大質量星・巨大星団の形成の謎を解く

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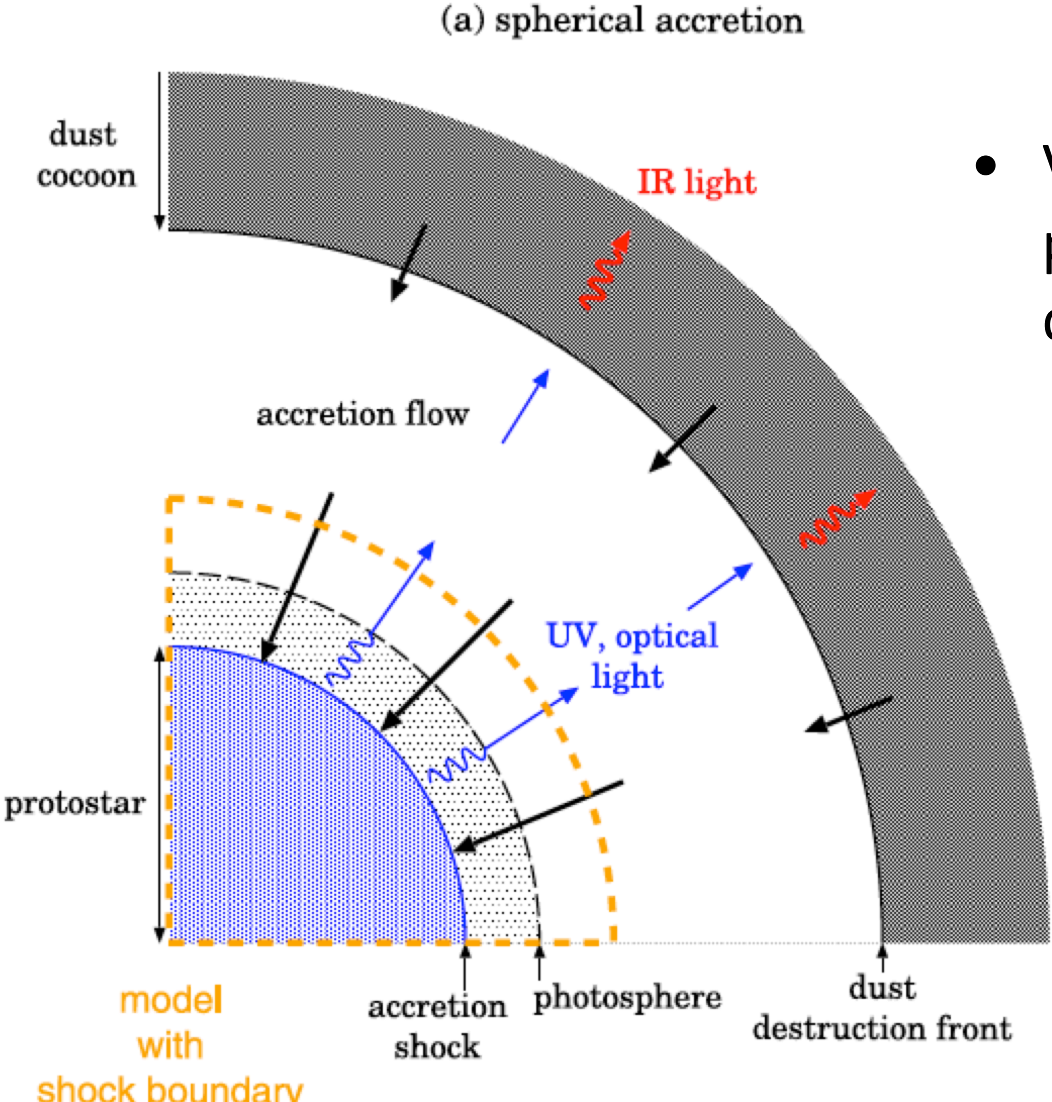
天文･天体物理若手夏の学校　31/07/2019

大質量星形成の難しさ

- 「大きな質量を小さな空間に集める」
  一途中で高密度になり、ゆっくりした過程では
  ガスは星になってしまう
- 星の放射圧がガス降着を妨げる

- 競争的質量降着（Bonnell 2002）
- 大質量ガス塊の重力収縮（Krumholtz+ 2009）
  定説にはなっていない

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 $M_\odot$
- Staller wind, strong UV, SNe, etc..

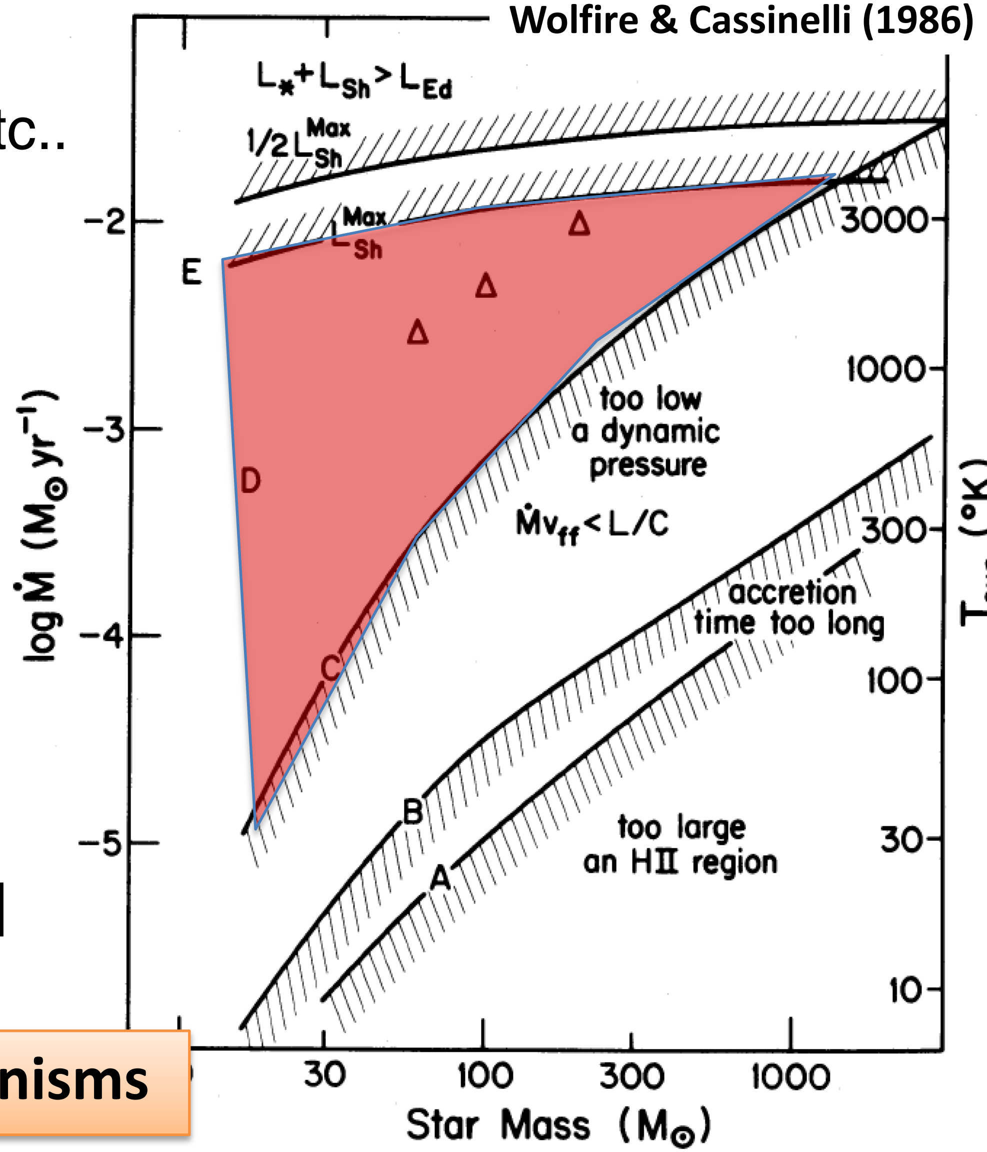
However, it is not known

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]

We need some triggering mechanisms

Wolfire & Cassinelli (1986)



大質量星形成の難しさ

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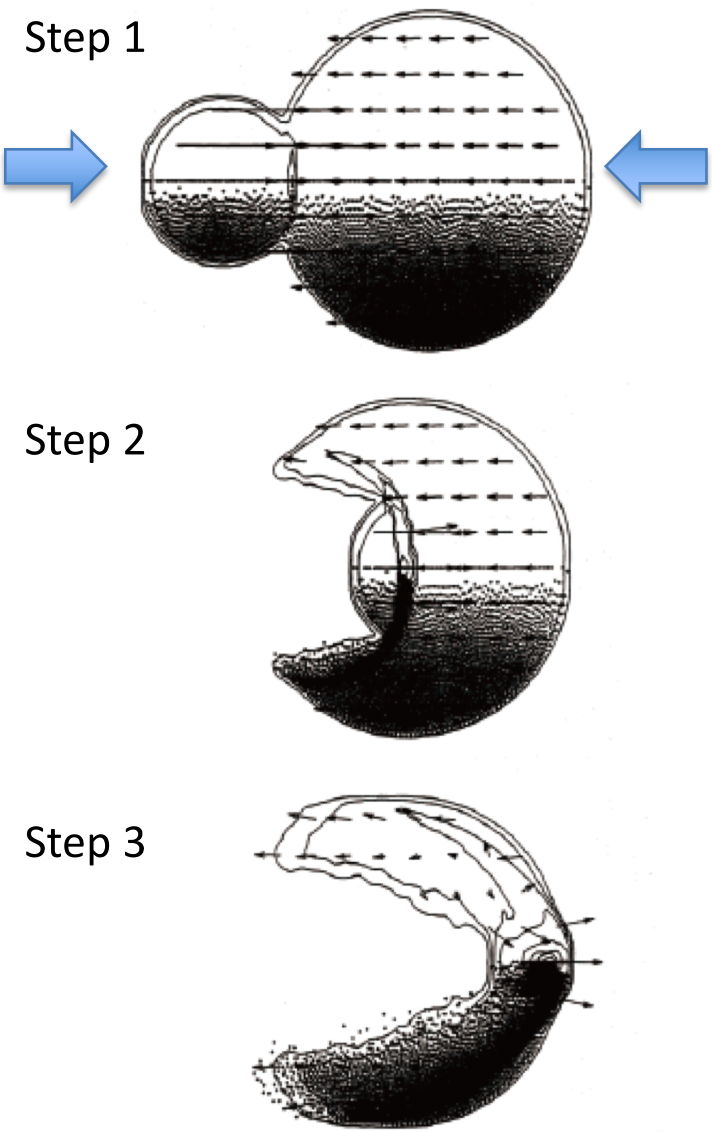
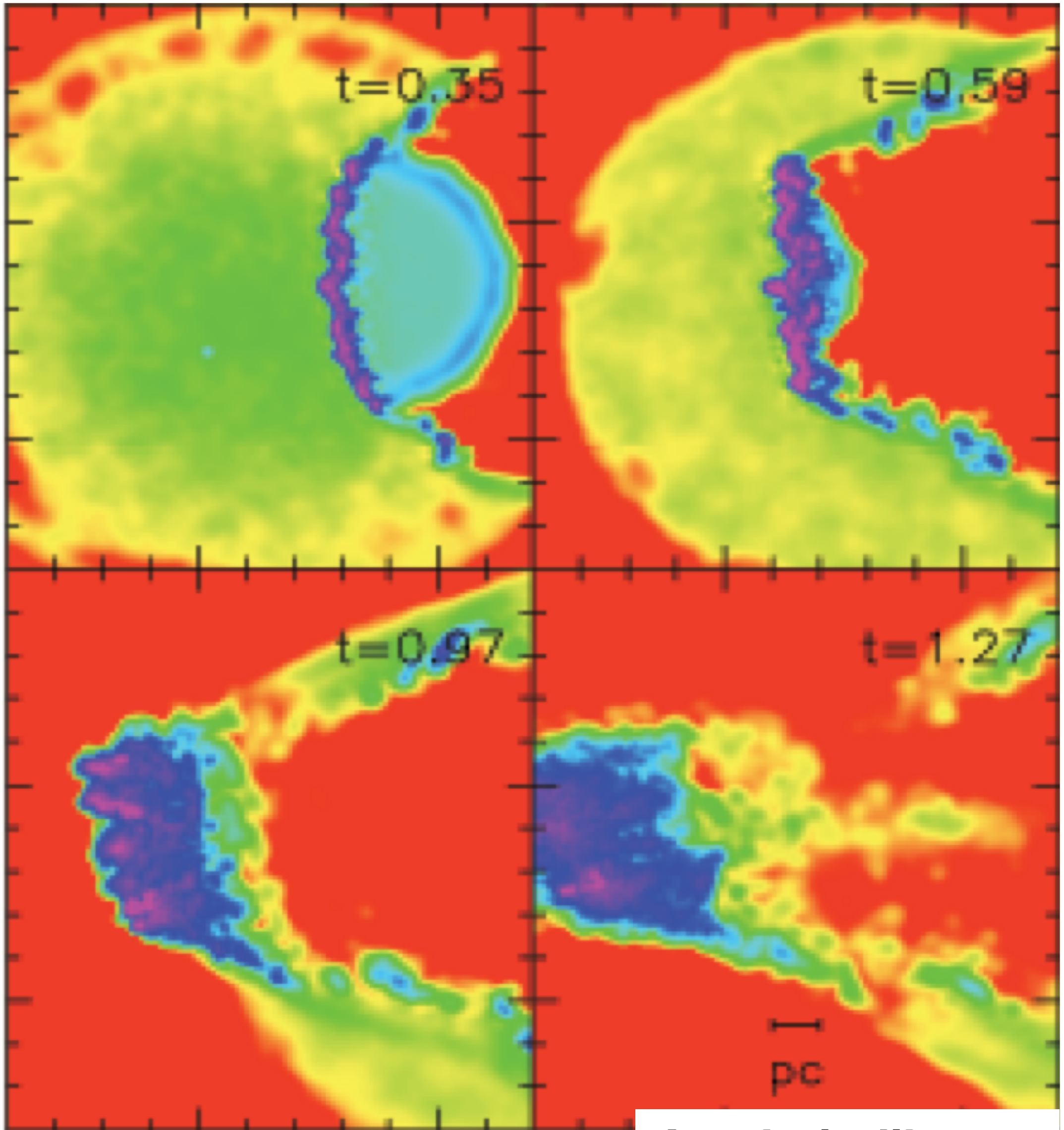
- 「星間雲衝突」が、これらの問題を解決する
  (Fukui, Torii, Inoue+ 2009-2019,
  more than 30　papers)
- 宇宙初期の球状星団形成にも波及

Numerical simulations of Cloud-Cloud Collisions

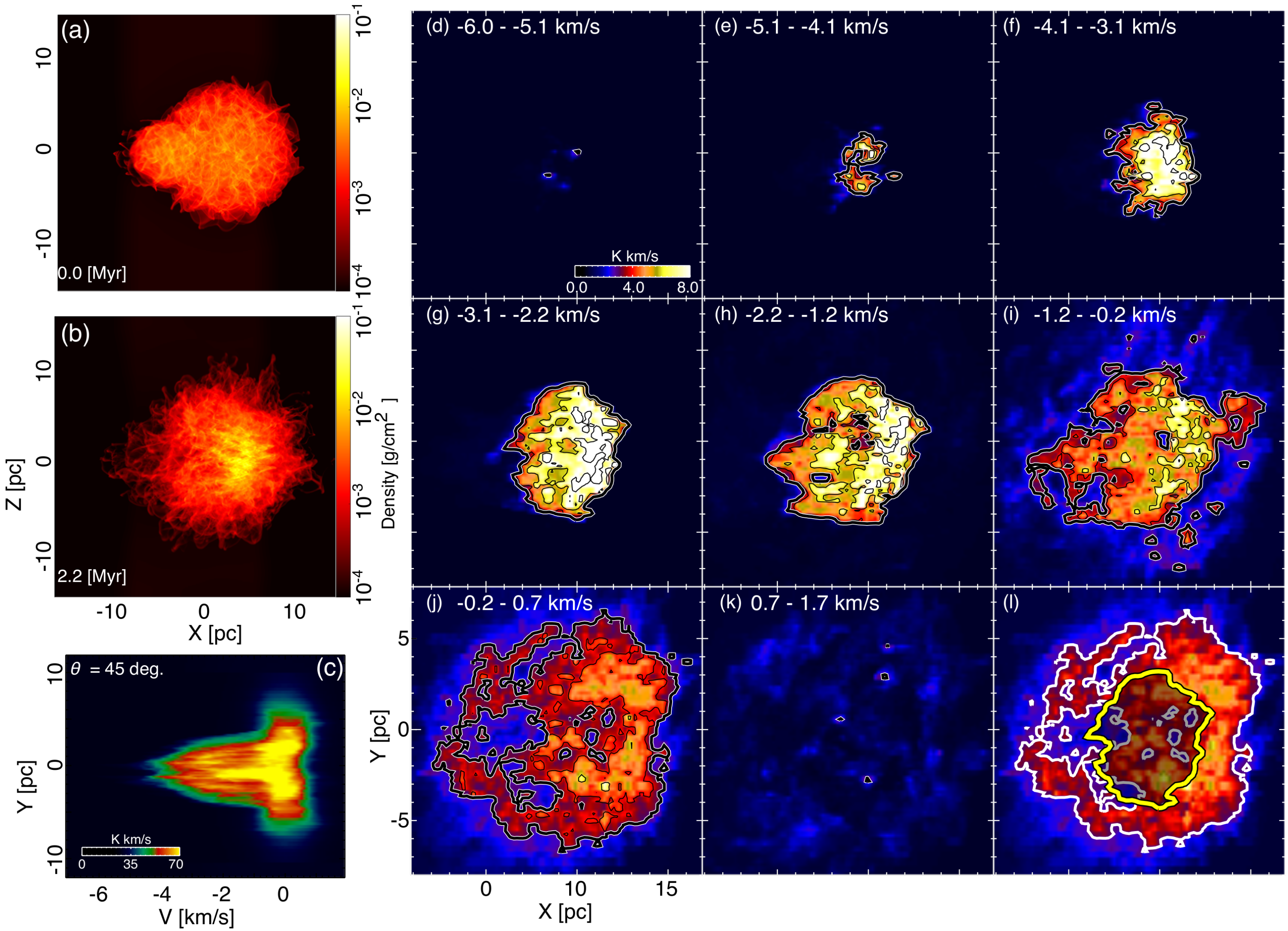


Habe & Ohta 92

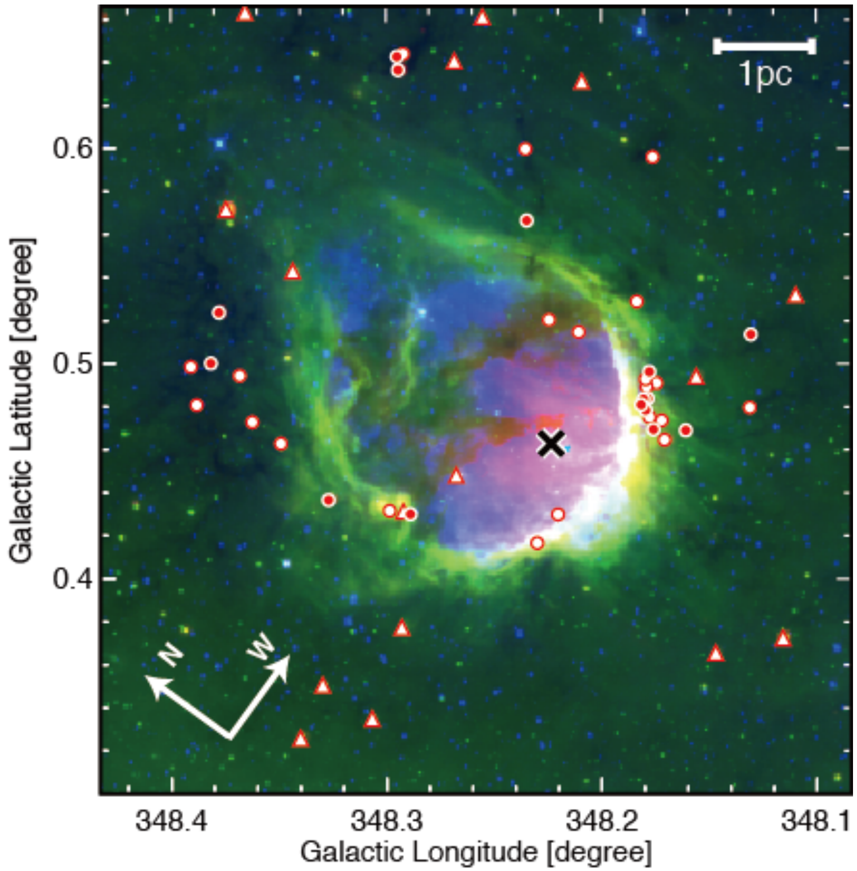


Anathpindika+12

Cloud-cloud collision simulation (Takahira+ 14, Fukui+ 18)



RCW120 (Spizter bubble S7)

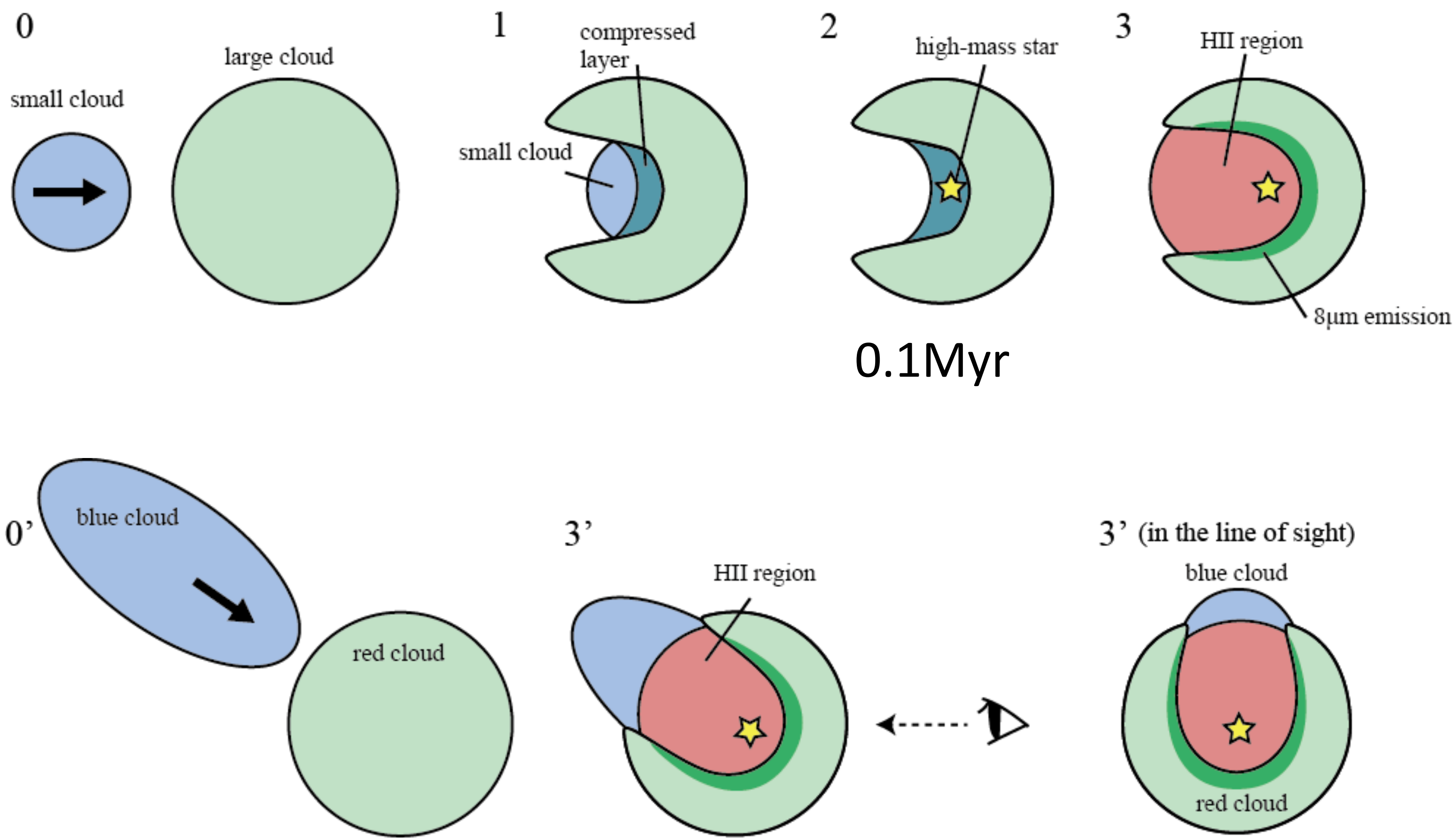


- A Spitzer bubble member
- d ~ 1.3 kpc (Rodgers+1960)
- Beautiful ring-like emission at 8 micron enclosing ionized gas.
- An exciting O8 star
- Expanding HII region? (e.g., Zavagno+2010)

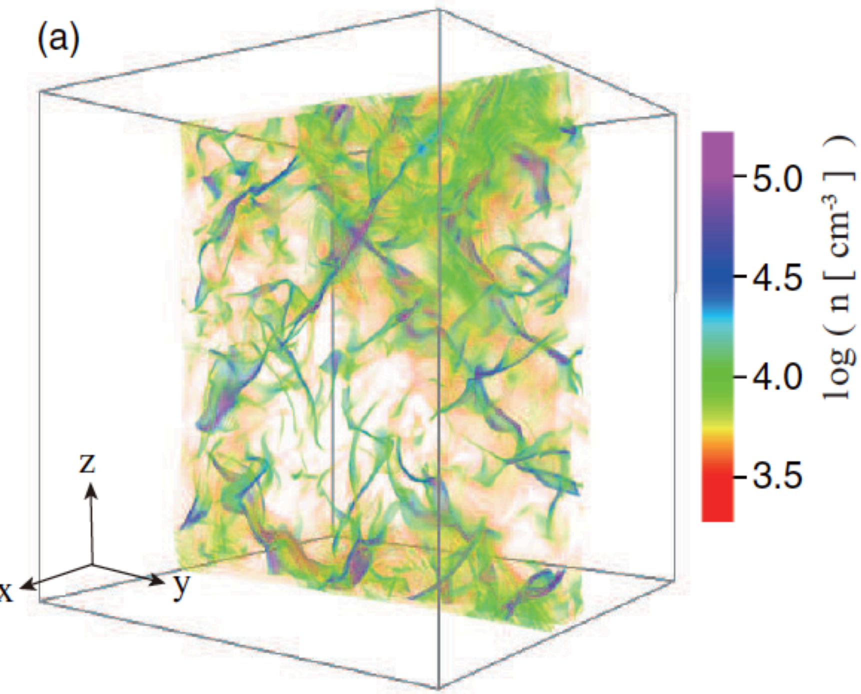
Green : 8um
Red : 24um
Blue : Hα

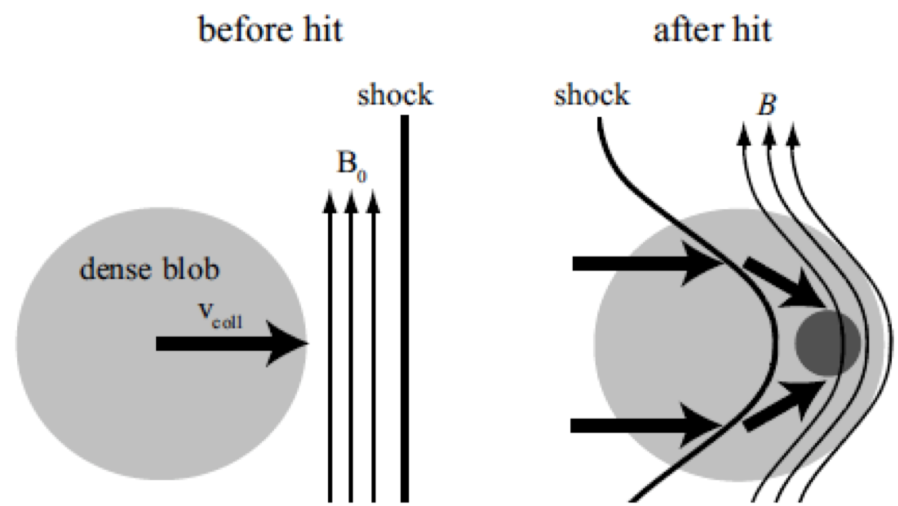
× : exciting star
○ : Class Ⅰ
△: Class Ⅱ

Cloud-cloud collision (Torii+ 15)



CCC triggers formation of massive dense core
MHD simulations



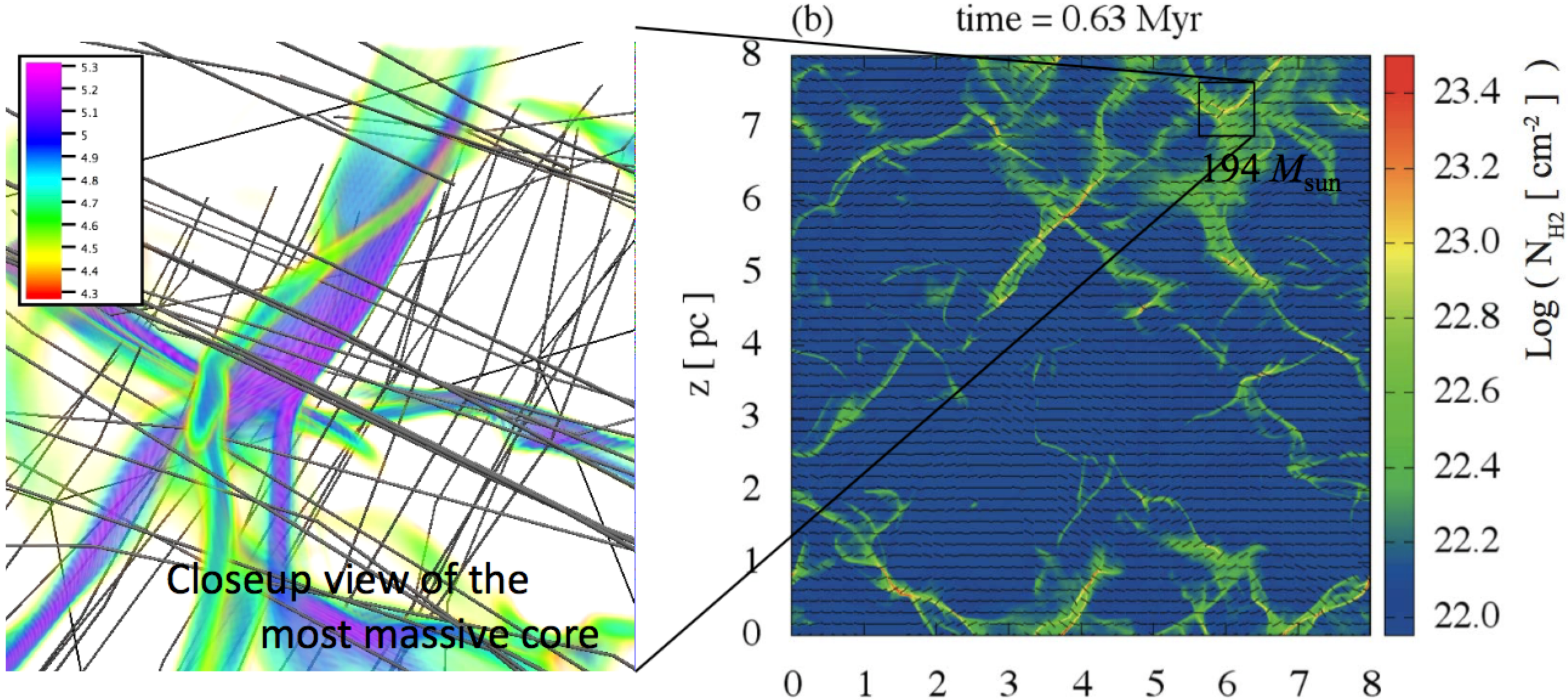


Inoue and Fukui 2013

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).

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

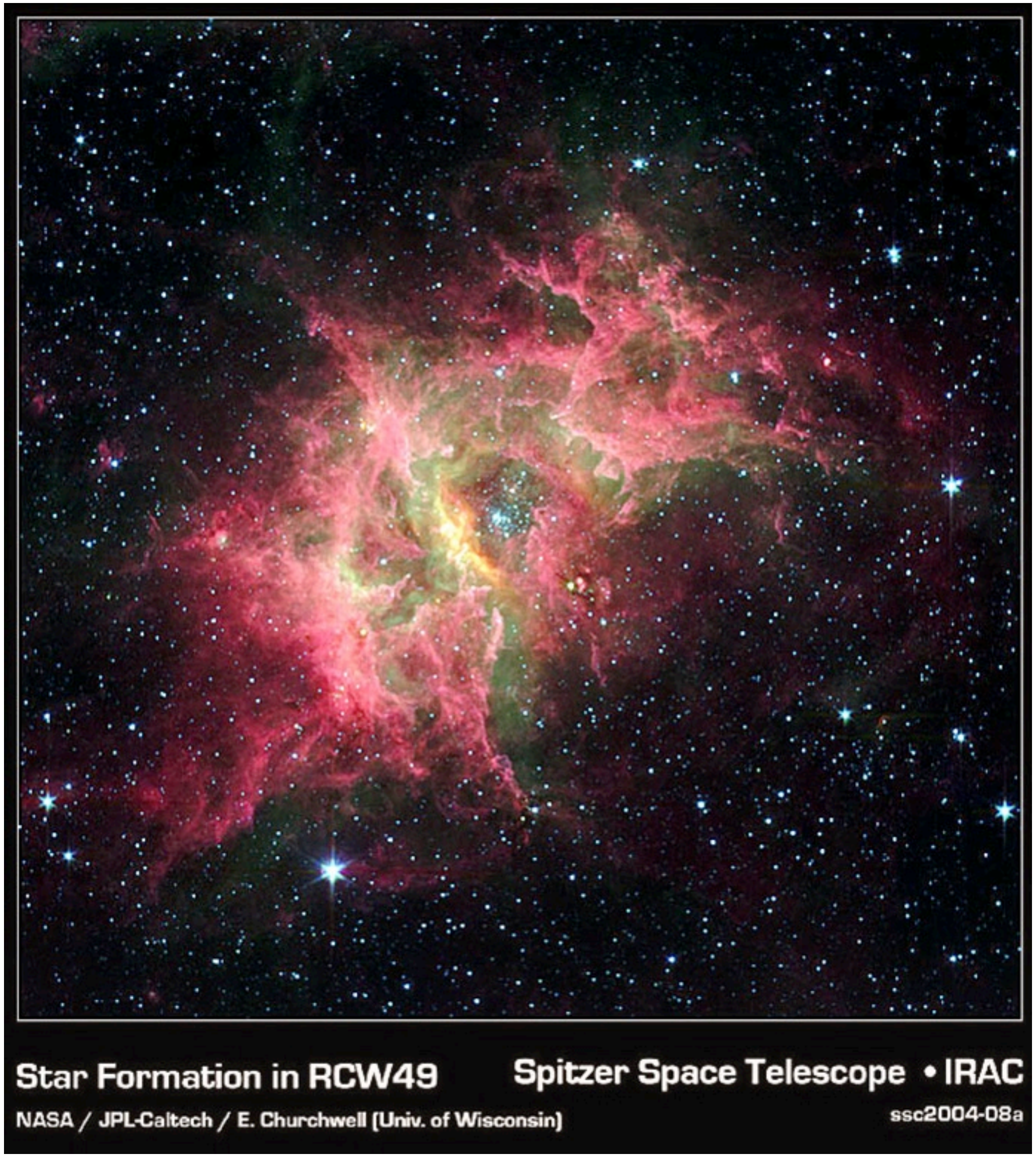
$|B| = 280\ \mu$G,
$\Delta v = 1.2$ km/s,
$\langle n \rangle = 0.8 \times 10^5\ {\rm cm}^{-3}$

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

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

Inoue & Fukui 13, ApJL

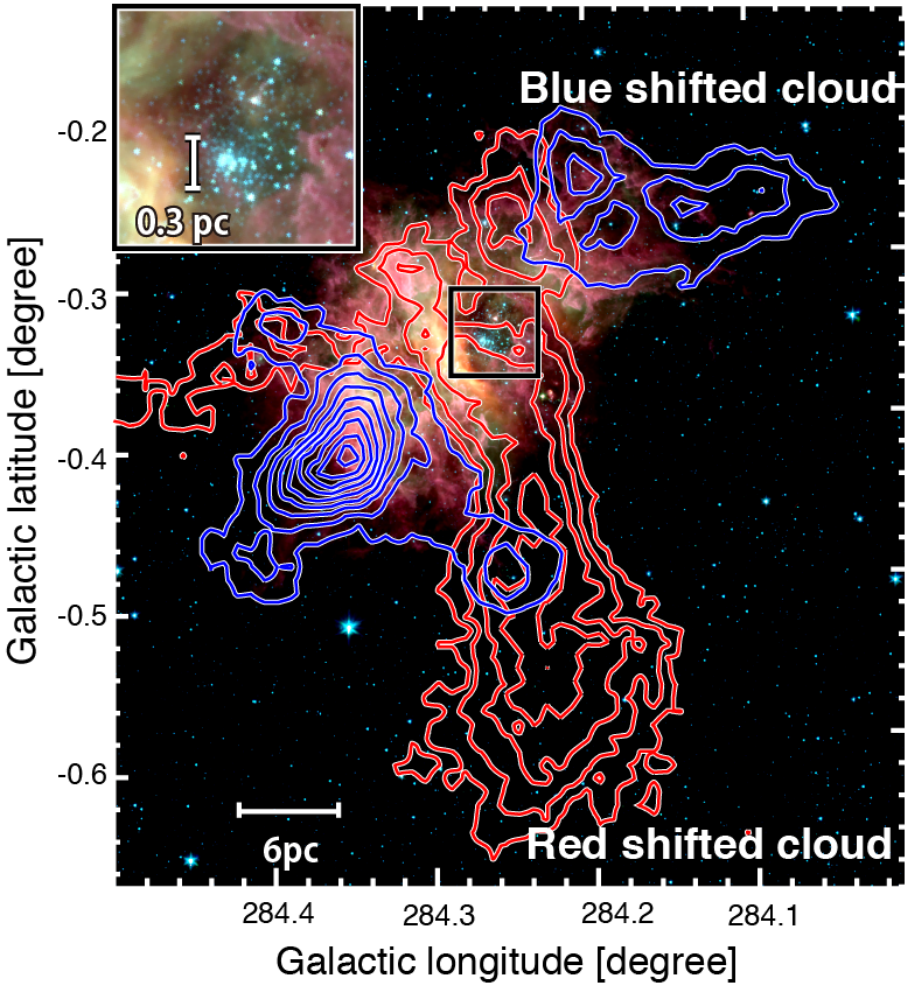
Super Star Cluster： Westerlund 2

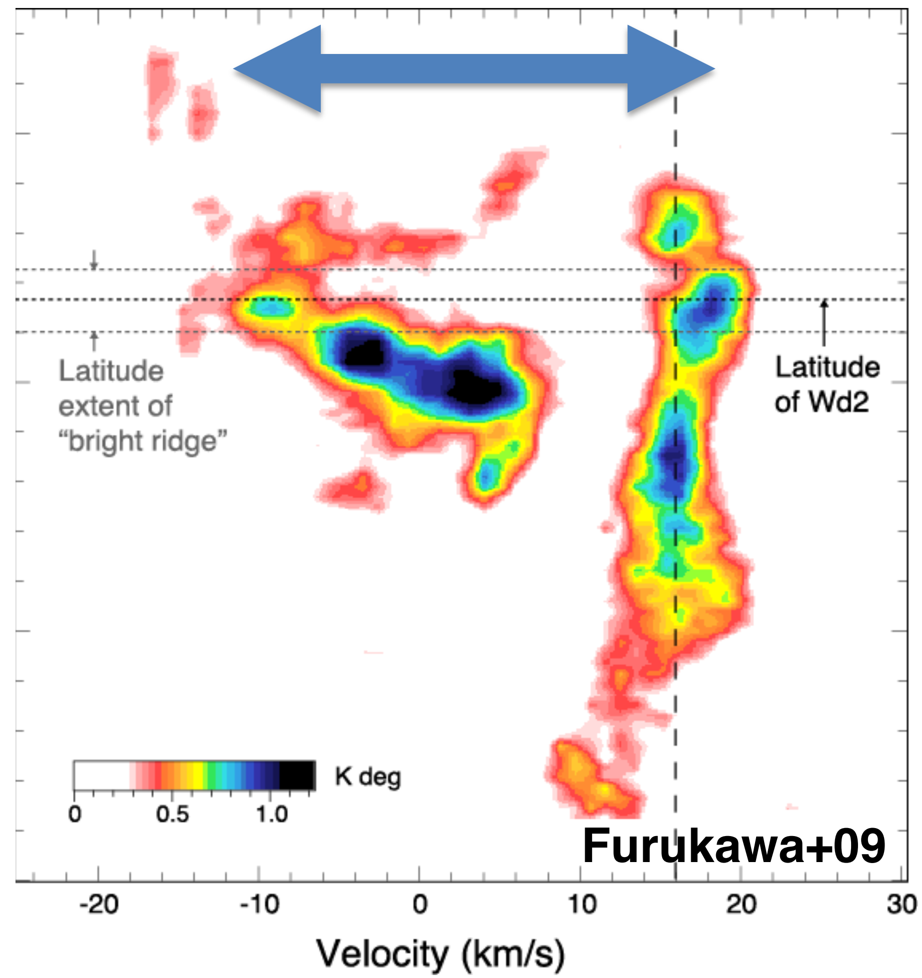


- (*l*, *b*) = (284°.27, -0 °.33)
- O-Star x 12, WR-star x 2
- Total mass of the stars 4,500 $M_\odot$ (Rauw+07)
- Age 2–3 Myr (Piatti+98)
- Distribution of dust influenced by stars (Churchwell+98)
- Star formation in progress
- YSO ~300 (Whitney+04)

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

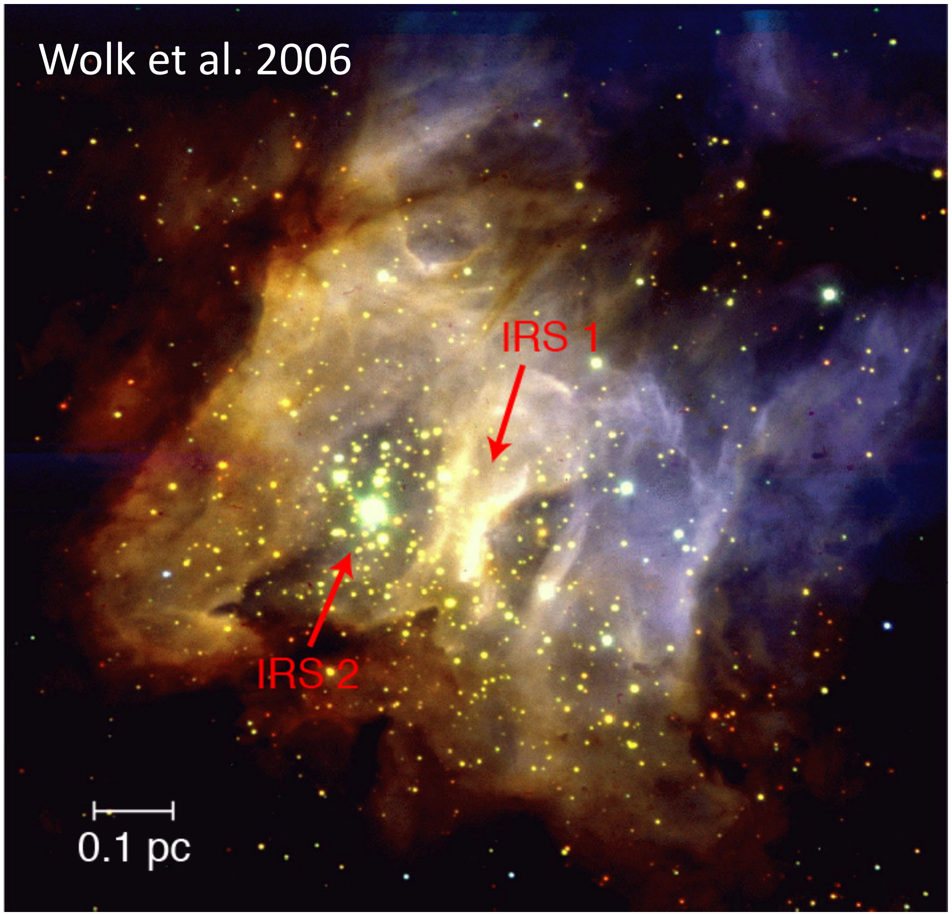
SSC: Westerlund 2 (Furukawa+09; Ohama+10)





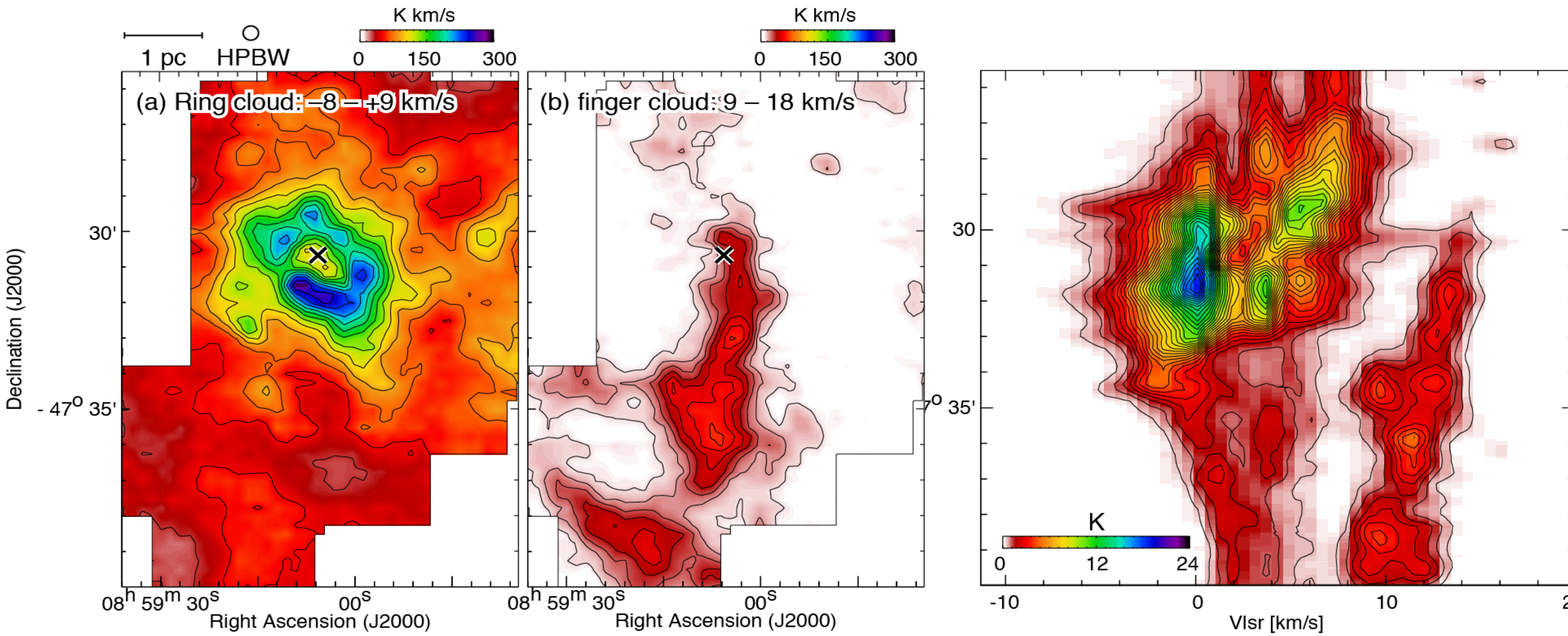
- Two GMCs (red/blue) are complementary distributed toward Westerlund2.
- The velocity separation of the two clouds is 15–25 km s^{-1}, can not be bound with the gravity.

RCW38



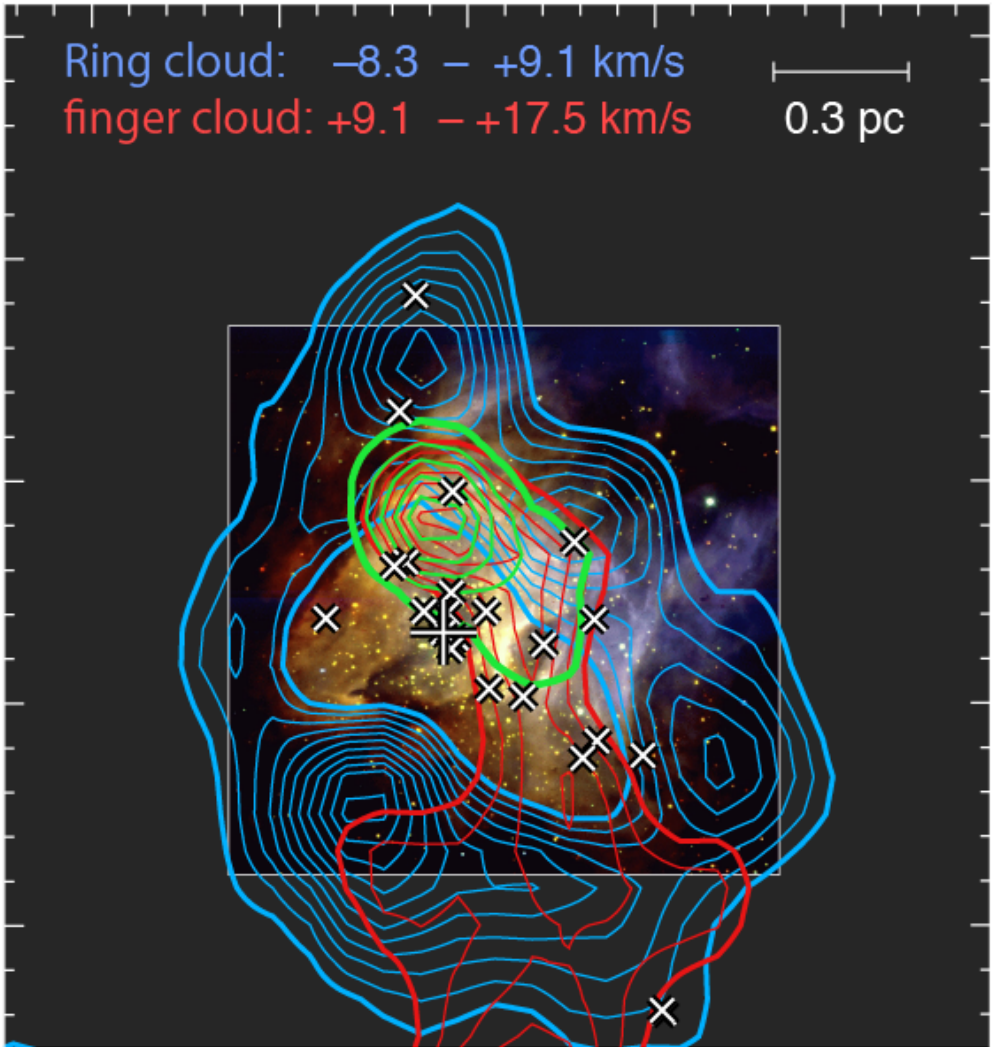
- 巨大星団 RCW38
- 距離: ~ 1.7kpc
- 励起星: O5.5型 (IRS2)
- O型星候補: ~20個
- 銀河系でもっとも若い巨大星団（~0.1Myr）(Fukui+16; Wolk+06)
- 赤外線の明るいリッジ構造 IRS1
- 中心部1pcに豊富なガス

RCW38 (Fukui+ 16)

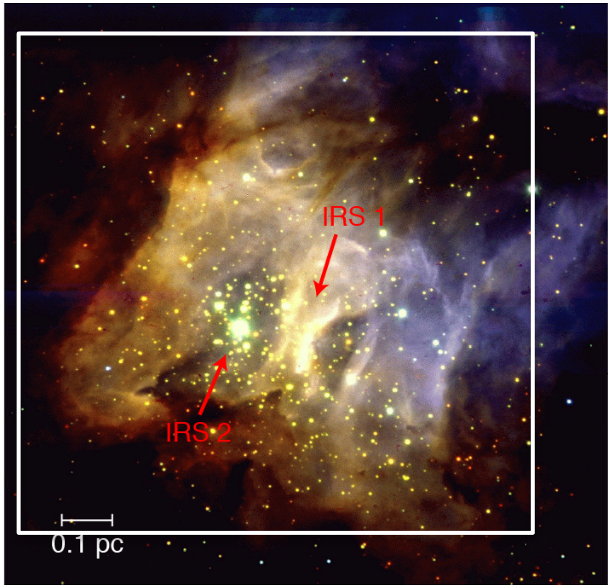


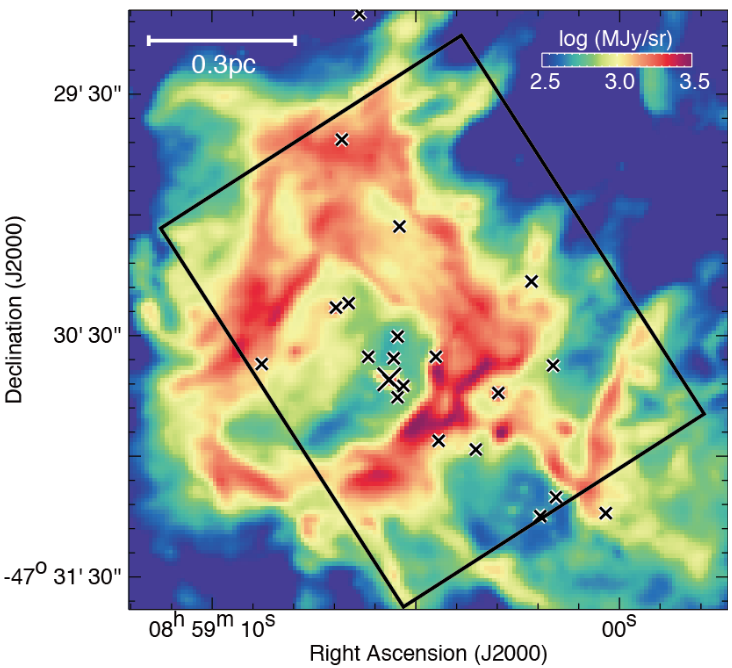
- CO J=1-0, 3-2輝線観測
- 速度差12km/sの2つ分子雲
  - Ring cloud (Blue-shifted), Finger cloud (Red-shifted)
- 2つの分子雲を速度上で結ぶbridge feature (Haworth+15a,b)
- 分子雲衝突

RCW38



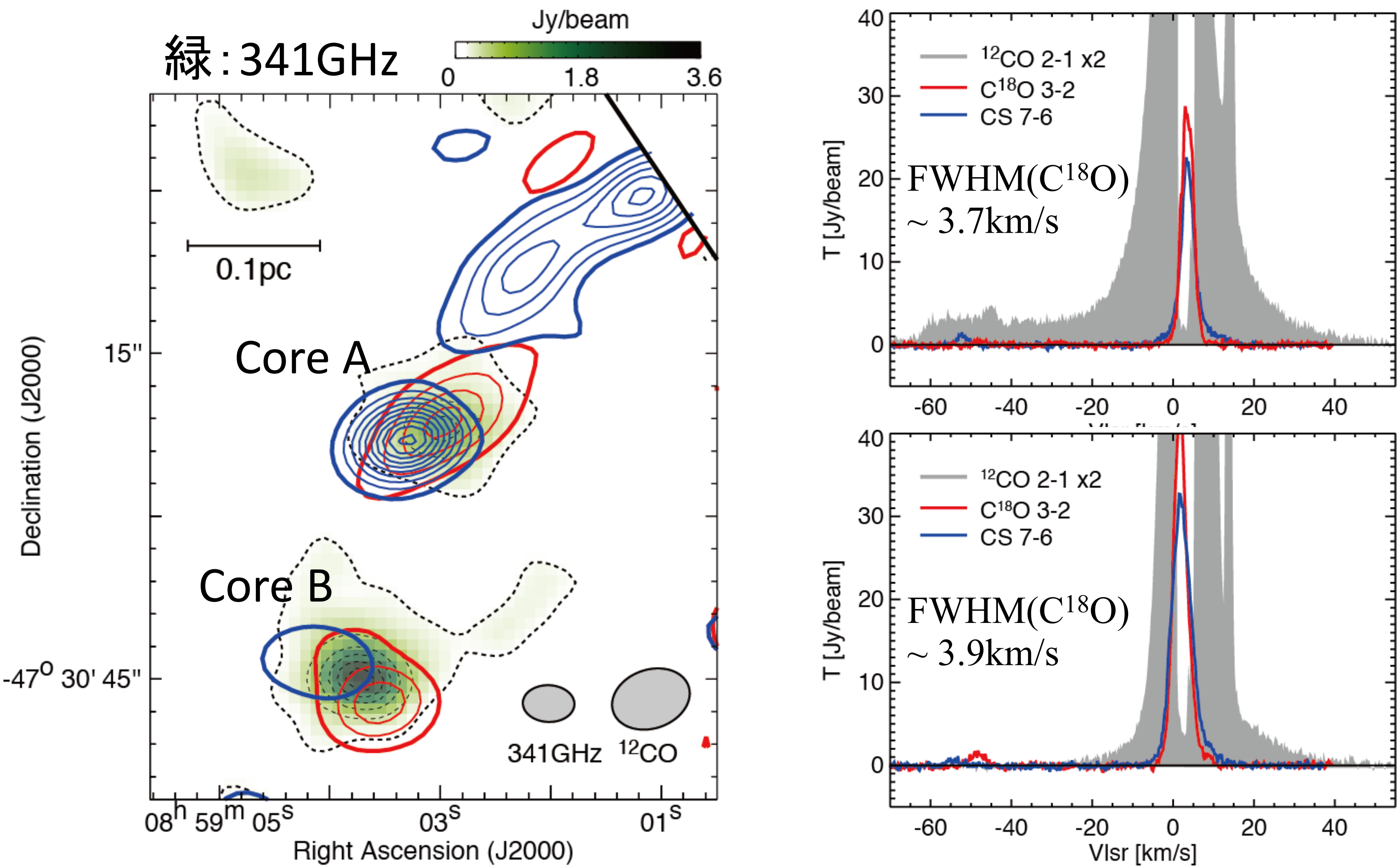
ALMA Cycle-3 7m+TP Observations





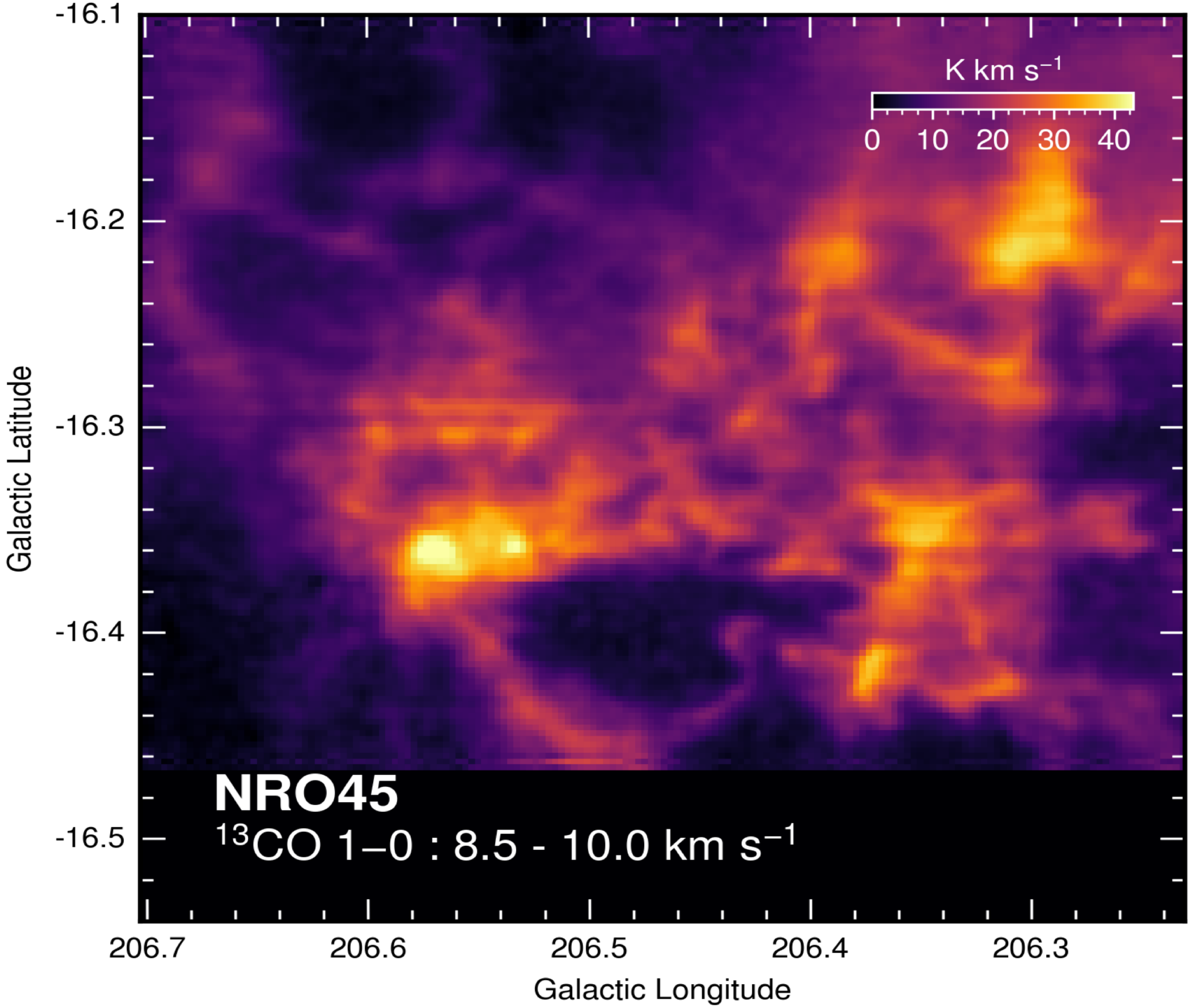
- 2015.1.01134 (PI Fukui)
- Band 6 - 7m(7 pointings) + TP
  - ^{12}CO, ^{13}CO, and C^{18}O (J=2-1), SiO (J=5-4), H30α, Continuum
- Band 7 - 7m(14 pointings) + TP
  - ^{13}CO and C^{18}O (J=2-1), CS(J=7-6), Continuum
- Spatial resolutions
  - Band 6: ~ 7" x 5" (~0.050pc)
  - Band 7: ~ 5" x 3.5" (~0.035pc)
- Velocity resolution: ~0.2 km/s
- Final r.m.s:
  - Lines: ~0.2 Jy/beam
  - Continuum: ~0.03 Jy/beam

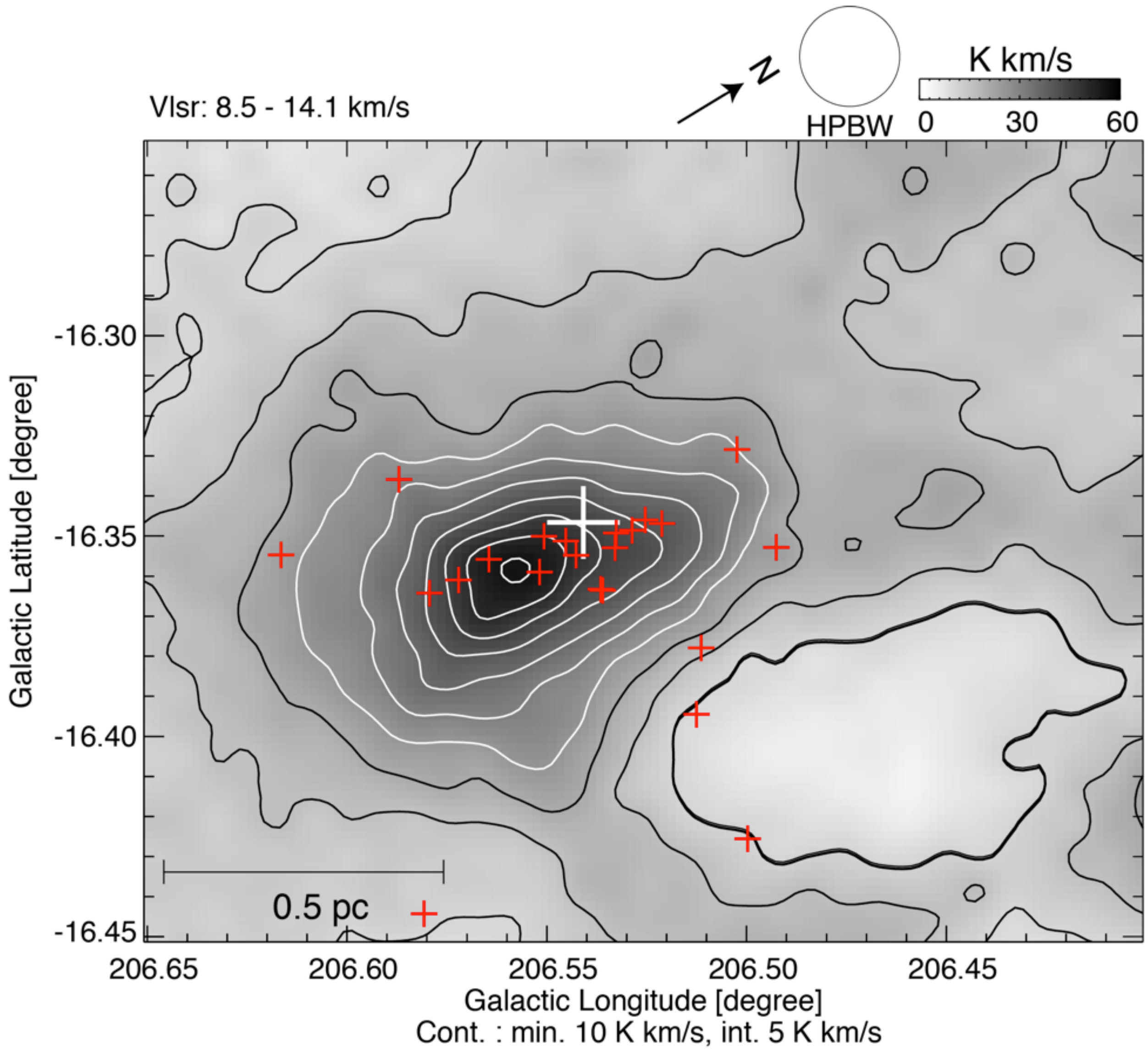
Core A, Bに付随する分子流 (Torii+ 19)



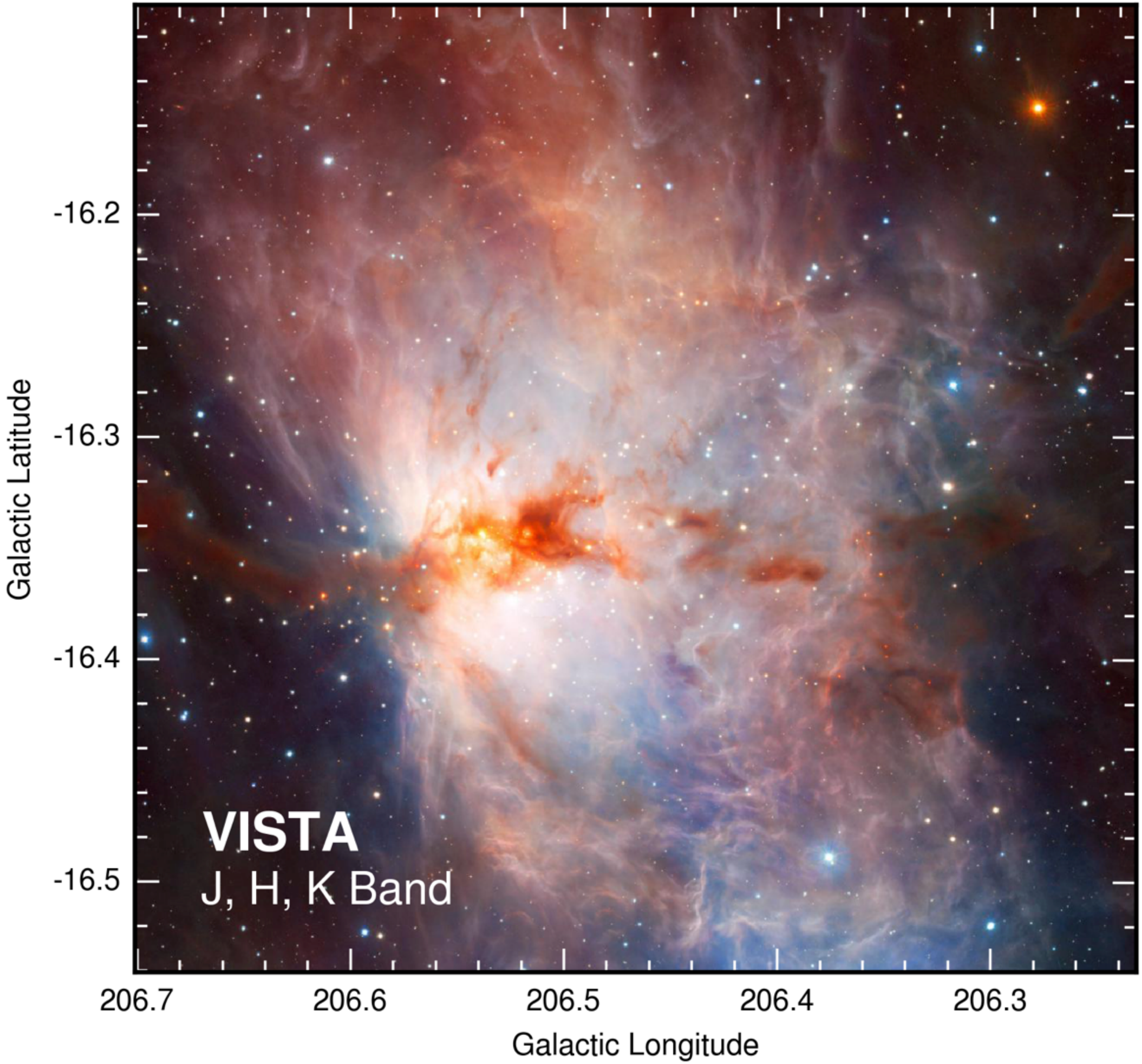
- 2つのコアの方向で片側20–50km/sのbipolar outflow

NGC2024 Enokiya+ 2019



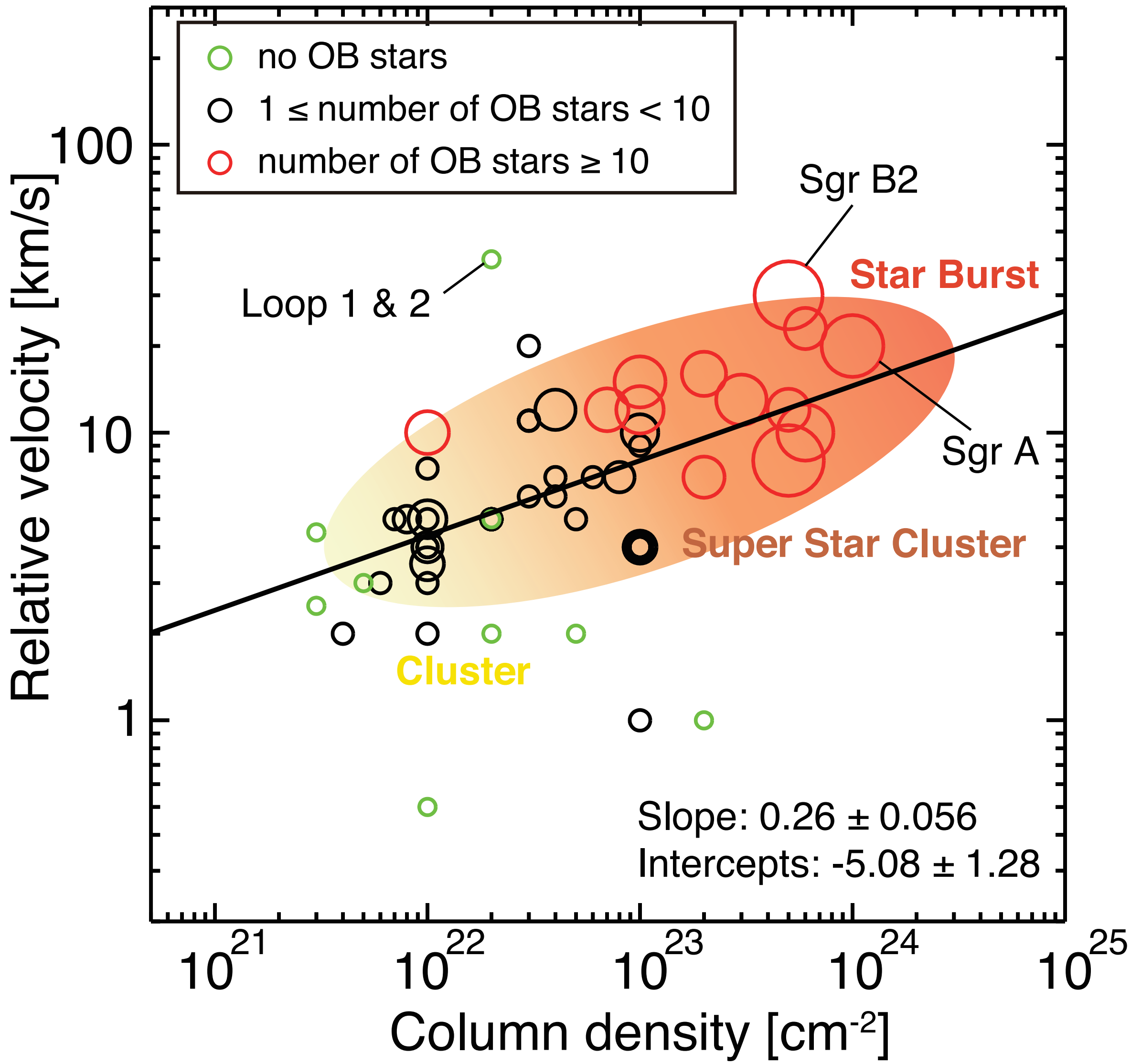


Vlsr: 8.5 - 14.1 km/s
N
HPBW
K km/s
0
30
60
-16.30
-16.35
-16.40
-16.45
Galactic Latitude [degree]
0.5 pc
206.65
206.60
206.55
206.50
206.45
Galactic Longitude [degree]
Cont. : min. 10 K km/s, int. 5 K km/s

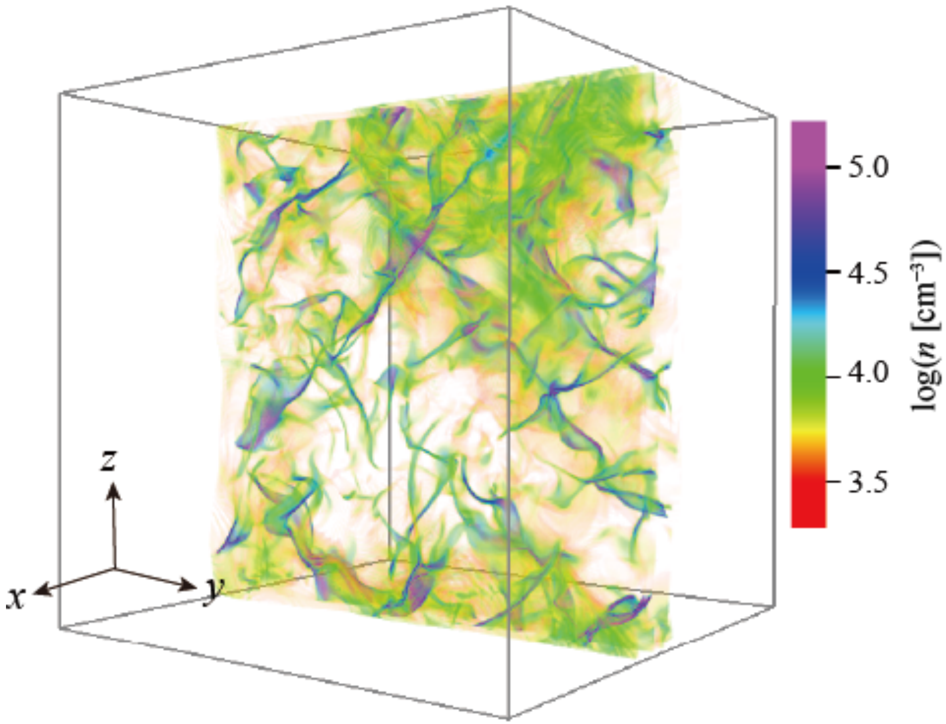


VISTA
J, H, K Band
-16.2
-16.3
-16.4
-16.5
Galactic Latitude
206.7
206.6
206.5
206.4
206.3
Galactic Longitude

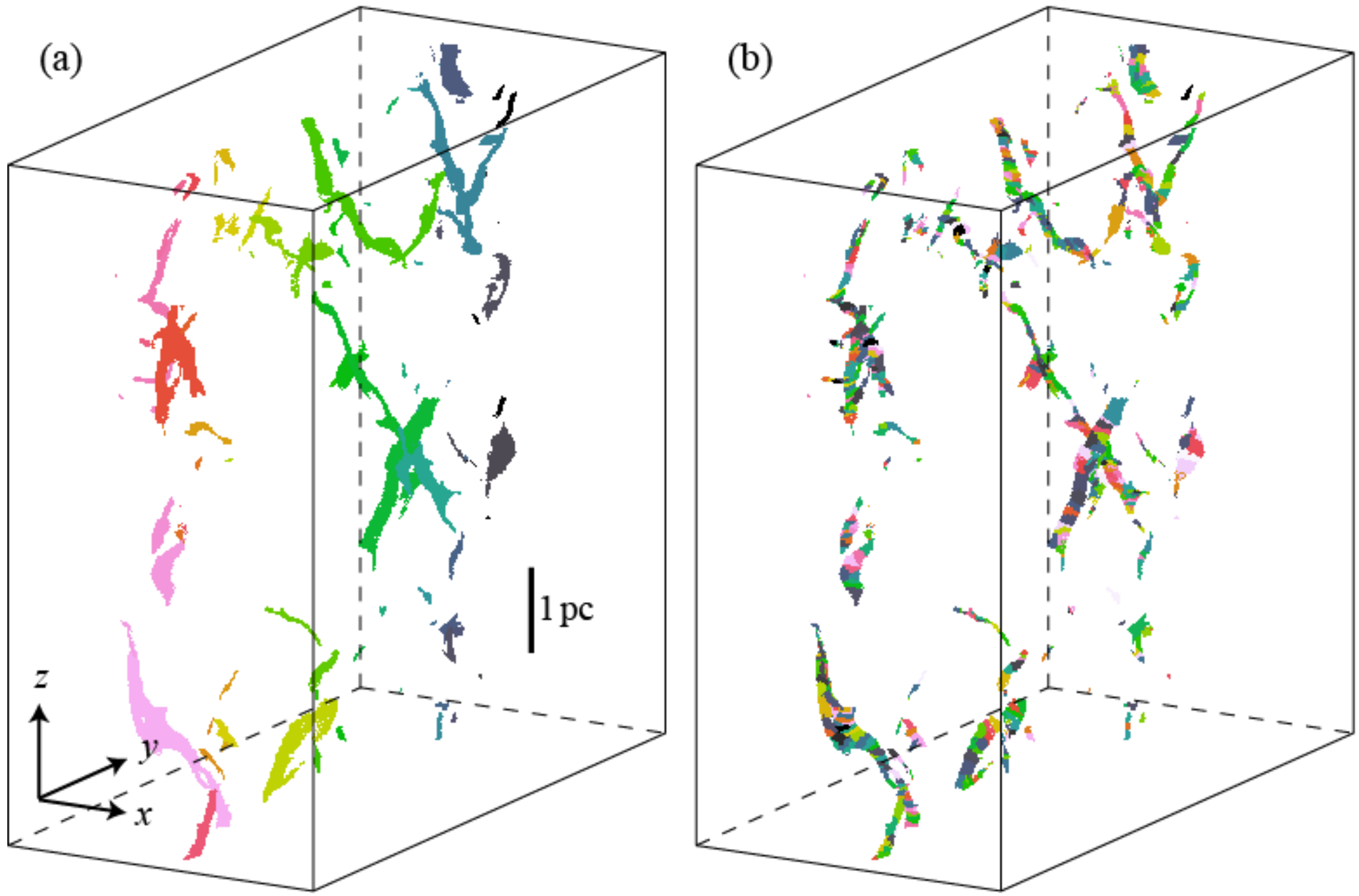
分子雲衝突と星形成 (Enokiya+ 2019)

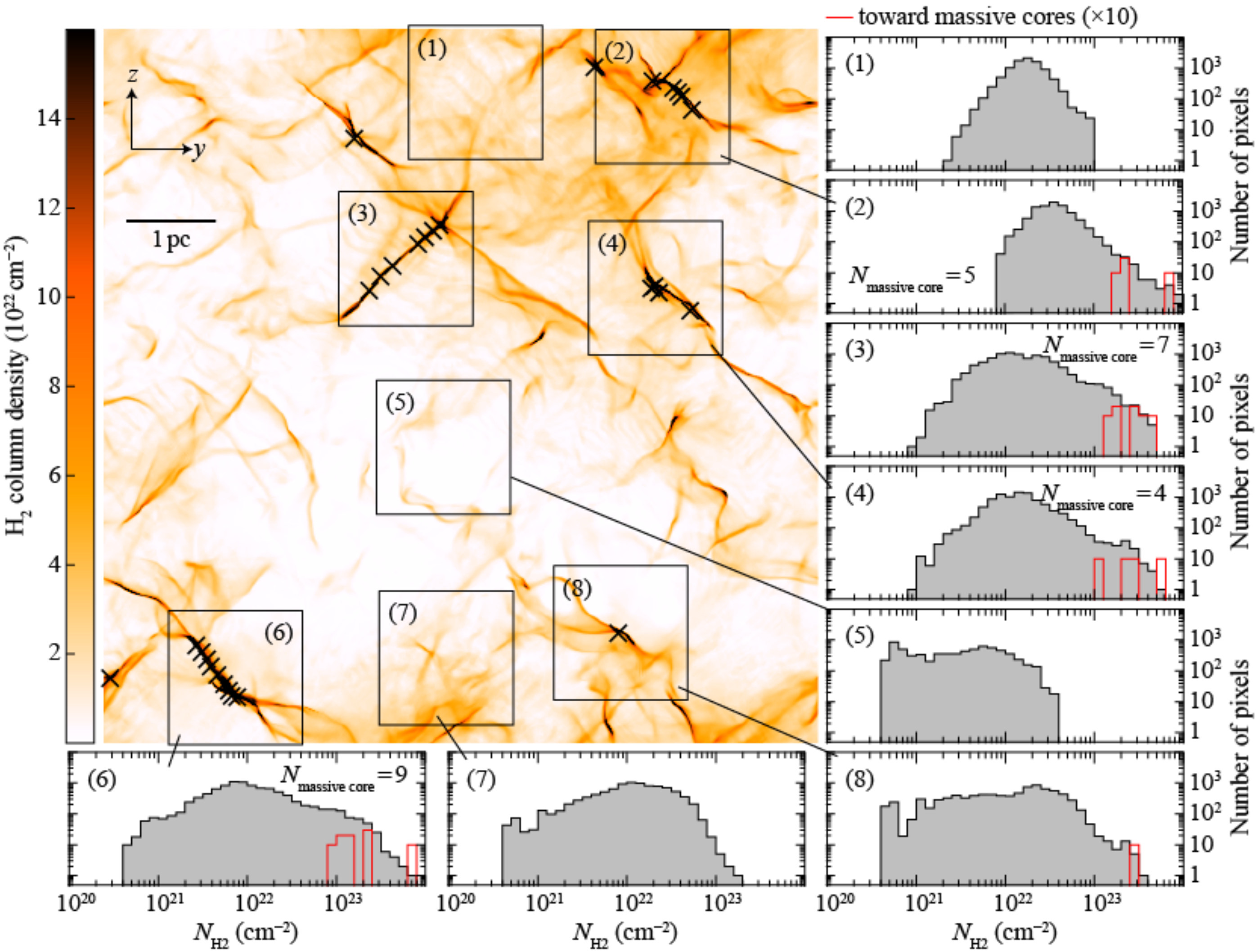


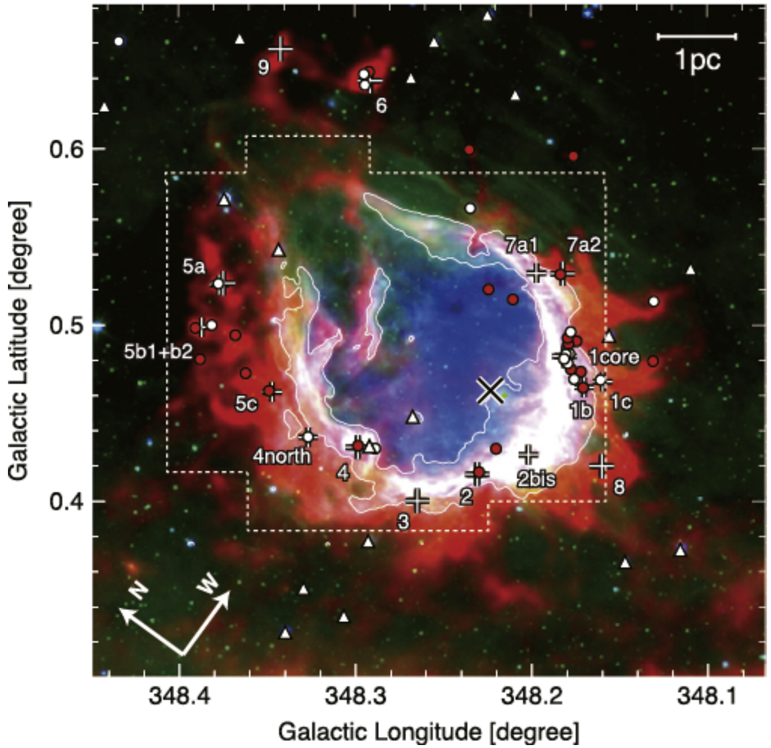
シミュレーション結果の解析
衝突による星形成の特徴 (Fukui+ 19)

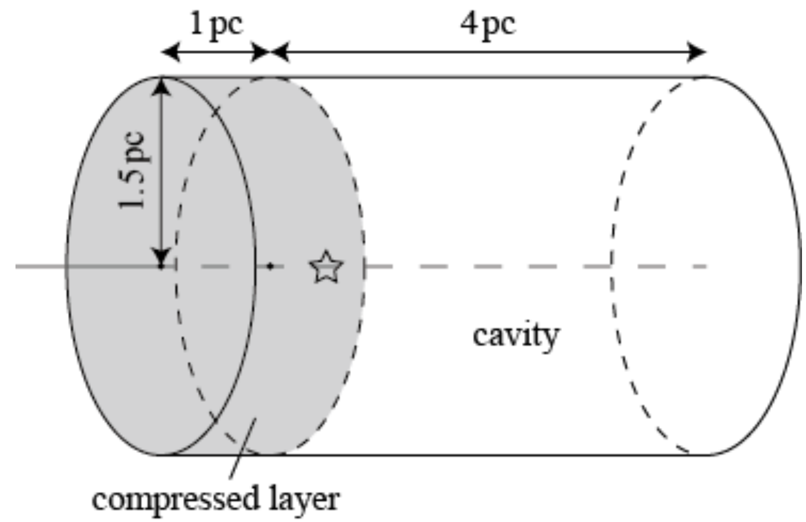


Parameter	Value
$\langle n \rangle_0$	300 cm^{-3}
$\Delta n/\langle n \rangle_0$	0.33
B_0	20 μG
V_{coll}	10 kms^{-1}
Resolution	(8.0/512) pc

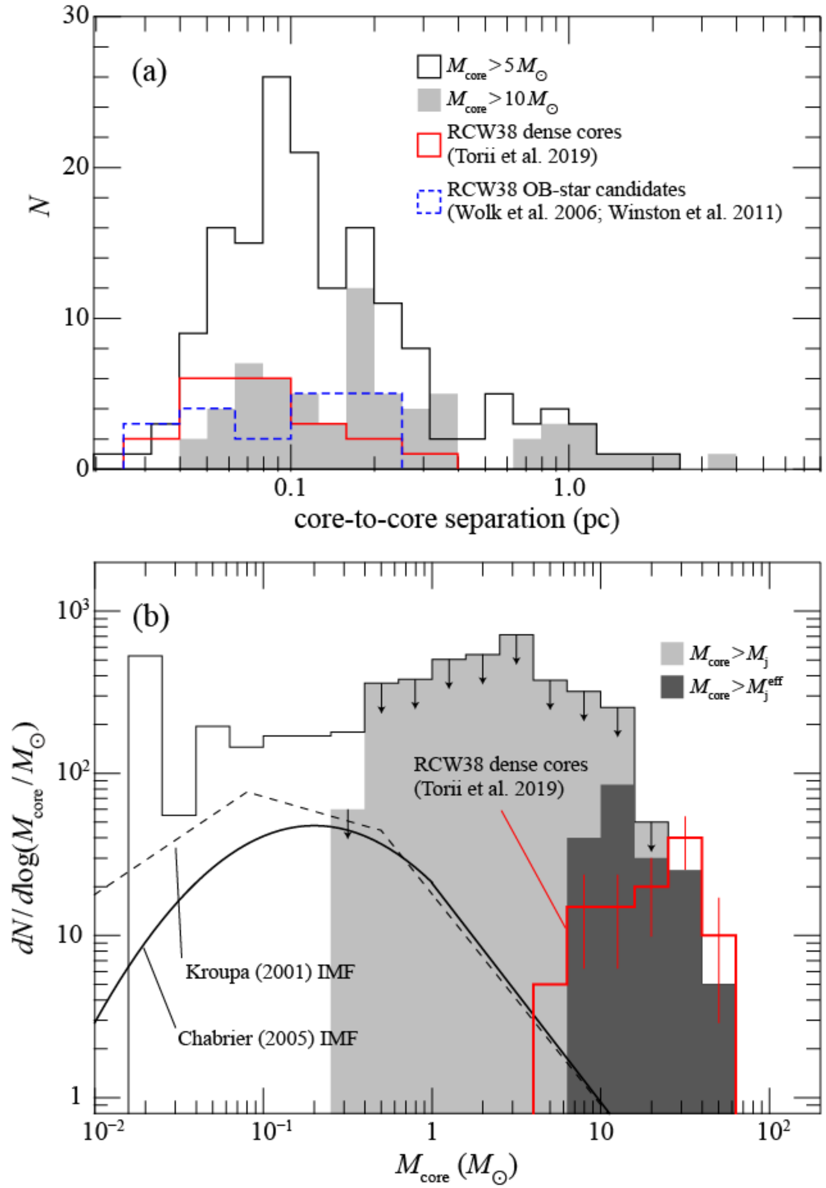

(a)
(b)
1 pc
z
y
x


toward massive cores (×10)
H2 column density (10^22 cm^-2)
z
y
1 pc
(1)
(2)
(3)
(4)
(5)
(6)
(7)
(8)
N massive core =5
N massive core =7
N massive core =4
N massive core =9
Number of pixels
N H2 (cm^-2)





The cavity	Radius	Length	Initial mass	Average density	Typical column density
	1.5 pc	4 pc	$500 M_{sol}$	300 cm^{-3}	1×10^{21} cm^{-2}
Collision compressed layer	Collision radius	Thickness	Current mass		
	1.5 pc	1 pc	$1000\ M_{sol}$	3000 cm^{-3}	1×10^{22} cm^{-2}

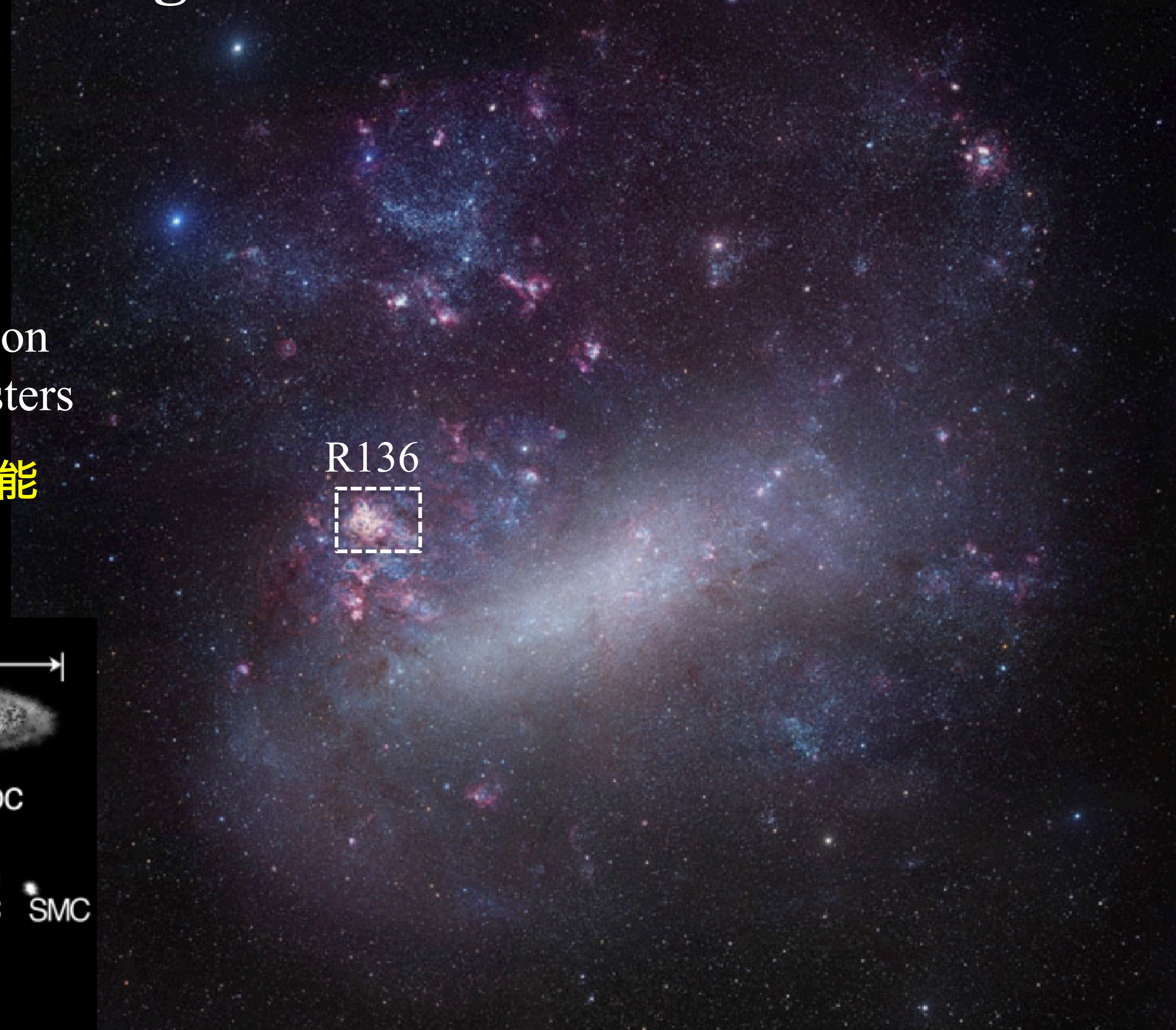


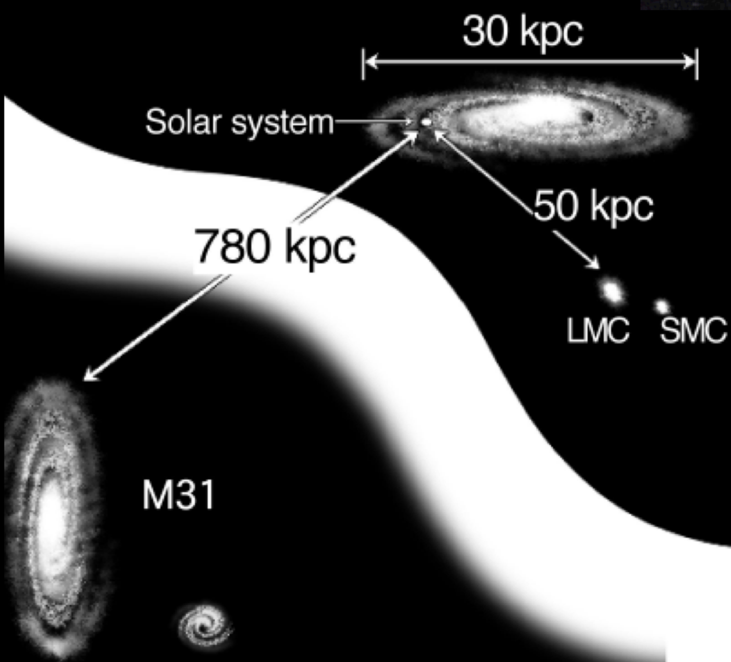
(a)
$M_{core} > 5\,M_\odot$
$M_{core} > 10\,M_\odot$
RCW38 dense cores
(Torii et al. 2019)
RCW38 OB-star candidates
(Wolk et al. 2006; Winston et al. 2011)
N
core-to-core separation (pc)
(b)
$M_{core} > M_j$
$M_{core} > M_j^{eff}$
RCW38 dense cores
(Torii et al. 2019)
Kroupa (2001) IMF
Chabrier (2005) IMF
$dN/d\log(M_{core}/M_\odot)$
M_{core} ($M_\odot$)

The Large Magellanic Cloud: LMC

- Distance: ~ 50 kpc
  (one of the nearest)
- Metallicity: ~1/2 $Z_{\odot}$
- Active star formation
  - Massive star formation
  - young populous clusters

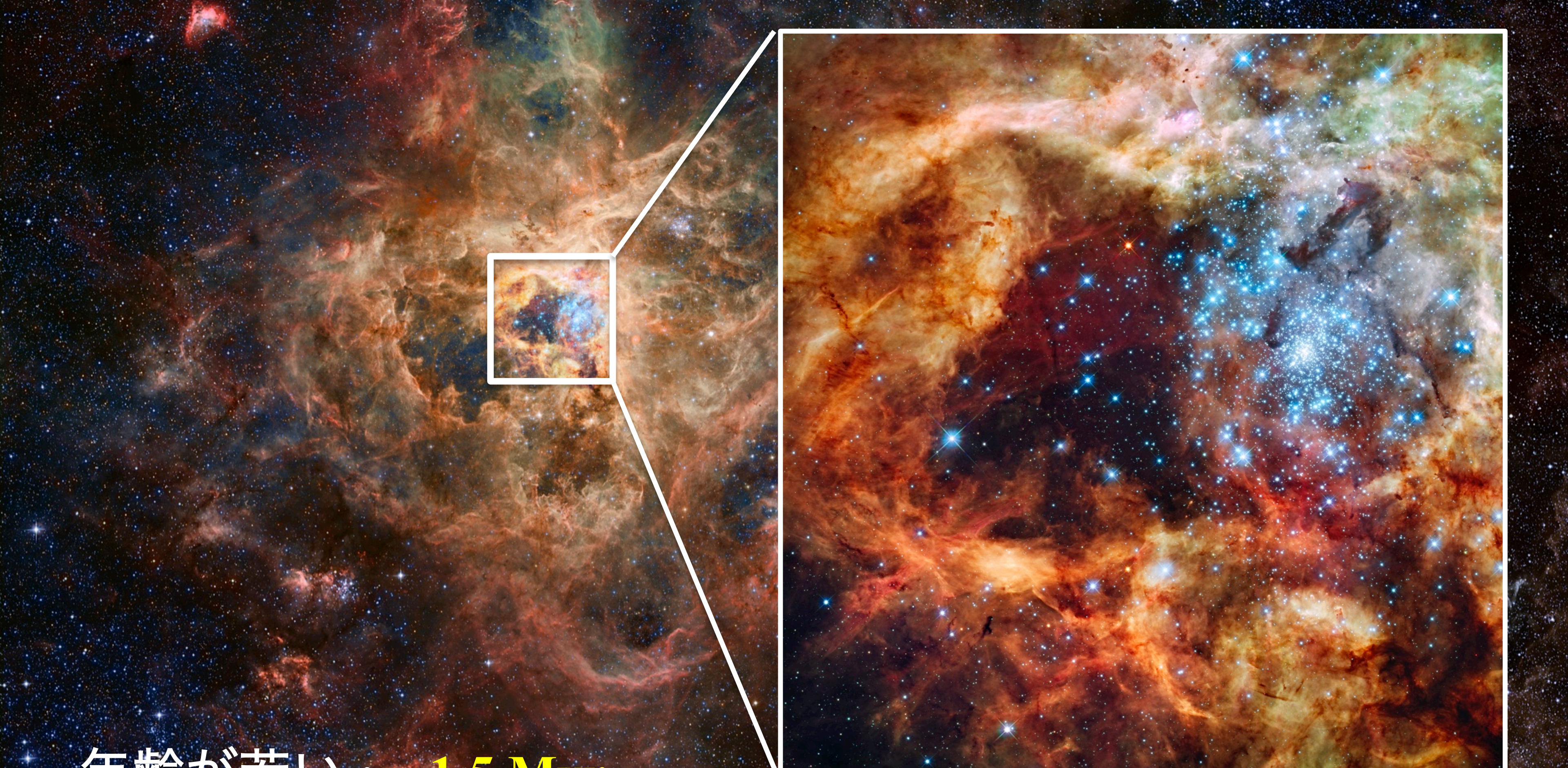
高空間分解能での観測が可能





RMC 136 (R136)

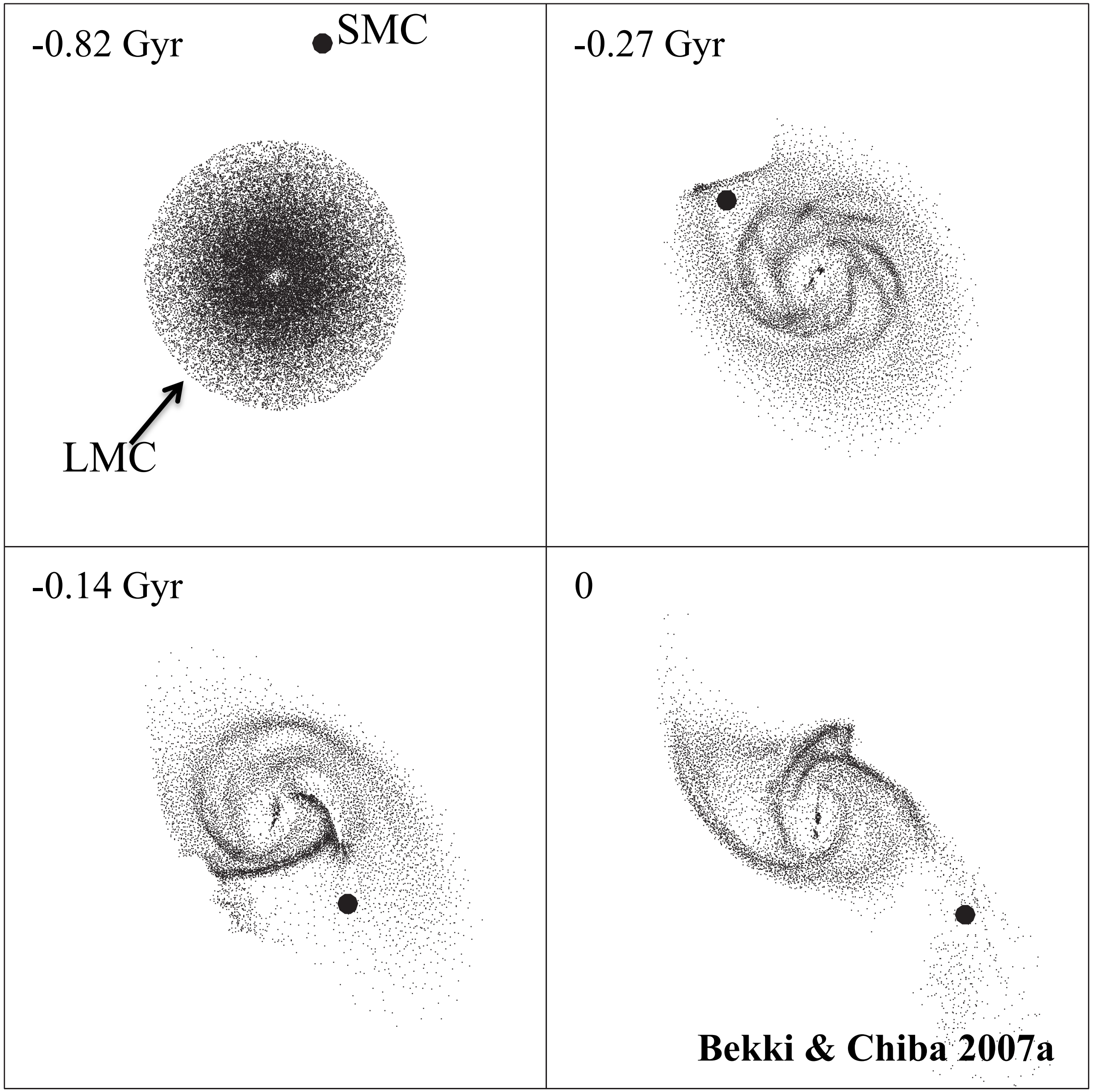
スーパースタークラスター



- 年齢が若い : ~ 1.5 Myr
- 局部銀河群で最大の星団 : ~10^5 $M_\odot$
- 超大質量の星が存在

  265 $M_\odot$, 195 $M_\odot$, 175 $M_\odot$, 135 $M_\odot$ の星が存在 (Crowther et al. 2010)

銀河間潮汐相互作用による巨大星団形成の可能性

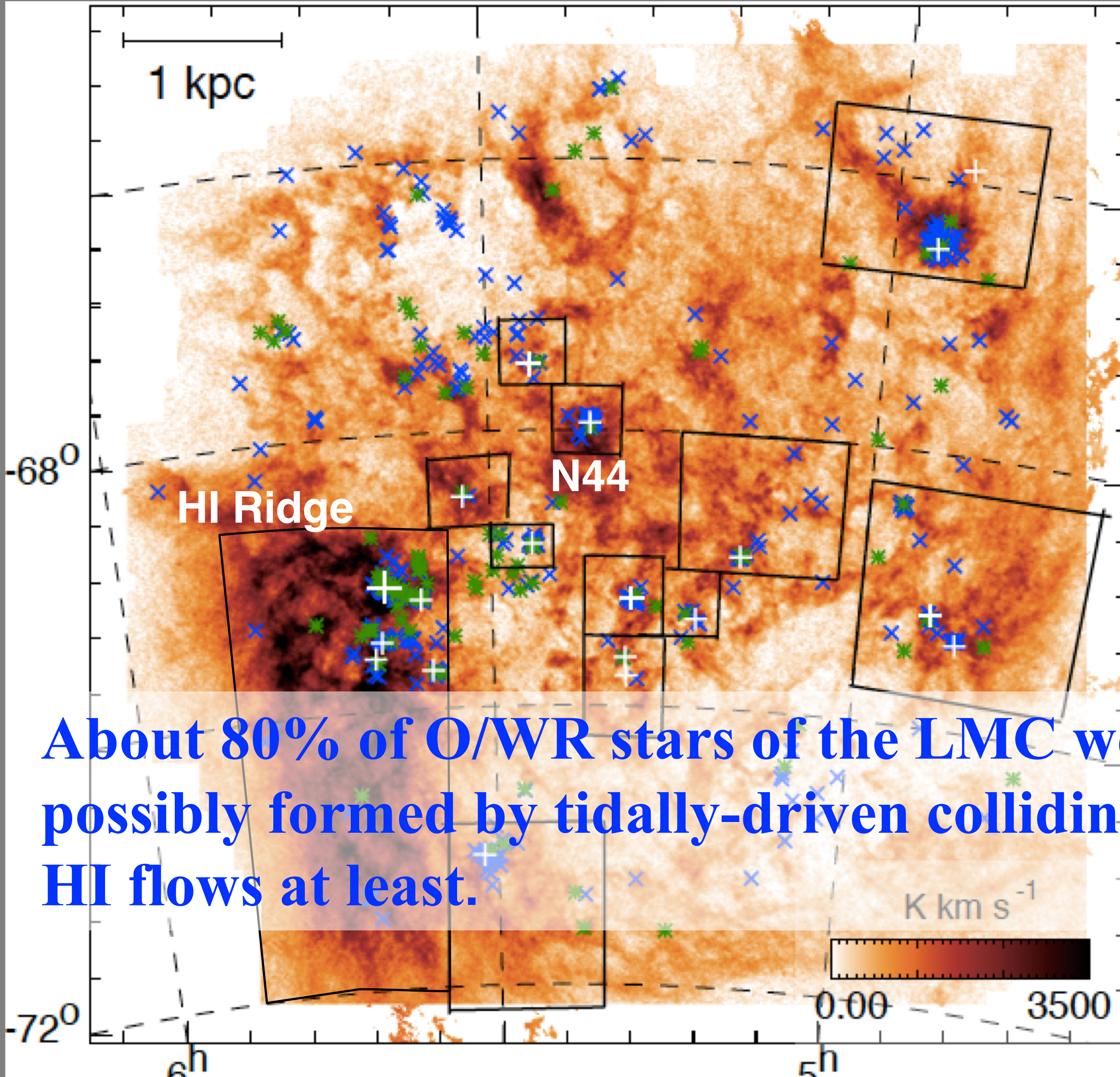


Fujimoto & Noguchi 1990
潮汐相互作用による
巨大星団形成を示唆.

- ~ 0.2 Gyr 前 LMC と SMC が近接遭遇

- LMC のガスの攪乱

O/WR star formation of the whole LMC



About 80% of O/WR stars of the LMC were possibly formed by tidally-driven colliding HI flows at least.

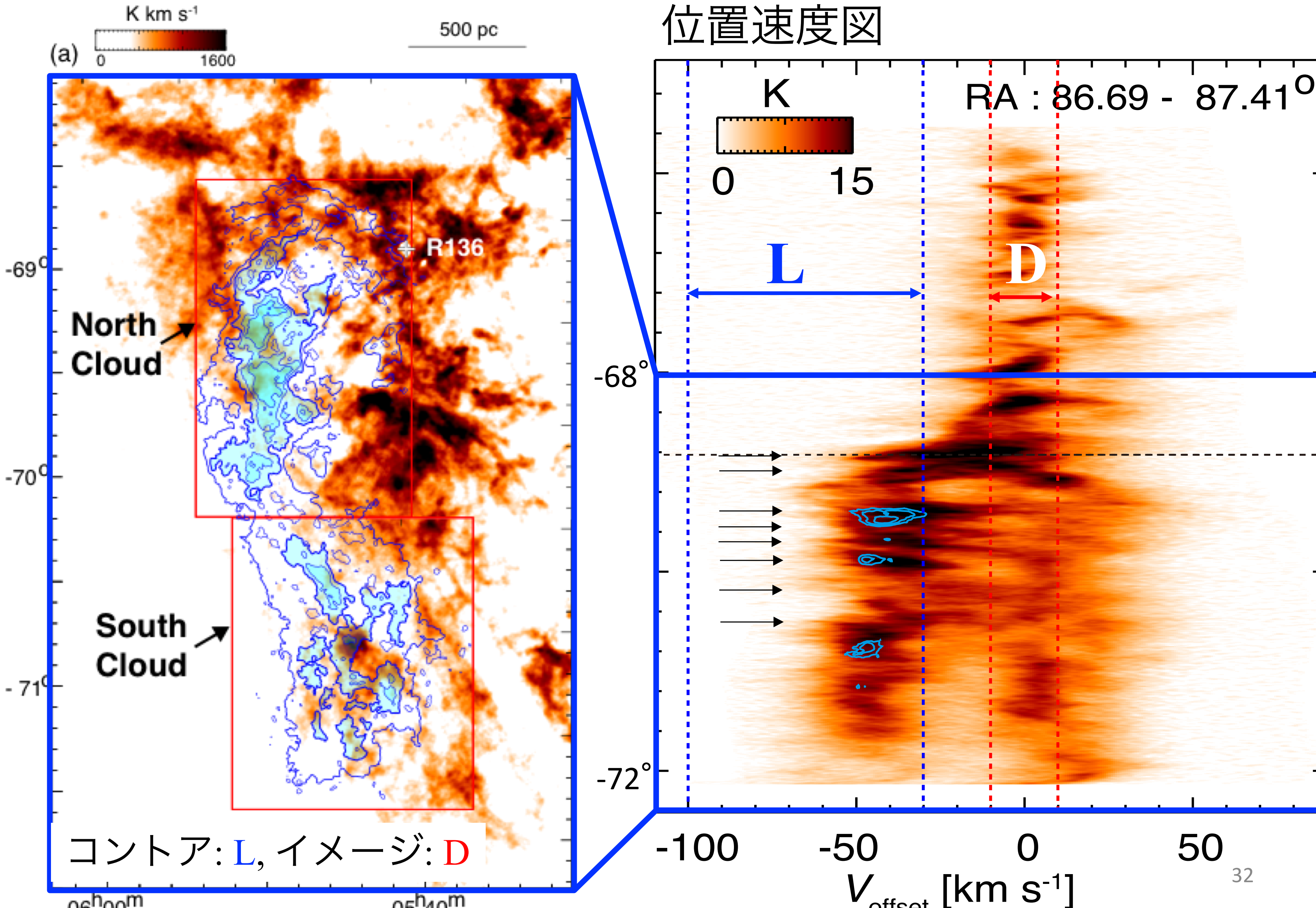
- Total number of O/WR stars ~ **700** (SAGE Meixner et al. 2006)
- O –type star ~ 600
- WR star ~ 100

- We analyzed 20 star forming regions

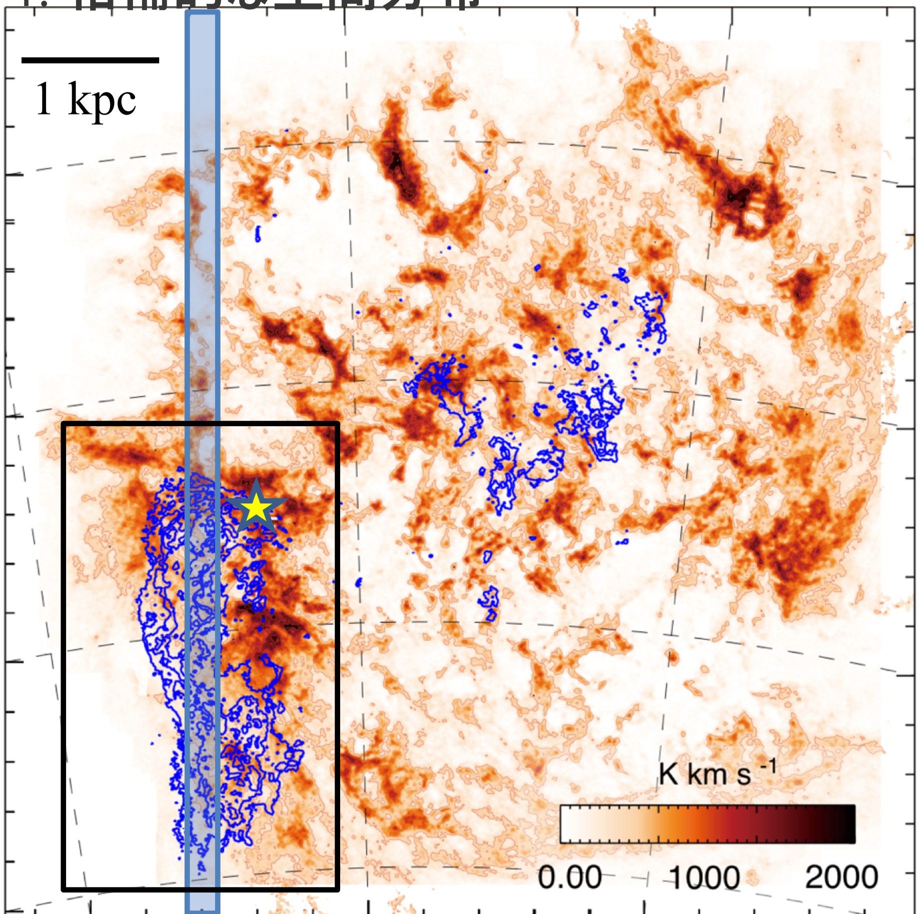
- **~ 560 O/WR stars** are possibly formed by the collision of HI flows caused by tidal interaction between the SMC and LMC.

× : O-type star
* : WR star

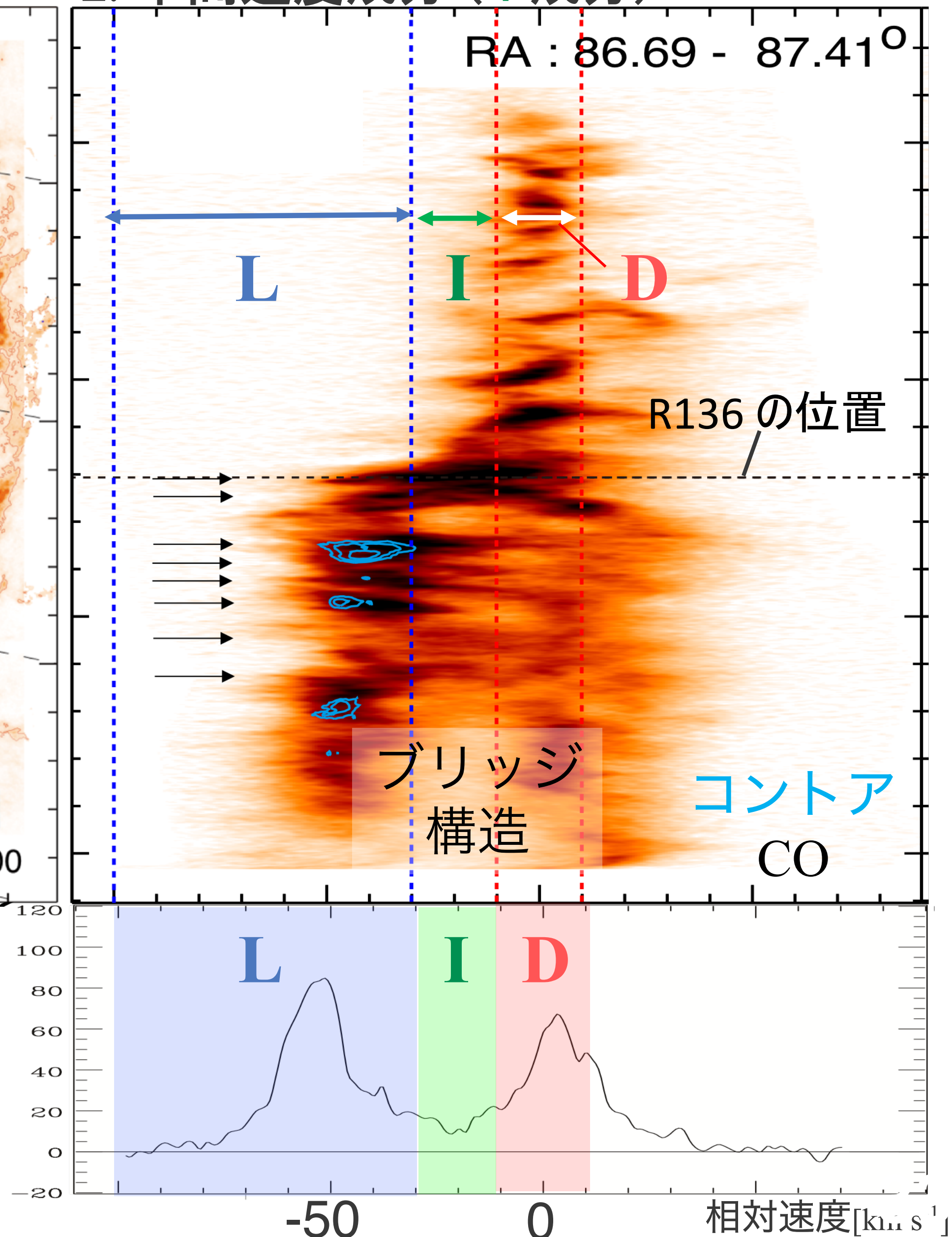
Collision of two HI components (Fukui+ 17)



1. 相補的な空間分布



2. 中間速度成分（I 成分）

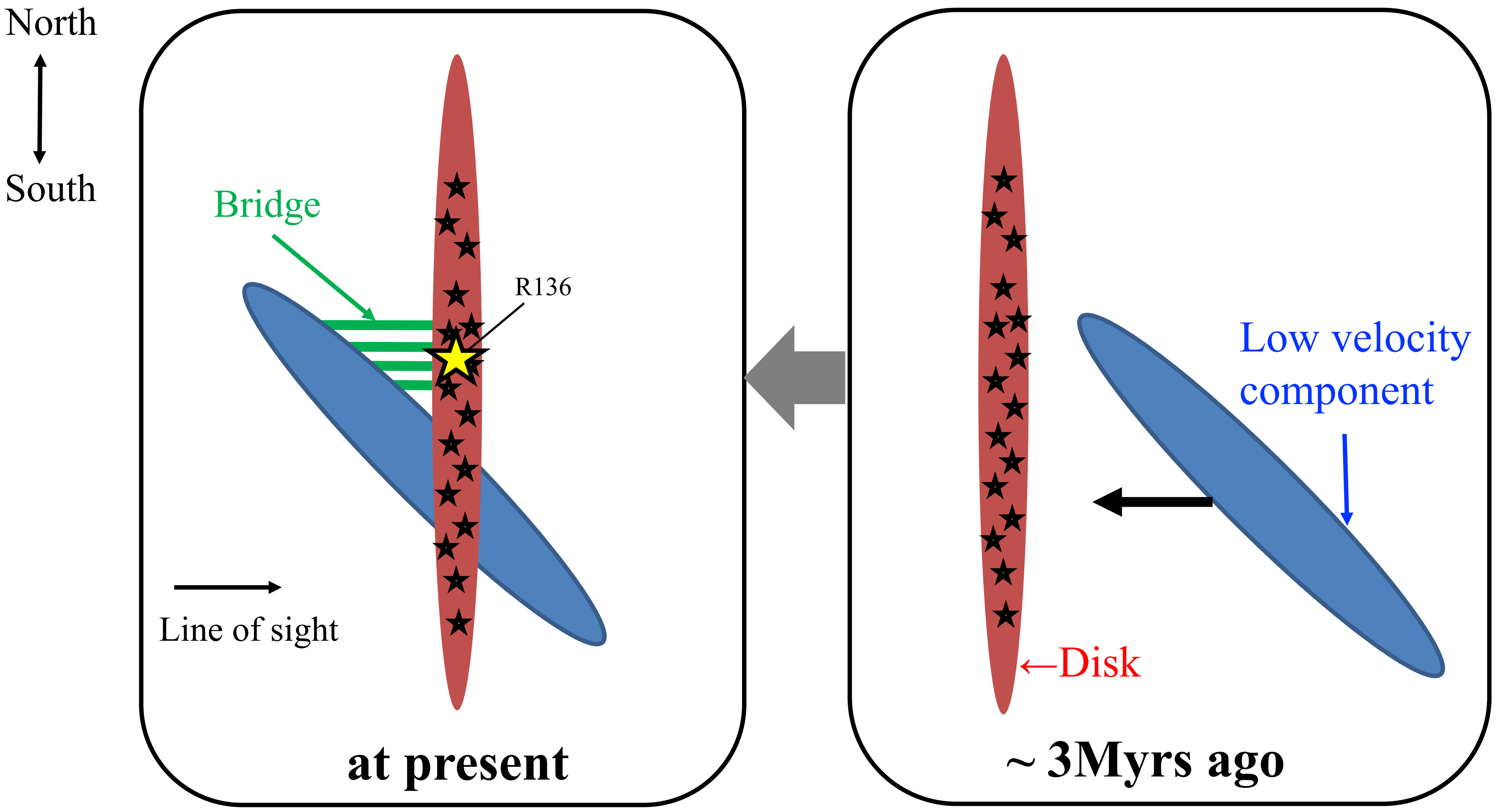


コントア: 低速度成分 L

イメージ: LMC のディスク成分 D

Fukui, Tsuge et al. 2017, Tsuge et al. 2019

Schematic diagram of the collision

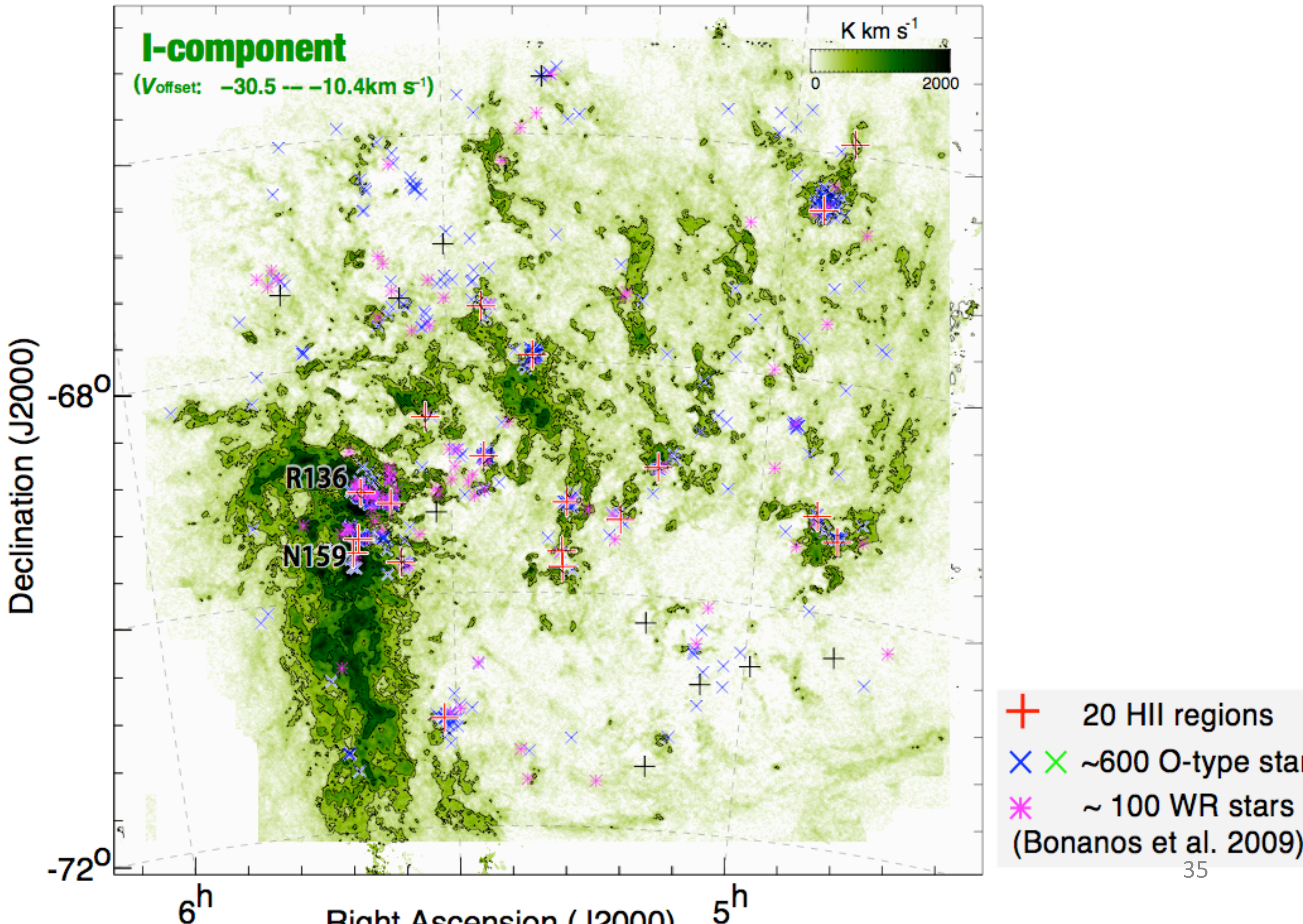


Scenario of the R136 formation (+ around massive stars)

Tidal interaction between the LMC and SMC 0.2 Gyr ago

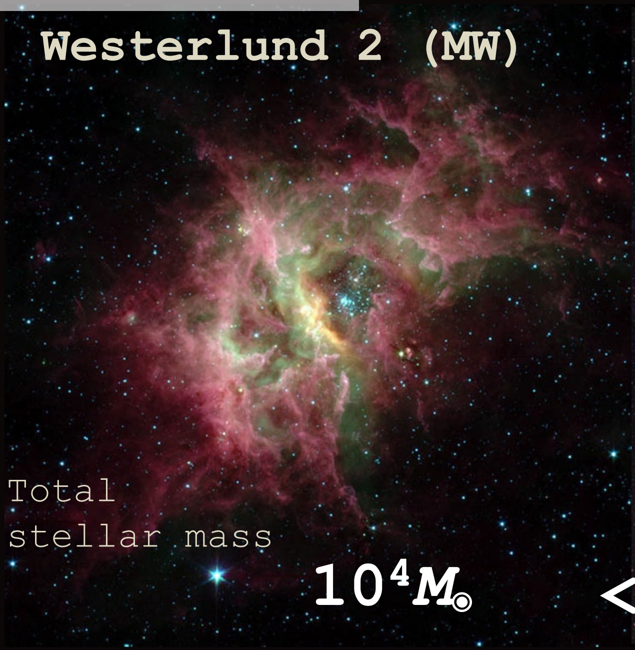
=> Collision of HI flow => massive star formation

中間速度成分 Tsuge+ 2019



Formation of massive star clusters

Superstar Clusters



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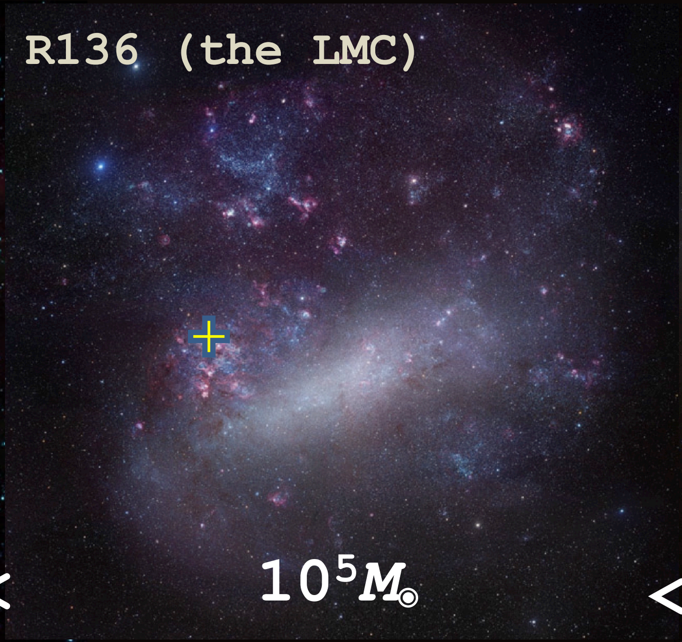

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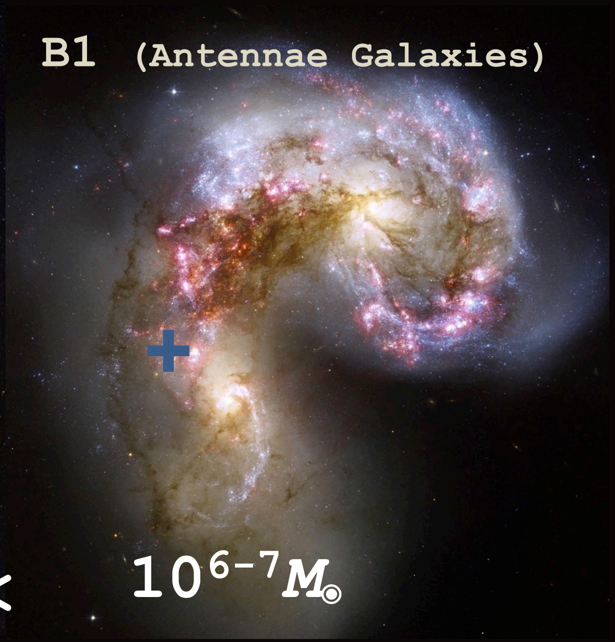
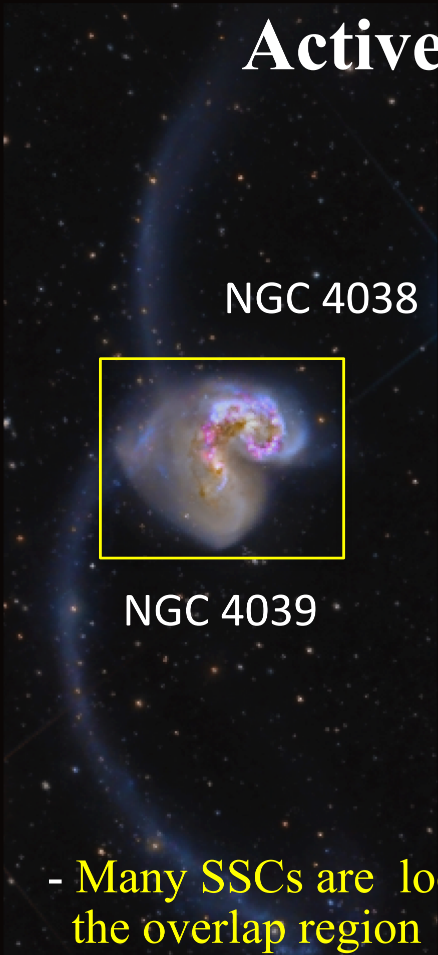


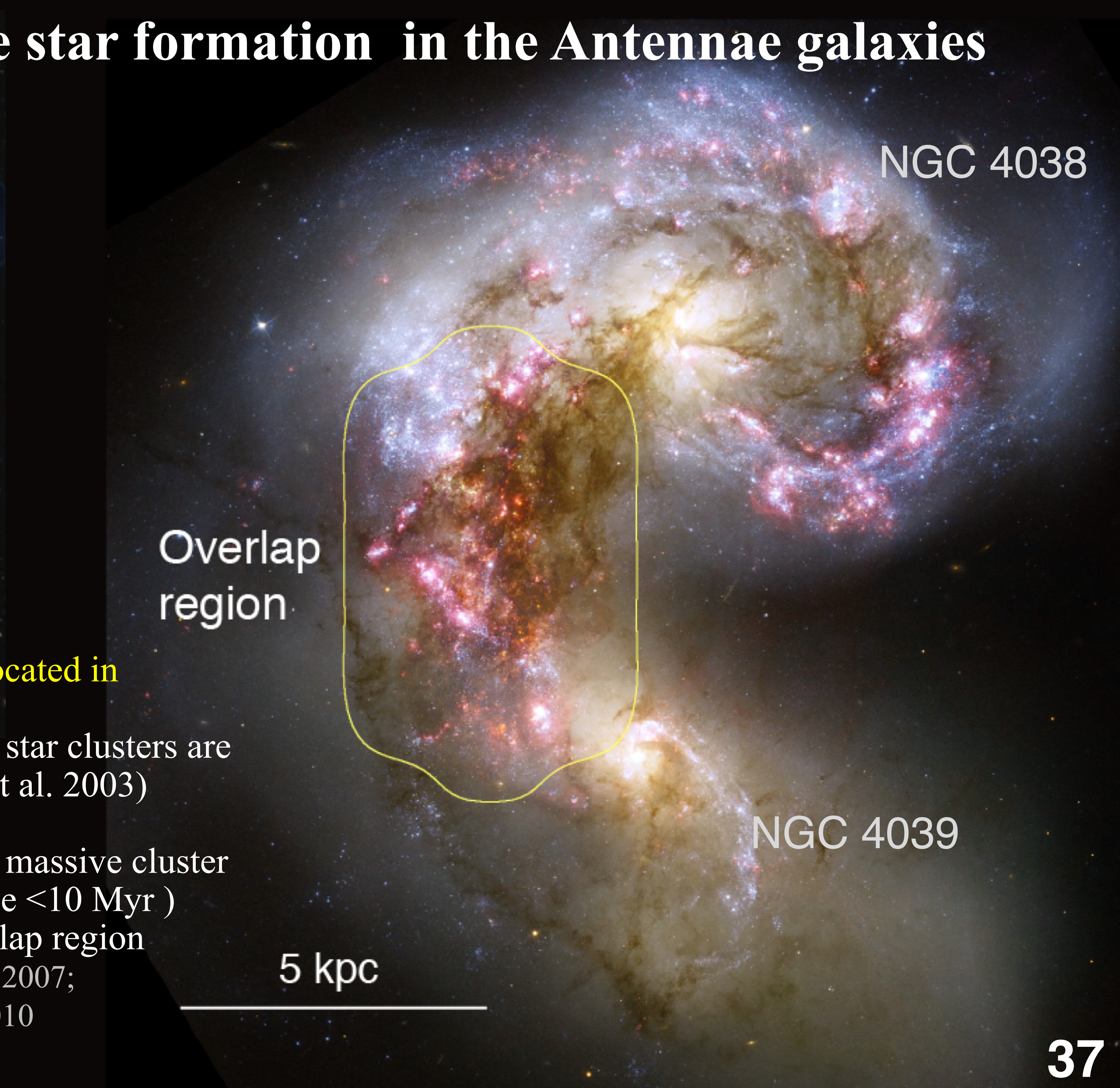
Staller wind, strong UV, SNe, etc..

=> Significant influence on the interstellar medium.

It is important to understand the evolution of matter and the star formation history of the universe.

Active star formation in the Antennae galaxies

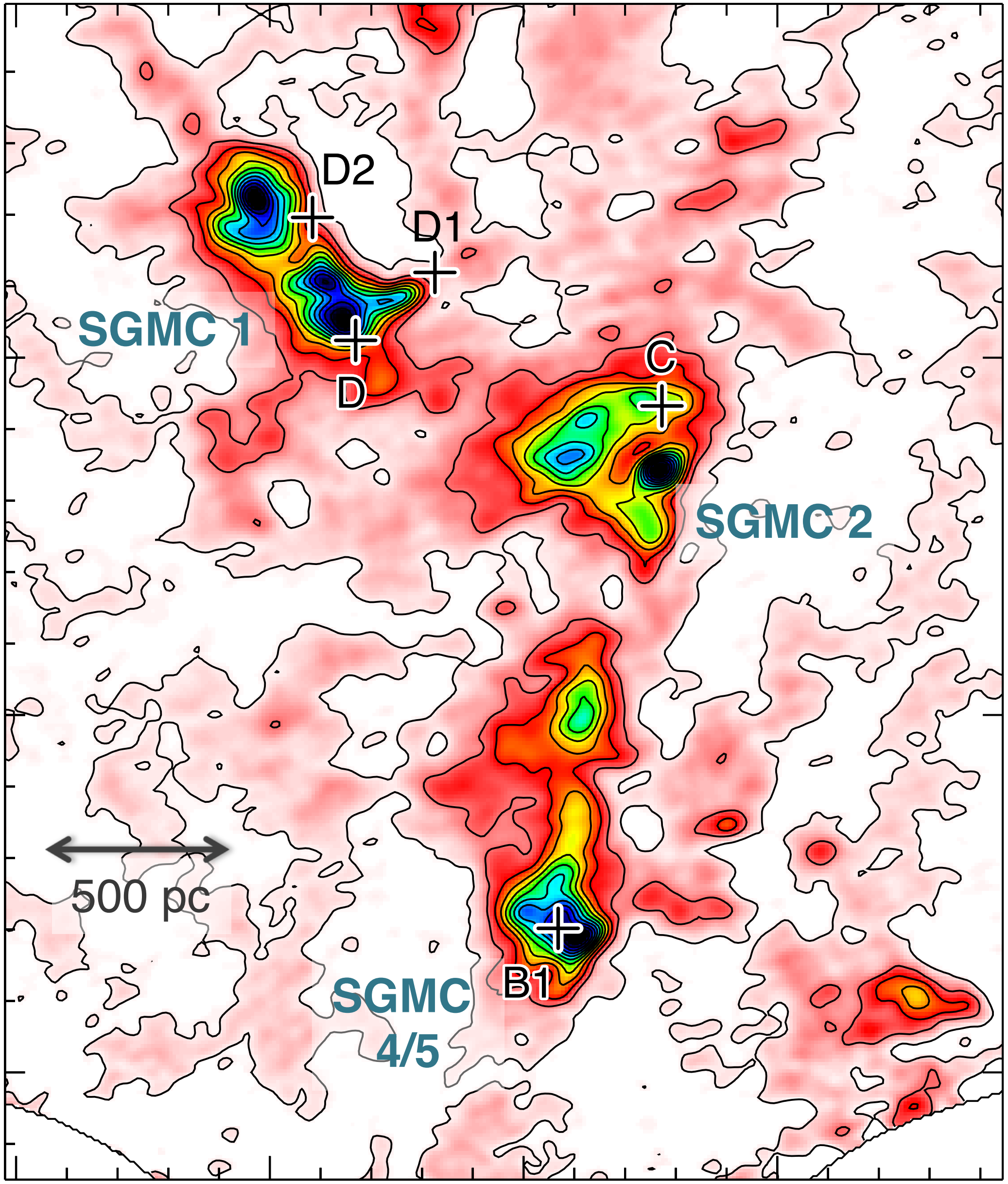




- Many SSCs are located in the overlap region
  (40% of youngest star clusters are located; Wilson et al. 2003)

- 5 out of 8 young massive cluster ($10^6 M_\odot$ > M , age <10 Myr) exist in the overlap region
  Gilbert & Graham 2007; Whitmore et al. 2010

Dataset: ALMA ^{12}CO (3-2) Tsuge+ 2019



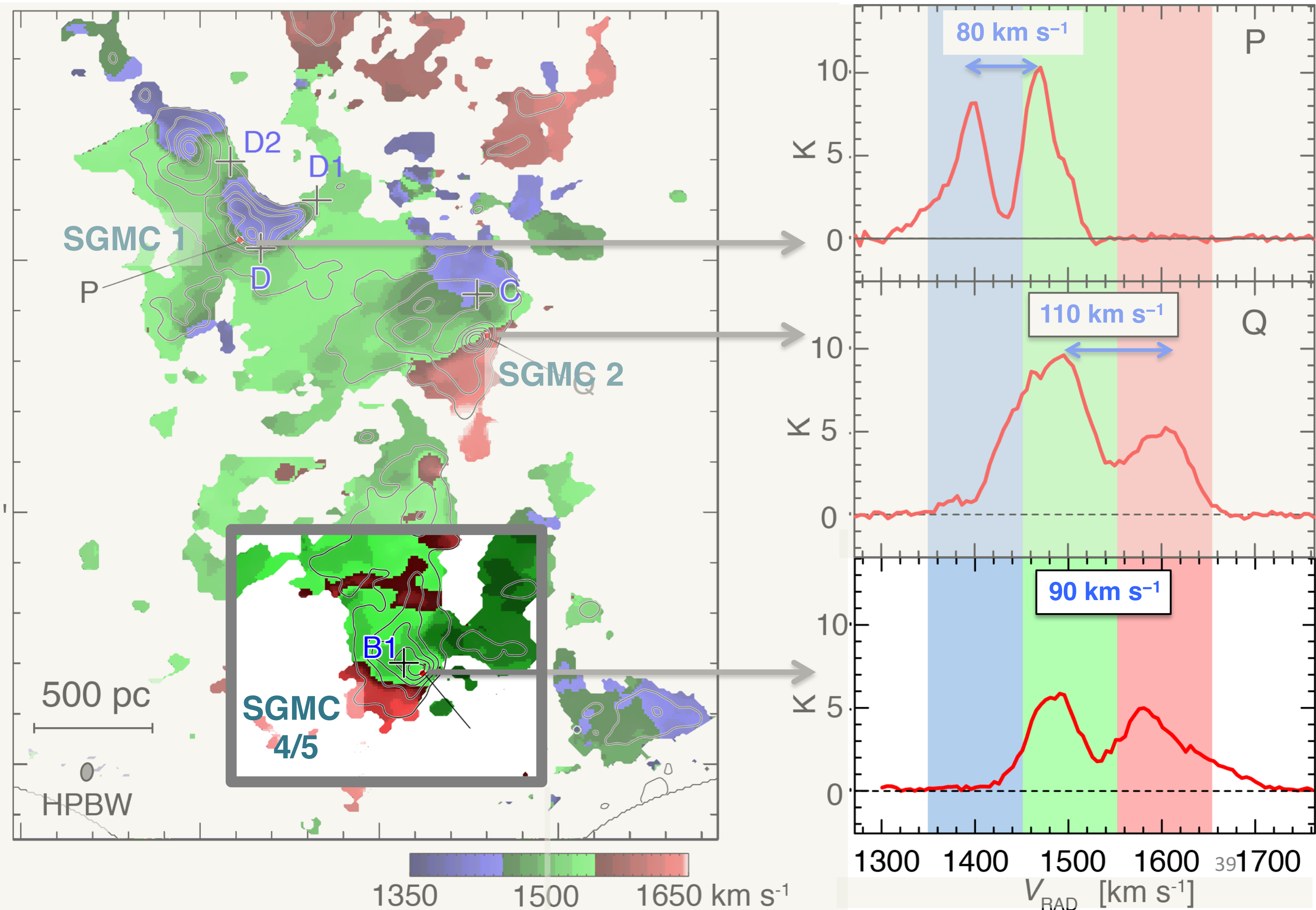
SGMC: Super Giant Molecular Complex

We reduced the archival ALMA data using the multiscale clean procedure.

ALMA cycle0, Band 7 (345 GHz)	
project	2011.0.00876
Angular resolution	~ 0.”70 x 0.”46
Spatial resolution	~70 × ~50 pc
Velocity resolution	5.0 km s^{-1}
1σ RMS at velocity resolution	~ 4.8 × 10^{-3} Jy/beam
reference	Whitmore et al. 2014

Recover extended emission, reducing negative level structures

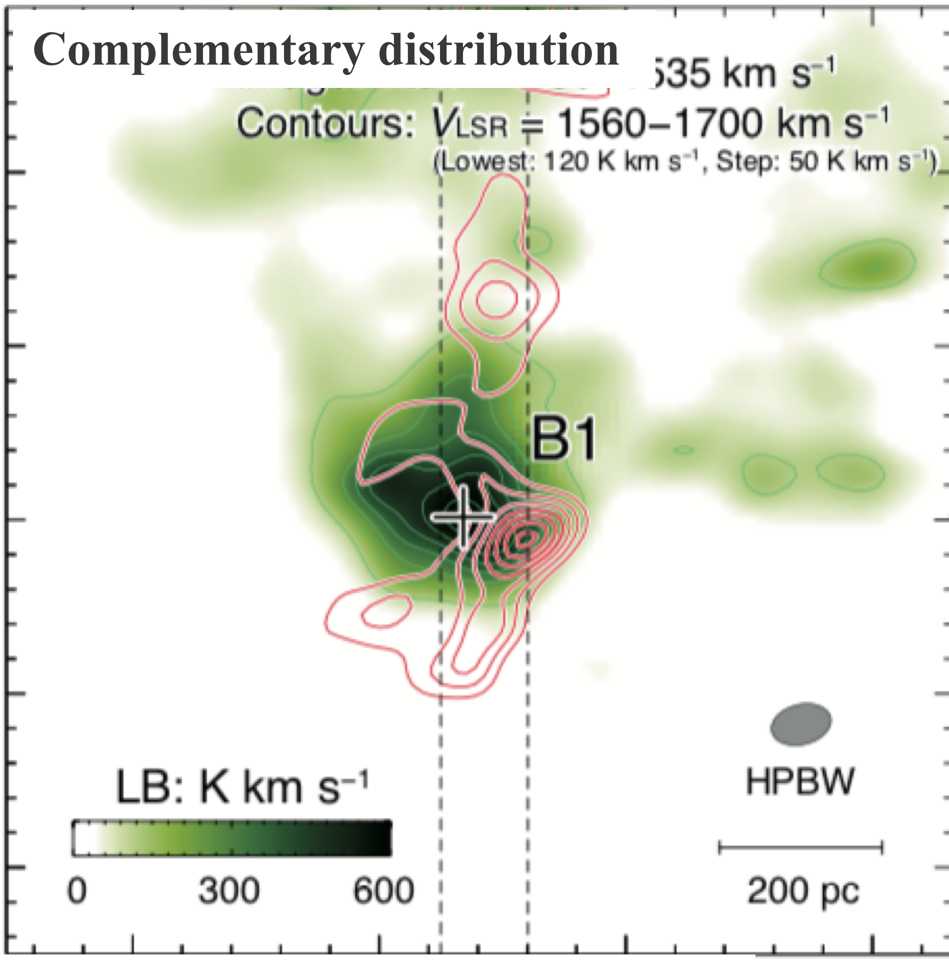
Velocity distribution

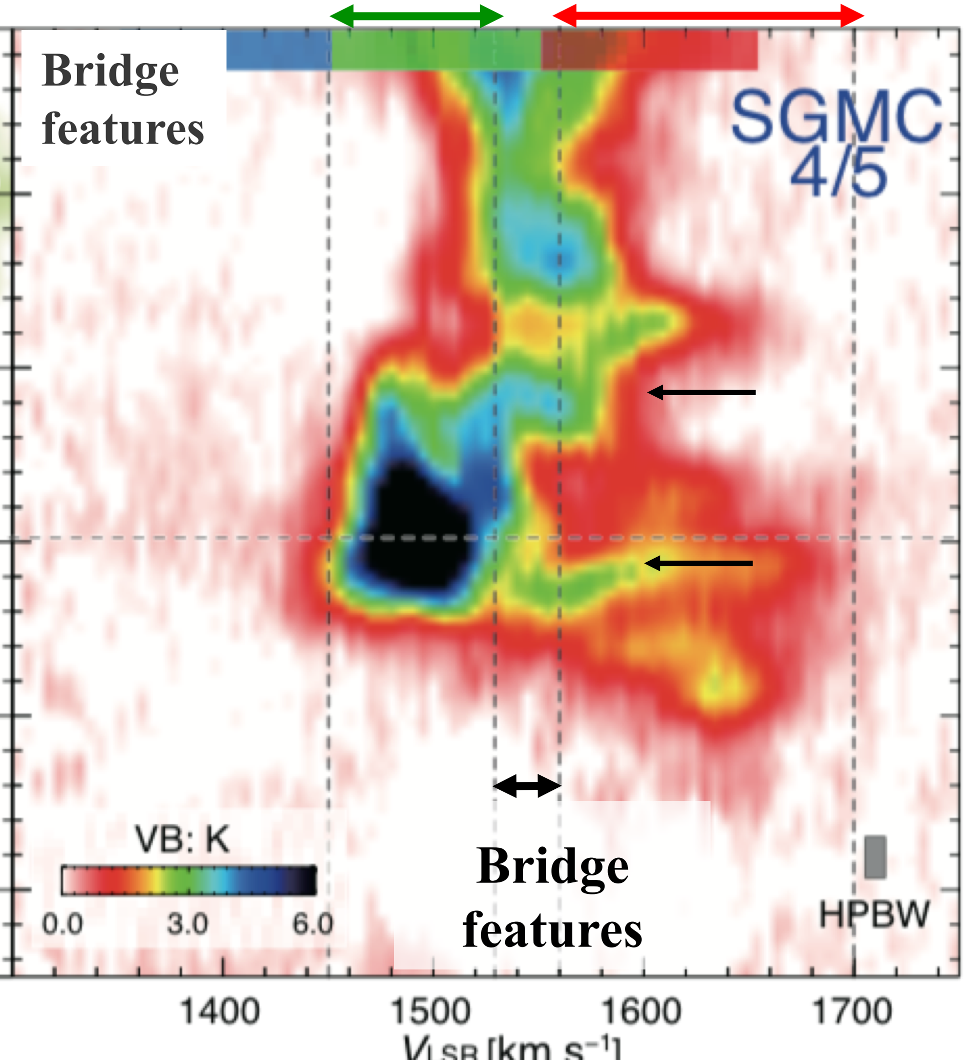


Discussion: cloud-cloud collision toward SSC B1

- Observational signatures of the cloud-cloud collision

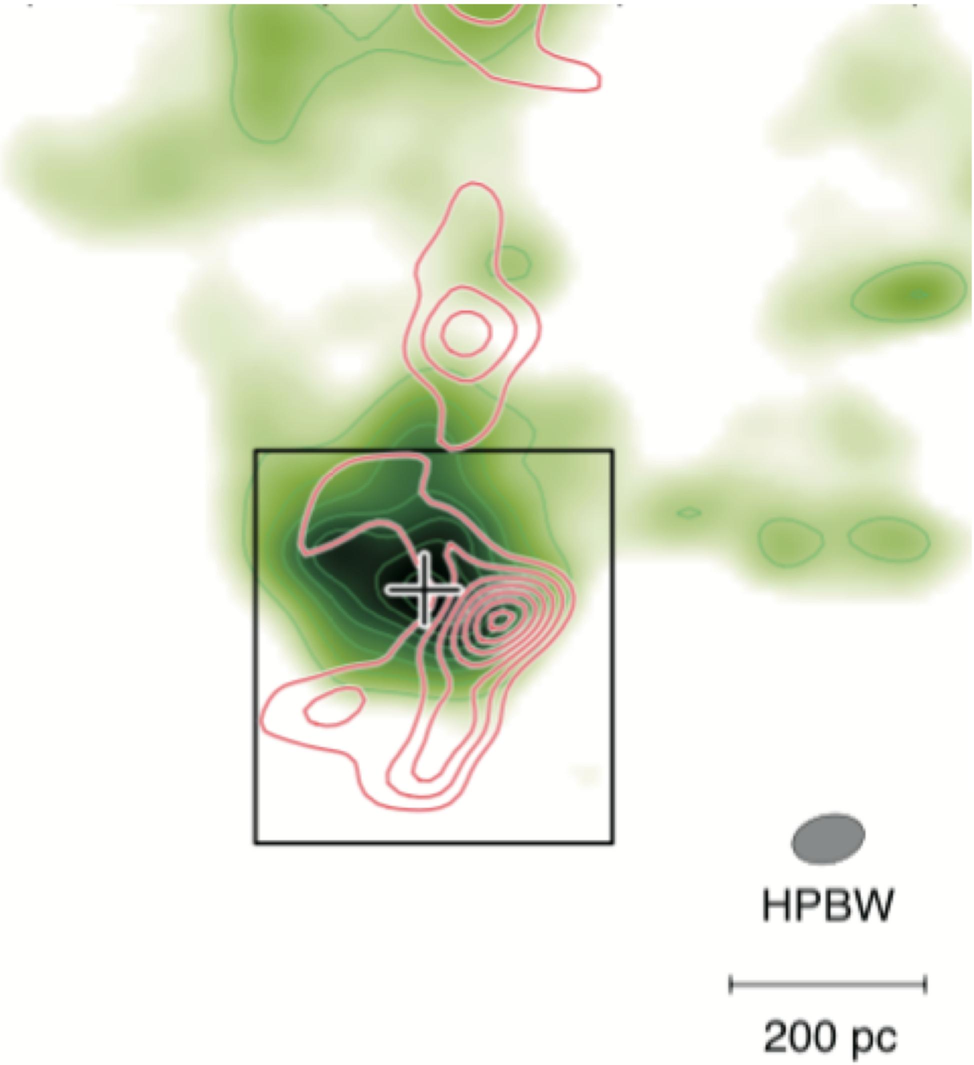
Observation: Furukawa et al. 2009 ; Ohama et al. 2010 ; Fukui et al. 2014 , 2015 , 2016 , 2017 ; Torii et al. 2011 , 2015 , 2017 ;Saigo et al. 2017, etc… , Numerical calculation; Habe & Ohta 1992; Anathpindika 2010; Takahira et al. 2014



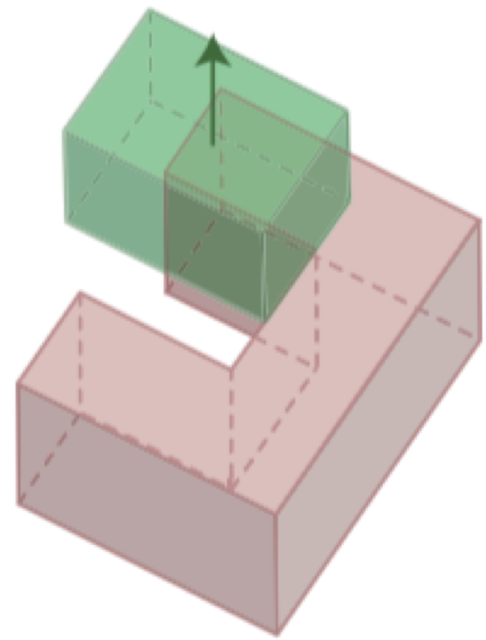


Discussion: Time scale of collision

Relative motion of two velocity components have inclination angle to the line of sight



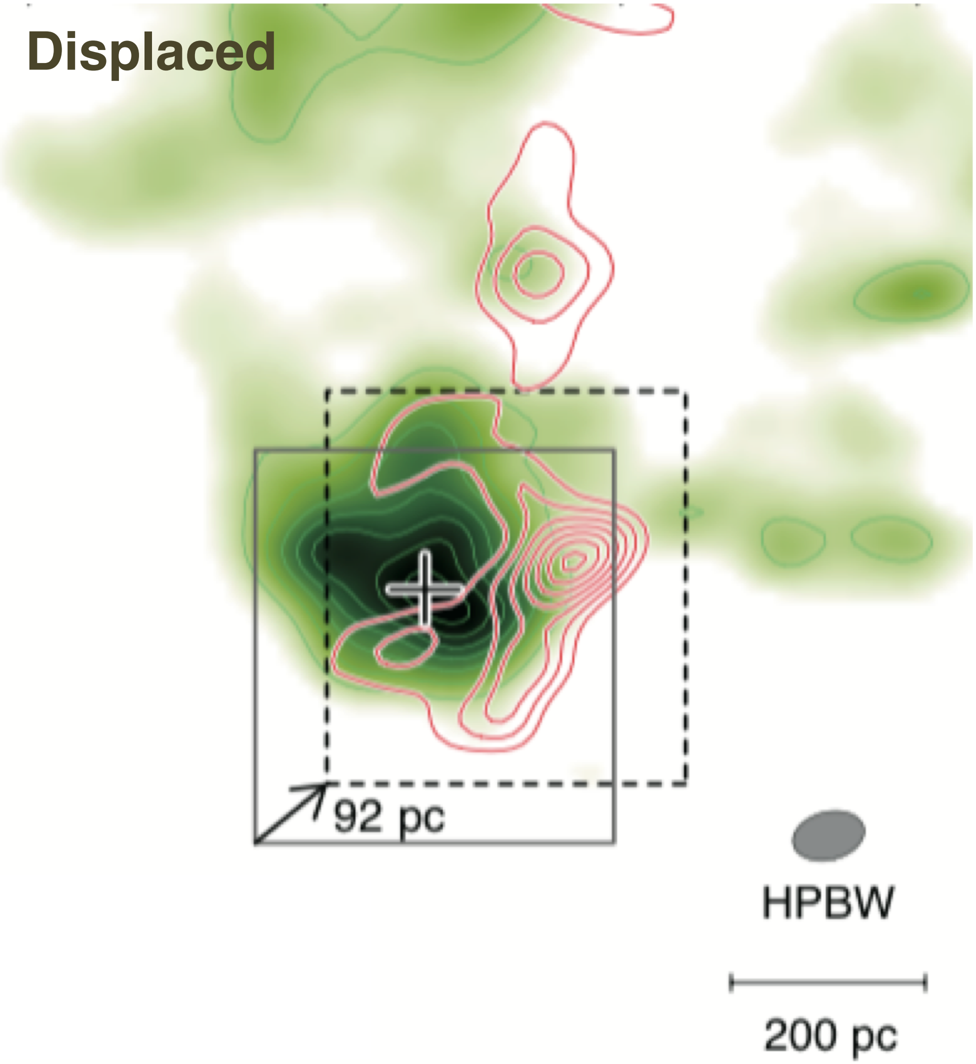
After collision



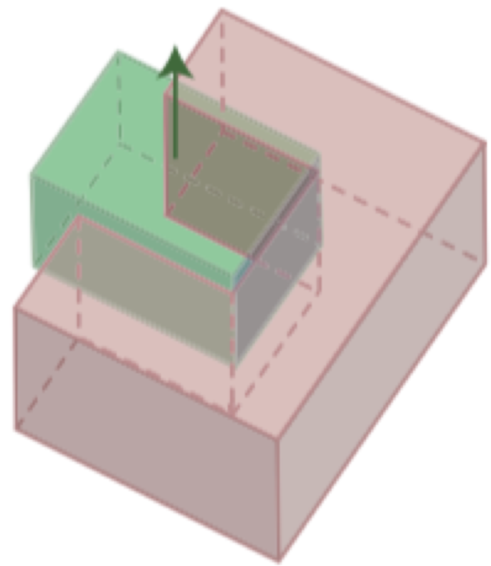
Discussion: Time scale of collision

Relative motion of two velocity components have inclination angle to the line of sight

Displaced

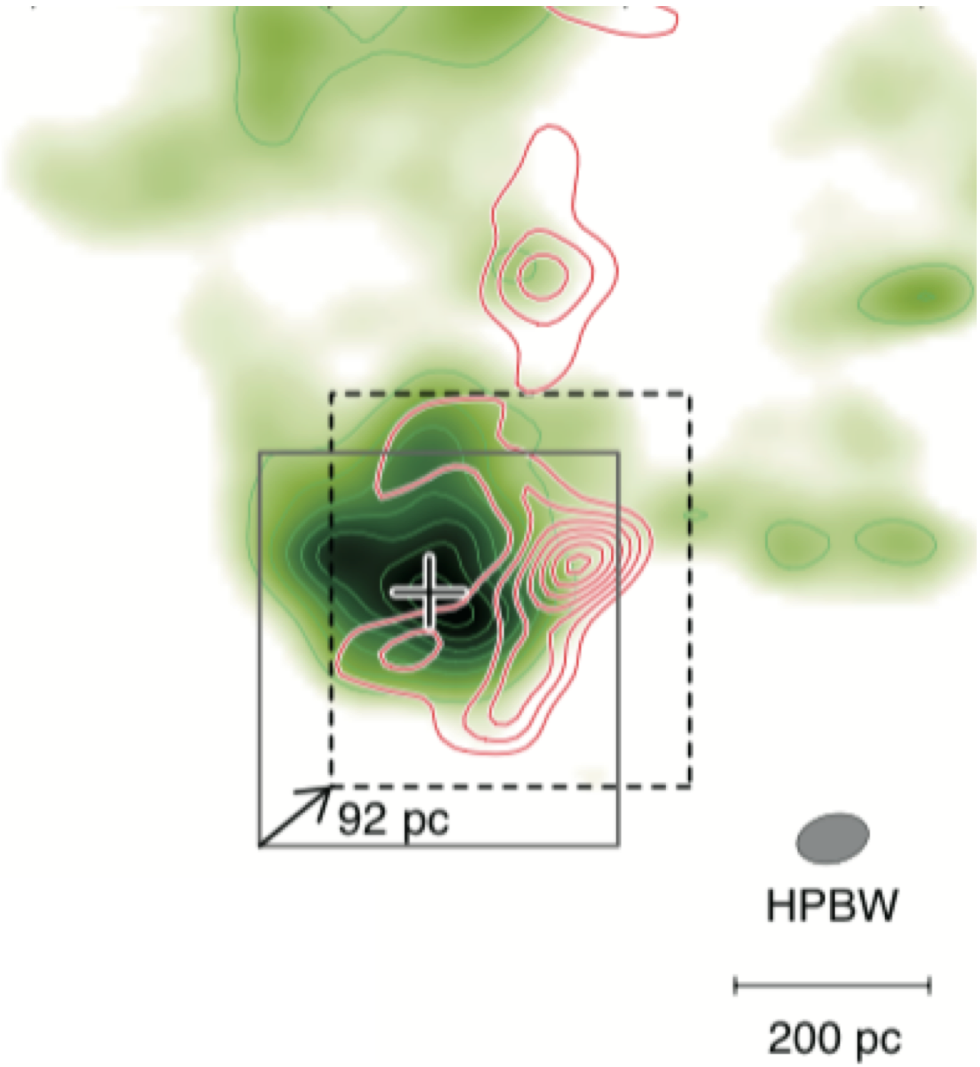


During collision



Discussion: Time scale of collision

The two velocity components with displacement of ~ 92 pc



Collision timescale: ~1 Myr

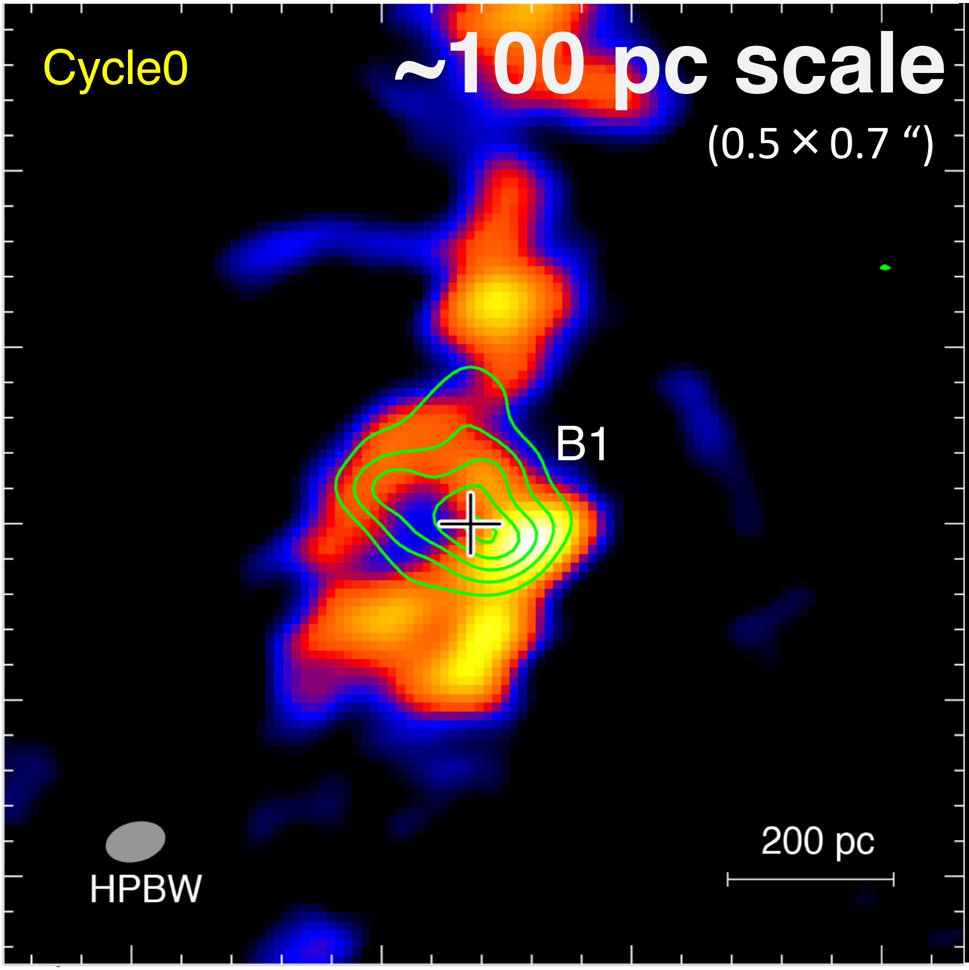
105 pc / 113 km s^{-1} = 0.9 Myr

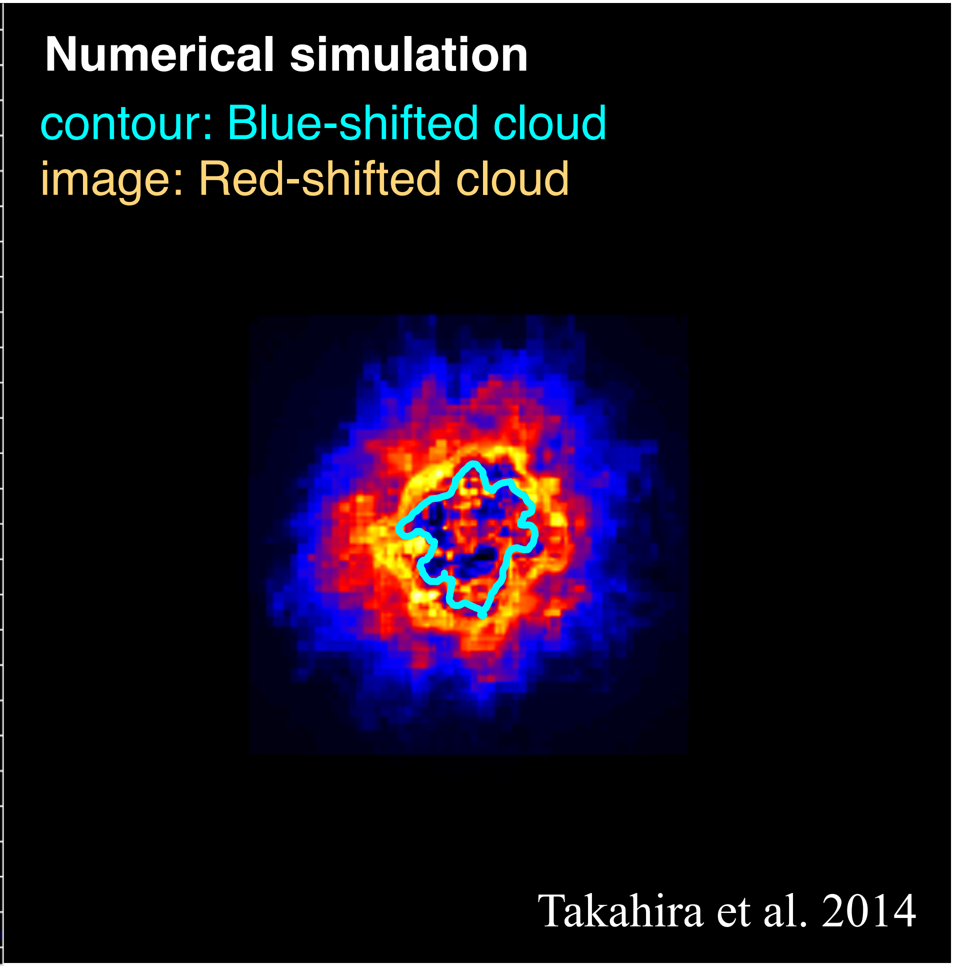
The angle of the relative motion to the line of sight is assumed to be 45 °

Cluster age: ~ 1 Myr (Whitmore et al. 2010)

Collision time scale is roughly consistent with the cluster age.

Spatial resolution is insufficient





- High resolution better than 15 pc will be required (size of SSC <15 pc)
- Detailed complementary spatial distribution suggested by numerical simulation cannot be verified.

=> Uncertainty of estimation of the displacement distance and angle is large.

むすび

- 星間雲衝突によってO型星が形成されることが初めて観測的に立証された
- 現在の宇宙では、その他の大質量星形成機構は重要ではない
- 超音速衝突がガスの急速な圧縮を可能にする
- 超音速の実現は、銀河内の重力・銀河間の重力による加速による
- 球状星団形成にも波及する可能性が高い