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

ORISTARS
erc project

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

Star Formation in GMCs: Lessons from Herschel Observations of the Aquila Complex

SF X Space & Time, ESTEC, Nov., 2014

HERSCHEL Gould Belt survey (HGBS)

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

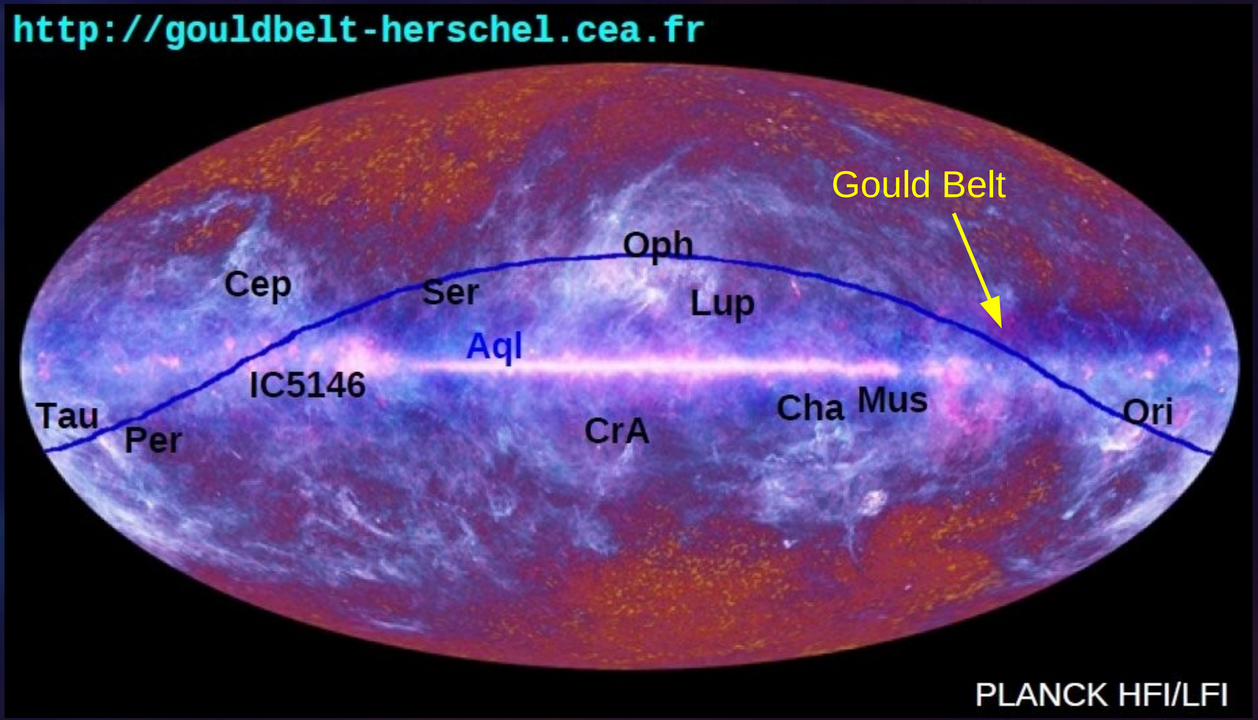
- wide-field submm continuum survey with SPIRE/PACS (461 hrs of GT)
- in nearby star-forming cloud complexes ($d \leq 500$ pc) of the Gould Belt
- probes **the origin of the stellar masses**

Scientific motivations, goals:

⇨ Link between the prestellar CMF and the stellar IMF ?

⇨ Provide a complete census of prestellar cores and protostars

⇨ Unravel the core formation mechanisms



HERSCHEL Gould Belt survey (HGBS)

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

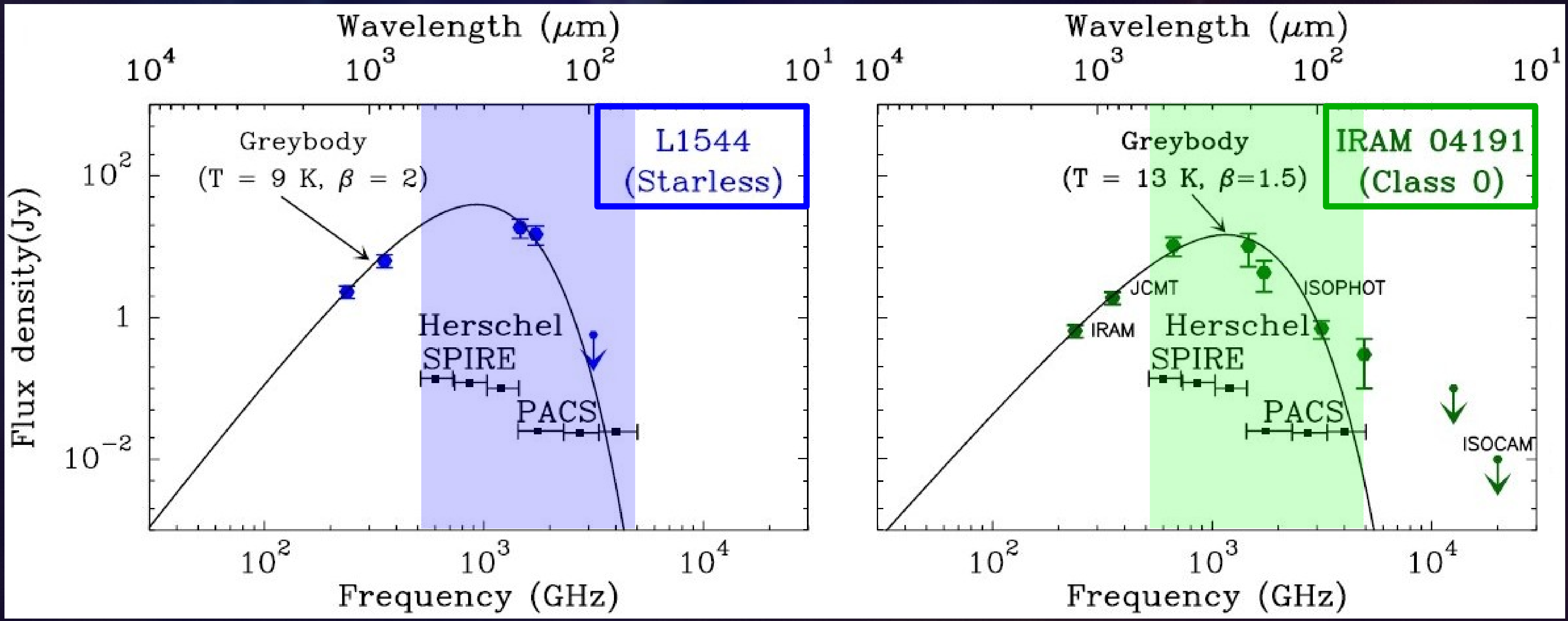
- in the 0.01–0.1 pc size range
- down to $M_{proto} \sim 0.01$–$0.1\ M_{\odot}$

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

Spectral energy distributions (SEDs)

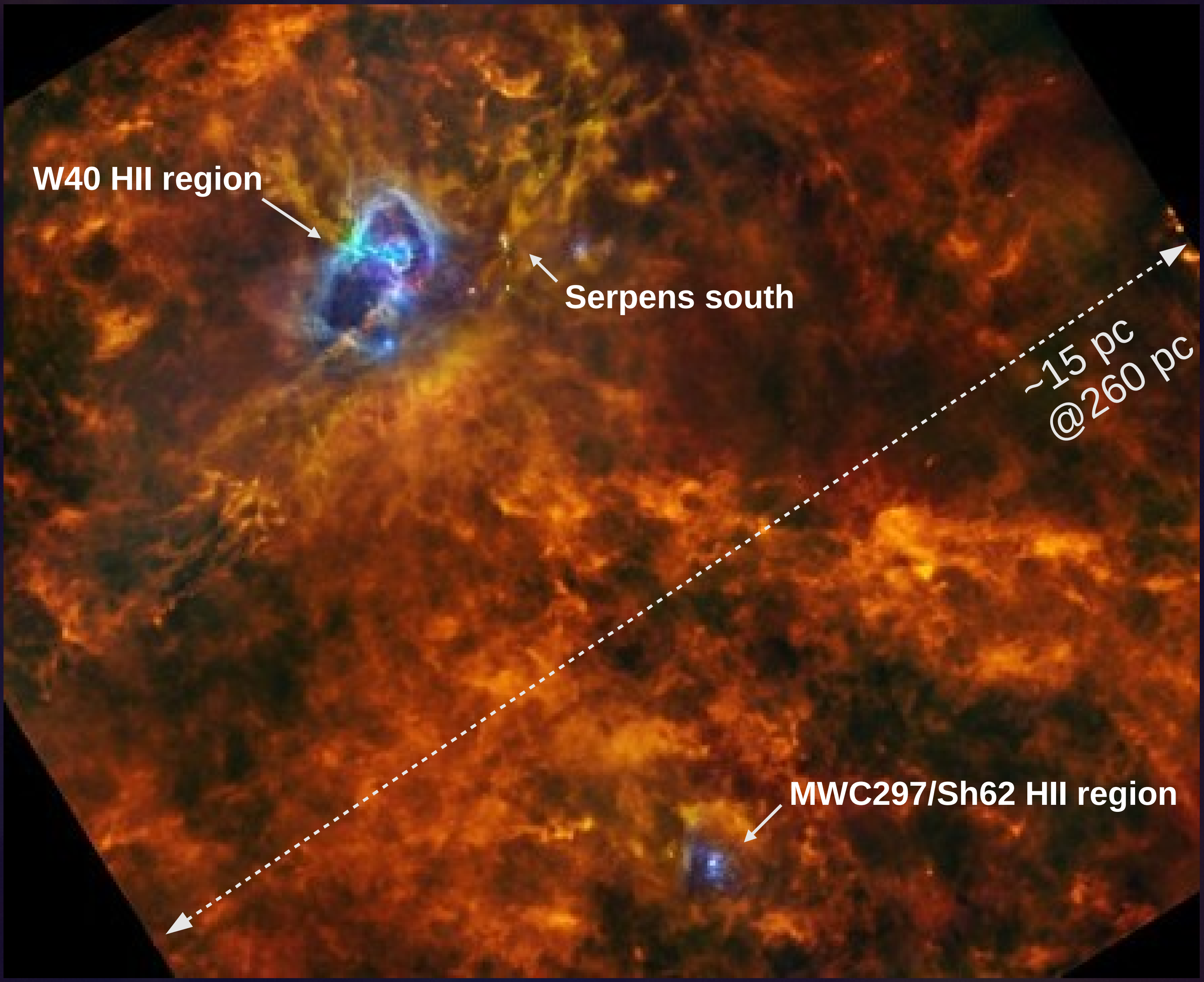
Ward-Thompson et al. (2002)

André at al. (1999)



HGBS: THE AQUILA CLOUD COMPLEX

RGB COMPOSITE



R-250 μm
G-160 μm
B- 70 μm

André et al. 2010
Könyves et al. 2010
Bontemps et al. 2010
Men'shchikov et al. 2010
Maury et al. 2011

Dust temperature (T_d) and column density (N_{H2}) maps

♥ Using smoothed (36.9″) maps of 160-250-350-500 μm; Planck offsets added (Bernard et al. 2010).

♥ Pixel-by-pixel SED fitting with a modified blackbody: $I_\nu = B_\nu(T_d)\kappa_\nu\Sigma$
- Assumption: single-temperature dust optically thin emission
- Dust emissivity index $\beta = 2$ (cf. Hildebrand, 1983)

♥ Weighting by calibration uncertainties (20%-160 μm, 10%-SPIRE bands)

⇨ $N_{H2} = \Sigma / \mu_{H2} m_H$

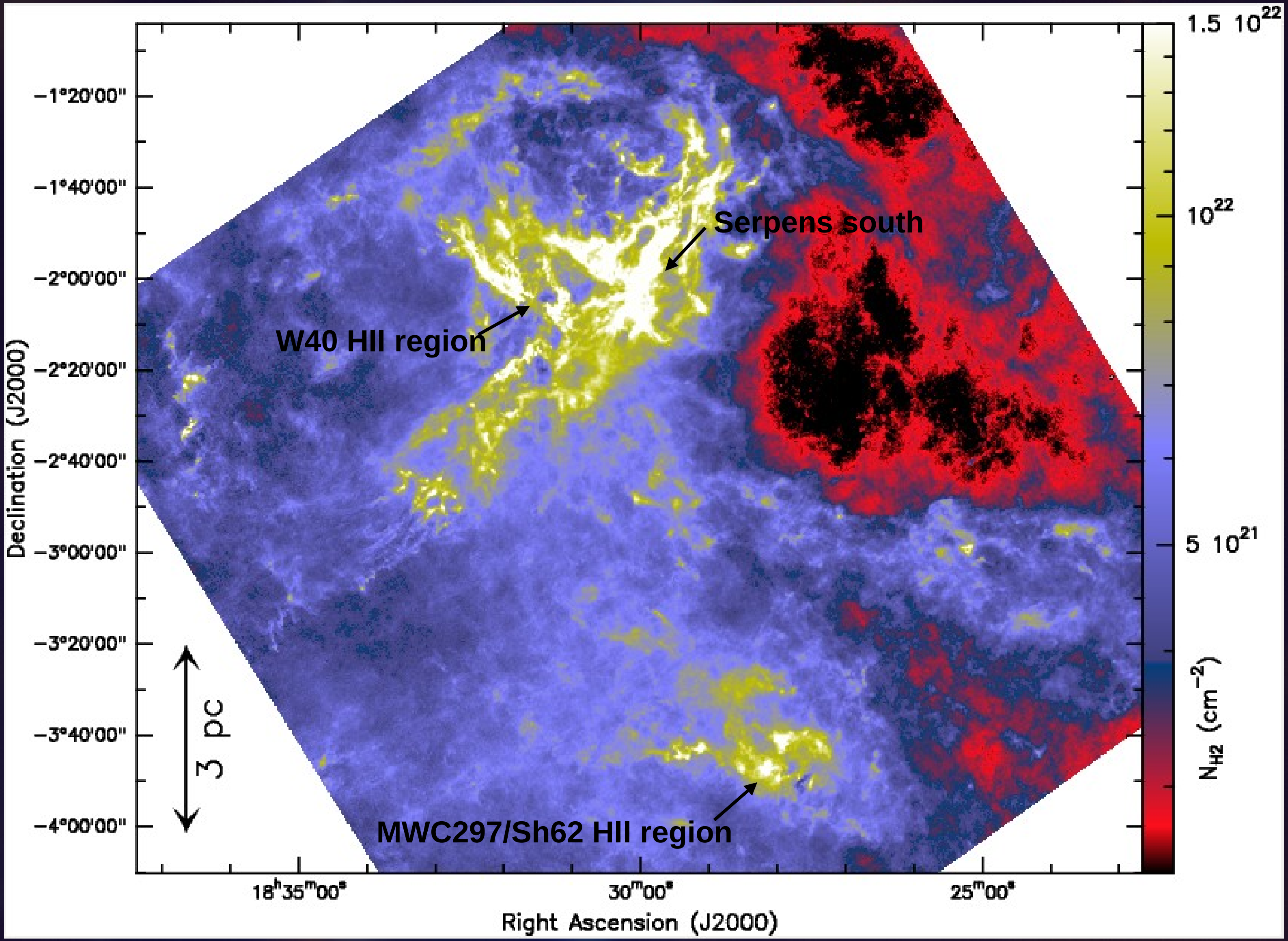
Deriving **high-resolution (18.2") column density maps** (see Palmeirim et al. 2013):

♣ Using the concept of multi-scale decomposition (Starck et al. 2004)

♣ Small scales are successively added up from 250 to 500 μm while conserving spectral informations from longer wavelengths.

HGBS: AQUILA

H_2 COLUMN DENSITY MAP



- **Cores** (starless, protostellar)
  Protostars
- **Filaments**

Könyves et al. 2010
Könyves et al., in prep.

HGBS: SOME „TECHNICAL” DETAILS

SOURCE DETECTION, IDENTIFICATION, PHYSICAL PROPERTIES

Source extraction

- Compact sources were extracted from the SPIRE/PACS images with ***getsources***, a multi-scale, multi-wavelength source finding algorithm (Men'shchikov et al. 2012)
- For checking purposes an other code was also ran: **CSAR** (Kirk et al. 2013).

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.

Selecting self-gravitating prestellar cores

- We used the **critical Bonnor-Ebert (BE) mass**, $M^{crit}_{BE} \approx 2.4\, R_{BE}\, c_s^2/G$,

as a surrogate for the virial mass, to determine if the cores are gravitationally bound.

Good candidate prestellar cores selected if $M_{BE} / M_{obs} \leq 2$.

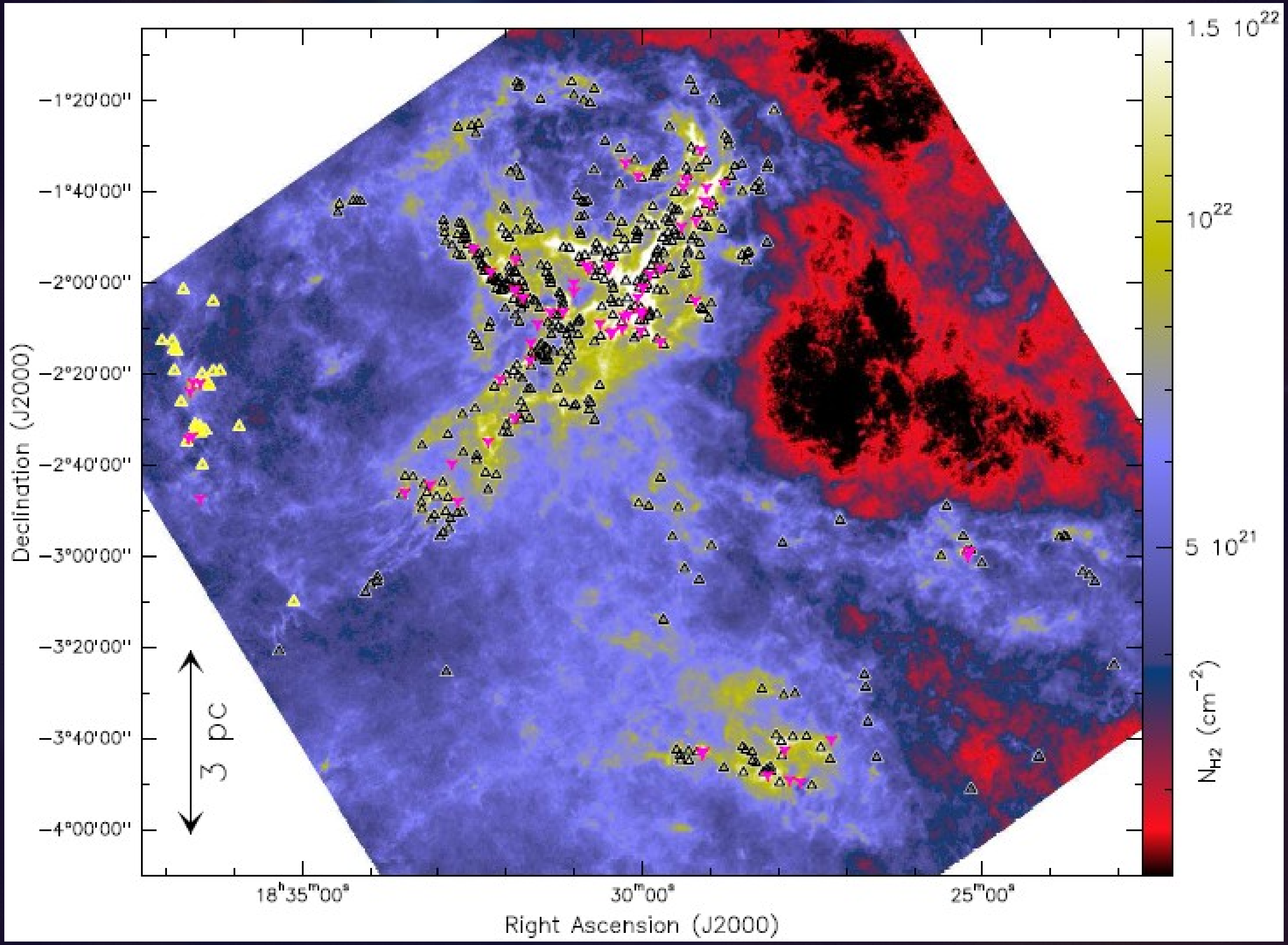
⇨ **~70%** of the starless cores selected as **prestellar**.

HGBS: AQUILA

H_2 COLUMN DENSITY MAP

H_2 column density map of Aquila (~11 deg^2) at 18.2″ angular resolution

- Black triangles: ~450 prestellar cores (out of ~650 starless cores)
- Pink stars: ~60 protostellar cores



Könyves et al. 2010
Könyves et al., in prep.

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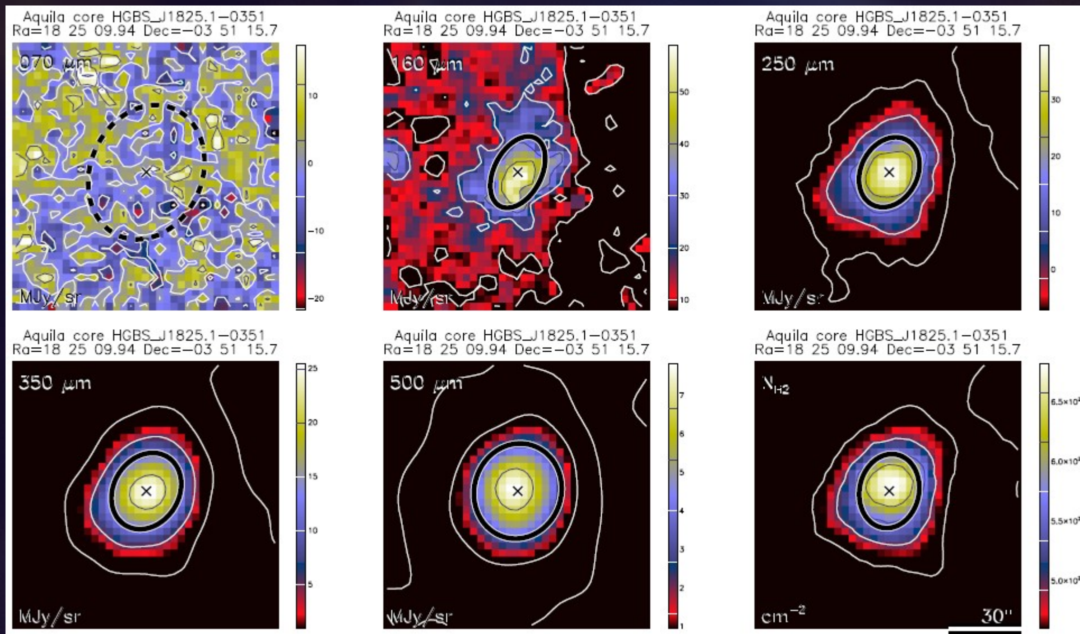
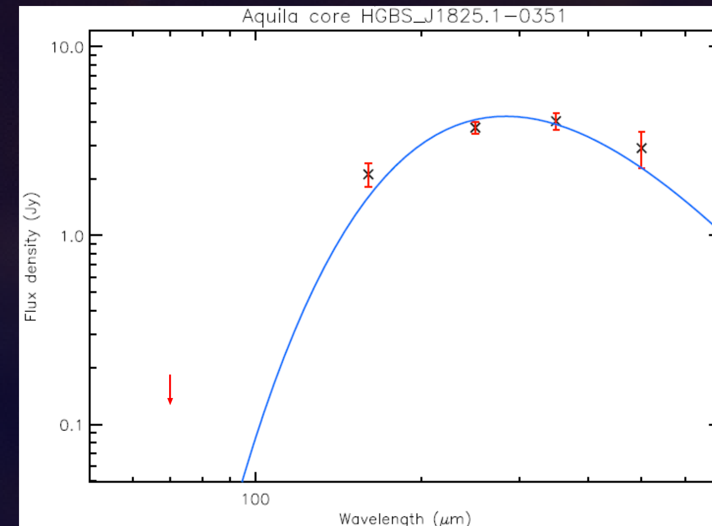
CORE LOOKS, SEDs



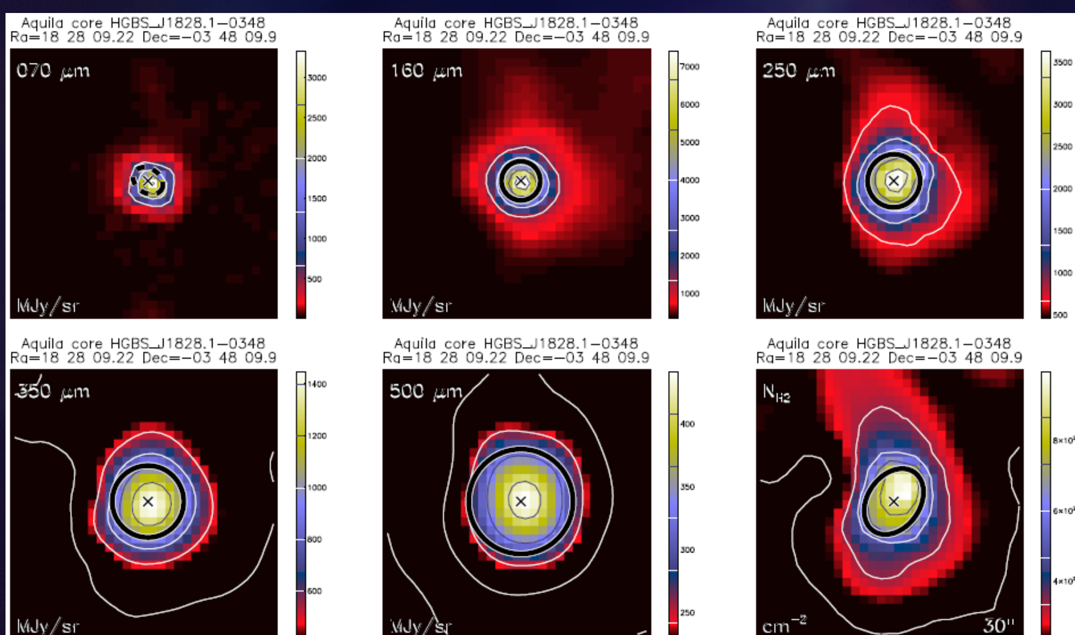


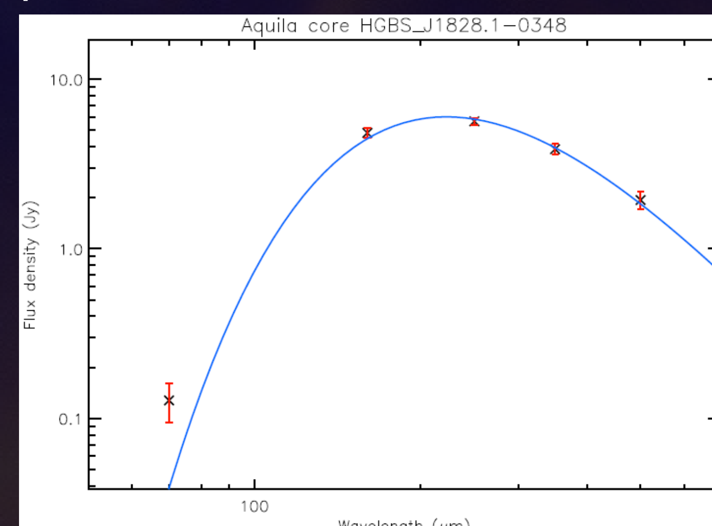
prestellar core

$R_{\mathrm{decon,FWHM}}$ ~ 0.03 pc ⟷

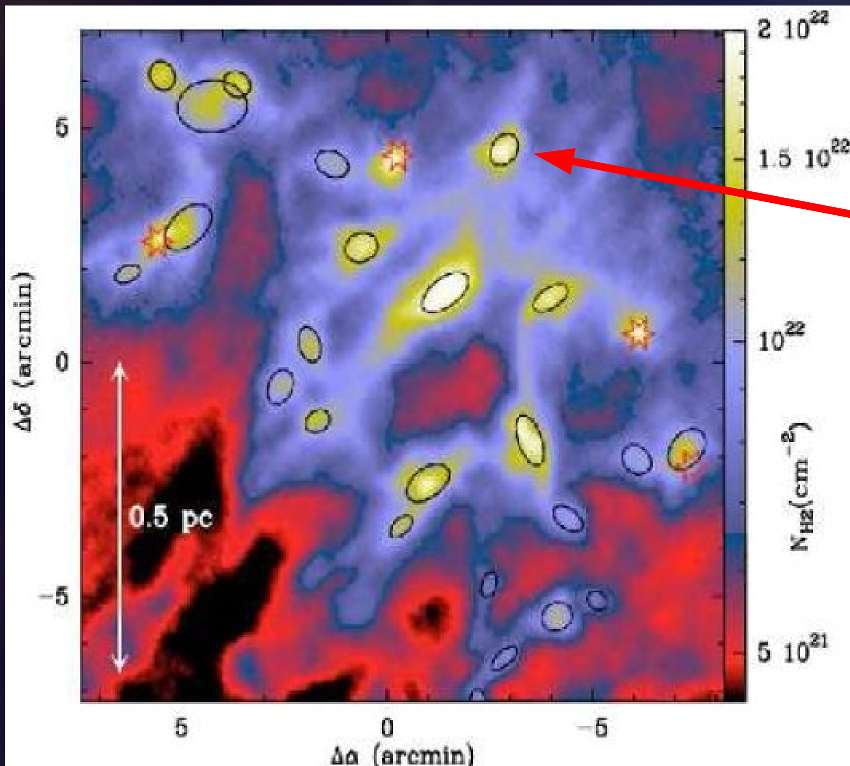
Könyves et al., in prep.

protostellar core





DEFINITION OF A CORE

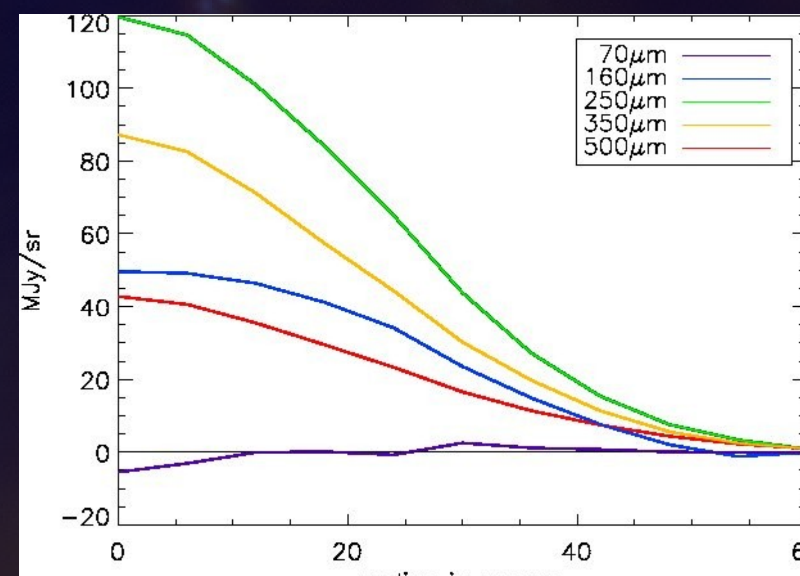


Close up column density image of starless cores and protostars in Aql.

A core:

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

(e.g. Myers 1983; Ward-Thompson et al. 1994; André et al. 2000; di Francesco et al. 2007; Sousbie 2011).

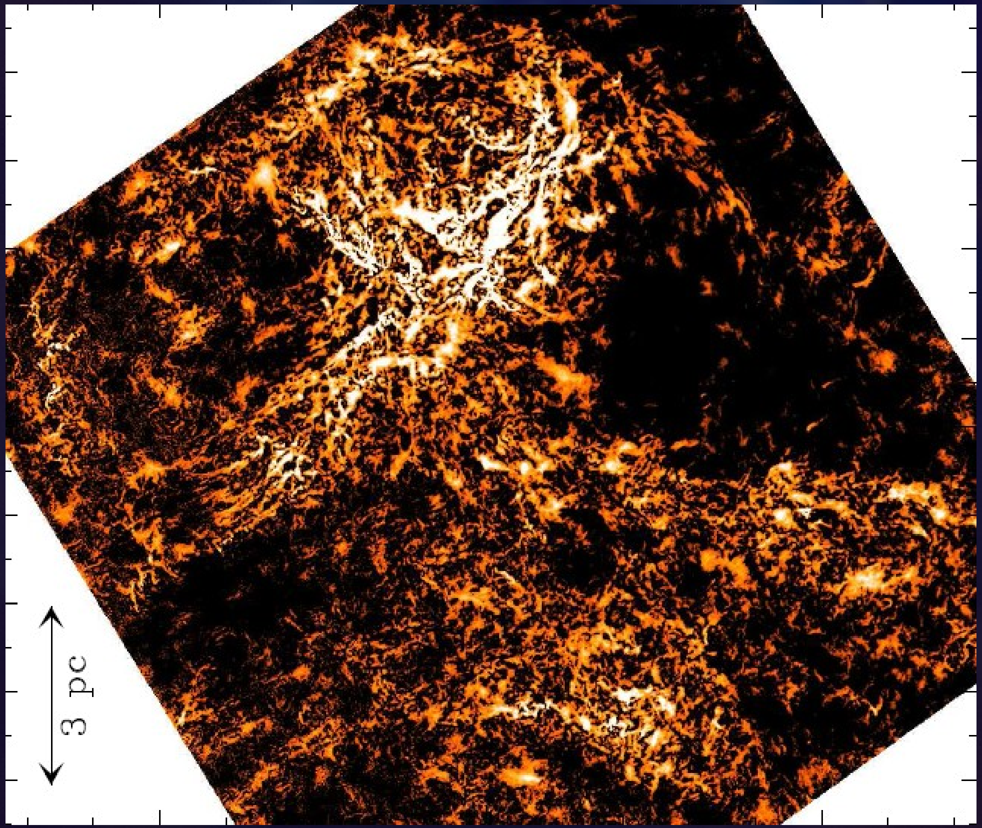


Radial intensity profiles returned by *getsources* for the starless core marked by arrow.

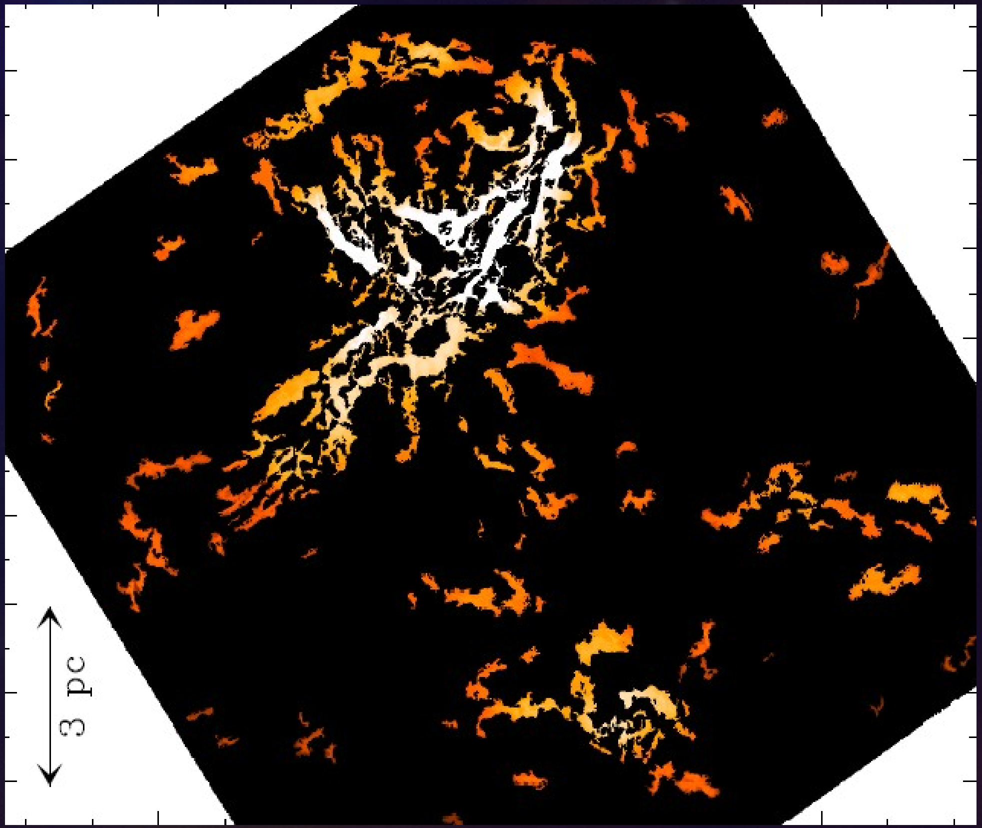
N_{H2} FILAMENTS

Column density filaments

Curvelet (Starck et al. 2003)



Getfilaments (Men'shchikov 2013)



N_{H2} FILAMENTS

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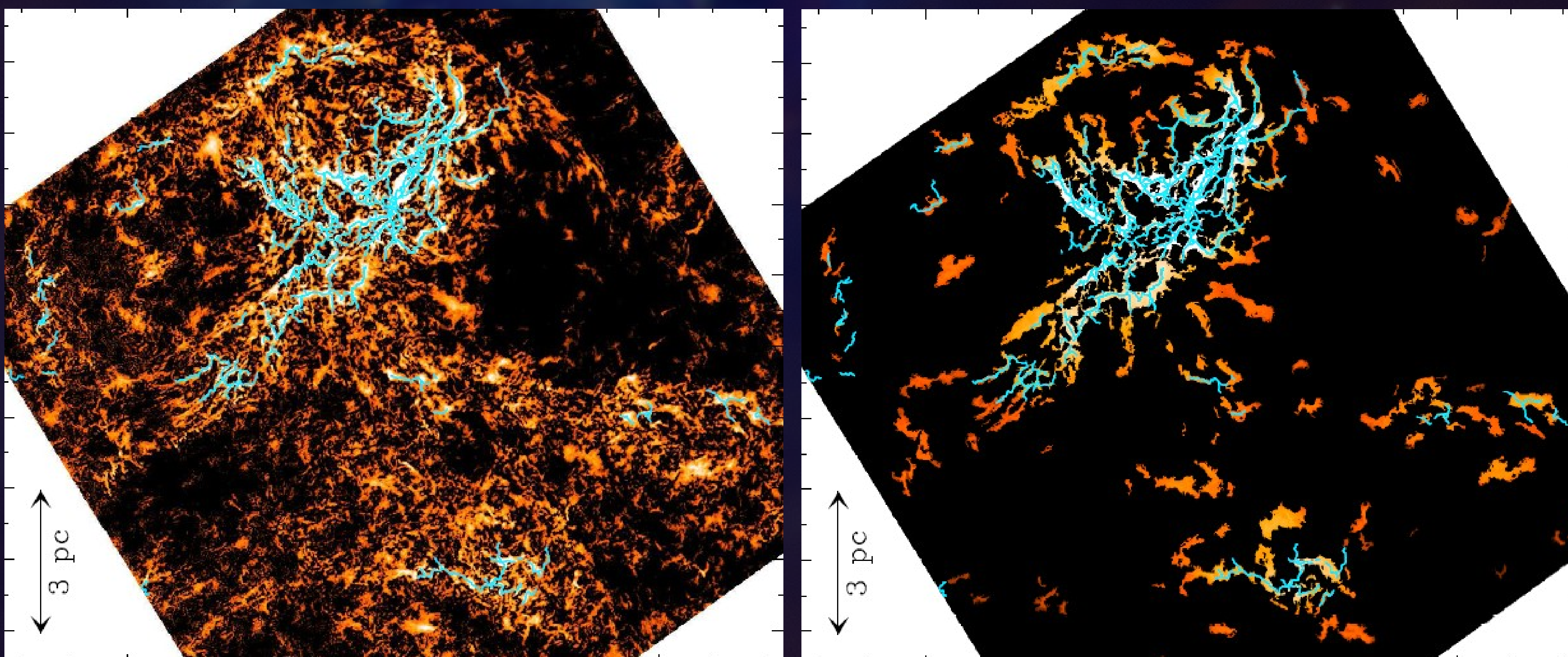

HGBS: AQUILA

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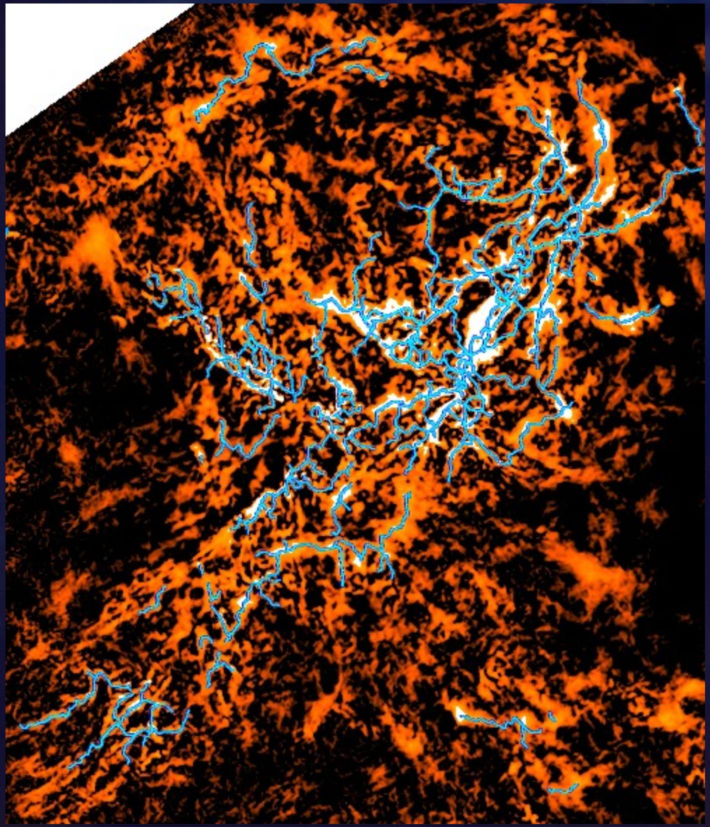
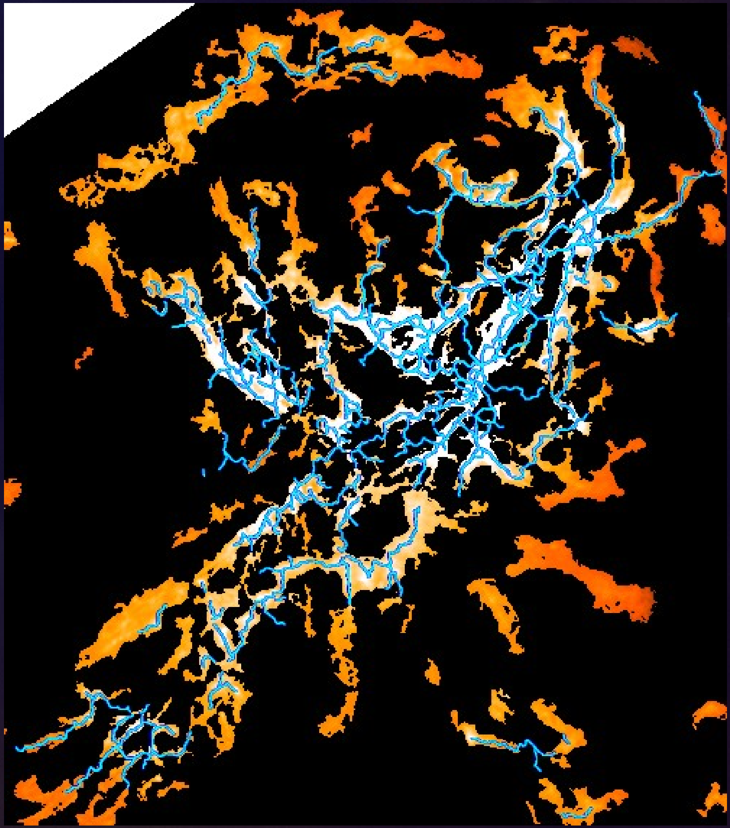


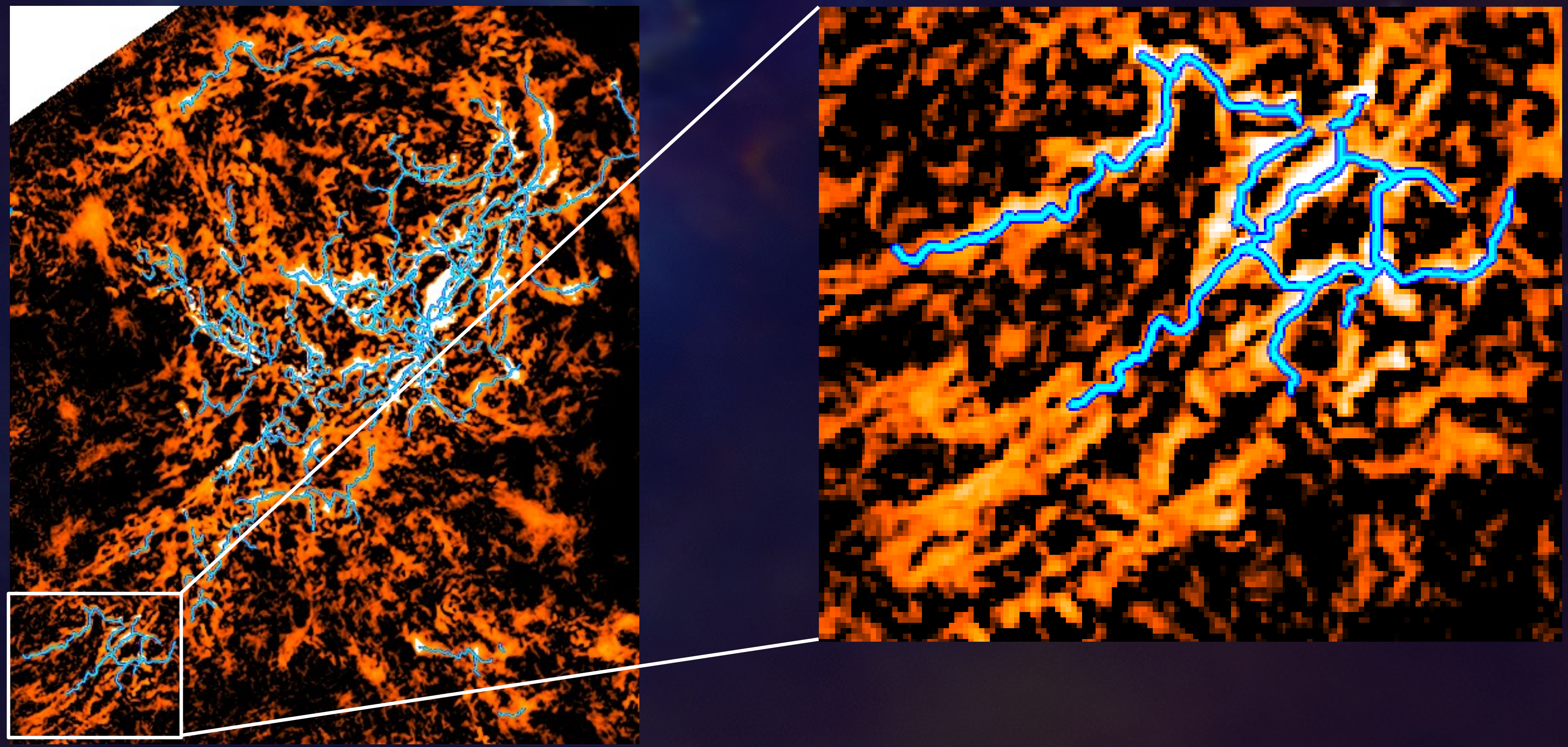


DEFINITION OF A FILAMENT

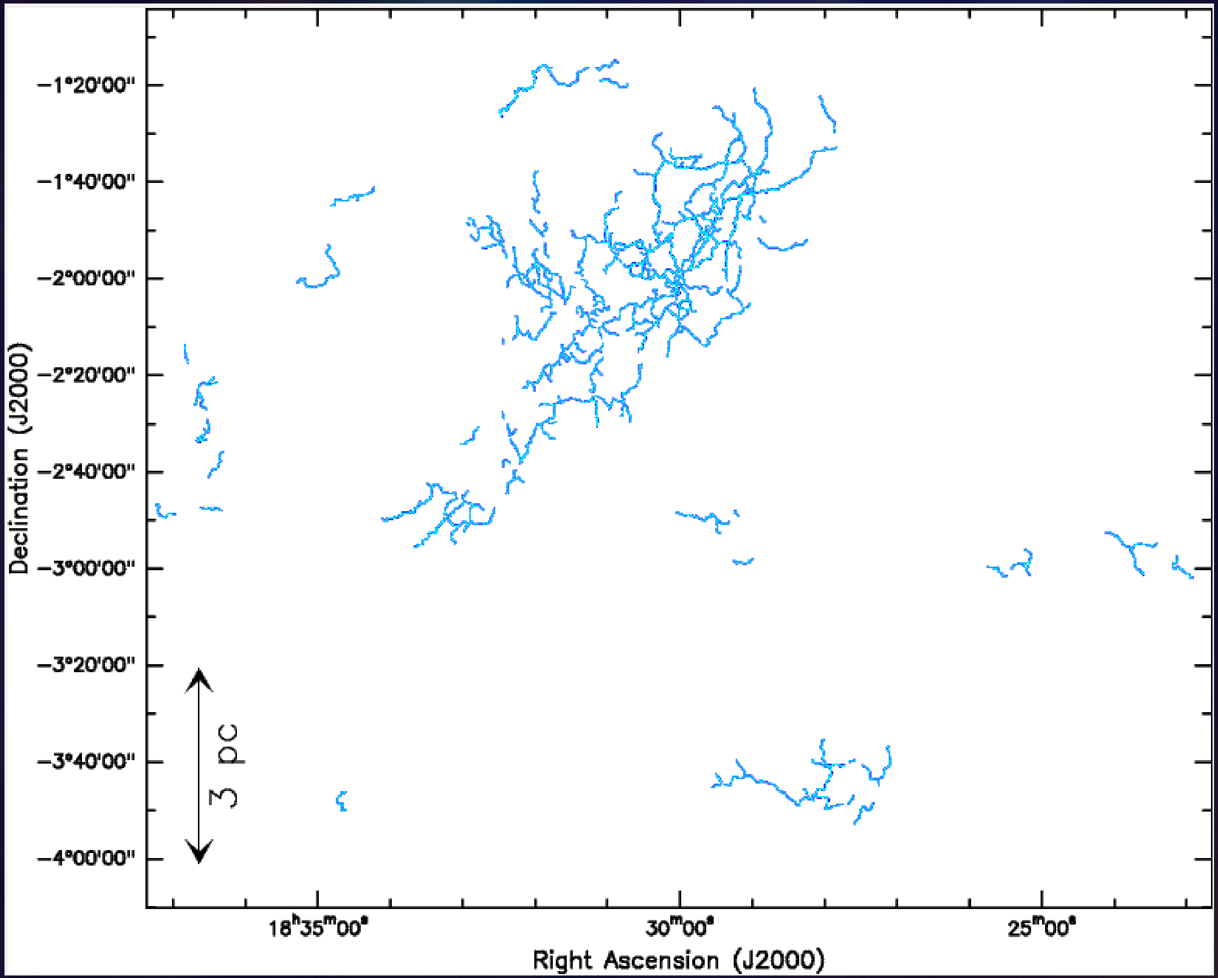
A filament:

- any elongated N_{H2} structure
- with aspect ratio ≥ 5-10
- significantly denser than its surroundings

Filament skeletons in the Aquila cloud, seen in column density (curvelet component).



Footprints of filaments



Footprints created from the DisPerSE skeleton

– – 0.1 pc
Arzoumanian et al. (2011)

– – 2 x 0.5 pc
Palmeirim et al. (2013)

N_{H2} FILAMENTS

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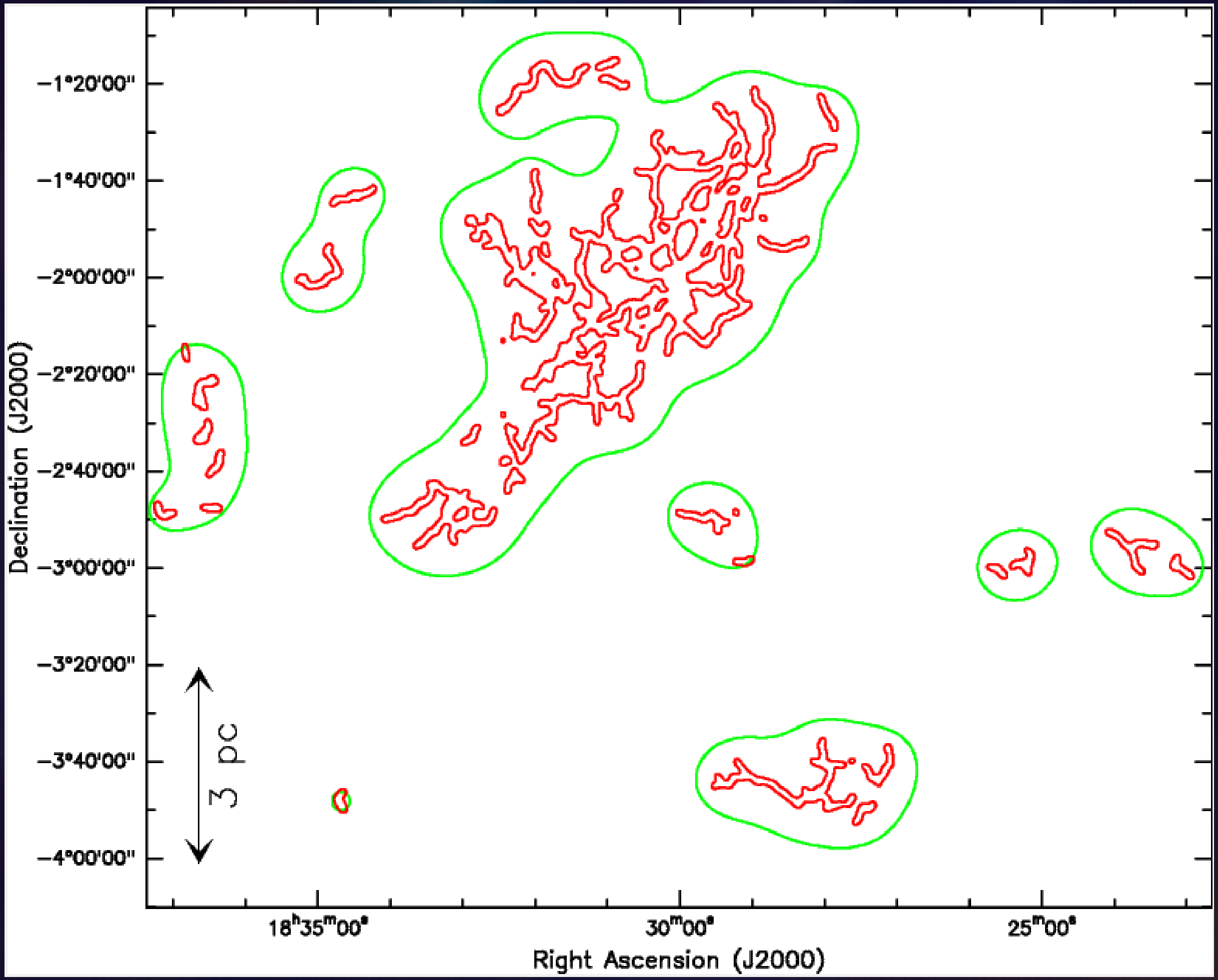

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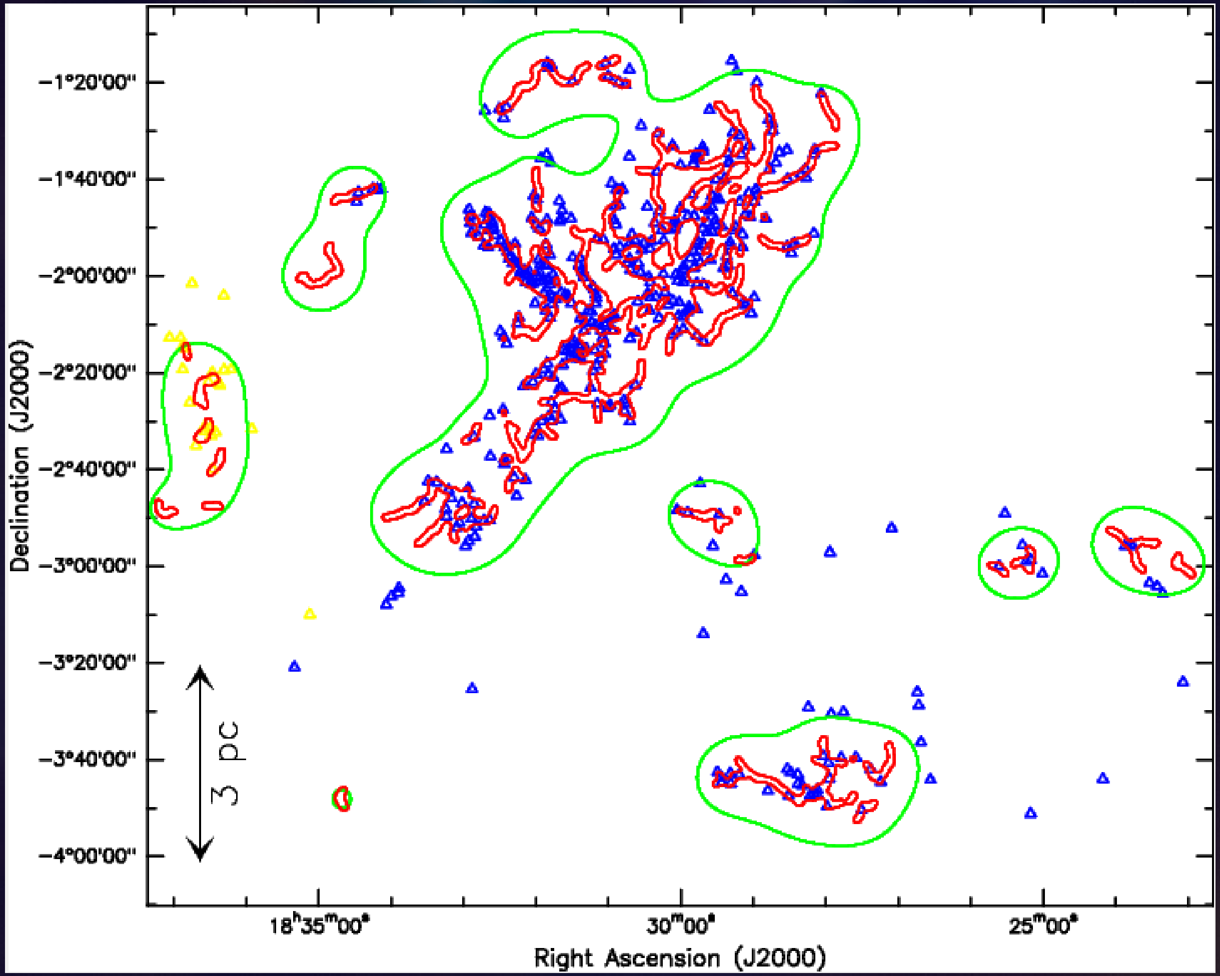
Spatial distribution of cores & association with filaments

$75\ \%^{+15\ \%}_{-5\ \%}$ of the bound cores found ON filaments



Filamentary structure is strongly correlated with the spatial distribution of compact dense cores. (Könyves et al., in prep.)

Filaments likely play a role in the SF process (André et al. 2014 for a recent review)

In Orion-A / L1641:
71% of prestellar cores are ON filaments (Polychroni et al. 2013)

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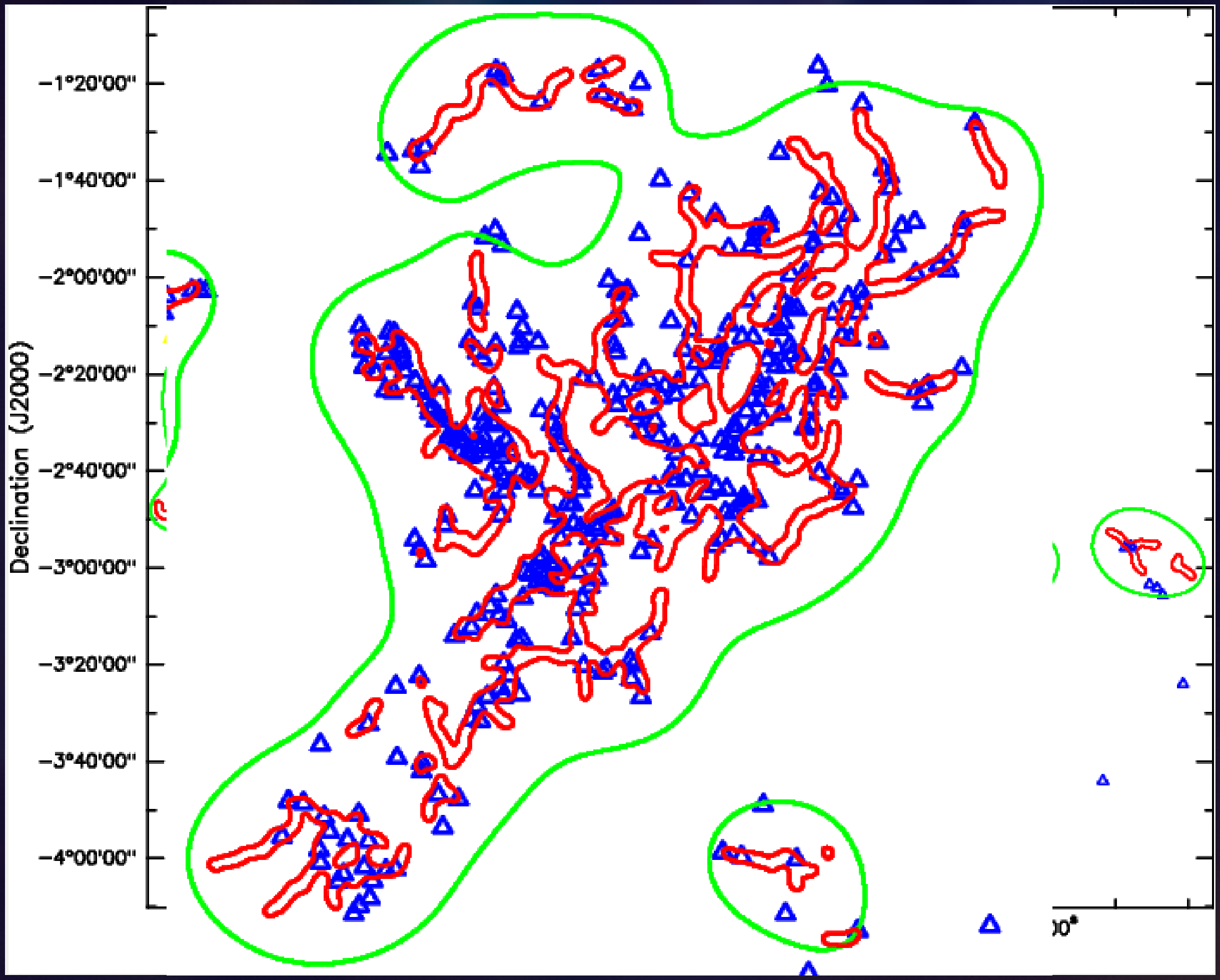

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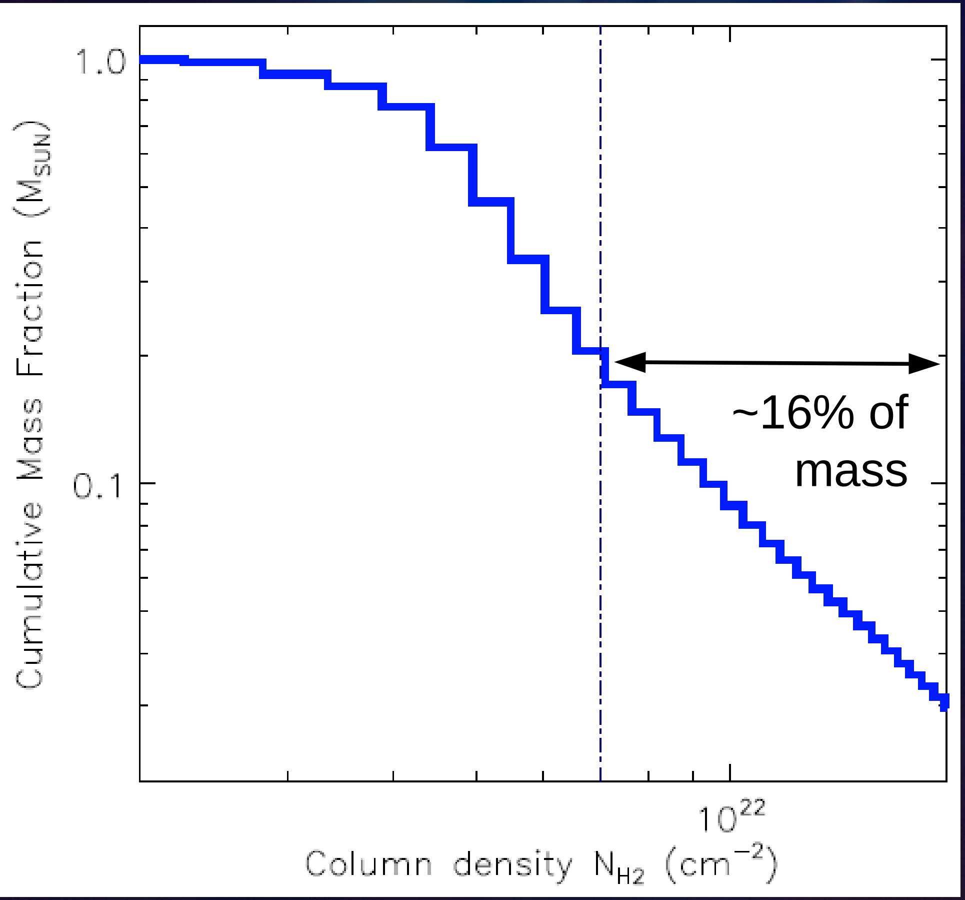
MASS OF THE CLOUD

Distribution of mass in the cloud



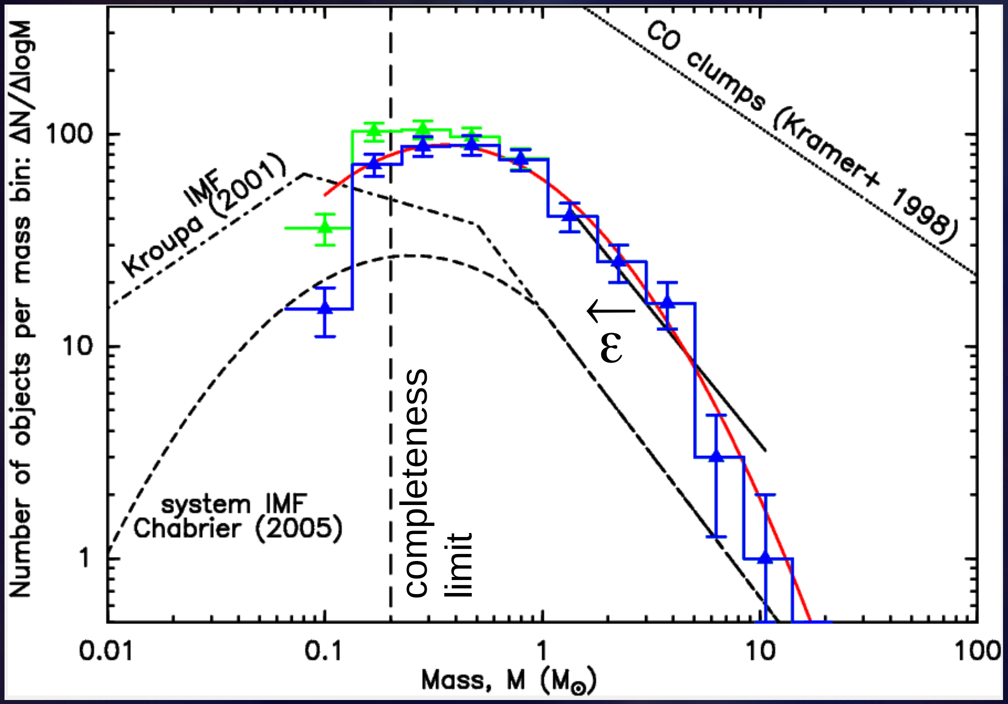
M_{cloud} ~ 26 000 $M_\odot$

> A_V ~ 7–8: $M_{dense\ mat.}$ ~ 4 200 $M_\odot$ (~16%)

Above which ~85% of the cores are found (André et al. 2011, 2014; Könyves et al. 2014 in prep.).

Normalized cumulative mass fraction

Close relationship between the prestellar CMF and the stellar IMF



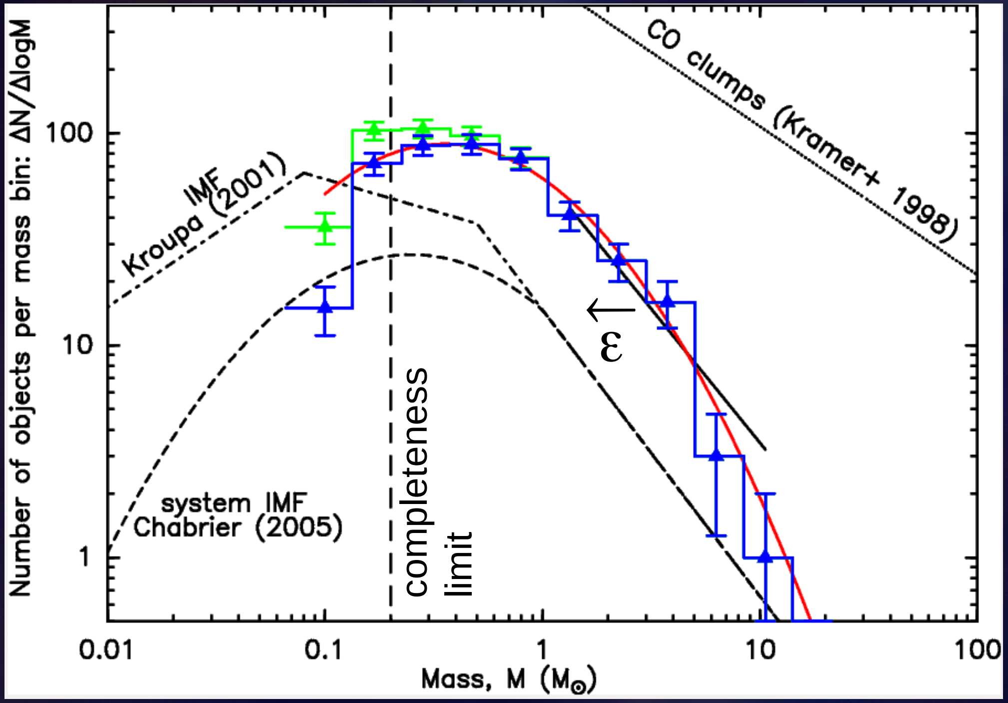
Differential mass function of ~650 starless cores and ~450 prestellar cores in Aquila.

- Lognormal fit peaks at 0.5±0.1 $M_\odot$
- fitted power-law: $dN/d\log M \propto M^{-1.26\pm0.27}$

André et al. 2010
Könyves et al. 2010
Könyves et al., in prep.

- $M_{*sys} = \varepsilon_{core}\, M_{core}$, $\varepsilon_{core} \sim 30–40$ %
- Gravitational fragmentation of supercrit. filaments produces the CMF peak. (Larson 1985)
- $f_{M_{pre}} \sim 15$ % (above $A_V \sim 8$ mag)

Close relationship between the prestellar CMF and the stellar IMF



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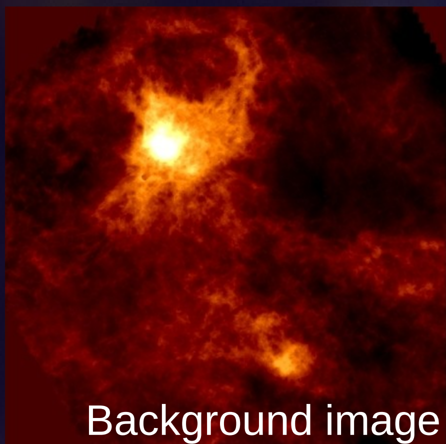
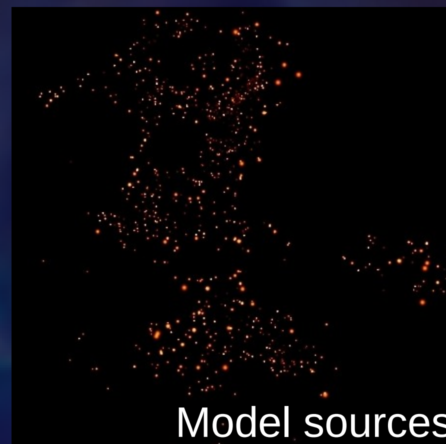
Accuracy of our mass estimates:

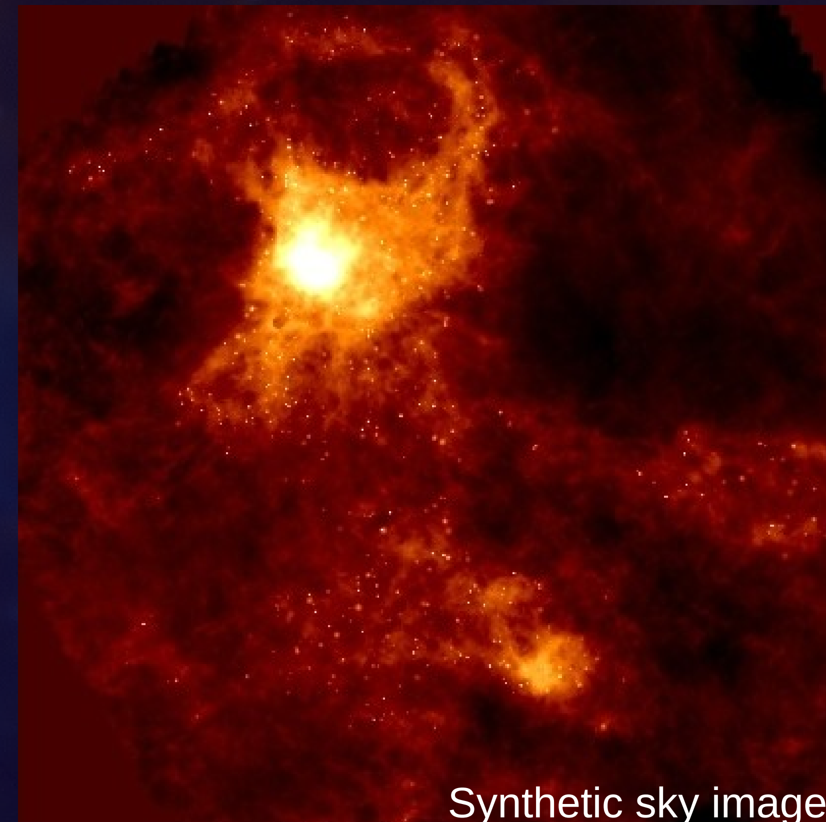
- A factor of 2 (dust opacity)
- Underestimation by ~30–40 % (LOS temperature effects)

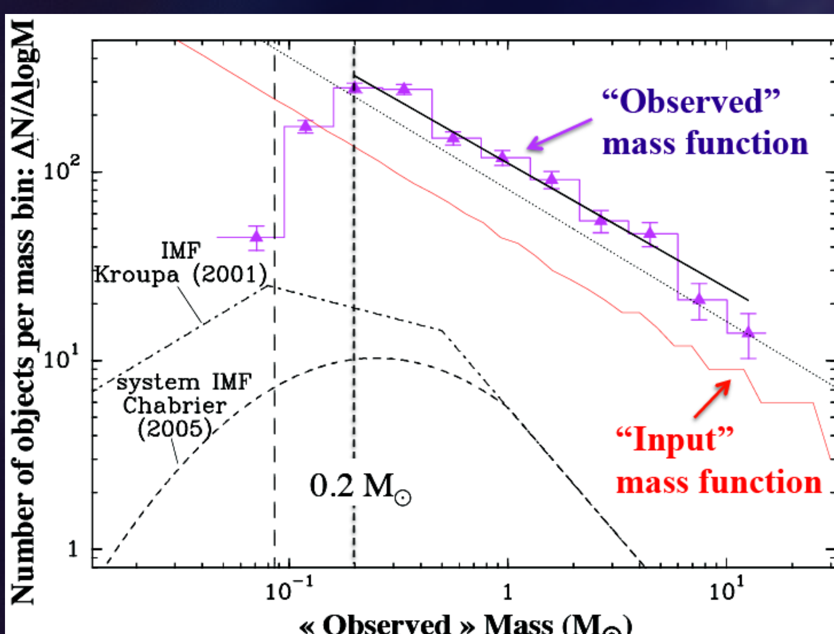
HGBS: AQUILA

COMPLETENESS LIMIT


Background image

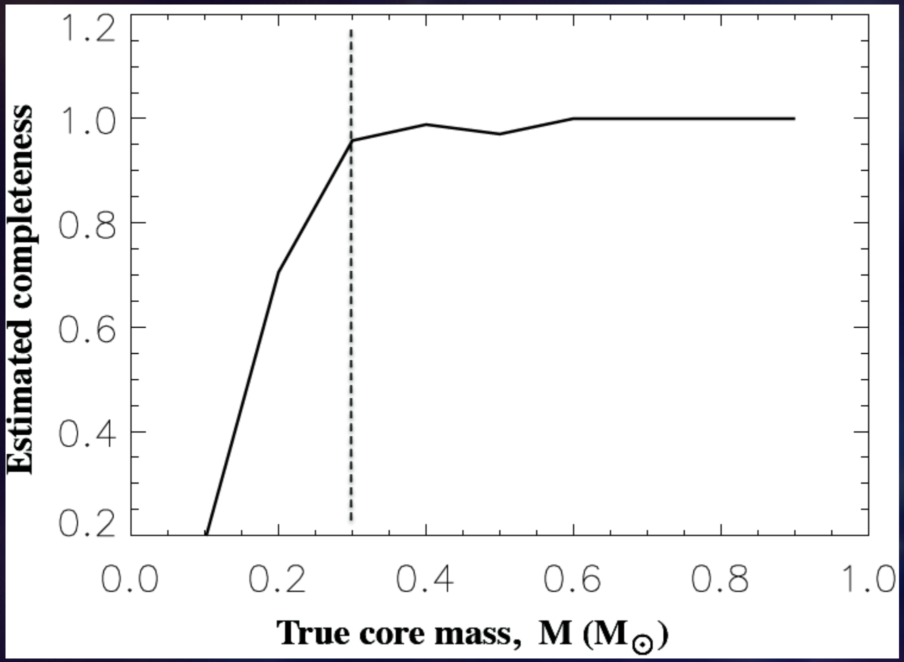

Model sources


Synthetic sky image

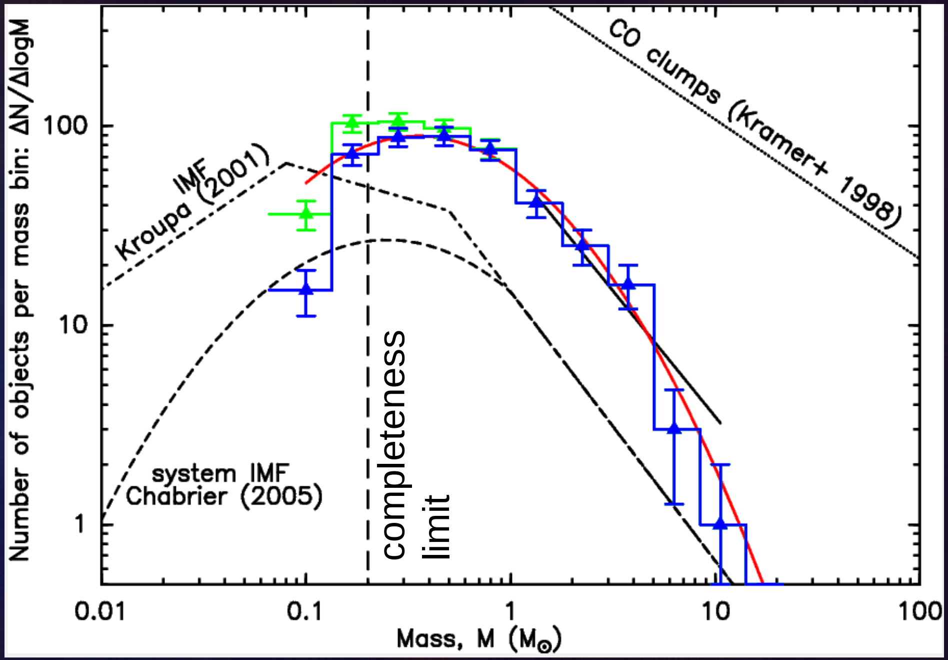


Observed vs. true mass function of the model cores.

COMPLETENESS LIMIT



Completeness curve of the Aql prestellar cores, estimated from M-C simulations.



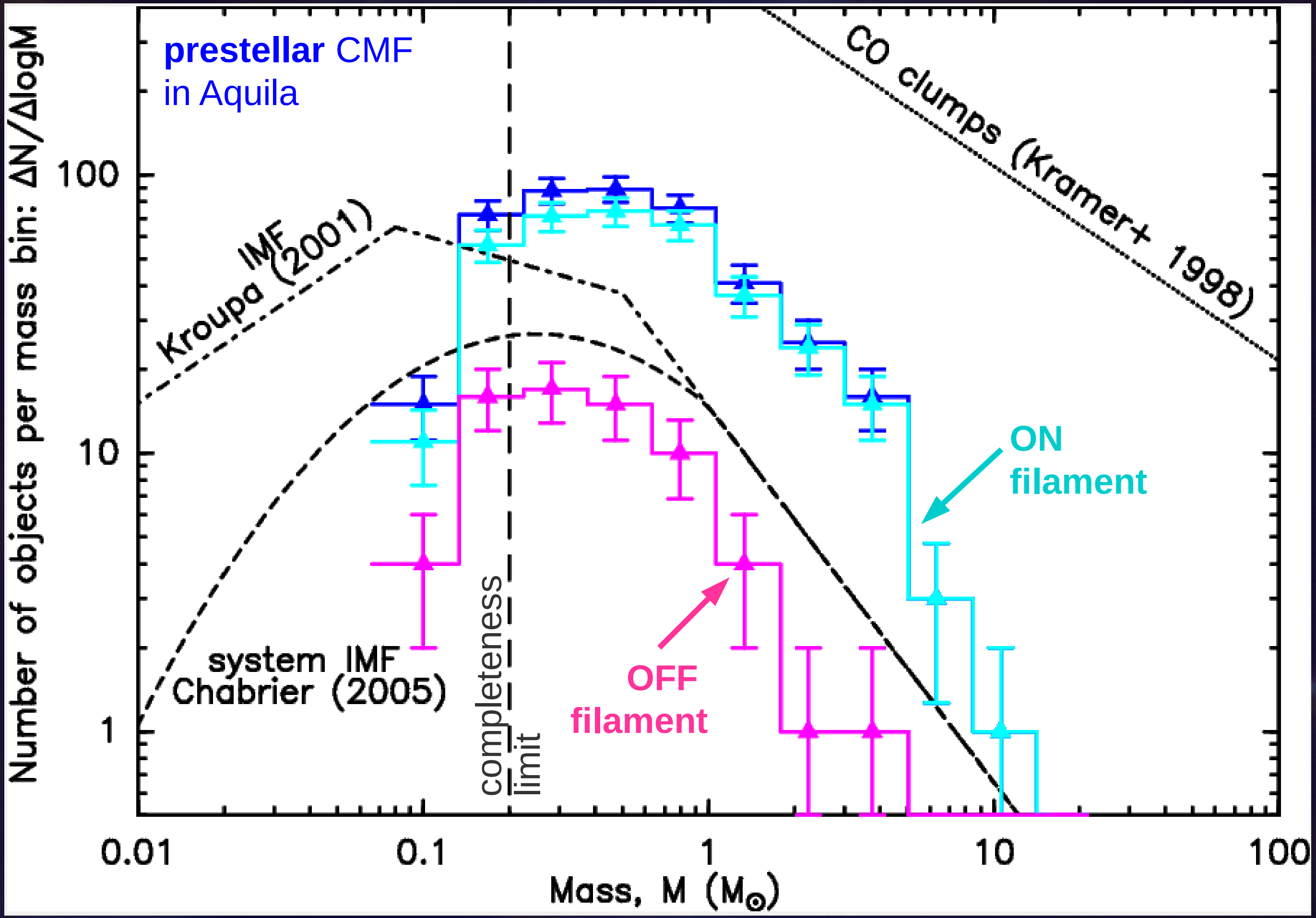
♥ **95% completeness** of observed prestellar cores above **~0.2 $M_{\odot}$**

But... the source completeness is background dependent!

Könyves et al., in prep.

HGBS: AQUILA

CORES SITTING ON-, OFF FILAMENTS



Differential mass function of ~450 prestellar cores in the entire Aquila field

André et al. 2010
Könyves et al. 2010
Könyves et al. In prep.

In Orion-A / L1641 Polychroni et al. (2013) found that prestellar cores sitting ON filaments seem to be more massive than the OFF-filament ones.

…there is no indication of this in Aquila.
(Environment dependent feature, or related to completeness issues...)

LIFETIME ESTIMATES

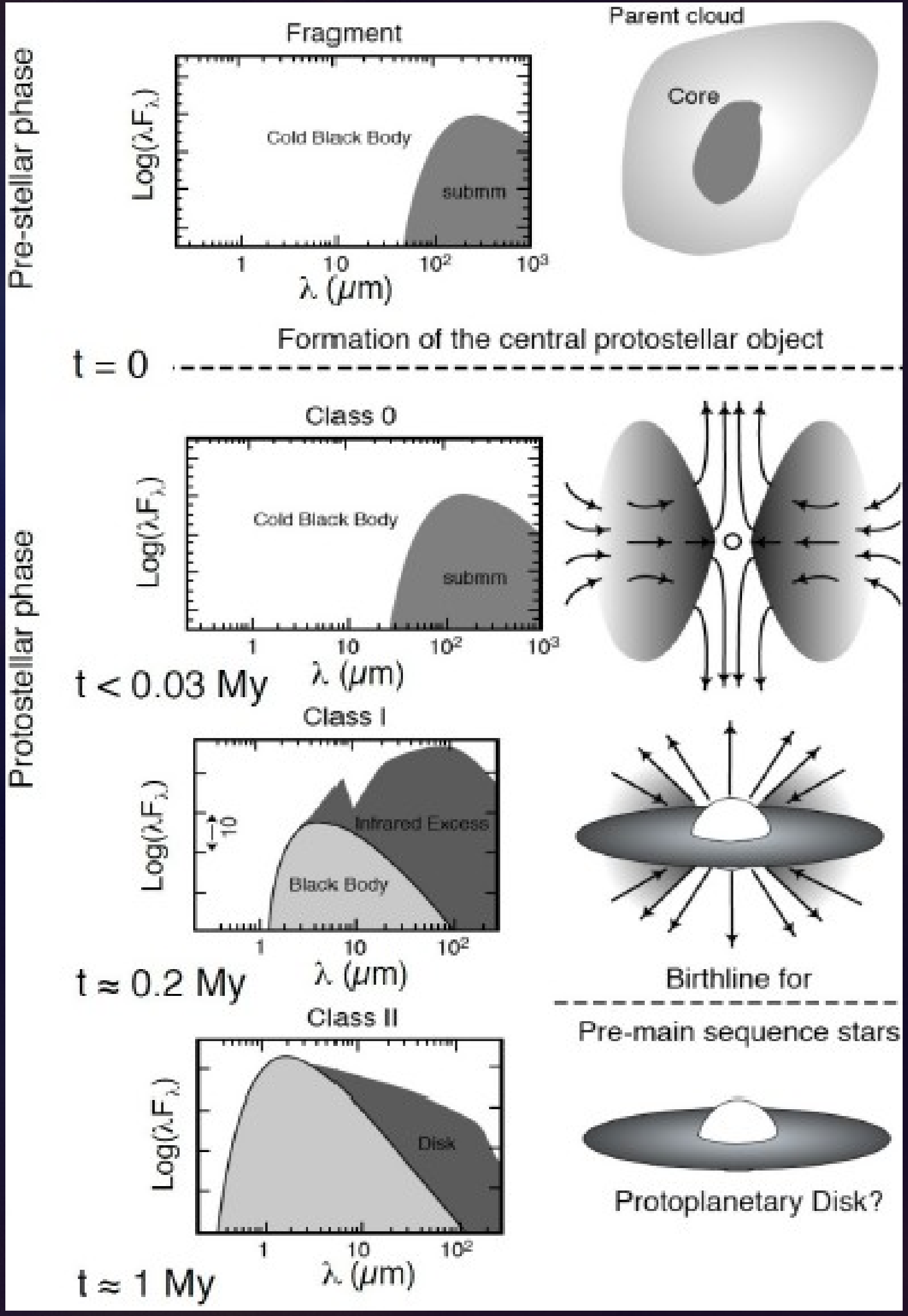
Core lifetime estimates

Based on number ratios:

- ♠ ~400 *Herschel* prestellar cores
  (t ~ 1 Myr)
- ♠ ~200 *Herschel* Class0/ClassI protostars
  (t ~ 0.5 Myr)
- ♠ ~800 *Spitzer* (Class II, YSOs)
  (t ~ 2 Myr, Evans et al. 2009)

Könyves et al., in prep.

Evolutionary sequence of solar-type stars



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

Star formation rate and implications

We can infer from *Herschel*/Aquila data:

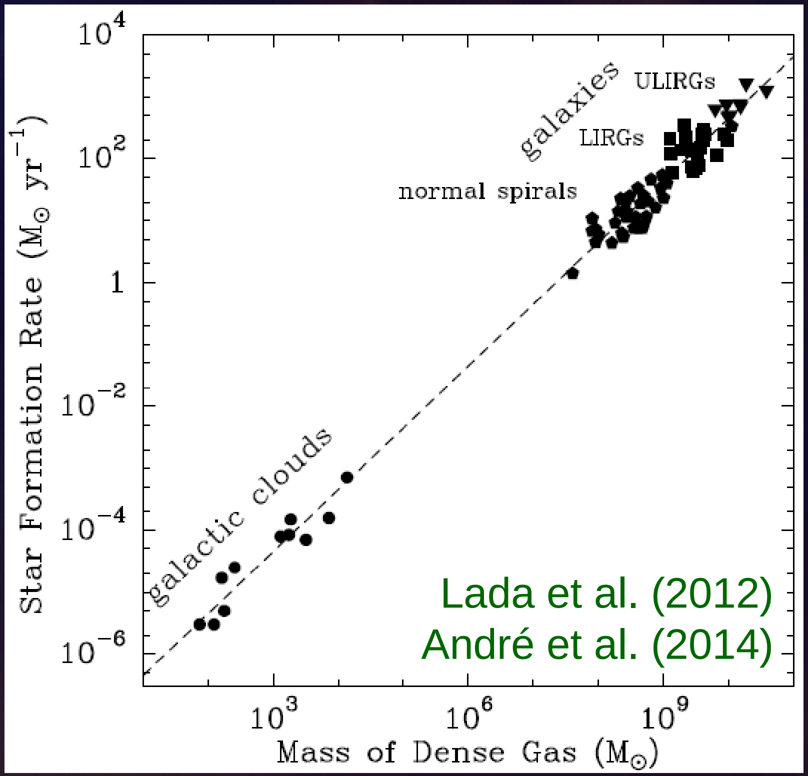
- ε_{core} ~ 30 %
- f_{pre} ~ 15 %
- t_{pre} ~ 10^6 yr

⇨ $SFR / M_{dense} = f_{pre} \times \varepsilon_{core} / t_{pre} \sim 4.5 \times 10^{-8}\ yr^{-1}$

Similar independent estimates:

Nearby clouds – Lada et al. (2010), Heiderman et al. (2010)

Galaxies – Gao and Solomon (2004)



Studies: Aquila – nearby clouds – galaxies

Derived star/core formation thresholds are similar too:

$A_v \sim 8$ or $\Sigma_{gas,\,bg} \sim 130\ M_\odot\ pc^{-2}$

⇨ **Universal star formation picture ?**

Thank You!