High-mass star-forming cores, their parental cloud and a proposed evolutionary scenario

Frédérique Motte
(IPAG Grenoble & AIM Paris-Saclay)

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and the *Herschel*/HOBYS, IRAM/W43-HERO, and ALMA-IMF consortia.

Outline

1. Introduction on the high-mass star formation scenario, this 10-15 years-old open question!

2. Quest of the earliest phases of high-mass star formation: Do high-mass pre-stellar cores exist?

3. Importance of the link of cores with their parental cloud: density, kinematics, magnetic field

I will be guilty of discussing about ~0.01 pc cores :
- independly of their Galactic environment
- ignoring their inner sub-structure, kinematics, B-field support, chemistry…

Evolutionary scenario for star formation in the 2000's

Following the low-mass star-formation scenario (e.g. André+ 2000):

Prestellar core → Protostar (Class 0, Class I) → Pre-main sequence star

Precursors of H II regions (e.g. Churchwell 1999; Hoare+ 2007)

1. Among high-luminosity IRAS or MSX sources

e.g. Bronfman+ 1996, Molinari+ 2000, Beuther+ 2002, Lumsden+2013

Sample of Galaxy-wide IRAS-selected sources

Wood & Churchwell sample selected with color-color criteria:

- Log(F25/F12) > 0.57 — 1 646 objects
- Log(F60/F12) > 1.3 — (mainly UCH IIs)

Bronfman, Nyman, & May (1996) subsample:

- CS detection

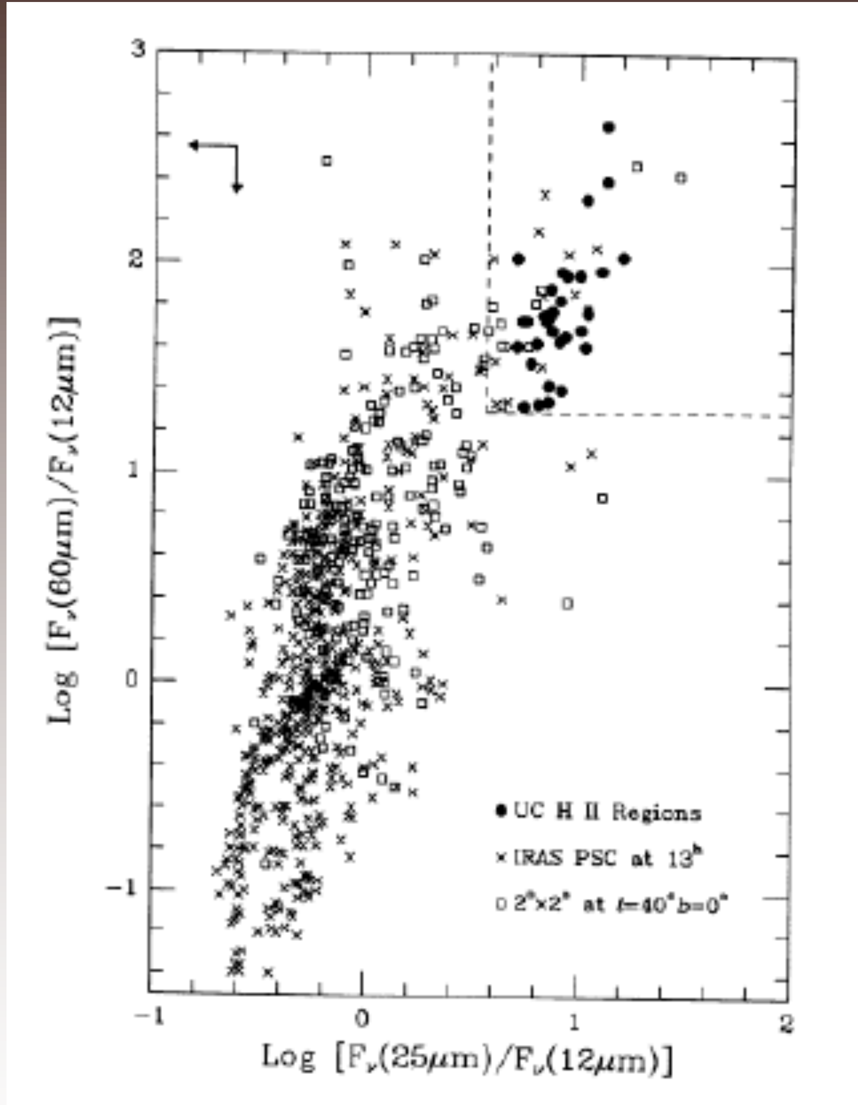
843 objects (UCH IIs and high-mass protostars)

Molinari and Sridharan/Beuther samples: mostly harbors high-mass protostars

- no or weak cm (free-free) emission

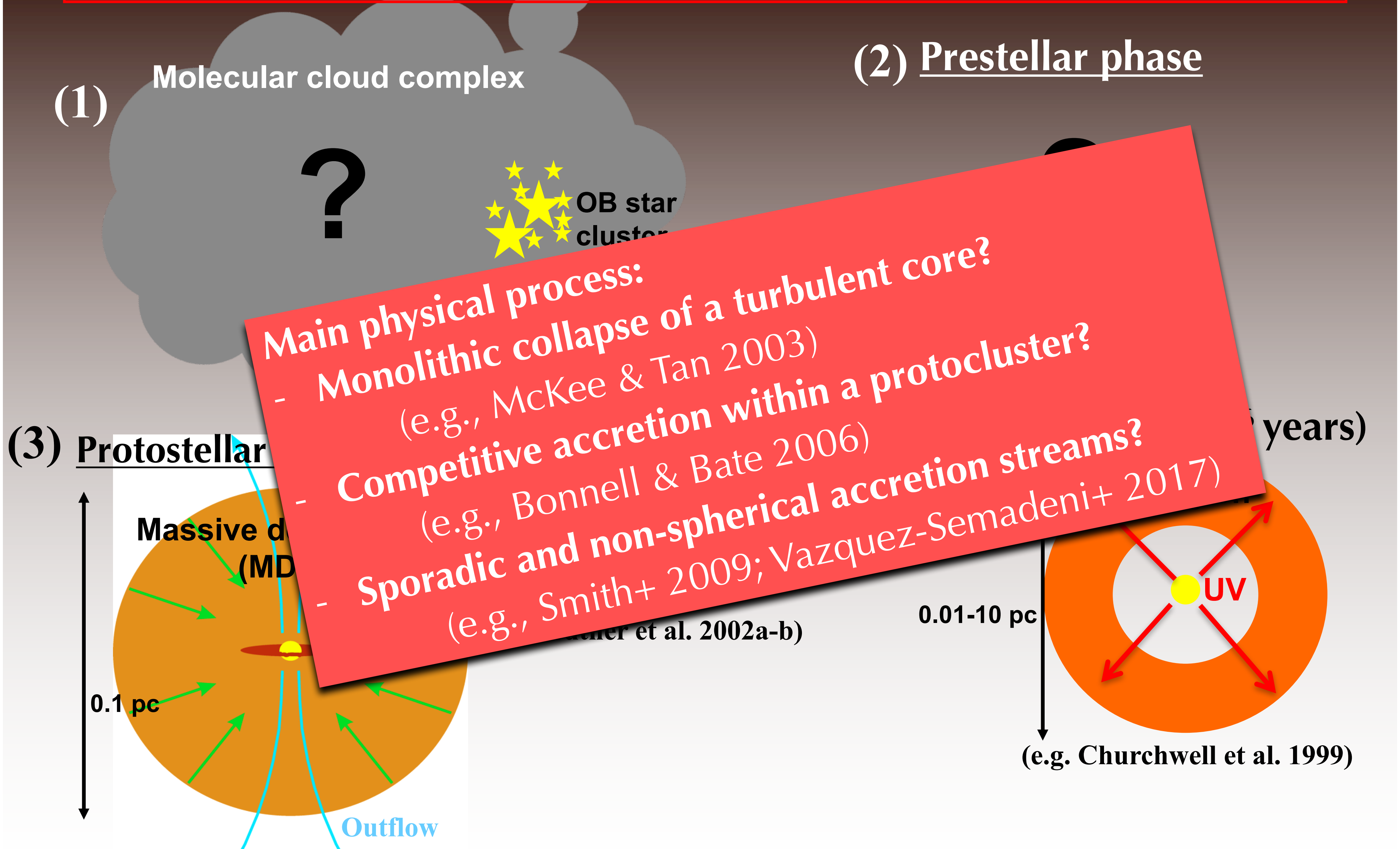
  163 objects (Molinari et al.1996)

  69 HMPOs (Sridharan et al. 2002)



Wood & Churchwell 1989

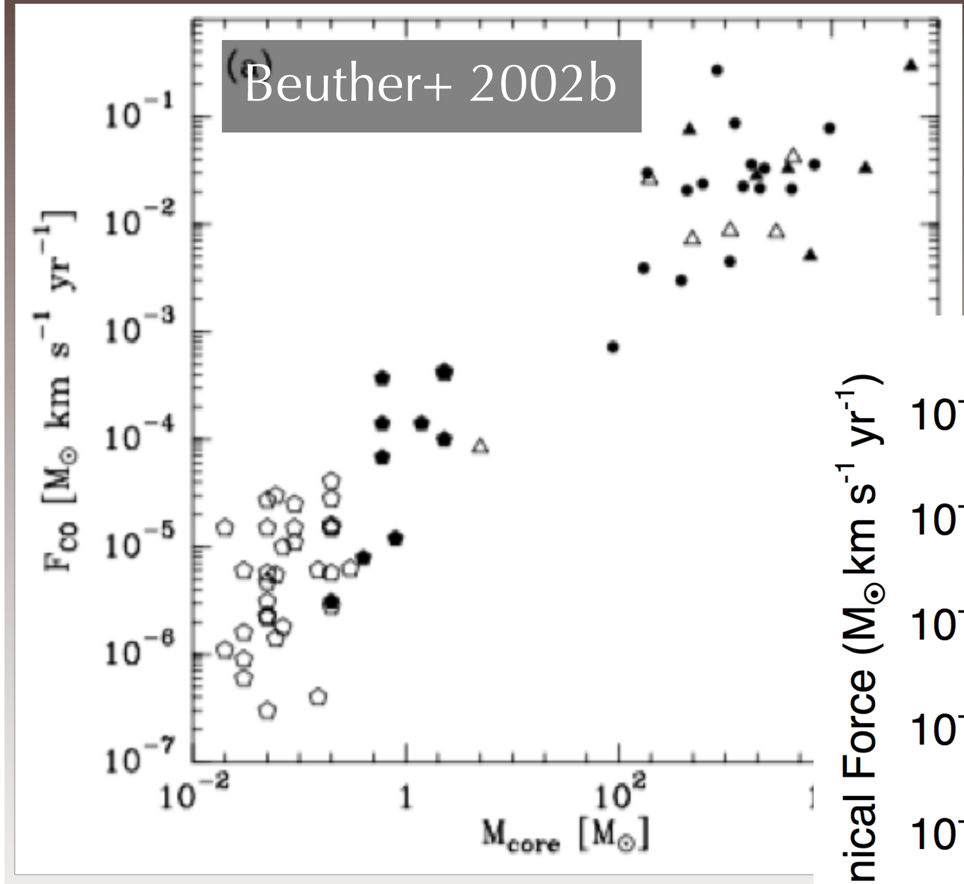
Evolutionary scenario for the formation of high-mass stars



Main physical process:

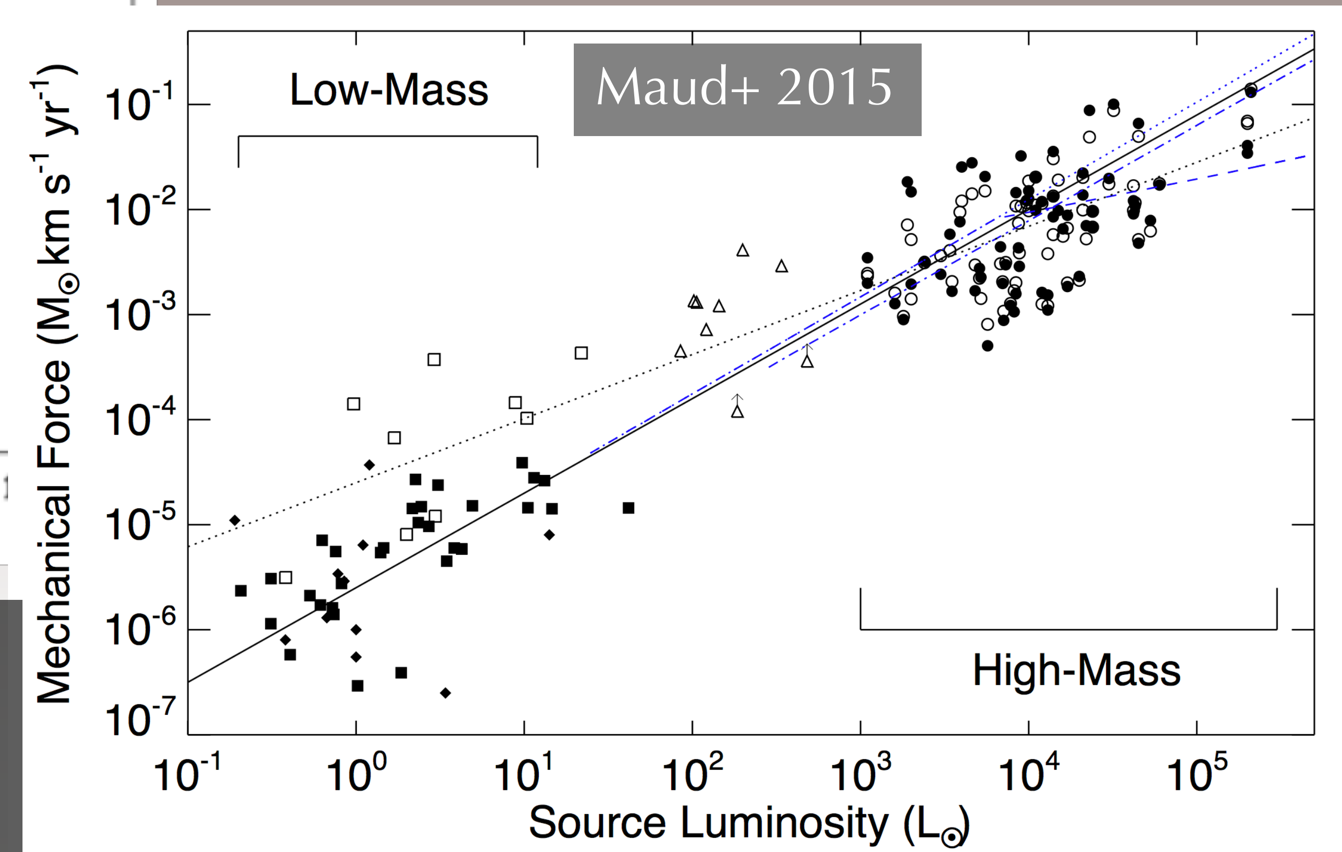
- **Monolithic collapse of a turbulent core?**
  (e.g., McKee & Tan 2003)
- **Competitive accretion within a protocluster?**
  (e.g., Bonnell & Bate 2006)
- **Sporadic and non-spherical accretion streams?**
  (e.g., Smith+ 2009; Vazquez-Semadeni+ 2017)

Arguments in favor of a scaled-up version of the low-mass star-formation scenario



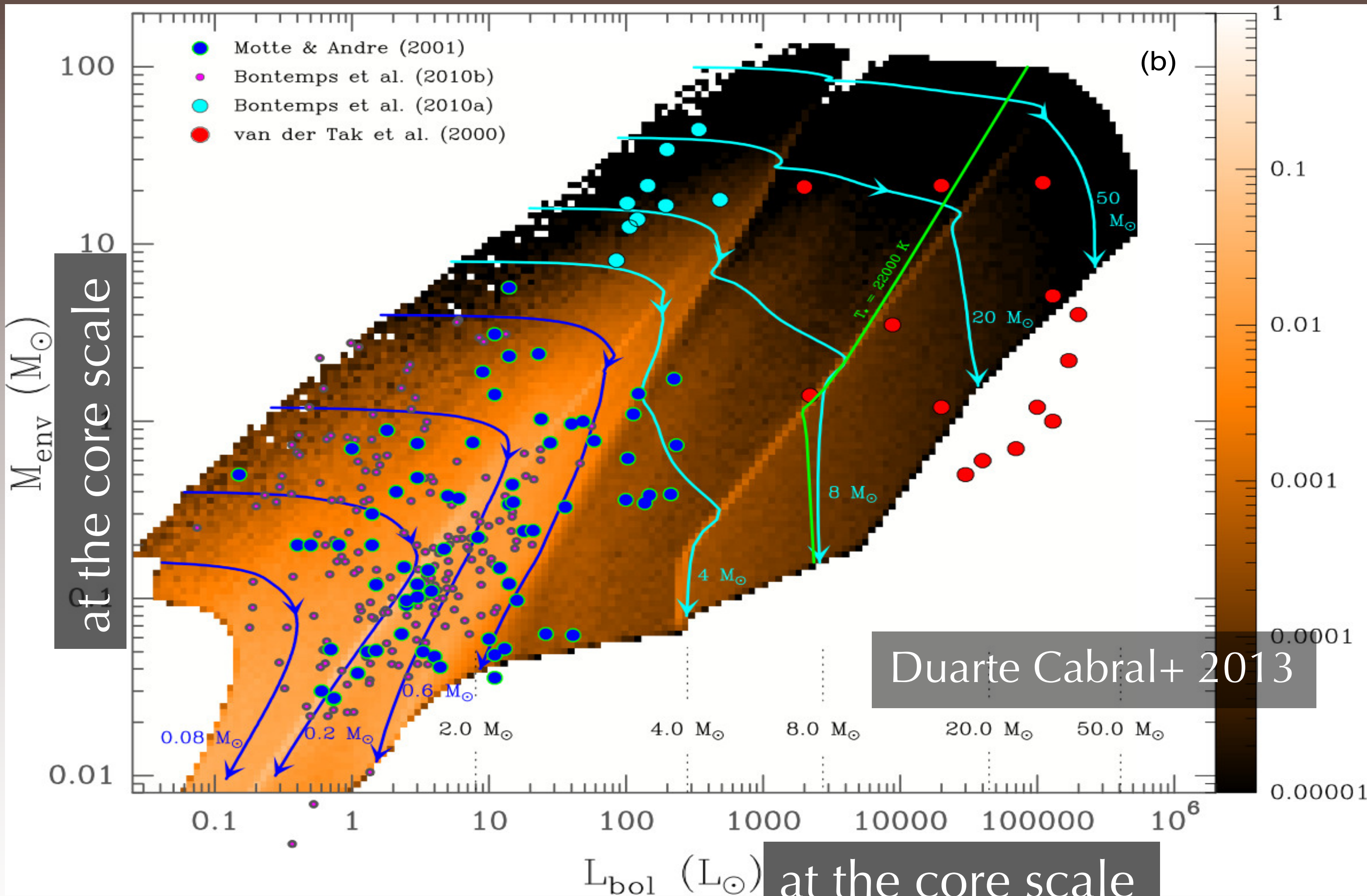
Outflow rate should be proportional to protostellar accretion.

⇒ scaled-up process?



…assuming the same single protostar drives the outflow and powers the luminosity!

High-mass protostellar accretion history: decreasing and intermittent



at the core scale

Duarte Cabral+ 2013

at the core scale

Consistent with decreasing accretion rates (e.g., Herpin+ 2016)

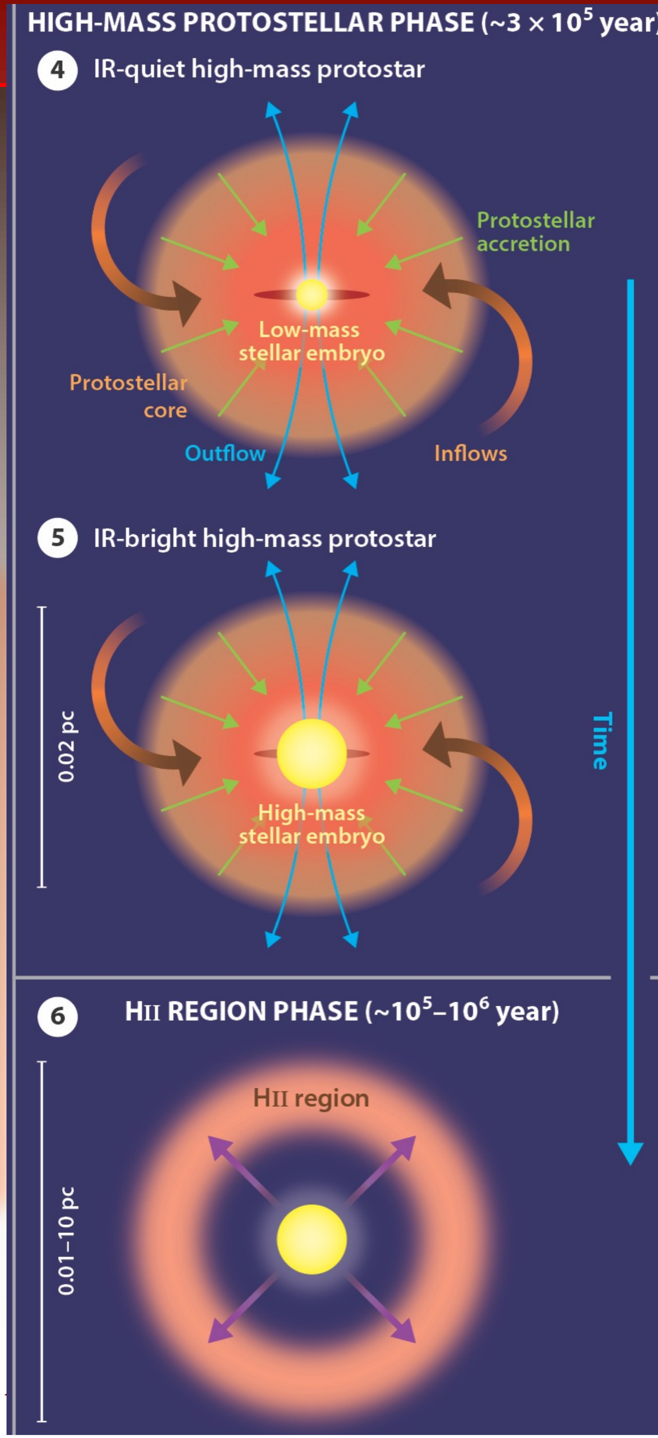
High-mass protostellar phase

IR-bright protostars within HMPOs
Many studies by the group of Beuther et al. suggest high accretion rates.

Constraints on the evolution from IR-quiet (young) and IR-bright (evolved) protostars:

⇒ Protostellar accretion is stronger in the IR-quiet phase (e.g., Herpin+ 2016).

⇒ Evolutionary diagrams $M_{env} - L_{bol}$ and $F_{outflow} - L_{bol}$ suggest strong and sporadic accretion (Duarte-Cabral+ 2013; Maud+ 2017).



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Precursors of H II regions (e.g. Churchwell 19

1. Among high-luminosity IR

e.g. Bronfman+ 19

2. Earli

- IR dar SO, MSX, or Spitzer

(e.g. Rathb 2006; Beutler & Tan 2009; Peretto & Fuller 2010)

- Submillimeter mapping close to maser and/or IR sources

(e.g. Walsh et al. 2003; Hill et al. 2005; Thompson et al. 2005)

Caveat:
Incomplete sample of high-mass star-formation sites
→ imaging of complete molecular complexes or Galactic-wide surveys

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Unbiased census of the earliest phases of high-mass stars

Massive dense cores (MDCs):

- small-scale cloud fragments ~0.1 pc
- with high masses > 50 $M_\odot$
- with high mean density n_{H2} > 10^5 cm^{-3}

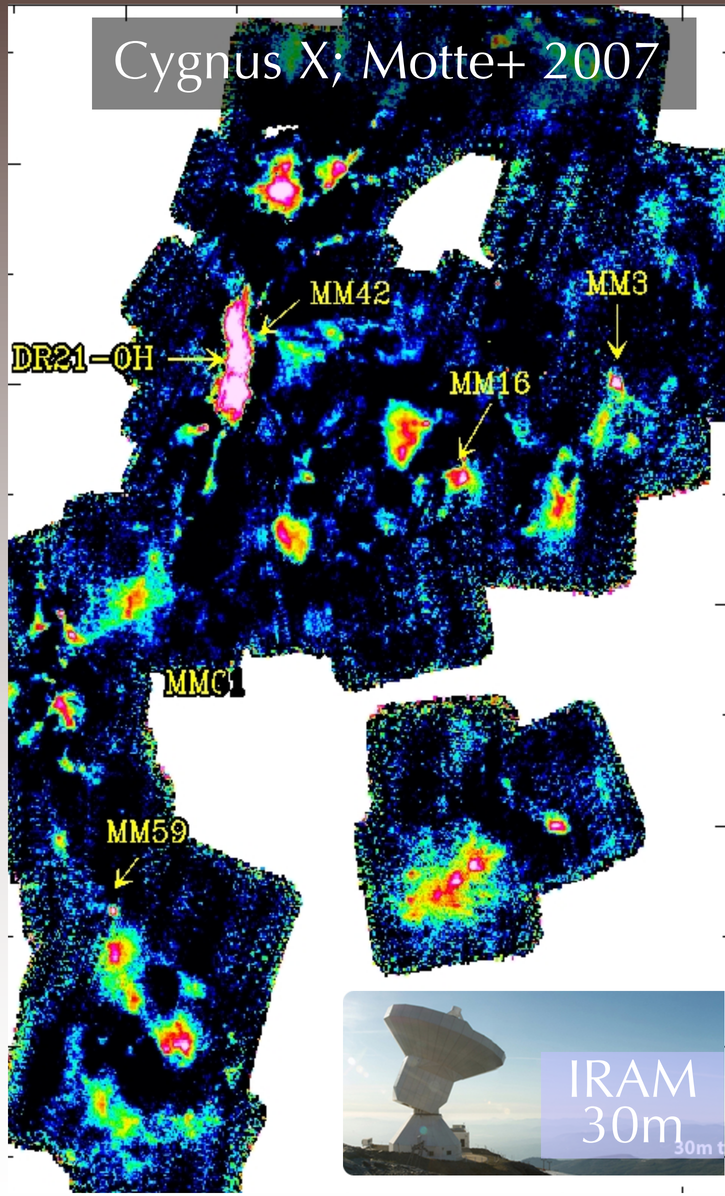
Starless MDCs are fewer in number than protostellar MDCs.

⇒ Prestellar lifetime < protostellar lifetime

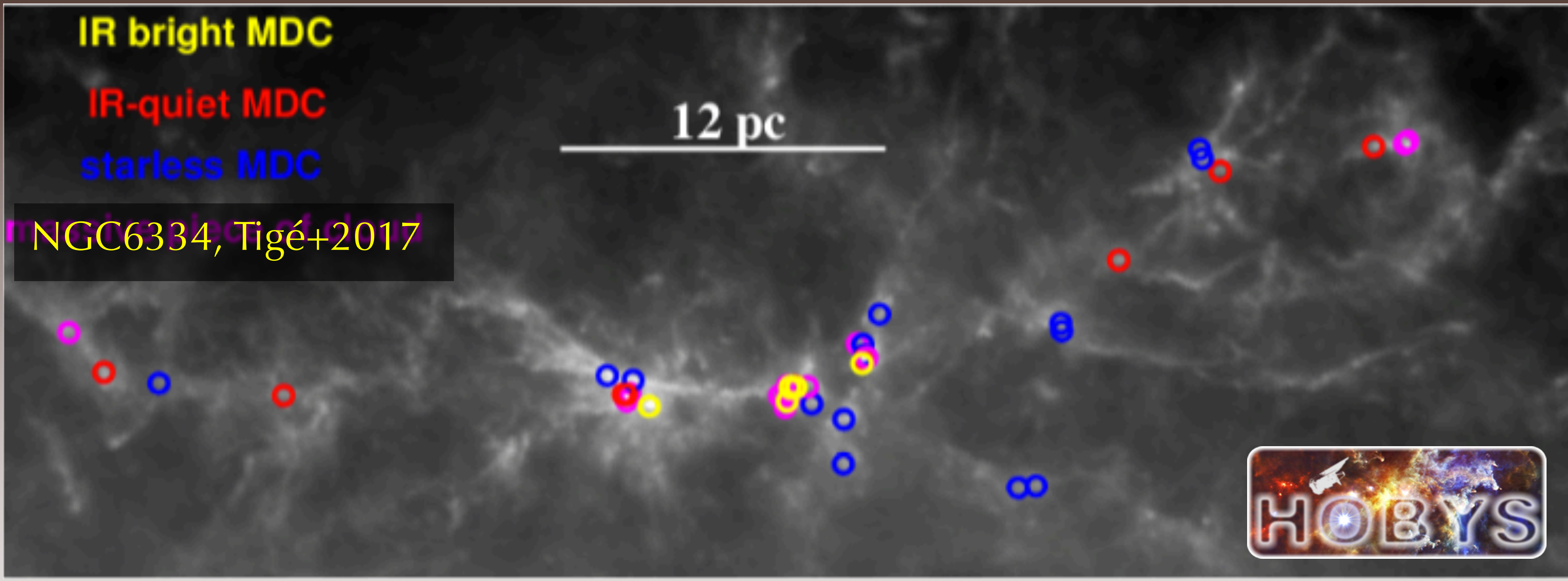
= $\tau_{free\text{-}fall}$ (Motte+ 2007; Russeil+ 2010)

Very few starless MDCs are found in the Galactic Plane surveys CSO/Bolocam-GPS, APEX/Atlasgal, Herschel/Hi-GAL.

(Ginsburg +2012; Csengeri+ 2014; Tackenberg+2014; Traficante+ 2015; Svoboda+ 2016; …)



Census of starless MDCs with *Herschel*/HOBYS data



Complete census of MDCs in the NGC6334 complex:

Starless MDCs are fewer than protostellar MDCs (Tigé+ 2017).

⇒ The starless MDC phase *statistically* lasts for less than one free-fall time! Does it exist?

The quest of high-mass pre-stellar cores

Low-mass pre-stellar core

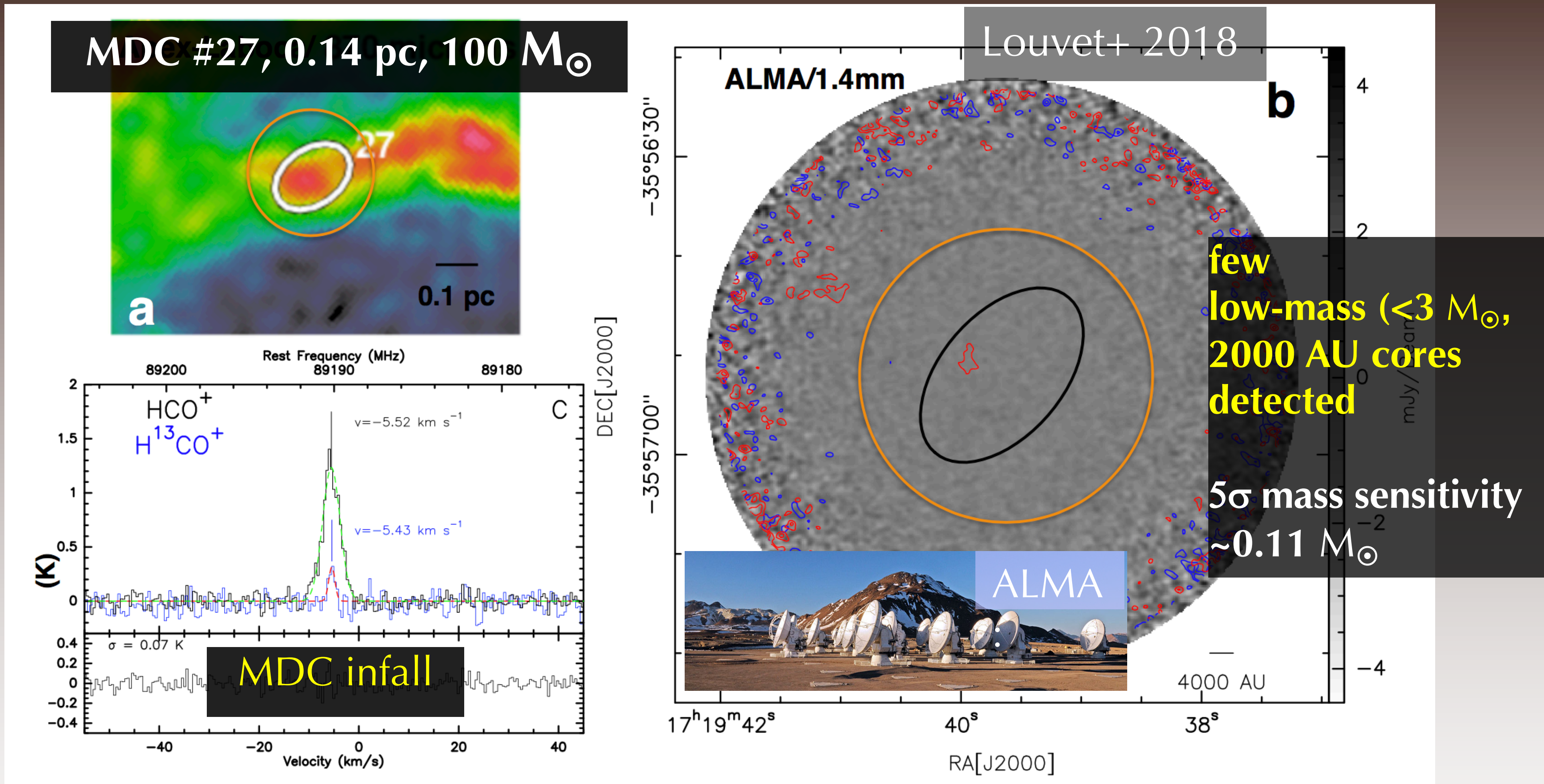
- Few 1 000 AU, few $M_{\odot}$, 10-15 K, Bonnor-Ebert shape, D chemistry…
- Quasi-statically contract over several/one free-fall times before collapse.

What could be the high-mass analog?

- More massive core with additional support against collapse.
  ⇒ Small-scale massive cloud fragment 0.01-0.1 pc, >10-100 $M_{\odot}$
  'Core-fed' accretion (e.g. McKee & Tan 2003).

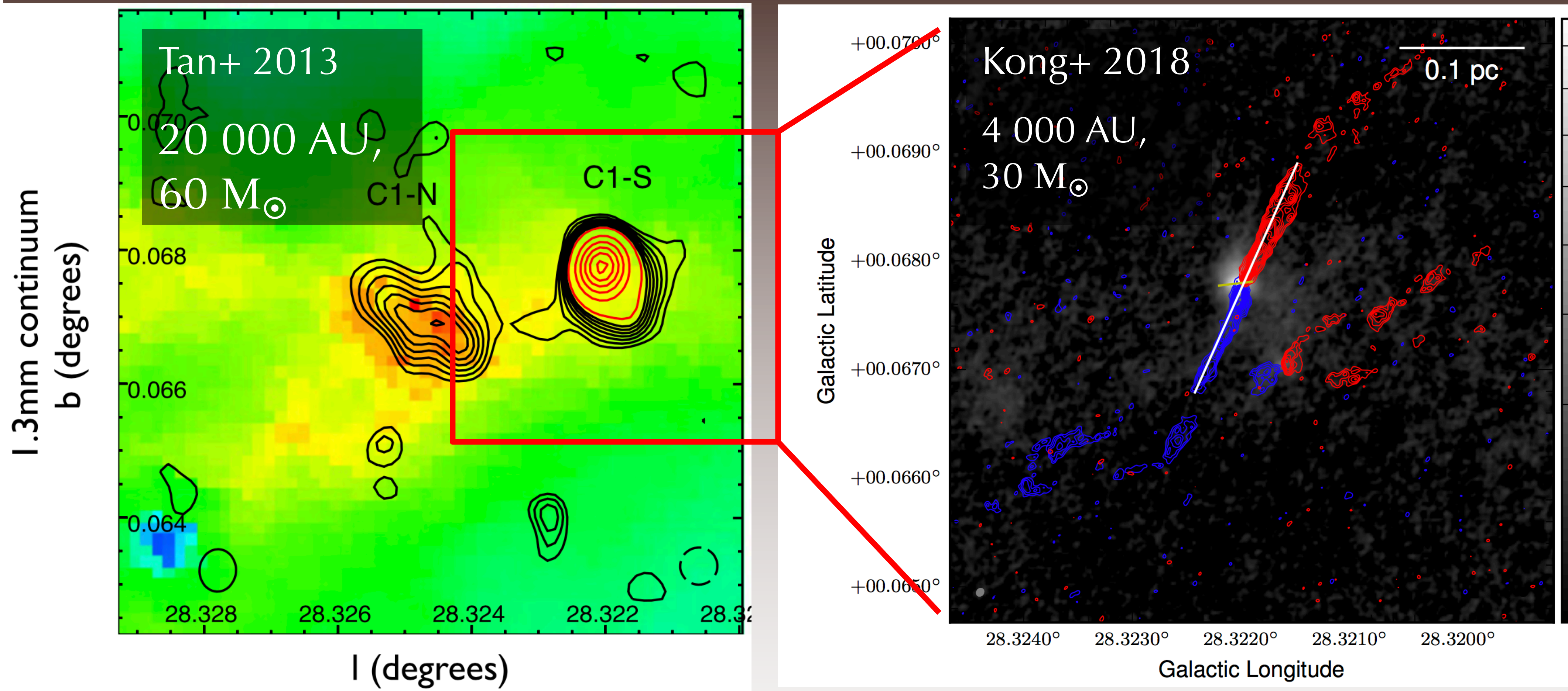
- Low-mass core within a massive dense core (MDC) / clump
  ⇒ Large-scale massive cloud fragment 0.1-1 pc, >100 $M_{\odot}$
  Small-scale (pre-stellar and then Class 0) core @ center of MDC
  'Clump-fed' accretion through gas flows (e.g. Smith+ 2009).

An ALMA view of the NGC 6334 starless MDCs



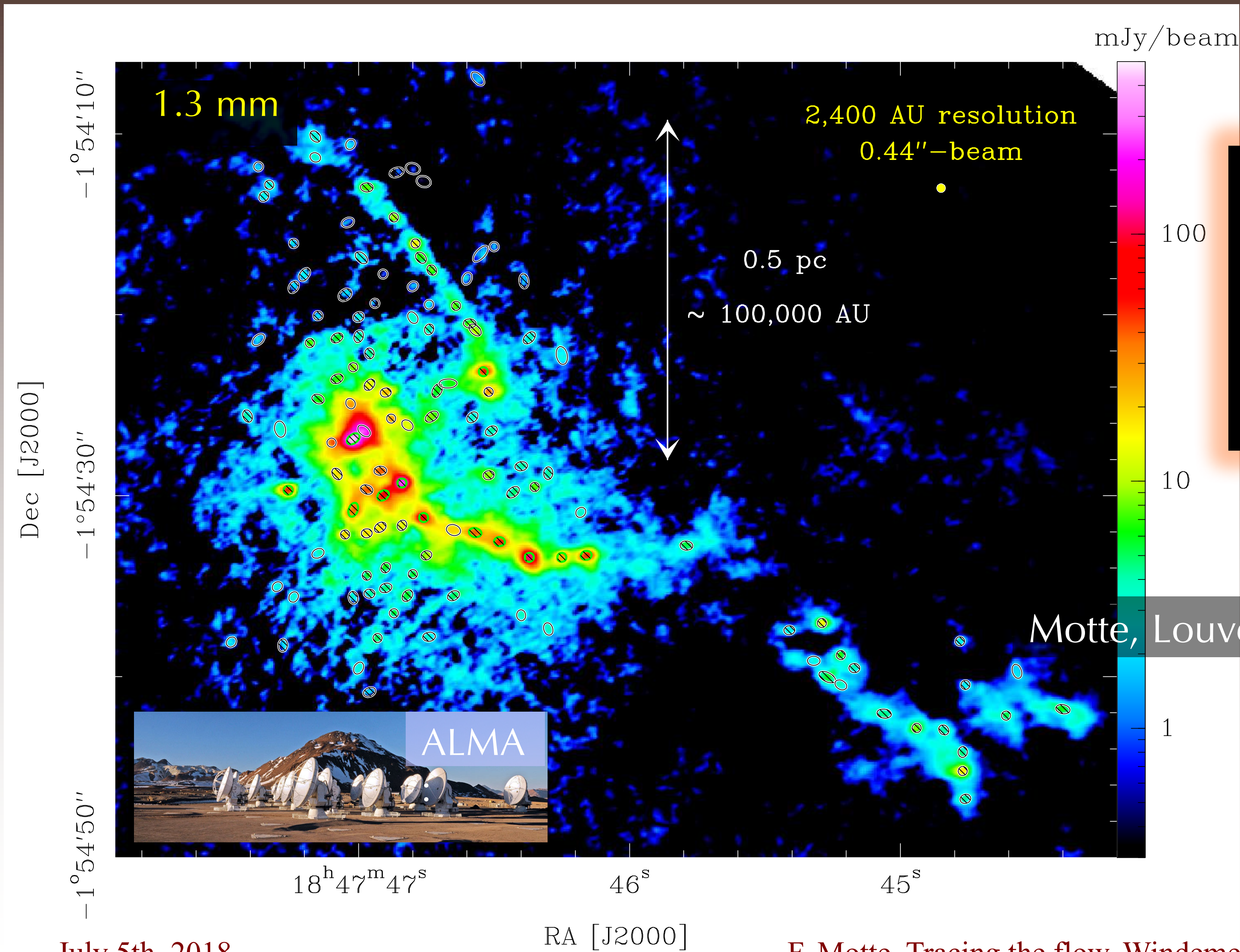
Within starless MDCs, no high-mass prestellar cores (Louvet+ 2018) but sometimes protostars… Same behavior in Cygnus X and W43-MM1 (Bontemps+ 2010; Nony+ in prep.)

ALMA searches for prestellar cores in IRDCs



Low-mass prestellar cores and protostars are found within IRDCs (Tan+2016; Kong+ 2018; Wang+ in prep.).

Unbiased census of high-mass cores in W43-MM1



⇒ 13 **high-mass cores**

(2 000 AU and 16-100 $M_\odot$)

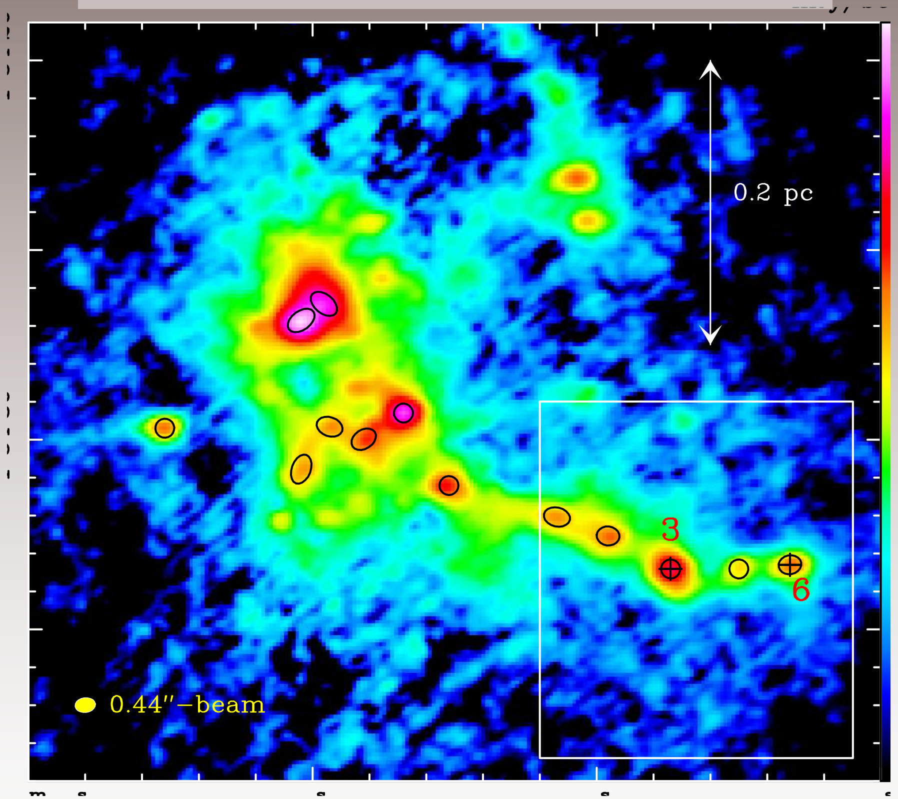
Search for high-mass prestellar cores

Protostellar activity signposts: Nony+ in prep.; Molet+ in prep.
- Outflows traced by CO(2-1) and SiO(5-4) line wings
- Hot cores /shocks traced by emission of complex organic molecules

Source	Mass ($M_\odot$)	Temp. (K)	CO	SiO outflows	Hot core	Nature
#1	102	74	Y	Y	Y	protostellar
#3	59	45	Y	Y	Y	
#2	55	59	Y	Y	Y	
#4	36	88	N	N	Y	
#16	36	21	Y	Y	Y	
#7	23	30	Y	Y	Y	
#14	19	22	N	N	Y	
#5	18	47	N	N	Y	
#9	18	50	Y	Y	Y	
#10	16	51	Y?(l)	Y? (B)	Y	
#12	31	23	N	Y? (R)	Y	undetermined
#18	28	23	Y? (B)	Y? (B)	N	
#6	56	23	N	N	N	prestellar ?

Comparison of two very massive cores

Zooming at the tip of the main filament …



… two 2000 AU cores with similar masses,

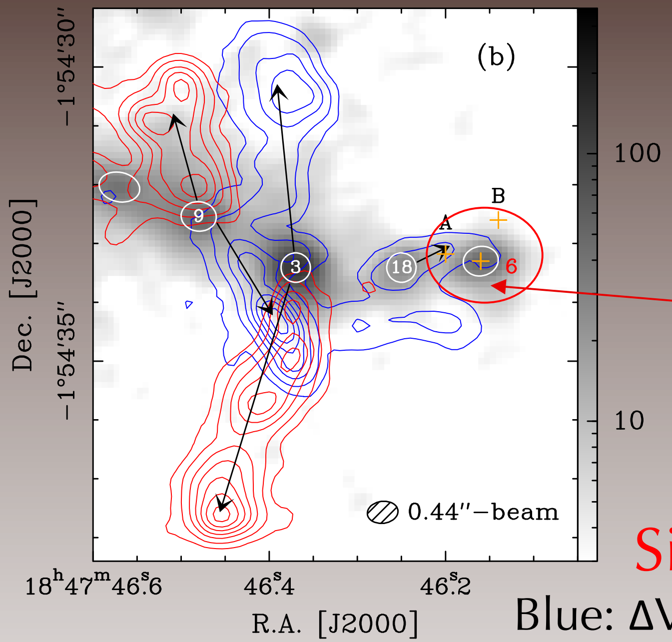
Core	FWHM	S^{peak}	T_d	M_{core}	α_{vir}
	[AU]	[mJy/beam]	[K]	[$M_\odot$]	
#3	1200	109 ± 2	45 ± 1	59 ± 2	0.2
#6	1300	46.8 ± 2	23 ± 2	56 ± 9	0.2-0.3

***… gravitationally bound** (α_{vir} < 1),*

M_{vir} calculated using the ^{13}CS(5-4) line width (ΔV ~ 3.5 km/s)

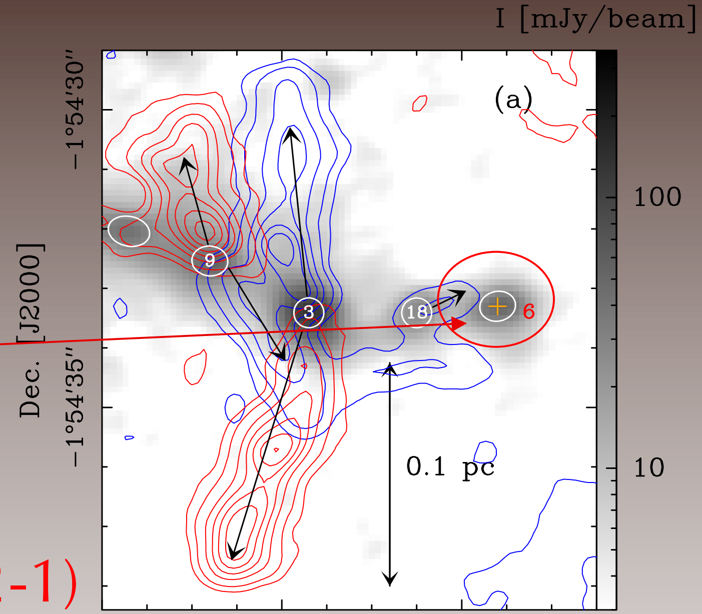
(Nony+ in prep.)

#6, a good high-mass prestellar core candidate



… and with different characteristics!

No outflow detected toward core #6



SiO (5-4)

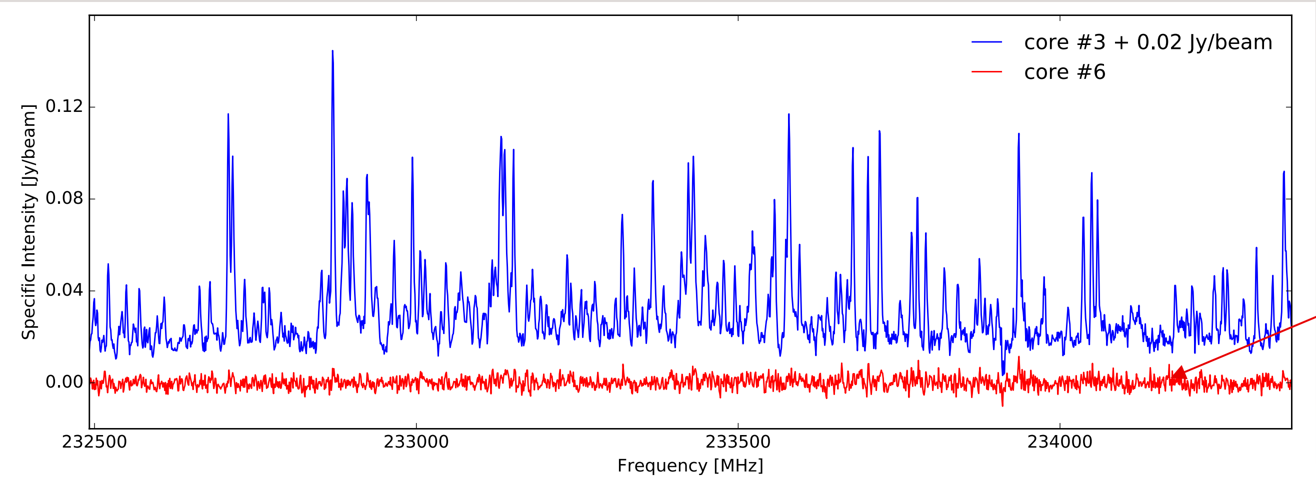
Blue: ΔV = -37 → -7 km/s

Red: ΔV = 7 → 37km/s

CO (2-1)

Blue: ΔV = -60 → -10 km/s

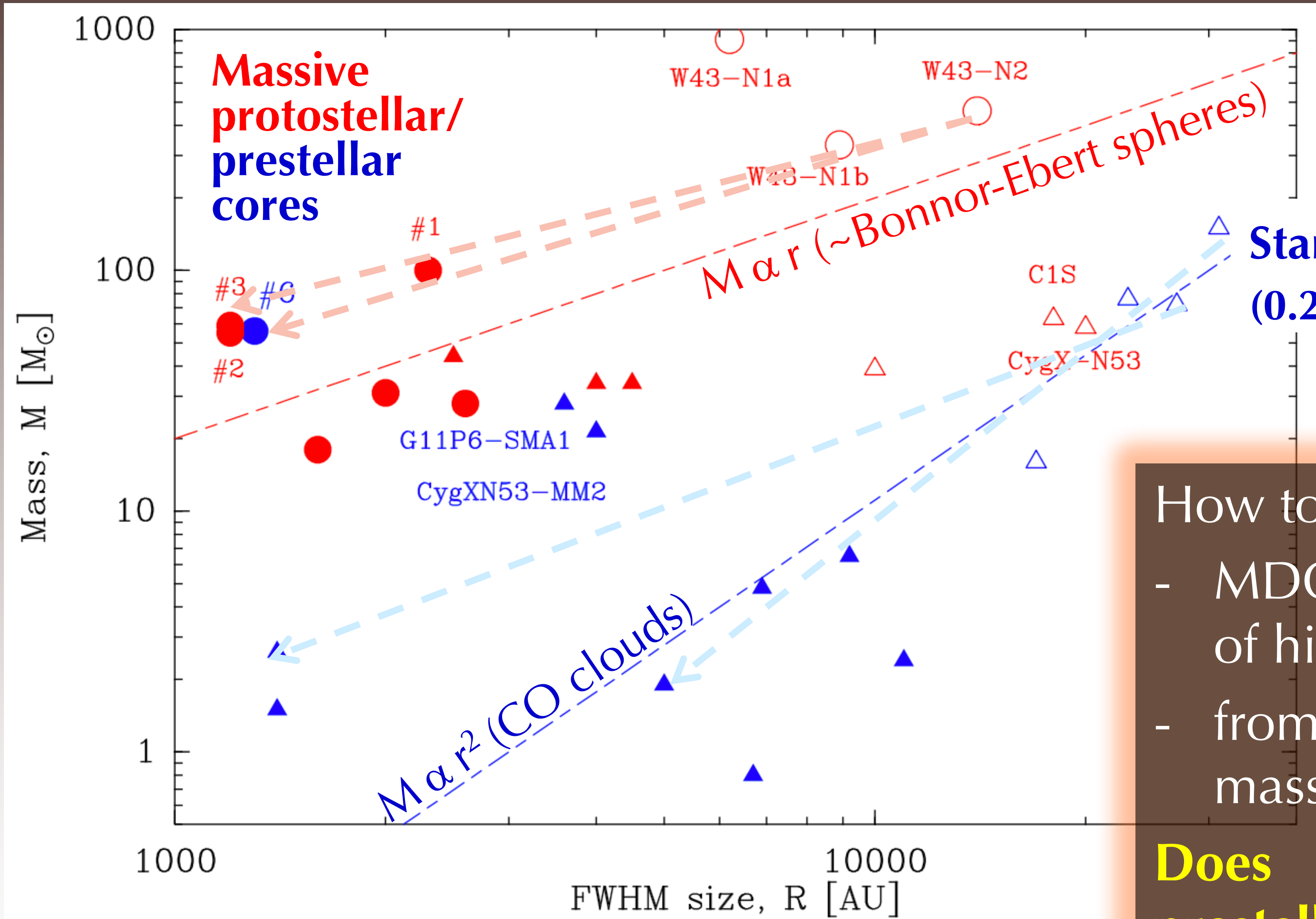
Red: ΔV = 10 → 60 km/s



(Nony+ in prep.)

Very few lines: no hot core powered by core #6

Concentration of the gas masses from the MDC scale down to the core scale



(Nony+ in prep.)

Starless MDCs
(0.2 pc, 100 $M_{\odot}$)

How to distinguish

- MDCs forming a couple of high-mass stars
- from those forming low-mass star clusters?

Does the high-mass prestellar core phase exist?

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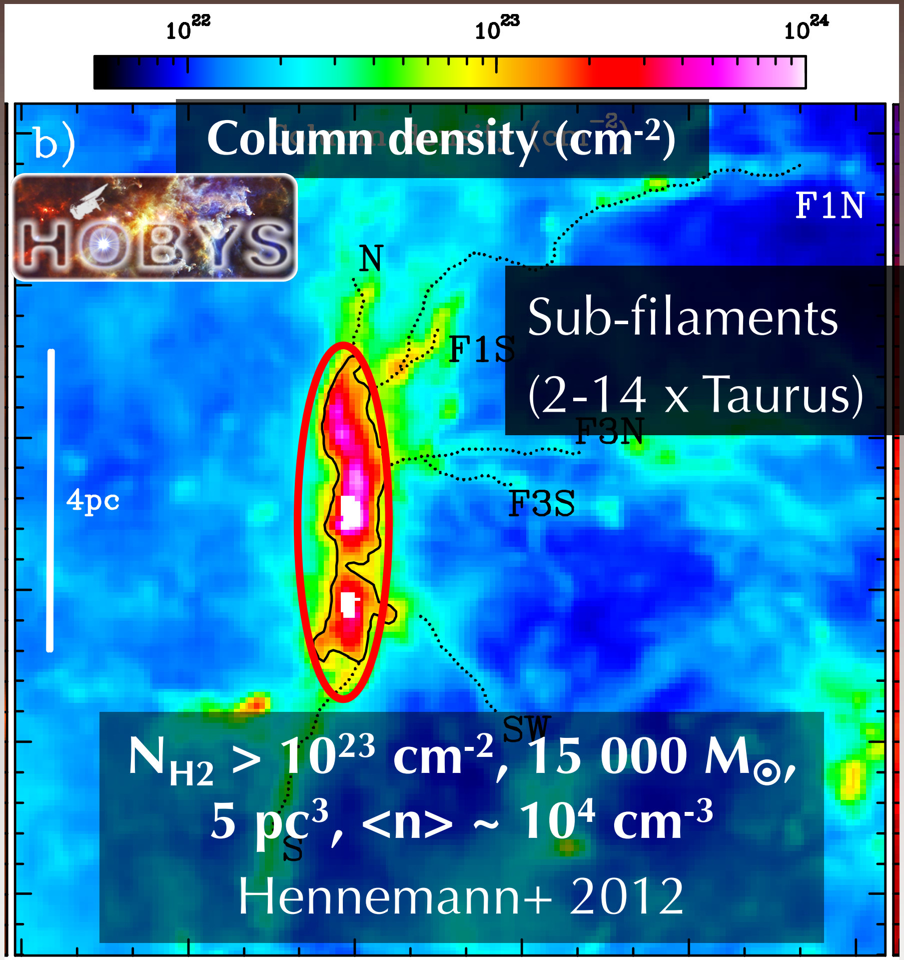
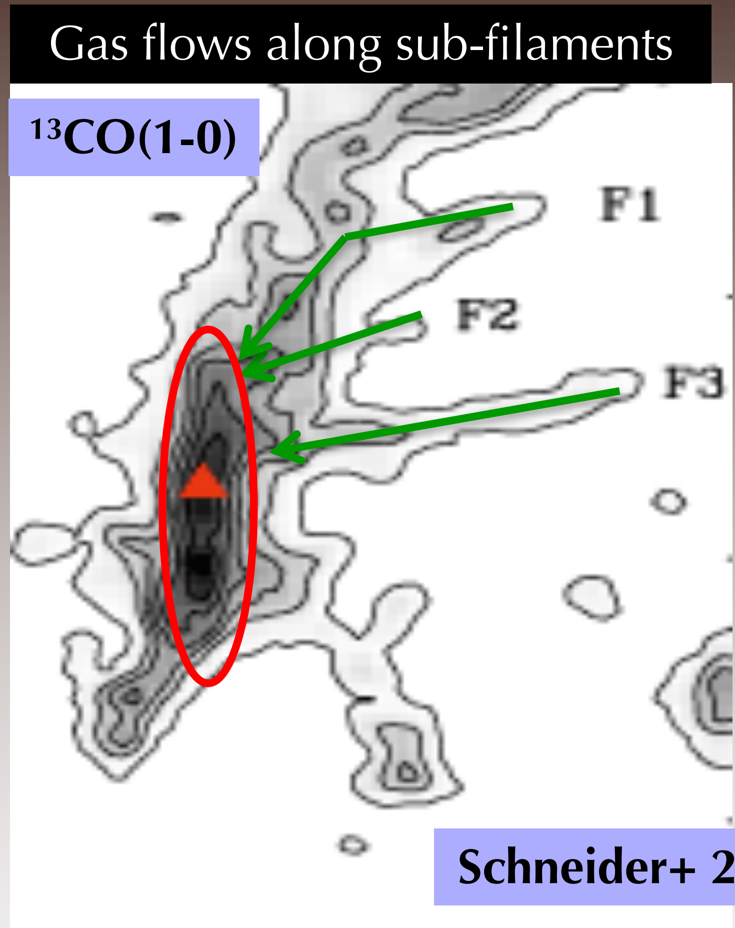
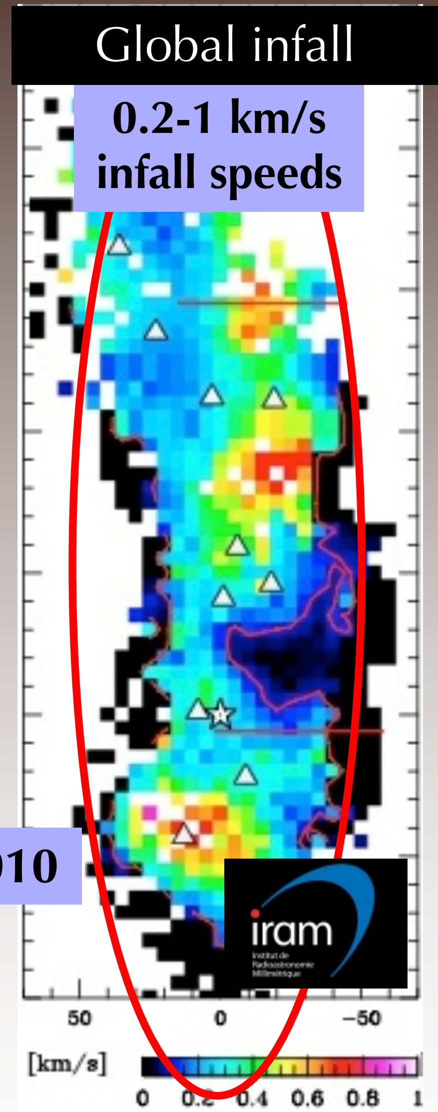
Most MDCs are within high-density ridges/hubs



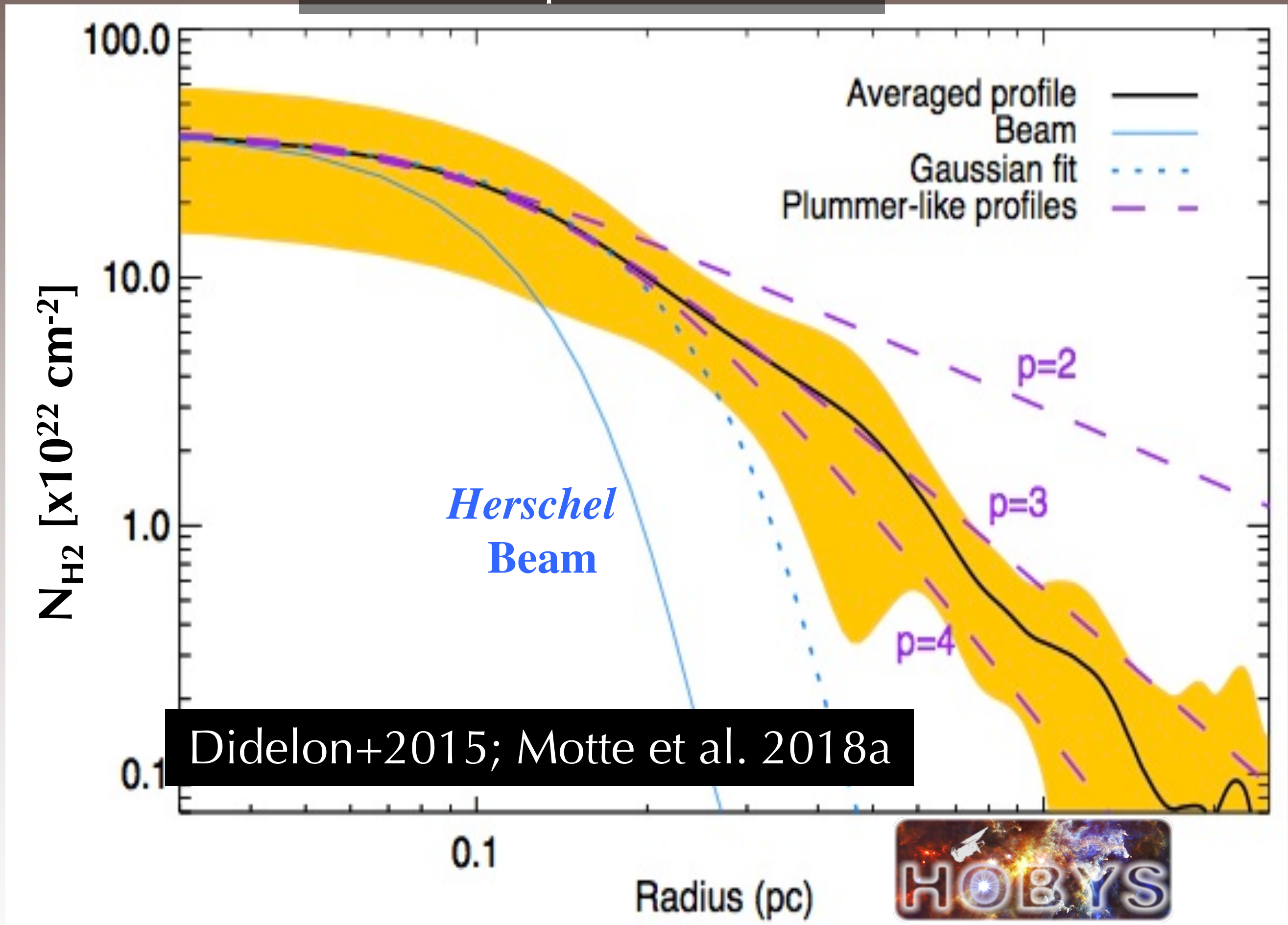


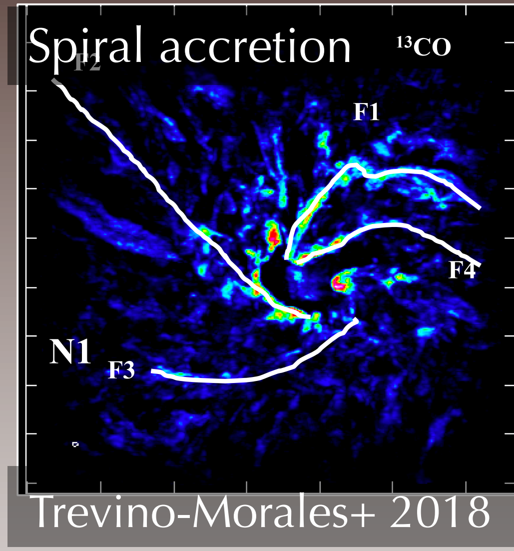


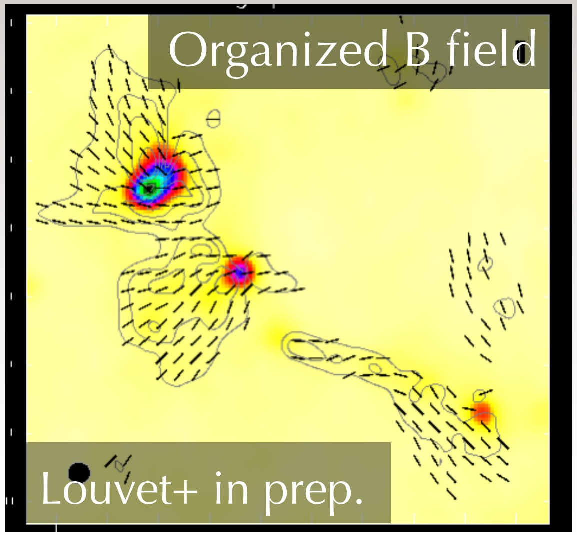
See also Peretto+ 2013, 2014; Henshaw+2014, 2016; Beuther+ 2012; Nakamura+ 2014…

Ridges/hubs are braids of filaments whose free-fall is slowed down by rotation and/or B-fields

Transverse profile of DR21

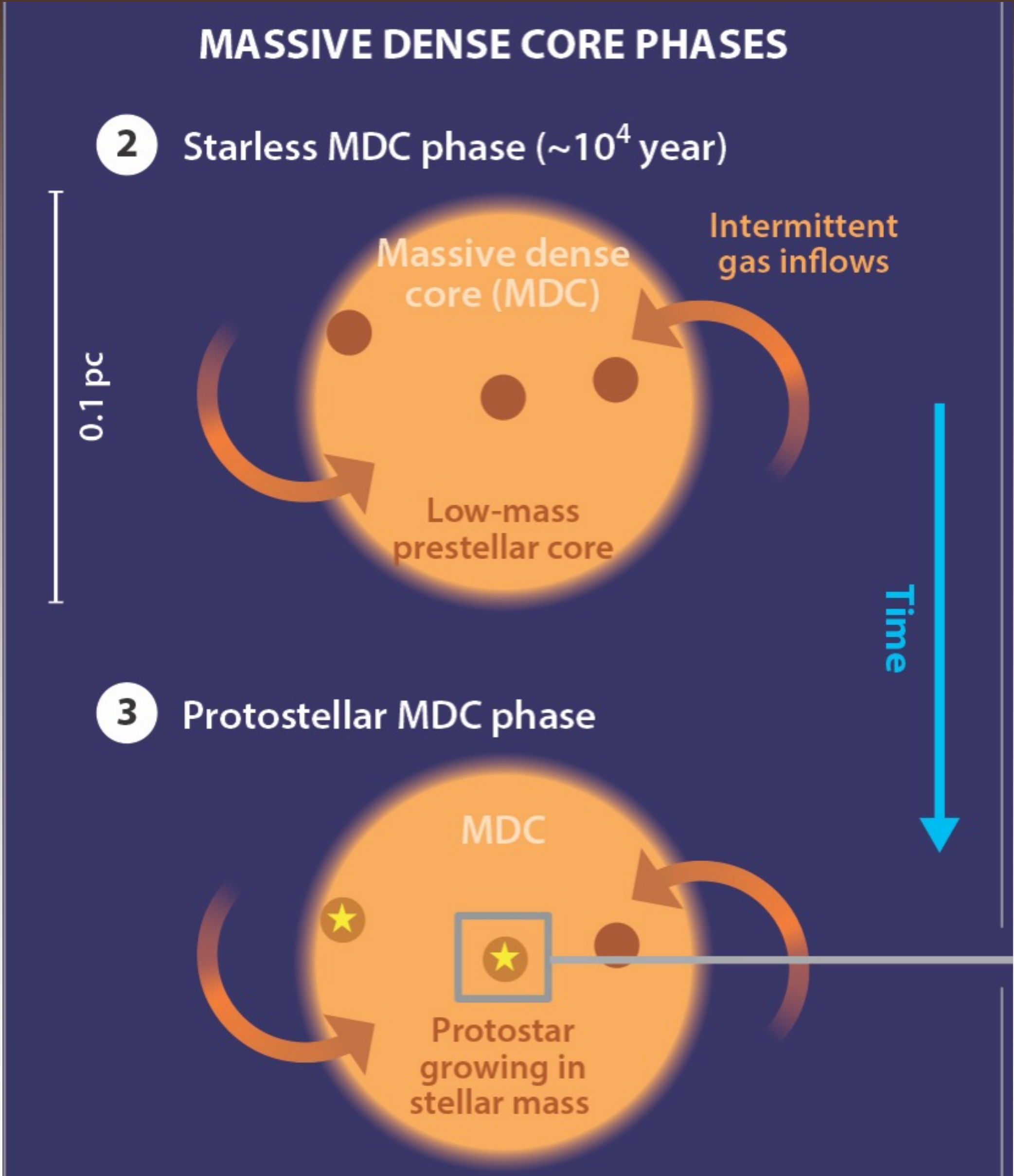






Consistent with PDF studies (Russeil+ 2013; Schneider+2015) and inflow studies (e.g. Wyrowski+ 2016).

In ridges & hubs, the "gas reservoir" is not a single "core"



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- Gas is accreted onto ridges, 0.1 pc MDCs, cores, and finally stellar embryos.

⇒ Accretion cascade model

- Stars, cores, and MDCs simultaneously grow from the mass of their parental ridge.

⇒ "clump-fed" model

⇒ No need of a high-mass prestellar core phase

Low-mass prestellar cores become protostars with increasing mass

Summary and prospects

- High-mass prestellar cores may not exist!

Shall we stop this illusory quest that already lasted for more than 10-years?

- Proposed evolutionary scenario:

Stars, cores, and MDCs simultaneously grow from the mass of their parental ridge.

- Lessons to learn:

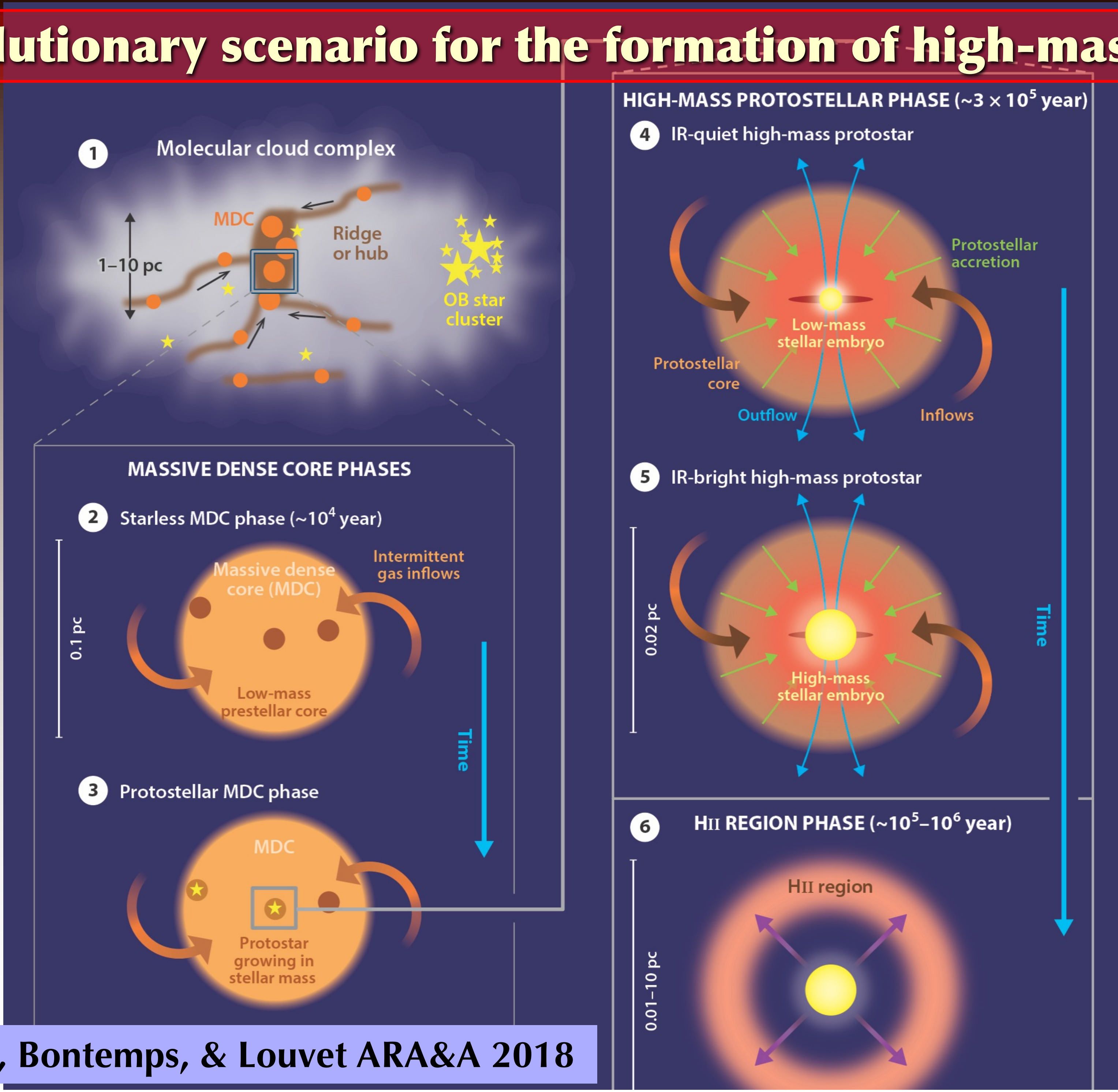
Avoid at all costs to extrapolate our knowledge of nearby clouds to typical Galactic clouds. Let's think wider!

- Future challenges for 0.01 pc cores:

Characterize their luminosity, outflow and angular momentum, turbulence level, magnetic field strength and topology, chemical evolution…

Characterize core populations (CMF, velocity dispersion…)

Evolutionary scenario for the formation of high-mass stars



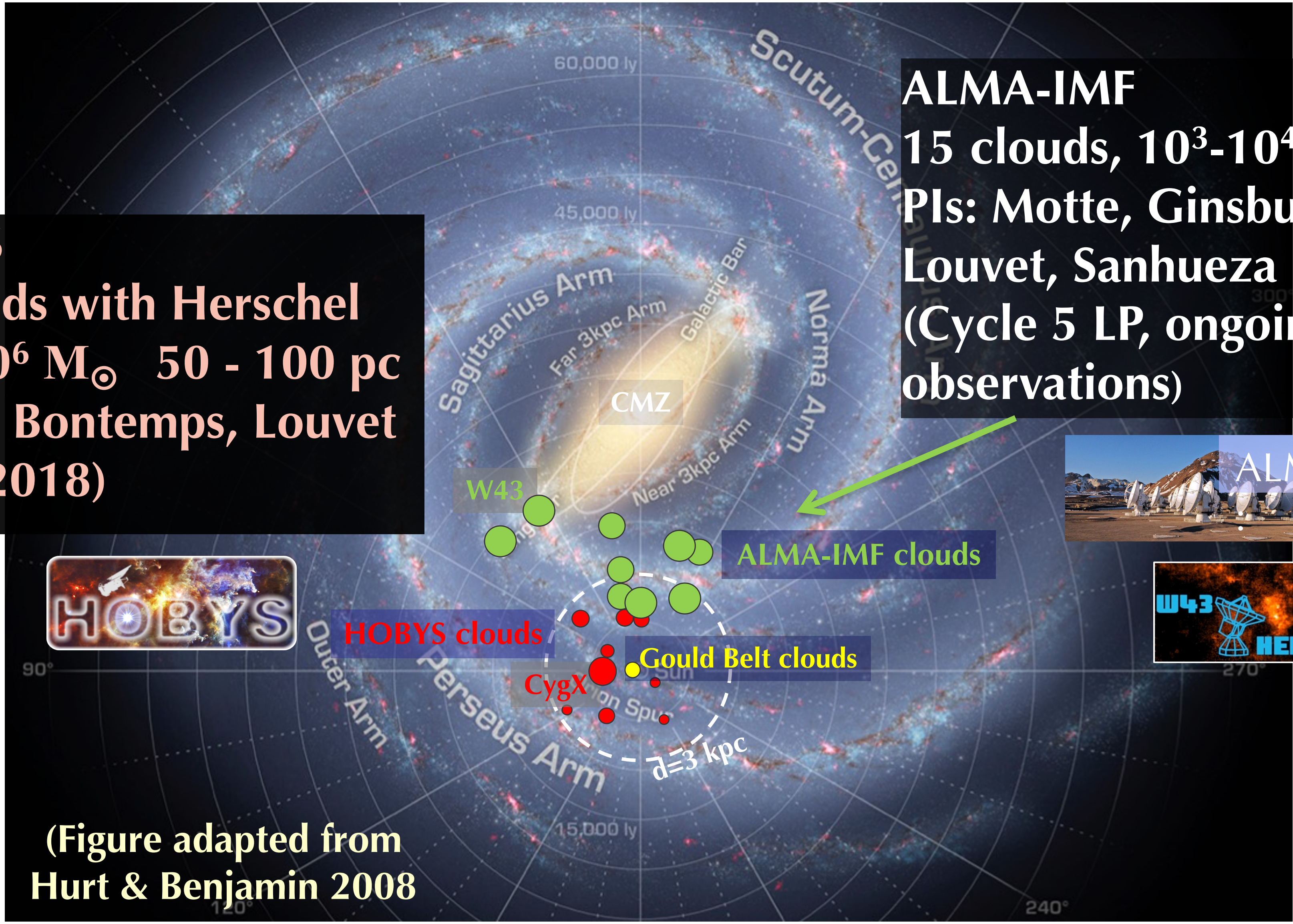
Motte, Bontemps, & Louvet ARA&A 2018

Thank you for your attention!

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

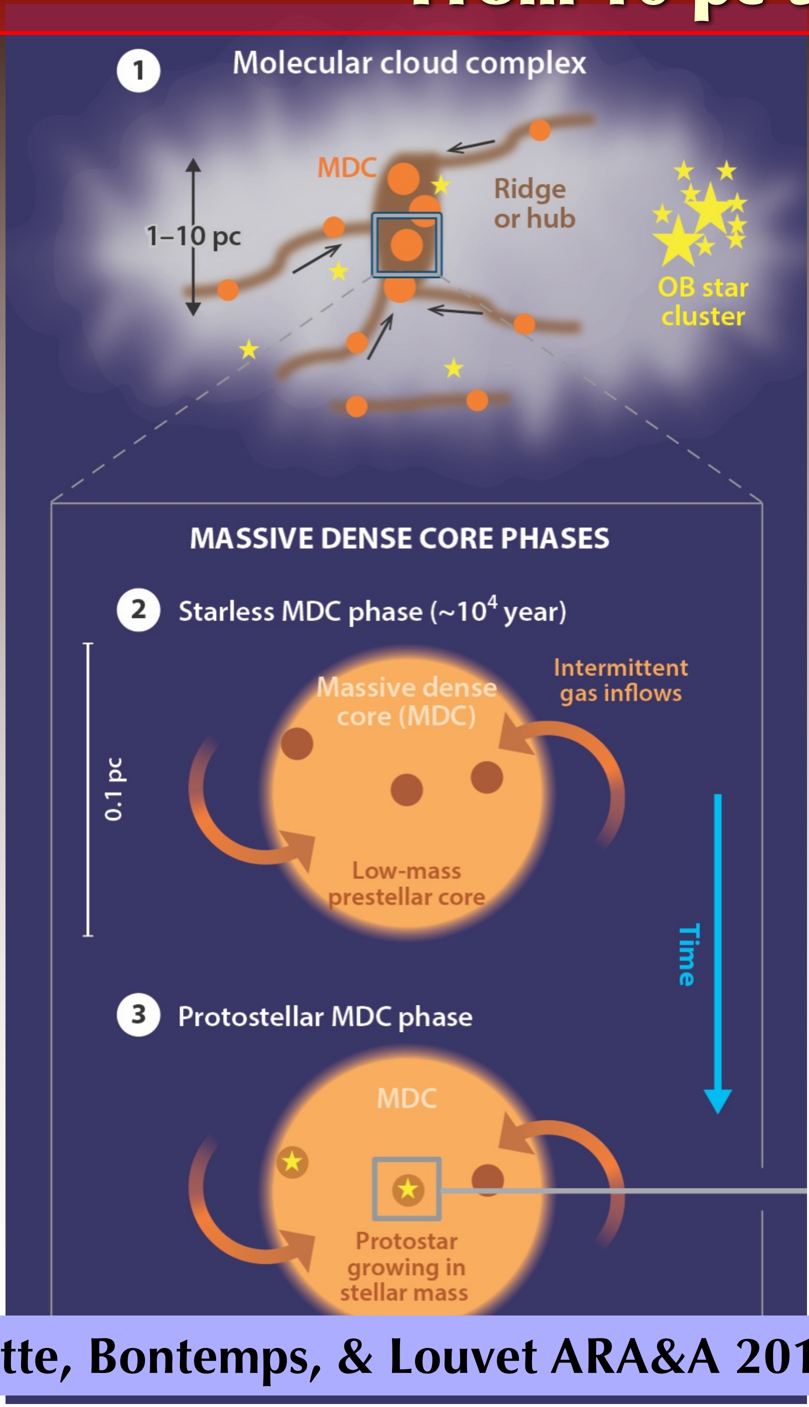
HOBYS
10 clouds with Herschel
10^5 - 10^6 $M_\odot$ 50 - 100 pc
(Motte, Bontemps, Louvet ARAA 2018)

ALMA-IMF
15 clouds, 10^3-10^4 $M_\odot$ 1 pc
PIs: Motte, Ginsburg, Louvet, Sanhueza
(Cycle 5 LP, ongoing observations)



(Figure adapted from Hurt & Benjamin 2008

From 10 pc to 0.02 pc scale...



- 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 collapsing cloud attracting even more filaments.

Stars and filaments simultaneously form and grow in mass and may not go through a high-mass prestellar core phase.

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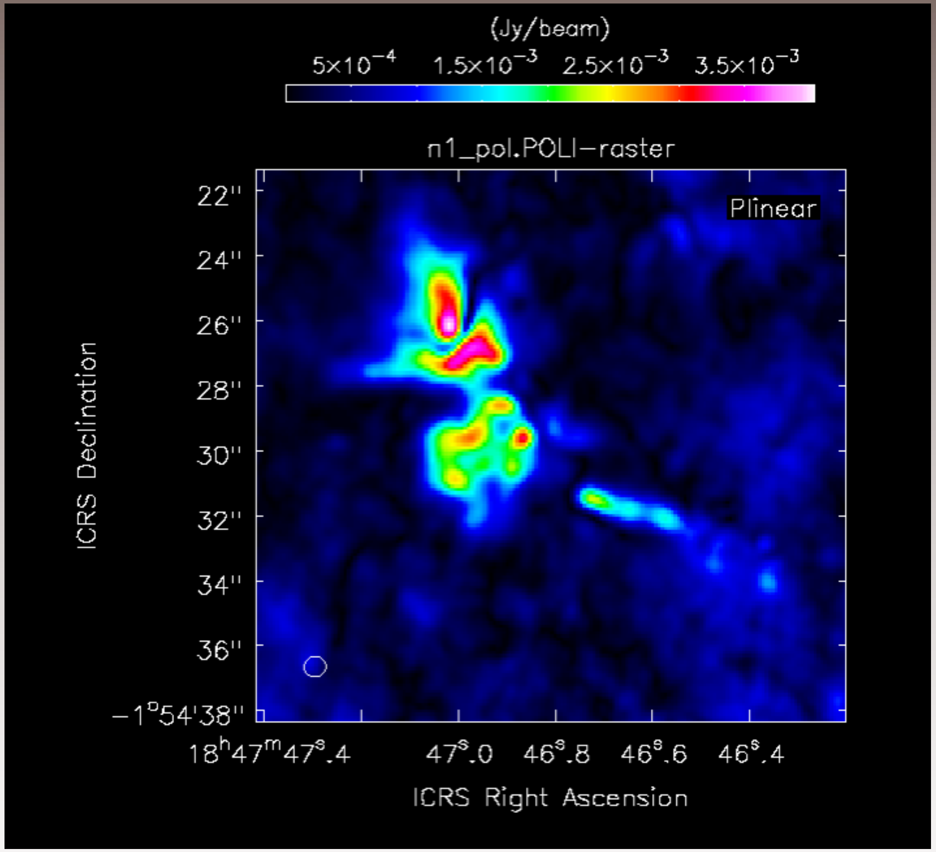
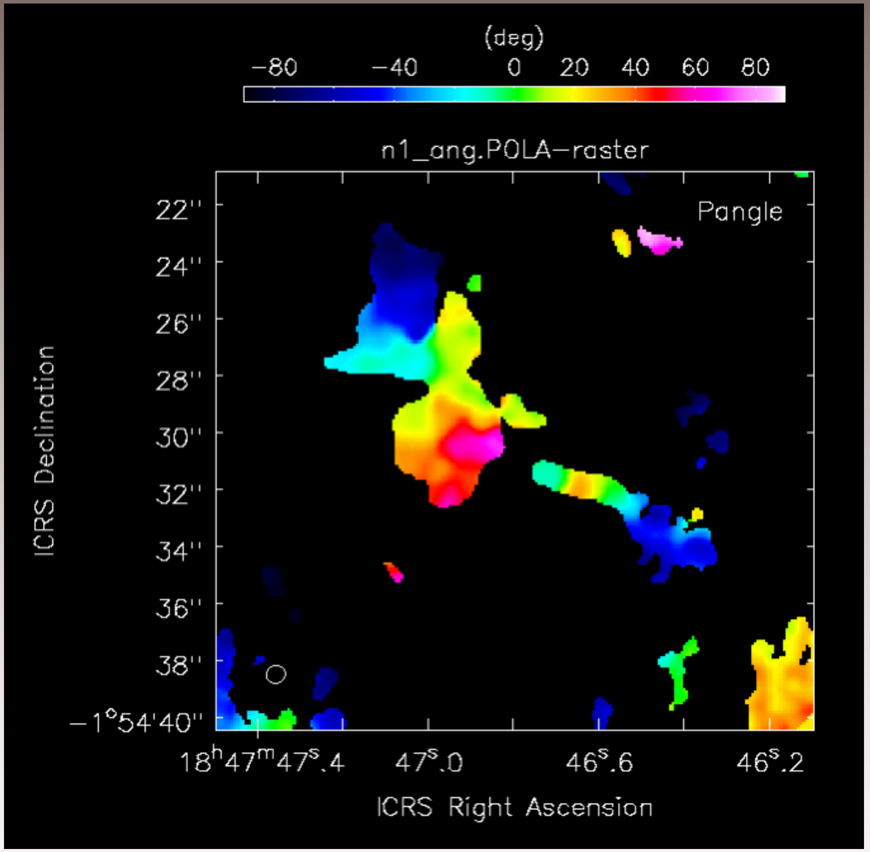
W43-N1 Polarization

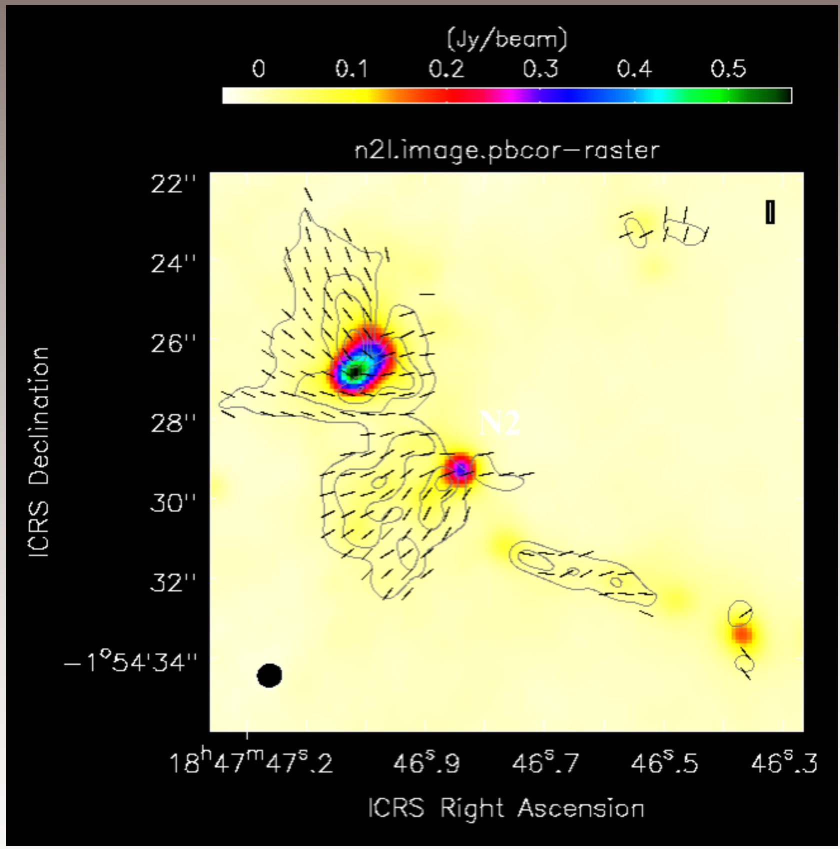


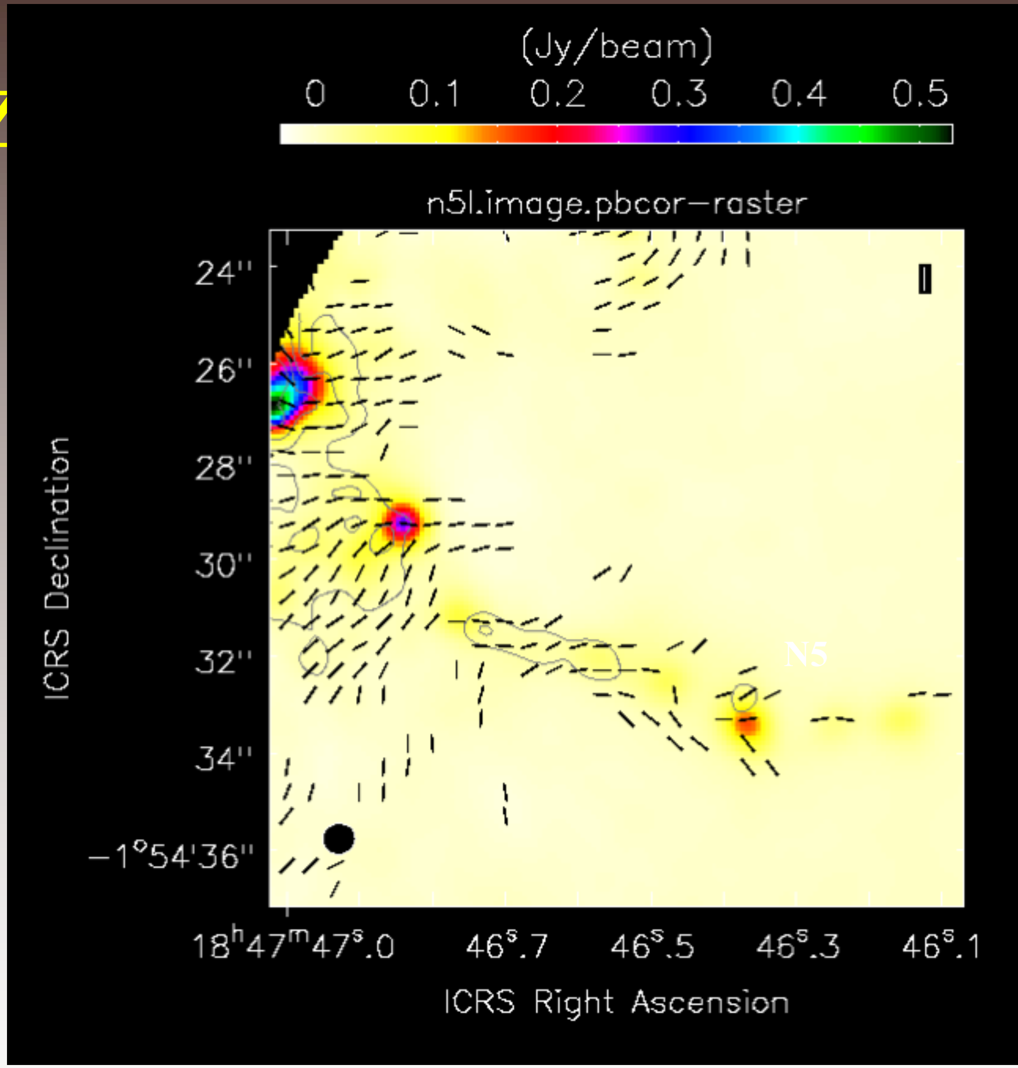
(a) Linear Polarization



(b) Polarization Angles

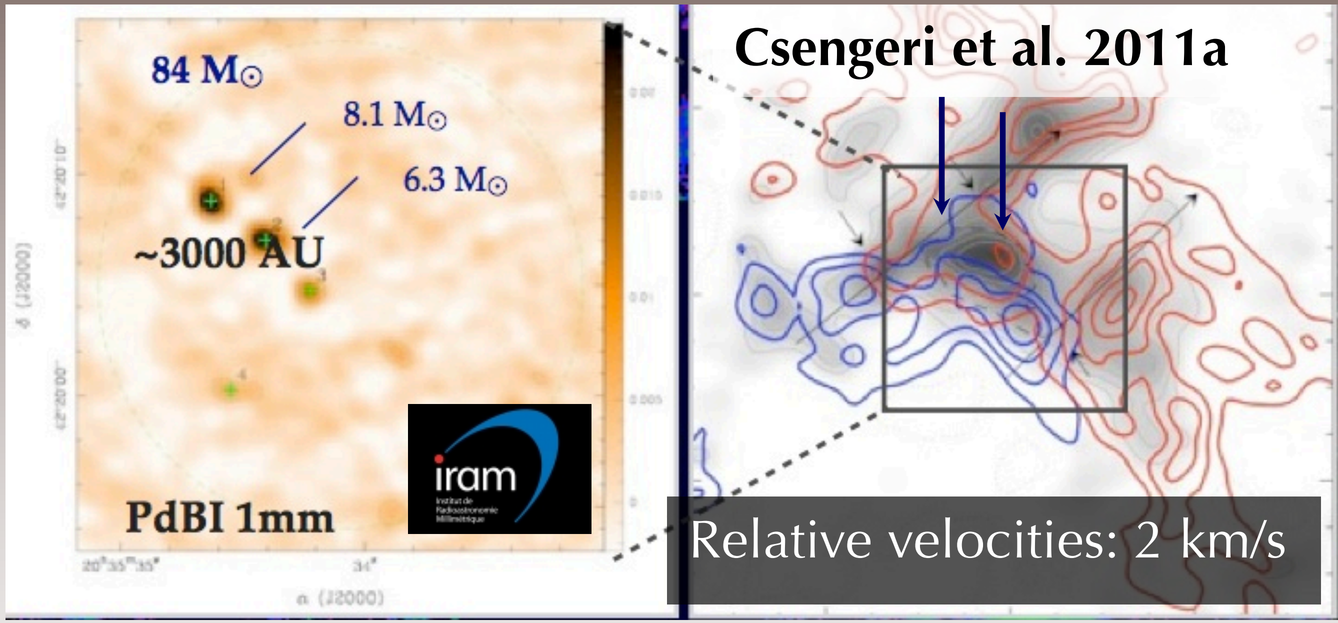
W43-MM1 Polariz

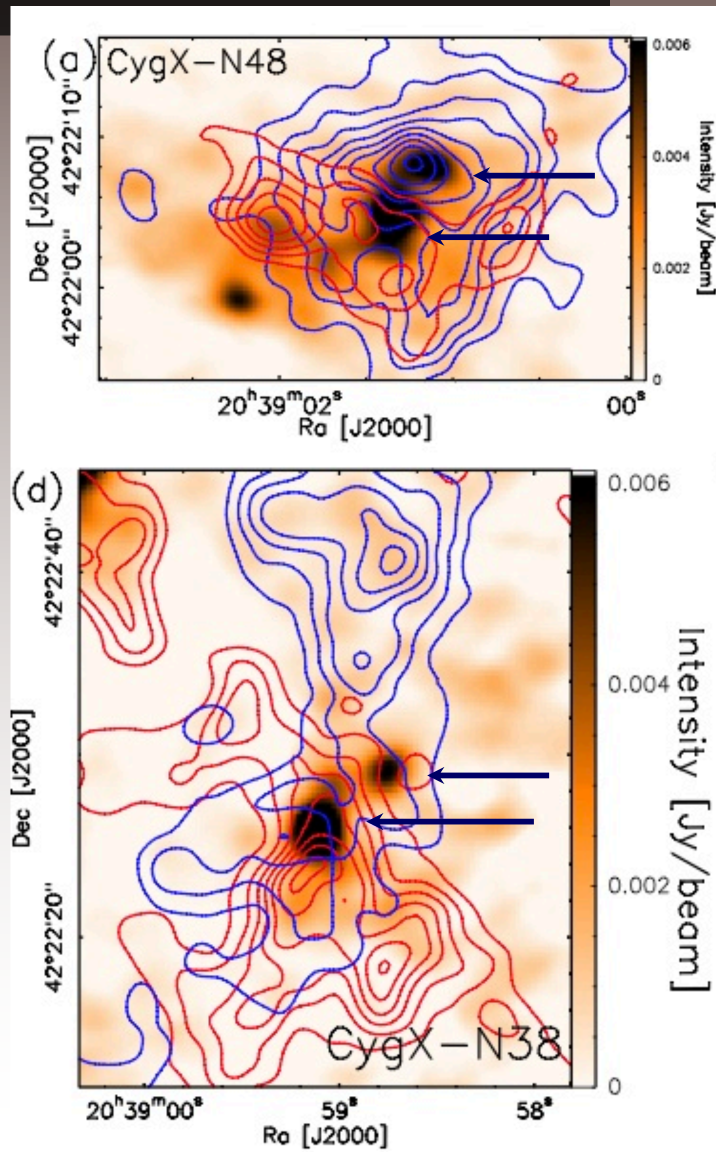




Velocity shears onto high-mass protostellar cores

Organized 0.05 pc flows in $H^{13}CO^+$ or N_2H^+ displaying shears at the location of high-mass protostars (Csengeri et al. 2011a, 2011b).



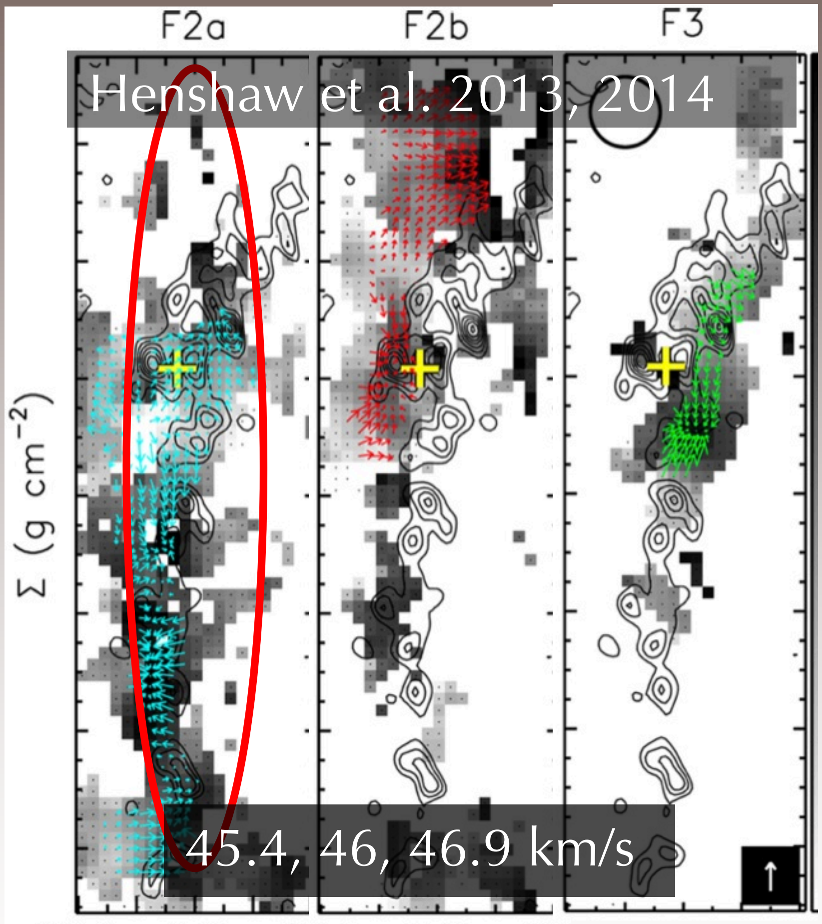


Consistent with numerical simulations by Smith et al. 2011, 2012.

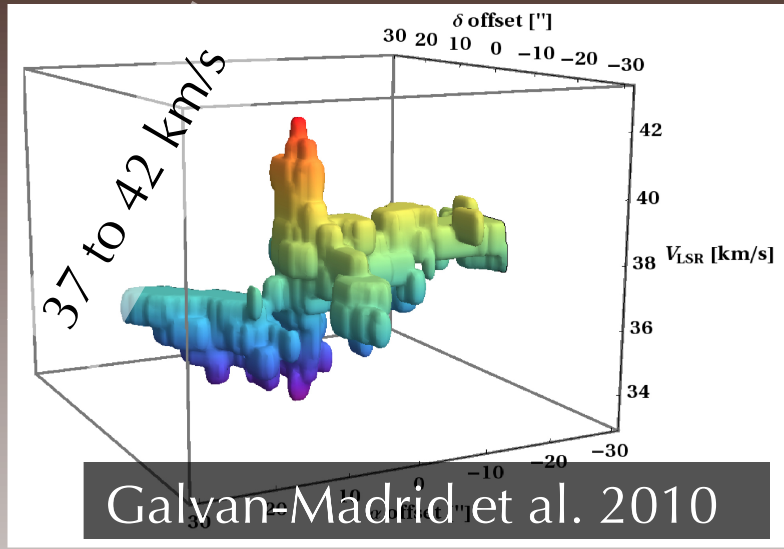
Consistent with shock tracers (Csengeri et al. 2011b; Jiménez-Serra et al. 2011; Nguyen Luong et al. 2013; Sanhueza et al. 2013; …)

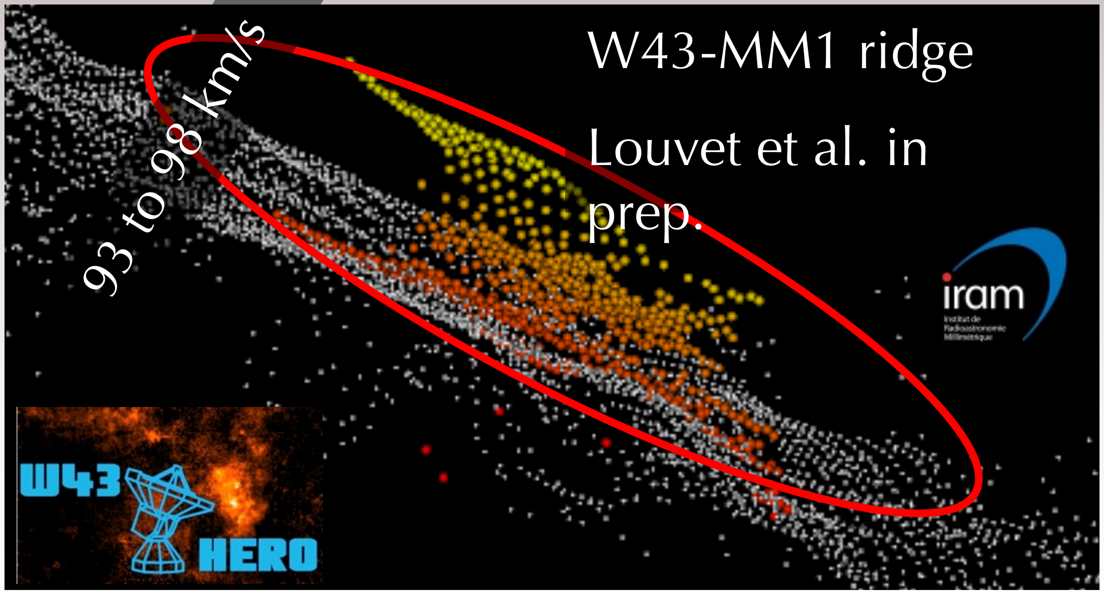
Ridges are bundles/braids of filaments/layers

Interferometric images in N_2H^+, NH_3 or $HN^{13}C$ display several pc filaments along ridges.

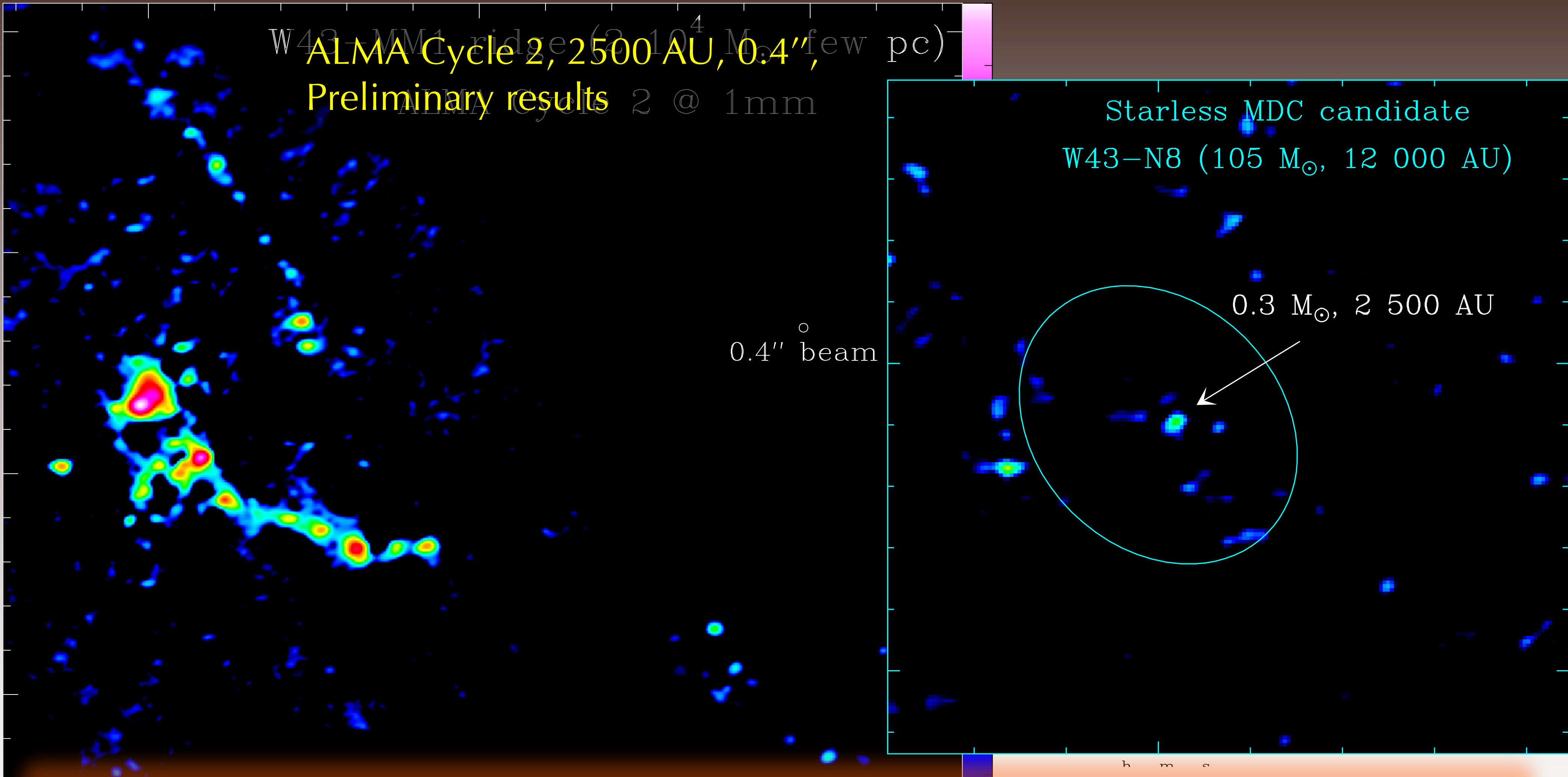


see also Tackenberg+ 2014





ALMA view of the W43-MM1 protocluster



- Protostellar MDCs split in a couple of high-mass cores.
- Starless MDCs mostly dissolve out and fragment into low-mass cores.