Nonrelativistic Perpendicular Shocks Modeling Young Supernova Remnants Through Kinetic Simulations

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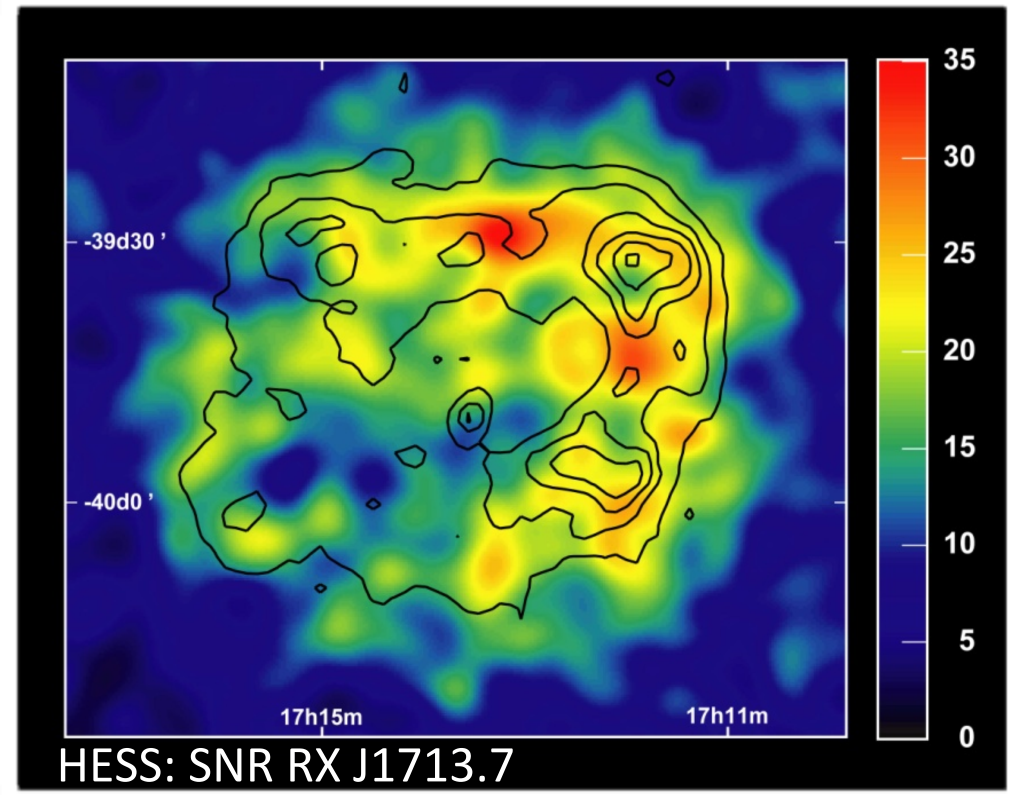
Setting the stage…

Diffusive Shock Acceleration (DSA) process at young SNR shocks assumed to provide the main part of Galactic cosmic-ray flux.



Attributes relevant for DSA:

- efficient acceleration requires strong magnetic turbulence that needs to be self-generated by accelerated particles
- particle pre-acceleration needed: electron injection constitutes the central unresolved issue

Attributes of young SNRs:

- high Alfven Mach number (supercritical) shocks:
  - regime of weakly magnetized plasma
  - shock structure driven by shock-reflected ions (but electron dynamics important)
- high-speed nonrelativistic shocks mediated by Weibel-type filamentation instabilities

Today's topic:

- nonrelativistic perpendicular high Mach number collisionless shocks
  - nonlinear shock structure
  - cyclic shock self-reformation
  - shock rippling
  - electron heating and injection (pre-acceleration)

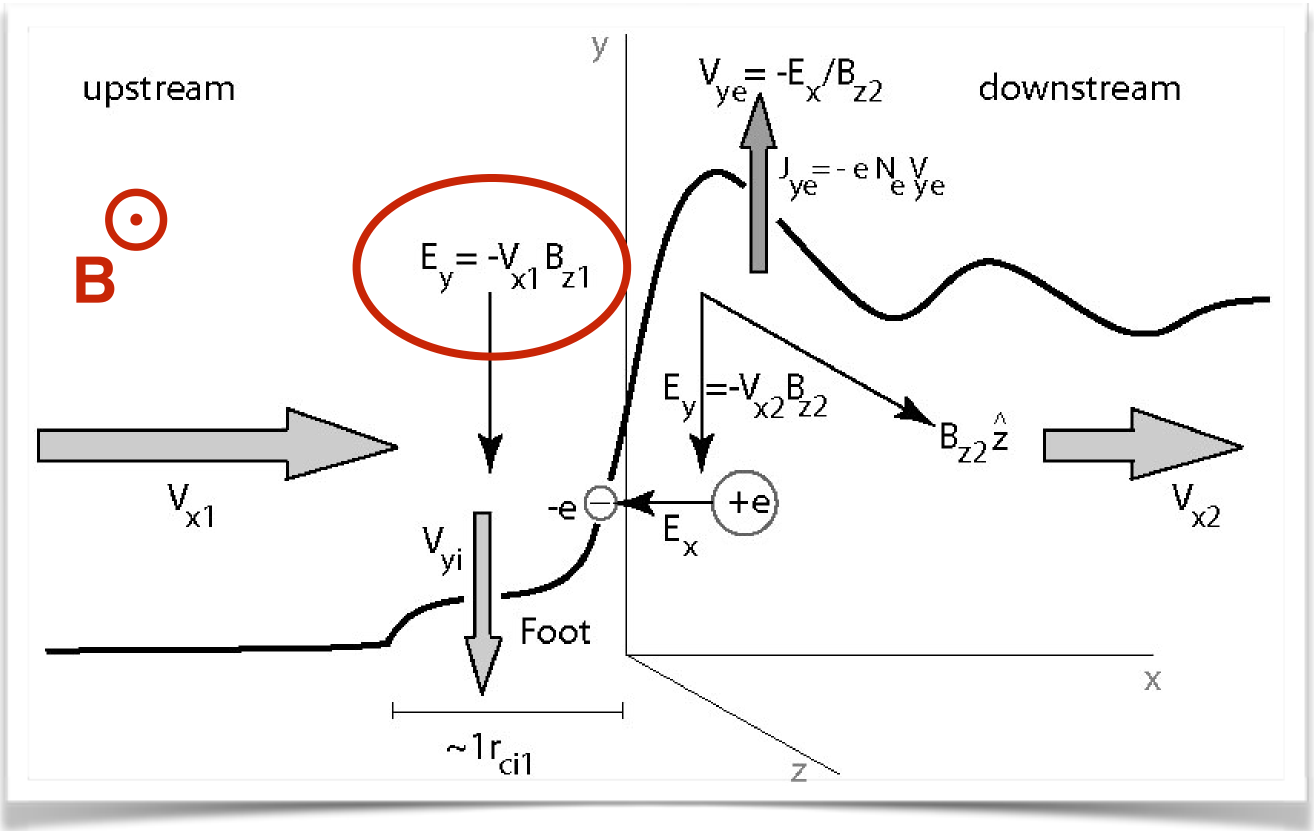
  - fully self-consistent Particle-In-Cell (PIC) simulations:

    Wieland et al. 2016, ApJ, 820:62
    Bohdan et al., in preparation

Artem Bohdan's talk: Turbulent magnetic reconnection and particle acceleration at nonrelativistic perpendicular shocks of young supernova remnants

Nonlinear perpendicular shock structure

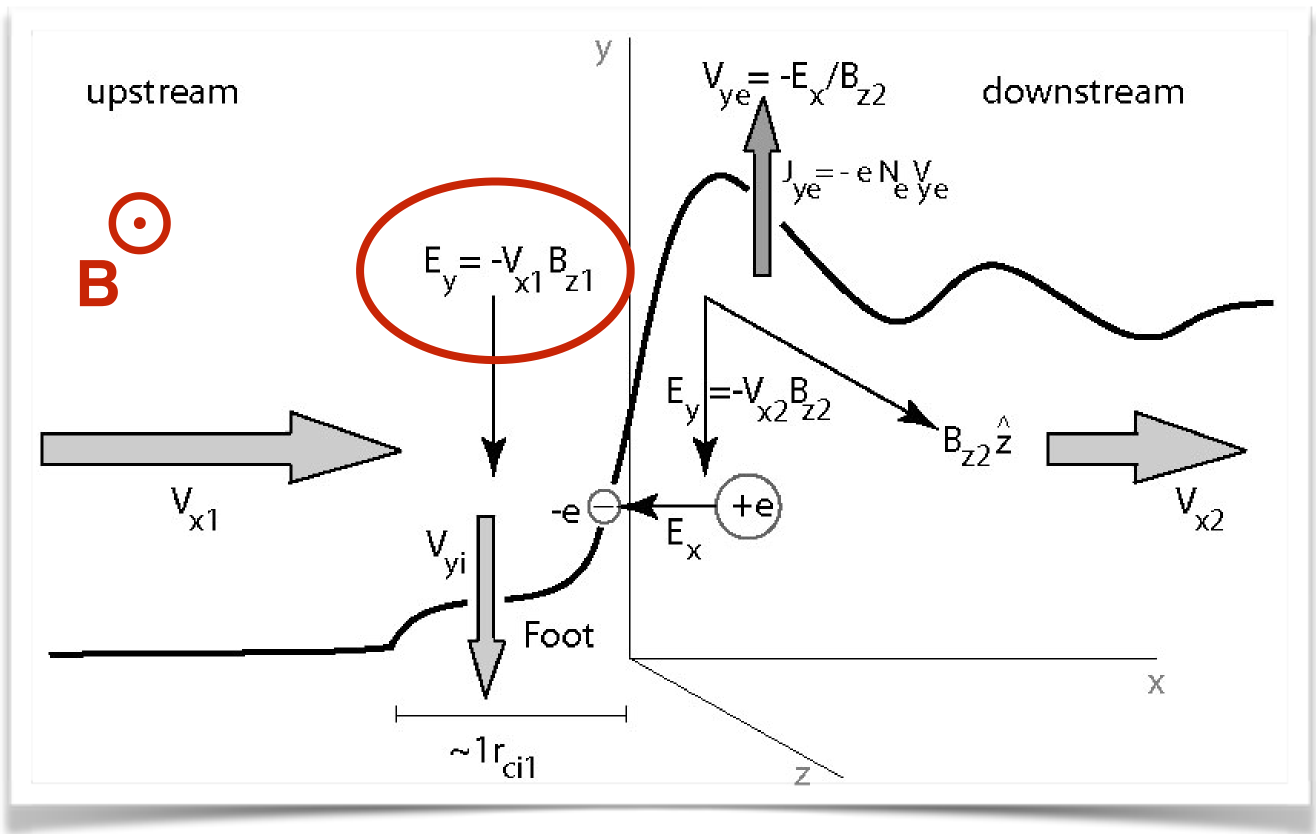
- portion of incoming ions reflected from the shock-potential electric field
- reflected ions accelerated in the upstream convection electric field (SDA, SSA)



Treumann & Jaroschek (2008)

Nonlinear perpendicular shock structure

- portion of incoming ions reflected from the shock-potential electric field
- reflected ions accelerated in the upstream convection electric field (grad-B drift)



Treumann & Jaroschek (2008)

- gyrating reflected ions excite ion beam Weibel instability that generates thin current sheets (magnetic filaments) in the shock ramp
- interaction between reflected ions and incoming electrons leads to electrostatic Buneman instability in the shock foot

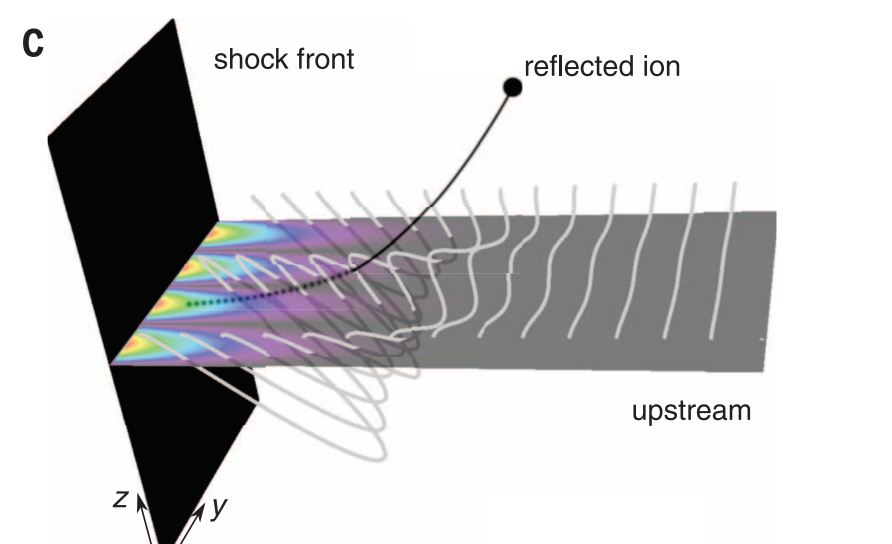
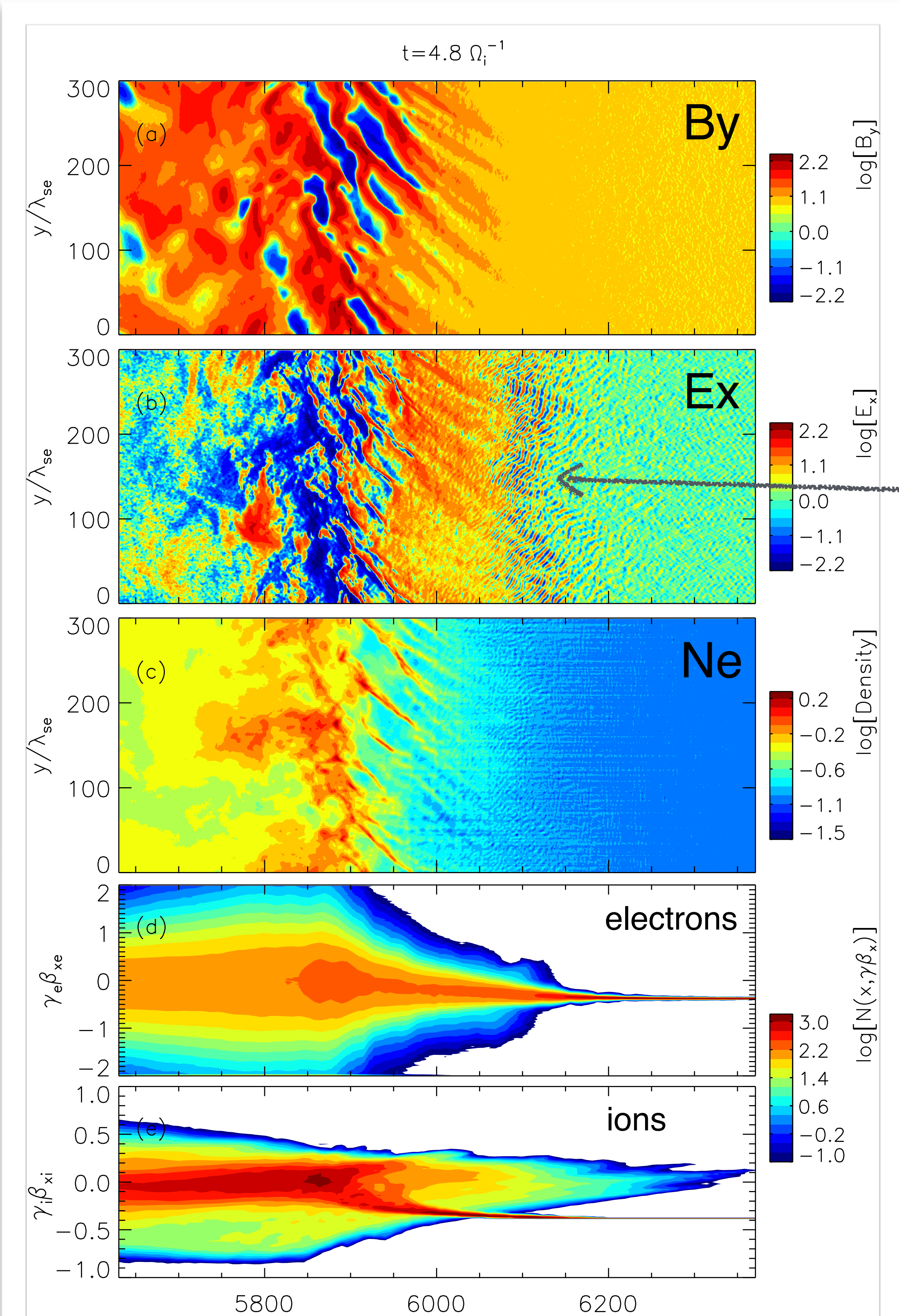


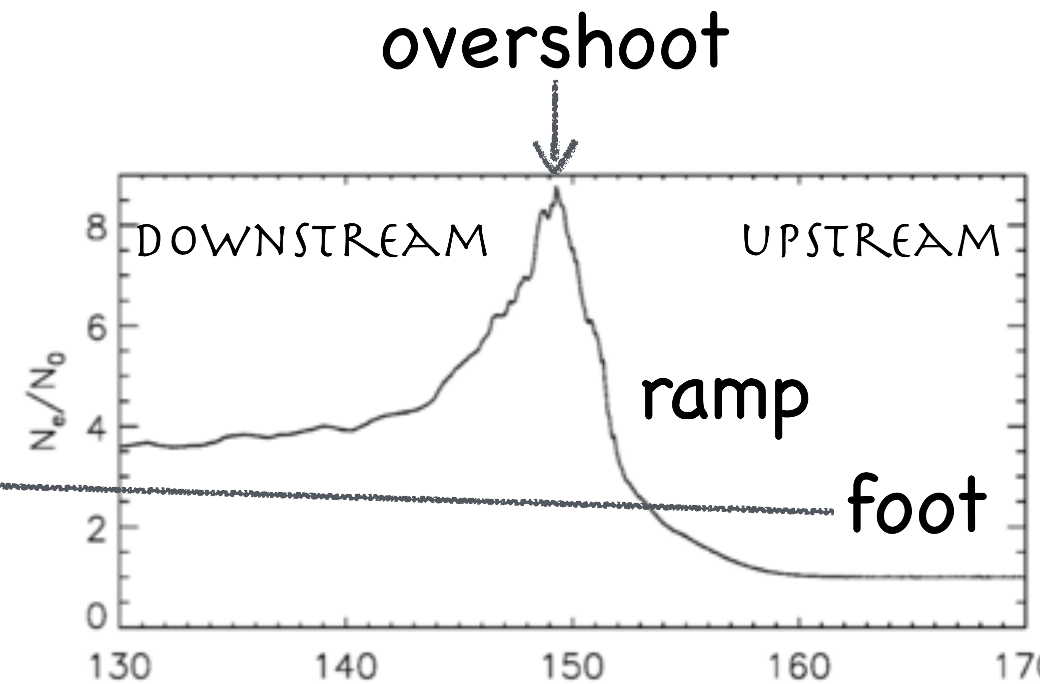
Fig. 2. Mechanism of current sheet formation.

Matsumoto et al. (2015)

Perpendicular shock structure

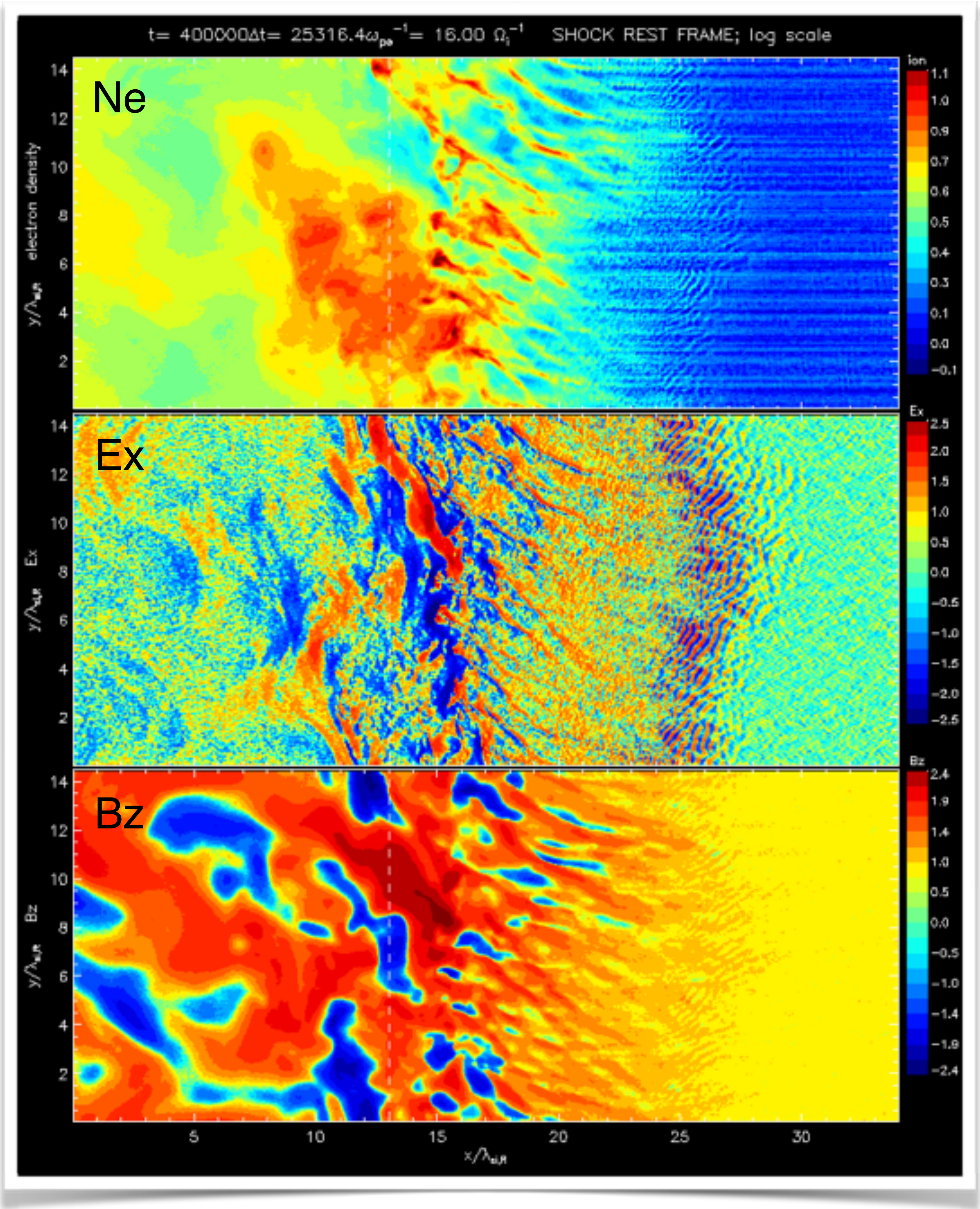


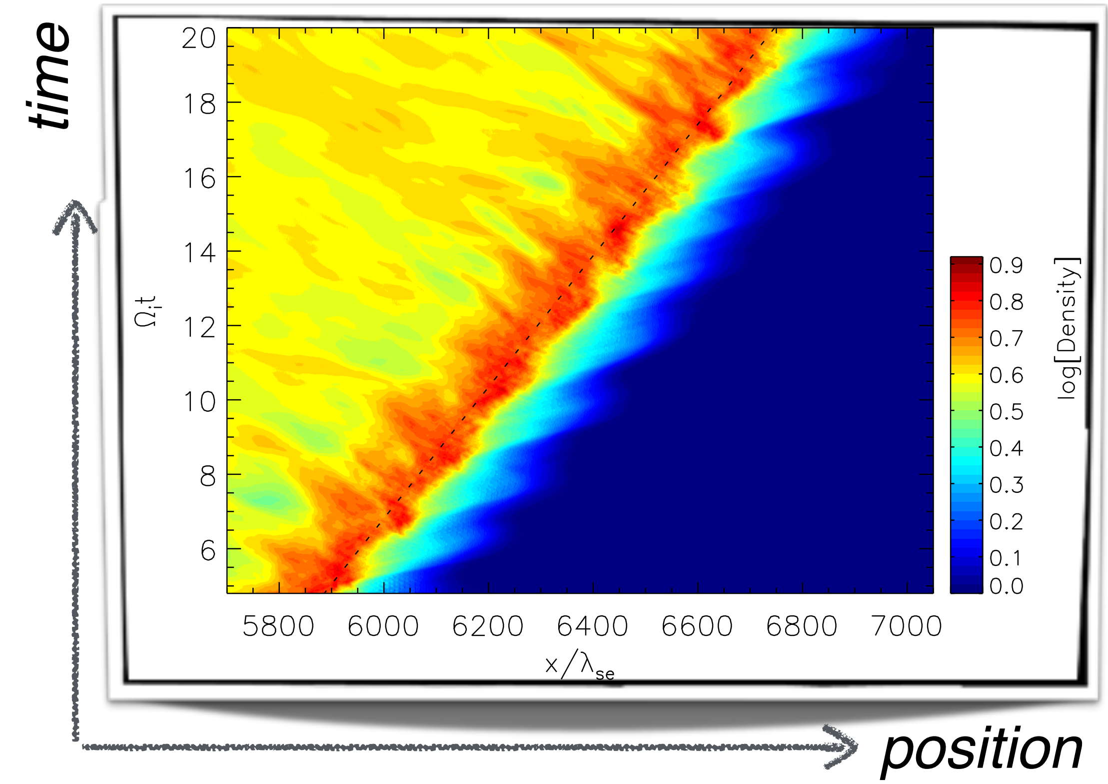
Forward shock at t=4.8 Ω_i^{-1}



Particle-in-cell simulations;
M_A=28

Shock reformation…

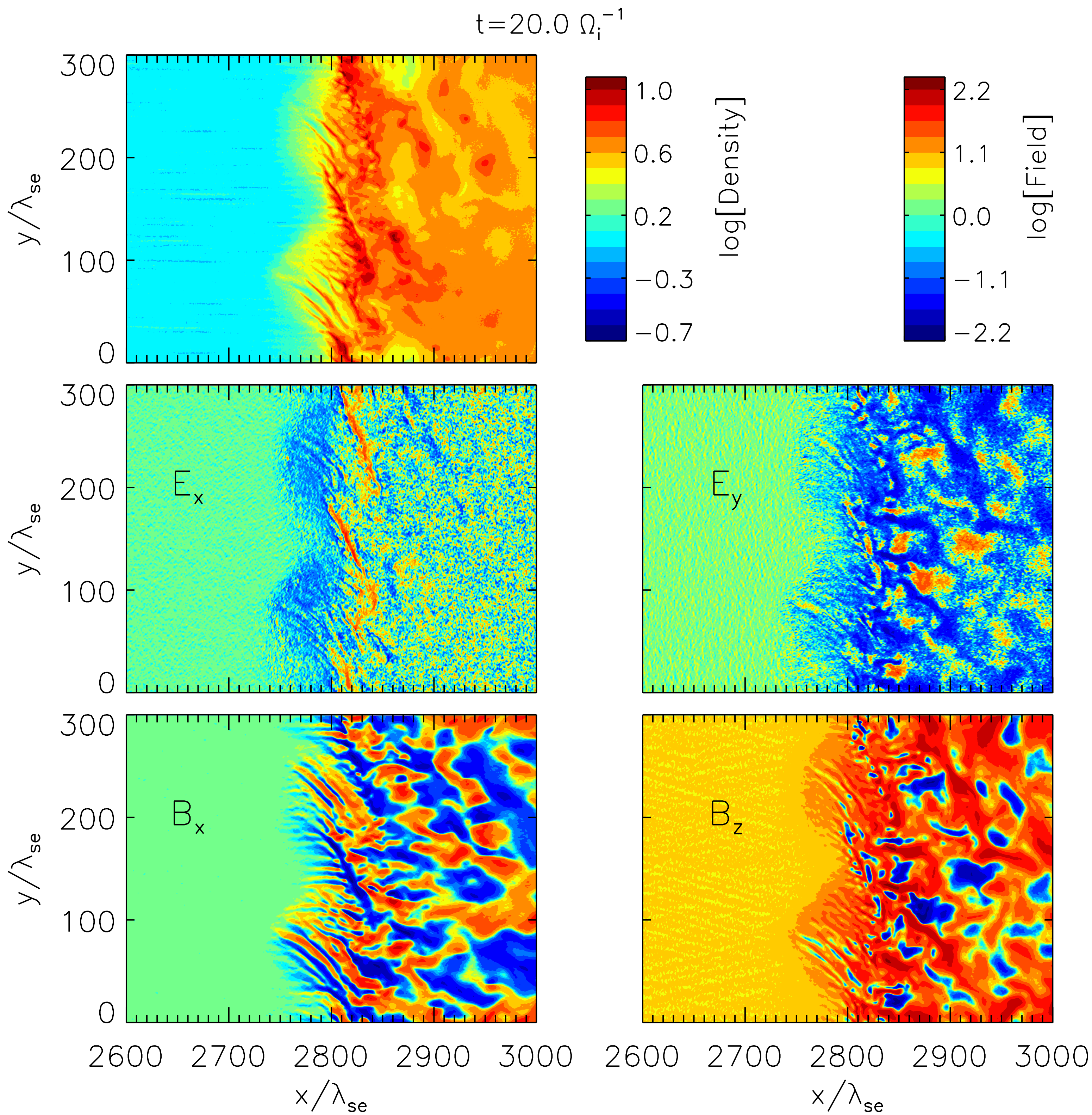




shock rest frame

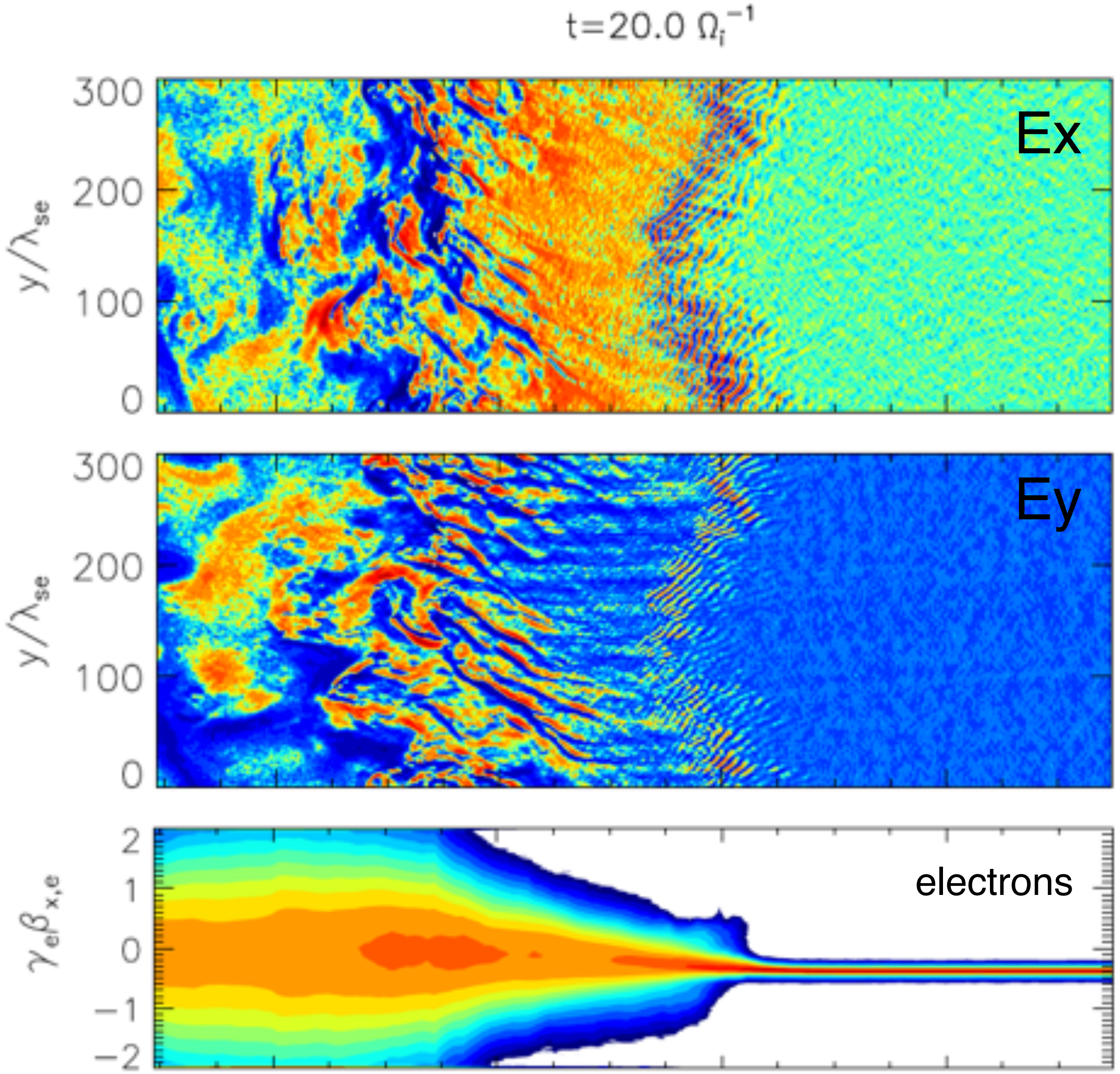
- cyclic shock self-reformation caused by non-steady dynamics of ion reflection from the shock and governed by the physics of current filament mergers in the shock ramp
- period of ~1.5 Ω_i^{-1}

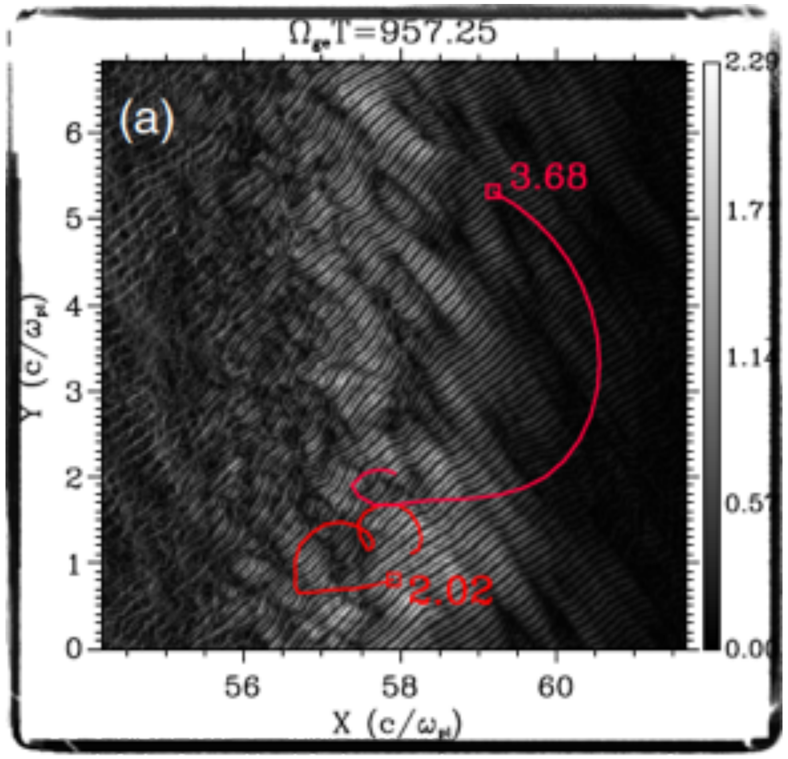
Shock reformation… and rippling



- spatial (~20 λ_{si}) and temporal scales given by gyro-motion of the shock-reflected ions spatially modulated along the shock surface (Burgess & Scholer (2007) for low-Mach-number shocks)
- enhanced localized electron heating and acceleration should occur

Electron heating and injection





Matsumoto et al. 2013

Unstable condition:

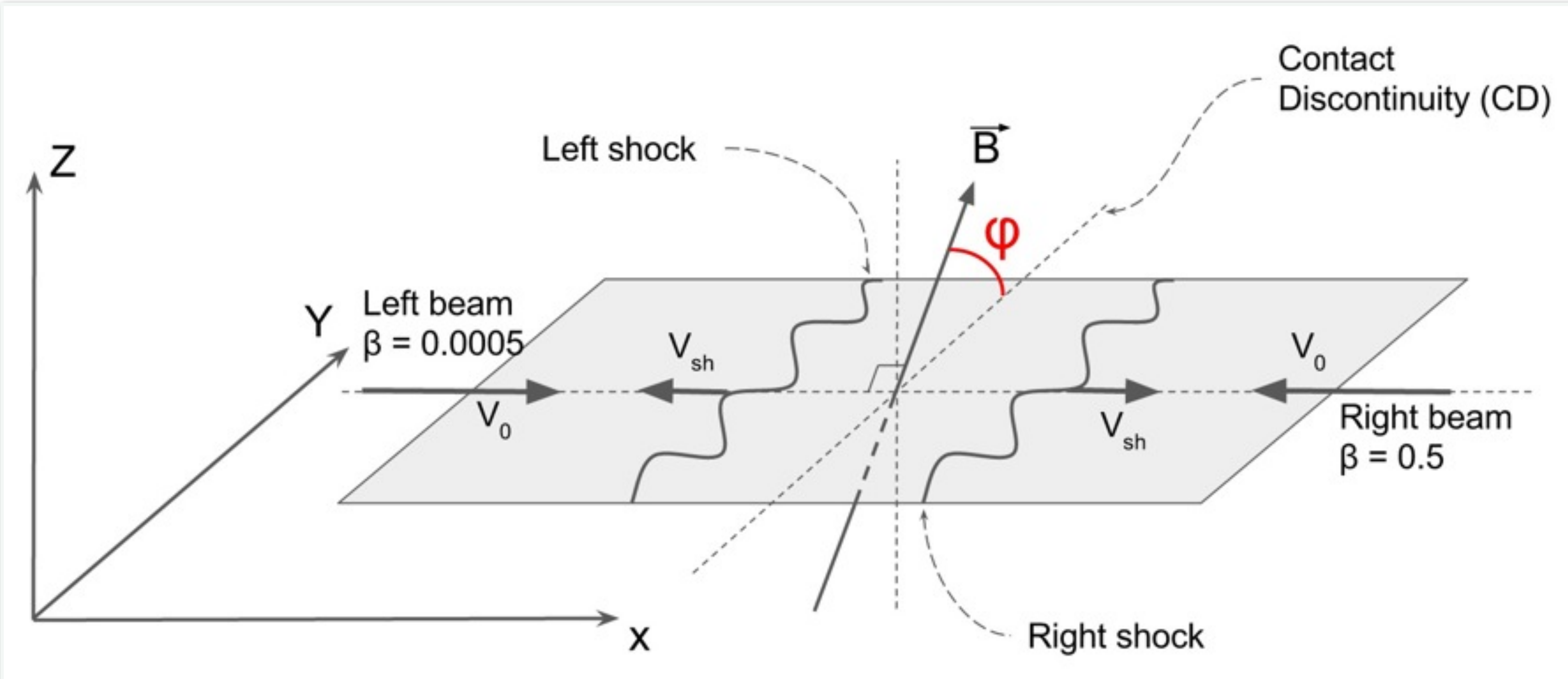
$$M_A \geqslant \frac{1+\alpha}{2}\sqrt{\beta_e}\left(\frac{M}{m}\right)^{\frac{1}{2}}$$

Trapping condition:

$$M_A \geqslant (1+\alpha)\left(\frac{M}{m}\right)^{\frac{2}{3}}$$

- electron shock-surfing acceleration (SSA)
  - stochastic acceleration in strongly nonlinear electrostatic Buneman waves
  - electrons escaping upstream further accelerated in the motional electric field
- mechanism effective if the upstream temperature is low or moderate
- acceleration efficiency strongly depends on dimensionality effects

2D3V PIC simulations of perpendicular shocks

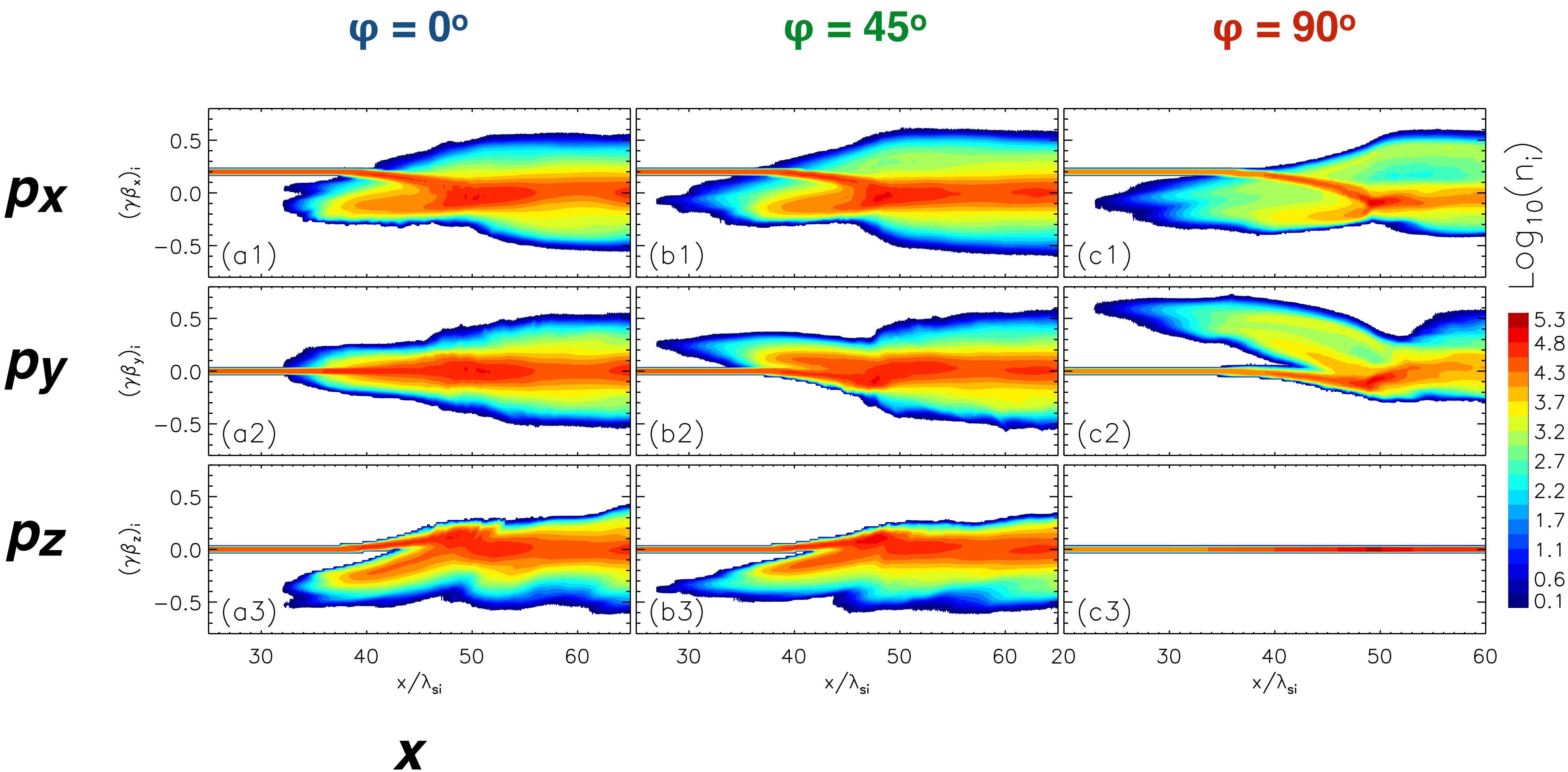


Simulations with different magnetic field geometry:

- **φ** = 0° - in-plane
- **φ** = 45°
- **φ** = 90° - out-of-plane

$M_A \sim 32$

$m_i/m_e=100$

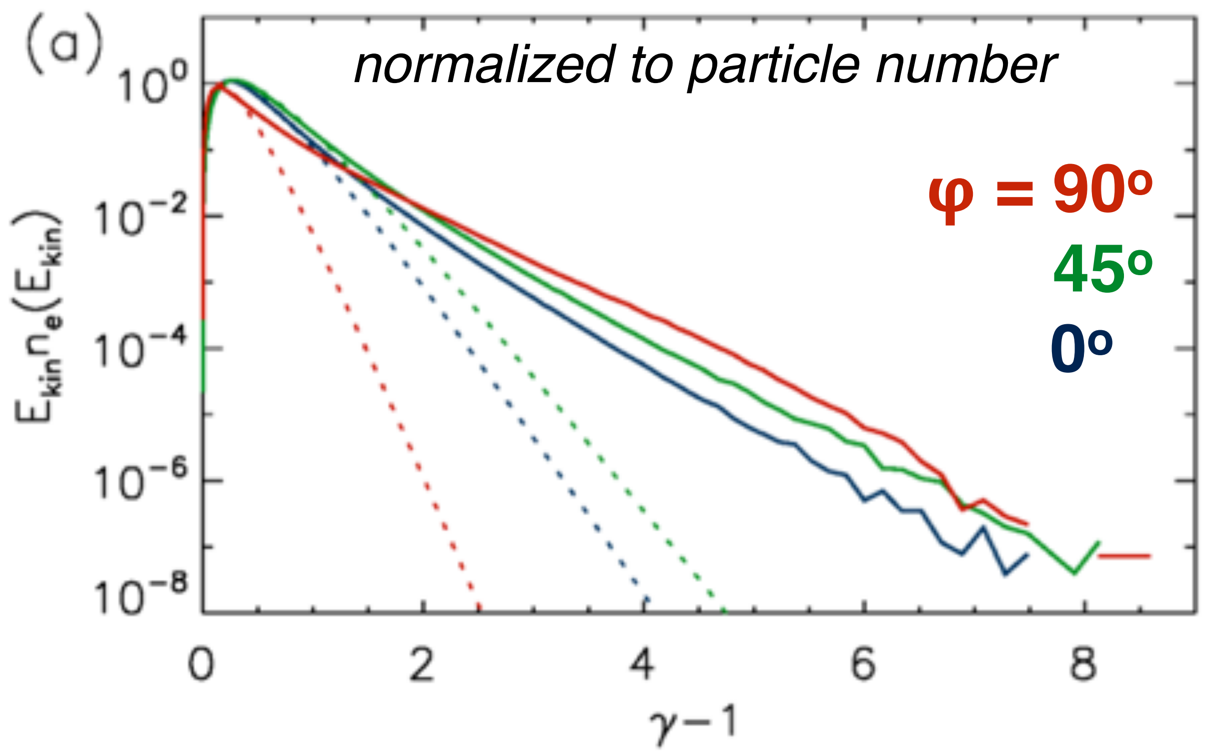


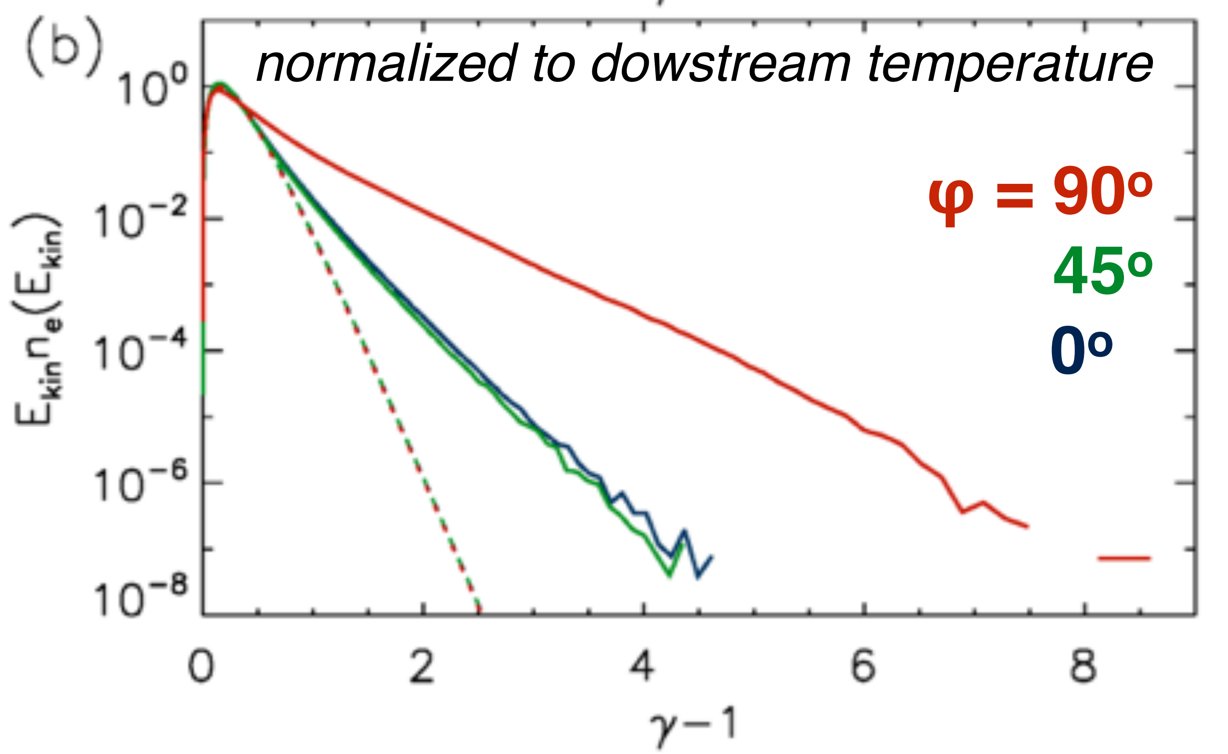
Ion phase-space at the shock

Electron pre-acceleration efficiency

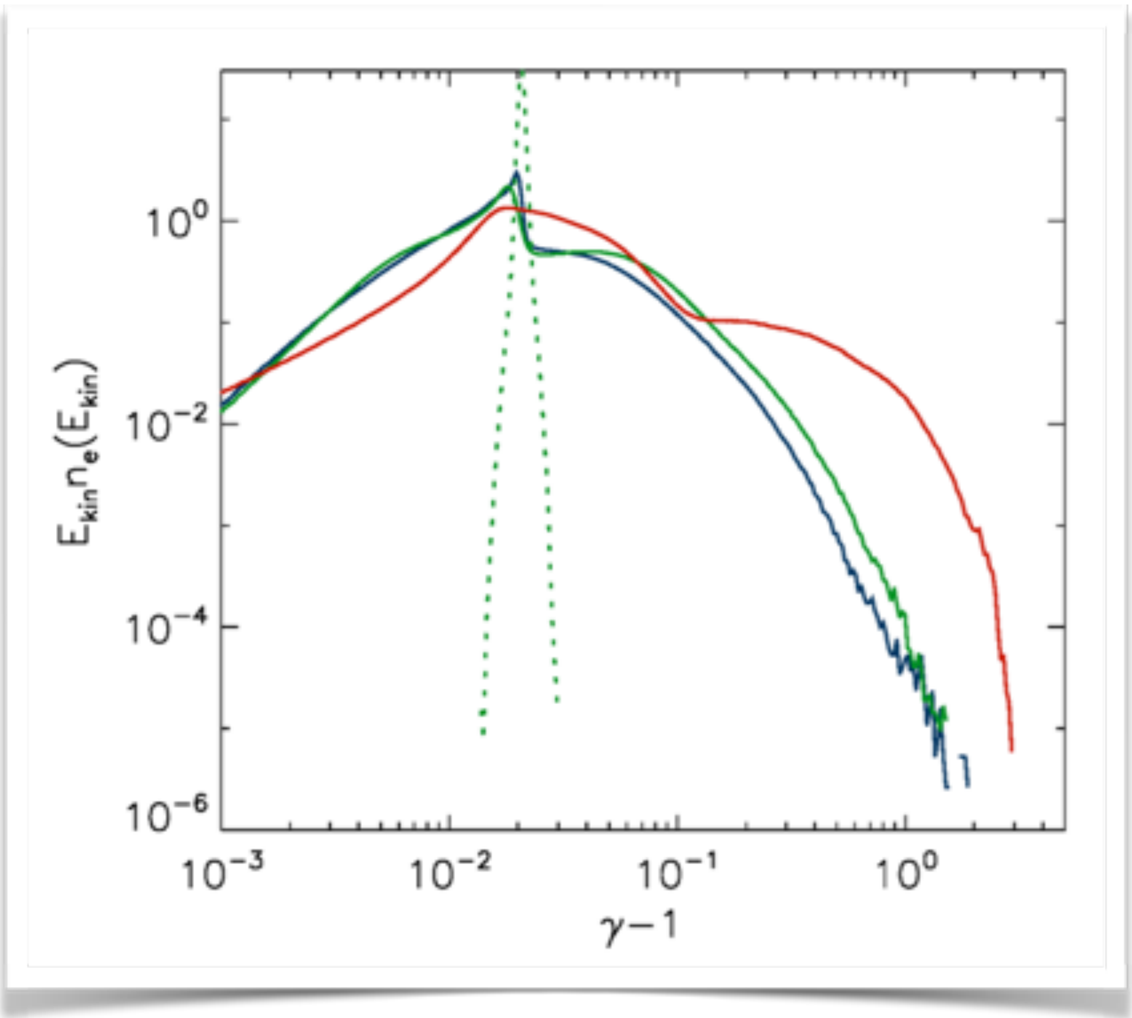
- acceleration most efficient for out-of-plane magnetic field configurations
- spectra vary with the phase of the cyclic shock reformation and plasma beta $\boldsymbol{\beta}_p$ (temperature)
- maximum efficiency (nonthermal electron fraction) in moderate-temperature plasmas ($\boldsymbol{\beta}_p$=0.5) varies from ~0.5% for $\boldsymbol{\varphi}$ = 0° and 45° and ~7% for $\boldsymbol{\varphi}$ = 90°
- in cold plasmas ($\boldsymbol{\beta}_p \ll 1$) acceleration efficiencies a factor of 2-3 smaller

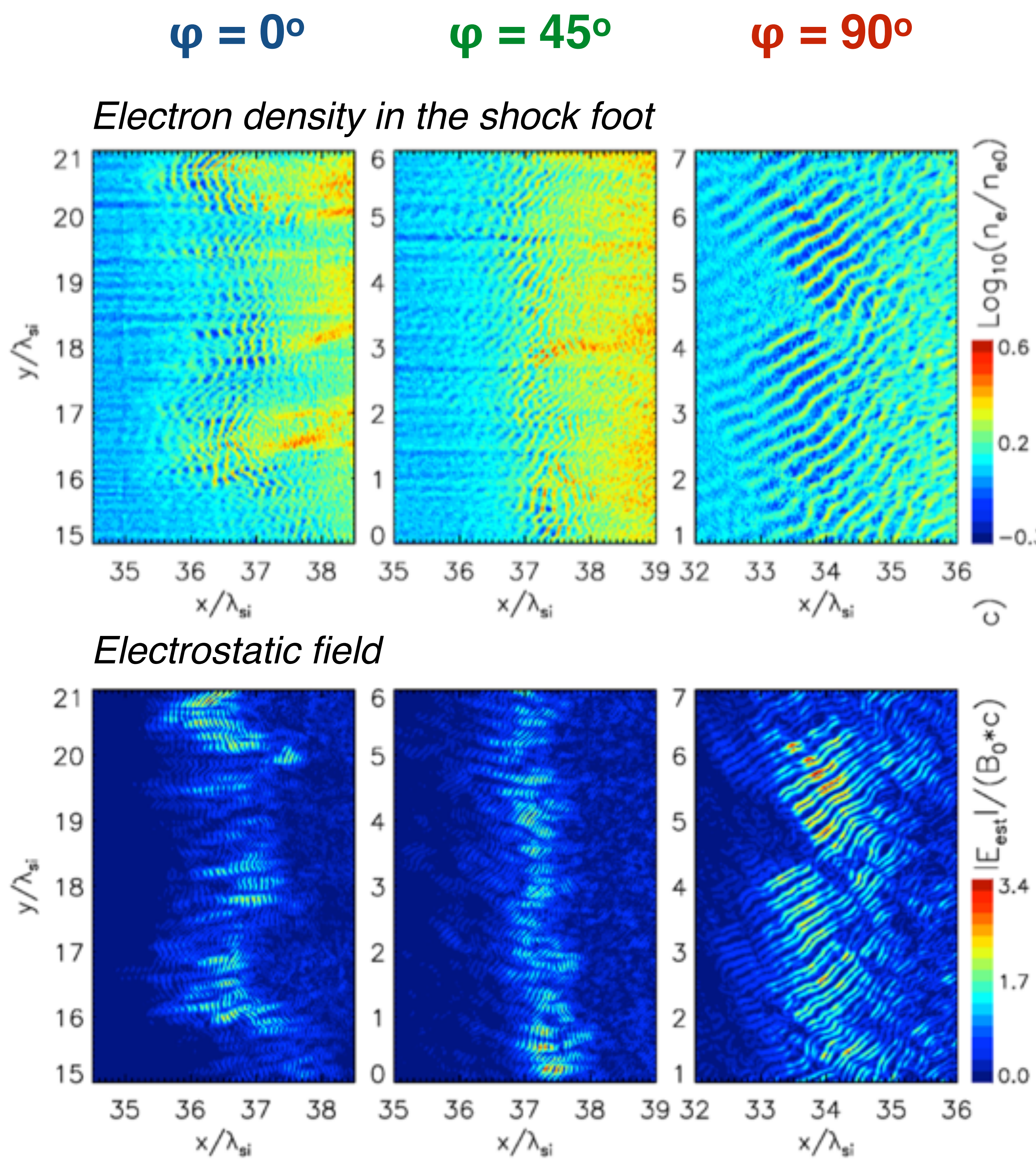
Downstream spectra:

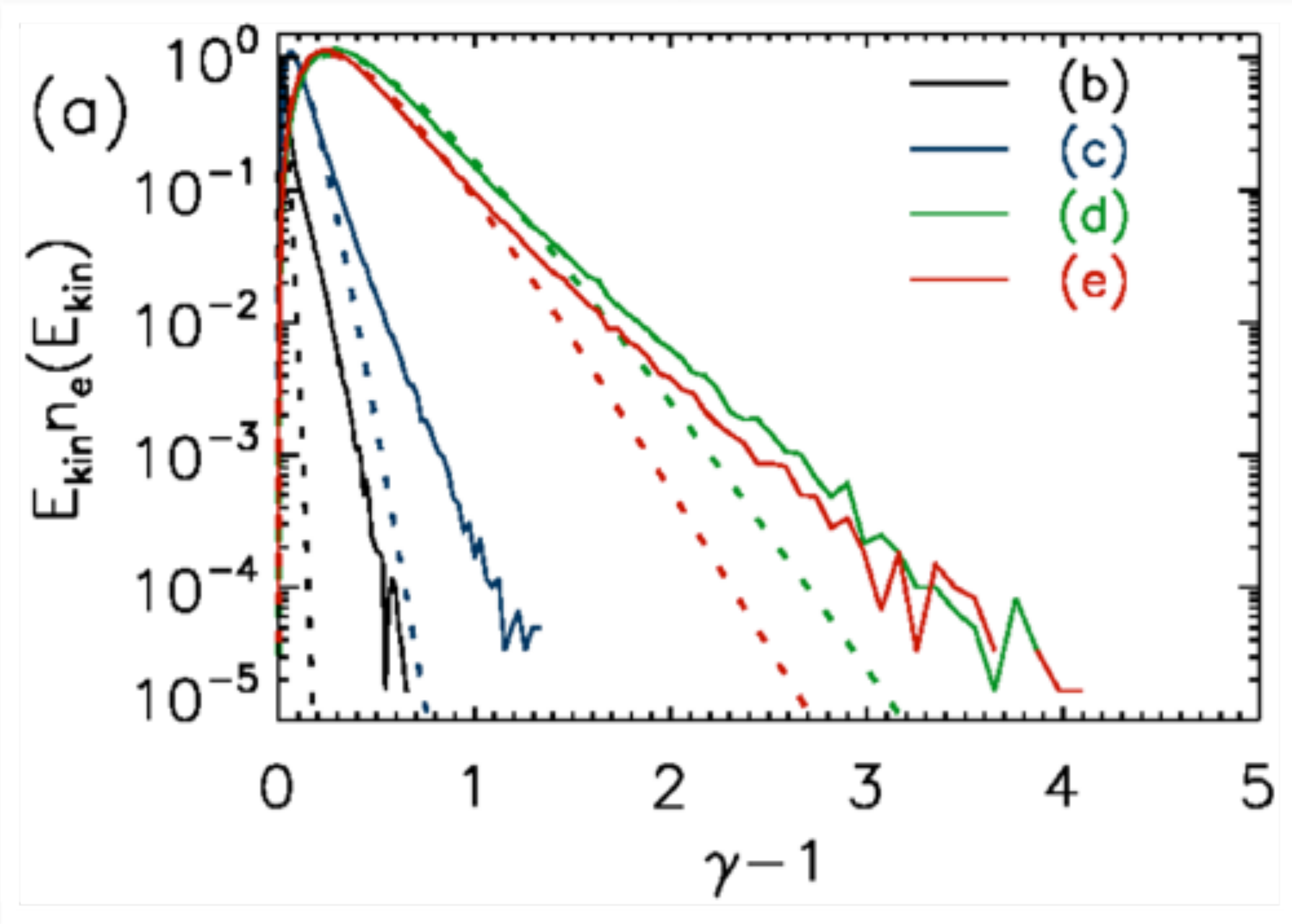


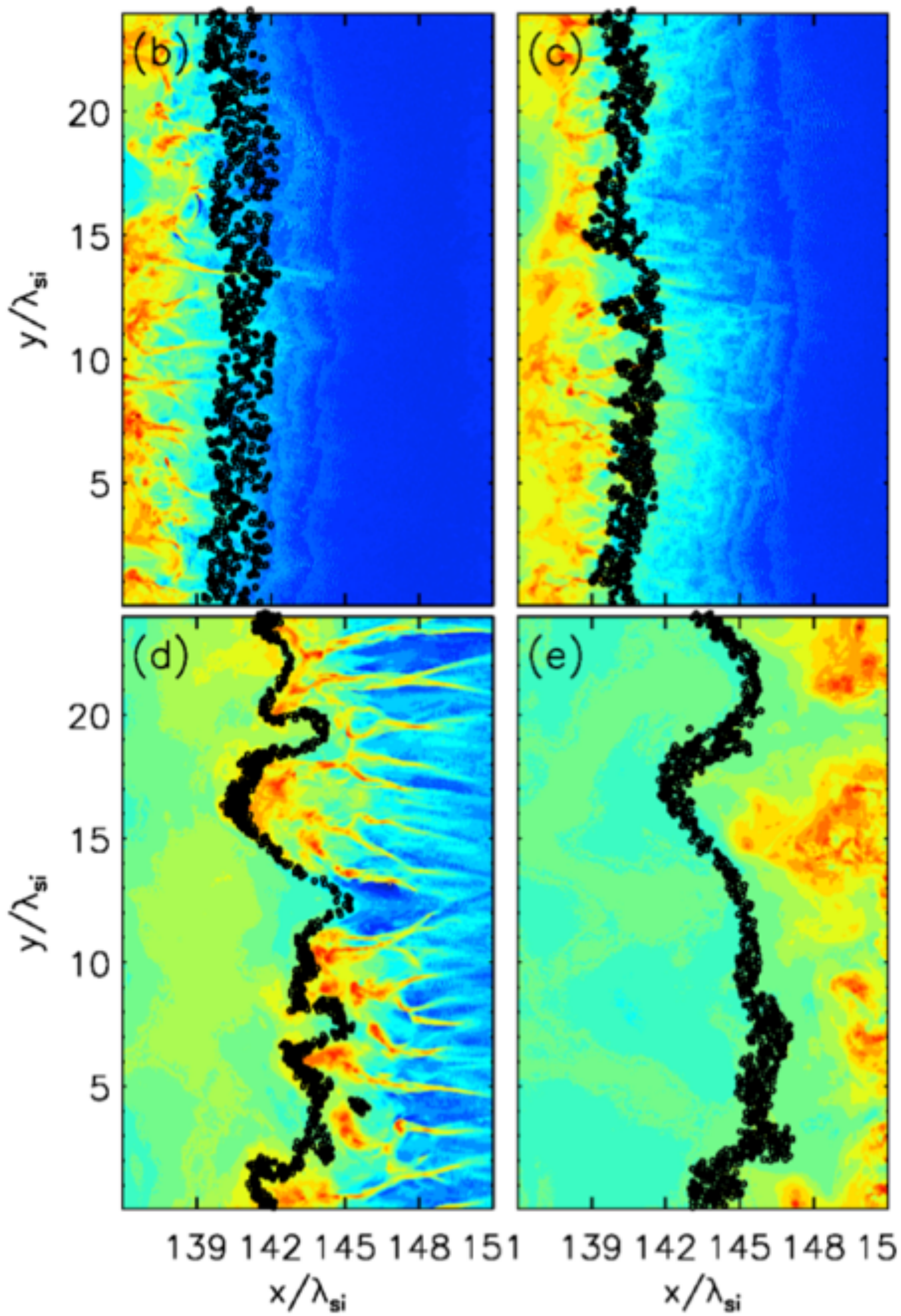


Shock-surfing acceleration of electrons



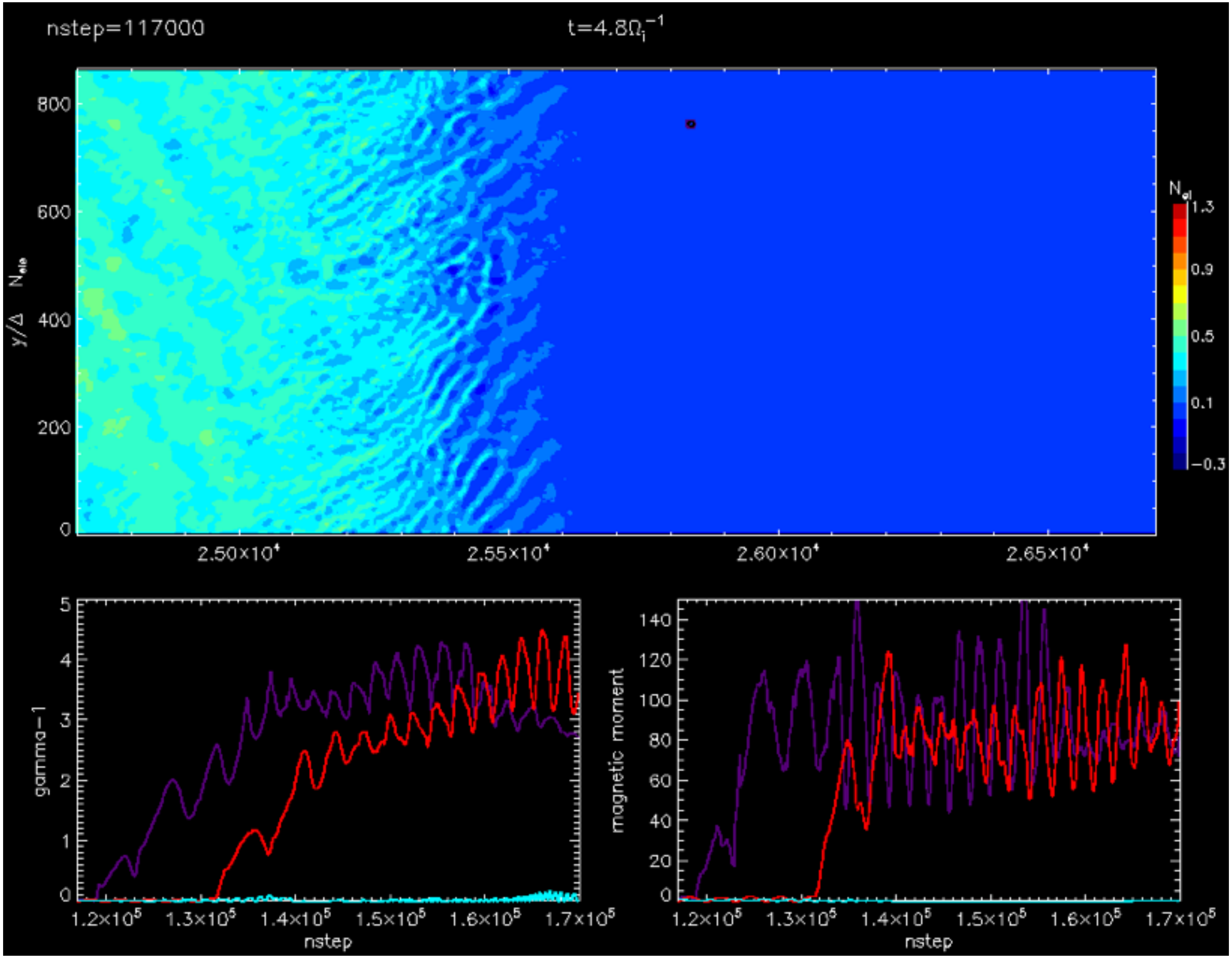




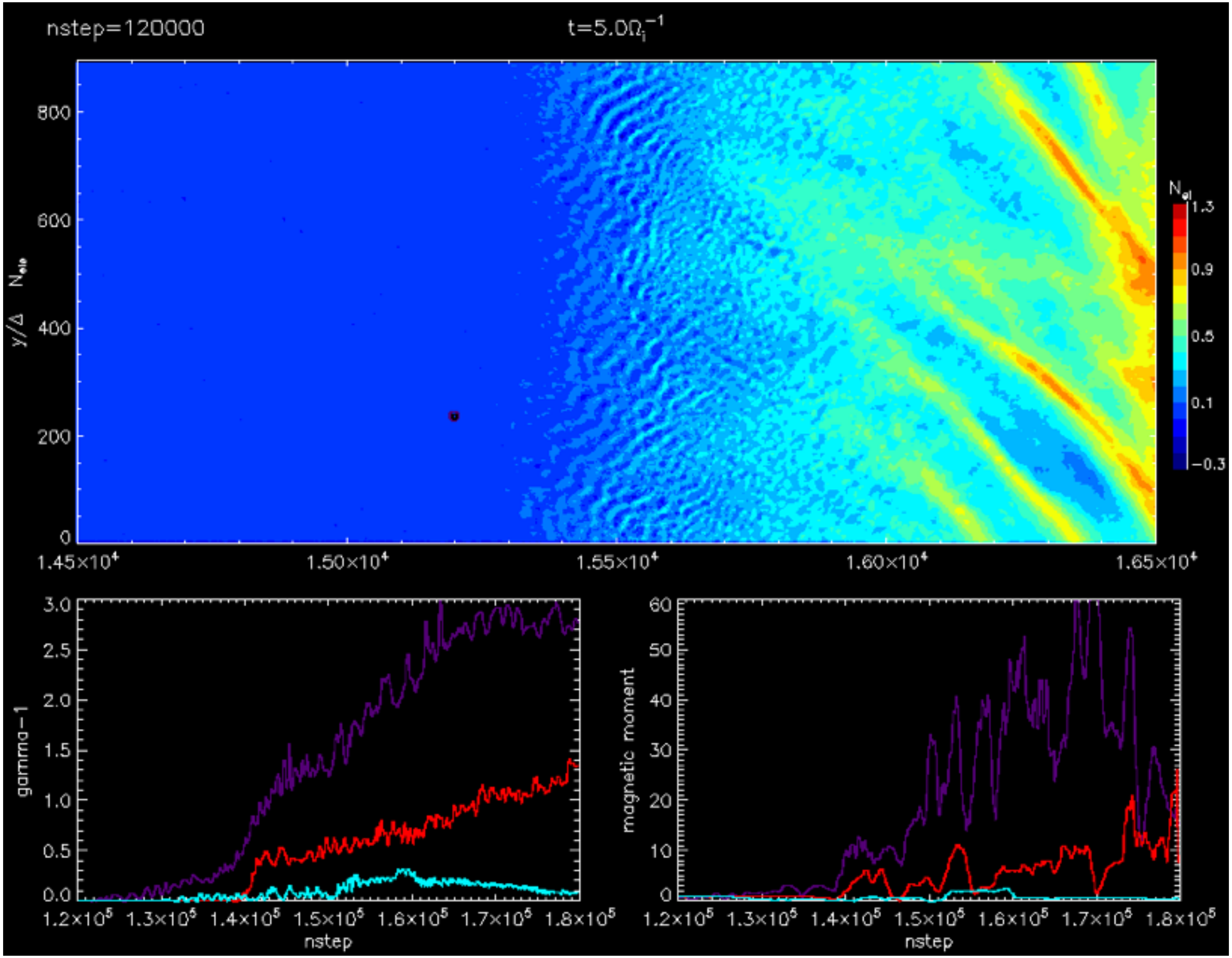


- nonthermal electron fraction determined by the SSA process

$\varphi=90^o$



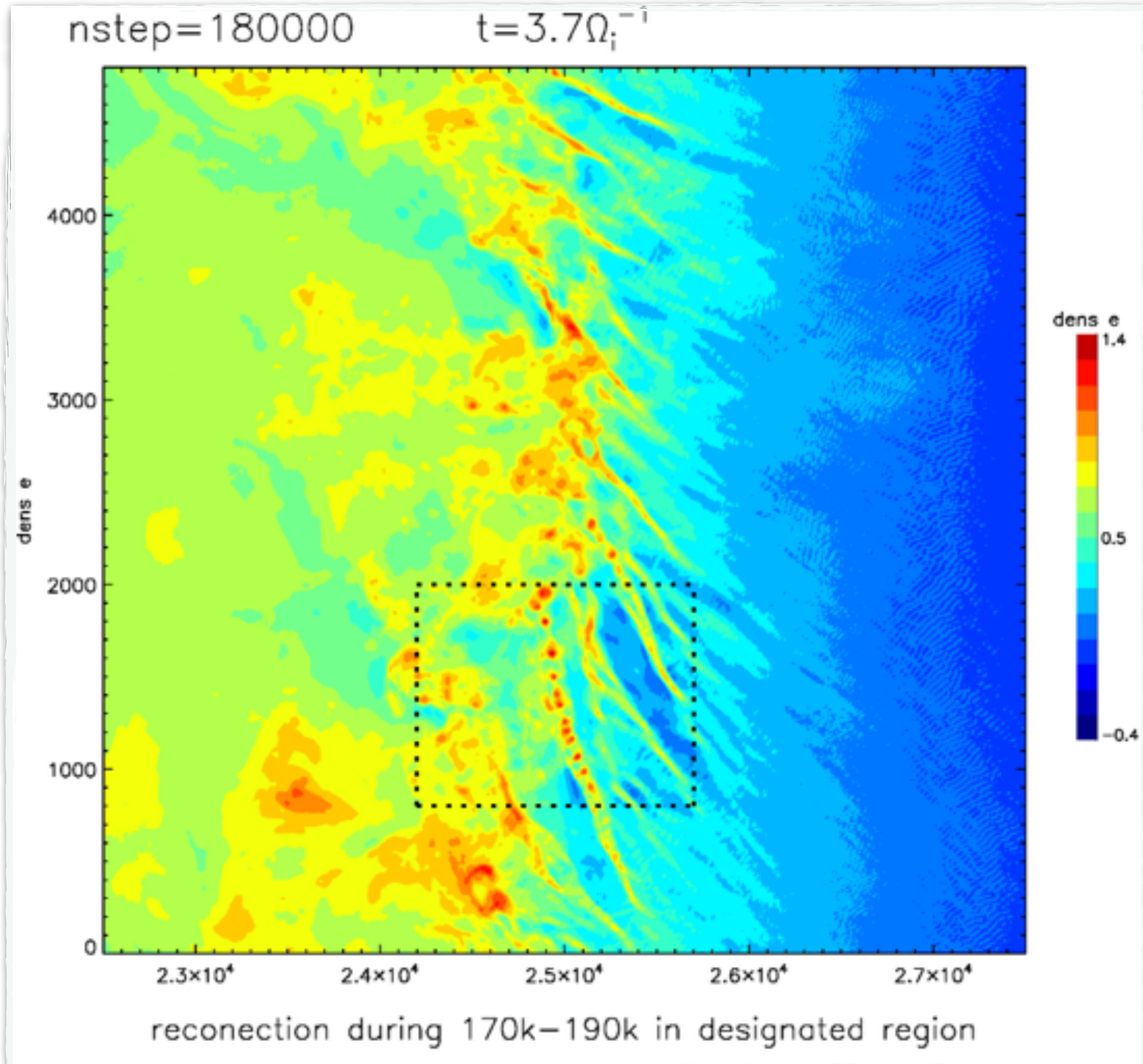
- double interaction with Buneman waves (red and violet particles) followed by adiabatic acceleration in the shock ramp through grad-B drift

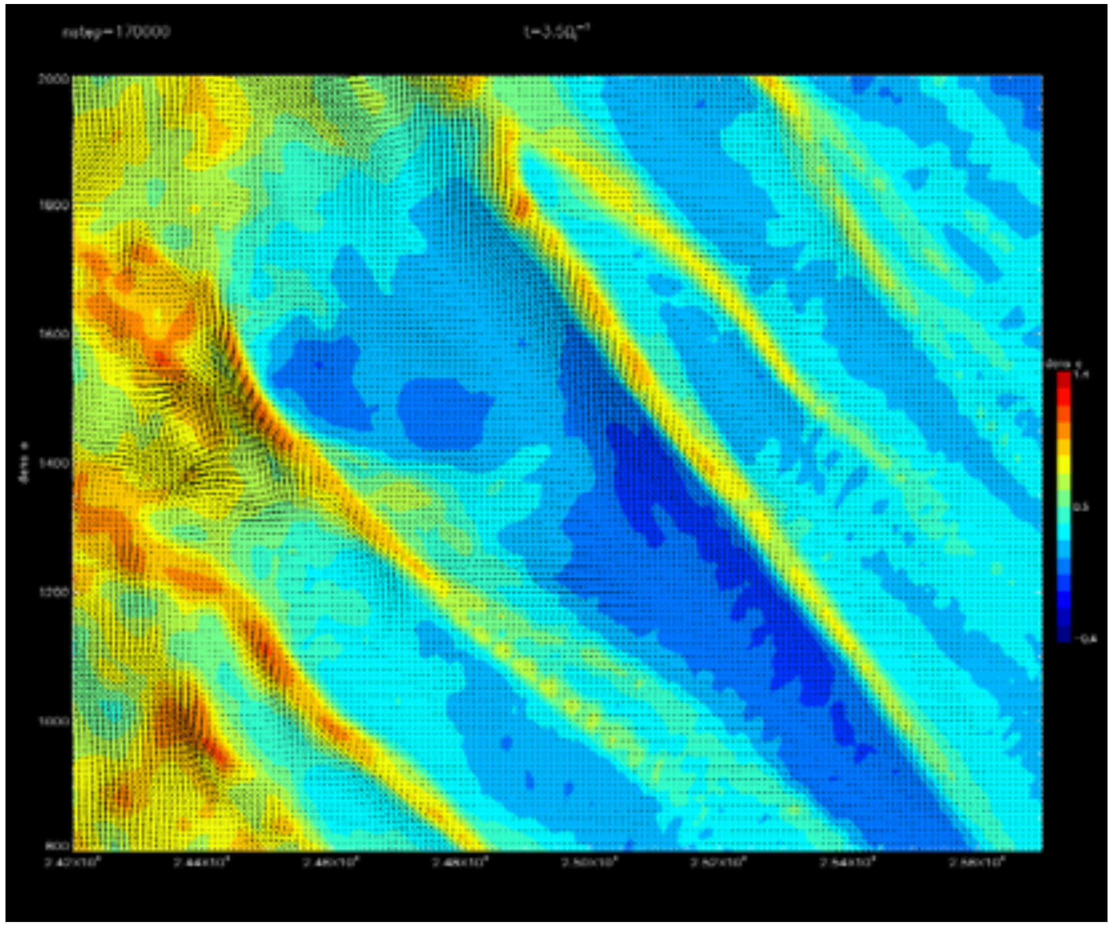


φ=45°
(and **φ=0°**)

- interaction with Buneman waves (red and violet particles) followed by non-adiabatic acceleration in collissions with moving magnetic structures

Spontaneous turbulent reconnection





$\vartheta = 45^o$

$\sim 0.4\Omega^{-1}$

- magnetic reconnection takes place in current sheets within filamentary shock transition and downstream. As a result, magnetic islands are formed along current sheets.
- turbulent reconnection observed only for in-plane (0^o) and oblique (45^o) configurations
- the process is intermittent, effectiveness vary with the phase of cyclic shock reformation
- additional electron energization occurs (Matsumoto et al. 2015) - see talk by A. Bohdan

Summary and conclusions

- high Mach number perpendicular shocks mediated by Weibel-like instabilities leading to current filaments
- shock structure is nonstationary - cyclic shock reformation and rippling are observed
- electron shock-surfing acceleration (SSA) is a viable process for electron injection; efficiency of SSA determines the nonthermal electron fraction
- true effectiveness of SSA requires further scrutiny with 3D simulations and realistic ion-to-electron mass ratios - need for exa-scale computing
- effects occurring on larger scales (e.g., shock rippling) may provide additional particle pre-acceleration