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M. Griffin, P. Hargrave, M. Huang, J. Kirk, J. Z. Li, P. Martin, V. Minier, S. Molinari, G. Olofsson,
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The *Herschel* prestellar core population in the Aquila Rift cloud complex

(*Herschel* Gould Belt survey)

CONSTELLATION meeting, Tenerife, 2010

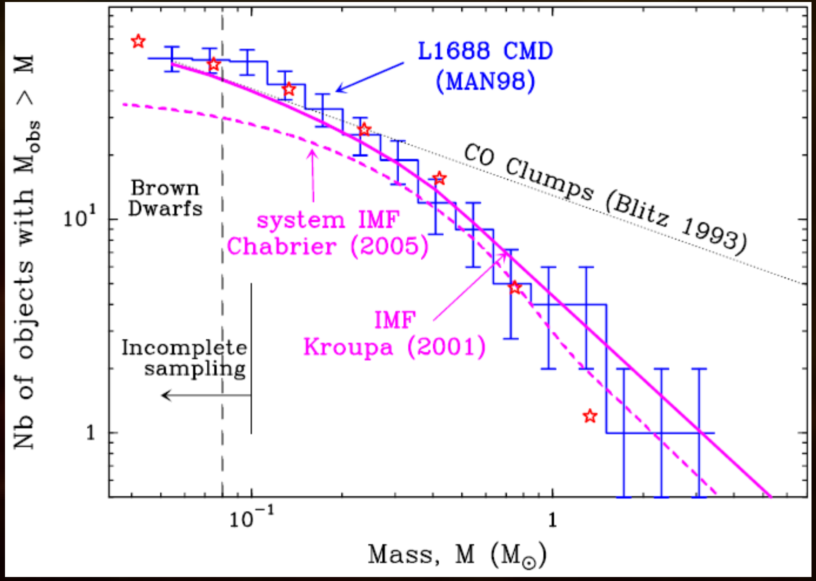
PRESTELLAR CORES IN AQUILA

THE HERSCHEL GOULD BELT KP

The ***Herschel* Gould Belt key program** is a wide-field photometric survey of nearby star-forming cloud complexes with *Herschel* SPIRE/PACS. (talk by Ph. André)

A scientific motivation of the KP is to determine the distribution of stellar masses at birth (IMF); **what is the link between the prestellar CMF and the stellar IMF?**

Earlier works: ground-based **(sub)-millimeter dust continuum surveys** of nearby cluster-forming clouds (e.g. ρ Ophiuchi, Serpens) **=> small samples** of prestellar cores, but their **CMF resemble the stellar IMF**.



References, e.g.:
Motte, André, Neri 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.

Cumulative mass distribution of 57 starless condensations in ρ Oph (Motte, André, Neri 1998; 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).

SDP Observations

SPIRE/PACS parallel-mode observations of the Aquila Rift complex:

- Observed on 24 October 2009
- A common ~11 deg^2 area was covered by both SPIRE/PACS
- Scan maps were taken with 60''sec^{-1} scanning speed

Data reduction

SPIRE (250/350/500 μm):

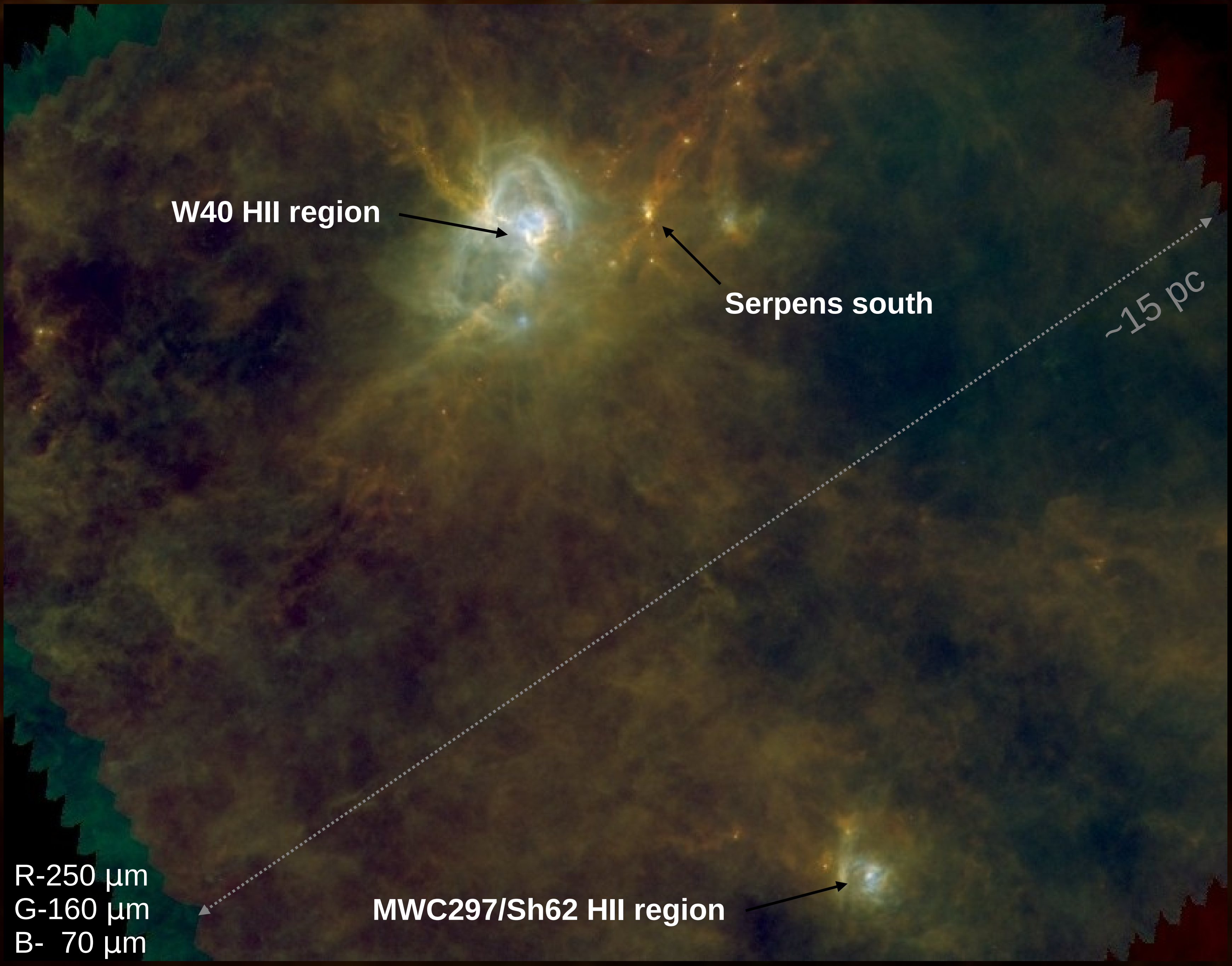
- Using HIPE version 2.0 with modified pipeline scripts, delivered with this version.
- Map making with 'naive' method.

PACS (70/160 μm):

- With HIPE version 3.0, applying standard steps of the default pipeline with modifications.
- Map making with photProject task (later on with madMap).
- *Many thanks to M. Sauvage, B. Ali, M. Hennemann, H. Aussel, N. Billot, B. Altieri, P. Chanial*

PRESTELLAR CORES IN AQUILA

RGB COMPOSITE IMAGE



DERIVATION OF PHYSICAL PARAMETERS

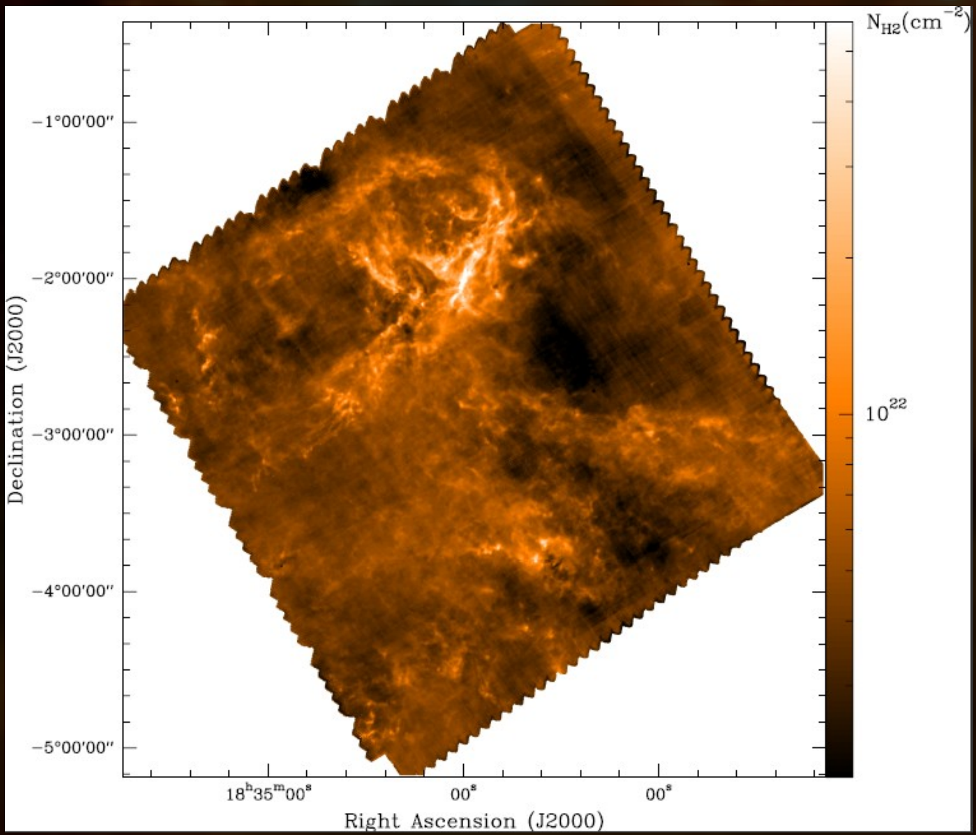
Dust temperature (T_d) and column density (Σ) maps, constructed from *Herschel* SPIRE/PACS data:

- **Weighted SEDs** constructed 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).
- The **two free parameters T_d and Σ were derived from the greybody fit** to the 5 *Herschel* data points for all pixels.

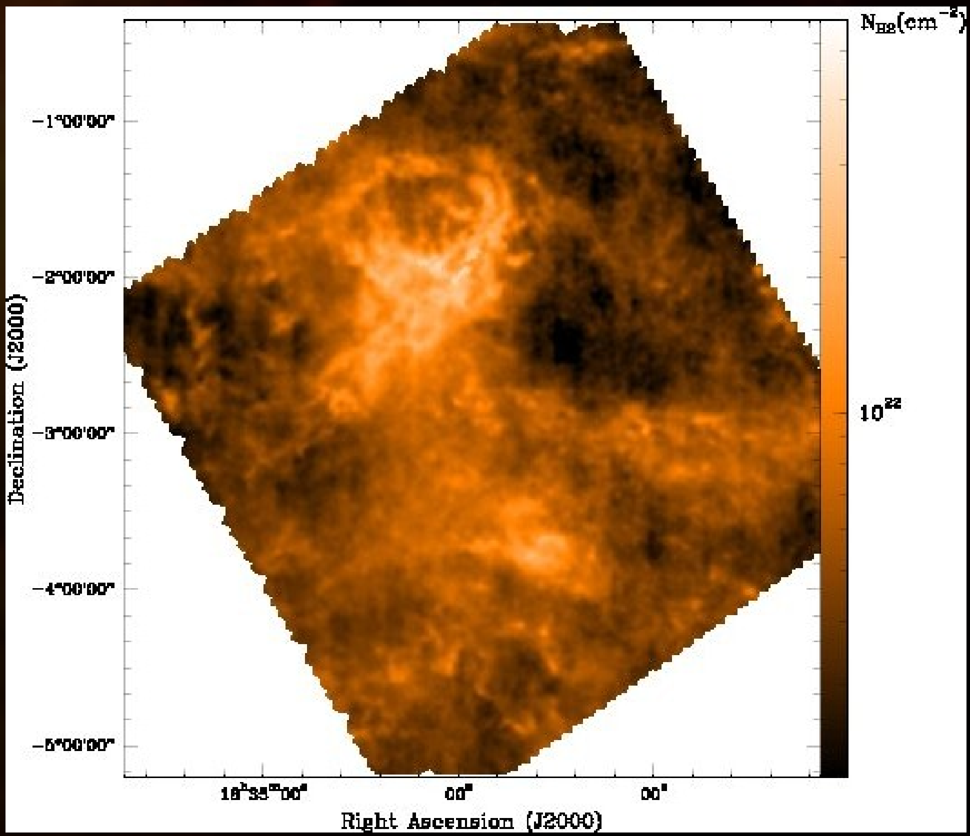
Estimation of dust temperature, column density, and mass of cores:

- A similar SED fitting procedure (above) was employed.
- These **SEDs were constructed from integrated flux densities** measured by `getsources` (Men'shchikov et al. 2010) for the extracted sources.
- **Core mass calculation** using 260 pc to Aquila (see discussion on distance uncertainty in Bontemps et al. 2010; André et al. 2010), estimated **mass uncertainty is a factor of ~2**, mainly due to κ_ν.

COLUMN DENSITY MAPS



'Planck-offsetted' column density map of the Aquila entire field derived from *Herschel* data. (FWHM = 36").

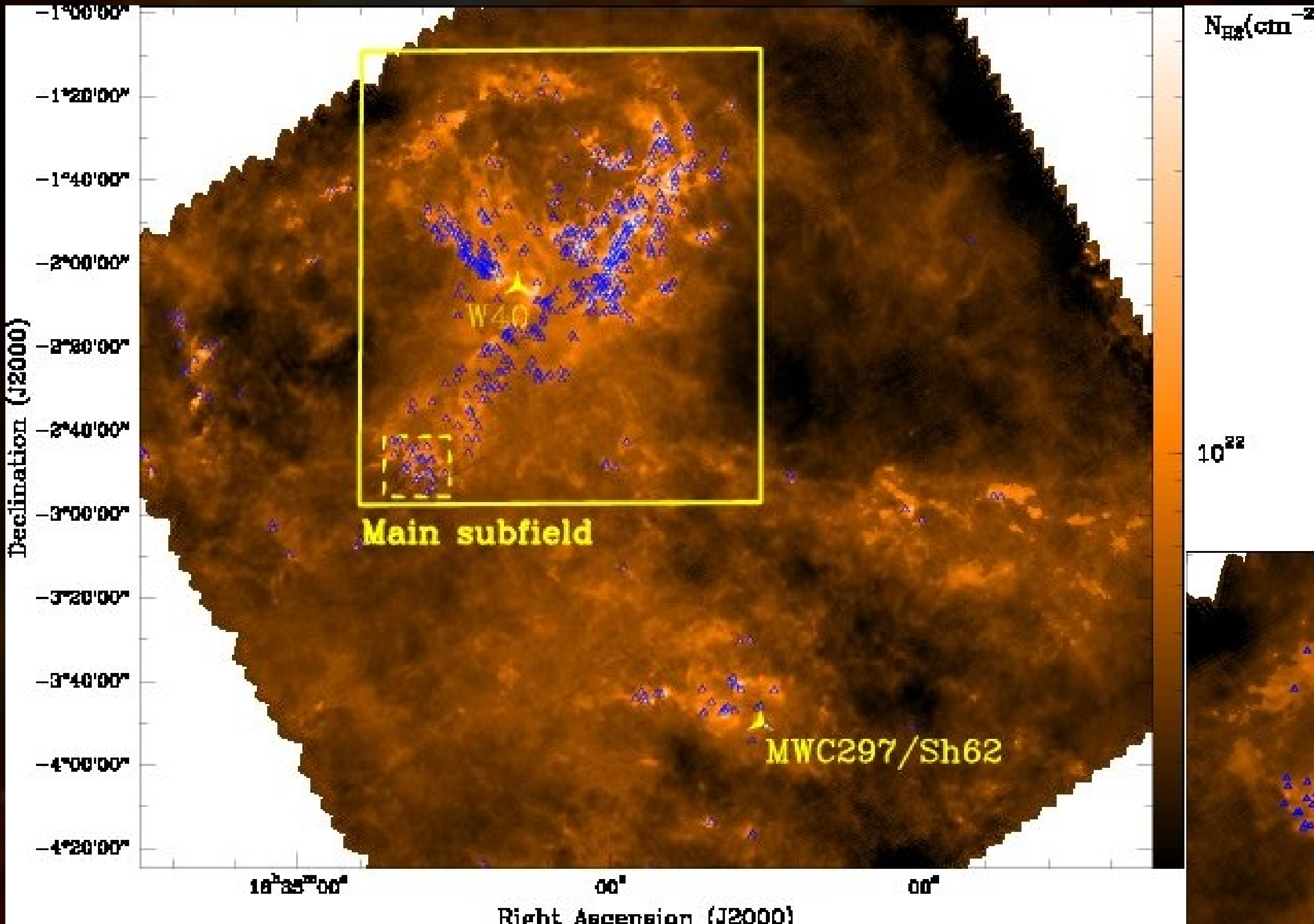


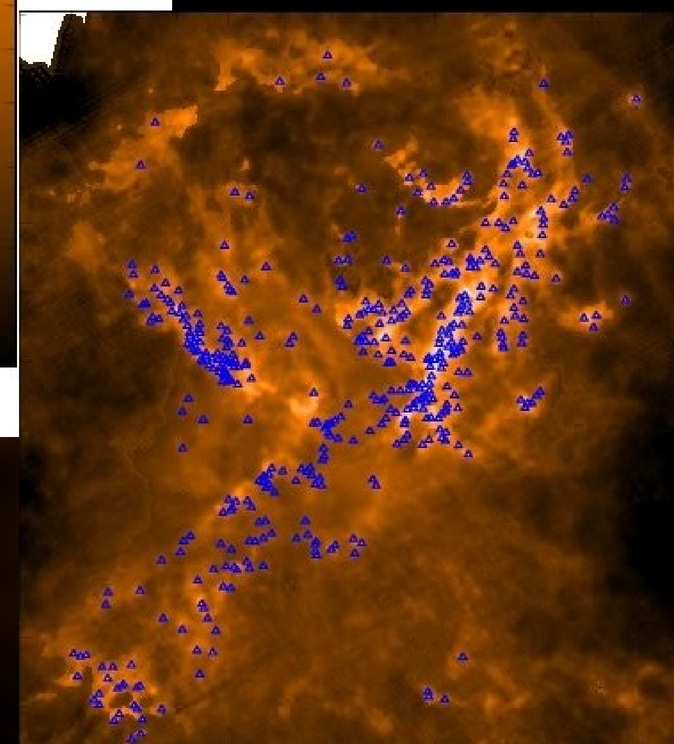
Near-IR extinction map based on 2MASS data (Bontemps et al. 2010), in units of column density, using the relation $N_{H2} = 10^{21}\ cm^{-2} \times A_V$ (FWHM = 2').

- *Herschel* mapping does not constrain the zero level of the background emission, so **we optimized the match with Planck data at each *Herschel* wavelengths** (J-Ph. Bernard). => our **column density maps were shifted** by a uniform offset $N^{off}_{H2} = 3.8 \times 10^{21}\ cm^{-2}$.
- This same **zero level was confirmed from near-IR extinction maps** (Bontemps et al 2010).

PRESTELLAR CORES IN AQUILA

STARLESS CORES IN THE FIELD





Offsetted (N^{off}_{H2} = 3.8 × 10^{21} cm^{-2}) column density map.

Blue triangles show the positions of **541 starless cores** in the entire field, and **452 starless cores** in the main subfield.

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. 2010).

Only **robust sources were considered** with significant (S/N > 7.5) detections in at least two SPIRE bands.

Distinction between starless cores and protostars/YSOs

Aquila main subfield: *Spitzer* 24 μm observations + PACS 70 μm data.

- **YSOs:** Detected in emission above the 5σ level at 70 μm and/or 24 μm
- **Starless cores:** undetected in emission (or detected in absorption) at both 70 μm and 24 μm.

=> 452 starless cores in the Aquila main subfield.

Aquila entire field: Only PACS 70 μm data

=> we identified a total of **541 starless cores** and **201 embedded YSOs** (**~50 Class 0 protostars**, Bontemps et al. 2010).

PRESTELLAR NATURE OF THE STARLESS CORES I

(I.) We used the **critical Bonnor-Ebert (BE) mass**, $M^{crit}_{BE} \approx 2.4\, R_{BE}\, a^2/G$, as a surrogate for the virial mass, to **determine if the cores are gravitationally bound or not**. R_{BE}: BE radius; a: isothermal sound speed; G: gravitational constant.

Assumptions: thermal motions are dominant over non-thermal motions in starless cores (André et al. 2007)

Then, **two estimates of the BE mass** were derived for each objects:

(1) $M_{BE}(R_{obs})$

(2) $M_{BE}(\Sigma_{cl})$, where Σ_{cl} is the column density of the local background cloud

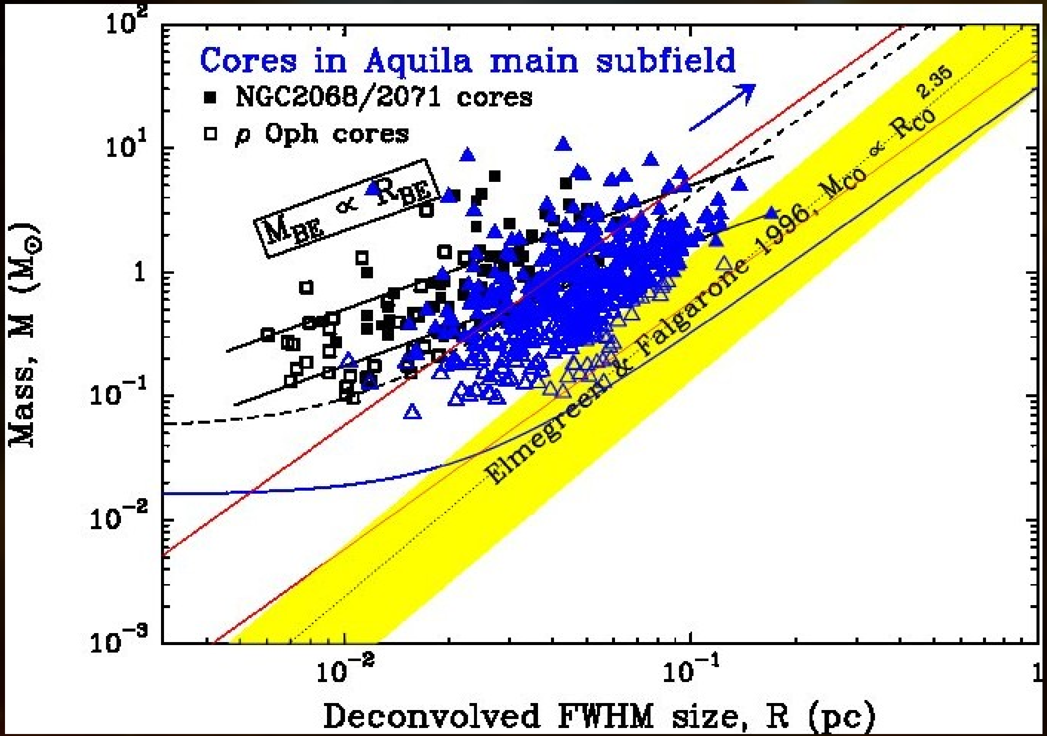
Good candidate prestellar cores, selected from starless cores if their BE mass ratio: $\alpha_{BE} \equiv \max[M_{BE}(R_{obs}), M_{BE}(\Sigma_{cl})] / M_{obs} \leq 2$.

=> ~70 % of the 452 starless cores in the main subfield,

and **more than 60 %** of the 541 starless cores in the entire field **were found to be gravitationally bound**.

PRESTELLAR NATURE OF THE STARLESS CORES II

(II.) The high fractions of bound objects are consistent with the locations of the Aquila starless cores **in a mass vs. size diagram**.



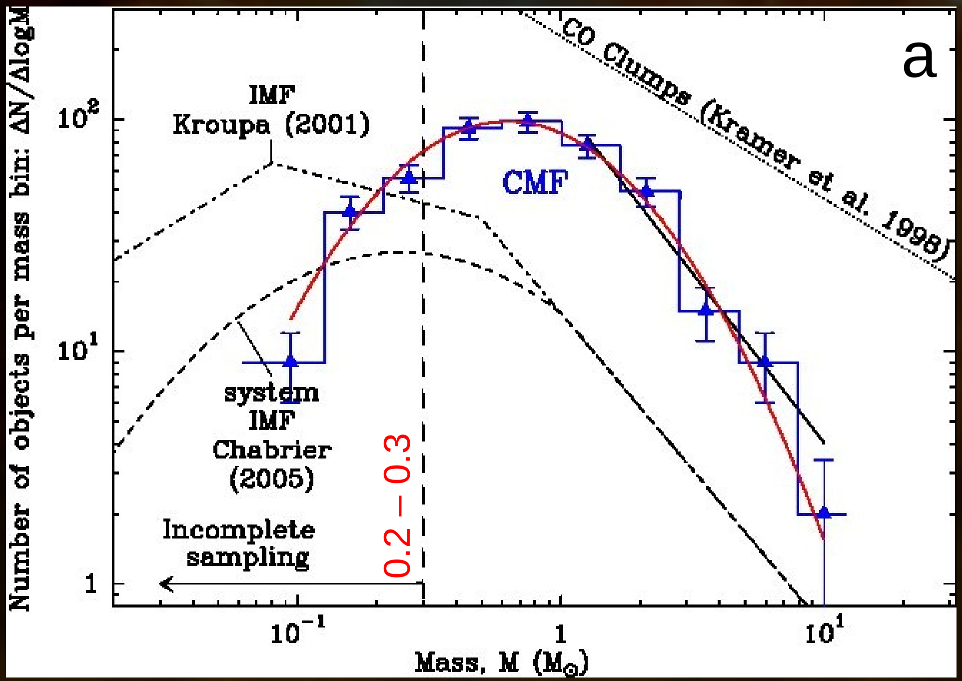
Mass vs. size diagram comparing the locations of 314 candidate prestellar cores (▲), and the rest starless cores (△), identified with *Herschel* in the Aquila main subfield, to both models of critical isothermal BE spheres (at T=7K, T=20K) and observed prestellar cores (Motte et al. 1998, 2001).

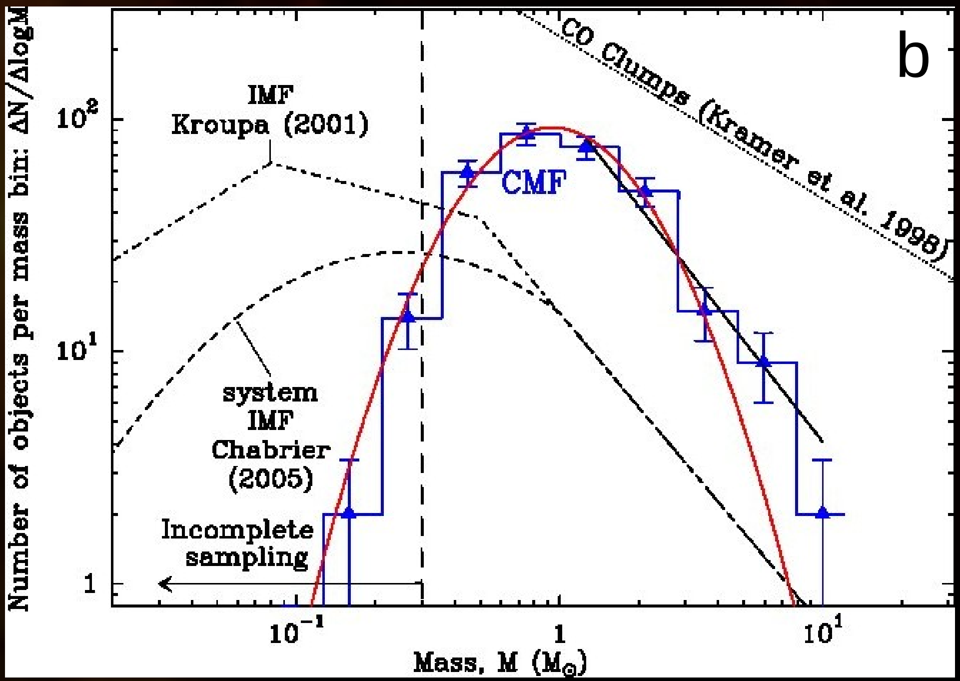
(III.) The **self-gravitating character** of most *Herschel* cores is supported **by their internal column density contrast:** Σ_{peak} / <Σ_{core}> (Johnstone et al. 2000);
similar way, **by the core intensity values**: I^{peak}_{ν} / <I_{ν}> (peak/mean intensities of the core).

(IV.) Column density contrast of the *Herschel* cores over the local background:
=> Also confirms that **most of the starless cores are** self-gravitating, and **prestellar in nature**.

PRESTELLAR CORES IN AQUILA

CORE MASS FUNCTIONS I





Differential mass function of 452 starless cores (a), and of 314 candidate prestellar cores (b) identified in the Aquila main subfield. The mass function is approximated with a lognormal fit, the high-mass end is fitted by a power-law (Könyves et al. 2010).

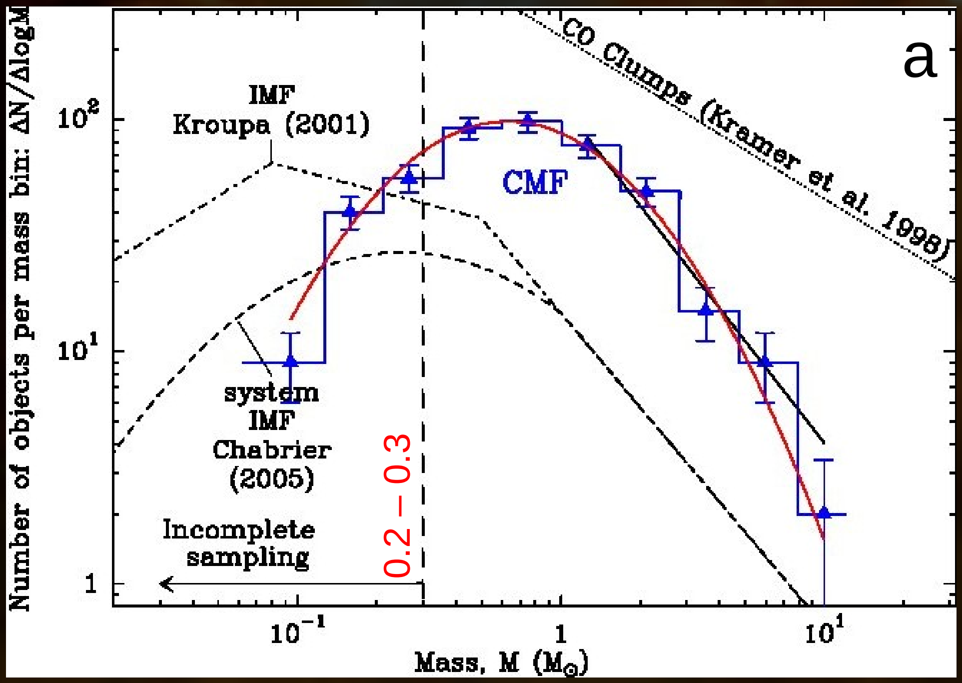
(a) Lognormal fit: peak at ~0.6 $M_\odot$, standard deviation ~0.42 in $\log_{10}$M.
fitted power-law: $dN/d\log M \propto M^{-1.5\pm0.2}$

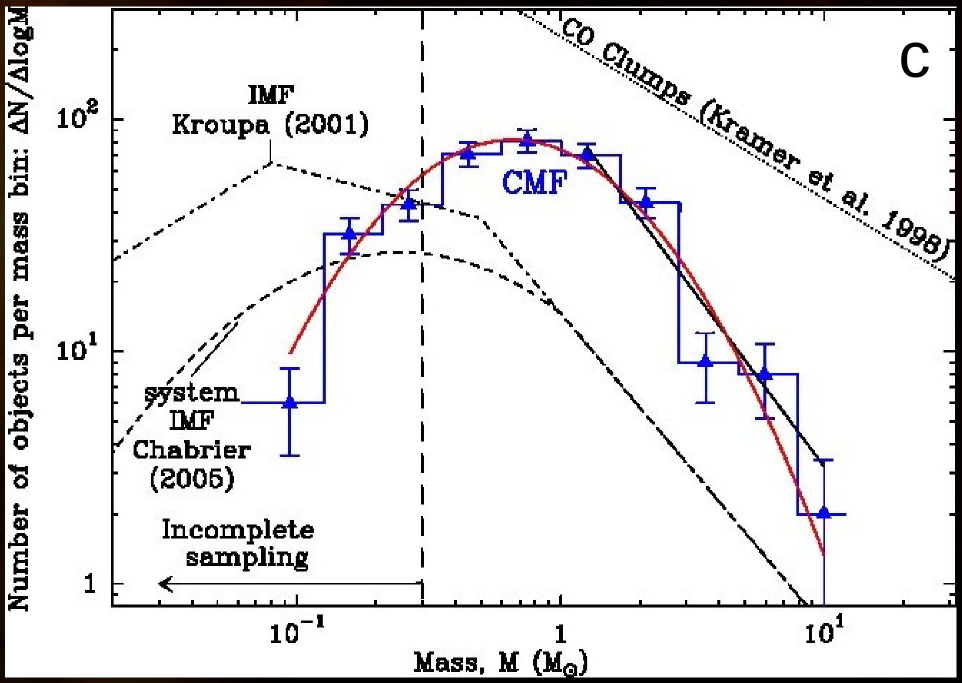
(b) Lognormal fit: peak at ~0.9 $M_\odot$, standard deviation ~0.30 in $\log_{10}$M.
fitted power-law: $dN/d\log M \propto M^{-1.45\pm0.2}$

while the **Salpeter IMF is** $dN/d\log M \propto M^{-1.35}$.

PRESTELLAR CORES IN AQUILA

CORE MASS FUNCTIONS II



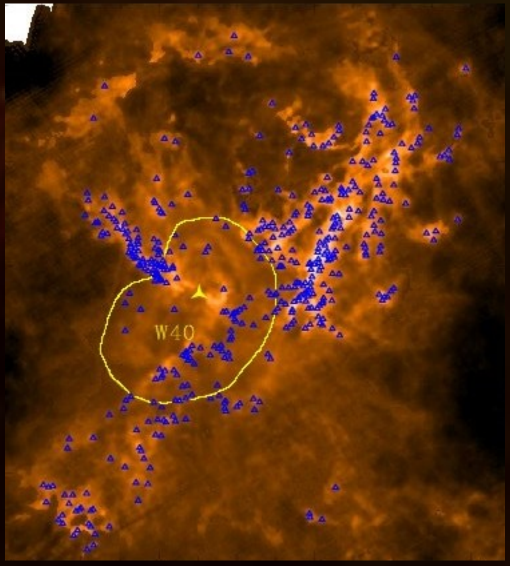


(a) as before (Könyves et al. 2010)

(c) Differential mass function of 368 starless cores, excluding 83 cores toward the PDR region.

(c) Lognormal fit: peak at ~0.7 $M_\odot$,
standard deviation ~0.40 in $\log_{10}M$.
fitted power-law: $dN/d\log M \propto M^{-1.5\pm0.3}$

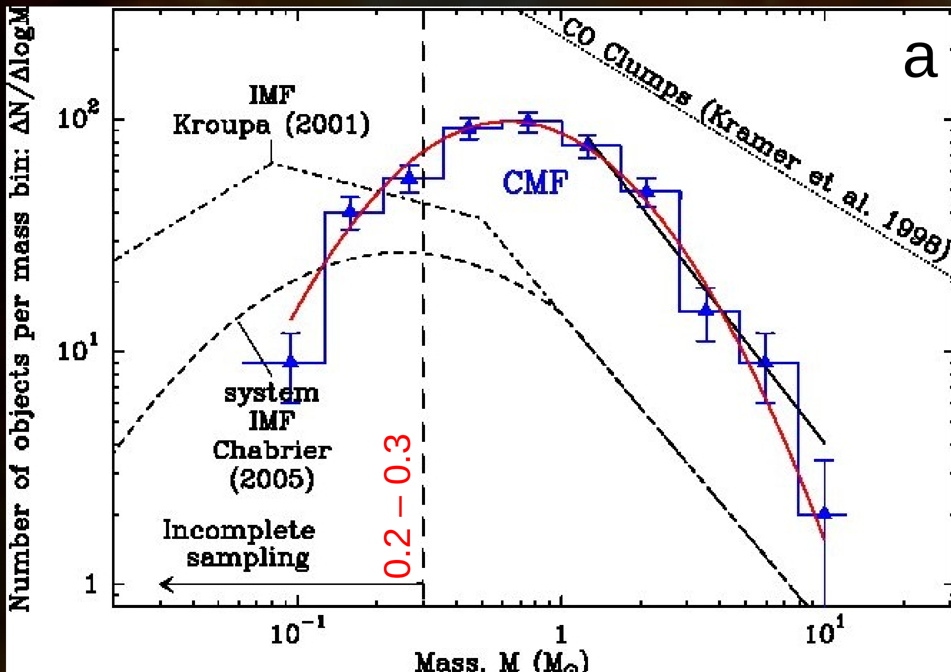
very close to (a), (b), and to the Salpeter power-law => robustness of our CMF



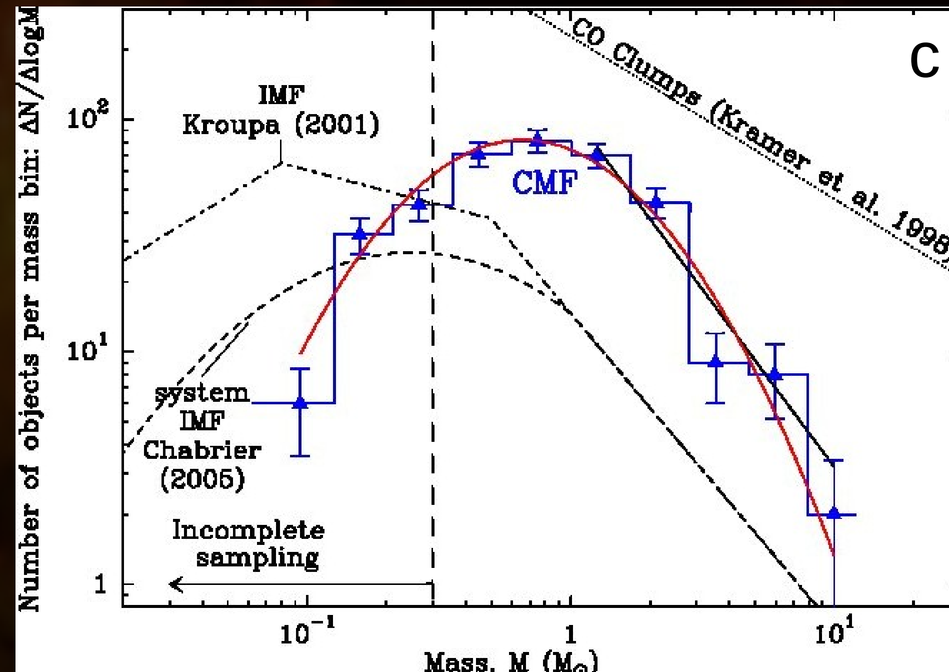
Column density map with starless cores in the Aqila main subfield. The PDR, with high infrared background emission, around the W40 HII region was defined using T_d map (Bontemps et al. 2010).

PRESTELLAR CORES IN AQUILA

CORE MASS FUNCTIONS II



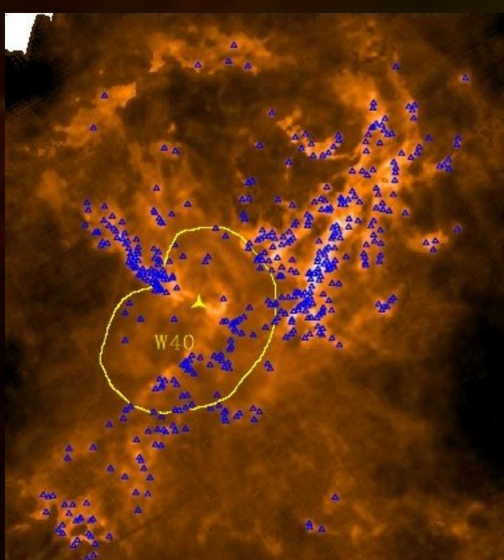
(a) as before (Könyves et al. 2010)



(c) Differential mass function of 368 starless cores, excluding 83 cores toward the PDR region.

(c) Lognormal fit: peak at $\sim 0.7\ M_\odot$,
standard deviation ~ 0.40 in $\log_{10}M$.
fitted power-law: $dN/d\log M \propto M^{-1.5\pm0.3}$

very close to (a), (b), and to the Salpeter power-law => robustness of our CMF



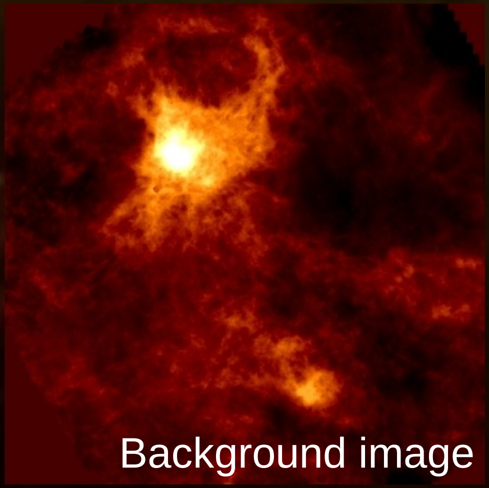
Column density map with starless cores in the Aqila main subfield. The PDR, with high infrared background emission, around the W40 HII region was defined using T_d map (Bontemps et al. 2010).

PRESTELLAR CORES IN AQUILA

COMPLETENESS ANALYSIS I

Monte Carlo simulations were preformed **to estimate the completeness level** of our SPIRE/PACS survey, summarized in the following steps:

- Subtraction of compact sources (`getsources`) from *Herschel* maps => **clean maps of background emission**.
- **Radiative transfer simulated objects** (Men'shchikov et al. In prep.): ~700 starless cores, ~200 protostars with 0.01 – 10 $M_{\odot}$, and $M \propto R$ => **inserted at quasi random positions in the clean-background images**.



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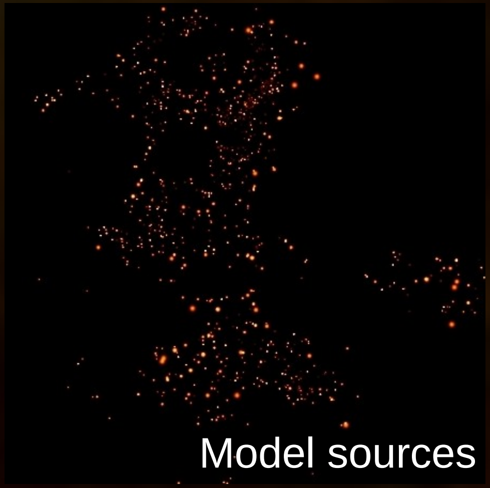

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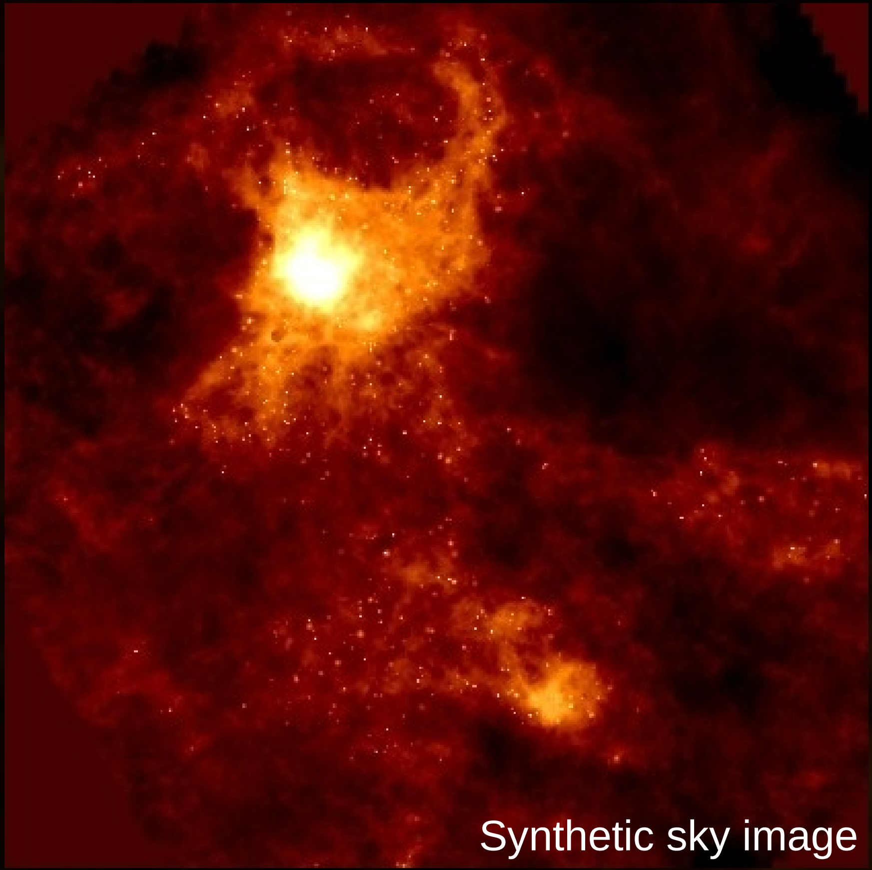
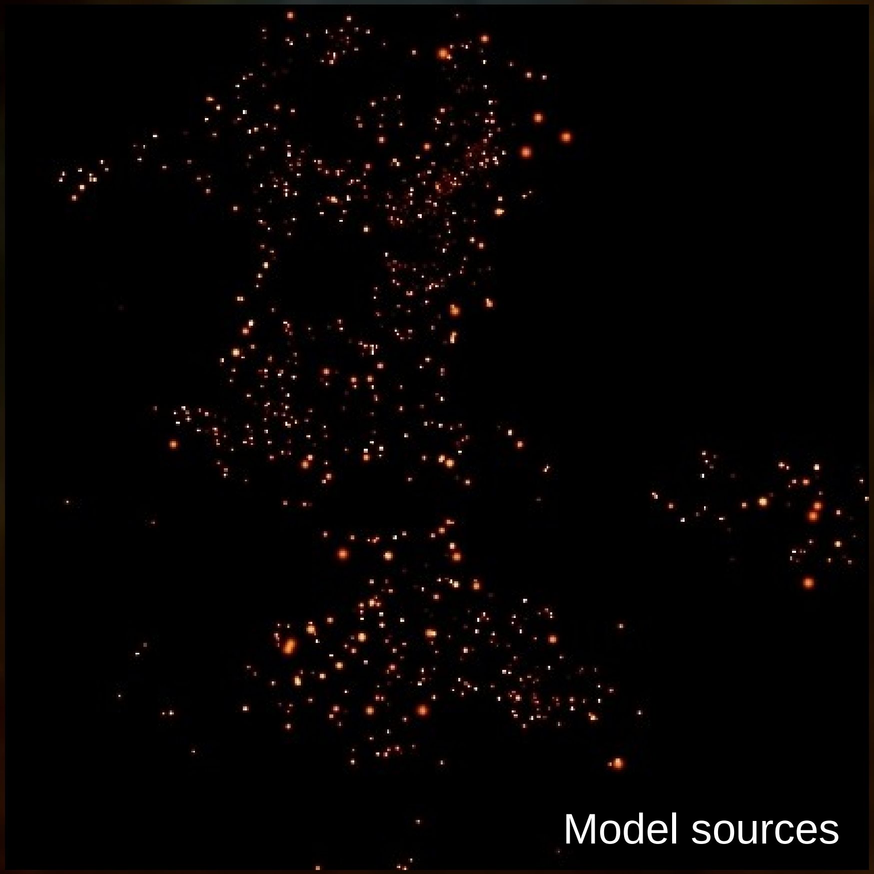
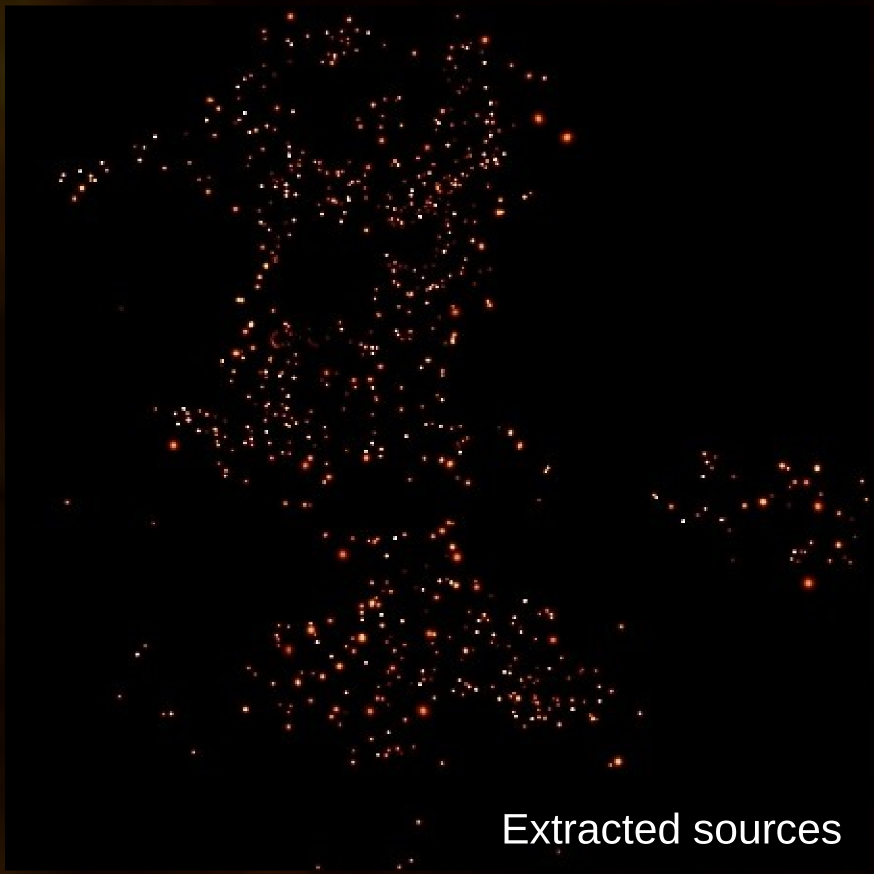


COMPLETENESS ANALYSIS II

- **Source extraction** (`getsources`) was performed again **on the synthetic skies**.





Estimated completeness level:

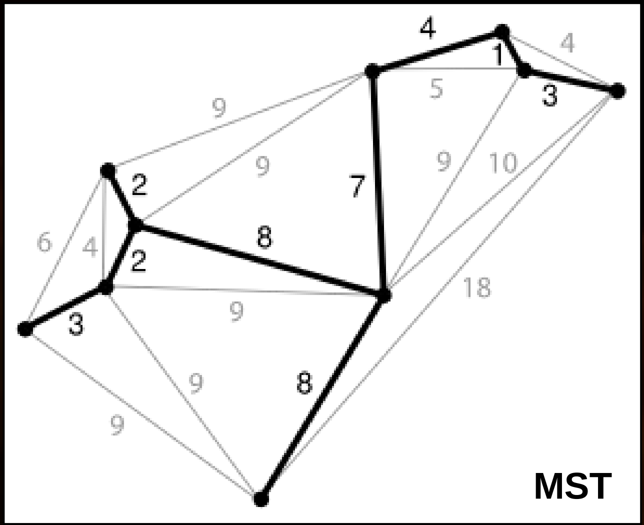
- **for prestellar cores:** 75 % and 85 % above a core mass of ~0.2 and ~ 0.3 $M_{\odot}$
- **for embedded protostars:** >90 % down to L_{bol}~0.2 $L_{\odot}$

Discussions and visits on the topic of **mass segregation of cores in the Aquila field**, using:

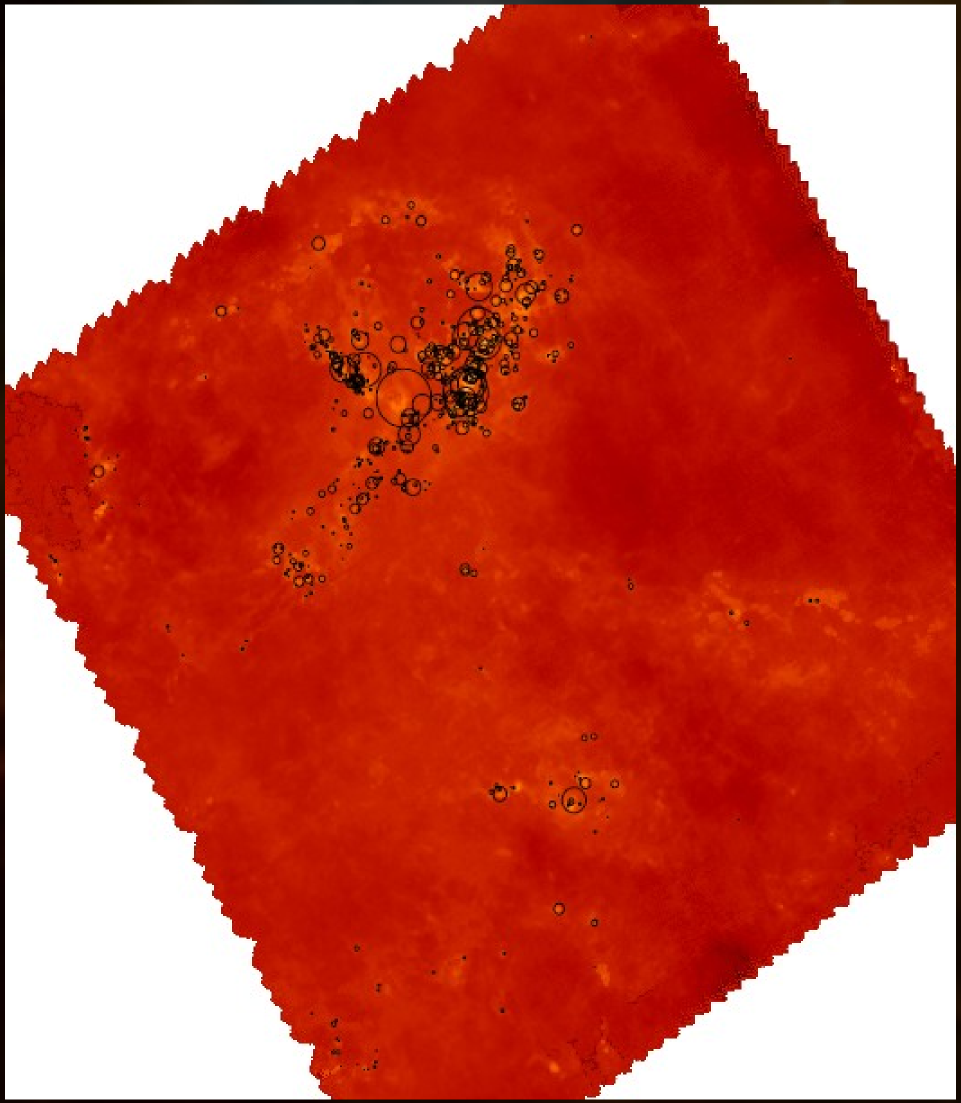
- our **large sample of *Herschel* starless cores** (Könyves et al. 2010; V. Könyves, CEA/Saclay)
- the **minimum spanning tree** (MST) method (Allison et al. 2009a) by S.P. Goodwin, R.J. Allison, R.J. Parker (University of Sheffield)
- Th. Maschberger's MST method (University of Cambridge)

The minimum spanning tree (MST) method:

- Network of connected points with minimum possible total length of connections (**path with the shortest possible pathlength**).
- Closed loops are not allowed.



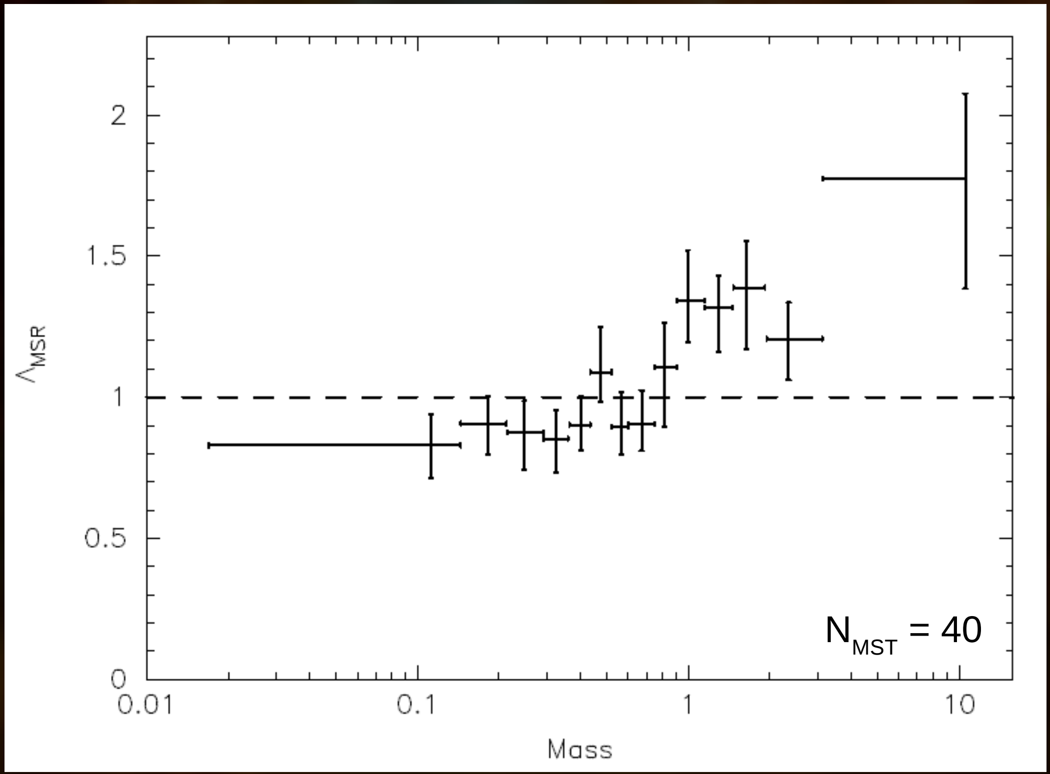
Mass segregation can be quantified (Λ_{MSR}) by comparing the typical MST of N cluster stars with the MST of the N most massive stars (Allison et al. 2009b).



The MST method finds the MST length of the N most massive stars ($l_{massive}$) and compares this to the MST length of sets of N random stars in the cluster ($\langle l_{norm} \rangle$)

Distribution of masses of 541 *Herschel* starless cores plotted on a 250 μm Aquila map.
The larger the symbol is, the larger the mass of the starless core has.

PRESTELLAR CORES IN AQUILA



Mass segregation measure of 541 starless cores in the entire Aquila field.

Measure of mass segregation (Λ):

$$\Lambda = \langle \ell_{norm} \rangle / \ell_{massive} \pm \sigma_{norm} / \ell_{massive}$$

1 σ error in Λ

$\langle \ell_{norm} \rangle$ = average random MST path length

$\ell_{massive}$ = length of the massive star/core MST

$\Lambda \sim 1$: massive cores are distributed in the same way as all other cores

$\Lambda > 1$: mass segregation

$\Lambda < 1$: inverse-mass segregation

Preliminary conclusions:

In the entire Aquila field $\Lambda > 1$ ($\ell_{massive} < \langle \ell_{norm} \rangle$) => massive cores have slightly more concentrated distribution, the ***Herschel* starless cores show mass segregation**.

These **results from *Herschel* observations can be compared with simulations** to investigate the early dynamical evolution of clusters.

CONCLUSIONS

Herschel **Gould Belt survey SDP observations of the Aquila Rift complex with SPIRE and PACS at 500 – 70 µm:**

- Provided **>500 starless cores in the entire field**, and >400 in the main subfield, **down to ~0.2 – 0.3 $M_{\odot}$**.
- **Most of these objects appear to be self-gravitating prestellar cores** that will likely form protostars in the near future.
- **Our results confirm that the shape of the prestellar CMF resembles the stellar IMF**, with much better statistics than earlier sub-millimeter ground-based surveys, and more accurate core masses.
- We conclude that **our mass distributions are robust**, not depending strongly on distance, different sets of extracted sources, and on different locations of the maps.
- **Ongoing collaborations on mass segregation** in Aquila (massive starless cores have slightly more concentrated distribution).

For more details, see in A&A, Vol. 518: Könyves et al. 2010; André et al. 2010; Bontemps et al. 2010; Men'shchikov et al. 2010

THANK YOU!