Formation of extreme high-mass star clusters: Lessons on Galactic mini-starbursts

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Star Formation across Space and Time,
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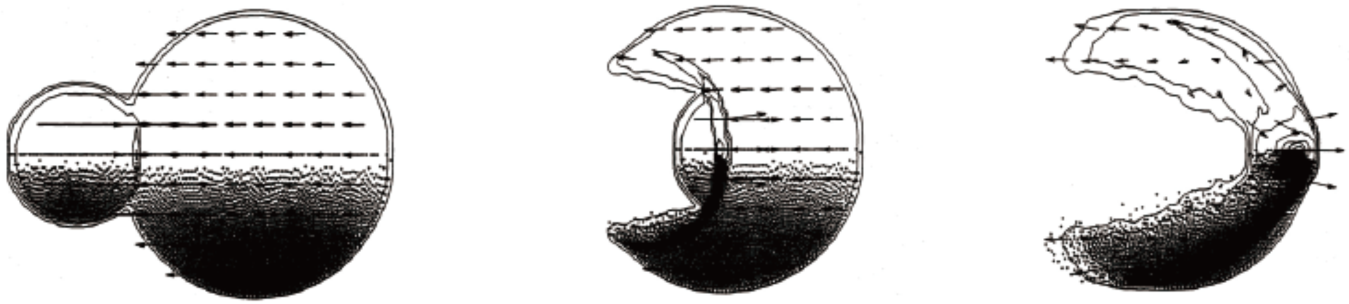
Cloud-cloud collision as a major process of extreme high-mass star formation

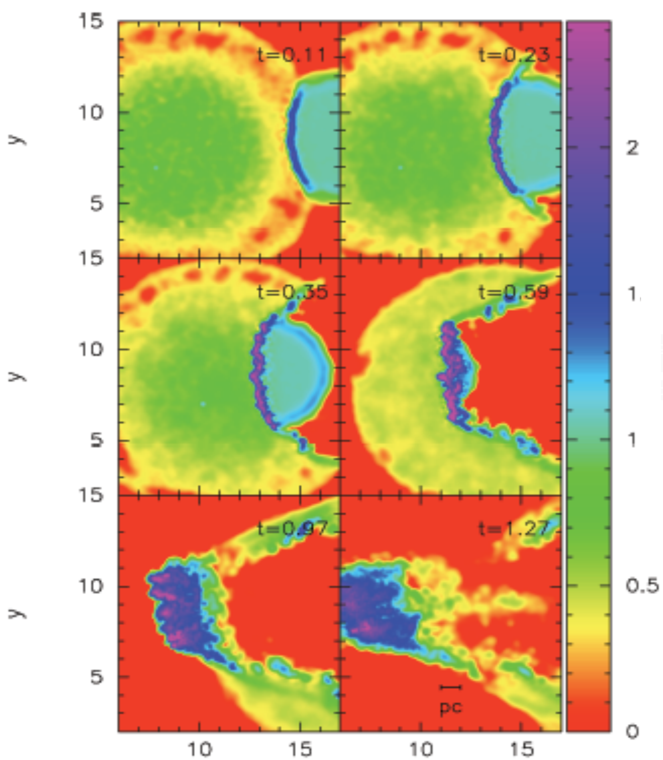
- High mass stars are influential- winds, UV, SN explosions
- High mass stars are too luminous for mass accretion [10^5-6Lo],
  --radiation pressure against mass accretion
- dM/dt has to be large 10^-3Mo/yr [e.g., Tan & McKee 2003]
- How to realize such high accretion rate?

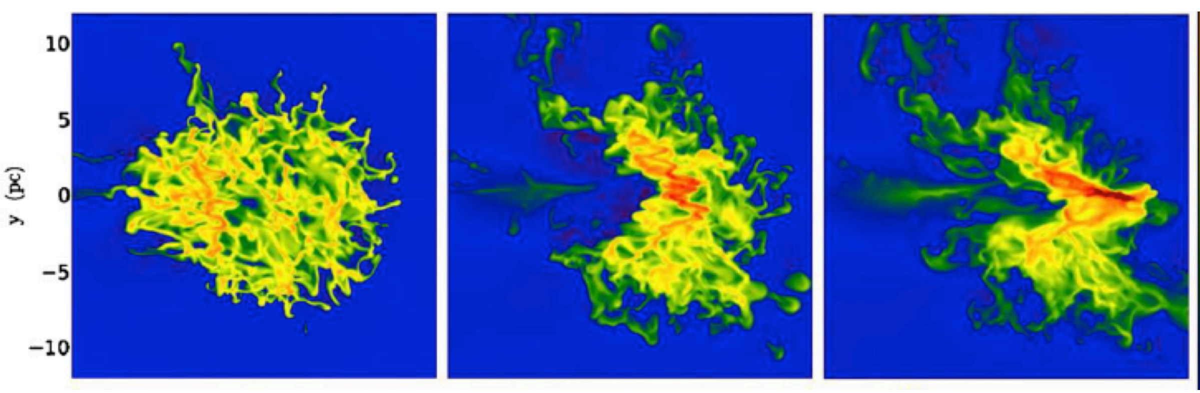
- Four super star clusters:
  Westerlund 2, NGC3603, RCW38 and DBS[2003]179
- (Furukawa et al. 2009;Ohama et al. 2010;Fukui et al. 2014)
- Star burst regions:
- NGC6334, 6357, W43 (Fukui et al. 2015)
- Individual HII regions:
- Spitzer bubbles RCW120, etc.(Torii et al. 2011, 2015)
- NANTEN2 and Osaka Prefecture University 1.85 m telescope (Fukui, Onishi et al.)
- MHD numerical simulations: (Inoue & Fukui 2013)

Cloud-cloud collision



Habe & Ohta 1992





Takahira et al. 2014

Anathpindika 2012

Setting of Simulation (Inoue & Fukui 2013)

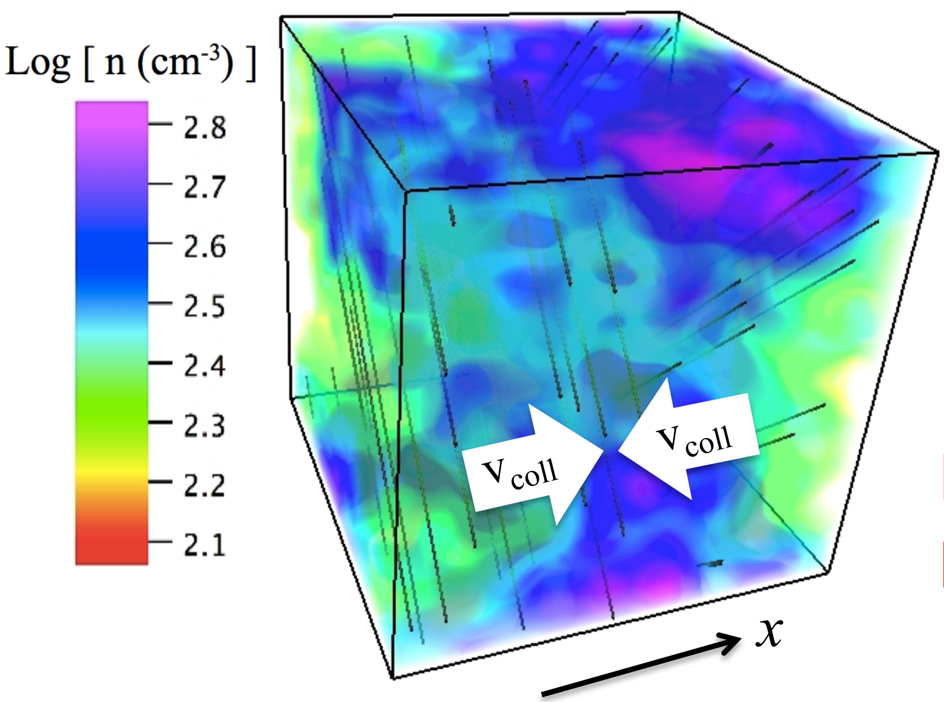
- Isothermal ($c_s = 0.2$ km/s) 3D MHD simulation in 3D box with self-gravity.
  - Fiducial setting

✓ $\langle n \rangle = 300\ \mathrm{cm}^{-3}$ + fluctuations with $P_{\log n}(\mathrm{k}) \propto k^{-4}$, $\Delta n / \langle n \rangle = 0.43$

↑ typical density spectrum in supersonic MHD turbulence (Beresnyak+05)

✓ Converging flows along x-axis with $v_{\mathrm{coll}} = 10$ km/s, which collide head on at center.

✓ $B = 20\ \mu\mathrm{G}$ in y-z plane



Volume = $(8\ \mathrm{pc})^3$

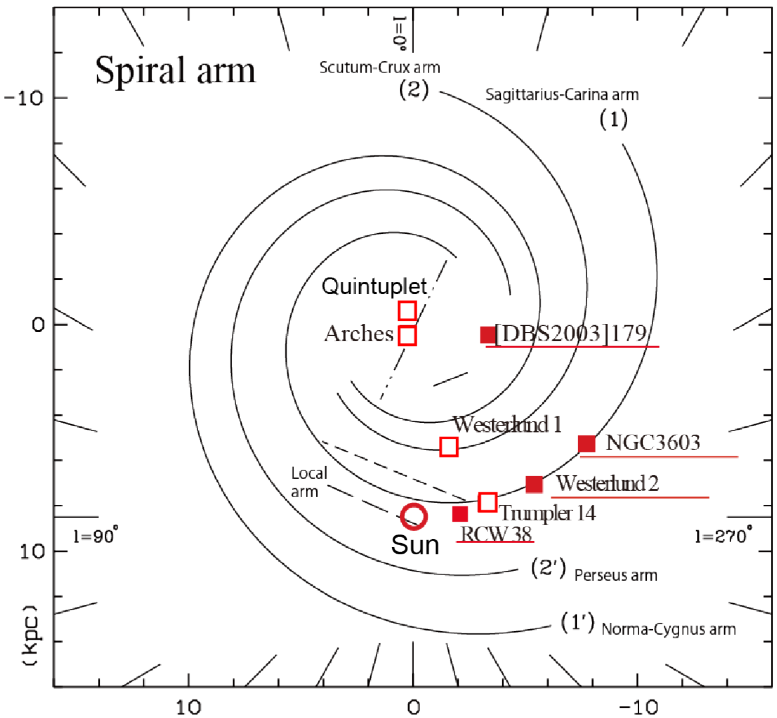
Resolution: $\Delta x = 8\ \mathrm{pc}/512 = 0.015\ \mathrm{pc}$

No need for a pre-stellar core

SSC catalog in the Galaxy

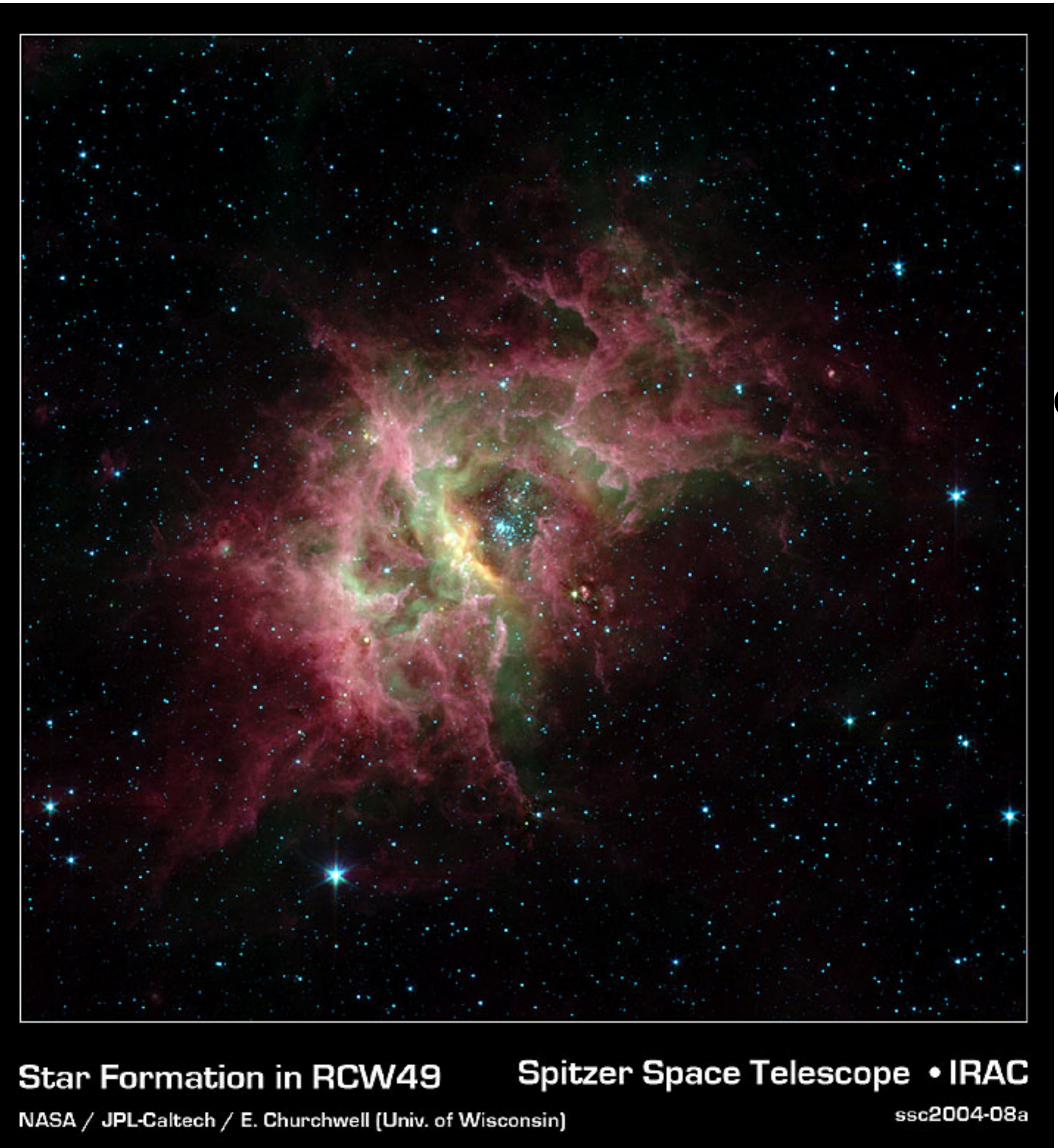
Portegies Zwart, McMillan & Giels (2010)

SSC	Age [Myr]	LogM$_*$ [M$_{sun}$]	Size [pc]	Mole-cular cloud
Arches	2.0	4.3	0.4	no
[DBS2003]179	3.5	3.8	1.2	yes
NGC3603	2.0	4.1	0.7	yes
Quintuplet	4.0	4.0	2.0	no
RCW38	<1.0	--	0.8	yes
Trumpler 14	2.0	4.5	0.5	no
Westerlund1	3.5	4.0	1.0	no
Westerlund2	2.0	4.2	0.8	yes



Distribution of SSC in the Milky way.
D.Russeil (2002)
Red circle is sun.

The massive star cluster Westerlund 2



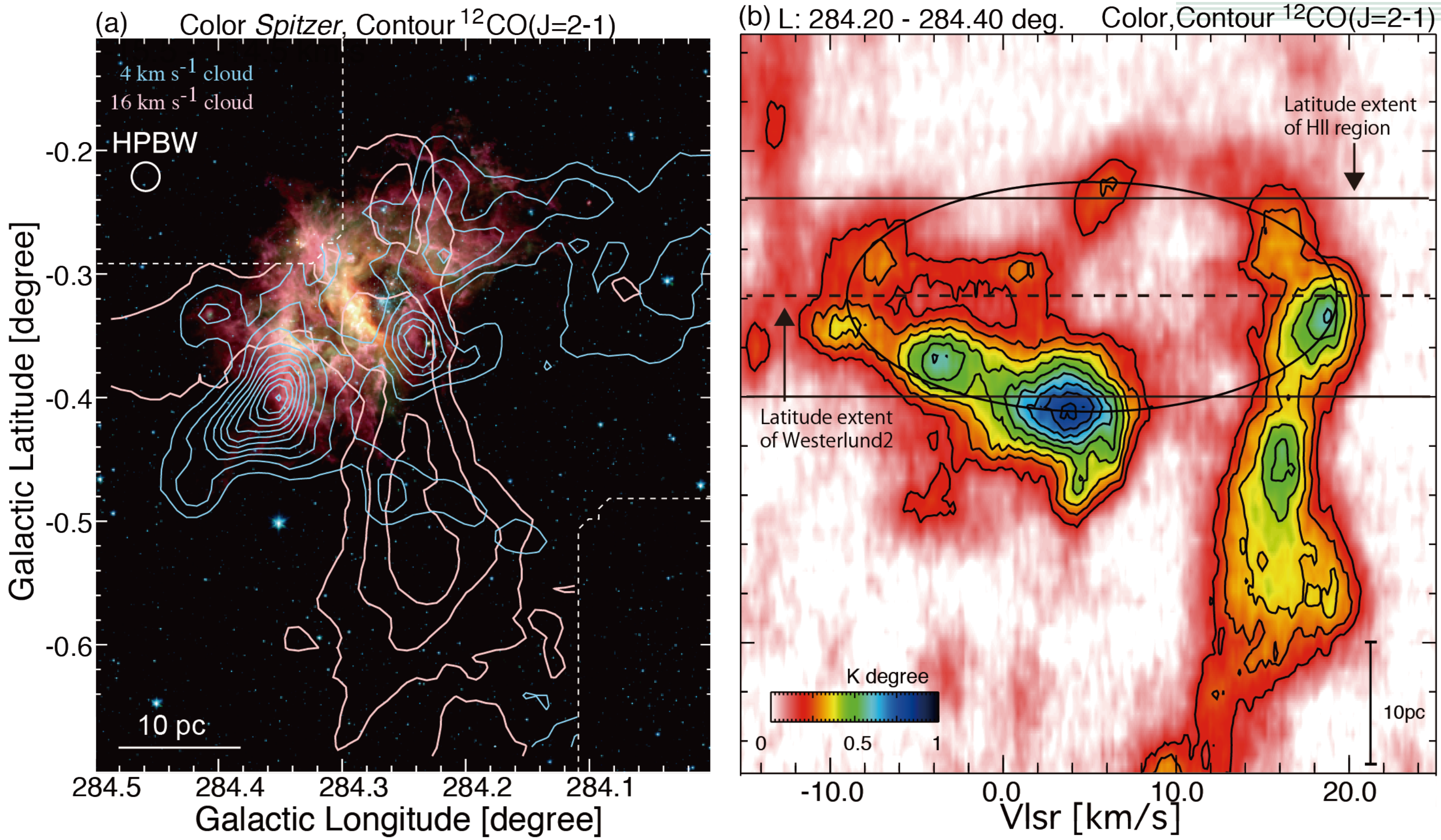
$(l, b) = (284^\circ.27, -0^\circ.33)$

- O Star 12
  WR Star 2
  WR20a, WR20b
- Total mass of stars 4500*Mo* (Rauw et al. 2007)
- Age 2-3 Myr (Piatti et al. 1998)

RCW 49

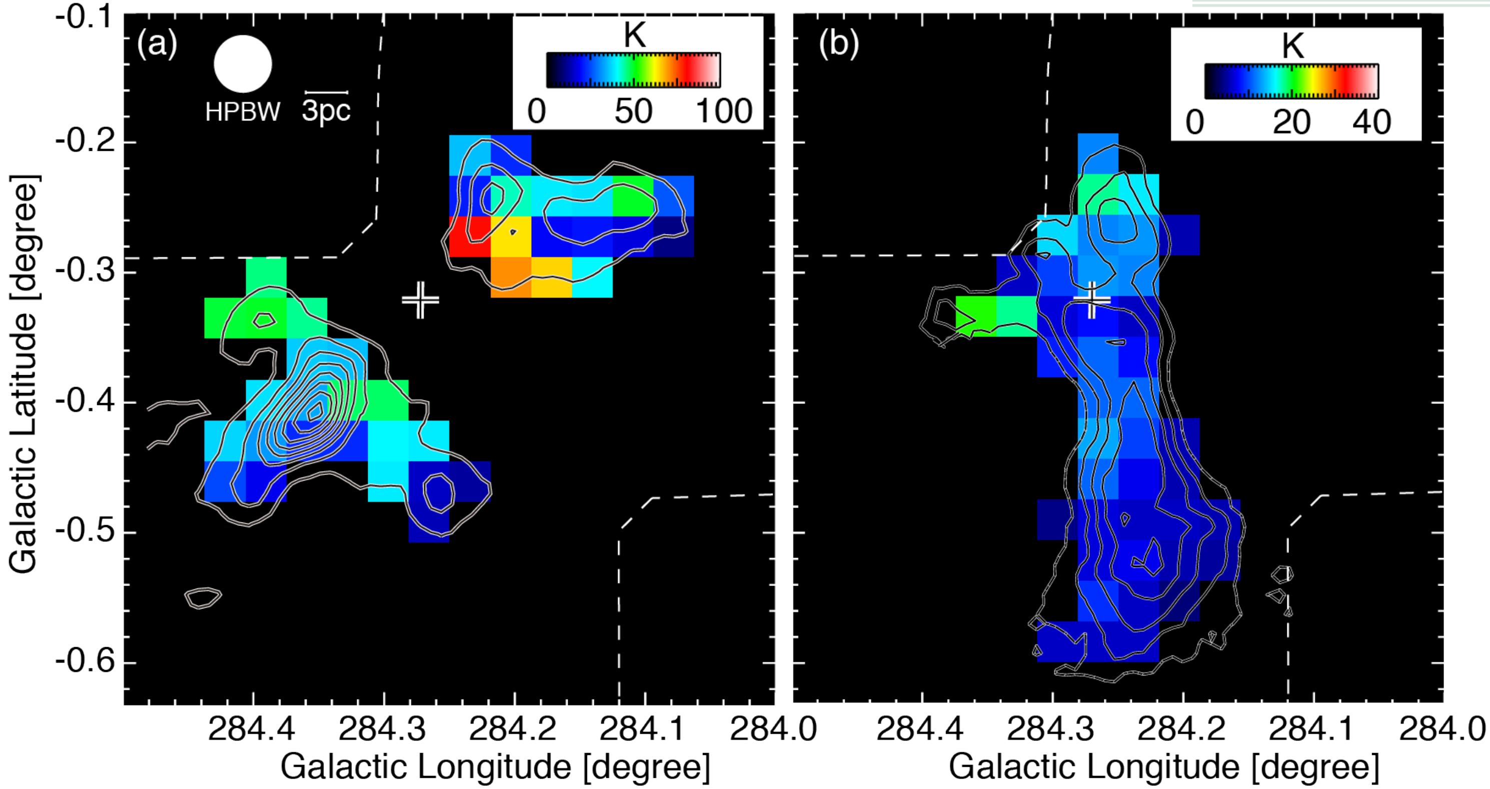
- Distribution of dust influenced by stars (Churchwell et al. 1998)
- Star formation in progress
- YSO 300 (Whitney et al. 2004)

Westerlund 2 (Furukawa et al. 09; Ohama et al. 10)



- Two giant molecular clouds (GMCs) are complementary distributed toward Westerlund 2.
- The velocity separation of the two clouds is 15–25 km/s, cannot be bound with the gravity.

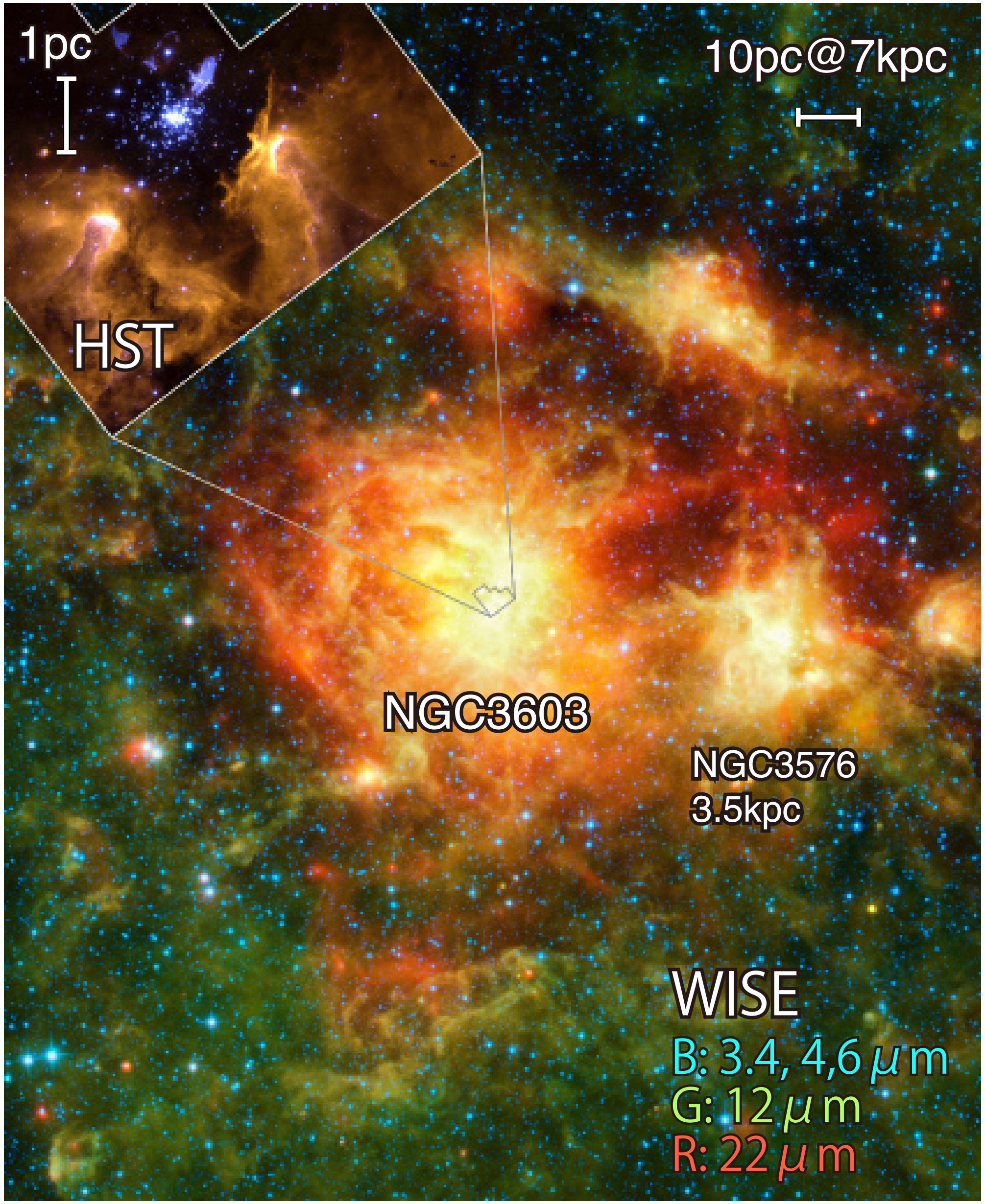
Westerlund 2 (Furukawa et al. 09; Ohama et al. 10)



- Both the two clouds are heated by the strong radiation from the massive star cluster.

-> Both the two clouds are physically associated with the cluster, although they have a large velocity separation.

NGC3603 (Fukui+2014)



◇one of MSC in the Milky Way

◇Carina arm
(l, b) = (291.6, -0.5)

◇Distance: 6-8 kpc (e.g. Russeil 2003)

◇Total mass of stars: > 10^4 M_{sun}
(Harayama et al. 2008)

◇Age:1-3 Myr (e.g. Sung & Bessell 2004)

◇O type Star: more than 30 (Moffat et al. 2004)

◇WR:1-4 (Schmutz W. et al. 1999)

◇Star formation in progress
(Stolte et al.2004)

WISE&HST credit: NASA/JPL-Caltech/UCLA

Rapid star formation in NGC3603

NGC3603

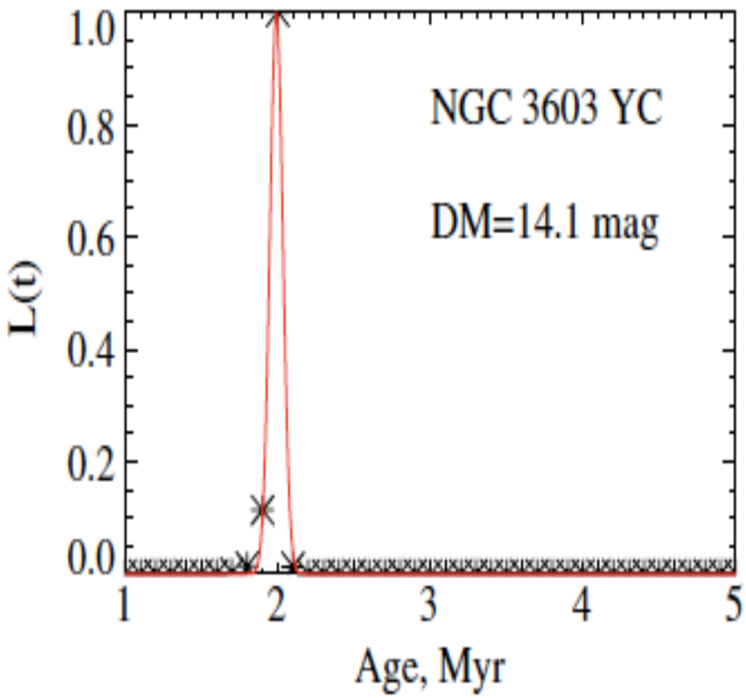
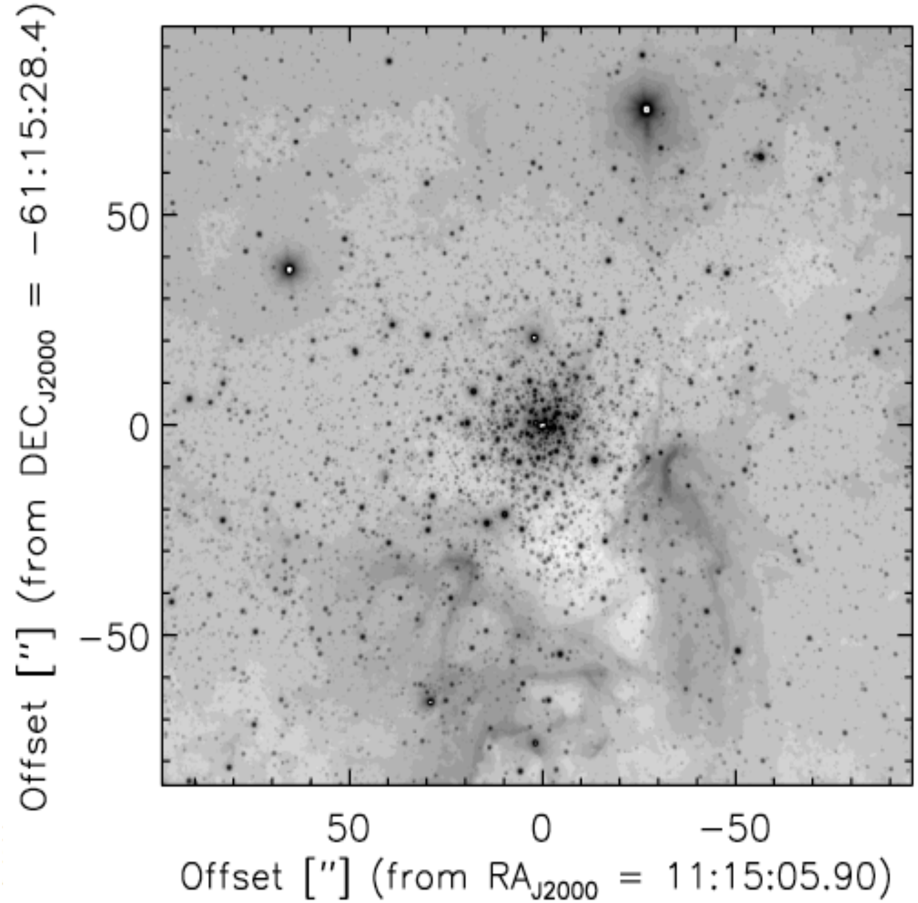


Figure 4. Normalized $L(t)$ for NGC 3603 YC at DM = 14.1 mag. Th
probable age is 2.0 Myr. The red curve is a fitted Gaussian function.

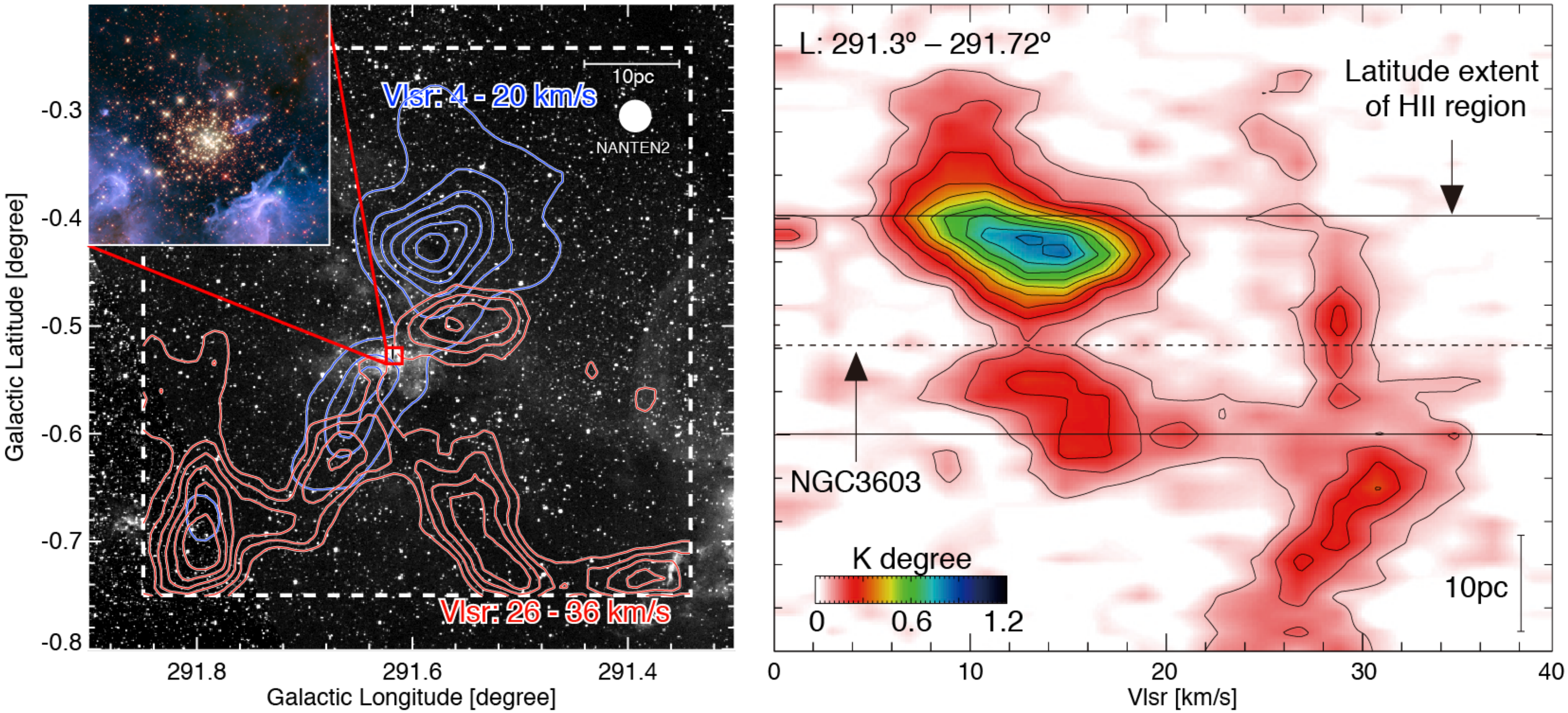
Kudryavtseva et al. 2012



Harayama et al. 2008

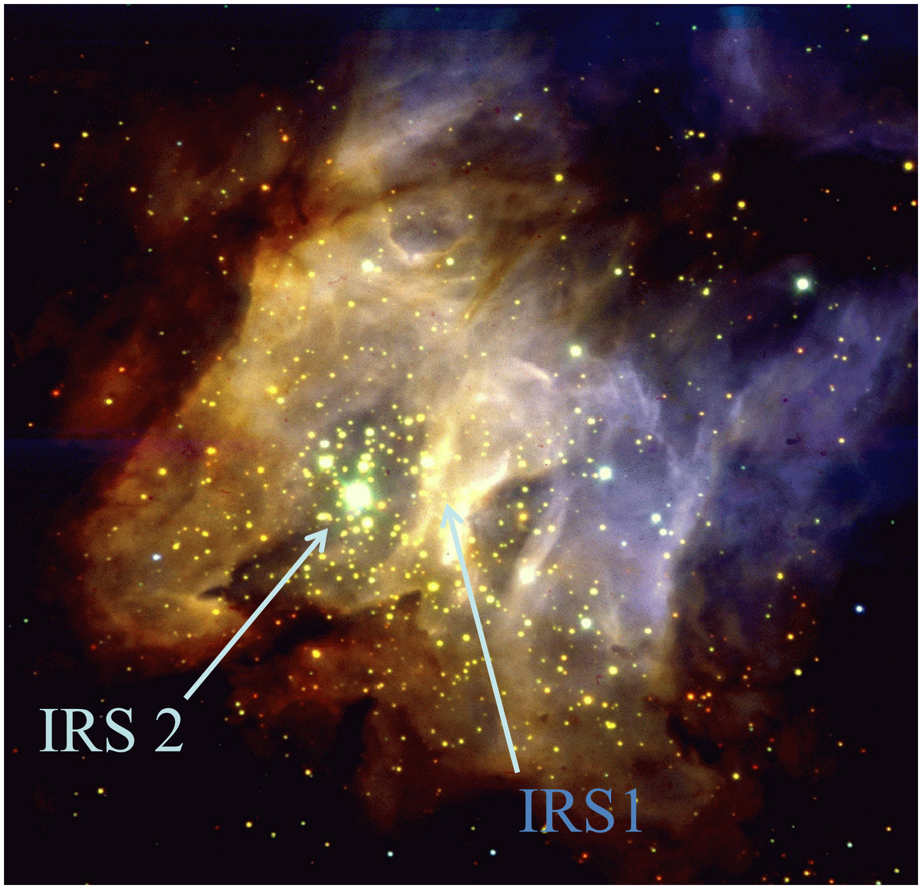
- All the high-mass stars in NGC3603 were formed ~2 Myrs ago in a very short timespan, ~0.1 Myr.

NGC3603 (Fukui et al. 2014)



- Two GMCs are seen toward NGC3603, having a similar velocity distribution to that in Westerlund 2.
- The velocity separation is ~20 km/s.

Extremely young super star cluster RCW38



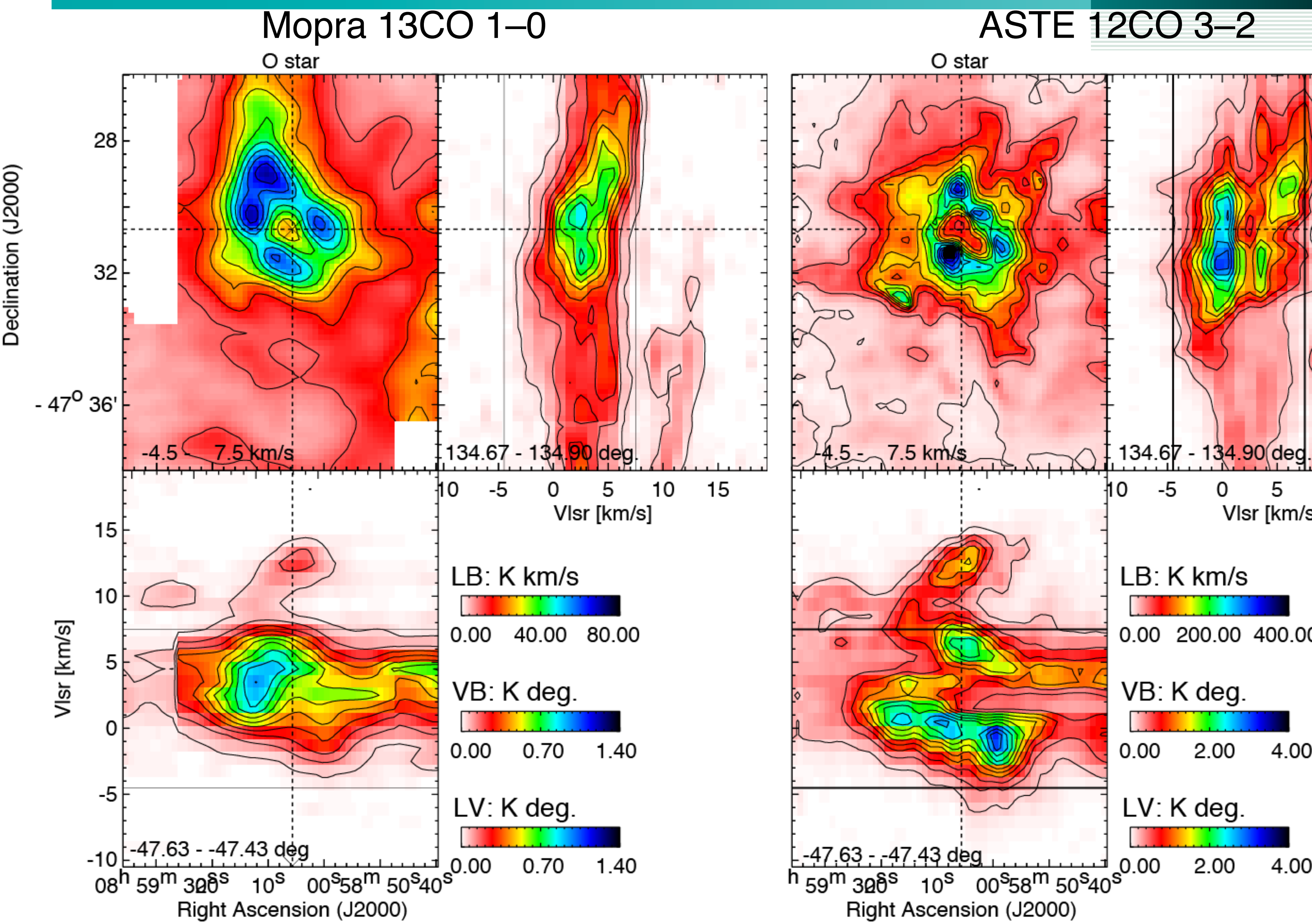
- High mass star-forming region
- Bright HII region
  (Rodgers, Campbell & Whiteoak, 1960)

- Position: (l, b) = (268°, -1°)
- Age: < 1Myr (young cluster)
- Distance: 1.7 kpc (Rodgers 1960)
- Number of stars: 10^3–10^4 (O-star:~30)
  (Wolk et al. 2006; Winston et al. 2011)

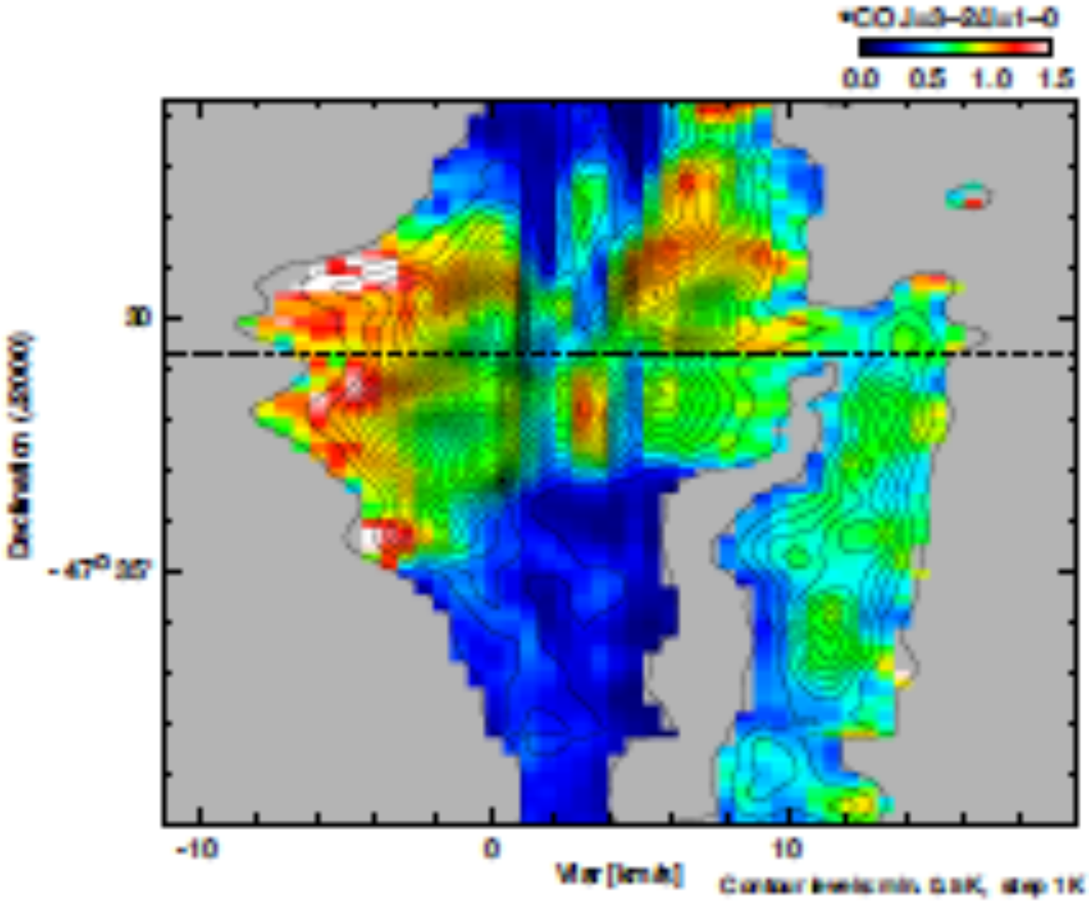
- Two bright mid-IR sources
  IRS 1 and IRS2
  (Frogel & Persson; 1974; Smith et al. 1999; DeRose et al. 2009)

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

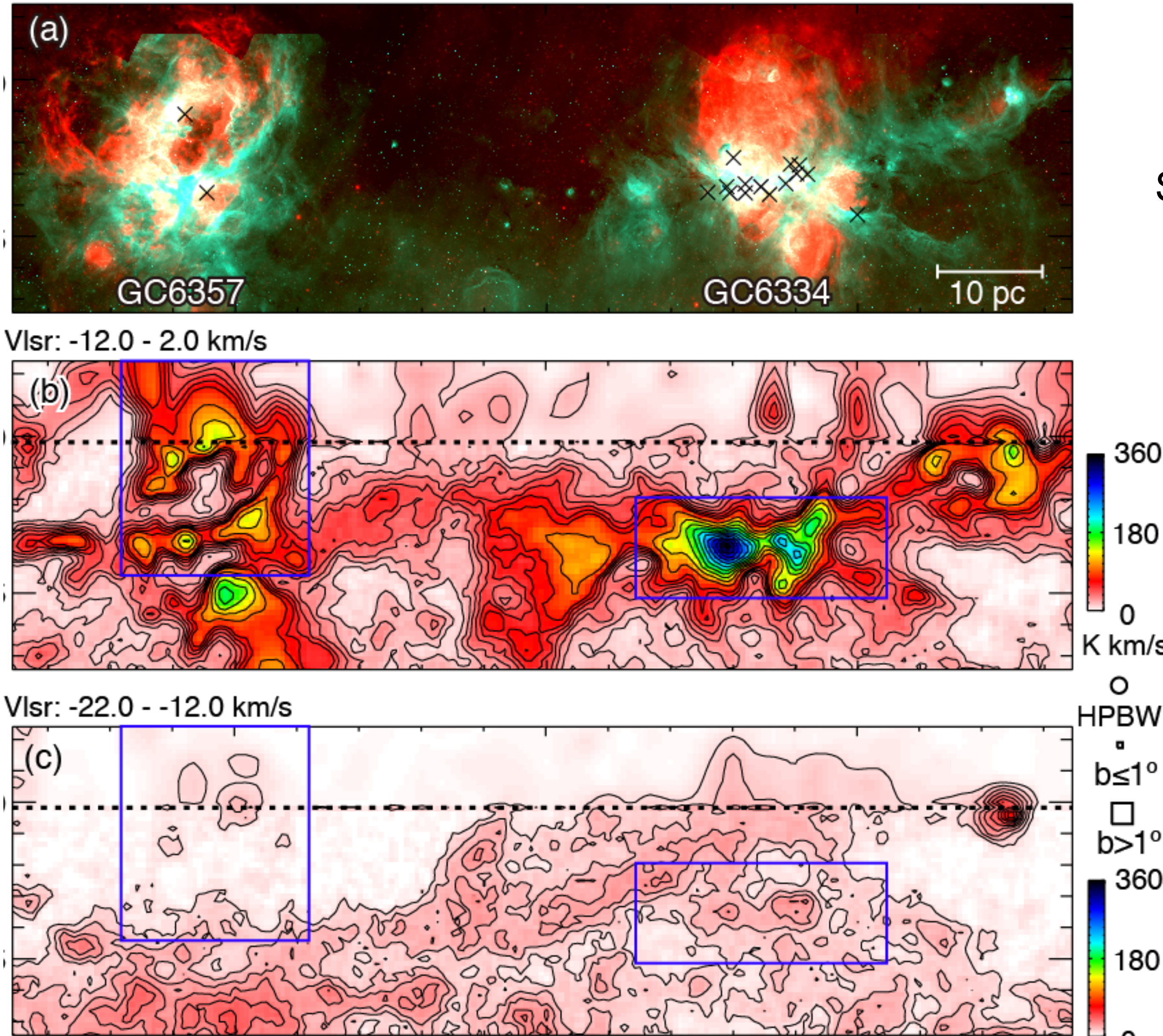
RCW38 (Torii et al. 2015)



CO (J=3-2)/(J=1-0) in RCW38

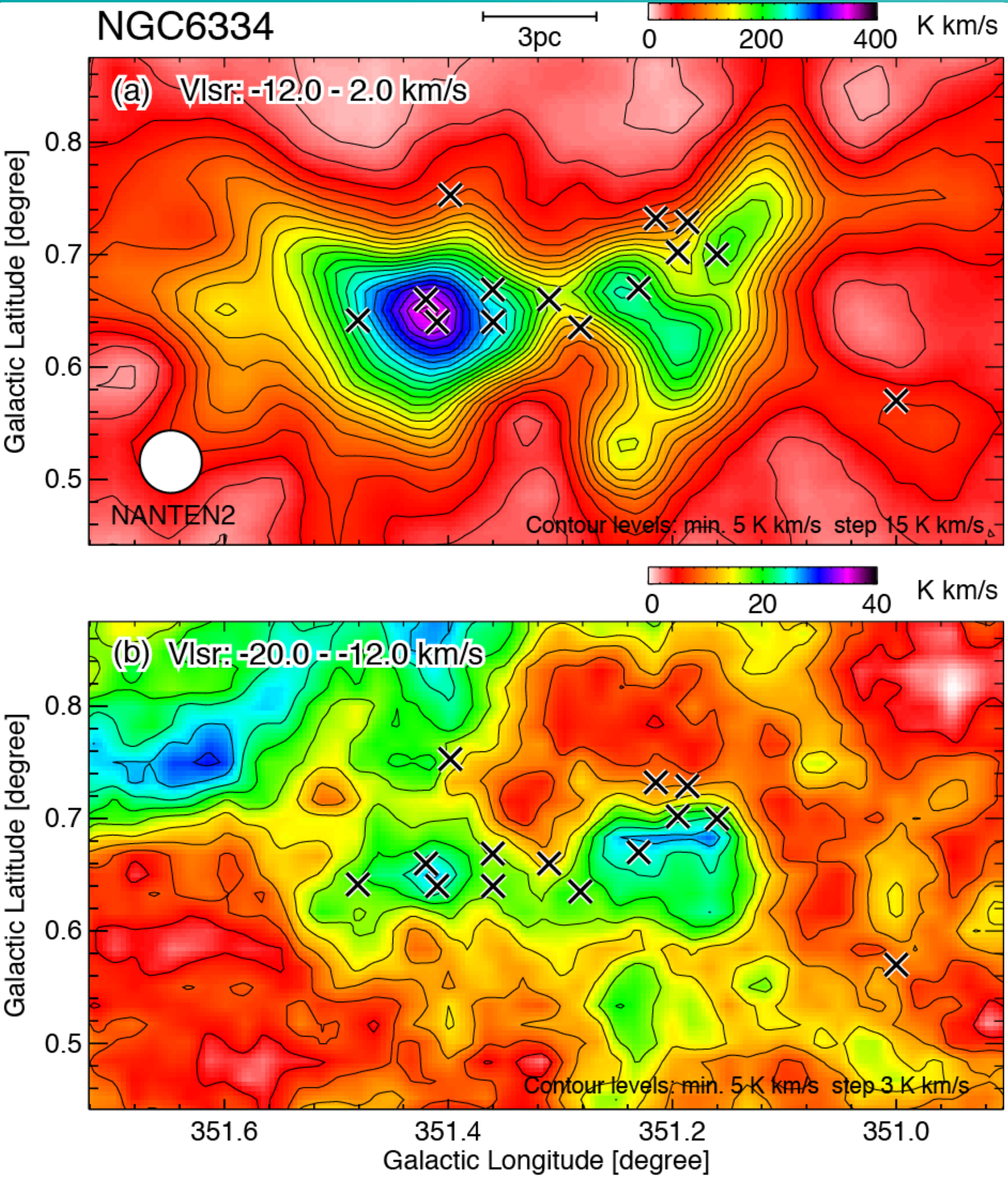


NGC6357 and NGC6334 in CO, Twin starbursts (Fukui et al.2015)



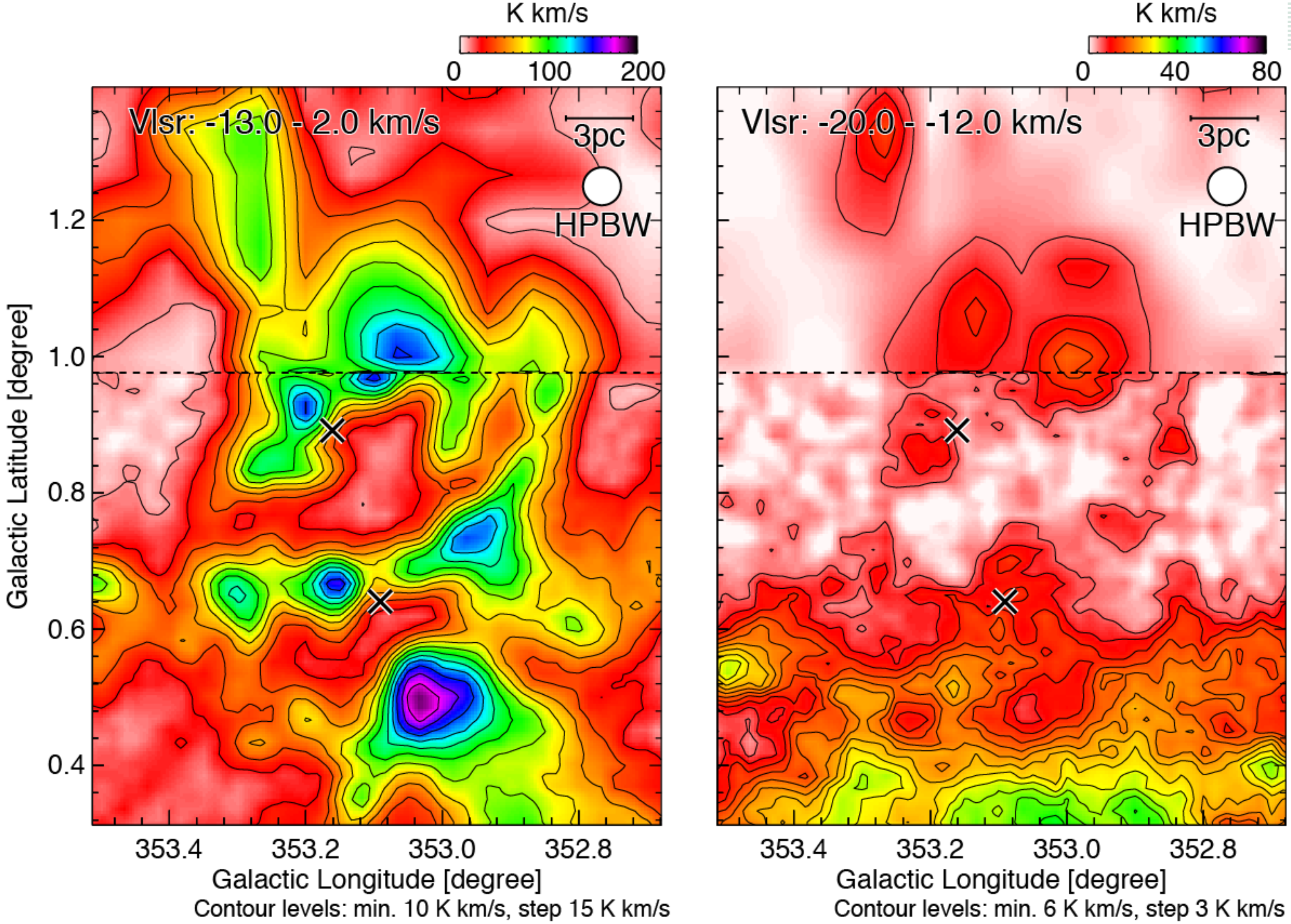
Spitzer

NGC6334



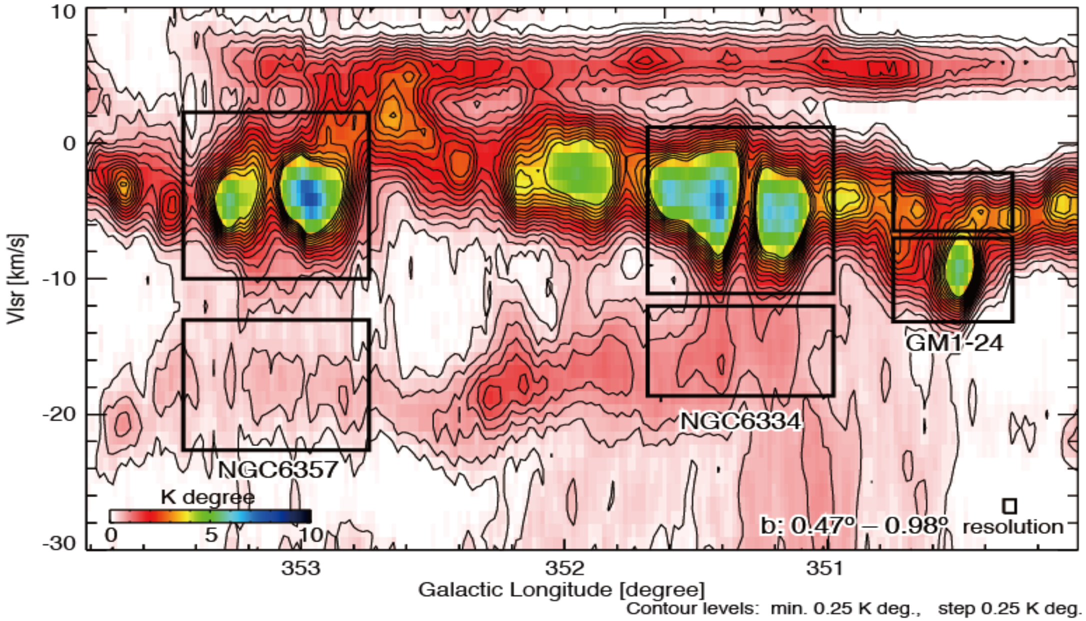
- Sizes and distributions are similar between the two clouds, although intensity is much different.

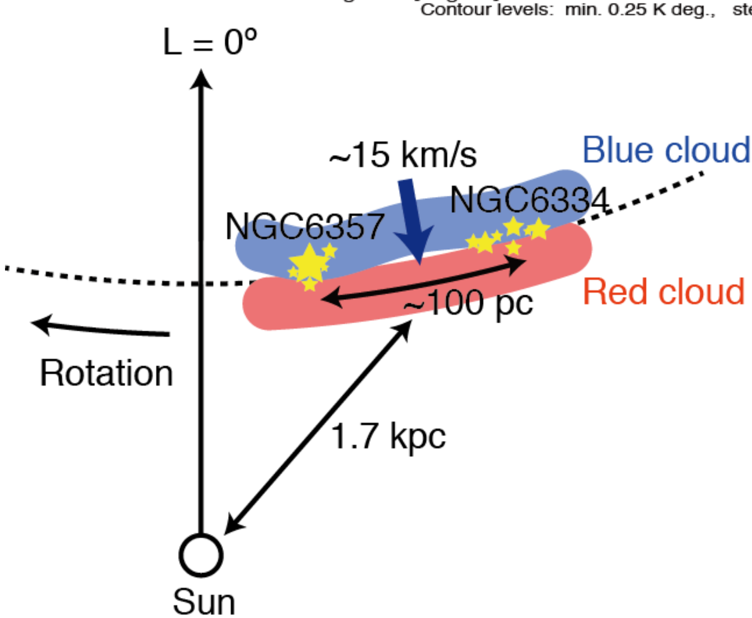
NGC6357



- Partly correlated and partly anti-correlated distributions

cloud-cloud collision

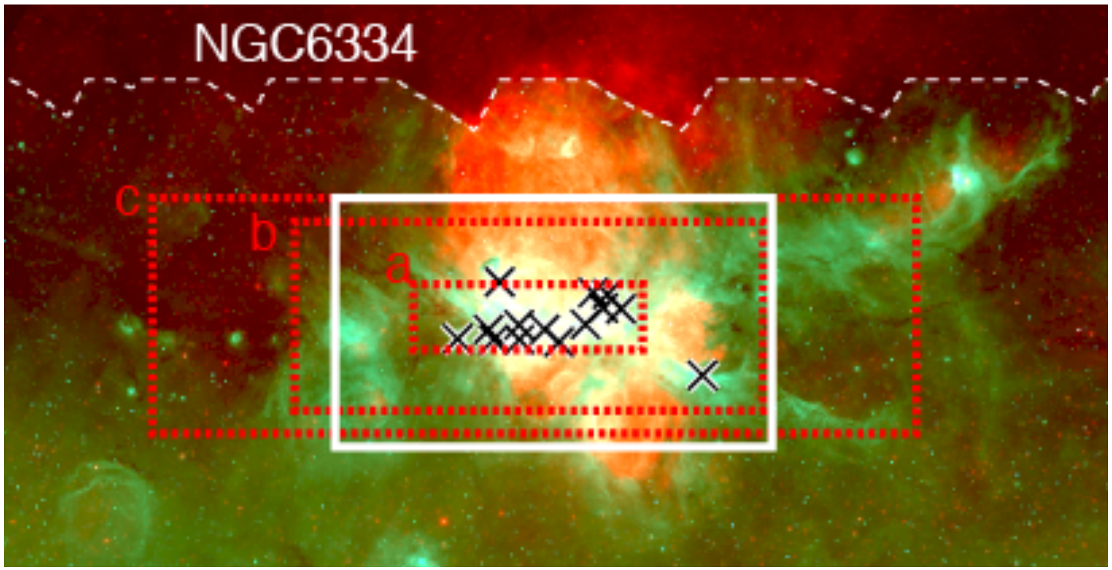




- > 100 pc elongated filamentary molecular clouds.
- Bridge-like features connecting the two clouds toward clusters.
- Timescale of the collision:5-10 pc/15 km/s

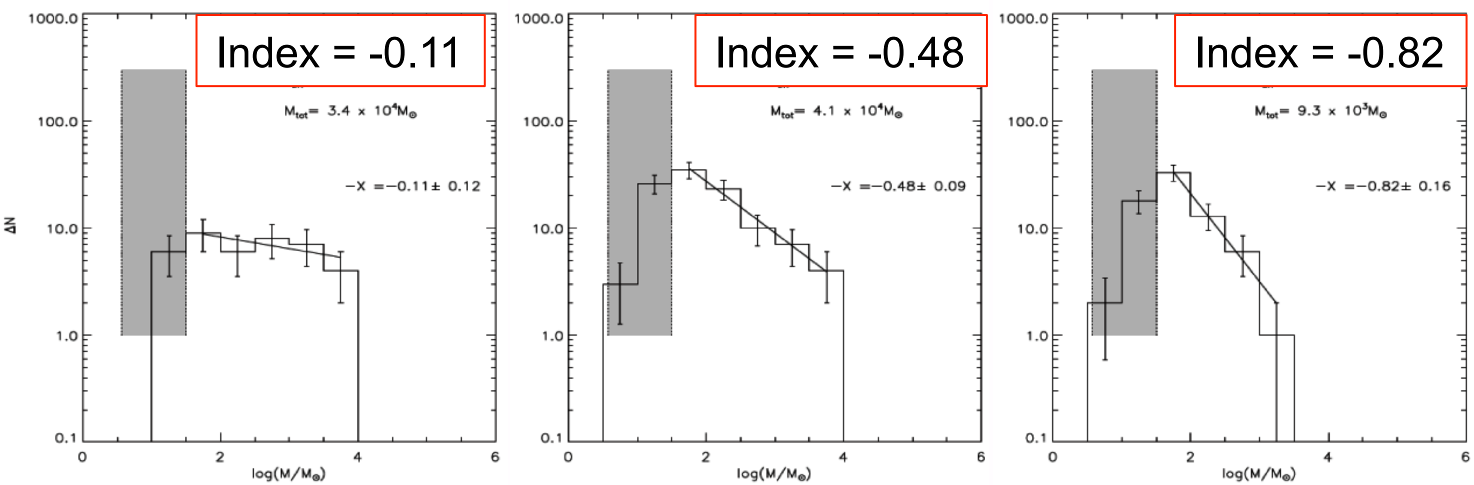
  ~ 0.2–0.5 Myrs

Core mass function at mm-wavelength

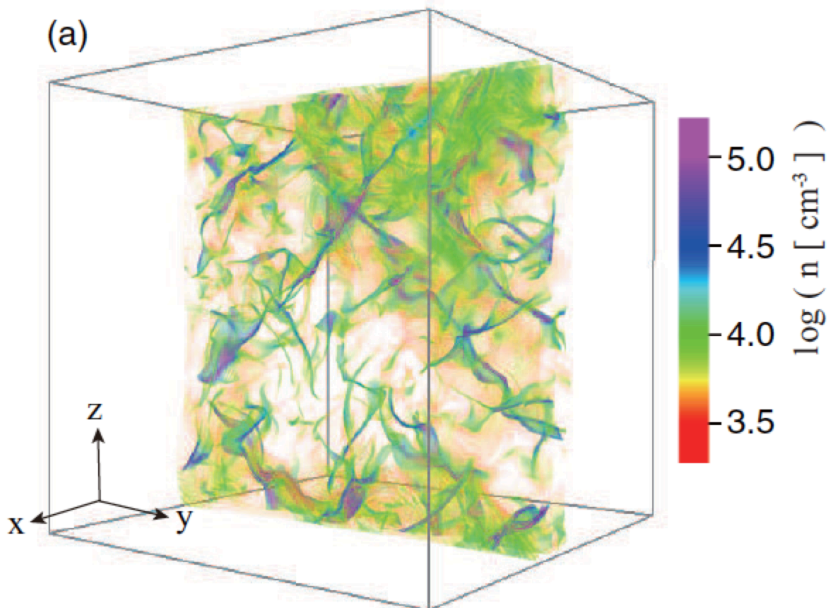


- Munoz et al. 07
- Core mass function with mm continuum from dust grains.
- Top heavy core mass function towards clusters.

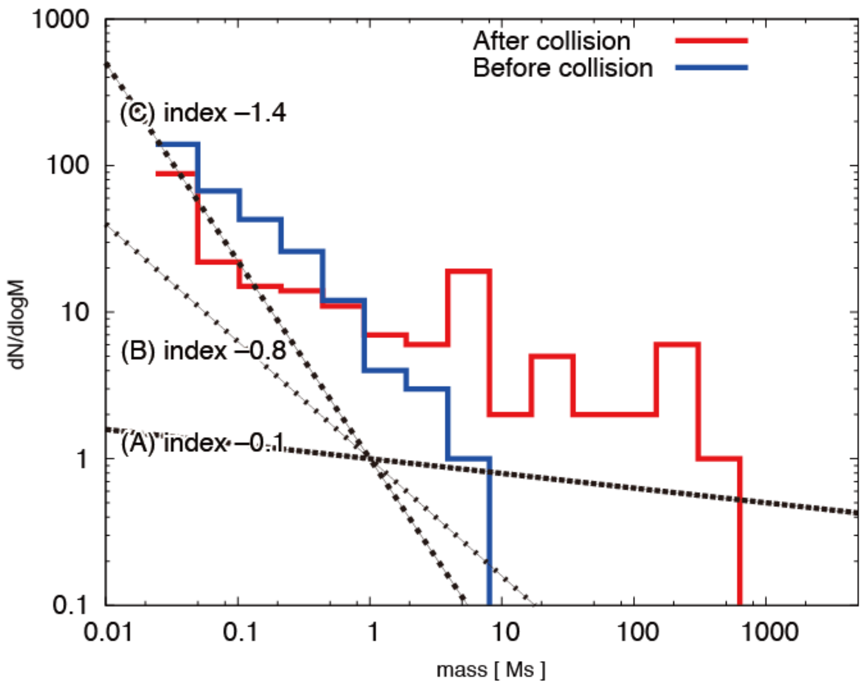
Munoz et al. 07



Core mass function by Inoue & Fukui (2013)

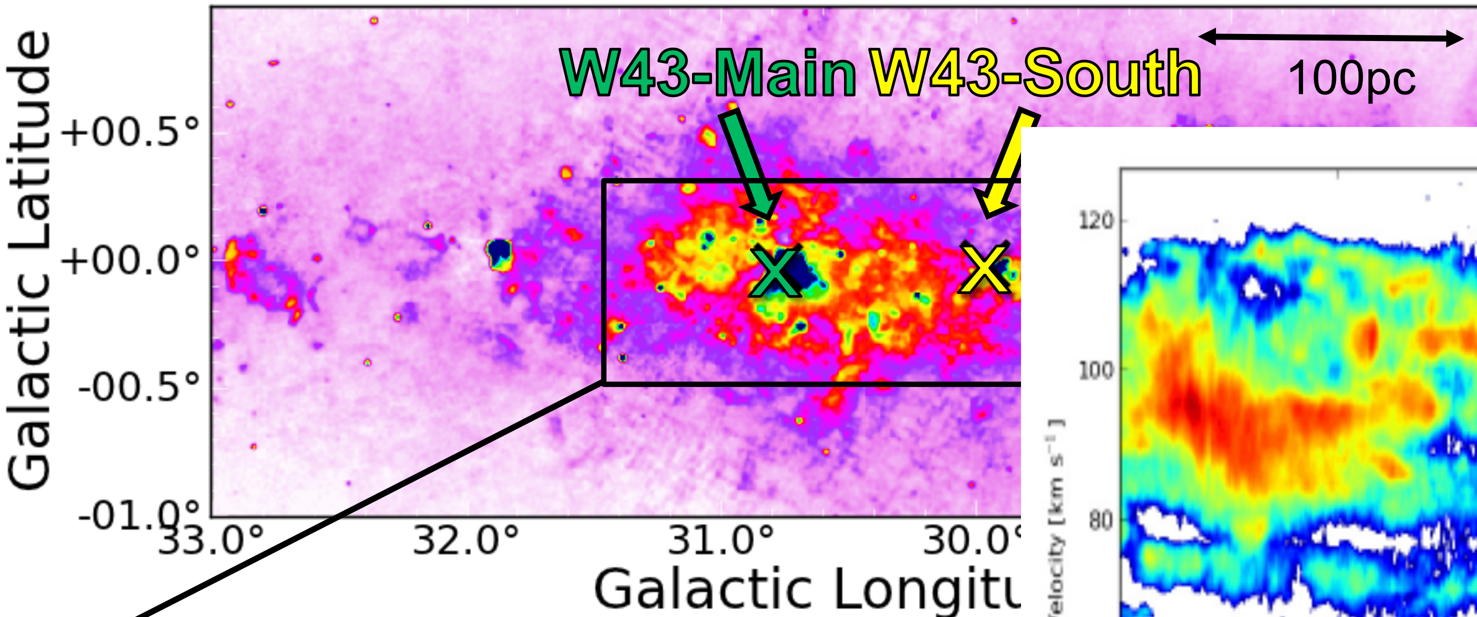


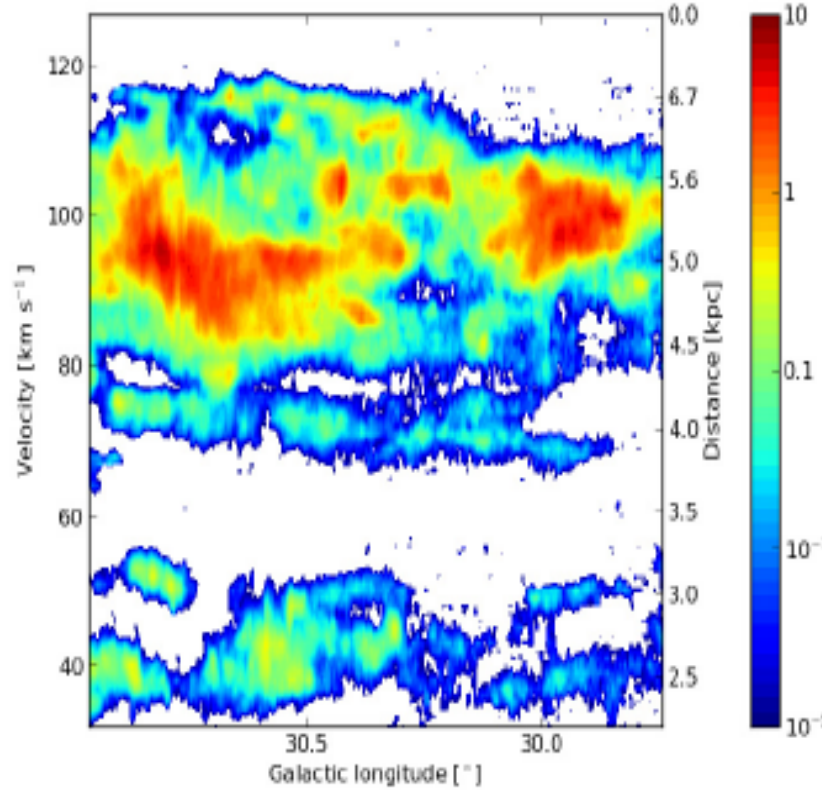
Inoue & Fukui (2013)

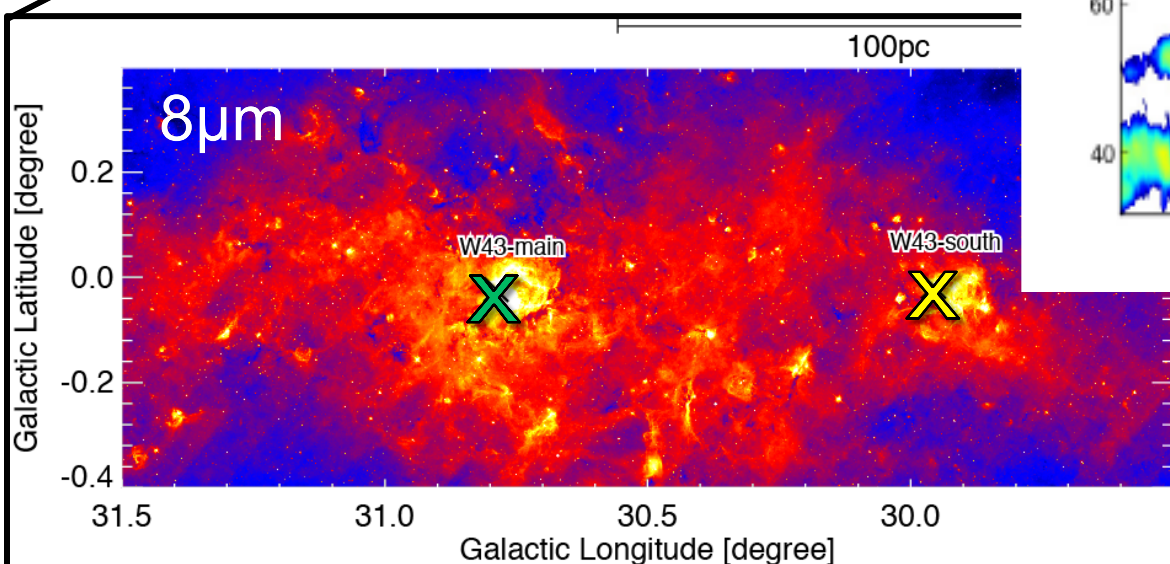


- Top heavy core mass function is reproduced in the MHD calculations.

W43



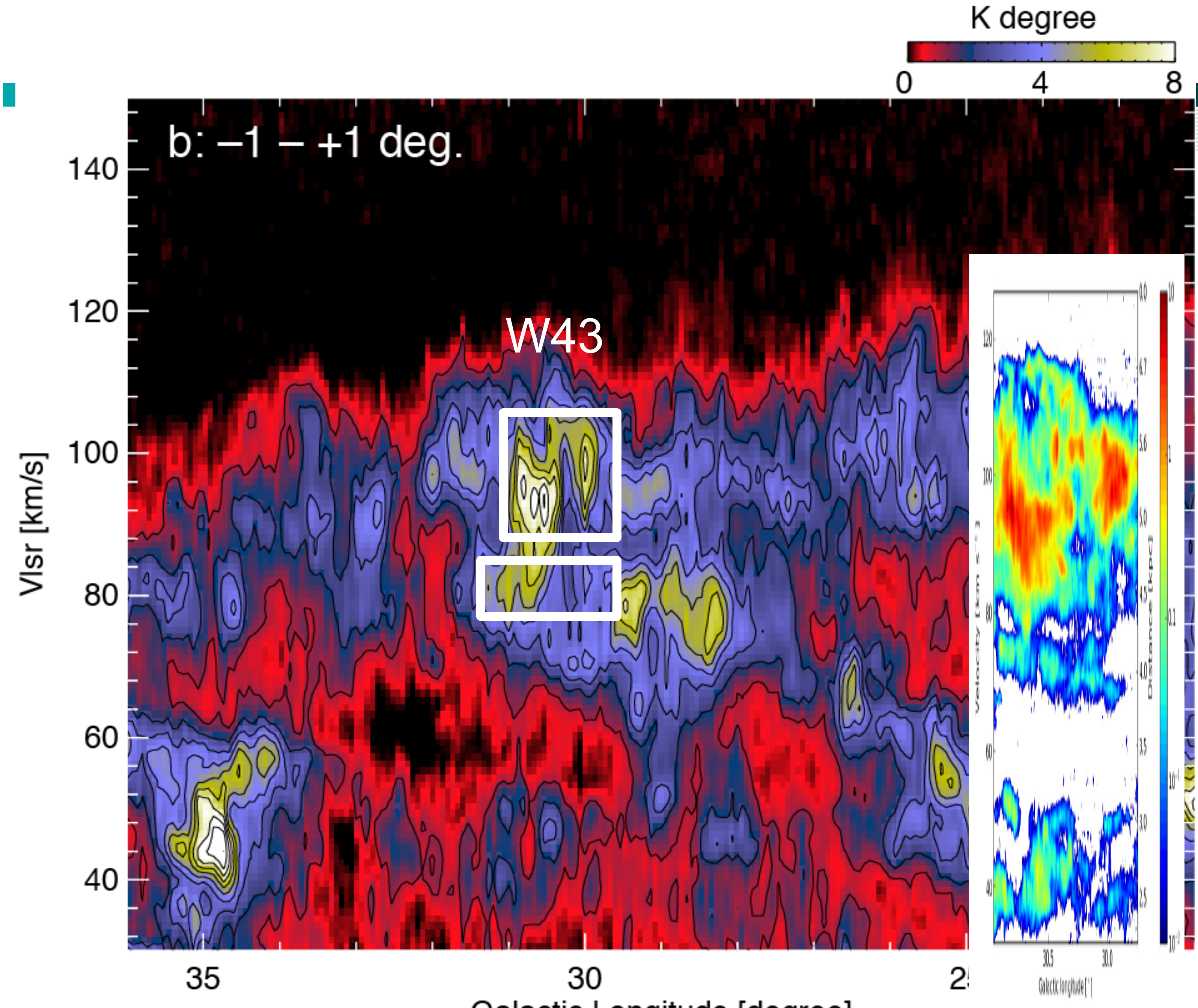




P. Carlhoff et al. 2013

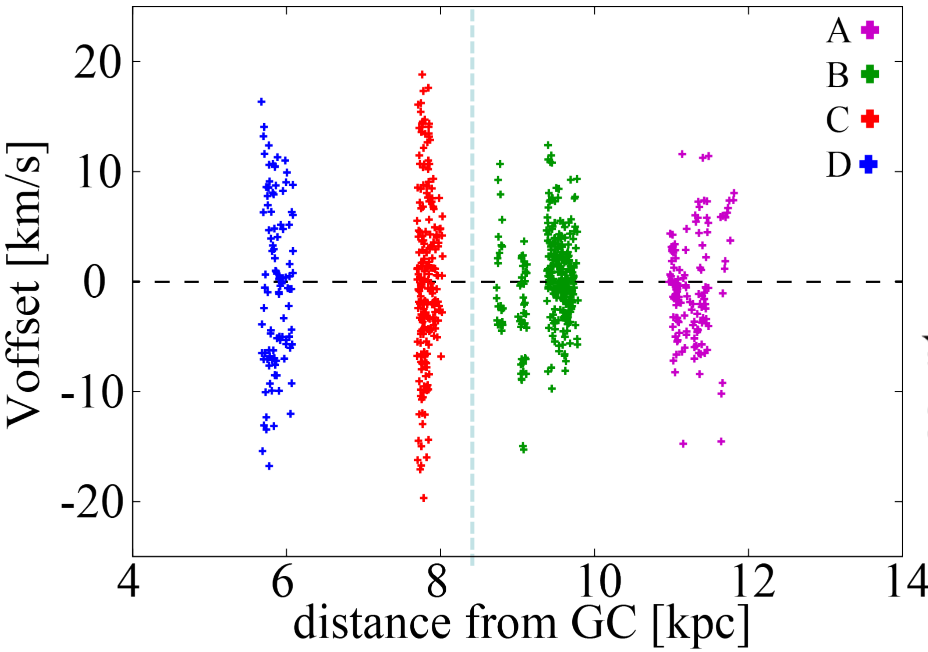
$L_{IR} \sim 1.6\times10^{7}\ L_{0}$

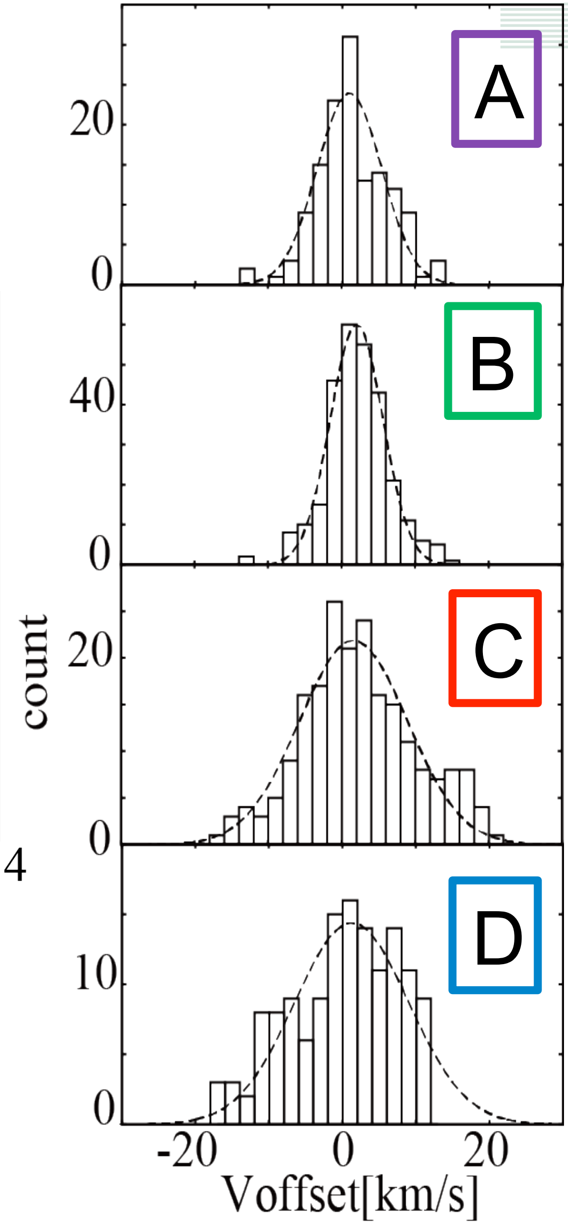
(Nguyen et al. 2011)


K degree
0
4
8
b: –1 – +1 deg.
W43
140
120
100
80
60
40
Vlsr [km/s]
35
30
Galactic Longitude [degree]

Cloud-cloud velocity dispersions

Velocity offsets from
the systematic velocities of the
individual regions





σ_V = 4.4±2.3 [km/s]

σ_V = 3.6 ±2.0 [km/s]

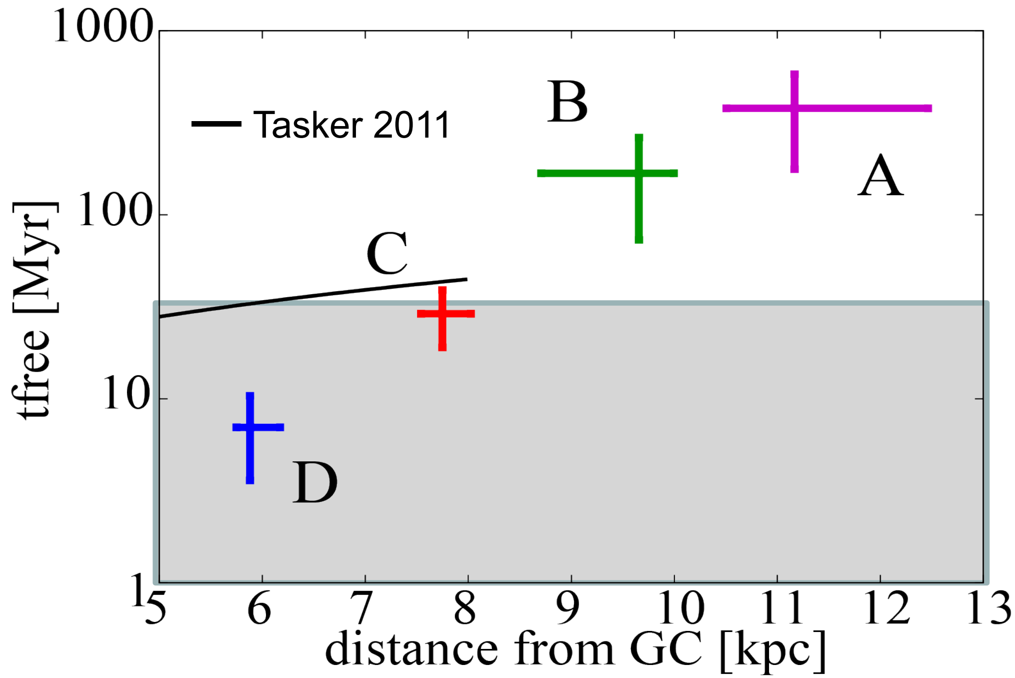
σ_V = 7.3±2.5 [km/s]

σ_V = 7.8 ±3.8 [km/s]

Velocity dispersions become larger in the inner region than the outer.

Frequency of the cloud-cloud collision

Probability of cloud-cloud collision $P = n \cdot \sigma \cdot \Delta V$



Region	t_{free} [Myr]
A	400
B	200
C	30
D	7

Lifetimes of GMC: 20 M yr (e.g., Fukui & Kawamura 2010)

Every cloud can have one collision within its lifetime.
Collisions frequently occur at the inner region of the MW.

High-mass star formation via cloud-cloud collision

- Collision between two molecular clouds can trigger the high-mass star formation
  - Rapid formation under large mass accretion
  - e.g.,10^{-3} Mo/yr × 0.1 Myr = 100 Mo
- Large colliding velocities of 10-20 km/s, highly supersonic
- Massive star cluster: GMC-GMC collision
- Multiple clusters: collision between arm clouds
- Top heavy core mass function as a result of cloud-cloud collision, e.g., NGC3603, MHD simulations [Inoue & Fukui 2013]
- Future: Statistical study with a large number of samples is crucial to understand deeply the role of the cloud-cloud collisions in triggering starbursts: with high dynamic range