Krajowy Naukowy Ośrodek Wiodący

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Electron injection at shocks in merging galaxy clusters

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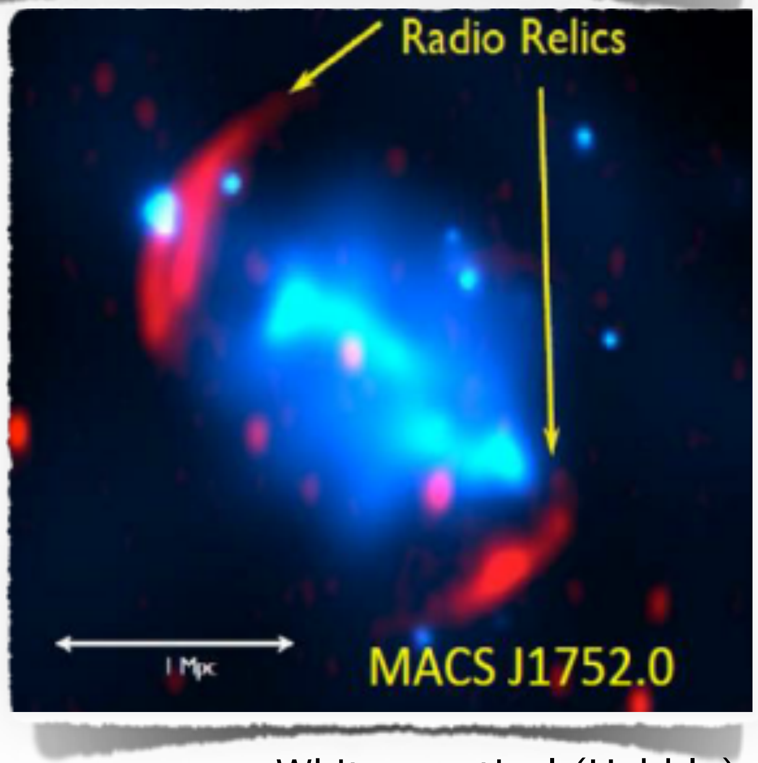
Introduction

- supersonic flows of baryonic matter induced during large-scale structure formation of the Universe produce shocks in hot intracluster (ICM) medium with high plasma beta ($\beta >> 1$)
- merger shocks are observed in radio and X-rays as so-called radio relics; their synchrotron emission indicates CR electron acceleration to high energies
- most energetic merger shocks have low Mach numbers ($M_s < 5$, $M_A < 10$)
- Diffusive Shock Acceleration (DSA) assumed to operate at these shocks but mechanism of electron injection that regulates the efficiency of CR acceleration is poorly known for galaxy cluster conditions



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

Alfvenic Mach number: $M_{\rm A} = \dfrac{v_{\rm sh}}{v_{\rm A}}$

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

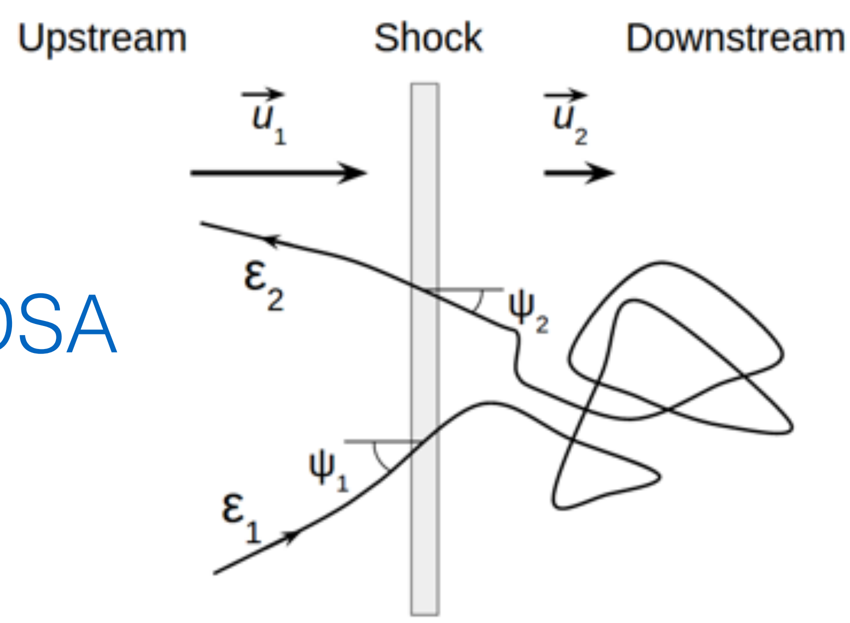
Plasma beta: $\beta = p_{\rm th}/p_{\rm mag}$

$$v_{\rm A} = \frac{B_0}{\sqrt{\mu_0(N_e m_e + N_i m_i)}}$$

$$c_s = \sqrt{2\Gamma k_B T_i/m_i}$$

Particle injection (pre-acceleration) to DSA

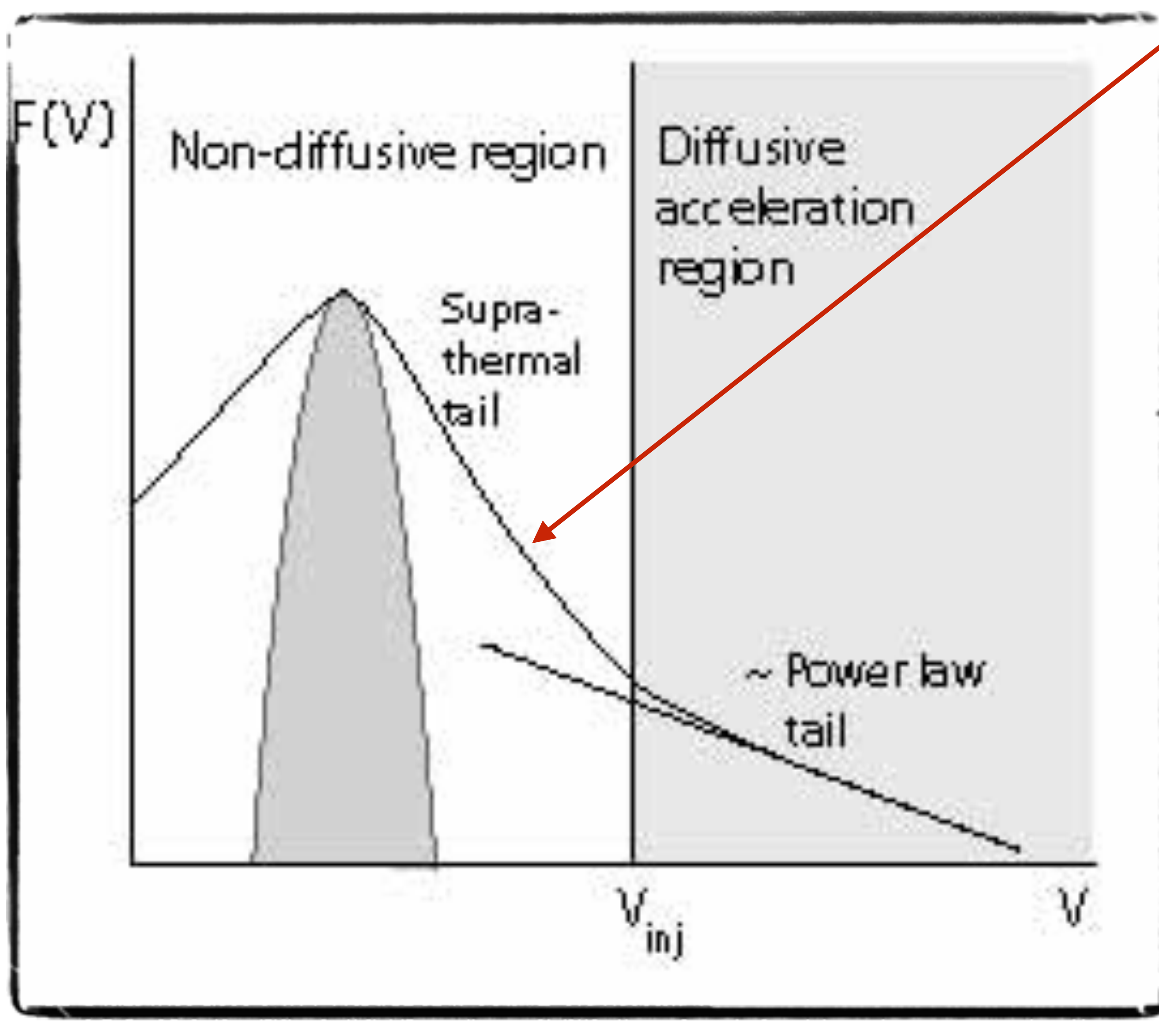
DSA



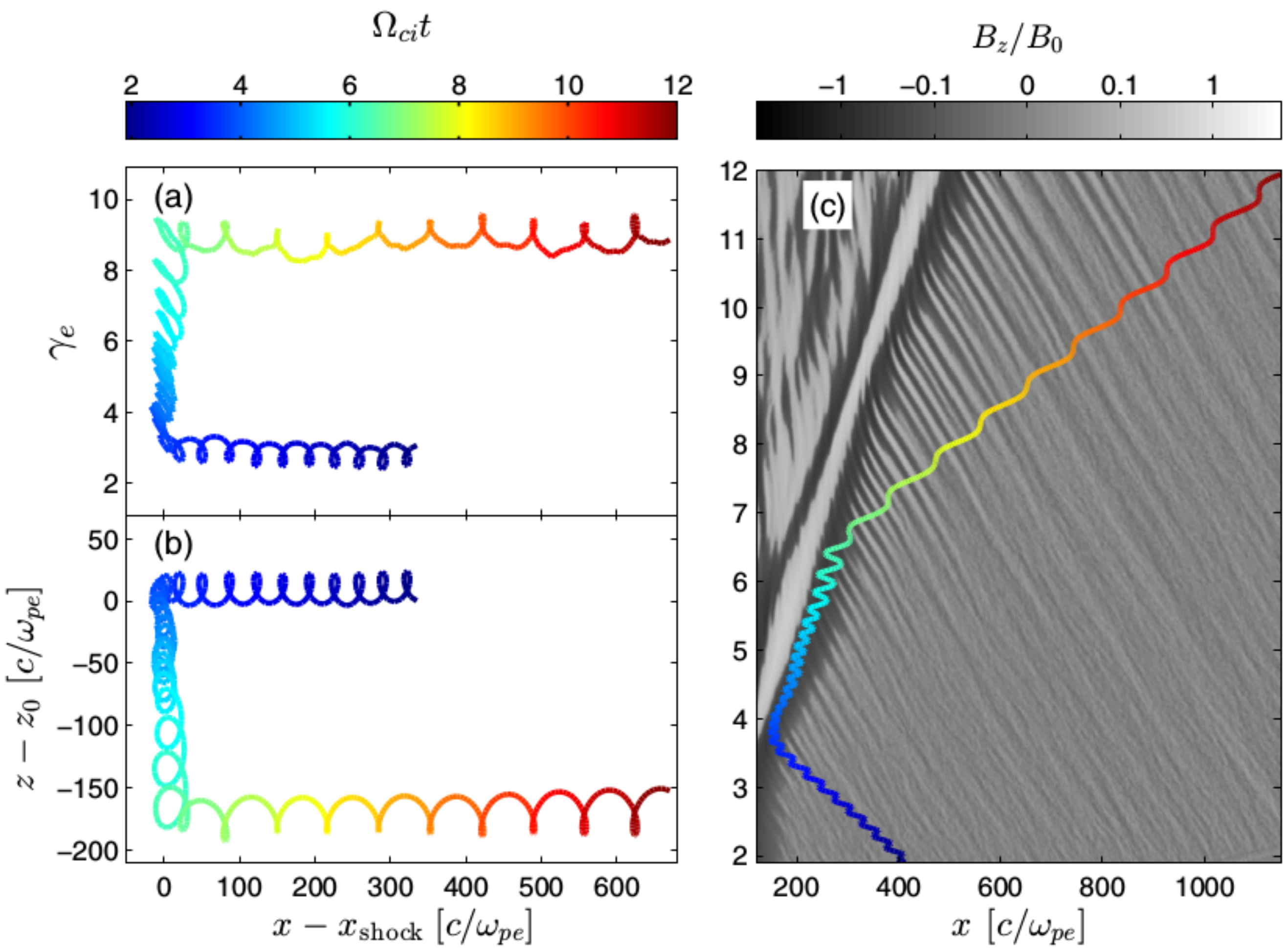
$d_{sh} \sim (1\text{-}100)\ \lambda_{gi}$

$r_g(\varepsilon_{inj}) > d_{sh}$

injection



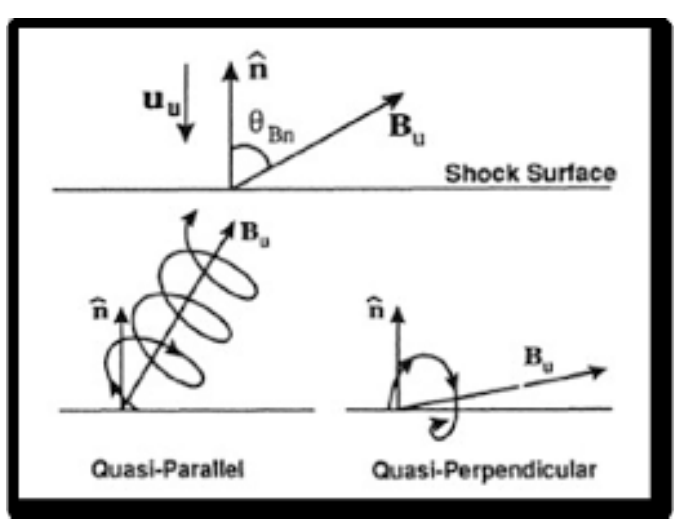
Electron injection at shocks in high beta plasmas: Shock Drift Acceleration (SDA)



Guo et al. 2014 (2D)

- particles gain energies from the motional electric field while drifting along the shock surface due to the magnetic field gradient
- some particles can be reflected from the shock back upstream (magnetic mirror effect) and form non-thermal upstream plasma component
- works at subluminal shocks: $v_t \leq c$
- acceleration time: $\sim \Omega_i^{-1}$
- energy gain:

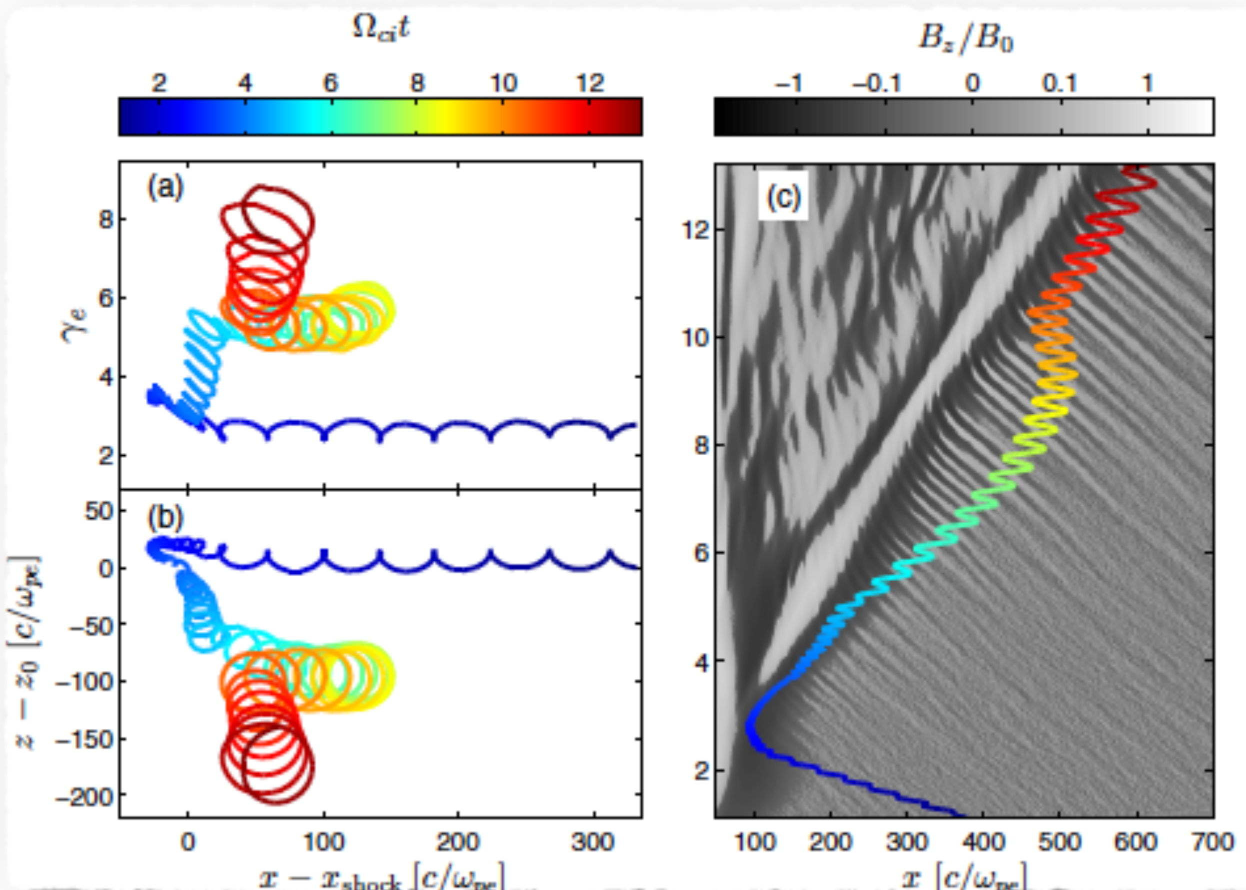
$$\Delta\gamma_{\rm SDA} = \frac{-e}{m_e c^2} \int E_z\, dz$$

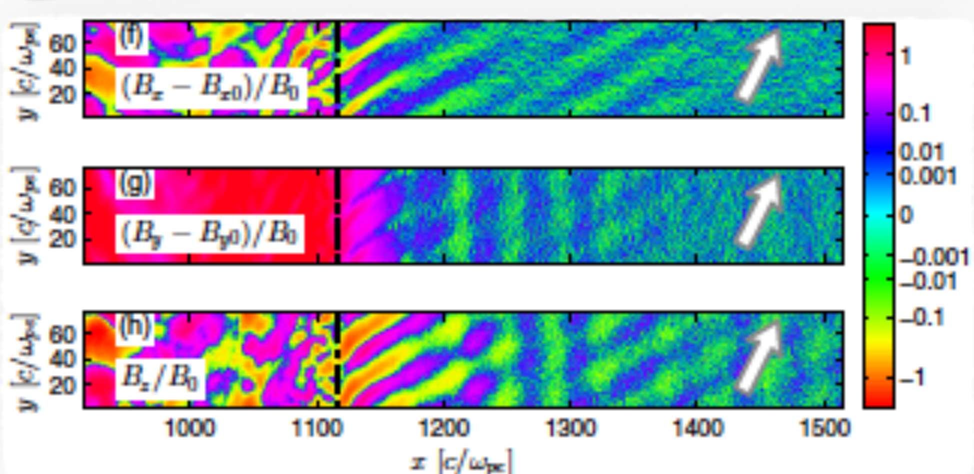


de Hoffman-Teller velocity:

$$v_t = u_{\rm sh}^{\rm up} / \cos\theta_{\rm Bn}$$

Multiple Shock Drift Acceleration cycles at quasi-perpendicular shocks

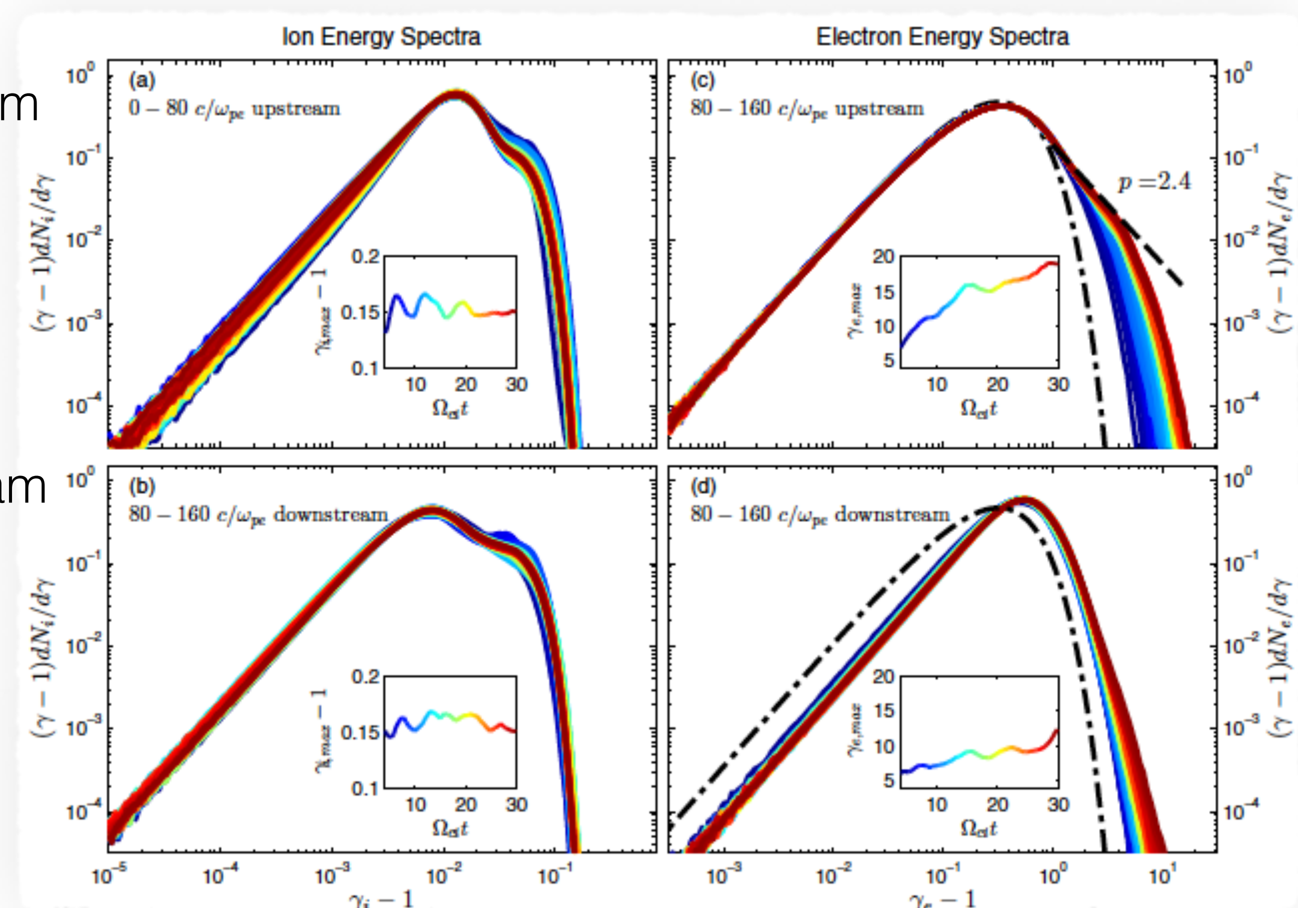




- SDA-reflected electrons scattered back towards shock by upstream self-generated waves - DSA-like process
- formation of upstream power-law spectra (and steep downstream spectra)
- more effective at high β
- $\gamma_{max} \ll \gamma_{inj}$?

upstream

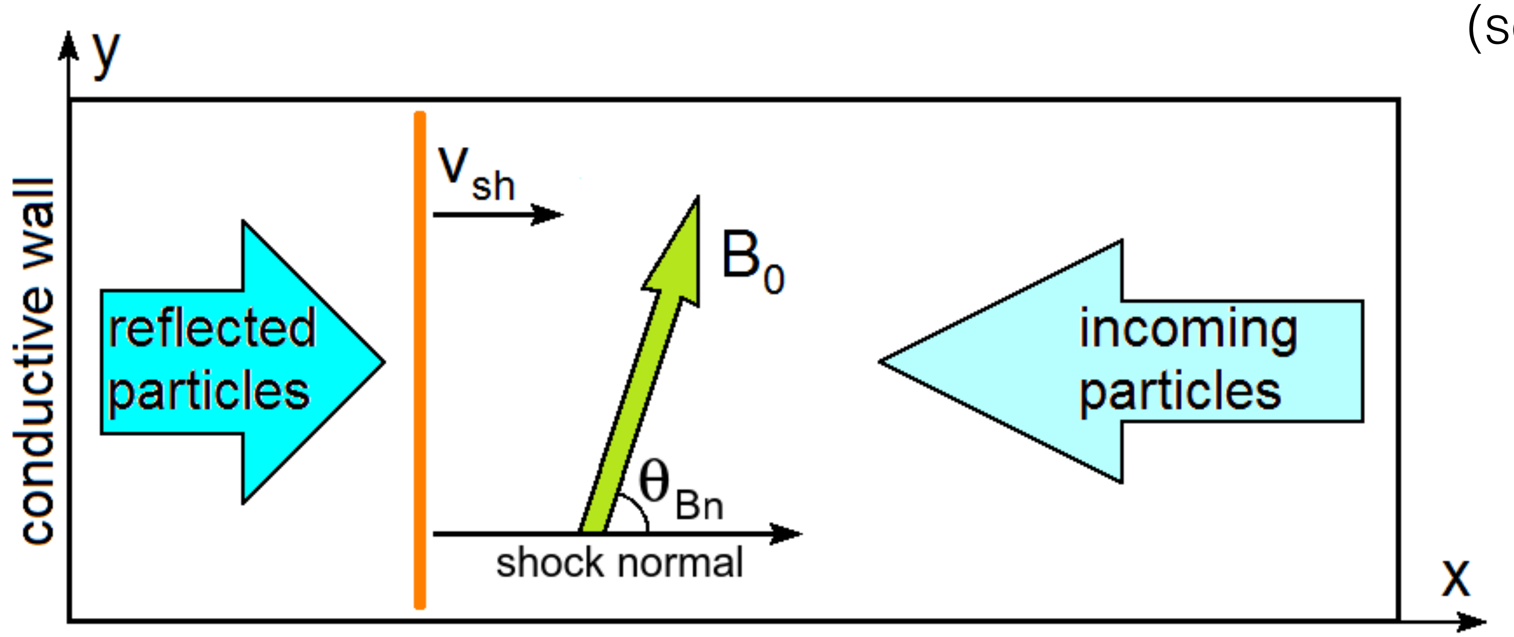
downstream



Matsukiyo et al. 2011 (1D)
Guo et al. 2014 (2D)
Kang et al. 2019 (2D)

Large-scale effects of the shock rippling on electron pre-acceleration with PIC simulations

Kobzar O., et al., ApJ 2021
Fułat K., M.Sc. thesis (2021)
(see also Matsukiyo & Matsumoto 2015)



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

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

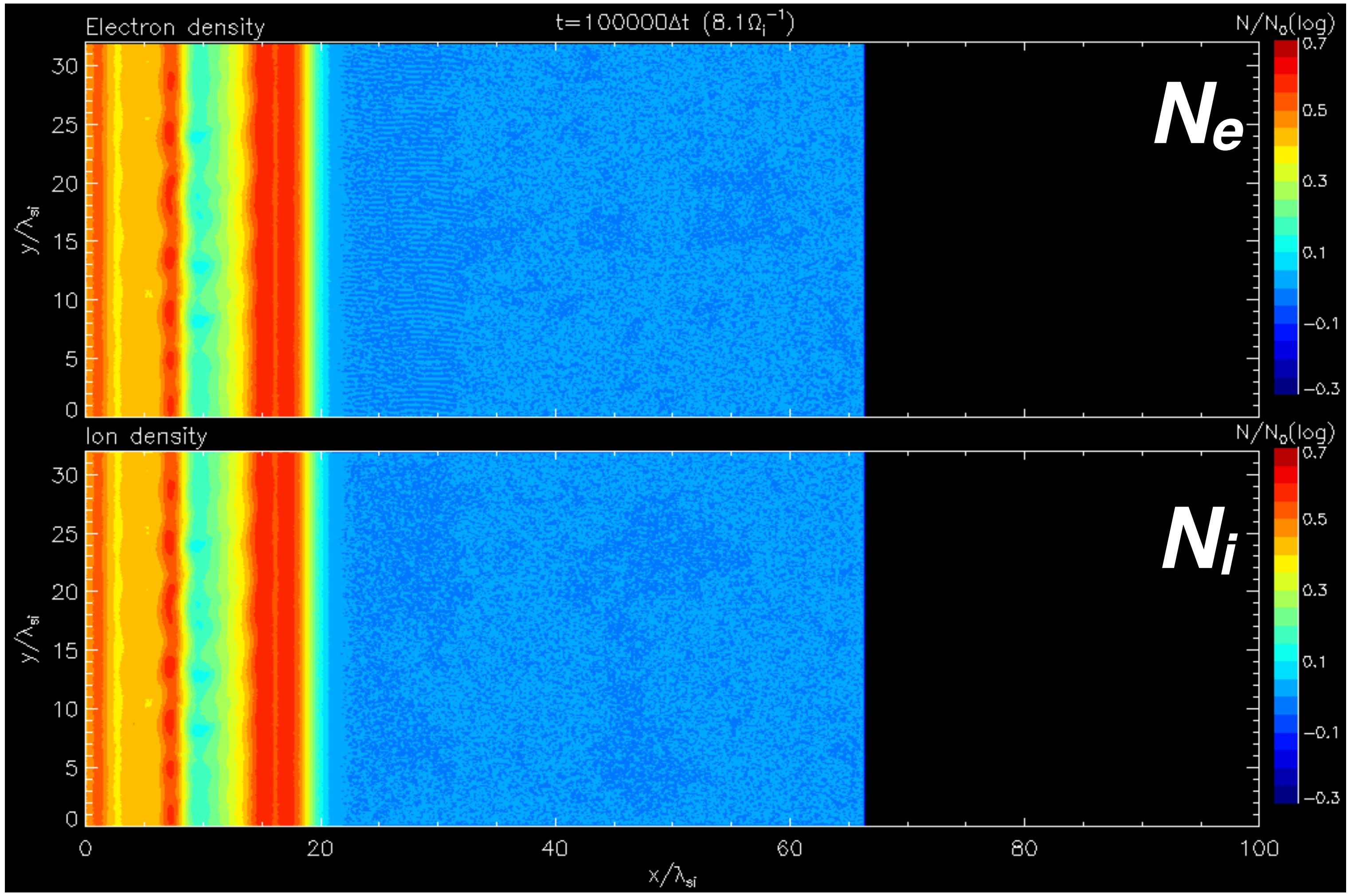
$$v_t \gtrsim v_{\mathrm{th,e}} \; (v_t = u_{\mathrm{sh}}^{\mathrm{up}} / \cos\theta_{\mathrm{Bn}})$$

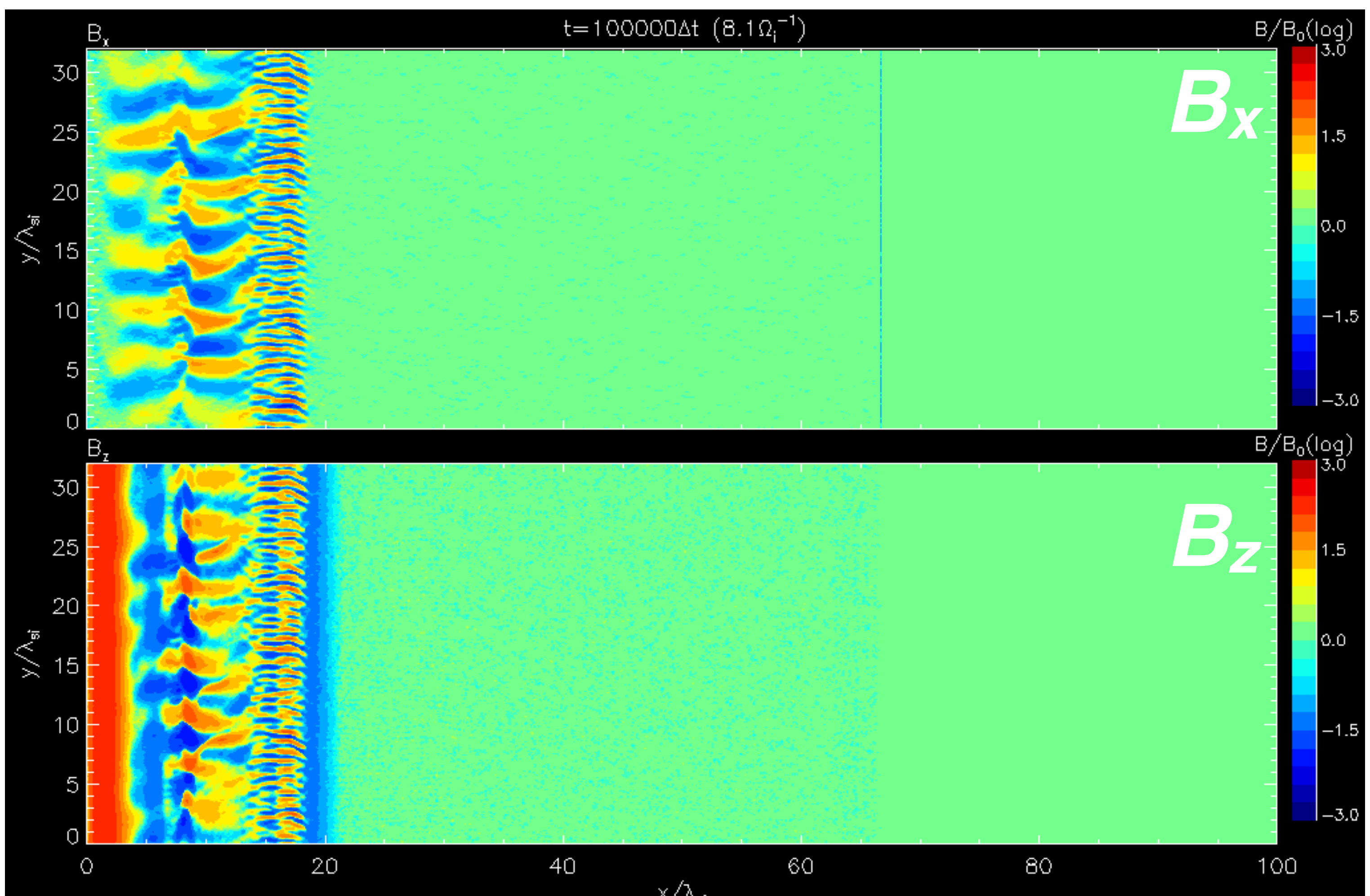
$$v_t \approx 1.5 v_{\mathrm{th,e}} \; (\theta_{\mathrm{Bn}} = 75^o)$$

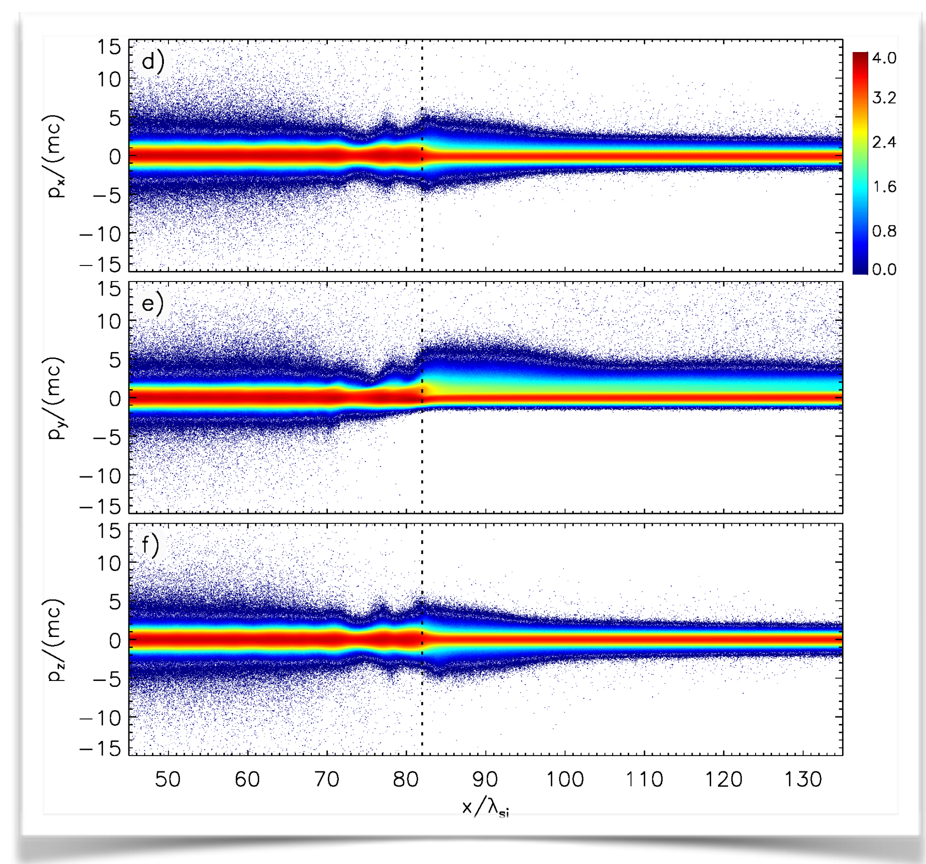
$$v_t \approx 1.9 v_{\mathrm{th,e}} \; (\theta_{\mathrm{Bn}} = 78^o)$$

Global shock structure: multi-scale turbulence (β=5, ϑ_{Bn}=75°)

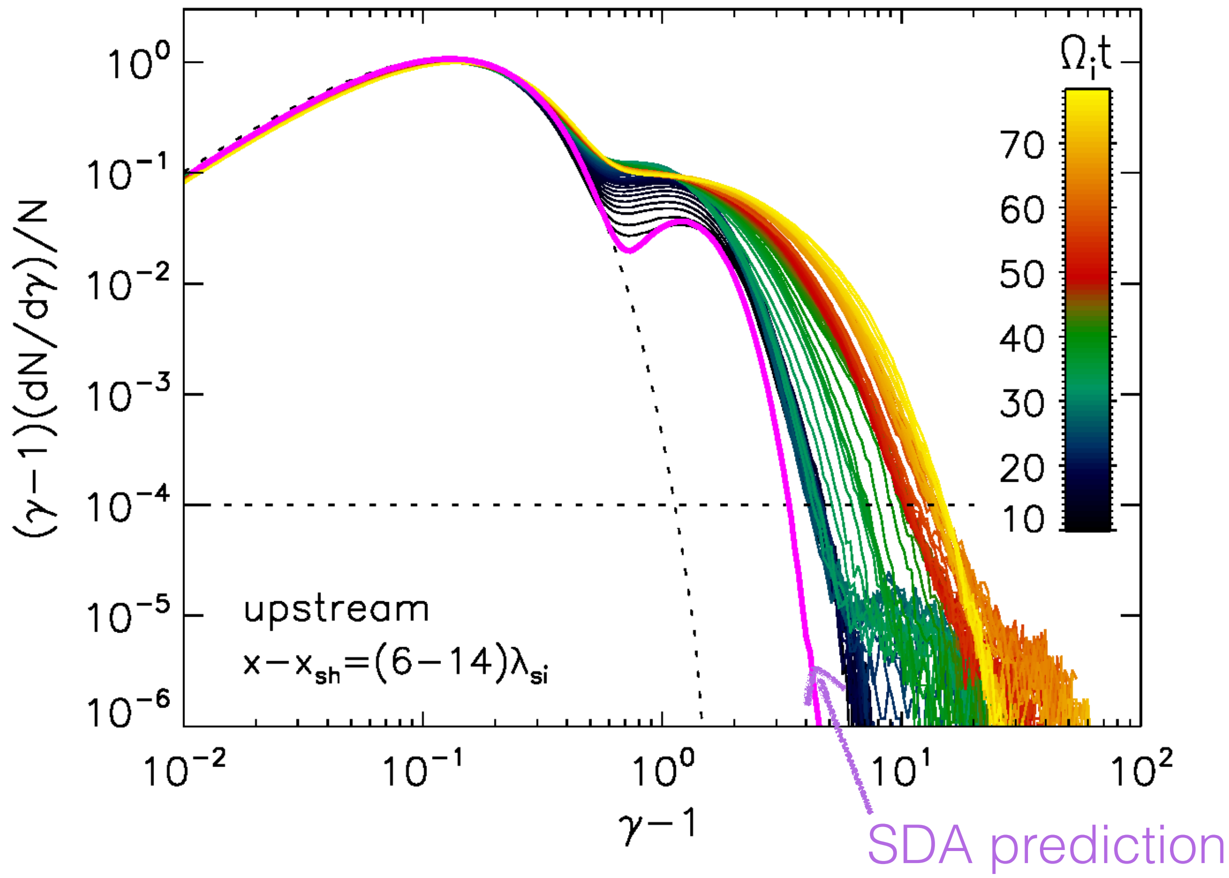
- rippling in the shock transition on different scales (overshoot-undershoot-2nd overshoot)
  - AIC and mirror modes
- short-scale whistler waves in the overshoot
- oblique and perpendicular modes of the electron firehose instability in the upstream, enhanced and modulated by the ripples

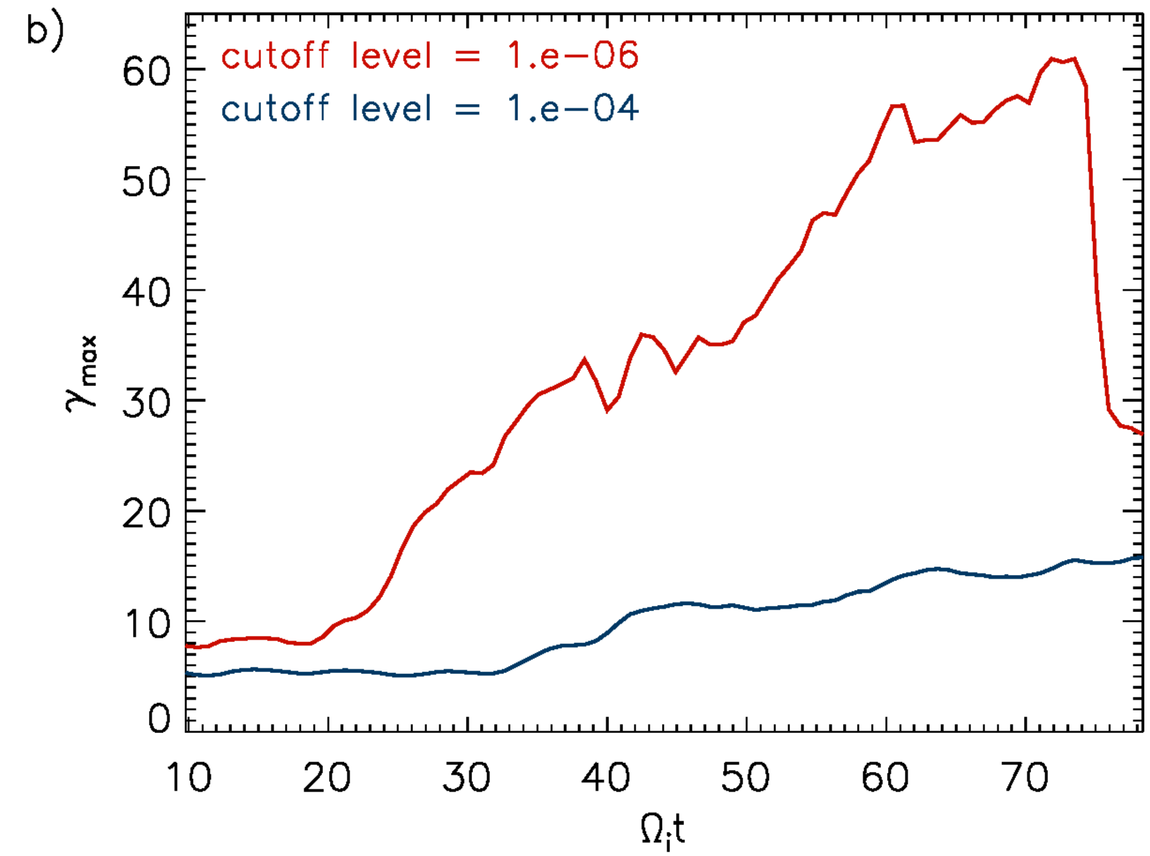


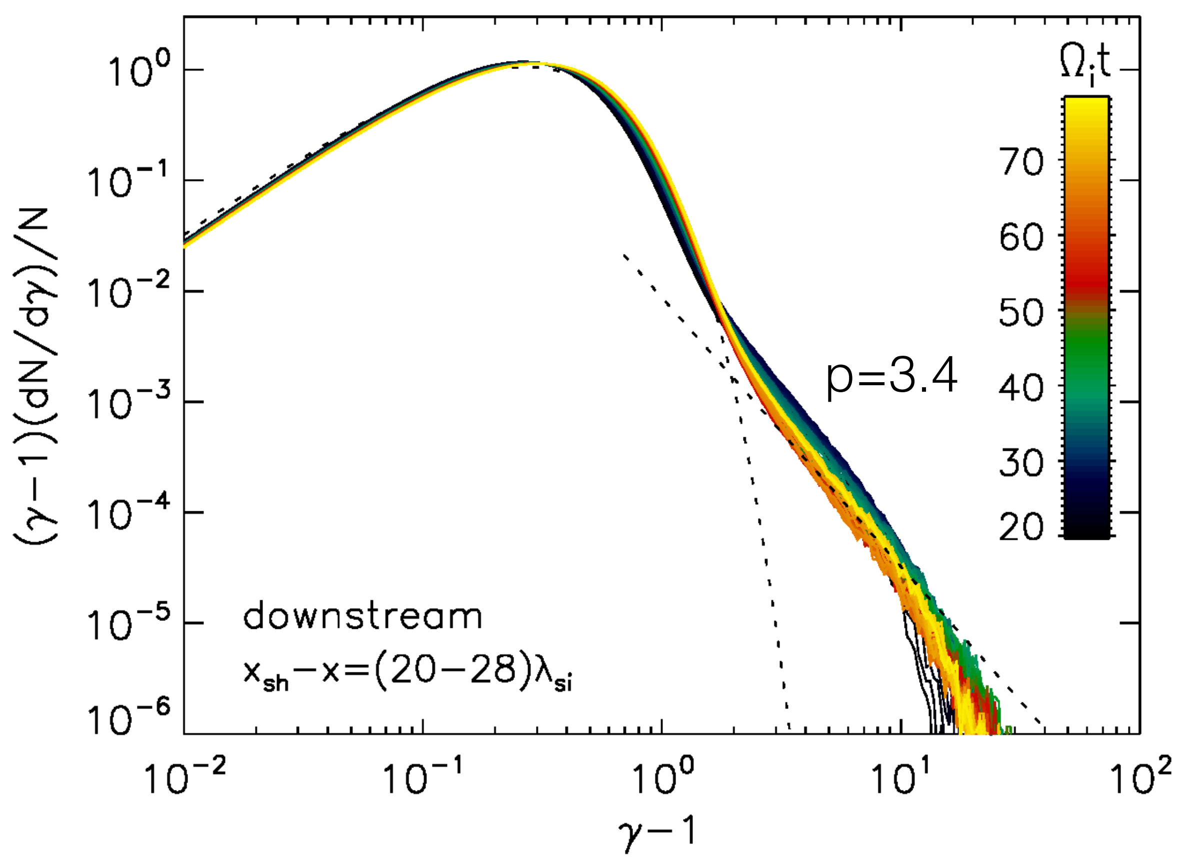




Electron spectra – time evolution (β=5, ϑ_{Bn}=75°)







- substantial increase in non-thermal tail production efficiency coincident with the onset of the shock rippling at $\Omega_{ci}t \approx 25$
- maximum electron energy sufficient for injection to DSA: $\gamma_{inj} \approx 25$ $(p_{inj} \sim 3p_{th,i})$

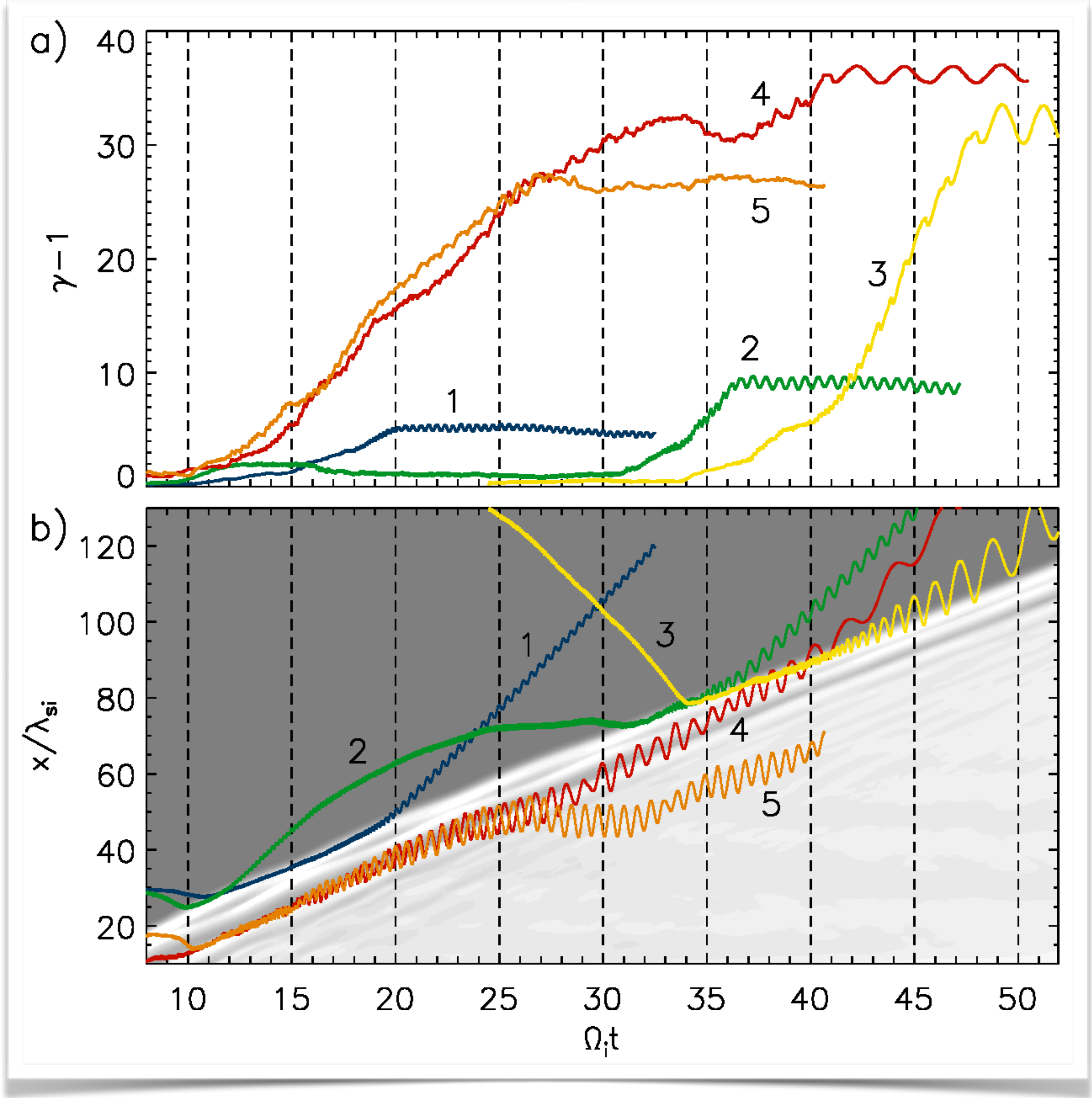
$$\gamma_{max,up} \approx 40 - 60$$

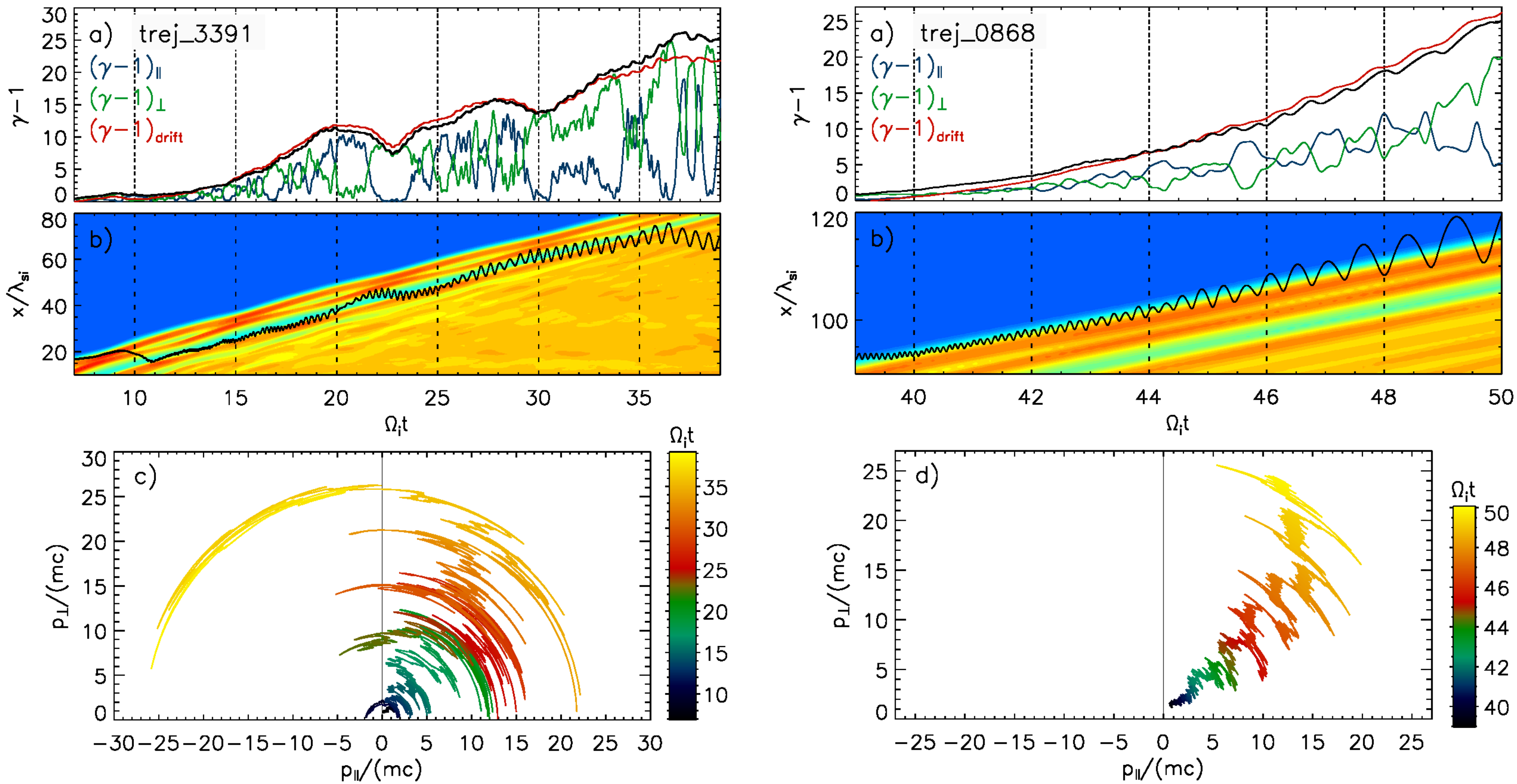
- limited-range power-law spectra downstream

Acceleration processes - typical particle trajectories

- most particles gain their energies in a single interaction with the shock
- acceleration time much longer than predicted by SDA ($\sim 1/\Omega_i$)
- highest-energy electrons produced at the shock front via interactions with long-wave ripples
- bulk of high-energy electrons accelerated deep in the shock transition

(β=5, ϑ_{Bn}=75^o)





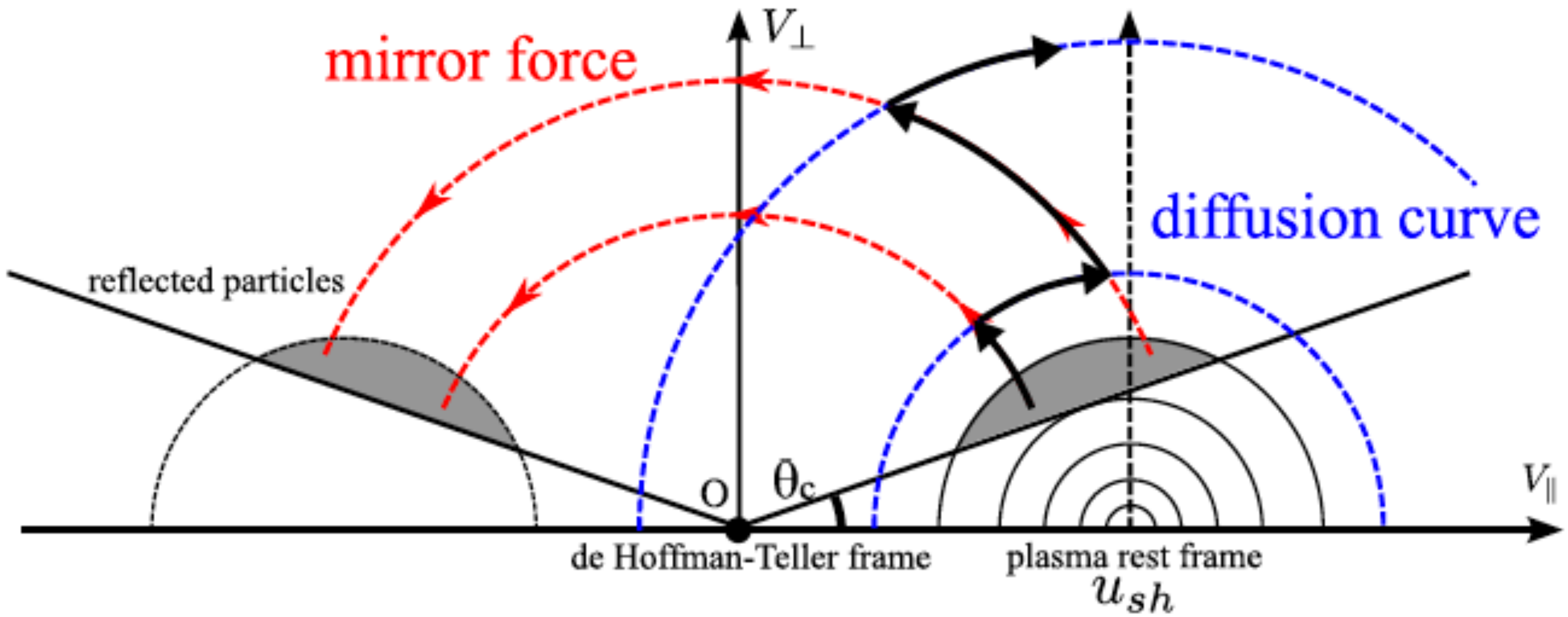
- most accelerations associated with an increase in $p_\perp$
- strong pitch-angle scattering (arcs in $p_\parallel$-$p_\perp$ momentum space)
- energy gain mostly through the drift along motional electric field:

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

➜ Stochastic Shock-Drift Acceleration (SSDA)

Stochastic Shock Drift Acceleration (SSDA)

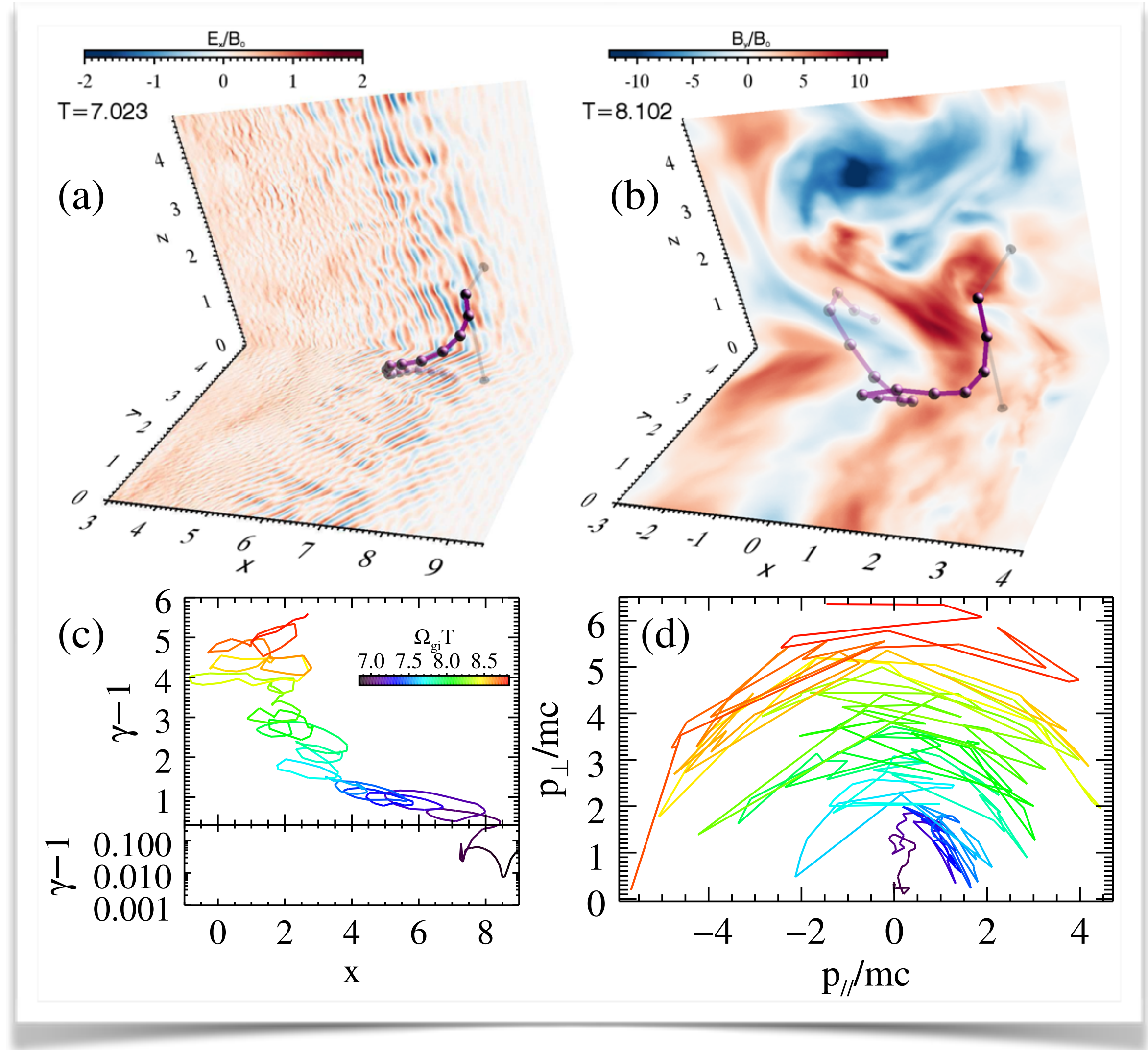
Katou & Amano (2019)



- 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

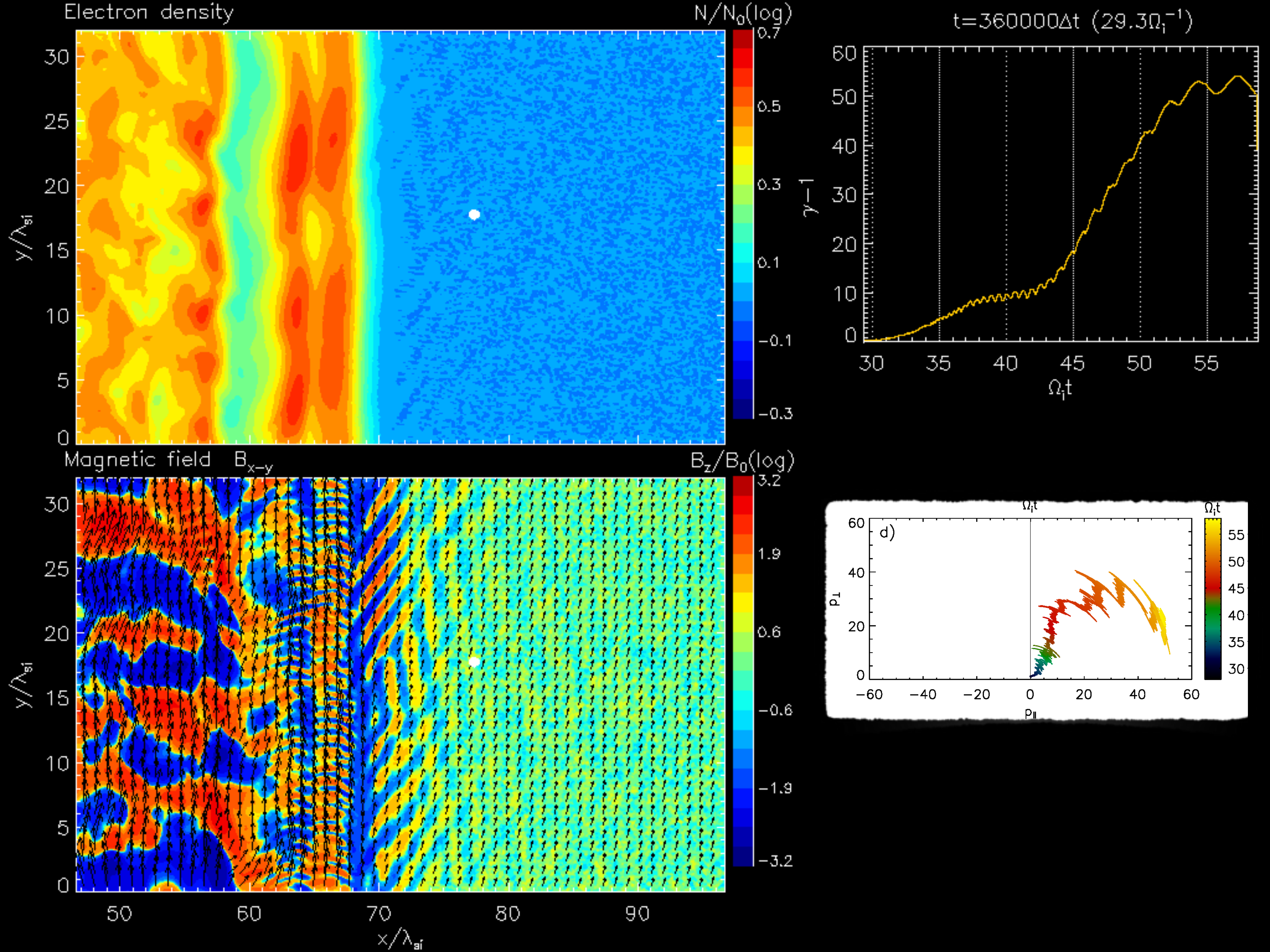
- observational evidence for electron injection via SSDA at the Earth's bow shock recently provided by Magnetospheric Multiscale mission (Oka et al. 2017, Amano et al. 2020) - high-frequency whistlers
- SSDA observed in 3D PIC simulations of quasi-perpendicular high Mach number shocks of young supernova remnants (M_s=22.8, β=1; Matsumoto et al. 2017) - Weibel instability modes at the shock foot
- also observed in hybrid PIC and test-particle studies of solar wind shocks (M_s=6.6, β=1; Trotta & Burgess 2019) - shock-surface fluctuations

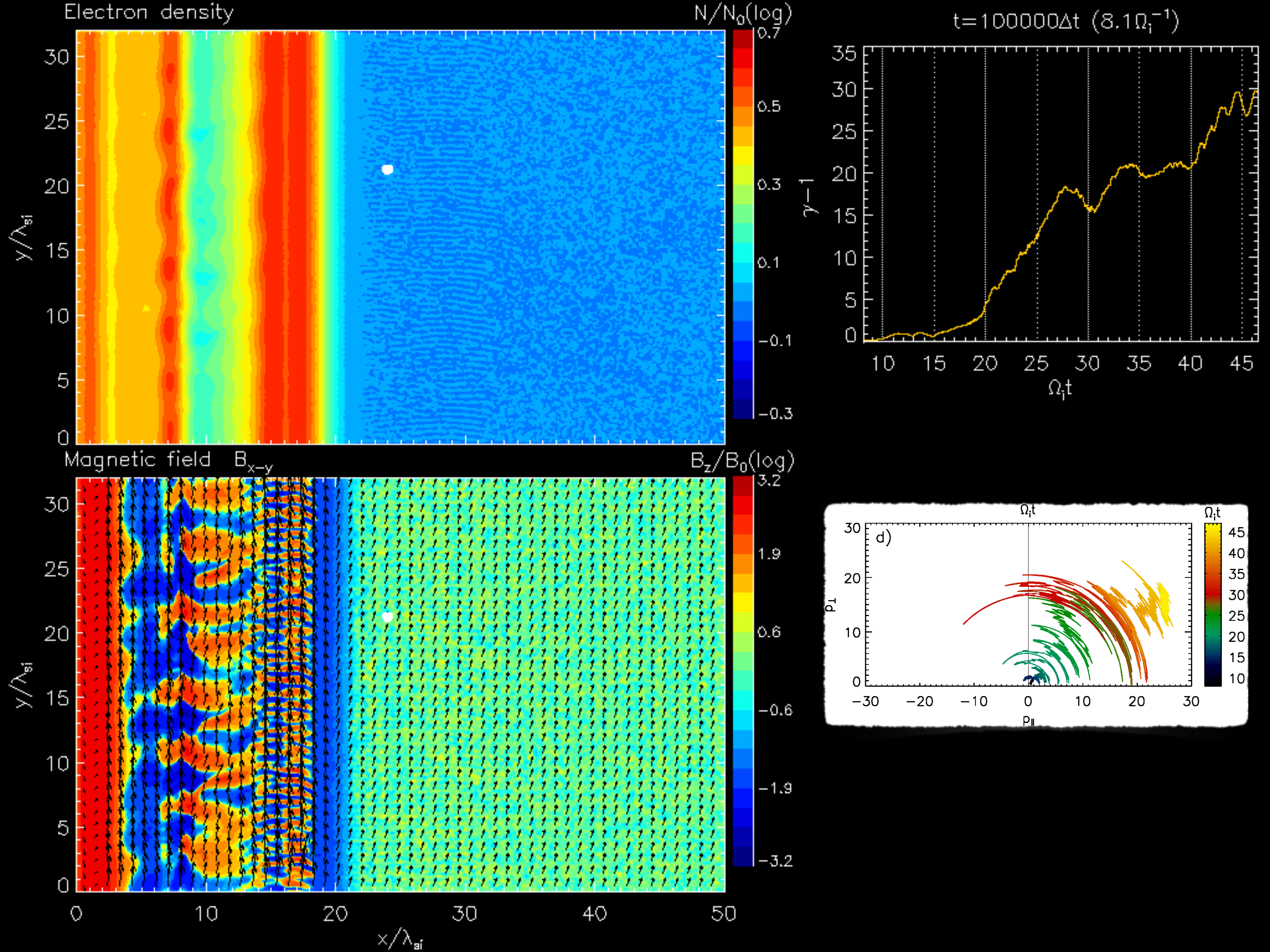


Matsumoto et al. (2017)

3D, M_A=20.8, M_s=22.8, ϑ=74.3^o, m_i/m_e=64, β=1

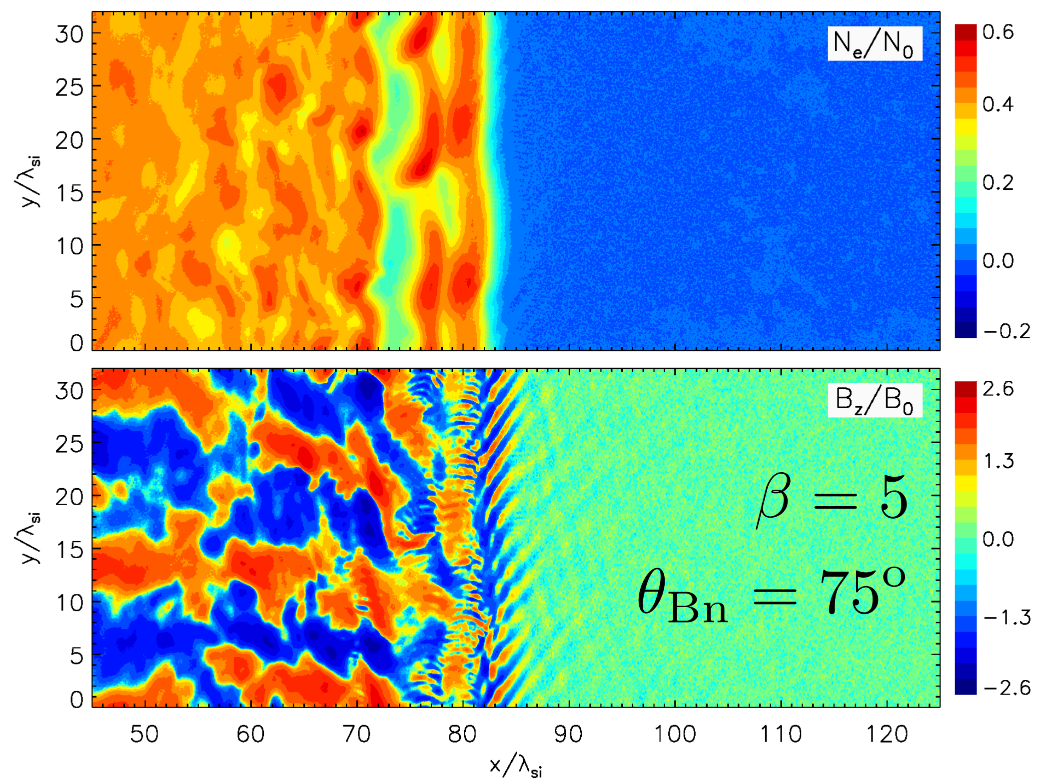
- results for shocks with β=5 and ϑ_{Bn}=75^o show that the electron scattering can be due to multi-scale (broad-band) turbulence in the entire shock transition

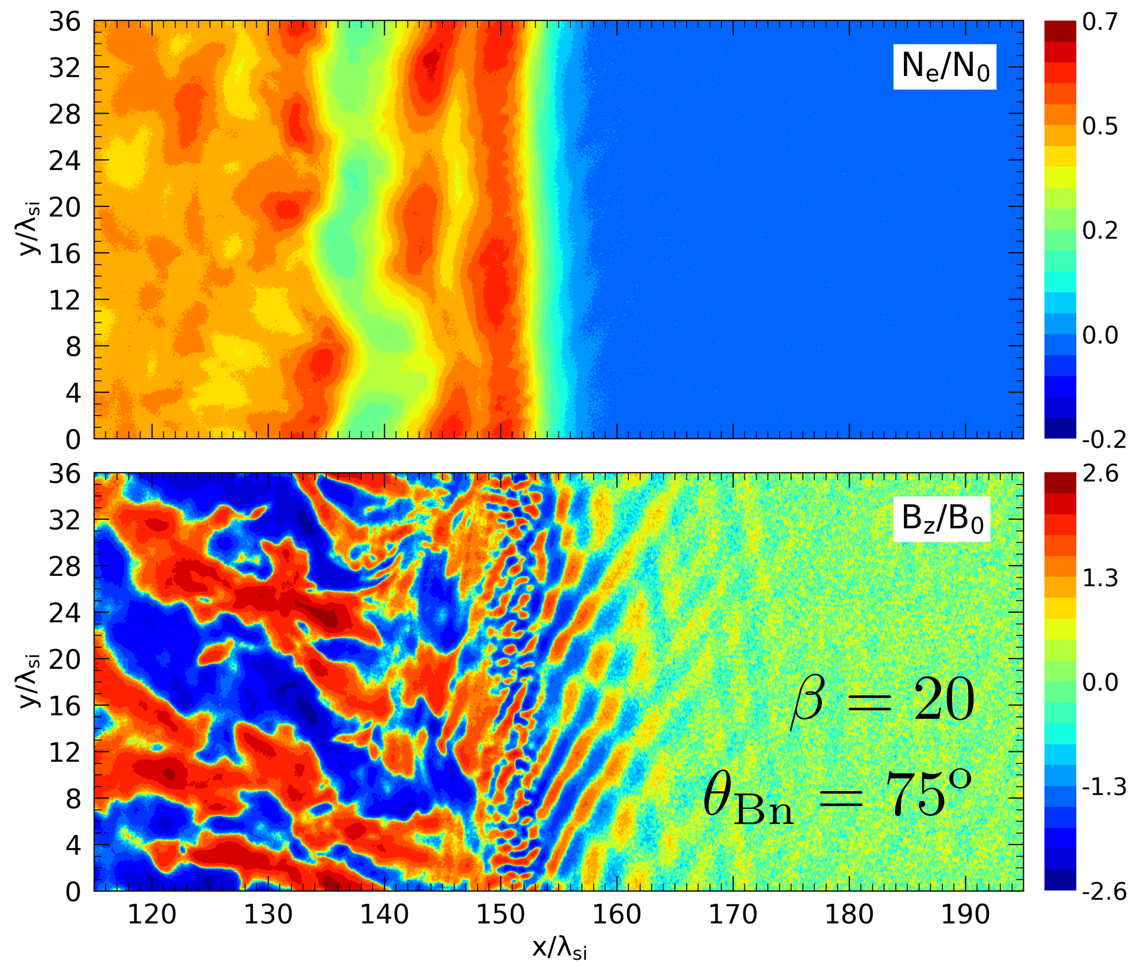

Electron density
N/N0(log)
Magnetic field Bx−y
Bz/B0(log)
y/λsi
x/λsi
t=360000Δt (29.3Ωi−1)
γ−1
Ωit
d)
p⊥
p∥
Ωit

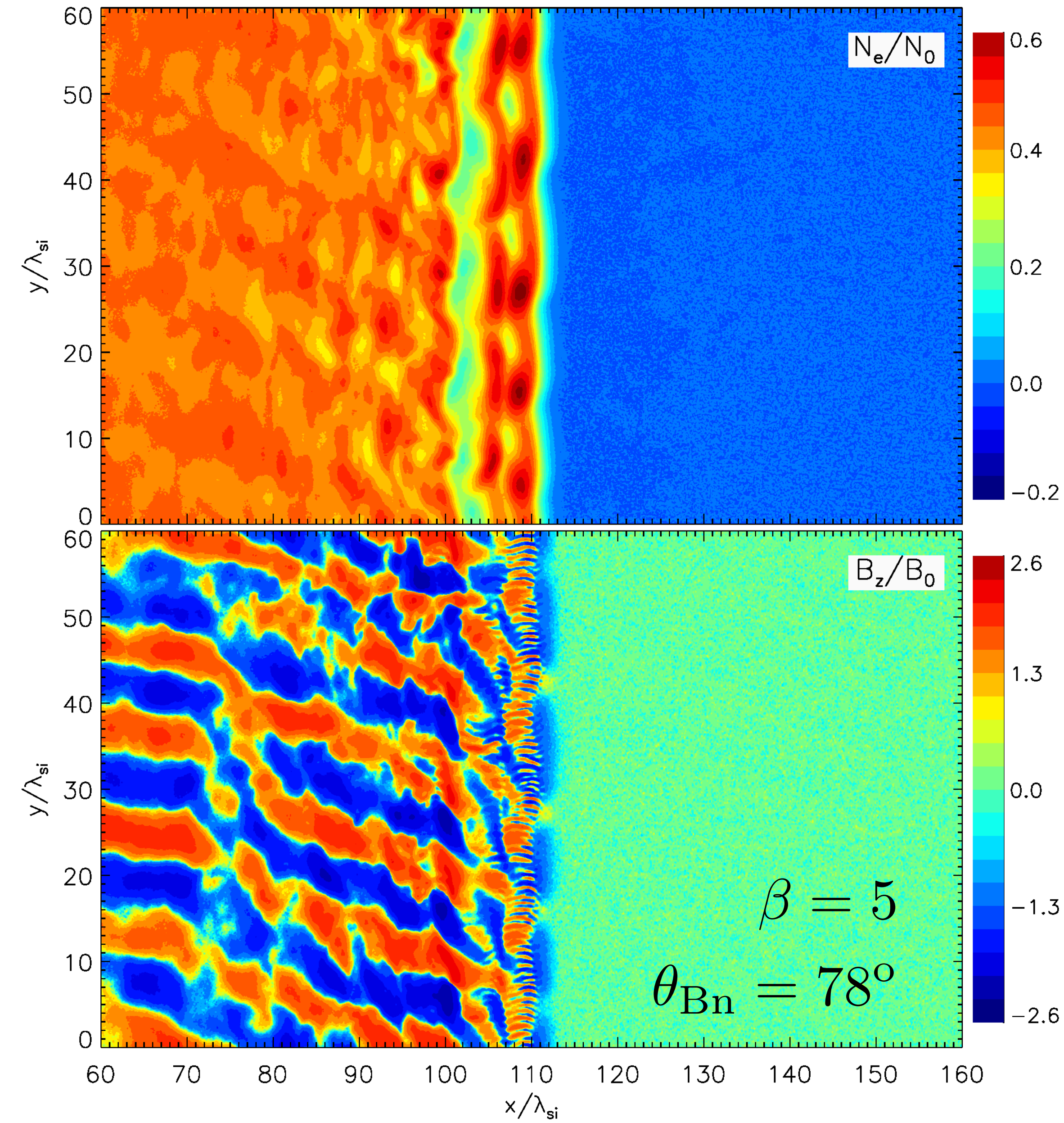


Electron density
N/N0(log)
y/λsi
Magnetic field Bx−y
Bz/B0(log)
x/λsi
t=100000Δt (8.1Ωi−1)
γ−1
Ωit
d)
p⊥
p∥
Ωit

Parameter dependence - multi-scale turbulence

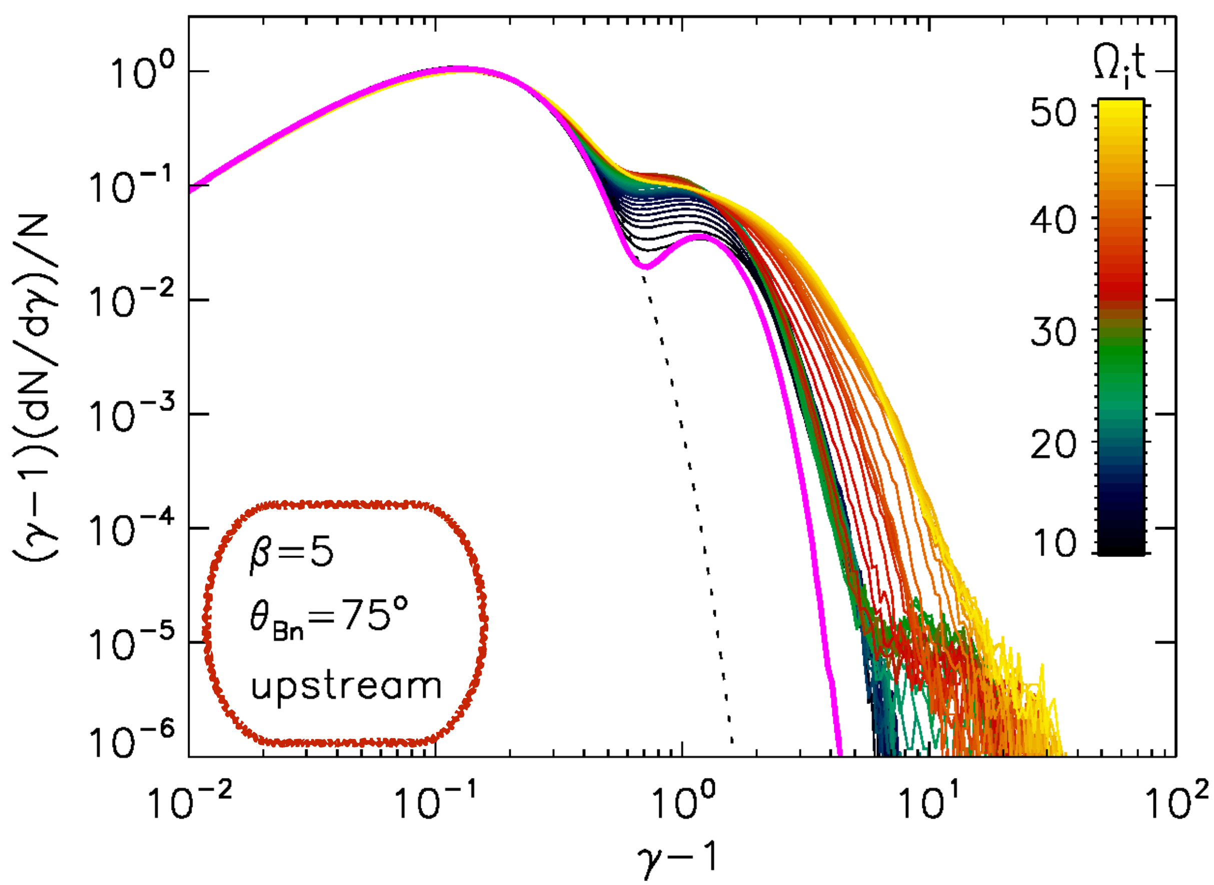


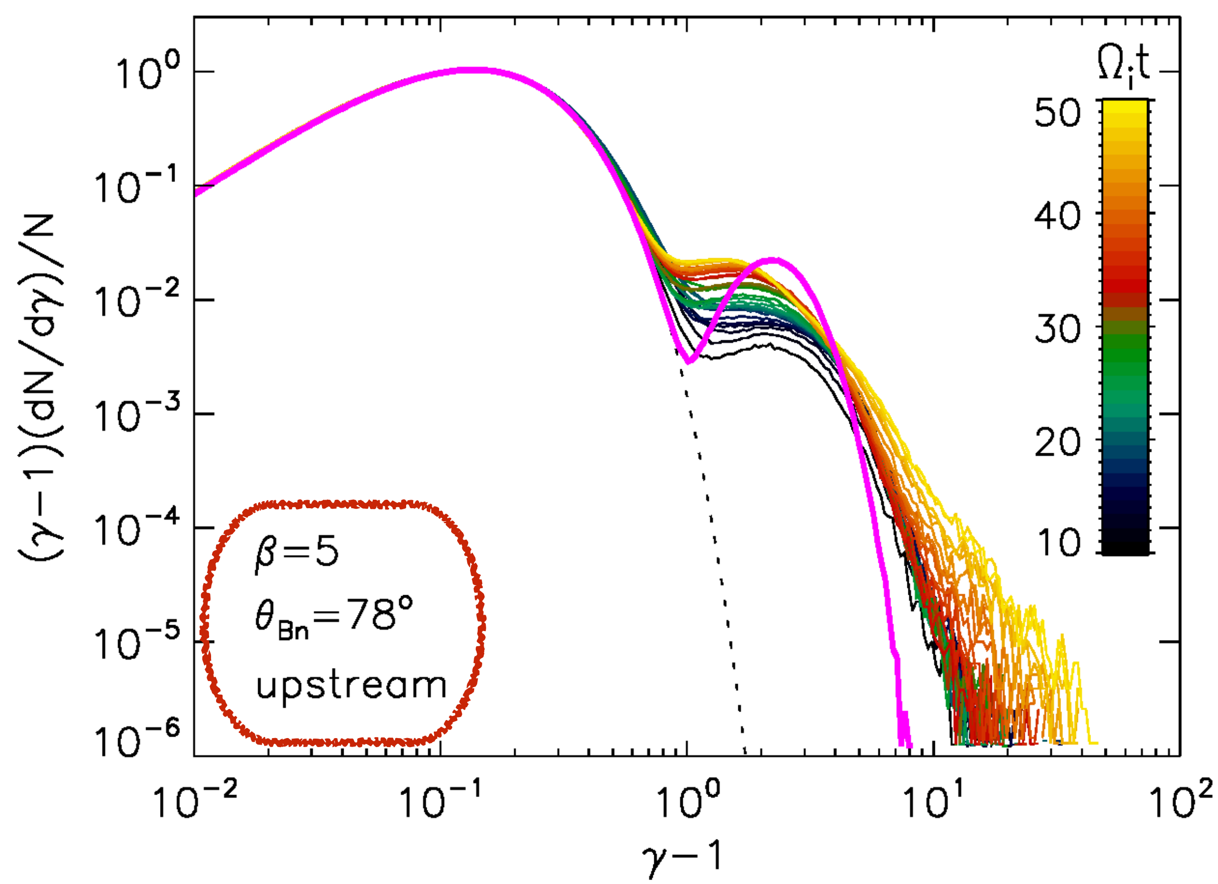


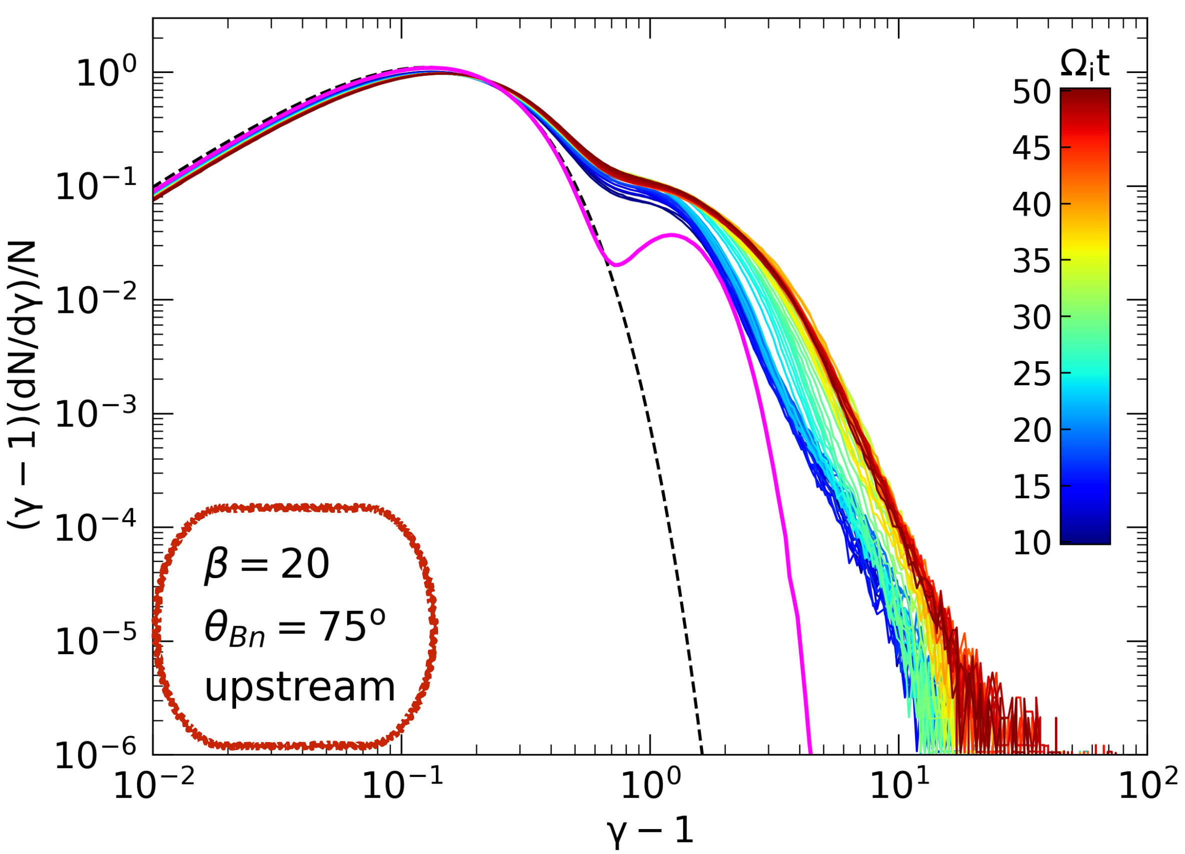


- features of multi-scale turbulence similar in all cases
- longer-wavelength ripples with growing β
- absence of EFI waves for higher θ_{Bn}
- stronger and longer-wavelength EFI modes with increasing β (after amplification in rippled shocks)

Parameter dependence - upstream spectra



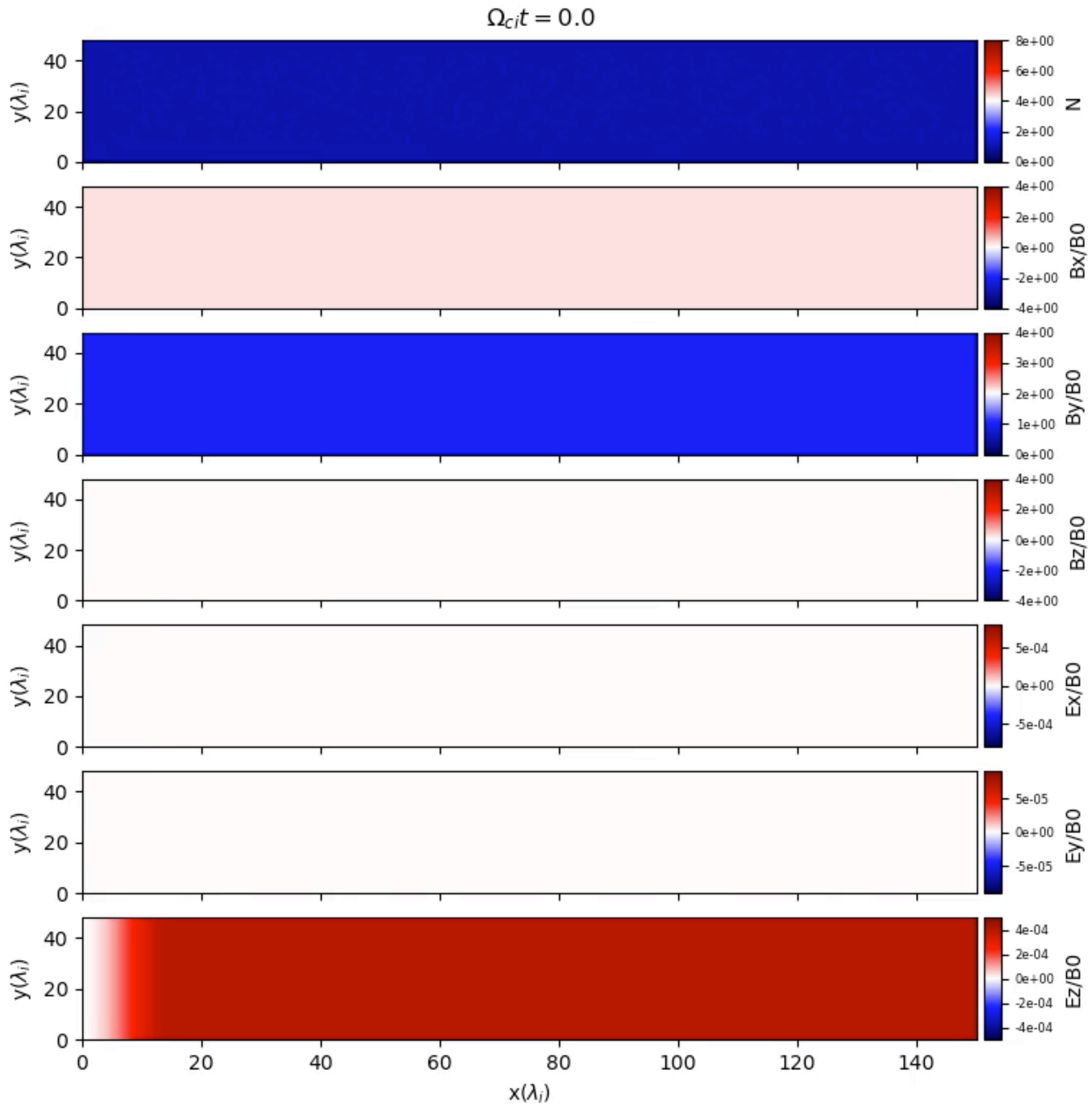




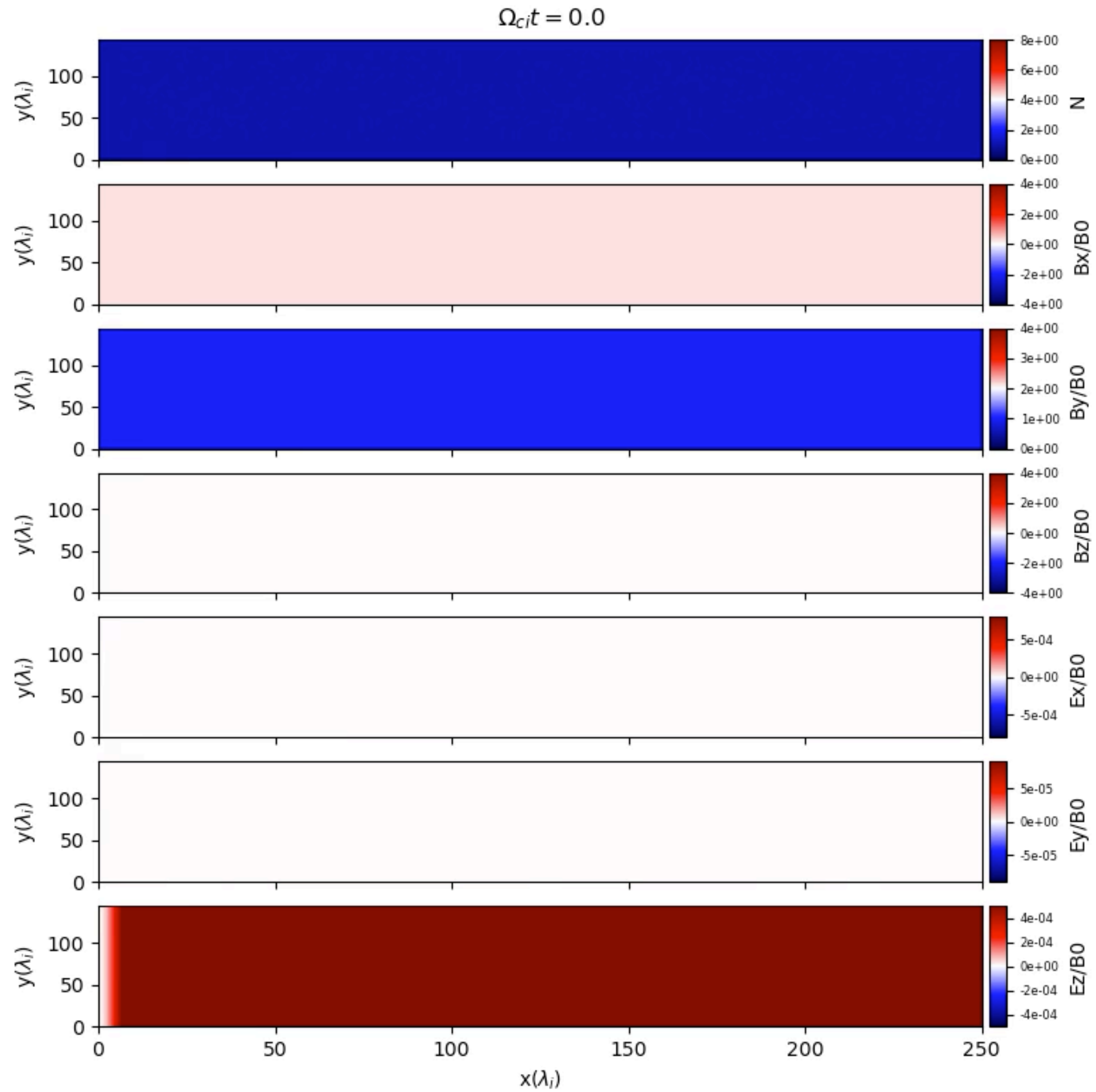
- SSDA in rippled shocks provides electron acceleration also for higher β=10-30 (up to β=100 - Ha et al. 2021)
- upstream spectra depend weakly on β
- maximum energies γ_{max}~30-40 > γ_{inj}
- multiple-cycle SDA is not critical for injection but may contribute to electron acceleration in high-β plasmas

Hybrid-kinetic simulations of M_s=3 shocks

(β=5, ϑ_{Bn}=75°)



(β=50, ϑ_{Bn}=75°)



See also Stella Boula's poster (P11)

Summary and conclusions

- kinetic modeling of particle acceleration at low Mach number shocks in high-beta plasmas requires multi-dimensional and large-scale effects to be taken into account
- the presence of multi-scale turbulence, including ion-scale shock rippling modes, is critical for efficient electron acceleration
- electrons can be injected to DSA at quasi-perpendicular sub-luminal ICM shocks that develop multi-scale turbulence
- electron injection proceeds mainly through the stochastic SDA process, effects of multi-SDA cycles can also occur
- pre-acceleration to high energies feasible, at which DSA starts to operate in the presence of long-wave (MHD) upstream turbulence

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