Probing the role of magnetic fields in filamentary star formation on various interstellar scales

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

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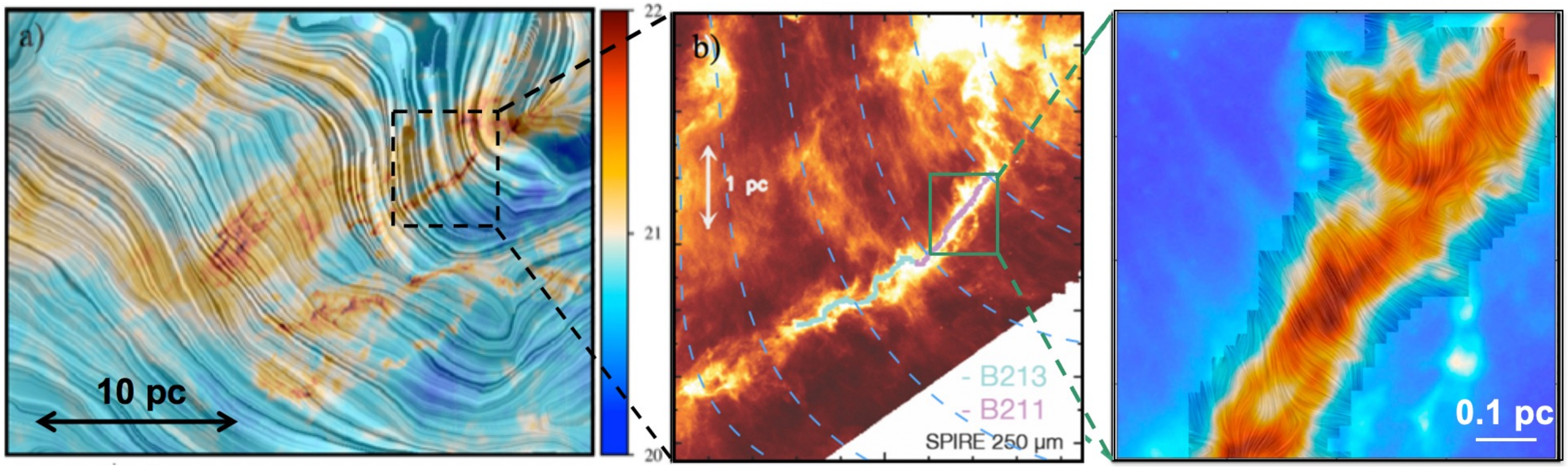
Thanks to: D. Arzoumanian, H. Ajeddig, A. Bracco, T.-A. Duong, M. Mattern, Y. Shimajiri,

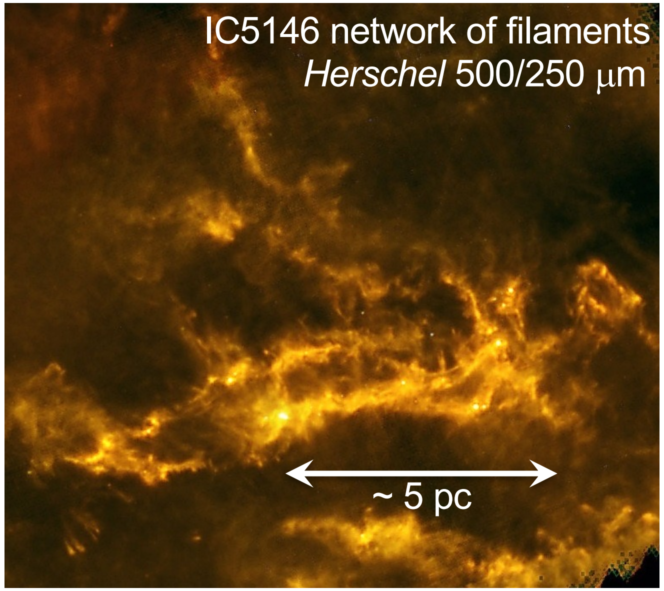
+ L. Rodriguez, V. Revéret

FIR2025: Future Role of FIR-Submm Space Observations – Leiden, 2 Apr 2025

Taurus: *Planck*   ***Herschel* + *Planck***   ***Herschel* + SOFIA/HAWC+**



Herschel observations suggest that dense molecular gas is primarily structured in the form of filaments with typical half-power width ~0.1 pc

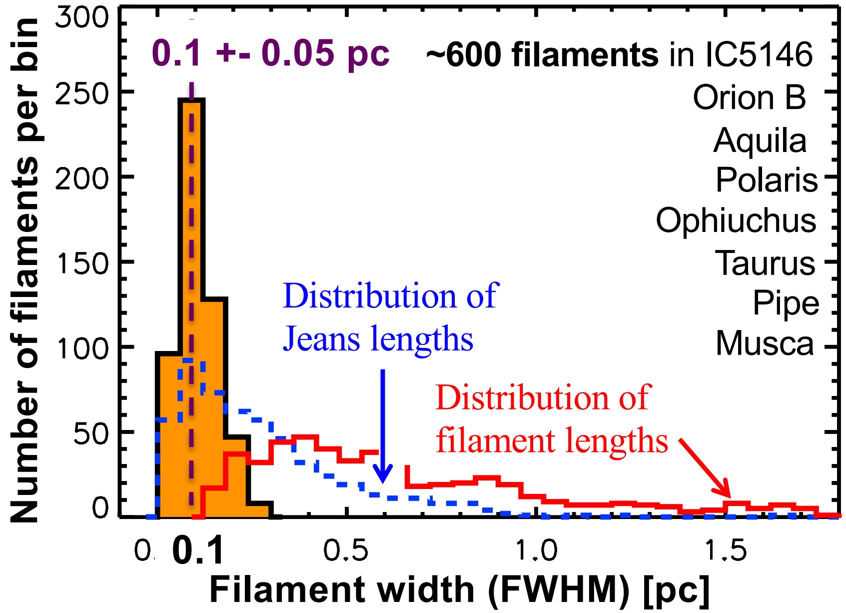


Molinari+2010
Schisano+2014

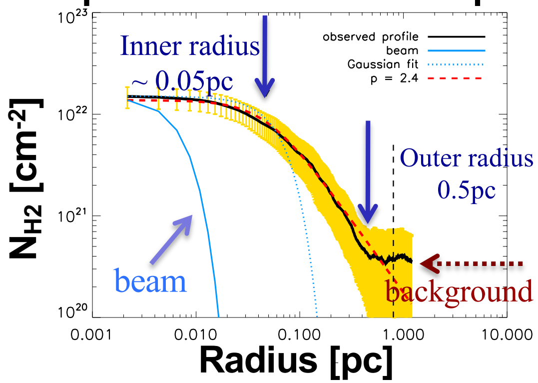
André+2010

A characteristic length/mass scale for SF and the IMF?

Nearby (< 500 pc) filaments have a common inner width ~ 0.1 pc



Example of a filament radial profile



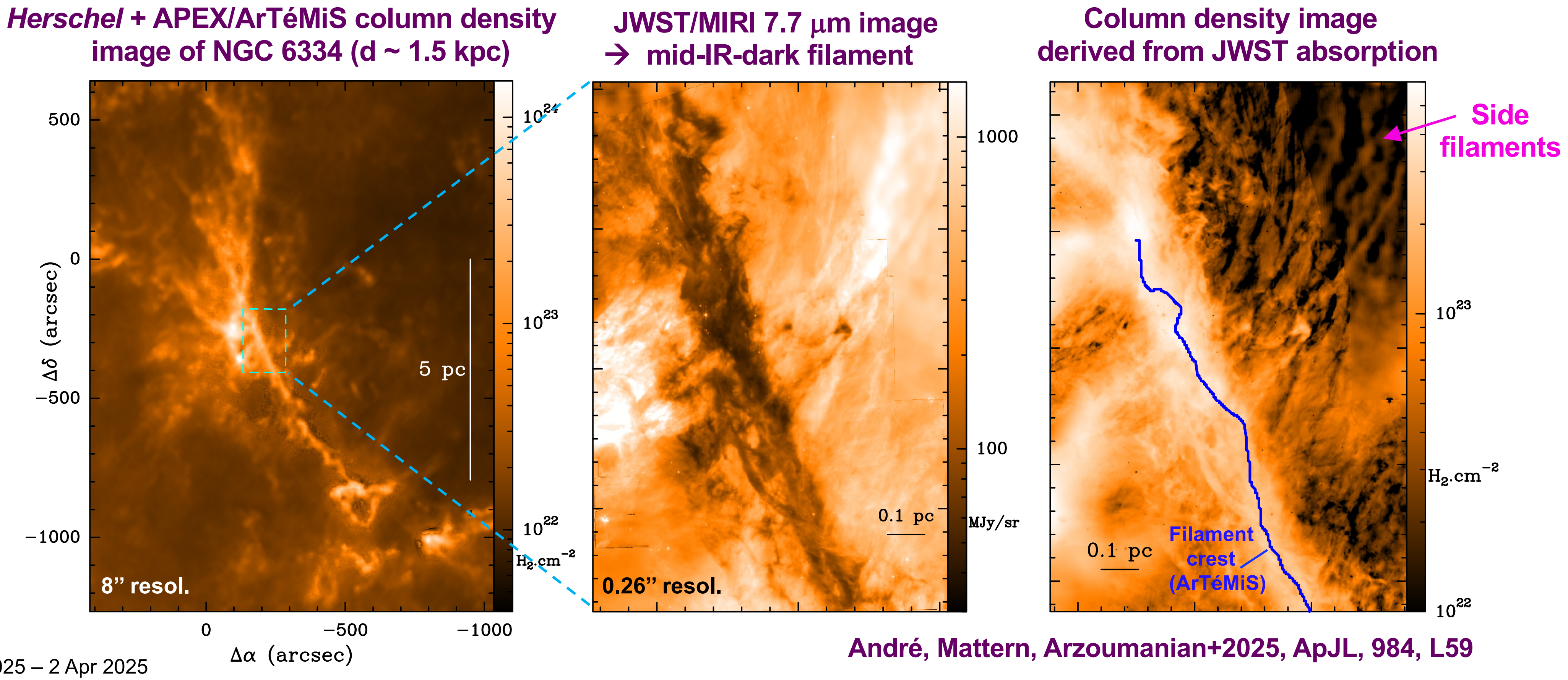
D. Arzoumanian+2011 & 2019 [see also Koch & Rosolowsky 2015]

May correspond to the magneto-sonic scale of turbulence & turbulence correlation length (cf. Padoan+2001; Federrath 2016; Jaupart & Chabrier 2021)

Challenging for numerical simulations but very promising recent results
(cf. R. Smith+2014; Ntormousi+2016) (Abe, Inoue, Inutsuka+2024, 2025)

Recent JWST/MIRI observations of infrared-dark filaments suggest that this typical filament width ~0.1 pc is not restricted to nearby clouds

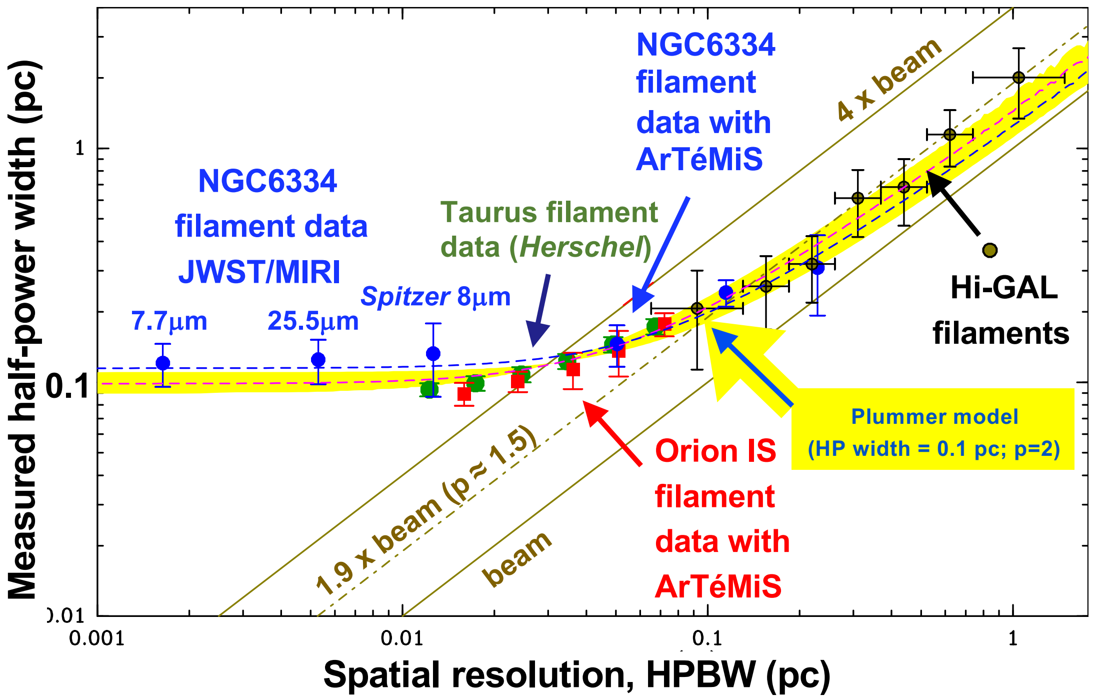
- JWST has revealed the fine structure of the NGC6634M filament and the presence of (magnetically-aligned?) side filaments with a projected spacing of ~0.1 pc



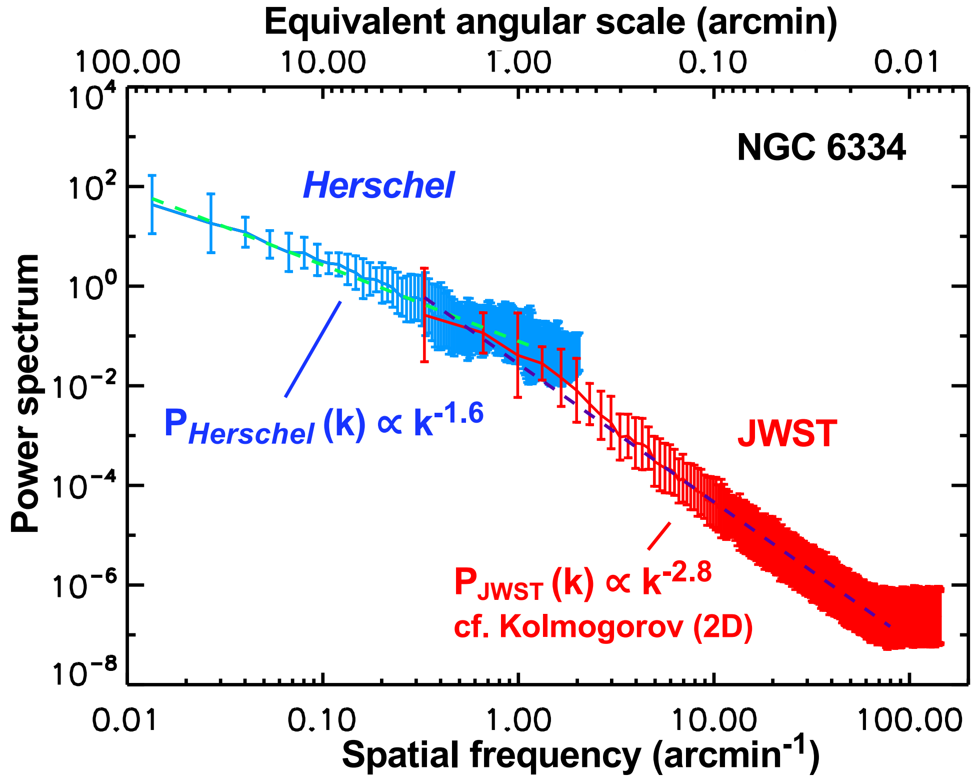
André, Mattern, Arzoumanian+2025, ApJL, 984, L59

JWST results support the conclusion that Galactic filaments have a common density profile with a typical half-power width ~0.1 pc

Convergence plot of measured filament widths vs. spatial resolution



Change in the slope of the power spectrum of density fluctuations at about ~0.1-0.2 pc

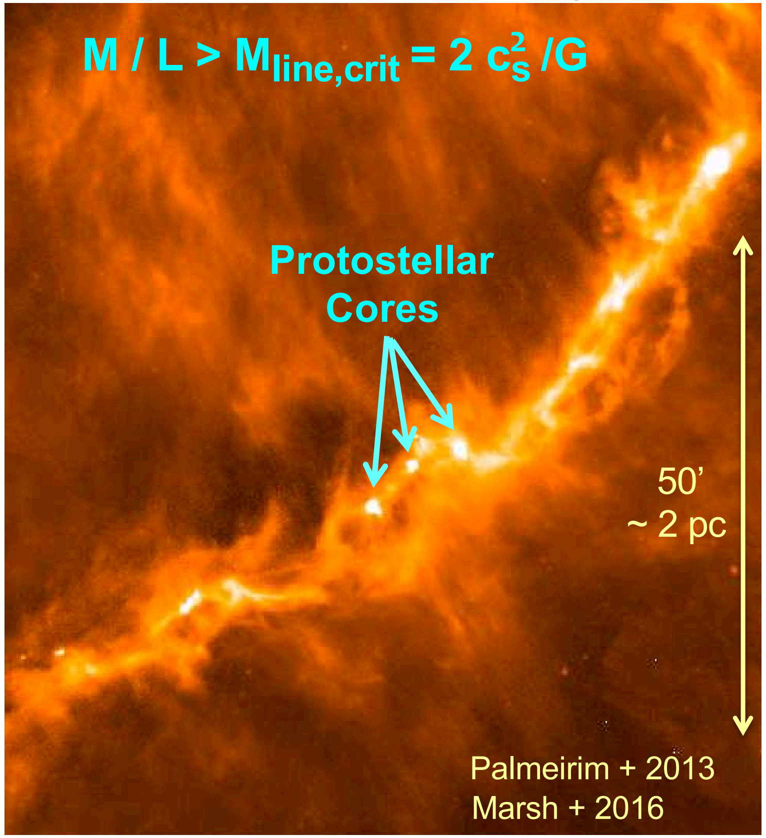


André, Mattern, Arzoumanian+2025, ApJL, 984, L59

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 $N_{H_2} \gtrsim 7 \times 10^{21}$ cm^{-2} <=> $\Sigma \gtrsim 160\ M_\odot/pc^2$
$M / L \gtrsim 16\ M_\odot/pc \sim M^{th}_{line,\ crit}$

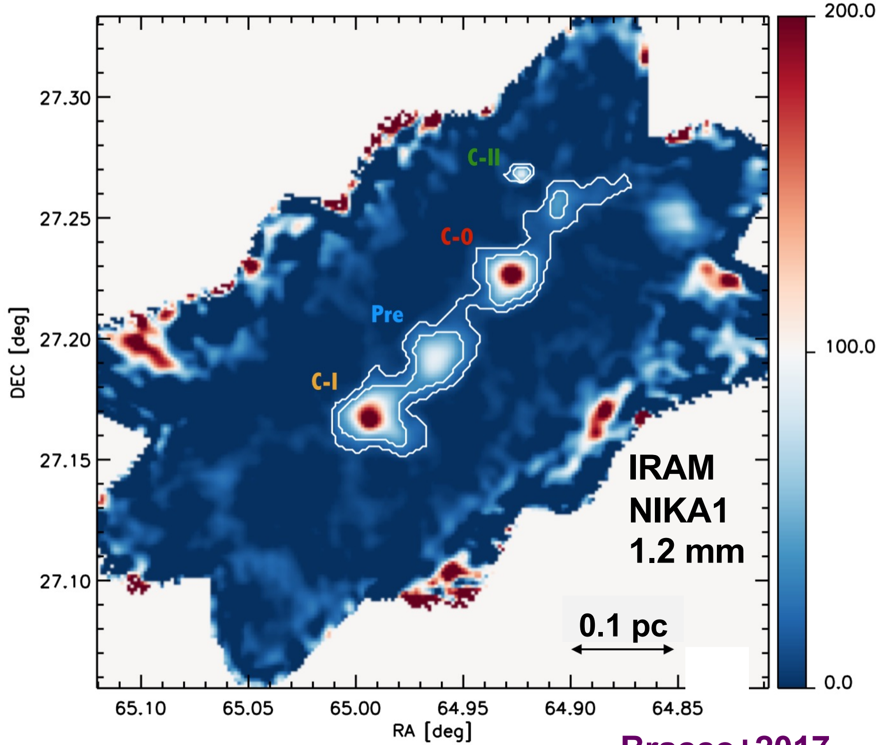
cf. Protostars & Planets VI chapter (André+2014)



Taurus B211/3 – *Herschel* 250 μm

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

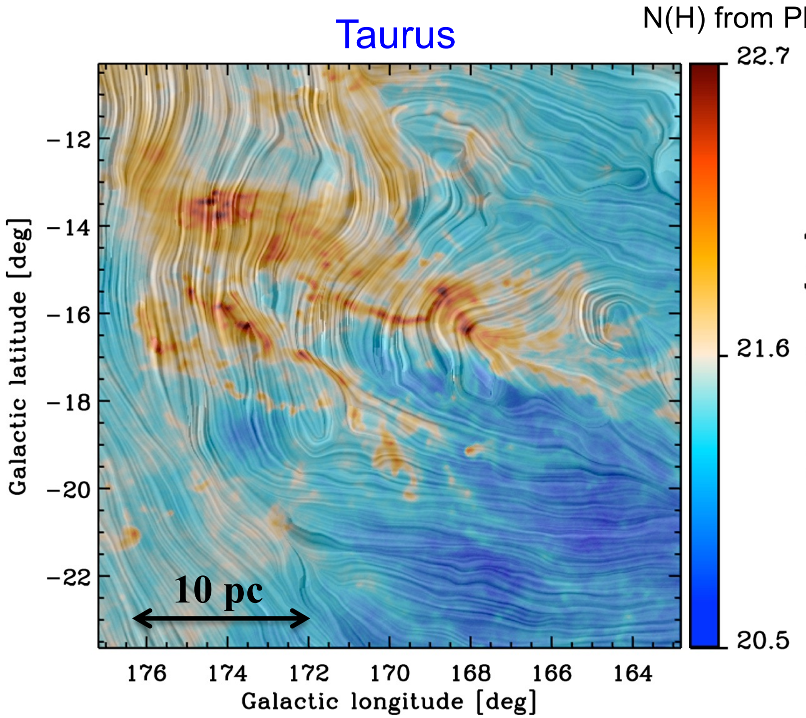
Chain of pre-/proto-stellar cores with ~0.1 pc spacing

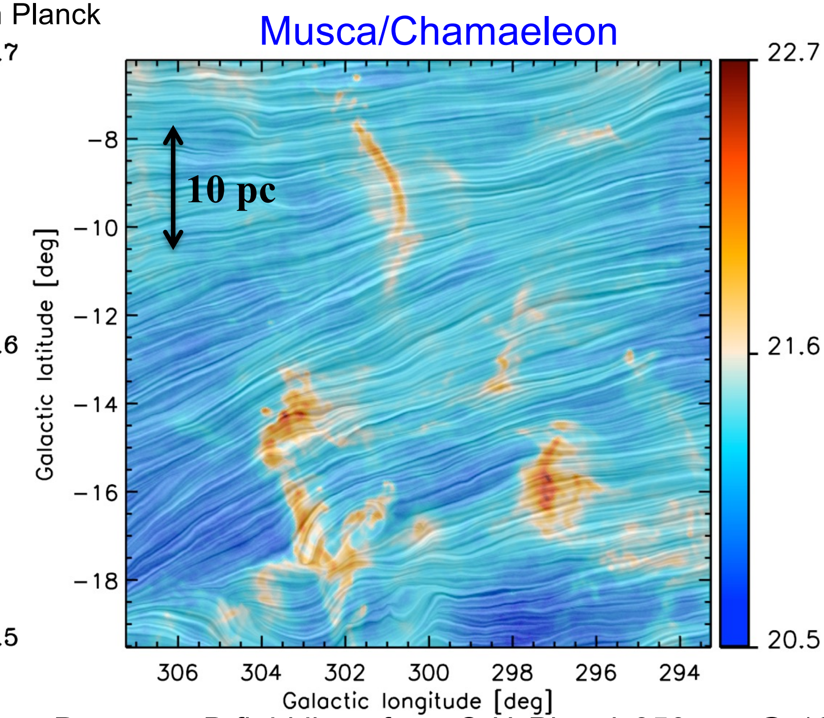


Bracco+2017

Major open issue: 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**

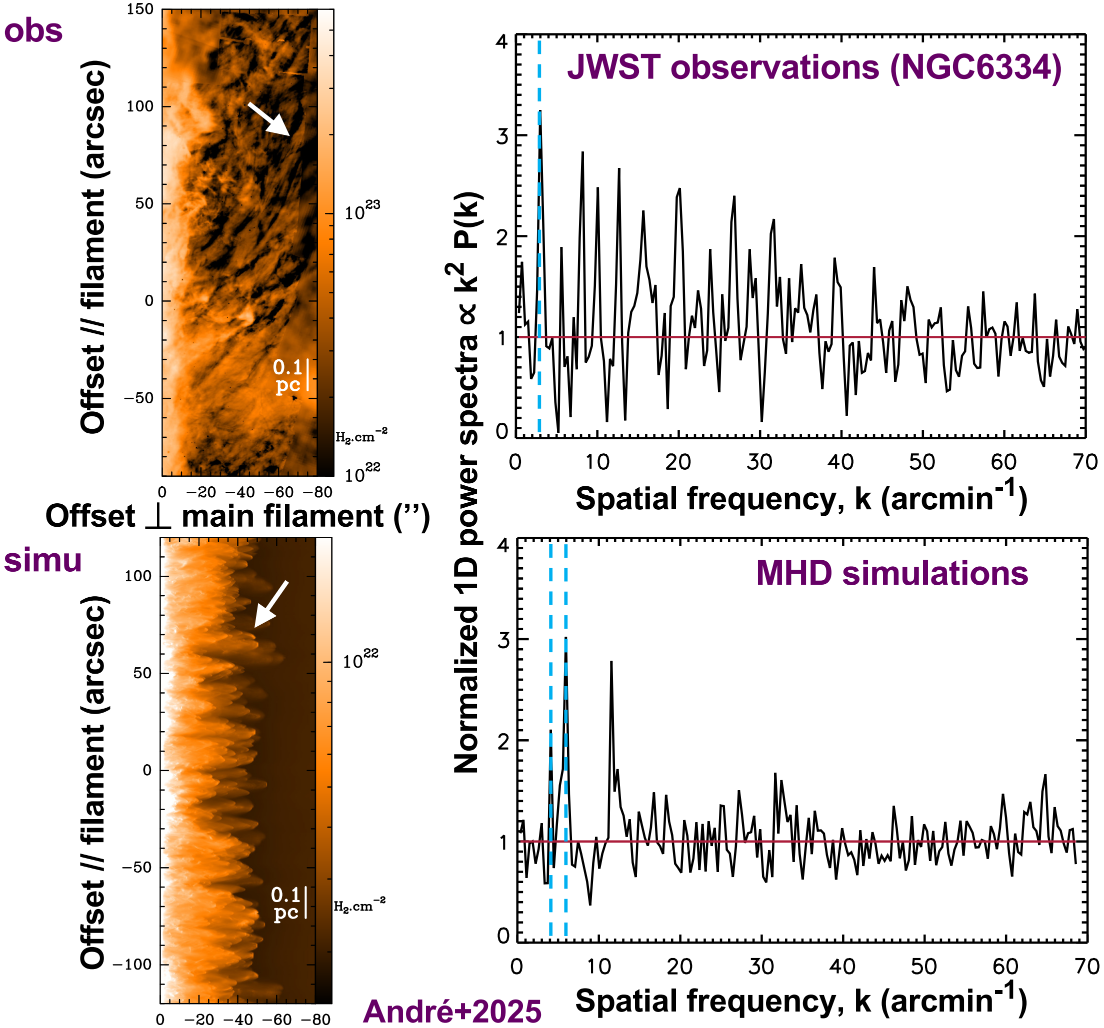




Planck int. results. XXXV. (2016) - Soler 2019 **Drapery:** B field lines from Q,U *Planck* 850 μm @ 10'

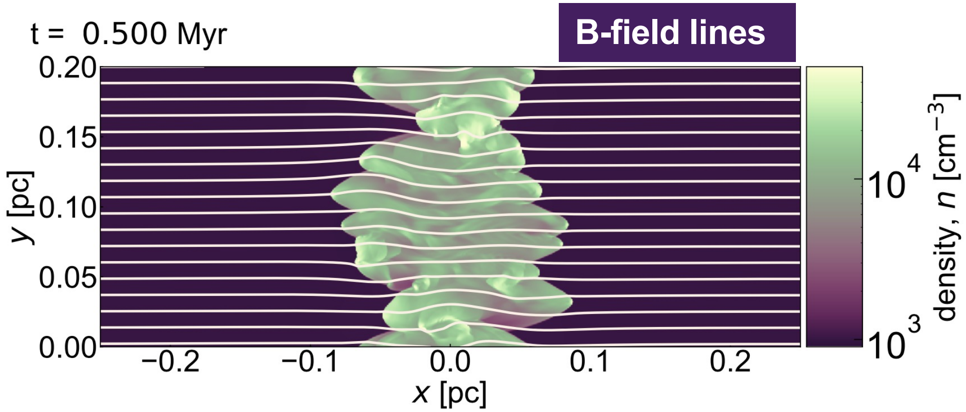
→ **Polarimetric imaging studies at much higher resolution than *Planck* are crucially needed**

Recent numerical MHD simulations also suggest that B fields do play a fundamental role in the physics of star-forming filaments



André+2025

- → Non-ideal MHD simulations show that the combination of the slow-shock MHD instability and ambipolar diffusion (AD) allow massive accreting filaments to retain a HP width ~ 0.1 pc (~ AD scale) while evolving.
- → *Magnetic fields are key in this process*



Abe, Inoue, Inutsuka+2025, ApJ

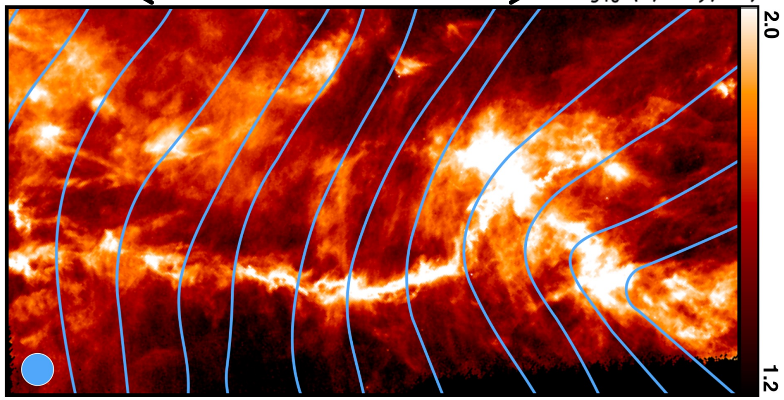
(~~SPICA-B-BOP~~) PRIMA Pol Imager will unveil the role of magnetic fields in filament evolution and core/star formation in nearby clouds

Taurus B211 filament

***Herschel* 250 μm**

+ *Planck* B lines

See SPICA-B-BOP White Paper (André+2019, PASA 36, e029)

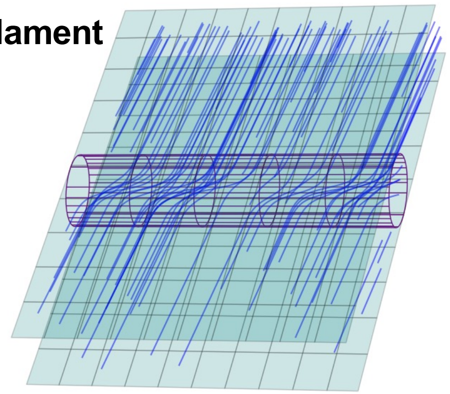


Palmeirim +2013

A. Bracco

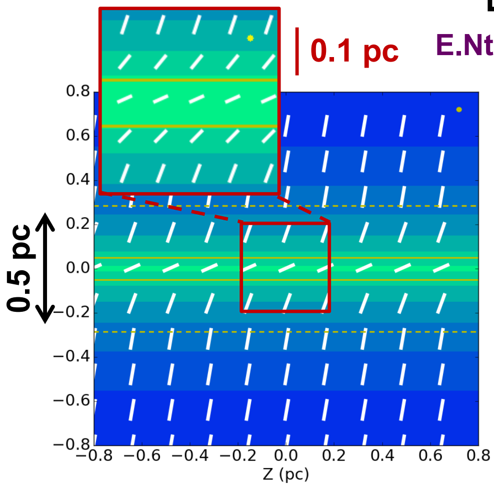
- ***Planck* resolution (> 10’ or > 0.4 pc) insufficient to resolve the 0.1 pc width of filaments.**
  Can be done with PRIMA in *nearby* (d ~140 pc) clouds
- **B fields within dense filaments may be key to prevent radial contraction and make SF possible**

Plausible model of the B field in the central filament



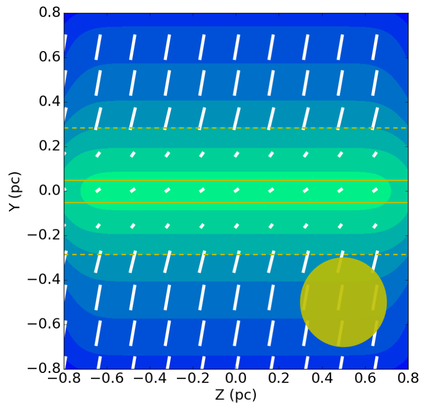
Synthetic polarization maps

PRIMA resolution



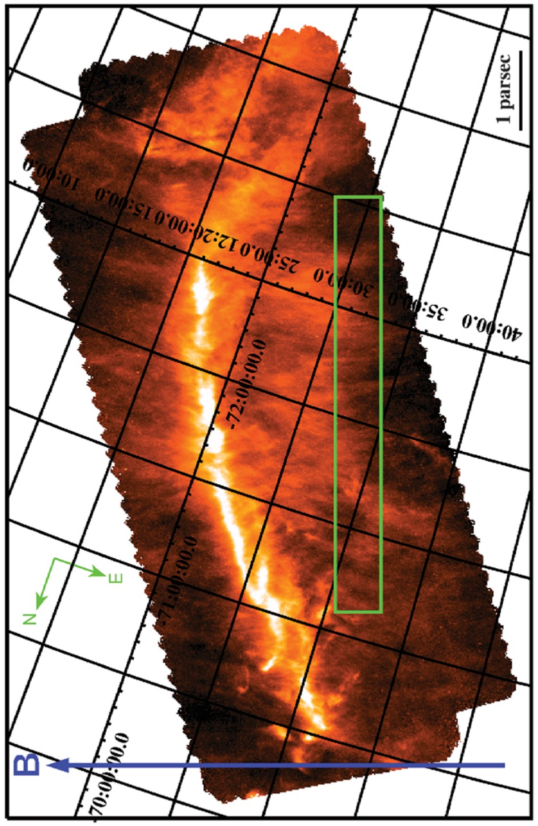
E.Ntormousi

***Planck* resolution**



PRIMA Pol imager can efficiently probe the magnetic field in low-density faint ‘striations’ and side filaments in the nearest clouds (Taurus, Chamaeleon, Musca…)

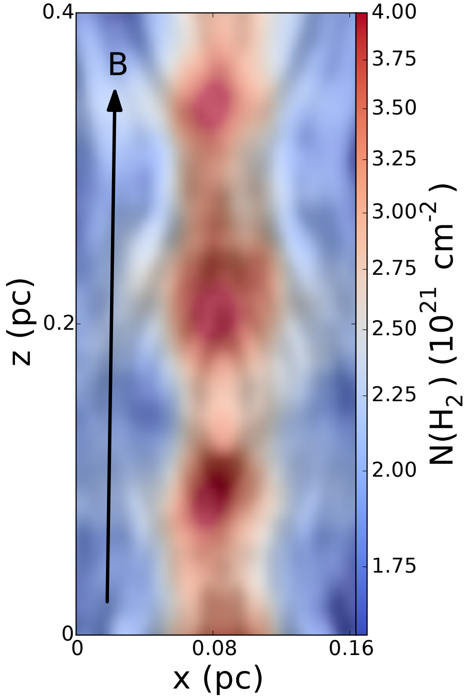
Musca - *Herschel* 250 μm



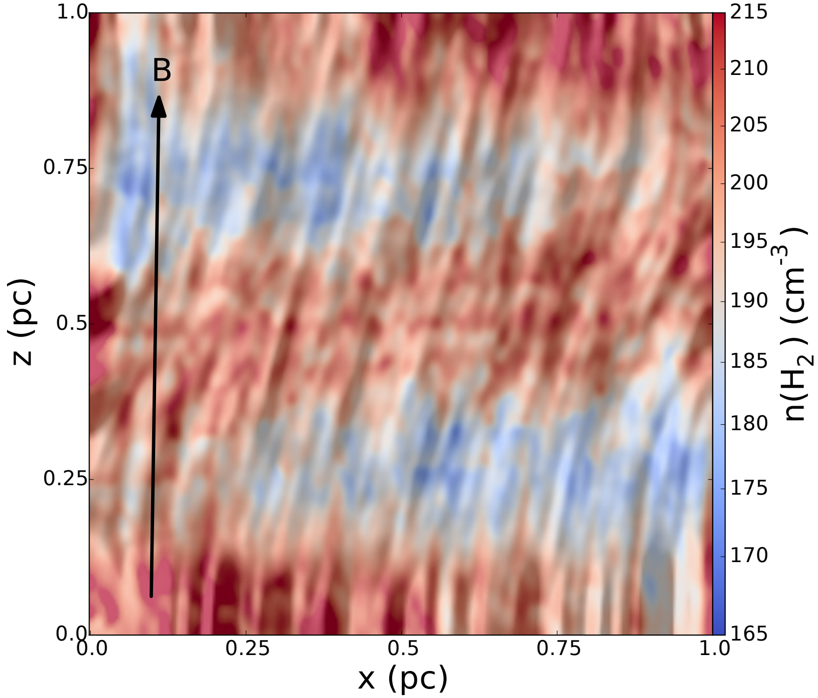
N. Cox+2016

Simulated striations at SPICA 200 μm resolution
~ PRIMA resolution at 172-235 μm

Zoomed-in
column density + B



Volume density + B



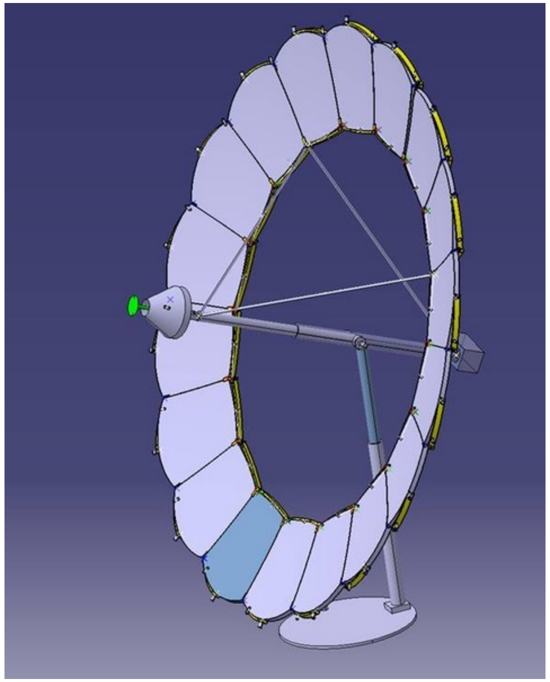
See Tritsis & Tassis 2016
and SPICA B-BOP White Paper (2019, PASA 36, e029)

To go farther out, a bigger FIR space telescope is needed
A possible concept: TALC (20m) equipped with a 'B-BOP' polarimeter

TALC

(Thinned Aperture Light Collector)

A deployable 20m annular telescope



Sauvage+2014, SPIE 9134

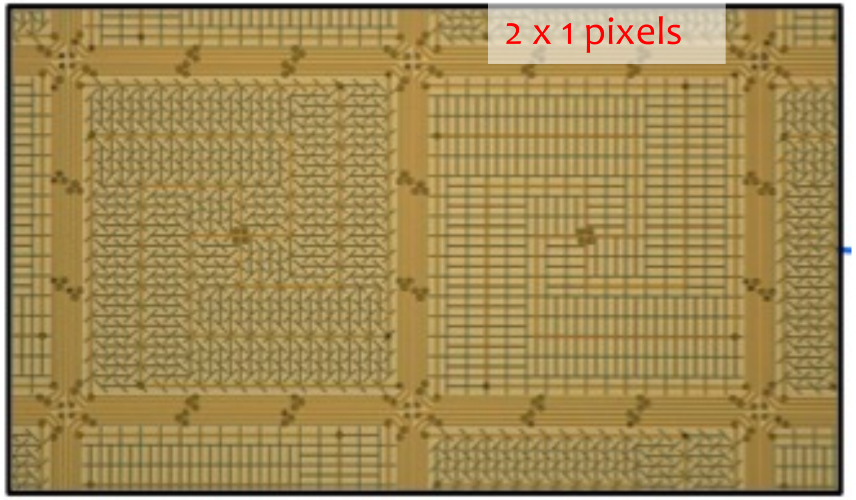
See Poster by L. Rodriguez

B-BOP = "B-fields with BOlometric Polarizers"

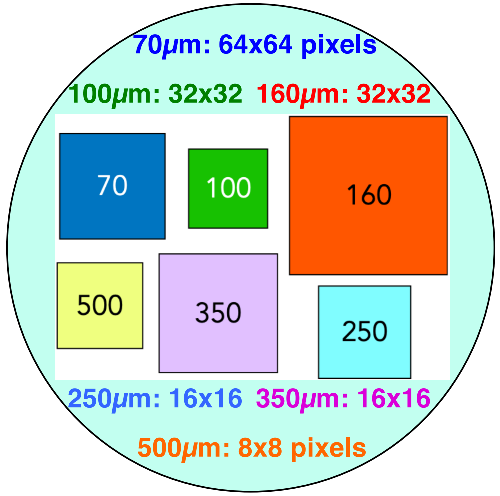
Instrument concept:
L. Rodriguez, V. Revéret, M. Sauvage

Talk by V. Revéret on Friday

Polarization-sensitive bolometers



- Pixels are alternately « 0° » and « 45° »
- **Stokes parameters Q, U in a "single shot"**



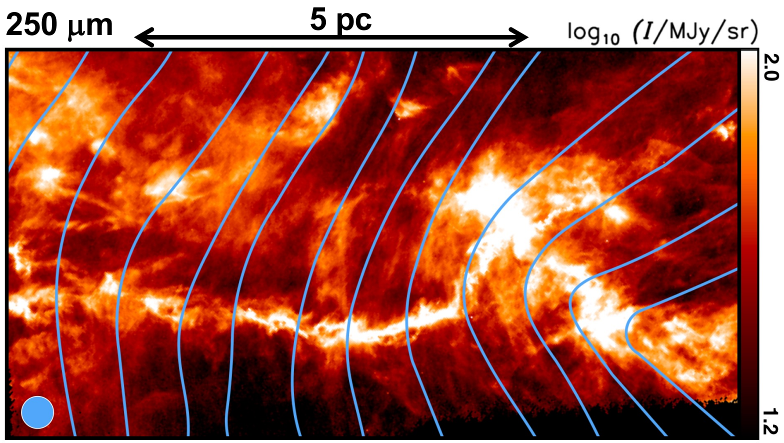
Possible B-BOP Focal Plane

Six bands between 70 μm and 500 μm (cf. *Herschel*) observing the sky <u>simultaneously</u>

~3" resolution @ 250 μm

TALC-B-BOP can unveil the role of magnetic fields in filament evolution and core/star formation out to massive GMCs in the Galactic disk

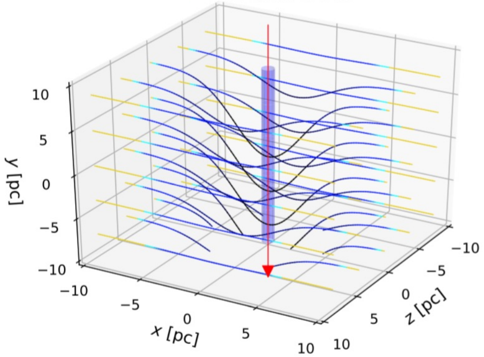
Taurus B211 filament
***Herschel* 250 μm**
***+ Planck* B lines**



Palmeirim +2013
A. Bracco

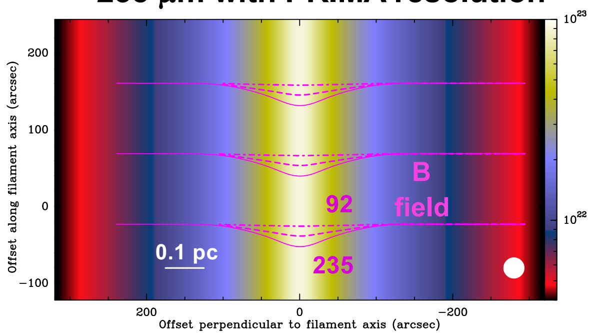
- **PRIMA resolution (28" at 235 μm) insufficient to resolve the ~0.1 pc width of molecular filaments beyond nearest clouds Can be done with TALC out to d~1.5-3 kpc**
- **TALC-B-BOP could deliver FIR polarized (Q, U) images with a S/N and dynamic range similar to *Herschel* images in I and a factor ~6 higher resolution**

Plausible model of the B field in a SF filament

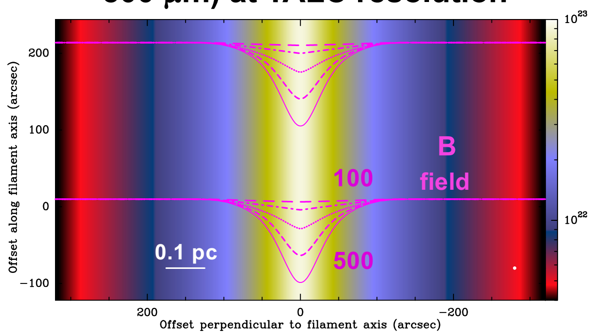


cf. Reissl+2018

B-field lines inferred at λ = 92, 172, and 235 μm with PRIMA resolution



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



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

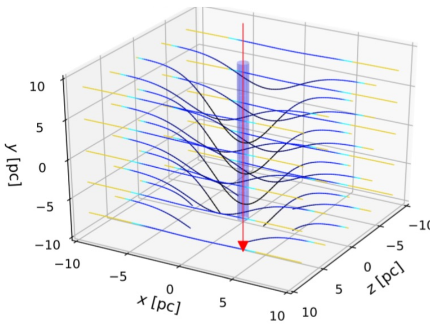
(for a model filament at d = 410 pc – cf. Orion)

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

Synthetic polarization maps for 0.1-pc wide model filaments at d = 1.5 kpc

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

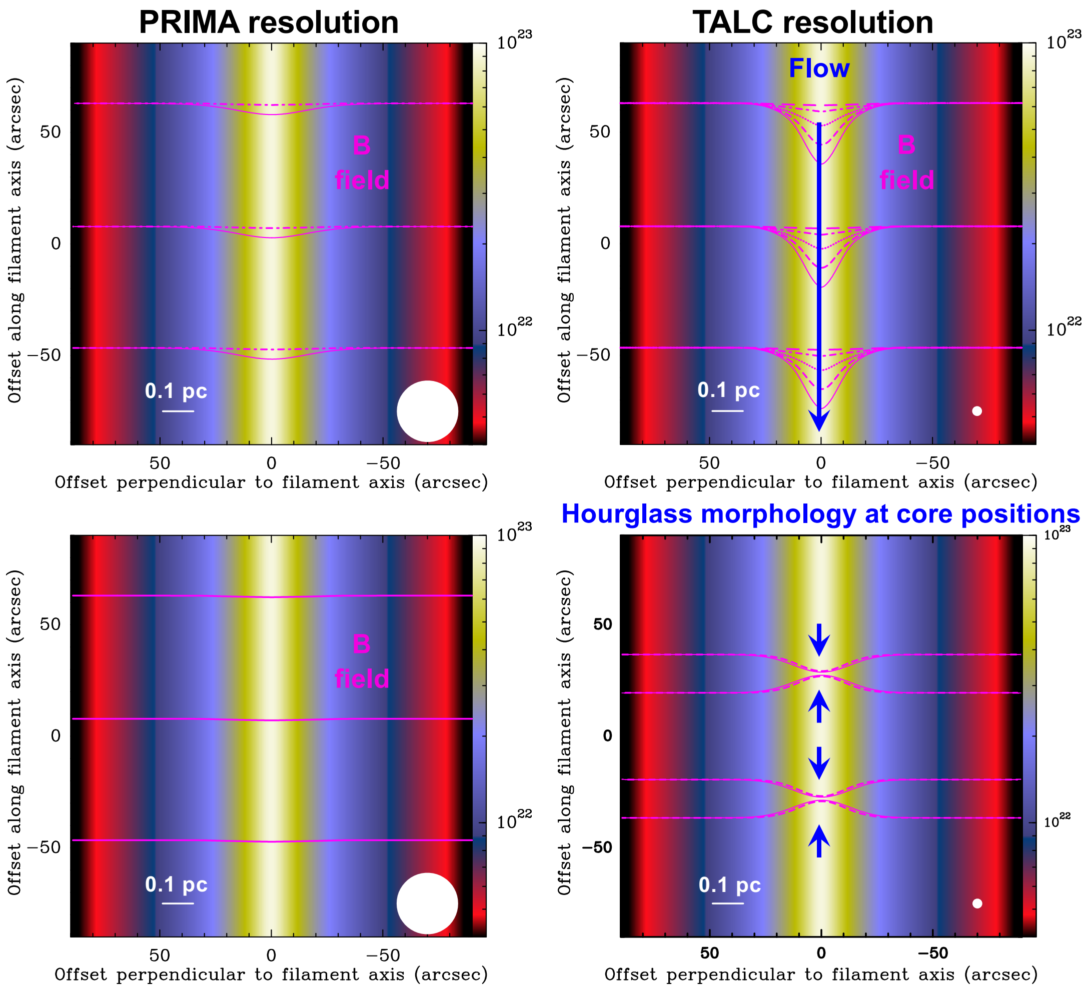
1) Dynamical flow



(cf. Gomez & Vazquez-Semadeni+2018)

2) Quasi-equilibrium model

(cf. Inutsuka & Miyama 1997)



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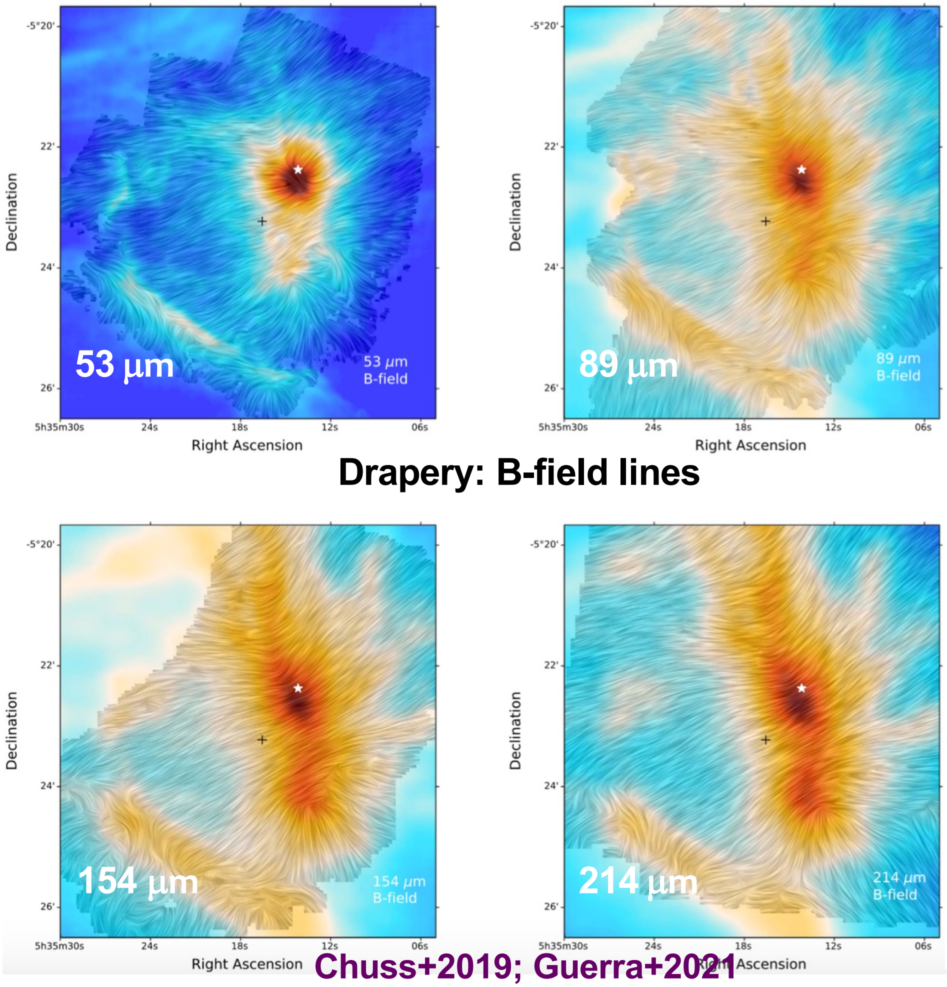
Far-IR and mm/submm imaging polarimetry results for Orion A OMC-1:
Hourglass pattern with more pronounced curvature at longer λs(?)

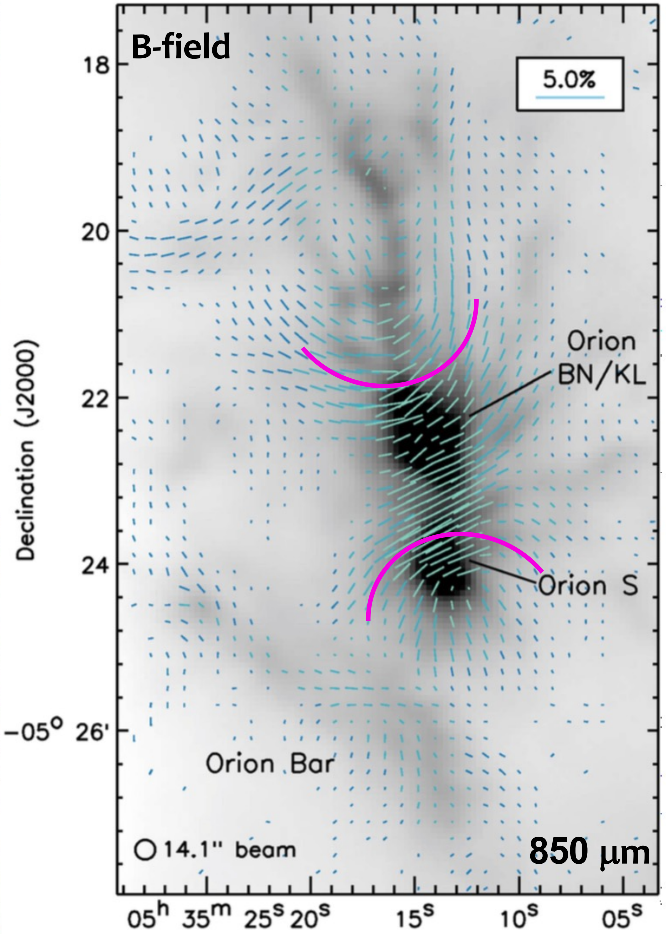
SOFIA - HAWC+

Drapery: B-field lines



Chuss+2019; Guerra+2021

JCMT–SCUBA2-POL2 (BISTRO)



Ward-Thompson+2017; Pattle+2017

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

- **High spatial dynamic range (~10^3), which cannot be achieved from the ground**
- **High angular resolution (TALC can resolve critical 0.1 pc scale out to ~1.5-3 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)**
- **A wide-field polarimetric imaging survey of Galactic molecular clouds at λ ~ 70-700 μm on a TALC-class telescope would revolutionize our understanding of the origin and role of B-fields in filament formation/fragmentation**

Preferred capabilities for the next FIR space mission

- **Angular resolution requirement: Resolve the critical ~0.1 pc scale by factor of $\gtrsim 2$ out to ~ 3 kpc at λ ~ 350 μm --> required diameter/baseline $\gtrsim$ 20m**

- **High angular resolution and sensitivity to low surface brightness structures + large spatial scales → large single dish or annular telescope :**
  Desired diameter: 20 m; Minimum diameter for filled single dish: 3.5 m.

- **(Diffraction-limited) Wavelength range: ~ 70 μm to ~ 750 μm**
  Equivalent frequency range: ~ 400 GHz to ~ 4300 GHz

- **Desired instrument: Multi-band polarimetric continuum imaging camera (minimum: 6 Herschel bands: 70, 100, 160, 250, 350, 500 μm; desired additional band: 700 μm)**
  Desired Instantaneous field of view: ~10'x10' (but not critical, multi-wavelength aspect more important; e.g., minimum of ~5'x5' also fine). Total number of pixels: $\gtrsim 10^4$

- **Very useful complement to above continuum camera: Heterodyne multi-beam camera allowing velocity-resolved spectro-imaging.**