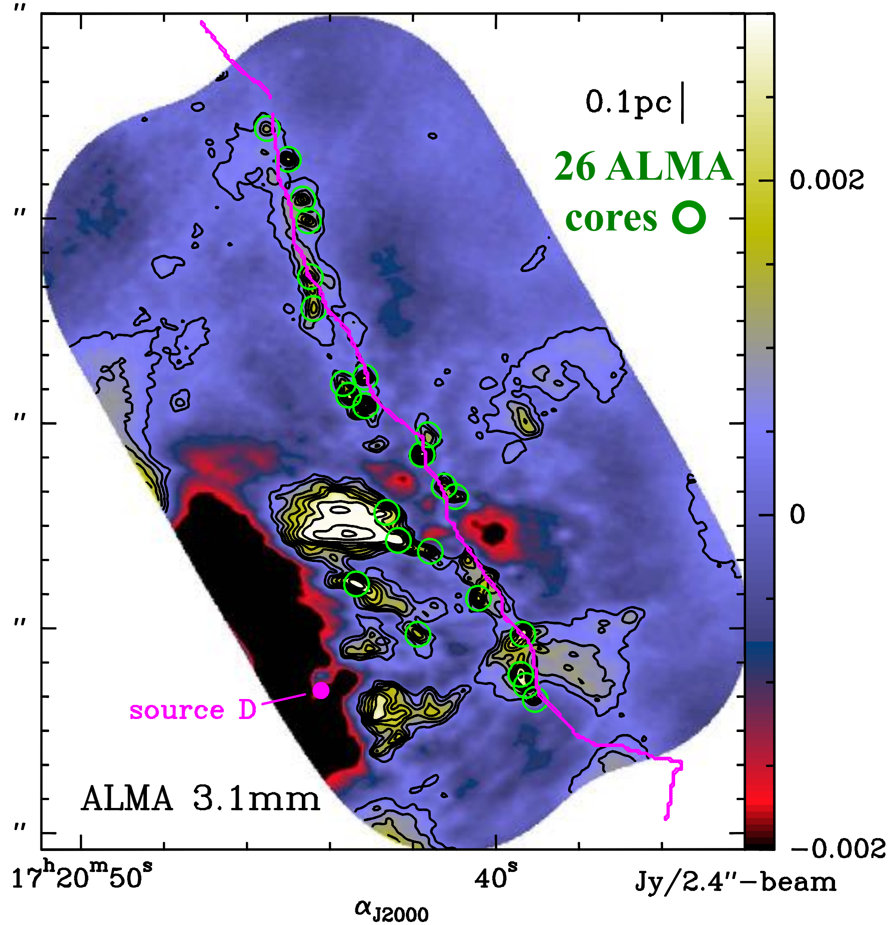
Evidence of two fragmentation modes in filaments:

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)**

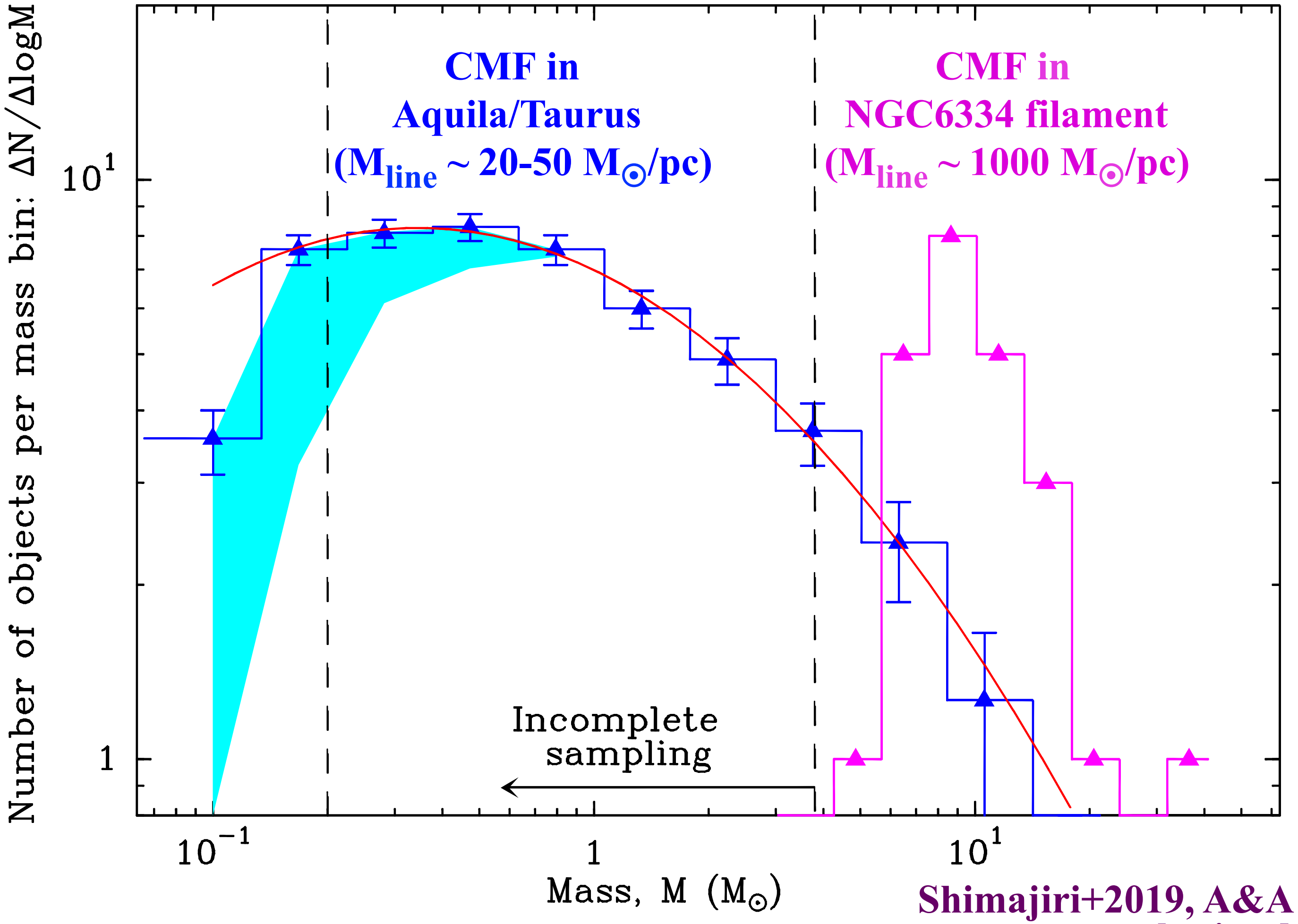
Shimajiri+2019, A&A, submitted

Detailed fragmentation manner of filaments?

➢ **Denser (higher M_{line}) filaments may form more massive prestellar cores, possibly due to a stronger B-field?**

Comparison of the core mass functions observed in nearby clouds/filaments and the NGC6334 filament

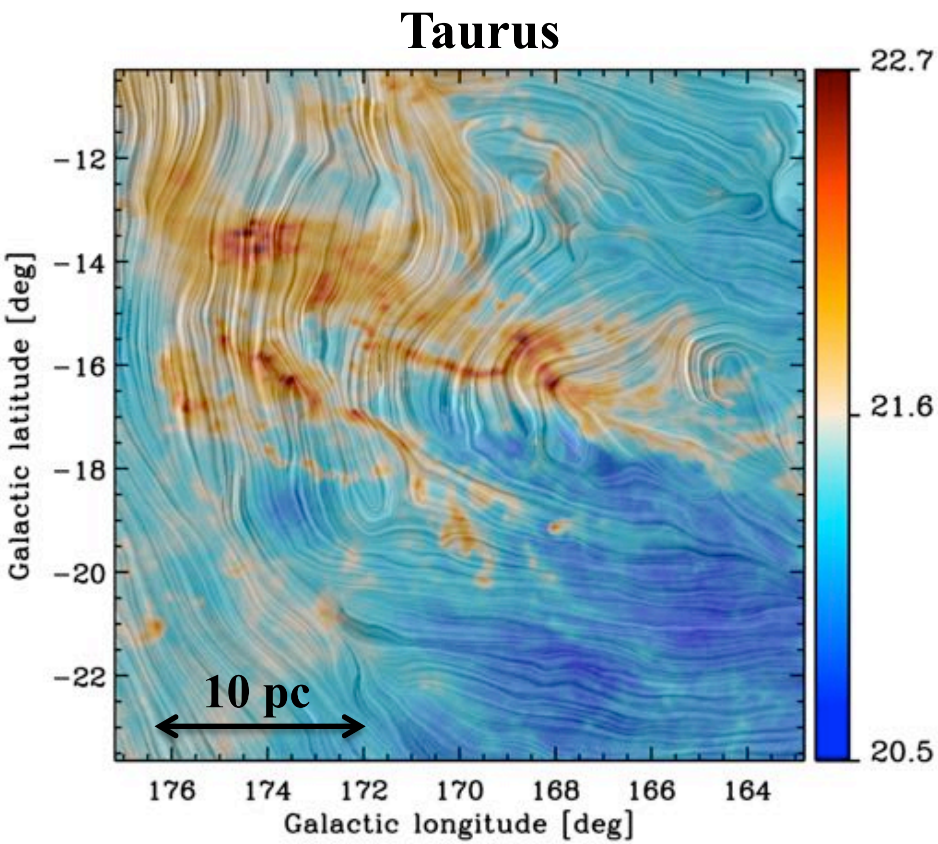
Full CMF/IMF from the superposition of the CMFs in individual filaments, coupled with a ~ Salpeter distribution of filament M/L?
(André+2019, A&A)

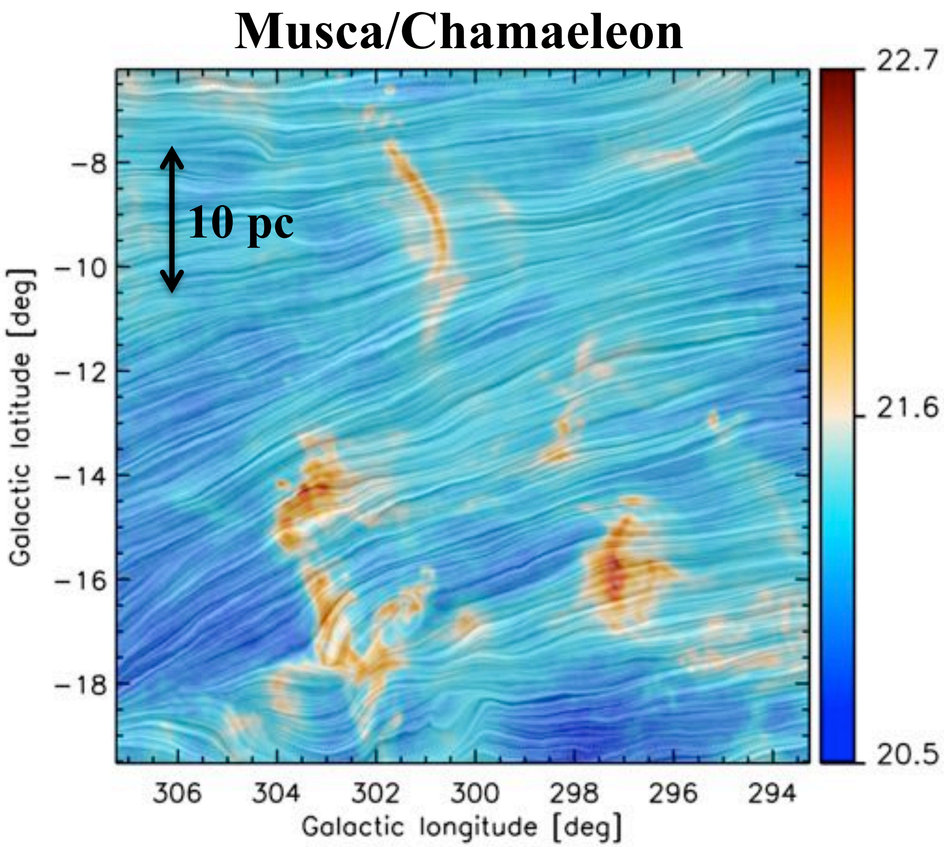


Shimajiri+2019, A&A submitted

Influence of B fields on filament fragmentation?

- *Planck* **polarization data reveal a highly 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**





Planck int. results. XXXV. (2016) - Soler 2019

Suggests sub-Alfvénic turbulence on cloud scales

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

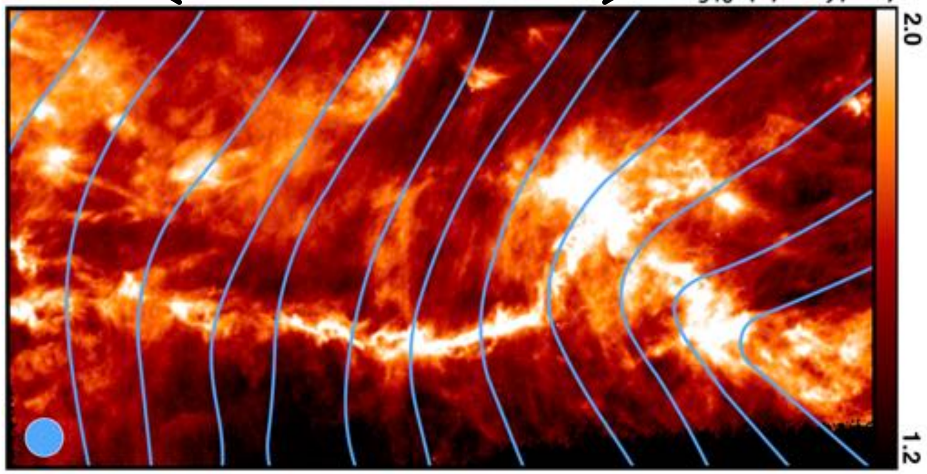
Drapery: B field lines from Q,U *Planck* 850 µm @ 10'

SPICA and Millimetron can unveil the role of magnetic fields in filament evolution and core/star formation

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

See SPICA-POL White Paper (arXiv:1905.03520)

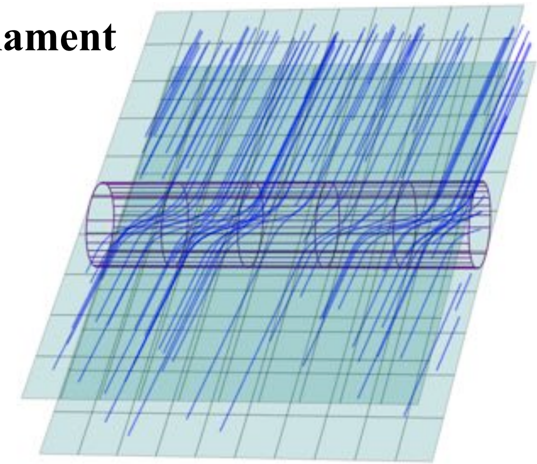
5 pc



Palmeirim +2013
A. Bracco

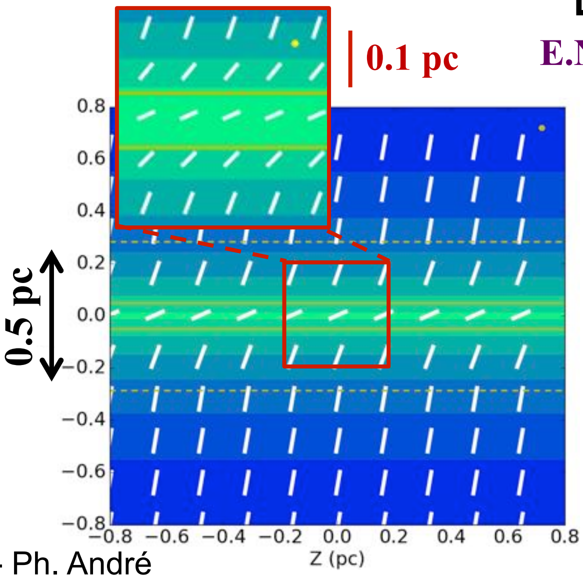
- ***Planck* resolution (> 10' or > 0.4 pc) insufficient to resolve the 0.1 pc width of filaments.**
  Can be done with SPICA/Mmtron
- **B fields within dense filaments may be key to prevent radial contraction and make SF possible.**
  (cf. Seifried & Walch 2015)

Plausible model of the B field in the central filament



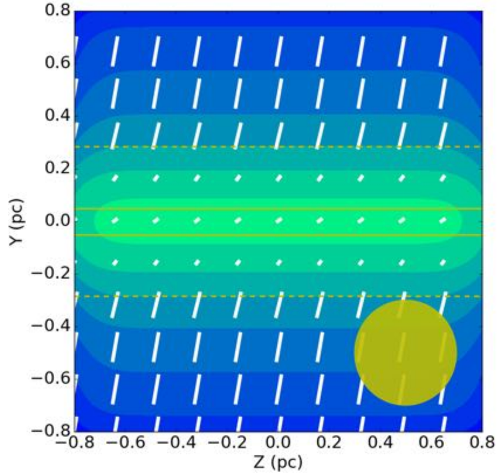
Synthetic polarization maps

SPICA resolution



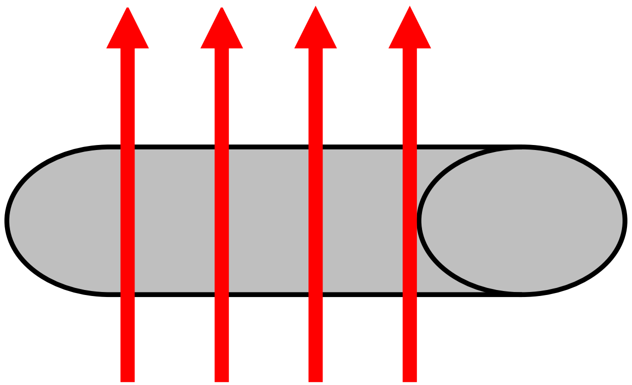
E.Ntormousi

***Planck* resolution**



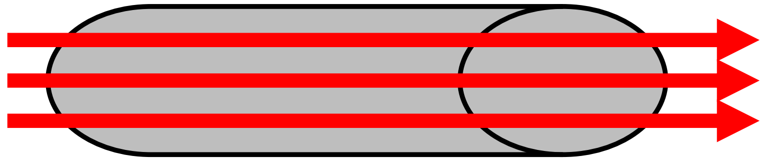
Two simple magnetic field configurations

B-field perpendicular to long axis of filament



B-field cannot prevent radial contraction of filament, but can regulate/slow down fragmentation

B-field parallel to long axis of filament



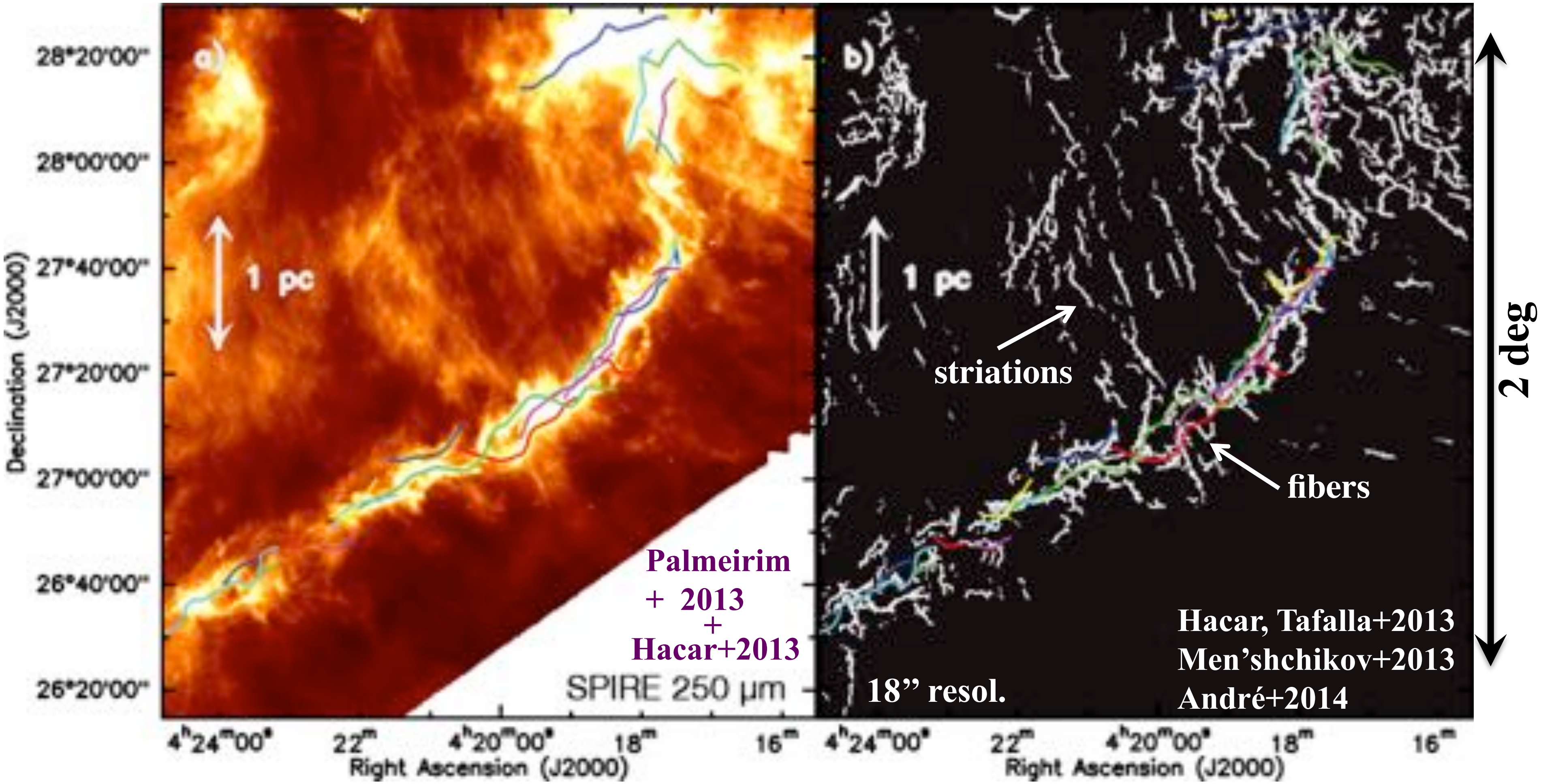
B-field can prevent indefinite radial contraction of filament, but cannot regulate fragmentation

Probing the magnetic link between striations and fibers

High resolution/dynamic range polar. imaging with SPICA & Mmtron

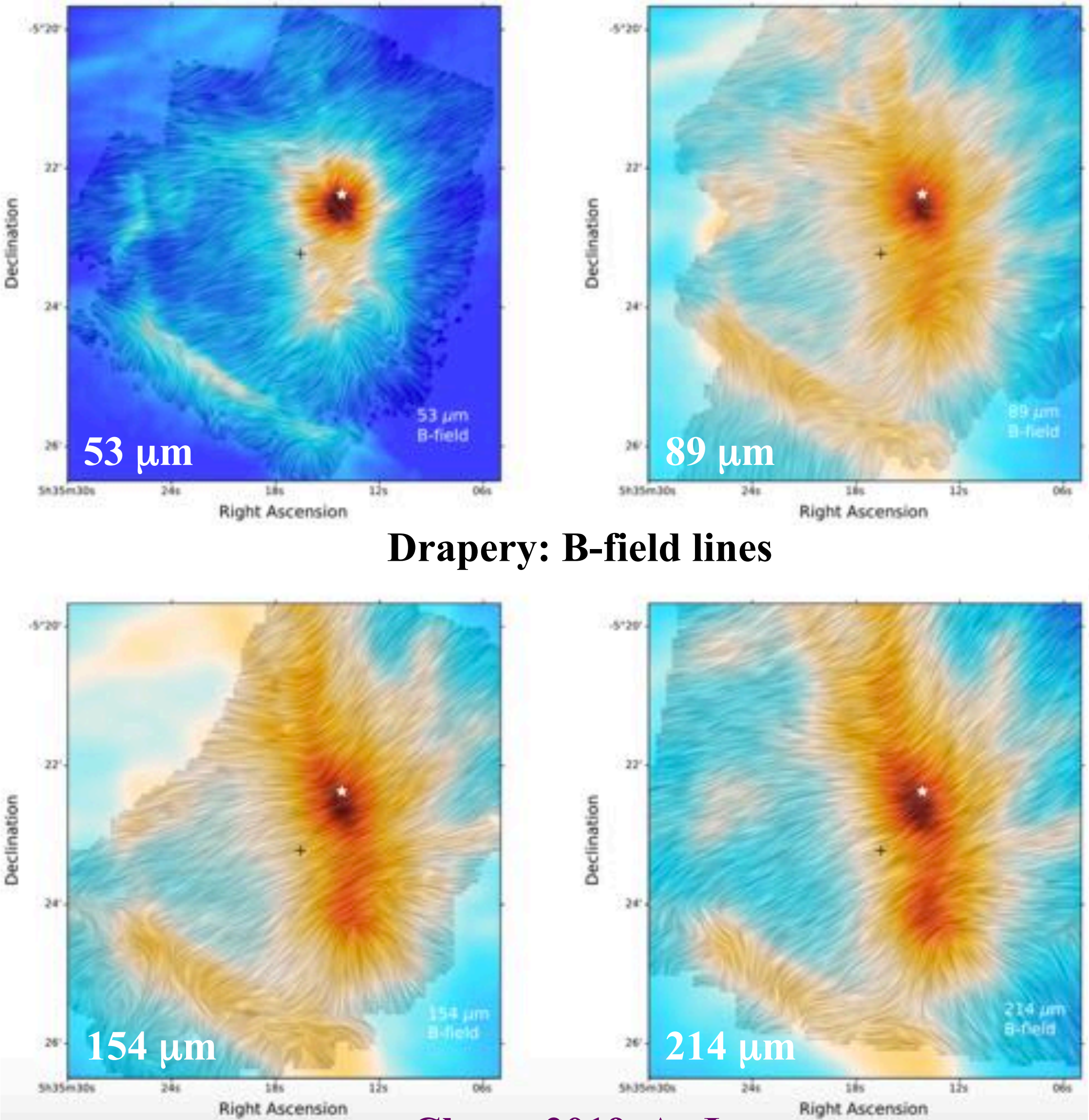
- Geometry of the B-field *within* the (~ 0.1 pc) system of intertwined « fibers » developing inside star-forming filaments and the connection with the striations seen on larger scales

SPICA-POL White Paper (arXiv:1905.03520)



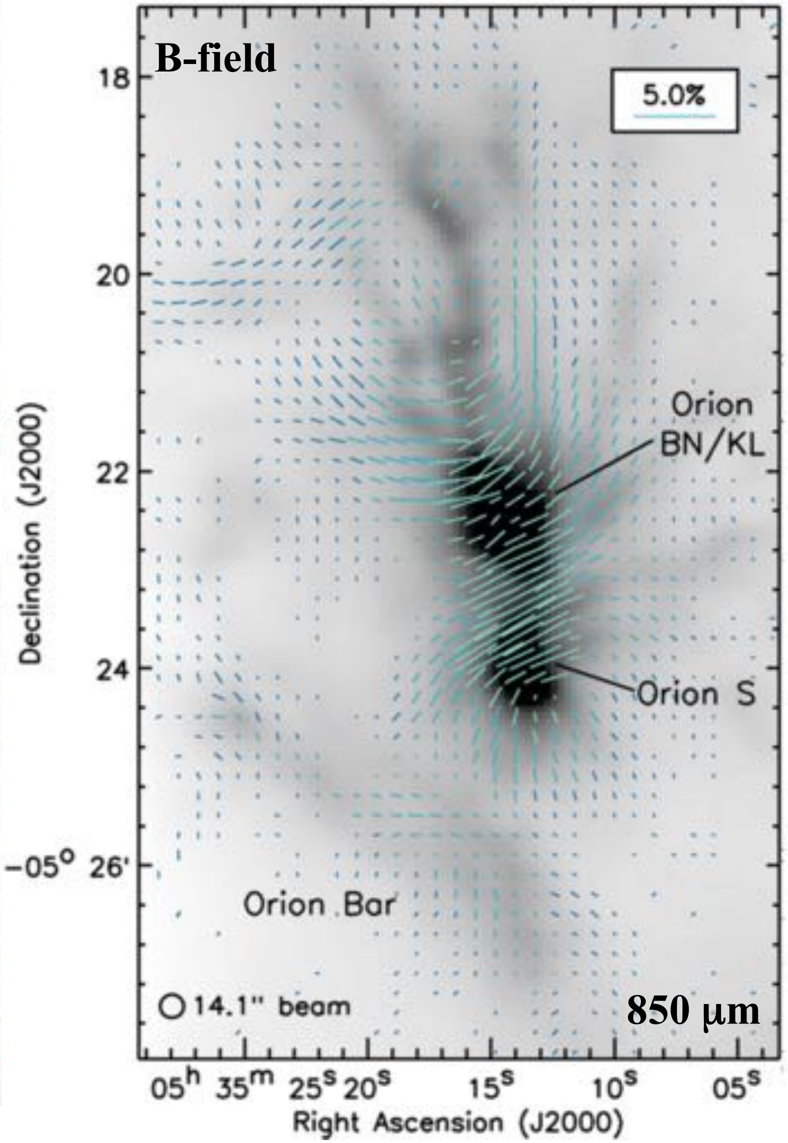
Recent FIR and submm imaging polarimetry results for Orion A

SOFIA - HAWC+



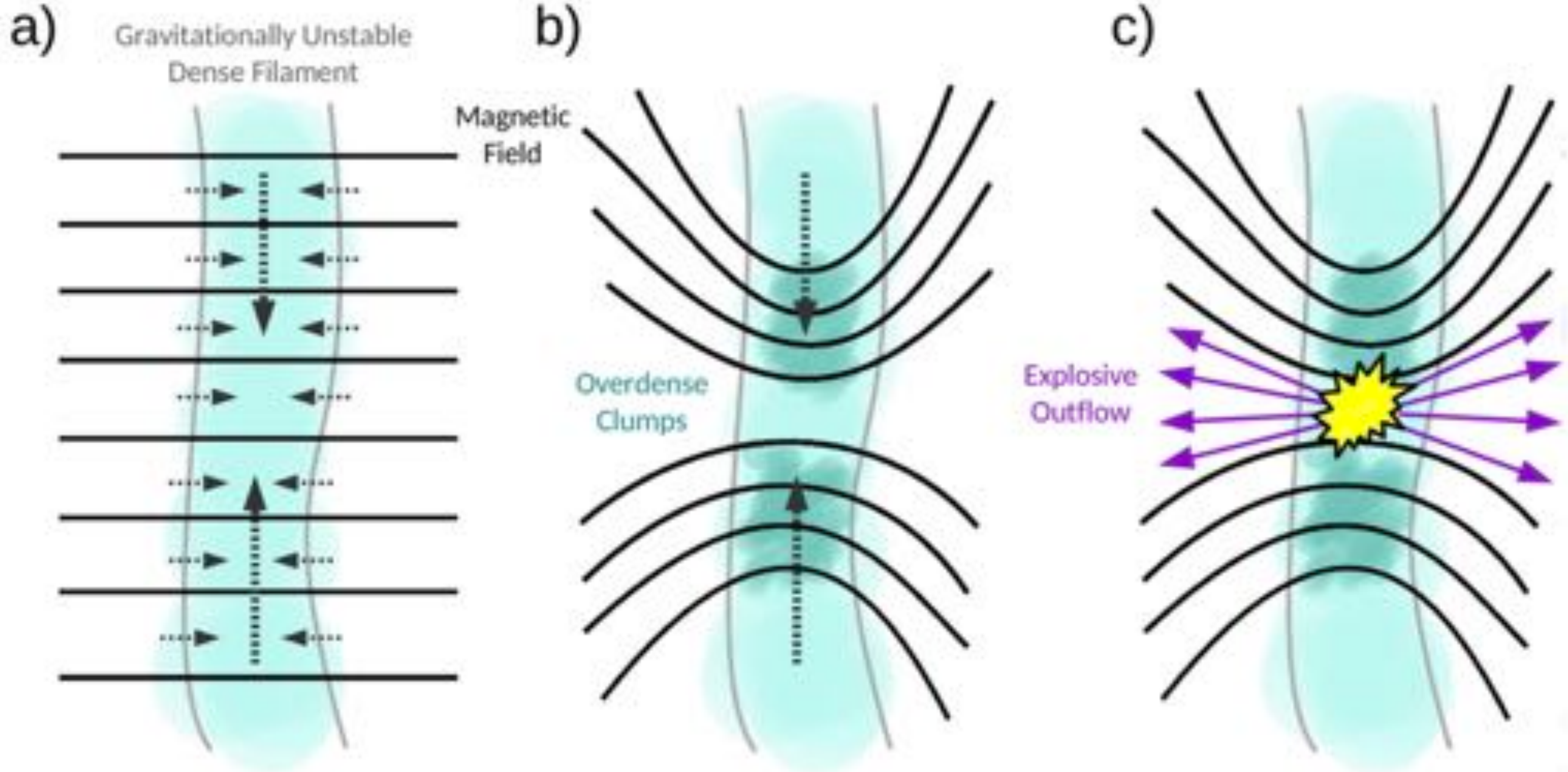
Chuss+2019, ApJ

JCMT – SCUBA2-POL



Ward-Thompson+2017; Pattle+2017

Sketch of possible origin of hourglass B-field pattern in Orion A



Pattle, Ward-Thompson et al. 2017

- ➢ **Curvature of hourglass pattern is more pronounced at longer λ (e.g. 850 μm)**
- ➢ **Suggests different λs probe different depths into the cloud**

➢ With SACS/LACS on Mmtron (8 bands), tomographic studies of the B-field will become possible for complete samples of filaments

Key advantages of a large, cooled space telescope such as Millimetron for this science

- **High spatial dynamic range (~10^3), which cannot be achieved from the ground**
- **High angular resolution (Mmtron can resolve critical 0.1 pc scale out to ~1.5 kpc, SPICA out to ~0.4 kpc)**
- **High sensitivity to low surface brightness structures (in contrast to interferometers – e.g. ALMA)**
- **Unique multi-wavelength polarimetric coverage of SACS/LACS in the far-IR/submm → tomography of the B-field + unique constraints on dust models**
- **Wide-field polarimetric imaging survey of nearby molecular clouds at $\lambda \sim$ 50-1000 μm with SACS and LACS on Mmtron would revolutionize our understanding of the origin and role of B-fields in filament formation/fragmentation**