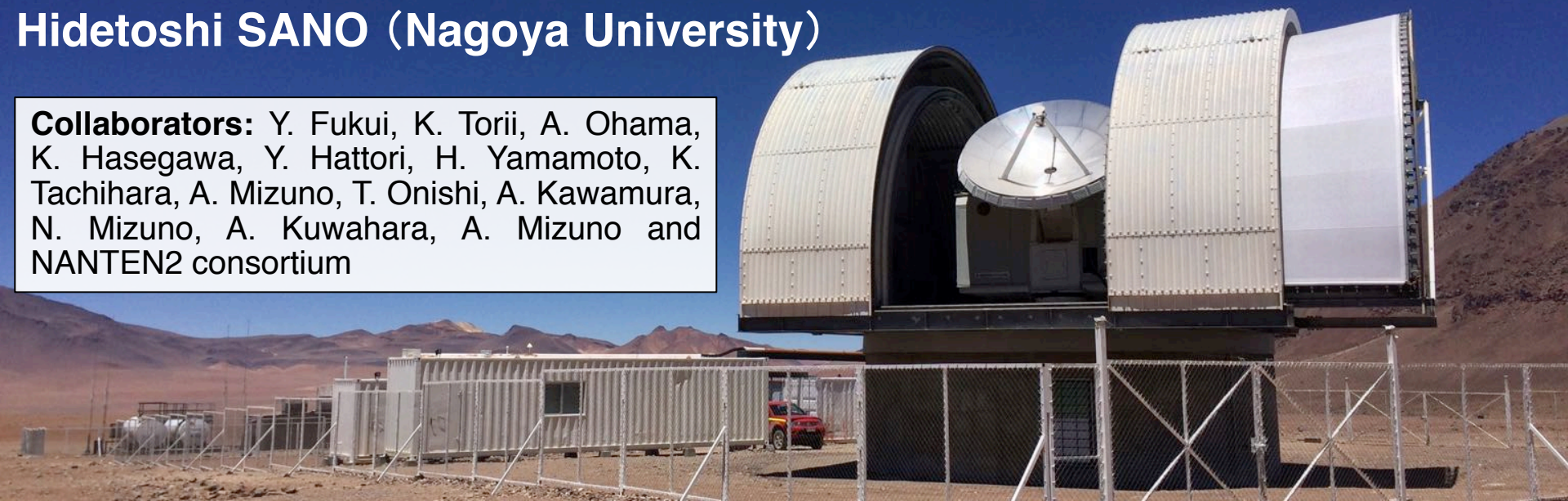
Cloud-Cloud Collisions:

a promising mechanism to trigger formation of high mass stars

Hidetoshi SANO（Nagoya University）

Collaborators: Y. Fukui, K. Torii, A. Ohama, K. Hasegawa, Y. Hattori, H. Yamamoto, K. Tachihara, A. Mizuno, T. Onishi, A. Kawamura, N. Mizuno, A. Kuwahara, A. Mizuno and NANTEN2 consortium

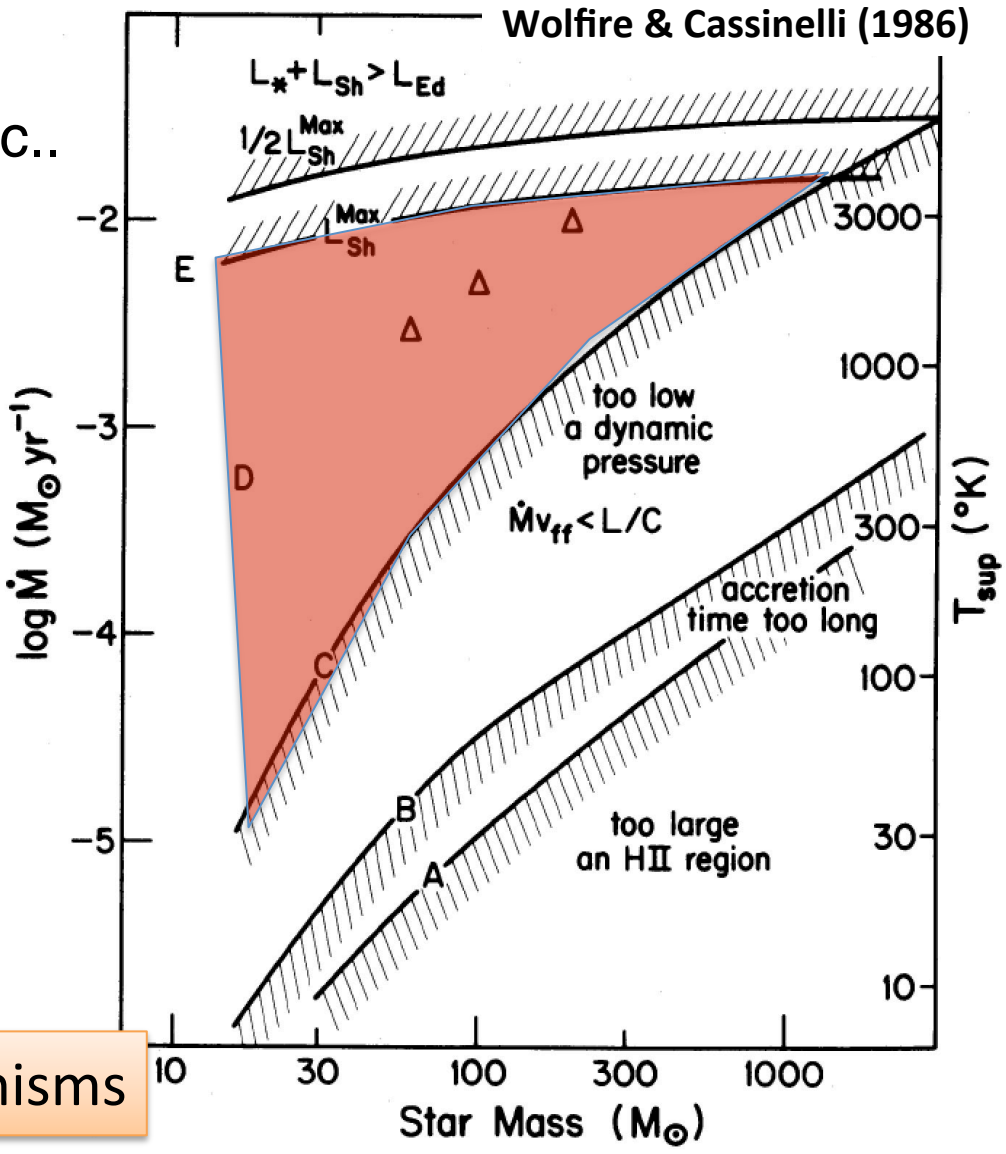


O stars and formation mechanism

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

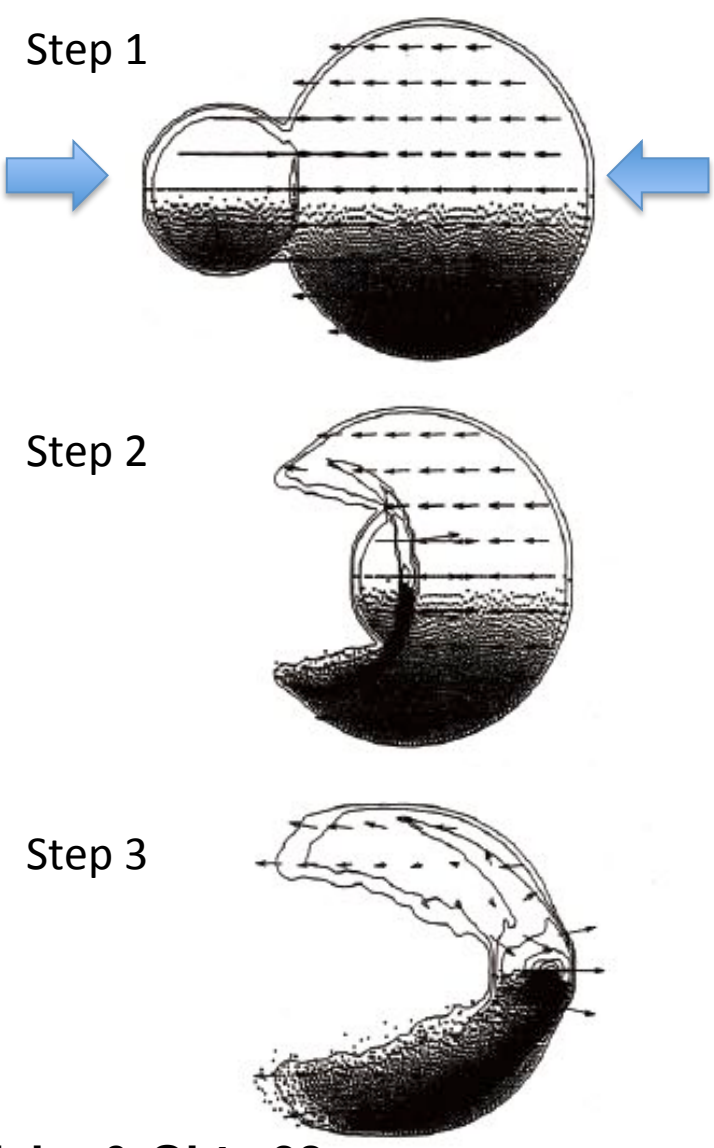
However, it is not known
how the O stars are formed?

- Observational issues
  - few, distant from us etc..
- Theoretical issues
  - large mass accretion rate etc.
    ~ 10^{-4}–10^{-3} $M_\odot$/yr
    [~10^{-6} $M_\odot$/yr for low-mass stars]

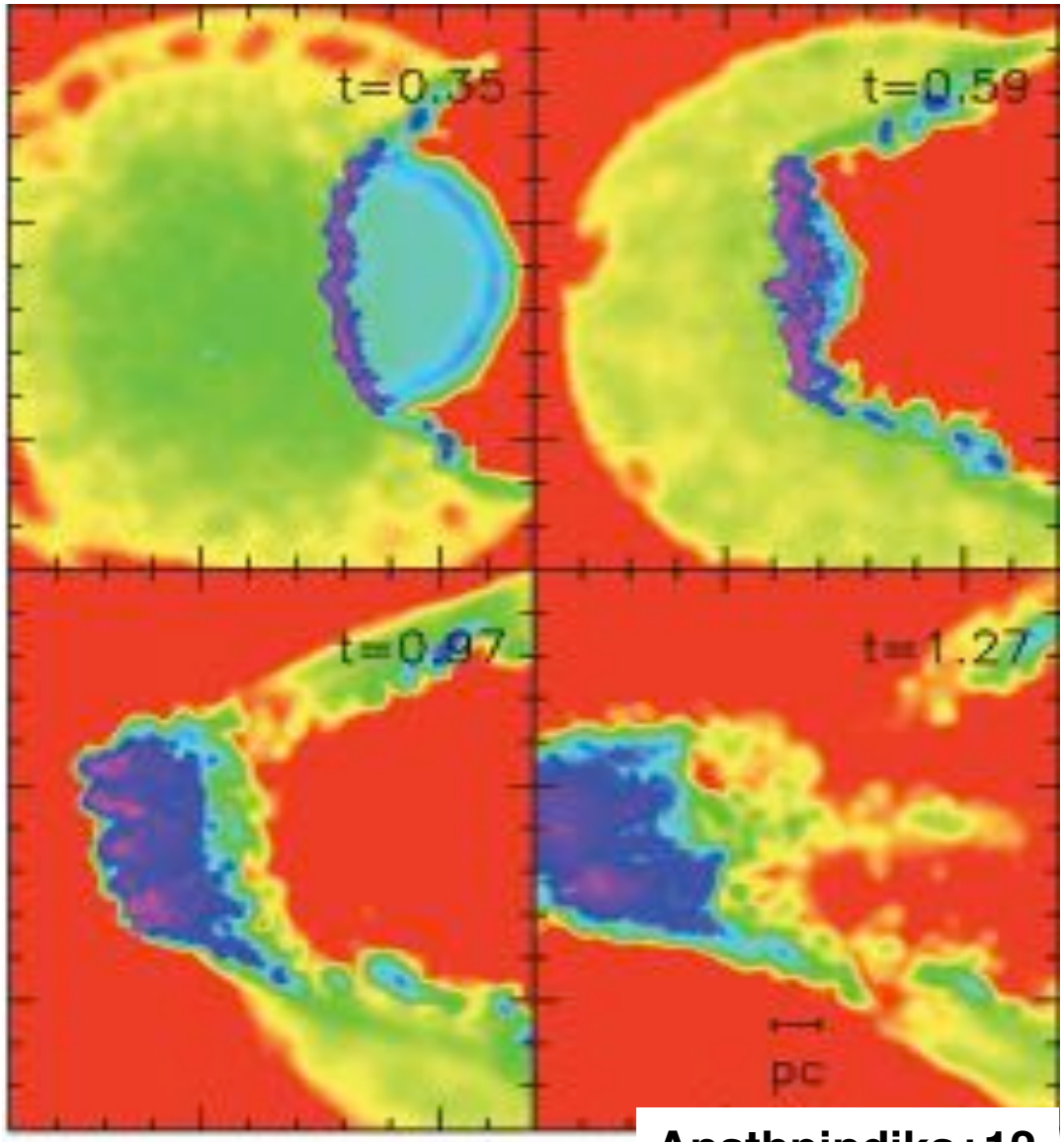


We need some triggering mechanisms

Numerical simulations of Cloud-Cloud Collisions



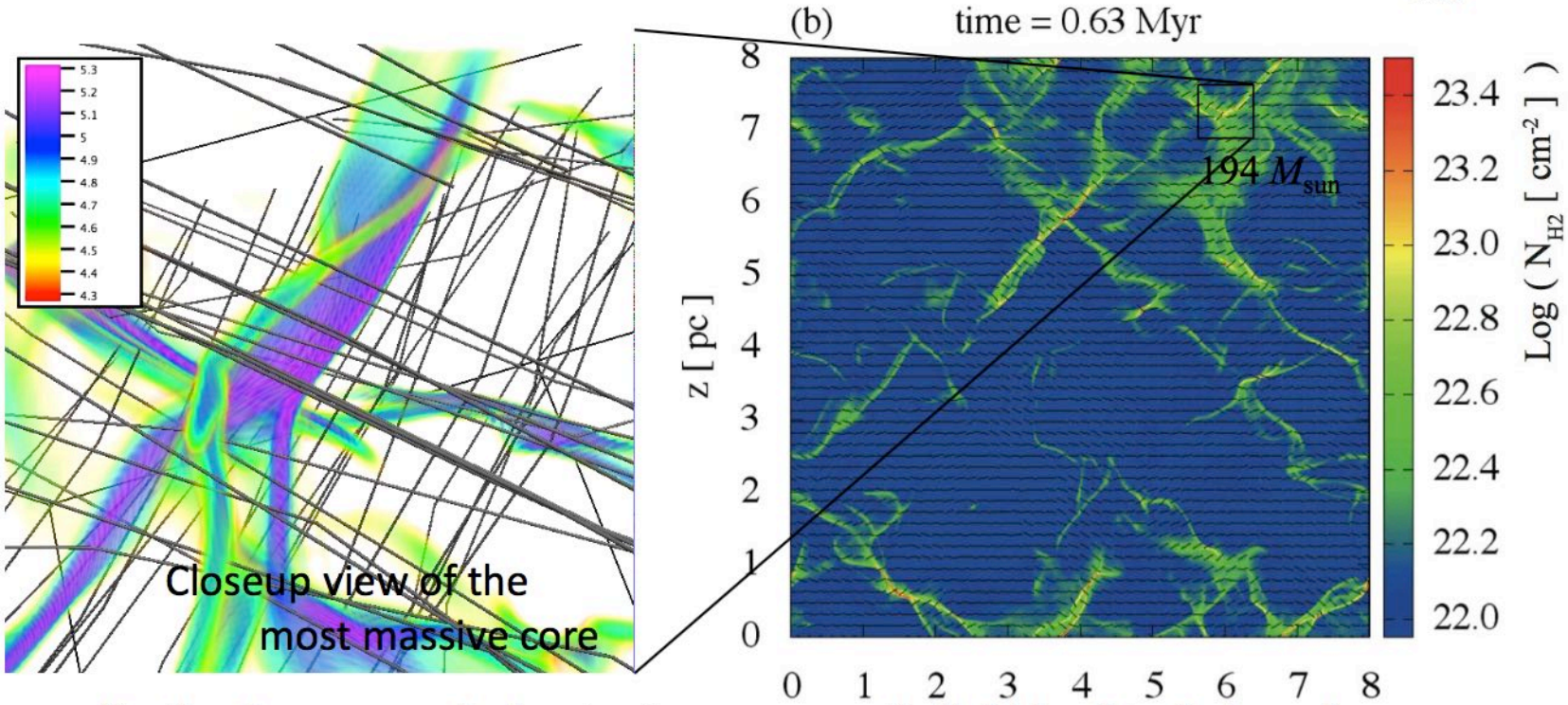
Habe & Ohta 92



Anathpindika+12

Numerical simulations of Cloud-Cloud Collisions

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



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

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

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

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

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

Inoue & Fukui 13, ApJL

courtesy by Inoue-san

Observational Evidence of Cloud-Cloud Collisions

- **Super star clusters**
  Westerlund 2, NGC 3603, RCW 38, DBS[2003]179, Trumpler 14 etc.
  (Furukawa+09; Ohama+10; Fukui+14; Fukui+15)

- **Star burst regions**
  NGC 6334 & NGC 6357 (Fukui 15), W43 (Fukui+16)

- **HII regions**
  M 20 (Torii+11), M43 / M42 (Fukui+16)
  Spitzer bubbles (Torii+15; + in prep.)
  Vela Molecular Ridge (HS+ in prep.), Gum 31 (Higuchi+ in prep.)

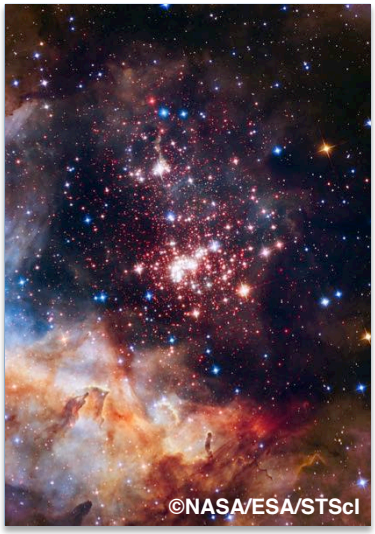
- **Ultra compact HII regions**
  RCW 116 (Ohama+ in prep.), Southern UCHII regions

- **Wolf-rayet nebula**
  NGC 2359 (HS+ in prep.)

using Mopra

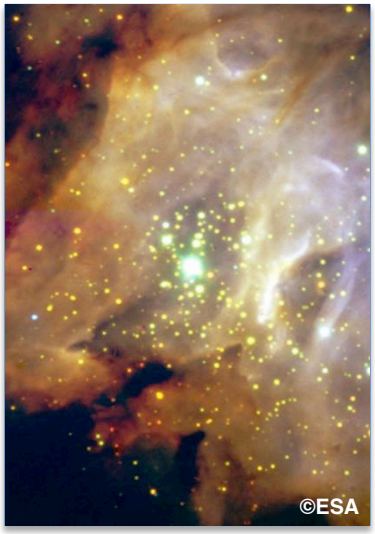
observed by NANTEN2 (2015)

Super star clusters (SSCs)



Westerlund 2

NGC 3603



RCW 38

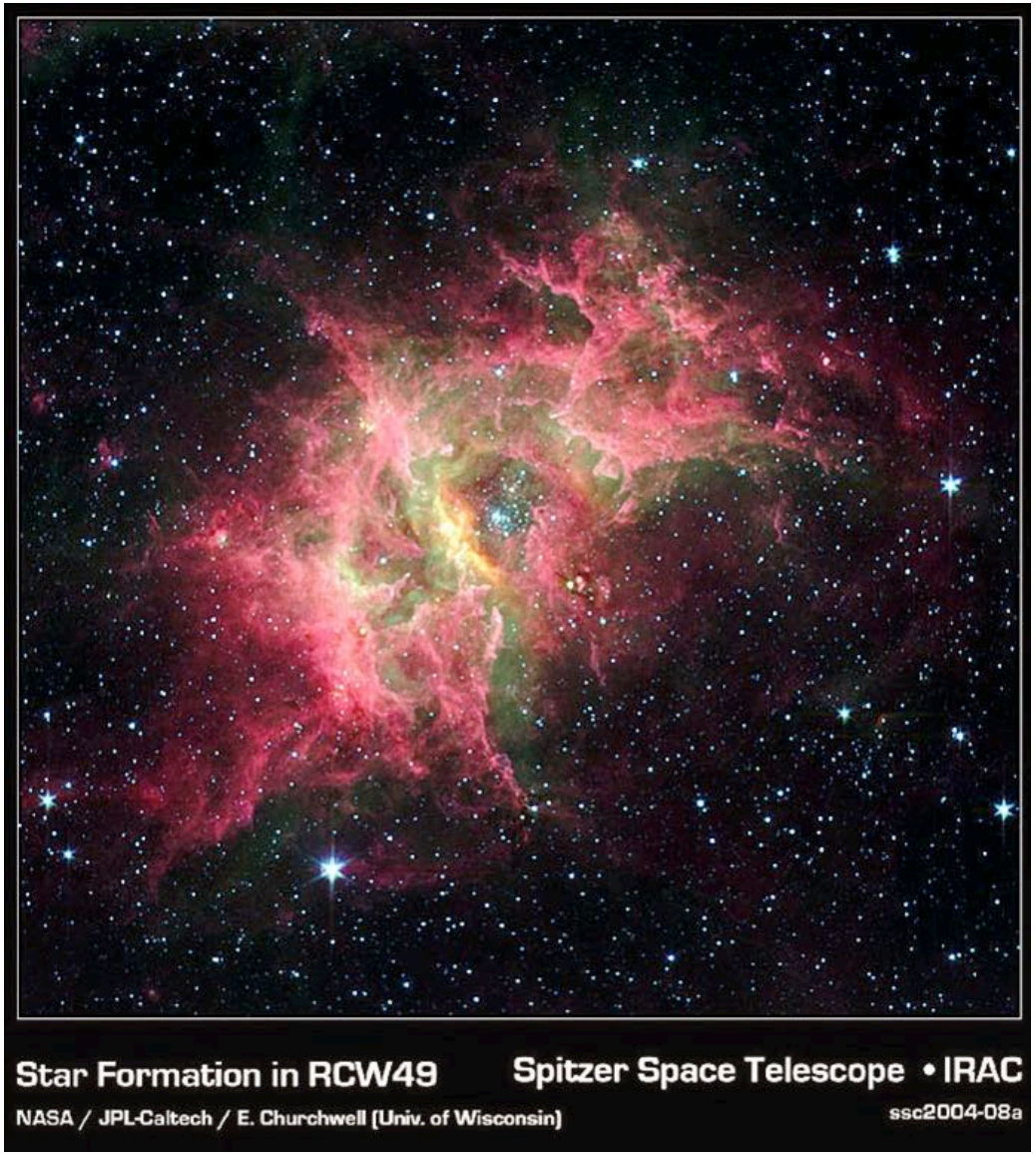
[DBS2003]179

Trumpler 14

- SSCs are rich clusters of 10^4 members incl. 20-30 O stars
- 5 SSCs are associated with ISM
- Ages are on average 2 Myrs

Cluster Name	Age [Myr]	Stellar Mass [Log $M_\odot$]	Size [pc]	Molecular clouds
Westerlund 2	2.0	4.0	0.8	Yes
NGC 3603	2.0	4.1	0.7	Yes
RCW 38	<1.0	--	0.8	Yes
[DBS2003]179	3.5	3.8	0.5	Yes
Trumpler 14	2.0	4.0	0.5	Yes
Arches	2.0	4.3	0.4	No
Westerlund 1	3.5	4.5	1.0	No
Quintuplet	4.0	4.0	2.0	No

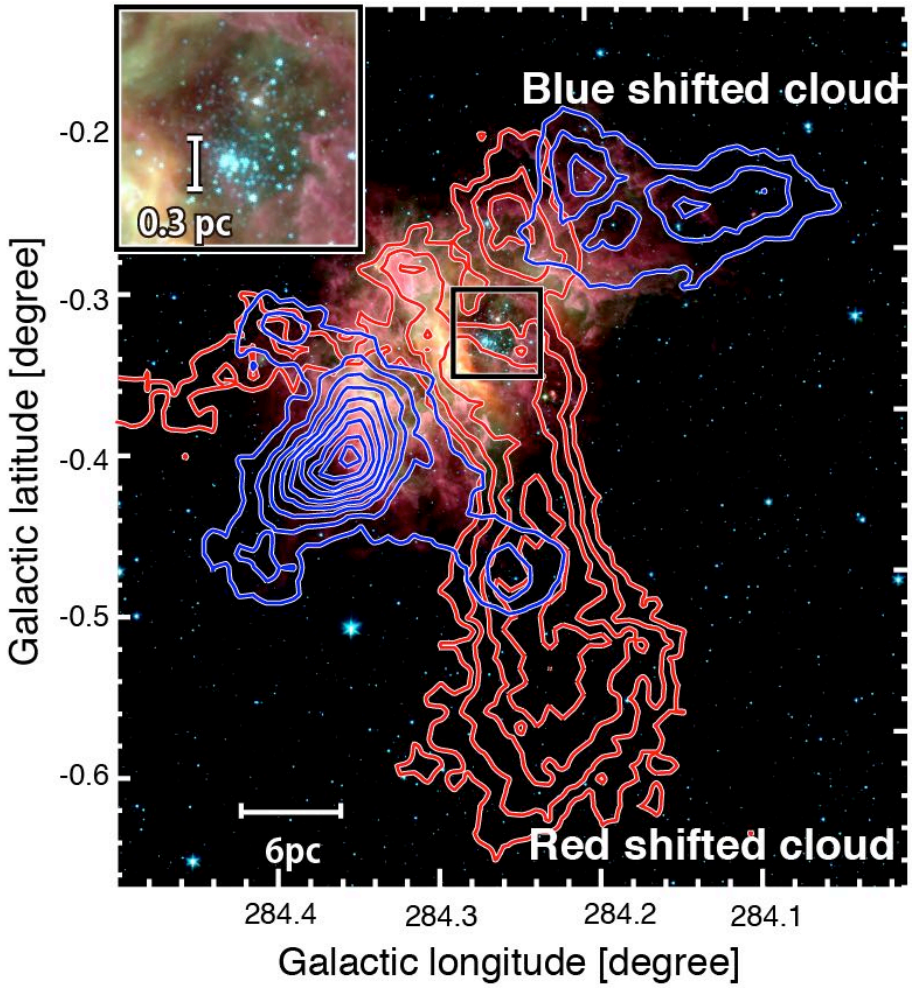
SSC : Westerlund 2

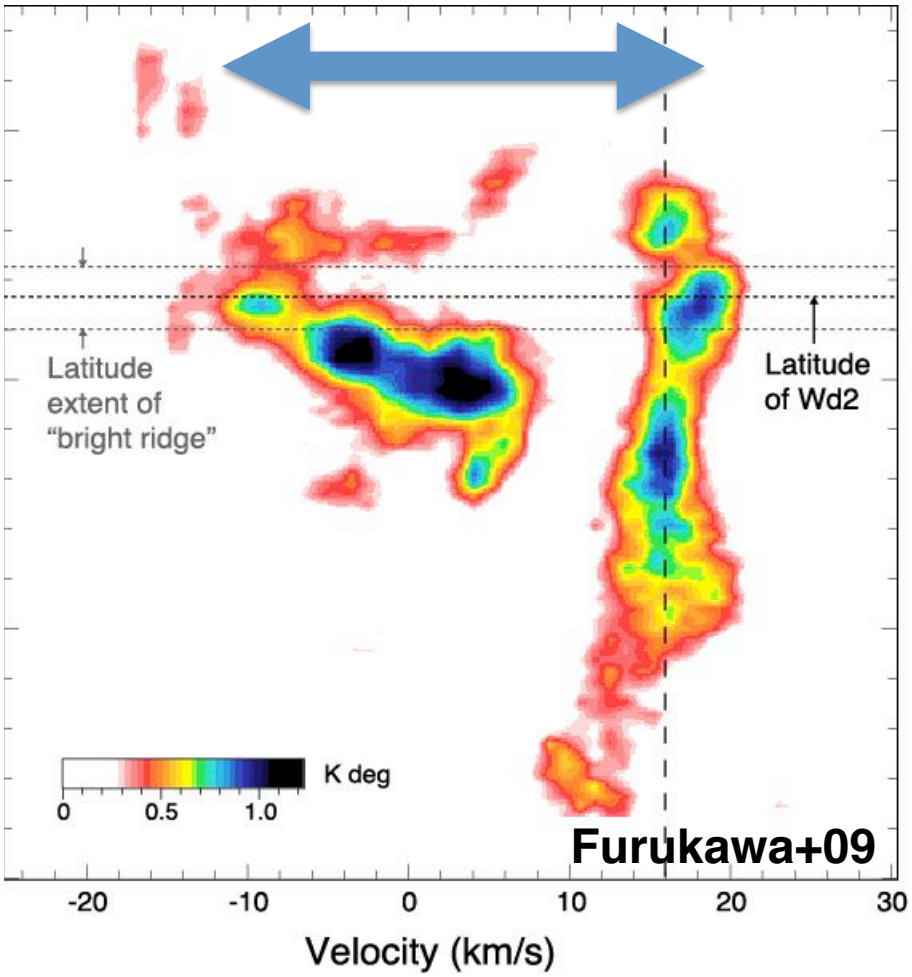


- (l, b) = (284°.27, -0 °.33)
- O-Star x 12, WR-star x 2
- Total mass of the stars 4,500 $M_{\odot}$ (Rauw+07)
- Age 2–3 Myr (Piatti+98)
- Distribution of dust influenced by stars (Churchwell+98)
- Star formation in progress
- YSO ~300 (Whitney+04)

We found two giant molecular clouds (GMCs) associated with Westerlund 2 (Furukawa+09; Ohama+10)

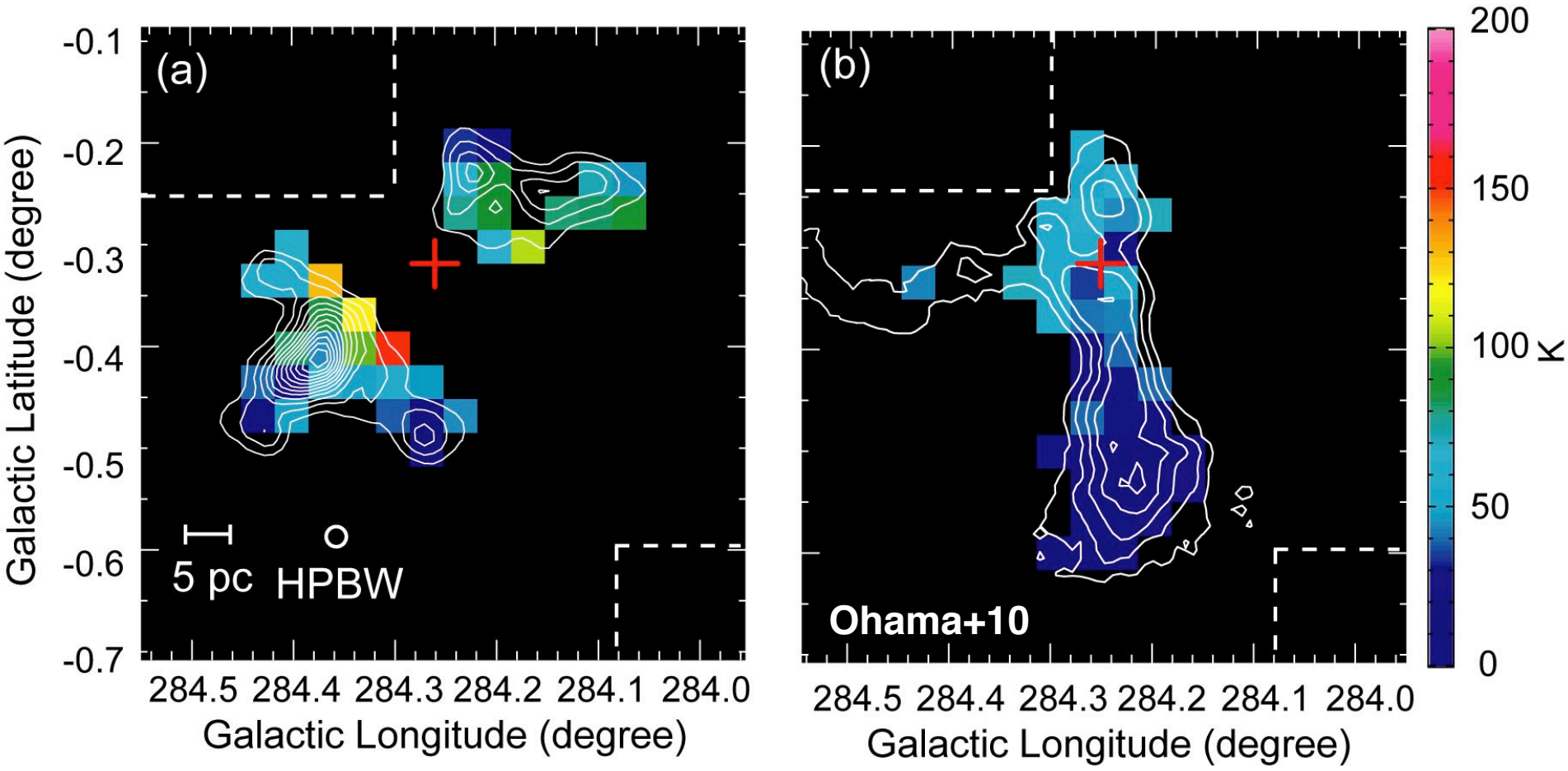
SSC: Westerlund 2 (Furukawa+09; Ohama+10)





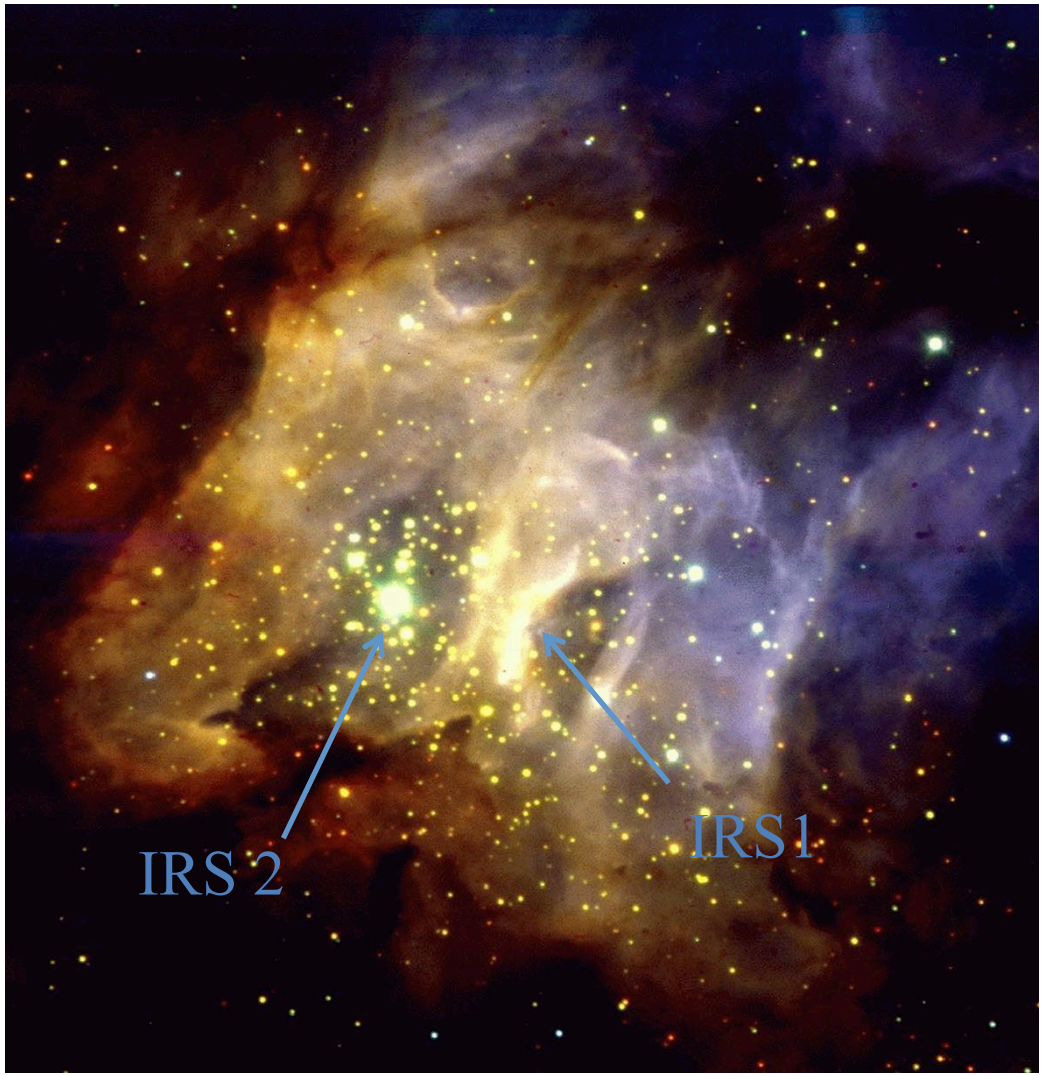
- Two GMCs (red/blue) are complementary distributed toward Westerlund2.
- The velocity separation of the two clouds is 15–25 km s^{-1}, can not be bound with the gravity.

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



- Both the two GMCs are heated by the strong UV radiation from the SSC
  → Both the two GMCs are physically associated with the SSC, although they have a large velocity separation.

SSC: RCW 38



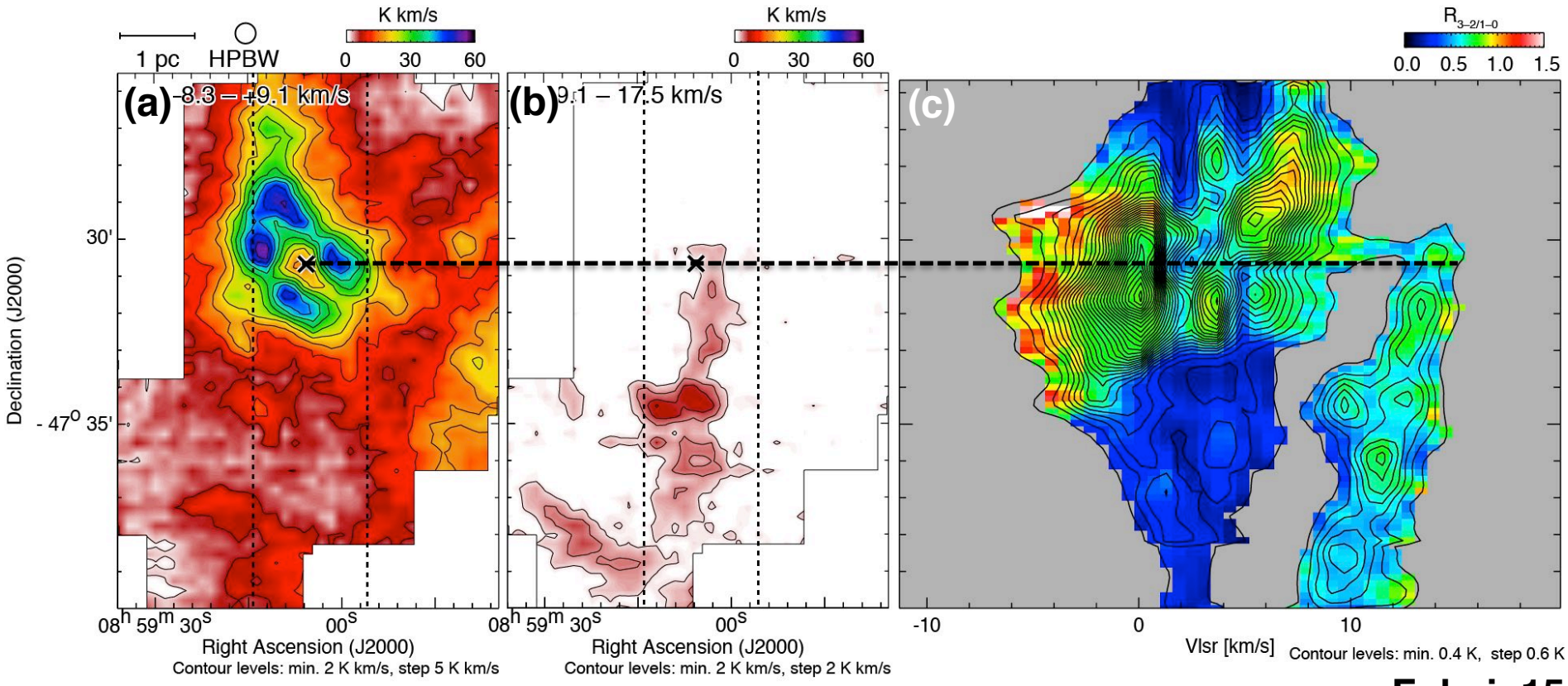
- High mass star-forming region
- Bright HII region
  (Rodgers, Campbell & Whiteoak 60)

- Position: (*l, b*) = (268°, -1°)
- Age: < 1 Myr (young cluster)
- Distance: 1.7 kpc (Rodgers 60)
- Number of stars: 10^{3-4} (O ~30)
  (Wolk+06; Winston+11)

- Two bright mid-IR sources IRS 1 and IRS 2
  (Frogel & Persson 74; Smith+99; DeRose+09)

A close-up of the central 2.5' (~1.2 pc) of RCW 38 (Wolk et al. 2006; credite ESO).
In this VLT image, Z band data are printed as blue, H band data are green and K band are red.

SSC: RCW 38 (Fukui+15, arXiv:1504.05391)

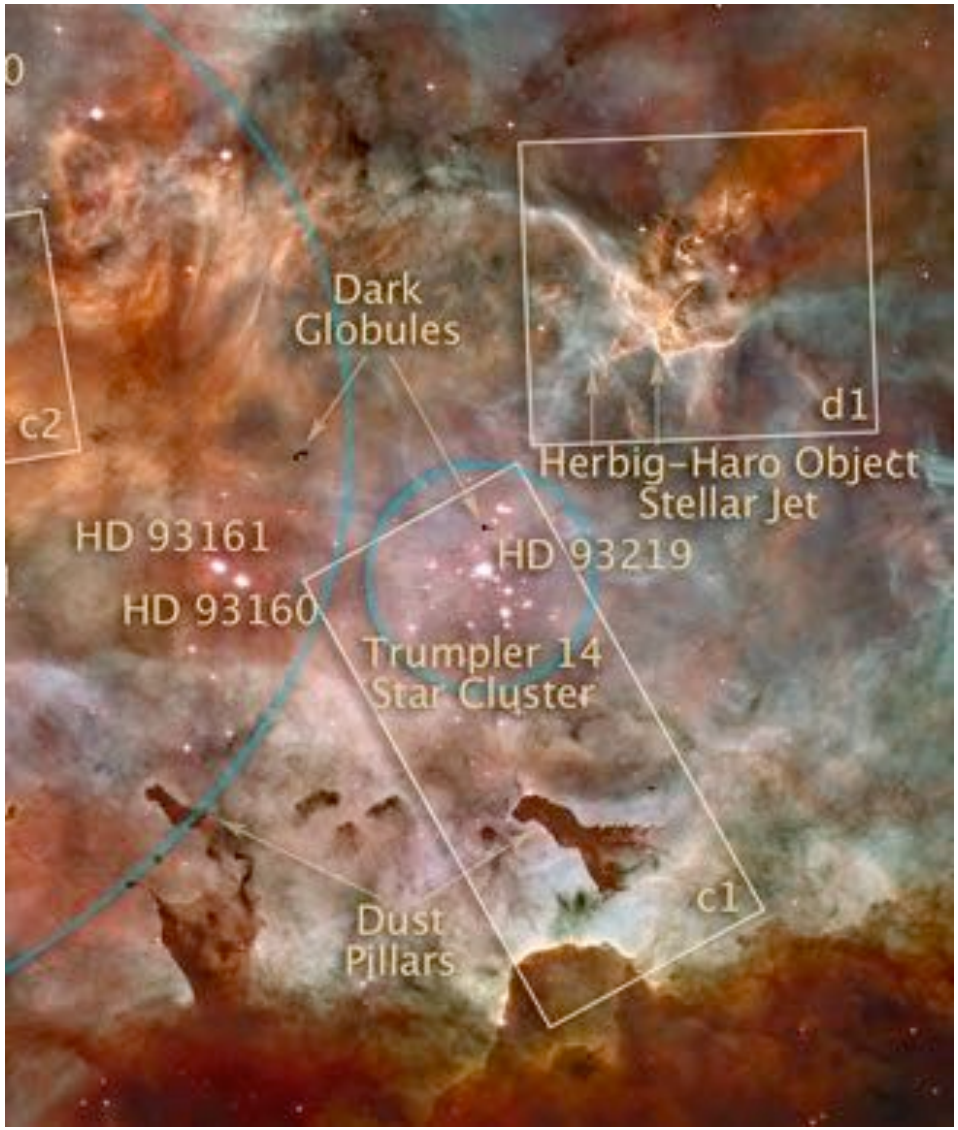


Fukui+15

(a-b) Mopra ^{13}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.

SSC : Trumpler 14



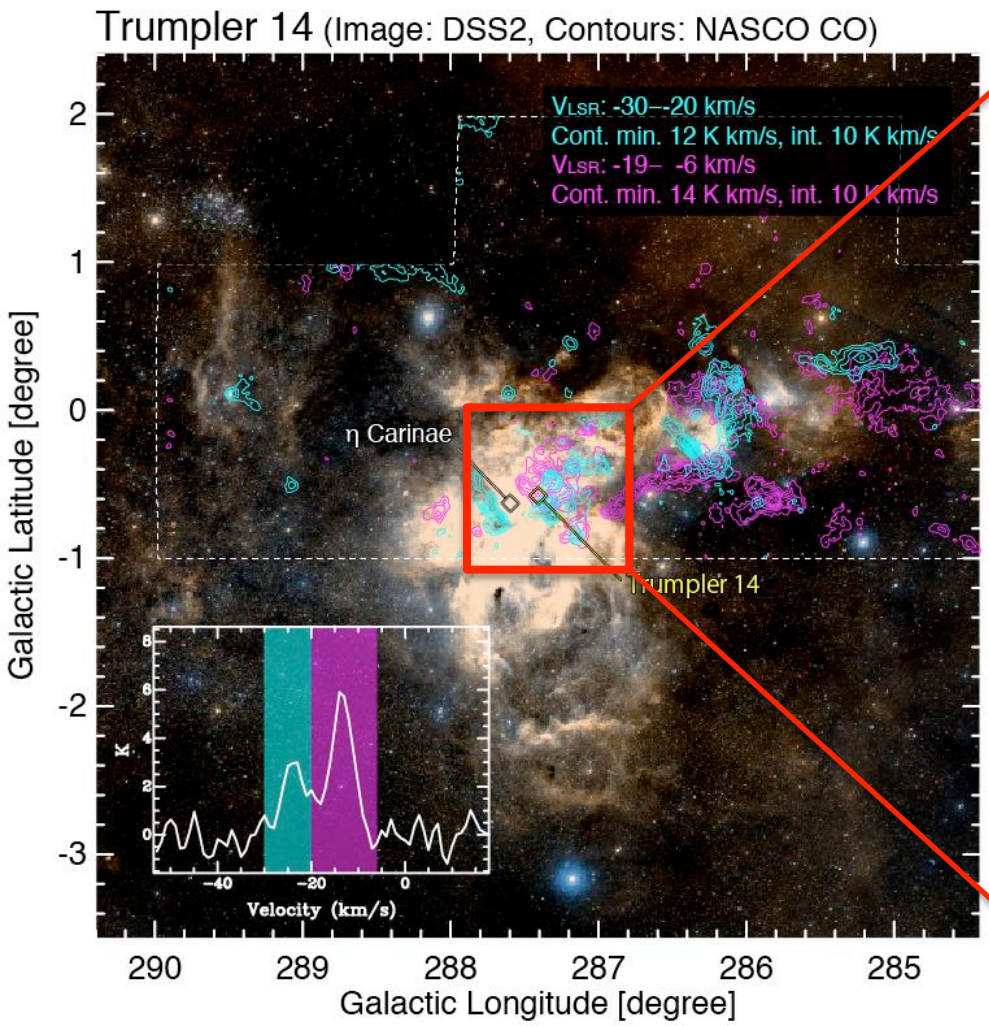
- SSC in the Carina nebula
  (e.g., Hur+12)
- Position: (*l, b*) = (287.4°, -0.6°)
- Age: 2-3 Myr (Hur+12)
- Distance: 2.3 kpc (Smith+06)
- Number of stars in the Carina nebula
  - O stars: > 65
  - Wolf-Rayet stars: 3
  - intermediate mass stars: ~100
  - low-mass pre-MS: ~10,000
  - η Carina

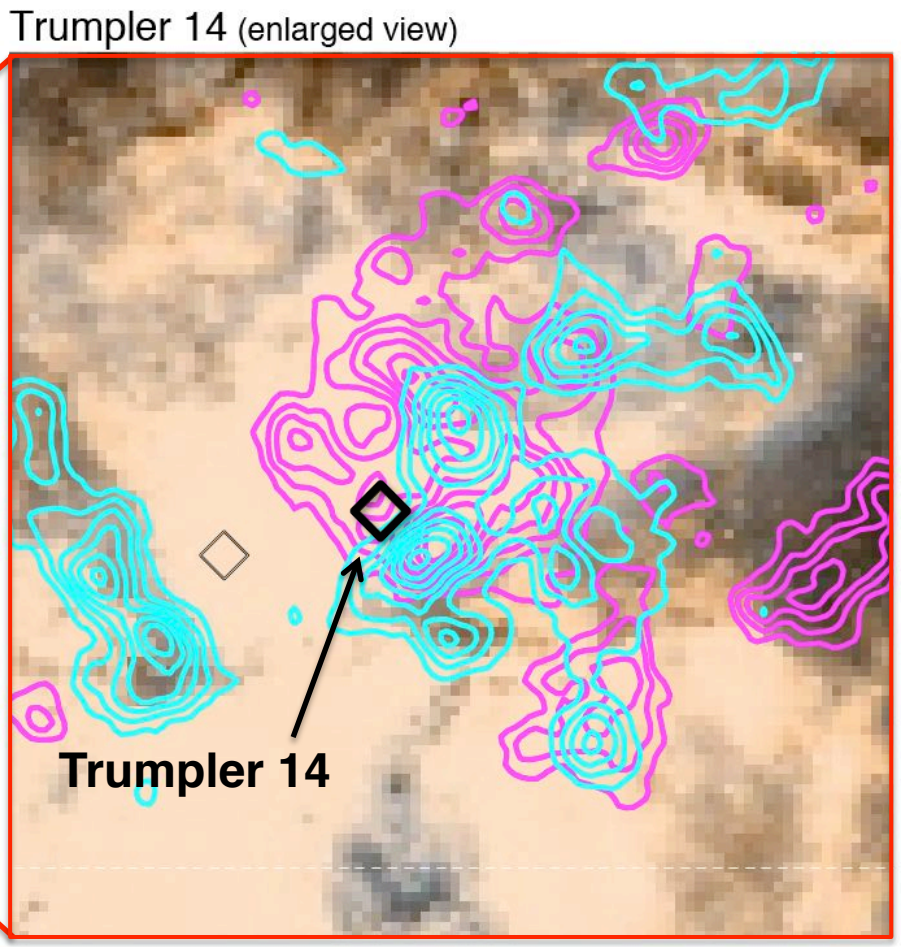
  (Smith+06; Corcoran+04)

Most recently, we found two molecular clouds associated with the SSC by using NANTEN2 CO datasets.

HST image toward the super star cluster Trumpler 14.

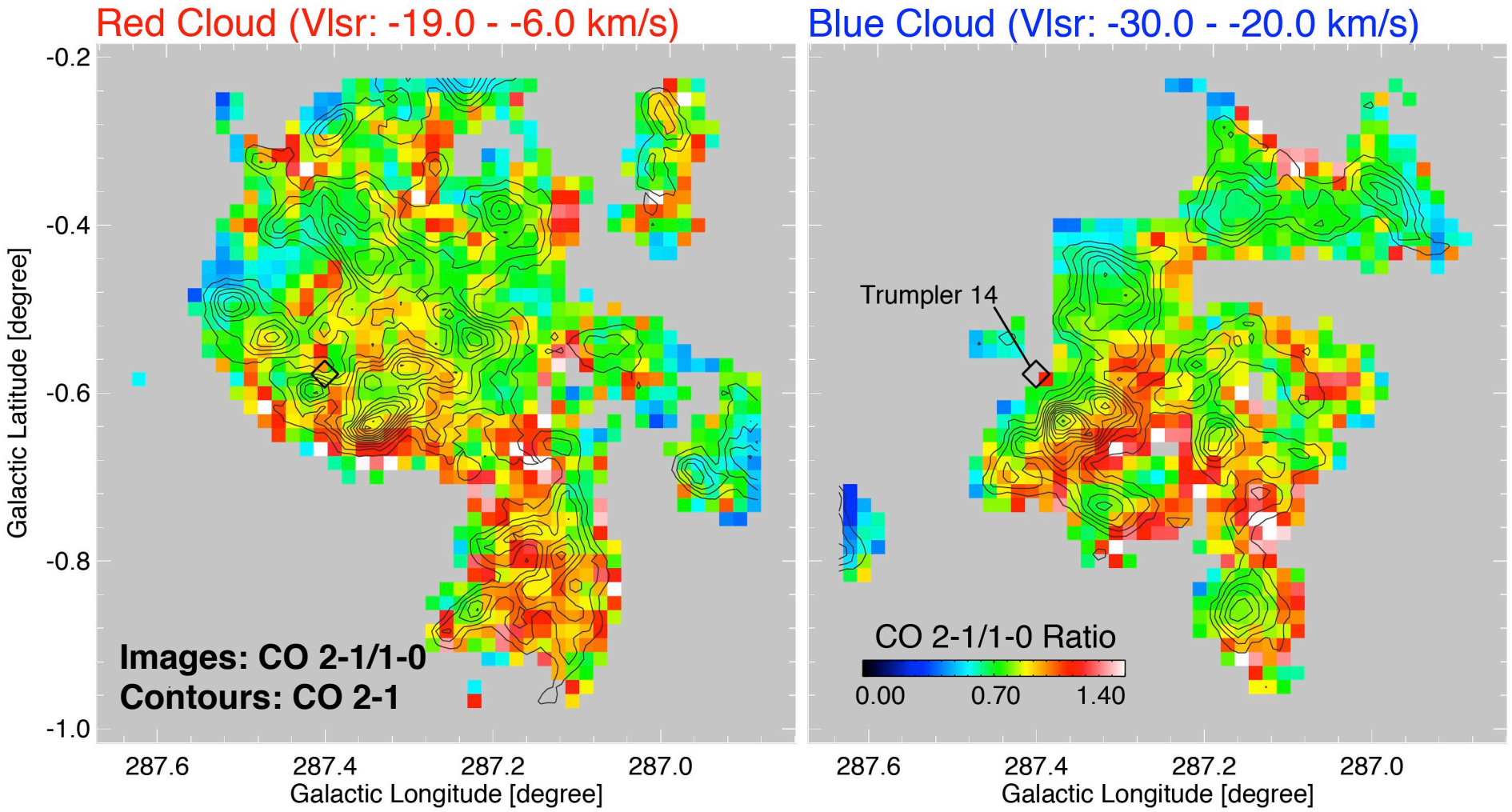
SSC : Trumpler 14





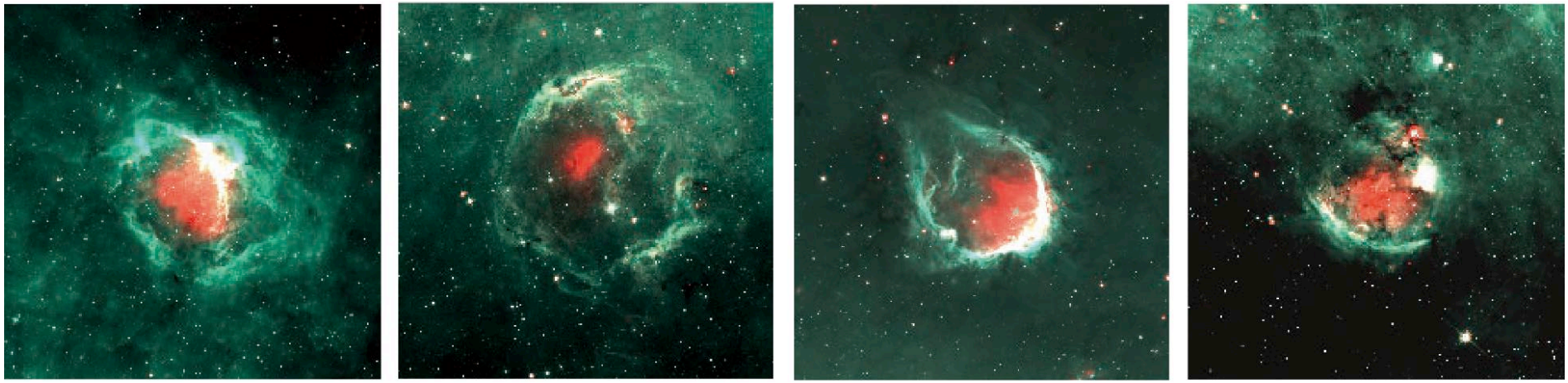
- Two clouds (red/blue) are complementary distributed toward Trumpler 14
  → We observed the two clouds using the NANTEN2 CO *J* = 2-1 lines

SSC：Trumpler 14（NANTEN2 2015）



- Both the red and blue clouds show a high-intensity ratio > 1.0
  → Evidence for physical association with the SSC and Carina nebula

Spitzer Bubbles

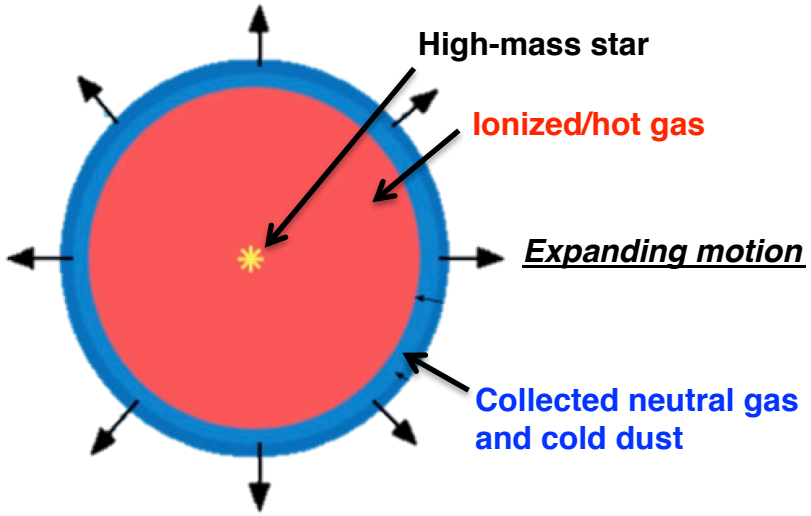


False color images of the Spizer bubbles (Green: 8 μm, Red: 24 μm).

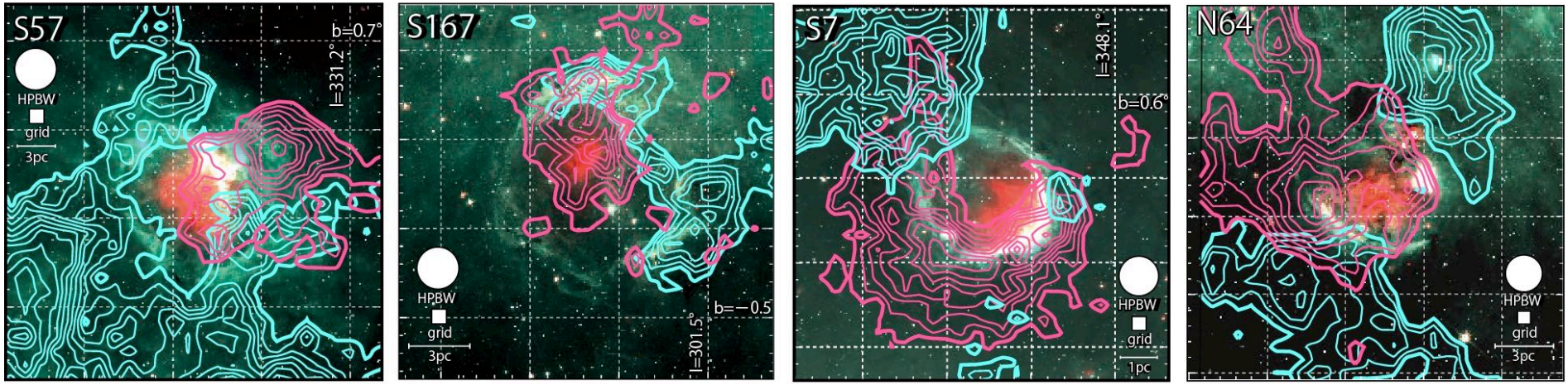
- Churchwell+06 identified ~600 ring-like structures using the *Spitzer* 8 μm. The work was followed by an expanded catalog of 5106 bubbles (Simpson+12).

- The pressure-driven expanding HII region is usually discussed to explain the formation of the Spitzer bubbles (e.g., Deharveng+10)

  → But, almost bubbles have no CO/HI gas having an expanding motion.

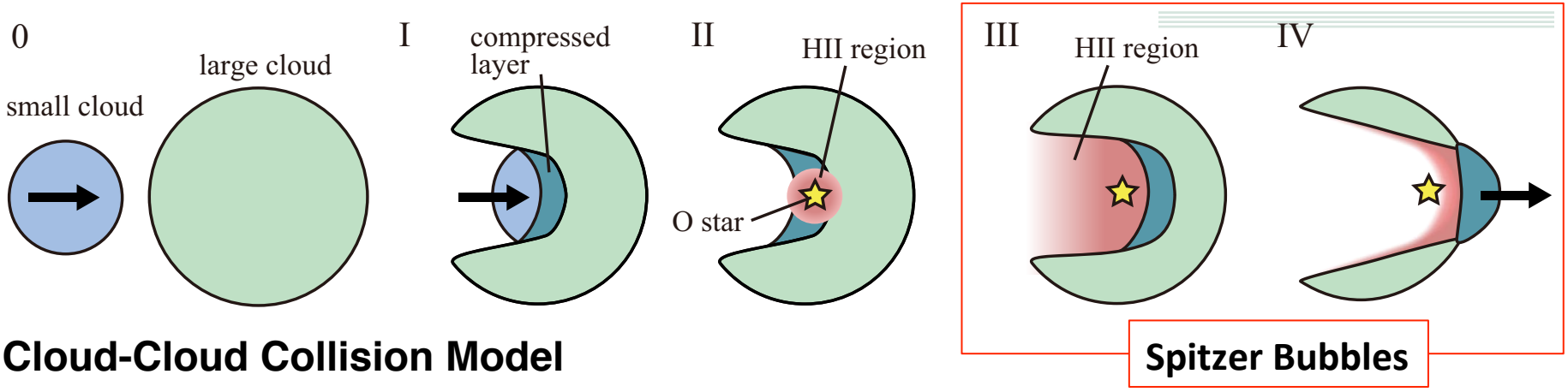


Spitzer Bubbles as the site of Cloud-Cloud Collision

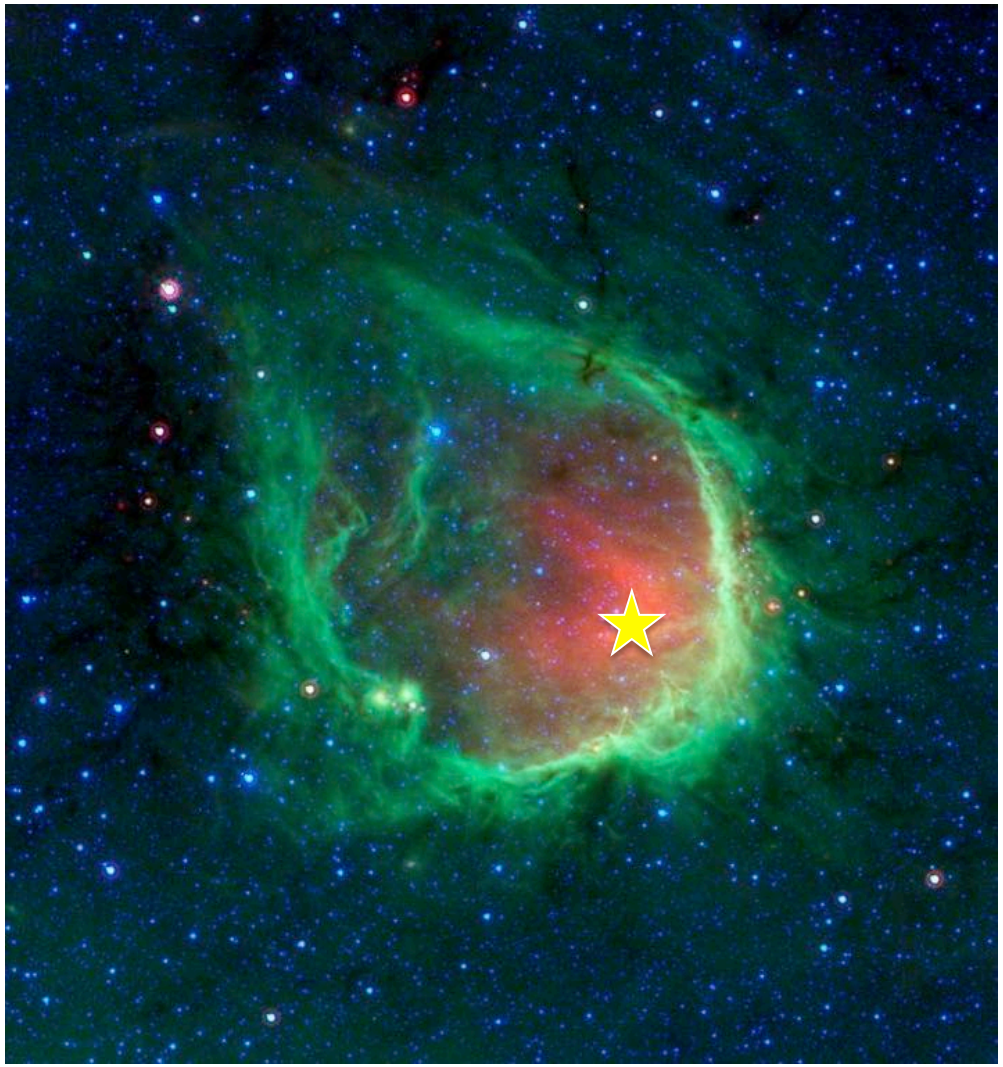


False color images of the Spizer bubbles (Green: 8 μm, Red: 24 μm).
Superposed contours show the CO clouds (red & blue shifted cloud) taken by NANTEN2.

- We observed ~60 Spitzer bubbles in CO lines using NANTEN2
  Almost bubbles have two clouds ($V_{sep.}$~10-30 km/s) →Cloud-Cloud Collision



Spitzer Bubbles: RCW 120



- Galactic HII region (Rodgers+60)
- Cataloged as S7 (Churchwell+06)

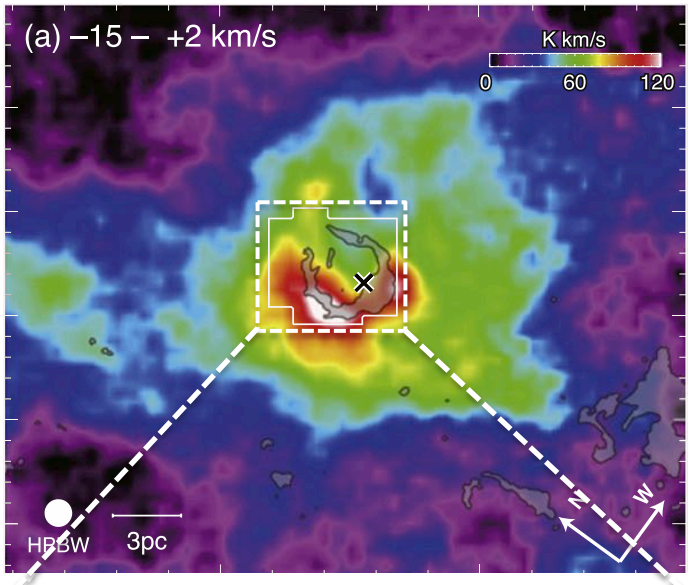
- Position: (*l, b*) = (348.3°, 0.5°)
- Age: < 5 Myr (e.g.,Martins+10)
- Distance: 1.3 kpc
- Single O8-star (~20 $M_{\odot}$)
- An HII region inside the ring

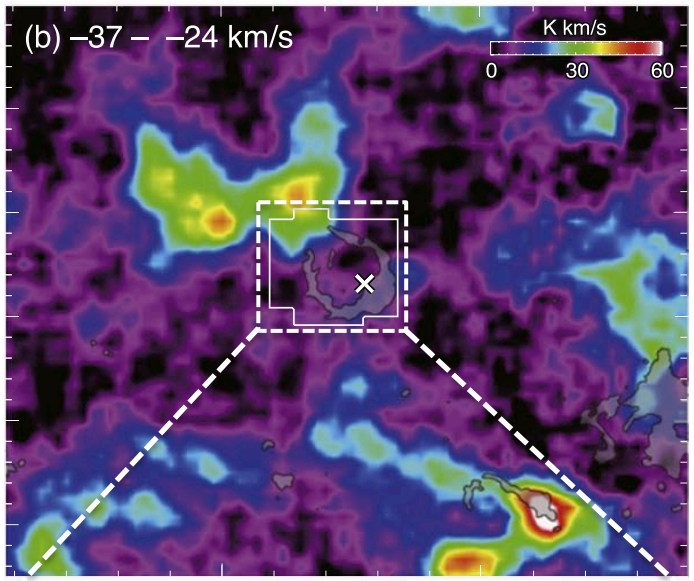
- The triggered star formation accumulated by the pressure-driven H II region
  (e.g., Zavagno+07; Deharveng+09)

We observed CO *J* = 1-0, 2-1, 3-2 using the NANTEN2, ASTE, and Mopra telescopes

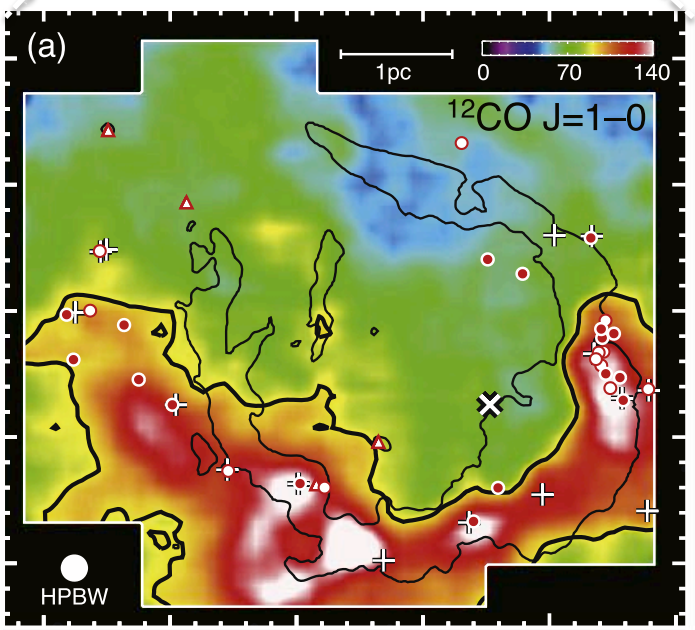
False color images of the RCW120 (Green: 8 μm, Red: 24 μm).
Star symbol shows position of the O star.

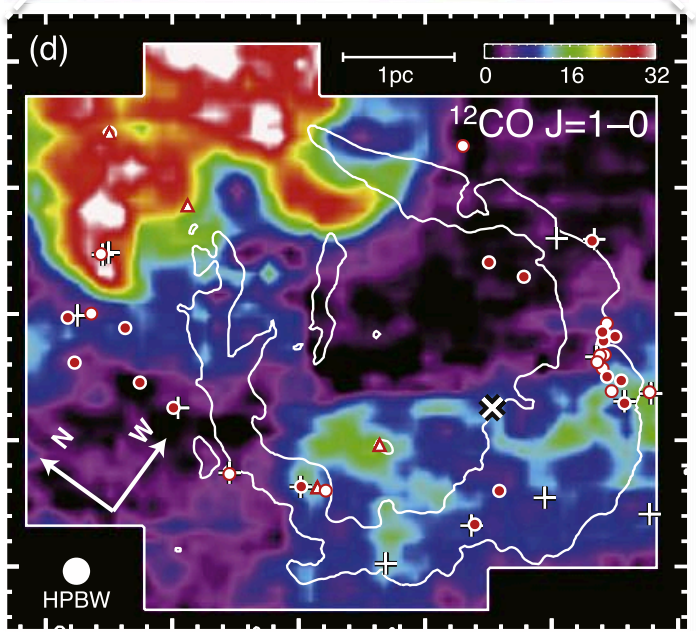
Spitzer Bubbles: RCW 120 (Torii+15)





← NANTEN2
^{12}CO(J = 1-0)
$\Delta\theta$ ~180”
⬇
For large scale

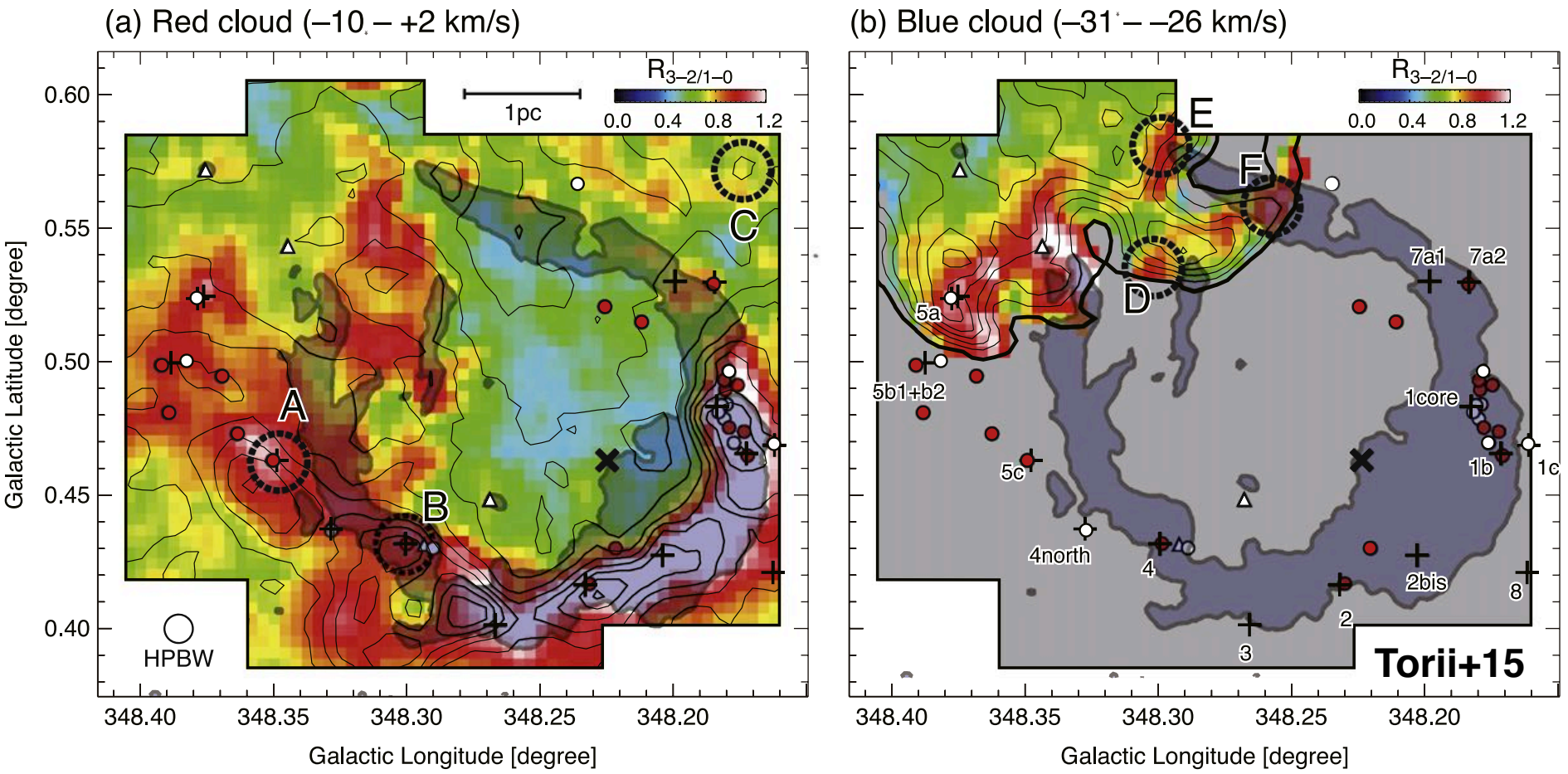




← Mopra
^{12}CO(J = 1-0)
$\Delta\theta$ ~45”
⬇
For small scale

Torii+15

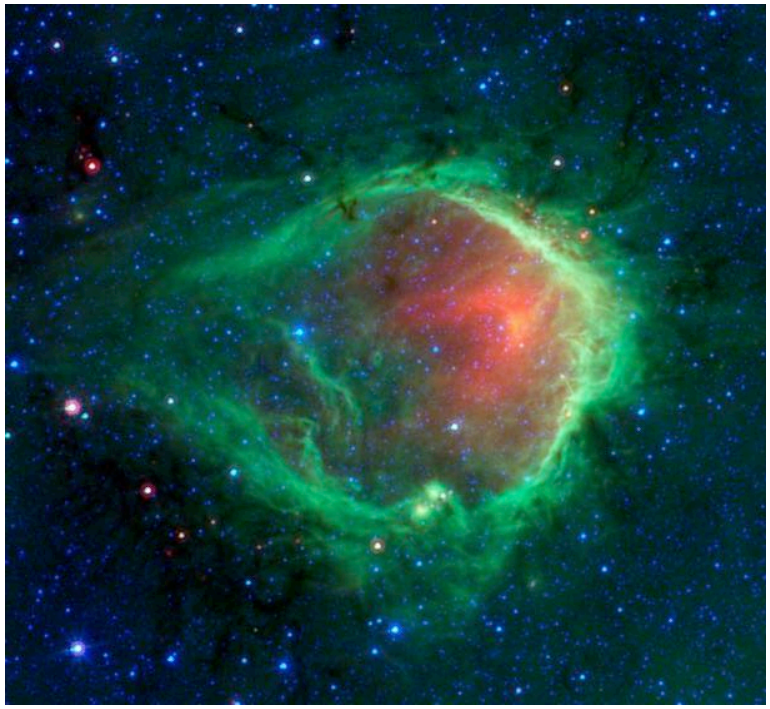
Spitzer Bubbles: RCW 120 (Torii+15)



Maps of ^{12}CO J = 3-2 / 1-0 intensity ratio using the Mopra & ASTE telescopes

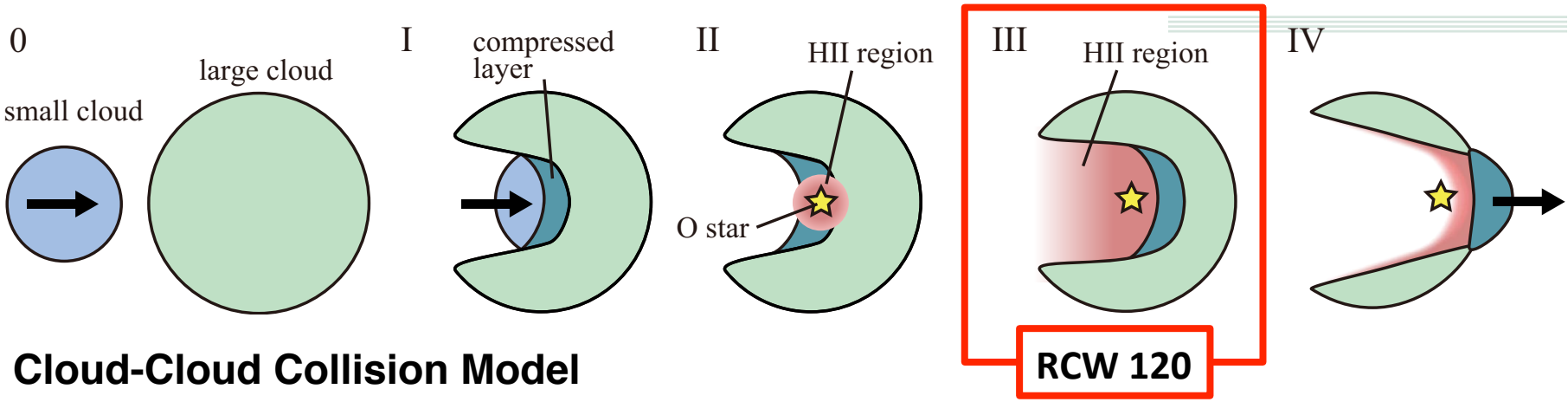
- Both the two clouds show a high-intensity ratio > 1.0
  → Evidence for physical association with the Spitzer bubble RCW 120
- No evidence for the expanding motion in the velocity space!!!

Spitzer Bubbles: RCW 120 (Torii+15)



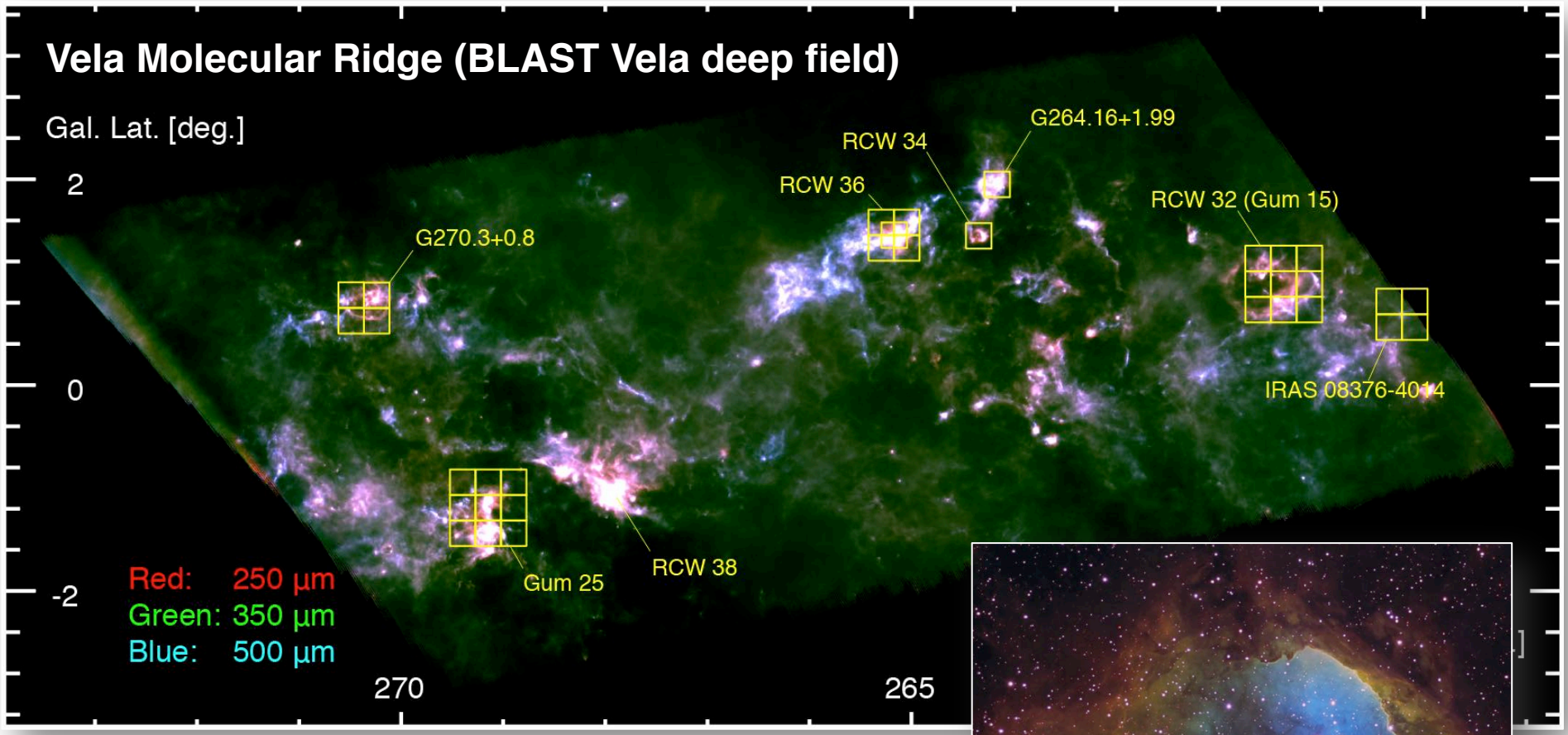
- RCW 120 is able to form by Cloud-Cloud Collision between the large cloud and the small cloud half of which is dissociated by strong UV radiation from the O star.

- Collision velocity ~30 km/s
- Time scale of O-star formation < 0.8 Myr
  → dM/dt > 2 × 10^{-5} $M_\odot$/yr
  (up to 10^{-4} $M_\odot$/yr)



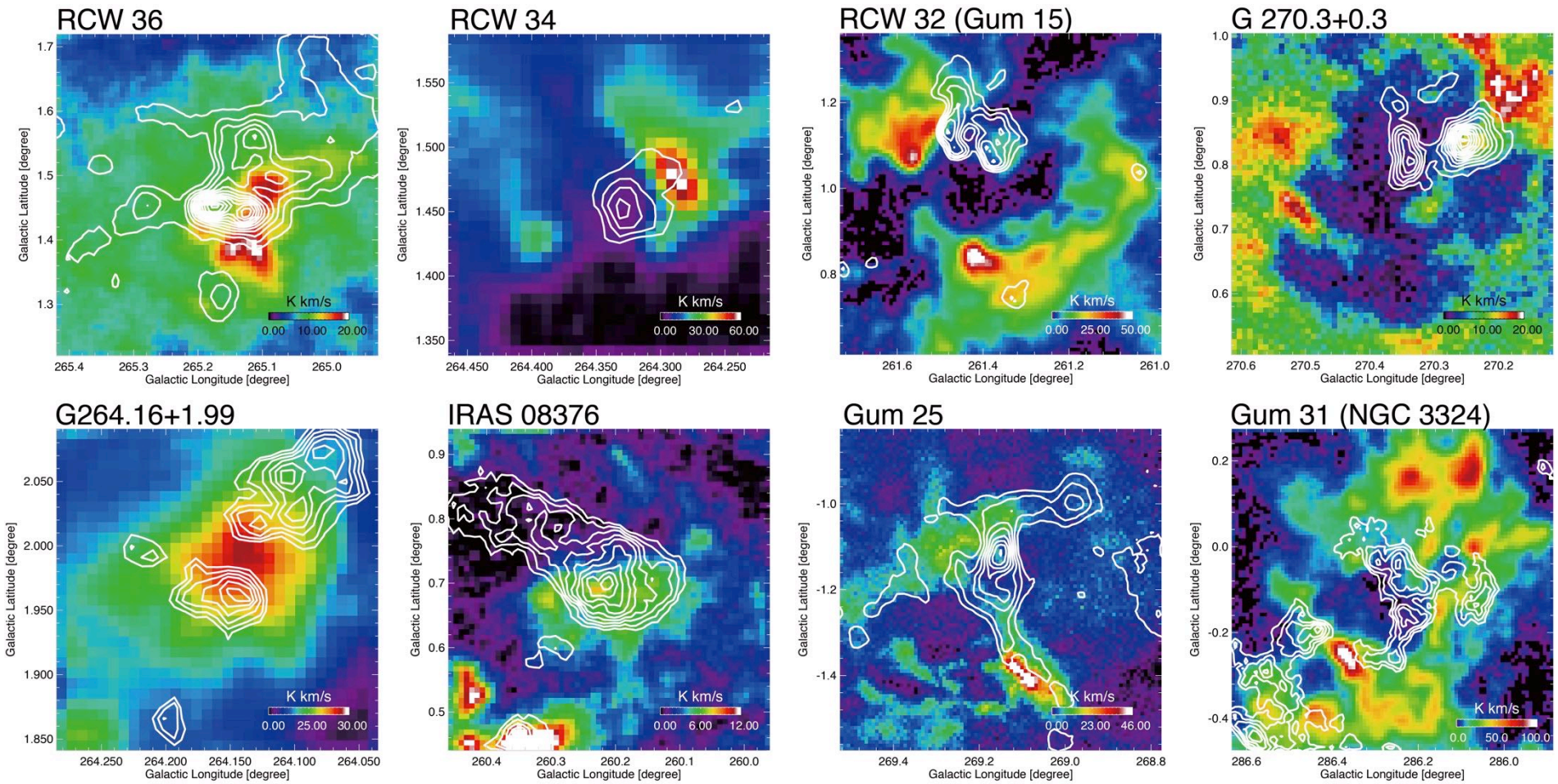
Cloud-Cloud Collision Model

HII Regions: Vela Molecular Ridge (VMR) & Gum 31



- We observed ~ 10 HII reigns in the Vela molecular ridge (VMR) and Gum 31 using the NANTEN2 CO 2-1 line in this season.

HII Regions: VMR (HS+) & Gum 31 (Higuchi+)

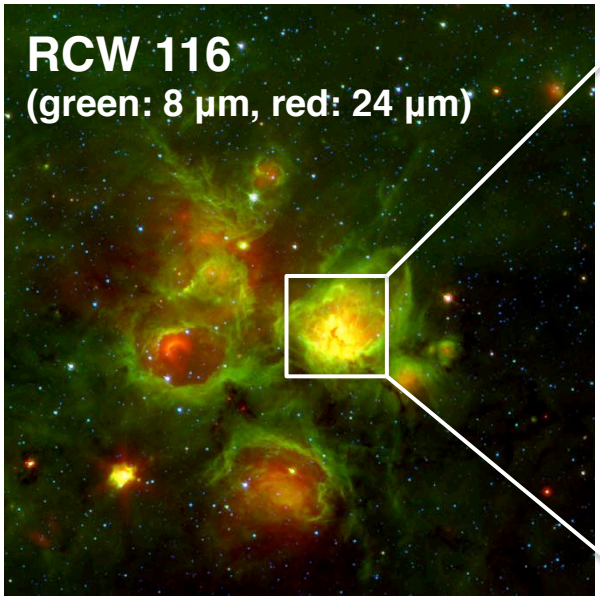


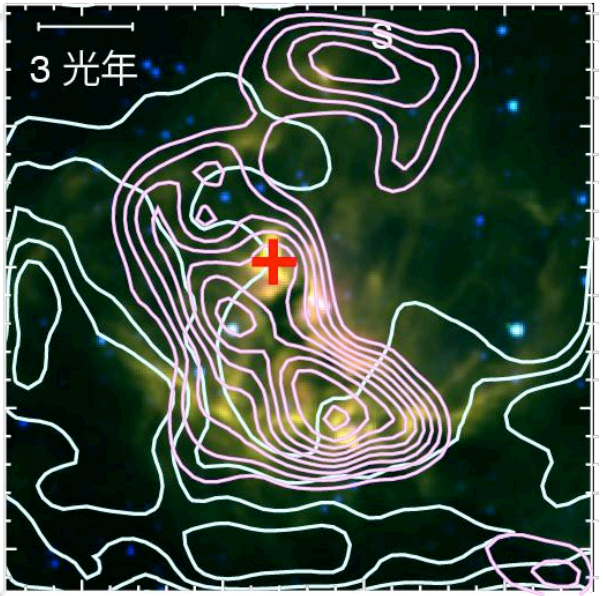
Images and contours show red and blue shifted clouds having V separation of 5-20 km/s

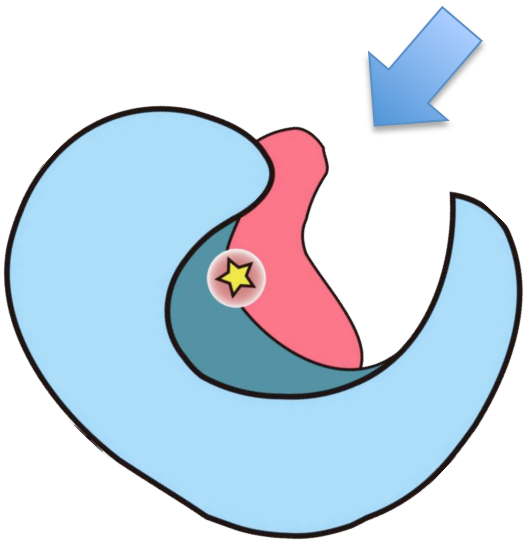
- All HII regions have two molecular clouds having different velocity.
- We are observing CO 3-2 using ASTE (PI: HS) → We need Mopra CO 1-0!!

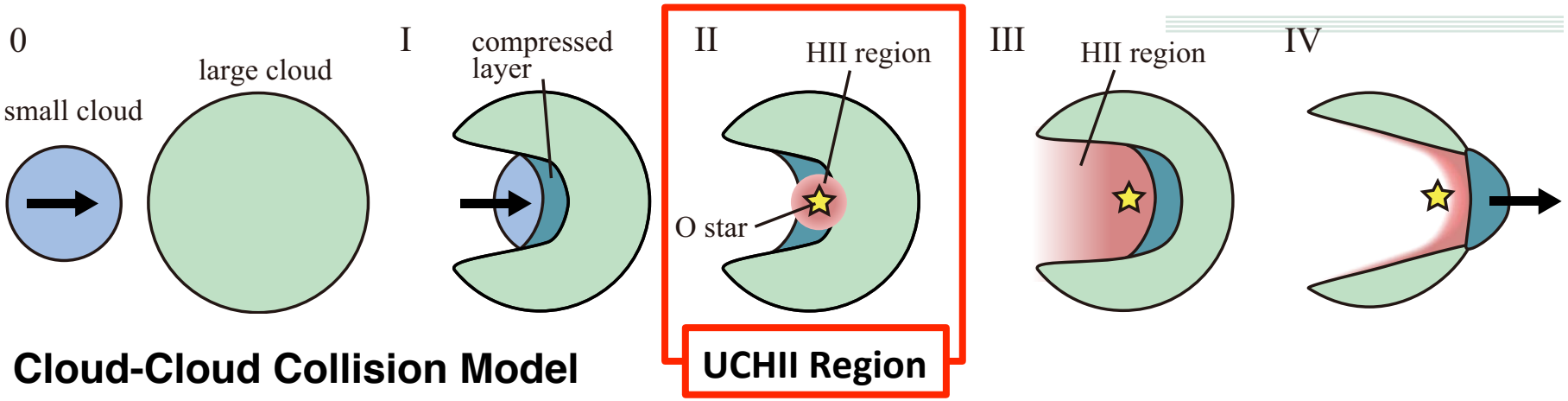
Ultra compact HII Regions (Ohama+)

- UCHII regions are also abele to understand as cloud-cloud collision

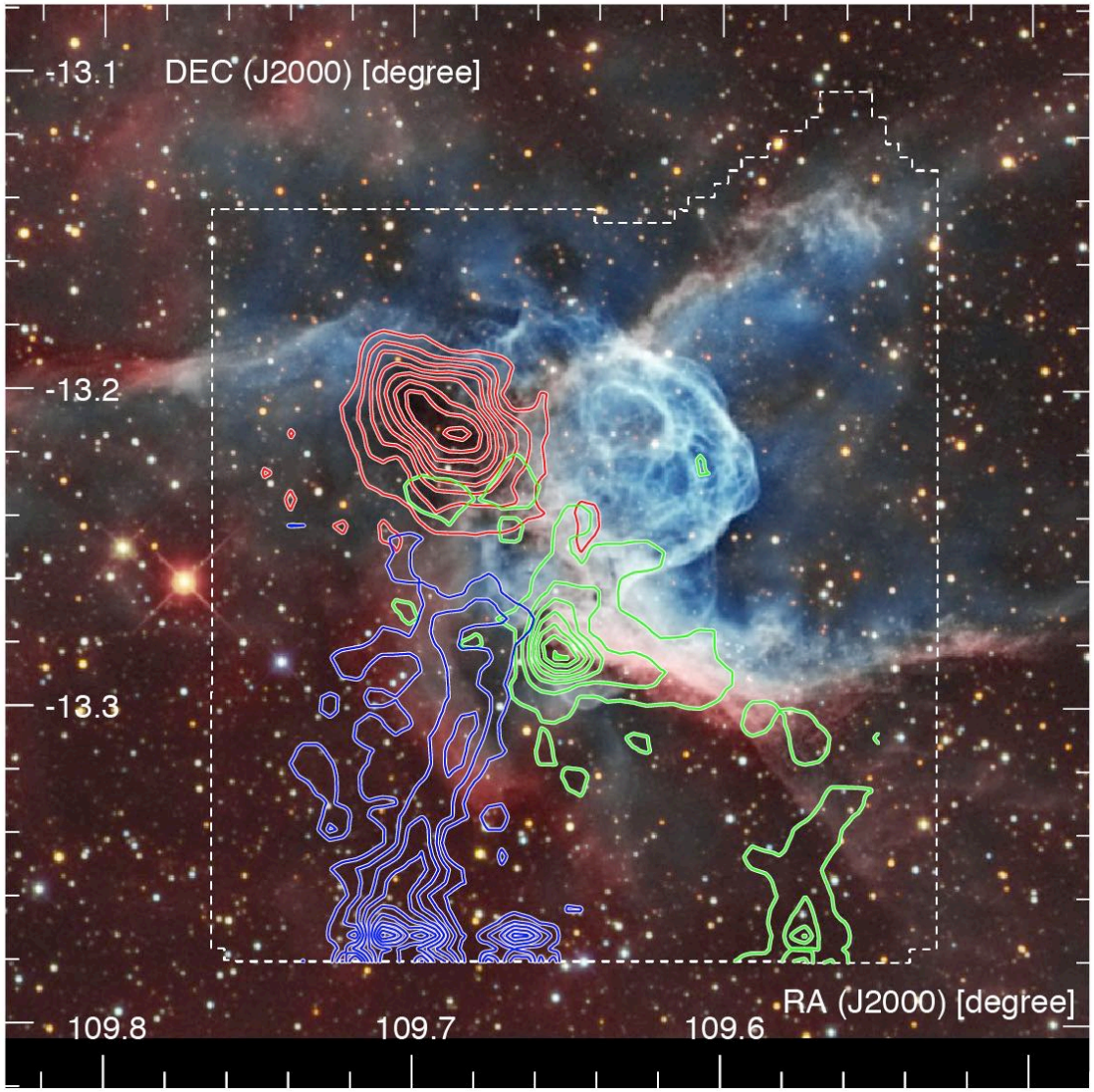








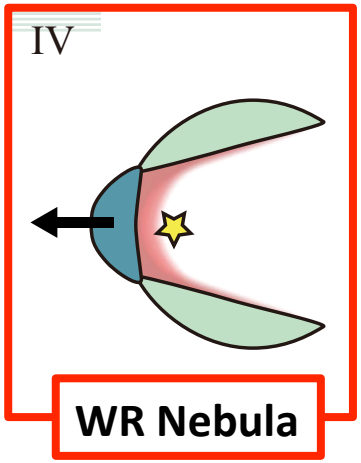
Wolf-rayet nebula NGC 2359 (HS+)



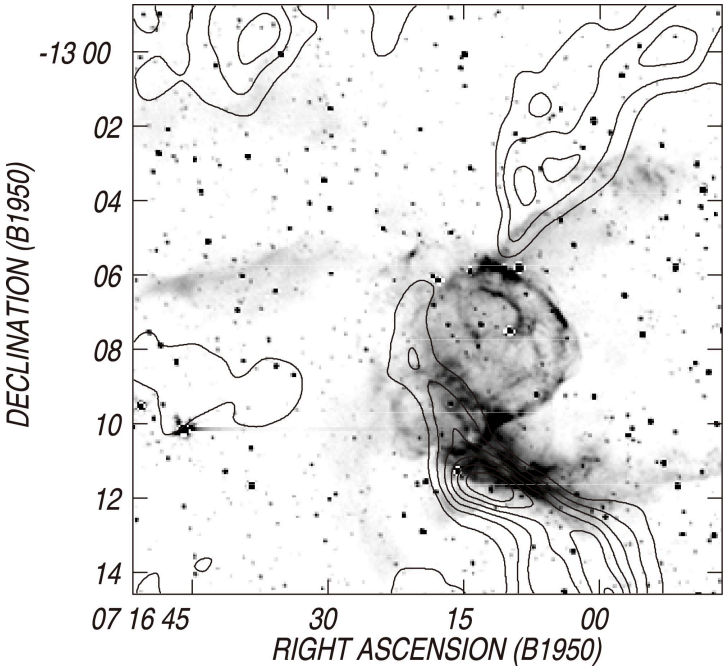
Contours: Nobeyama 45-m ^{12}CO *J*=1-0 (HS+ in prep.)

Red: 35-39 km/s, Green: 52-57 km/s, Blue: 65-68 km/s

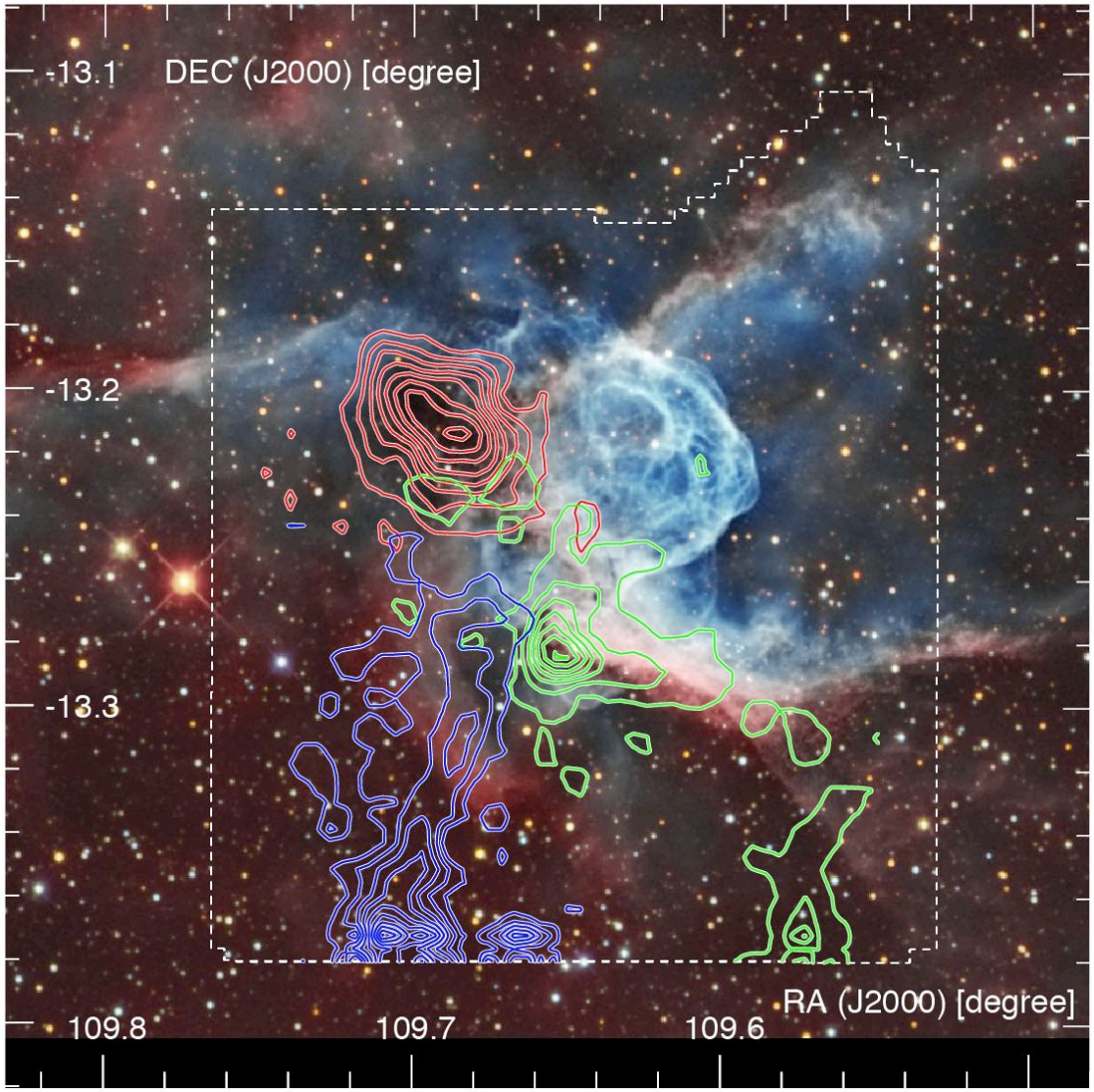
NGC 2359 (WR nebula)

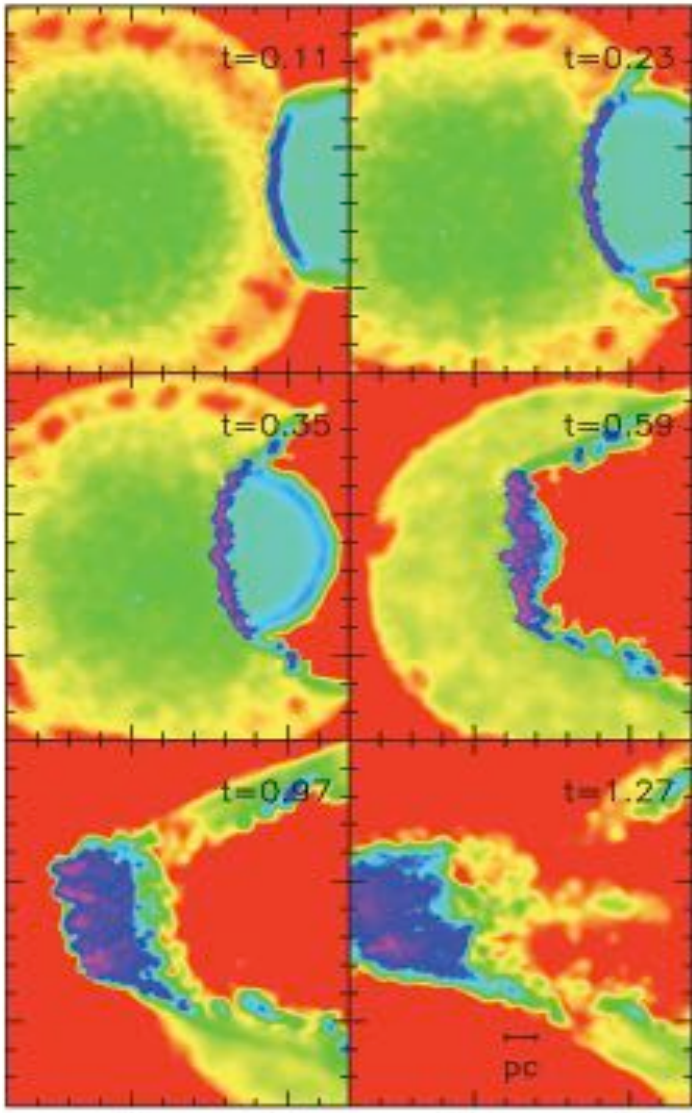


Contours: HI (Cappa+99)



Wolf-rayet nebula NGC 2359 (HS+)





Contours: Nobeyama 45-m ^{12}CO *J*=1-0 (HS+ in prep.)

Red: 35-39 km/s, Green: 52-57 km/s, Blue: 65-68 km/s

Observational Evidence of Cloud-Cloud Collisions

- **Super star clusters**
  Westerlund 2, NGC 3603, RCW 38, DBS[2003]179, Trumpler 14 etc.
  (Furukawa+09; Ohama+10; Fukui+14; Fukui+15)
- **Star burst regions**
  NGC 6334 & NGC 6357 (Fukui 15), W43 (Fukui+16)
- **HII regions**
  M 20 (Torii+11)
  Spitzer bubbles (Torii+15; + in prep.)
  Vela Molecular Ridge (HS+ in prep.), Gum 31 (Higuchi+ in prep.)

Only 38 sources have been observed

- **Ultra compact HII regions**
  RCW 116 (Ohama+ in prep.) , Southern UCHII regions

Only 8 sources have been observed

- **Wolf-rayet nebula**
  NGC 2359 (HS+ in prep.)

We should be observed many sources (red) by using Mopra!