THE INITIAL CONDITIONS OF STELLAR CLUSTER FORMATION: GAS OBSERVATIONS

Sarah Ragan (Cardiff University)

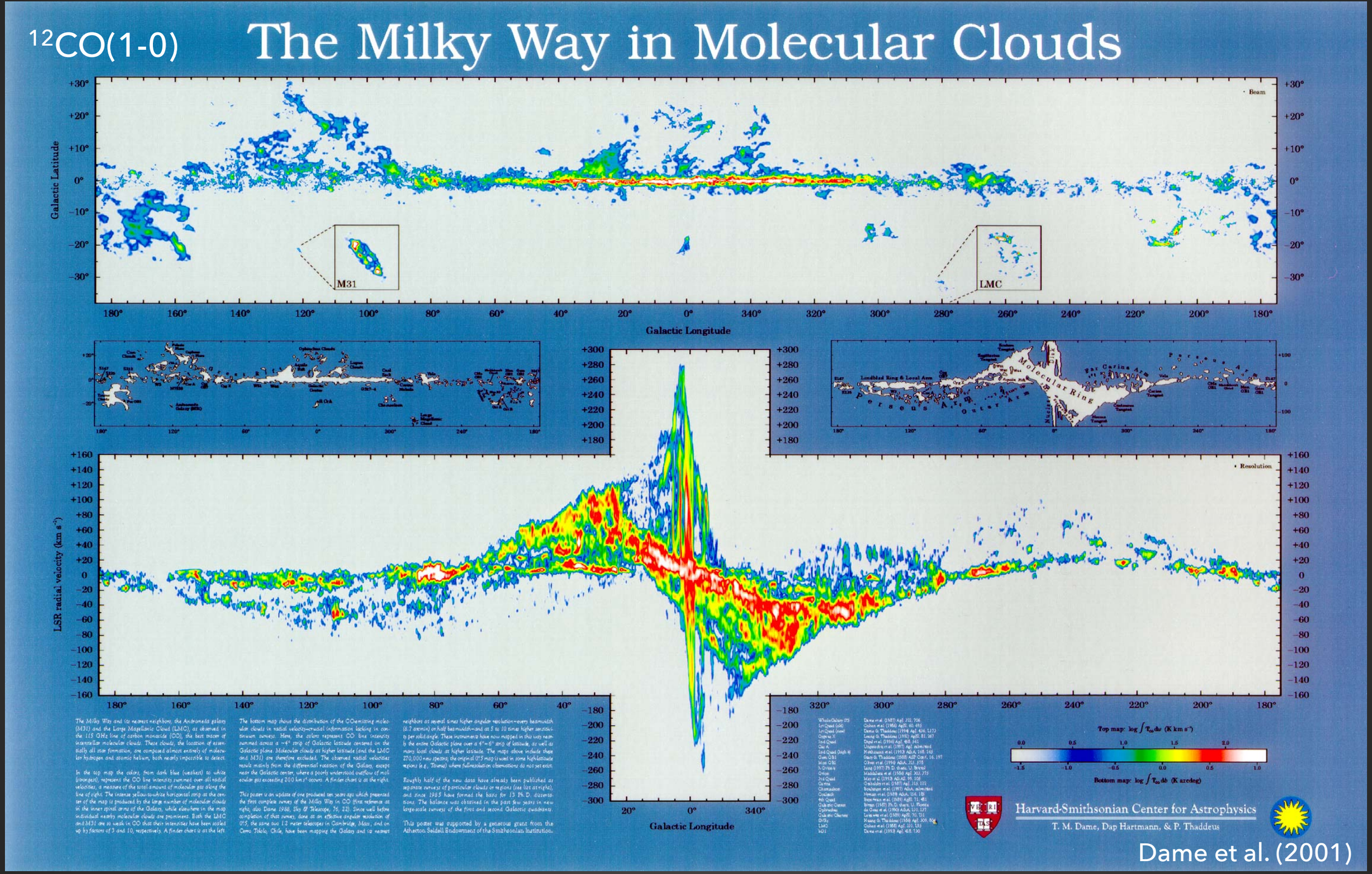
CARDIFF UNIVERSITY
PRIFYSGOL CAERDYDD
MARIE CURIE ACTIONS

THE INITIAL CONDITIONS OF STAR CLUSTER FORMATION

M51: Hubble + PdBI CO(1-0) emission (blue) PAWS: Schinnerer et al.

GALACTIC PLANE SURVEYS: HOW WE FIND THE INTERESTING BITS OF ISM

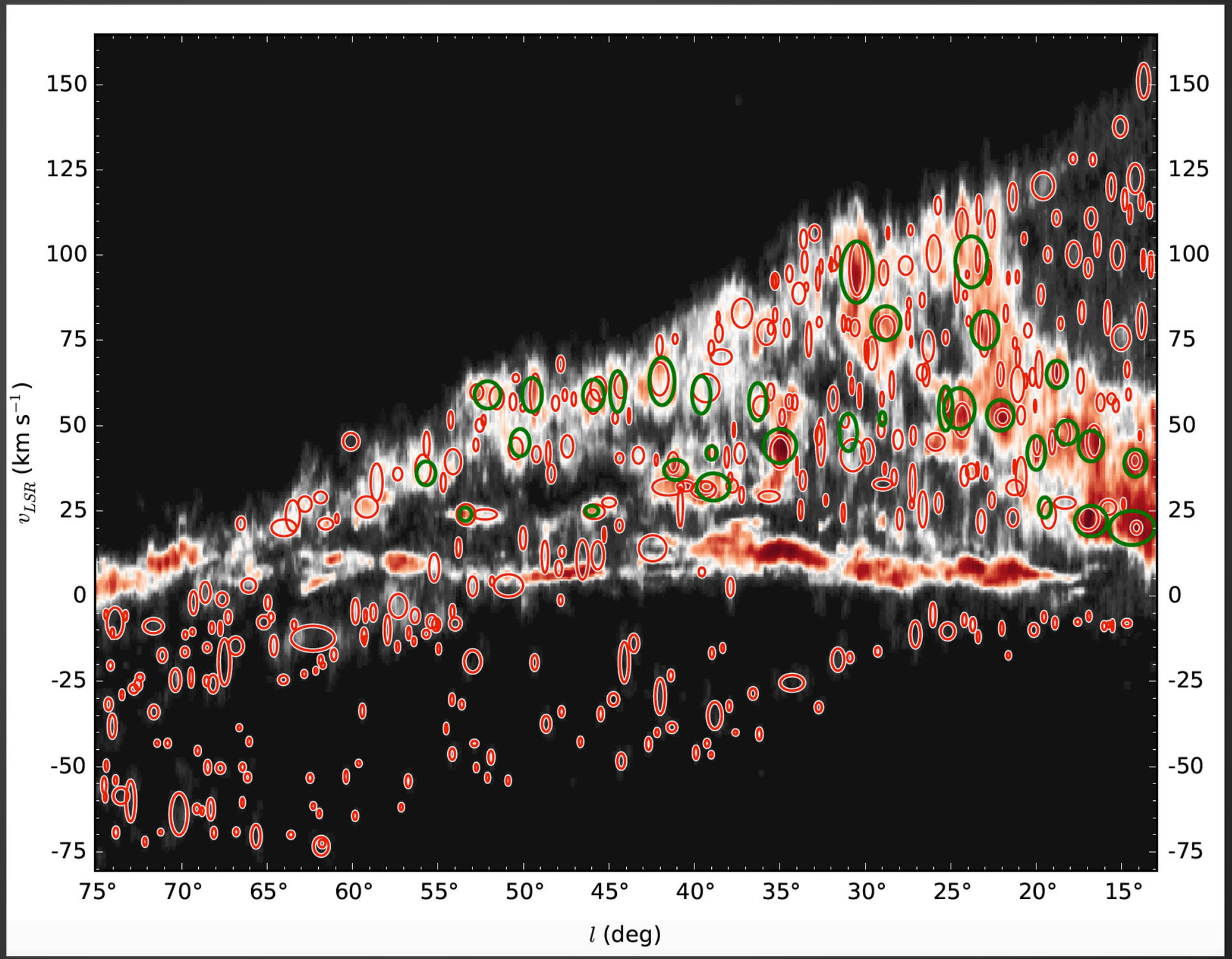
^{12}CO(1-0)



Dame et al. (2001)

CHIMPS ^{13}CO(3-2), C^{18}O(3-2): Rigby et al (2016); COHRS ^{12}CO(3-2): Dempsey et al. (2013);
GRS (^{13}CO(1-0); Jackson et al. (2006)

MOLECULAR CLOUDS



Rice et al. (2016)

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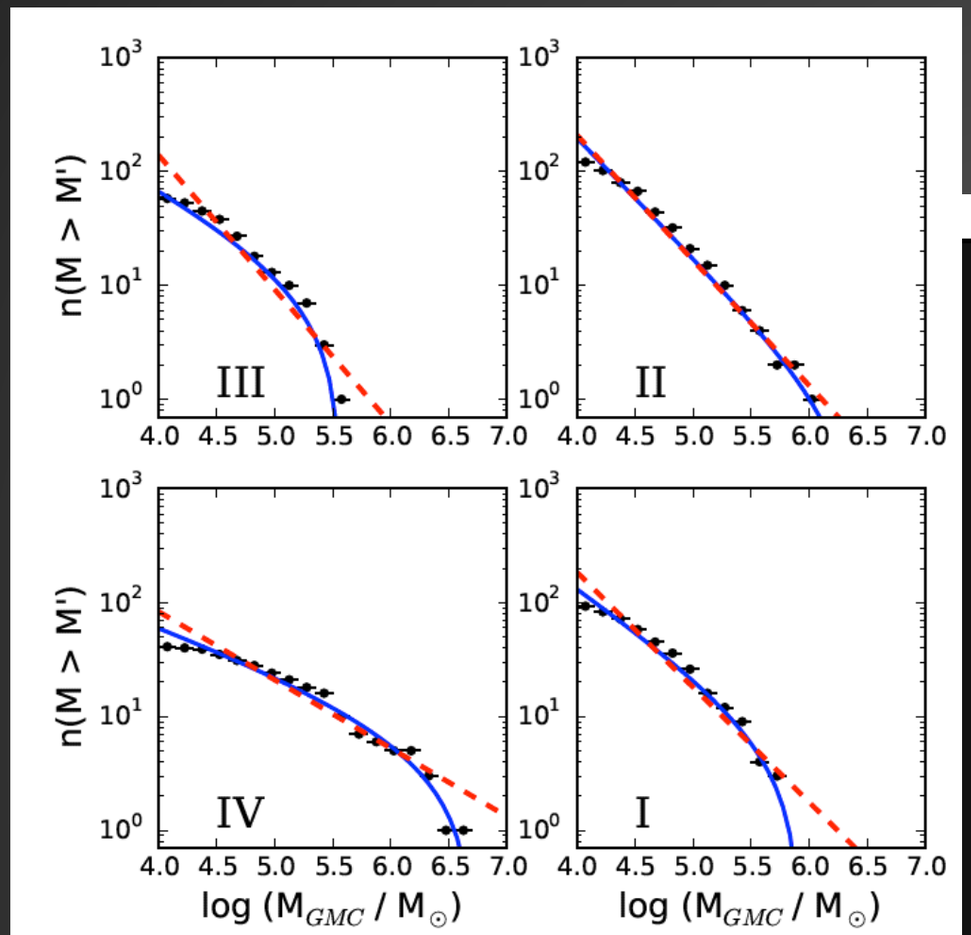
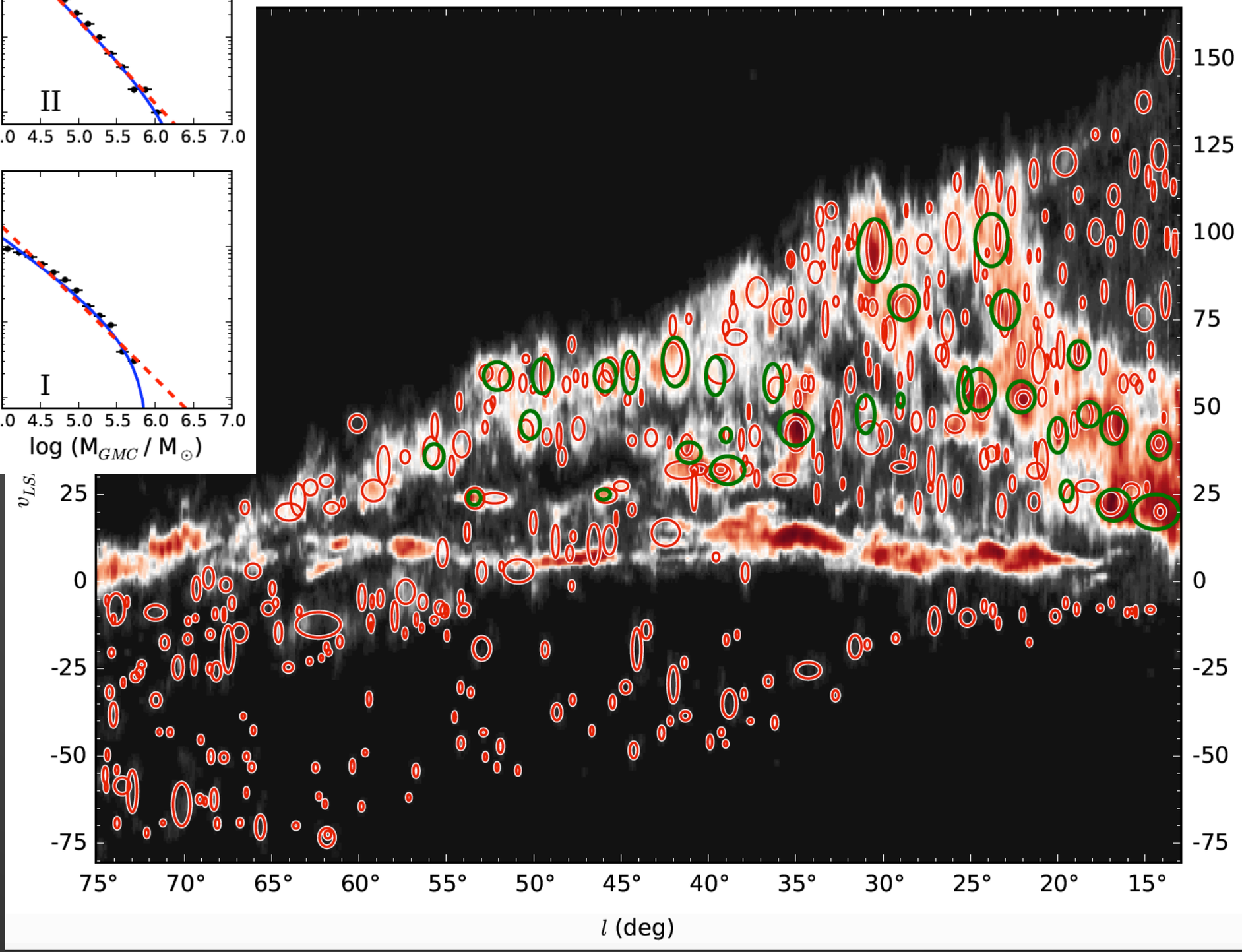


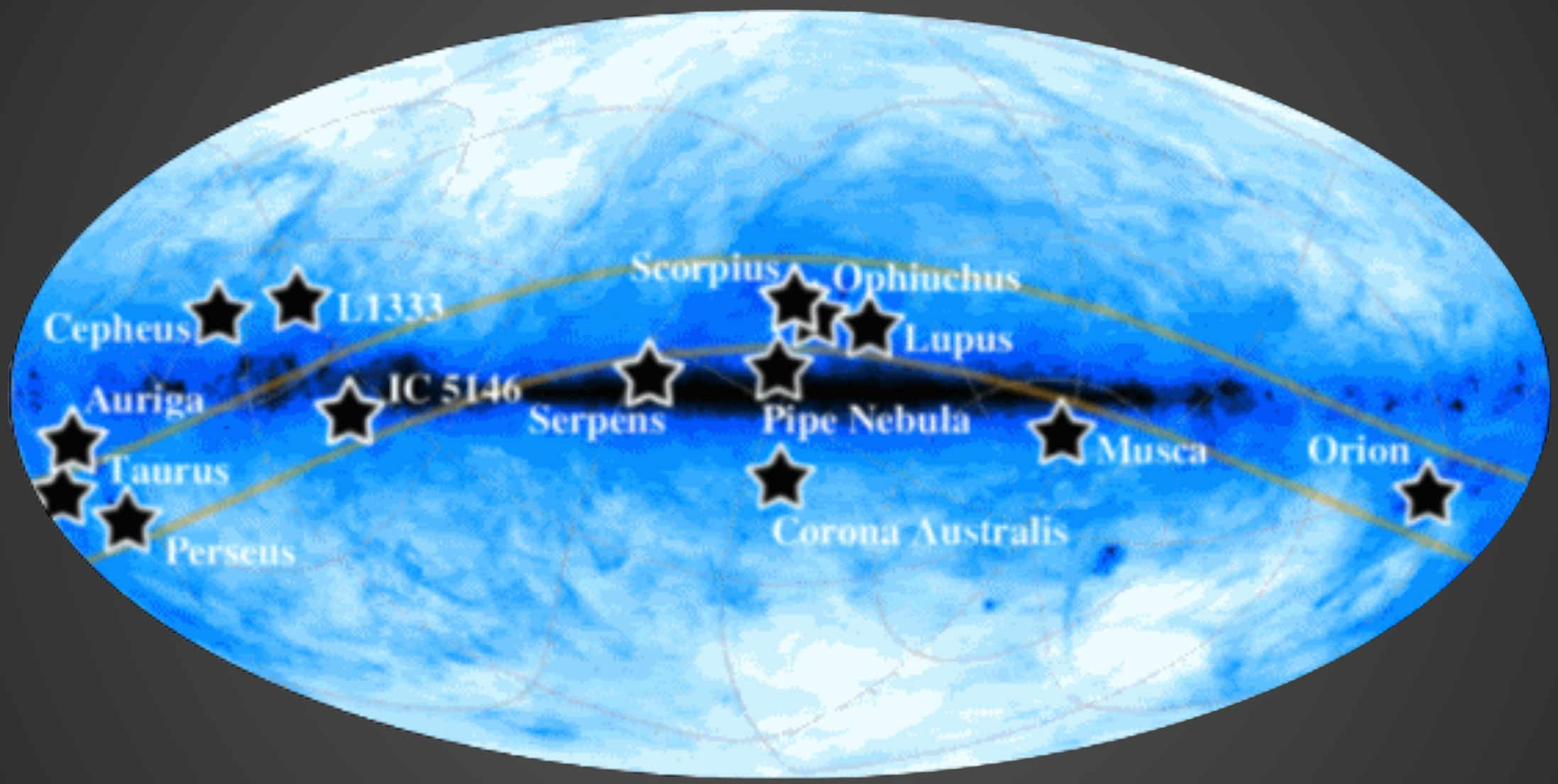


Rice et al. (2016)

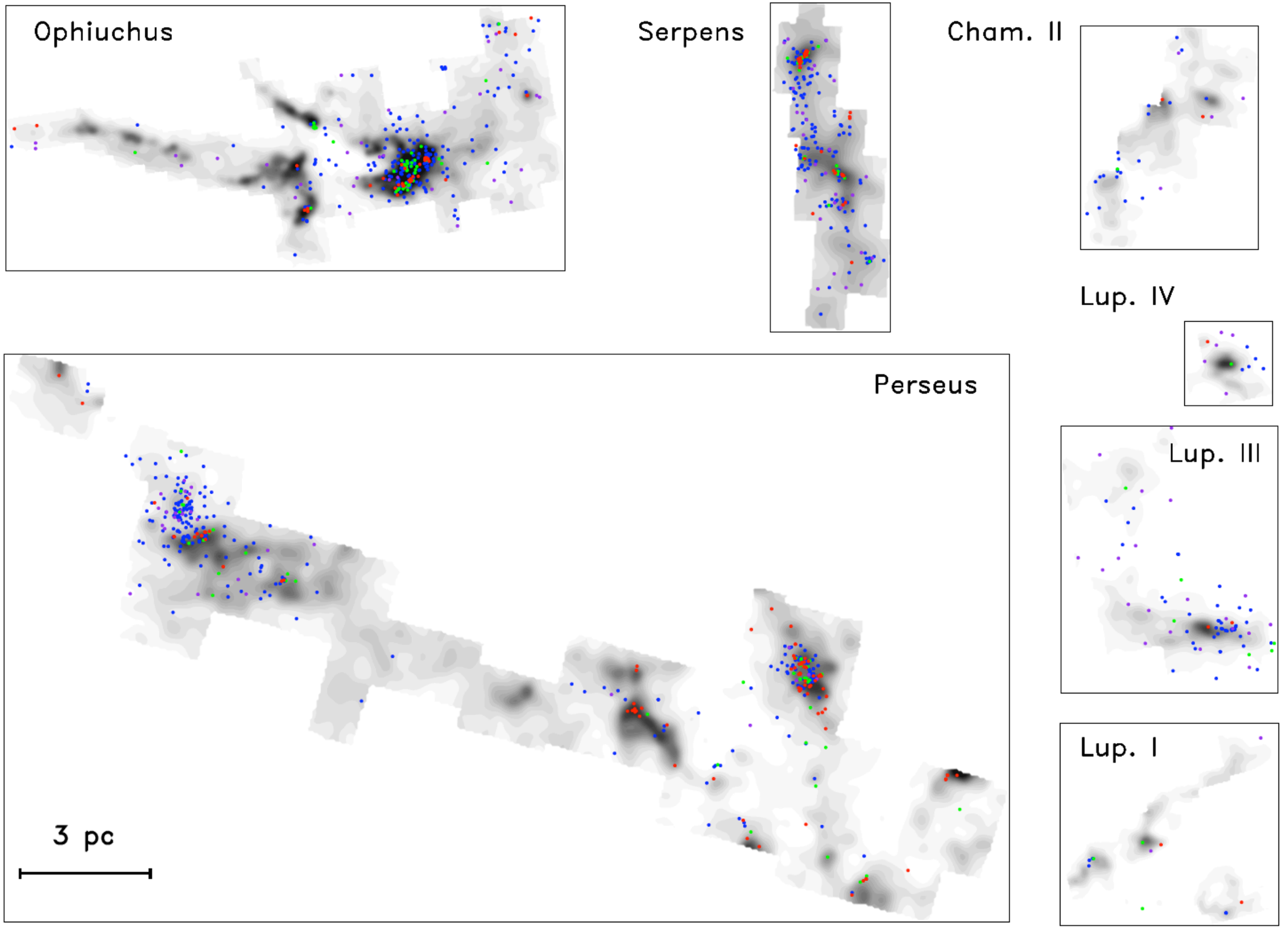
	Clouds[a]	Clumps[b]	Cores[c]
Mass ($M_\odot$)	$10^3 - 10^4$	50–500	0.5–5
Size (pc)	2–15	0.3–3	0.03–0.2
Mean density (cm^{-3})	50–500	10^3–10^4	10^4–10^5
Velocity extent (km s^{-1})	2–5	0.3–3	0.1–0.3
Crossing time (Myr)	2–4	≈1	0.5–1
Gas temperature (K)	≈10	10–20	8–12

Bergin & Tafalla (2007)

MOLECULAR CLOUDS: GOULD BELT

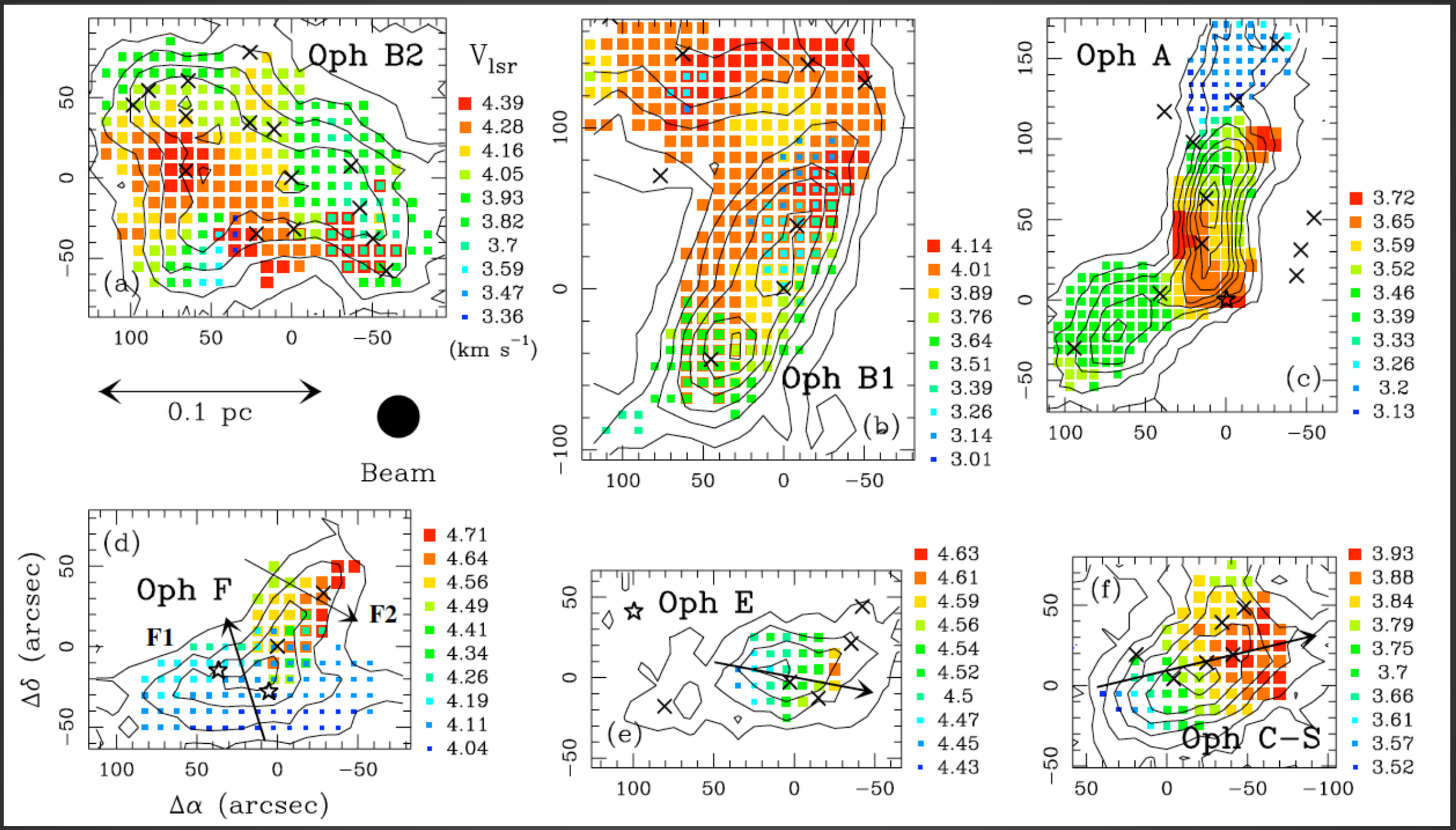


LOCAL MOLECULAR CLOUDS



Spitzer c2d programme: Evans et al. (2009)

DYNAMICS OF LOCAL MOLECULAR CLOUDS

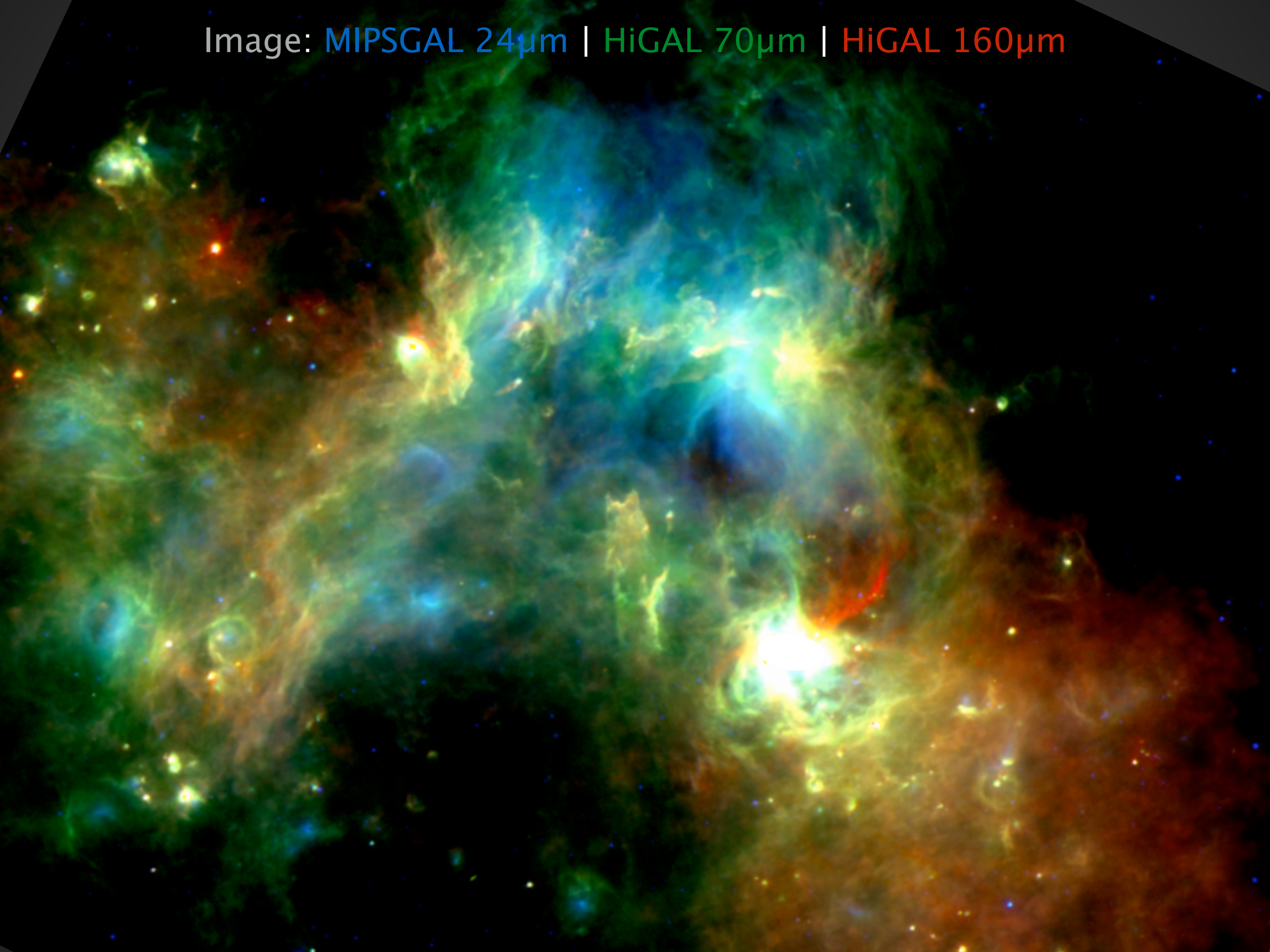


sub-/tran-sonic internal turbulence ⇨ cores are bound and pre-stellar (lifetime: 2-5 x 10^4 yr)

coherent v_{cent} between condensations ⇨ interactions unlikely

André et al. (2007)

Image: MIPSGAL 24μm | HiGAL 70μm | HiGAL 160μm



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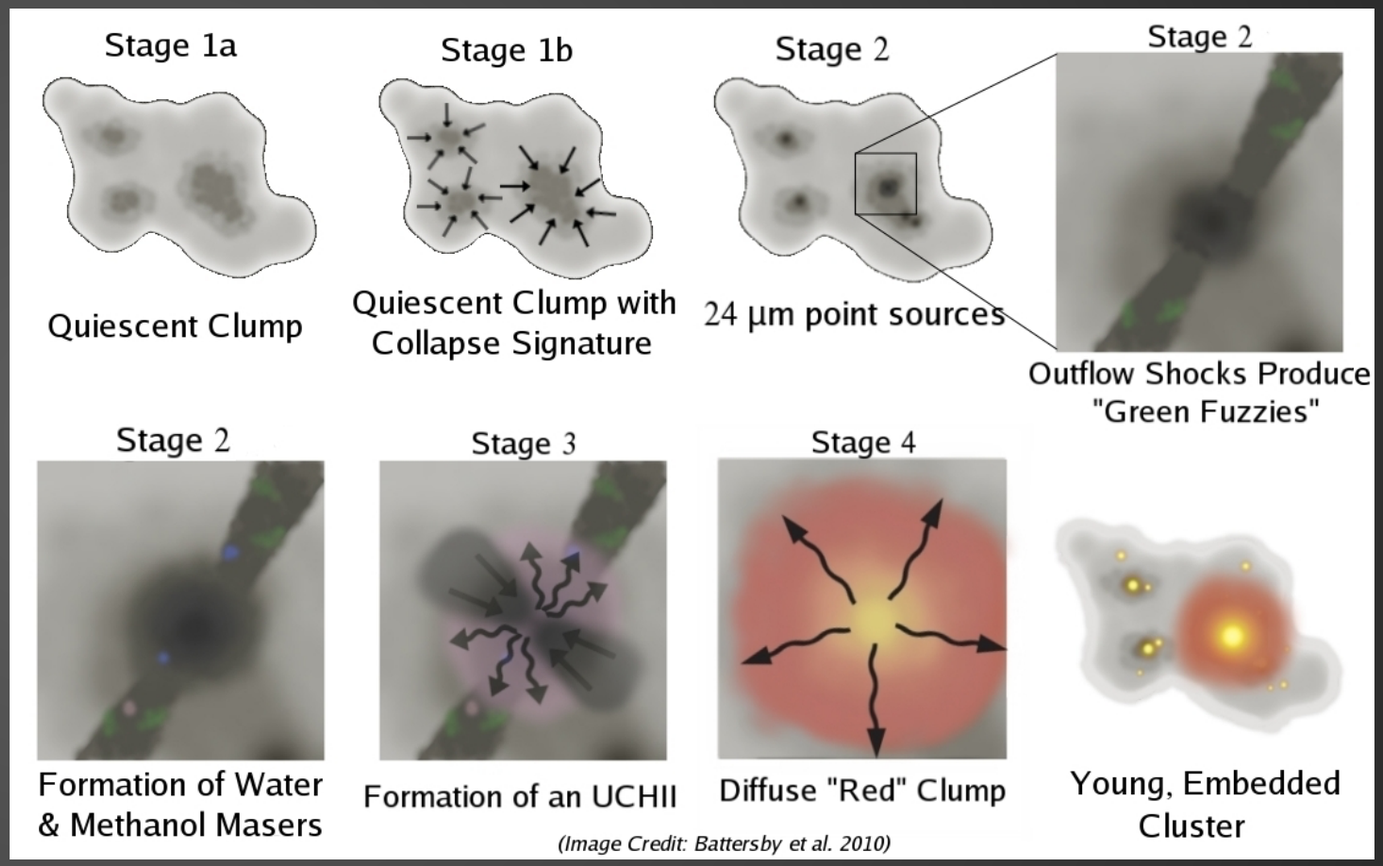
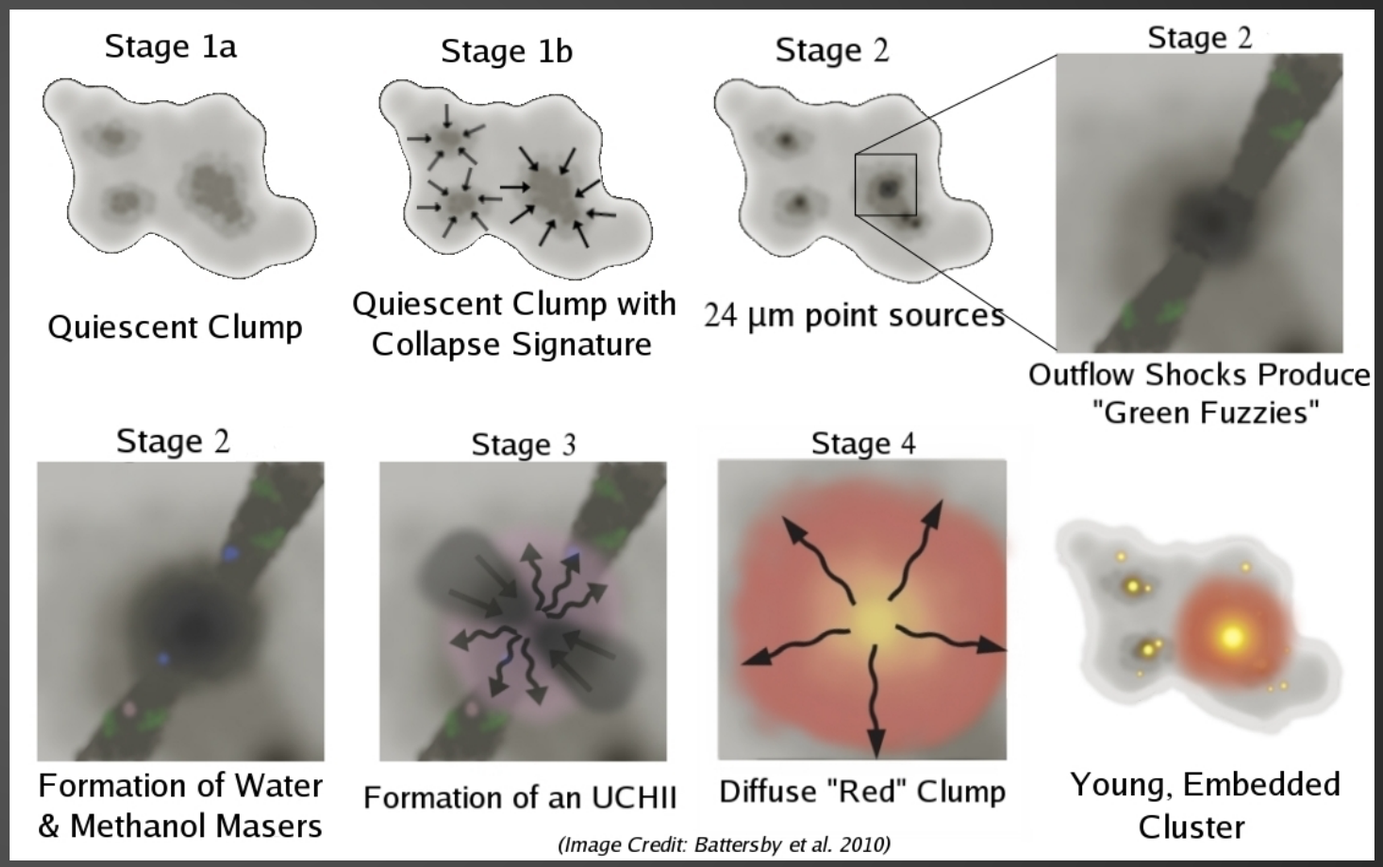


(Image Credit: Battersby et al. 2010)

- Infrared-dark “clouds” (IRDCs) represent earliest phase of cluster formation

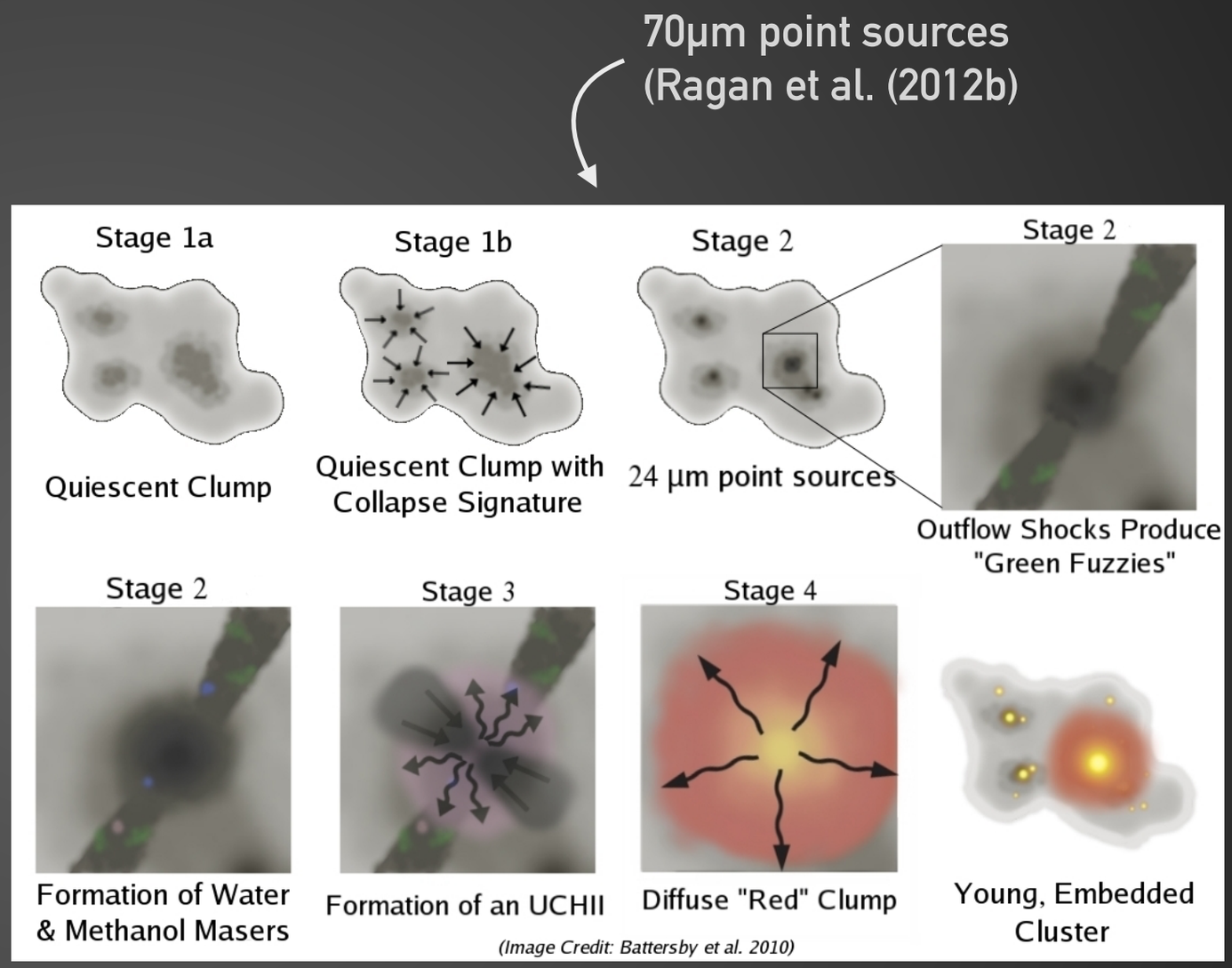
70μm point sources (Ragan et al. (2012b)



(Image Credit: Battersby et al. 2010)

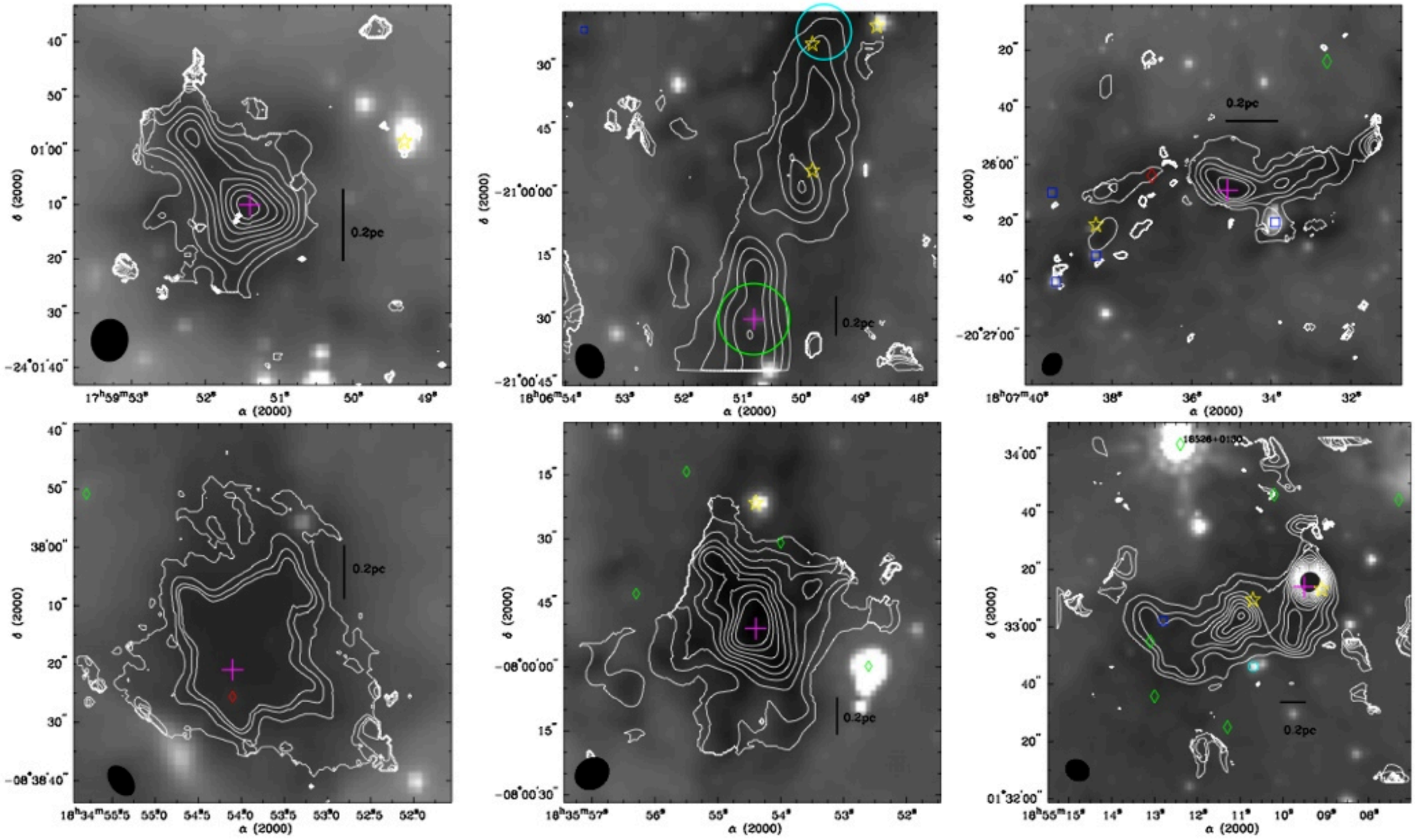
- Infrared-dark “clouds” (IRDCs) represent earliest phase of cluster formation

- Gas observations helps us determine:
  - Physical properties
  - Gravitational stability
  - Gas flows (infall / outflow)



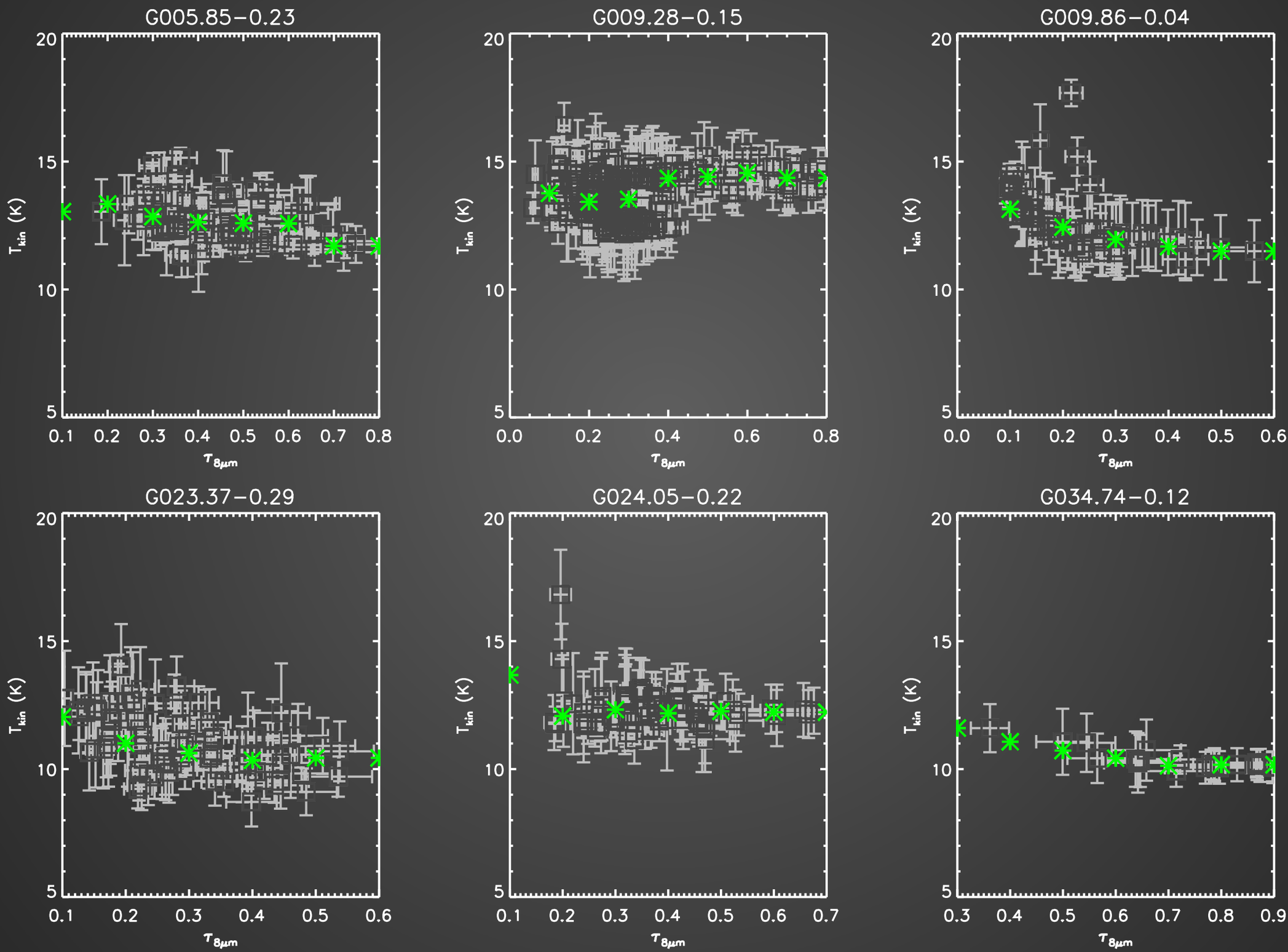
Ragan et al. (2006, 2009, 2011, 2012a, 2012b, 2013, 2015)

THE ASTROPHYSICAL JOURNAL, 736:163 (10pp), 2011 August 1



Ragan et al. (2011, 2012a)

CLOUD ⇨ CLUMP ⇨ CORE



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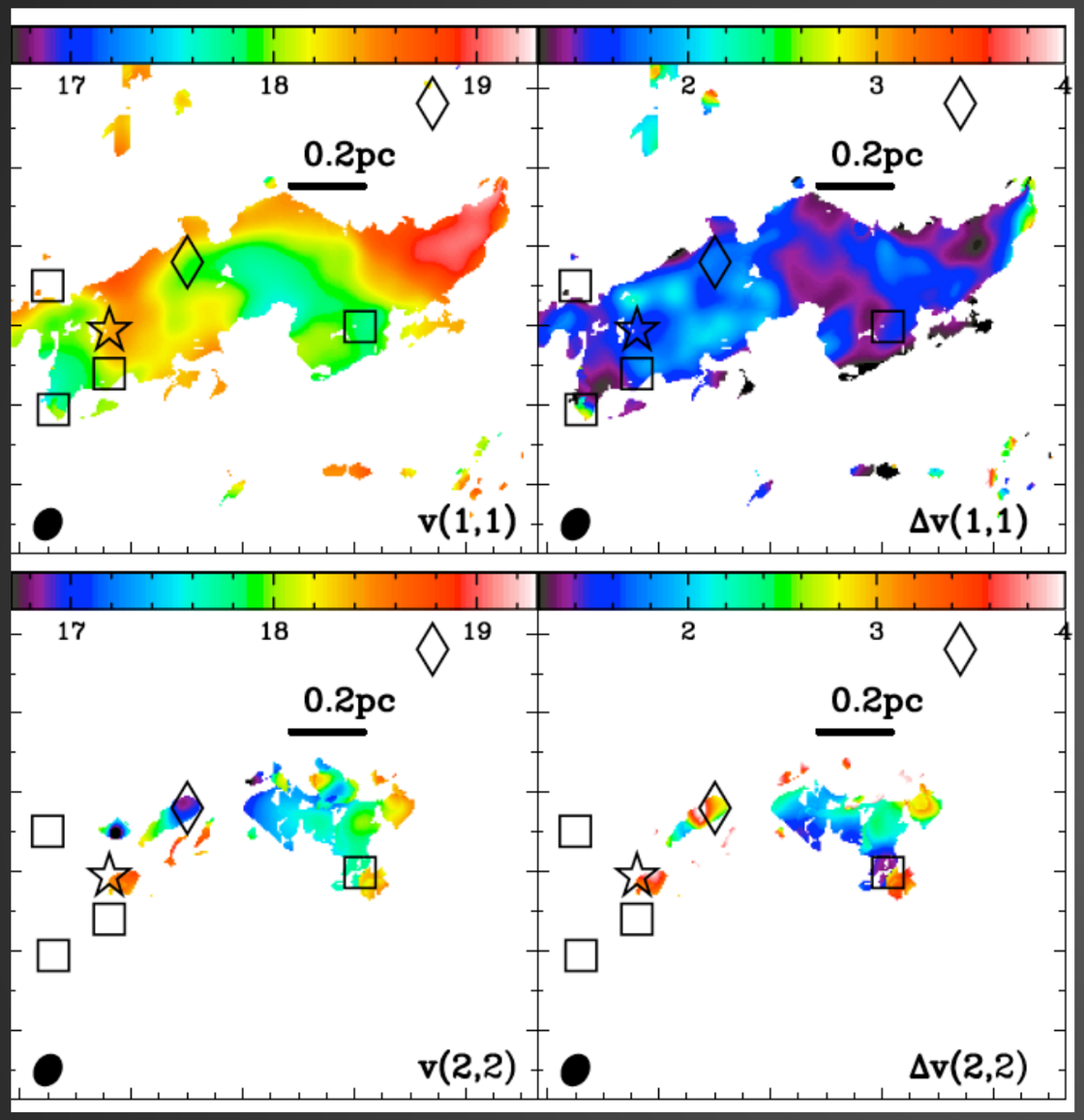
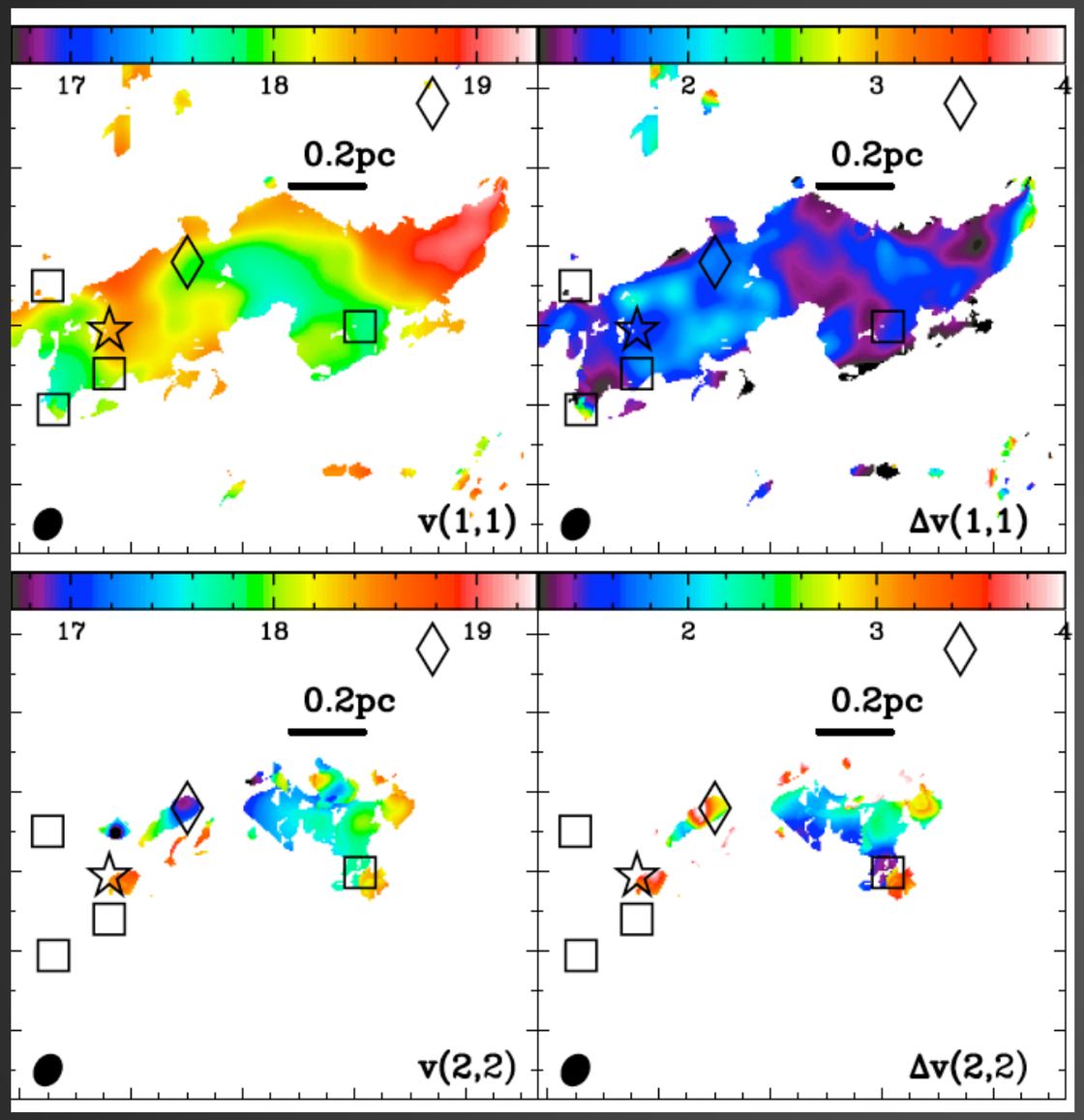


Ragan et al. (2012a)

see Ballesteros-Paredes (2006)



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$$M_{\rm vir} \propto R\sigma^2 \sim 10^2 - 10^3 M_\odot$$

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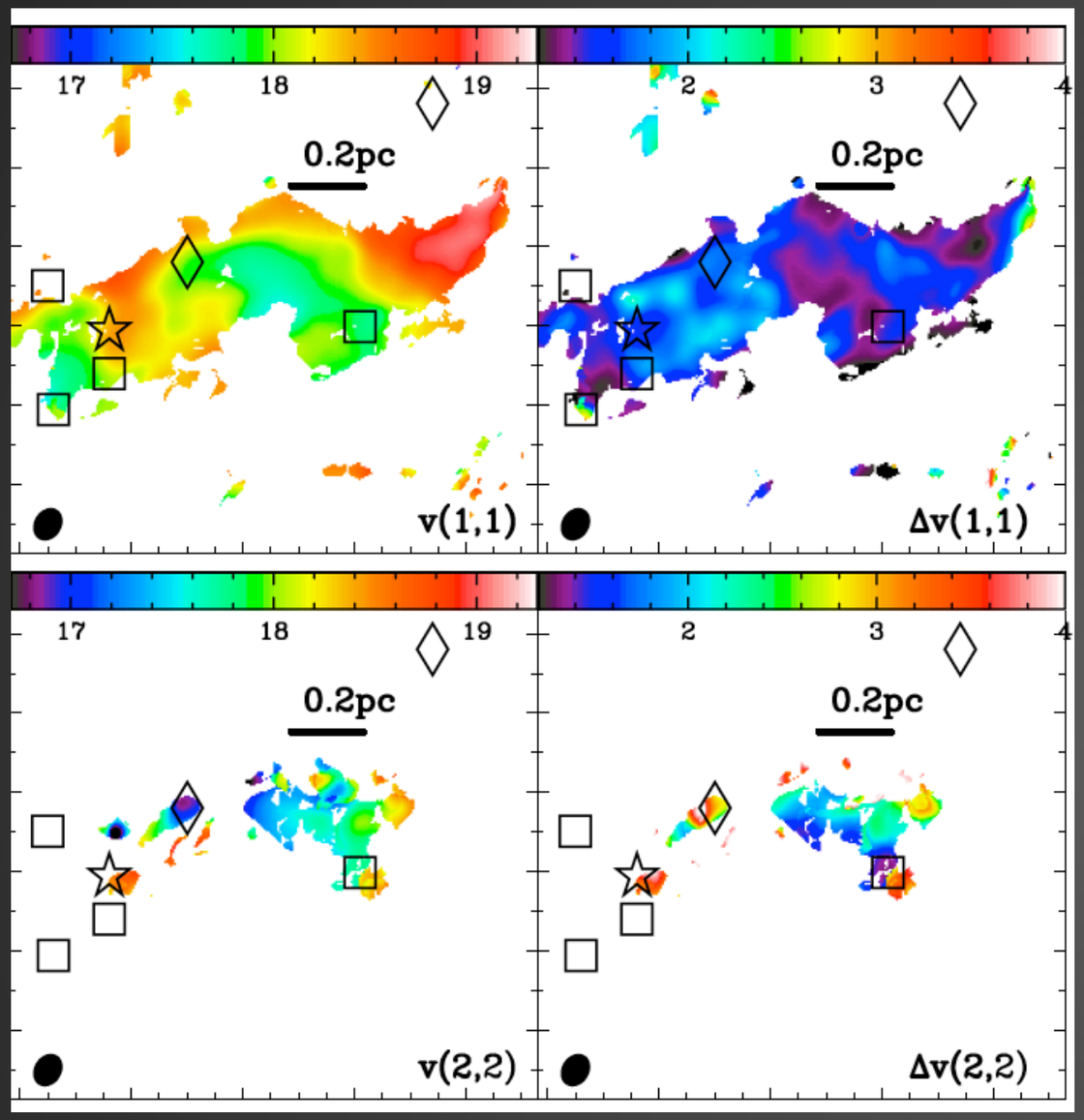

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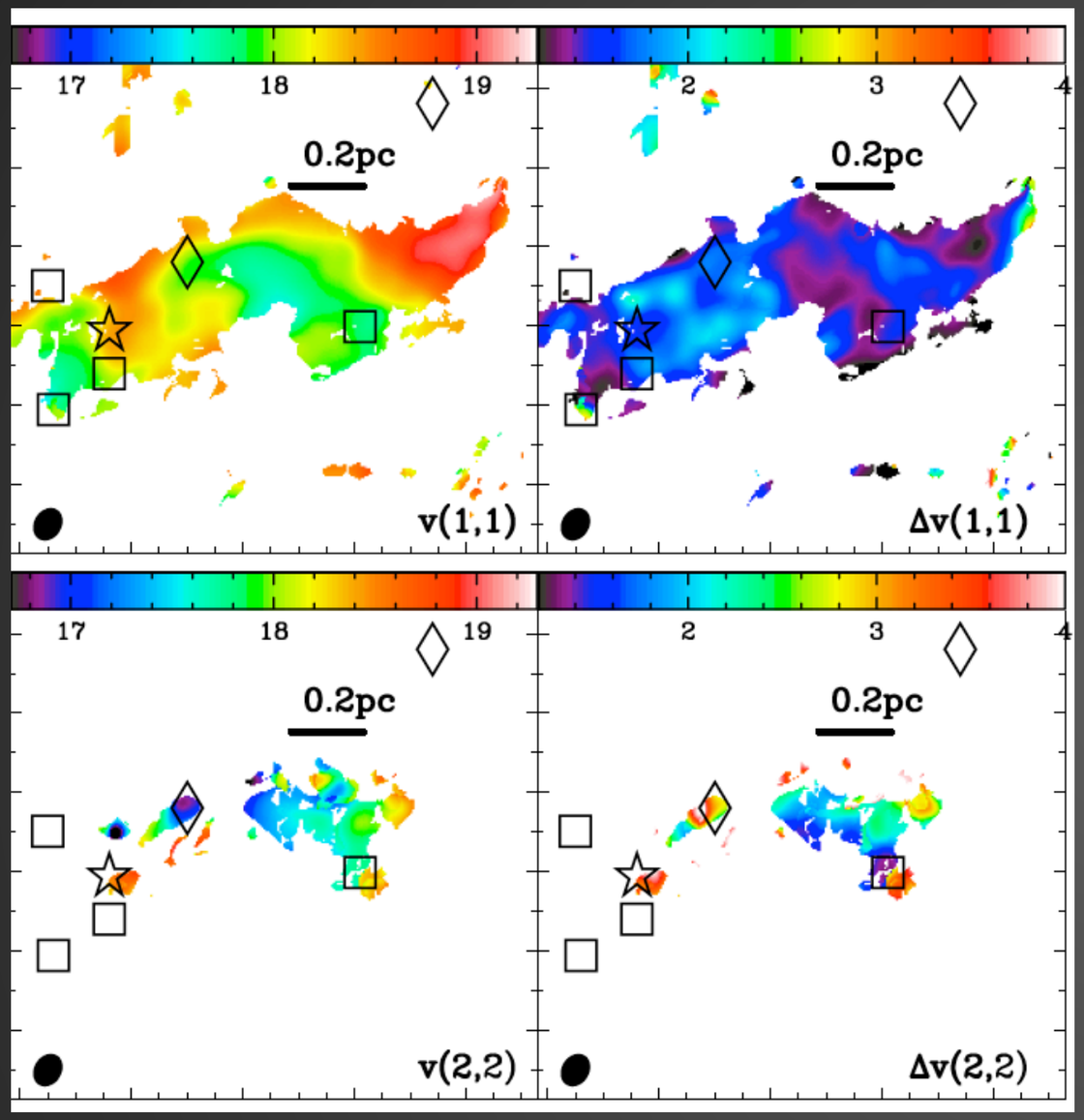

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IRDCs are unstable to gravitational collapse.

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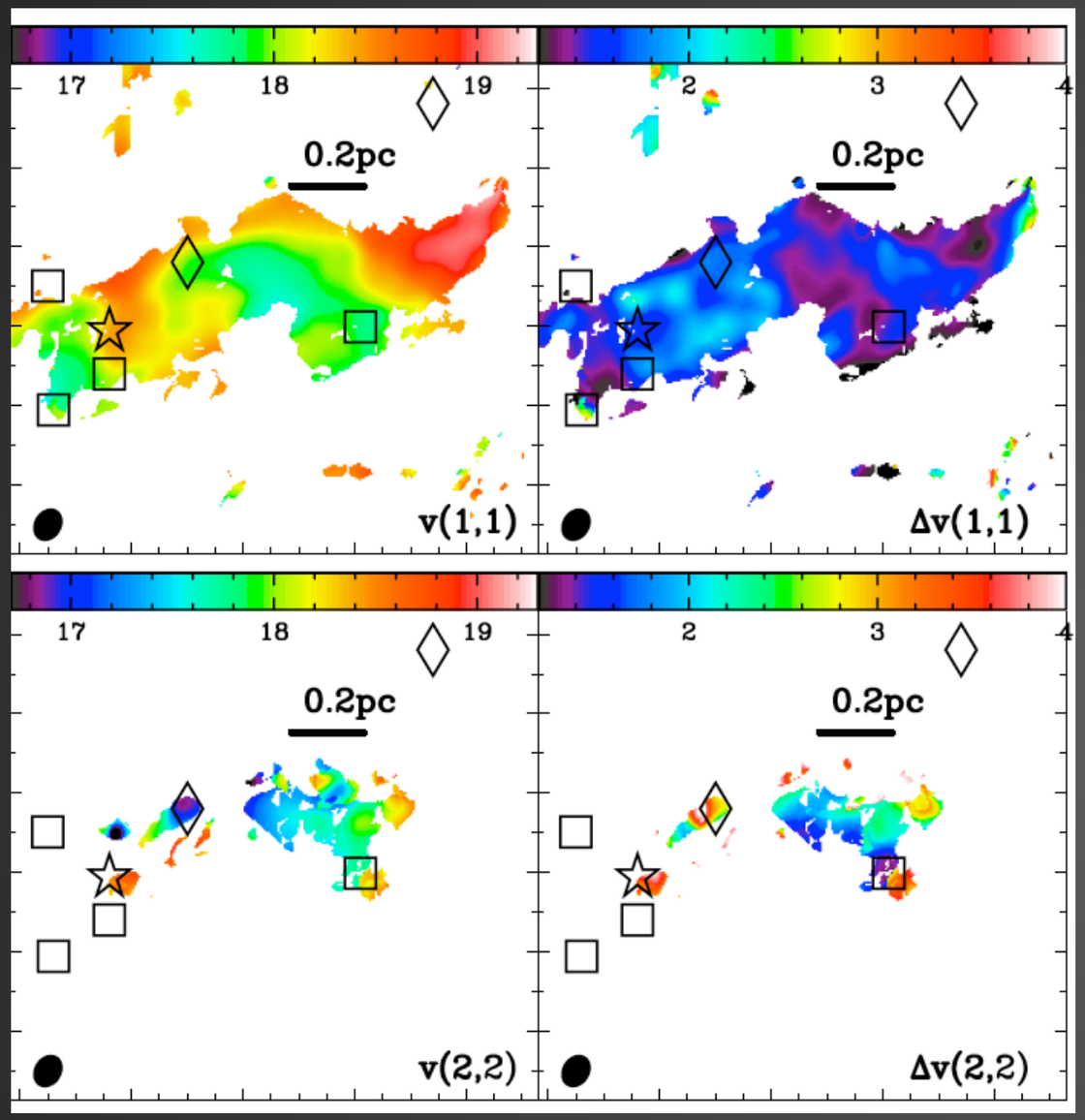

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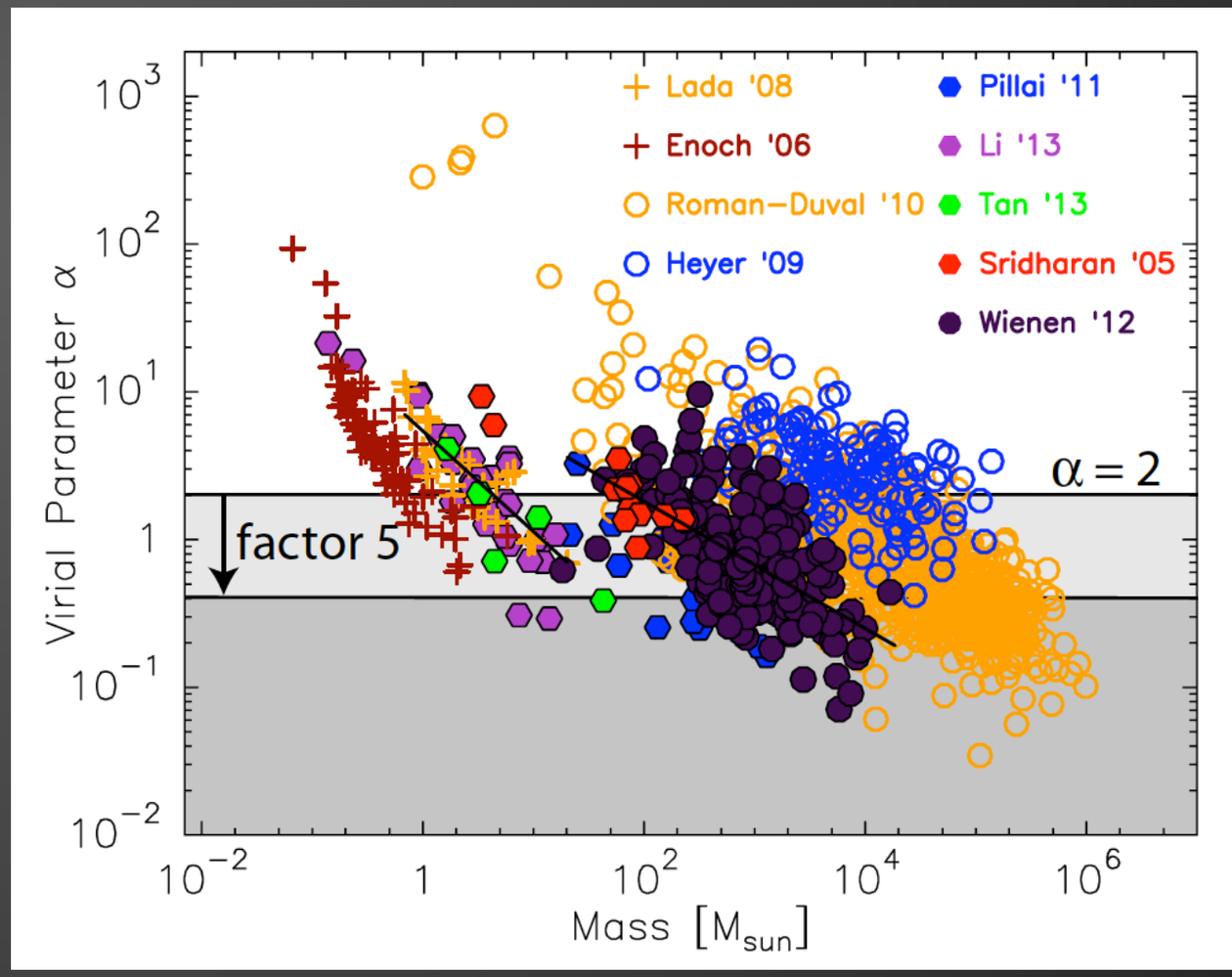
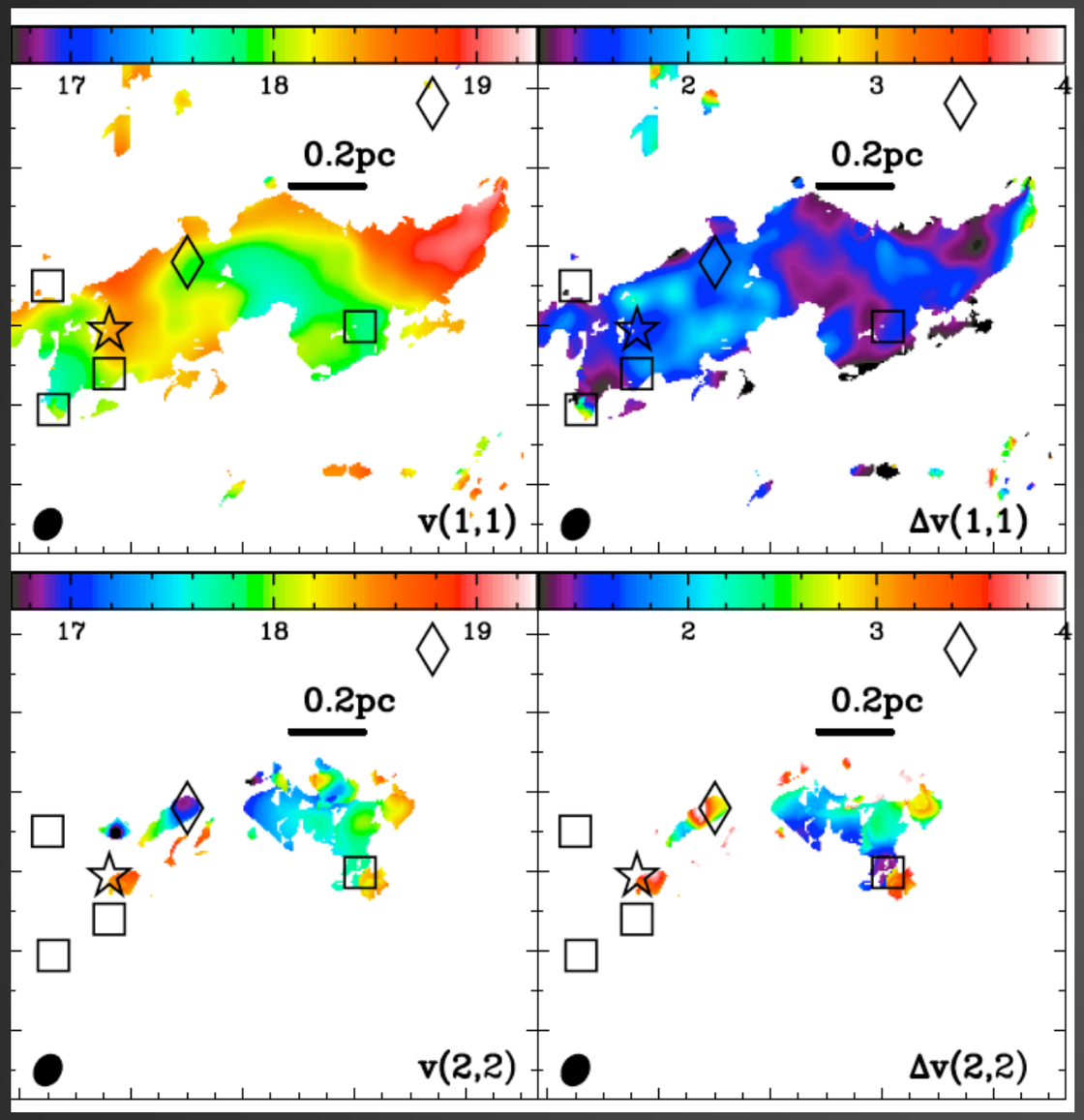


Kauffmann et al. (2013)

see Ballesteros-Paredes (2006)



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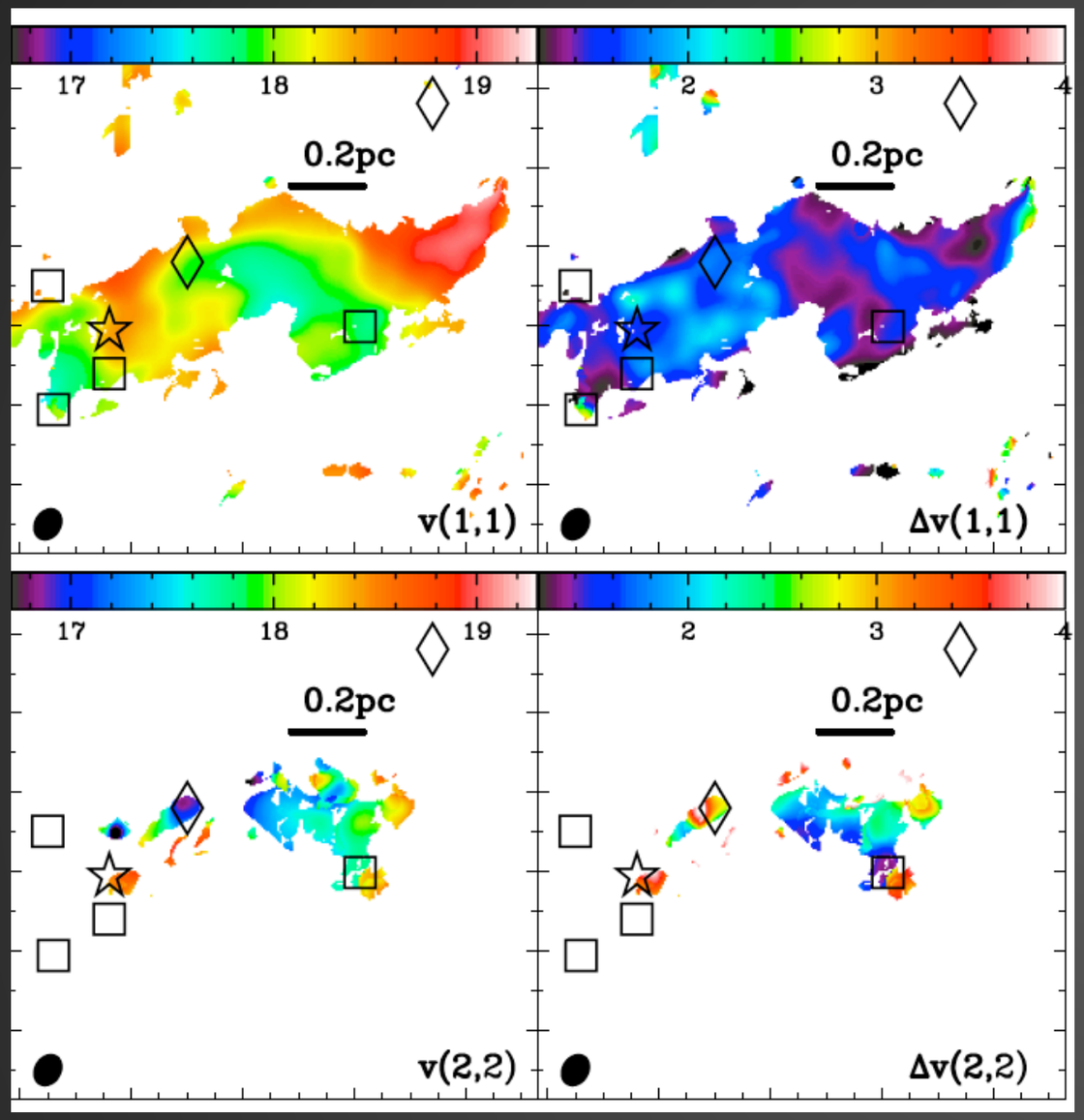
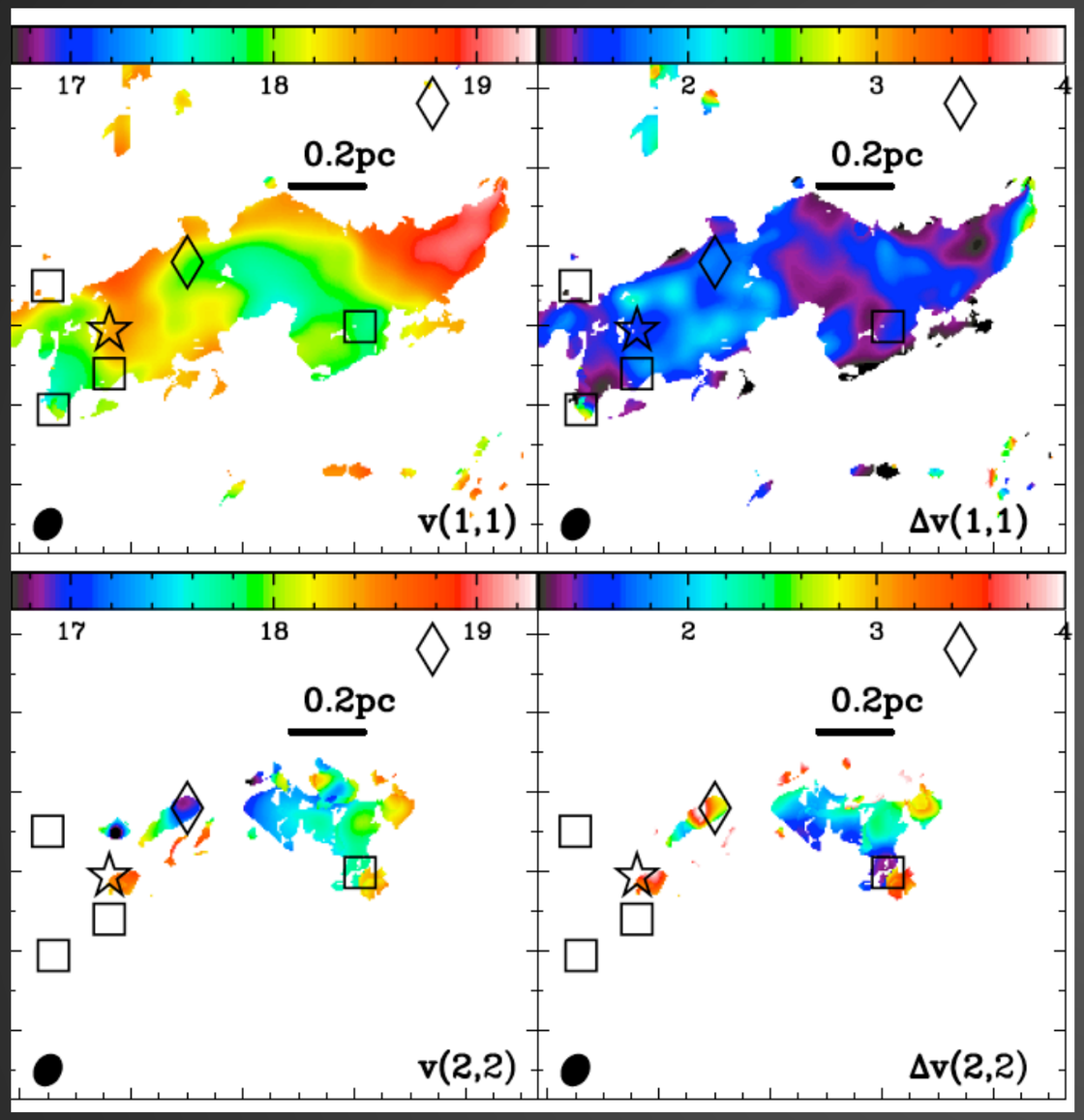


Ragan et al. (2012a)

Ratio of thermal to non-thermal pressure:

$$R_p = c_s^2/\sigma_{\rm NT}^2 \sim 0.05 - 0.1$$



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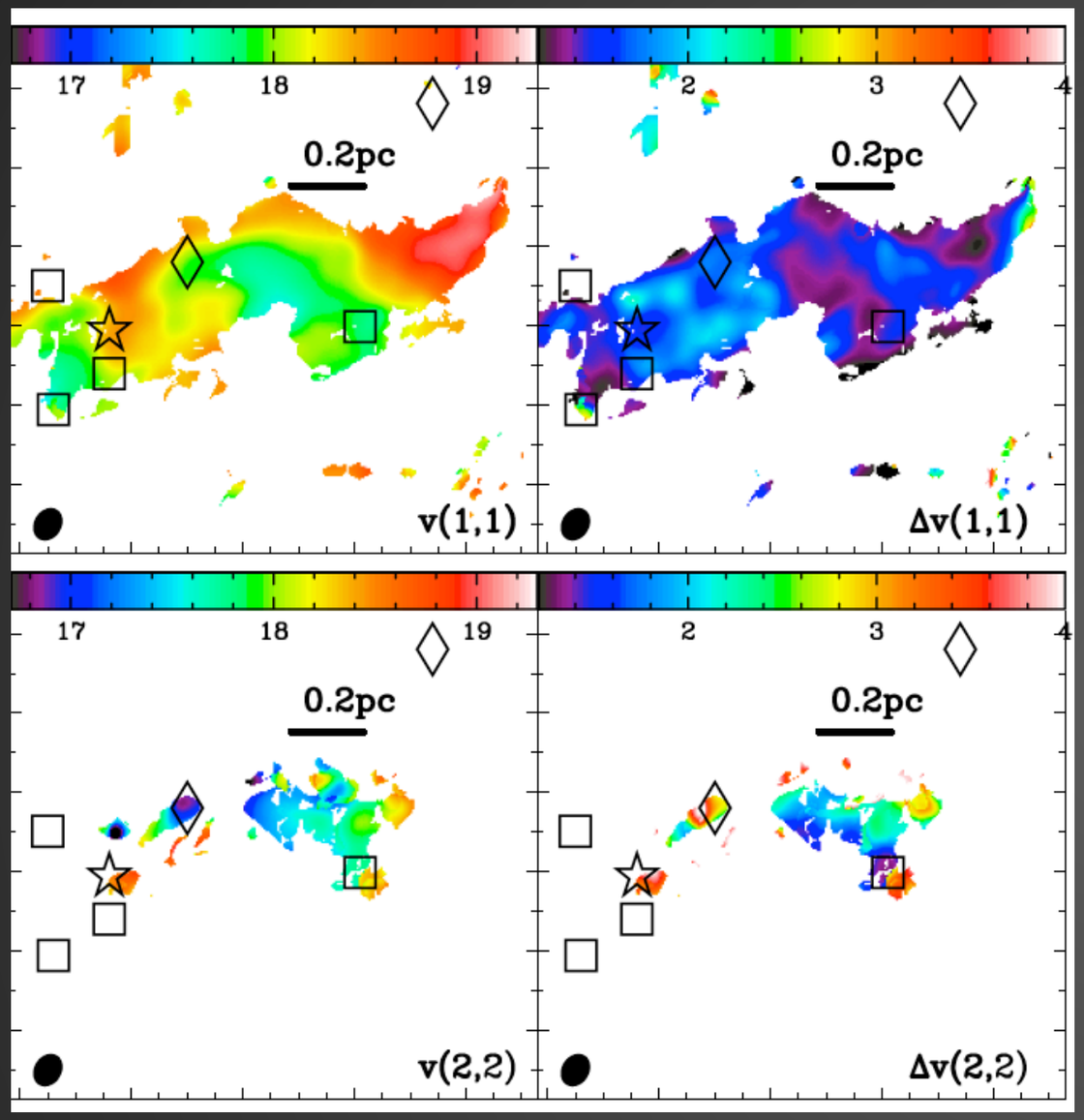

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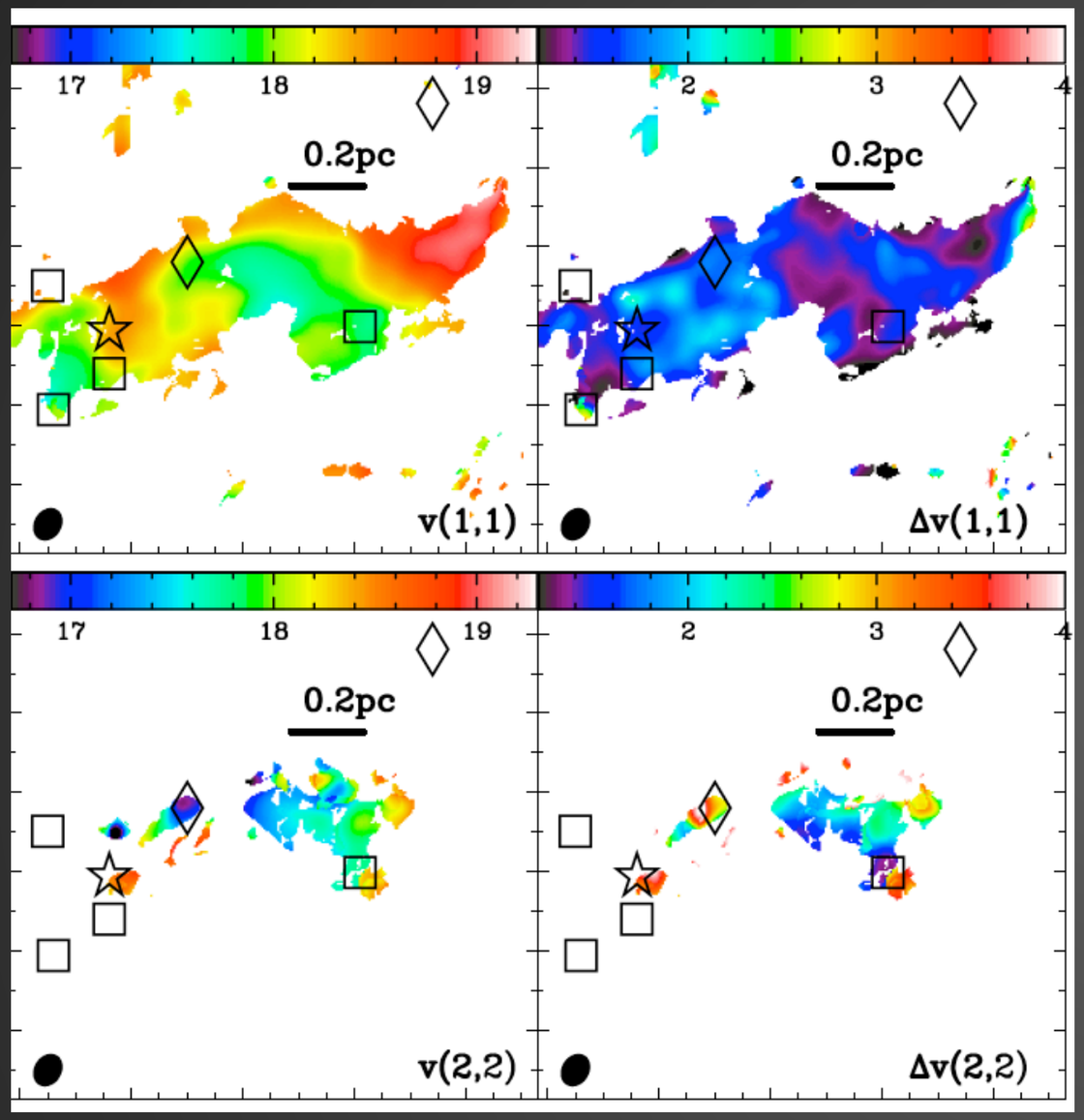

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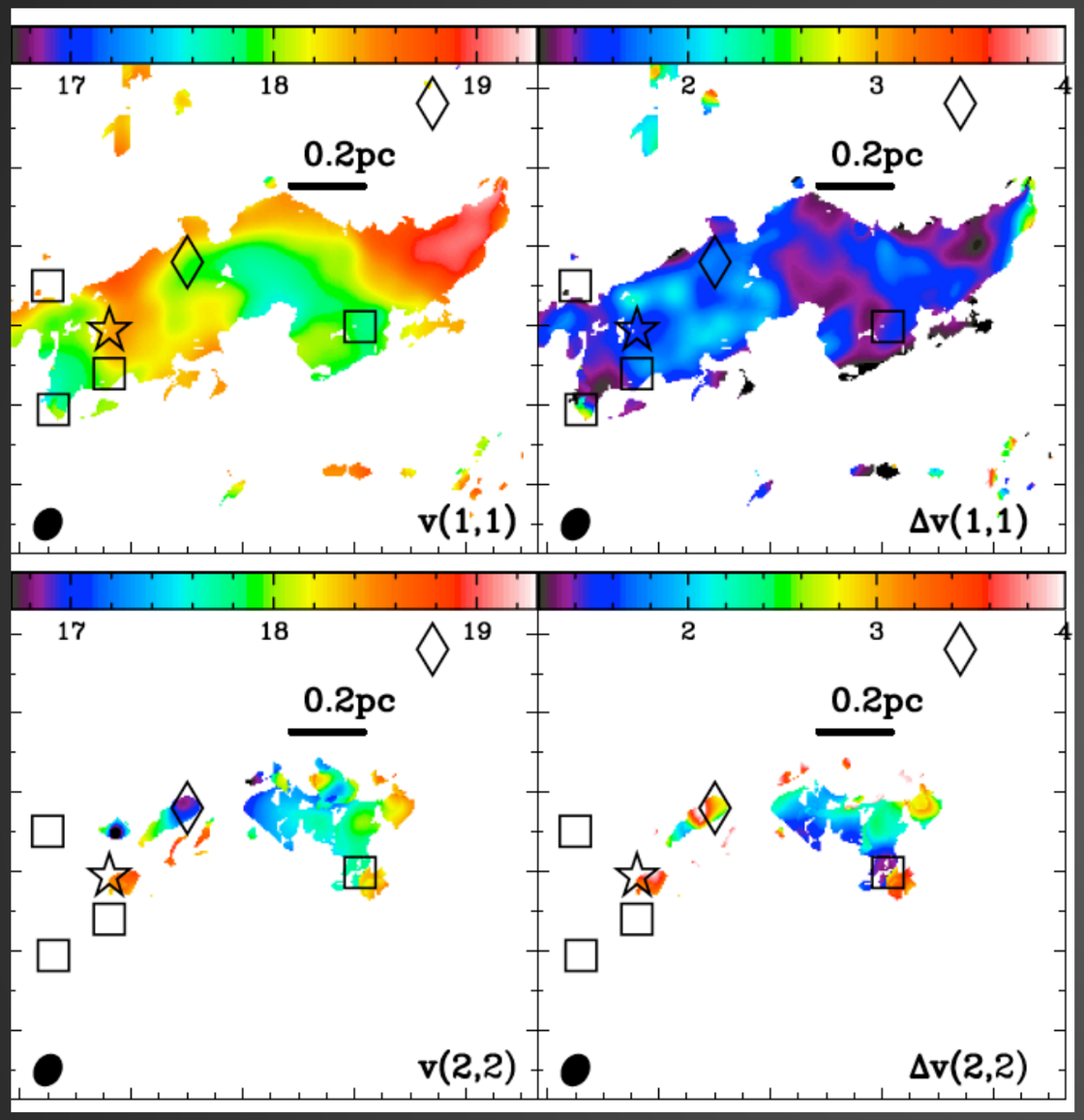

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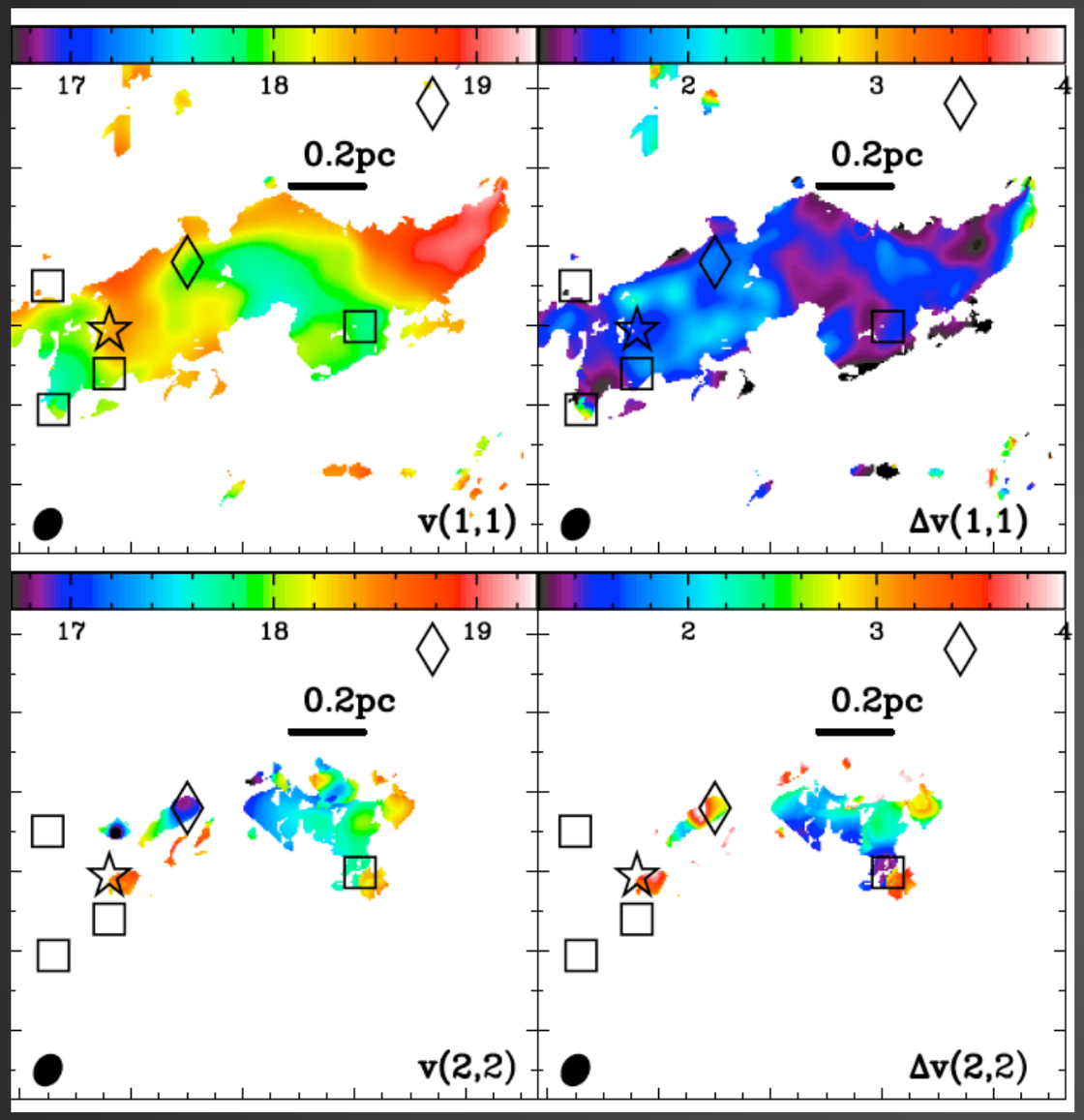

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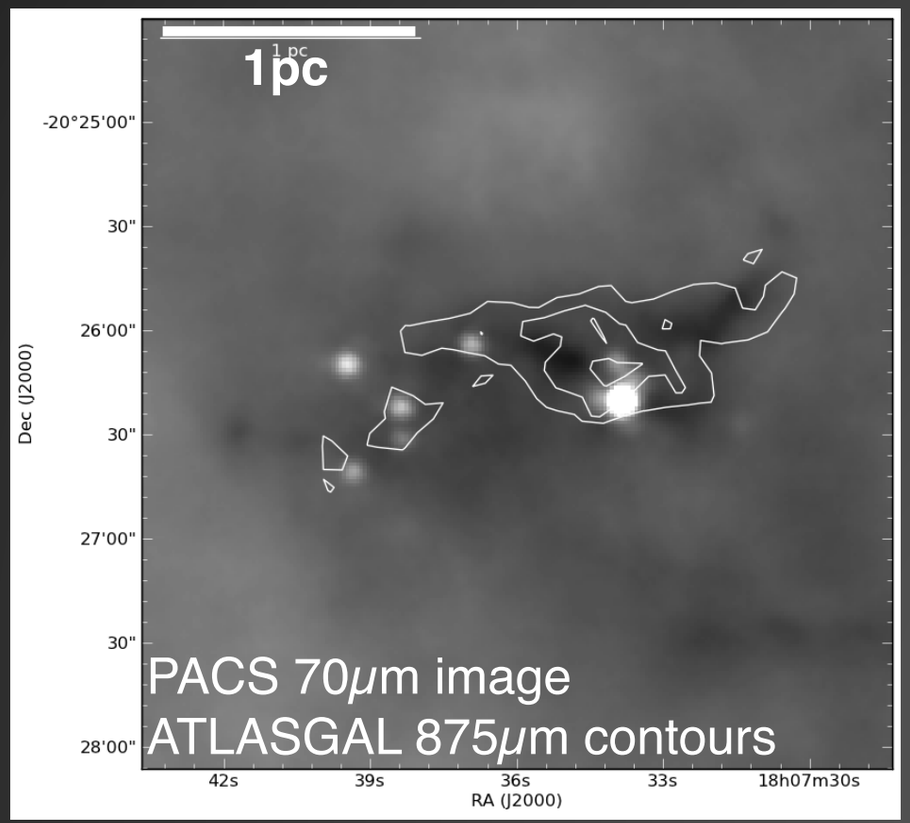
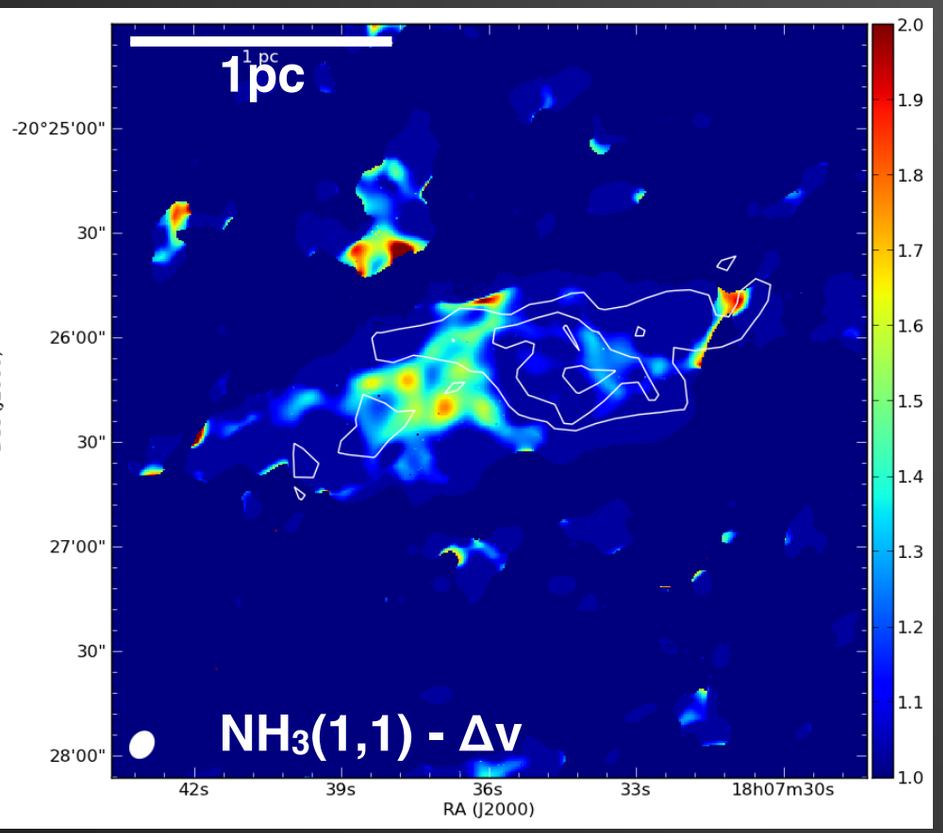
“Micro-turbulence”

CLOUD ⇨ CLUMP ⇨ CORE





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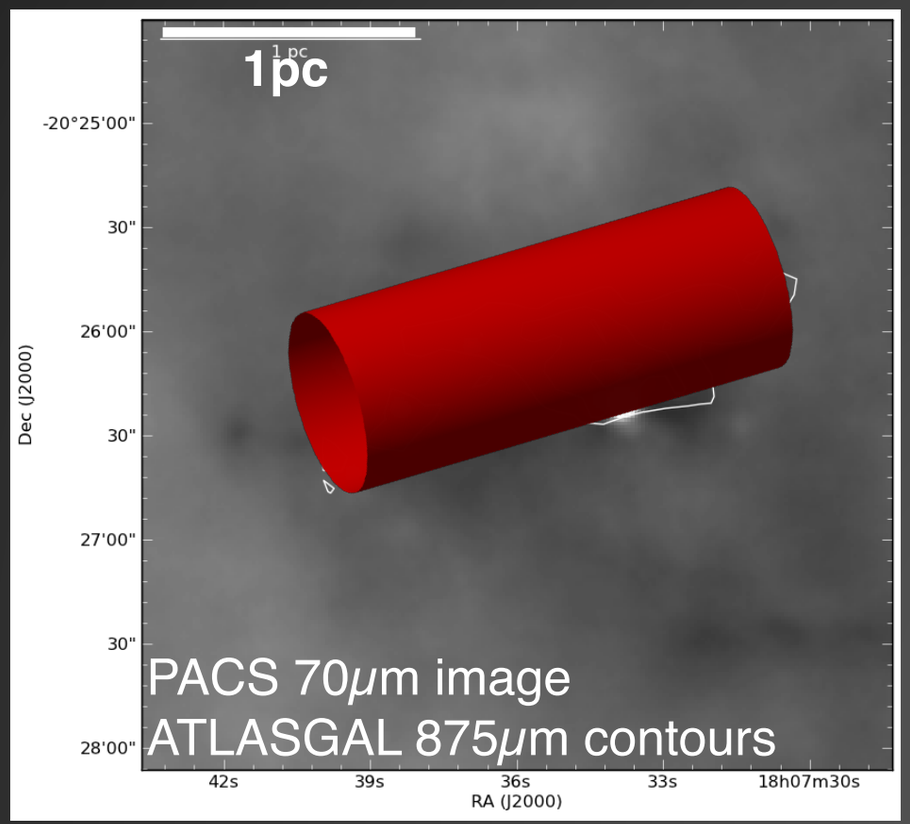

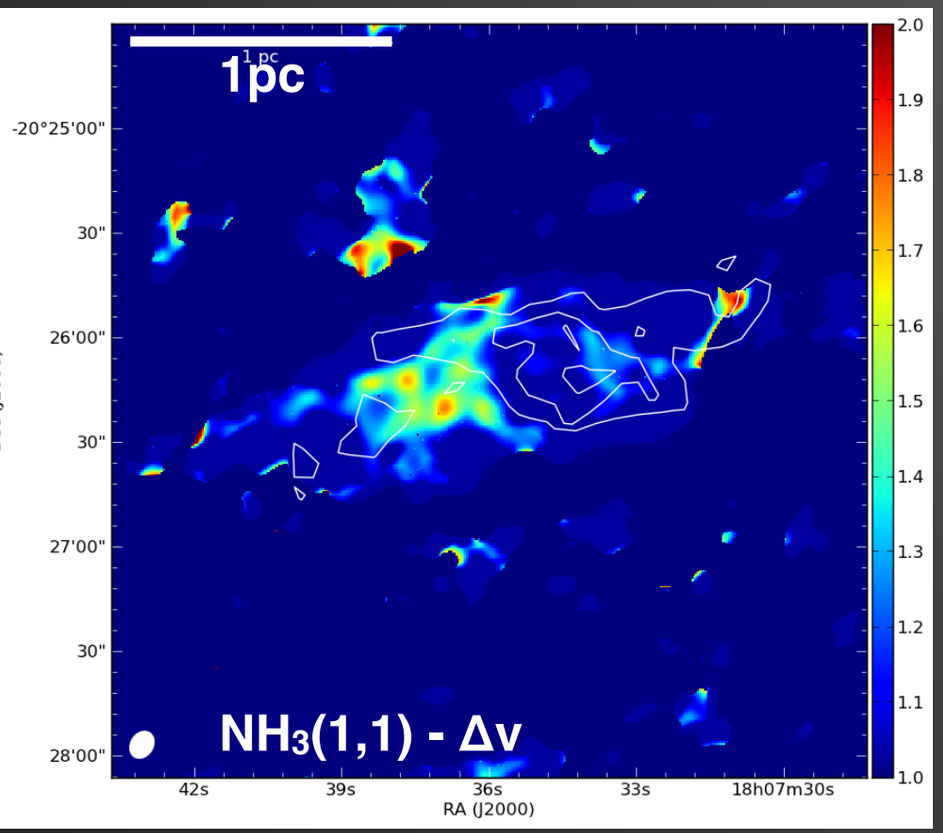

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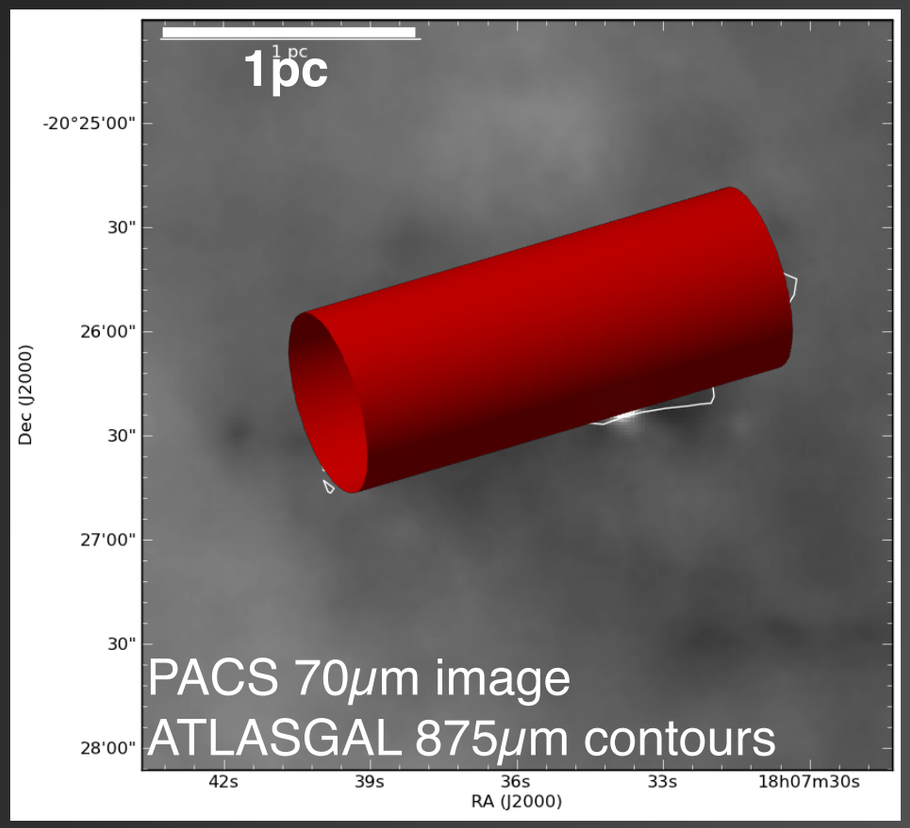

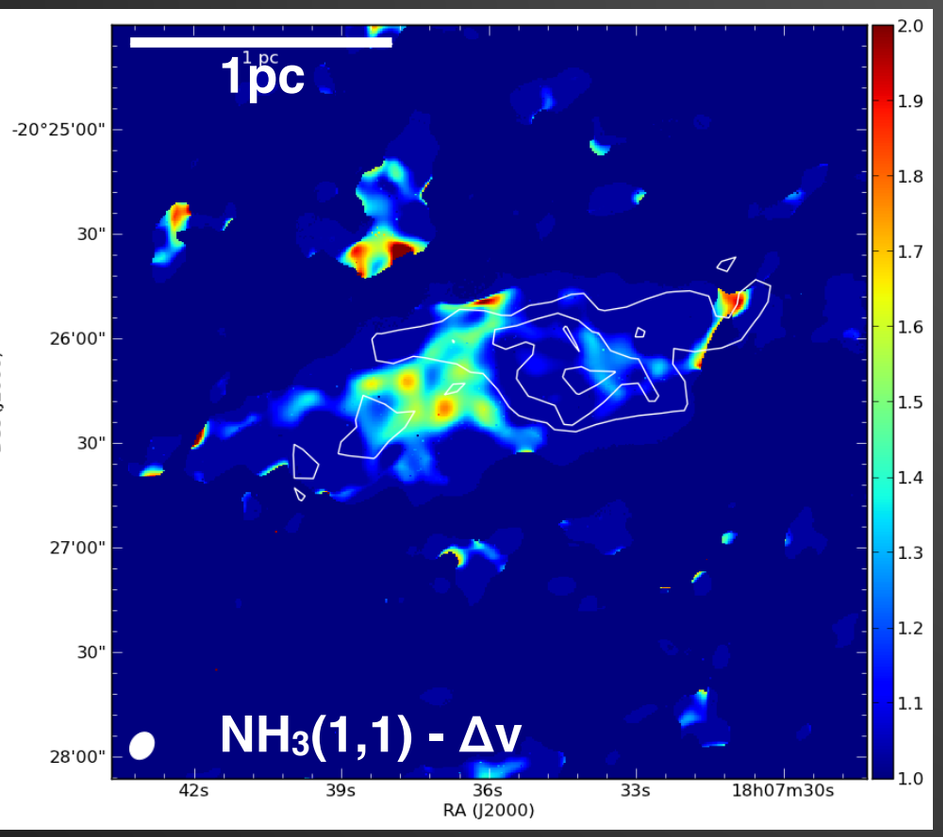

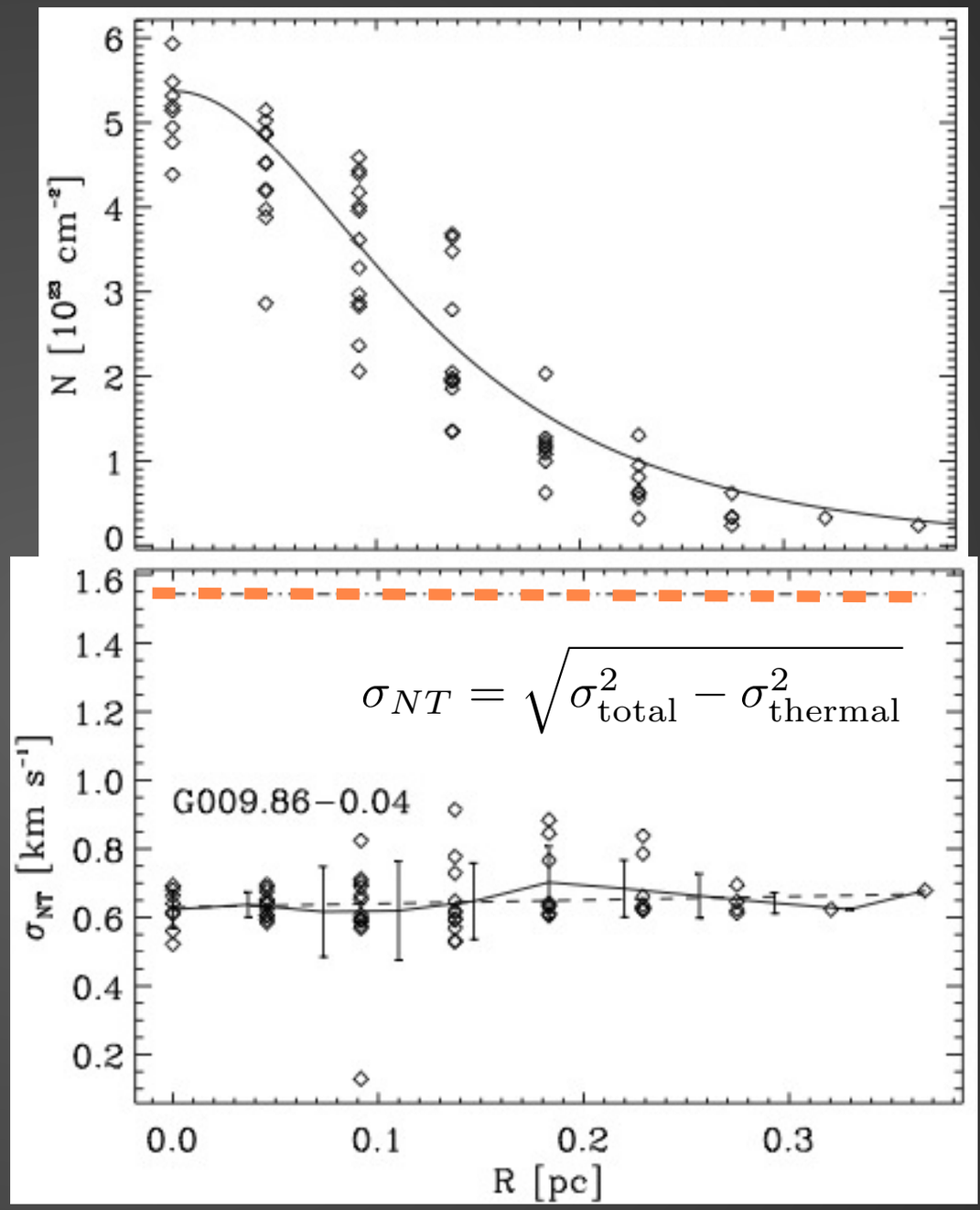

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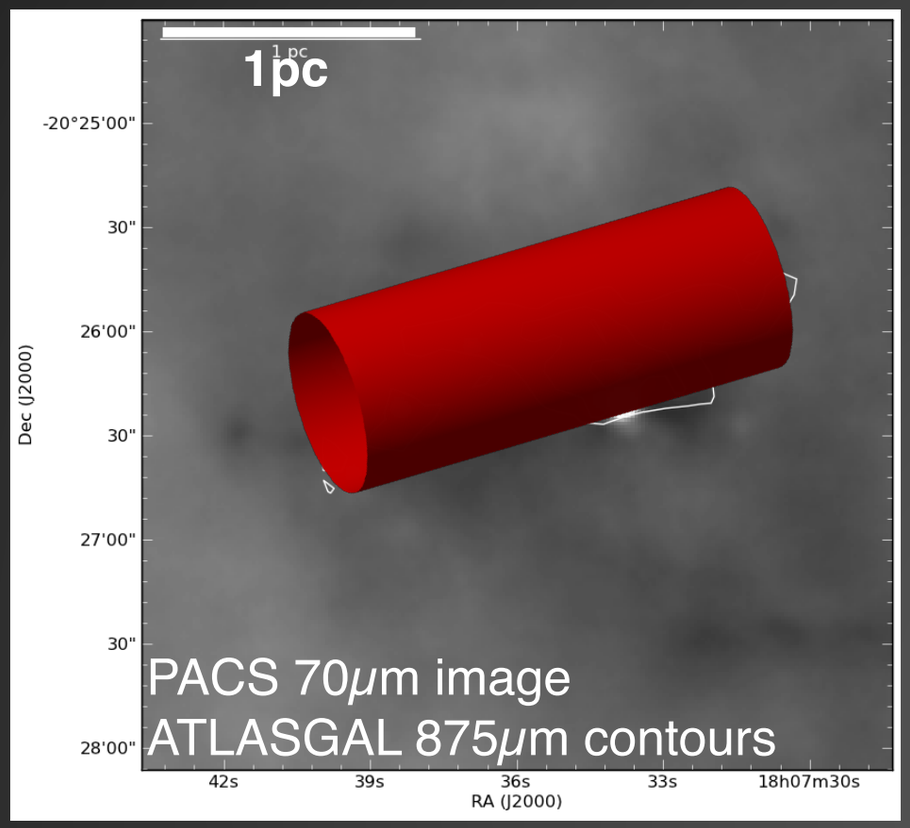

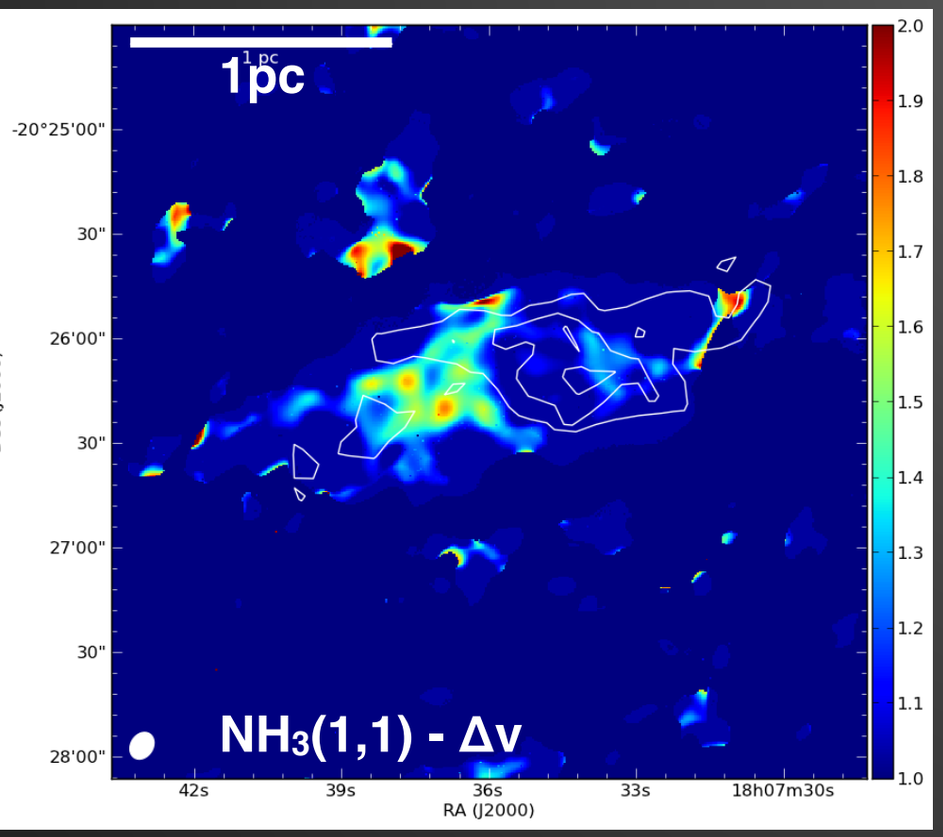

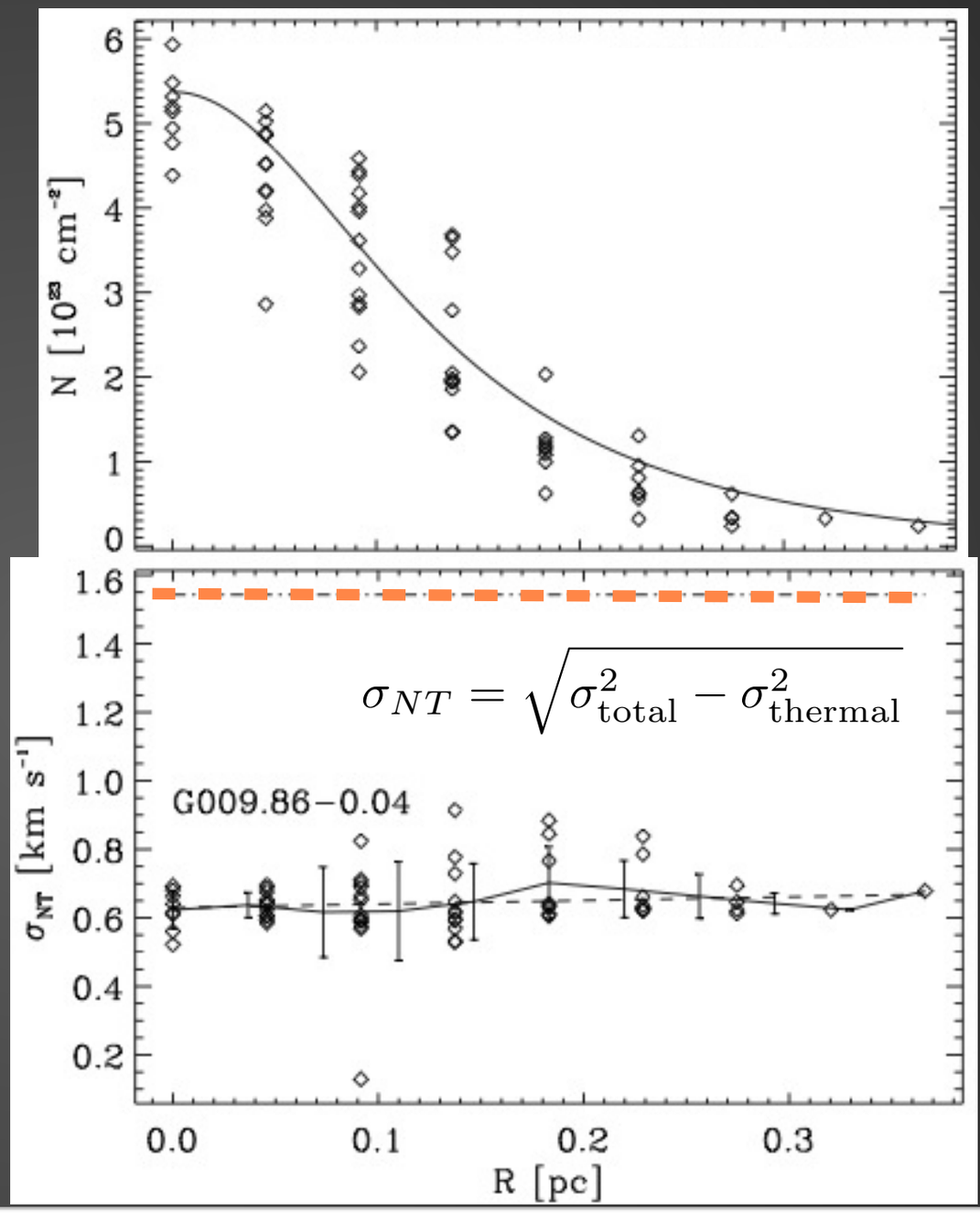

Non-thermal ("turbulent") pressure is insufficient to oppose global gravitational collapse (Ragan et al. 2012a).

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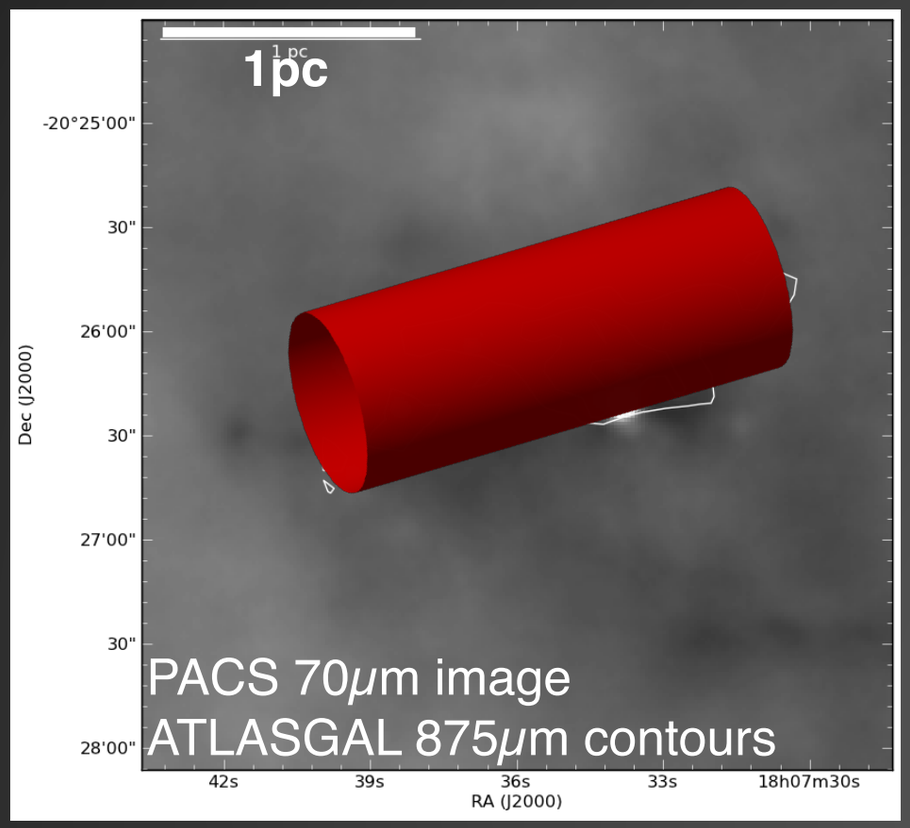

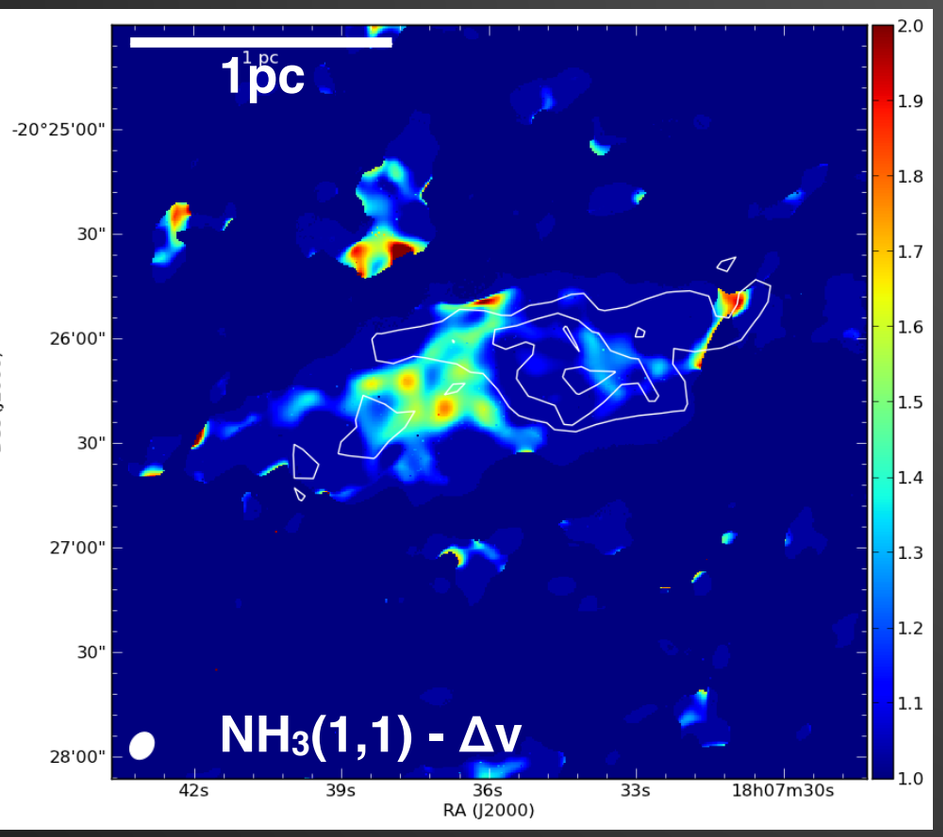

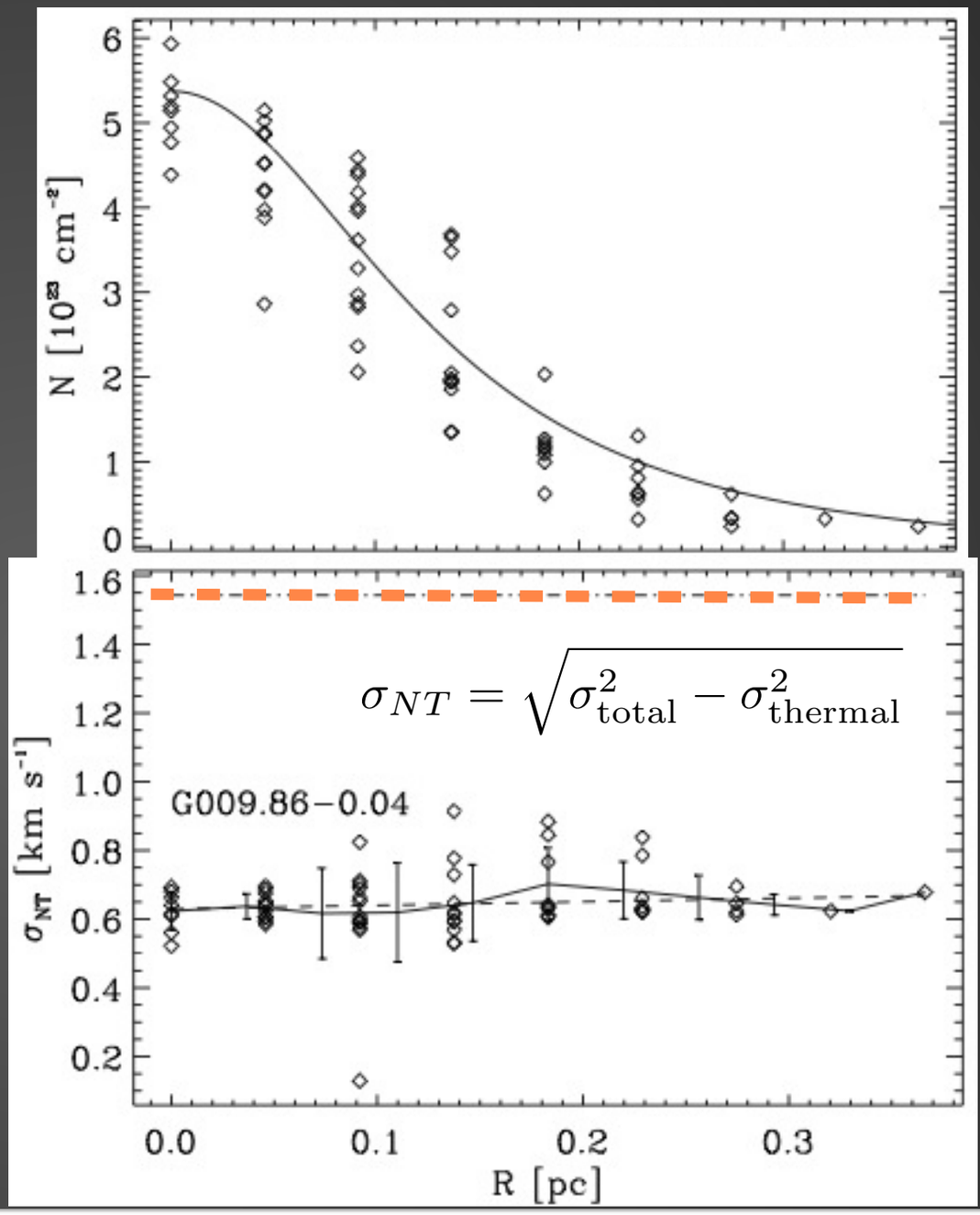

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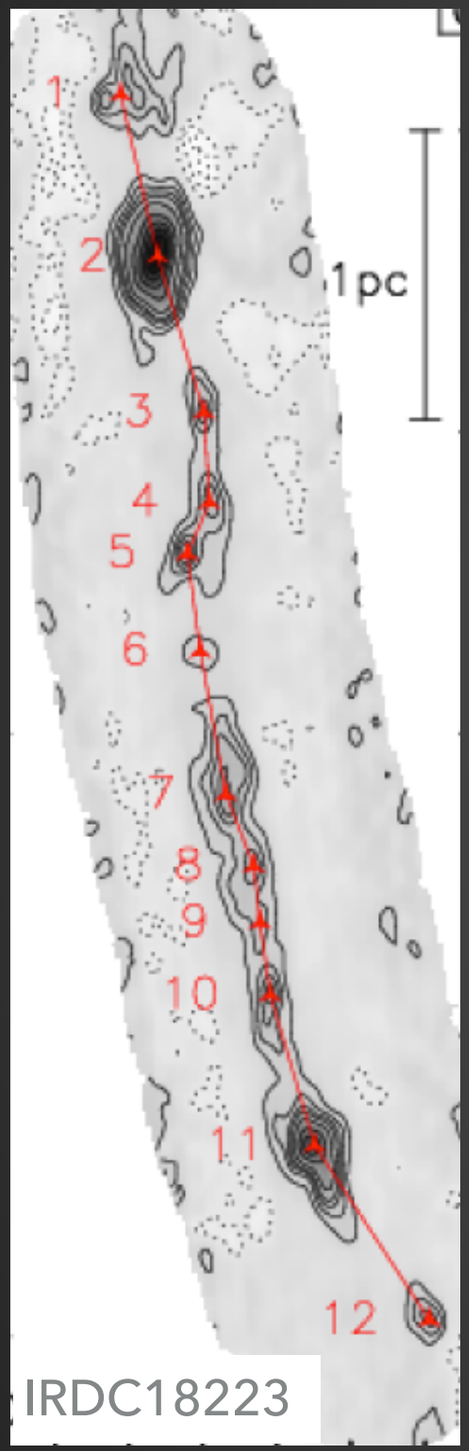
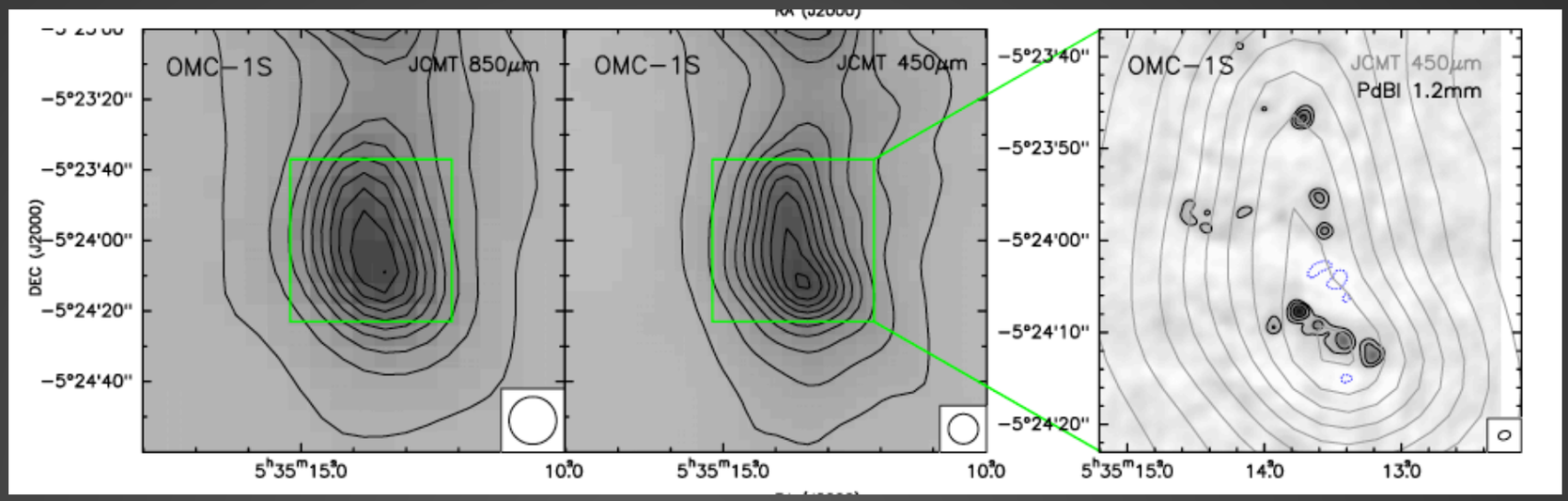
see also Beuther et al. (2013), Peretto et al. (2013), **Ragan et al. (2015)**

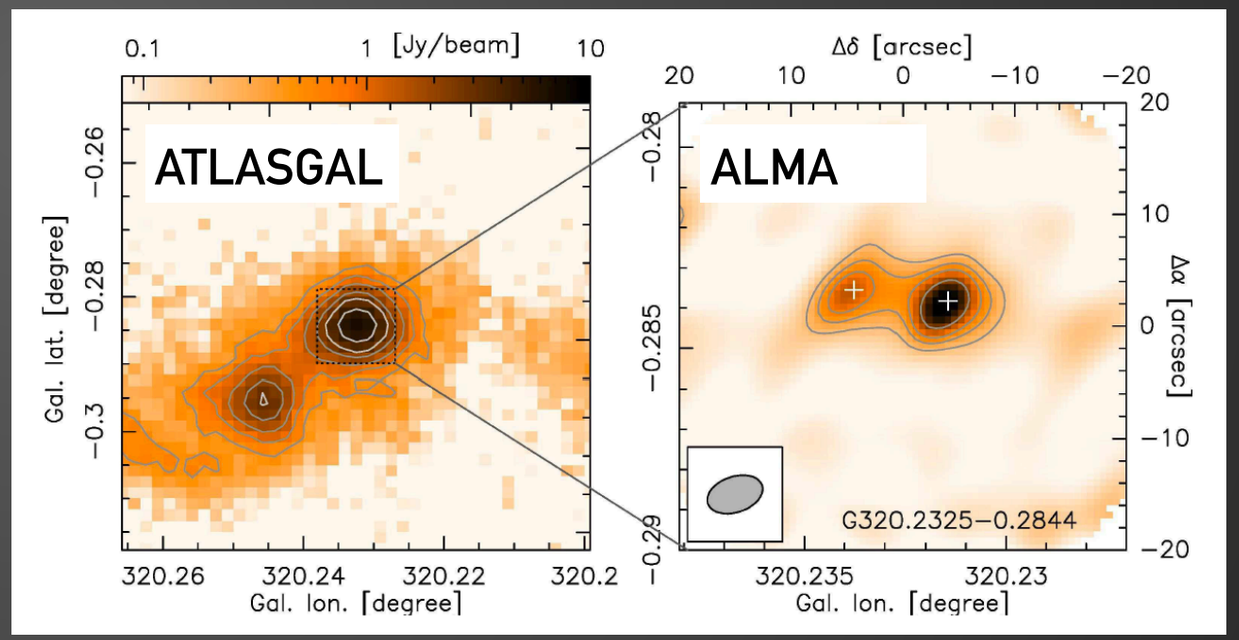
Clump fragmentation: realm of interferometry



Beuther et al. (2015)



Palau et al. (2014)



Csengeri et al (2017)

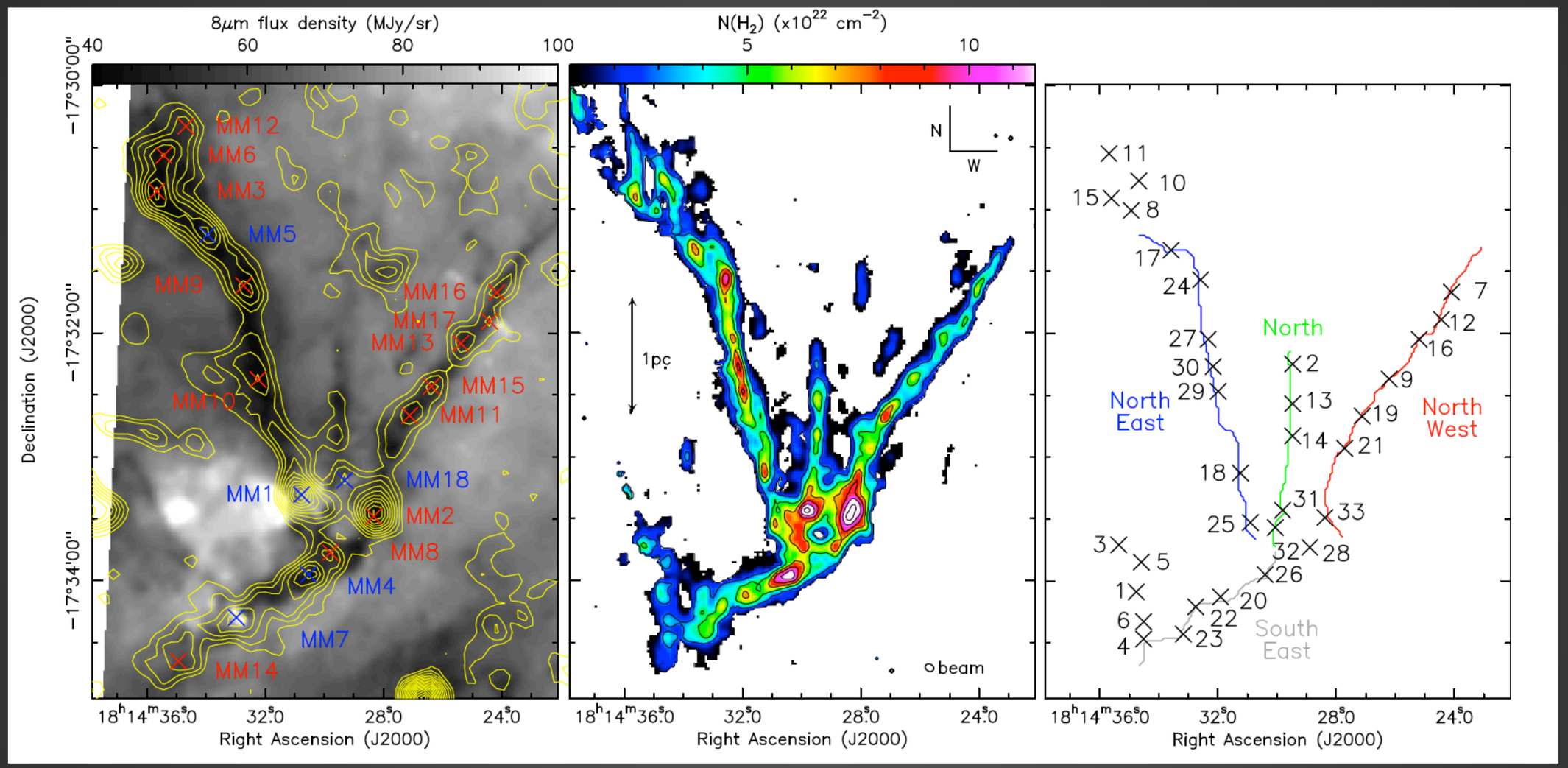
Filaments / clumps fragment into cores.

Limited (2-3 fragments per parsec)

Spacing between tends to be regular (0.2 - 0.4 pc)

Bontemps et al. (2010), Palau et al. (2014), Ragan et al. (2015), Beuther et al. (2015), Csengeri et al (2017)

SDC 13: NH_3 @ JVLA + GBT



Gwen Williams et al. (submitted)

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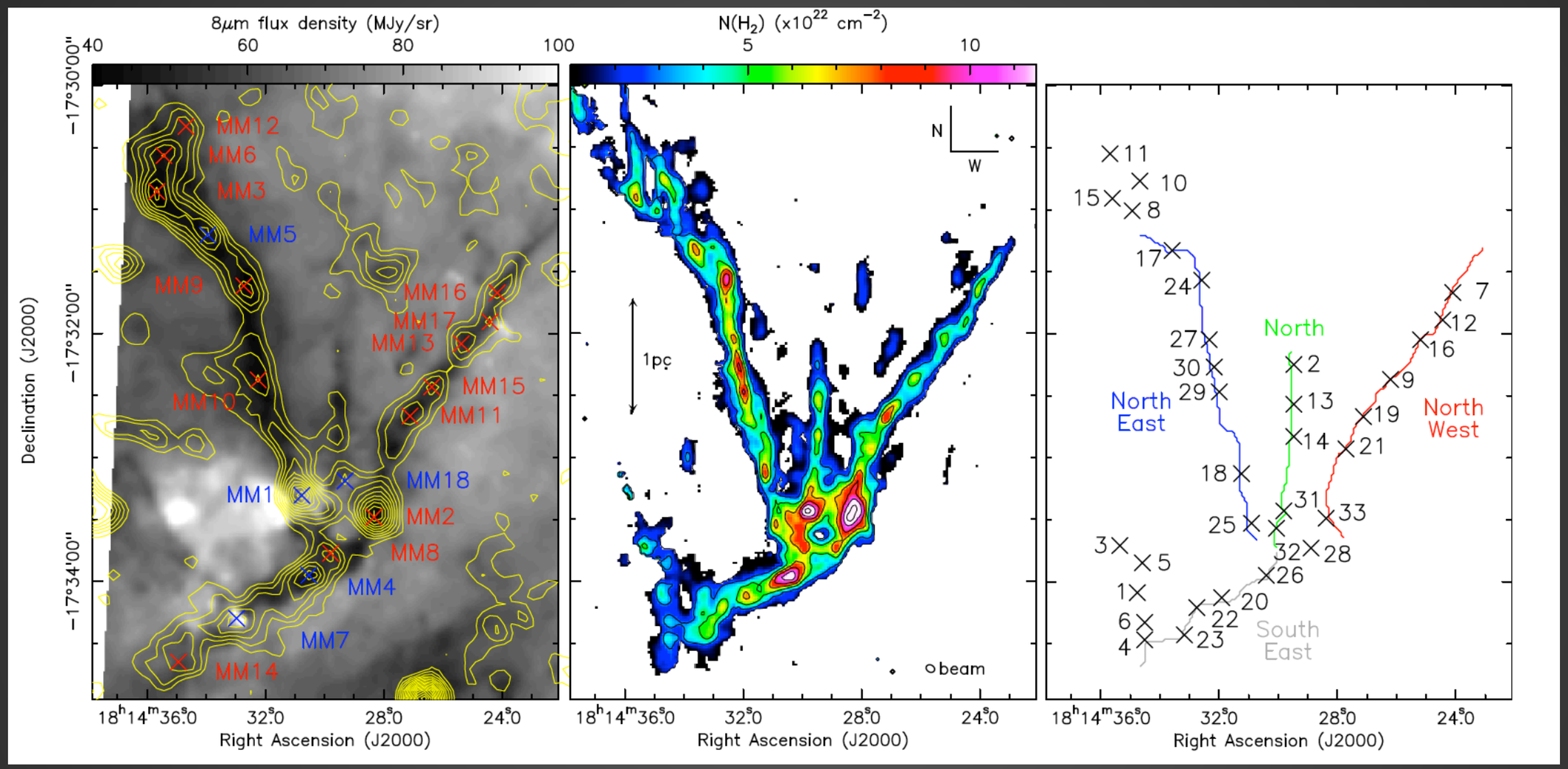

$$M_{\rm line,crit} = 2c_s^2/G$$

$$= 23 M_\odot {\rm pc}^{-1}$$

Critical value for radial contraction and fragmentation. Ostriker (1964)

Gwen Williams et al. (submitted)

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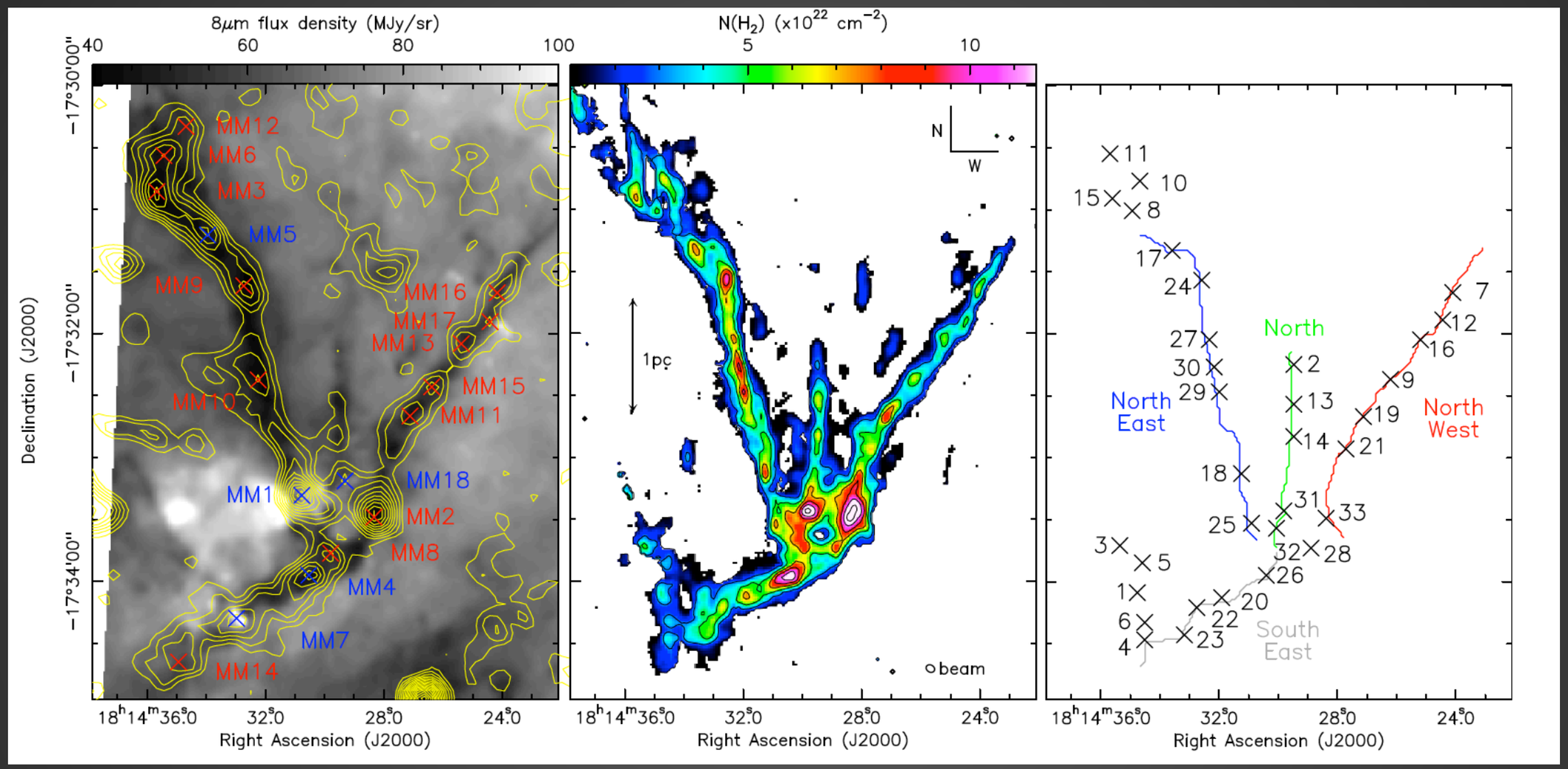

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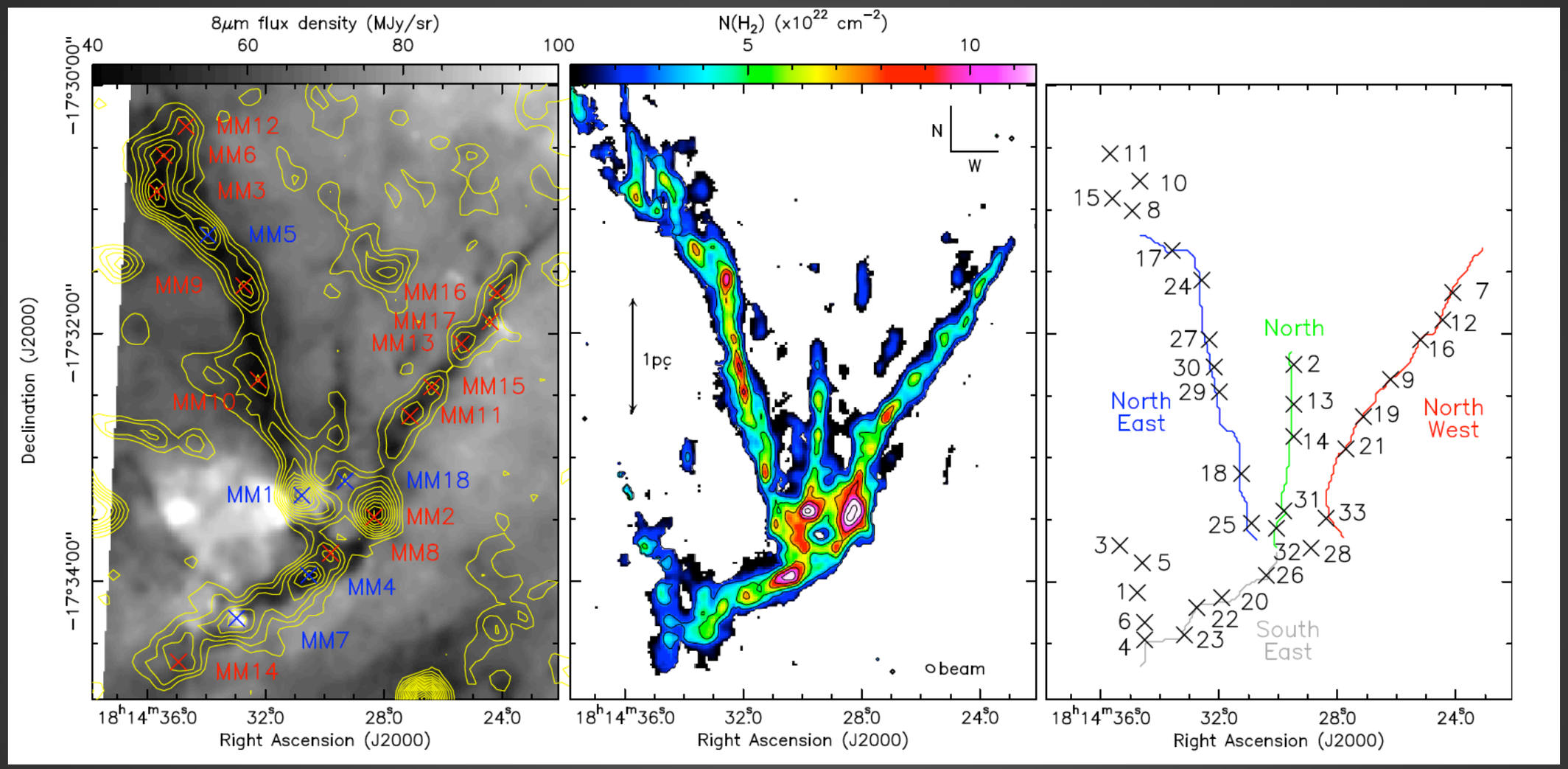
Gwen Williams et al. (submitted)

SDC 13: NH_3 @ JVLA + GBT



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SDC 13 filaments are thermally supercritical.

… and also turbulently supercritical.

Gwen Williams et al. (submitted)

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(Clarke & Whitworth 2015)

aspect ratio

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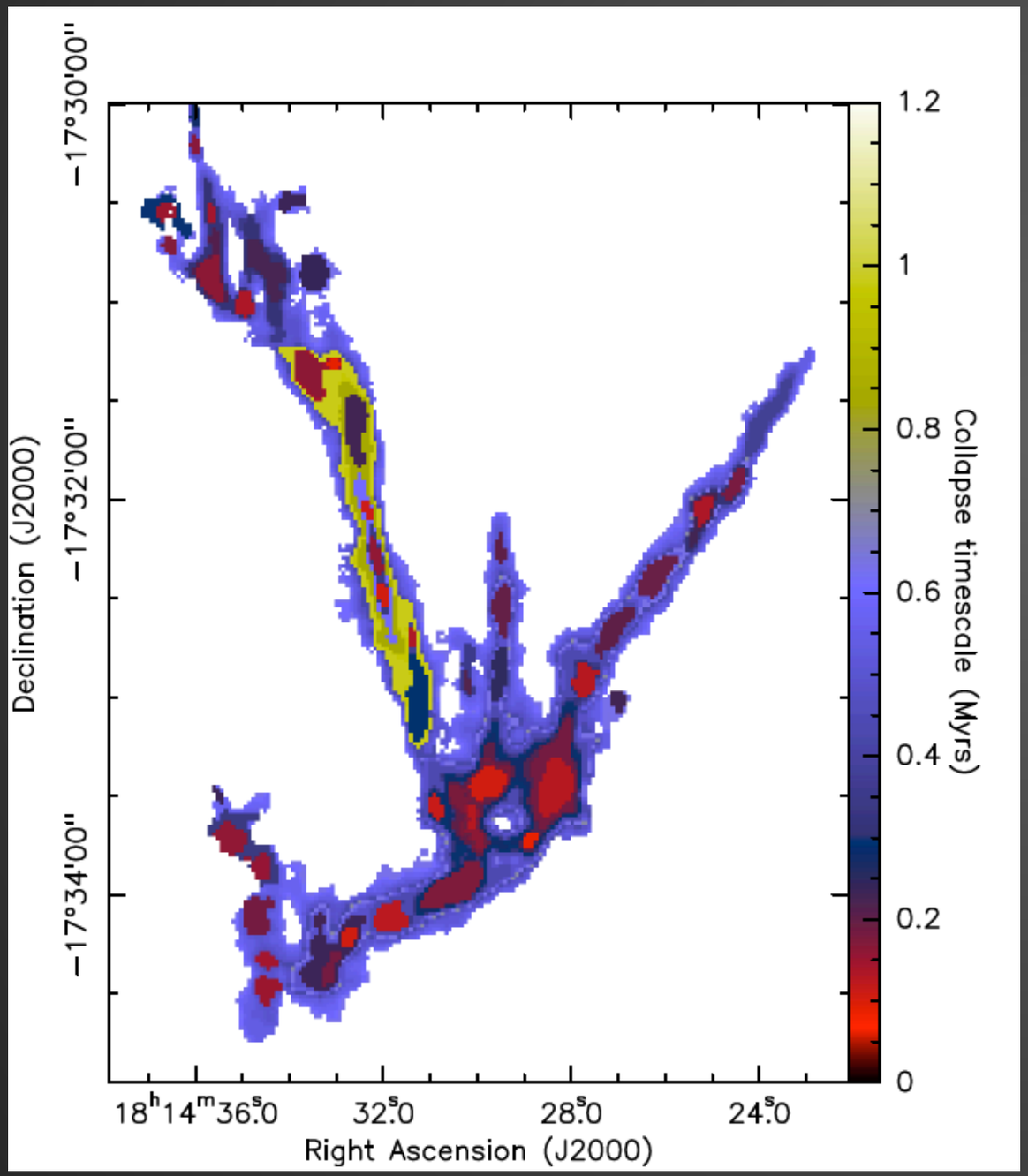

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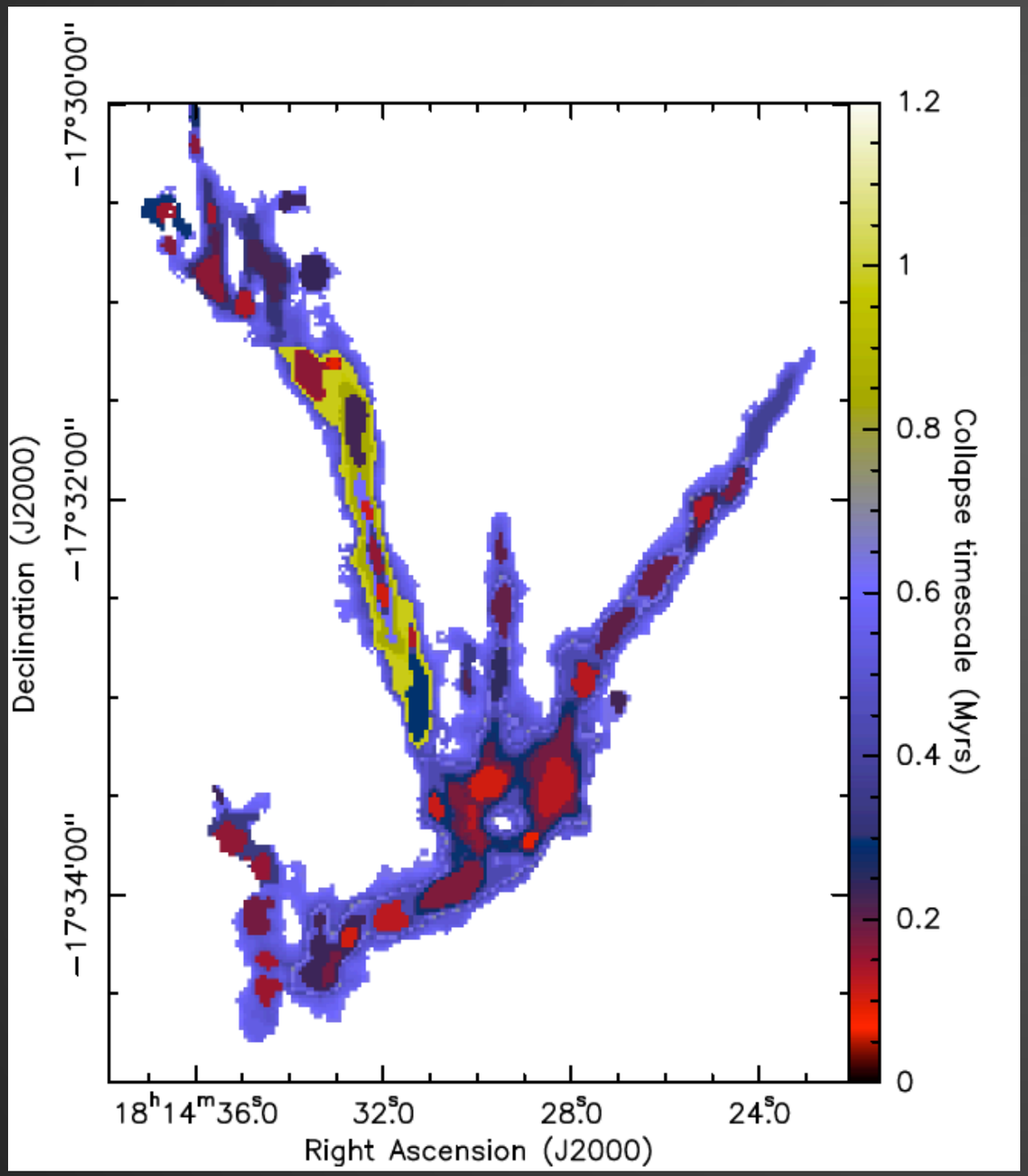

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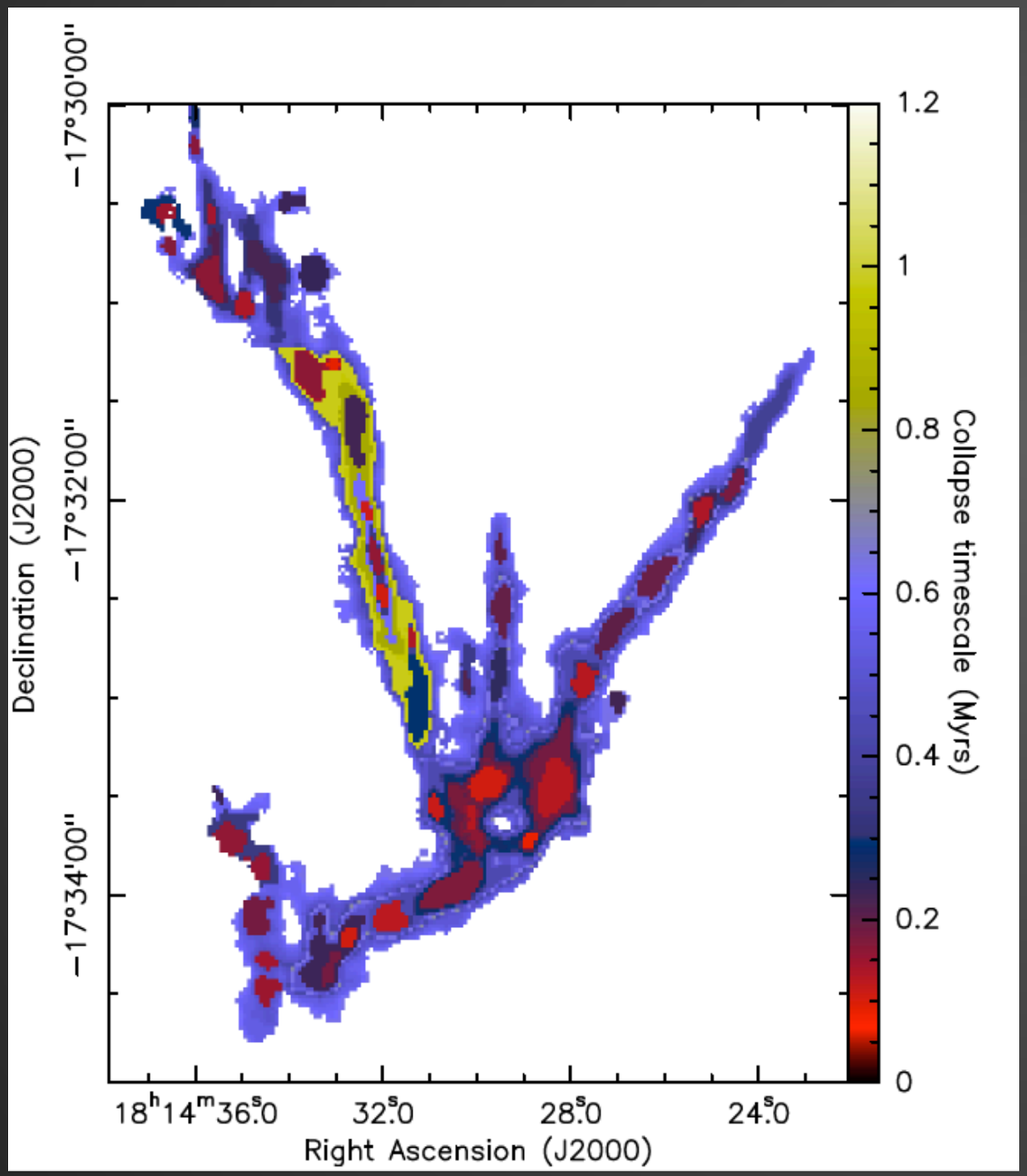
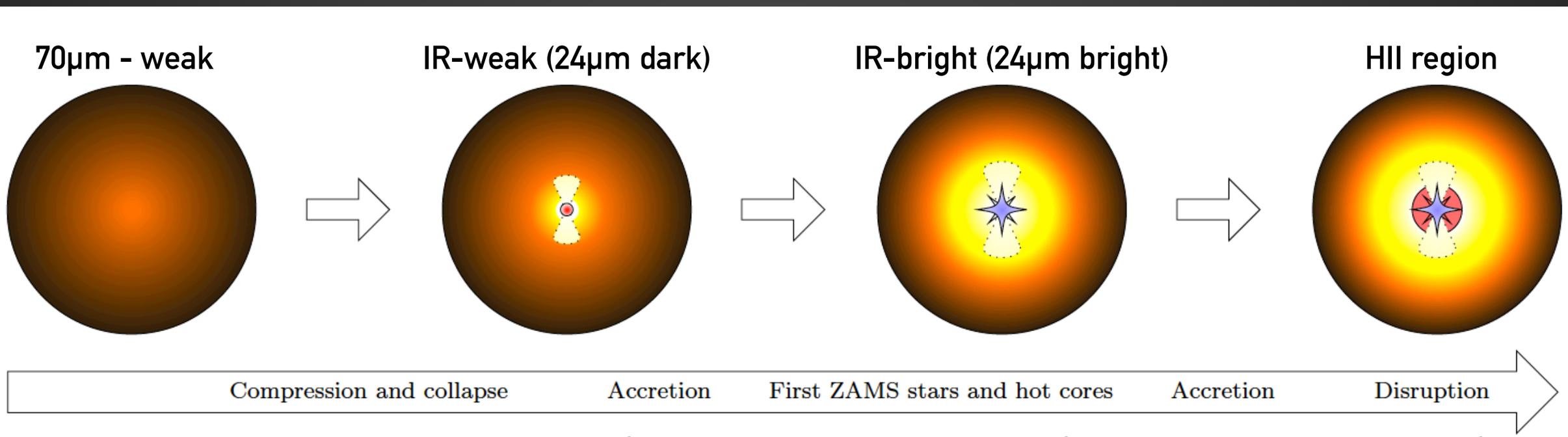


Decrease of collapse time from 0.6 to 0.1 Myr from largest to smallest structures.

Cores collapse before the filaments.

Gwen Williams et al. (submitted)



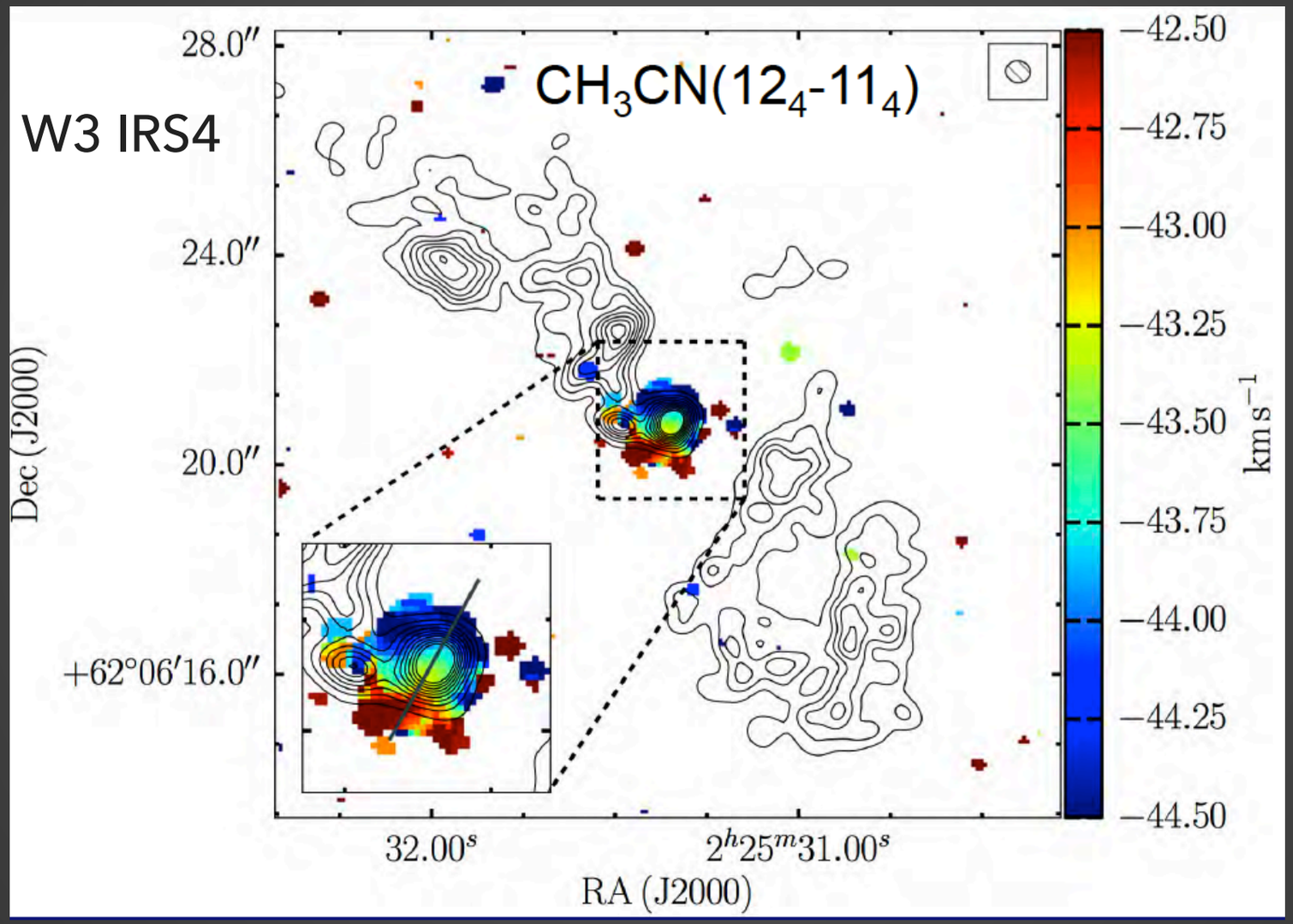
Giannetti et al. (2017)

Table 2 Characteristics and lifetime estimates of high-mass star precursors

	Median FWHM [pc]	Envelope Mass [$M_\odot$]	Density $< n_{H_2} >^a$ [cm^{-3}]	Statistical Lifetime^{b,c} [yr]
Massive starless clumps	∼0.5	$100 - 10^4$	$10^3 - 10^5$	$<1 - 3 \times 10^4$
UCHII regions	∼0.1	$1 - 10^3$	$10^3 - 10^5$	$\sim 3 \times 10^5$
IR-bright MDCs	∼0.1	$40 - 10^3$	$10^5 - 10^7$	$0.6 - 0.9 \times 10^5$
IR-quiet MDCs	∼0.1	$40 - 10^3$	$10^5 - 10^7$	$0.5 - 1 \times 10^5$
Starless MDCs	∼0.1	$30 - 80$	$\sim 10^6$	$<1 \times 10^4$
IR-bright high-mass protostars	$\sim 0.02^d$			$\sim 1.2 \times 10^5$
IR-quiet high-mass protostars	∼0.02	$10 - 100$	$10^6 - 10^8$	$\sim 2 \times 10^5$
All high-mass protostars	∼0.02	>10	$\sim 10^7$	$\sim 3 \times 10^5$
High-mass prestellar cores	$0.01 - 0.1^d$	$>30^d$	$10^5 - 10^{7\ d}$	$<1 - 7 \times 10^4$

Motte et al. (2017)

Core dynamics



Mottram et al. (in prep)
CORE PdBI large program (PI: Beuther)

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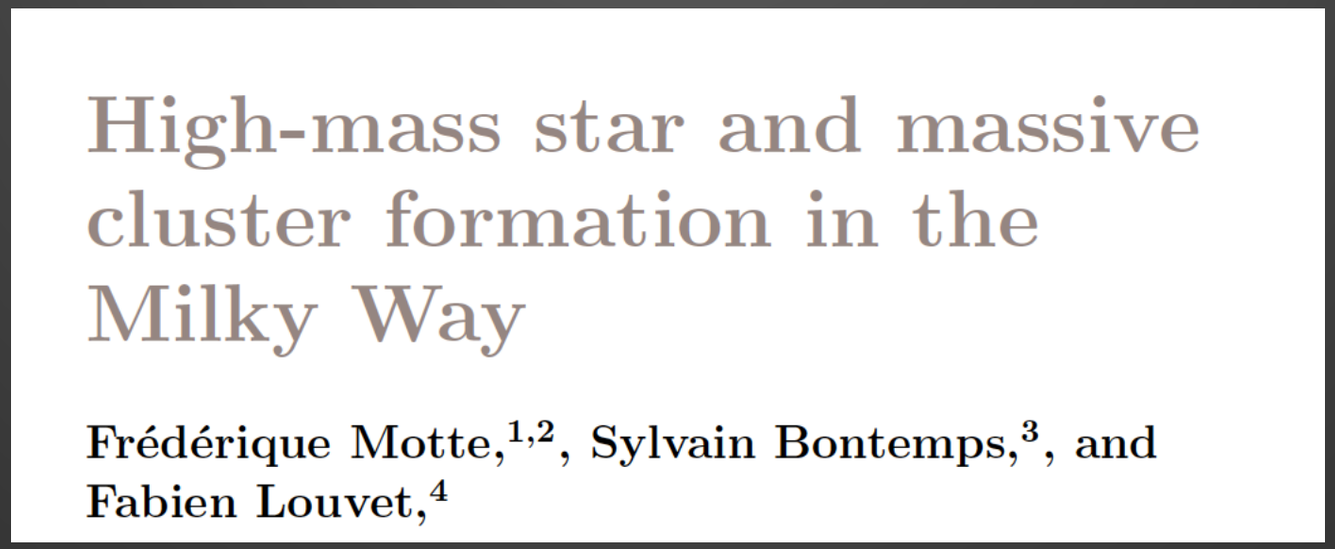

High-mass star and massive cluster formation in the Milky Way

Frédérique Motte,[1,2], Sylvain Bontemps,[3], and Fabien Louvet,[4]

Motte et al. (2017), to appear ARA&A, arXiv/1706.00118