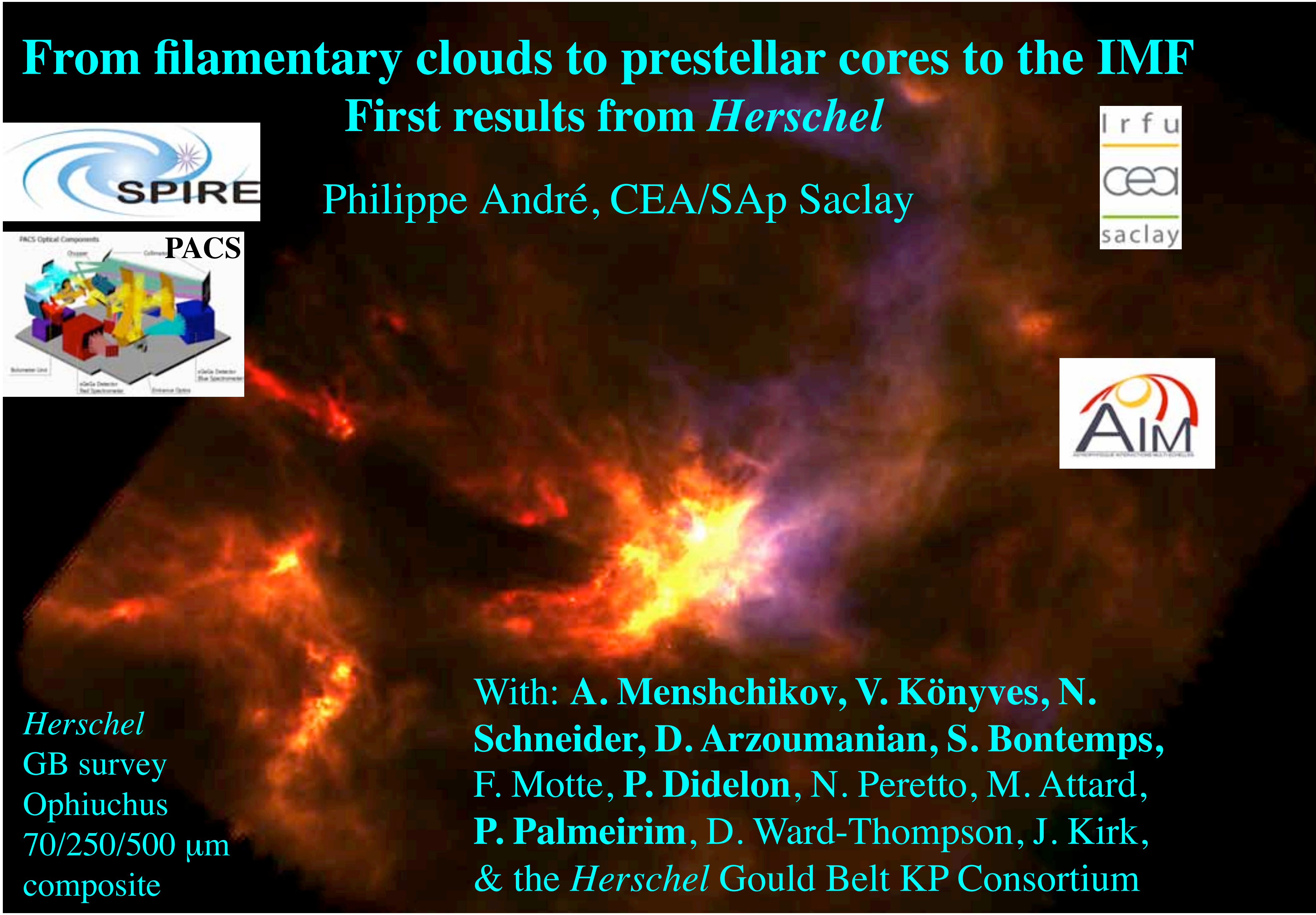
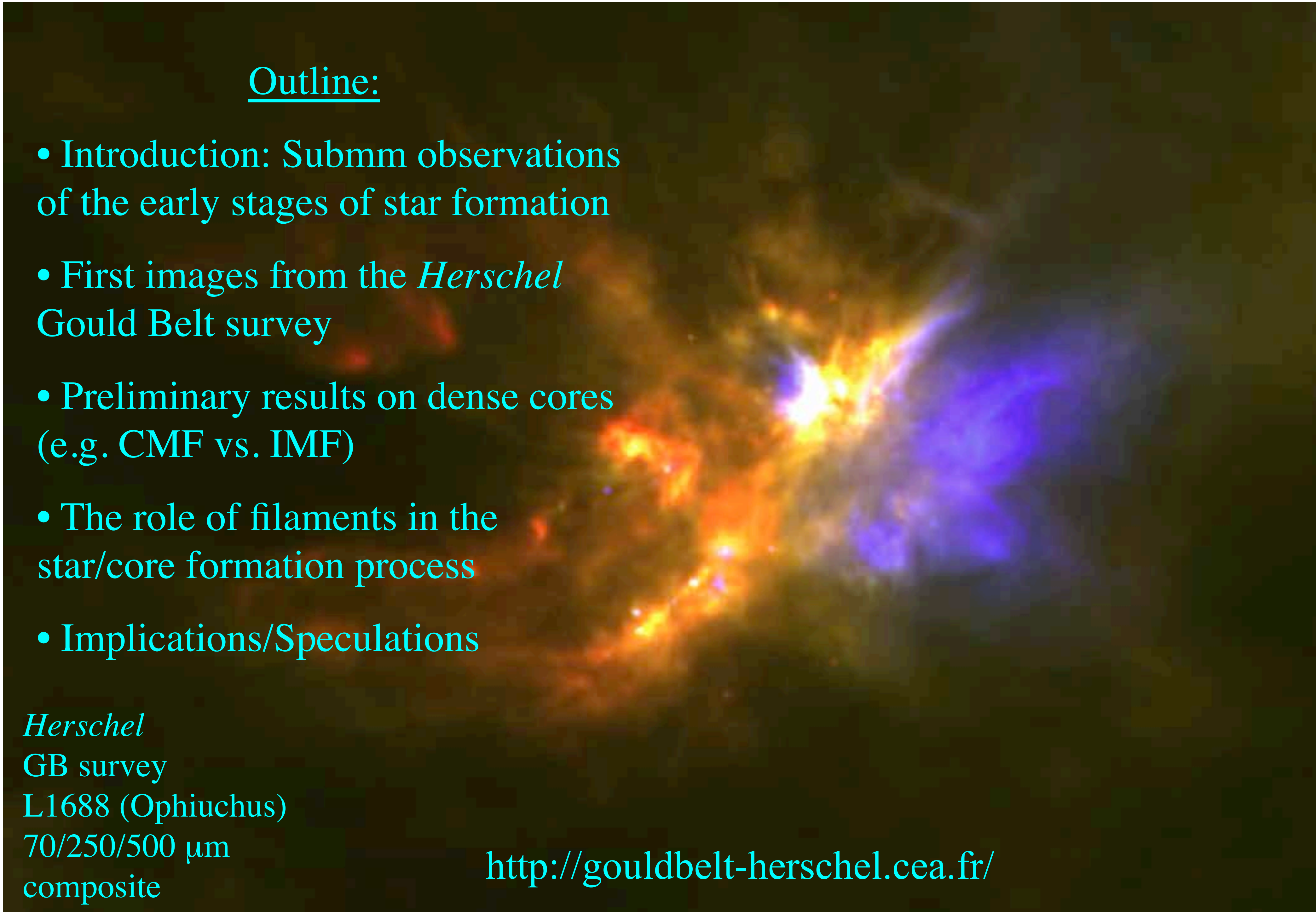
From filamentary clouds to prestellar cores to the IMF
First results from *Herschel*

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

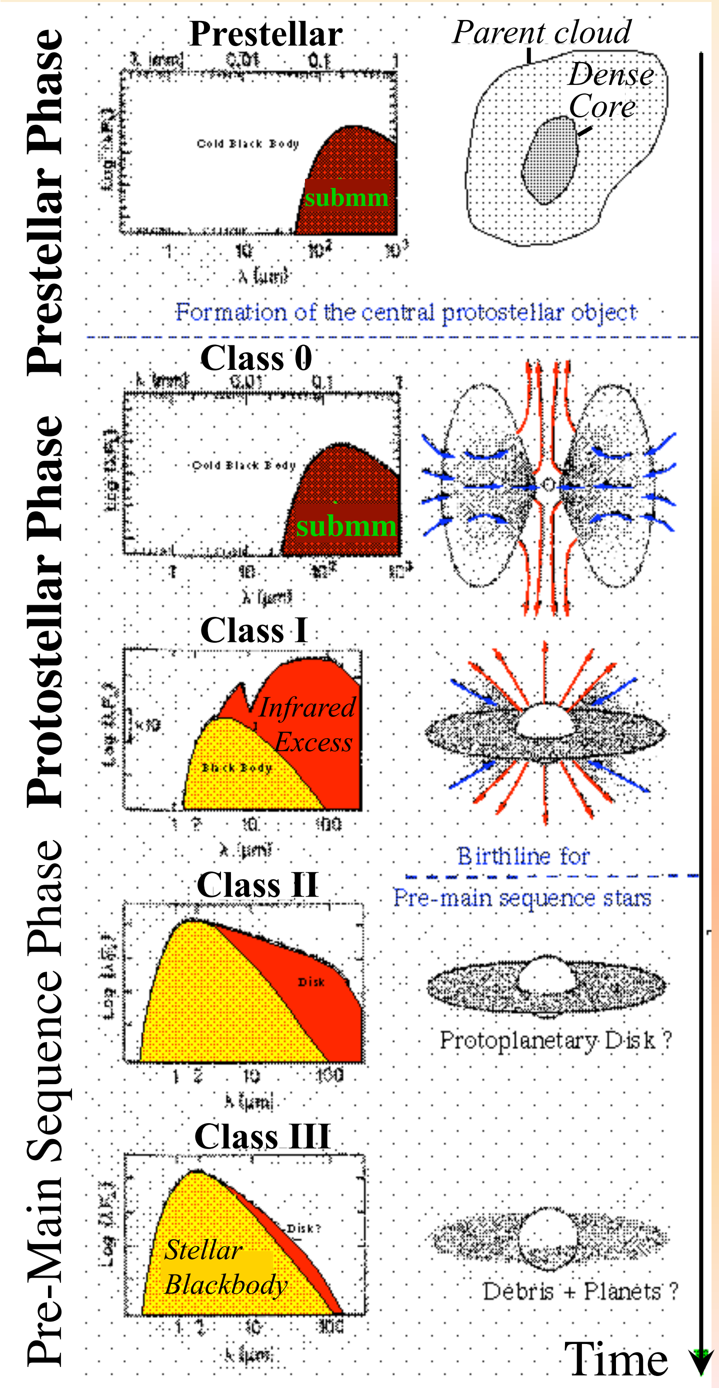


Outline:

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

Herschel
GB survey
L1688 (Ophiuchus)
70/250/500 μm
composite

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



Lada 1987 + André, Ward-Thompson, Barsony 2000

Formation of solar-type stars

Reasonably well established evolutionary sequence but physics of early stages unclear

Many open issues:

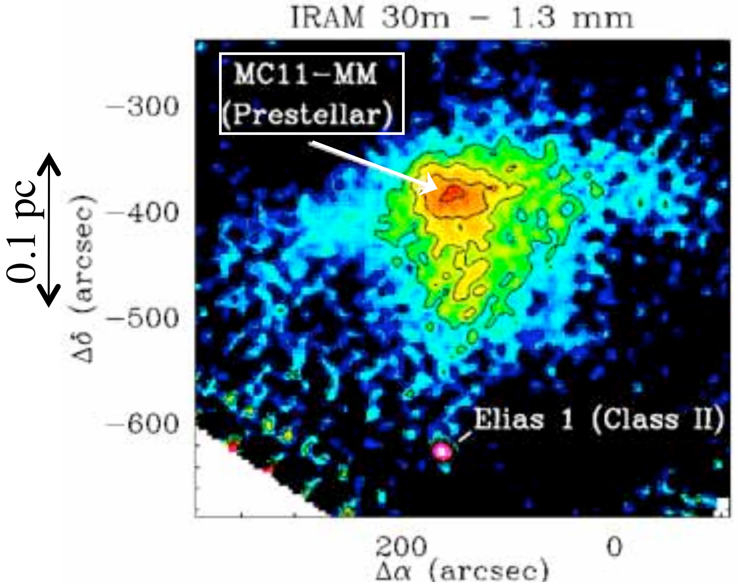
- **What determines the masses of forming stars (« IMF ») ?**
- **What controls the efficiency of the star formation process ?**
- **Is star formation rapid or slow ? …**

- **Key:** Study of the earliest evolutionary stages → initial conditions of star formation process

Prestellar Cores ($t < 0$) → Class 0 protostars ($t > 0$)

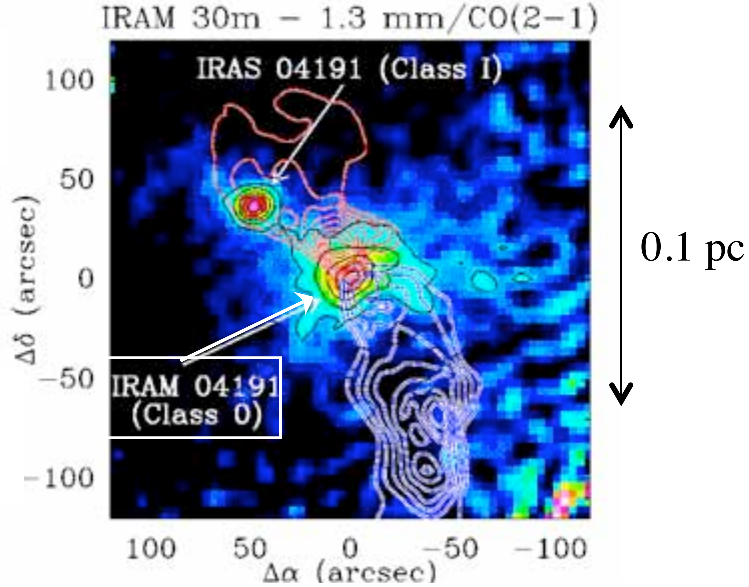
The progenitors of protostars

Protostars in the build-up phase



Representative of the collapse initial conditions

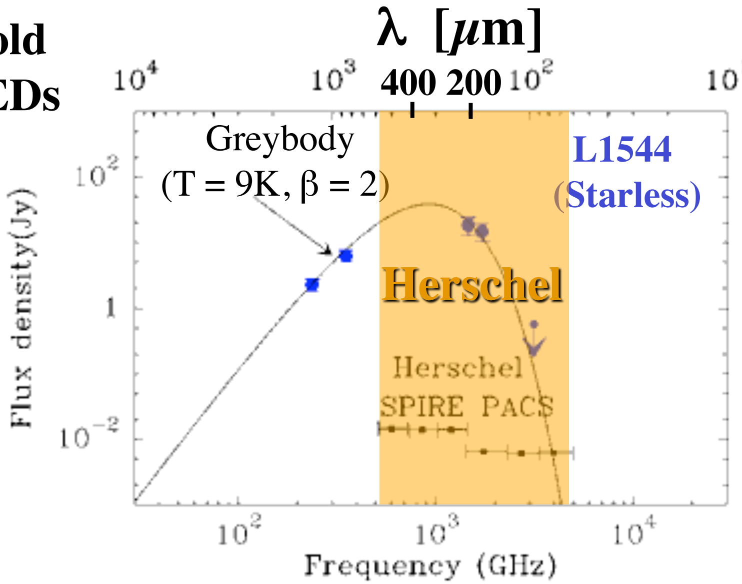
No complete census from the ground



Gravitationally bound ($M \sim M_{VIR}$, $M_* = 0$)

Massive envelopes ($M_{env} > M_*$)

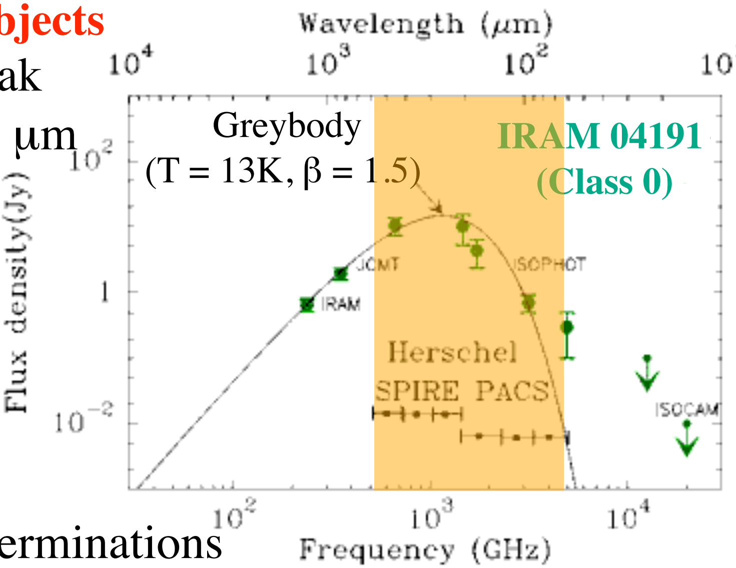
Cold SEDs



Submm-only objects whose SEDs peak @ λ ~ 100-400 µm

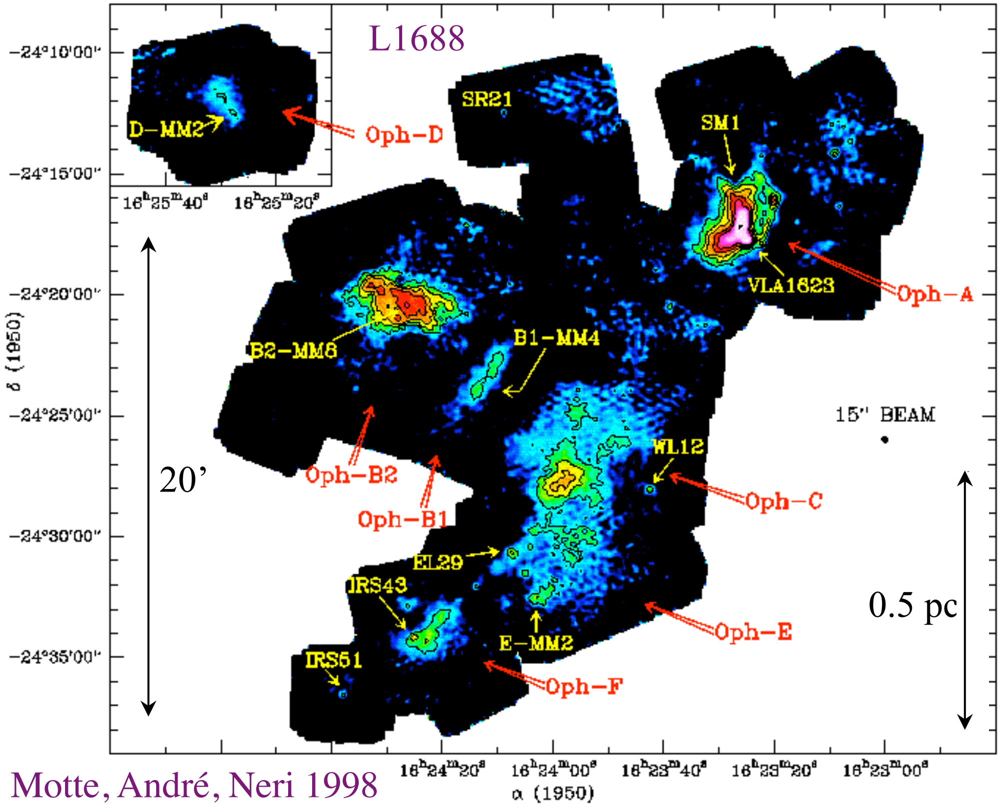
↓

Herschel bands essential for luminosity and temperature determinations



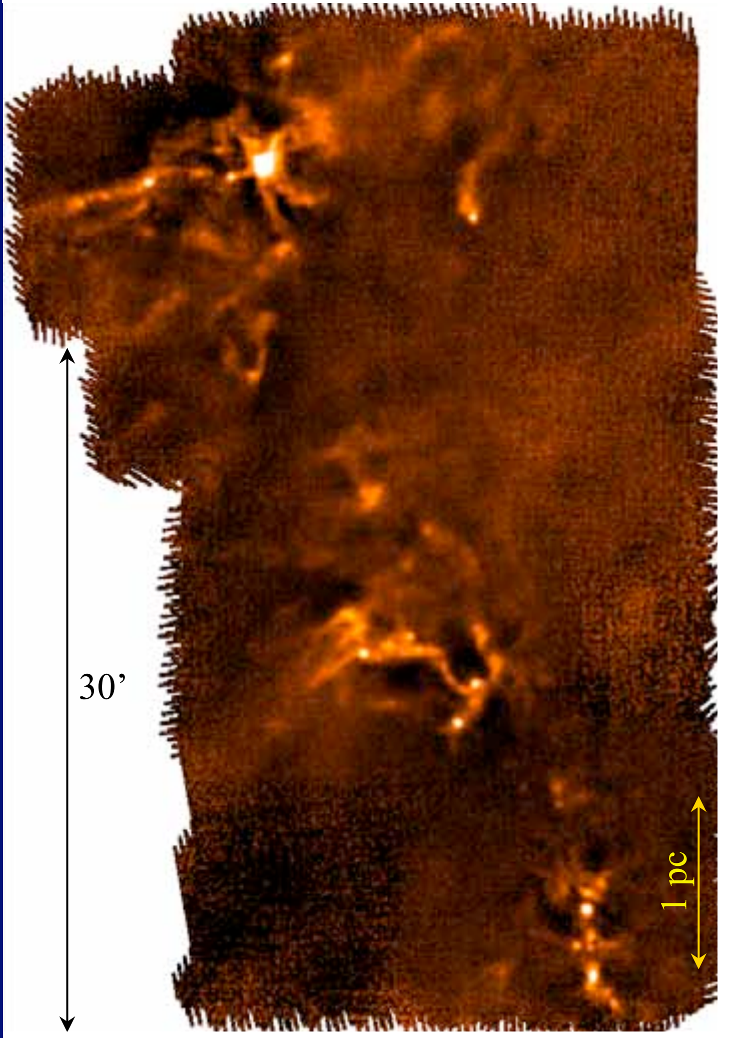
Census of prestellar cores and Class 0 protostars from (sub)mm dust continuum mapping

1.3mm mosaic of ρ Oph main cloud (IRAM 30m + MAMBO)



Motte, André, Neri 1998

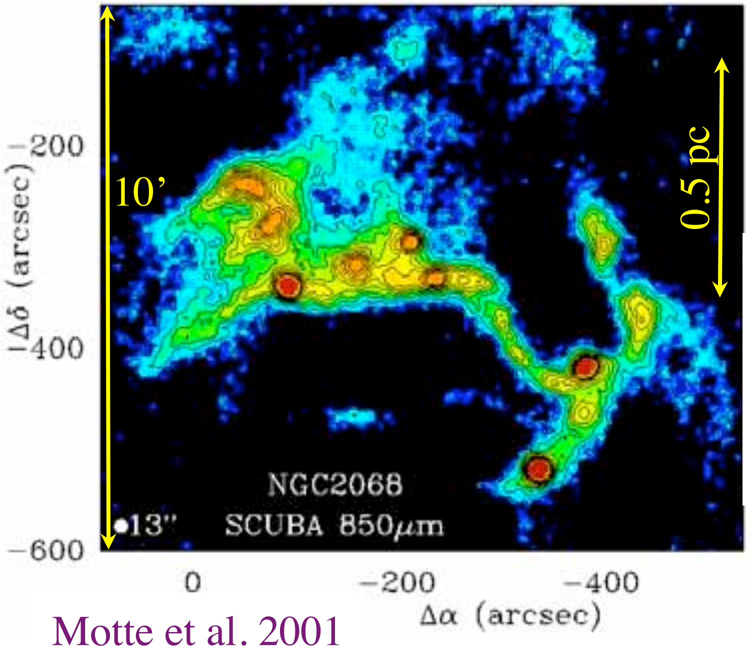
850 μm mosaic of Orion BN (JCMT+ SCUBA)



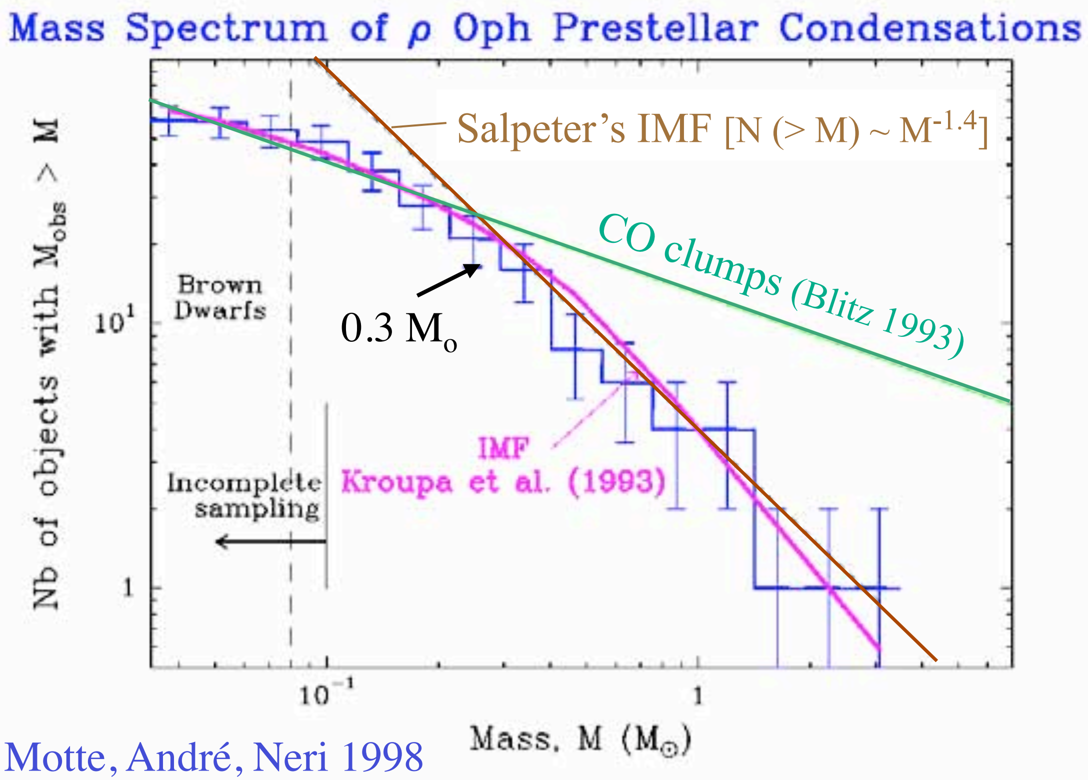
Johnstone et al. + Motte et al = Nutter et al. 07

The prestellar core mass function (CMF) resembles the IMF

NGC2068 at 850 µm



Motte et al. 2001



Motte, André, Neri 1998

➜ The IMF is at least partly determined by pre-collapse cloud fragmentation (~ 0.1 - 5 $M_\odot$)

- **Limitations:** Small-number statistics, incompleteness at low-mass end (?) + assume uniform dust temperature

➜ *Herschel* needed to confirm/extend conclusions toward lower/higher masses

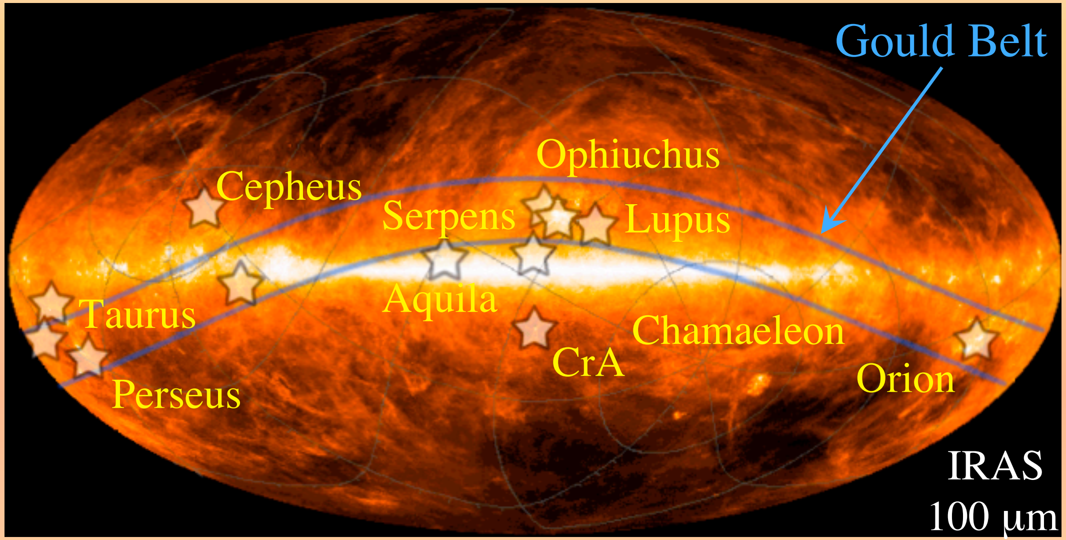
See also: Testi & Sargent 1998;
Johnstone et al. 2001;
Stanke et al. 2006; Alves et al. 2007
Nutter & Ward-Thompson 2007

And for massive cores:
Beuther & Schilke 2004;
Reid & Wilson 2006

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

←→

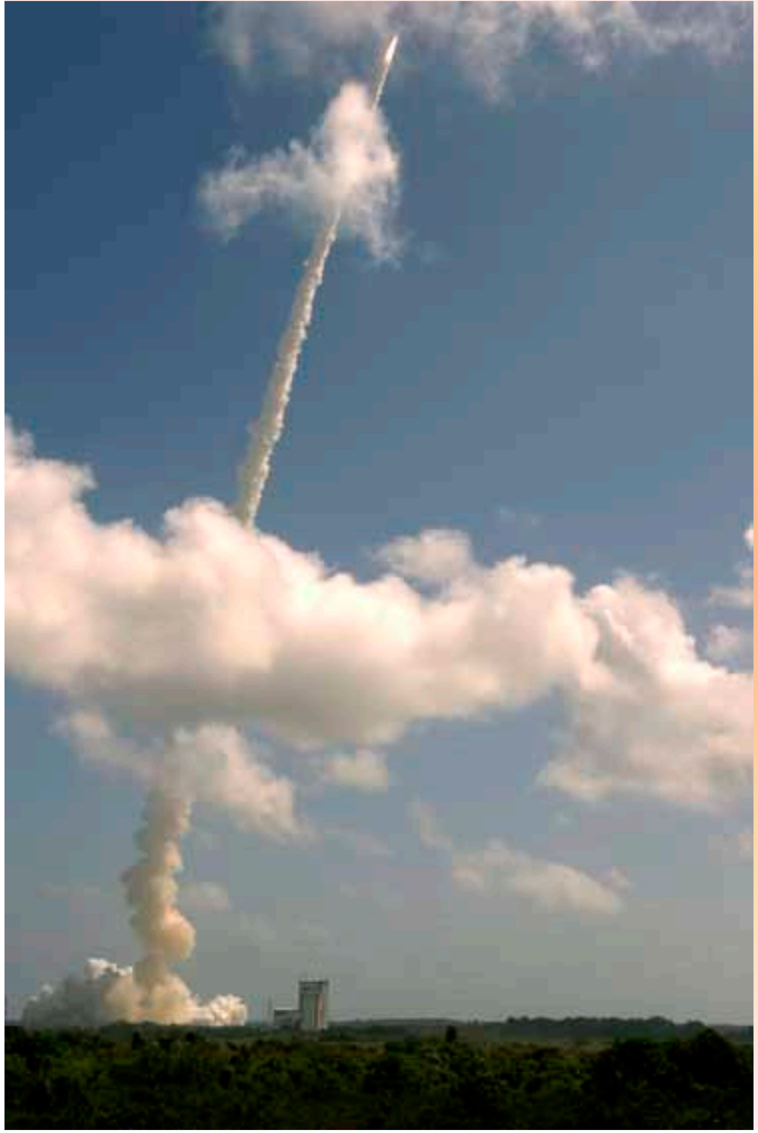
~ 0.02 pc
< Jeans length
@ d = 300 pc

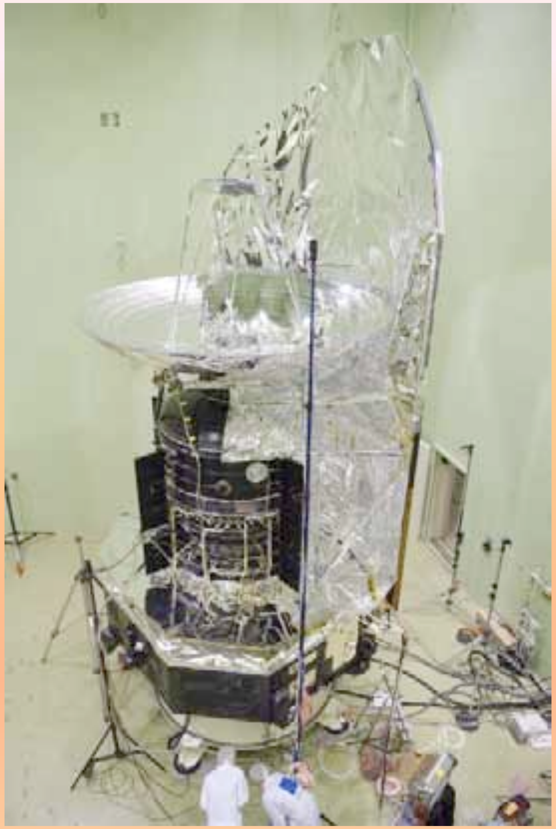
Motivation: Key issues on the early stages of star formation

- 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 ?

The Herschel Space Observatory

Successfully launched by Ariane 5 on 14 May 2009 !



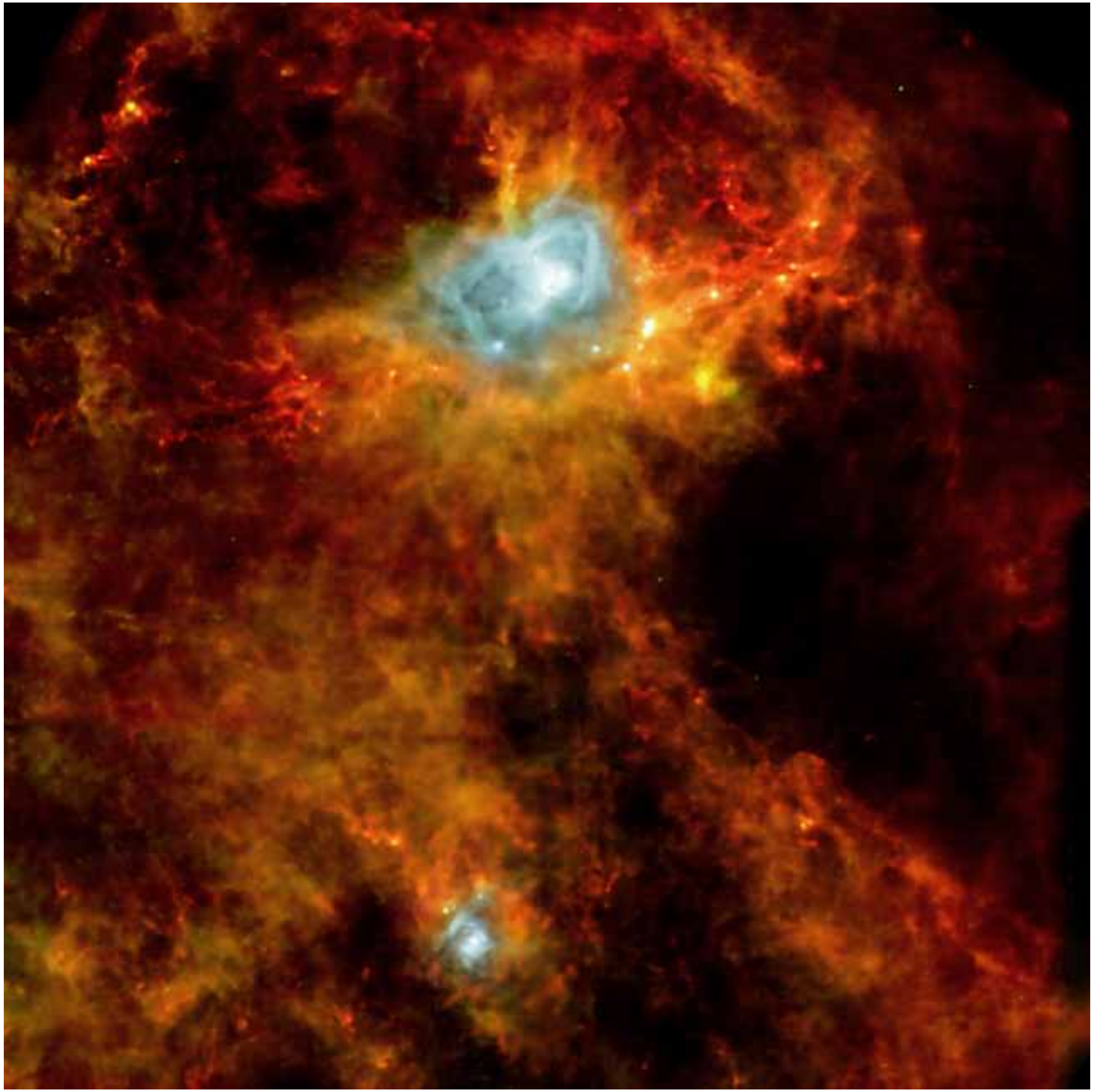


Major far-IR/submm Observatory (ESA ‘cornerstone’) 3.5 m telescope

- First light on 14 June 2009
- First science during « Science demonstration (SD) phase » in Oct./ Nov. 2009
- Currently in « routine operations phase »
- Lifetime ~ 3.5 yr (end ~ December 2012)
- First Results in a special issue of A&A (Vol. 518 Jul-Aug 2010)

(See also http://herschel.esac.esa.int/FirstResultsSymposium.shtml)

"First images" from the Gould Belt Survey



PACS/SPIRE // mode
70/160/250/350/500 μm

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

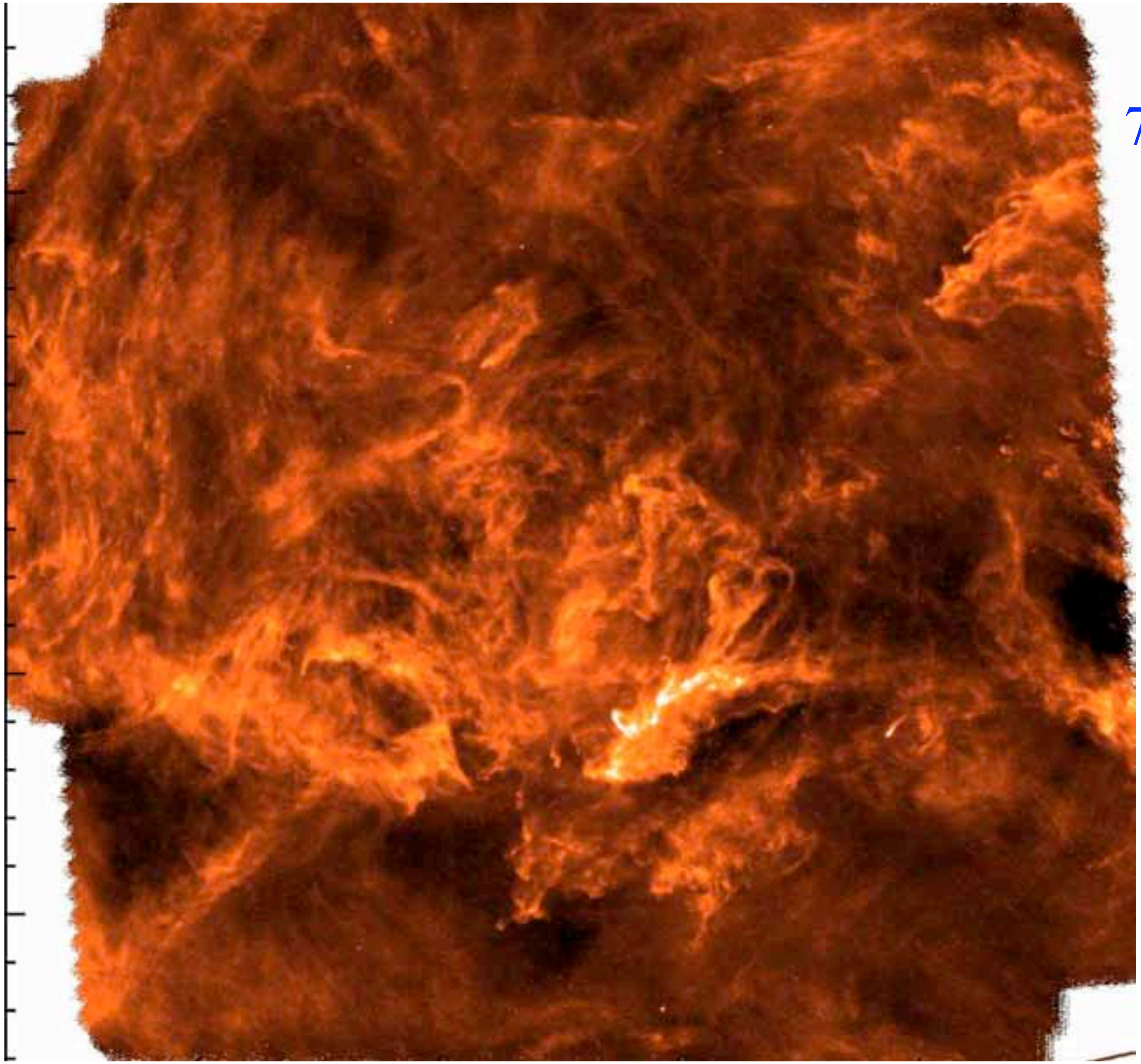
http://gouldbelt-herschel.cea.fr/

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

~ 3.3° x 3.3° field

André et al. 2010
Könyves et al. 2010
Bontemps et al. 2010
Men'shchikov et al. 2010
A&A special issue (vol. 518)

“First images” from the Gould Belt Survey



SPIRE 250 μm image

PACS/SPIRE // mode
70/160/250/350/500 μm

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

Thermal Continuum Emission from Cold Dust ($T_d \sim$ 5-50 K)

- **Optically thin dust emission at (sub)mm wavelengths**

→ Direct mass/column density estimates :

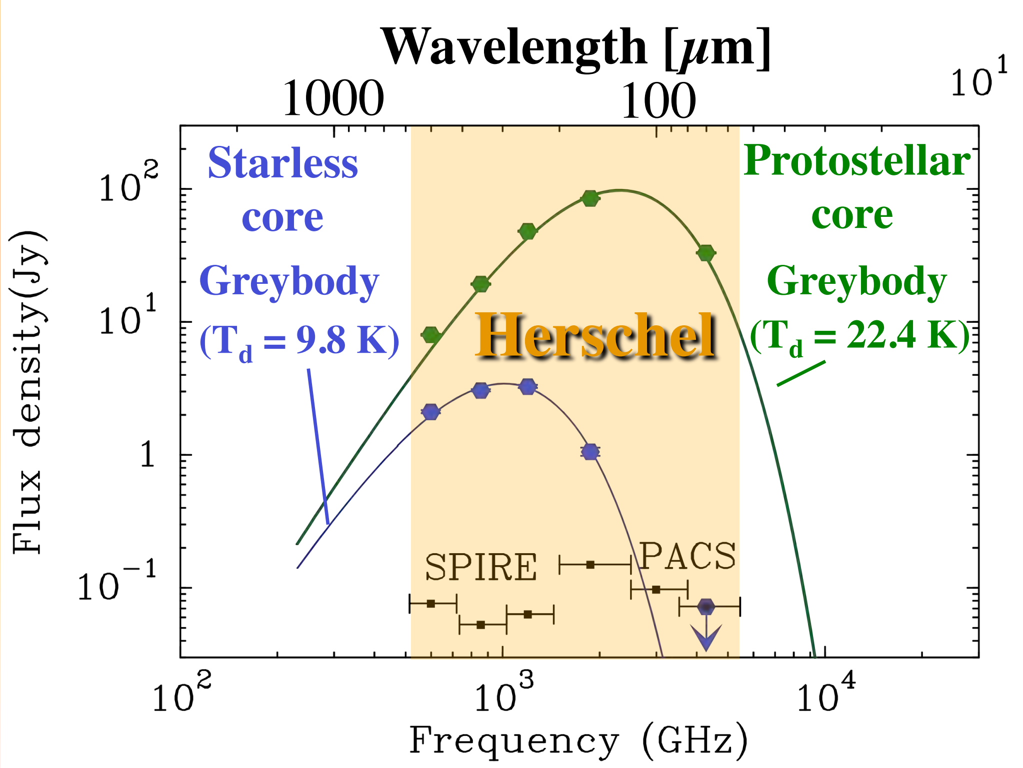
$$M = \frac{S_\nu \, d^2}{B_\nu(T_d)\,\kappa_\nu} \qquad \Sigma = \frac{I_\nu}{B_\nu(T_d)\,\kappa_\nu}$$

S_ν : Integrated flux density

I_ν : Surface brightness

Σ : Column density (g cm^{-2})

- **$\lambda \sim$ 100–500 μm : good diagnostic of the dust temperature (T_d)**



With *Herschel*, simple dust temperature estimates based on greybody fits to the observed SEDs (5-6 points between 70 and 500 μm):

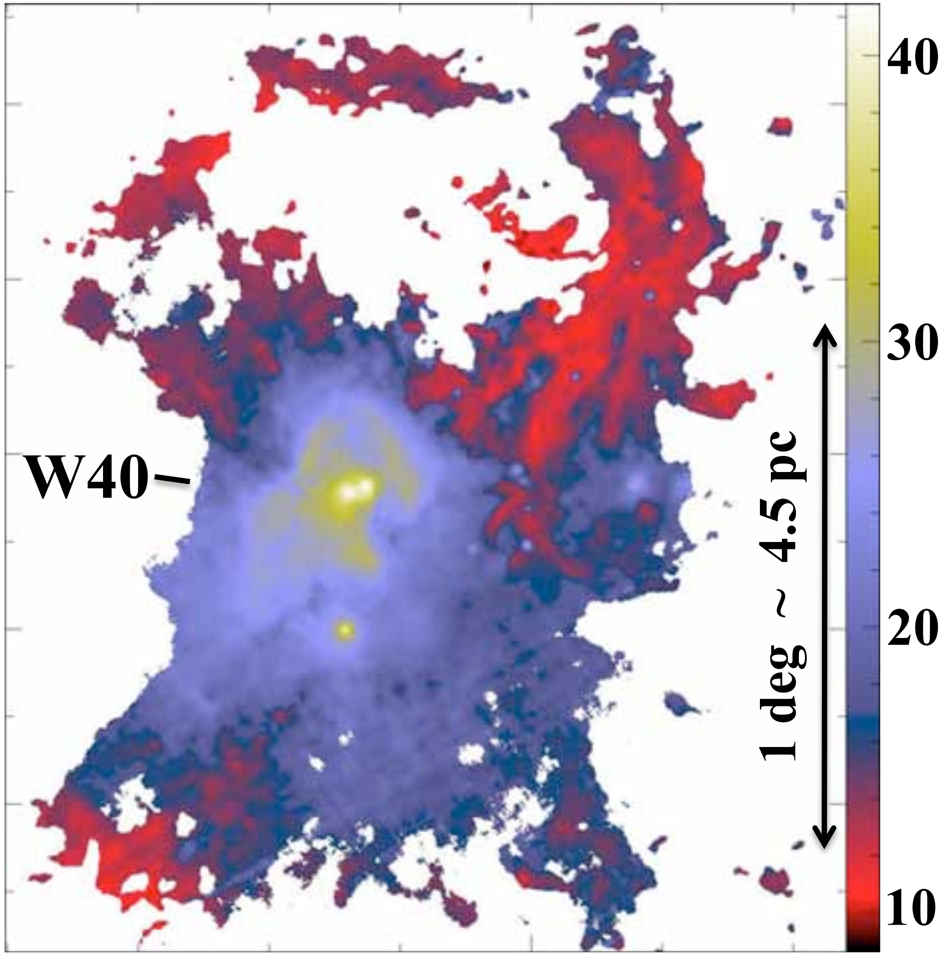
$$I_\nu \sim B_\nu(T_d)(1 - e^{-\tau_\nu})$$
$$\sim B_\nu(T_d)\,\tau_\nu = B_\nu(T_d)\,\kappa_\nu\,\Sigma$$

κ_ν = dust opacity

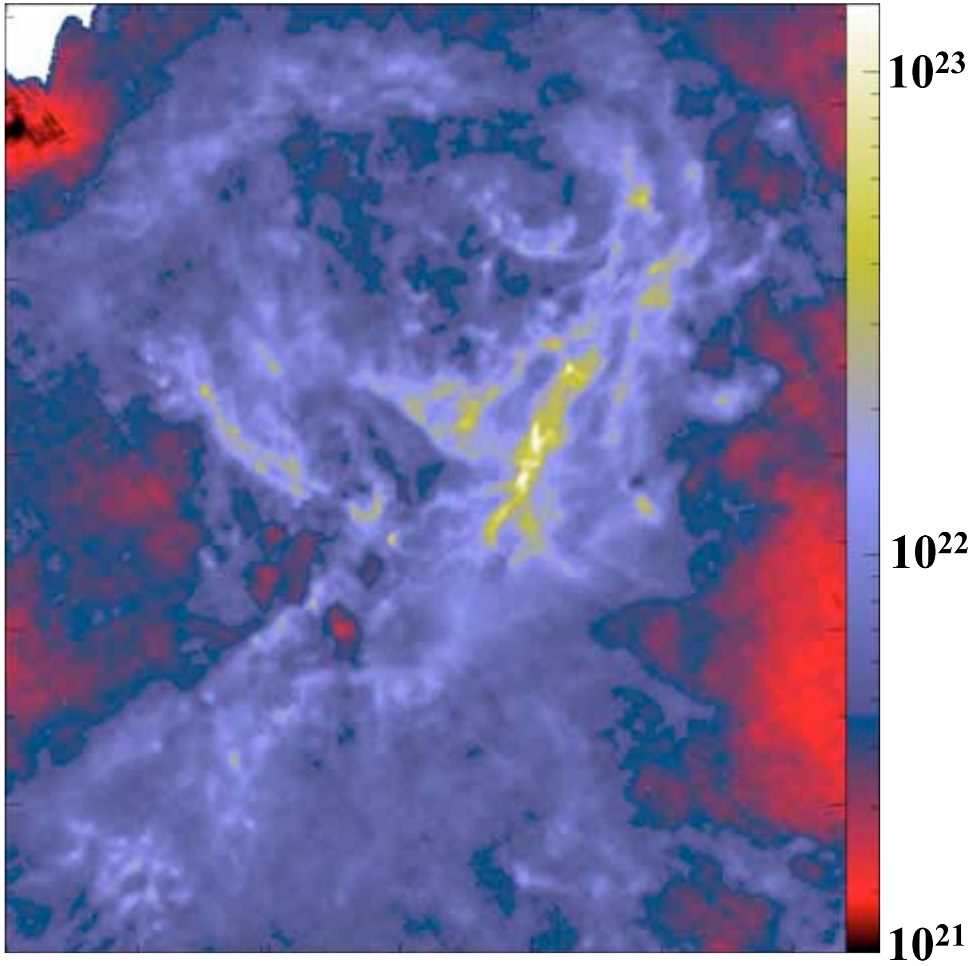
(eg Hildebrand 83; Ossenkopf & Henning 94)

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)



Dense cores form primarily in filaments

Morphological Component Analysis:

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

***Herschel* Column density map**

=

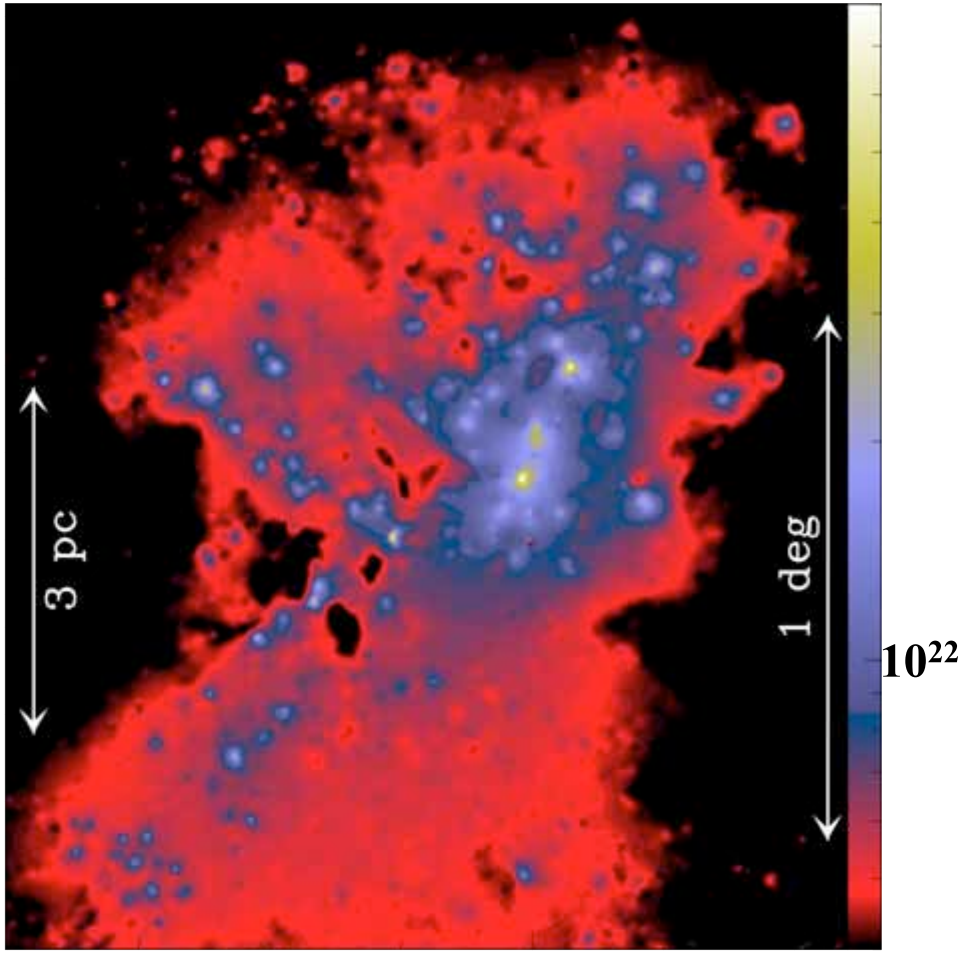
Cores

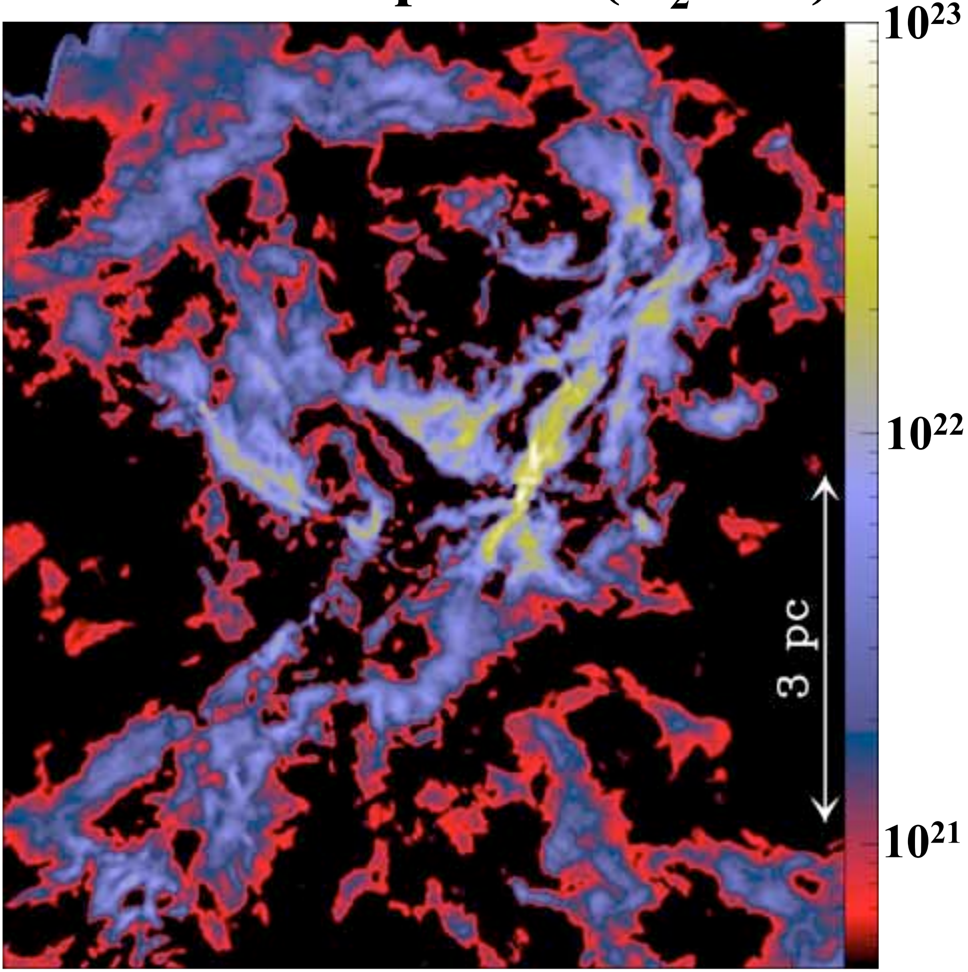
Wavelet component (H_2/cm^2)

+

Filaments

Curvelet component (H_2/cm^2)

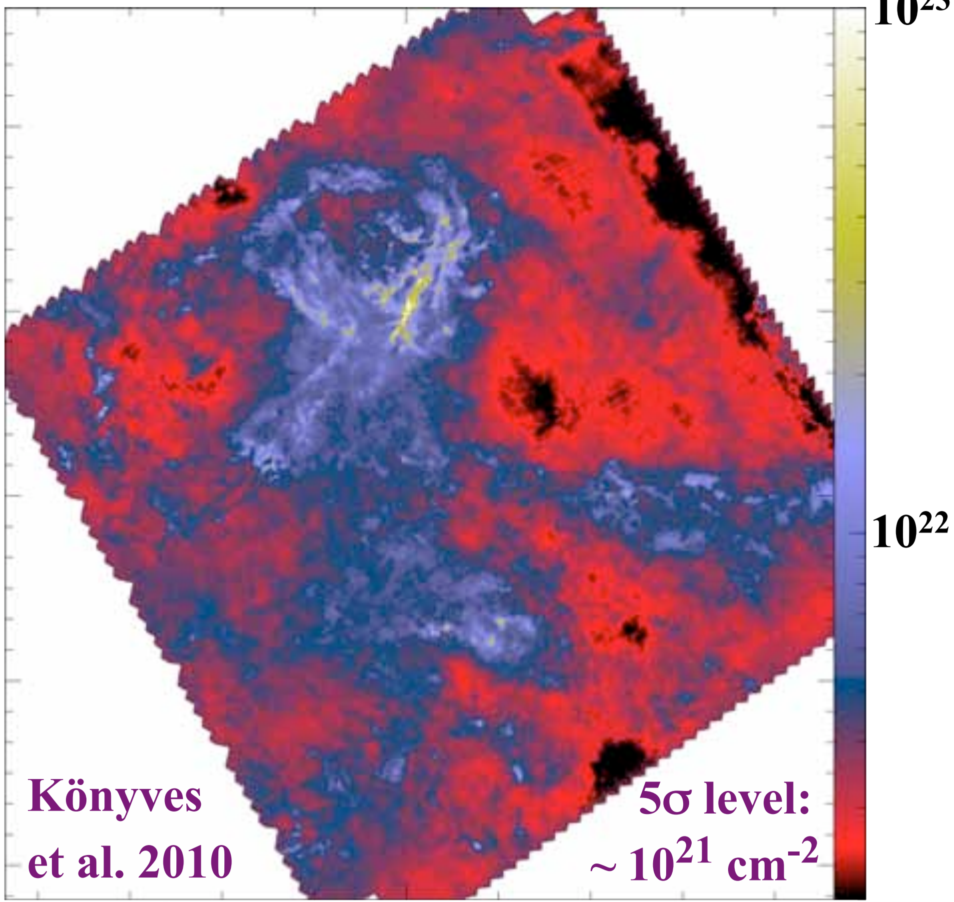




Aquila: `Compact' Source Extraction

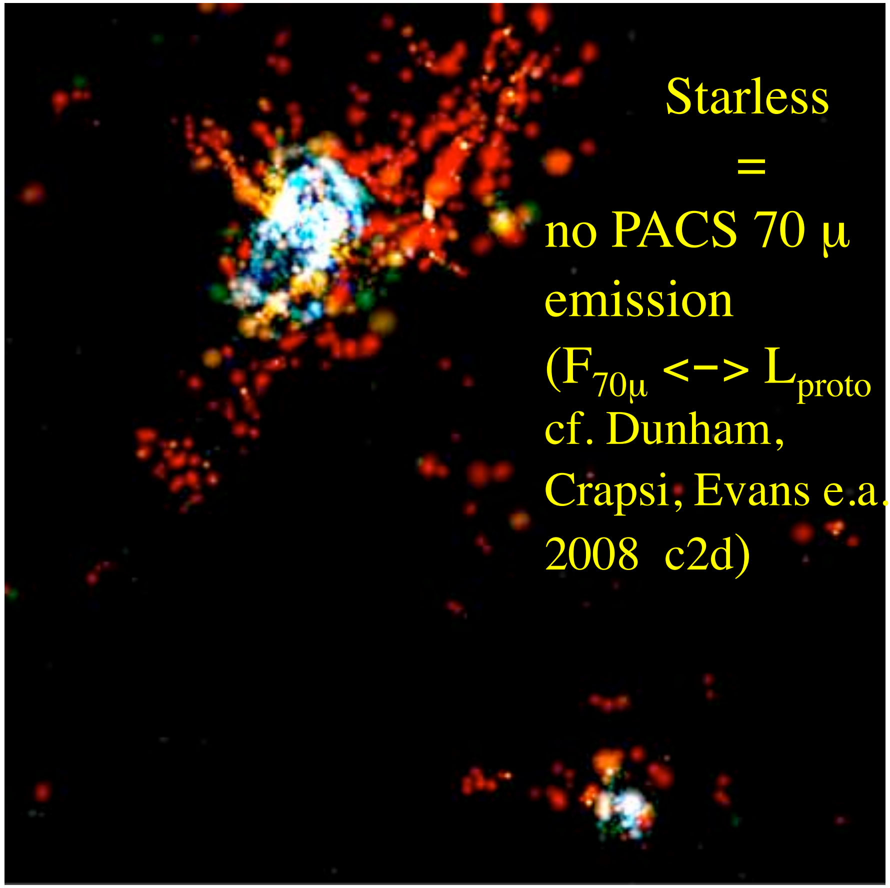
(using "getsources" – A. Menshchikov et al. 2010)

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



3 deg ~ 14 pc

Spatial distribution of extracted cores
- 541 starless
- 201 YSOs



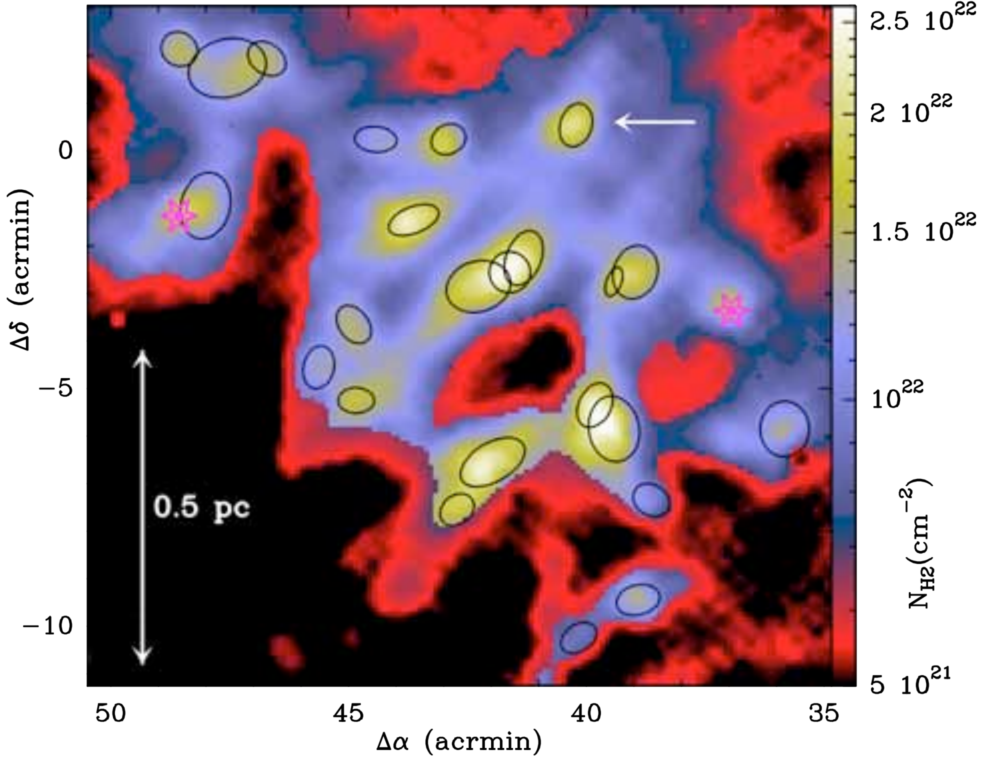
Starless
=
no PACS 70 μ emission
($F_{70\mu}$ <–> L_{proto}
cf. Dunham, Crapsi, Evans e.a. 2008 c2d)

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

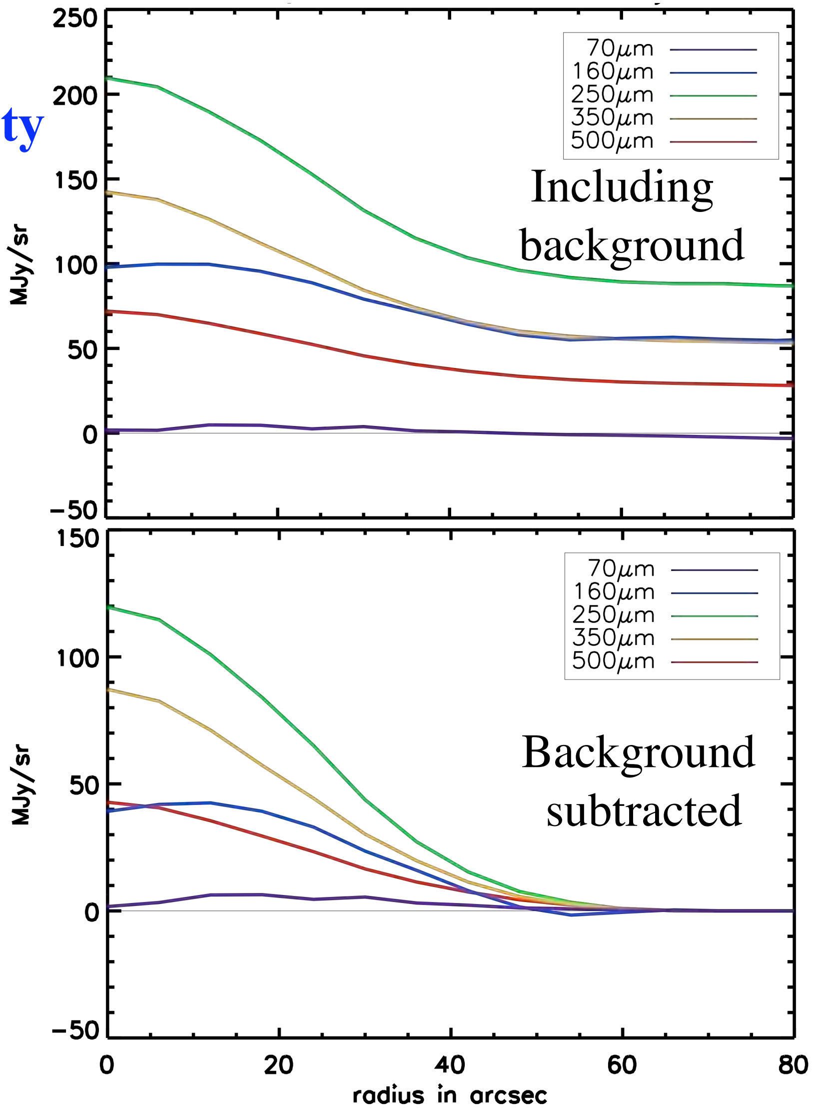
Herschel **N_{H_2} map (cm^{-2})**



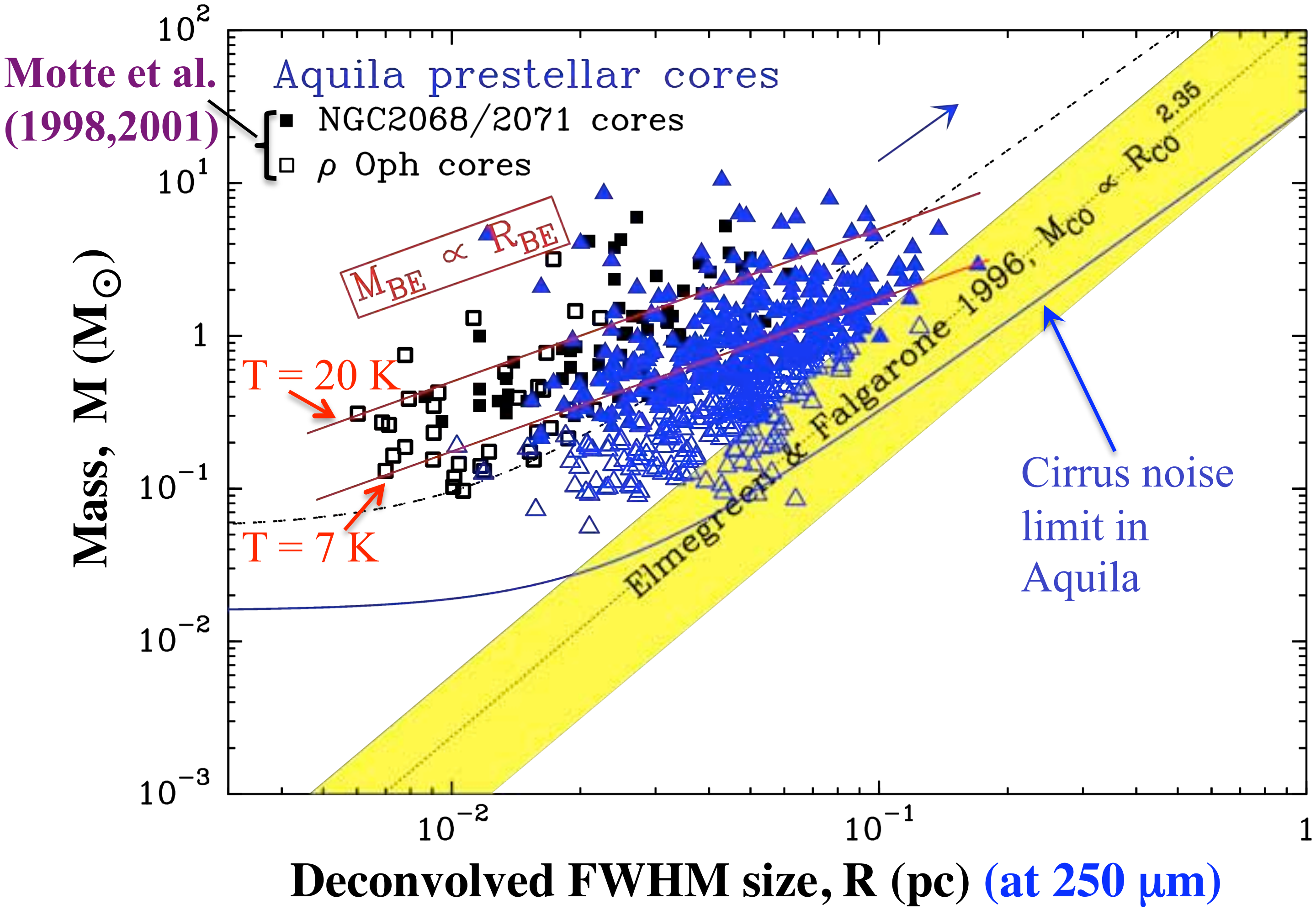
Ellipses: FWHM sizes of 24 starless cores at 250 µm

Könyves et al. 2010, A&A special issue

Radial intensity profiles



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

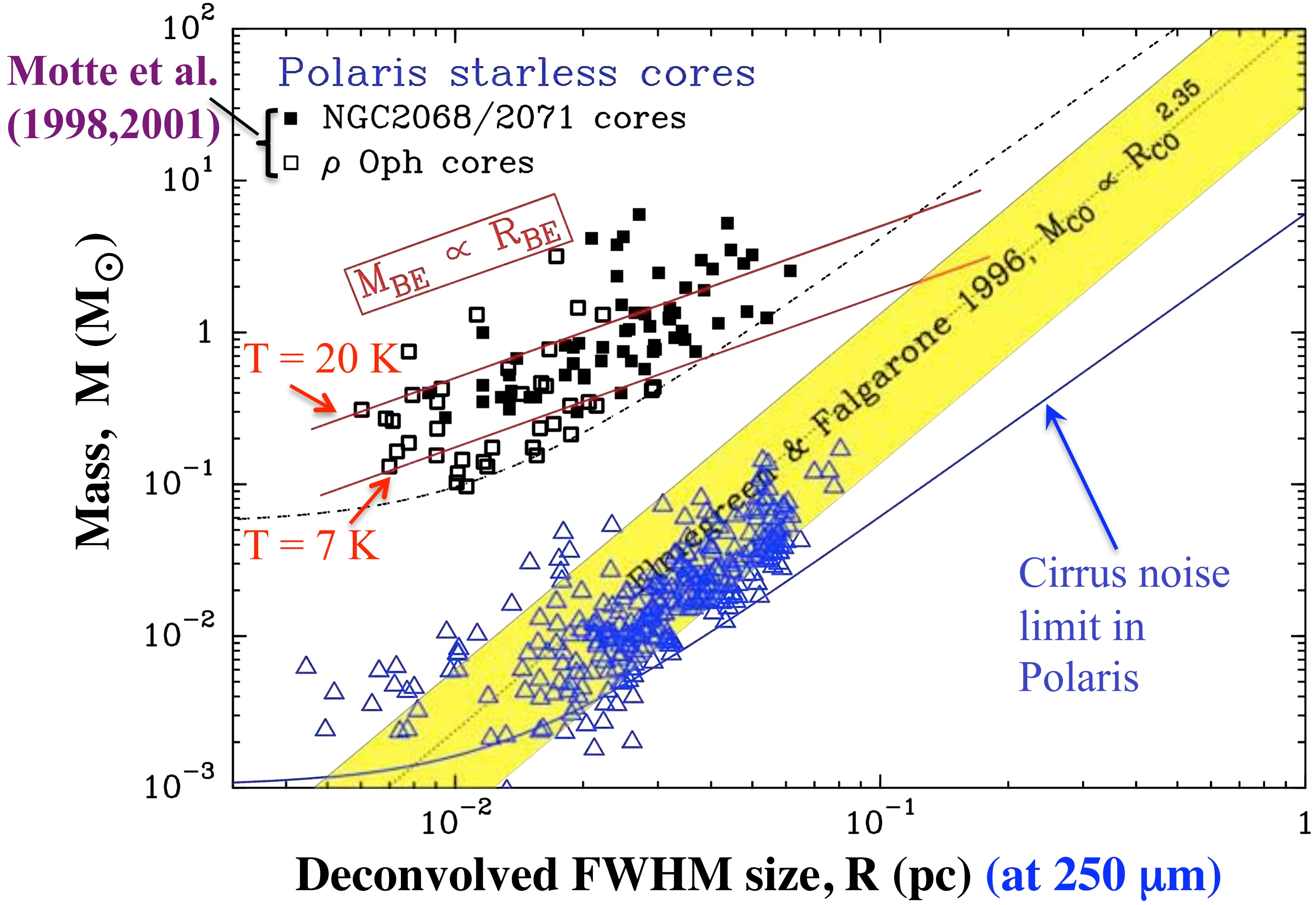


➢ **> 60% are likely prestellar in nature**

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

Most of the ~300 Polaris starless cores are unbound

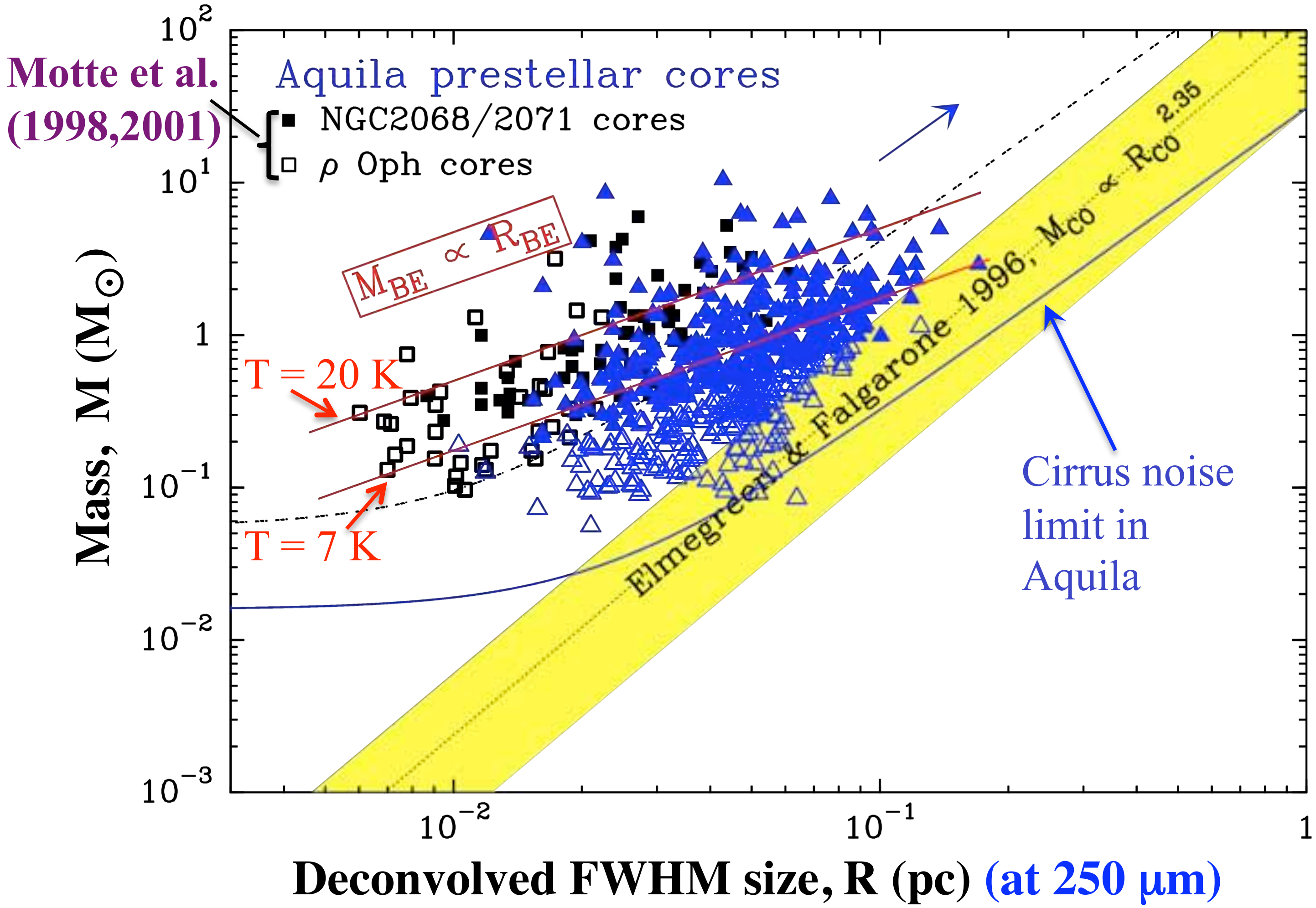


➢ not (yet ?) prestellar

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

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

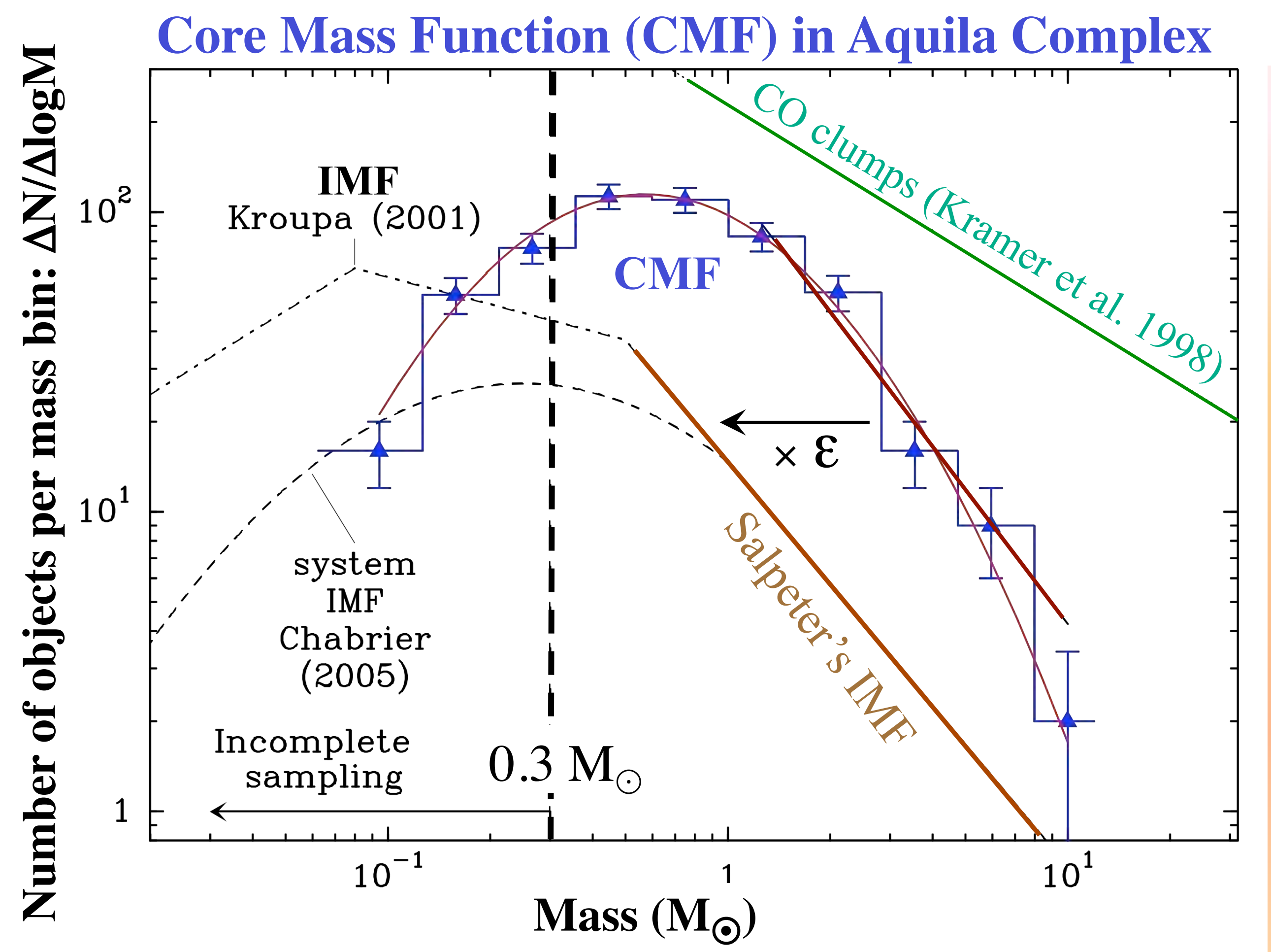
Confirming the link between the prestellar CMF & the IMF

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

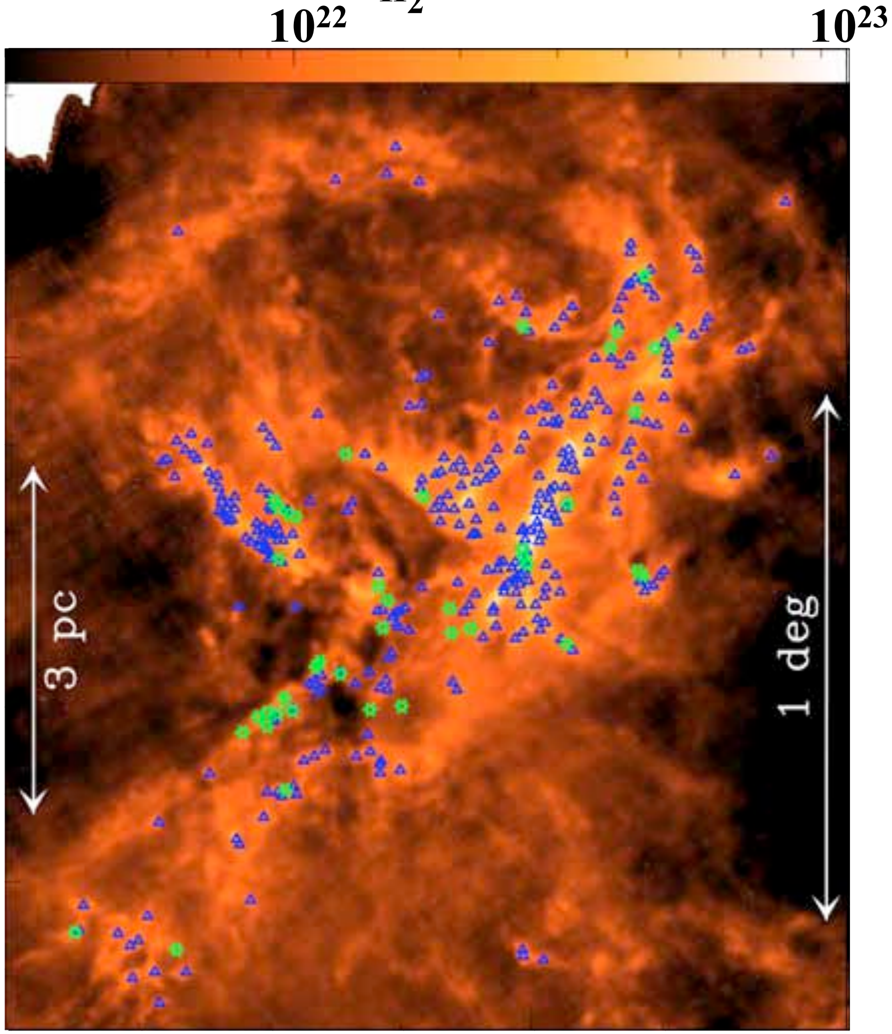


- **Good (~ one-to-one) correspondence between core mass and stellar system mass: $M_* = \varepsilon\, M_{core}$ with $\varepsilon \sim 0.2$-0.4 in Aquila**
- **The IMF is at least partly determined by pre-collapse cloud fragmentation** (cf. models by Padoan & Nordlund 2002, Hennebelle & Chabrier 2008)

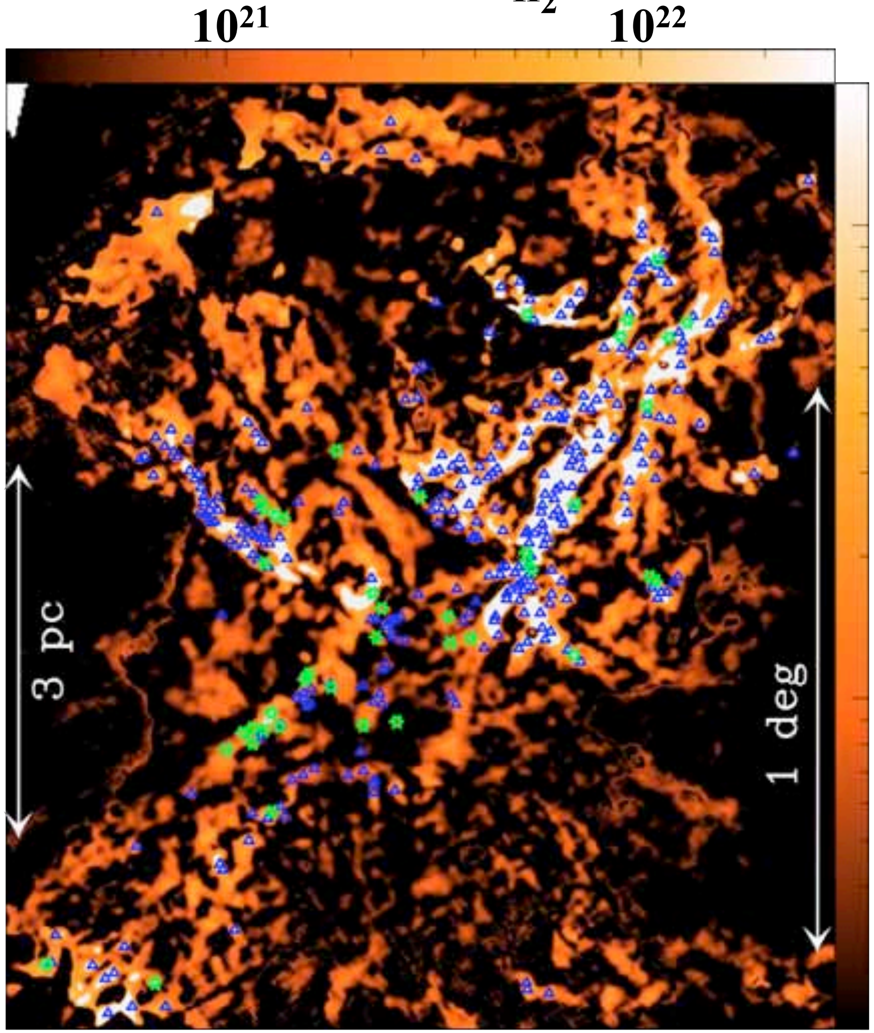
Prestellar cores form out of a filamentary background

★ : Class 0 protostars △ : Prestellar cores

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

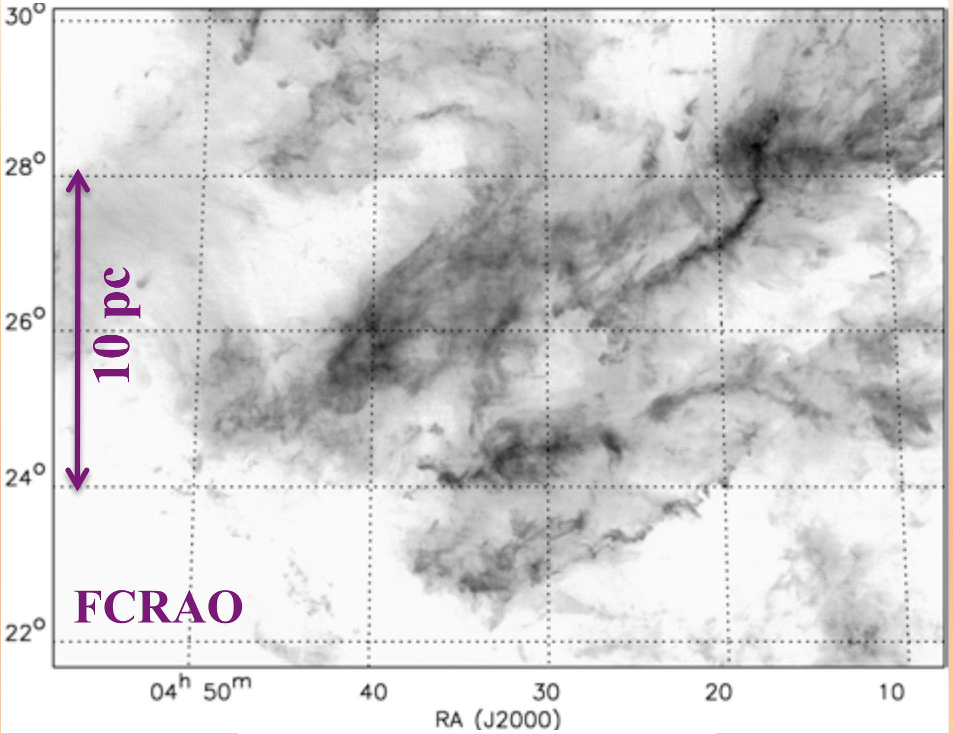


Aquila curvelet N_{H_2} map (cm^{-2})



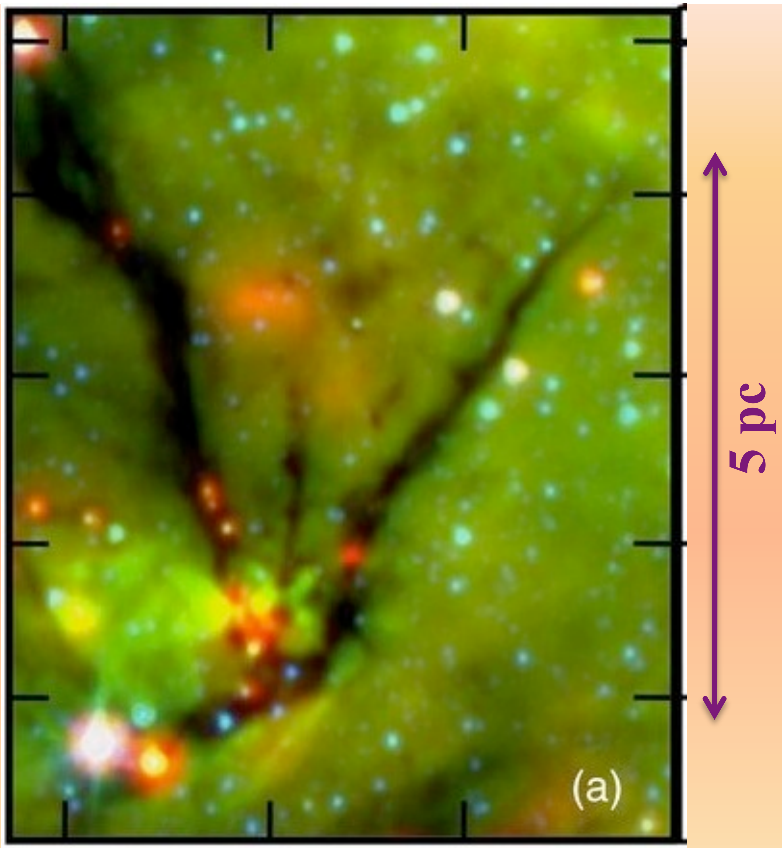
Evidence of the importance of filaments prior to *Herschel*

Taurus
H_2 column density from CO(1-0)



Goldsmith et al. 2008

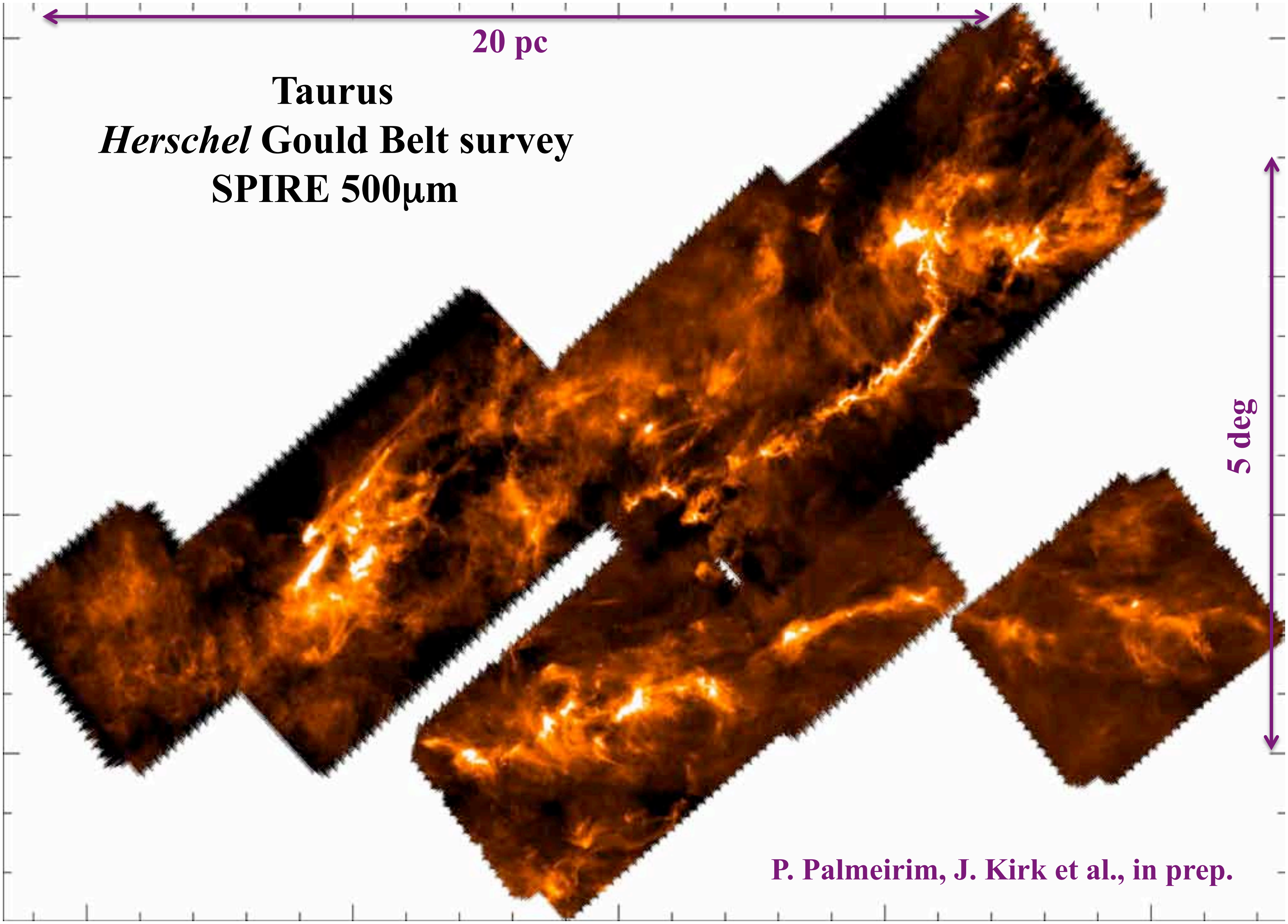
Infrared Dark Clouds
***Spitzer* (3.6/8/24 μm) composite**



Peretto & Fuller 2009, 2010

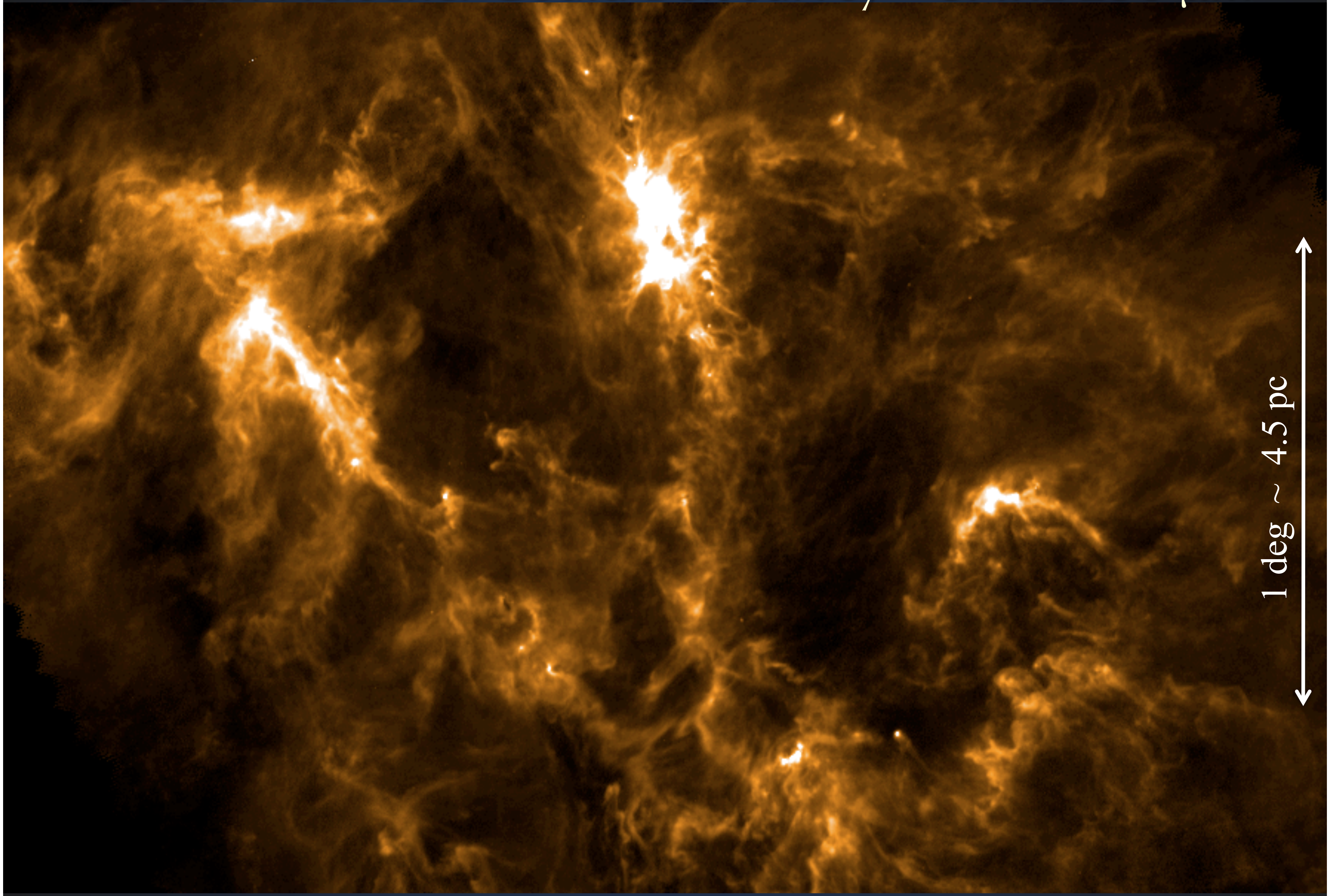
See also:
Schneider & Elmegreen 1979;
Abergel et al. 1994; Hartmann 2002;
Hatchell et al. 2005; Myers 2009 …

Taurus
Herschel Gould Belt survey
SPIRE 500μm



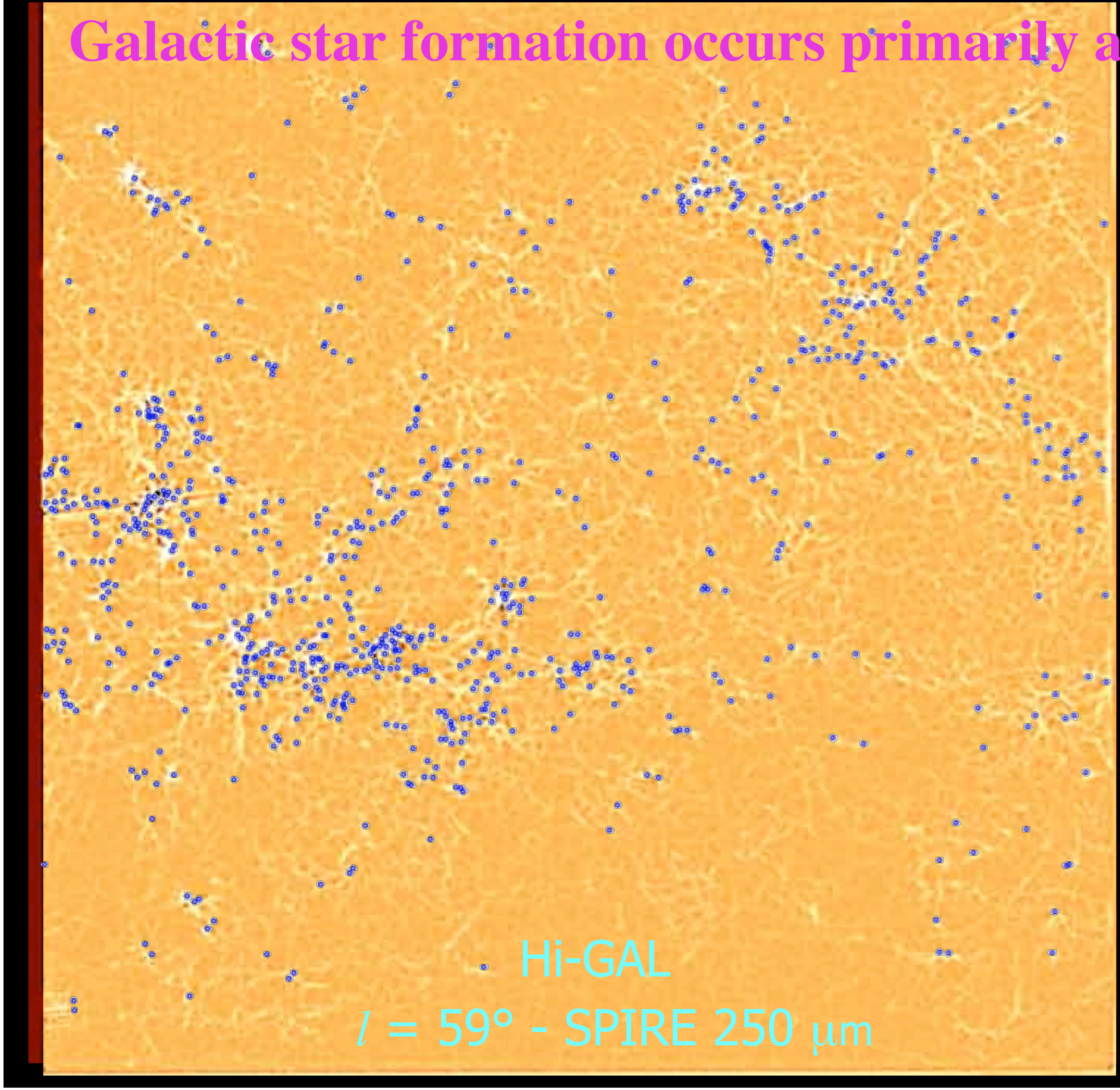
P. Palmeirim, J. Kirk et al., in prep.

Perseus: *Herschel* Gould Belt survey – SPIRE 250 μm



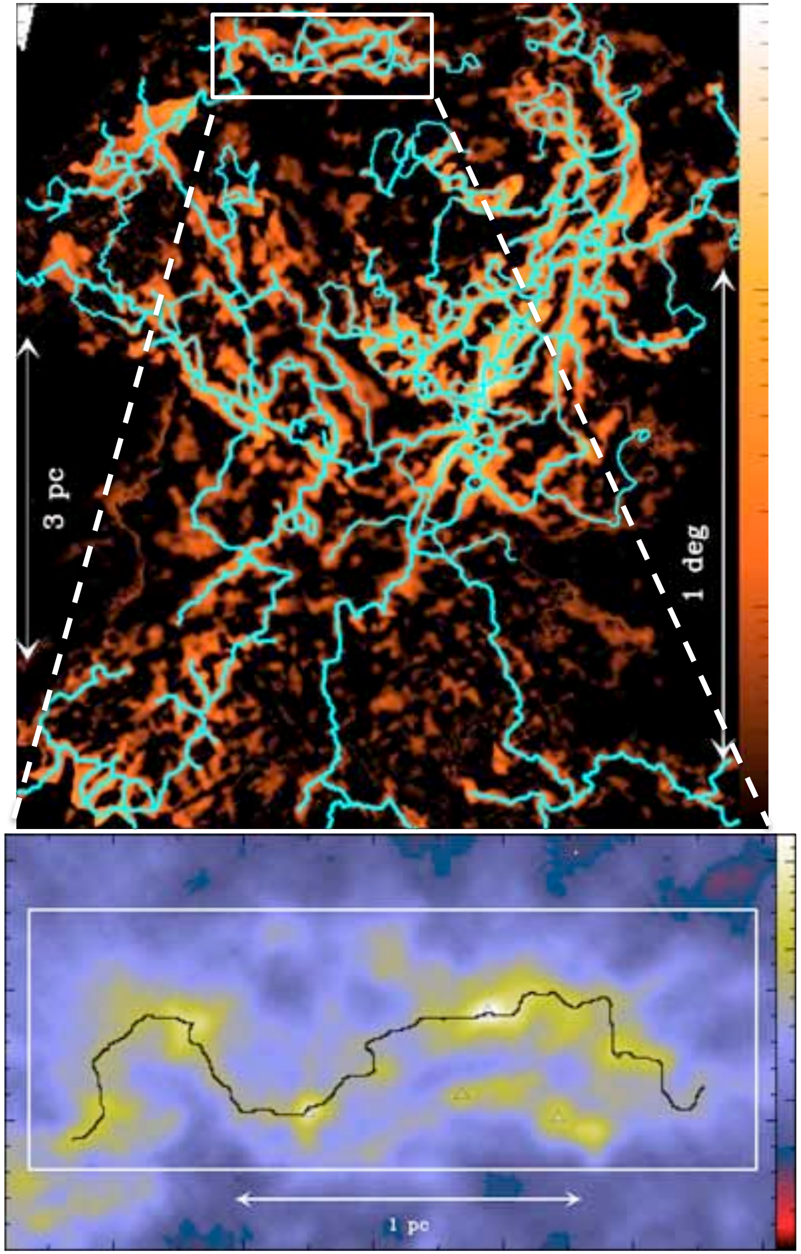
Pezzuto et al.; Sadavoy, Di Francesco et al. + *Herschel* Gould Belt survey consortium (2010)

Galactic star formation occurs primarily along filaments

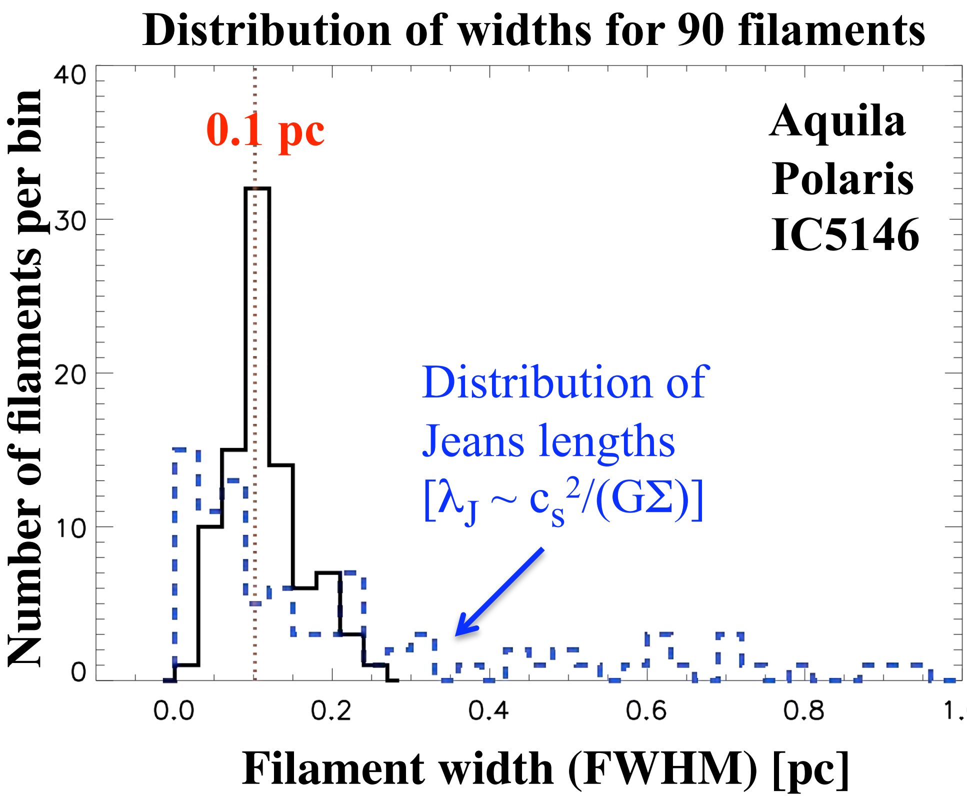


Molinari
et al. 2010
A&A special issue

Preliminary radial profile analysis of the filaments



- Typical FWHM width ~ 0.1 pc (deconvolved)



Using the 'skeleton' or DisPerSE algorithm (Sousbie, Pichon et al. 2008, 2010) to trace the ridge of each filament

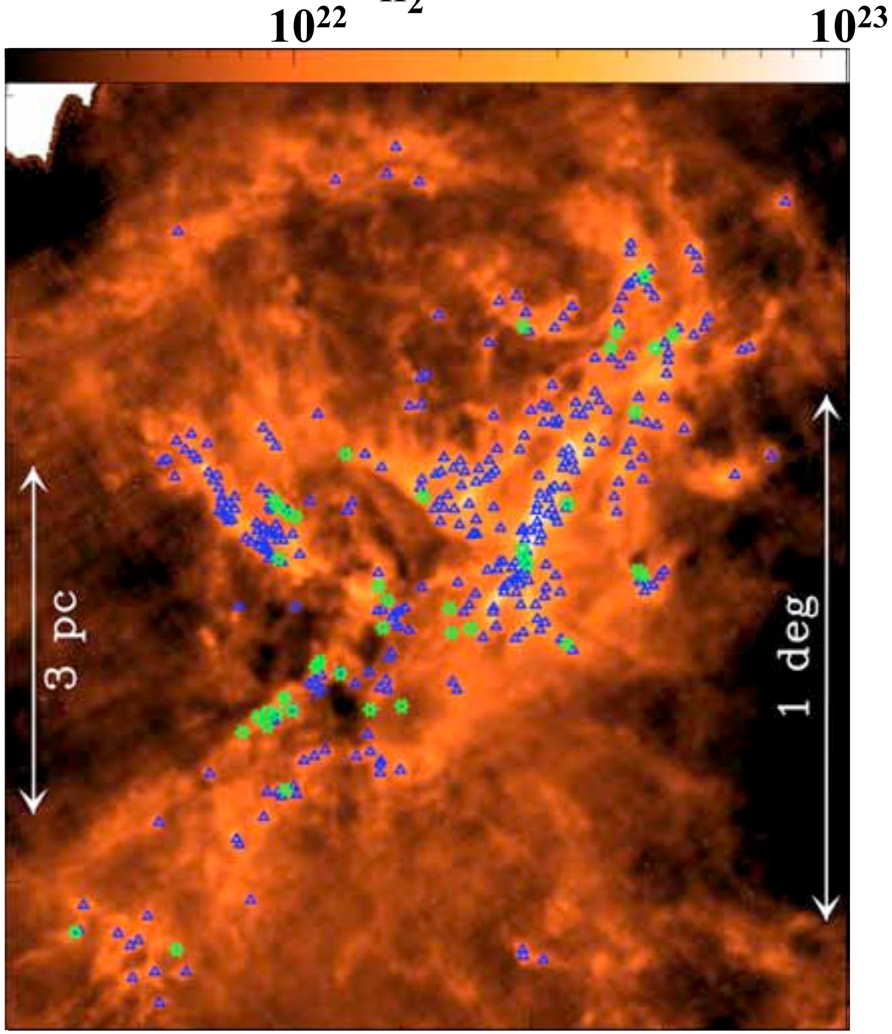
D. Arzoumanian et al., in prep.

Prestellar cores form out of a filamentary background

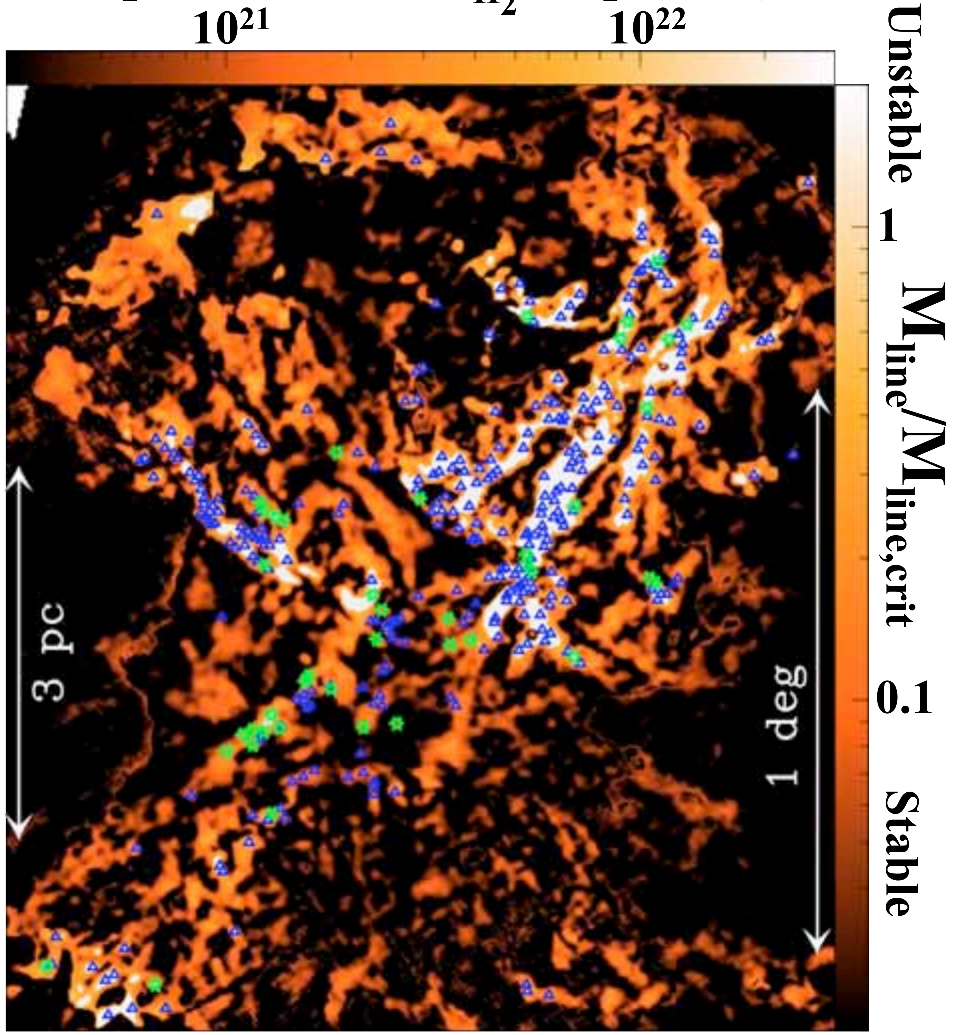
★ : Class 0 protostars

△: Prestellar cores - 90% found at A_V(back) > 7

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

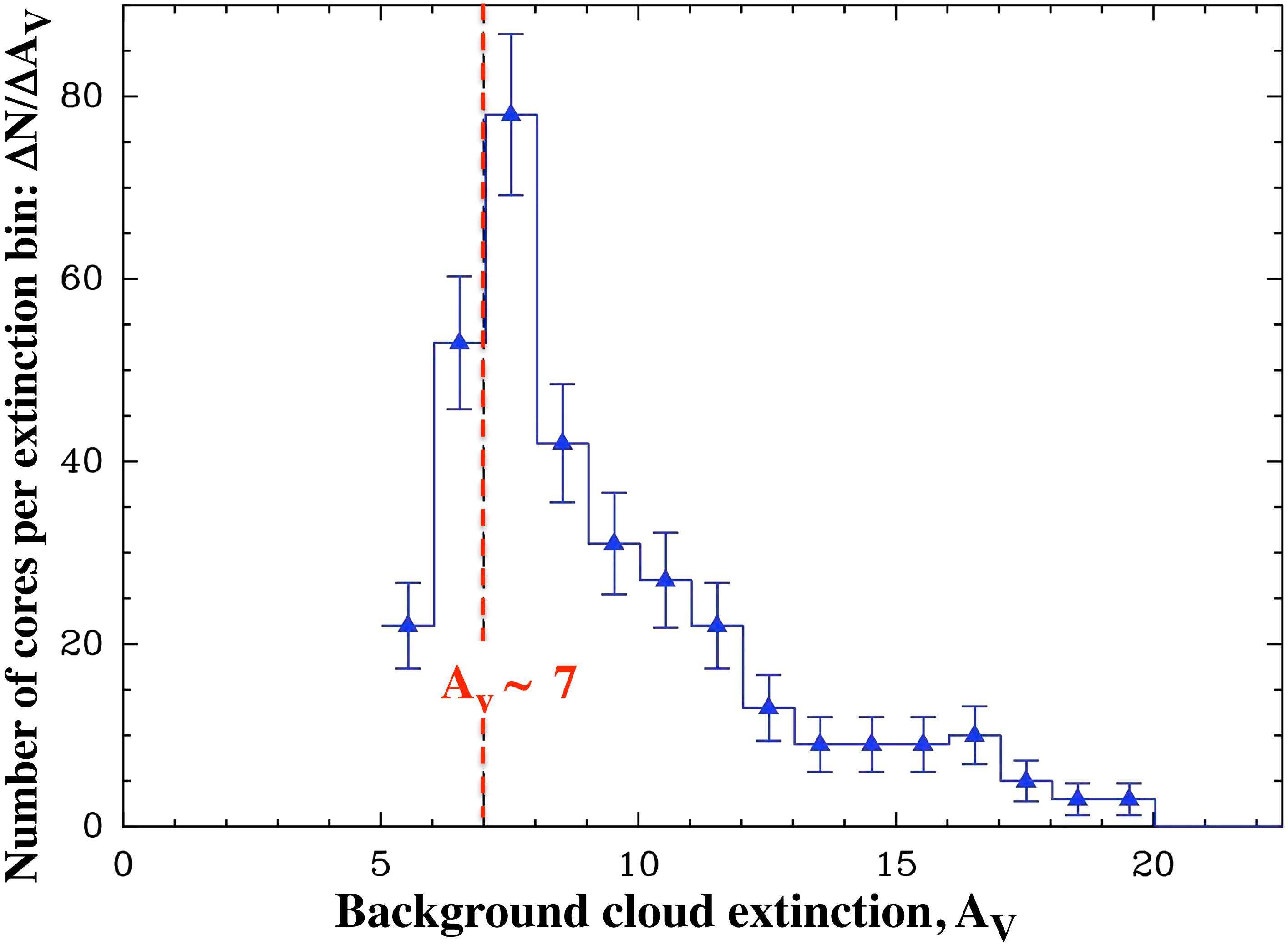


Aquila curvelet N_{H_2} map (cm^{-2})



Confirmation of an extinction "threshold" for the formation of prestellar cores

Distribution of background extinctions for the Aquila prestellar cores



In Aquila, ~90% of the prestellar cores identified with *Herschel* are found above A$_v$ ~ 7 ⇔ $\Sigma \sim 150\ M_\odot\ pc^{-2}$

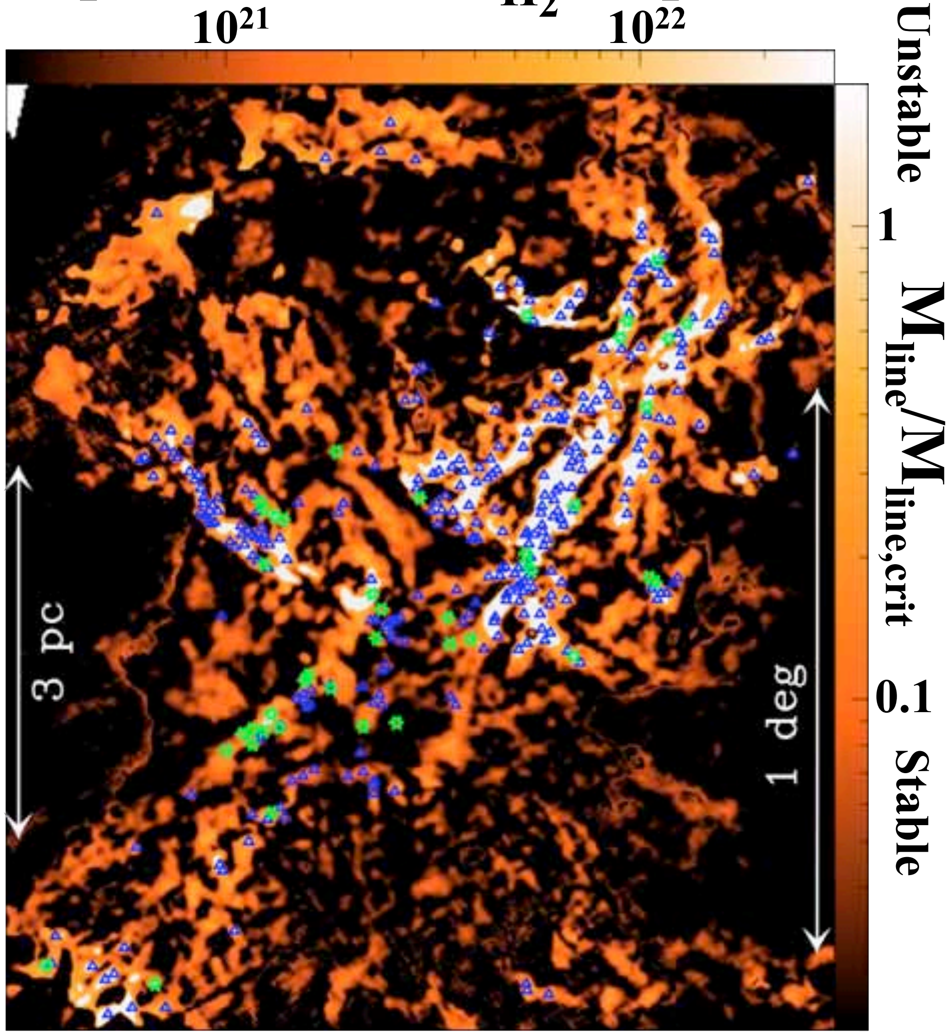
cf. Onishi et al. 1998 (Taurus)

Johnstone, Di Francesco, Kirk '04 (Ophiuchus)

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

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

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



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

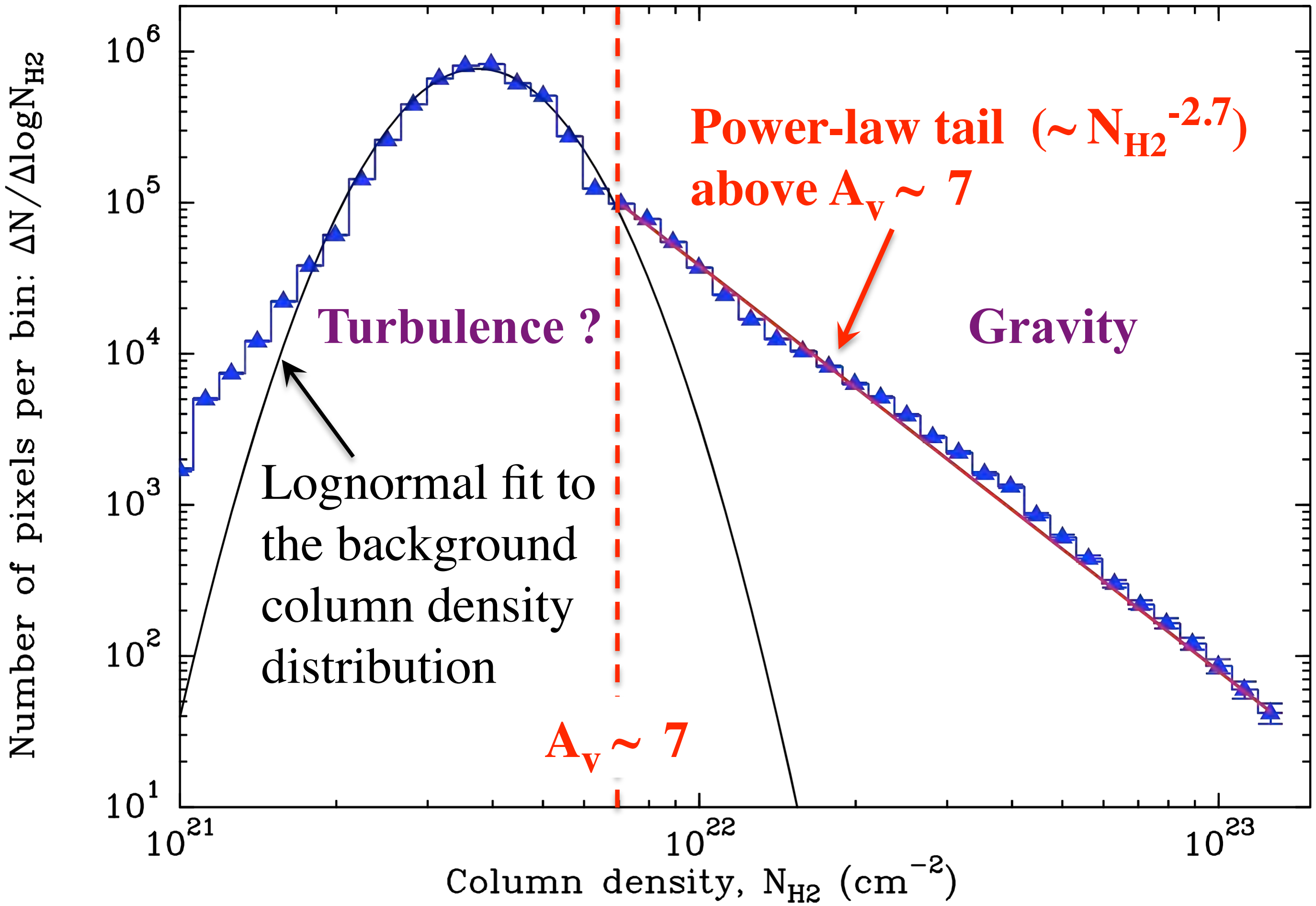
- ➢ Simple estimate:

$M_{line} \propto N_{H2} \times$ Width (~ 0.1 pc)

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

Other manifestation of the threshold

Column Density PDF for the Aquila Complex



Given the typical filament width ~ 0.1 pc (FWHM), **$A_V \sim 7$ (or $\Sigma_{th} \sim 150\ M_\odot\ pc^{-2}$) roughly corresponds to $M_{line, crit} \sim 15$ Mo/pc**

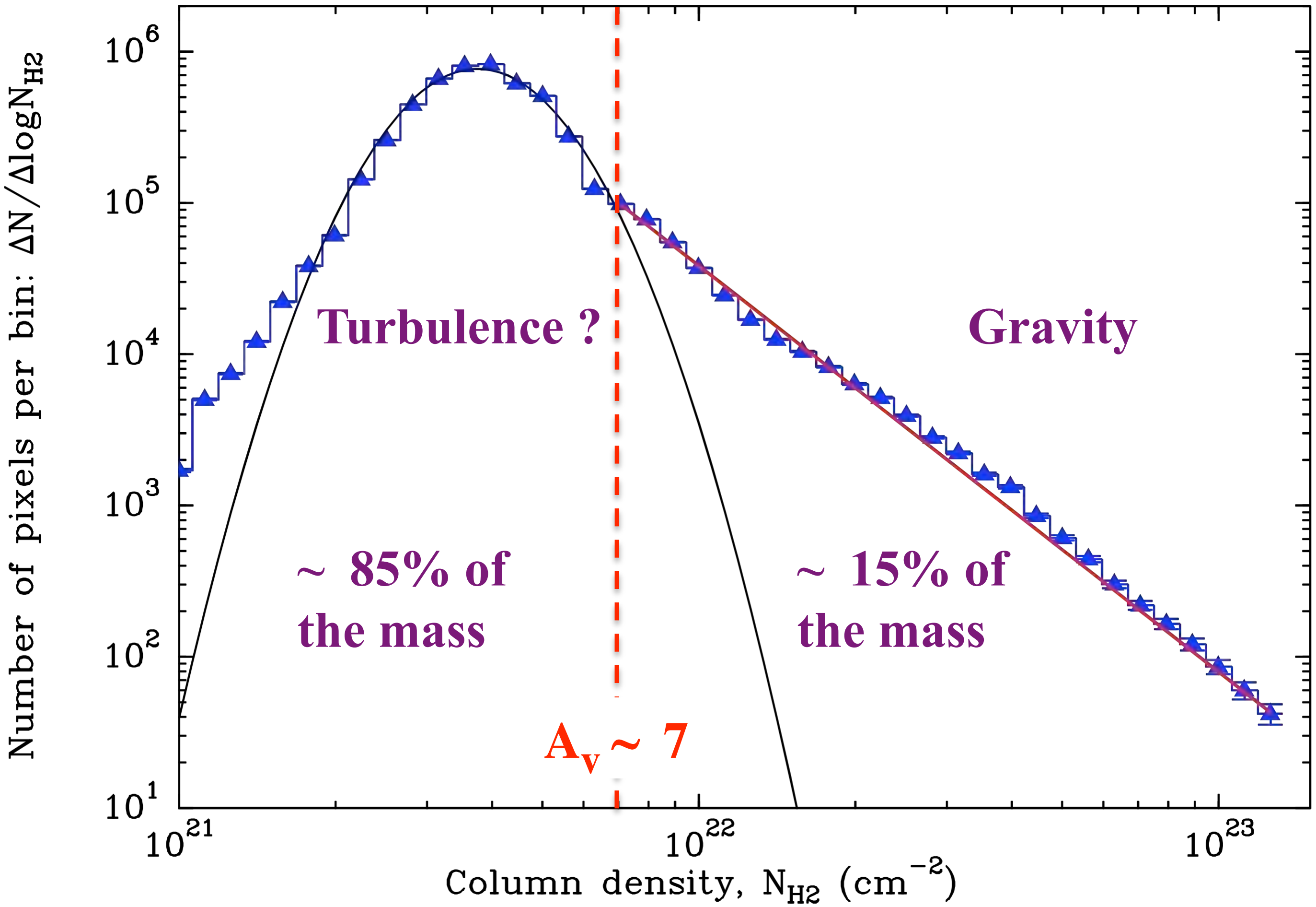
⇔

Threshold above which the filaments are gravitationally unstable

- **Similar column density PDFs in near-IR extinction studies (Kainulainen et al. '09)**
- **Supersonic turbulence generates lognormal column density PDFs (e.g. Ostriker et al. 2001, but see Tassis et al. 2010); gravity creates power-law tails**

Implication of the extinction threshold

Column Density PDF for the Aquila Complex

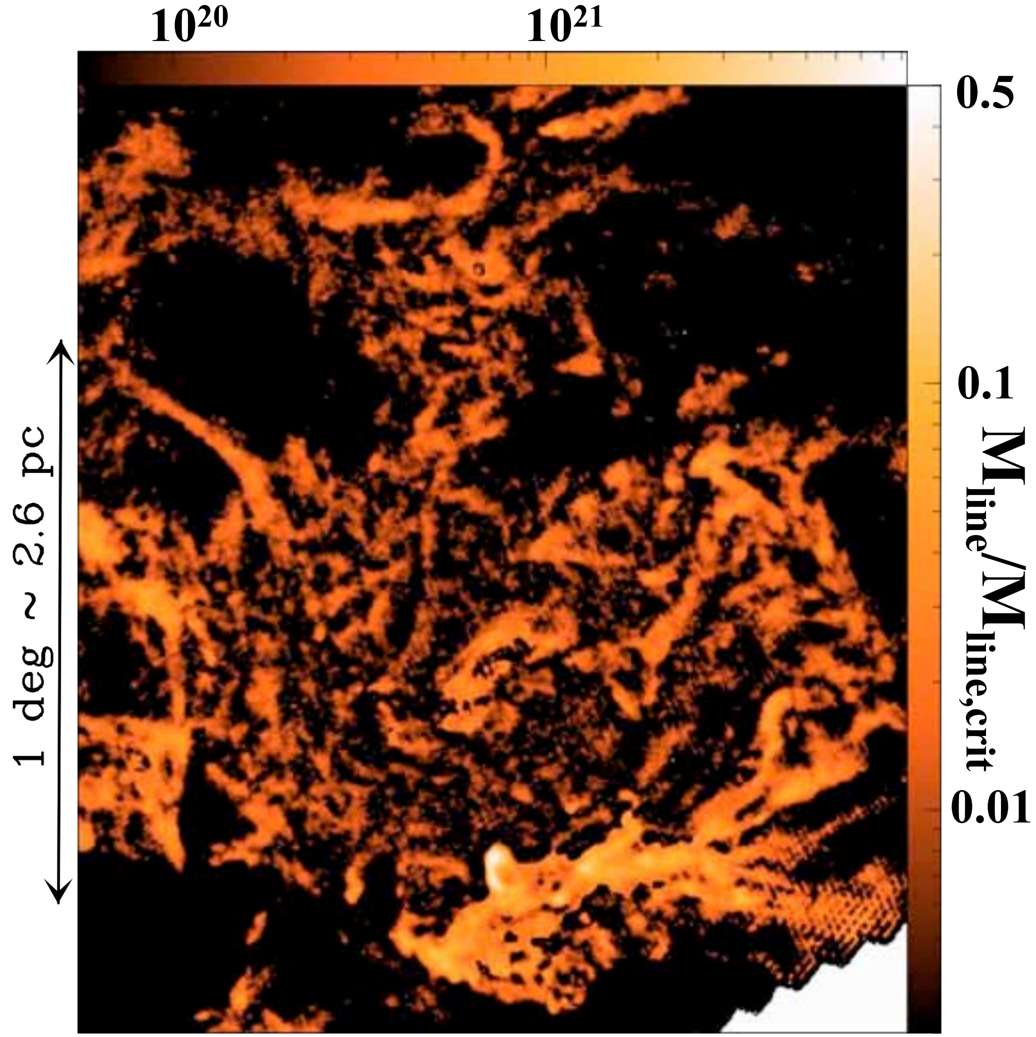


Only ~ 15% of the molecular cloud's mass above A_V ~ 7 threshold, only ~ 2% of the mass in prestellar dense cores → Inefficiency of the star formation process

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

No prestellar cores (yet ?) in Polaris

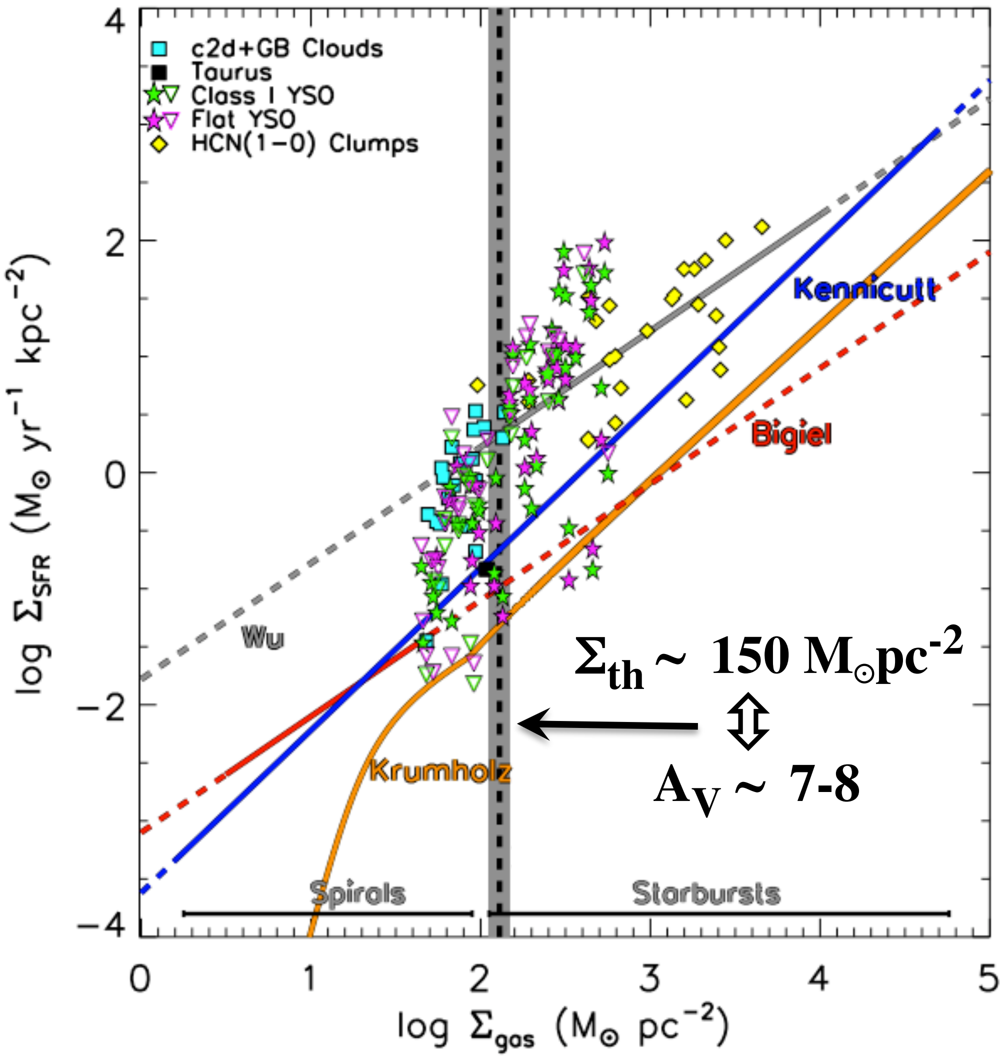
Polaris curvelet N_{H_2} map (cm^{-2})



- 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

Importance of the star formation threshold on (extra)galactic scales

Star formation rate vs. Gas surface density



$\Sigma_{th} \sim$ 150 $M_\odot pc^{-2}$

⇕

$A_V \sim$ 7-8

Heiderman, Evans et al. 2010

$\Sigma_{SFR} \propto \Sigma_{gas}$

for

$\Sigma_{gas} > \Sigma_{threshold}$

Heiderman et al. 2010

Lada et al. 2010

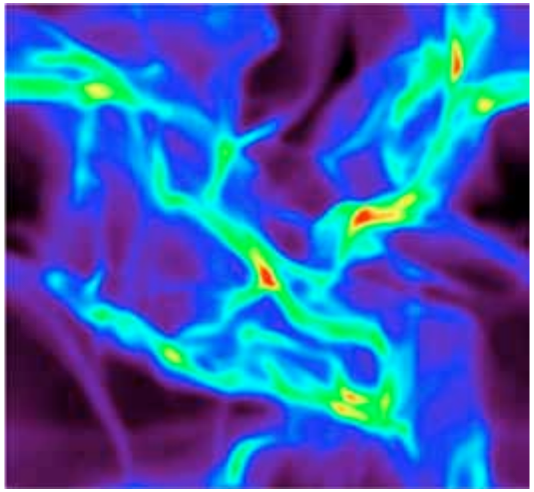
See also

Gao & Solomon 2004

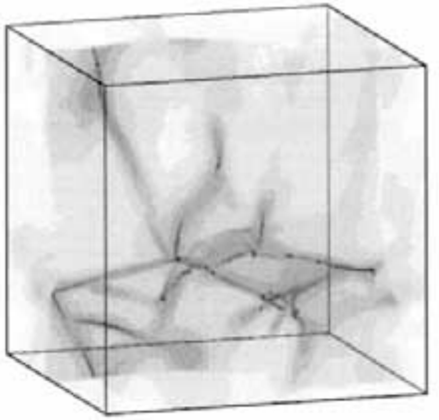
for external galaxies

Origin of the filaments: Large-scale turbulence ?

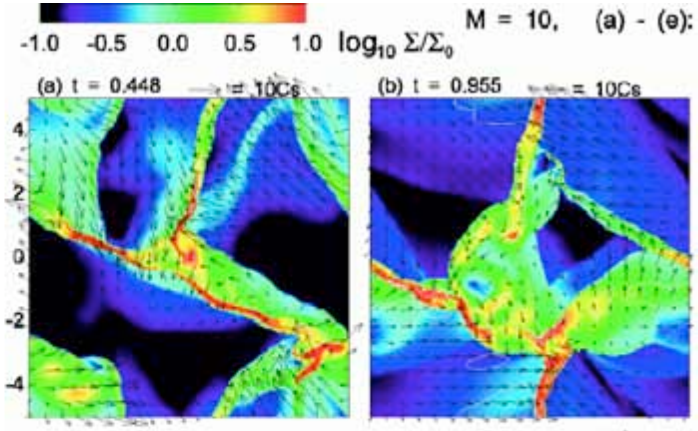
Numerical simulations including large-scale turbulence:



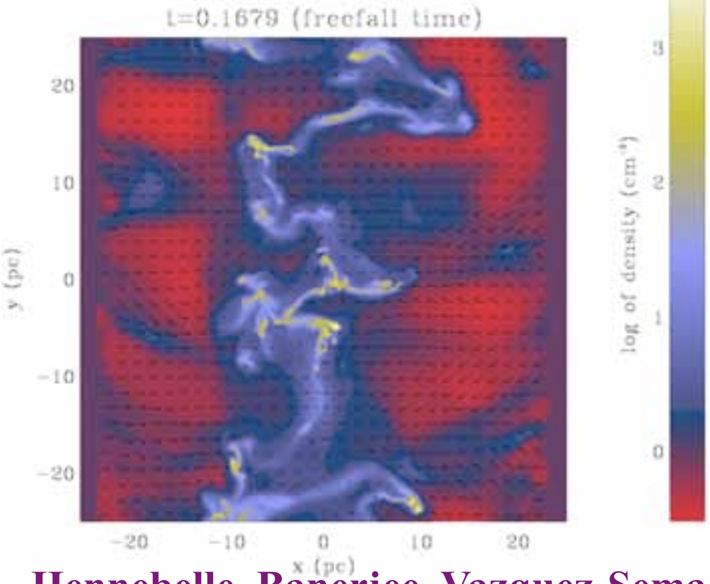
Padoan, Juvela, Goodman, Nordlund (2001)



Klessen & Burkert (2000)



Li & Nakamura (2004)

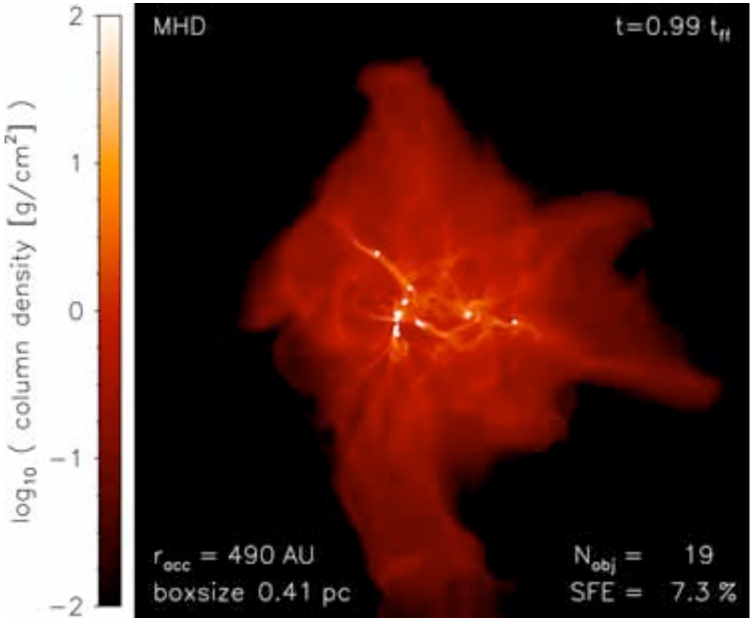


Hennebelle, Banerjee, Vazquez-Semadeni et al. (2008)

Also:

Bate, Bonnell, Bromm (2003)

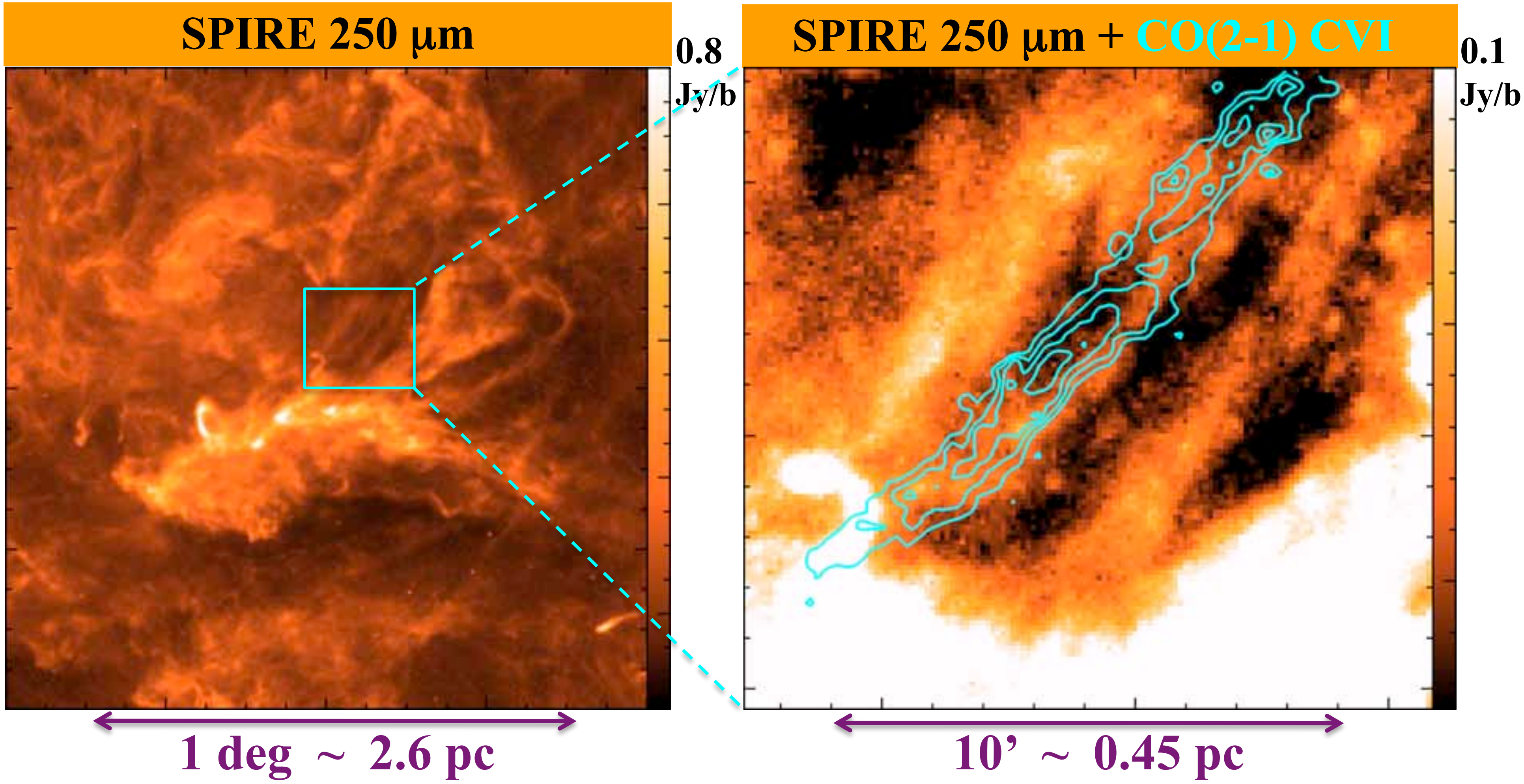
Basu, Ciolek et al. (2009)



Duffin, Pudritz et al. 2010

Turbulence dissipation and filament formation

- In Polaris, one of the most tenuous filaments detected by SPIRE coincides with a CO(2-1) structure of intense velocity shear (~ 40 km/s/pc) found at IRAM 30m (Hily-Blant & Falgarone 2009)



Filaments permeate the ISM on all scales

(from ~0.1 pc to > 50 pc)

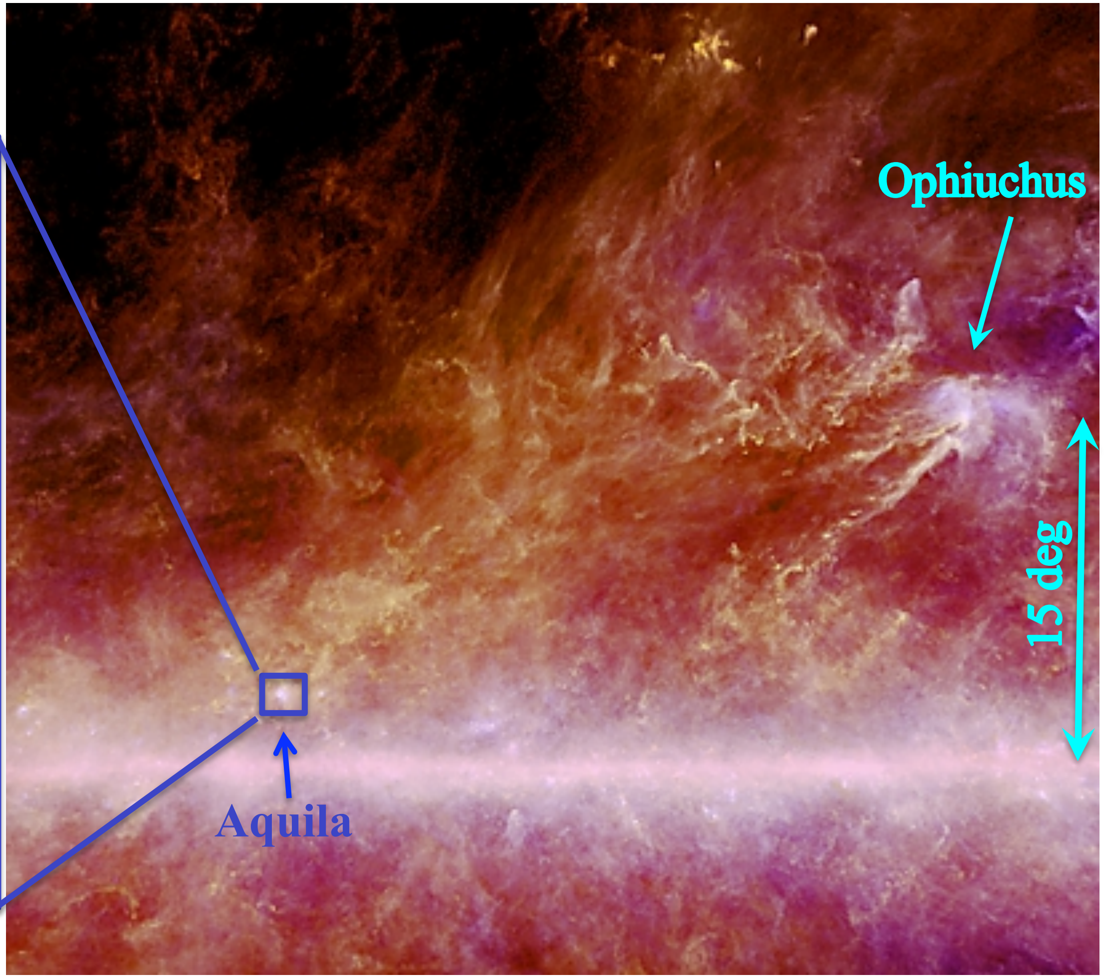
Herschel

SPIRE 500 μm
+
PACS 160/70 μm

ESA and the Gould Belt KP

Planck

HFI 540/350 μm + IRAS 100 μm



ESA and the HFI Consortium

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.