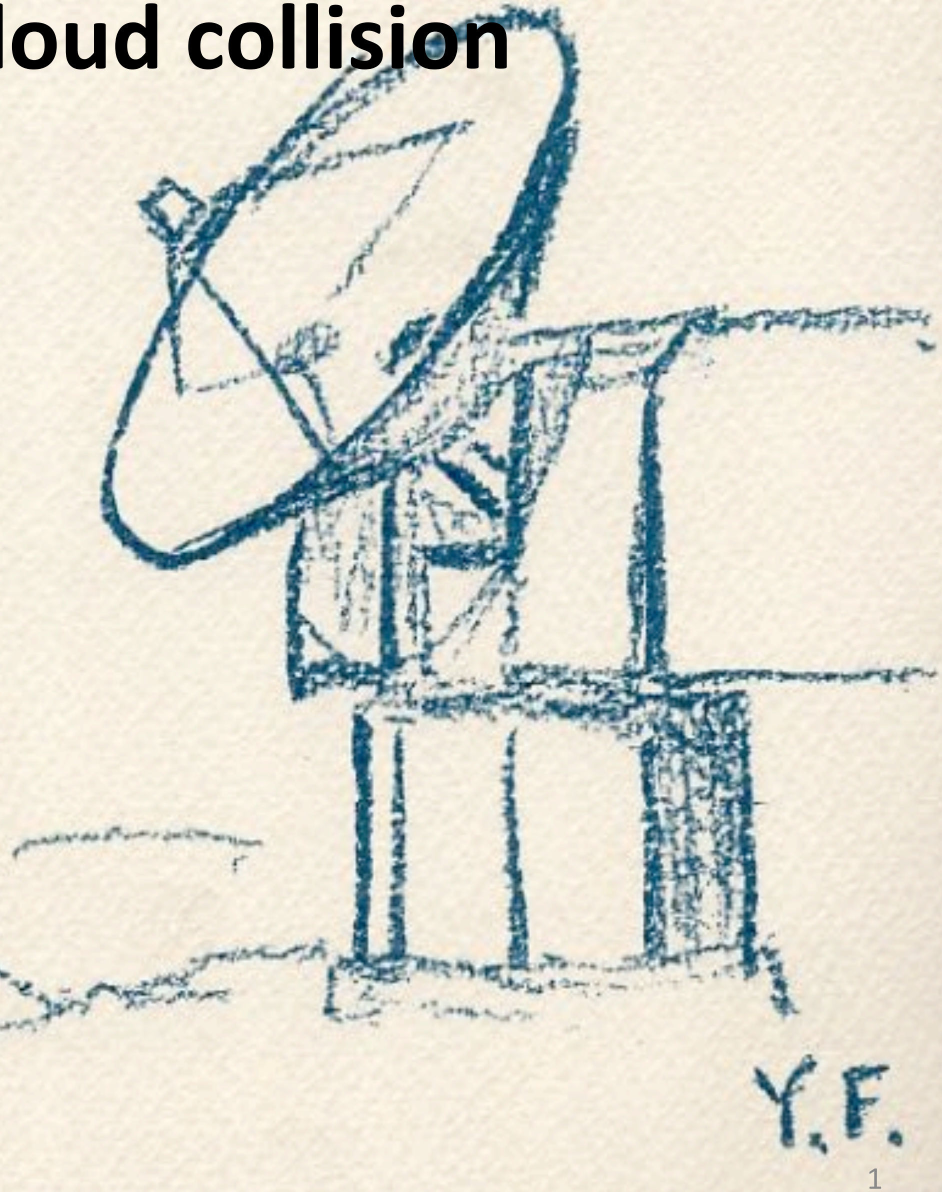
Massive cluster/O star formation triggered by cloud-cloud collision



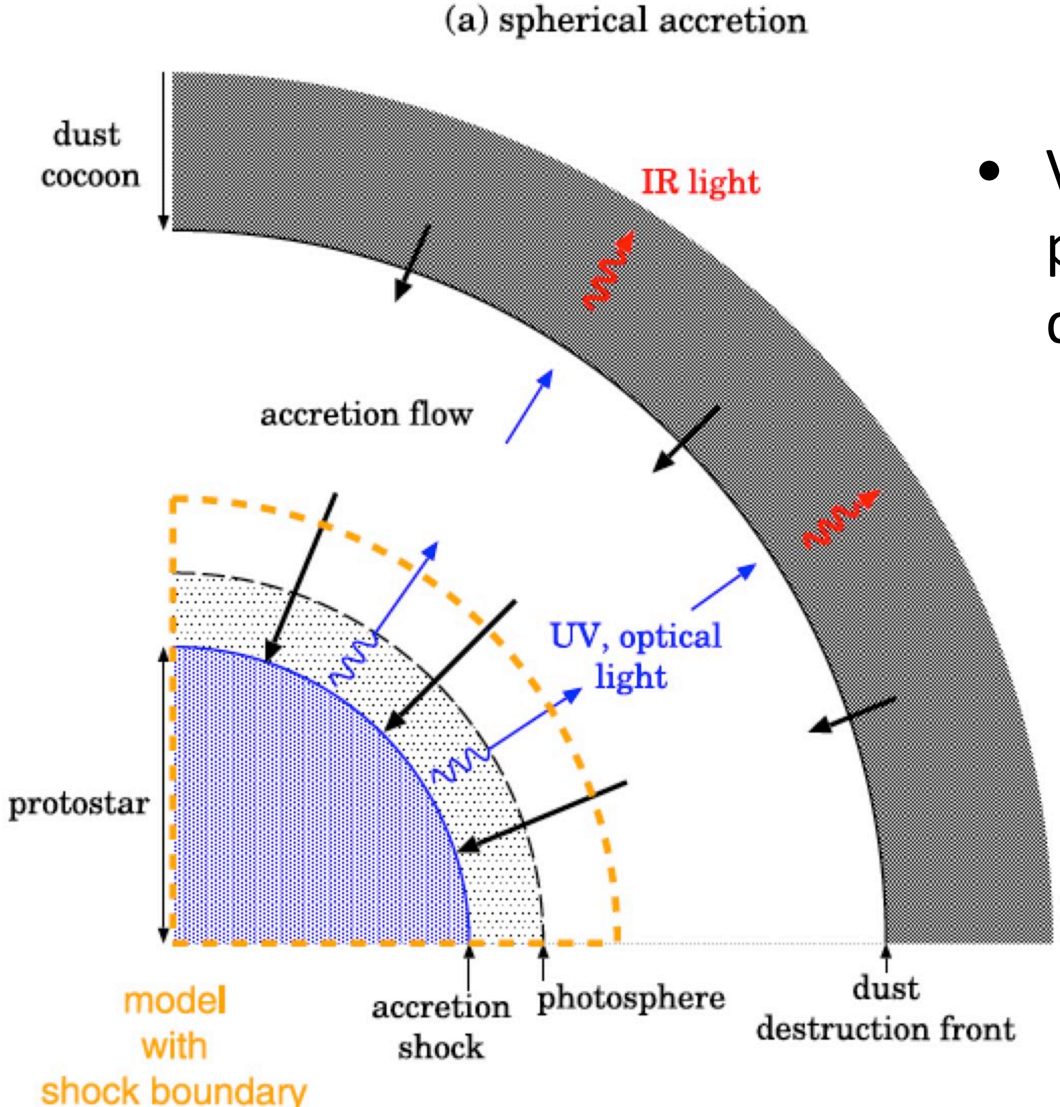
Yasuo Fukui
Nagoya University

ISM Workshop, Bamberg,
March 26-28, 2018

Why cloud-cloud collisions =CCC are rare?

- Collision signatures are subtle,
- Double peak, but not always;CCC looks like a single cloud
- Bridges, not always; linewidth less than cloud linewidth
- Complementary distributions, not always;
- Ionization of the parent clouds is rapid by 10-30 O stars, collision signatures are quickly lost
- Theoretical model for CCC is useful
- Collisions are rare, and O stars are rare
- GMC collision is every 8 Myrs, accounts for O star number (Fujimoto+ 2015; Dobbs+ 2014)

Radiation pressure barrier in high-mass star formation



Hosokawa et al. 2010

- Very strong radiation pressure at the dust destruction front

Lam pressure (ρv^2) > radiation pressure ($L/4\pi r^2 c$)

$$\dot{M} > \frac{L}{cu}$$

O stars and formation mechanism

- Stars having more than 20 $M_\odot$
- Steller wind, strong UV, SNe, etc..

However, it is not known

how the O stars are formed?

- <u>Observational issues</u>

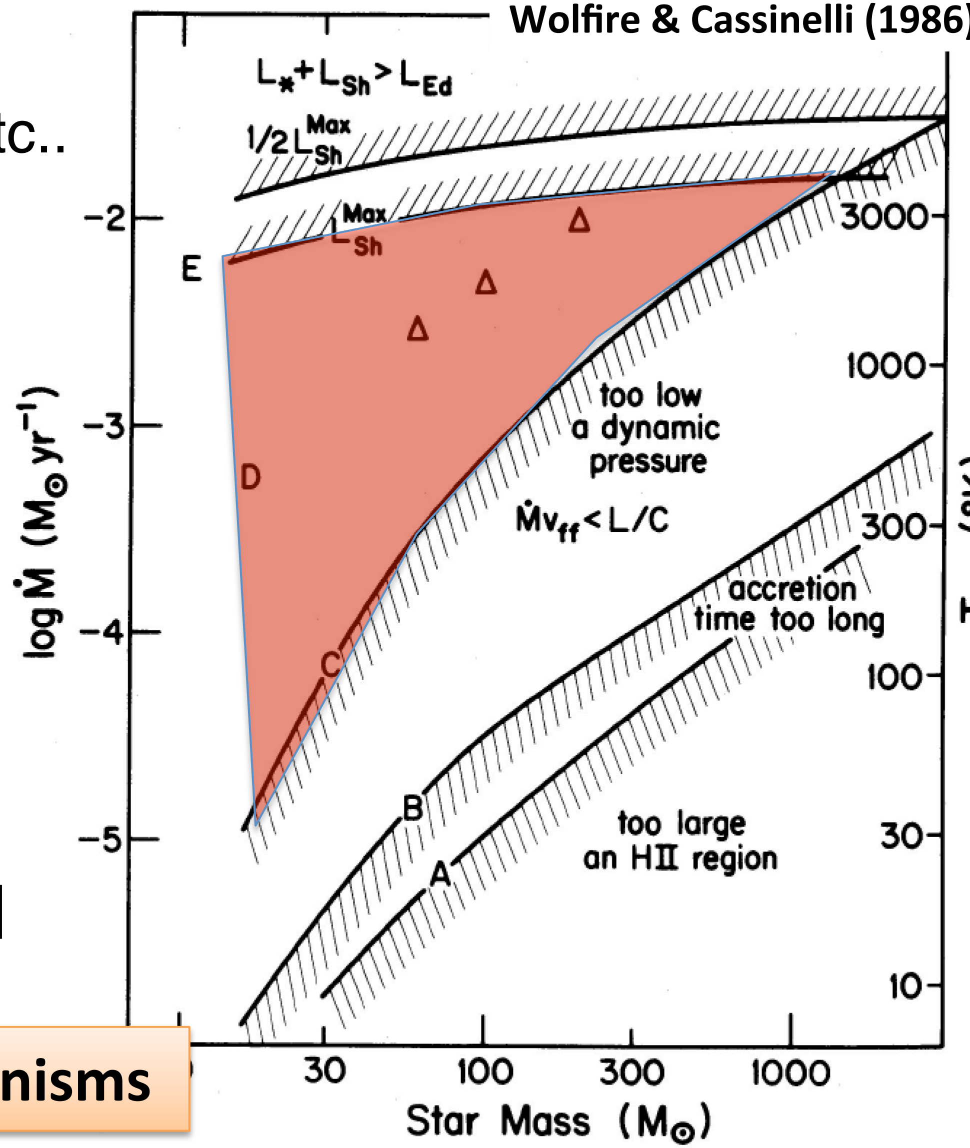
  - few, distant from us etc..
- <u>Theoretical issues</u>

  - large mass accretion rate etc.

  $\sim 10^{-4}$–10^{-3} $M_\odot$/yr

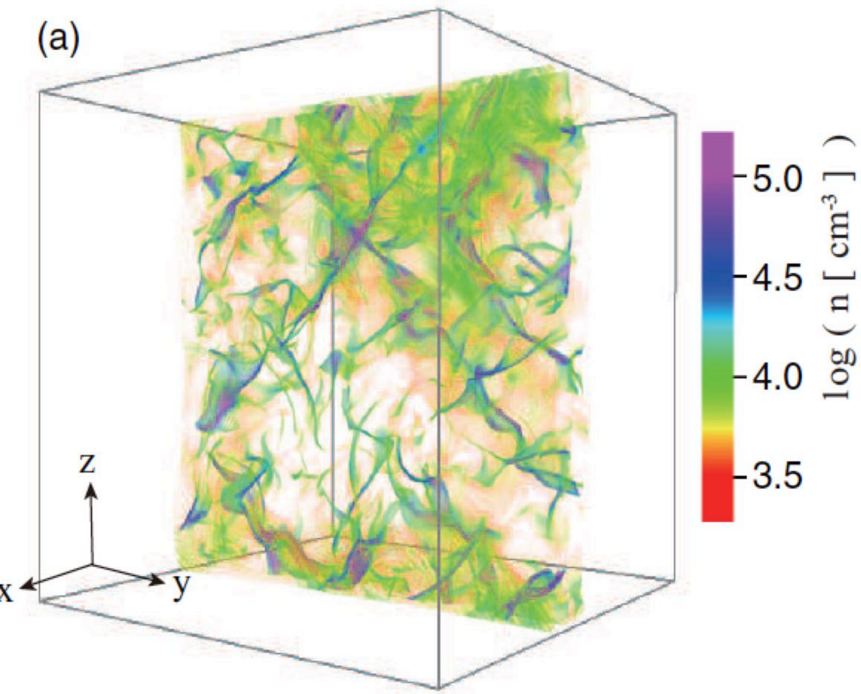
  [~10^{-6} $M_\odot$/yr for low-mass stars]

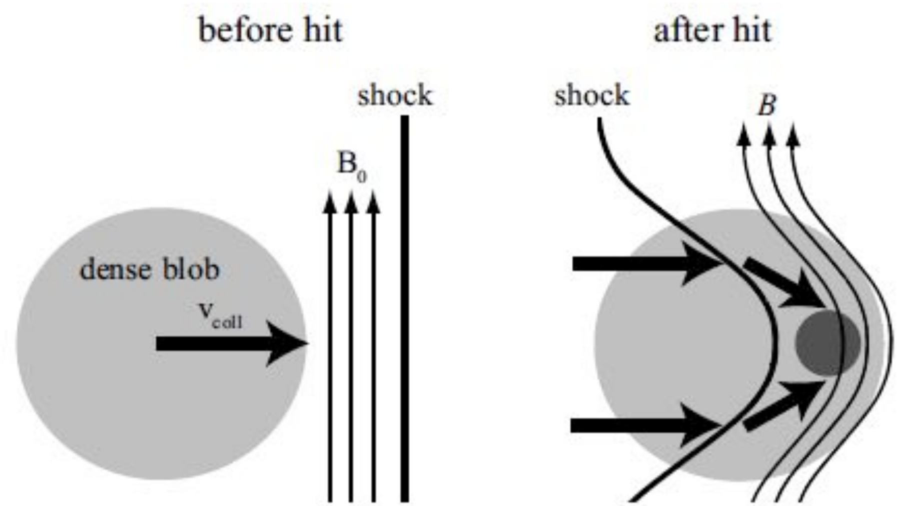
Wolfire & Cassinelli (1986)



We need some triggering mechanisms

CCC triggers formation of massive dense core
MHD simulations



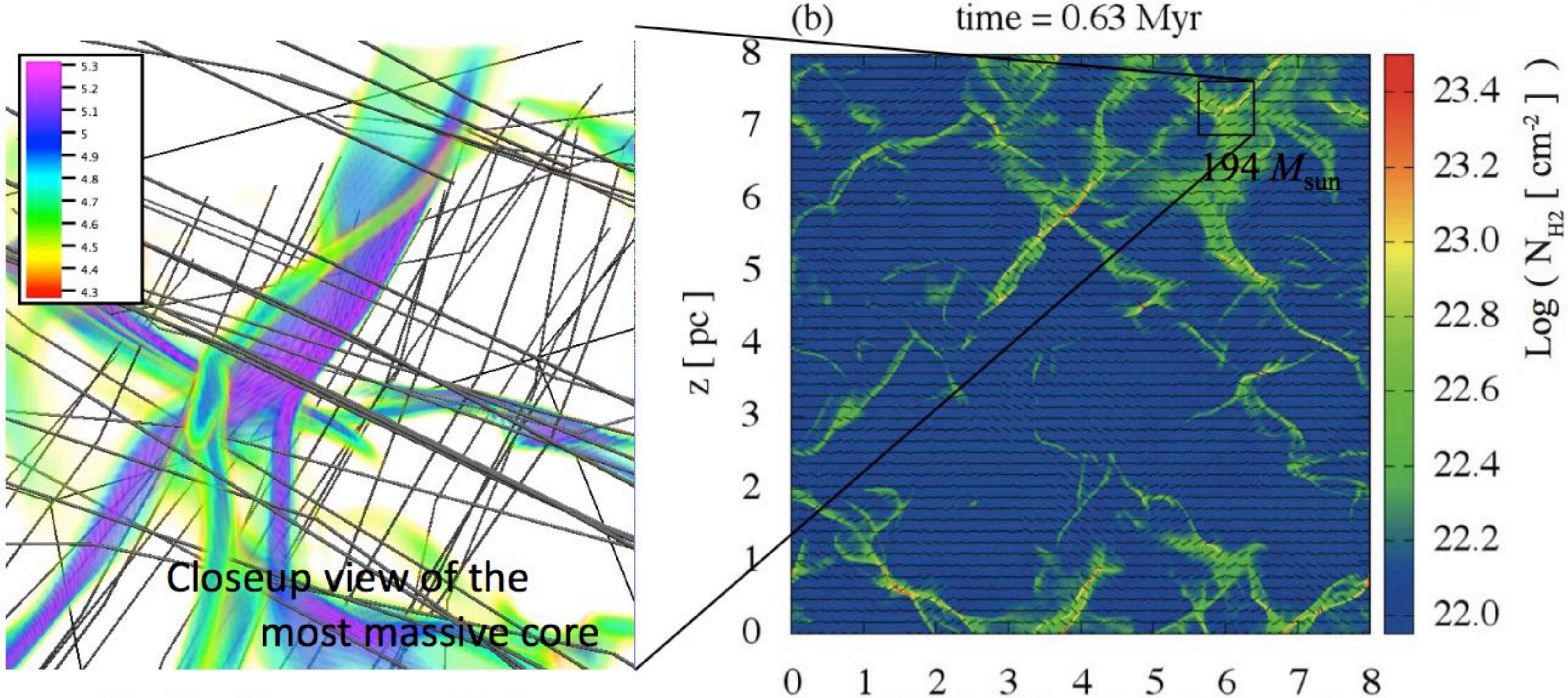


Inoue and Fukui 2013

FIG. 1.— Schematics of the gas stream before (*left*) and after (*right*) the interaction between a shock and a dense blob. Because the deformed shock wave leads to a kink of stream lines across the shock, stream lines are headed toward convex point of the deformed shock wave.

Numerical simulations of Cloud-Cloud Collisions

- Massive, gravitationally bound core with $M = 194\ M_{sun}$ is formed at t = 0.63 Myr.
  - The massive core is embedded in network of massive filaments with $M \sim 10^3\ M_{sun}$



- Large effective Jeans mass is due to strong magnetic field (and turbulence).

$$M_{J,eff} \approx (c_s^3 + c_A^3 + \Delta v^3)/(G^{3/2}\rho^{1/2}) \qquad c_s^3 : c_A^3 : \Delta v^3 = 1 : 333 : 196$$

$|B| = 280\ \mu G$,
$\Delta v = 1.2$ km/s,
$\langle n \rangle = 0.8 \times 10^5\ cm^{-3}$

→ Large mass accretion rate: $dM/dt \approx (c_s^3 + c_A^3 + \Delta v^3)/G$

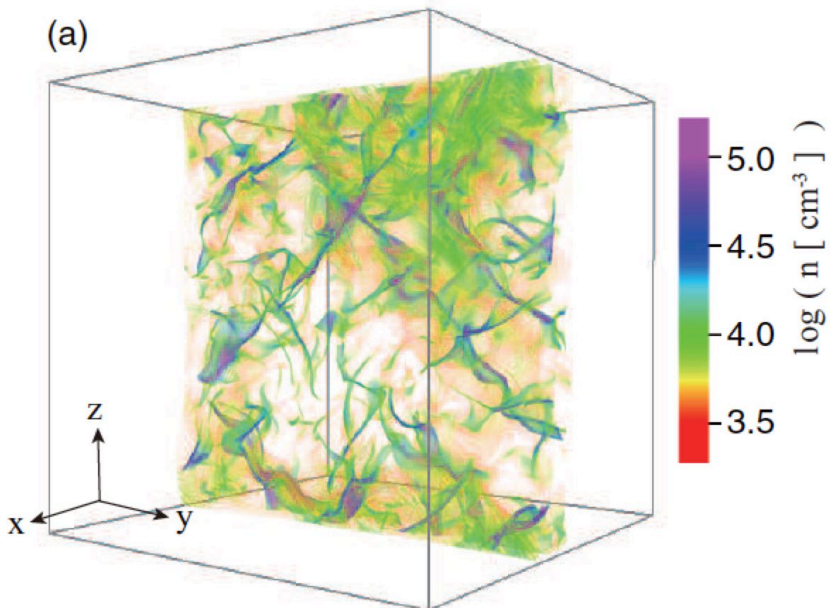
$= 4 \times 10^{-3}\ M_{sun}/yr$

Inoue & Fukui 13, ApJL

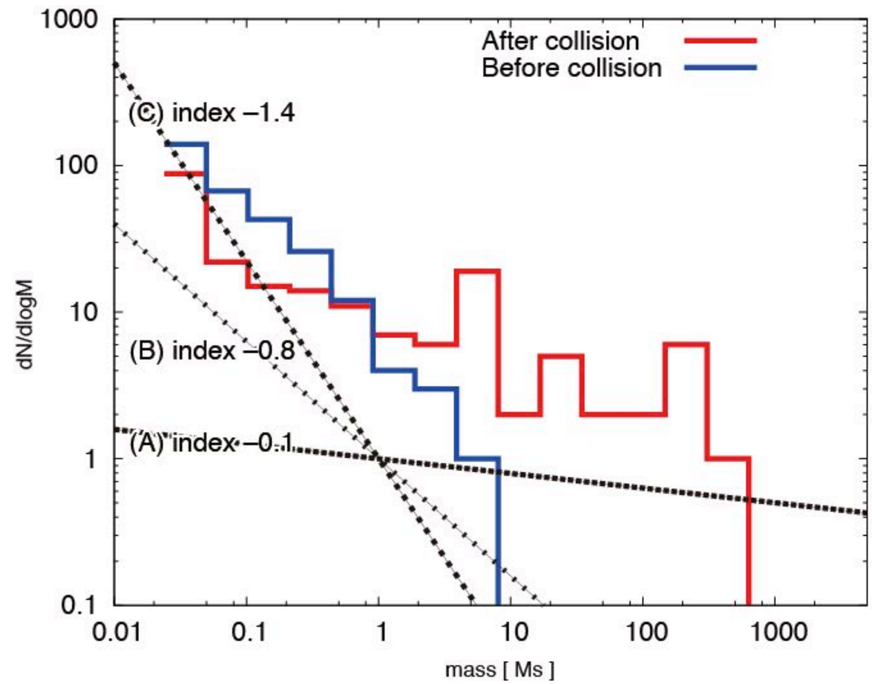
courtesy by Inoue-san

We need CCC to form O stars

Core mass function by Inoue & Fukui (2013)

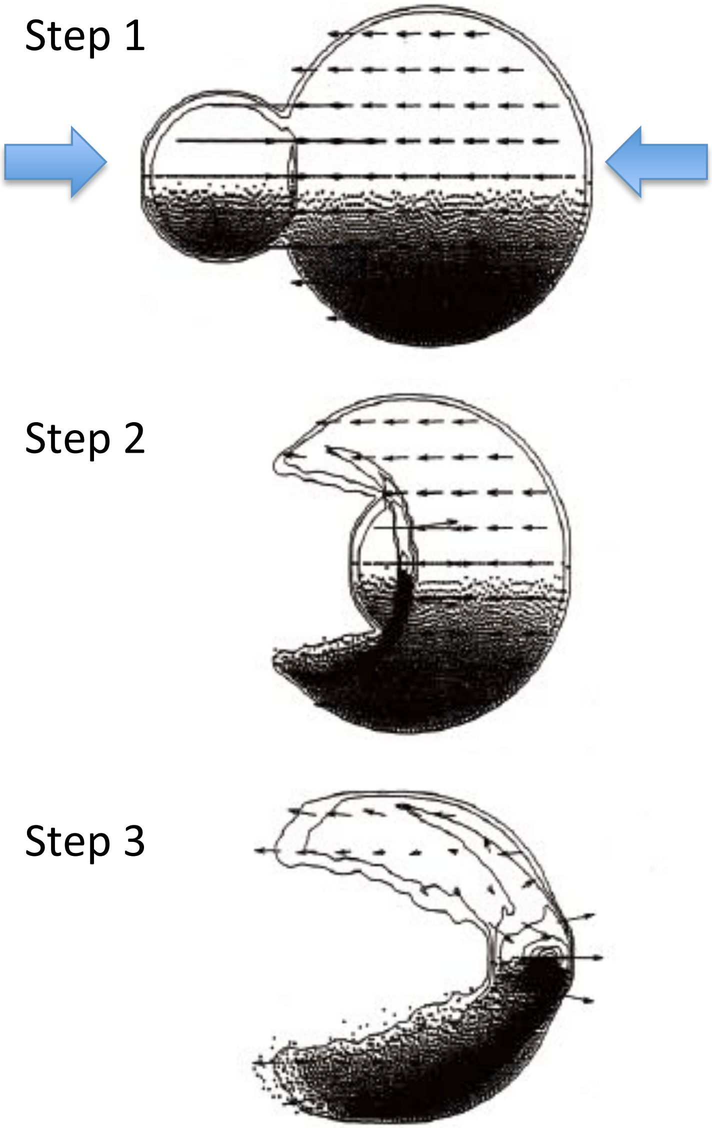


Inoue & Fukui (2013)

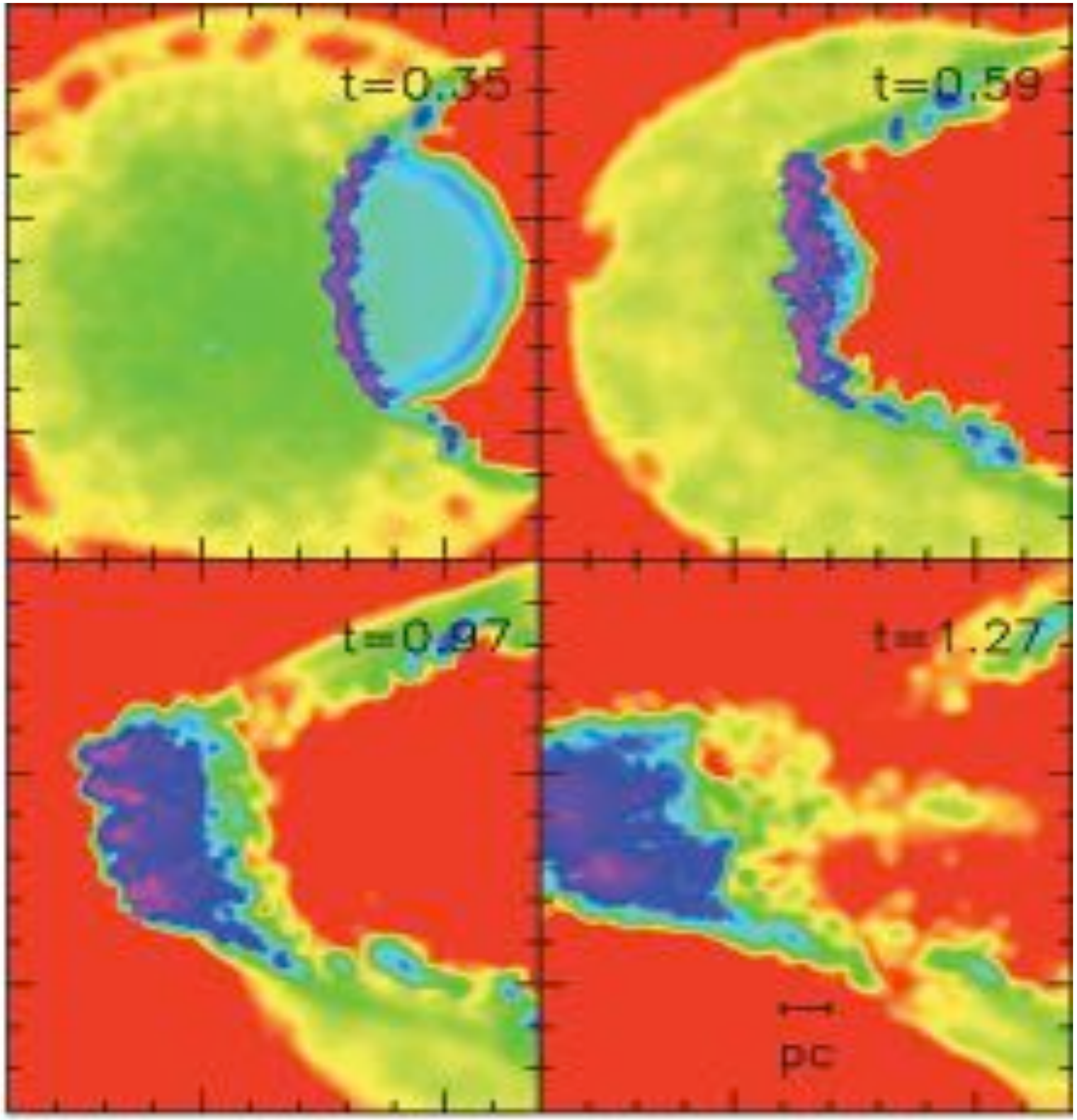


- Top heavy core mass function is reproduced in the MHD calculations.

Numerical simulations of Cloud-Cloud Collisions

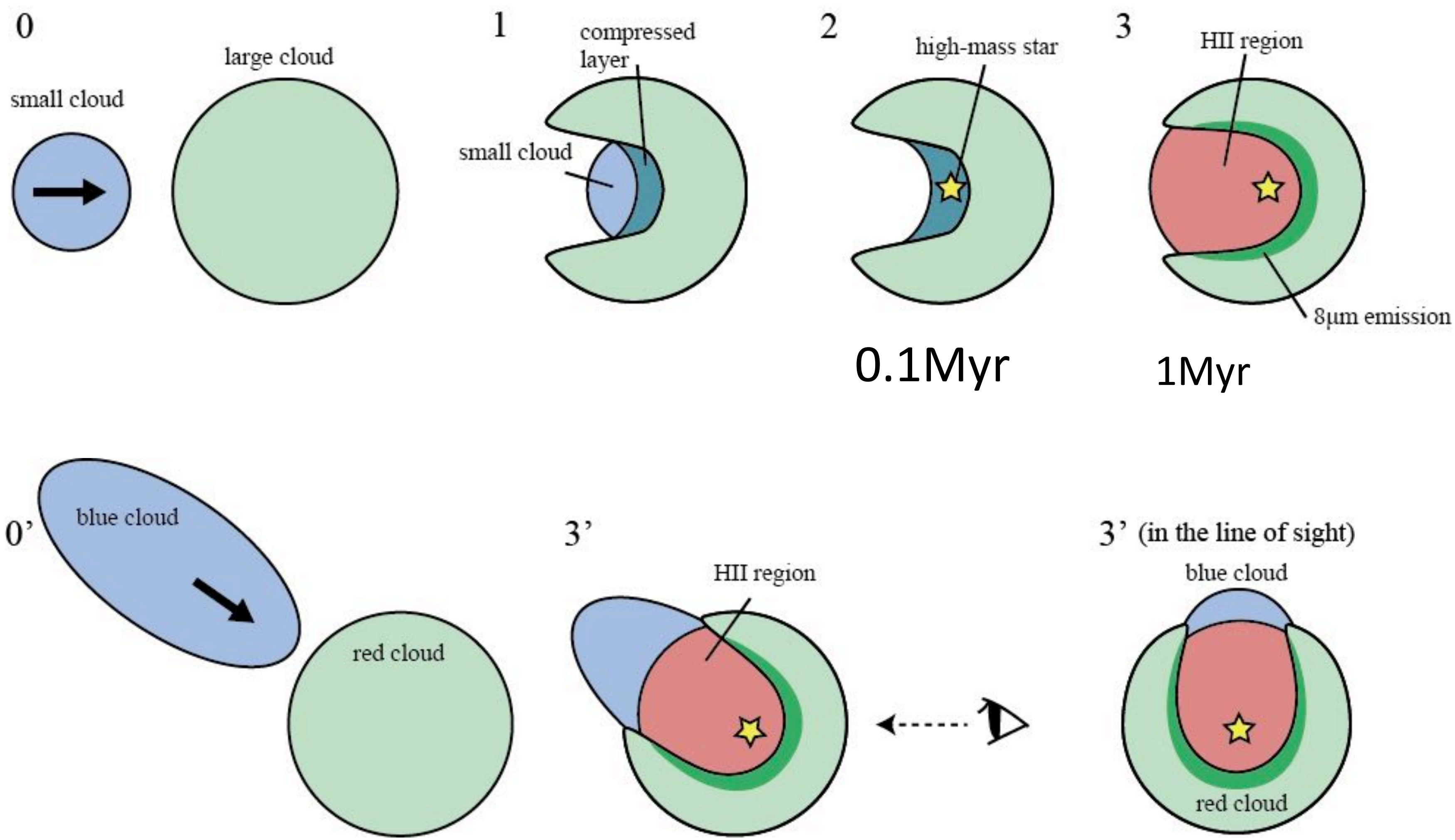


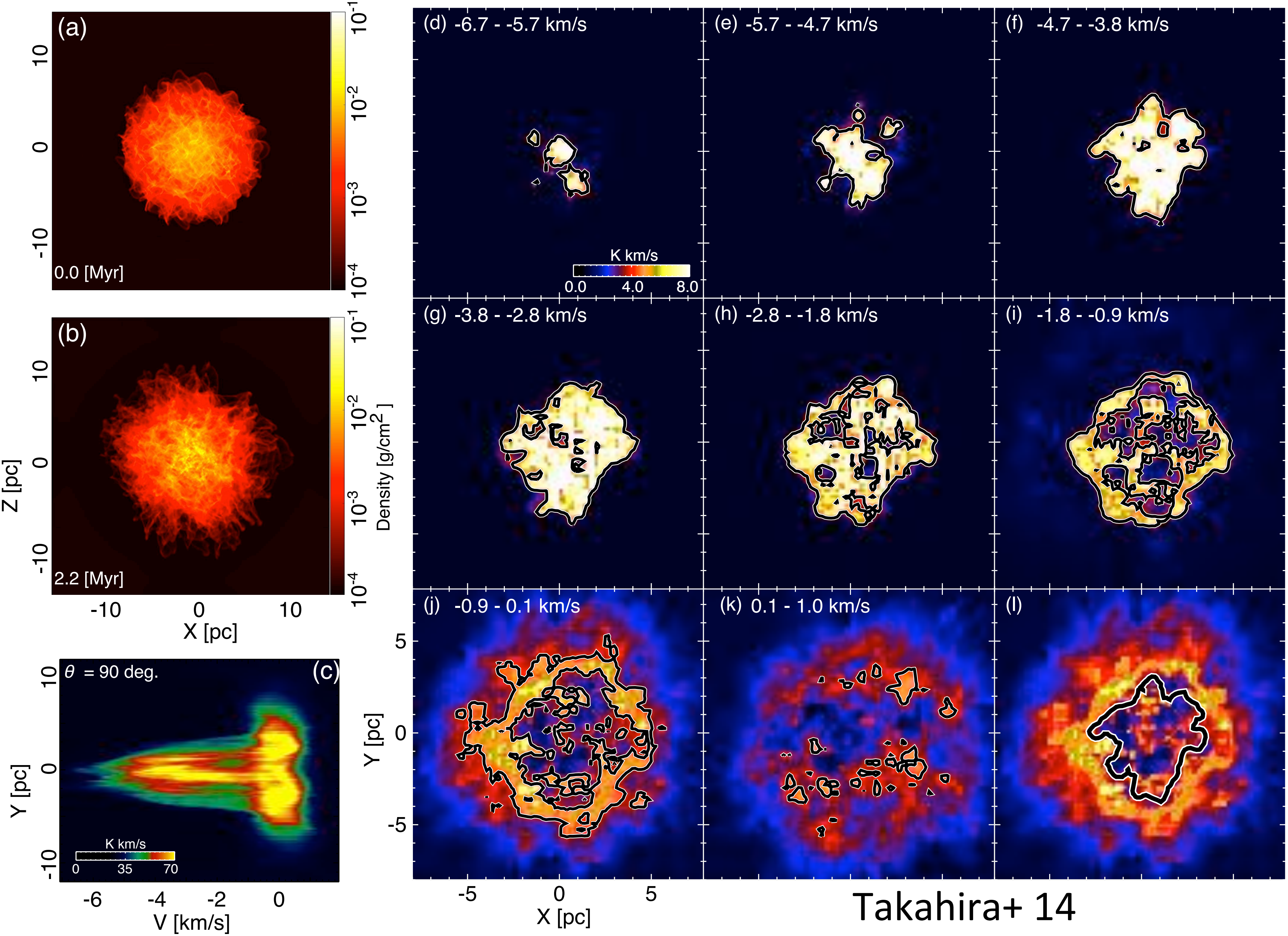
Habe & Ohta 92



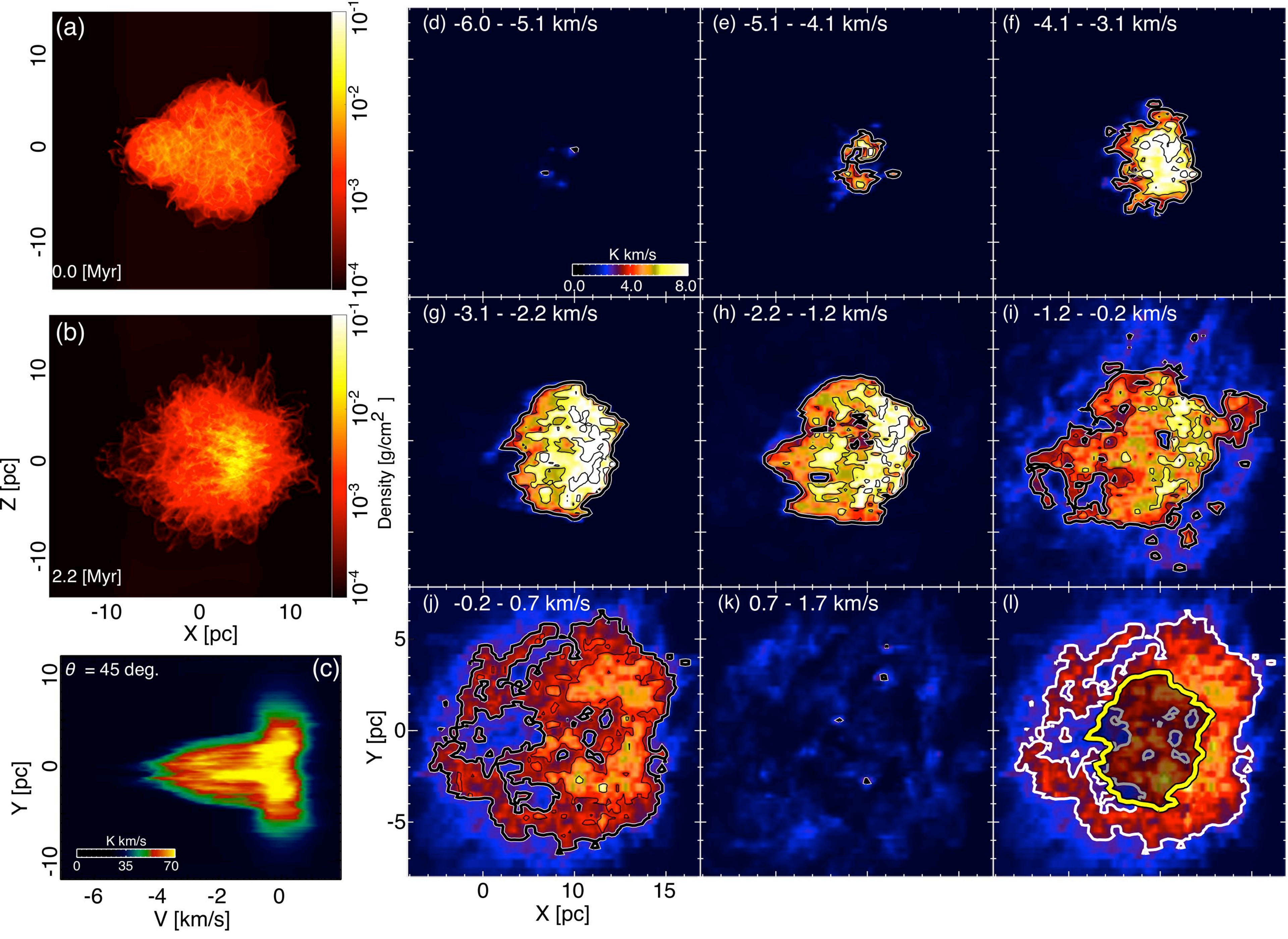
Anathpindika+12

Cloud-cloud collision




(a)
0.0 [Myr]
(b)
2.2 [Myr]
Z [pc]
X [pc]
Density [g/cm^2]
(c)
θ = 90 deg.
K km/s
Y [pc]
V [km/s]
(d) -6.7 - -5.7 km/s
(e) -5.7 - -4.7 km/s
(f) -4.7 - -3.8 km/s
(g) -3.8 - -2.8 km/s
(h) -2.8 - -1.8 km/s
(i) -1.8 - -0.9 km/s
(j) -0.9 - 0.1 km/s
(k) 0.1 - 1.0 km/s
(l)
K km/s
Y [pc]
X [pc]

Takahira+ 14



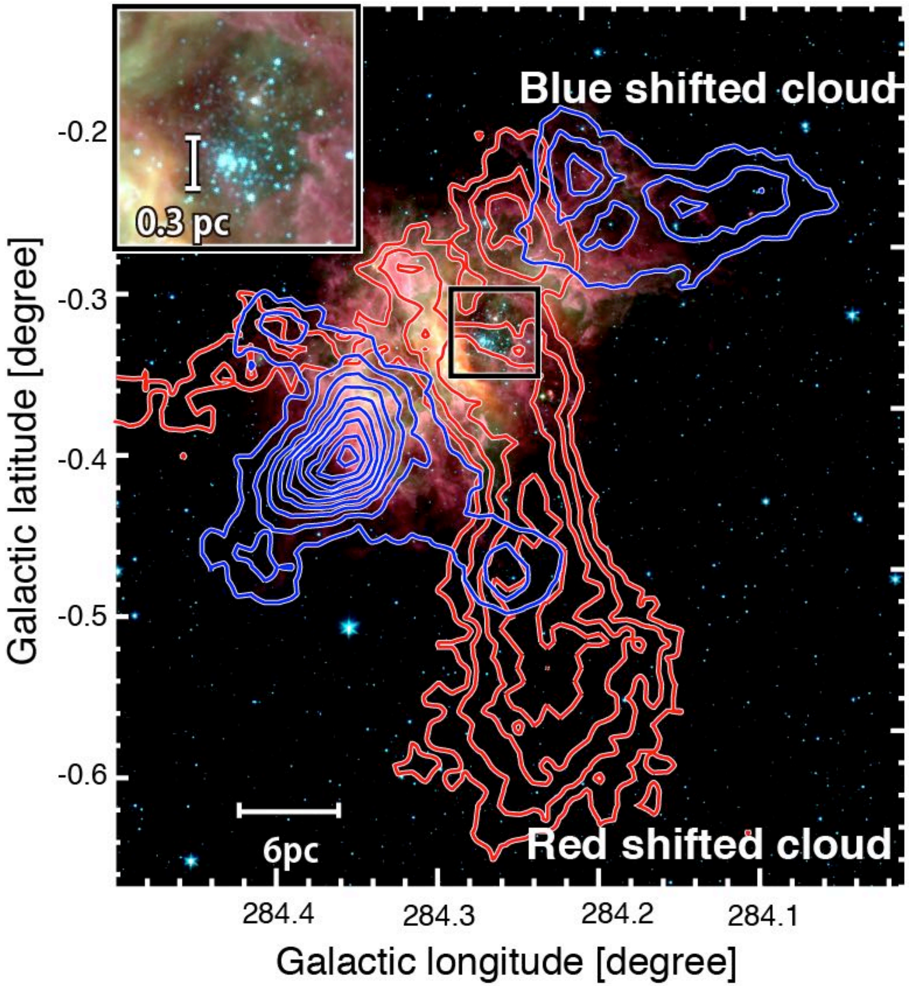
(a)
0.0 [Myr]
(b)
2.2 [Myr]
Z [pc]
X [pc]
Density [g/cm^2]
10^{-1}
10^{-2}
10^{-3}
10^{-4}
(c)
θ = 45 deg.
Y [pc]
V [km/s]
K km/s
0
35
70
(d) -6.0 - -5.1 km/s
(e) -5.1 - -4.1 km/s
(f) -4.1 - -3.1 km/s
K km/s
0.0
4.0
8.0
(g) -3.1 - -2.2 km/s
(h) -2.2 - -1.2 km/s
(i) -1.2 - -0.2 km/s
(j) -0.2 - 0.7 km/s
(k) 0.7 - 1.7 km/s
(l)
Y [pc]
X [pc]

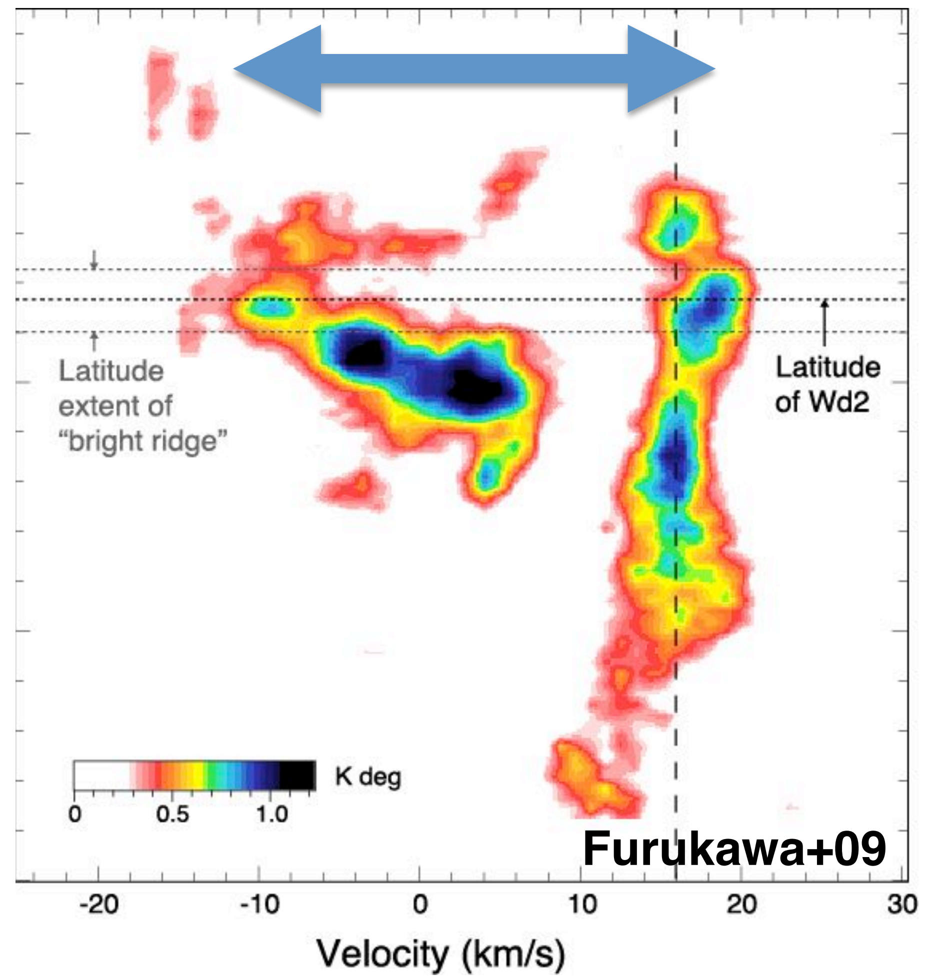
Observations of Cloud-Cloud Collisions, 30 cases

- **Super star clusters**
  Westerlund 2, NGC 3603, RCW 38, DBS[29003]179 etc.
  (Furukawa+09; Ohama+10; Fukui+14; Fukui+18 etc.)
- **Star burst regions**
  NGC 6334 & NGC 6357 (Fukui+18), GM24 (Fukui+18)
- **HII regions**
  M17, M8 (Nishimura+18), M 20 (Torii+11), M42/M43 (Fukui+18)
  RCW120 (Torii+16), RCW79, RCW166 (Ohama+18)
  Vela Molecular Ridge RCW36, 34, 32 (Sano+ 2018 etc.) etc.
- **RCW136, N44, N159E/W in LMC, NGC604 in M33, The Antennae**
  R136 (Fukui, Tsuge+ 2017) , N44 (Tsuge+ 2018),
  NGC604 (Tachihara et al. 2018) etc.

- **PASJ special issue, Aril 2018**
  “Triggered Star Formation by CCC”,

SSC: Westerlund 2 (Furukawa+09; Ohama+10)



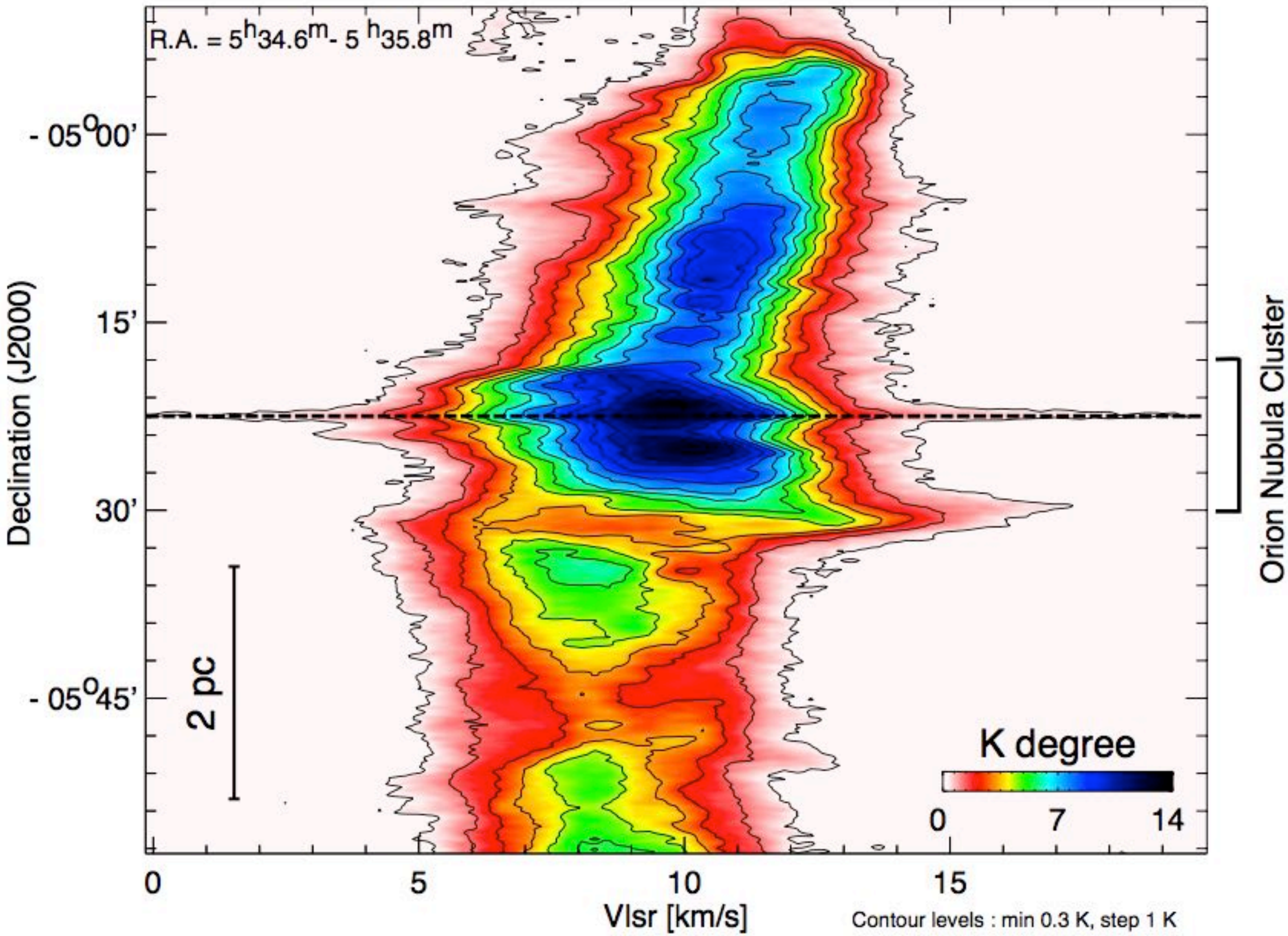


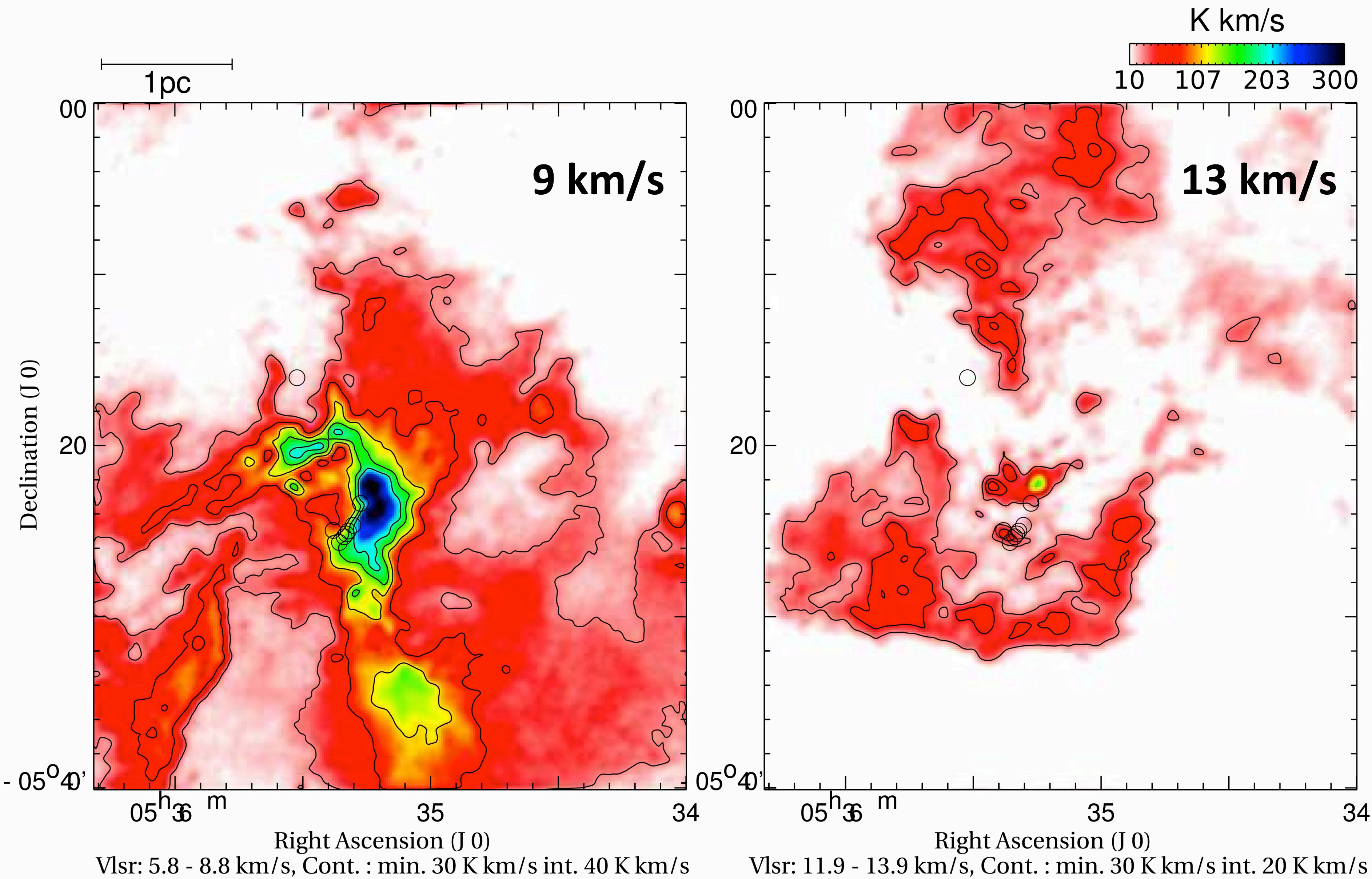
- Two GMCs (red/blue) are complementary distributed toward Westerlund2.
- The velocity separation of the two clouds is 15–25 km s^{-1}, can not be bound with the gravity.

M42

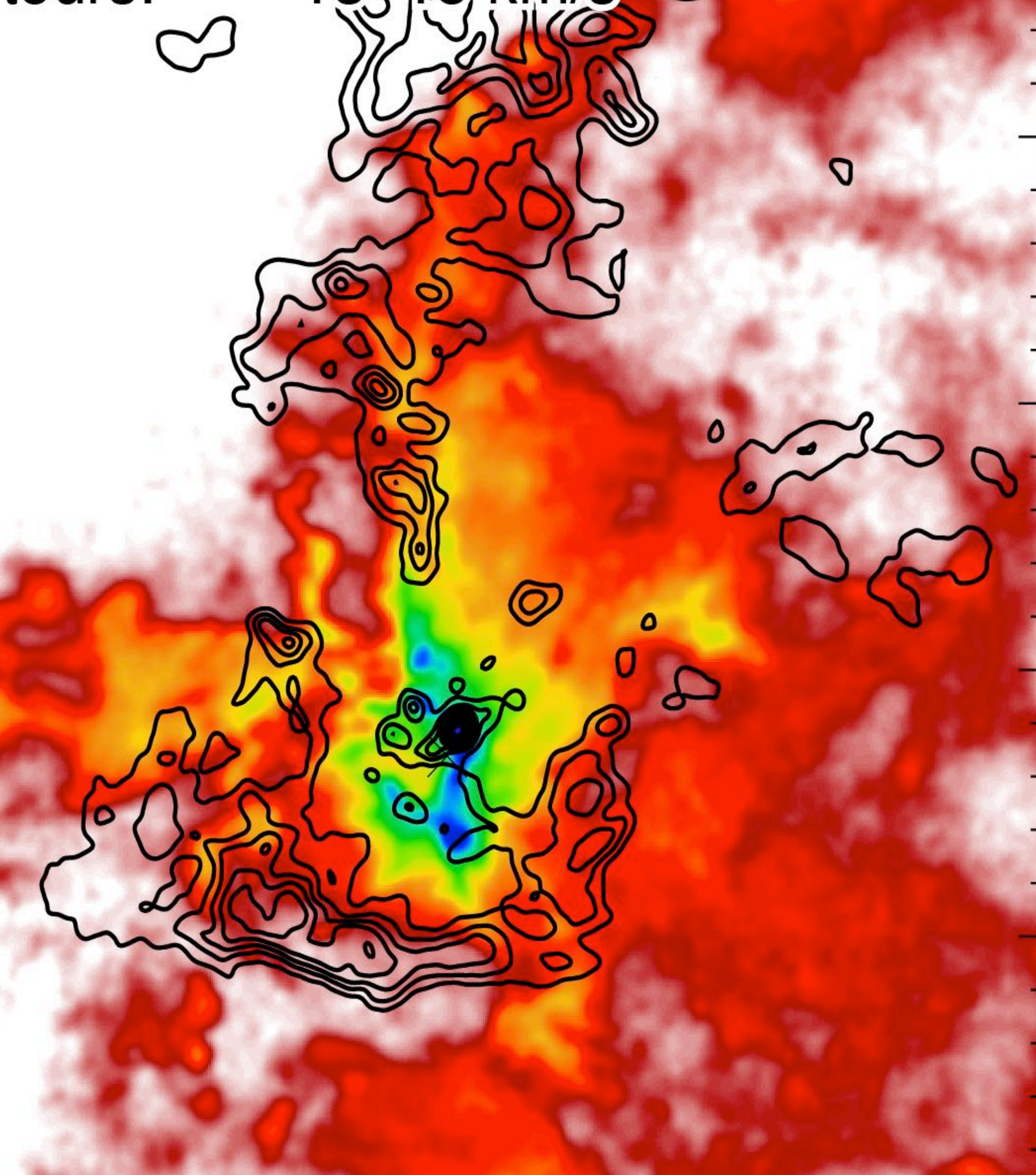
NASA

M42 CO J=1-0 45m telescope

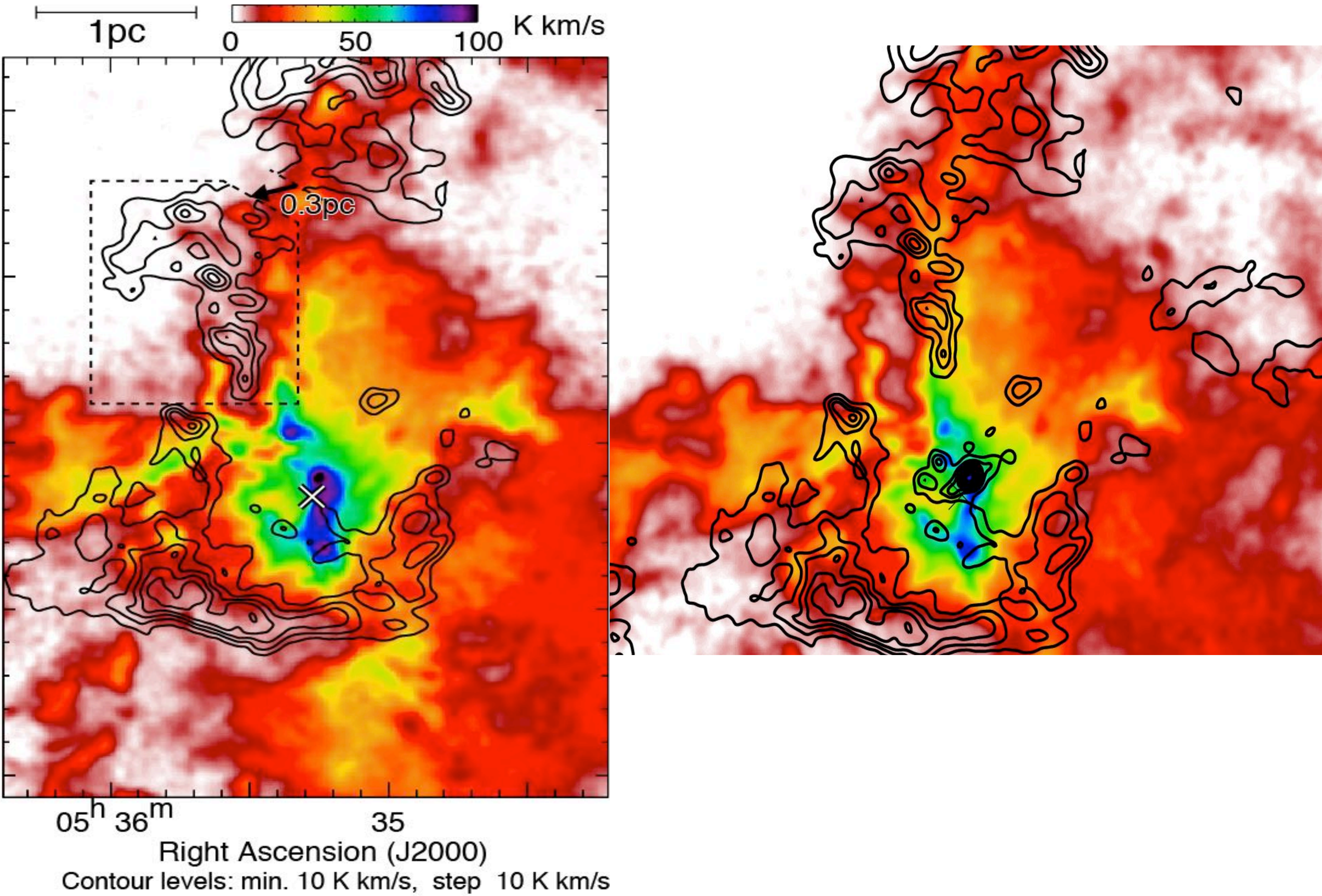




K km/s
10
107
203
300
1pc
9 km/s
13 km/s
00
20
- 05°40'
05°40'
05h36m
35
34
Declination (J 0)
Right Ascension (J 0)
Vlsr: 5.8 - 8.8 km/s, Cont. : min. 30 K km/s int. 40 K km/s
Right Ascension (J 0)
Vlsr: 11.9 - 13.9 km/s, Cont. : min. 30 K km/s int. 20 K km/s

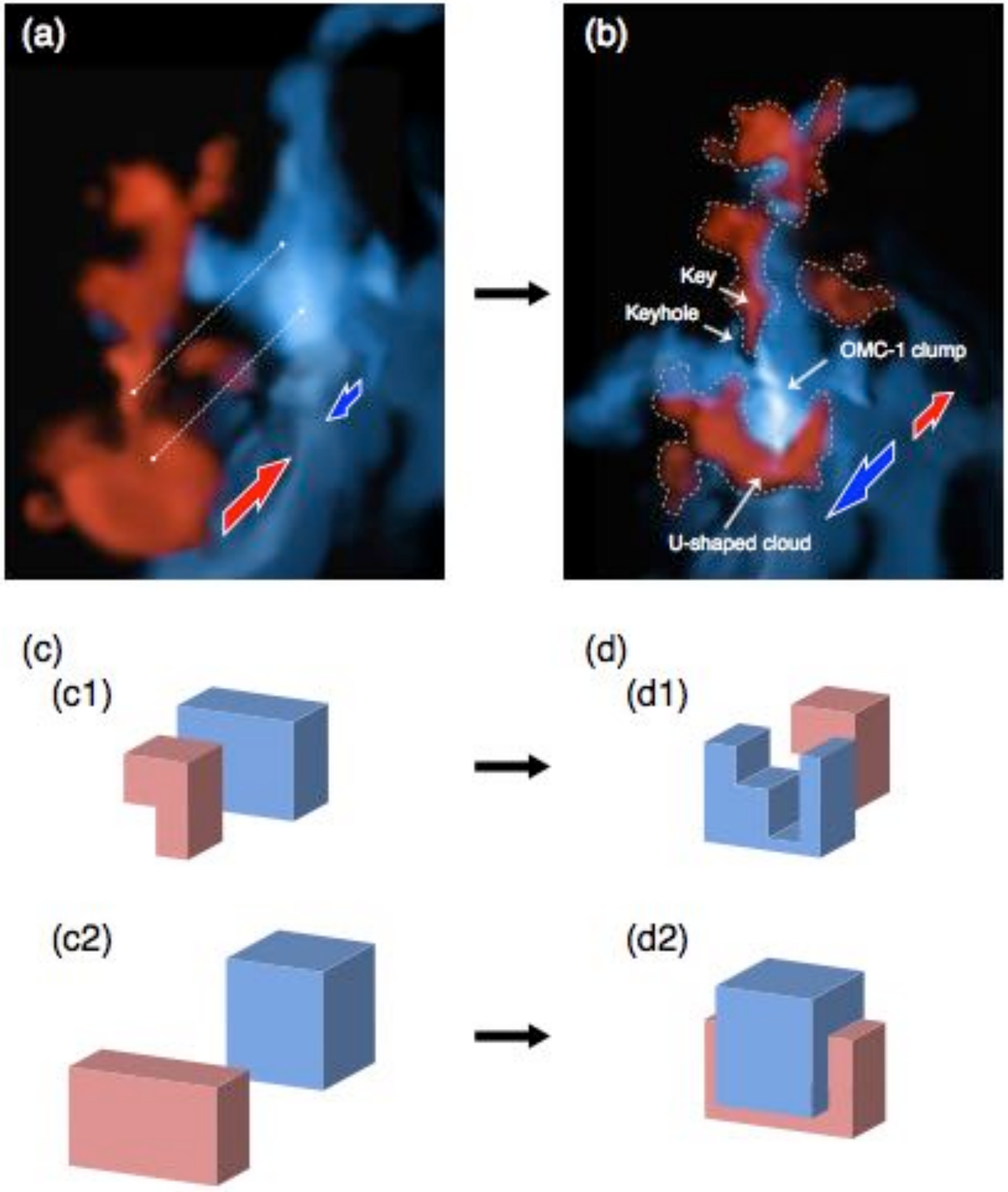


2 ^{12}COJ=1-0

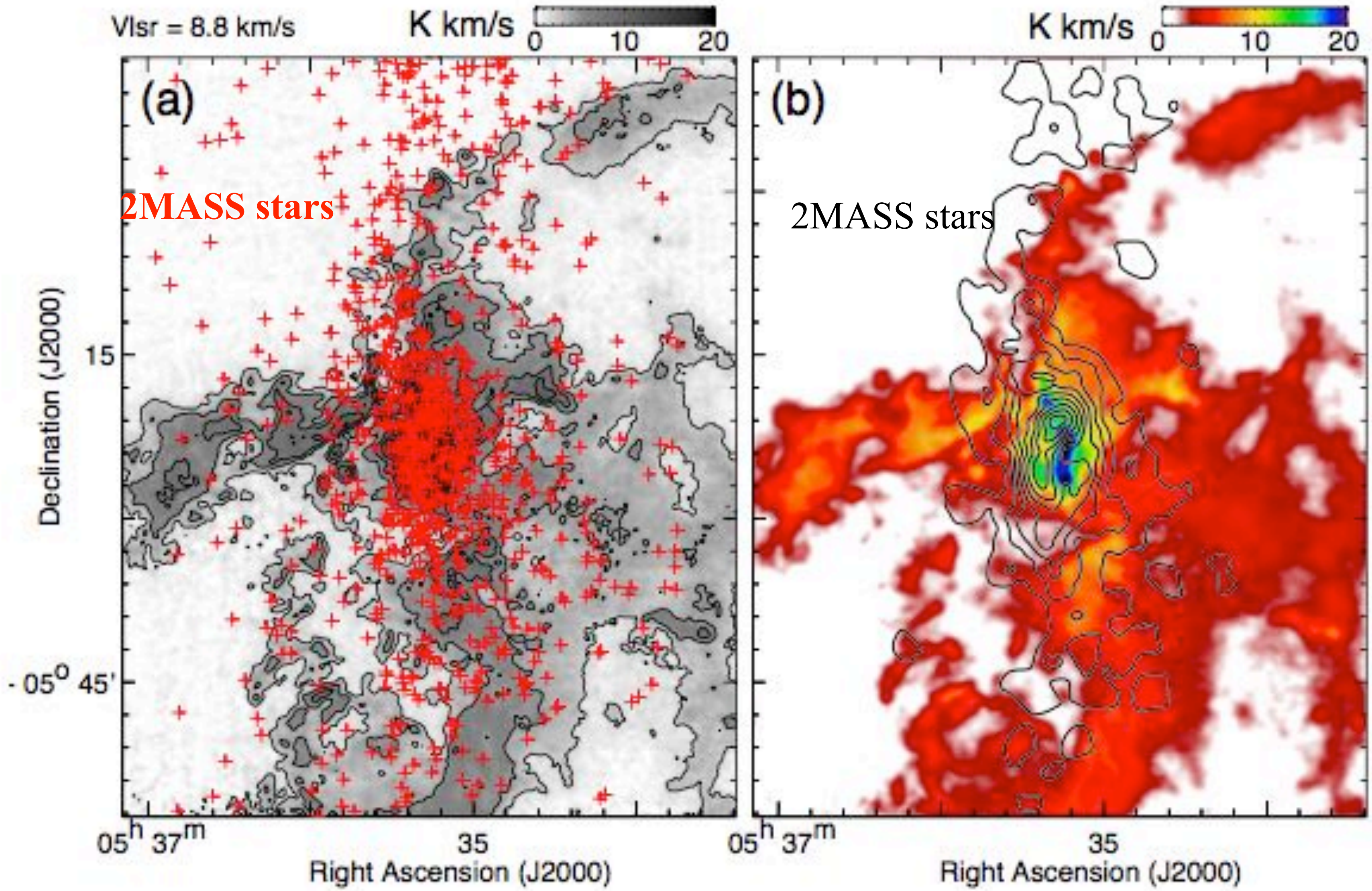


1pc
0
50
100
K km/s
0.3pc
05h 36m
35
Right Ascension (J2000)
Contour levels: min. 10 K km/s, step 10 K km/s

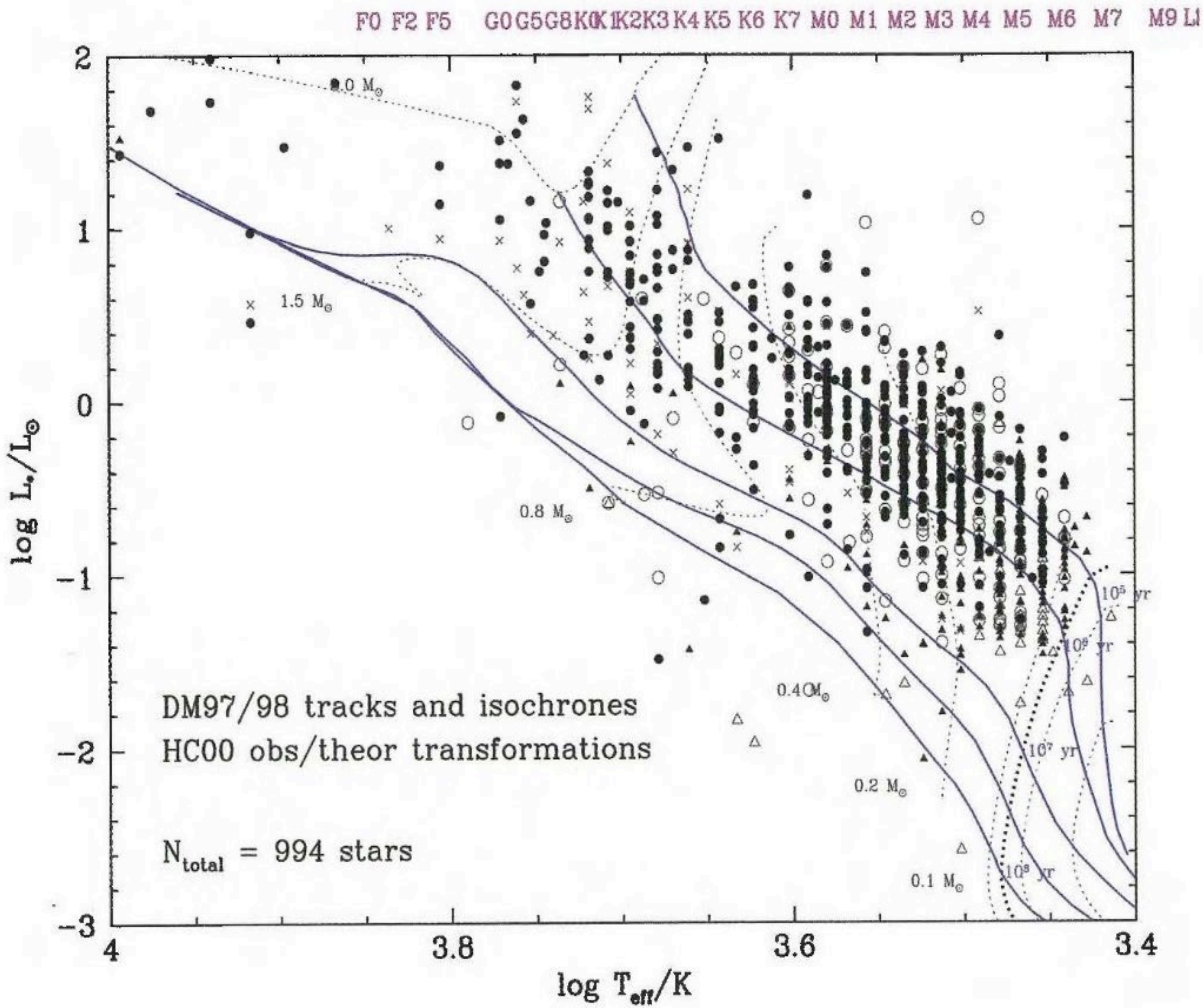
M42



M42

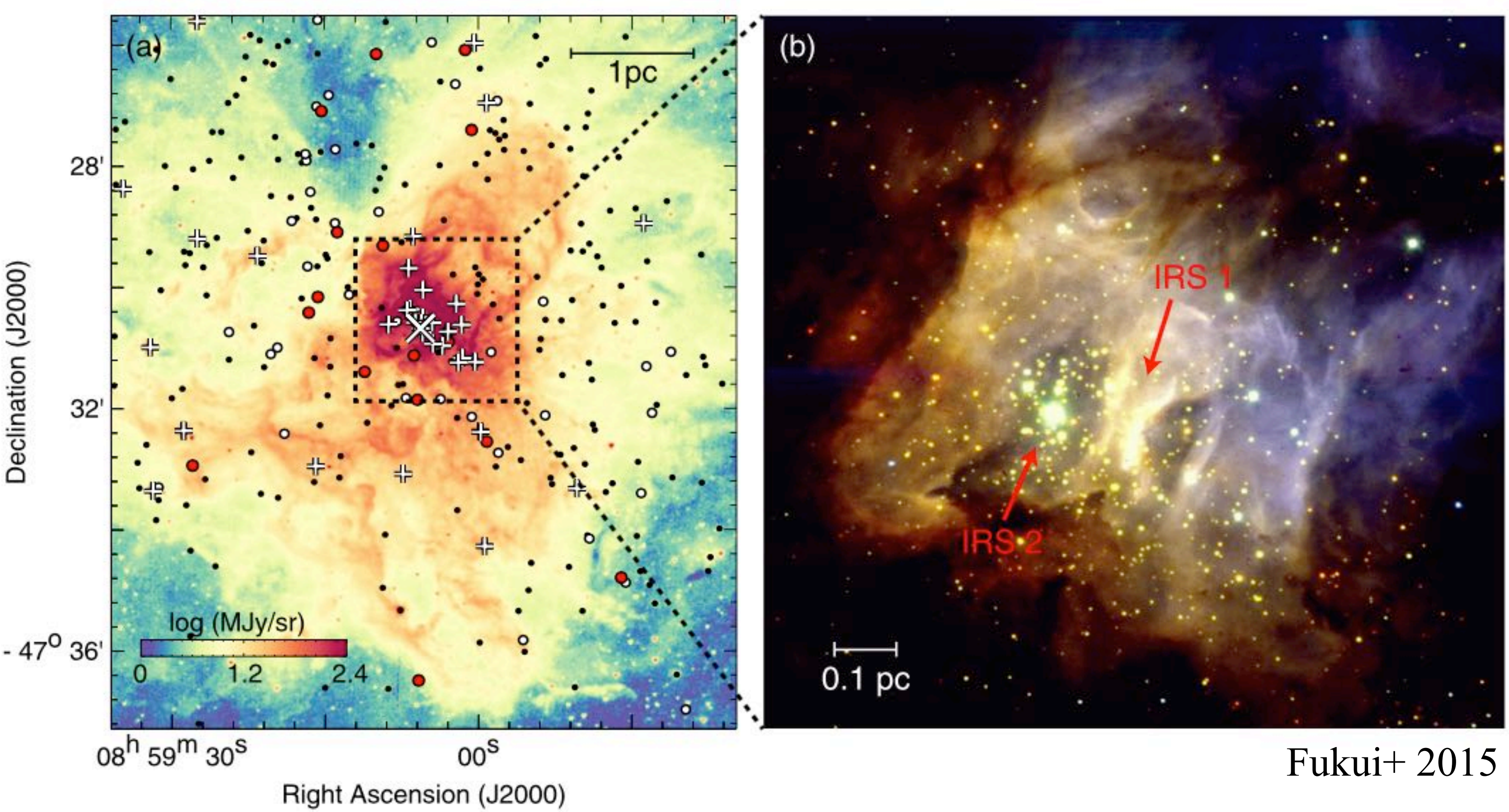


Vlsr = 8.8 km/s
K km/s
0
10
20
(a)
2MASS stars
Declination (J2000)
15
- 05° 45'
05h 37m
35
Right Ascension (J2000)
K km/s
0
10
20
(b)
2MASS stars
05h 37m
35
Right Ascension (J2000)



Hirainbrand+ 2000?

RCW 38



Fukui+ 2015

Spitzer/IRAC 3.6 μm

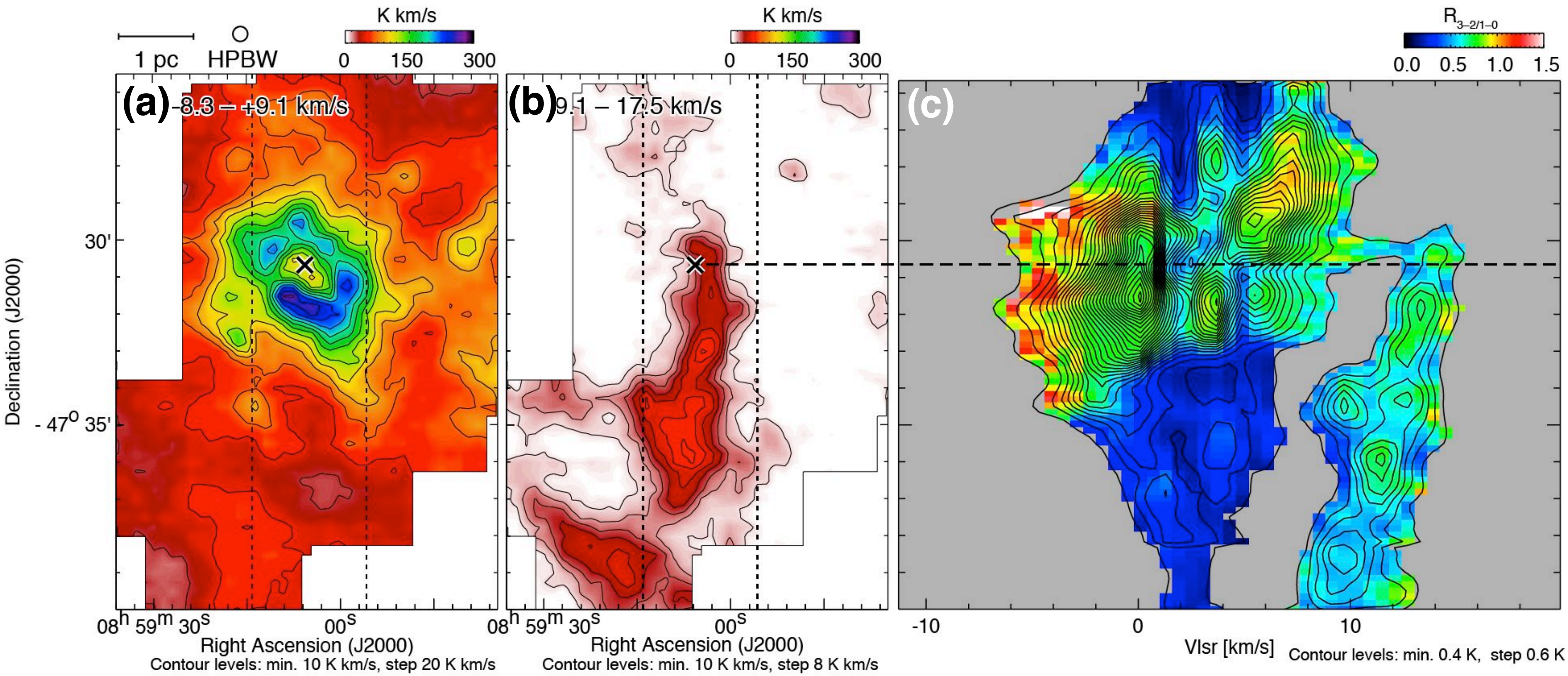
× : O5.5

+ : O-star candidates

○ : YSOs

Z (blue), H (green), K band (red)

SSC：RCW 38 (Fukui+ 16)

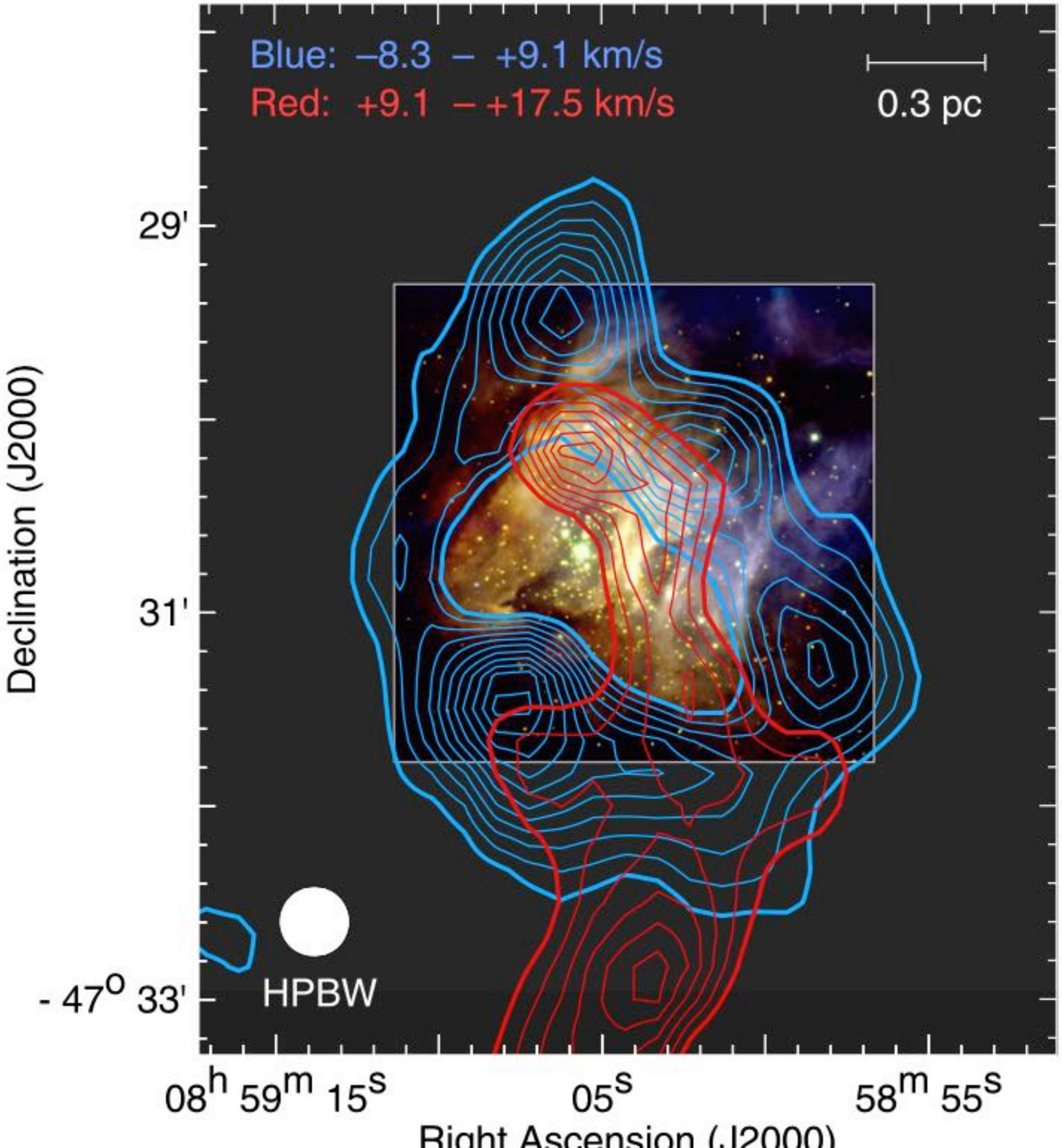


Fukui+15

(a-b) Mopra ^{12}CO J=1-0 intensity maps
(c) p-v diagram of ^{12}CO J=3-2/1-0 ratio using the Mopra & ASTE telescopes

- The ring-like and filamentary clouds are located toward the SSC.
- Both the two clouds show a high-intensity ratio > 0.6
  → Evidence for physical association with the SSC.

RCW 38


Blue: –8.3 – +9.1 km/s
Red: +9.1 – +17.5 km/s
0.3 pc
29'
31'
- 47o 33'
Declination (J2000)
HPBW
08h 59m 15s
05s
58m 55s
Right Ascension (J2000)

Why cloud-cloud collisions =CCC are rare?

- Collision signatures are subtle,
- Double peak, but not always; CCC looks like a single cloud
- Bridges, not always; linewidth less than cloud linewidth
- Complementary distributions, not always
- Ionization of the parent clouds is rapid by 10-30 O stars, collision signatures are quickly lost; **time scale is short**
- Theoretical model for ccc is useful
- Collisions are rare, and O stars are rare;
- GMC collision is every 8 Myrs, accounts for O star number (Fujimoto+ 2014; Dobbs+ 2014)
- **O stars are formed by CCC**
- Nishimura's talk, Tsuge's talk, this afternoon

Collapse of massive cloud cannot form isolated O stars

Outcomes of theory:

- Massive cloud takes time to form O stars, ~Myrs
- Massive cloud forms low mass stars in its early phase, then, in the end, forms O stars in the center, no directivity
- O stars not isolated

Observations :

- M42, ONC, has the O stars on the near side only, anisotropic
- Many single O stars, 300 or more in the MW;

SFR (O stars, 20 Mo higher) =0.01 Mo/yr

This is large as compared with 1Mo/yr for the whole stellar mass range