The ALMA-IMF large observational program

“ALMA transforms our view of the origin of stellar masses”

Frédérique Motte (IPAG Grenoble)

ALMA-IMF PIs: F. Motte, A. Ginsburg, F. Louvet, P. Sanhueza
Management Team: 4 PIs + T. Csengeri, S. Bontemps, R. Galván-Madrid, F. Nakamura, A. Stutz
Consortium members: 70+ researchers from 11 countries in Europe (50%), N+S+C America, Chile, East Asia

https://www.almaimf.com
Outline

• Introduction on the Initial Mass Function (IMF) and its origin

• Massive protoclusters targeted by ALMA-IMF

• First results and prospects of ALMA-IMF
  o Core mass functions (CMF)
  o Protostellar activity: hot cores, outflows
  o Kinematics: from cloud to core

Conclusion
A universal Initial Mass Function?

The shape of the IMF studied in our solar neighborhood and nearby clusters seems universal. But is it really?

Top-heavy IMFs are measured:
• in the 30Dor starburst cluster (Schneider+ 2018)
• in young massive clusters near the Galactic Center (Hosek+ 2019; Hußmann+2012, Lu+ 2013)
• in young clusters of Cygnus X (Maia+ 2016)
• …
One-to-one relationship between the core mass function (CMF) and the IMF


The IMF is at least partly determined by fragmentation at the pre-stellar stage. Studies limited to <5 $M_\odot$ stars… in regions not typical of the main mode of star formation in galactic disks.

PCMI biennial conference, October 25 2022
Frédérique Motte, IPAG
Assumptions behind the CMF/IMF comparison

1. Measured core mass = total mass available to form a star
   - Neglecting gas mass feeding
   - Assuming an homogeneous core multiplicity

2. Uniform gas-to-star mass conversion, $\varepsilon = \text{constant}$
   - Assuming that outflows regulate $\varepsilon$
   - Neglecting the increase of $\varepsilon$ 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.
$\Rightarrow$ conspiracy like the central limit theorem? or
$\Rightarrow$ obs. uncertainties too large to see that the CMF is not so universal?
We tend to use and take for granted far too-simple cloud and star-formation recipes.  
⇒ The universality of the physical processes in the ISM does not imply that the star-formation prescriptions have to be universal.

The association of gas density peaks to gas reservoirs used during the protostellar collapse is abusive: resolution issues (Louvet+ 2021), multi-fractal nature of coherent cloud structures (Robitaille+ 2020), dynamical environments (Motte+ 2018)...

Constraints were for long limited to observations of stars and clouds in the solar neighborhood. Extrapolation to all regions in the Milky Way, and even worse to the whole Universe, cannot be valid!
Outline

• Introduction on the Initial Mass Function (IMF) and its origin

• Massive protoclusters targeted by ALMA-IMF

• First results and prospects of ALMA-IMF
  o Core mass functions (CMF)
  o Protostellar activity: hot cores, outflows
  o Kinematics: from cloud to core

Conclusion
Selection of the ALMA-IMF protocluster clouds

Objective = Constrain the temporal emergence of star clusters cover massive pc-size clouds → rich protoclusters reach cores (HPBW = 2000 AU) with $\sigma = 0.2 \, M_\odot$ @ young to partly evolved evolutionary stages

- From the 200 most massive ATLASGAL clumps (Csengeri+ 2017)
  - Distance filter for ALMA mosaics: $2 \, \text{kpc} < d < 5.5 \, \text{kpc}$
  - Integrated flux filter: $S_{870\mu m} > 25 \, \text{Jy}$
  
    ➔ the 28 most massive ($>10^3 \, M_\odot$) ATLASGAL clumps

- Inspecting LABOCA & Spitzer images to
  - Select massive clouds associated with ATLASGAL clumps
  - Rebalance the sample between IR-quiet and IR-bright
  
    ➔ 15 of the richest protoclusters clouds
Evolutionary stages of ALMA-IMF protoclusters

Criteria used:

• **Gas heating** traced by mid-IR fluxes of *Spitzer* (Csengeri+ 2017)
  - IR-quiet → IR-bright

• **Ionized gas** traced by our ALMA data (Motte+ 2022; Galván-Madrid+)
  - 1.3mm/3mm flux ratio to separate thermal dust from free-free emission
  - Free-free emission estimated from the H41α recombination line
  - Young dust filaments → Intermediate dust filaments + UCHIIIs → Evolved protoclusters developed HII regions

• **Starburst development** traced by the ratio of protostellar cores,
  - R=N_{proto}/N (Nony+ subm.; Pouteau+ subm.)
  - Pre-burst → Burst (ratio enhanced) → Post-burst
Massive protoclusters at various evolutionary stages

Contours: 870 μm → massive clouds
RGB = 24μm /8μm /3.6μm → IR-bright or IR-quiet
RGB = 1.3mm / 3mm / free-free @ 3mm

orange = thermal dust
green = diffuse free-free
blue = strong free-free
### Catalog of 15 ALMA-IMF massive protoclusters

<table>
<thead>
<tr>
<th>Protocluster cloud name(^1)</th>
<th>RA(^1) [ICRS]</th>
<th>Dec(^1) [km s(^{-1})]</th>
<th>(d) [kpc]</th>
<th>Evolutionary stage(^2)</th>
<th>Imaged areas(^3) [pc × pc]</th>
<th>(M_{\text{cloud}})(^{(3)}) (870\ \mu\text{m})</th>
<th>(A_{1.3\text{mm}}) (\times10^{3} \text{ M}_{\odot})</th>
</tr>
</thead>
<tbody>
<tr>
<td>W43-MM1</td>
<td>18:47:47.00</td>
<td>−01:54:26.0</td>
<td>+97</td>
<td>5.5±0.4</td>
<td>Young</td>
<td>3.1 × 2.3</td>
<td>5.1 × 4.0</td>
</tr>
<tr>
<td>W43-MM2</td>
<td>18:47:36.61</td>
<td>−02:00:51.1</td>
<td>+97</td>
<td>5.5±0.4</td>
<td>Young</td>
<td>2.6 × 2.4</td>
<td>5.1 × 4.0</td>
</tr>
<tr>
<td>G338.93</td>
<td>16:40:34.42</td>
<td>−45:41:40.6</td>
<td>−62</td>
<td>3.9±1.0</td>
<td>Young</td>
<td>1.6 × 1.6</td>
<td>2.9 × 2.8</td>
</tr>
<tr>
<td>G328.25</td>
<td>15:57:59.68</td>
<td>−53:58:00.2</td>
<td>−43</td>
<td>2.5±0.5</td>
<td>Young</td>
<td>1.4 × 1.4</td>
<td>2.2 × 1.9</td>
</tr>
<tr>
<td>G337.92</td>
<td>16:41:10.62</td>
<td>−47:08:02.9</td>
<td>−40</td>
<td>2.7±0.7</td>
<td>Young</td>
<td>1.2 × 1.1</td>
<td>2.1 × 2.0</td>
</tr>
<tr>
<td>G327.29</td>
<td>15:53:08.13</td>
<td>−54:37:08.6</td>
<td>−45</td>
<td>2.5±0.5</td>
<td>Young</td>
<td>1.3 × 1.3</td>
<td>1.9 × 1.8</td>
</tr>
<tr>
<td>G351.77</td>
<td>17:26:42.62</td>
<td>−36:09:20.5</td>
<td>−3</td>
<td>2.0±0.7</td>
<td>Intermediate</td>
<td>1.3 × 1.3</td>
<td>1.8 × 1.7</td>
</tr>
<tr>
<td>G008.67</td>
<td>18:06:21.12</td>
<td>−21:37:16.7</td>
<td>+37.6</td>
<td>3.4±0.3</td>
<td>Intermediate</td>
<td>2.2 × 1.4</td>
<td>3.1 × 2.1</td>
</tr>
<tr>
<td>W43-MM3</td>
<td>18:47:41.46</td>
<td>−02:00:27.6</td>
<td>+97</td>
<td>5.5±0.4</td>
<td>Intermediate</td>
<td>2.7 × 2.4</td>
<td>5.1 × 4.0</td>
</tr>
<tr>
<td>W51-E</td>
<td>19:23:44.18</td>
<td>+14:30:29.5</td>
<td>+55</td>
<td>5.4±0.3</td>
<td>Intermediate</td>
<td>2.6 × 2.4</td>
<td>4.2 × 3.9</td>
</tr>
<tr>
<td>G353.41</td>
<td>17:30:26.28</td>
<td>−34:41:49.7</td>
<td>−17</td>
<td>2.0±0.7</td>
<td>Intermediate</td>
<td>1.3 × 1.3</td>
<td>1.8 × 1.7</td>
</tr>
<tr>
<td>G010.62</td>
<td>18:10:28.84</td>
<td>−19:55:48.3</td>
<td>−2</td>
<td>4.95±0.5</td>
<td>Evolved</td>
<td>2.3 × 2.2</td>
<td>3.8 × 3.6</td>
</tr>
<tr>
<td>W51-IRS2</td>
<td>19:23:39.81</td>
<td>+14:31:03.5</td>
<td>+55</td>
<td>5.4±0.3</td>
<td>Evolved</td>
<td>2.6 × 2.4</td>
<td>4.2 × 3.9</td>
</tr>
<tr>
<td>G012.80</td>
<td>18:14:13.37</td>
<td>−17:55:45.2</td>
<td>+37</td>
<td>2.4±0.2</td>
<td>Evolved</td>
<td>1.5 × 1.5</td>
<td>2.2 × 2.1</td>
</tr>
<tr>
<td>G333.60</td>
<td>16:22:09.36</td>
<td>−50:05:58.9</td>
<td>−47</td>
<td>4.2±0.7</td>
<td>Evolved</td>
<td>2.9 × 2.9</td>
<td>3.9 × 3.7</td>
</tr>
</tbody>
</table>

1.3- 8 pc\(^2\) clouds, with 2.5-21 \(10^{3}\) \(M_{\odot}\) and ~11 cores /pc\(^2\)

6 young + 5 intermediate + 4 evolved

Motte+ 2022
ALMA-IMF targets: 15 massive clouds along Galactic arms

ALMA-IMF LP (PI: Motte, Ginsburg, Louvet, Sanuheza)

Targets:
- A large sample of massive protoclusters at <6 kpc.
- More representative of Milky Way star-forming clouds.
- At various evolutionary stages of the gas-dominated phase.

(Figure adapted from Hurt & Benjamin 2008)
ALMA-IMF observations and database

- Proposal: Cycle 5, #2017.1.01355.L
  Configurations: 12M (compact + extended) + ACA/7M + TP
  10/2017-08/2019: 69 hours 12M + 172 hours ACA + 595 hours TP

- Spatial resolution and sensitivity:
  requested (0.37’’-0.95’’) = 2000 AU (typical ‘core’ size)
  and 3σ = 0.2 M☉ (1 M☉ @ 3mm)

- Areas covering large protoclusters:
  Mosaics: 7 to 85 fields @ 1mm, total area ~53 pc²

- Data calibration & reduction
  Recalibration of line cubes
  12M: ALMA-IMF pipeline for continuum self-calibration
  Continuum and line data release (Ginsburg+ 2022; Cunningham et al. subm.)

A. Lopez-Sepulcre
IRAM/ARC

A. Ginsburg

N. Cunningham

PCMI biennial conference, October 25 2022
Frédérique Motte, IPAG
Outline

• Introduction on the Initial Mass Function (IMF) and its origin

• Massive protoclusters targeted by ALMA-IMF

• First results and prospects of ALMA-IMF
  o Core mass functions (CMF)
  o Protostellar activity: hot cores, outflows
  o Kinematics: from cloud to core

Conclusion
Scientific working groups

• Core WG  led by T. Nony & F. Motte
  o IMF origin: CMF evolution with time and cloud properties
  o Mass inflow: core mass growth and CMF evolution
  o High-mass star formation: high-mass prestellar core?
  o Protostars: accretion history, mass segregation

• Hot core/chemical enrichment WG  led by T. Csengeri
  o Toward protostars: statistics, dependence on mass, evolutionary sequence
  o Throughout the cloud: outflow, protostellar accretion, …

• Kinematics WG  led by A. Stutz & M. Fernandez-Lopez
  o Multiscale properties: turbulence, rotation, inflow
  o Filaments: evolution of their density and velocity with time
  o Filament formation: inflow and shocks
  o Outflows: varying with cloud properties, generating turbulence
An ALMA view of the W43-MM1 mini-starburst protocluster (pilot study of ALMA-IMF)

W43 @ 5.5 kpc

1.3 mm sensitivity:
Scales 0.5”-7”

Mass completeness
~1.6 \(M_\odot\)

131 cores detected with getsources (2000 AU, ~1-100 \(M_\odot\)), among which 13 forming high-mass stars.
Core Mass Function within the W43-MM1 ridge

The 1.6-100 $M_\odot$ part of the CMF is much flatter than usually found. => It would suggest an atypical IMF for stars of 1-50 $M_\odot$ ($\varepsilon=50\%$).

Top-heavy IMFs
Lu+ 2013, Maia+ 2016, Hosek 2019

or CMF evolution
or complex CMF/IMF relation

See also Kong 2019
(Zhang+2015; Sanchez-Monge+2017; Cheng+2018; Liu+ 2018)
• Line-free continuum (1.3mm & 3mm) images smoothed to the same physical resolution, 2700 AU.
• Catalog of ~700 cores extracted by *getsf* and *GExt2D* (Men’shchikov+ 2021; Bontemps+ prep.).
→ 0.15-250 $M_{\odot}$ (with 20 K to 75 K dust temperatures)
Global CMFs in ALMA-IMF clouds

**Core catalog is split between Young, Intermediate, and Evolved clouds:**

- **Young and Intermediate CMFs are top-heavy.**
- **Evolved CMF reconciles with the Salpeter slope of the canonical IMF.**

Global CMF of ALM-IMF clouds is top-heavy again!

CMF evolution with time?
Subregion properties (evolutionary stage, $N_{\text{H}_2}$)

Column density image of W43-MM2&MM3 subregions

PCMI biennial conference, October 25 2022
Frédérique Motte, IPAG
PDF secondary tail versus CMF high-mass end

Tentative correlation of their slopes!

PDF of the column density in subregions

CMF of subregions

Pouteau+ subm.
Evolutionary scenario for star-forming bursts

Quiescent
- Outskirts: MM51
- Pre-burst: MM10

Main-burst
- MM12
- Massive cores: Accretion, Ridge or hub
- Core mass segregation: Enhanced protostellar activity

Post-burst
- MM3
- Expanding HII region
- Stellar feedback – Complex core mass segregation

Quiescent or pre-burst:
- η–PDF and CMF
  ~ low-mass star-forming regions.

Main burst:
- η–PDF is flatter and CMF is top-heavy

Post-burst:
- PDF is flatter and CMF is top-heavy and bottom-light.

Evolved clouds?

Proposed by Pouteau+ subm.
Molecular complexity: hot cores and shocks

Catalog of >65 hot cores (detected with CH3OCHO) associated with 2-200 $M_\odot$ cores.
→ Are the low-mass cores hot corinos?

Bonfand et al. in prep.
Relative homogeneity of the molecular content of 7 hot cores in W43-MM1

In Brouillet+ 2022 abstract:

« The excitation temperature of CH3CN, whose emission is centred on the cores, is of the same order for all of them (120–160 K). »

« There is a factor of up to 30 difference in the intensity of the complex organic molecules (COMs) lines. However the molecular emission of the hot cores appears to be the same within a factor 2–3. »
Rich clusters of protostellar outflows

46+51 outflow lobes detected using CO(2-1) and SiO(5-4)
$L_{\text{max}}$ from 0.02 to 0.4 pc; $\Delta V_{\text{max}}$ from 10 to 100 km s$^{-1}$
SiO outflow catalog by Towner et al. (in prep.)
Global protocluster kinematics and filaments identification with N$_2$H$^+$

Velocity streams (N$_2$H$^+$) tracing rotation, inflow...

Tentative variation of the N$_2$H$^+$ structure with cloud evolutionary stage (Stutz et al. in prep.)
Complex lines (optically thick or several velocity components) are disregarded.

⇒ DCN likely is « our best core tracer » (~50% of the cores are detected)

### G338.93 test field - **42 continuum cores**

<table>
<thead>
<tr>
<th>Lines</th>
<th>Frequency (GHz)</th>
<th>Temp</th>
<th>Critical Density (cm^-3)</th>
<th>#Detected</th>
<th>Complex</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>DCN (3-2)</td>
<td>217.238</td>
<td>~20K</td>
<td>~1(5)-1(6)</td>
<td>20</td>
<td>7</td>
<td>27 (64%)</td>
</tr>
<tr>
<td>13CS (5-4)</td>
<td>231.220</td>
<td>~30K</td>
<td>4(6)</td>
<td>7</td>
<td>11</td>
<td>18 (43%)</td>
</tr>
<tr>
<td>N2D+ (3-2)</td>
<td>231.322</td>
<td>~20K</td>
<td>4(6)</td>
<td>11</td>
<td>2</td>
<td>13 (31%)</td>
</tr>
<tr>
<td>OCS (19-18)</td>
<td>231.060</td>
<td>~110K</td>
<td>5(5)</td>
<td>7</td>
<td>11</td>
<td>18 (43%)</td>
</tr>
<tr>
<td>C18O (2-1)</td>
<td>219.560</td>
<td>~15K</td>
<td>9.9(3)</td>
<td>12</td>
<td>22</td>
<td>34 (81%)</td>
</tr>
</tbody>
</table>
• ALMA-IMF continuum images are delivered, line data cubes will soon be (Motte+ 2022; Ginsburg+ 2022; Cunningham+ subm.)

• ALMA-IMF will provide catalogs of cores, filaments, hot cores, outflows…

• ALMA-IMF started to revisit the IMF origin by revealing top-heavy CMFs and correlating the powerlaw index of their high-mass end with cloud properties and evolutionary stage (Pouteau+2022, subm.; Nony et al. subm.; Louvet et al. in prep.).

• A lot more is expected from
  o the kinematical studies, starting now,
  o the comparison of observed and simulated protoclusters,
  o the variation of cloud molecular complexity (Brouillet+ 2022),
  o …