Collisionless Weibel shocks and electron acceleration in gamma-ray bursts

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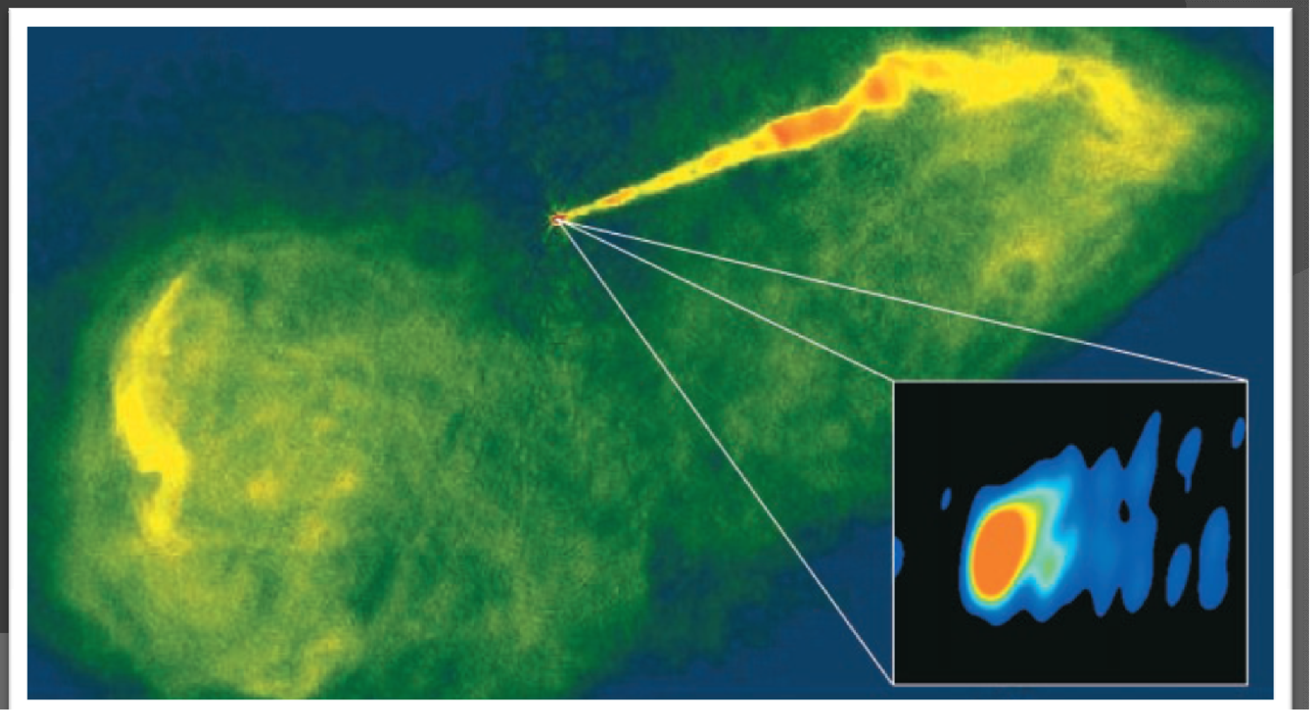
Motivations

High energy astrophysics phenomena include collimated flows of plasma with speeds close to the speed of light (relativistic jets):

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

Biretta & Junor (1999)

The jet in the galaxy M87



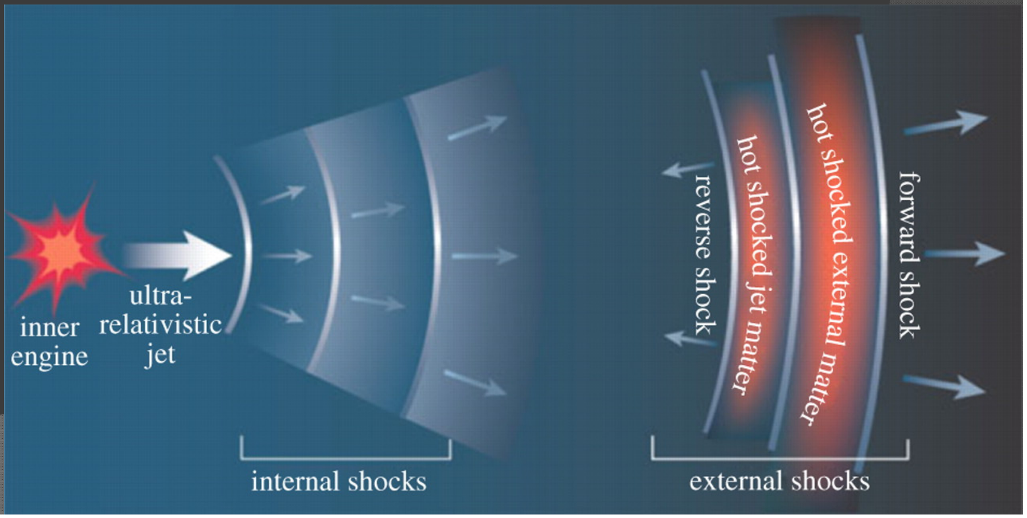
Astrophysical shocks

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

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

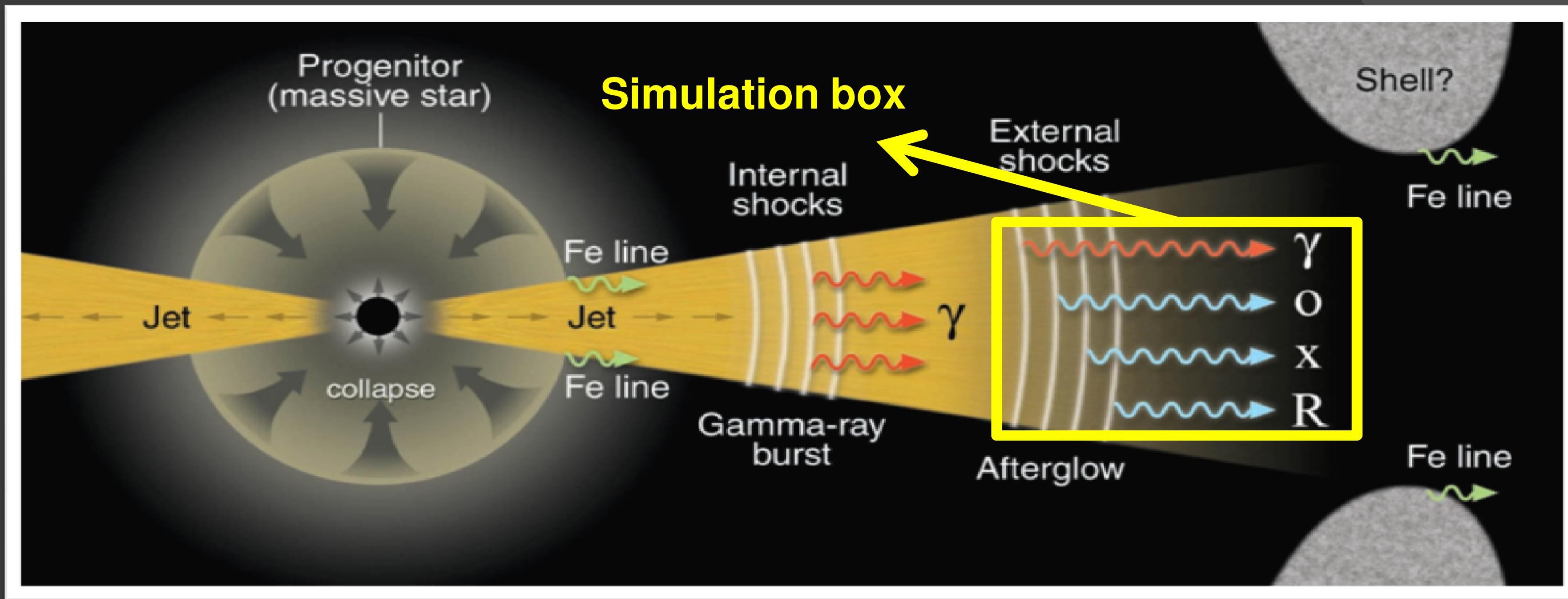
Astrophysical collisonless shocks can:

- Amplify magnetic fields
- Exchange energy between electrons and ions
- Accelerate particles
- Highly non-thermal radiation



Issues and Questions

Meszaros (2001)



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

II. **Where do these processes mainly take place?**

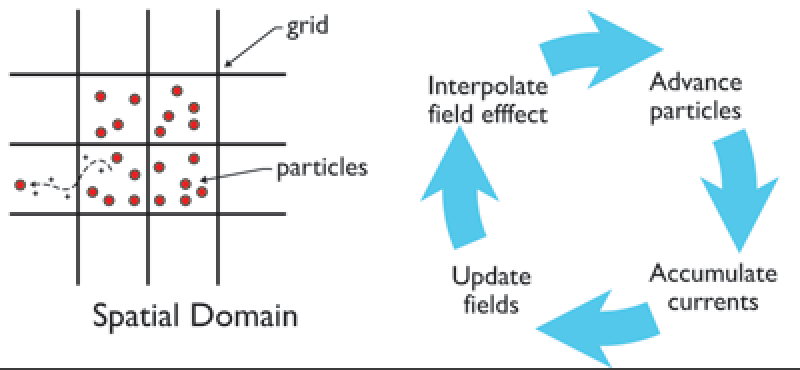
III. **What is the resulting associated electron energy spectrum?**

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

Particle-in-Cell (PIC) simulation

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

- **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)

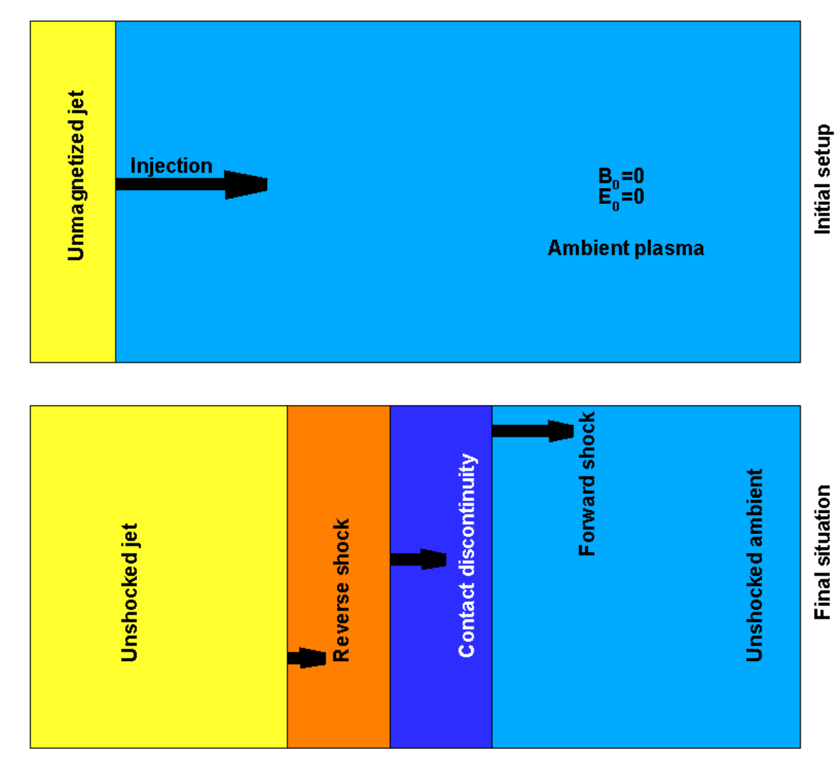
- **Appropriate boundary conditions for double shock generation**
- **Performing on KDK supercomputer, Kyoto University**

Problem setup

Unmagnetized simulations

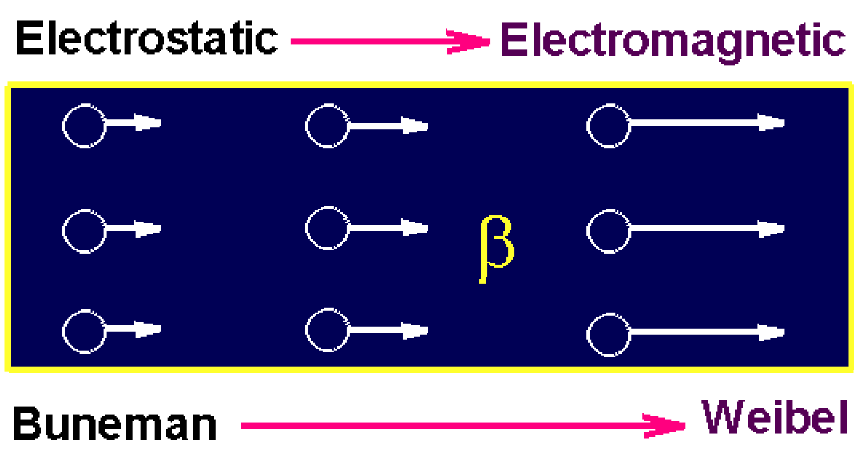
Parameters	Run A	Run B
Grid (L_x, L_y, L_z)	(1025,165,165)	(8005,245,245)
ppc (ambient) (n_a)	12	6
Jet density ratio (n_j/n_a)	0.715	1.7
Injection speed (γ)	5	10
Mass ratio (m_j/m_a)	20	16
$c:\lambda_{ce} : \lambda_d$	1: 5Δ : 0.5Δ	1: 5Δ : 0.25Δ
$\Delta t\omega_{pe}$	0.025	0.01

- Rigid reflecting boundary for the ambient particles in x-direction
- Open boundary condition for jet particles in x-direction
- Radiating boundaries for fields in x-direction
- Periodic boundary condition at all other boundaries



Two-stream instability

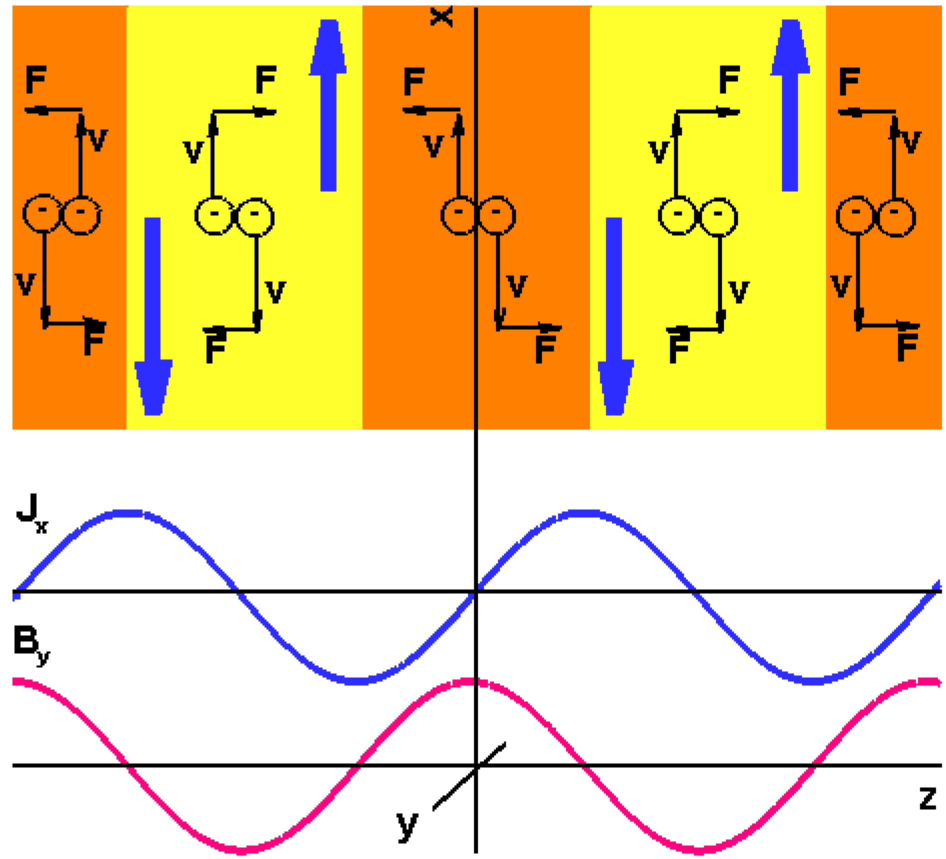
$$\vec{B} = \vec{\beta} \times \vec{E}$$



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 & Filamentation (Run A)

- **Electron Weibel instability**

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

- **Ion Weibel instability**

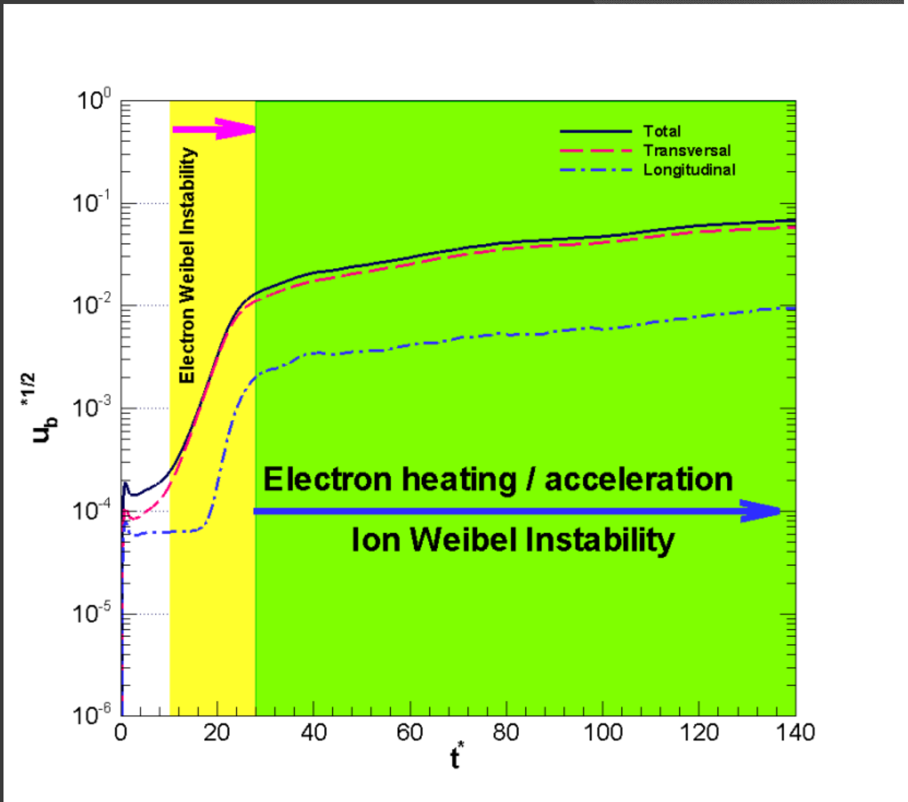
$$t^* > 26; \Gamma_i^* = 0.05$$

- **Debye shielding by electron**

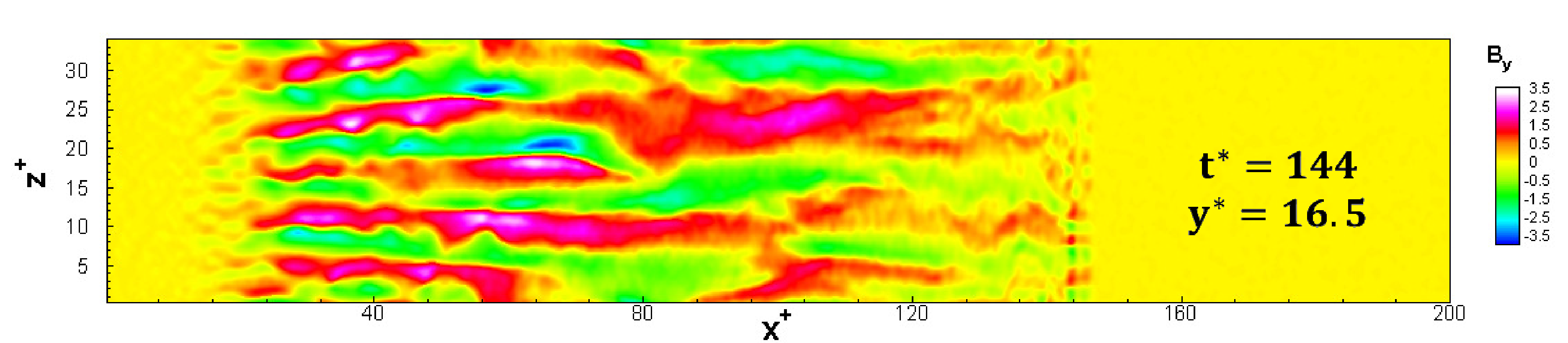
- **Electron heating / acceleration**

$$u_b^* = u_b / \sum_i n_i m_i \gamma_i c^2 ; u_b = B^2 / 2\mu_0$$

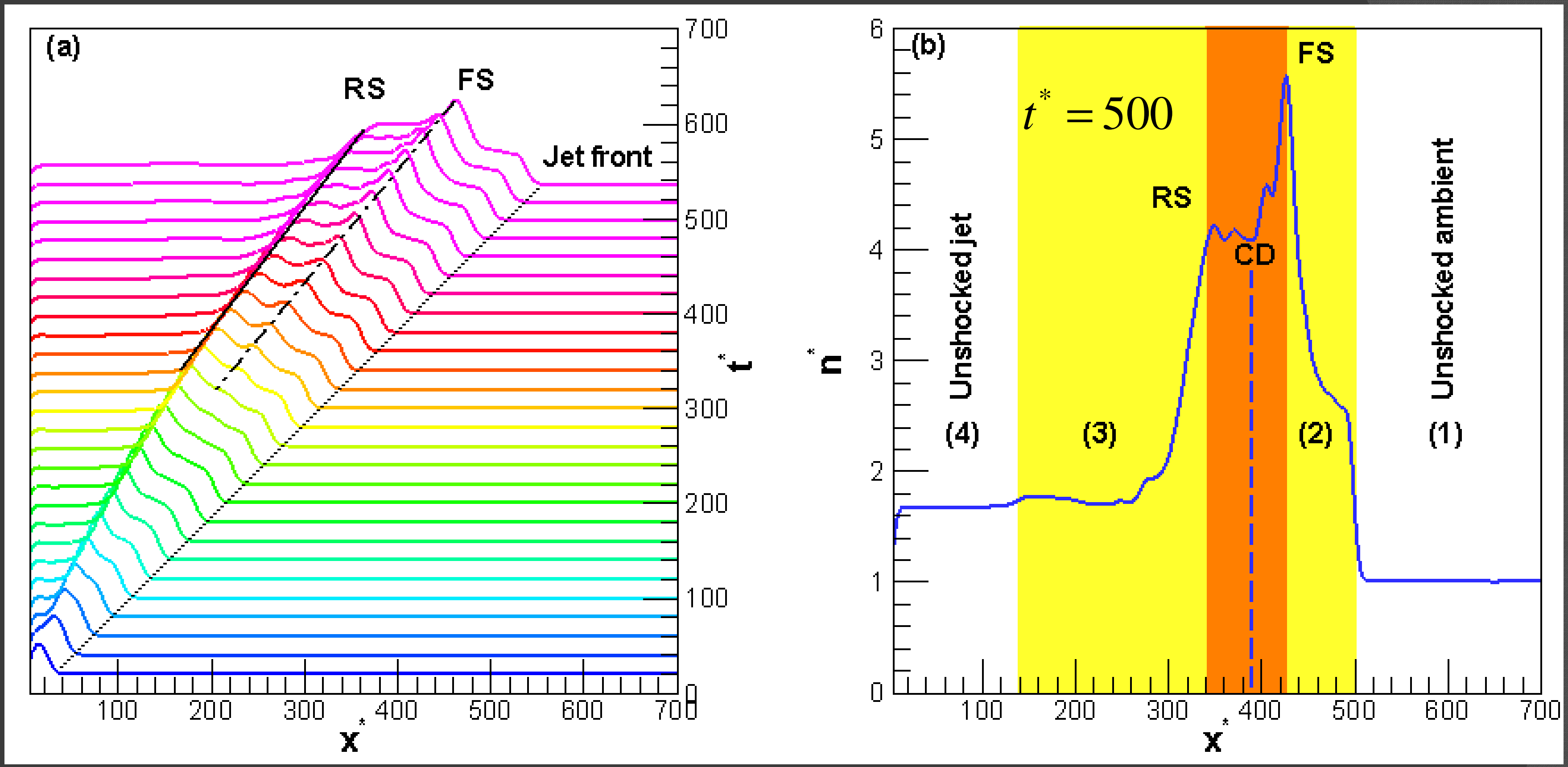
$$t^* = t\omega_{pe} ; x^* = x\omega_{pe} / c$$



Ardaneh et al (2014)



Double shock structure & validation (Run B)



Ardaneh et al (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: $0.85 \leq \beta_{fs} \leq 0.90$

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

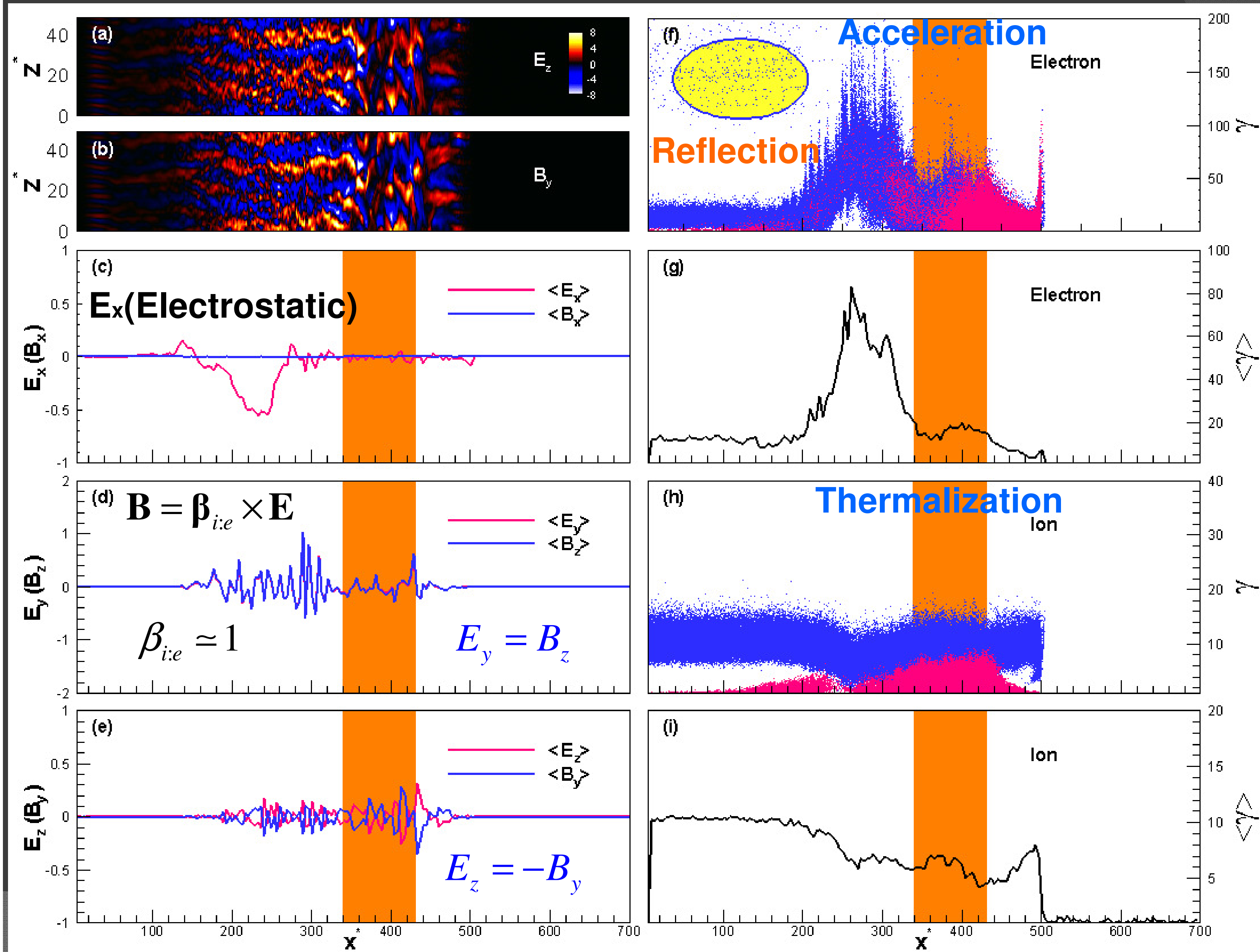
CD:

PIC: $\beta_{CD} = 0.80$

Theory: $\beta_{CD} = 0.80$

Double shock structure (Run B)

Ardaneh et al (2015)



Electron spectrum (Run B)

Ardaneh et al (2015)

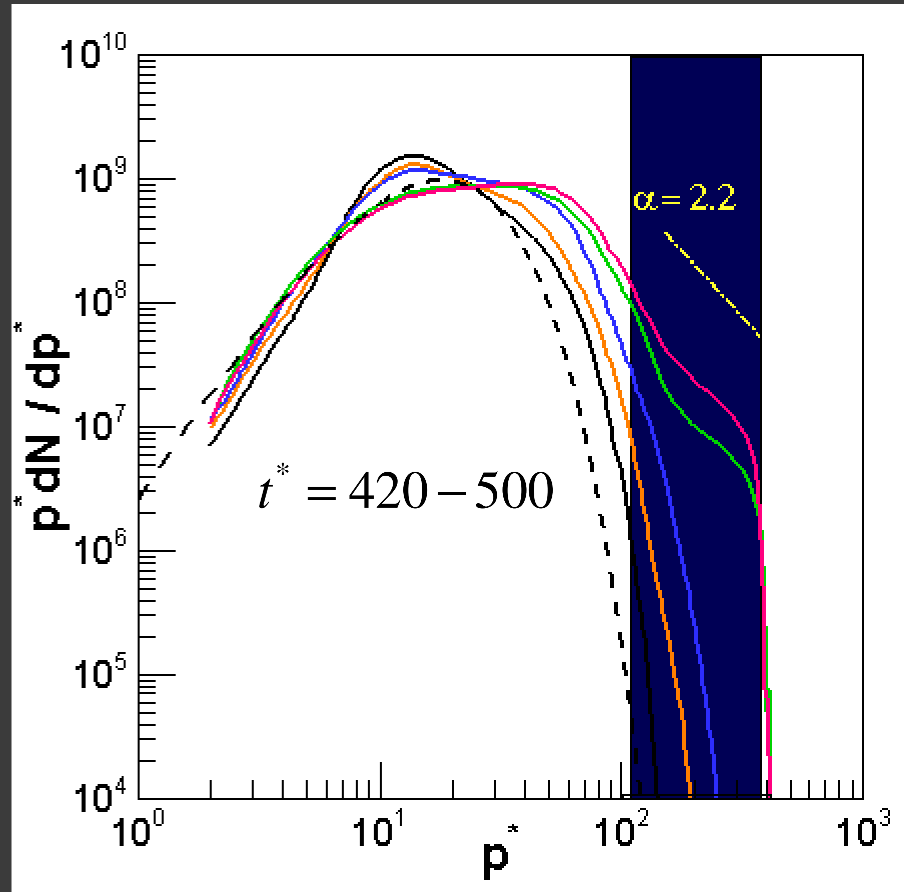
RS transition region

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

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

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

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



PDF evolution in time

Electrons are heated by γ=100

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

$$\frac{dN(\gamma)}{d\gamma} \propto \gamma^{-\alpha}; \alpha = 2.2$$

Particle acceleration in shock systems (PIC simulation)

Dimension				
Composition		1D	2D	3D
	e-e+	Hoshino (2001) SSA under MSW	Spitkovsky, ApJ (2008), DSA	Sironi &Spitkovsky ApJ (2009), DSA
	e-ion	Hoshino & Shimada(2002) SSA under ESW	Amano &Hoshino, ApJ (2009), SSA under ESW Martins et al, ApJ (2009), DSA Guo et al, ApJ (2014), SDA	Hededal et al, ApJ (2004), E×B Weibel fields Sironi &Spitkovsky ApJ (2011), DSA

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

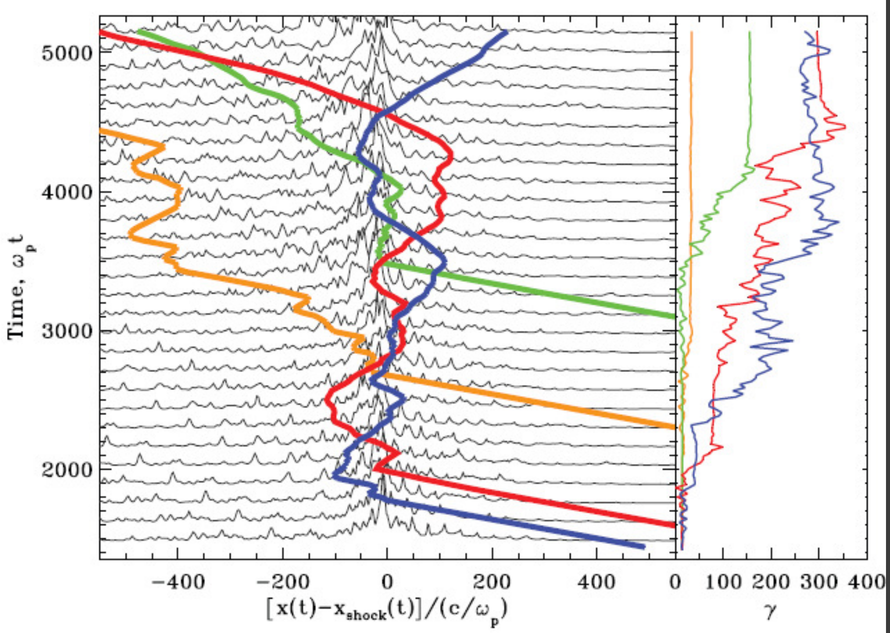
Particle acceleration (DSA)

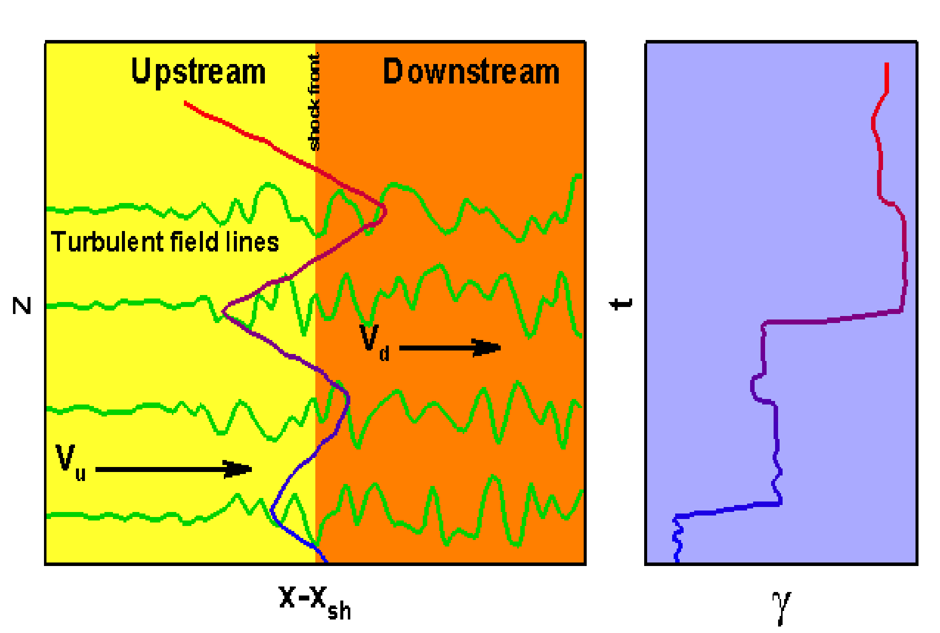
First order Fermi acceleration

(Krymsky 1977, Bell 1978, Blandford & Ostriker 1978)

$$\frac{dN(\gamma)}{d\gamma} \propto \gamma^{-\alpha}; \alpha \geq 2$$

Spitkovsky (2008)

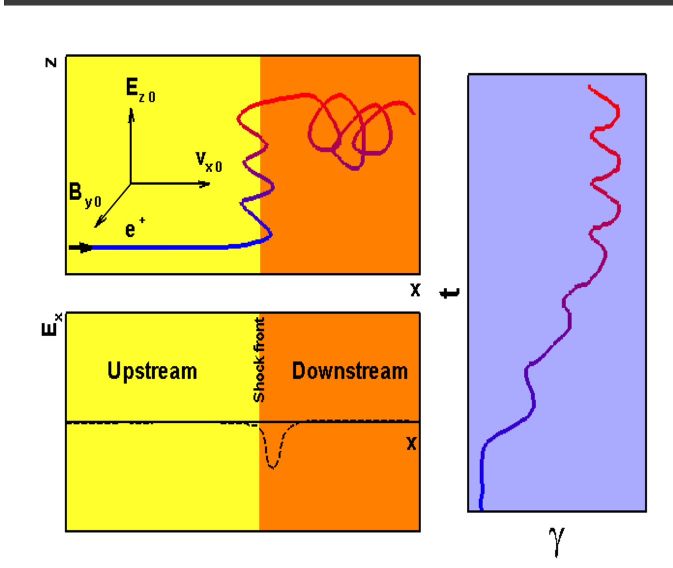




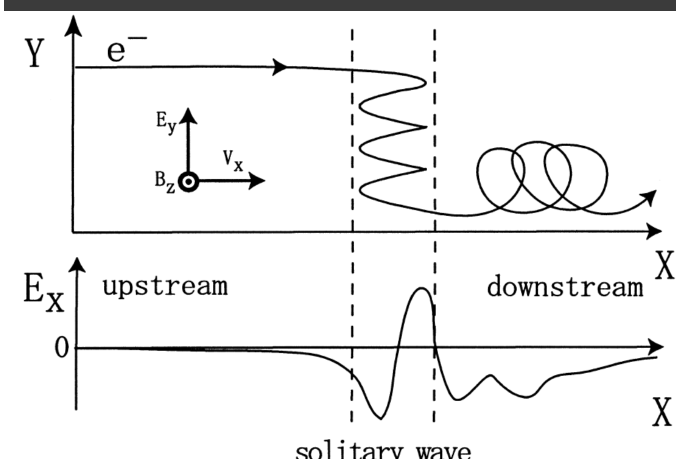
Efficient scattering of particles is required.
Particles diffuse around the shock.

2D PIC simulation: Spitkovsky (2008), Martins et al (2009)
3D PIC simulation: Sironi & Spitkovsky (2009; 2011)

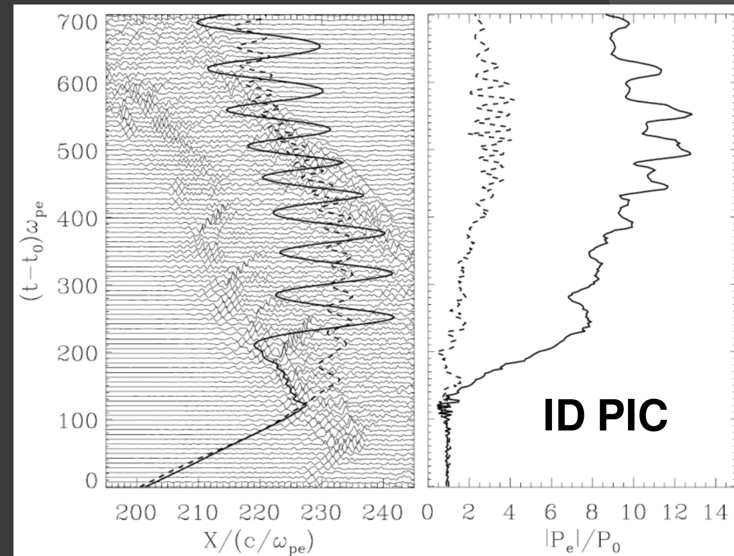
Particle acceleration (SSA)



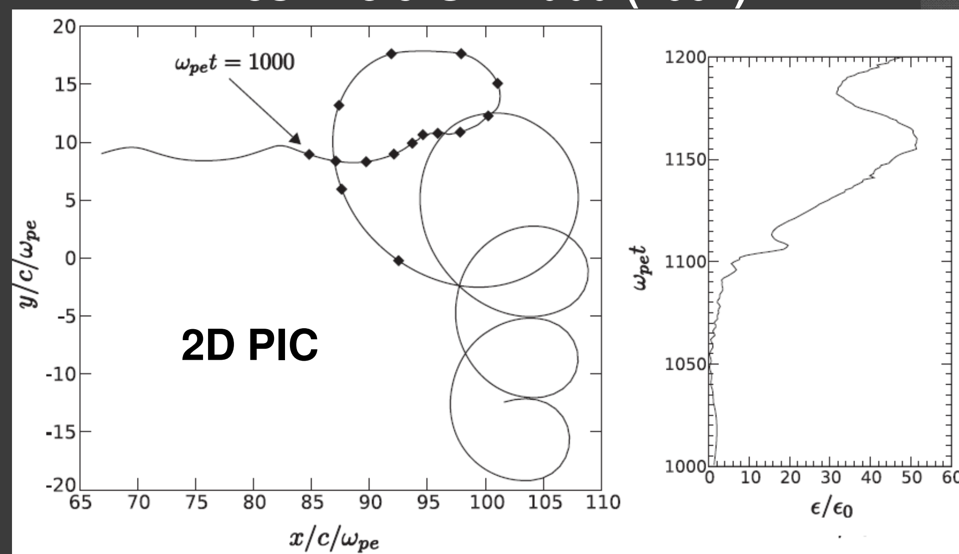
SSA for ions



SSA for electron



Hoshino & Shimada (2002)

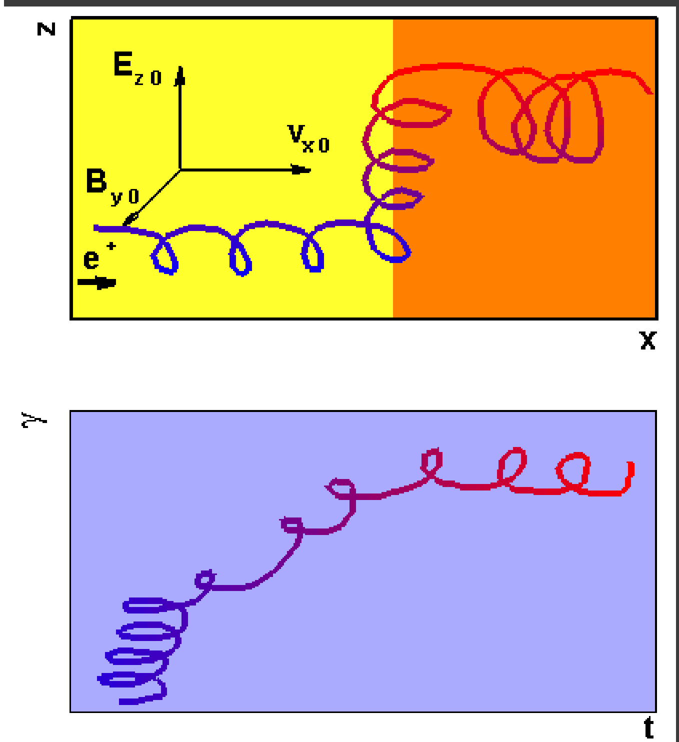


Amano & Hoshino (2009)

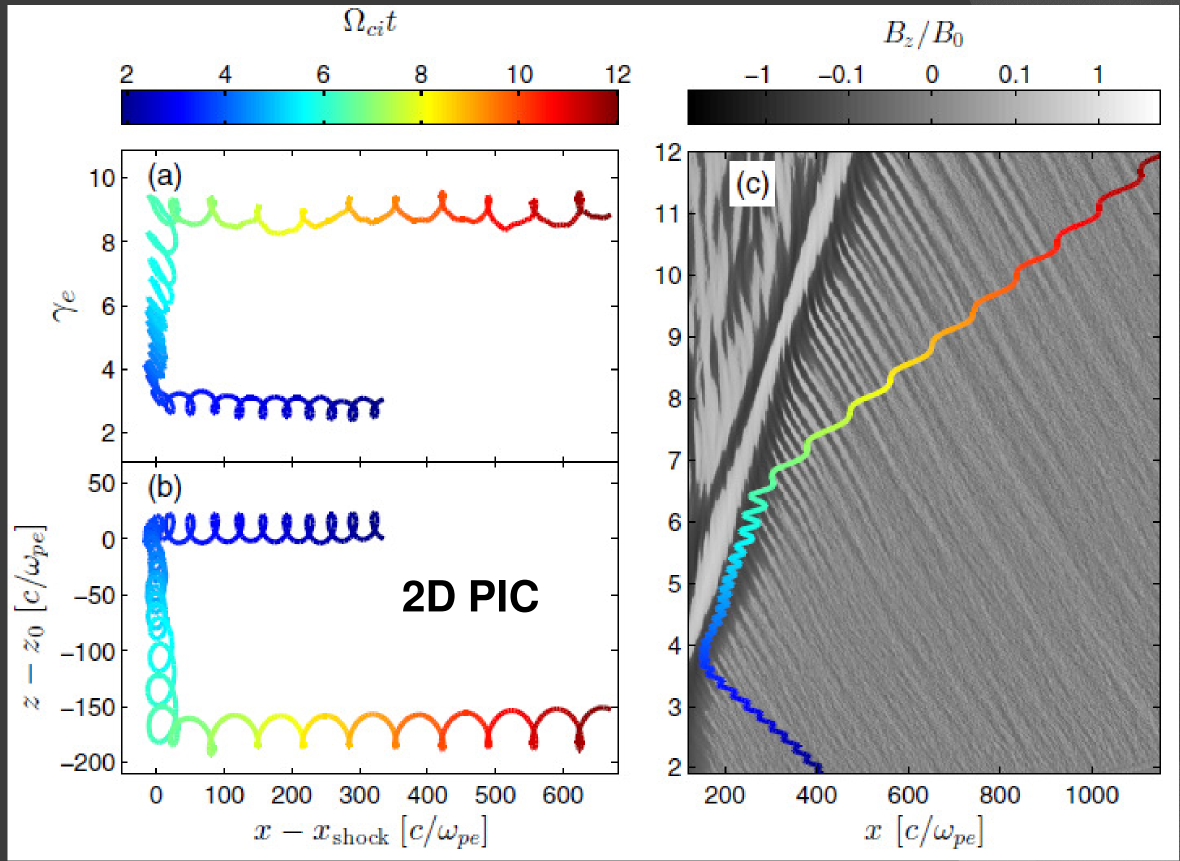
- ➢ESWs due to the interaction between incoming electrons and reflected ions
- ➢Electrons trapping in the ESWs and acceleration by the convective electric field

Particle acceleration (SDA)

Ball & Melrose (2001)



Guo et al (2014)



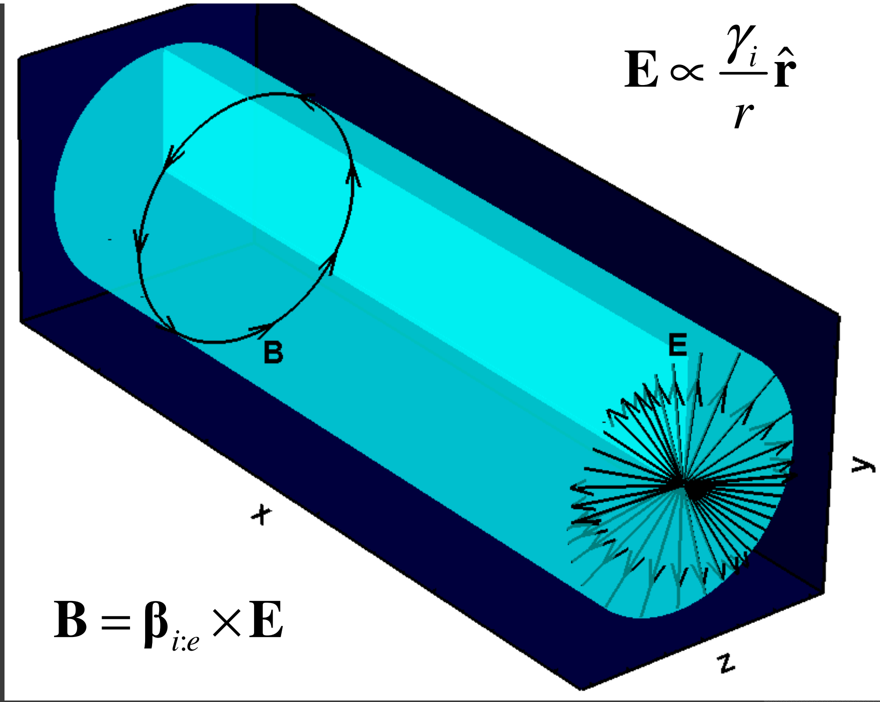
DSA for electrons

- Grad-B causes an incoming electron to drift along z direction $\mathbf{v}_d \propto \dfrac{\mathbf{B}\times\nabla B}{B^3}$
- The electron is accelerated by the upstream convective electric field

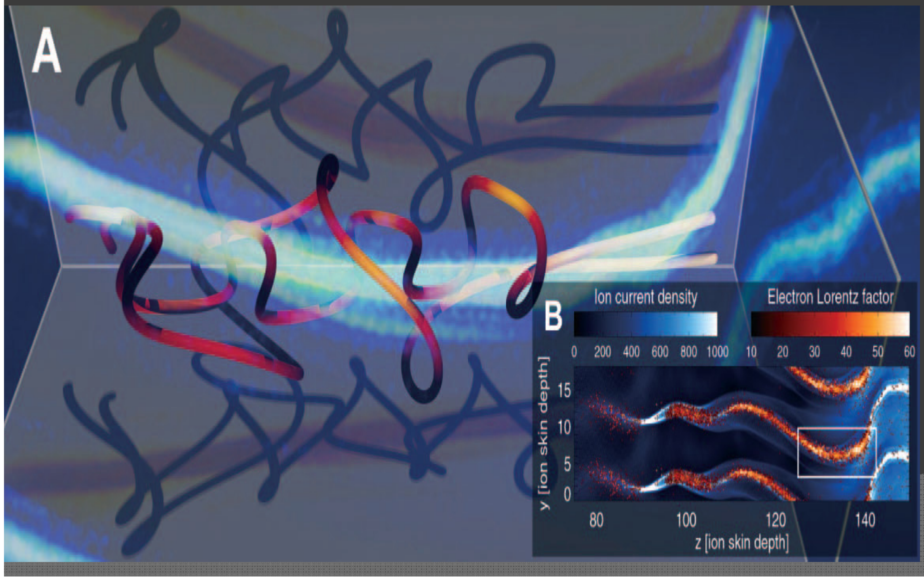
Electron heating (Run B)

- Ion Weibel instability,
- Ion current filaments,

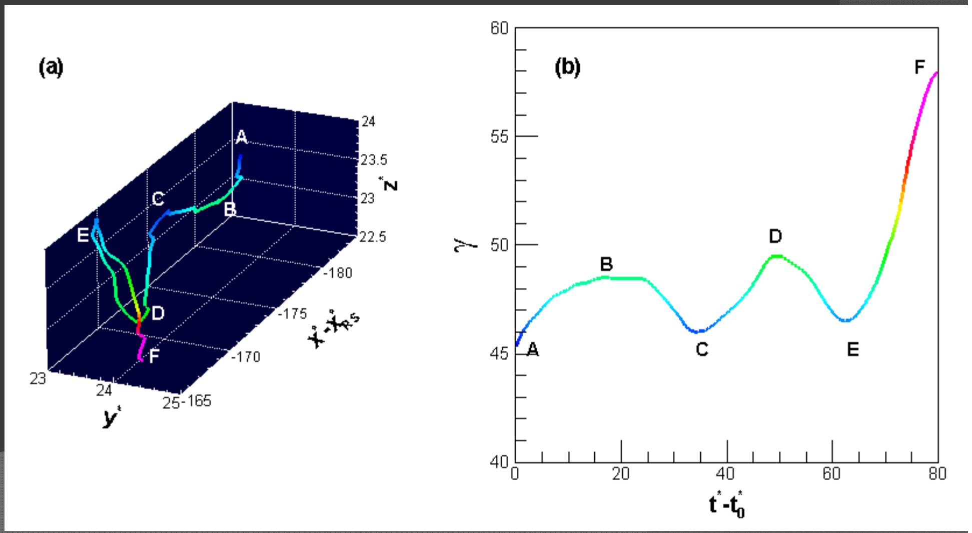
$$\mathbf{E}\times\mathbf{B} \;\; \text{drift}$$



Hededal et al (2004)

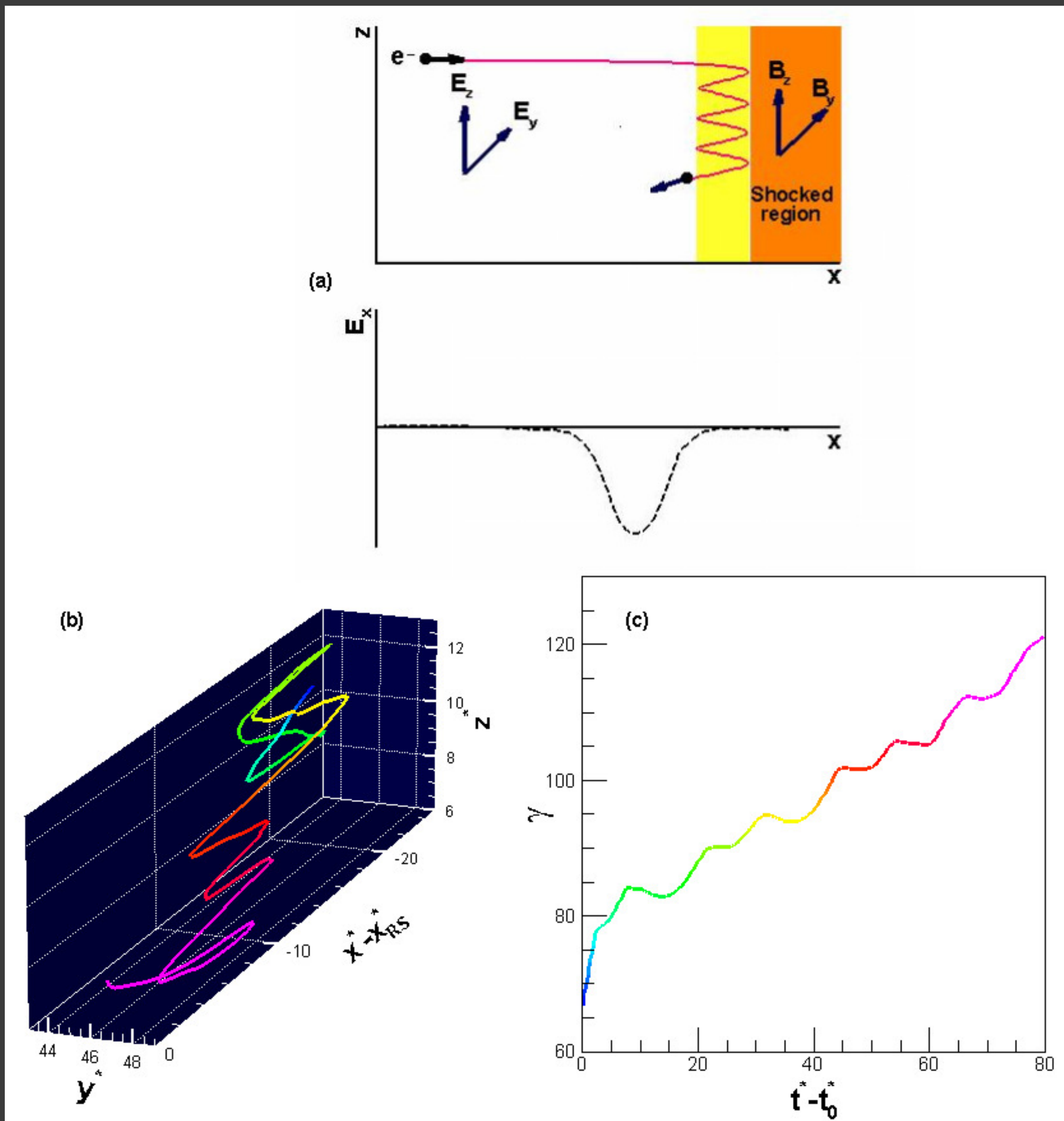


Ardaneh et al (2015)



SSA for electron (Run B)

Ardaneh et al (2015)



RS transition region

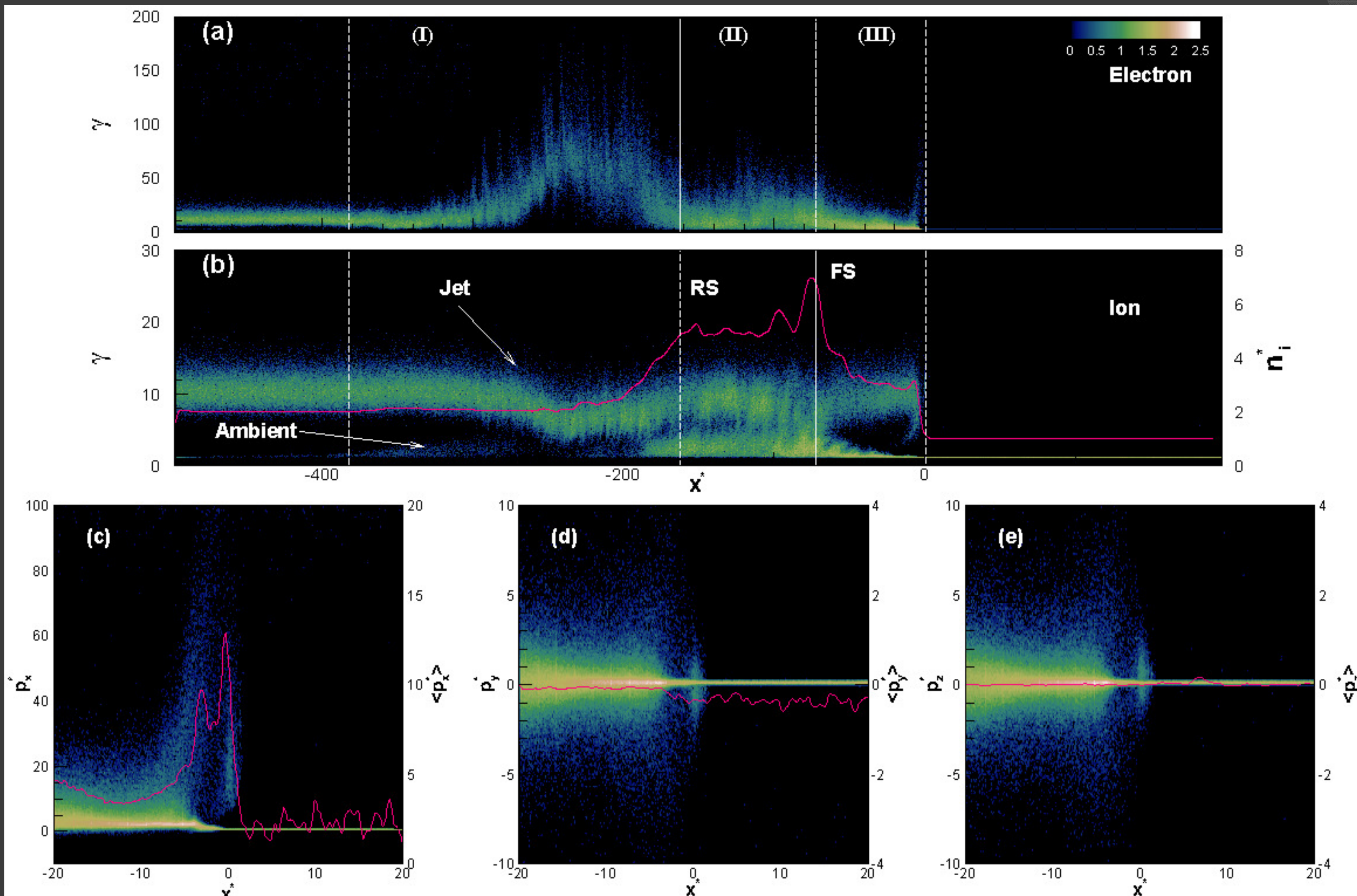
Trapping behind the RS

Drift in YZ plane

Acceleration by E_y and E_z Weible fields is accompanied by acceleration by E_x

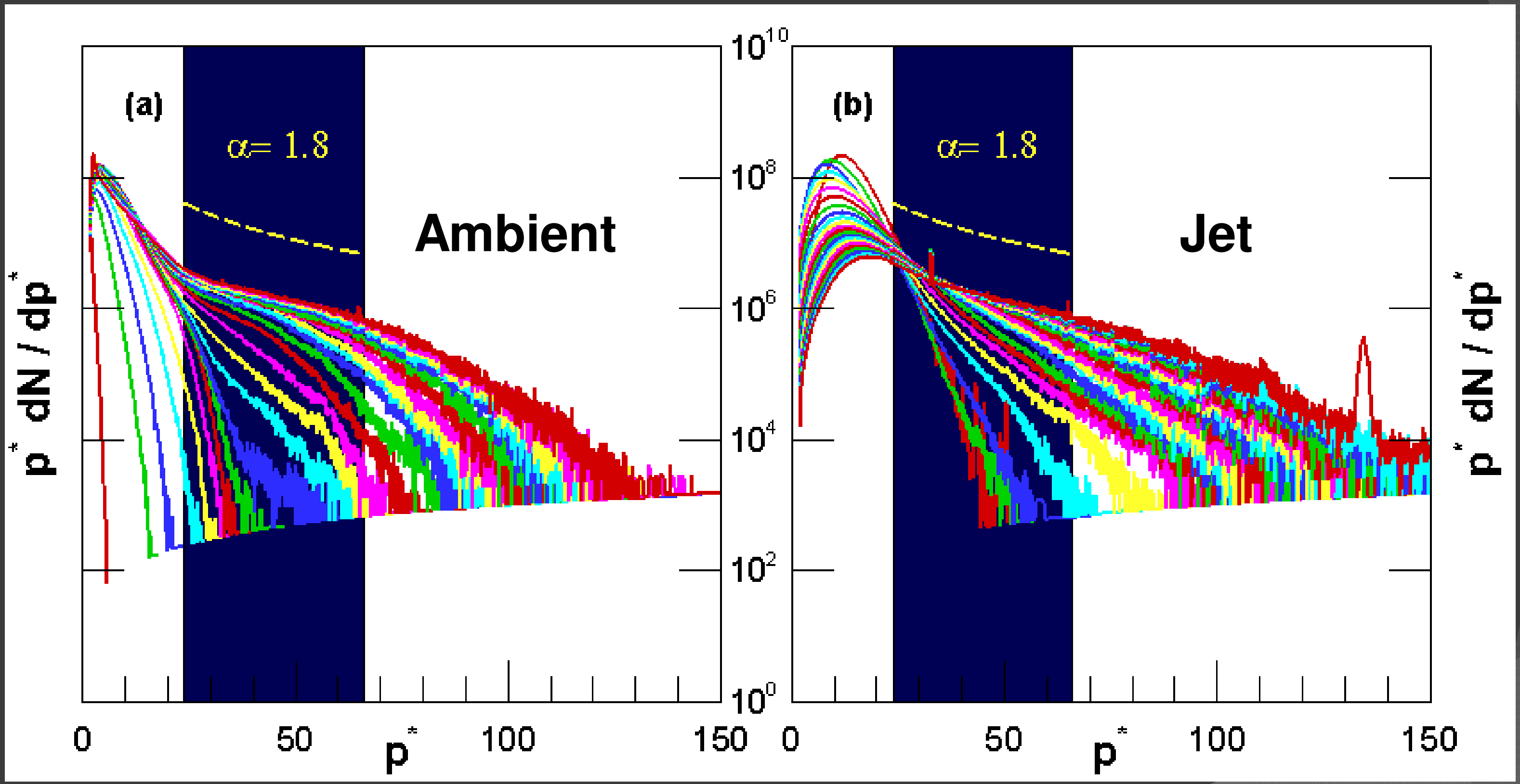
Electron acceleration in the precursor region (Run B)

Energy & momentum distribution



Electron spectrum (Run B)

PDF evolution in time $t^* = 20 - 500$

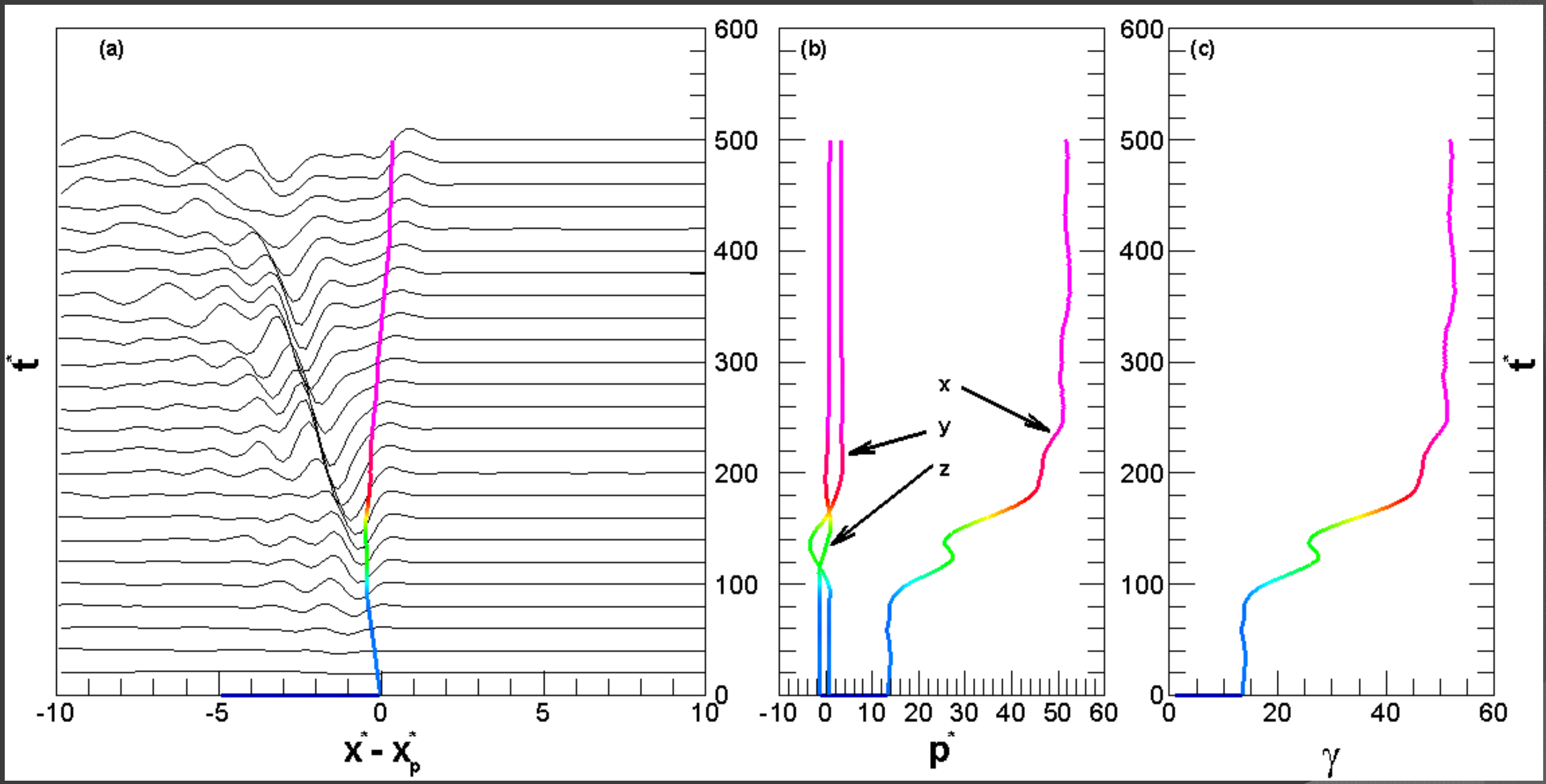


Precursor region $\frac{dN(\gamma)}{d\gamma} \propto \gamma^{-\alpha}; \alpha = 1.8$

Electron acceleration in a double layer plasma (Run B)

Particle tracing

Electron trajectory & momentum, & energy



Conclusions

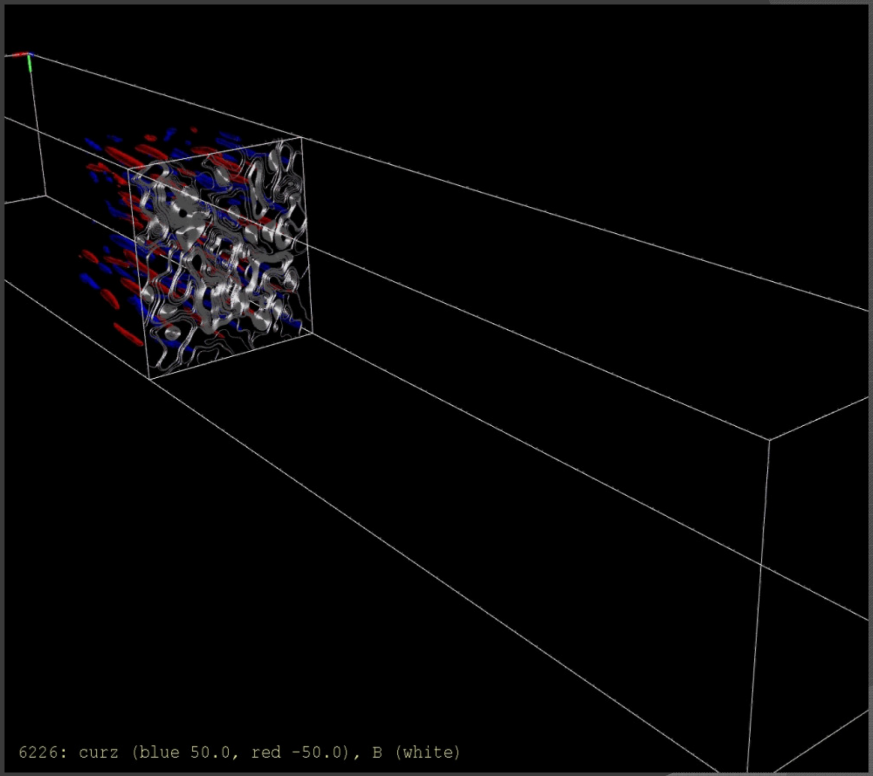
- *Ion Weibel instability: sources of transversal EM fields,*
- *Double layer plasma: sources of longitudinal E fields,*
- *Most accelerated electron are located in the RS transition region,*
- *Electron spectrum in the RS transition region: non-thermal population with power-law index 2.2,*
- *Electron spectrum in the precursor region: non-thermal population with power-law index 1.8,*
- *Electron heating due to the $E \times B$,*
- *Electron acceleration via SSA in RS transition region,*
- *Electron acceleration by longitudinal E_x in precursor region.*

Thank you

Weibel instability (filamentation)

electron-ion

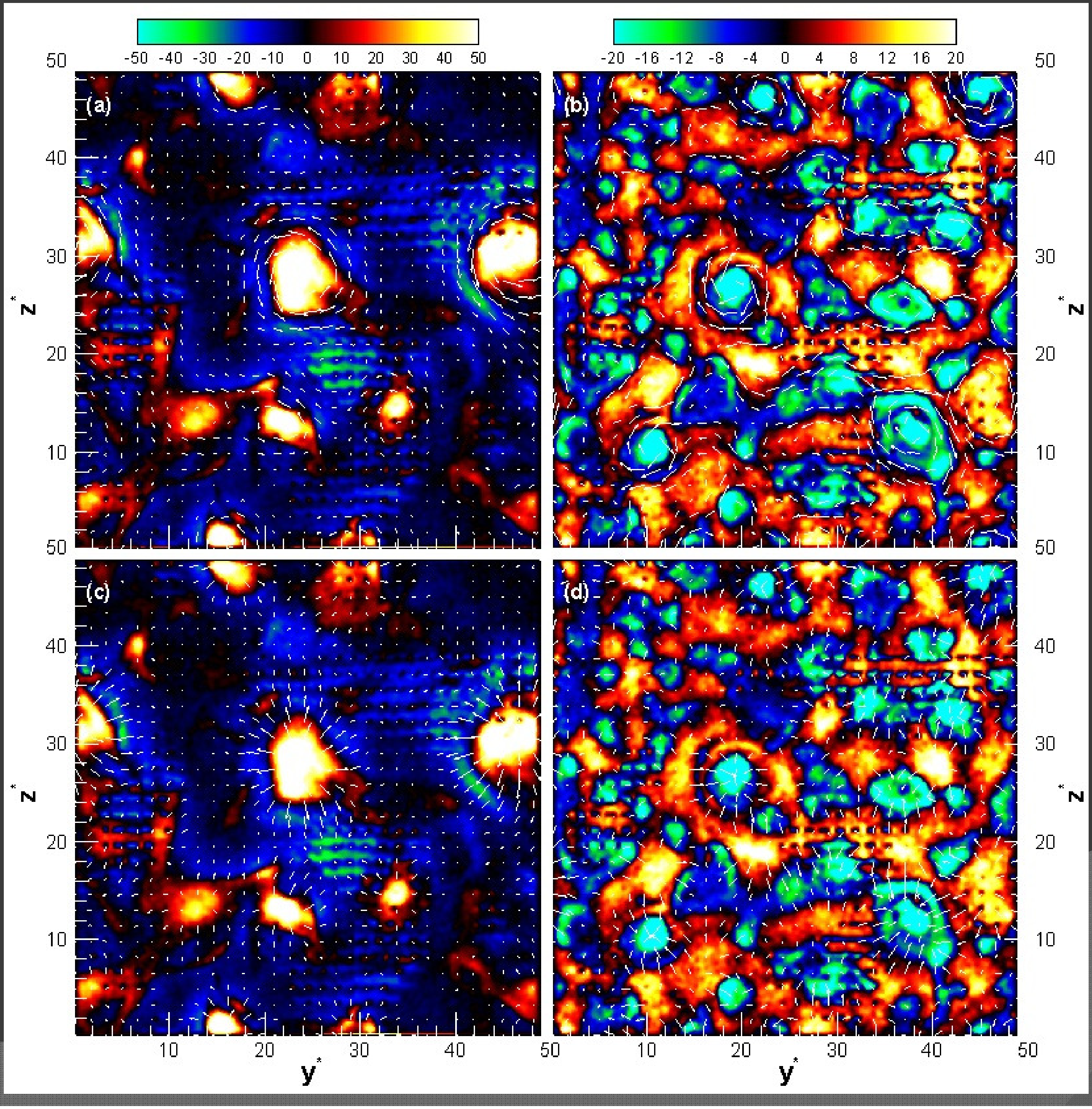
electron-positron



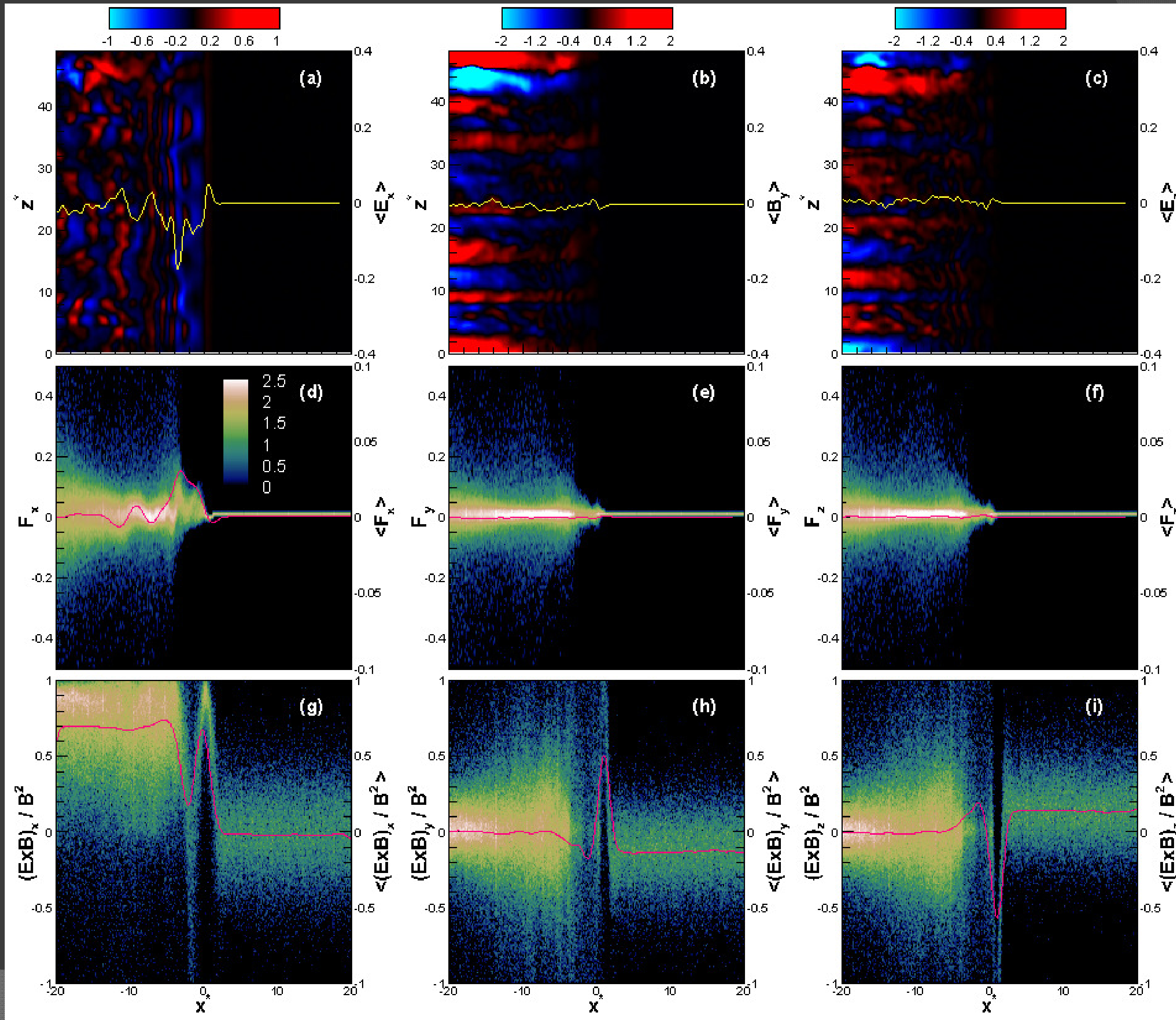
(+J_x: blue, -J_x:red) local magnetic field lines (white lines)

Nishikawa et al (2003, 2005, 2009)

Transverse fields

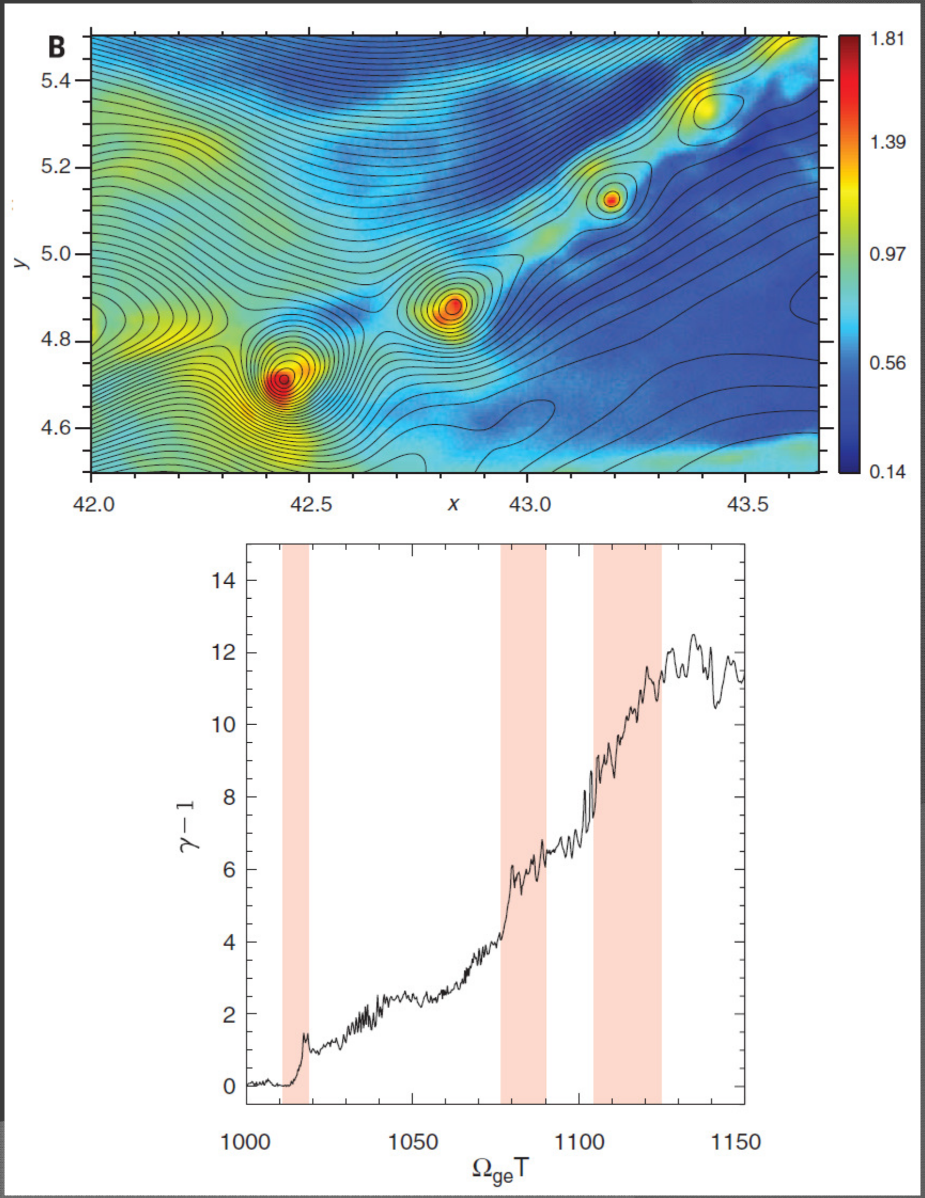


Double layer plasma



How about turbulent reconnection?

Matsumoto et al (2015)



No evidence for turbulent reconnection