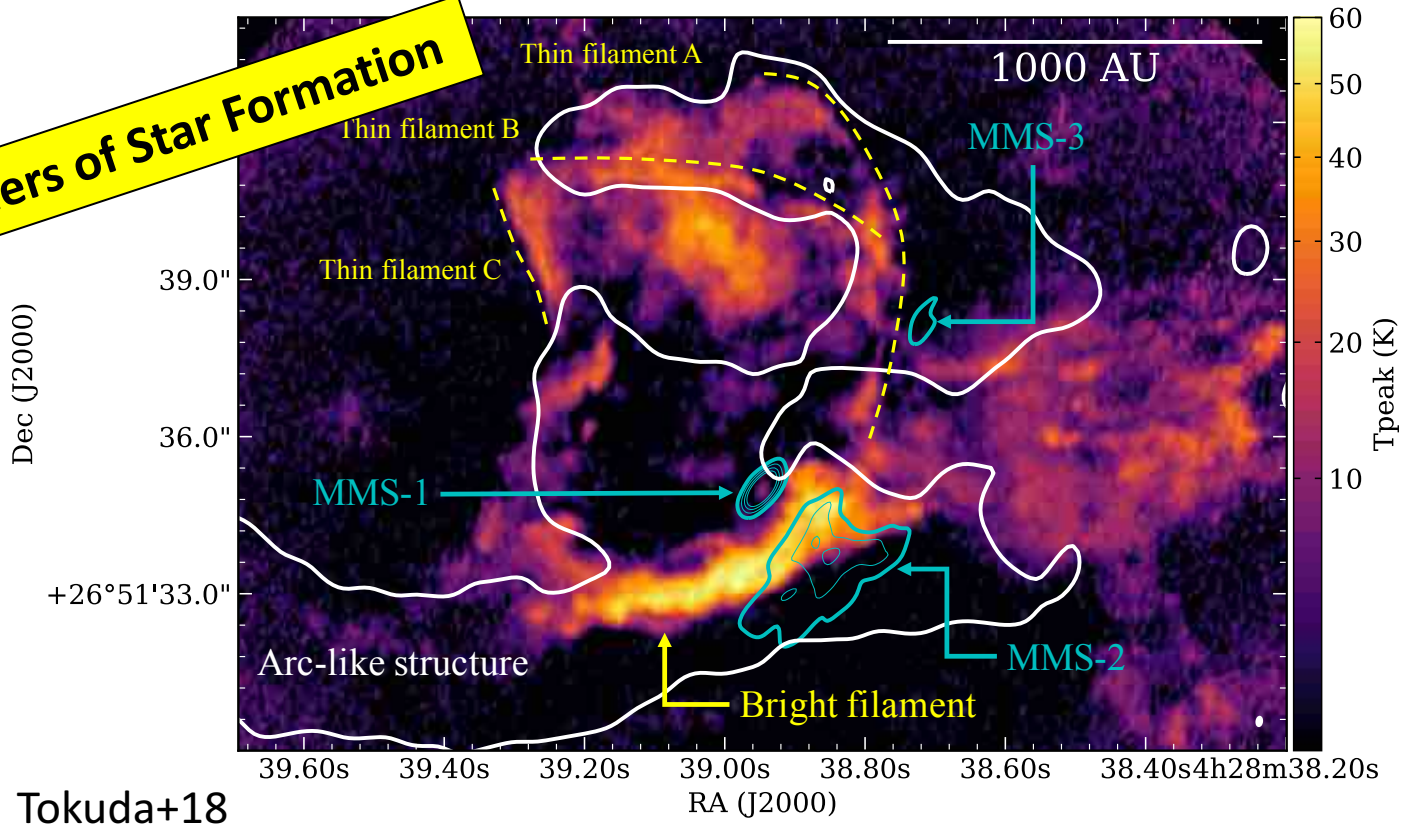
A detailed ALMA study of an early stage protostar formation in a highly dynamical dense core

Tokuda, Kazuki (Osaka Pref. Univ./NAOJ)

The Wonders of Star Formation



Tokuda+18

References

・Tokuda+14, ApJL, 789, L4, ・Tokuda+16, ApJ, 826, 26,
・Tokuda+17, ApJ, 849, 101, ・Tokuda+18, ApJ, 862, 8

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Collaborators:

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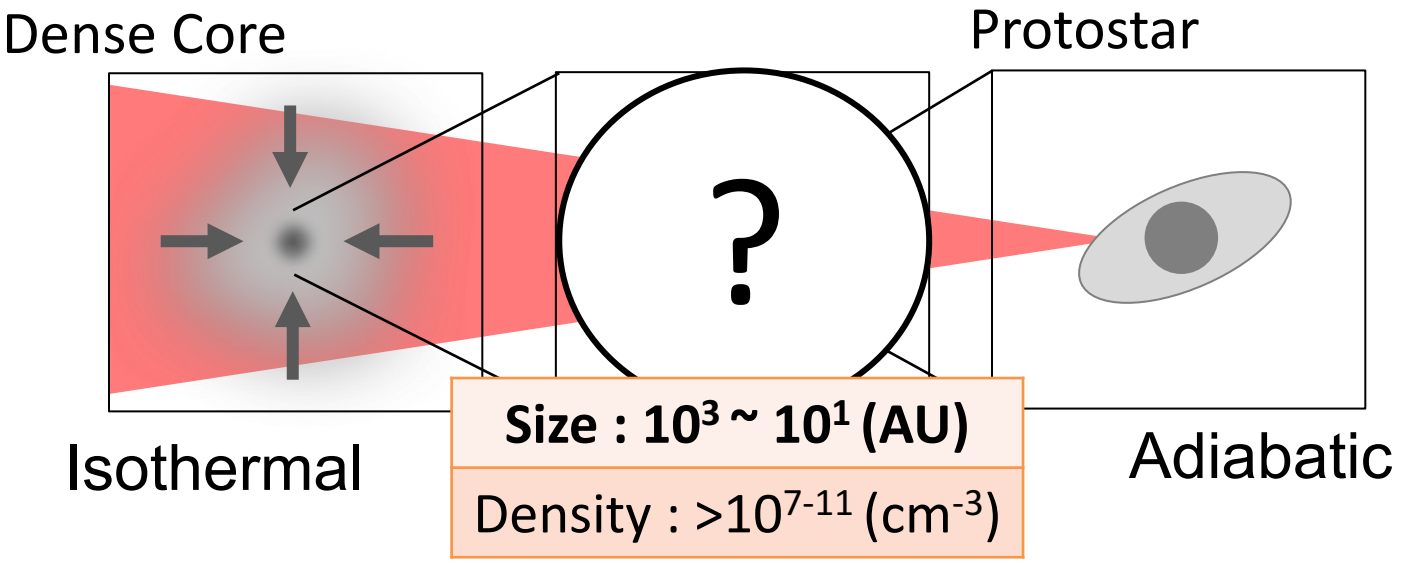
Contents:

References

・Tokuda+14, ApJL, 789, L4, ・Tokuda+16, ApJ, 826, 26,
・Tokuda+17, ApJ, 849, 101, ・Tokuda+18, ApJ, 862, 8

Introduction

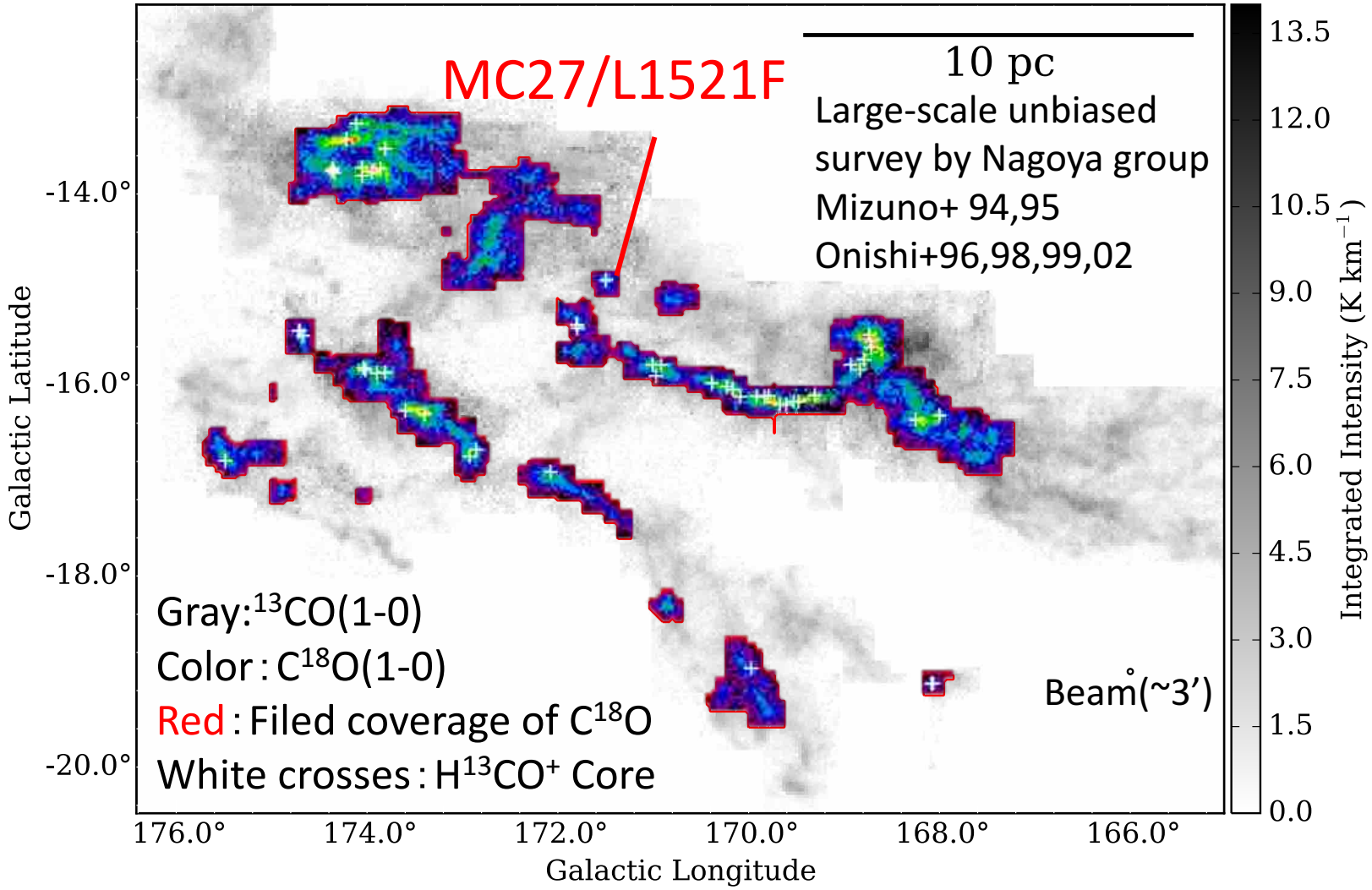
Quest for the moment of the star formation



Expected phenomena	Revealing processes
First protostellar core object	Adiabatic core formation
Compact outflow	Initial mass function
Fragmentation of dense gas	Multiple star formation

e.g., Larson69, Shu77,Masunaga+98, Matsumoto+03,Machida+08,Tomida+13…

Introduction : searching for high-density cores

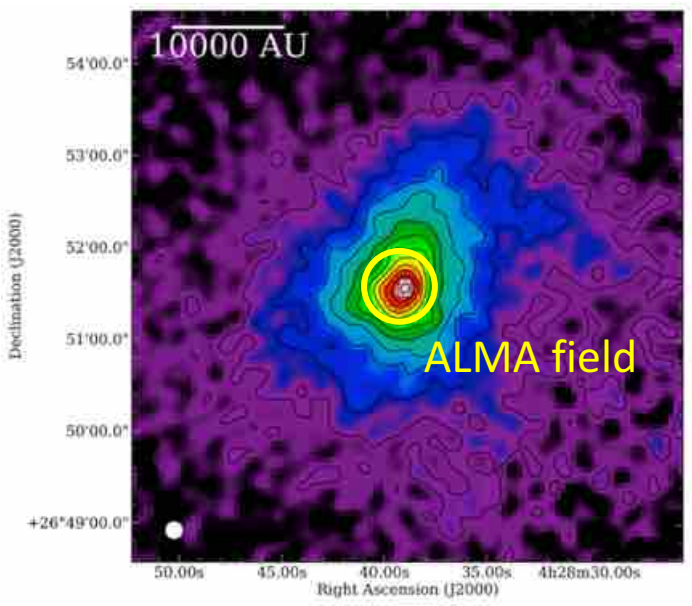


Observation strategy: Optically thick lines=> Optically thin lines

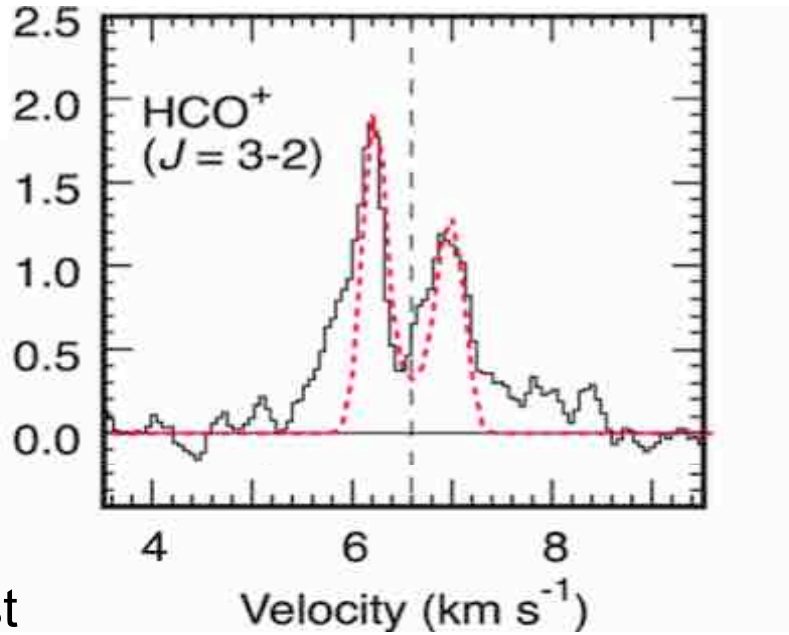
=> Discovered ~50 high-density (~10^5 cm^{-3}) condensations in Taurus

MC27/L1521F has the highest density among the starless cores

Introduction what is MC27/L1521F?



IRAM 30m/MAMBO-2: 1.2 mm dust
(Kauffmann+08, Tokuda+16)



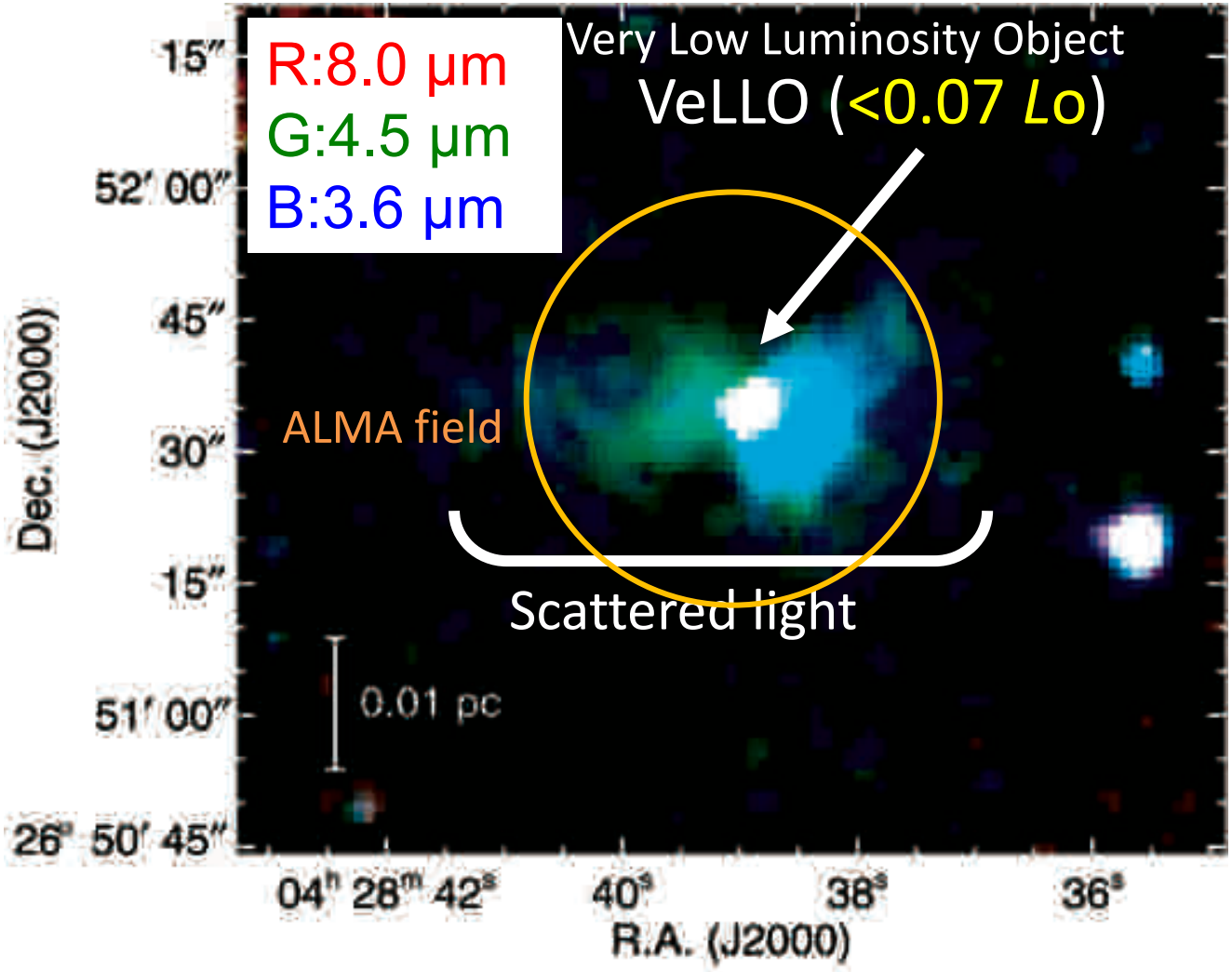
Onishi+ 99

- *Features (Before ALMA)*
  1. One of the *densest cores* in low-mass star forming regions (e.g Onishi+99,02, Crapsi+04)
  2. Indication of outflowing/inflowing motion (e.g. Onishi+99)

Total mass~3–4 *Mo*, Density~10^6 cm^{-3}, Temperature ~10 K

Introduction what is MC27/L1521F?

I.R. observations with ***Spitzer*** space telescope



Bourke+ 2006, Tereby+ 2009

Internal summary of MC27/L1521F

Before ALMA obs. v.s. After ALMA obs.

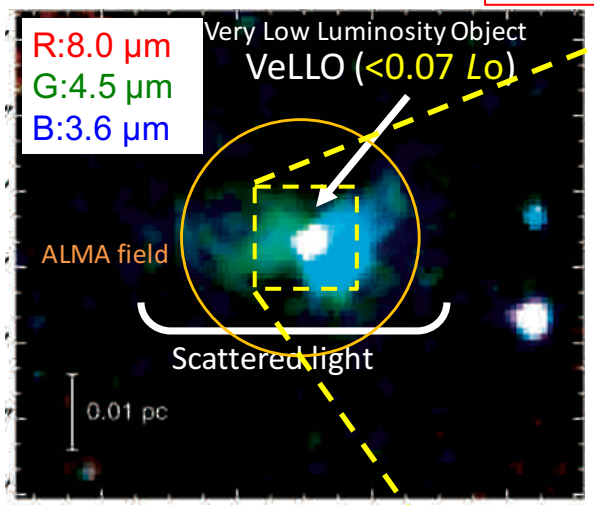
	Single-dish Obs.	ALMA Obs.
Shape	(Nearly) spherical	Complex structures
Central Density	~10^6 cm^{-3}	10^6-10^7 cm^{-3} (MMS2,3)
Single or Multiple?	Single (VeLLO)	(Possible) Multiple
Outflow evidence	Scattered light	Compact molecular outflow?
Protostellar mass	<0.1 *Mo* ?	~0.2 *Mo*
Accretion rate	10^{-5}–10^{-6} Mo/yr?	<10^{-8} *Mo*/yr
Disk size	Large (>100AU) ?	*R*~10 AU
Temperature	~10 K	Warm CO gas, 15-60 K

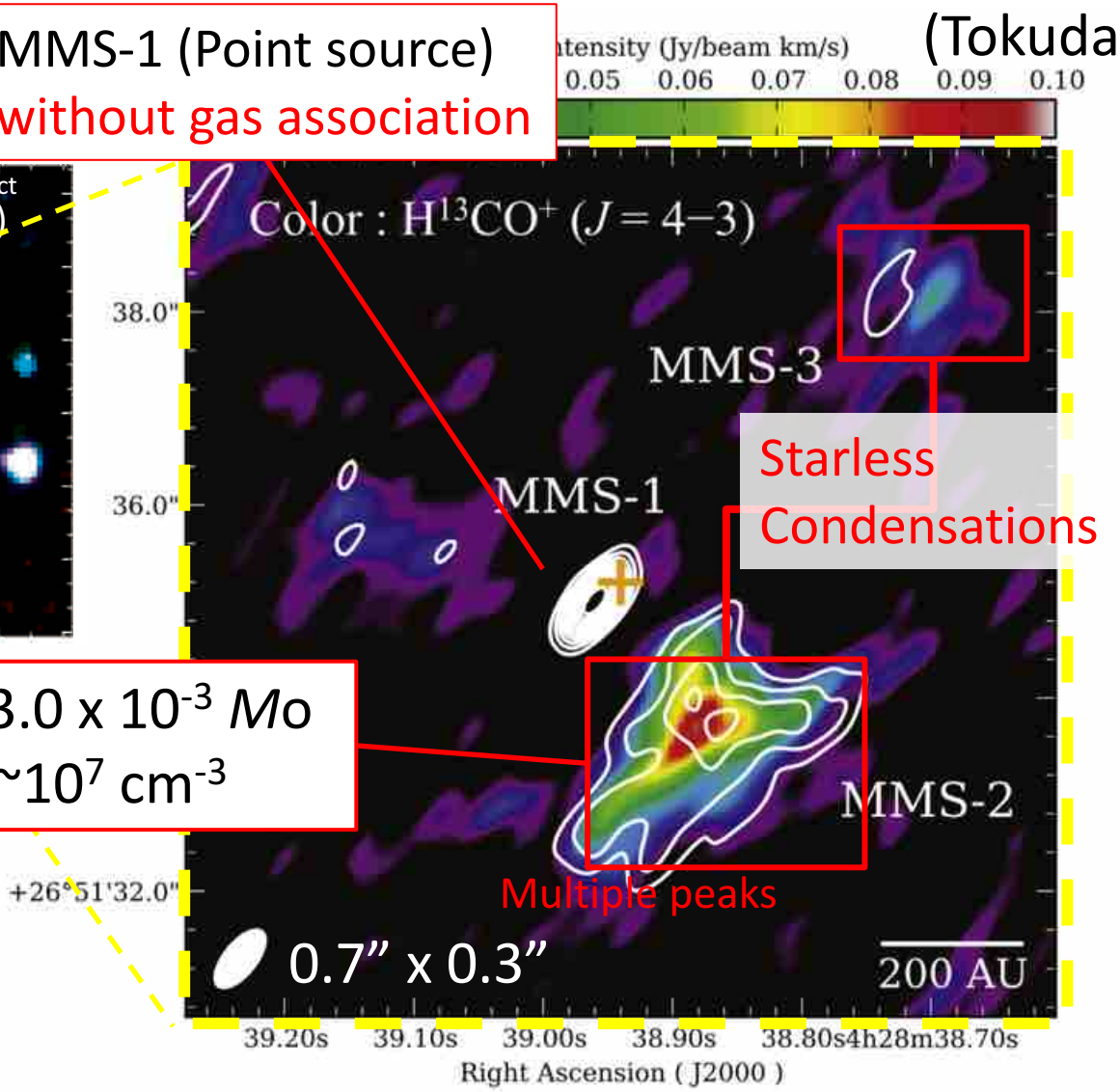
Is it a typical protostellar core in an early stage of star formation ?

Protostar and condensations at the center of the core

MMS-1 (Point source)
without gas association

(Tokuda+14,16)



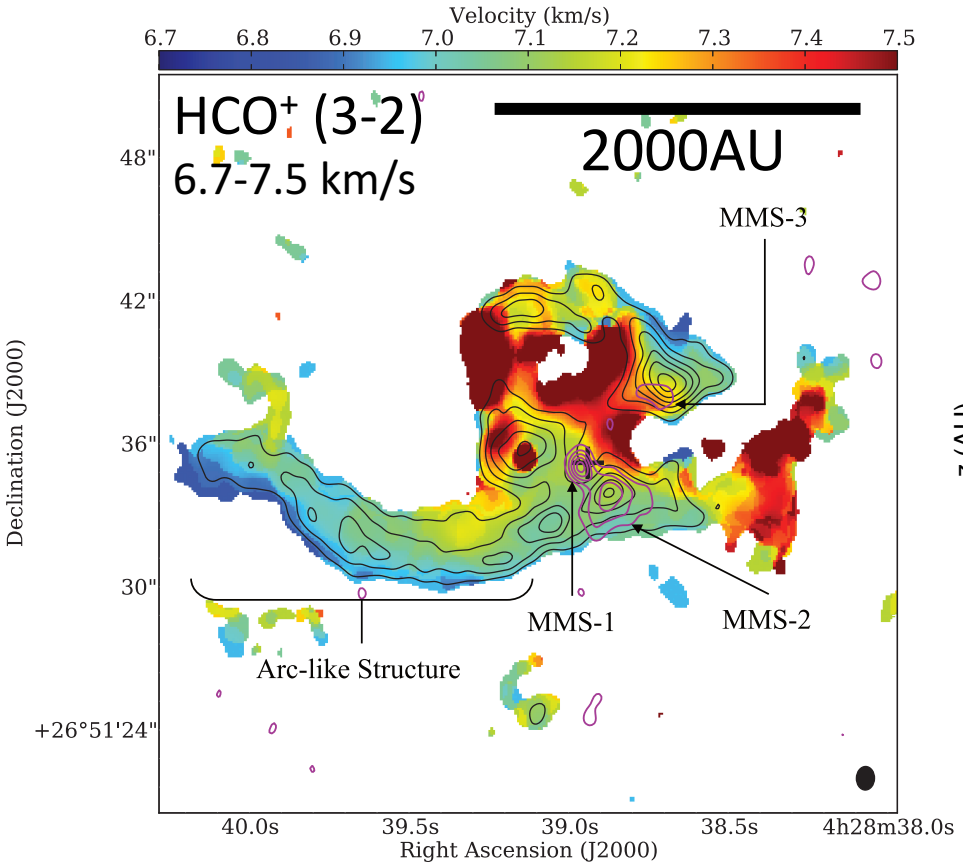


Mass ~ 3.0 x 10^{-3} *Mo*
density ~10^{7} cm^{-3}

Color : $H^{13}CO^{+}$ (4-3), Contour : 0.87 mm Cont.

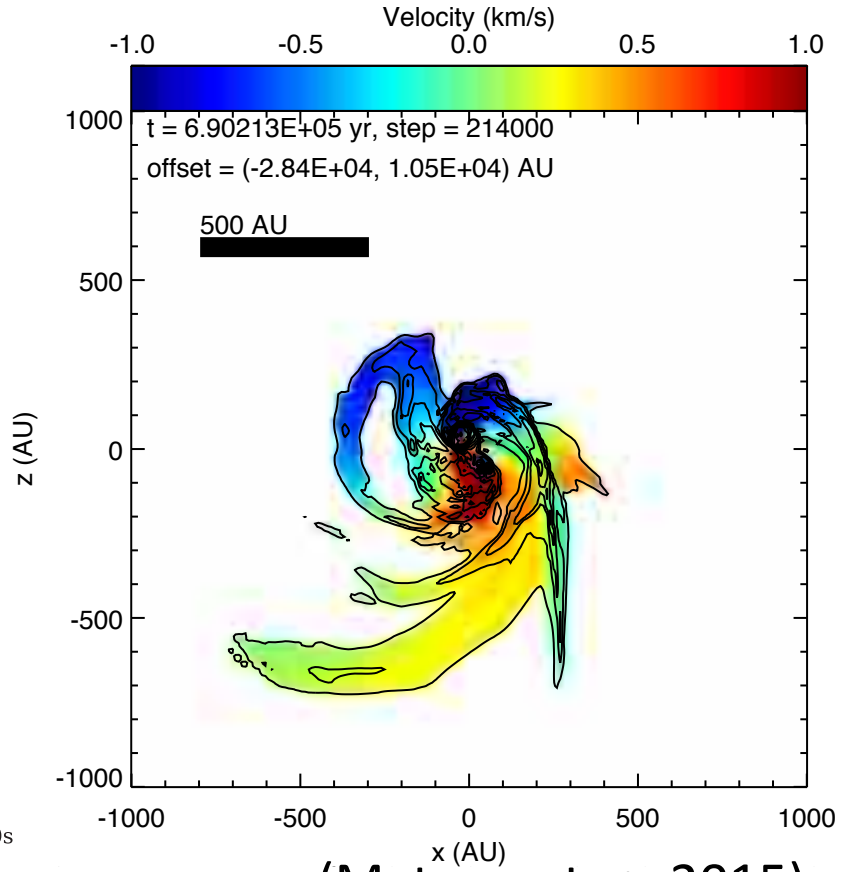
Complex velocity/spatial structures: Turbulence?

ALMA Observation



Tokuda+14

Simulation



(Matsumoto+ 2015)

- Are the arcs corresponding to the cavity edges? => Unlikely
- A possible origin of ~2000 AU arc-like feature

=>Waves caused by gravitational torque of multiple system

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A highly dynamical protostellar core?

ALMA Cycle 3 Observations

Table: Specifications

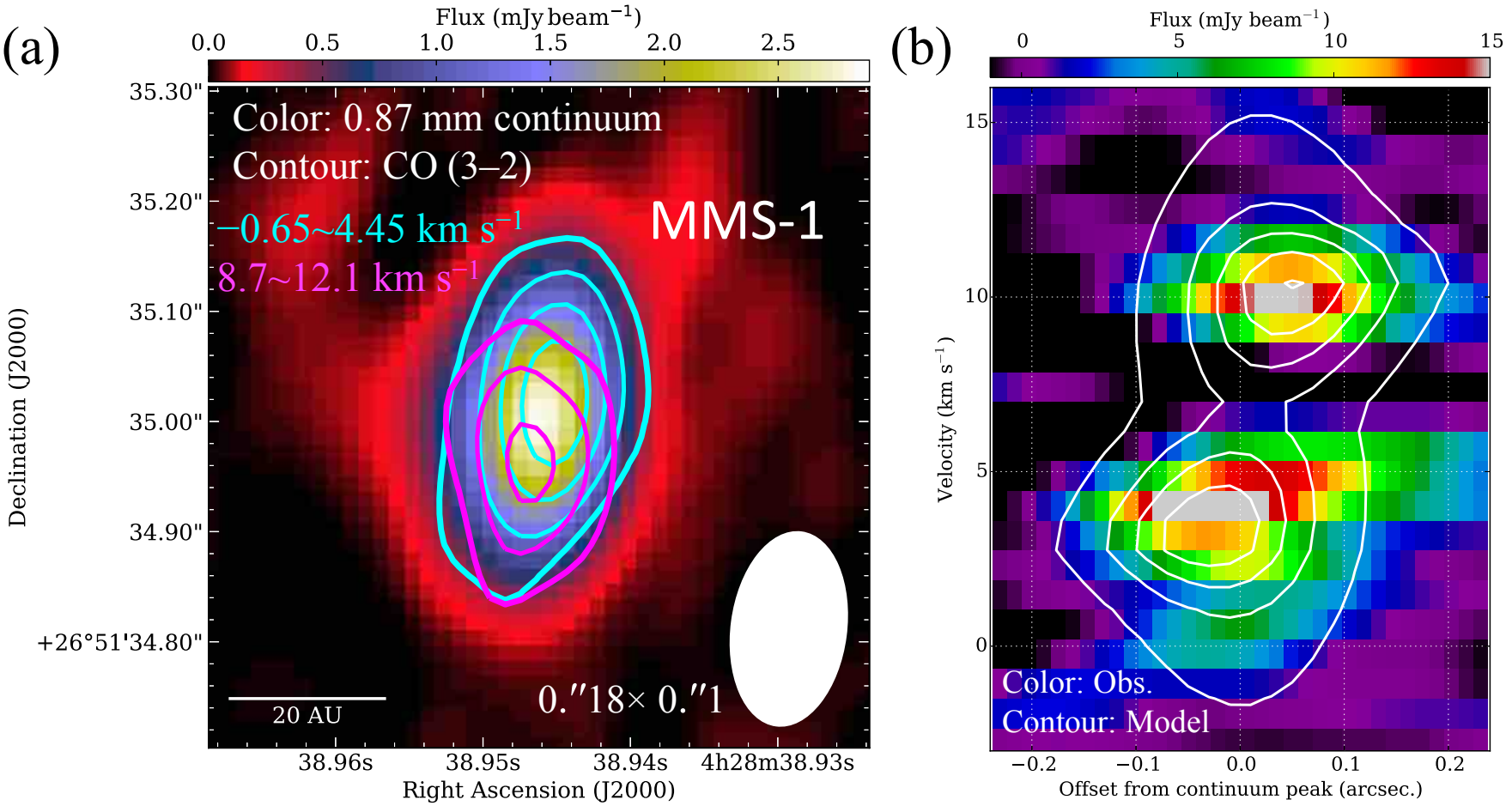
Period	ALMA Cycle 3
Target	MC27(=L1521F)
Beam size	0."18 x 0."1 (25 x 14 AU)
Velocity resolution	0.85 km/s
Lines	CO(3−2), $H^{13}CO^+$(4−3), $C^{17}O$(3−2), 0.87 mm continuum

*ALMA 12m array alone (7m, TP observations in Cycle 1)

Main Results

1. *R* ~10 AU disk around ~0.2 $M_\odot$ protostar (Tokuda+17)
2. Warm CO gas generated by possible turbulent shocks (Tokuda+18)
   - warm (15−50 K) gas, very thin filaments, and compact clumps

A possible Keplerien disk around the VeLLO ?



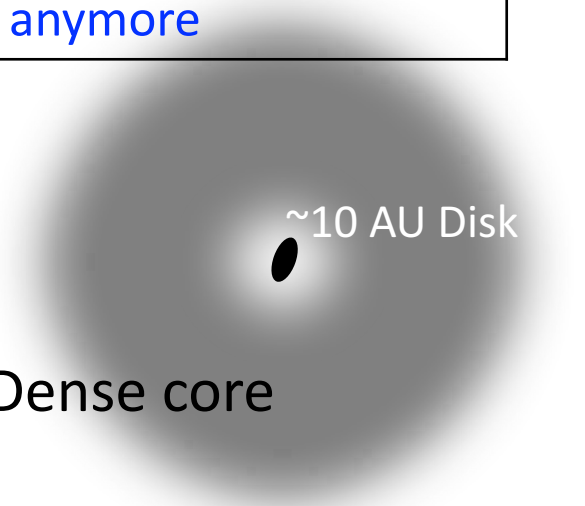
Constrained physical properties form simulated observations ^{12}CO and 0.87mm

M_*	M_{disk}	R_{disk}
0.18 ±0.05 $M_\odot$	8 x 10^{-5} $M_\odot$	9 AU

Disscussion

Witnessing the final stage of the formation of ~0.2 $M_\odot$ protostar?

Observed features	**Indications**
・Low-luminosity (<0.07 *Lo*) ・Tiny outflow	Quite low-accretion rate (<2e-8 Mo/yr)
・Scatted light seen in *Spitzer*	・Large accretion activities in the past
・Braking radius of the column density profile ~3000 AU	・Accretion late (2e-6 $M_\odot$/yr) * time (7e4 yr) ~0.1 $M_\odot$
・ No-high density envelope around the protostar ・Rdisk ~10 AU	The disk is detached from envelopes => Mass accretion through the disk does not occur anymore



Schematic view of detached disk

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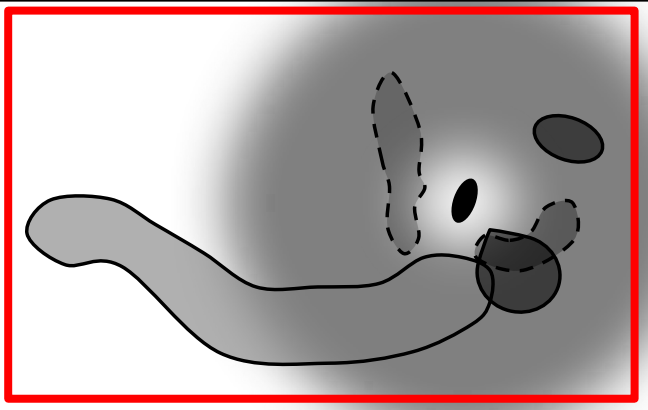
Posibility

The intrinsically larger disk was stripped by the surrounding gas in the turbulent environment.



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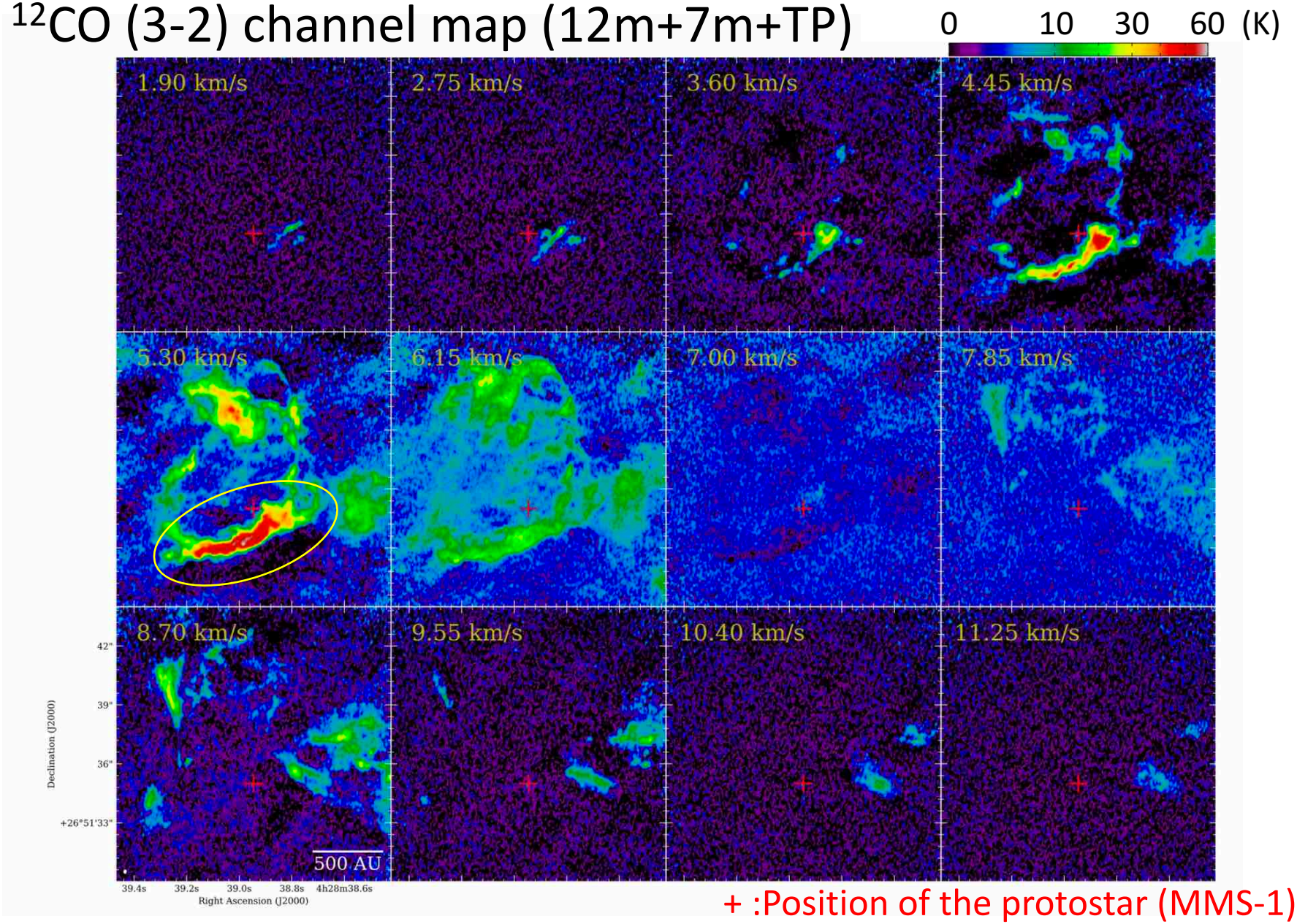
^{12}CO (3-2) channel map (12m+7m+TP)

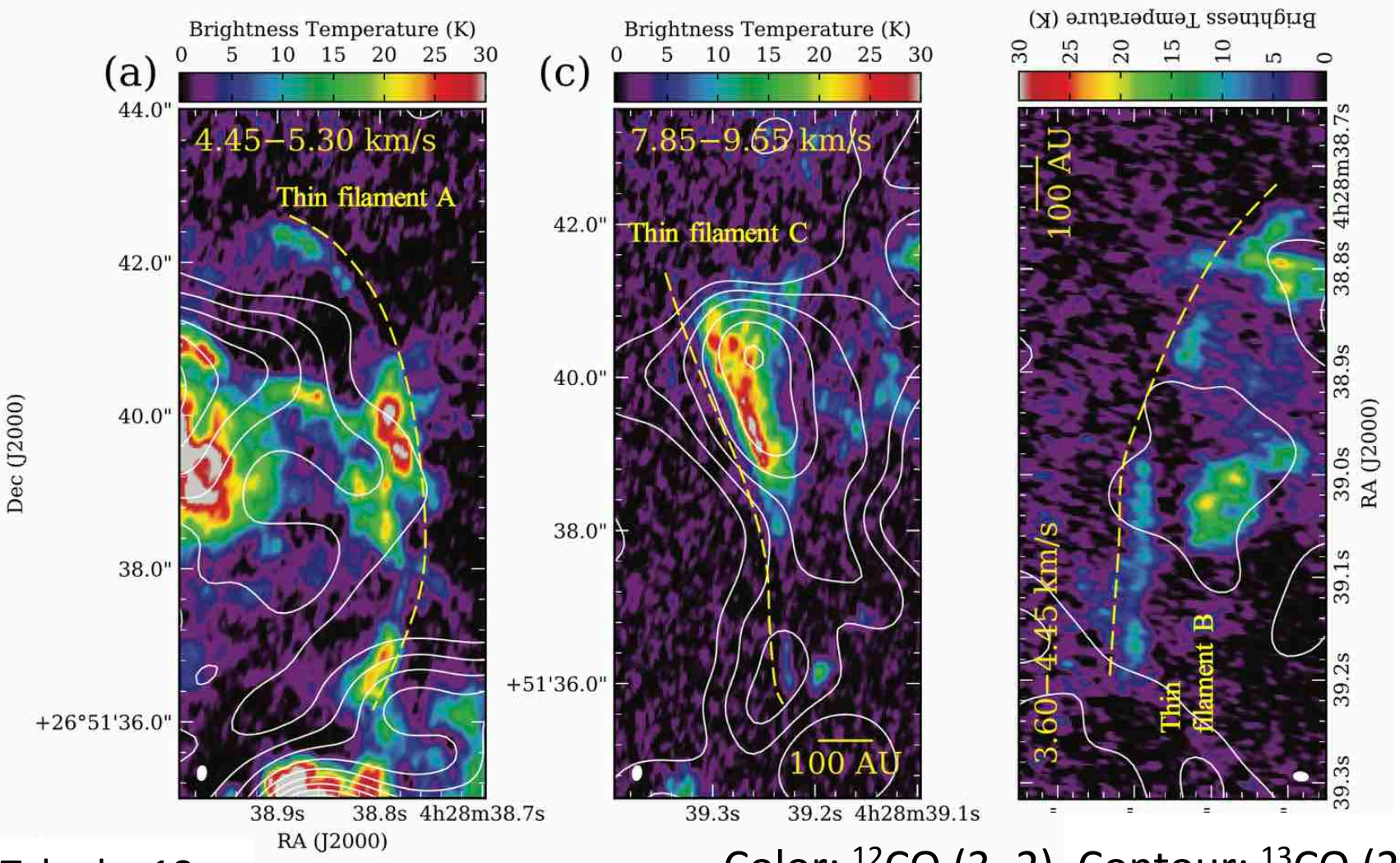


+ :Position of the protostar (MMS-1)

- Warm (>50K) gas around 4-5 km/s
- Many filamentary and clumpy structures

Tokuda+18

Thin filaments in MC27 with the width scale of a few tens AU

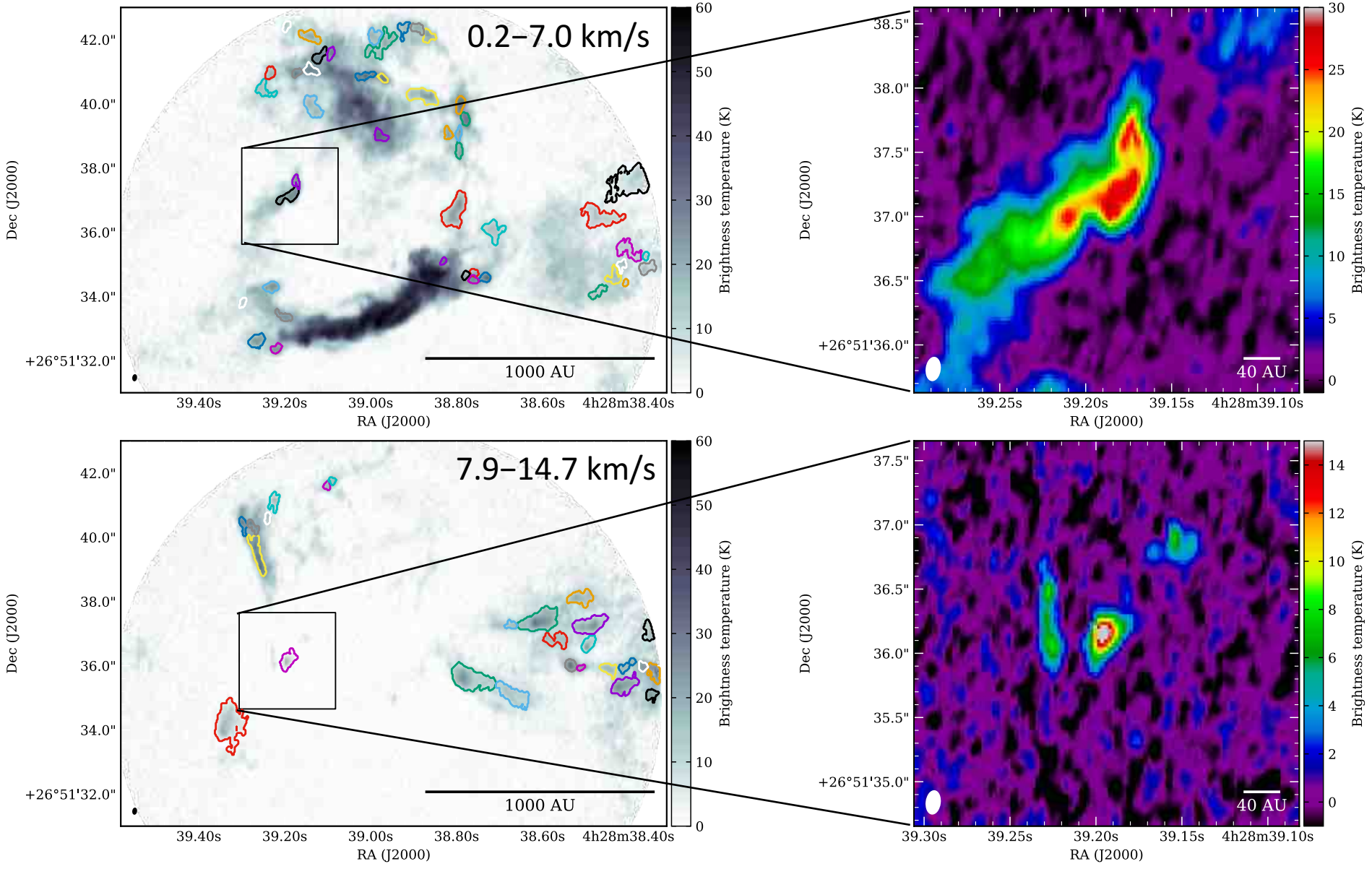


Tokuda+18

Color: ^{12}CO (3–2), Contour: ^{13}CO (2–1)

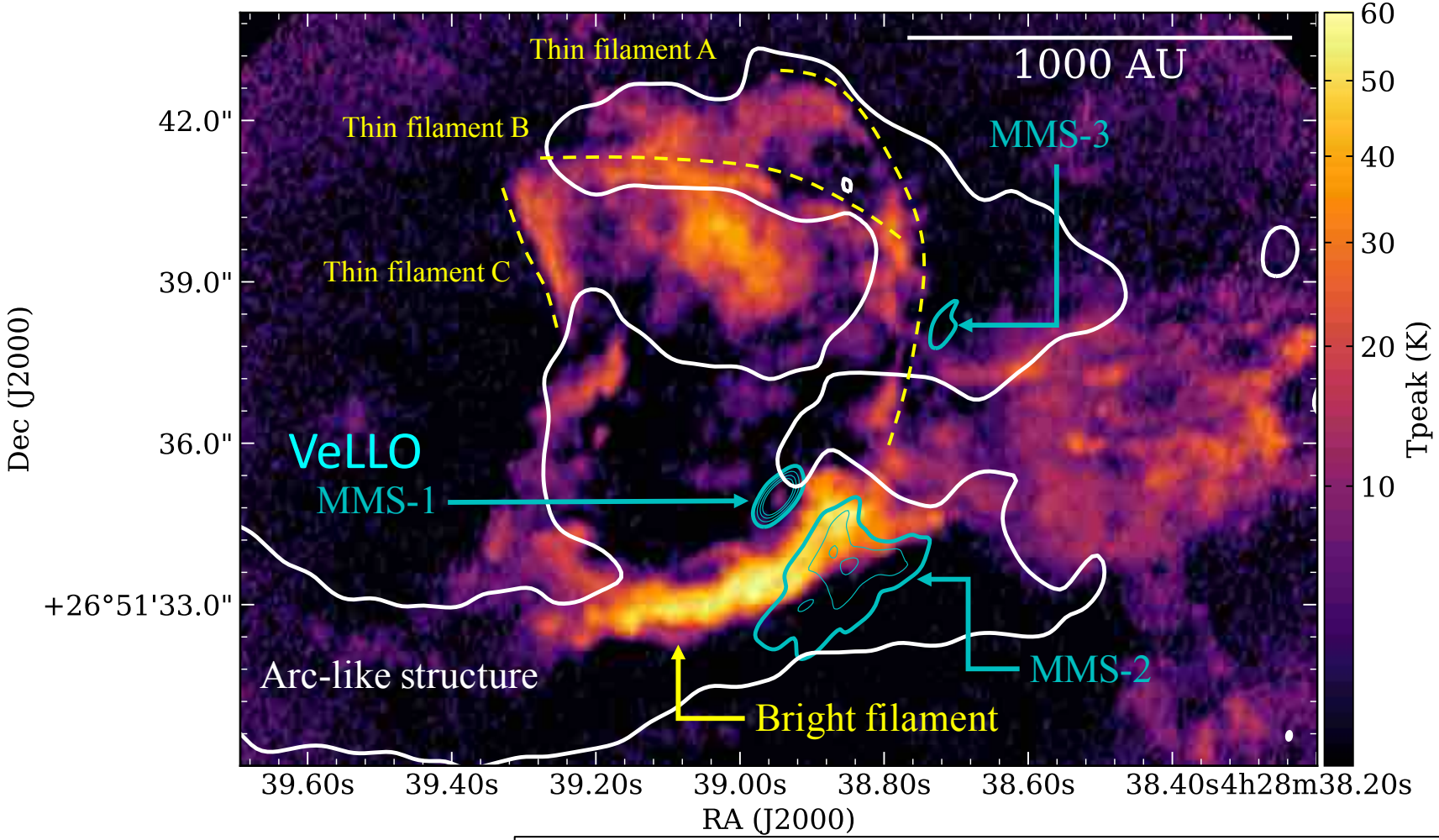
Several very thin filamentary gas => Possible shocked layers ?

Tiny CO clumps



Tokuda+18

Warm CO filamentary gas generated by possible turbulent shocks



Color: ^{12}CO (3-2) peak temp.
White contour : HCO^+ (3-2)
Cyan contour: 0.87mm continuum

Tokuda+18

Possible interpretations:

- Warm gas formed by shock heating
- Thermal instability (c.f., Koyama+00, Aota+13)

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Possible origin: Dynamical (turbulent) motion in this system?