The formation of molecular clouds by compression of two-phase atomic gases

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Iwasaki, Tomida, Inoue, and Inutsuka, arXiv: 1806.03824 (under revision)

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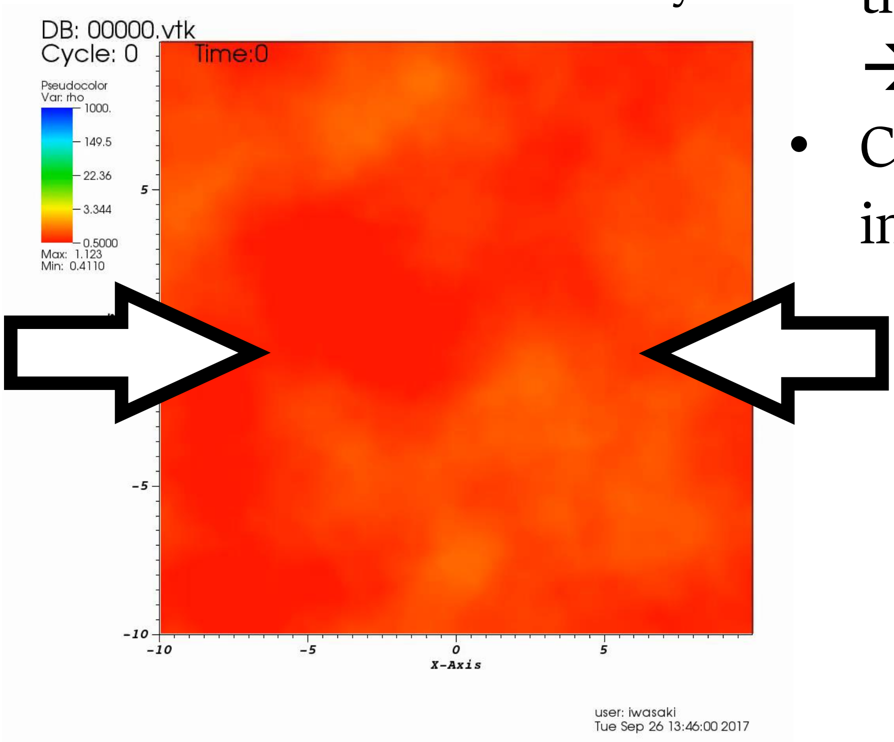
Cold Cloud Formation by Shock Compression

Nonlinear disturbance (supernovae, super-bubbles, spiral waves) makes WNM thermally unstable (Hennebelle & Perault 1999,, Koyama & Inutsuka 2000)

WNM colliding flow simulations
color: density



- shock compression of WNM induces the thermal instability
  → CNM clumps are generated.
- CNM clumps move with **a supersonic δv** in the surrounding warm gas.

Koyama & Inutsuka 2002, Audit & Hennebelle 2005, Heitsch et al. 2005, 2006, Vazquez-Semadeni et al. 2006, 2007, Hennebelle & Audit 2007, Hennebelle et al. 2007, 2008, Inoue & Inutsuka 2008, 2009, Heitsch et al. 2009, Banerjee et al. 2009, Audit & Hennebelle 2010, Vazquez-Semadeni et al. 2010, 2011, Clark et al. 2012, Kortgen & Banerjee 2015, Valdivia et al. 2016, Zamora-Aviles et al. 2018,..

Molecular Cloud Formation by Accretion of Dense HI Gas

Molecular cloud formation not from low-density WNM ($n \leq 1\ \mathrm{cm}^{-3}$) but from dense HI gas

- WNM may be too rarefied to form MC within several tens Myrs (Kawamura et al. 2009). (Pringle et al. 2001, Inoue & Inutsuka 2009, 2012)
- Observations suggest molecular clouds are formed by accretion of HI gas with a density of $\langle n \rangle \sim 10\ \mathrm{cm}^{-3}$ (Blitz et al. 2007, Fukui 2009, 2017)
- Dense HI gas has **thermally bistable structure (clumpy HI clouds embedded by WNM).** ← need to be considered.
- Inoue & Inutsuka (2012) investigated MC formation by compression of two phase HI gas. but only parallel field case (compression ∥ B field) (also see Carroll-Nellenback et al. 2014 for hydro)

→We investigated the MC formations in various conditions.

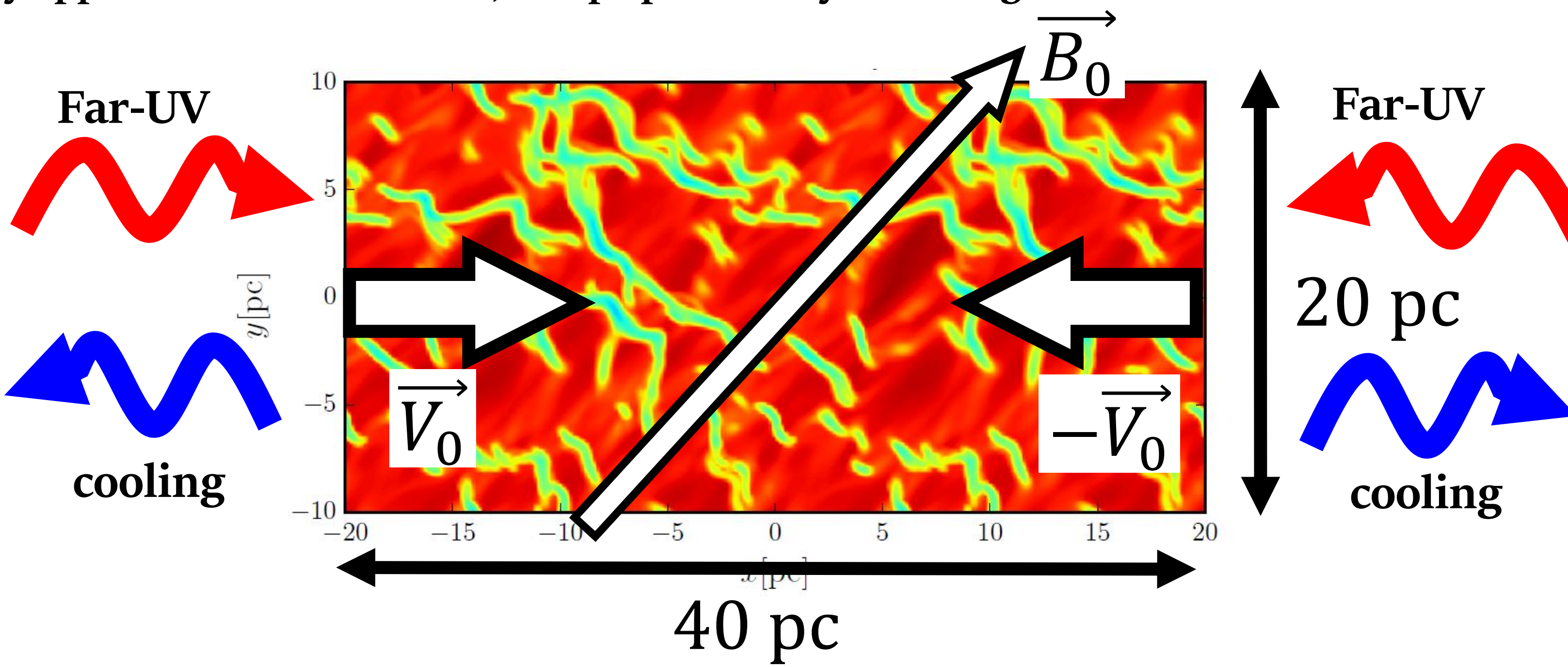
(mean density, collision speed, field strength, field angle)

Head-on Collision of HI Gases

***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

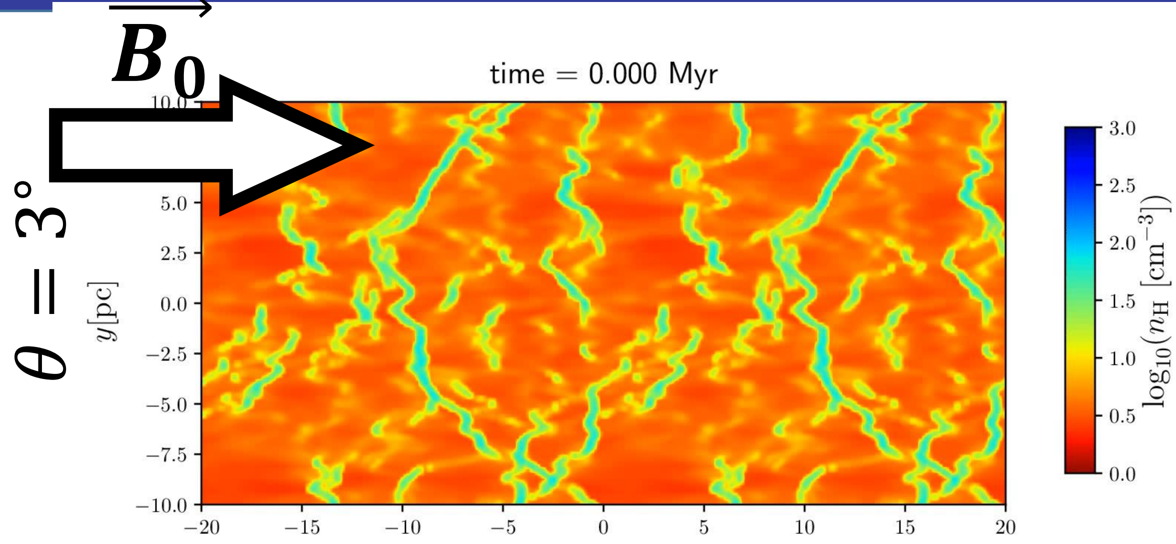


the fiducial parameter set: $\langle n_0 \rangle = 5\mathrm{cm}^{-3}, |\overrightarrow{B_0}| = 5\mu\mathrm{G}, V_0 = 20\mathrm{km/s}$

$\boldsymbol{\theta}$: the angle between $\overrightarrow{V_0}$ and $\overrightarrow{B_0}$ $(\theta = 3°, \quad \theta = 11°)$

Evolution of Post-shock Layers (Density Slice)

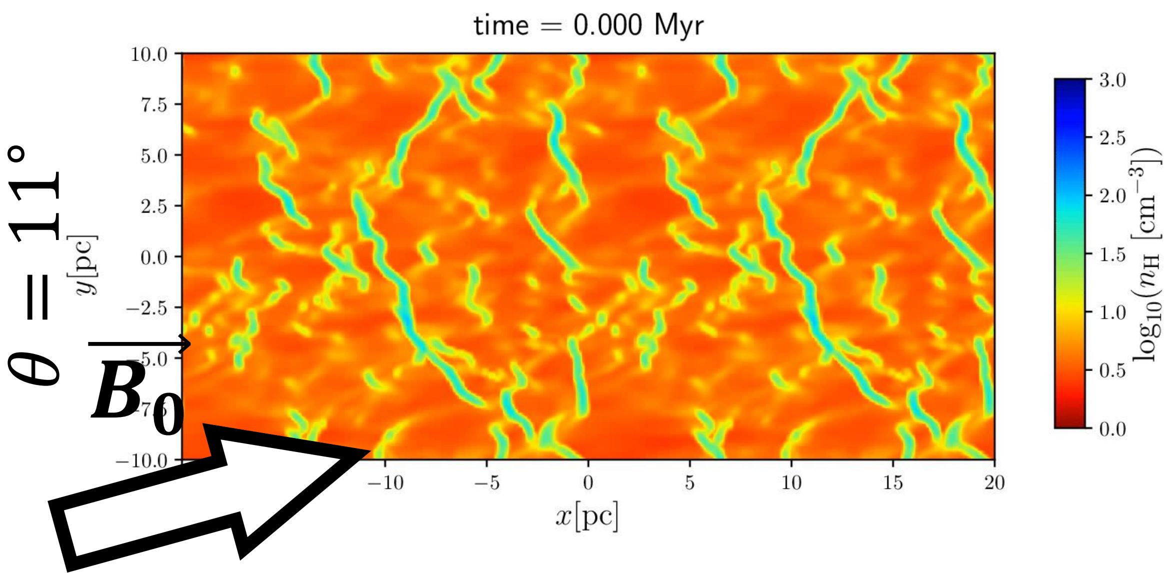
(**Iwasaki** et al. under revision)



- **Accretion of inhomogeneous HI gas**

→ the post-shock layer rapidly expands

- **super Alfvenic δv**



- **Well confined and denser than the $\theta = 3°$ case.**
- **trans- or sub-Alfvenic δv**

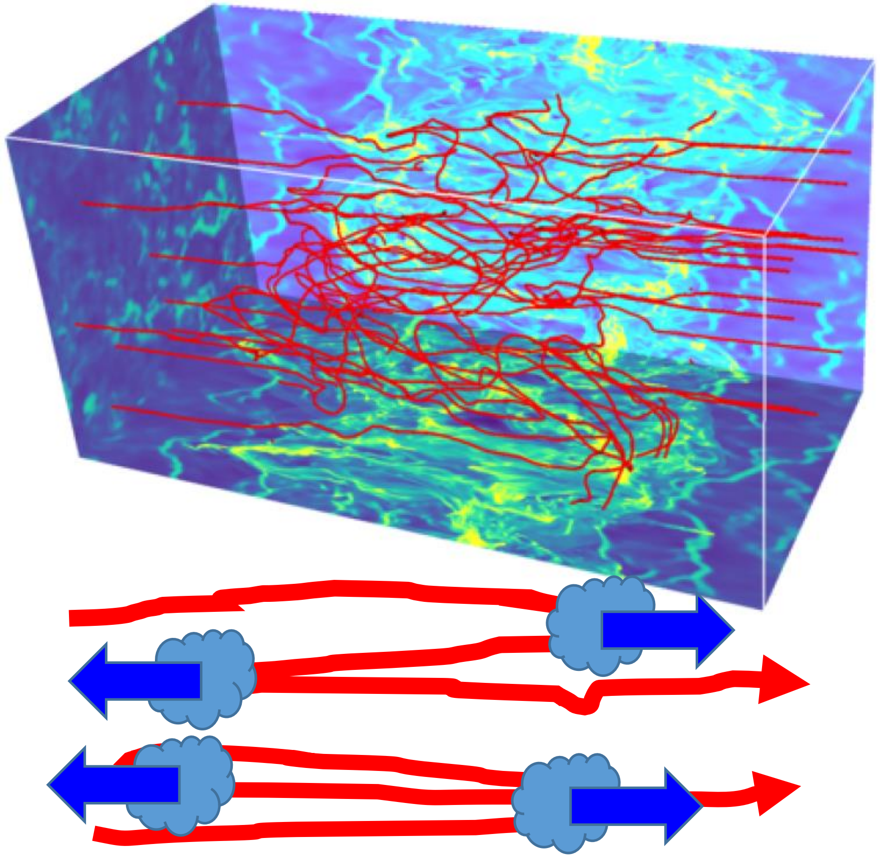
Small change of θ makes the big difference of the post-shock layers!

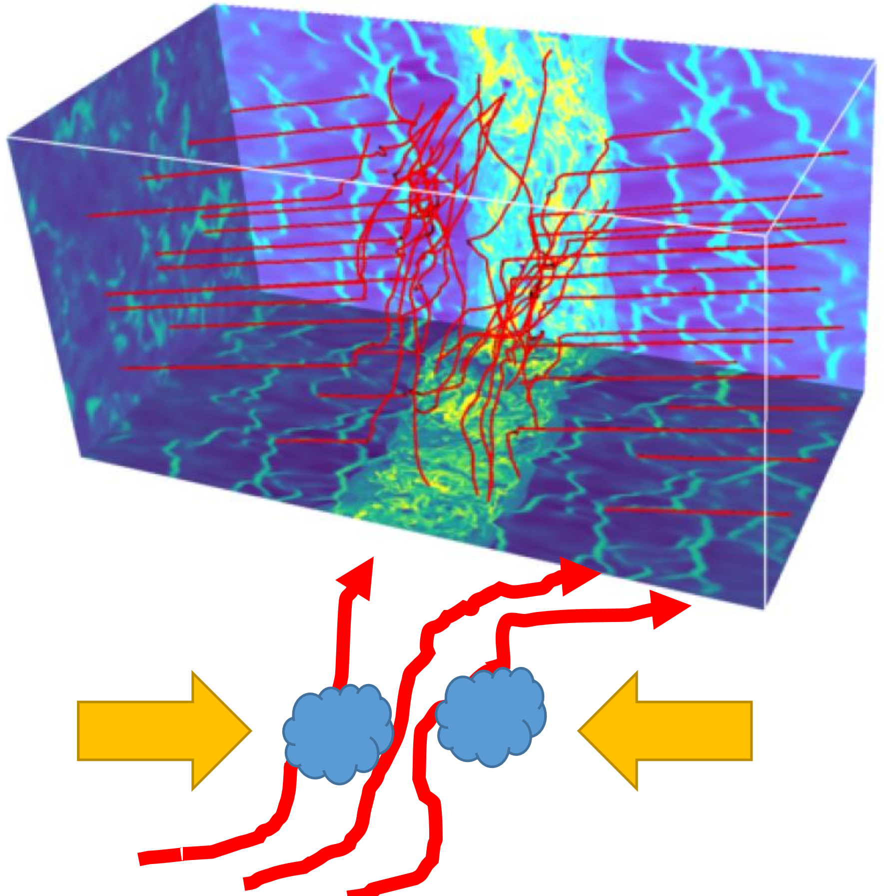
Role of Magnetic Fields

$\theta = 3^\circ$ case

$\theta = 11^\circ$ case

@ t=5 Myr





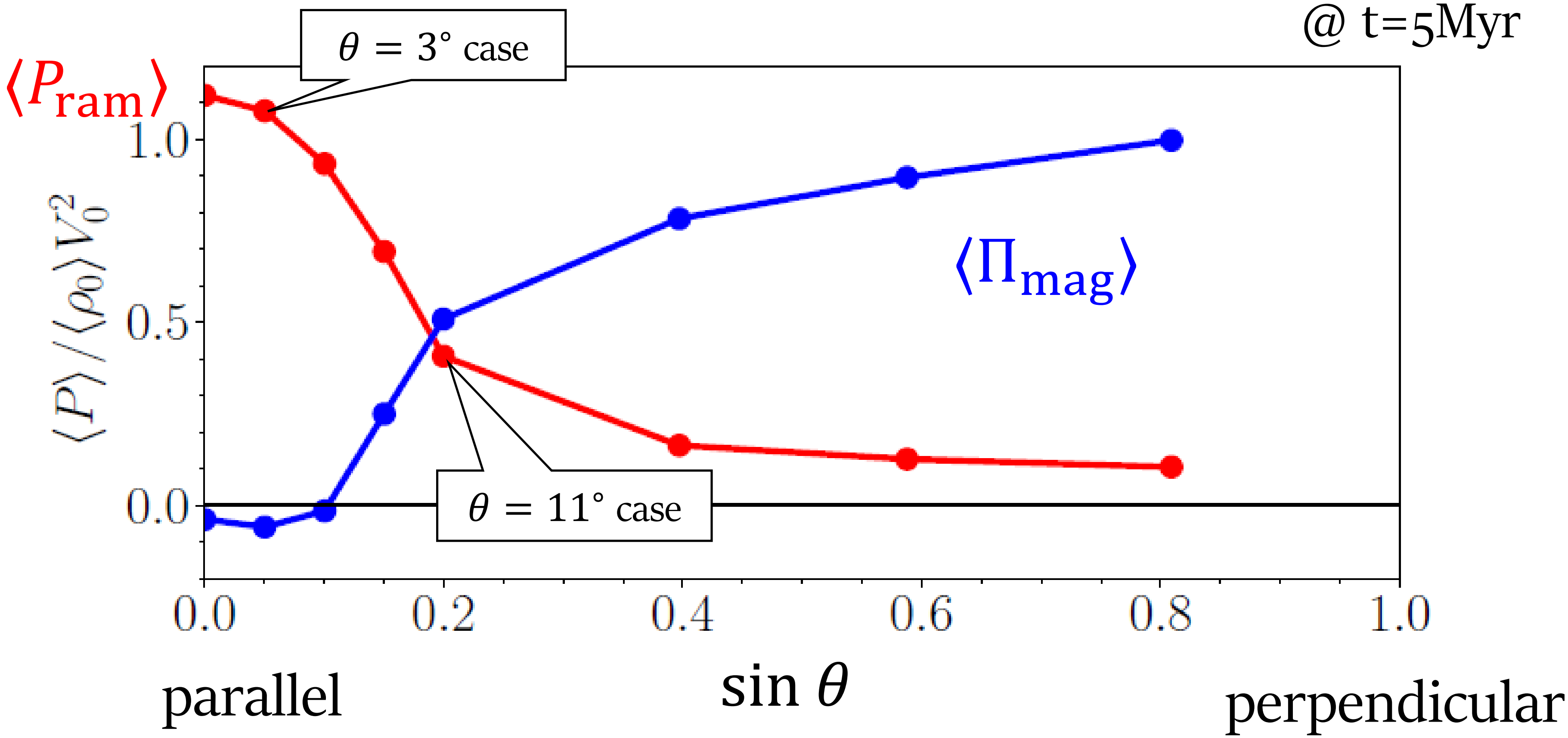
the B field is **passively** stretched by the counter-moving clumps

the shock-amplified B field pulls the clumps back.

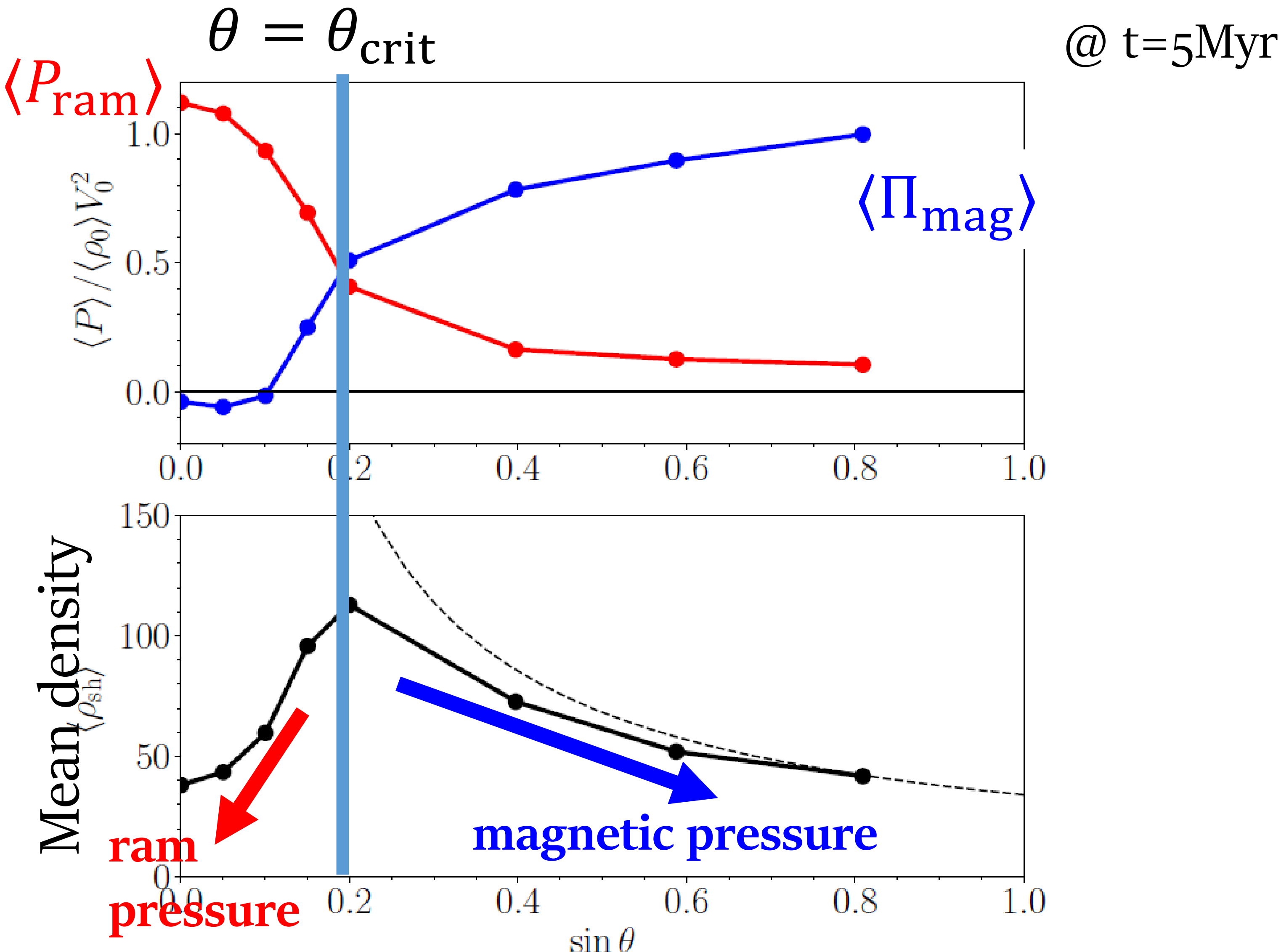
Mean Ram and Magnetic Pressures As a Function of θ

$$\langle P_{\rm ram} \rangle = \langle \rho v_x^2 \rangle$$

$$\langle \Pi_{\rm mag} \rangle = \frac{\langle B_\perp^2 - B_x^2 \rangle}{8\pi}$$



Mean Post-shock Density As a Function of θ



What determines θ_{crit} ?

Criterion for Pram-dominated

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

Velocity dipsersion

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

Conversion factor~ 0.25

Alfven speed in the post-shock layer

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

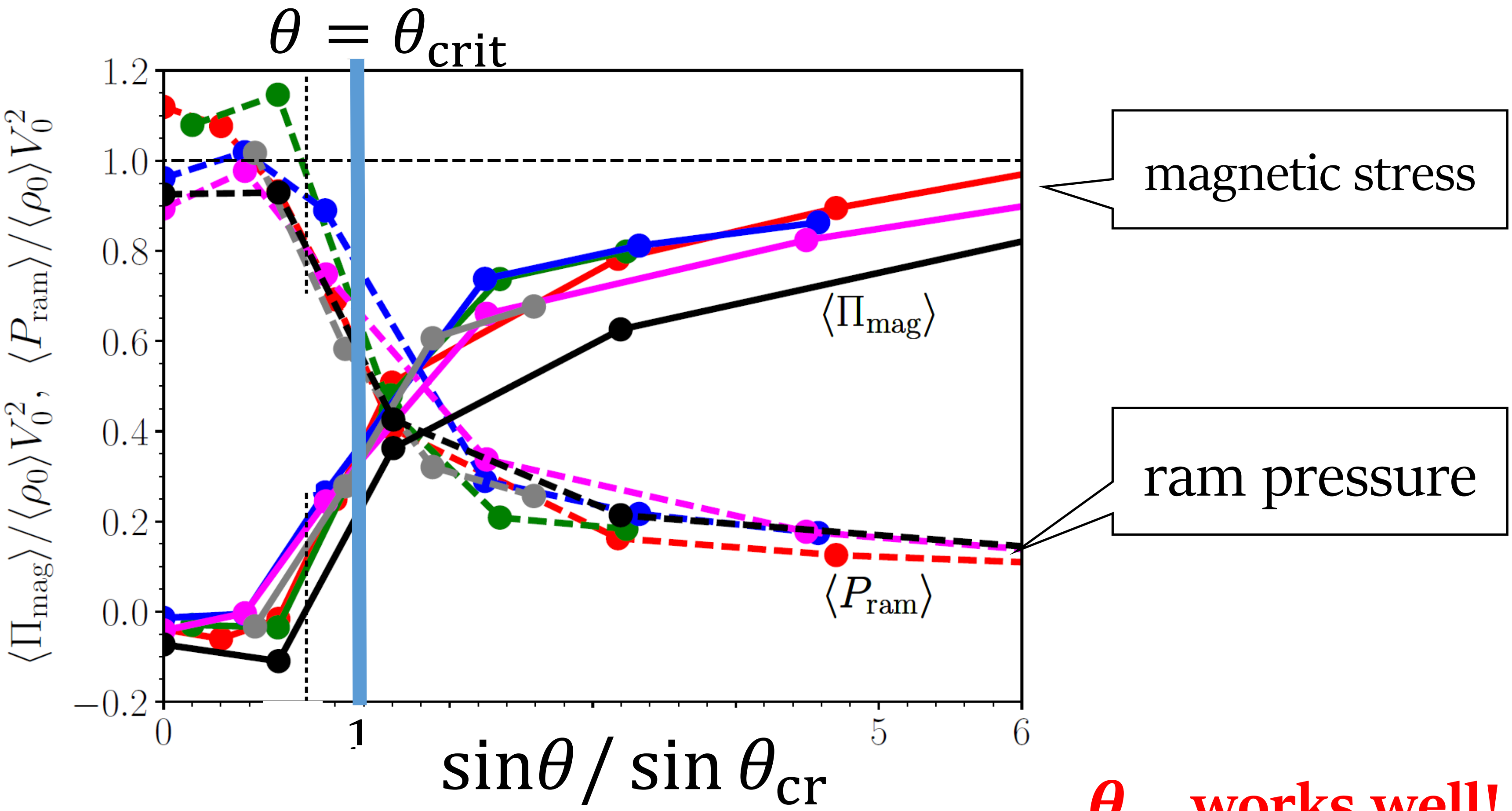
the critical angle

$$\sin\theta_{crit} = 0.2 \left(\frac{f}{0.25}\right)^2 \left(\frac{\langle n_0\rangle}{5\ cm^{-3}}\right)^{1/2} \left(\frac{V_0}{20\ km/s}\right) \left(\frac{|\mathbf{B}_0|}{5\ \mu G}\right)^{-1}$$

valid only for $V_0 \gg B_0/\sqrt{4\pi\rho_0}$

Parameter Survey

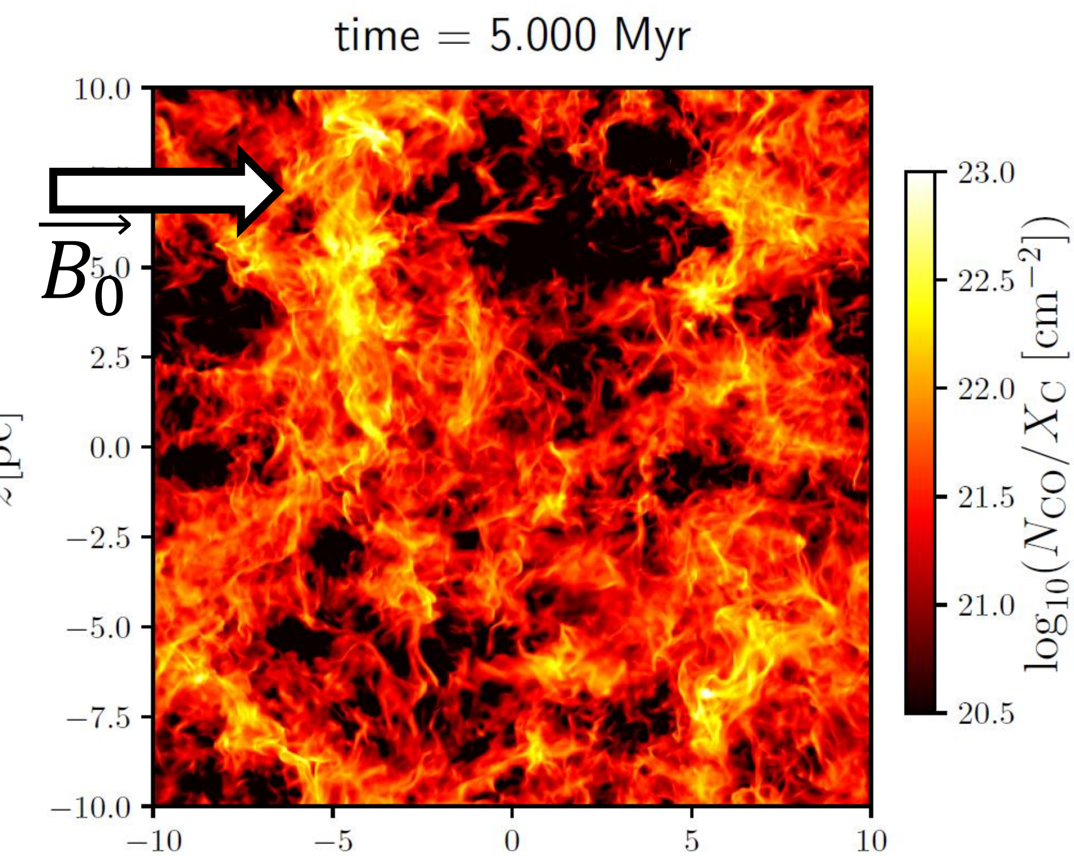
- Parameter survey is performed by changing a parameter set of $(\langle n_0 \rangle, V_0, |\overrightarrow{B_0}|)$.
- In each parameter set, we performed simulations with different θ.



$\theta_{\rm cr}$ works well!

Simulations with Self-gravity (on-going)

- Calculation including the self-gravity implemented by Tomida-san (cost ~ 0.2 x MHD)
- Resolution ~ 0.04 pc (insufficient)
- $\langle n_0 \rangle = 10\ \mathrm{cm}^{-3}, \mathrm{V}_0 = 20\ \mathrm{km/s},\ B_0 = 5\mu G,\ \theta = 11°$



CO column density integrated along compression dir.

Around t ~ 5Myr, a dense core collapses.

many filamentary structures are visible

Summary

- We performed simulations of the MC formation by taking into account chemical reactions, radiative transfer, and heating/cooling.
- We investigated the dependence of the MC formation on B direction.
- **At a certain angle θ_{cr}, the mean shocked density becomes the maximum.**

  ➡ there is a preferential angle $\theta \neq 0$ for the MC formation

  - $\theta < \theta_{cr}$: extended post-shock layers (super Alfvenic)
    gravity will make the post-shock layer compact in the later stage.
  - $\theta \sim \theta_{cr}$: dense post-shock layers (sub Alfvenic)
  - $\theta > \theta_{cr}$: extended post-shock layers due to magnetic pressure.
- This result may produces a diversity of molecular clouds.

Future work

- long-term simulations with high resolution enough to resolve the core size with self-gravity.
- Connection to global scales.