

Magnetic fields in star-forming filaments NIKA2-POL as a pathfinder for SPICA-B-BOP

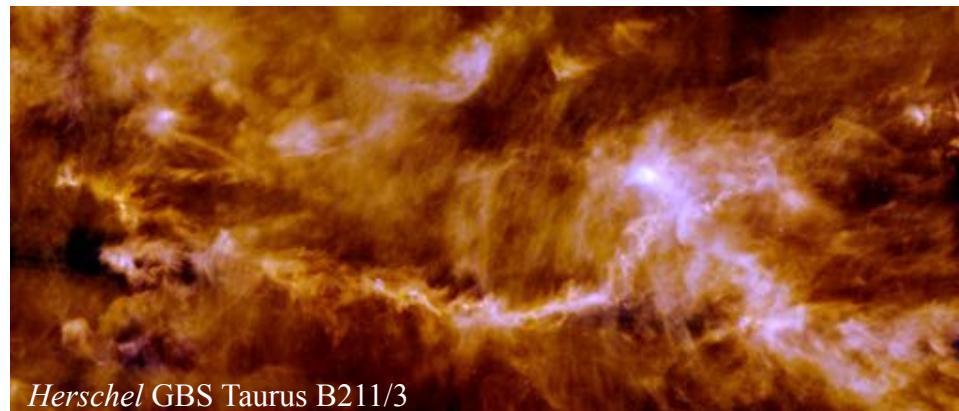


Ph. André CEA - Lab. AIM Paris-Saclay



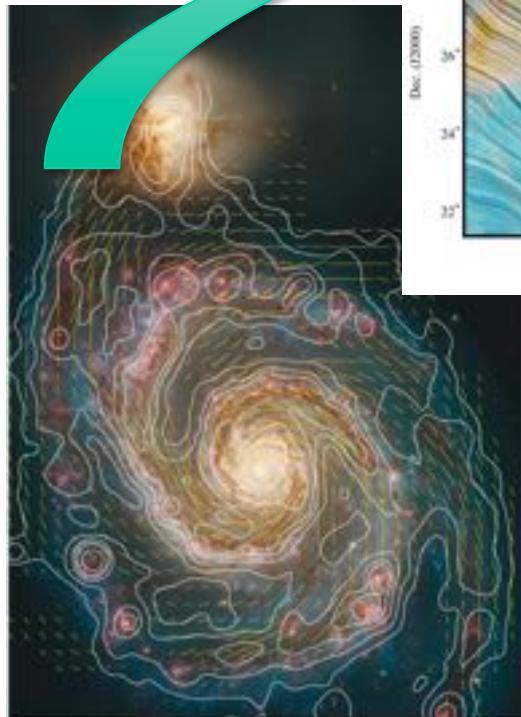
on behalf of the NIKA2 collaboration and B-FUN LP Team

Special thanks to: A. Bracco, D. Arzoumanian, J. Soler, S. Bontemps, F. Motte, I. Ristorcelli, V. Guillet, F. Boulanger, M. Galametz + NIKA2-POL Commissioning Team (A. Maury, N. Ponthieu, A. Ritacco, H. Ajeddig, Y. Shimajiri, A. Andrianasolo)

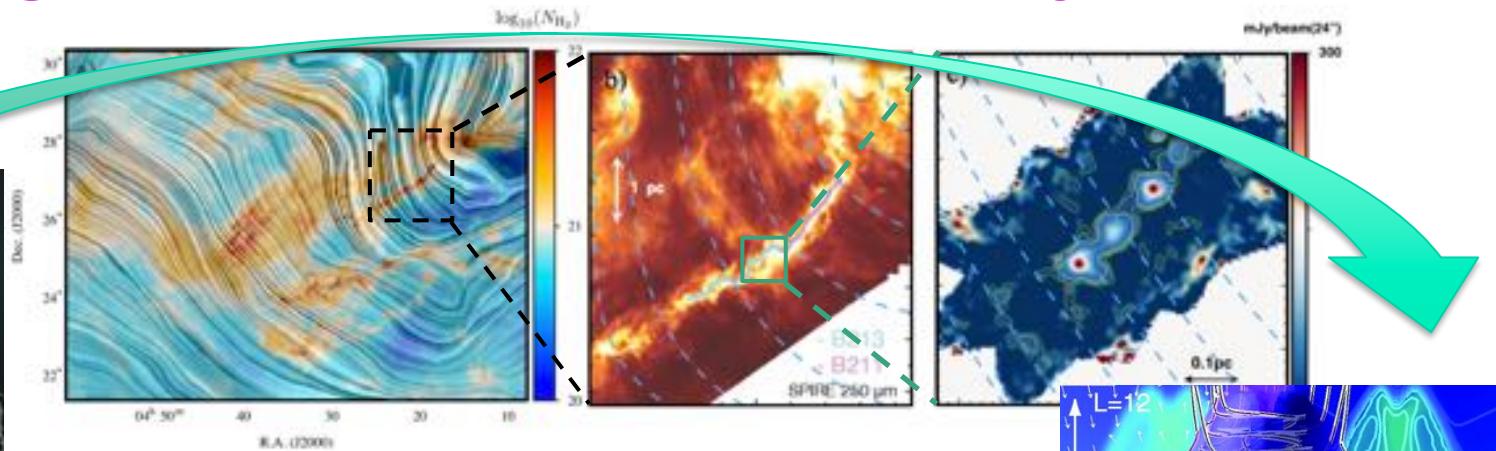


Magnetic fields: A largely unexplored “dimension” of the cold (mm) Universe

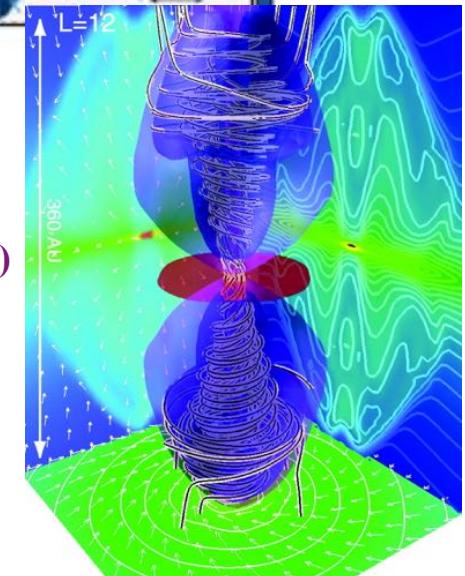
A key ‘dark’ ingredient of the star formation process from galactic scales to protoplanetary disks



See talk by A. Hughes
on Thursday

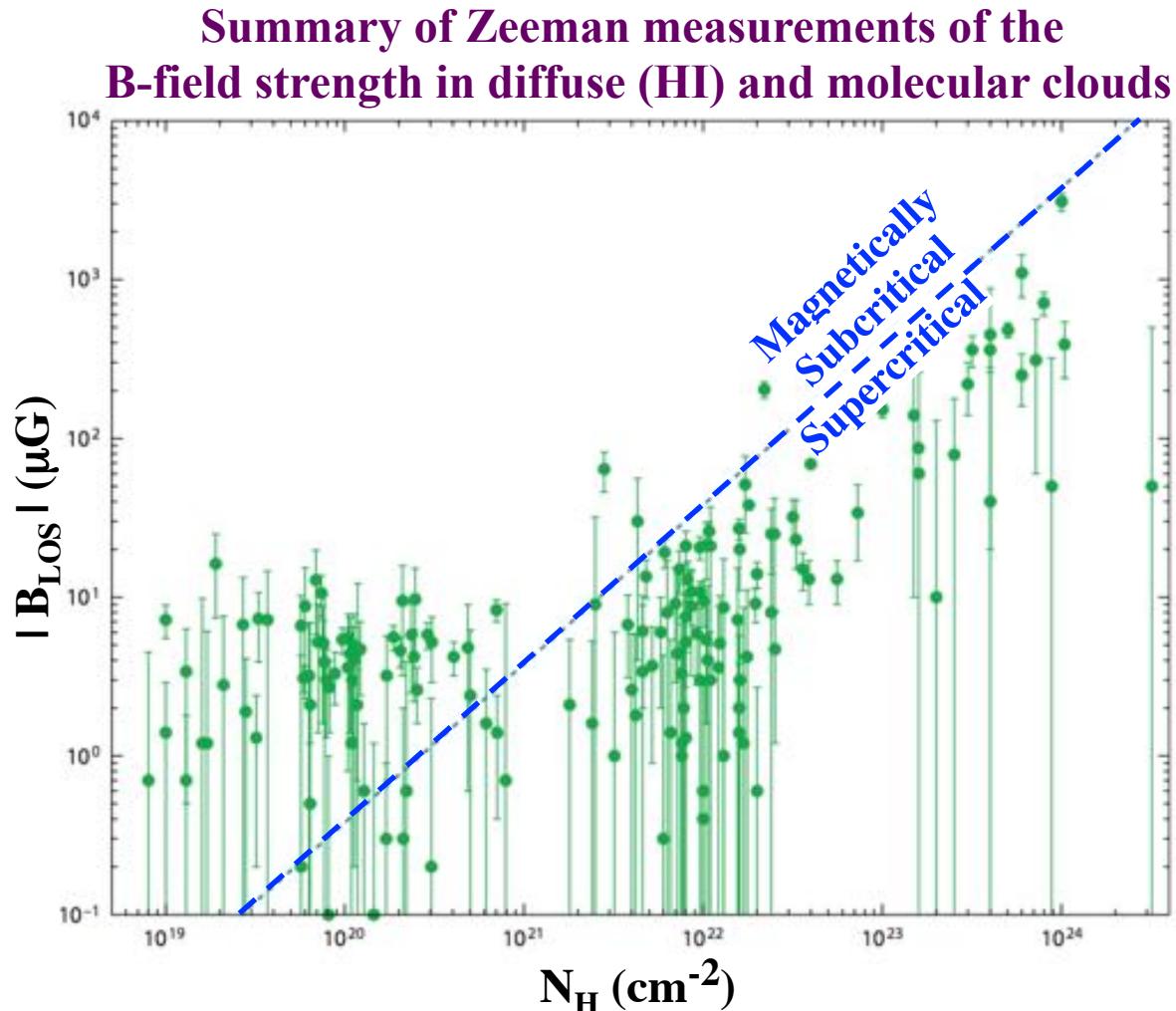


- On large scales (GMCs $> 10\text{-}100$ pc), regulate the formation of molecular clouds and filaments (Mouschovias & Ciolek 1991, McKee & Ostriker 2007, Inutsuka+2015...)
- On small scales (proto* cores < 0.1 pc), key role to generate protostellar outflows and control disk formation
- Very poorly constrained observationally (e.g. Crutcher 2012 ARA&A)



Machida+2008

Magnetic field measurements in molecular clouds



- In the ISM, magnetic and kinetic energy densities are in \sim equipartition.
- $B \sim 6\text{-}10 \mu\text{G}$, independent of column density, for $N_H \lesssim 5 \times 10^{21} \text{ cm}^{-2}$
- $B \propto N_H$ for $N_H \gtrsim 5 \times 10^{21} \text{ cm}^{-2}$ (molecular clouds)
- Molecular clouds are magnetically supercritical by a factor $\sim 2\text{-}3$

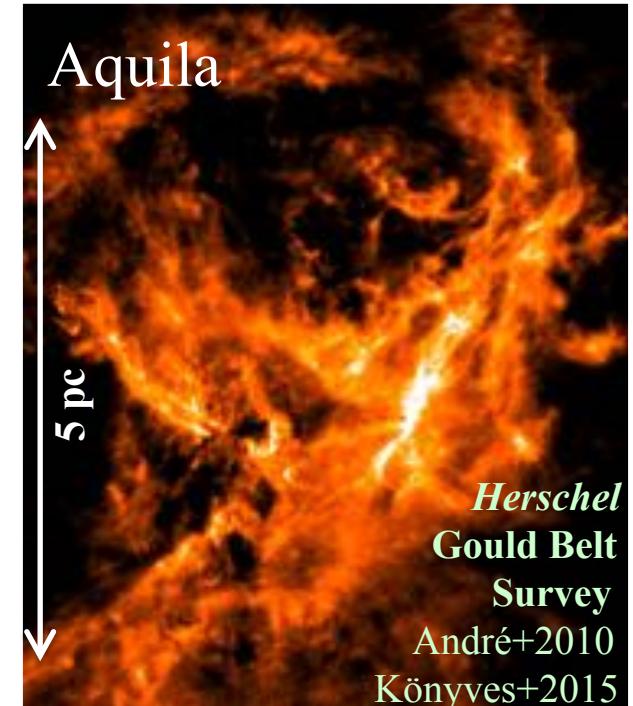
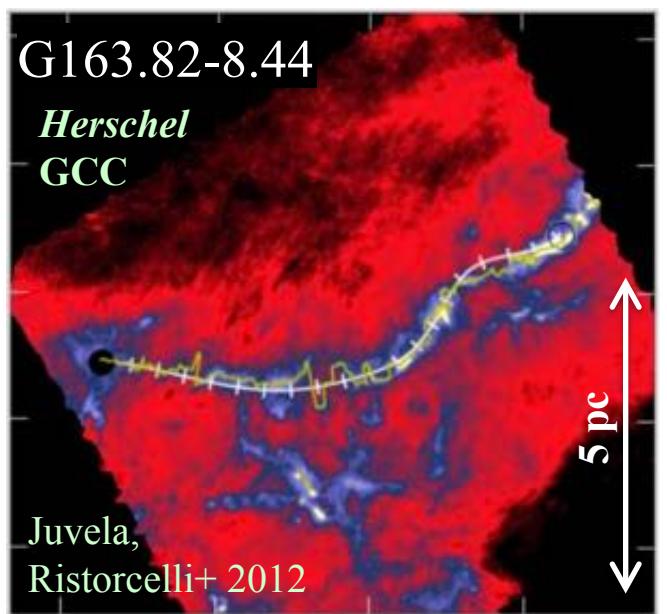
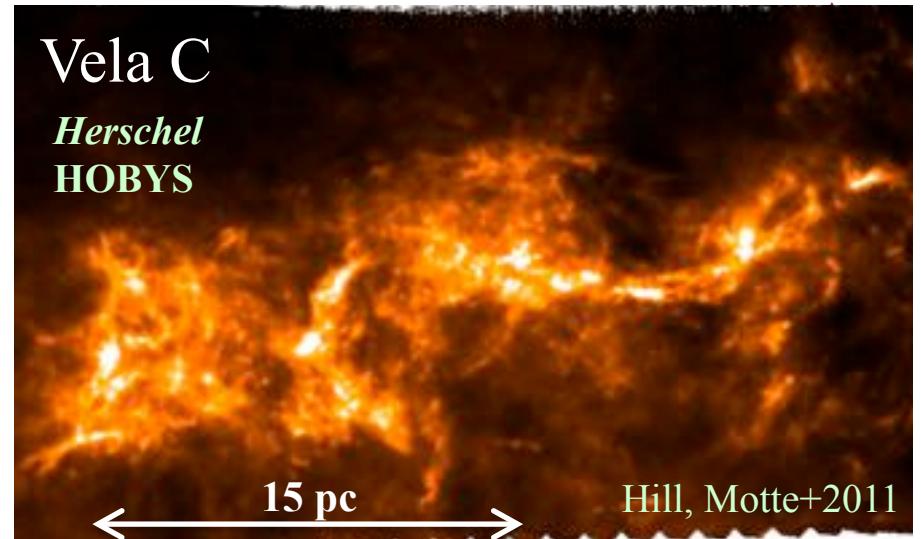
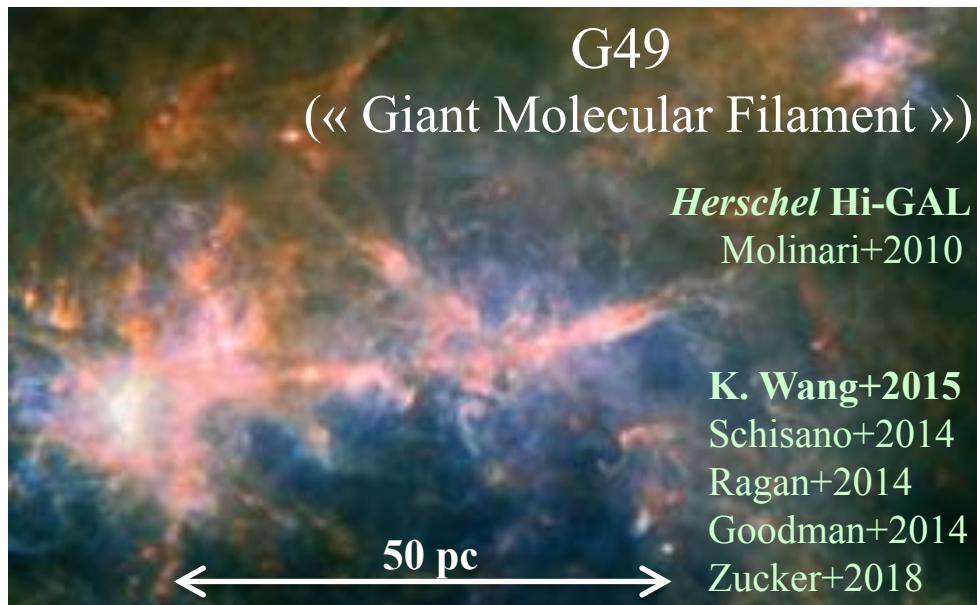
Crutcher 2012 ARA&A

Magnetic fields in star-forming filaments NIKA2-POL as a pathfinder for SPICA-B-BOP

- Outline:
- Motivation: *Herschel* and *Planck* results on filaments → A filament paradigm for star formation
 - Role of B fields in the evolution/fragmentation of filaments?
 - Prospects with NIKA2-LP ‘B-FUN’ and (later) SPICA B-BOP

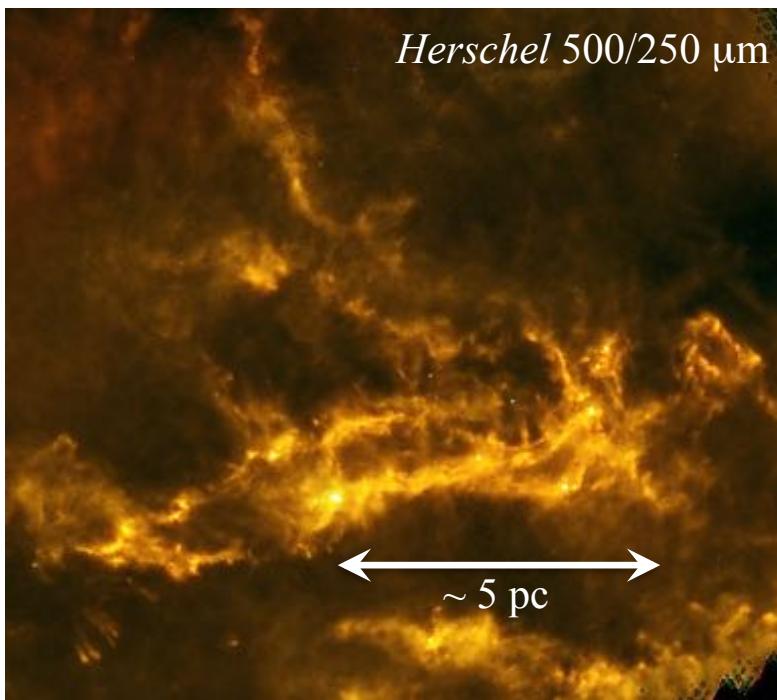


Herschel has confirmed the presence of a ‘universal’ filamentary structure in the cold ISM

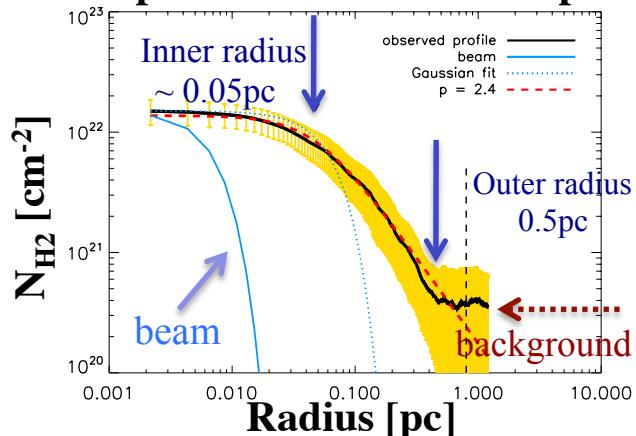


Nearby filaments have a common inner width ~ 0.1 pc

Network of filaments in IC5146



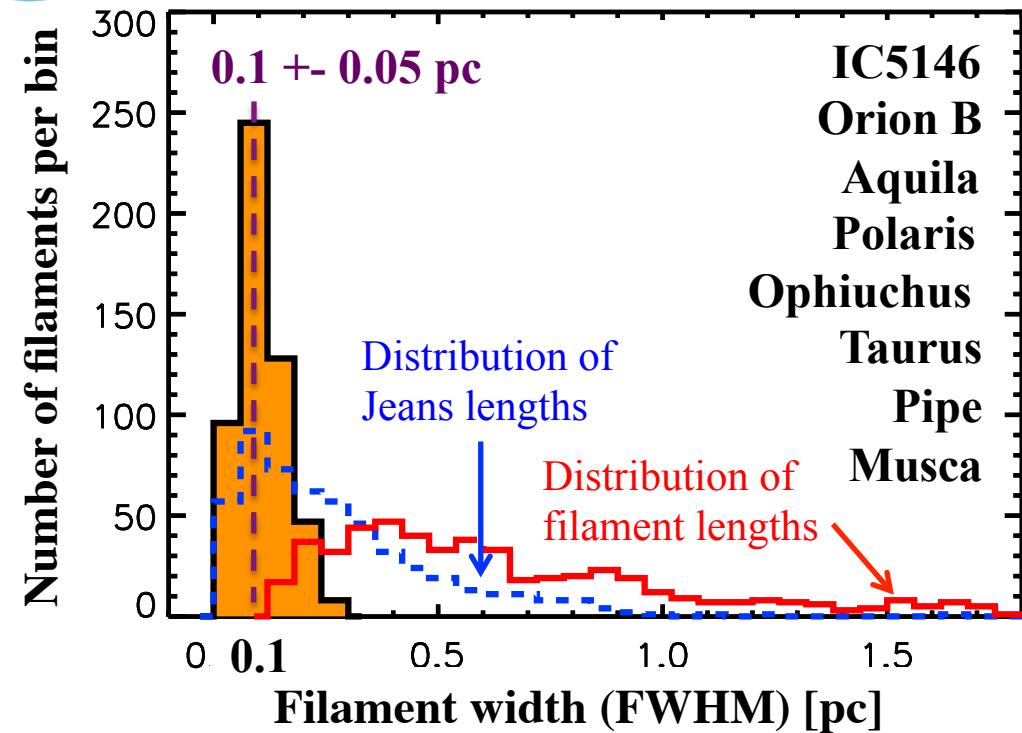
Example of a filament radial profile



Ph. André – NIKA2 Conference – Grenoble – 5 June 2019



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

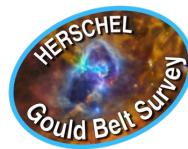
(cf. Padoan+2001; Federrath 2016)

Challenging for numerical simulations

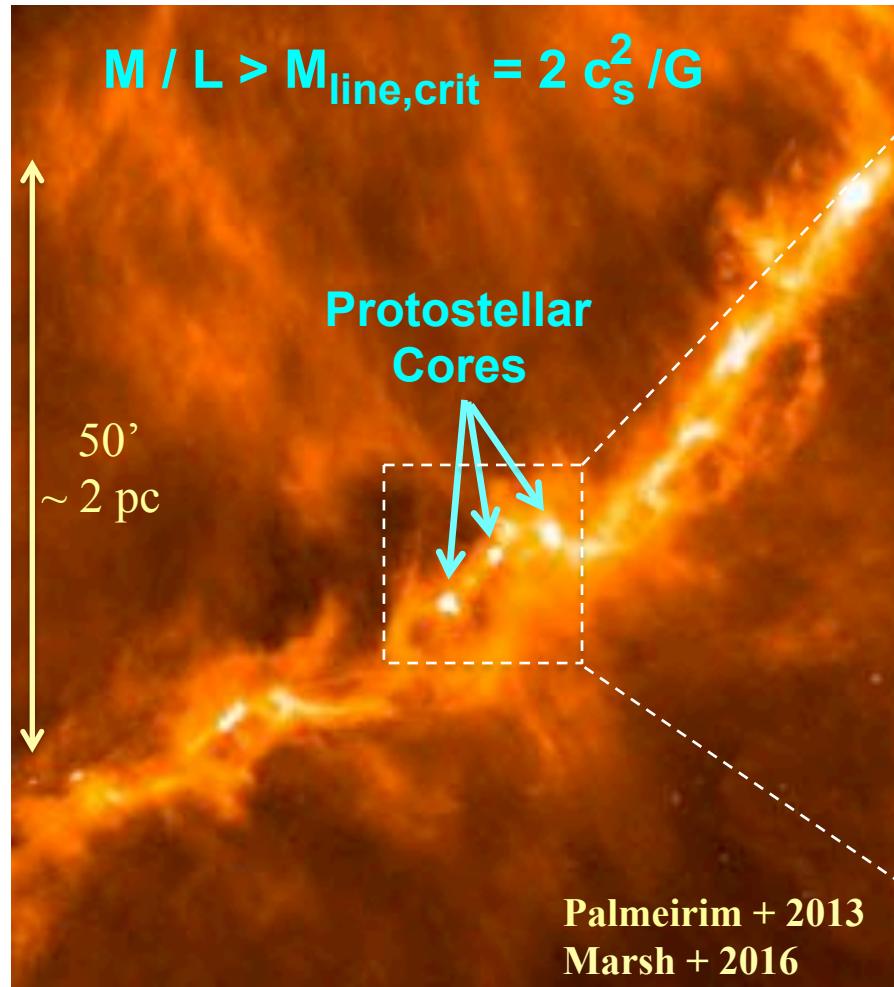
(cf. R. Smith+2014; Ntormousi+2016)

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

$\Leftrightarrow \Sigma \gtrsim 150 \text{ M}_\odot/\text{pc}^2$ or $M / L \gtrsim 15 \text{ M}_\odot/\text{pc} \sim M_{\text{line, crit}}$

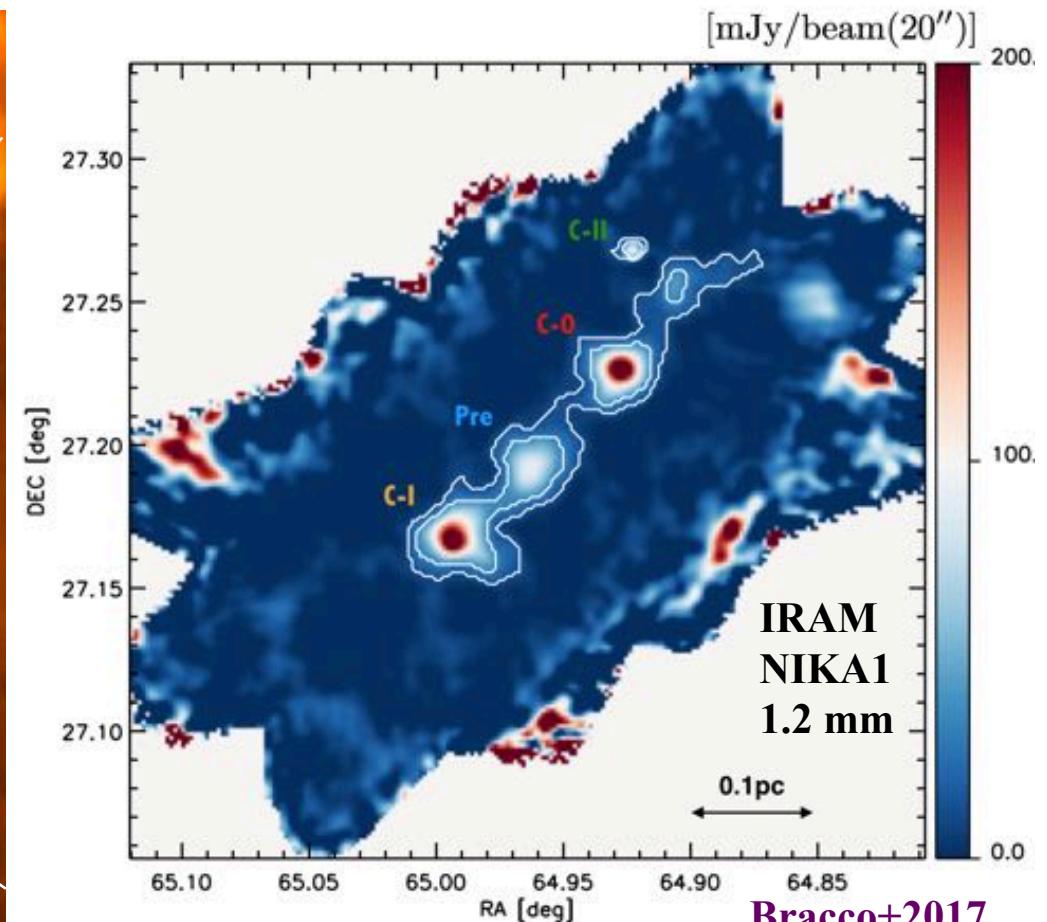


cf. Protostars & Planets VI chapter
André, Di Francesco, Ward-Thompson+2014



Taurus B211/3 – *Herschel* 250 μm

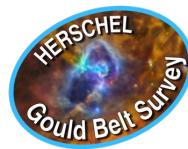
Könyves+2015, 2019; Marsh+2016; Bresnahan+2018



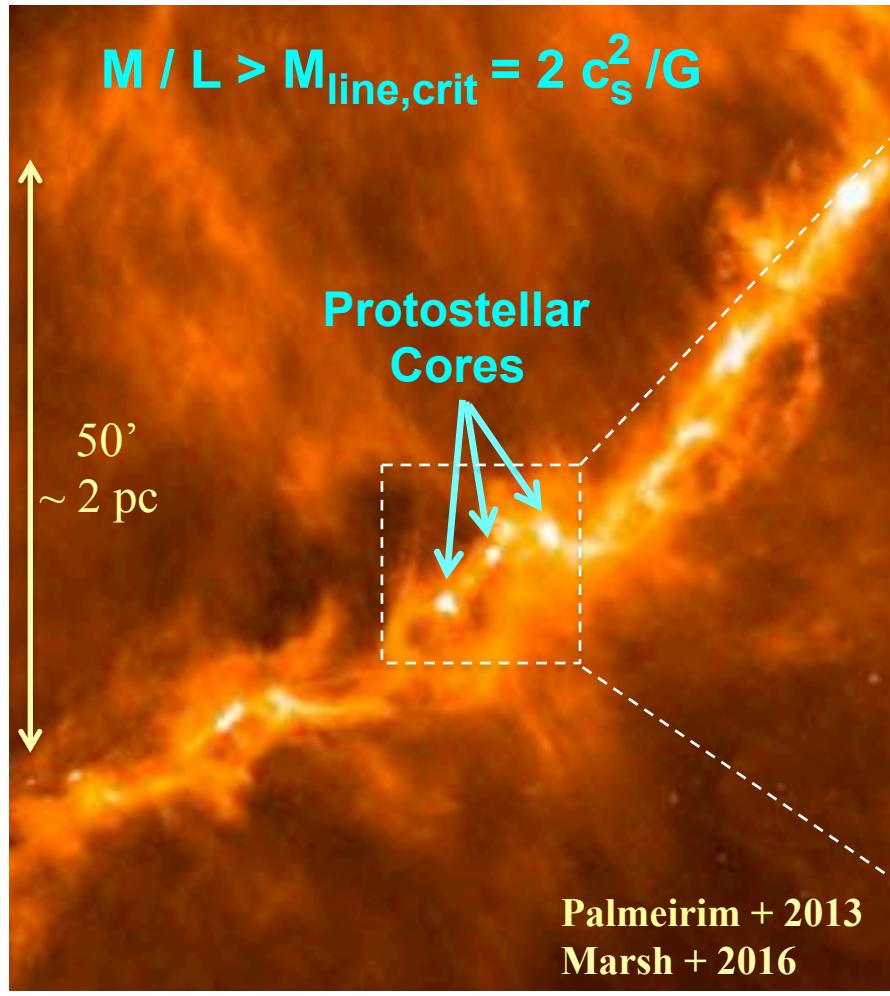
Ph. André – NIKA2 Conference – Grenoble – 5 June 2019

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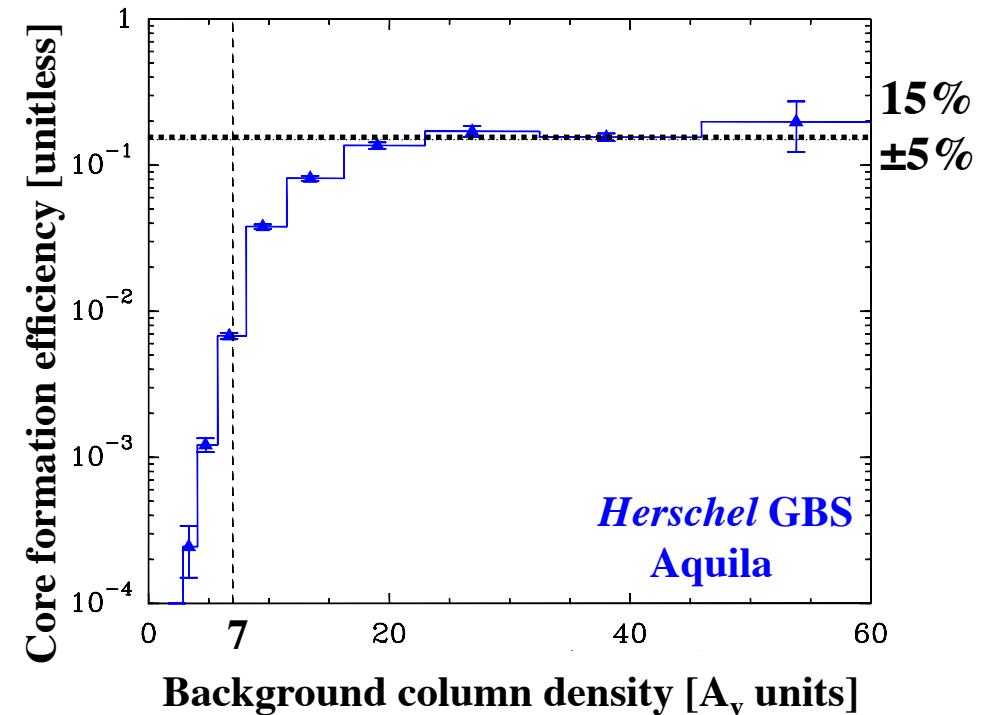
cf. Protostars & Planets VI chapter
André, Di Francesco, Ward-Thompson+2014



Taurus B211/3 – *Herschel* 250 μm

Könyves+2015, 2019; Marsh+2016; Bresnahan+2018

Prestellar CFE as a function of background A_V



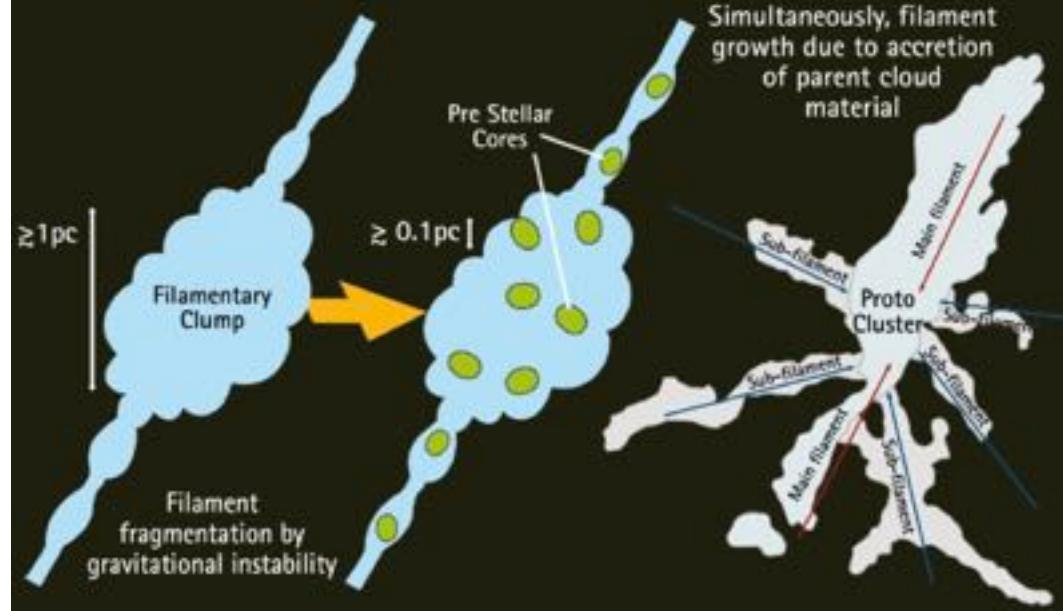
Könyves+2015

A filamentary paradigm for $\sim M_{\odot}$ star formation

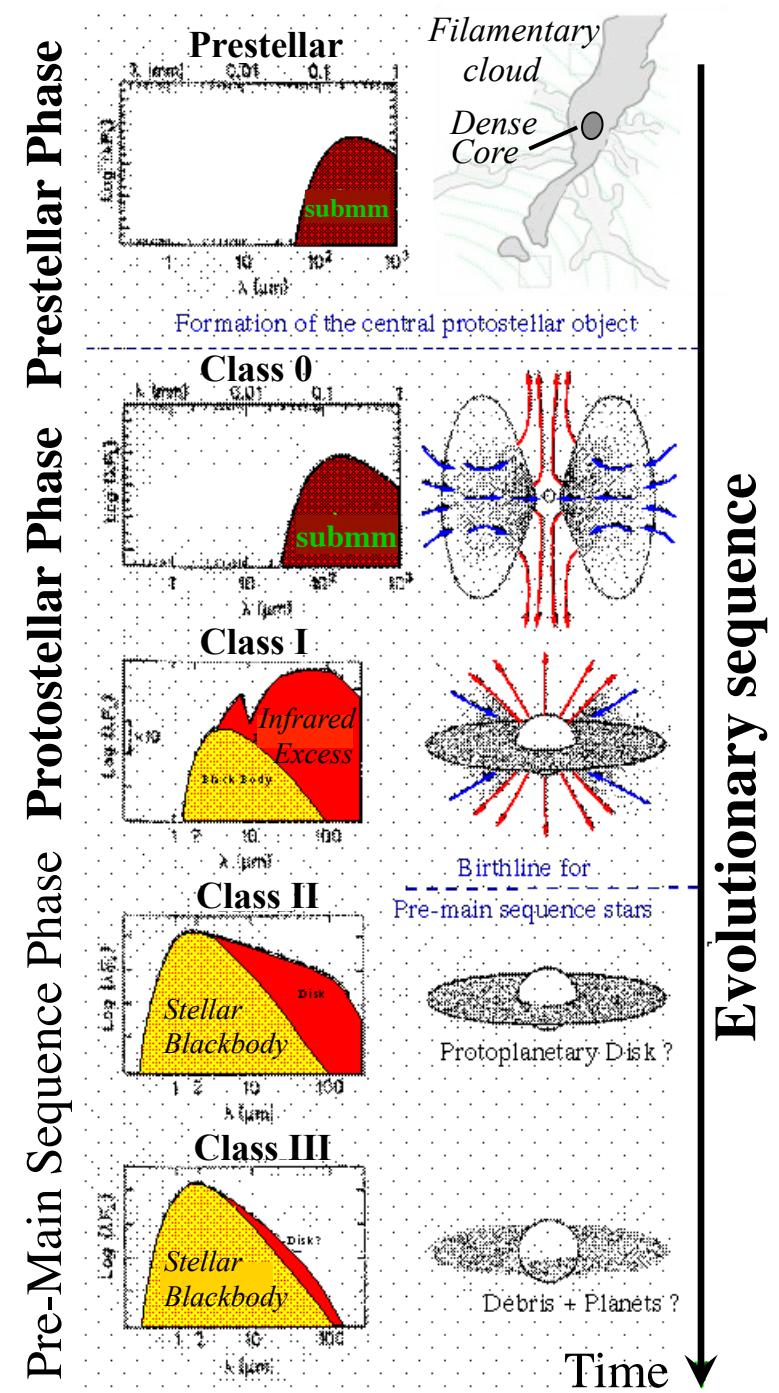
Schneider & Elmegreen 1979; Larson 1985; Inutsuka & Miyama 1997...

cf. Protostars & Planets VI chapter

(André, DiFrancesco, Ward-Thompson, Inutsuka, Pudritz, Pineda 2014)



- 1) Large-scale MHD compressive flows create ~ 0.1 pc-wide filaments
- 2) Gravity fragments the densest filaments into prestellar cores above $M_{\text{line,crit}} \sim 16 M_{\odot} \text{ pc}^{-1}$
- 3) Prestellar cores collapse to protostars/YSOs



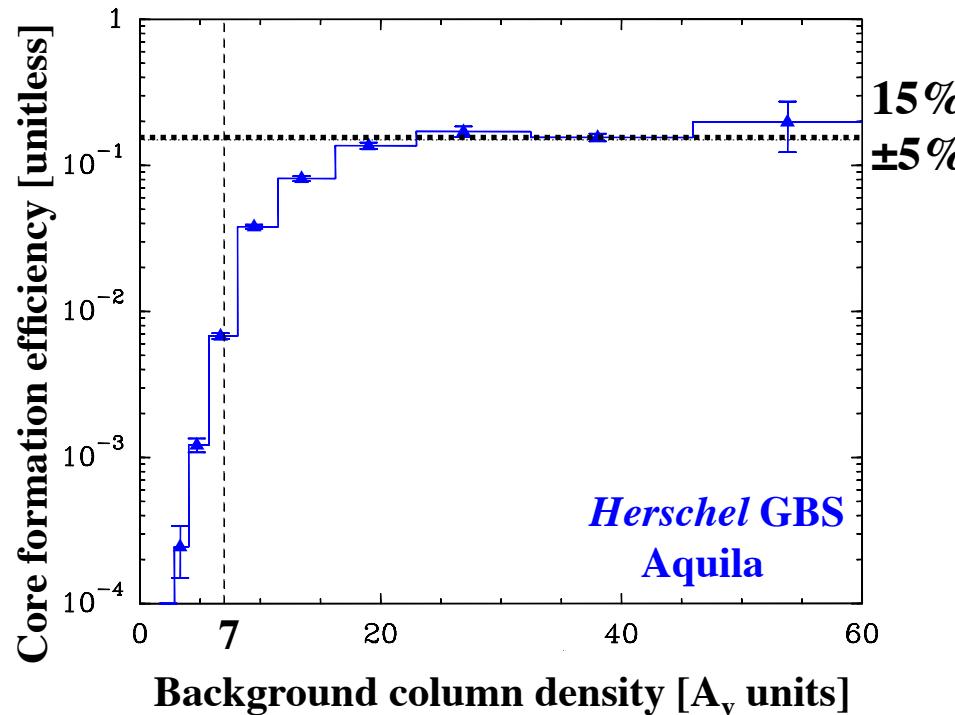
Importance of ISM filaments on galaxy-wide scales?

A characteristic prestellar core formation efficiency in dense gas filaments

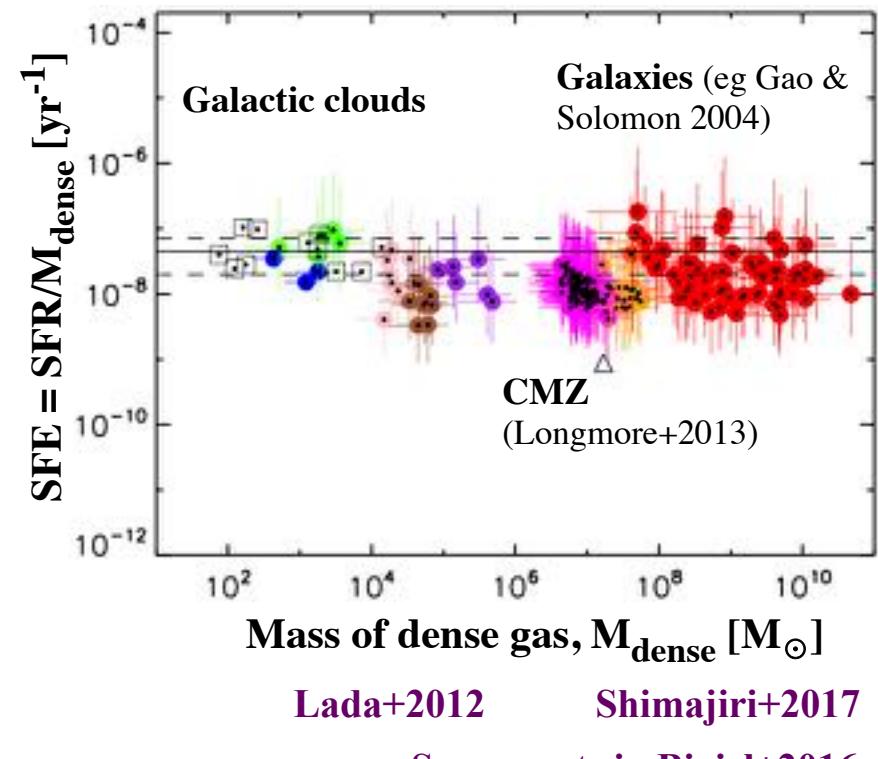


Responsible for a common star formation efficiency in the dense ($> 10^4 \text{ cm}^{-3}$) molecular gas of galaxies?

Prestellar CFE as a function of background A_V



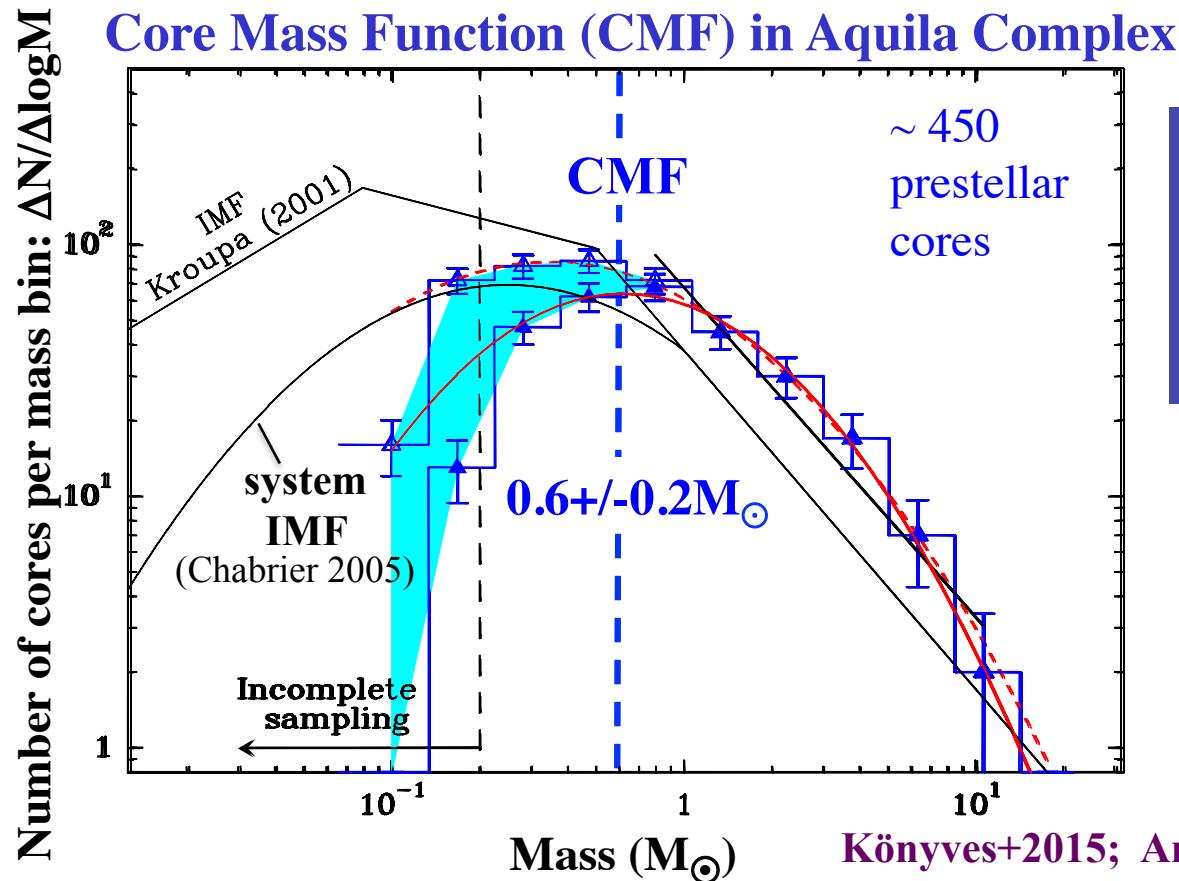
Könyves+2015



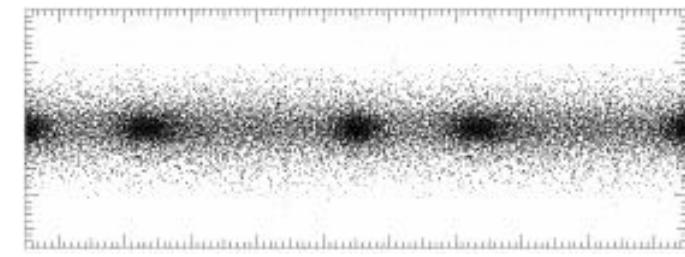
See caveats in Bigiel+2016

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

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



Jeans mass:

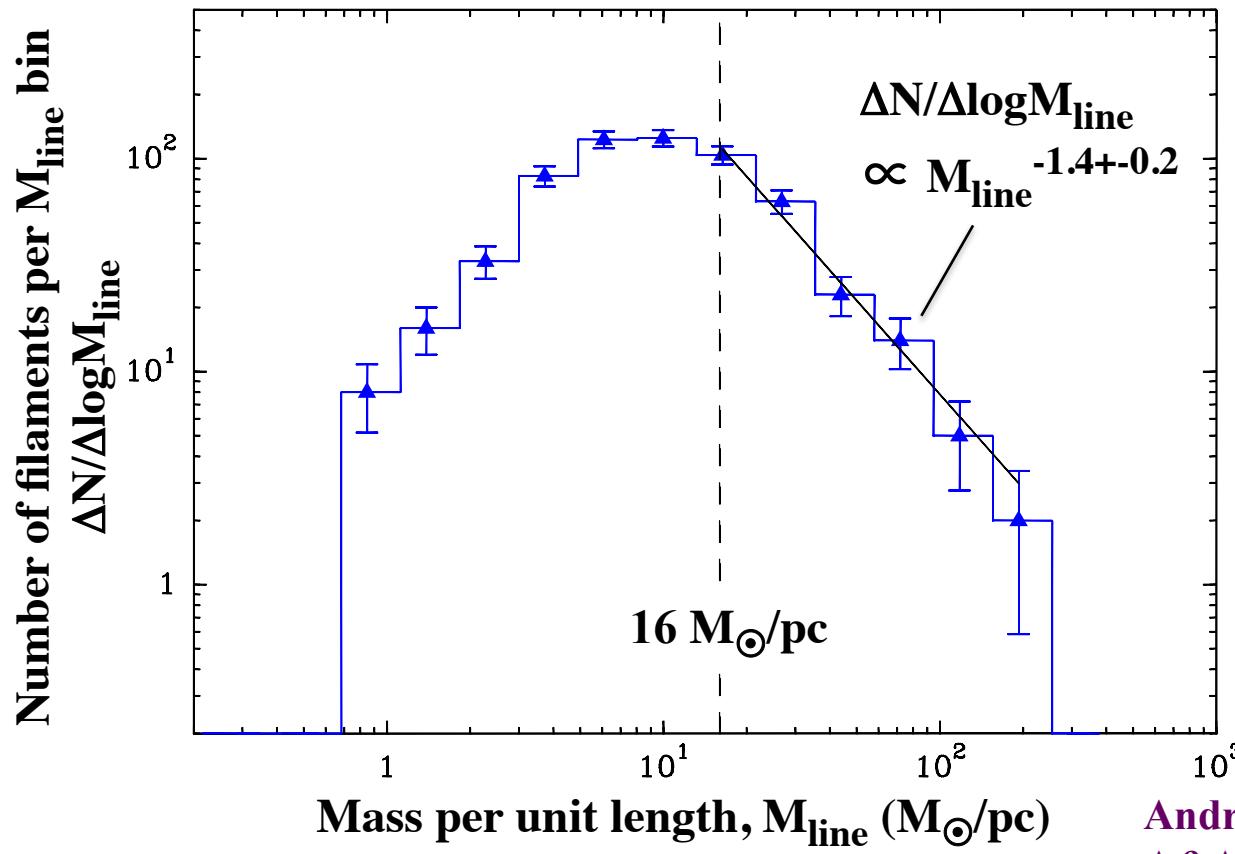
$$M_{\text{Jeans}} \sim 0.5 M_\odot \times (T/10 \text{ K})^2 \times (\Sigma_{\text{crit}}/160 M_\odot \text{ pc}^{-2})^{-1}$$


Inutsuka & Miyama 1997

- CMF peaks at $\sim 0.6 M_\odot \approx$ Jeans mass in marginally critical filaments
- Close link of the prestellar CMF with the stellar IMF: $M_\star \sim 0.4 \times M_{\text{core}}$
(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, Arzoumanian+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 ($M_{\text{line}} > 16 M_{\odot}/\text{pc}$) according to tests

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

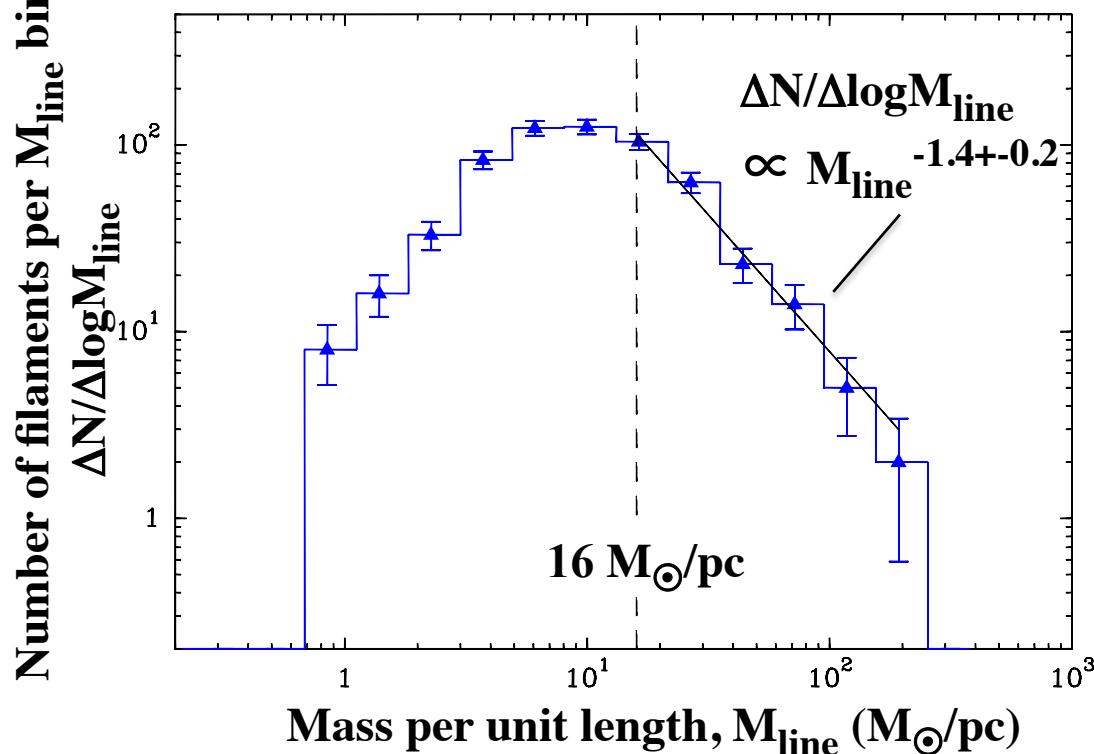
Local effective Jeans mass in a thermally supercritical filament:

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

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

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

Distribution of line masses for HGBS filaments



A&A, submitted
See also André+2014 PPVI

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

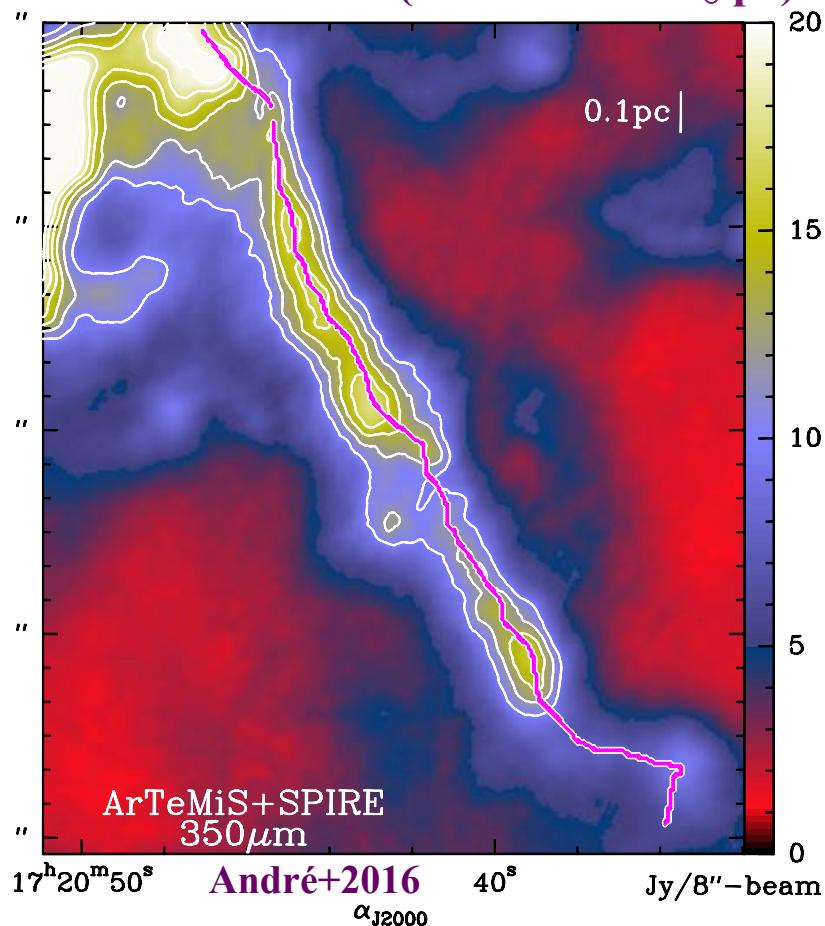
(Salpeter index: -1.35)

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)

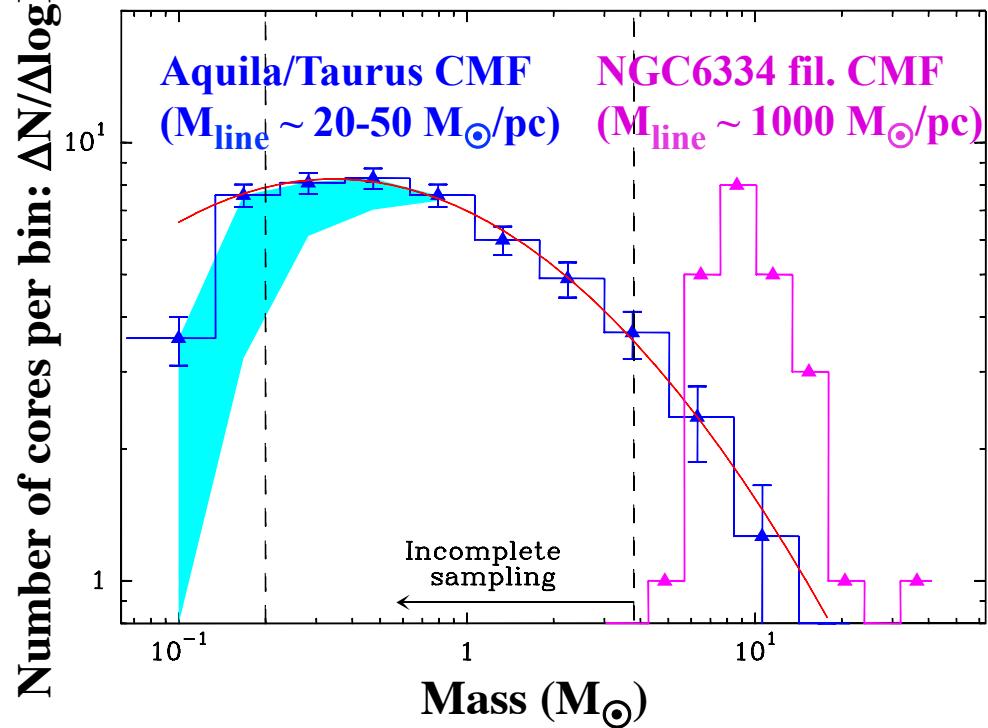
Tentative determination of the CMF resulting from a single (massive) filament: NGC6334 ($M/L \sim 1000 M_{\odot}/pc$)

$$W = 0.15 \pm 0.05 pc$$

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



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



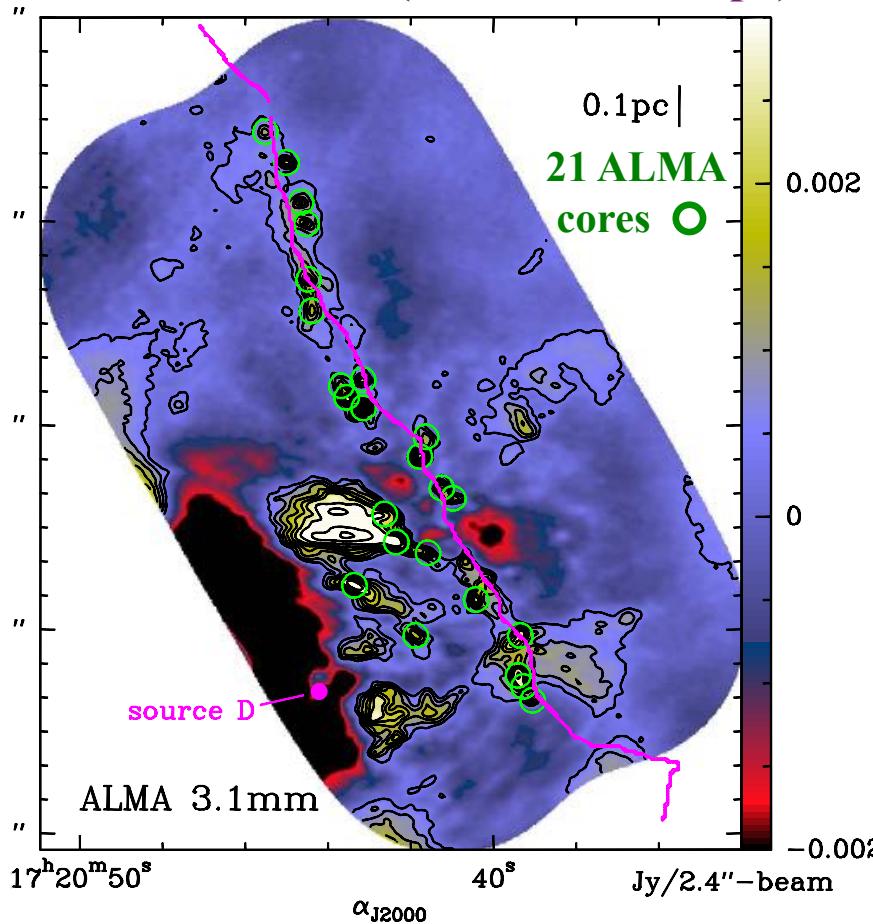
Shimajiri+2019, A&A, submitted

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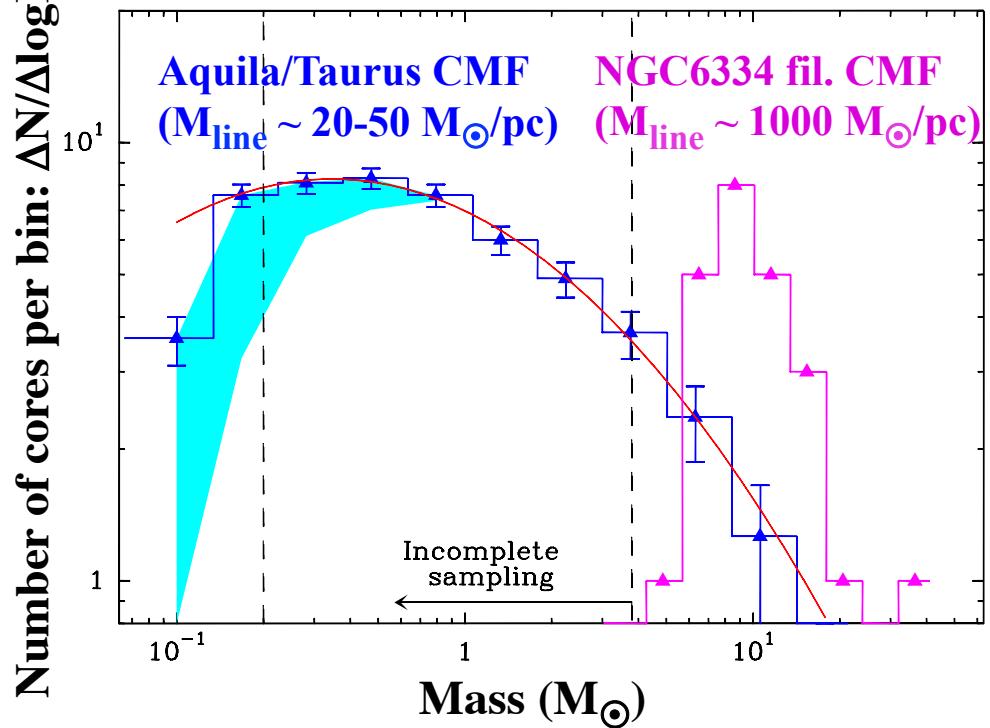
$$W = 0.15 \pm 0.05 pc$$

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

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

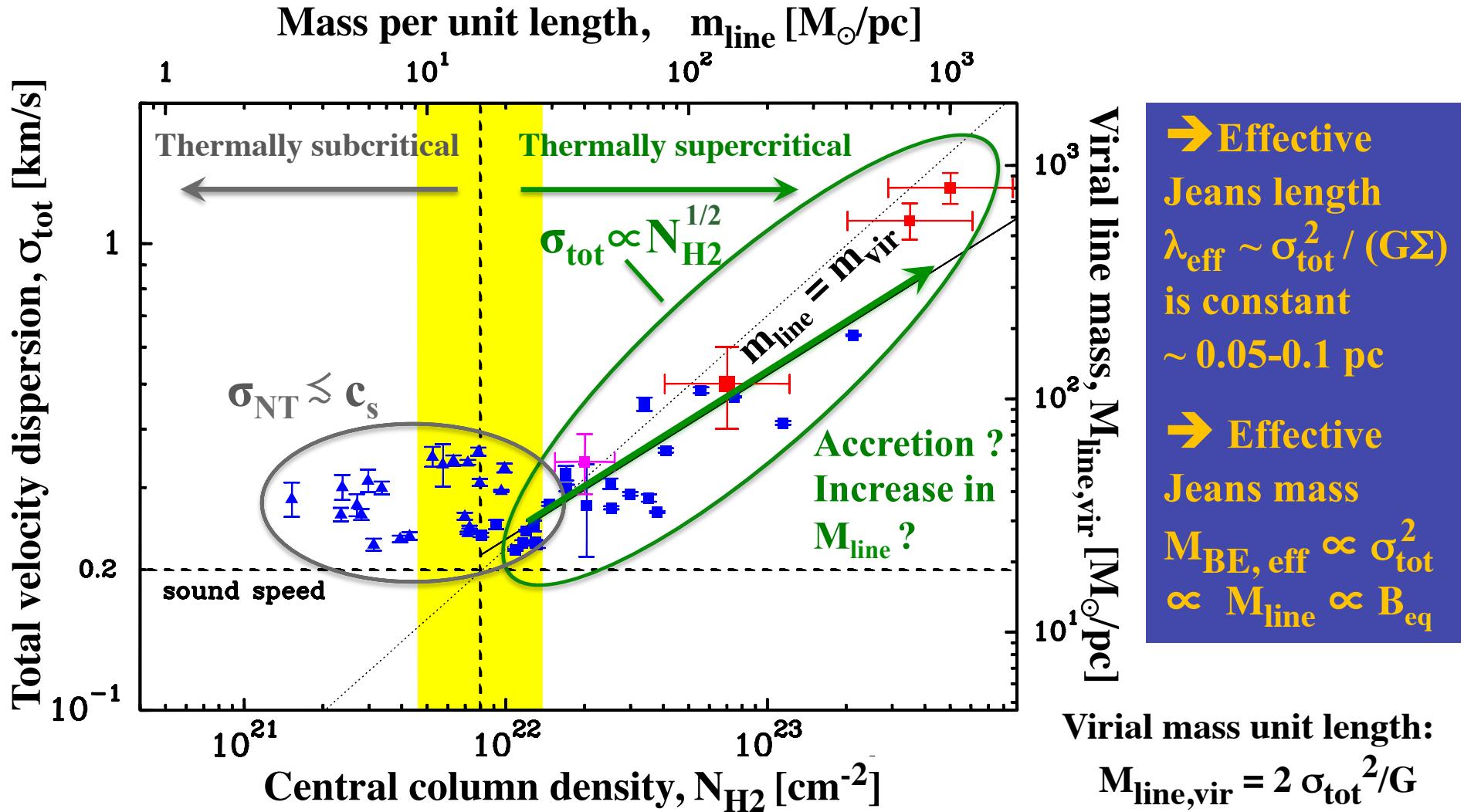


Comparison of the CMFs observed in nearby clouds/filaments and the NGC6334 filament



Shimajiri+2019, A&A, submitted

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

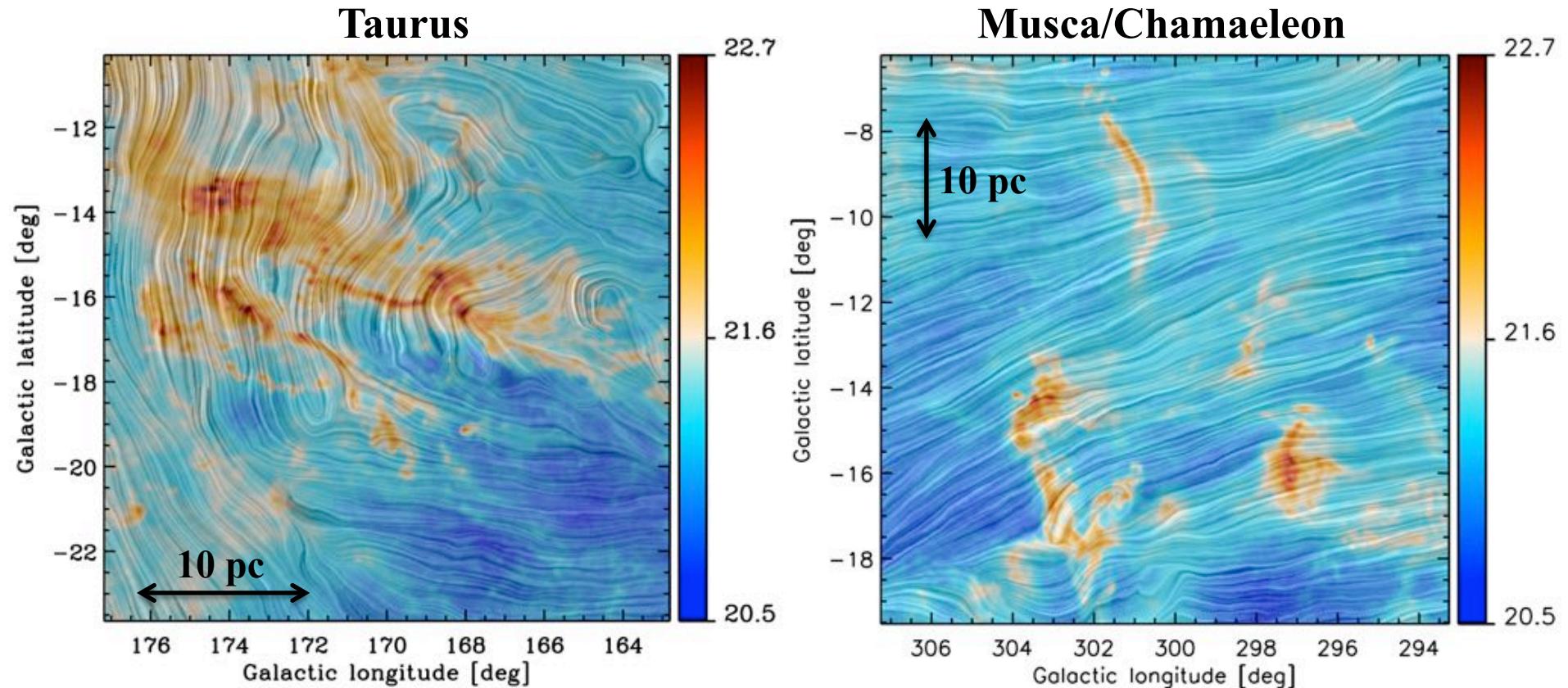


Arzoumanian+2013

(based on IRAM 30m/EMIR observations)

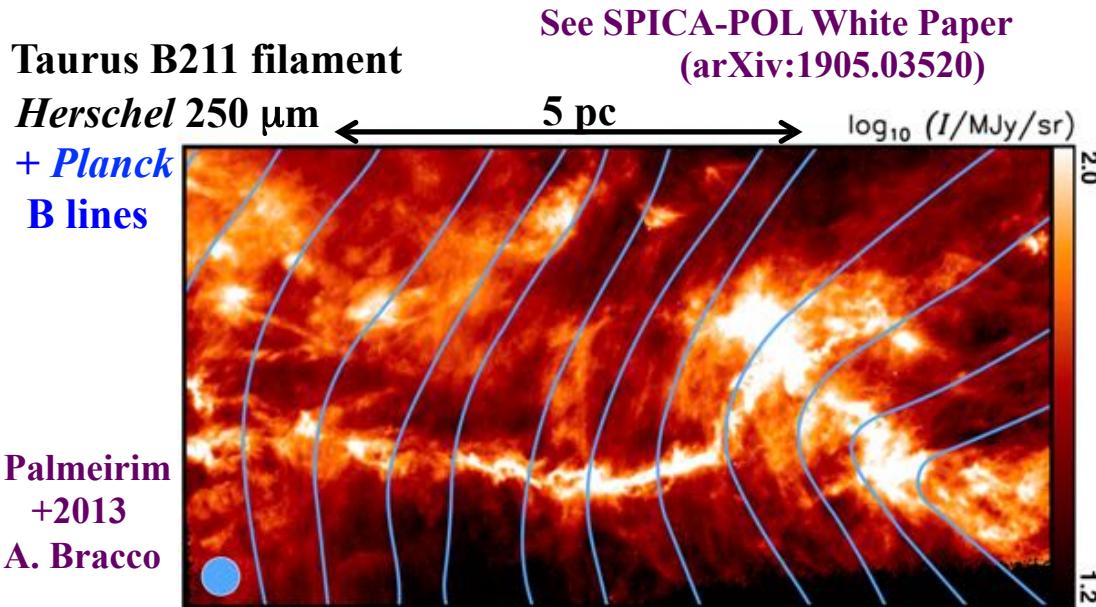
A major open issue: Role of magnetic fields?

- **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**

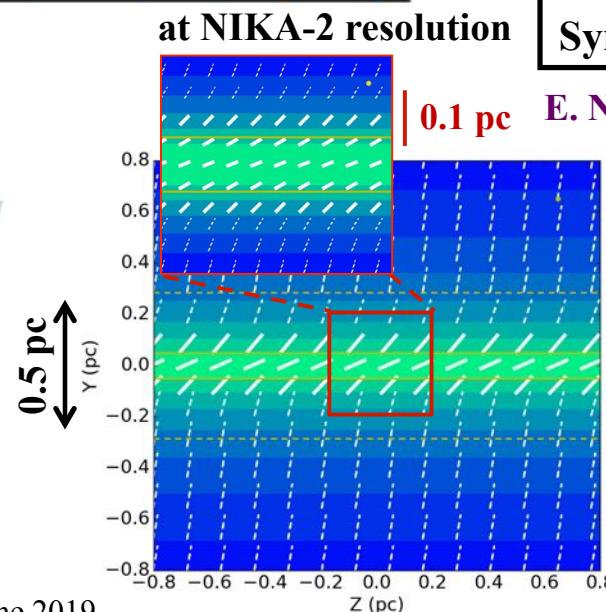
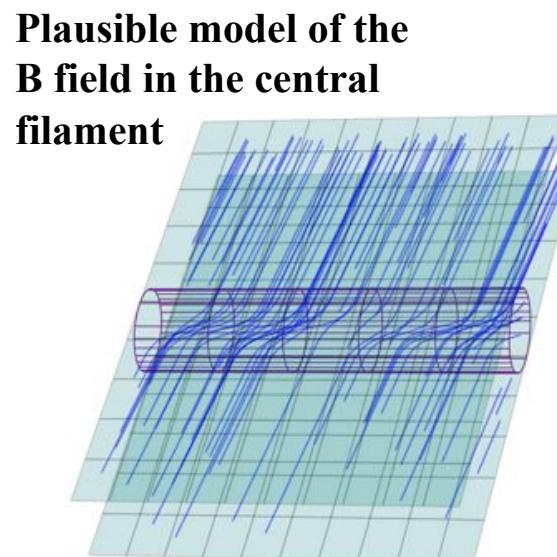


Planck intermediate results. XXXV. (2016 J. Soler) Color: N(H) from Planck data @ 5' resol. (~ 0.2-0.3 pc)
Suggests sub-Alfvénic turbulence on cloud scales Drapery: B field lines from Q,U Planck 850 μm @ 10'

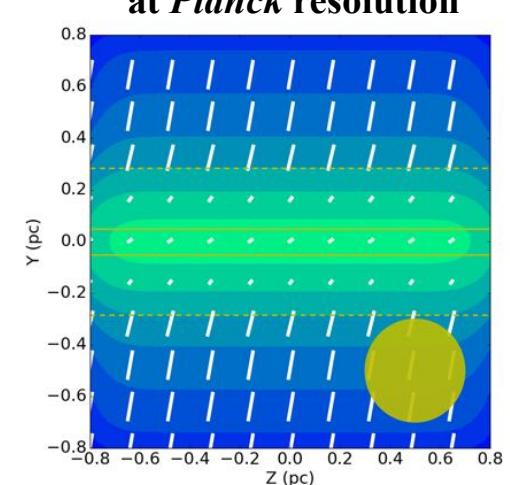
NIKA2-POL & SPICA-POL can unveil the role of magnetic fields in filament evolution and core/star formation



- *Planck* resolution ($> 10'$ or $> 0.4 \text{ pc}$) insufficient to resolve the 0.1 pc width of filaments.
Can be done with NIKA2 & SPICA.
- B fields within dense filaments may be key to prevent radial contraction and make SF possible.
(cf. Seifried & Walch 2015)

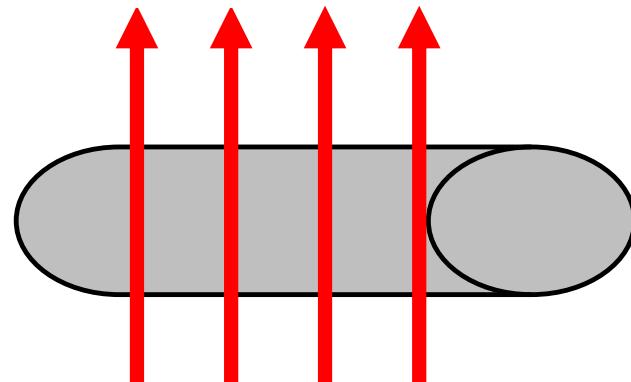


Synthetic polarization maps



Two simple magnetic field configurations

B-field perpendicular
to long axis of filament



B-field parallel
to long axis of filament

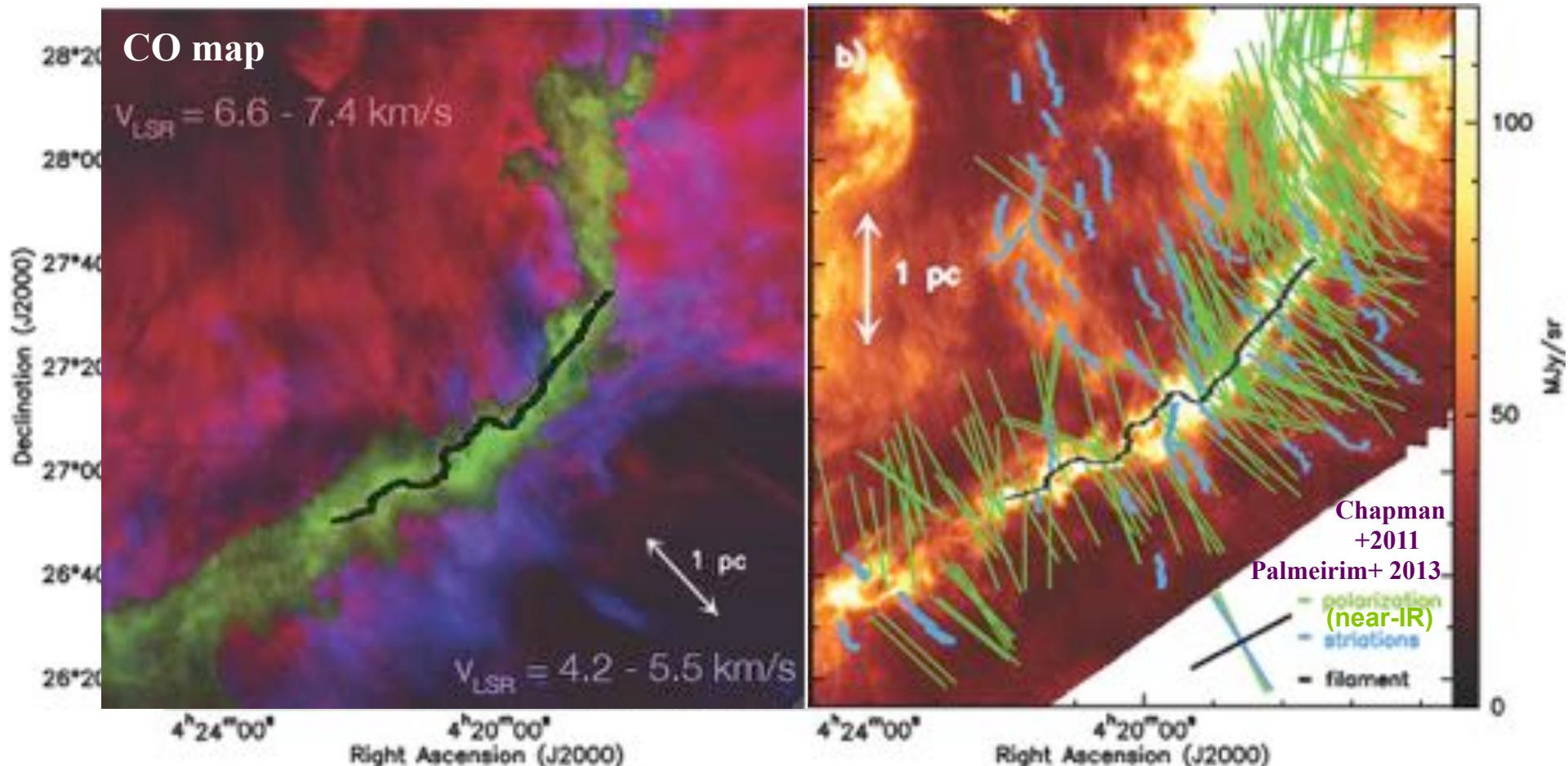


B-field cannot prevent
radial contraction of
filament,
but can regulate/slow
down fragmentation

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

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

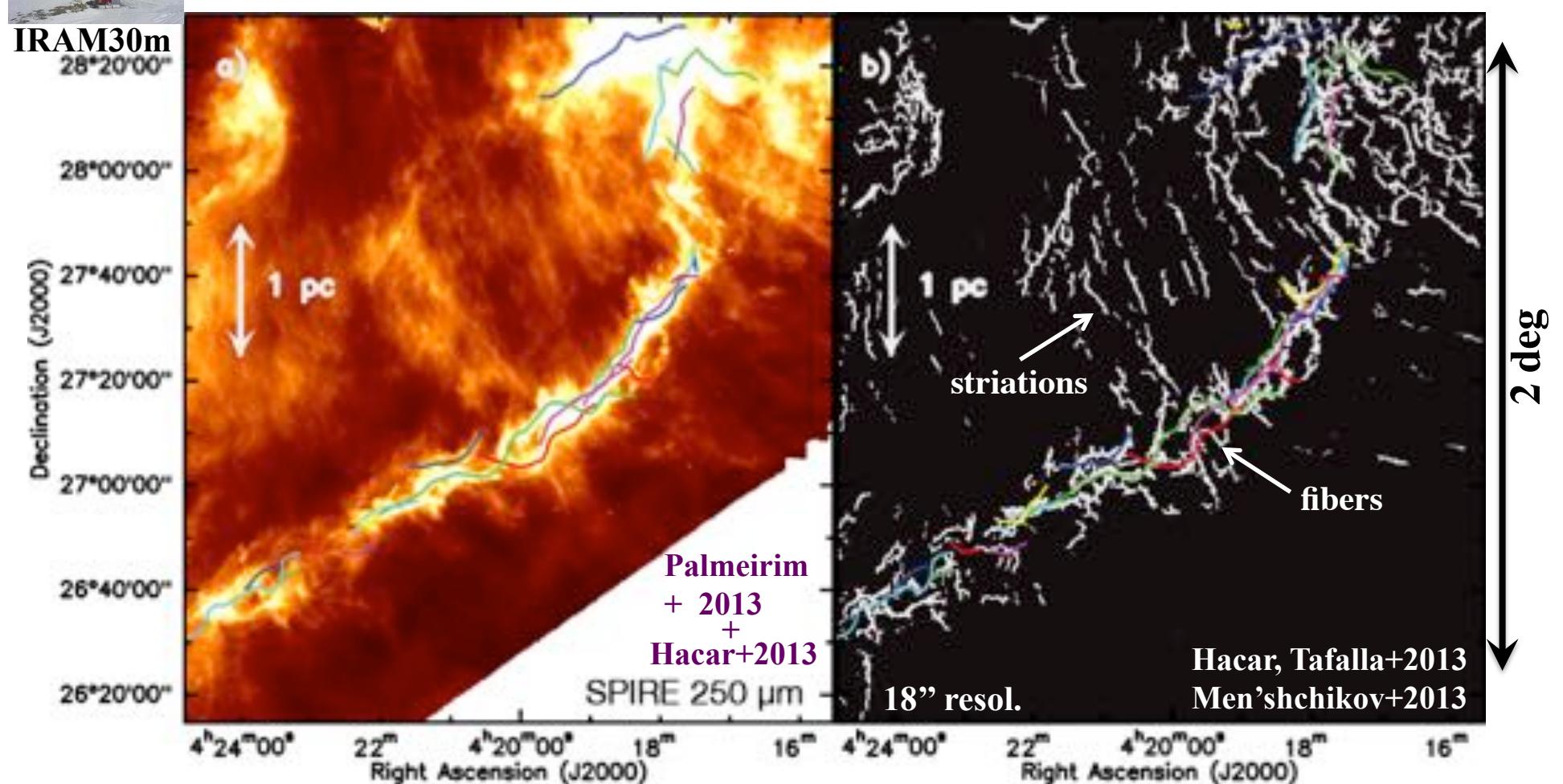
- Striations and sub-filaments are suggestive of accretion flows into the star-forming filaments - Tend to be // to the large-scale B field



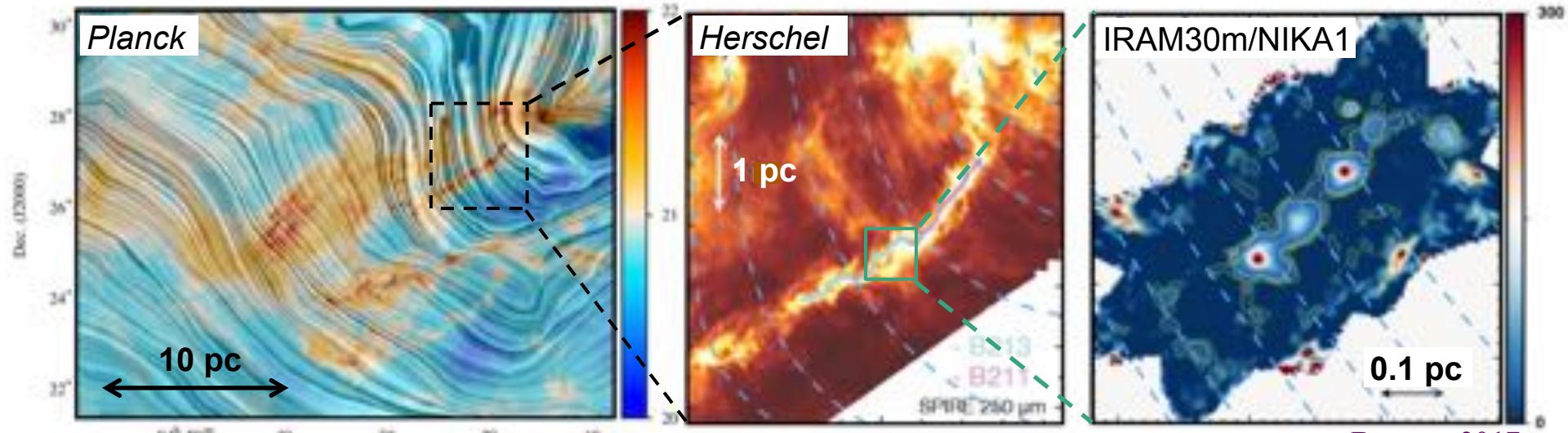
CO observations from Goldsmith+2008
Taurus B211/3: $M_{\text{line}} \sim 50 M_{\odot}/\text{pc}$

Estimated mass accretion rate:
 $\dot{M}_{\text{line}} \sim 50 M_{\odot}/\text{pc/Myr}$ Palmeirim+2013

NIKA2-POL LP ‘B-FUN’: High-resolution 1.2mm dust polarimetric imaging of ~10 nearby SF filaments (range of M/L)

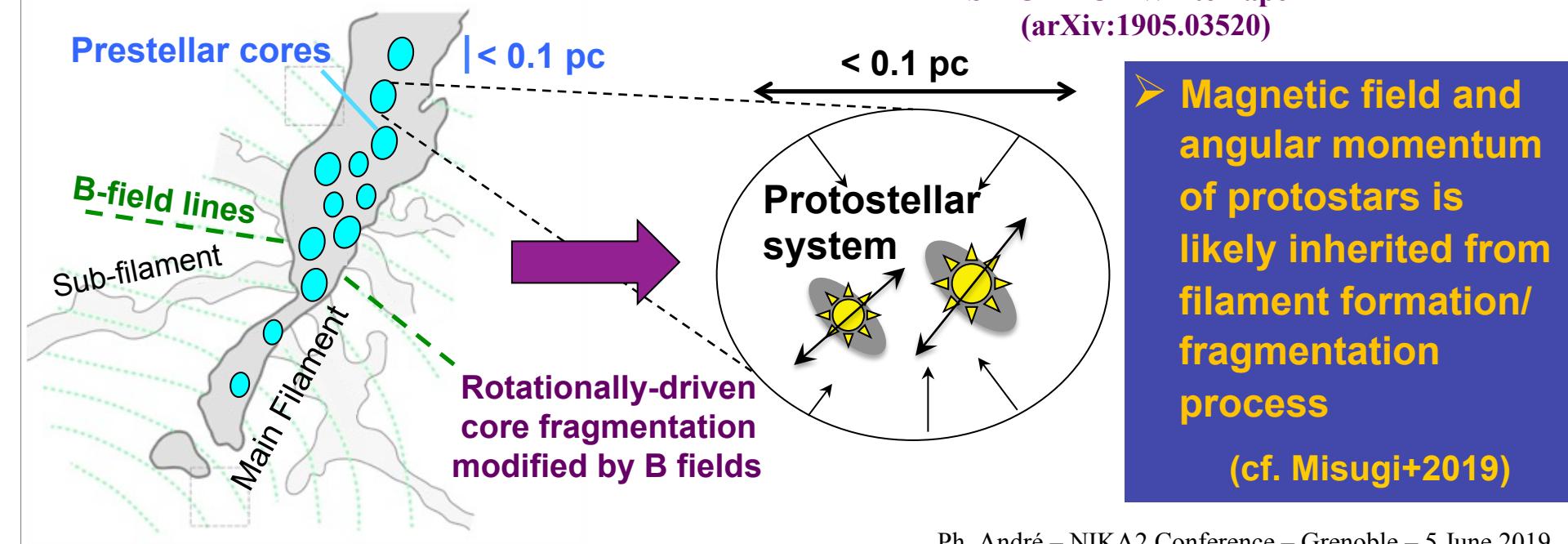


Role of B fields in regulating filament fragmentation and protostellar collapse to stellar/solar systems?



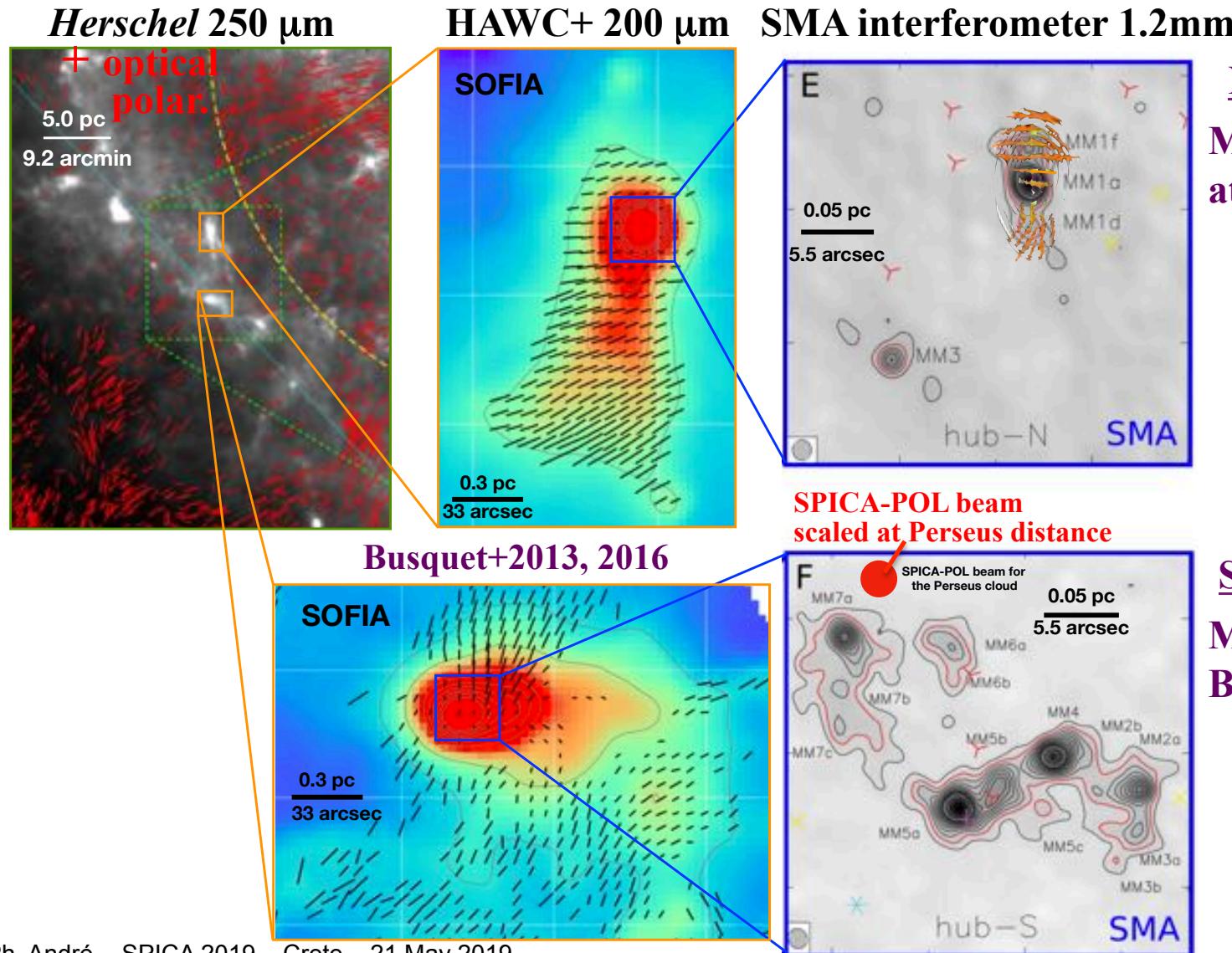
SPICA-POL White Paper
(arXiv:1905.03520)

Bracco+2017



Role of B fields in controlling the sub-fragmentation of dense cores and the typical outcome of protostellar collapse?

G14.225-0.506 massive IRDC

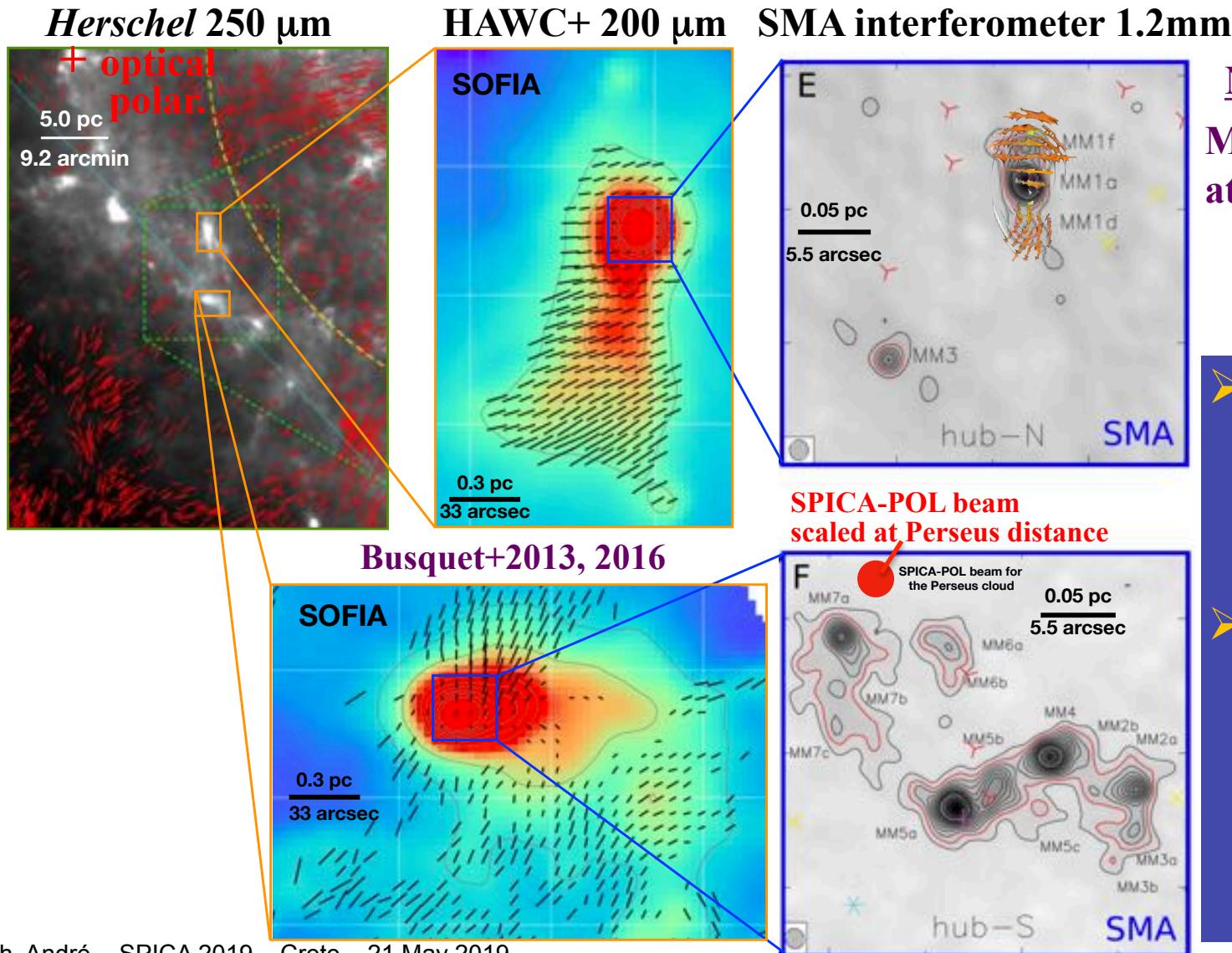


Northern « Hub »:
More regular B field at $\sim 0.1\text{-}0.3$ pc scales
→ Lower level of fragmentation

Southern « Hub »:
More perturbed B field at $\sim 0.1\text{-}0.3$ pc scales
→ Higher level of fragmentation

Role of B fields in controlling the sub-fragmentation of dense cores and the typical outcome of protostellar collapse?

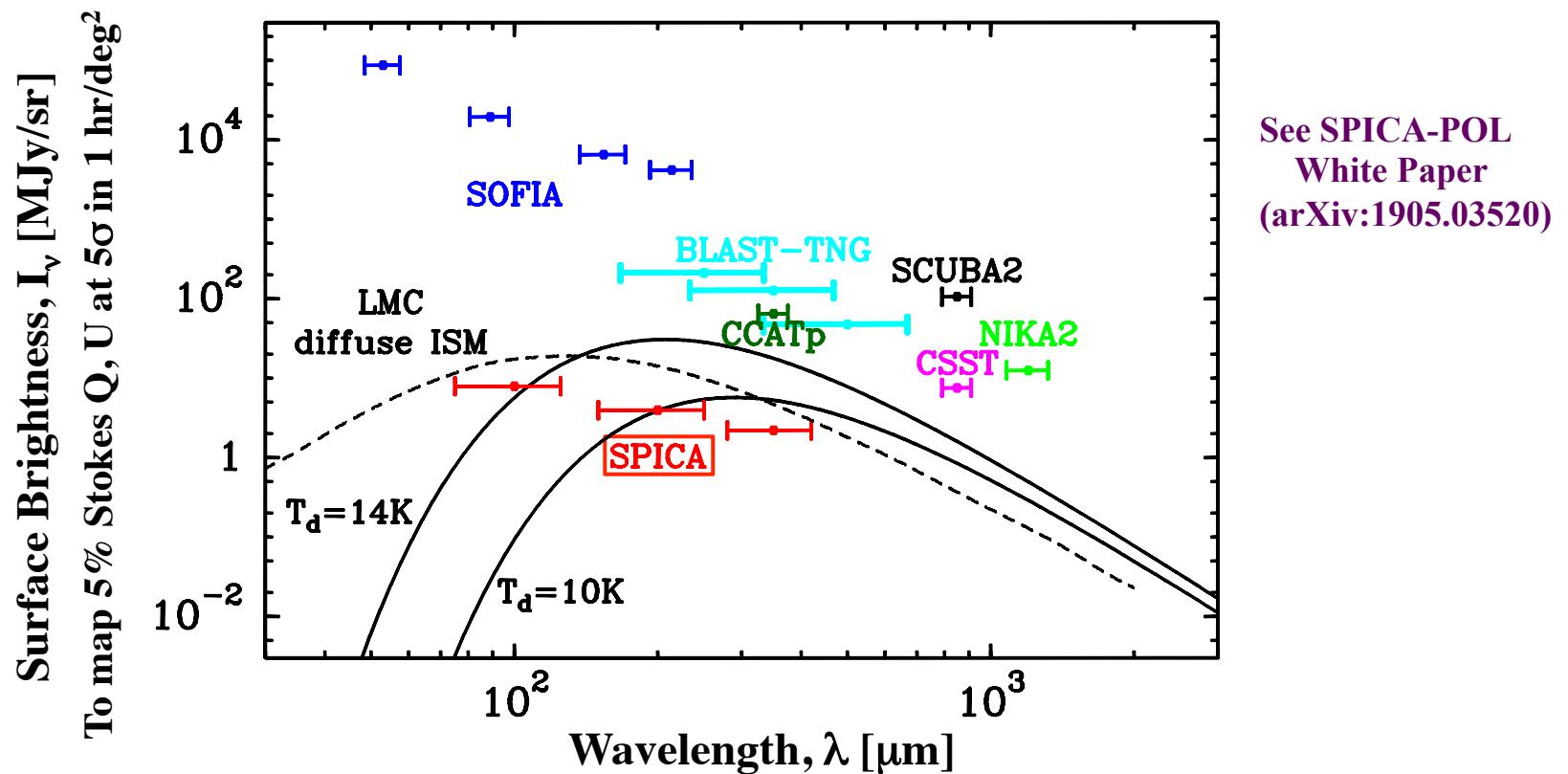
G14.225-0.506 massive IRDC



- Present studies limited to the few brightest regions only
- Interferometers (ALMA) cannot probe the magnetic connection between cores and filaments

SPICA: A future revolution in FIR polarimetric imaging (2032?)

- Thanks to a cooled telescope, SPICA-POL = B-BOP will be 2-3 orders of magnitude more sensitive (4-6 orders of magnitude faster) than other far-IR/submm imaging polarimeters



- B-BOP will deliver wide-field 100-350 μ m images of polarized emission (Stokes Q, U) with a resolution, S/N ratio, and intensity/spatial dynamic ranges comparable to *Herschel* images in total intensity (I).

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**
- **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/mm λ s with NIKA2-POL and SPICA-B-BOP can lead to **decisive progress**