From the filamentary structure of molecular clouds to the formation and properties of prestellar cores

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, D. Ward-Thompson, J. Kirk, M. Attard, J. Di Francesco, P. Martin, P. Saraceno, P. Palmeirim, L. Testi & the *Herschel* Gould Belt KP Consortium

Outline:

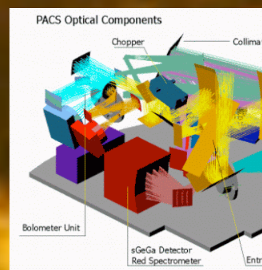
http://gouldbelt-herschel.cea.fr/

- First results from the *Herschel* Gould Belt survey
- Preliminary statistics on dense cores (e.g. CMF vs. IMF)
- The role of filaments in the core/star formation process
- Toward a universal scenario ?

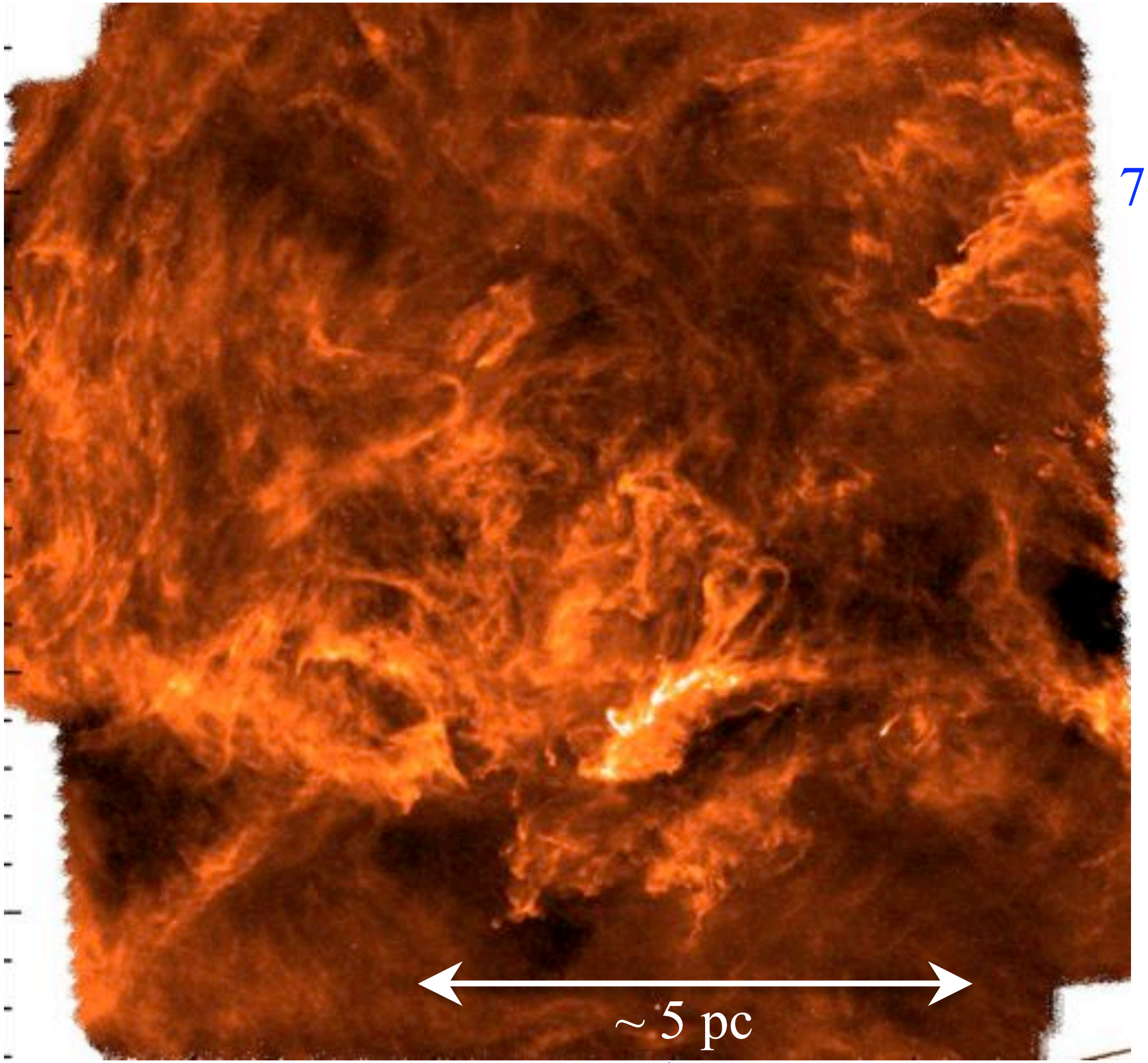
Herschel GB survey IC5146 Arzoumanian et al. 2011

~ 5 pc

PACS



Structure of the cold ISM prior to star formation



SPIRE 250 μm image

Gould Belt Survey
Herschel // mode
70/160/250/350/500 μm

Polaris flare translucent cloud
(d ~ 150 pc)

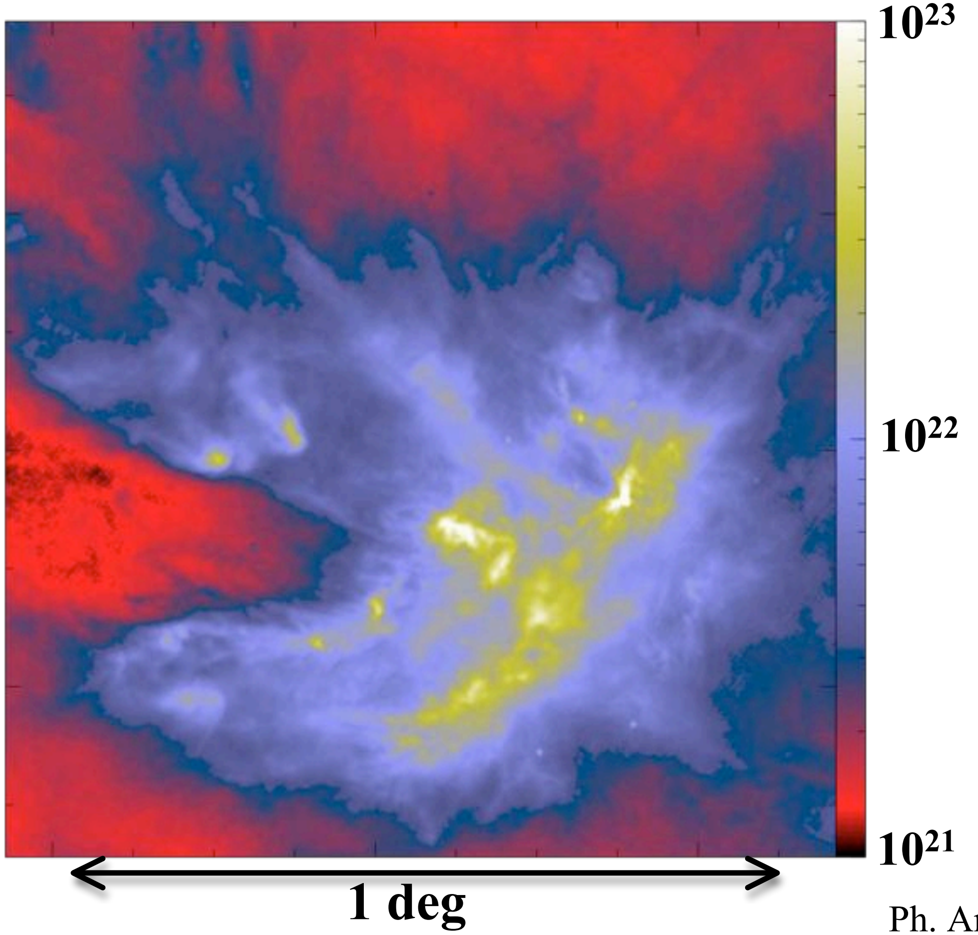
~ 5500 $M_\odot$ (CO+HI)
Heithausen & Thaddeus '90

~ 13 deg^2 field

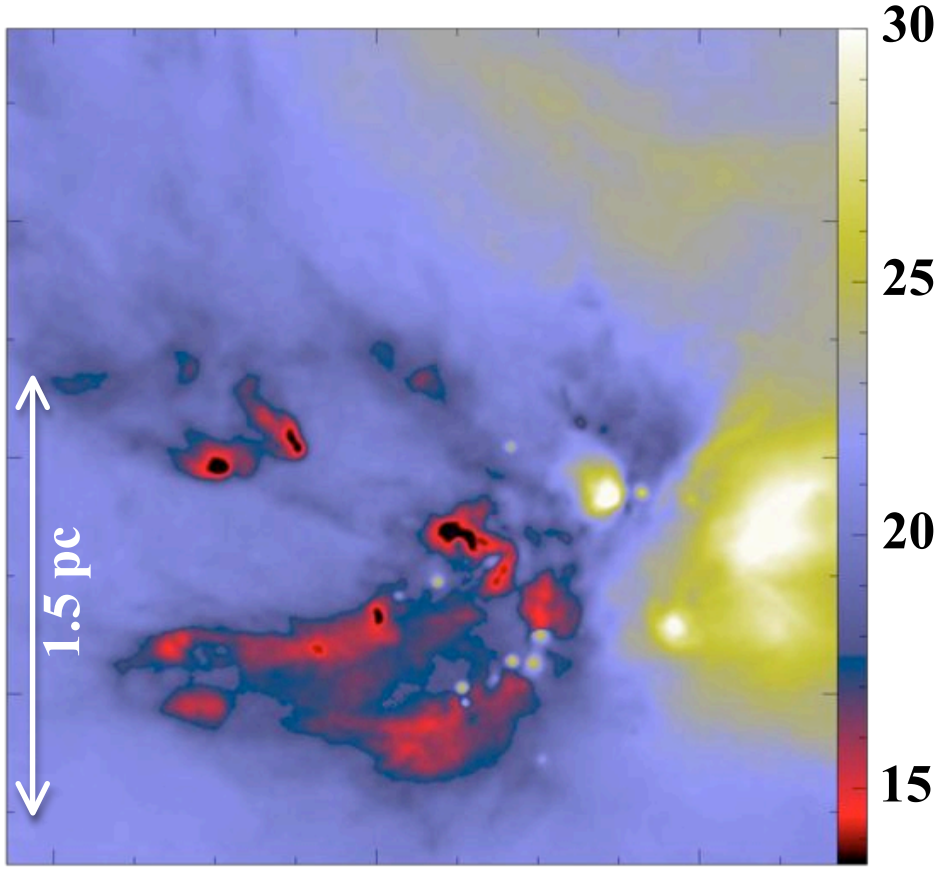
Miville-Deschênes et al. 2010
Ward-Thompson et al. 2010
Men'shchikov et al. 2010
A&A vol. 518

L1688 in Ophiuchus (d ~ 140 pc): Column density and dust temperature maps

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



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



Dense cores form primarily in filaments

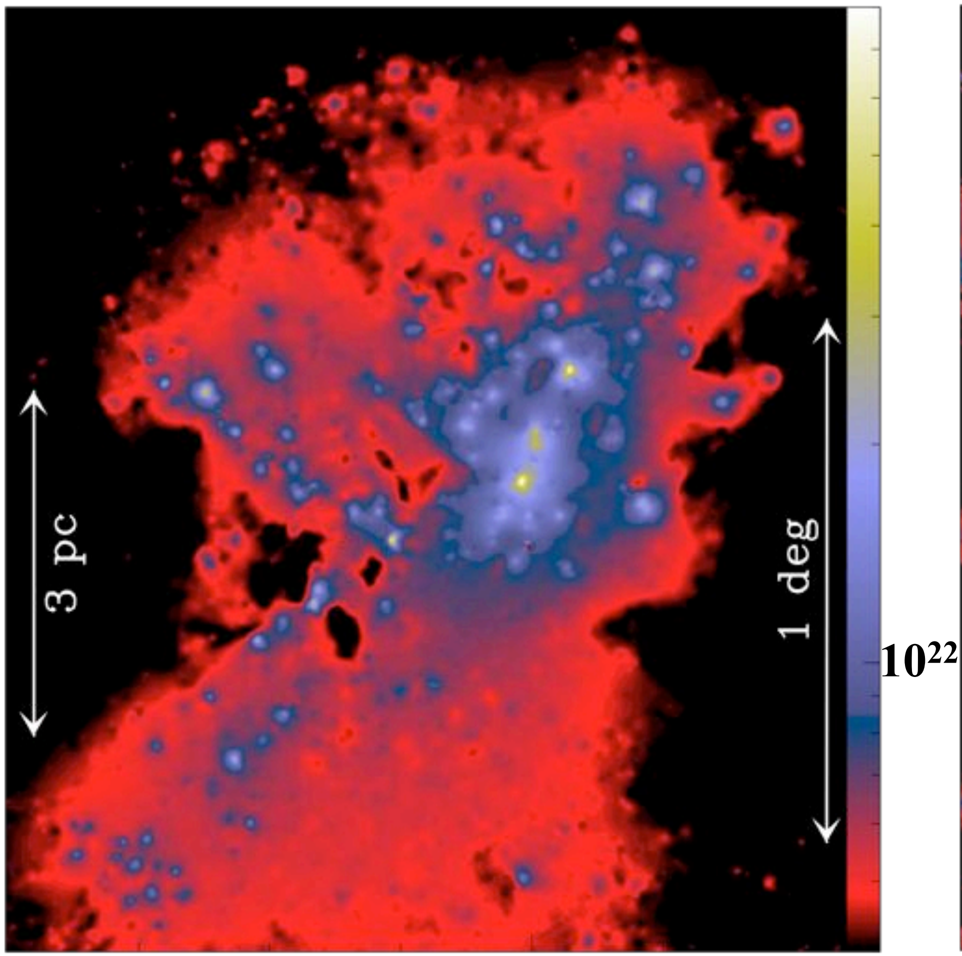
Morphological Component Analysis:

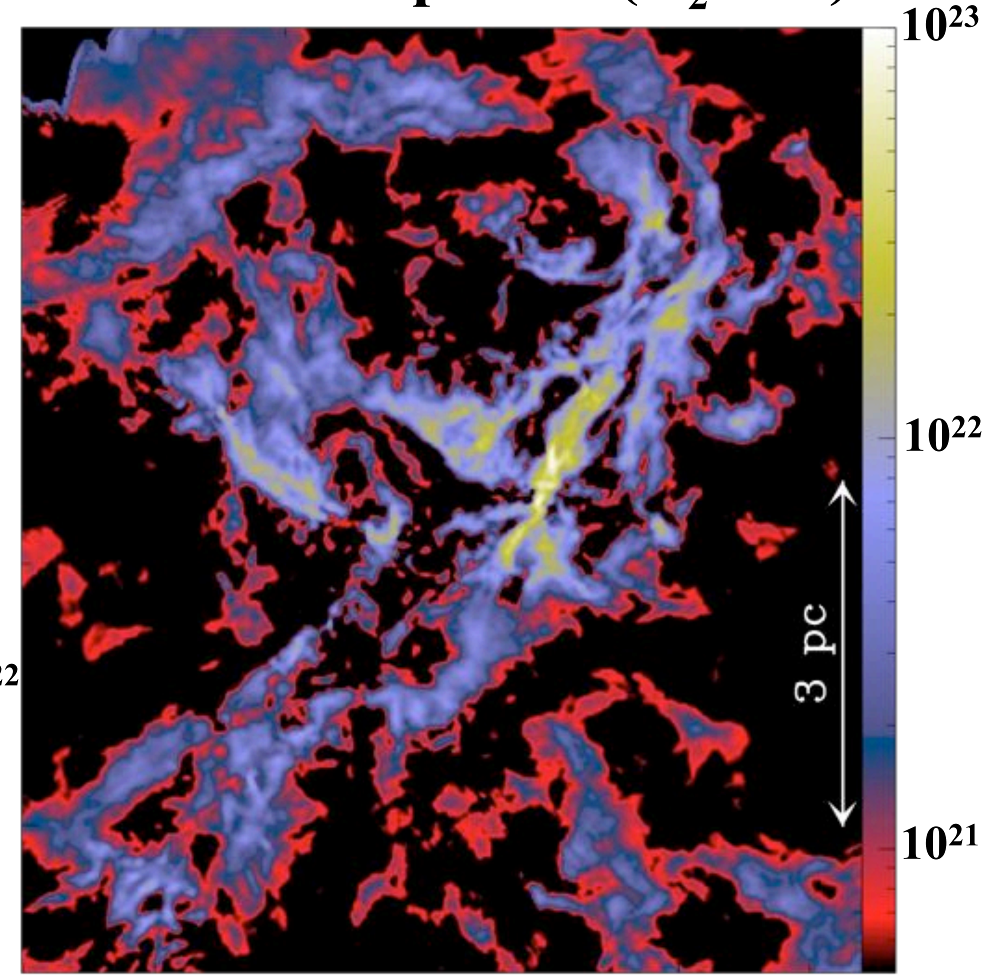
***Herschel* Column density map**

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

Cores = Filaments

Wavelet component (H_2/cm^2) + Curvelet component (H_2/cm^2)





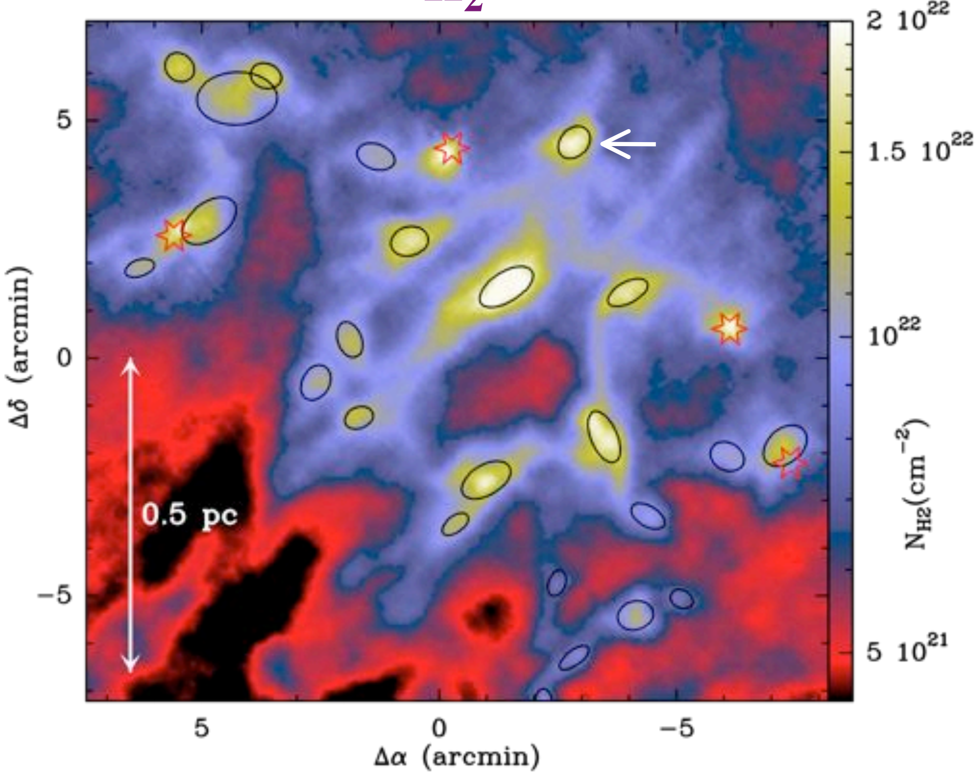
Core extraction using "getsources"

(A. Men'shchikov et al. 2010, 2011)

- **Core = single star-forming entity**
  (Need to resolve ~ 0.01-0.1 pc)
- **Prestellar = bound & starless**

Examples of starless cores in Aquila

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



Könyves et al. 2010, A&A special issue

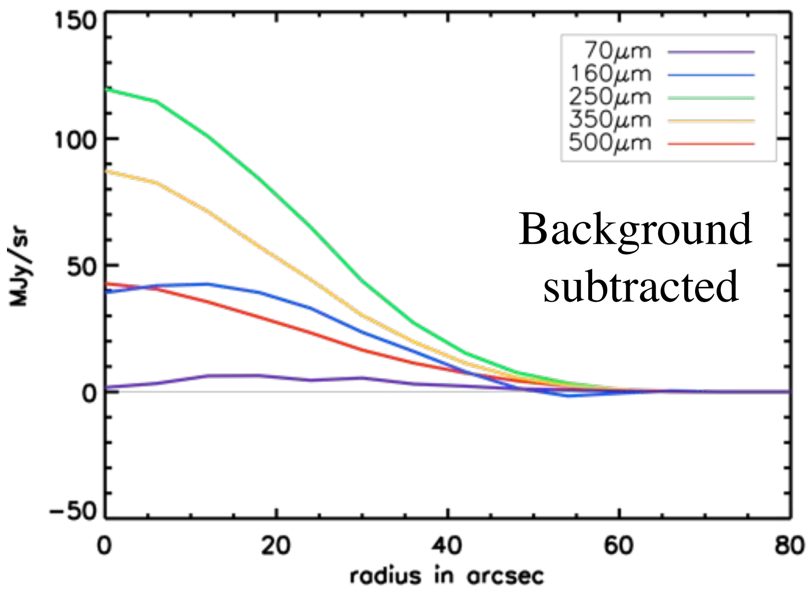
541 starless cores (no PACS 70 µm), including > 341 prestellar cores

+

201 YSOs (with PACS 70µm)

identified with *getsources* in Aquila

Examples of radial intensity profiles

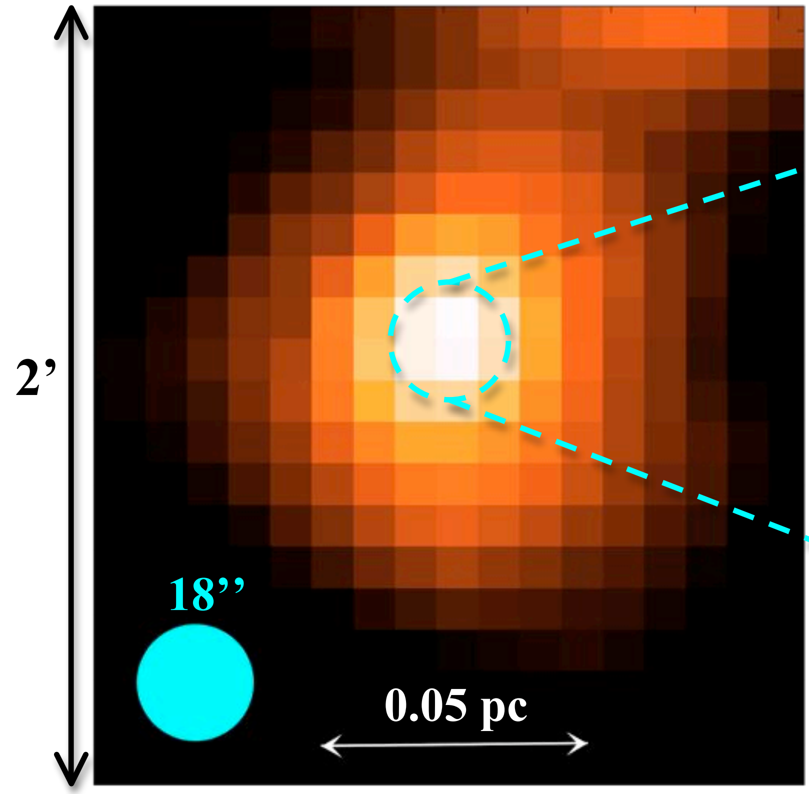


At most limited sub-fragmentation within the cores identified with *Herschel* in nearby (d < 500 pc) clouds

➢ **Progenitors of individual stars or binary systems, not "clusters"**

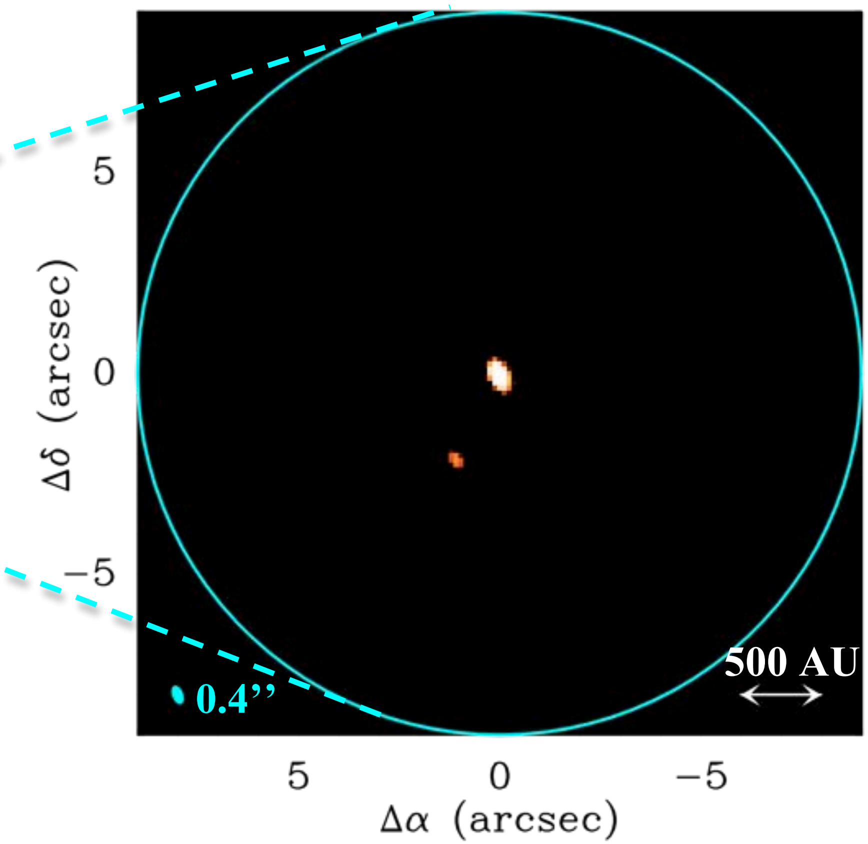
Herschel **~ 15'' resolution at λ ~ 200 µm ⇔ ~ 0.02 pc < Jeans length @ d = 300 pc**

L1448-C: Herschel/SPIRE 250 µm



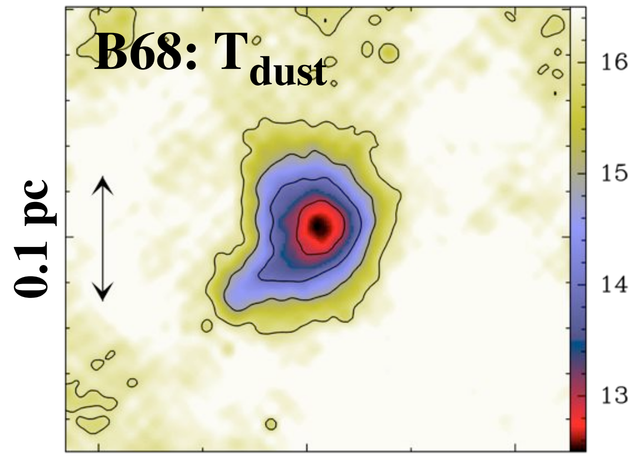
Pezzuto, Sadavoy et al., in prep.

L1448-C: IRAM-PdB interferometer 1.3mm



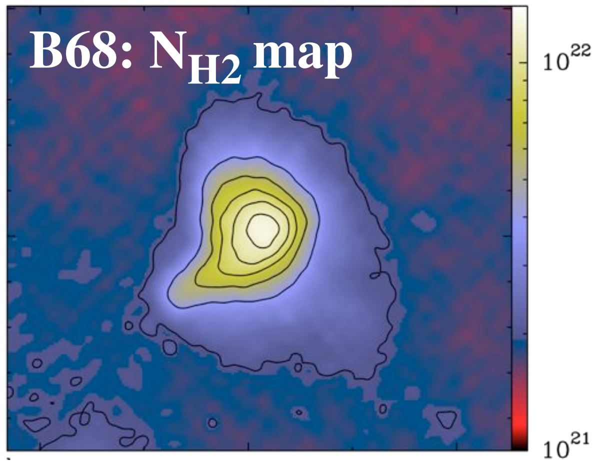
Maury et al. 2010 - see also Schnee et al. 2010

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

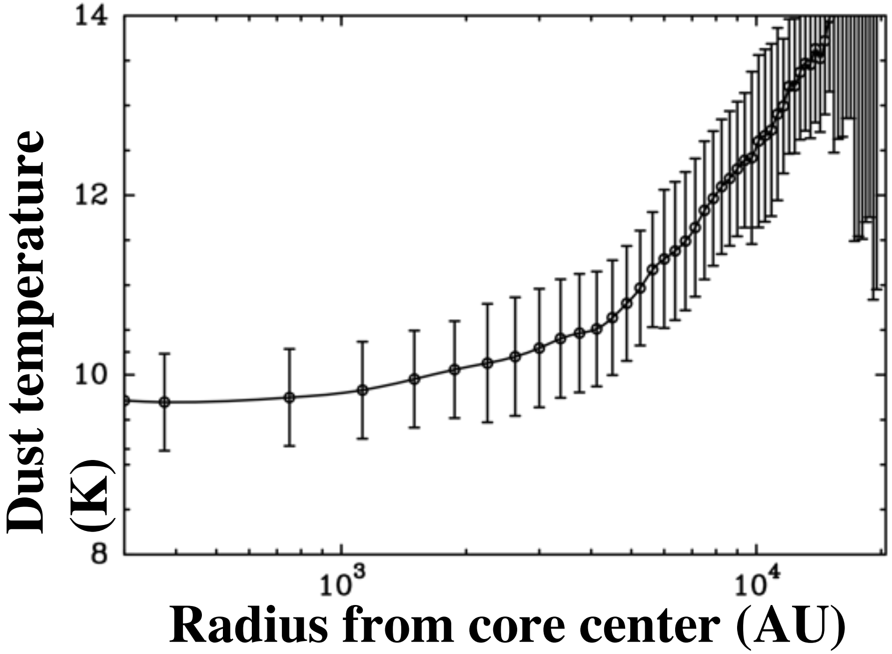


M. Attard et al.

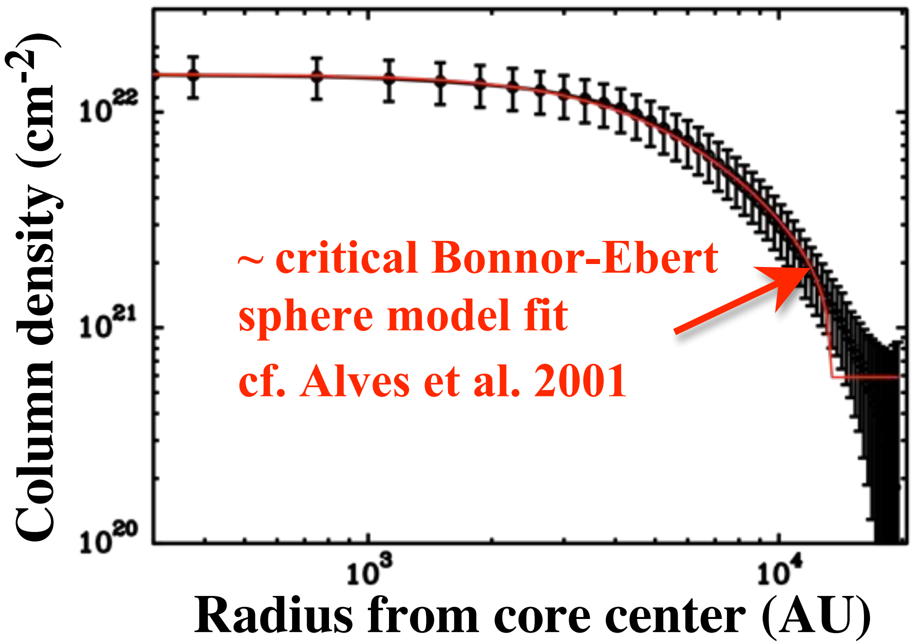
See also
A.Stutz et al.
EPOS Program



Temperature profile of B68

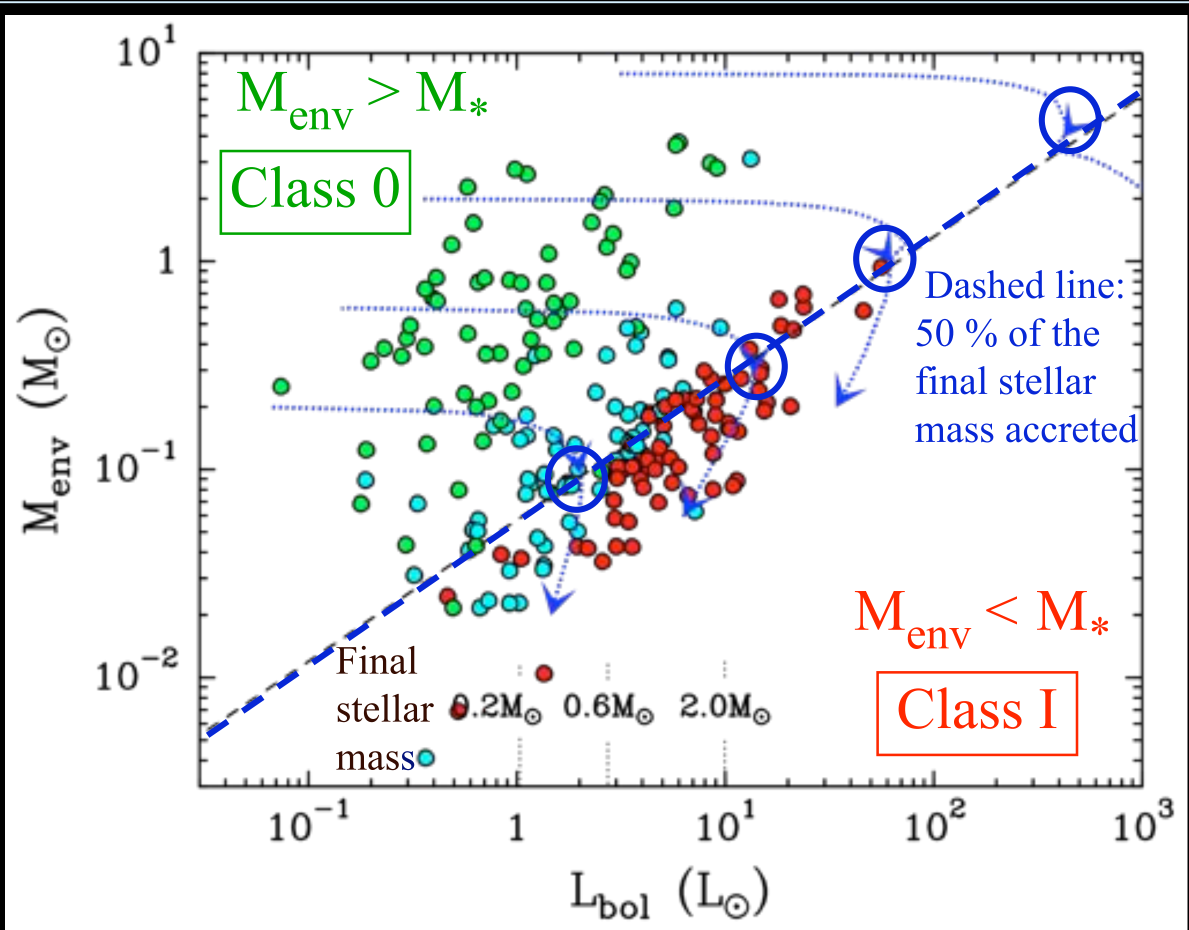


Column density profile of B68



Preliminary Protostar Evolutionary Diagram for Aquila

- 201 protostars detected with PACS at 70 μm down to ~ 0.2 $L_{\odot}$
- M_{env} vs. L_{bol} diagram to distinguish between Class 0 and Class I protostars
- Revised estimate of the Class 0 lifetime: ~ 1/5 of Class I lifetime ~ 4-9 x 10^4 yr (see Evans et al. 2009 for the Class I lifetime)

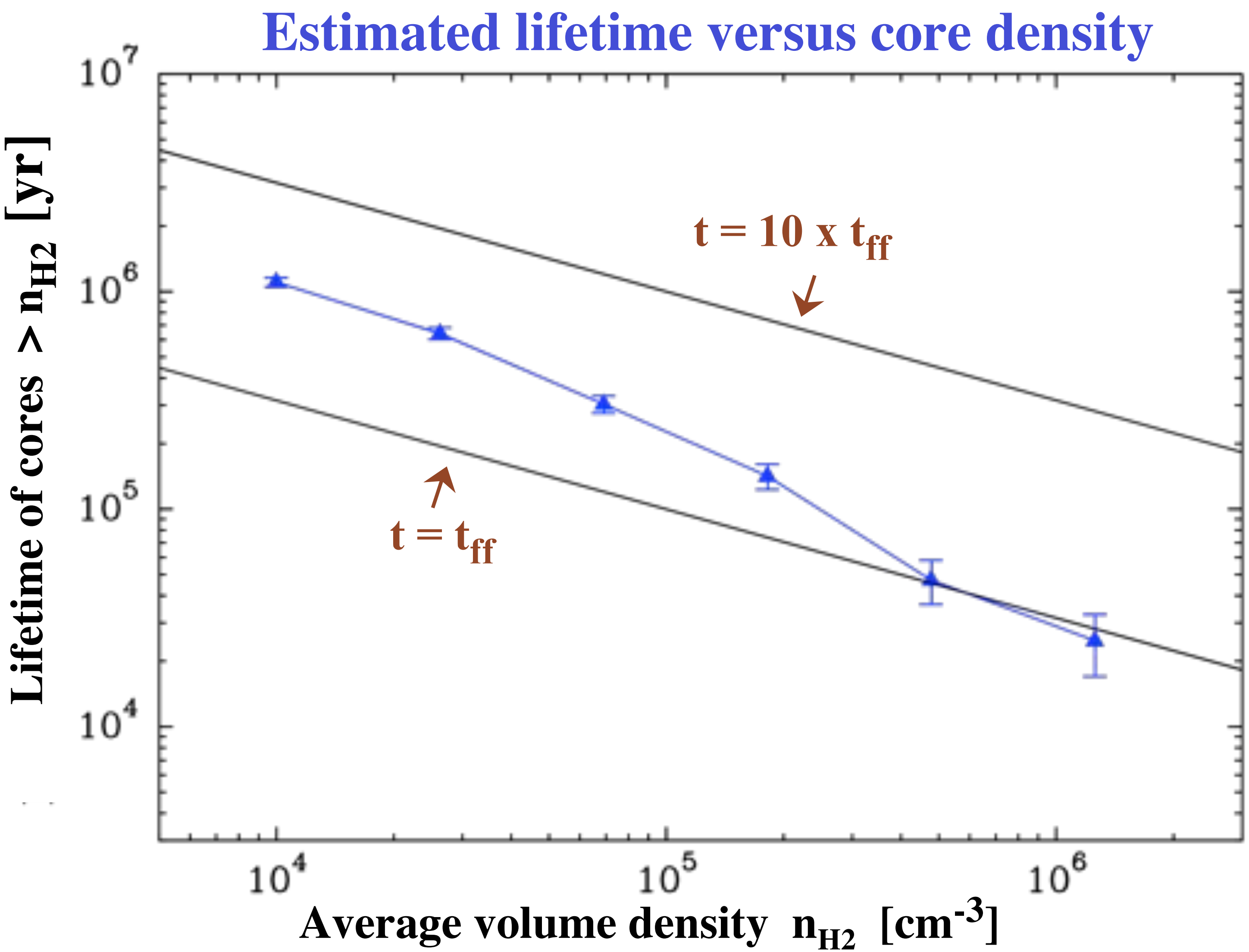


~ 35 Class 0s In Aquila

5 of them (~ 15%) not detected by *Spitzer* at 24 μm

Bontemps et al. (2010)
Maury et al. (2011)

Preliminary estimates of core lifetimes in Aquila



541 *Herschel* starless cores

$t \sim 1$ Myr
$\sim 3\ t_{ff}$

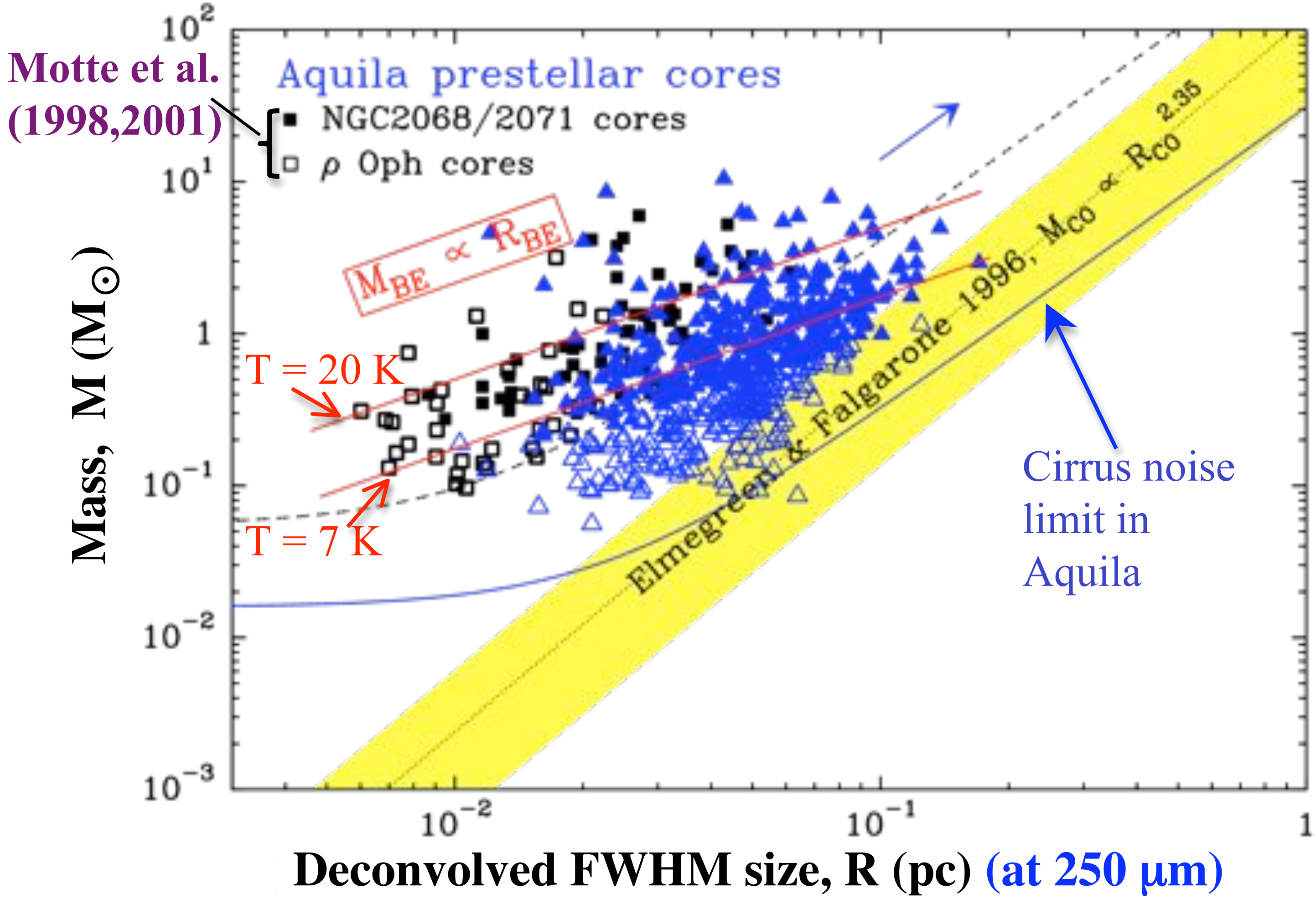
201 *Herschel* Class0/ClassI protostars ($t \sim 0.5$ Myr)

~1000 *Spitzer* (Class II) YSOs ($t \sim 2$ Myr)

cf. Ward-Thompson et al. 2007 PPV

Könyves et al. in prep.

Selection of prestellar cores based on the locations of extracted starless sources in a mass vs. size diagram



➢ **In Aquila, > 60% of the *Herschel* starless cores are likely self-gravitating, hence prestellar**

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

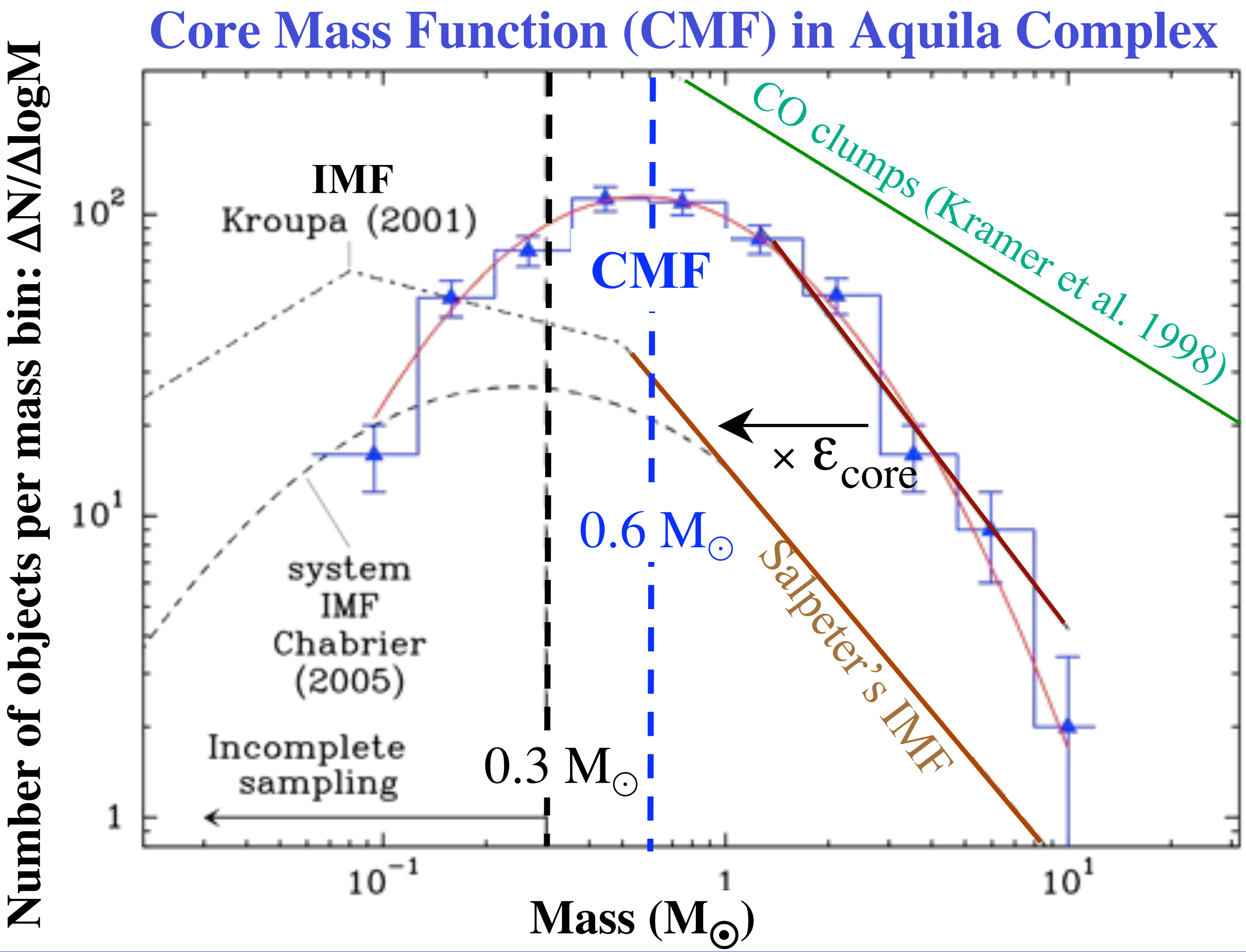
Confirming the link between the prestellar CMF & the IMF

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; Testi & Sargent 1998; Nutter & Ward-Thompson 2007; Alves et al. 2007)



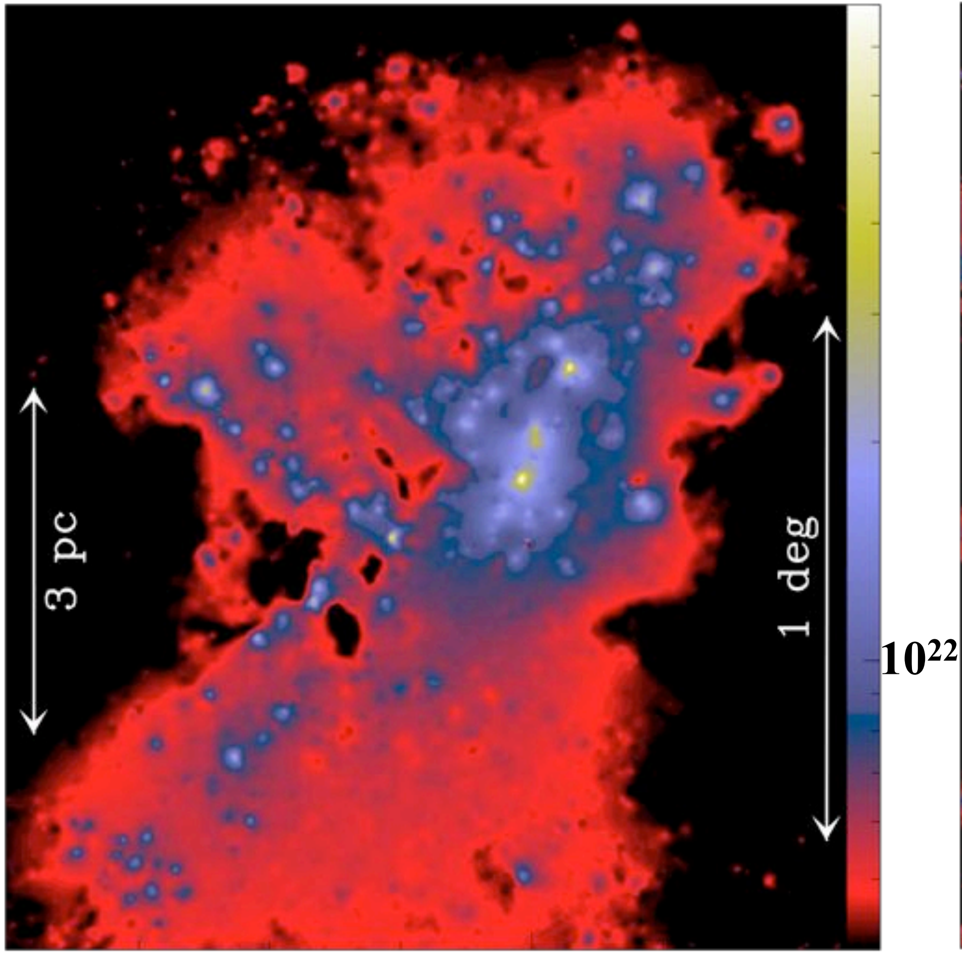
➢ **Good (~ one-to-one) mapping between core mass and stellar system mass: $M_* = \varepsilon_{core}\ M_{core}$ with $\varepsilon_{core} \sim 0.2\text{-}0.4$ in Aquila**

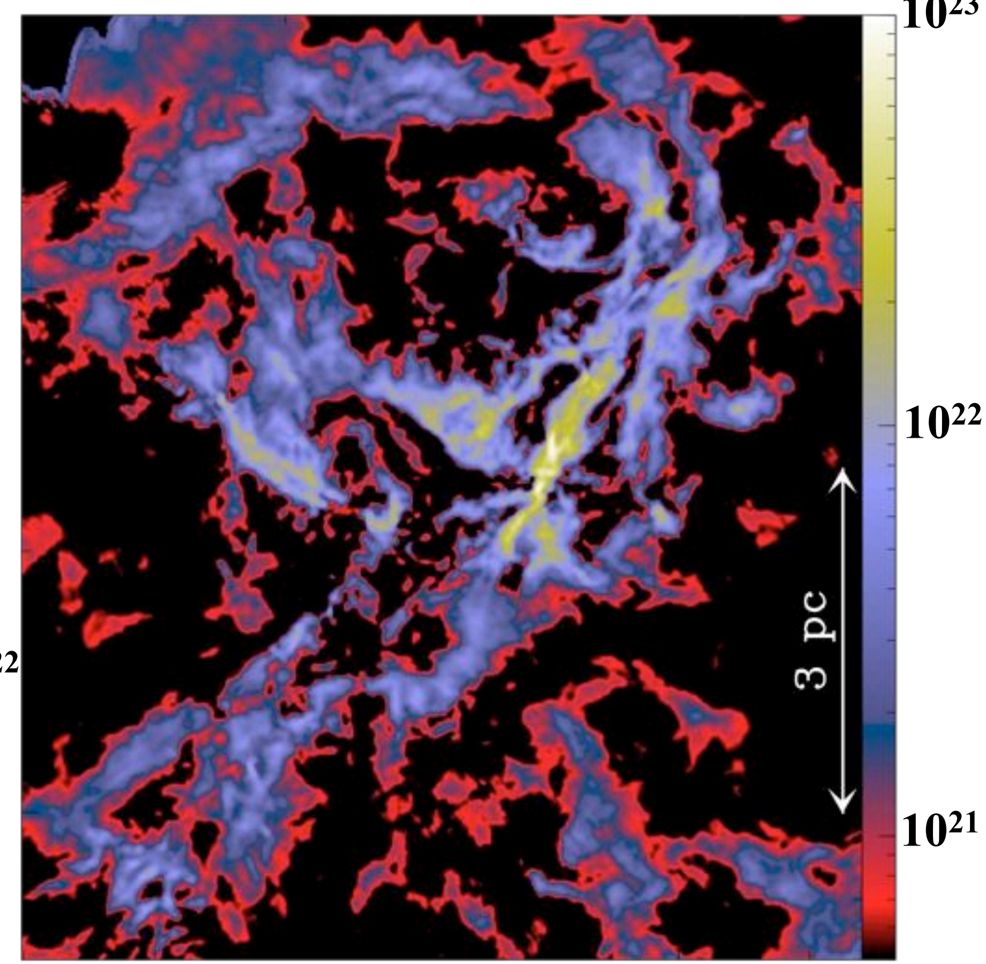
➢ **The IMF is at least partly determined by pre-collapse cloud/filament fragmentation** (cf. models by Padoan & Nordlund 2002, Hennebelle & Chabrier 2008)

Prestellar cores form out of a filamentary background

Cores = Filaments

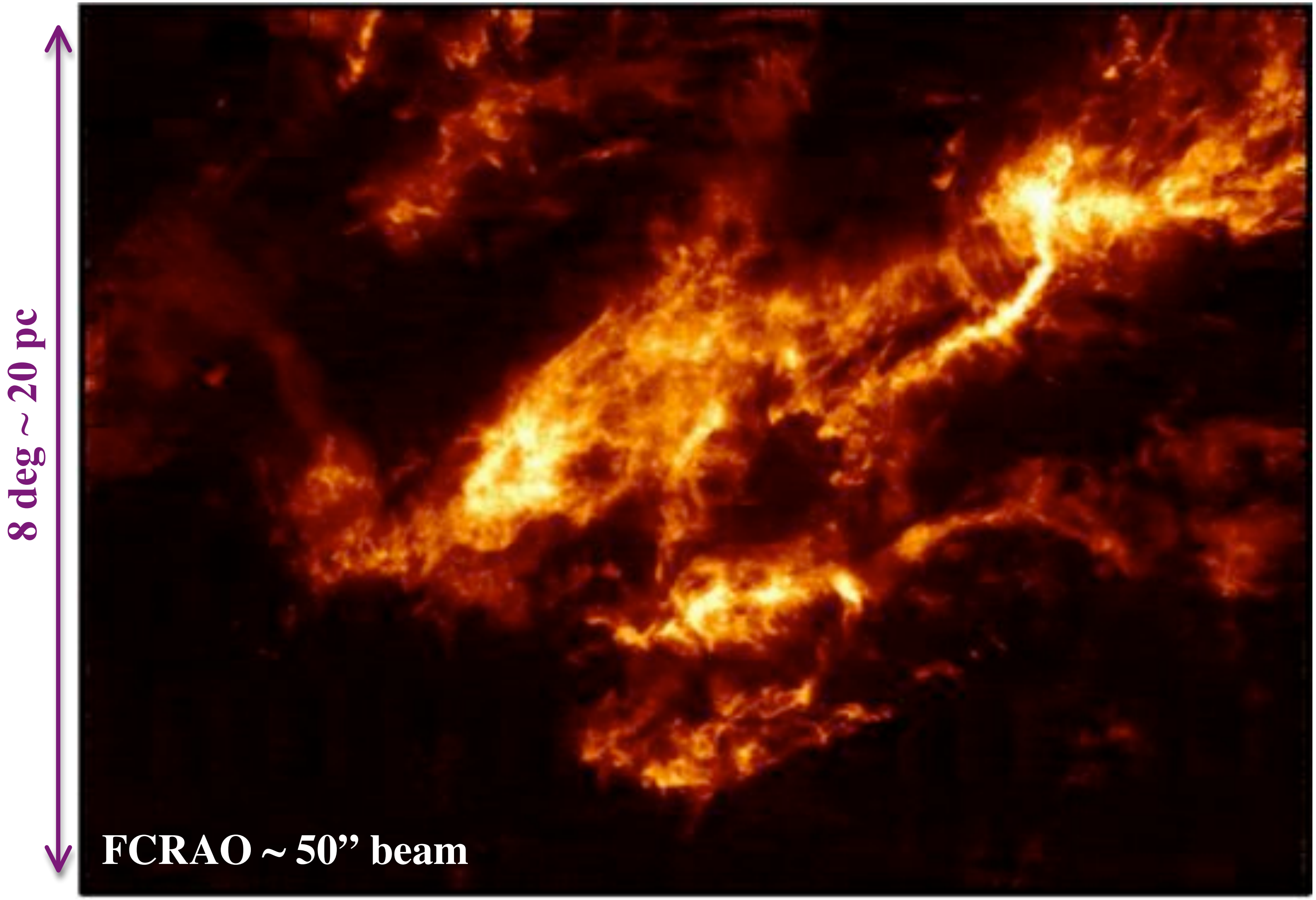
Wavelet component (H_2/cm^2) + Curvelet component (H_2/cm^2)





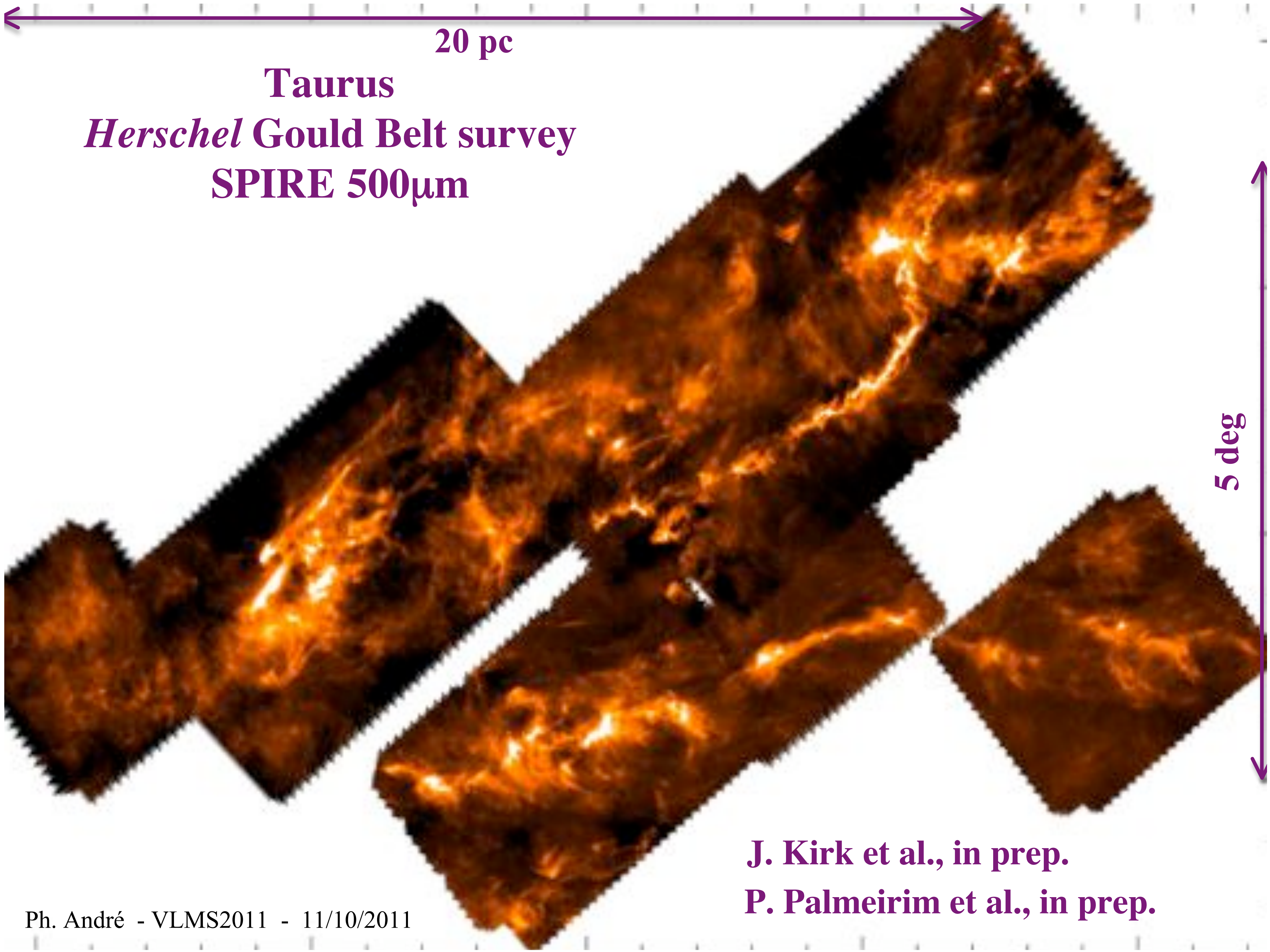
Evidence of the importance of filaments prior to *Herschel*

Taurus: ^{13}CO integrated intensity map (Goldsmith et al. 2008)



See also Schneider & Elmegreen 1979, Abergel et al. 1994, Hartmann 2002, Myers 2009 …

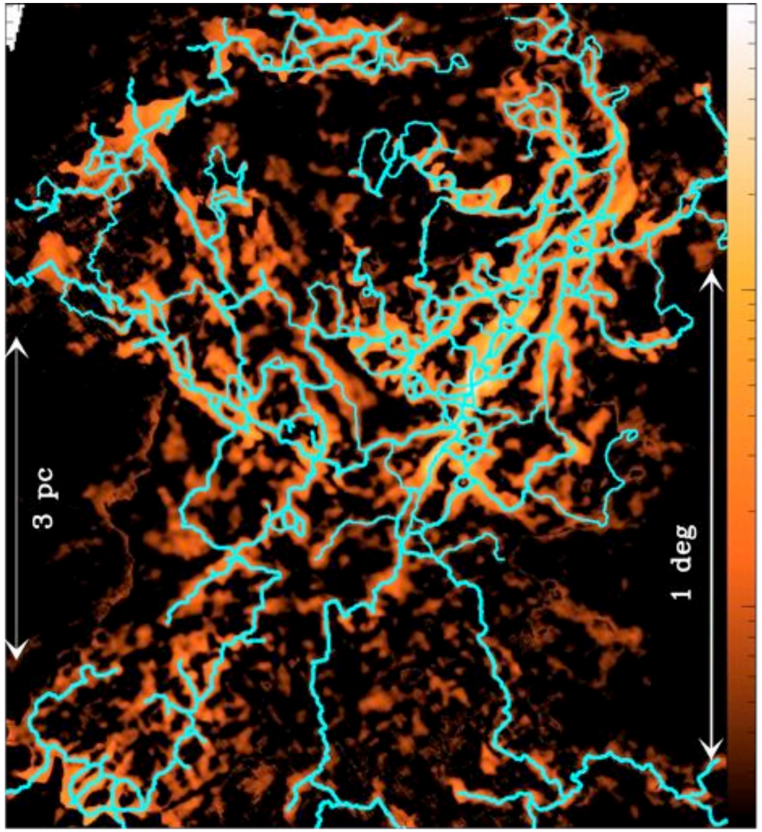
Taurus
Herschel Gould Belt survey
SPIRE 500µm



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

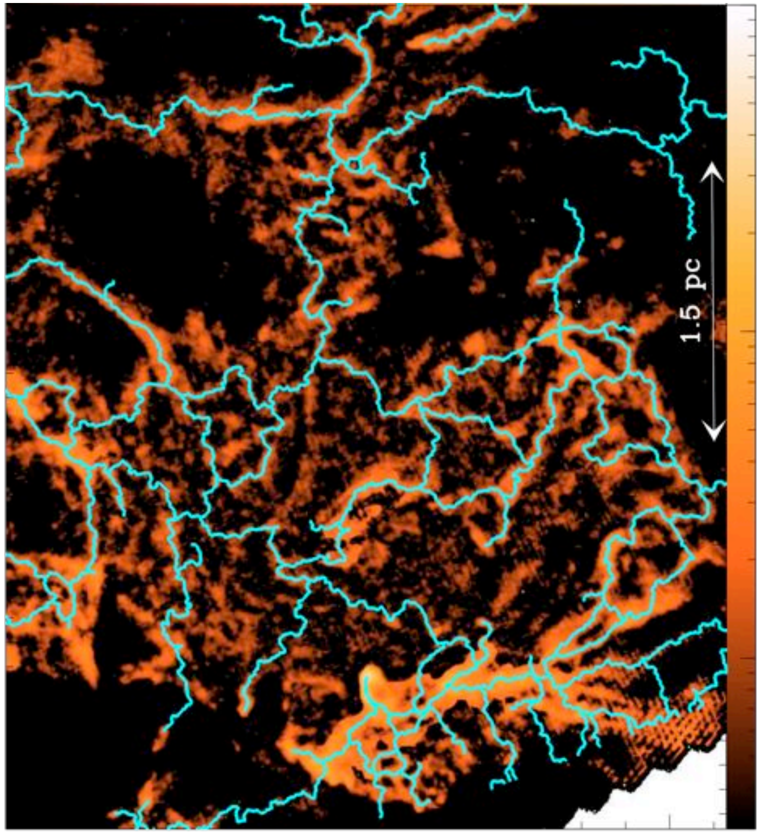
Herschel reveals a rich network of filaments in every interstellar cloud

Aquila: Actively star forming



Network of filaments in Aquila

Polaris: Non star forming



Network of filaments in Polaris

***Herschel* Gould Belt survey** (André et al. 2010, Men'shchikov et al. 2010, Arzoumanian et al. 2011)

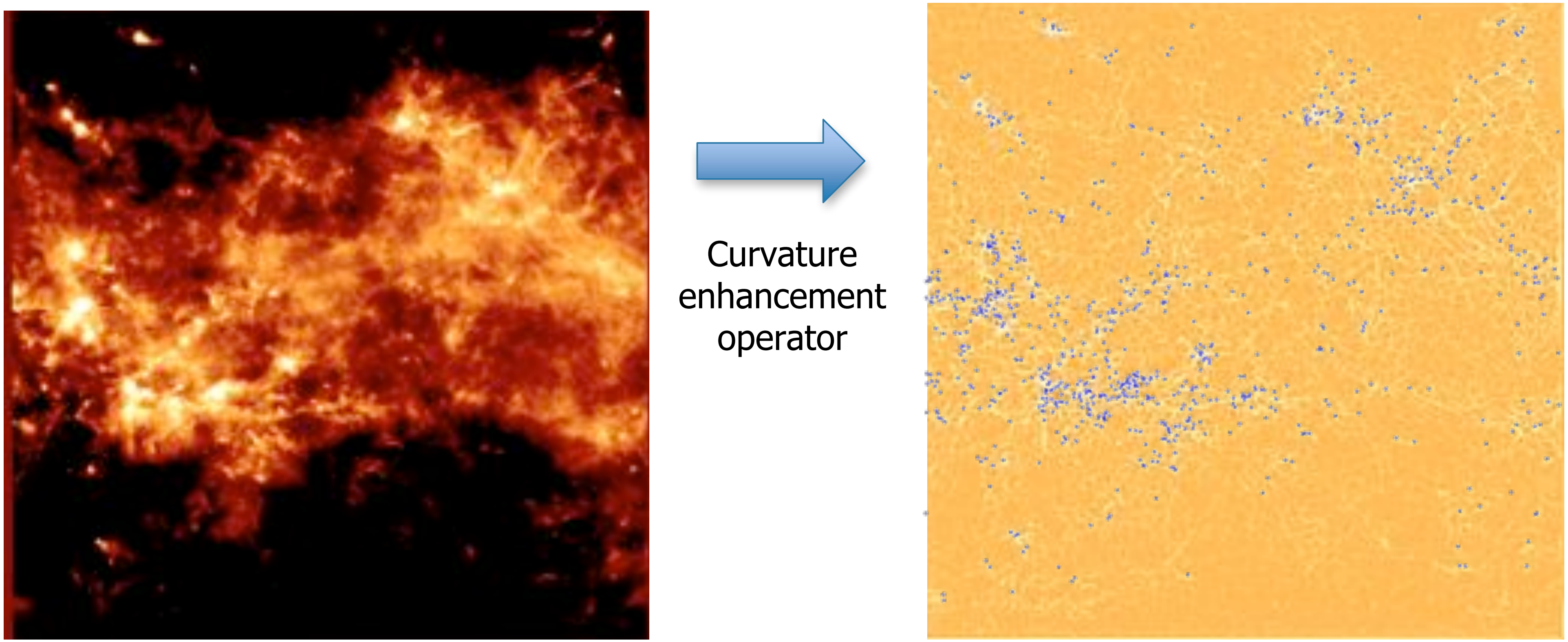
Using the 'skeleton' or DisPerSE algorithm (Sousbie 2011) to trace the network of filaments in each cloud

Galactic star formation occurs primarily along filaments

HI-GAL image of MW (Molinari et al. 2010)

Galactic star formation occurs primarily along filaments

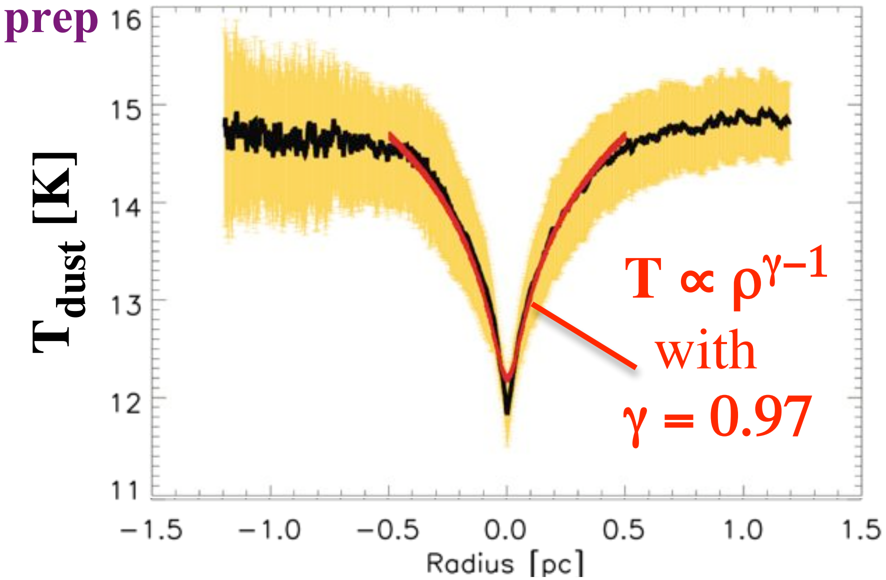
HI-GAL image of MW (Molinari et al. 2010)

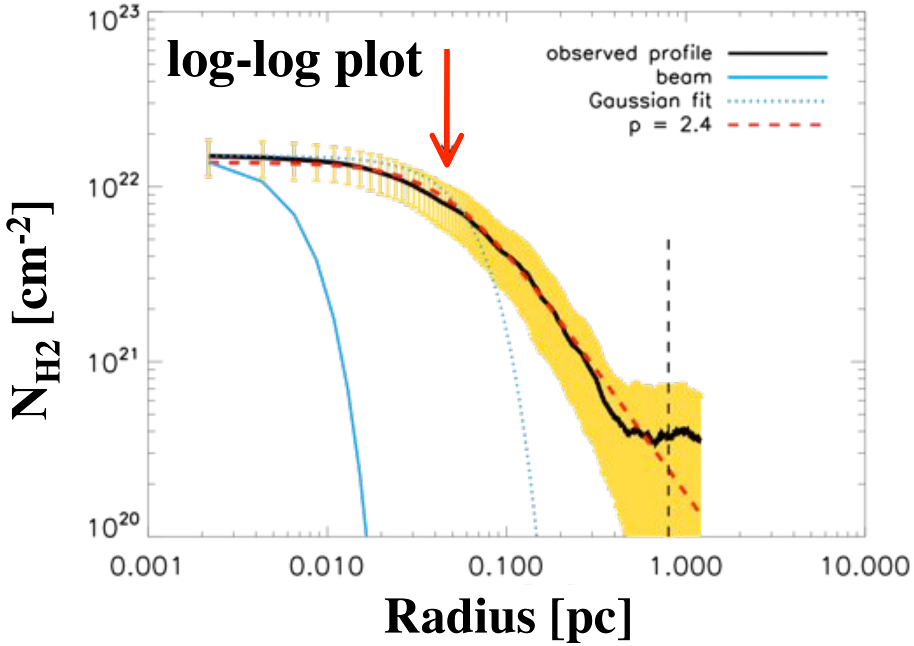


Characterizing the structure of filaments with *Herschel*

Taurus B213 filament
SPIRE 250µm

Palmeirim et al. in prep





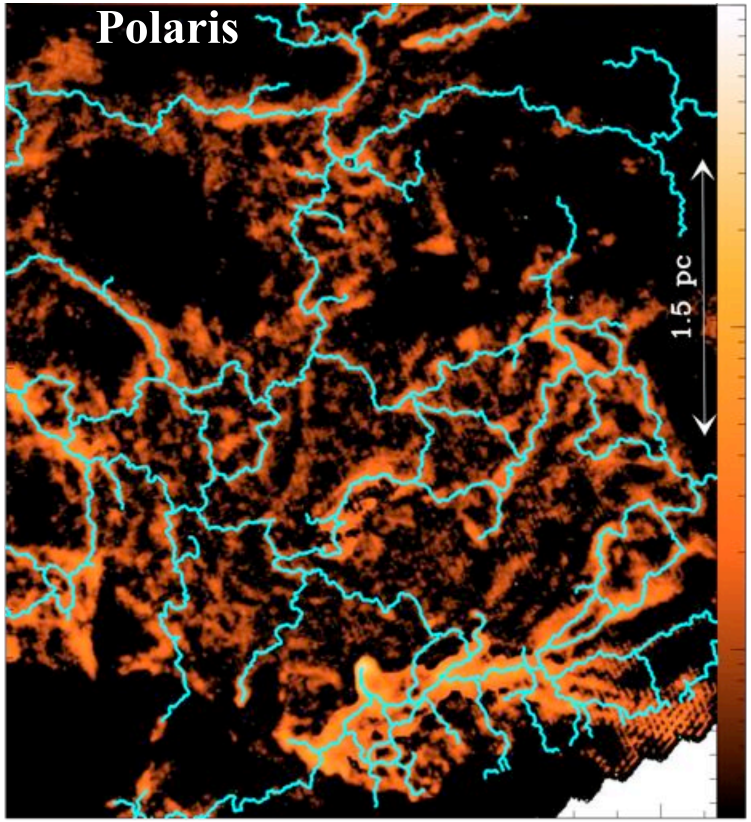
Plummer-like density profile:

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

with $R_{flat} \sim 0.05$ pc

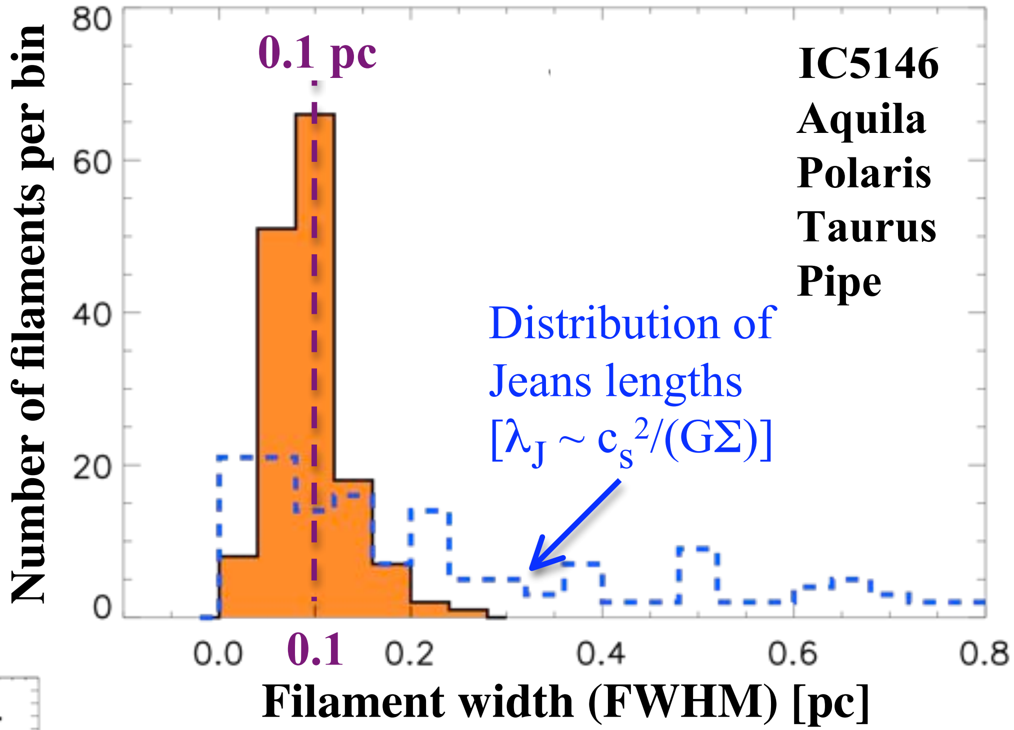
Diameter of flat inner plateau ~ 0.1 pc

Filaments have a characteristic width ~ 0.1 pc

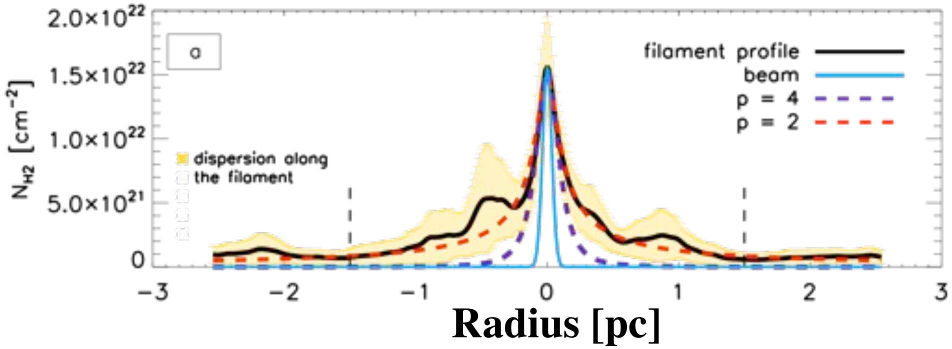


D. Arzoumanian et al. 2011, A&A, 529, L6

Statistical distribution of widths for 150 filaments



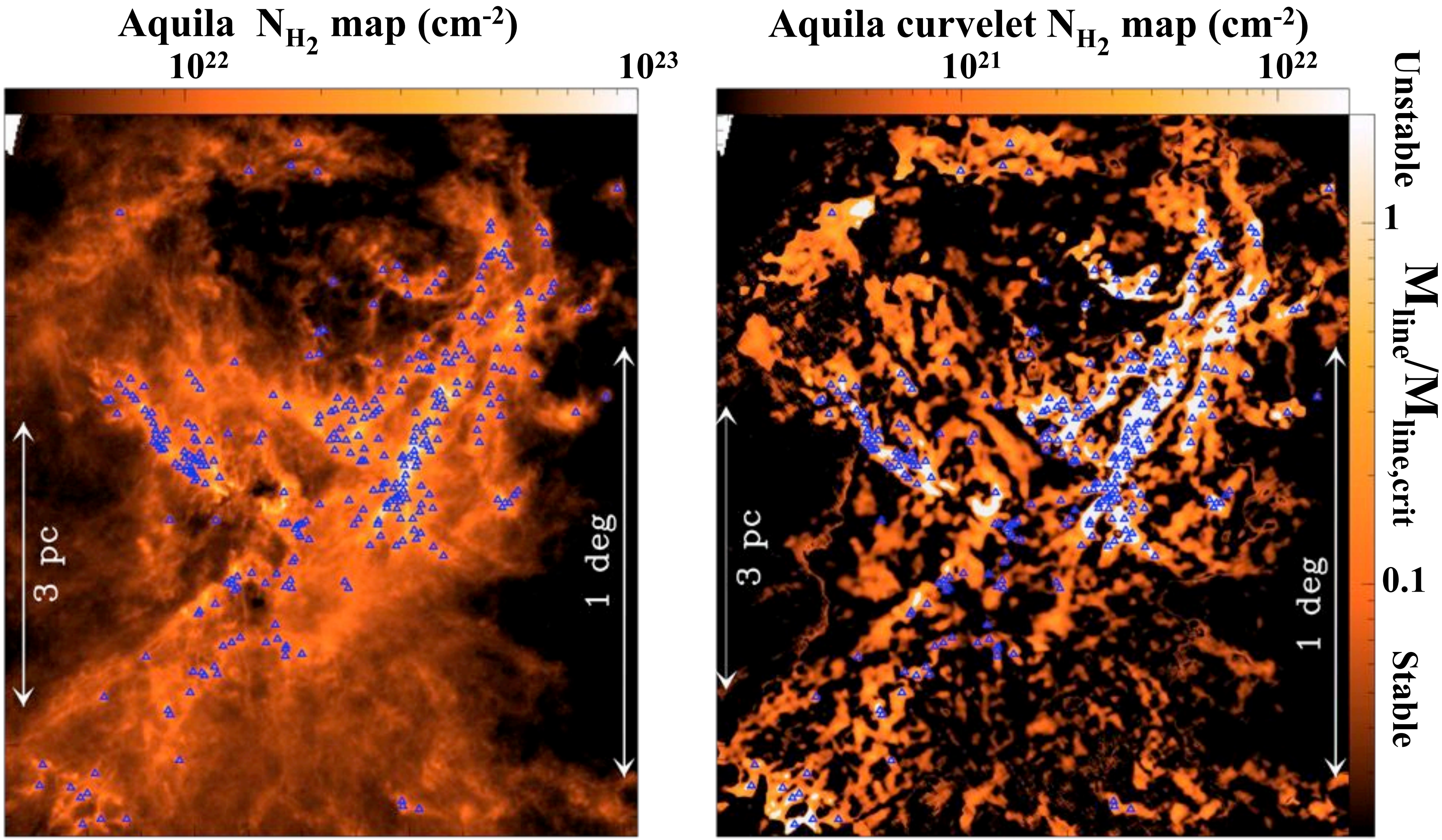
Example of a filament radial profile



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

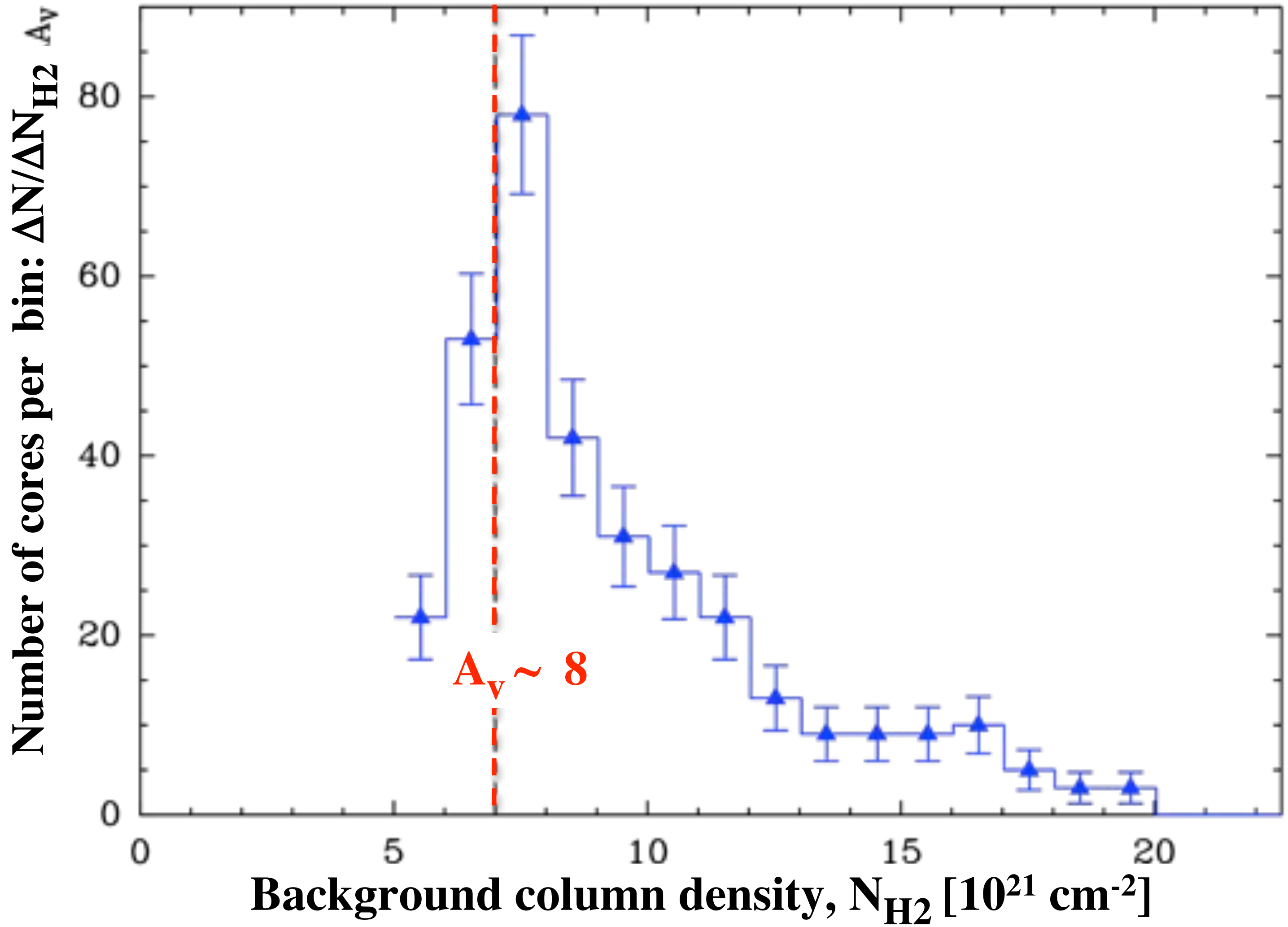
Prestellar cores are preferentially found within the densest filaments

△ : Prestellar cores - 90% found at $N_{H_2} > 7x10^{21}$ cm^{-2} <=> A_v(back) > 8



Strong evidence of a column density "threshold" for the formation of prestellar cores

Distribution of background column densities for the Aquila prestellar cores



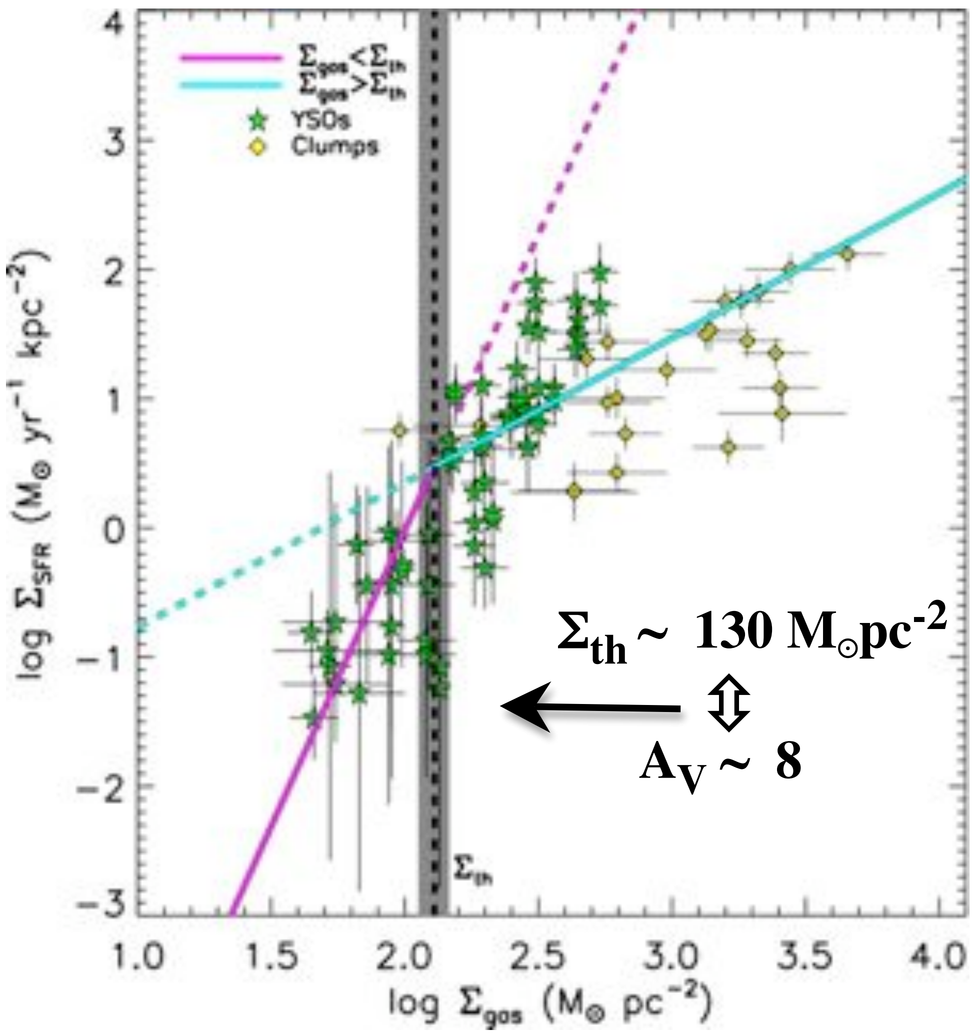
In Aquila, ~90% of the prestellar cores identified with *Herschel* are found above $A_v \sim 8$ ⇔ $\Sigma \sim 130\ M_\odot\ pc^{-2}$

cf. Onishi et al. 1998
Johnstone et al. 2004

André et al. IAU270, Könyves et al. in prep

Similar threshold for YSOs in Galactic clouds

Star formation rate vs. Gas surface density



Heiderman, Evans et al. 2010

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

for

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

Heiderman et al. 2010

Lada et al. 2010

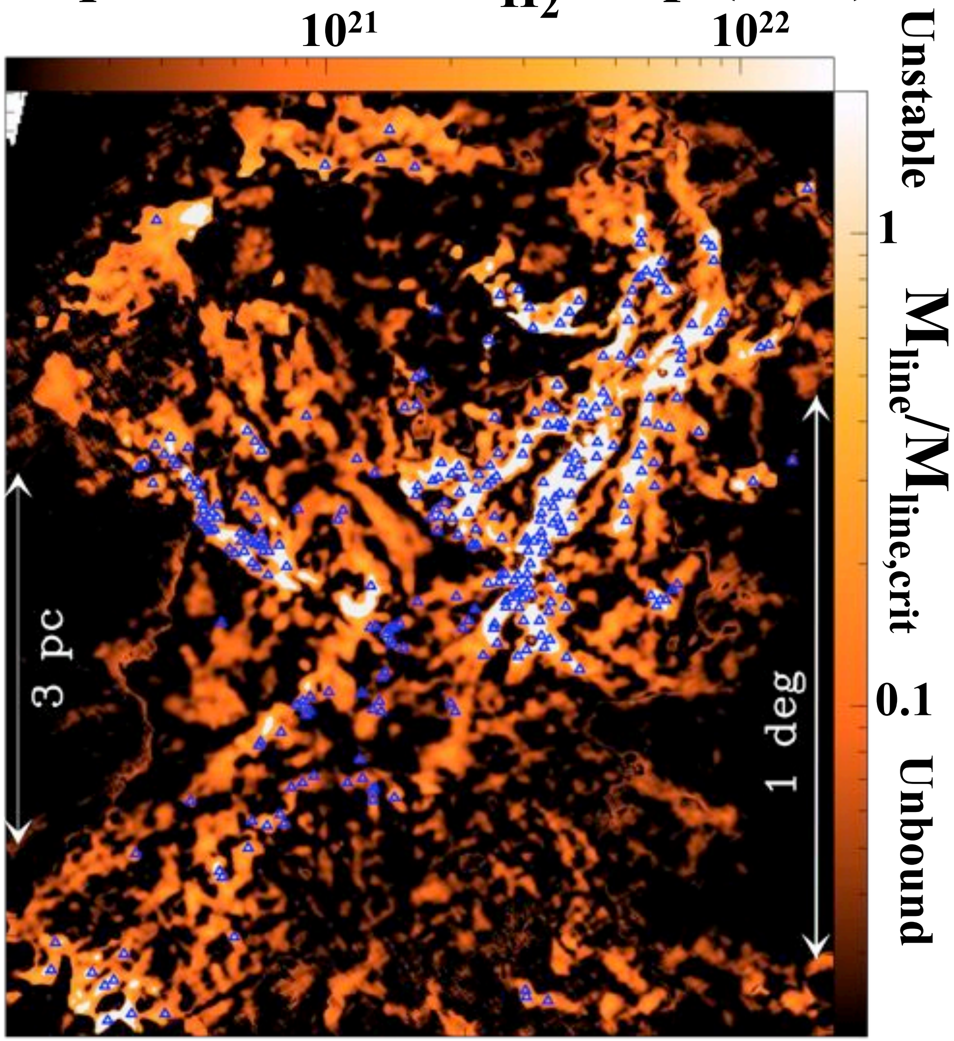
[NB: however, Gutermuth et al. 2011 find $\Sigma_{SFR} \propto \Sigma_{gas}{}^2$]

Interpretation of the star formation threshold:

Σ or M/L threshold above which filaments are gravitationally unstable

△ : 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):

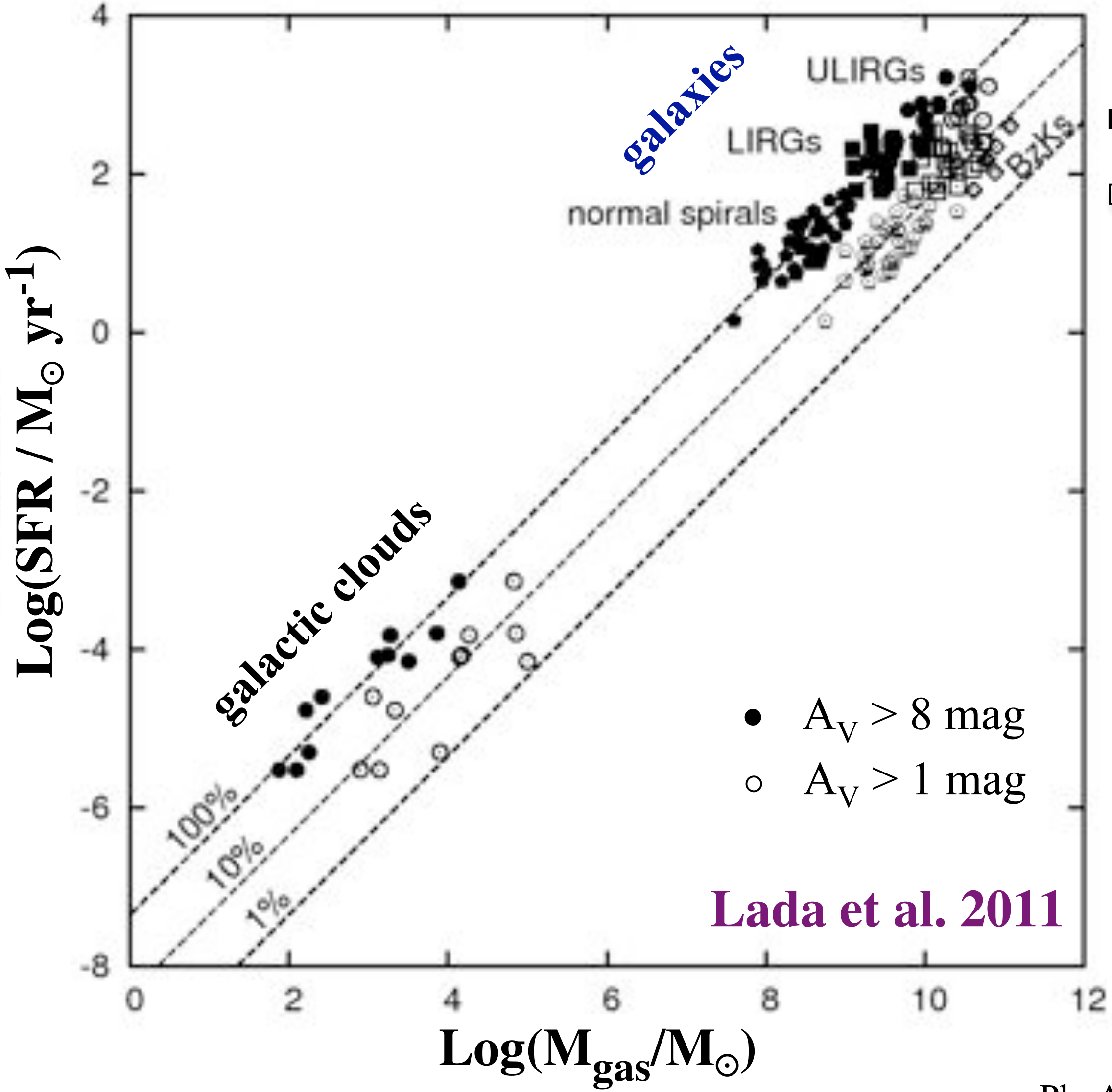
- unstable if $M_{line} > M_{line, crit}$
- unbound if $M_{line} < M_{line, crit}$
- $M_{line, crit} = 2\, c_s^2/G \sim 15\, M_\odot/pc$ for T ~ 10K ⇔ Σ threshold $\sim 150\, M_\odot/pc^2$

➢ Simple estimate:

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

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

Importance of the threshold on galactic scales: A universal star formation law above the threshold ?



■ HCN Gao & Solomon 2004

□ CO Gao & Solomon 2004

$$\mathrm{SFR}\ (M_\odot/\mathrm{yr}) \simeq 4.5 \times 10^{-8}\ f_{dense}\ M_{gas}(M_\odot)$$

$$= \varepsilon_{core} \times f_{pre} \times M_{dense} / t_{pre} \simeq 0.3 \times 0.15 \times M_{dense}(M_\odot)/10^6$$

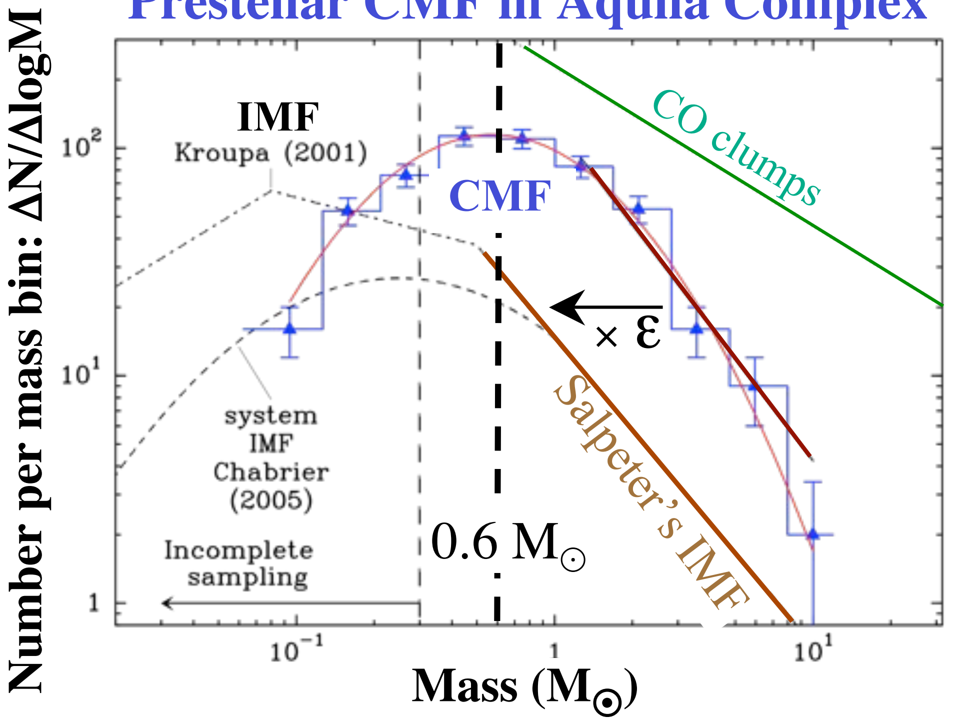
Herschel results on Aquila prestellar cores

Filament fragmentation produces the prestellar CMF and may account for the "base" of the IMF

Jeans/Bonnor-Ebert mass:

$$M_{BE} \sim 0.6\, M_\odot \times (T/10\, K)^2 \times (\Sigma/150\, M_\odot pc^{-2})^{-1}$$

Prestellar CMF in Aquila Complex



André et al. 2010, Könyves et al. 2010 A&A Vol. 518

- ➢ Same median prestellar core mass ~ 0.6 $M_\odot$ in Ophiuchus and Aquila

- ➢ The Jeans/Bonnor-Ebert mass at T ~ 10 K within marginally critical filaments with $\Sigma = \Sigma_{th} \sim 150\, M_\odot pc^{-2}$ is $M_{BE} \sim 0.6\, M_\odot$

→ characteristic stellar system mass $M_* = \varepsilon_{core}\, M_{core} \sim 0.2\, M_\odot$ for a typical efficiency $\varepsilon_{core} \sim 0.3$

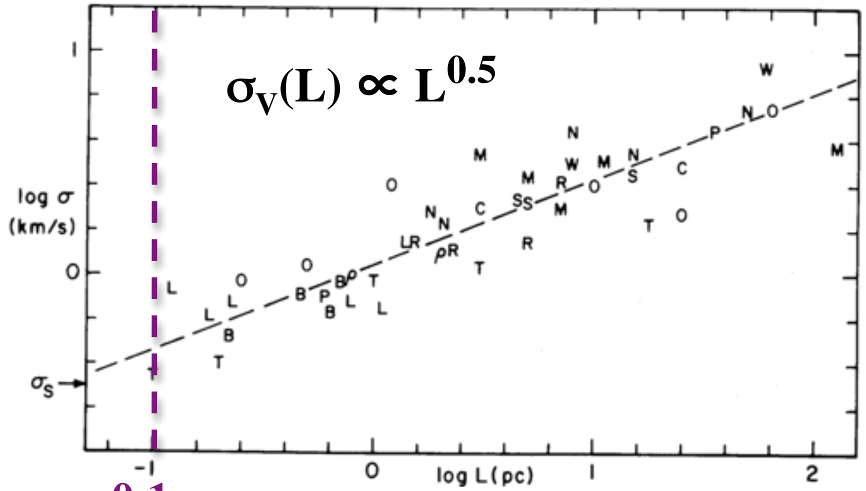
(cf. Larson 1985's interpretation of the peak of the IMF)

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

(e.g. Larson 1981, Heyer et al. 2009)

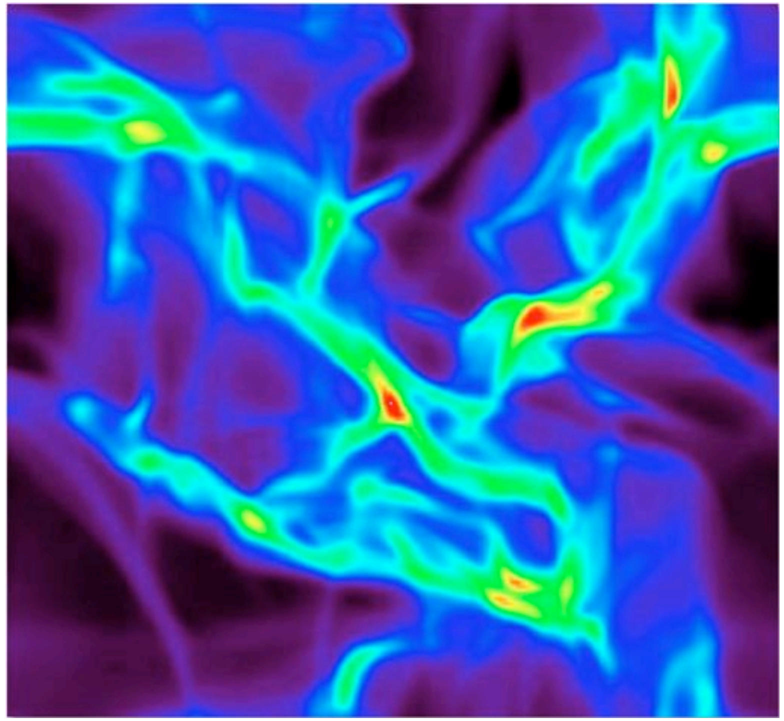
Log (Velocity Dispersion) [km/s]



0.1 pc
Sonic scale

Log (Size) [pc]

Simulations of turbulent fragmentation



Padoan, Juvela et al. 2001

$\lambda \sim L/\mathcal{M}(L)^2 \sim 0.1$ pc

compression ratio (HD shock)

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

Conclusions:
Toward a universal scenario for star formation ?

- *Herschel* results suggest **core formation occurs in 2 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 threshold $\Sigma_{th} \sim 150\ M_{\odot}\ pc^{-2} \Leftrightarrow A_V \sim 8$

- Filament fragmentation appears to produce the prestellar CMF and likely accounts for the « base » of the IMF

- Candidate pre-brown dwarfs are being found in nearby regions, but interferometric observations are required to confirm that they are self-gravitating cores

- The same scenario may possibly also account for the global rate of star formation on galactic scales