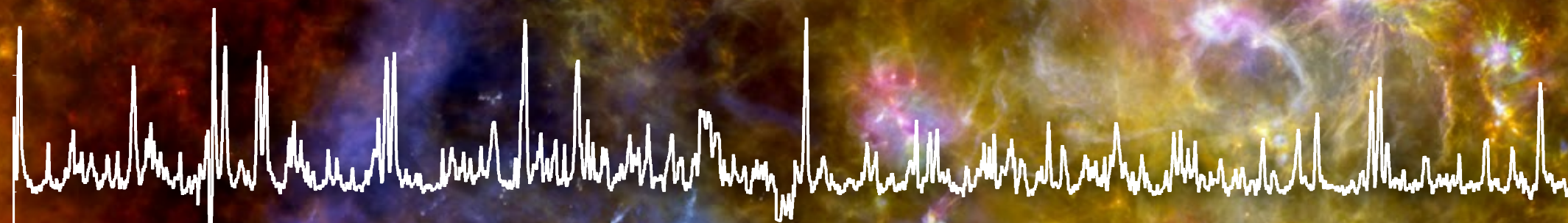


<https://nascent-stars.cnrs.fr/>



# Emerging molecular complexity towards high-mass protostars



## Lessons learned from ALMA-IMF and NASCENT-stars

*Lessons learned from ALMA-IMF and NASCENT-stars*



**Dr. Timea Csengeri**

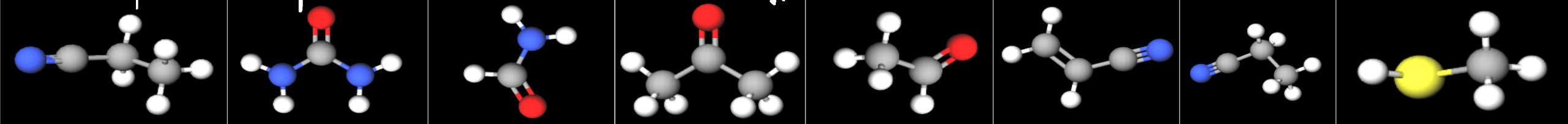
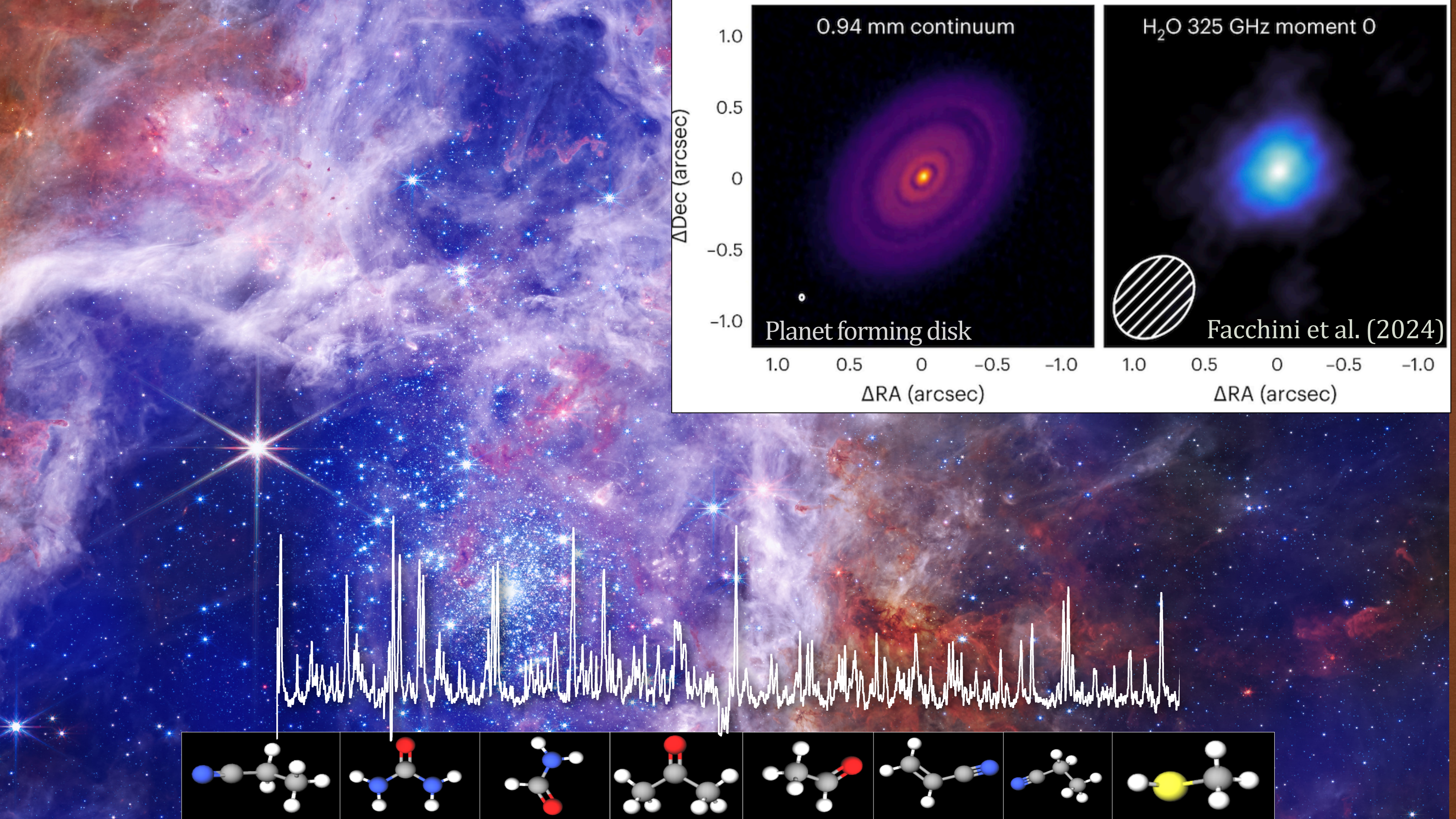
**Motte (PI); Ginsburg (co-PI); Sanhueza (co-PI); Louvet (co-PI);**

Csengeri, T.; Pouteau, Y.; Stutz, A. M.; **Bontemps**, S.; Cunningham, N.; López-Sepulcre, A.; **Brouillet**, N.; Galván-Madrid, R.; Maud, L.; Men'shchikov, A.; Nakamura, F.; Nony, T.; Álvarez-Gutiérrez, R. H.; Armante, M.; Baug, T.; Bonfand, M.; Busquet, G.; Chapillon, E.; Díaz-González, D.; Fernández-López, M.; Guzmán, A. E.; **Herpin**, F.; Liu, H. -L.; Olguin, F.; Towner, A. P. M.; Bally, J.; Battersby, C.; **Braine**, J.; Bronfman, L.; Chen, H. -R. V.; Dell'Ova, P.; Di Francesco, J.; González, M.; Gusdorf, A.; Hennebelle, P.; Izumi, N.; Joncour, I.; Lee, Y. -N.; Lefloch, B.; Lesaffre, P.; Lu, X.; Menten, K. M.; Mignon-Risse, R.; Molet, J.; Moraux, E.; Mundy, L.; Nguyen Luong, Q.; Reyes, N.; Reyes Reyes, S. D.; Robitaille, J. -F.; Rosolowsky, E.; Sandoval-Garrido, N. A.; Schuller, F.; Svoboda, B.; Tatematsu, K.; Thomasson, B.; Walker, D.; Wu, B.; Whitworth, A. P.; Wyrowski, F.

**Csengeri (PI), Bouscasse (coordinator at IRAM)**

Arumgum, Lopez-Sepulcre, Le Gal (IRAM), **Baudry, Bontemps, Braine, Brouillet**, Guilloteau, **Herpin, Kessler, Panda, Valeille-Manet** (LAB), Louvet, Motte (IPAG), **Coutens, Espagnet, Vastel** (IRAP), Wyrowski, Menten (MPIfR), Beuther, (MPIA), Galvan-Madrid (UNAM), Ortiz-Leon (INAOE), Garrod, Bonfand (U Virginia), Ginsburg (U Florida), Commercon (ENS-Lyon), Cunningham (SKA), **Dannhauer**, Simon, **Schneider** (U. Cologne), Gusdorf (LPENS)





# Molecular composition of protostellar envelopes

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How does the molecular composition, in particular the abundance and diversity of COMs, depend on physical properties, such as age and mass of the protostar?

*large bandwidth*

How does the complex interplay of physical processes such as radiative heating from the protostar, luminosity bursts and shocks impact the emergence of molecular complexity?

*resolution*

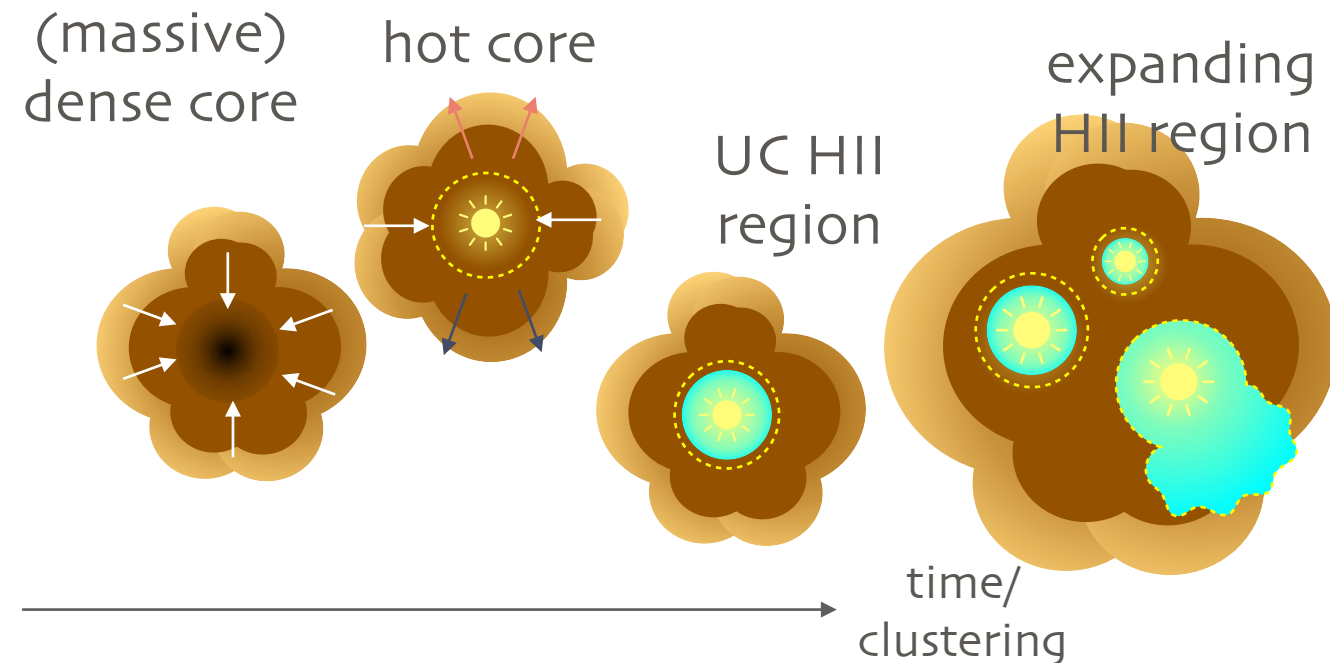
Does the external environment (radiation field, multiplicity) play a role in the chemistry of star forming cores?

*survey*

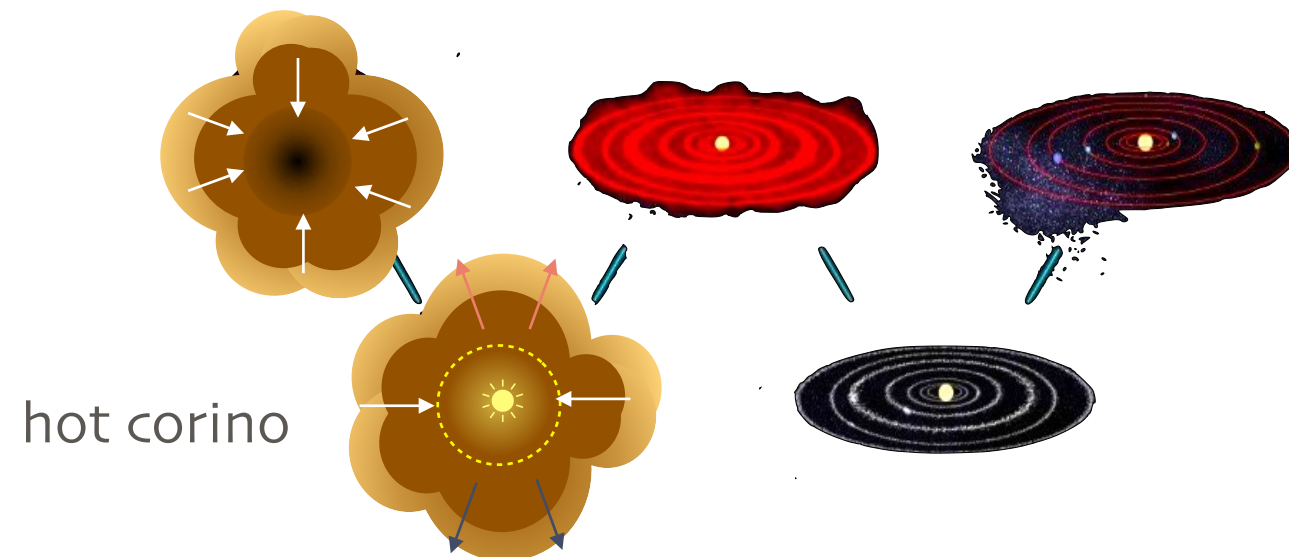
**Statistical astrochemistry** : *ALMA + NOEMA can provide a sensitive view of the molecular composition of envelopes and that over a range of protostellar masses*

# Emerging molecular complexity: when and where?

## O and early B-type stars



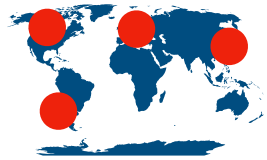
## Low mass stars



- Compared to Solar type stars, physical conditions for high-mass star and cluster formation is different (density, thermal history, radiation field)
- Different path for high-mass and low-mass star formation:
  - ▶ Radiative and mechanical feedback is significant ( $M_{\star} > 8-15 M_{\odot}$ )
  - ▶ High-mass stars mostly form in clusters: deeply embedded sources (well traced in thermal dust emission + molecular lines)

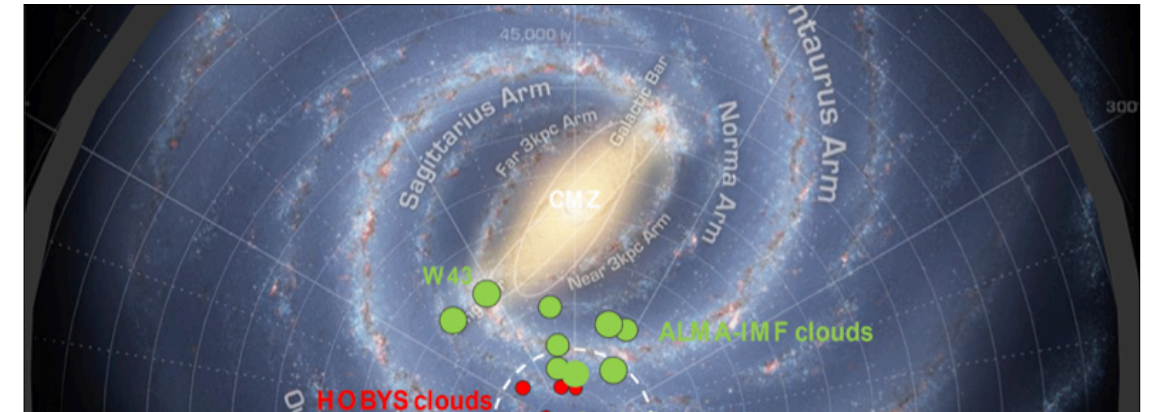
***Chemical differences between low and high-mass envelopes?***

# ALMA-IMF maps 15 high-mass star forming regions

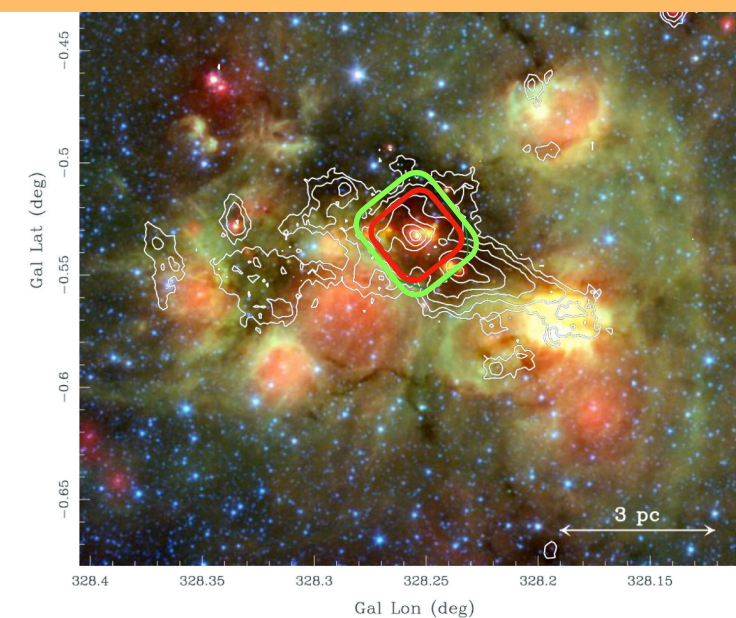
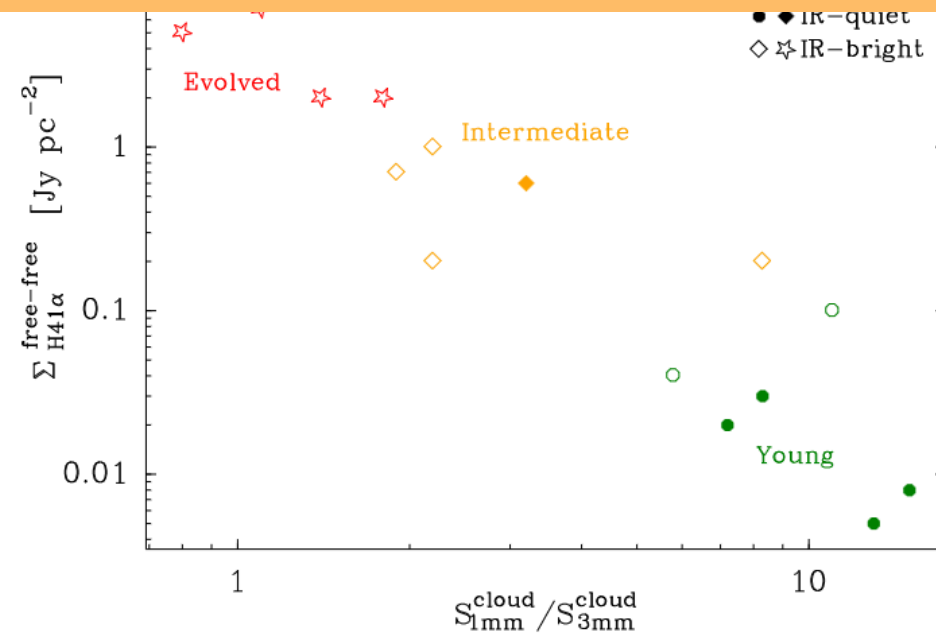
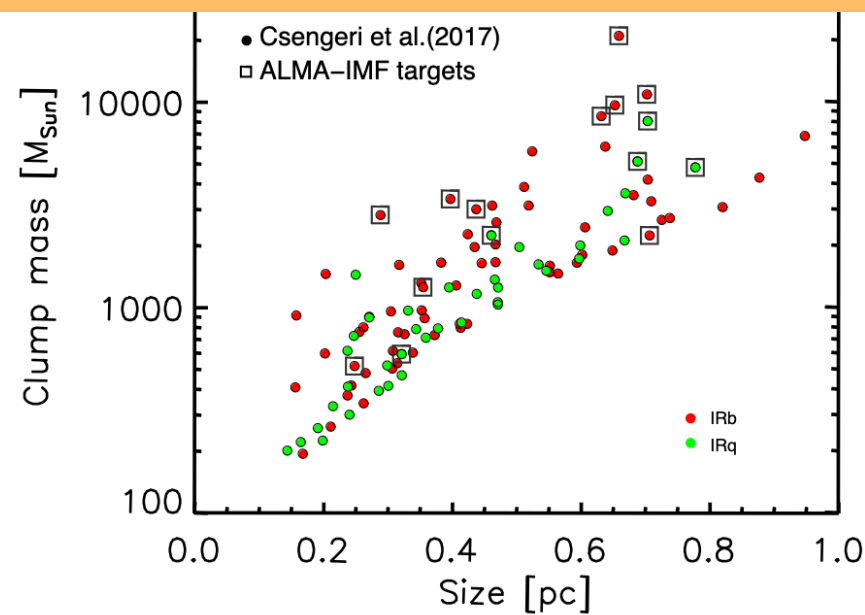


**PIs:** F. Motte, F. Louvet (IPAG), P. Sanhueza (NAOJ), A. Ginsburg (U. Florida)

- Massive clumps from ATLASGAL Schuller et al. (2009)  
Csengeri et al. (2014)
- Representative of different evolutionary stages:

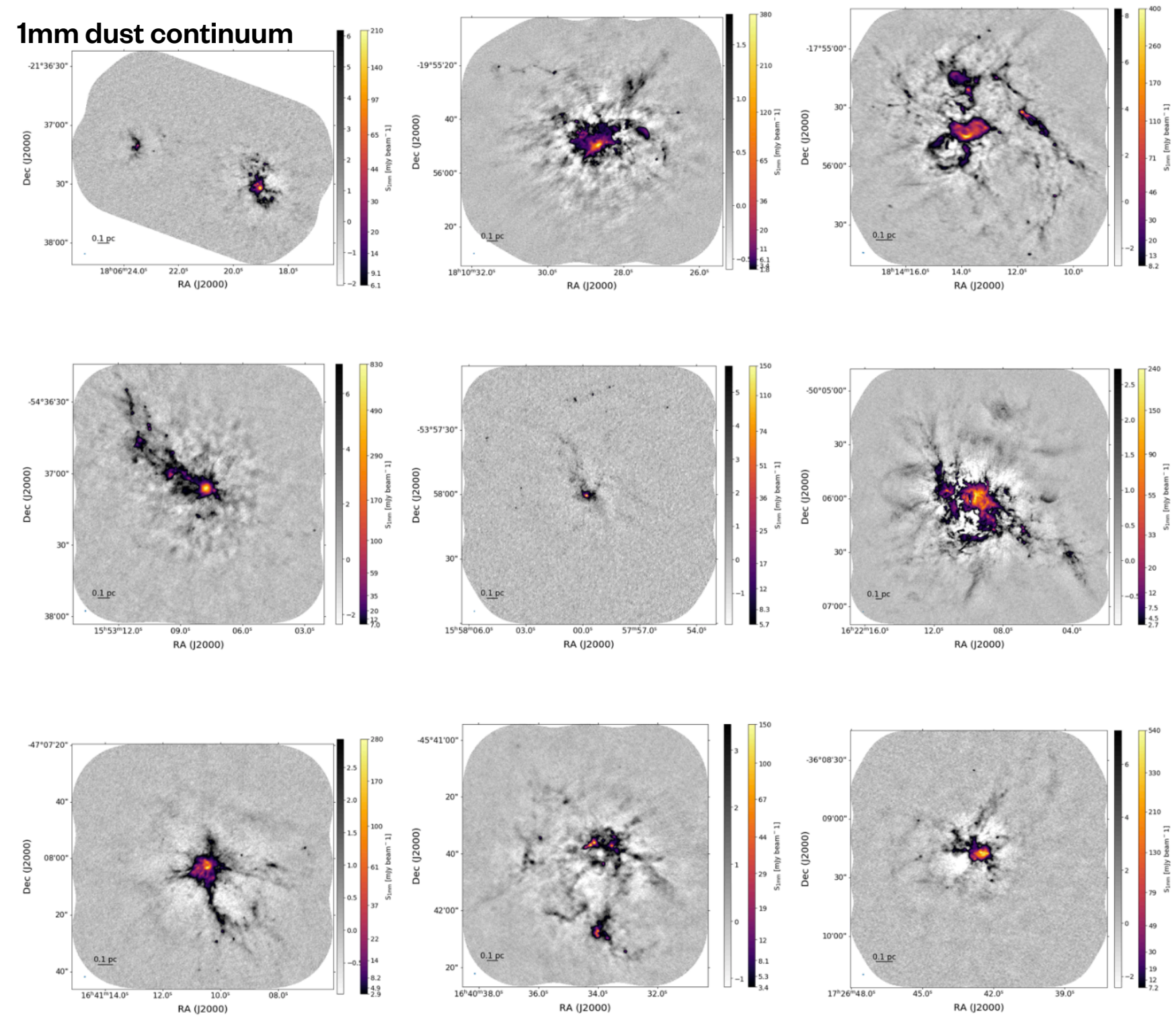


*What is the link between the stellar IMF and the core mass function of Galactic protoclusters?*

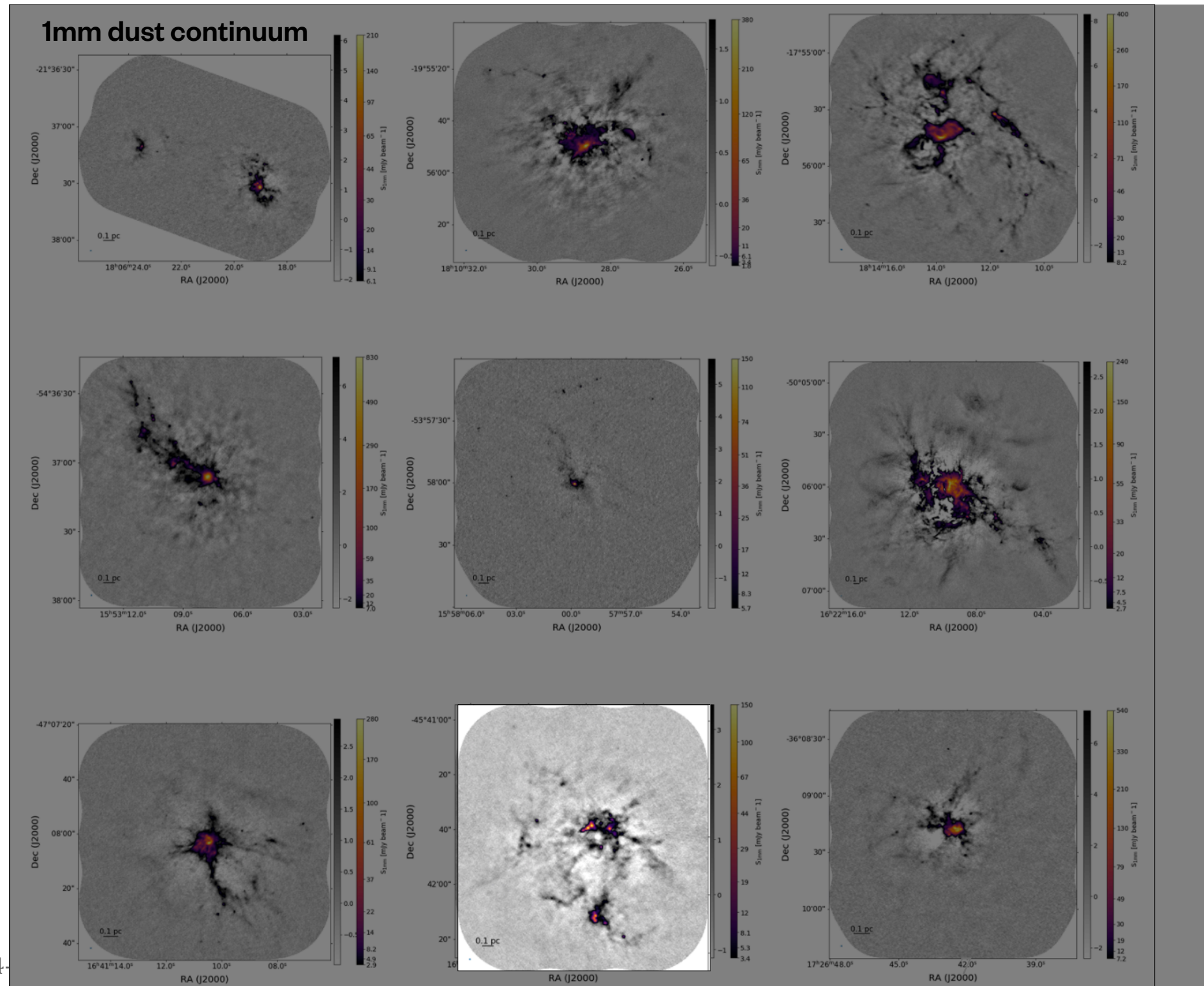


	(1)	(2)
W43-MM1	2 430	
W43-MM2	2 540	
G338.93	2 080	
G328.25	1 350	
G337.92	1 460	
G327.29	1 650	
<hr/>		
G351.77	1 540	
G008.67	2 250	
W43-MM3	2 690	
W51-E	1 640	
G353.41	1 590	
<hr/>		
G010.62	2 310	
W51-IRS2	2 560	
G012.80	2 110	
G333.60	2 330	

# ALMA-IMF reveals a rich population of protostars



# ALMA-IMF reveals a rich population of protostars



**ALMA-IMF. I.** Investigating the origin of stellar masses: Introduction to the Large Program and first results  
**Motte et al. (2022)**

**ALMA-IMF. II.** Investigating the origin of stellar masses: Continuum images and data processing  
**Ginsburg et al. (2022)**

**ALMA-IMF. III.** Investigating the origin of stellar masses: top-heavy core mass function in the W43-MM2&MM3 mini-starburst  
**Pouteau et al. (2022)**

**ALMA-IMF. IV.** A comparative study of the main hot cores in W43-MM1: Detection, temperature, and molecular composition  
**Brouillet et al. (2022)**

**ALMA-IMF. V:** Prestellar and protostellar core populations in the W43 cloud complex  
**Nony et al. (2023)**

**ALMA-IMF VI:** Investigating the origin of stellar masses: Core mass function evolution in the W43-MM2&MM3 mini-starburst  
**Pouteau et al. (2023)**

**ALMA-IMF VII:** First Release of the full Spectral Line Cubes: Core Kinematics Traced by DCN  $J=(3-2)$   
**Cunningham et al. (2023)**

**ALMA-IMF. VIII.** Combination of Interferometric Continuum Images with Single-dish Surveys and Structural Analysis of Six Protoclusters  
**Diaz-Gonzalez et al. (2023)**

**ALMA-IMF. IX.** Catalog and Physical Properties of 315 SiO Outflow Candidates in 15 Massive Protoclusters  
**Towner et al. (2024)**

**ALMA-IMF. X.** The core population in the evolved W33-Main (G012.80) protocluster  
**Armante et al. (2024)**

**ALMA-IMF. XI.** The sample of hot core candidates: A rich population of young high-mass protostars unveiled by the emission of methyl formate  
**Bonfand et al. (2024)**

**ALMA-IMF. XII.** Point-process mapping of 15 massive protoclusters  
**Dell'Ova et al. (2024)**

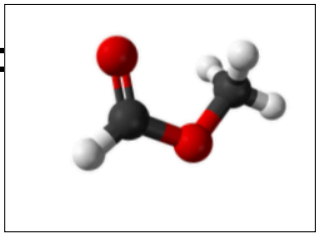
**ALMA-IMF: XIII.** N<sub>2</sub>H<sup>+</sup> kinematic analysis of the intermediate protocluster G353.41  
**Alvarez-Gutierrez et al. (2024)**

**ALMA-IMF. XIV.** Free-Free Templates Derived from H41 $\alpha$  and Ionized Gas Content in 15 Massive Protoclusters  
**Galvan-Nadrid et al (2024)**

**ALMA-IMF: XV.** Core mass function in the high-mass star formation regime  
**Louvet et al (2024)**

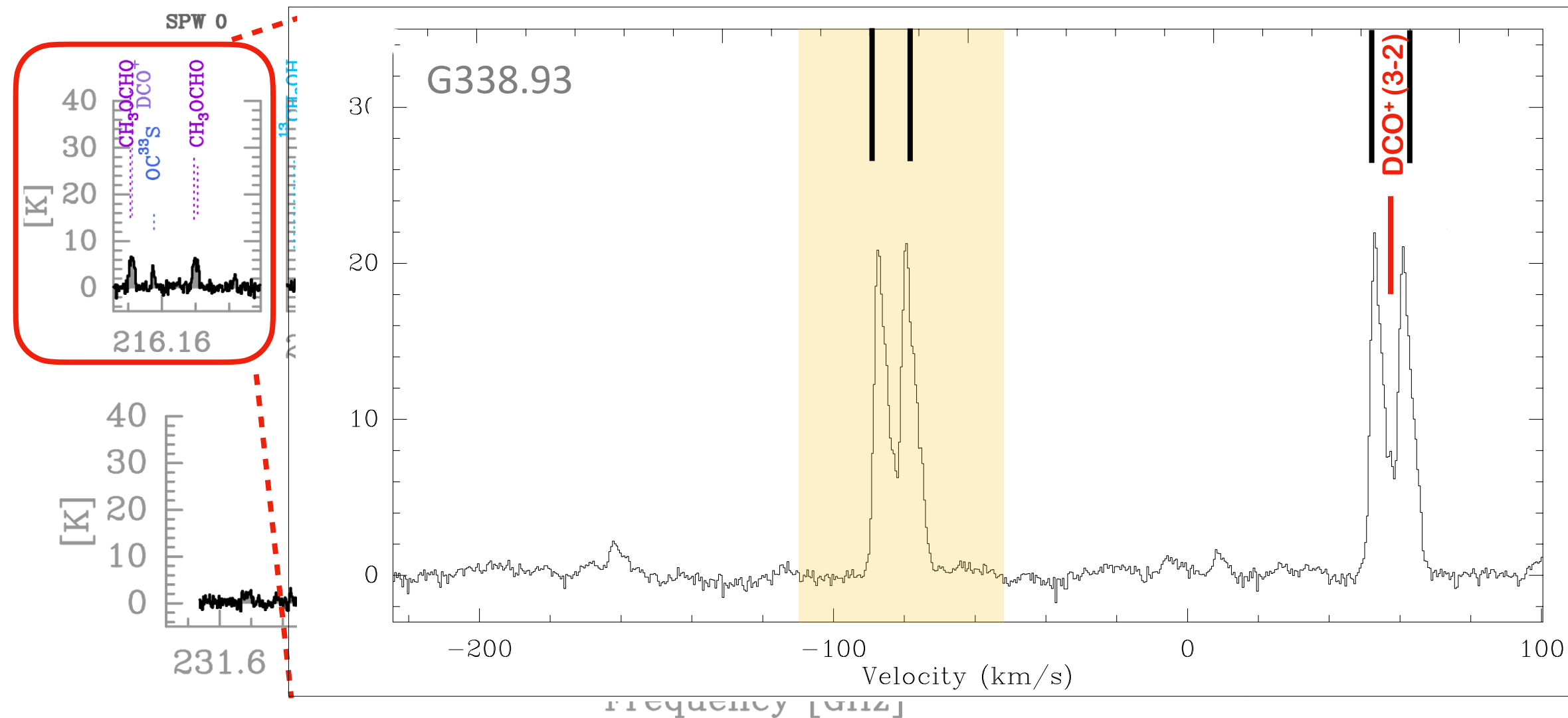


# Chemically rich sites in ALMA-IMF



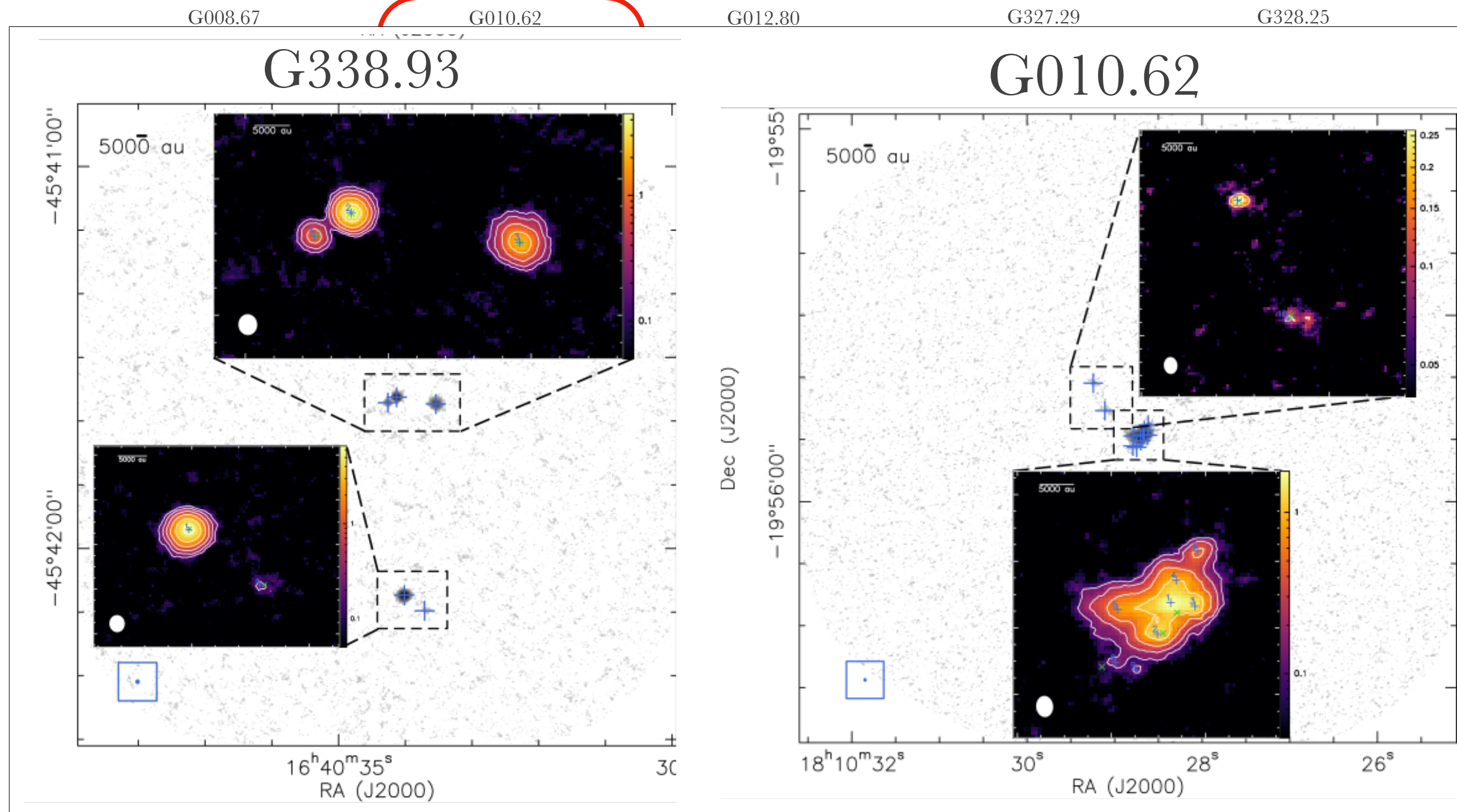
- ALMA-IMF Band 6 setup covers the 216.1 GHz  $\text{CH}_3\text{OCHO}$  lines
- **Tracer to search for chemically rich sites:**
  - Where do hot cores emerge?

Methyl formate ( $\text{CH}_3\text{OCHO}$ )



# Methyl formate emission in ALMA-IMF

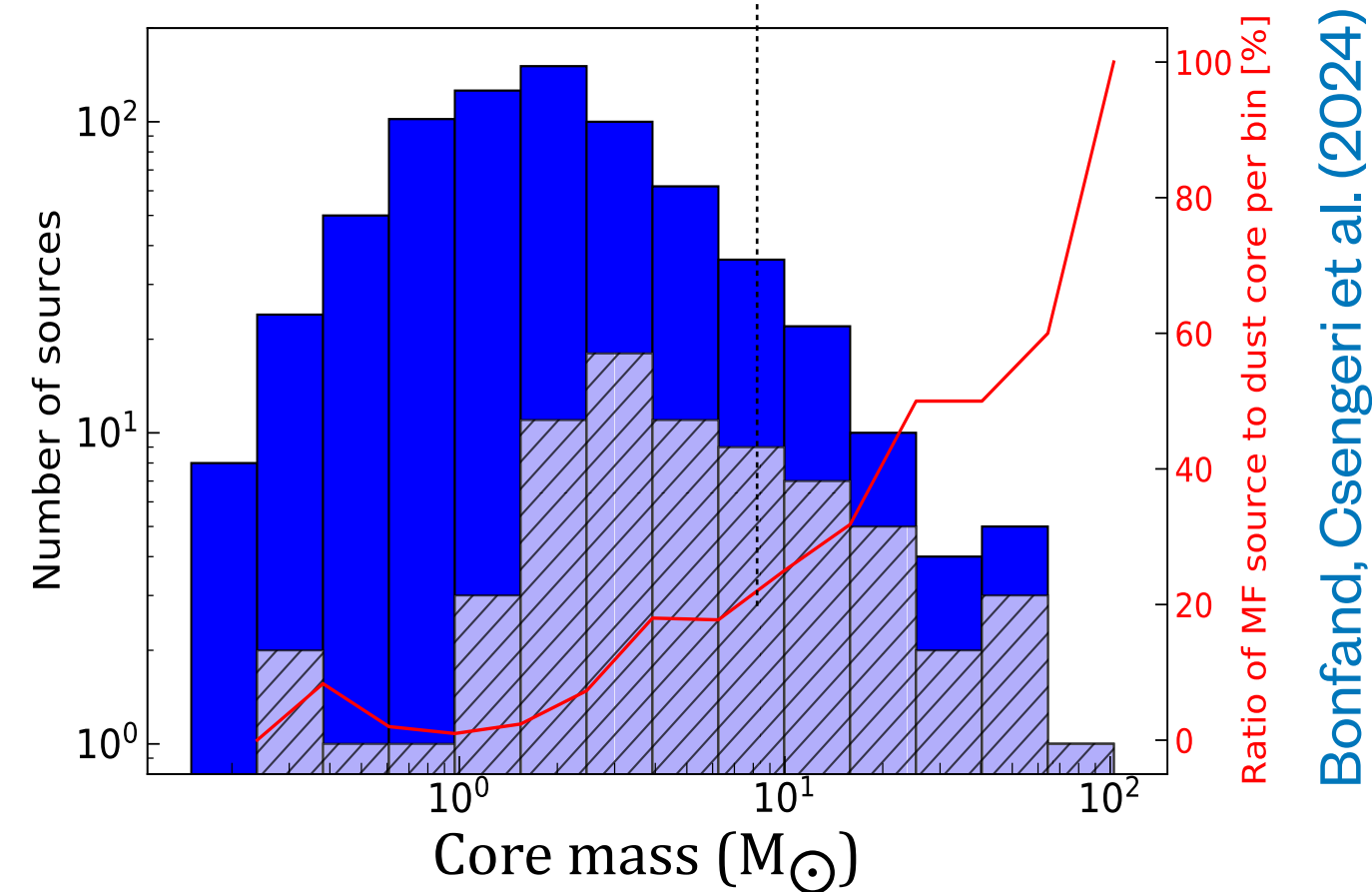
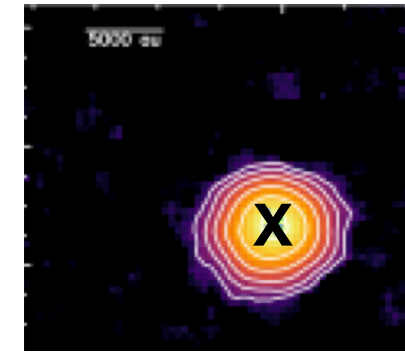
- Integrated intensity of the CH<sub>3</sub>OCHO lines at 216.2 GHz ( $E_{\text{up}}/k \sim 100$  K)



Bonfand, Csengeri et al. (2024)

# High-mass protostars all become hot cores

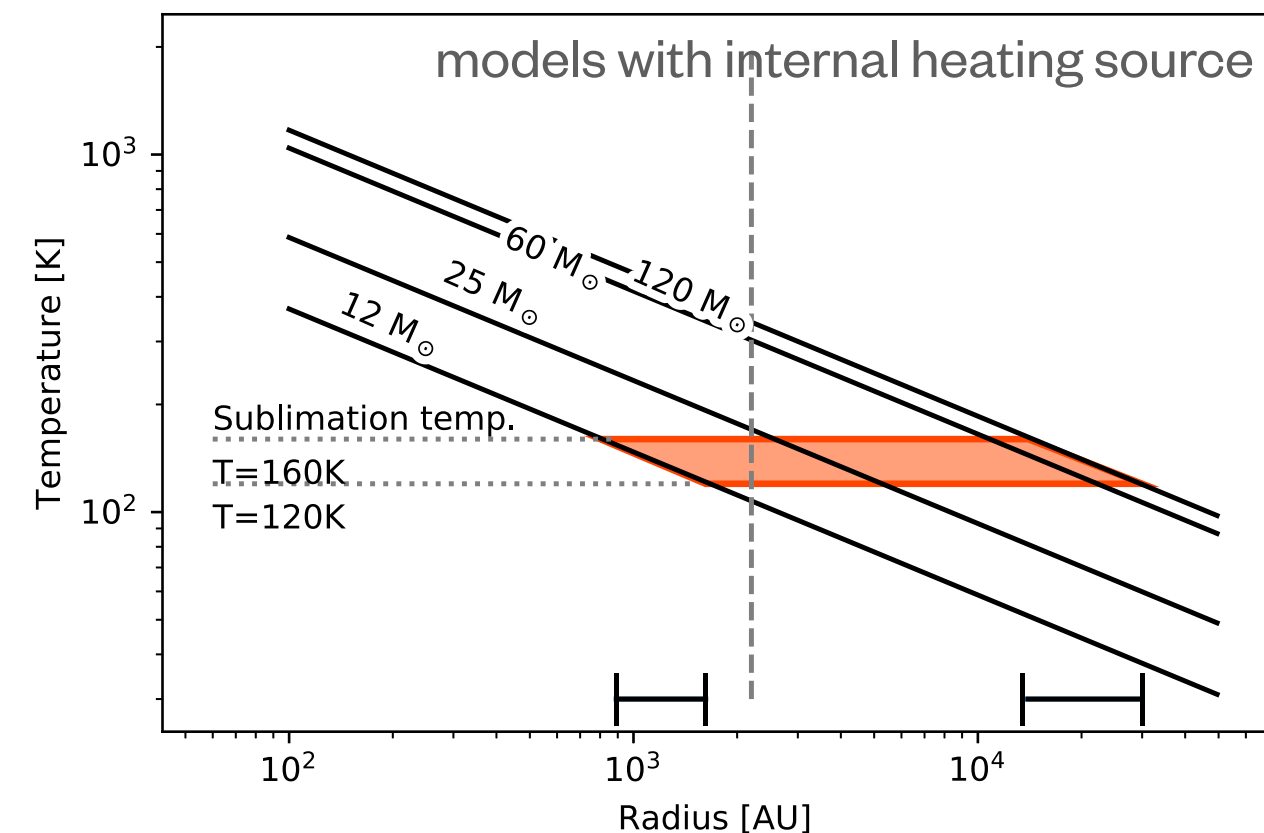
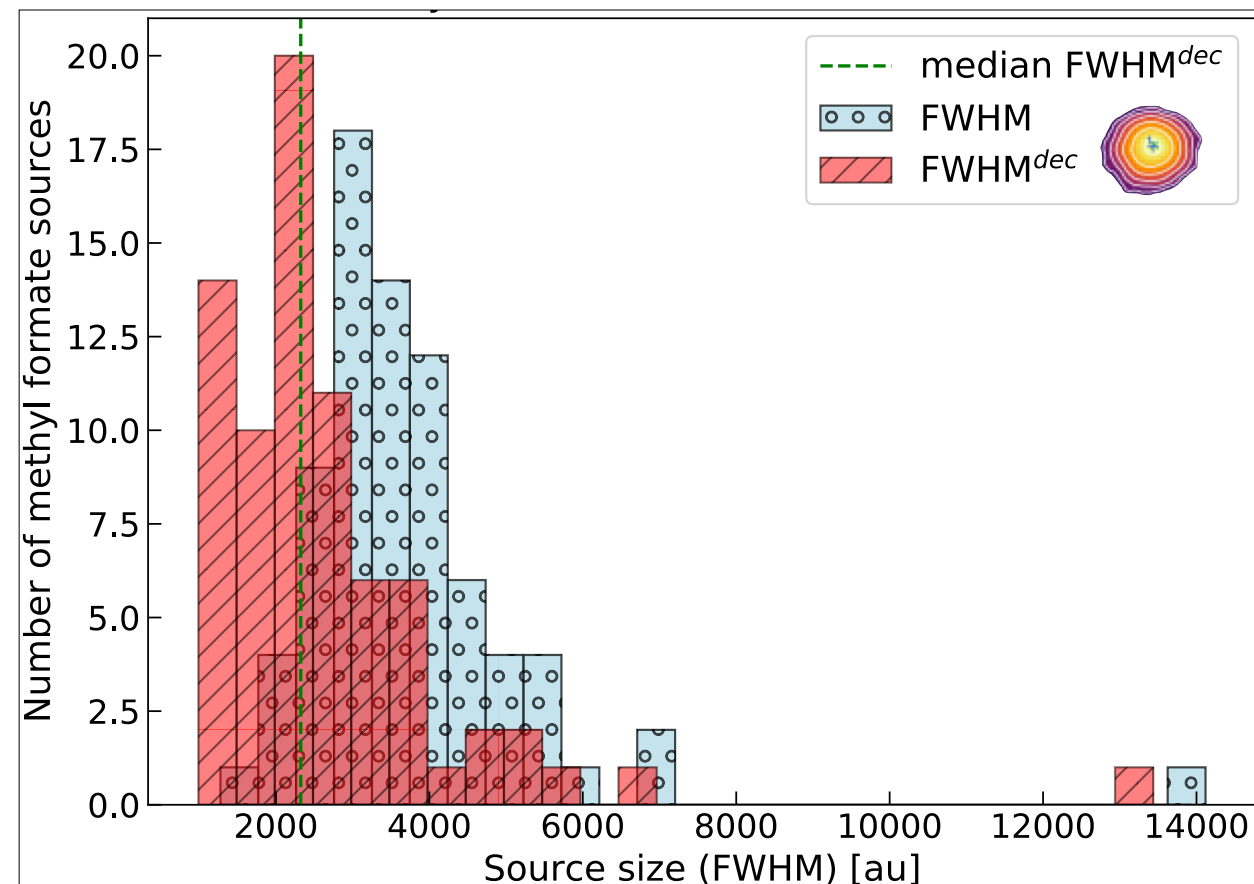
- Two classes: compact (central heating) and extended regions (collective effects, chemistry)
- Source extraction with GExt2D ~ 70 compact sources with region to region variations
- Correlation with the dust continuum cores:
  - ▶ Continuum emission towards all compact methyl formate sources, but association to compact continuum cores is not always trivial
- Most massive cores (excluding free-free sources) are all hot core candidates



Bonfand, Csengeri et al. (2024)

# Are all methyl formate sources hot cores?

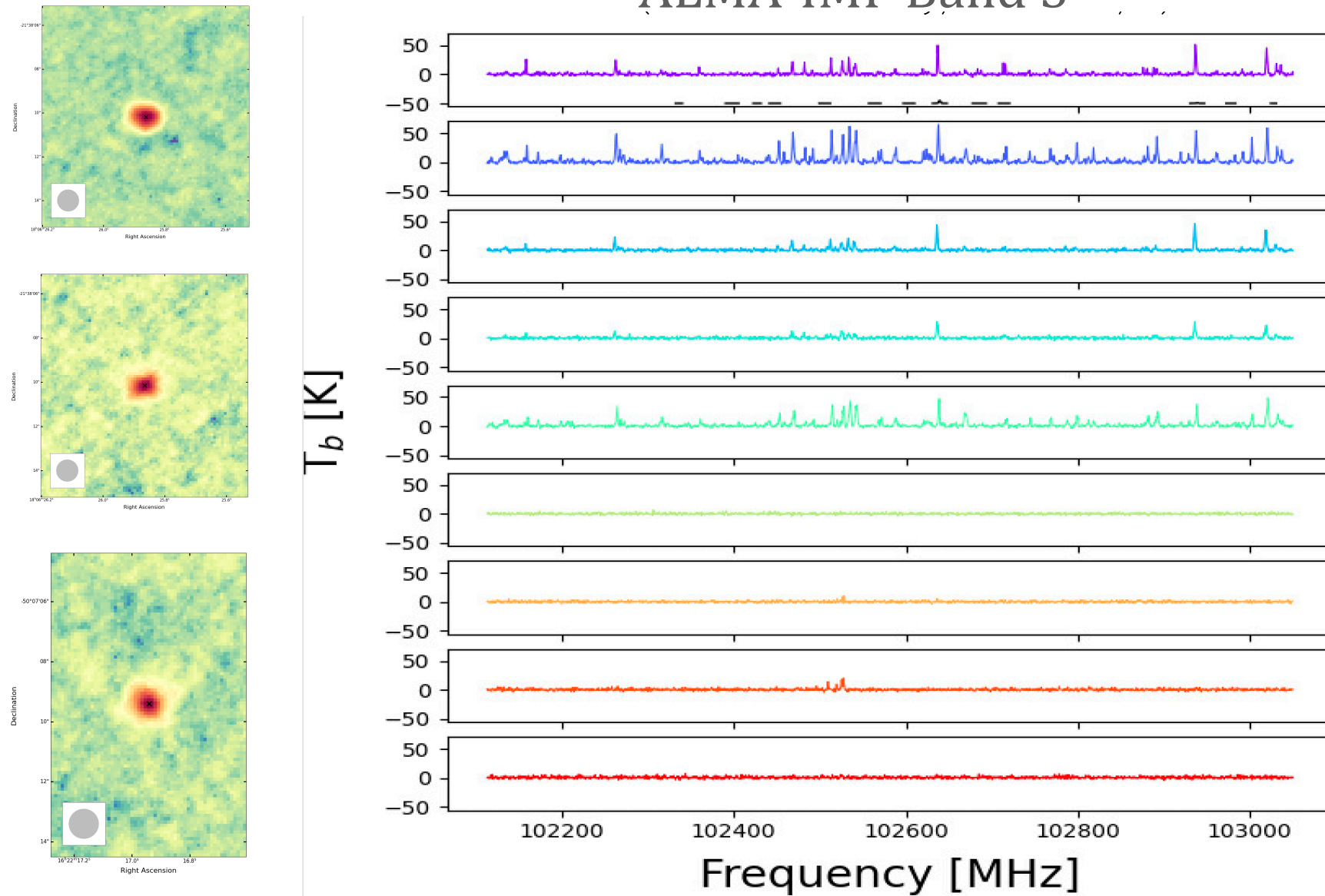
- Most massive cores: **population of hot cores with several new hot cores identified (76%)**
- Size distribution : 500 - 13200 au
- About 50% of the sources are lower mass cores
- Most extended “extreme” hot cores: could be consistent with a single very massive protostar of  $\sim 10^6 L_{\text{sol}}$
- **Low-mass  $\text{CH}_3\text{OCHO}$ : intermediate mass sources, large hot corinos or shocks?**



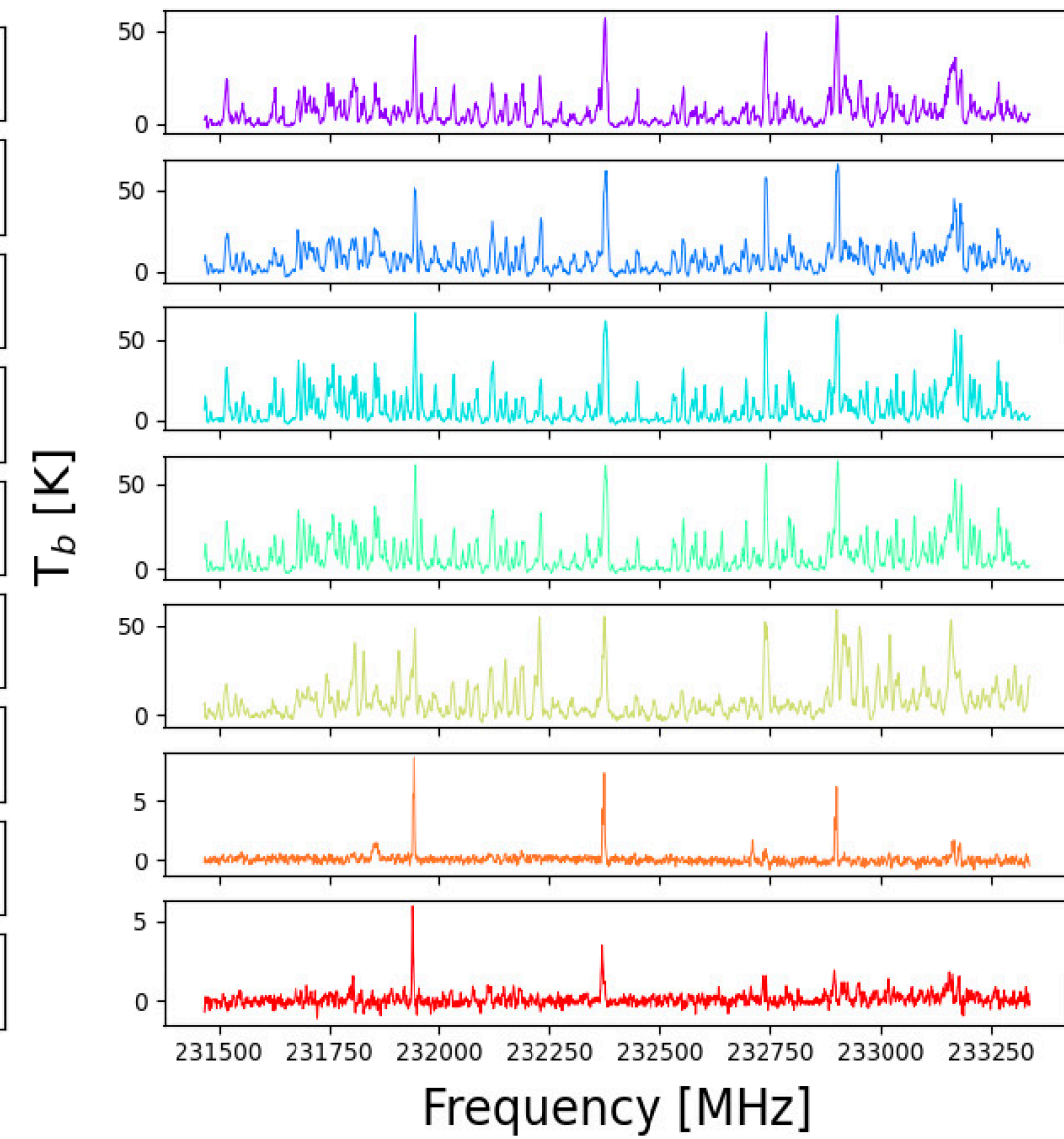
# Towards a statistical sample

Methyl formate cores from the W51-E protocluster

ALMA-IMF Band 3



ALMA-IMF Band 6

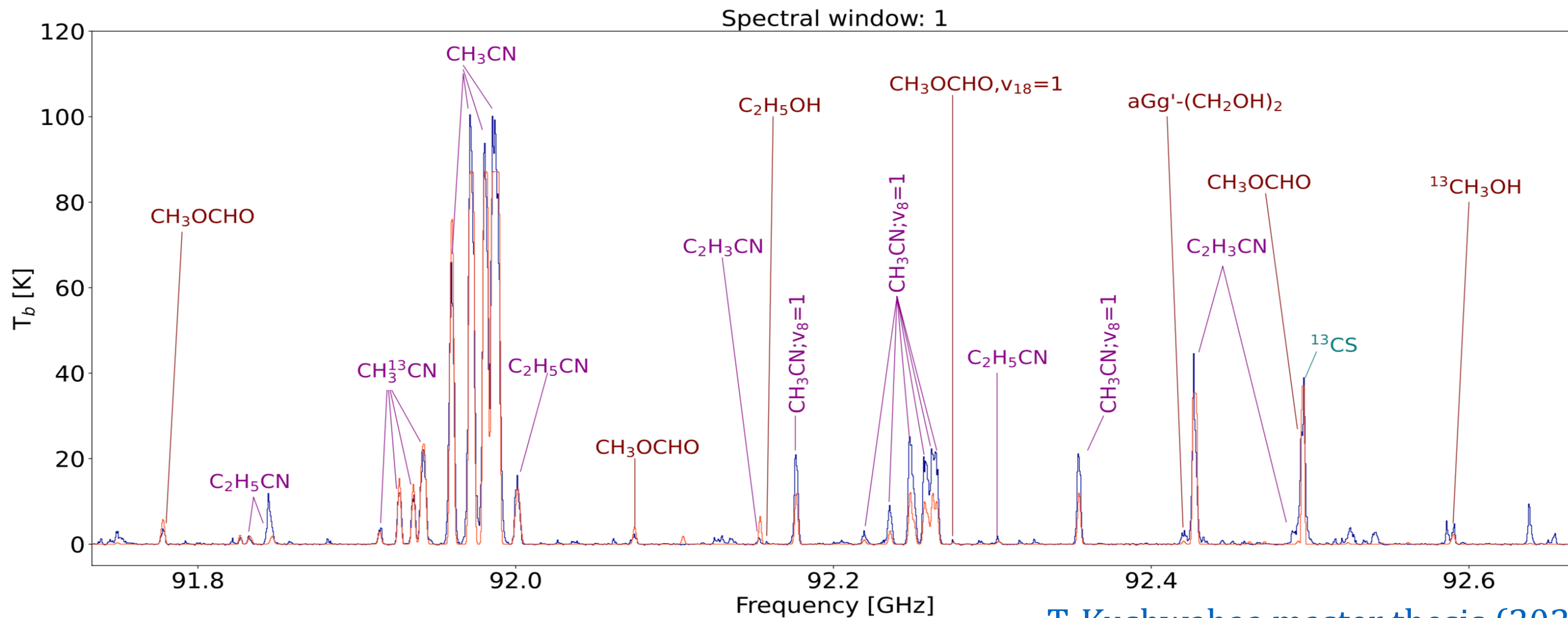


*Dichotomy of hot cores?*

T. Csengeri et al. (in prep)

# Molecular composition of hot core candidates

- Line fitting: LTE model for 70 sources with XCLASS (MAGIX) using B3 and B6  $\longrightarrow$   $(N, T_{\text{ex}})$
- Using about  $\sim 10$  species: an automatic line fitting often fails, be aware of caveats!
- Reasonable results, but many lines are still unidentified + the fit needs to be improved



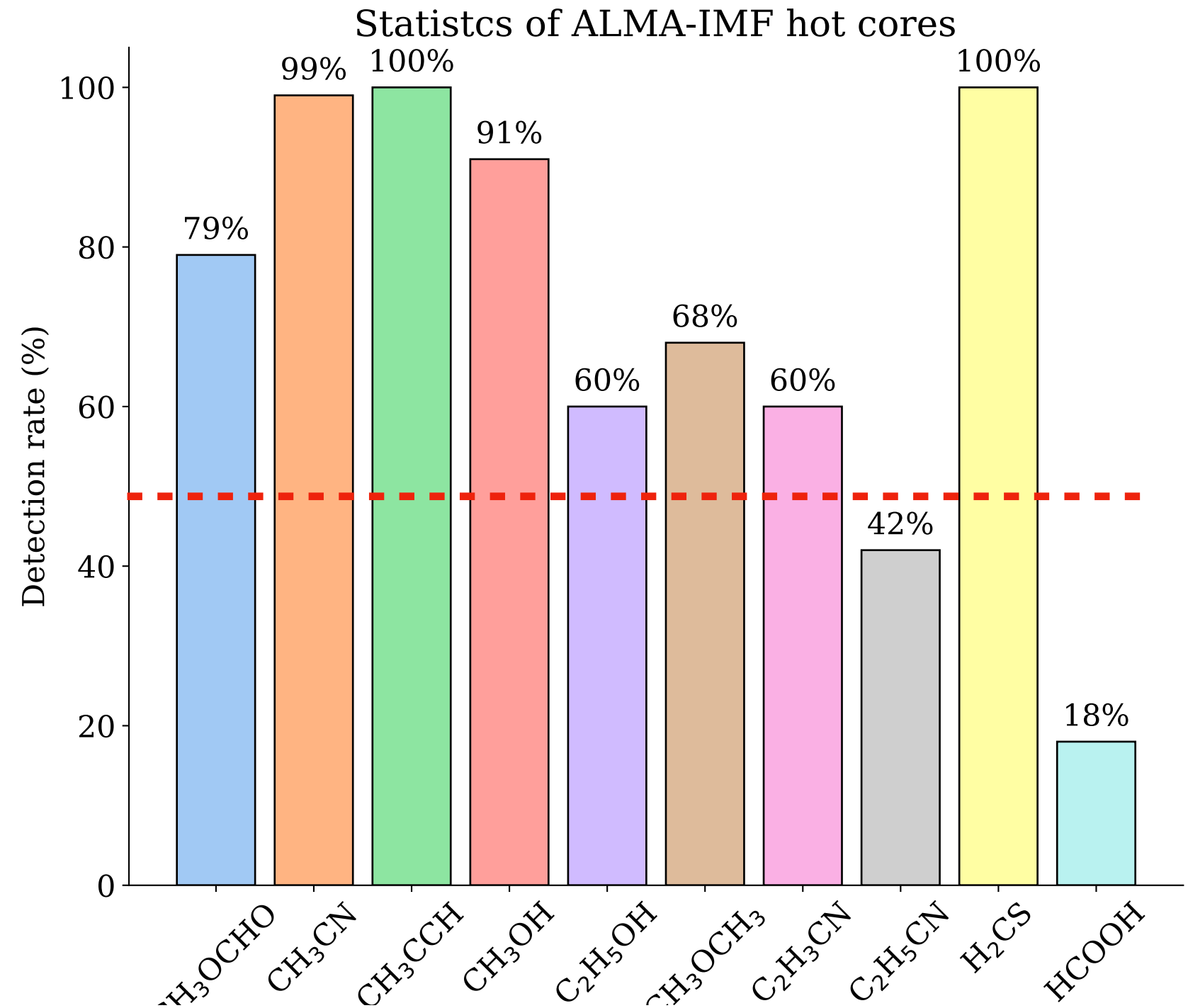
**COMs:** methanol (+ vib. states), ethanol, complex cyanides (+ vib. states), methyl formate (+ vib. state), dimethyl ether,  $\text{CH}_3\text{CHO}$ , ethylene glycol, acetaldehyde, formamide,  $\text{CH}_3\text{NCO}$

T. Kushwaha master thesis (2022)

# What are the best tracers of hot cores?

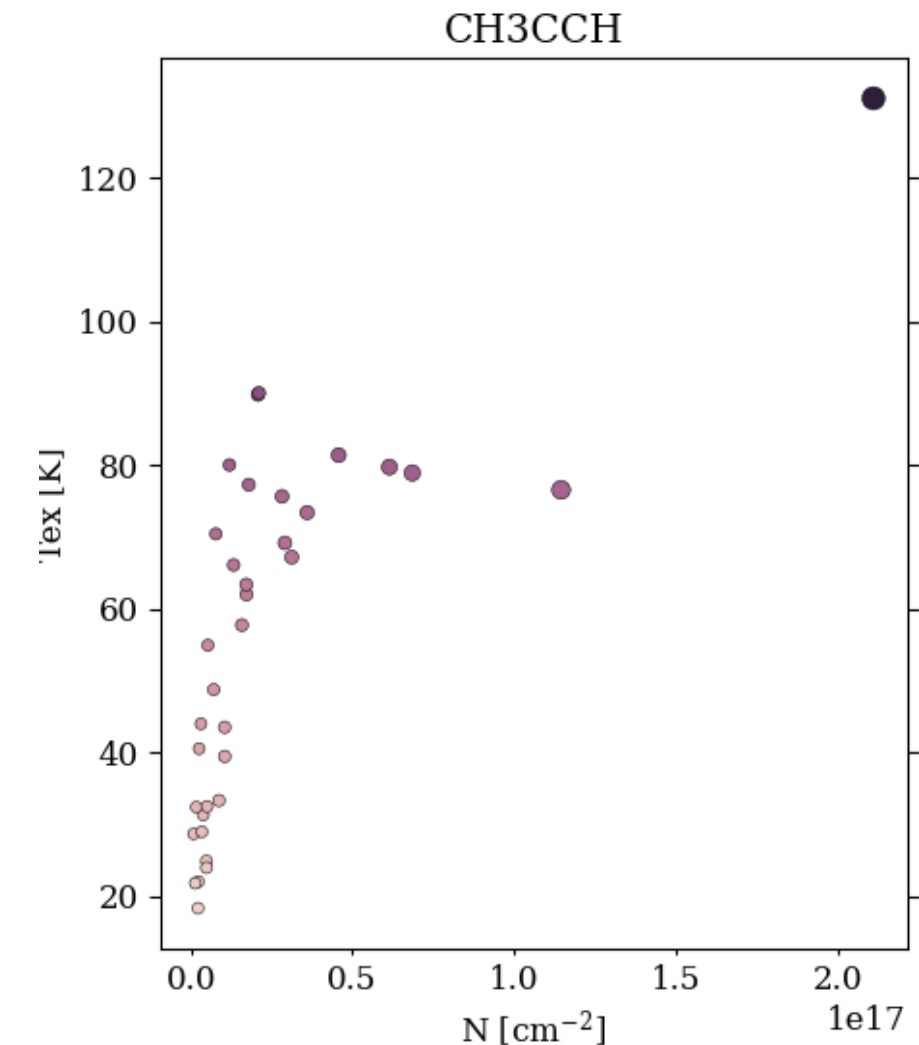
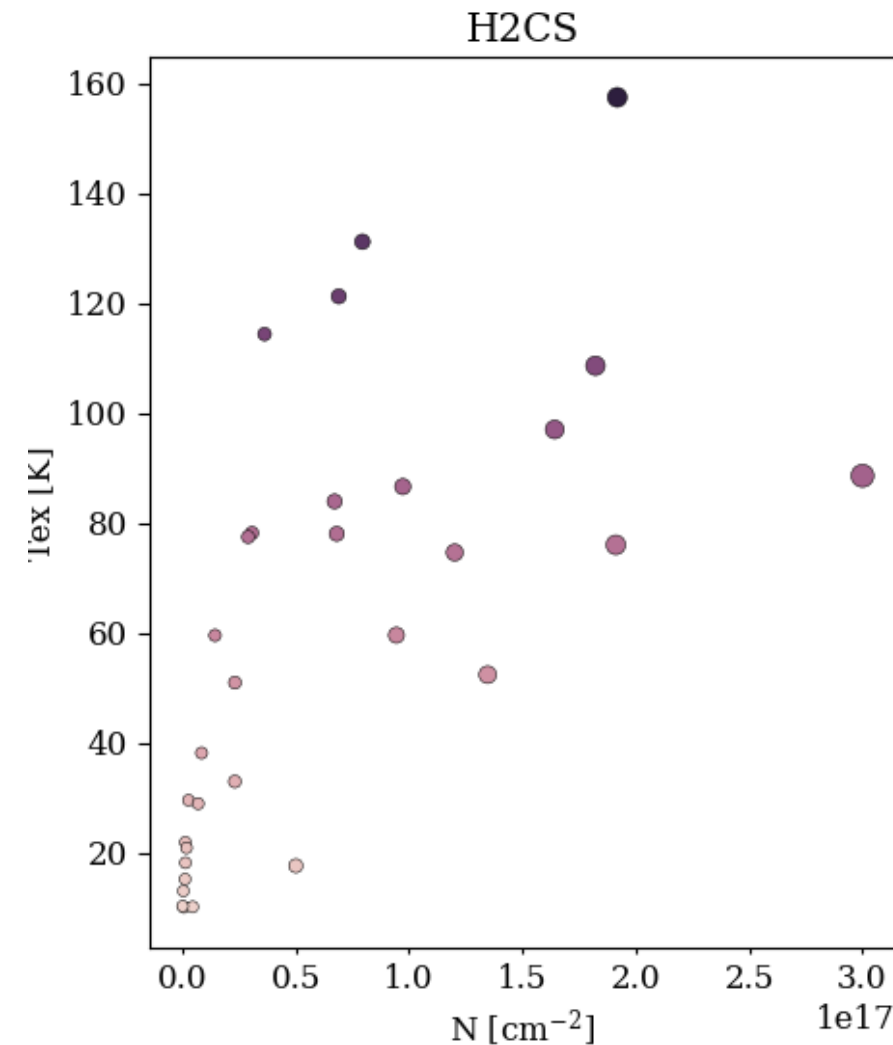
(Note: identification was based on B6 CH<sub>3</sub>OCHO emission)

- CH<sub>3</sub>CN & CH<sub>3</sub>CCH ~ 100%:
- CH<sub>3</sub>CH K=3 line has lower detection rate, K=0 line is too extended
- CH<sub>3</sub>OH : quite extended
- *Heavy complex cyanides have lower detection rates*
- *About half of our sample are rich hot cores*



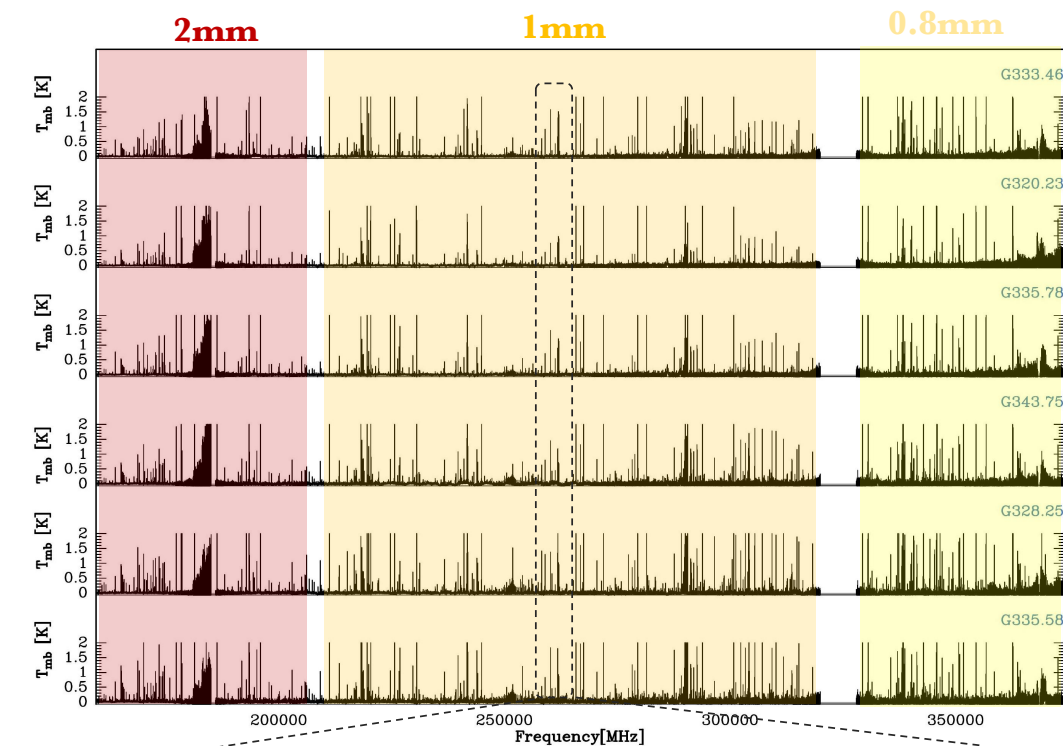
# Statistics of molecular composition

- Blind fitting of COMs with a large number of free parameters is difficult !
- Suitable minimisation methods help, but manual check is still needed
- Caveats: high  $T_{\text{ex}}$  is not always well constrained !

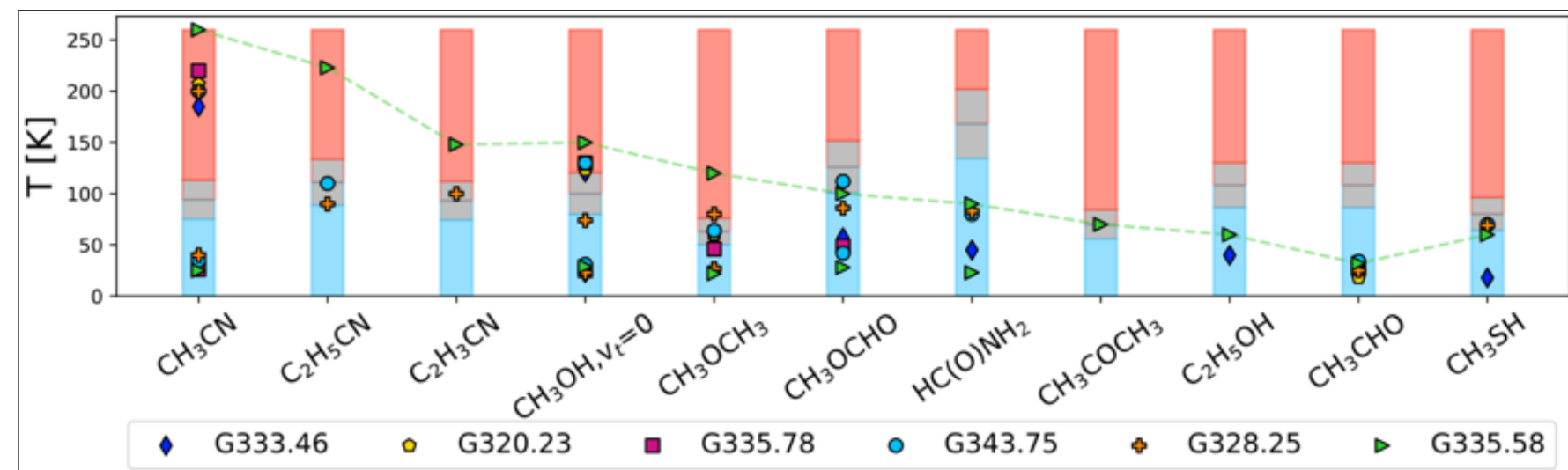


# Early warm-up phase chemistry

- “Complete” spectral survey of six SPARKS sources with the APEX telescope
- Multiple transitions of the same species allow us to infer the excitation conditions
- **Early warm-up phase seems to be well traced by O-bearing COMs (often below the thermal desorption temperature)**
  - Highest  $T_{\text{ex}}$  for cyanides:  $\text{CH}_3\text{CN}$ ,  $\text{C}_2\text{H}_5\text{CN}$ ,  $\text{C}_2\text{H}_3\text{CN}$
  - Non-thermal desorption for O-bearing COMs



(Bouscasse et al. 2022, 2024)



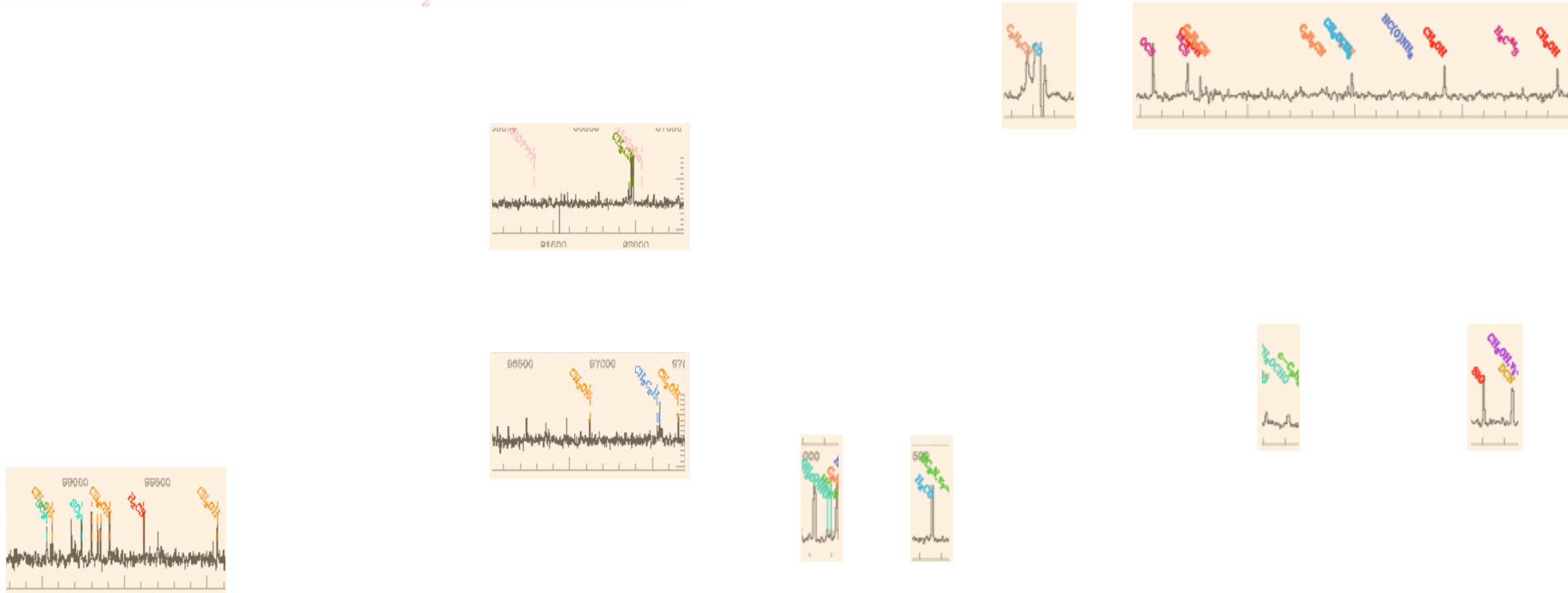
PhD thesis of L. Bouscasse (MPIfR)

# NOEMA ASTROCHEMISTRY OF CYGNUS-X PROTOSTARS

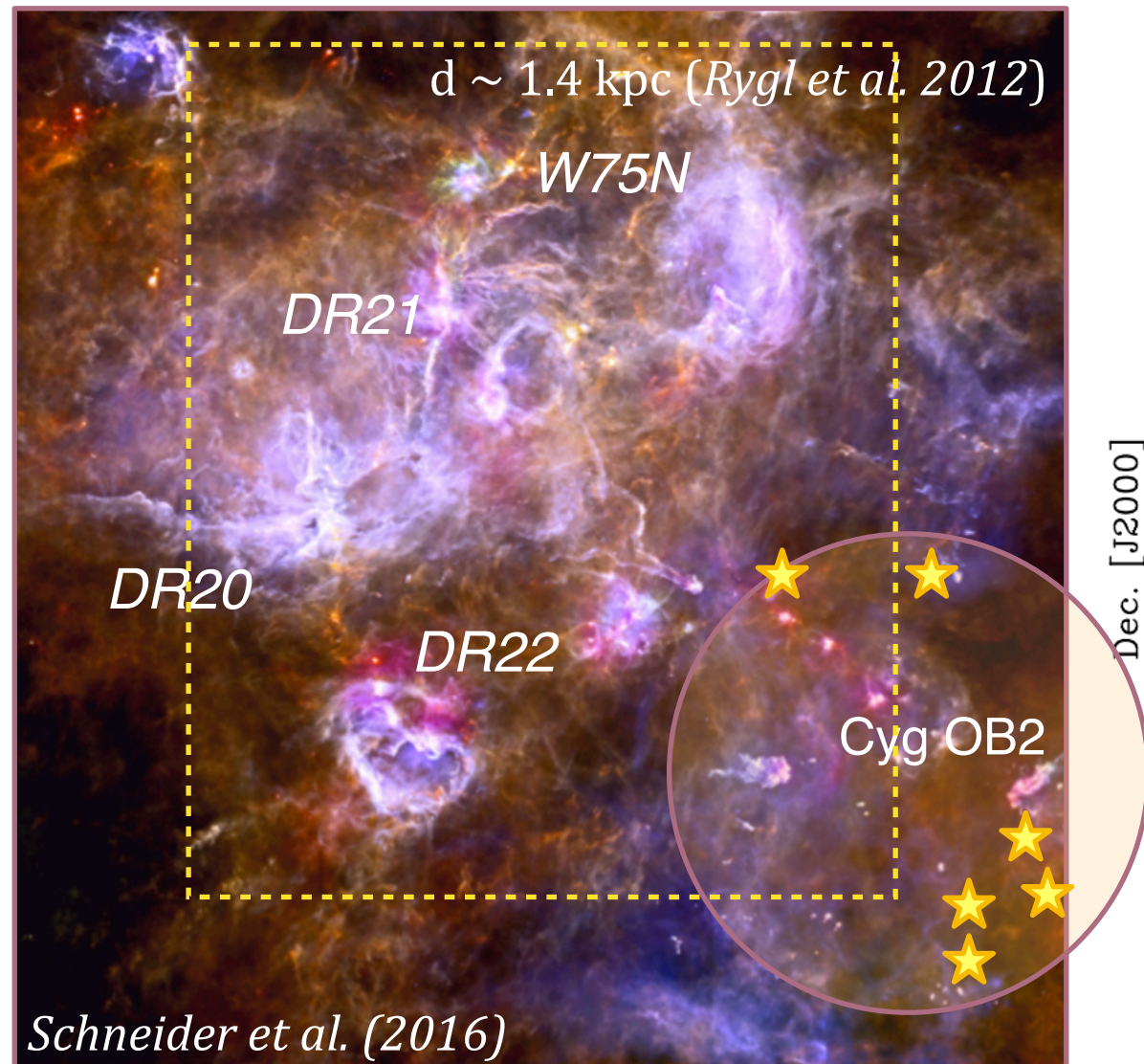
## NASCENT STARS

3mm

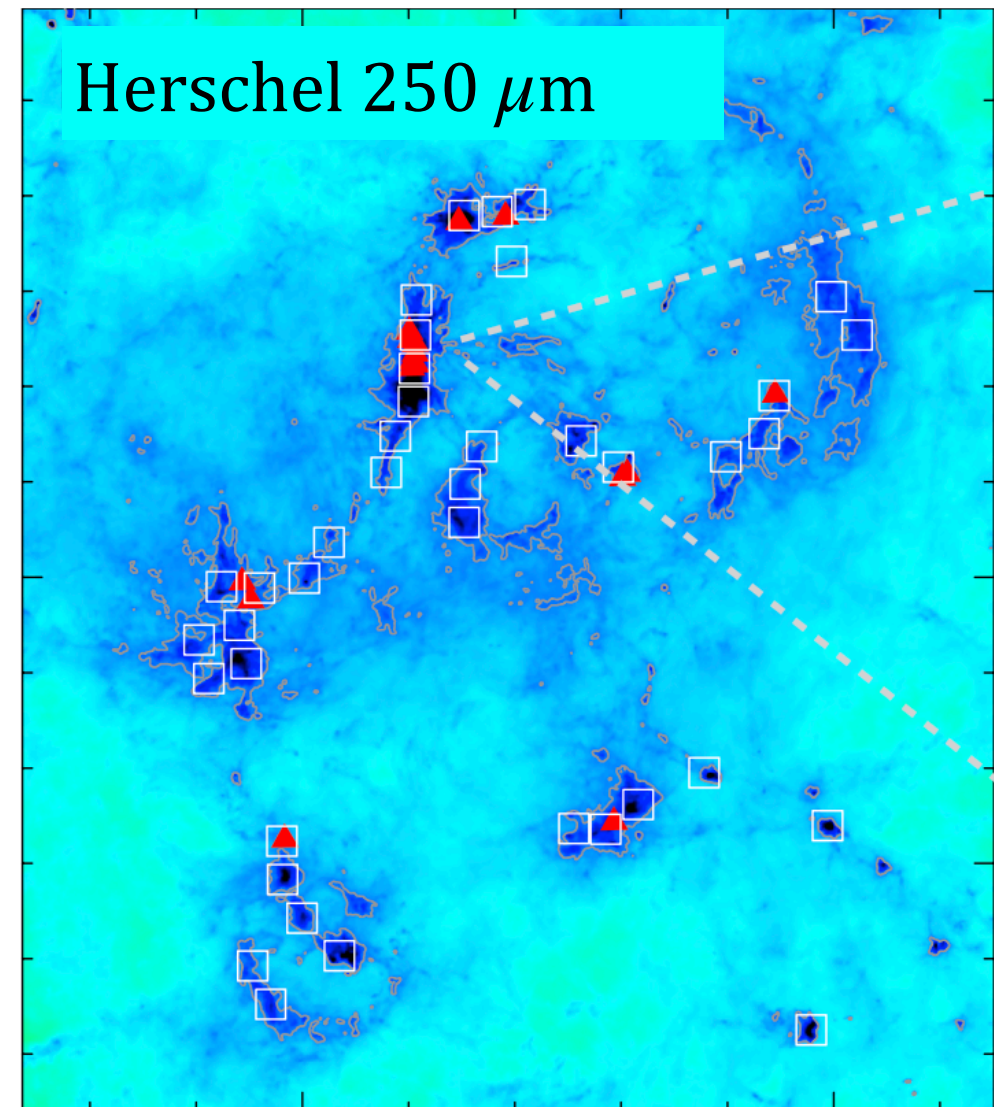
1mm



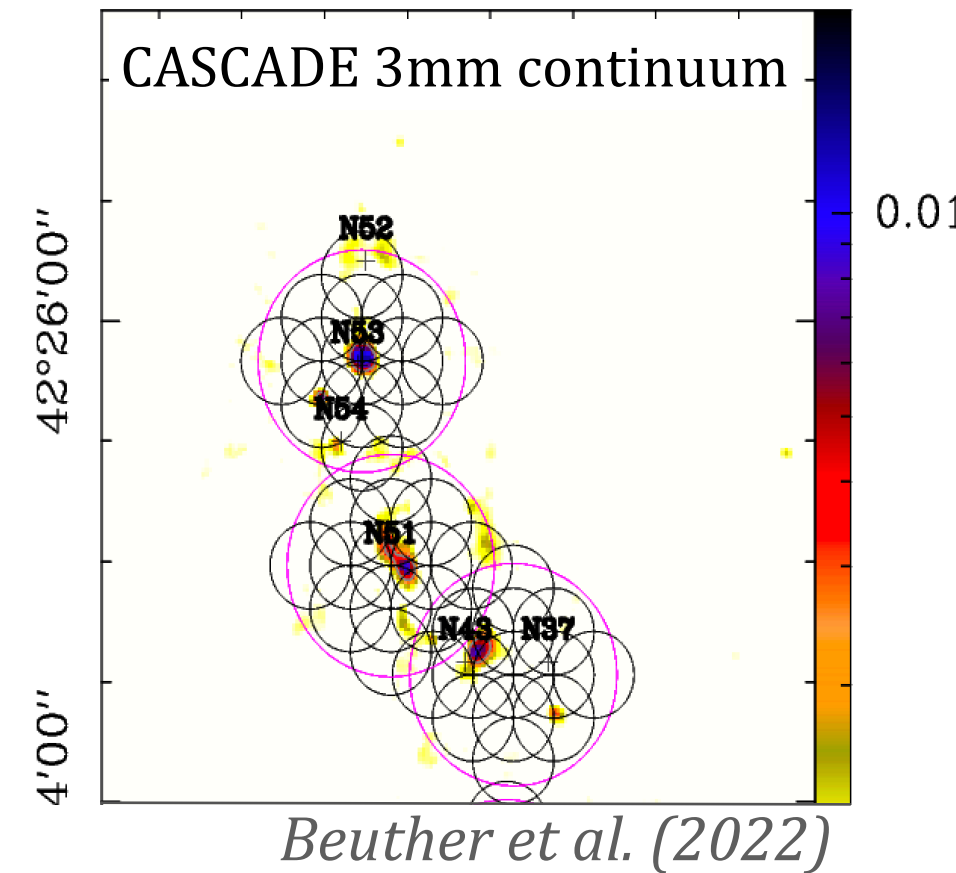
# Cygnus-X: an active site of star formation



Cygnus X is one of the most nearby massive molecular cloud still actively forming stars



Locations of active star formation have been identified and well characterised



**Target selection:** 17 source

- 3mm: single pointing
- 1mm: mosaics
- matching  $\sim 1''$  beam
- (1400 au)

# Legacy value of NASCENT-stars

---

- 228 h allocated array time starting from 2023 WS
  - A+C config @ 3mm, C @ 1mm : **Double (wide)-band** interferometric spectral survey
  - Ancillary dataset from the radio to the near-IR
- |                           |   |  |
|---------------------------|---|--|
| <b>Evolutionary stage</b> | — | ionising vs. non ionising source<br>(1mm/3mm continuum, RLs)                                   |
| <b>Outflows</b>           | — | CO (J=2-1, J=1-0)<br>SiO (J=5-4, J=2-1)  |
| <b>Excitation</b>         | — | Complex Organic Molecules (COMs),<br>CH <sub>3</sub> CCH, H <sub>2</sub> CO, S-bearing species |
| <b>Temperature</b>        | — | Mass estimate<br>Density and temperature profiles  |
| <b>Kinematics</b>         | — | N <sub>2</sub> H <sup>+</sup> , CS, HCN, HCO <sup>+</sup>                                      |

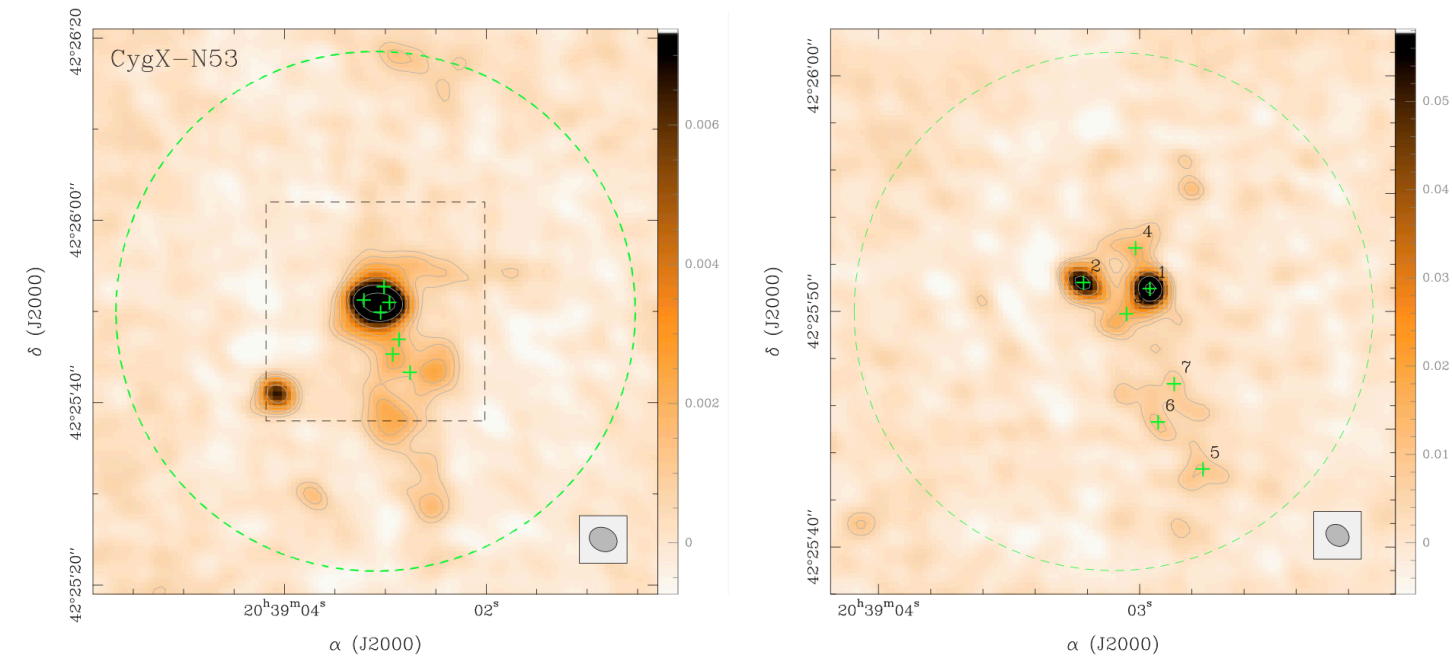
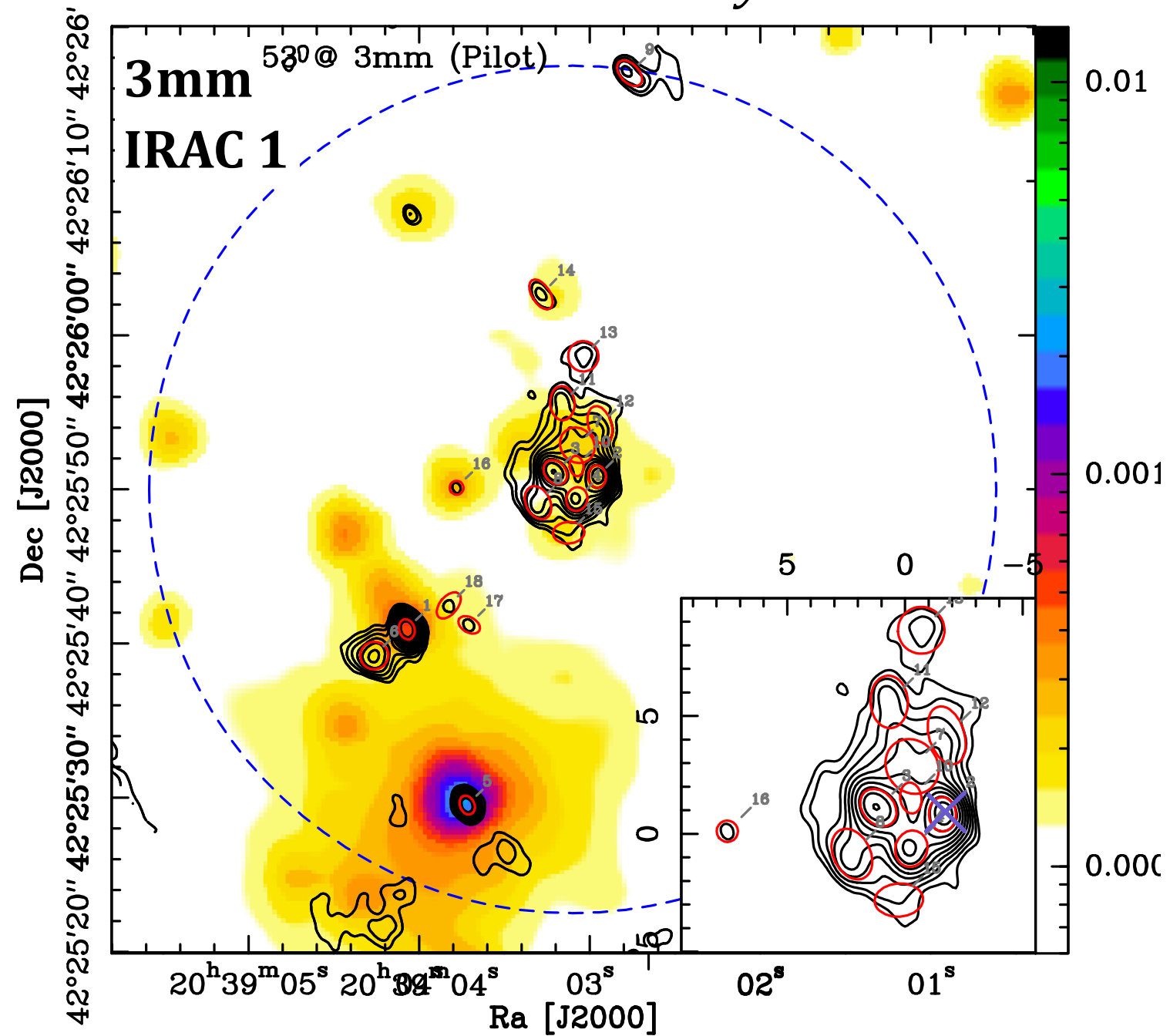
## Project status



*More relaxed timeline compared to ALMA LPs: data acquisition is distributed over 6 semesters*

# Pilot observations (CygX-N53)

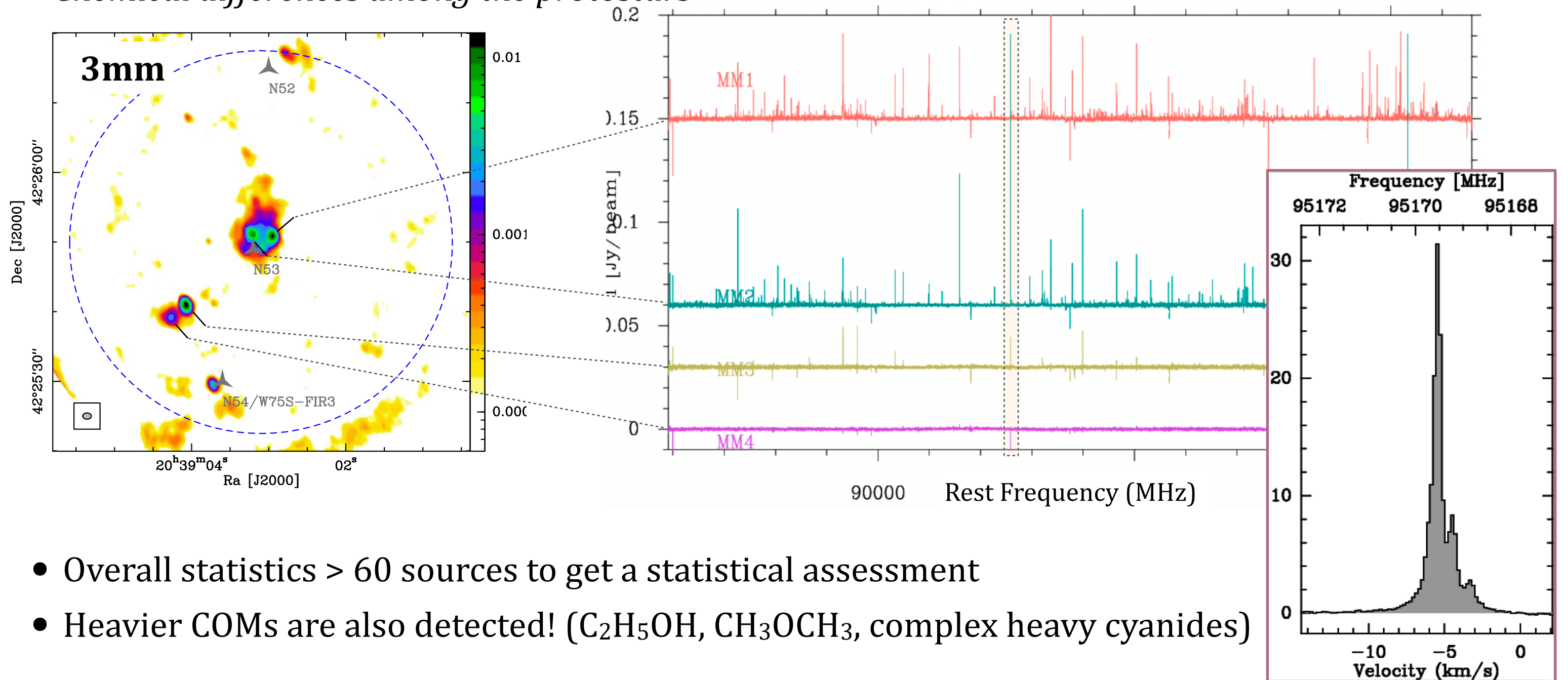
*Gain in continuum sensitivity*



- Bontemps et al. (2010): 7 sources @ 1mm
- NASCENT-stars: 18 sources down to  $5\sigma$  ( $25 \mu\text{Jy}$  @ 3mm)
- Low-, intermediate-, high-mass protostellar envelopes
- Disks?

# Pilot observations (CygX-N53)

*Chemical differences among the protostars*



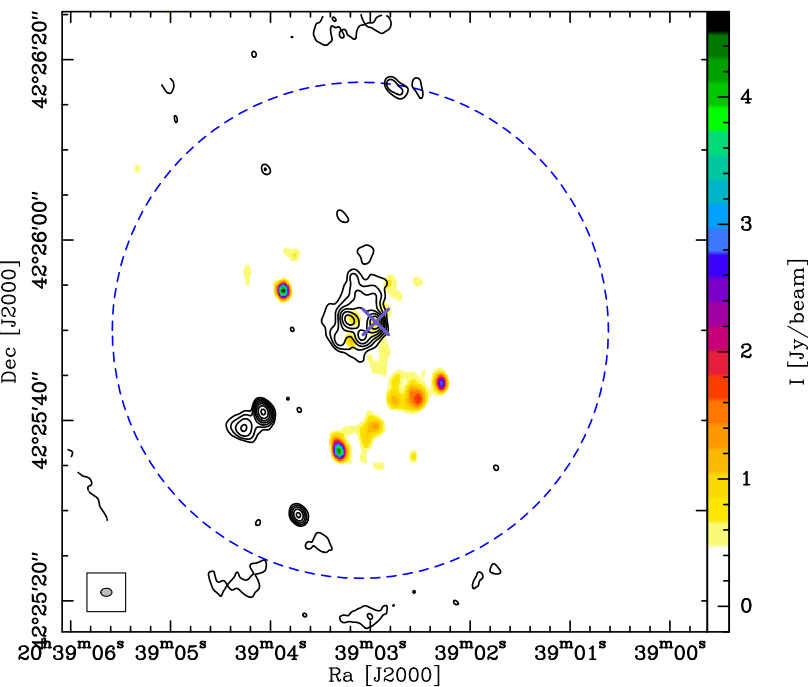
- Overall statistics > 60 sources to get a statistical assessment
- Heavier COMs are also detected! ( $C_2H_5OH$ ,  $CH_3OCH_3$ , complex heavy cyanides)



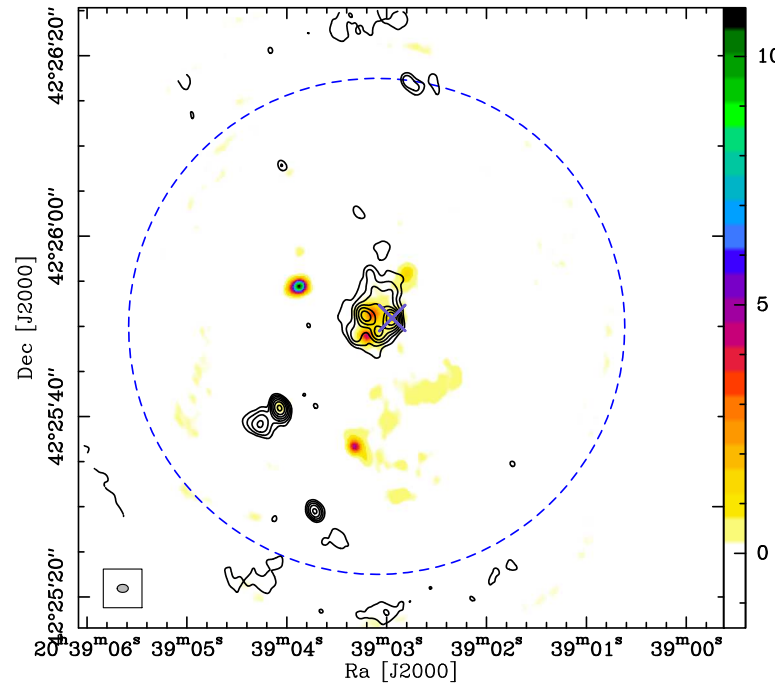
# Age sequencing of protostellar envelopes (CygX-N53)

*(Csengeri et al. in prep)*

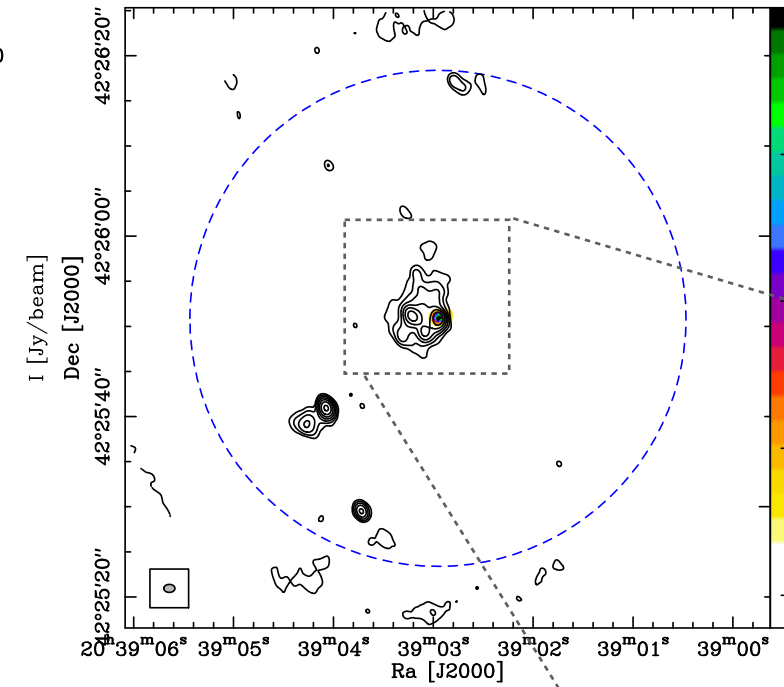
84.5 GHz Class I



95 GHz Class I

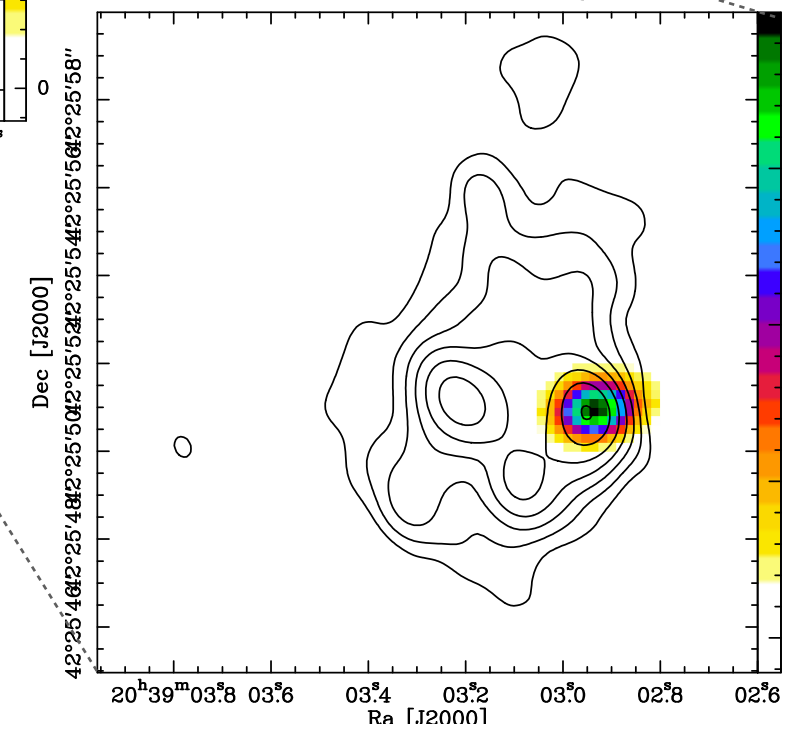


6.7 GHz Class II (VLA)



*Synergy with GLOSTAR  
(Brunthaler et al. 2021)*

*Ortiz-Leon et al. (2021)*



**Class I CH<sub>3</sub>OH masers :** No association with continuum sources


**Class II CH<sub>3</sub>OH masers:** Association with continuum suggests that it has a high-mass proto star

**MM1 :** The most massive and more evolved stage protostellar envelope

**MM2 :** Potentially equally massive, but younger

# Processing large dataset with AI/ML based new methods

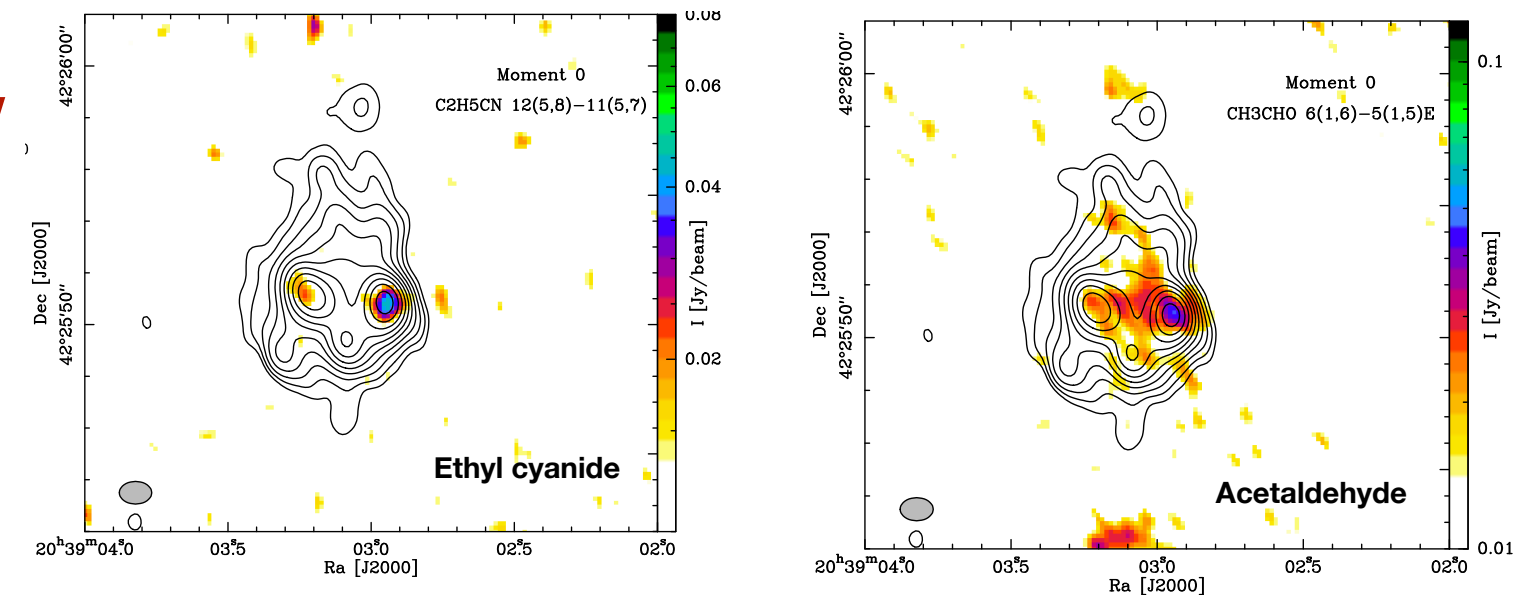
**COMs are detected with NASCENT-stars!**

- PhD thesis of N. Kessler (U. Bordeaux, Artificial Intelligence special action): AI for spectral line analysis (  )

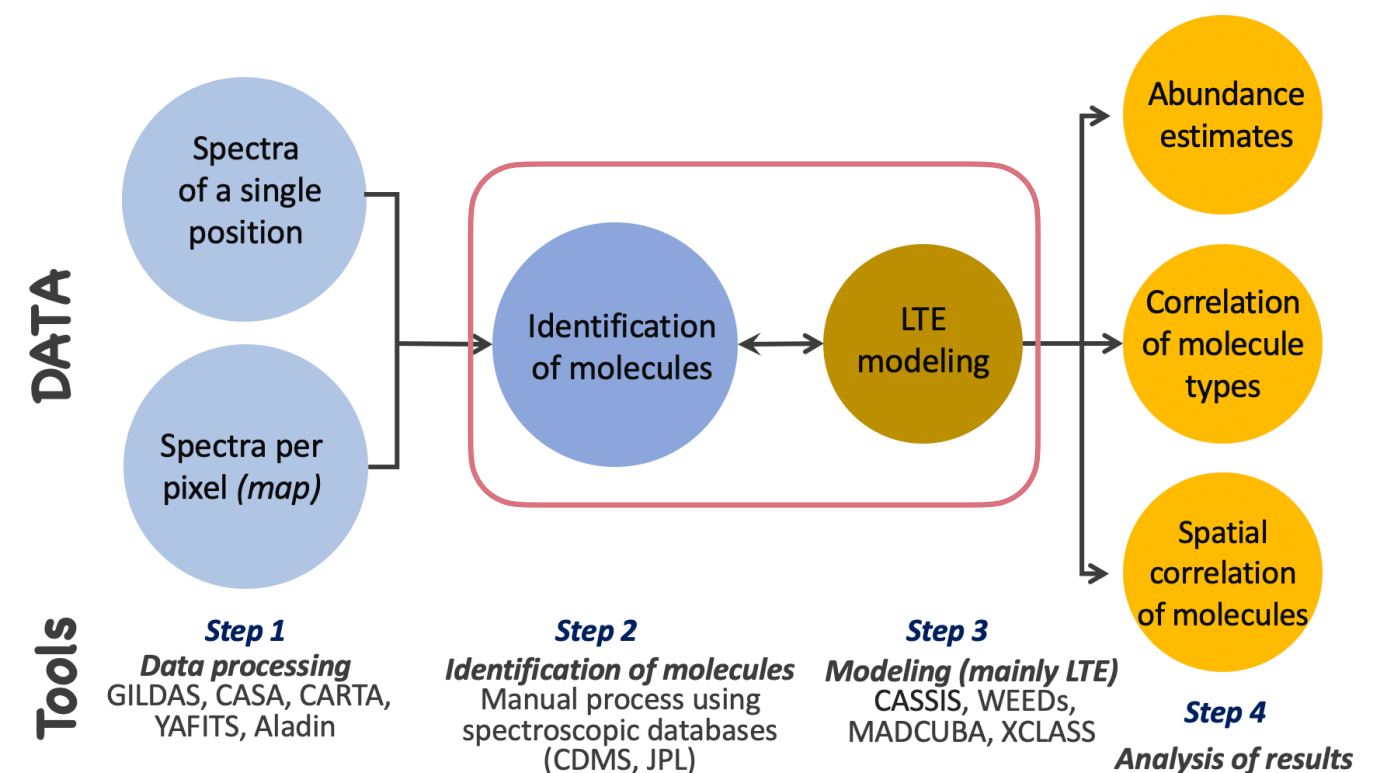
*Cornu et al. (2022)*

- Goal: quick assessment of molecular content & extracting temperatures and column densities

*see the talk by Nina Kessler!*



Typical analysis sequence of complex millimeter spectra



Kessler et al (in prep)

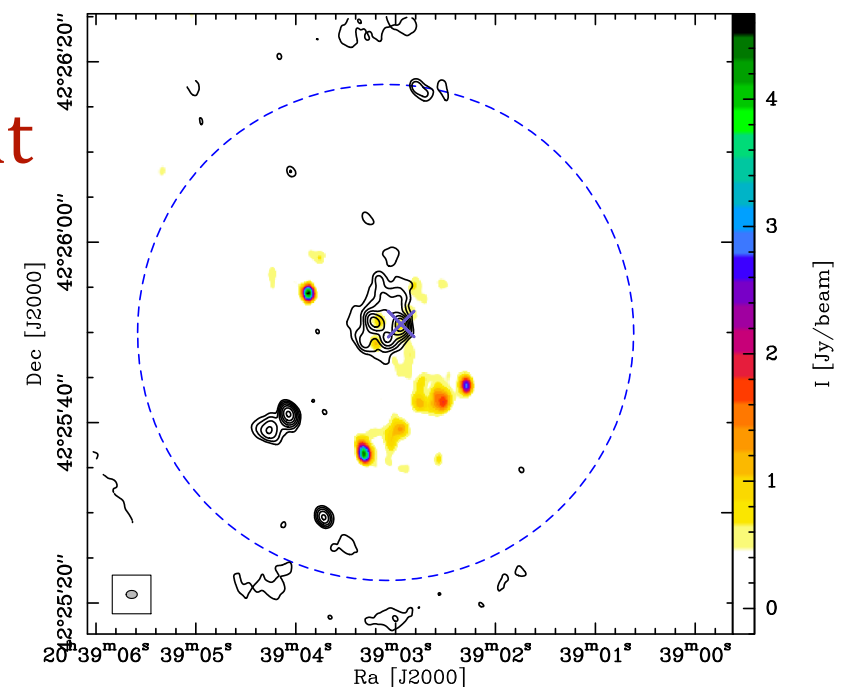
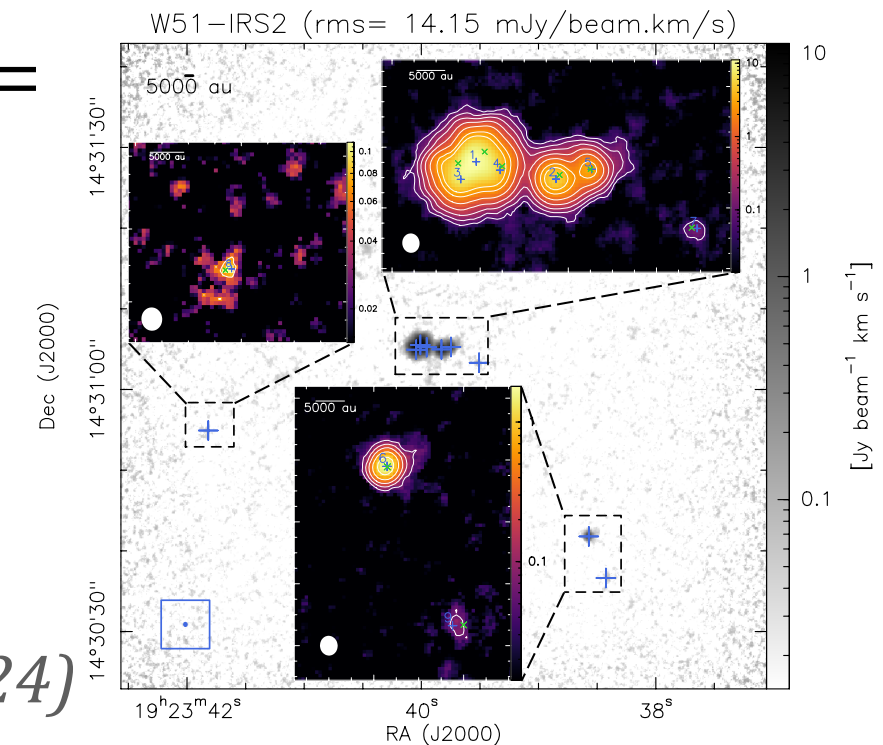
# Conclusions

## ALMA-IMF: statistical sample of hot cores

- ▶ ALMA-IMF (PI: F. Motte) was the first large program at ALMA to investigate the origin of high-mass star and cluster formation  
*Motte et al. (2022), Ginsburg et al. (2022)*
- ▶ Chemically rich regions systematically identified using CH<sub>3</sub>OCHO emission  
*Bonfand, Csengeri et al. (2024)*
- ▶ Non-continuous 6.7 GHz bandwidth provides *limited* access to excitation analysis of COMs

## NASCENT-stars: interferometric wide-band spectral surveys represent extremely powerful tools

- ▶ Astrochemistry: precise estimates of molecular abundances
- ▶ Detection of strong Class I CH<sub>3</sub>OH masers towards our first target (N53)
- ▶ Goal: constrain the evolutionary stage of protostellar envelopes using their molecular content



# Molecular diversity in hot cores

