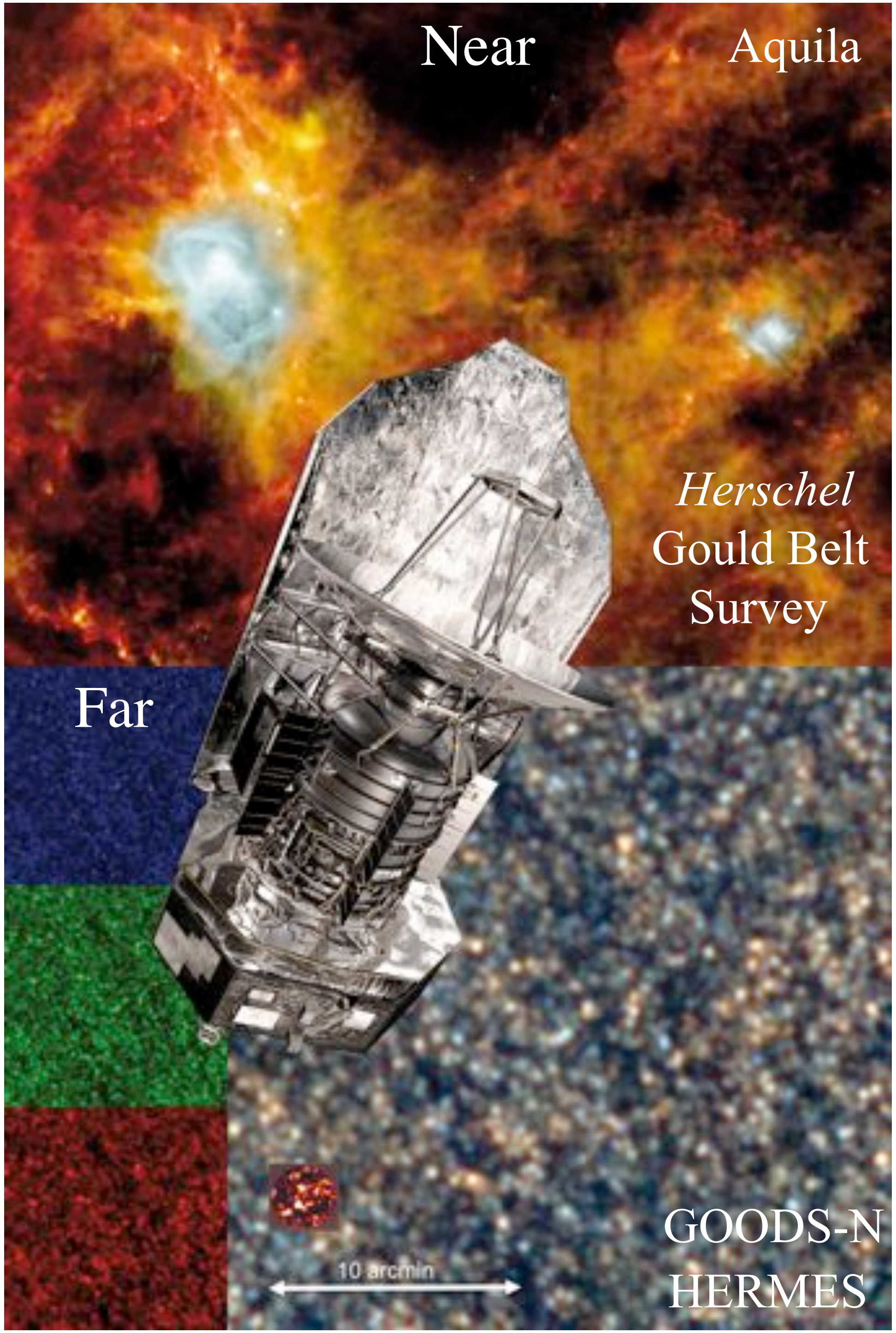
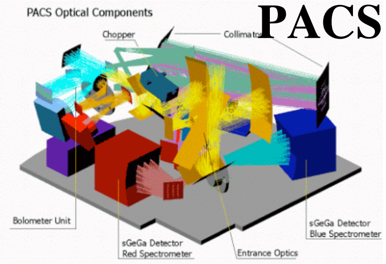


From the filamentary structure of the ISM to prestellar cores to the IMF: Recent *Herschel* results

Philippe André
CEA
Laboratoire AIM Paris-Saclay



The International School Daniel Challonge
15th Paris Cosmology Colloquium – 22/07/2011

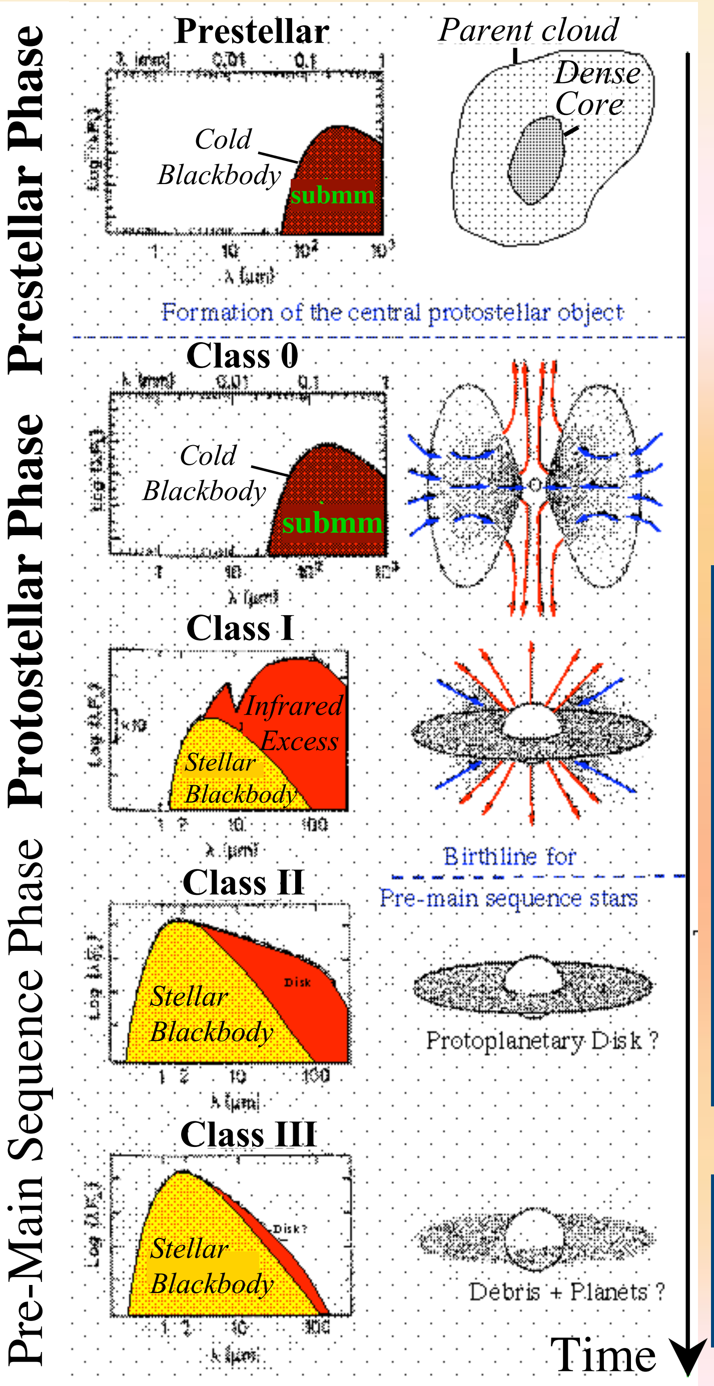
Outline:

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

- Submm observations of the initial conditions 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 core/star formation process
- Implications/Speculations

Herschel
GB survey
IC5146
Arzoumanian
et al. 2011

PACS



Lada 1987 + André, Ward-Thompson, Barsony 2000

Formation of solar-type stars

Reasonably well established evolutionary sequence but physics of early stages unclear

(cf. McKee & Ostriker 2007 vs. Shu et al. 1987)

Many open issues:

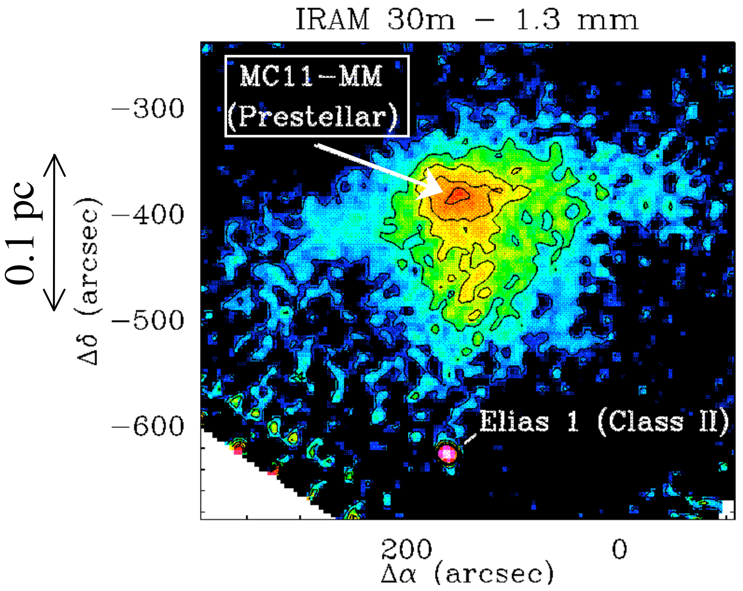
- **What determines the masses of forming stars (« IMF ») ?**
- **What controls the star formation efficiency and the star formation rate on global scales ?**
- **Is star formation rapid or slow ? …**

• **Key: Study of the earliest evolutionary stages → initial conditions of SF process**

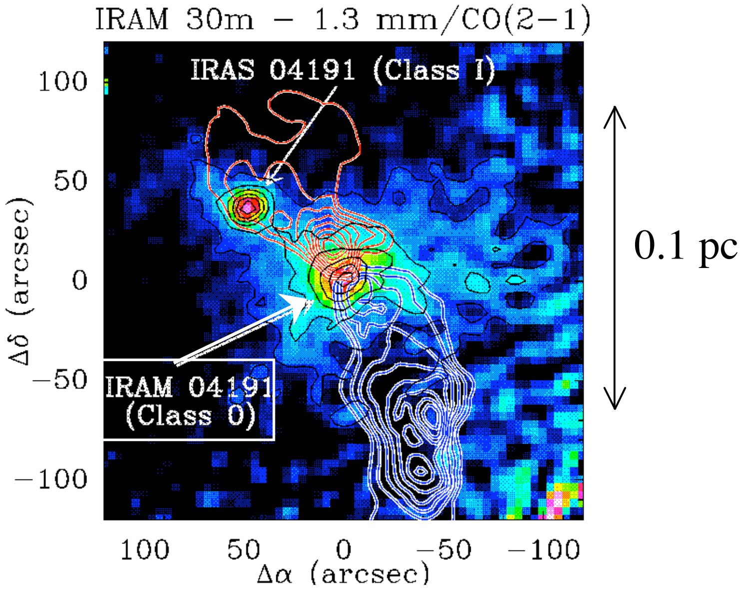
Prestellar Cores (t < 0) → Class 0 protostars (t > 0)

The progenitors of protostars

Protostars in the build-up phase



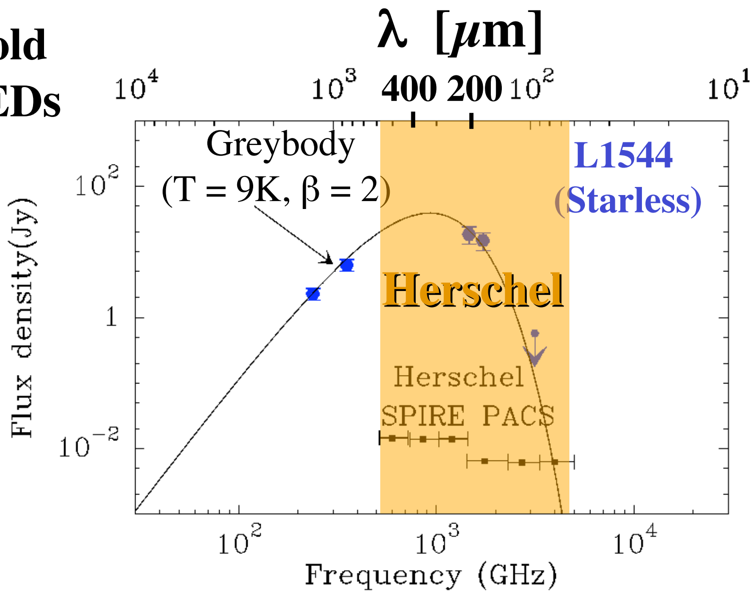
Representative of the collapse initial conditions



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

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

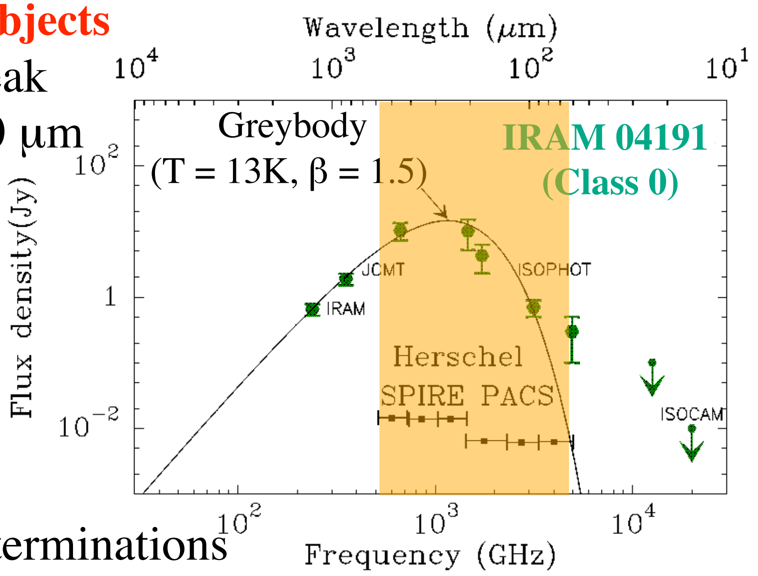
Cold SEDs



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

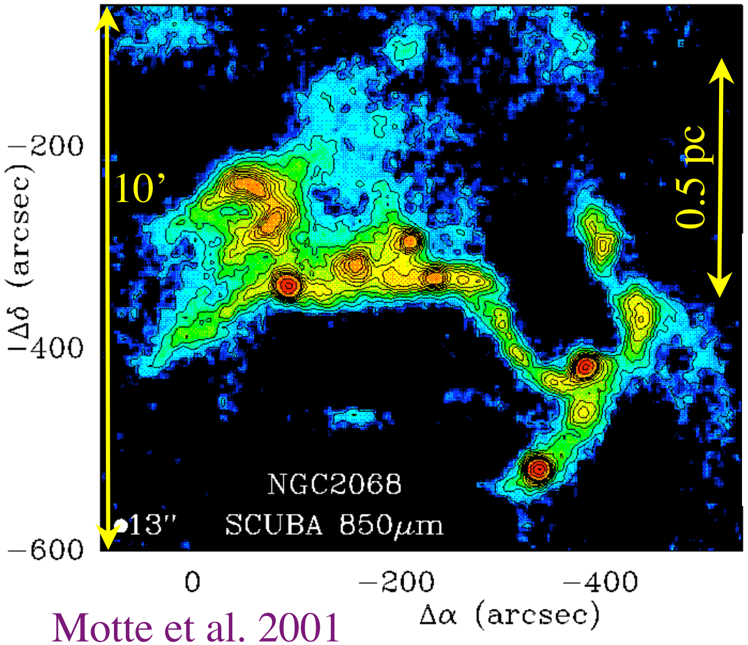
↓

Herschel bands essential for luminosity and temperature determinations



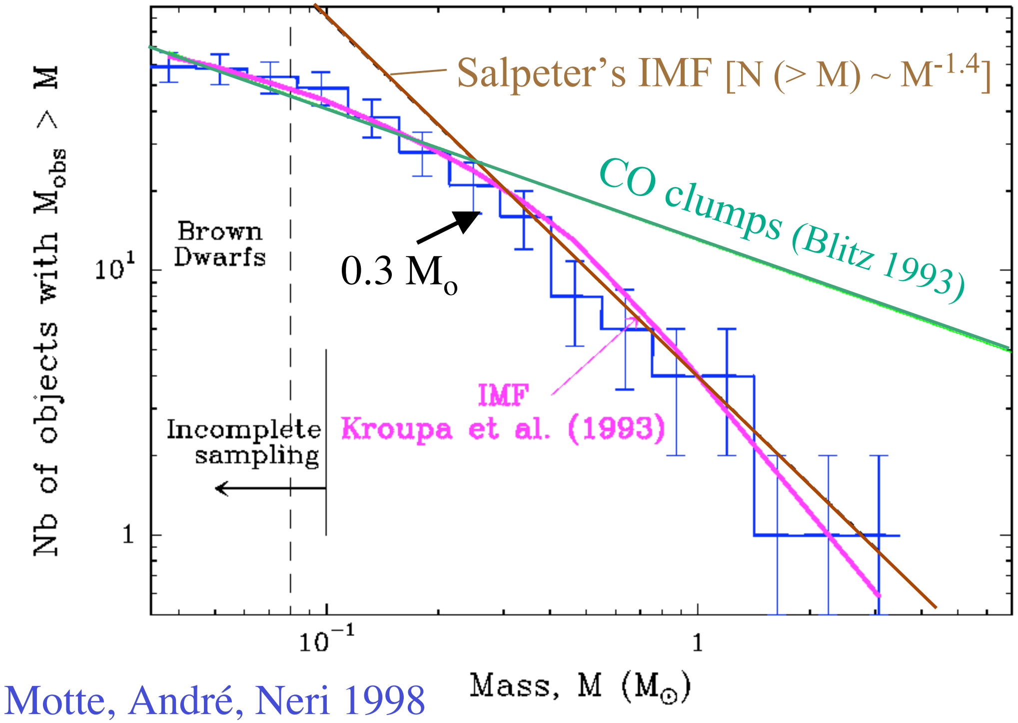
The prestellar core mass function (CMF) resembles the IMF

NGC2068 at 850 µm



Motte et al. 2001

Mass Spectrum of ρ Oph Prestellar Condensations



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

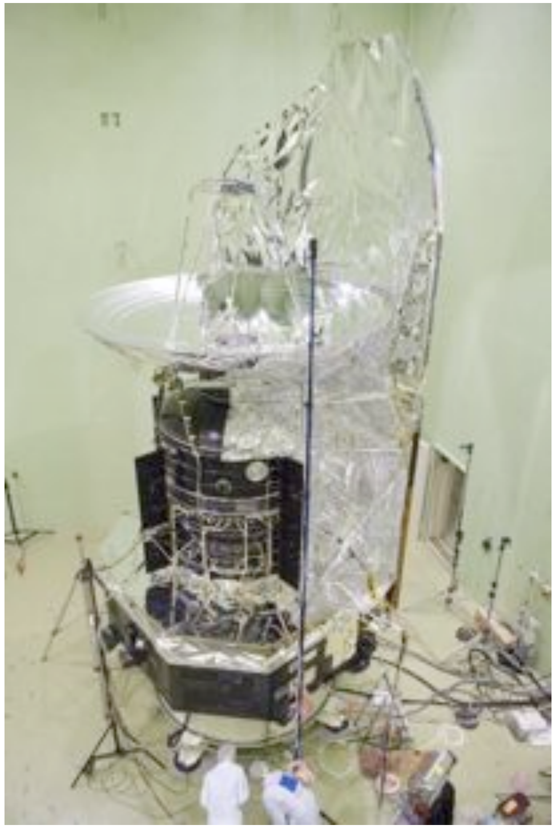
→ ***Herschel* needed to confirm/extend conclusions toward lower/higher masses**

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

The Herschel Space Observatory

Successfully launched by Ariane 5 on 14 May 2009 !

Lifetime ~ 3.5 yr

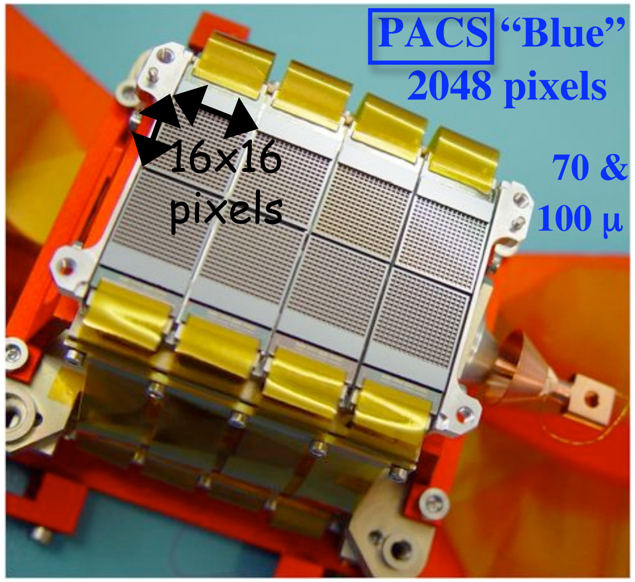


Major far-IR/submm Observatory (ESA 'cornerstone') 3.5 m telescope

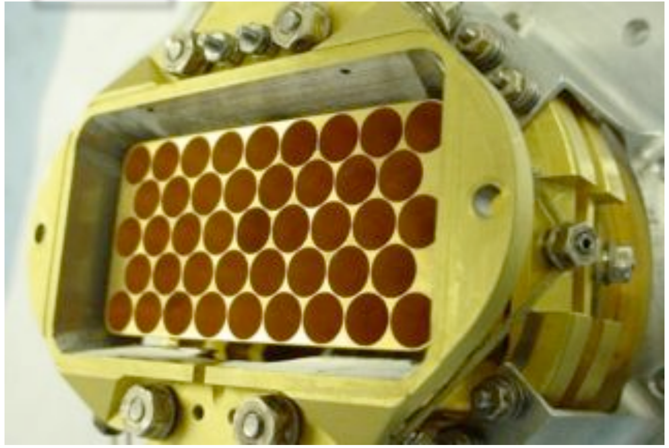
Pilbratt et al. 2010

Cutting-edge instruments

Poglitsch et al. 2010



SPIRE 43 bolometers @ 500 μm

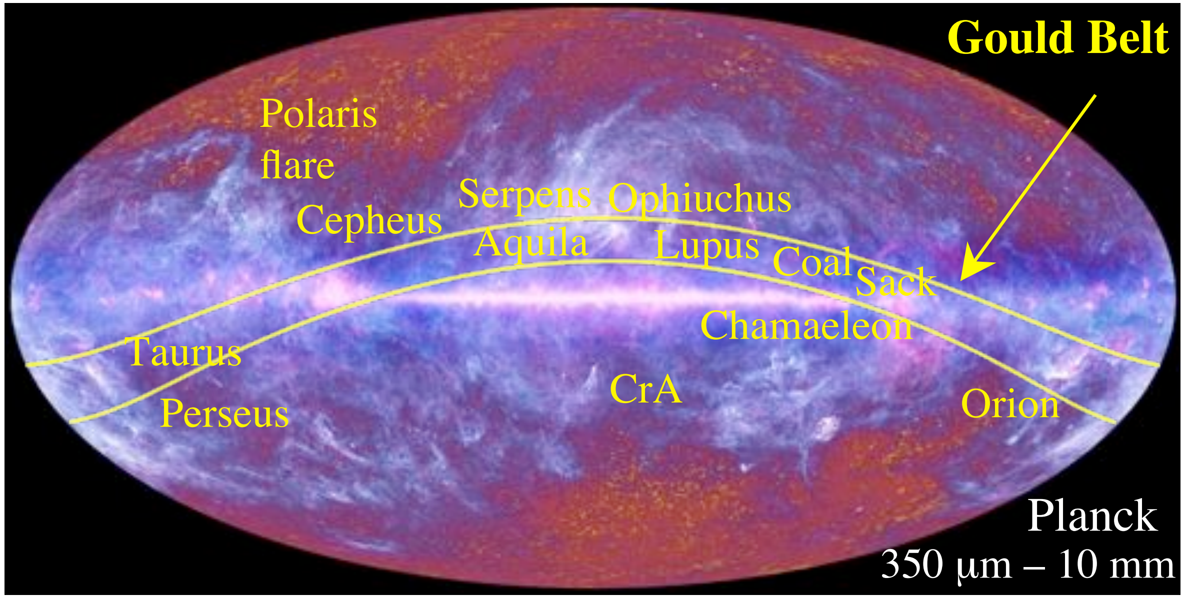


Griffin et al. 2010

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

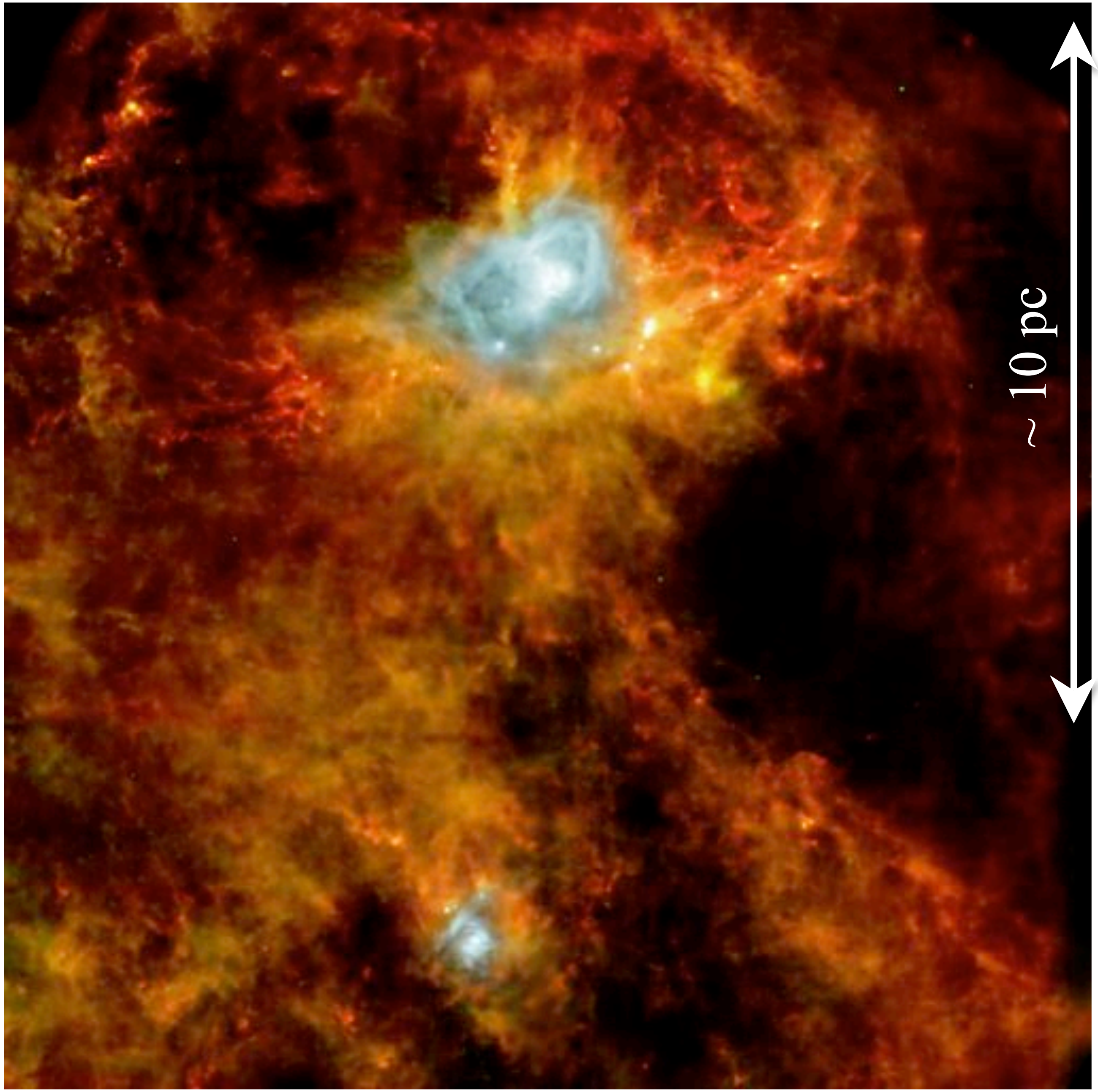
←→

~ 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 ?

"First images" from the Gould Belt Survey



PACS/SPIRE // mode

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

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

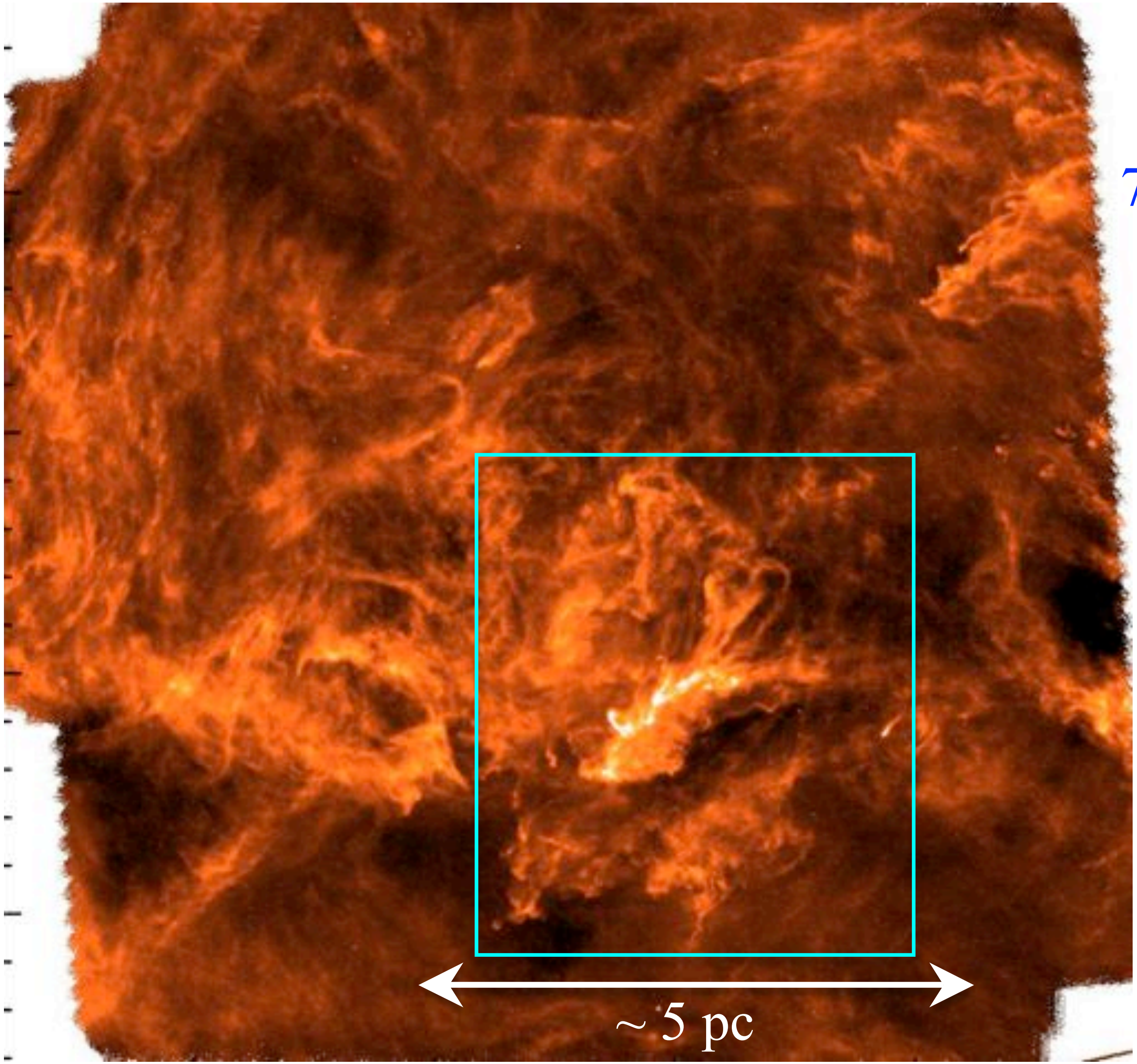
Red : SPIRE 500 μm
Green : PACS 160 μm
Blue : PACS 70 μm

~ 3.3^o x 3.3^o field

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

Ph. André – 22/07/2011

Structure of the cold ISM prior to star formation



SPIRE 250 µm image

Gould Belt Survey
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 vol. 518

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 :

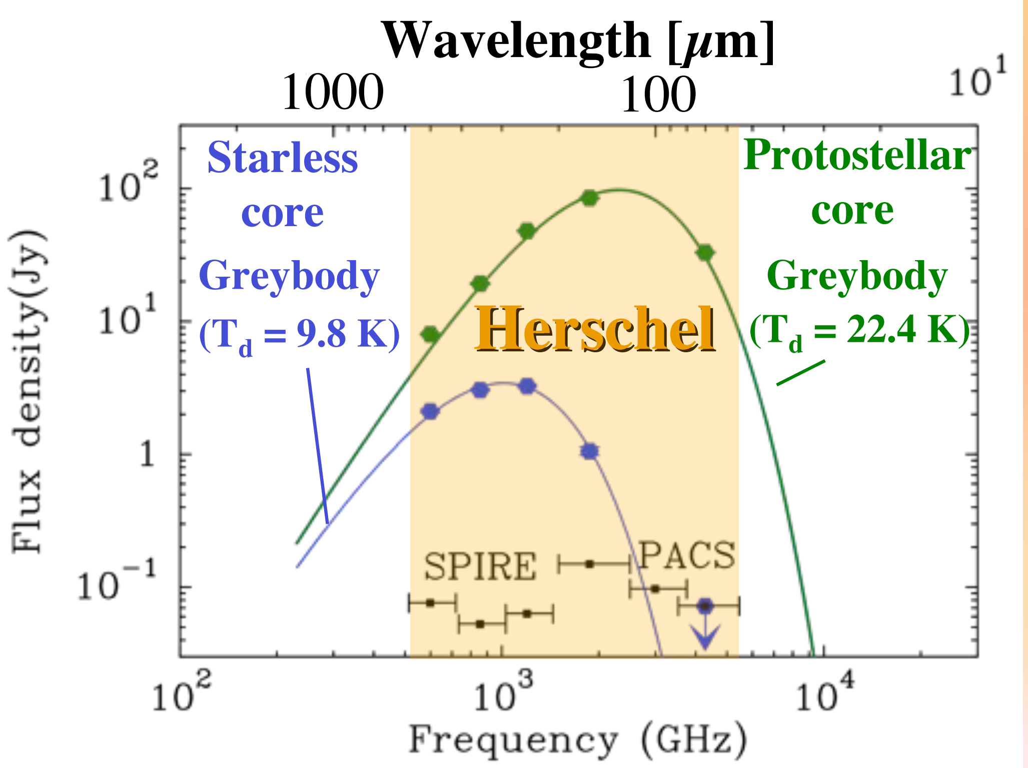
$$M = \frac{S_\nu d^2}{B_\nu(T_d)\,\kappa_\nu} \qquad \Sigma = \frac{I_\nu}{B_\nu(T_d)\,\kappa_\nu}$$

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):

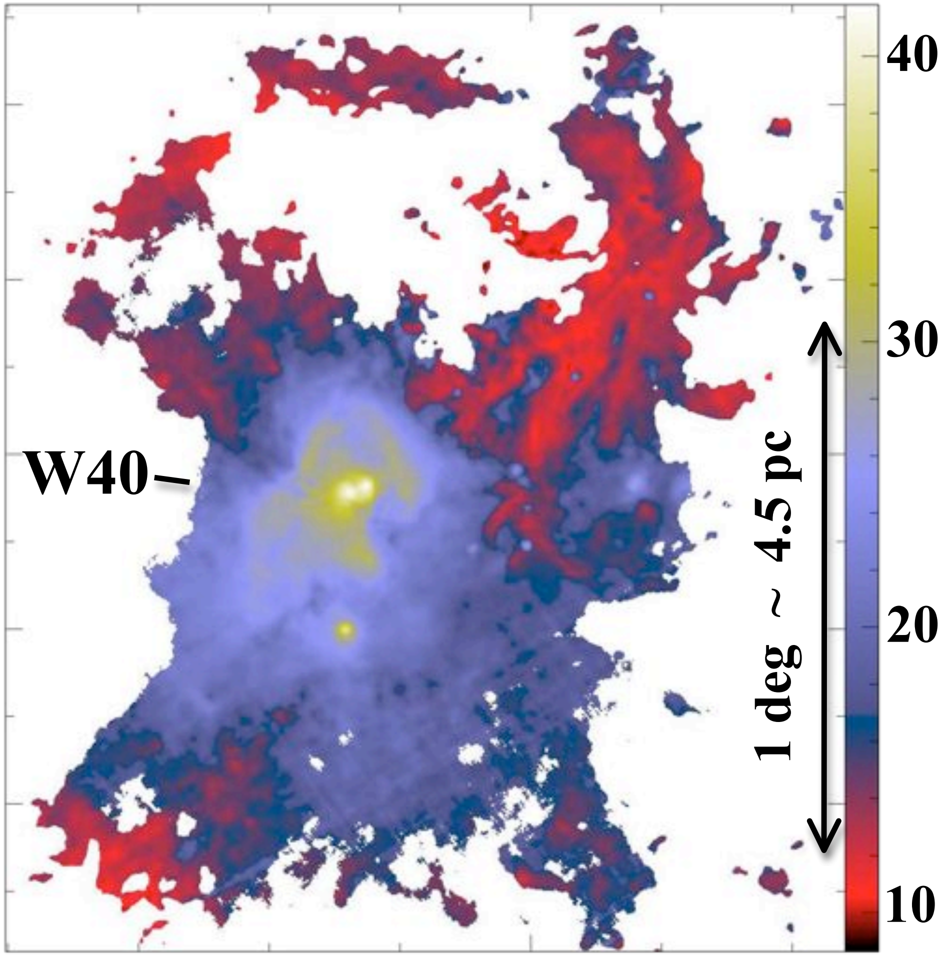
$$I_\nu \sim B_\nu(T_d)\,\tau_\nu = B_\nu(T_d)\,\kappa_\nu\,\Sigma$$

κ_ν = dust opacity

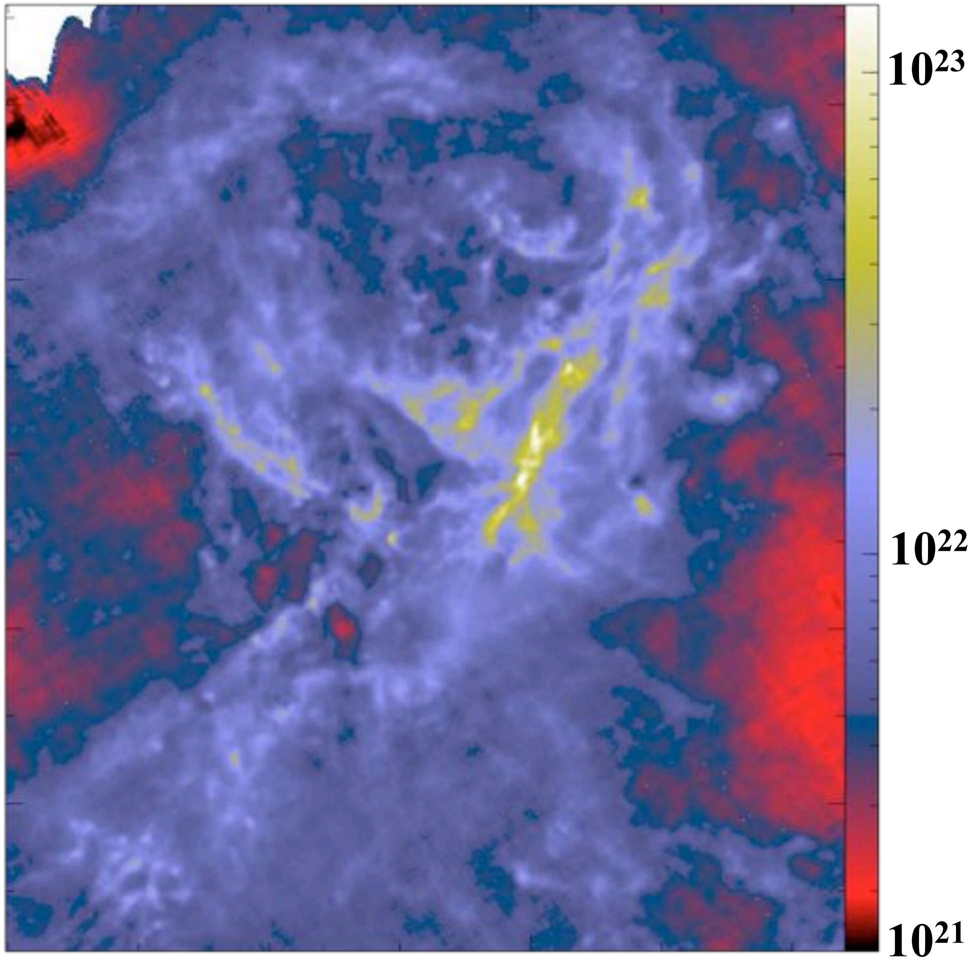
(eg Hildebrand 83; Ossenkopf & Henning 94)

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:

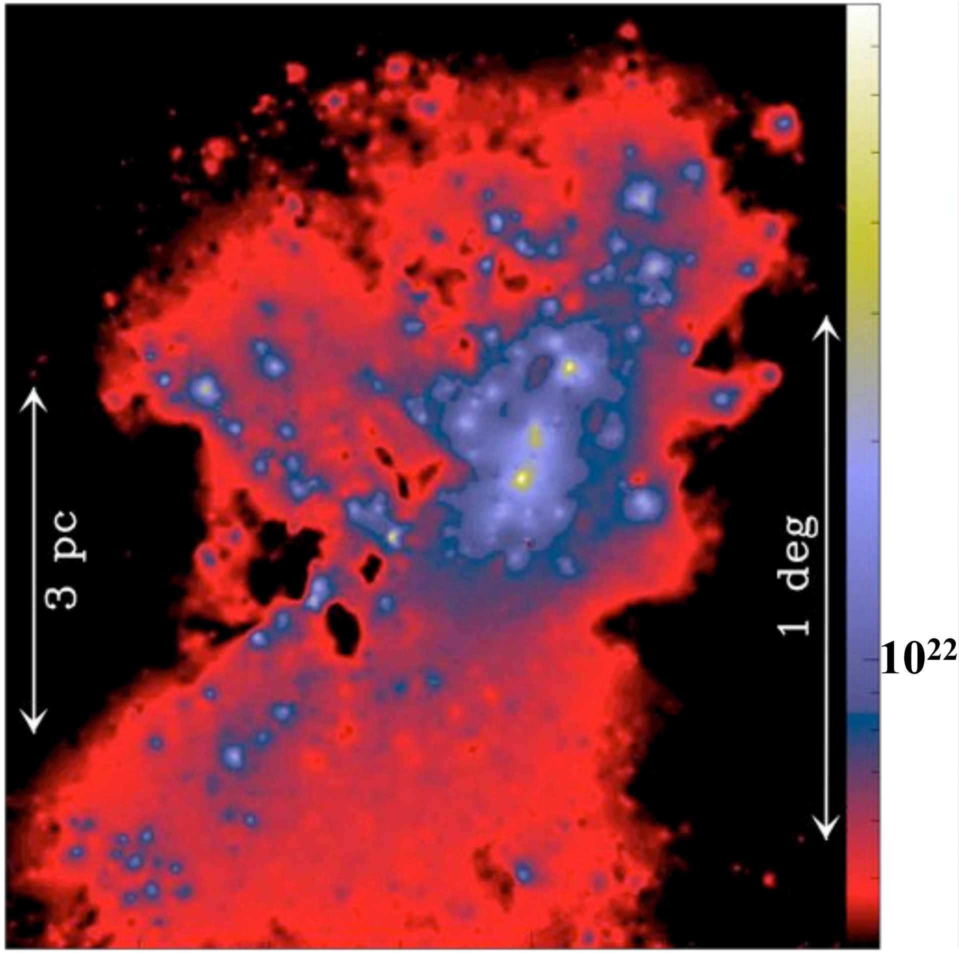
(P. Didelon based on Starck et al. 2003)

***Herschel* Column density map**

=

Cores

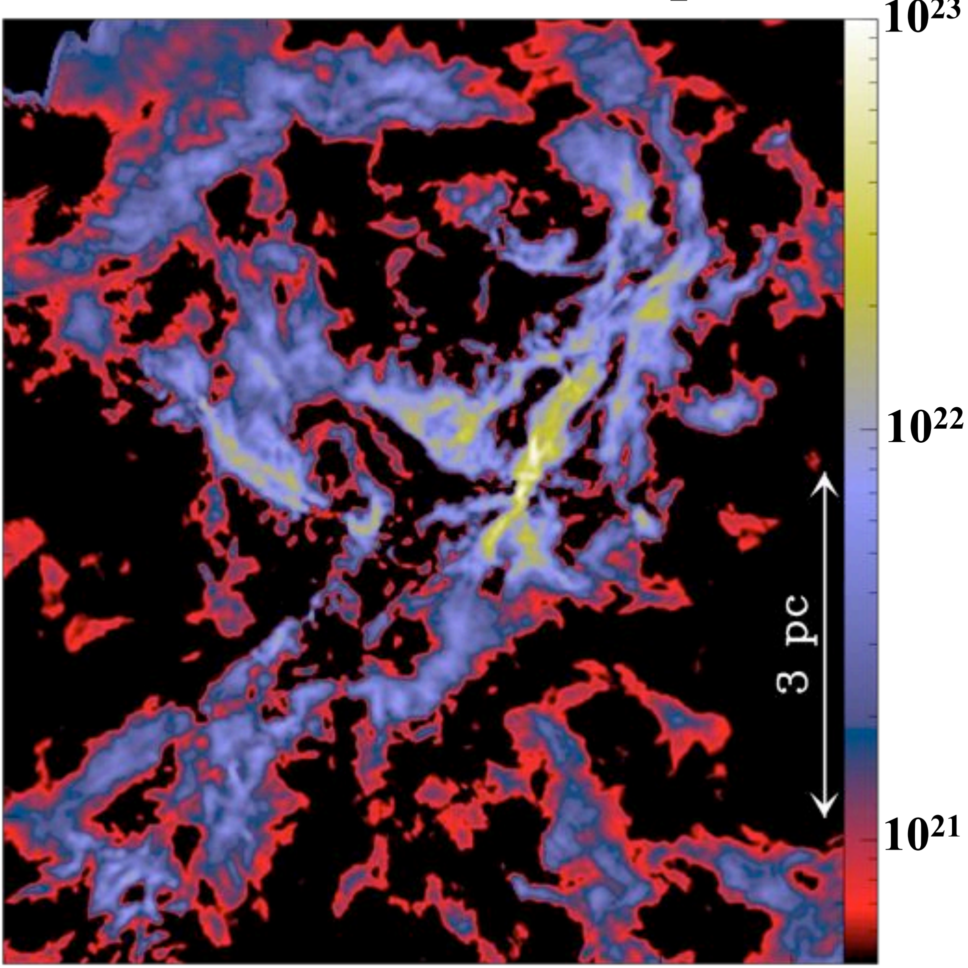
Wavelet component (H_2/cm^2)



\+

Filaments

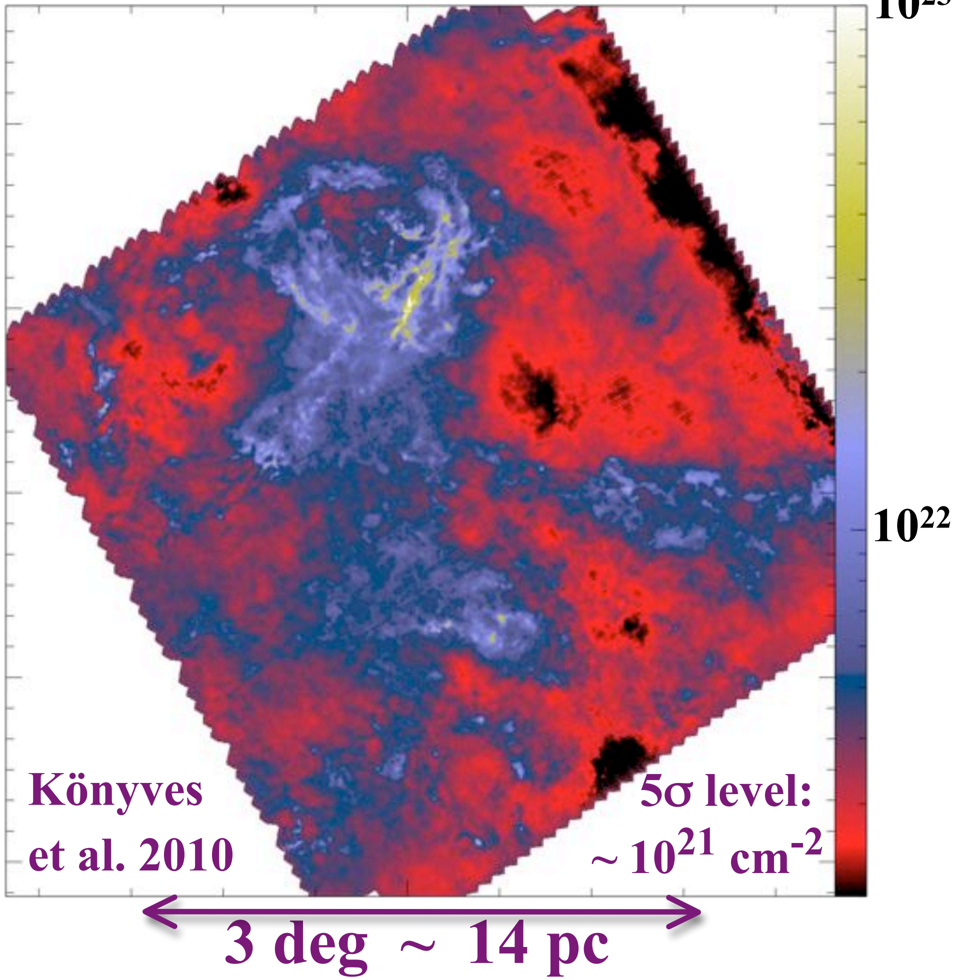
Curvelet component (H_2/cm^2)



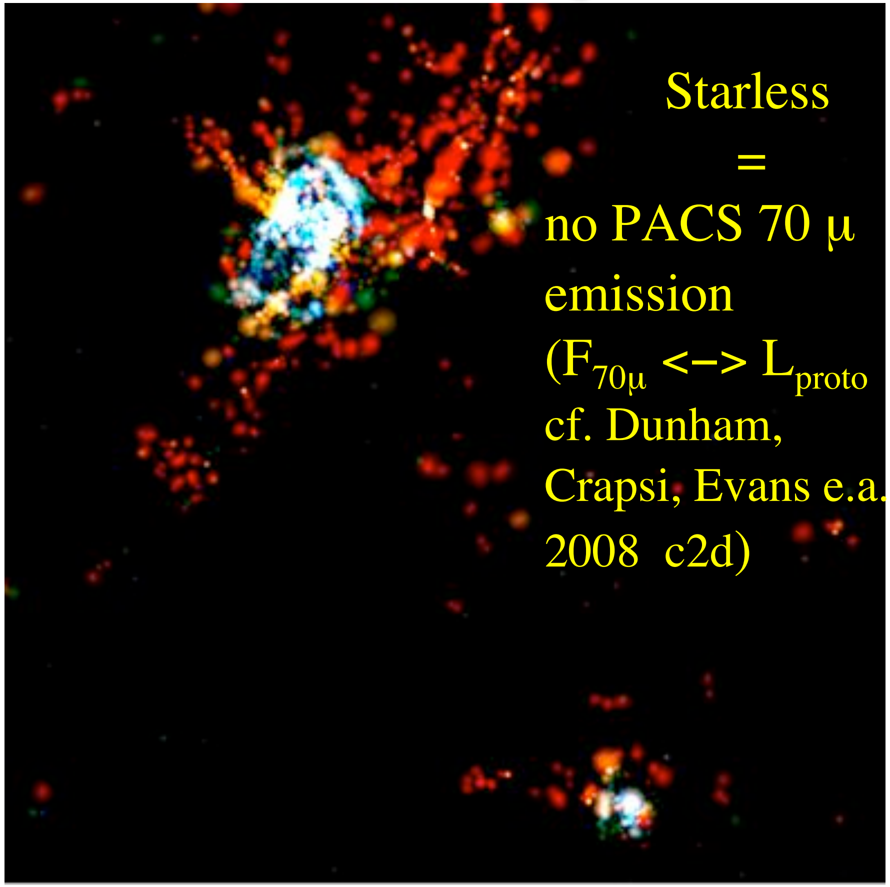
`Compact’ Source Extraction in Aquila

(with “getsources”: multi-scale, multi-λ core-finding algorithm
Menshchikov et al. 2010-11)

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



Spatial distribution of extracted cores
- 541 starless
- 201 YSOs

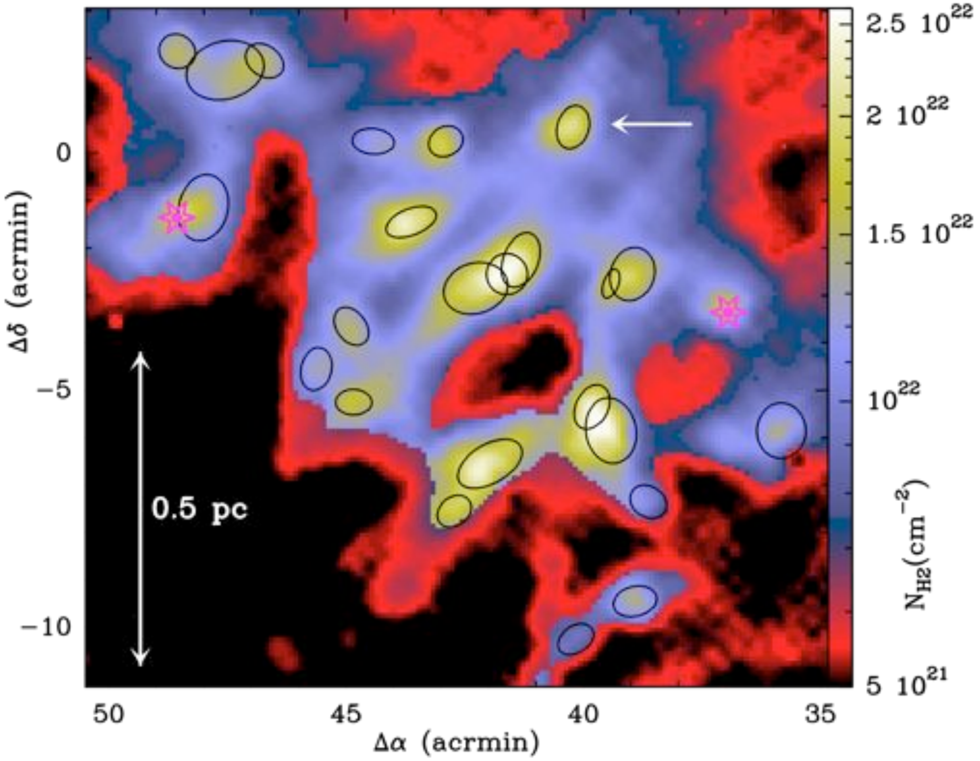


70/160/500 μm composite image

Examples of starless cores in Aquila

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

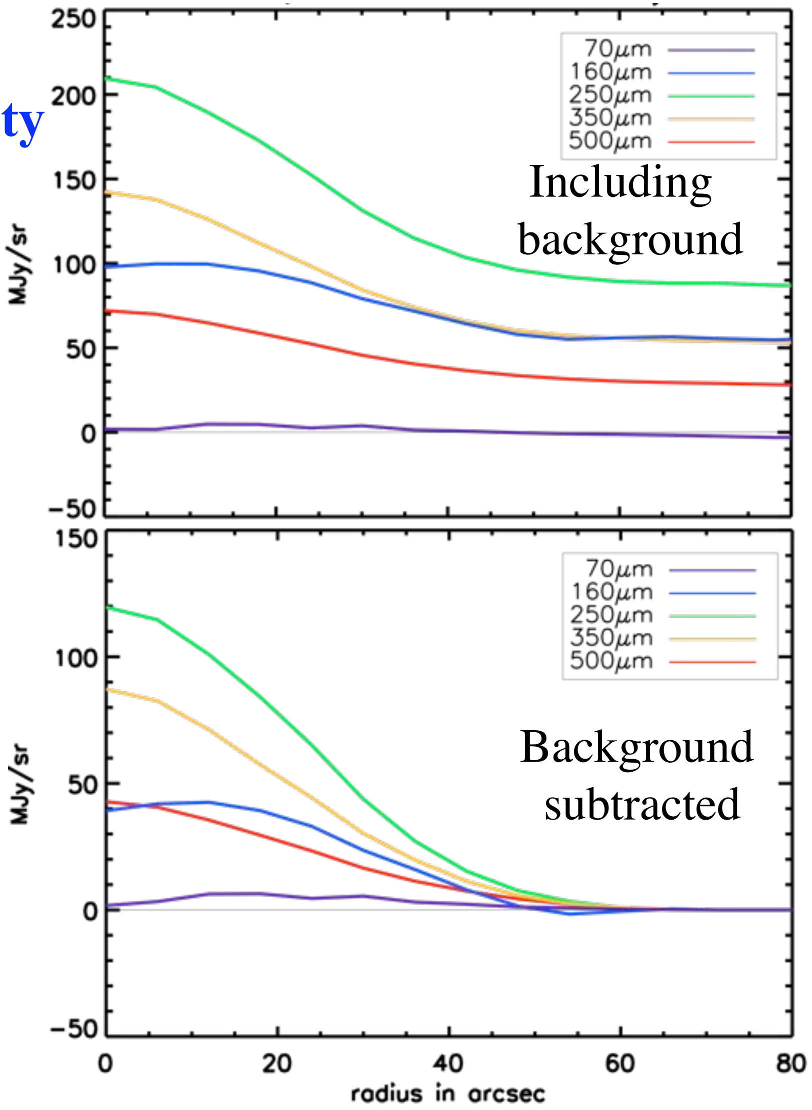
Herschel **N_{H_2} map (cm^{-2})**



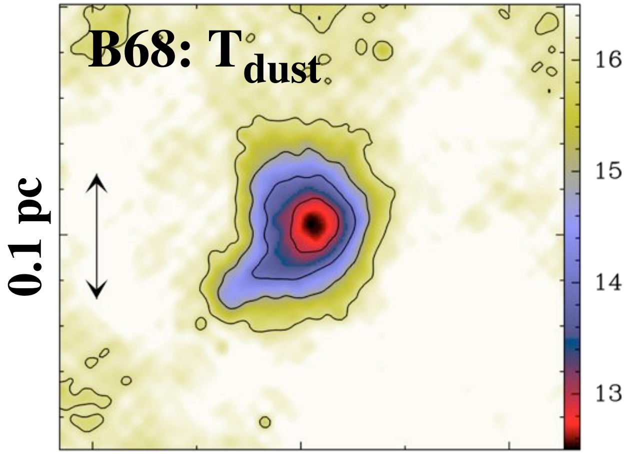
Ellipses: FWHM sizes of 24 starless cores at 250 µm

Könyves et al. 2010, A&A special issue

Radial intensity profiles

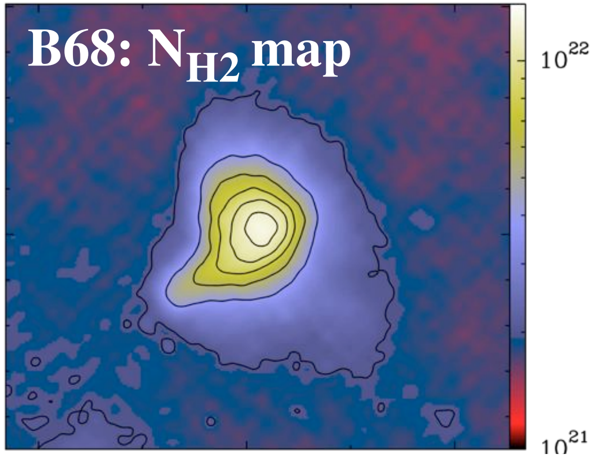


Examples of temperature and density profiles derived from *Herschel* data

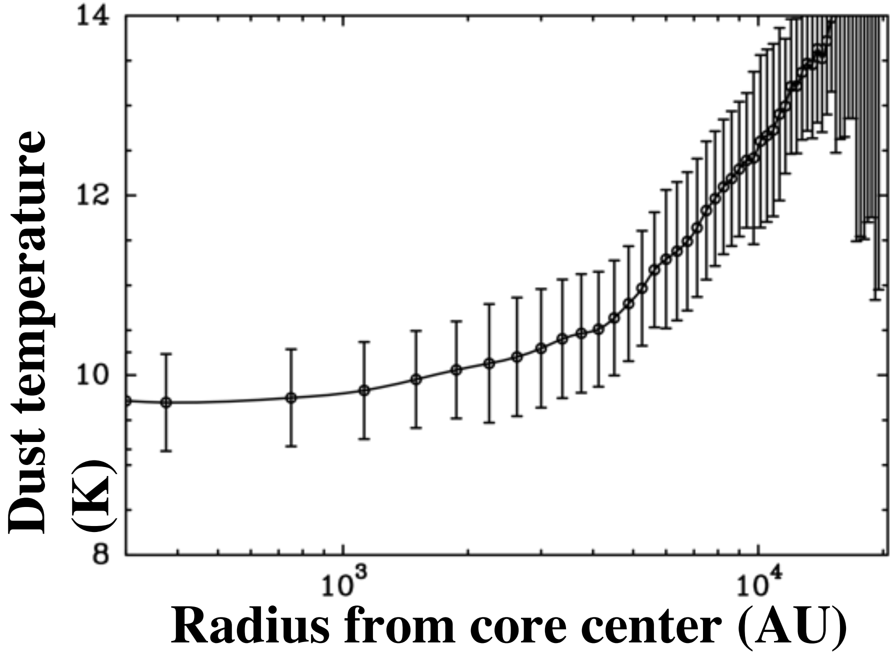


M. Attard et al.

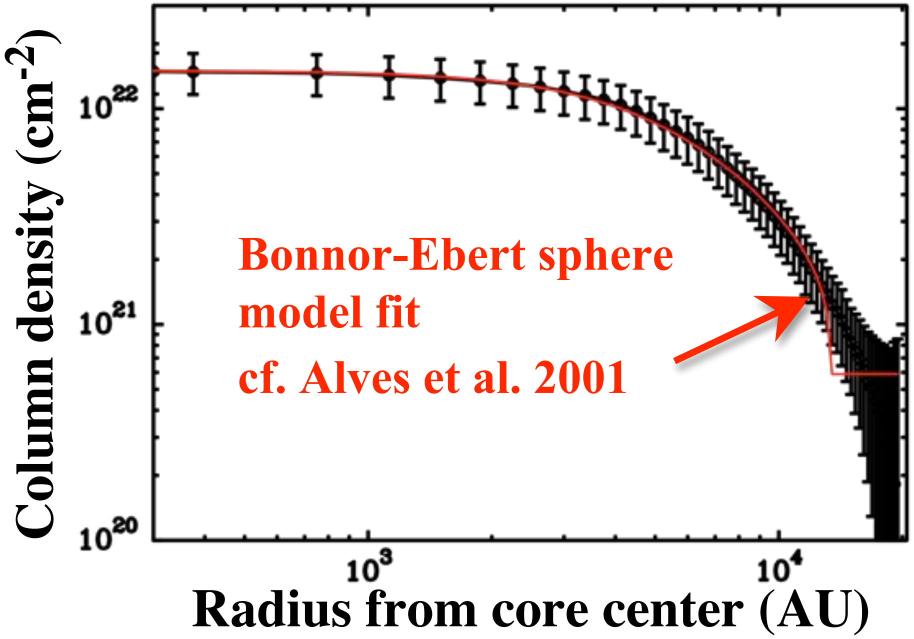
See also
A.Stutz et al.
EPOS Program



Temperature profile of B68



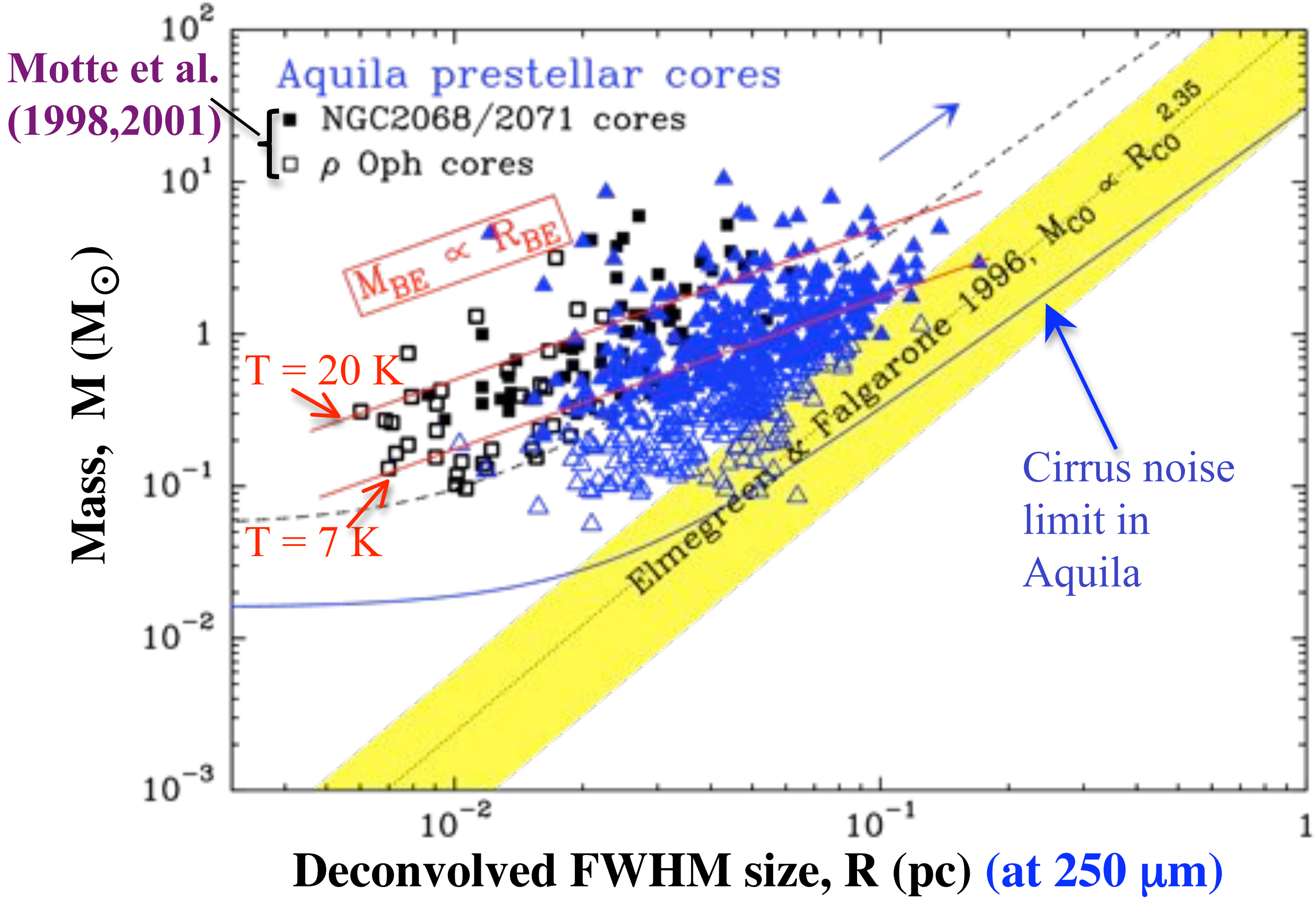
Column density profile of B68



Bonnor-Ebert sphere model fit

cf. Alves et al. 2001

Most of the Aquila starless cores are self-gravitating



- **> 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

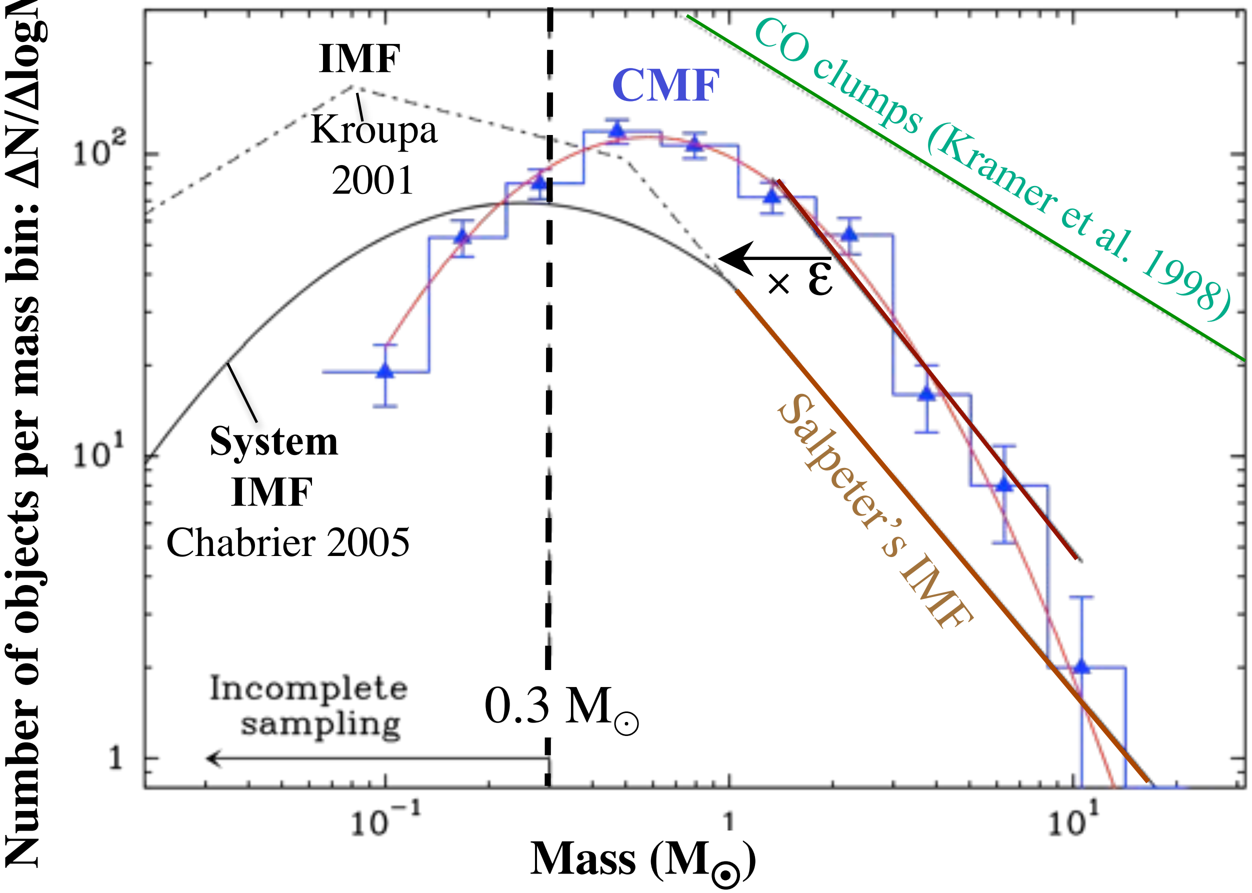
André et al. 2010
Könyves et al. 2010
A&A vol. 518

341-541 prestellar cores in Aquila

Factor ~ 2-9 better statistics than earlier CMF studies

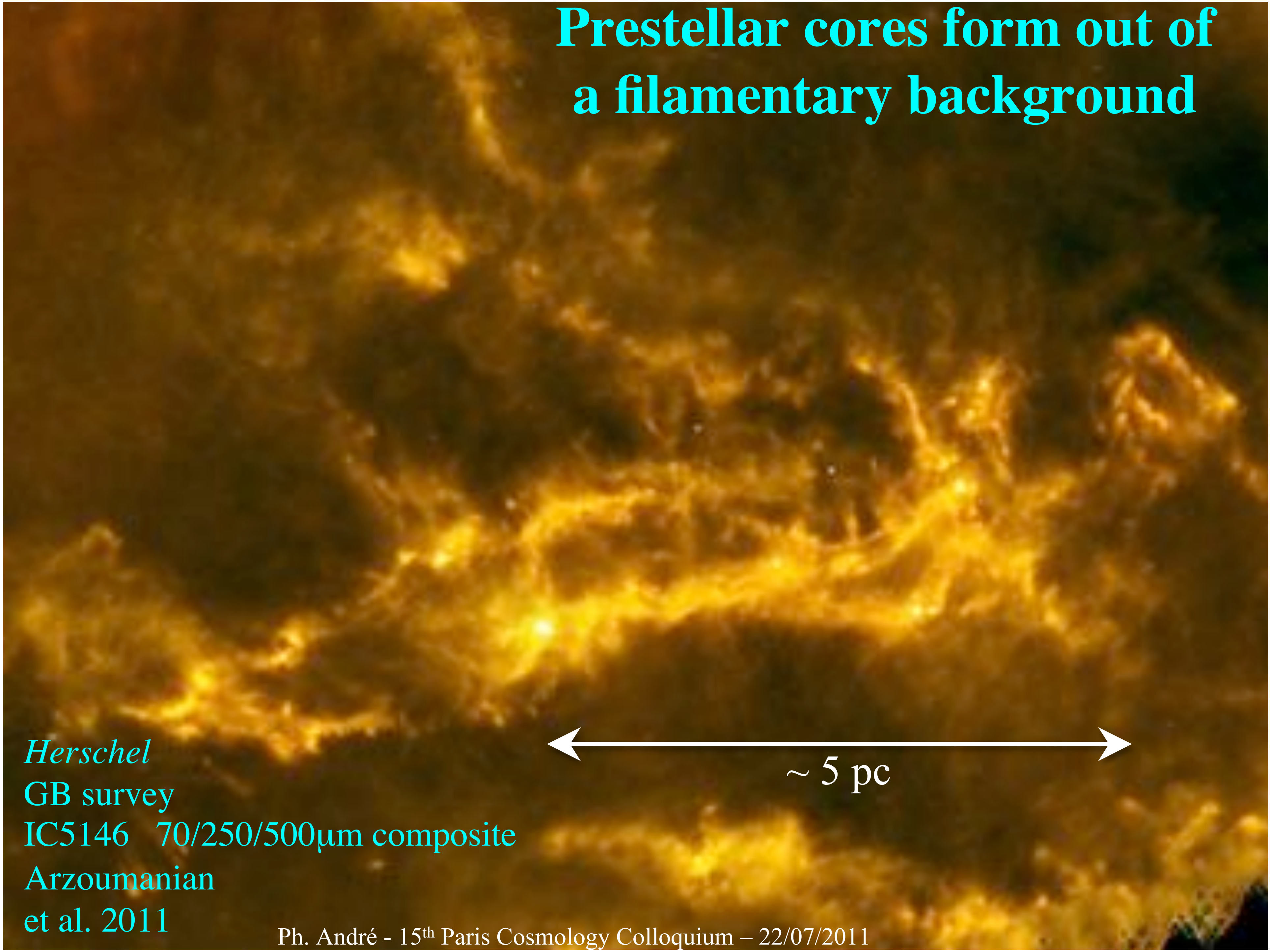
(e.g Motte, André, Neri 1998; Alves et al. 2007)

Core Mass Function (CMF) in Aquila Complex



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

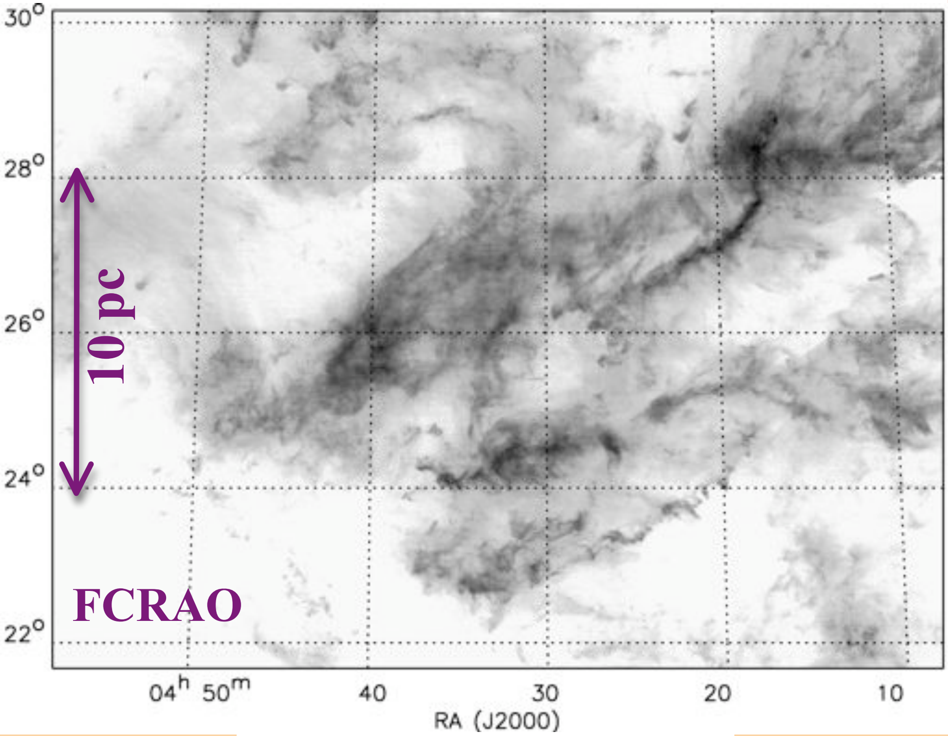
Prestellar cores form out of a filamentary background



Herschel
GB survey
IC5146 70/250/500μm composite
Arzoumanian
et al. 2011

Evidence of the importance of filaments prior to *Herschel*

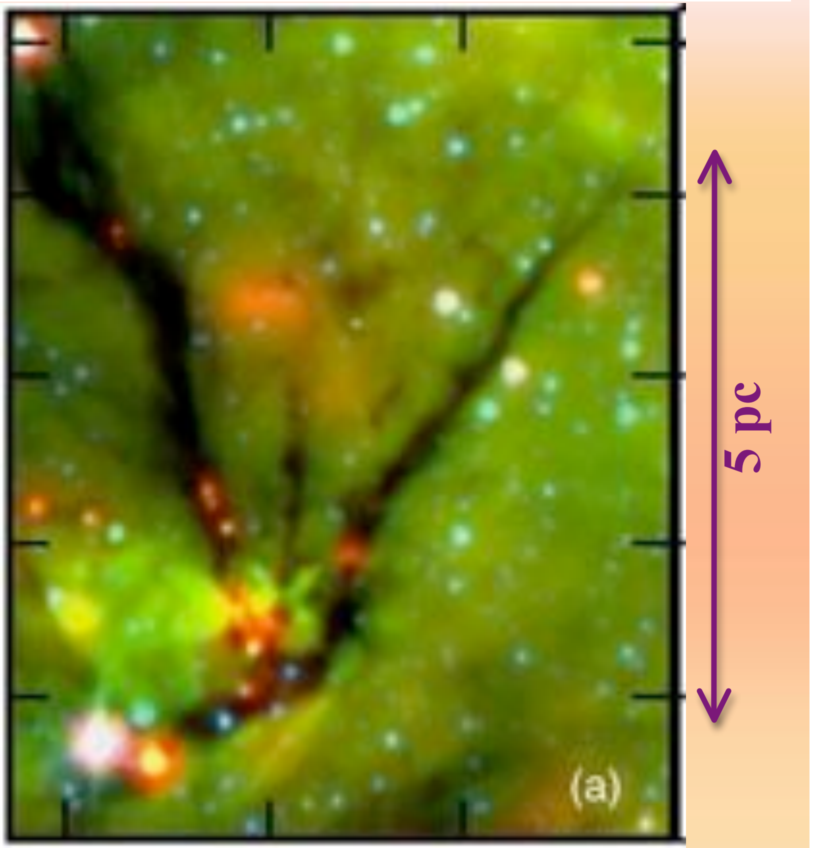
Taurus
H_2 column density from CO(1-0)



Goldsmith et al. 2008

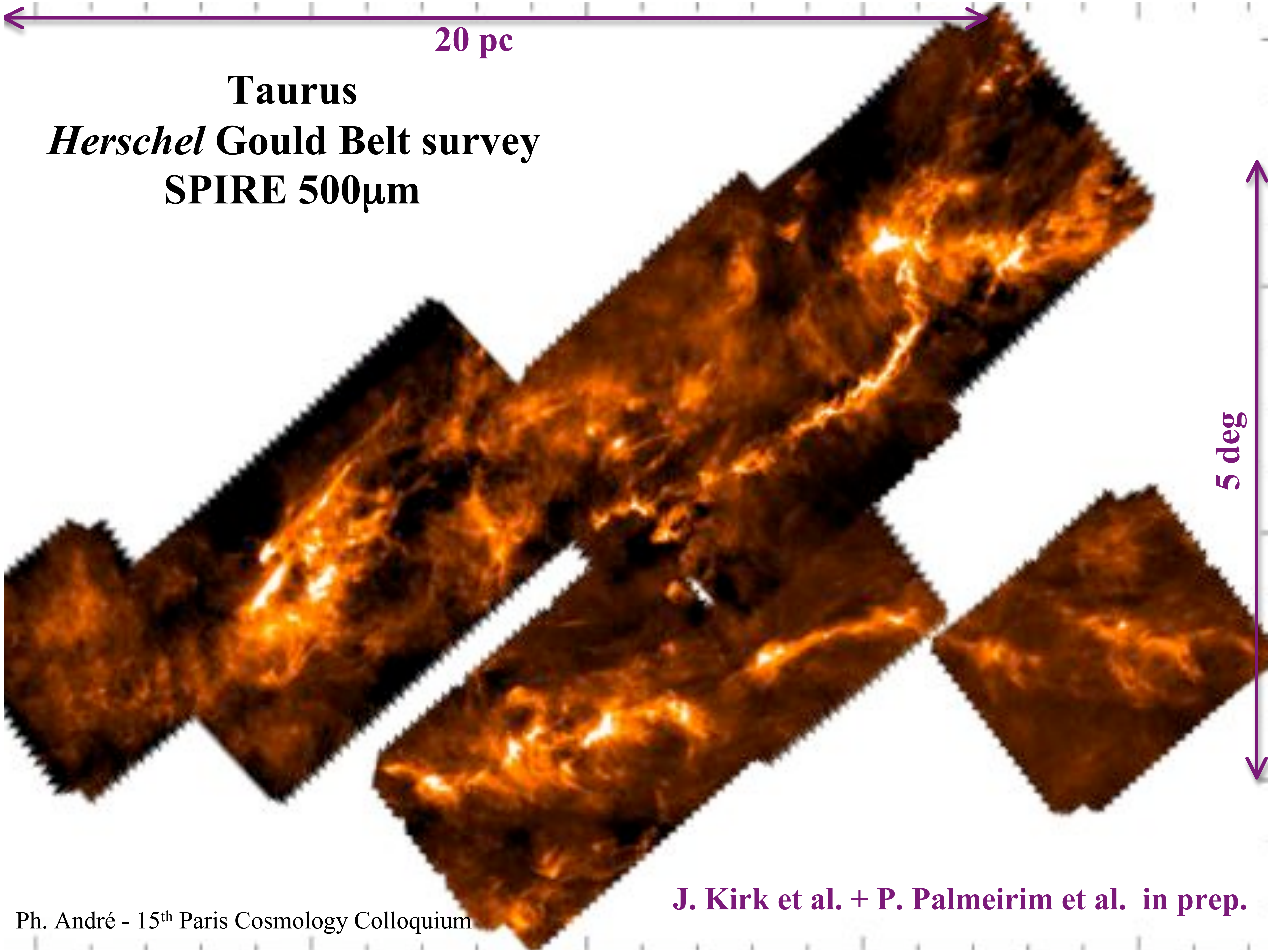
See also:
Schneider & Elmegreen 1979;
Abergel et al. 1994; Hartmann 2002;
Hatchell et al. 2005; Myers 2009 …

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



Peretto & Fuller 2009, 2010

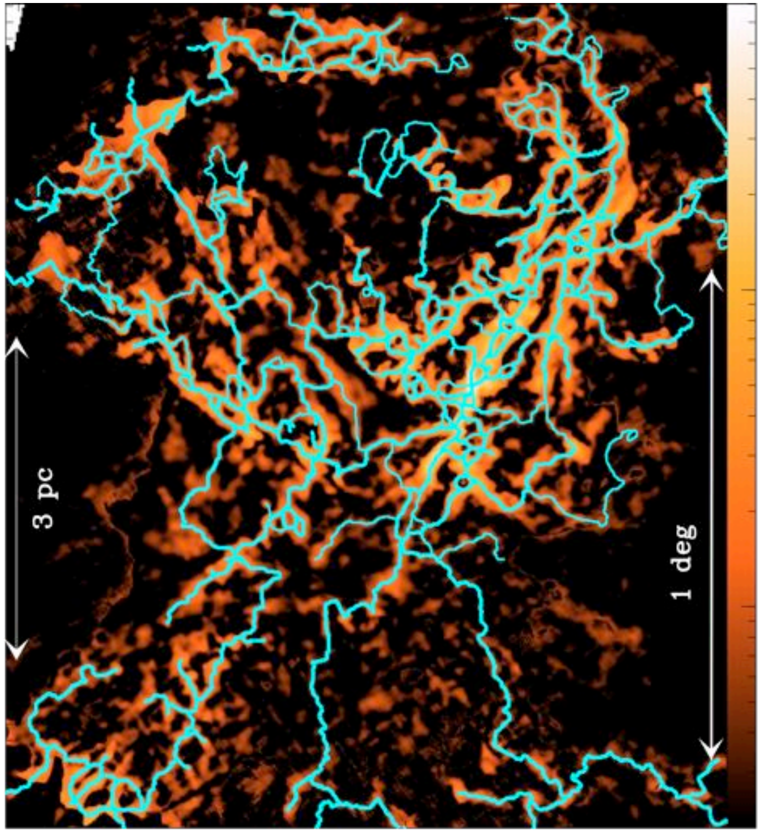
Taurus
Herschel Gould Belt survey
SPIRE 500µm



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

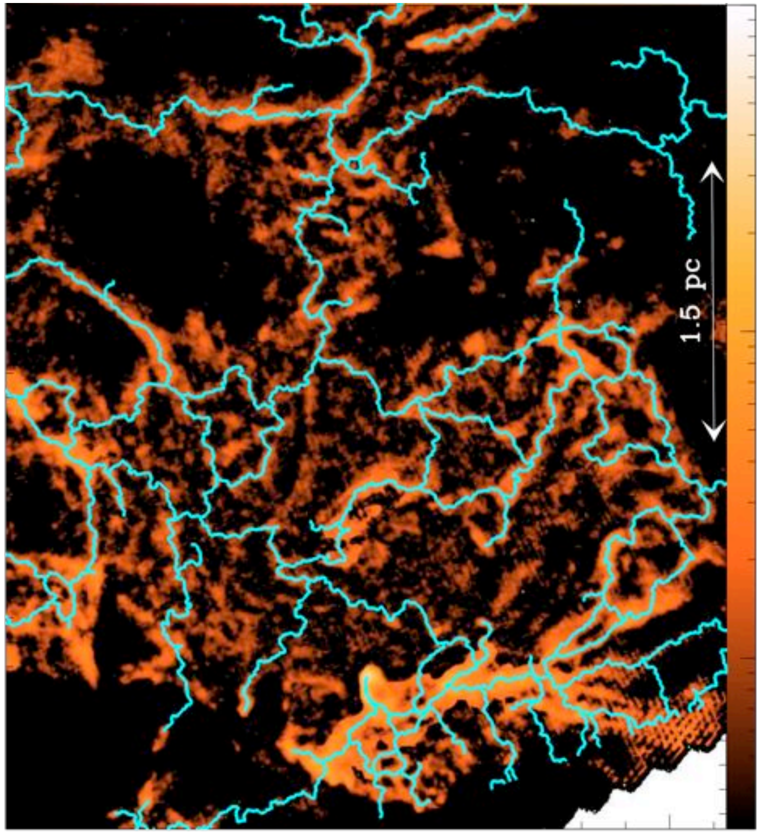
Herschel reveals a rich network of filaments in every interstellar cloud

Actively star forming



Network of filaments in Aquila

Non star forming



Network of filaments in Polaris

Gould Belt KP (André et al. 2010, Men'shchikov et al. 2010, Arzoumanian et al. 2011)

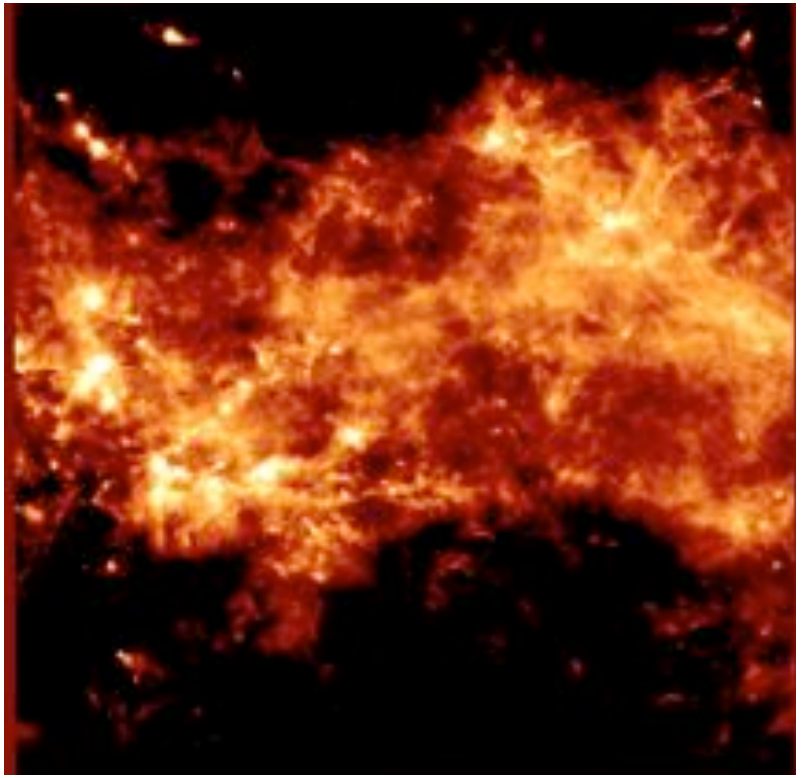
Using the 'skeleton' or DisPerSE algorithm (Sousbie 2011) to trace the ridge of each filament

Galactic star formation occurs primarily along filaments

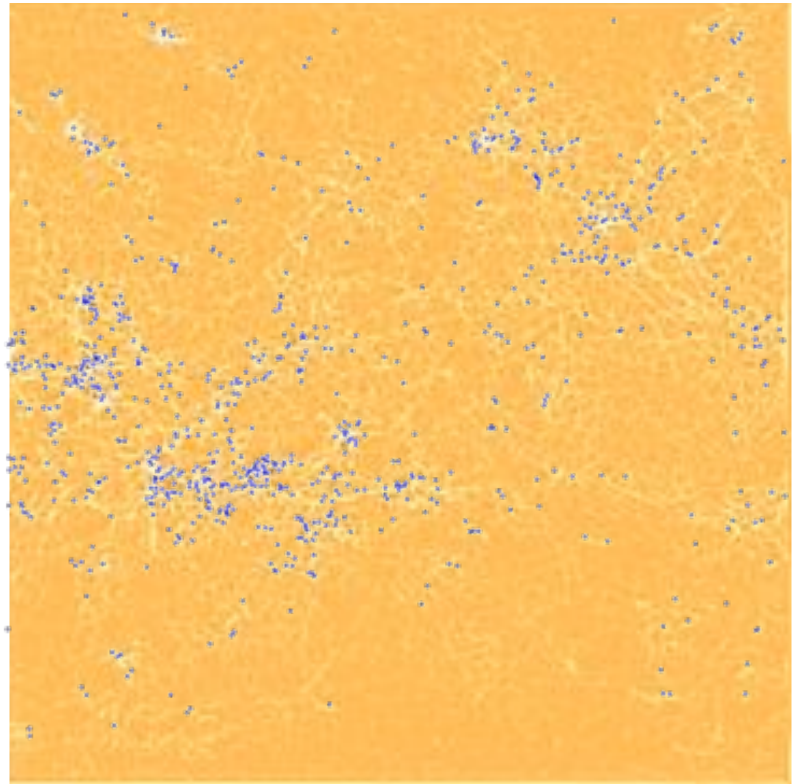
HI-GAL image of (part of) the Milky Way (Molinari et al. 2010)

Galactic star formation occurs primarily along filaments

HI-GAL image of (part of) the Milky Way (Molinari et al. 2010)



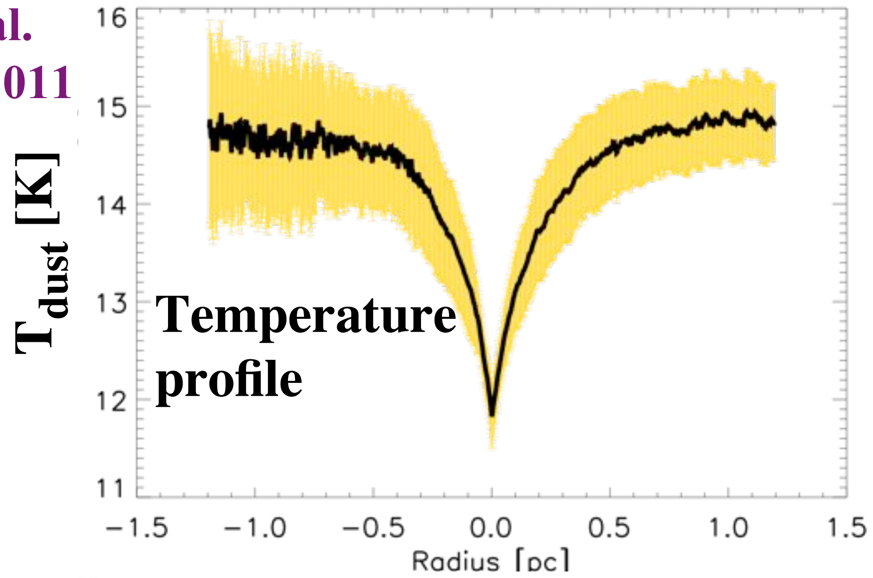
Curvature enhancement operator



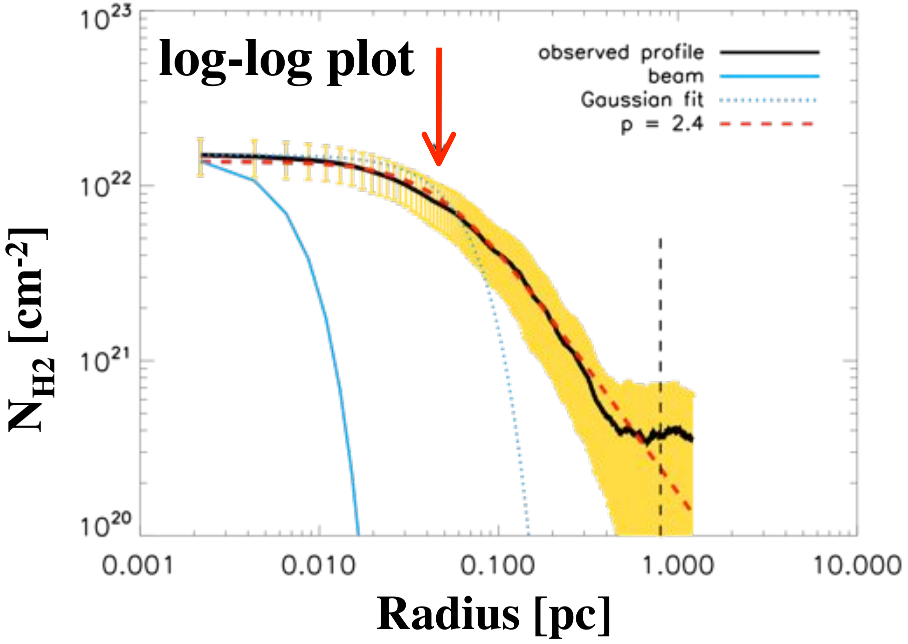
Characterizing the structure of filaments with *Herschel*

Taurus B213 filament
SPIRE 250μm

Arzoumanian et al.
Palmeirim et al. 2011



Temperature profile



log-log plot

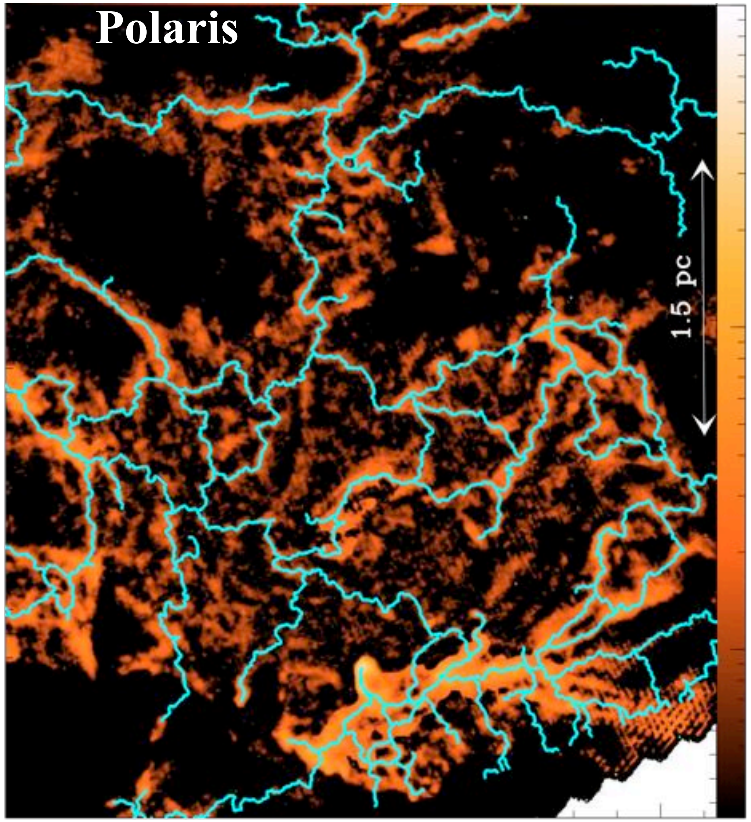
Plummer-like density profile:

$\rho(r) = \rho_c / [1 + (r/R_{flat})^2]$

with $R_{flat} \sim 0.05$ pc

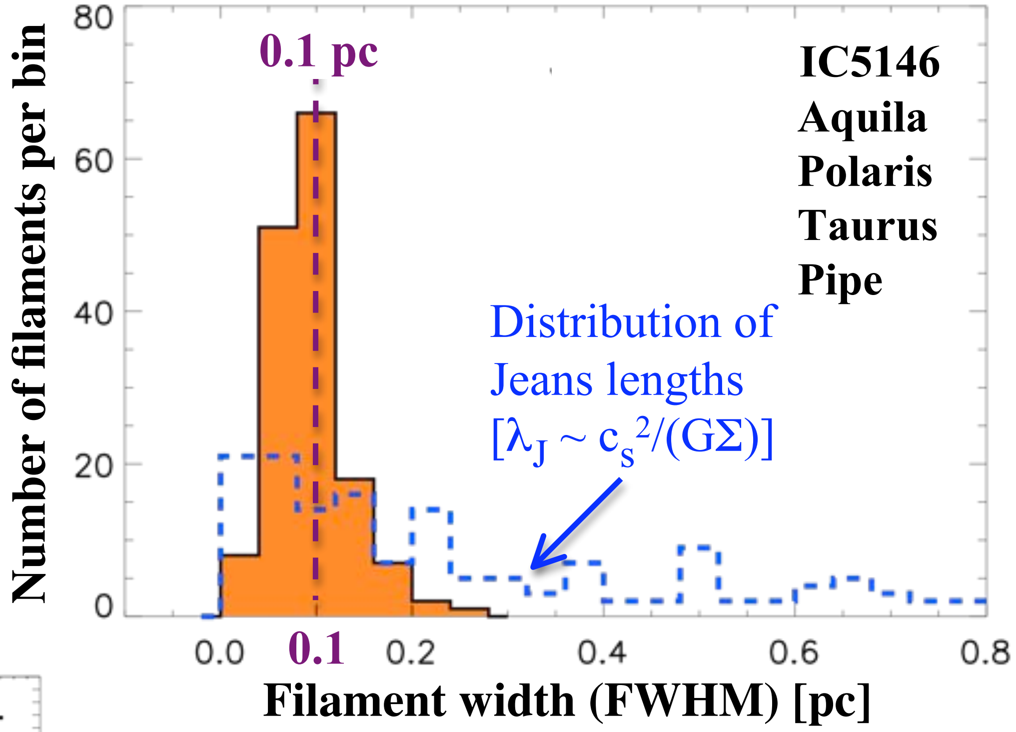
Diameter of flat inner plateau ~ 0.1 pc

Filaments have a characteristic width ~ 0.1 pc

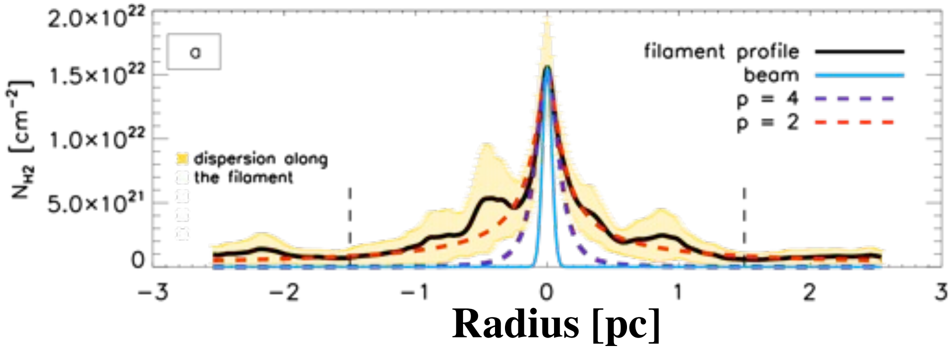


D. Arzoumanian et al. 2011, A&A, 529, L6

Statistical distribution of widths for 150 filaments



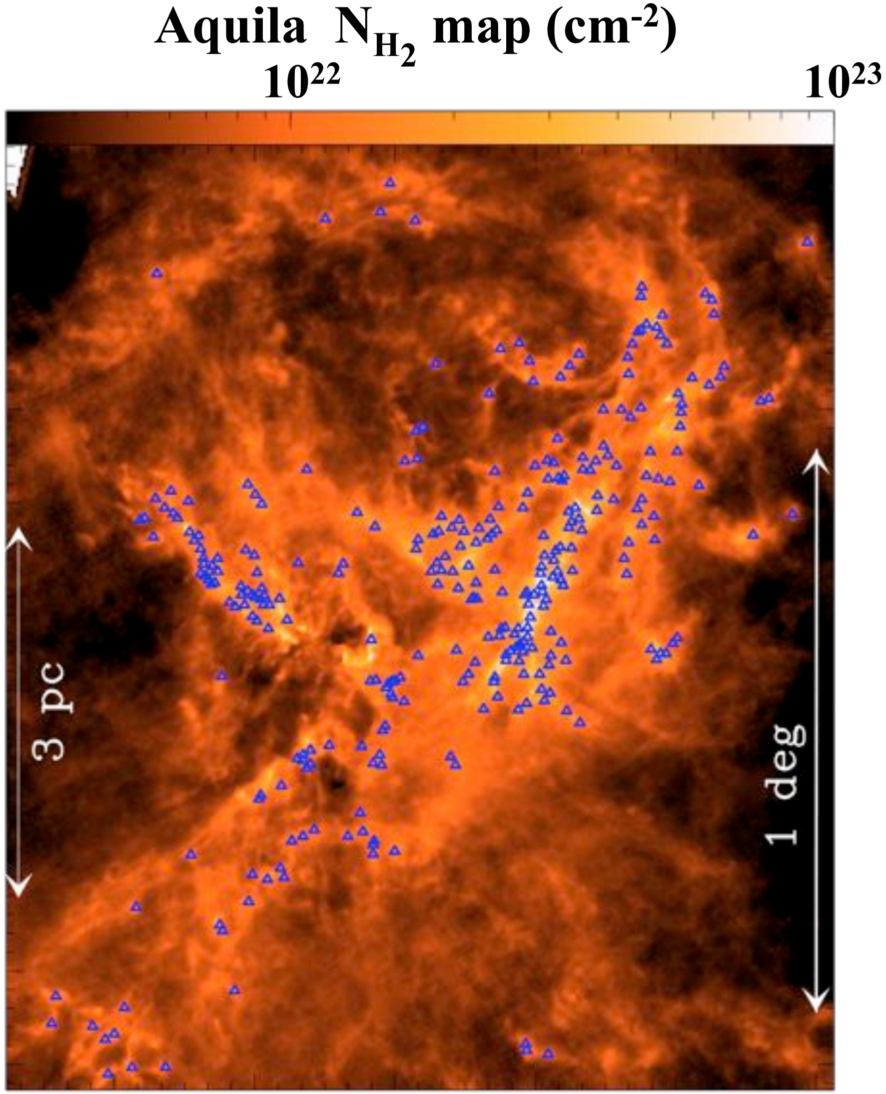
Example of a filament radial profile

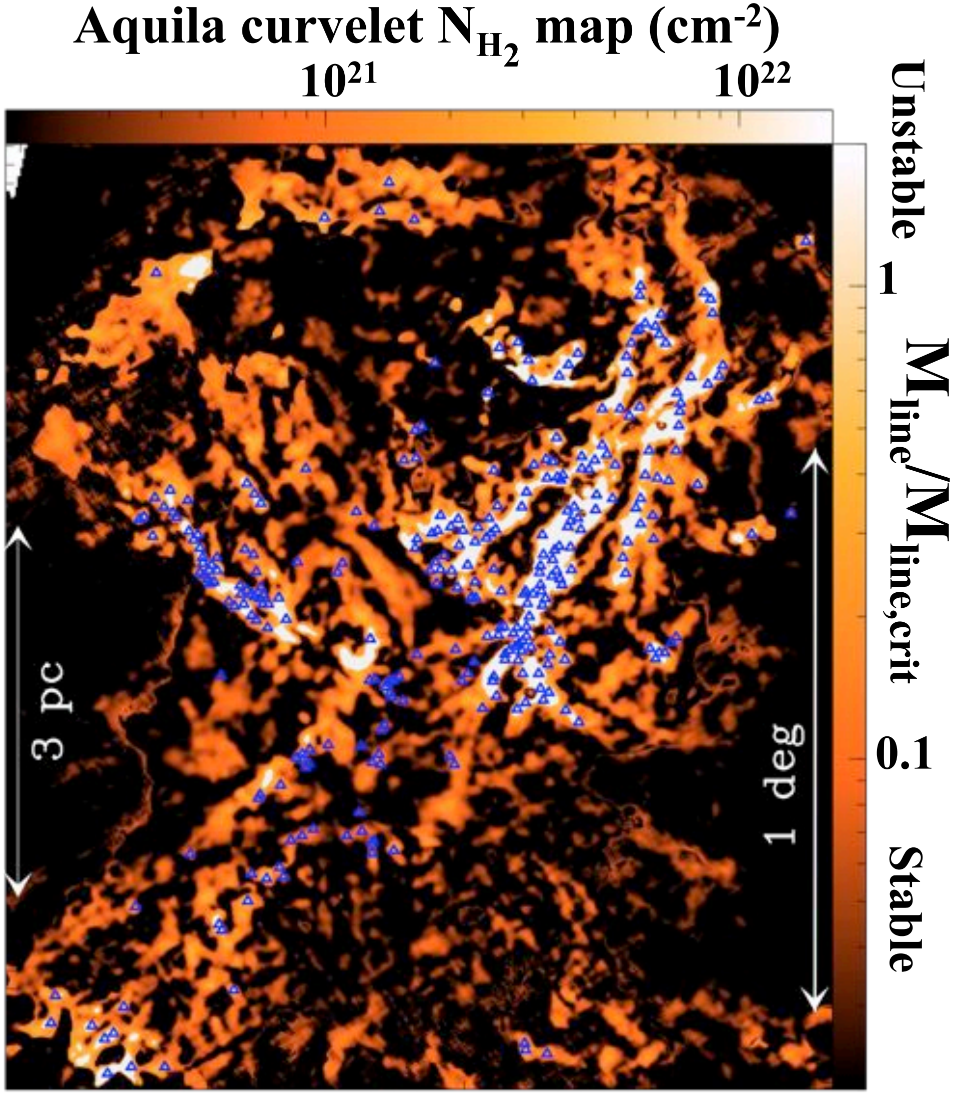


Using the ‘skeleton’ or DisPerSE algorithm (Sousbie 2011) to trace the ridge of each filament

Prestellar cores are preferentially found within the densest filaments

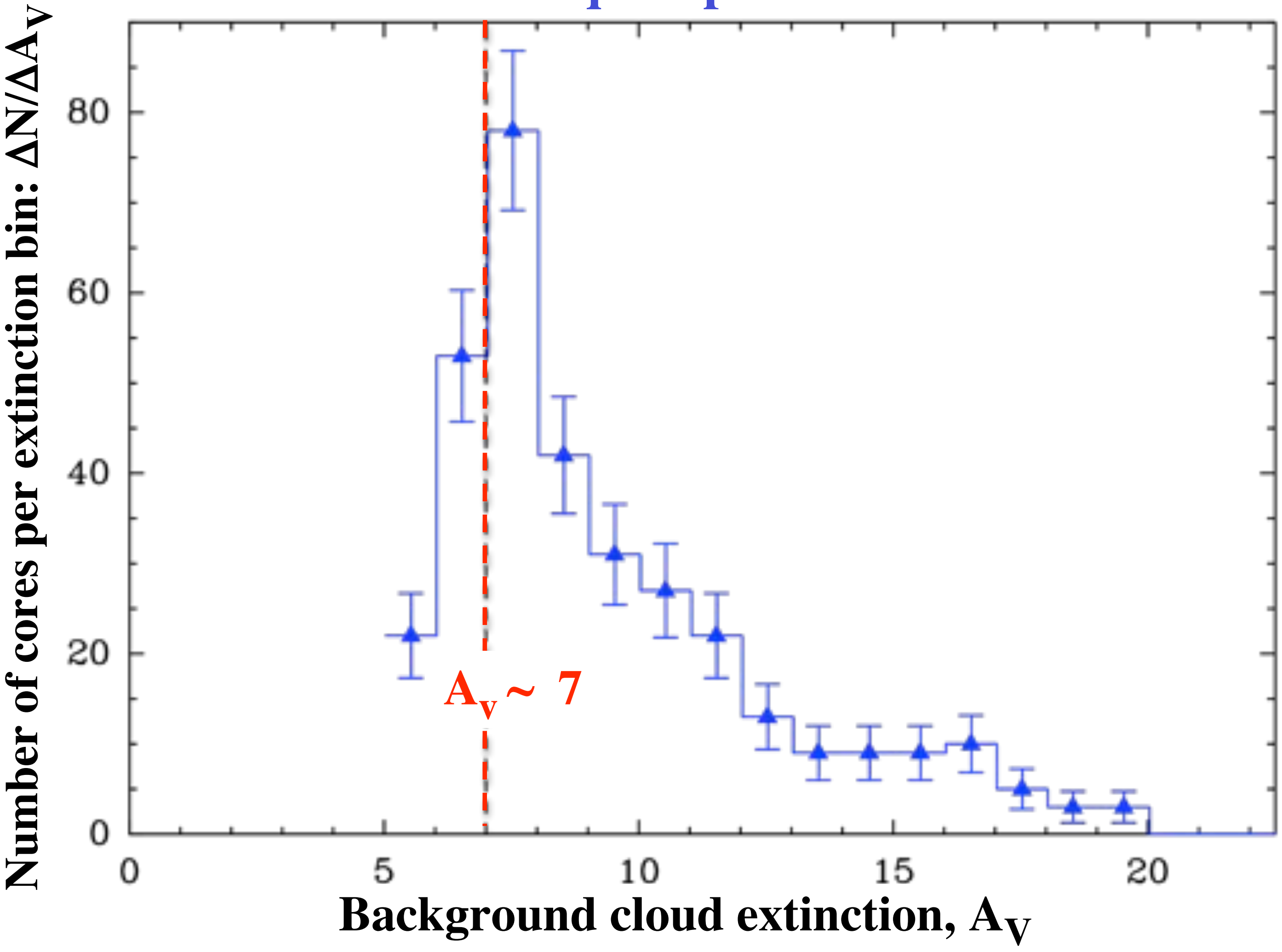
△ : Prestellar cores - 90% found at $N_{H_2} > 7\times10^{21}$ cm^{-2} <=> A_v(back) > 7





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 $A_v \sim 7$

⇔

$N_{H_2} \sim 7 \times 10^{21} cm^{-2}$

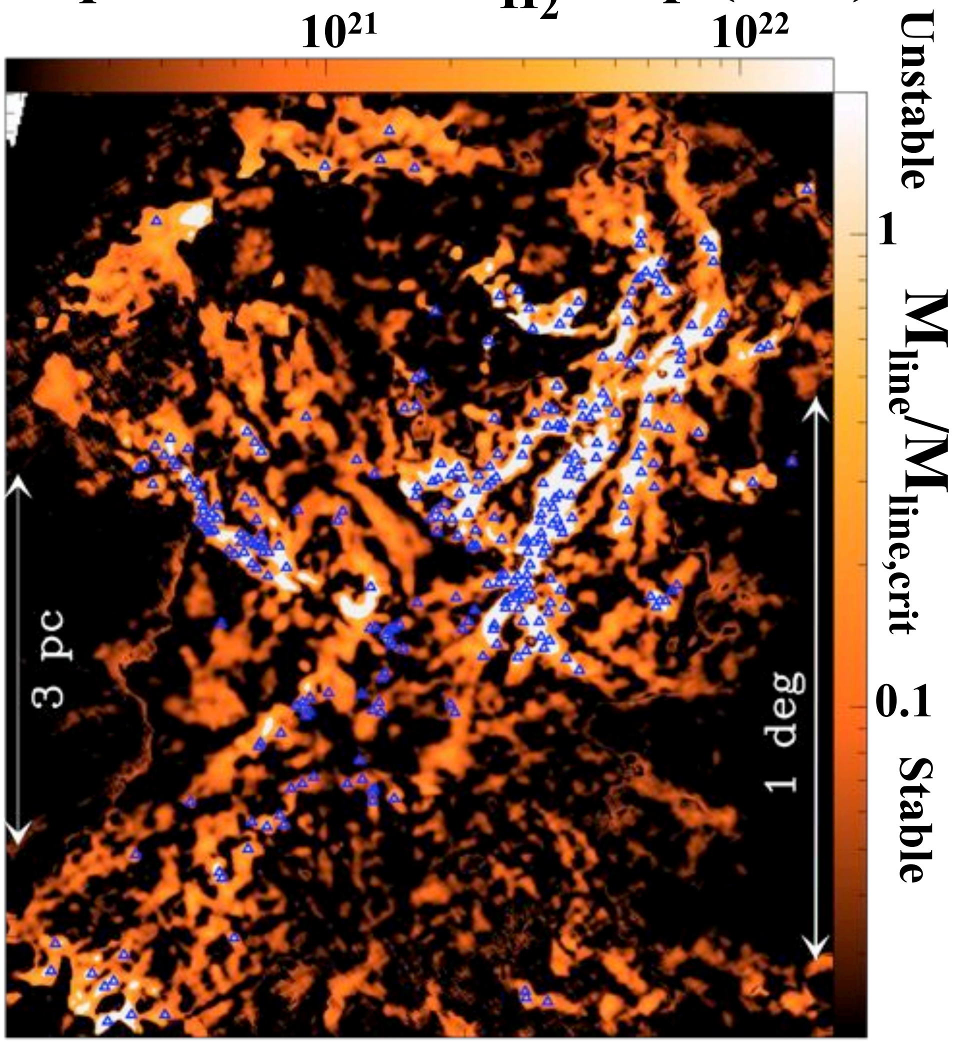
⇔

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

cf. Onishi et al. 1998 (Taurus)

Johnstone et al. 2004 (Ophiuchus)

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 Vol. 518

➢ The gravitational instability of filaments is controlled by the mass per unit length M_{line} (cf. Ostriker 1964, Inutsuka & Miyama 1997):

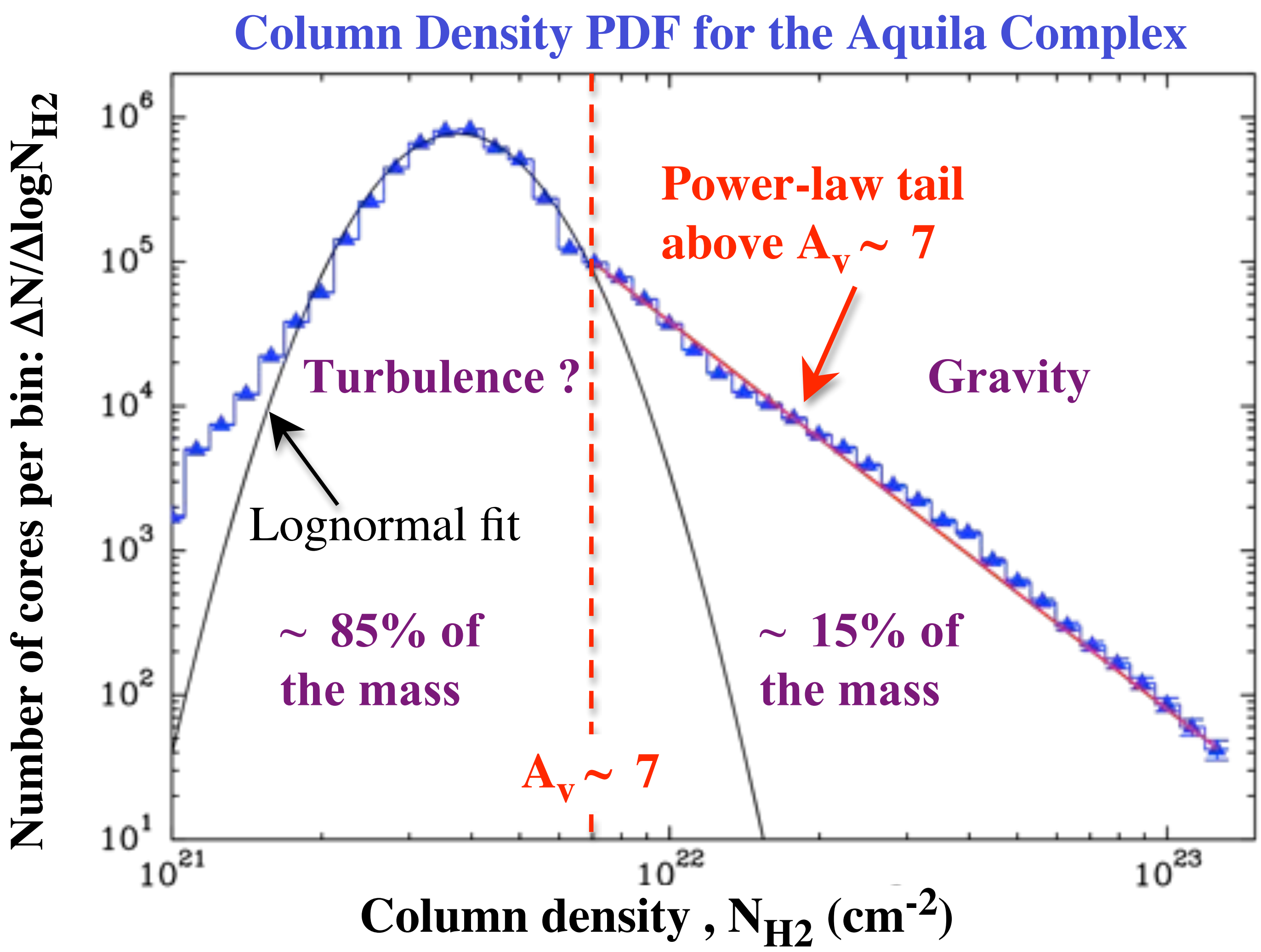
- unstable if $M_{line} > M_{line,\,crit}$
- unbound if $M_{line} < M_{line,\,crit}$
- $M_{line,\,crit} = 2\,c_s^2/G \sim 15\ M_\odot/pc$ for T ~ 10K ⬄ Σ threshold $\sim 150\ M_\odot/pc^2$

➢ Simple estimate:

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

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

Implication of the column density threshold

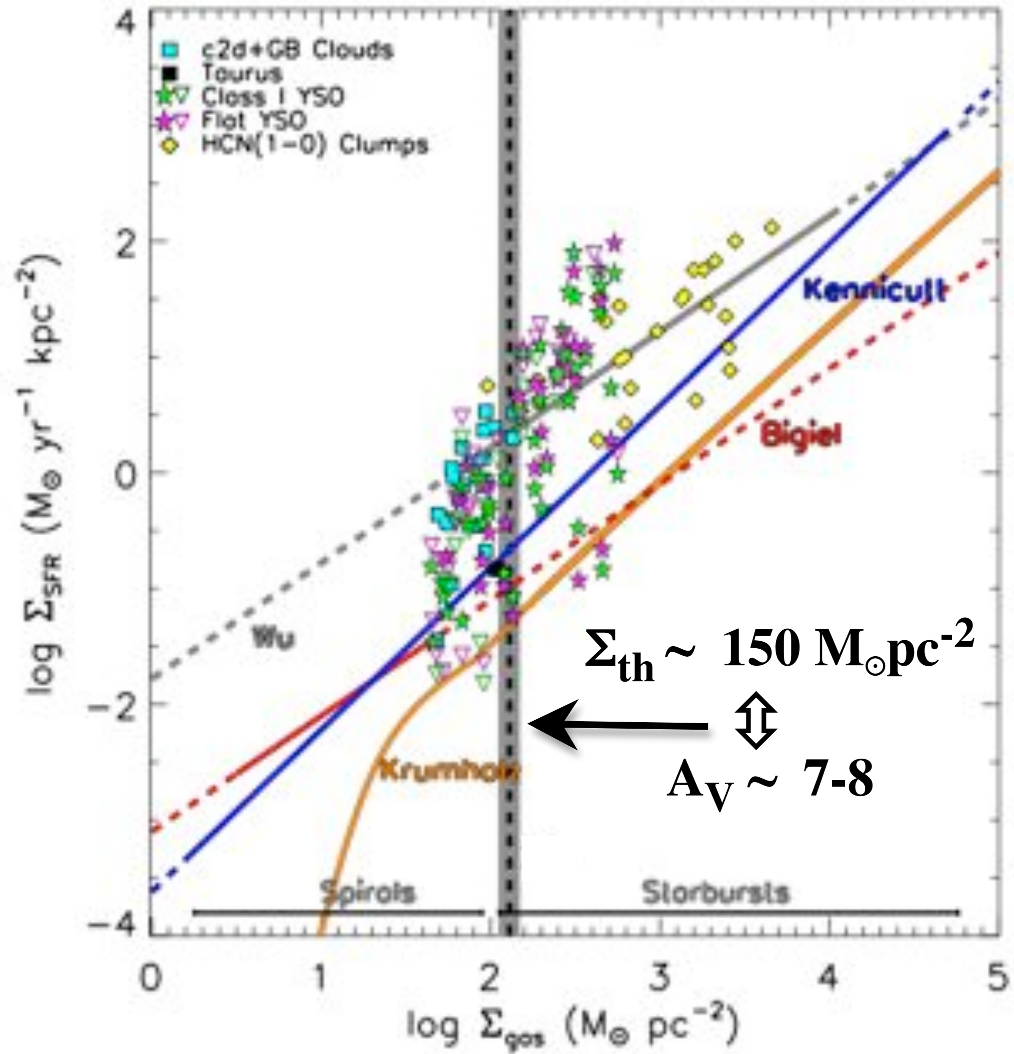


- Only ~ 15% of the molecular cloud's mass above the star formation threshold ($A_V \sim 7$)

→ **Inefficiency of the star formation process**

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

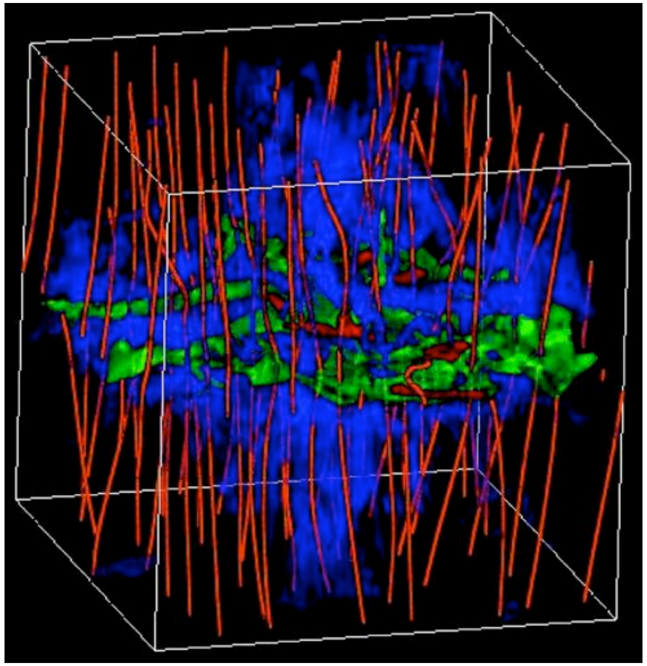
Gao & Solomon 2004

for external galaxies

NB: $\Sigma_{th} \sim$ surface density of galaxy DM halos (e.g. de Vega & Sanchez 2011, Donato et al. 2009)

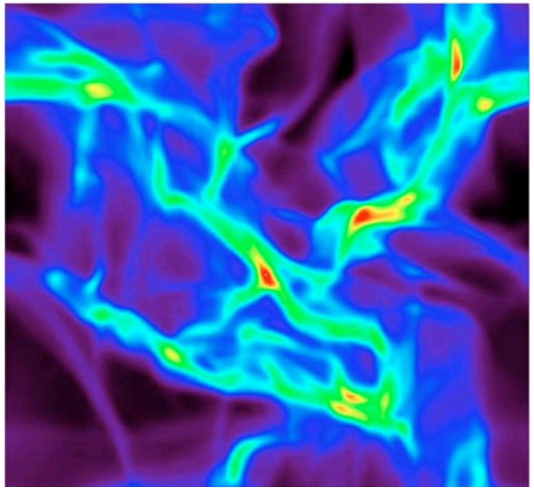
Origin of interstellar filaments? 3 possible paradigms

Magnetically-regulated star formation



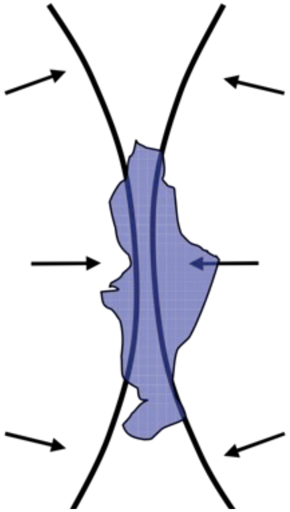
Magnetically-critical condensed sheet, fragmented into filaments and cores (e.g. Nakamura & Li 2008; Basu, Ciolek etal. '09)

Turbulent fragmentation



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

Gravity-dominated cloud/star formation



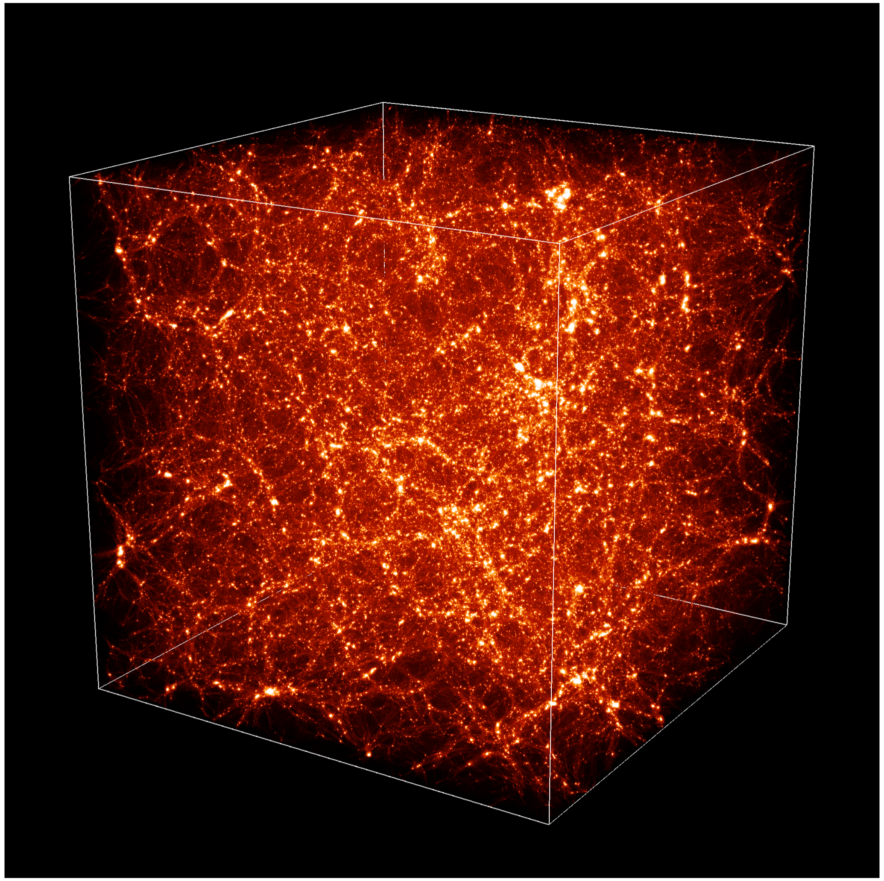
Filaments from global cloud collapse
Cores from local gravity
(e.g. Burkert & Hartmann '04; Heitsch et al. '08; also Nagai et al. '98)

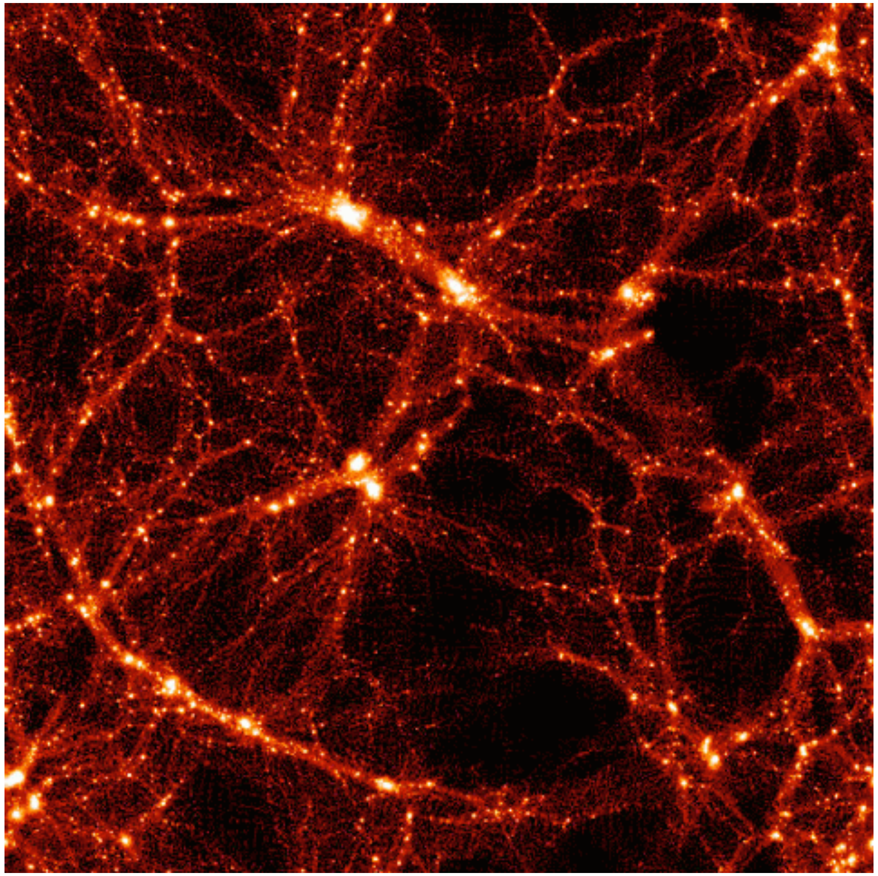
Bate, Bonnell et al. 2003 …

The observed interstellar filaments are reminiscent of the “cosmic web” of intergalactic gas

Numerical simulations of structure formation in the Universe:

Horizon Project (R. Teyssier et al.)



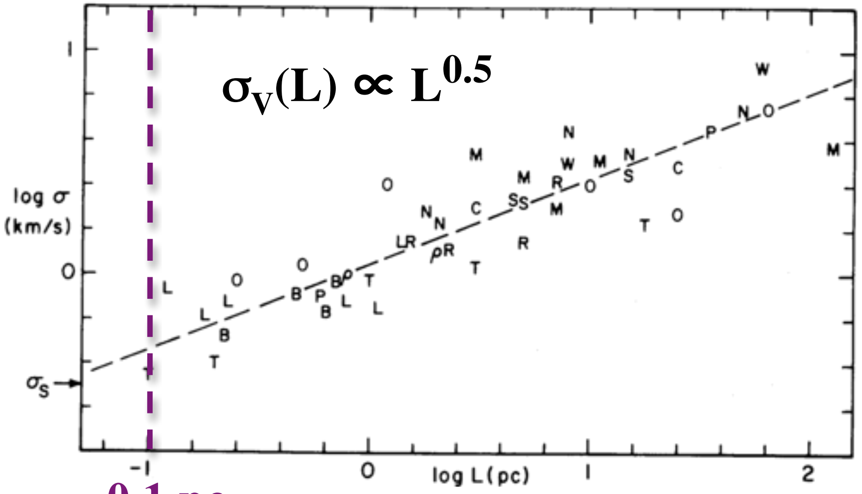


- Would naively suggest that gravity is at play in the ISM as well
- However, gravity is difficult to invoke in unbound ISM clouds (e.g. Polaris)

The turbulent fragmentation picture accounts for the ~ 0.1 pc characteristic width of interstellar filaments: ~ sonic scale of ISM turbulence

Linewidth-Size relation in clouds

(Larson 1981)



$\sigma_V(L) \propto L^{0.5}$

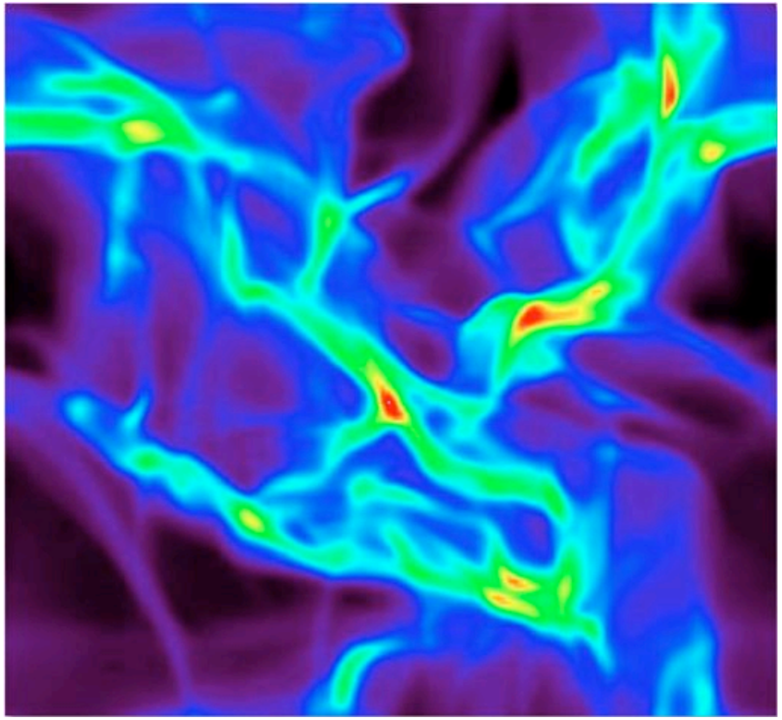
Log (Velocity Dispersion) [km/s]

Log (Size) [pc]

0.1 pc

Sonic scale

Simulations of turbulent fragmentation



Padoan, Juvela et al. 2001

- Corresponds to the typical thickness λ of shock-compressed structures/filaments in the turbulent fragmentation scenario

$$\lambda \sim L/\underbrace{\mathcal{M}(L)^2}_{\text{compression ratio (HD shock)}} \sim 0.1 \text{ pc}$$

Conclusions

First results from *Herschel* on star formation are very promising:

- Confirm the **close link between the prestellar CMF and the IMF**, although the whole Gould Belt 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 $A_V \sim 7 \Leftrightarrow \Sigma_{th} \sim 150\ M_{\odot}\ pc^{-2}$

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