Magnetic field amplification by the relativistic shock-clump interaction

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Sara Tomita（Tohoku University）

Yutaka Ohira（The University of Tokyo）

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

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Magnetic field around Collisionless Shocks

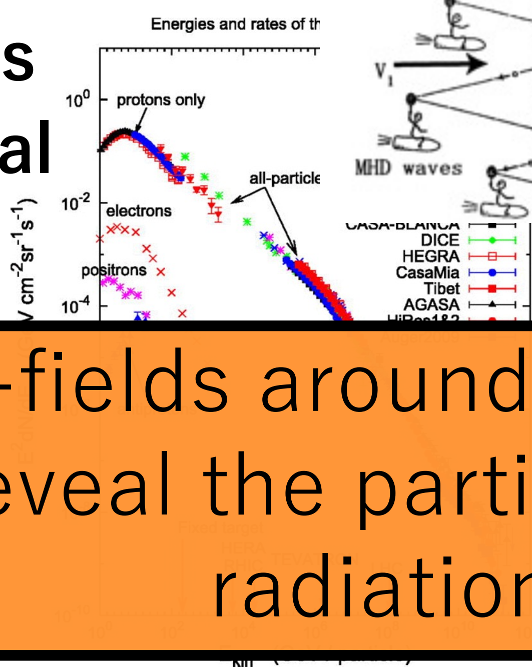
Thermal particles
Non-thermal particles
Strong b-fields？
etc.

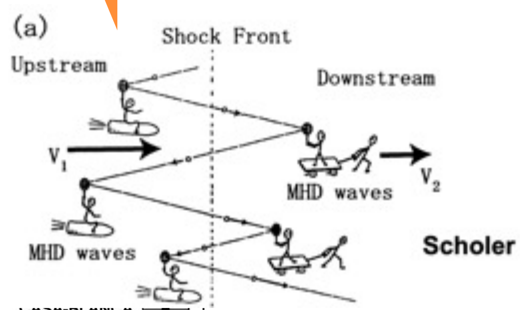
⬇？

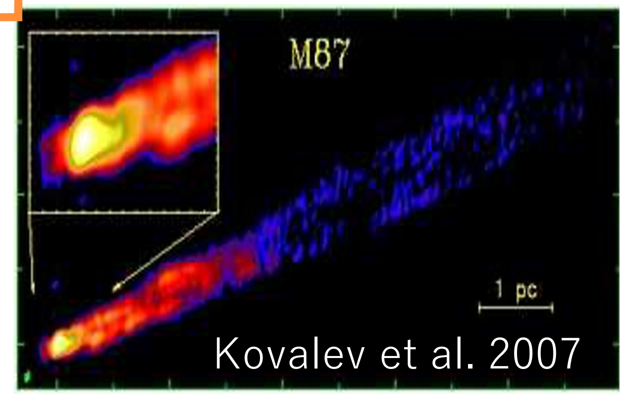
Cosmic rays
Non-thermal radiations

Thermalization
(Particle scattering by turbulent b-fields)

Kinetic energies of outflows from astrophysical objects



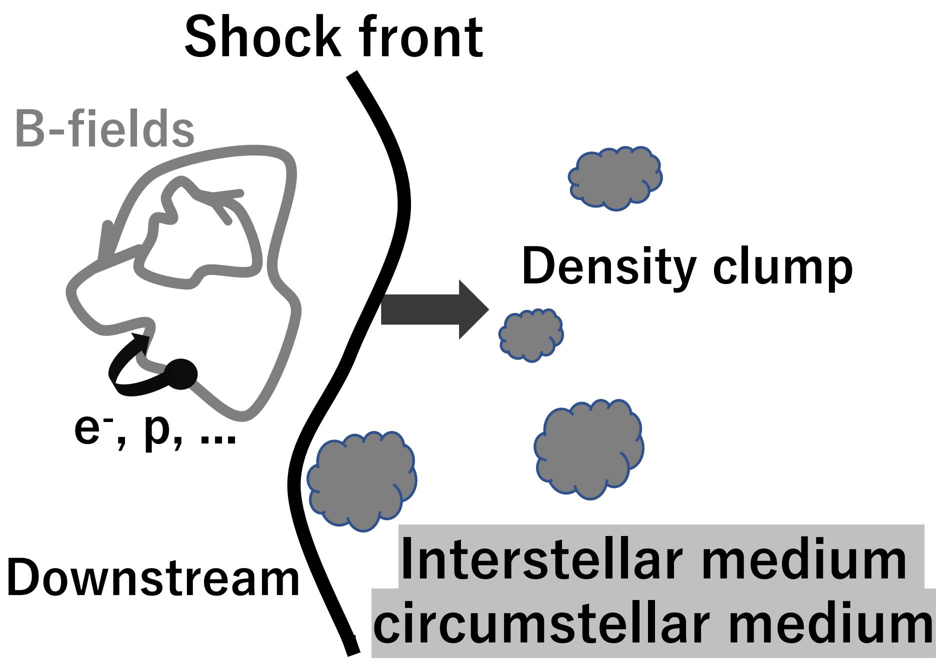


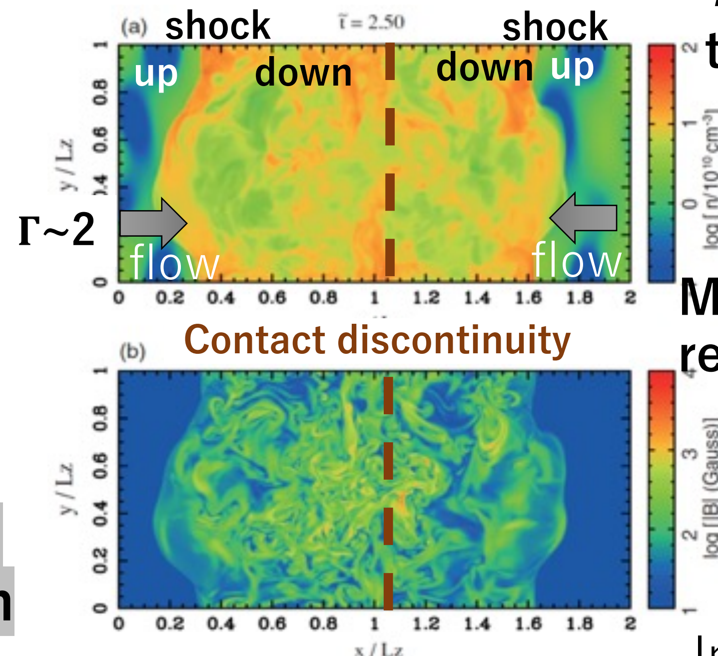


B-fields around shocks is needed to reveal the particle acceleration and radiation mechanism.

Magnetic Field Amplification in Collisionless Shocks

😁Turbulent dynamo amplifies b-fields in the large scale $\lambda_{\delta B} \gg r_{\mathrm{g}}$.





r_{g}: Gyroradius of thermal particles

MHD simulation of relativistic shocks

Inoue et al. 2011

😥MHD simulation cannot solve b-fields amplification concerning high-energy particles.

🤔Particle diffusion is negligible?? Density structures are maintained in post-shock regions?

Particle-In-Cell simulation is needed!!

Simulation Set Up

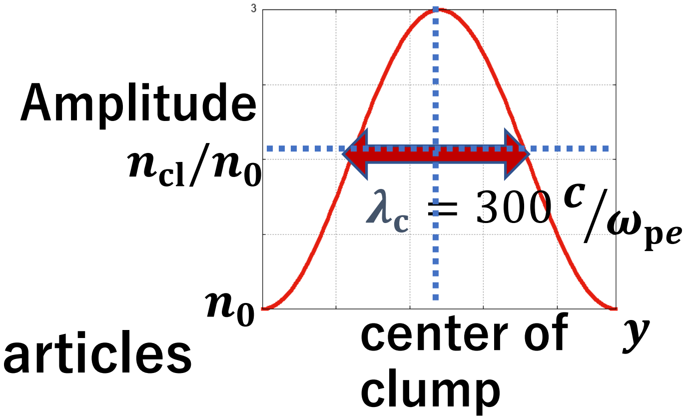
*Source code given by Matsumoto Y.(Chiba Univ.)

●Particle-in-cell (PIC) simulation

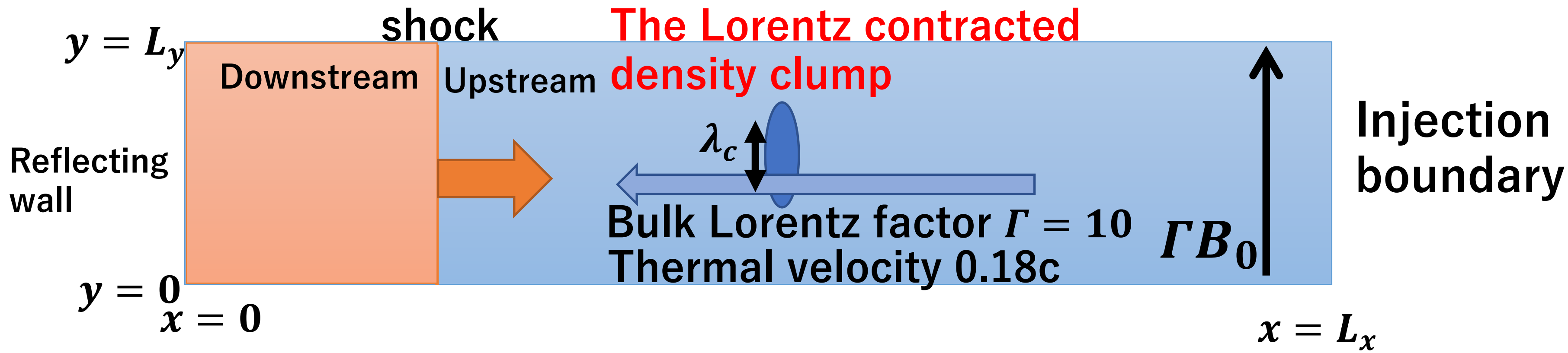
- Two－dimensional electromagnetic PIC code*.
- $e^{\pm}$ plasmas
- Calculator：Cray XC50（3000core）@NAOJ
- Box size ： $L_x = 3120\ c/\omega_{pe}$, $L_y = 1200\ c/\omega_{pe}$

  $(\Delta x = \Delta y = 0.1\ c/\omega_{pe})$
- Number of particles : n_0=120/cell, Total~10^{12}particles

Spatial distribution of $e^{\pm}$



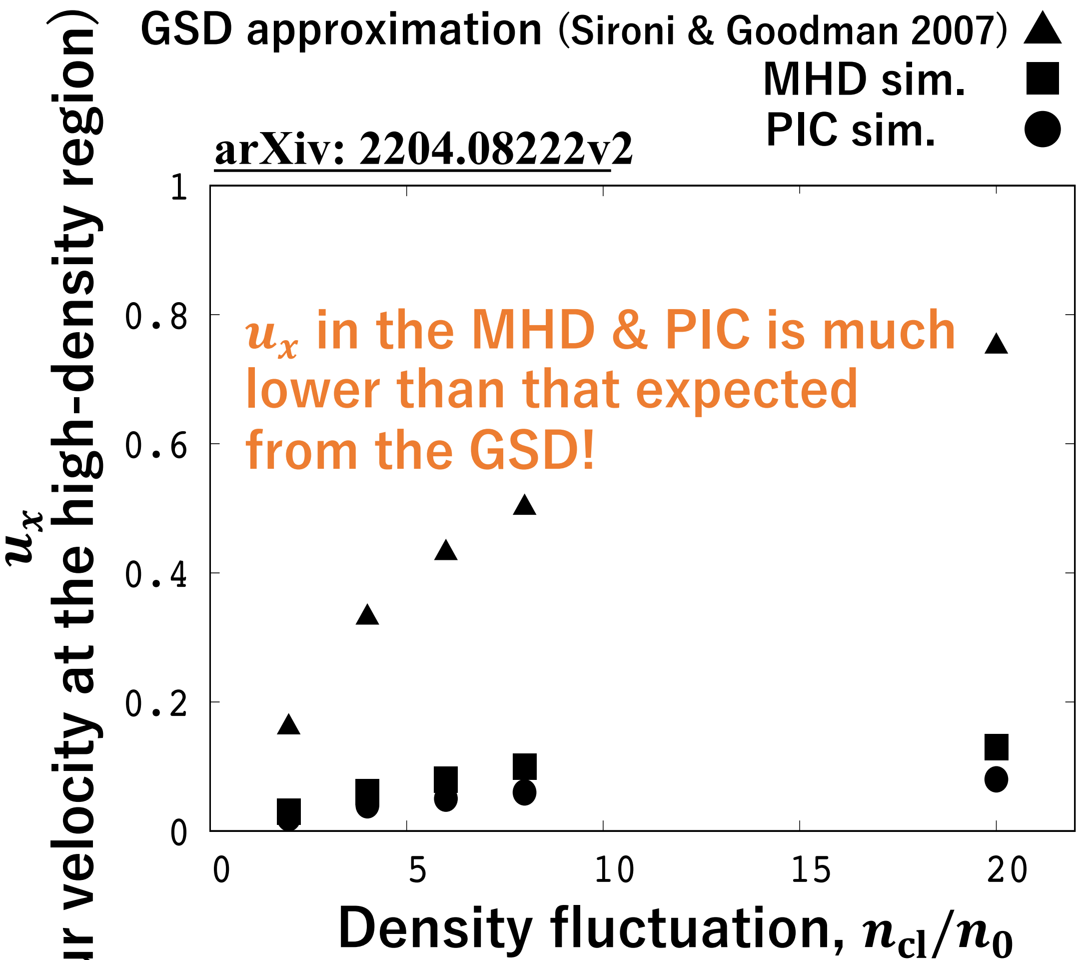
Downstream rest frame



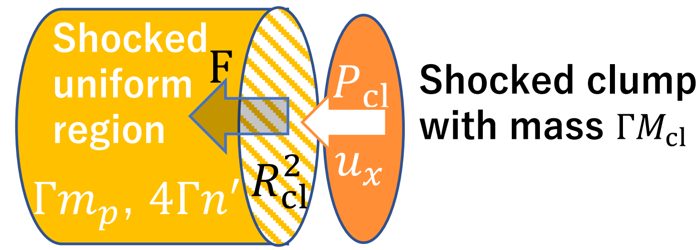
●MHD simulations are also performed in the same setup.

Athena++ MHD code.

Velocity of the shocked clump u_x



Theoretical estimation based on GSD did not take the clump deceleration into account.



P_{cl} : Momentum of the shocked clump

F : Momentum flux that clump sweeps

$$P_{cl} = \mathrm{F} t_{dec}$$

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

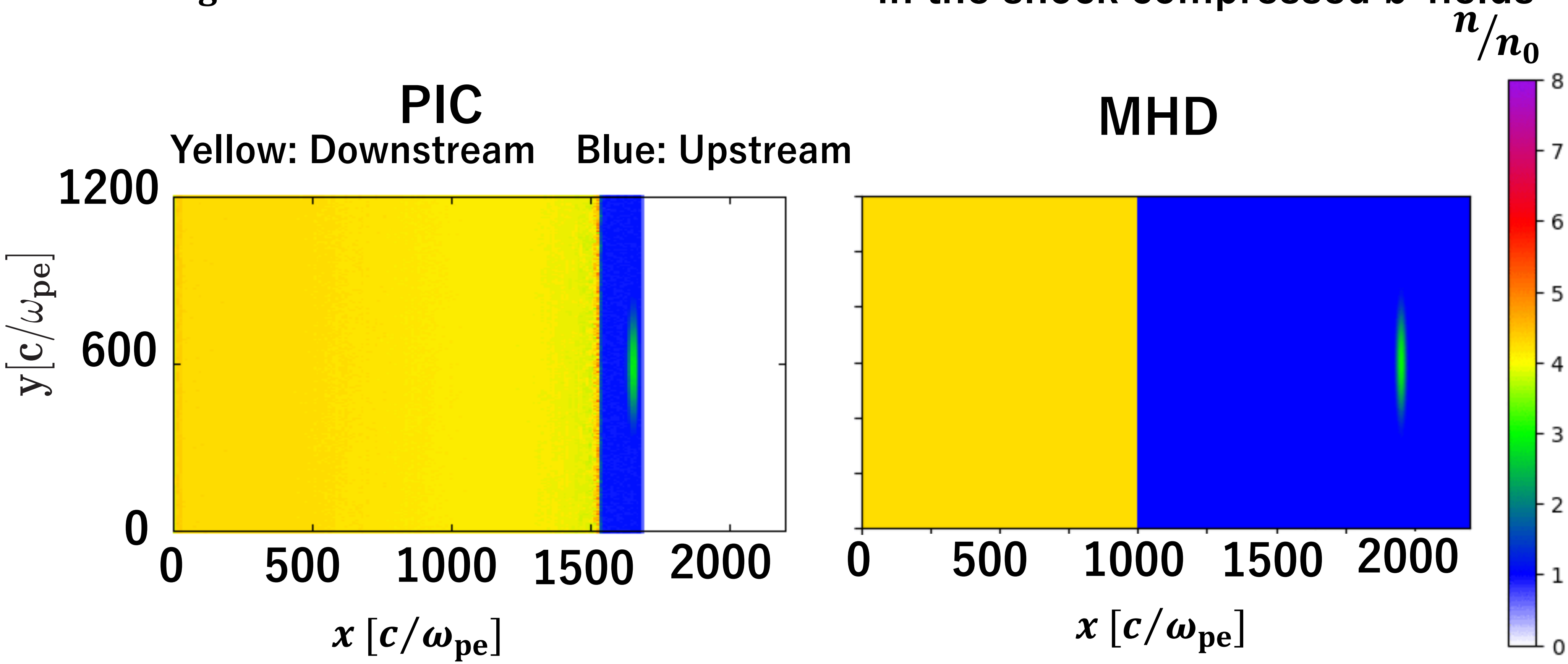
Our simulations: Γ=10

In relativistic shocks, the shocked clump decelerates Γ times quickly than that in non-relativistic shocks!!

Density distribution n/n_0

- $\lambda_c/r_{ge} = 53.7$, $n_{cl}/n_0 = 2$

r_{ge} : Gyroradius of thermal particles in the shock compressed b-fields

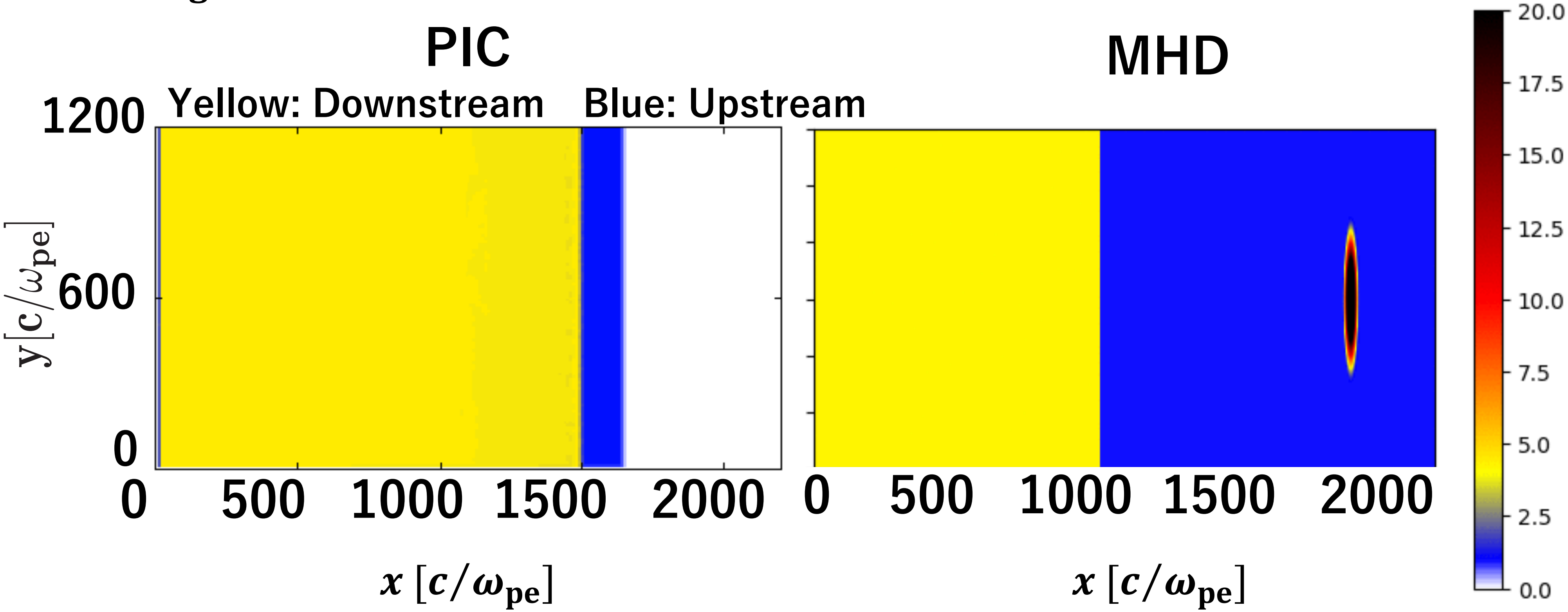


MHD : Clump is deformed in the shock normal direction.
PIC : Density distribution is uniform in the y-direction due to particle streaming.

Density distribution n/n_0

r_{ge} : Gyroradius of thermal particles in the shock compressed b-fields

- $\lambda_c/r_{ge} = 53.7$, $n_{cl}/n_0 = 20$



MHD : Vortex is generated.
PIC : Particle streaming suppresses the vortex motion.

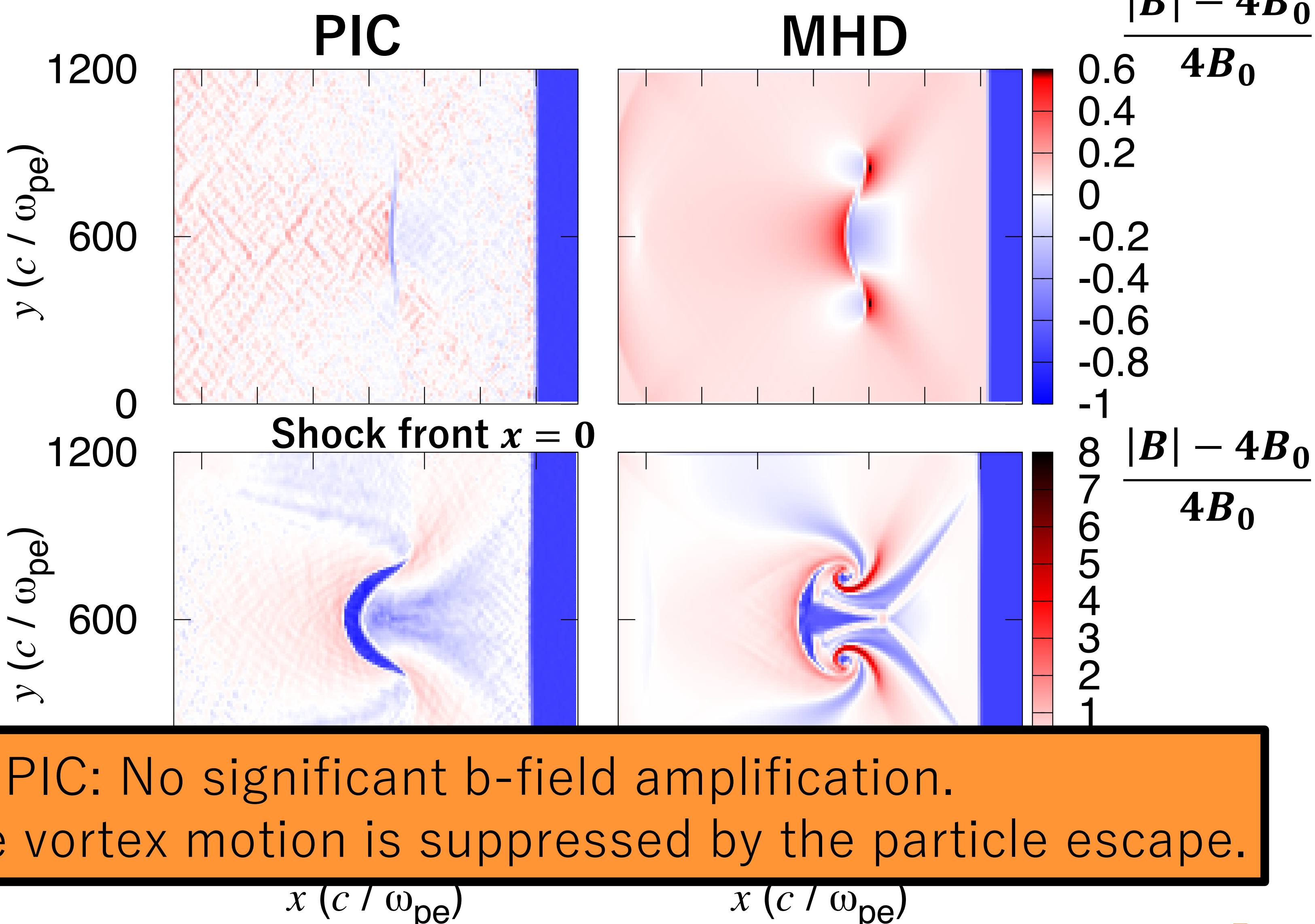
$|B_{max}|$ distribution ($\lambda_c/r_{ge} = 53.7$, $n/n_0 = 2, 20$)

- $n_{cl}/n_0 = 2$

T=$1450\omega_p^{-1}$
The elapsed time since the clump interacts with the shock.

- $n_{cl}/n_0 = 20$

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



PIC: No significant b-field amplification.
Because the vortex motion is suppressed by the particle escape.

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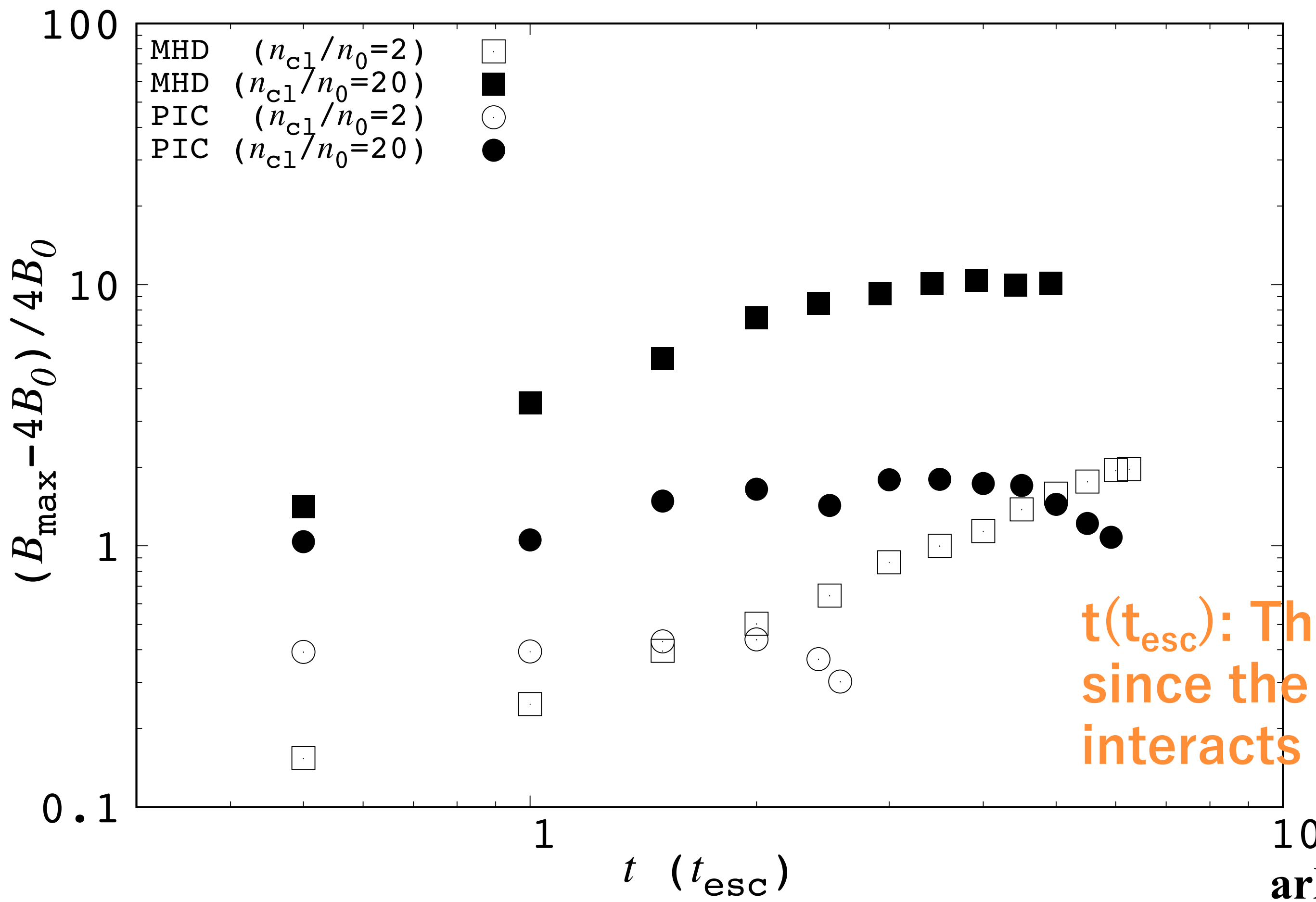
Time evolution of the $|B_{max}|$



$t(t_{esc})$: The elapsed time since the clump interacts with the shock

arXiv: 2204.08222v2

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

Summary

In relativistic collisionless shocks,

- the shocked clump quickly decelerates.
- particle escape from the clump suppresses the vortex motion.
- B-field amplification due to the turbulent dynamo caused by the shock-clump interaction is not efficient.

Future work：

- the dependence of the ratio of $\lambda_{\mathrm{c}}/r_{\mathrm{ge}}$ on the effect of escape and diffusion?
- the dependence of the plasma parameter（magnetization etc.）
- When shocks interacts with multiple clumps, sound waves or weak shocks interact with each other. -> turbulence occurs?

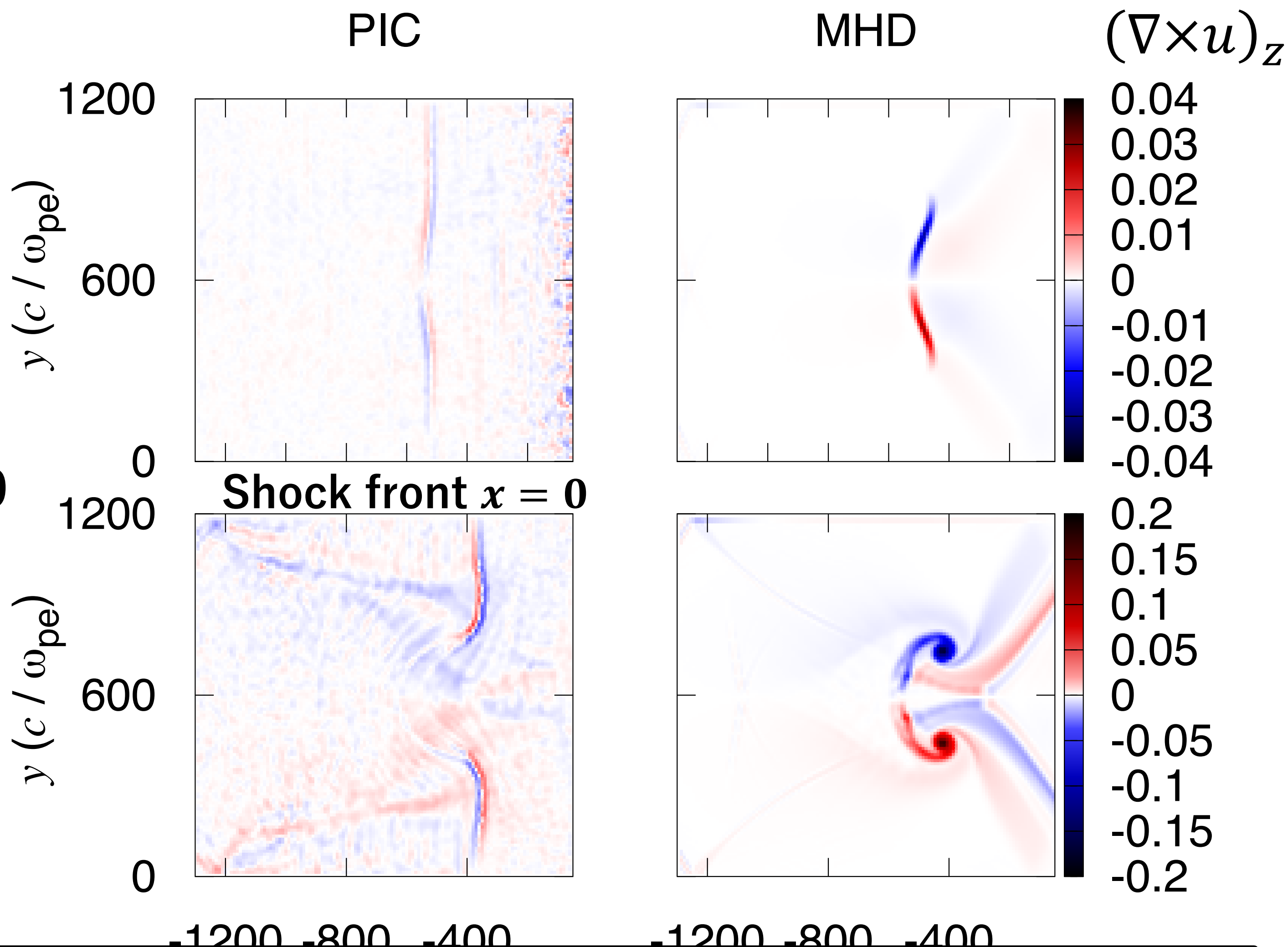
Vorticity distribution$(\lambda_c/r_{ge} = 53.7, n/n_0 = 2, 20)$

- $n_{cl}/n_0 = 2$

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.

Particle-in-Cell(PIC) Simulation

Fundamental Equations：

- **Equation of motion of N particles**

$$\frac{d\boldsymbol{u}_s}{dt} = \frac{q_s}{m_s}\left(\boldsymbol{E} + \frac{\boldsymbol{u}_s}{c\gamma_s}\times\boldsymbol{B}\right),$$

$$\frac{d\boldsymbol{x}_s}{dt} = \frac{\boldsymbol{u}_s}{\gamma_s}$$

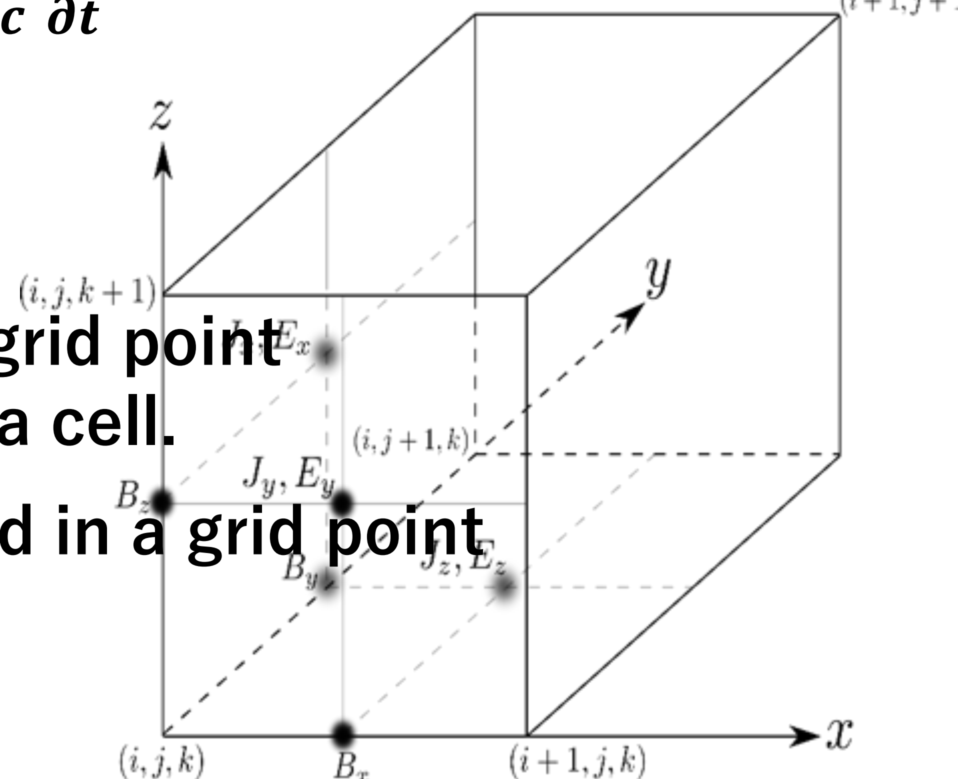
- **Maxwell equations**

$$\frac{1}{c}\frac{\partial\boldsymbol{E}}{\partial t} = \nabla\times\boldsymbol{B} - \frac{4\pi}{c}\boldsymbol{j},$$

$$\frac{1}{c}\frac{\partial\boldsymbol{B}}{\partial t} = -\nabla\times\boldsymbol{E}$$

The Algorithm:

1. **Compute charge density in a grid point from velocities of particle in a cell.**
2. **Compute electromagnetic field in a grid point from the charge density.**
3. **Update velocity and position.**



pCANS HP