## “Star-forming regions, clumps, and cores”

# Star formation process at intermediate scales: from clumps to cores

IPAG

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**Lecture 1 (FM): Cores**
**Lecture 2 (FM): Cores within protoclusters/clumps**
**Lecture 3 (AT): Star-forming regions**
**Lecture 4 (AT): Clumps**

Observational Projects: HOBYS, W43 HERO, ALMA IMF

# Outline / Part I

1. Introduction
    - The necessarily complex definition of cores
2. Algorithms to identify large populations of cores
3. Variety of environment in the MW
4. Core mass functions (CMFs)
5. The resulting IMF…

# Summary of Lecture 1

Cores are assumed to be the direct progenitors of stars

Observationally, they are gravitationally bound small-scale (0.02-0.1 pc) fragments.

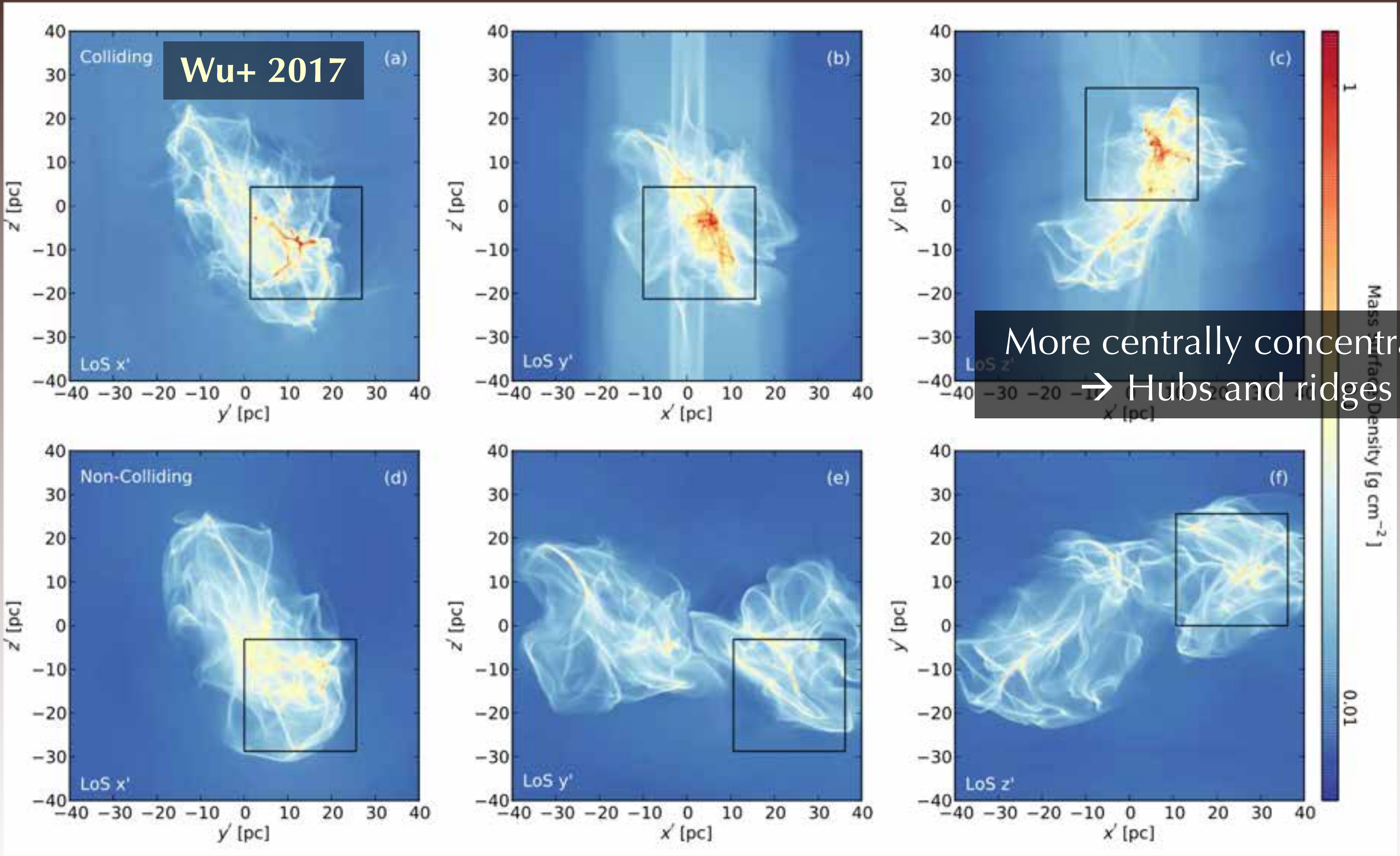
They are mainly studied in the FIR-mm wavelength range.

Prestellar cores, on the verge of collapse, evolve into protostars.

Caveats: Cores form in multi-fractal clouds, which may be traversed by hierarchical inflowing gas.

**Lecture 2**
**“Demography of cores in protoclusters to constrain SF”**

# Quasi-static versus dynamical pictures



**Wu+ 2017**

More centrally concentrated
→ Hubs and ridges

Numerical simulations of kpc-pieces of a galaxies argue for a hierarchy of cloud structures and inflows (Hennebelle2018; Vazquez-Semadeni+2019; Padoan+2020)

# Specificity of the formation of high-mass stars

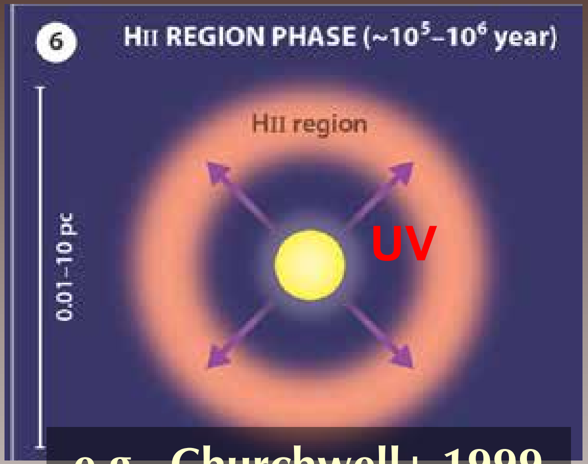
- HII regions → Accretion barrier?

Initial high-mass star formation models:

- Monolithic collapse of a turbulent core (McKee & Tan 2003)
- Competitive accretion within a protocluster (Bonnell & Bate 2006)

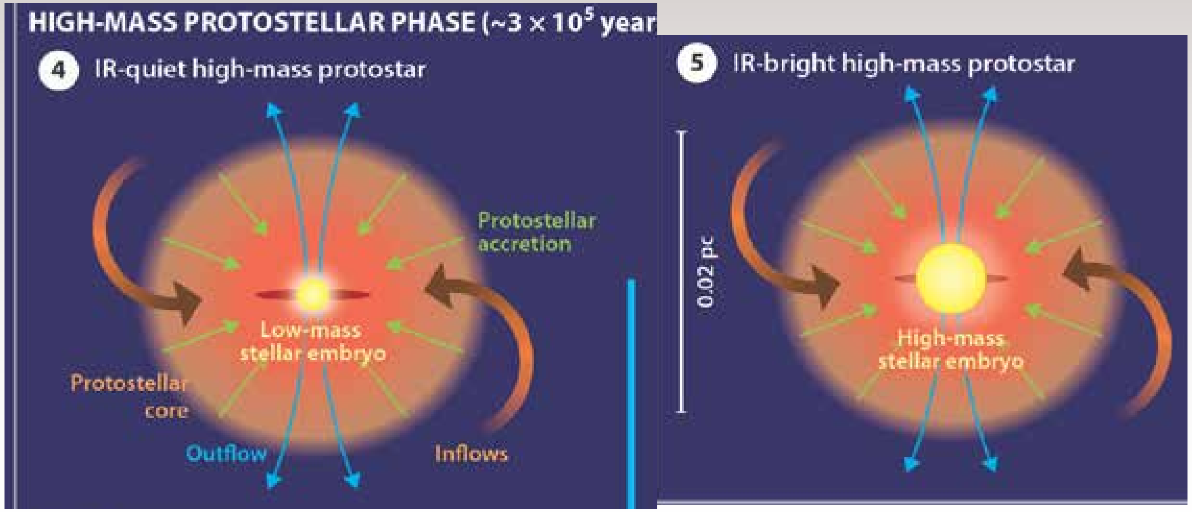
- Gas inflow and lack of prestellar cores → Dynamical process?

- Sporadic and non-spherical accretion streams (e.g., Smith+ 2009; Vazquez-Semadeni+ 2017)



e.g., Churchwell+ 1999

**Ionization & expansion**

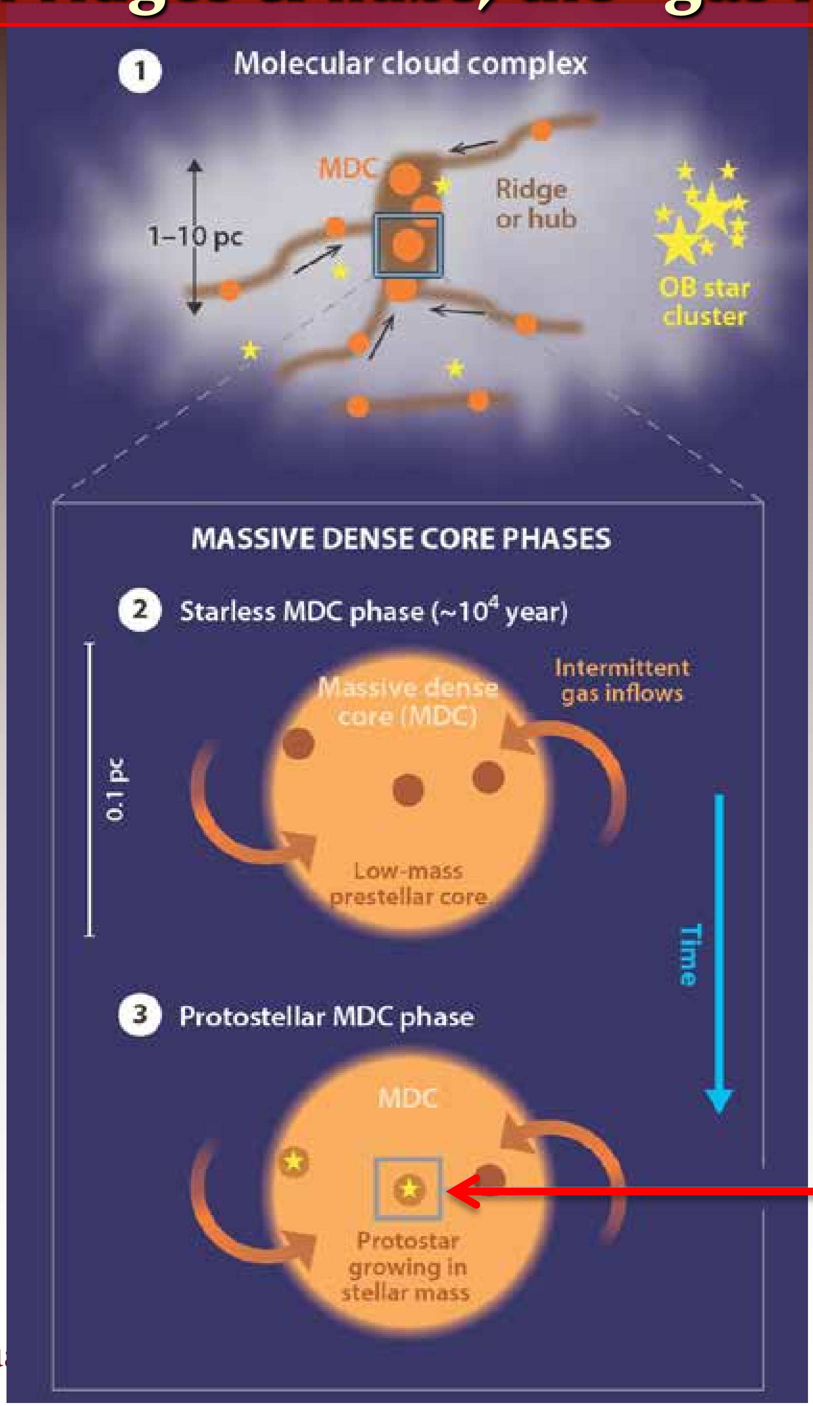


**Protostellar accretion and ejection (strong and variable)**

**Luminous (>$10^5$ $L_\odot$) phase**
(e.g., Beuther+ 2002a-b)

**IR-quiet ($10^2$ $10^4$ $L_\odot$) phase**
(e.g., Motte+ 2007)

# In ridges & hubs, the "gas reservoir" is not a single "core"



- Gas is accreted onto ridges, clumps, cores, and finally stellar embryos.

⇒ Accretion cascade model

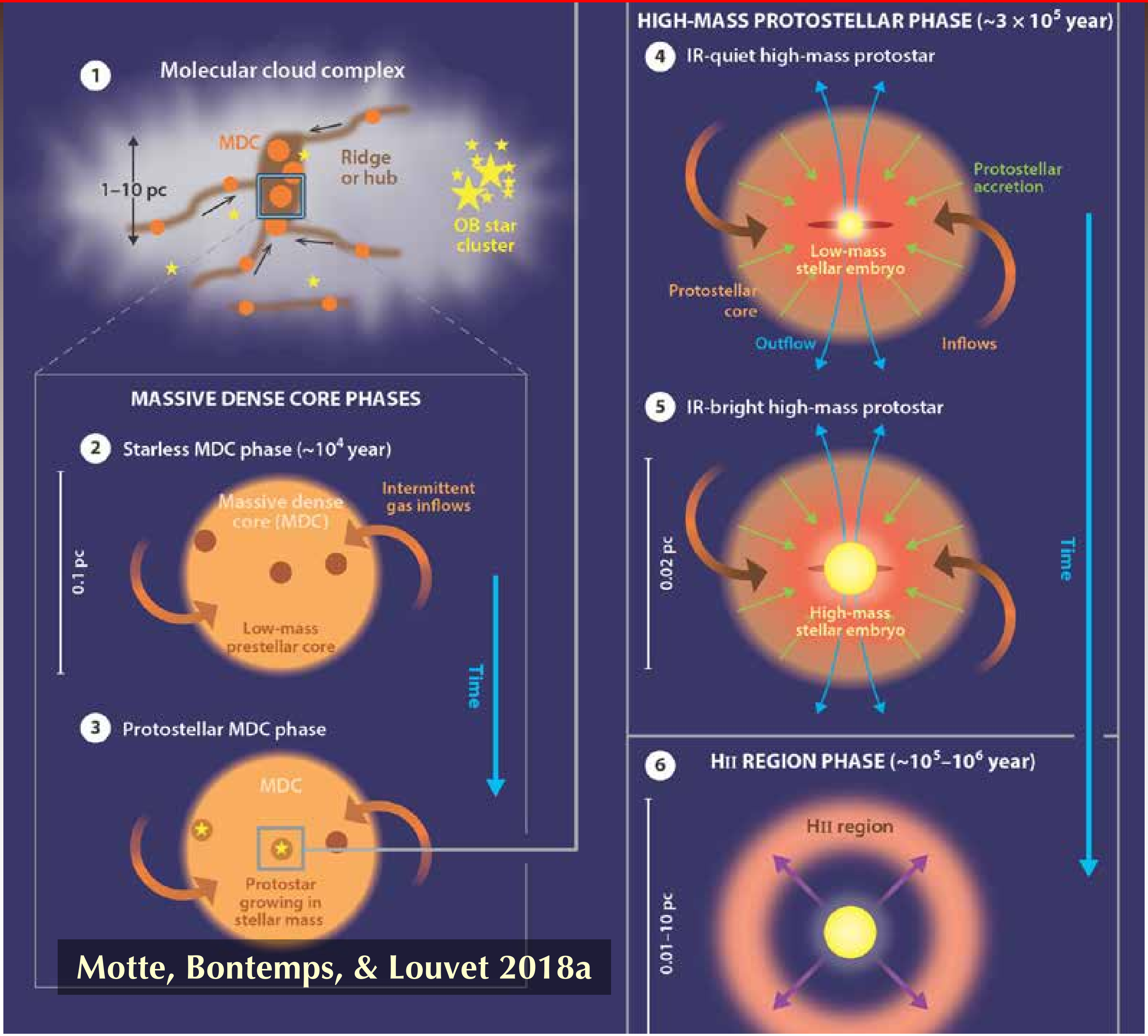
- Stars, cores, and clumps simultaneously grow from the mass of their parental ridge.

⇒ "clump-fed" model

No need for a high-mass prestellar core phase

Low-mass prestellar cores become protostars with increasing mass

# Evolutionary scenario for the formation of high-mass stars



Motte, Bontemps, & Louvet 2018a

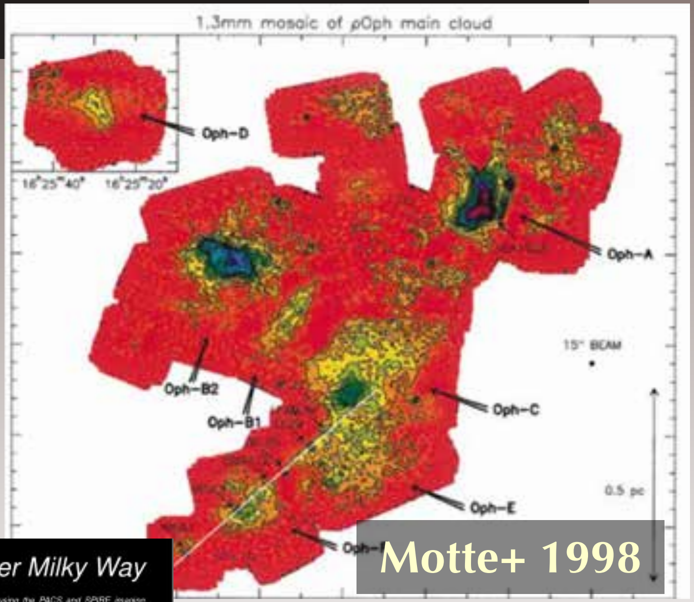
# Outline / Part II

1. Introduction
2. Algorithms to identify large populations of cores
   - Unbiased surveys of cores
   - Core extractions techniques
3. Variety of environment in the MW
4. Core mass functions (CMFs)
5. The resulting IMF…

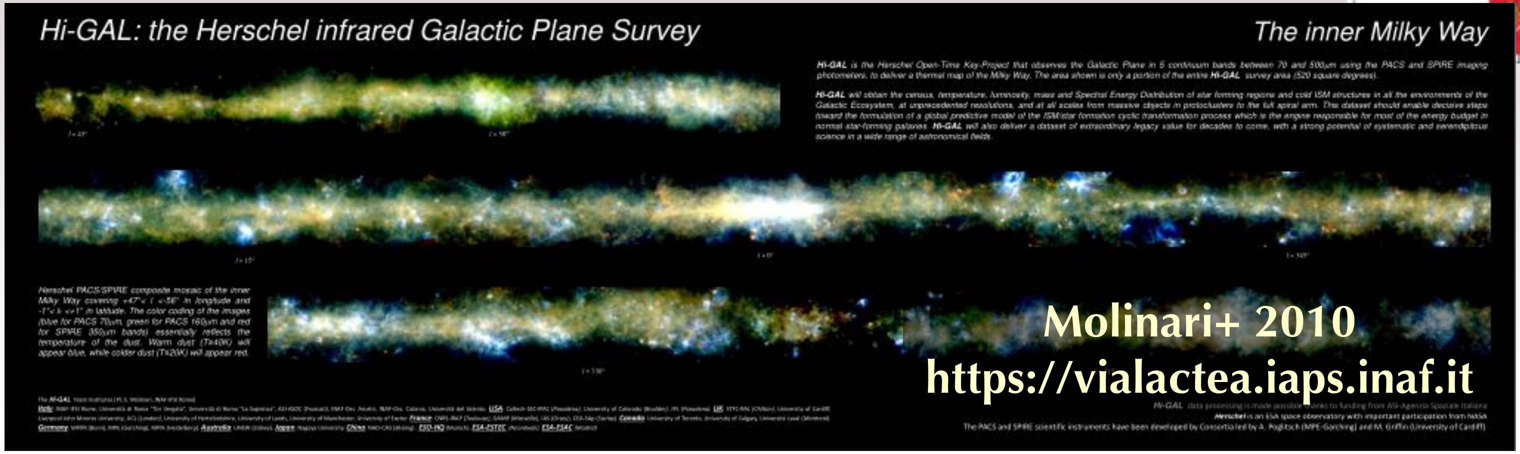
# Surveys of cores

2000-2010: Ground-based surveys of nearby clouds (< 500 pc)
@ (sub)mm wavelengths (Motte+ 1998; Testi & Sargent 1998; Stanke+ 2006; Enoch+ 2008; …)

>2010: *Herschel* surveys (databases)
Gould Belt: 100-500 pc clouds (André+ 2010)
HOBYS: 1-3 kpc clouds (Motte+ 2010)
Hi-GAL: Galactic plane (Molinari+ 2010)
PGCC: Planck clumps (Juvela+ 2010)



Motte+ 1998



Hi-GAL: the Herschel infrared Galactic Plane Survey

The inner Milky Way

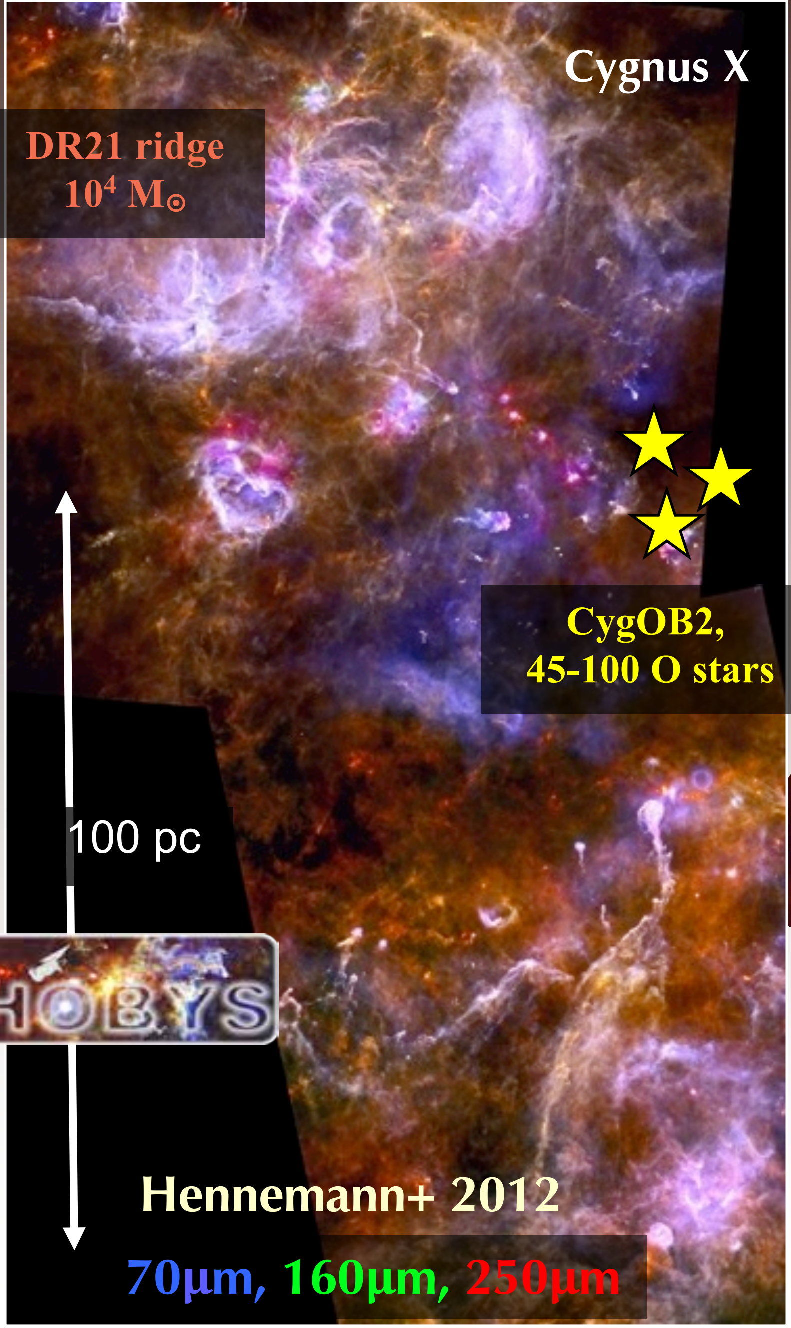
**Hi-GAL** is the Herschel Open-Time Key-Project that observes the Galactic Plane in 5 continuum bands between 70 and 500μm using the PACS and SPIRE imaging photometers, to deliver a thermal map of the Milky Way. The area shown is only a portion of the entire **Hi-GAL** survey area (520 square degrees).

**Hi-GAL** will obtain the census, temperature, luminosity, mass and Spectral Energy Distribution of star forming regions and cold ISM structures in all the environments of the Galactic Ecosystem, at unprecedented resolutions, and at all scales from massive objects in protoclusters to the full spiral arm. This dataset should enable decisive steps toward the formulation of a global predictive model of the ISM/star formation cyclic transformation process which is the engine responsible for most of the energy budget in normal star-forming galaxies. **Hi-GAL** will also deliver a dataset of extraordinary legacy value for decades to come, with a strong potential of systematic and serendipitous science in a wide range of astronomical fields.

Herschel PACS/SPIRE composite mosaic of the inner Milky Way covering +47°< l <-56° in longitude and -1°< b <+1° in latitude. The color coding of the images (blue for PACS 70μm, green for PACS 160μm and red for SPIRE 350μm bands) essentially reflects the temperature of the dust. Warm dust (T≈40K) will appear blue, while colder dust (T≈20K) will appear red.

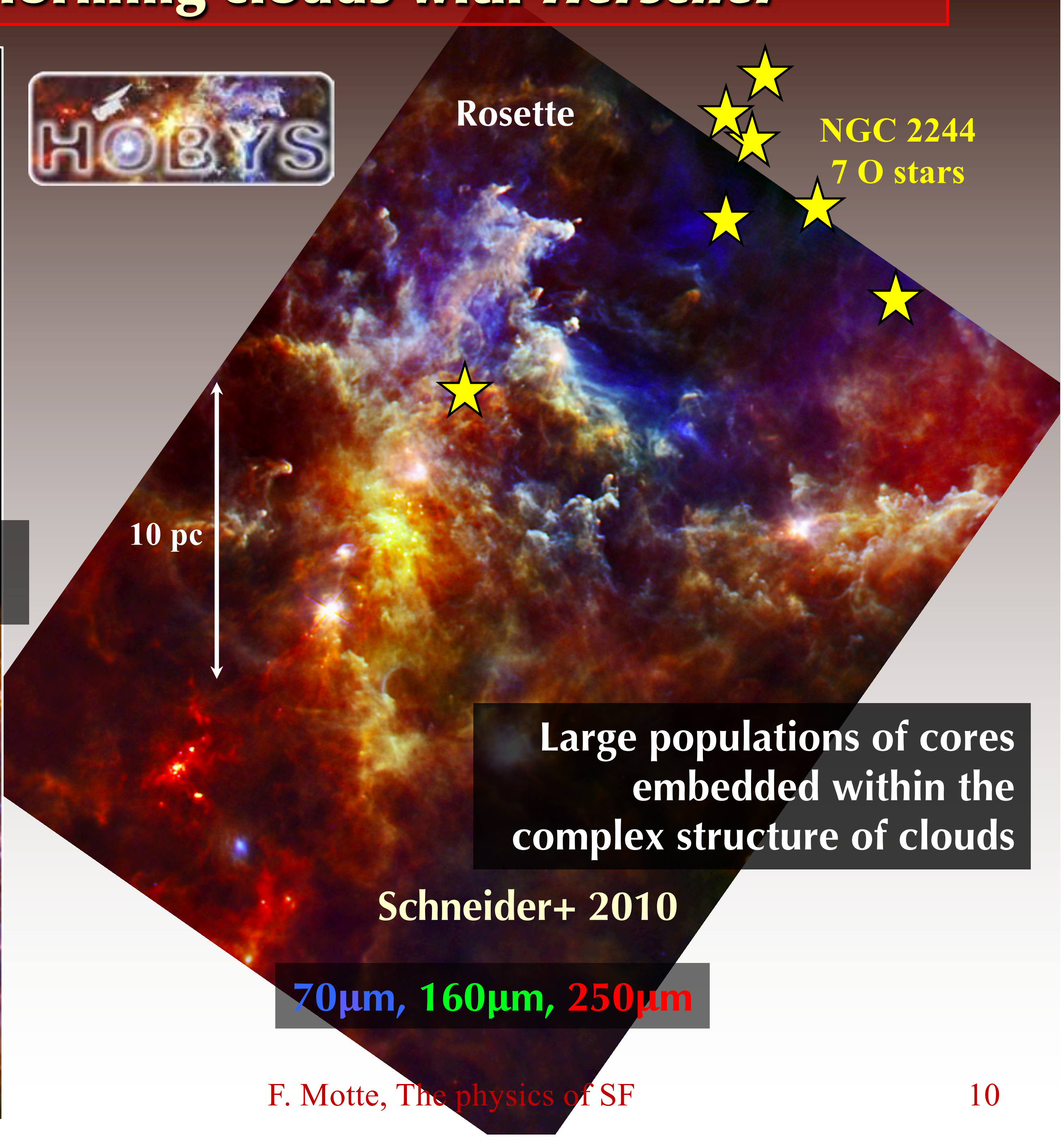
Molinari+ 2010
https://vialactea.iaps.inaf.it

# High-mass star-forming clouds with *Herschel*



Hennemann+ 2012

70µm, 160µm, 250µm



Large populations of cores embedded within the complex structure of clouds

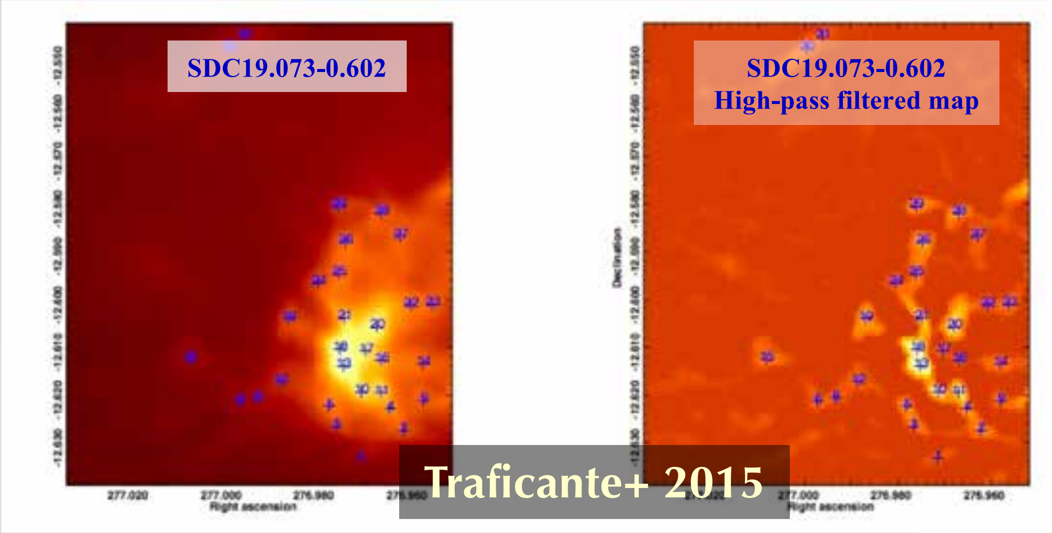
Schneider+ 2010

70µm, 160µm, 250µm

# Initial core extraction techniques

Initial techniques

- Clumpfind (Williams 1994)
  → threshold, 3D contours
- Gaussclump (Kramer+ 1998)
  → multiscale 3D Gaussians



Traficante+ 2015

Peaks in high-pass filtered maps

- MRE-GCL (Motte+ 2007) → Gaussian fits
- Hyper (Traficante+ 2015) → aperture integrations, deblending

Herschel SEDs analysis need either:

- The *SAME* area to integrate flux at all wavelengths (Traficante+ 2015)
- To rescale fluxes assuming an intensity distribution (Motte+ 2010)

# Classical core extraction techniques

Cores identified as clear local peaks

- getsf (Men'shchikov 2021)

  Previously: getsources (Men'shchikov+ 2012) and MRE-GCL (Motte+ 2007)

- CuTEx (Molinari+ 2017) or GExt2D (Bontemps+ prep.)

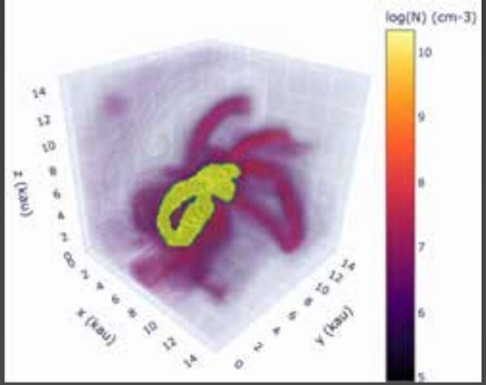
Cores identified as pixels within closed contours

- dendrogram (Rozolowski 2008)

  Previously: Clumpfind (Williams+ 1994)

Cores identified as labelled pixels

- CNN-Extract (Robitaille+ in prep)



Cores identified as Virialized structures: See talk by Simon Chevalier

# Cores extraction with getsf

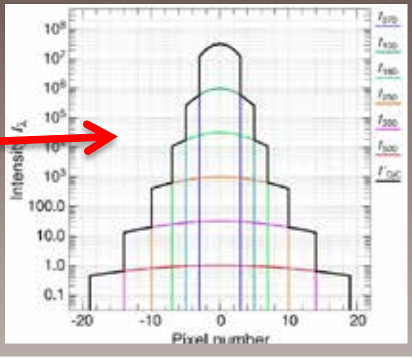
**Men'shchikov+ 2021**

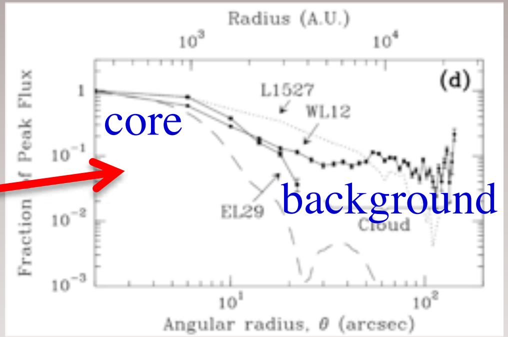
- Getsf decomposes each image into single-scale images.
- Combines all detection images to optimize source detection.
- For each source, it defines the scales and the area over which it emits in the wavelength-combined image.

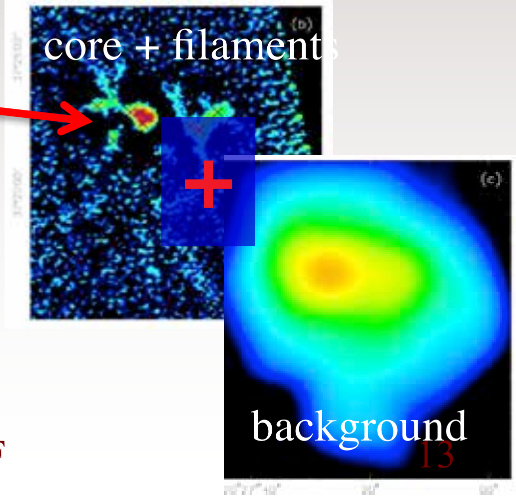
Use multi-resolution images and radial intensity profiles to define core footprints.

- For each source at each wavelength, it estimates and subtract the local background, filaments, and it deblends sources.

⇒ Final table will contain for each source: **a single position** with fluxes and sizes at all wavelengths.







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⇒ Final table will contain for each source: **a single position** with fluxes and sizes at all wavelengths.

Pros:

- Multi-wavelength
- Good source deblending

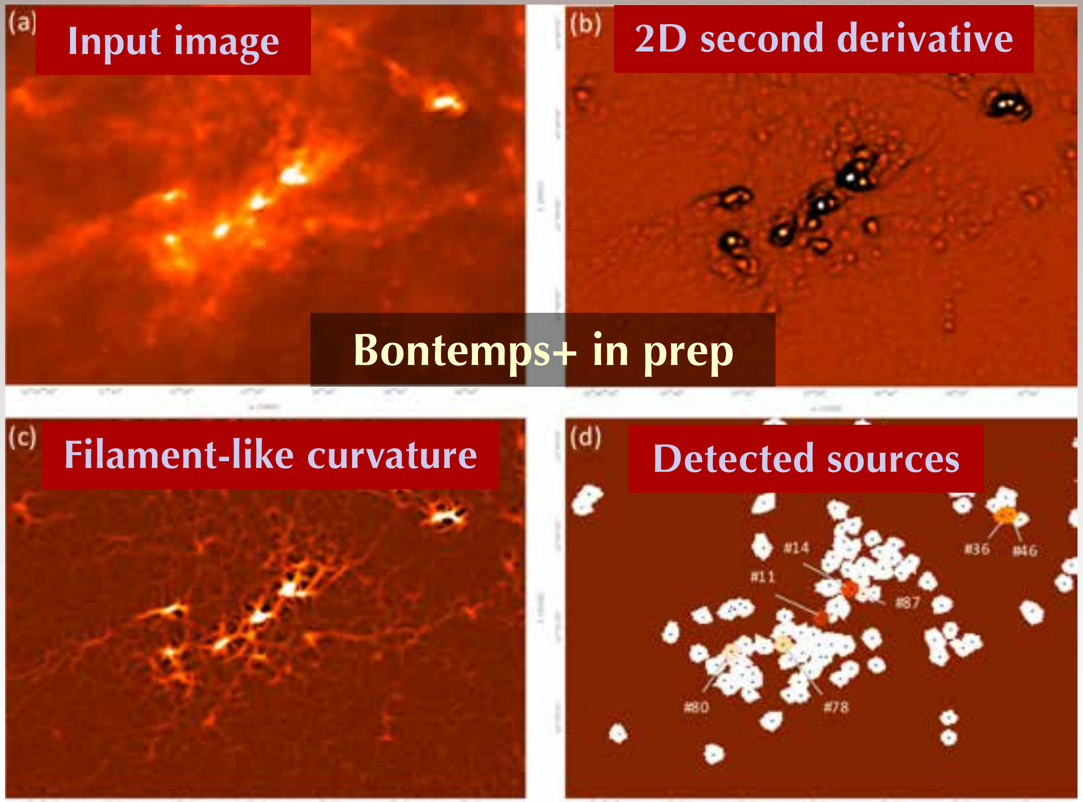
Cons:

- Heavy!
- 2D only

# Cores extraction with CuTEX

CuTEx (Molinari+ 2016) or GExt2D (Bontemps+ in prep)

- identify compact sources with the second derivative
- remove their local background and
- perform multi-Gaussian fits on background-subtracted images.



Pros:

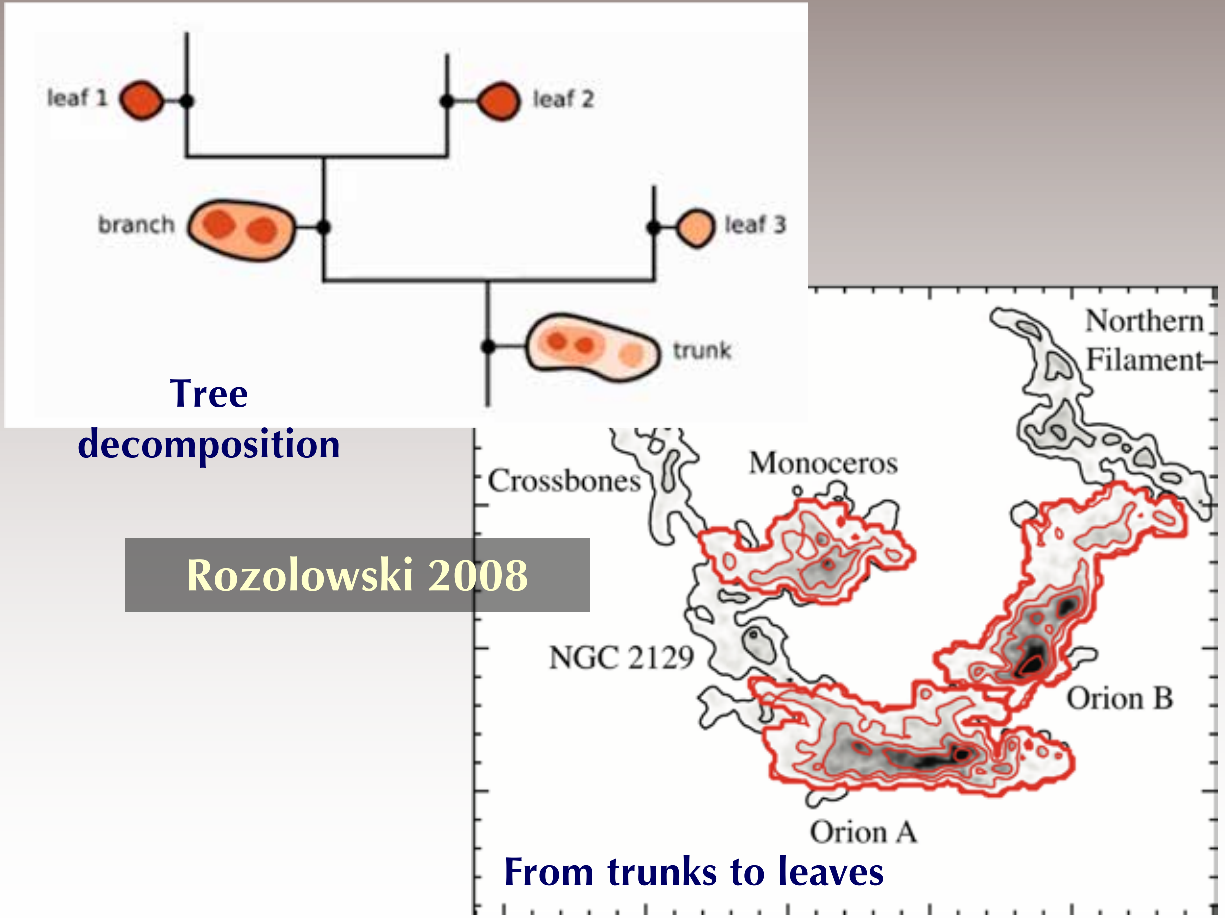
- Efficient core detection
- Good source deblending

Cons:

- Single wavelength
- Filaments can be identified as a series of cores if not removed (?)

# Cores extraction with Dendrogram

dendrogram is a connected tree statistics that defines cores/leaves as its smallest-scale structures outlined as closed contours.
Recent studies apply an initial large-scale filtering → Now focuses more on peaks



**Tree decomposition**

**Rozolowski 2008**

**From trunks to leaves**

Pros:

- Tree statistics
- Can be applied to PPV cube

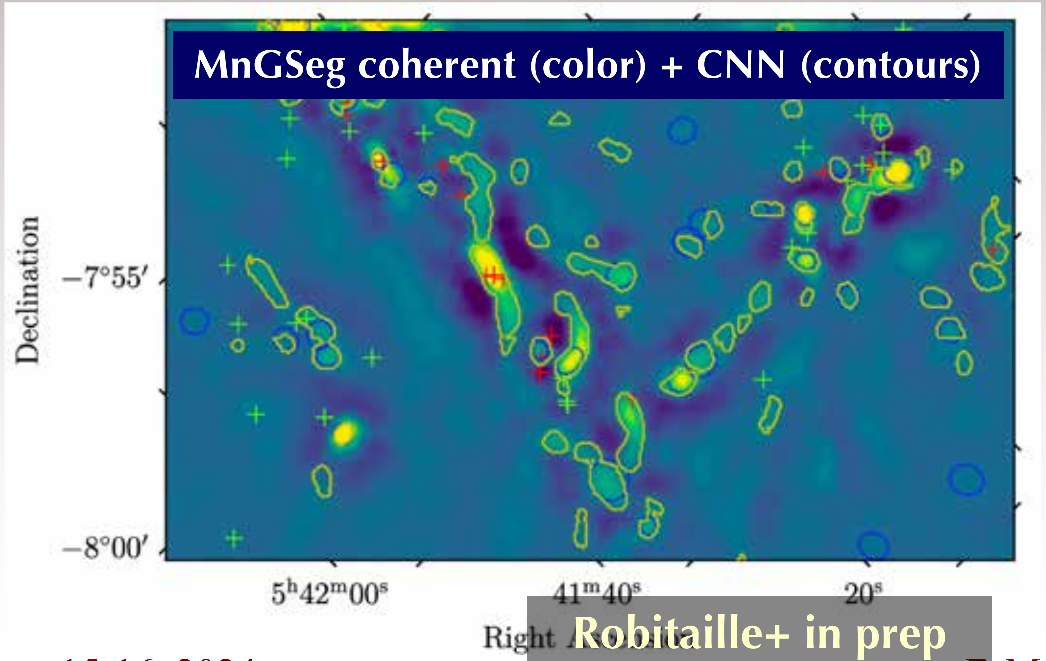
Cons:

- Single wavelength
- Without initial filtering, leaves tend to be elongated & structured

# Cores extraction with AI

Algorithm based on

- a fully convolutional neural network (CNN) trained on ‘fBm’ models
- The inference built for an Herschel $N_{H2}$ image shows that overdense gas components correspond to filaments + cores, the coherent structures identified by MnGSeg.



MnGSeg coherent (color) + CNN (contours)

Robitaille+ in prep

Pros:

- Fast

Cons:

- Extract both spherical and elongated structures.
- Needs more tests

# Part II
# Algorithms to identify large populations of cores

We entered the survey era for cores.

Many core extraction algorithms have been developed. They tend to converge because our community has now the same definition for cores: local peaks in $N_{H2}$ or $n_{H2}$ images.

Newer algorithms are developed: with IA techniques or with more physics.

**QUESTIONS!**

# Outline / Part III

1. Introduction

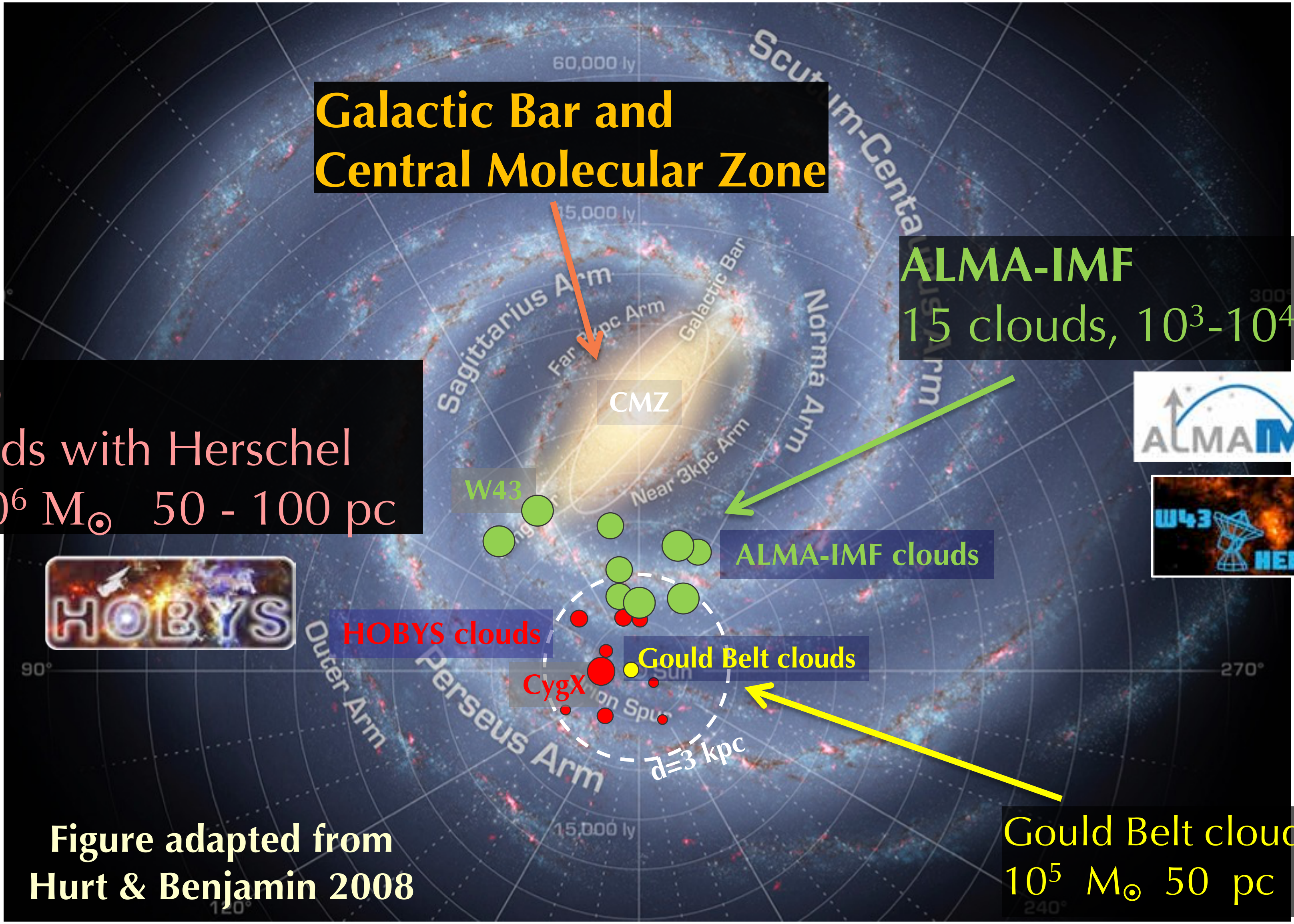
2. Algorithms to identifying large populations of cores

3. Variety of environment in the MW
    - Local (100-500 pc) Gould Belt clouds
    - HOBYS and Hi-GAL clouds, the tip of the Galactic bar
    - the Central Molecular Zone

4. Core mass functions (CMFs)

5. Effect of the fragmentation cascade

# Cloud diversity: local clouds, clouds in the closest MW arms, at the tip of the Galactic bar and in the CMZ



Galactic Bar and
Central Molecular Zone

**ALMA-IMF**
15 clouds, $10^3$-$10^4$ $M_\odot$ 1 pc

**HOBYS**
10 clouds with Herschel
$10^5$ - $10^6$ $M_\odot$ 50 - 100 pc

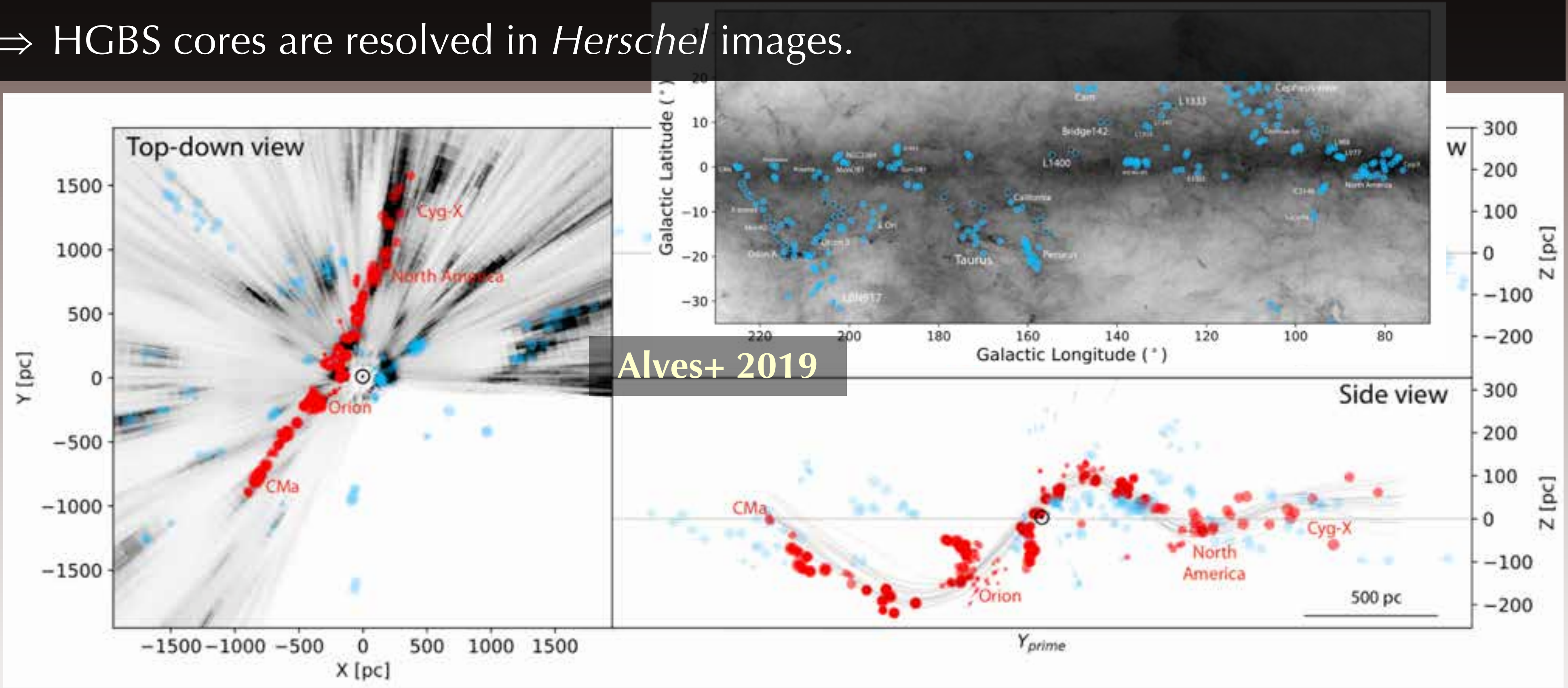
Gould Belt clouds:
$10^5$ $M_\odot$ 50 pc

Figure adapted from
Hurt & Benjamin 2008

# The Gould Belt clouds in a local gas wave

Local system of clouds that form low-mass stars in the solar neighborhood (100-500 pc)

⇒ HGBS cores are resolved in *Herschel* images.



Alves+ 2019

Using photometric surveys and the Gaia astrometric survey, Alves+2019 found that the Gould Belt is NOT an expanding ring

but a narrow arrangement of cloud: 160 pc x 2000 pc

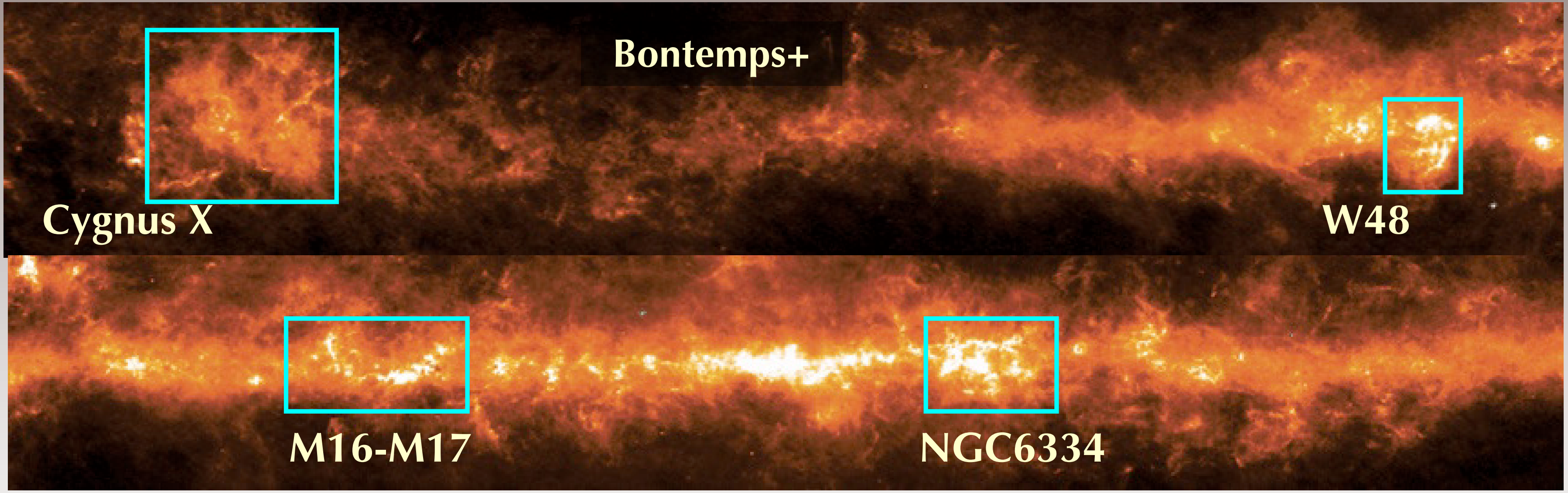
undulating like a “Radcliffe wave”

# *Herschel* /HOBYS cloud complexes

HOBYS clouds (Motte, Bontemps & Louvet 2018)

the 10 closest 1-3 kpc massive cloud complexes (50 - 100 pc, $10^5$ - $10^6$ $M_\odot$)
forming high-mass (>8 - 150 $M_\odot$) stars
imaged with *Herschel* (20 $deg^2$)

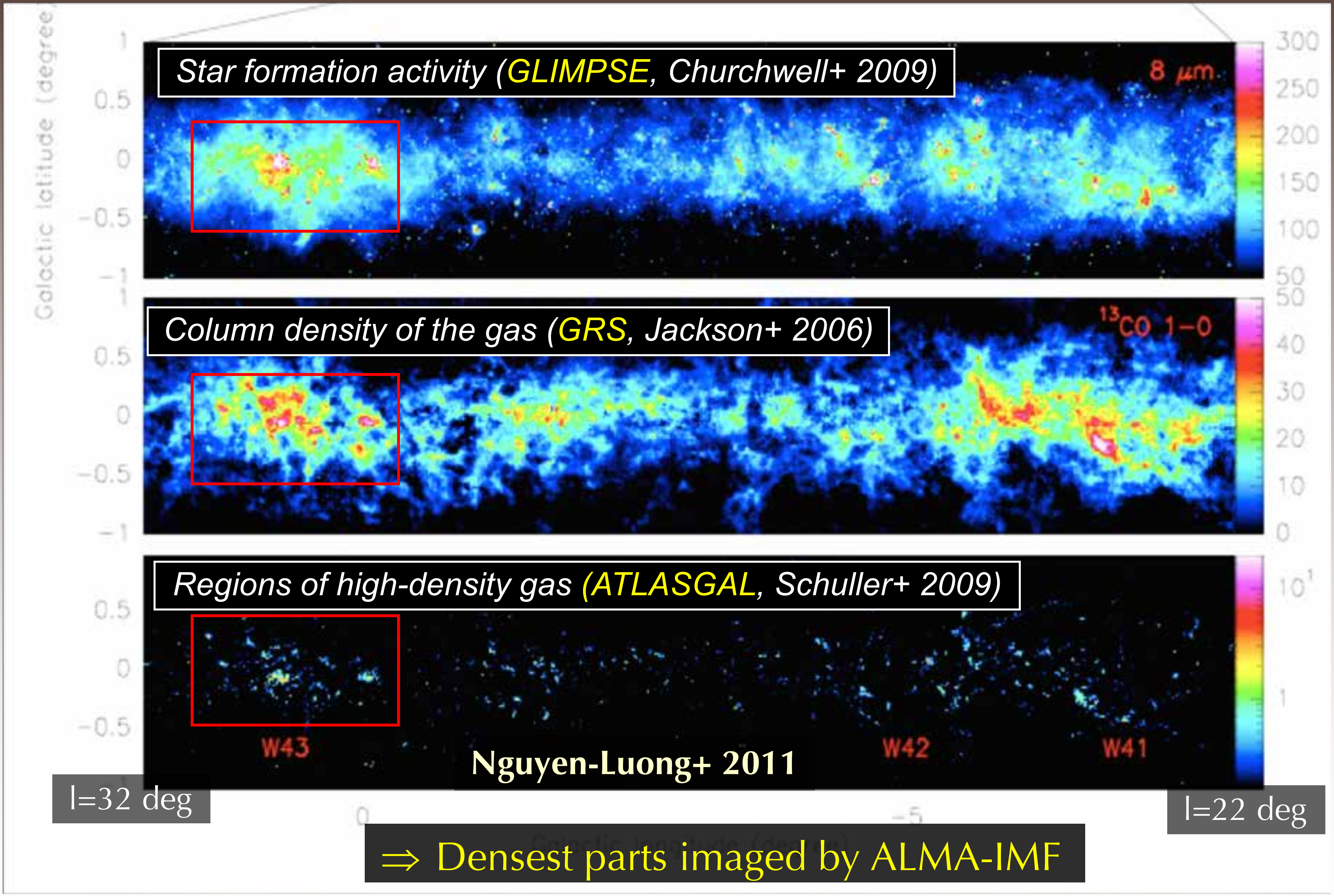
Clouds defined from a NIR extinction image of the MW + CO cubes



Nessy-like (100 pc long, Jackson+2010) filaments along the Galactic arms (> 1 kpc)

⇒ HOBYS and Hi-GAL cores are not resolved in *Herschel* images. ALMA follow-ups with single pointings (Louvet+ 2018; ALMAGAL survey).

# W43, an extreme molecular complex of the Milky Way



*Star formation activity (GLIMPSE, Churchwell+ 2009)*

*Column density of the gas (GRS, Jackson+ 2006)*

*Regions of high-density gas (ATLASGAL, Schuller+ 2009)*

**Nguyen-Luong+ 2011**

l=32 deg

l=22 deg

⇒ Densest parts imaged by ALMA-IMF

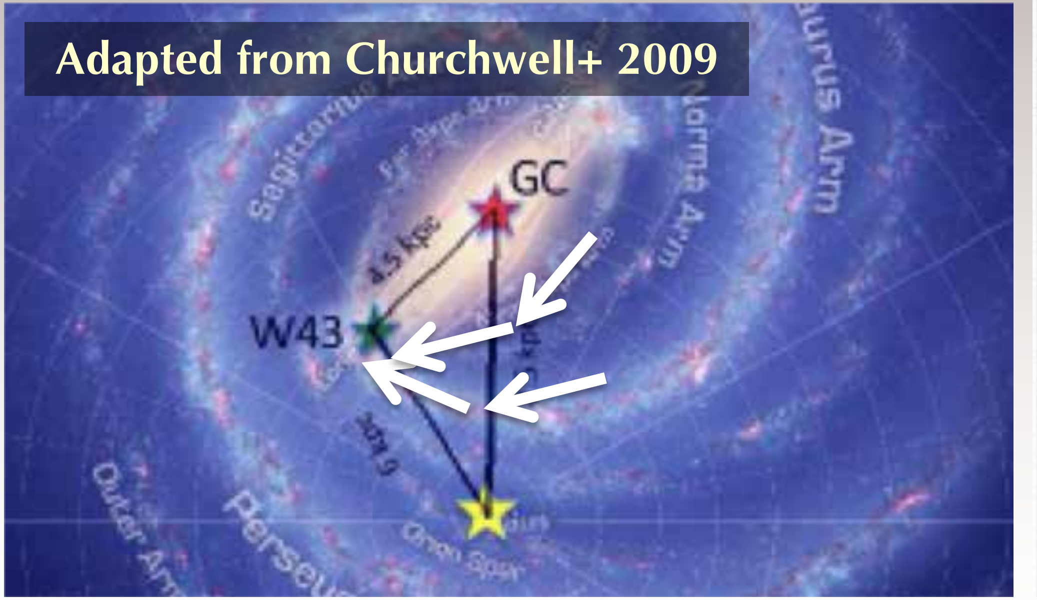
870 μm

# W43, a cloud agglomeration at the tip of the Galactic bar

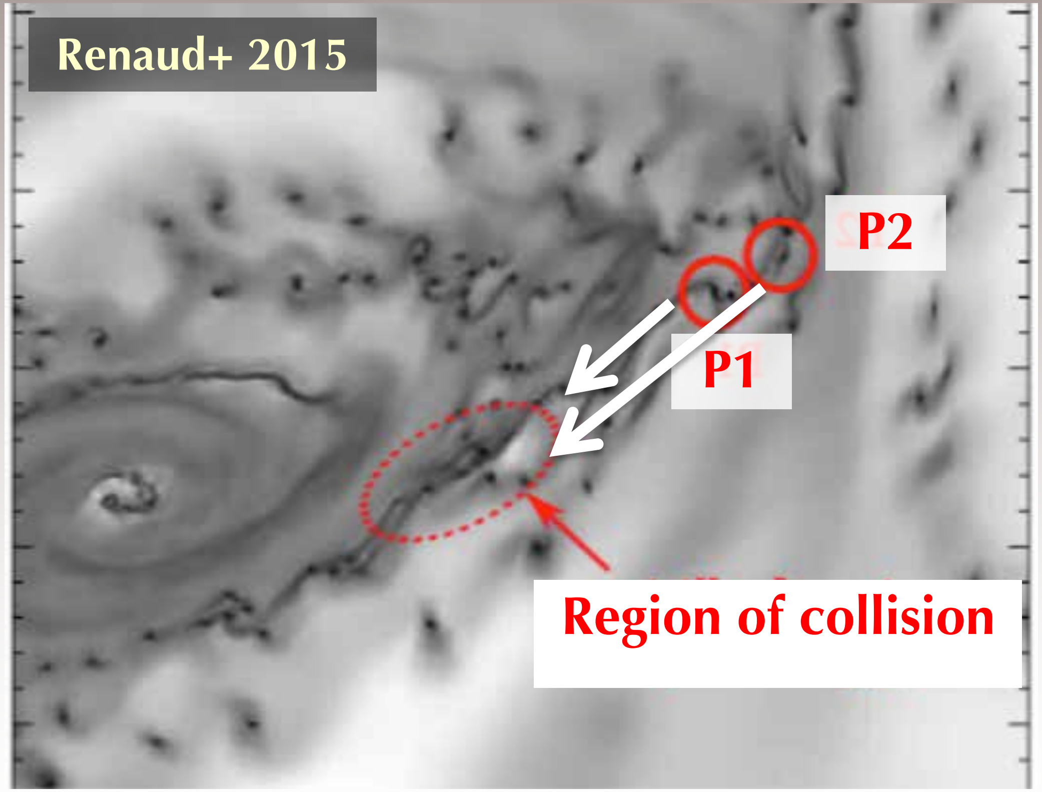
W43 is located in front of the Galactic long bar (Nguyen Luong+ 2011b; Carlhoff+ 2013).

$^{12}$CO gas flows along the Galactic arm and forms W43 through cloud-cloud collision (Motte+ 2014).

Scenario in agreement with numerical models of cloud collision at the edge of galactic bars (Renaud+ 2015)

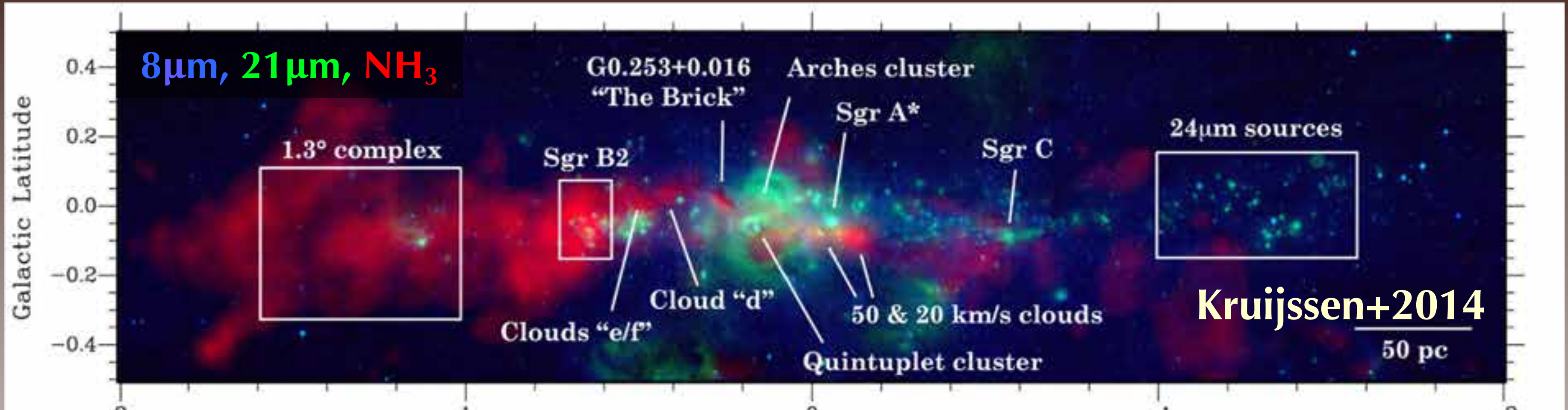


Adapted from Churchwell+ 2009

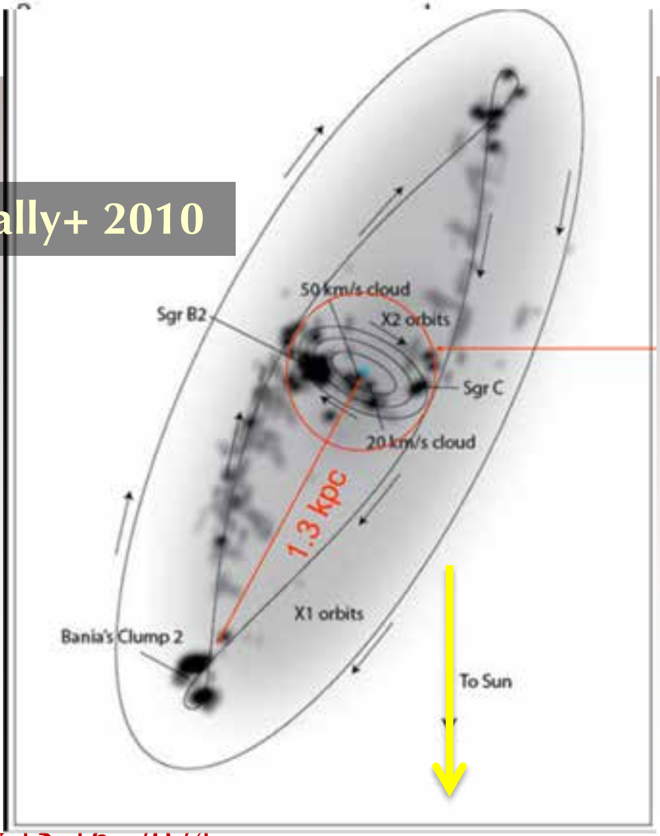


Renaud+ 2015

# Central Molecular Zone (CMZ)



Kruijssen+2014



Bally+ 2010

Cartoon based on the model by Rodriguez-Fernandez+ 2006, 2008

Central molecular zone
= nuclear ring (seen by Herschel)
+ kpc connecting arms arms/rings

⇒ Partly imaged by ALMA/ACES

Galactic center = 200 pc ring
(Molinari+ 2011)

# Part III
# Variety of environments in the Milky Way

Groups of Galactic clouds:

- local (100-500 pc) Gould Belt clouds
- 1-3 kpc HOBYS clouds
- the tip of the Galactic bar
- the Central Molecular Zone

These cloud complexes correspond to pieces of Galactic arms.

Defining groups of clouds allows to perform homogeneous statistical studies with single observational facilities.

**QUESTIONS!**

# Outline / Part IV

1. Introduction

2. Algorithms to identifying large populations of cores

3. Variety of environment in the MW

4. Core mass functions (CMFs)
   - in local (100-500 pc) Gould Belt clouds
   - The ALMA-IMF and ALMAGAL Large Programs
   - ALMA-IMF results on the CMF

5. The resulting IMF…

# The Initial Mass Function (IMF)

***Initial mass function of stars (IMF)***
***= mass distribution of stars at birth***

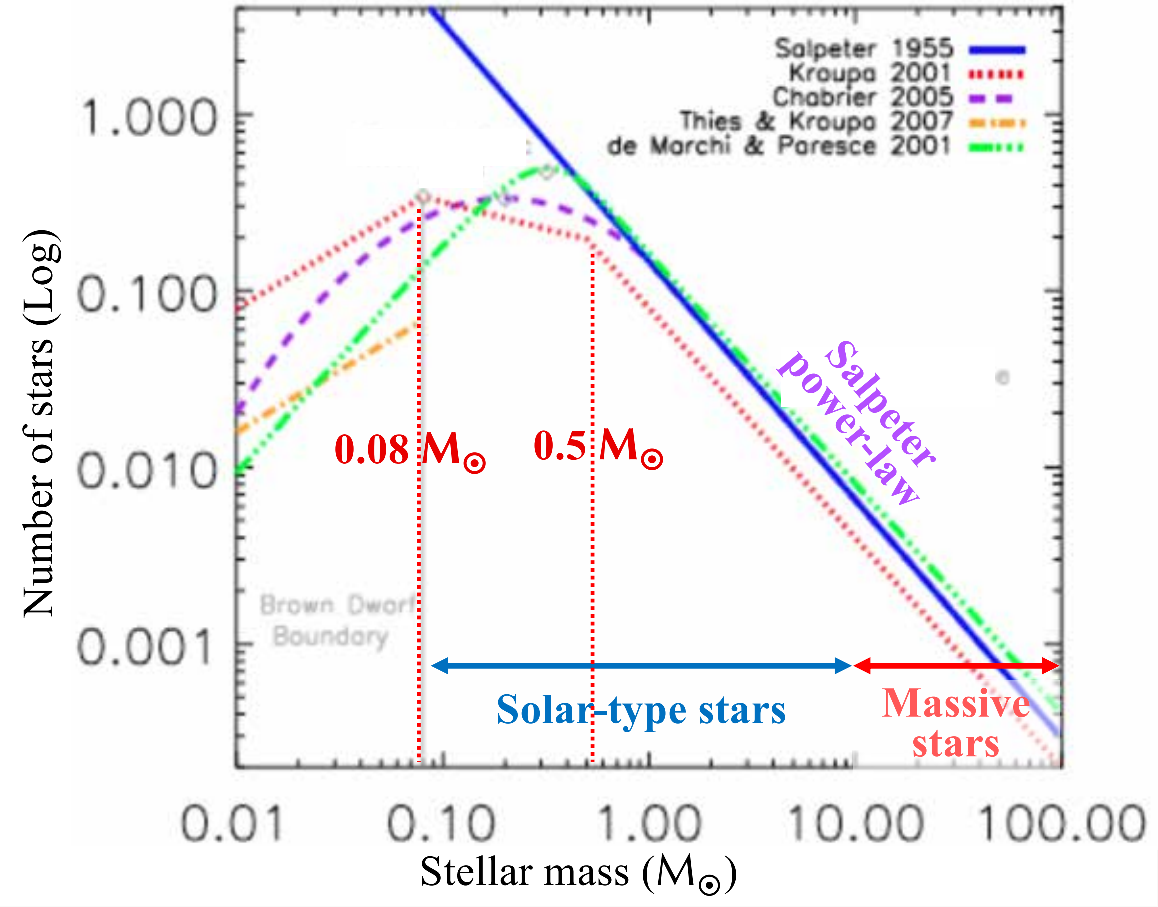


**Figure adapted from Offner+ 2014**

The shape of the IMF has long been considered universal (Bastian +2010; Kroupa +2013, see however Hopkins 2018; Hennebelle ARAA 2024).

But it might not be so universal.

Modeled by broken power-laws or a log-normal function plus a power-law (Kroupa+ 2001; Chabrier+2005).

# The origin of the initial Mass Function (IMF)

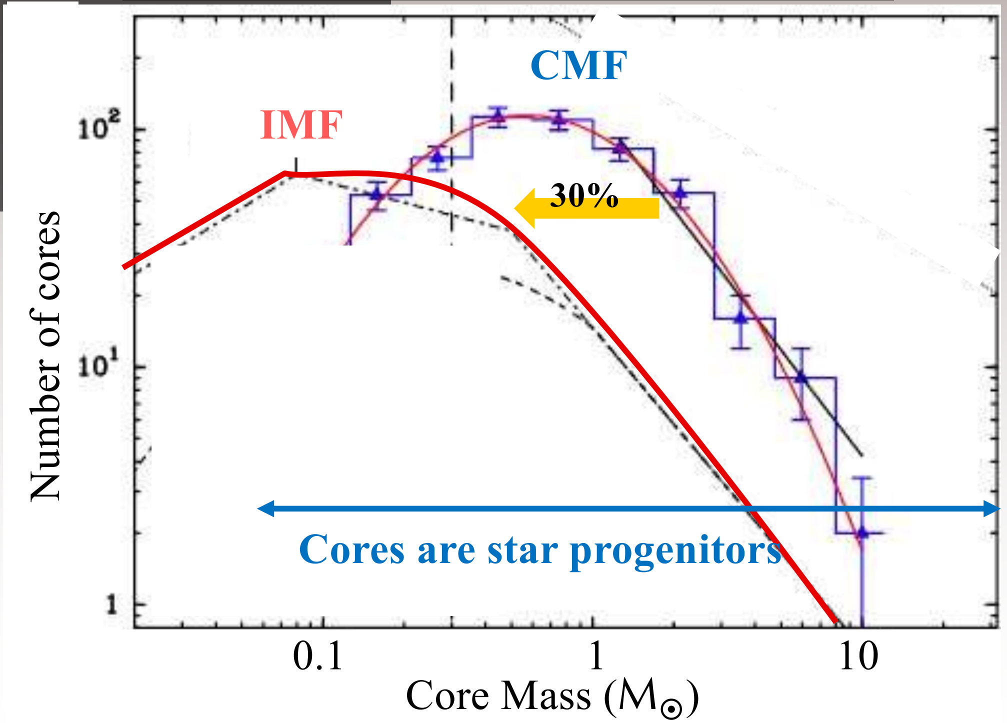
If we assume that cores are star progenitors, the IMF should be inherited by the mass distribution of cores, the CMF.

The IMF and CMF are two fundamental notions of star formation and are prescriptions used to

- measure star formation rates (SFR) in galaxies
- perform galaxy and cosmology models.

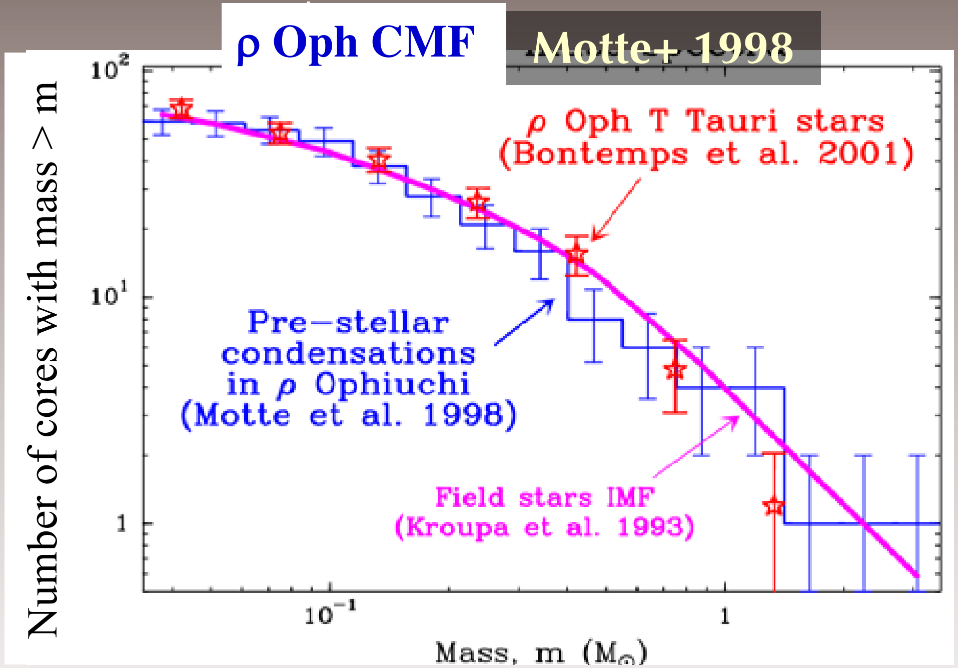
Even if the relation between the CMF and IMF is not direct, the CMF remains a good metric to investigate the effect of environment on the SF process.

*IMF and Core Mass Function (CMF)*

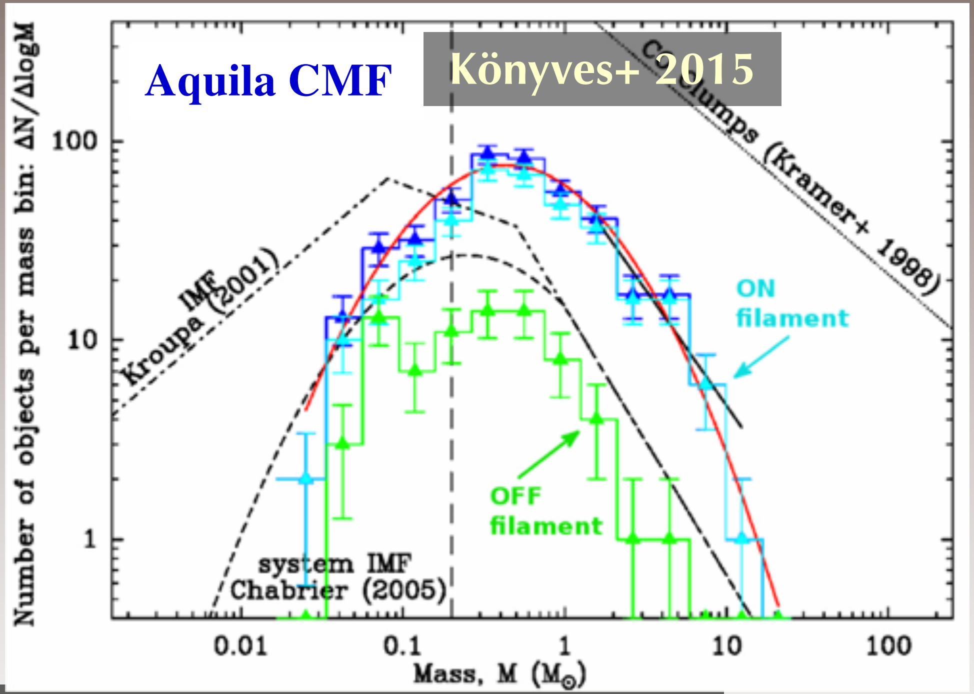


# One-to-one relationship between the CMF and IMF

Surveys of the past 2 decades suggested a direct link between the IMF and the CMF → Fragmentation could determine stellar masses


ρ Oph CMF

Motte+ 1998


Aquila CMF

Könyves+ 2015

See also Testi & Sargent 1998; Stanke+ 2006; Alves+ 2007; Nutter & Ward-Thompson 2007; Enoch+ 2008; many HGBS papers; …

But studies in regions not typical of the main mode of star formation in galactic disks and limited to progenitors of <5 $M_\odot$ stars…

# Assumptions behind the CMF/IMF comparison

1. Measured core mass = total mass available to form a star

- ➢ Gas mass feeding?
- ➢ Multiplicity?

2. Uniform gas-to-star mass conversion, ε (m) = cst

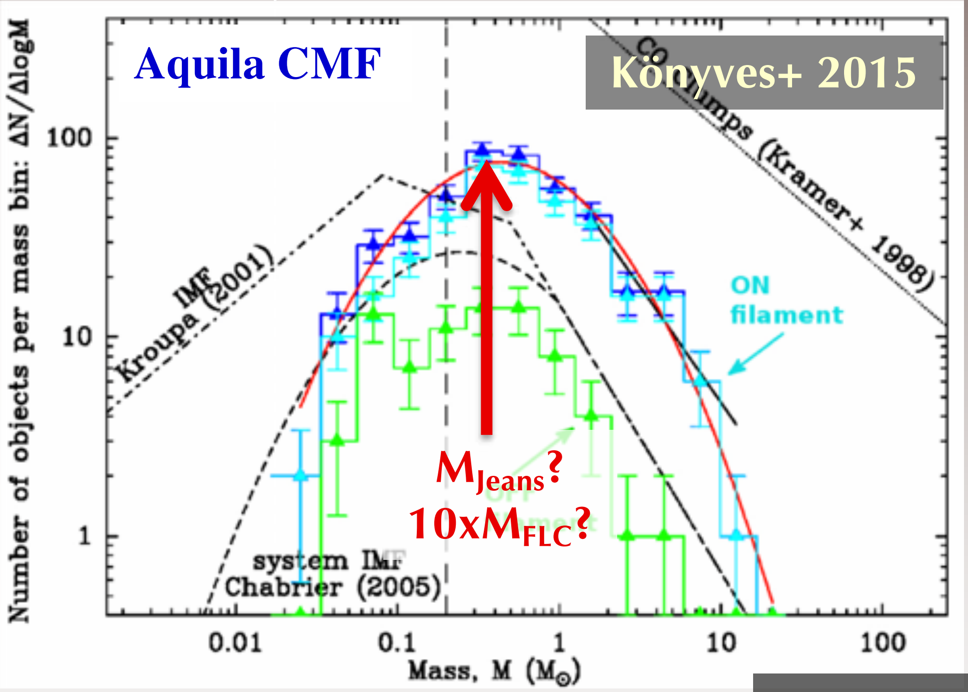
- ➢ Outflows regulate ε?
- ➢ ε increases with density?

3. Lifetime independent of the core mass, snapshot = true CMF

These effects should cancel out to keep the CMF/IMF shapes so similar.
⇒ conspiracy like the central limit theorem?
⇒ or uncertainties of IMF and CMF observations too large?

# Resolution issues for the shape of the CMF

The peak of the CMF could correspond to the $M_{Jeans}$ mass, or 10 x $M_{FLC}$ or could be a resolution artefact… Is the high-mass slope more robust?

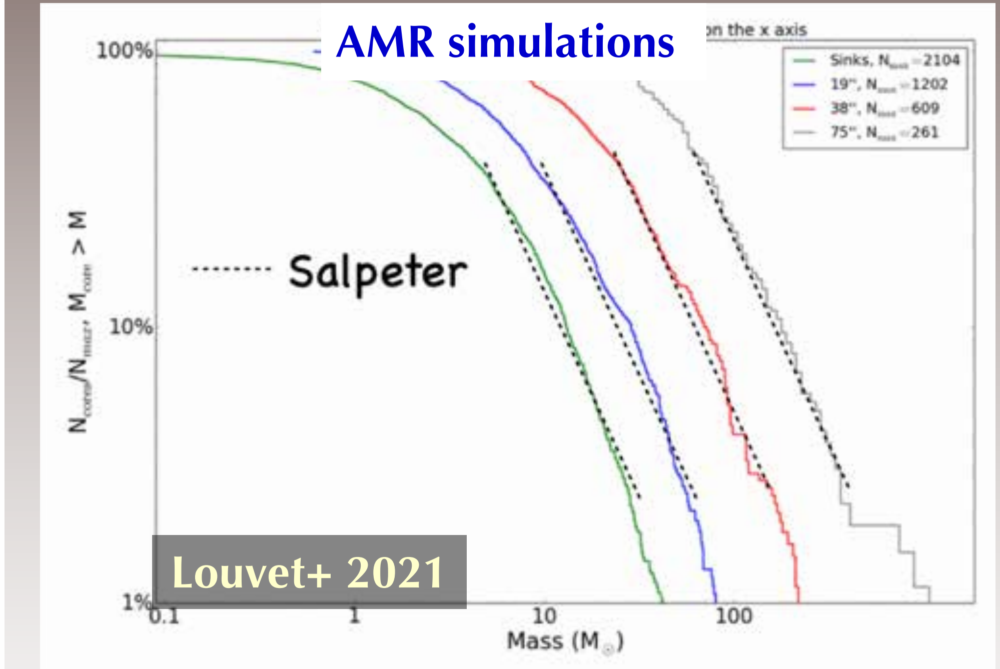


**Aquila CMF**

**Könyves+ 2015**

$M_{Jeans}$?

$10xM_{FLC}$?



**AMR simulations**

**Louvet+ 2021**

See also Reid+ 2010; Tatematsu+ 2021; Pelkonen+ 2021

CMFs of larger-scale clumps, observed in continuum and with lines, all have a Salpeter slope @ high-mass end!

# ALMA-IMF targets: 15 massive gas-dominated protoclusters clouds

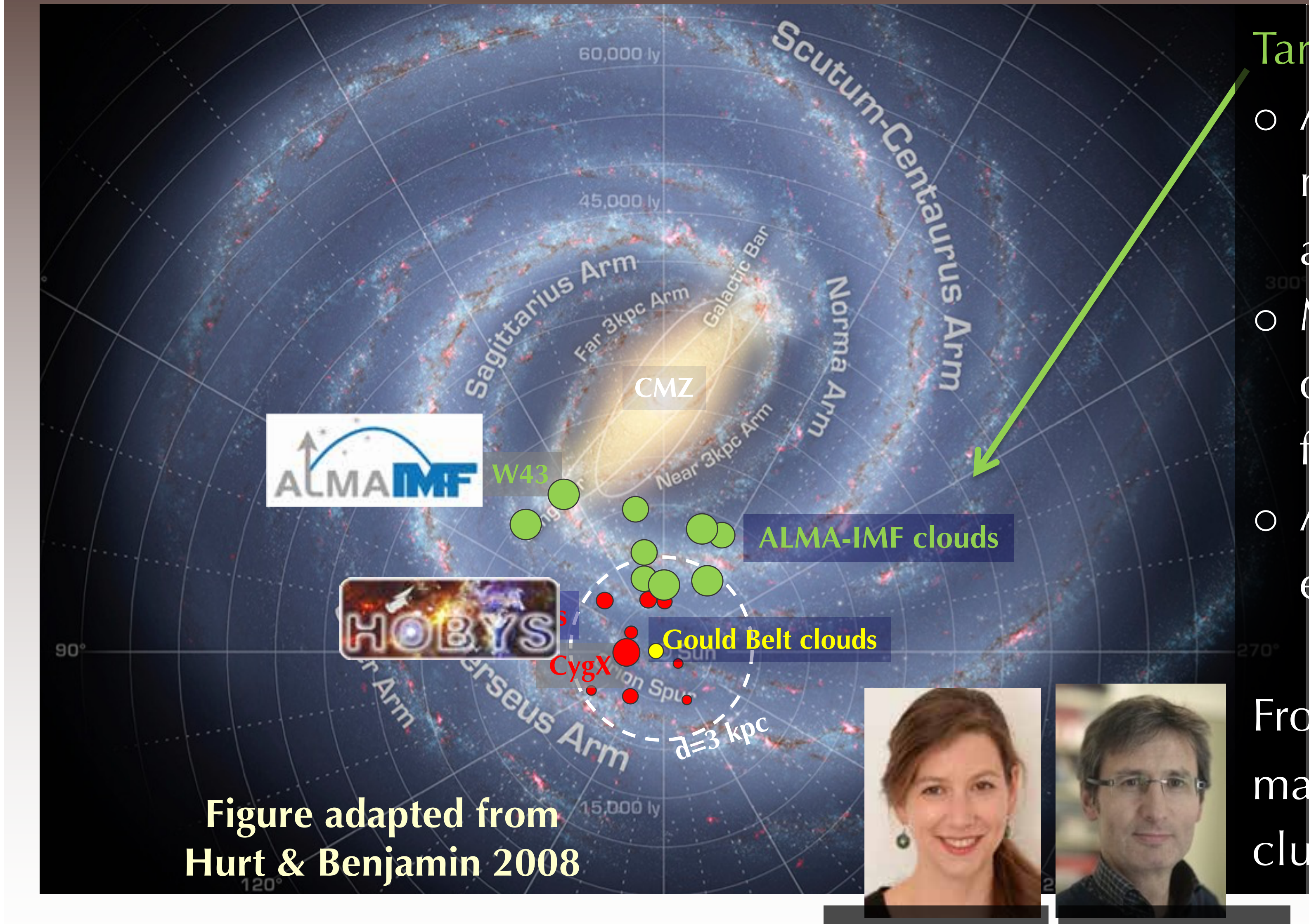


Figure adapted from Hurt & Benjamin 2008

T. Csengeri

S. Bontemps

Targets (Motte+ 2022):

- A large sample of massive protoclusters at <6 kpc
- More representative of Milky Way star-forming clouds
- At various evolutionary stage

From the 200 most massive ATLASGAL clumps (Csengeri+ 2017)

# ALMAGAL targets: 1013 massive clumps

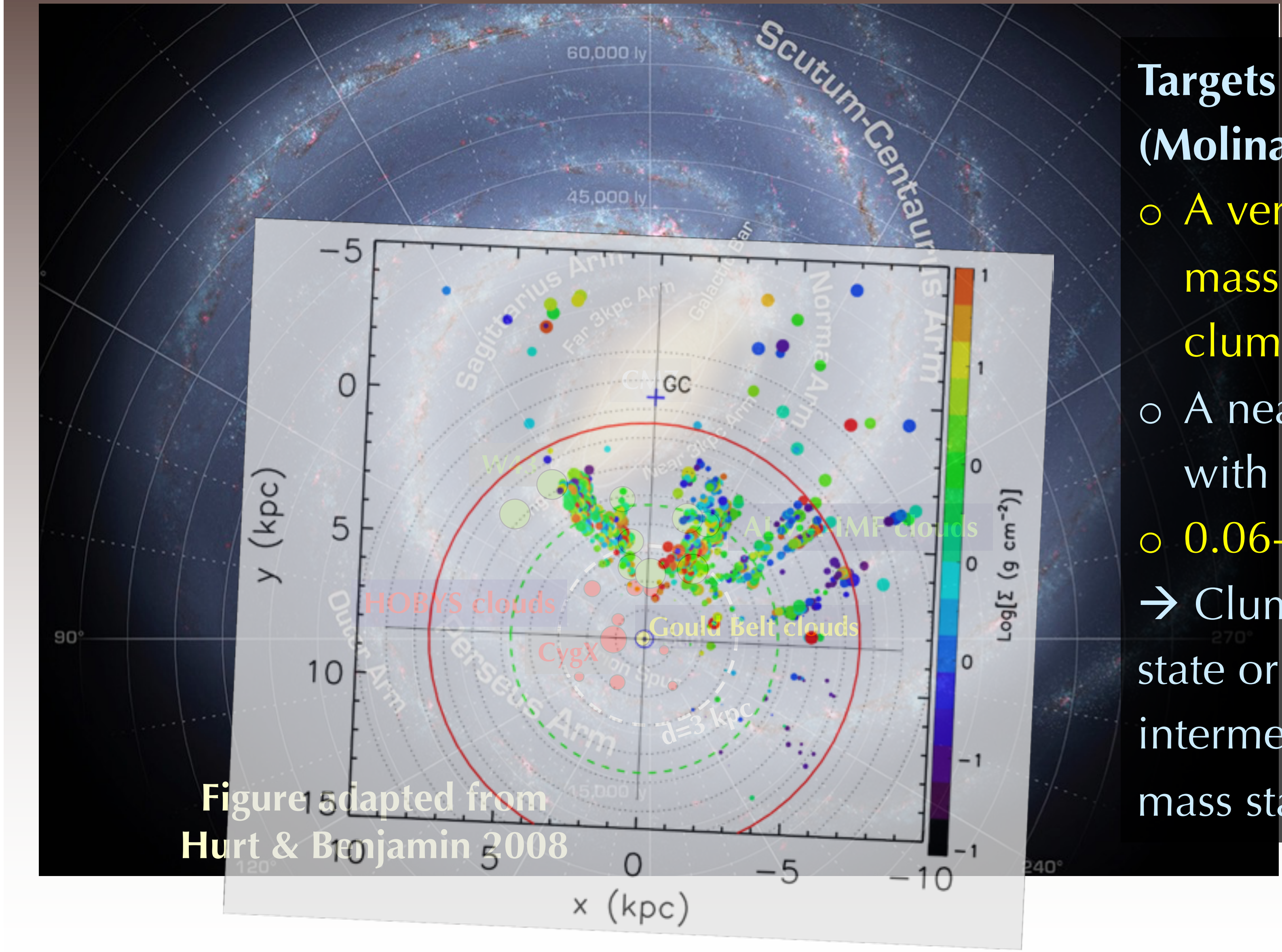


Figure adapted from
Hurt & Benjamin 2008

**Targets**
**(Molinari+ in prep):**

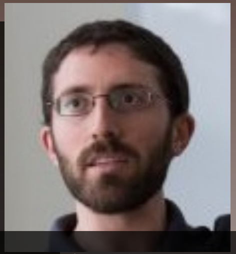
- A very large sample of massive (> 500 M$_\odot$) clumps @ <6 kpc
- A near and a far sample with d=4.7 kpc
- 0.06-400 L$_\odot$ /M$_\odot$

→ Clump evolutionary state or its ability to form intermediate- or high-mass stars

# ALMA-IMF observations and database

https://www.almaimf.com/

- Proposal: Cycle 5, #2017.1.01355.L (thanks IRAM/ARC!)
  10/2017-08/2019: 69 hours 12M + 172 hours ACA + 595 hours TP



A. Ginsburg

- Resolution: 0.31″-0.87″ ~ 2100 AU (typical ‘core’ size)
  Sensitivity: $3\sigma = 0.2\ M_\odot$ ($1\ M_\odot$ @ 3mm)
  Mosaics (7 to 85 fields @ 1mm ) covering protoclusters, total area ~53 $pc^2$

N. Cunningham

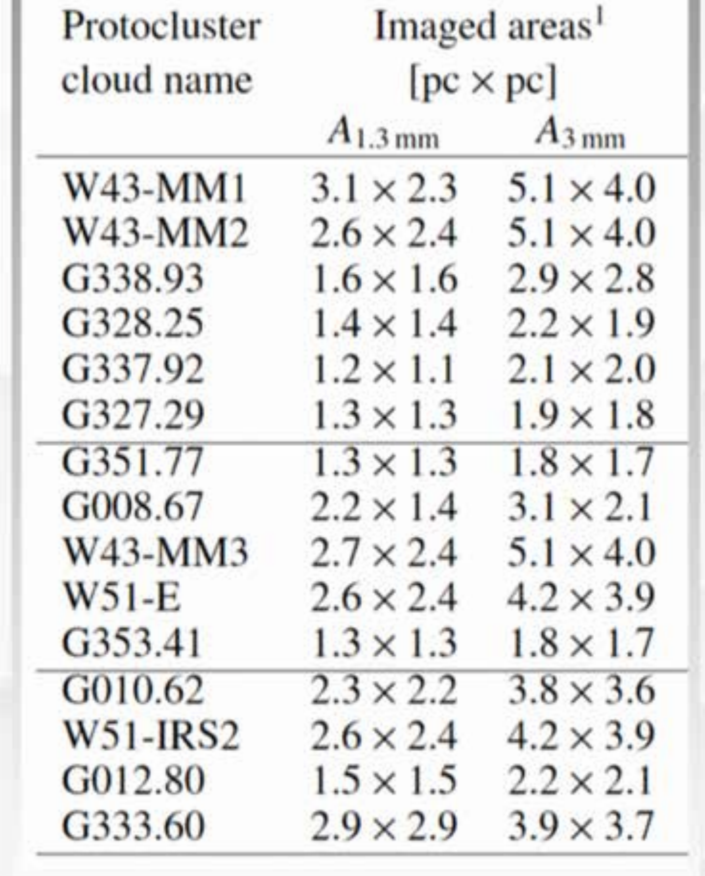
- Huge effort for data calibration & reduction
  Recalibration ($T_{sys}$) of line cubes (thanks JAO!)
  Automatic pipeline for homogeneous and reproducible data reduction. It combines all array configurations and applies phase self-calibration. https://github.com/ALMA-IMF

R. Galván-Madrid

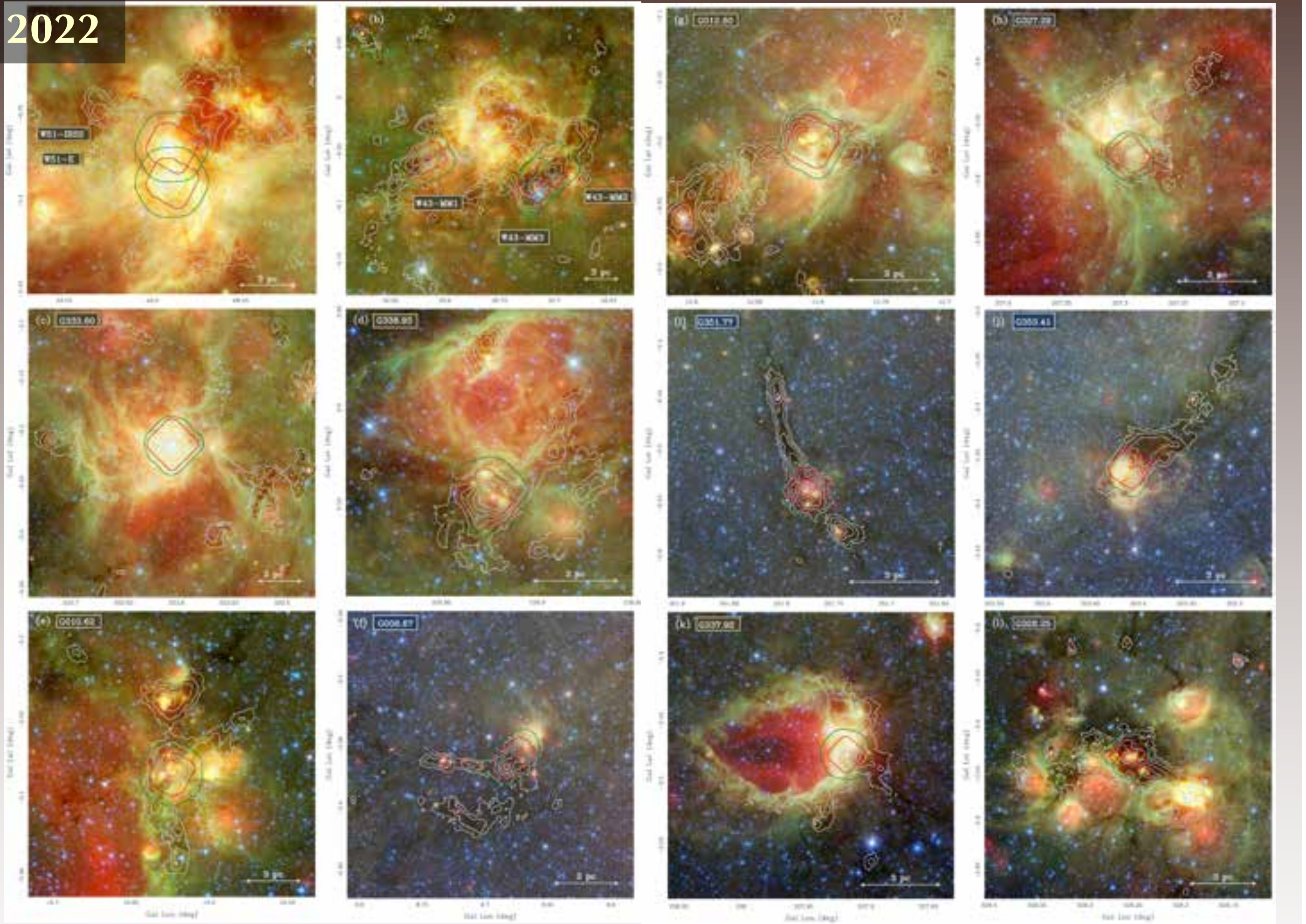
- Continuum images: Ginsburg+ 2022
  https://zenodo.org/record/5702966#.YzWq_S2w1TY
  Line data cubes (>50 Tb): Cunningham+ 2023
  https://dataverse.harvard.edu/dataverse/alma-imf-line

# ALMA-IMF protoclusters, in various environments

Motte+ 2022



| Protocluster cloud name | Imaged areas[1] [pc × pc] | |
|---|---|---|
| | $A_{1.3\,\mathrm{mm}}$ | $A_{3\,\mathrm{mm}}$ |
| W43-MM1 | 3.1 × 2.3 | 5.1 × 4.0 |
| W43-MM2 | 2.6 × 2.4 | 5.1 × 4.0 |
| G338.93 | 1.6 × 1.6 | 2.9 × 2.8 |
| G328.25 | 1.4 × 1.4 | 2.2 × 1.9 |
| G337.92 | 1.2 × 1.1 | 2.1 × 2.0 |
| G327.29 | 1.3 × 1.3 | 1.9 × 1.8 |
| G351.77 | 1.3 × 1.3 | 1.8 × 1.7 |
| G008.67 | 2.2 × 1.4 | 3.1 × 2.1 |
| W43-MM3 | 2.7 × 2.4 | 5.1 × 4.0 |
| W51-E | 2.6 × 2.4 | 4.2 × 3.9 |
| G353.41 | 1.3 × 1.3 | 1.8 × 1.7 |
| G010.62 | 2.3 × 2.2 | 3.8 × 3.6 |
| W51-IRS2 | 2.6 × 2.4 | 4.2 × 3.9 |
| G012.80 | 1.5 × 1.5 | 2.2 × 2.1 |
| G333.60 | 2.9 × 2.9 | 3.9 × 3.7 |



1.3- 8 pc$^2$ massive clouds/clumps, with 2.5-21 $10^3$ M$_\odot$

Contours: 870 μm → massive clouds

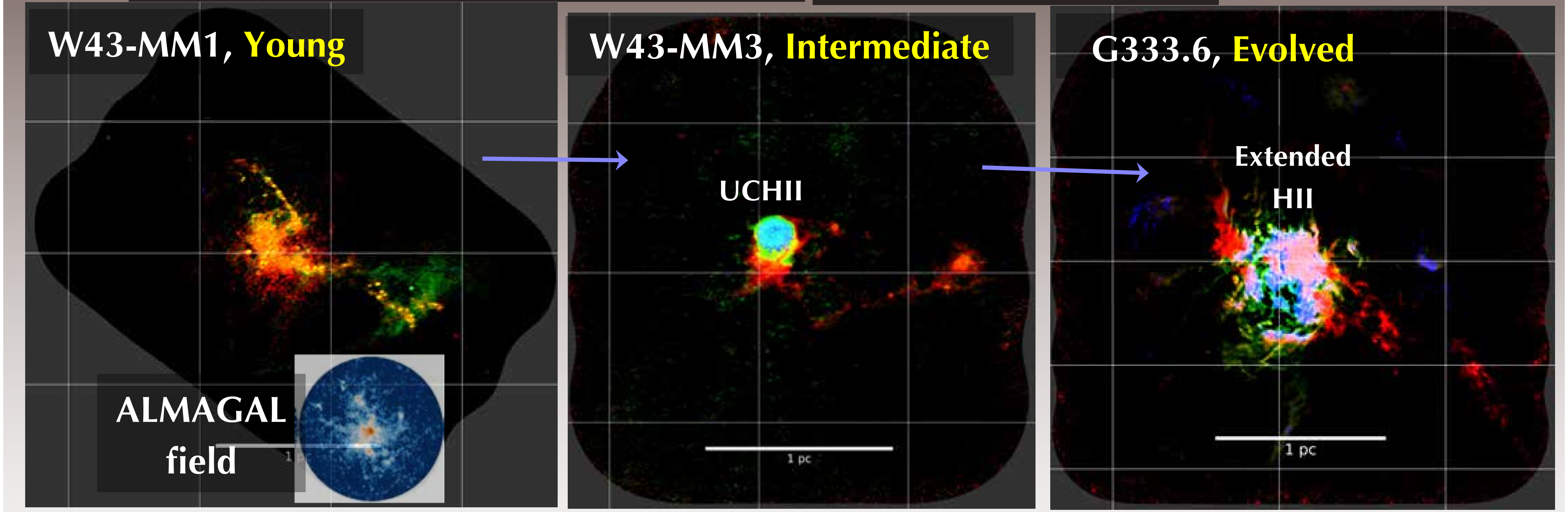
RGB = 24μm /8μm /3.6μm → IR-bright or IR-quiet

# Protoclusters @ different evolutionary stages

RGB = 1.3mm / 3mm / free-free @ 3mm
(continuum) (from H41$\alpha$)

orange = thermal dust
green = diffuse free-free
blue = strong free-free

**Motte+ 2022**



**W43-MM1, Young**

**W43-MM3, Intermediate**

**G333.6, Evolved**

In young and intermediate regions, thermal dust filaments dominate.
In evolved region, there is a mix between thermal dust filaments and HII regions.

ALMA-IMF: 15 clouds, 1-25 $10^3$ $M_\odot$, 5-140 $10^4$ $L_\odot$, 12-110 $L_\odot$ /$M_\odot$

**Dell’Ova+ subm**

# Continuum emission corrected for COM and H41α line emission

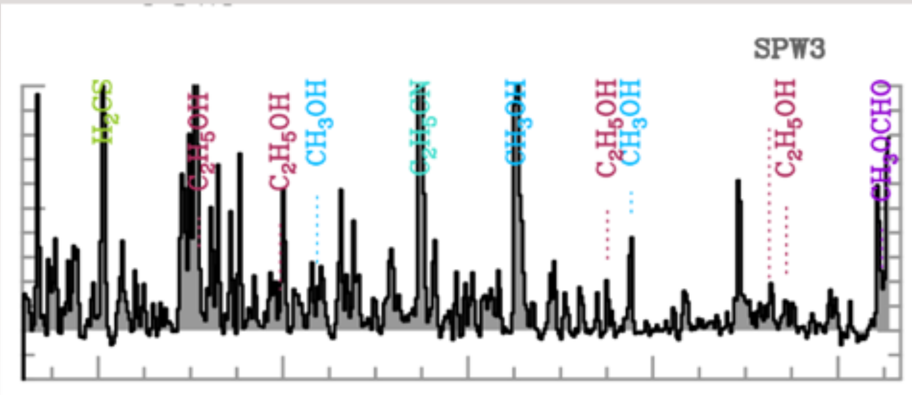
Cores = density peaks, which are well detected by thermal dust emission.

Cores' flux must be corrected for

- free-free emission of ionized gas

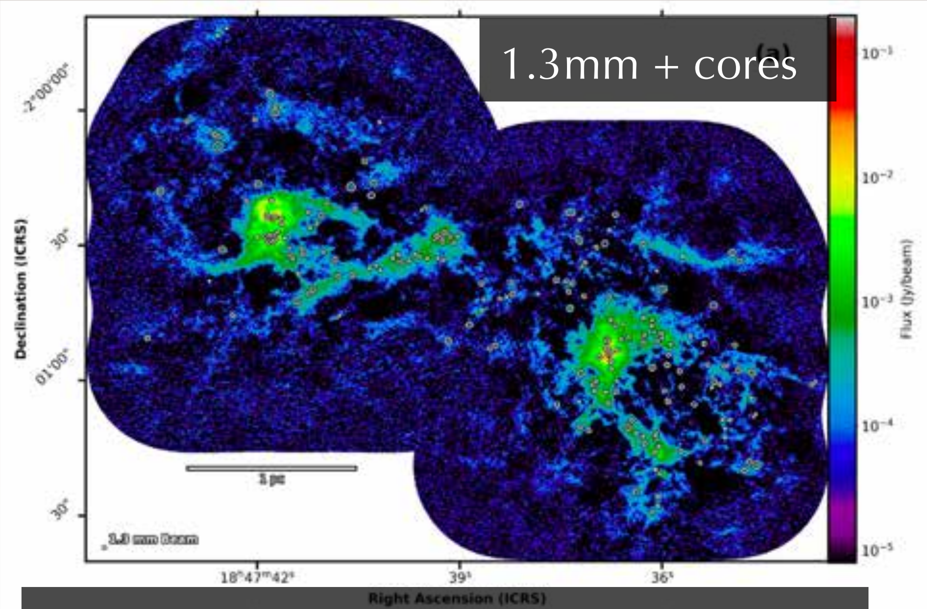
→ estimated from H41α ALMA images (Galván-Madrid +subm)

- line emission of, e.g., COMs



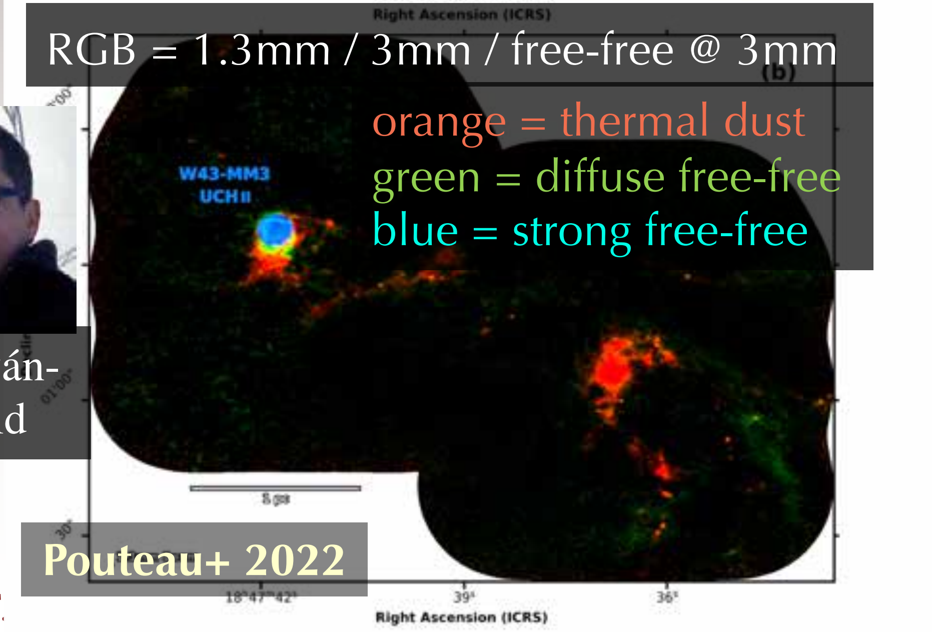
Motte+ 2022; Bonfand+ 2024

R. Galván-Madrid



1.3mm + cores

RGB = 1.3mm / 3mm / free-free @ 3mm



orange = thermal dust
green = diffuse free-free
blue = strong free-free

Pouteau+ 2022

# Core extraction in 1.3 mm images

2 types of continuum maps:

- cleanest = a reduced line contamination, selecting ~40 to 90% of bandwidth
- bsens-CO = the maximal sensitivity, selecting all bandwidths

A. Men’shchikov

2 algorithms to extract cores (density peaks) from their background: getsf (Men’shchikov+ 2021) and GExt2D (Bontemps+).

S. Bontemps

⇒ First catalog of ALMA-IMF cores (Louvet+ subm)

~700 true cores (+112 free-free peaks) with 2700 AU sizes and 0.15-250 $M_\odot$

**ALMAGAL: 6303 sources**

⇒ Deeper catalogs of cores (Pouteau+ 2022; Nony+ 2023; Armante+ in 2024; Cunningham+), using bsens-CO images and denoised images

https://www.almaimf.com/

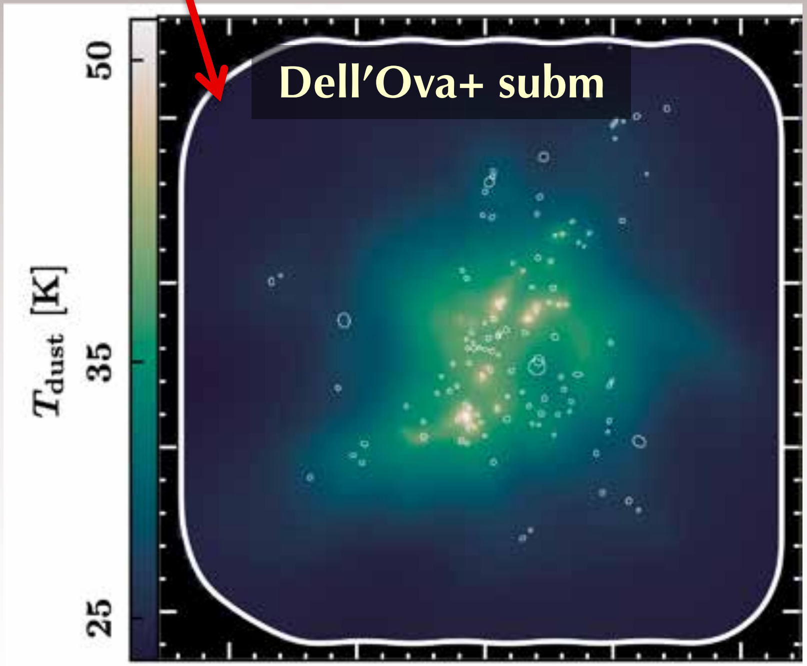
# Mass estimate of cores

We correct for the (moderate) optical depth of cores at submm λ:

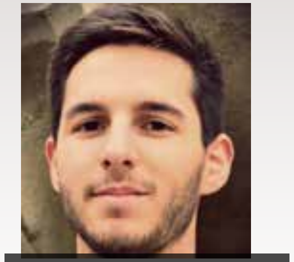
→ increase the mass of 20 cores by 10 to 35% ($\tau \sim 0.2$-$0.6$)

We estimate the mean dust temperature of ALMA cores, using

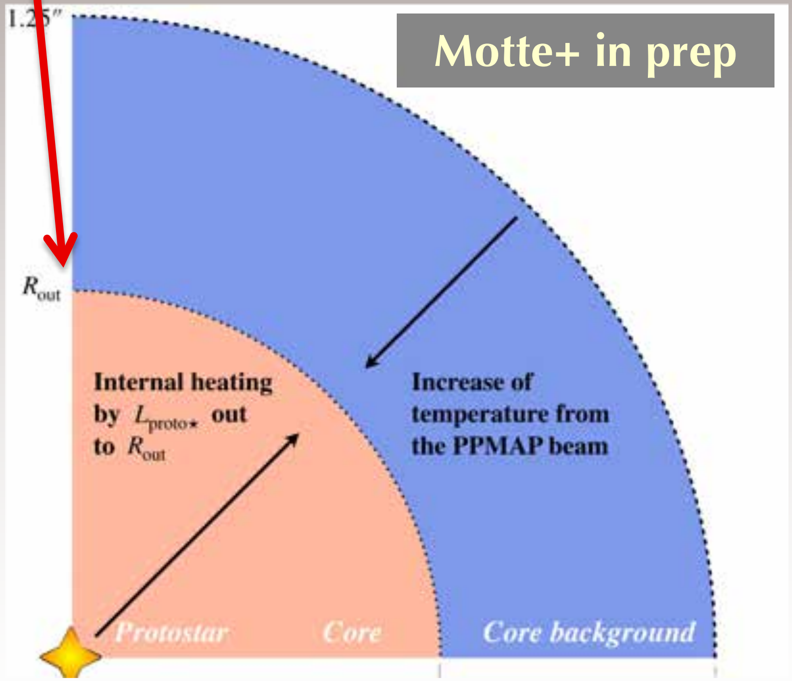
1. A map of the temperature background of cores at 2.5″, estimated from bayesian SED fits using PPMAP (Dell'Ova+ subm)
2. An extrapolation at ~0.5″ assuming protostar heating or core self-screening



**Dell'Ova+ subm**

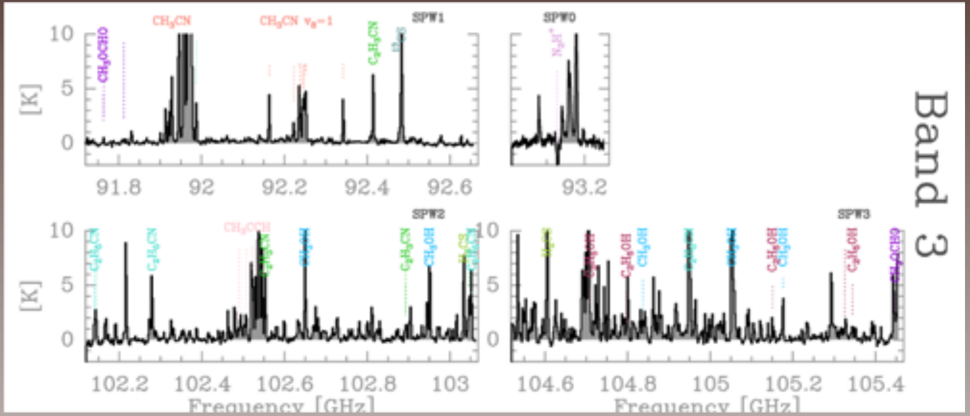


P. Dell'Ova

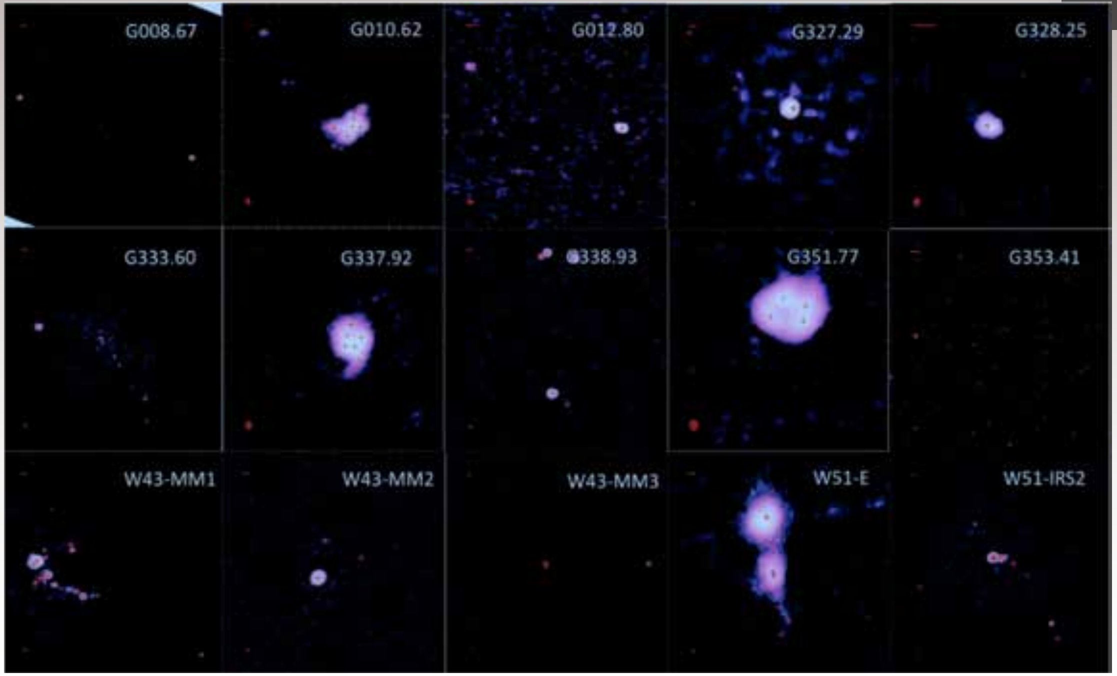


**Motte+ in prep**

# Molecular lines, the other temperature tracer



Motte+ 2022; Bonfand+ 2024



Catalog of 68 hot core candidates (detected with $CH_3OCHO$) associated with 2-200 $M_\odot$ cores.

→ The 150-300 K temperatures of hot cores are at odds with $L_{bol}$ measurements! …

Molecular complexity studied with surveys of complex organic molecules, COMs, (Csengeri+ in prep)

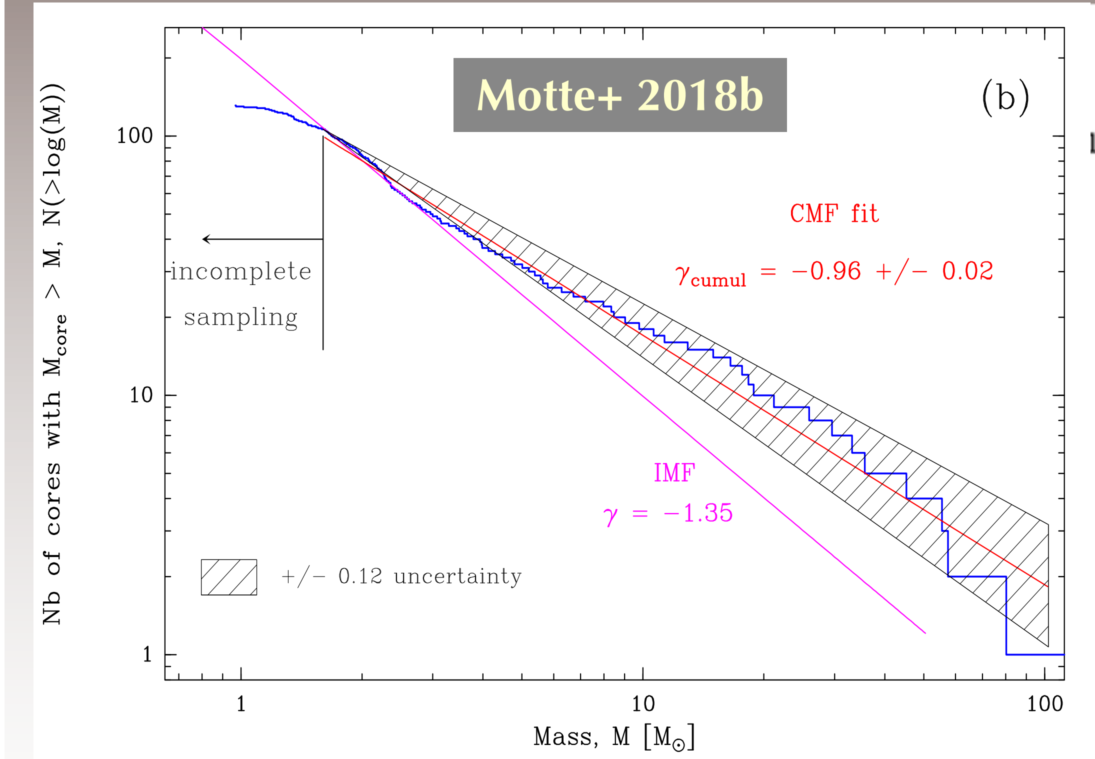
M. Bonfand

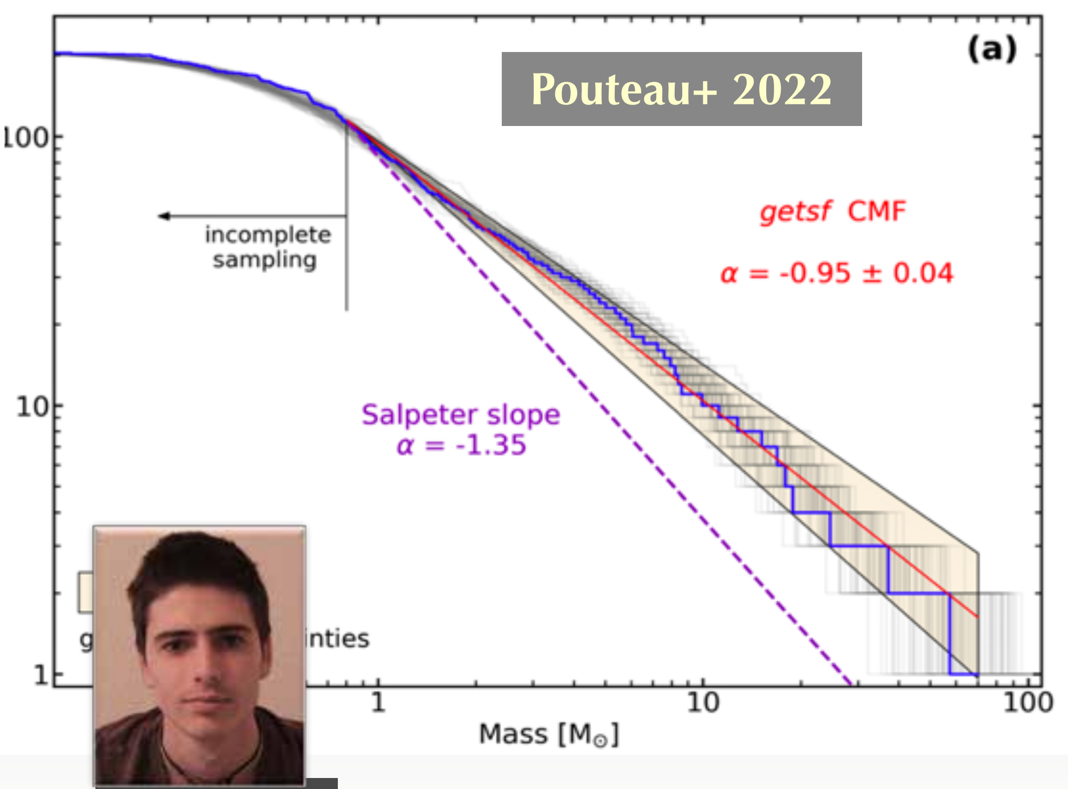
T. Csengeri

# Top-heavy CMFs for the W43 protoclusters

The 1-100 M$_\odot$ parts of the W43 CMFs are much flatter than usually found (Motte+ 2018b; Pouteau+ 2022).

=> It would suggest an atypical IMF for stars of 0.5-50 M$_\odot$ (ε=50%).

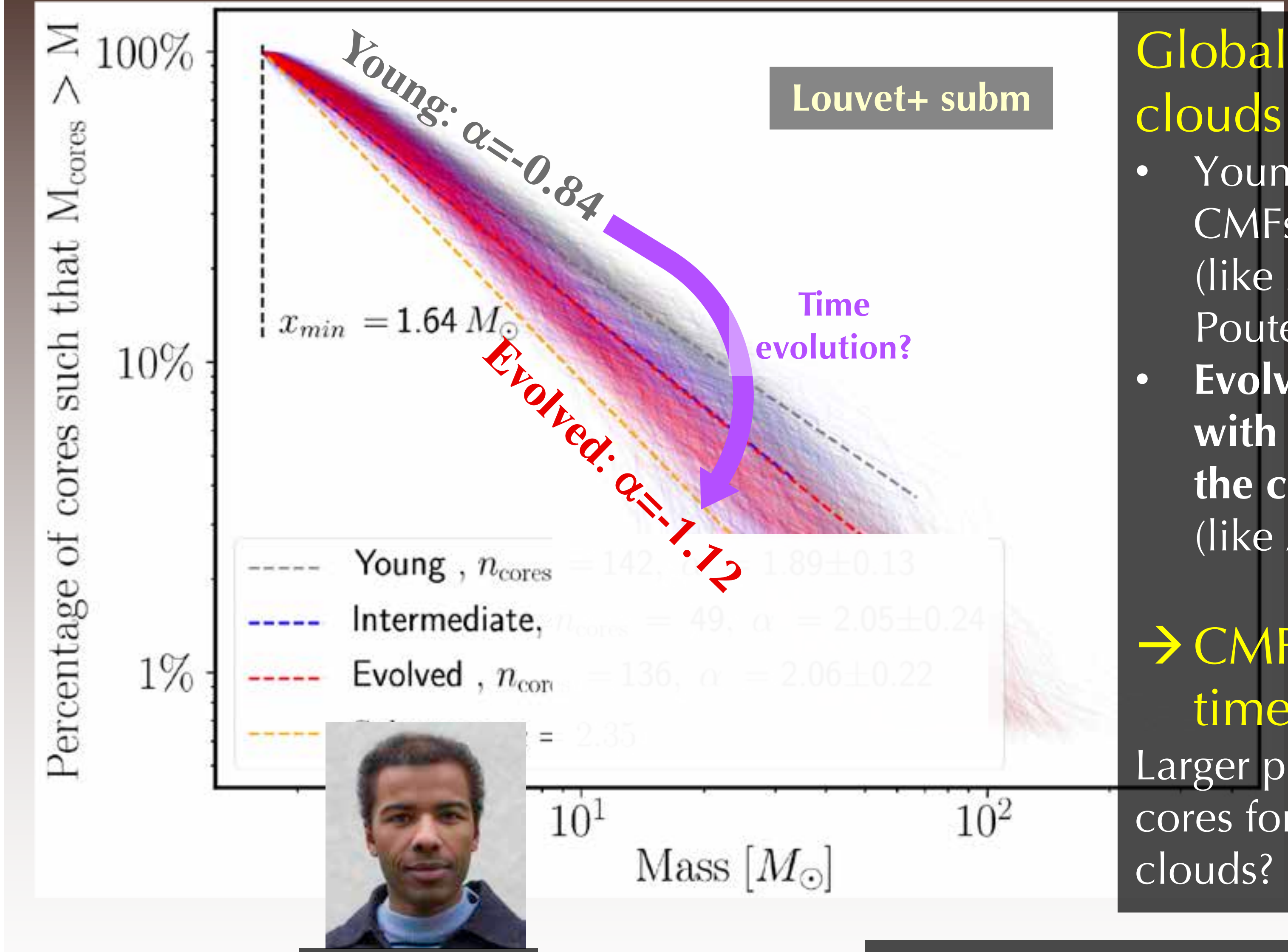

Motte+ 2018b


Pouteau+ 2022

Y. Pouteau

6-25 L$_\odot$ /M$_\odot$ on the clump scale

# Global CMFs in all ALMA-IMF clouds



F. Louvet

## Global CMF of ALMA-IMF clouds is again top-heavy!

- Young and Intermediate CMFs are top-heavy (like Motte+ 2018b; Pouteau+ 2022, 2023).
- **Evolved CMF reconciles with the Salpeter slope of the canonical IMF** (like Armante+ 2024).

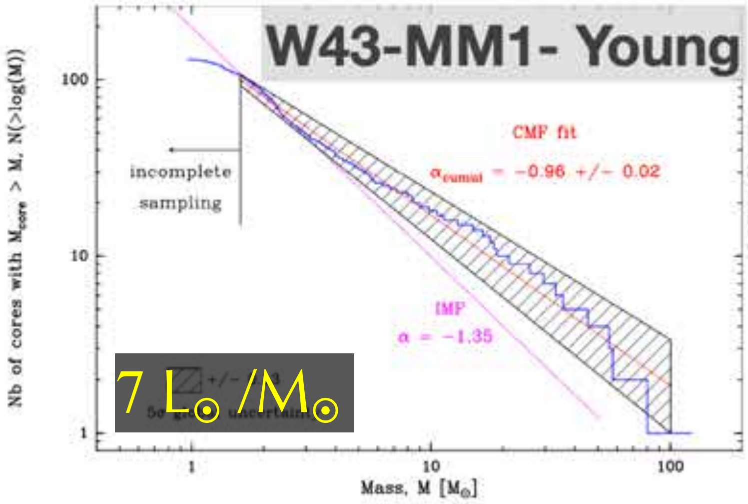
→ CMF evolution with time?

Larger proportion of low-mass cores forming in Evolved clouds?

Fit using MLE (Alstott+ 2014)

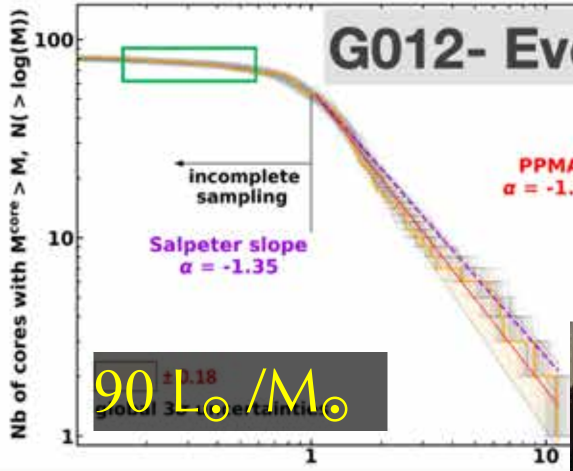
# Evolution of CMFs during SF bursts

## CMF steepening with evolution.



**Main burst**
**Enhanced star formation**
**Top heavy CMF**

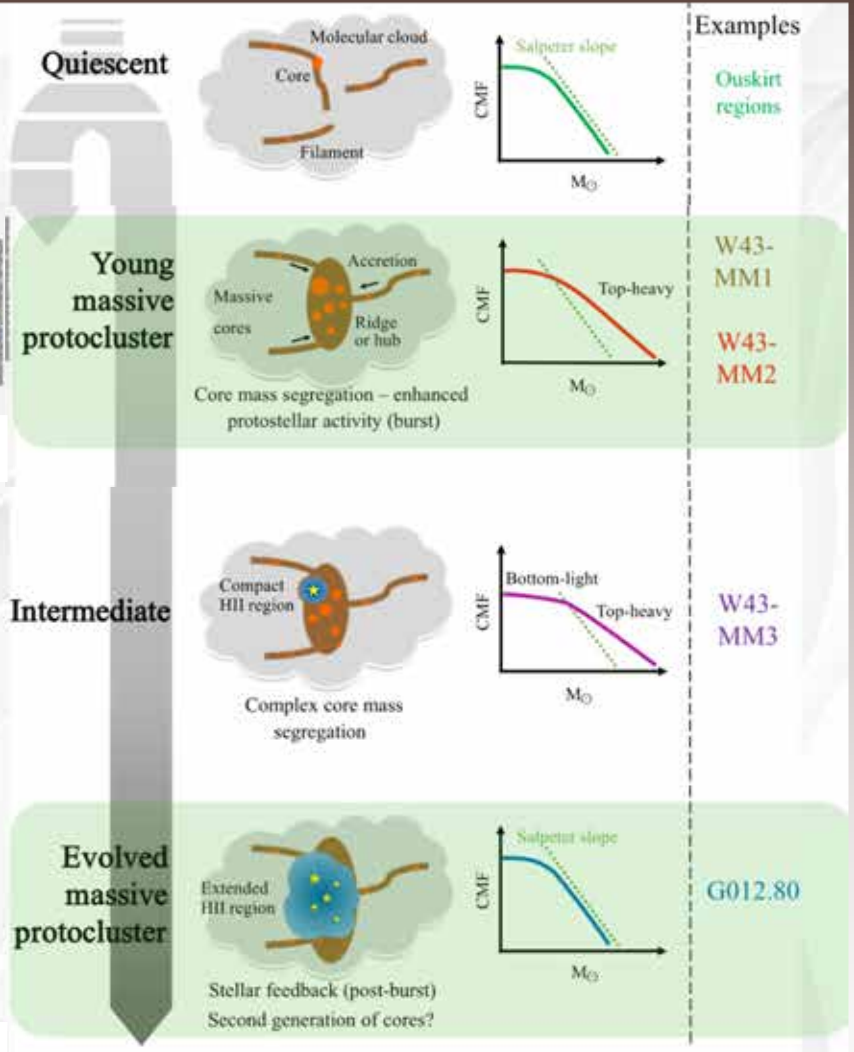
***Motte + 2018b***



M. Armante

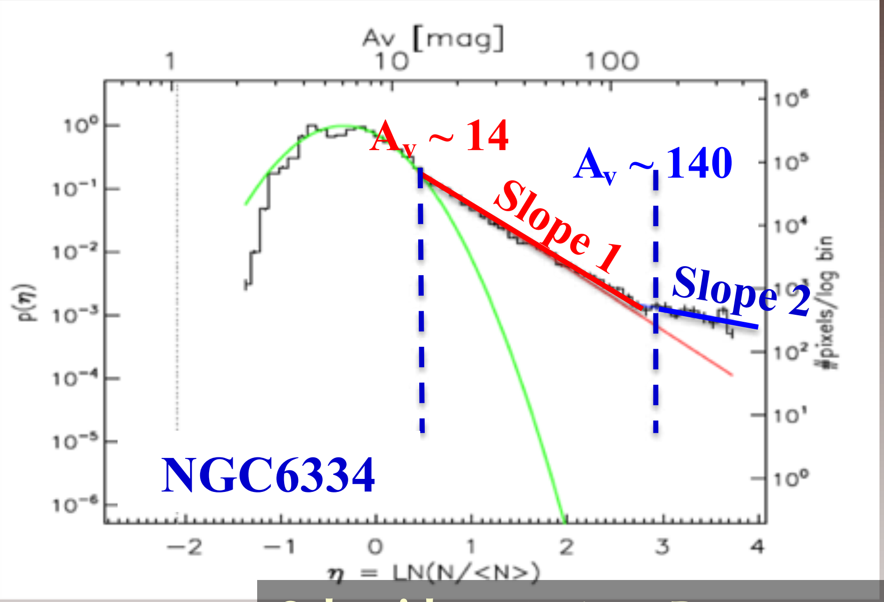
**Post burst**
**Extended HII regions**
**Salpeter CMF**

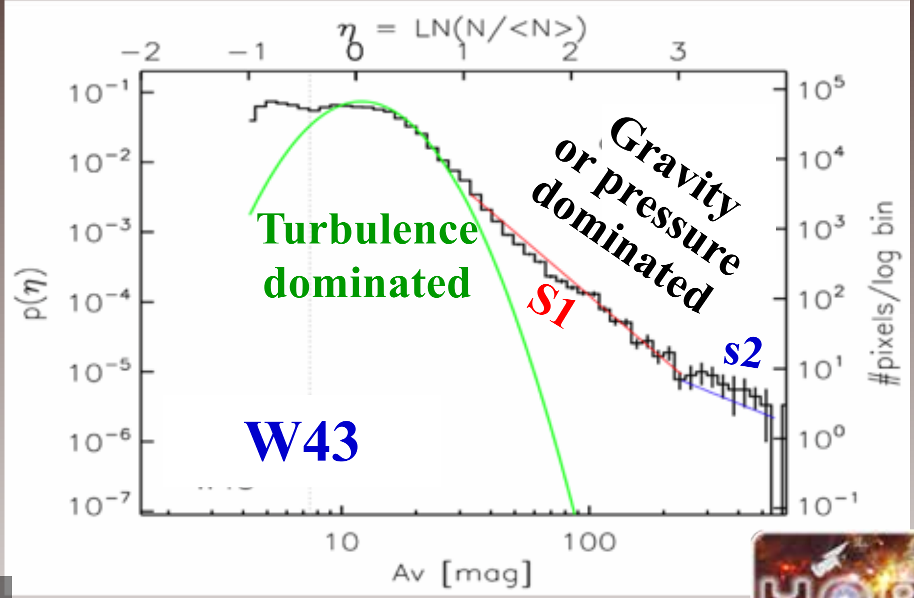
***Armante + 2024***



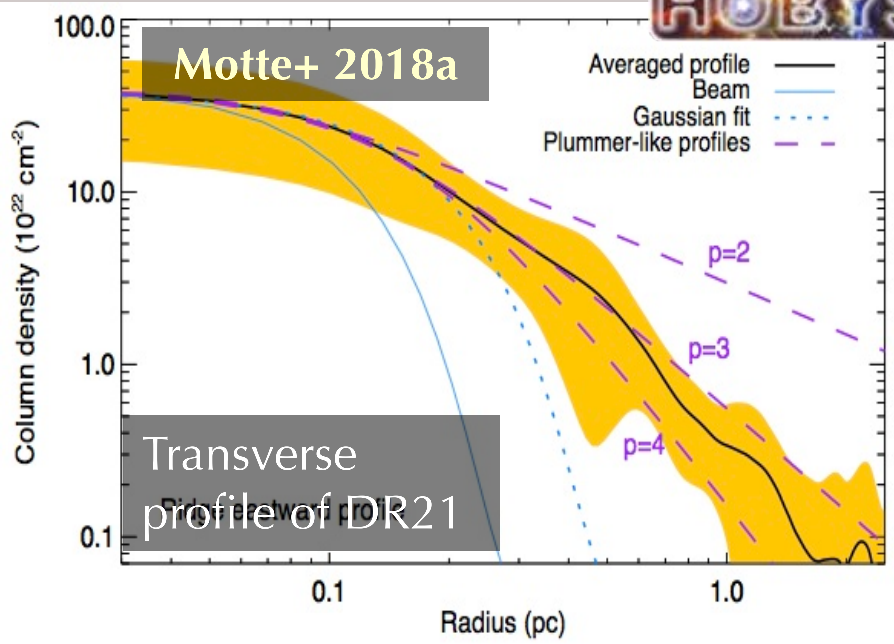
**Pouteau+ 2023; Armante+ 2024**

# PDFs with 2 power-law tails seem characteristic of high-mass SF clouds





Schneider+ 2015c; Rayner+ 2017



Motte+ 2018a

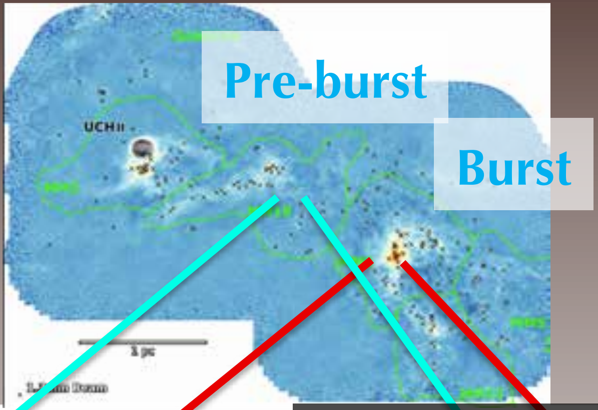
Transverse profile of DR21

Slopes suggest centrally concentrated ridges/hubs with atypical density profiles

→ Confirmed by direct measurements (Didelon+ 2015; Motte+ 2018).

# The more concentrated the cloud gas (SF burst), the flatter the CMF

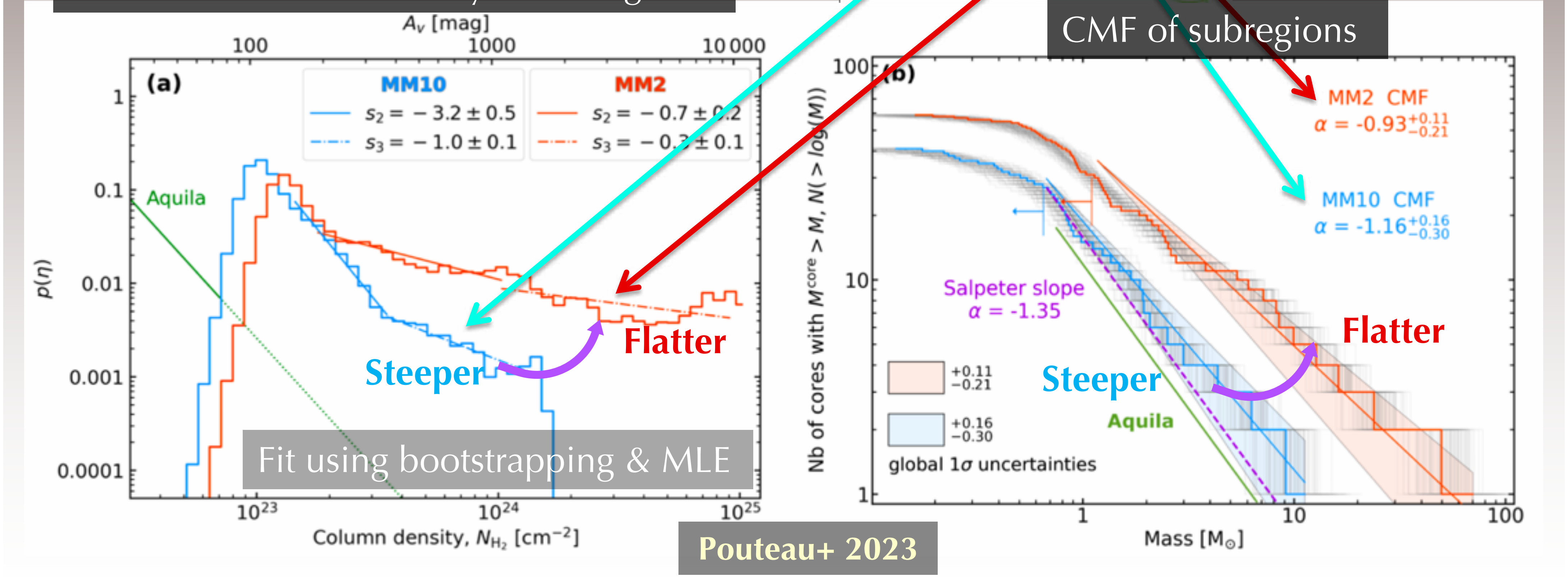
Correlation of the slopes of
- the secondary tail of $N_{H2}$ PDF
- the high-mass end of the CMF



Y. Pouteau

PDF of the column density in subregions

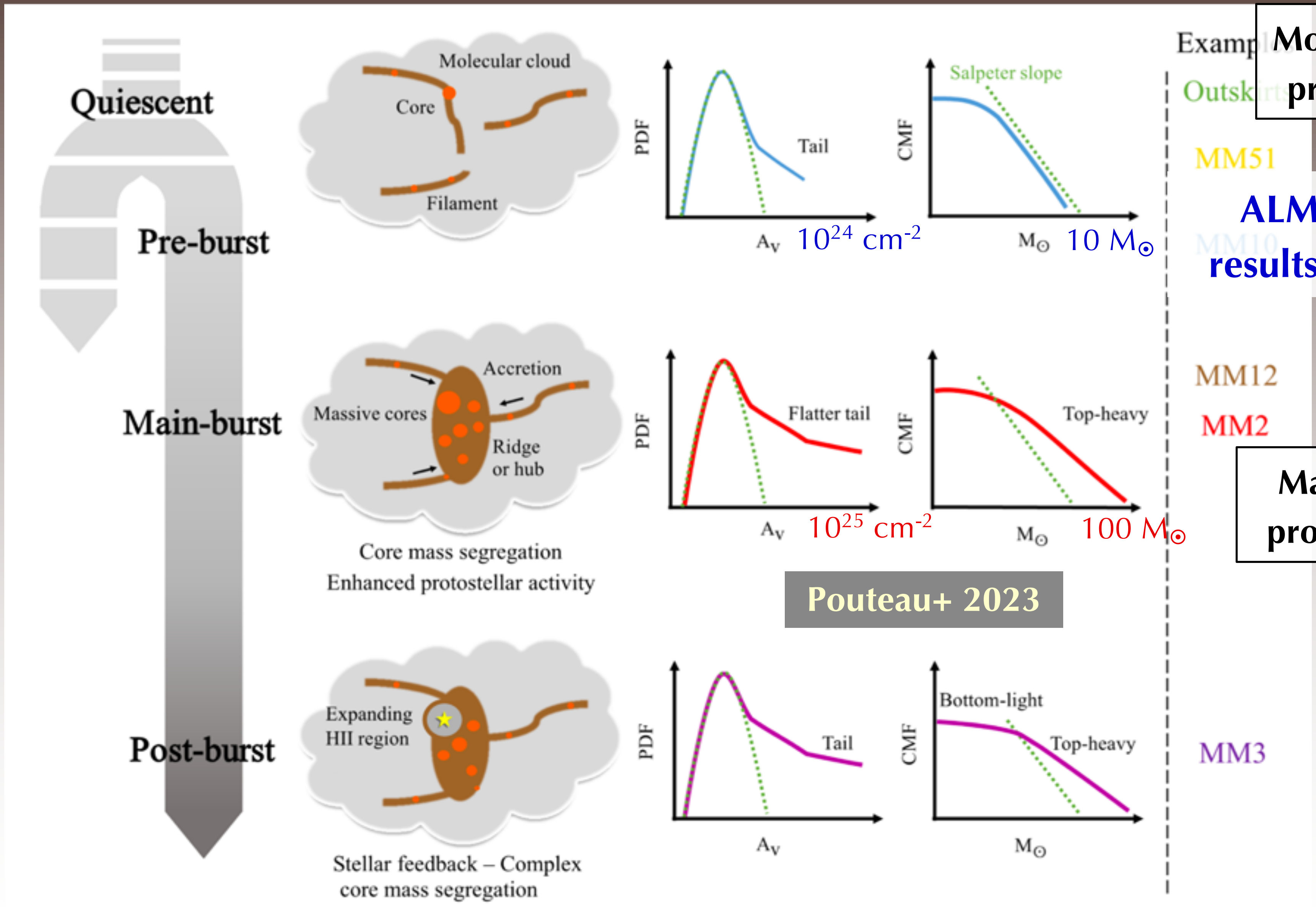
CMF of subregions



Fit using bootstrapping & MLE

Pouteau+ 2023

# Link between the cloud PDFs and CMFs during SF bursts



Pouteau+ 2023

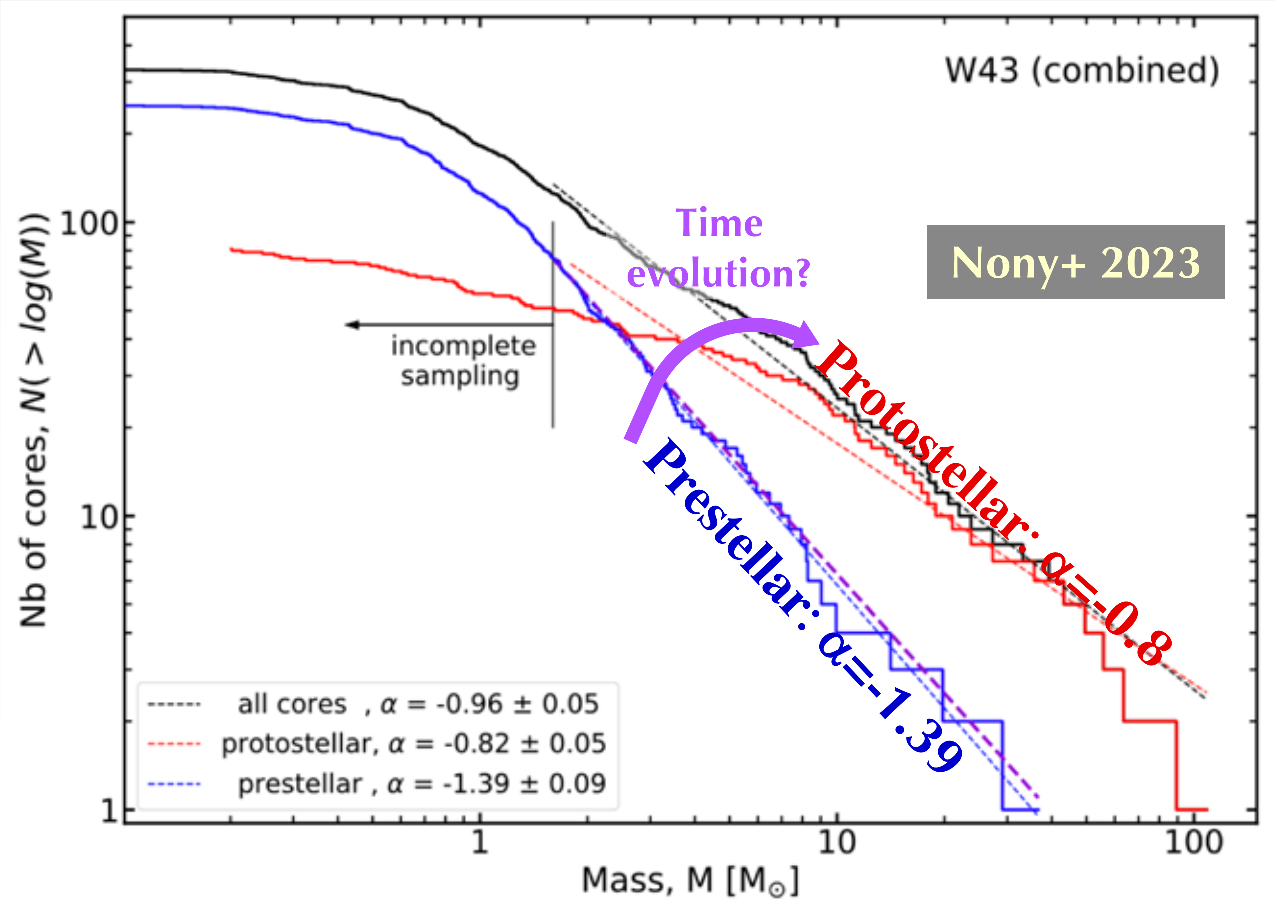
Mostly low-mass, prestellar cores

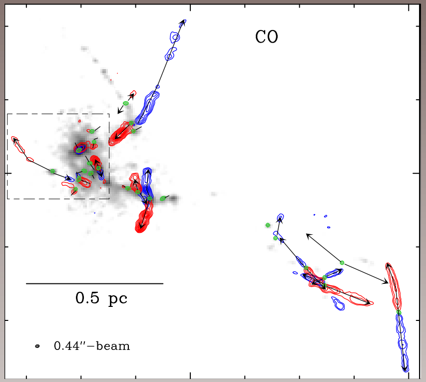
**ALMAGAL 1st results with L/M?**

Many high-mass protostellar cores

# Prestellar versus protostellar CMFs

Cores before collapse are prestellar. Cores collapsing and driving outflows (Nony+ 2019, 2023, in prep; Towner+ 2024; Valeille-Manet + in prep) are protostellar.





T. Nony

- Protostellar CMF is top-heavy
- Prestellar CMF reconciles with the Salpeter slope of the canonical IMF.

→ CMF evolution with time?

Run away accretion at young stages?

# Part IV
# Observed core mass functions

The CMF/IMF ressemblance in local clouds suggests a direct relationship between core mass and star mass.

But in denser, more dynamical clouds (ridges & hubs), the situation complexifies…

- pre-burst → "classical" $N_{H2}$ PDF → Salpeter-like CMF
- burst → more material at high $N_{H2}$ → top-heavy CMF
- Post-burst → back to the "classical" $N_{H2}$ PDF → Salpeter-like CMF

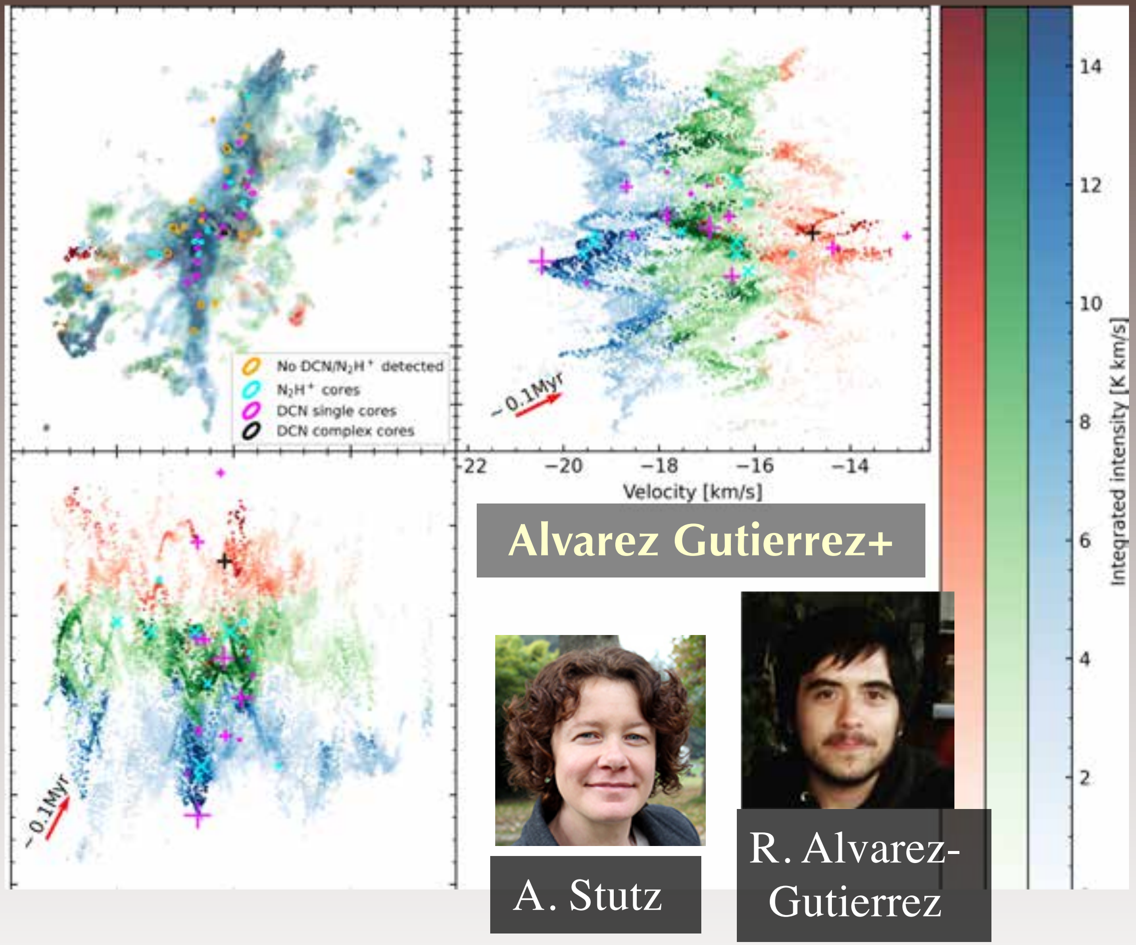
We must now take into account core mass growth and sub-fragmentation to predict the resulting IMF

**QUESTIONS!**

# Outline / Part V

1. Introduction
2. Algorithms to identify large populations of cores
3. Variety of environment in the MW
4. Core mass functions (CMFs)
5. The resulting IMF…
    - Core mass growth associated with gas flows
    - Core sub-fragmentation associated with a fragmentation cascade

# $N_2H^+$ gas mass inflow toward cores



**Alvarez Gutierrez+**

A. Stutz

R. Alvarez-Gutierrez

Cores coupled to the dense gas (DCN versus $N_2H^+$ $V_{LSR}$).

Multiple $N_2H^+$ velocity components within ~4 km/s.

“v-shaped” structures in PV digrams (Alvarez Gutierrez et al.+; Sandoval Garrido+; Salinas Cornejo+)

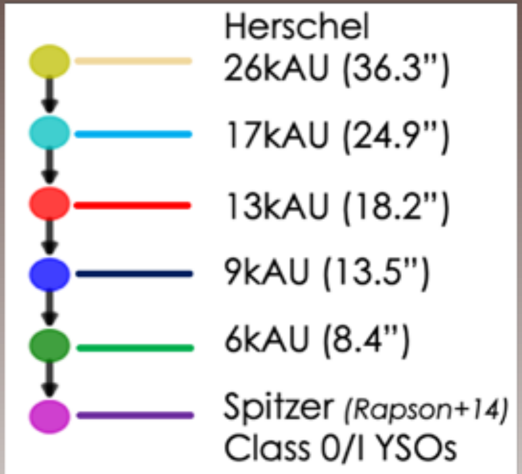
“v-shaped” structures may indicate inflow. Gradients give timescales of ~50 kyr → Core mass growth estimation and CMF evolution TBD

# Hierarchical cascade of cloud fragmentation

Graph multi-scale analysis connecting catalogs of Herschel clumps-to-cores objects and Spitzer YSOs (Thomasson+ 2022).
YSOs population : ~50% located in hierarchical structures.

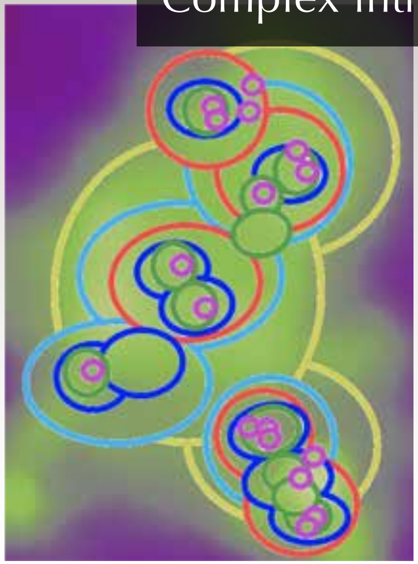
Single object : linear structure

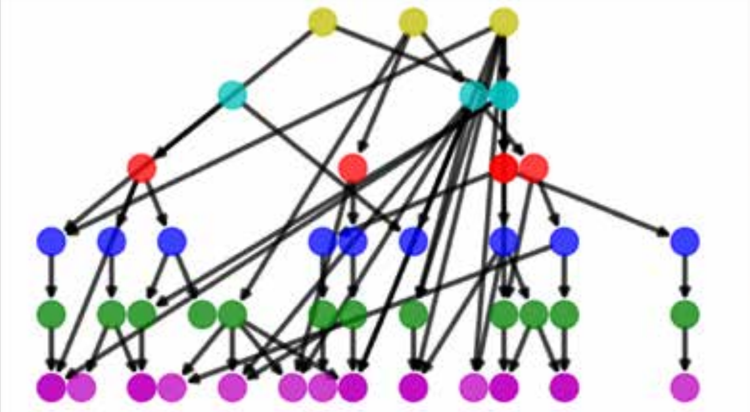
Network representation



In NGC2264, average fragments multiplicity (assuming fractal network):
$\mathcal{F}$ ~1.45 +/- 0.12
→ ~2 children/parent at each scale reduction!

Complex intrication : hierarchical structure



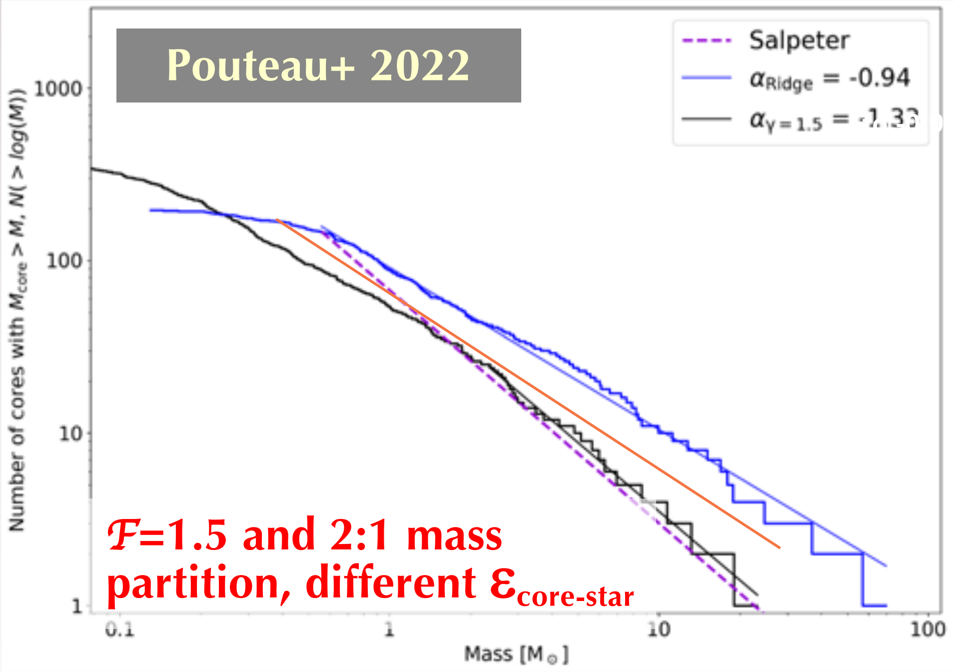


Thomasson+ 2022

# Core sub-fragmentation and resulting IMF

Scenarios of core sub-fragmentation to predict the resulting IMF:

- Thermal Jeans fragmentation
  → out of question.
- Hierarchical cascade down to 1000 au (Pouteau+ 2022)
- Hierarchical cascade down to 40-100 au, with varying mass partition (Thomasson+)



$\mathcal{F}$=1.5 and 2:1 mass partition, different $\varepsilon_{\text{core-star}}$

→ The CMF high-mass end could reconcile with the Salpeter slope (Thomasson+). The fractality coefficient and mass partition needs to be constrained in ALMA-IMF protoclusters…

# Take-away messages

The definition of gas mass reservoirs for the formation of single stars/little systems is necessarily complex.

Core extraction techniques focus on local peaks in images tracing $N_{H2}$.

The high-mass end CMF of young, massive protoclusters departs from the Salpeter slope. It is probably related to the gas distribution @ high $N_{H2}$.

Predicting the resulting IMF requires knowledge of the core mass growth and core sub-fragmentation.

What's next? ALMA @ higher resolution, M-L diagrams…
Confrontation observations/simulations
→ talk to Arturo Nunez, Simon Chevalier…

# Thanks!

Questions…