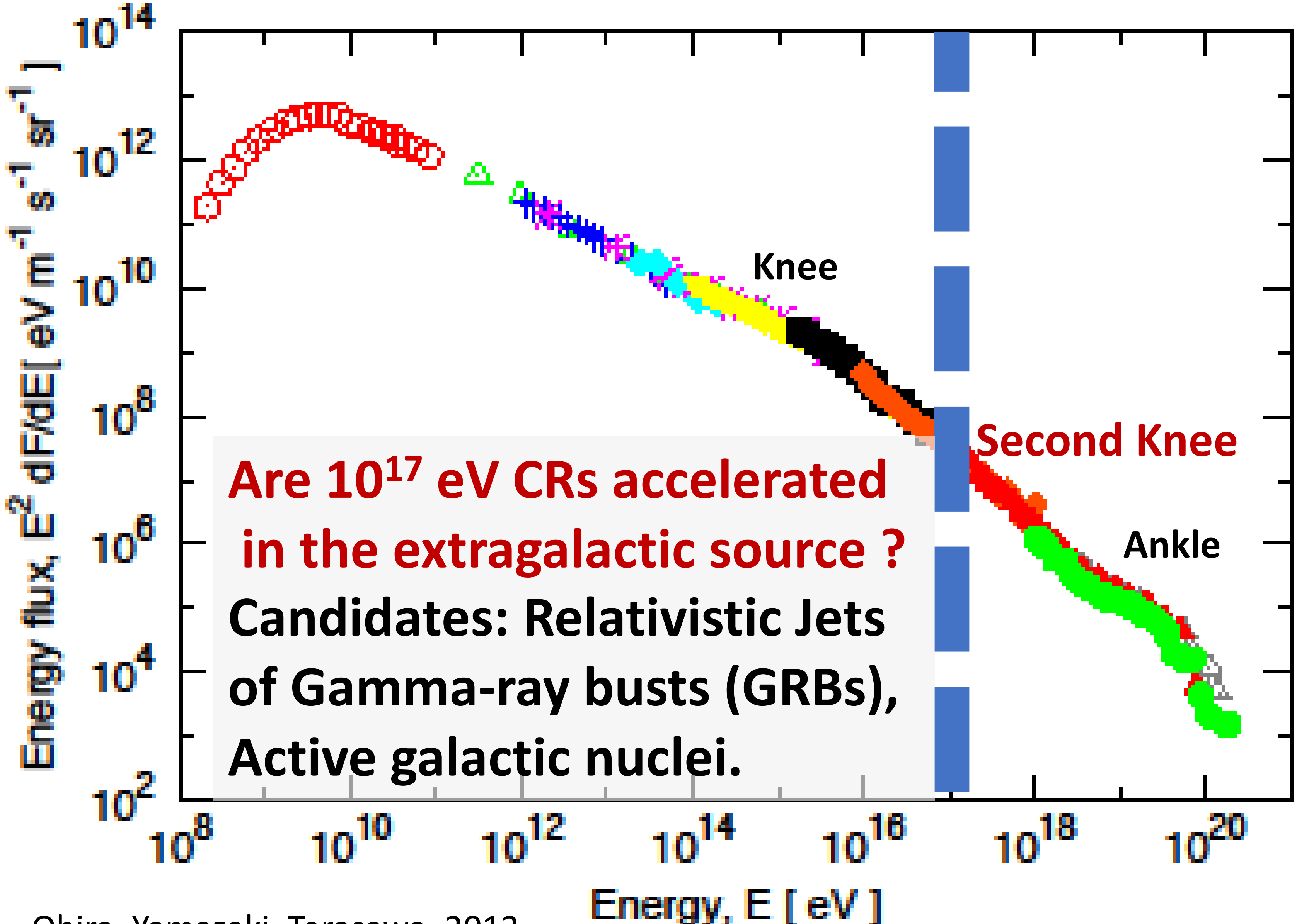
The Weibel-mediated shocks Propagating into Inhomogeneous Media

Sara Tomita and Yutaka Ohira
(Aoyama Gakuin University) (University of Tokyo)

The origin of 10^{17}eV cosmic-rays (CRs)



Are 10^{17} eV CRs accelerated in the extragalactic source ?

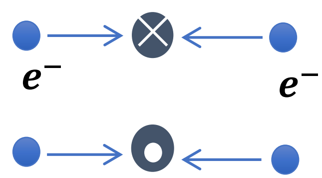
Candidates: Relativistic Jets of Gamma-ray busts (GRBs), Active galactic nuclei.

Ohira, Yamazaki, Terasawa, 2012

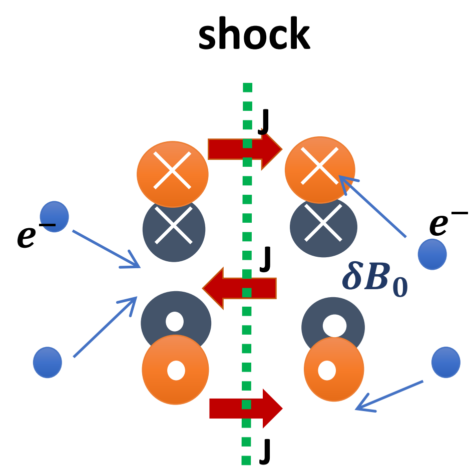
The relativistic jet interacts with interstellar medium (ISM) or circum-stellar medium (CSM).

→ Relativistic collisionless shocks mediated by the Weibel instability

Counter-streaming plasmas
= anisotropic-temperature plasmas



Pertubation of magnetic field δB_0



The streaming plasmas are deflected by δB, so that currents are generated.
The currents amplify δB. → Unstable.

The Weibel instability makes magnetic fields.

Particle-in-Cell simulations of Relativistic Collisionless Shocks:

CRs are accelerated up to 10^{17} eV if the b-fields persist in the far downstream region.

For $\mathbf{r_g} \gg \lambda_{\delta \mathrm{B}}$, $\mathbf{D(E)} \sim= \mathbf{c}\lambda_{\delta\mathrm{B}} \left(\frac{\mathbf{E}}{\mathbf{eB}\lambda_{\delta\mathrm{B}}} \right)^{\mathbf{2}}$

$$\frac{\gamma_{\max}}{\gamma_0} \sim (\mathbf{2}\epsilon_{\mathrm{B}}\lambda_{\delta_{\mathrm{B}}}\omega_{\mathbf{pi}}\mathbf{t})^{\mathbf{1/2}}$$

At $\mathbf{t} = \mathbf{t_{age}} \sim \mathbf{R_{dec}}/\mathbf{\Gamma c}$

$$\mathbf{R_{dec}} \sim \mathbf{10^7 E_{0,54}^{1/3} n_{ISM}^{-1/3} \Gamma_{0,2}^{-2/3} cm}$$

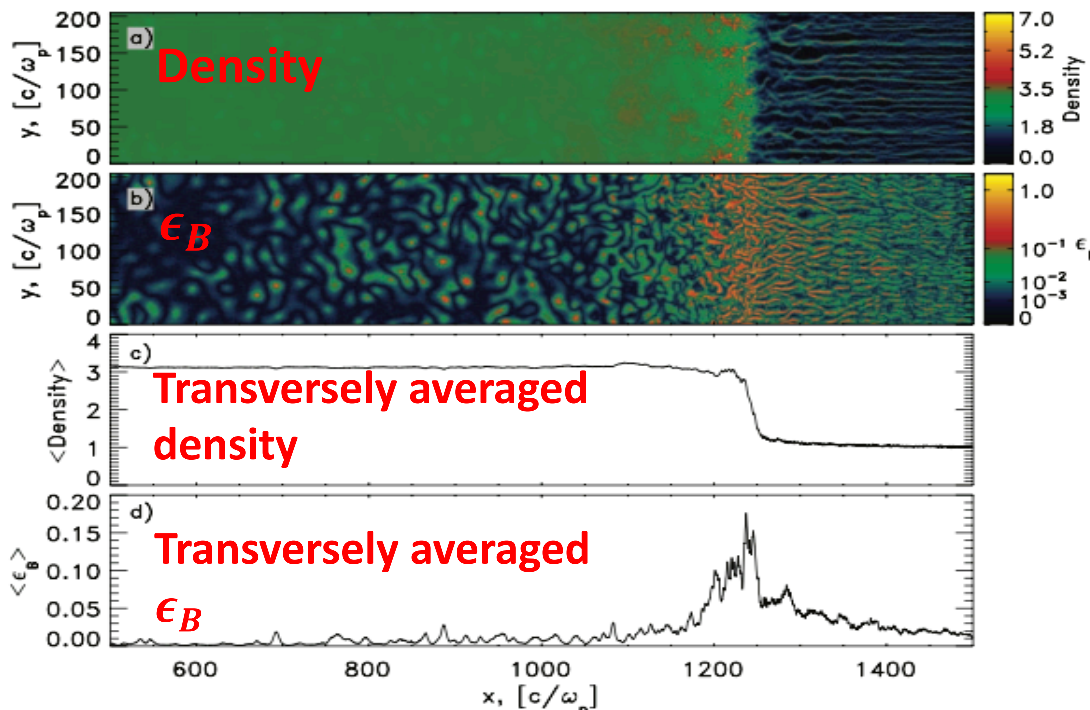
$\epsilon_{\mathrm{B},-1}\lambda_{\mathbf{c}/\omega_{\mathrm{pi}}} \sim \mathbf{0.1}$ **(from PIC simulation)**

$$\gamma_{\max,i} \approx \mathbf{10^8 E_{0,54}^{3/4} n_{ISM,0}^{-1/2} R_{dec,17}}$$

In ISM frame

Shalchi & Dosch 2009; Plotnikov et al. 2011, 2013; Sironi et al. 2013

Downstream **Upstream**



Chang et al. 2008

However, the Weibel generated b-field rapidly decays.
$\lambda_{\delta B} \ll r_g$ is inefficient for particle acceleration.

Amplified B-field in GRBs afterglows

Observations:

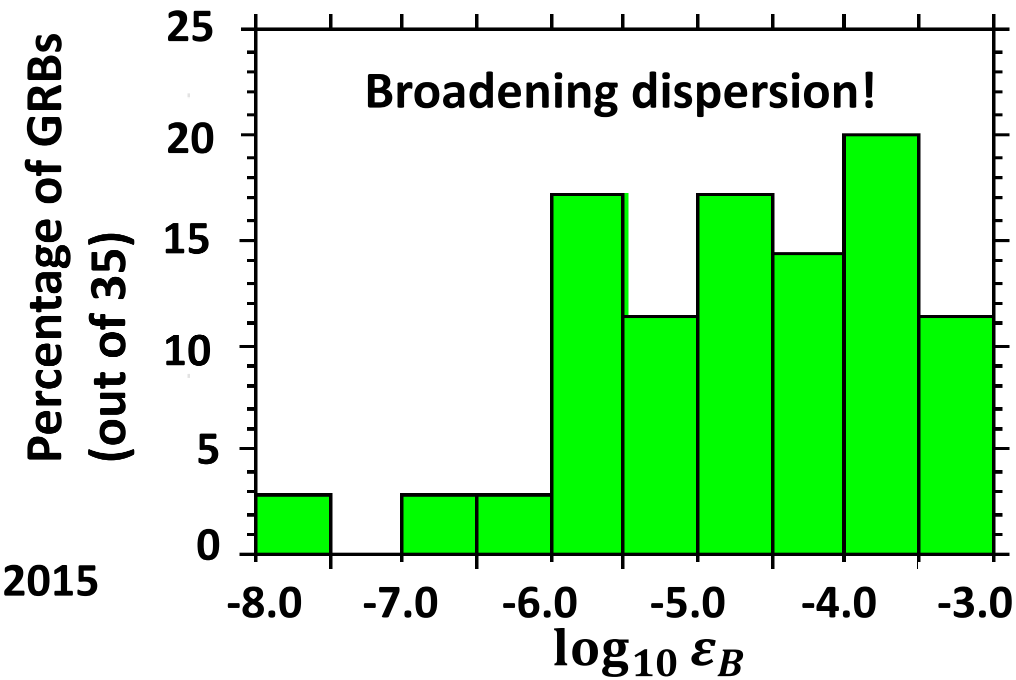
B-fields are strongly amplified in large emission regions.

$$\epsilon_B = \frac{B^2/8\pi}{4\Gamma mnc^2} \sim 10^{-8} - 10^{-3} \quad \textbf{Average: } 10^{-5}$$

(Santana et al. 2014)

→The post-shock b-field is amplified to about 100 times the shock-compressed value.

the process of the b-filed amplification is an open question.



Kumar et al. 2015

Previous PIC simulation :

Nonlinear evolution of the Weibel instability for shocks in uniform plasmas → B-fields rapidly decay.

There should be density fluctuations, $\delta\rho$, in the ISM or CSM.

Ex.)

- **Large-scale inhomogeneity:**

  The injection scale of $\delta\rho$ is 1-100 pc for the ISM turbulence.

  Stellar winds or binary systems can generate $\delta\rho$ with a smaller scale.

  Armstrong et al. 1995, Chugai & Danzieger 1994, Smith et al. 2009, Yalinewich & Zwart 2019

- **Small-scale inhomogeneity:**

  The CR precursor can generate a much smaller scale less than the precursor scale.

  Drury & Falle 1986, Ohira 2013, 2014, 2016

Purpose of our study

In previous MHD simulation :

Large-scale magnetic field amplification by the turbulent dynamo

Inoue et al. 2011, Mizuno et al. 2014

However, MHD simulation cannot solve physics of the kinetic scale.

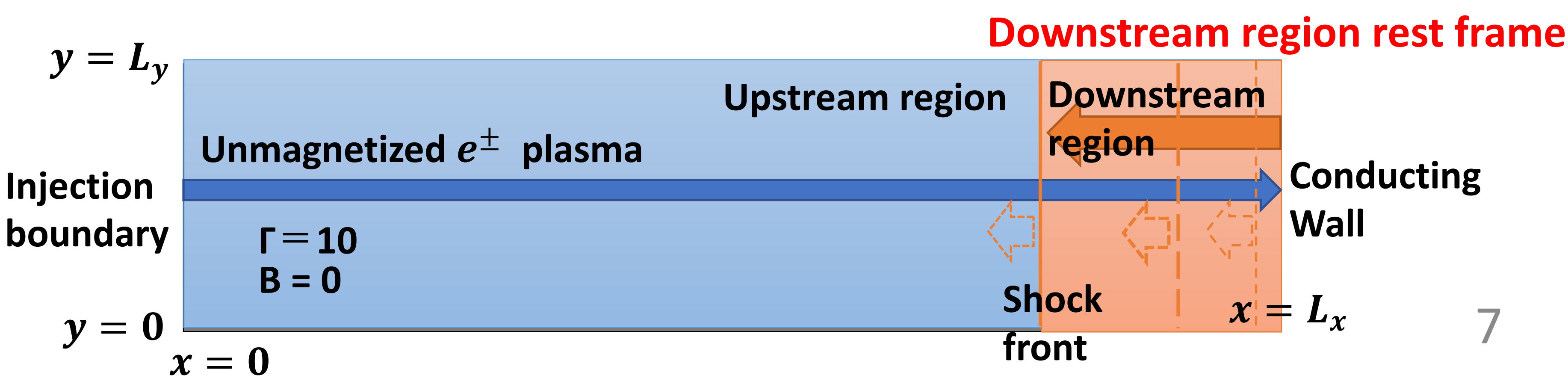
In this study:

We investigate a magnetic field amplification in the downstream region of the relativistic collissionless shock propagating into the inhomogeneous ISM, by using two-dimensional PIC simulations.

Simulation Set Up

- **Two-dimensional electromagnetic PIC code (pCANS)**
- **X-Y plane with periodic boundary condition in the y-direction.**
- **Box Size:** $L_x = 1.2\times10^4\ {}^{c}/_{\omega_p}, L_y = 86\ {}^{c}/_{\omega_p}$, **Cell Size: ΔX=ΔY=0.1**${}^{c}/_{\omega_p}$
- **Unmagnetized** $e^{\pm}$ **plasmas** ($n_{e^+} = n_{e^-}$) **with Lorentz factor Γ = 10,**v_{th}**=0.1c.**
- **Initial spatial distribution of** $e^{\pm}$**:**

$$n(x, y) = n_0\{1 + 0.5\sin(2\pi kx/L_x)\}$$



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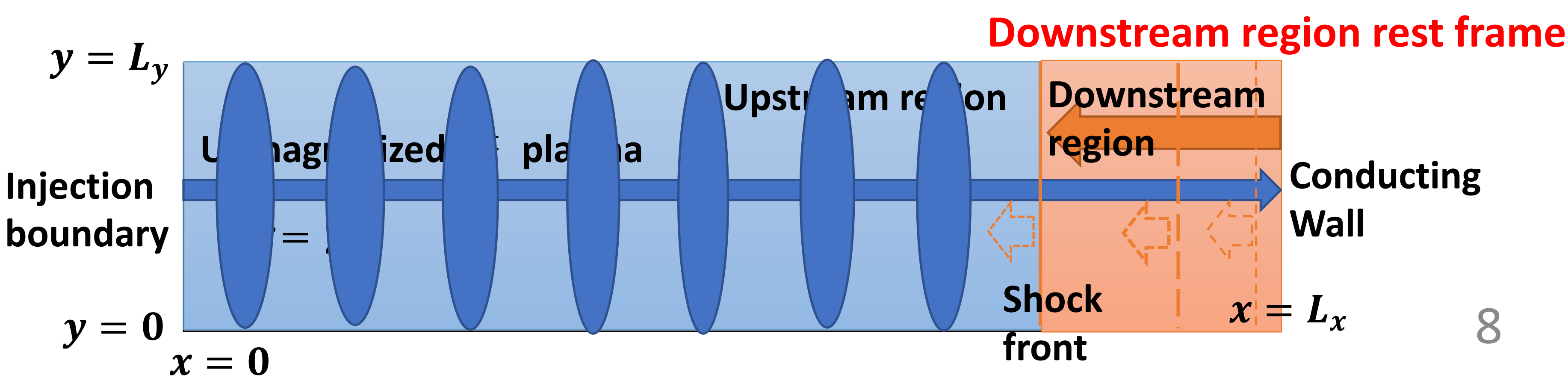
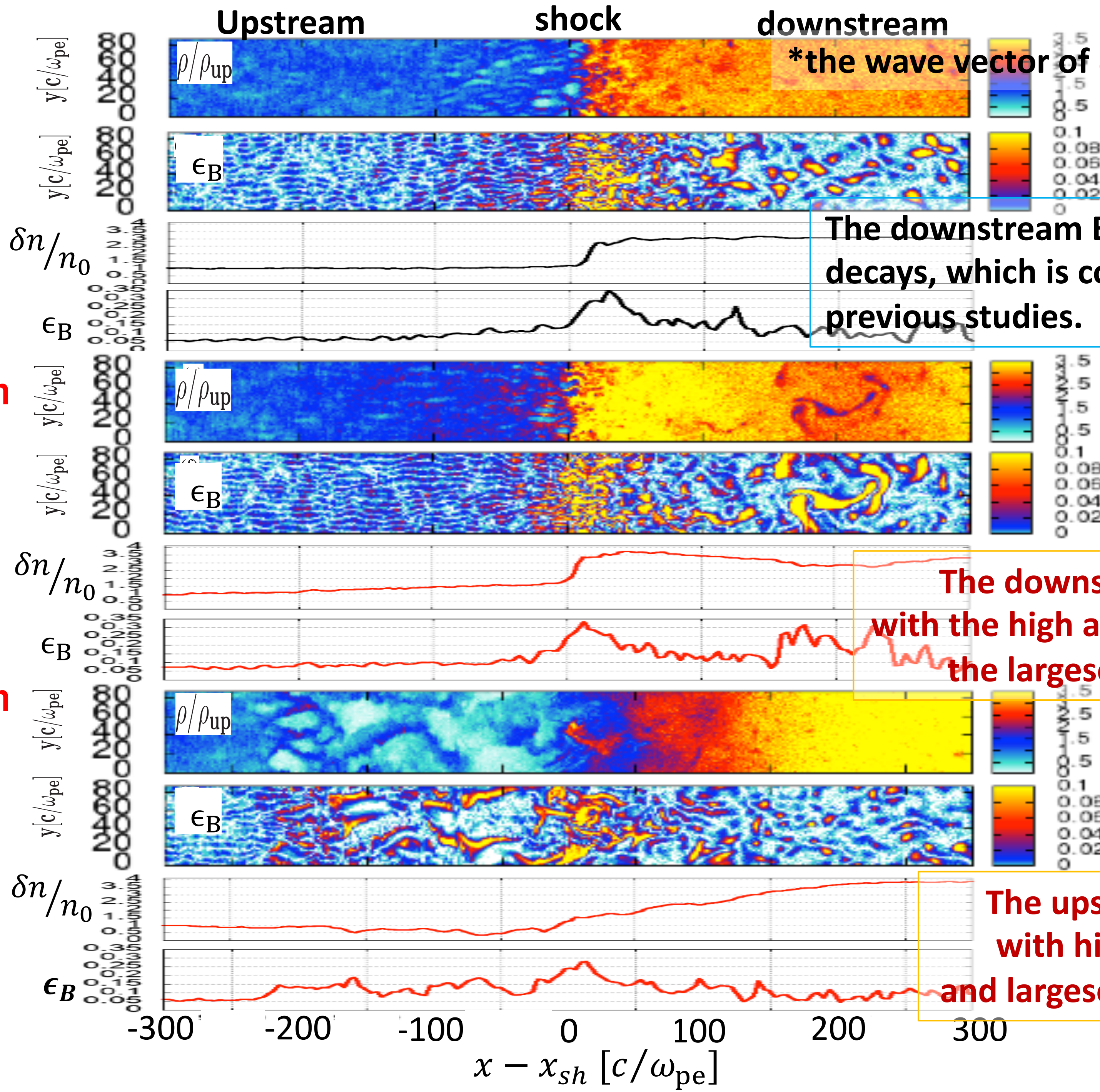


Uniform
(at $t\omega_{pe} = 5000$)

*the wave vector of $\delta B \perp \vec{v}_{flow}$



The downstream B-field simply decays, which is consistent with previous studies.

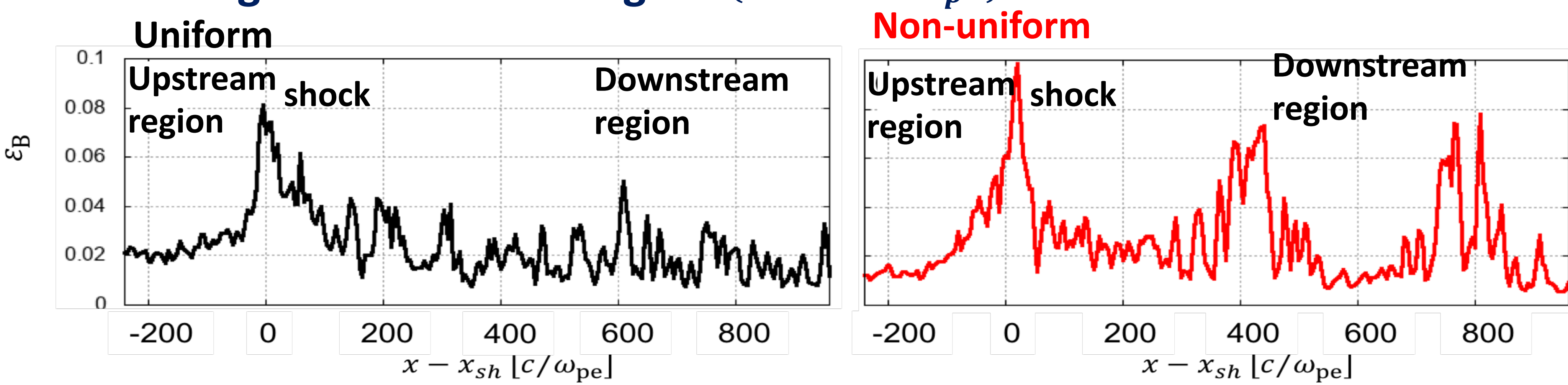
No-uniform
(shock in the $\frac{n_0+\delta n}{n_0} = 1.5$ region)
at $t\omega_{pe} = 4800$

The downstream B-field with the high amplitude and the largescale structure

No-uniform
(shock in the $\frac{n_0+\delta n}{n_0} = 0.5$ region)
at $t\omega_{pe} = 5200$

The upstream B-field with high amplitude and largescale structure

The spatial evolution of the transversely averaged ε_B in the larger downstream region $(t = 6100\omega_p^{-1})$



Uniform:

The magnetic field simply decays.

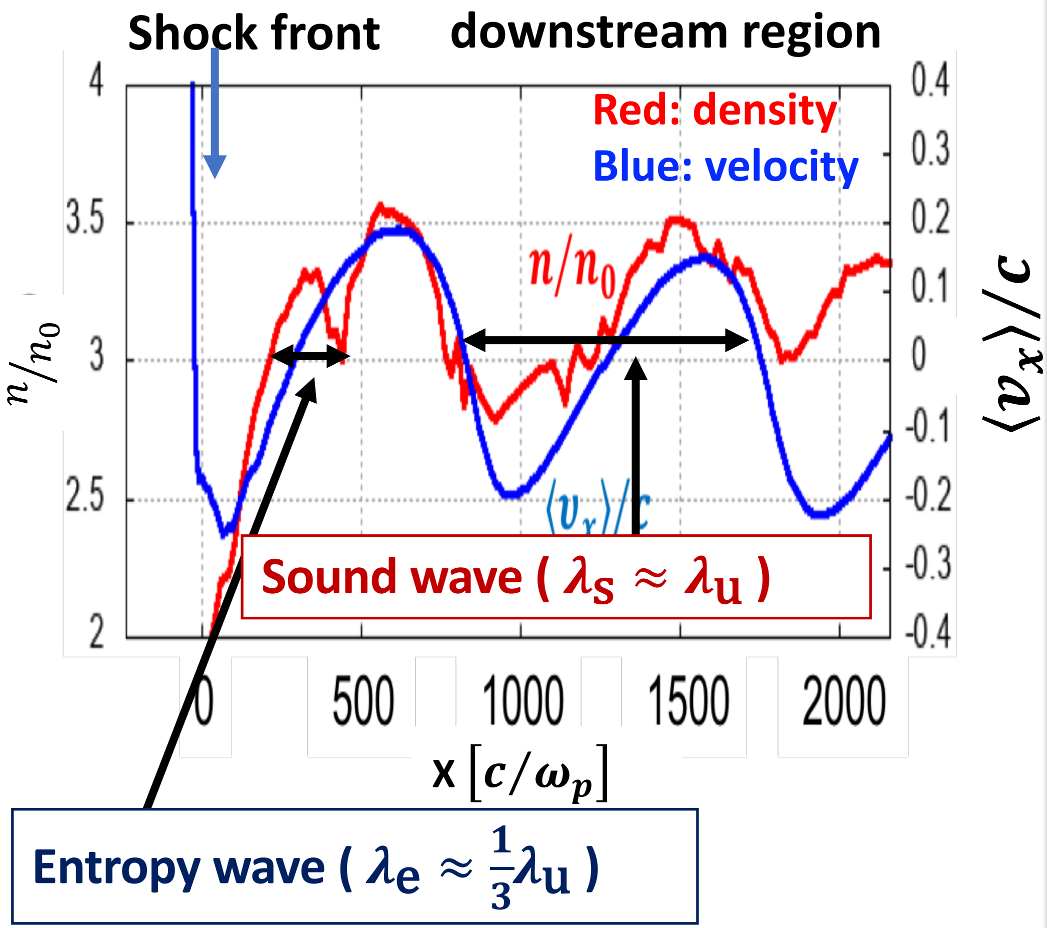
Non-uniform:

The magnetic field decays much slower than uniform case.
Two peaks of ϵ_B were generated when the shock was passing through the low-density region.

The inhomogeneity of the upstream density is crucial in the generation of the downstream magnetic field.

$L_x \times L_y = 1.2 \times 10^4 \times 86\ ^c/_{\omega_p}$

Density & velocity in the x-direction $(t = 6100\omega_p^{-1})$



λ_e:wavelength of the entropy wave

λ_S: wavelength of the sound wave

λ_u:wavelength of the upstream incoming wave

Sound waves and entropy waves are generated as expected by hydrodynamic analysis of the shock-wave interaction.

Each wavelength is consistent with result from the linear analysis for the shock front.

The sound wave might play crucial role on the particle acceleration!

Summary

- ✓ **There really are some density fluctuations in ISM or CSM**

We investigated the b-field amplification in the downstream region of collisionless shocks propagating into inhomogeneous media.

- ✓ **A larger-scale magnetic field is generated in the shock precursor region and hardly decay after it is advected downstream.**

- ✓ **The sound and entropy wave are generated in the downstream region. The sound wave could be crucial for the particle acceleration.**

- ✓ **Temperature anisotropy is produced by the sound wave and the diffusion of high-energy particles.**
  It is expected that larger magnetic field is generated by the Weibel instability far downstream compared with the uniform case.