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Electron pre-acceleration at merger shocks of galaxy clusters

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Abstract

Particle pre-acceleration constitutes a central unresolved problem in the theory of diffusive shock acceleration (DSA). This process acting at merger shocks in galaxy clusters is thought to produce relativistic electrons forming the so-called radio relics through their radio and X-ray emissions. DSA may also be a source of high- and ultra-high-energy cosmic rays and associated gamma-rays and neutrinos. We report on our recent studies of electron pre-acceleration in cluster shocks with large-scale 2D kinetic particle-in-cell simulations that allow us to investigate the effects of the ion-scale rippling of the shock front and the multi-scale turbulence in the shock transition and downstream. We show that electron injection to DSA can be provided through the process of stochastic shock-drift acceleration (SSDA), in which electrons are confined in the shock transition by pitch-angle scattering off turbulence and gain energy from the motional electric field. Through analysis of multi-scale turbulence in the shock at different pre-shock conditions we demonstrate a crucial role of the shock rippling in electron acceleration via SSDA.

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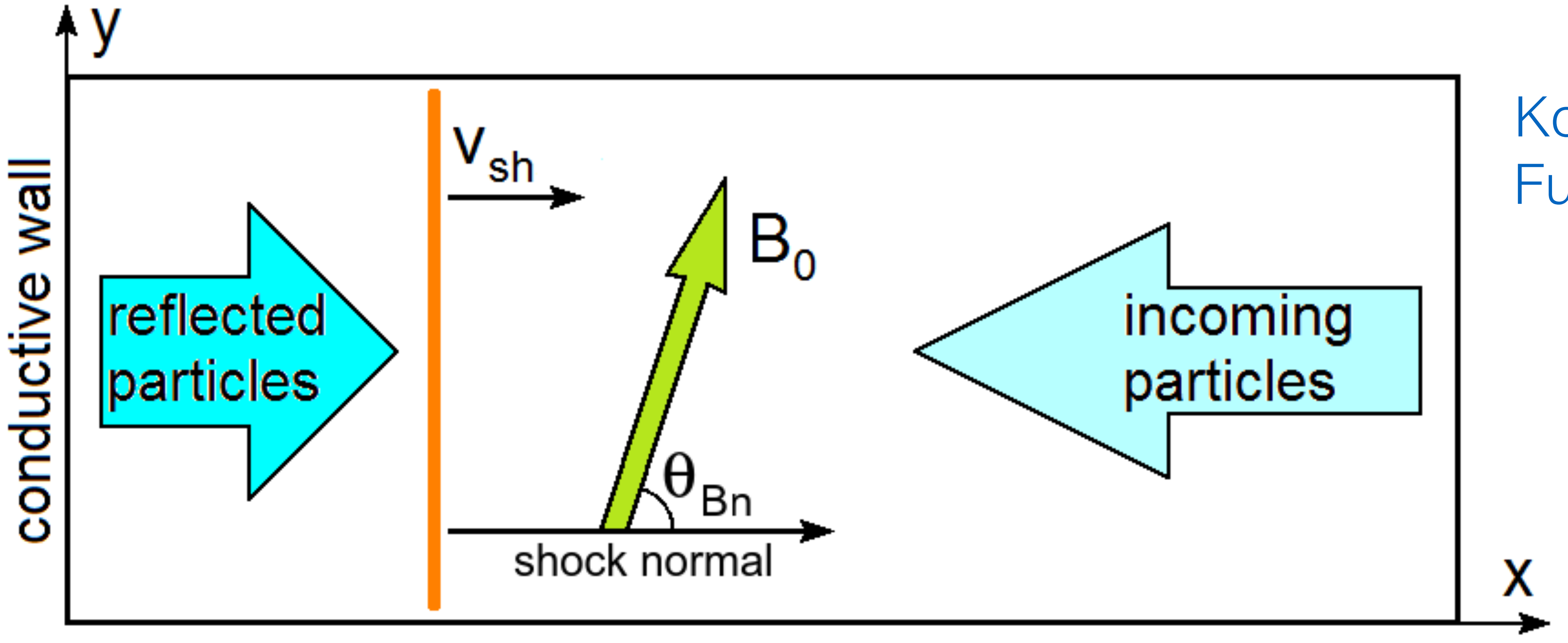
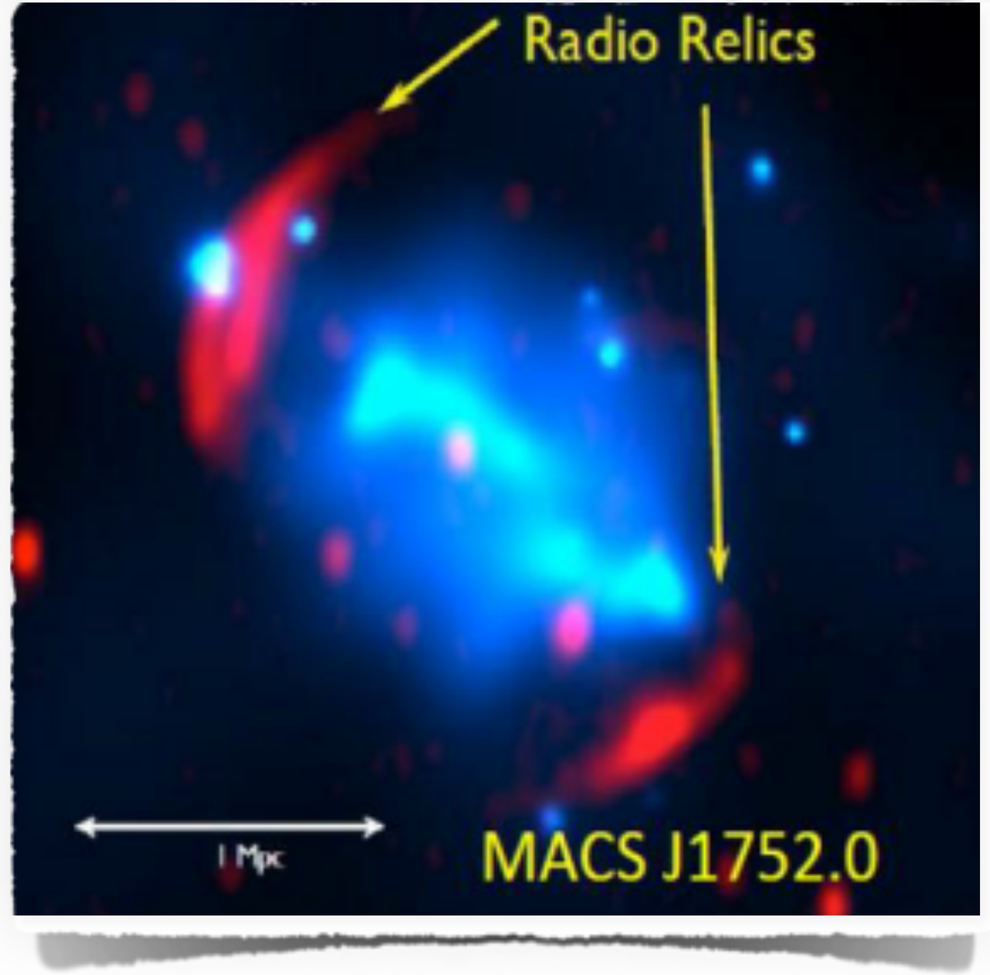
Electron acceleration at low Mach number subluminal shocks is studied with 2D PIC simulations. Physical conditions are appropriate for merger shocks in galaxy clusters. Effects of the shock front corrugations on electron energization are investigated.



Large-scale 2D3V Particle-In-Cell (PIC) simulations

Kobzar O., et al., ApJ 2021
Fułat K., M.Sc. thesis (2021)



White - optical (Hubble)
Blue - X-ray (Chandra)
Red - radio (VLA)

- M_s=3, m_i/m_e=100, v_0=0.1c, β=5, 10, 20, 30 (plasma temperature $k_B T \approx 40$ keV)
- subluminal shocks: ϑ_{Bn}=75°, 78° ($\vartheta_{cr} \approx 81,4°$)
- conditions of inefficient EFI mode driving in the laminar shock phase:

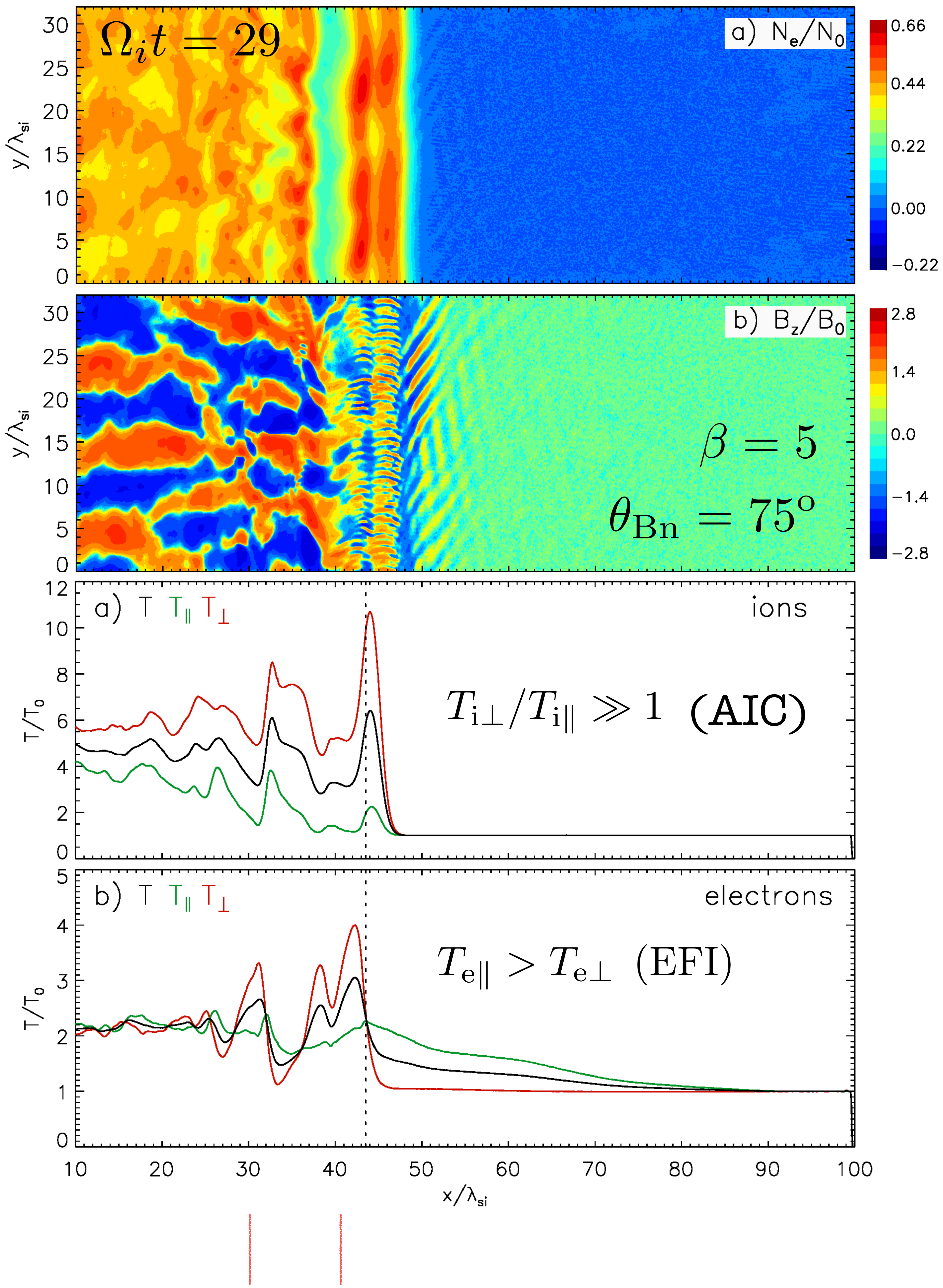
$$v_t \approx 1.5 v_{\rm th,e} \; (\theta_{\rm Bn} = 75^o)$$
$$v_t \approx 1.9 v_{\rm th,e} \; (\theta_{\rm Bn} = 78^o)$$

$$v_t \gtrsim v_{\rm th,e} \; (v_t = u_{\rm sh}^{\rm up} / \cos\theta_{\rm Bn})$$

Sonic Mach number: $M_{\rm s} = \frac{v_{\rm sh}}{c_{\rm s}}$

Plasma beta: $\beta = p_{\rm th}/p_{\rm mag}$

Global shock structure: multi-scale turbulence



$\Omega_i t = 29$

$\beta = 5$

$\theta_{\rm Bn} = 75^{\rm o}$

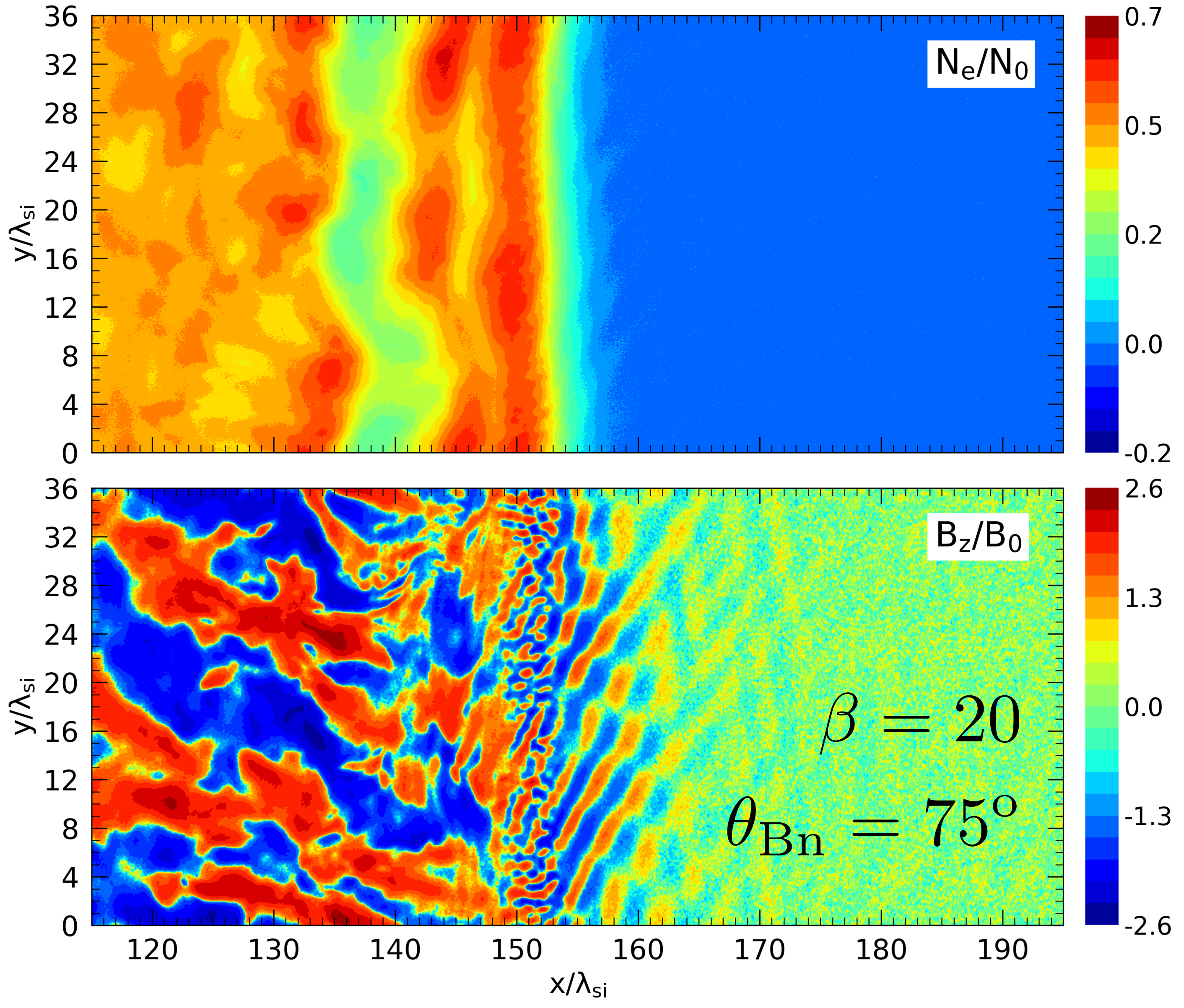
$T_{i\perp}/T_{i\parallel} \gg 1$ (AIC)

$T_{e\parallel} > T_{e\perp}$ (EFI)

$T_{e\perp} > T_{e\parallel}$ (whistlers)

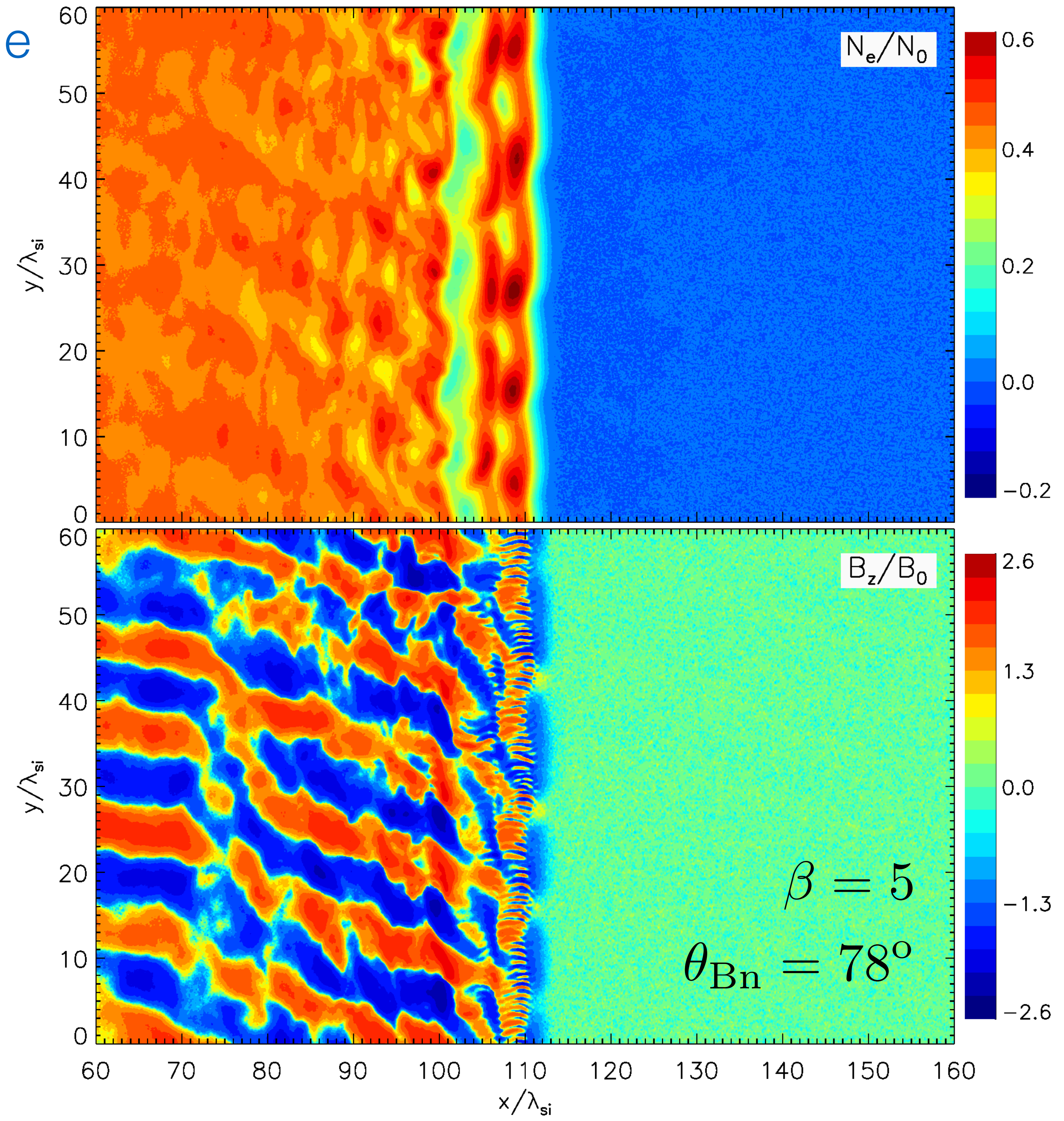
Features of multi-scale turbulence similar at different physical conditions:

- rippling in the shock transition on different scales (overshoot-undershoot-2nd overshoot)
  - AIC and mirror modes
  - ripple wavelength longer with growing β
- short-scale whistler waves in the overshoot
- oblique and perpendicular modes of the electron firehose instability (EFI) in the upstream, enhanced and modulated by the ripples at lower β
- absence of EFI waves for higher θ_{Bn}



$\beta = 20$

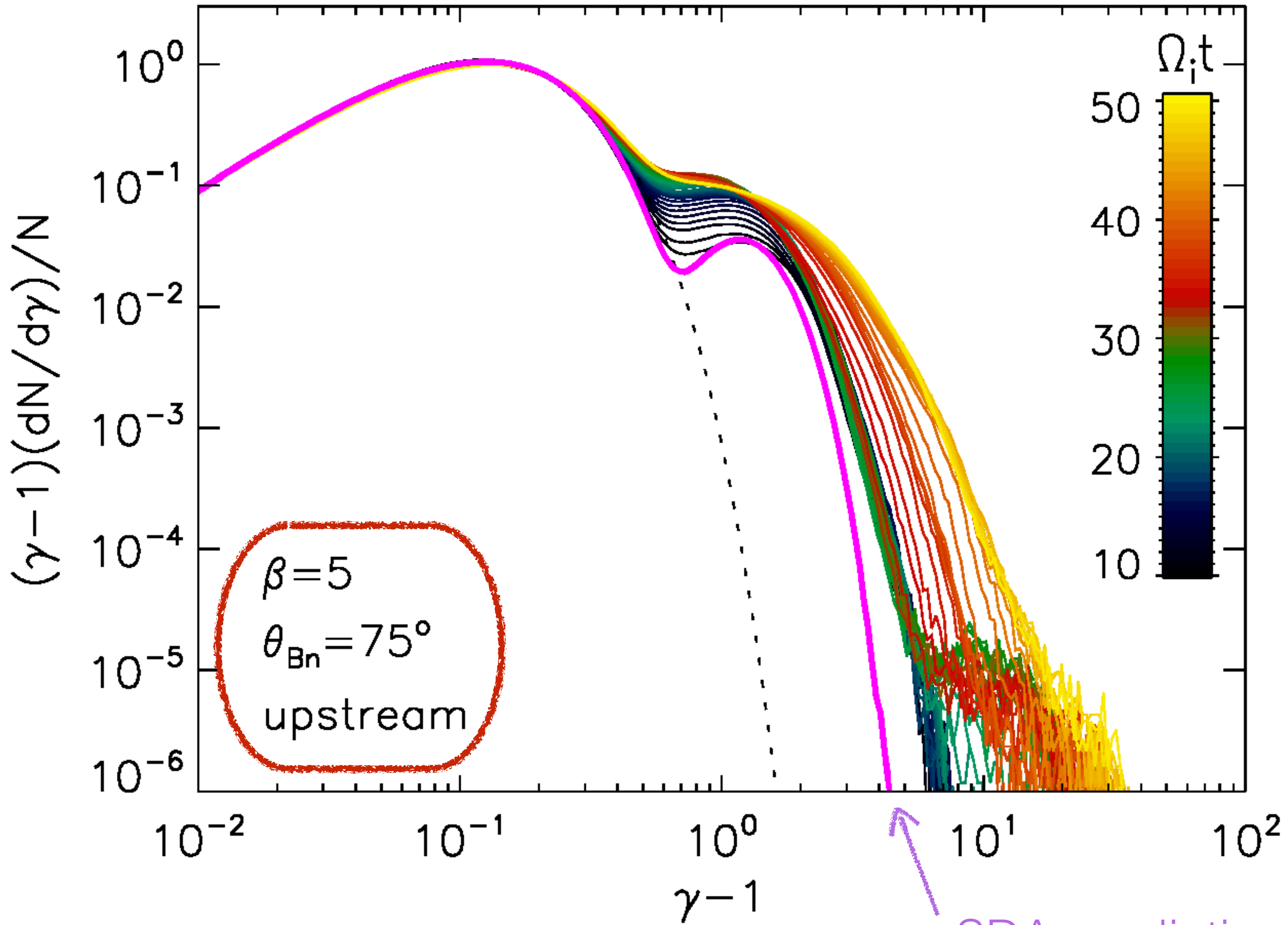
$\theta_{\rm Bn} = 75^{\rm o}$



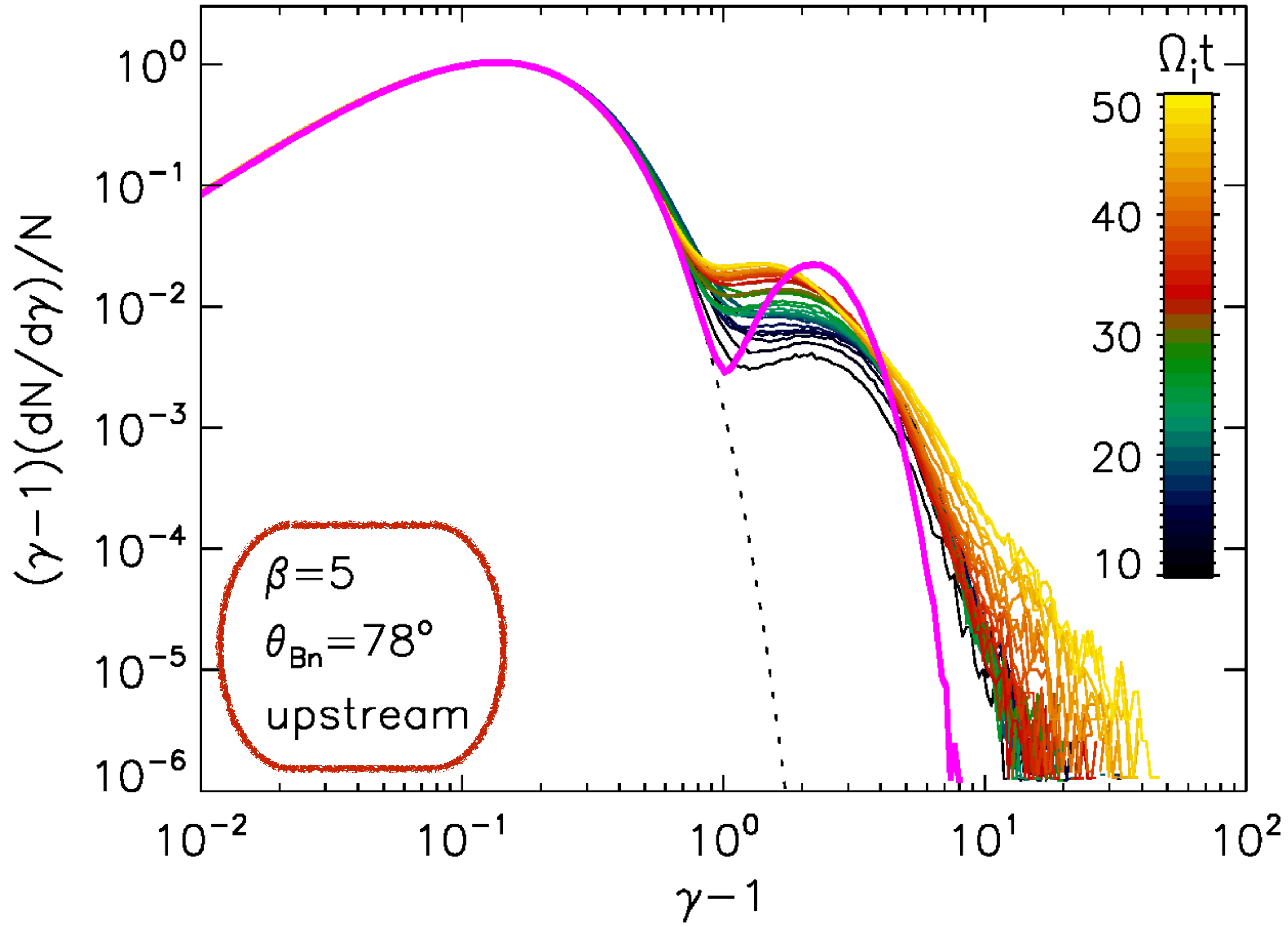
$\beta = 5$

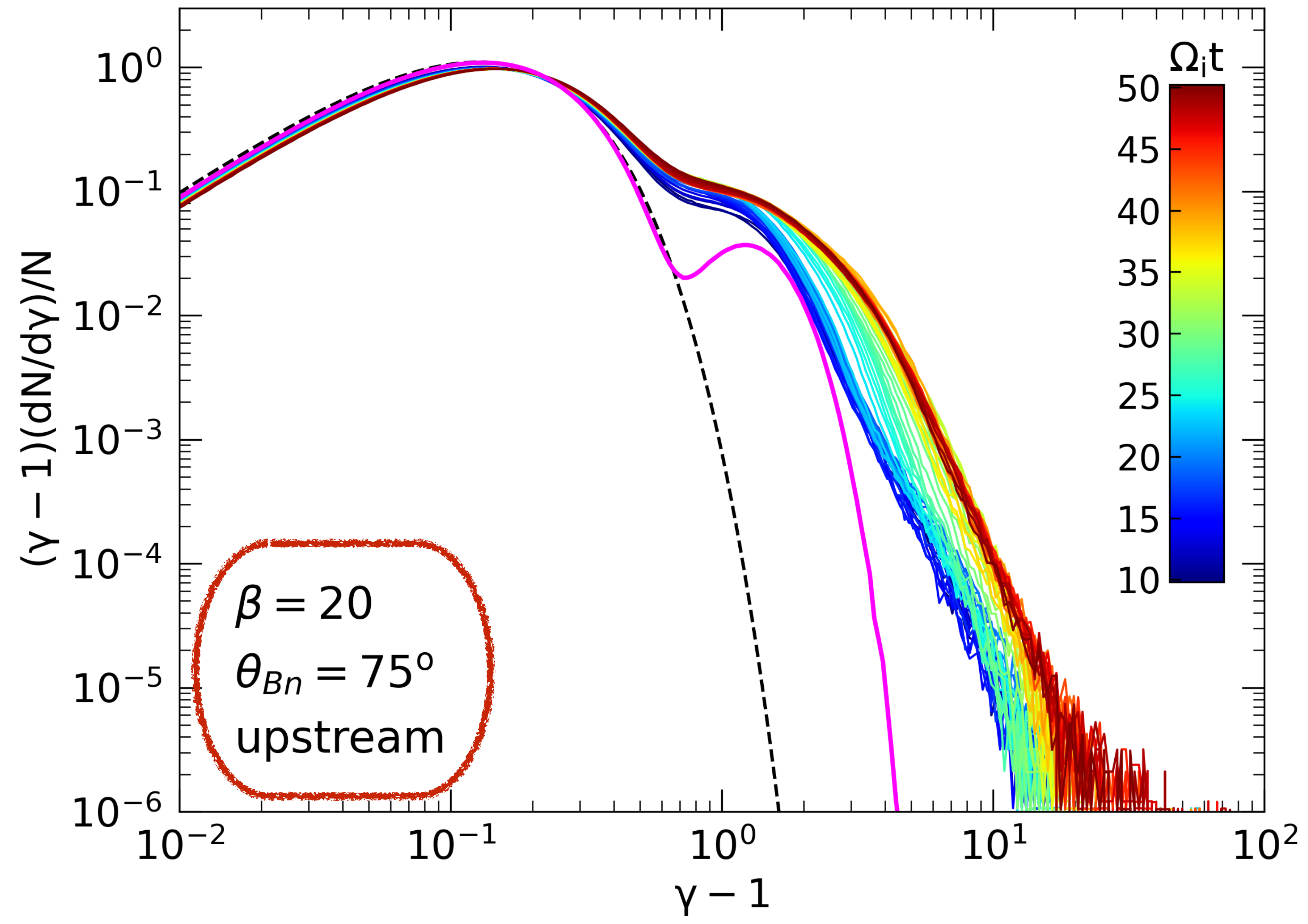
$\theta_{\rm Bn} = 78^{\rm o}$

Upstream Electron Spectra



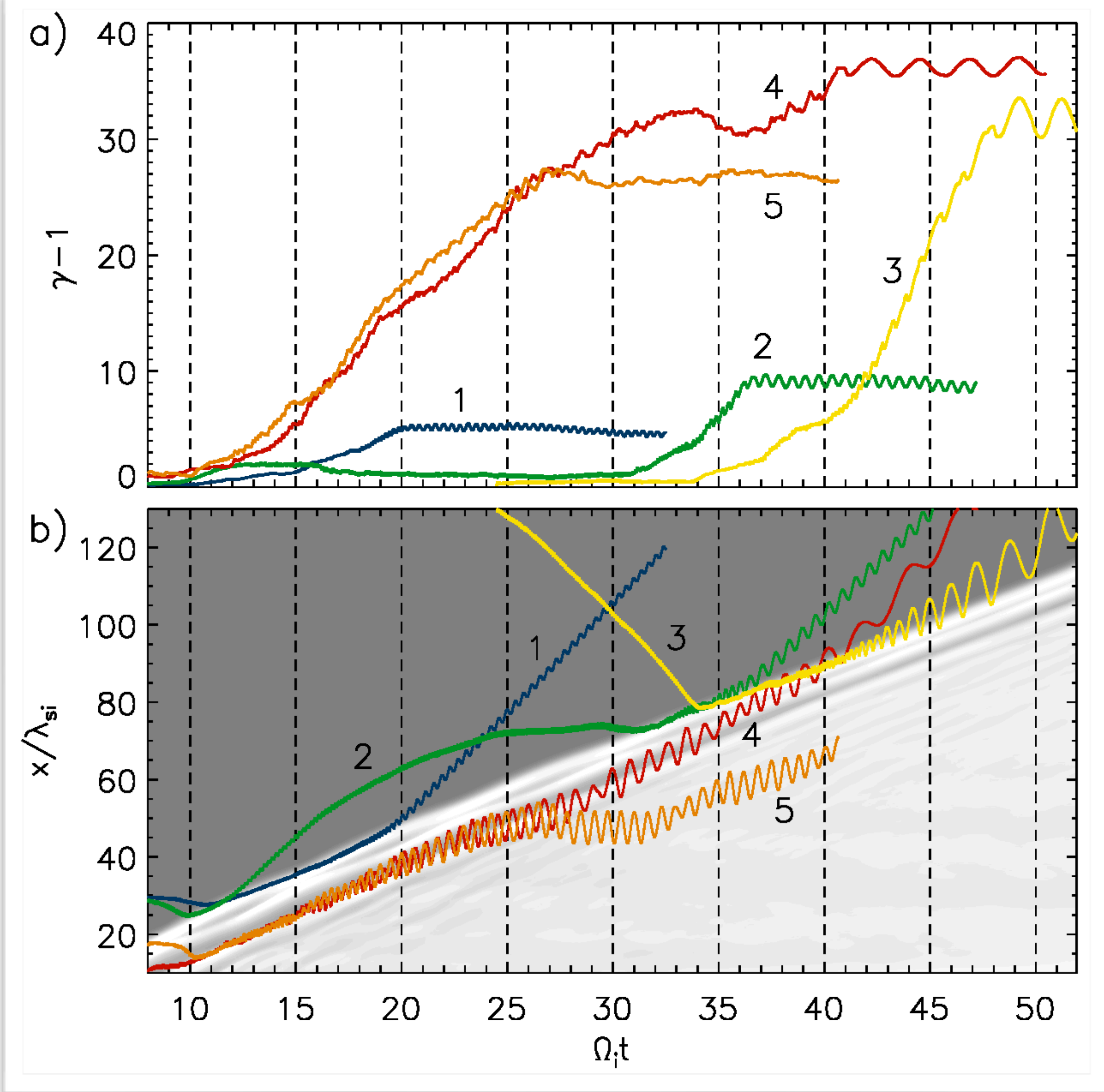
SDA prediction





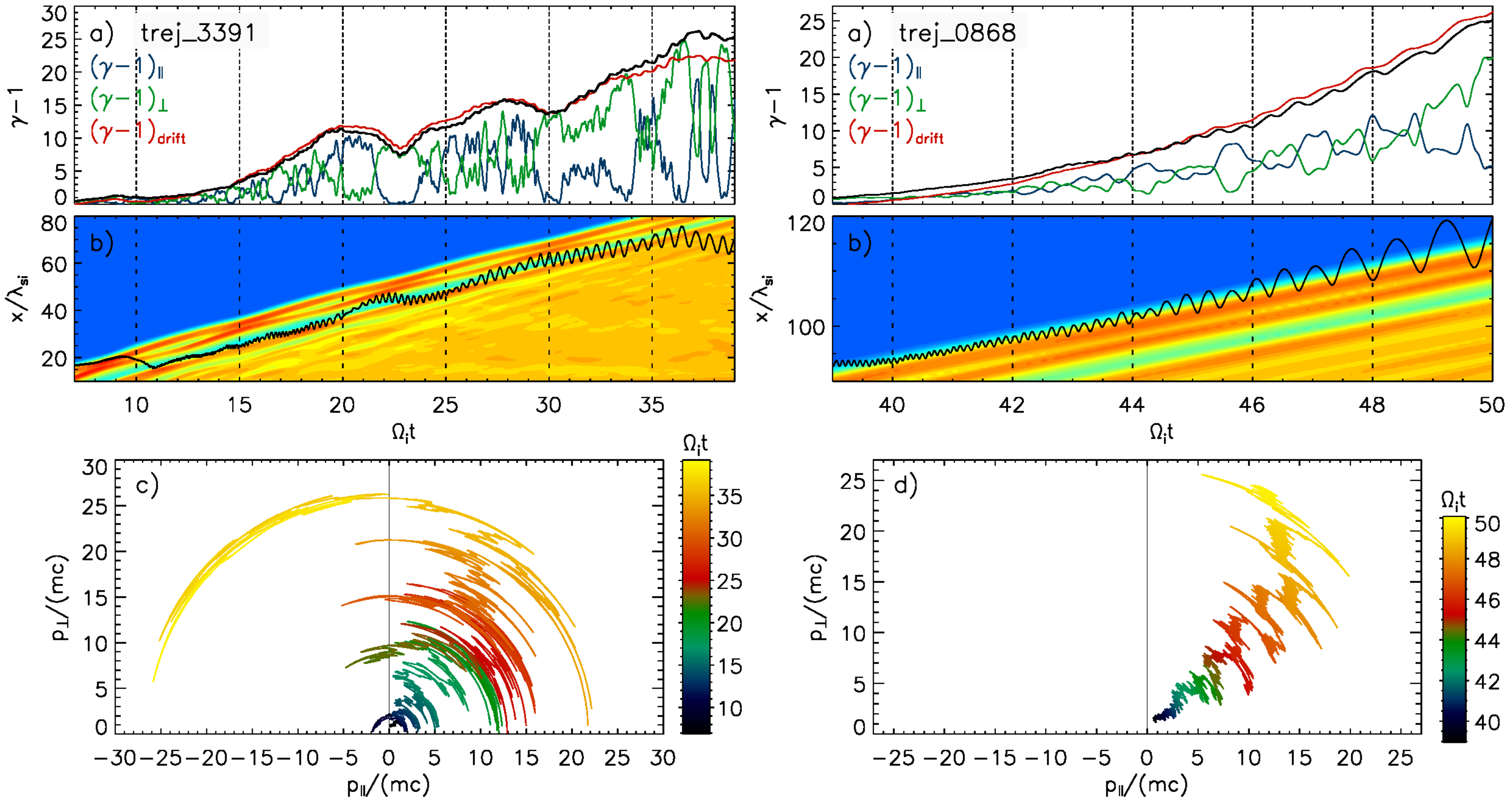
- electron energisation to energies much beyond Stochastic Shock Drift (SDA) predictions
- spectra depend weakly on β
- maximum energies γ_{max}~30-60 > γ_{inj}
- pre-acceleration to high energies feasible, at which DSA starts to operate in the presence of long-wave (MHD) upstream turbulence

$$\gamma_{\rm inj} \approx 25 \;\; (p_{\rm inj} \sim 3\, p_{\rm th,i})$$



Typical particle trajectories for β=5 and θ_{Bn} =75°

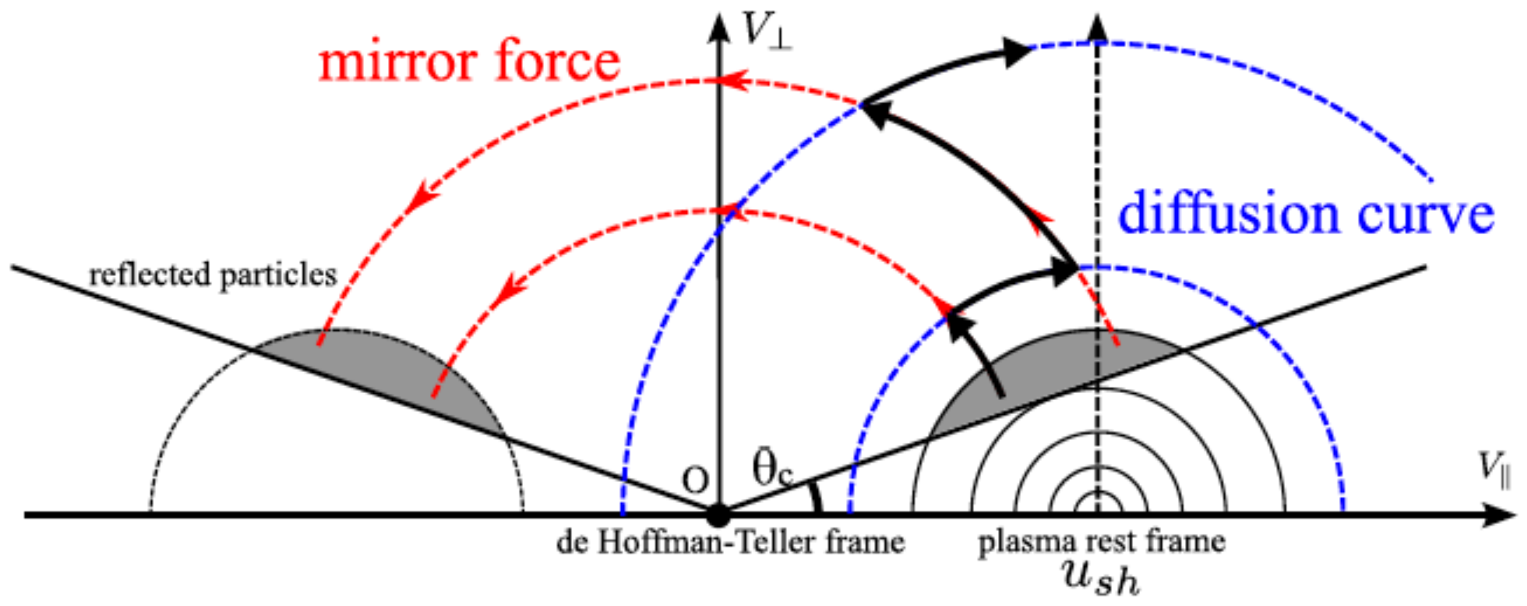
Stochastic Shock Drift Acceleration (SSDA)



- most accelerations associated with an increase in $p_\perp$
- strong pitch-angle scattering (arcs in $p_\parallel$-$p_\perp$ momentum space)
- energy gain mostly through the drift along motional electric field:

$$\Delta\gamma_{\mathrm{drift}} = (-e/m_{\mathrm{e}}c^2)\int E_z\,dz$$

Katou & Amano (2019)



- adiabatic mirror reflection in the HTF
- elastic scattering (diffusion) in the plasma rest frame

- electrons are confined in the shock transition region by stochastic pitch-angle scattering off magnetic turbulence and gain energy through SDA (non-adiabatic acceleration)
- longer particle confinement increases energy gains and enables more efficient acceleration than standard SDA
- at merger shocks electron scattering provided through multi-scale (broad band) turbulence in the entire shock transition