Massive Star Formation Triggered by Collisions of Molecular Clouds

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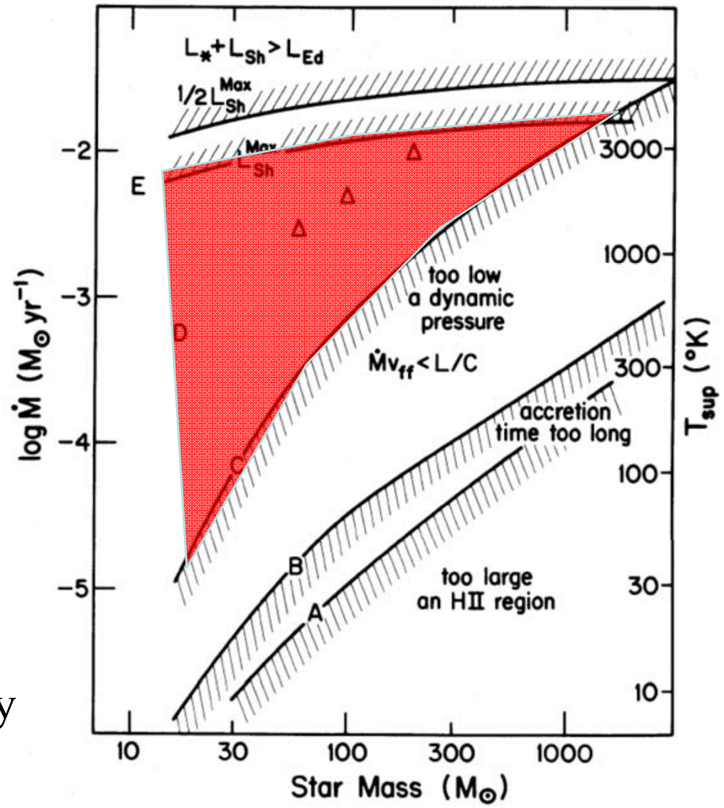
High-mass star formation

- Stars with masses > 8 M_{SUN}
- Release huge energy to the interstellar space via stellar winds, UV radiation, supernova explosions
- influential to the evolution of galaxies

- How did they form?
- Observational difficulties
  - small sample, large distance, disruptive activity
- key: high mass accretion rate dM/dt
  - 100 times larger dM/dt than that in low-mass stars.

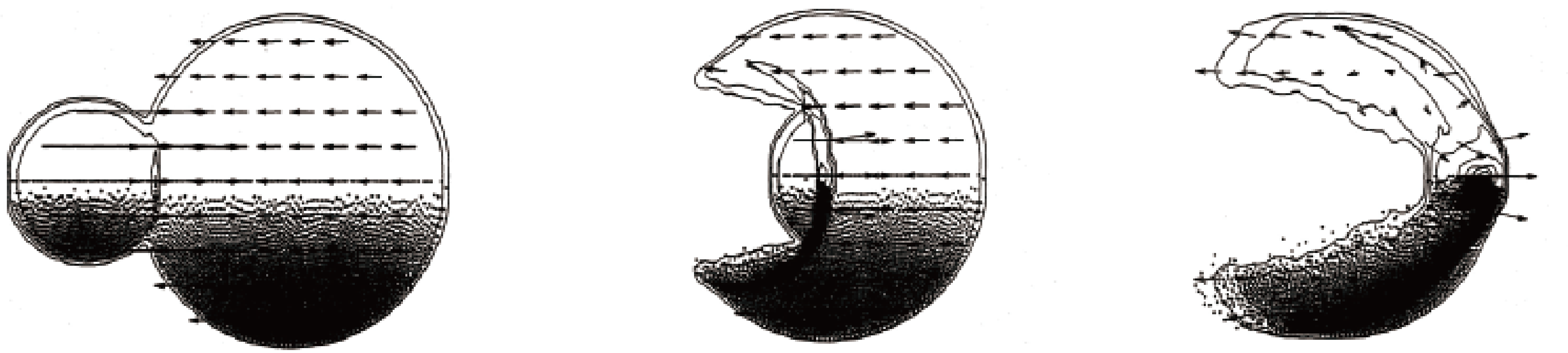
  ~ 10^{-4} – 10^{-3} M_{SUN}/yr is required.
- External trrigering?



Wolfire & Cassinelli (1986)

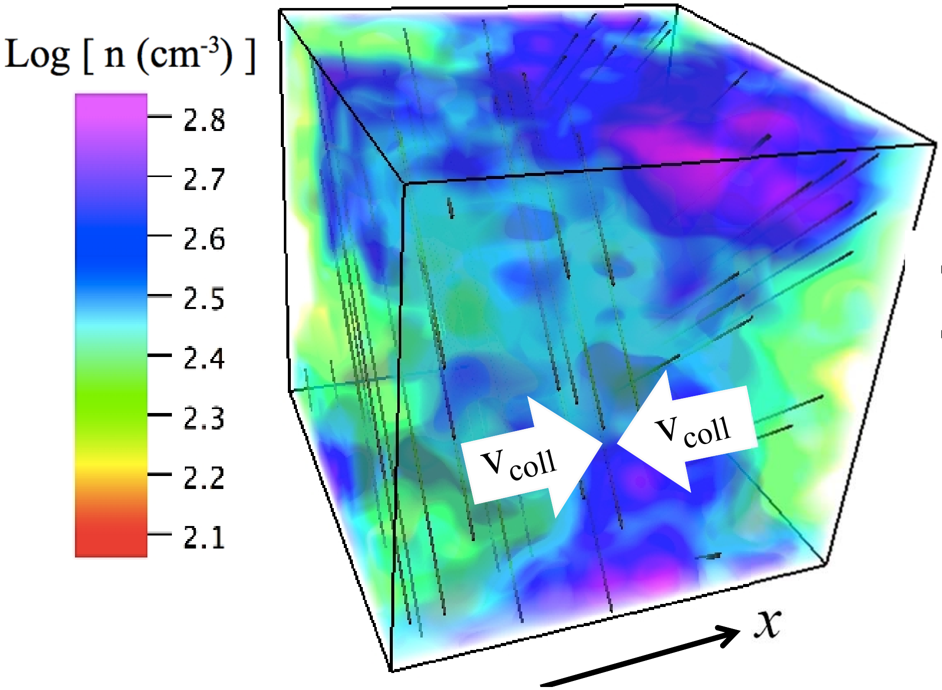
High-mass star formation via cloud-cloud collision (CCC)

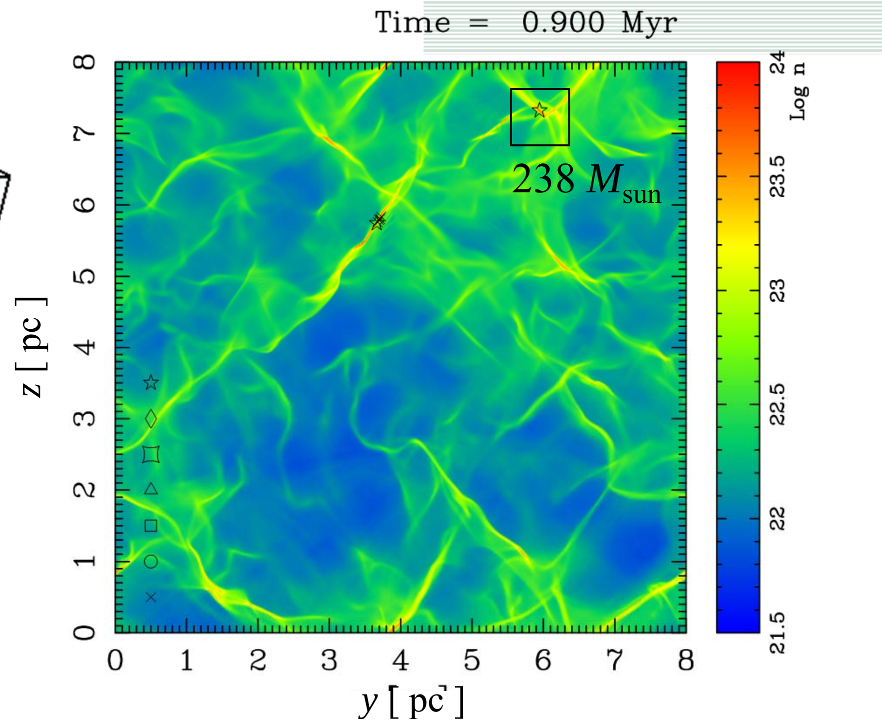
- Strong compression of the molecular gas leads the high-mass star formation
  - Rapid formation (~0.1Myrs) with high dM/dt
- Large velocity separation between the two colliding clouds (10–20 km/s)
  - cannot be interpreted as a gravitational bound clouds
  - cannot be explained with stellar feedbacks from the high-mass stars



Habe & Ohta 1992

MHD numerical calculations Inoue & Fukui (2013)





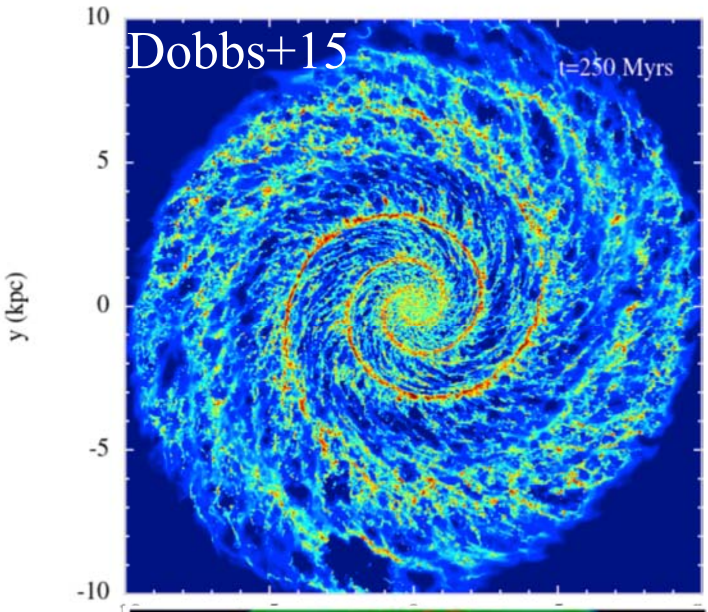
$$\dot{M} \sim \frac{M_J}{t_{ff}} = \frac{c_s^3}{G} \sim 2 \times 10^{-6} M_\odot/\mathrm{yr} \left(\frac{T}{10K}\right)^{3/2}$$

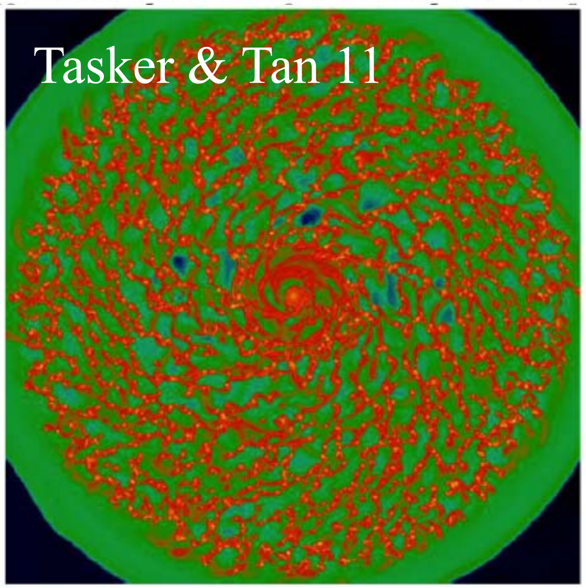
$$M_{\mathrm{J,eff}} \approx (c_s^3 + c_A^3 + \Delta v^3)/(G^{3/2}\rho^{1/2}) \qquad c_s^3 : c_A^3 : \Delta v^3 = 1:125:90$$

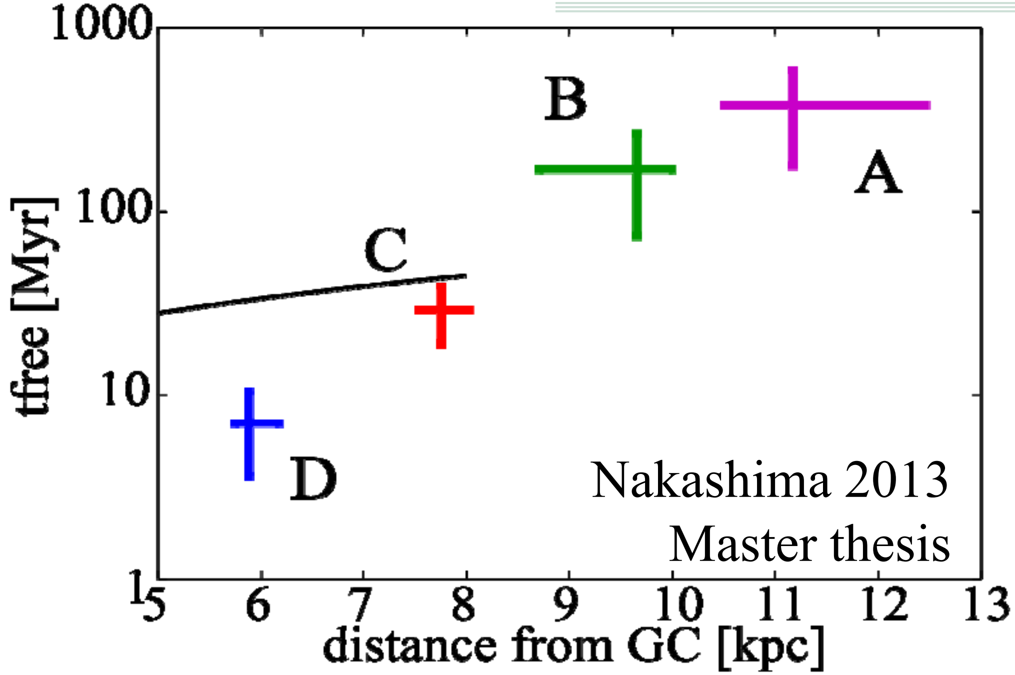
- Amplified magnetic field and gas turbulence increase dM/dt

$$\mathrm{dM/dt} = 5 \times 10^{-4} - 4 \times 10^{-3}\ M_{\mathrm{sun}}/\mathrm{yr}$$

Frequency of CCC in a MW-like spiral galaxy

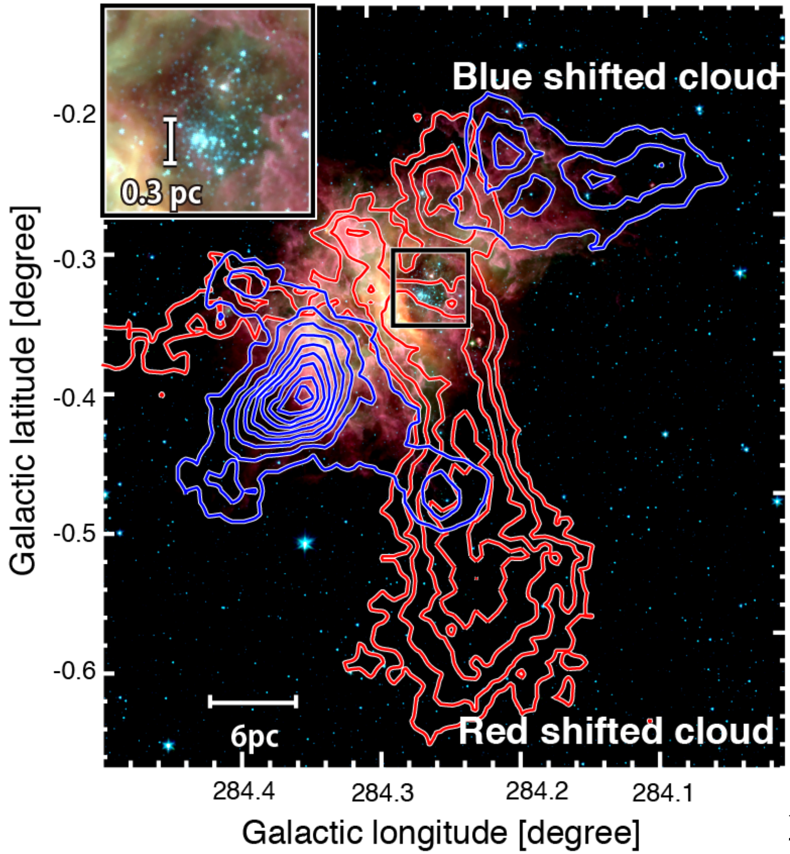


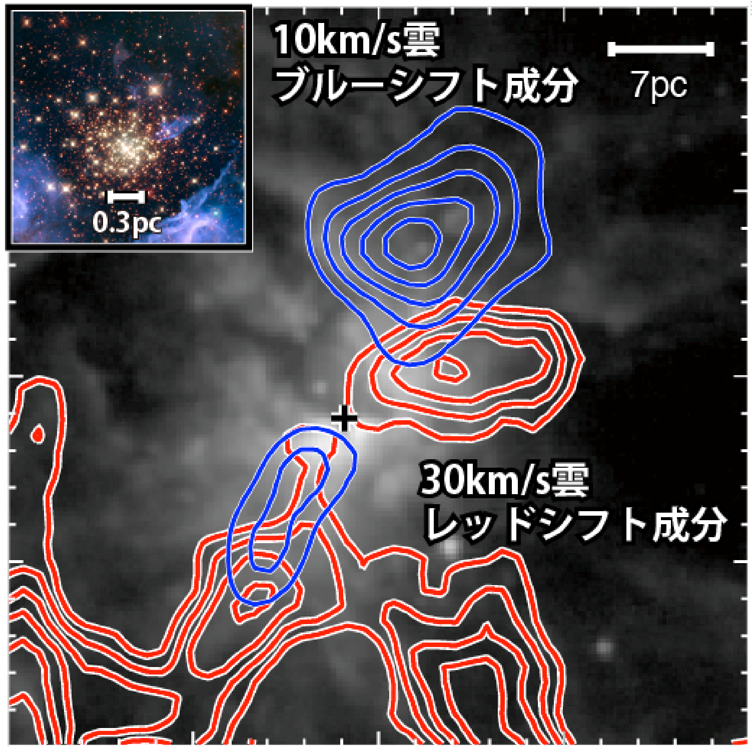




- Mean free time of CCC is estimated as ~10Myr in numerical calculations and molecular observations of the molecular clouds.

Massive cluster formation via CCC





ınd2 and NGC3603

(Furukawa et al. 2009; Ohama et al. 2010; Fukui et al. 2014)

- Total stellar mass 10^4 M_{SUN} is concentrated within < $1pc^3$.
- Two giant molecular clouds collided at a velocity separation ~20 km/s
- Timescale of the collision: ~ 0.1Myr

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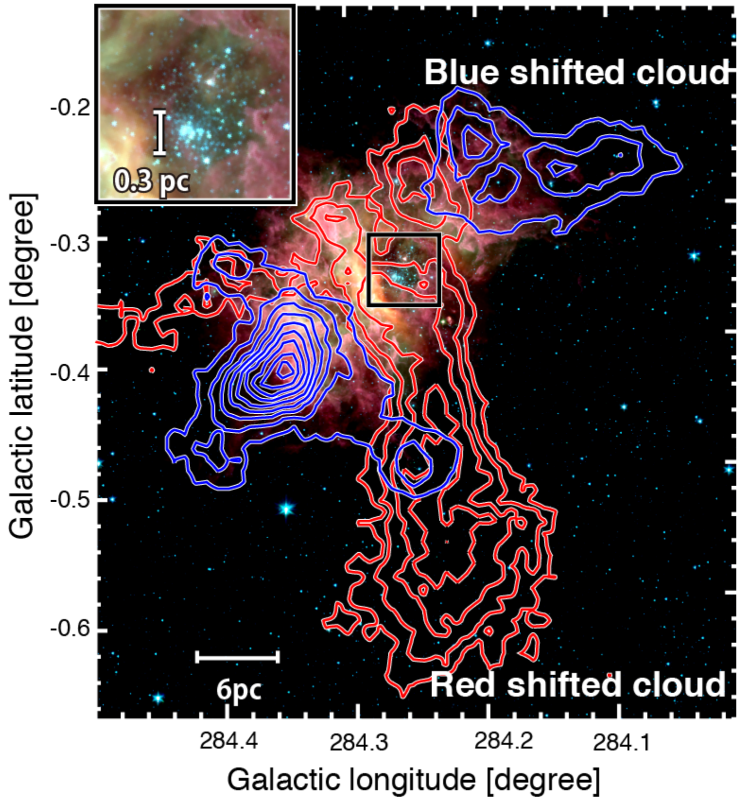

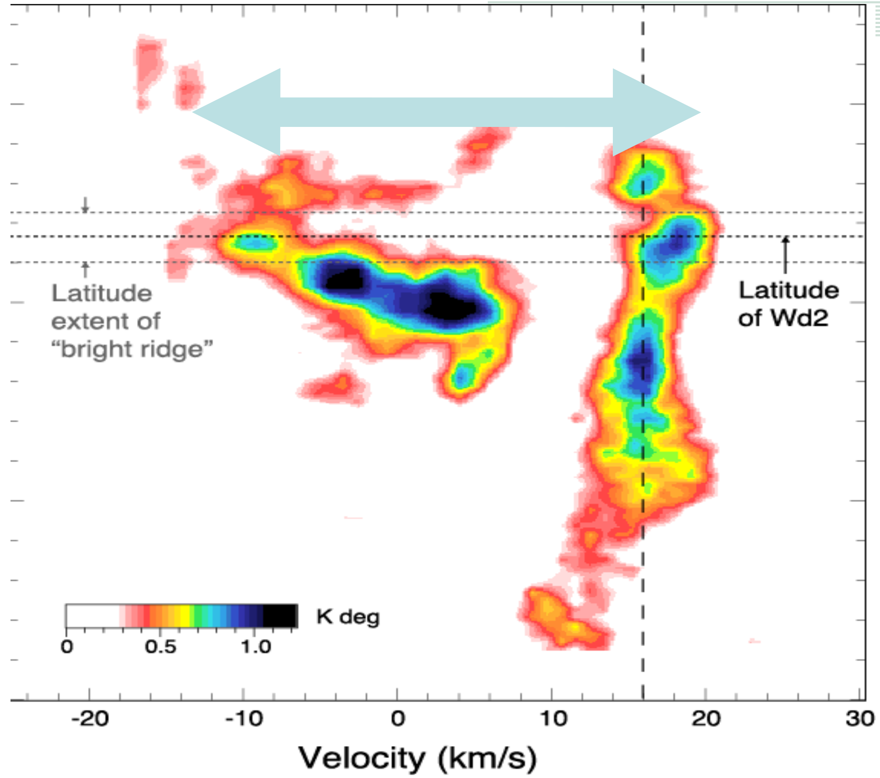

- Massive star clusters Westerlund2 and NGC3603
  (Furukawa et al. 2009; Ohama et al. 2010; Fukui et al. 2014)
- Total stellar mass $10^4\ M_{SUN}$ is concentrated within < $1pc^3$.
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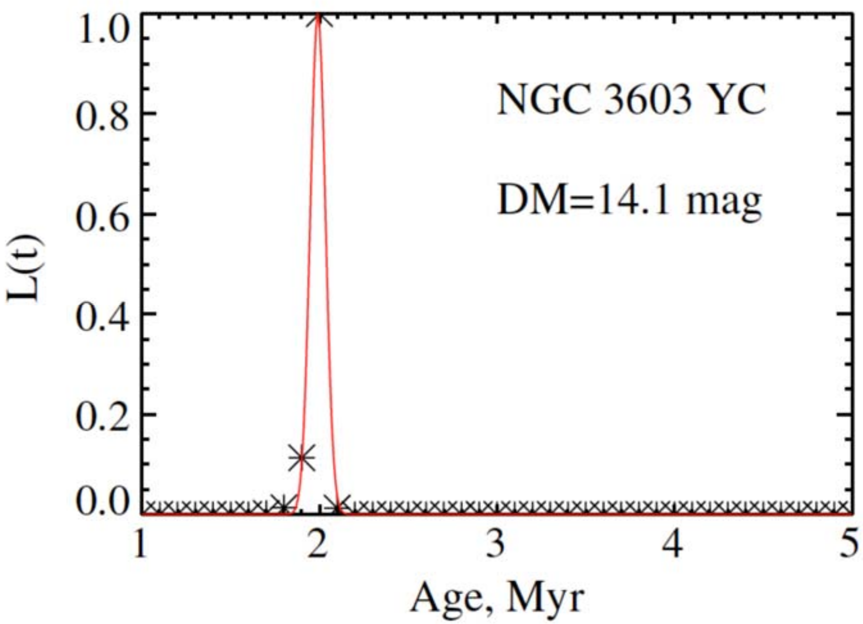
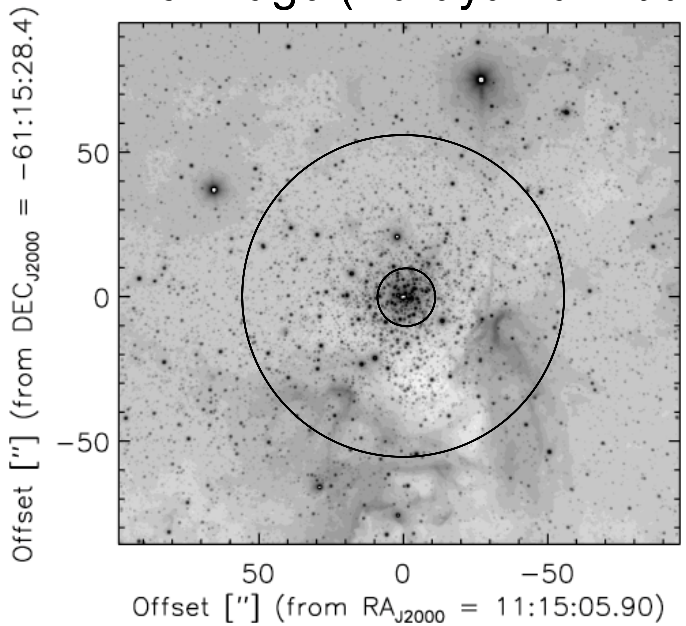
Age spread of the cluster members in NGC3603

Posterior probability distribution
(Kudryavtseva+2012)



Ks image (Harayama+2008)

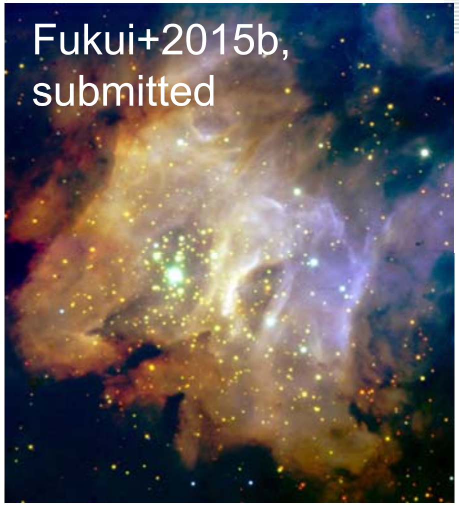


- Age and age spread of the cluster members in NGC3603 is ~2 Myr and ~0.1Myr, respectively (Kudryavtseva+2012)
- Massive stars are concentrated in the cluster center -> cannot be explained with the gravitational migration.
- Consistent with the rapid high-mass star formation via CCC.

CCC in massive star clusters (MSCs)

Westerlund2

NGC3603



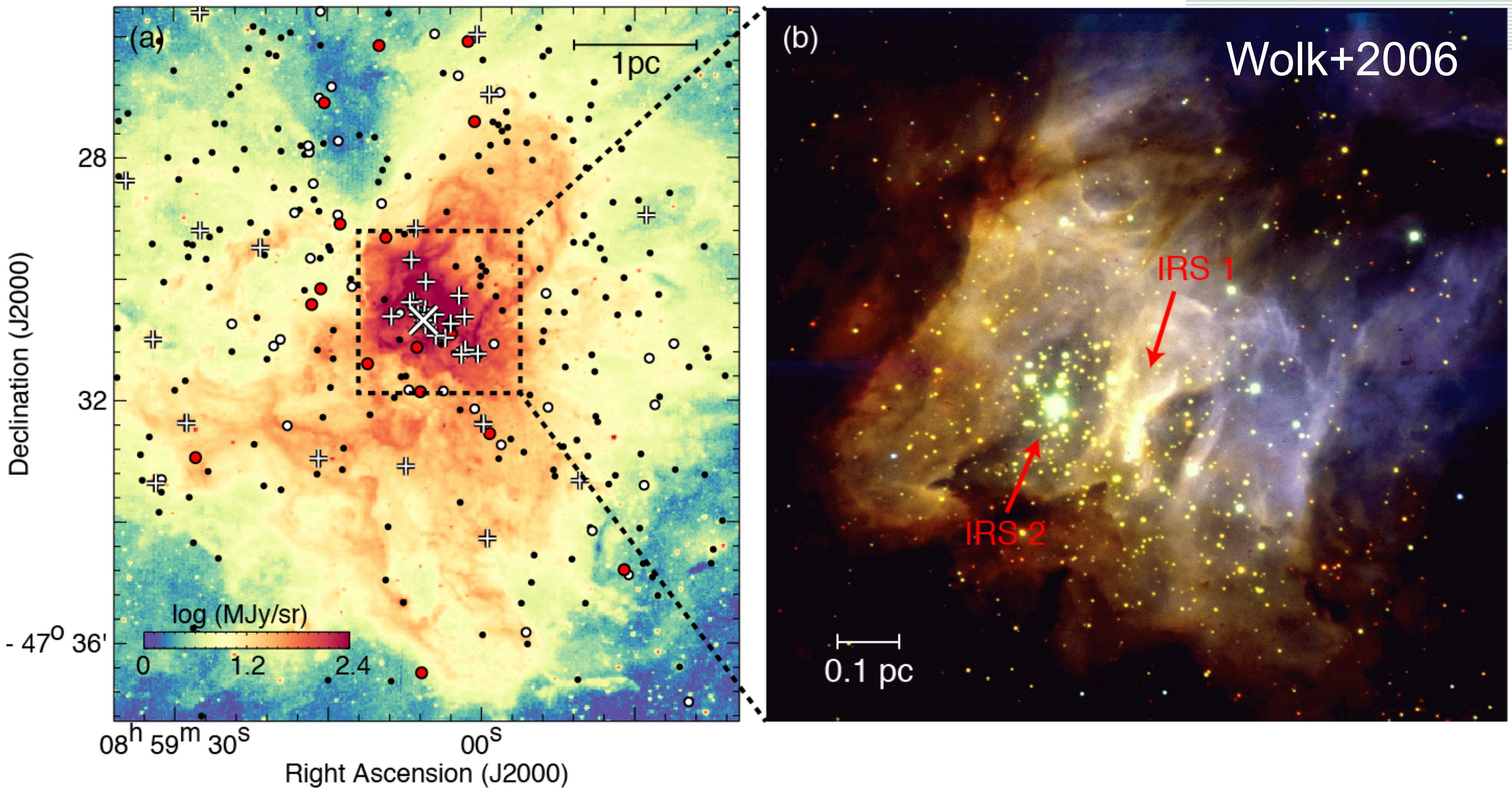
RCW38

[DBS2003]179

- MSCs are rare objects.
- Four of the known MSCs have nebulosities, meaning that their natal clouds still survive.
- Two molecular clouds are identified in all of the four.

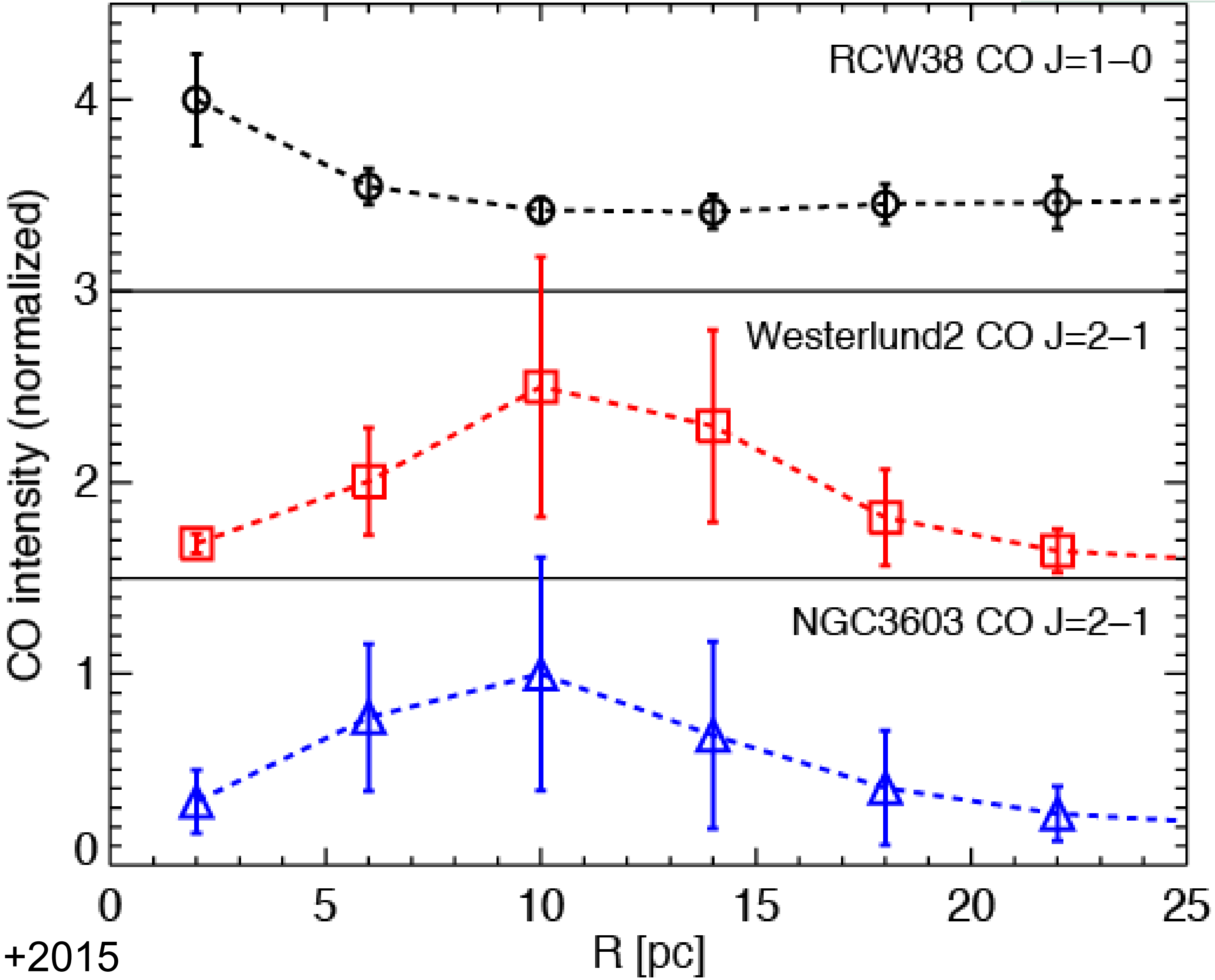
cluster	Age [Myr]	LogM$_*$ [M_{sun}]	Size [pc]	Nebulosities?
NGC3603	2.0	4.1	0.7	yes
Westerlund2	2.0	4.2	0.8	yes
[DBS2003]179	2-4	3.8	0.5	yes
Westerlund1	3.5	4.0	1.0	no
Trumpler 14	2.0	4.5	0.5	--
Arches	2.0	4.3	0.4	no
Quintuplet	4.0	4.0	2.0	no
RCW38	<1.0	--	0.8	yes

RCW38; the youngest MSC in the Milky Way



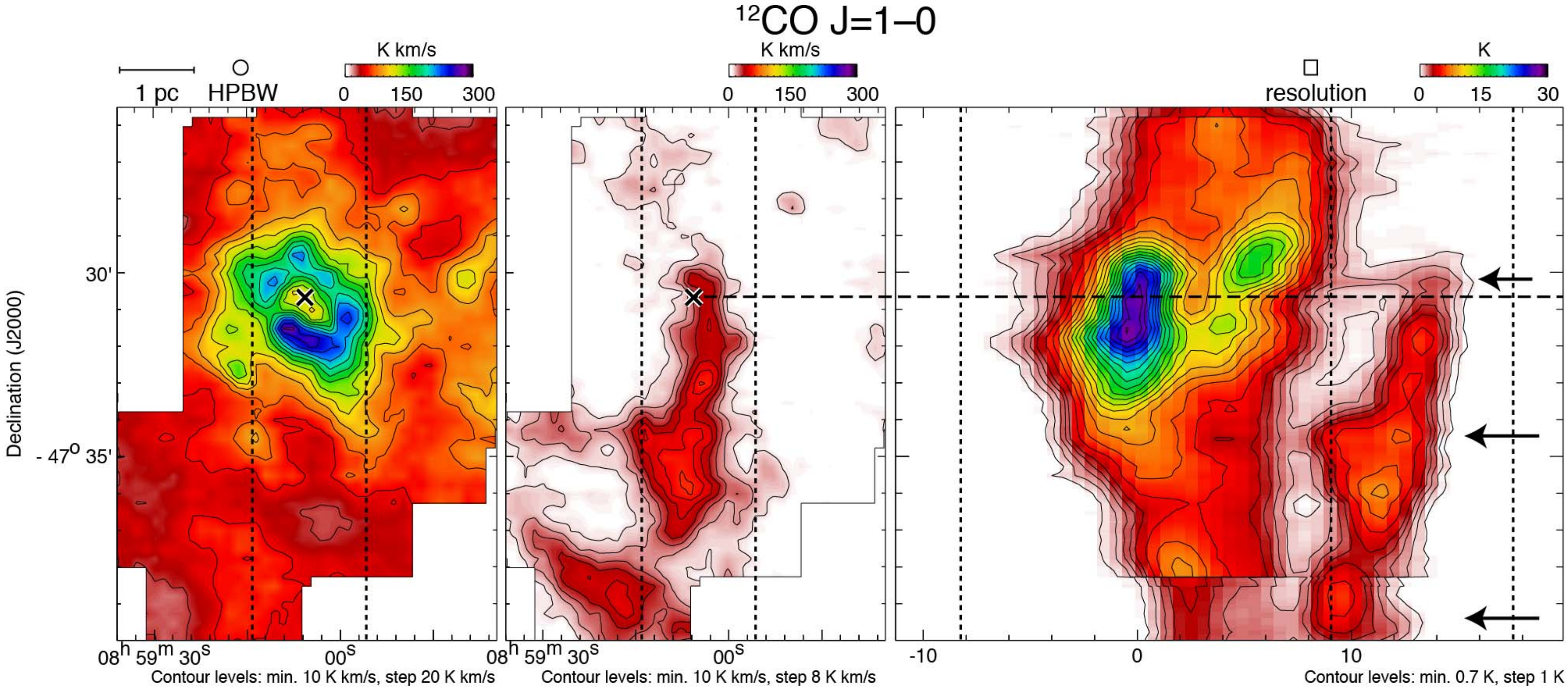
- distance ~ 1.7kpc, Age 0.5 – 1Myr (Wolk+06)
- The exciting O5.5 star (IRS2) and bright infrared ridge（IRS1）
- A cavity across 0.5pc toward the cluster center, which coincides with the about 20 O stars.

RCW38; the youngest MSC in the Milky Way



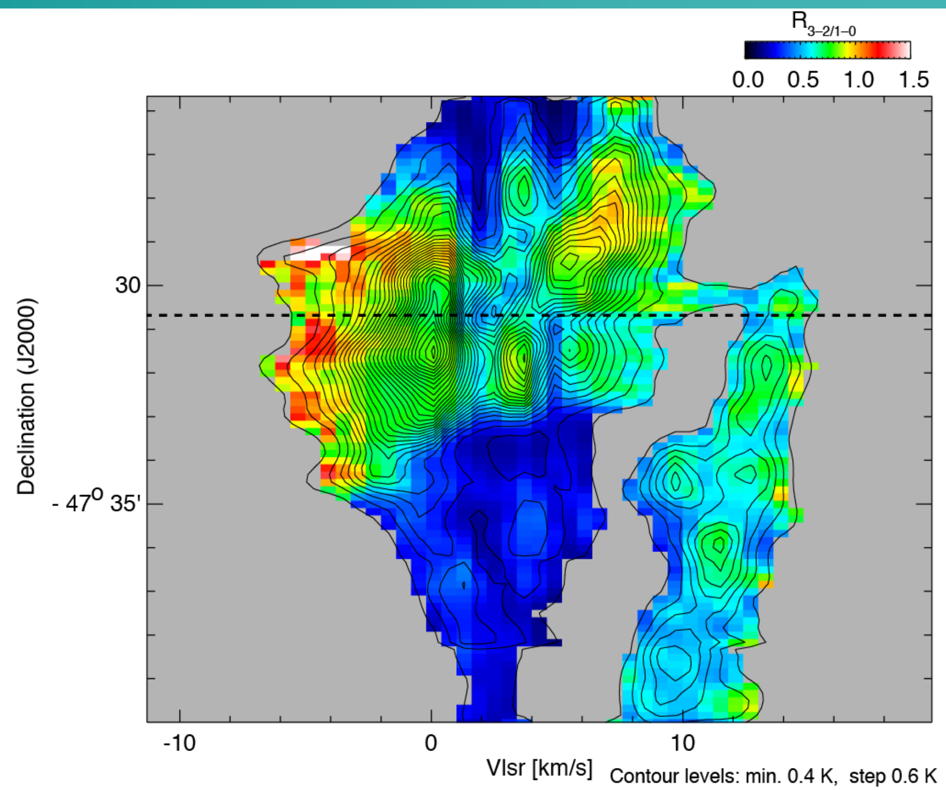
Fukui+2015

CO distributions (Fukui, Torii et al. 2015, submitted)



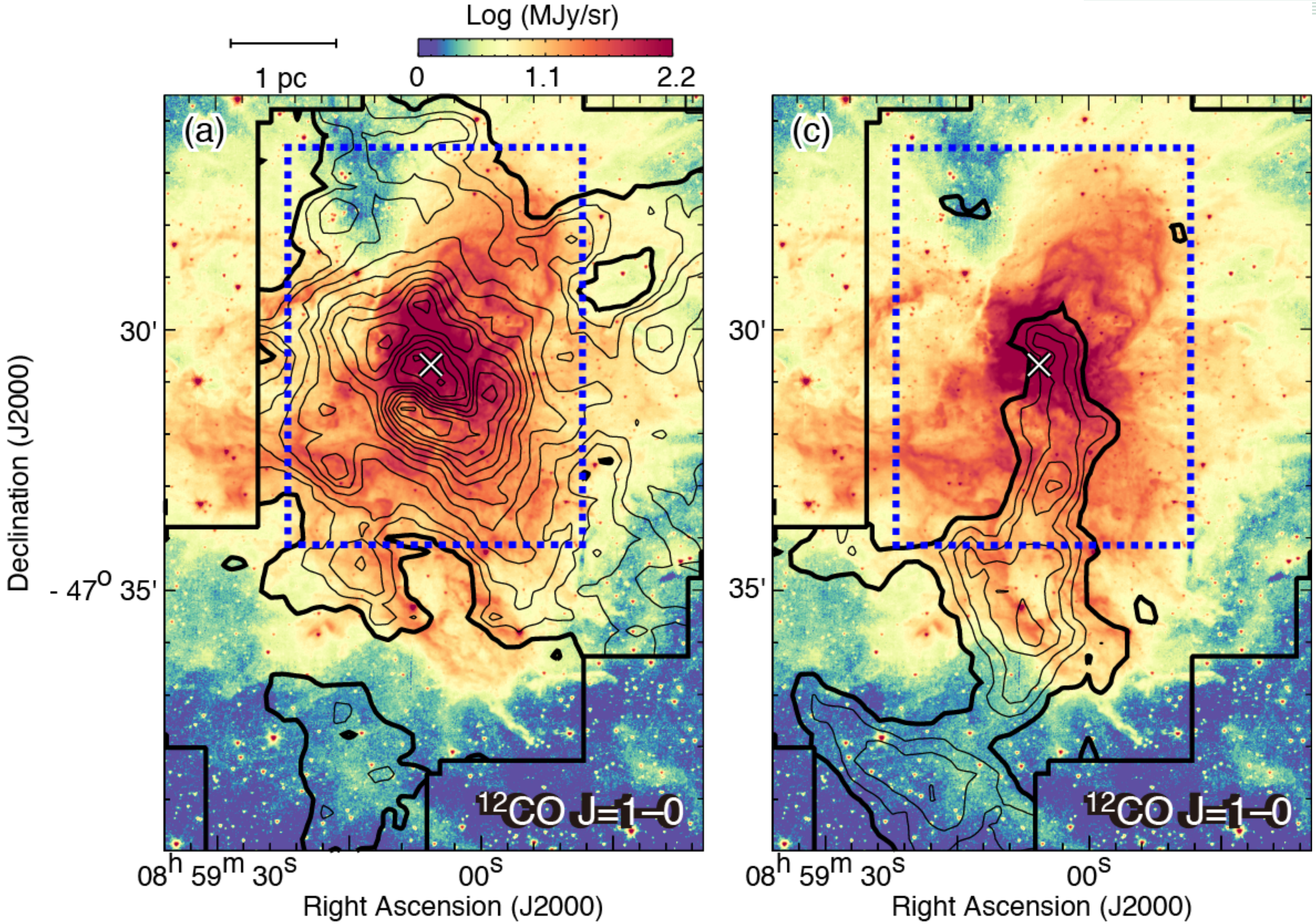
- Two molecular clouds toward RCW38;
- The ring cloud at ~2 km/s and the finger cloud at ~ 14 km/s.
- The velocity separation ~ 12 km/s.
- A bridge feature connecting the two clouds in the velocity space.

12CO 3-2/1-0 ratio in the p-v diagram



- Both of the two clouds have high ratios of > 0.8, which corresponds to Tk > 30 K with a LVG analysis.
- The RCW38 cluster is the heating source, suggesting that both of the two clouds are associated with RCW38 although they have a large velocity separation of ~12 km/s, which cannot be gravitationally bound with the total mass of the region.

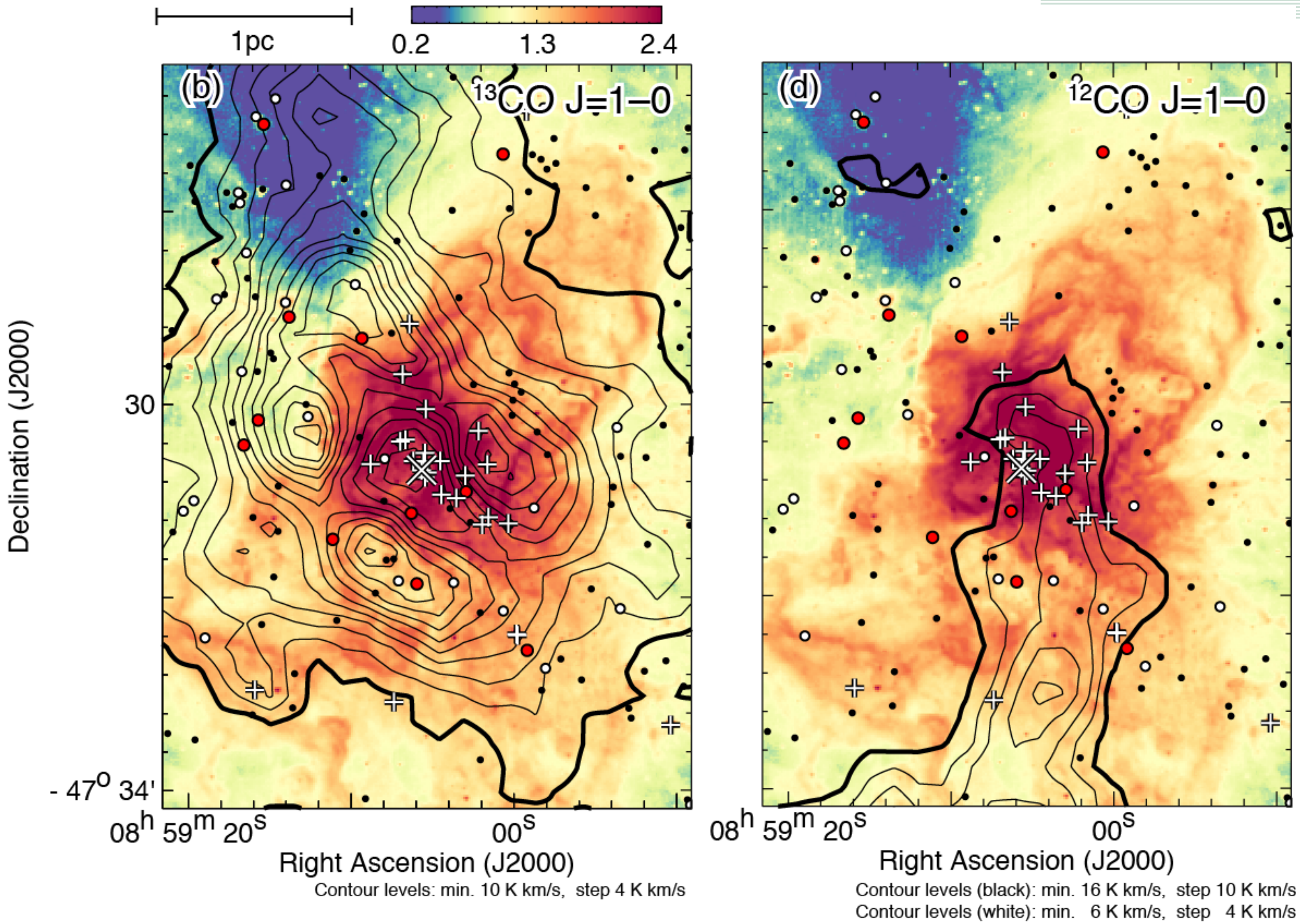
Comparisons with the Spitzer 3.6 micron



Contour levels: min. 50 K km/s, step 10 K km/s & 20 K km/s (from 70 K km/s)

Contour levels: min. 16 K km/s, step 10 K km/s

Comparisons with the Spitzer 3.6 micron



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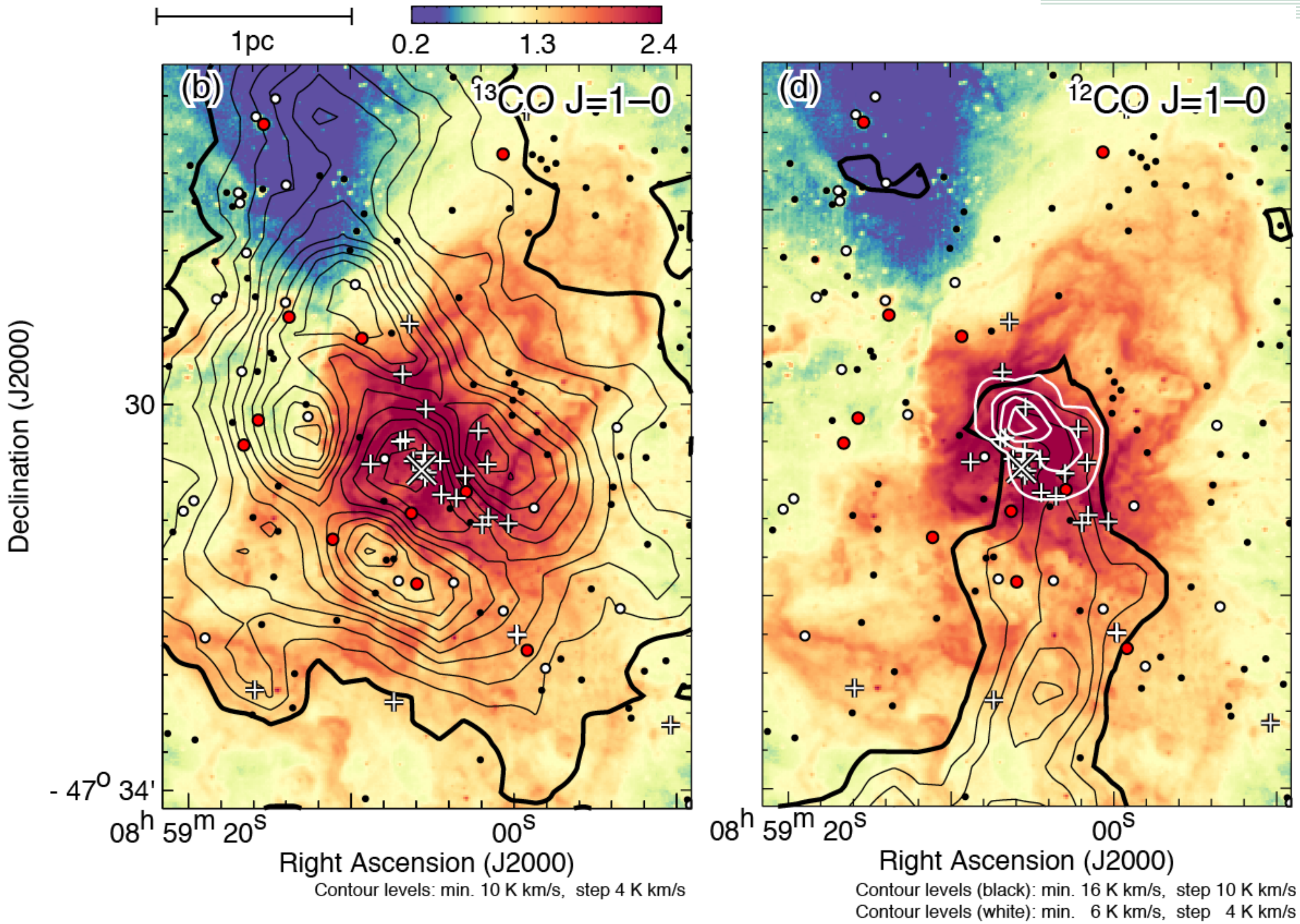
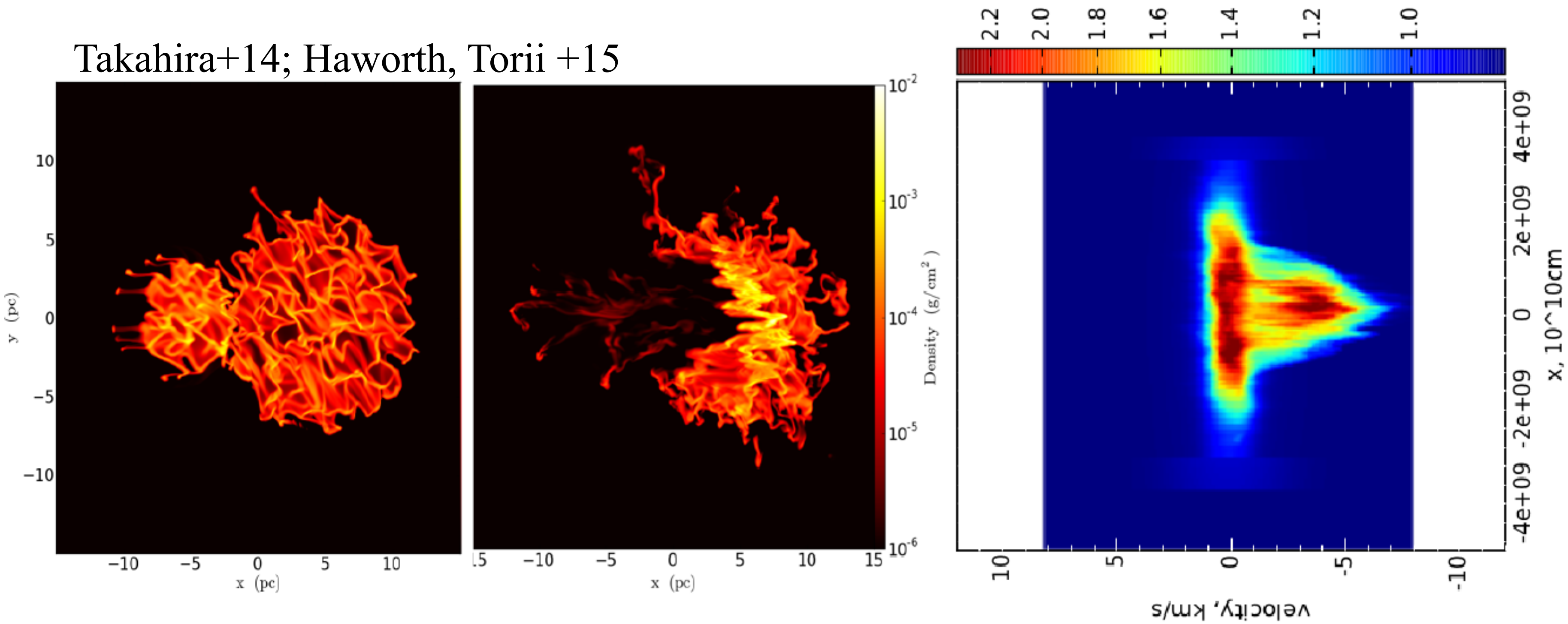


The red-shifted cloud in CO 3-2 and the VLT image

Contour levels: min. 16 K km/s, step 4 K km/s

Intermediate bridge feature

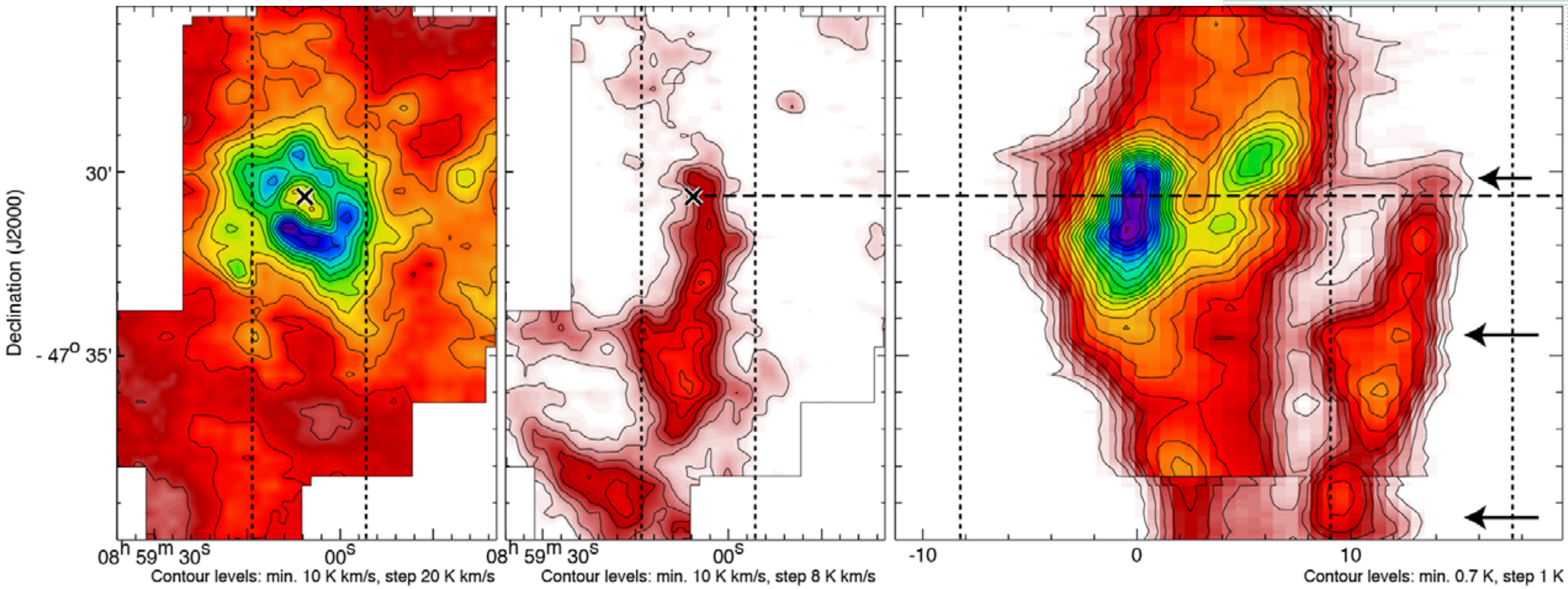
Takahira+14; Haworth, Torii +15



- 3D numerical calculations of CCC (Takahira+14)
- Synthesis CO observations and position-velocity diagram (Haworth+15a, b)
- Intermediate velocity feature in the p-v diagram: turbulent motion of the gas excited by the collision

→ The bridge feature detected in the CO observations in RCW38

Cloud-cloud collision in RCW38



- Red cloud: mass ~ 10^4 M_{SUN}, column density ~ 10^{23}cm^{-2}
- Blue cloud: mass ~ $10^3 M_{SUN}$, column density ~ 2×10^{21}cm^{-2}
- Collision velocity : ~15km/s.
- Timescale of the collision ~ 3×10^4 yr
- Mass accretion rate: ~10^{-3}Mo yr^{-1} for IRS2 (40 M_{SUN})

Comparison of the CCC regions

Table 3: Comparison of the five of cloud-cloud collision regions.

Name	cloud masses $[M_\odot]$	column densities $[\mathrm{cm}^{-2}]$	velocity separation $[\mathrm{km\,s^{-1}}]$	# of O stars	reference
(1)	(2)	(3)	(4)	(5)	(6)
RCW 38	$(2 \times 10^4, 3 \times 10^3)$	$(1 \times 10^{23}, 1 \times 10^{22})$	12	~ 20	This study
NGC 3603	$(7 \times 10^4, 1 \times 10^4)$	$(1 \times 10^{23}, 1 \times 10^{22})$	20	~ 30	[1]
Westerlund 2	$(8 \times 10^4, 9 \times 10^4)$	$(2 \times 10^{23}, 2 \times 10^{22})$	13	14	[2, 3]
M 20	$(1 \times 10^3, 1 \times 10^3)$	$(1 \times 10^{22}, 1 \times 10^{22})$	7	1	[4]
RCW 120	$(4 \times 10^3, 5 \times 10^4)$	$(8 \times 10^{21}, 3 \times 10^{22})$	20	1	[5]

Note. — Column: (1) Name. (2, 3) Molecular masses and column densities of the two colliding clouds. (blue-shifted cloud, red-shifted cloud) (4) Relative radial velocity between the two clouds. (5) Number of O stars created via cloud-cloud collision. (6) References: [1] Fukui et al. (2014), [2] Furukawa et al. (2009), [3] Ohama et al. (2010), [4] Torii et al. (2011), [5] Torii et al. (2015).

Short summary and lessons from CCC in RCW38

- We identified two molecular clouds toward RCW38, the youngest MSC in the MW, interpreting that they were formed by the collision of the two clouds.
- A intermediate bridge feature seen in the velocity space can be naturally interpreted as the turbulent gas excited by the collision.

Q.1 *How are the mass and number of the formed O stars determined?*

A.1 High molecular column density of ~10^{23} cm^{-2} is crucial for the MSC formation. We see no strong dependence on the collision velocity.

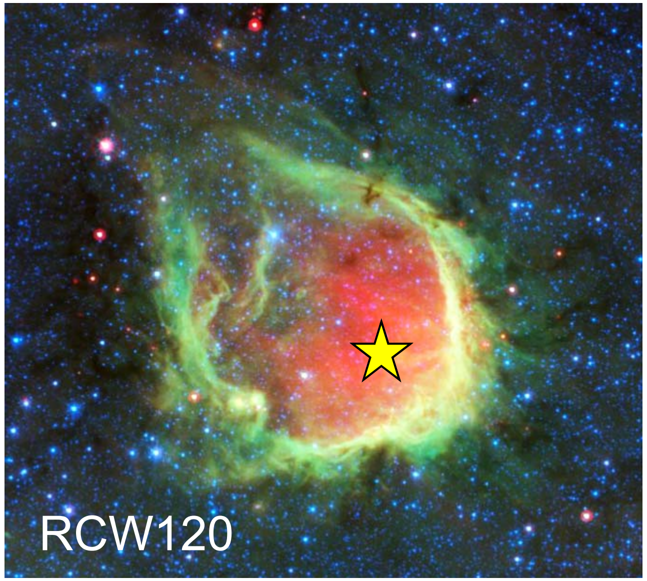
Q.2 *What is the origin of the mass segregation/stellar distribution in MSCs.*

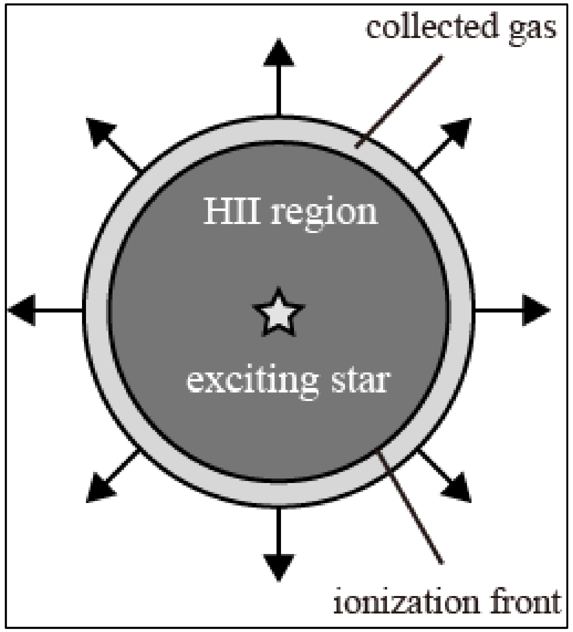
A.2 O star distribution holds the distribution of the collisional interaction at least right after the formation.

Q.3 *How about the single O star?*

A.3 See next.

RCW120 (Torii et al. 2015, ApJ, 806, 7)





RCW120

- Distance ~ 1.3 kpc
- Single O7 star (~$20M_{SUN}$)
- Infrared ring feature (PAH)
- An HII region inside the ring

Previous discussion

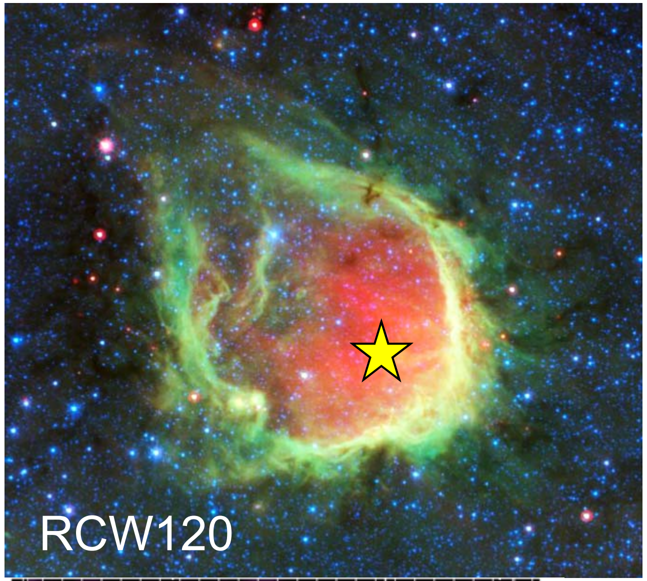
- An expanding shell created by HII region

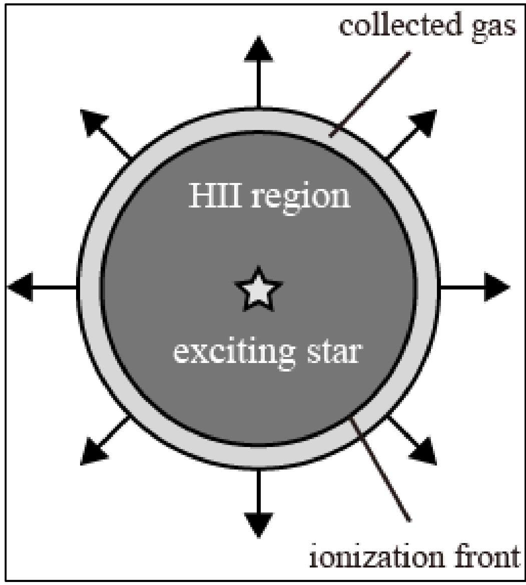
This study

- CO observations (NANTEN2, Mopra, ASTE)
- No expanding motion is seen.

→ cannot be explained with the previous model.

RCW120 (Torii et al. 2015, ApJ, 806, 7)





pc

~20M_{SUN})

ture (PAH)

nside the ring

n

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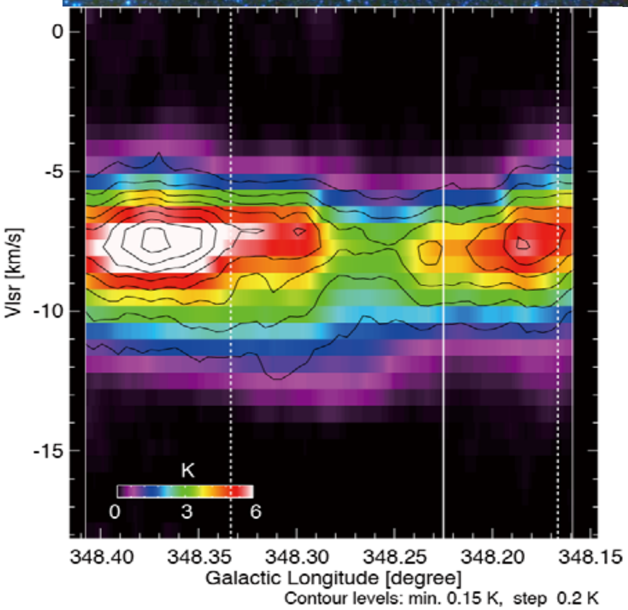

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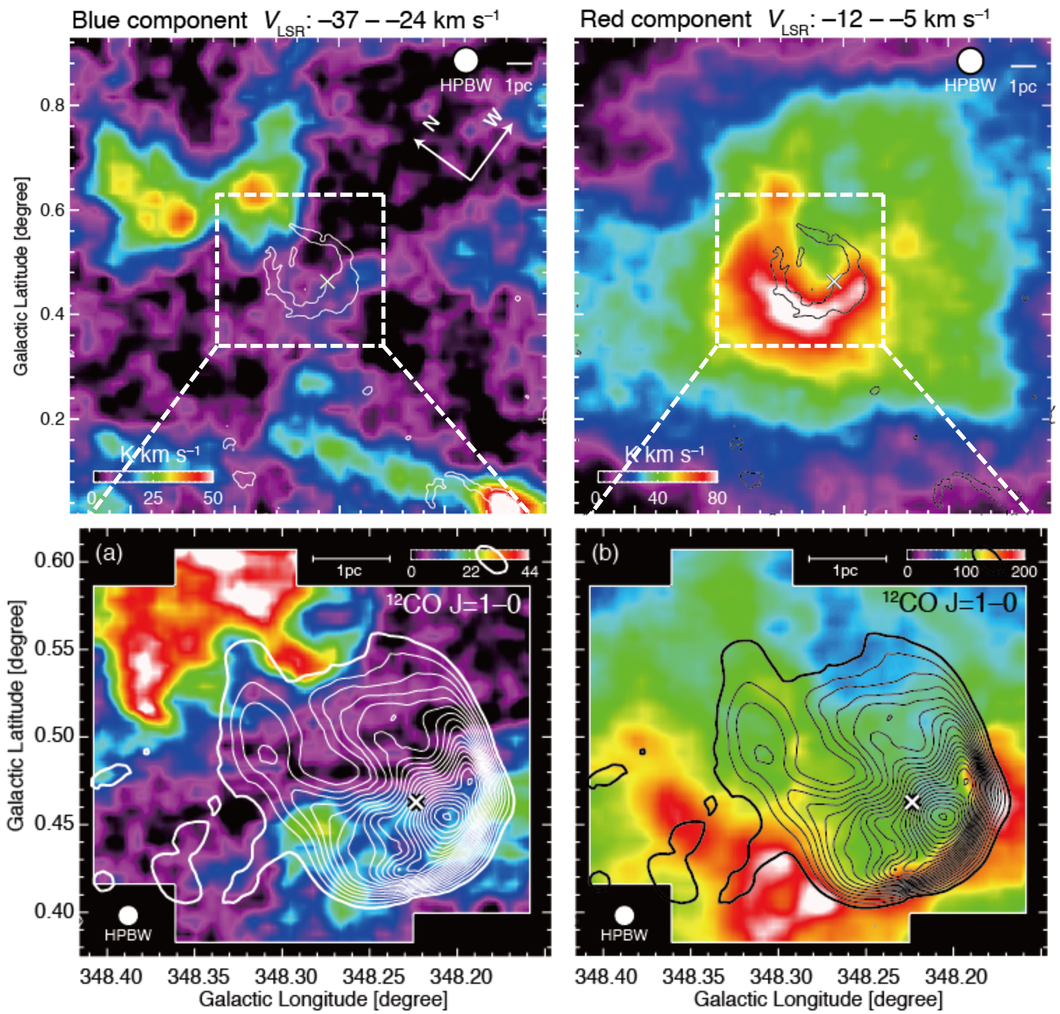
研究成果 RCW120 (Torii et al. 2015, ApJ, 806, 7)

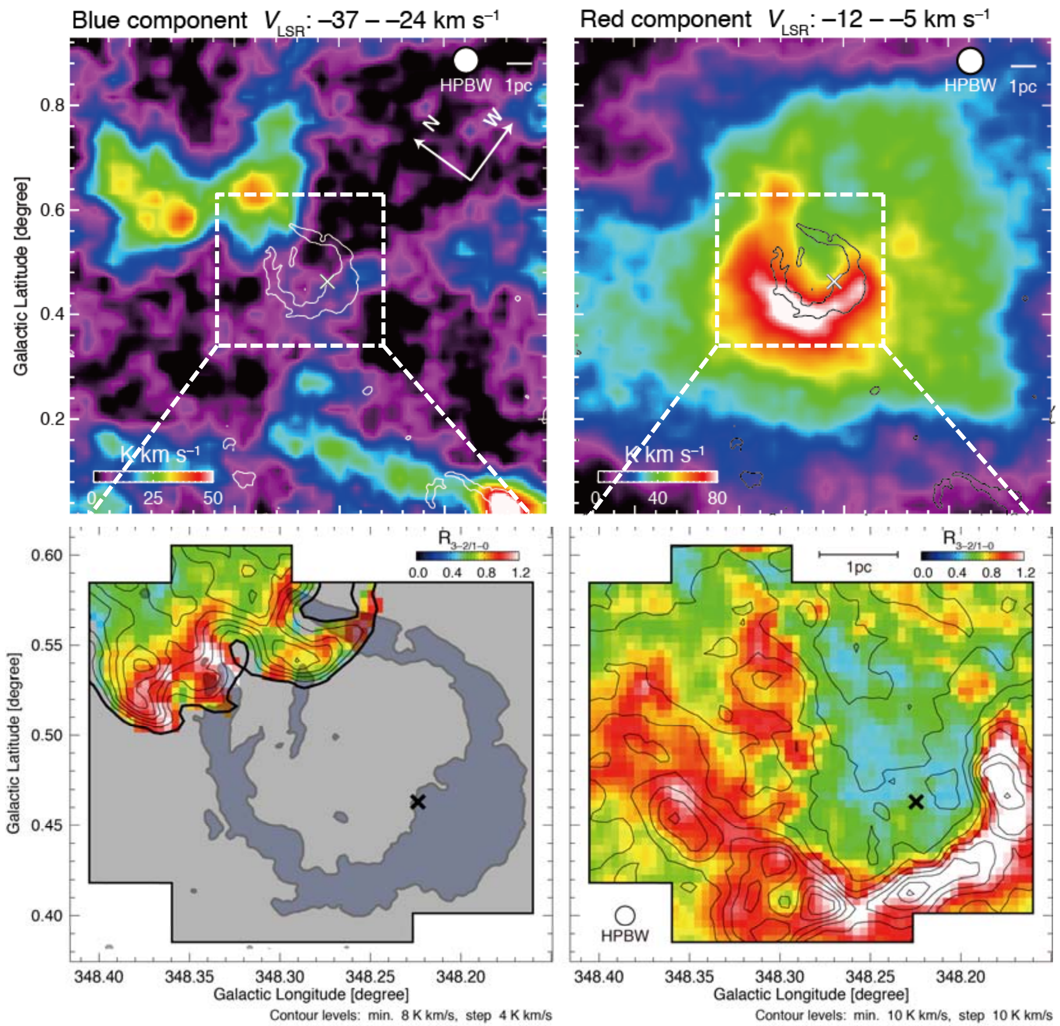


- Identified two molecular clouds having a velocity separation of 20 km/s.
- Both of the two clouds are:
  - distributed along the rim of the HII region.
  - High CO 3-2/1-0 ratio near RCW120.

→ UV radiative heating by the exciting O star.

Both of the two clouds are associated with RCW120

研究成果　RCW120 (Torii et al. 2015, ApJ, 806, 7)



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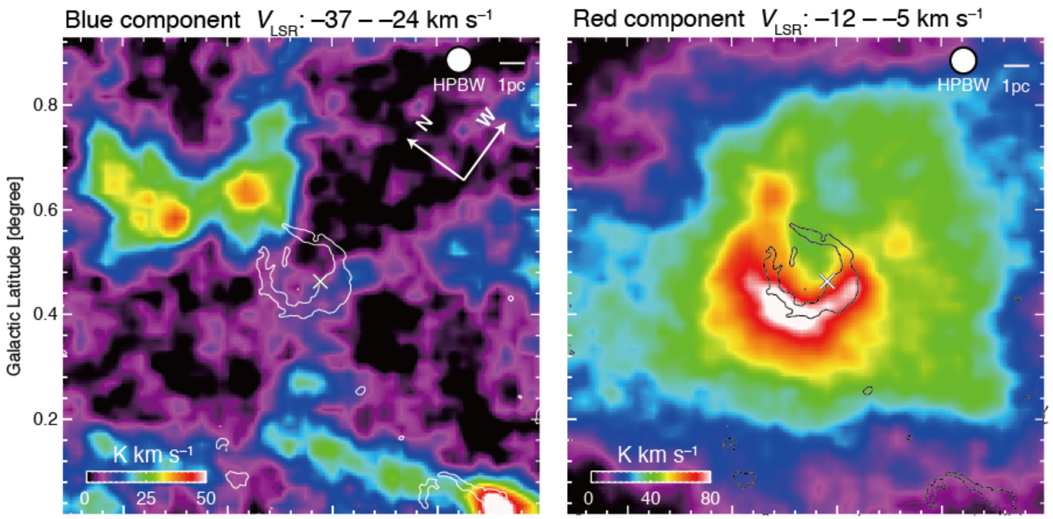
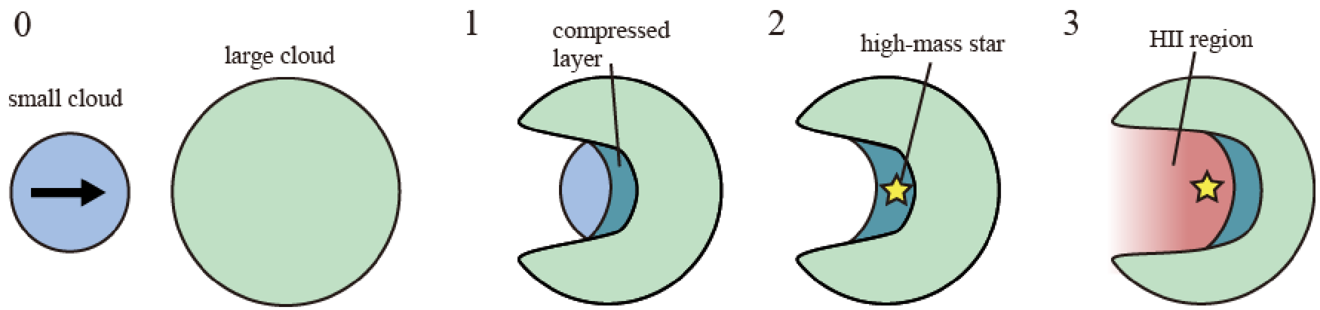
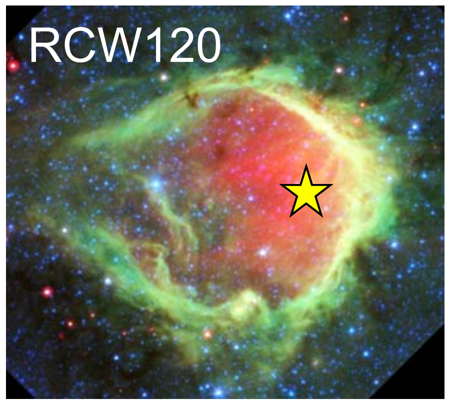


CCC model

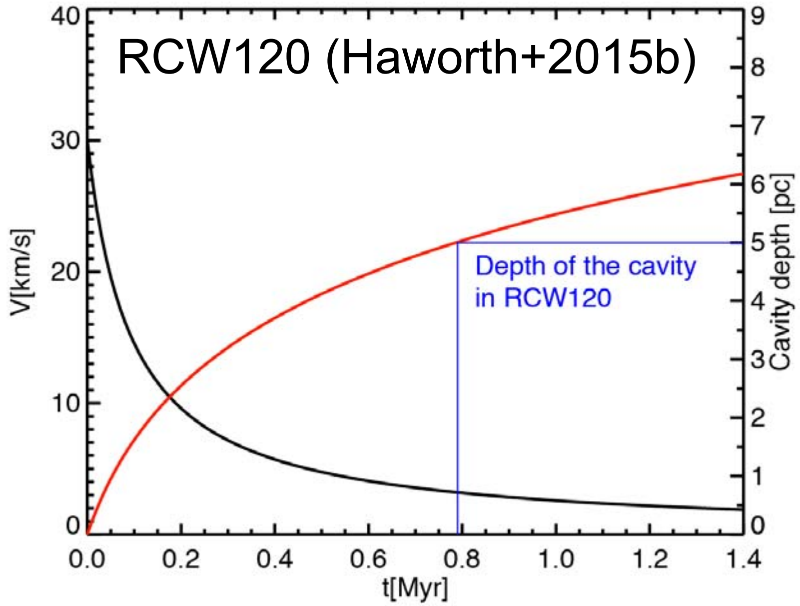
- Collision between a large cloud and a small cloud.
- Cavity creation inside the large cloud, followed by the O star formation.
- HII region fills the cavity.





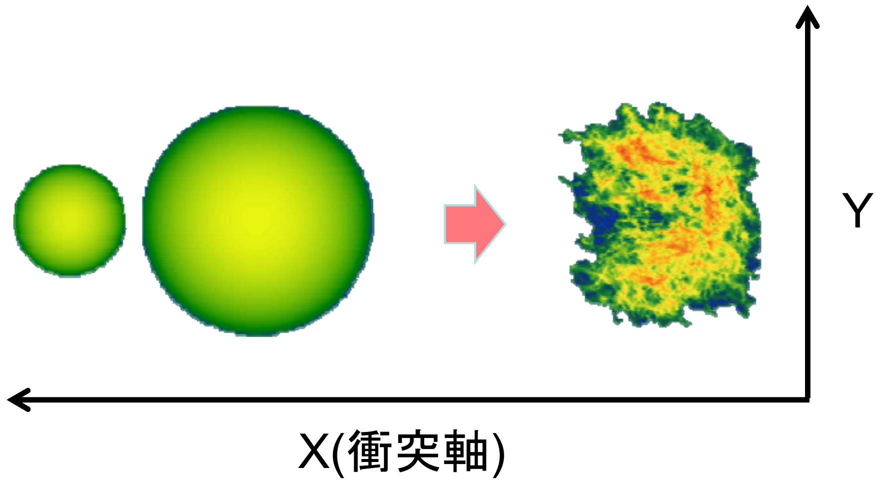
Collision velocity ~ 30 km/s, Timescale of CCC < 0.8 Myr →
dM/dt > 2×10^{-5} M_{Sun}/yr , up to 10^{-4} M_{Sun}/yr

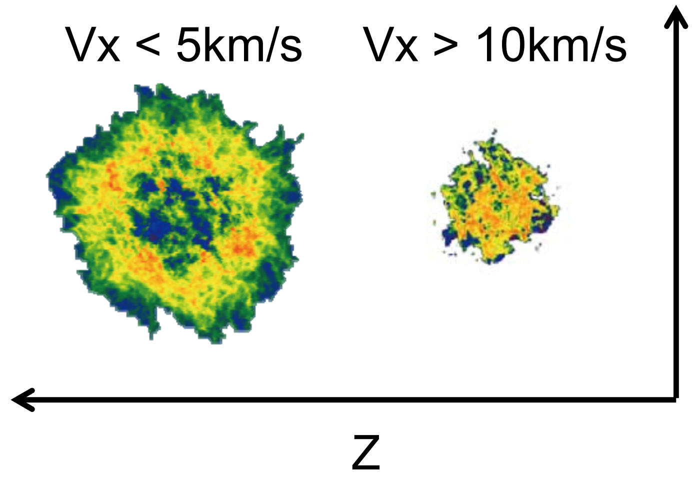
Cavity creation in CCC objects



- The colliding velocity decreases during the collision.
- Cavity depth in RCW120: ~ 5pc, which corresponds to a timescale of the cavity creation of 0.8 Myrs.
- The O star was probably formed at the first 0.2 Myrs.

分子雲衝突計算（Takahira et al. 2014; Habe et al. in prep.）





Star formation rate (SFR) in the Spitzer bubbles

- Number of Spitzer bubbles in the MW ~ 2000 (Churchwell et al. 2006)
- Lifetime = Crossing time ~ 0.5 Mo/yr (5[pc]/10[km/s])
- Stellar mass range of the Spitzer bubbles ~ 15 – 60 Mo (IMF weighted average value ~ 26 M_{SUN}) (e.g., Beaumont & Williams 2008)
- SFR in the Spitzer bubbles ~ 0.06 Mo/yr

- Ratio of the stars with 15–60 M_{SUN}: ~ 7%
- SFR in the MW: ~ 0.7 – 1.5 Mo/yr (Robitaille & Whitney 2010)

  → Massive SFR in the MW~ 0.05 – 0.11 Mo/yr

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Short summary and lessons from RCW120

- Collision between two molecular clouds at a collision velocity of ~30 km/s formed a O7 star. → Single O star also can be formed by the cloud-cloud collision.
- We constructed a basic scenario of the cloud-cloud collision, which can be applied to the Spitzer bubbles.
- Cloud-cloud collision can create a cavity in a larger one of two colliding clouds.

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Q.3 *How about the single O star?*

A.3 Yes. Single O star can be formed at molecular column density of 10^{22} cm^{-2}.

Q.4 *Are CCCs one of the major modes of O star formation?*

A.4 An open question. The Spitzer bubbles are important targets to answer the question.

Future tasks

1. Search and identify the CCC regions in the MW

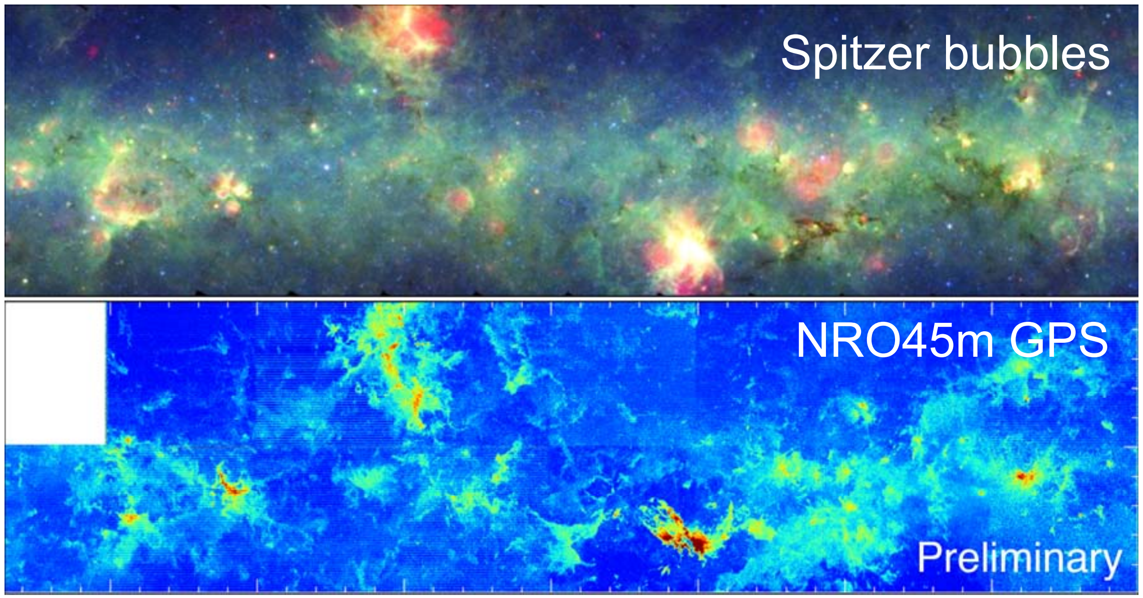
   Large scale survey datasets in radio and infrared

   – Galactic plane CO surveys (NANTEN2, NRO45m, JCMT, etc.)

   Taking intensity ratios of different J levels (Torii et al. 2011, 2015)

   – Allsky/GP infrared surveys (AKARI, Spitzer, Hershcel etc.)

   HII regions, PDR regions



Future tasks

2. Detailed studies of the individual CCC regions

   – Cloud properties before the collision (size, density, velocity, etc.)

   – Stars and star formation (SFR, stellar distribution, mass function, age distribution, dynamics)

   – Effects of the collision and star formation on the environment

3. Establish a general model of the CCC

   – Statistical studies comparing the CCC regions.

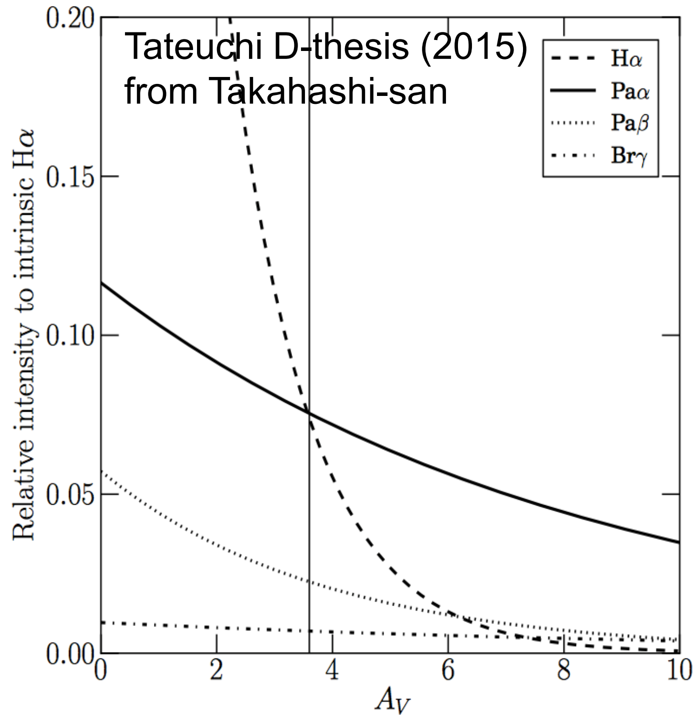
4. Expand to the extra-galaxies

   – Large-scale comparisons between the star formation indicators and the molecular gas distribution/dynamics

   – Small-scale studies of the individual molecular clouds using ALMA.

SWIMS/TAO

- Hα is important to know the distribution of the ionized gas at high spatial resolutions, however it strongly suffers from dust extinction.
- Young high mass star forming regions in the MW are deeply embedded inside the dense cloud (Av ~ 5 – 50, up to over 100)
- Paschen α still works over Av = 10.



<u>Large-scale Paα/β survey in the CCC regions in the Galactic plane</u>

- A large FoV is preferable for CCC regions in the MW.
- Spitzer bubbles (typically 3'–10') are reasonable targets. In may bubbles, information of the exiting stars and detailed distribution of the HII region are unclear.