Collisionless Weibel shocks and electron acceleration in gamma-ray bursts

Kazem Ardaneh, Dongsheng Cai
CAVE Lab, Department of CS, University of Tsukuba, Japan

Ken-Ichi Nishikawa
Department of Physics, University of Alabama in Huntsville, USA

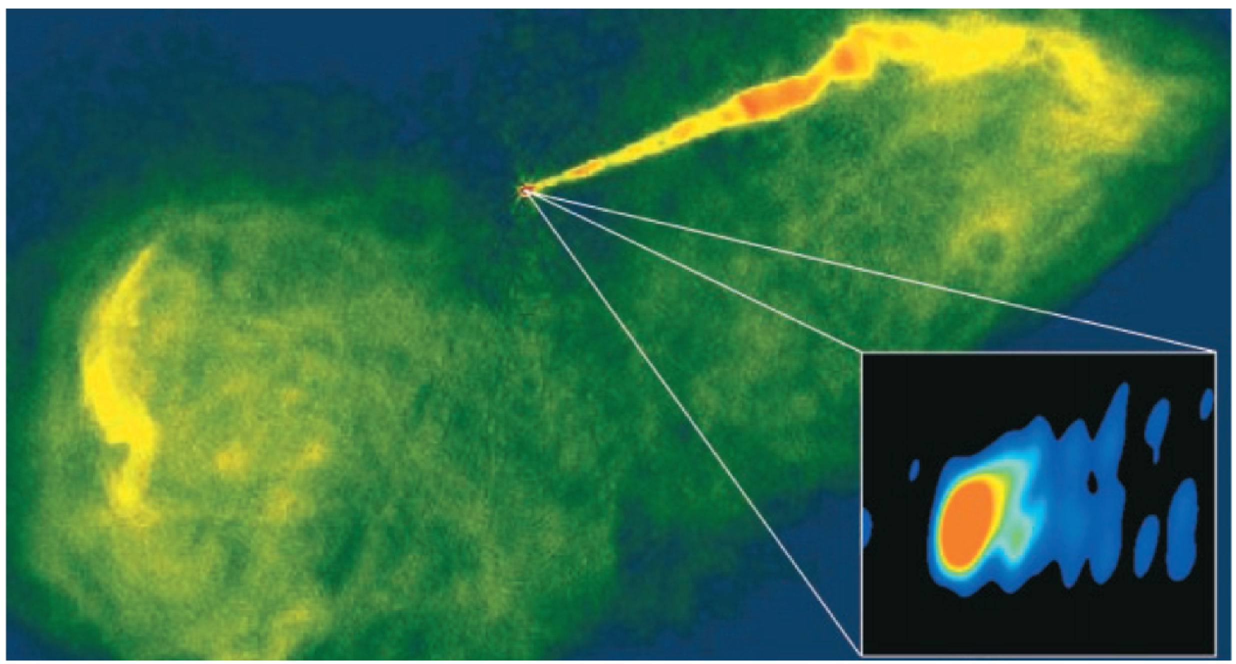
and
Bertrand Lembege
LATMOS, UVSQ, France

Motivations

High energy astrophysics phenomenon involve interactions of relativistic jet (bulk $\gamma >> 1$) plasma with ambient plasma:

- GRBs: Colliding plasma shells (internal shocks), external double shocks
- AGN jets: Bow-shocks

The jet in the galaxy M87



Biretta and Junor, Nature (1999)

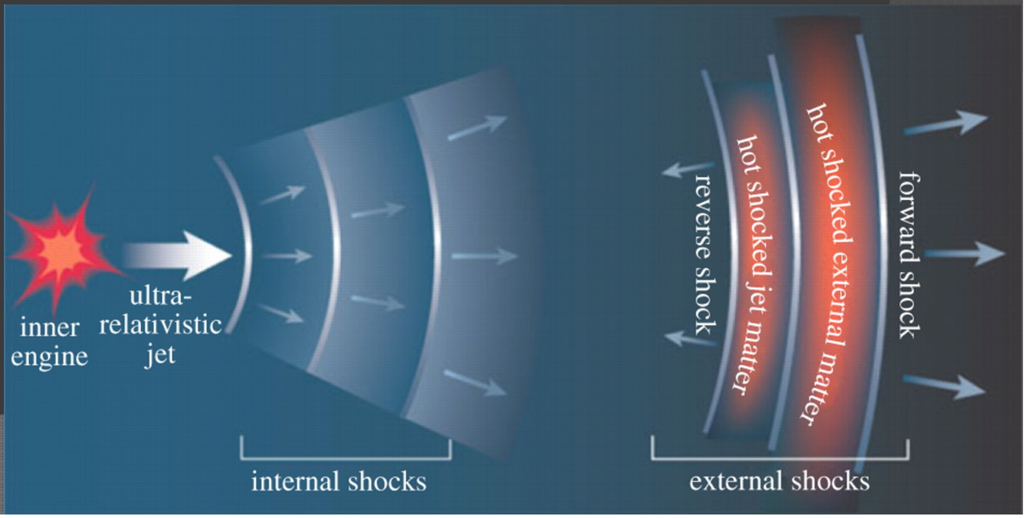
Astrophysical shocks

Astrophysical shocks are collisionless (mean free path >> system size)

Shocks span a range of parameters:
Non-relativistic to relativistic flows (Solar Wind < Jets < GRB < PWN)
Magnetization (magnetic/kinetic energy ratio: GRB< Jets< Solar Wind)
Composition (pairs: e-ions / pairs: e-e+)

Astrophysical collisonless shocks can:

1. Amplify magnetic fields
2. Exchange energy between electrons and ions
3. Accelerate particles
4. Highly non-thermal radiation



Relativistic shock Particle-in-cell research

Composition / Dimension		1D	2D	3D
	e-e+	Hoshino, ApJ (2002) SSA under MSW	Spitkovsky, ApJ (2008), DSA	Nishikawa et al, ApJ (2009), No acceleration study
	e-ion	Hoshino, ApJ (2002) SSA under ESW	Amano and Hoshino, ApJ (2009), SSA under ESW Martins et al, ApJ (2009), DSA Guo et al, ApJ (2014), SDA	Hededal et al, ApJ (2004), Electron heating by E×B Weibel fields

No discussion about particle acceleration in 3D full shock configuration

SSA: Sock surfing acceleration

MSW: Magnetic solitary wave

ESW: Electrostatic solitary wave

DSA: diffusive shock acceleration

SDA: Sock drift acceleration

What changed?

Advances in computer hardware and better algorithms have enabled running large enough simulations to resolve shock formation, and particle acceleration,

- **The code: Relativistic 3D EM TRISTAN,** **Buneman (1993)**
- **Parallelized by MPI,** **Niemiec et al. (2008)**
- **Optimized for large-scale simulations,**

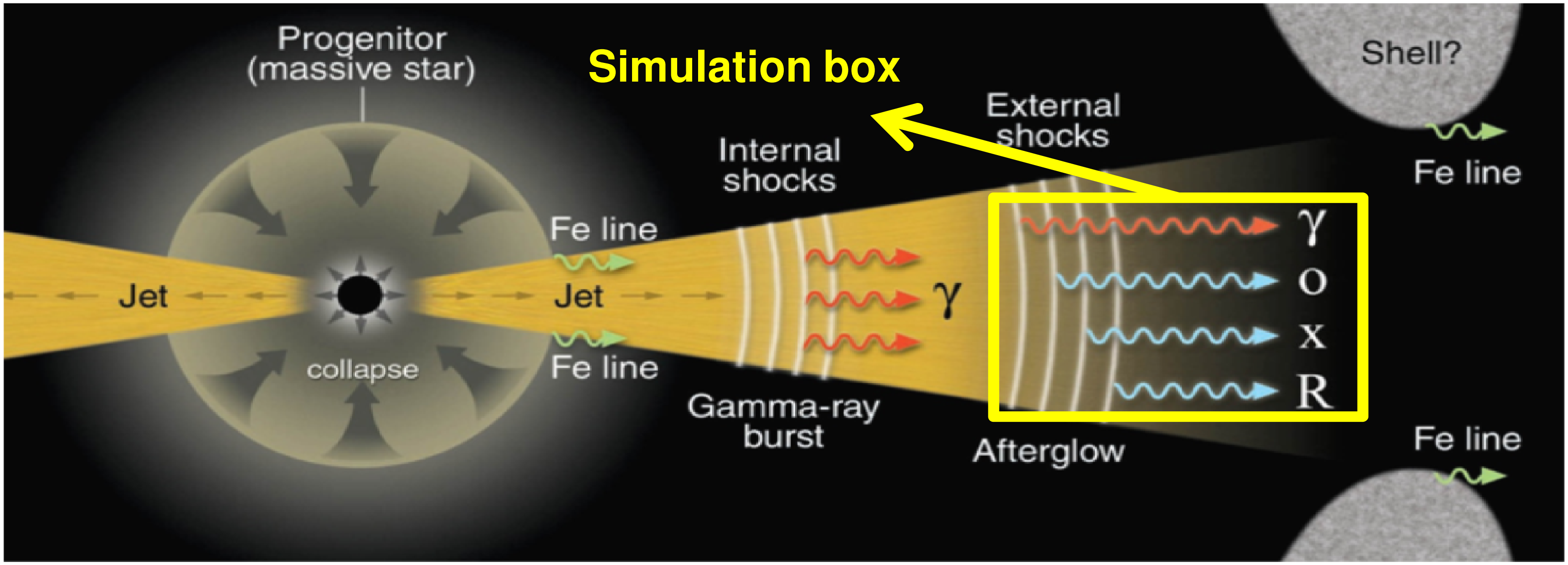
Noise reduction of the curl operator in FDTD	**Filtering implementation**

Attenuate the numerical Cerenkov radiation
Greenwood et al. (2004)

- **Appropriate boundary conditions for shock generation,**
- **Proper diagnostics for particle acceleration analysis,**

Issues and Questions

Meszaros, Science (2001)



What are the field structures responsible for the processes of electron heating, and acceleration?

Where do these processes mainly take place?

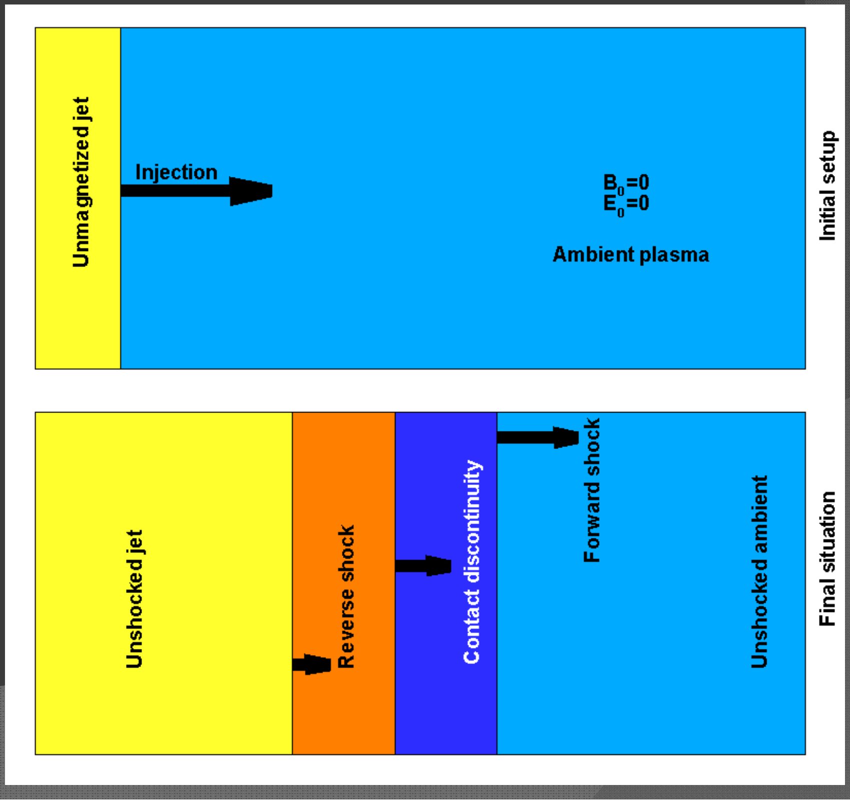
What is the resulting associated electron energy spectrum?

What are the principal mechanisms responsible for electron heating, and acceleration?

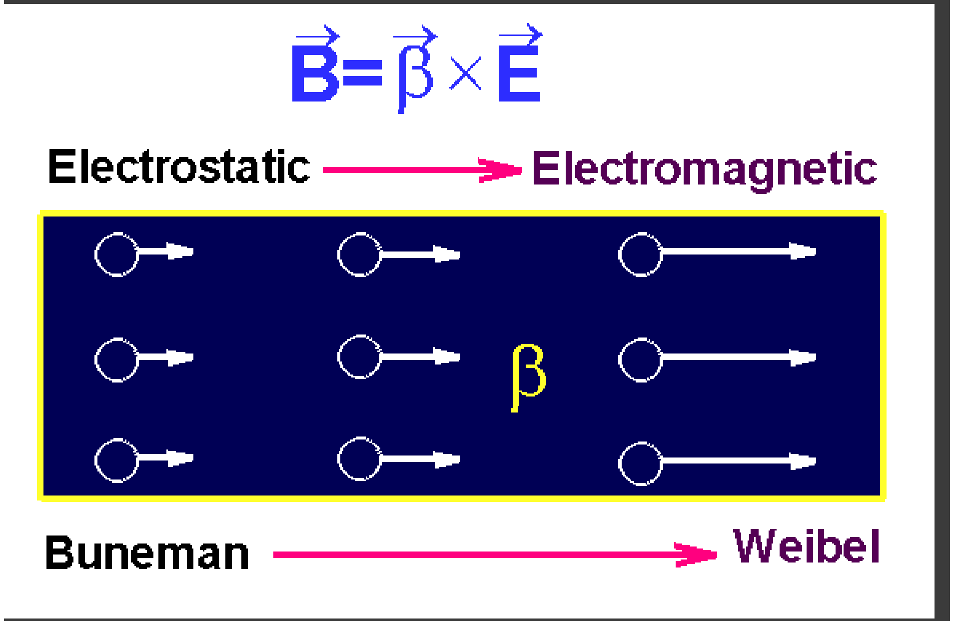
Problem setup

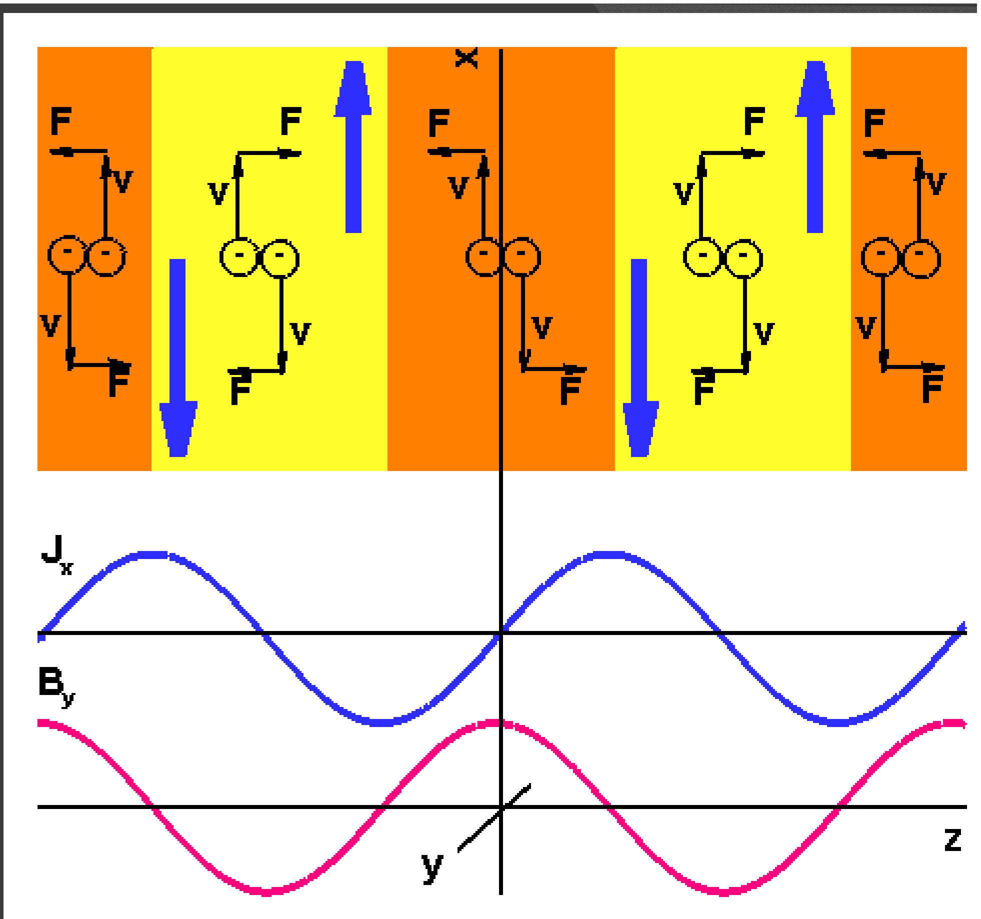
Parameters	Run 1	Run 2
Grid	(1025,165,165)	(8005,245,245)
ppc (ambient)	12	6
Jet density ratio	0.715	1.7
Injection speed	$\gamma = 5$	$\gamma = 10$
Mass ratio	20	16
λ_{ce}	5Δ	5Δ
$\Delta t \omega_{pe}$	0.025	0.01

- Stiff reflecting boundary for the ambient particles in x-direction,
- Open boundary condition for jet particles in x-direction,
- Periodic boundary condition at all other boundaries



Two-stream instability





Electrostatic Buneman instability

Electromagnetic Weibel instability

Buneman (1958)
Weibel (1959)
Moiseev & Sagdeev (1963)
Medvedev & Loeb (1999)

Filamentation of plasma

Spatial scale: $L \approx c/\omega_{pe} = 10\mathrm{km}\sqrt{\gamma/n_0\left[\mathrm{cm}^{-3}\right]}$

Time scale: $T \approx 1/\omega_{pe} = 30\mu\mathrm{s}\sqrt{\gamma/n_0\left[\mathrm{cm}^{-3}\right]}$

Weibel instability (Run 1)

- **Electron Weibel instability**

$$t^* \le 26; \Gamma_e^* = 0.28$$

- **Ion Weibel instability**

$$t^* > 26; \Gamma_i^* = 0.05$$

- **Debye shielding by electron**

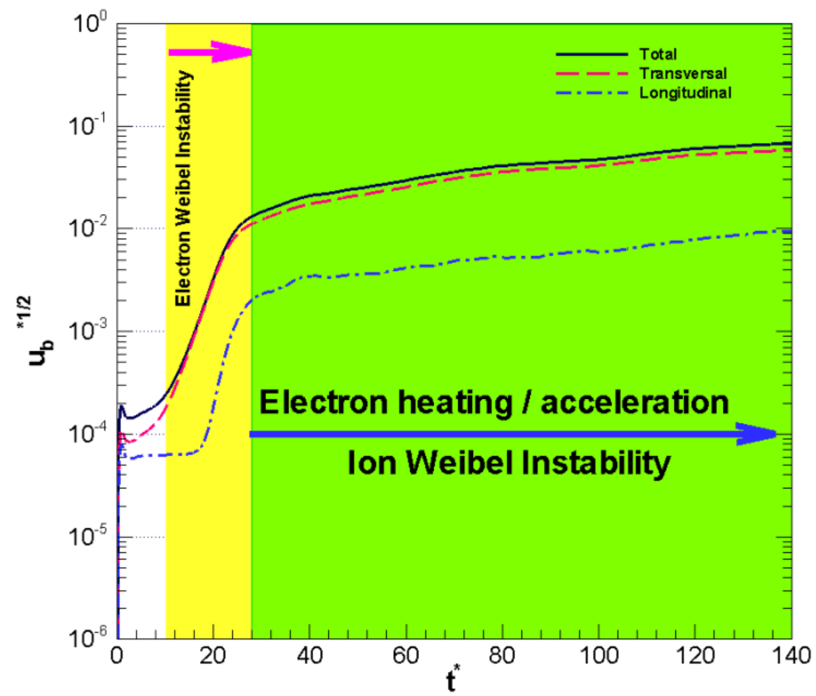
- **Electron heating / acceleration**

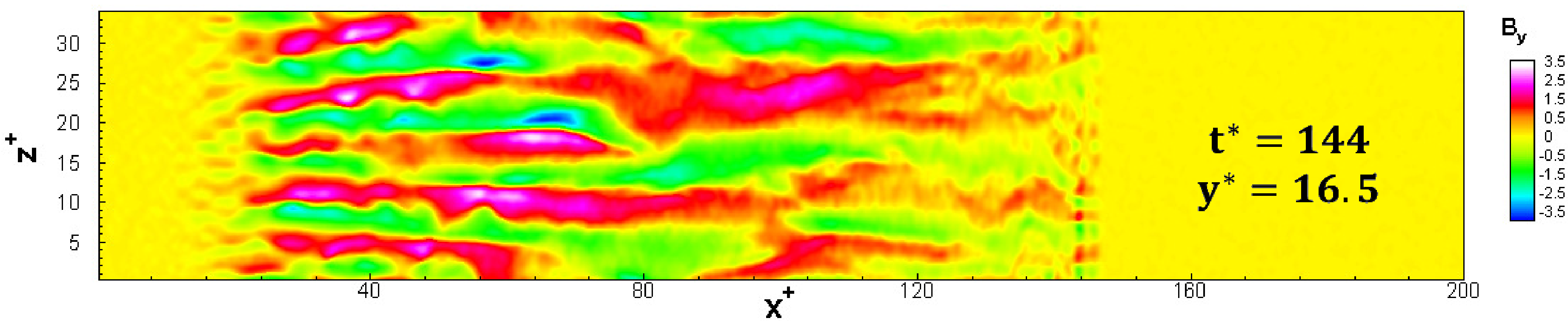
$$u_b^* = u_b / \sum_i n_i m_i \gamma_i c^2$$

$$t^* = t\omega_{pe}; x^* = x\omega_{pe} / c$$

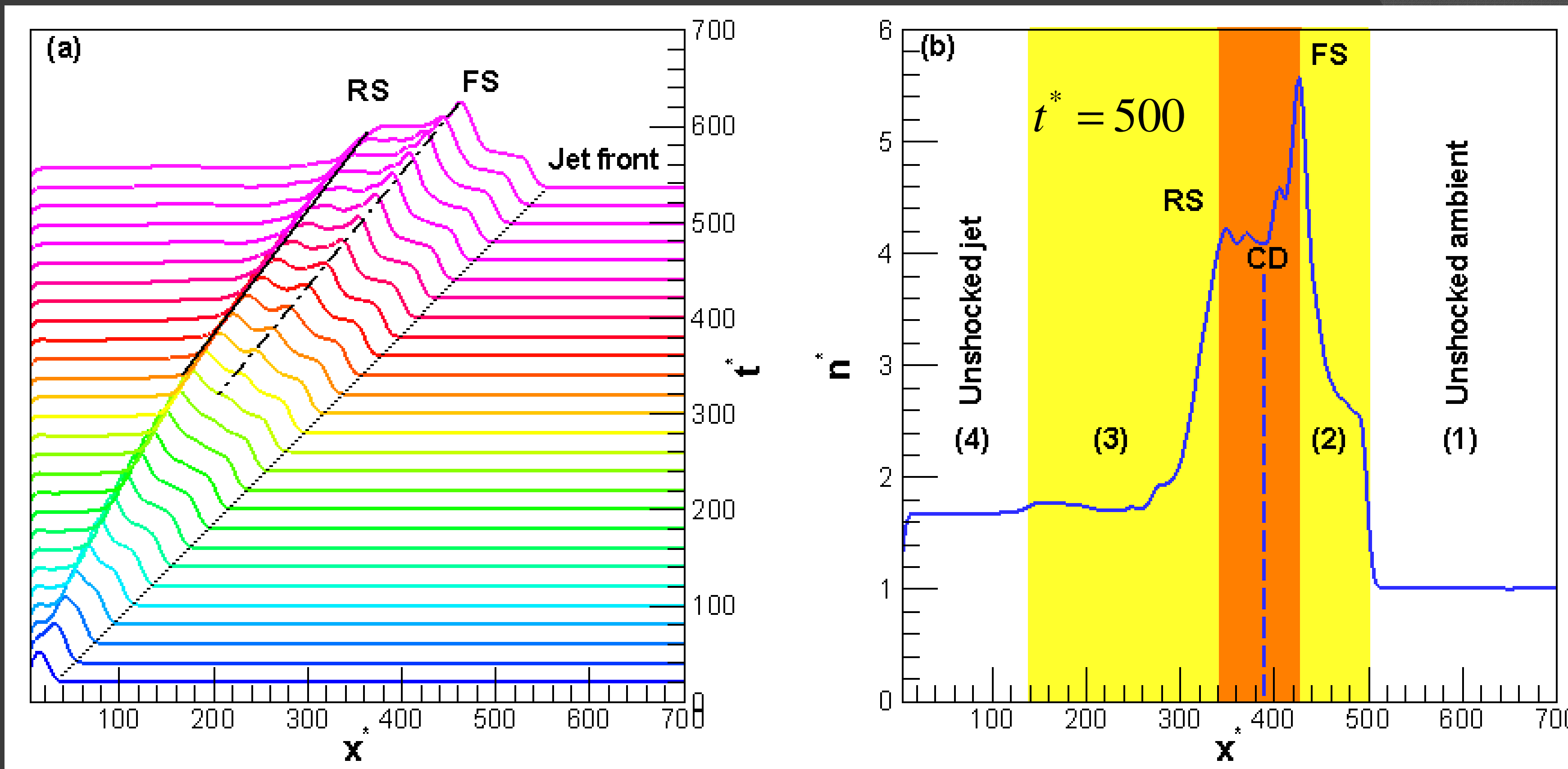
Ardaneh et al, New A.(2014)

Ardaneh et al, NeW A.(2014)





Double shock structure & validation (Run 2)



Ardaneh et al, ApJ.(2015)

RS:

PIC: $\beta_{rs} = 0.70, n_{31}/n_{41} = 2.3$

Theory: $0.51 \leq \beta_{fs} \leq 0.70$

$1.7 \leq n_{31}/n_{41} \leq 2.7$

FS:

PIC: $\beta_{fs} = 0.89, n_{21}/n_1 = 6$

Theory: $0.85 \leq \beta_{fs} \leq 0.90$

$9.4 \leq n_{21}/n_1 \leq 16$

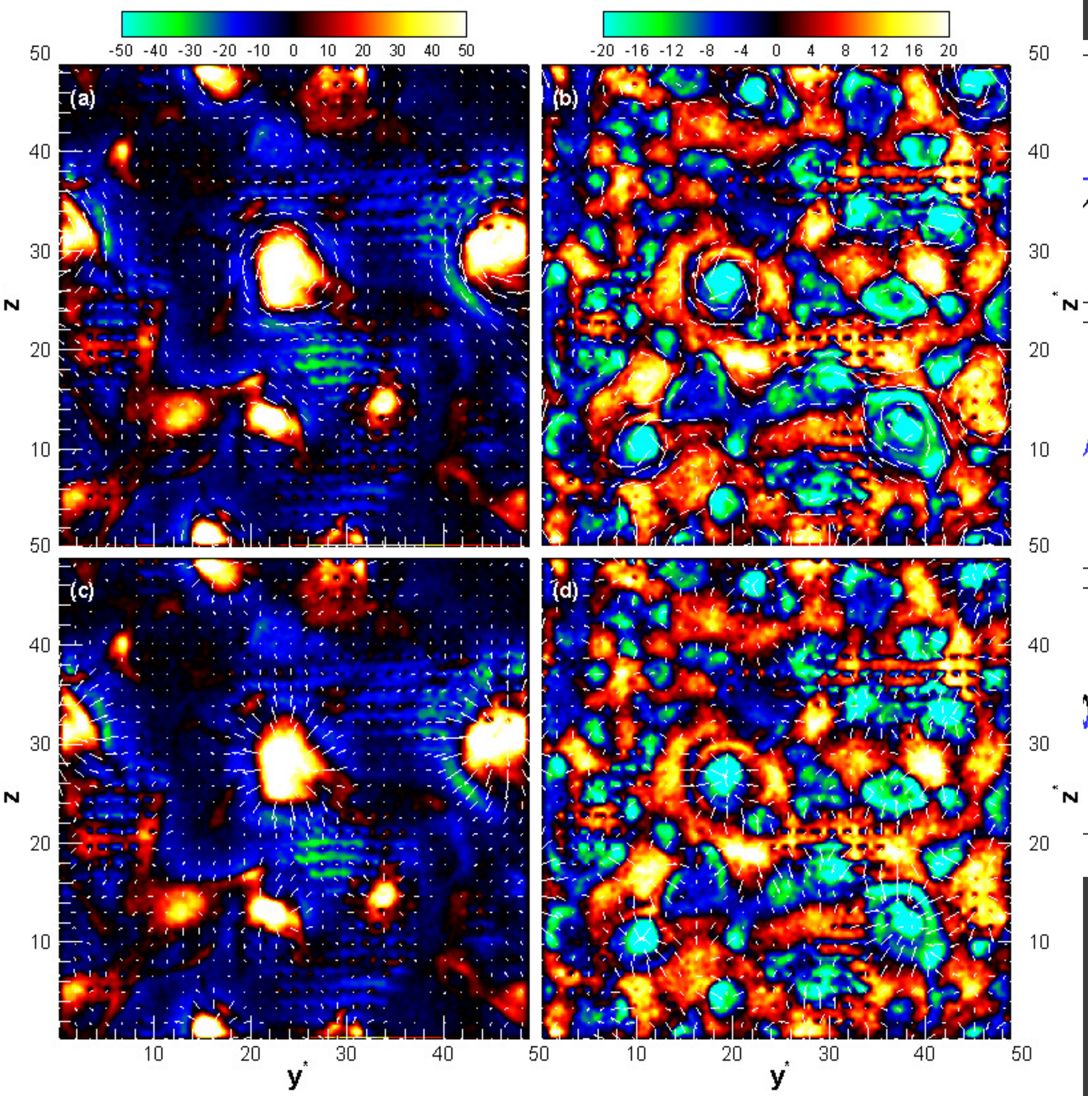
CD:

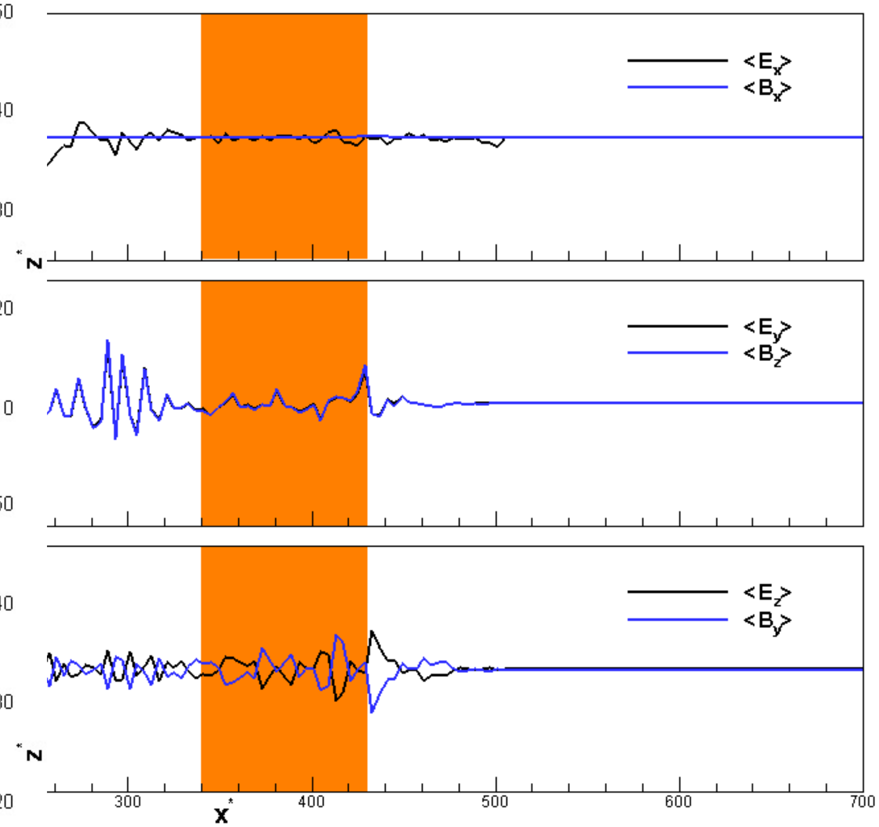
PIC: $\beta_{CD} = 0.80$

Theory: $\beta_{CD} = 0.80$

Double shock structure (Run 2)

Ardaneh et al, ApJ.(2015)





$$\mathbf{B} = \boldsymbol{\beta}_{i:e} \times \mathbf{E}$$

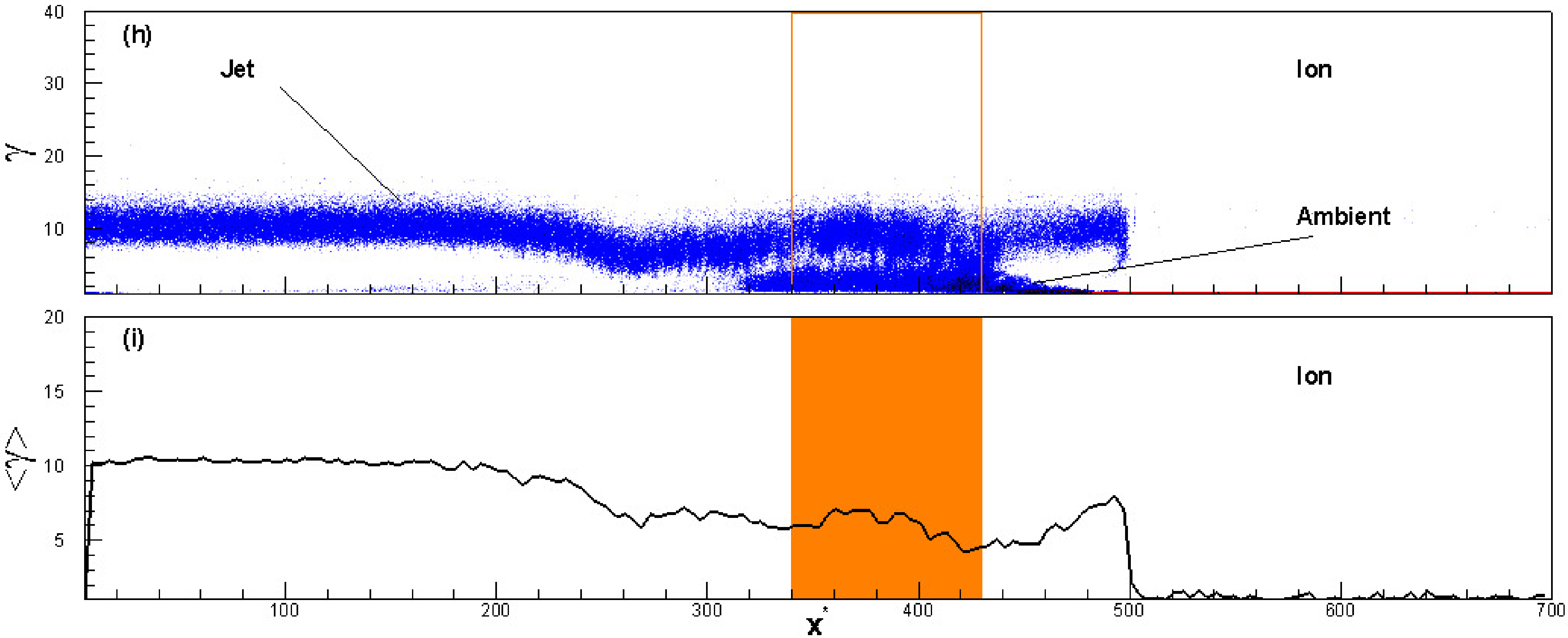
$$\beta_{i:e} \simeq 1 \Rightarrow$$

$$E_y = B_z ; E_z = -B_y$$

Ex (electrostatic field) due to the density gradient and different mobilities of charges

Particle distribution (Run 2)

Ardaneh et al, ApJ.(2015)



❖Fully thermalized electrons

❖Jet electrons trapping by the Ex

❖Effectively acceleration by Ey, and Ez

❖High-energy electron reflection by By, and Bz in the shocked region

❖Slowing down Ex

❖Transferring the jet kinetic energy to the heating of ambient particles

❖Fully thermalization has not occurred for ions

Electron spectrum (Run 2)

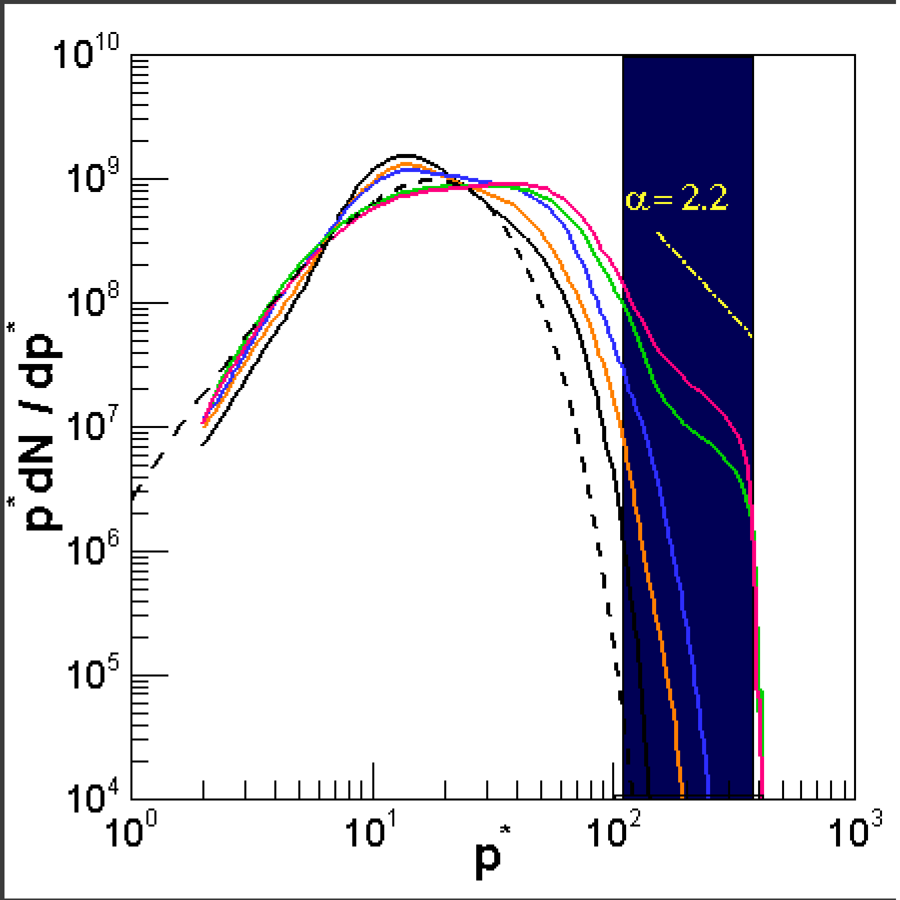
Ardaneh et al, ApJ.(2015)

$$f(p^*) = \frac{p^{*2}}{K_2(1/T^*)T^*}\exp(-\gamma/T^*)$$

$$p^* = \frac{p}{m_0 c} = \gamma\beta$$

$$T^* = \frac{K_B T}{m_0 c^2}$$

$$T^* = \frac{(\gamma_0 - 1)n_j}{3n_a} = 5$$



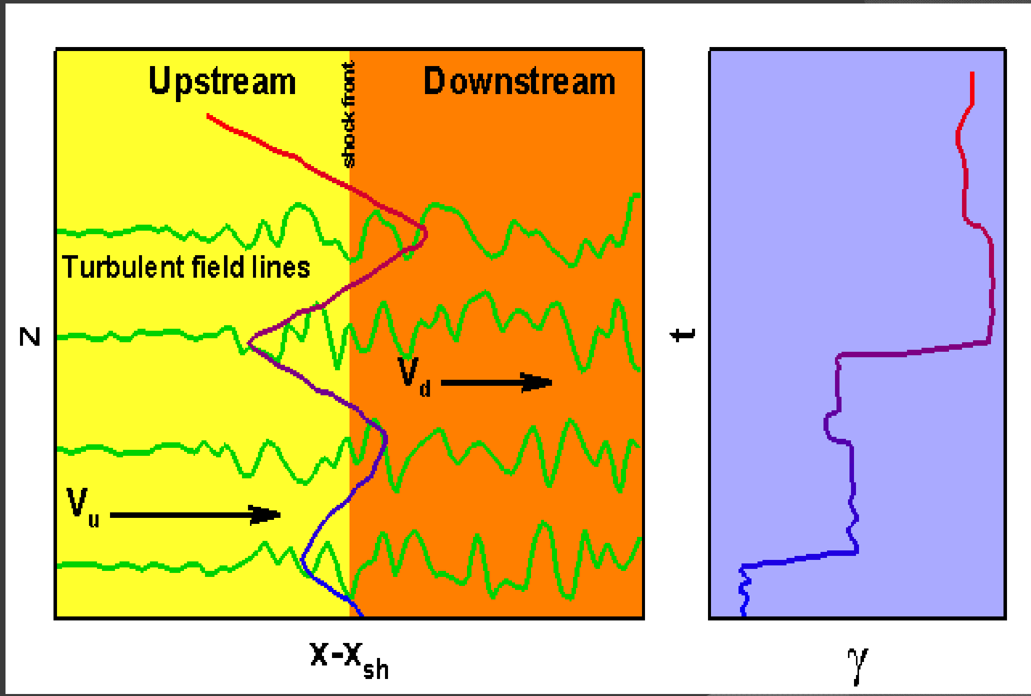
Electrons are heated by γ=100

Electrons are accelerated by γ=360 with a power-law regime

Particle acceleration (DSA)

First order Fermi acceleration (Krymsky 1977, Bell 1978, Blandford & Ostriker 78)

$$\frac{dN(\varepsilon)}{d\varepsilon} \propto \varepsilon^{-p}$$



Efficient scattering of particles is required.
Particles diffuse around the shock.

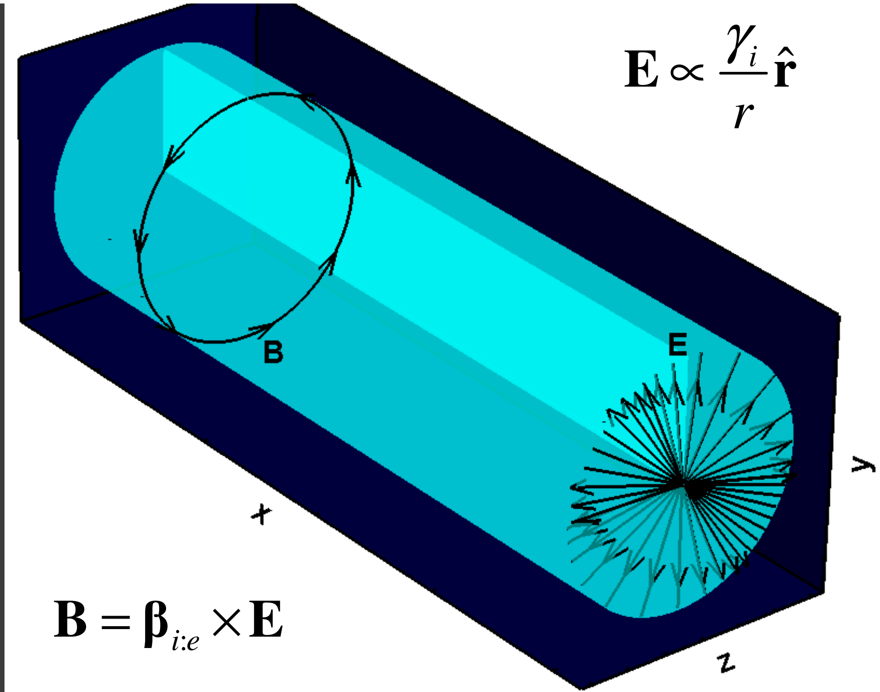
2D PIC simulation:
Spitkovsky, ApJ (2008), Martins et al, ApJ (2009)

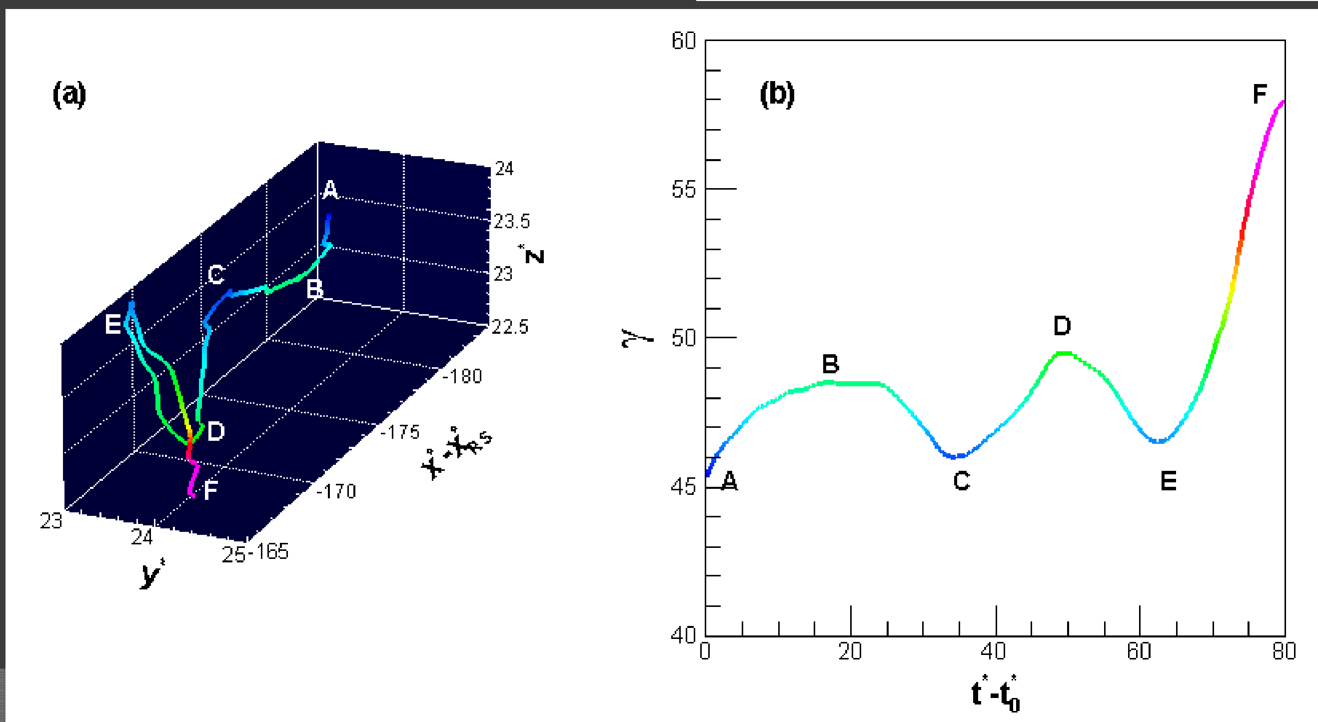
Electron heating (Run 2)

- Ion Weibel instability,
- Ion current filaments,

$$\mathbf{E}\times\mathbf{B} \ \ \text{drift}$$

Ardaneh et al, ApJ.(2015)

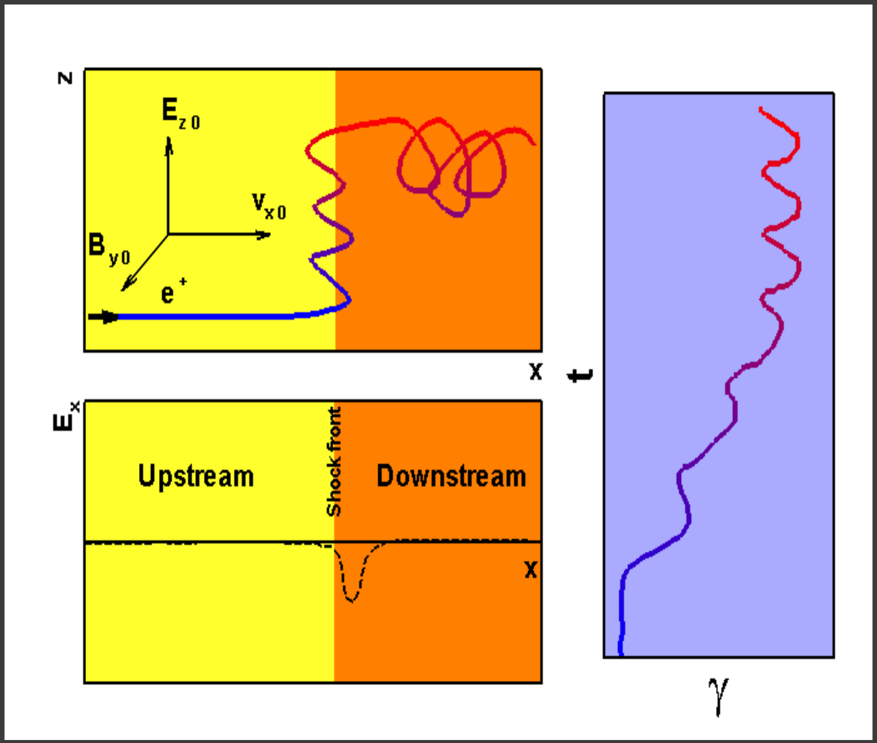




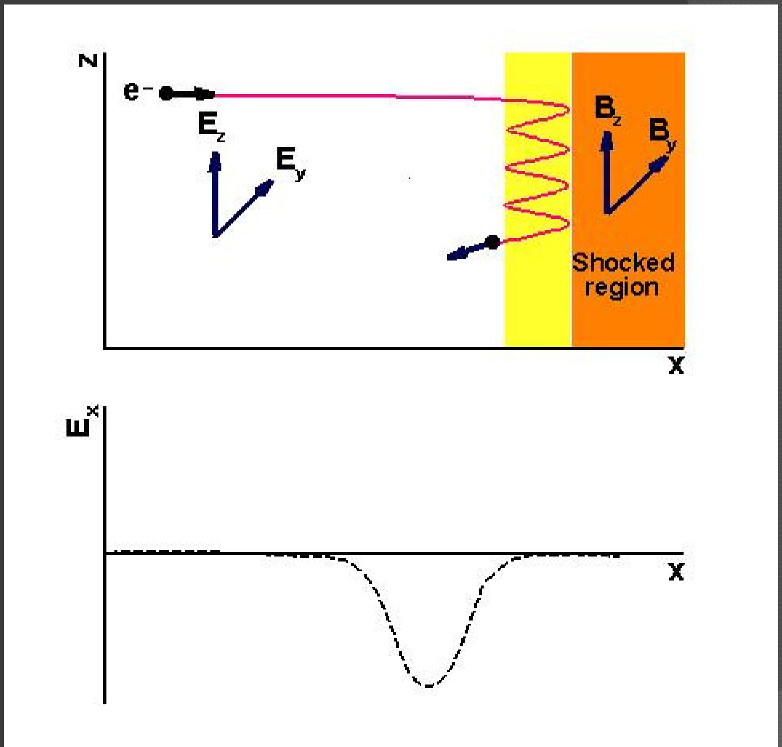
Particle acceleration (SSA)

Sagdeev & Shapiro 1974,
Zank et al. 1996,
Lee et al. 1996

Ardaneh et al, ApJ.(2015)



SSA for ions

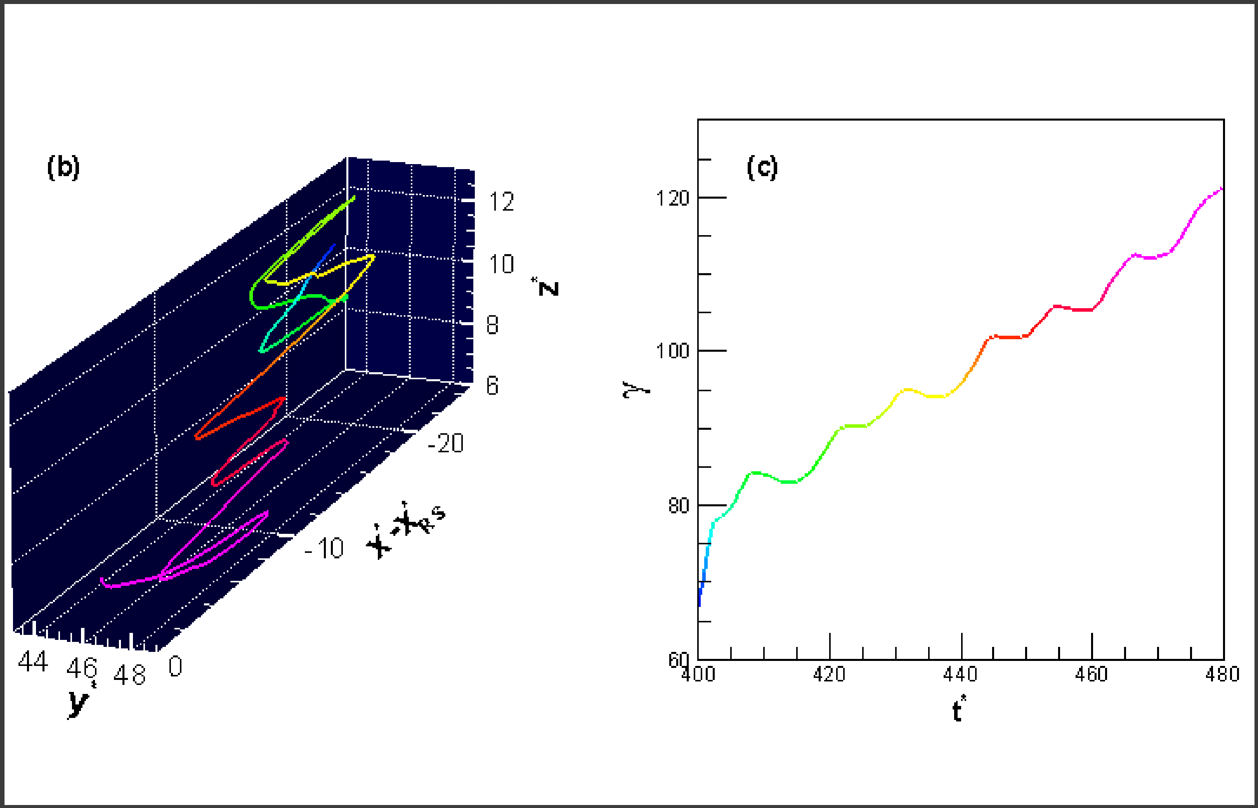


SSA for electrons

SSA for electron under ESWs:
1D PIC simulations by Hoshino (2001); Hoshino & Shimada (2002)
2D PIC simulations by Amano & Hoshino (2009); Matsumoto et al. (2012)

SSA for electron (Run 2)

Ardaneh et al, ApJ.(2015)



Trapping behind the RS

Drift in YZ plane

Acceleration by E_y and E_z Weible fields

Conclusions

- ***Ion Weibel : sources of EM fields,***
- ***Most accelerated electron are located in the RS transition region,***
- ***Electron spectrum in the RS transition region include non-thermal electrons with power-law index 2.2,***
- ***Electrons are heated up to the $\gamma = 100$ due to the $E \times B$ drift ,***
- ***Electron are accelerated via SSA process in RS transition region.***

Thank you