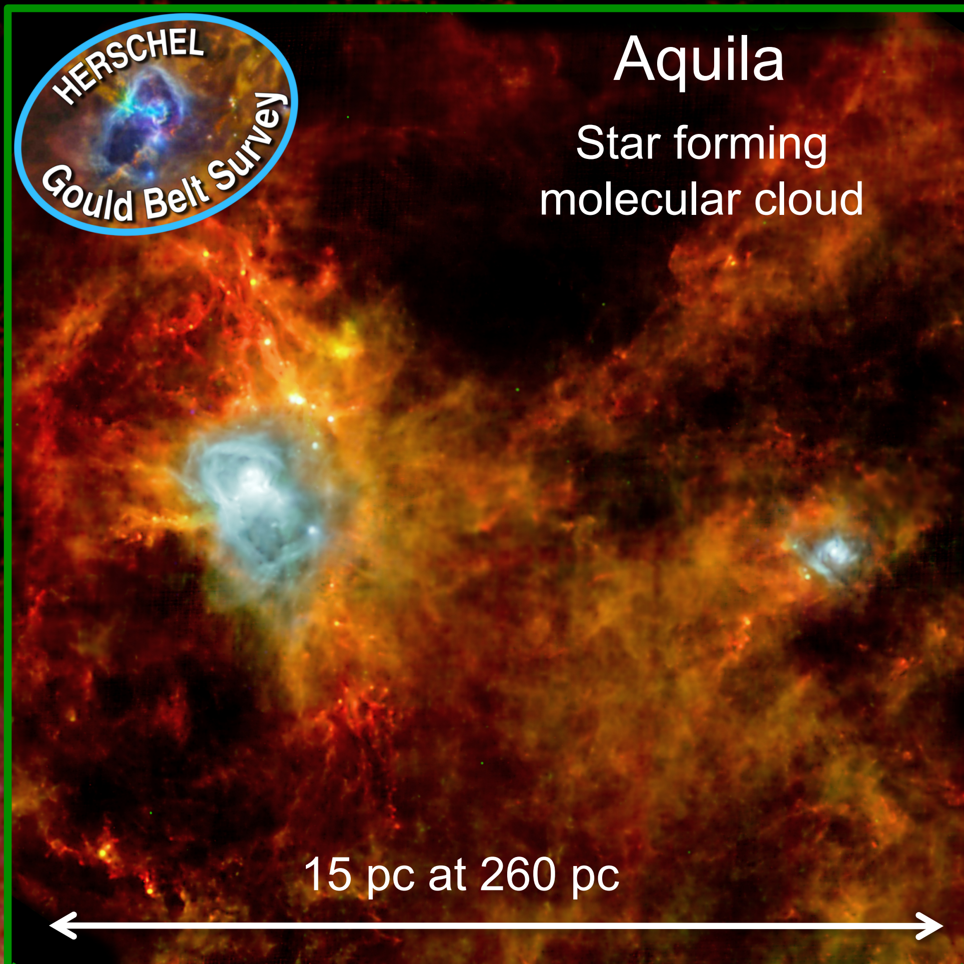
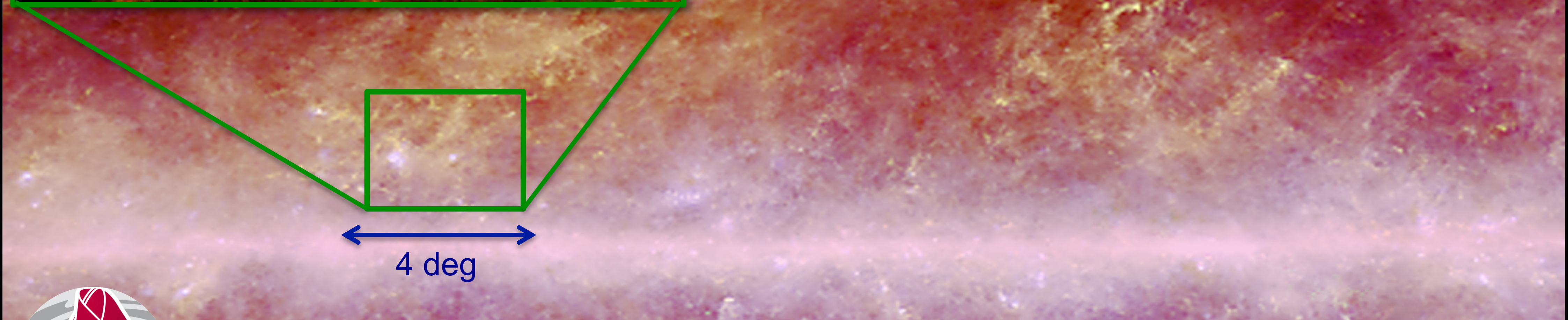
# Observed properties of interstellar filaments

Doris Arzoumanian
(JSPS fellow, Nagoya University)




Dust emission of the Galactic ISM as seen by *Planck* and *Herschel*

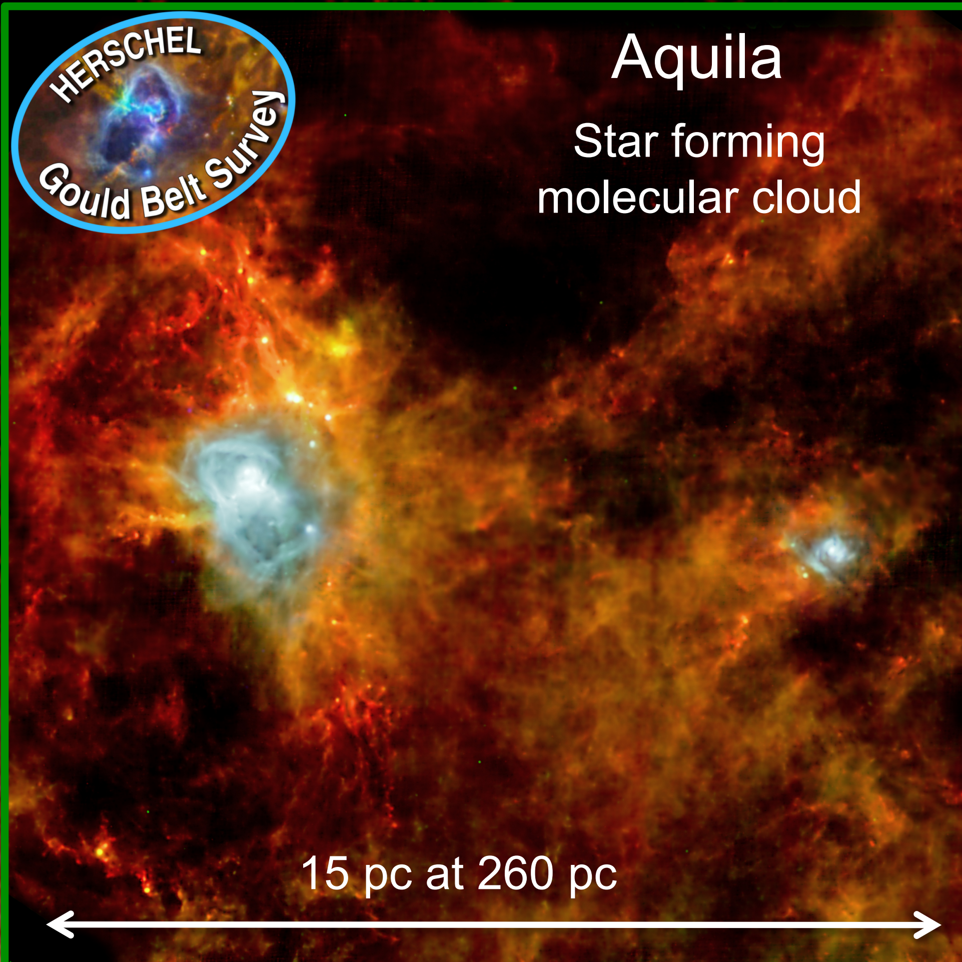
**Planck**

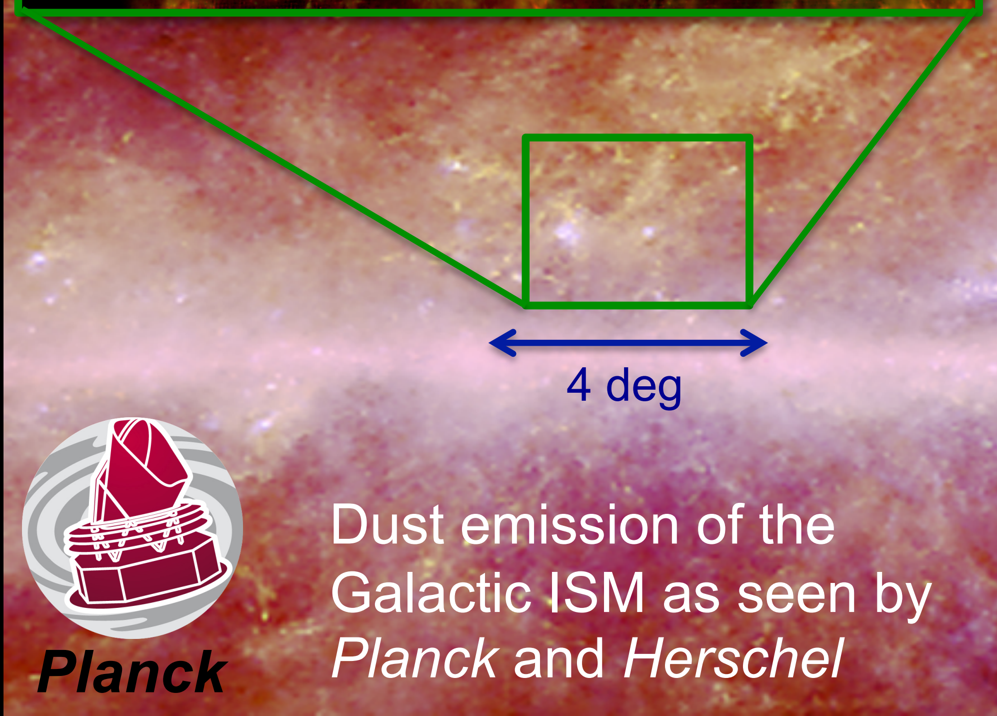
**02/05/2017**
**EAO Seminar, Hilo, Big Island**

# Observed properties of interstellar filaments

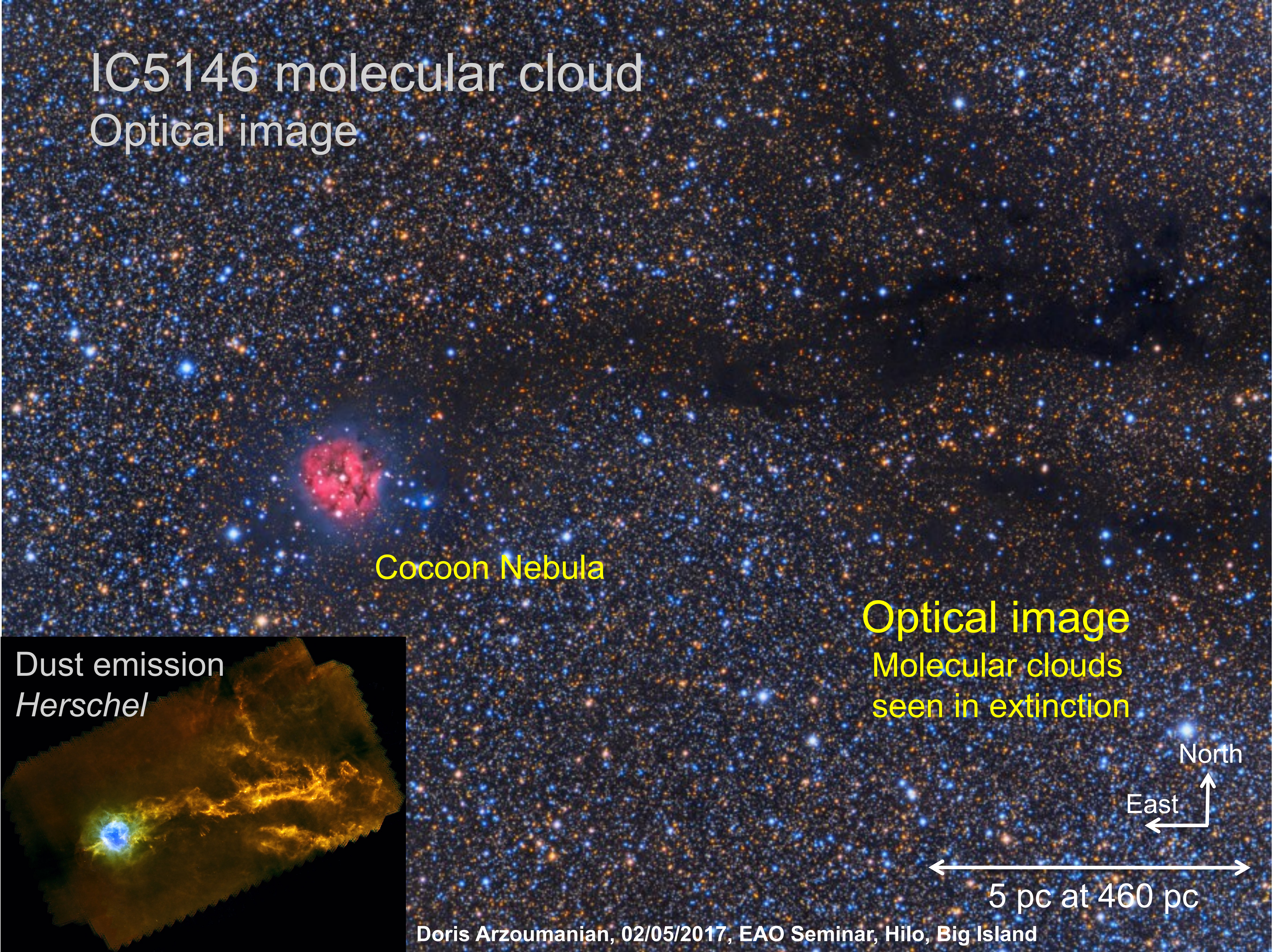
Doris Arzoumanian
(JSPS fellow, Nagoya University)

**02/05/2017**
**EAO Seminar, Hilo, Big Island**

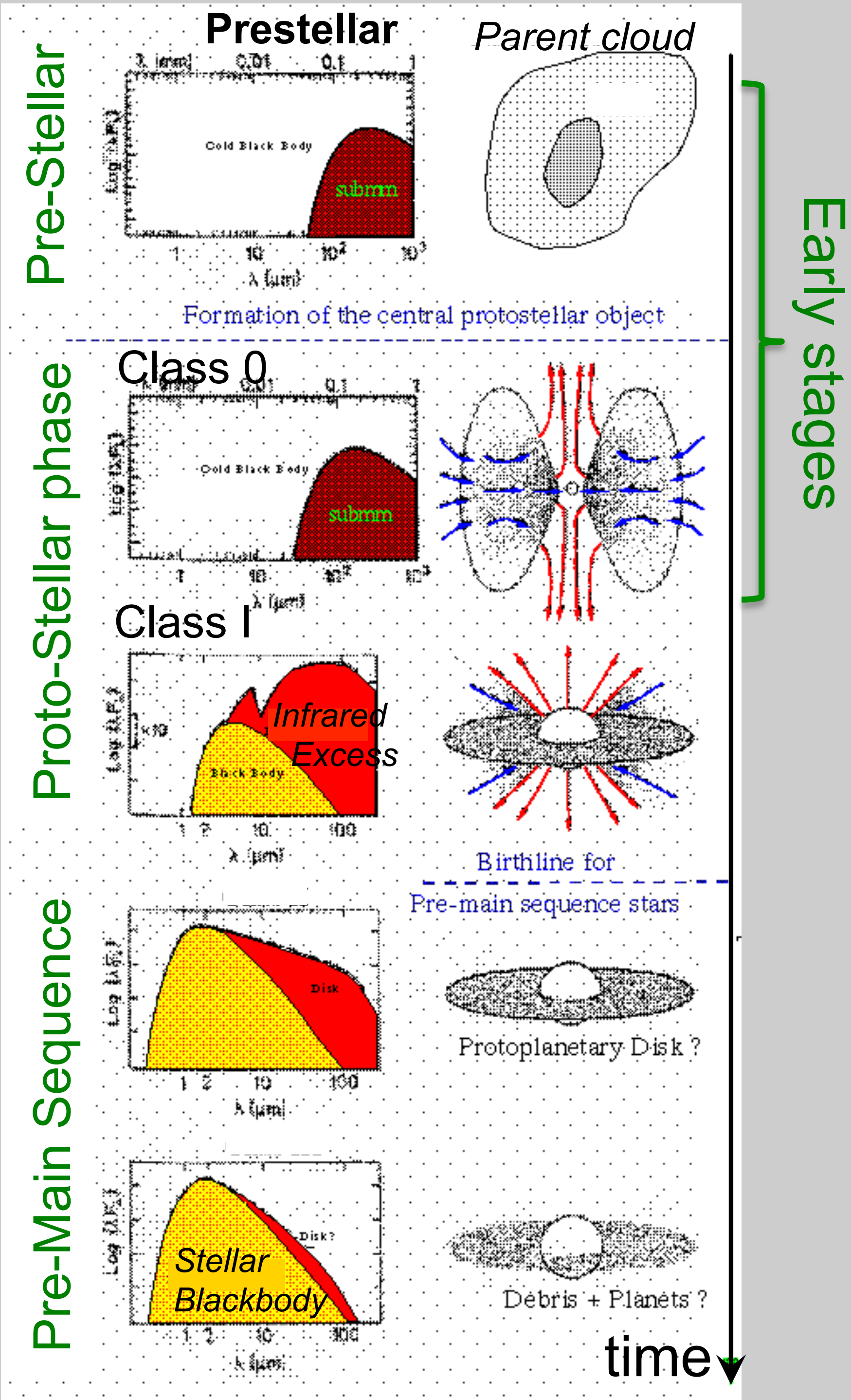



- PhD thesis at CEA Saclay, France (November 2009-2012)
  *"Characterizing interstellar filaments as revealed by the Herschel Gould Belt survey: Insights into the initial conditions for star formation"* PhD supervisor: Philippe André
- Post-Doc at IAS Orsay, France (2013 -2015)
  *"Analysis of the polarized emission from the Galactic dust observed by Planck towards interstellar filaments"*
  Working in the group of François Boulanger, part of the ERC MISTIC project
- Currently JSPS fellow at Nagoya University
  *"Combining theory and observations"*
  In the group of Shu-ichiro Inutsuka


IC5146 molecular cloud
Optical image
Cocoon Nebula
Optical image
Molecular clouds
seen in extinction
North
East
5 pc at 460 pc
Dust emission
Herschel
Doris Arzoumanian, 02/05/2017, EAO Seminar, Hilo, Big Island

Evolutionary sequence




(Lada 1987, André et al. 2000)

# Formation of solar-type stars

Evolutionary sequence well established but physics of early stages still unclear
(McKee & Ostriker 2007, Shu et al. 1987)

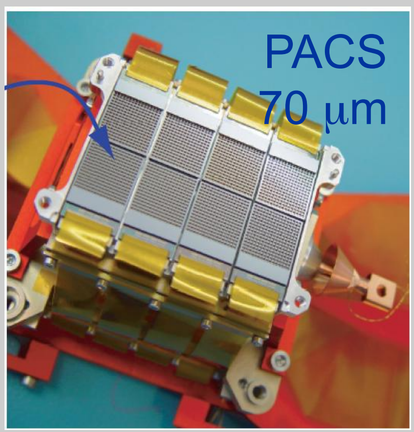
Open questions:

- What generates prestellar cores in molecular clouds and governs their evolution?
- What sets the mass of star forming cores and stars?
- What is the link between star formation and the structure of the parent clouds

# *Herschel* observes the peak emission of the cold dust

*Herschel*
(Pilbratt et al. 2010)

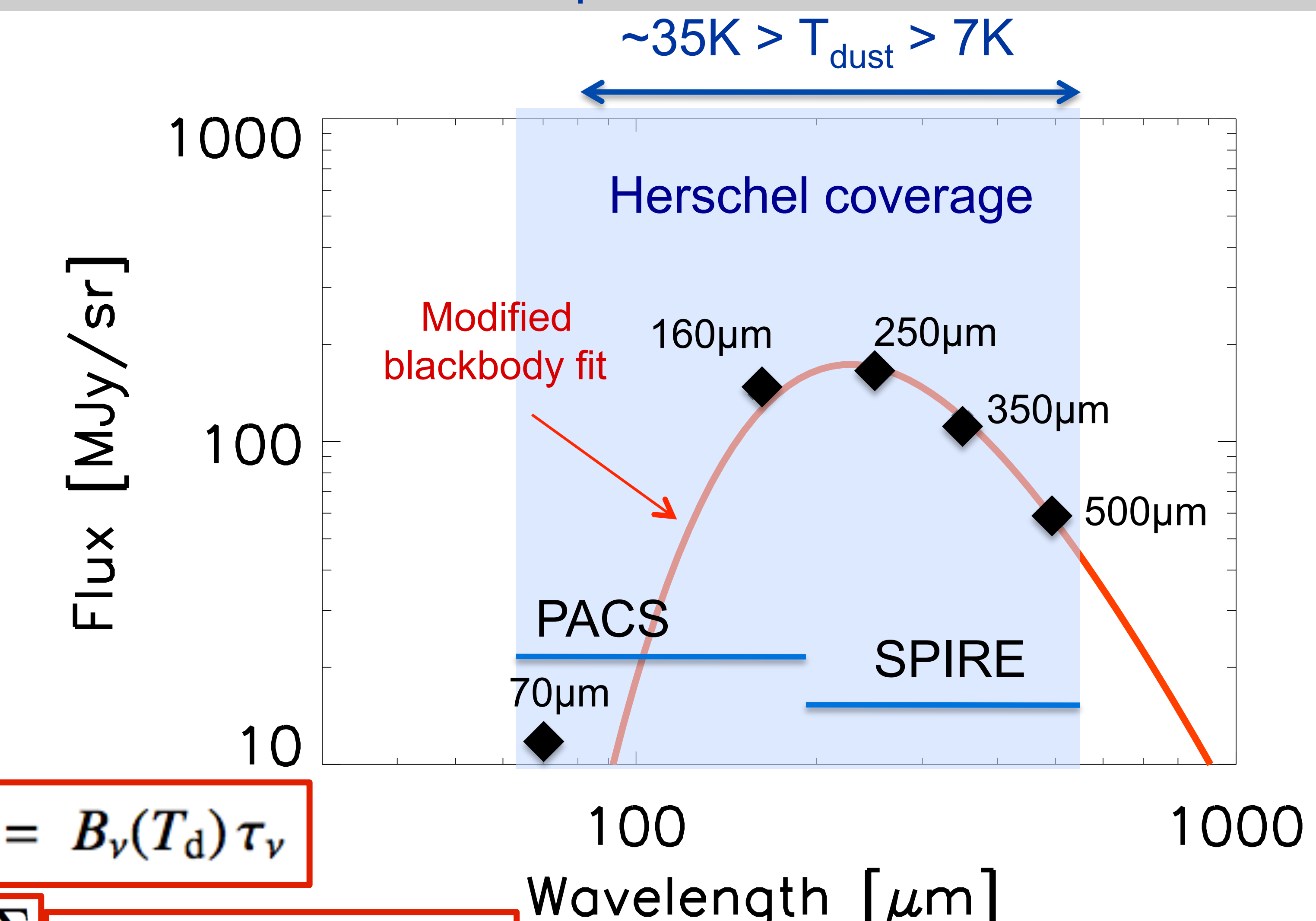
*Herschel* bands cover the peak dust emission and are essential for gas column density and dust temperature determination




(Poglitsch et al. 2010)


(Griffin et al. 2010)

Dust temperature range probed with *Herschel*



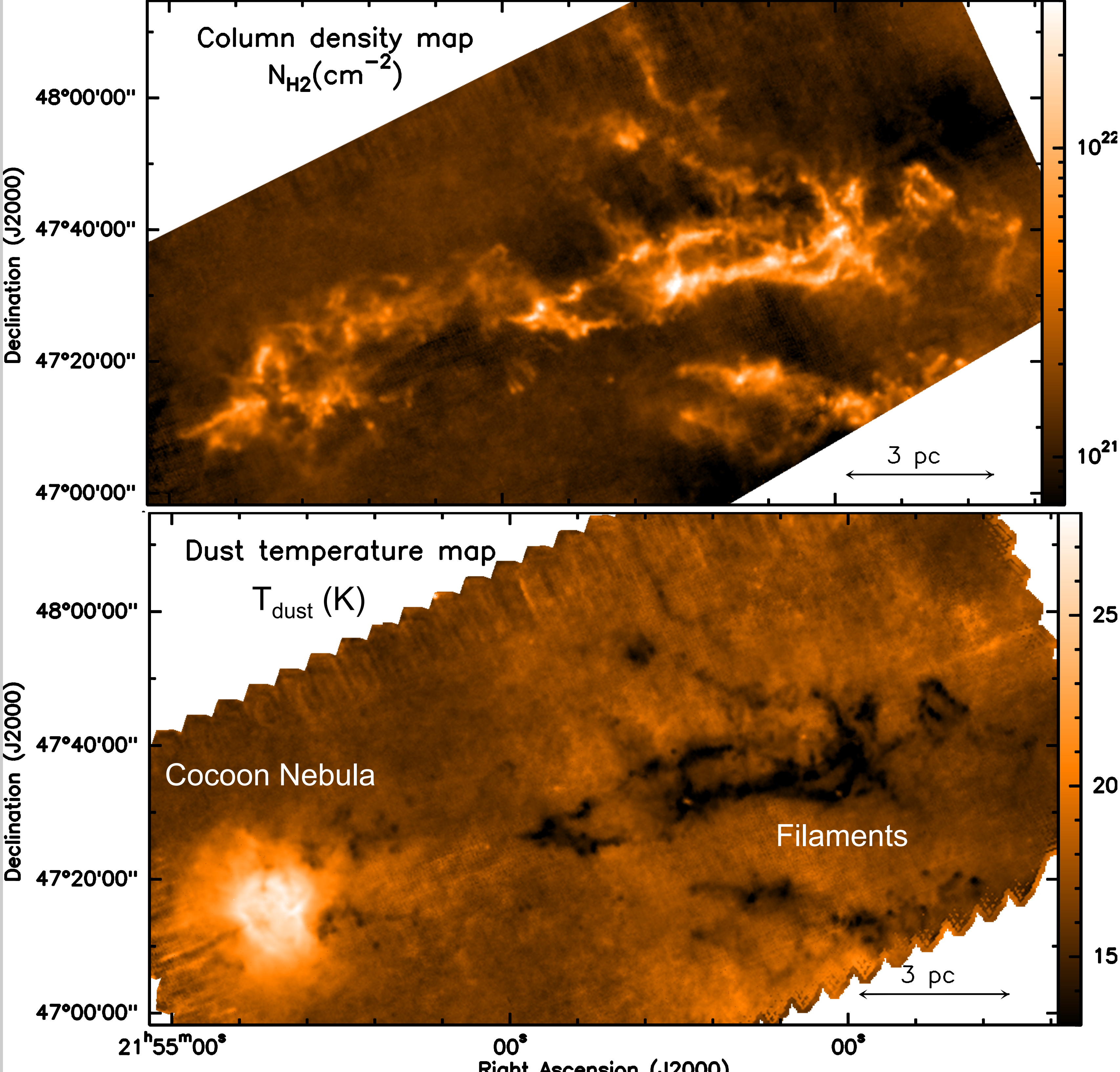

$$I_\nu = B_\nu(T_d)\,\tau_\nu$$

$$\tau_\nu = \kappa_\nu \Sigma \qquad \kappa_\nu = 0.1\,(\nu/1000\ \mathrm{GHz})^\beta\ \mathrm{cm^2/g}$$

# Gas column density and dust temperature maps (e.g. IC5146)

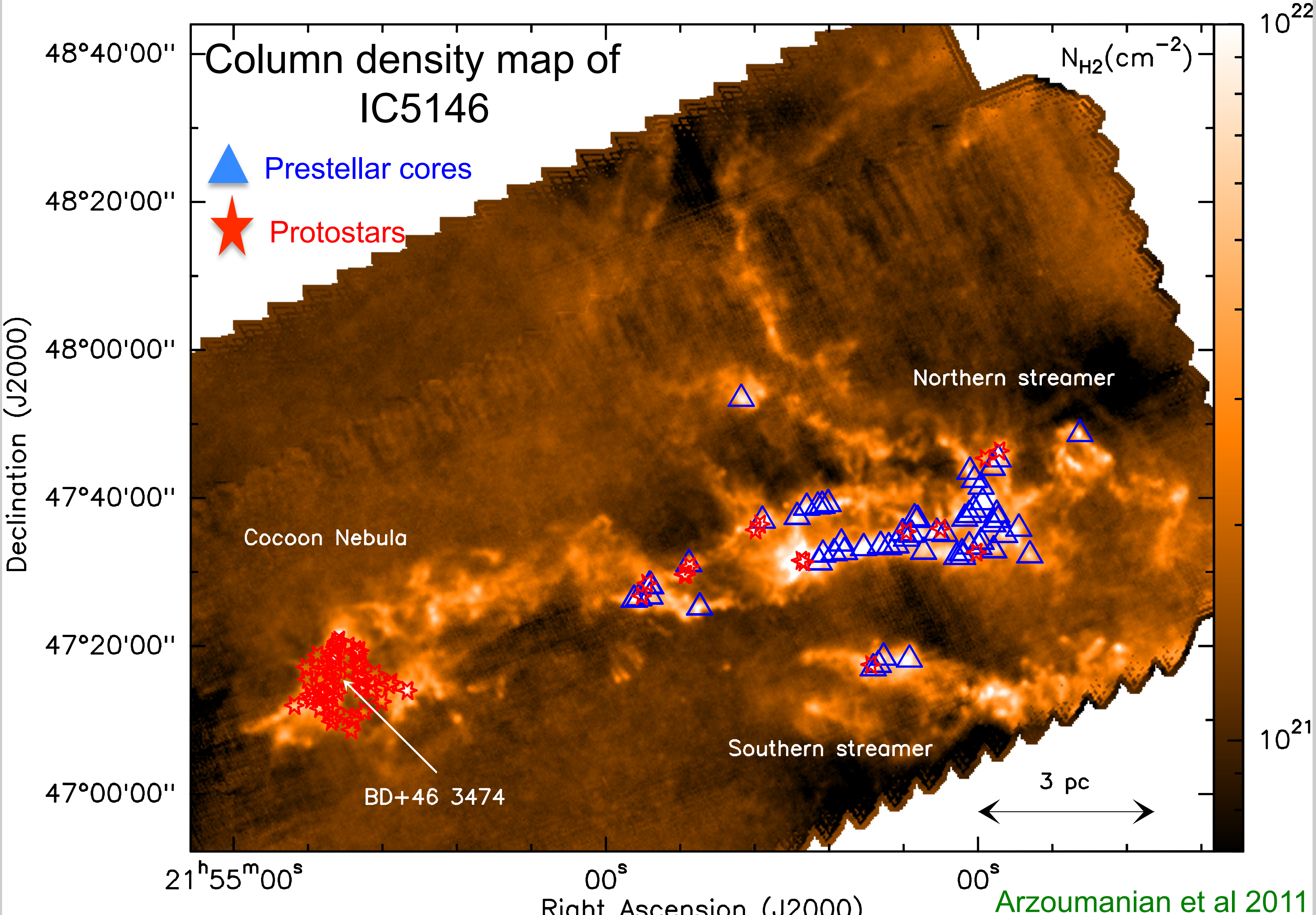
PACS & SPIRE
160 – 500 μm
4 λ SED fitting
(pixel by pixel)
with
a modified blackbody function

Maps at 36.3" resolution of SPIRE 500 μm



# Spatial distribution of prestellar cores within the densest Filaments

## Sources extracted with *getsources* Men'shchikov et al. 2010, (2012)

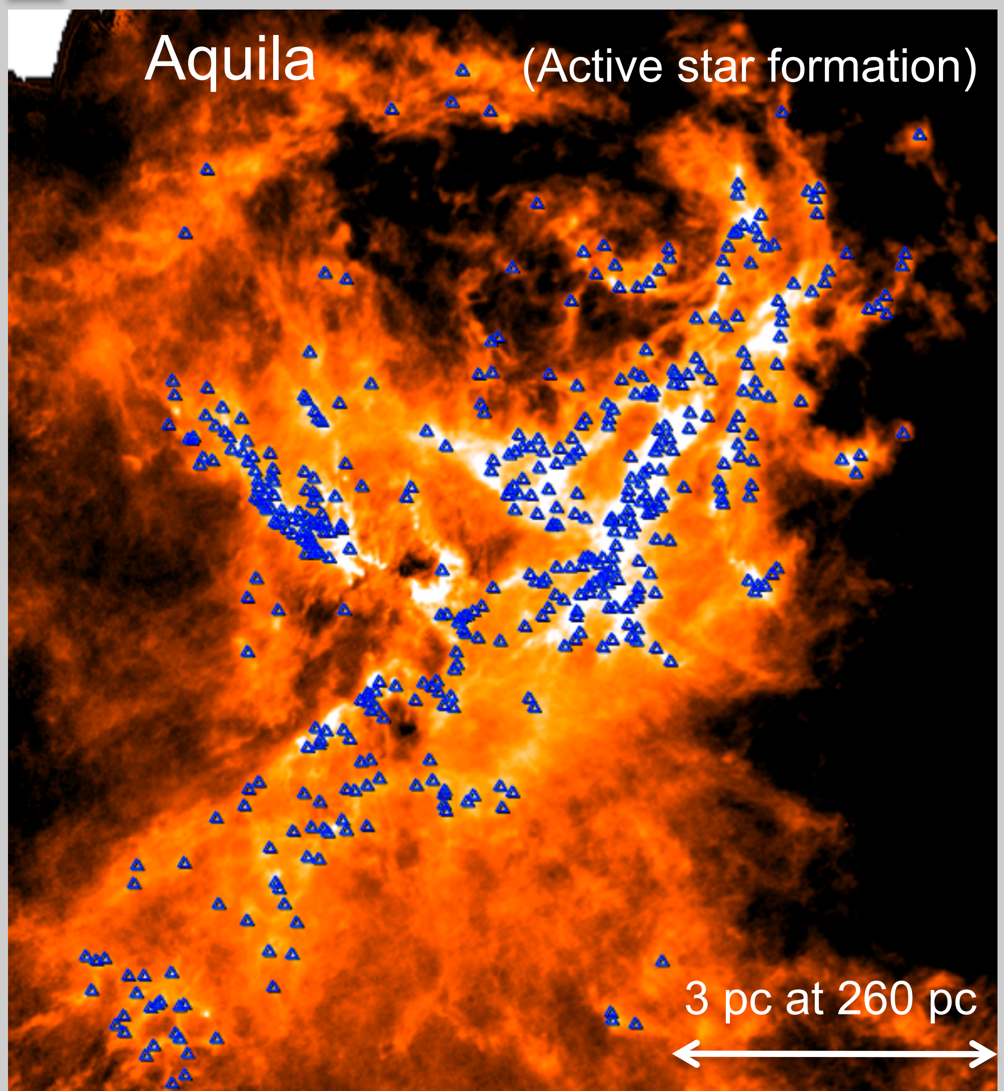


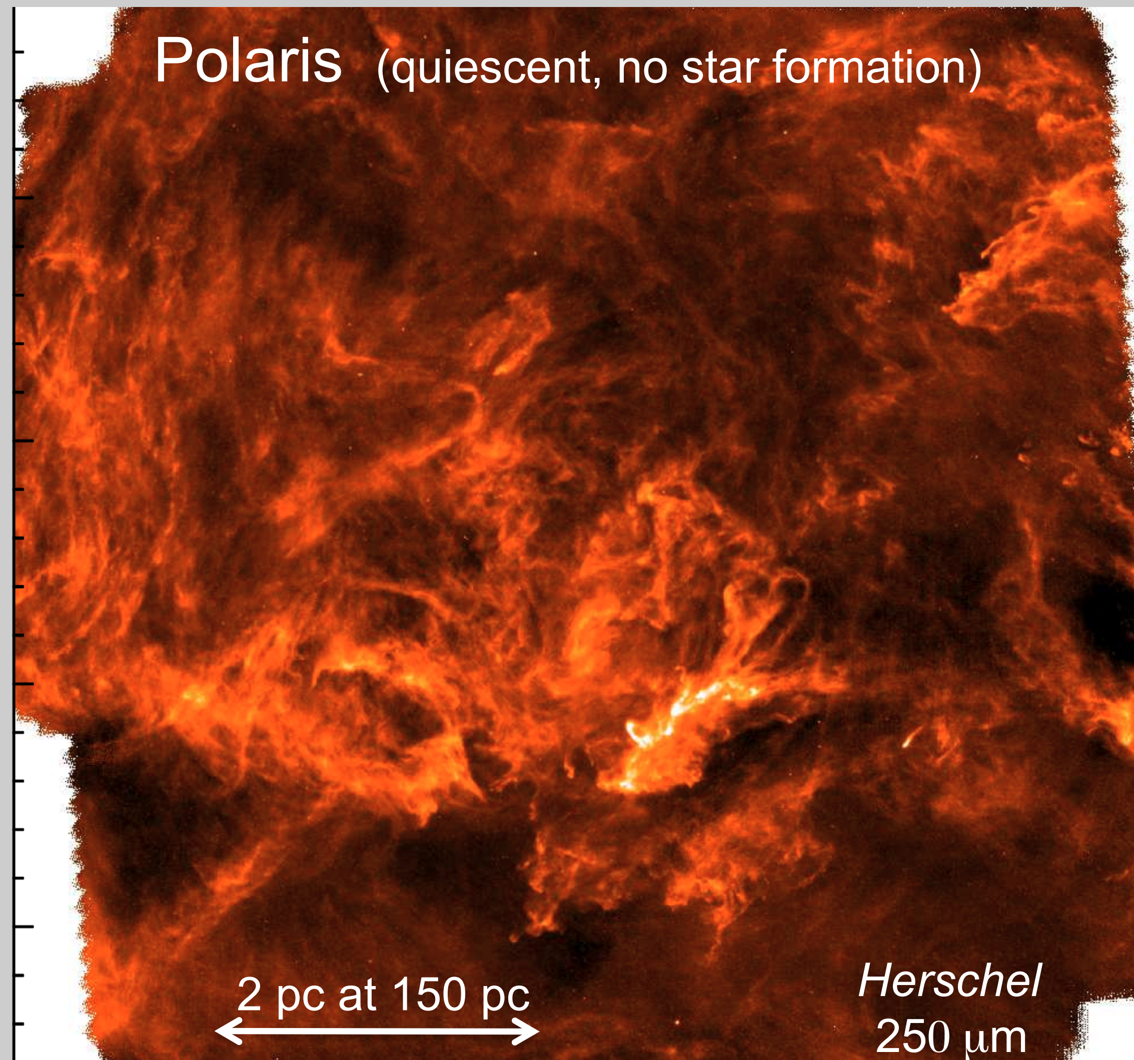

Arzoumanian et al 2011


# 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



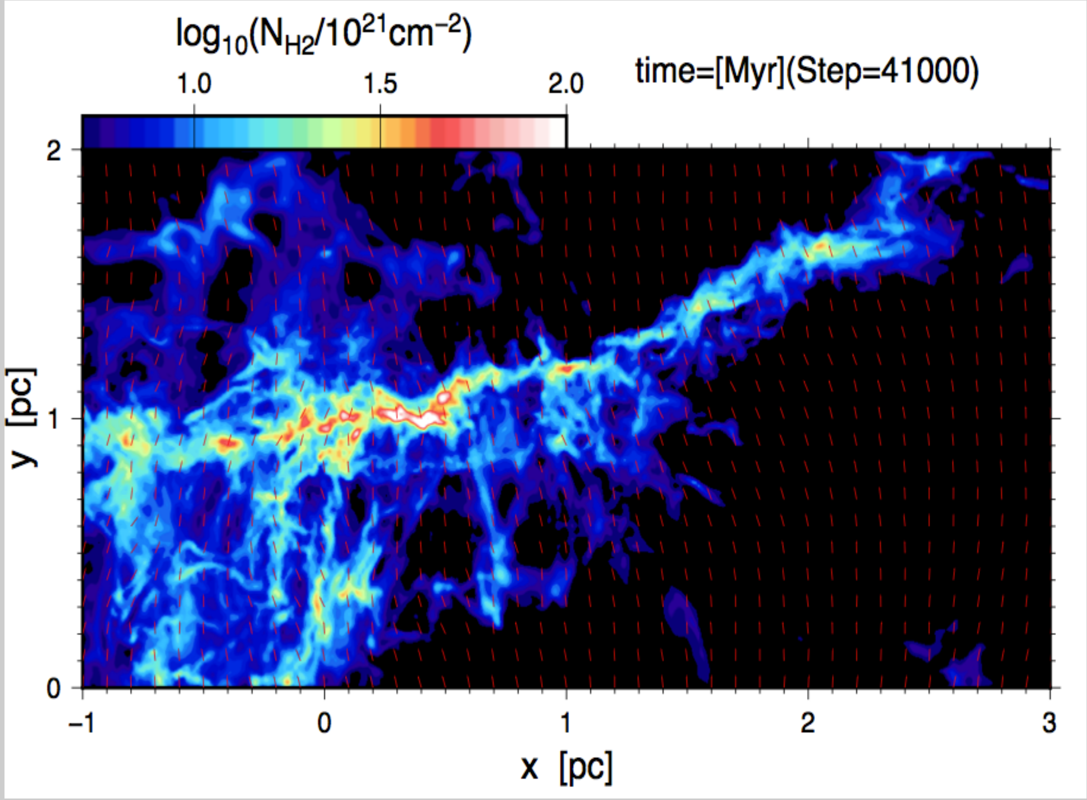

André et al., Bontemps et al., Könyves et al., Men'shchikov et al., Miville-Deschênes et al. 2010

# Star formation along dense filaments

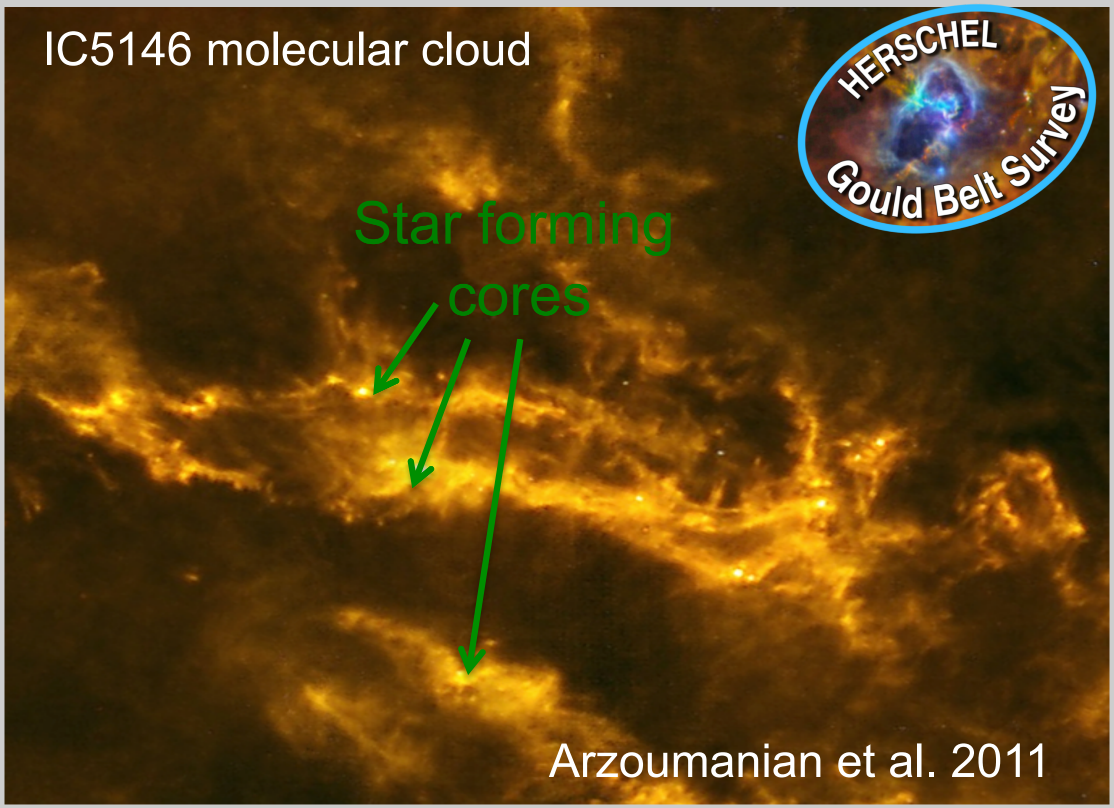
- Interstellar filaments are observed in star forming and quiescent clouds (e.g, André et al. 2010. Miville-Deschenes et al. 2010, Juvela et al. 2012)
- Dense filaments are the main sites for star formation (André et al. 2010, 2014)
- Filaments are produced by (all kinds of) numerical simulations (e.g, Hennebelle et al. 2008, Federrath et al. 2010, Mac Low & Klessen 2004, Inutsuka 2015)

>> Filament formation prior to any star forming activity
>> Insights into the initial conditions for star formation?

MHD simulation (Courtesy: Kazunari Iwasaki)




*Herschel* observations of submm dust emission



Questions:

How do interstellar filaments form and evolve in a magnetohydrodynamical turbulent interstellar medium?

What is the role of interstellar filaments in the star formation process?

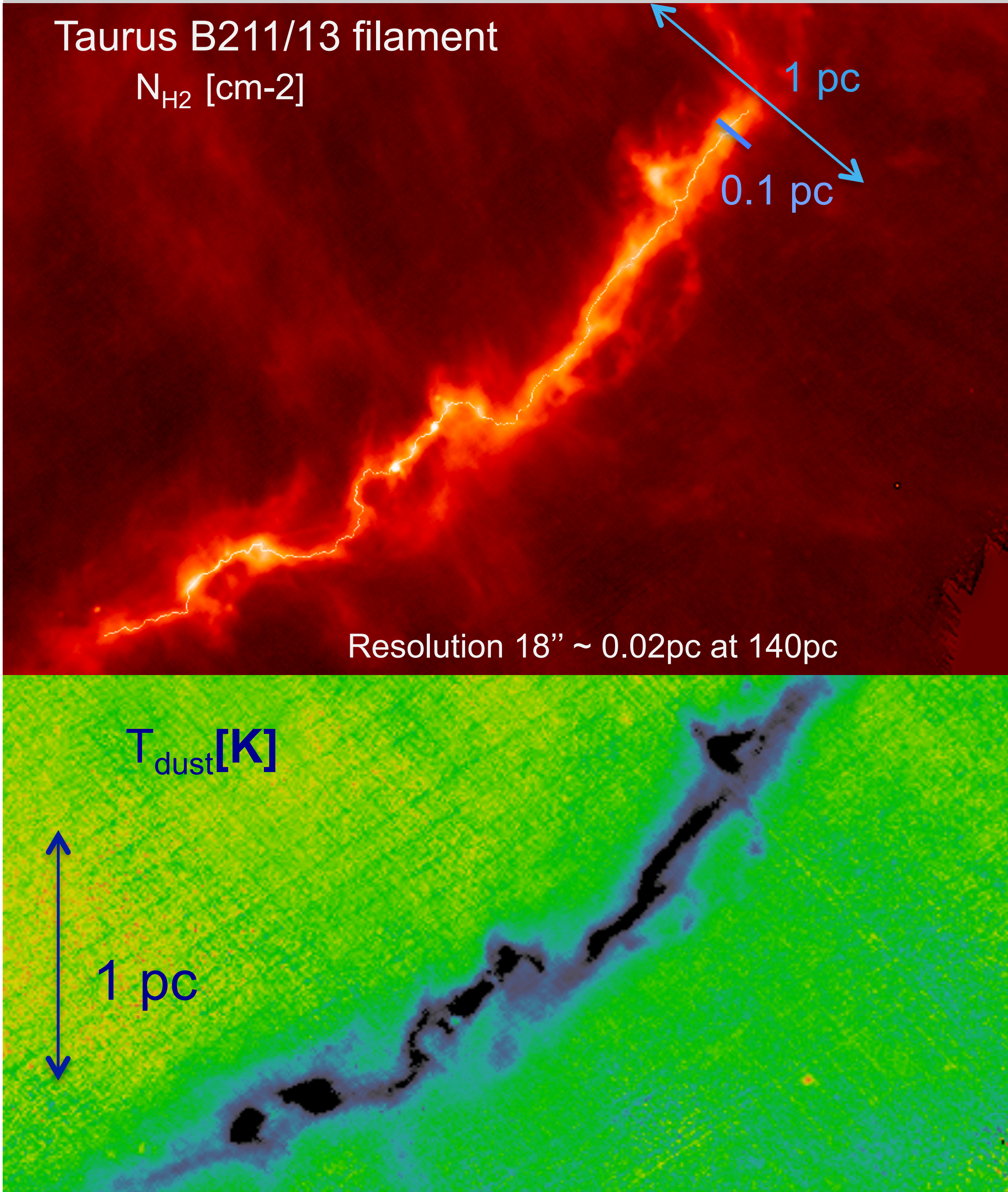
As an observer…

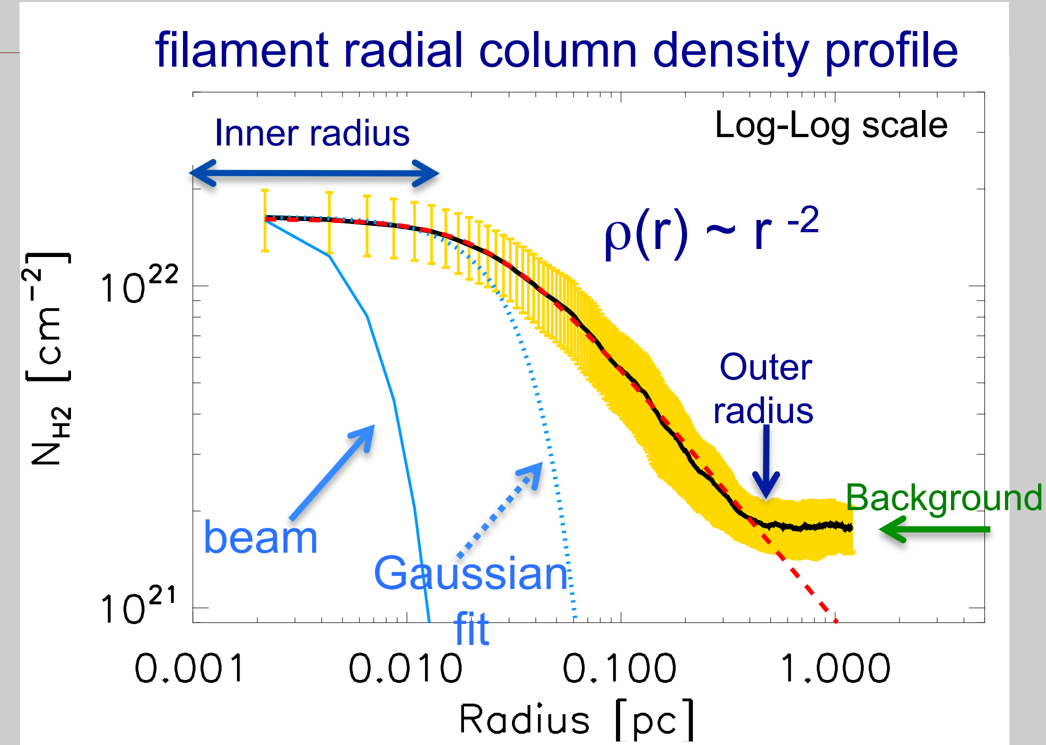
What are the observed properties of interstellar filaments?

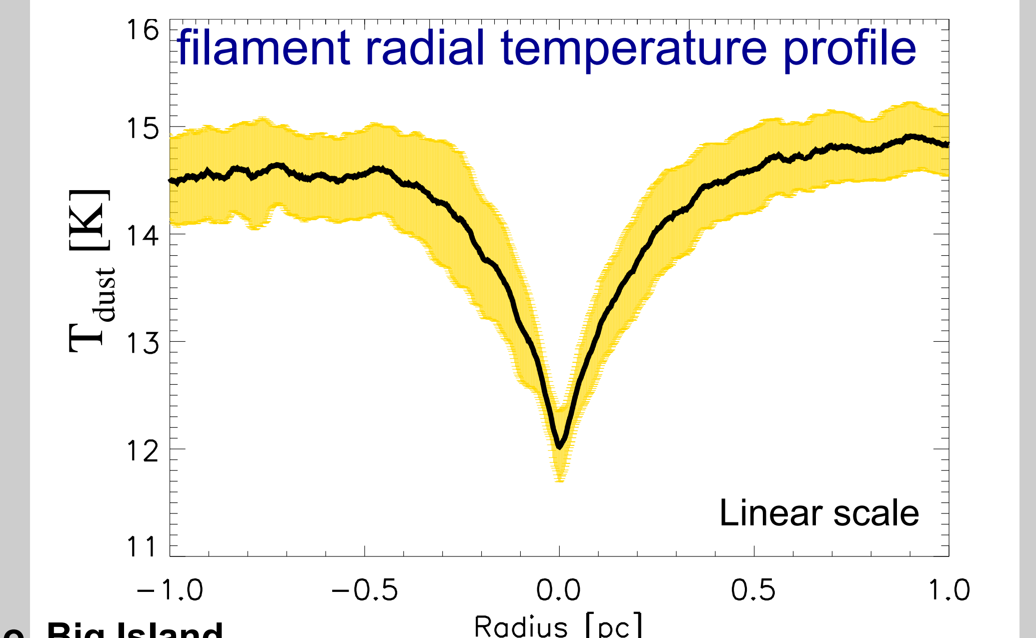
- Column density and temperature distributions of the filaments observed with *Herschel* dust continuum observations
- Signature of the magnetic field structure from *Planck* dust polarization observations
- Velocity structure of interstellar filaments derived from Molecular line observations

# Filament properties as derived from *Herschel* observations

Arzoumanian et al. 2011, Palmeirim et al. 2013

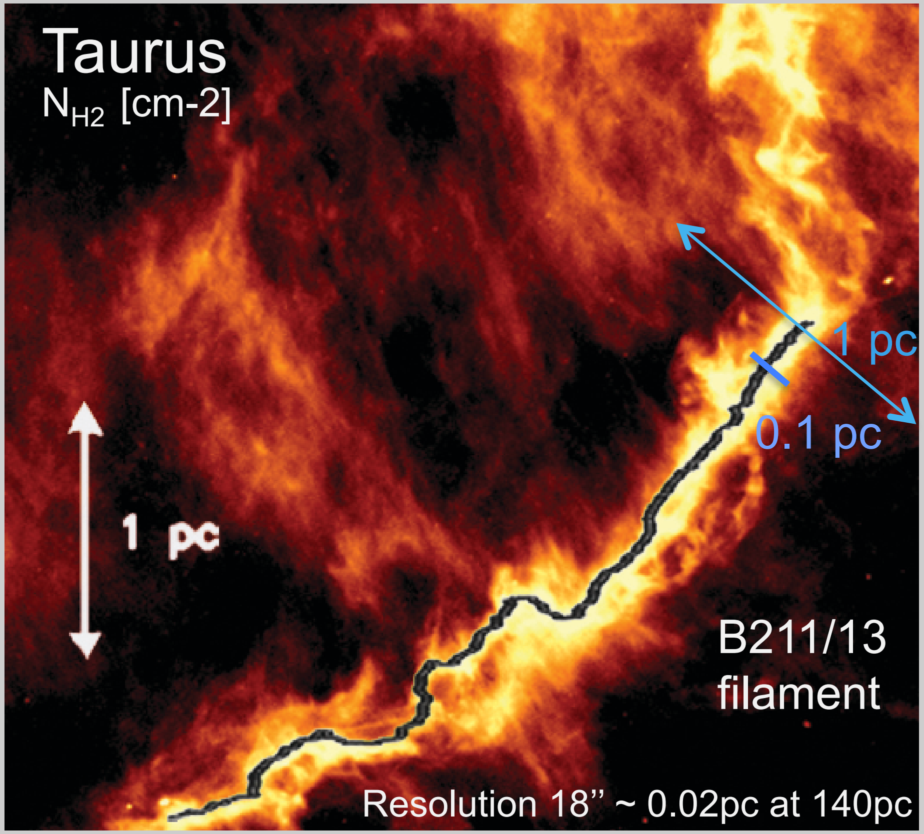


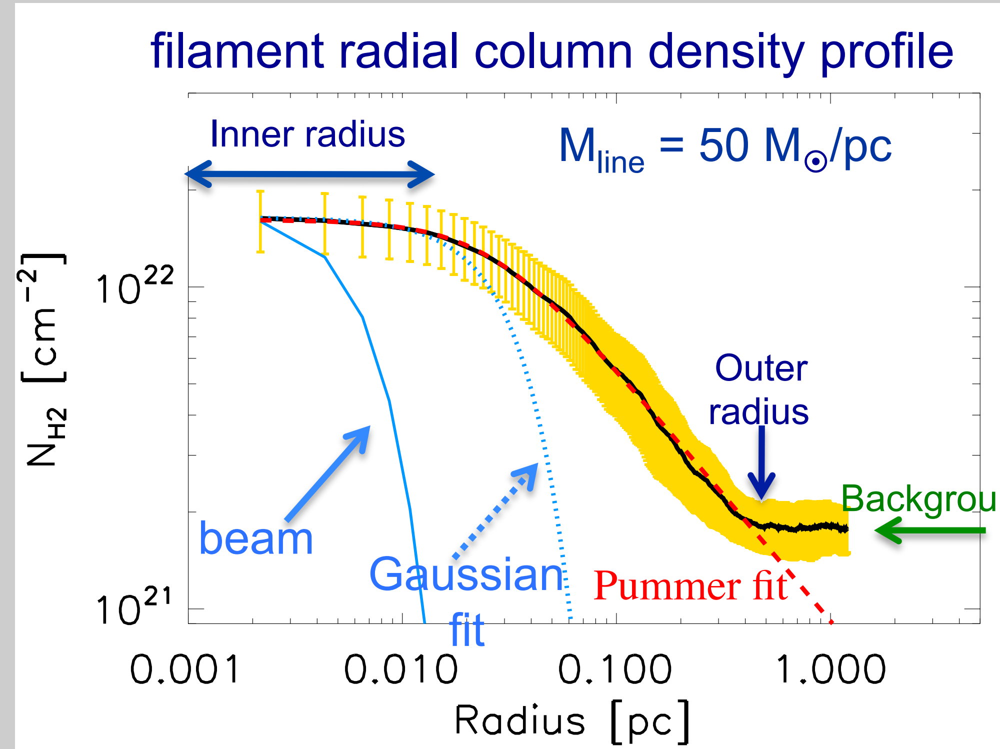



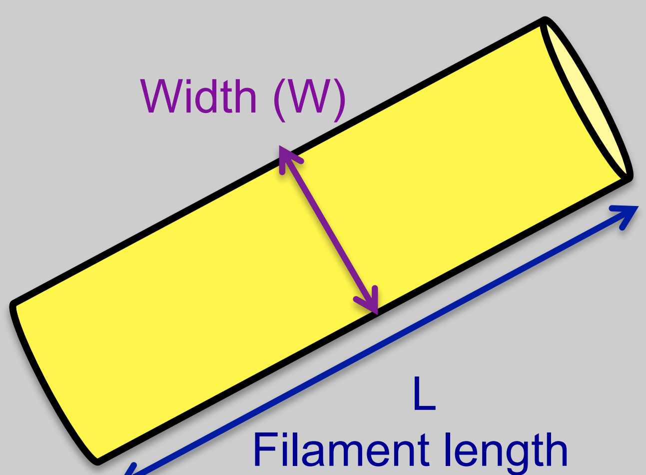



# Filament Mass per unit length: Stability of cylindrical filaments

Arzoumanian et al. 2011, Palmeirim et al. 2013



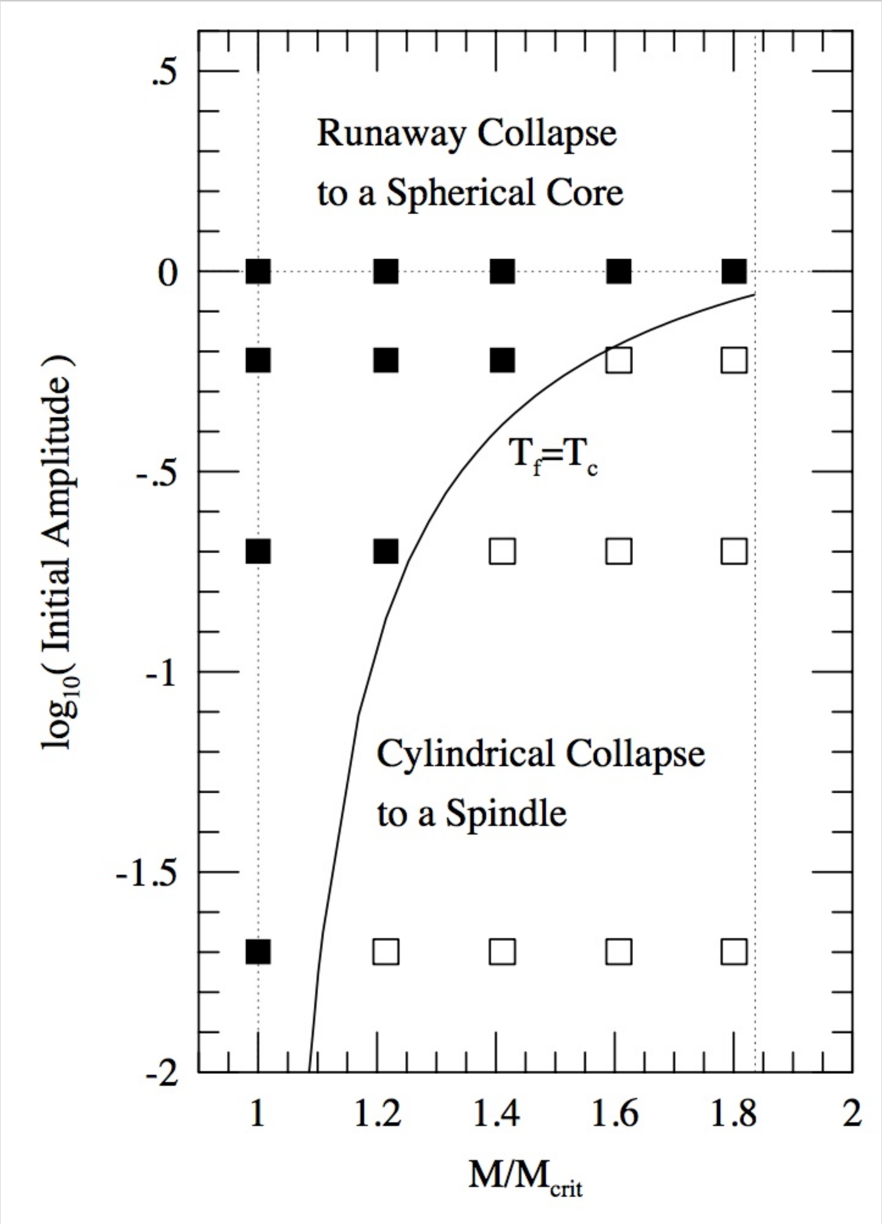

$M_{line}=M/L$

Thermally supercritical filament with $M_{line} > M_{line,crit}$ are unstable for radial collapse and gravitational fragmentation (Inutsuka & Miyama 1997)

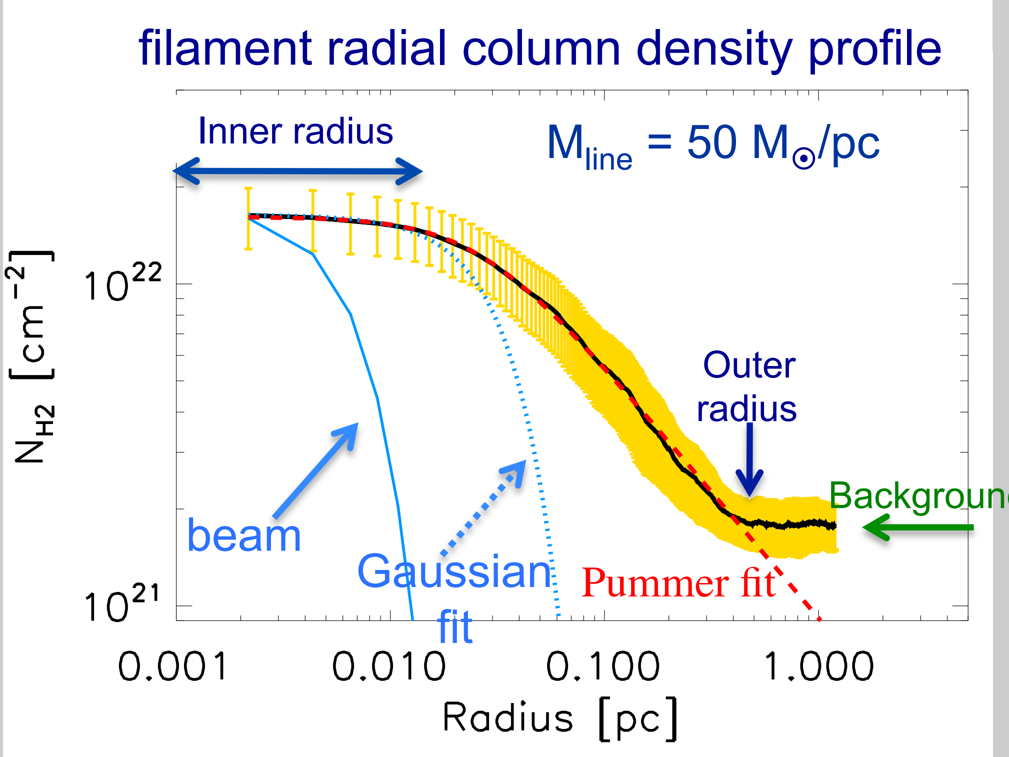
The critical (thermal) mass per unit length is $M_{line,crit} = 2c_s^2/G$, where $c_s$ is the sound speed (unmagnetized hydrostatic equilibrium solution) (Stodolkiewicz 1963, Ostriker 1964)

# Filament Mass per unit length: Stability of cylindrical filaments

## Runaway collapse of thermally supercritical filaments with $M_{line} > 2M_{line,crit}$



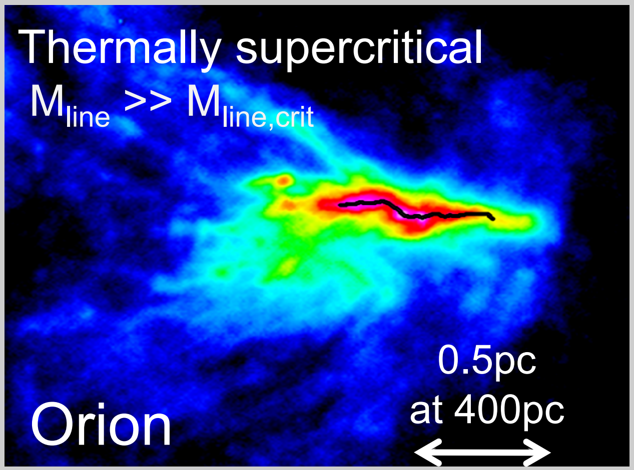

(Inutsuka & Miyama 1992,1997)

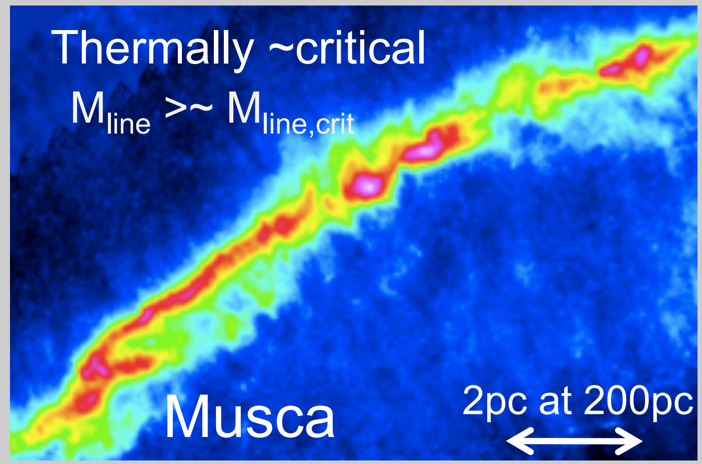


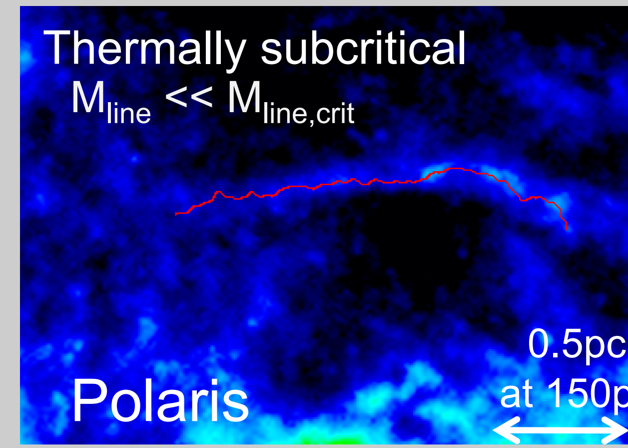

Thermally supercritical filament with $M_{line} > M_{line,crit}$ are unstable for radial collapse and gravitational fragmentation (Inutsuka & Miyama 1997)

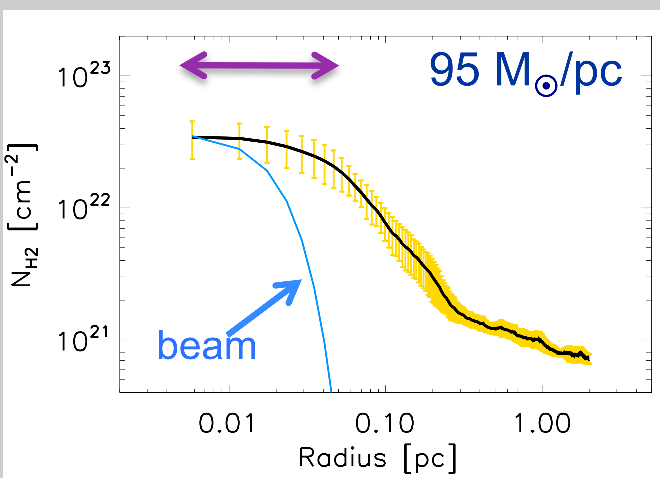
The critical (thermal) mass per unit length is $M_{line,crit} = 2c_s^2/G$, where $c_s$ is the sound speed (unmagnetized hydrostatic equilibrium solution) (Stodolkiewicz 1963, Ostriker 1964)

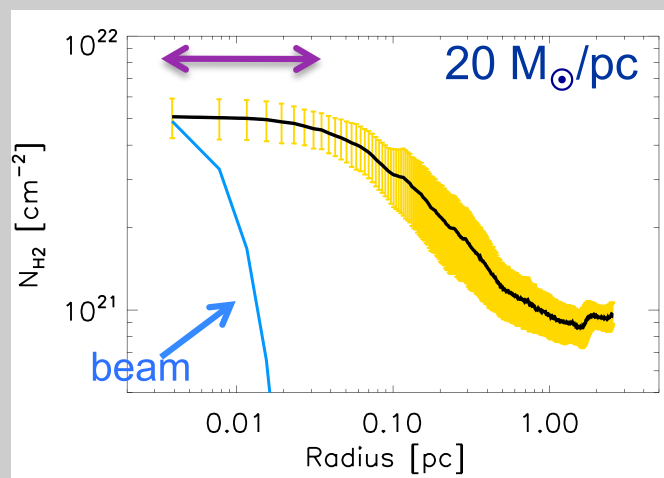
# Radial profiles and masses per unit length of filaments derived from *Herschel* column density maps

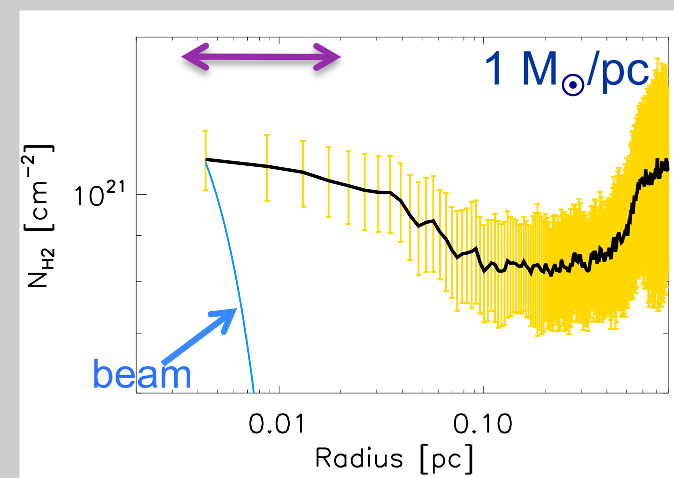


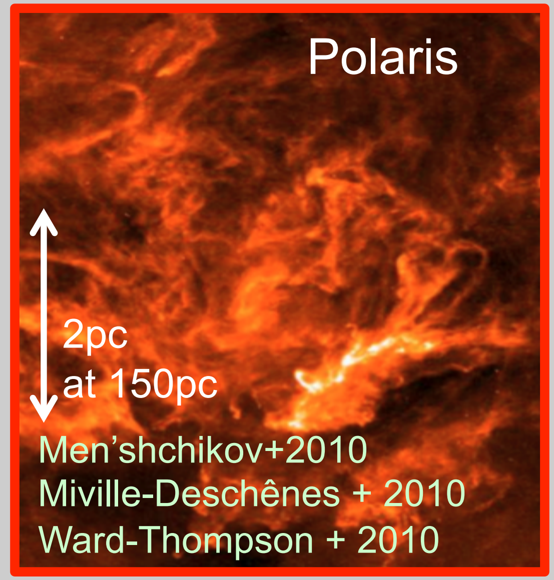

$M_{line} > M_{line,crit}$ $M_{line} >\sim M_{line,crit}$ $M_{line} < M_{line,crit}$

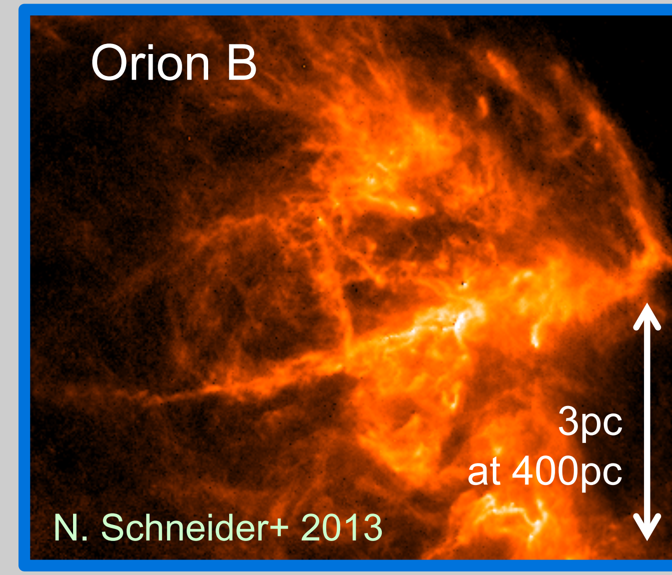
All three filaments have similar inner widths ~0.1 pc

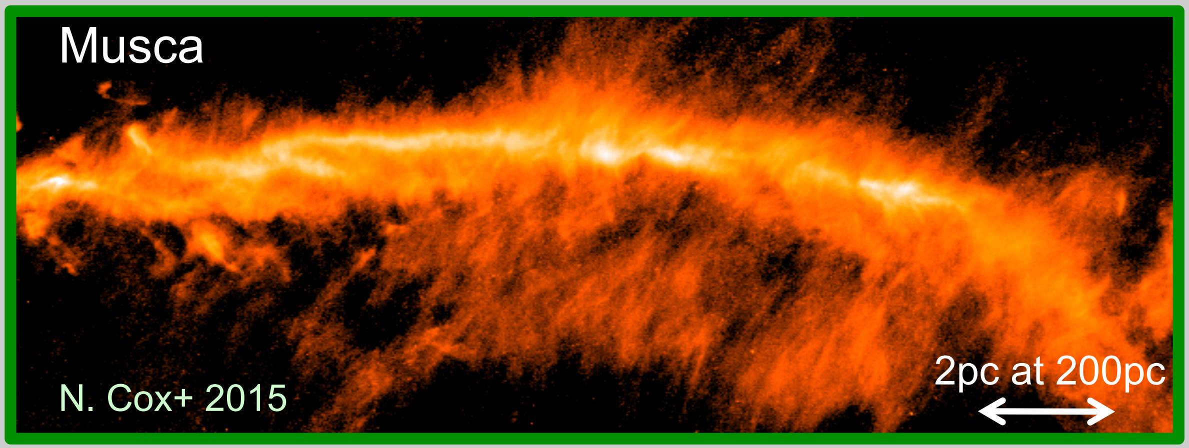
Critical mass per unit length $M_{line,crit} = 2c_s^2/G \sim 16\ M_\odot$/pc for T~10 K

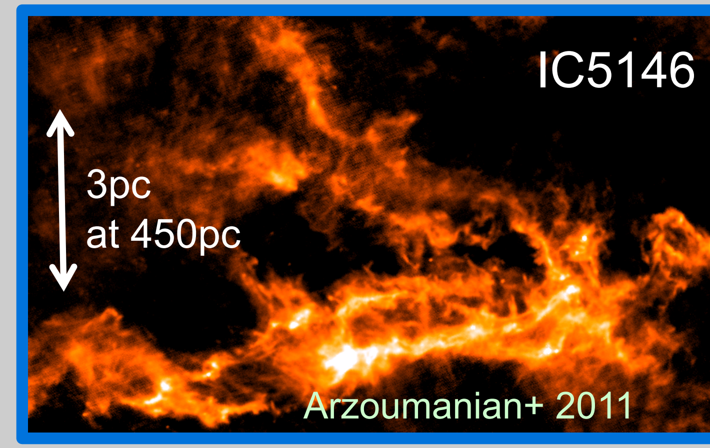
# Filamentary structures of nearby molecular clouds as seen by

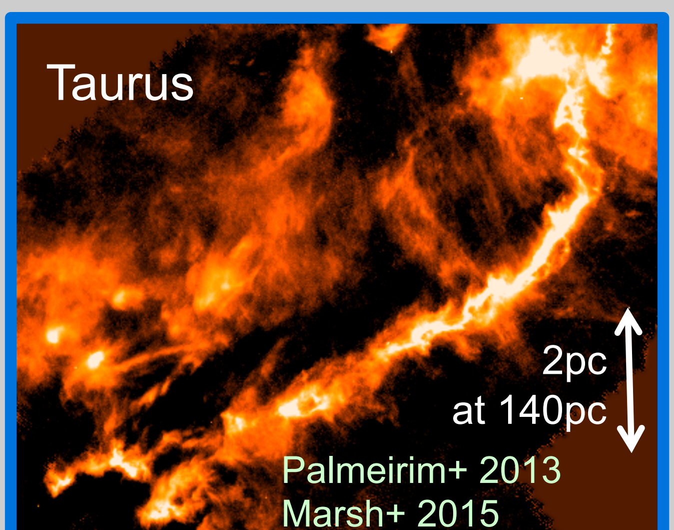
HERSCHEL Gould Belt Survey

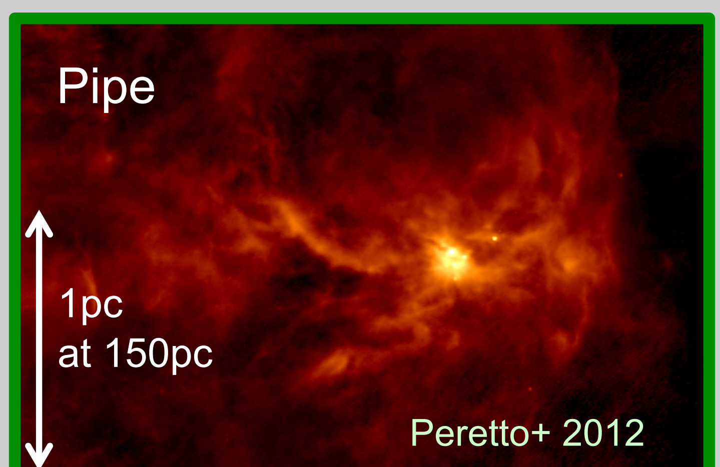


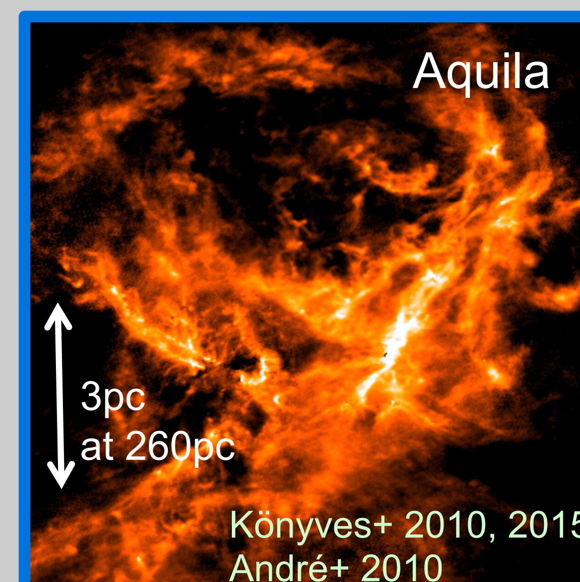



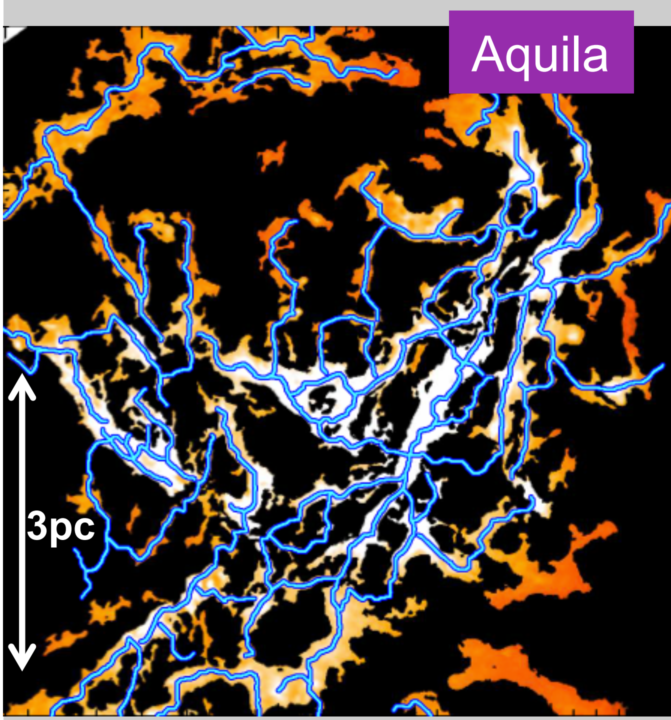
# Tracing the filamentary networks observed in the ISM

## Algorithms and methods to identify/trace filaments in 2D maps:

DisPerSE algorithm (Sousbie 2011), MCA (Starck et al. 2003), *getfilaments* (Men'shchikov 2013)
The Hessian matrix / Second derivatives (*Planck* XXXII 2014,arXiv:1409.6728, Schisano et al. 2014)
Rolling Hough Transform (Clark et al. 2014), *FilFinder* (Koch & Rosolowsky 2015)

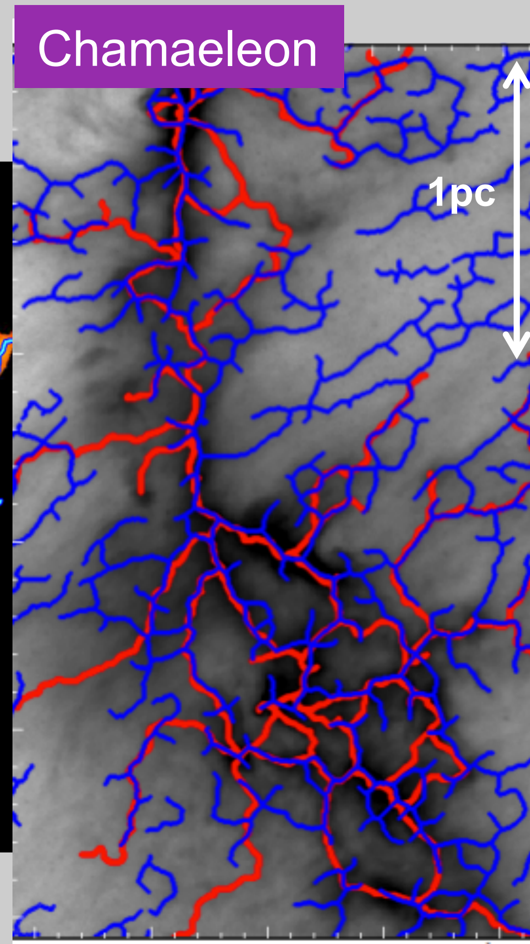
Examples on *Herschel* maps

*Getfilaments* + DisPerSE



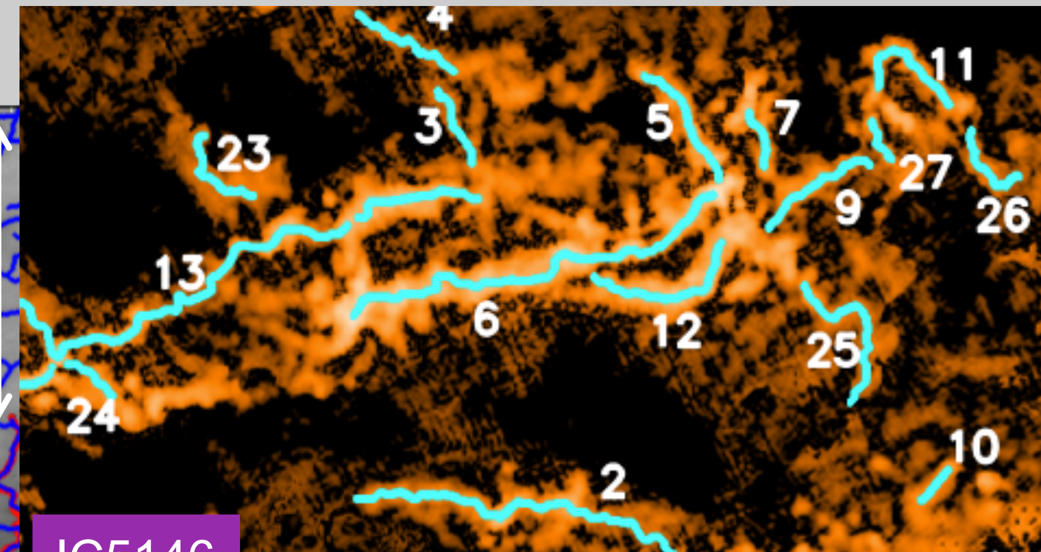

Könyves et al. 2015

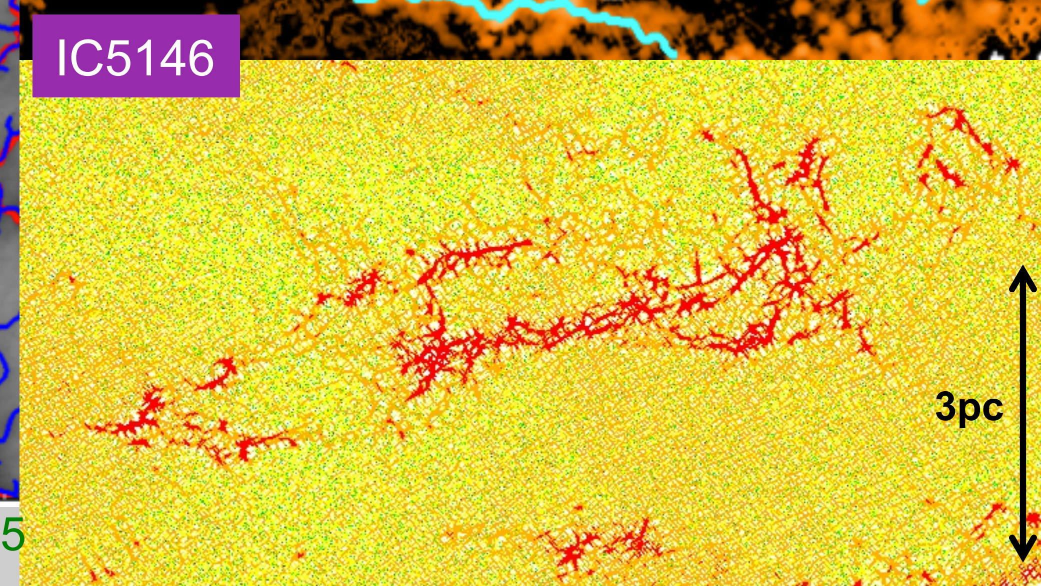
*FilFinder* + DisPerSE




Koch & Rosolowsky 2015

Arzoumanian et al. 2011 MCA + DisPerSE



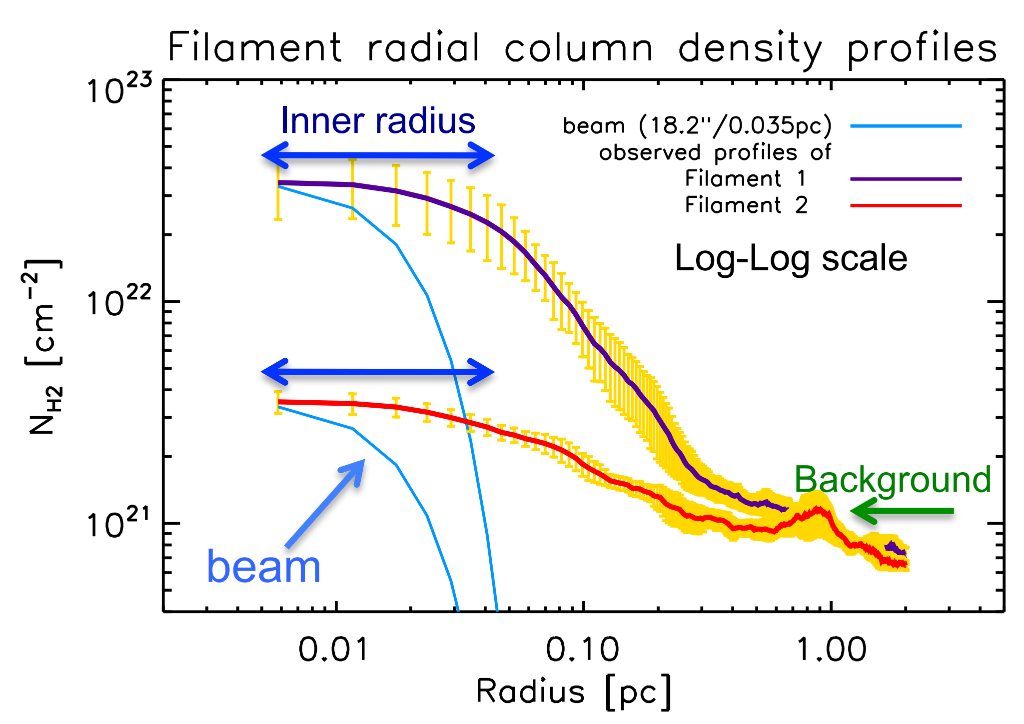



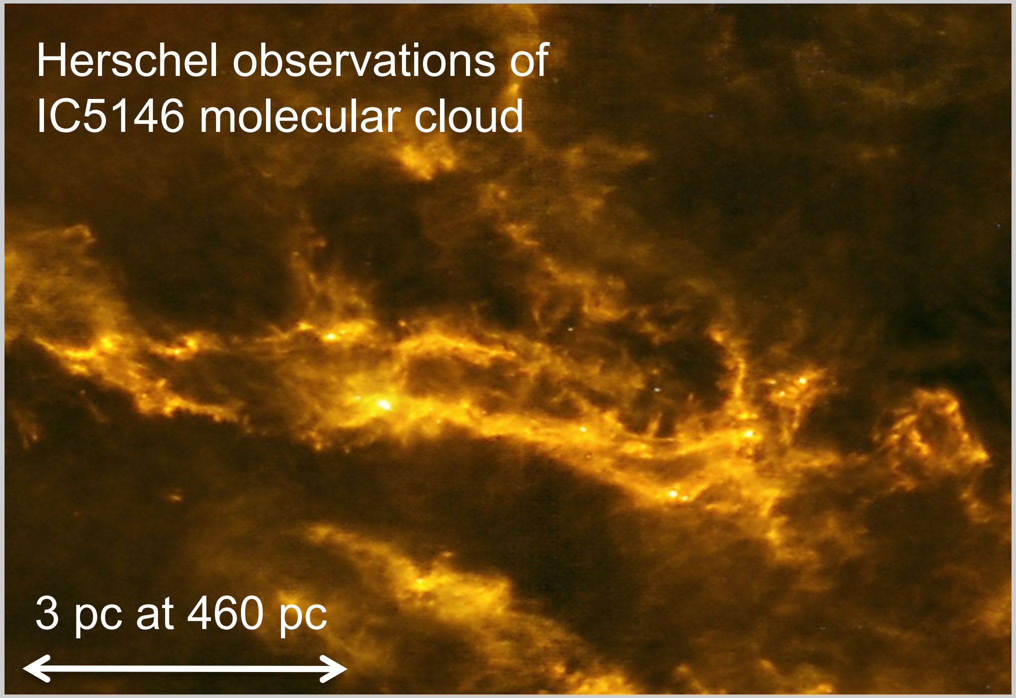

Minimum curvature map derived from the Hessian matrix analysis

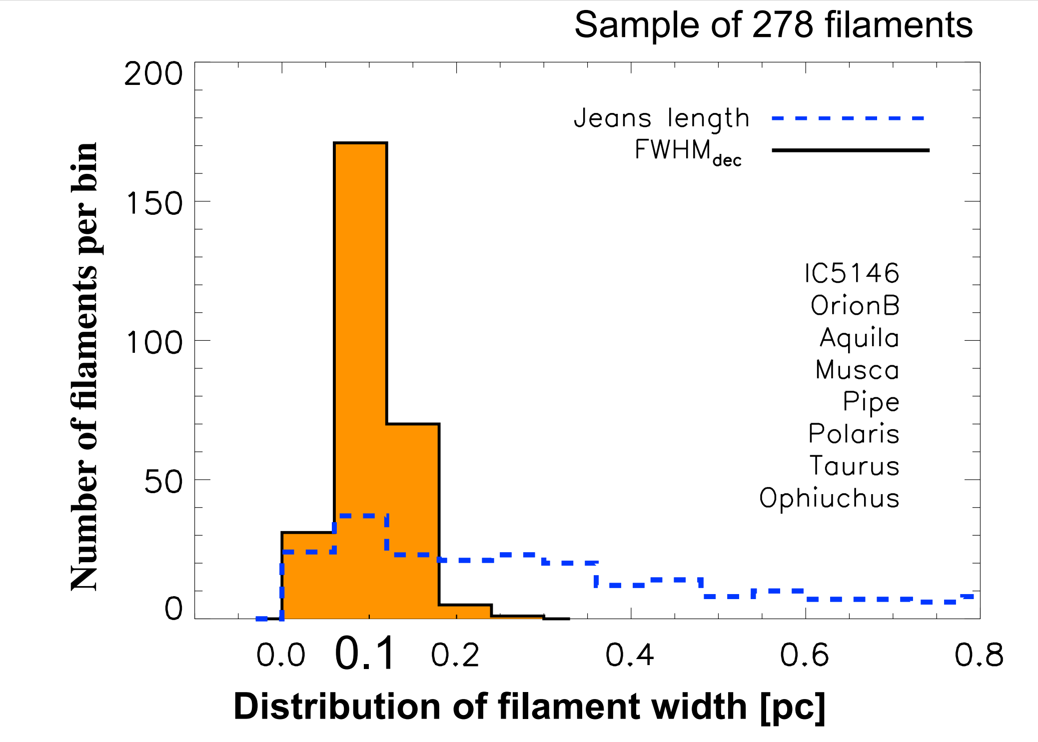
Doris Arzoumanian, 02/05/2017, EAO Seminar, Hilo, Big Island

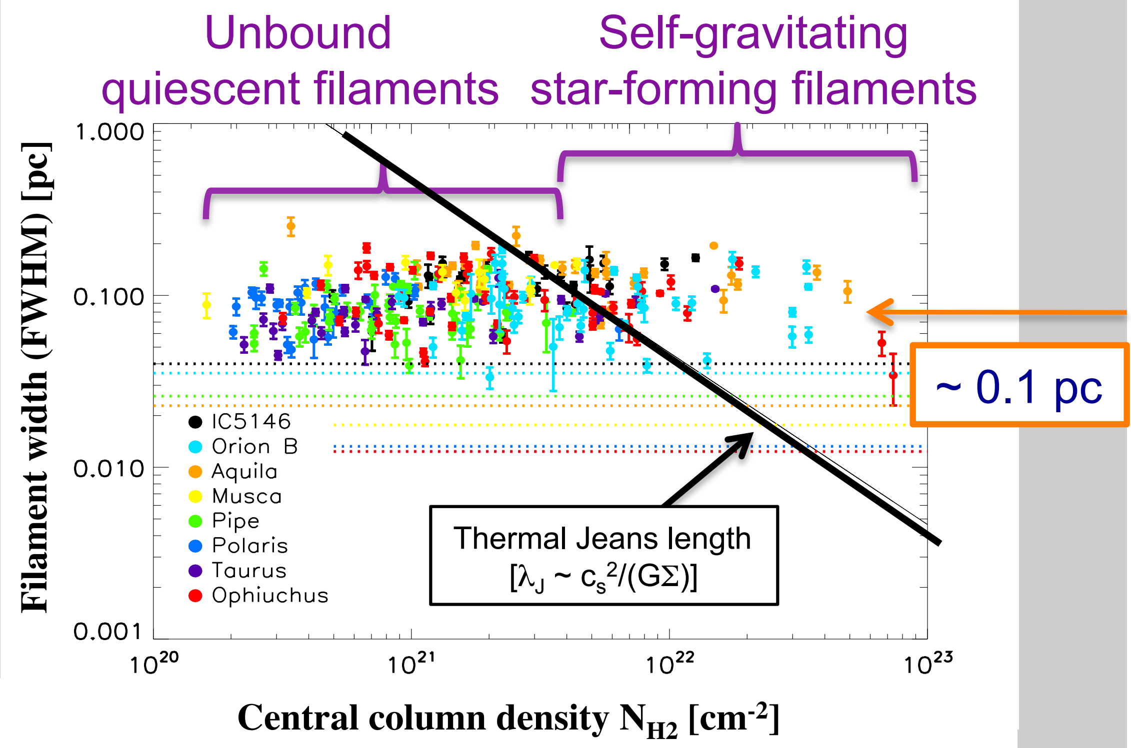
# Interstellar filaments share a common inner width of 0.1pc while they span a wide range in column density

Arzoumanian et al. 2011, 2013, André et al 2014

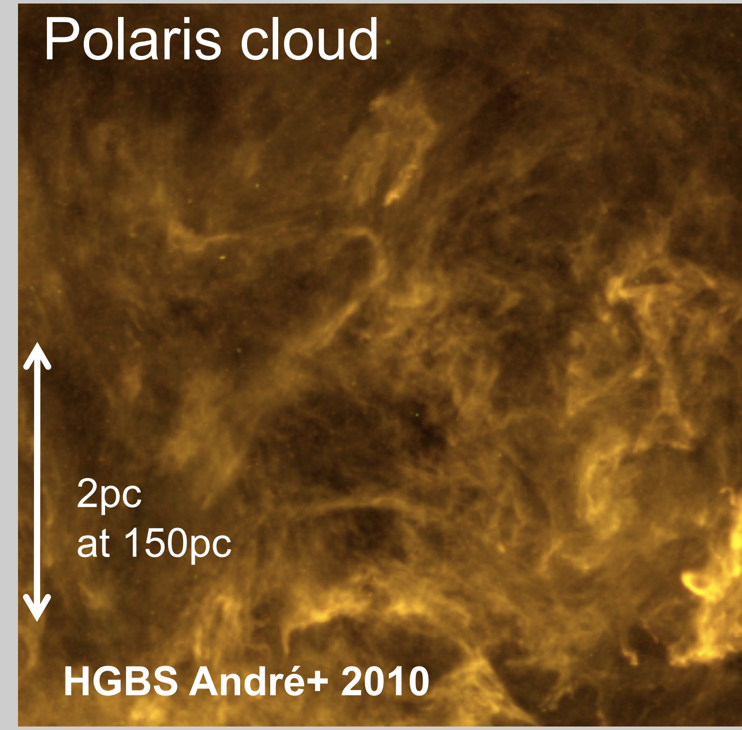


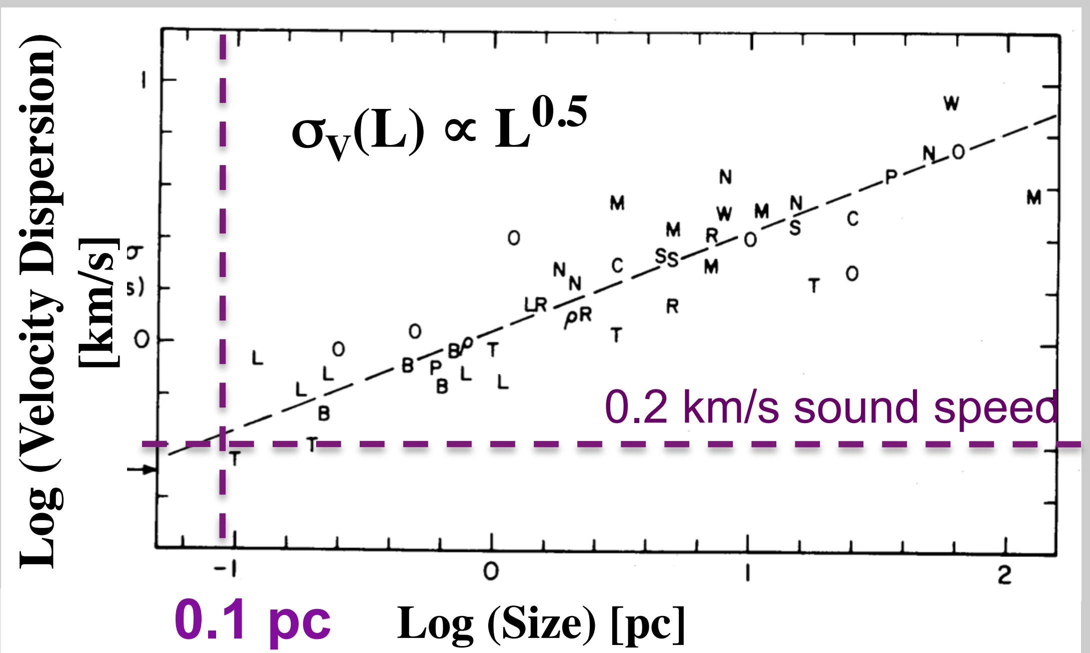



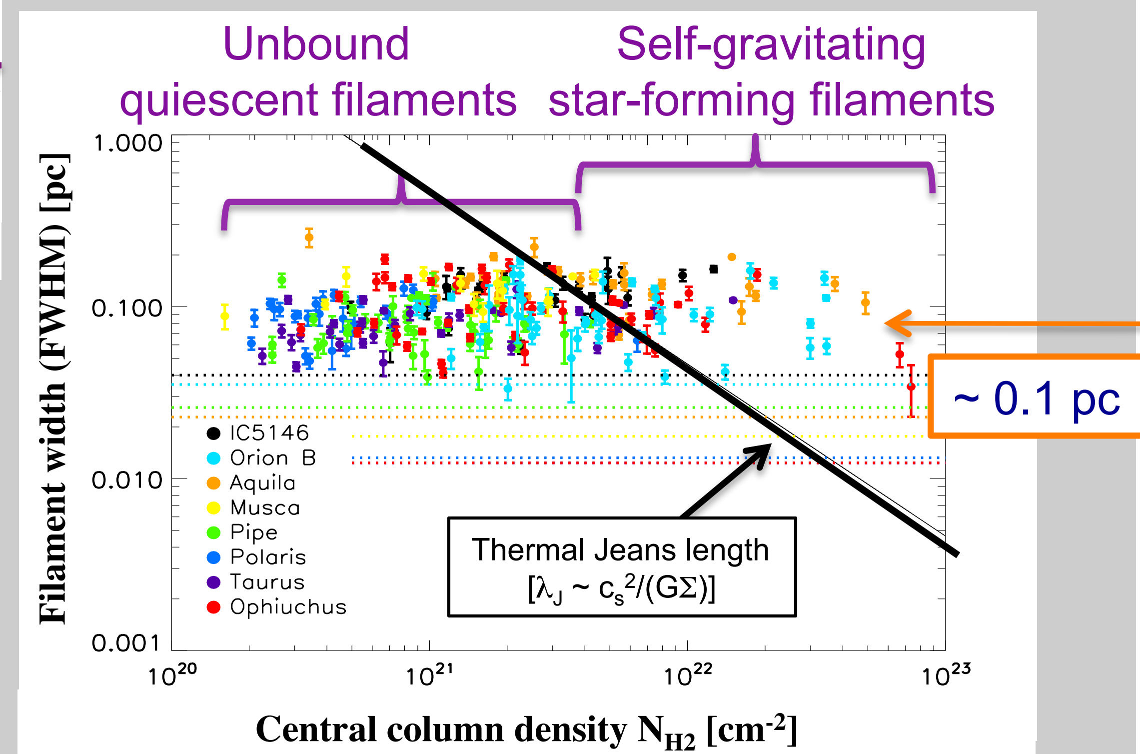
# Filament formation from the dissipation of supersonic interstellar turbulence?




Linewidth-Size relation in clouds (Larson 1981)




Arzoumanian et al 2011



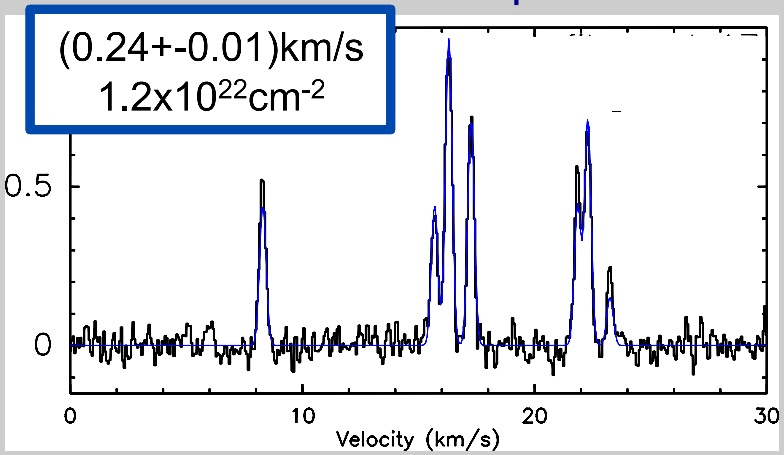

Sonic scale of the cold ISM (Goodman et al. 1998, Falgarone et al. 2009 Federrath et al. 2010)

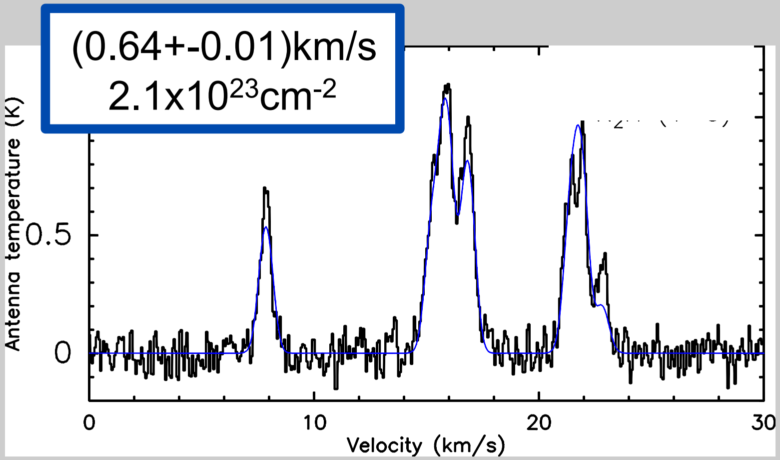
Sonic scale: transition scale between supersonic and subsonic turbulence

# Velocity dispersion of interstellar filaments

Two regimes for filaments
Subcritical and unbound / supercritical and self gravitating

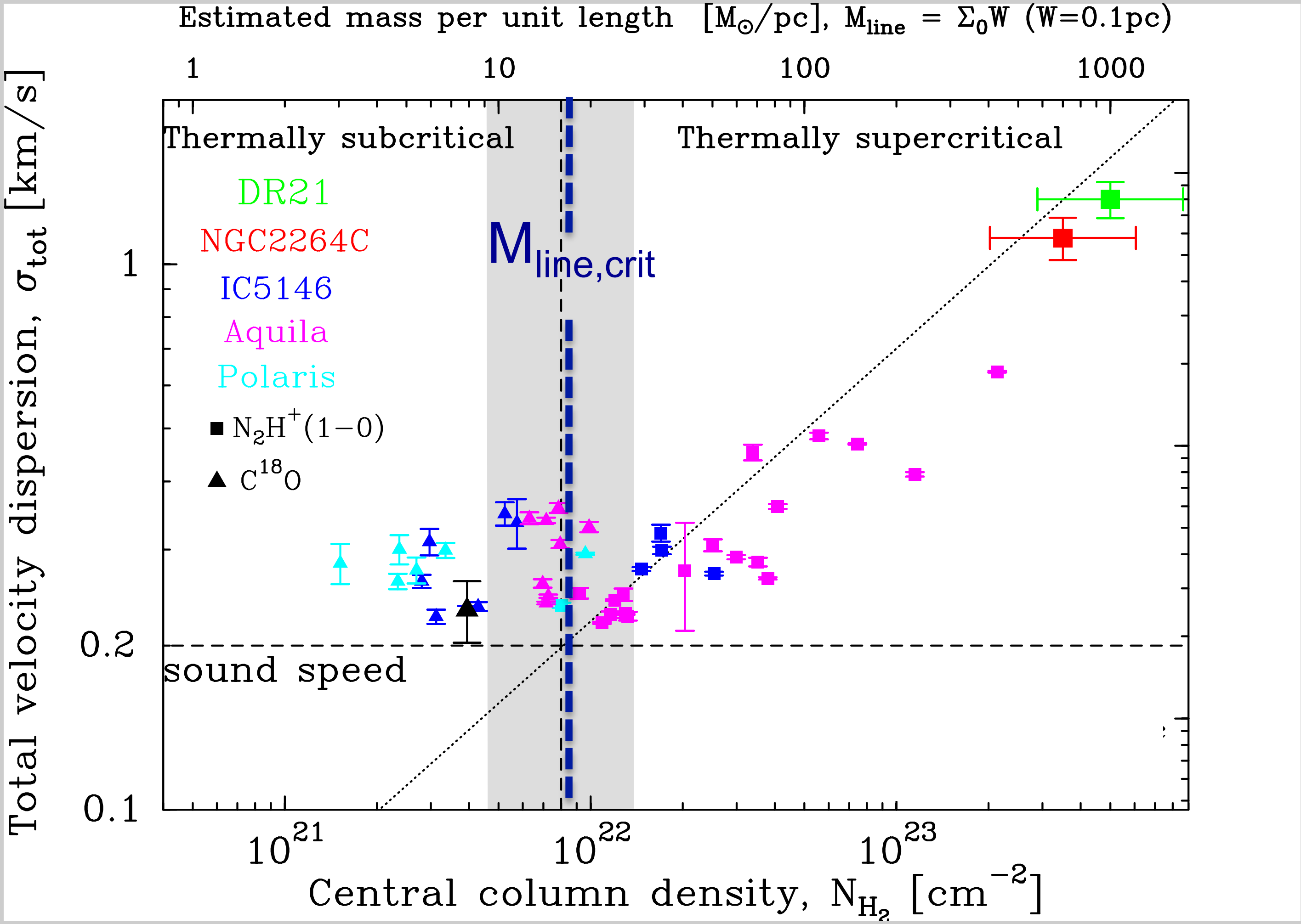
$N_2H^+$(1-0) spectra towards
2 filaments in Aquila




$$\sigma_{tot}^2 = \sigma_{NT}^2 + \sigma_T^2$$

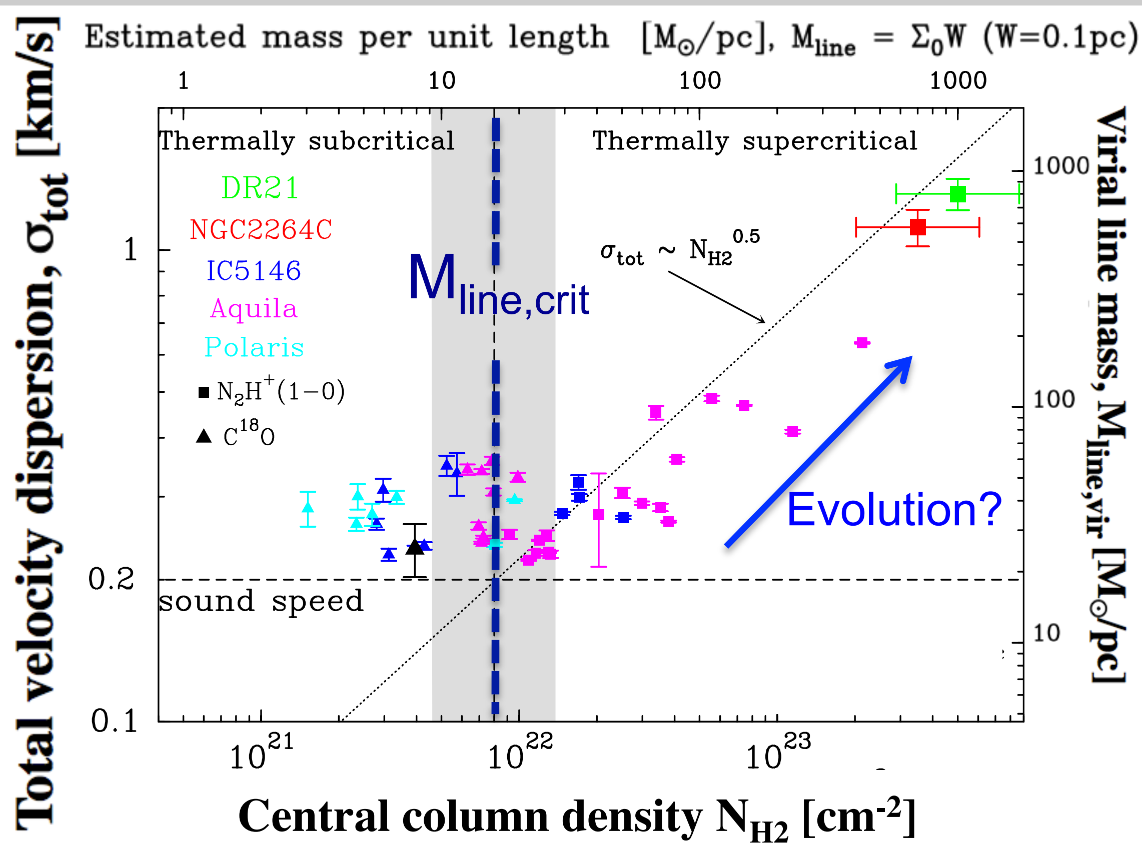
Arzoumanian et al 2013



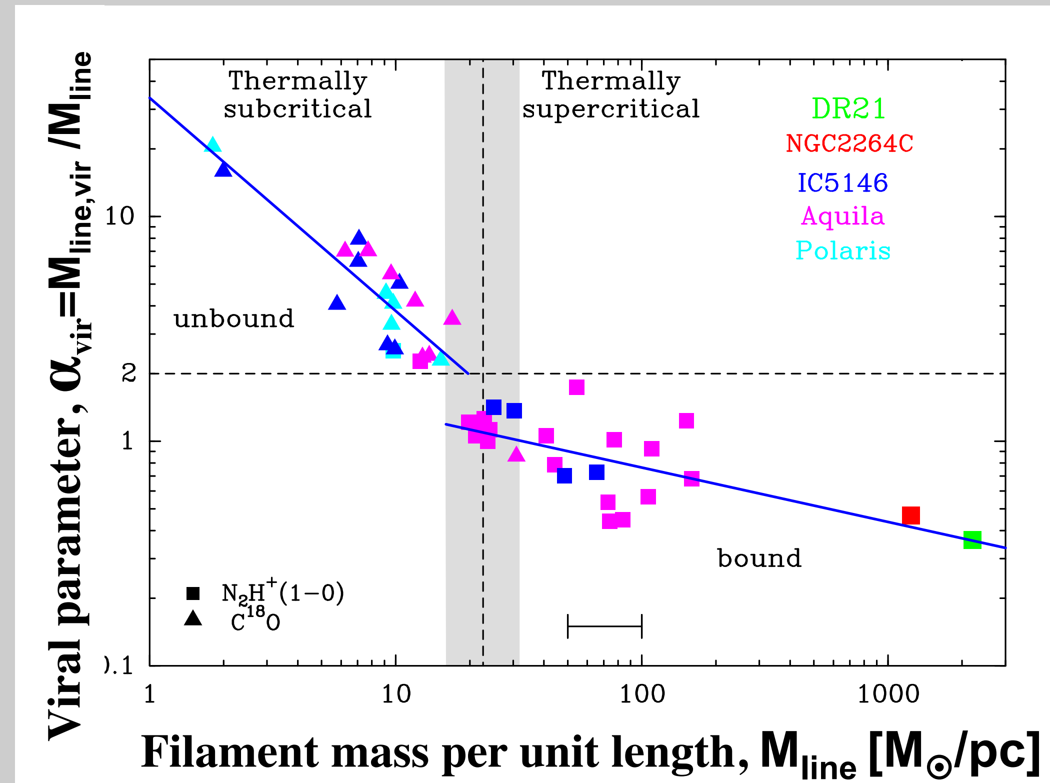

$M_{line,crit} = 2c_s^2/G \sim 16\ M_\odot$/pc for T=10K,
equivalent to $N_{H2} \sim 8 \times 10^{21}\ cm^{-2}$

# Hint of the evolution of supercritical filaments from their observed velocity dispersion?

Arzoumanian et al 2013




Supercritical filaments are observed to be in nearly virial balance




Increase of the total velocity dispersion with central column density for supercritical filaments driven by the accretion of matter?

(Klessen & Hennebelle 2010, Hennebelle & André 2013)

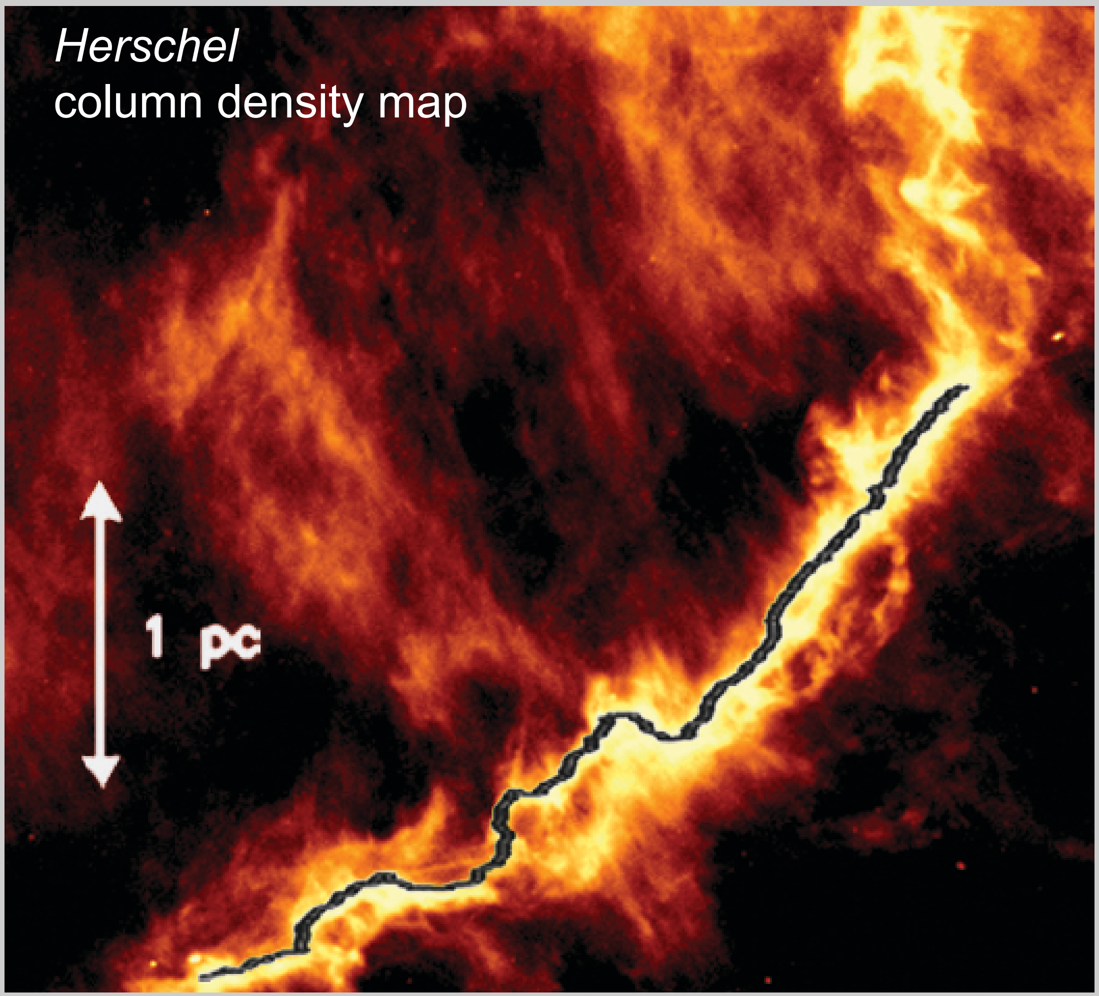
$$M_{line,crit} = 2c_s^2/G$$
$$M_{line,vir} = 2\sigma^2_{tot}/G$$

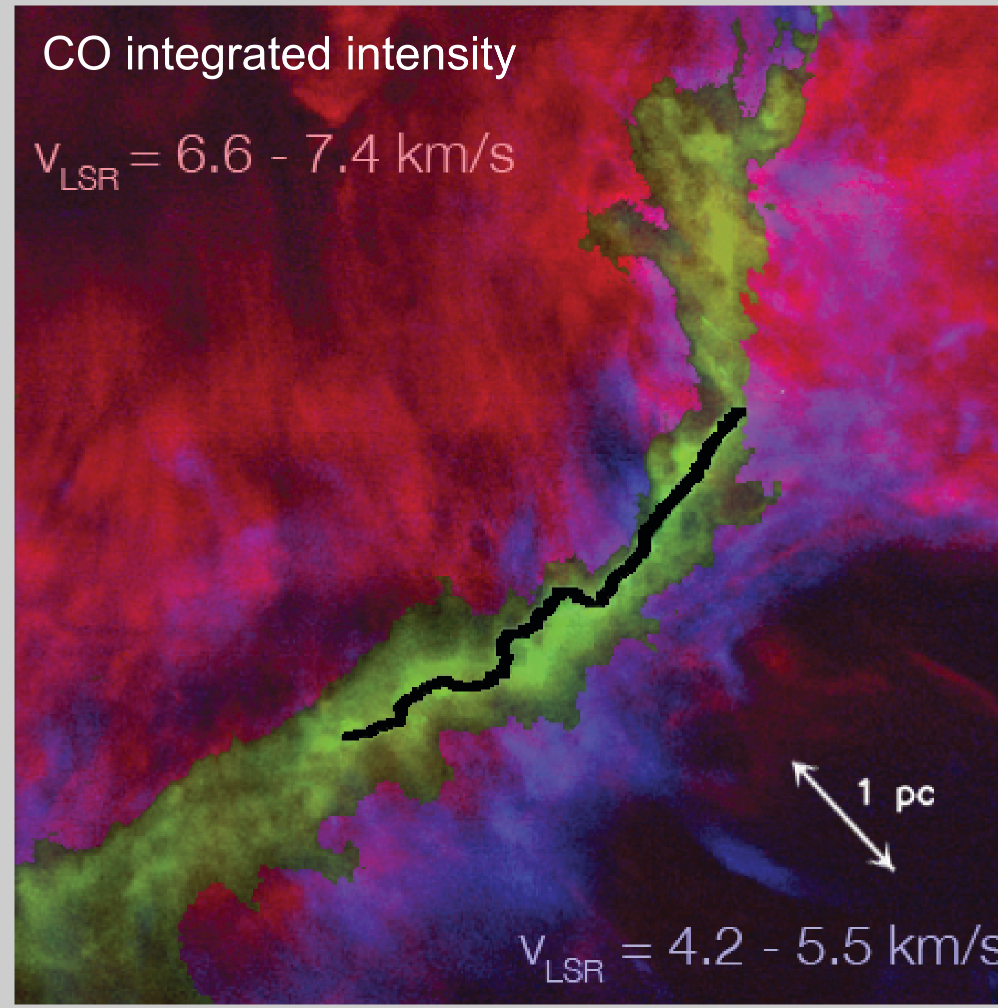
Virial mass per unit length (Fiege & Pudritz 2000)

**Doris Arzoumanian, 02/05/2017, EAO Seminar, Hilo, Big Island**

# Indirect evidence of accretion of surrounding material onto dense filaments

Example of the B211/B213 filament in the Taurus molecular cloud
Palmeirim et al. 2013, Shimajiri et al. in prep.




Low column density filaments or striations seem to be feeding the dense filament

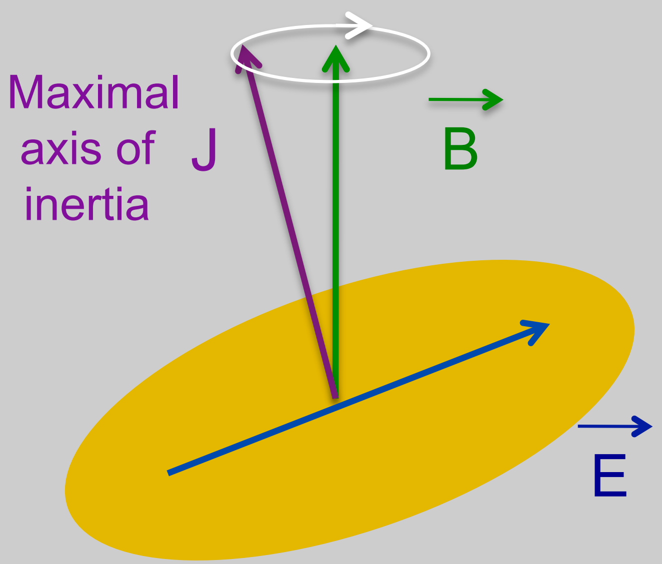
CO observations from Goldsmith et al. (2008)

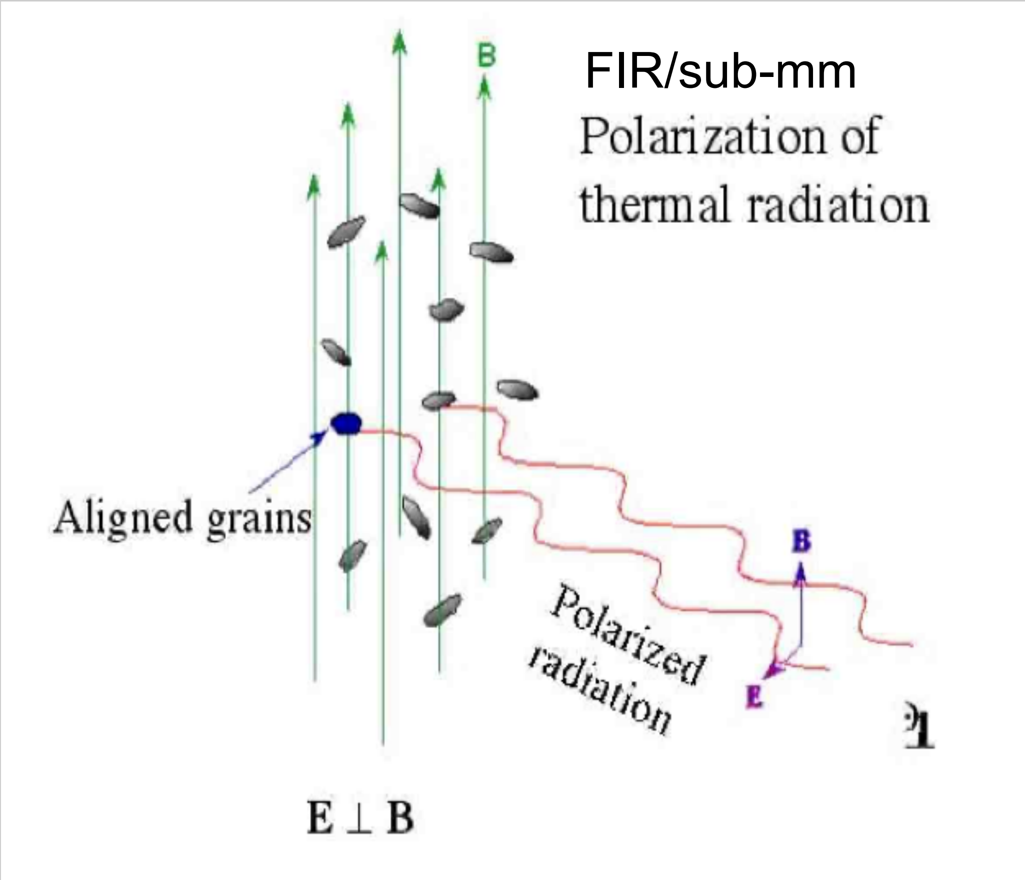
# What about the magnetic field structure?

Information on the plane of the sky projected orientation of the magnetic field in the ISM derived from dust polarization observations

# Why do dust grains emit linearly polarized light?

• Linear polarization results from non-spherical spinning dust grains, which precess around the ambient magnetic field (Davis & Greenstein 1951, Vaillancourt 2007)



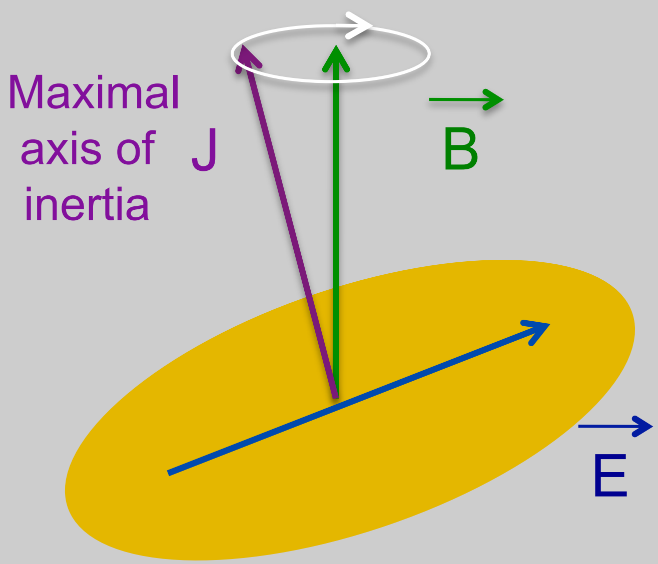



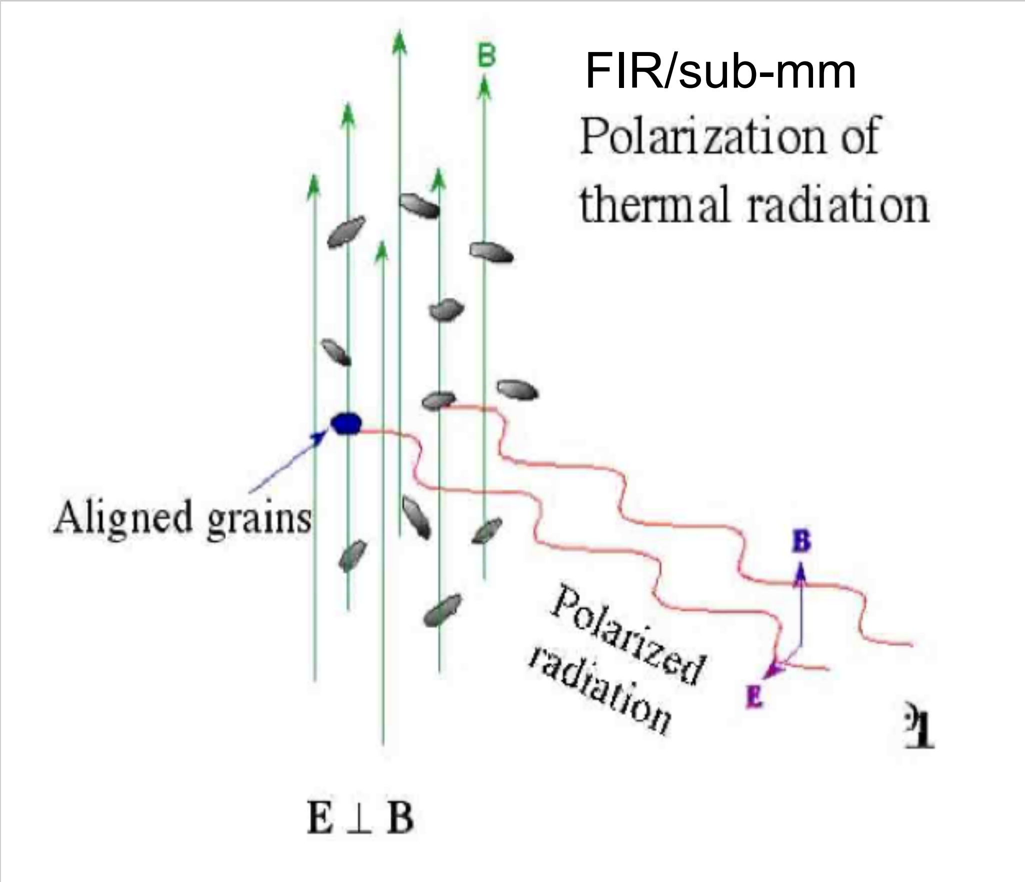

**B** orientation = pol. direction + 90°

# Why do dust grains emit linearly polarized light?

Dust polarization depends on (Lee & Draine 1985, Hildebrand 1983):

1) Dust properties (shape, size, composition),
2) Grain alignment efficiency with the local magnetic field
3) The structure of the magnetic field



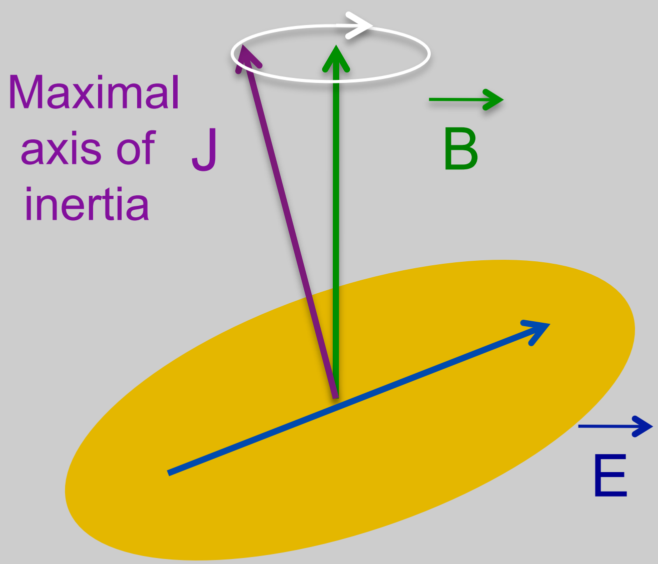



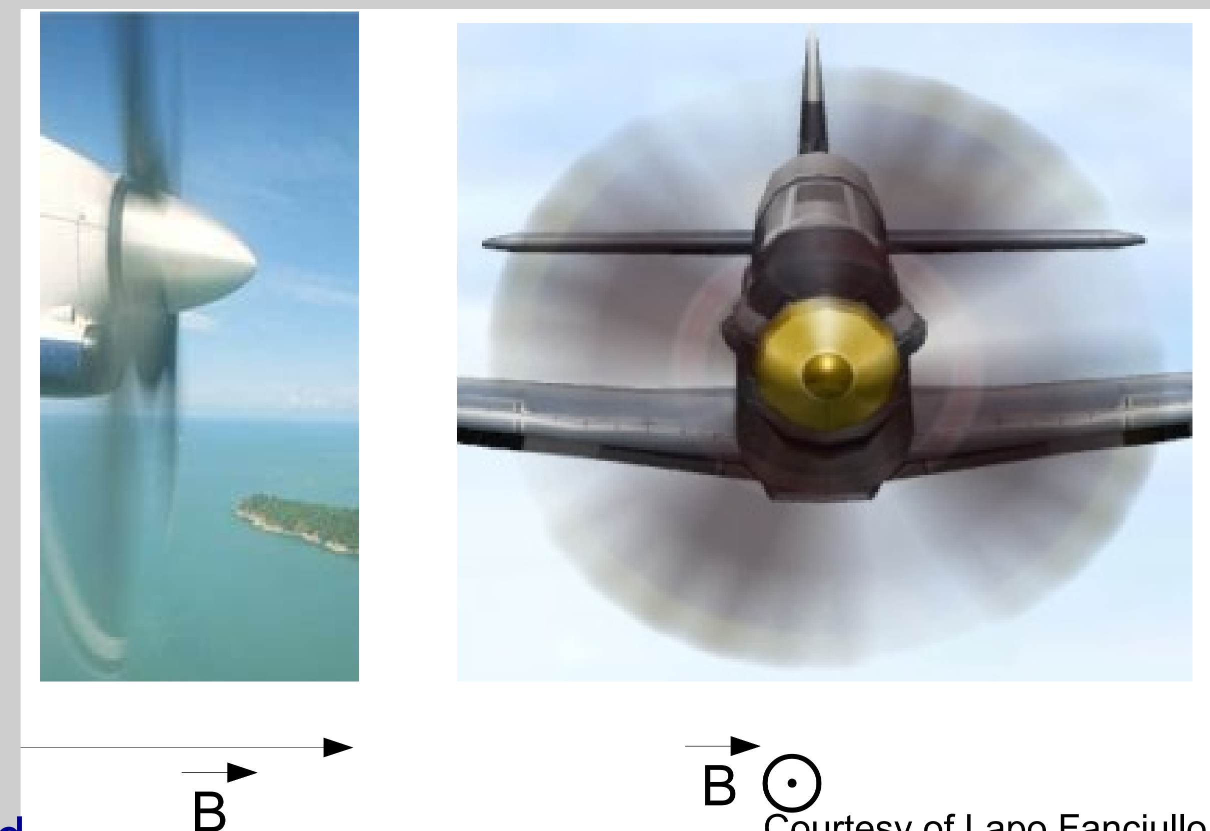

**B** orientation = pol. direction + 90°

# Why do dust grains emit linearly polarized light?

Dust polarization depends on (Lee & Draine 1985, Hildebrand 1983):

1) Dust properties (shape, size, composition),
2) Grain alignment efficiency with the local magnetic field
3) The structure of the magnetic field




Derived quantities:

Total polarized intensity (P)

Polarization fraction (p=P/I)

Polarization angle (orientation of **B** field projected on the plane of the sky)

**B** in the plane of the sky: P/I maximal

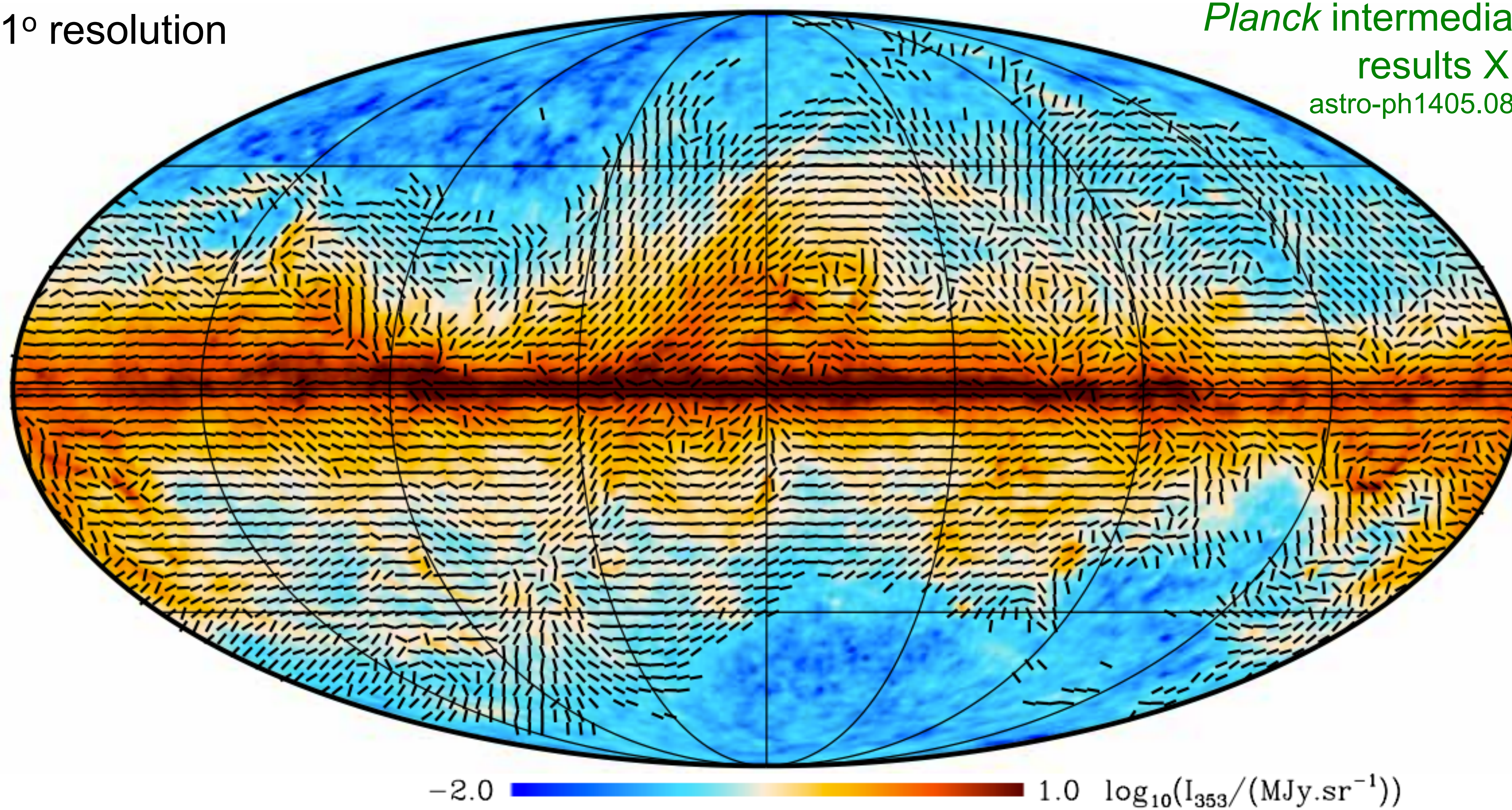
**B** along the line of sight: P/I=0

# Large scale magnetic field structure of the ISM derived from the dust polarized emission observed by *Planck*

**_Planck_**

1° resolution

*Planck* intermediate results XIX
astro-ph1405.0871

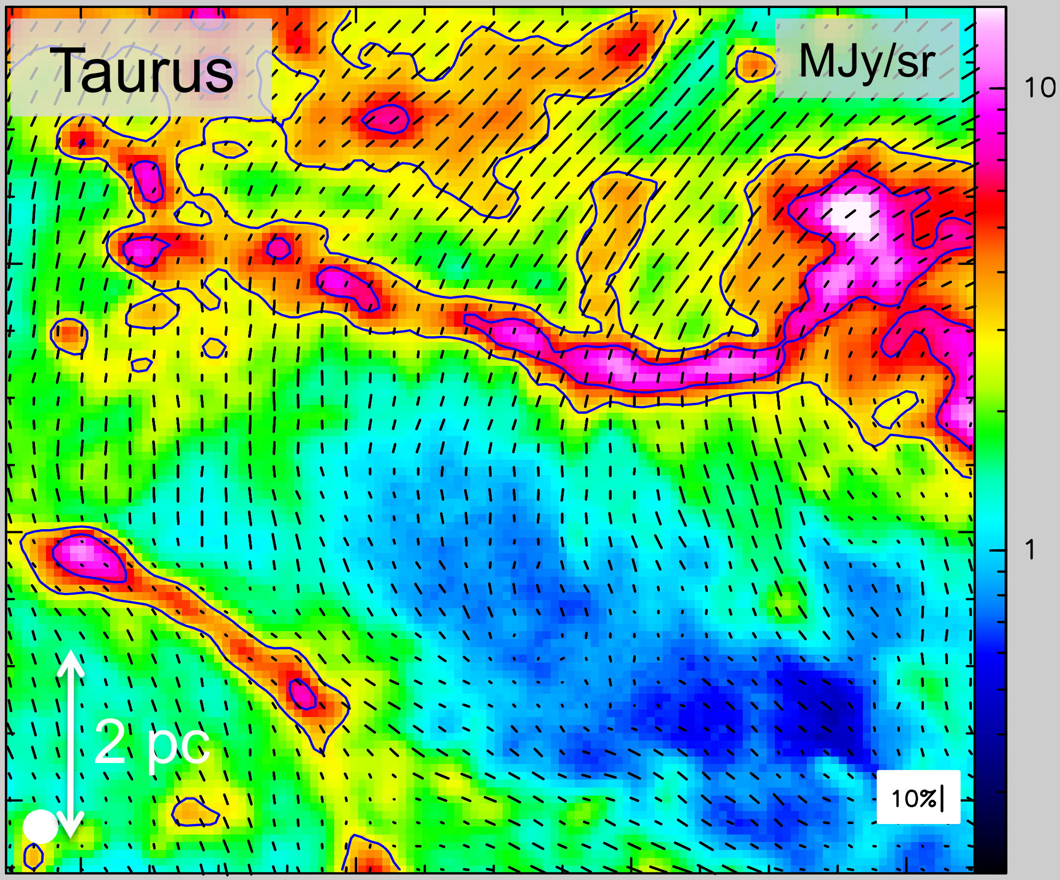



Total intensity at 353 GHz, with plane-of-the-sky magnetic field ($B_{POS}$) orientation (segments with normalized length)

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

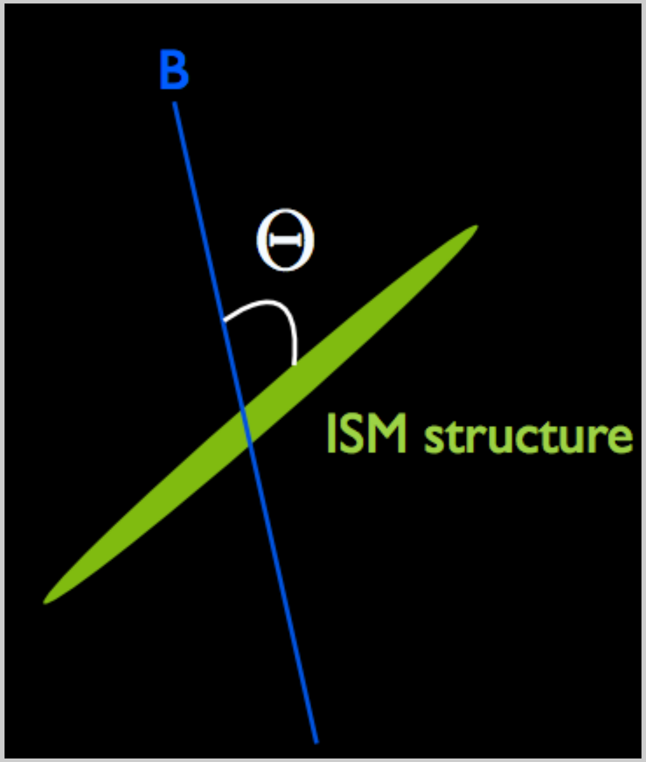
In molecular clouds, high column density structures/filaments appear to be perpendicular to the local $\boldsymbol{B}_{\mathrm{POS}}$ , while fainter filaments are parallel to $\boldsymbol{B}_{\mathrm{POS}}$

*Planck* XXXV 2015 (1502.04123), XXXII 2014 (1409.6728)




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

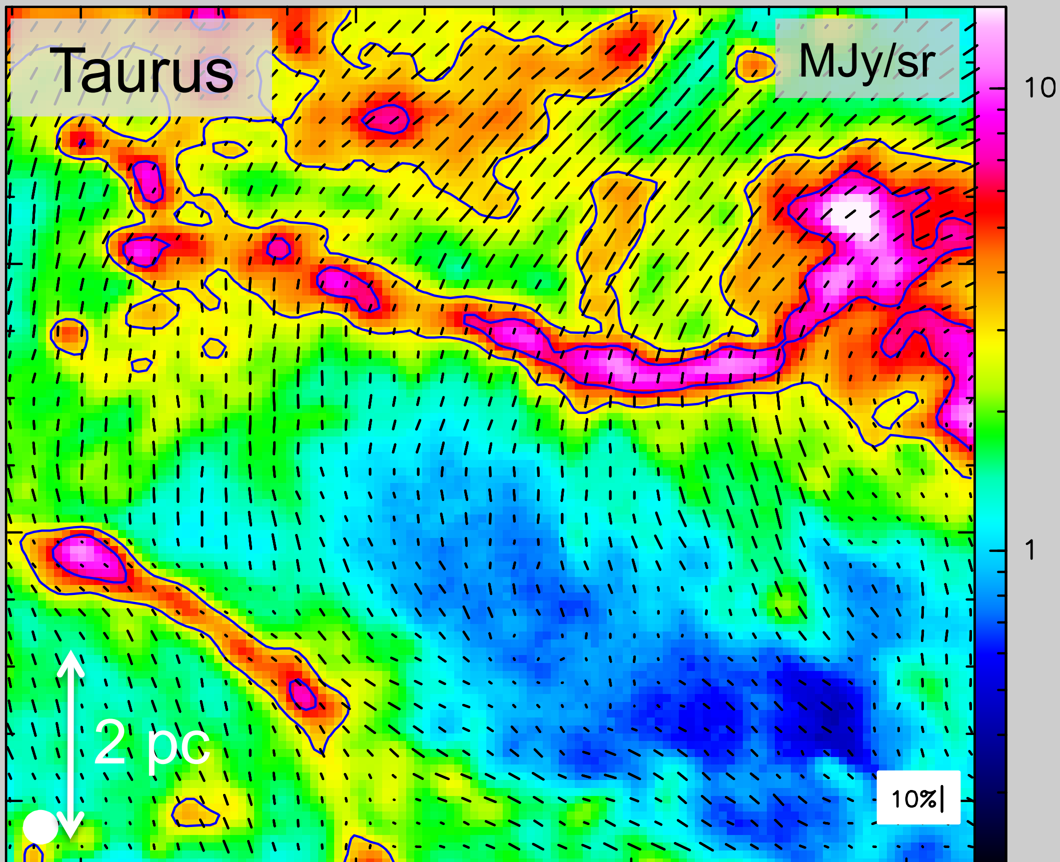
Relative orientation between the angle of $\boldsymbol{B}_{\mathrm{POS}}$ and intensity structures on the plane of the sky



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

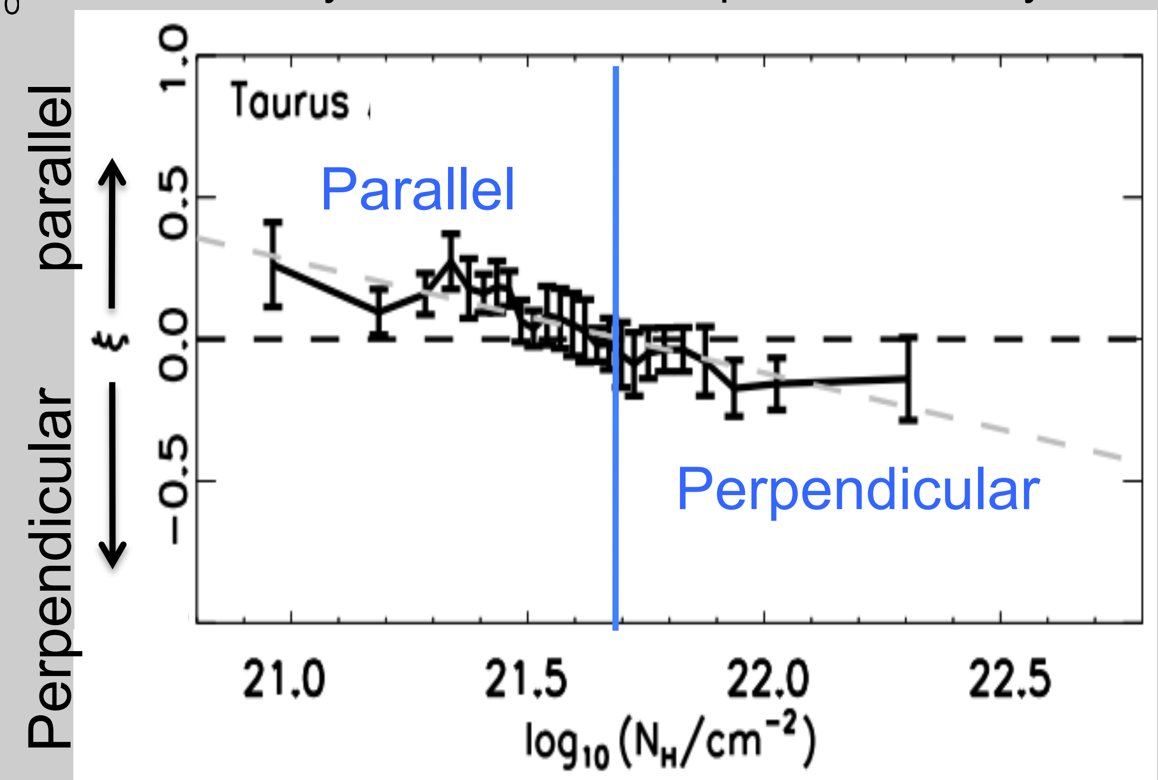
In molecular clouds, high column density structures/filaments appear to be perpendicular to the local $\boldsymbol{B}_{\mathrm{POS}}$ , while fainter filaments are parallel to $\boldsymbol{B}_{\mathrm{POS}}$

*Planck* XXXV 2015 (1502.04123), XXXII 2014 (1409.6728)




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

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




This trend is also observed in ten other clouds of the Gould Belt

*Planck* XXXV 2015 (1502.04123)

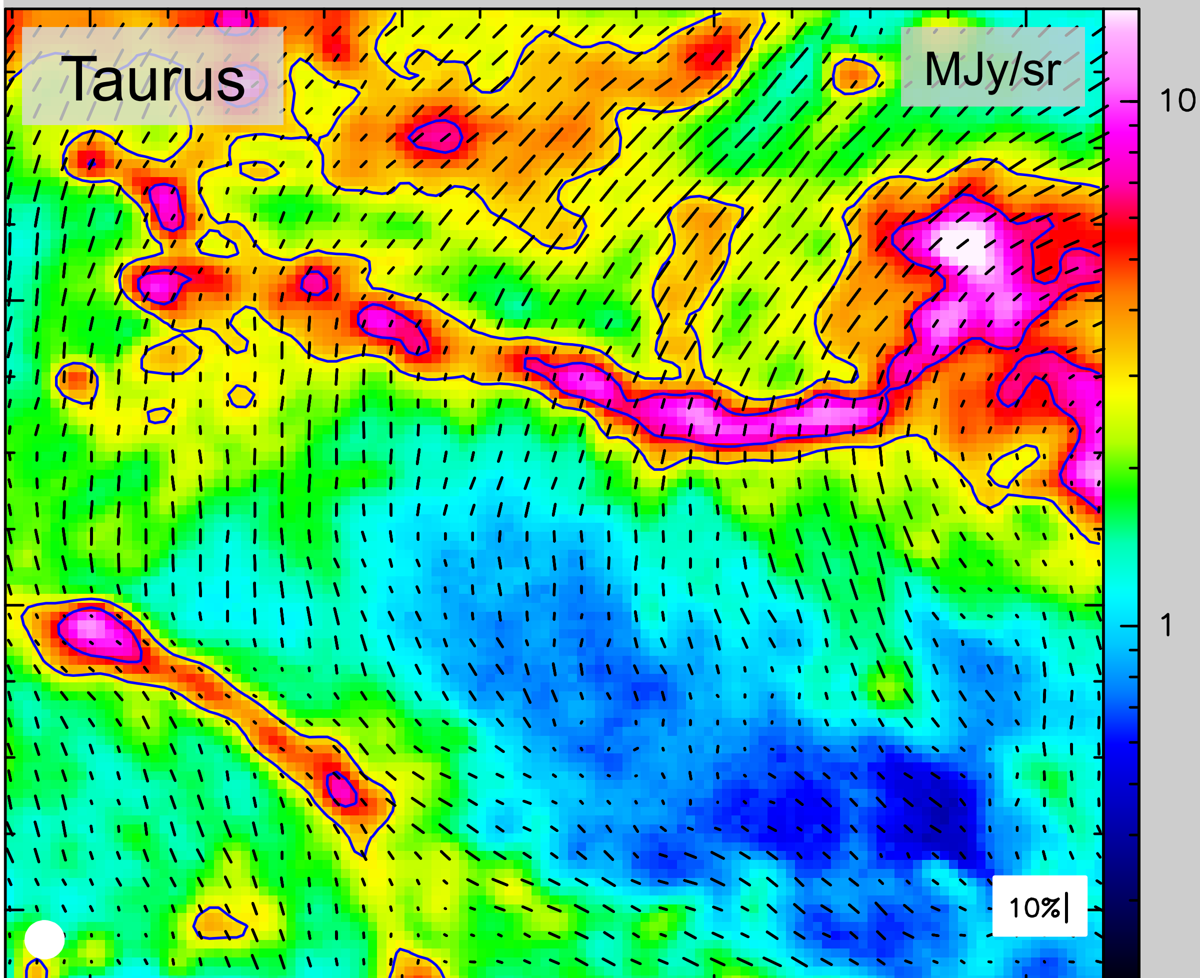
# Ordered magnetic field structure in molecular clouds

The observations suggest that, at the scales probed by *Planck*, the magnetic field is dynamically important in the formation of structures/filaments

*Planck* XXXII 2014 (1409.6728), XXXV 2015 (1502.04123)

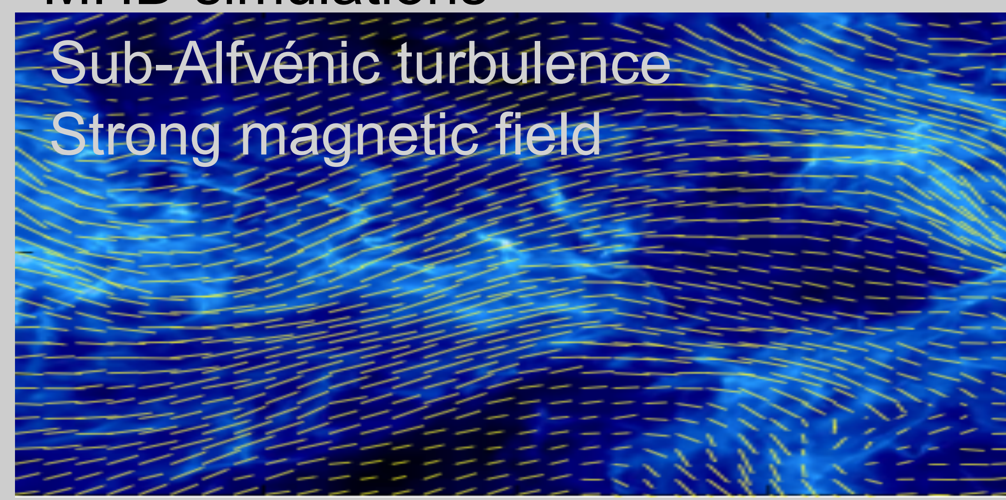
Comparison with MHD numerical simulations (e.g., Falceta-Gonçalves et al. 2008, Soler et al. 2013) and with estimates of field strength from Chandrasekhar-Fermi method (e.g., Chapman et al. 2011)

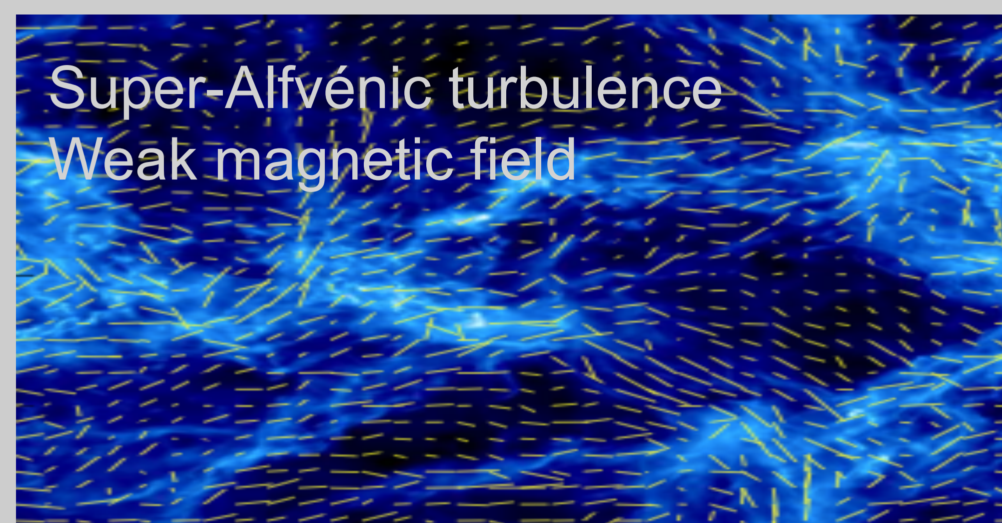
*Planck* observations




MHD simulations

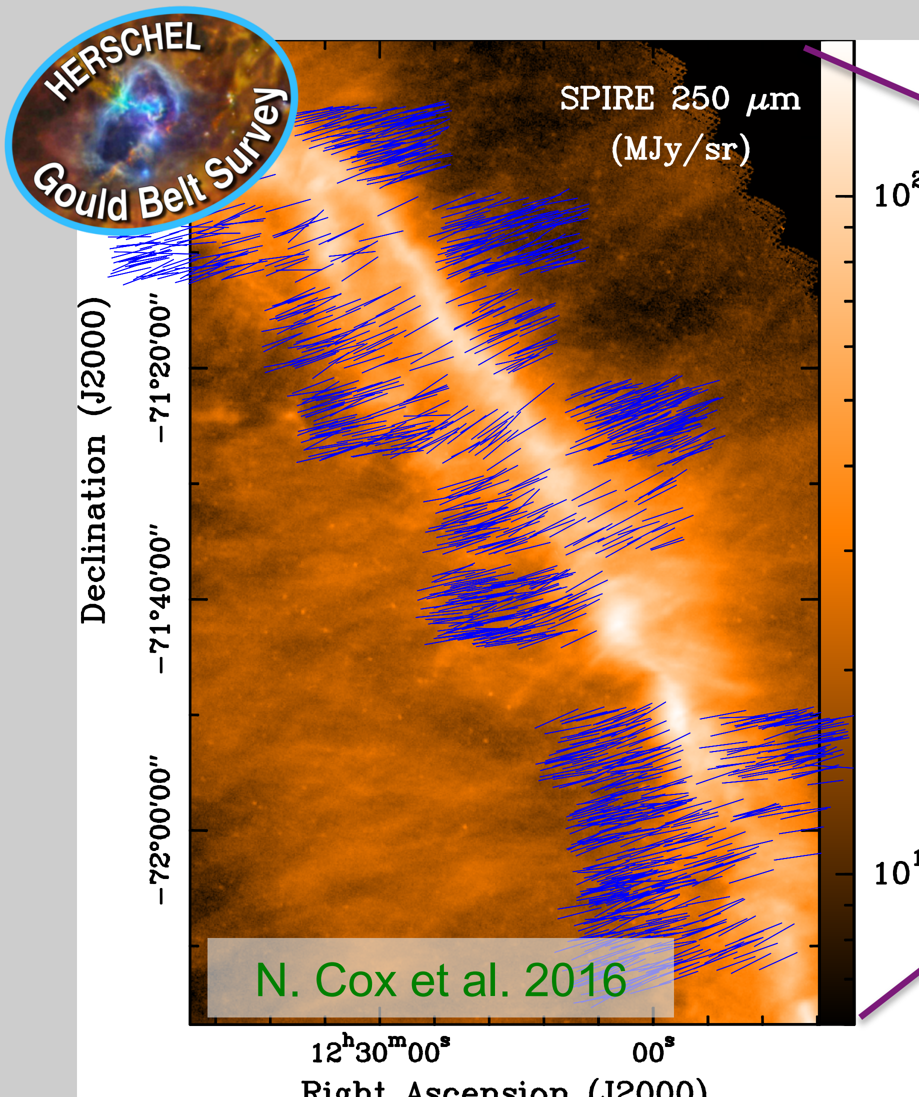
Soler et al. 2013



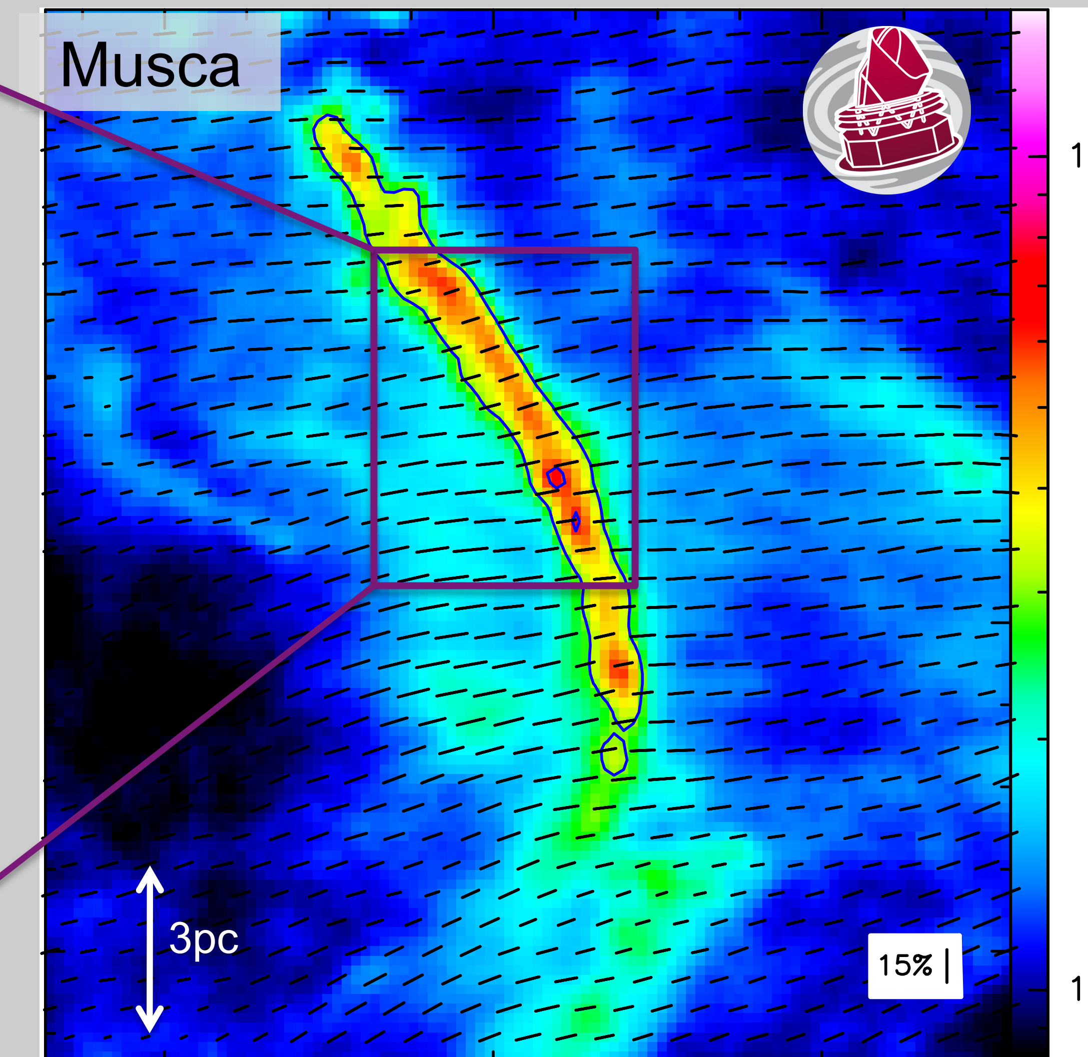



## Plane of the sky magnetic field orientation perpendicular to the long axis of high column density filaments

## Suggesting filament formation from matter flow along magnetic field lines?




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

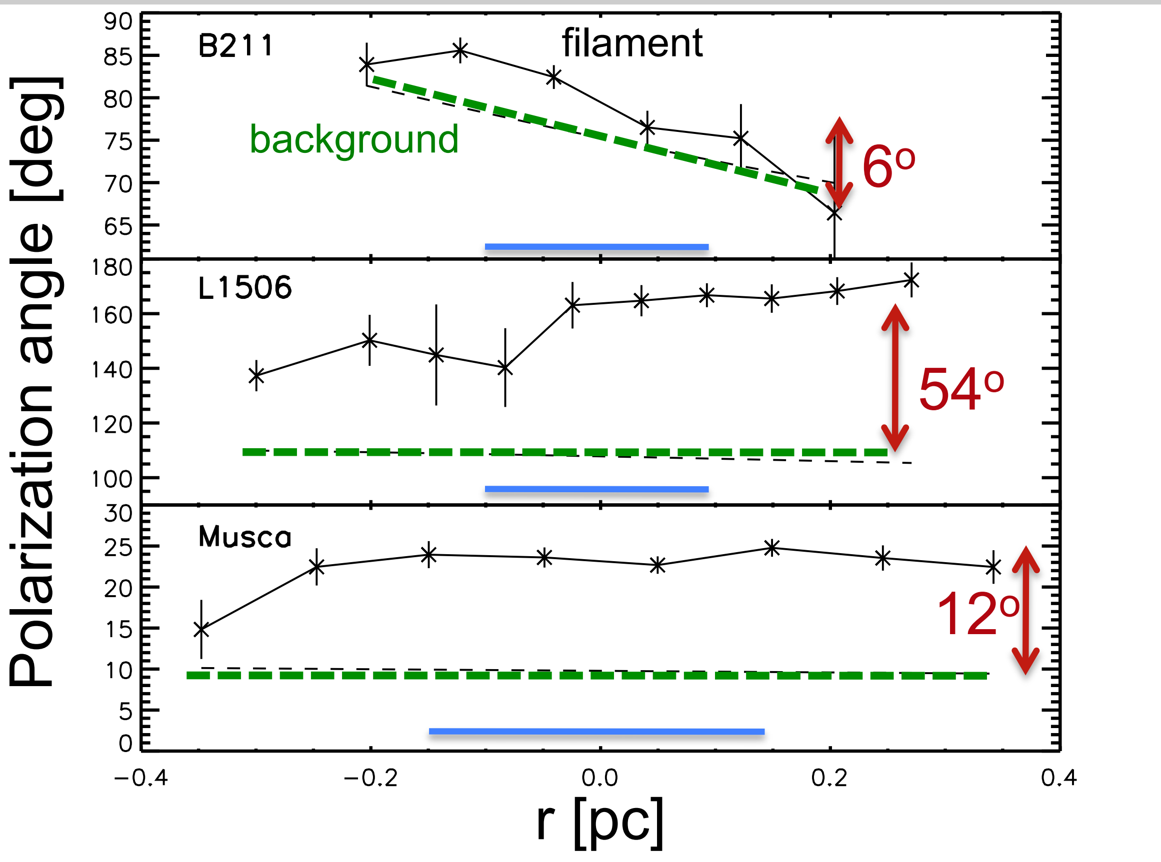


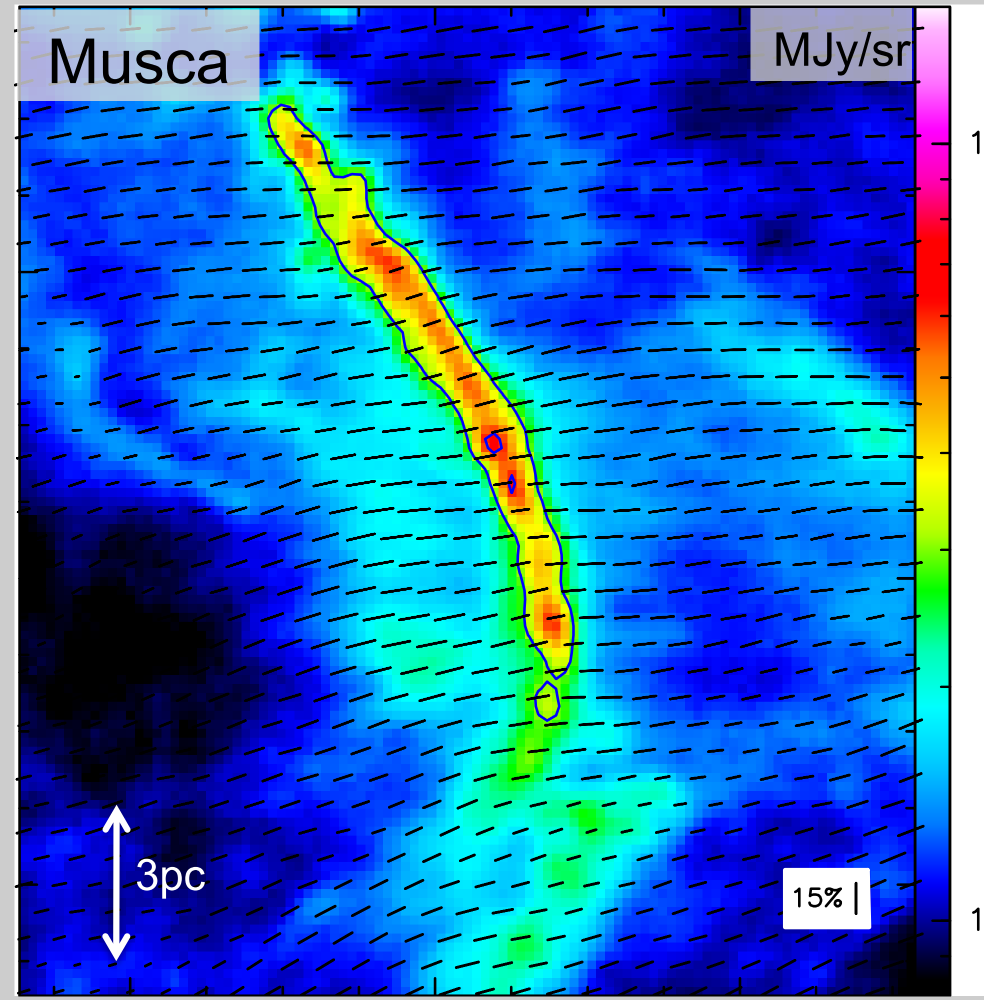

*Planck* total intensity at 353GHz (850μm) in MJy/sr
Segments: $\boldsymbol{B}_{POS}$ length ~ polarization fraction (p) (10' resolution) *Planck* XXXIII 2016 (arXiv:1411.2271)

# Variation of the polarization angle (i.e., orientation of $\boldsymbol{B}_{POS}$) from the parent cloud to the filament

*Planck* XXXIII 2015 (arXiv:1411.2271)

Polarization angle across the filaments (perpendicular to the major axis)




Beam: 0.2pc for Taurus, 0.3pc for Musca

Total intensity map at 353GHz (850 μm), Resolution: 5', black segments: orientation of $\boldsymbol{B}_{POS}$, length ~ p, Resolution: 10'

Doris Arzoumanian, 02/05/2017, EAO Seminar, Hilo, Big Island

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

The polarization fraction depends on (Lee & Draine 1985, Hildebrand 1983):

1) Dust properties (shape, size, composition),
2) Grain alignment efficiency with the local magnetic field
3) The structure of the magnetic field

*Planck* XXXIII 2015 (arXiv:1411.2271)

Polarization fraction across the Musca filament

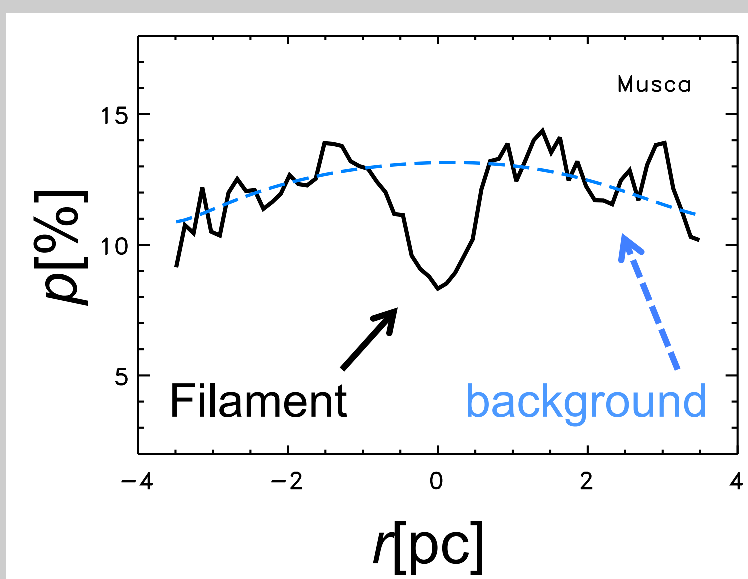
Polarization fraction

$$p = P/I$$

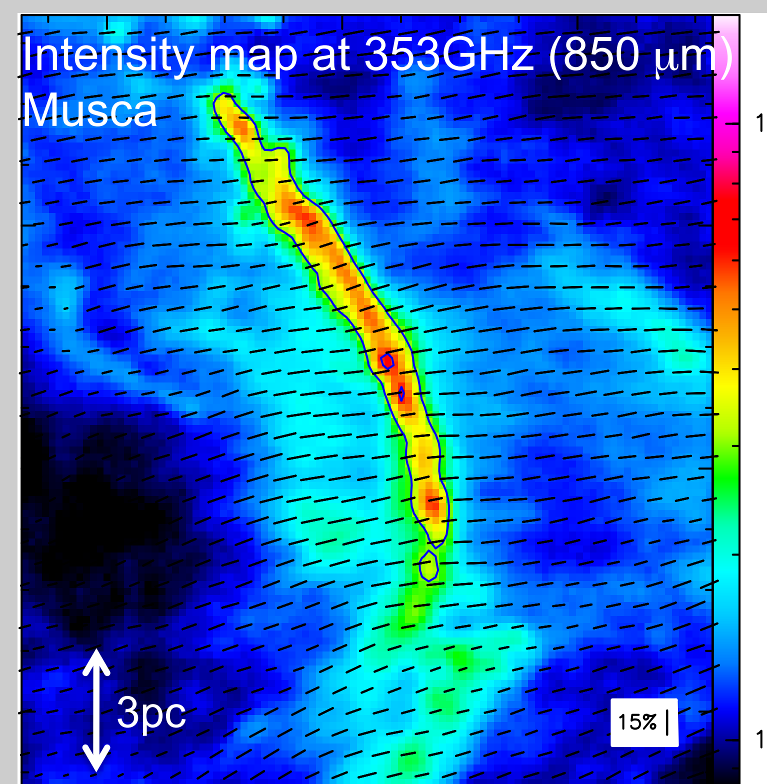
Polarized intensity

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

*I*: total intensity




Resolution of 5', 0.3pc at 200pc



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

The polarization fraction depends on (Lee & Draine 1985, Hildebrand 1983):

1) Dust properties (shape, size, composition),
2) Grain alignment efficiency with the local magnetic field
3) The structure of the magnetic field

The decrease of *p* may be due to the 3D structure of ***B*** in the filaments
>> higher resolution observations and theoretical modelling are needed

Polarization fraction

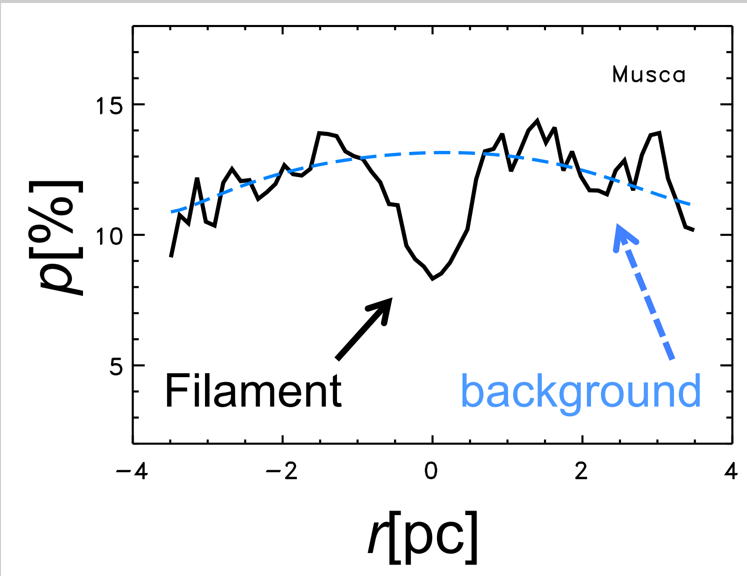
$$p = P/I$$

Polarized intensity

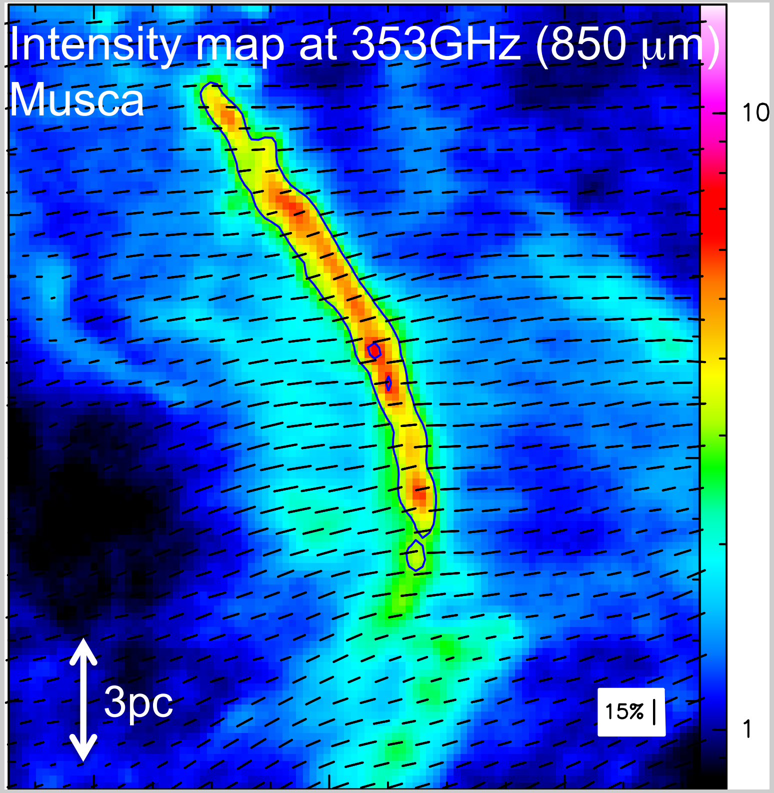
$$P = \sqrt{Q^2 + U^2}$$

***I***: total intensity

*Planck* XXXIII 2015 (arXiv:1411.2271)
Polarization fraction across the Musca filament



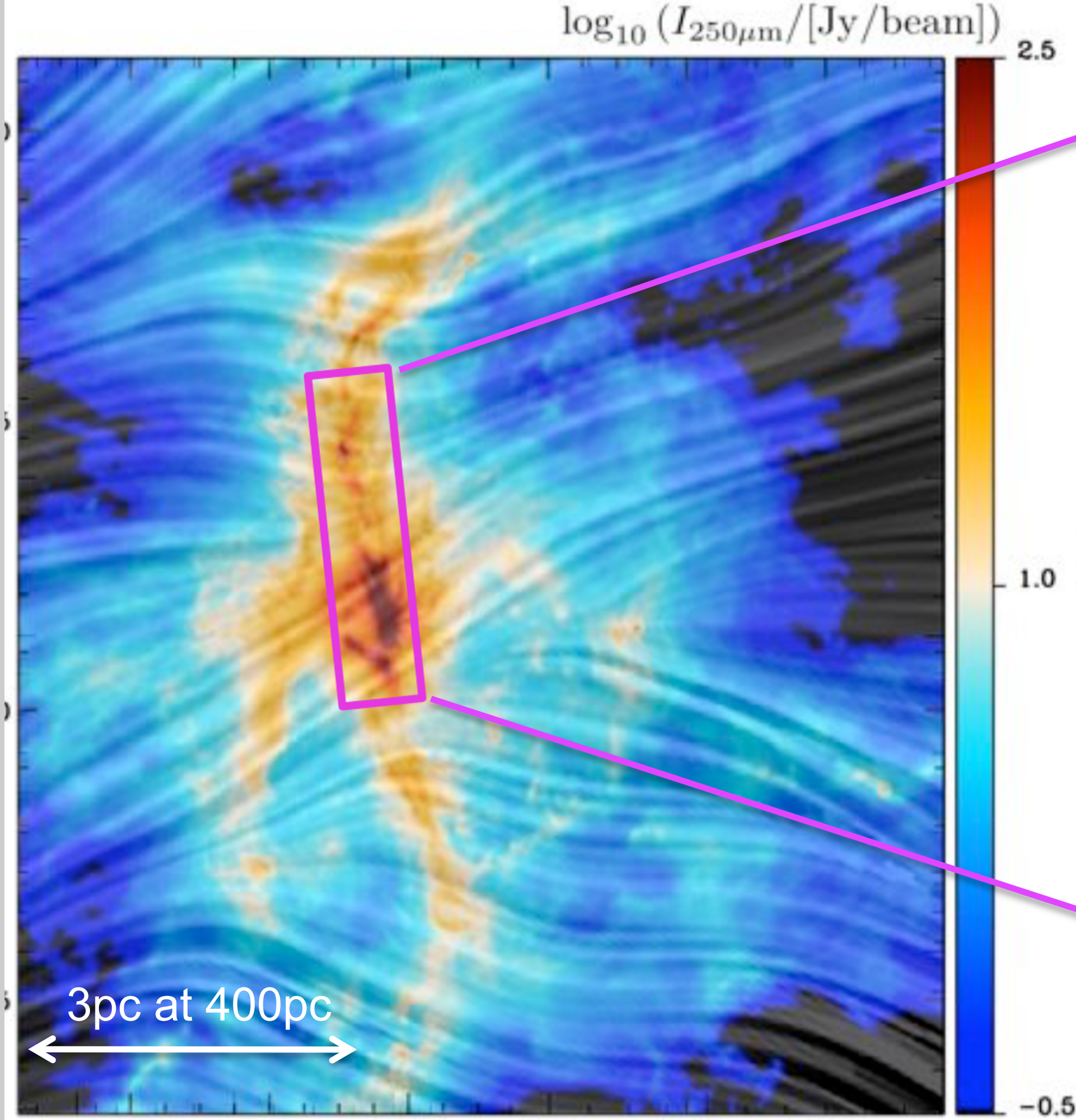

Resolution of 5', 0.3pc at 200pc



# Large and small scale magnetic field structures of the Orion A molecular cloud as inferred from Planck and JCMT/SCUBA2-POL2

## BISTRO project 1st results

Ward-Thompson et al. 2017



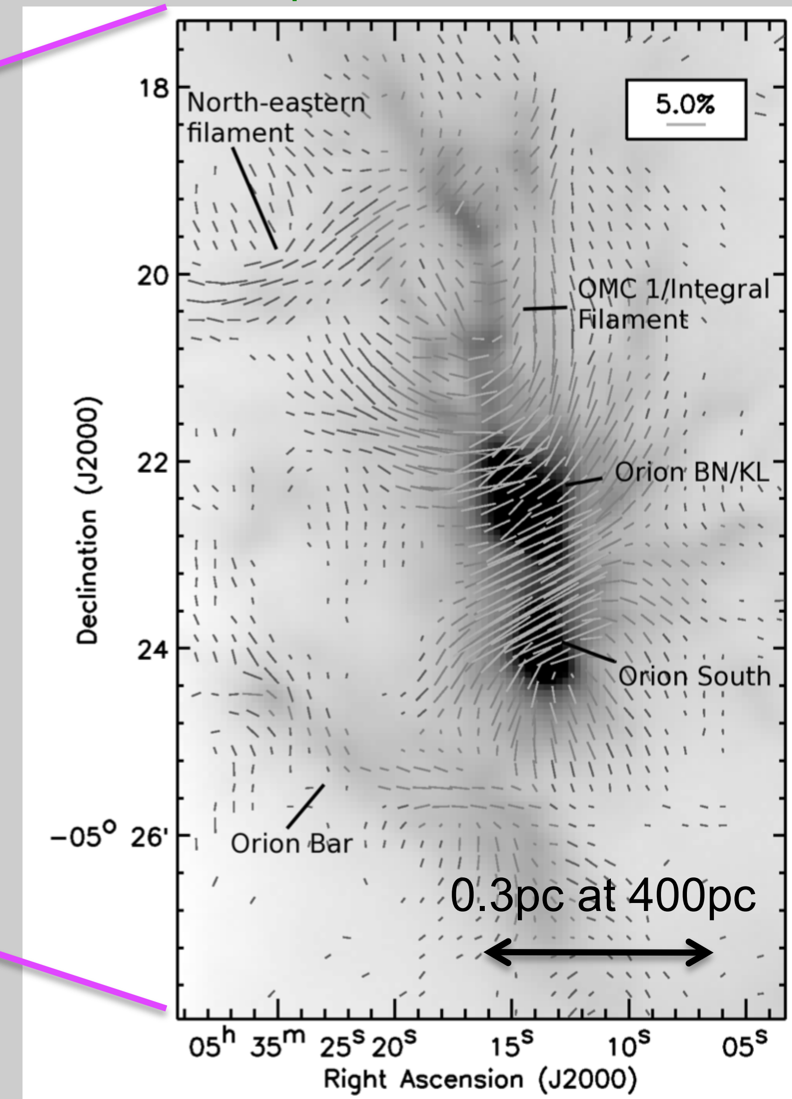




Image: Herschel 250μm (18.2”)
Drapery pattern: large-scale POS B-field orientation from Planck dust polarization at 850μm (5’)

Image: SCUBA2 at 850μm (14.1”)
Segments: small scale POS B-field from POL2 at 850μm (14.1”)

# Summary

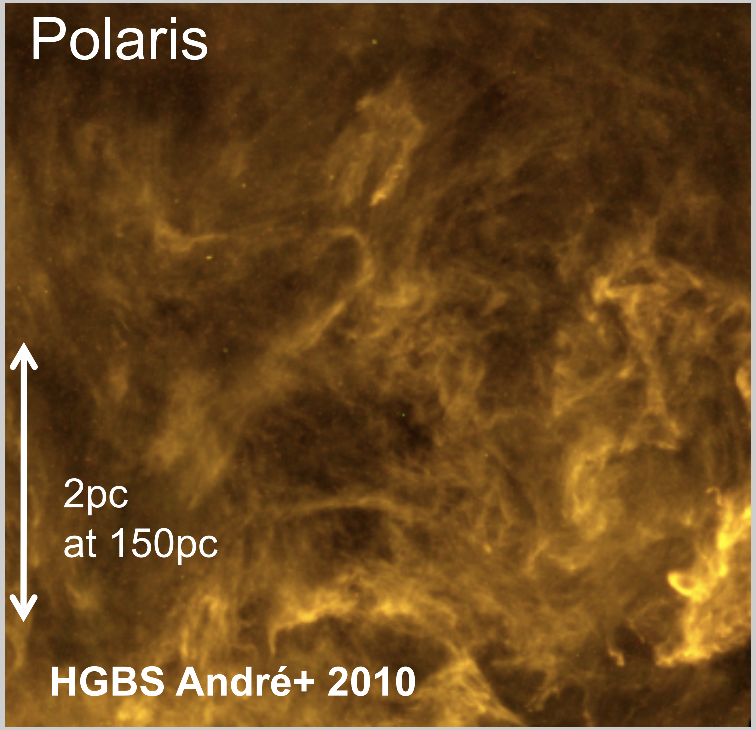
- *Herschel* and *Planck* observations reveal the ubiquity of interstellar filaments in the ISM

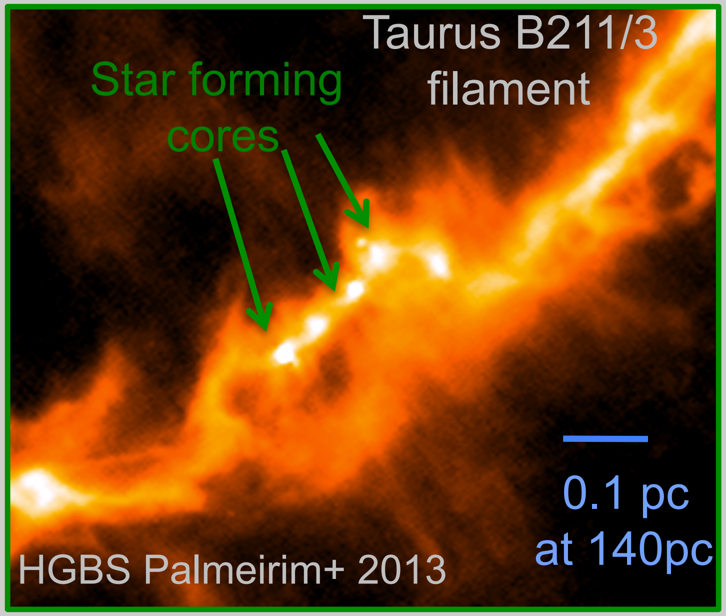
- "Two filament families": subcritical / unbound and supercritical / self-gravitating
  - Common properties: inner width ~ 0.1 pc (origin?)
  - Wide range in length, column density, $M_{line}$

- Filament formation?
  - Prior to any star formation activity (initial conditions for star formation?)
  - Role of the dissipation of MHD interstellar turbulence (origin of the 0.1pc-width?)

- Evolution of self-gravitating filaments?
  - Gravitational fragmentation of supercritical filaments in star forming cores
  - Role of the magnetic field?
  - Velocity field structure of the filaments and their surroundings

- The observed properties set strong constraints on theoretical models



# …and perspective

→ Linking the large scale magnetic field structure (*Planck*) with the small scale structure (ground based single-dish telescopes and interferometers)

New polarization observations:
Single-dish: 30m/NIKA2-pol, JCMT/SCUBA2/POL2 (e.g., BISTRO)
Interferometers: SMA, ALMA, NOEMA
Future space mission(?): SPICA/SAFARI/POL

→ Systematic analysis of the velocity field and magnetic field structures

→ Comparing with numerical simulations of molecular cloud formation and evolution

Large scale $\mathbf{B}_{pos}$ structure from *Planck* polarization observations