二相中性水素ガスの圧縮による分子雲形成過程

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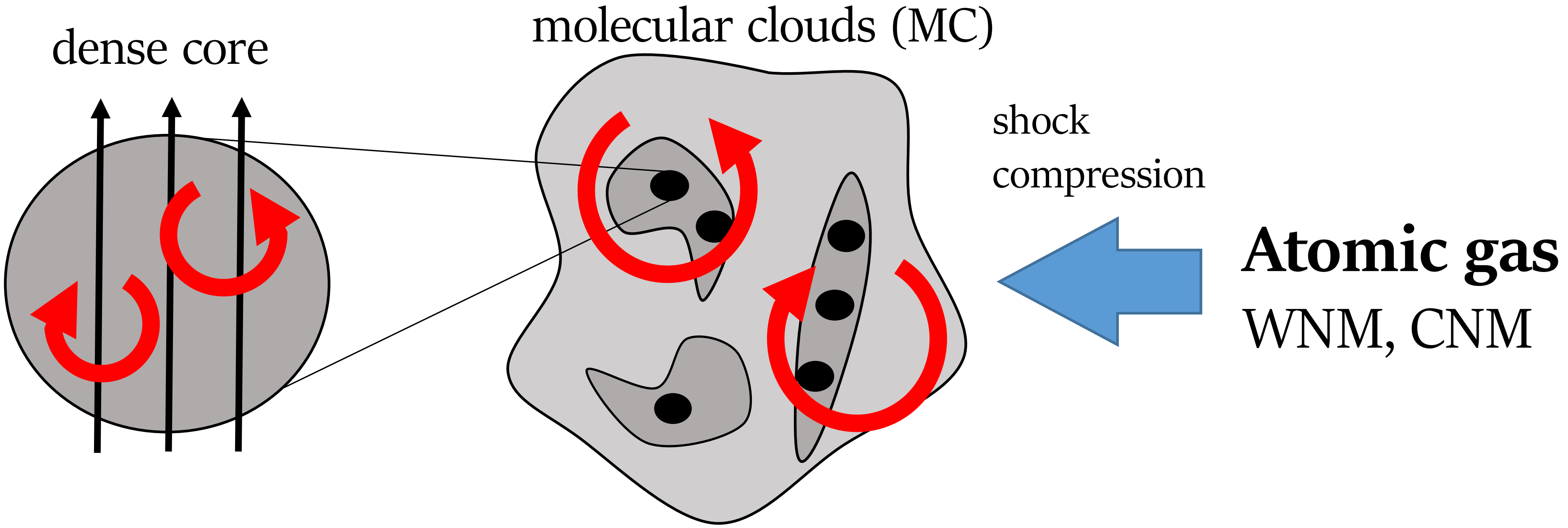
Formation of Molecular Clouds

Initial Condition of Star Formation



dense core

molecular clouds (MC)

shock compression

Atomic gas

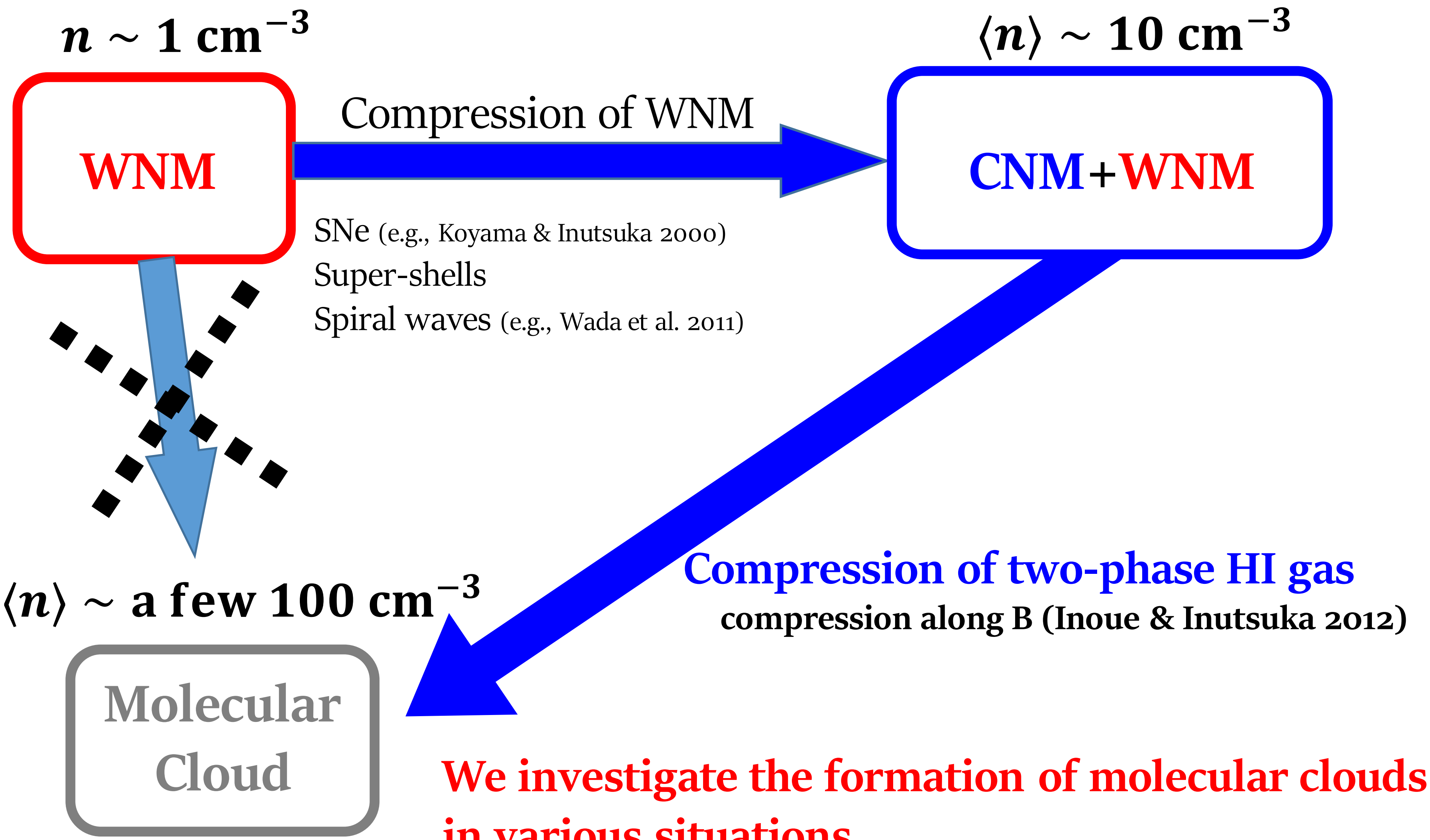
WNM, CNM

- **Physical properties of dense cores**
  - Velocity, magnetic fields, density structure (strongly influences the star formation (Machida et al. 2016)
  - Core mass function ~ IMF (e.g., Motte et al. 1998, Ikeda & Kitamura 2009, Andre et al. 2010)
- **Star formation efficiency (great diversity among molecular clouds)**
  - Dense gas mass (e.g., Lada et al. 2010, Heiderman et al. 2010, Evans et al. 2014...)

➡ it is crucial to understand SF from MC formation

Molecular Cloud Formation by Multiple Shock Compression

Inoue & Inutsuka (2009, 2012), Inutsuka et al. (2015)



$n \sim 1\ \mathrm{cm}^{-3}$

WNM

Compression of WNM

SNe (e.g., Koyama & Inutsuka 2000)
Super-shells
Spiral waves (e.g., Wada et al. 2011)

$\langle n \rangle \sim 10\ \mathrm{cm}^{-3}$

CNM+WNM

Compression of two-phase HI gas
compression along B (Inoue & Inutsuka 2012)

$\langle n \rangle \sim$ a few $100\ \mathrm{cm}^{-3}$

Molecular Cloud

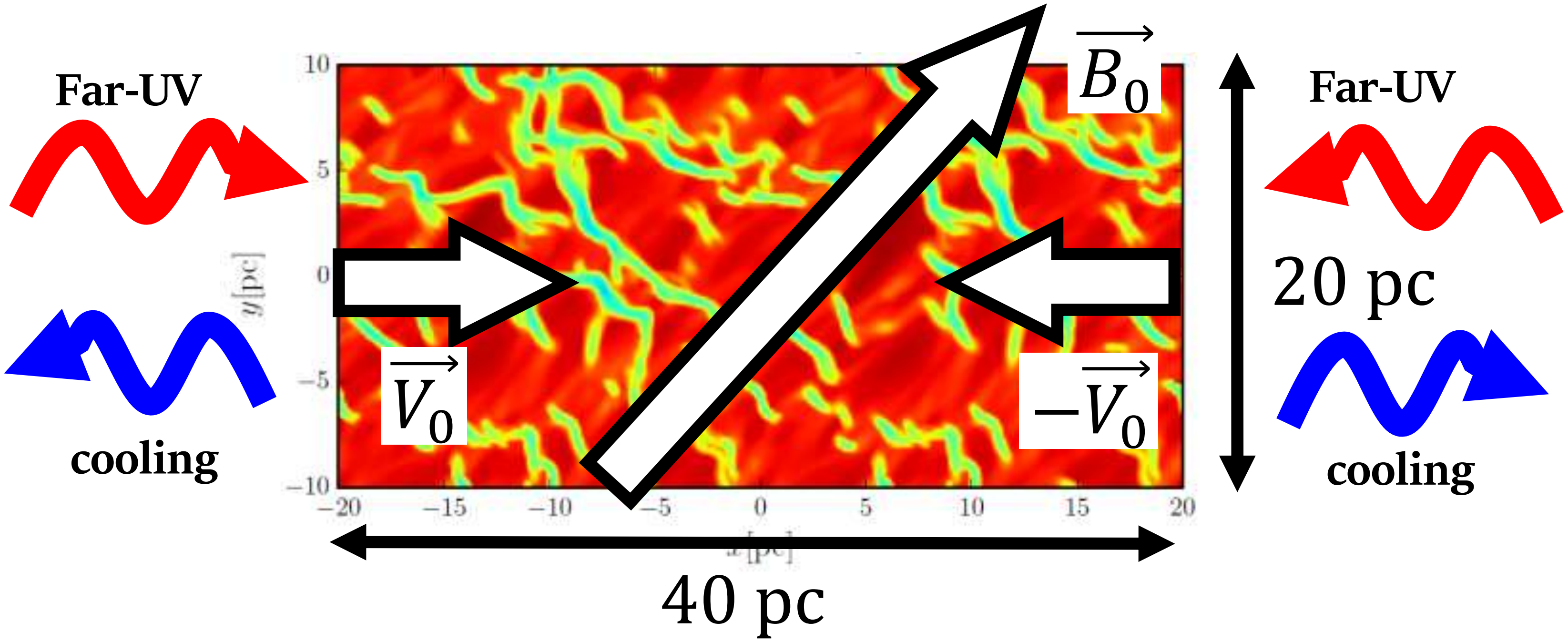
We investigate the formation of molecular clouds in various situations

Head-on Collision of Two-phase HI gas

Athena++ (Stone, Tomida, and White in prep.) **without self-gravity** $(1024 \times 512 \times 512)$

+ **Simplified chemical reactions (H+, H, H_2, He, He+, C, C+, CO) + Heating/Cooling processes**

2-ray approx. extinction of FUV, escape probability of cooling photons



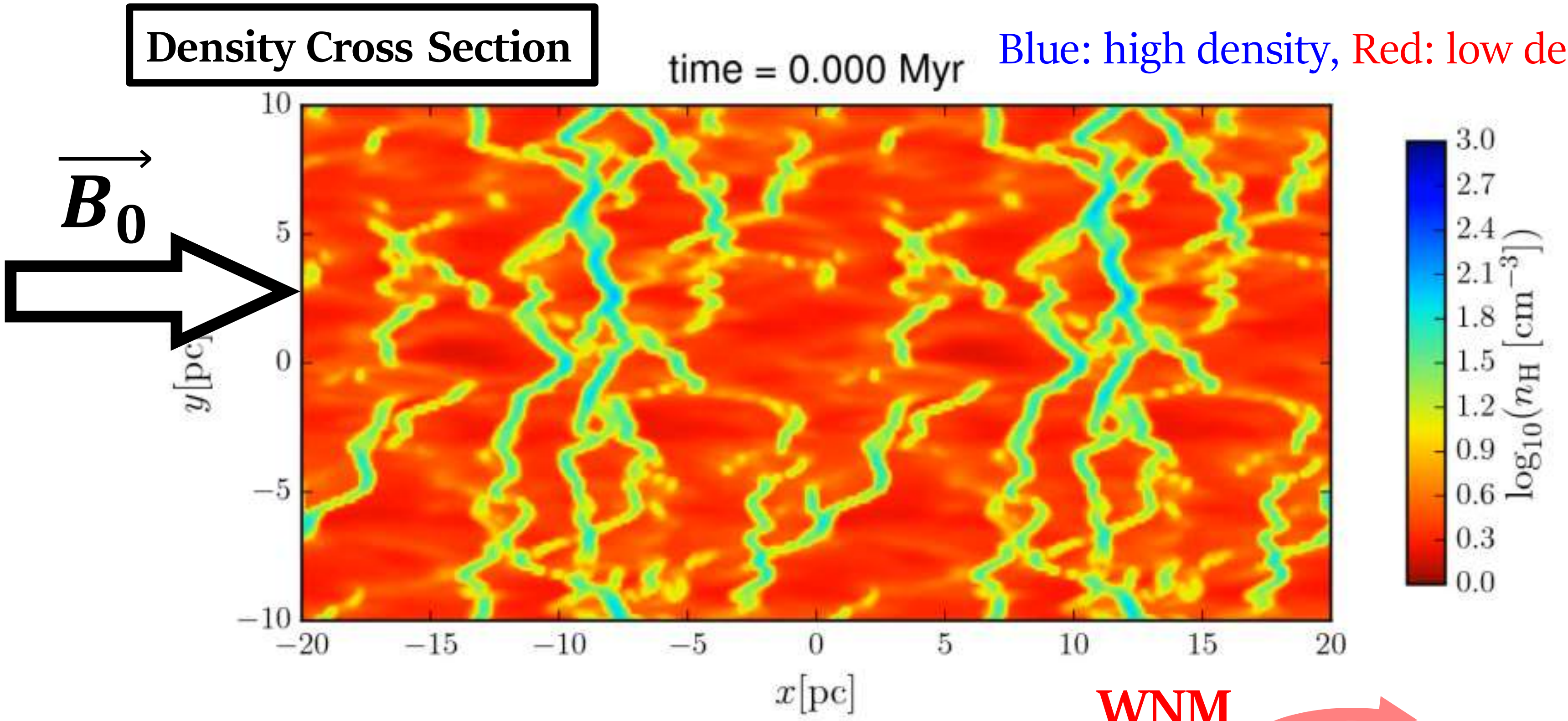
$$\langle n_0 \rangle = 5\mathrm{cm}^{-3}, |\overrightarrow{B_0}| = 5\mu\mathrm{G}, V_0 = 20\mathrm{km/s}$$

Parameter $\boldsymbol{\theta}$: the angle between $\overrightarrow{V_0}$ and $\overrightarrow{B_0}$:

Parallel Magnetic Field $\theta = 0$

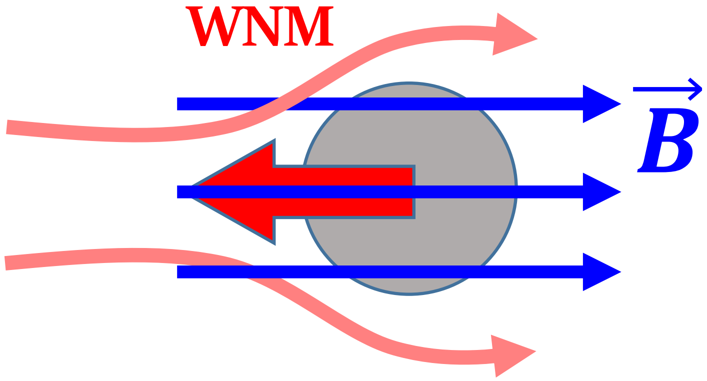
Density Cross Section

Blue: high density, Red: low density



- The shocked region broadens.

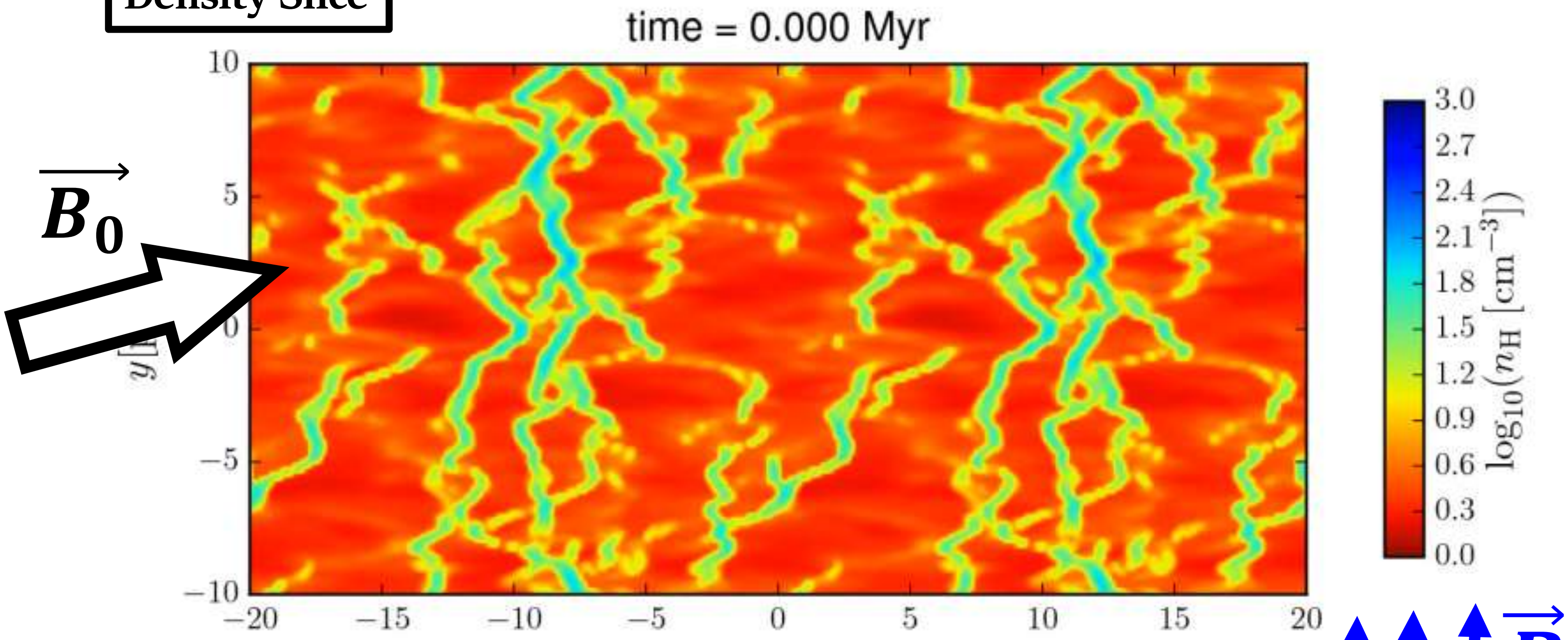
Two phase effect

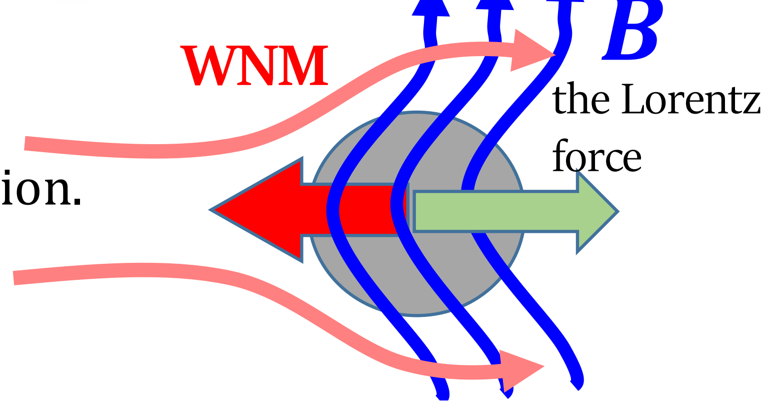


Slightly Tilted Magnetic Field

$(\theta = 0.064\pi = 11度)$

Density Slice

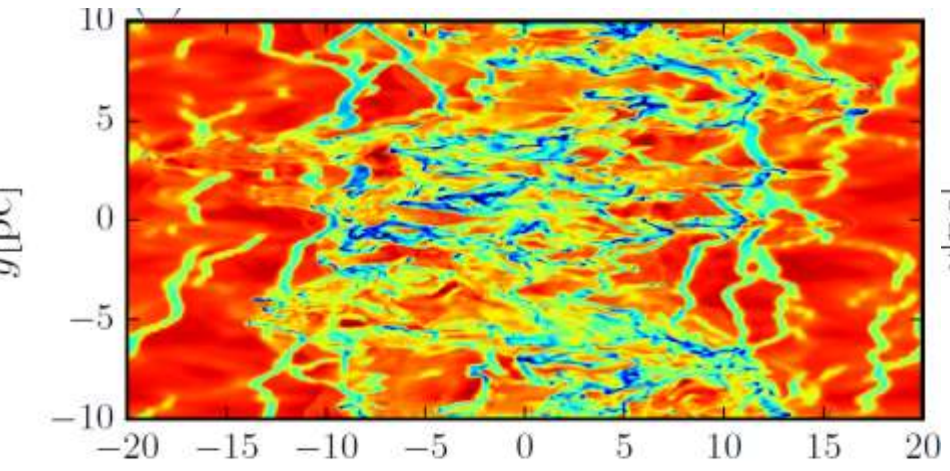




- The shocked gas is confined in narrower region.
- The amplified transvers B decelerates the motion of CNM clumps.

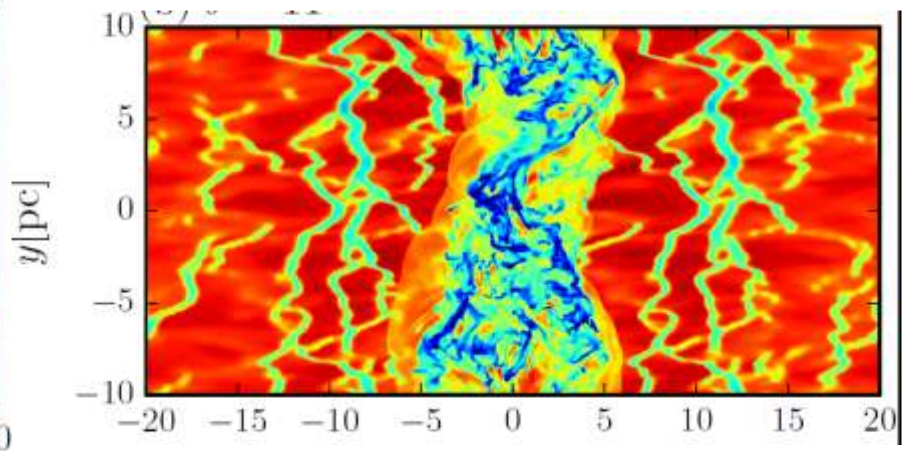
Impact of $\overrightarrow{B_0}$ on Turbulence Properties

parallel B case



Anisotropic turbulence
$\delta v_x \gg \delta v_y, \delta v_z$

slightly-tilted B case



Nearly isotropic turbulence
$\delta v_x \sim \delta v_y \sim \delta v_z$

The total mass of dense gases
are almost independent of θ

What determines this transition ?

Transition From Anisotropic to Isotropic Turbulence

if $\theta = 0$,
bulk motion ➡ random motion (x-dir.)

$$\delta v_{x,\theta=0} \sim \boxed{f} \times V_0$$

conversion efficiency
~ 0.3 (from the simulations)

if the transverse B is important,
the post-shock Alfven speed:

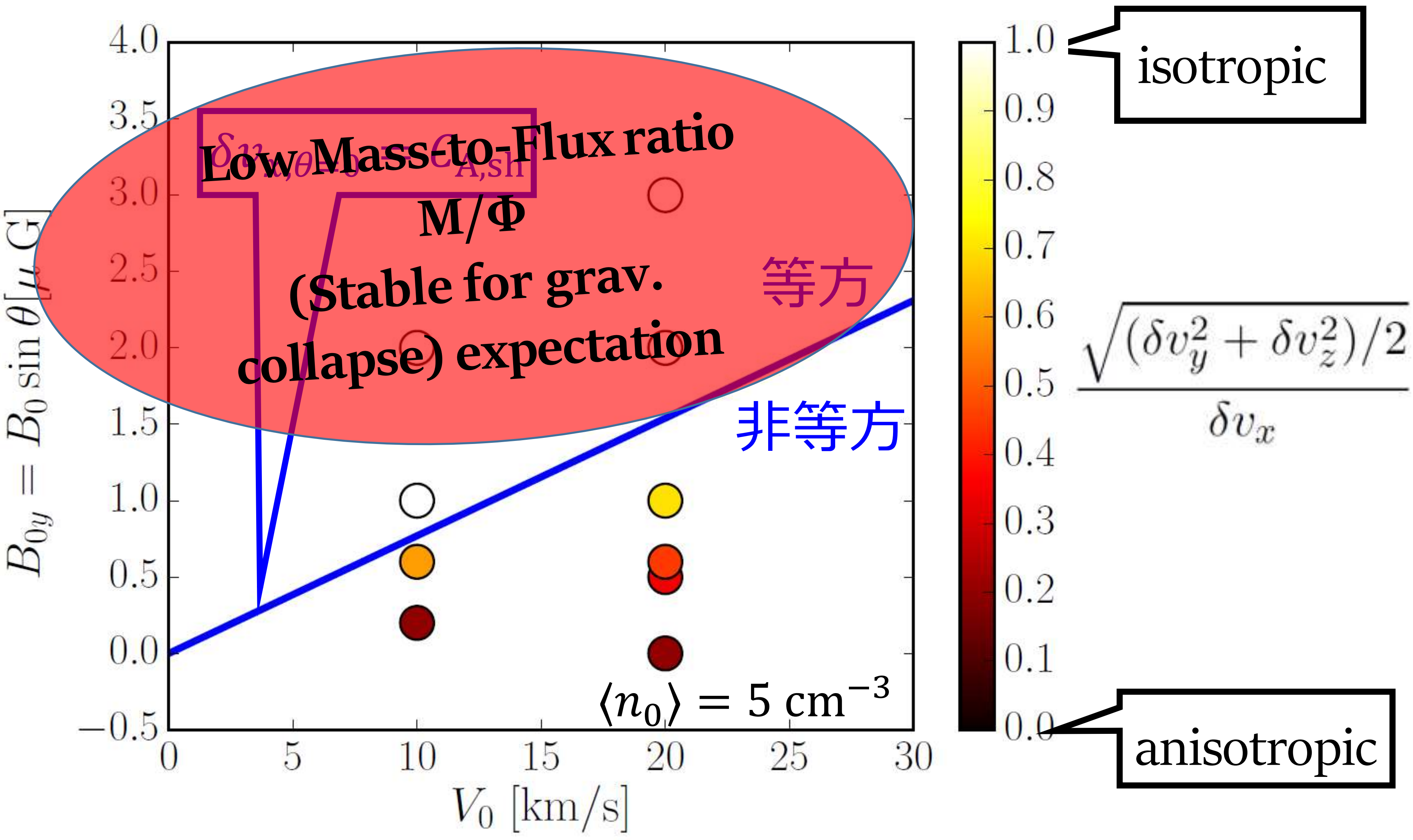
$$C_{\mathrm{A,sh}} \sim (2\pi)^{-1/4} \frac{(B_0 \sin\theta)^{1/2} V_0^{1/2}}{\langle\rho_0\rangle^{1/4}}$$

$$\frac{B_{\mathrm{sh}}^2}{8\pi} \sim \langle\rho_0\rangle V_0^2 \qquad \frac{B_{\mathrm{sh}}}{\langle\rho_{\mathrm{sh}}\rangle} \sim \frac{B_0 \sin\theta}{\langle\rho_0\rangle}$$

Criterion for driving anisotropic turb.

$$\delta v_{x,\theta=0} > C_{\mathrm{A,sh}}$$

(V_0 - $B_0\sin\theta$) Diagram (Preliminary)



$\langle n_0 \rangle = 5\ \mathrm{cm}^{-3}$

$\delta v_{x,\theta=0} = C_{\mathrm{A,sh}}$

Low Mass-to-Flux ratio

M/Φ

(Stable for grav. collapse) expectation

等方

非等方

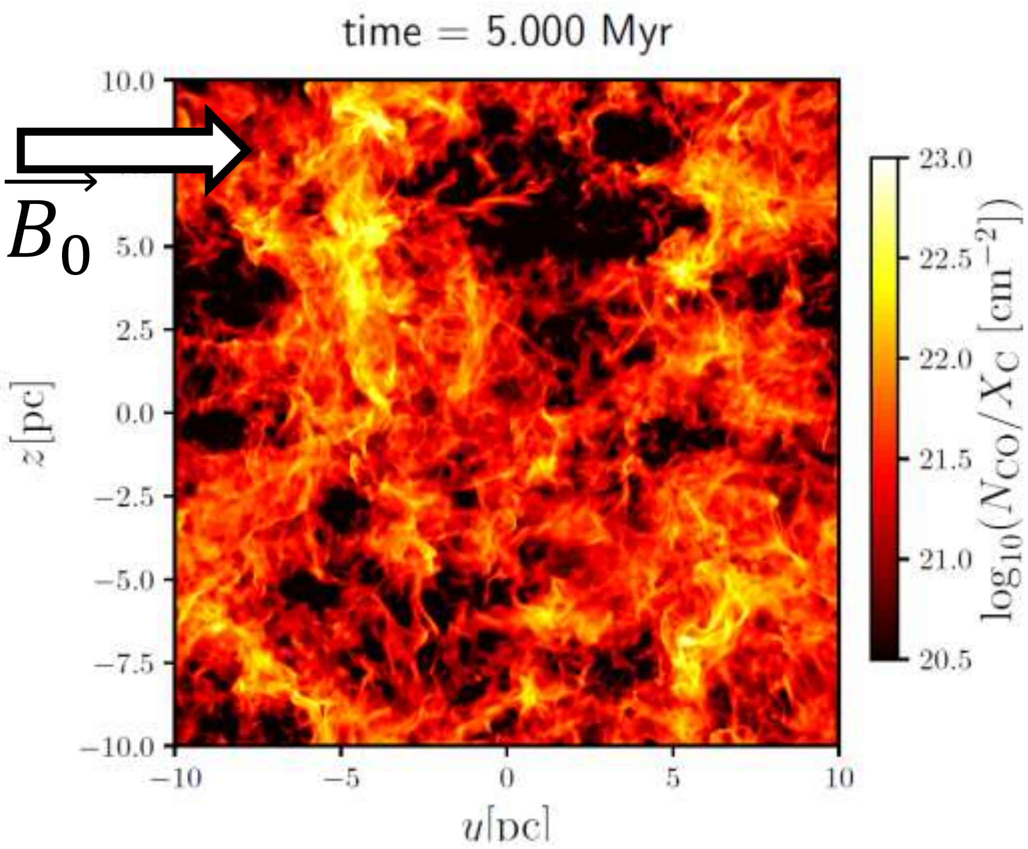
$$\frac{\sqrt{(\delta v_y^2 + \delta v_z^2)/2}}{\delta v_x}$$

isotropic

anisotropic

With Self-gravity (Preliminary)

- Test calculation including the self-gravity implemented by Tomida-san
- Resolution ~ 0.04 pc (insufficient)
- $\langle n_0 \rangle = 10\ \mathrm{cm}^{-3}, V_0 = 20\ \mathrm{km/s}, B_0 = 5\mu G, \theta = 0.064\pi$ (slightly anisotropic turb.)



CO column density
integrated along compression dir.

At t ~ 5Myr,
a dense core collapses.

many filamentary structures exist

Summary and Future Works

- We performed simulations of the MC formation by taking account of the detailed physics, chemical reactions, radiative transfer, and heating/cooling.
- We investigated the dependence of the MC formation on B direction.
- B field greatly changes the turbulence properties in the post-shock region
  - The total mass of dense gases ($n > 100\ \mathrm{cm}^{-3}$) is almost independent of θ.
    - The cold clouds can survive in a strong shear motion of surrounding WNM owing to efficient cooling.
  - As θ increases, turbulence changes from anisotropic to isotropic.
  - We derive a simple analytic criterion for anisotropic turbulence.

Future Works

- Mechanism determining f : conversion efficiency from bulk motion to random motion
  - interaction between shock front and CNN clumps, interaction between CNM and WNM
- How the sensitive dependence of B on turbulence affects the star formation.
  - perform simulations with high resolution enough to resolve the core size 0.1pc with self-gravity.
- Connection to global scales.