Formation of Massive Star Clusters by Fast HI Gas Collision

Nagoya Univ. TA-Lab

Ryunosuke MAEDA

Collaborator　Tsuyoshi INOUE
Yasuo FUKUI

初代星・初代銀河研究会 2019.11.13

Young Massive Clusters (YMC)

What is YMC ?

- Typical mass & age
  $M \sim 10^4 \mathrm{M}_\odot \quad t_{\mathrm{age}} \lesssim 100 \mathrm{Myr}$
- Energetic interaction with interstellar matter (Supernova , UV radiation, stellar wind)
- Many stars packed in only a few pc scale

We don’t know high density star formation mechanism

✓ YMC

$M \sim 10^4 \mathrm{M}_\odot$
$R \sim \mathrm{pc}$

✓ Solar neighborhood

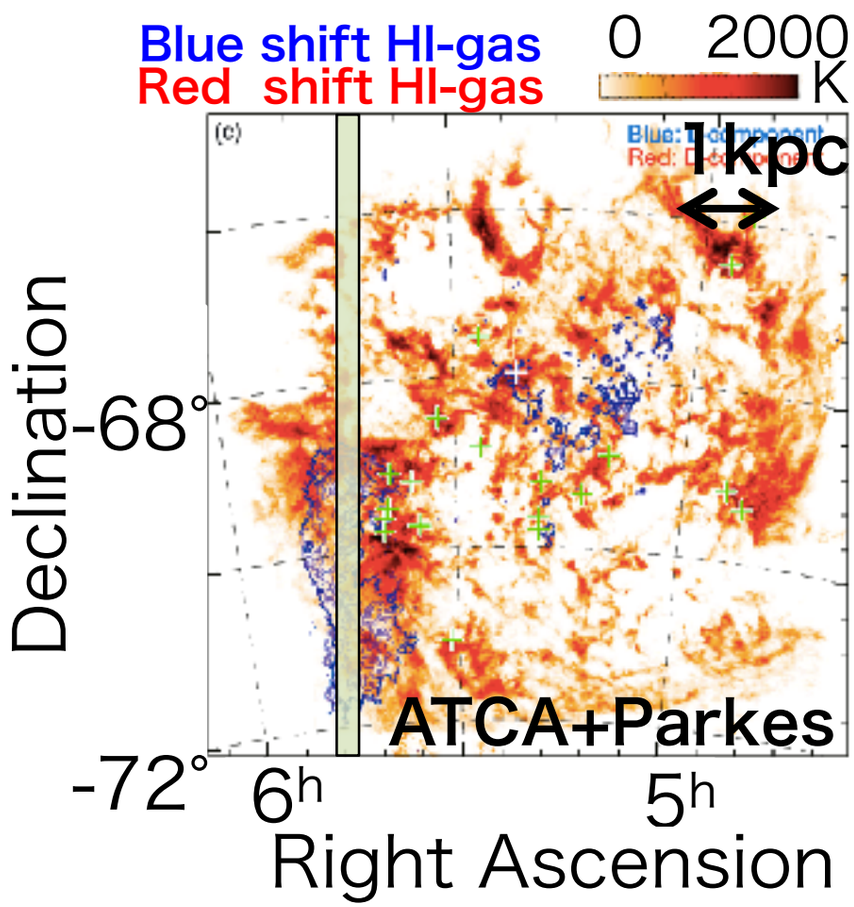
Nearest star
$\sim \mathrm{pc}$

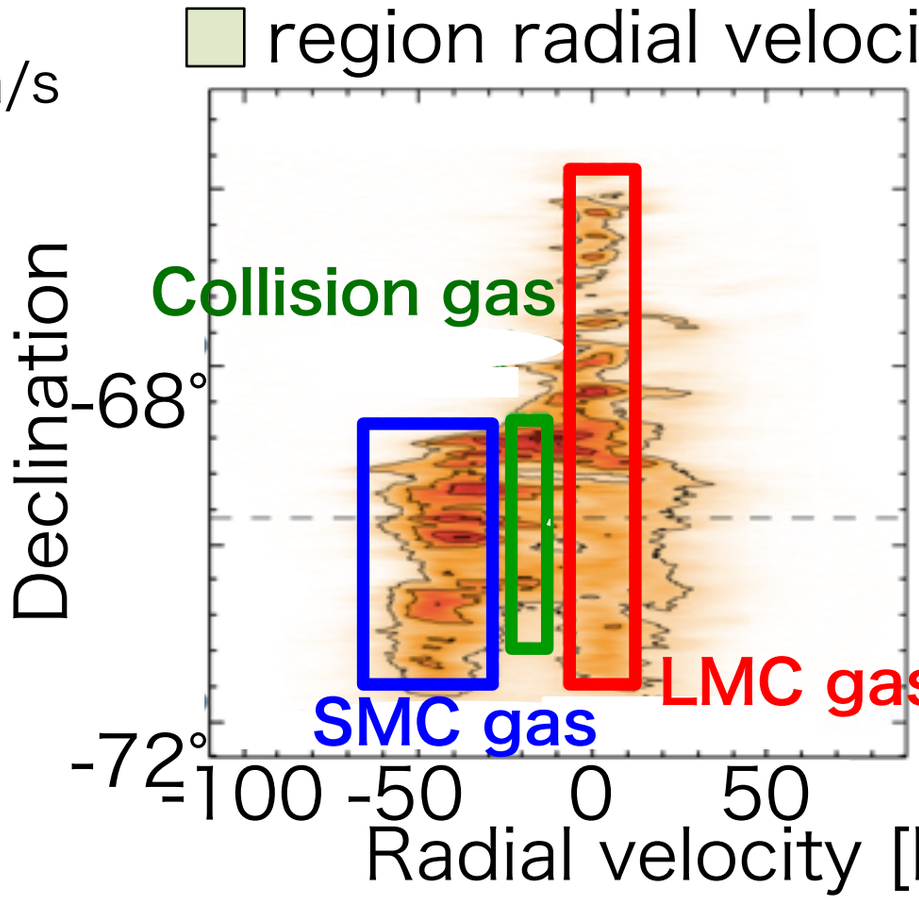
Recent observation suggest YMC formation by fast HI gas collision

Fukui et al. (2017), Tsuge et al. (2109)

Massive Star Cluster is Found in HI Gas Colliding Region

HI-gas map @LMC Fukui et al. (2017), Tsuge et al. (2019)





Suggestion

Relative velocity

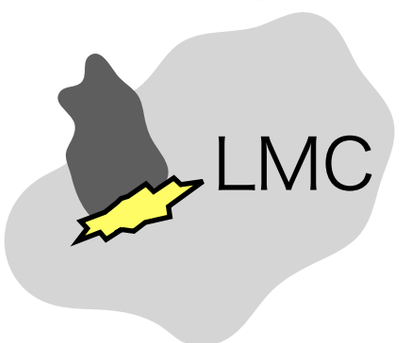
$\sim 100\ [\mathrm{km/s}]$

Super sonic

Bridge feature

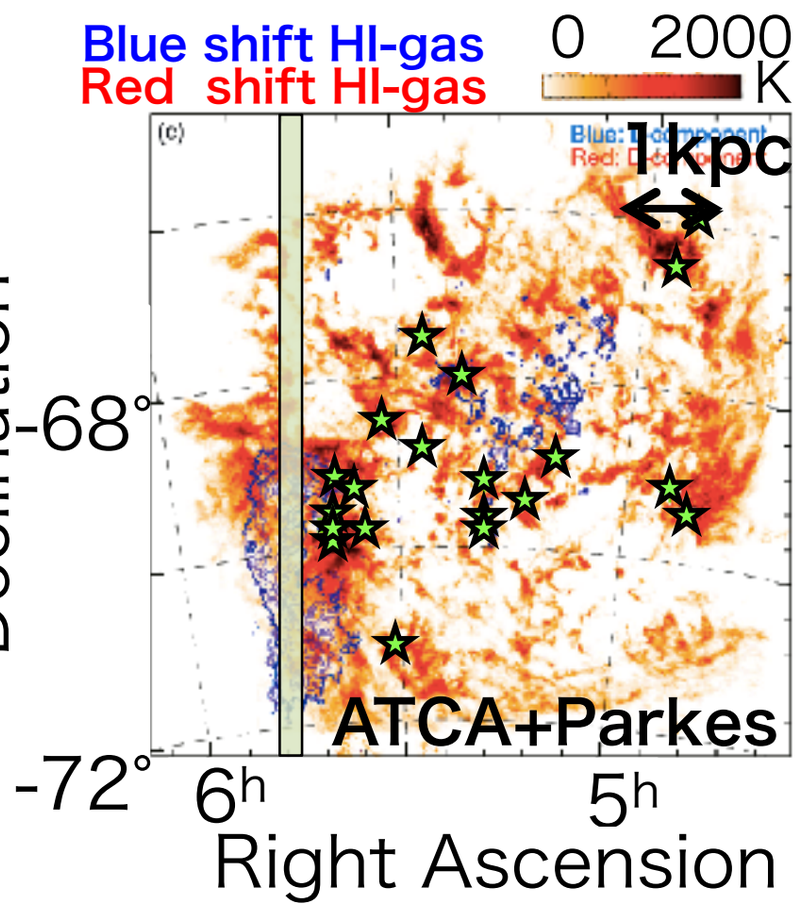
HI gas Collision

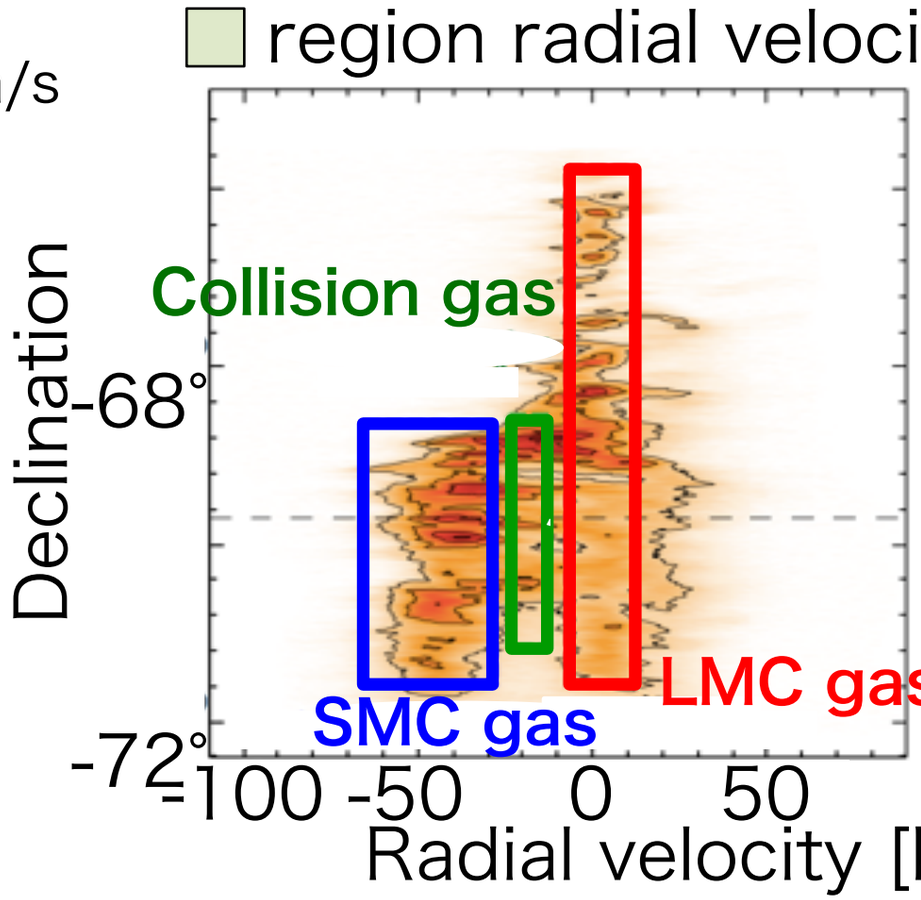
Situation



Massive Star Cluster is Found in HI Gas Colliding Region

HI-gas map @LMC Fukui et al. (2017), Tsuge et al. (2019)





Suggestion

Relative velocity

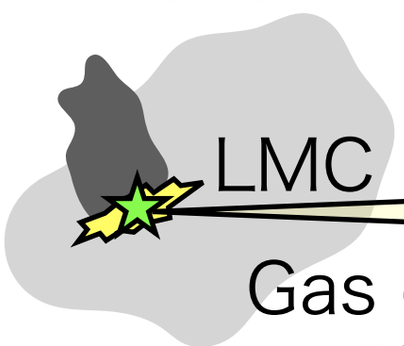
$\sim 100\ [\mathrm{km/s}]$

Super sonic

Bridge feature

HI gas Collision

Situation



YMCs in active star forming regions: ★

ex) ➢ R136 (YMC)

$M \sim 10^5 \mathrm{M}_\odot$

$R \sim 5\,\mathrm{pc}$

\+ N44…

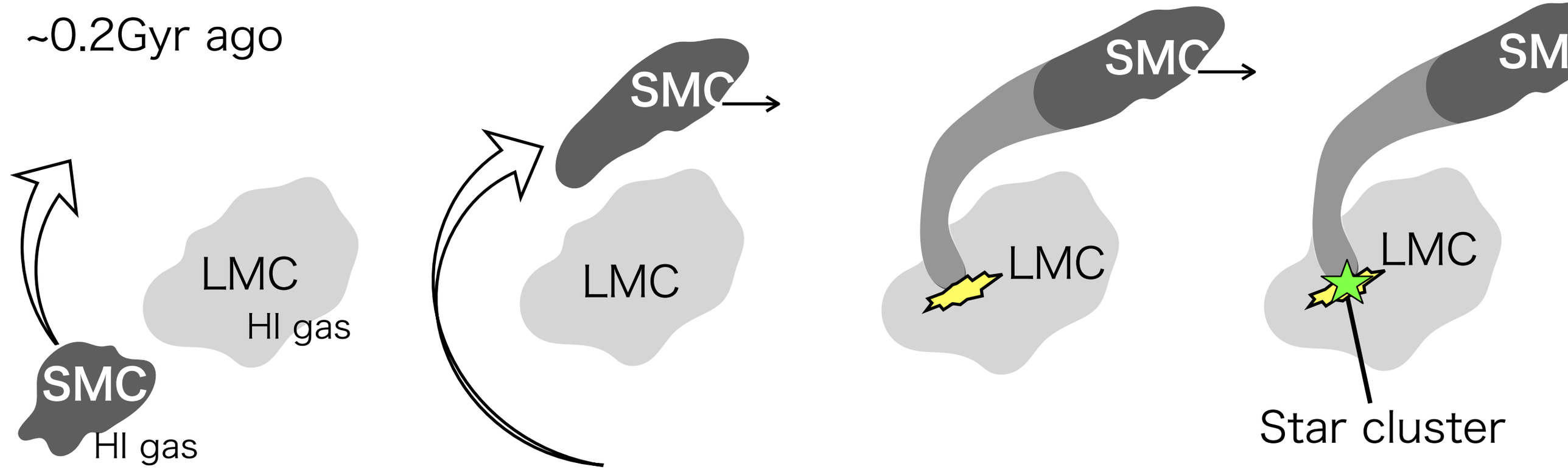
YMCs are formed at gas colliding region

Cluster Formation Scenario

Close Encounter of LMC & SMC　Fujimoto & Noguchi(1990)　Bekki & Chiba(2007)

Time

~0.2Gyr ago



Close encounter (LMC & SMC)

SMC Gas is stripped (tidal interaction)

Stripped gas fall down

Gas collision & Cluster formation

Fukui et al. (2017)

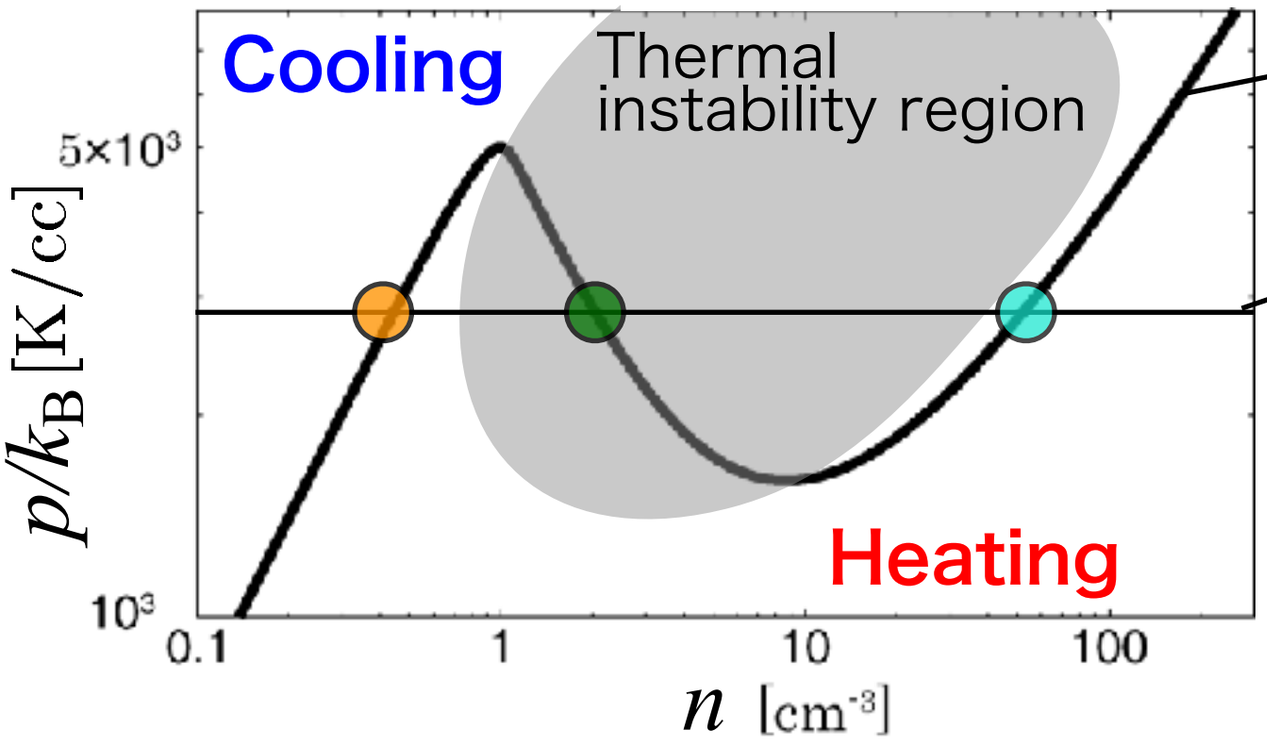
Suggestions

- HI gas falls down due to **close encounter of LMC & SMC**
- Fast(~100km/s) **HI gas collision** occur @LMC
- Massive **Star clusters are formed** in HI gas colliding region

We check this part using computer simulation

Cooling & Heating in The Interstellar Medium

Thermal equilibrium curve Wolfire(1995)



Cooling = Heating

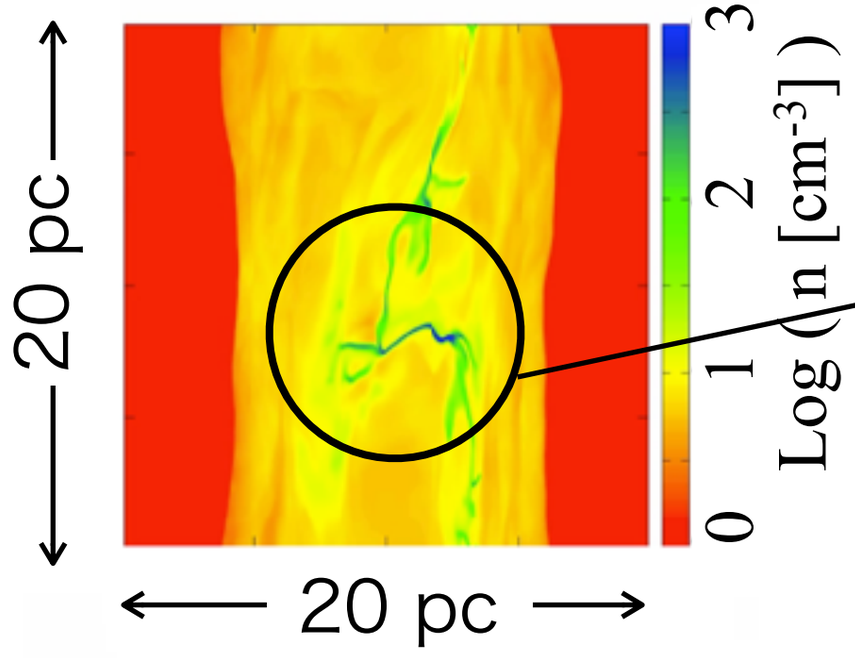
HI gas have 3(● ● ●)
Cooling = Heating point

- ● Cold Neutral Medium (CNM)
- ● Warm Neutral Medium (WNM)
- ● **HI gas goes to two stable phases**

→**Thermal instability** Field (1965)

MHD simulation of HI gas collision with cooling & heating

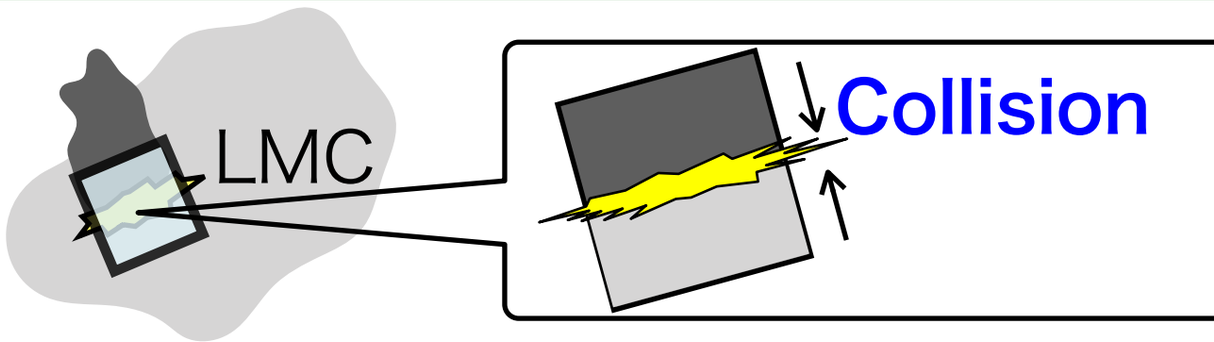
Inoue & Inutsuka (2009,2016)



HI gas goes to
two stable point(● ●) due to cooling

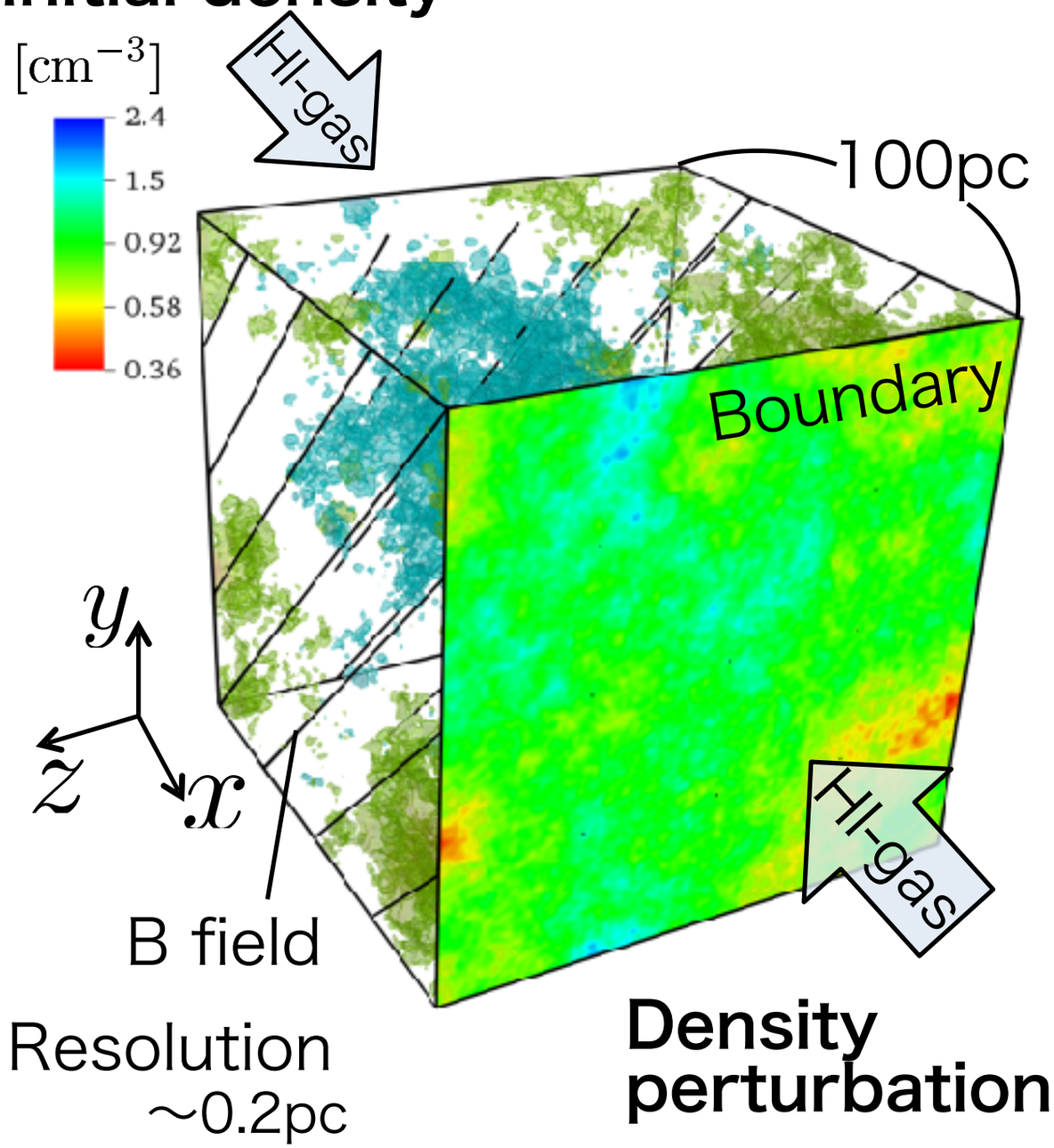
Thermal instability grows in shock compressed layer

Simulation Setup (Fast HI Gas Collision)



We focus on local colliding region
⟶Computer simulation

Initial density



Resolution
∼0.2pc

Density perturbation

Basic equations

Ideal MHD＋Heating & Cooling
＋Heat Conduction＋Self Gravity

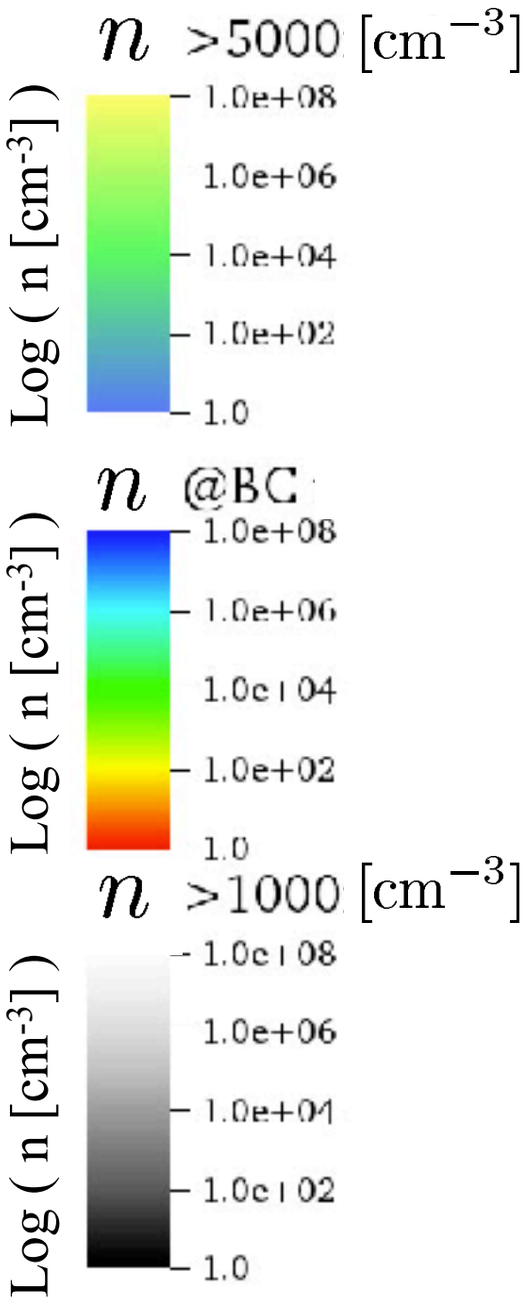
Boundary conditions

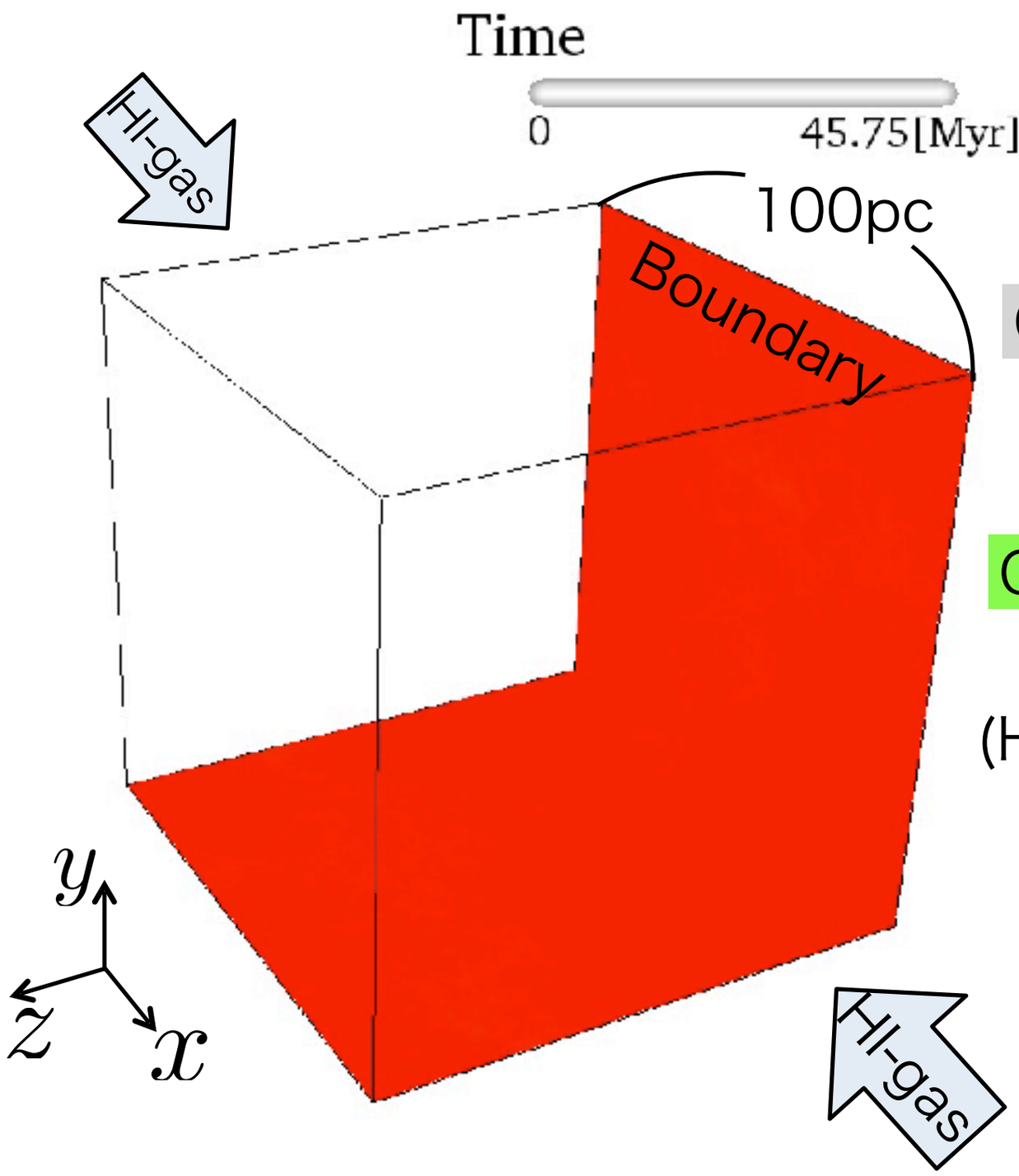
xy Plane	Continuous HI gas inflow
yz, zx Surface	Periodic Boundary

Initial conditions

$v_{\mathrm{rel}} = 100\mathrm{km/s}$: relative velocity
$n_0 \sim 1\ \mathrm{cm}^{-3}$: number density
$B_0 = 1, 3\ \mu\mathrm{G}$: magnetic field
$Z = 1, 0.2\ \mathrm{Z}_\odot$: metalicity

Simulation Result (Fast HI Gas Collision)





Gray region

> 1000 [cm^{-3}]

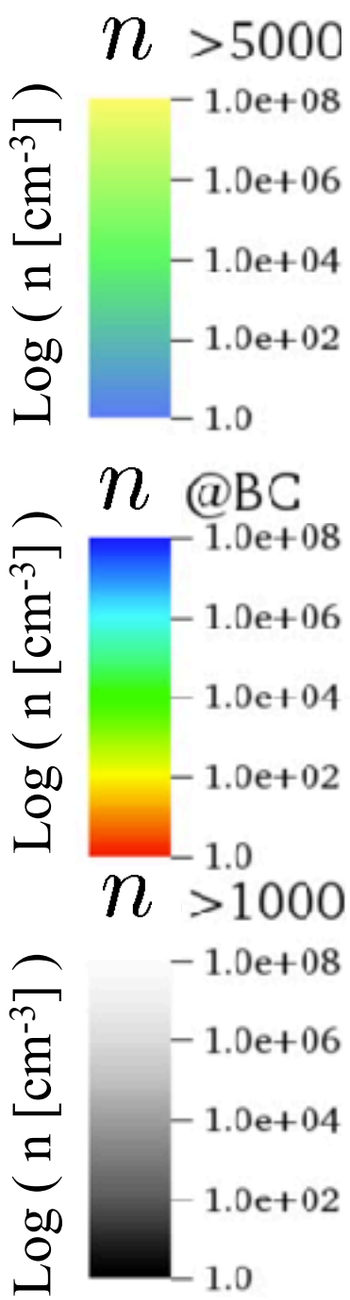
(High density region)

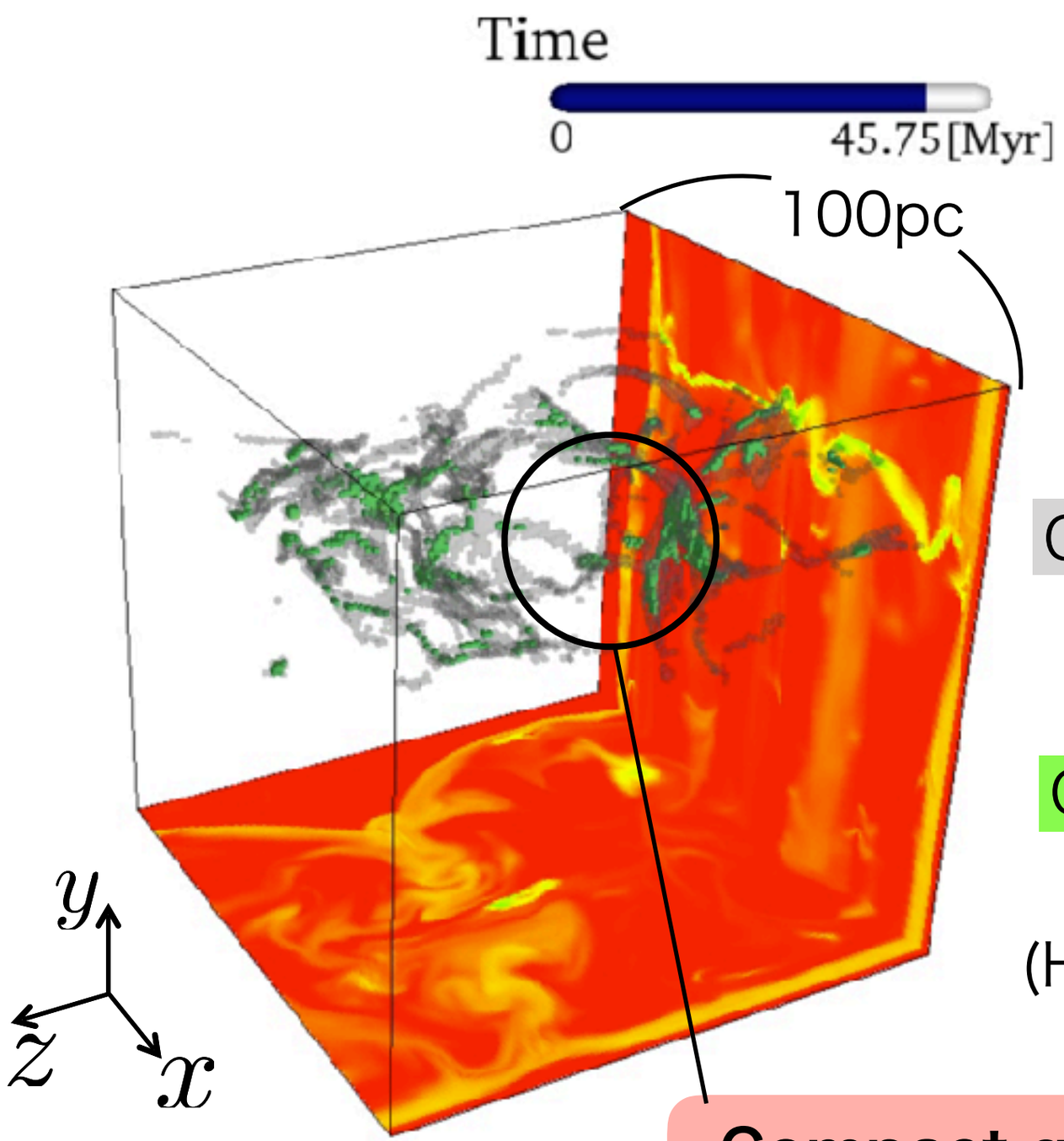
Green region

> 5000 [cm^{-3}]

(Higher density region)

Massive Clumps are formed @Shocked region





Gray region

> 1000 [cm^{-3}]

(High density region)

Green region

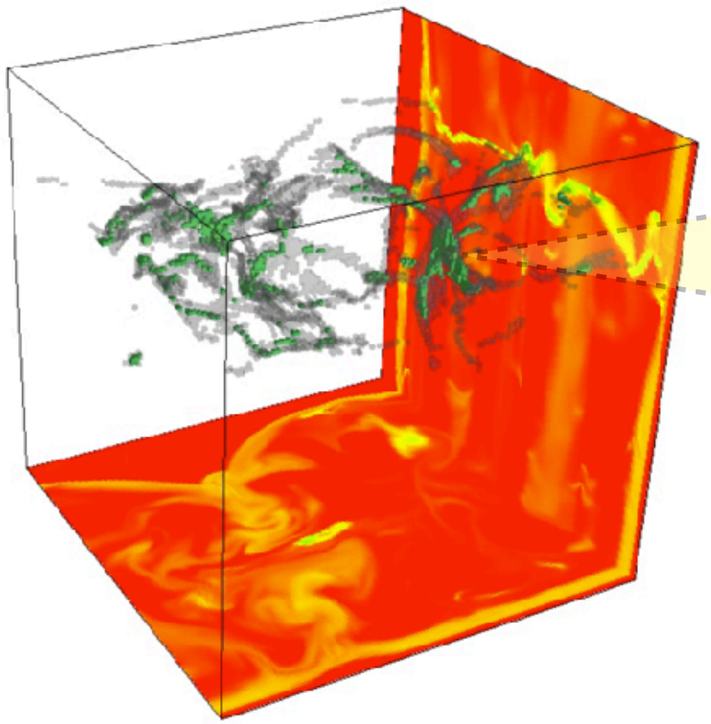
> 5000 [cm^{-3}]

(Higher density region)

Compact gas clump?

⟶ Detailed analysis

Gas clump in shock compressed layer



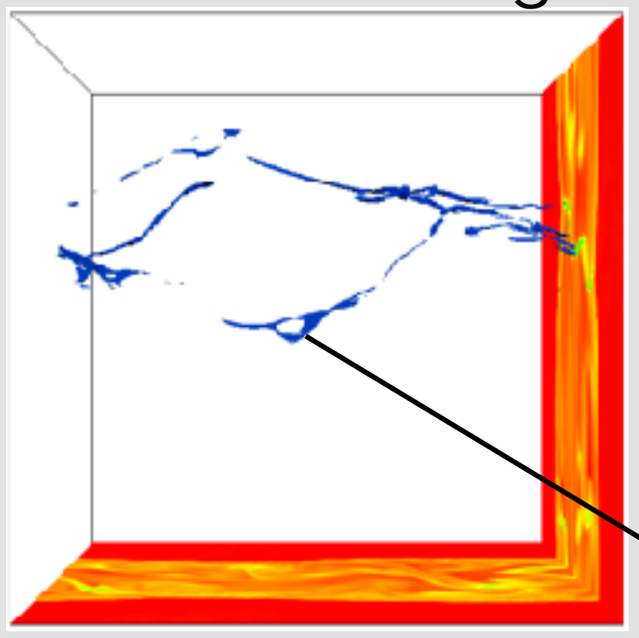
What is the gas that forms the star cluster?

Gas needs to be packed into a compact area before star formation occurs

➢ We identify dense gas clumps
➢ Is star formation is occurring at the clump

Dense clumps are identified by friend-of-friend algorithm

Trace dence region



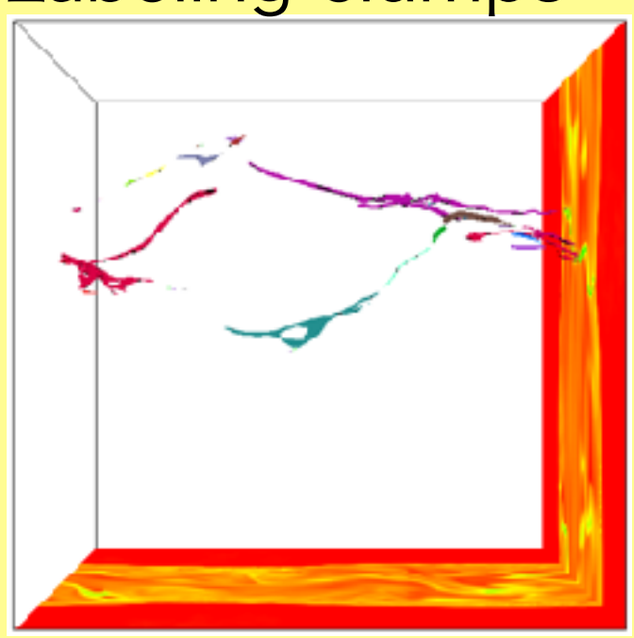
・Density threshold

$10^2, 10^{2.5}, 10^3, 10^{3.5}, 10^4$ $[\mathrm{cm}^{-3}]$

$n_{\mathrm{th}} = 10^4\ [\mathrm{cm}^{-3}]$

Labeling

Labeling clumps

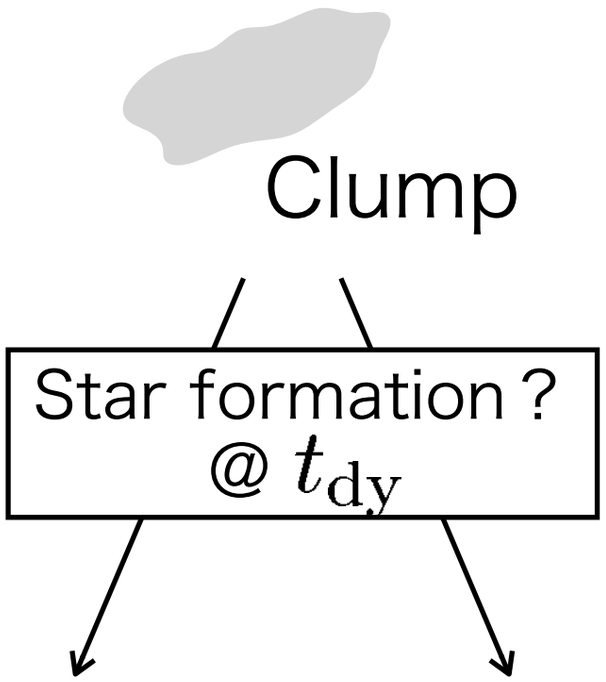


Color…Different clumps

Cluster forming clump

Analysis for identified clumps

Statistically estimation of stellar mass
(resolution～0.2pc)



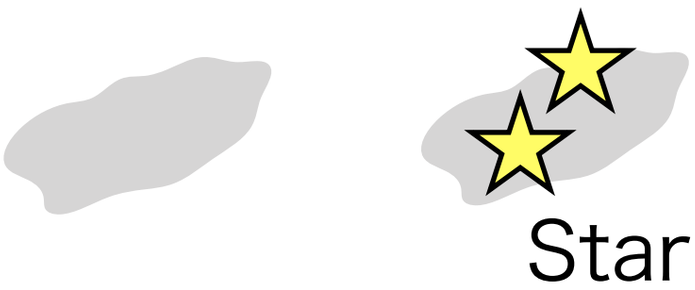
➢ **Estimation of clump's SFR(Star Forming Rate)**
…Gas becomes star at free fall time

$$\dot{M} = \int_{\rm lab} f_{\rm SFE} \frac{\rho}{t_{\rm ff}} {\rm d}V$$

$f_{\rm SFE}$ Star Formation Efficiency
$t_{\rm ff}$ Free Fall time

We assume $f_{\rm SFE} = 5\%$

➢ **Estimation of stellar mass**
…How many stars are formed
in the clump during dynamical time

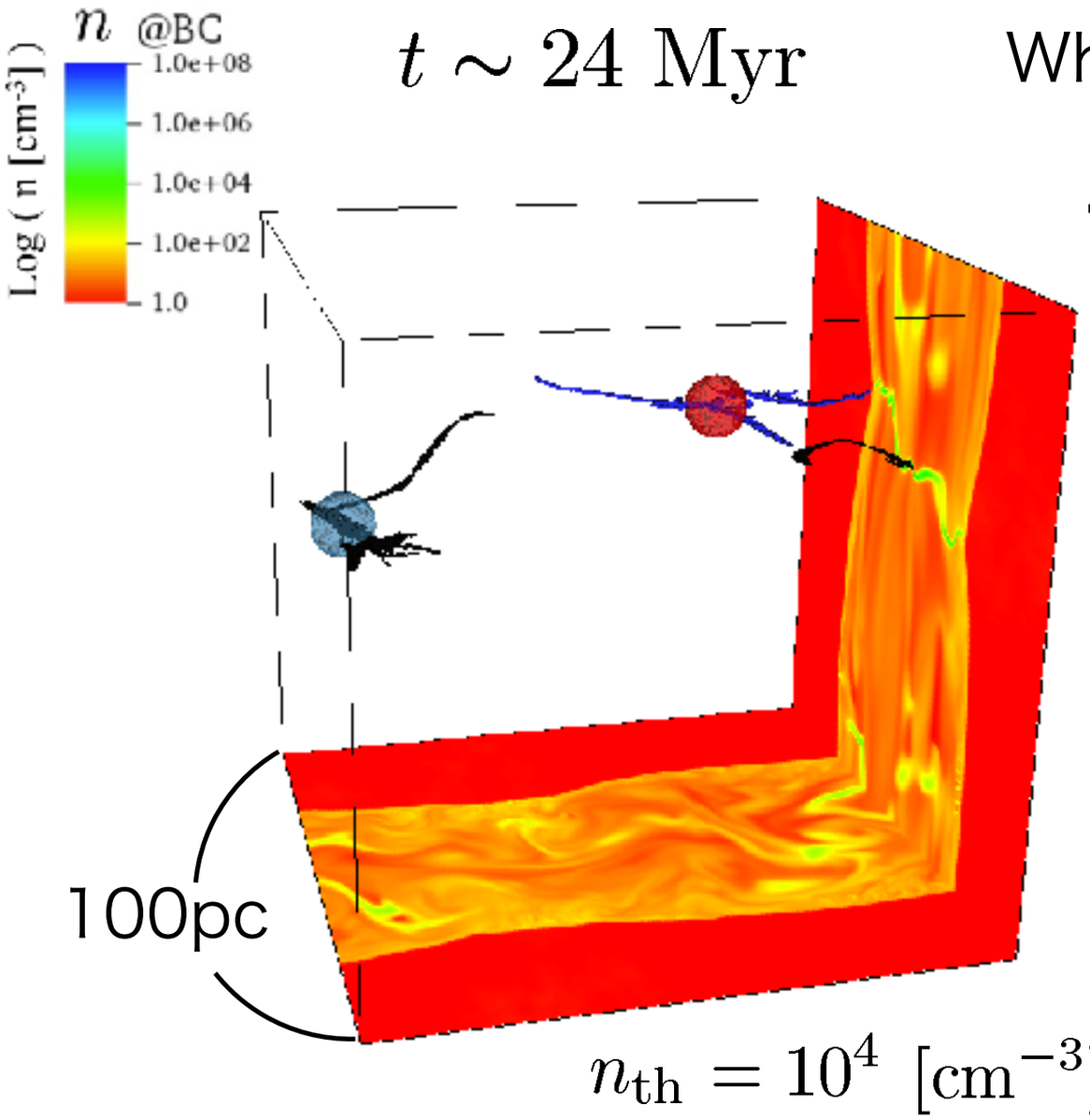


$$M_{\rm star} = \dot{M} \underbrace{\frac{L}{\Delta v}}_{t_{\rm dy}} \qquad M_{\rm gas} = \int_{\rm lab} \rho \, {\rm d}V$$

L :length scale
Δv :velocity dispersion

Cluster forming clumps are identified when $M_{\rm star} \sim M_{\rm gas}$

Result : Massive Cluster Forming Clumps



$t \sim 24$ Myr

When $t \sim 24$ Myr , $M_{\rm star} \sim M_{\rm gas}$

Two massive clumps are identified

Blue region

$M \sim 2.8 \times 10^4 {\rm M}_\odot$
$L \sim 4$ pc

Black region

$M \sim 1.8 \times 10^4 {\rm M}_\odot$
$L \sim 4$ pc

Massive compact cluster forming clumps can be formed @shock compressed layer

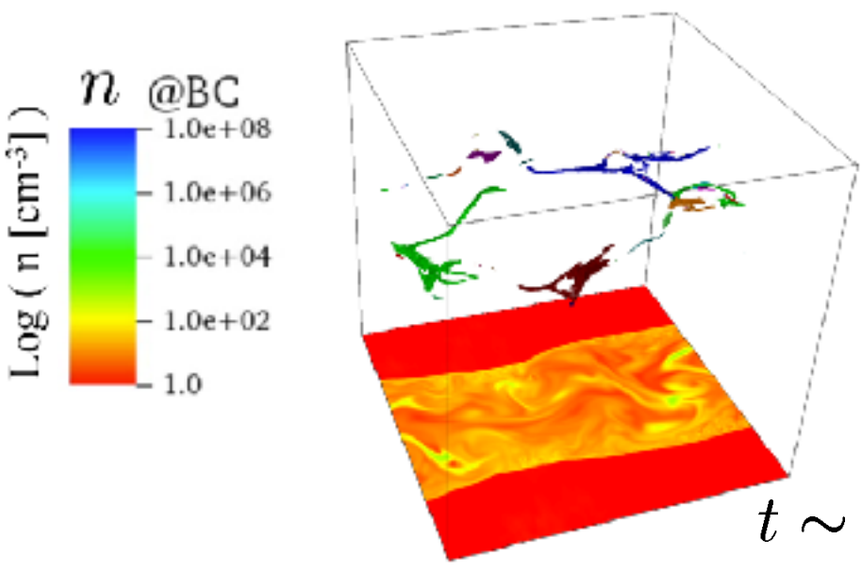
(YMC mass : $M \sim 10^4 {\rm M}_\odot$)

⟶ Parameter search (metallicity , B-field , collision speed ⋯)

Low metal simulation

※LMC:1/3 , SMC:1/10 $Z_\odot$

Solar metalicity



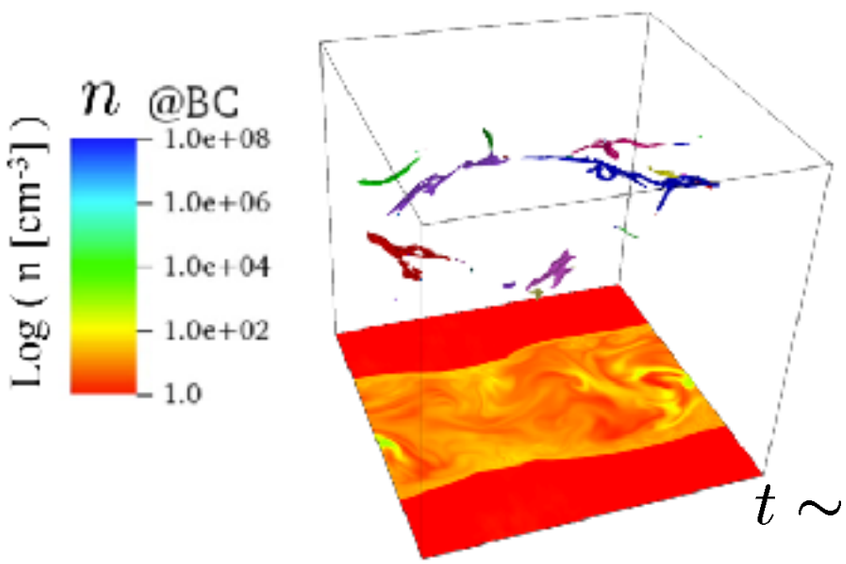
$t \sim 24$ Myr

$n_{\rm th} = 10^4$ [cm^{-3}]

Most massive clump

$M \sim 2.8 \times 10^4 \mathrm{M}_\odot$

One fifth of solar metalicity



$t \sim 24$ Myr

$n_{\rm th} = 10^4$ [cm^{-3}]

Color…Different clumps

Most massive clump

$M \sim 3.4 \times 10^4 \mathrm{M}_\odot$

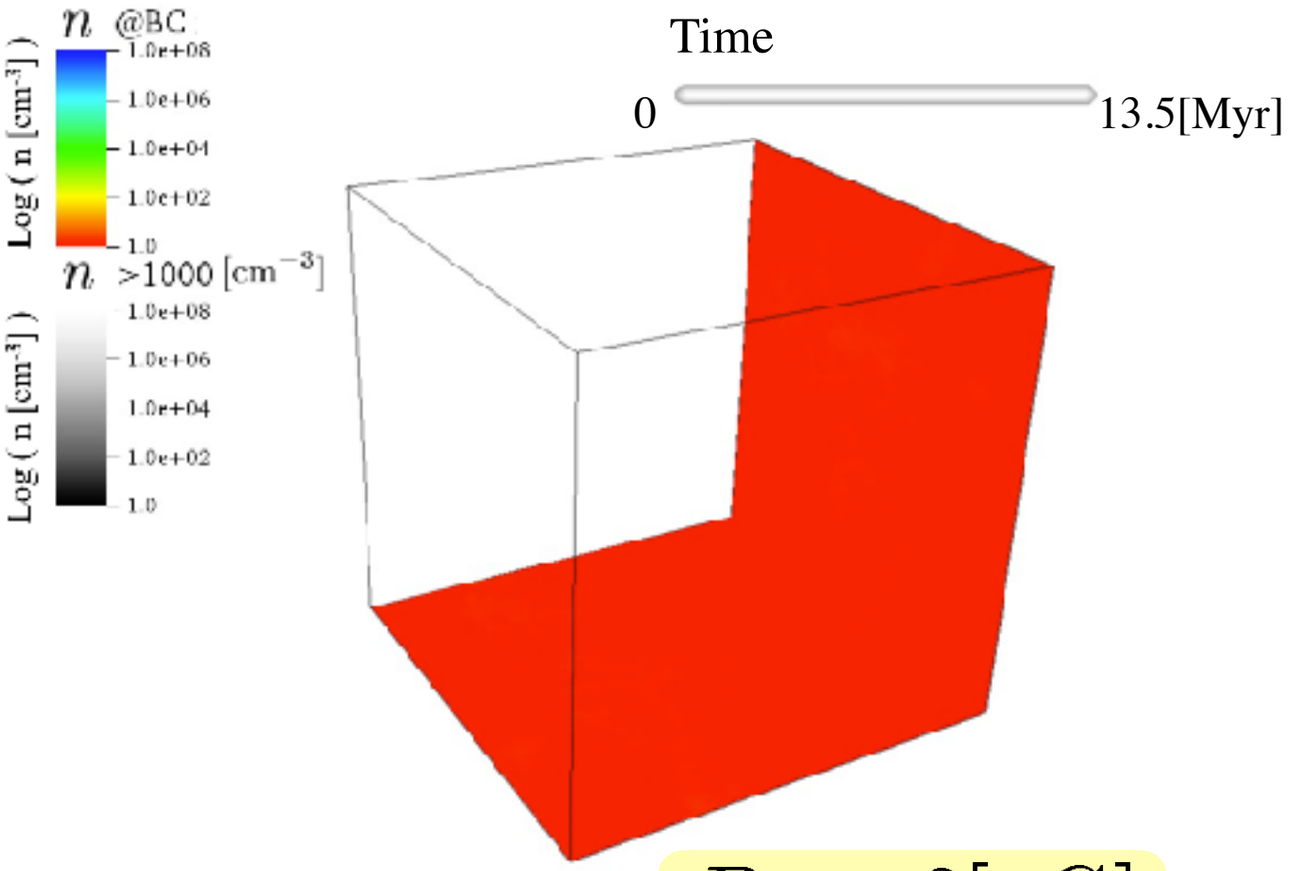
Cluster mass was found to be less dependent on metalicity

$$t_{\rm cool} \simeq 0.4 \mathrm{Myr}\,(Z/Z_\odot)^{-1}\, n_1^{-3/2}\,(p/k_{\rm B})_5^{1/2} \times \exp\left[10^{-2} T_{\rm line,2}\, n_1\,(p/k_{\rm B})_5^{-1}\right]$$

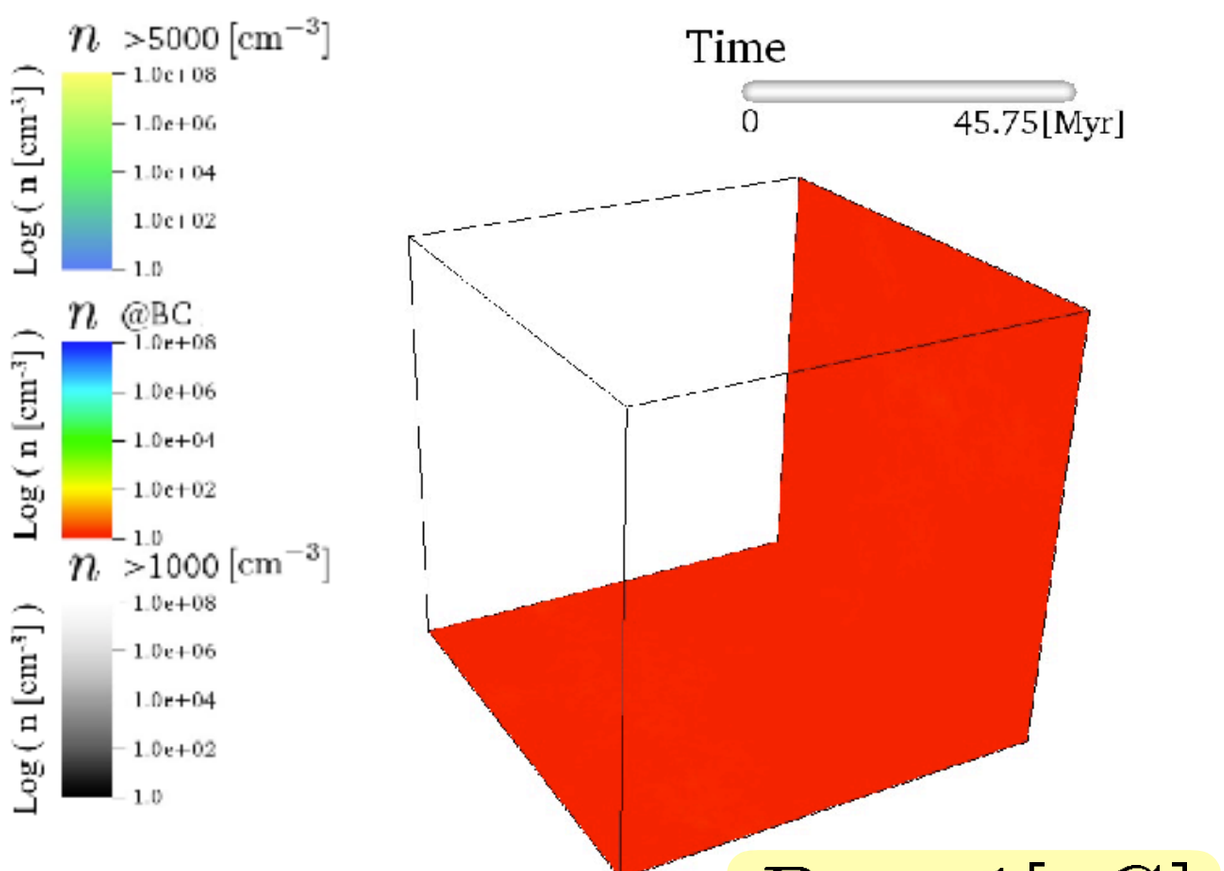
Inoue & Omukai (2014)

※ $n_1 = n/1\mathrm{cm}^{-3}$ $\quad (p/k_{\rm B})_5 = (p/k_{\rm B})/10^5 \mathrm{Kcm}^{-3}$ $\quad T_{\rm line,\,2} = T_{\rm line}/100\mathrm{K}$

Strong B-field simulation



$B_0 = 3[\mu\mathrm{G}]$



$B_0 = 1[\mu\mathrm{G}]$

When the magnetic field was strong, it was found that high density clumps were not formed

→ Clumps can't be formed because B-field at shock compressed layer is strong

Summary & Future Work

Summary

LMC observation suggests that
massive star clusters were formed by HI gas collision

We modeled massive star cluster formation
using MHD simulation with heating, cooling & self-gravity

Massive compact cluster forming cores($M \gtrsim 10^4 \mathrm{M}_\odot$, $L \sim 4\mathrm{pc}$)
are formed in shock compressed layer

Future work

Parameter survey will be done by future work
(metallicity , B-field , collision speed …)

Lagrangian dynamics of clumps will be studied (Test particles)