

Magnetic Field Amplification Driven by a Relativistic Shock-Clump Interaction in Collisionless Plasma Systems



**Tomita S., Ohira Y., Kimura S.S., Tomida
K., Toma K., 2022 ApJL 936 L9**

Sara Tomita (Tohoku University) 

Yutaka Ohira (The University of Tokyo)

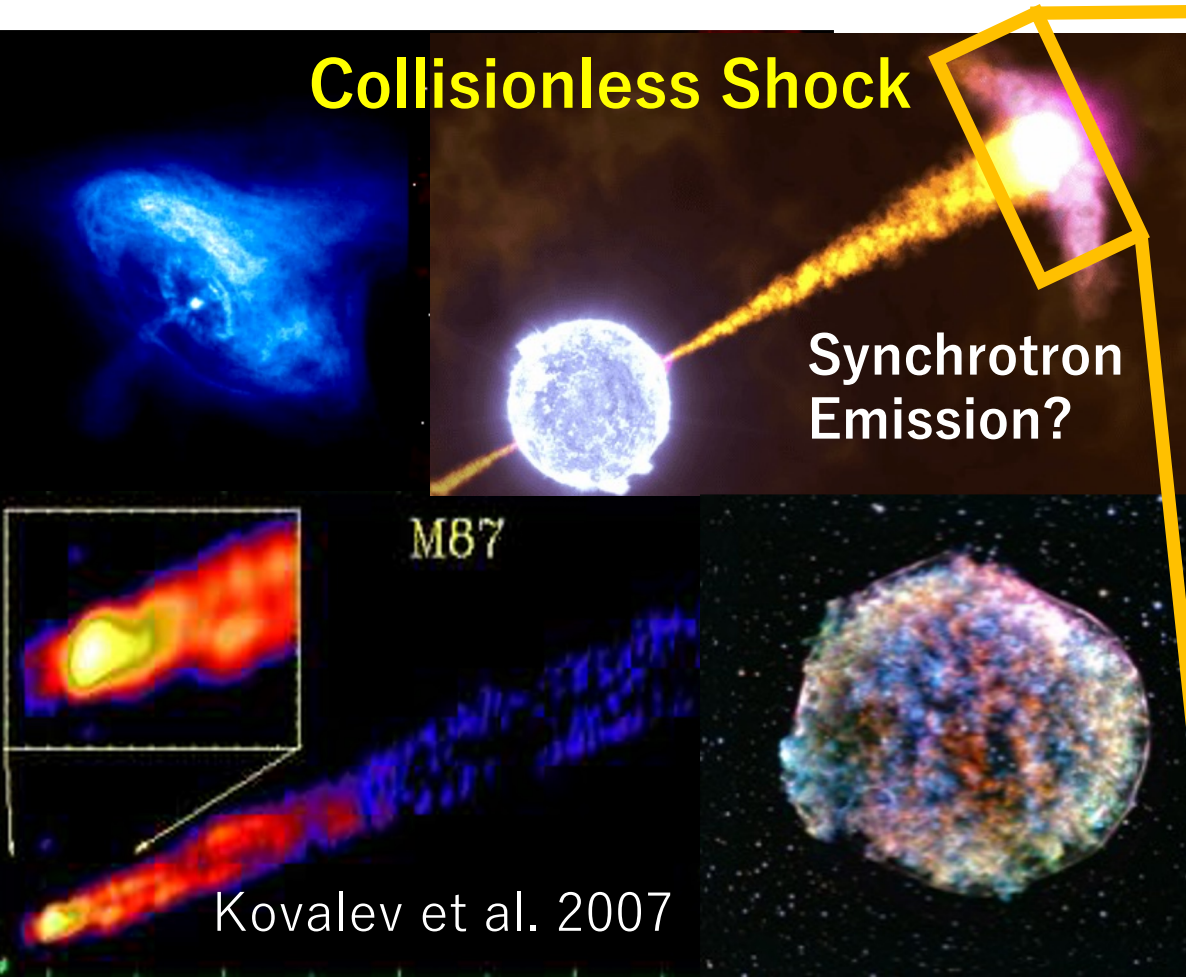
Shigeo S. Kimura, Kengo Tomida, Kenji Toma(Tohoku University)

The 32nd Texas Symposium on Relativistic Astrophysics, Shanghai, China, Dec. 11-16, 2023

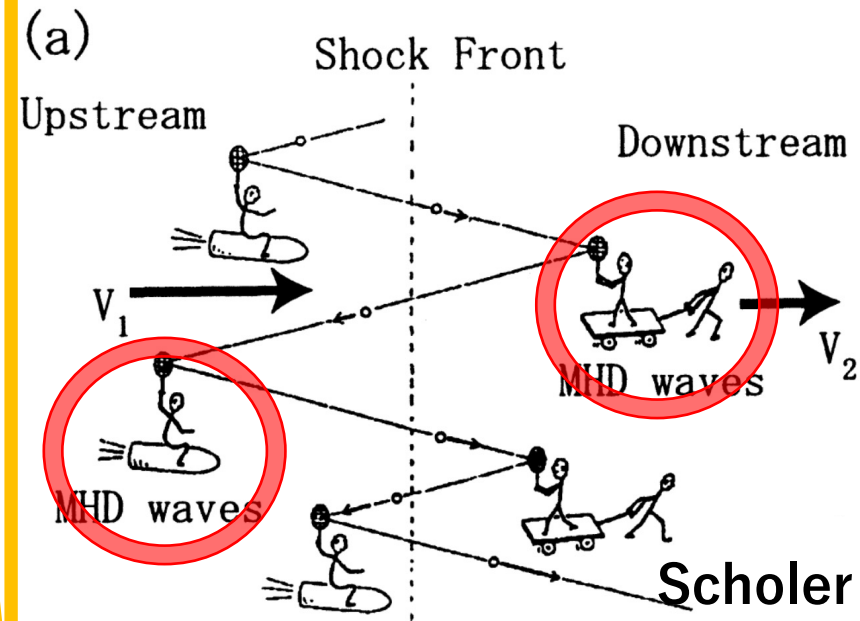
Strong Magnetic fields around Collisionless Shocks

✓ Non-thermal emission in high-energy astrophysical phenomena

Collisionless Shock



✓ Cosmic ray acceleration

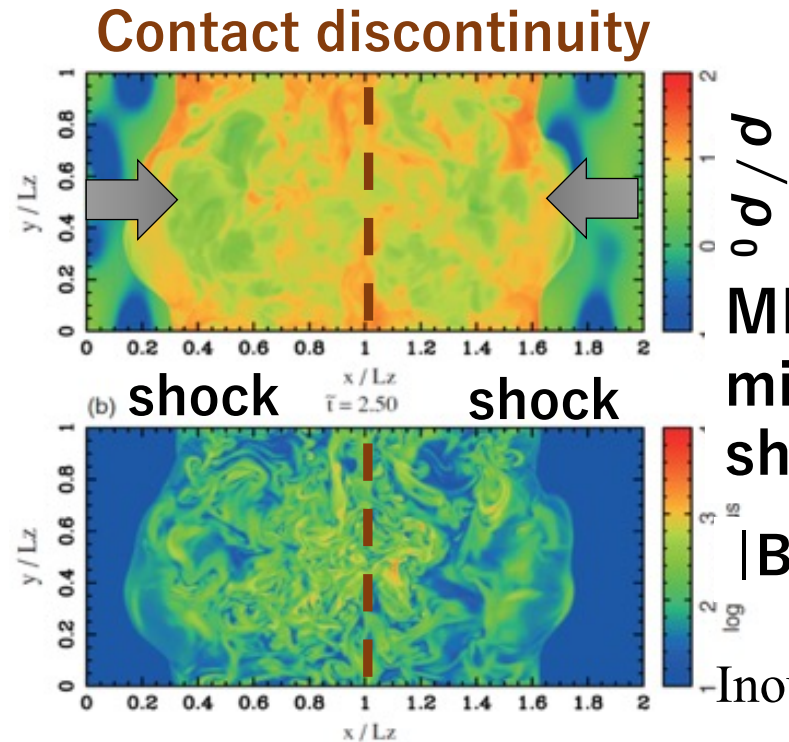
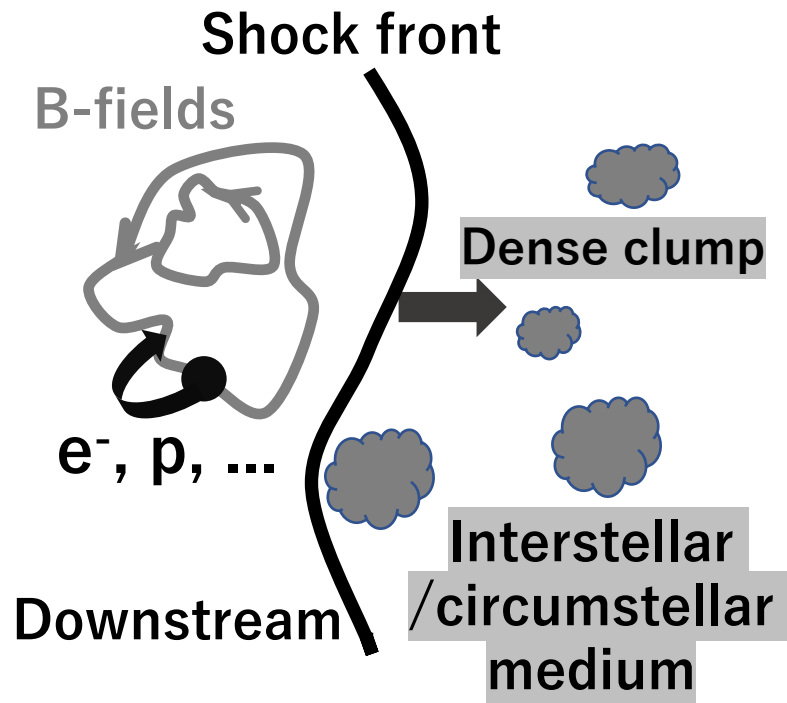


Strong B-fields ($\gg 3 \mu\text{G}$)?

B-fields around shocks is a crucial key to understand the origin of the CRs and emission mechanism.

Magnetic Field Amplification in Collisionless Shocks

😊 Turbulent dynamo amplifies b-fields in the large scale $\gg r_g$.



r_g : Gyroradius of thermal particles

MHD sim. of mildly-relativistic shocks ($\Gamma \sim 2$)

Inoue et al. 2011

😓 It's unknown whether b-fields are amplified by turbulent dynamo in a **relativistic** ($\Gamma \gg 1$) shock.

🤔 **Particle diffusion is negligible??**

Density structures are maintained in post-shock regions? 2

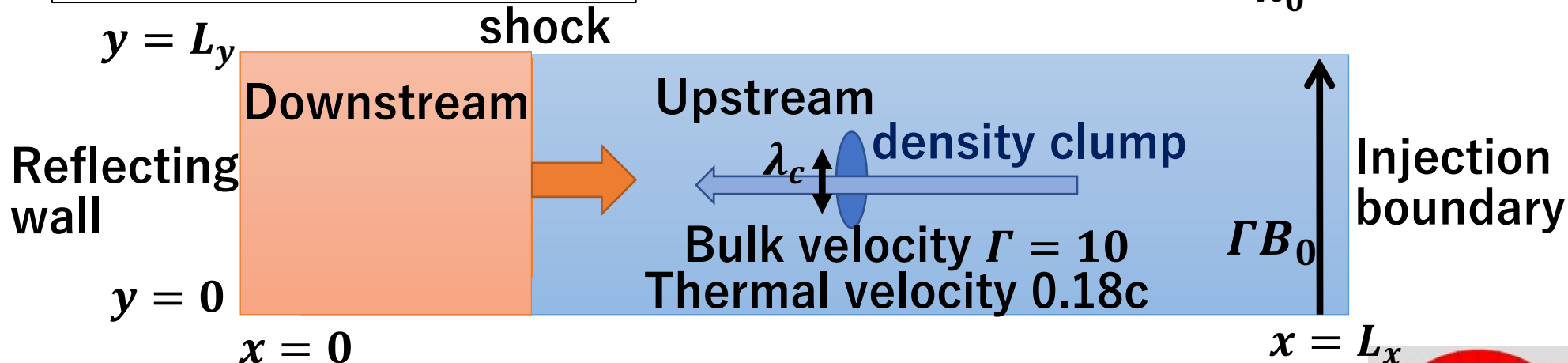
Simulation Set Up

*Source code given by Matsumoto Y.(Chiba Univ.)

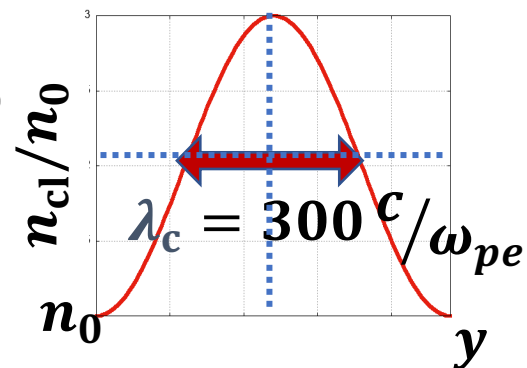
●Particle-in-cell (PIC) simulation

- Two – dimensional electromagnetic PIC code*.
- $e^\pm$ plasmas
- $L_x = 3120 c/\omega_{pe}$, $L_y = 1200 c/\omega_{pe}$ ($\Delta x = \Delta y = 0.1 c/\omega_{pe}$)
- $n_0=120$ particles/cell, total $\sim 10^{12}$ particles

Downstream rest frame

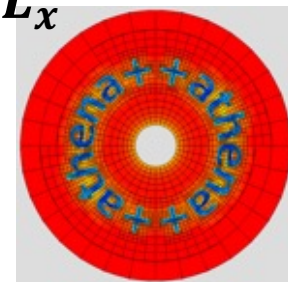


Clump Structure



●MHD simulations are also performed in the same setup.

Athena++ MHD code.



Velocity of the shocked clump u_x

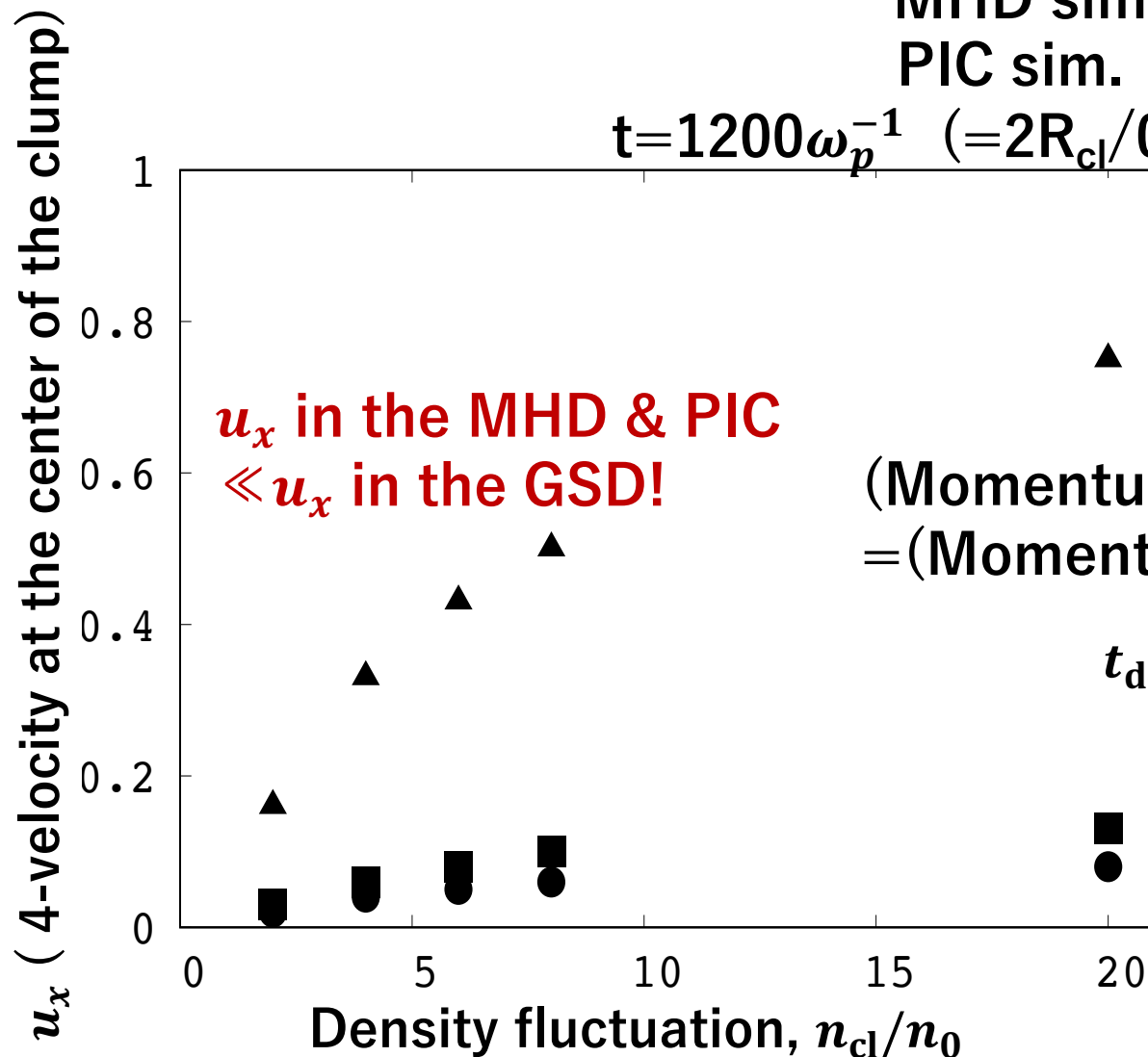
Tomita et al. 2022 ApJL

GSD approximation (Sironi & Goodman 2007) ▲

MHD sim. ■

PIC sim. ●

$t = 1200 \omega_p^{-1} (= 2R_{cl}/0.5c)$



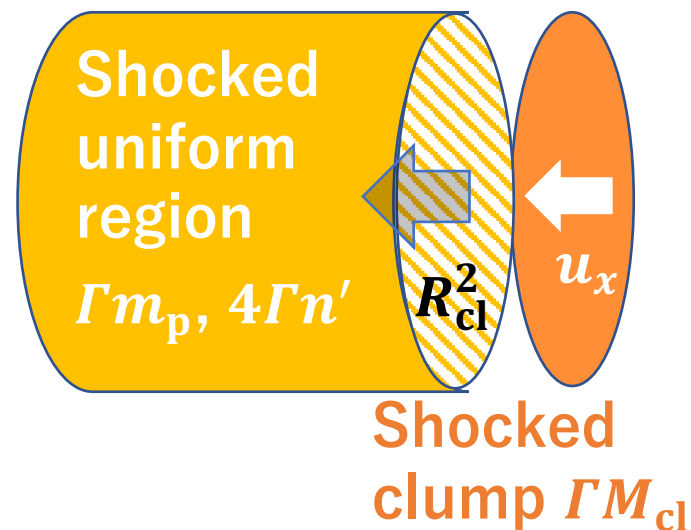
u_x in the MHD & PIC
 $\ll u_x$ in the GSD!

(Momentum of the shocked clump)
= (Momentum flux) $\times$ (Deceleration time)

$$t_{dec} = \frac{M_{cl}}{\Gamma n' m_p v_{cl,d} R_{cl}^2} = \frac{n'_{cl}}{\Gamma n'} t_{eddy}$$

Clumps decelerate before
one eddy-turnover time
if $n'_{cl}/n' < \Gamma$!

For ISM, $n'_{cl}/n' \sim 1-10^2$,
GRB, AGN jets $\Gamma \sim 10-10^3$ 4



Influence of Particle Diffusion on the Deceleration

GSD approximation (Sironi & Goodman 2007)

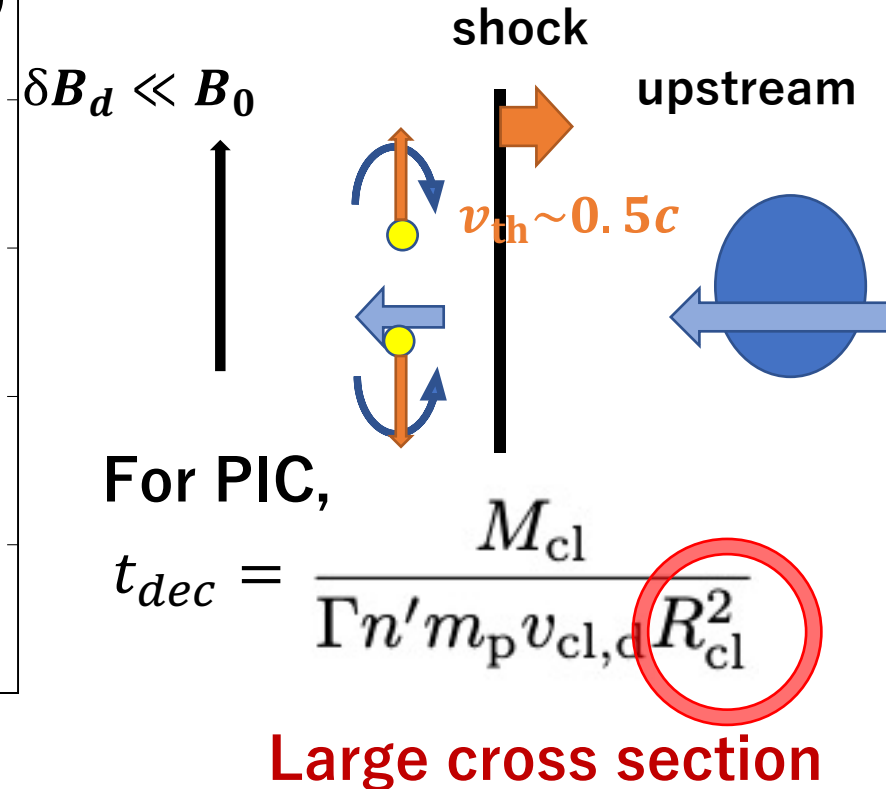
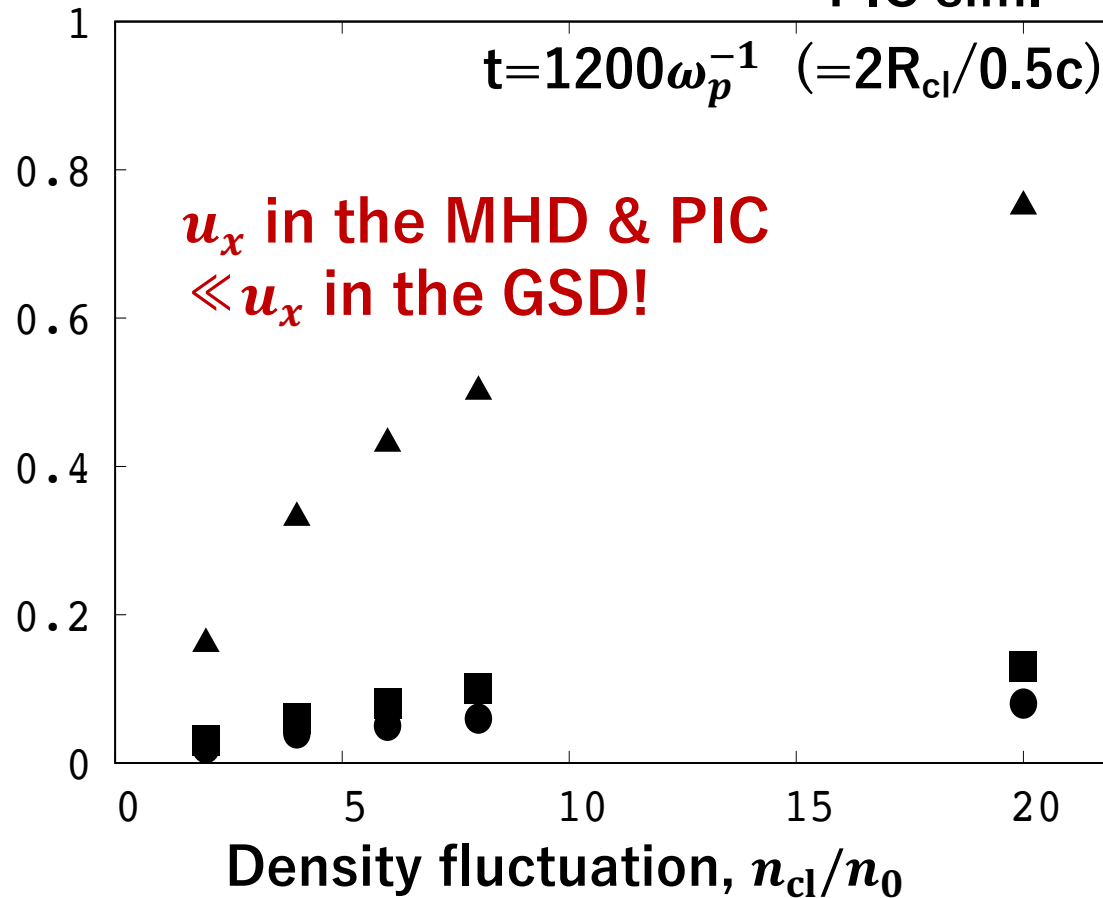
Tomita et al. 2022 ApJL

MHD sim.

PIC sim.

Uniform downstream rest frame

u_x (4-velocity at the center of the clump)



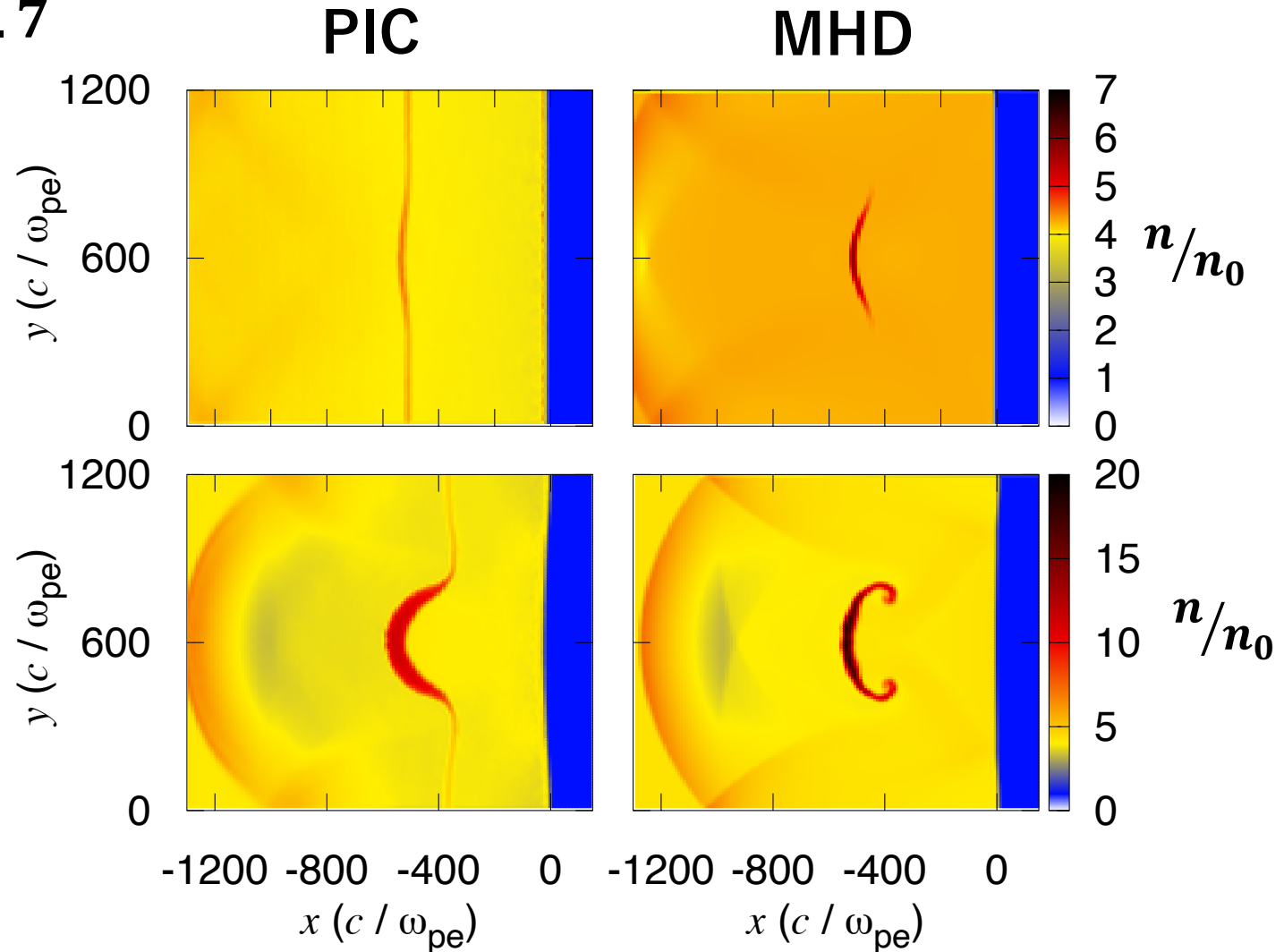
In relativistic shocks, the clump decelerate farther due to the particle streaming from the clump.

Density distribution n/n_0

- $\lambda_c/r_{ge} = 53.7$

- $n_{cl}/n_0 = 2$

- $n_{cl}/n_0 = 20$



MHD : Vortex is generated.

PIC : Particle streaming suppresses the vortex motion.

Vorticity distribution ($\lambda_c/r_{ge} = 53.7, n/n_0 = 2, 20$)

Tomita et al. 2022 ApJL

● $n_{cl}/n_0 = 2$

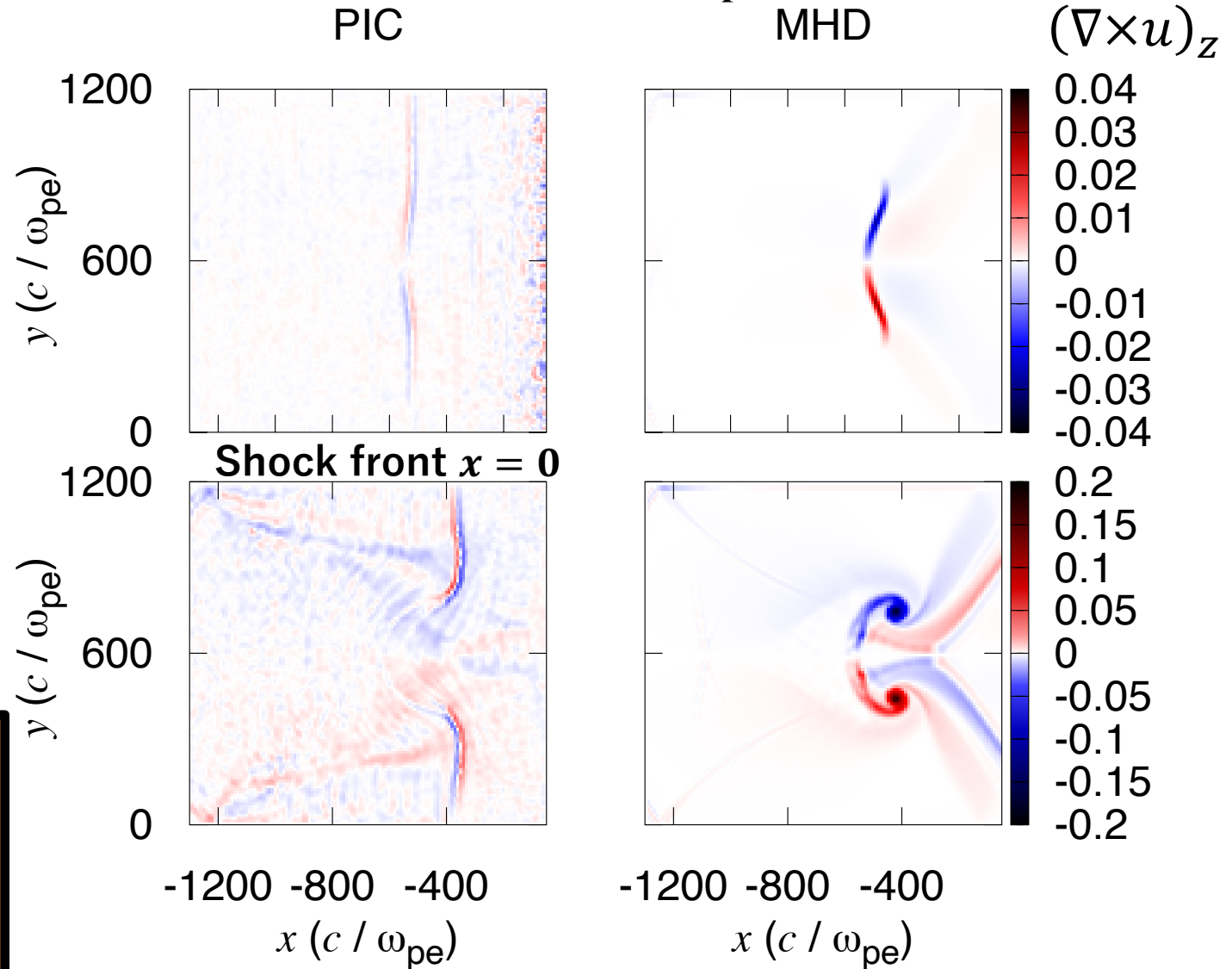
$T = 1450 \omega_p^{-1}$

The elapsed time since the clump interacts with the shock.

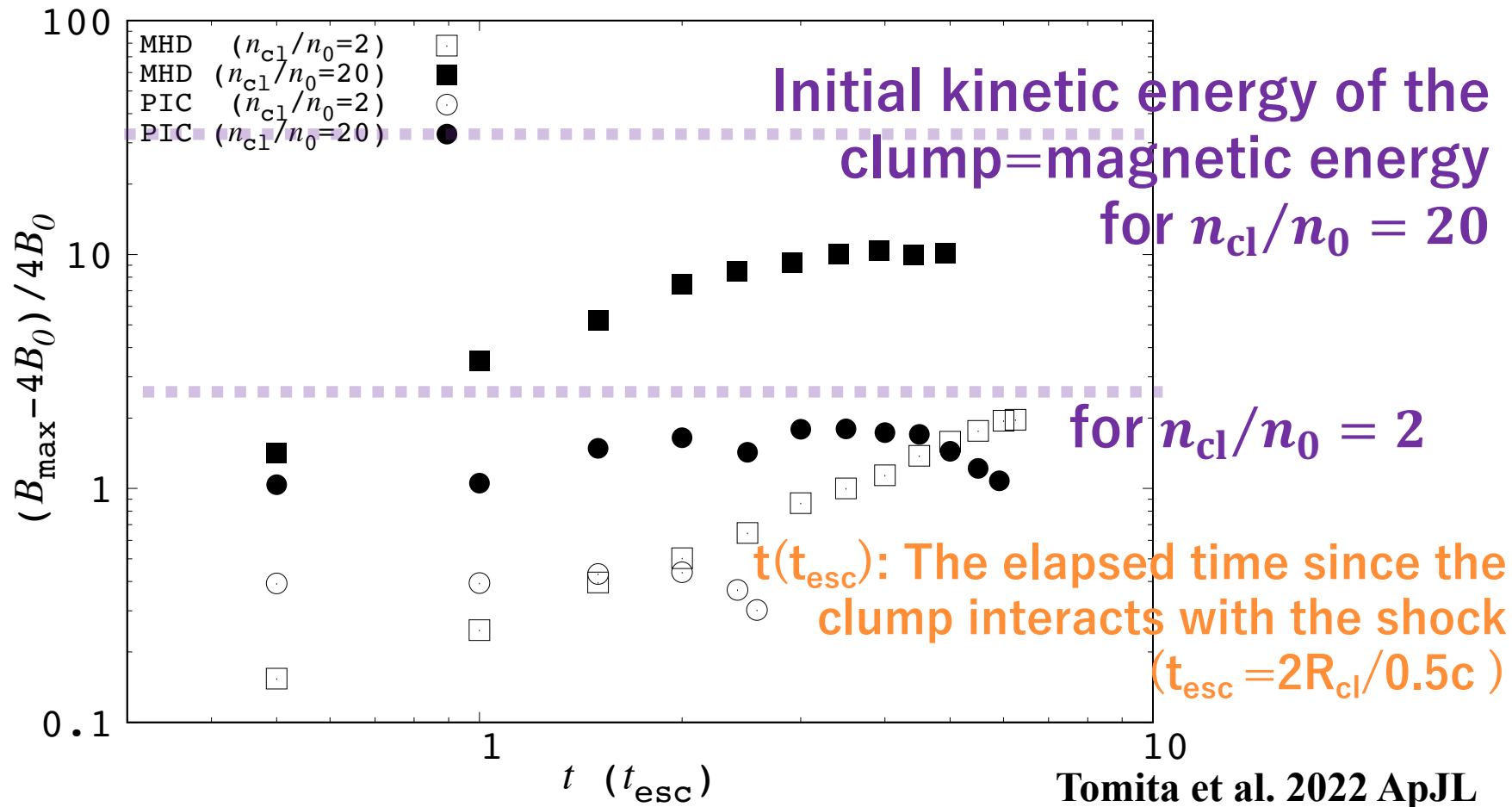
● $n_{cl}/n_0 = 20$

$T = 1450 \omega_p^{-1}$

The vorticity in the PIC is much smaller than that in the MHD.



Time evolution of the $|B_{\max}|$



Conclusion:

B-field amplification due to the turbulent dynamo caused by the shock-clump interaction does not work efficiently.

Summary

In relativistic collisionless shocks,
due to the **quick deceleration** and **particle escape**, the turbulent dynamo caused by the shock-clump interaction could **not be efficient**.

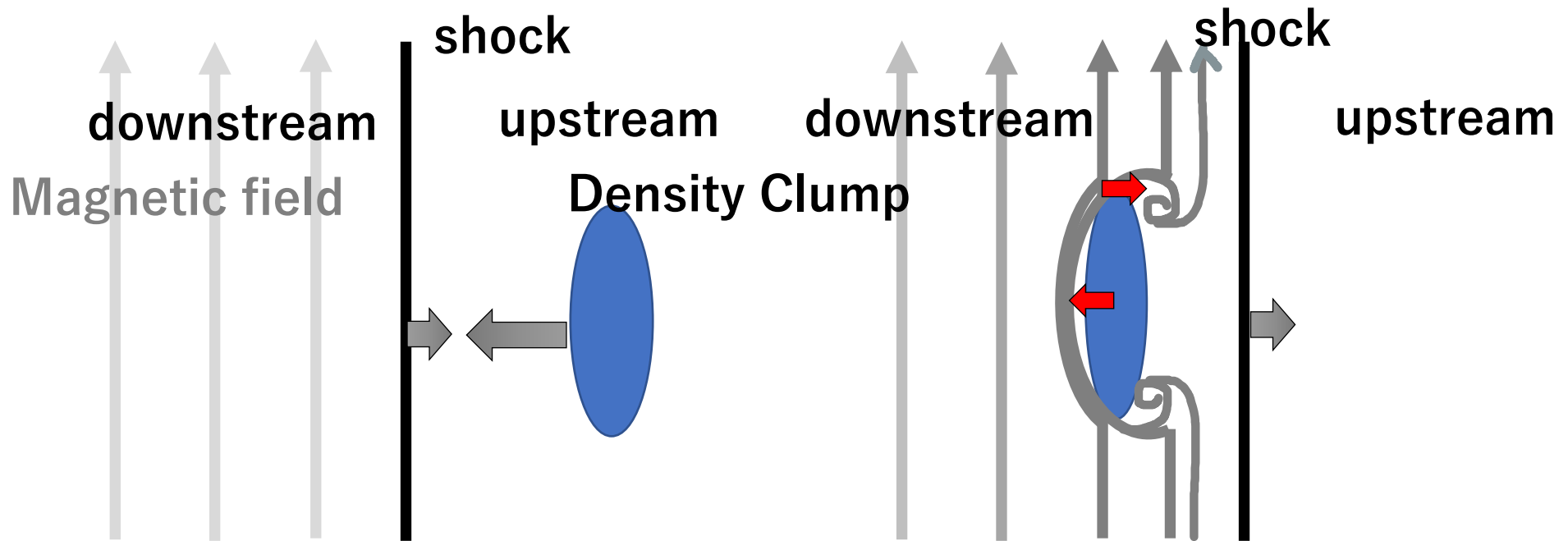
Tomita S., Ohira Y., Kimura S.S., Tomida
K., Toma K., 2022 ApJL 936 L9

Discussion

- The dependence of the ratio of λ_c/r_{ge} and plasma parameters (magnetization etc.) on the effect of escape and diffusion?
- When shocks interacts with multiple clumps, sound waves or weak shocks interact with each other.
 - > particle acceleration in the turbulence?

A relativistic shock-clump interaction

Downstream rest frame



Our work:

- Particle-in-Cell(PIC) simulation of a relativistic shock-clump interaction.
- Comparison between the evolution of the magnetic field amplification in PIC and MHD results.