The ALMA-IMF large observational program

"ALMA transforms our view of the origin of stellar masses"

Frédérique Motte (IPAG Grenoble)

https://www.almaimf.com

- 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

Outline

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

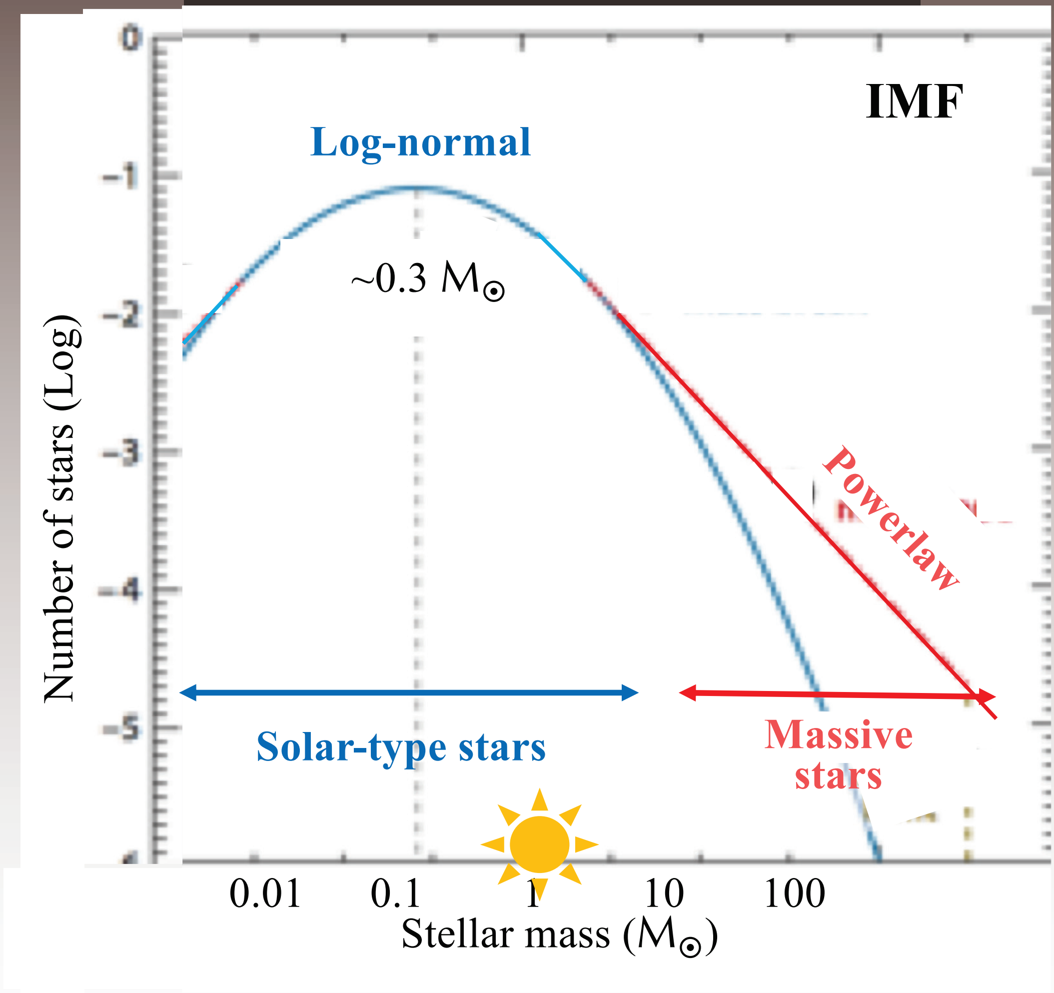
- Massive protoclusters targeted by ALMA-IMF

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

Conclusion

A universal Initial Mass Function?

Initial mass function (IMF) of stars



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

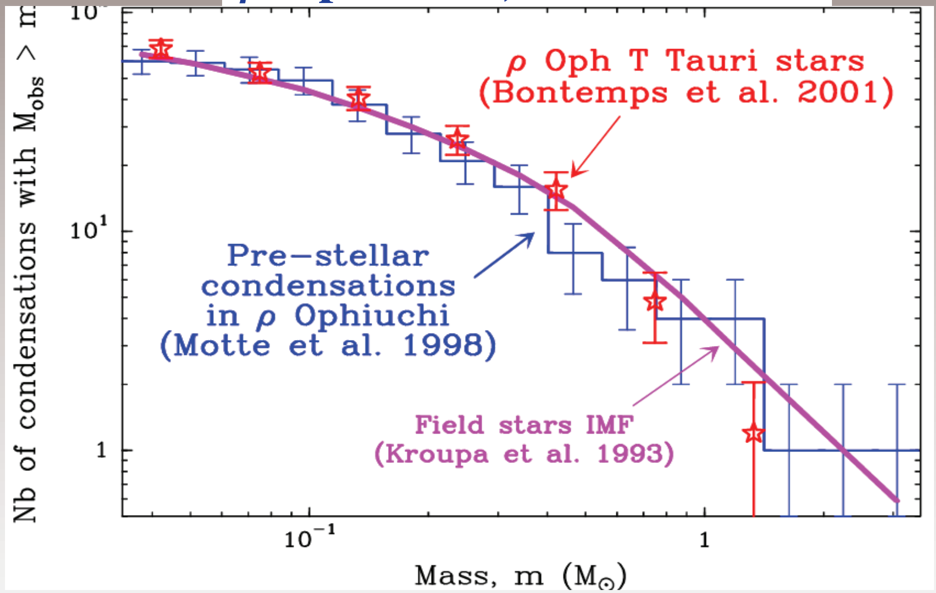
Top-heavy IMFs are measured:

- 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)
- …

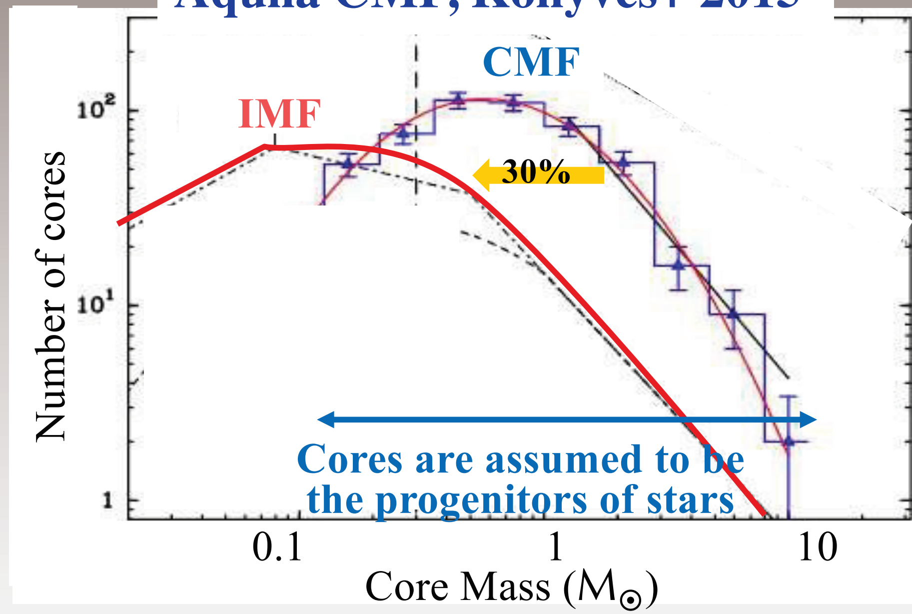
One-to-one relationship between the core mass function (CMF) and the IMF

Submm ground-based, *Herschel*, and NIR extinction surveys of the past 2 decades (Motte+ 1998, 2001; Testi & Sargent 1998; Johnstone+ 2000; Stanke+ 2006; Alves+ 2007; Nutter & Ward-Thompson 2007; Enoch+ 2008; André+ 2010; Könyves+ 2015, …).

ρ Oph CMF, Motte+ 1998



Aquila CMF, Könyves+ 2015



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.

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, ε = constant

- Assuming that outflows regulate ε
- Neglecting the increase of ε 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?

How to go forward?

- 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!

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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

T. Csengeri

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

  ➔ the 28 most massive ($>10^3\ M_\odot$) ATLASGAL clumps

S. Bontemps

- 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

R. Galván-Madrid

- 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

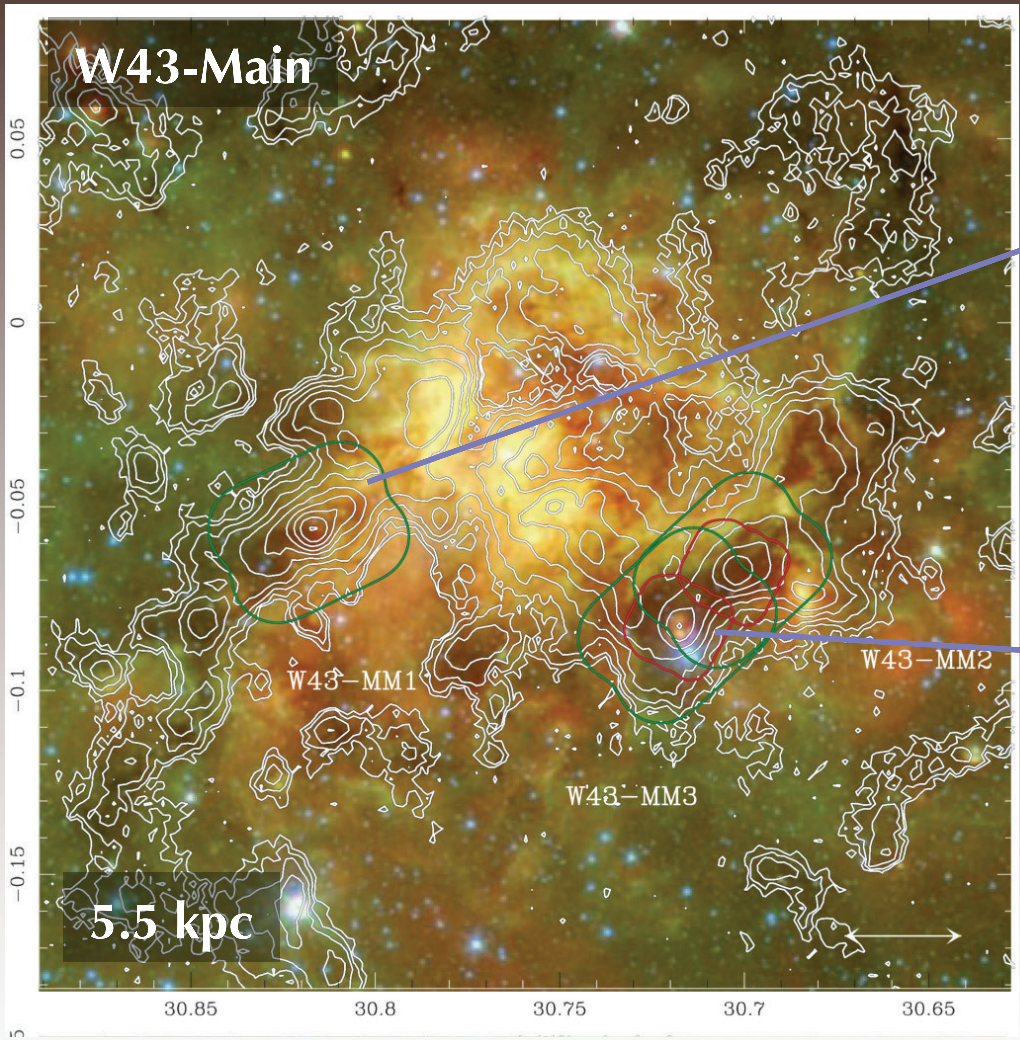
  Young dust filaments → Intermediate dust filaments + UCHIIs → Evolved protoclusters developed HII regions

T. Nony

- Starburst development traced by the ratio of protostellar cores, $R=N_{proto}/N$ (Nony+ subm.; Pouteau+ subm.)

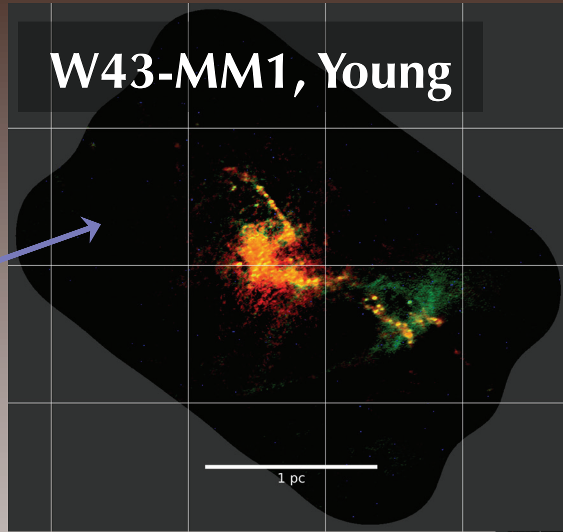
  Pre-burst → Burst (ratio enhanced) → Post-burst

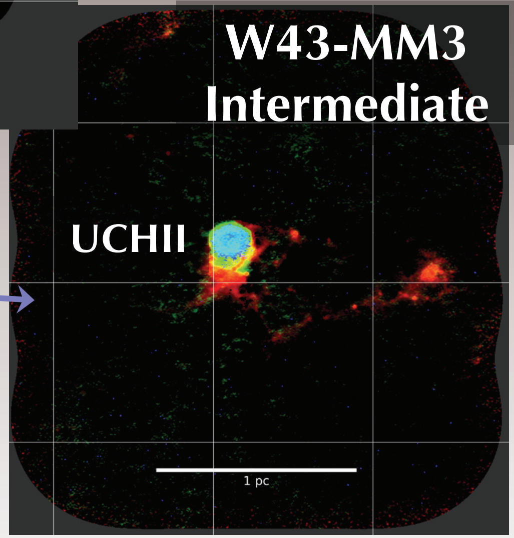
Massive protoclusters at various evolutionary stages



Contours: 870 µm → massive clouds
RGB = 24µm /8µm /3.6µm → IR-bright or IR-quiet

Motte+ 2022





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

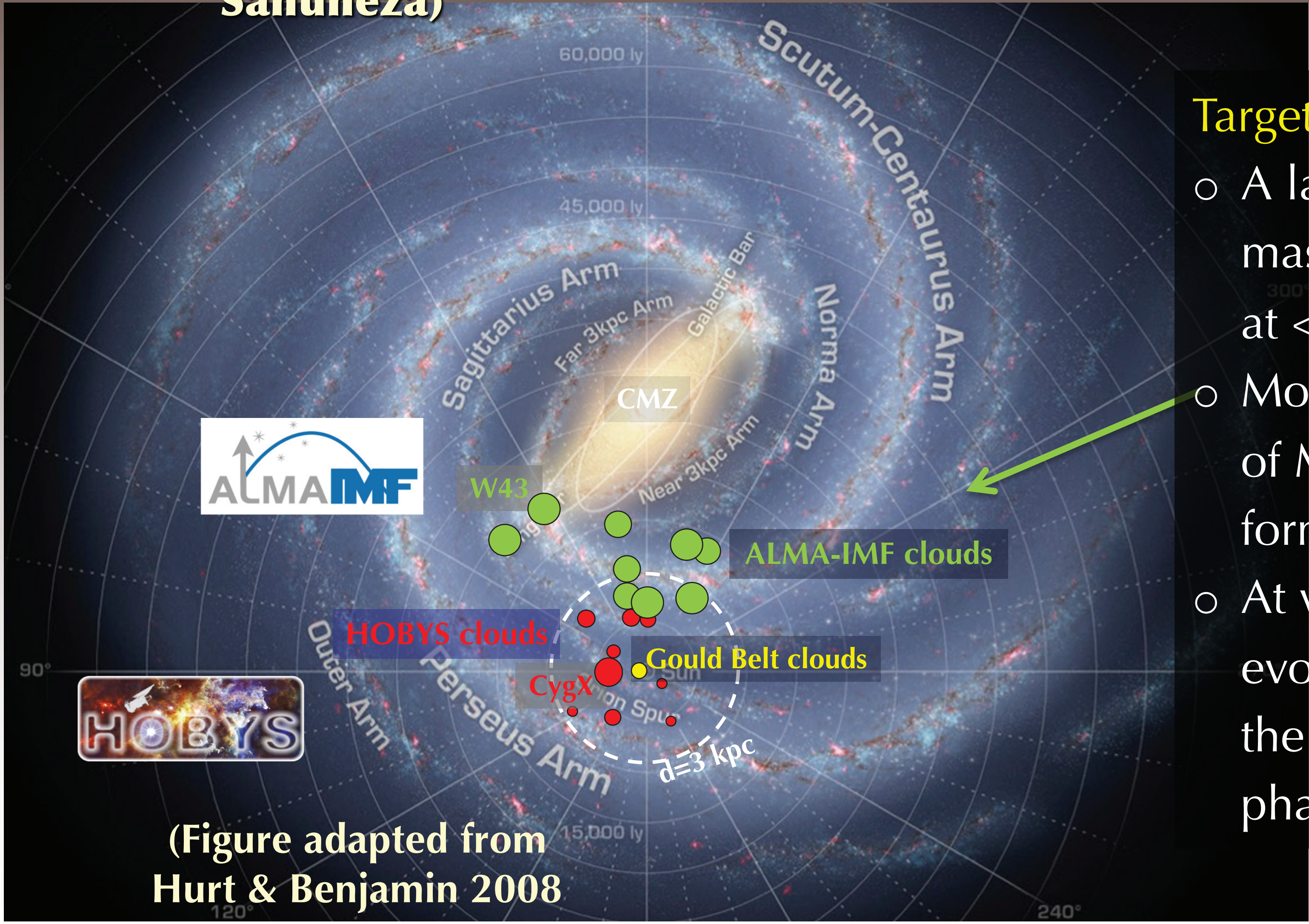
Protocluster cloud name[1]	RA[1] [ICRS]	Dec[1] [ICRS]	V_{LSR}[1] [km s^{-1}]	d [kpc]	Evolutionary stage[2]	Imaged areas[3] [pc × pc] $A_{1.3\,mm}$	Imaged areas[3] [pc × pc] $A_{3\,mm}$	$M^{cloud}_{870\,\mu m}$ (3) $A_{1.3\,mm}$ [$\times 10^3\ M_\odot$]
W43-MM1	18:47:47.00	−01:54:26.0	+97	5.5±0.4	Young	3.1 × 2.3	5.1 × 4.0	13.4
W43-MM2	18:47:36.61	−02:00:51.1	+97	5.5±0.4	Young	2.6 × 2.4	5.1 × 4.0	11.6
G338.93	16:40:34.42	−45:41:40.6	−62	3.9±1.0	Young	1.6 × 1.6	2.9 × 2.8	7.1
G328.25	15:57:59.68	−53:58:00.2	−43	2.5±0.5	Young	1.4 × 1.4	2.2 × 1.9	2.5
G337.92	16:41:10.62	−47:08:02.9	−40	2.7±0.7	Young	1.2 × 1.1	2.1 × 2.0	2.5
G327.29	15:53:08.13	−54:37:08.6	−45	2.5±0.5	Young	1.3 × 1.3	1.9 × 1.8	5.1
G351.77	17:26:42.62	−36:09:20.5	−3	2.0±0.7	Intermediate	1.3 × 1.3	1.8 × 1.7	2.5
G008.67	18:06:21.12	−21:37:16.7	+37.6	3.4±0.3	Intermediate	2.2 × 1.4	3.1 × 2.1	3.1
W43-MM3	18:47:41.46	−02:00:27.6	+97	5.5±0.4	Intermediate	2.7 × 2.4	5.1 × 4.0	5.2
W51-E	19:23:44.18	+14:30:29.5	+55	5.4±0.3	Intermediate	2.6 × 2.4	4.2 × 3.9	32.7
G353.41	17:30:26.28	−34:41:49.7	−17	2.0±0.7	Intermediate	1.3 × 1.3	1.8 × 1.7	2.5
G010.62	18:10:28.84	−19:55:48.3	−2	4.95±0.5	Evolved	2.3 × 2.2	3.8 × 3.6	6.7
W51-IRS2	19:23:39.81	+14:31:03.5	+55	5.4±0.3	Evolved	2.6 × 2.4	4.2 × 3.9	20.6
G012.80	18:14:13.37	−17:55:45.2	+37	2.4±0.2	Evolved	1.5 × 1.5	2.2 × 2.1	4.6
G333.60	16:22:09.36	−50:05:58.9	−47	4.2±0.7	Evolved	2.9 × 2.9	3.9 × 3.7	12.0

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)



(Figure adapted from Hurt & Benjamin 2008

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.

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 $3\sigma = 0.2\ M_\odot$ ($1\ M_\odot$ @ 3mm)

- Areas covering large protoclusters:

  Mosaics: 7 to 85 fields @ 1mm, total area ~53 pc^2

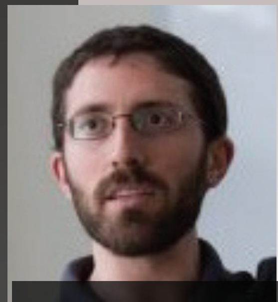
- Data calibration & reduction

  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

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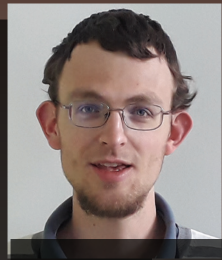
Scientific working groups

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

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

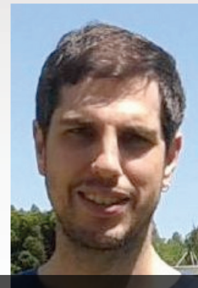
- Kinematics WG led by A. Stutz & M. Fernandez-Lopez
  - Multiscale properties: turbulence, rotation, inflow
  - Filaments: evolution of their density and velocity with time
  - Filament formation: inflow and shocks
  - Outflows: varying with cloud properties, generating turbulence


T. Nony


F. Motte


T. Csengeri


A. Stutz

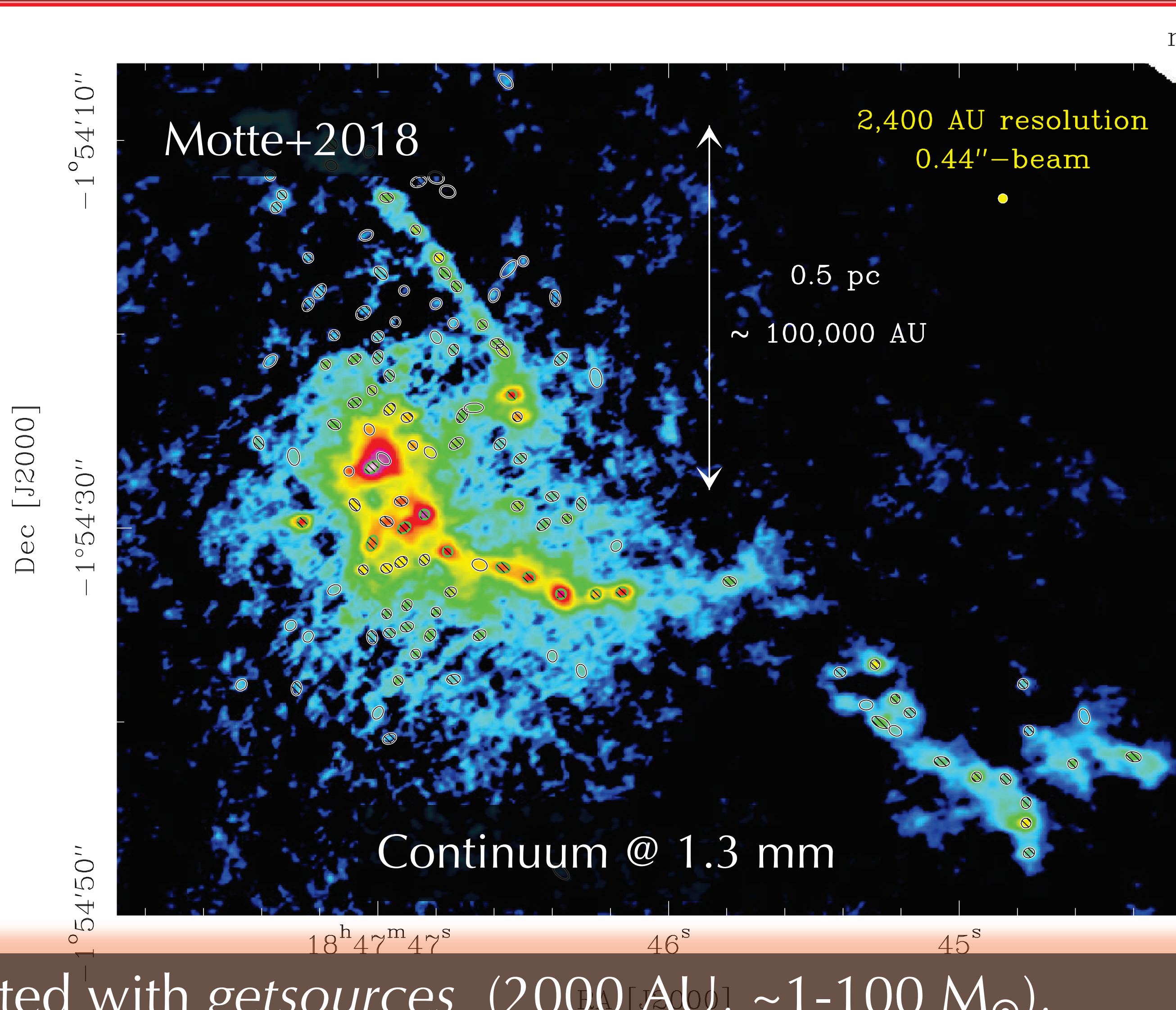

M. Fernandez-Lopez

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$_\odot$




F. Motte

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

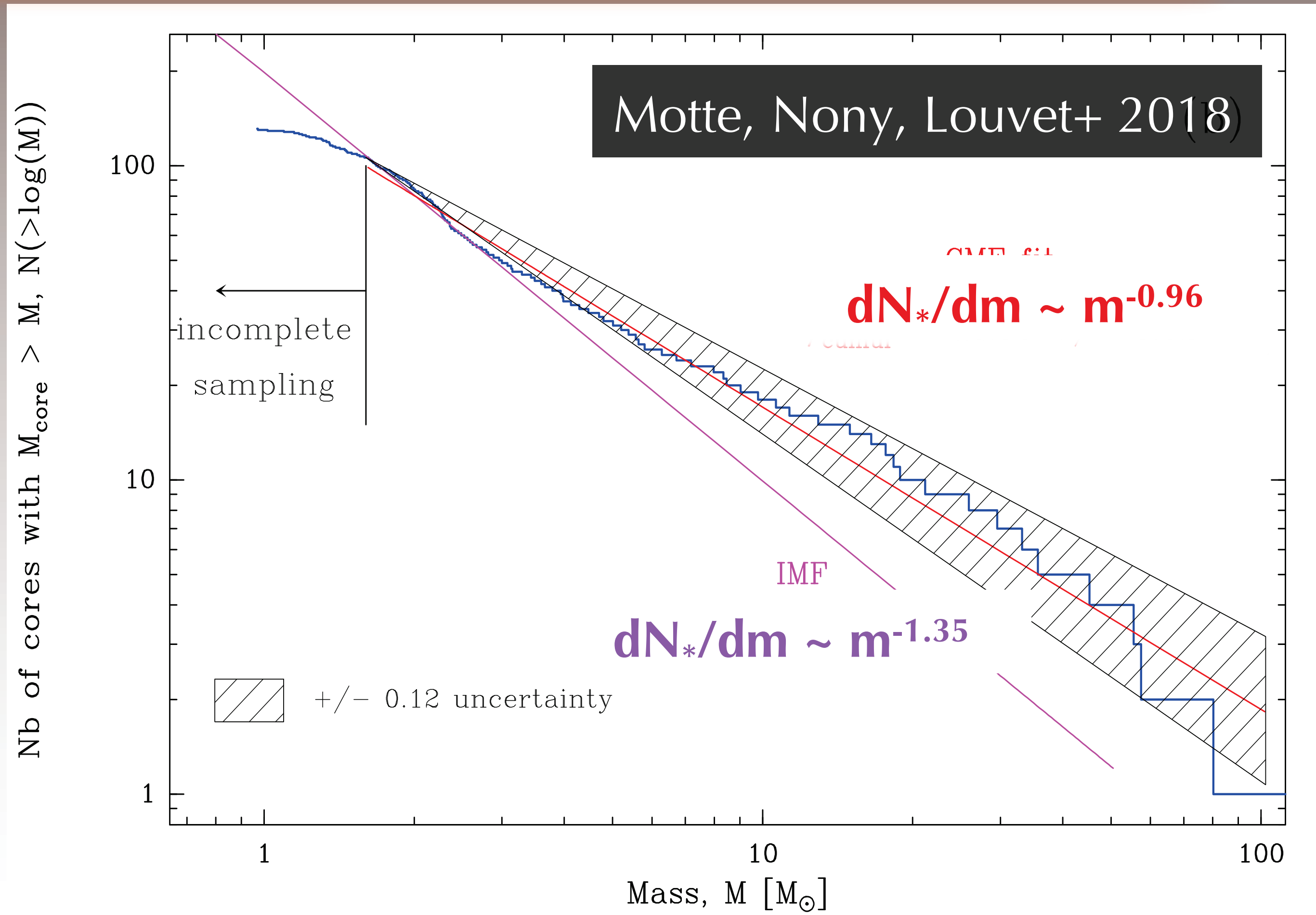
The 1.6-100 $M_\odot$ part of the CMF is much flatter than usually found.
=> It would suggest an atypical IMF for stars of 1-50 $M_\odot$ (ε=50%).

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

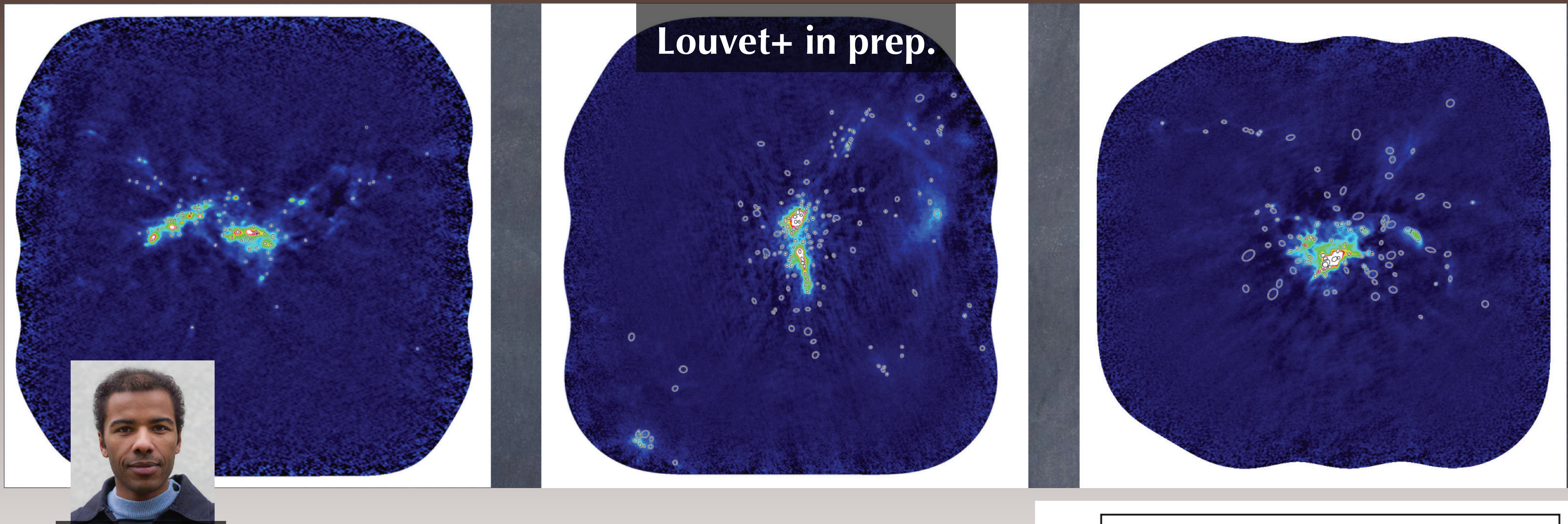
or CMF evolution

or complex CMF/IMF relation

See also Kong 2019 (Zhang+2015; Sanchez-Monge+2017; Cheng+2018; Liu+ 2018)



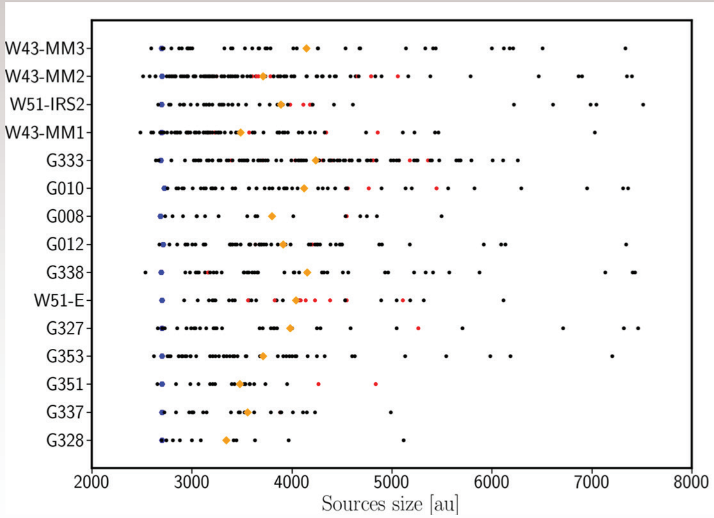
Complete core population in ALMA-IMF clouds



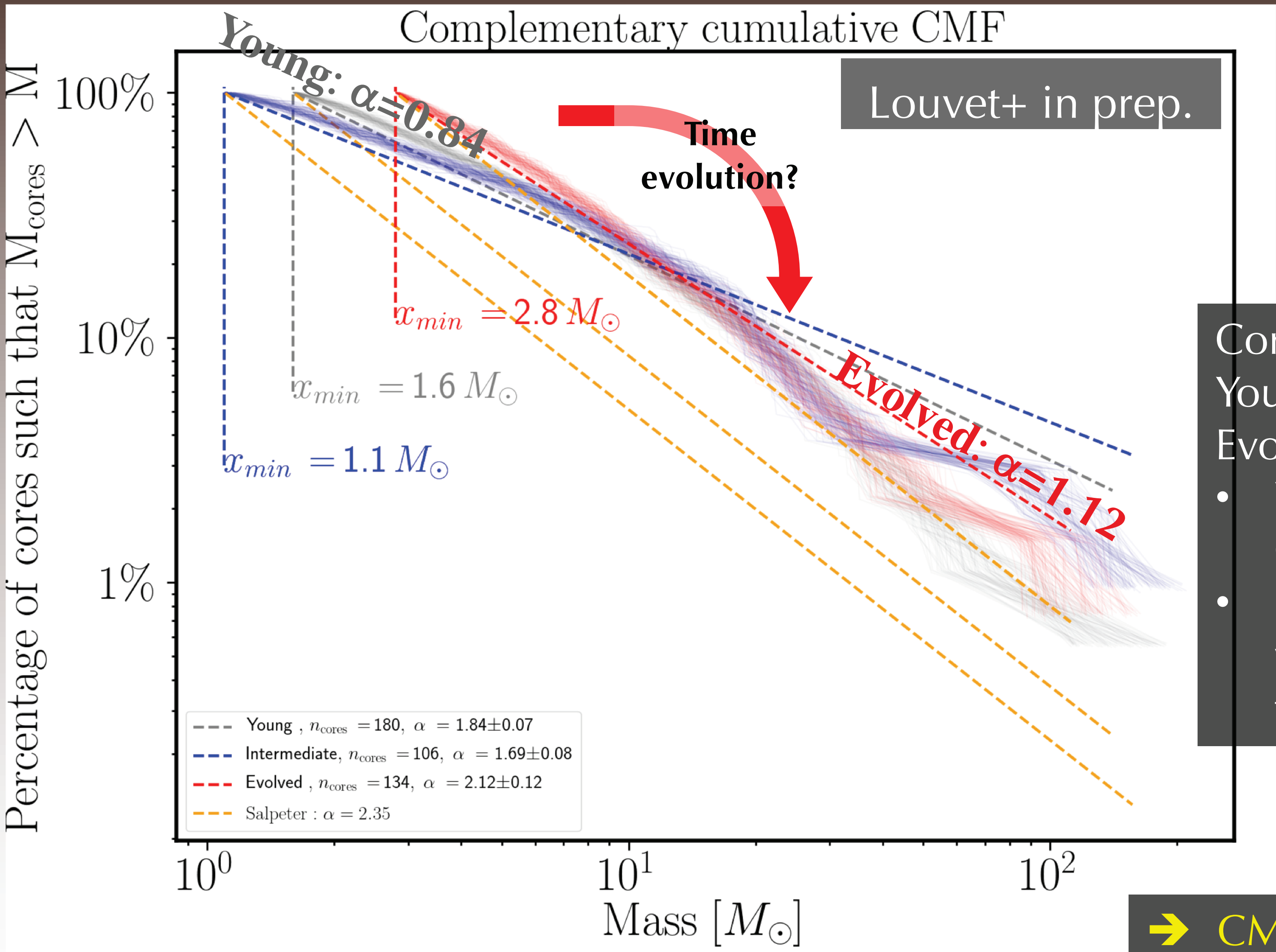
F. Louvet

- 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



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

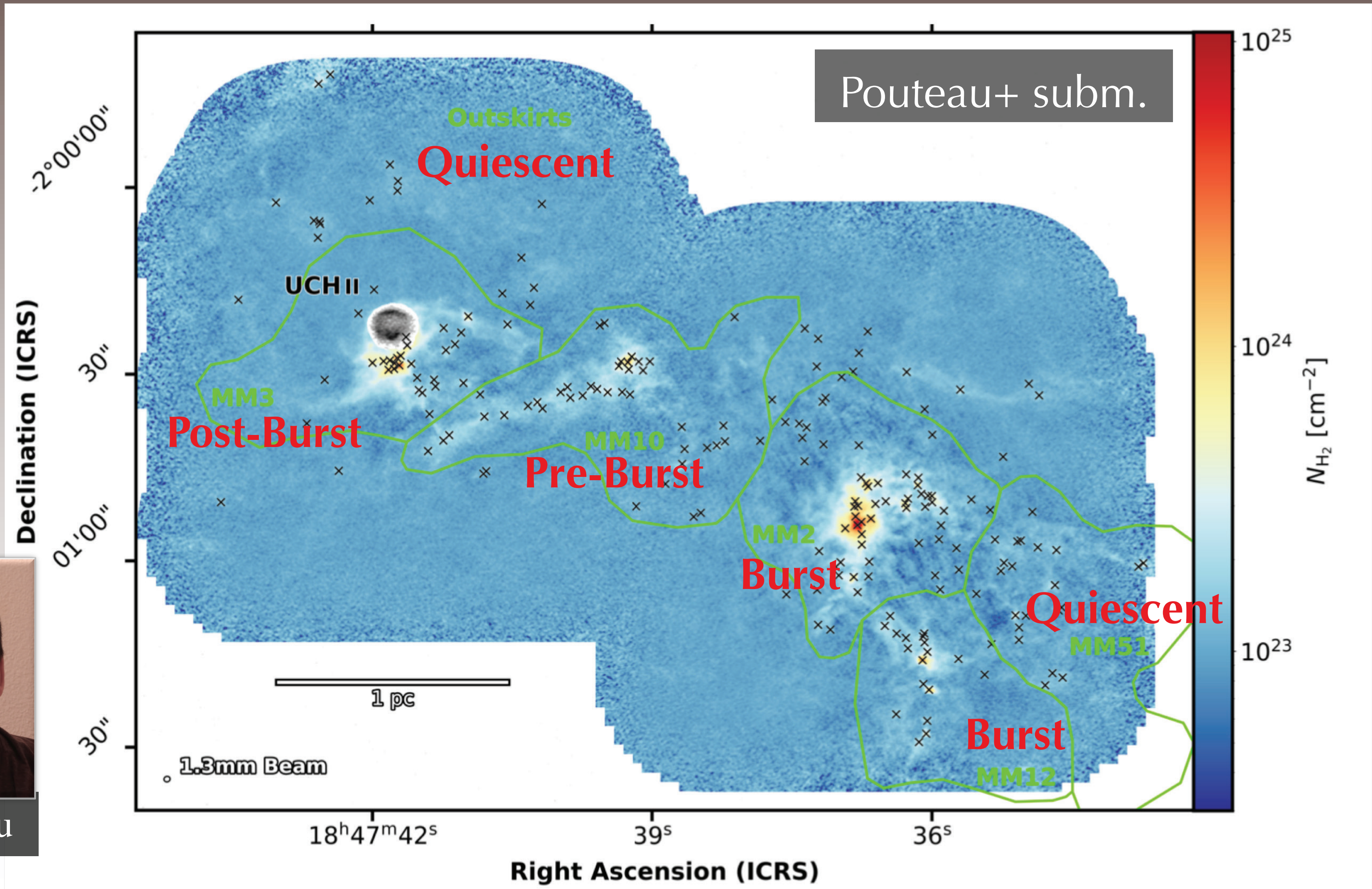
Core catalog is split between Young, Intermediate, and Evolved clouds:

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

➔ CMF evolution with time?

Subregion properties (evolutionary stage, N_{H2})

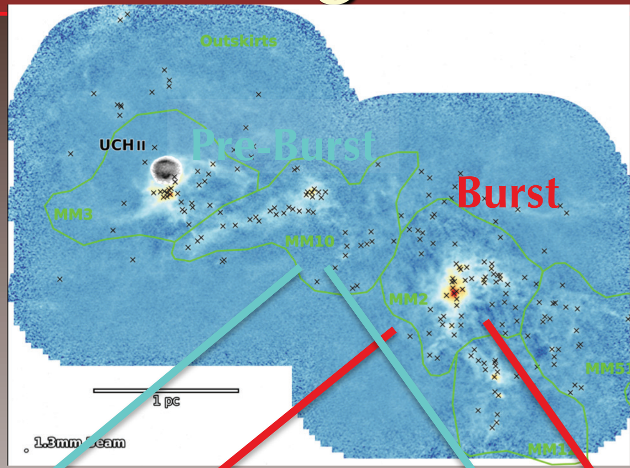
Column density image of W43-MM2&MM3 subregions



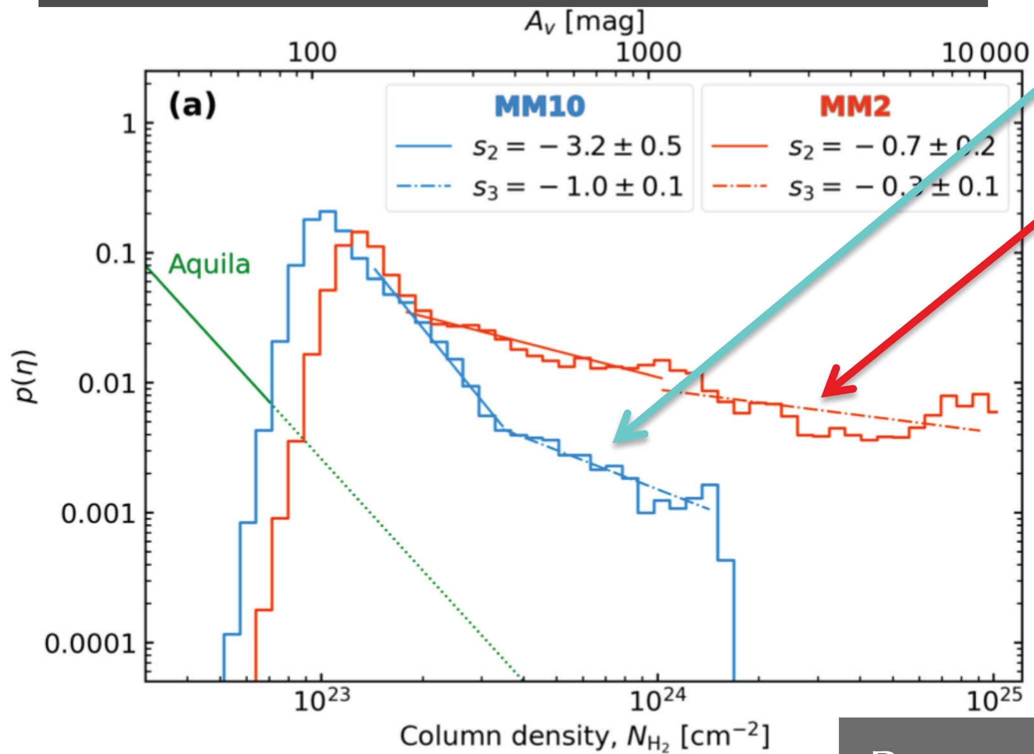
Y. Pouteau

PDF secondary tail versus CMF high-mass end

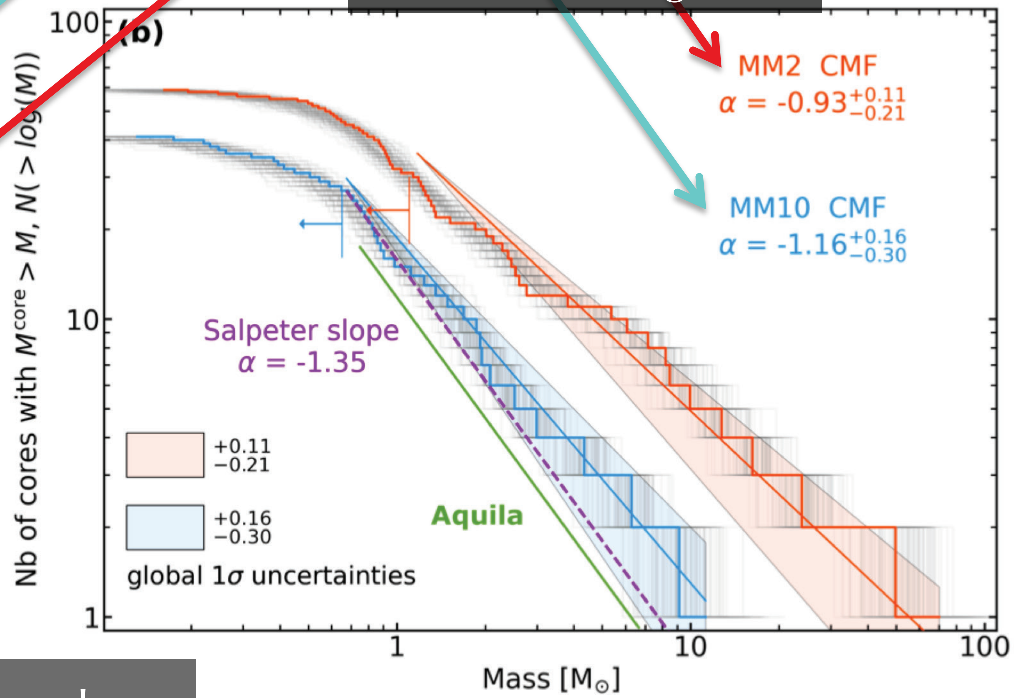
Tentative correlation of their slopes!



PDF of the column density in subregions



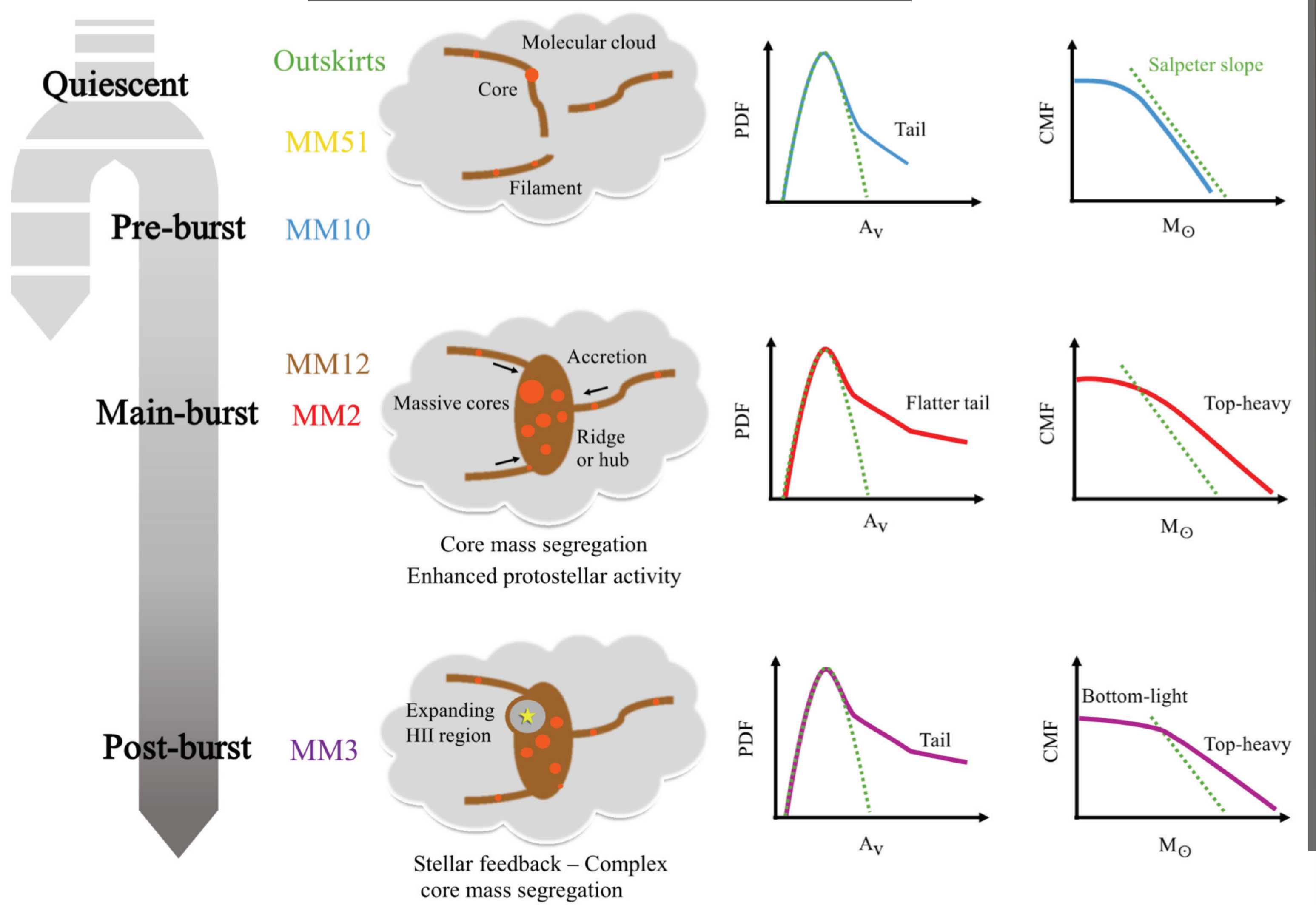
CMF of subregions



Pouteau+ subm.

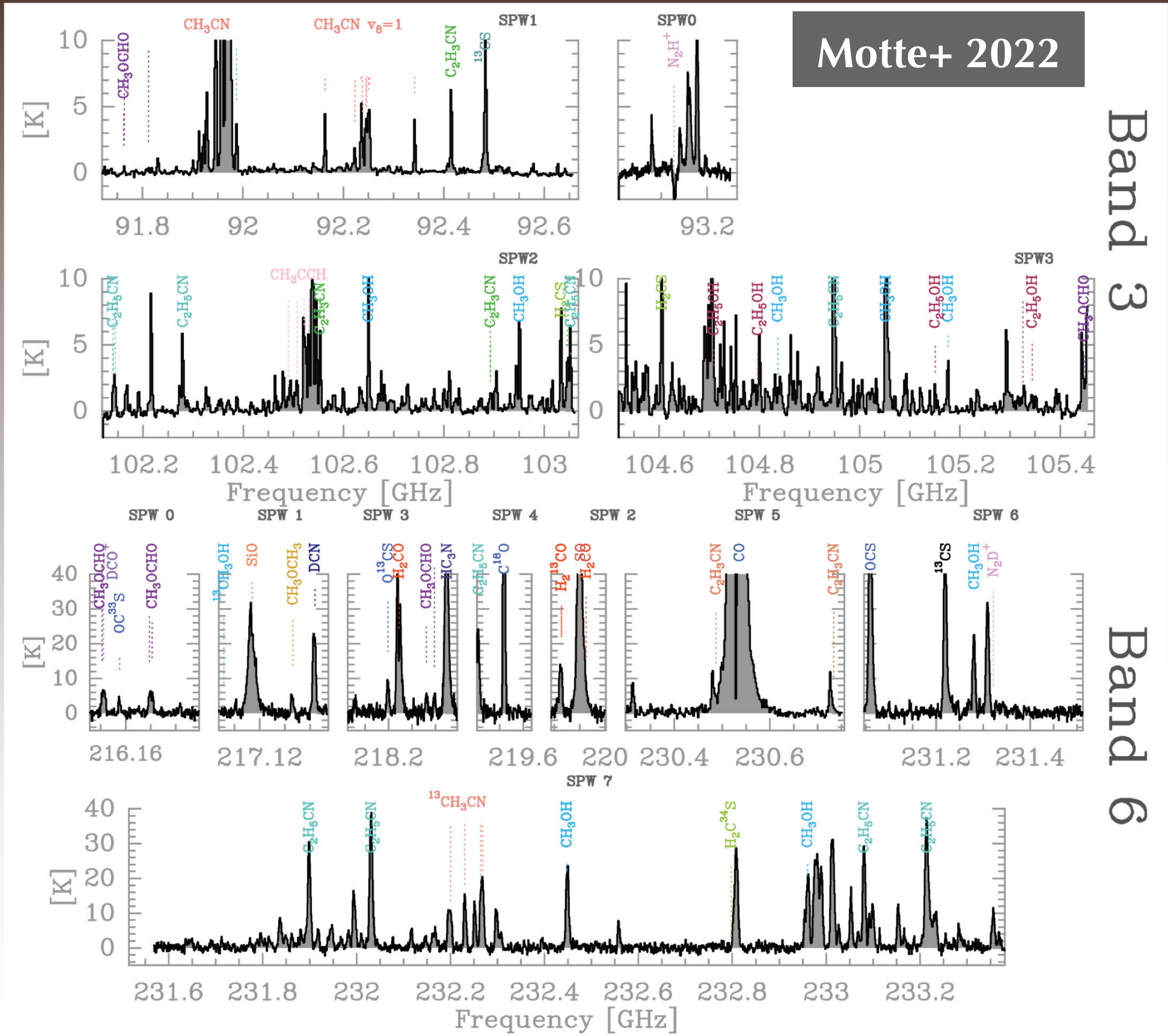
Evolutionary scenario for star-forming bursts

Proposed by Pouteau+ subm.



- 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?

Molecular complexity: hot cores and shocks



M. Bonfand

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

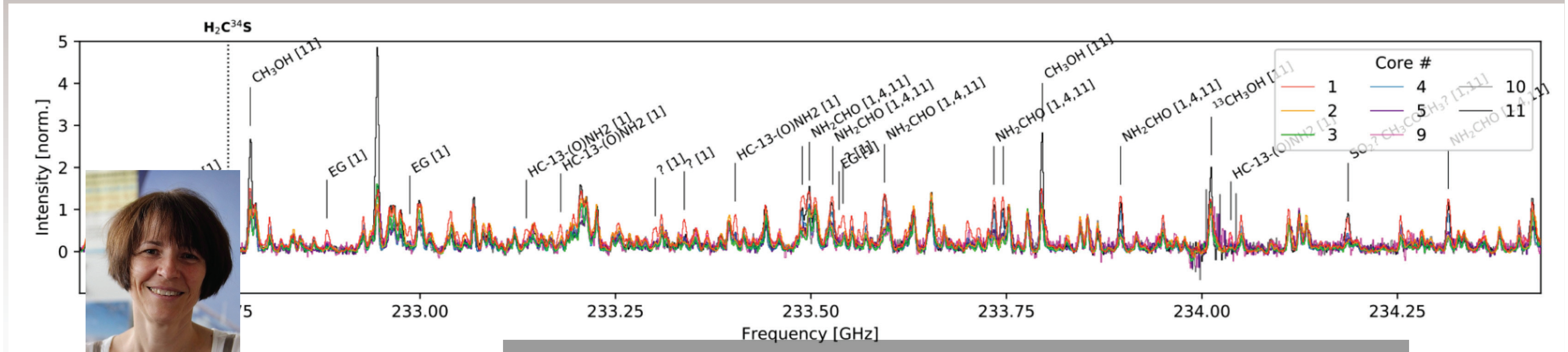
Bonfand et al. in prep.

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. »



N. Brouillet

Brouillet+ 2022 (normalisation with methylformate)

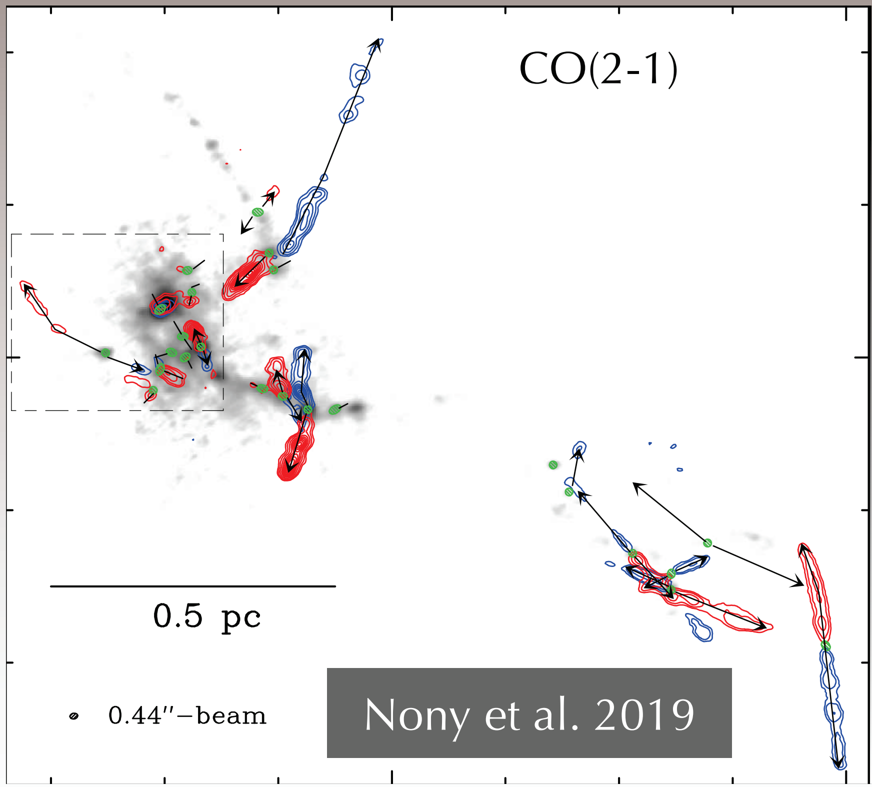
Rich clusters of protostellar outflows

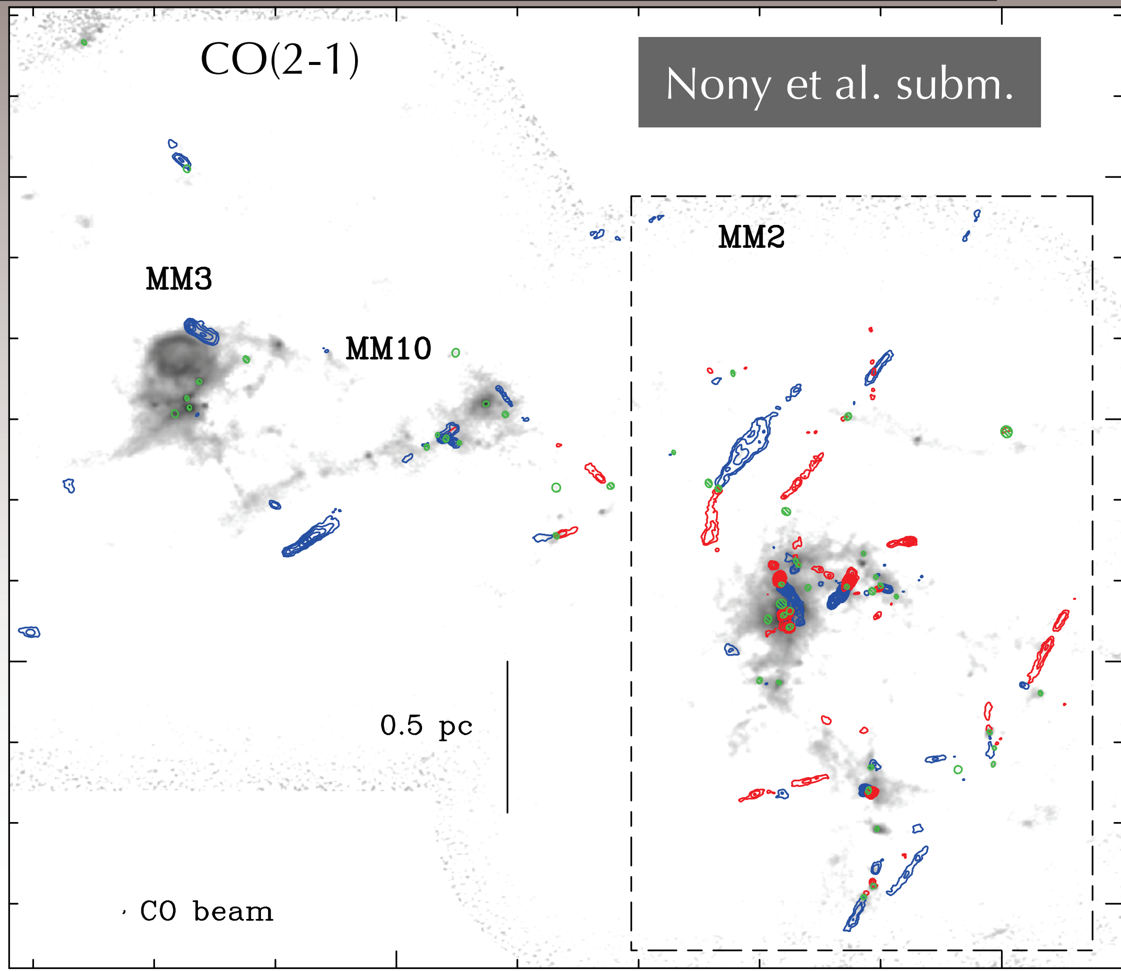
T. Nony

46+51 outflow lobes detected using CO(2-1) and SiO(5-4)

L_{max} from 0.02 to 0.4 pc ; ΔV_{max} from 10 to 100 km s^{-1}

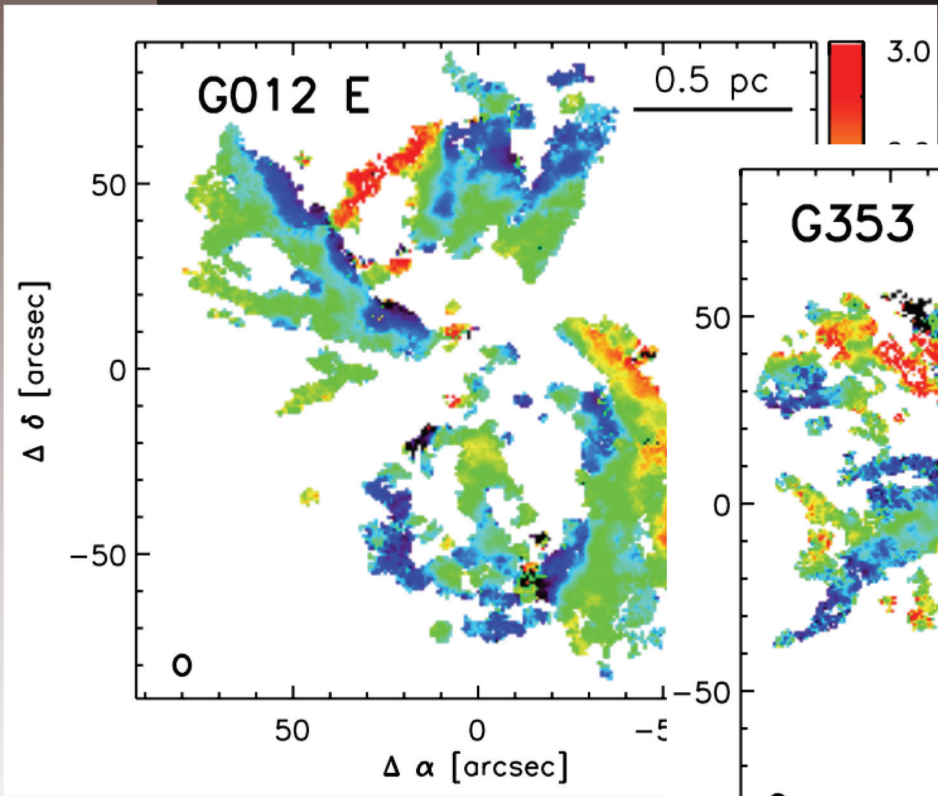
SiO outflow catalog by Towner et al. (in prep.)

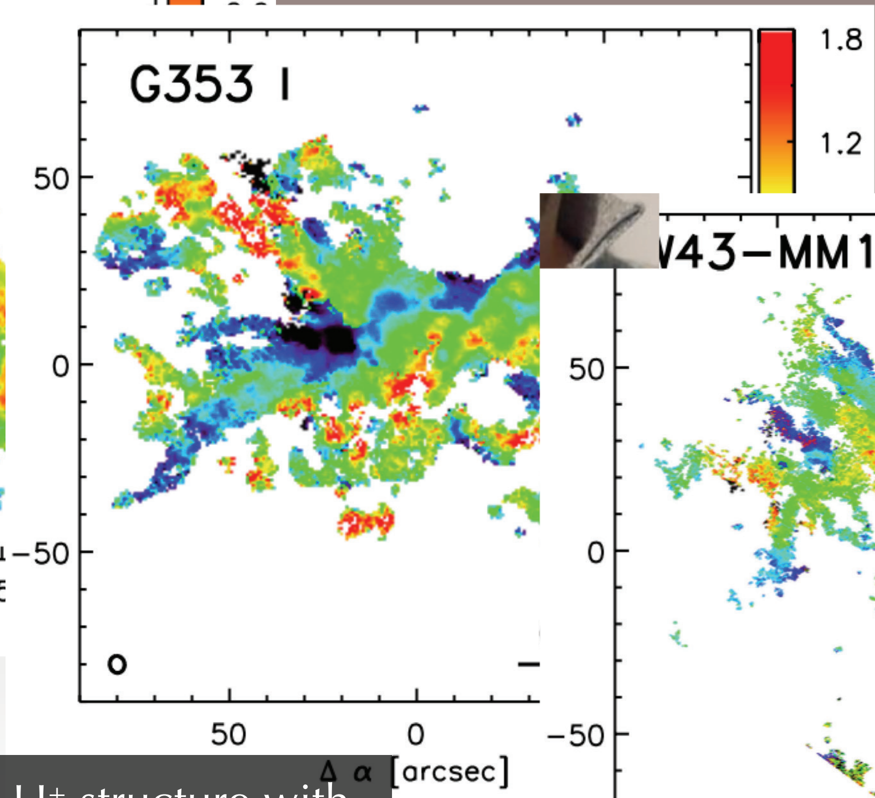


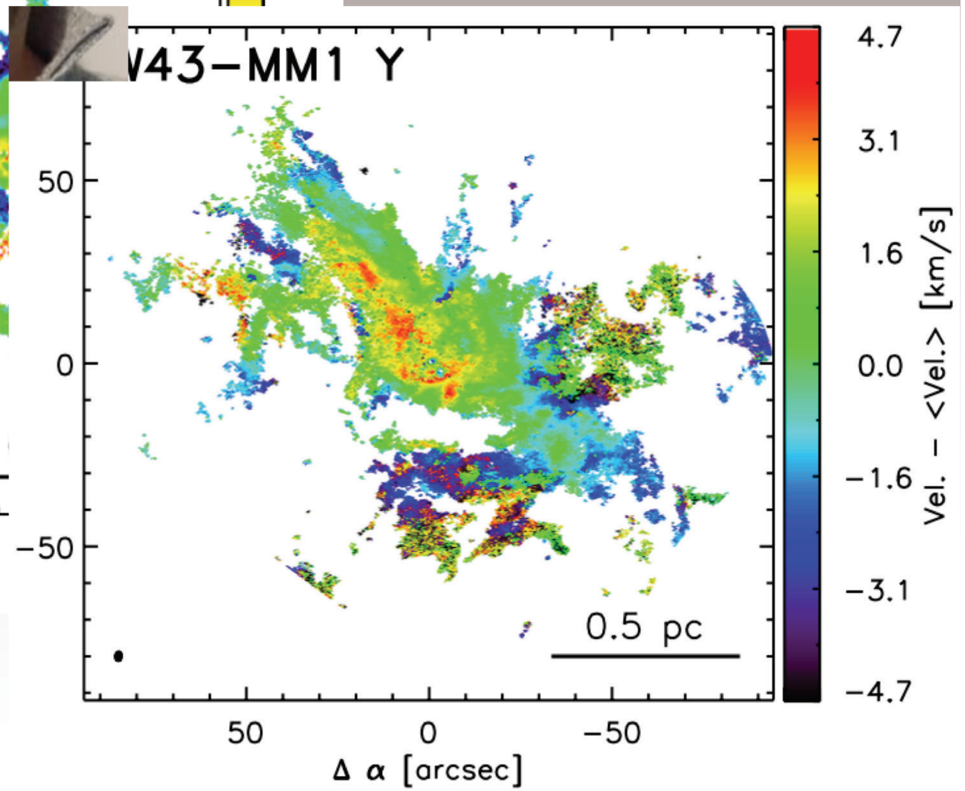


Global protocluster kinematics and filaments identification with N_2H^+

Velocity streams (N_2H^+) tracing rotation, inflow…







A. Stutz

M. Fernandez-Lopez

Tentative variation of the N_2H^+ structure with cloud evolutionary stage (Stutz et al. in prep.)

Core kinematics with DCN

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**

Cunningham+ subm.

Lines	Frequency (GHz)	Temp	Critical Density (cm-3)	#Detected	Complex	Total
DCN (3-2)	217.238	~20K	~1(5)-1(6)	20	7	27 (64%)
13CS (5-4)	231.220	~30K	4(6)	7	11	18 (43%)
N2D+ (3-2)	231.322	~20K		11	2	13 (31%)
OCS (19-18)	231.060	~110K	5(5)	7	11	18 (43%)
C18O (2-1)	219.560	~15k	9.9(3)	12	22	34 (81%)

N. Cunningham

Summary and perspectives

- 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
  - the kinematical studies, starting now,
  - the comparison of observed and simulated protoclusters,
  - the variation of cloud molecular complexity (Brouillet+ 2022),
  - …