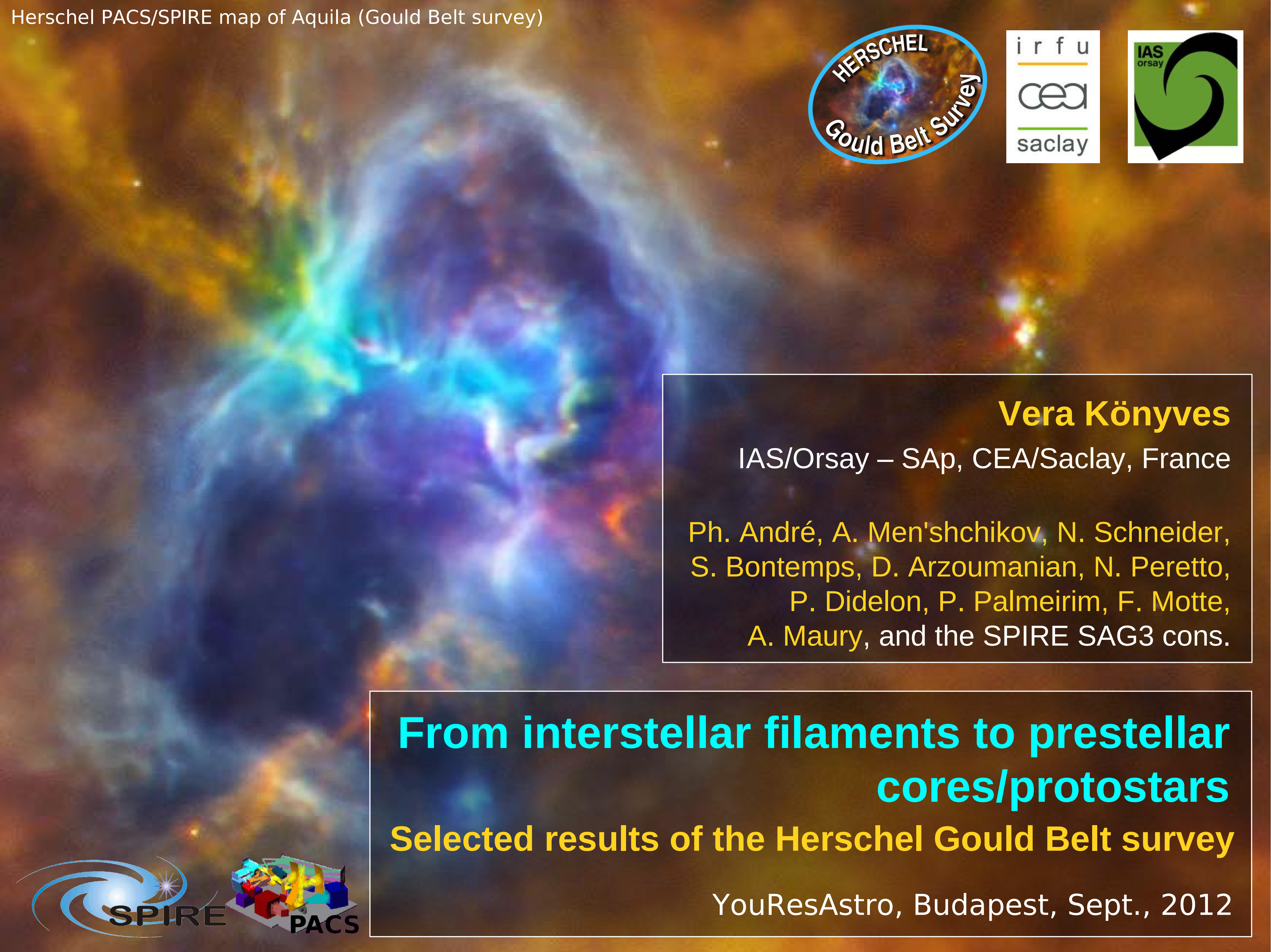


Herschel PACS/SPIRE map of Aquila (Gould Belt survey)

Vera Könyves

IAS/Orsay – SAp, CEA/Saclay, France

Ph. André, A. Men'shchikov, N. Schneider,
S. Bontemps, D. Arzoumanian, N. Peretto,
P. Didelon, P. Palmeirim, F. Motte,
A. Maury, and the SPIRE SAG3 cons.

From interstellar filaments to prestellar cores/protostars

Selected results of the Herschel Gould Belt survey

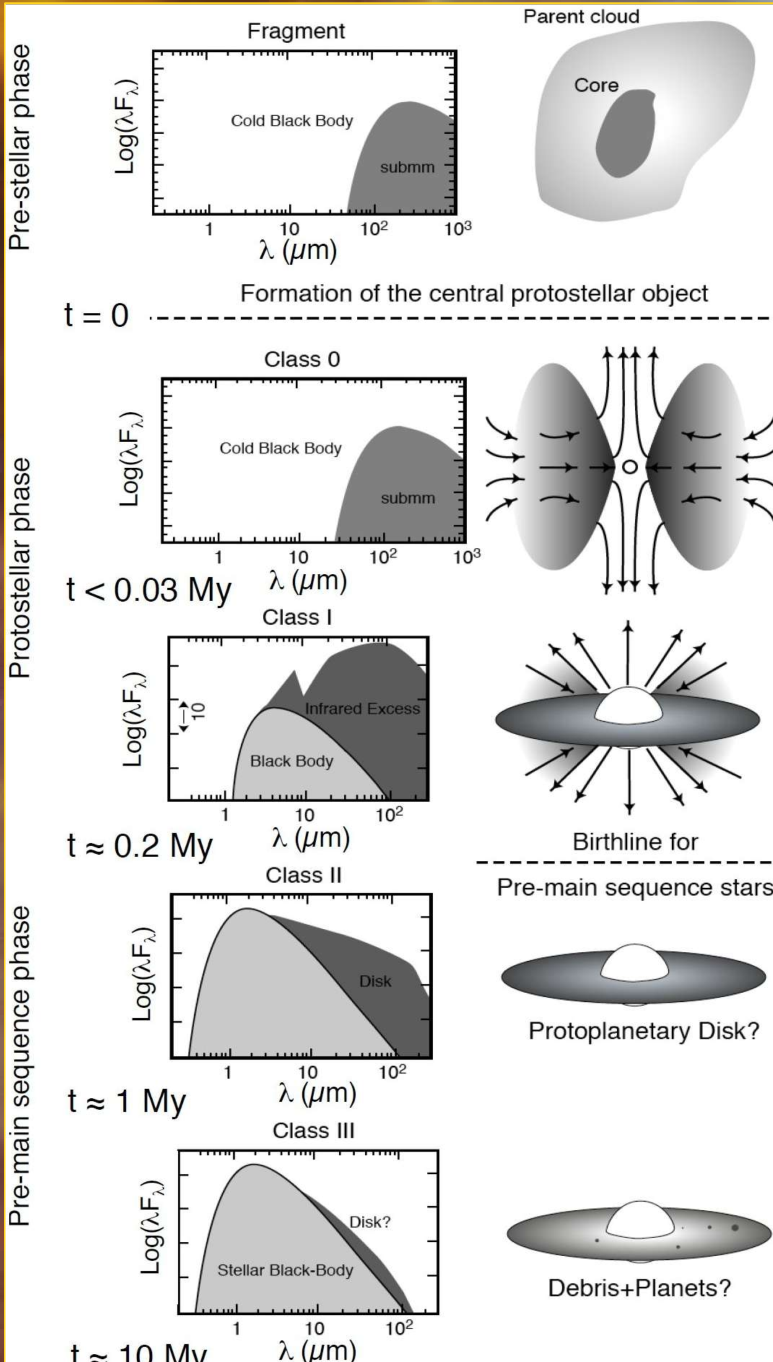
YouResAstro, Budapest, Sept., 2012

OUTLINE OF THE TALK

- Introduction
- The Herschel Gould Belt survey
  - Aquila
  - Orion B
  - IC5146
  - A coherent star formation scenario
- Other Herschel Galactic surveys

INTRODUCTION

EARLY STAGES OF STAR FORMATION



Evolutionary sequence of solar-type stars

Physics of early stages still unclear (cf. McKee & Ostriker 2007 vs. Shu et al. 1987)

Open questions:

- What determines the distribution of stellar masses at birth (IMF)? Link between CMF and stellar IMF?
- What generates prestellar cores in molecular clouds and governs their evolution?
- Is core/star formation a slow, quasi-static, or a fast, dynamic process?

Lada (1987);
André, Ward-Thompson, Barsony (2000)

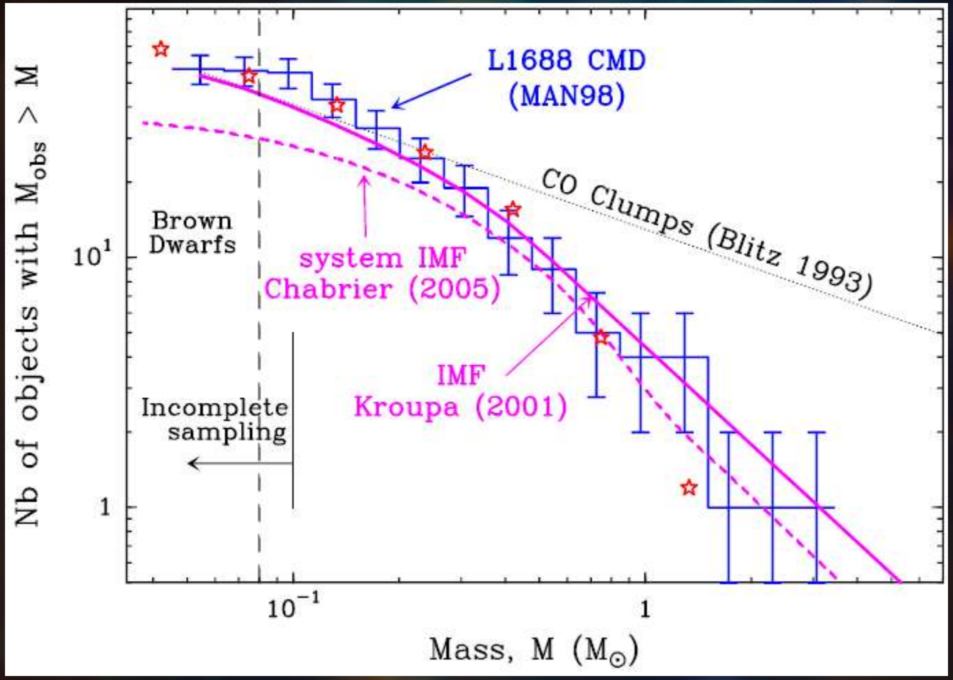
INTRODUCTION

EARLIER STUDIES ON CMF

Ground-based **(sub)-millimeter dust continuum surveys** of nearby, compact cluster-forming clouds (e.g. ρ Ophiuchi, Serpens, Orion B):

- Give 'complete' but small samples of prestellar cores
- Their associated **core mass functions (CMF) resemble the stellar IMF**

E.g.: Motte et al. 1998; Testi & Sargent 1998; Johnstone et al. 2000; Stanke et al. 2006; Enoch et al. 2006; Nutter & Ward-Thompson 2007; Alves et al. 2007; André et al. 2007.



⇨ **Scientific motivations of the *Herschel* Gould Belt survey** (André at al. 2010)

Cumulative mass distribution of 57 starless condensations in ρ Oph (André et al. 2007)

Favored theoretical scenario: **The IMF of solar-type stars is largely determined by pre-collapse cloud fragmentation** (Padoan & Nordlund 2002; Hennebelle & Chabrier 2008).

INTRODUCTION

THE *HERSCHEL* PROMISE

Herschel is ideally suited for **taking a census of resolved cores and protostars** in nearby molecular complexes ($d \leq 0.5$ kpc):

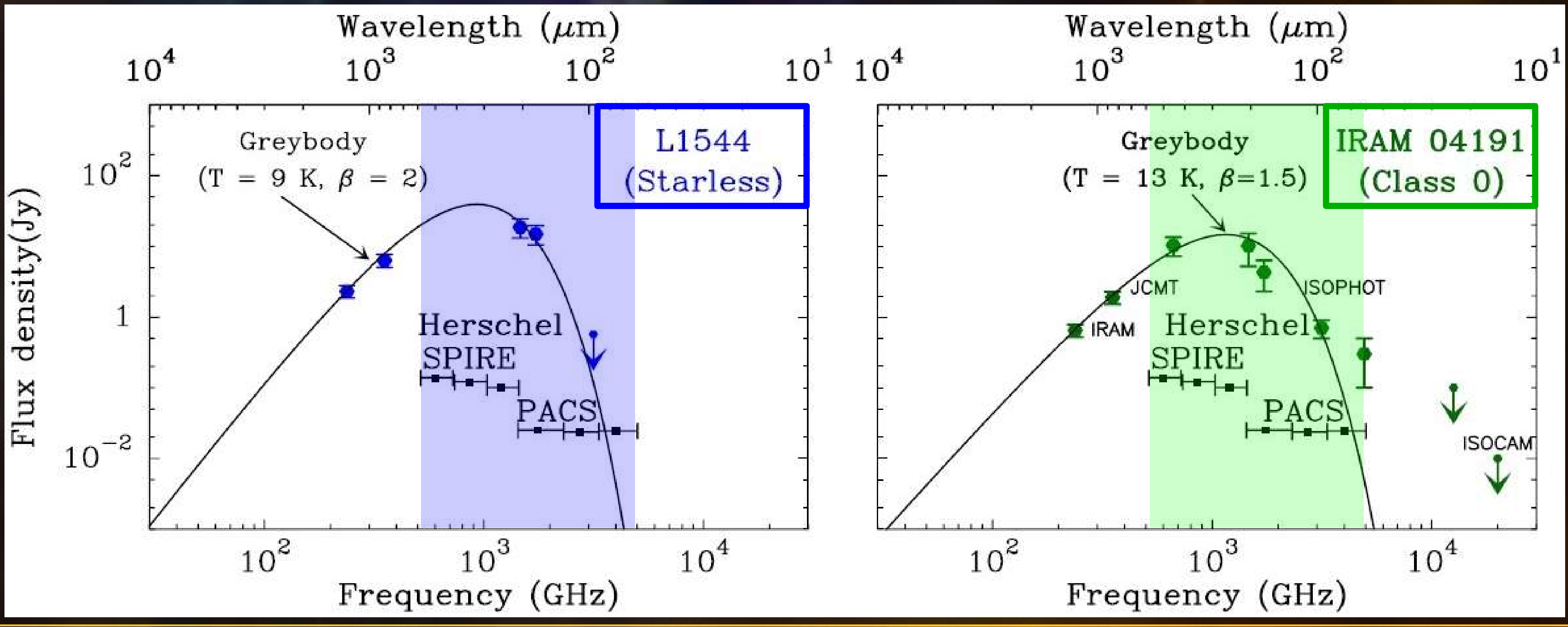
- in the 0.01–0.1 pc size range
- down to $M_{proto} \sim 0.01–0.1\ M_{\odot}$

Herschel bands are **essential for luminosity and temperature determinations**

Spectral energy distributions (SEDs)

Ward-Thompson et al. 2002

André at al. 1999



ESA *HERSCHEL* SPACE OBSERVATORY

- Launch (*Herschel+Planck*): 14th May 2009
- ~3.8 year mission
- 3.5 m primary mirror

Pilbratt et al. (2010)

- Three on-board instruments
  - **SPIRE** (Spectral and Photometric Imaging Receiver)
    250, 350, 500 μm photometer
  - **PACS** (Photoconductor Array Camera and Spectrometer)
    70, 100, 160 μm array camera
  - **HIFI** - Hetrodyne instrument

HERSCHEL Gould Belt survey (HGBS)

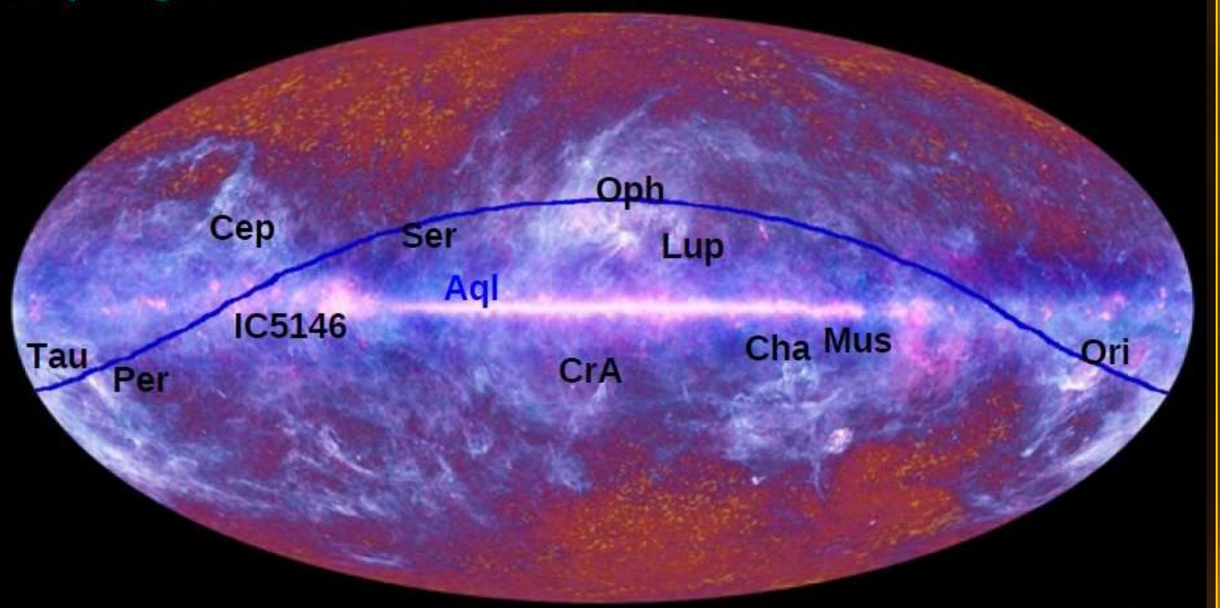
Herschel Gould Belt Key Program (André et al. 2010)

- wide-field submm continuum survey with SPIRE/PACS
- 461 hrs of GT (SPIRE+PACS Consortia)
- in nearby star-forming cloud complexes ($d \leq 500$ pc) of the Gould Belt
- probes **the origin of the stellar masses**

Scientific motivations, goals:

- ⇨ What is the link between the pre-stellar CMF and the stellar IMF
- ⇨ To provide a complete census of prestellar cores and protostars
- ⇨ To unravel the core formation mechanisms

http://gouldbelt-herschel.cea.fr



PLANCK HFI/LFI

HGBS: SOME „TECHNICAL” DETAILS

OBSERVATIONS, DATA REDUCTION

Observations of Aquila, Orion B, IC5146, and Polaris Flare

- **With SPIRE/PACS parallel-mode of Herschel.**
- Large scan maps, taken with 60''sec^{-1} scanning speed

Data reduction

SPIRE 250/350/500 µm (reduced by N. Schneider):

- Using HIPE for data processing; map making with **HIPE 'naive' method**.

PACS 70/160 µm (reduced by V. Könyves):

- HIPE for data processing; map making with **Scanamorphos** (Roussel 2012, subm.).

Map-making benchmark

Joint efforts of PACS/SPIRE ICCs + Herschel parallel mode DPUG in **benchmarking the map maker tools** (photProject, madMap, SPIRE pipeline, scanamorphos, sanepic, tamasis, romagal). A workshop is planned to be held on the benchmark results.

HGBS: SOME „TECHNICAL” DETAILS

SOURCE DETECTION, IDENTIFICATION, PHYSICAL PROPERTIES

Source extraction

Compact sources were extracted from the SPIRE/PACS images **using `getsources`**, a multi-scale, multi-wavelength source finding algorithm (Men’shchikov et al. 2012).

Distinction between starless cores and protostars/YSOs

- **YSOs:** Detected in emission above the 5σ level at 70 μm
- **Starless cores:** undetected in emission (or detected in absorption) at 70 μm.

Dust temperature (T_d) and column density (Σ) maps

- **Weighted SEDs** for all map pixels from the 5 SPIRE/PACS wavelengths.
- SEDs **fitted by a greybody**, $I_\nu = B_\nu(T_d)(1 - e^{-\tau\nu})$

  I_ν: observed surface brightness at ν; $\tau_\nu = \kappa_\nu\Sigma$: dust optical dept; κ_ν: dust opacity per unit (dust+gas) mass, $\beta = 2$ (e.g. Hildebrand 1983).
- **T_d and Σ were derived from the fit** to the 5 *Herschel* data points for all pixels.
- Similar SED fitting procedure was employed to estimate the core properties.

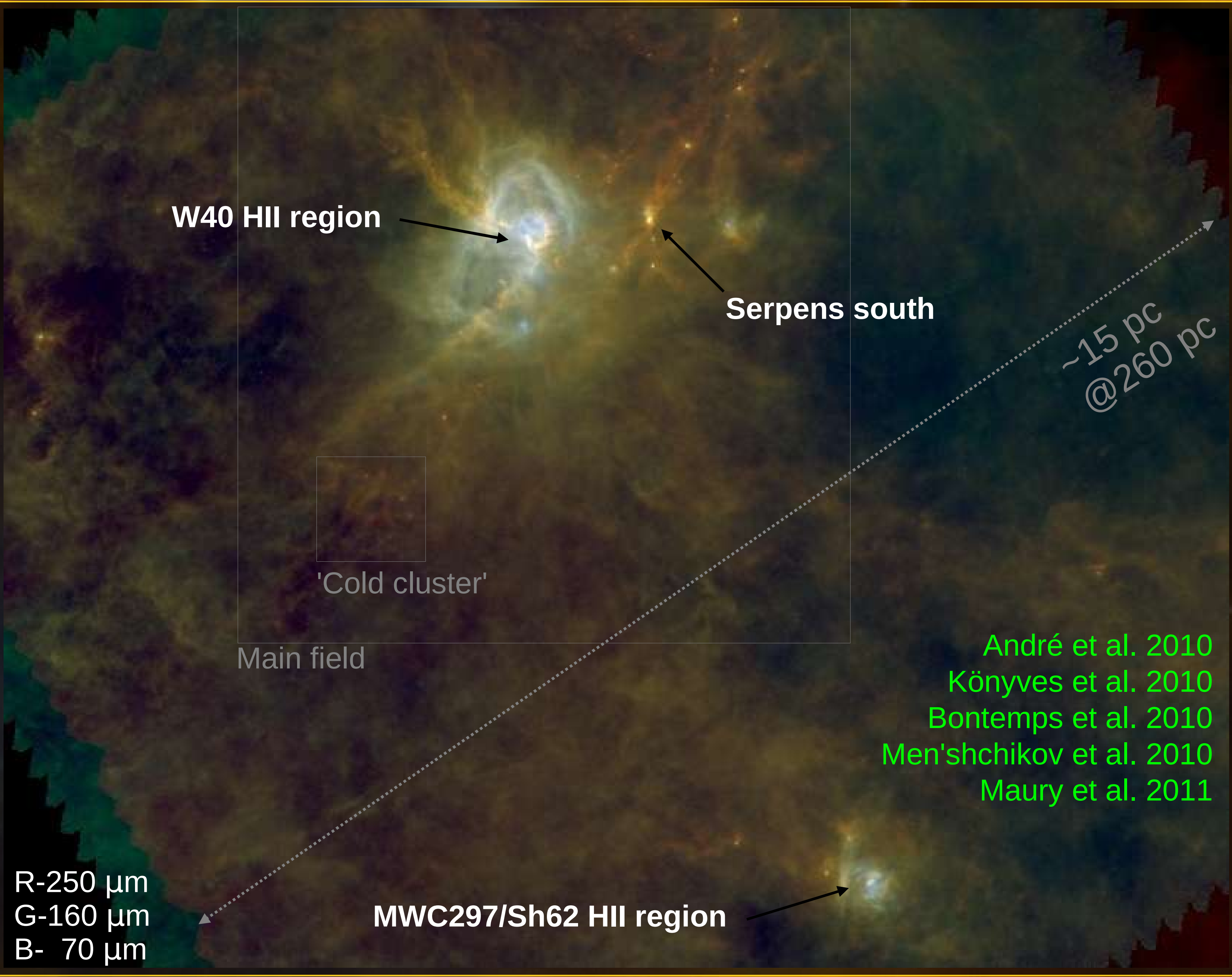
AQUILA

Highlights:

- Prestellar cores
- CMF
- Lifetimes
- Core formation “threshold”, PDF

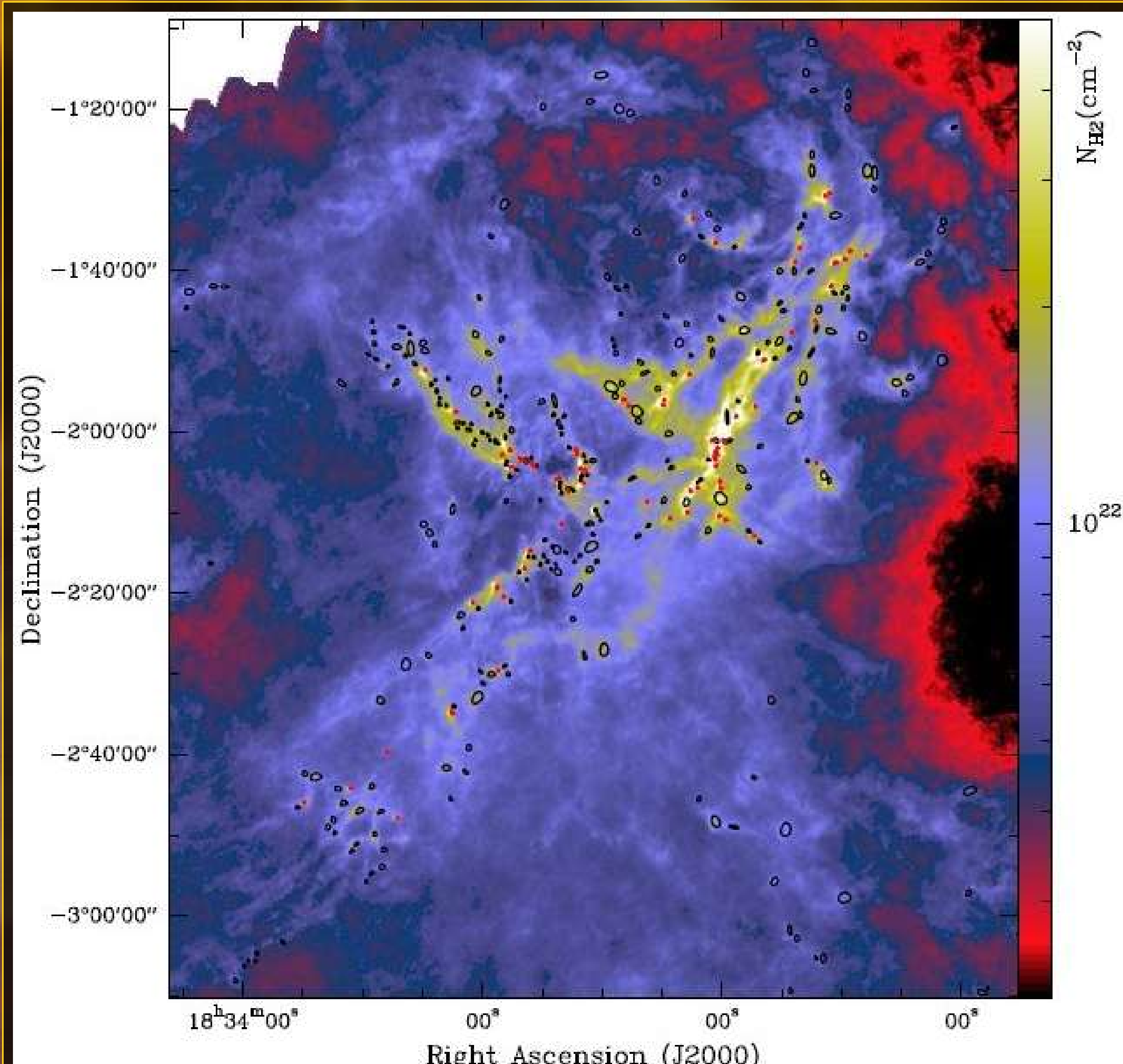
HGBS: THE AQUILA FIELD

RGB COMPOSITE



HGBS: AQUILA

SOURCES IN THE AQUILA MAIN PART



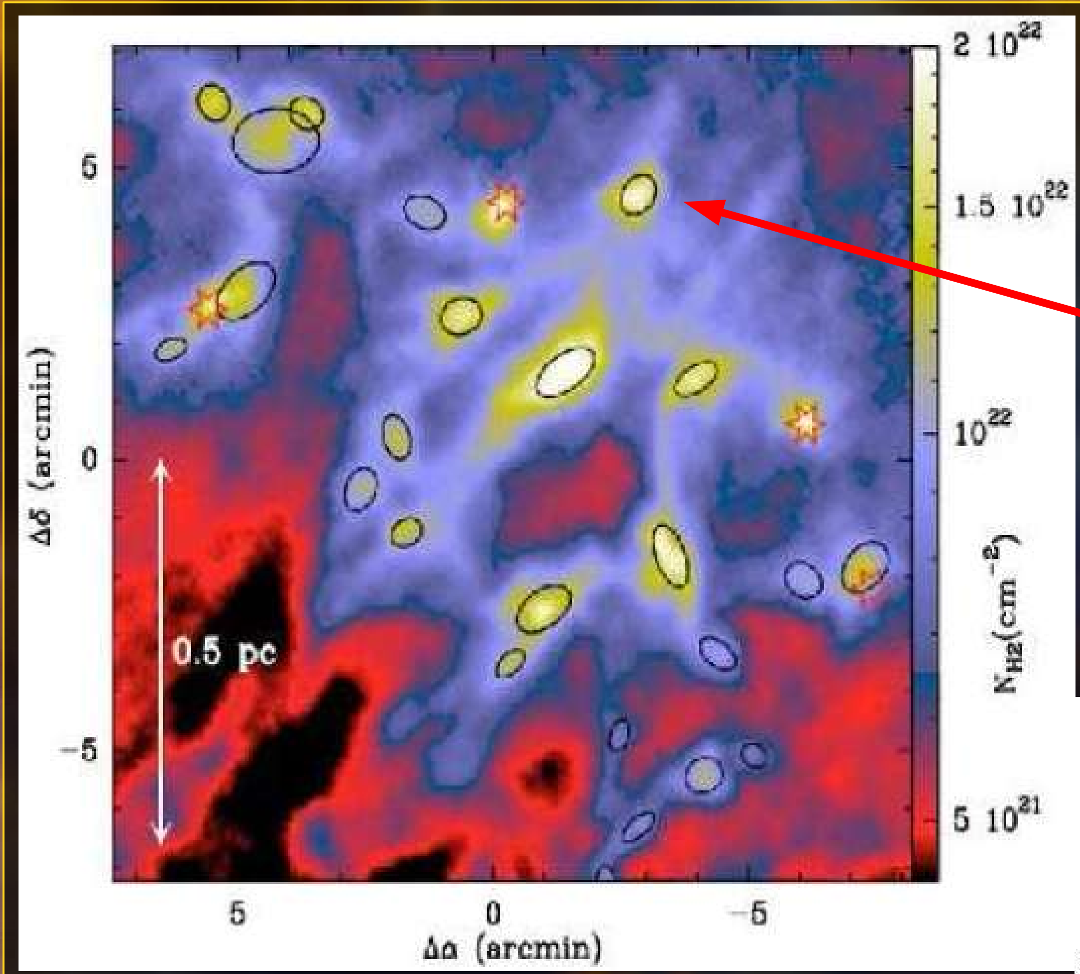
In Aquila -entire- field (~10 deg^2)**:**

~ 500 starless cores (O)
~ 350 prestellar cores (60 %)
~ 200 protostars (O)
(~ 35 class 0)

Background: column density map (Planck offsets added)

André et al. 2010
Könyves et al. 2010
Bontemps et al. 2010
Maury et al. 2011

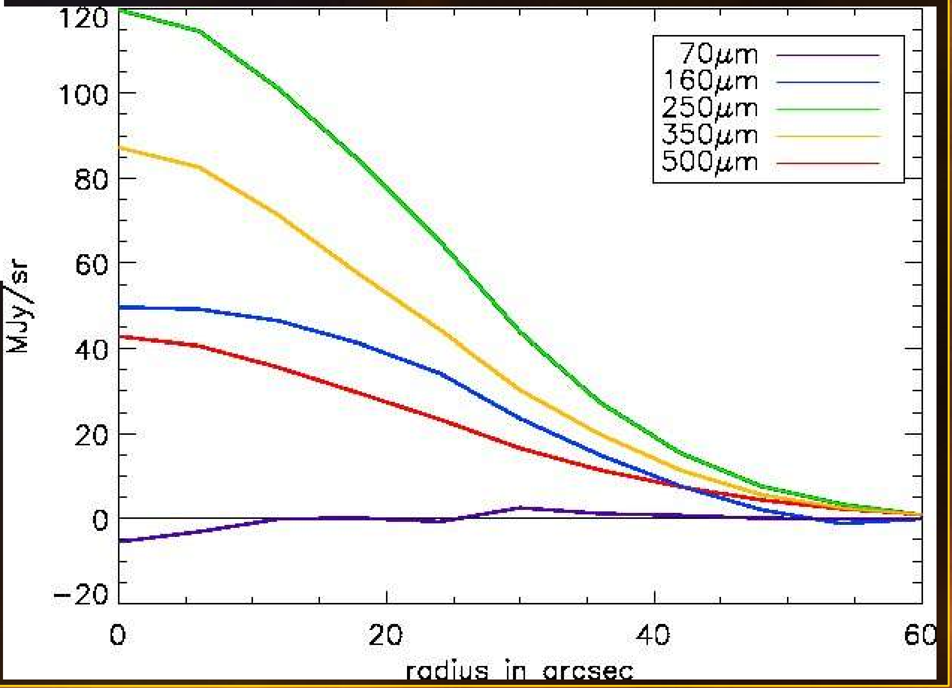
CLOSE UP VIEW OF EXTRACTED SOURCES



Close up column density image of starless cores and protostars ('Cold cluster').

A core:

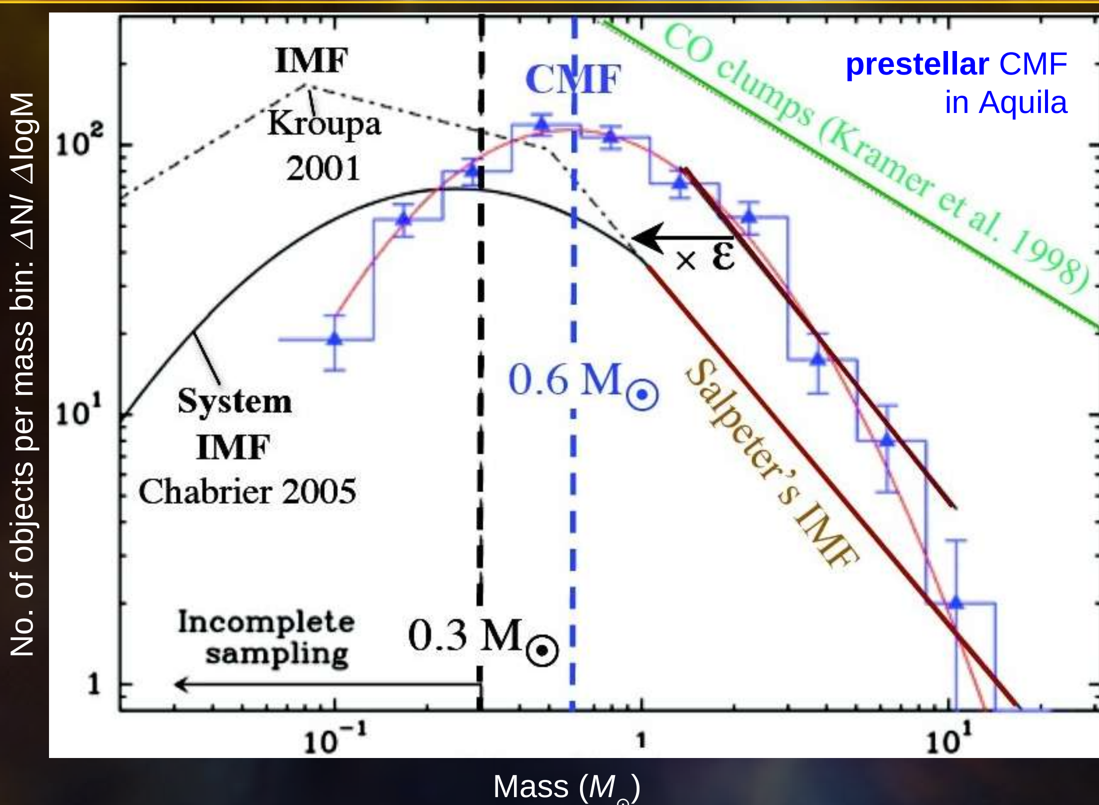
- local column density peak
- simple (convex) shape
- no substructure at Herschel resol.
- potential single star-forming entity



Radial intensity profiles returned by `getsources` for the starless core marked by arrow.

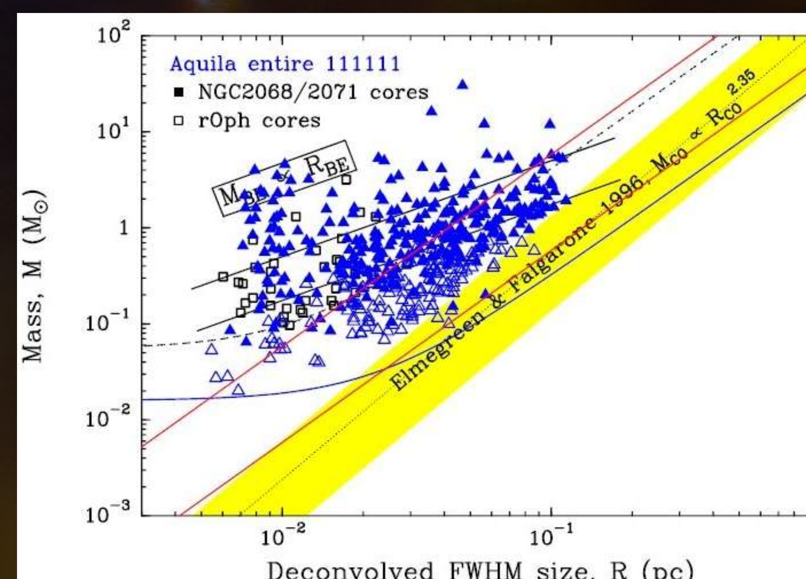
HGBS: AQUILA

CORE MASS FUNCTION (CMF)



André et al. 2010
Könyves et al. 2010

Mass vs. size diagram comparing the locations of ~300 candidate prestellar cores (▲), and the rest starless cores (△), to both models of critical isothermal BE spheres (at T=7K, T=20K) and observed prestellar cores (Motte et al. 1998, 2001).



Differential mass function of >400 starless cores in the entire Aquila field. ~60% of them is bound, a.k.a., prestellar cores.

Lognormal fit peaks at ~ 0.6 $M_\odot$

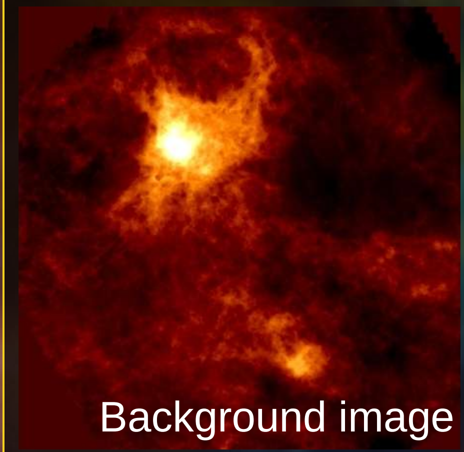
fitted power-law: $dN/d\log M \propto M^{-1.5\pm0.2}$

The fitted properties are robust

In the end the whole survey will be used to fully characterize the nature of the CMF-IMF link

HGBS: AQUILA

COMPLETENESS LIMIT



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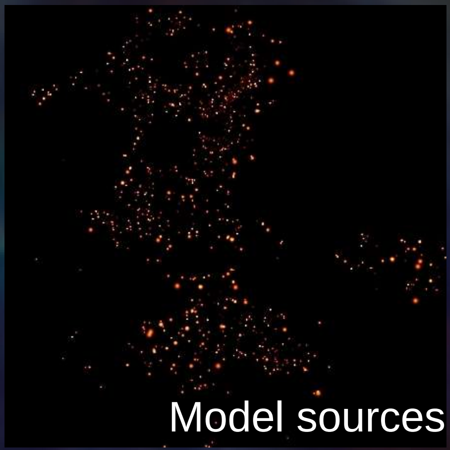

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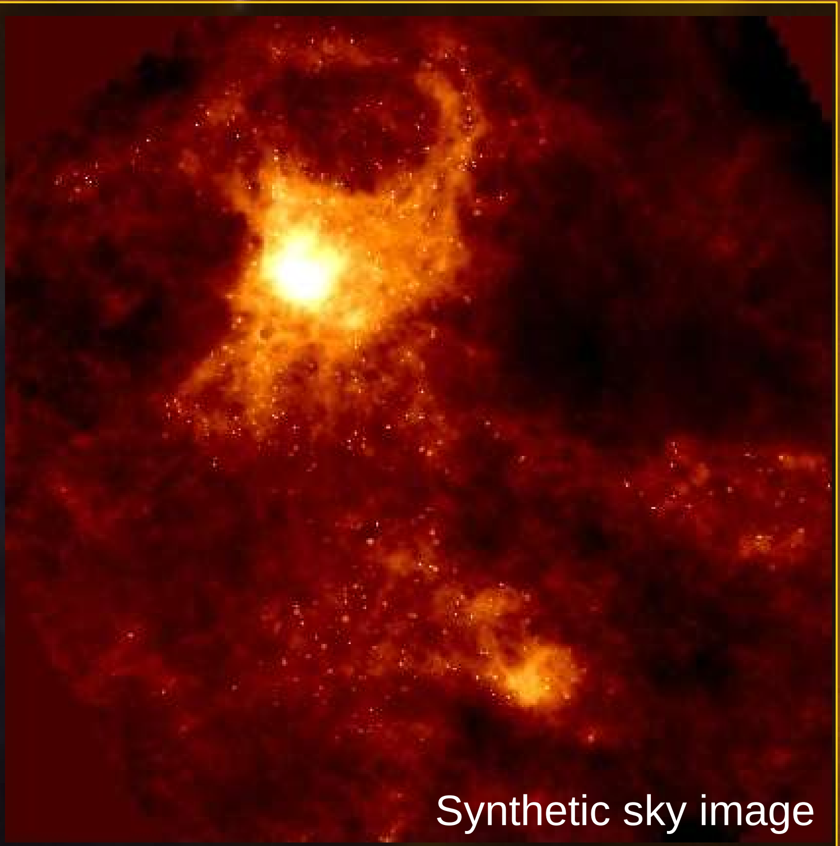
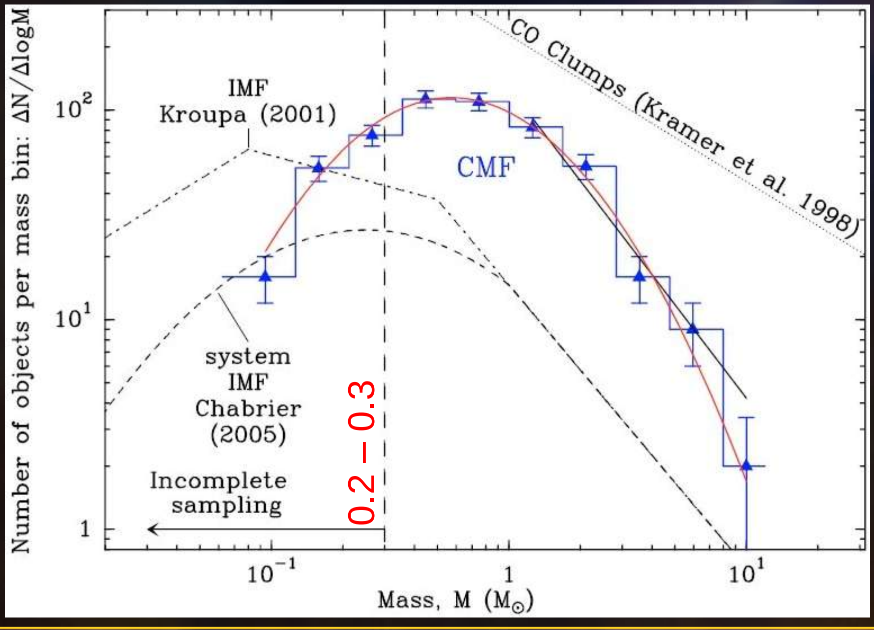




- **prestellar cores:**
  85 % above a core mass of ~ 0.3 $M_\odot$
- **embedded protostars:**
  >90 % down to L_{bol}~0.2 $L_\odot$

Könyves et al. 2010, André et al. 2010

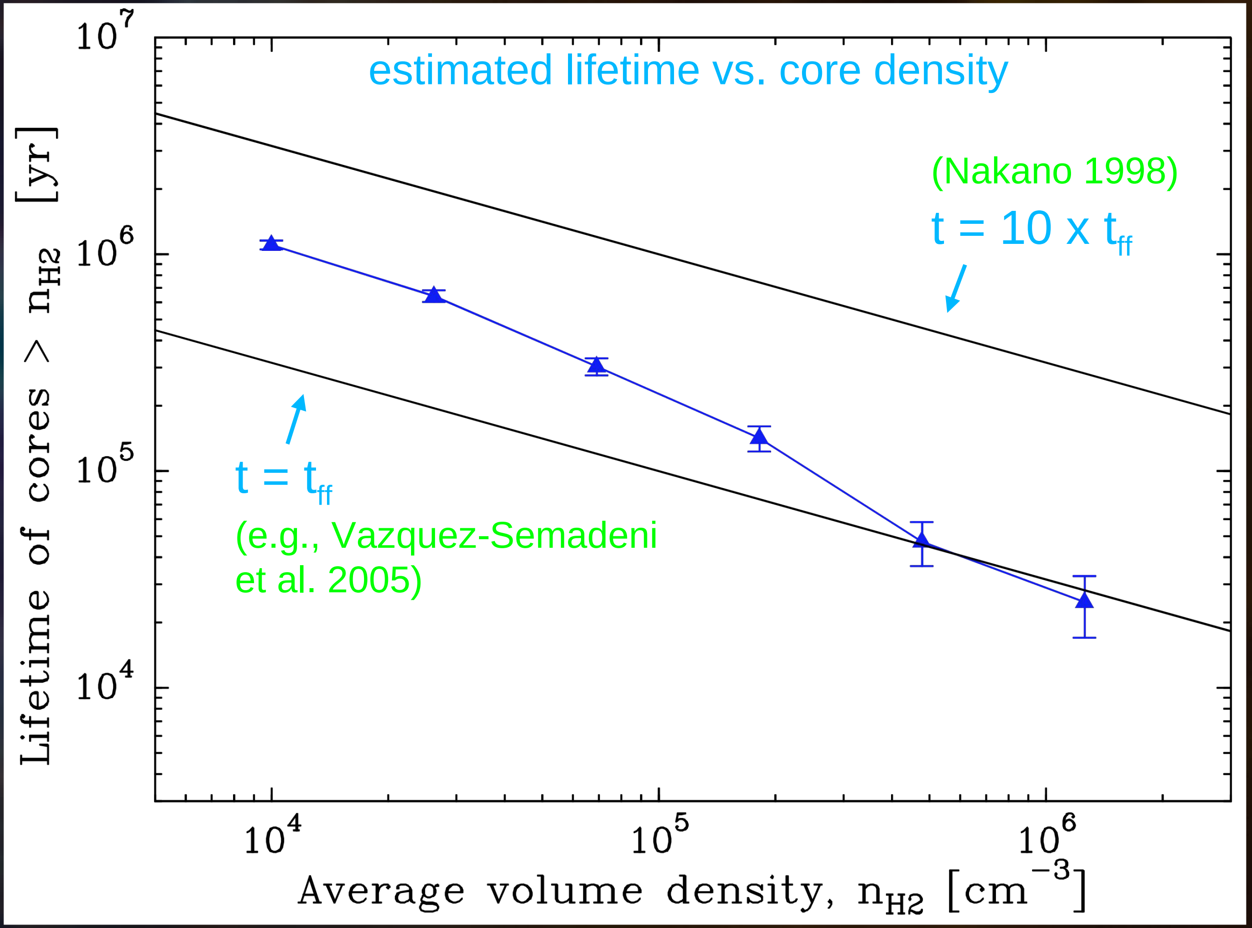
PRELIMINARY LIFETIME ESTIMATES

Core lifetime estimates

(I.) Based on number ratios:

- ~500 *Herschel* starless cores (t ~ 1 Myr)
- ~200 *Herschel* Class0/ClassI protostars (t ~ 0.5 Myr)
- ~1000 *Spitzer* (Class II, YSOs (t ~ 2 Myr, Evans et al. 2009)

Könyves et al. in prep.



(II.) Preliminary **estimates of core lifetimes in Aquila lie between the two timescale models** on the **estimated lifetime versus core density plot.**

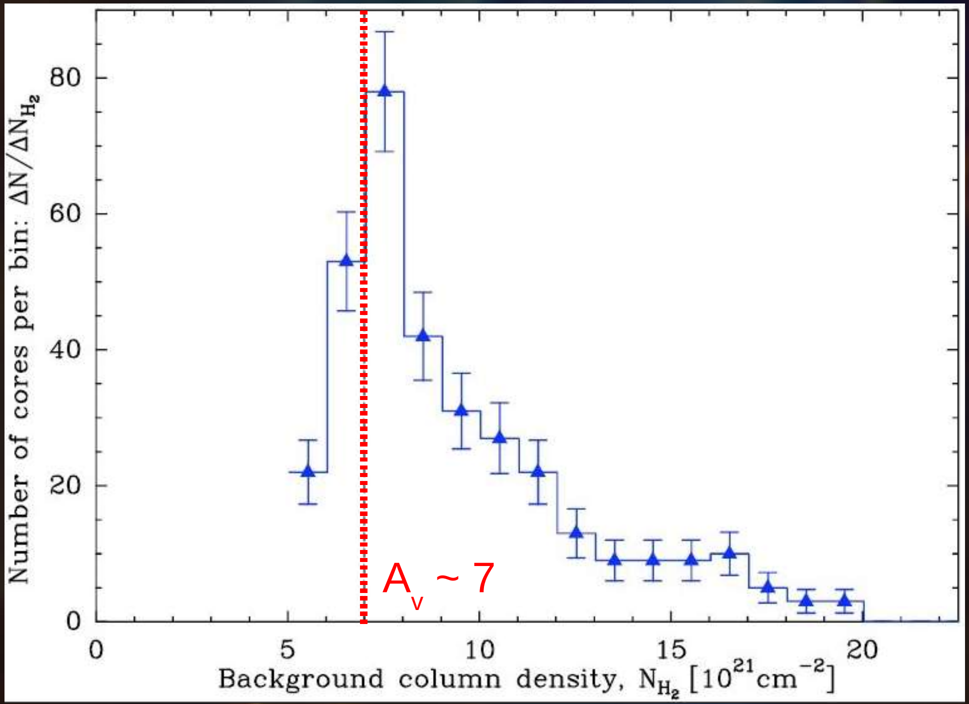
Literature estimates for **observed core timescales of various data-sets gave similar constraints** (Ward-Thompson et al. 2007).

STAR FORMATION THRESHOLD?

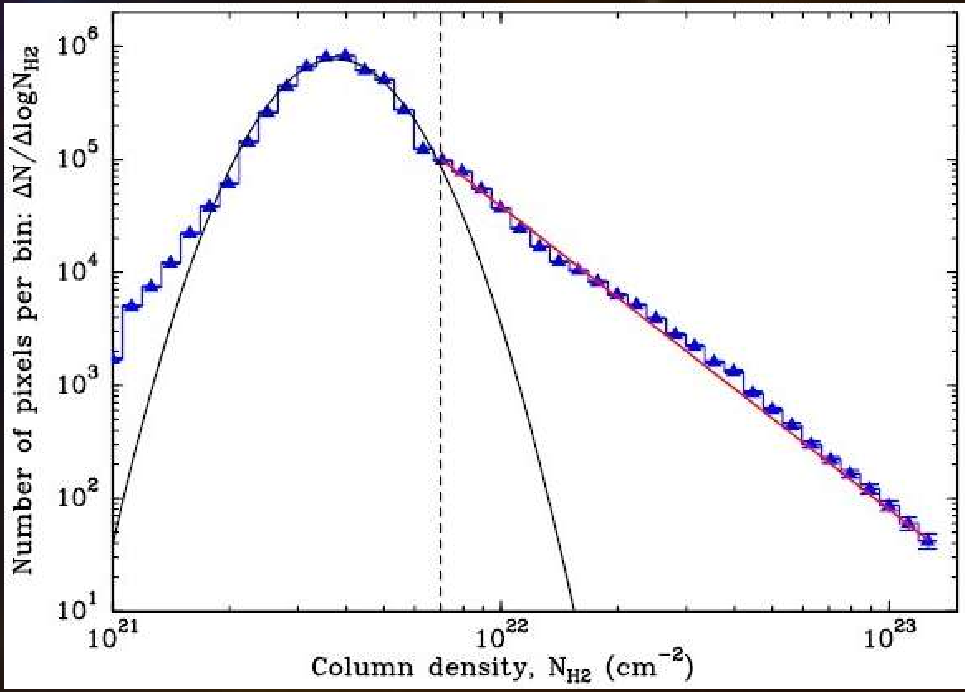
Strong evidence of a **column density "threshold" for the formation of prestellar cores** in Aquila

In Aquila, ~ 90% of the Herschel prestellar cores are found above
$A_v \sim 7 \Leftrightarrow \Sigma \sim 150\ M_{\odot}\ pc^{-2}$

Distribution of bg cloud column densities 'behind' the prestellar cores.



PDF of column densities in Aquila



André et al. IAU270
Könyves et al. in prep

ORION B

Highlights:

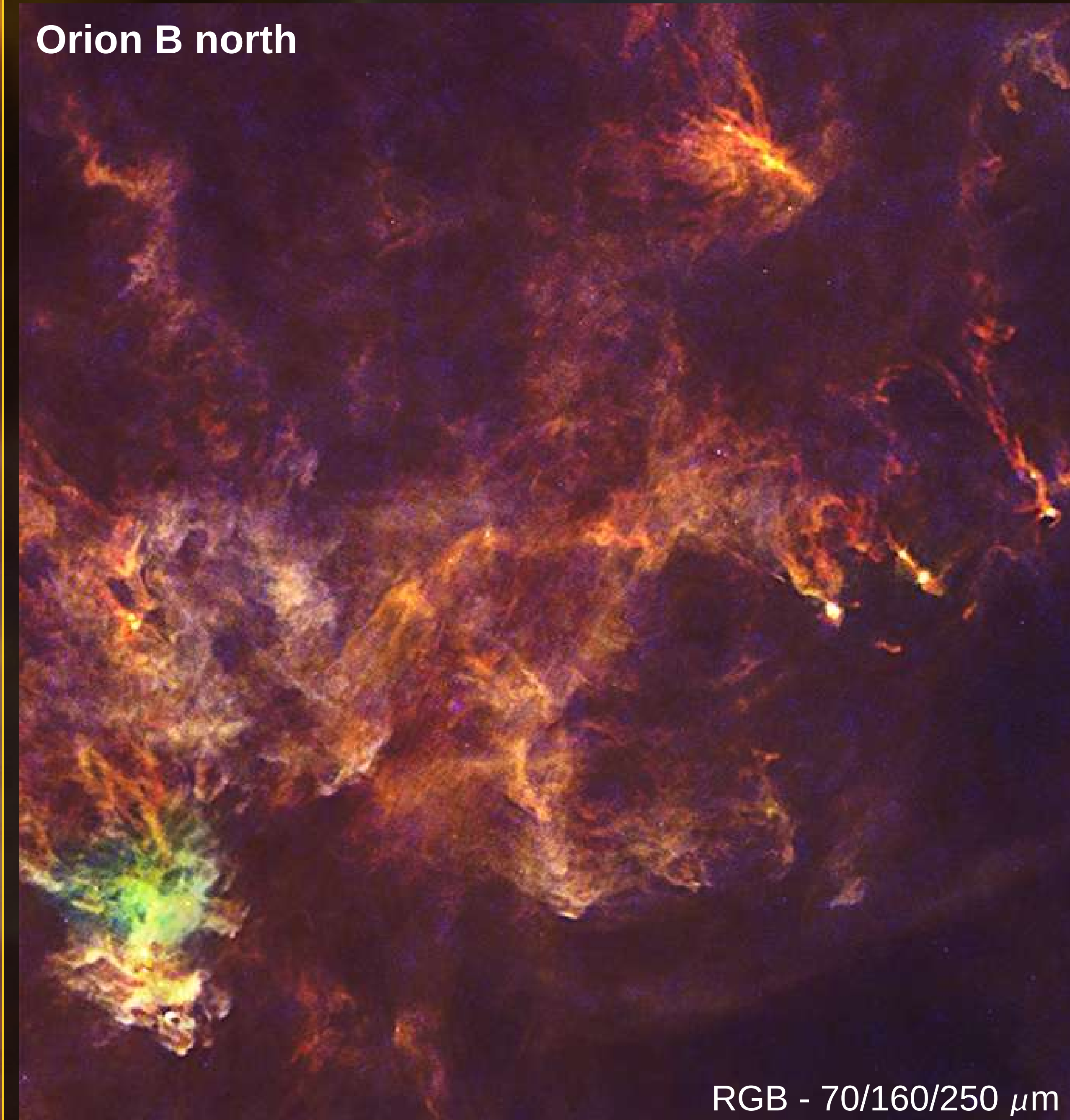
- Cores, potostars
- Core formation “threshold”
- PDFs

ORION B

Herschel Gould Belt Survey

Könyves et al. in prep.
Schneider et al. in prep.

ORION B

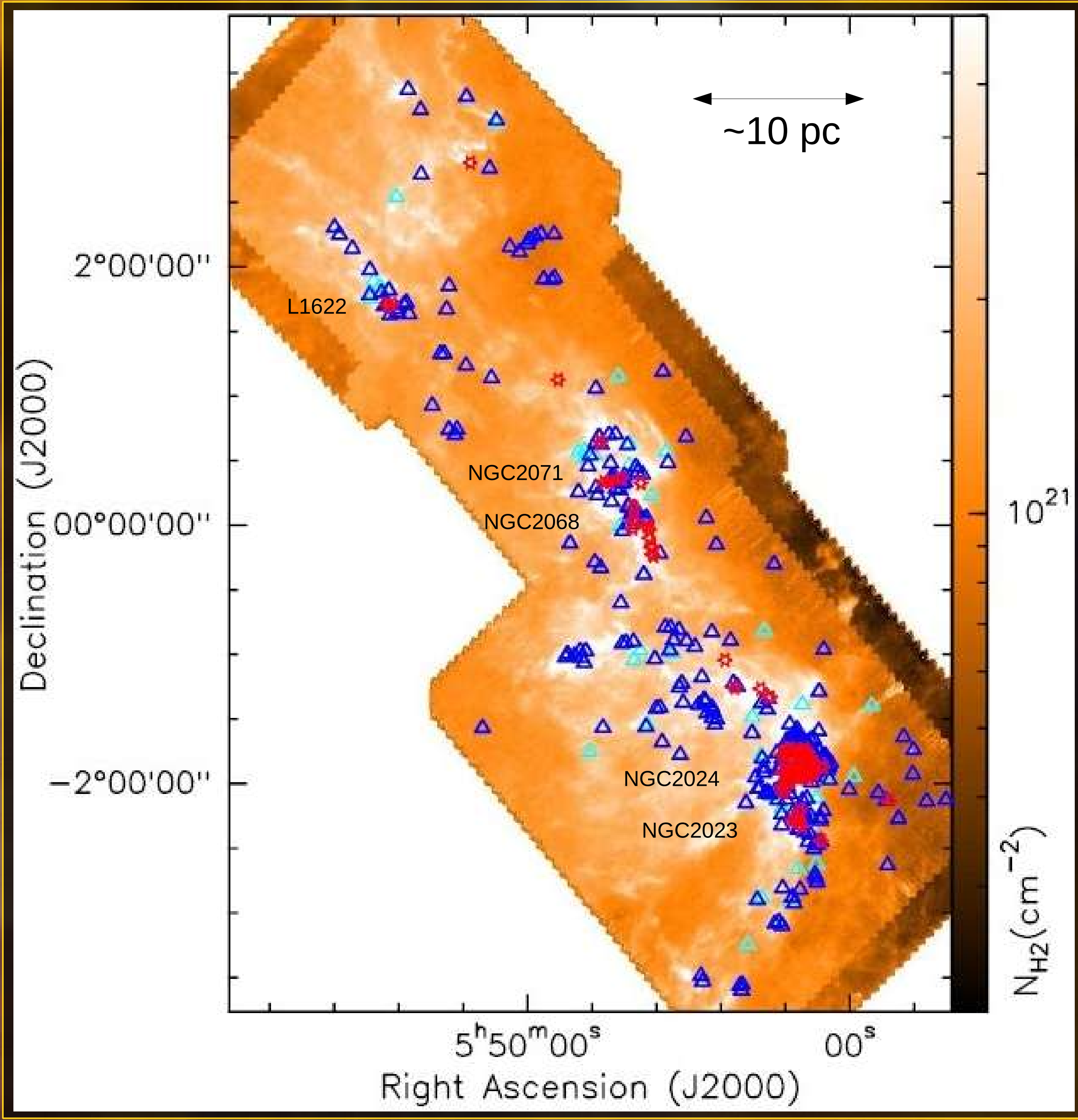


Herschel Gould Belt Survey

Könyves et al. in prep.
Schneider et al. in prep.

ORION B

SOURCES IN ORION B



In Orion B, entire field (~15 deg^2)**:**

~ 400 starless
~ 350 prestellar (> 80 %, △)
~ 60 protostars (✡)
(~ 20 class 0)

Very preliminary numbers!

Background: column density map (Planck offsets added)

Könyves et al. in prep.

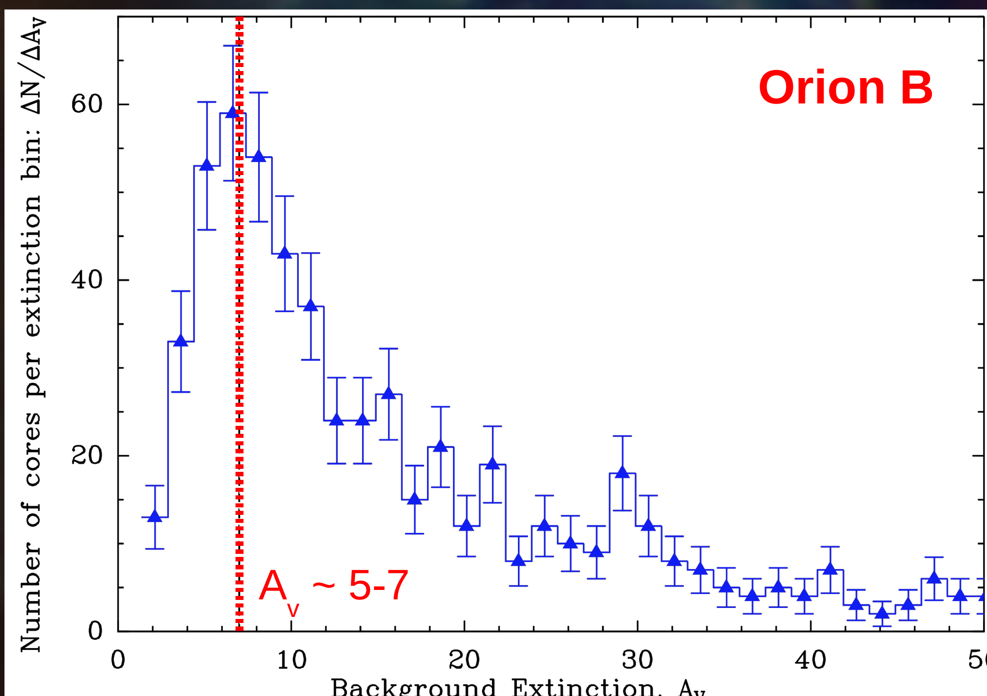
ORION B

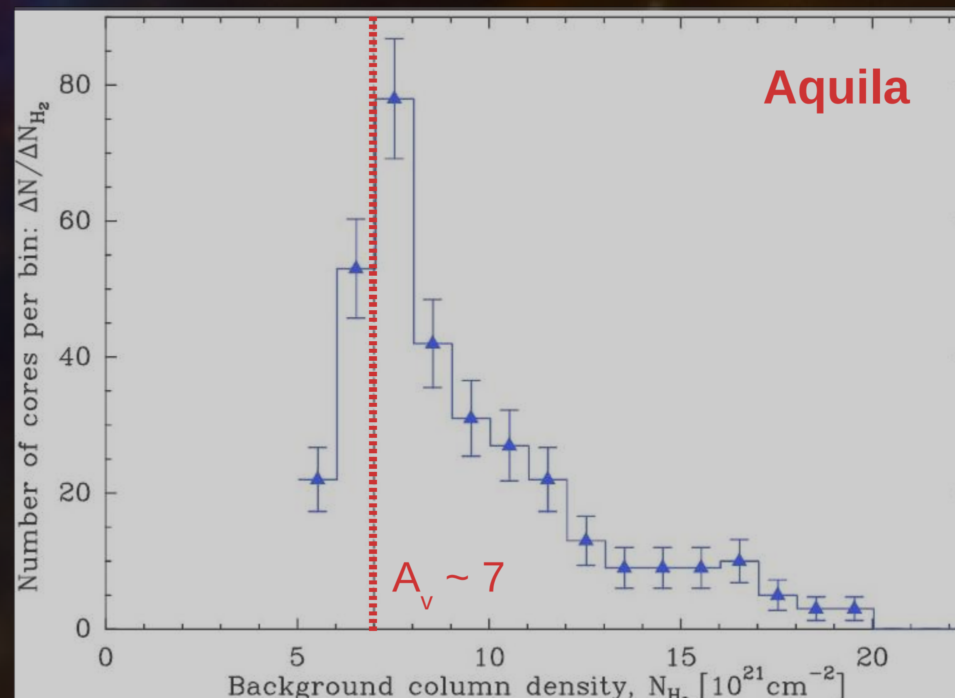
STAR FORMATION THRESHOLD?

Strong evidence of a **background extinction / column density "threshold" for the formation of prestellar cores** in Orion B

In Orion B, > 75% of the Herschel prestellar cores are found above $A_v \sim 7 \Leftrightarrow \Sigma \sim 150\ M_\odot\ pc^{-2}$

Distribution of background extinction 'behind' the prestellar cores.



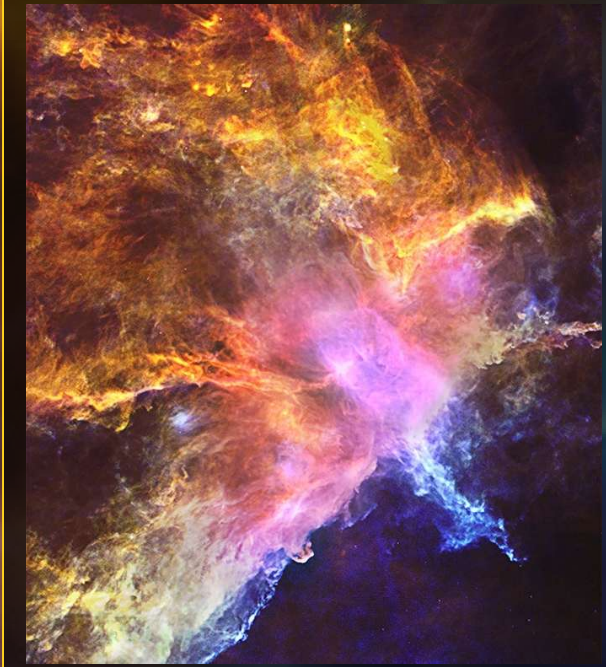


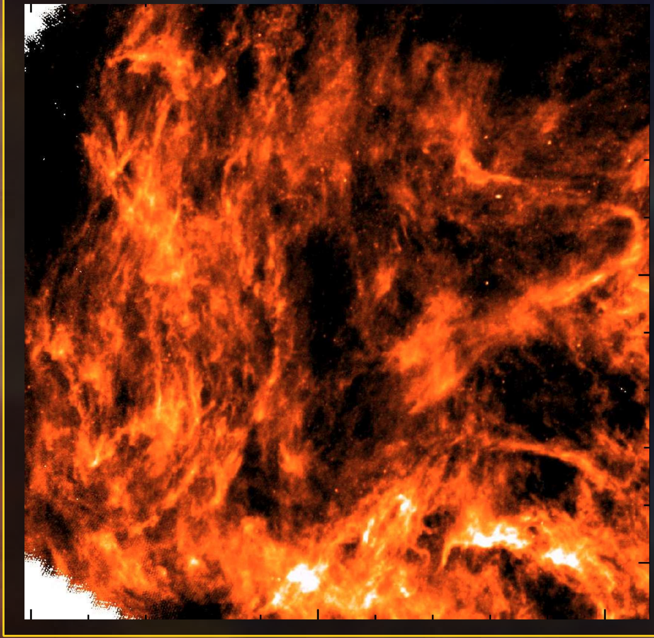
Könyves et al. in prep.

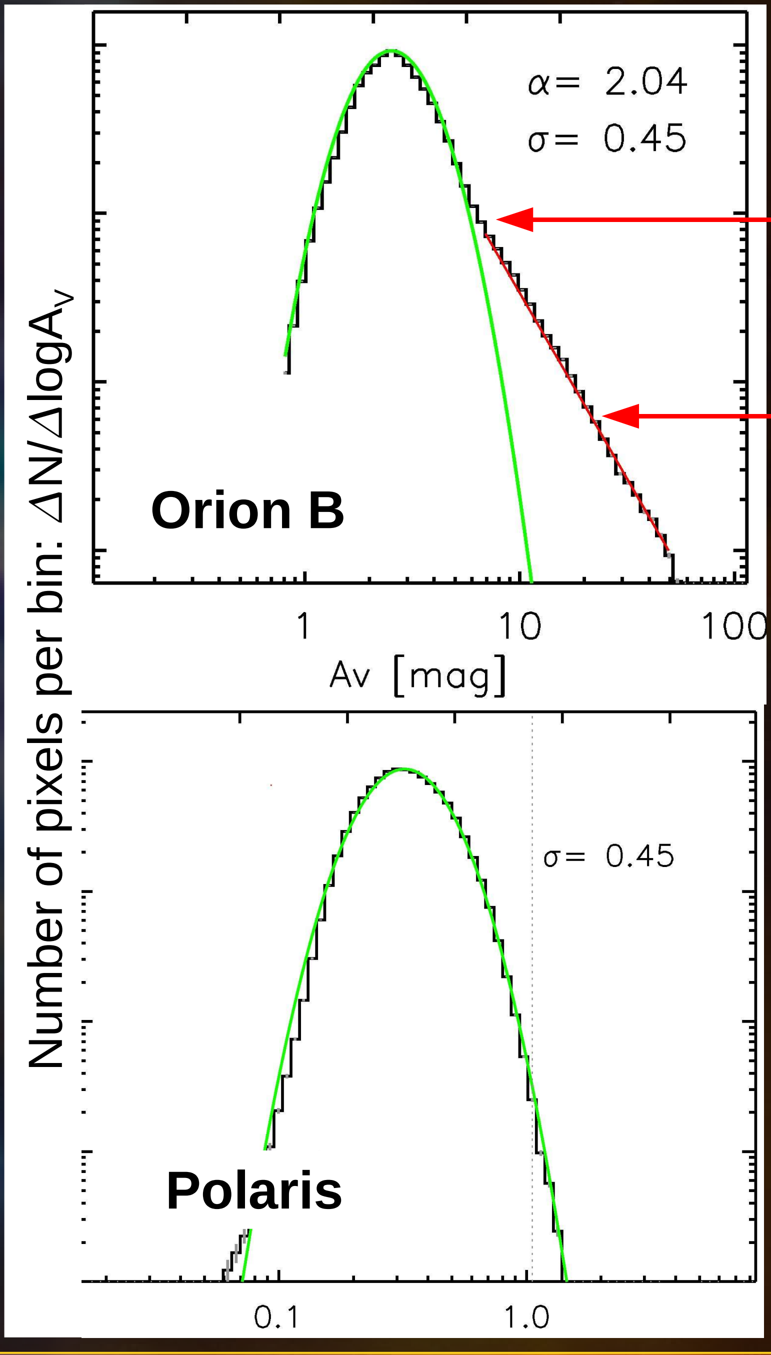
André et al. IAU270
Könyves et al. in prep

ORION B

COLUMN DENSITY PDFs







deviation
at A_v ~ 5-7

- power-law tail
- gravity?

- log-normal PDF
- turbulence?

Schneider et al.
in prep.

IC5146

Highlights:

- Filaments with uniform inner widths
- Connection of cores with filaments

„Filamentary" background and definitions

Interstellar filamentary structures:

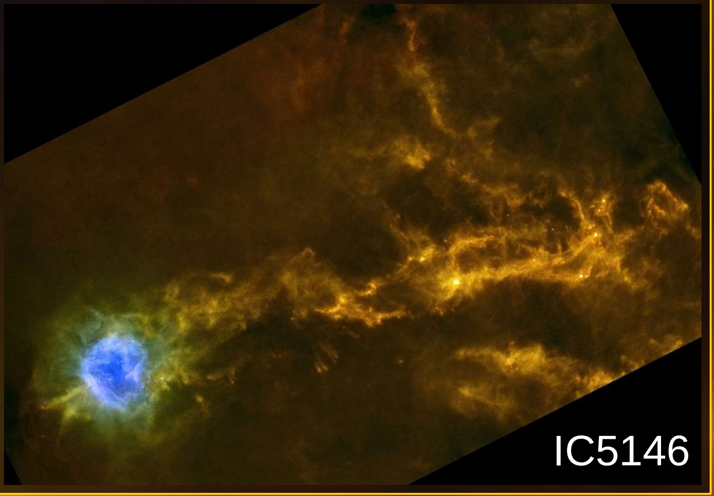
- Everything which is elongated (aspect ratio > 2) in column density maps
- exhibits a central ridge
- no characteristic mass, nor size

Hydrostatic equilibrium solutions of isothermal infinite cylinders are given by Ostriker (1964):

- density profile $\rho \propto r^{-4}$, and
- critical mass per unit length $M_{line,crit} = 2c_s^2/G$

Criterium for fragmenting filaments (Inutsuka & Miyama1997):

- If $M_{line} > M_{line,crit}$, filaments fragment ⇨ **supercritical**
- If $M_{line} < M_{line,crit}$, filaments are unbound ⇨ **subcritical**



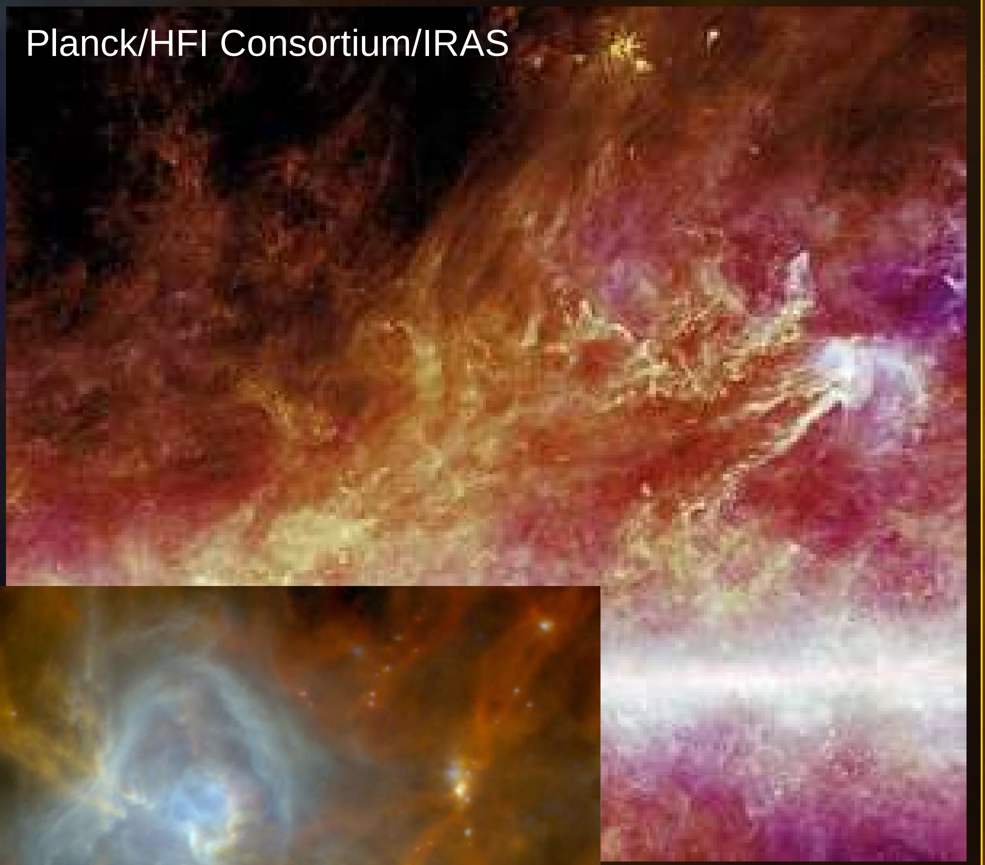
THE LARGE-SCALE STRUCTURE OF THE COLD INTERSTELLAR MATTER IN THE GALAXY

Shells, loops, bubbles

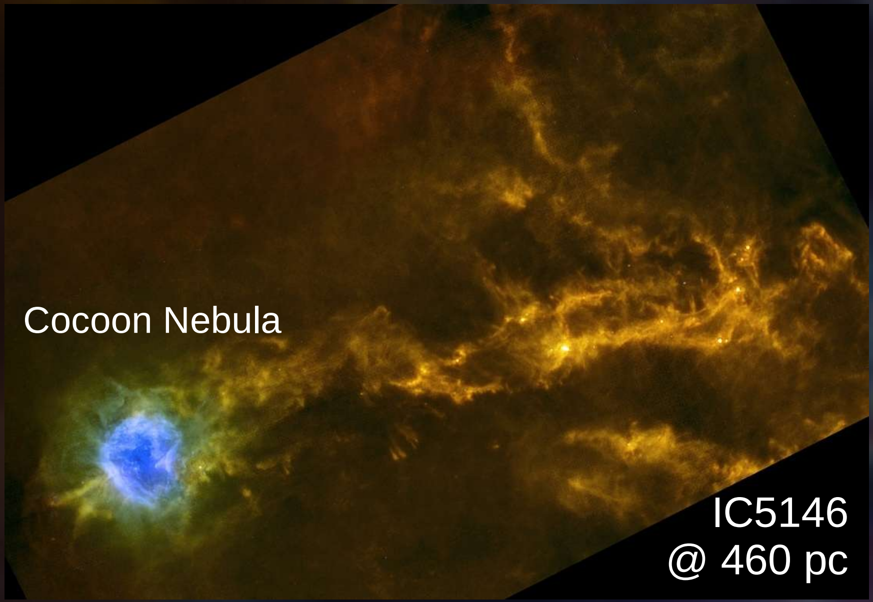
e.g., Large et al. 1962, 1966;
Könyves et al. 2007

Filaments

e.g., Schneider & Elmegreen 1979;
HERSCHEL; *PLANCK*



Filament width as measured with Herschel

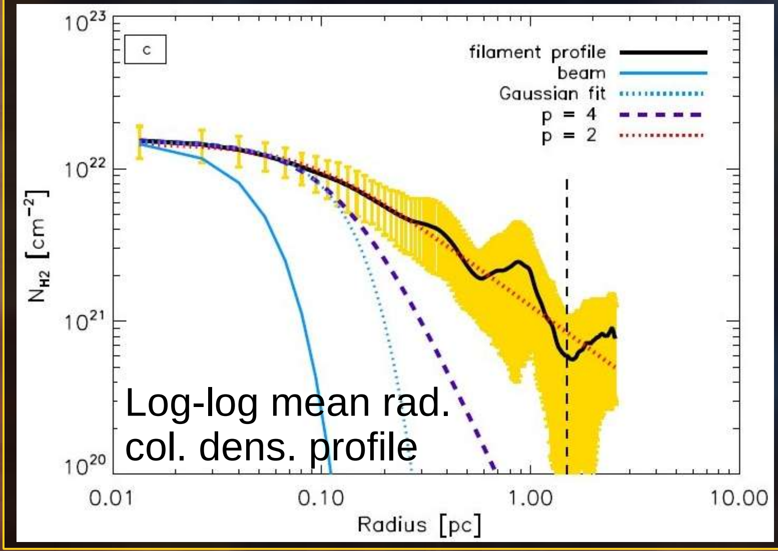


Skeleton of the filamentary network **traced with DisPerSE** algorithm (Sousbie 2011)

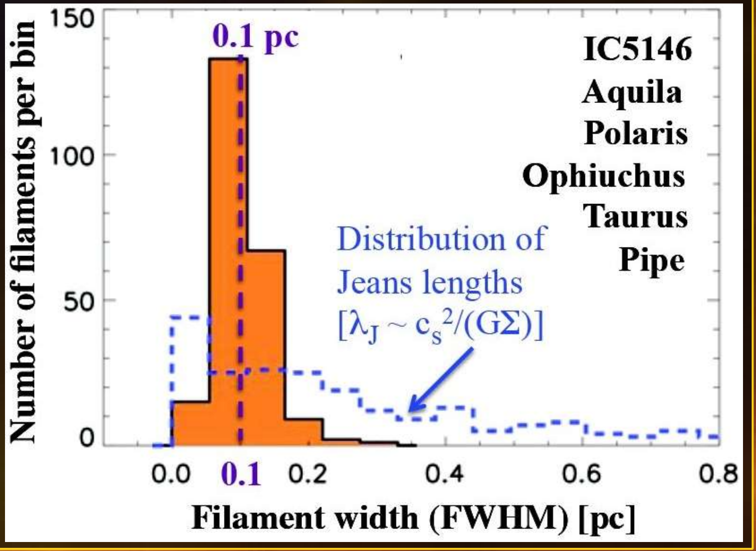
Filament width distribution peaks at **~ 0.1pc** (independent of length or column density)

⇨ sonic scale below which interstellar **turbulence becomes subsonic** (Federrath et al. 2010)

⇨ filaments may form via the dissipation of large-scale turbulence (Padoan et al. 2001)



Arzoumanian et al. (2011)



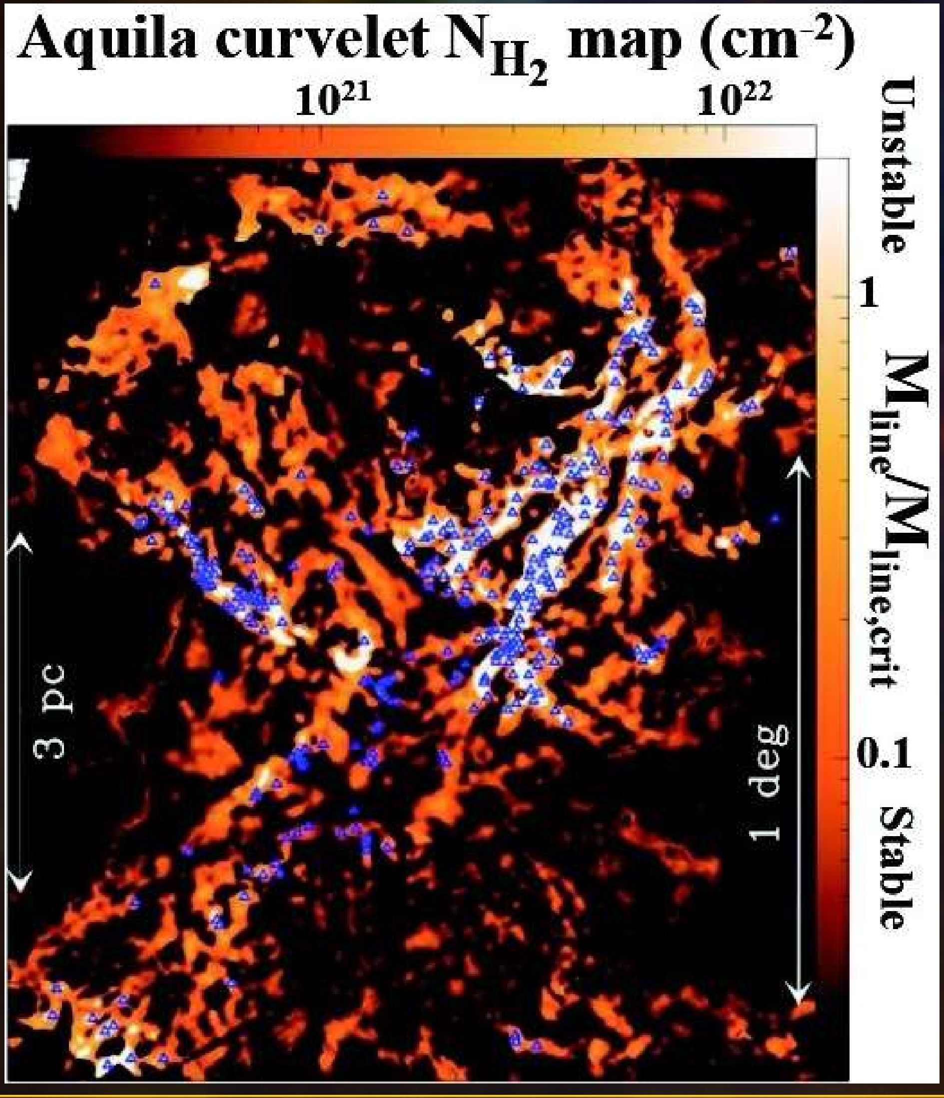
Early results of the Herschel Gould Belt survey:
a coherent star formation scenario

HGBS: SF SCENARIO FROM ORIONB, AQUILA, POLARIS DATA

CORES SITTING IN DENSE FILAMENTS

Prestellar cores are preferentially found within the densest filaments

90% of prestellar cores (△) found at $N_{H2} > 7 \times 10^{21}$ cm^{-2} ⇔ $A_{v,\,bg} > 7$



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

- **unstable if $M_{line} > M_{line,\,crit}$**
- unbound if $M_{line} < M_{line,\,crit}$

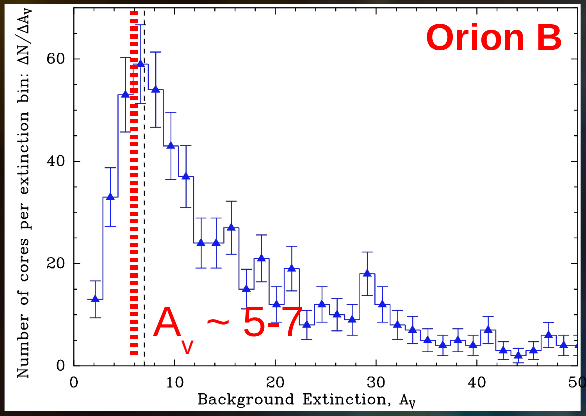
$M_{line,\,crit} = 2c_s^2/G \sim 15\ M_\odot \mathrm{pc}^{-1}$, with $c_s \sim 0.2$ km/s at $T \sim 10$K

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

⇔ $A_V \sim 7$, given the filament width of ~ 0.1pc

Unstable filaments highlighted in white in the N_{H2} map (André at al. 2010)

HGBS: SF SCENARIO FROM ORIONB, AQUILA, POLARIS DATA



Bg extinction of cores
André et al. 2011
Könyves et al., in prep.

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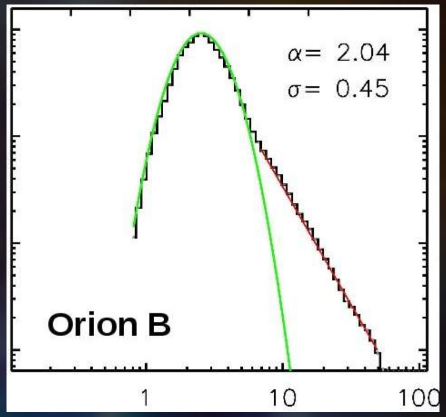

N_{H2} PDF
Schneider et al., in prep

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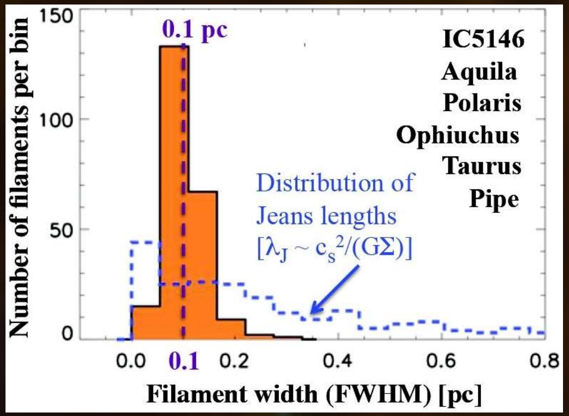


Filament width (0.1pc)
Arzoumanian et al. 2011

Suggested prestellar core formation scenario: in 2 main steps (André et al. 2010, 2011):

1) Filaments form first in the cold ISM, probably as a result of the dissipation of **MHD turbulence** (reflected in the 0.1 pc filament width)

2) The densest filaments then fragment into prestellar cores via **gravitational instability** above the approximately corresponding $A_{V,crit} \sim 5$–7 and $M_{line,crit} \sim 15\ M_\odot$/pc (T ~ 10K) thresholds.

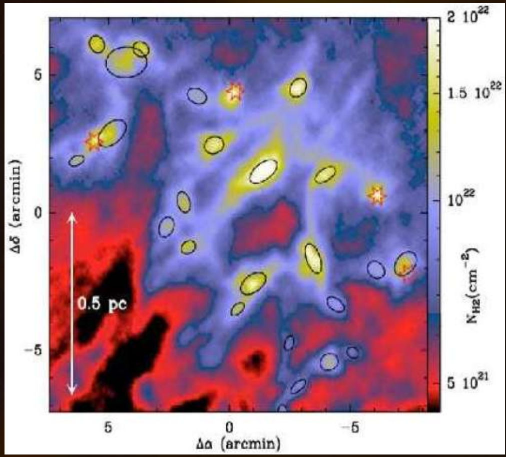
Spectroscopic and polarimetric **follow-up observations** are planned to clarify the roles of turbulence, magnetic fields, gravity in forming the filaments.

Filament fragmentation can produce the observed prestellar CMF

Median spacing between Aquila starless cores is ~0.08 pc

⇨ this roughly matches the thermal Jeans length in marginally critical filaments (at T ~ 10 K, and background A_V ~ 7)

⇨ Gravitational fragmentation is the dominant physical mechanism generating prestellar cores in filaments.

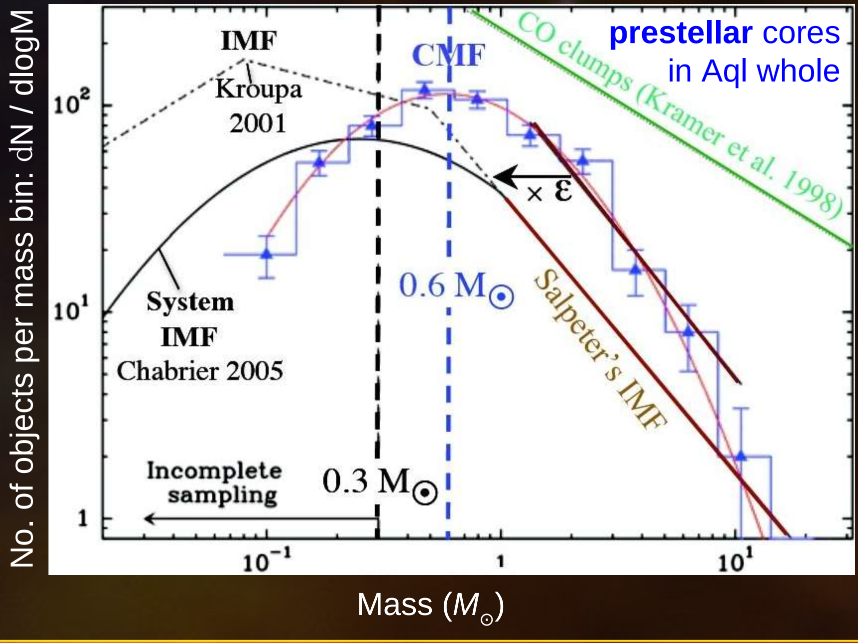


André et al. (2011)

Prestellar CMF: why not narrow, peaking at the median thermal Jeans mass ?

If turbulence generates the initial density fluctuations in the filaments

⇨ It can broaden the CMF (cf. Inutsuka 2001).



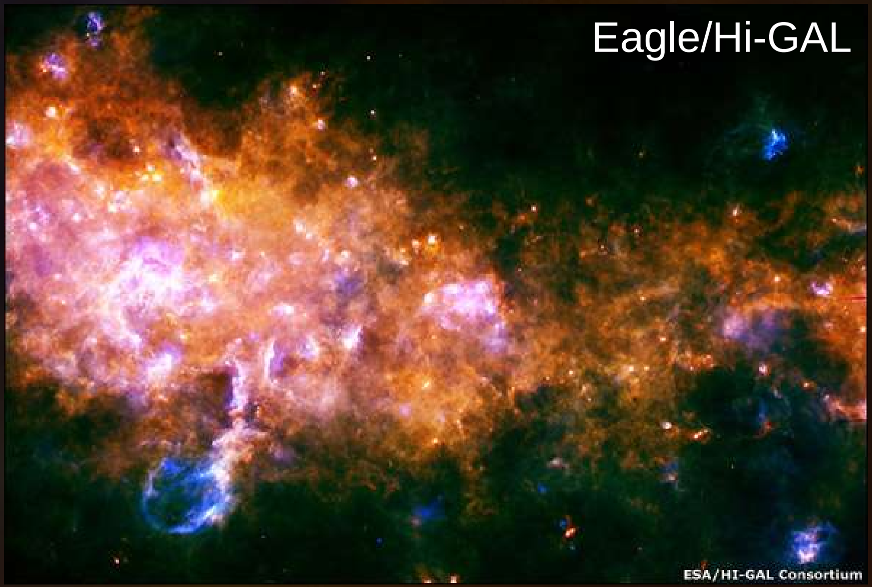
OTHER HERSCHEL GALACTIC SURVEYS

More Herschel Galactic surveys (filaments and -massive- star formation):

HOBYS (Motte et al. 2010): 70-500 μm S/P parallel-mode, slow scanning, survey of regions forming OB-type stars between 0.7-3 kpc from the Sun.

Unbiased census of massive prestellar cores and massive class 0-like protostars

Hi-GAL (Molinari et al. 2010): 70-500 μm S/P parallel-mode survey of the Galactic Plane (|l| < 60°, |b|<1°)



Distribution of (massive) star formation in the Milky Way

Thank You!