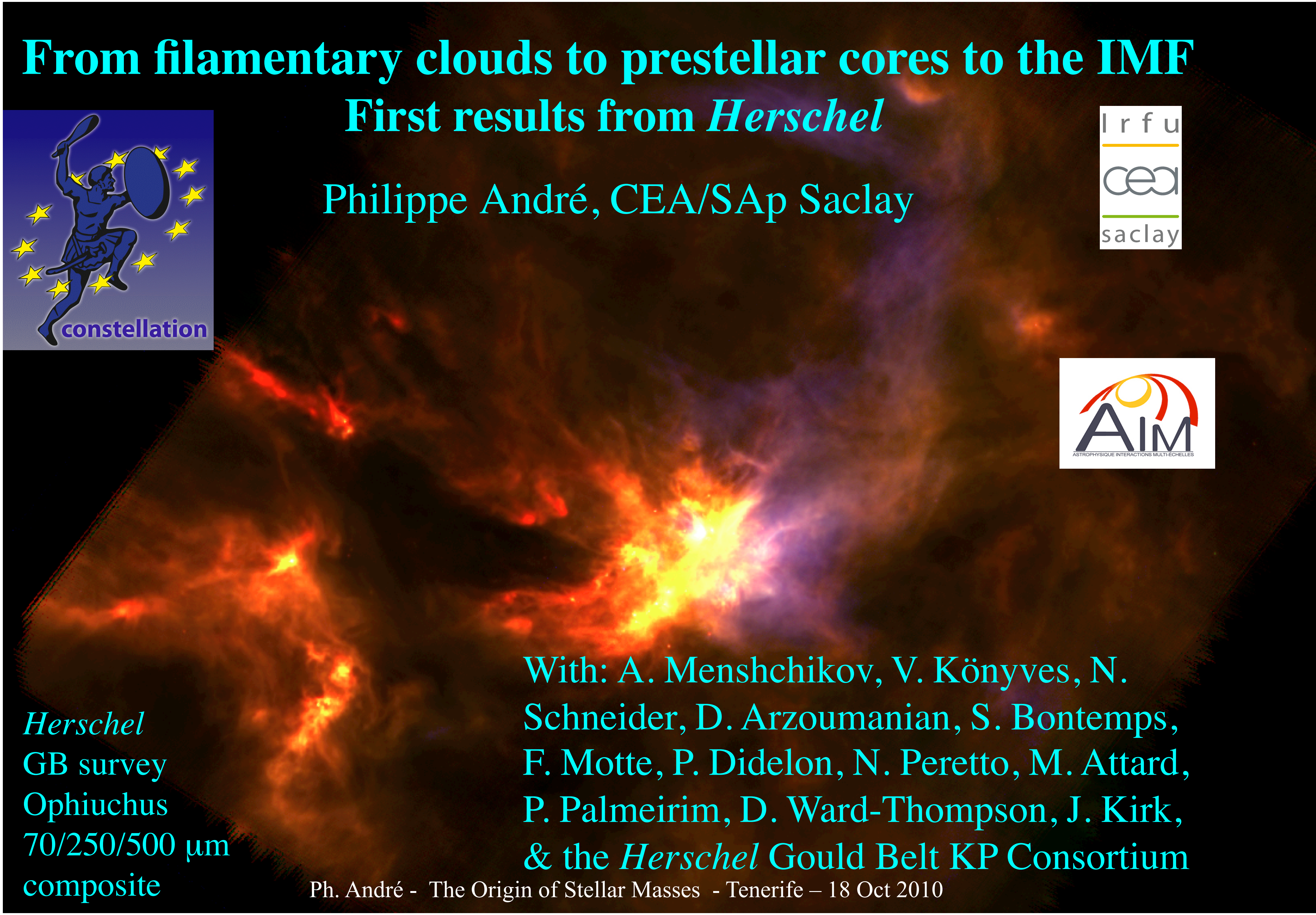
From filamentary clouds to prestellar cores to the IMF

First results from *Herschel*

Philippe André, CEA/SAp Saclay



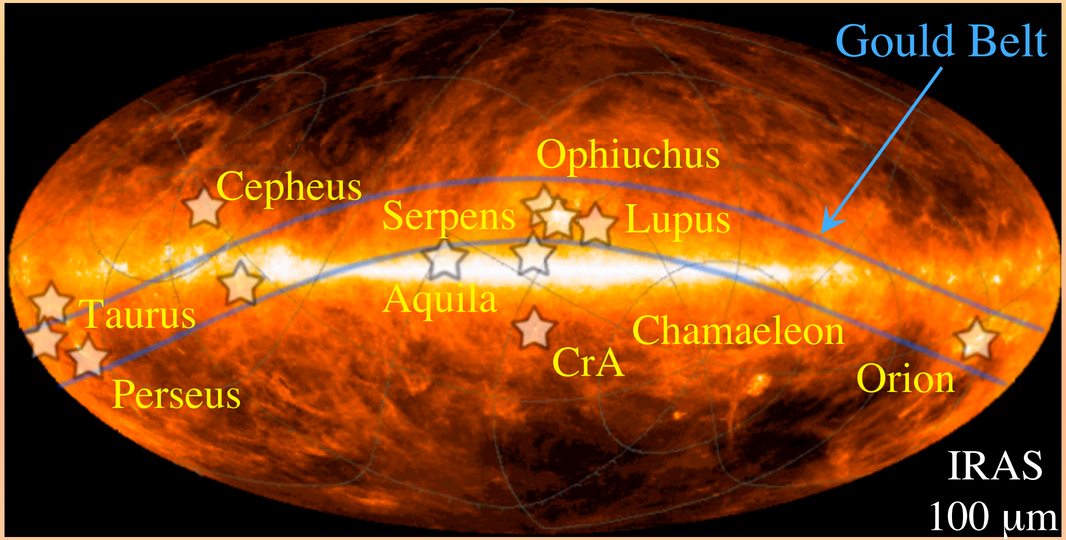
Herschel
GB survey
Ophiuchus
70/250/500 µm
composite

With: A. Menshchikov, V. Könyves, N. Schneider, D. Arzoumanian, S. Bontemps, F. Motte, P. Didelon, N. Peretto, M. Attard, P. Palmeirim, D. Ward-Thompson, J. Kirk, & the *Herschel* Gould Belt KP Consortium

The *Herschel* Gould Belt Survey

SPIRE/PACS 70-500 µm imaging of the bulk of nearby (d < 0.5 kpc) molecular clouds (~ 160 deg^2), mostly located in Gould's Belt.

➢ Complete census of prestellar cores and Class 0 protostars.



~ 15" resolution at λ ~ 200 µm

↔

~ 0.02 pc
< Jeans length
@ d = 300 pc

Motivation: Key issues on the early stages of star formation

- Nature of the relationship between the CMF and the IMF ?
- What generates prestellar cores and what governs their evolution to protostars and proto-brown dwarfs ?

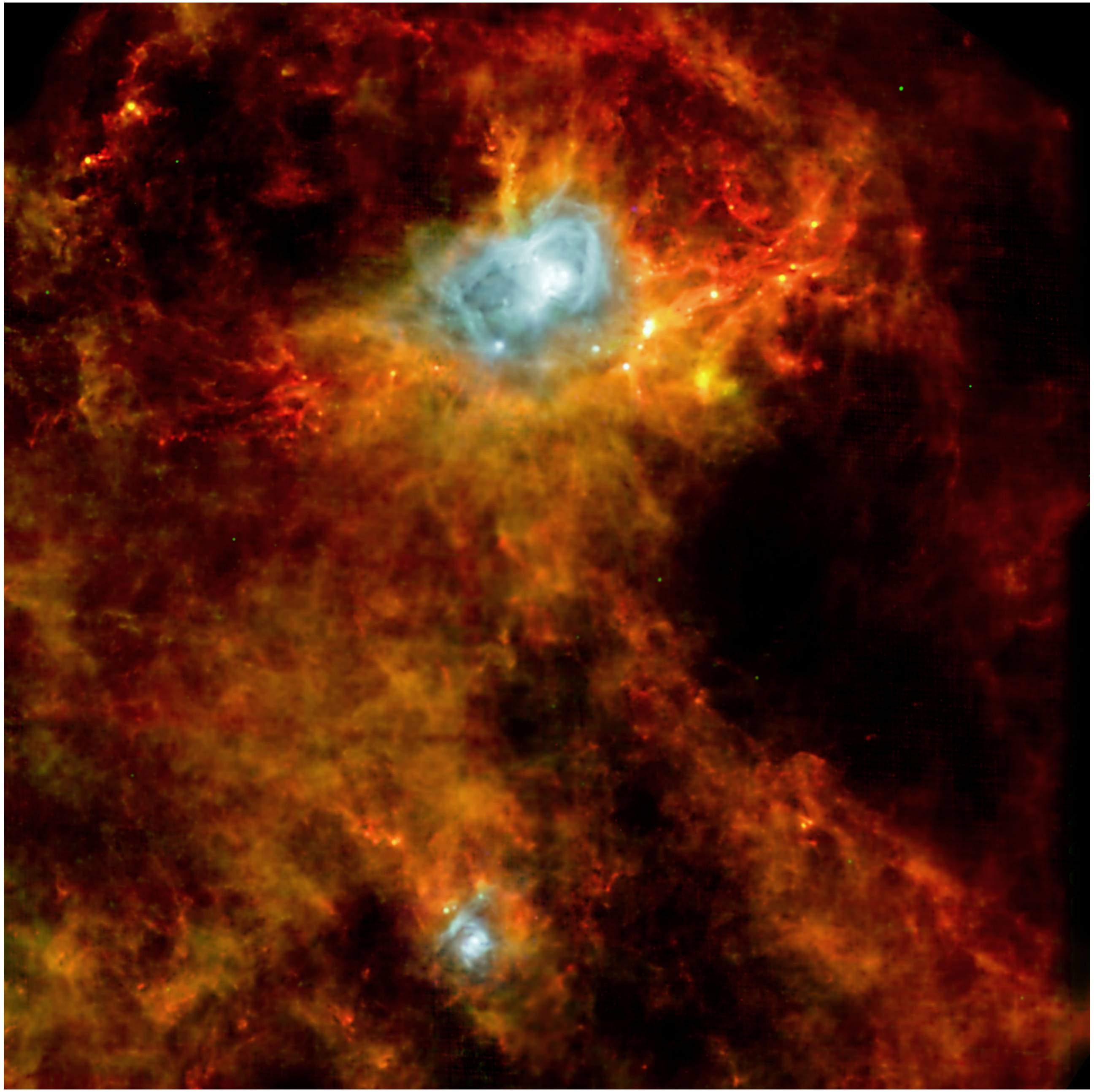
Outline:

- First images from the *Herschel* Gould Belt survey
- Preliminary results on cores (e.g. CMF vs. IMF)
- The role of filaments in the core formation process
- Implications/Speculations

Herschel
GB survey
L1688
70/250/500 μm
composite

http://gouldbelt-herschel.cea.fr/

“First images” from the Gould Belt Survey



1) **Aquila Rift star-forming cloud** (d ~ 260 pc)

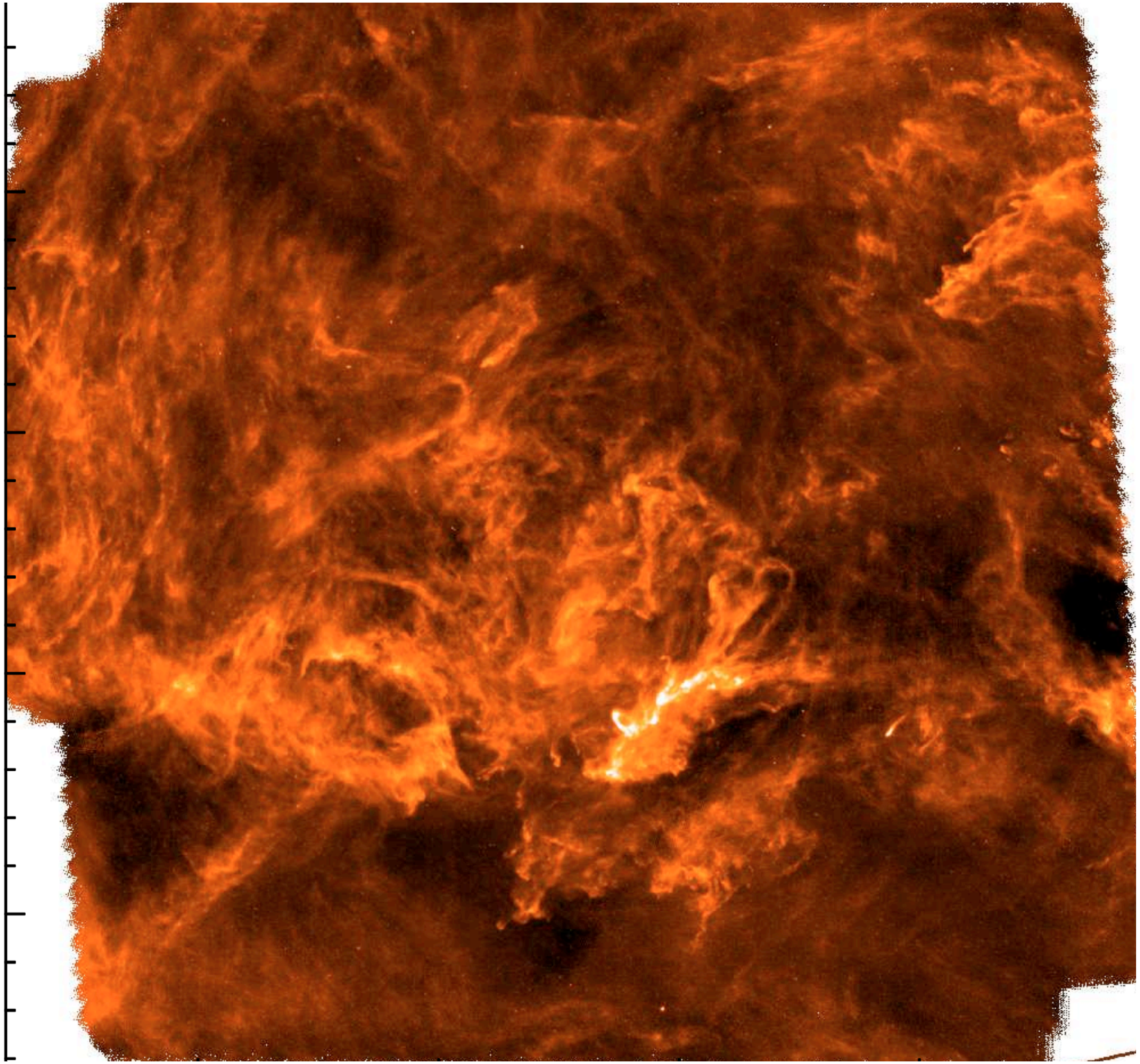
cf. http://oshi.esa.int

Red : SPIRE 500 μm
Green : SPIRE 160 μm
Blue : PACS 70 μm

~ 3.3 deg x 3.3 deg field

André et al. 2010
Könyves et al. 2010
Bontemps et al. 2010
A&A *Herschel* special issue

"First images" from the Gould Belt Survey



PACS/SPIRE // mode
SPIRE 250 μm image

2) Polaris flare translucent cloud
(d ~ 150 pc)

~ 5500 $M_{\odot}$ (CO+HI)
Heithausen & Thaddeus '90

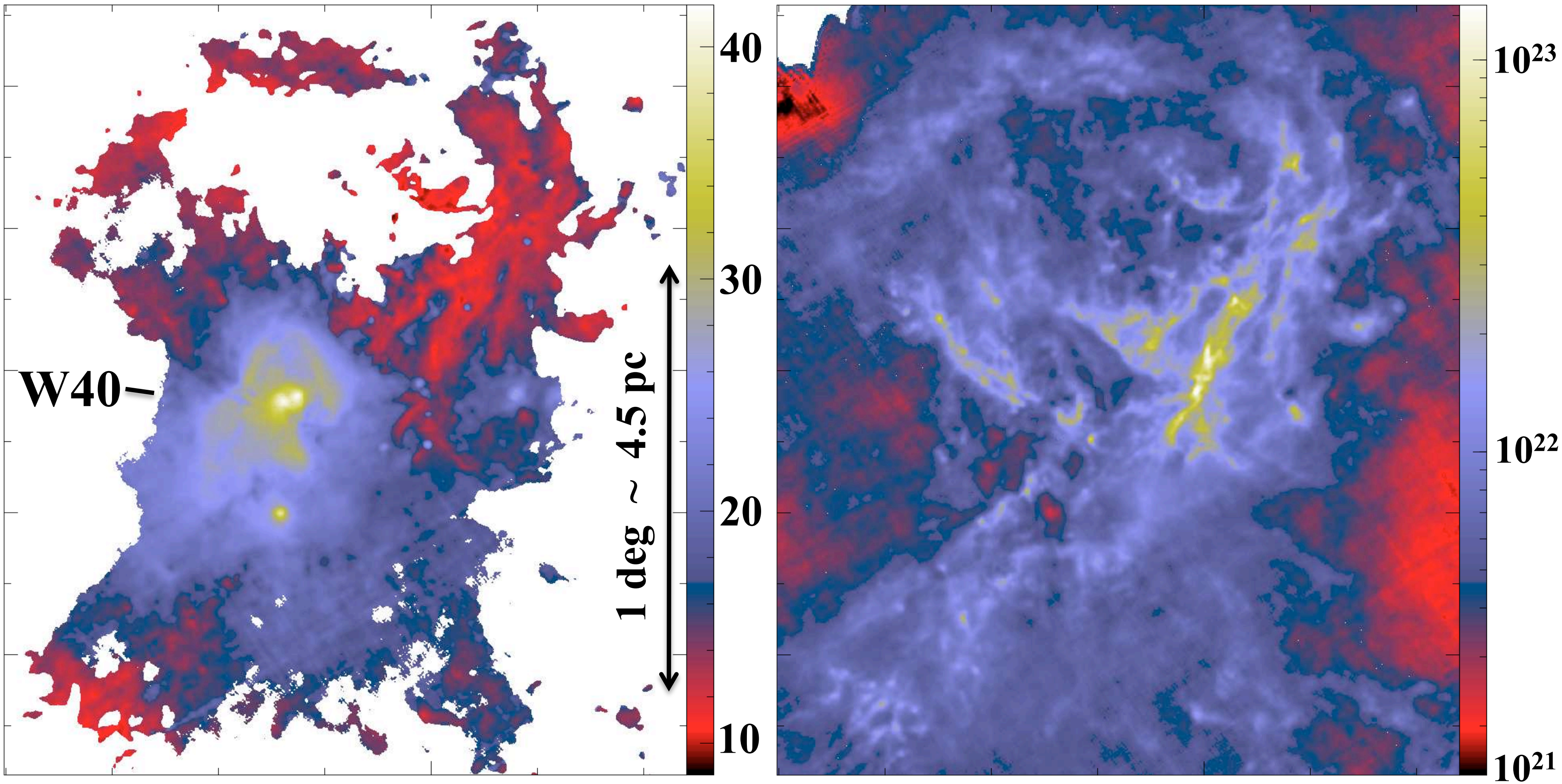
~ 13 deg^2 field

Miville-Deschênes et al. 2010
Ward-Thompson et al. 2010
Men'shchikov et al. 2010
A&A special issue

Revealing the structure of one of the nearest infrared dark clouds (Aquila Main: d ~ 260 pc)

Herschel (SPIRE+PACS)
Dust temperature map (K)

Herschel (SPIRE+PACS)
Column density map (H_2/cm^2)

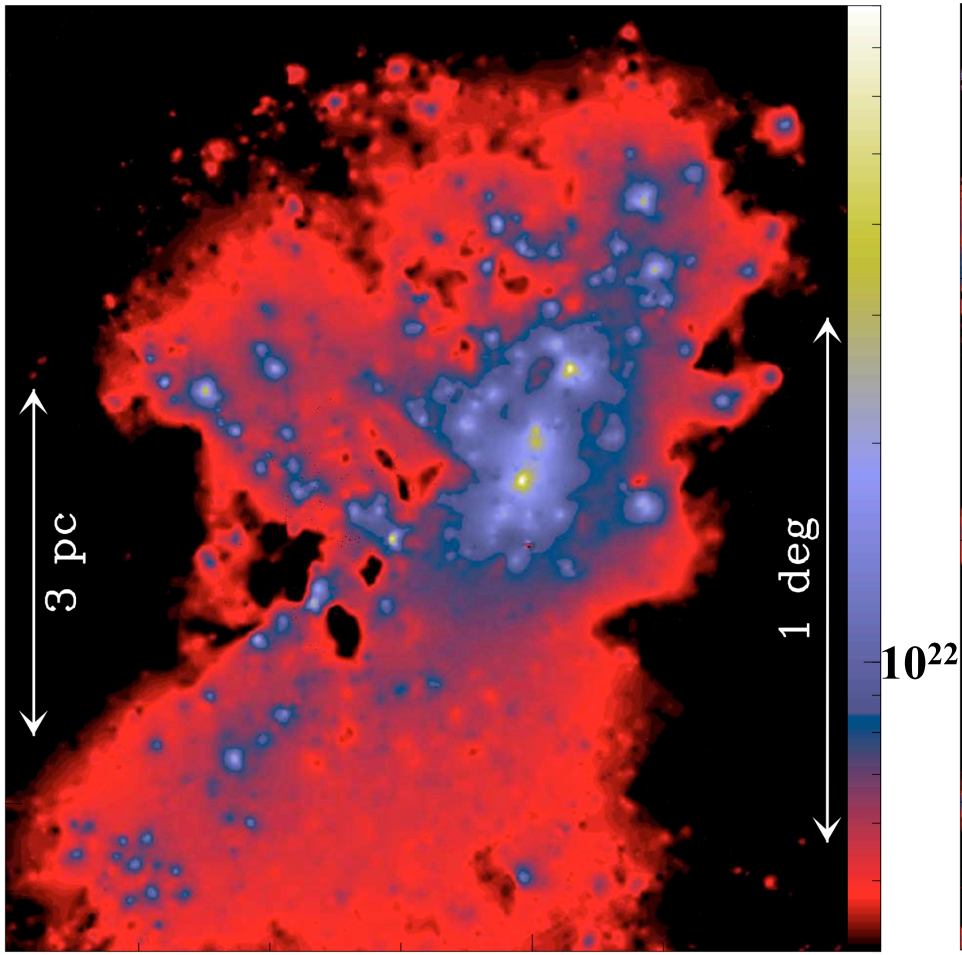


Morphological Component Analysis: Decomposition on wavelets and curvelets

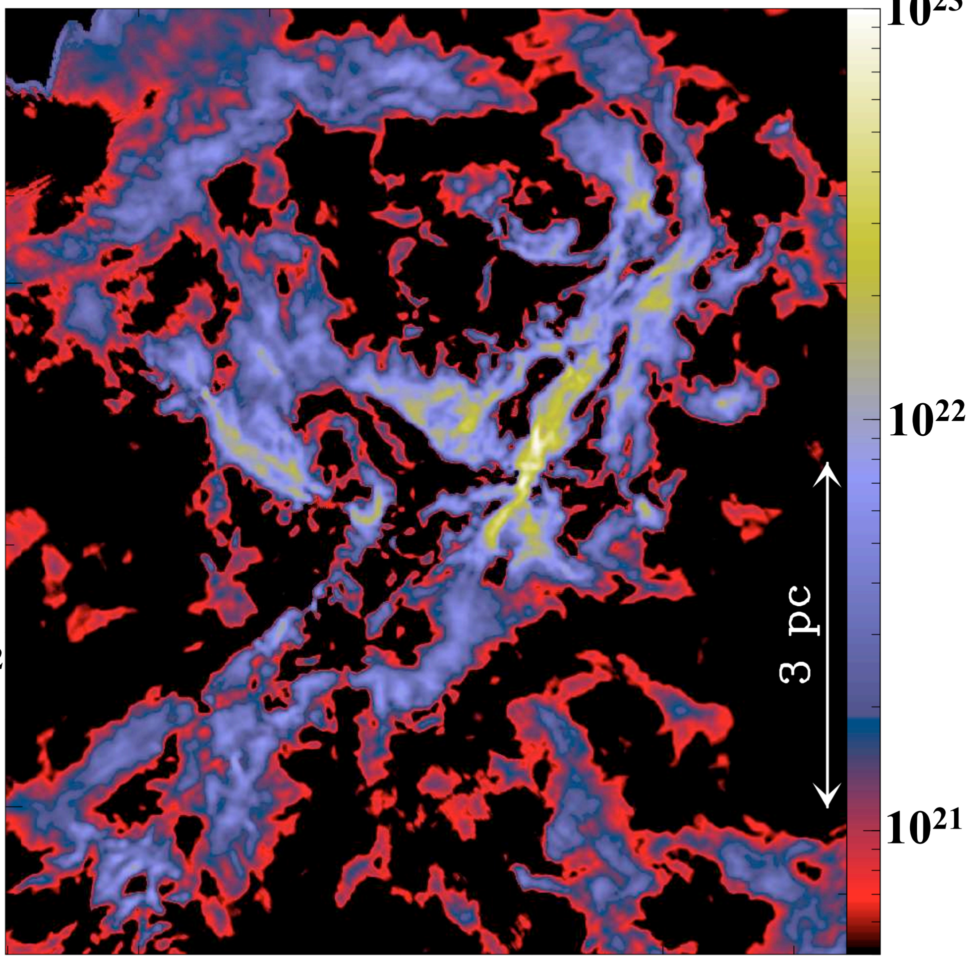
(P. Didelon based on Starck et al. 2003)

Herschel (SPIRE+PACS) Column density map

Wavelet component (H_2/cm^2)



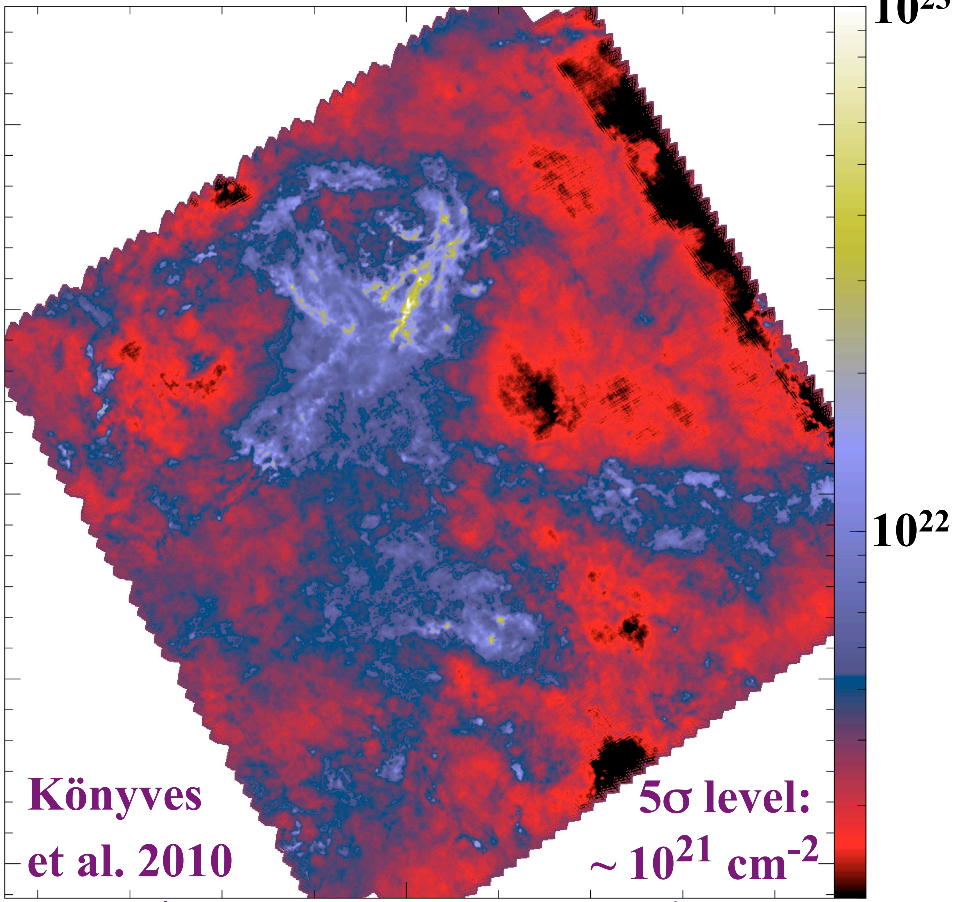
Curvelet component (H_2/cm^2)



Aquila: `Compact' Source Extraction

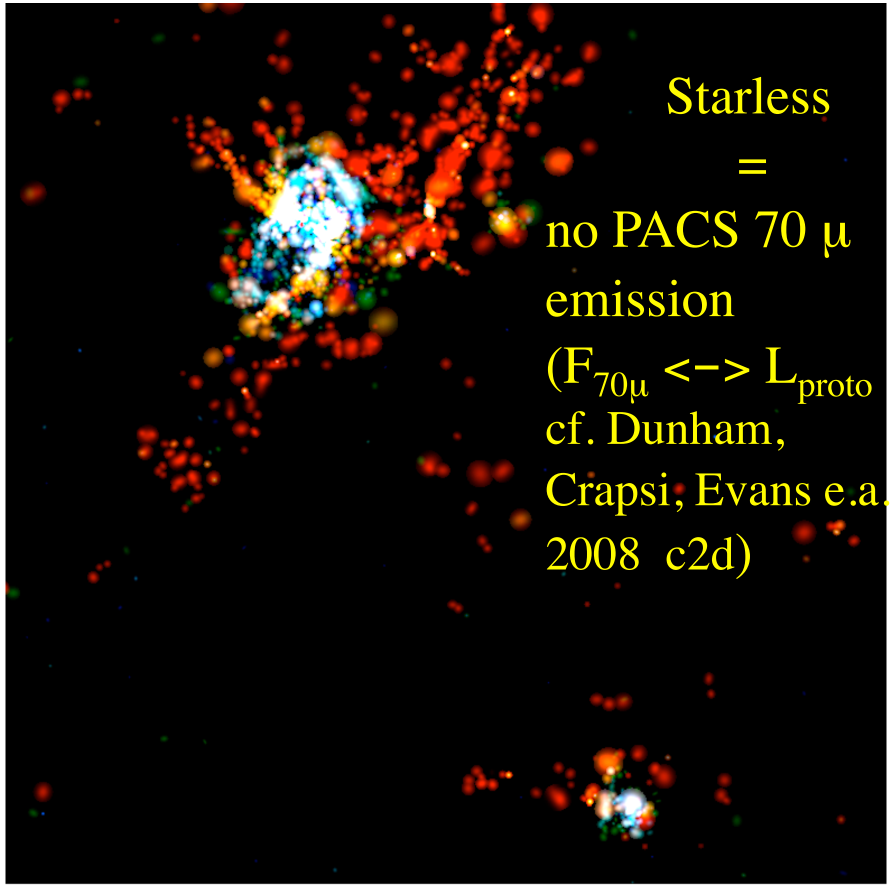
(using "getsources" – A. Menshchikov et al. 2010)

Herschel (SPIRE+PACS)
Aquila entire field: N_{H_2} (cm^{-2})



3 deg ~ 14 pc

Spatial distribution of extracted cores { 541 starless, 201 YSOs }

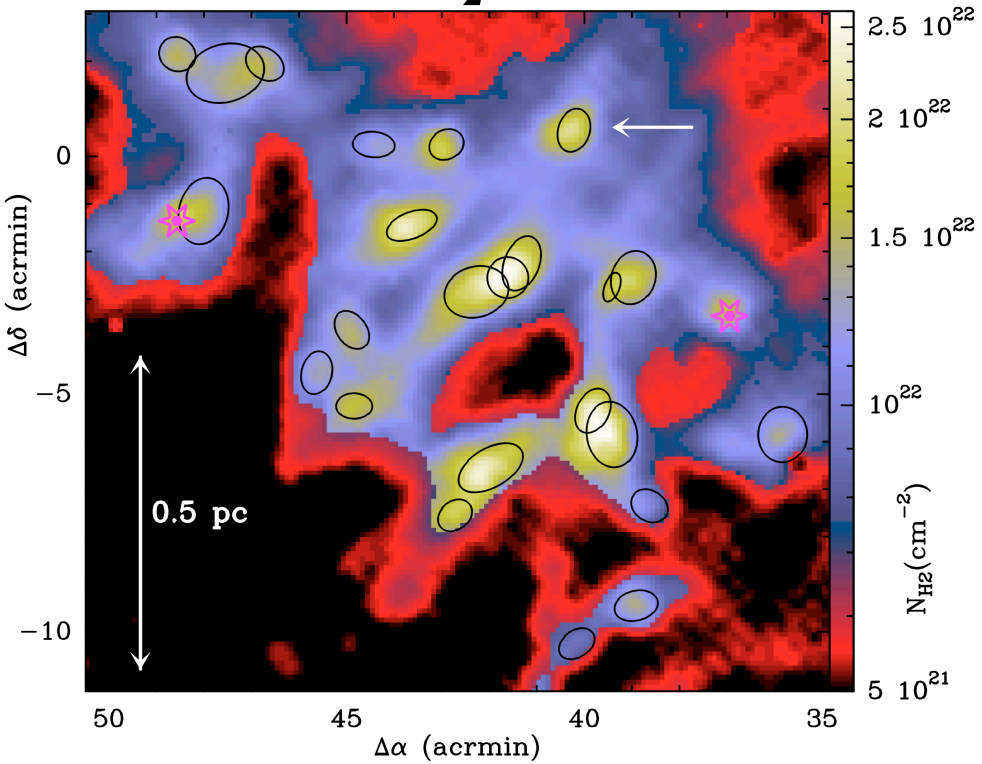


70/160/500 μm composite image

Examples of starless cores in Aquila-East

Core:
- local column density peak
- simple (convex) shape
- no substructure at *Herschel* resol.
- ➢ potential single star-forming entity

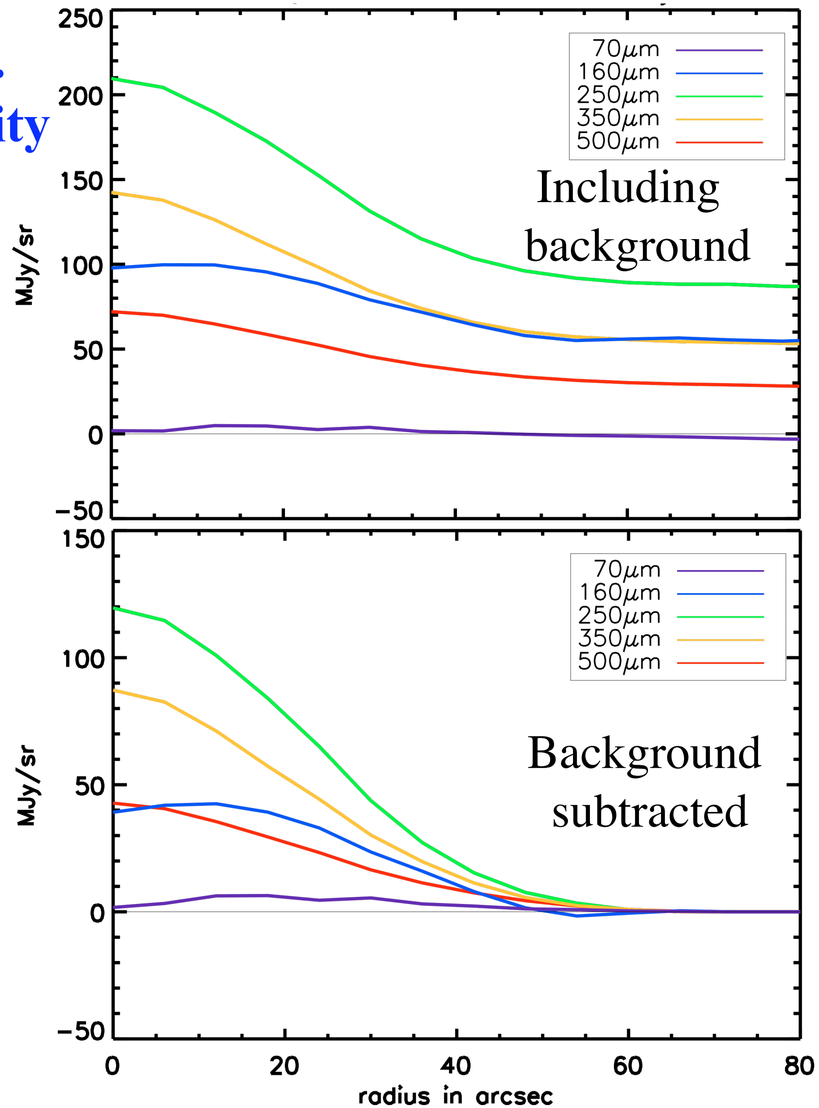
Herschel **N_{H_2} map (cm^{-2})**



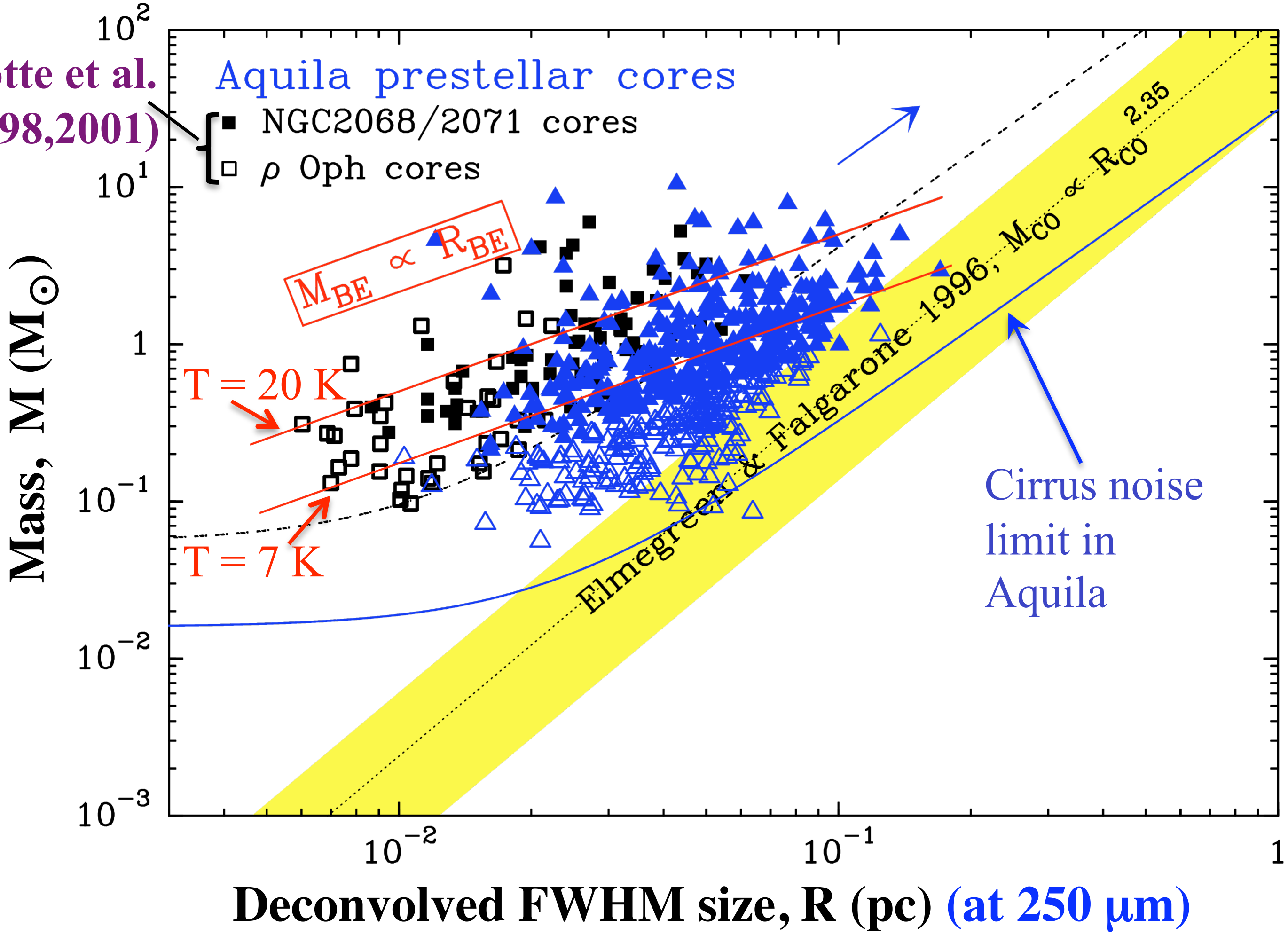
Ellipses: FWHM sizes of 24 starless cores at 250 µm

Könyves et al. 2010, A&A special issue

Radial intensity profiles



Most of the *Herschel* starless cores in Aquila are bound

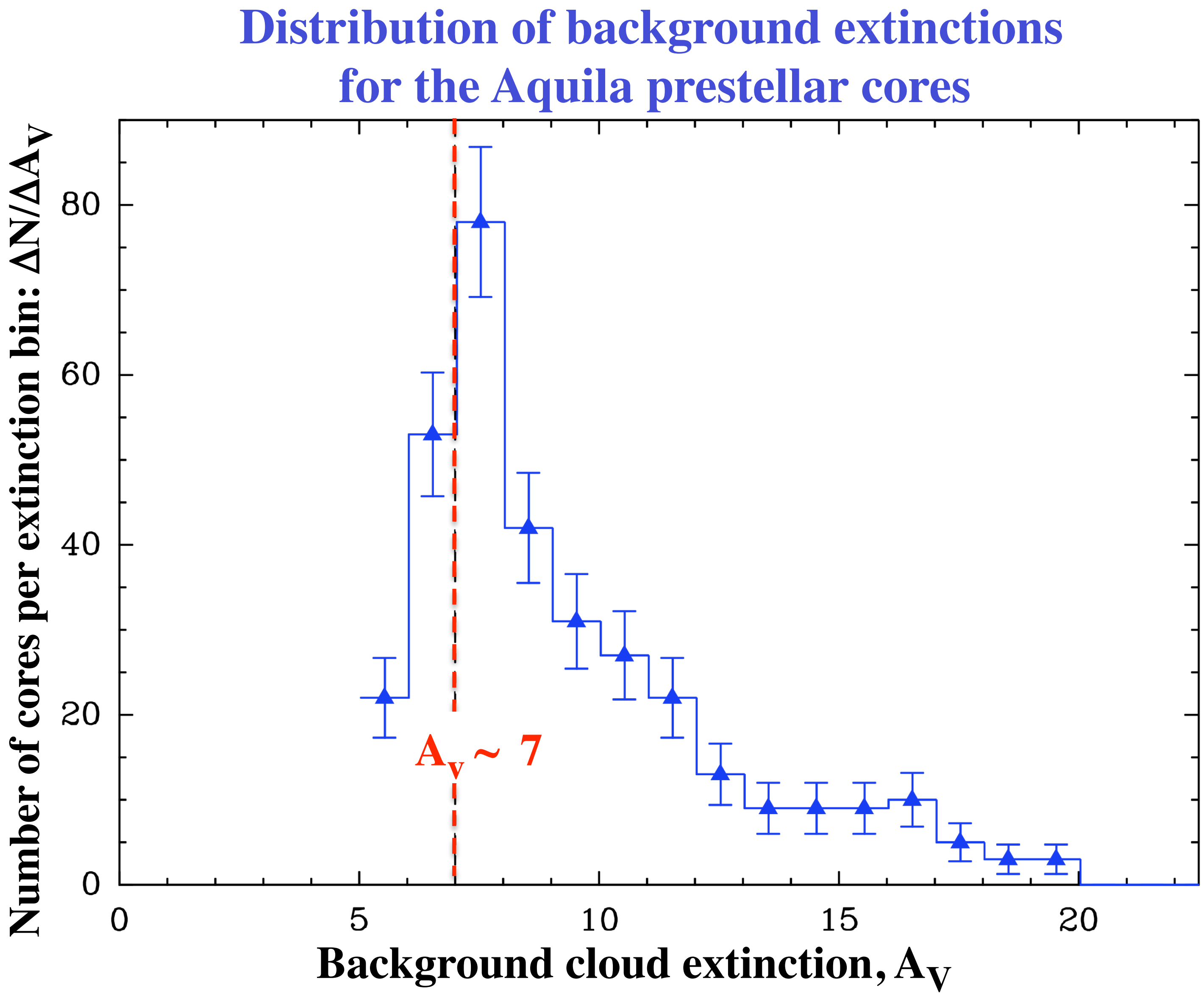


➢ > 60% are likely prestellar in nature

Könyves et al. 2010

➢ **Positions in mass vs. size diagram**, consistent with ~ critical Bonnor-Ebert spheroids: $M_{BE} = 2.4\ R_{BE}\ c_s^2/G$ for T ~ 7-20 K

Confirmation of an extinction “threshold” for the formation of prestellar cores



In Aquila, ~90% of the prestellar cores identified with *Herschel* are found above A_v ~ 7

cf. Onishi et al. 1998 (Taurus)

Johnstone et al. 2004 (Ophiuchus)

H. Kirk et al. 2006 (Perseus)

See also (for YSOs): Heiderman, Evans et al. 2010; Lada et al. 2010

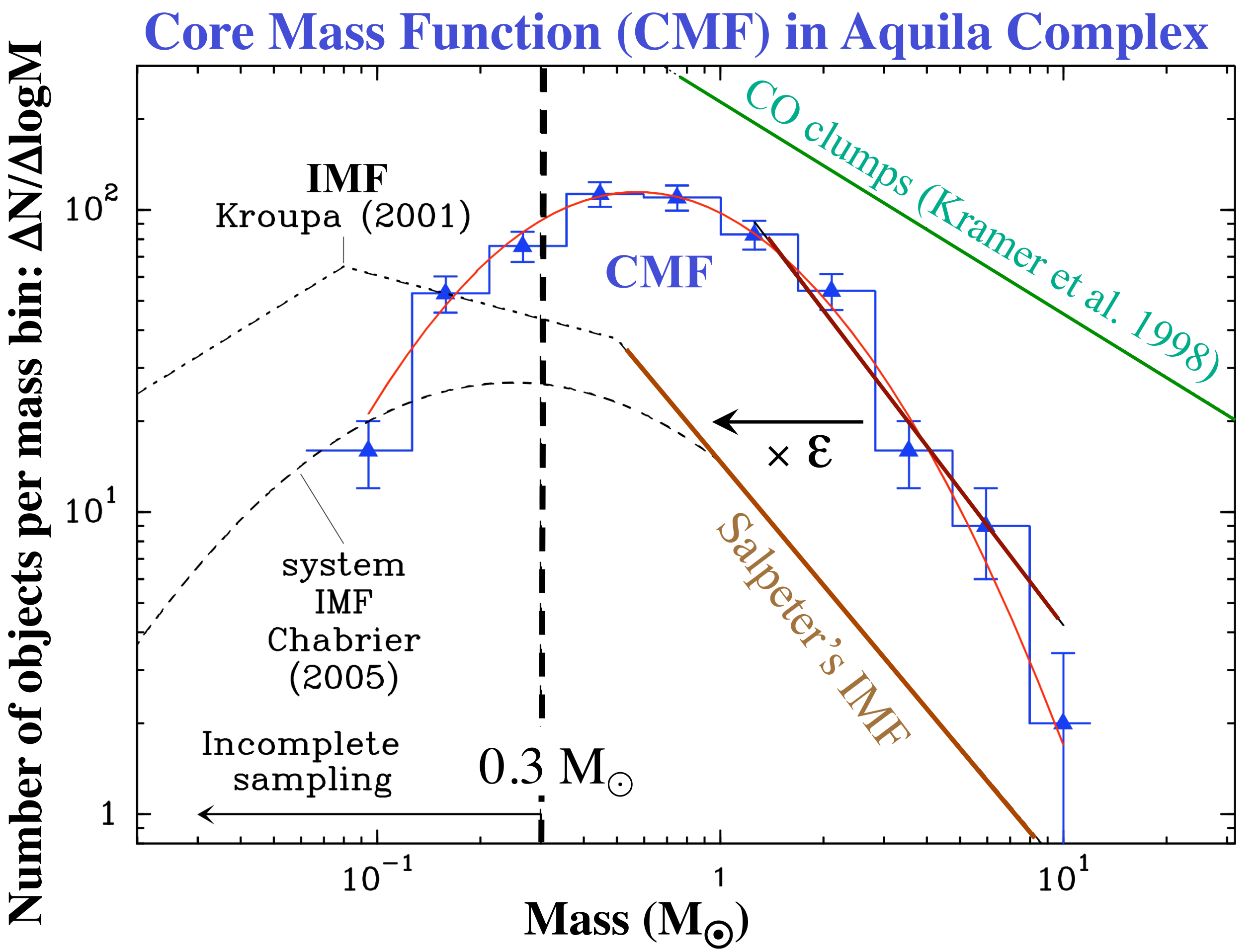
Confirming the link between the prestellar CMF & the IMF

Könyves et al. 2010
André et al. 2010
A&A special issue

341-541 prestellar cores in Aquila

Factor ~ 2-9 better statistics than earlier CMF studies:

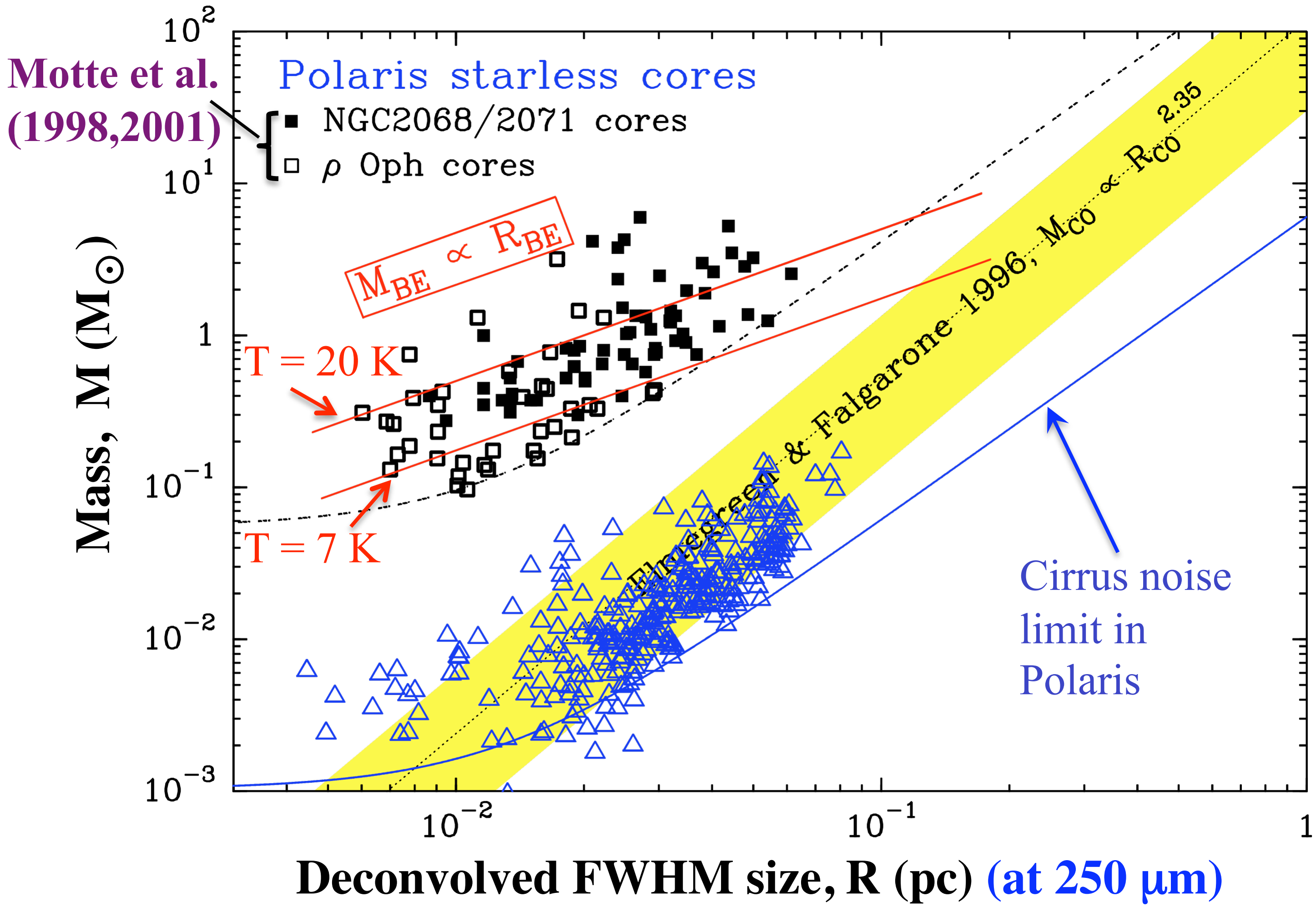
e.g. Motte, André, Neri 1998; Johnstone et al. 2000; Stanke et al. 2006; Enoch et al. 2006; Alves et al. 2007; Nutter & Ward-Thompson 07



➢ **Good (~ one-to-one) correspondence between core mass and system mass: $M_* = \varepsilon\, M_{core}$ with ε ~ 0.2-0.4 in Aquila**

➢ **The IMF is at least partly determined by pre-collapse cloud fragmentation** (cf. models by Padoan & Nordlund 2002, Hennebelle & Chabrier 2008)

Most of the ~300 Polaris starless cores are unbound

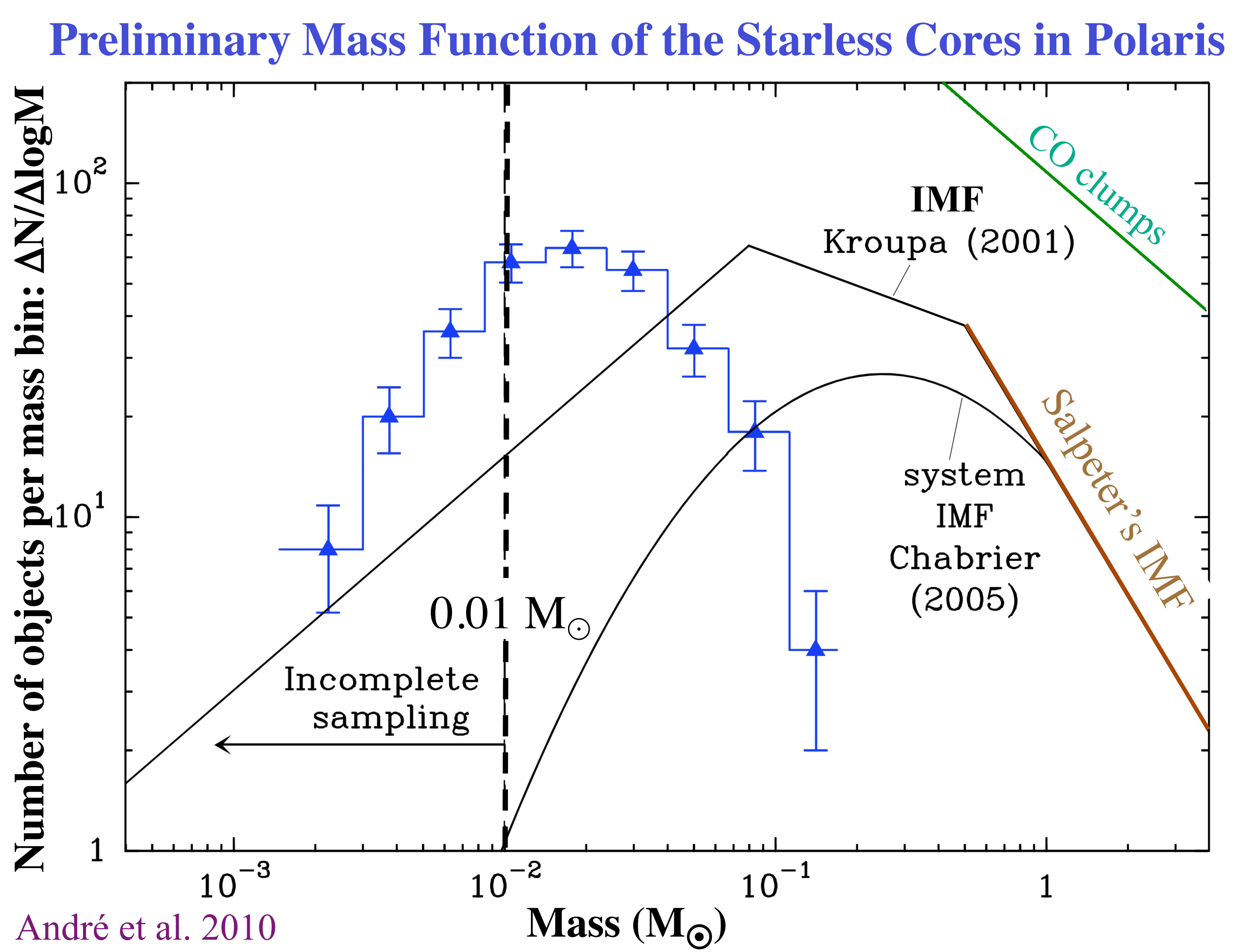


➢ not (yet ?) prestellar

André et al. 2010
Ward-Thompson et al. 2010

➢ **Locations in mass vs. size diagram:** 2 orders of magnitude below the density of self-gravitating Bonnor-Ebert isothermal spheres

The Polaris starless cores are not massive enough to form stars



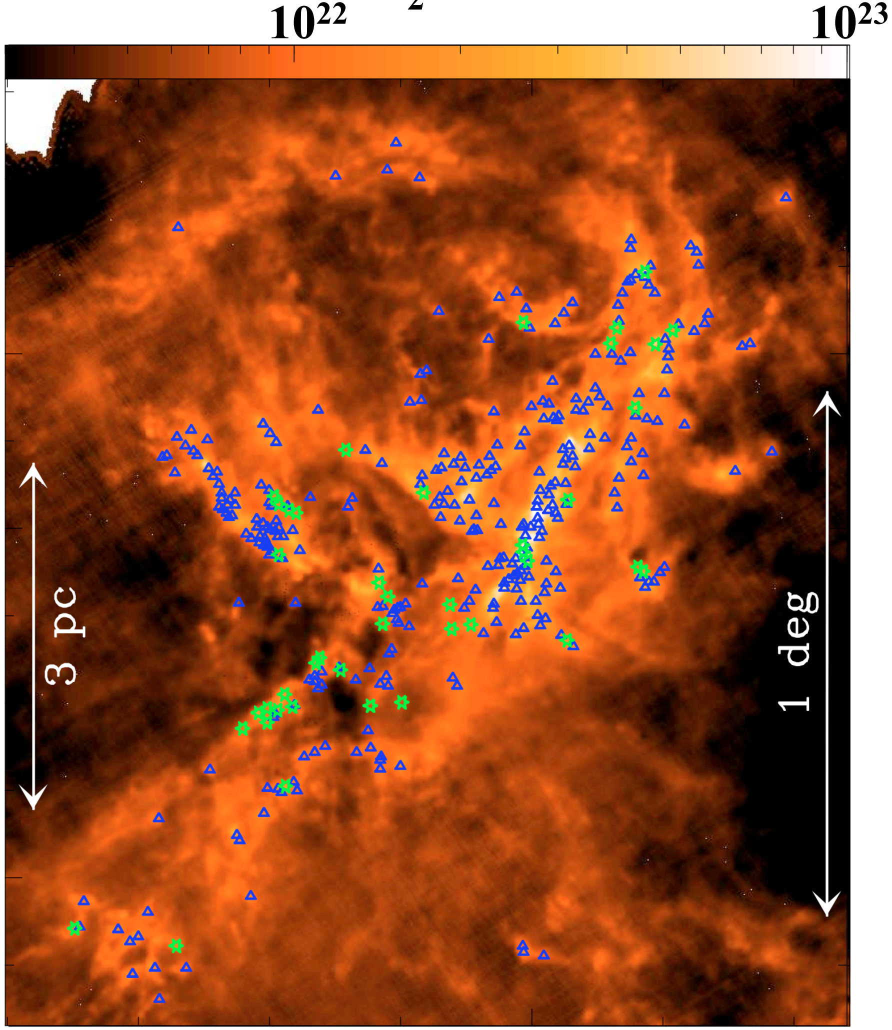
The mass function of Polaris starless cores peaks at ~ 0.02 $M_\odot$, i.e., ~ one order of magnitude below the peak of the stellar IMF

Prestellar cores form out of a filamentary background

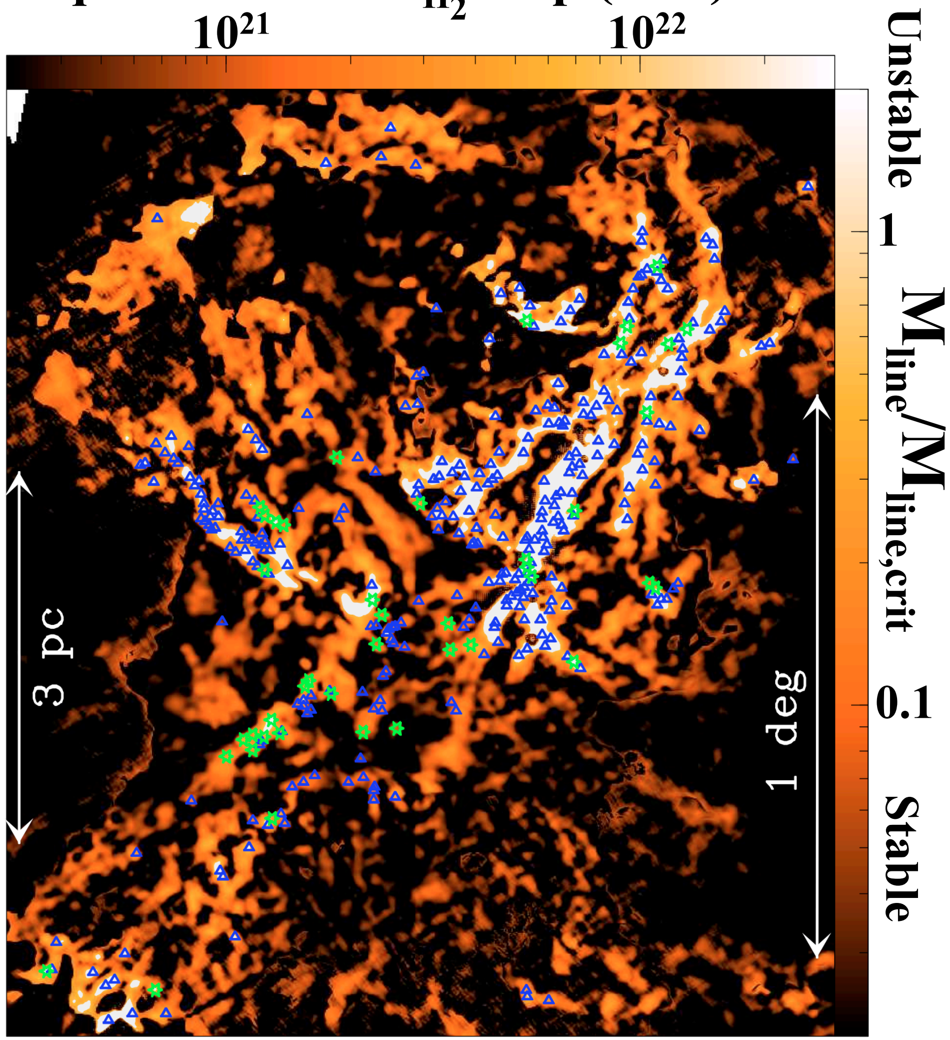
☆ : Class 0 protostars

△ : Prestellar cores - 90% found at A_v(back) > 7
Mean separation ~ 0.08 pc ~ Jeans length at A_v = 7

Aquila N_{H_2} map (cm^{-2})

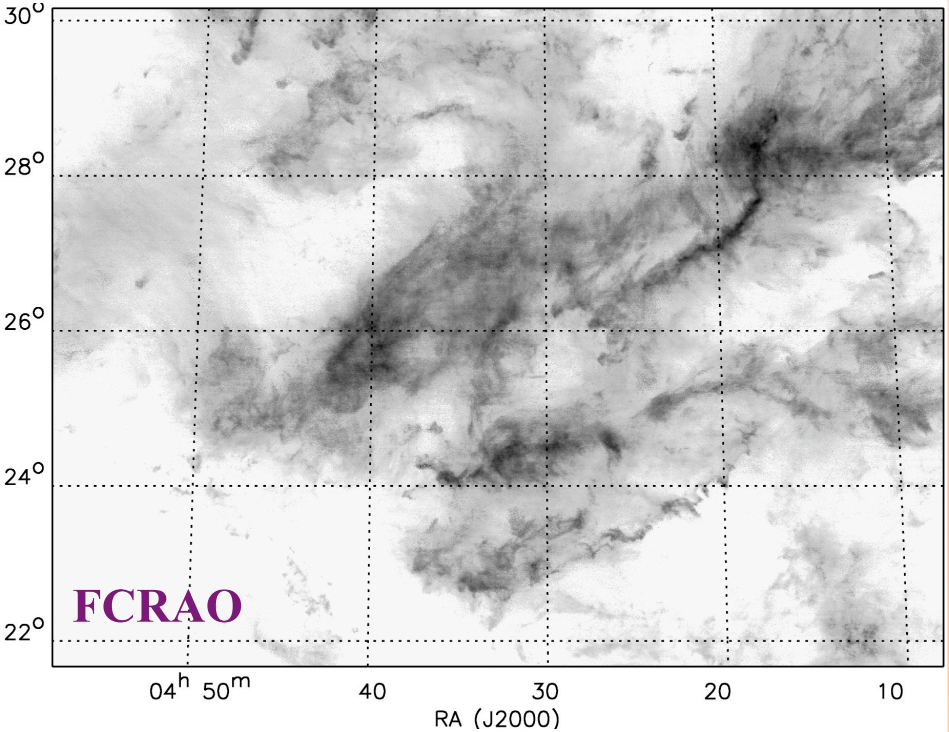


Aquila curvelet N_{H_2} map (cm^{-2})



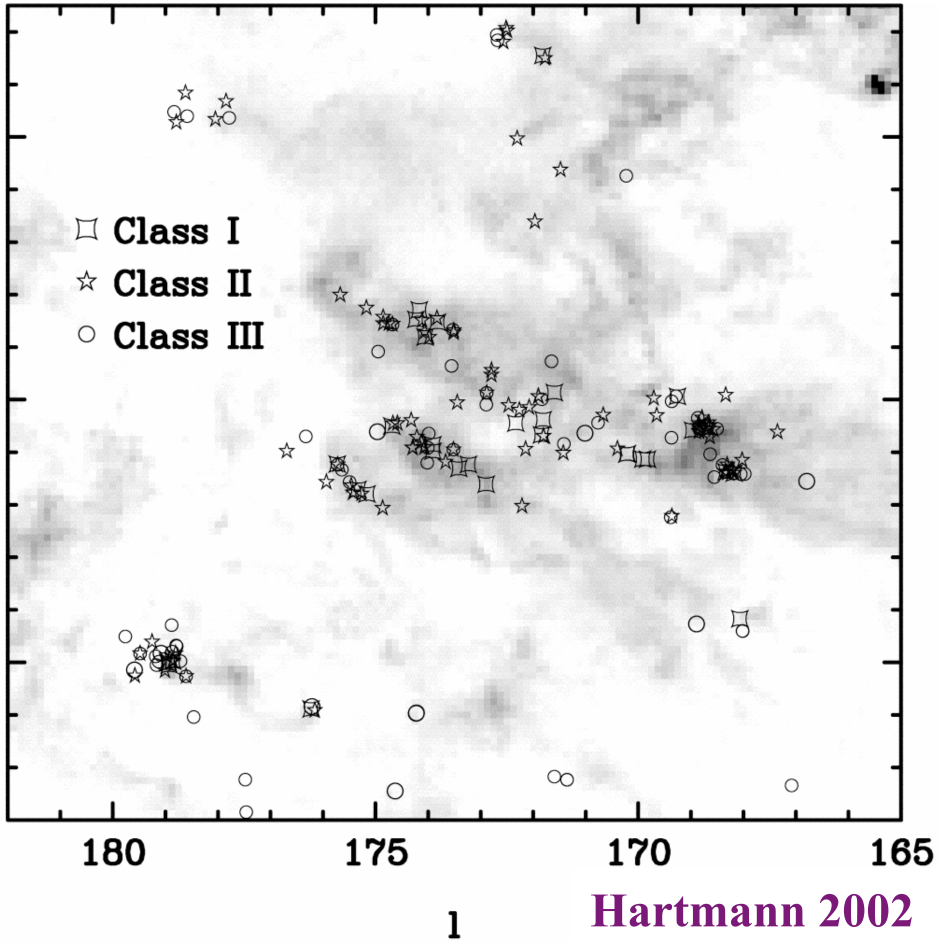
Evidence of the importance of filaments prior to Herschel

Taurus
H_2 column density from CO(1-0)



Goldsmith et al. 2008

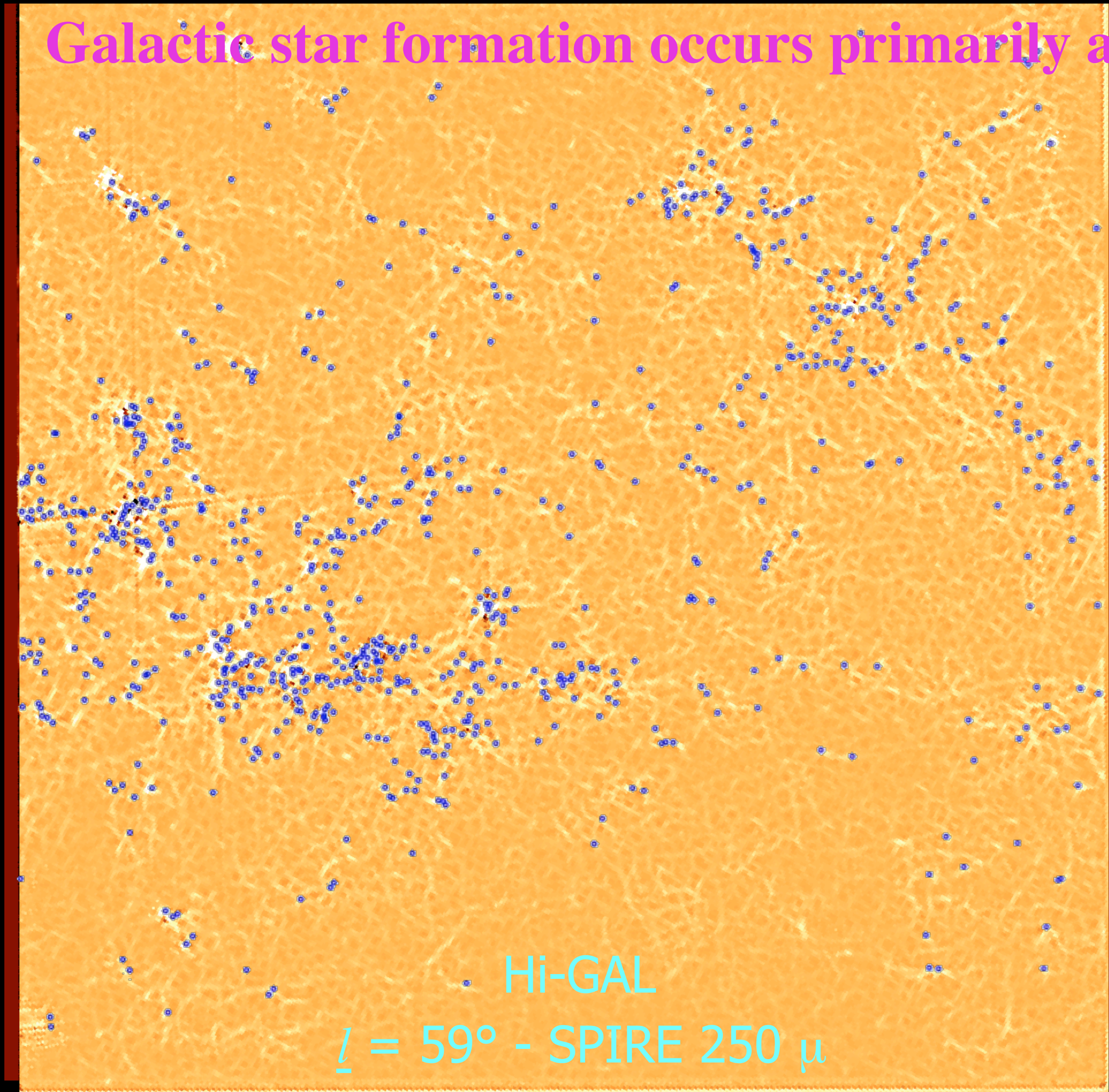
Taurus
YSOs superposed on CO map



Hartmann 2002

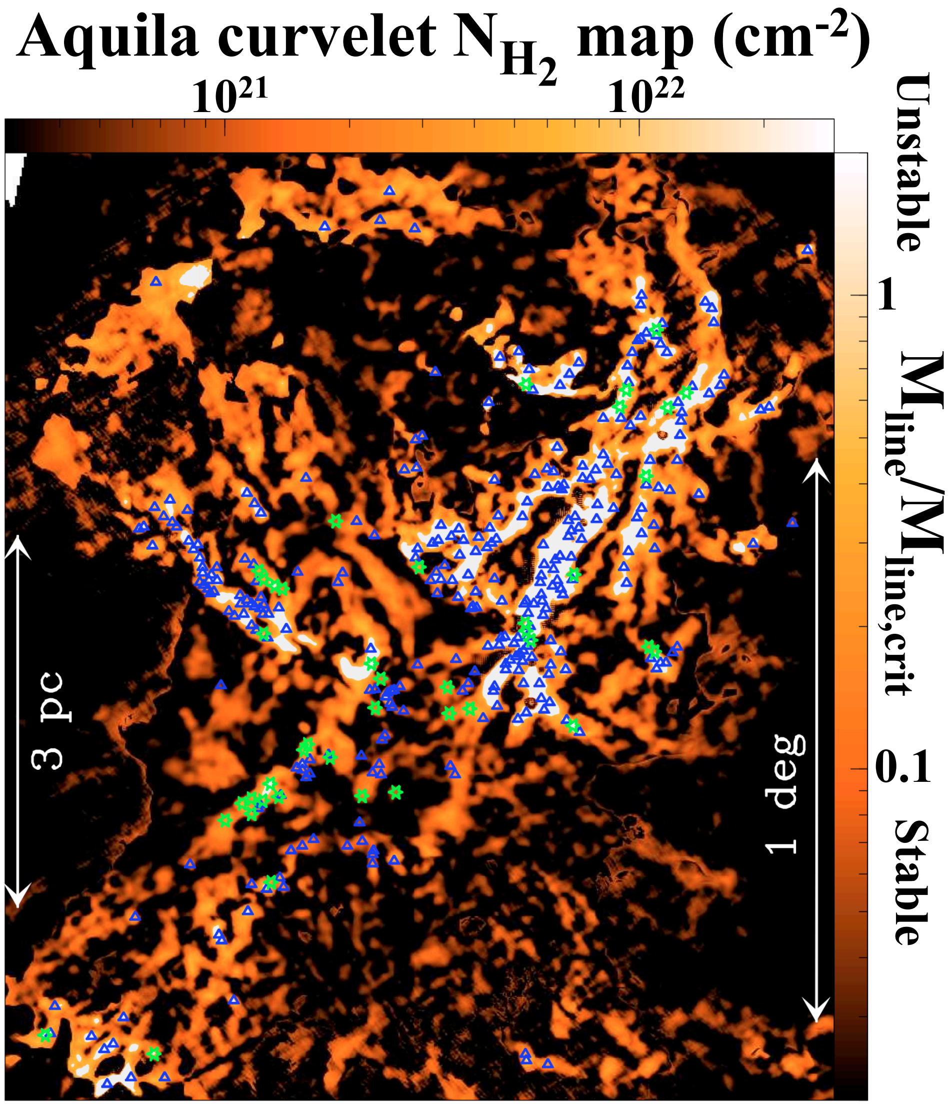
See also:
Schneider & Elmegreen 1979;
Abergel et al. 1994; Mizuno et al. 1995;
Hatchell et al. 2005; Myers 2009 …

Galactic star formation occurs primarily along filaments



Molinari et al. 2010
A&A special issue

Only the densest filaments are gravitationally unstable and contain prestellar cores (△)

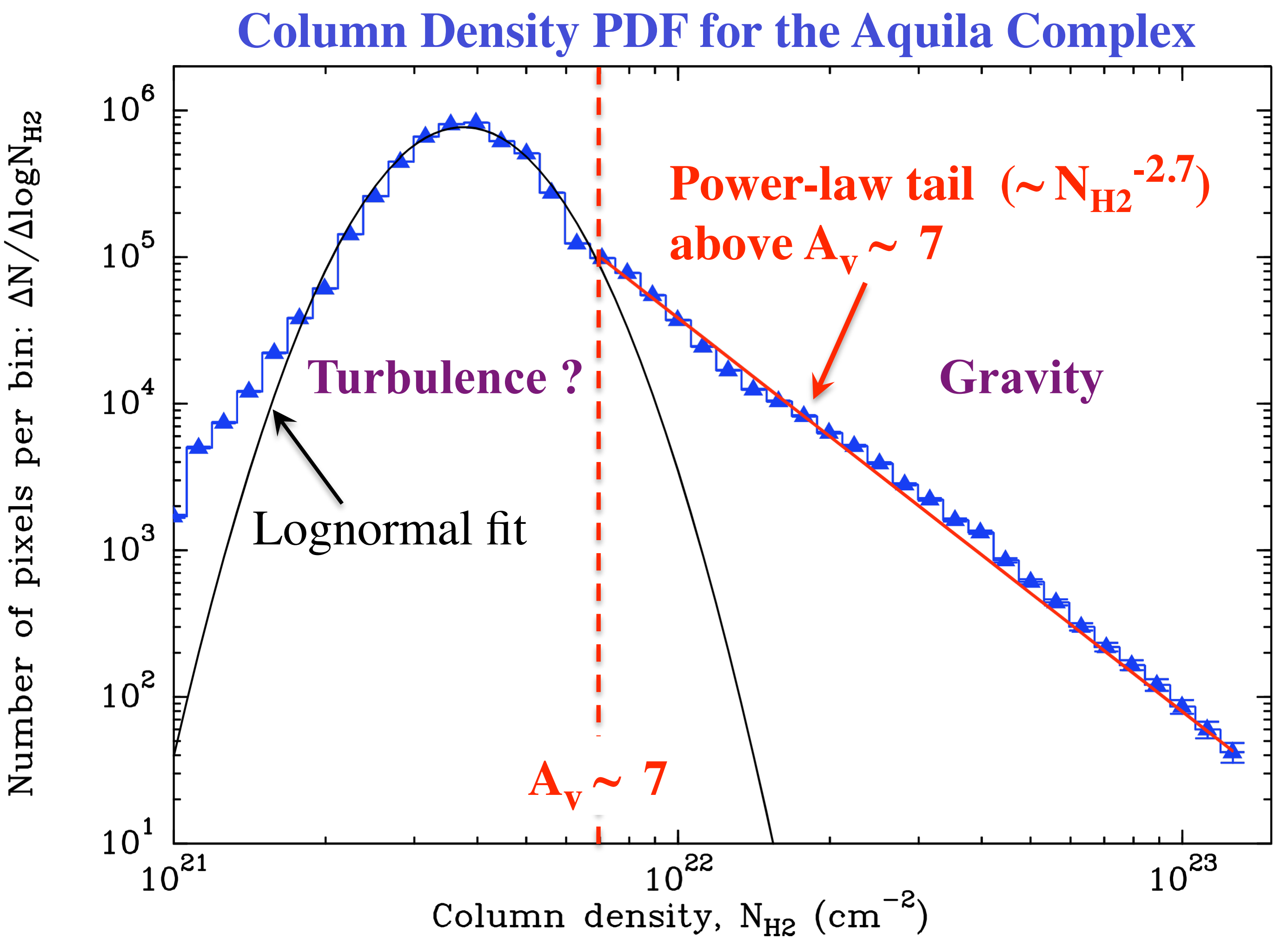


André et al. 2010, A&A Special issue

- ➢ The gravitational instability of filaments is controlled by the mass per unit length M_{line} (cf. Ostriker 1964, Inutsuka & Miyama 1997):
- • unstable if $M_{line} > M_{line, crit}$
- • unbound if $M_{line} < M_{line, crit}$
- • $M_{line, crit} = 2\, c_s^2/G \sim 15\, M_\odot/pc$ for $T \sim 10K$ ⇔ A_V threshold
- ➢ Simple estimate: $M_{line} \propto N_{H2}$ x Width (~ 0.1 pc)

Unstable filaments highlighted in white in the N_{H2} map

Other manifestation of the threshold

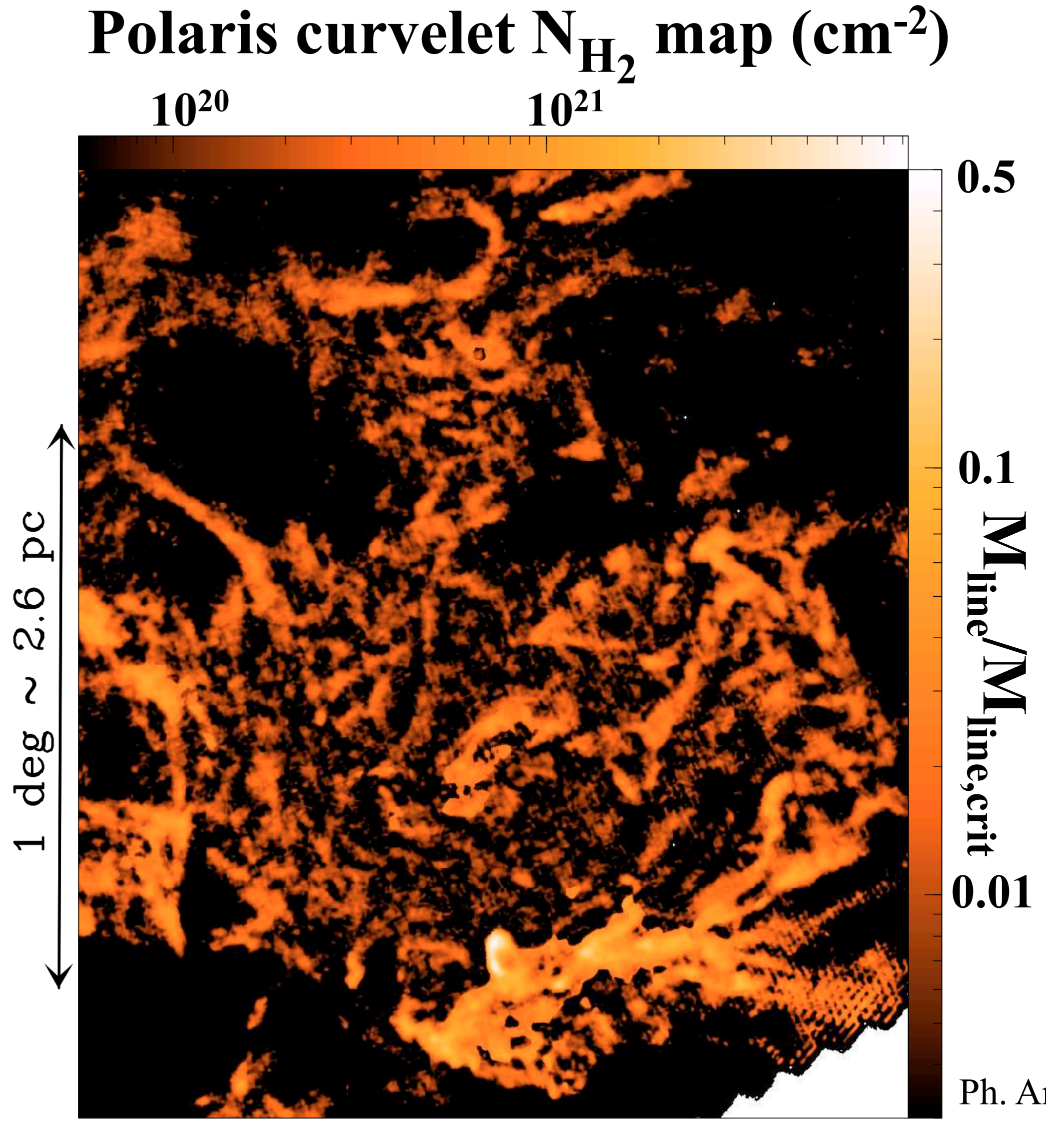


Given the typical filament width ~ 0.1 pc (FWHM), **A_v ~ 7 roughly corresponds to $M_{line, crit}$ = Threshold above which the filaments are gravitationally unstable**

Similar column density PDFs are found in near-IR extinction studies of nearby star-forming clouds (Kainulainen et al. 2009)

Polaris (d ~ 150 pc): Structure of the cold ISM prior to any star formation

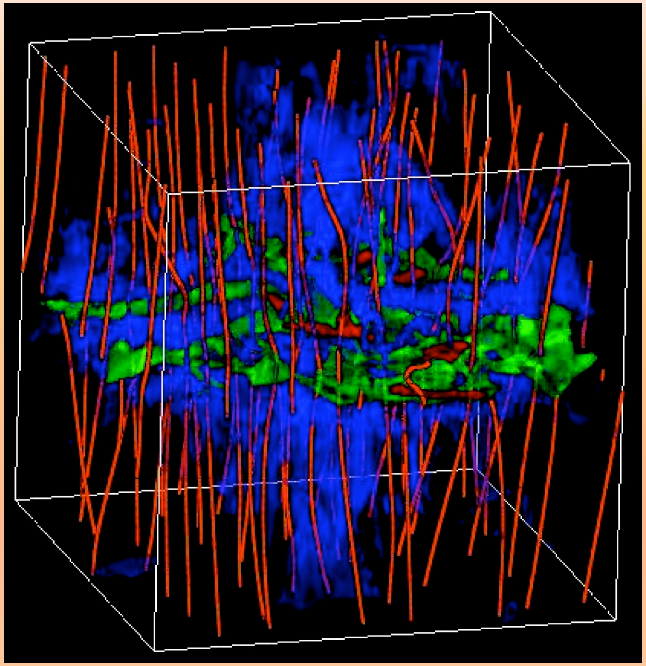
No prestellar cores (yet ?) in Polaris



- Filaments are already widespread prior to star formation
- The maximum value of $M_{line}/M_{line,\,crit}$ observed in the Polaris filaments is ~ 0.5
- The Polaris filaments are gravitationally unbound and unable to form prestellar cores and protostars at present

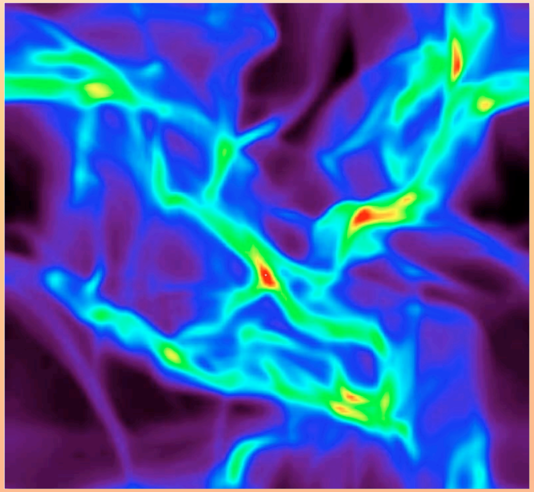
Origin of filaments and cores: Three possible paradigms

Magnetically-regulated star formation



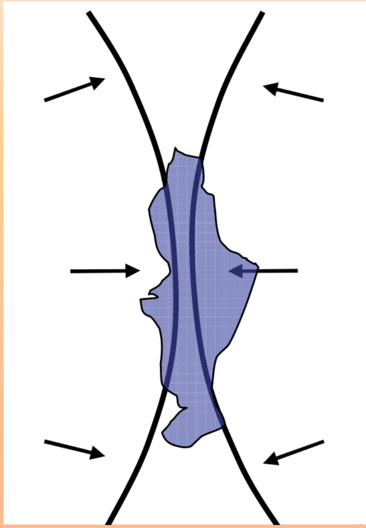
Magnetically-critical condensed sheet, fragmented into filaments and cores (e.g. Nakamura & Li 2008; Basu, Ciolek etal. '09)

Turbulent fragmentation



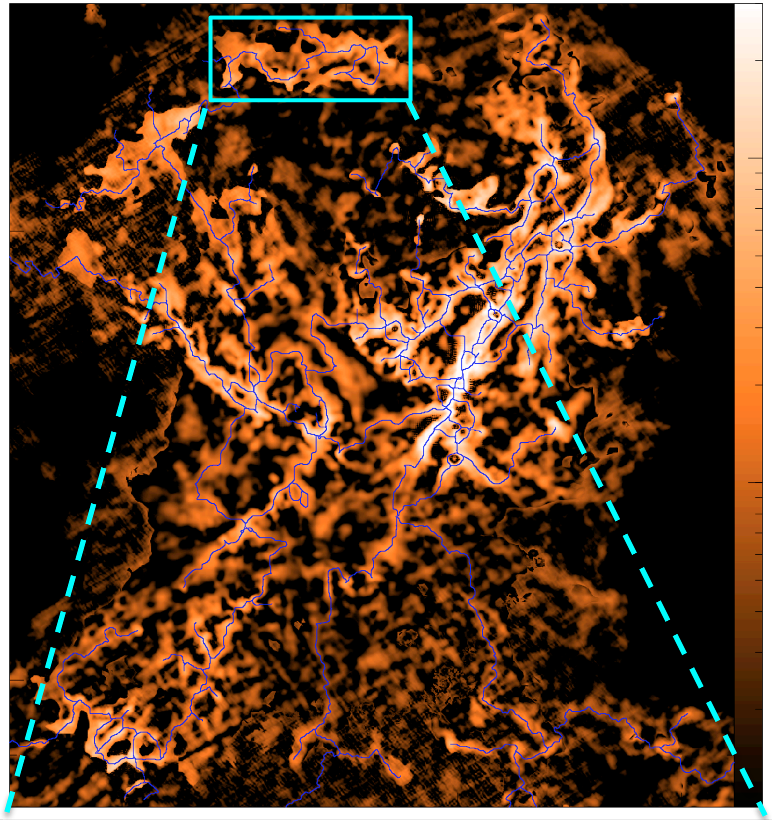
Filaments and cores from shocks in large-scale, supersonic turbulence
(e.g. Padoan et al. 2001; MacLow & Klessen '04)
Bate, Bonnell et al. 2003 …

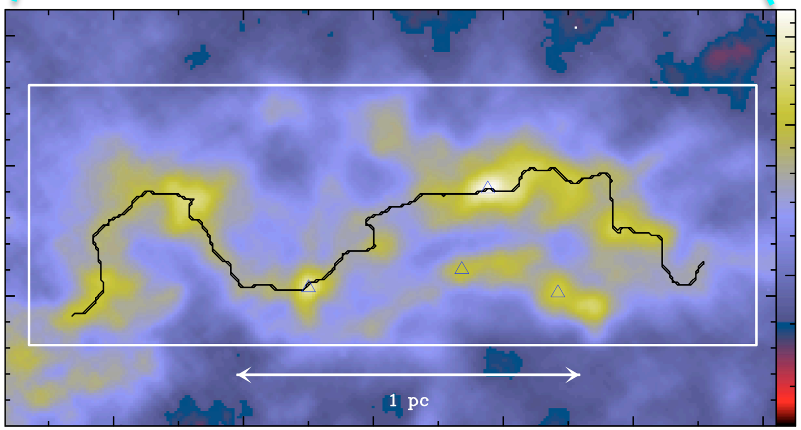
Gravity-dominated cloud/star formation

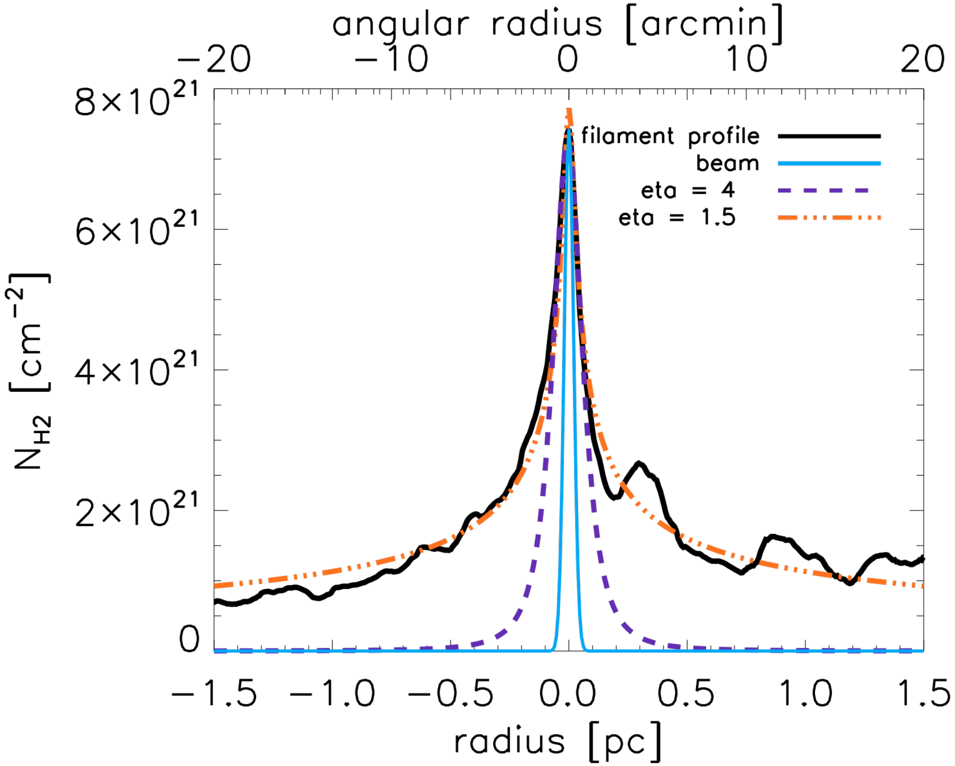


Filaments from global cloud collapse
Cores from local gravity
(e.g. Burkert & Hartmann '04; Heitsch et al. '08; also Nagai et al. '98)

Preliminary radial profile analysis of the filaments





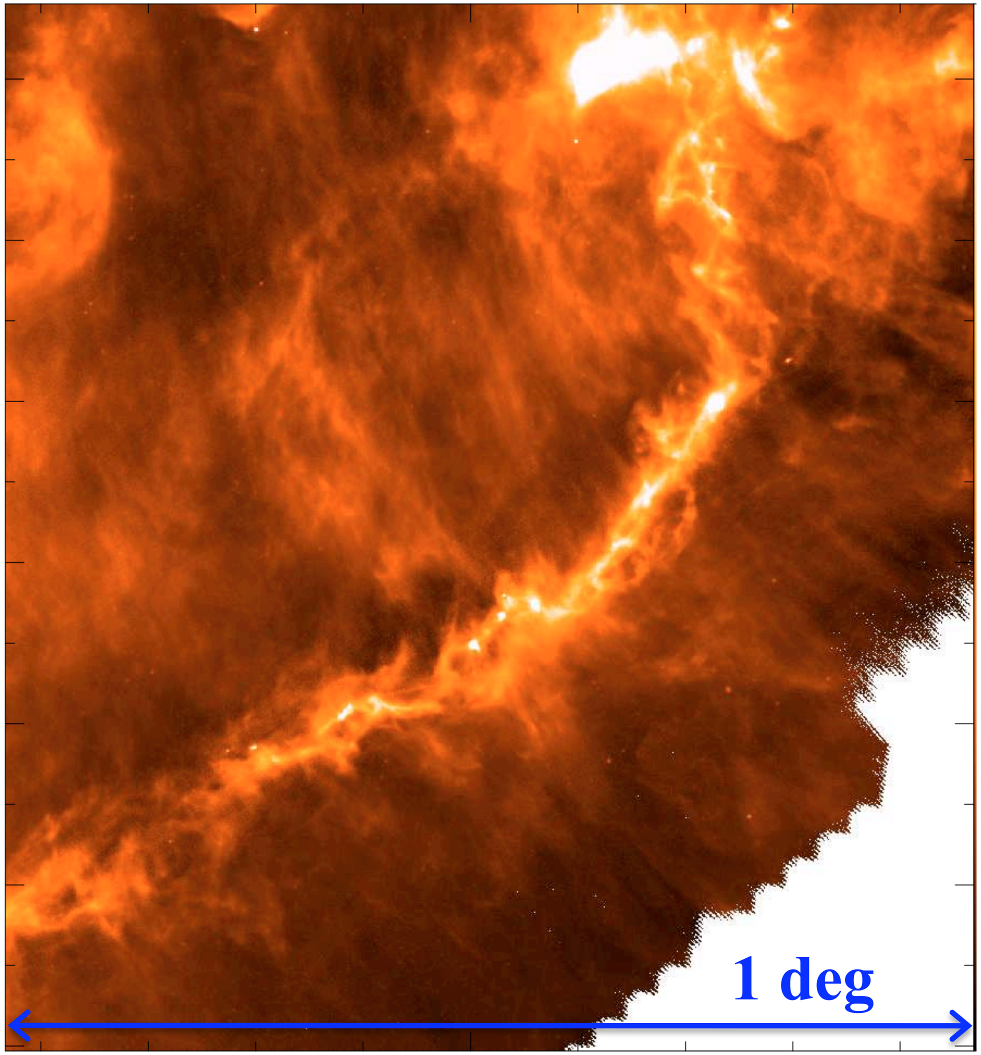


- **Typical FWHM width ~ 0.1 pc**
- **Profiles are shallower than the steep ($\rho \propto r^{-4}$) profile of unmagnetized hydrostatic equilibrium filaments (Ostriker 1964)**
- **Models of magnetized filaments (Fiege & Pudritz 2000) agree better with observations**

D. Arzoumanian et al., in prep.

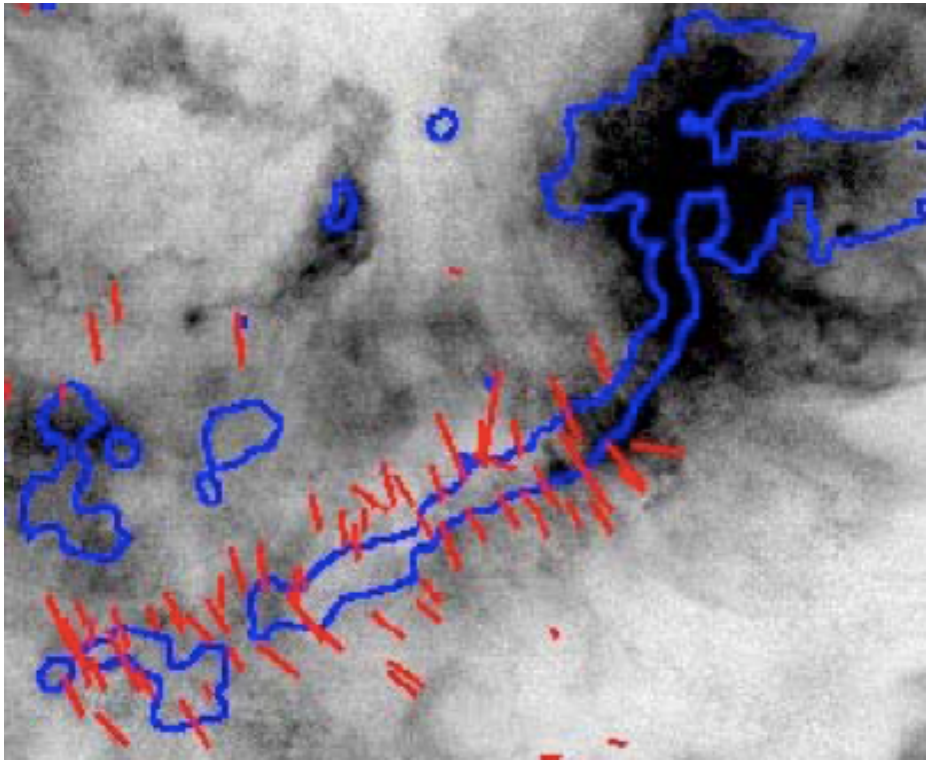
Taurus: (part of) B213 Filament

***Herschel*/SPIRE 250μm**



P. Palmeirim, J. Kirk et al., in prep.

^{12}CO(1-0) + polarization vectors



Goldsmith, Heyer et al. 2008

➢ **In the Nakamura & Li (2008) model, the striations trace mass accumulation along the magnetic field lines.**

Conclusions

First results from *Herschel* are very promising:

- Confirm the **close link between the prestellar CMF and the IMF**, although the whole survey will be required to fully characterize the nature of this link.

- Suggest that **core formation occurs in two main steps**:
  1) Filaments form first in the cold ISM, probably as a result of the dissipation of **MHD turbulence**; **2)** The densest filaments then fragment into prestellar cores via **gravitational instability** above a critical extinction threshold at $A_V \sim 7$.

- Spectroscopic and polarimetric observations required to clarify the roles of turbulence, B fields, gravity in forming the filaments.