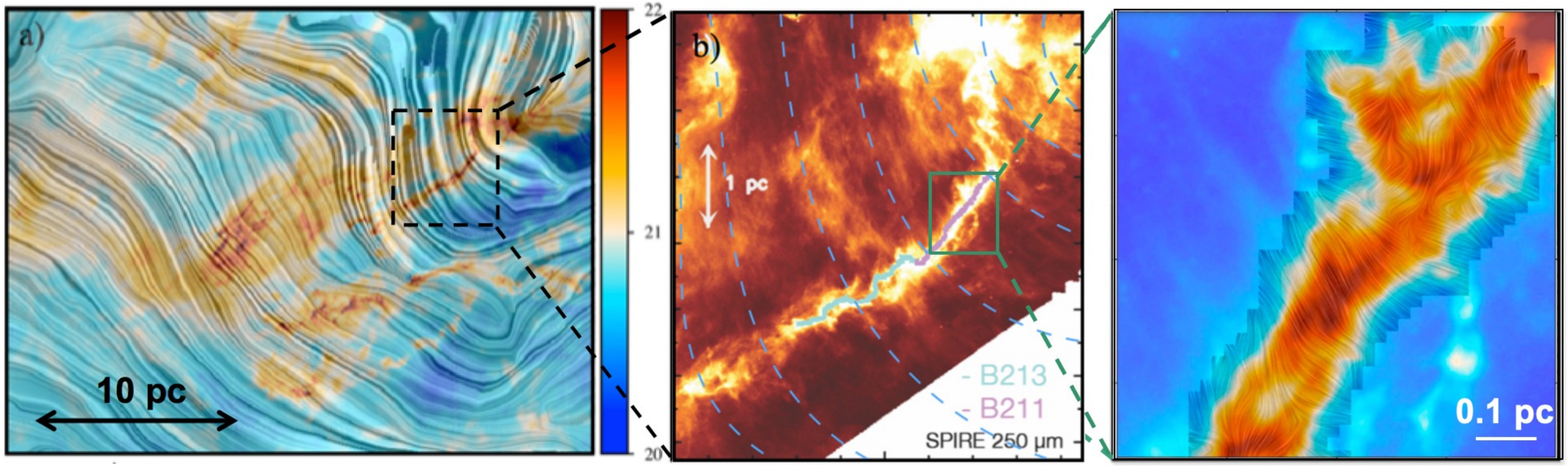
Probing magnetic fields and star formation in filamentary clouds with far-infrared polarimetric imaging

From *Herschel/Planck/*SOFIA to the next large far-IR space telescope

Ph. André CEA - Lab. AIM Paris-Saclay

Thanks to: D. Arzoumanian, H. Ajeddig, A. Bracco, T.-A. Duong, M. Mattern, Y. Shimajiri,
F. Schuller + L. Rodriguez, V. Revéret

Heritage of SOFIA – Scientific Highlights and Future Perspectives – 22 Apr 2024

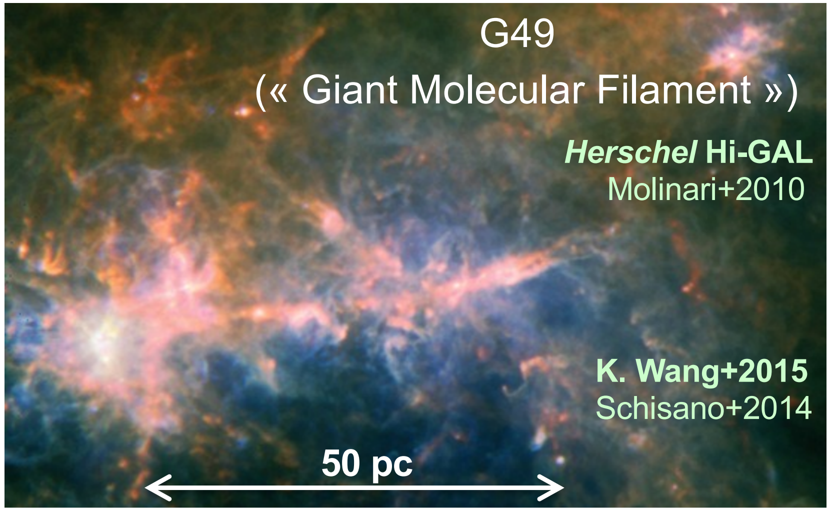


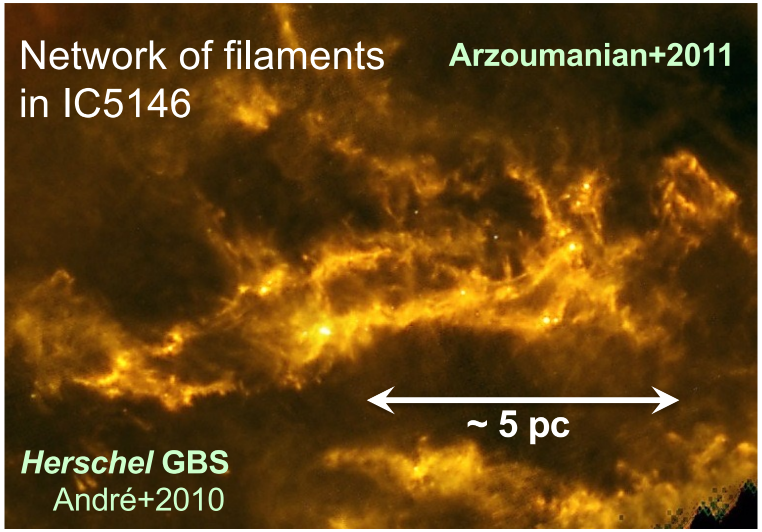
Taurus: *Planck*

Herschel + *Planck*

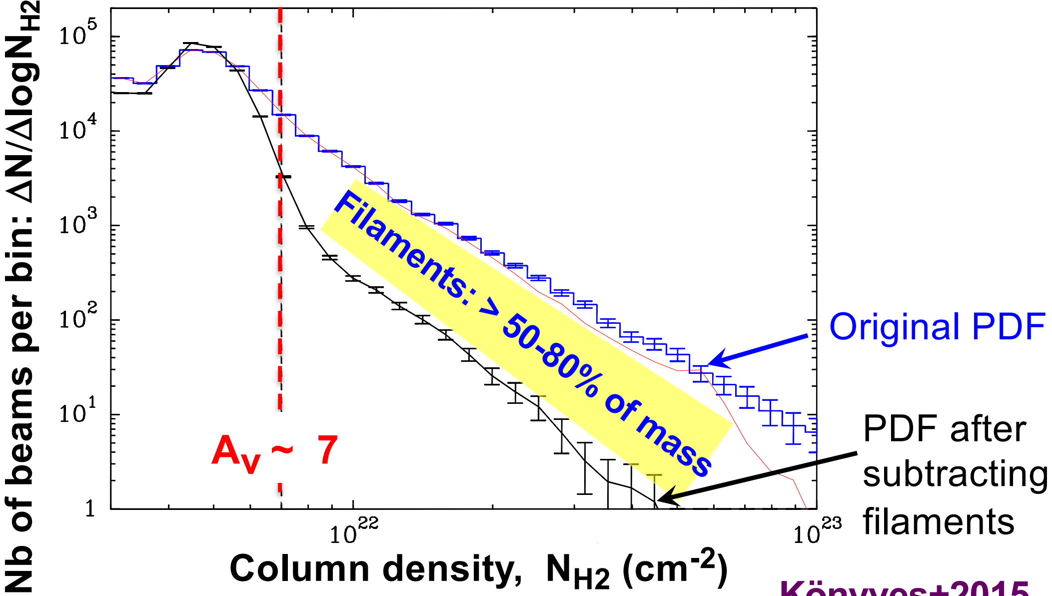
Herschel + SOFIA/HAWC+

Herschel results show that filaments dominate the mass budget of GMCs at high (column) densities





Herschel (HGBS)
Column Density PDF for Aquila GMC



Könyves+2015

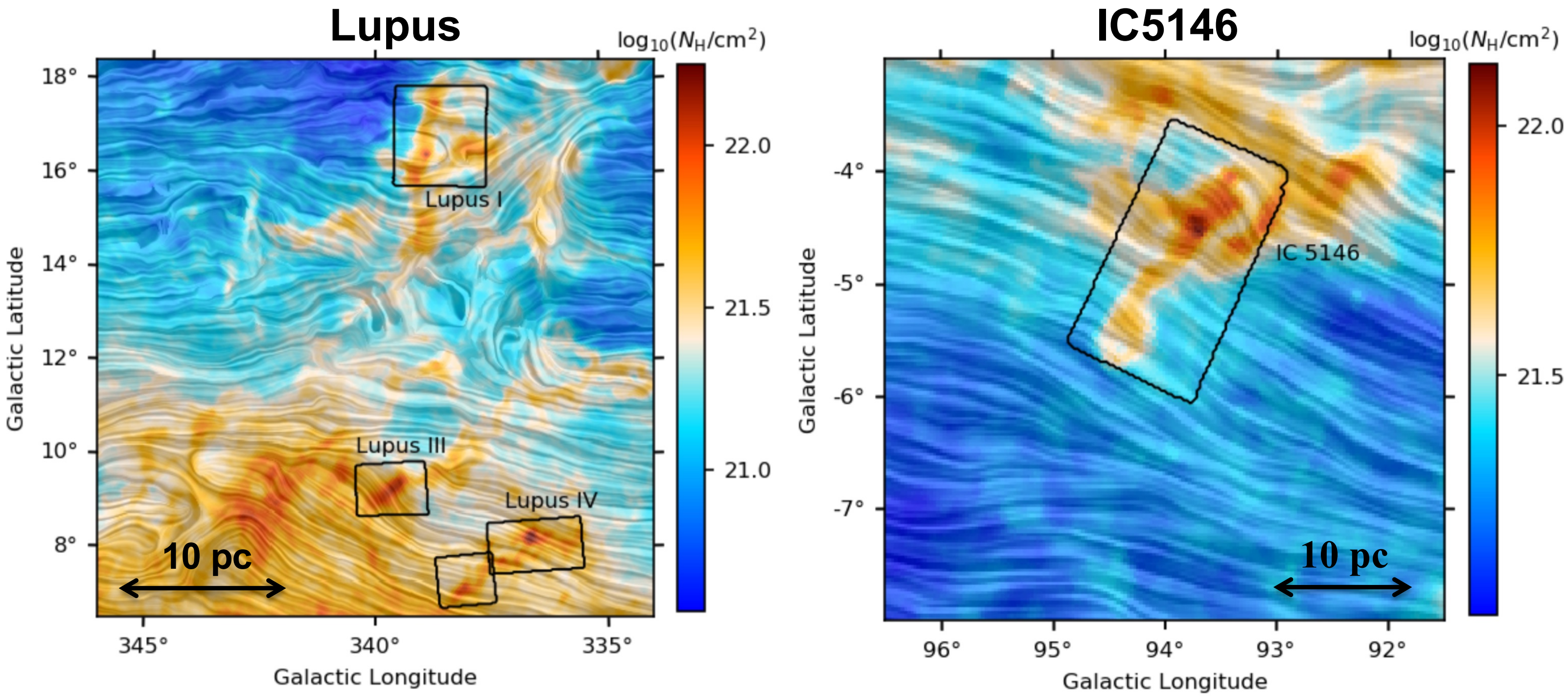
- Below A_V ~ 7: ~ 10-20 % of the mass in the form of filaments
- **Above A_V ~ 7: > 50-80 % of the mass in the form of filaments**

Arzoumanian+2019

(see also Schisano+2014
based on Hi-Gal data)

Planck polarization results show that ISM filaments are magnetized

- **Highly organized B field on large scales**
  ~ perpendicular to dense star-forming filaments, ~ parallel to low-density filaments



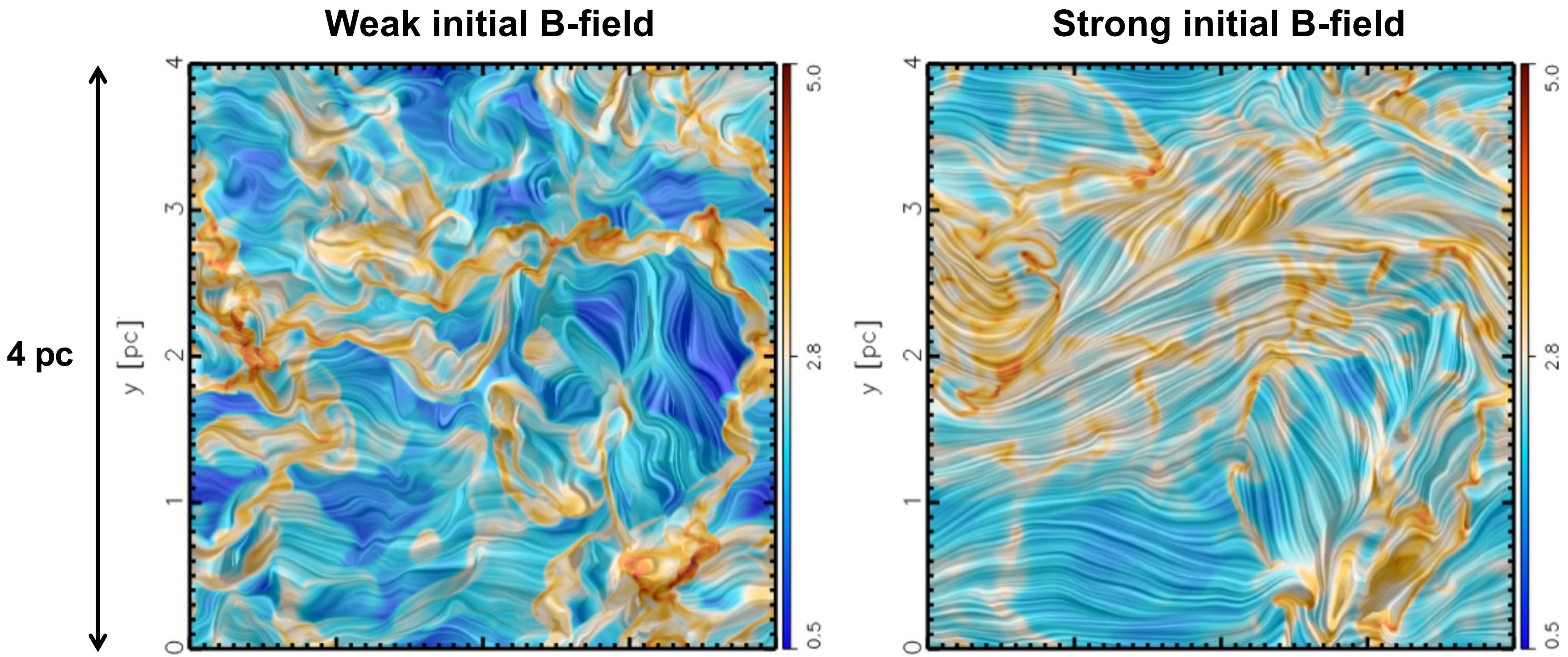
Color: N(H) from Planck data @ 5' resol. (~ 0.2-0.3 pc)

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

Planck 2015 intermediate results. XXXV.
Soler 2019

Planck polarization results suggest that the B-field is « strong »/significant

- **Comparison with numerical MHD simulations of cloud structure formation/evolution**



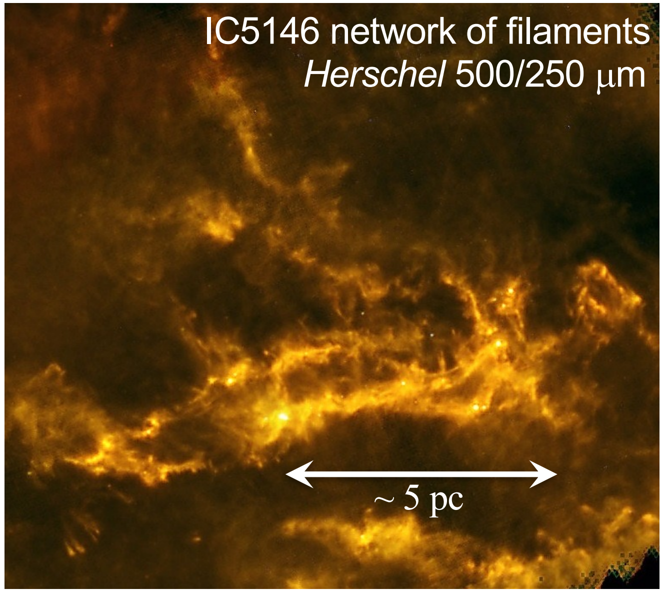
B-field aligned with filamentary density structures

Filamentary structures parallel to B-field at low N_{H2}
but perpendicular at high N_{H2}

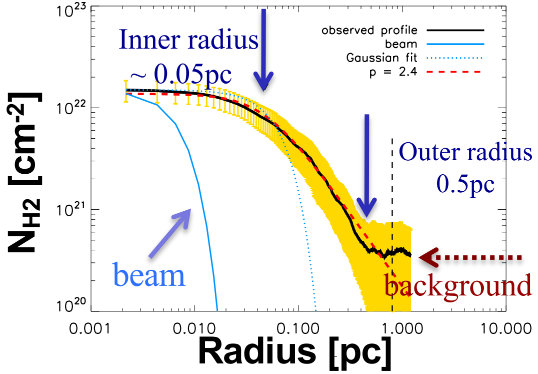
- **Sub-Alfvénic turbulence on pc scales**

Planck 2015 int. res. XXXV; Soler & Hennebelle 2017

Herschel observations of nearby (< 500 pc) clouds suggest that filaments have a common half-power width ~0.1 pc ~ sonic scale of ISM turbulence



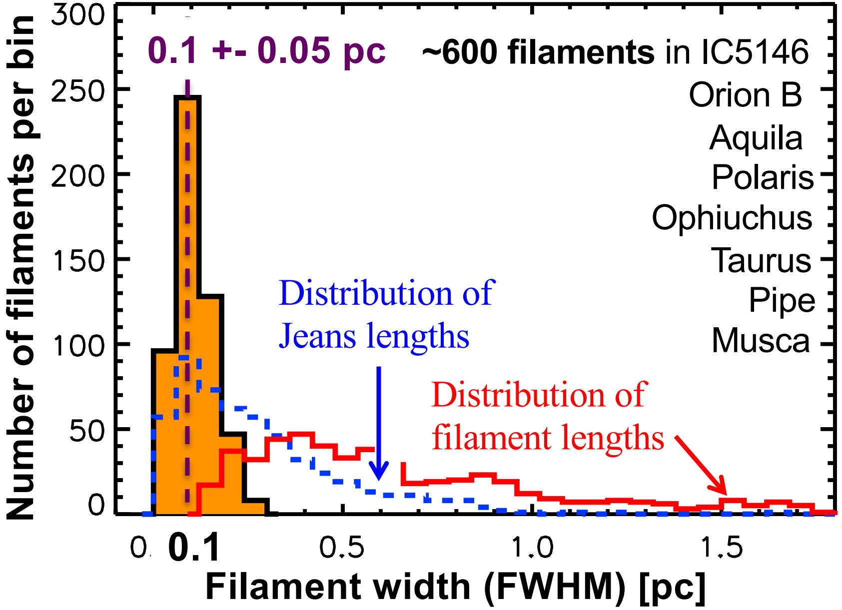
Example of a filament radial profile



Arzoumanian+2011
Palmeirim+2013

A characteristic scale for SF?

Nearby filaments have a common inner width ~ 0.1 pc



D. Arzoumanian+2011, 2019 [see also Koch & Rosolowsky 2015; André+2022]

May correspond to the magneto-sonic scale of turbulence

(cf. Padoan+2001; Federrath 2016)

Challenging for numerical simulations but very promising recent MHD results

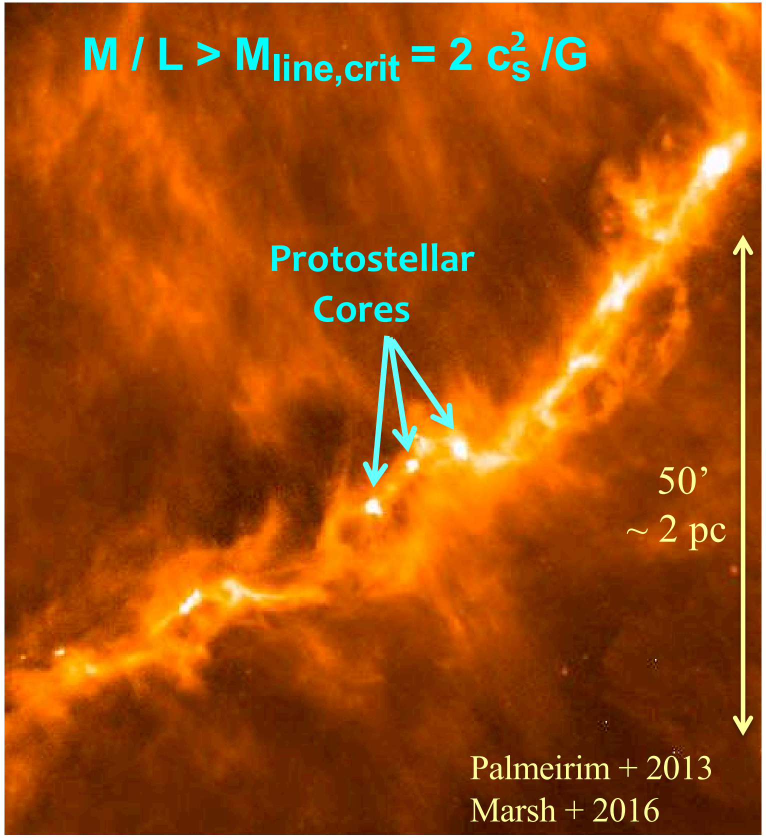
(cf. R. Smith+2014; Ntormousi+2016) (Abe, Inoue, Inutsuka+2024)

Herschel results show that molecular filaments play a key role in the star formation process → A filament paradigm for ~$M_\odot$ core/star formation

~ 75^{+15}_{-5}% of prestellar cores form in supercritical or transcritical filaments, above a typical column density $N_{H_2} \gtrsim 7\times10^{21}$ cm^{-2} <=> $\Sigma \gtrsim 160\ M_\odot/pc^2$

$M / L \gtrsim 16\ M_\odot/pc \sim M^{th}_{line,\,crit}$

cf. Protostars & Planets VI chapter (André+2014)

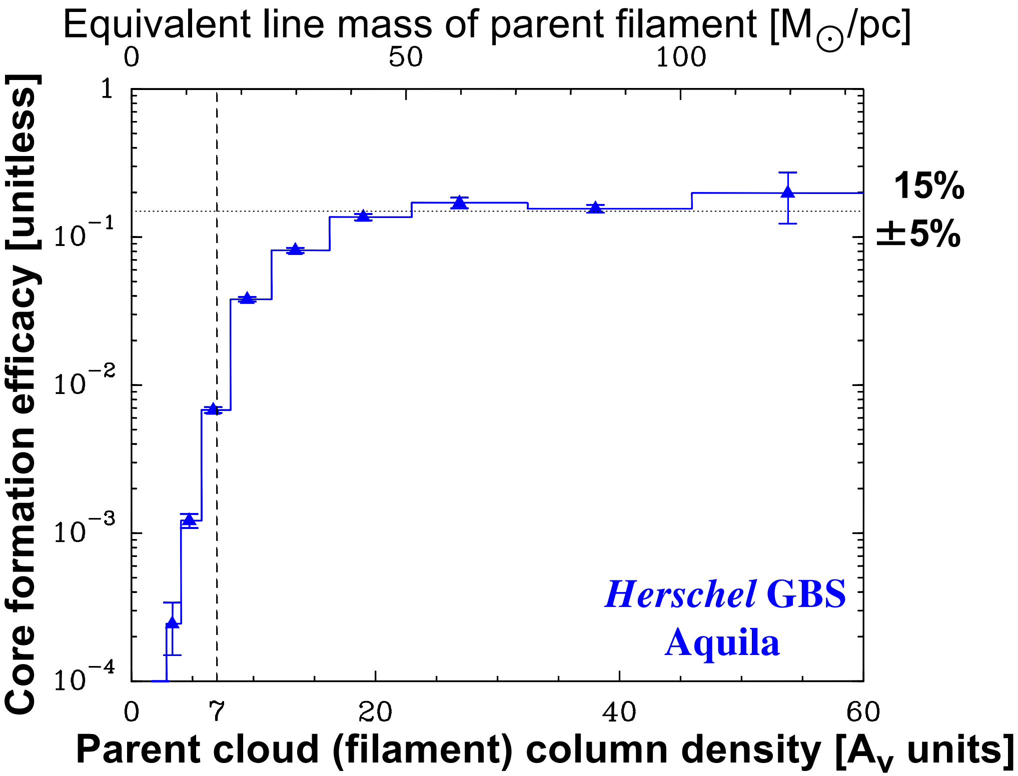


Taurus B211/3 – *Herschel* 250 μm

Könyves+2015, 20;
Marsh+2016;
Bresnahan+18;
Ladjelate+2020;
Di Francesco+2020

$$\mathrm{CFE}(A_V) \equiv \frac{\Delta M_{cores}(A_V)}{\Delta M_{cloud}(A_V)}$$

Core Formation Efficiency versus background A_V



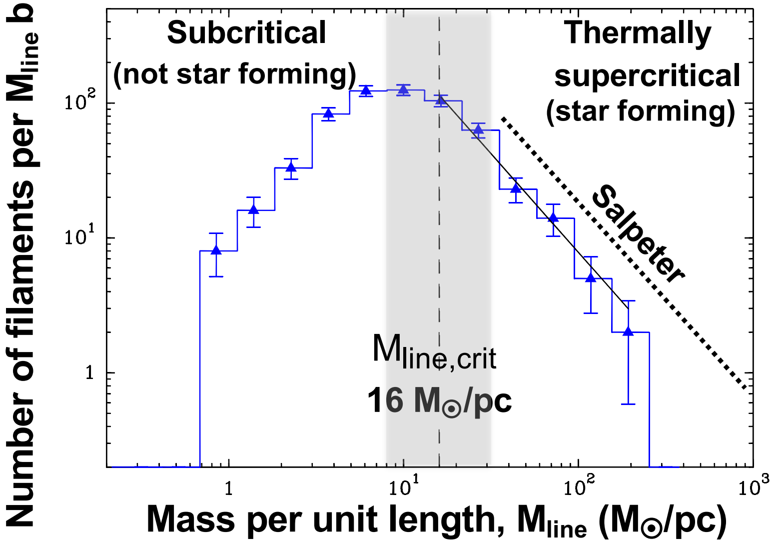
A filament scenario for ~$M_\odot$ core/star formation and the 'base' of the prestellar CMF / stellar IMF?

Thermal Jeans mass: $M_{BE,\,th} \sim 1.3\, c_s^4/(G^2\Sigma_{fil})$ or $M_{BE,\,th} \sim 0.5\, M_\odot \times (T/10\, K)^2 \times (\Sigma_{crit}/160\, M_\odot pc^{-2})^{-1}$ (in transcritical filaments)

Most star-forming filaments are transcritical

(M / L within a factor 2 of $M_{line,crit}$)

Filament Line Mass Function for *Herschel* GBS filaments



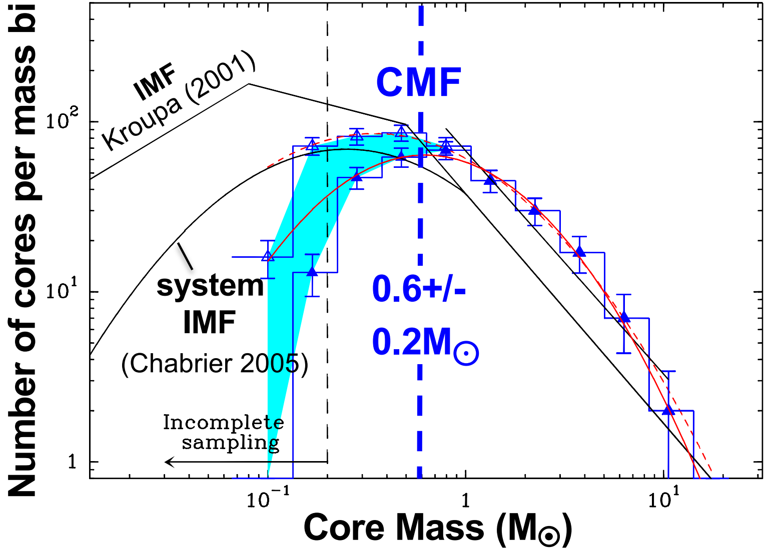
André+2019

➔

Base of the prestellar CMF from the fragmentation of transcritical filaments

(CMF peak ~ Jeans mass in transcritical filaments)

Prestellar Core Mass Function (CMF)



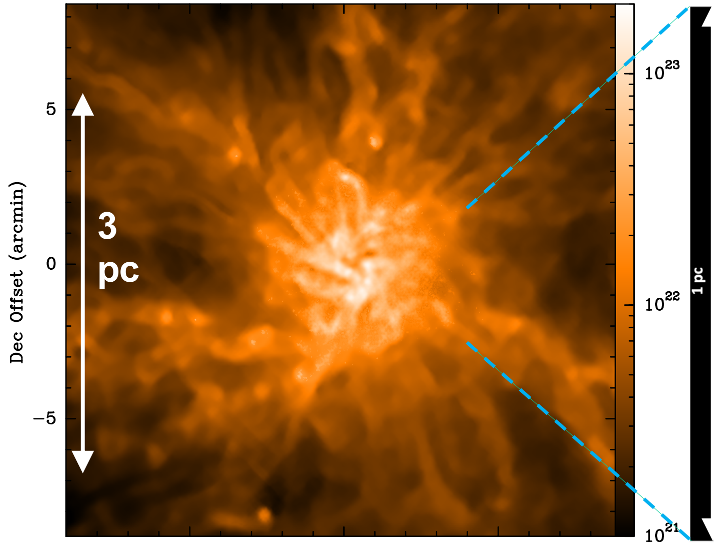
Könyves+2015; Di Francesco+2020

Magnetized filamentary accretion plays a key role in massive SF

- **Massive prestellar cores may not exist; high-mass protostars gather mass from pc-scale `hub-filament' systems** = networks of converging filaments with signs of global collapse (Myers 2009; Peretto+2013/14)

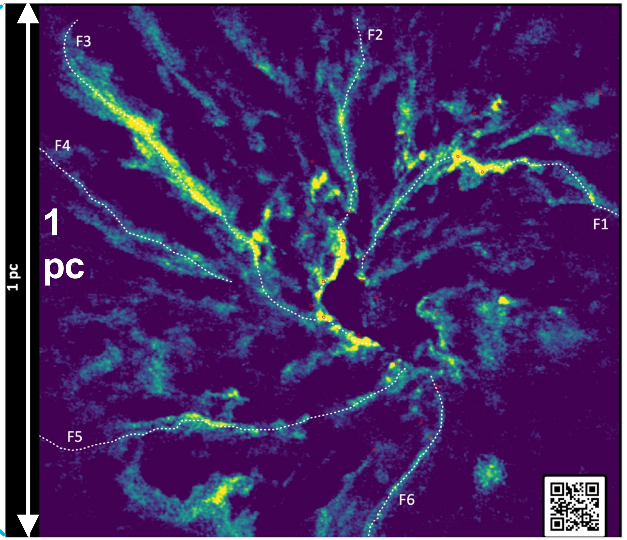
MonR2 Example: HFS with spiral-like structure + rotation/infall motions – B-field follows spiral pattern

ArTéMiS+*Herschel* N_{H2} map (8" res.)



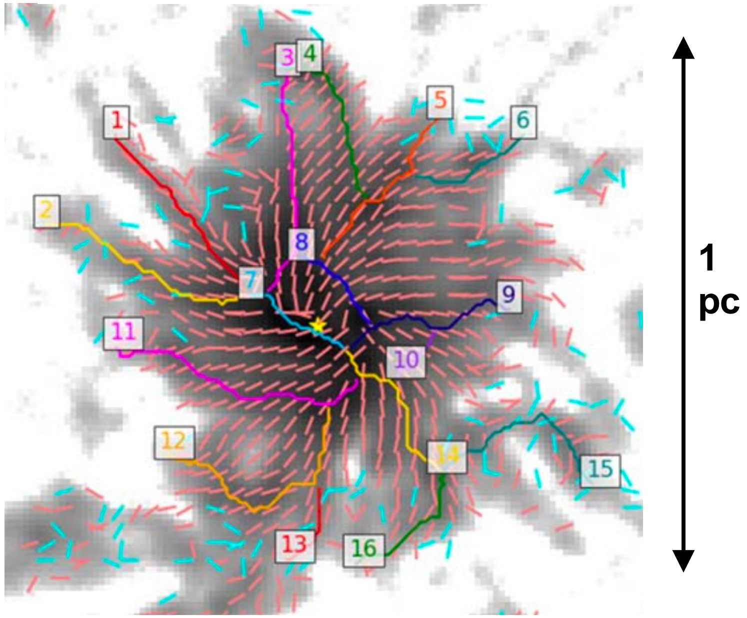
Mattern+2024

ALMA $C^{18}O$(1-0) map



Trevino-Morales+2019

SCUBA2/POL2 850 μm B-field map



Hwang+2022 (BISTRO project)

- Close to ~100% of O-type stars may form in dense ($A_V >> 100$, $M/L > 100 \times M_{line,crit}$) 'ridges'/'hubs' at the junctions of (supercritical) filaments (cf. Schneider+2012)

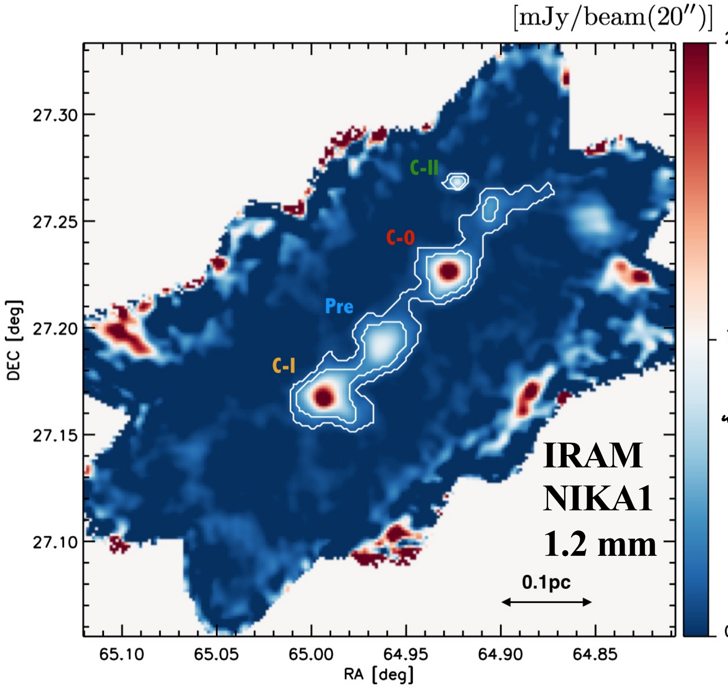
Motte+2018; Kumar, Palmeirim+2020

Detailed fragmentation manner of filaments? Role of B-fields?

- Low- and high-M_{line} supercritical filaments appear to have similar widths and fragmentation spacings ~ 0.1 pc ~ effective Jeans length

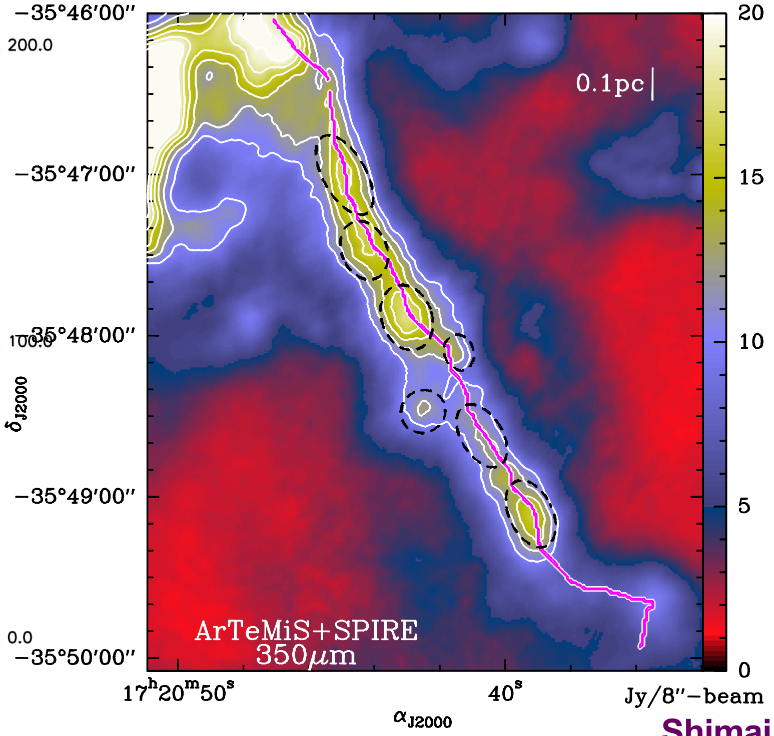
Low-mass filament: Taurus/B213 (M_{line} ~ 30-50 $M_{\odot}$/pc)

High-mass filament: NGC6334 (M_{line} ~ 500 $M_{\odot}$/pc)

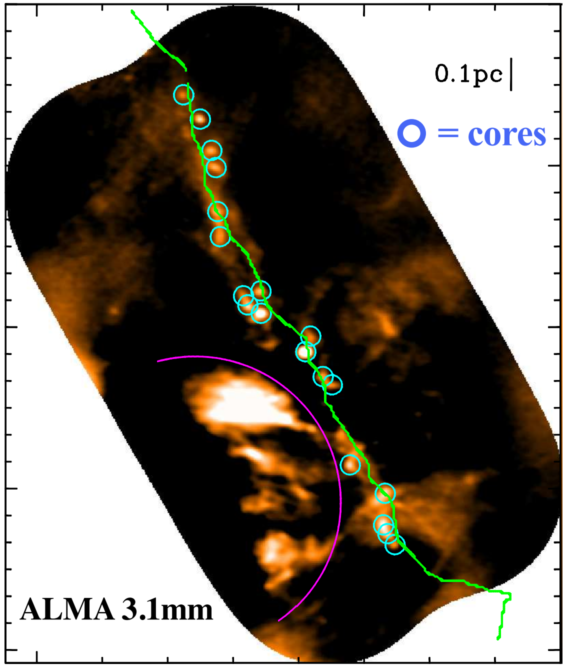


Bracco+2017; Marsh+2016

ArTéMiS+SPIRE 350 μm image



ALMA: chain of 26 massive cores



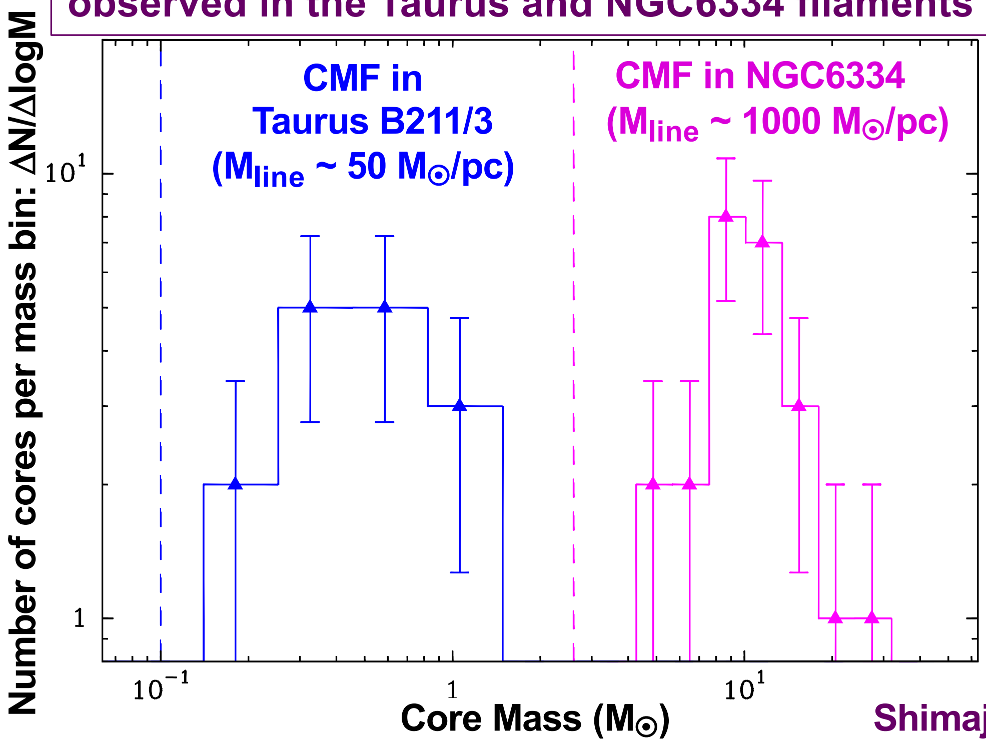
Shimajiri+2019

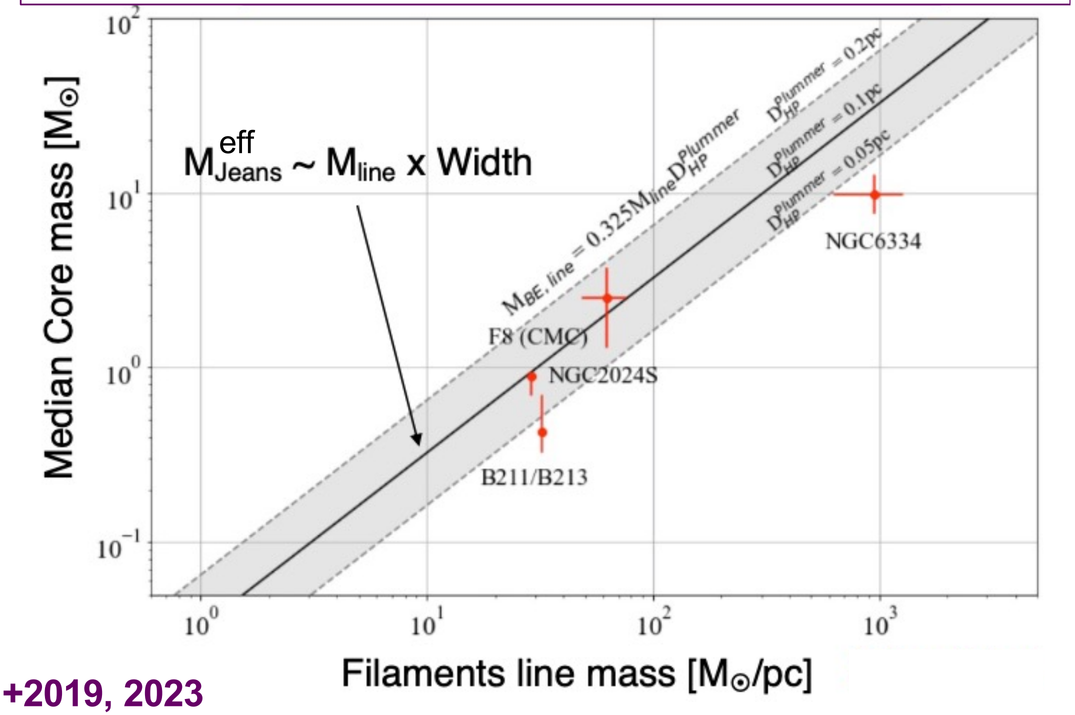
Denser (higher M_{line}) filaments tend to form higher-mass cores, possibly due to stronger B-fields

- The NGC6334 filament with M_{line}~ 1000 $M_\odot$/pc forms cores a factor of > 10 more massive than Taurus B211/3

Comparison of the core mass functions observed in the Taurus and NGC6334 filaments

Median core mass vs. Line mass of parent filament



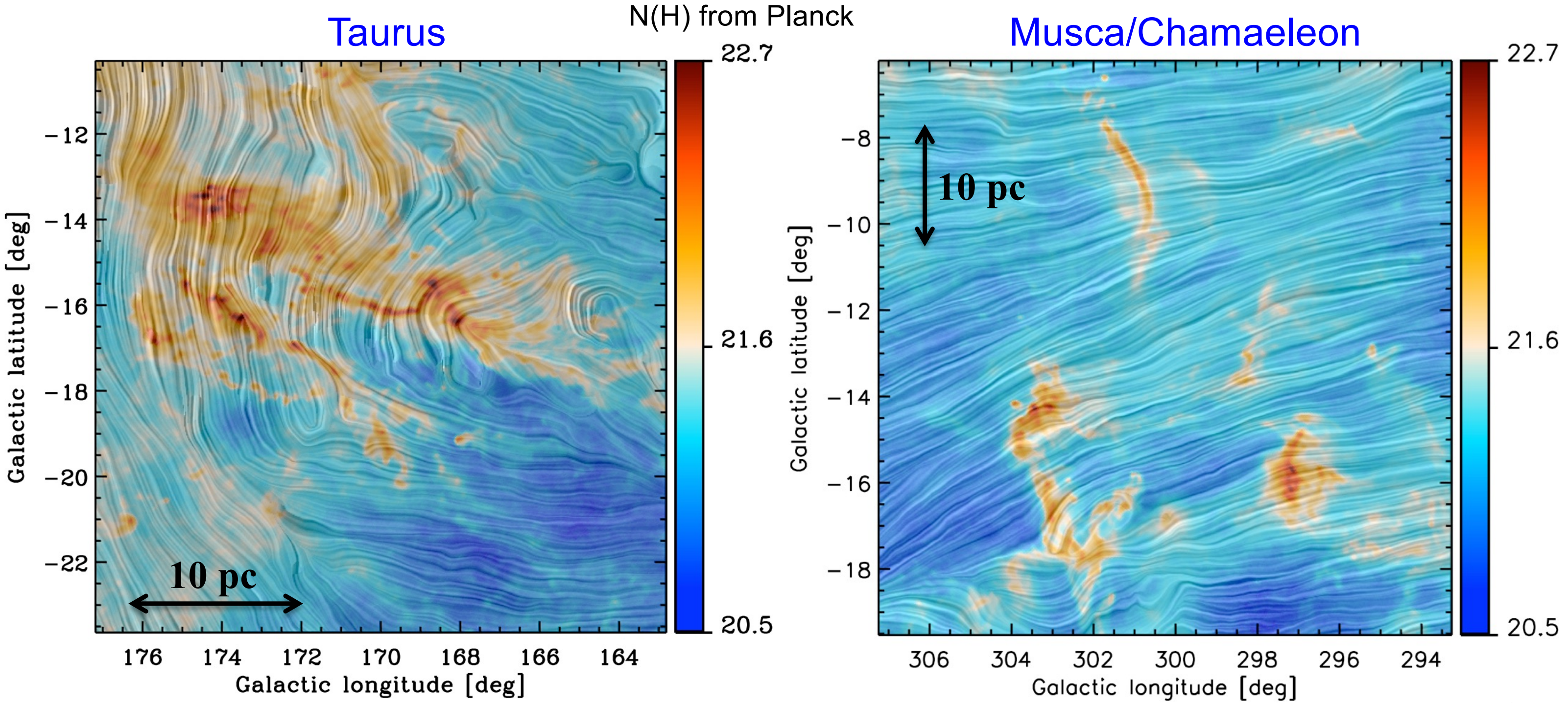


Shimajiri+2019, 2023

- **Results consistent with the peak mass of the CMF in a given filament scaling roughly as M_{line}**

Role of B fields in filament formation & 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

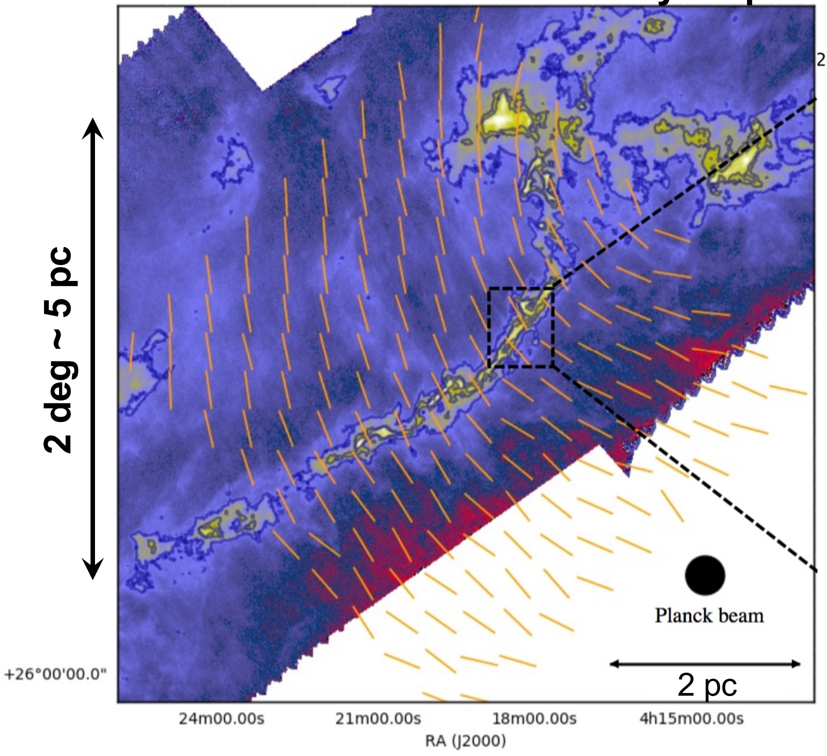
Drapery: B field lines from Q,U *Planck* 850 µm @ 10'

→ Polarimetric imaging studies at much higher resolution than *Planck* are crucially needed

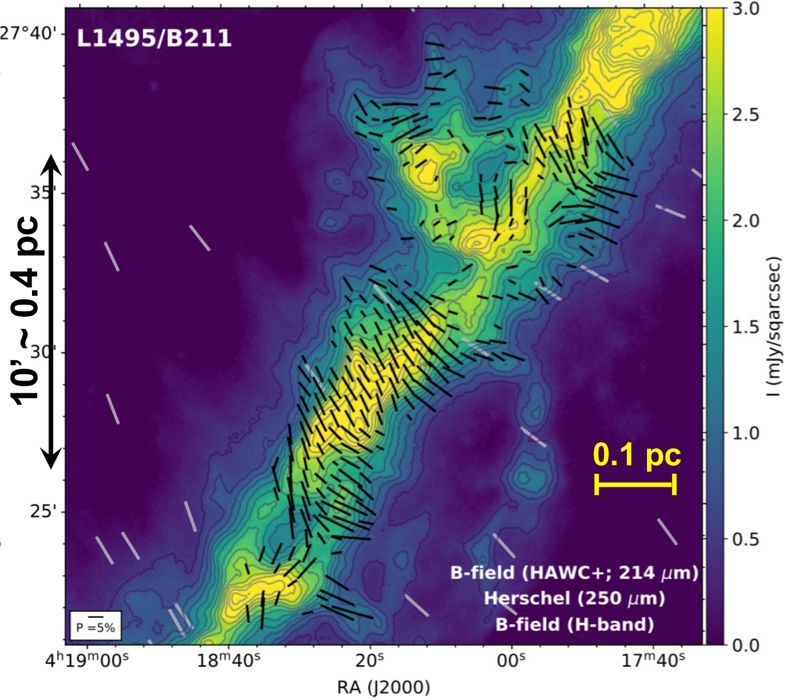
Role of B-fields with SOFIA: Example of the Taurus B211 filament

- **SOFIA/HAWC+ 214 μm mapping toward a pristine portion of B211 (M/L ~ 30 $M_{\odot}$/pc)**

***Planck* B-field vectors overlaid on *Herschel* column density map**



HAWC+ (and near-IR) **B-field vectors overlaid on *Herschel* 250 μm map**

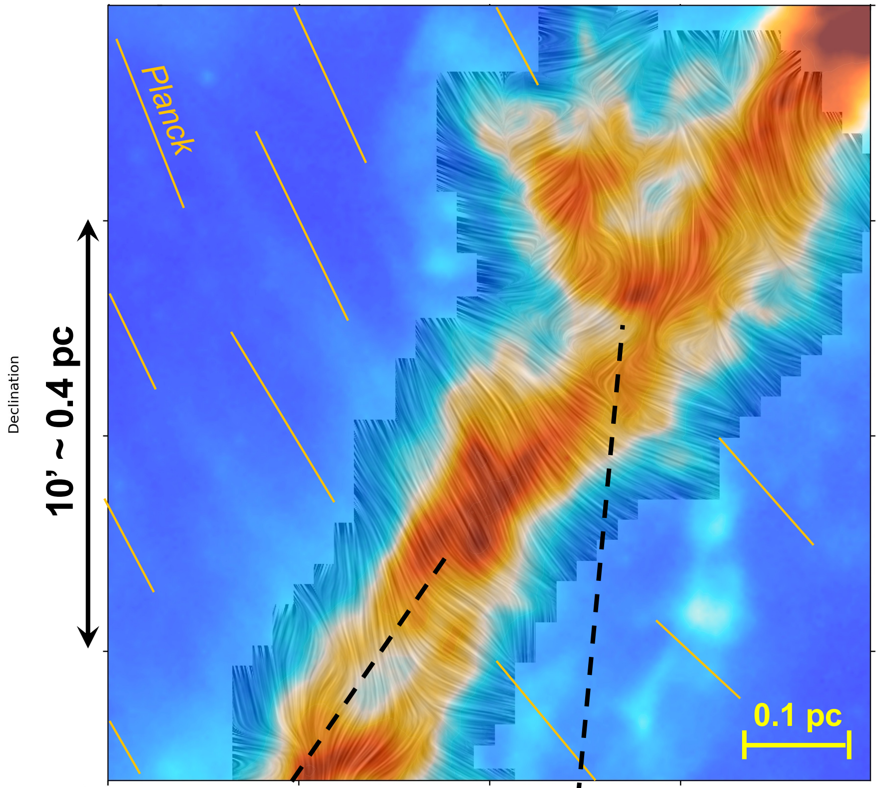


- *Planck* independent measurements at 10' resolution.
- SOFIA HAWC+ independent measurements at 28'' resolution.

P.S. Li, E. Lopez-Rodriguez, H. Ajeddig et al. 2022, MNRAS

Role of B-fields with SOFIA: Example of the Taurus B211 filament

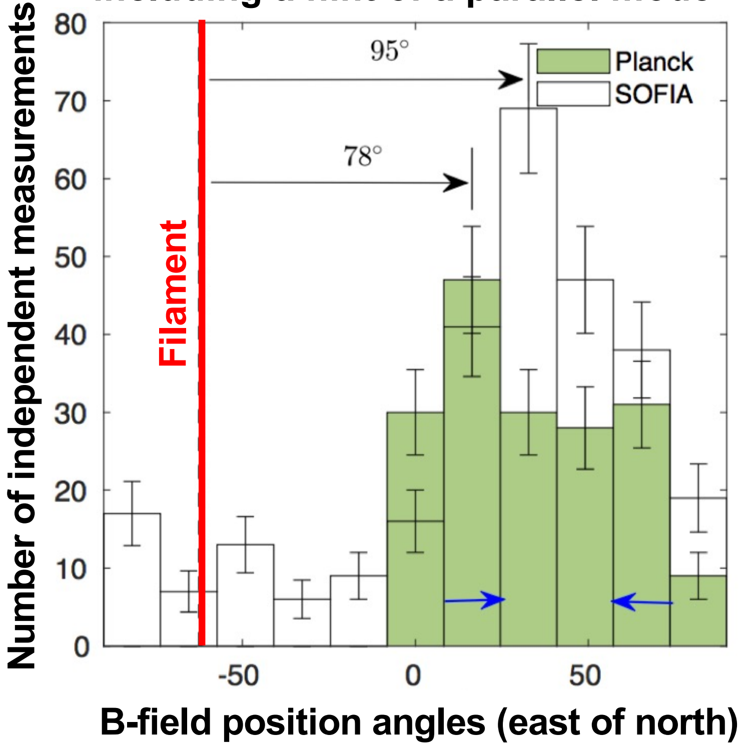
Drapery: HAWC+ B-field on *Herschel* 250 μm



B ~ 70 μG
(~ critical M/Φ)

B ~ 30 μG
(× 2-3 supercritical M/Φ)

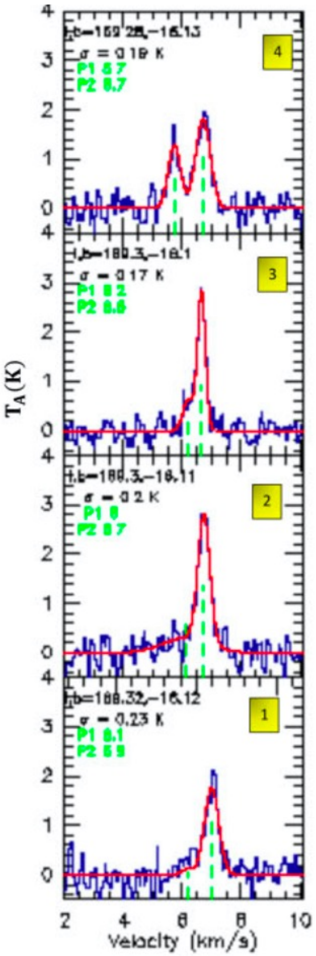
HAWC+ reveals a perturbed B-field in the interior of the B211 filament, including a hint of a parallel mode



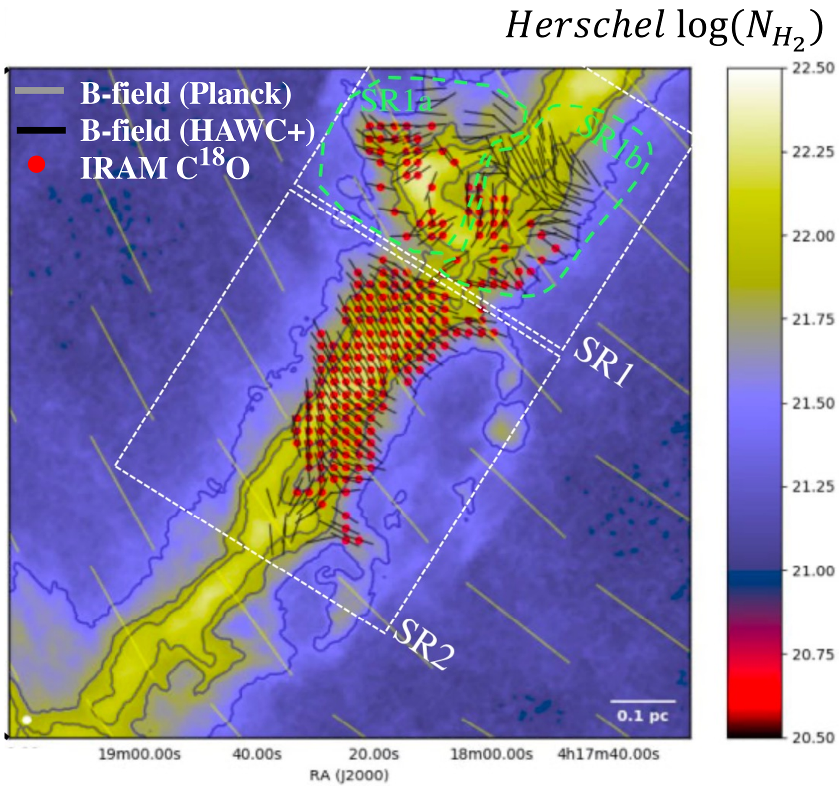
P.S. Li, E. Lopez-Rodriguez, H. Ajeddig et al. 2022, MNRAS

Role of B-fields with SOFIA: Summary of findings in the Taurus/B211 filament

IRAM 30m $C^{18}O(1-0)$



Magnetic field strength estimates using the DCF method and its variants



P.S. Li, E. Lopez-Rodriguez, H. Ajeddig+2022

$$B_{POS} = \alpha_{corr}\sqrt{4\pi\rho}\,\frac{\delta V}{\tan \delta\theta}$$

Chandrasekhar & Fermi 1953

or

$$B_{POS} = \sqrt{2\pi\rho}\,\frac{\delta V}{\sqrt{\delta\theta}}$$

Skalidis & Tassis 2021

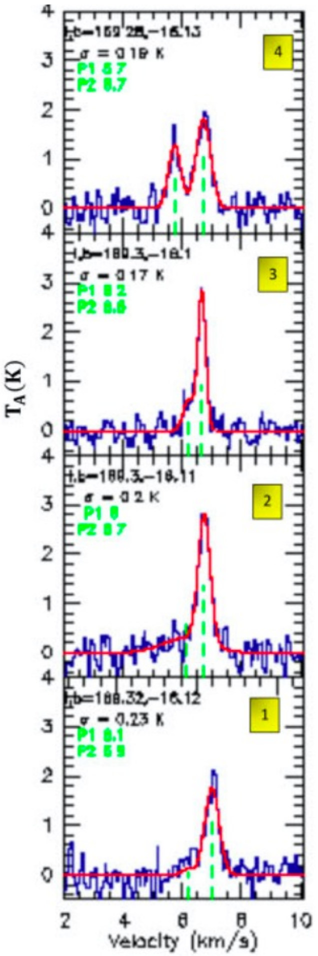
B211 filament:

1. Thermally supercritical ($M_\ell > 16\ M_\odot.pc^{-1}$)
2. Magnetically transcritical ($\mu_\phi \sim 1$-2)
3. Transcritical mass per unit length ($M_\ell \sim M_{\ell,\,crit}/2$) taking magnetic field and velocity dispersion into account

Region	SR1	SR2
$M_\ell (M_\odot\ \mathrm{pc}^{-1})$	54	36
$B_{0,\mathrm{DCF}}$ (μG)	13 - 23	65 - 82
$\mu_{\Phi,\,\mathrm{DCF}}$	2.7 - 2.1	1.2 - 1.0
$M_\ell / M_{\mathrm{crit},\ell}$	0.50-0.49	0.43 - 0.42

Role of B-fields with SOFIA: Summary of findings in the Taurus/B211 filament

IRAM 30m C^{18}O(1-0)



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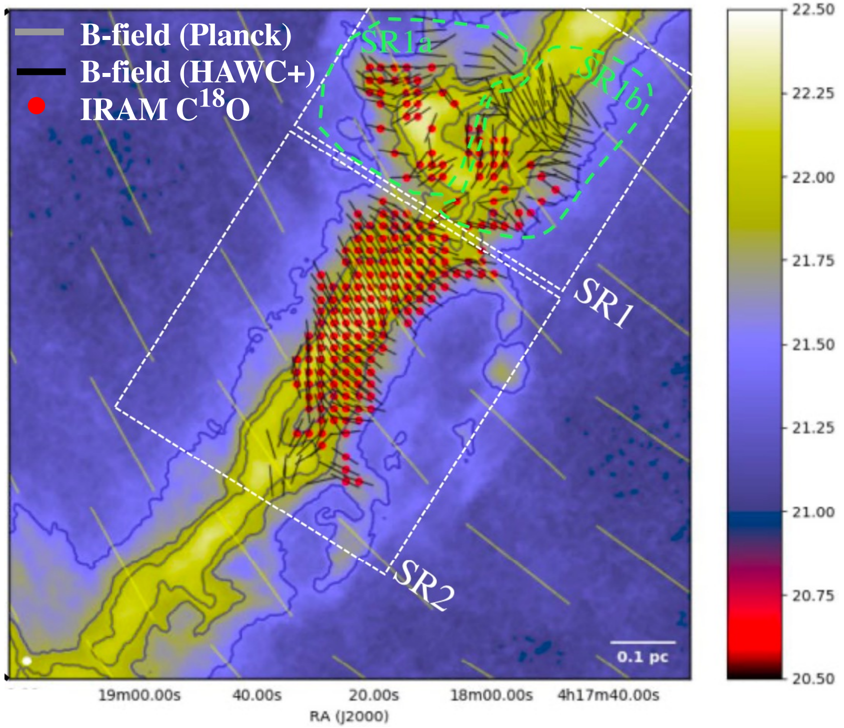
Chandrasekhar & Fermi 1953

Skalidis & Tassis 2021

Herschel $\log(N_{H_2})$



P.S. Li, E. Lopez-Rodriguez, H. Ajeddig+2022

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3. Transcritical mass per unit length $(M_\ell \sim M_{\ell,crit}/2)$ taking magnetic field and velocity dispersion into account

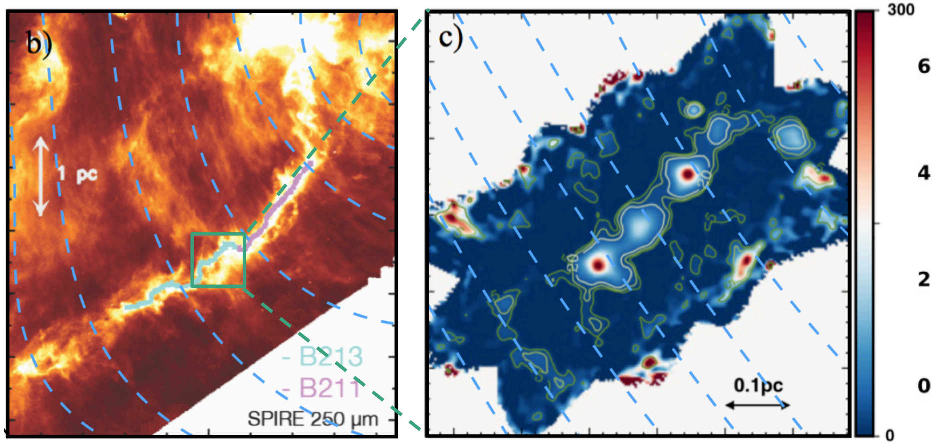
→ **The B211 filament may be able to fragment into cores thanks to presence of a significant magnetic field.**

Current ground-based polarimetric facilities are limited by sensitivity to the brightest/densest molecular filaments

- ➢ In a transcritical filament such as Taurus B211/B213 (M_{line} ~ 30 $M_{\odot}$/pc), SCUBA2-POL2 provides B-field polarization vectors only toward dense cores…

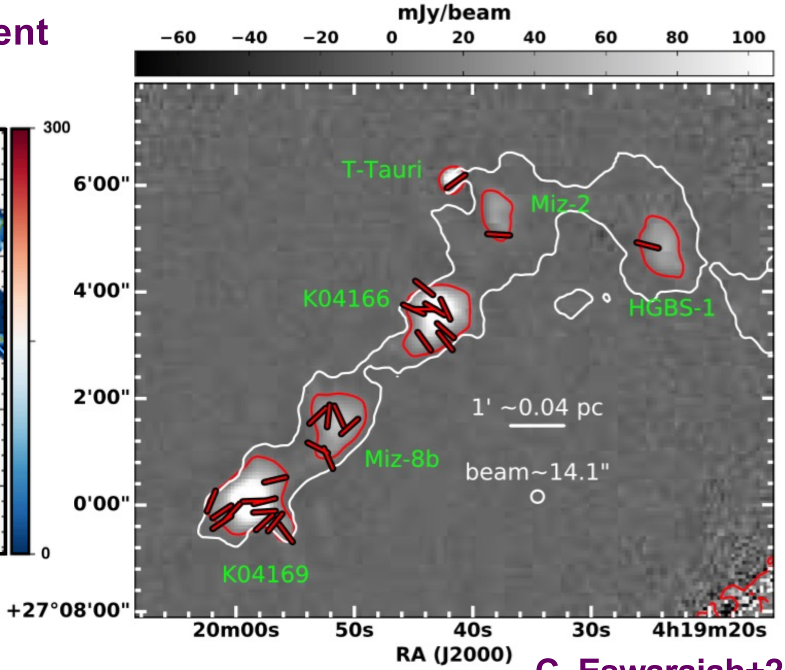
Taurus
B211/B213: A prototypical low-mass SF filament

***Herschel*/SPIRE 250µm** **IRAM 30m/NIKA 1.2mm**



Palmeirim+2013 **Bracco+2017**

JCMT–SCUBA2-POL 850 µm (BISTRO)

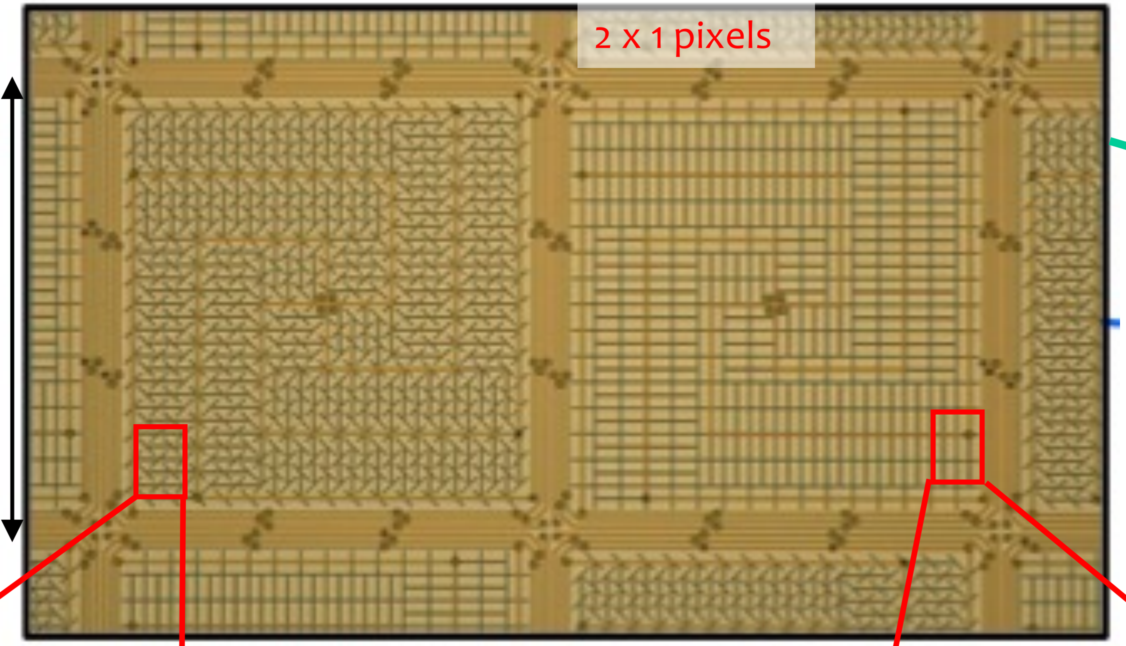


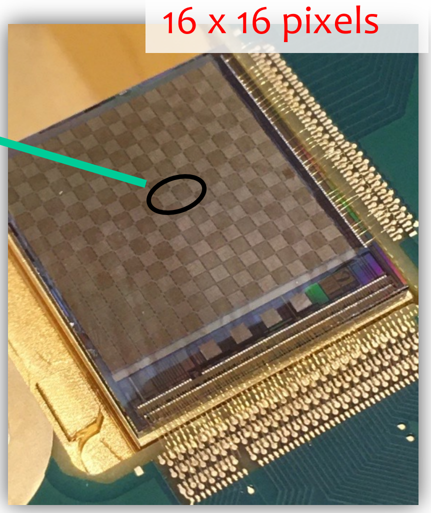
C. Eswaraiah+2021, ApJL

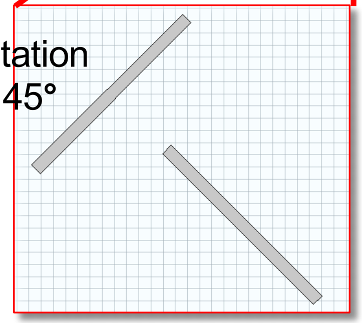
→ Extensive polarimetric imaging studies of molecular clouds/filaments will only be possible with a FIR telescope from space

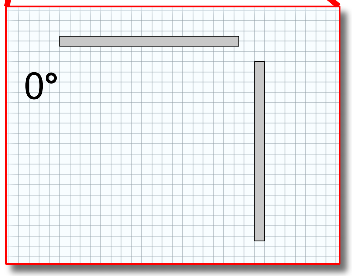
New polarization-sensitive bolometer detectors developed for B-BOP (imaging polarimeter for a future large FIR telescope: ~~SPICA~~, Mmtron?, SALTUS?)

The "Stokes" pixels of B-BOP





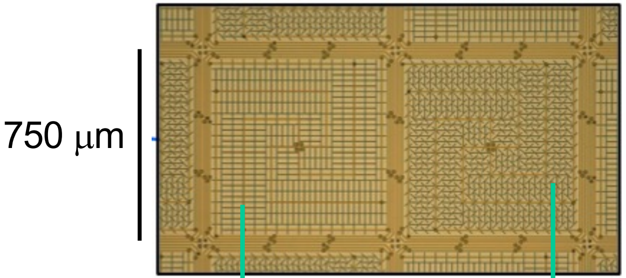




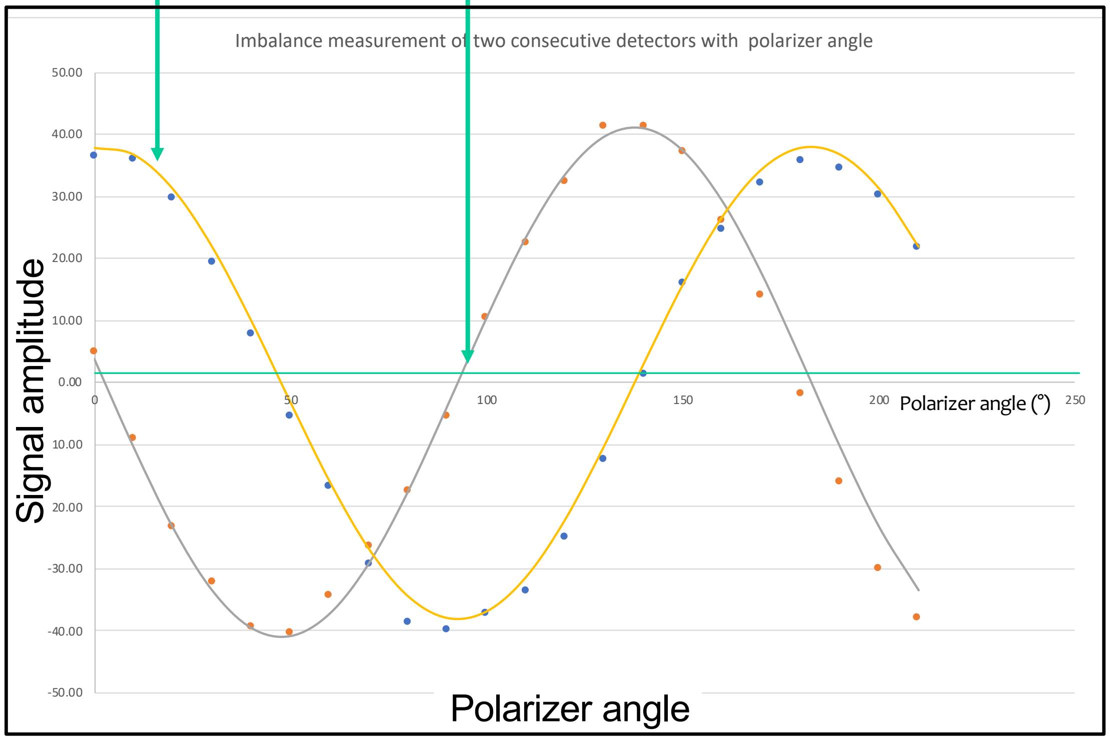
- Pixels are alternately « 0° » and « 45° »
- **Stokes parameters Q, U can be obtained in a "single shot"**
- No need for a rotating HWP

(**L. Rodriguez**, S. Bounissou, O. Adami, A. Poglitsch)

Successful tests of the polarization-sensitive detector concept in the Lab using 100 µm bolometer prototypes



Detectors illuminated by a source + rotating polarizer



Strong imbalance signal with polarizer rotation angle

No changes in the total power signal.

- **Stokes pixels react in phase quadrature** as expected for two absorbers rotated by 45°

L. Rodriguez+2023, LTD20

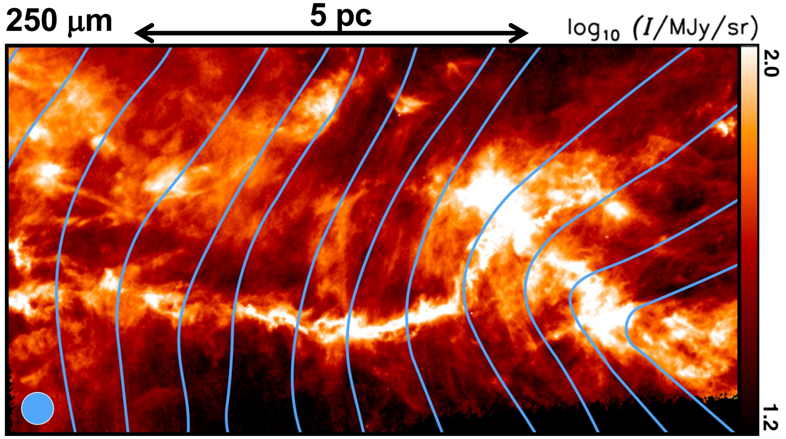
(Mmtron?? or SALTUS?..)-B-BOP can unveil the role of magnetic fields in filament evolution and core/star formation

See SPICA-POL White Paper (André+2019, arXiv:1905.03520)

Taurus B211 filament

***Herschel* 250 µm**

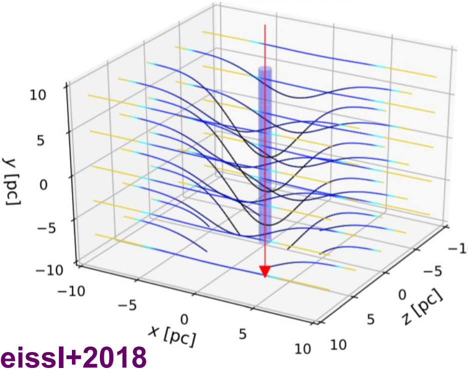
***+ Planck* B lines**



Palmeirim +2013
A. Bracco

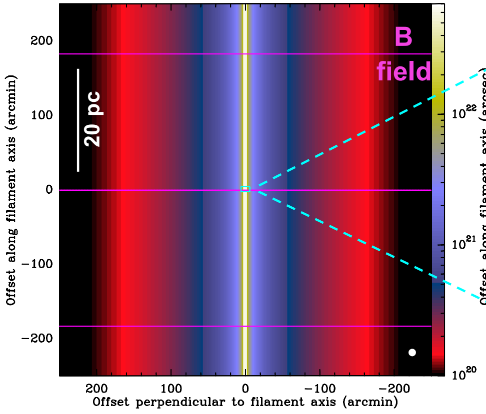
- ***Planck* resolution (> 10' or > 0.4 pc) insufficient to resolve the ~0.1 pc width of filaments.**
  Can be done with Mmtron or SALTUS
- **B-BOP would deliver FIR polarized (Q, U) images with a S/N and dynamic range similar to *Herschel* images in I and a factor ~3 higher resolution**

Plausible model of the B field in a SF filament

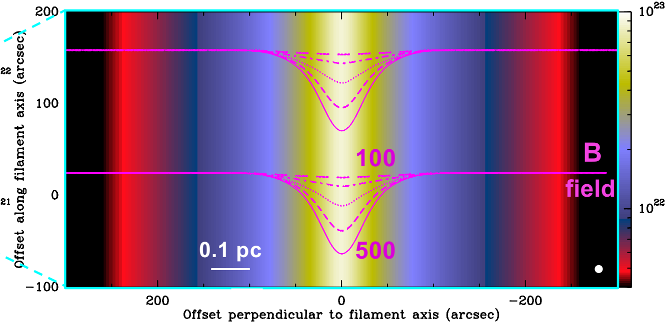


cf. Reissl+2018

Planck resolution



B-field lines inferred at ≠ λ (from 100 to 500 µm) at Millimetron resolution



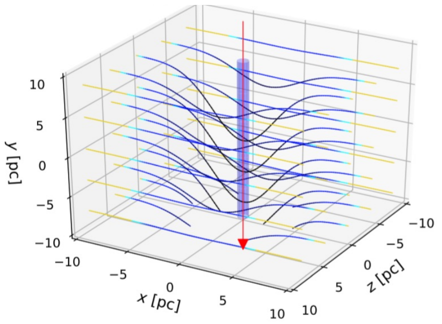
(for a model filament at d = 500 pc)

- **Different wavelengths probe different depths within the filament**

Discriminating between competing models for the dynamical state of star-forming filaments

Two Plausible models of the B-field in a SF filament

1) Dynamical flow



(cf. Gomez & Vazquez-Semadeni+2018)

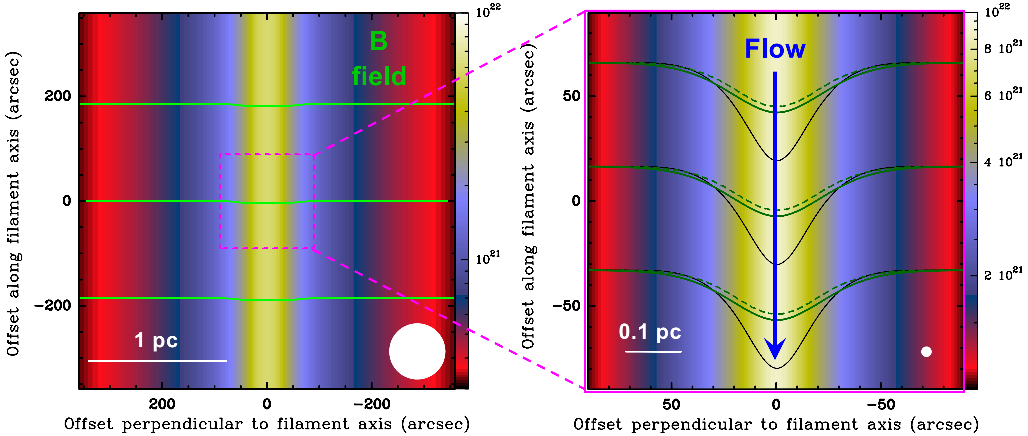
2) Quasi-equilibrium model

(cf. Inutsuka & Miyama 1997)

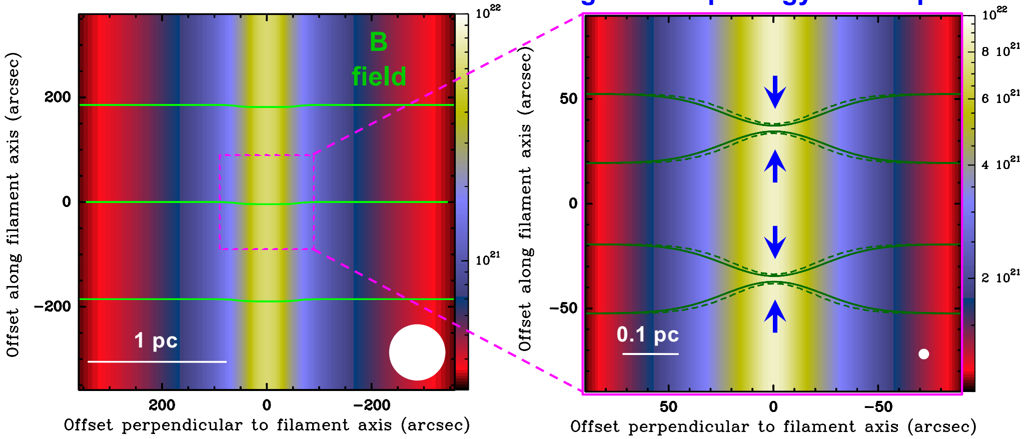
Synthetic polarization maps for 0.1-pc wide model filaments at d = 800 pc

Planck polar. resolution (10')

Millimetron resolution



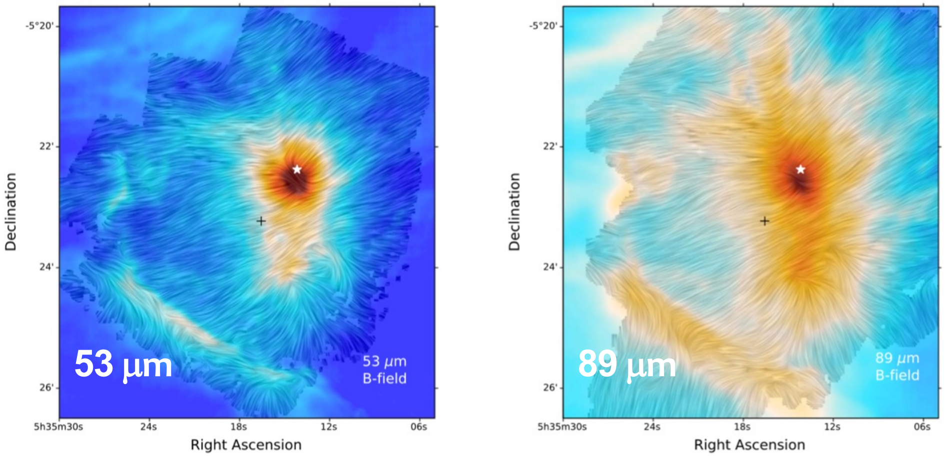
Hourglass morphology at core positions



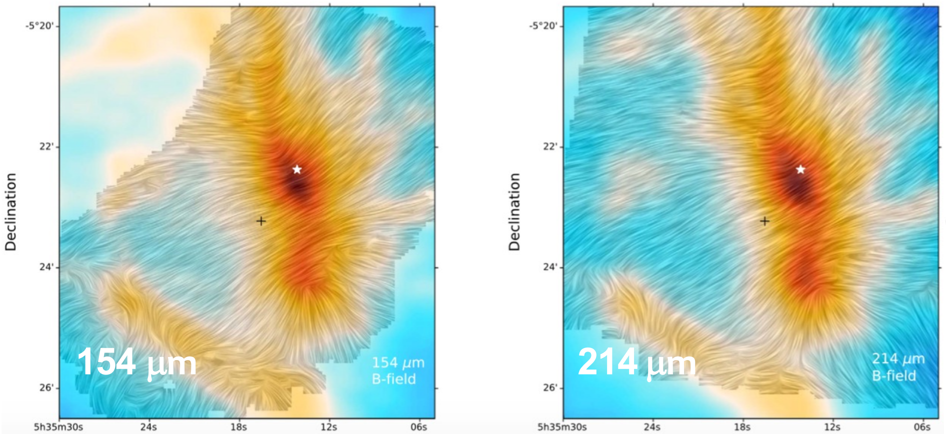
Far-IR and mm/submm imaging polarimetry results for Orion A OMC-1:

Hourglass pattern with more pronounced curvature at longer λs

SOFIA - HAWC+

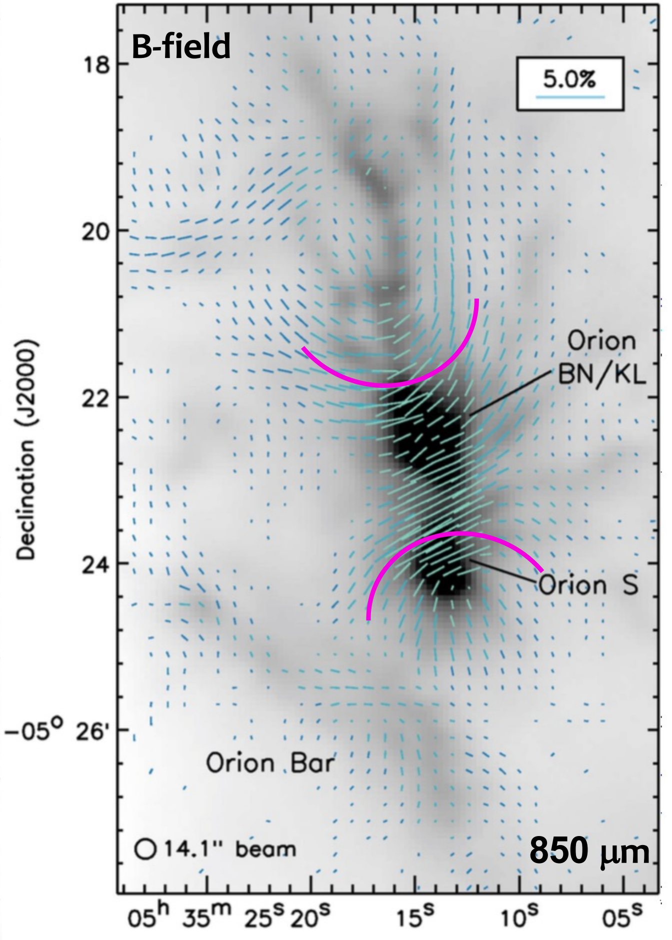


Drapery: B-field lines



Chuss+2019; Guerra+2021

JCMT–SCUBA2-POL2 (BISTRO)

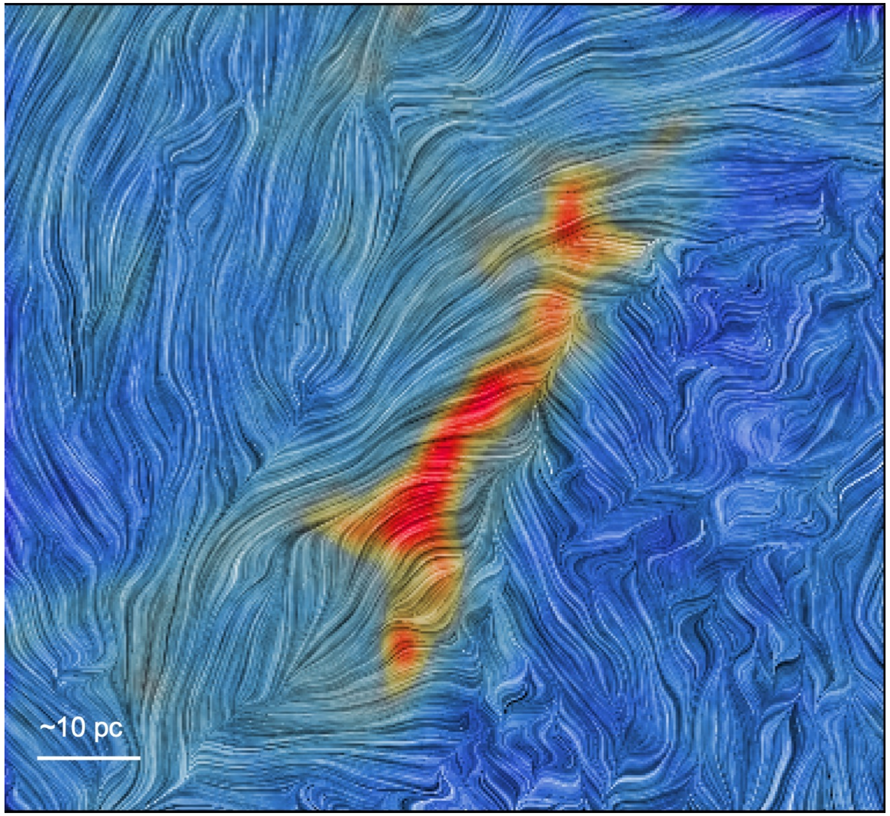


Ward-Thompson+2017; Pattle+2017

‘Heritage of SOFIA – Ph. André

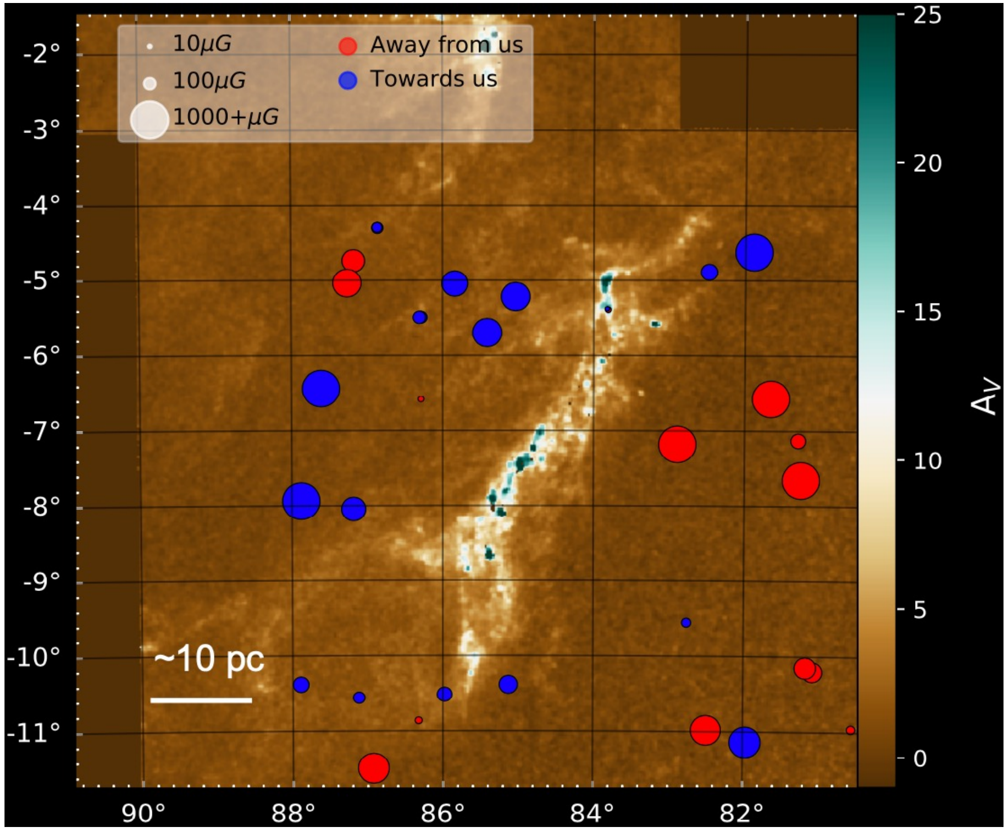
Combining plane-of-sky B-fields from FIR polarimetry with line-of-sight B-fields from Faraday rotation to reconstruct the 3D magnetic field

***Planck* polar. map of Orion A molecular cloud**



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

Faraday rotation measurements toward Orion A

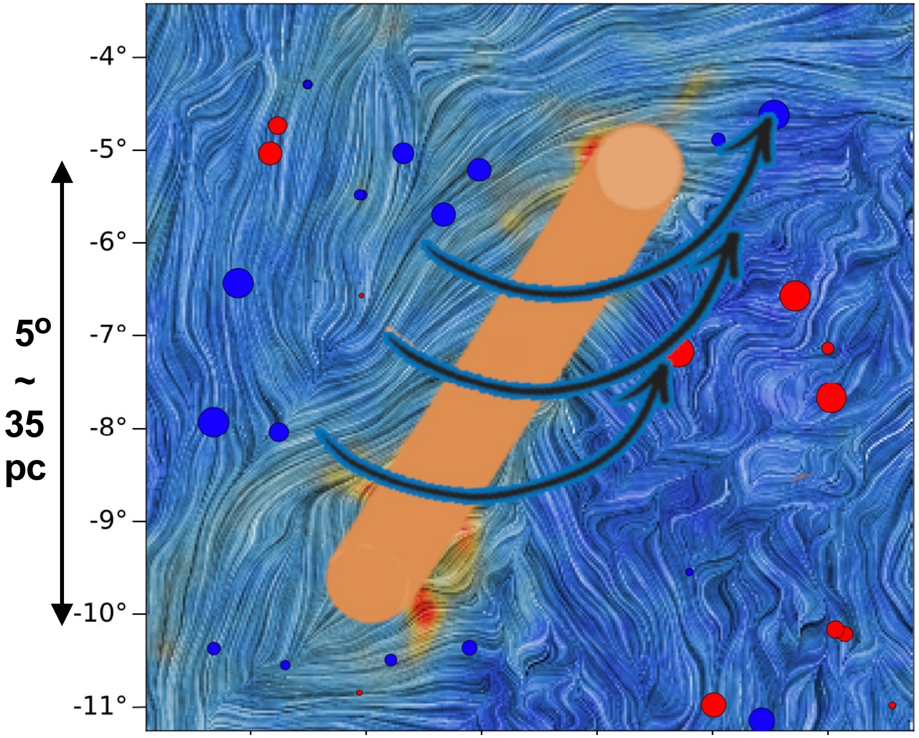


$$\psi_{\rm rot} \sim \lambda^2 \int n_e\, B_{//} . dl \sim \lambda^2\, RM$$

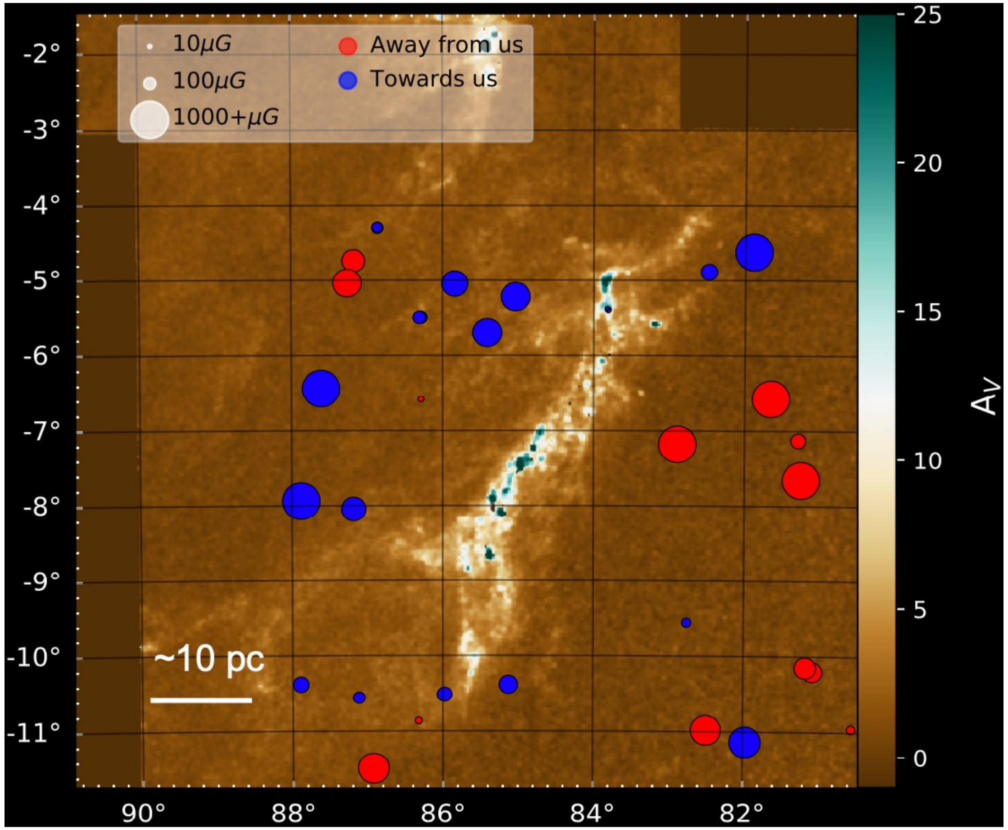
M. Tahani+2018

Combining plane-of-sky B-fields from FIR polarimetry with line-of-sight B-fields from Faraday rotation to reconstruct the 3D magnetic field

Planck polar. map + Faraday R.Measures in Orion A



Faraday rotation measurements toward Orion A



- ➢ **Most likely 3D structure: Arc-shaped B-field**

M. Tahani+2019, A&A, 632, A68

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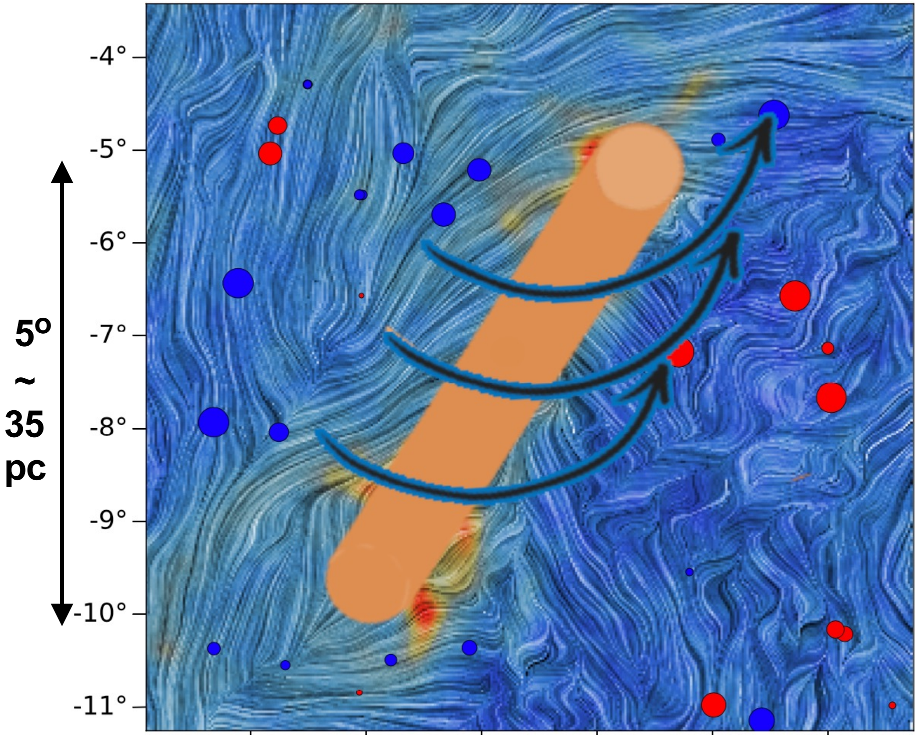
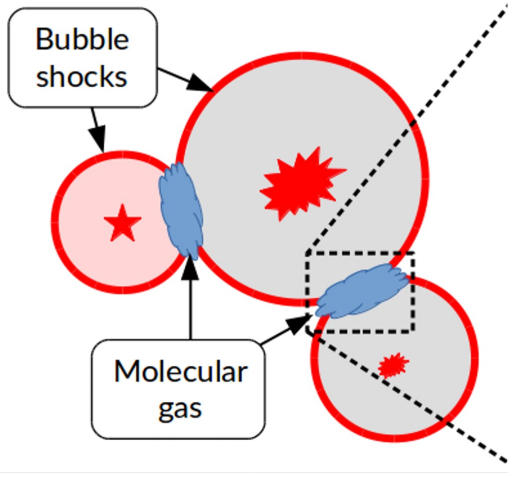


- ➢ **Most likely 3D structure: Arc-shaped B-field**

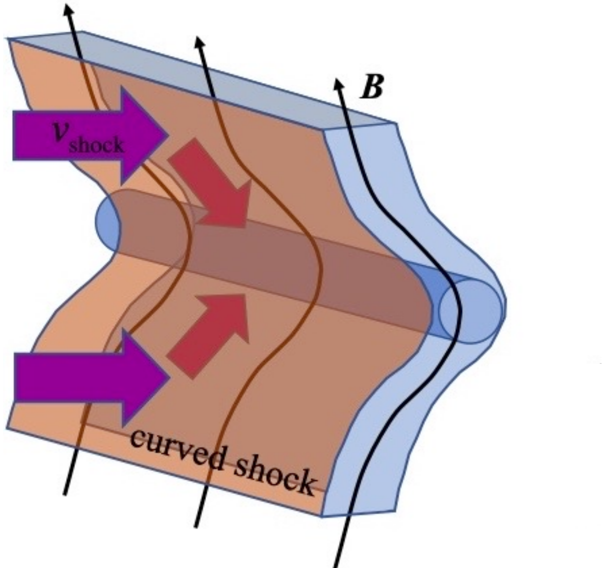
M. Tahani+2019, A&A, 632, A68

- ➢ Qualitative agreement with one of the leading scenarios for the formation of dense molecular filaments



S. Inutsuka+2015

Oblique MHD shock induced flow



D. Abe, T. Inoue+2021

- ➢ Now: Only cloud-scale 3D magnetic field (a few degs)
- ➢ Future: SKA will provide RMs for single SF filaments
- ➢ More extensive high-res. FIR polarization maps needed

Key advantages of an imaging polarimeter on a large FIR space telescope such as Mmtron or SALTUS for this science

- **High spatial dynamic range (~10^3), which cannot be achieved from the ground**

- **High angular resolution (Mmtron or SALTUS can resolve critical 0.1 pc scale out to ~1.5 kpc)**

- **High sensitivity to low surface brightness structures (in contrast to interferometers – e.g. ALMA)**

- **Multi-wavelength polarimetric coverage in the far-IR/submm**
  → tomography of the B-field + unique constraints on dust models

- **Combined with Faraday rotation measures from SKA, 3D structure of the B-field on sub-pc scales (individual filaments)**

- **Wide-field polarimetric imaging survey of nearby molecular clouds at $\lambda \sim 70\text{-}500\ \mu\text{m}$ on a Mmtron- or SALTUS-class telescope would revolutionize our understanding of the origin and role of B-fields in filament formation/fragmentation**