Challenging the relation between core masses and stellar masses: from W43-MM1 to the ALMA- IMF LP

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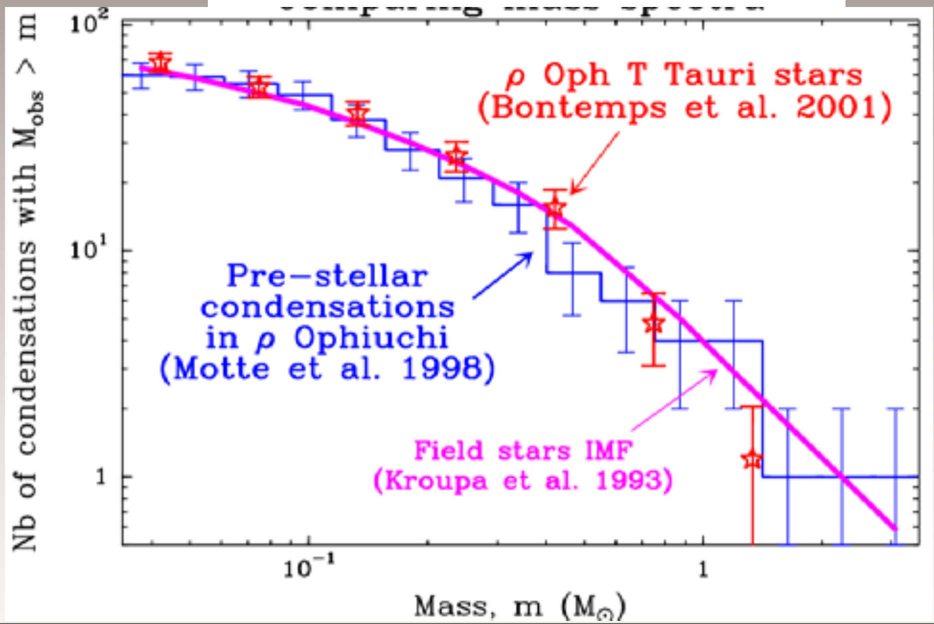
Special credits to Thomas Nony (IPAG), Fabien Louvet (U. Chile), and Sylvain Bontemps (LAB)

with T. Csengeri, P. Didelon, A. Gusdorf, P. Hennebelle, K. Marsh, A. Maury, Q. Nguyen Luong, F. Renaud, N. Schneider, A. Zavagno, …
and the *Herschel*/HOBYS, IRAM/W43-HERO, and ALMA-IMF consortia.

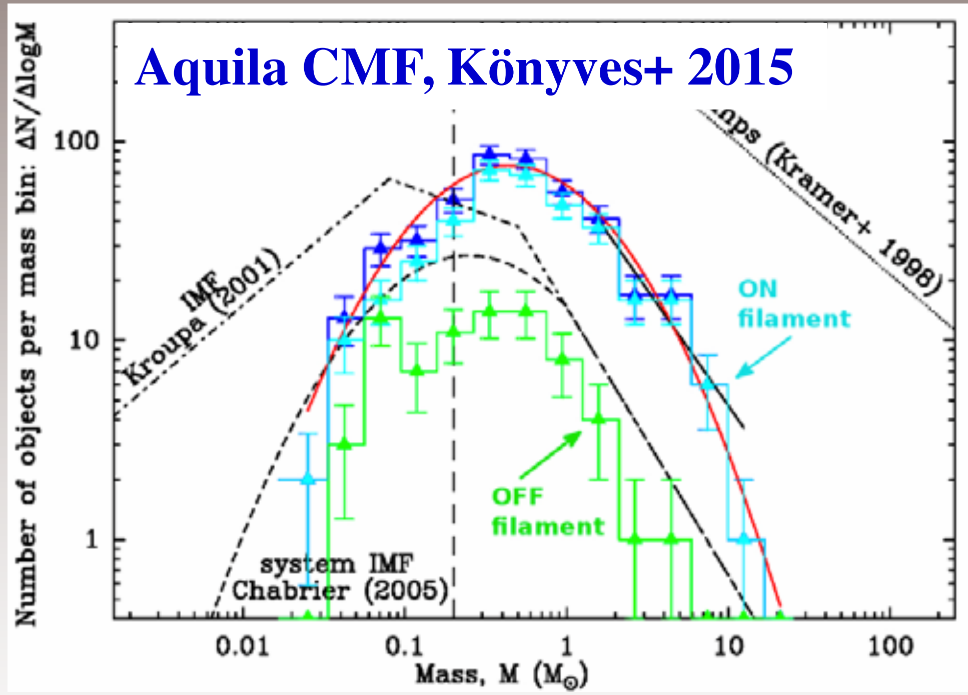
One-to-one relationship between the core and stellar mass functions (CMF vs IMF)

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

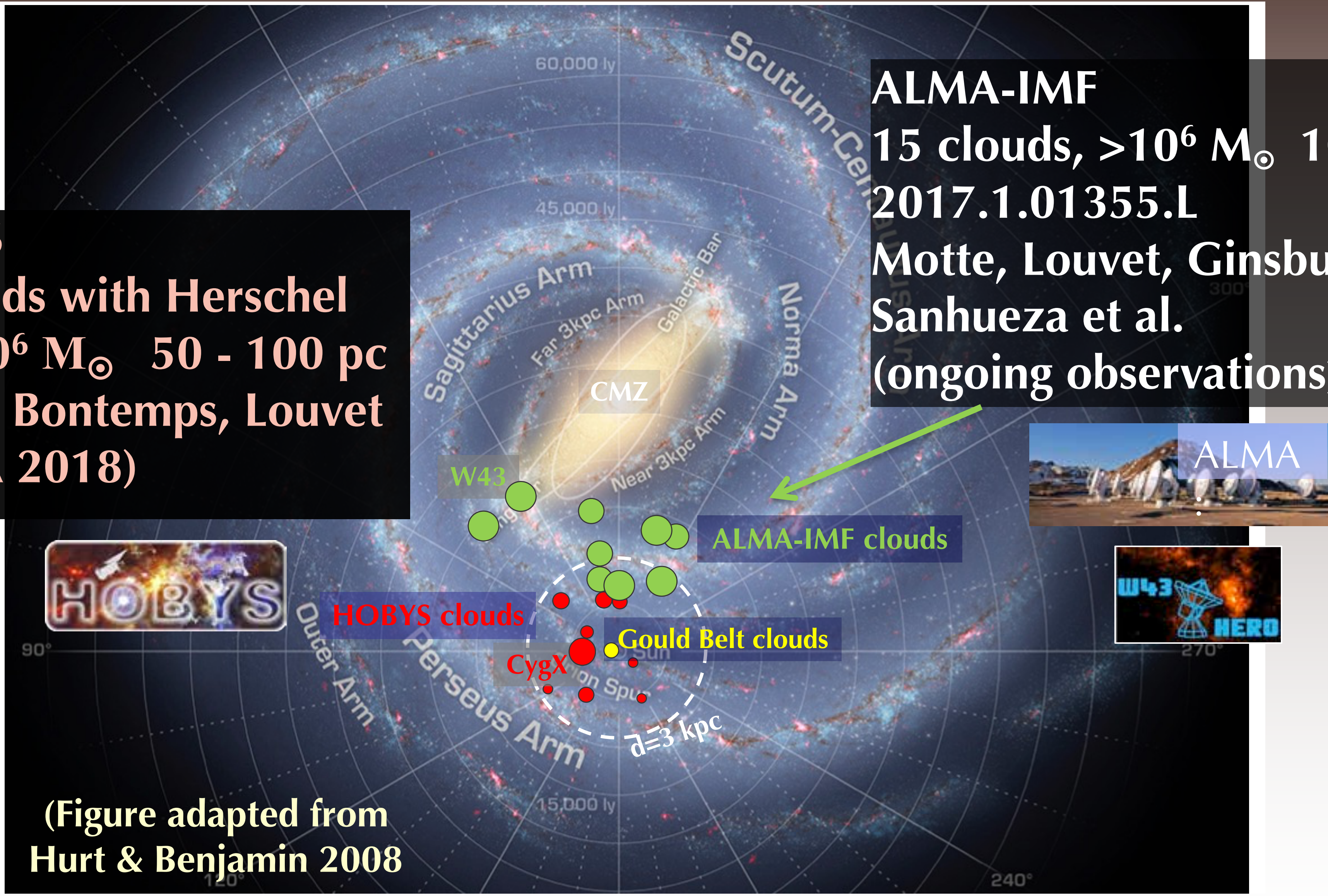
Studies limited to <5 $M_{\odot}$ stars…

in regions not typical of the main mode of star formation in galactic disks.

From local clouds to molecular cloud complexes more typical of the Galactic disk

HOBYS
10 clouds with Herschel
10^5 - 10^6 $M_\odot$ 50 - 100 pc
(Motte, Bontemps, Louvet ARA&A 2018)

ALMA-IMF
15 clouds, >10^6 $M_\odot$ 100 pc
2017.1.01355.L
Motte, Louvet, Ginsburg, Sanhueza et al.
(ongoing observations)

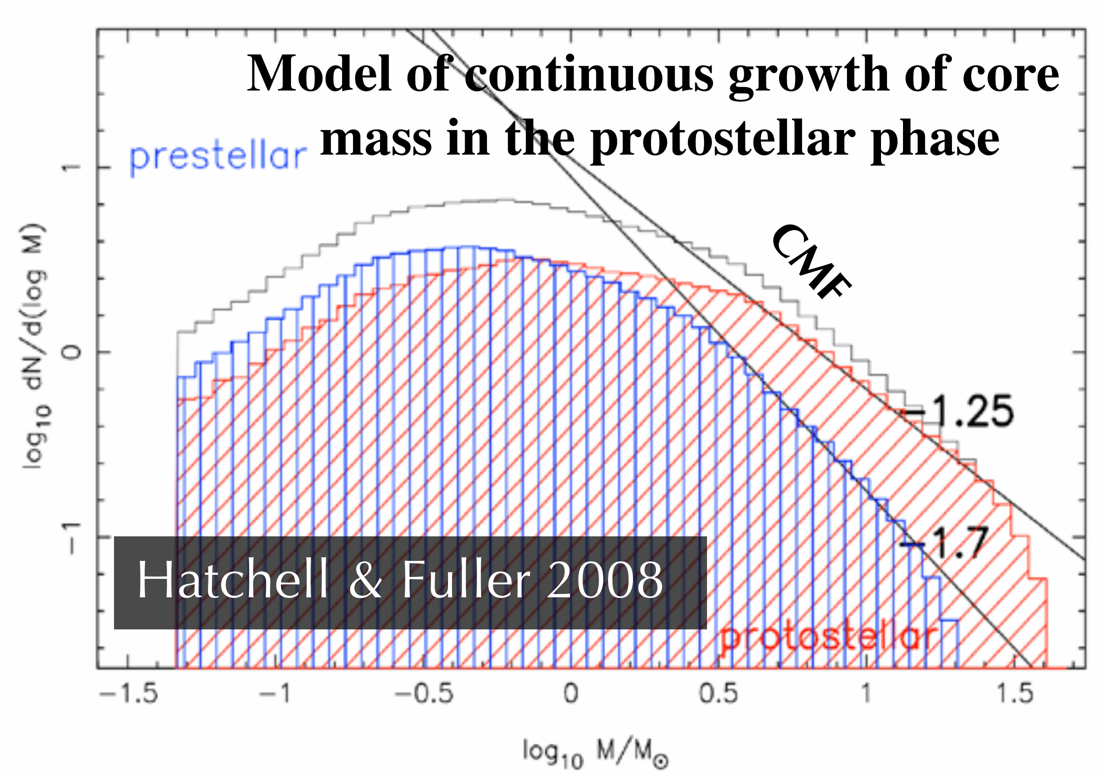


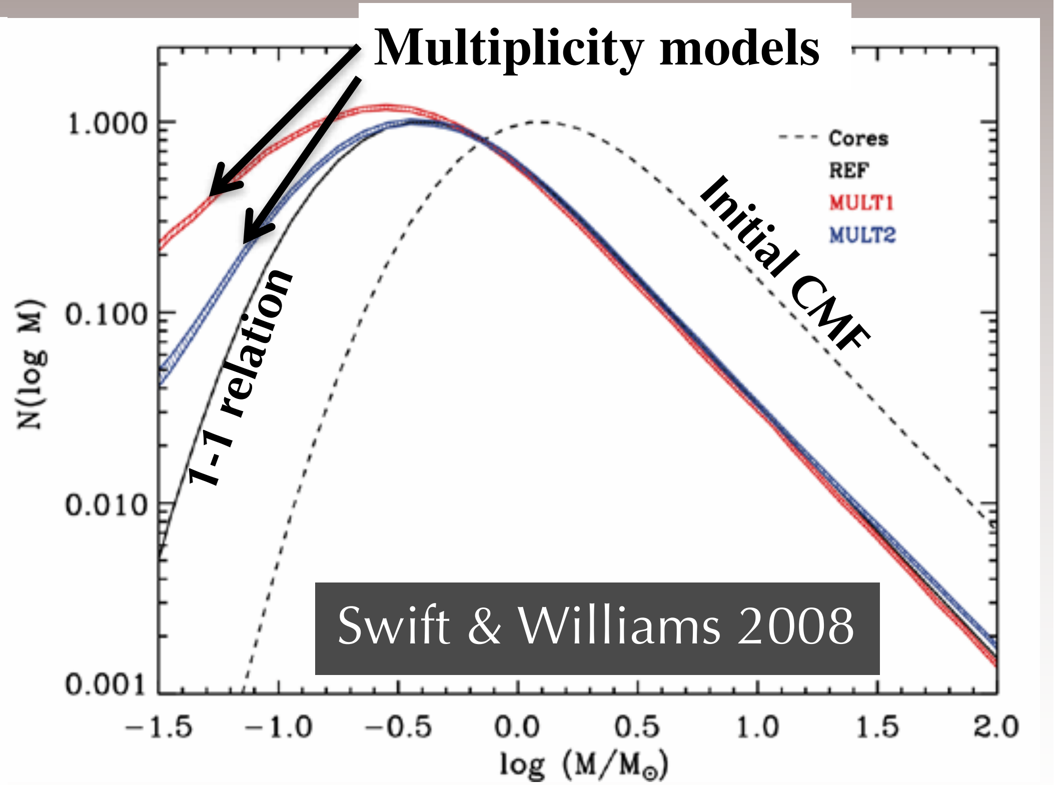
(Figure adapted from Hurt & Benjamin 2008

Assumptions behind the CMF/IMF comparison (1)

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

- Is gas mass feeding from surroundings negligible? Accretion streams are observed toward high-mass cores (e.g., Csengeri+ 2001a).
- Multiplicity and feedback should be taken into account.





Assumptions behind the CMF/IMF comparison (2)

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

- Outflows regulate ε (Matzner & McKee 2000)? or
- ε increases with core density like in clumps (e.g., Louvet+ 2014)?

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

- Deficit of intermediate-mass cores (Hatchell & Fuller 2008) and
- Missing high-mass prestellar cores (e.g., Motte+ 2007; Tigé+ 2017; Svoboda+ 2016; Nony+ 2018).

These effects should cancel out to keep the CMF/IMF shapes so similar.

$\Rightarrow$ conspiracy?

$\Rightarrow$ or central limit theorem?

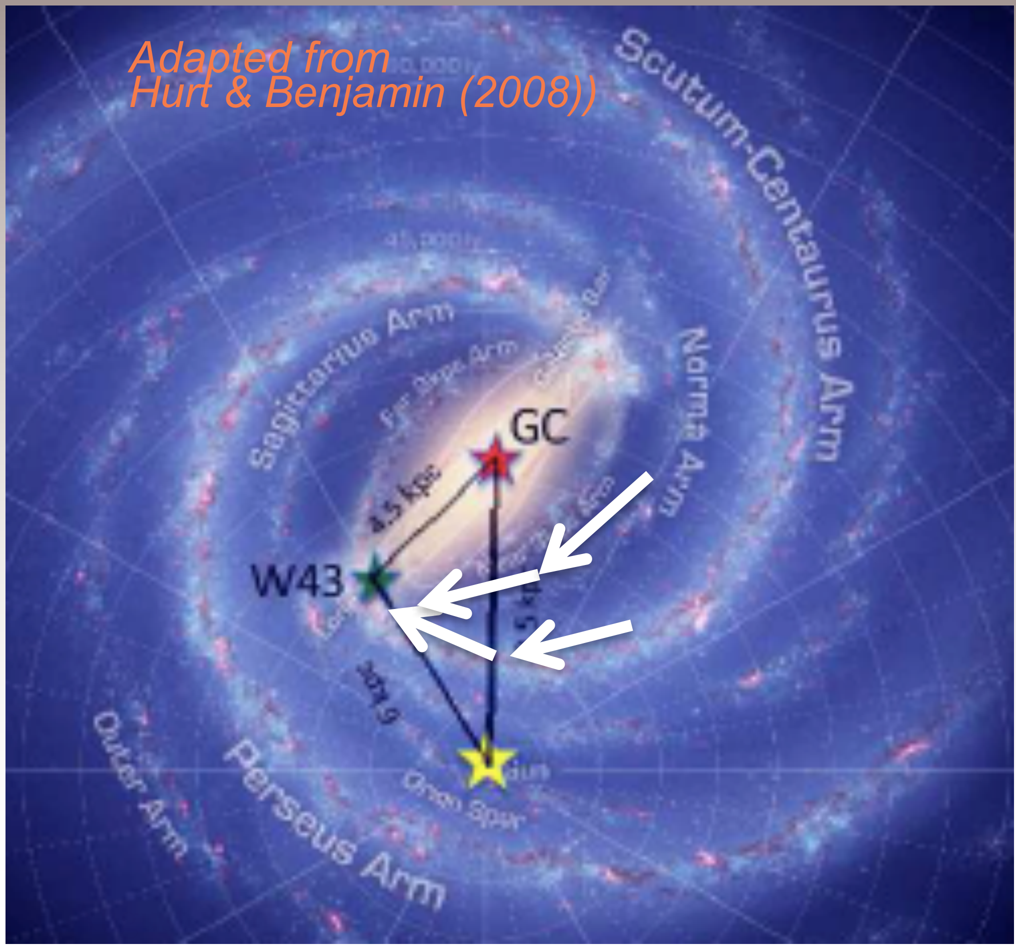
$\Rightarrow$ or obs. uncertainties too large to see that IMF is not so universal?

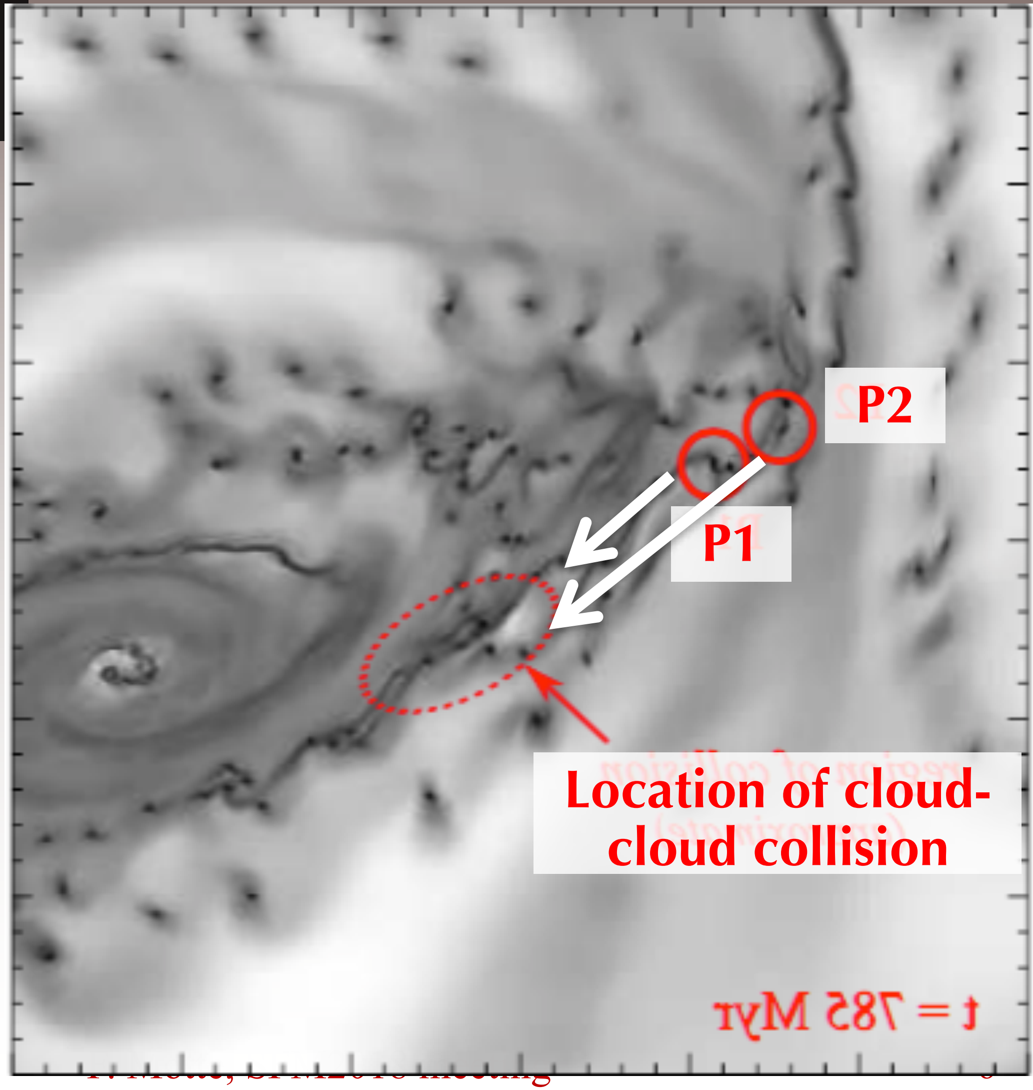
W43, a cloud agglomeration at the tip of the Galactic bar

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

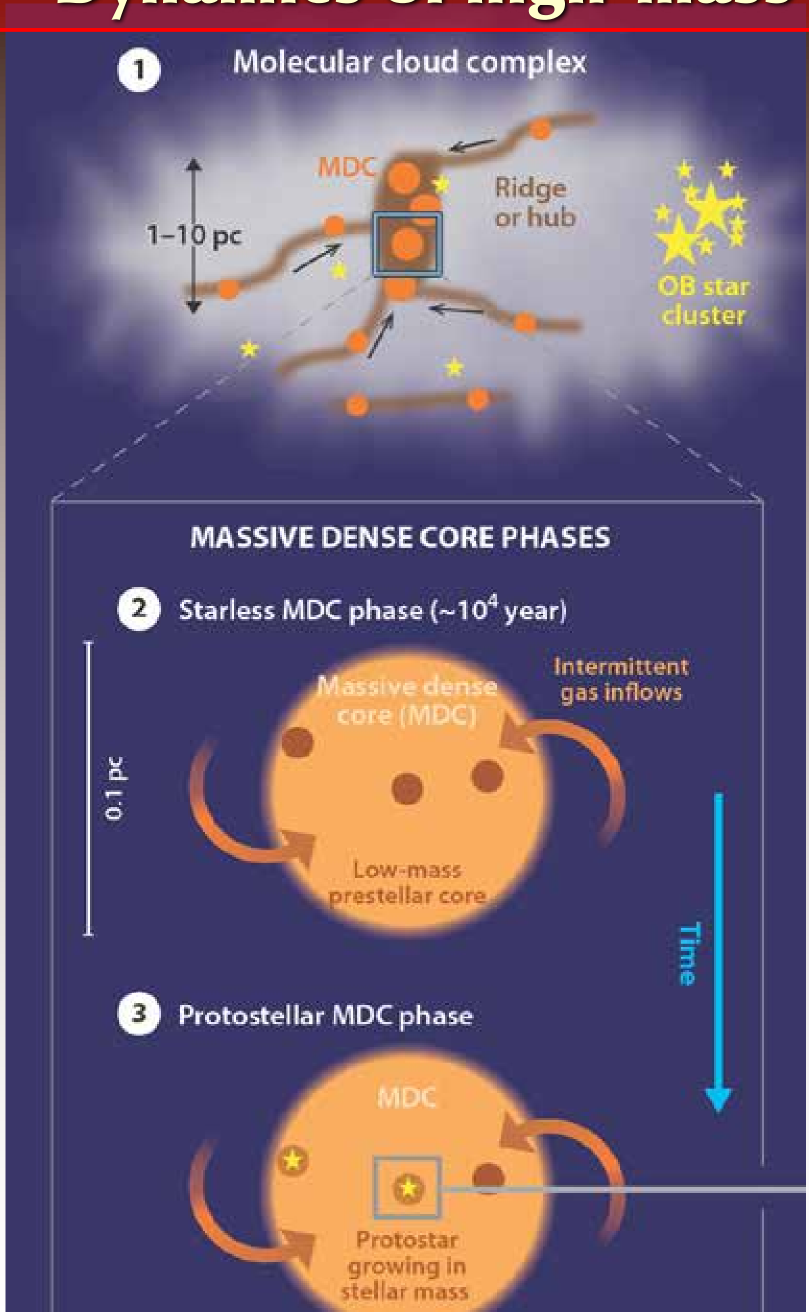
- ^{12}CO gas flows along the Galactic arm and forms W43 through cloud-cloud collision *(Motte+ 2014).*

- Scenario in agreement with numerical models of cloud collision at the edge of galactic bars (Renaud+ 2016)





Dynamics of high-mass star-forming ridges & cores



- Clouds forming high-mass stars and massive clusters:

They are high-density, massive, and dynamical clouds, which we call *ridges or hubs* (2-10 pc^3 @ $>10^4$-10^5 cm^{-3}).

- Star formation in ridges/hubs:

Gravity braids filaments in a globally-collapsing clump and attracts even more filaments.

Stars, cores (0.02 pc) and MDCs (0.1 pc) simultaneously form and grow in mass. There may not exist a high-mass prestellar core phase.

Motte, Bontemps, & Louvet ARA&A 2018

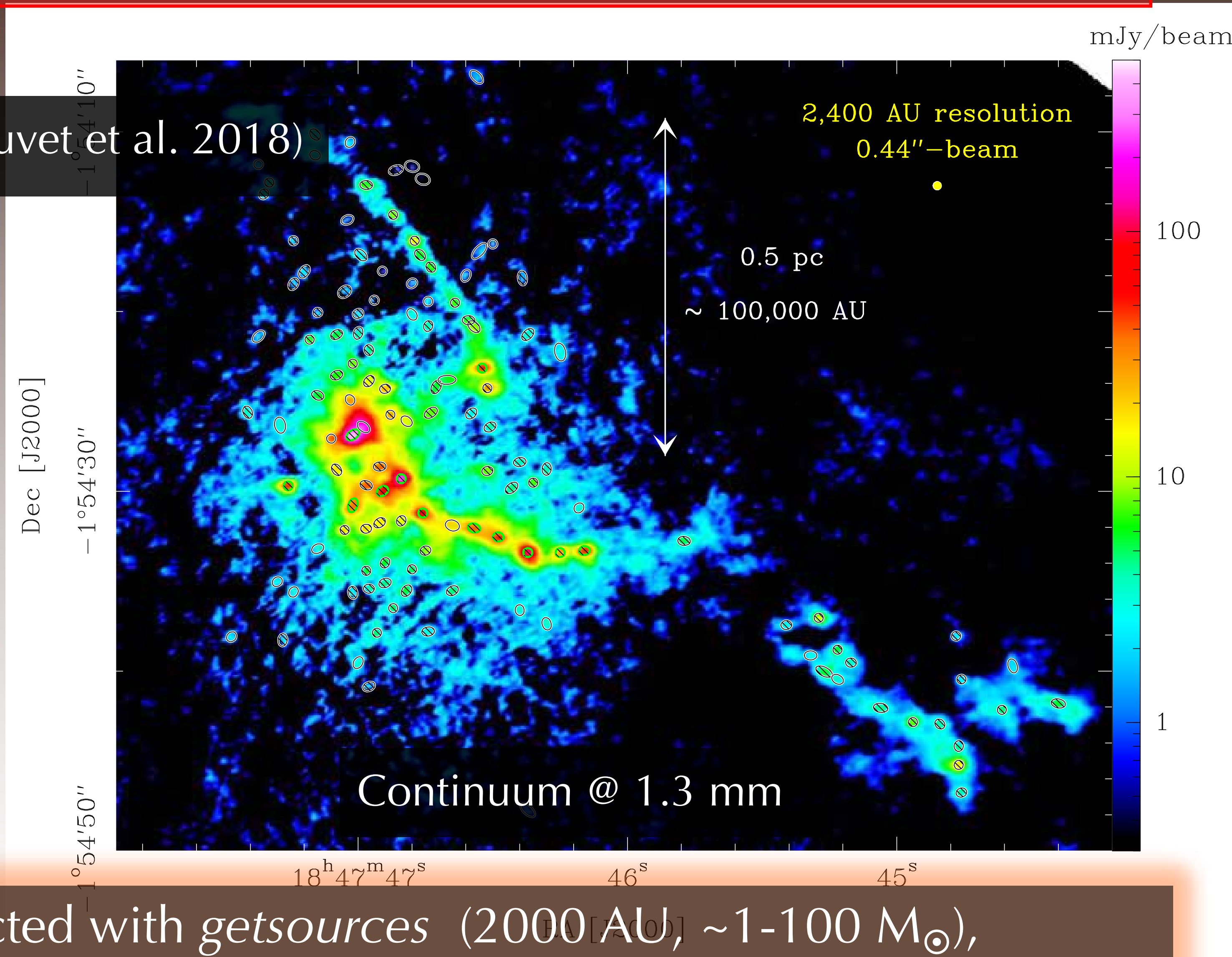
An ALMA view of the W43-MM1 mini-starburst protocluster

(Motte, Nony, Louvet et al. 2018)

W43 @ 5.5 kpc

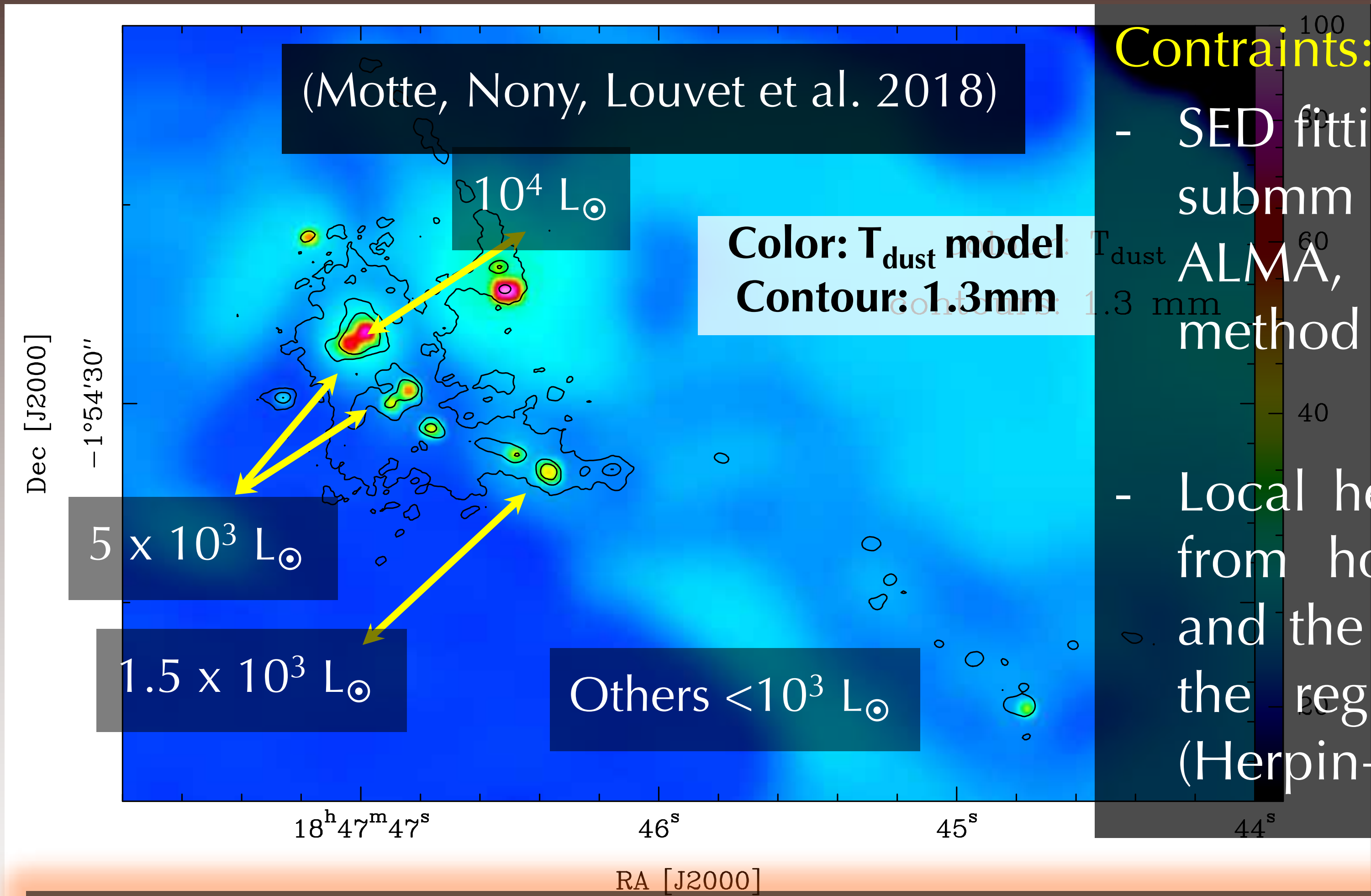
1.3 mm sensitivity: Scales 0.5″-7″

Mass completeness ~1.6 $M_\odot$



131 cores detected with *getsources* (2000 AU, ~1-100 $M_\odot$), among which 13 forming high-mass stars.

Temperature model and core evolutionary status



Contraints:

- SED fitting of Herschel and submm images, including ALMA, with PPMAP method (Marsh+ 2016).
- Local heating extrapolated from hot cores detection and the total luminosity of the region, 2 x 10^4 L⊙ (Herpin+ 2012; Mollet+).

⇒ All detected cores are in an early stage of their evolution. They are prestellar cores or IR-quiet/Class 0 protostars (+a possible HC HII).

⇒ M_{core} = total mass currently available for a binary star to form.

Tests and uncertainties on the CMF

Supplementary Table 2 — Tests performed to evaluate the uncertainty of the reference CMF fit of Fig. 2b.

	Mass range	γ
Reference cumulative CMF of all cores extracted by *getsources*	$>1.6\,M_\odot$	$-\mathbf{0.96 \pm 0.02}$
with 5σ uncertainty derived from the mass uncertainties	$>1.6\,M_\odot$	$\mathbf{-0.96 \pm 0.13}$
low-mass regime	$1.6-20\,M_\odot$	-0.93 ± 0.02
(high-mass regime, 9 cores)	$(>20\,M_\odot)$	(-1.3 ± 0.3)
with a lower completeness level	$>4.5\,M_\odot$	-0.99 ± 0.04
CMF of the 94 most robust cores	$>1.6\,M_\odot$	-0.90 ± 0.02
CMF with core masses estimated in the optical thin approximation	$>1.6\,M_\odot$	-0.98 ± 0.04
Differential CMF with all cores and default assumptions	$>1.6\,M_\odot$	-0.90 ± 0.06
CMF built from cores extracted in a classic-cleaned image	$>1.6\,M_\odot$	-1.10 ± 0.05
in a merged (7 m + 12 m) image	$>1.6\,M_\odot$ or $>5\,M_\odot$	-1.10 ± 0.04
with MRE-GaussClumps	$>1.6\,M_\odot$ or $>5\,M_\odot$	-1.08 ± 0.04

Notes: CMFs are fitted by power-laws of the form $N(>\log(M)) \propto M^\gamma$, except for the differential CMF where the power-law is $dN/d\log(M) \propto M^\gamma$. Several mass ranges are used to fit the CMFs of less-constrained core samples derived from the merged (7 m + 12 m) image and the MRE-GaussClumps algorithm. Except when specified otherwise, all uncertainties given here are 1σ.

Uncertainties on κ, T_{dust}, and fluxes used in MC simulations
⇒ ±0.13 uncertainty

Synthetic observations/extractions
⇒ 90% completeness limit = $1.6\,M_\odot$

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%).

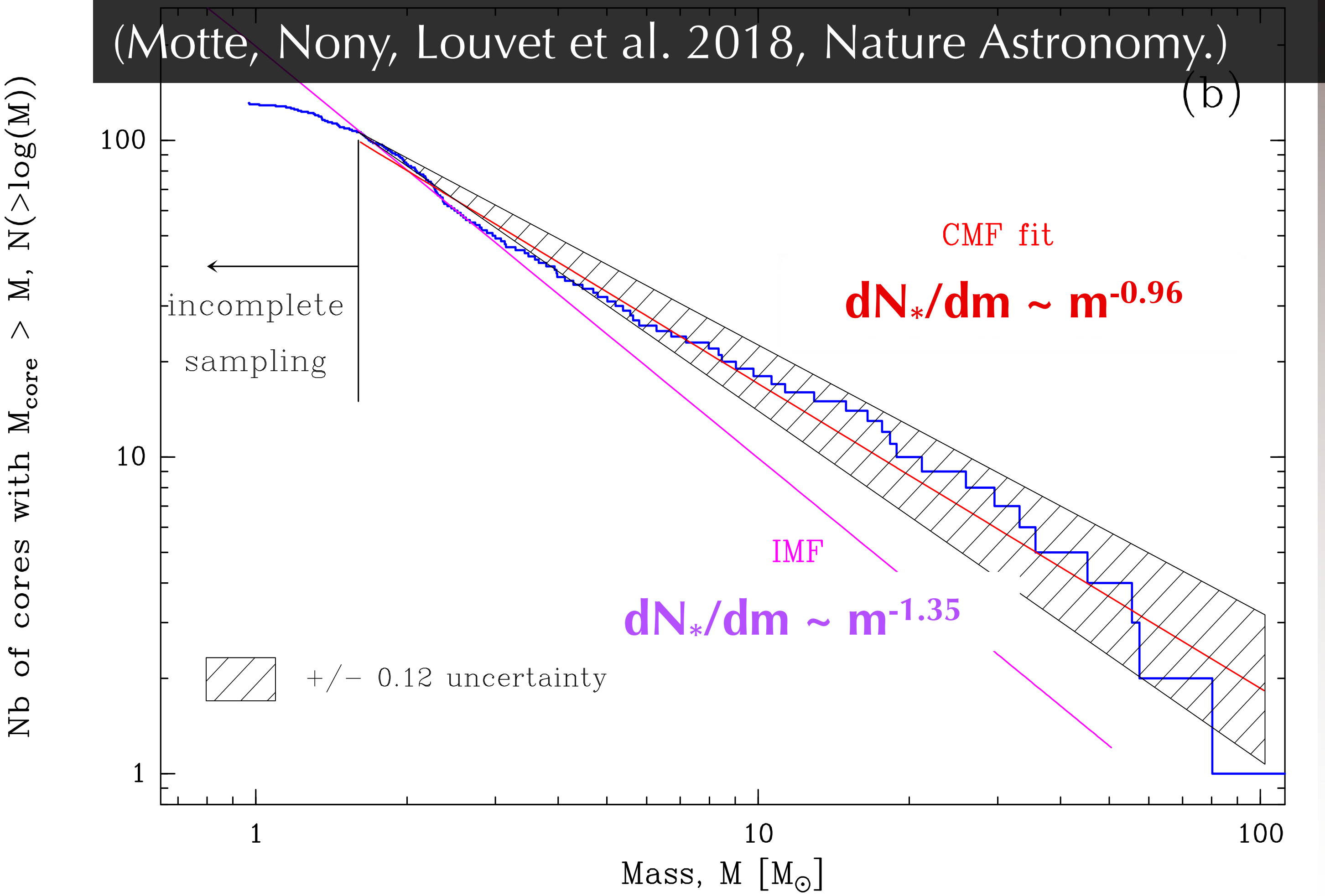
Or CMF evolution

Or complex CMF/IMF relation

But why would the "conspiracy" not apply for low-mass cores in W43-MM1?

See also Zhang+2015; Sanchez-Monge+2017; Cheng+2018; …

(Motte, Nony, Louvet et al. 2018, Nature Astronomy.)



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(Motte, Nony, Louvet et al. 2018, Nature Astronomy.)

Or CMF evolution:

- Continuous mass growth of cores

$\Rightarrow$ flatter

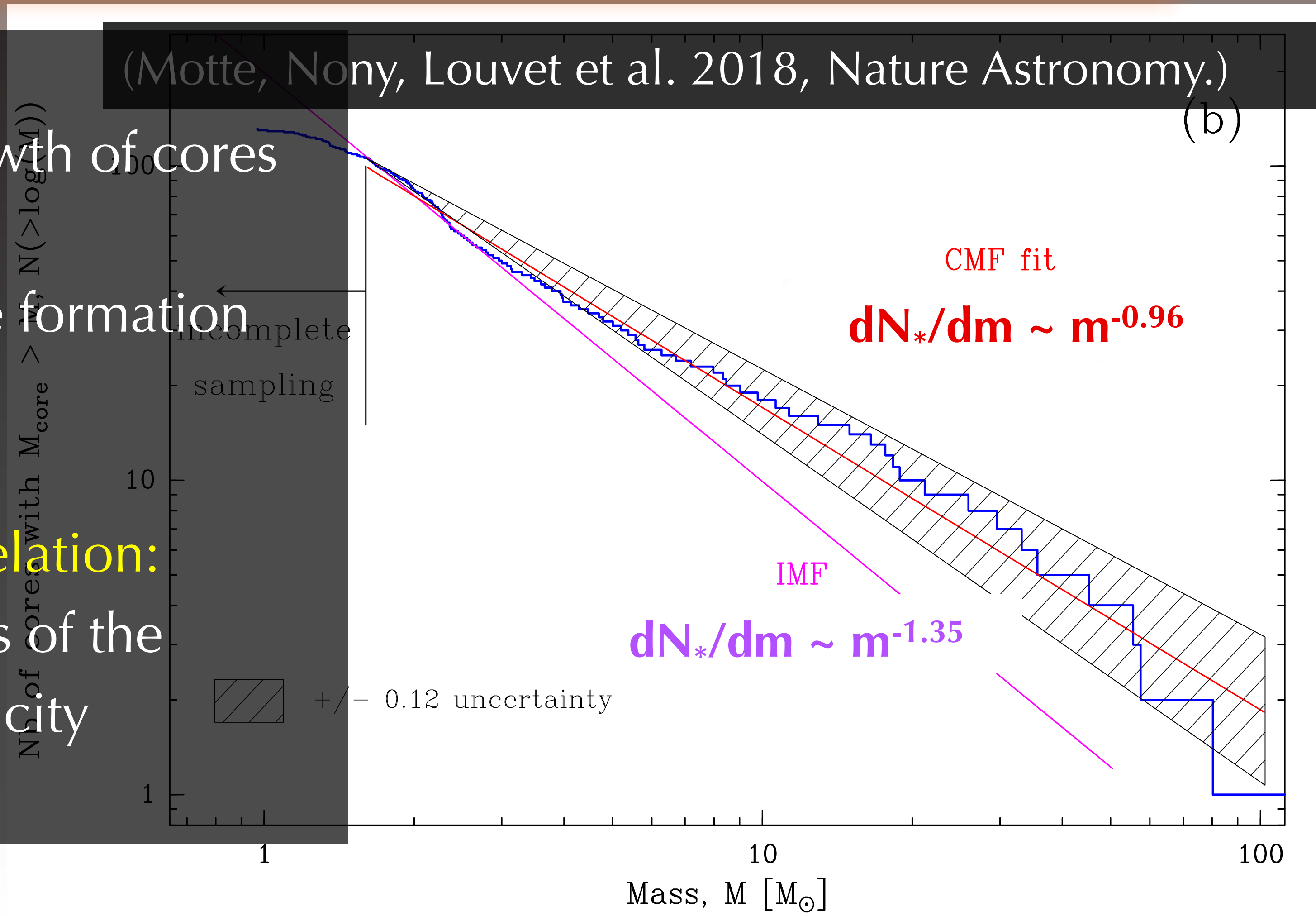
- New episodes of core formation

$\Rightarrow$ maybe steeper

Or complex CMF/IMF relation:

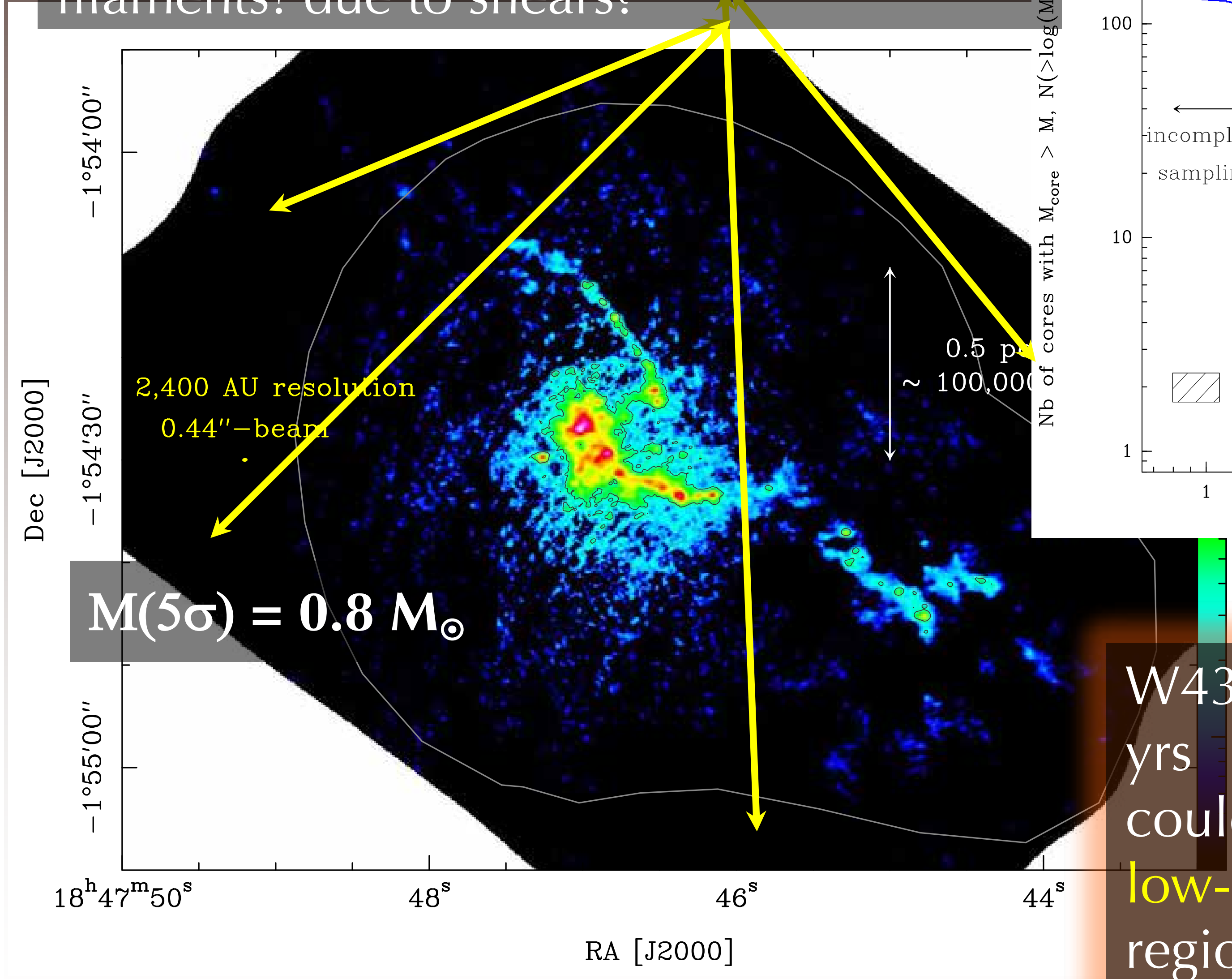
Variation with core mass of the

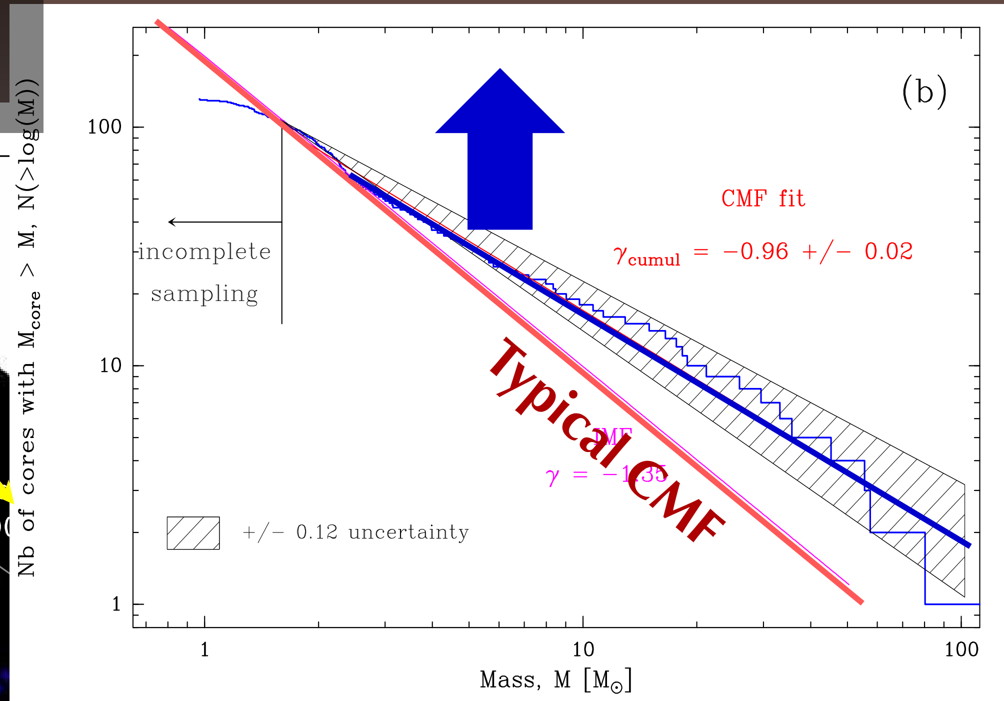
- Core and star multiplicity
- Core lifetime, …



Why low-mass cores would be underpopulated?

Missing low-mass cores and low-density filaments! due to shears?





M(5σ) = 0.8 M$_\odot$

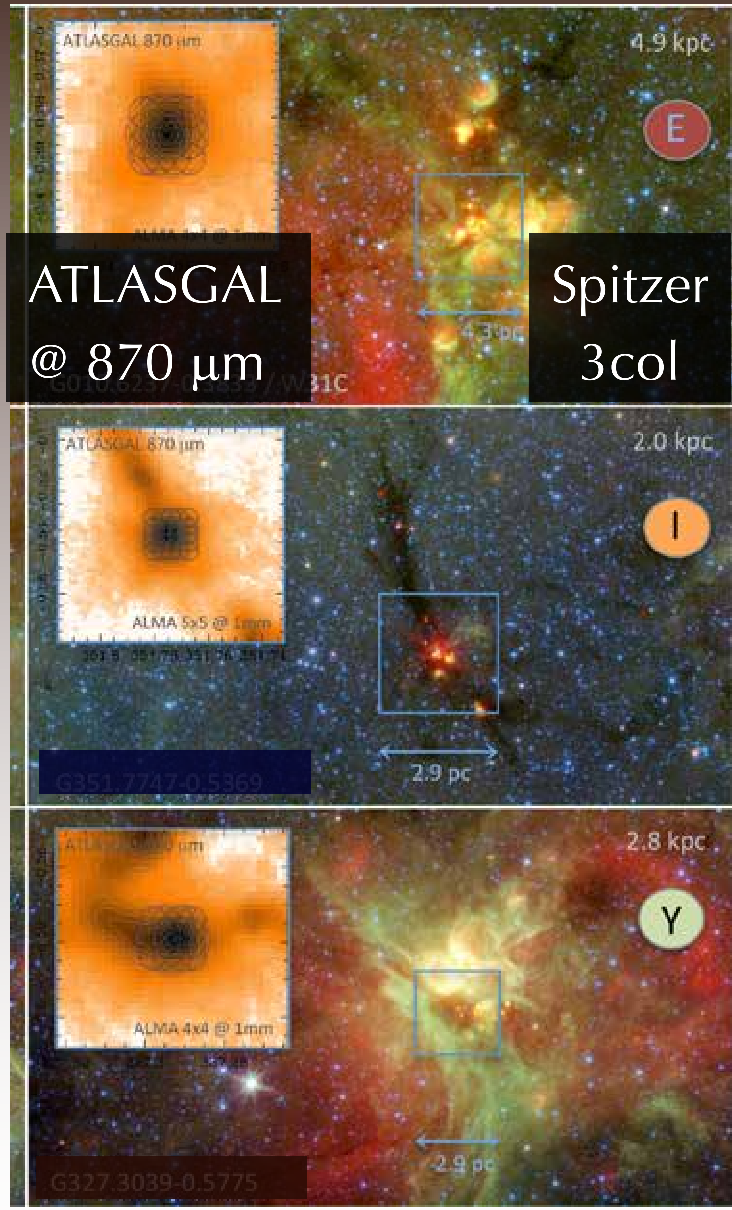
W43-MM1 protocluster is ~10^5 yrs old only. New filaments could form and host additional low-mass cores before HII regions blow the ridge gas.

ALMA-IMF targets

Table 1: *Complete sample of massive protoclusters at <6 kpc, of*

Name	d [kpc]	$M(<pc^2)$ $[M_\odot]$	L_{bol}/M $[L_\odot/M_\odot]$	Mosaic, Resol $[''\times'', '']$
Young protoclusters				
	5.5	16×10^3	3.9	20 × 80, 0.37
	3.9	8.0×10^3	9.3	5 × 55, 0.51
	2.8	6.5×10^3	10	0 × 70, 0.67
	5.5	13×10^3	11	0 × 60, 0.37
	2.8	4.2×10^3	13	0 × 70, 0.67
	2.0	3.3×10^3	13	0 × 100, 0.95
	3.4	2.7×10^3	16	7
Intermed protoclusters				
	5.4	22×10^3	25	7
	2.0	2.2×10^3	29	0 × 100, 0.95
	5.5	6.6×10^3	30	0 × 60, 0.37
	2.4	5.2×10^3	46	0 × 100, 0.95
Evolved protoclusters				
	3.6	3.0×10^3	50	5 × 55, 0.51
	4.9	7.4×10^3	54	0 × 60, 0.37
	5.4	14×10^3	69	0 × 60, 0.37
	4.2	13×10^3	130	10 × 110, 0.51

Evolution with time



Complete sample of 1pc-size clumps at <6 kpc with masses above few 1000 $M_\odot$.

ALMA-IMF Cycle 5 LP

ALMA-IMF large program:

- PIs: F. Motte, A. Ginsburg, F. Louvet, P. Sanhueza
- Management Team:

4 PIs + T. Csengeri, S. Bontemps, R. Galvan-Madrid, F. Nakamura, A. Stutz

- Consortium members:
  - ALMA experts: A. Lopez-Sepulcre, L. Maud, N. Cunningham
  - PhDs: T. Nony, J. Molet, R. Mignon-Risse
  - Theoreticians: P. Hennebelle, Y.-N. Lee, M. Gonzalez, G. Gomez

and

J. Bally, C. Battersby, J. Braine, L. Bronfman, N. Brouillet,V. Chen, J. di Francesco, R. Finger, A. Gusdorf, A. Guzman, F. Herpin, I. Joncour, B. Ladjelate, H.-L. Liu, X. Lu, K. Marsh, A. Maury, K. Menten, E. Moraux, Q. Nguyen Luong, S. Ohashi, F. Olguin, N. Reyes, J.-F. Robitaille, E. Rosolowsky, T. Sakai, B. Svoboda, K. Tatematsu, F. Wyrowski…

Science objectives of ALMA-IMF

- IMF origin: CMF per region, as a function of cloud mass, cloud evolution, density…
- Mass inflow: Formation of filaments, shocks, angular momentum
  Core mass growth and CMF evolution
- Initial conditions of high-mass star formation: high-mass prestellar core or very young protostar?
- Protostars: history of the accretion (via outflows, luminosity), lifetime
- Chemical enrichment: hot cores (new lines, evolutionary sequence?) and shocks (cloud collision, outflow, protostellar accretion)
- Outflows: generating turbulence, correlation with filament elongation and magnetic direction
- Core and filament distribution: mass, age segregation, relation to large-scale cloud characteristics
- SFR,
- …

Take-away message

- Ridges & Hubs

Ridges are high-density, massive, and dynamical clouds, where star formation is intense and cluster of high-mass stars form. They could represent the precursors of starburst clusters.

Typical star-formation sites have characteristics between ridges and GB clouds…

- Origin of the IMF – Cycle 5 ALMA LP

The CMF of the W43-MM1 mini-starburst does not mimic the IMF!

More massive protoclusters need to be investigated to understand:

- If mini-starbursts have atypical CMF,
- How their cores content evolves from young (like W43-MM1) to more evolved star-forming clouds (like W51).

- Open question: The dependence of the CMF & IMF with galactic environments.