Formation of Massive Filamentary Cloud Cores behind Shock Wave

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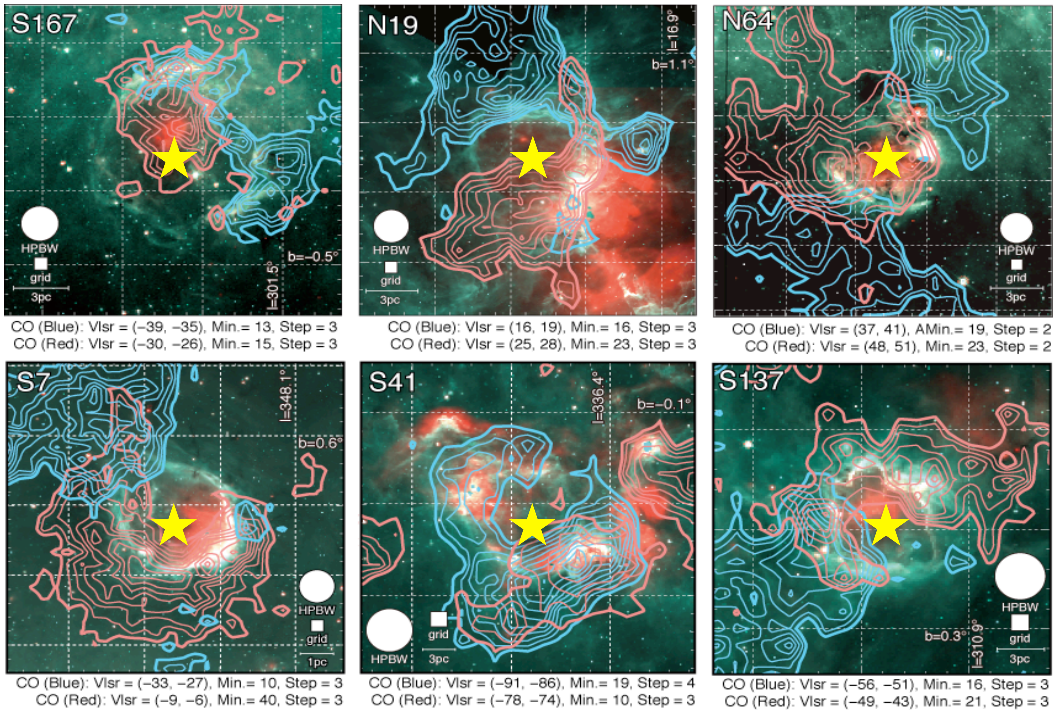
Motivation: Cloud Collision

- Recent observations suggest massive star/cluster formation is triggered by cloud collision（e.g., Furukawa+09, Ohama+10 for Westerlund2, Torii+11 for M20 and Fukui+14 for NGC3603）.



Color: Spitzer 8, 24μm (Benjamin+03, Carey+09)
Contour: NANTEN2 ^{12}CO J=1-0 (Fukui+15 in prep.)

- Representative sites of cloud-cloud collision where massive stars are located at centers of each panel. (Fukui+15 in prep.)

- Large typical collision velocity:

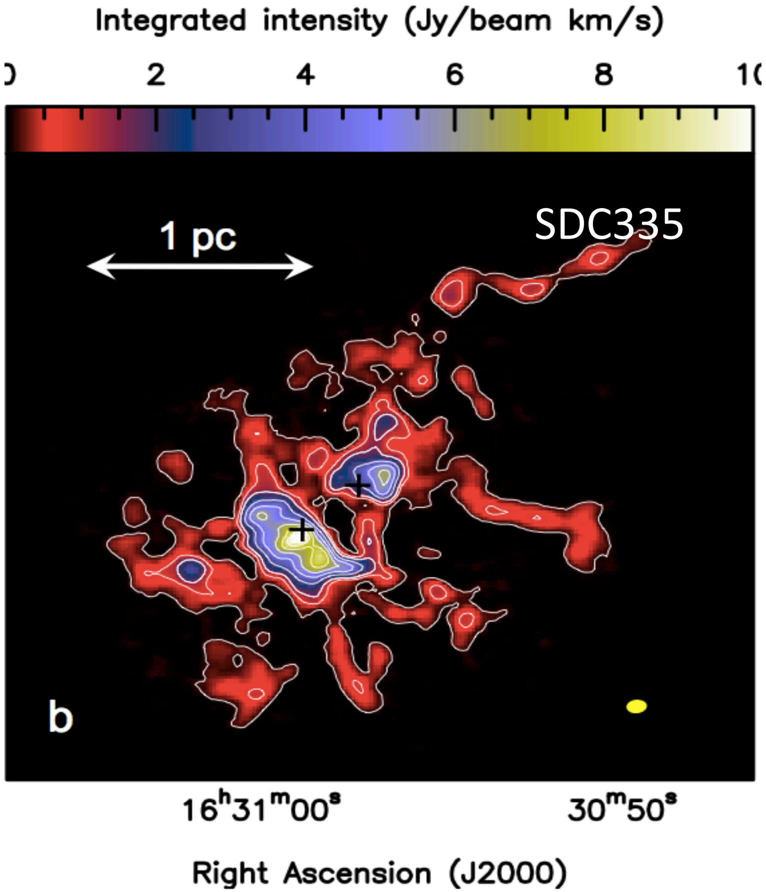
  ✓ $v_{\rm rel} \sim 20$ km/s

  $>> c_s \sim 0.2$ km/s @ $T = 10$K

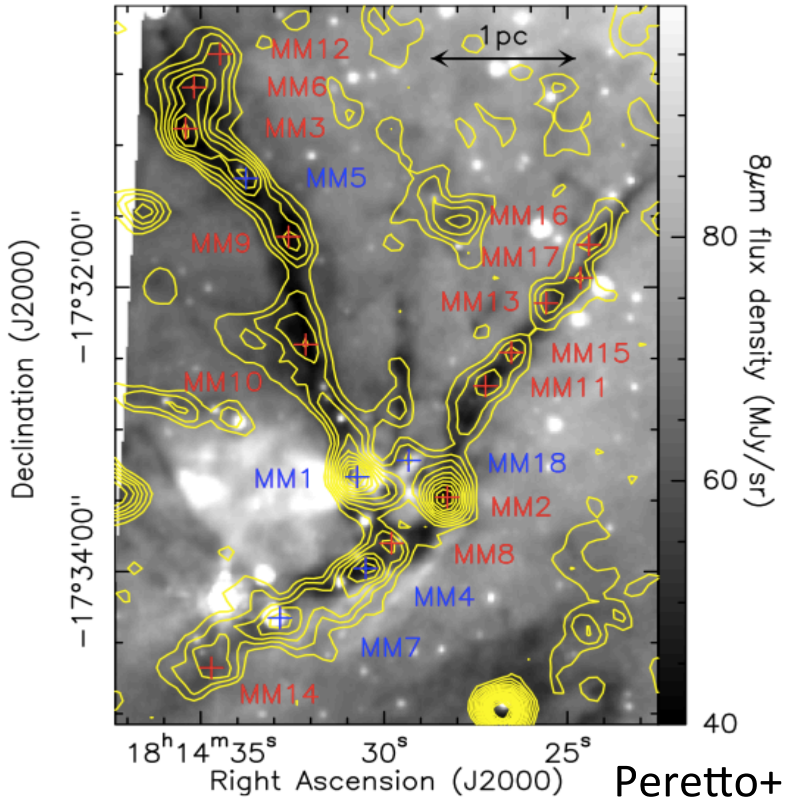
  → Strong shock trigger massive star formation?

Massive Filaments

- High-resolution observations of massive cloud cores ($M_{core} \sim 10^2\ M_{sun}$) indicate that massive cores are embedded in massive molecular filaments ($M \sim 10^3\ M_{sun}$).



ALMA cycle 0 N_2H^+ image (Peretto+13)

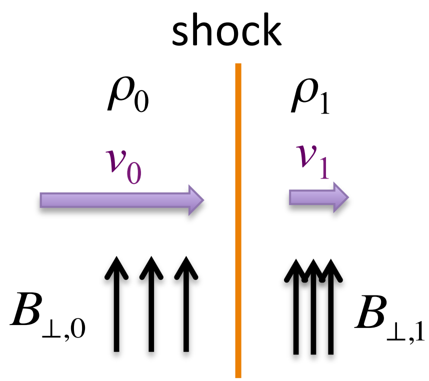


Peretto+14

Fig. 1. *Spitzer* 8 μm image of SDC13 in grey scale on top of which we overlaid the IRAM 30 m MAMBO 1.2 mm dust continuum contours (from 3 mJy/beam to 88 mJy/beam in step of 5 mJy/beam). The positions of the identified 1.2 mm compact sources within the SDC13 filaments are marked as crosses, red for starless sources and blue for protostellar sources.

Basics of Isothermal MHD Shock

- Observed cloud collisions are characterized by large collision velocity > 10 km/s
  → High Mach number shock ($M_s \sim 100$) is induced and plays a crucial role.
- Isothermal MHD shock jump condition:



- if $B_{\perp,0} < B_{cr}$ $\quad \rho_1 / \rho_0 \approx M_s^2$

  Sonic Mach number: $\quad M_s \equiv \dfrac{v_{sh}}{c_s}$

- if $B_{\perp,0} > B_{cr}$ $\quad \rho_1 / \rho_0 \approx \sqrt{2}\, M_A$

  Alfven Mach number: $\quad M_{\mathrm{Alf}} \equiv \dfrac{v_{\mathrm{sh}}}{c_{\mathrm{Alf}}} = \dfrac{\sqrt{4\pi\rho_0}\, v_{\mathrm{sh}}}{B_{\perp,0}}$

- $$B_{cr} = \sqrt{8\pi\rho_0}\,\frac{c_s^2}{v_{sh}} = 0.1\,\mu\mathrm{G}\left(\frac{v_{sh}}{10\,\mathrm{km/s}}\right)^{-1}\left(\frac{n_0}{300\,\mathrm{cm}^{-3}}\right)^{1/2}\left(\frac{c_s}{0.2\,\mathrm{km/s}}\right)^{2}$$

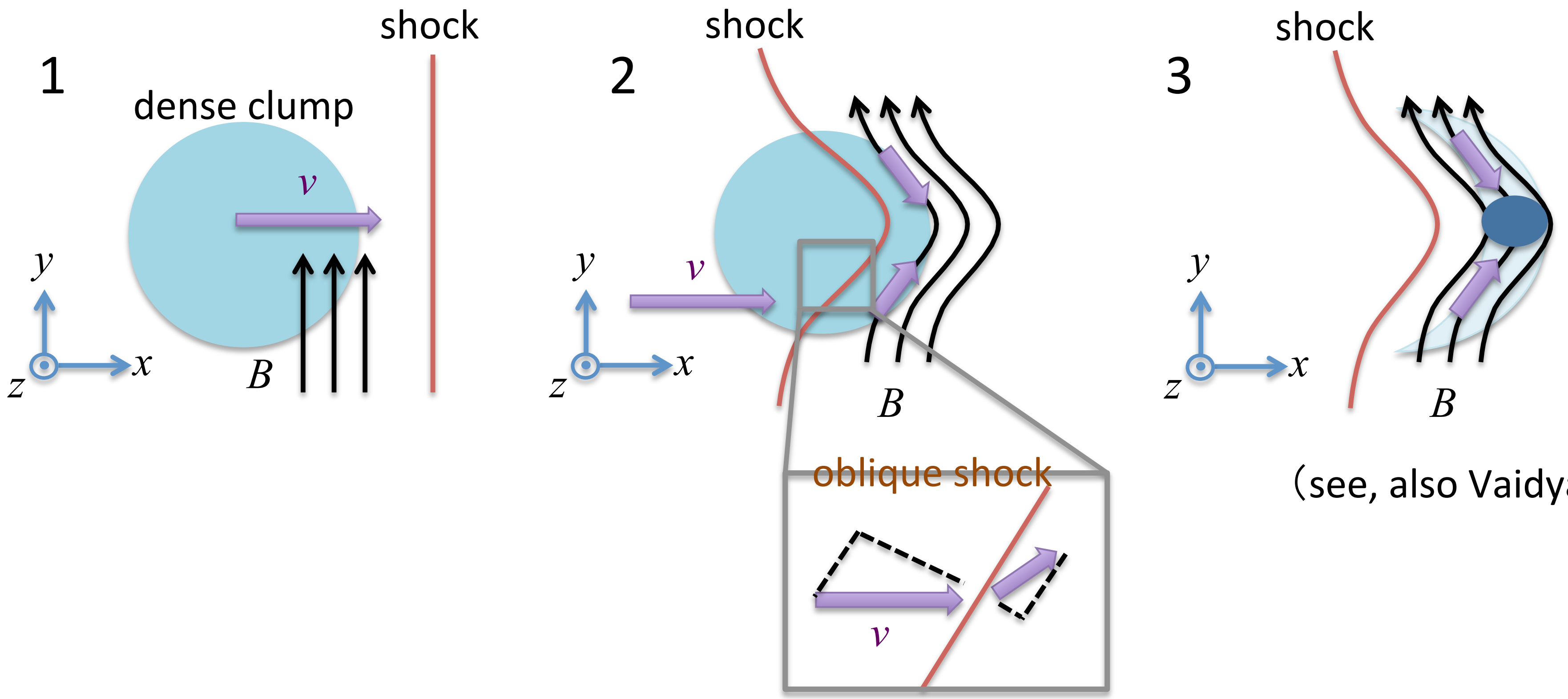
→ The effect of magnetic field is always important for the shock in molecualt cloud.

(see also, Padoan+02)

Filament Formation behind MHD Shock

- Molecular clouds are characterized by supersonic turbulence.
  → clouds are expected to be very clumpy due to turbulent mixing/compression.

- What happens when a dense clump is swept by a shock?



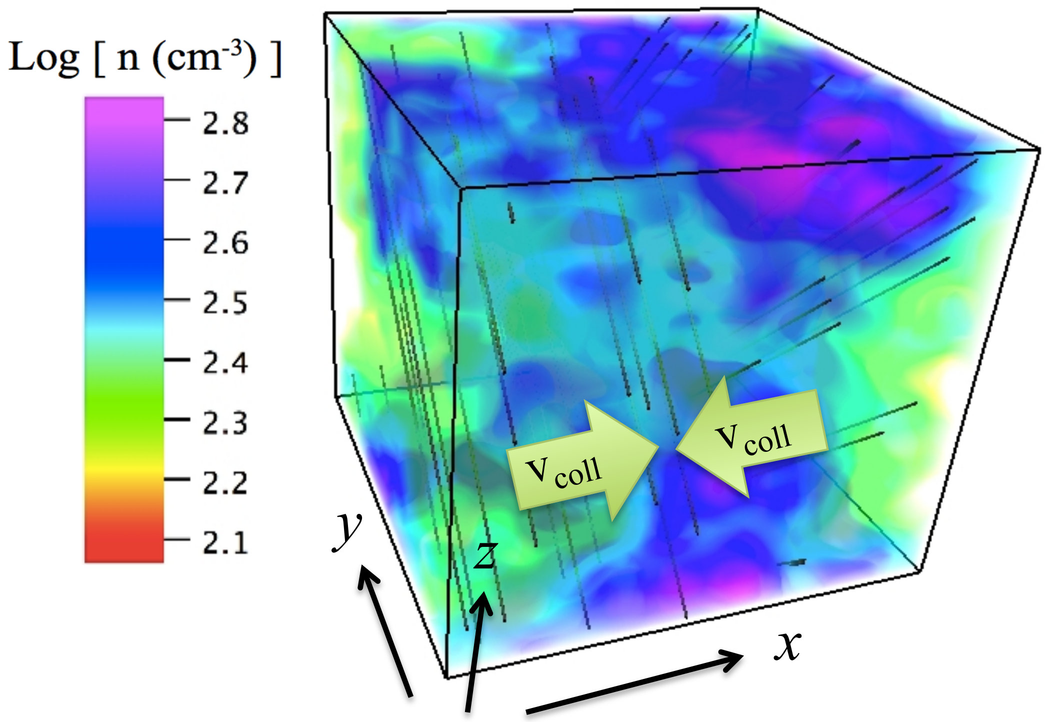
(see, also Vaidya+13)

＊ Compression doesn't happen in the direction perpendicular to B field.
→ MHD shock compression of a dense blob leads to a filament formation.

Setting of Simulation

- Isothermal ($c_s = 0.2$ km/s) 3D MHD simulation of cloud collison with self-gravity.
  - Fiducial setting
    - ✓ $\langle n \rangle$=300 cm^{-3} + fluctuations with $P_{\log n}(\mathrm{k}) \propto k^{-4}$, $\Delta n / \langle n \rangle = 0.43$

      ↑ typical density spectrum in supersonic turbulence (Beresnyak+05)
    - ✓ $B = 20$ μG in the y-z plane (cloud is magnetically supercritical with $\mu/\mu_{cr} \sim 2$)
    - ✓ Converging flows along x-axis with $v_{coll} = 10$ km/s, which collide head on at center.



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

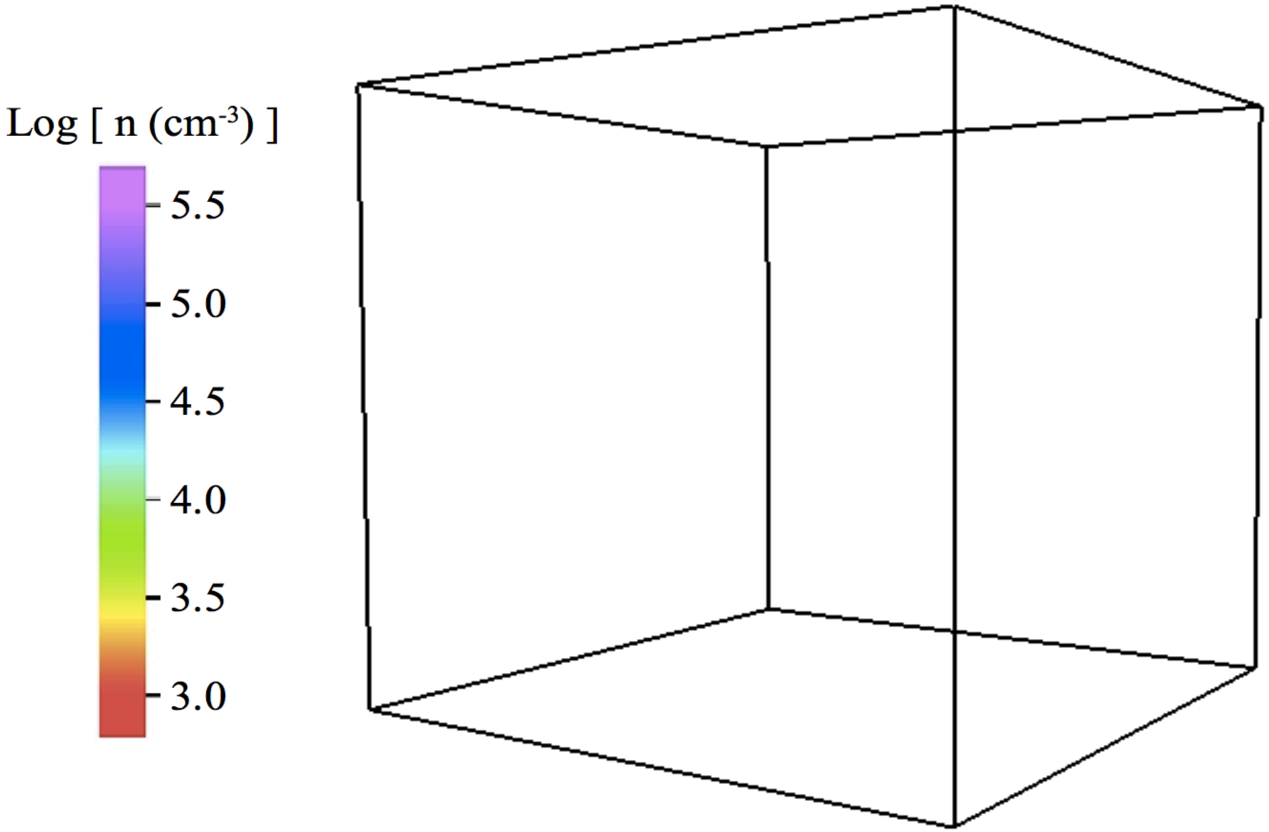
Resolution = 1024^3

→ $\Delta x = 0.008$ pc

Result

Inoue & Fukui 13, ApJL

3D structure of number density

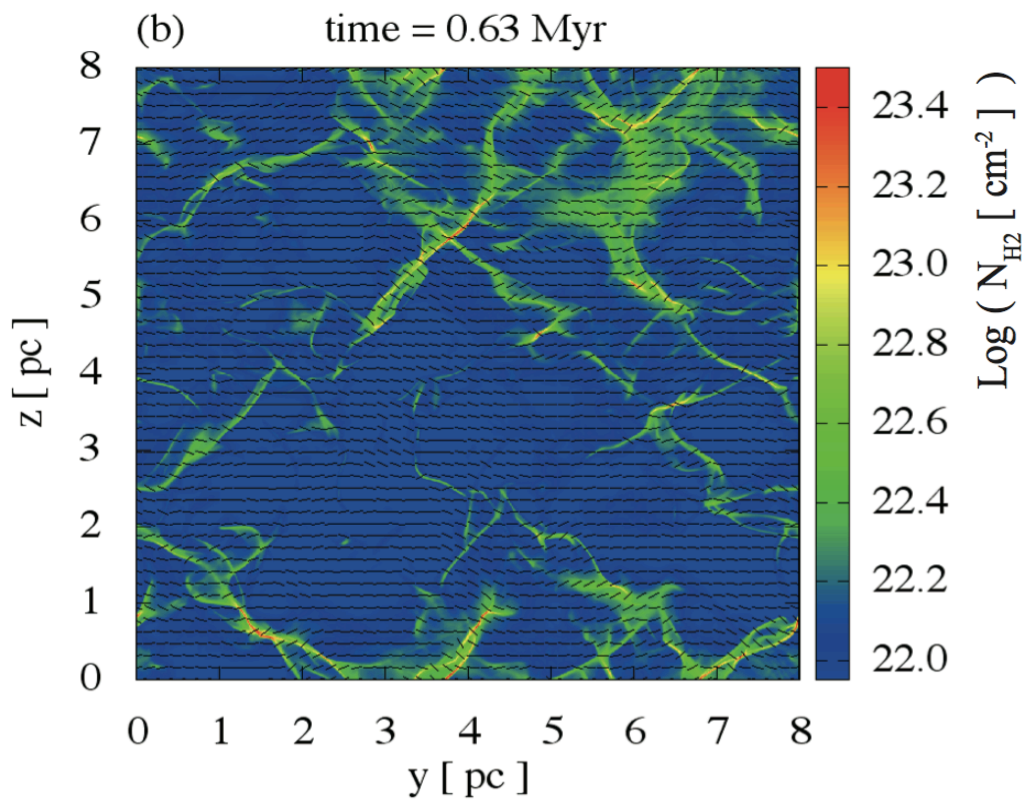


- Only shocked dense gas ($n > 10^3$ cm^{-3}) is shown.
- Filaments are formed as expected.

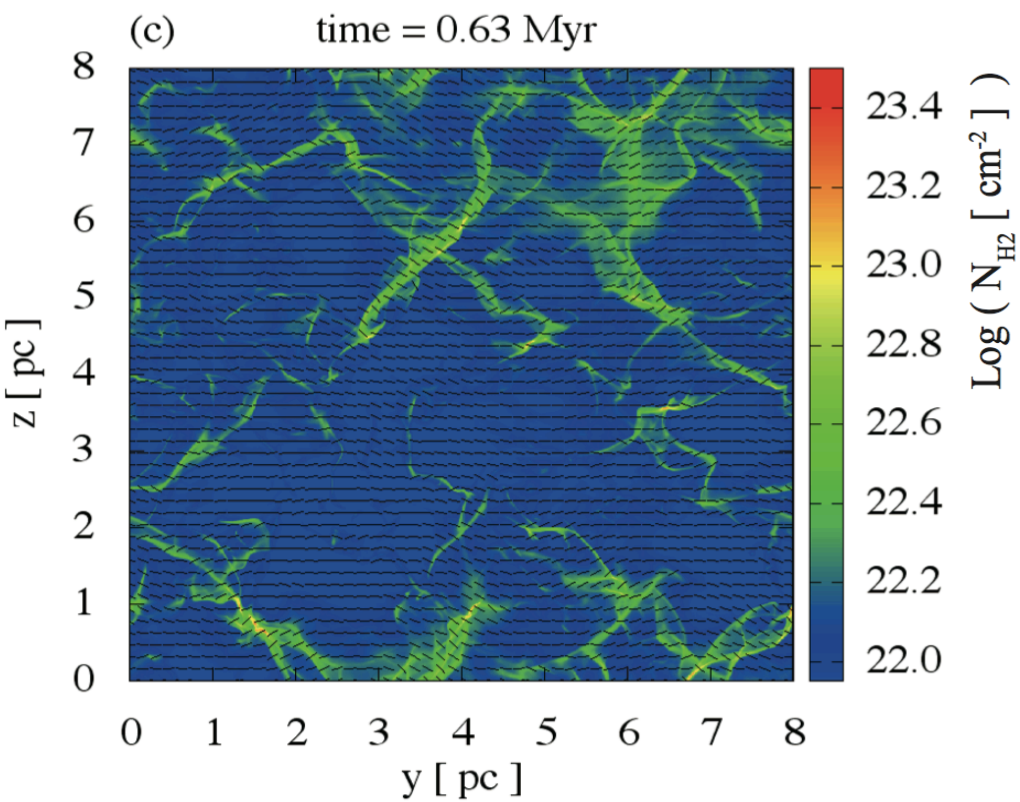
Result

Inoue & Fukui 13, ApJL

Column density structure（w self-gravity）



Column density structure（w/o self-gravity）



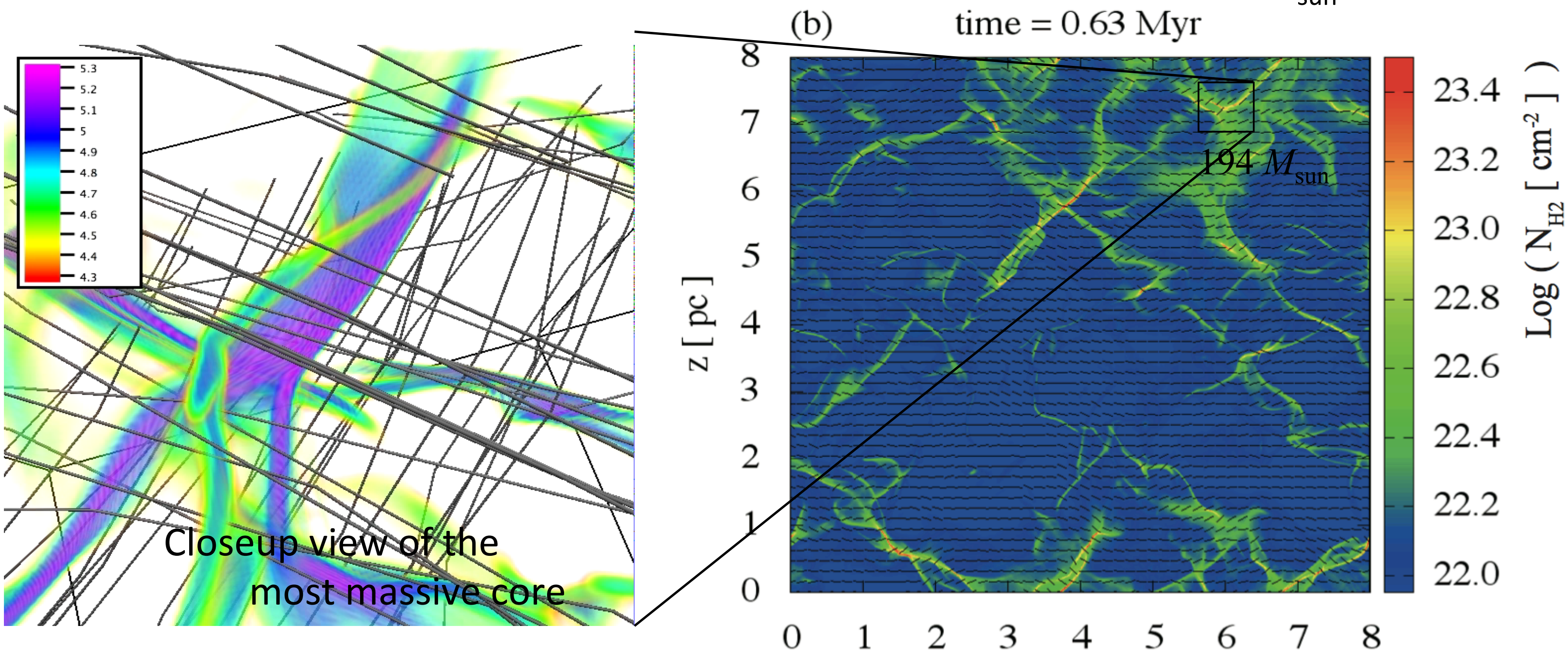
- Filaments are formed even in the result of simulation w/o self-gravity

  → Filaments are formed by the MHD effect, not by gravity as expected.
- In the result with self-gravity, some high-N regions begin to collapse.

Massive Filamentary Core

Inoue & Fukui 13, ApJL

- 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 ~ $10^3\ M_{sun}$



- Large effective Jeans mass is due to strong magnetic field (and turbulence).

$$M_{J,eff} \sim M_{J,th}(c_s) + M_{J,mag}(c_A) + M_{J,turb}(\Delta v)$$

$$M_{J,th} : M_{J,mag} : M_{J,turb} = 1 : 333 : 196$$

$\langle B \rangle_{core} = 280\ \mu G$

$\langle \Delta v \rangle_{core} = 1.2$ km/s

$\langle n \rangle_{core} = 0.8 \times 10^5\ cm^{-3}$

→ Large mass accretion rate: $dM/dt \approx (c_s^2 + c_A^2 + \Delta v^2)^{3/2}/G \sim 4 \times 10^{-3}\ M_{sun}/yr$

Influence of Initial Parameters

- Influence of initial parameters on core mass.

  - Average postshock state:

$$\langle \rho_1 \rangle \approx \sqrt{2}\,\rho_0\, M_A = \sqrt{8\pi}\,\rho_0^{3/2} v_{\rm sh} / B_0 \qquad v_{\rm sh} \sim v_{\rm coll}$$

$$\langle B_1 \rangle \approx \sqrt{2}\, B_0\, M_A = \sqrt{8\pi\rho_0}\, v_{\rm sh}$$

↑ Shock jump conditions of isothermal MHD shock

  - Effective Jeans mass:

$$M_{\rm J,eff} \sim M_{\rm J,mag} \propto \frac{\langle B \rangle_{\rm core}^3}{\langle \rho \rangle_{\rm core}^2}$$

  - If we substitute $\langle f_1 \rangle$ for $\langle f \rangle_{\rm core}$, we obtain upper limit of core mass.

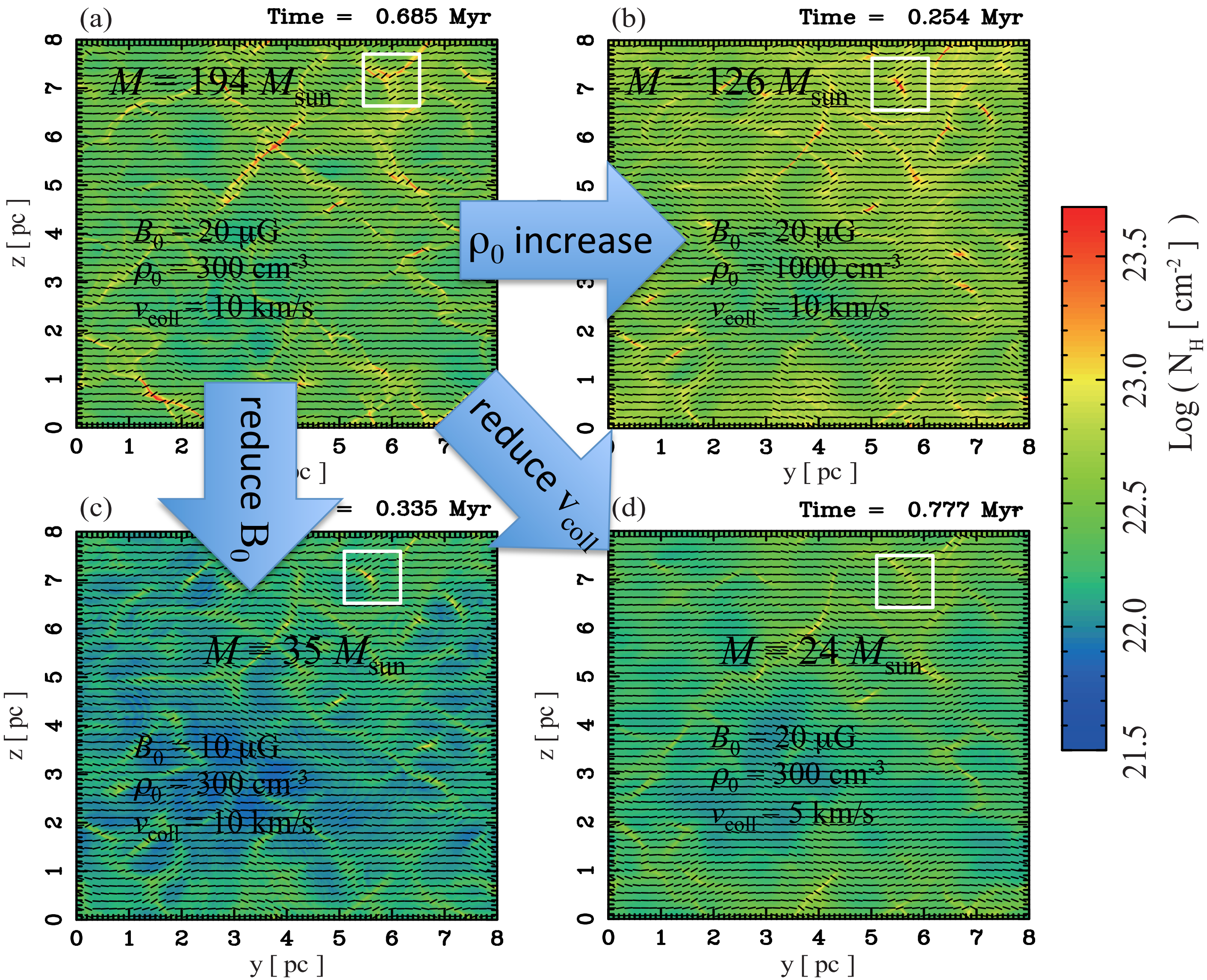
$$M_{\rm J,eff} \leq \frac{B_0^2\, v_{\rm sh}}{\rho_0^{3/2}}$$

→ Core mass is expected to be increasing function of B_0 and $v_{\rm coll}$, and decreasing function of ρ_0.

Influence of Initial Parameter

- Core mass is indeed increasing function of B_0 and v_{coll}, and decreasing function of ρ_0, as expected.

$$M_{\mathrm{J,eff}} \propto \frac{B_0^2 v_{\mathrm{sh}}}{\rho_0^{3/2}}$$



Summary

- We have studied cloud collision using 3D isothermal MHD simulation with self-gravity.

  - Shock-clump interaction induces downstream focusing flows along B field.

    → Formation of dense filament behind the shock wave.

  - Massive filaments perpendicular to B field with total mass $\sim 10^3$ M_{sun} can be created.

  - Owing to the strong B field (and turbulence), effective Jeans mass can be huge ($M_{core} > 100\ M_{sun}$ depending on parameters).

  - Core mass is a increasing function of B_0 and v_{sh}, and decreasing function of ρ_0:

$$M_{J,eff} \leq \frac{B_0^2 v_{sh}}{\rho_0^{3/2}}$$

→ High collision velocity is necessary for triggering massive star formation.