Magnetic field amplification by turbulent dynamo in relativistic collisionless shocks

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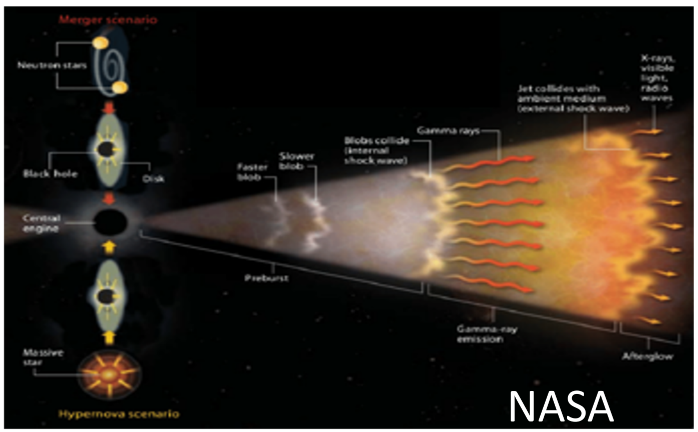
Magnetic field around Collisionless Shocks

<u>Collisionless shocks in high-energy astrophysical phenomena:</u>

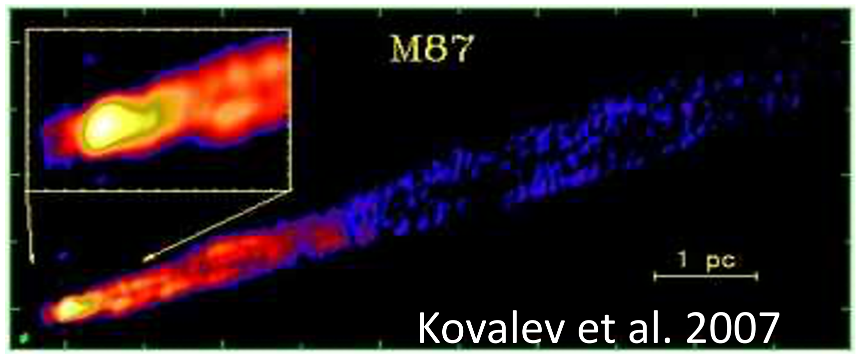
- **Acceleration site for cosmic rays (CRs).**
- **High-energy emission regions.**

→ b-fields around a shock have a crucial role,
it's highly uncertain!!

Sato, T. et al. 2019



NASA



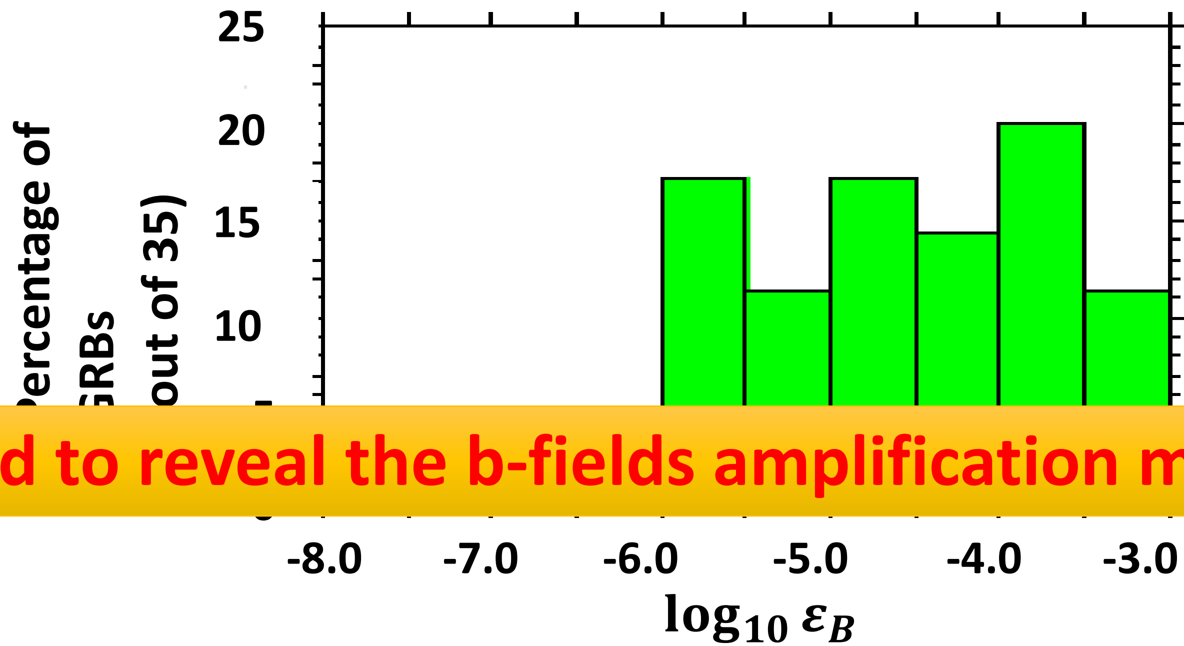
Kovalev et al. 2007

It's the key to unveil

- **the acceleration mechanism of CRs.**
- **the environment of astrophysical objects.**

Problems about b-fields around the shock

- **When the interstellar magnetic fields (~μG) are compressed by the shock,** $\epsilon_B = \frac{B^2/8\pi}{\Gamma mnc^2} \sim 10^{-9}$



We need to reveal the b-fields amplification mechanism !!

- **The structure of magnetic field？**
- **Usually, there is no information about pre-shock region.**

Magnetic Field Amplification in Collisionless Shocks

- **Plasma Instabilities**

Weibel1959; Lucek & Bell 2000; Bell 2004; Spitokovsky 2008; Drury & Downes 2012; Tomita et al. 2016, 2019

- **Turbulent Dynamo ←Today's talk (relativistic shocks)**

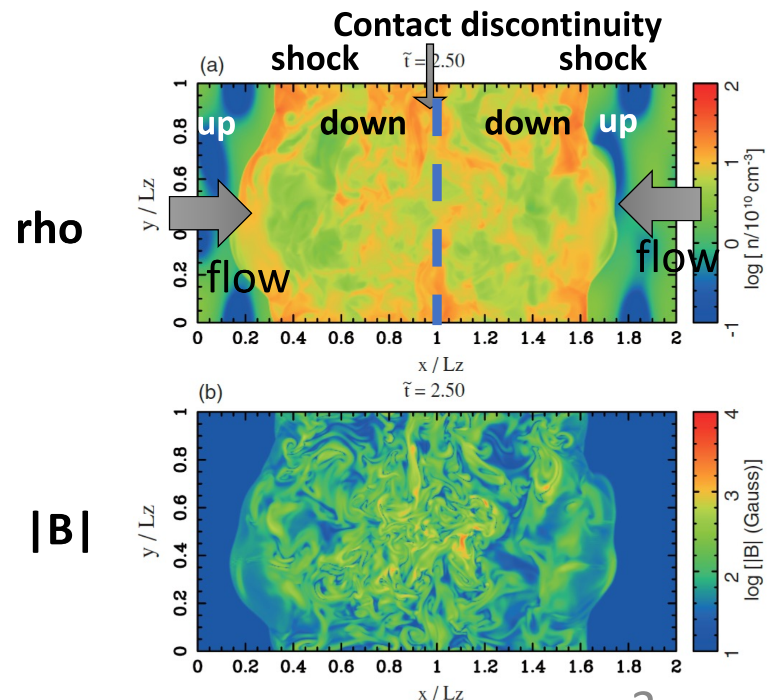
Both mechanisms are required.

Balsara & Kim 2001; Giacalone & Jokipii 2007; Inoue et al. 2009, 2011; Zhang et al. 2009; Mizuno et al. 2011

B-field amplification by turbulent dynamo in 3D MHD simulation (Inoue et al. 2011)

Kinetic energy of the downstream turbulence	>	**Magnetic energy**
		Sano, T. et al. 2013

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



In the downstream region of collisionless shocks, MHD approximation is always valid?

Density structures are maintained in post-shock regions?

- **Collisionless shocks generate non-thermal particles.**
- **Particle diffusion is negligible??**

In order for the MHD approximation to be applicable in downstream regions of collisionless shocks,

"gyro radius < size of density fluctuations" ?

≪ How large ?

+ Amplitude of density fluctuations?

Purpose of Our Study:

We search the surrounding environment required for b-field amplification by the turbulent dynamo.

(+ particle acceleration via turbulence??)

Method:

Particle-in-Cell(PIC) simulation (L~ plasma skindepth) of a relativistic collisionless shock propagating into inhomogeneous media (L $\gg$ plasma skindepth).

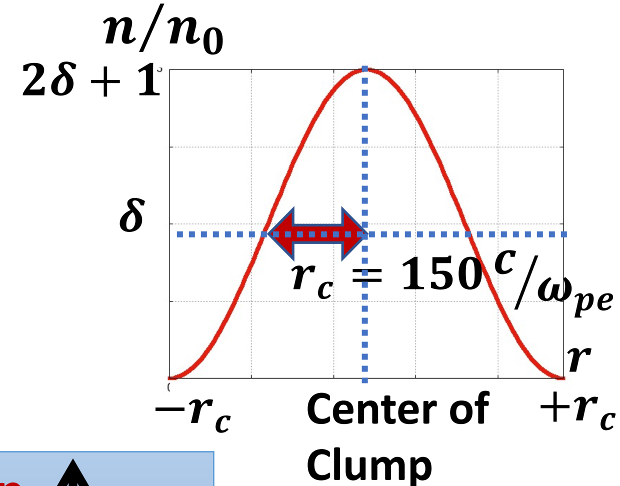
Today's talk:

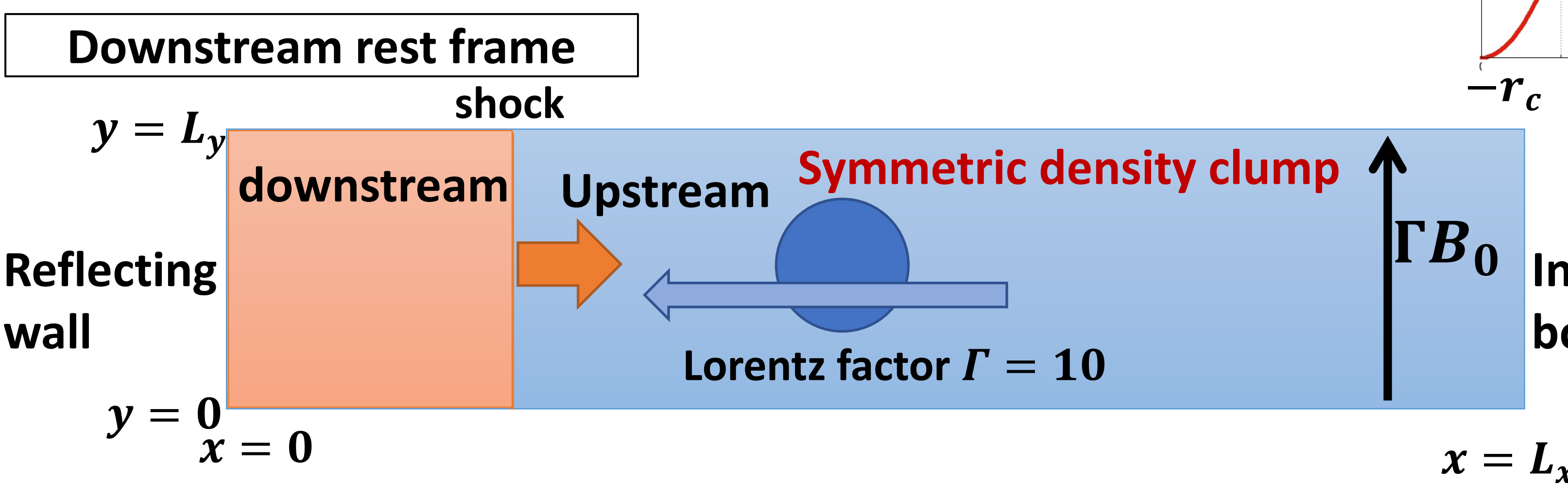
When the density fluctuation has a small amplitude ($\delta n_1/n_1 \leq 0.5$), MHD turbulence does not work in the downstream region of the relativistic collsionless shocks.

Simulation set up

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

- Two-dimensional electromagnetic PIC code* & Athena++ MHD code.
- $e^{\pm}$plasmas ($\fallingdotseq e^{-}$-ion plasmas in the downstream regions of relativistic shocks.)
- Calculator: Cray XC50（520 core）@NAOJ
- Box Size: $L_x = 3120\, {}^{c}/_{\omega_{\rm pe}}$, $L_y = 1200\, {}^{c}/_{\omega_{\rm pe}}$ ($\Delta x = \Delta y = 0.1\, {}^{c}/_{\omega_{\rm pe}}$)
- Number of particles: n_0 = 80/cell, total～10^{10} particles





Simulation set up

- **Upstream magnetization $\sigma_{\mathrm{e}} = B_0^2/4\pi\Gamma n_0 m_{\mathrm{e}} c^2$.**
- **(Clump size $2r_{\mathrm{c}}$)/ (Gyroradius r_{ge}), Amplitude δ :**

	δ	σ_{e}	$2\mathrm{r_c}/\mathrm{r_{ge}}$
case1	**0.5**	**10^{-3}**	**9.5**
case2	**0.5**	**10^{-5}**	**0.9**
case3	**10.0**	**10^{-3}**	**9.5**

(For the case of GRB afterglows)
The required ratio of the Clump size to the Gyroradius,
for b-field amplification by the turbulent dynamo is 10-100
in the downstream region (downstream rest frame).

The ratio of a Clump Size to a Gyroradius

The condition required for turbulent dynamo to work

"Eddy Turn Over Time $\leq$ Decceleration time of the shock",

predicts the maximum size of the upstream density fluctuations.

For Gamma-ray bursts, $t_{\mathrm{dec}} \approx 10^4 \,\mathrm{sec} \left(\frac{E_{\mathrm{iso},53}}{n_{\mathrm{ISM},0}}\right)^{\frac{1}{3}} \Gamma_{\mathrm{sh},2}^{-\frac{5}{3}}, \qquad (n_1 \approx const.).$

(*Downstream rest frame)

Since $t_{\mathrm{eddy}} \approx \frac{\lambda}{c} \leq t_{\mathrm{dec}}$ **,**

$$\lambda \lesssim 10^{14} \left(\frac{E_{\mathrm{iso},53}}{n_{\mathrm{ISM},0}}\right)^{1/3} \Gamma_{\mathrm{sh},2}^{-5/3} cm \approx 10^{7} \left(\frac{E_{\mathrm{iso},53}}{n_{\mathrm{ISM},0}}\right)^{1/3} \Gamma_{\mathrm{sh},2}^{-5/3} \frac{c}{\omega_{\mathrm{pp}}}.$$

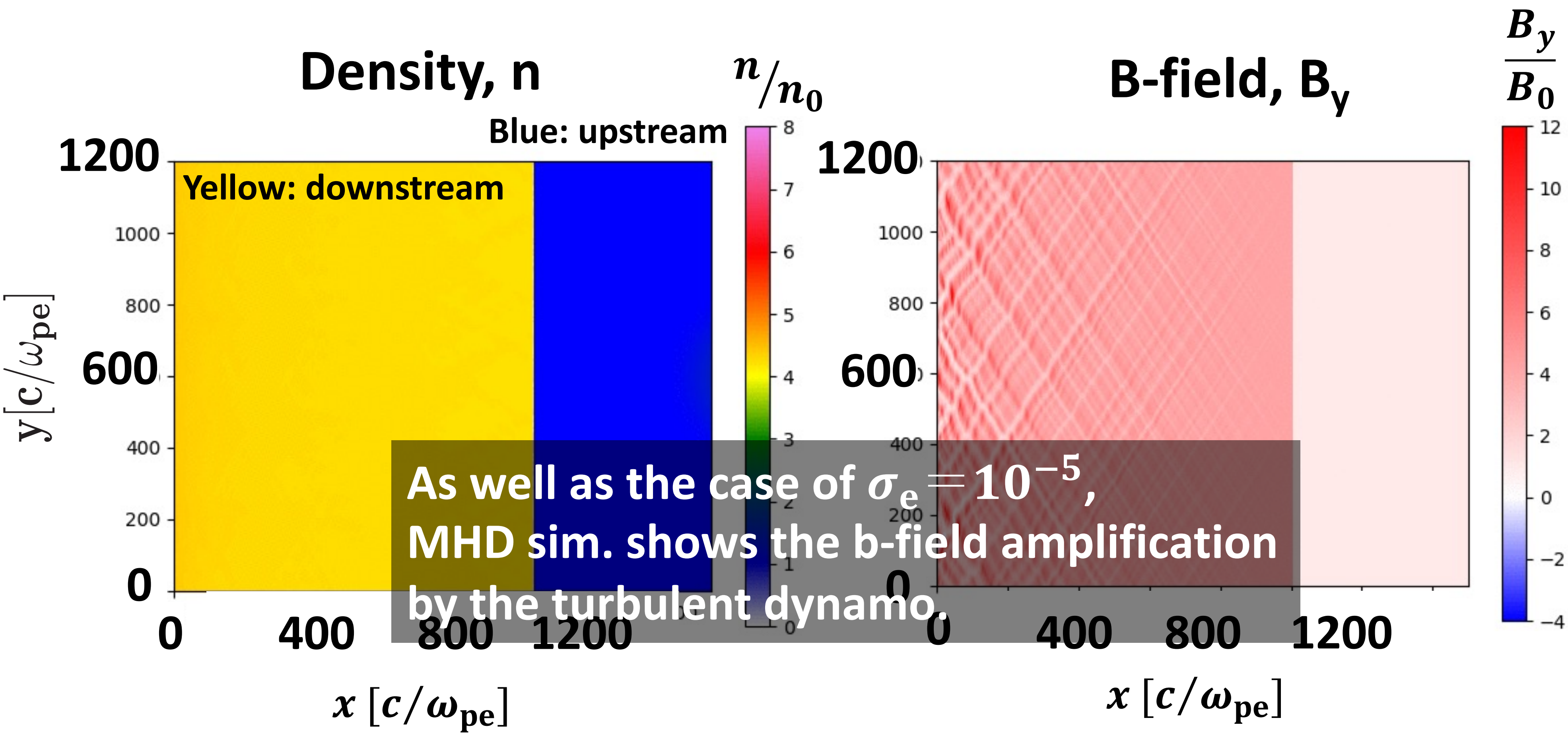
If the upstream b-field is 3μG,

the gyroradius of downstream thermal protons, $r_{\mathrm{gp}} \approx 10^4 \left(\frac{\sigma}{10^{-9}}\right)^{-\frac{1}{2}} \frac{c}{\omega_{\mathrm{pp}}}.$

Thus, when the downstream clump size is $\lambda = 10^5 - 10^6 \frac{c}{\omega_{\mathrm{pp}}}$**,**

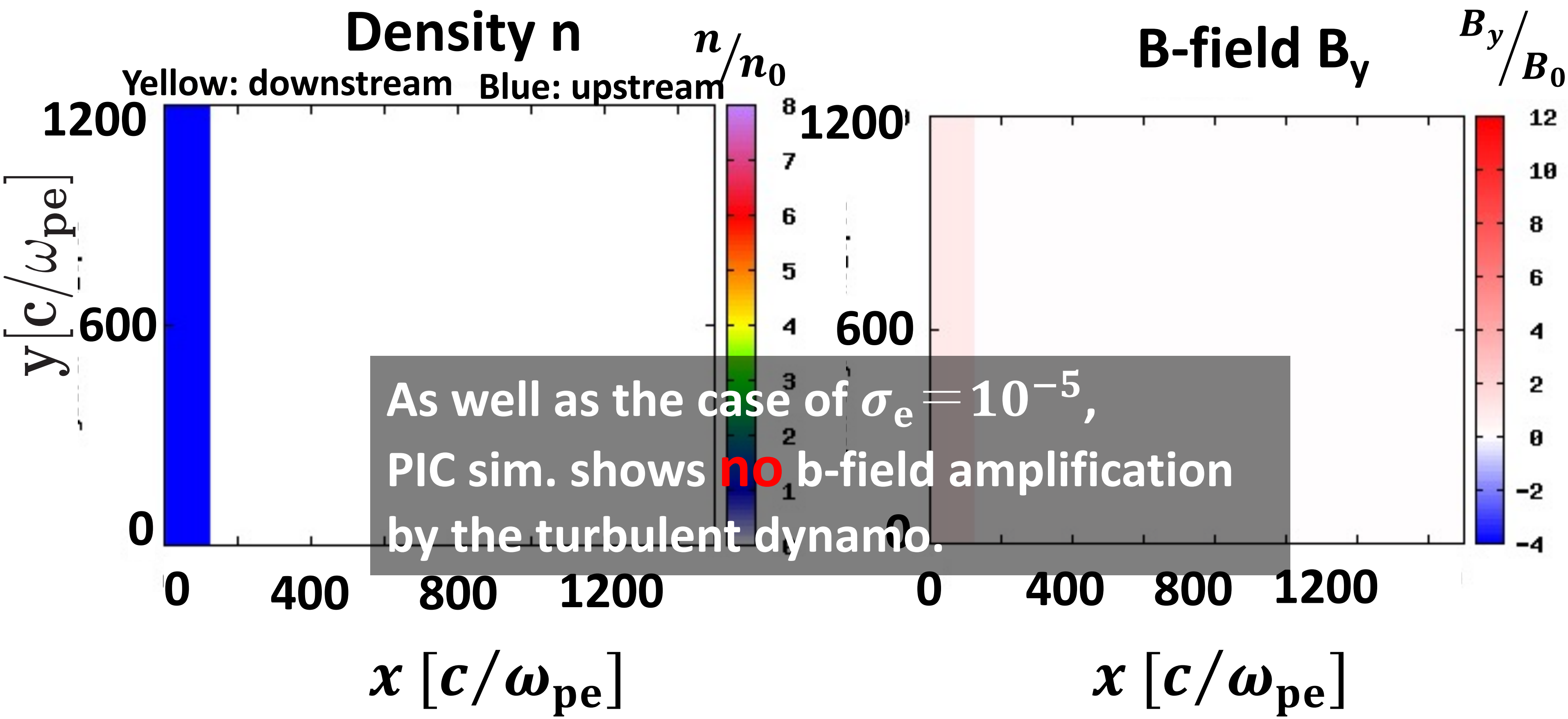
The ratio of the clump size to the gyroradius is $\frac{\lambda}{r_{\mathrm{gp}}} \approx$**10-100.**

Results: MHD ($\sigma_e = 10^{-3}$, Amplitude $\boldsymbol{\delta} = 0.5$)



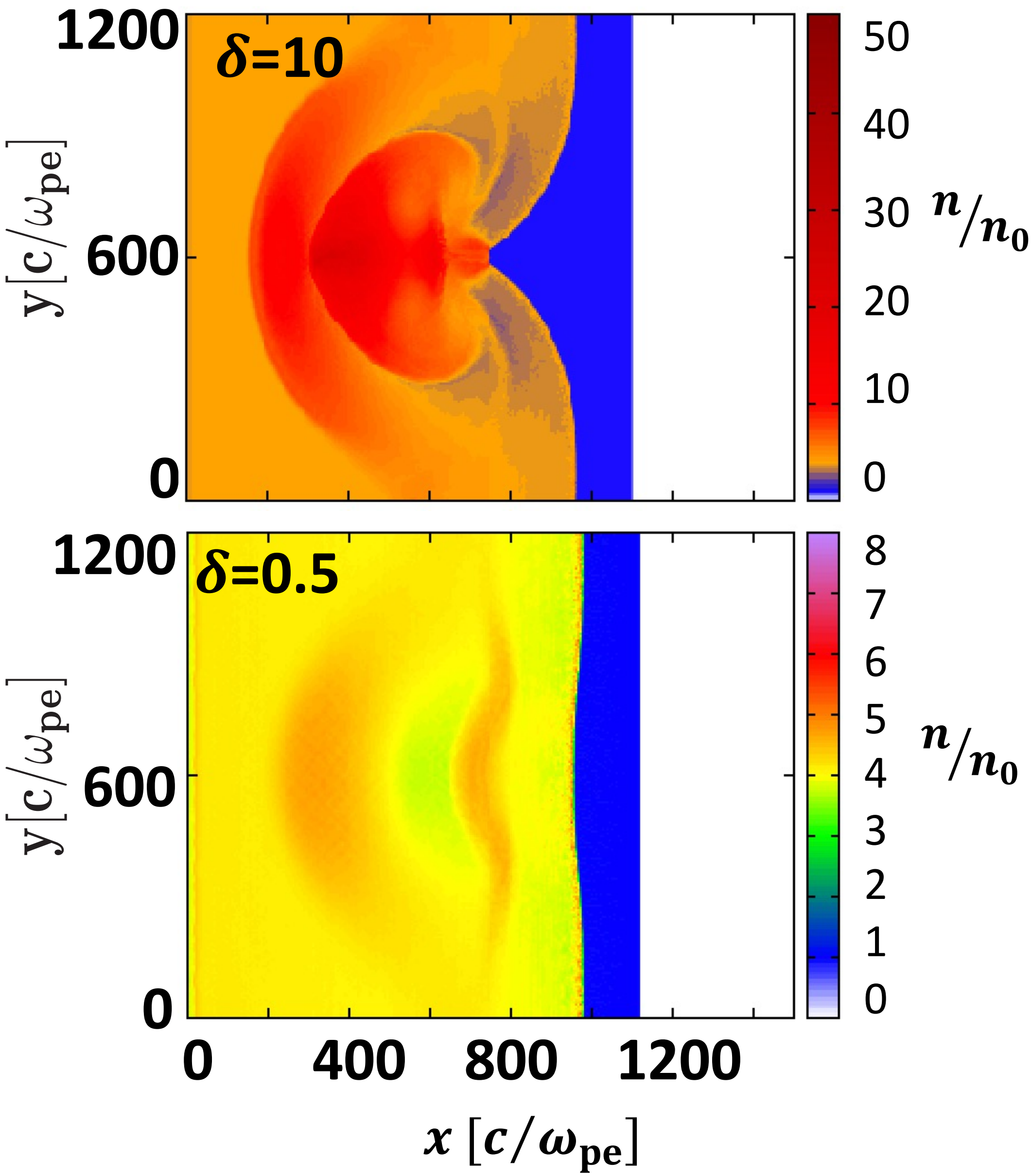
As well as the case of $\sigma_e = 10^{-5}$,
MHD sim. shows the b-field amplification
by the turbulent dynamo.

Results: PIC ($\sigma_e = 10^{-3}$, Amplitude $\delta = 0.5$)



＊There is no injection particles in the white region in density distribution yet.

PIC, Amplitude dependence: Density 2D plots

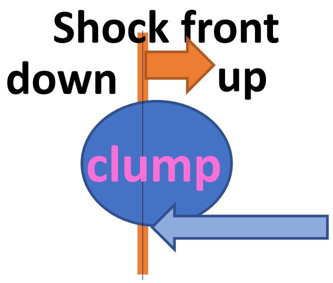


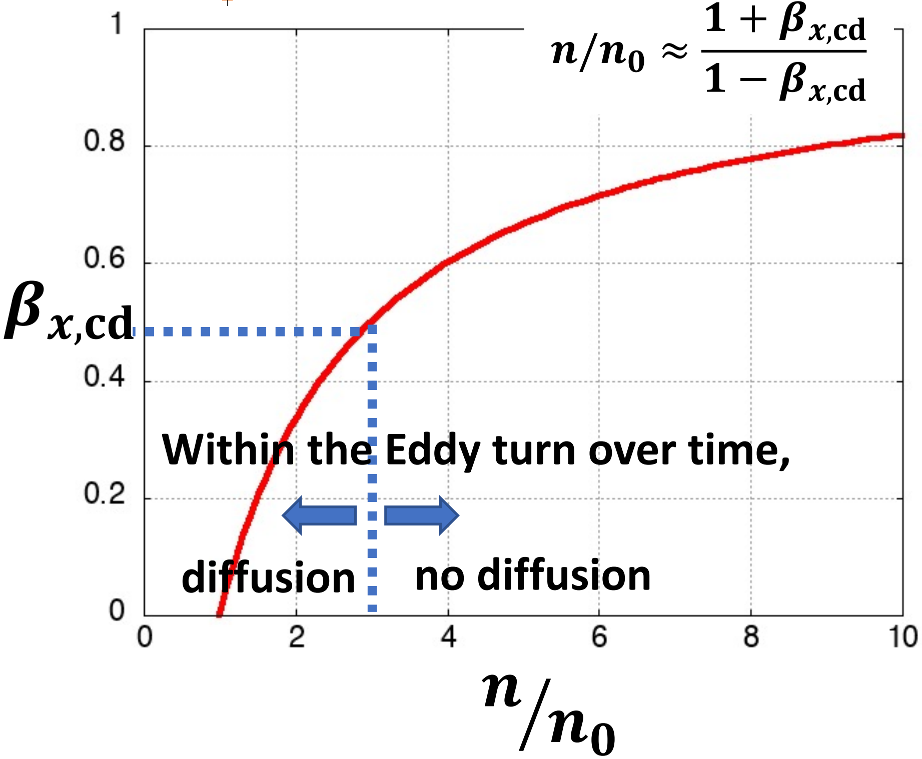
Particle diffusion is suppressed, so that the b-field is amplified by the turbulent dynamo!

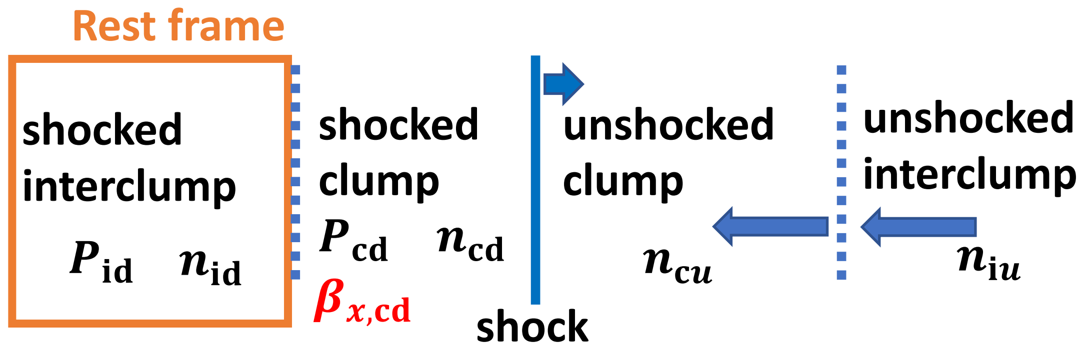
Why does the particle diffusion is suppressed?

Thermal velocity of particles in the clump becomes lower than that for $n/n_0 = 0.5$?

The required amplitude $^{n}/_{n_0}$ for keeping the density fluctuation from particle diffusion







From $P_{\mathrm{id}} = P_{\mathrm{cd}}$,

$$n/n_0 \approx \frac{1+\beta_{x,\mathrm{cd}}}{1-\beta_{x,\mathrm{cd}}}$$

"Velocity of the Shocked clump"
> " Mean velocity of the particles diffusing along the b-field line". Thus,

$$\beta_{x,\mathrm{cd}} > \langle \beta_{\mathrm{th},\parallel} \rangle \approx 0.5c$$

$$\Rightarrow {}^{n}/_{n_0} \gtrsim 3$$

$\beta_{x,\mathrm{cd}}$: Velocity of the Shocked clump

Summary

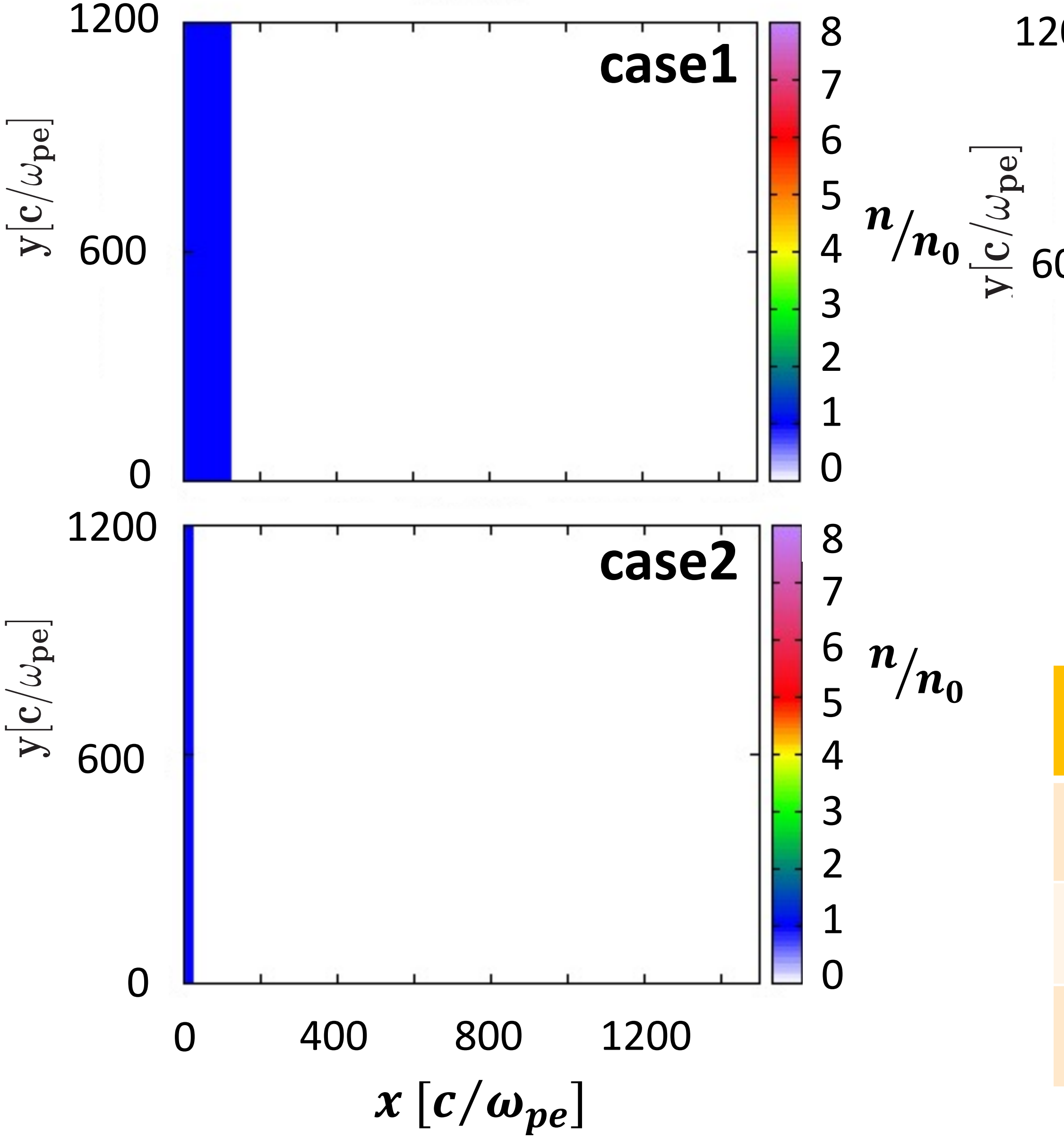
PIC simulations of a relativistic collisionless shock propagating into $e^{\pm}$ plasmas with the density clump:

Even if the clump size is larger than the gyroradius of the upstream plasma,
the density fluctuation with small amplitude ($n/n_0 < 1$) could not drive efficient magnetic field amplification by the turbulent dynamo.

Future work:

We are performing many PIC simulations to understand the parameter dependence on the downstream turbulence and e^- energy distribution.

σ_e dependence: Density 2-dimensional(2D) plots



	δ	σ_e	$2r_c/r_{ge}$
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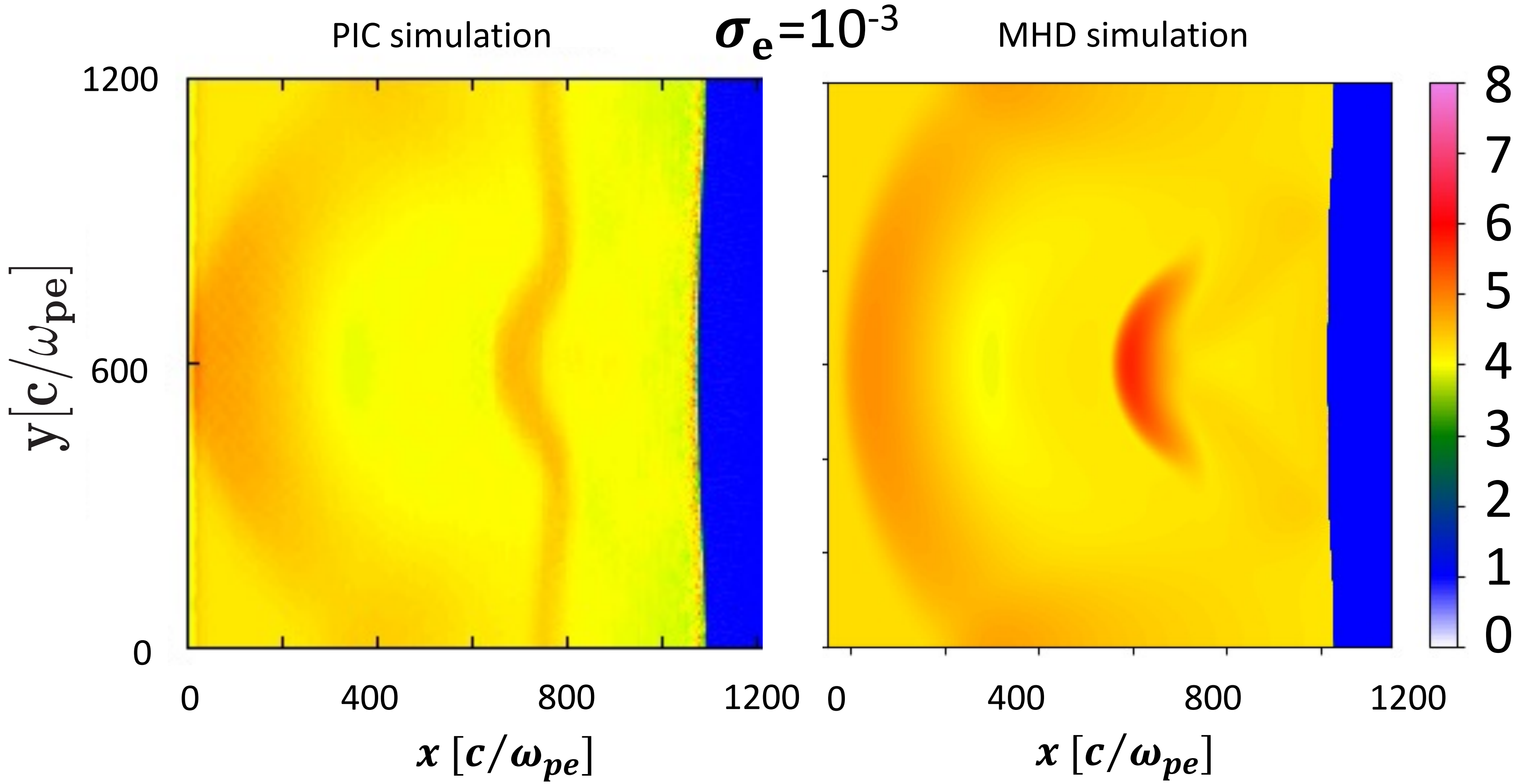
Density 2D plots: Comparison between PIC & MHD



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*** For Gamma-ray bursts,** $t_{\rm dec} \approx 10^3 {\rm sec}\, E_{\rm iso,53} \upsilon_{\rm WR,8.3} \dot{M}_{WR,-5}^{-1} \Gamma_{sh,2}^{-3}$, $(n_1 \propto r^{-2})$,

$$\approx 10^4 \text{ sec } \left(\frac{E_{\rm iso,53}}{n_{\rm ISM,0}}\right)^{\frac{1}{3}} \Gamma_{\rm sh,2}^{-\frac{5}{3}}, \qquad (n_1 \approx const.).$$

(*Downstream rest frame)

Since $t_{\rm eddy} \approx \frac{\lambda}{c} \leq t_{\rm dec}$, $\lambda \lesssim 10^{14} \left(\frac{E_{\rm iso,53}}{n_{\rm ISM,0}}\right)^{1/3} \Gamma_{\rm sh,2}^{-5/3} cm \approx 10^7 \frac{c}{\omega_{\rm pp}}$.

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If the upstream b-field is 3μG, the gyroradius of thermal protons,

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Thus, when the clump size is $\lambda = 10^5 - 10^6 \frac{c}{\omega_{\rm pp}}$,

The ratio of the clump size to the gyroradius is $\frac{\lambda}{\rm r_{gp}}$ **≈10-100.**

Particle-in-Cell(PIC) Simulation

Fundamental Equations：

- **Equation of motion of N particles**

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

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

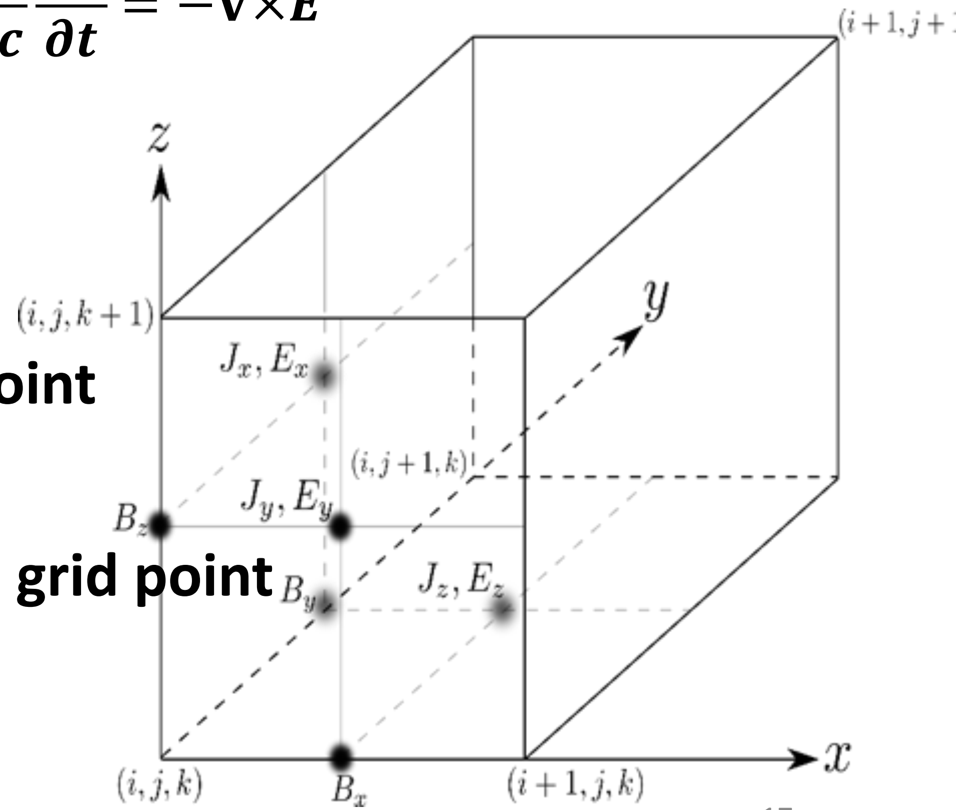
- **Maxwell equations**

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

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

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.**



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