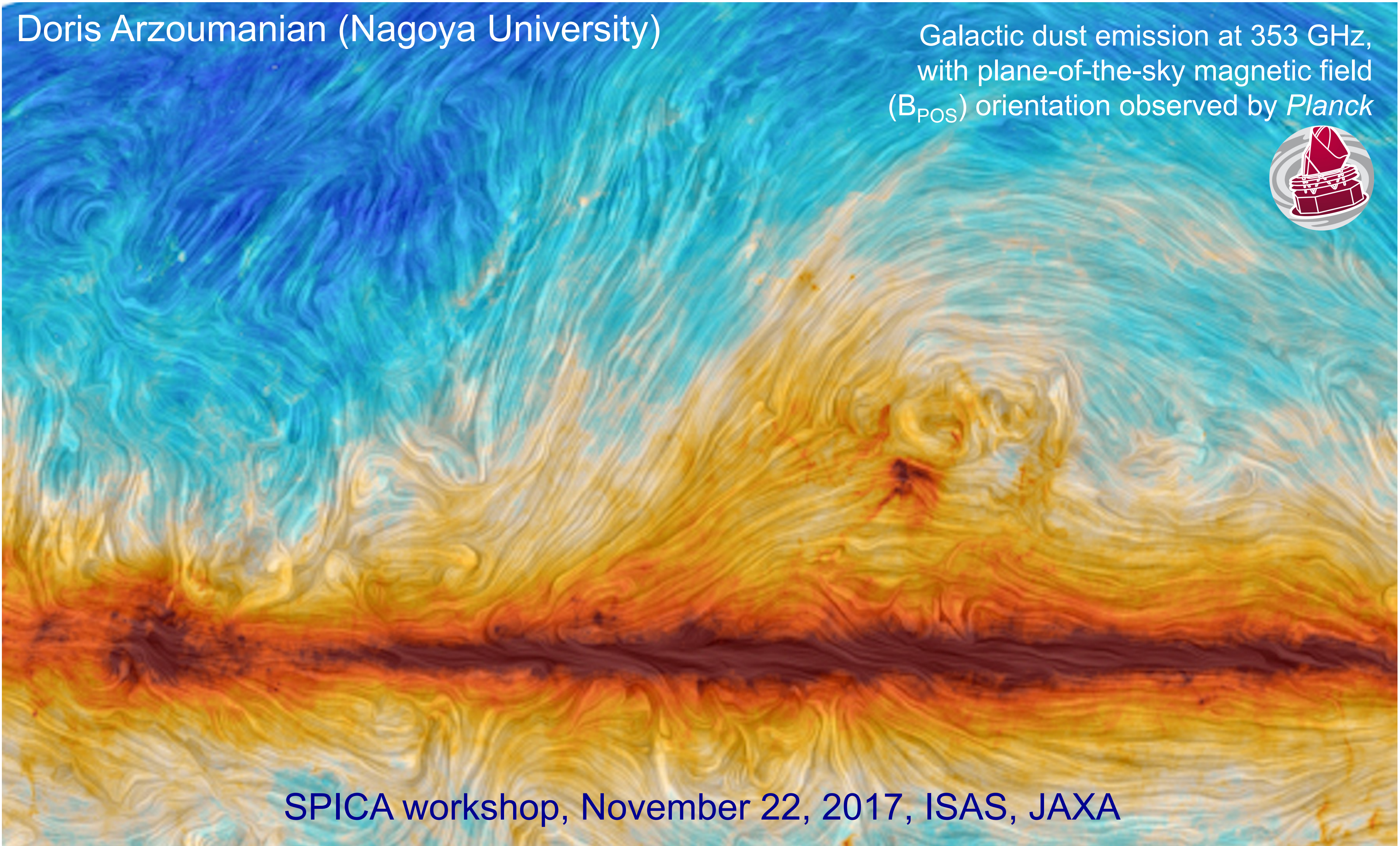
Understanding the role of magnetic fields in the formation and evolution of interstellar filaments

Promises from SPICA/SAFARI-POL dust polarization observations

Doris Arzoumanian (Nagoya University)



Galactic dust emission at 353 GHz, with plane-of-the-sky magnetic field (B_{POS}) orientation observed by *Planck*

SPICA workshop, November 22, 2017, ISAS, JAXA

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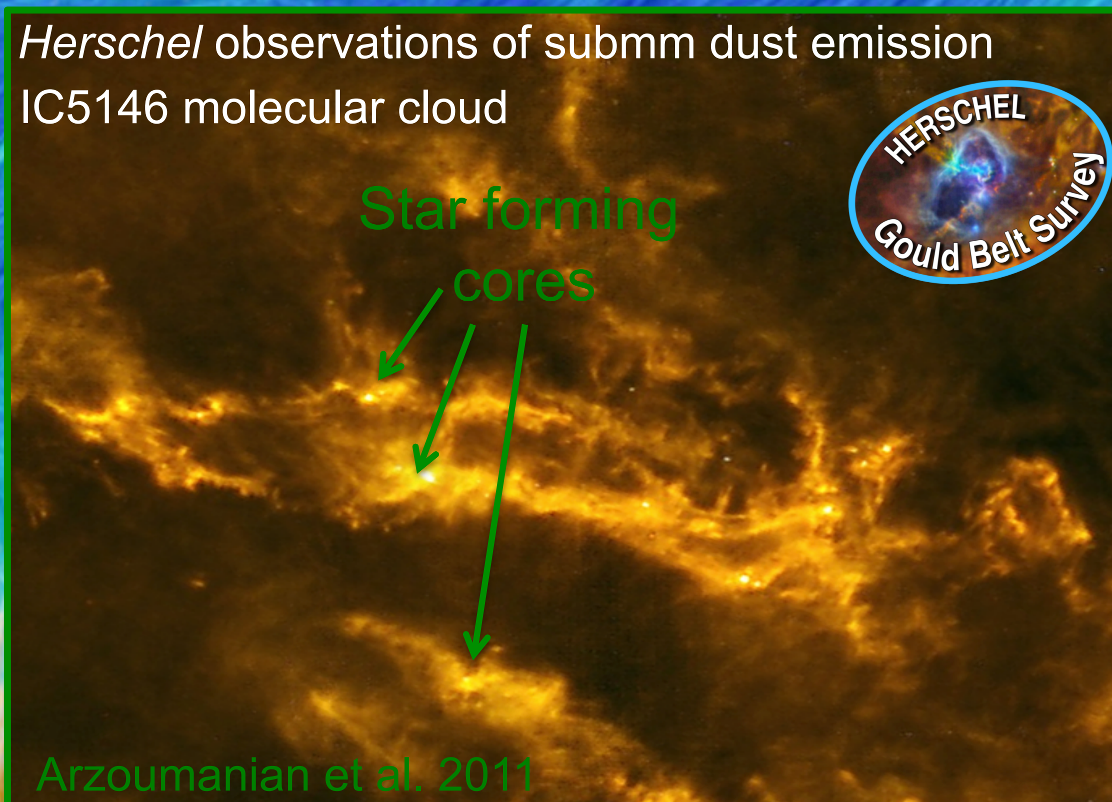


Galactic dust emission at 353 GHz, with plane-of-the-sky magnetic field (B_{POS}) orientation observed by *Planck*

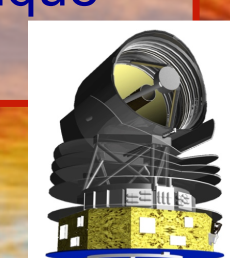
With Ph. André, F. Boulanger, A. Bracco, J. Soler

Outline

• Motivation: what have we learned from *Herschel* and *Planck*
-Properties of filaments
-Role of filaments in star formation

• Open questions:
-Role of magnetic field in the formation and evolution of filaments

• SPICA/SAFARI-POL as a unique opportunity to make progress



SPICA

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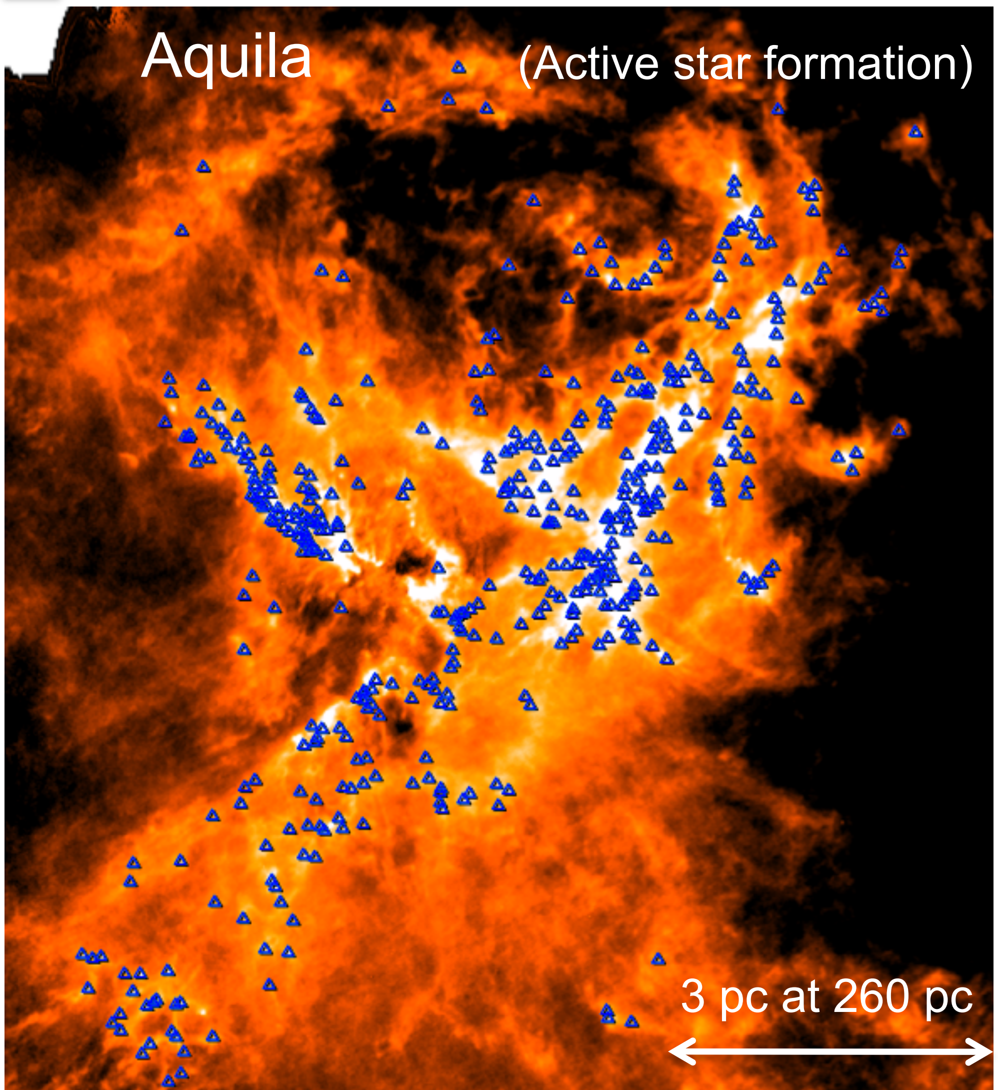
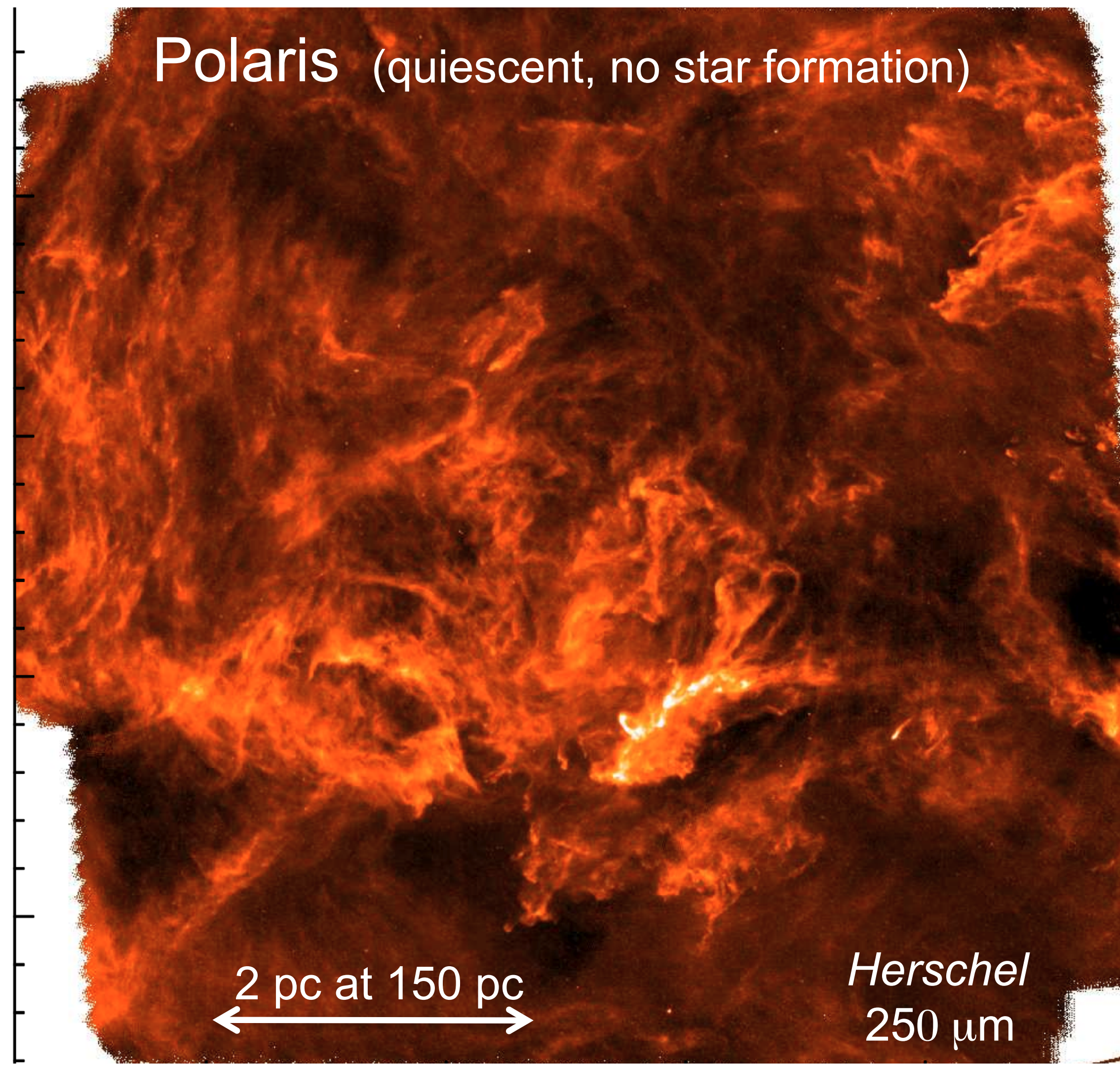
Omnipresence of filamentary structures both in star forming regions and in quiescent clouds

Herschel probes simultaneously the large scale structures (~10 pc) and the small scale prestellar cores (~0.01 pc) of the nearby interstellar medium (ISM)

Prestellar cores ~75% along supercritical filaments

André et al. 2010, 2014

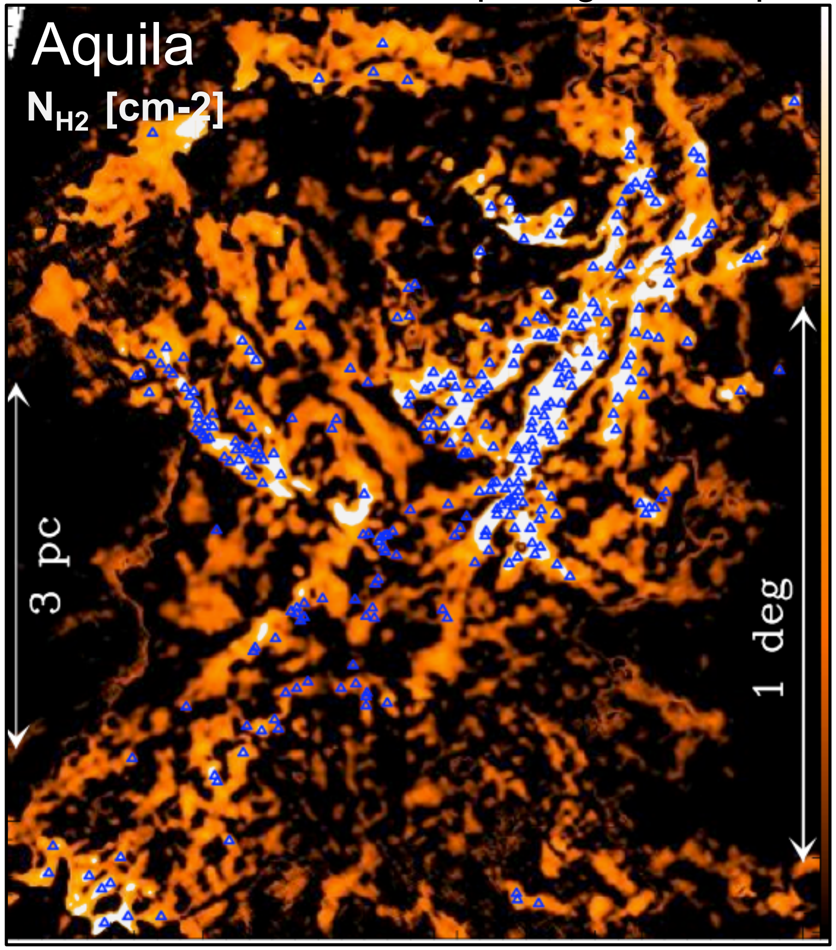




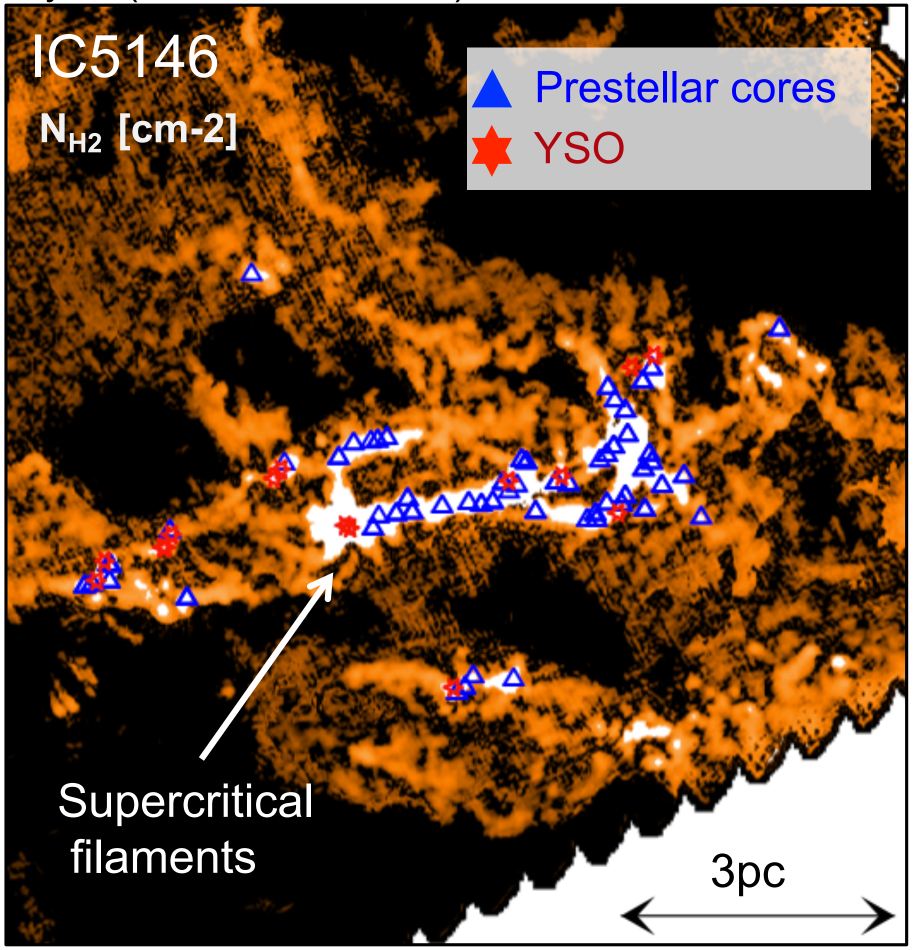
Star formation along supercritical filaments as observed by *Herschel*

A large fraction of star forming (prestellar) cores are observed along supercritical filaments with $M_{line} > M_{line,crit}$ (André et al. 2010, 75% in Aquila Könyves et al. 2015), where $M_{line,crit} = 2c_s^2/G \sim 16\ M_{\odot}/pc$ (for T~10K)

Curvelet component of the *Herschel* column density maps derived from a Morphological Component Analysis (Starck et al. 2003)



André et al. 2010, Könyves et al. 2015



Arzoumanian et al 2011

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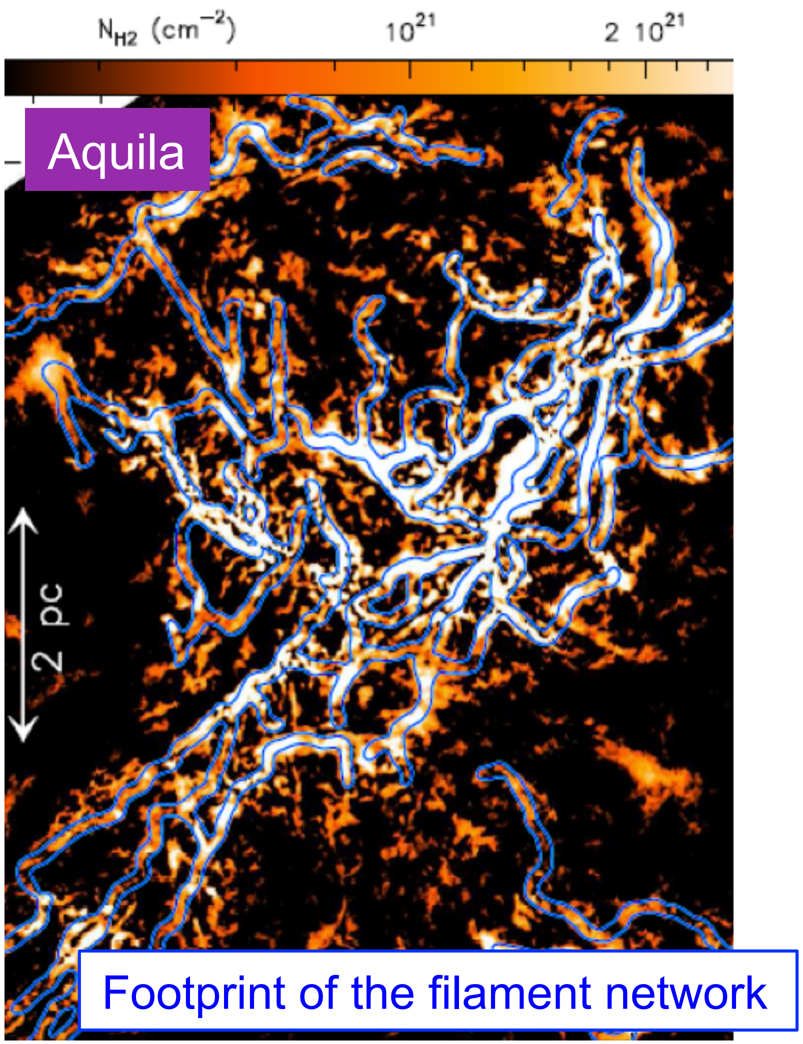
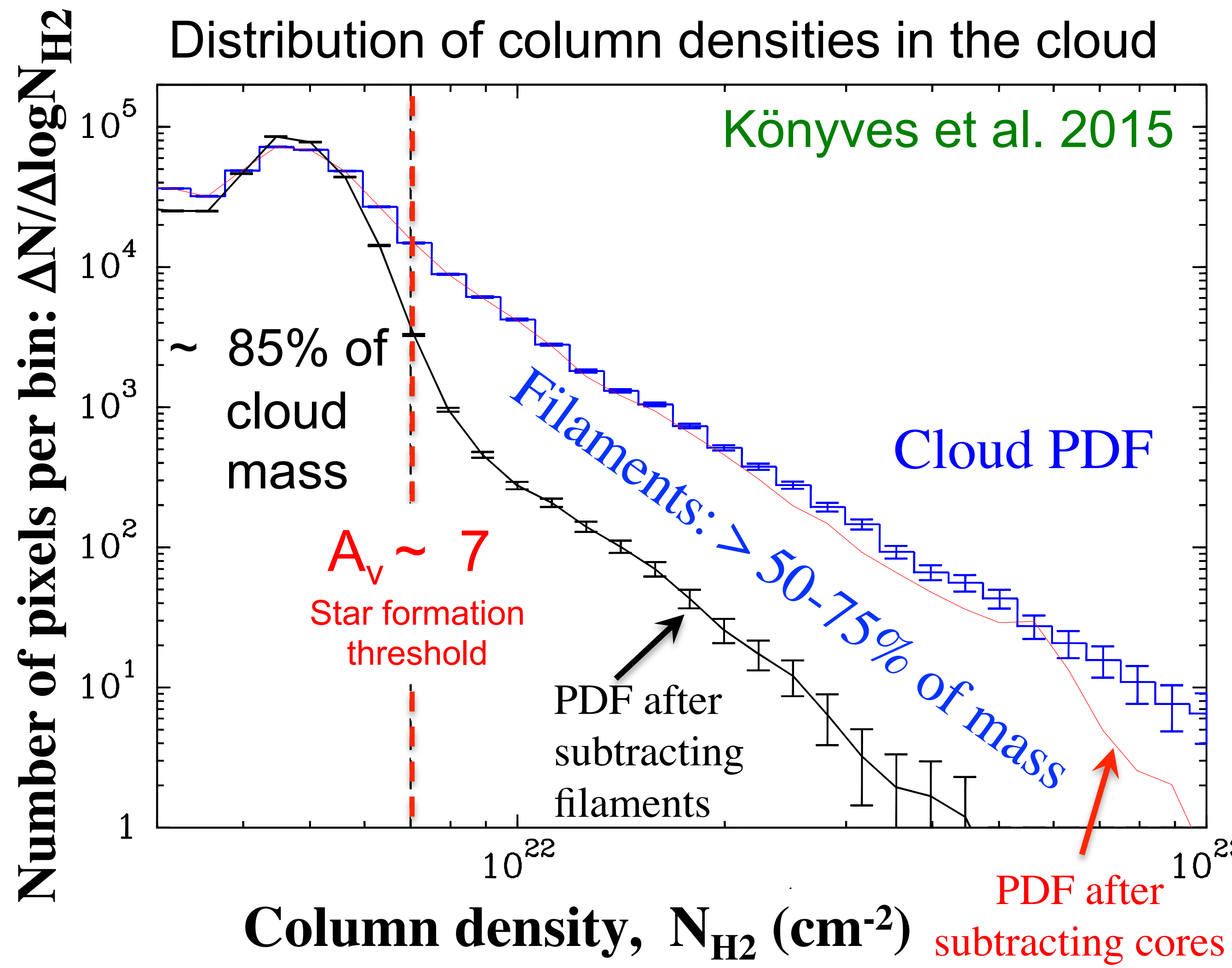
A large fraction of the mass of dense gas in form of supercritical star forming filaments

Supercritical filaments give the initial conditions of (solar mass) star formation





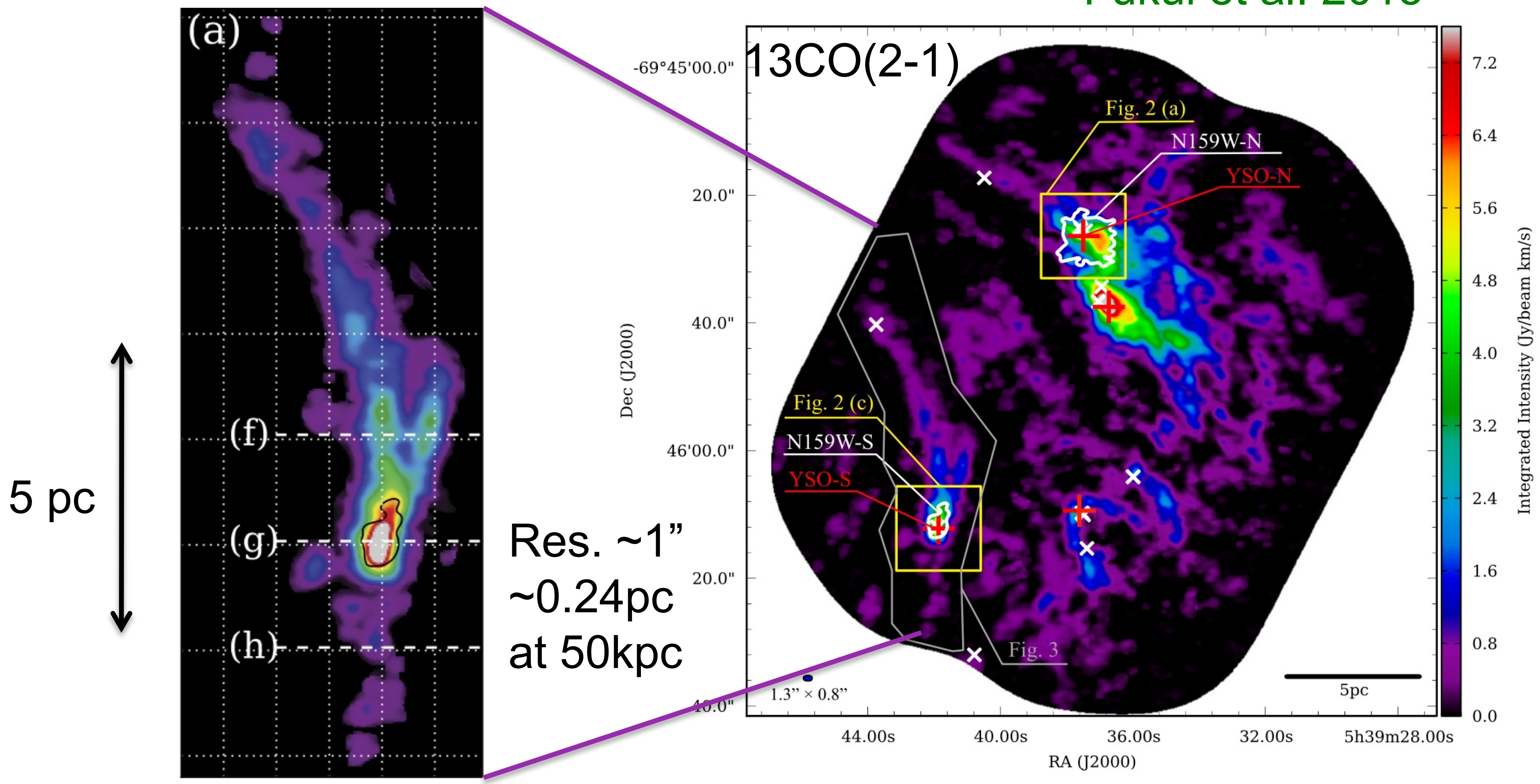
→$A_V < 7$: ~10-20% of the mass is in form of (mostly subcritical, $M_{line} < M_{line,crit}$) filaments

→$A_V > 7$: ~50-75% of the mass is in form of (mostly supercritical, $M_{line} > M_{line,crit}$) filaments
~15% of the mass is in the form of prestellar cores

Filaments are also observed to be main structures of the interstellar medium of other galaxies

ALMA observations of pc-scale filaments in the LMC

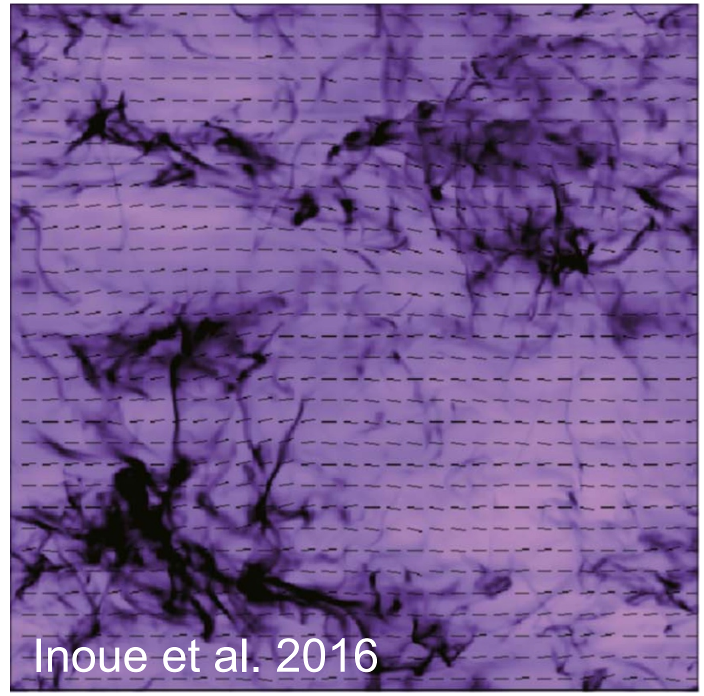
Fukui et al. 2015

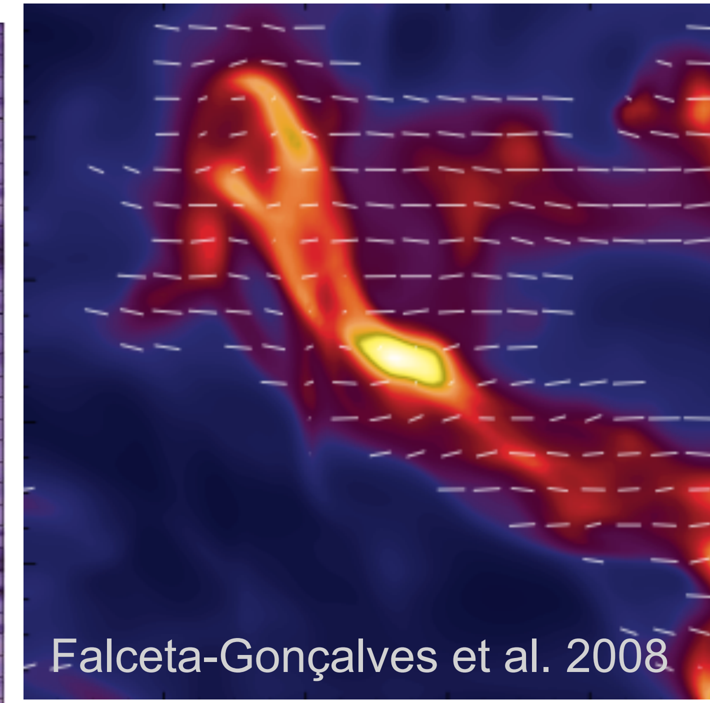


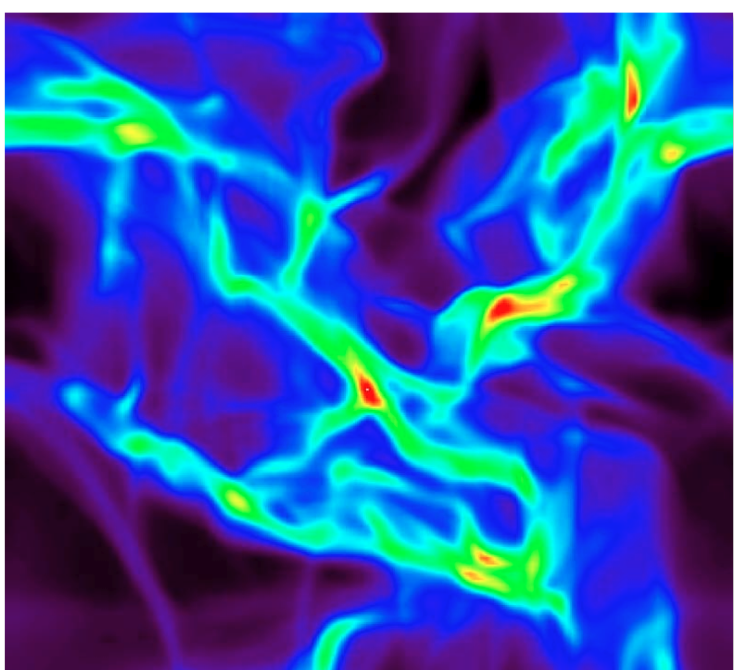
Filaments may help understanding the initial conditions of star formation in galaxies (cf. Lada et al. 2012)

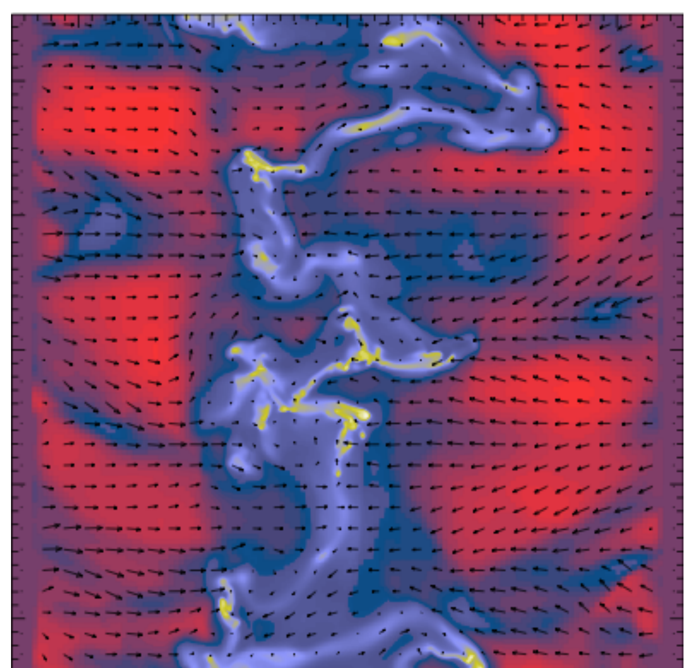
Filaments in numerical simulations of molecular cloud formation

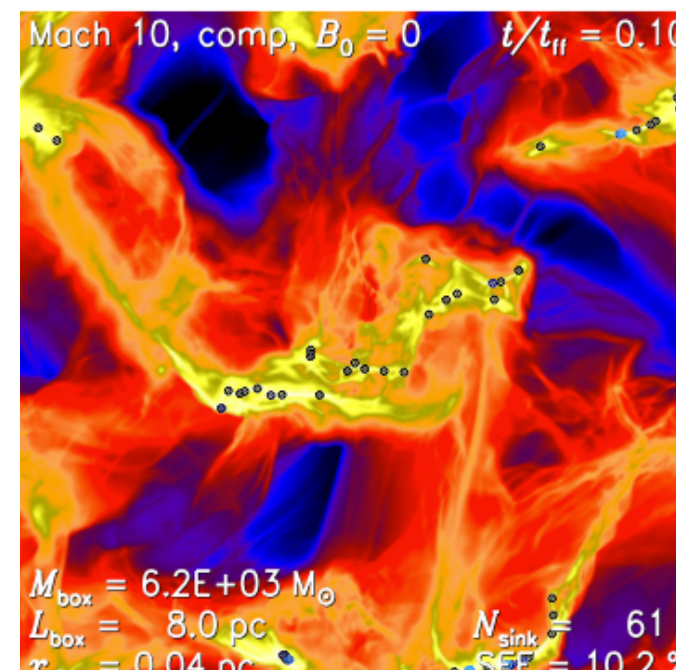
Filaments are easily produced by numerical simulations of molecular cloud formation and evolution that includes hydrodynamic or magnetohydrodynamic turbulence


Inoue et al. 2016


Falceta-Gonçalves et al. 2008


Padoan et al. 2001


Hennebelle et al. 2008



Federrath et al. 2008

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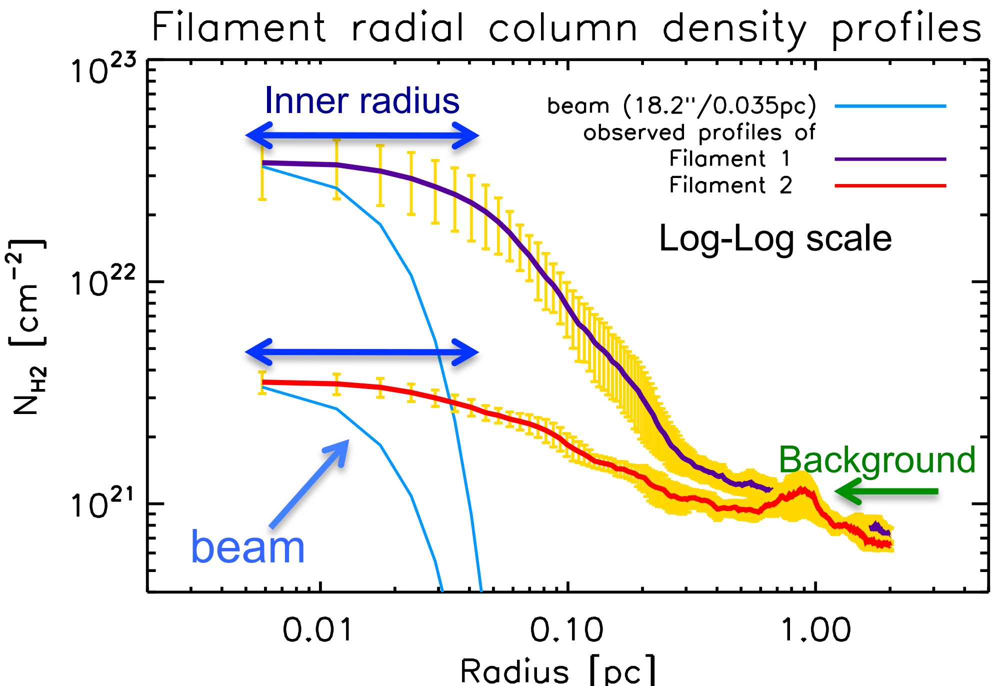
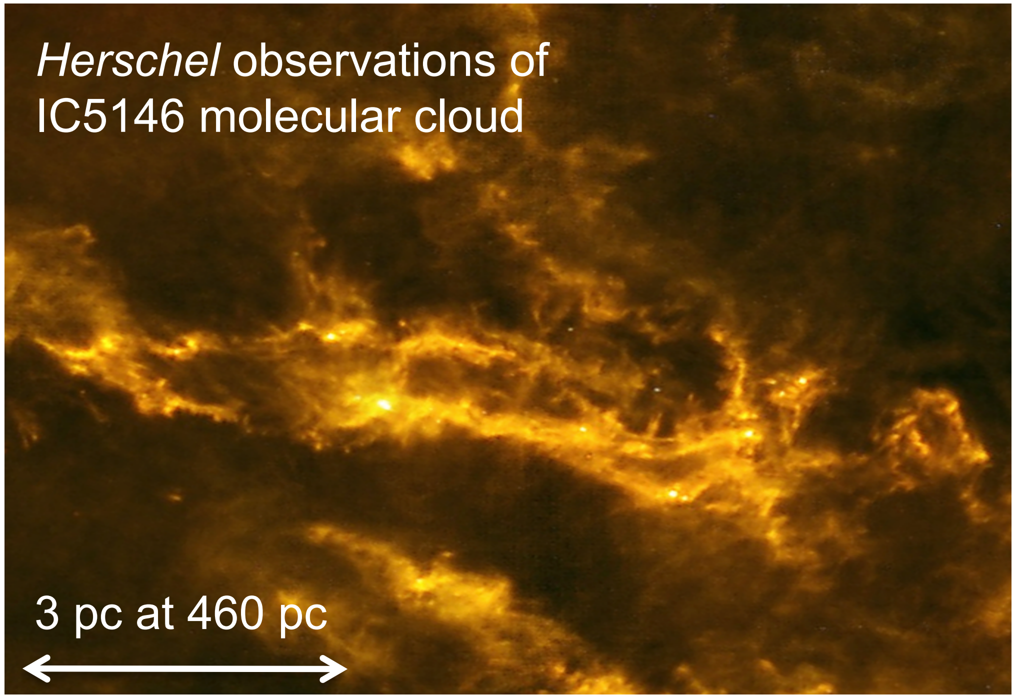
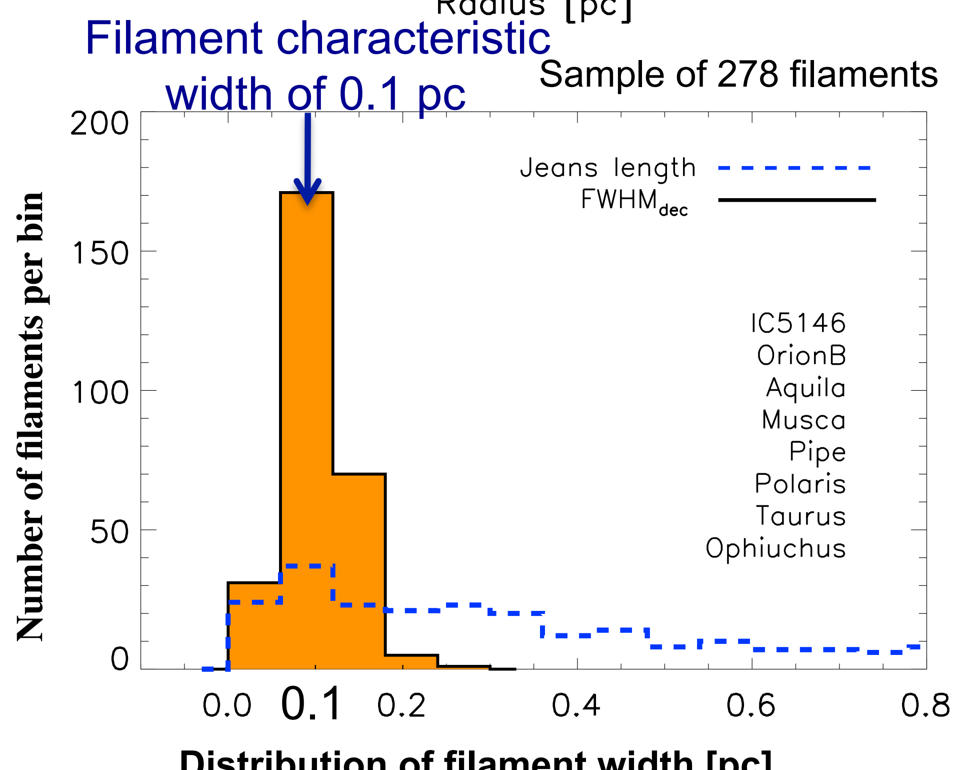
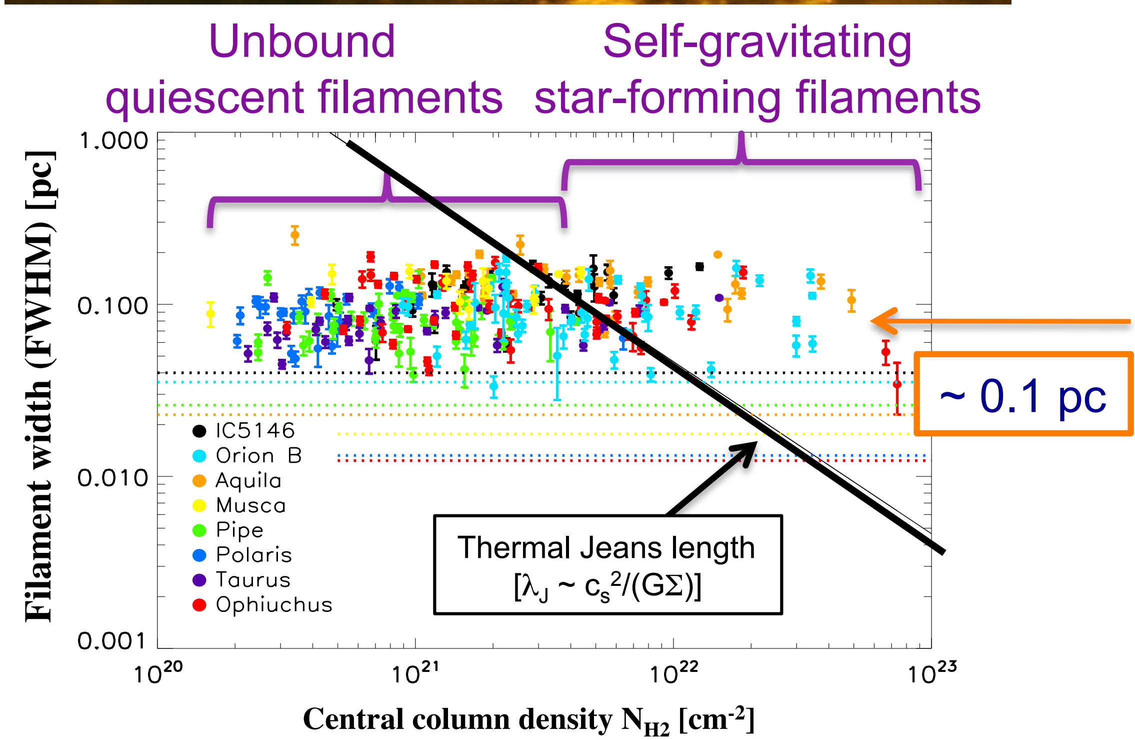
Interstellar filaments share a common inner width of 0.1pc while they span a wide range in column density

Arzoumanian et al. 2011, 2013, + in prep.









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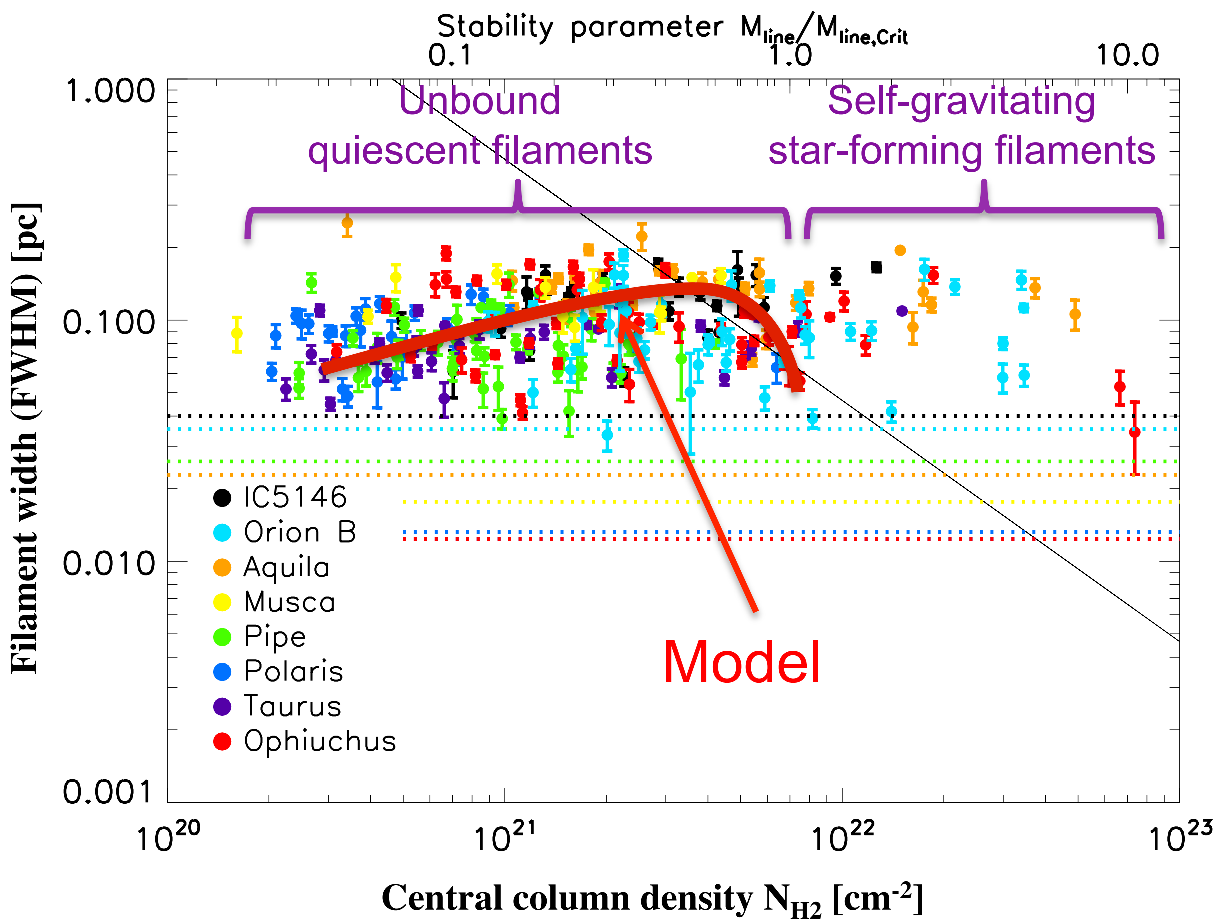
Understanding the observed properties: Model of non isothermal filaments in pressure equilibrium with the ambient medium



Model of polytropic filaments
$P \sim \rho^{\gamma}$
with
$\gamma = 0.8$ and
$P_{ex} / k_B \sim 5 \times 10^4$ K cm^{-3}

Reasonable agreement with the observations for subcritical filaments

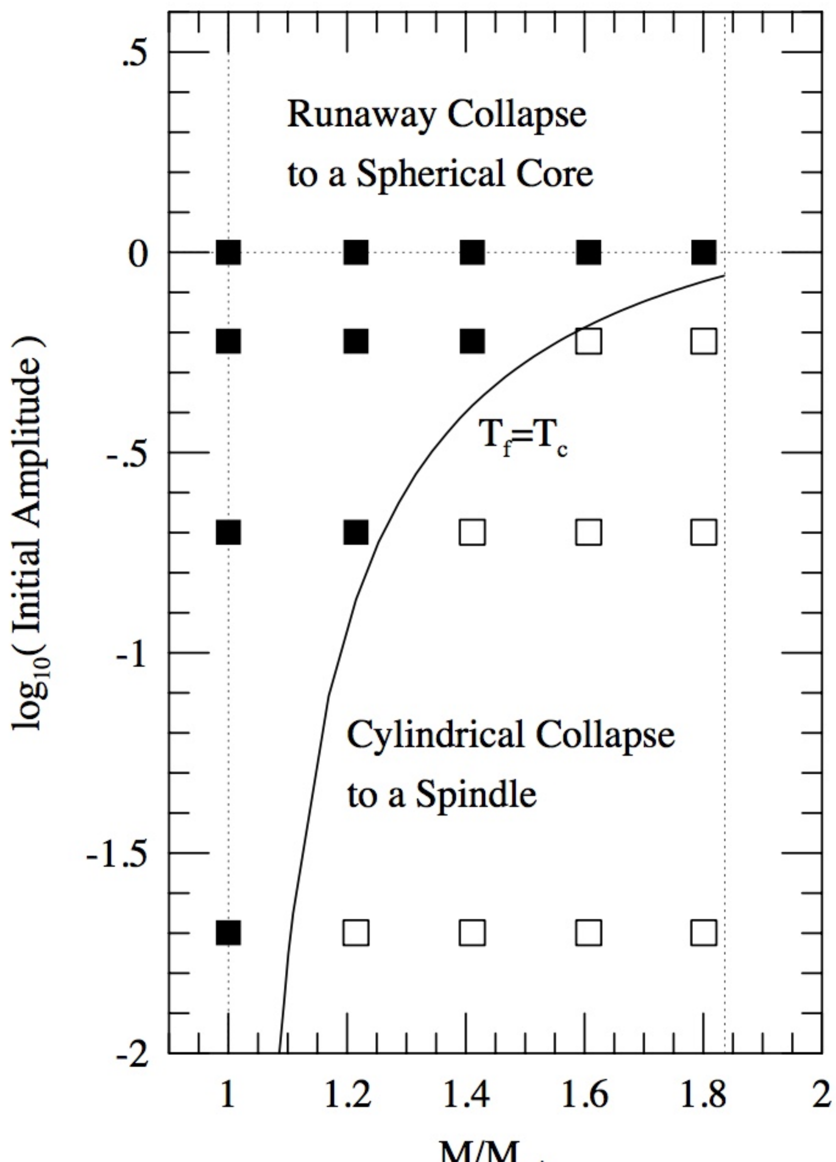
(Inutsuka et al. in prep.)

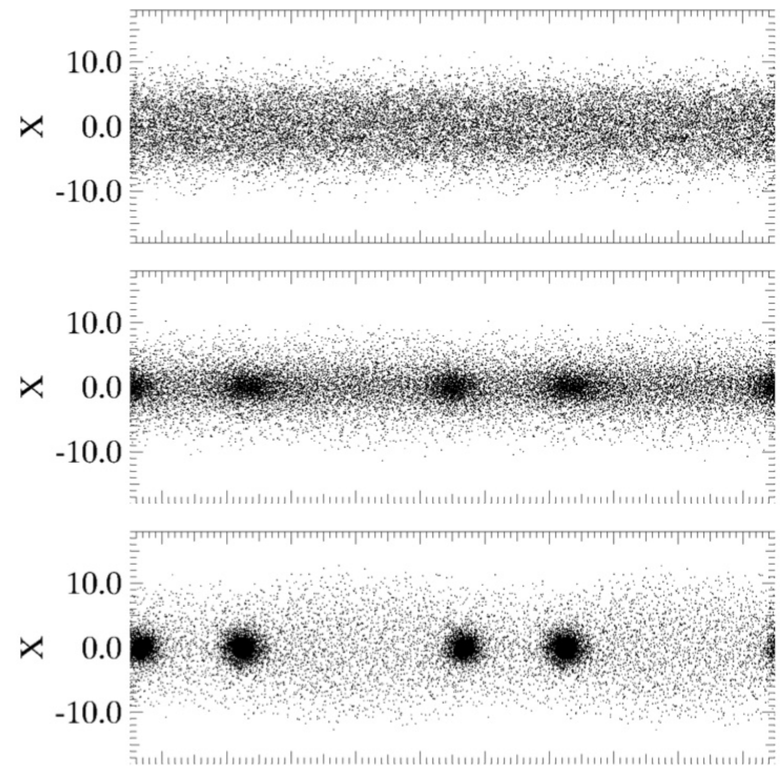
Cf. Fischera & Martin 2012 for a model of isothermal filaments

Tension between filament models and observations

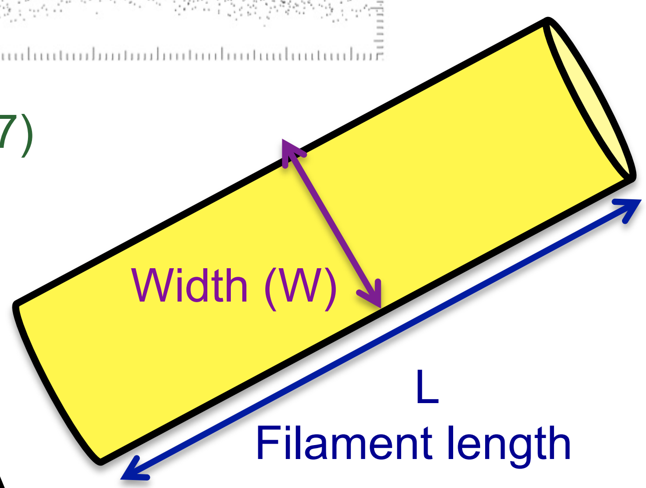
- Thermally supercritical filament with M_{line} > $M_{line,crit}$ are unstable for radial collapse and gravitational fragmentation (Inutsuka & Miyama 1992, 1997)
- Runaway collapse of thermally supercritical filaments with M_{line} > $2M_{line,crit}$

Star forming supercritical filaments with M_{line} >> $2M_{line,crit}$ are observed





(Inutsuka & Miyama 1997)



M_{line}=M/L

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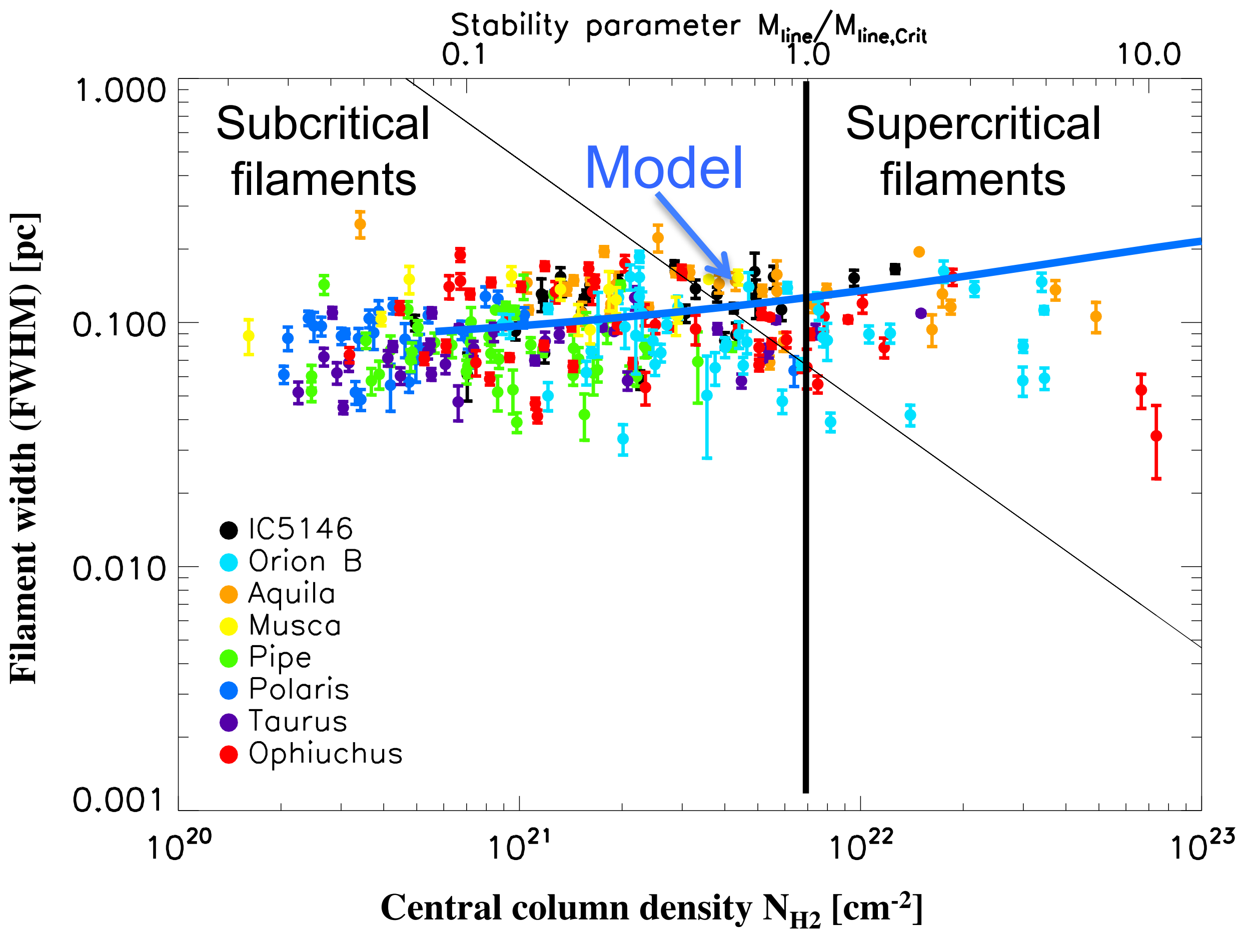
Understanding the observed properties: Model of accreting dense/self-gravitating filaments

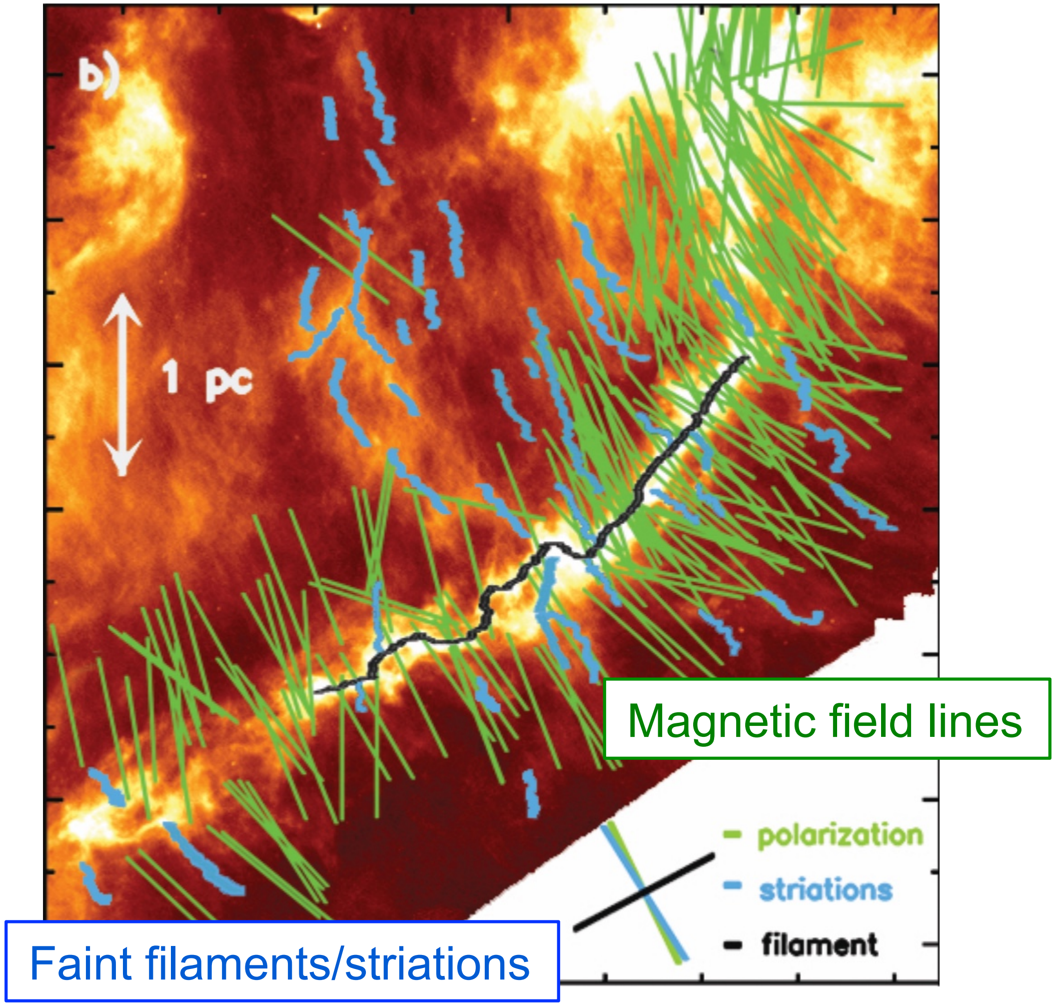


Balance between accretion-driven turbulence (Klessen & Hennebelle 2010) and dissipation of turbulence due to ion-neutral friction (Hennebelle & André 2013)

See also numerical simulations of gravitational infall onto molecular filaments (Heitsch 2013)

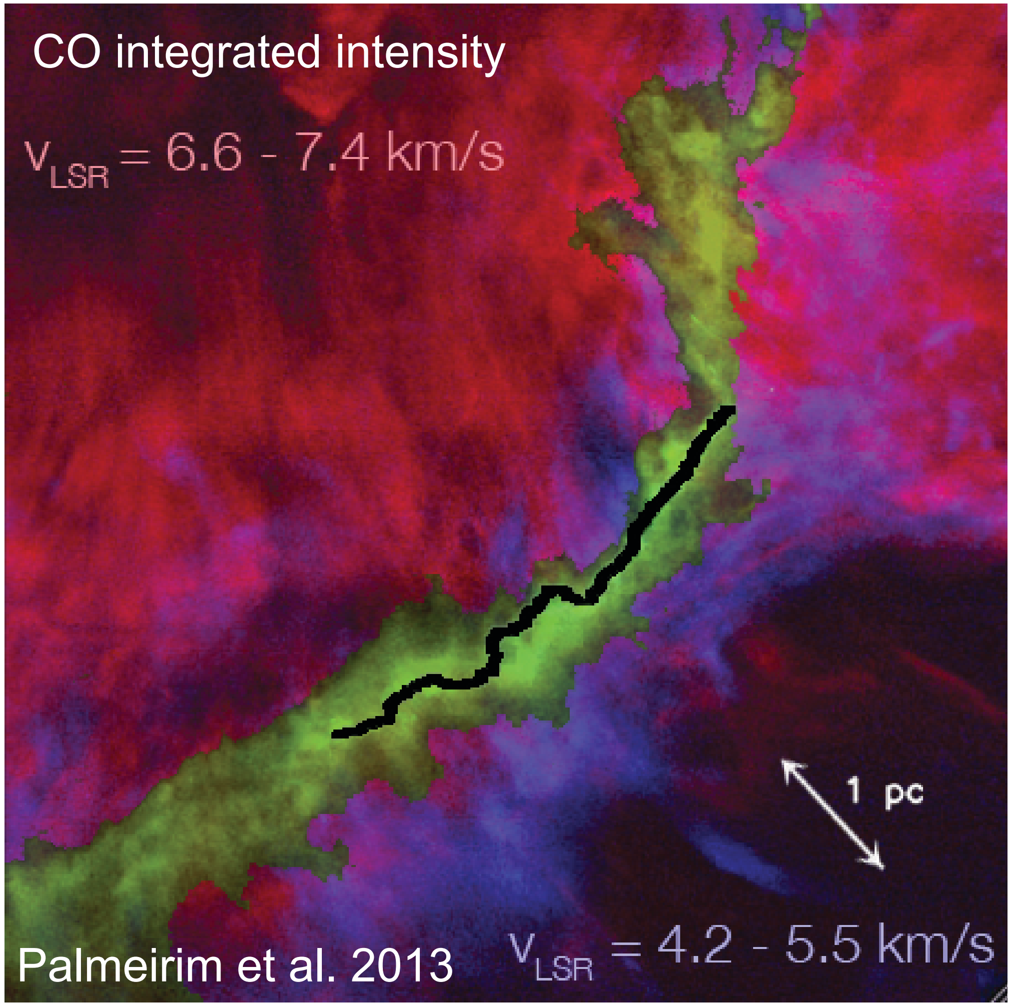
Hint of the evolution of supercritical filaments from Accretion of surrounding material channeled by the magnetic field?

Low column density filaments or striations aligned with the magnenetic field seem to be feeding the dense filament



Herschel column density map
Palmeirim et al. 2013

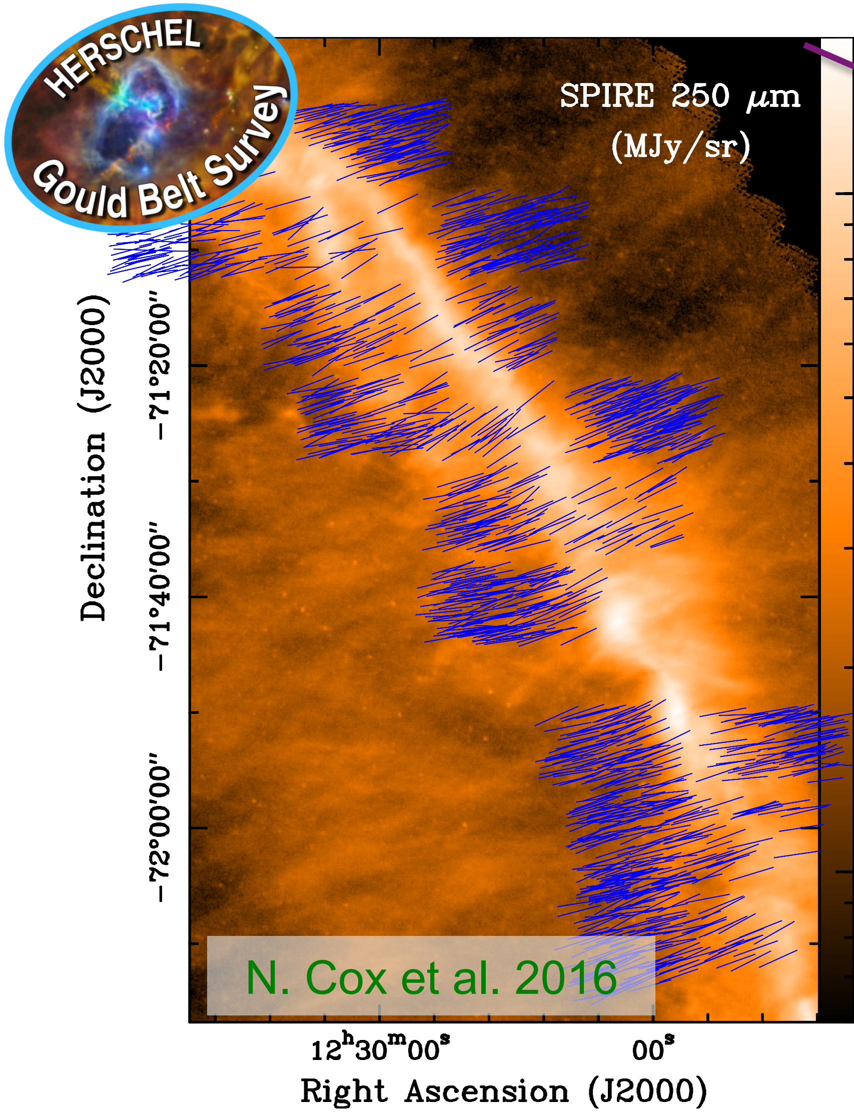
Red-shifted and blue-shifted velocity gradients on both sides of the filament trace flows of surrounding matter being accreted onto the filament?



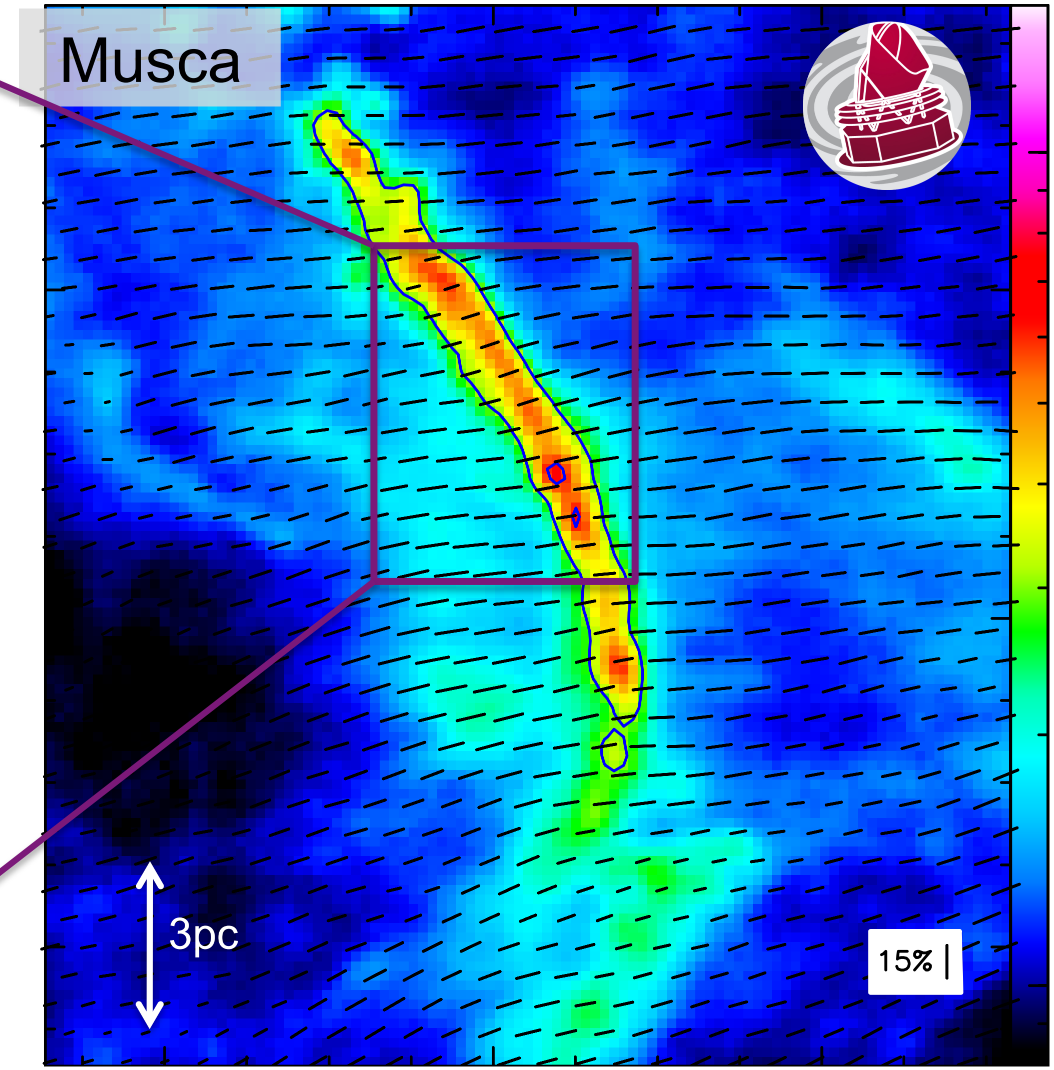
CO observations from Goldsmith et al. 2008

Magnetic field orientation derived from *Planck* dust polarization observations

- Thanks to *Planck,* we have now fully sampled maps of polarized emission of the filaments and their parent clouds from a tracer of the interstellar matter
- The polarization angle gives the orientation of the magnetic field on the plane of the sky ($\boldsymbol{B}_{POS}$)



Optical polarization tracing the magnetic field orientation (Pereyra & Magalhaes 2004)

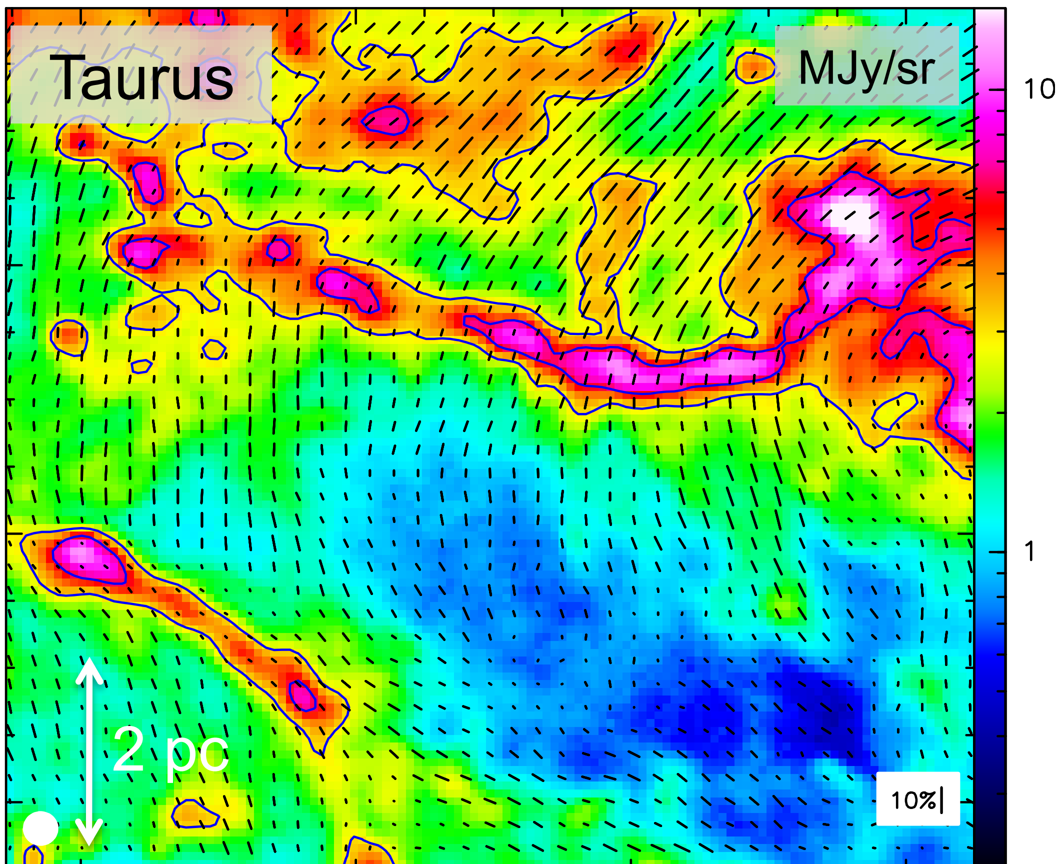


Planck total intensity at 353GHz (850μm) in MJy/sr
Segments: $\boldsymbol{B}_{POS}$ length ~ polarization fraction (p)
(10' resolution) *Planck* XXXIII 2016 (arXiv:1411.2271)

Statistical analysis of the relative orientation between magnetic field and intensity structures observed by *Planck*

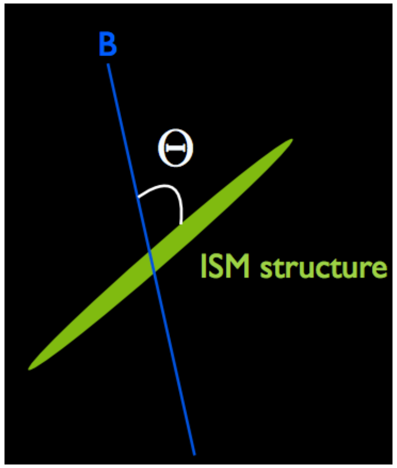
→ In molecular clouds, high column density structures/filaments appear to be perpendicular to the local $\boldsymbol{B}_{POS}$, while fainter structures are parallel to $\boldsymbol{B}_{POS}$

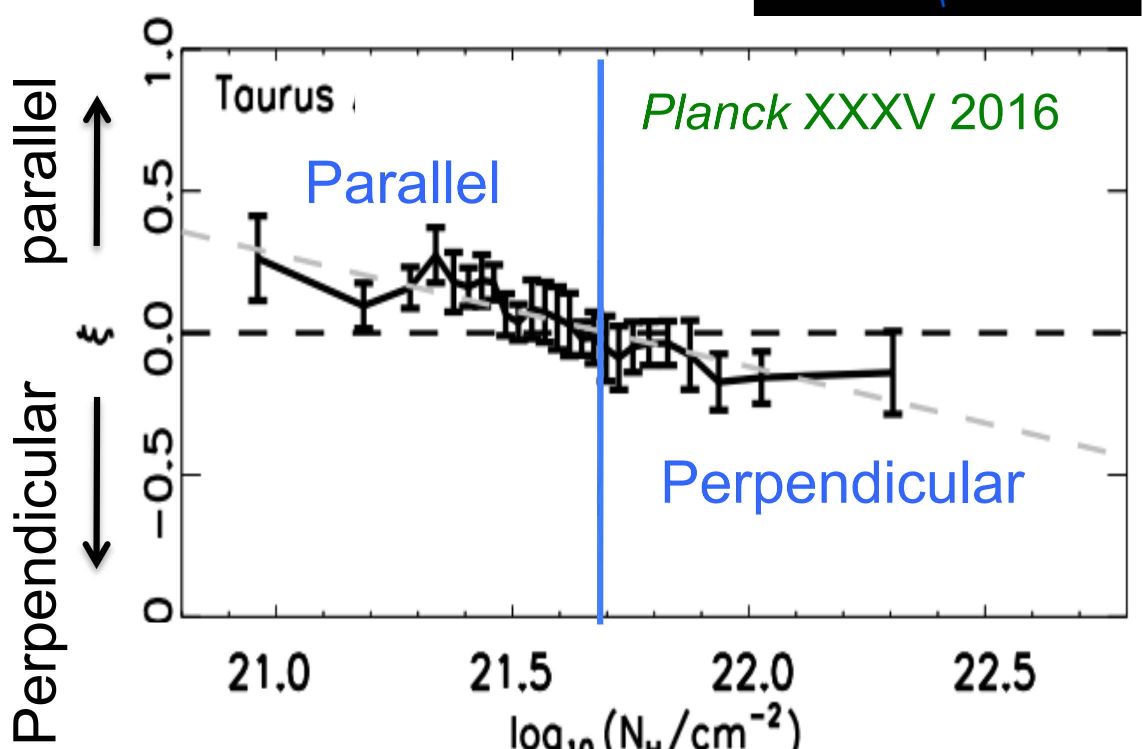
→ the magnetic field is dynamically important in the formation and evolution of structures/filaments



Total intensity map at 353GHz, blue contours: *I* (3 & 6 MJy/sr), Resolution: 5’,
black segments: B_{POS} orientation,
length ~ polarization fraction,
Resolution: 10’

Relative orientation between the angle of $\boldsymbol{B}_{POS}$ and intensity structures on the plane of the sky





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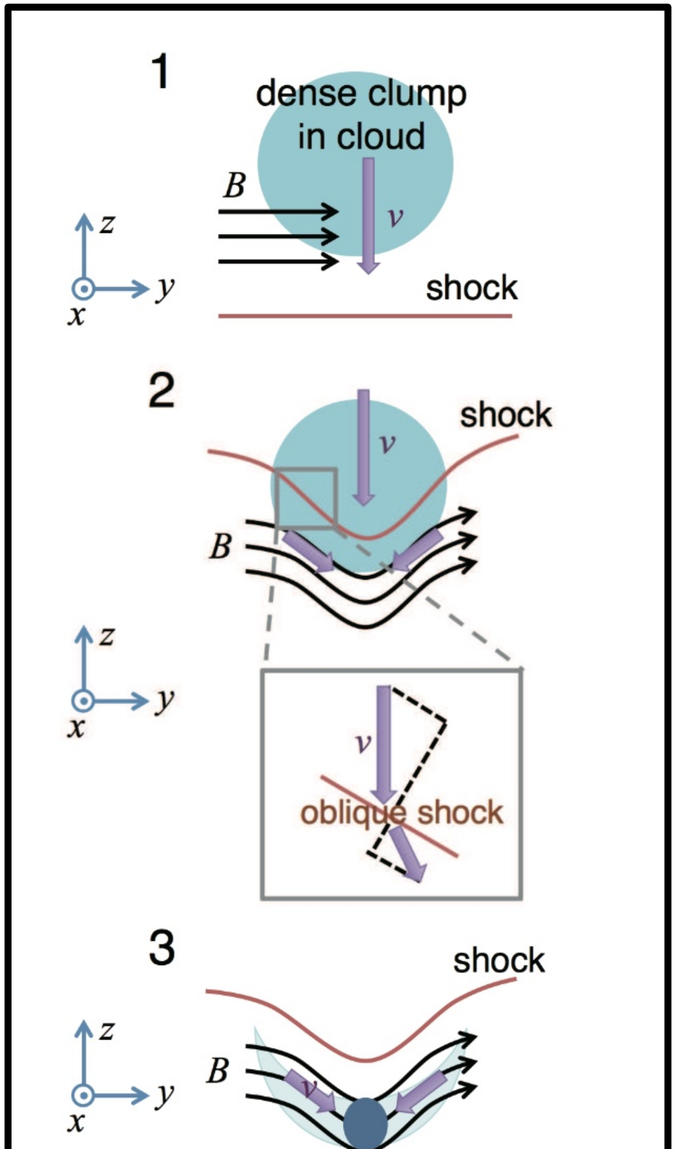
Formation of filaments by accumulation of matter along a curved magnetised "sheet like structure" induced by a shock compression

Theoretical model



Inoue et al. 2017

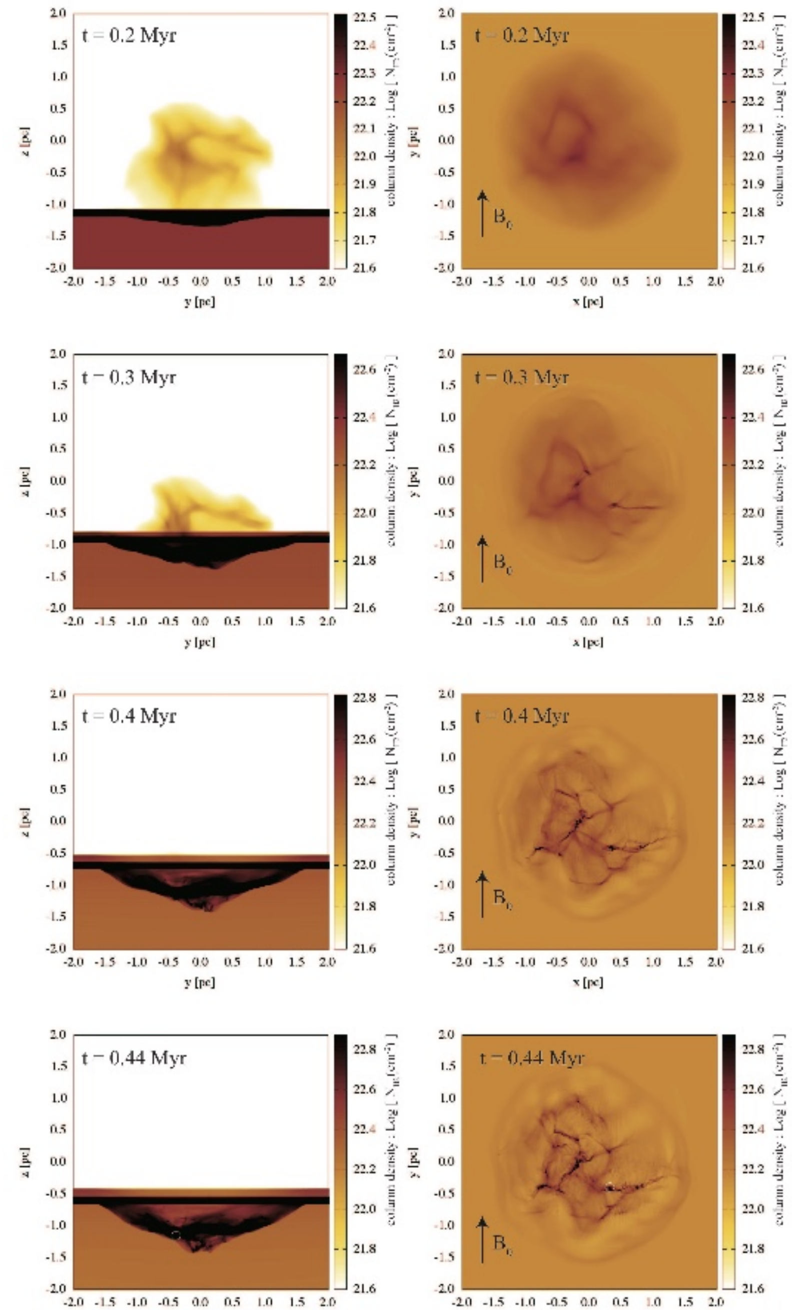
See also Inoue & Fukui 2013

Filament orientation ⊙

Numerical simulation

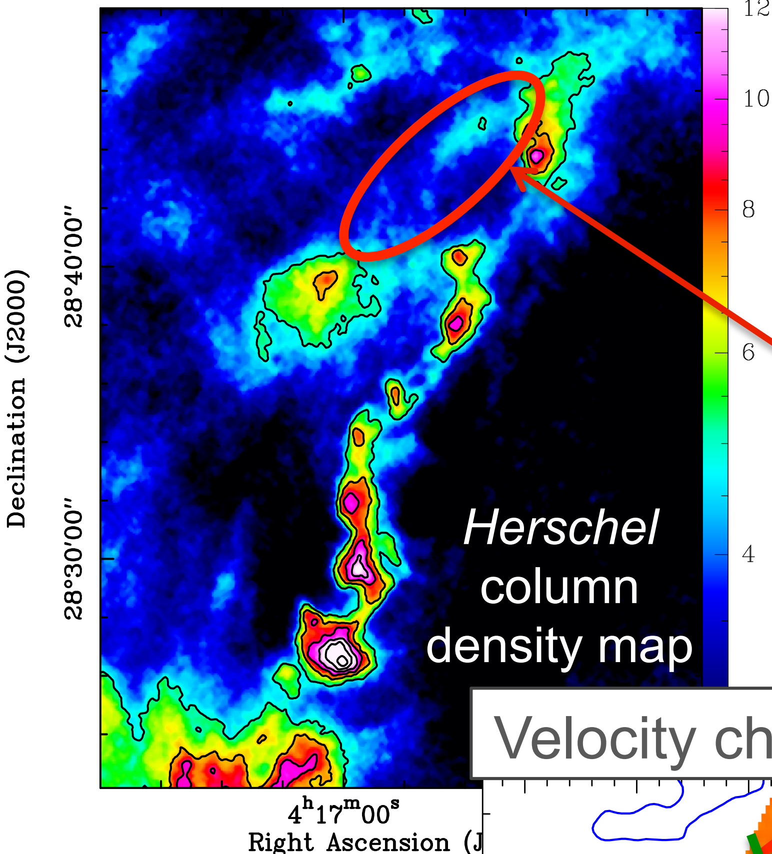
Edge on view

Face on view



Time

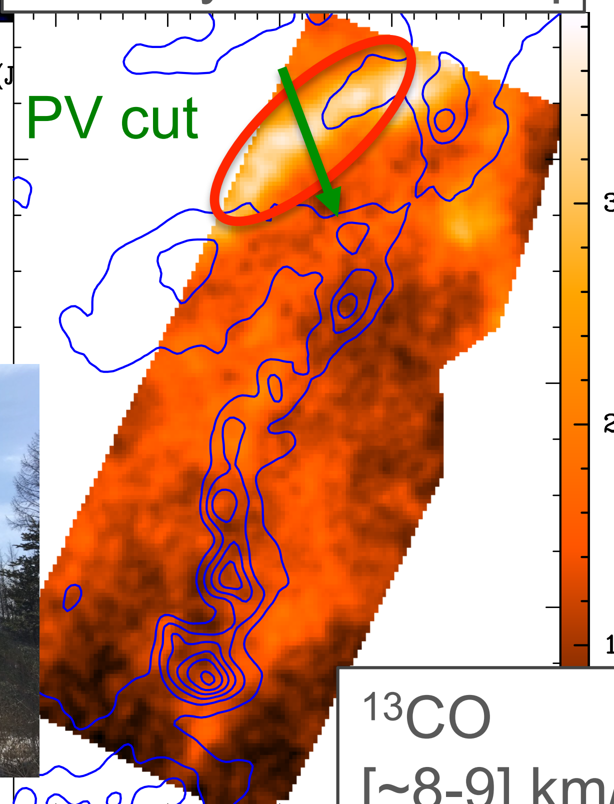
Velocity structure around a low column density filament observed in Taurus



Filament with $M_{line} \sim 1\ M_{sun}/pc$

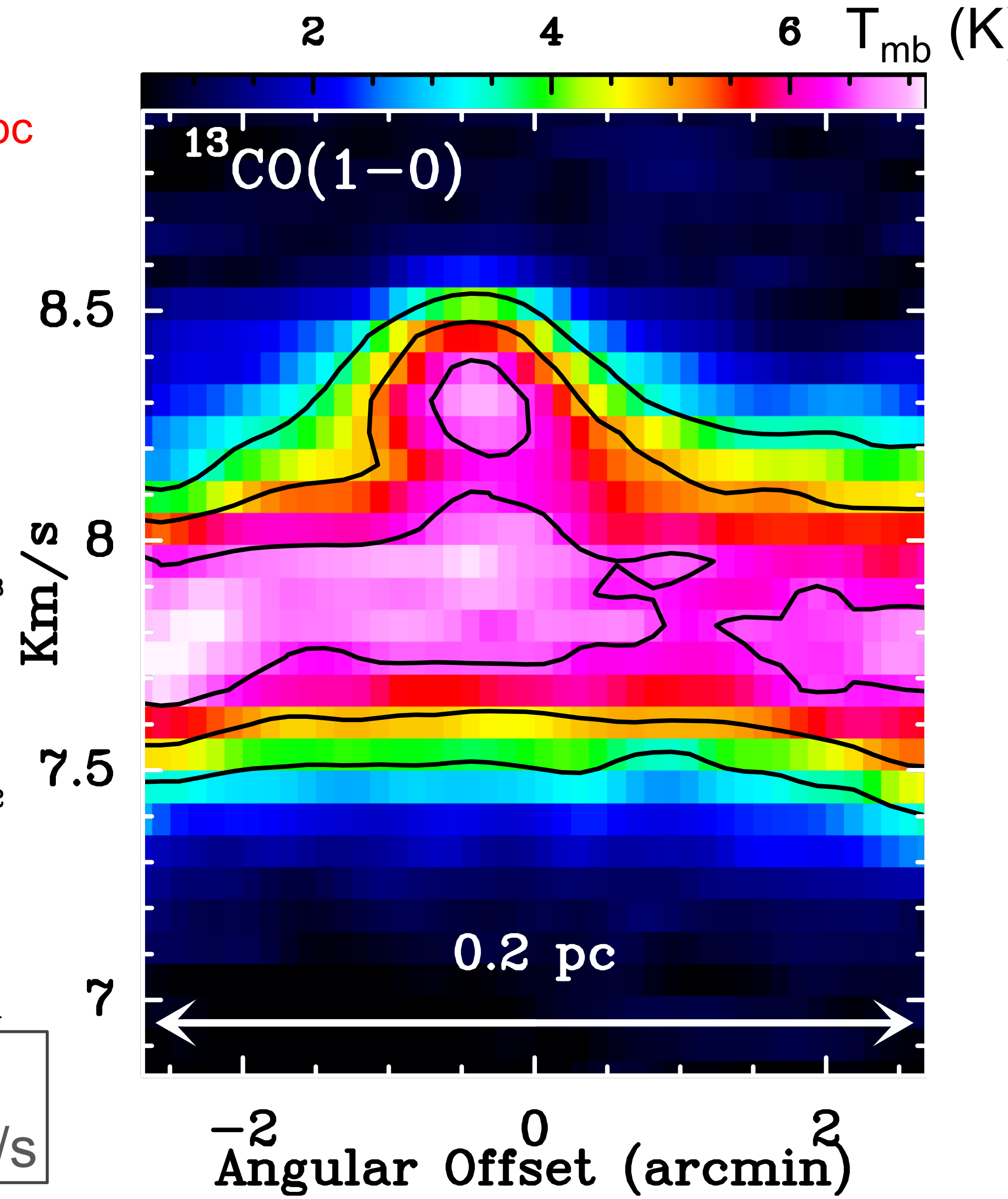
Arzoumanian et al. in prep.

Velocity channel map



^{13}CO [~8-9] km/s

Position-velocity map perpendicular to the filament axis



Nobeyama 45m Telescope observations

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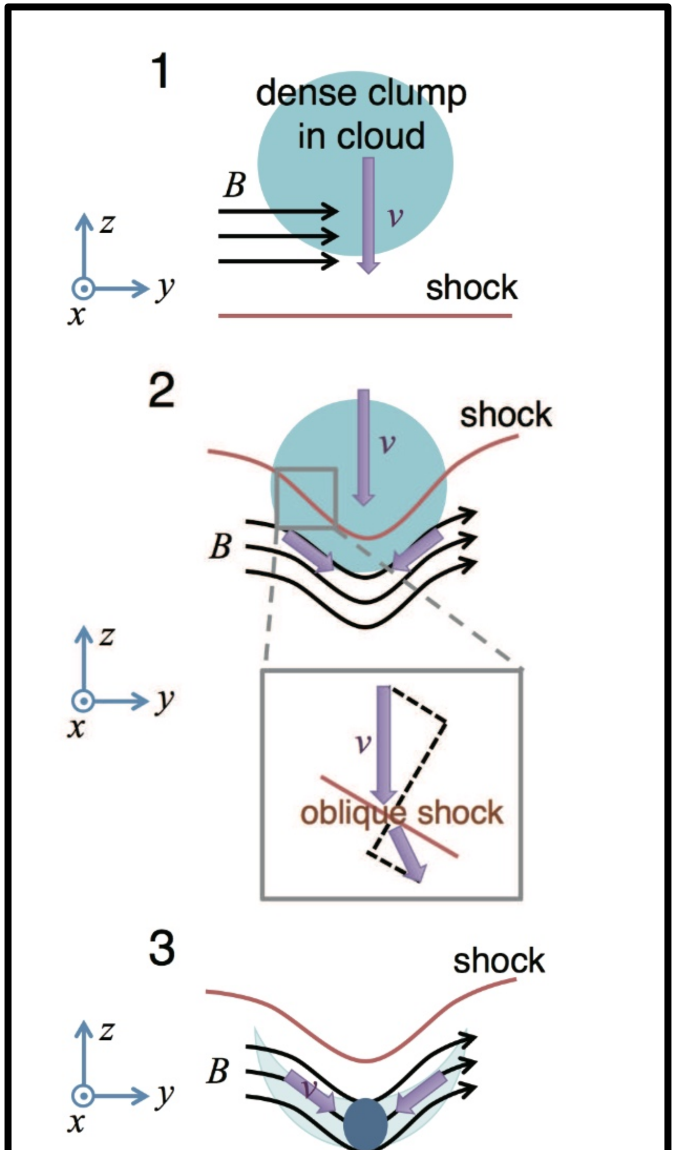
Formation of a filament by accumulation of matter along a curved magnetised “sheet like structure” induced by a shock compression

Theoretical prediction

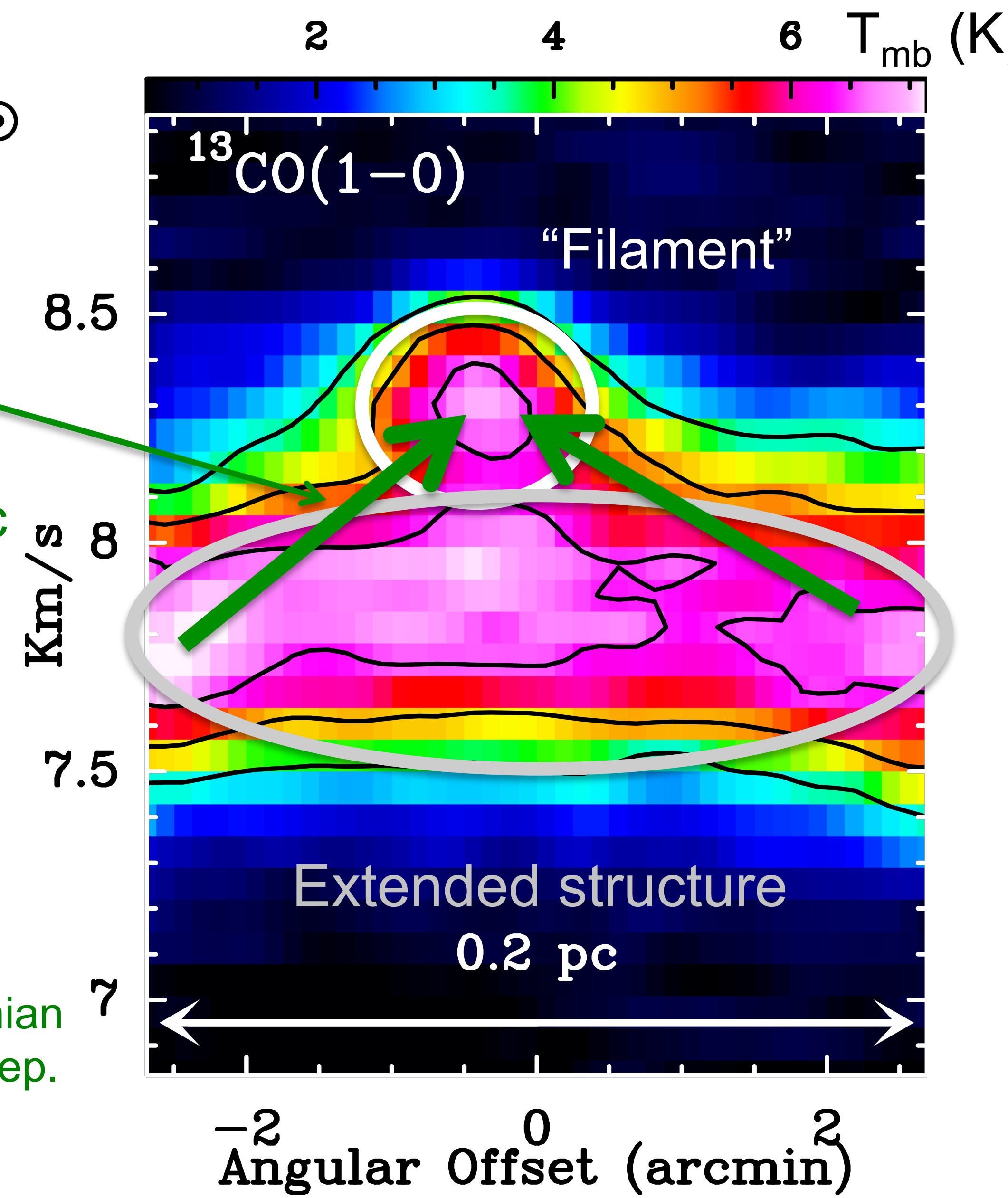


Inoue et al. 2017
See also Inoue & Fukui 2013

Molecular line observations

Filament orientation ⊙

Velocity gradient
~ 0.5km/s
over 0.1pc



Arzoumanian et al. in prep.

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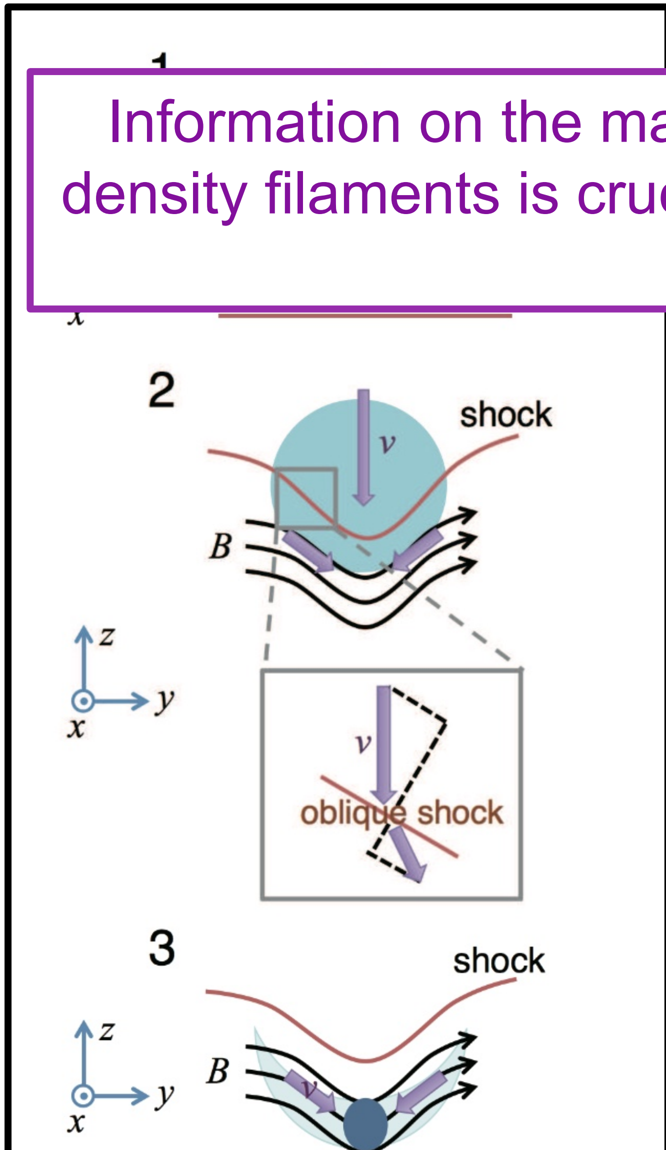
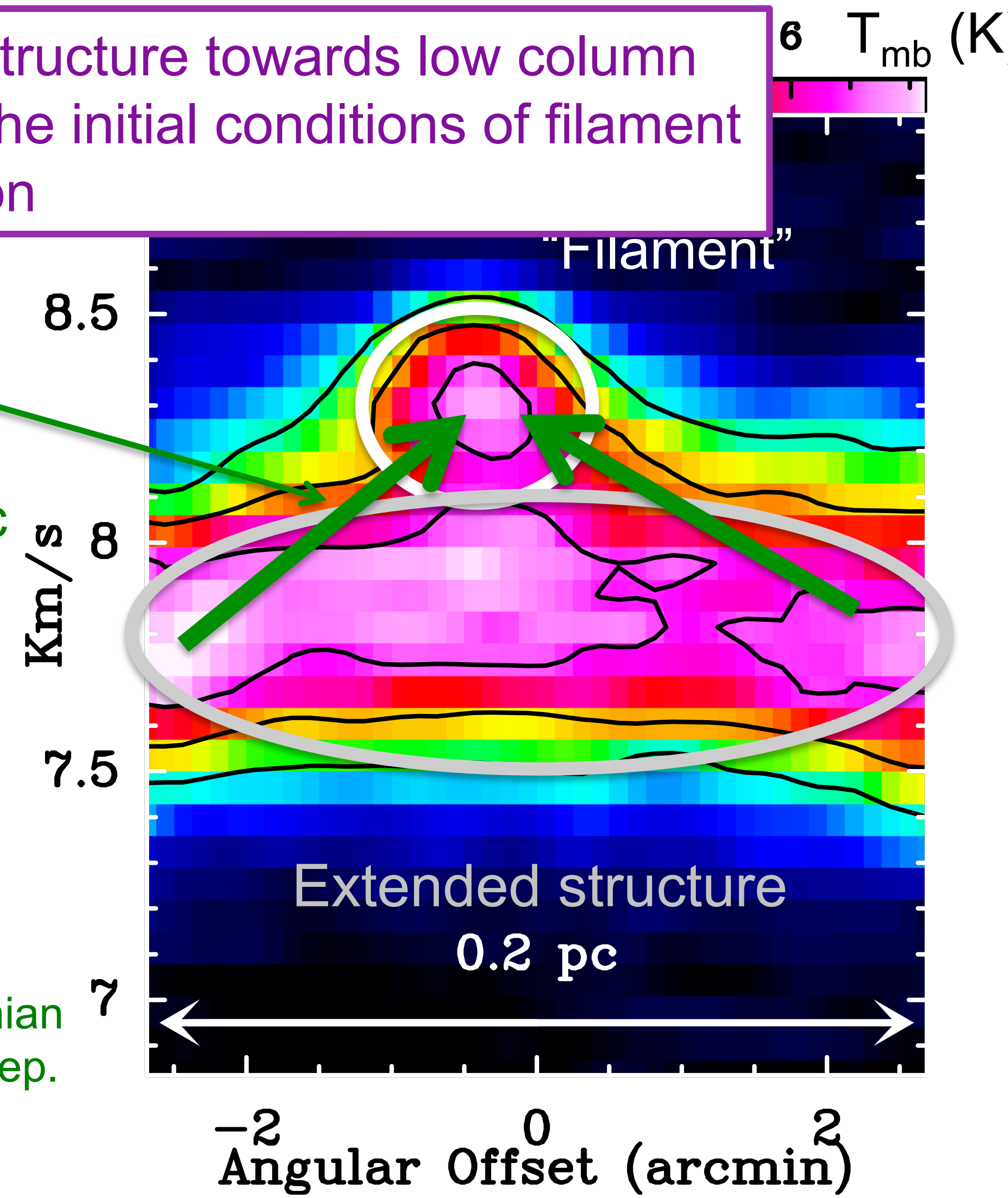


Inoue et al. 2017
See also Inoue & Fukui 2013

Molecular line observations

Information on the magnetic field structure towards low column density filaments is crucial to study the initial conditions of filament formation

Velocity gradient ~ 0.5km/s over 0.1pc



Arzoumanian et al. in prep.

Variations of the polarization angle and the polarization fraction: Insight on the 3D magnetic field structure in the filaments?

Intrinsic magnetic field structure of star forming filaments different than that of the surrounding cloud is traced as variations of both polarization fractions and angles

Planck XXXIII 2016 (arXiv:1411.2271)

I: total intensity

Polarized intensity

$$P = \sqrt{Q^2 + U^2}$$

Polarization fraction

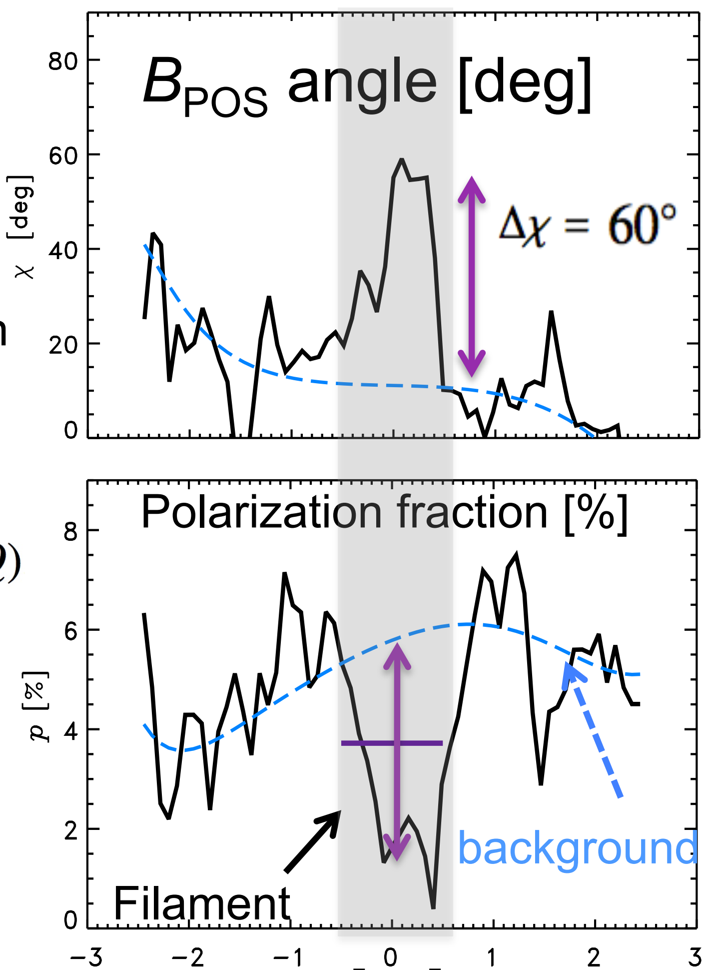
$$p = P/I$$

Polarization angle

$$\psi = 0.5 \arctan(U, Q)$$

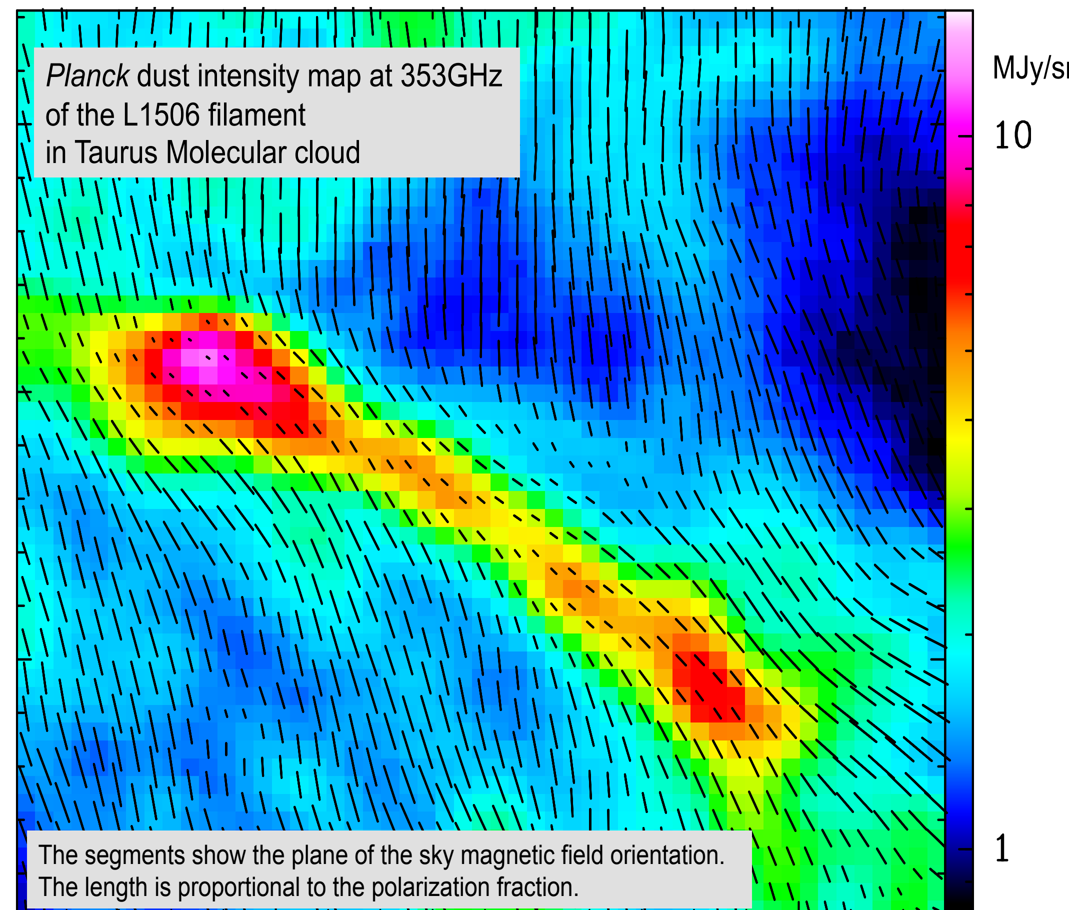
+ 90° orientation of $\boldsymbol{B}$ field projected on the plane of the sky

Radial profiles perpendicular to the filament axis



Resolution of 5’, 0.2pc at 140pc

The L1506 filament in the Taurus molecular cloud

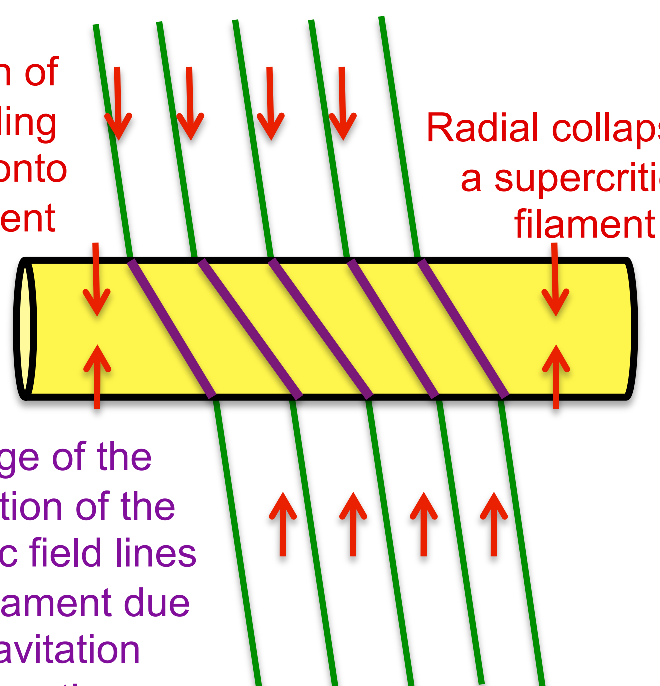


Planck total intensity at 353GHz (850μm) in MJy/sr
Segments: $\boldsymbol{B}_{POS}$ length ~ polarization fraction (10’ resolution)

Variations of the polarization angle and the polarization fraction: Insight on the 3D magnetic field structure in the filaments?

Role of the geometry of the magnetic field in the observed 0.1 pc width of filaments?

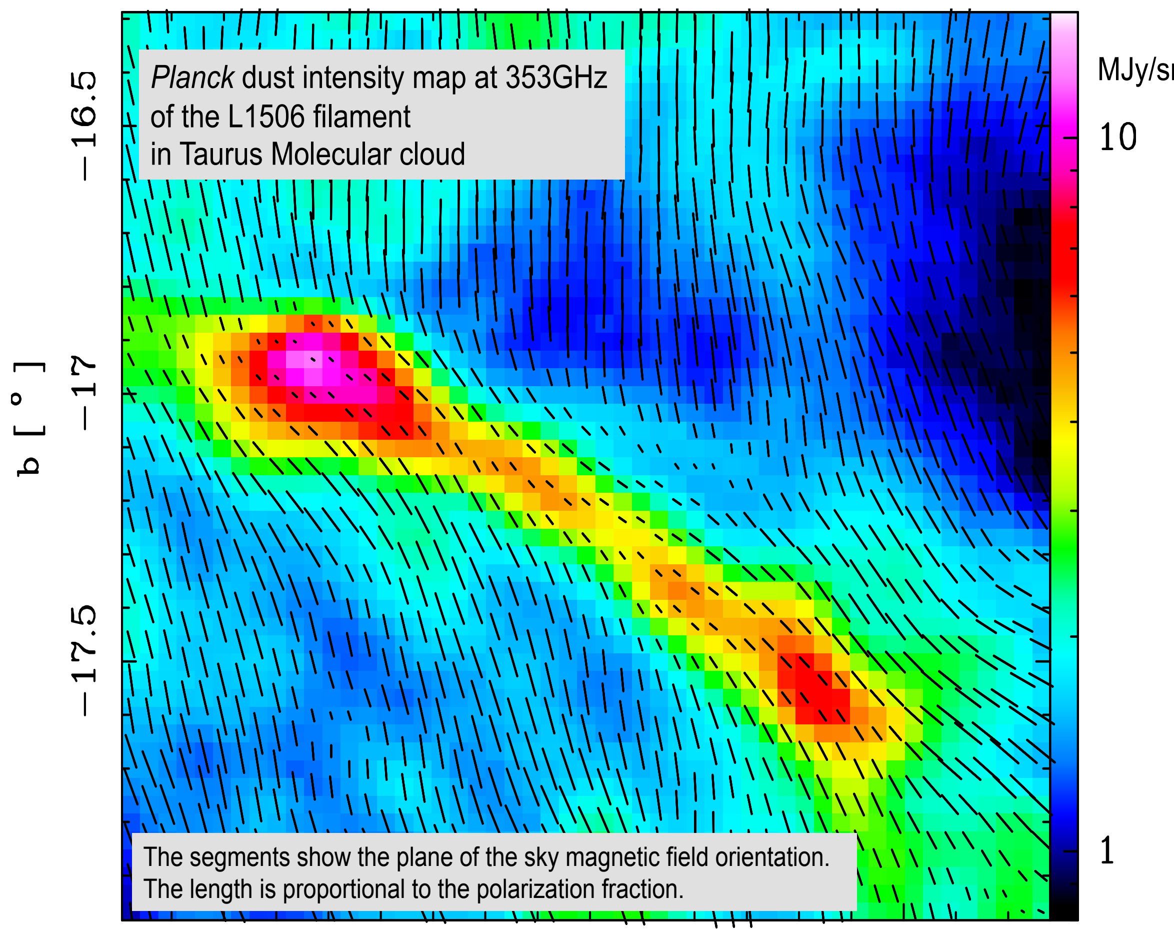
Increase of the magnetic pressure due to the compression of the magnetic field lines: may prevent the further collapse of the filament?



Other possible configurations: helical field (Fiege & Pudritz 2000), magnetohydrostatic configuration (Tomisaka 2015, Auddy et al. 2017)

Planck XXXIII 2016 (arXiv:1411.2271)

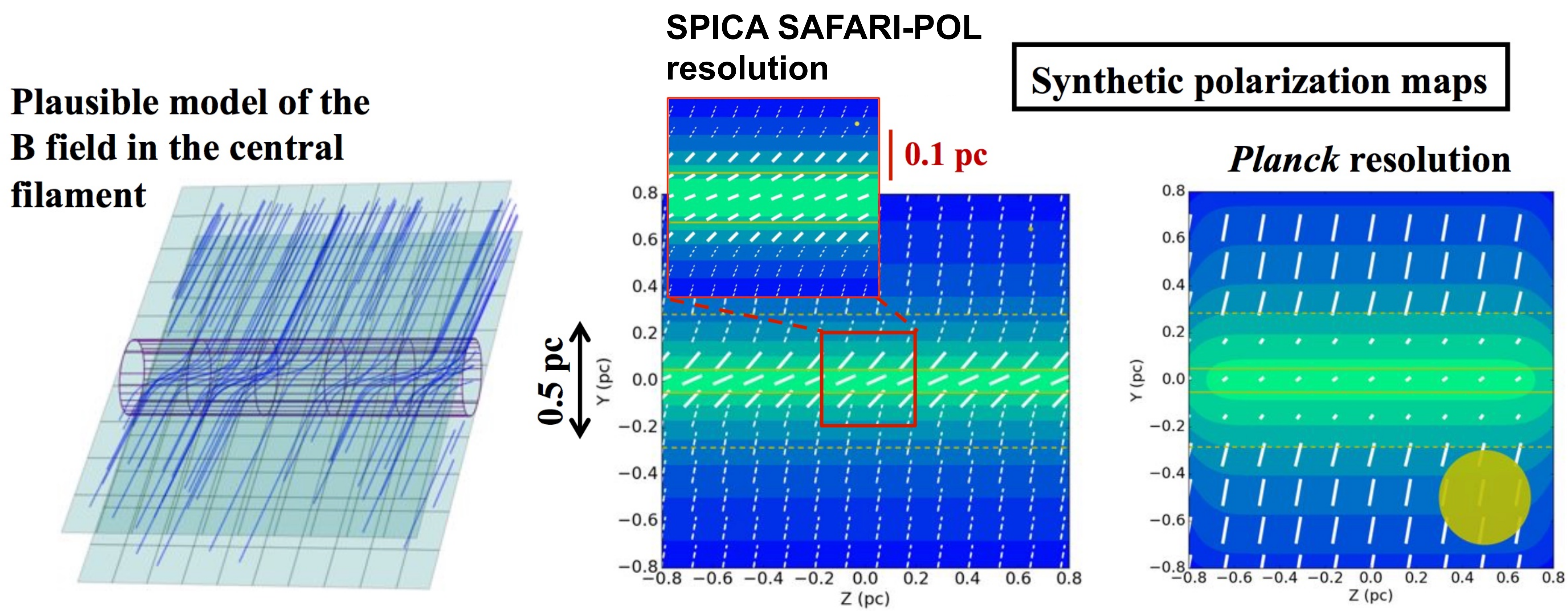
The L1506 filament in the Taurus molecular cloud



Planck total intensity at 353GHz (850μm) in MJy/sr
Segments: $\boldsymbol{B}_{POS}$ length ~ polarization fraction (10’ resolution)

What is the role of the magnetic field in the evolution of self-gravitating filaments and the fragmentation into star forming cores?
What is the magnetic field structure of star forming filaments?

High resolution and high sensitivity observations are needed to resolve the 0.1 pc scale of the filaments mapping simultaneaously the lower column density surroundings



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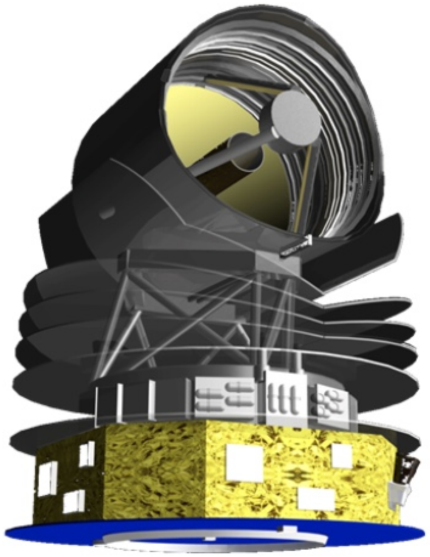
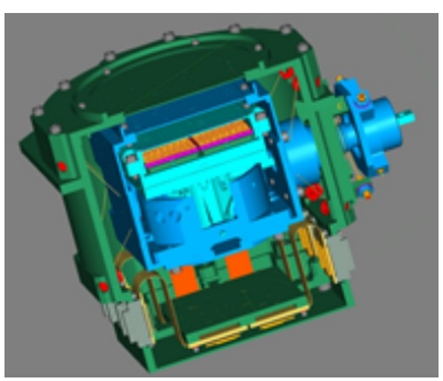
Understanding the role of magnetic fields in the formation and evolution of interstellar filaments with SPICA far-IR imaging polarimeter: SAFARI-POL



- Large telescope (~2.5m), cryogenically cooled space telescope, powerful detector

- High resolution → Resolving the inner (0.1pc, 40" at 500pc) part of the filaments, scale of fragmentation into cores

- High sensitivity, high spacial and intensity dynamic range → Image simultanouesly the dense filaments and the surrouding lower column density cloud (from 10" to >5deg and Av~0.5 to Av>100)



- High SNR in polarized intensity (Q,U) → Observing the low polarization fraction in dense filaments (2-5%)

- High mapping speed → Large regions of the clouds can be observed to provide the requiered statistics

- Polarization in 3 bands (100, 200, and 350 μm) → important to constrain dust models (polarization SED), to understand dust grain alignement and dust grain properties (dust evolution)

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Understanding the role of magnetic fields in the formation and evolution of interstellar filaments with SPICA far-IR imaging polarimeter: SAFARI-POL

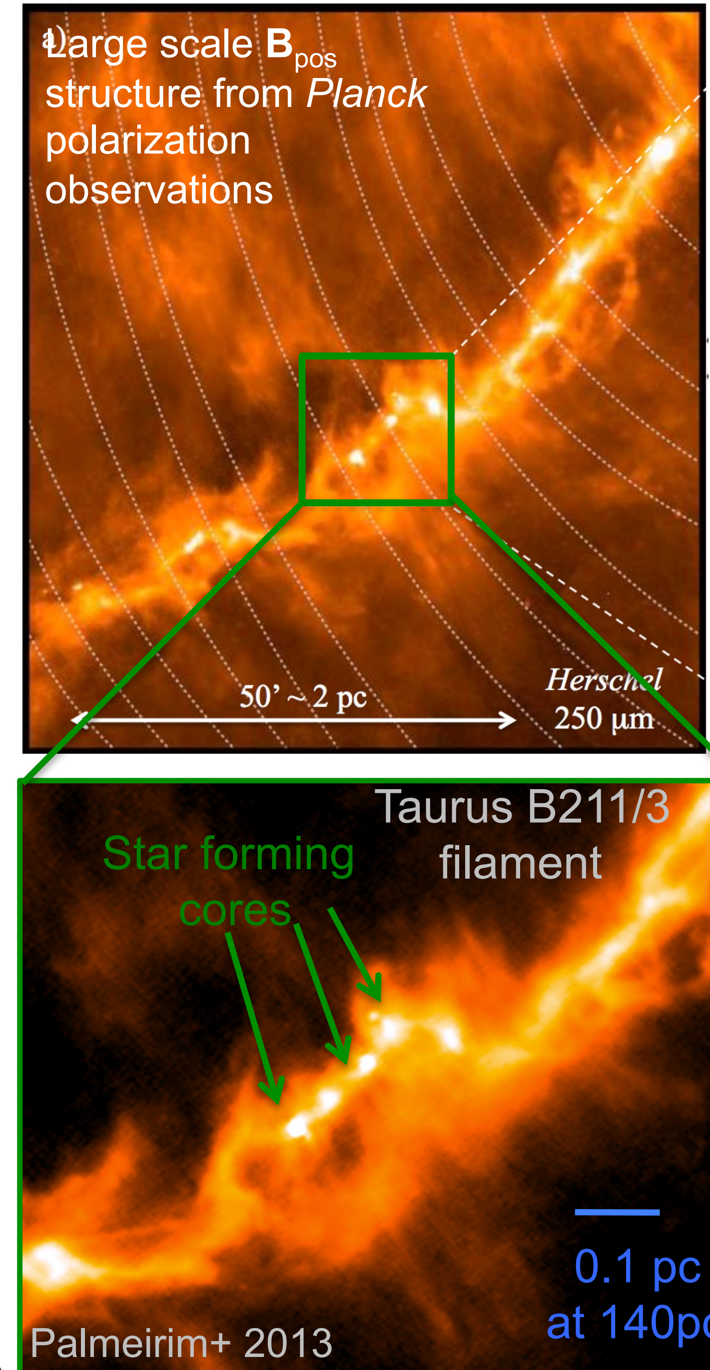
With SPICA SAFARI-POL

Mapping ~500 deg^2 of the Galactic interstellar clouds in ~500h for SNR=5 (Q,U) at 350μm in the low-density (Av=0.5) with typical polarization fraction of 5%.

Why SPICA SAFARI-POL is unique?

→ *Planck* resolution (5' or > 0.2 pc) far too low to resolve filaments
→ Submm balloon-borne experiments (Pilot, BLAST-Pol, Super-BLAST-Pol) do not have not have enough sensitivity
→ Ground-based (sub)mm imaging polarimeters (e.g. SCUBA2-Pol, PolKa, NIKA2-Pol) are even less sensitive
→ ALMA polarimetry at 0.8-3mm have exquisite resolution (and good sensitivity to small scales) but is insensitive to scales > 1'
→ Optical/near-IR imaging polarimetry not fully sampled maps and has much more limited dynamic range (only Av~ 1-10)

Taurus (star forming cloud)



Summary

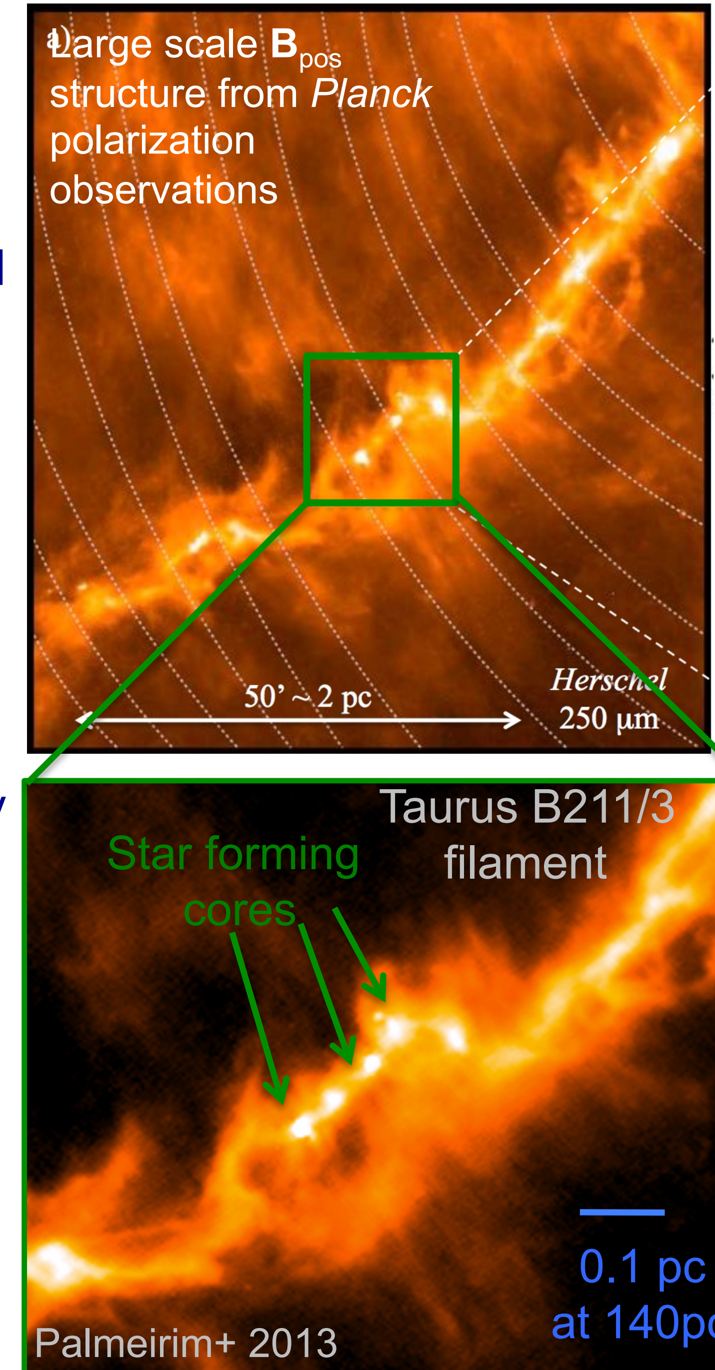
- *Herschel* and *Planck* observations reveal the ubiquity of interstellar filaments in the ISM

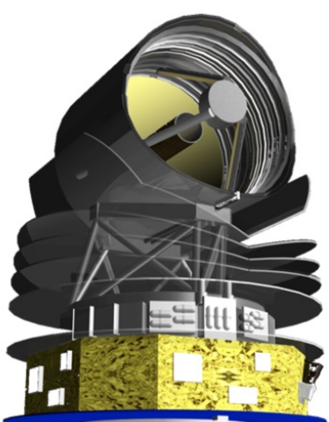
- The *Herschel* results support a “filamentary paradigm” for star formation, where 0.1pc filaments are generated in the ISM from large-scale compression of matter in supersonic MHD flows, and the densest of them fragment into star forming cores

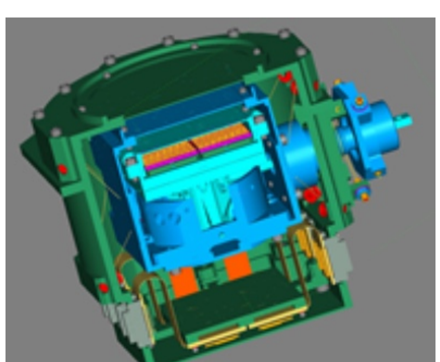
- *Planck* dust polarization observations suggest that magnetic fields play a key role in the formation and evolution of filaments

→However the role of magnetic fields is not well understood
→SPICA SAFARI-POL is needed to map at high resolution (resolving the 0.1pc filament width) and sensitivity, high spacial and dynamic range, a large fraction of molecular clouds to clarify the role played by magnetic fields in shaping the filamentary structure of the ISM where stars are forming

Taurus (star forming cloud)







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