UNIVERSITY OF COLOGNE

# Embracing diversity in Star Formation

Peter Schilke, UoC

- Often one gets the impression people look for THE solution for star formation, both in theory and observations
  - (in)famous example (still in the introduction of every second ALMA high-mass SF proposal):

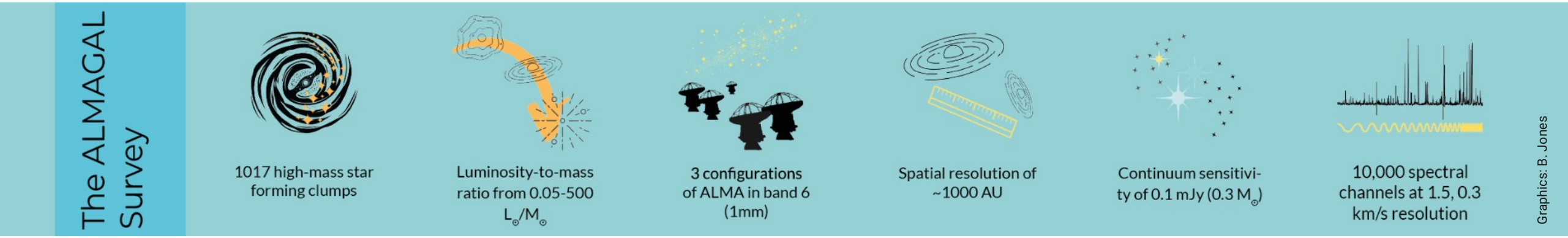
    monolithic collapse vs. competitive accretion
- Most people accept now that none of these models, as originally conceived, captures reality entirely, but have we gone consistently from aiming to find THE solution to looking for the parameter space of solutions?

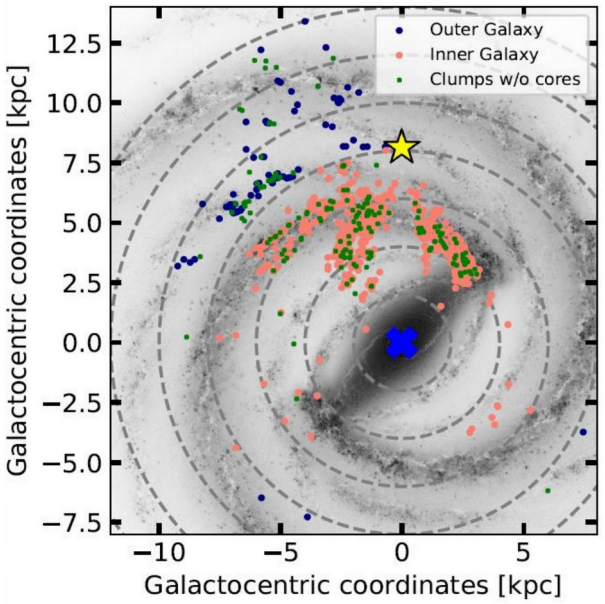
# Why not?

- Theory
  - Very expensive to do models
  - Prohibitively expensive to explore large parameter space:
  - wide variety of initial conditions, often rather artificial (box with driven turbulence, massive starless core), dependence on metallicity, environment (shocks or no shocks, external UV radiation) etc.
- Observations
  - Looking for commonalities rather than differences
  - In the past: low statistics with biased samples – this is changing now and I'll give a taste of it by showing some ALMAGAL results
  - We have to exploit the better statistics properly
    - My impression is that we (as a community) are behind in the use of statistical tools (compared to e.g. the high-redshift galaxy community)

# The ALMAGAL Survey

Cycle 7 ALMA Large Program
PIs: Sergio Molinari (I), Peter Schilke (D), Cara Battersby (US), Paul Ho (Tw)




**Science goals**

Fragmentation, chemistry, cluster evolution history, intra-clump core dynamics, core-clump feedback, outflows, disks, …

**Large sample size: 1013 unique sources**

**Complete** within the selection criteria (> 500 $M_\odot$, < 7 kpc, < 0° dec, outside CMZ)

**But** single pointings – may lose outer cluster members

Technical working group lead:
**Álvaro Sánchez-Monge**

**Joint deconvolution of all configurations**
3 years
12M CPU hours @ JSC
450 TB FITS products

**ALMAGAL Survey Overview:** Sergio Molinari et al. (2025)
**ALMAGAL Technical Paper:** Álvaro Sánchez-Monge et al. (2025)

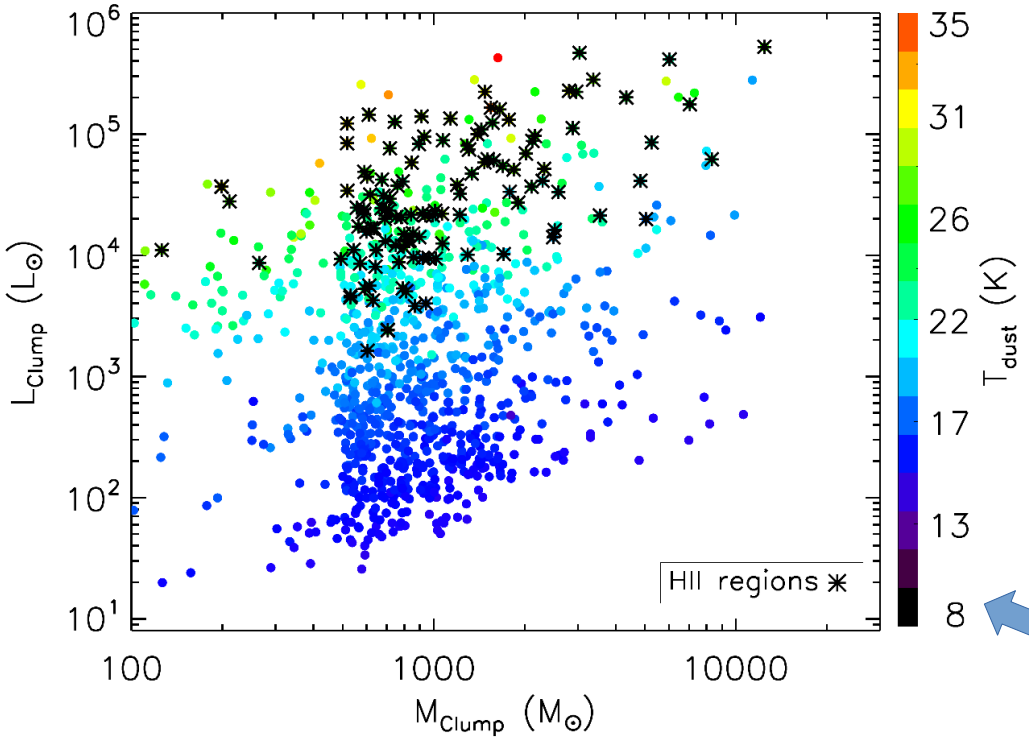
A&A, 696, A149 (2025)
https://doi.org/10.1051/0004-6361/202452702

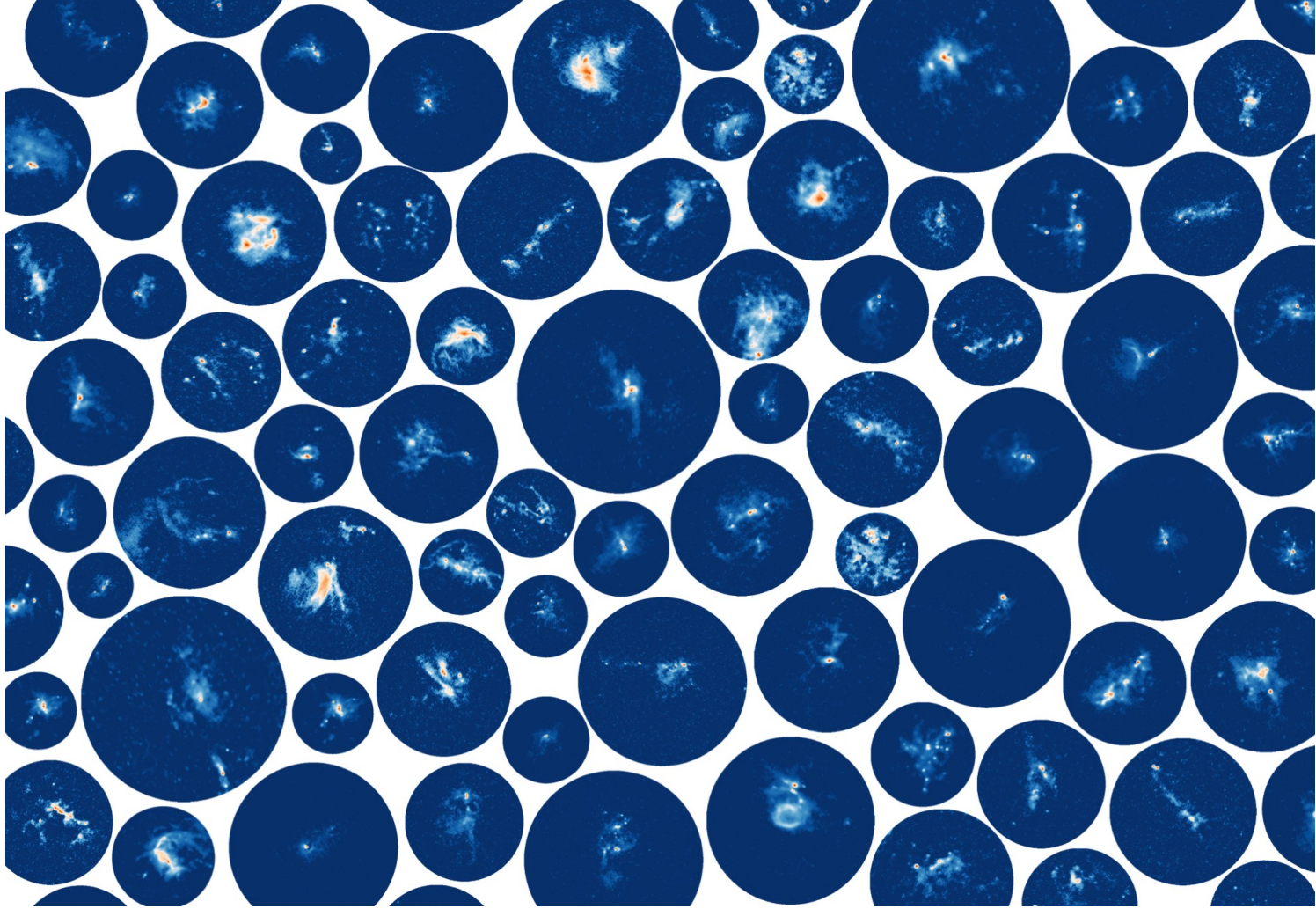

Astronomy & Astrophysics

# ALMAGAL

## I. The ALMA evolutionary study of high-mass protocluster formation in the Galaxy: Presentation of the survey and early results

S. Molinari[1,*], P. Schilke[2], C. Battersby[3], P. T. P. Ho[4], Á. Sánchez-Monge[5,6], A. Traficante[1], B. Jones[2], M. T. Beltrán[19], H. Beuther[7], G. A. Fuller[9,2], Q. Zhang[13], R. S. Klessen[10,11,13,14], S. Walch[2,12], Y.-W. Tang[4], M. Benedettini[1], D. Elia[1], A. Coletta[1,47], C. Mininni[1], E. Schisano[1], A. Avison[8], C. Y. Law[19], A. Nucara[1,16], J. D. Soler[1], G. Stroud[9], J. Wallace[3], M. R. A. Wells[7], A. Ahmadi[17], C. L. Brogan[15], T. R. Hunter[15], S.-Y. Liu[4], S. Pezzuto[1], Y.-N. Su[4], B. Zimmermann[2], T. Zhang[2], F. Wyrowski[18], F. De Angelis[1], S. Liu[1], S. D. Clarke[4], F. Fontani[19,20,21], P. D. Klaassen[22], P. Koch[4], K. G. Johnston[23], U. Lebreuilly[25], T. Liu[26], S. L. Lumsden[24], T. Moeller[2], L. Moscadelli[19], R. Kuiper[28], D. Lis[30], N. Peretto[32], S. Pfalzner[29], A. J. Rigby[24], P. Sanhueza[31,33], K. L. J. Rygl[27], F. van der Tak[35,36], H. Zinnecker[37], F. Amaral[2], J. Bally[38], L. Bronfman[44], R. Cesaroni[19], K. Goh[2], M. G. Hoare[24], P. Hatchfield[30], P. Hennebelle[25], T. Henning[7], K.-T. Kim[40,41], W.-J. Kim[2], L. Maud[42], M. Merello[44,45], F. Nakamura[33], R. Plume[43], S.-L. Qin[46], B. Svoboda[34], L. Testi[39], V. S. Veena[2,18], and D. Walker[9]



Large diversity of morphologies (image credit Chiara Mininni)

Large sample (1013 unique sources), but still spread over a large L/M space, which means part of the parameter space are still poorly sampled.

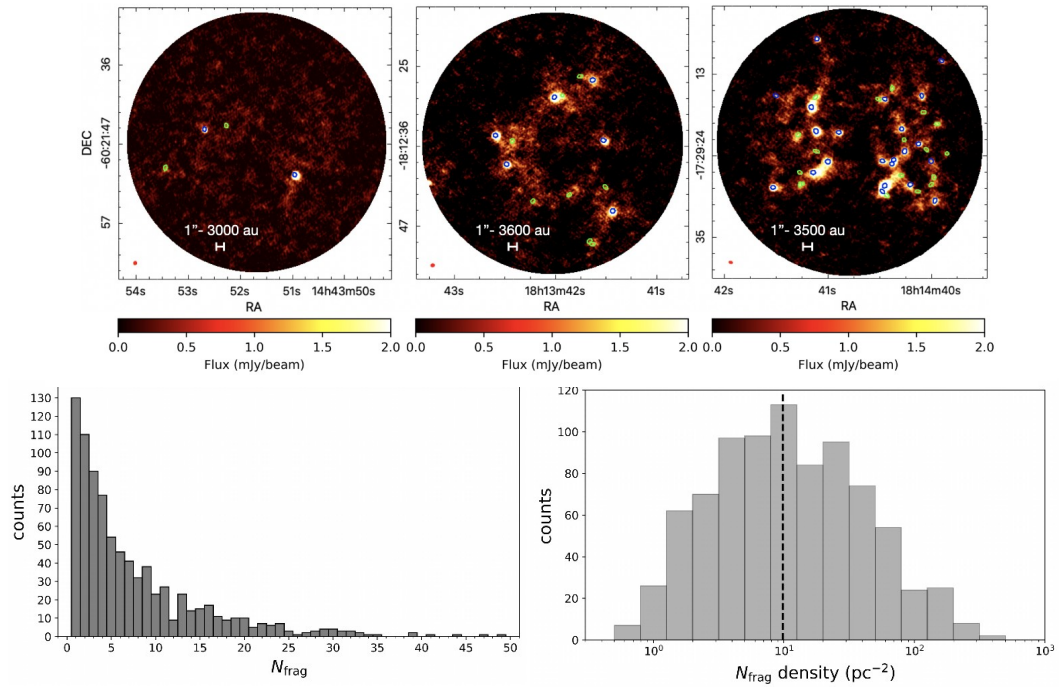
A&A, 696, A151 (2025)
https://doi.org/10.1051/0004-6361/202452706


Astronomy & Astrophysics

# ALMAGAL

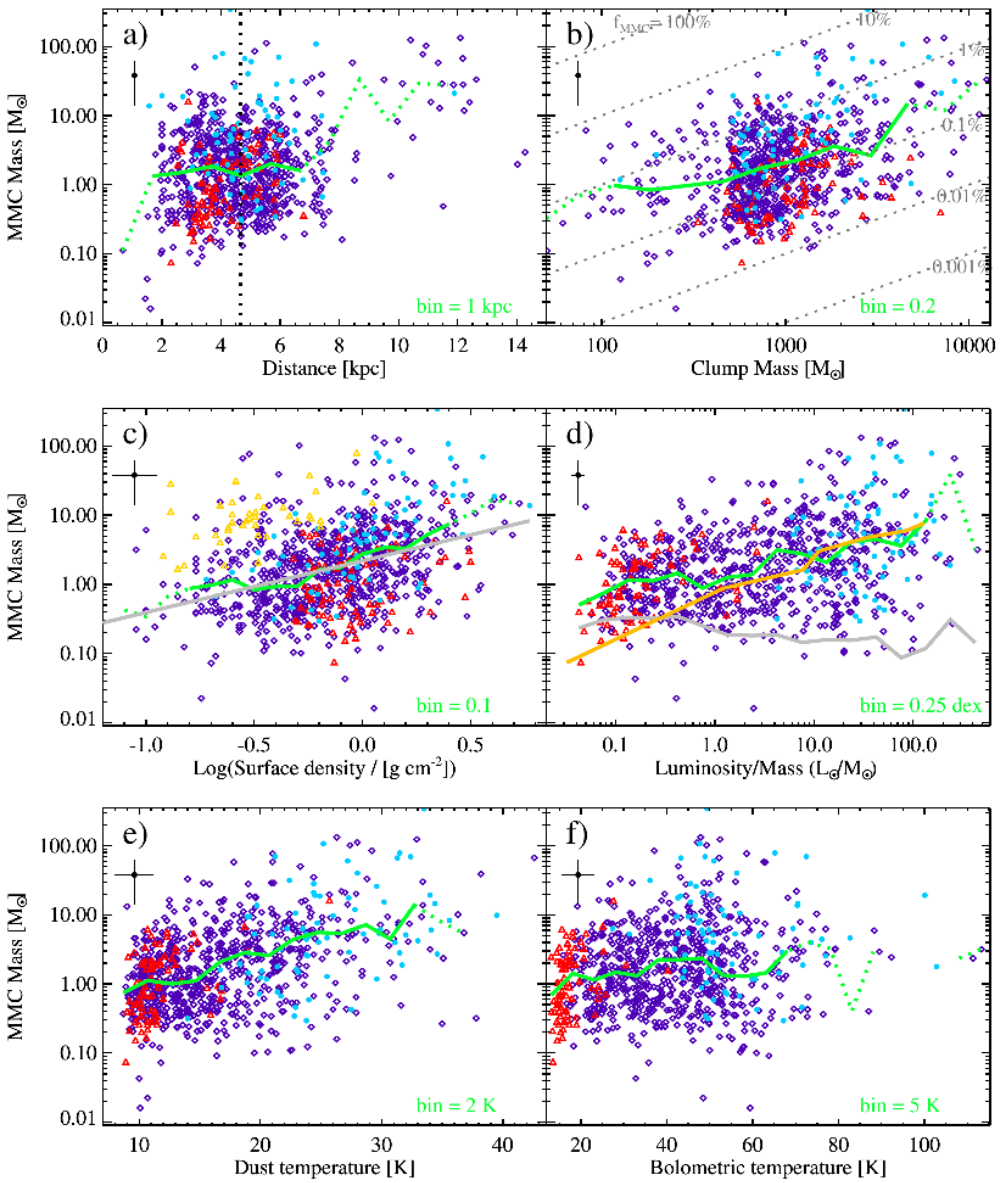
## III. Compact source catalog: Fragmentation statistics and physical evolution of the core population

A. Coletta[1,2,⋆], S. Molinari[1], E. Schisano[1], A. Traficante[1], D. Elia[1], M. Benedettini[1], C. Mininni[1], J. D. Soler[1], Á. Sánchez-Monge[3,4], P. Schilke[5], C. Battersby[6], G. A. Fuller[7,5], H. Beuther[8], Q. Zhang[9], M. T. Beltrán[10], B. Jones[5], R. S. Klessen[11,12], S. Walch[5,13], F. Fontani[10,14,15], A. Avison[16,7,17], C. L. Brogan[18], S. D. Clarke[19], P. Hatchfield[20], P. Hennebelle[21], P. T. P. Ho[19,22], T. R. Hunter[18], K. G. Johnston[23], P. D. Klaassen[24], P. M. Koch[19], R. Kuiper[25], D. C. Lis[20], T. Liu[26], S. L. Lumsden[27], Y. Maruccia[28], T. Möller[5], L. Moscadelli[10], A. Nucara[29,1], A. J. Rigby[27,30], K. L. J. Rygl[31], P. Sanhueza[32,33], F. van der Tak[34,35], M. R. A. Wells[8], F. Wyrowski[36], F. De Angelis[1], S. Liu[1], A. Ahmadi[37], L. Bronfman[38], S.-Y. Liu[19], Y.-N. Su[19], Y. Tang[19],



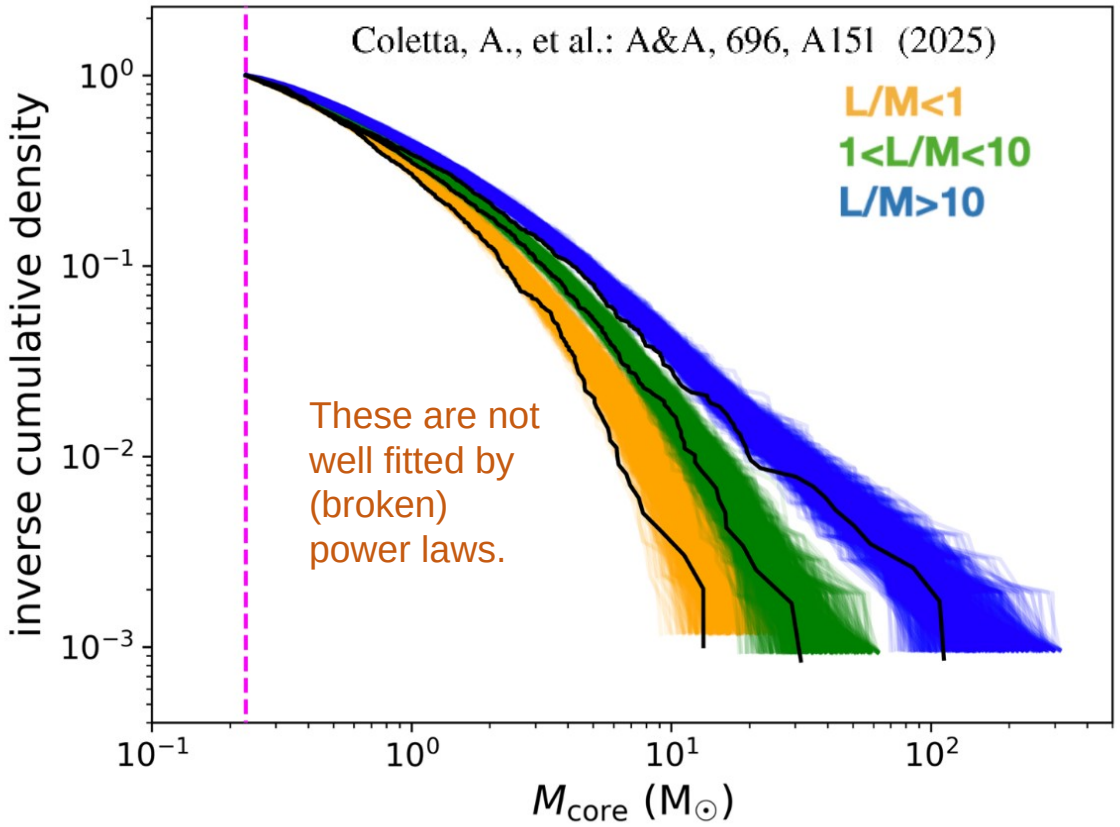

Large range of fragmentation properties.






Most Massive Clump vs. clump parameter – not much of a correlation. (Red open triangles: quiescent clumps, dark blue open diamonds: star-forming clumps, light blue filled circles: UCHII regions.

mentioned by Henrik and Thomas earlier




Seems to favor a clump-fed competitive accretion scenario, **but**

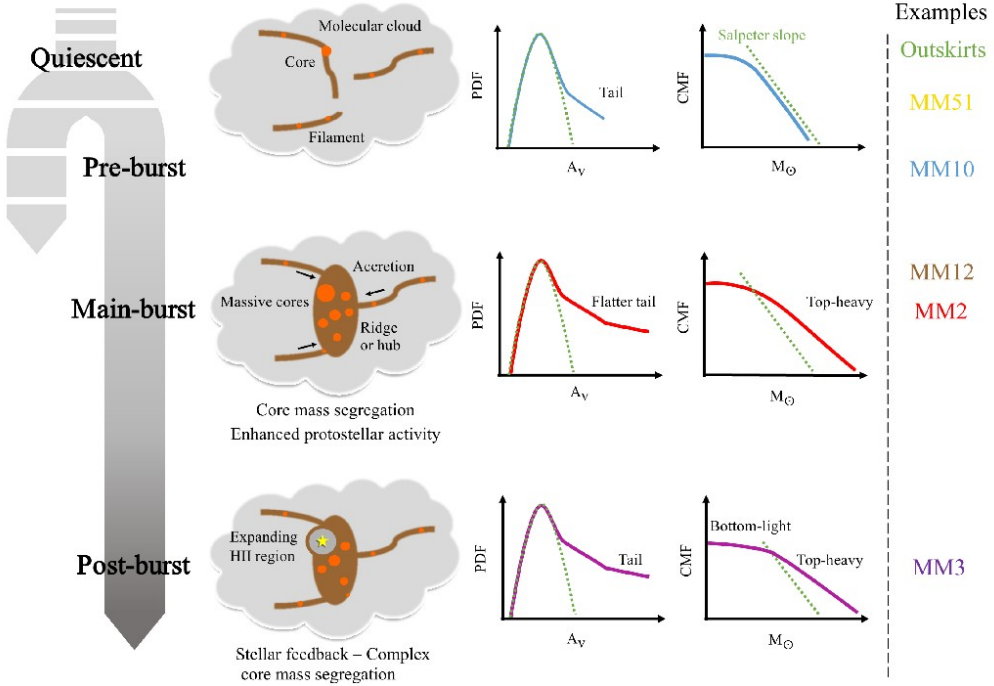
- Uncertainties due to e.g temperature determination (see Beth Jones later)
- This is an aggregate CMF over all clumps in many different evolutionary stages, environments etc.
  ⇒ needs further study

**Fig. 18.** Observed CMFs (black lines, expressed as inverse cumulative number density distributions) for the three populations of ALMAGAL cores classified, as reported, according to the $L/M$ evolutionary indicator of the hosting clump, as explained in Sect. 5.2.1. The three colored bands trace, for each population, the 1000 MC realizations of CMFs computed by assigning to each core a random temperature within the ranges defined in Table 6. Less evolved sources (i.e., with $L/M \leq 1\ L_\odot/M_\odot$) are marked by golden lines, the intermediate ones ($1 < L/M \leq 10\ L_\odot/M_\odot$) by green lines, and the more evolved sources ($L/M > 10\,L_\odot/M_\odot$) by blue lines. Note: we include only cores above the mass completeness value of $0.23\,M_\odot$, marked by the vertical dashed magenta line (see text for explanation).

**ALMA-IMF**

**VI. Investigating the origin of stellar masses: Core mass function evolution in the W43-MM2&MM3 mini-starburst**

**Pouteau et al. 2023**




Ringberg 2025: Puzzles of Star Formation

# Caveats

- Confirmation bias
  - Tendency to look for confirmation of anticipated properties
  - Both in planning observations and in interpreting results
    - Fitting pre-conceived functional forms
    - Effect gets amplified if using Maching Learning: ML can only find what it has been taught to find: challenge of designing and creating realistic and complete training sets
    - Find credibility intervals of parameters derived (MCMC, SBI for speed)
    - Make sure one tests if the underlying models do actually fit (ML speak: distribution shifts)
- Conclusions often based on low statistics
  - From a recent paper on high-mass disks reporting the detection of **one** disk:
  - *These results suggest that accretion disks around massive stars are more massive and hotter than their low-mass siblings, but they still are quite stable.*
- *With the statistically relevant samples we have, we also have to use statistical tools.*

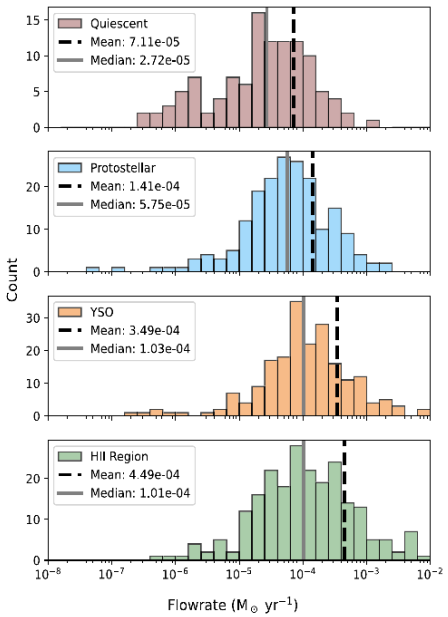
A&A, 690, A185 (2024)
https://doi.org/10.1051/0004-6361/202449794


Astronomy & Astrophysics

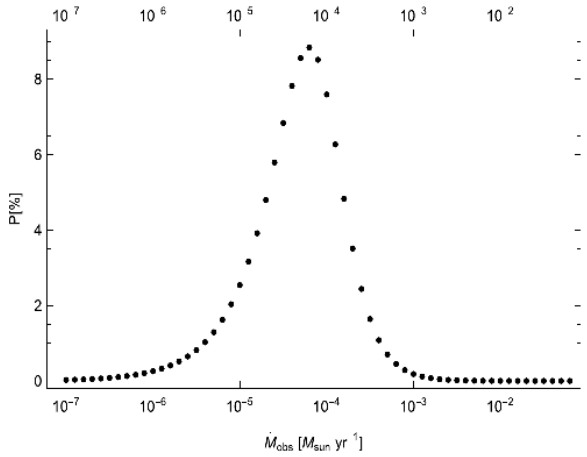
## Dynamical accretion flows

### ALMAGAL: Flows along filamentary structures in high-mass star-forming clusters

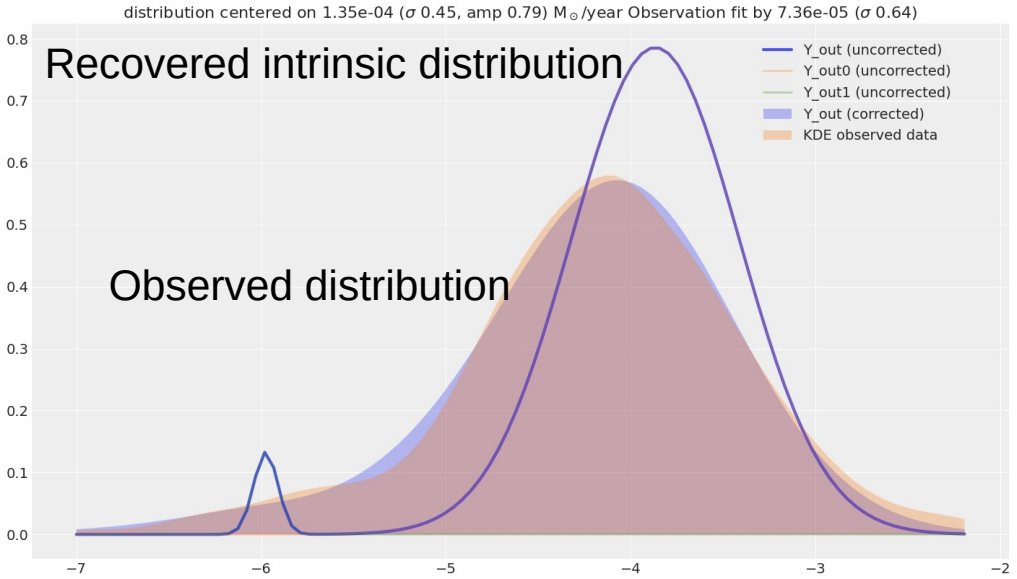
M. R. A. Wells[1,★], H. Beuther[1], S. Molinari[2], P. Schilke[3], C. Battersby[4], P. Ho[5,6], Á. Sánchez-Monge[7,8], B. Jones[3], M. B. Scheuck[1], J. Syed[1], C. Gieser[38], R. Kuiper[25], D. Elia[2], A. Coletta[2,24], A. Traficante[2], J. Wallace[4], A. J. Rigby[39], R. S. Klessen[9,10], Q. Zhang[11], S. Walch[3,12], M. T. Beltrán[13], Y. Tang[5], G. A. Fuller[3,14], D. C. Lis[15], T. Möller[3], F. van der Tak[16,17], P. D. Klaassen[18], S. D. Clarke[3,5], L. Moscadelli[13], C. Mininni[2], H. Zinnecker[37], Y. Maruccia[2], S. Pezzuto[2], M. Benedettini[2], J. D. Soler[2], C. L. Brogan[19], A. Avison[14,20,21], P. Sanhueza[22,23], E. Schisano[2], T. Liu[26], F. Fontani[13,27,28], K. L. J. Rygl[29], F. Wyrowski[30], J. Bally[31], D. L. Walker[20], A. Ahmadi[32], P. Koch[5], M. Merello[33], C. Y. Law[34,35], and L. Testi[13,36]

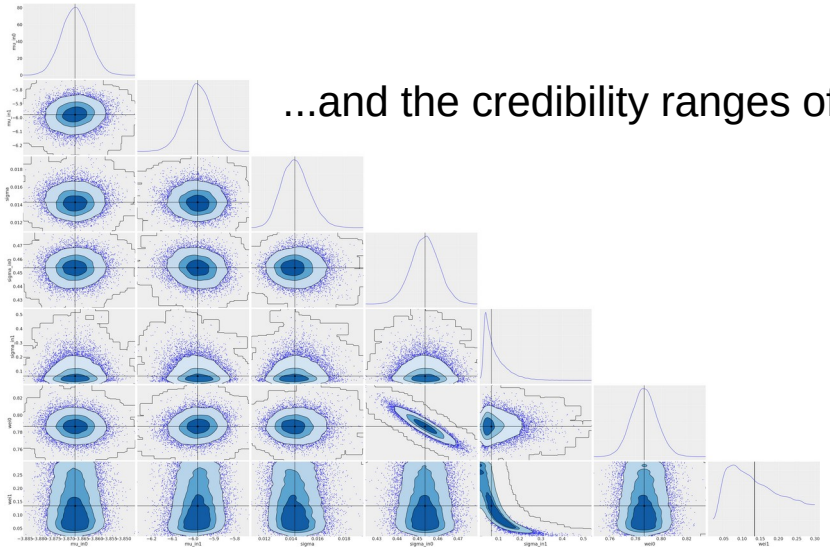



remember Molly's talk



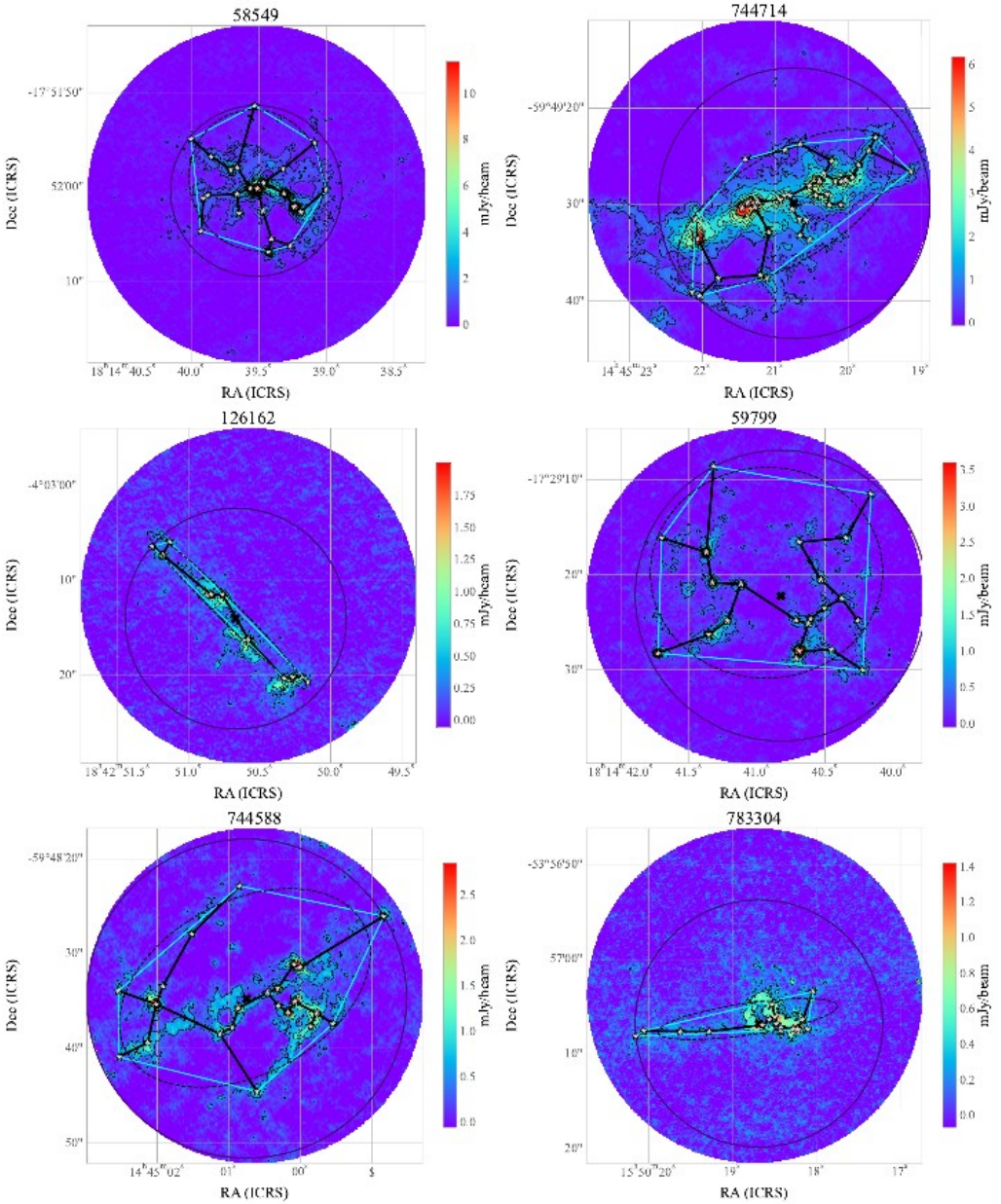

By applying Bayesian methods, one can recover the intrinsic distribution of accretion rates



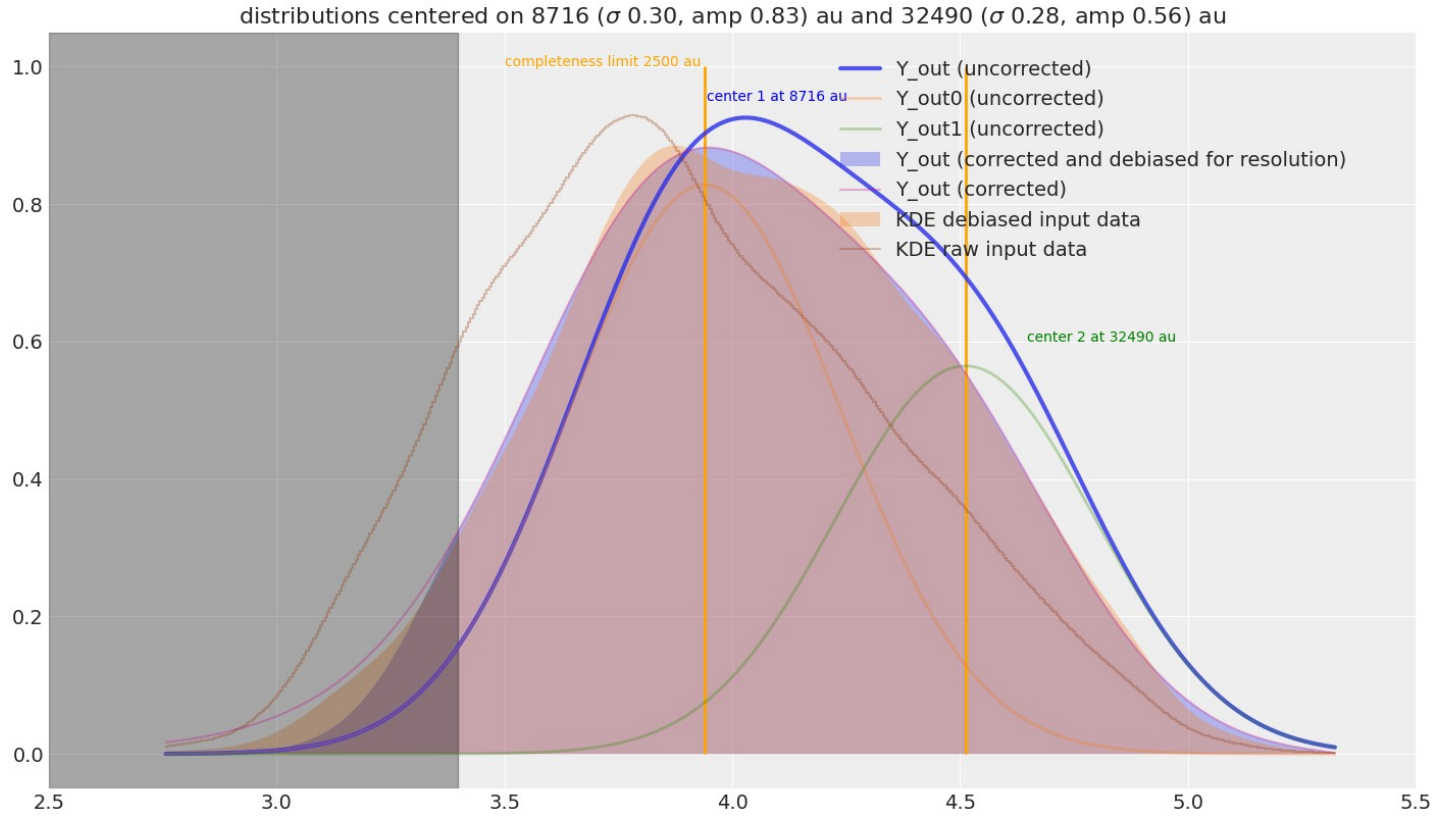



...and the credibility ranges of parameters

E. Schisano et al.: ALMAGAL VI. The spatial distribution of the dense cores in the early evolution of cluster-forming clumps (in prep)




(subm.)

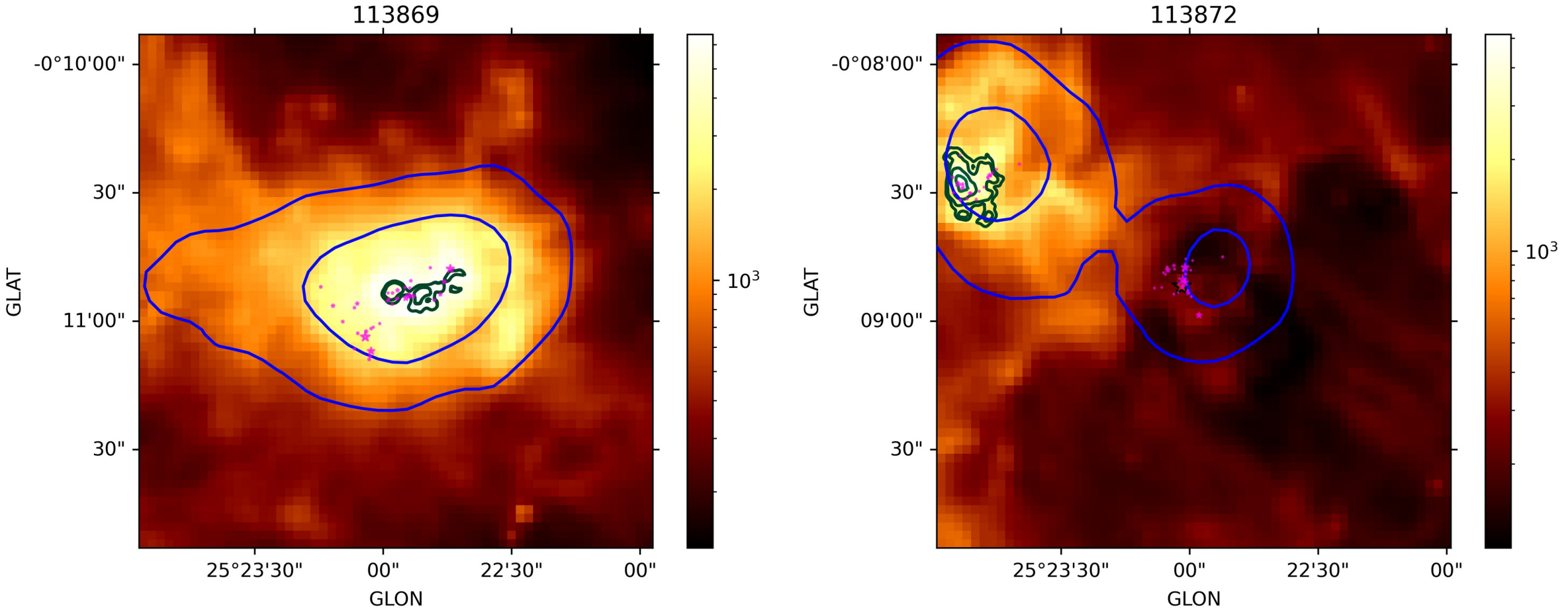



Statistics II: average distances between core

Filled: observed distribution of length
Line: deconvolved distribution

Needs to be checked if there is a dependence on L/M, galactocentric distance, clump mass, or external environment

Ringberg 2025: Puzzles of Star Formation




External environment: GLIMPSE 8 μm (color), ATLASGAL (blue contours), CORNISH HII regions (green contours), ALMAGAL cores (pink stars)
How does it affect the properties? Are some cores already so evolved that they are not longer visible in ALMAGAL, but in the IR?

Connection to larger scale mass reservoir: are the clumps isolated, or do they also still accrete? Follow the flow!

# Questions

- What is the range of parameters that can realize high-mass stars in nature?
  - (angular momentum, turbulence, magnetic field strength, magnetic field orientation, initial mass, connection to a larger mass reservoir, metallicities, neighborhood…)
- How do these environmental conditions determine the distribution of the results? Which ones are important?
  - (size, fragmentation, disks around protostars, properties of resulting binary or multiple systems)
- Do we have the right and complete metrics (compare also Álvaro Hacar's talk)?