Collisionless High Mach Number Shocks in 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. Possibly relevant for mildly-relativistic flows in AGN jets.

Attributes relevant for DSA:

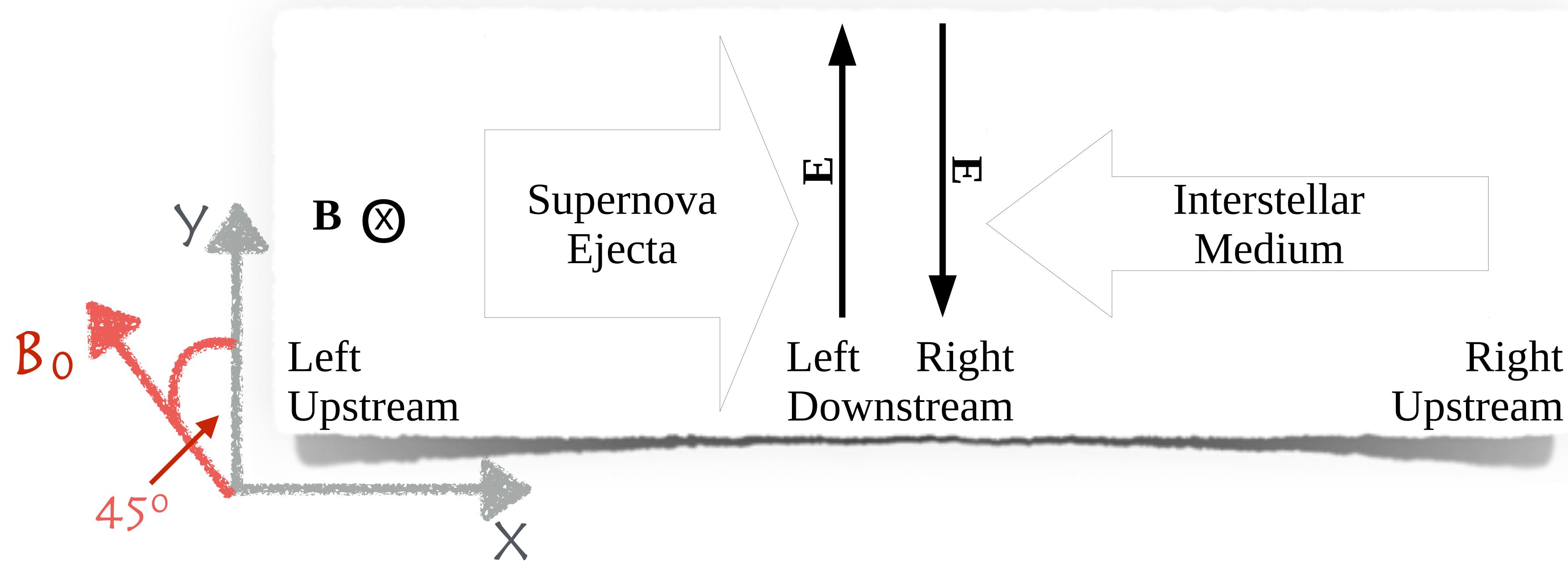
- shock structure: ion driven but electron dynamics important
- EM field amplitudes
- particle pre-acceleration processes: electron injection constitutes the central unresolved issue

Current main interest:

- high Alfven Mach number shocks: regime of weakly magnetized plasma
- high-speed nonrelativistic shocks: mediated by Weibel-type filamentation instabilities

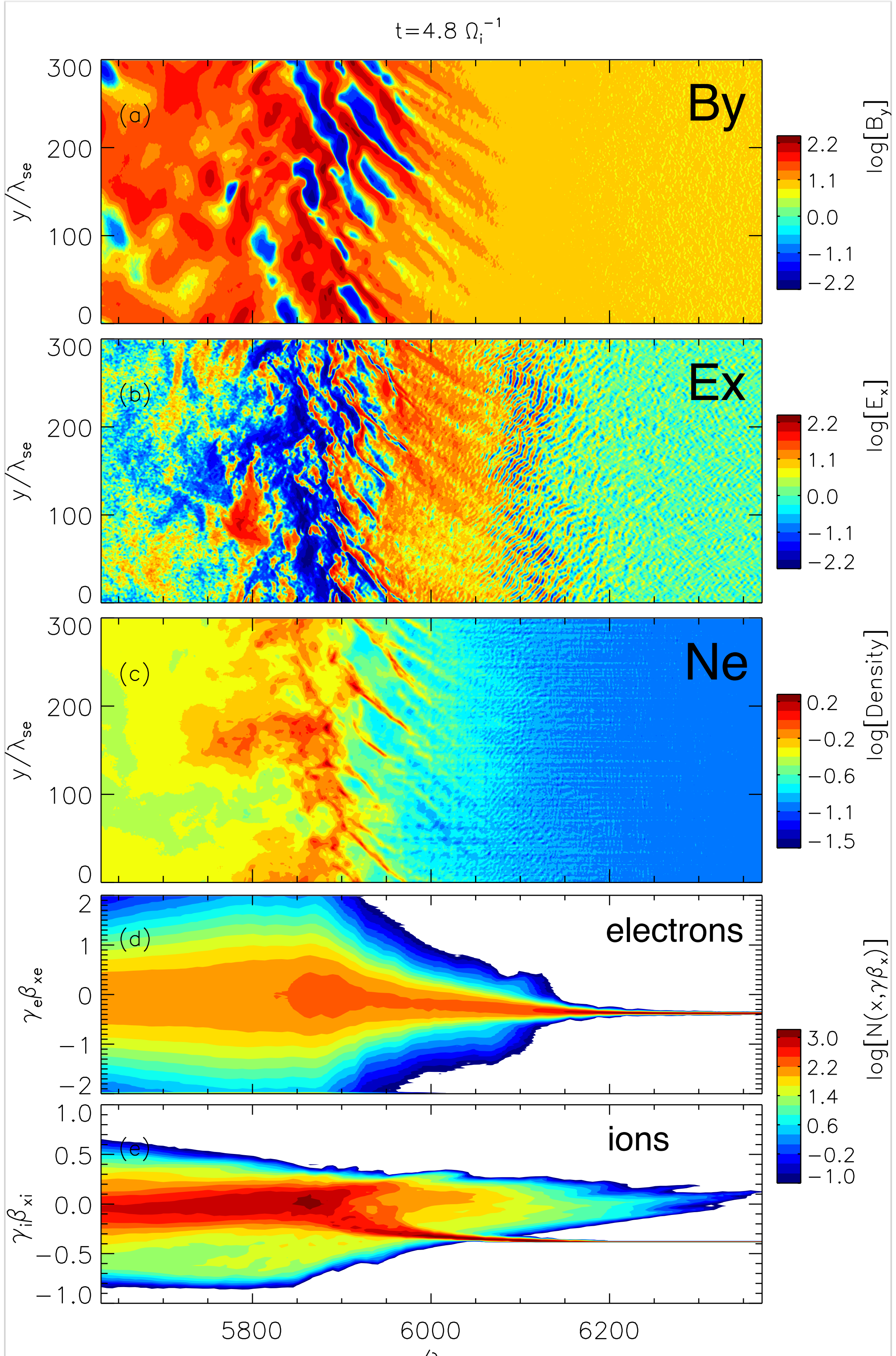
Today's topic: perpendicular shocks

Wieland et al. 2015, in preparation

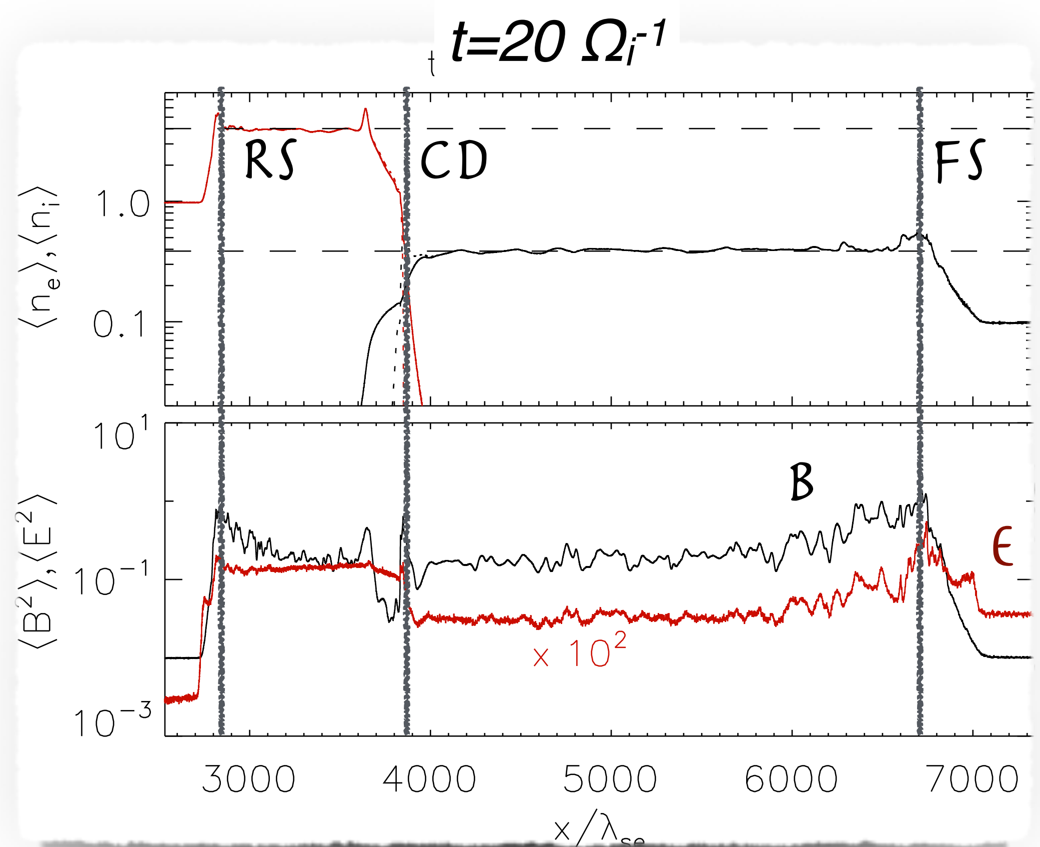


- 2D3V kinetic PIC simulations (m_i/m_e=50)
- high relative collision speed (v_{rel}=0.38c)
- stream-counterstream density asymmetry of 10: system of forward and reverse shock + CD
- Alfven Mach numbers for both shocks: $M_A \sim 28$
- different sonic Mach numbers: $M_S \sim 755$ (forward); $M_S \sim 250$ (reverse)
- magnetic field at 45° to the x-y plane
- low plasma beta $\beta_e \ll 1$: initially cold plasma flows or medium influenced by prior CR-induced magnetic field amplification
- simulations complement recent 2D3V PIC studies of high Mach fast nonrelativistic shocks in the regime of moderate or high β_e and for strictly in-plane or out-of-plane MF orientations (*Amano, Hoshino, Kato, Matsumoto, 2009-2015*)

Shock structure

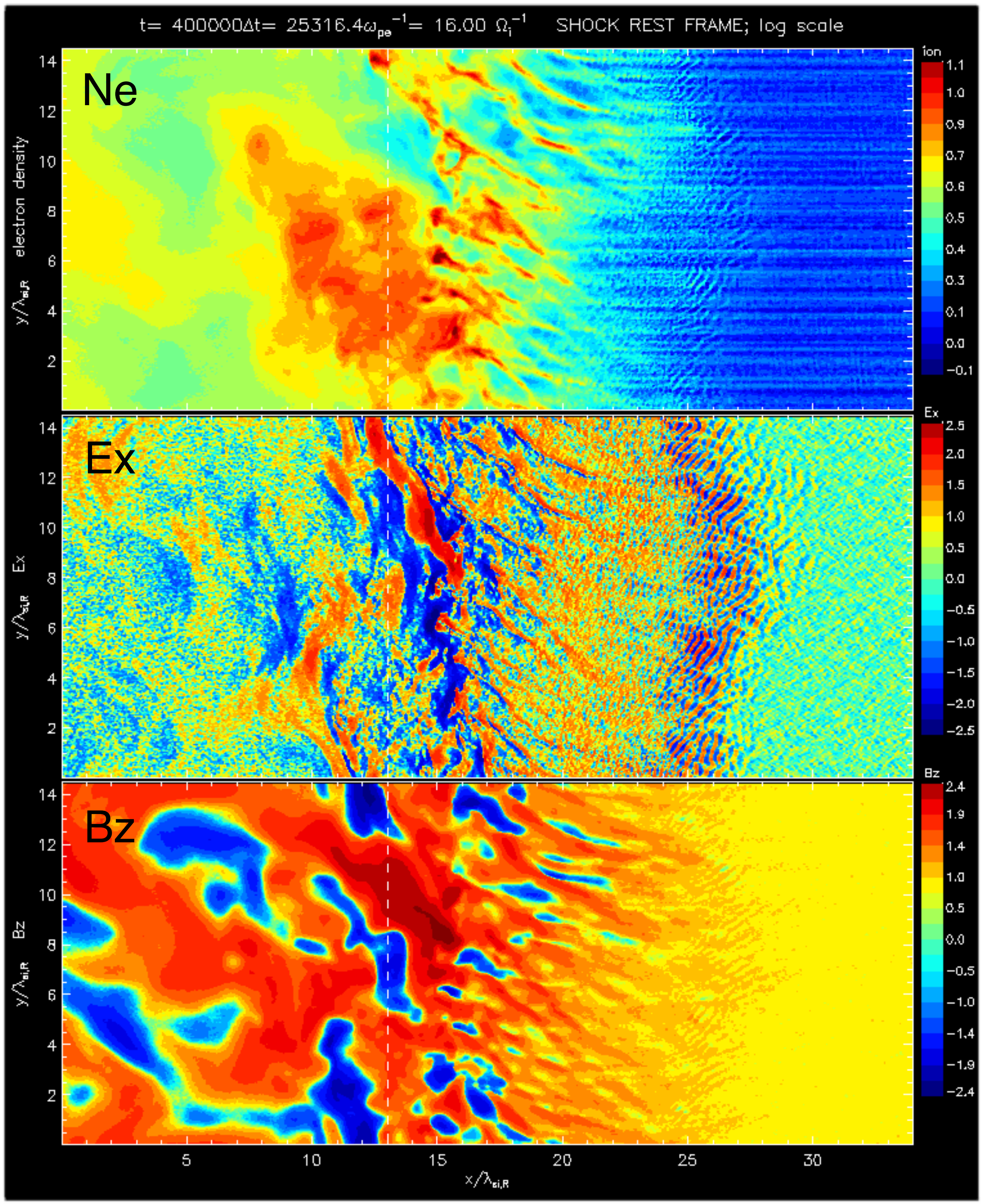


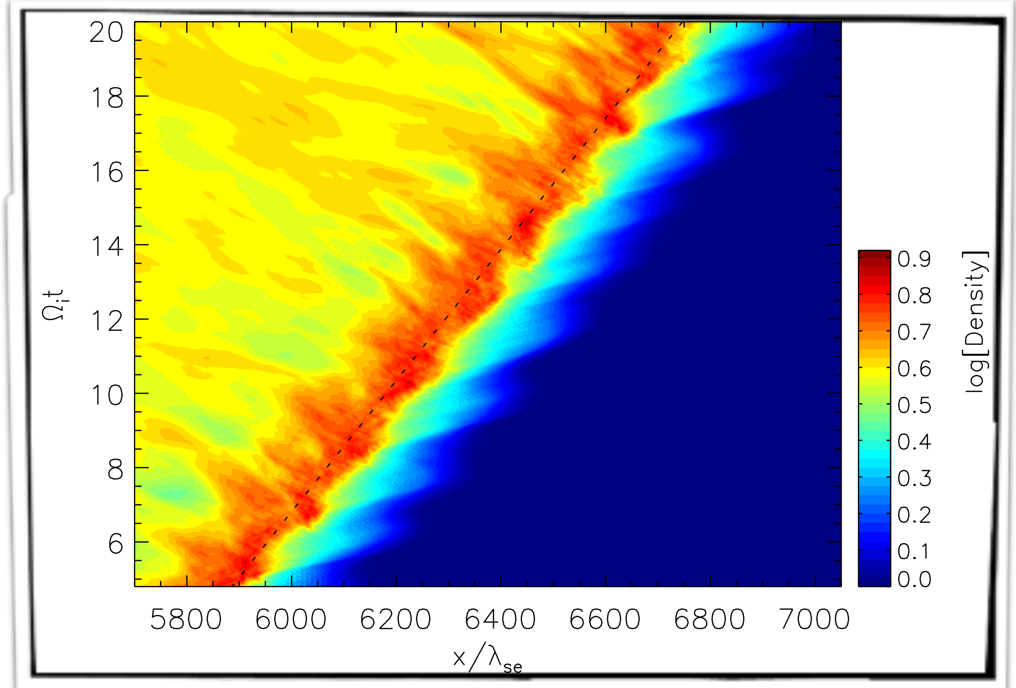
Forward shock at t=4.8 Ω_i^{-1}



- steady-state system of shocks separated by CD formed within a few ion cyclotron times
- structure governed by ion reflection
- shocks mediated by ion-beam Weibel-type filamentation instabilities that generate mainly magnetic turbulence
- strong Buneman modes in the shock foot

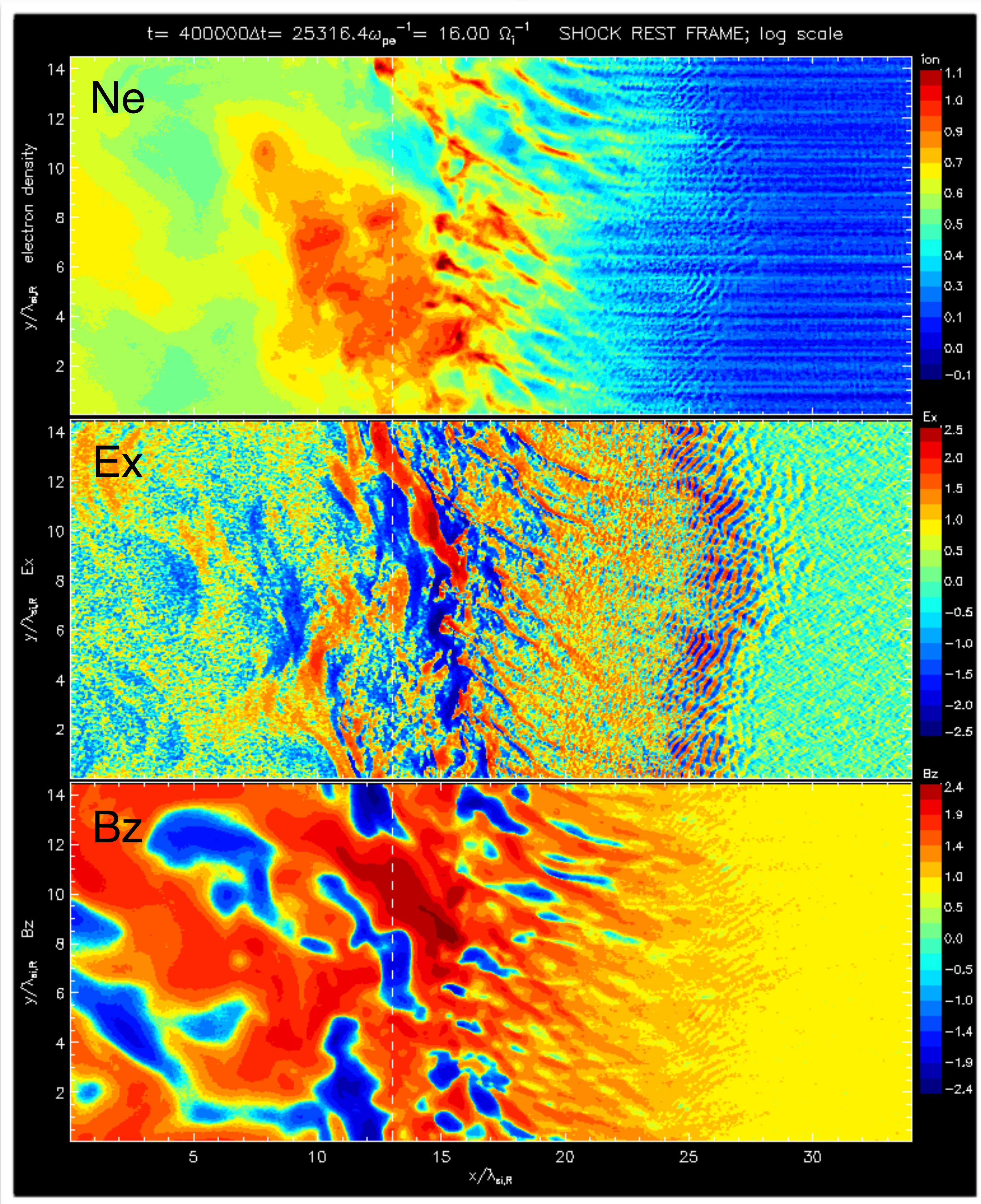
Shock reformation…

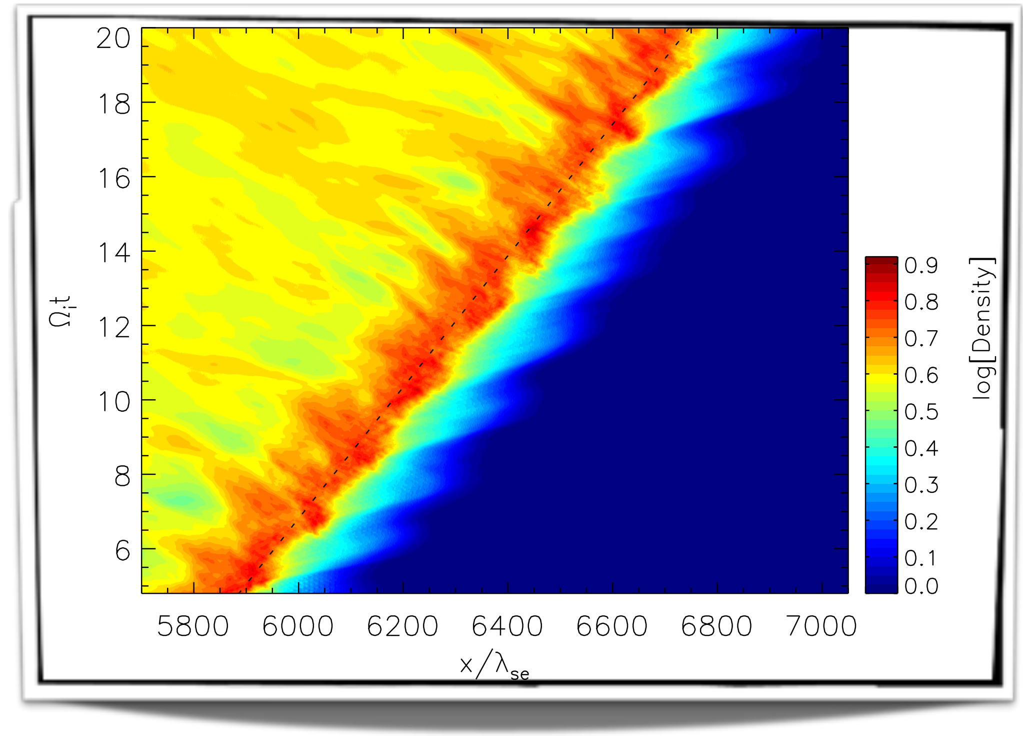




- cyclic shock self-reformation caused by dynamics of shock-reflected ions governed by the physics of current filament mergers in the shock ramp
- period of ~1.5 Ω_i^{-1} similar at both shocks and roughly constant throughout the simulation

Shock reformation…





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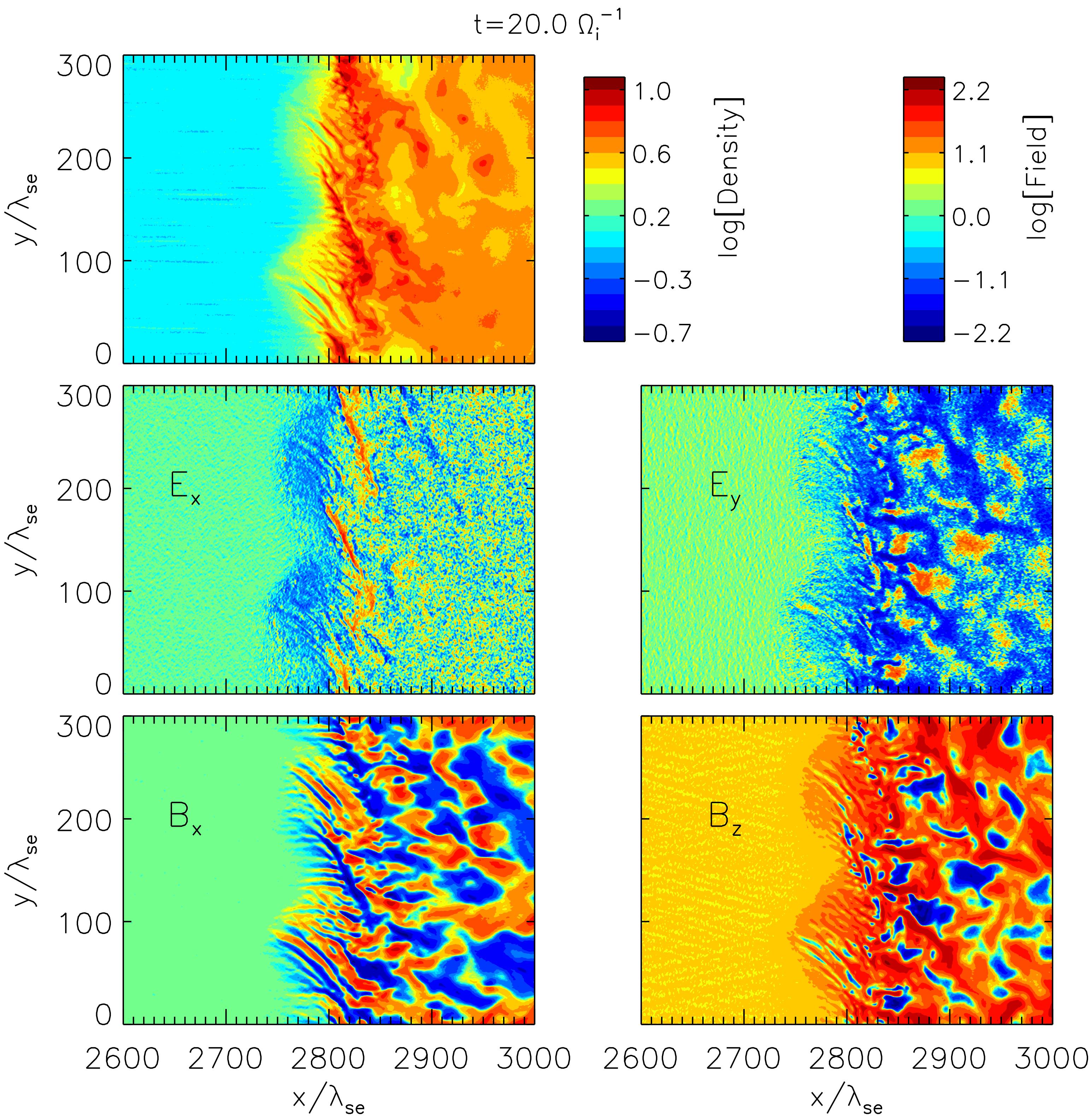
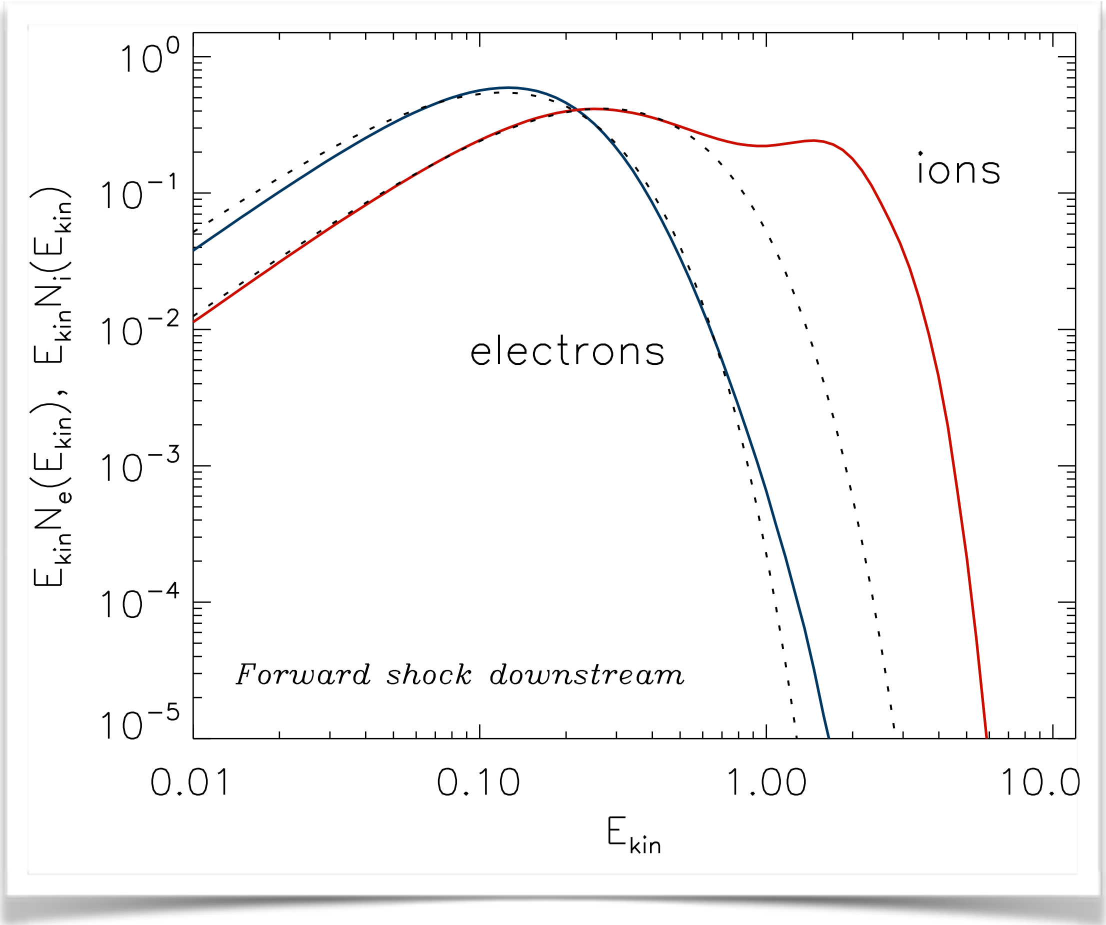
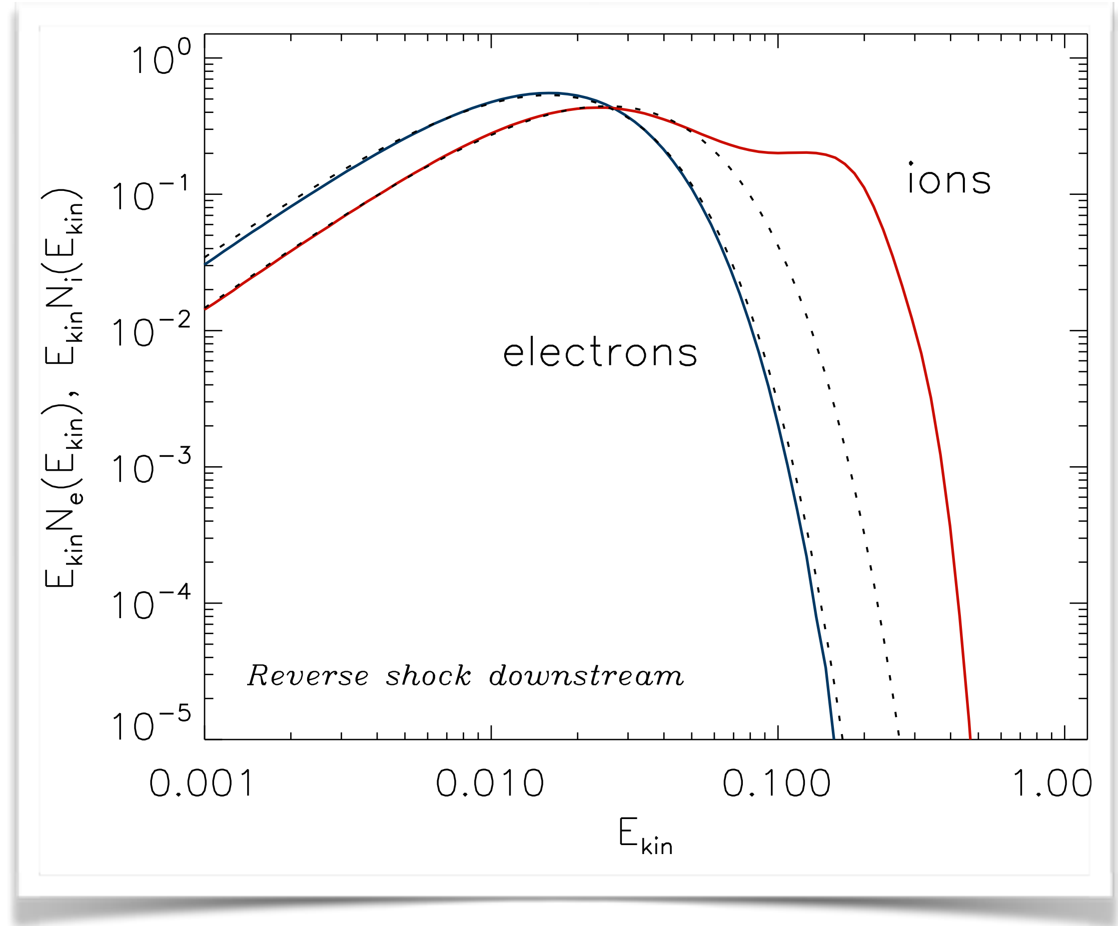
Shock reformation… and rippling



- amplitude of rippling significantly larger at reverse shock with lower sonic Mach number
- spatial scale of $\sim 20\ \lambda_{si}$

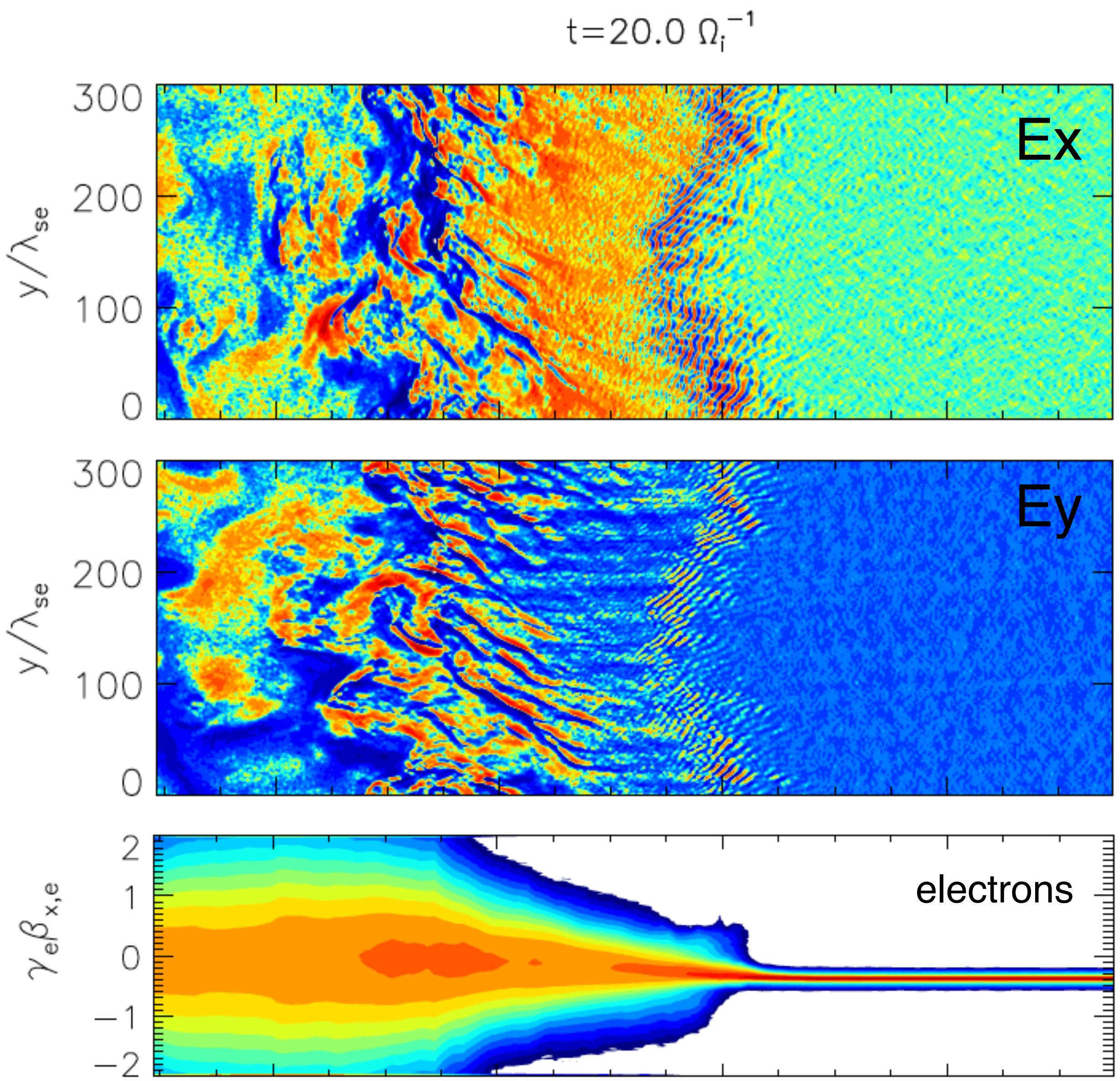
Particle pre-acceleration

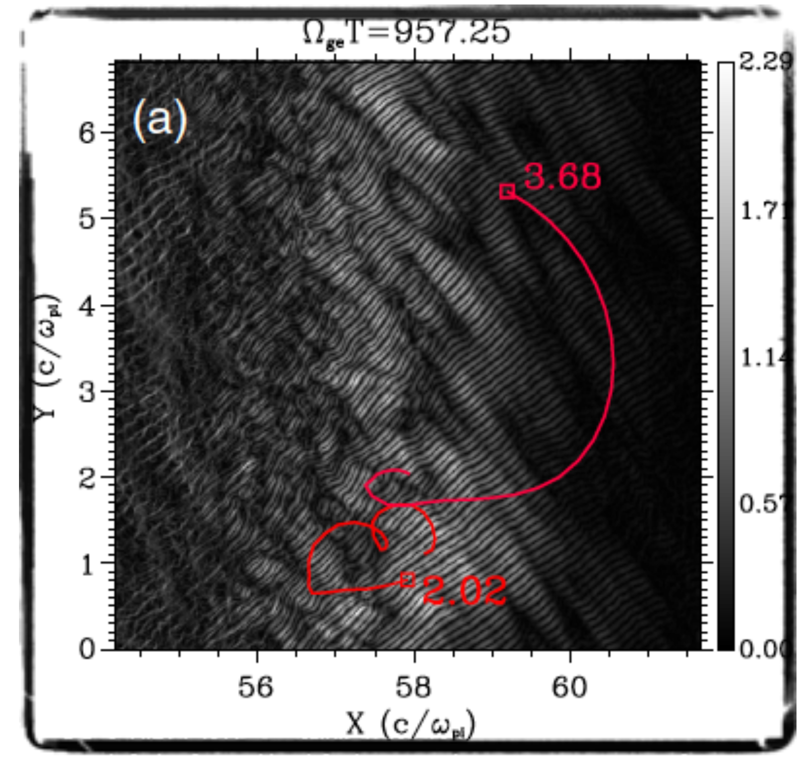




- stable suprathermal tails in ion spectra resulting from shock-surfing acceleration (SSA)
- efficient electron heating; no or marginal electron acceleration

Notes on electron injection





Matsumoto et al. 2013

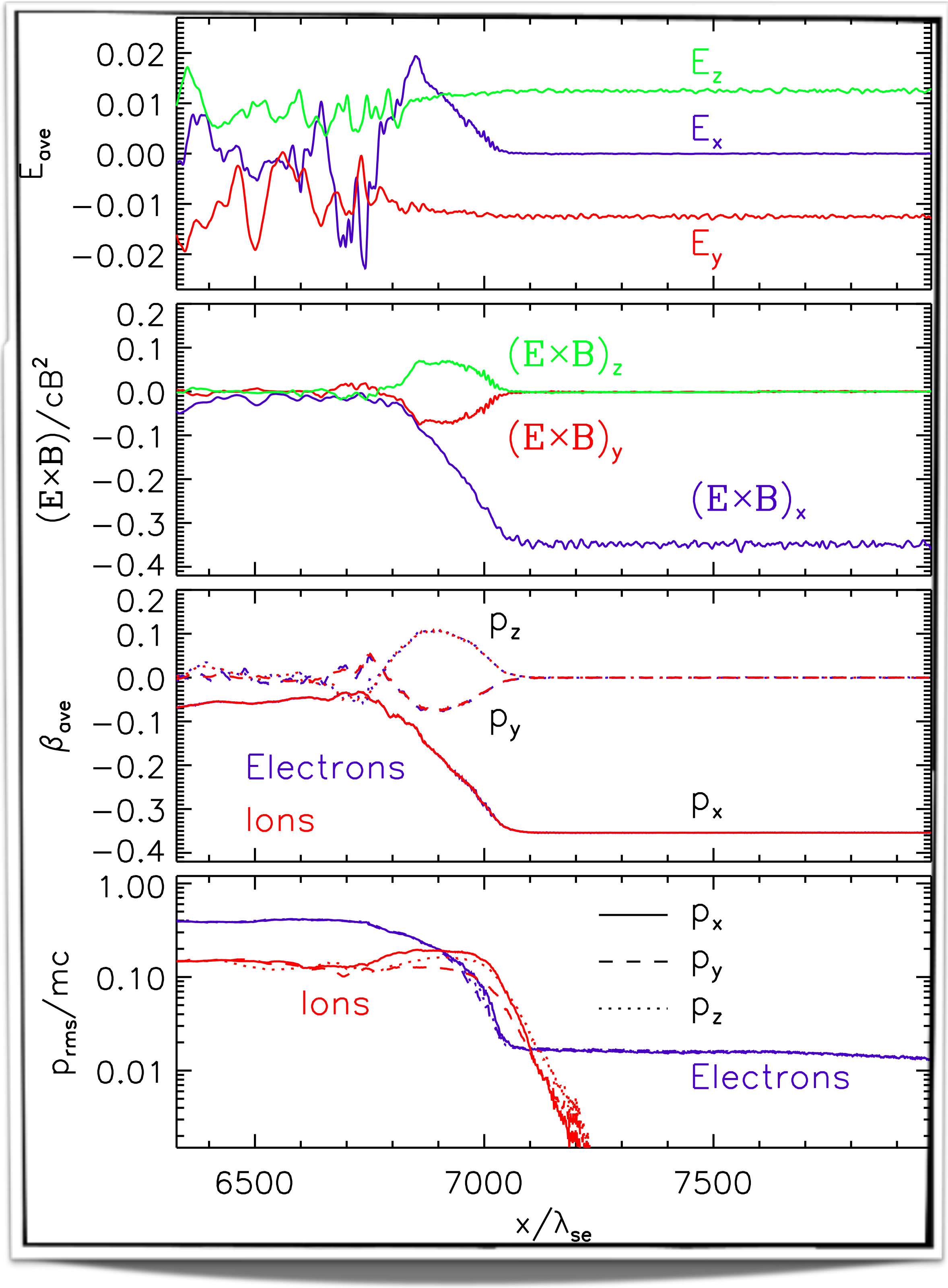
- despite suitable conditions exist ($M_A \gtrsim 16$; Matsumoto et al. 2012) electron SSA is not observed because the amplitude of Buneman modes in the shock foot is insufficient for trapping relativistic electrons

$$E_B \sim cB_0$$

- bulk electron thermalization occurs instead

- inefficient electron acceleration observed by us (low β_e) and by Kato & Takabe (2010; high β_e) suggests that β_e is not deciding factor for the generation of non-thermal tails in the electron SSA
- possible reasons for discrepancy: MF orientation, electron-ion mass ratio, additional factors in the microphysics of high-Mach number shocks mediated by filamentation instability, …

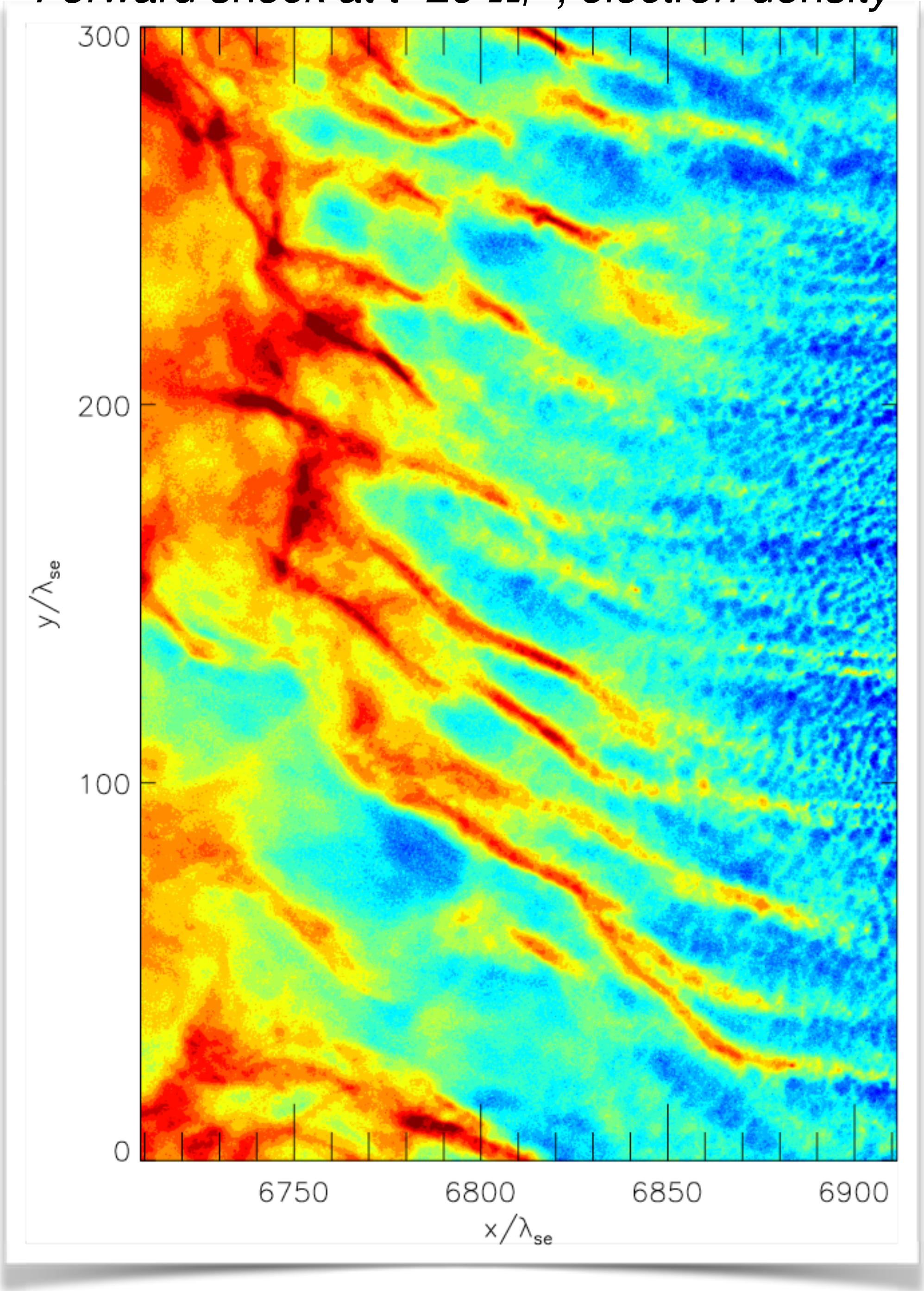
Notes on electron injection

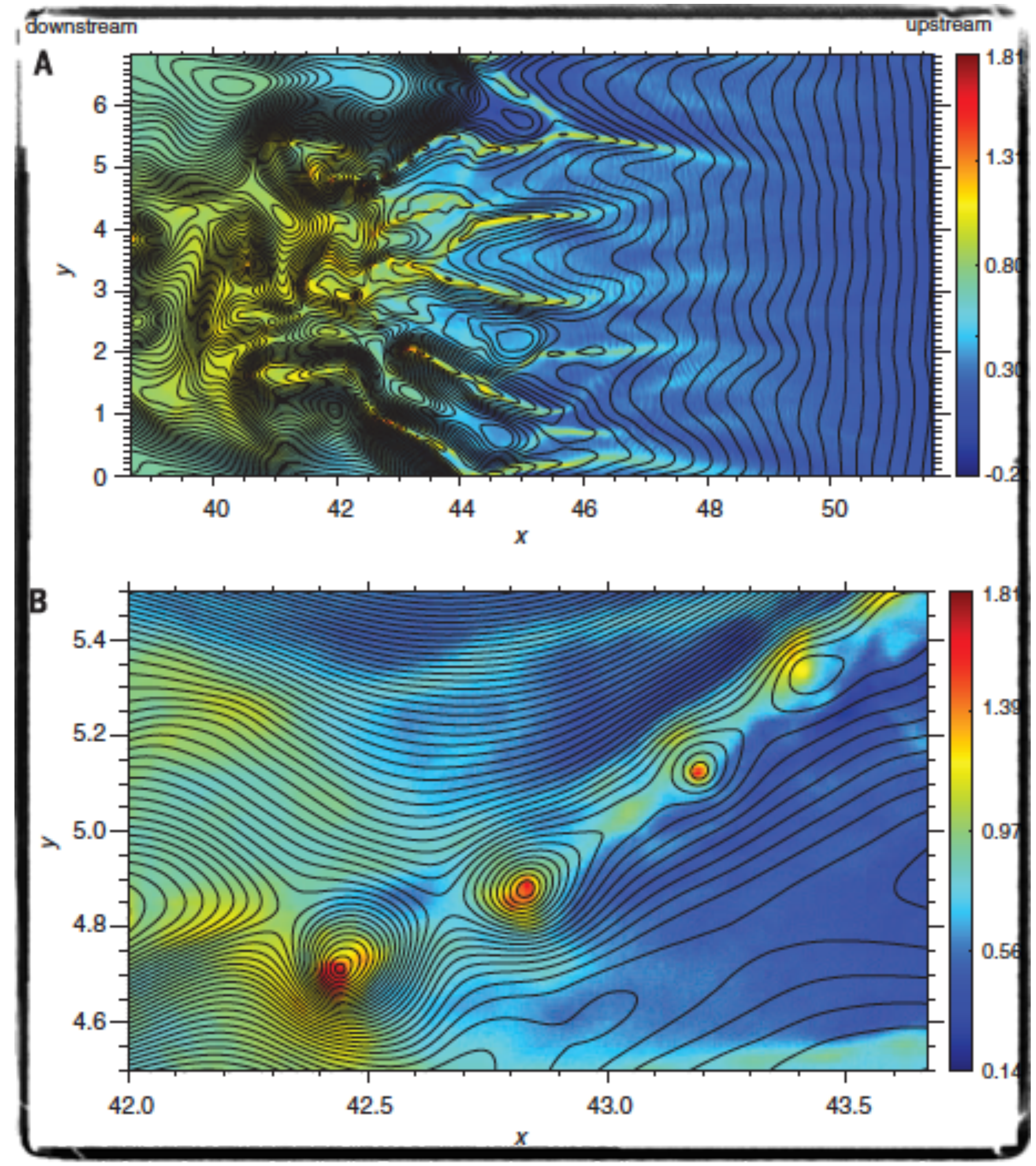


- gradient drift - necessary for shock-drift acceleration (SDA) - is also not observed: local MF gradients dominate the global gradient accross the shock
- bulk electron and ion motion commensurate with ***E*x*B*** drift in direction and amplitude

Notes on electron injection

Forward shock at t=20 Ω_i^{-1}; electron density





Matsumoto et al. 2015

- no evidence for turbulent reconnection

Final remarks

- efficient electron acceleration via SSA process at high Mach number fast nonrelativistic shocks seen in studies with large-scale magnetic field strictly out-of-plane
- they tend to use a larger ion-to-electron mass ratios (cf. turbulent reconnection at shocks)
- additional factors related to the microphysics of filamentation-mediated shocks in multi dimensions possibly important
- effects at oblique quasi-perpendicular shocks even more relevant
- further investigation through high-resolution 2D and full 3D simulations required