Electron pre-acceleration through Stochastic Shock Drift Acceleration at shocks in merging galaxy clusters

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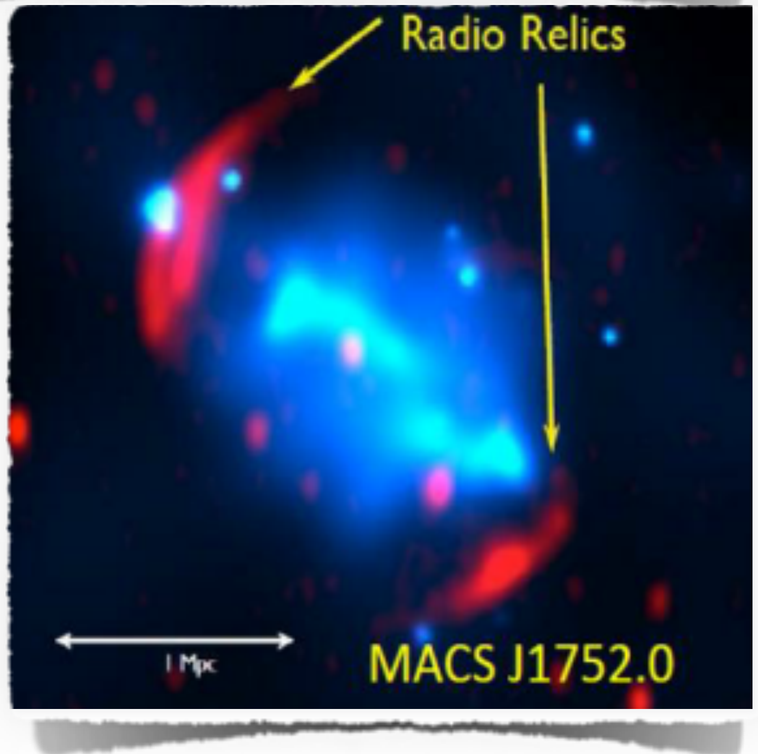
Introduction

- 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: $M_A = \frac{v_{sh}}{v_A}$

Sonic Mach number: $M_s = \frac{v_{sh}}{c_s}$

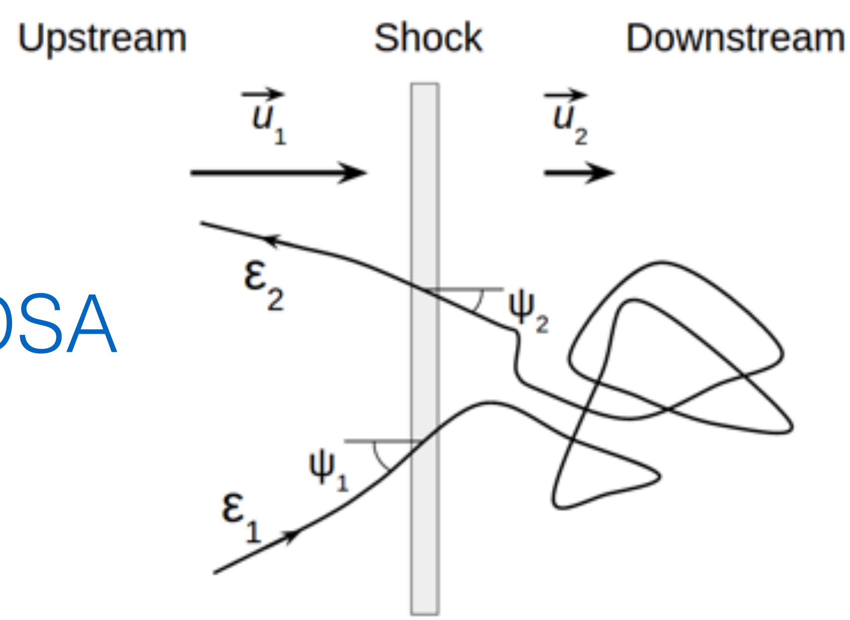
Plasma beta: $\beta = p_{th}/p_{mag}$

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

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

Particle injection (pre-acceleration) to DSA

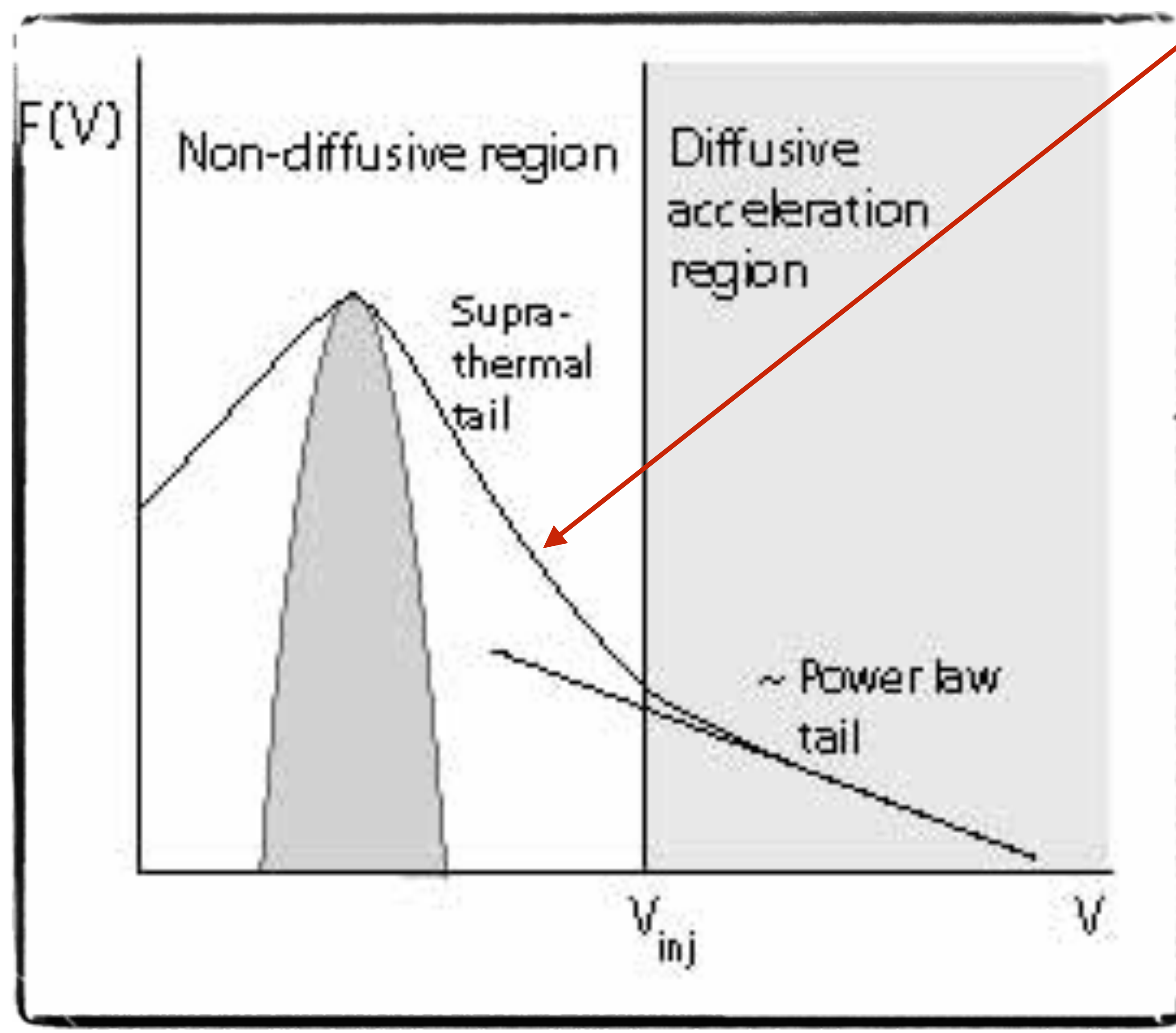
DSA



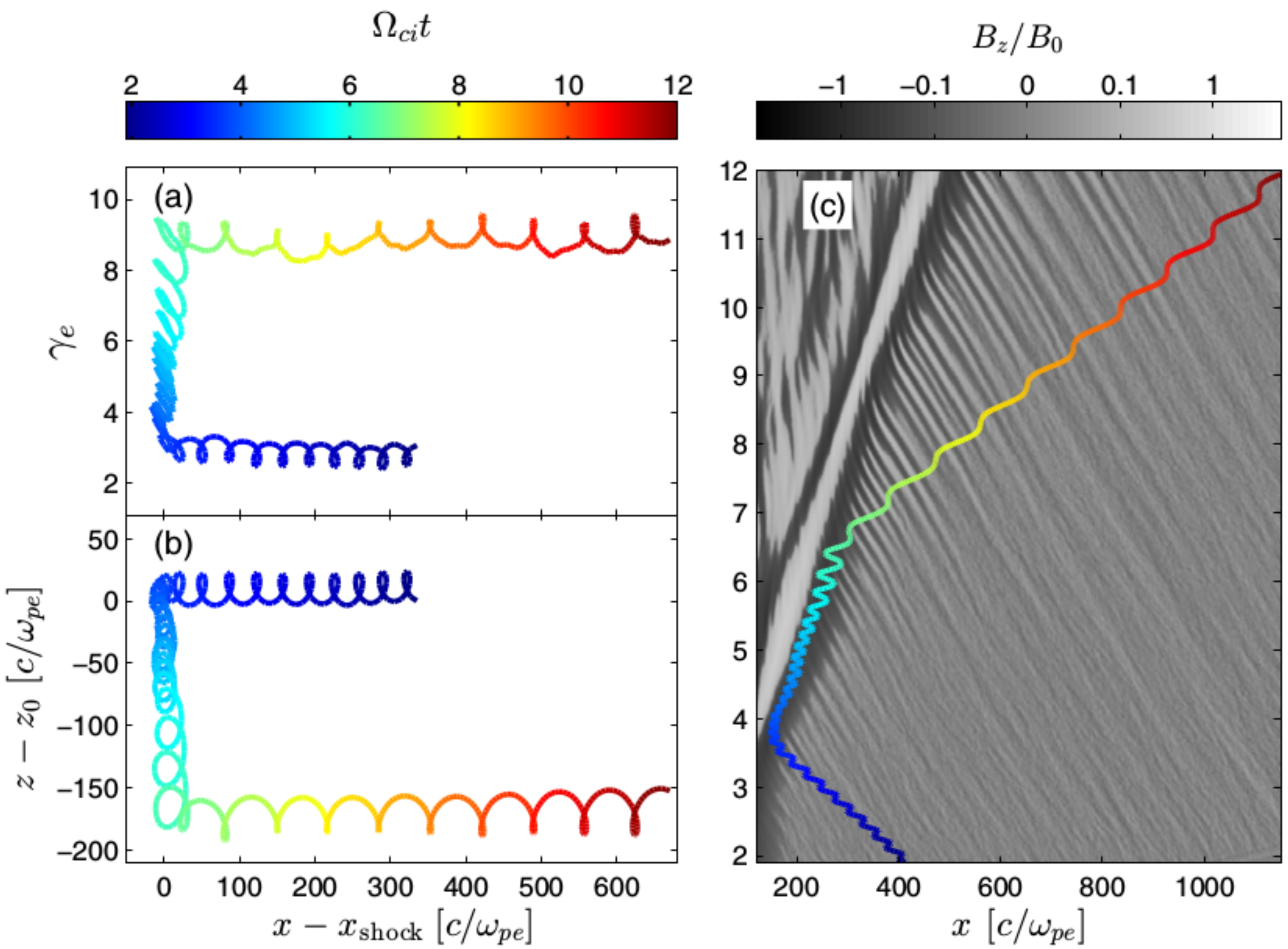
$d_{sh} \sim (1\text{-}100)\ \lambda_{gi}$

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

injection



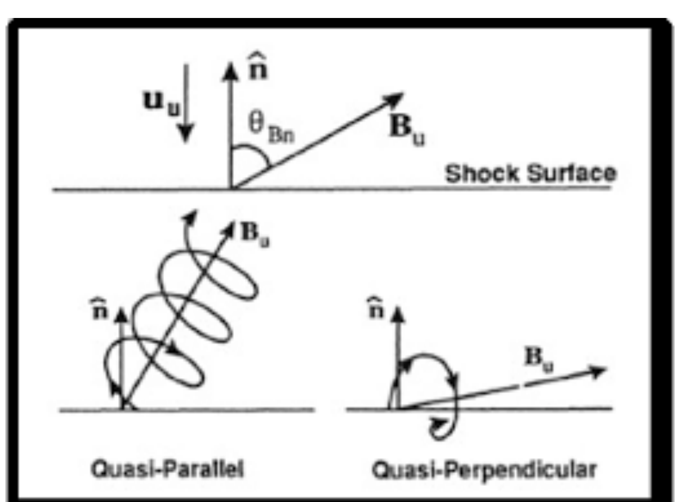
Electron injection at shocks in high beta plasmas: Shock Drift Acceleration (SDA)



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:

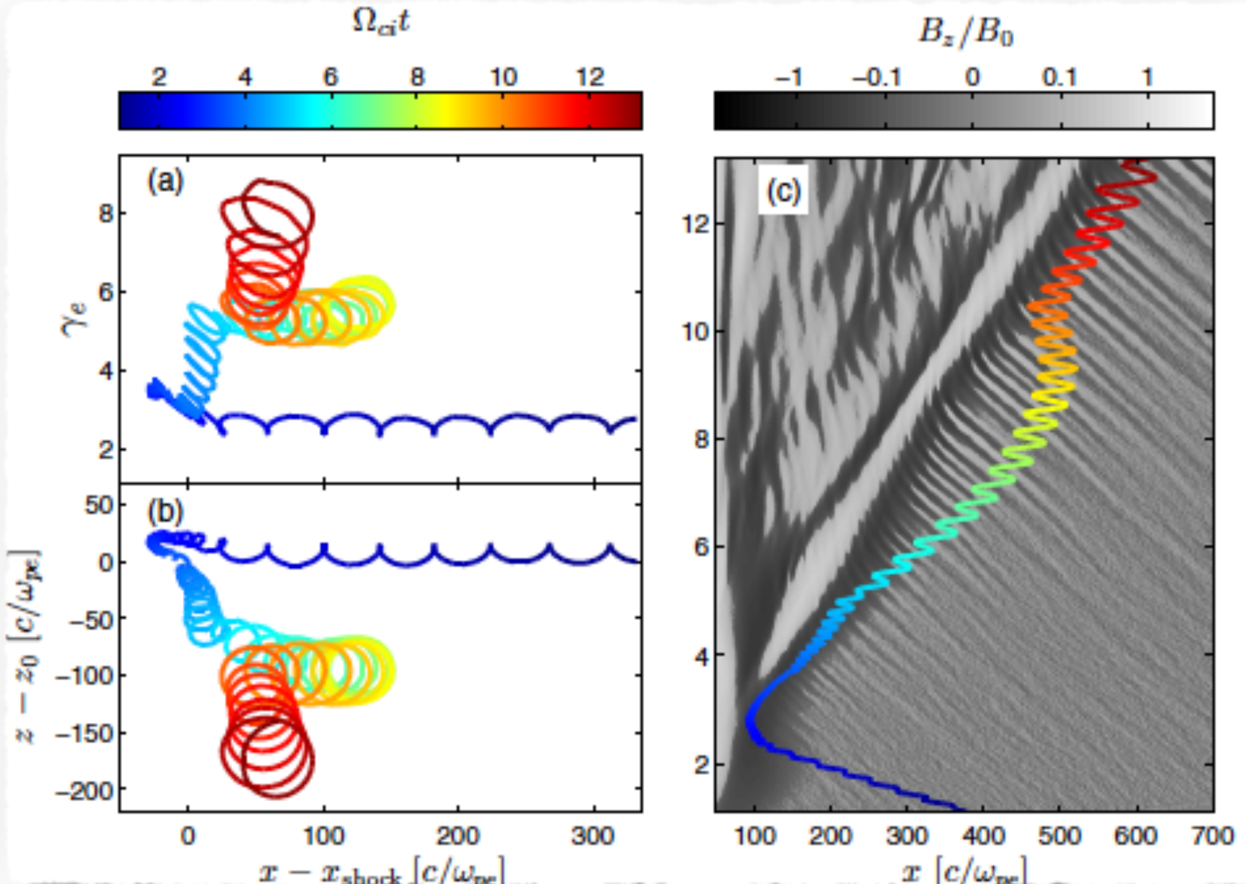
$$\Delta\gamma_{\rm SDA} = \frac{-e}{m_e c^2}\int E_z\, dz$$



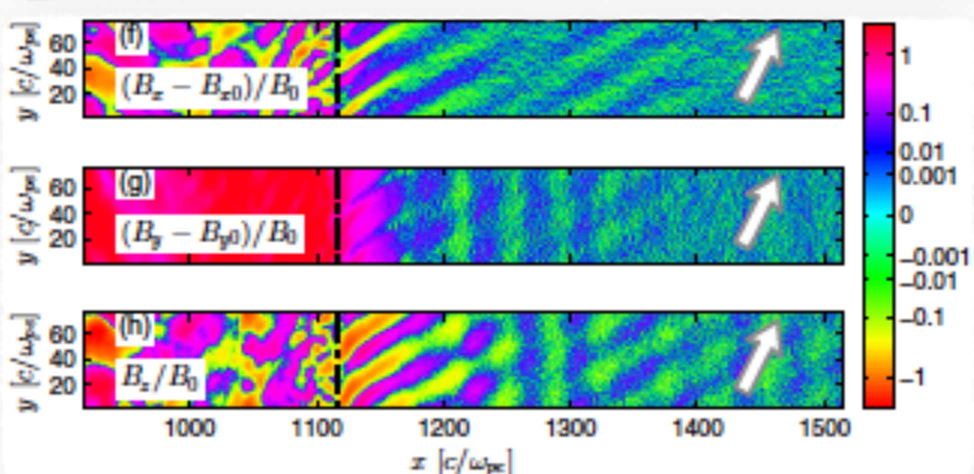
de Hoffman-Teller velocity:

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

Previous work: multiple Shock Drift Acceleration cycles at quasi-perpendicular shocks

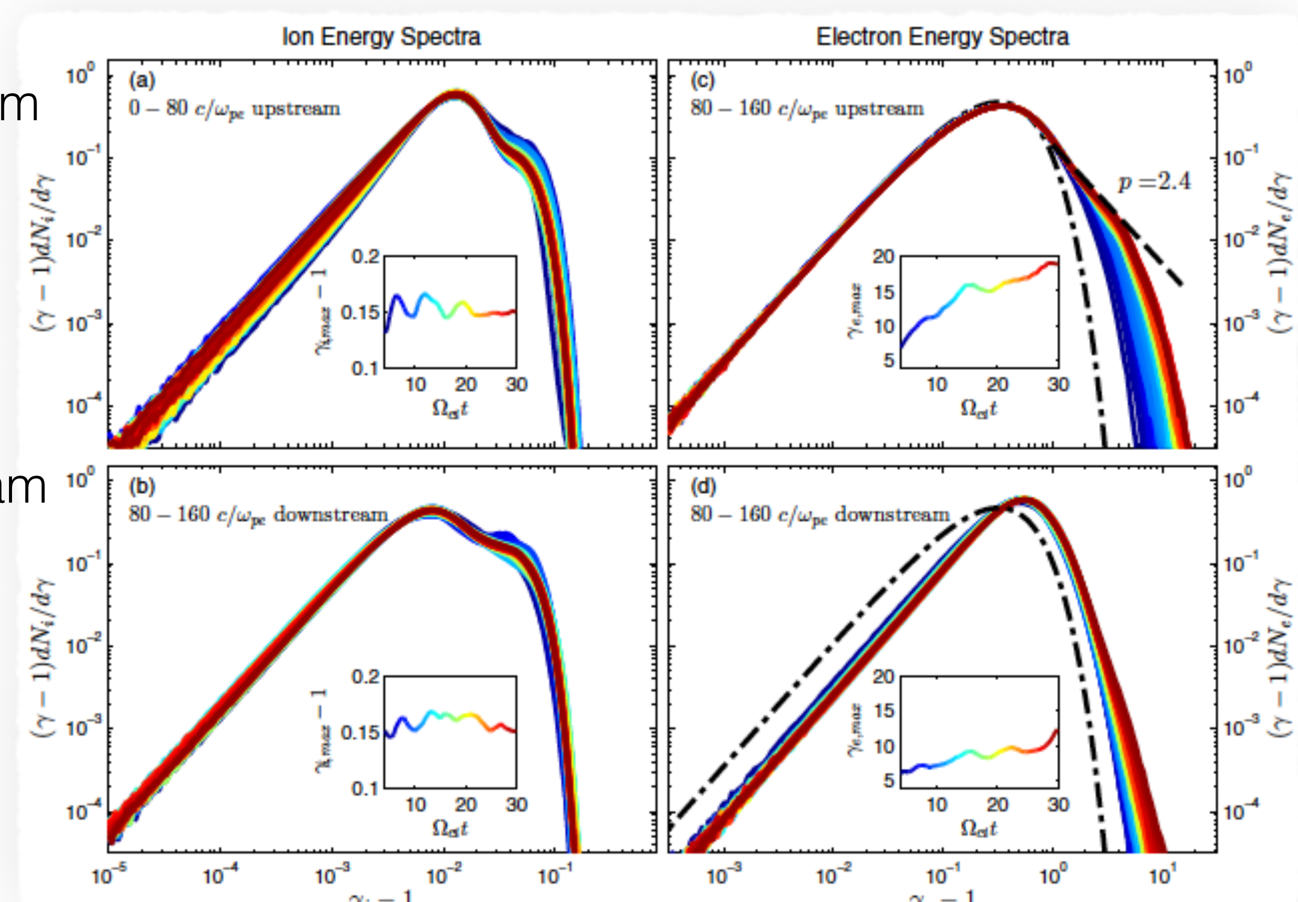


- SDA-reflected electrons scattered back towards shock by upstream self-generated waves - DSA-like process
- formation of upstream power-law spectra (and steep downstream spectra)
- more effective at high β
- $\gamma_{max} \ll \gamma_{inj}$?



upstream

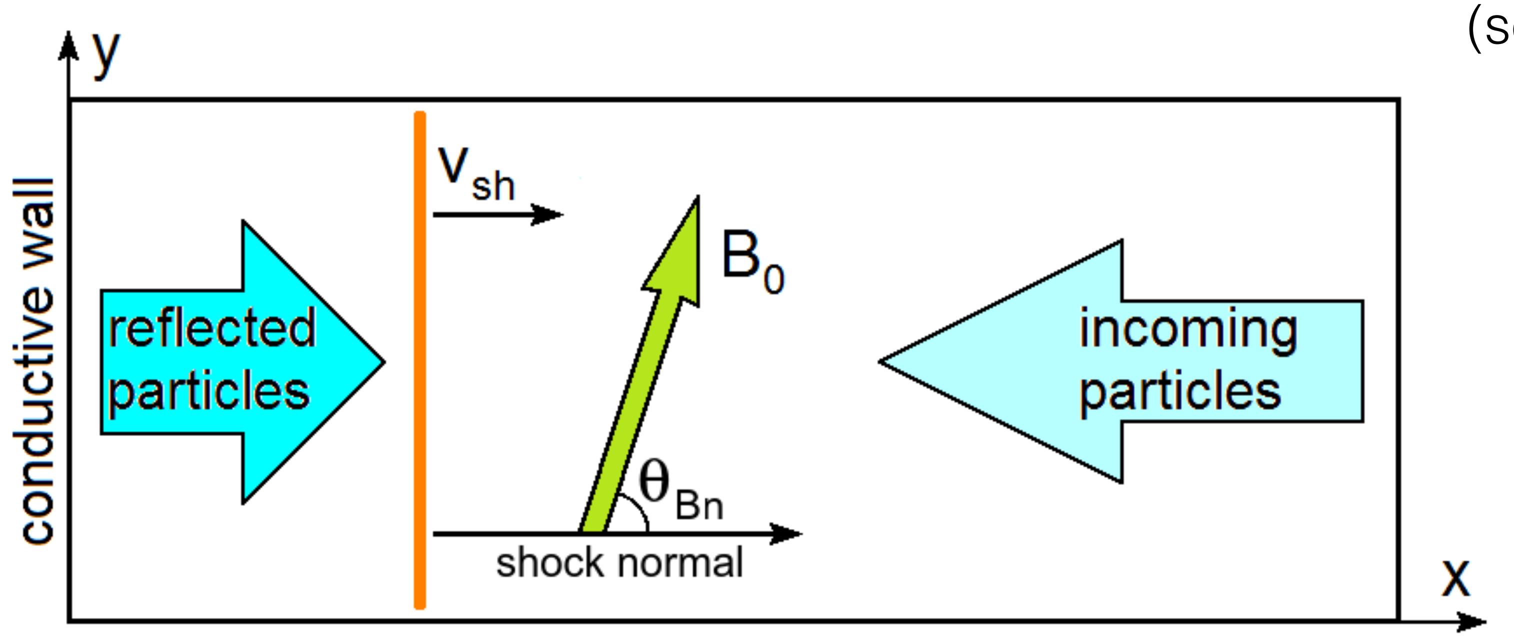
downstream



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

This work: investigate the effects of the shock rippling on electron pre-acceleration

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, 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:

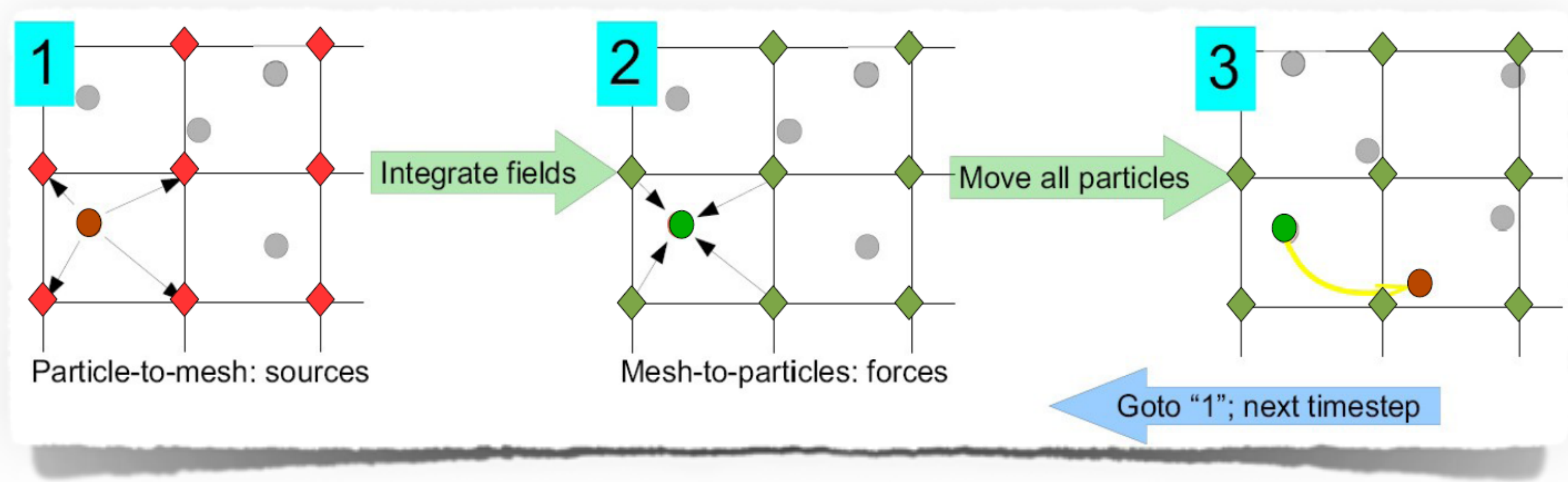
$$v_t \gtrsim v_{\rm th,e} \; (v_t = u_{\rm sh}^{\rm up} / \cos\theta_{\rm Bn})$$

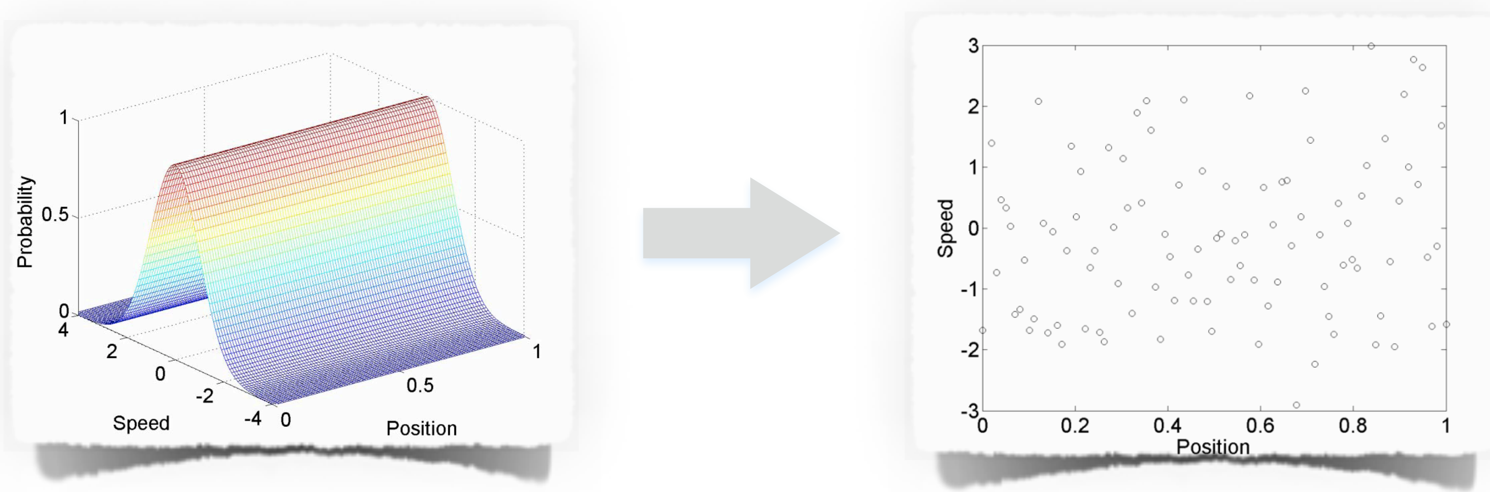
$$v_t \approx 1.5 v_{\rm th,e} \; (\theta_{\rm Bn} = 75^o)$$
$$v_t \approx 1.9 v_{\rm th,e} \; (\theta_{\rm Bn} = 78^o)$$

Method of Particle-In-Cell Simulations

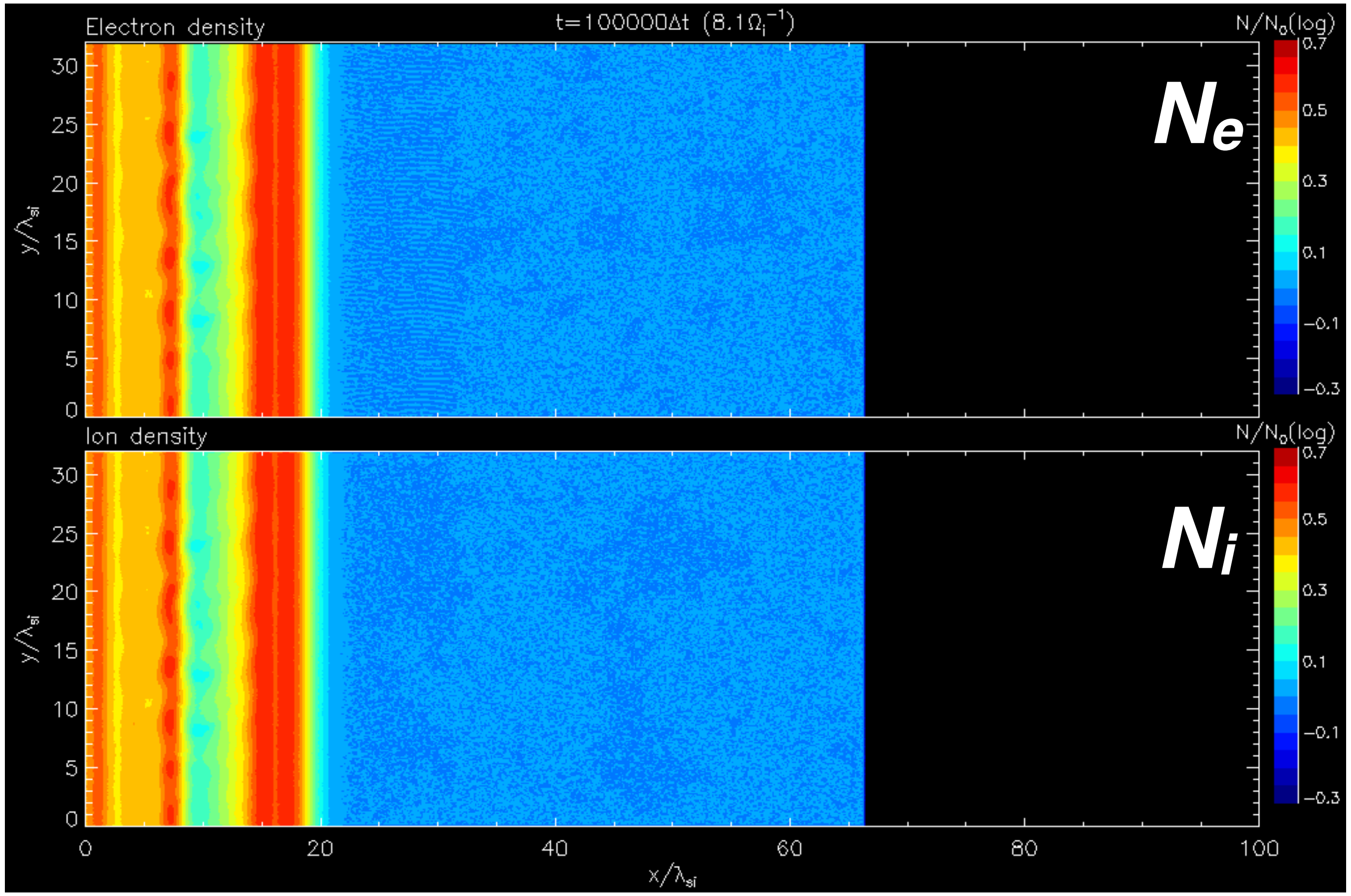
- Fully self-consistent description of collisionless plasma:
  - Vlasov equation (kinetic theory; time evolution of particle distribution function *f*(***x***,***v***,*t*) in phase-space) + Maxwell's equations

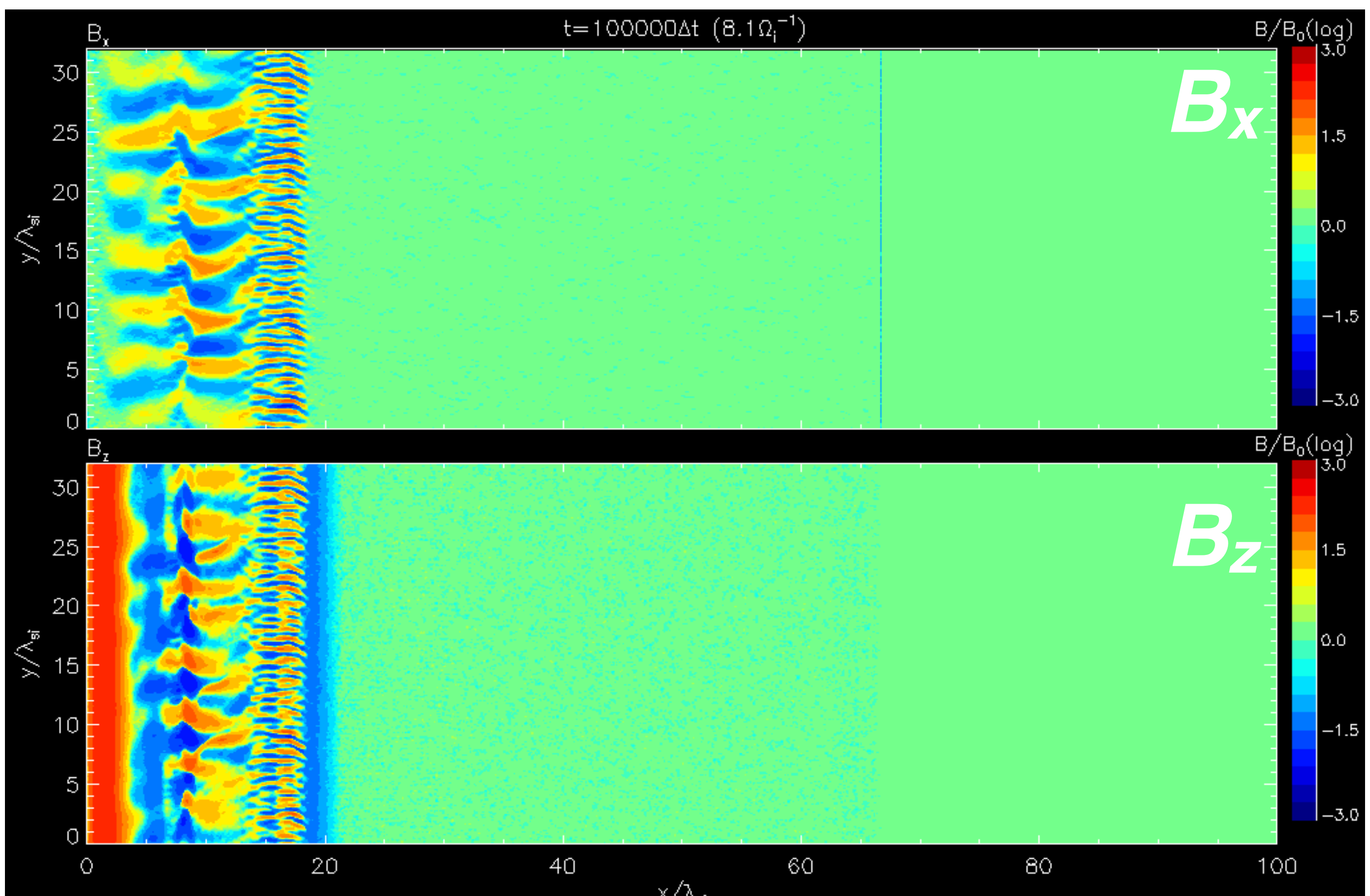
- Particle-In-Cell modeling - an *ab-initio* method of Vlasov equation solution through:
  - integration of Maxwell's equations on a numerical grid
  - integration of relativistic particle equations of motion in collective self-consistent EM field





Particle distribution function represented by macroparticles on a numerical grid.
(Macroparticles represent a small volume of particle phase-space; equations of motion as for realistic particles)



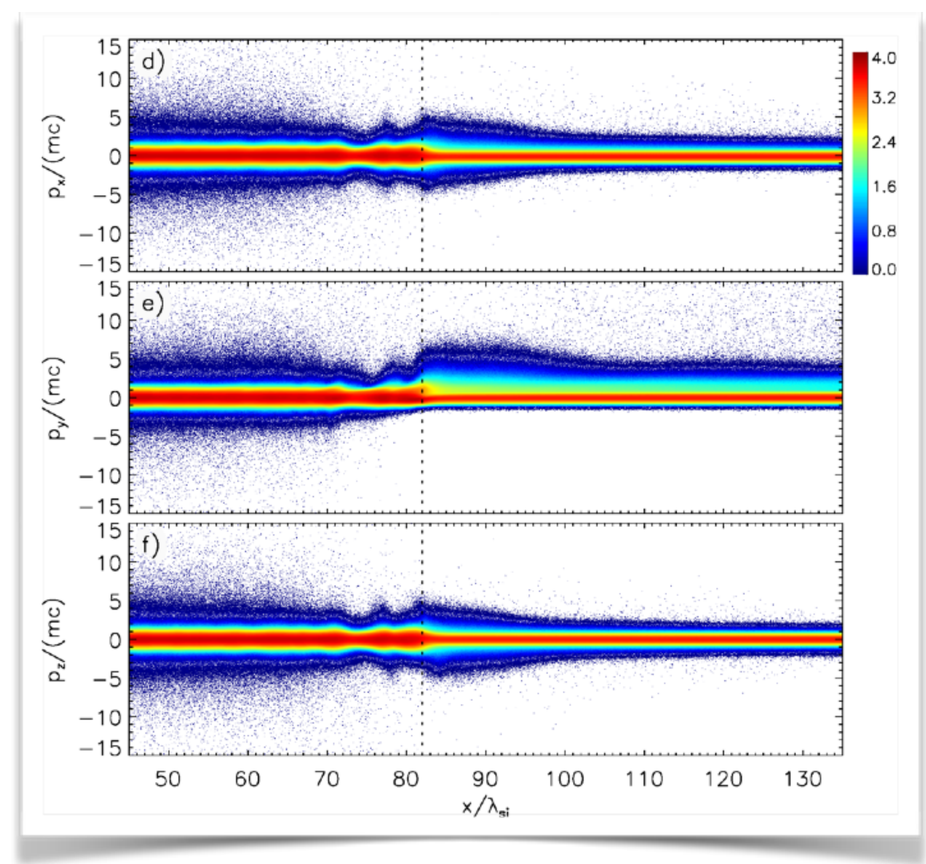


Global shock structure:

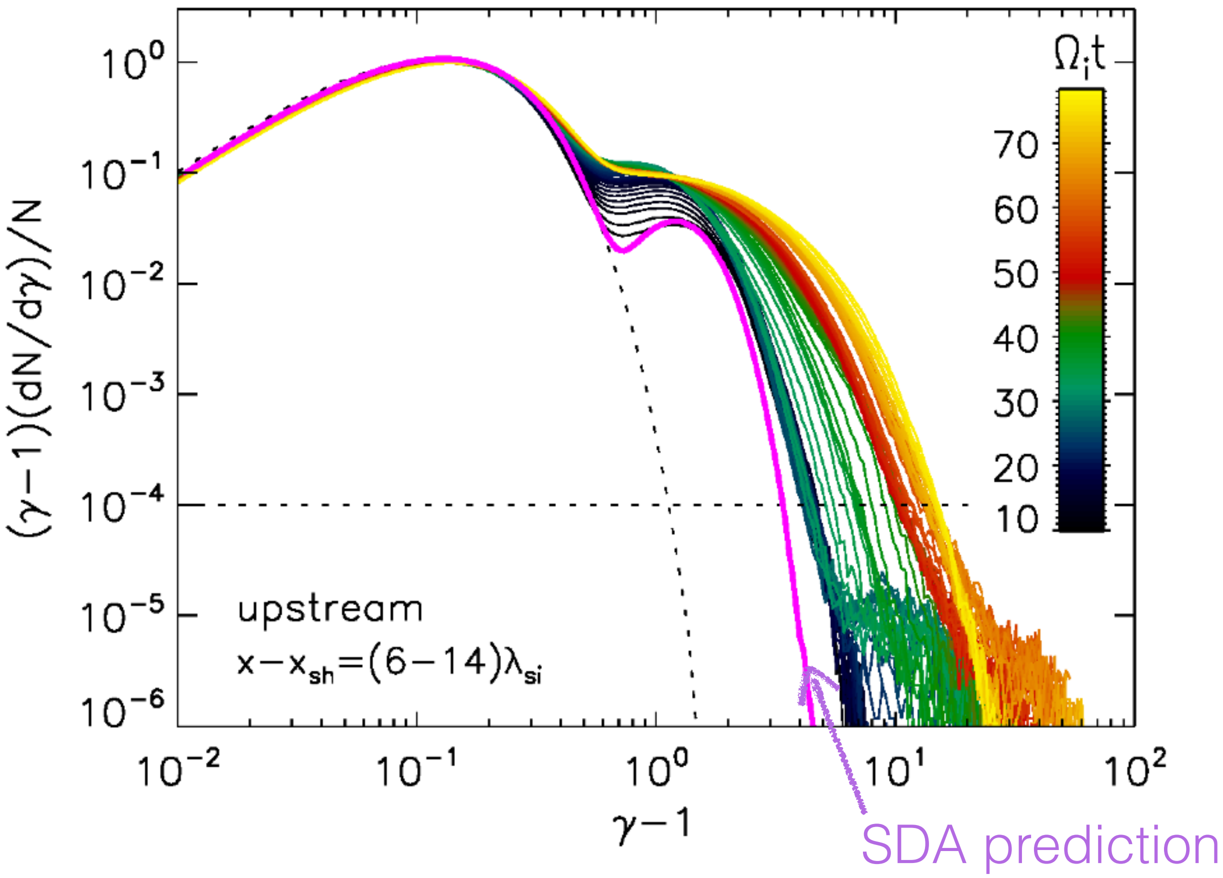
multi-scale turbulence

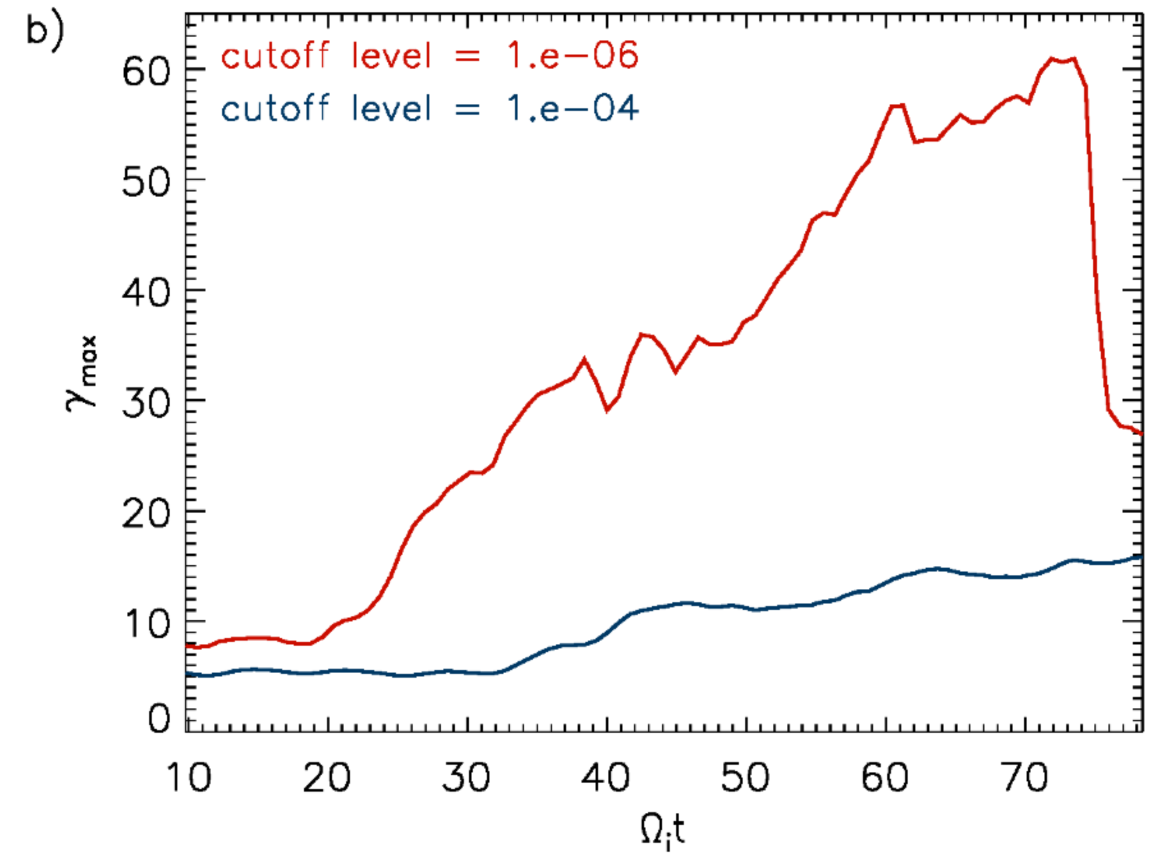
(β=5, ϑ_{Bn}=75^o)

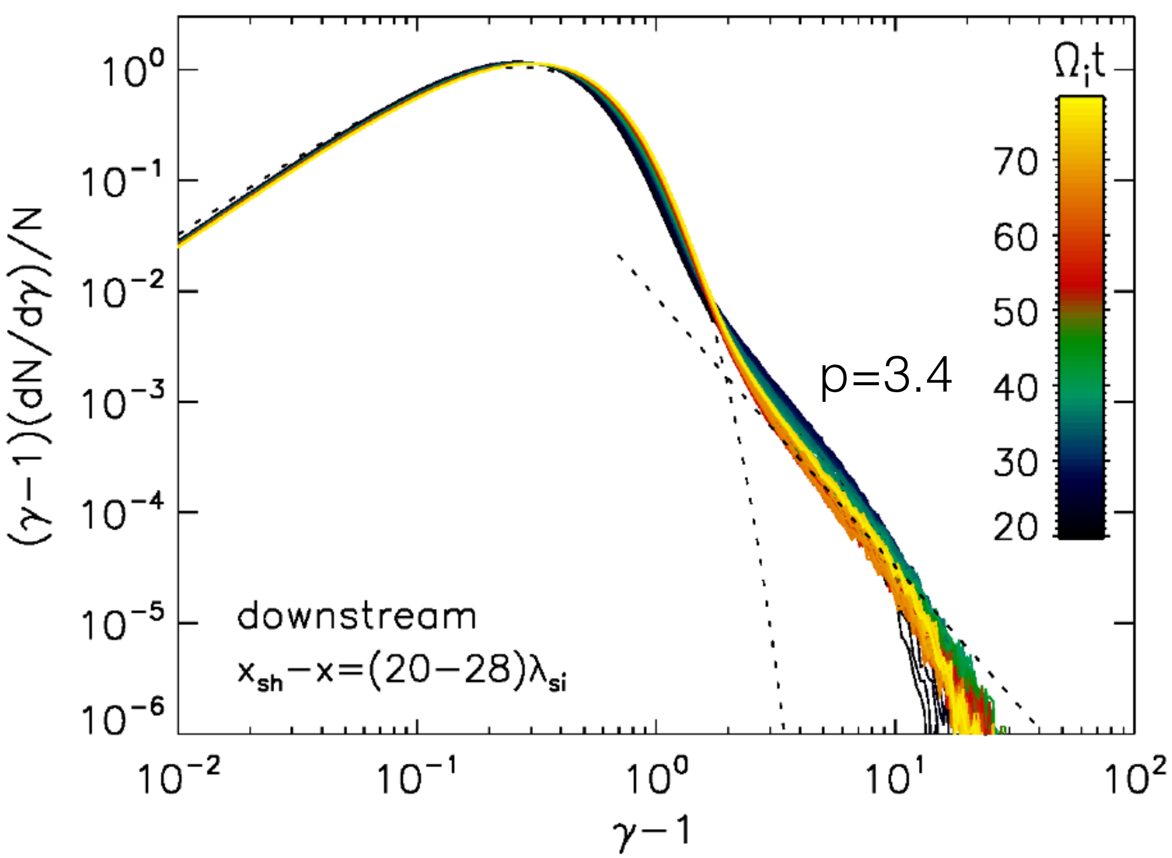
- rippling in the shock transition on different scales (overshoot-undershoot-2nd overshoot)
  - AIC and mirror modes
- short-scale whistler waves in the overshoot
- oblique and perpendicular modes of the electron firehose instability in the upstream, enhanced and modulated by the ripples



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







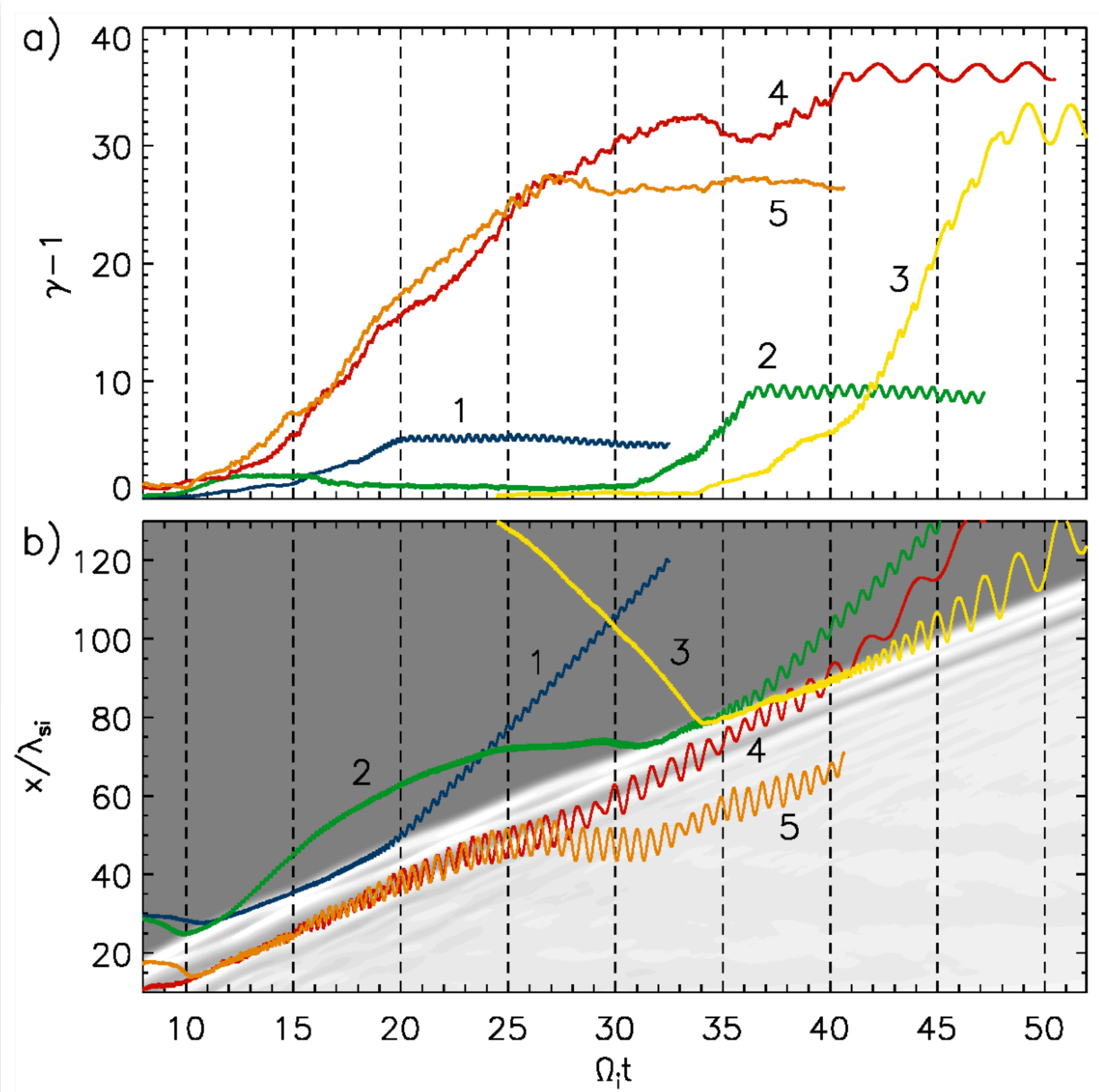
- substantial increase in non-thermal tail production efficiency coincident with the onset of the shock rippling at $\Omega_{ci}t \approx 25$
- maximum electron energy sufficient for injection to DSA: $\gamma_{\rm inj} \approx 25$ $(p_{\rm inj} \sim 3p_{\rm th,i})$

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

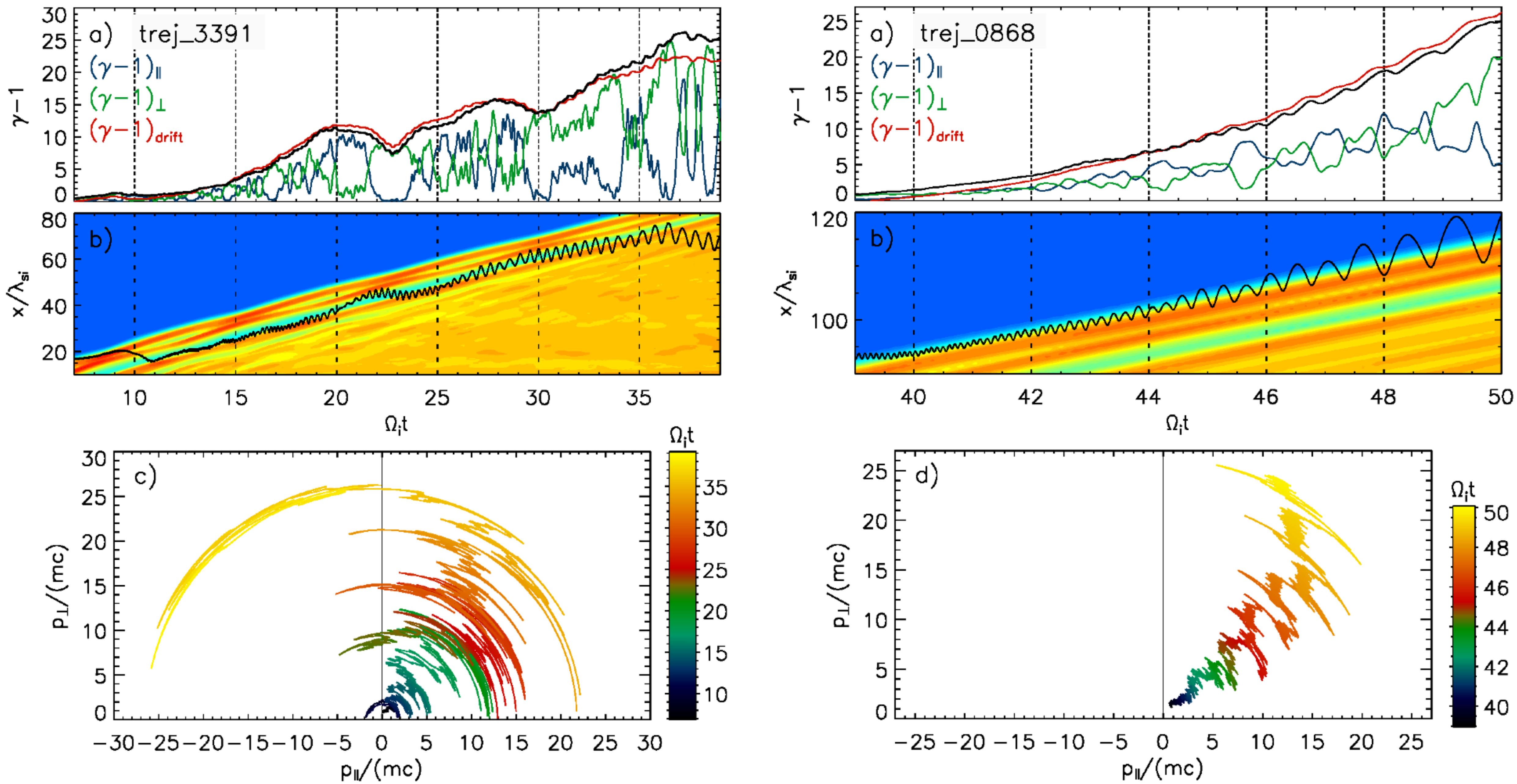
- limited-range power-law spectra downstream

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°)



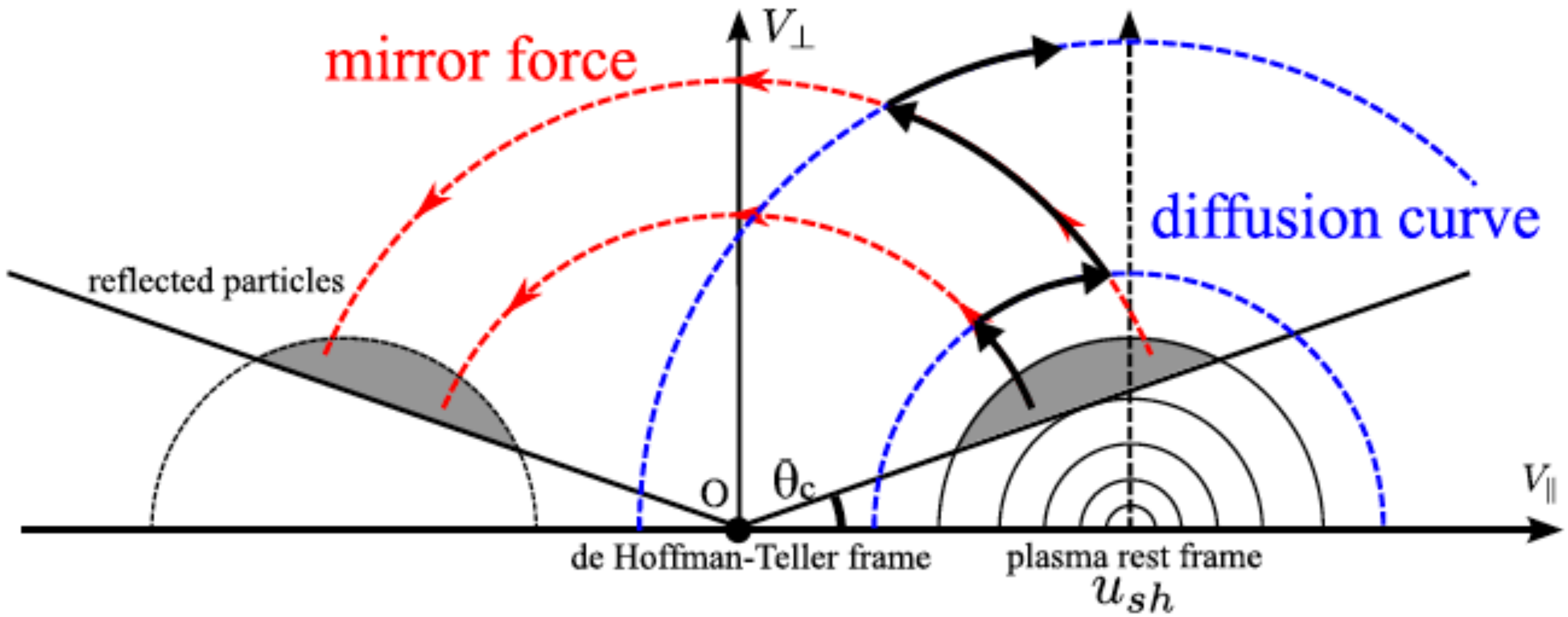
- most accelerations associated with an increase in $p_\perp$
- strong pitch-angle scattering (arcs in $p_\parallel$-$p_\perp$ momentum space)
- energy gain mostly through the drift along motional electric field:

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

➜ Stochastic Shock-Drift Acceleration (SSDA)

Stochastic Shock Drift Acceleration (SSDA)

Katou & Amano (2019)



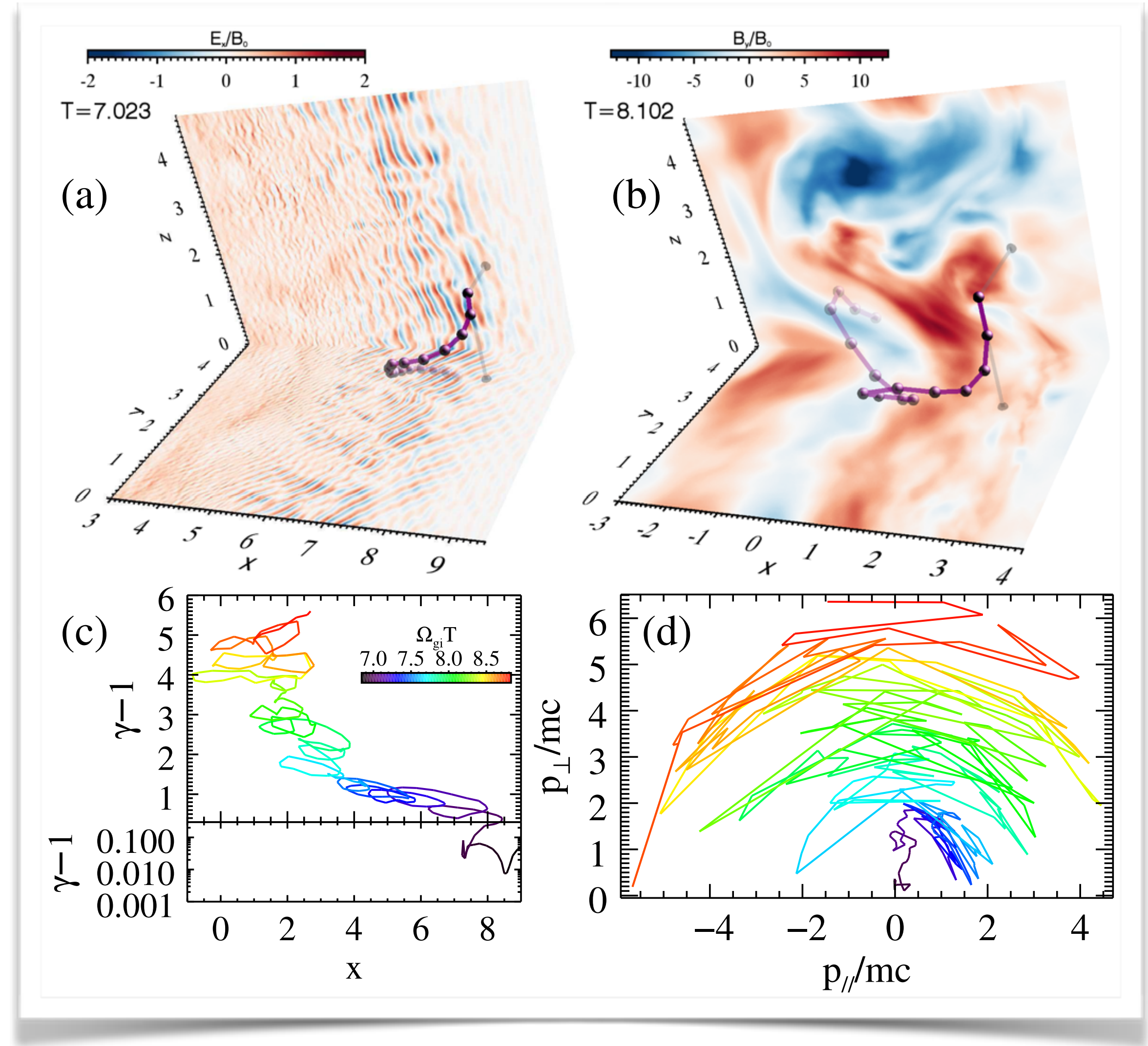
- adiabatic mirror reflection in the HTF
- elastic scattering (diffusion) in the plasma rest frame

- 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

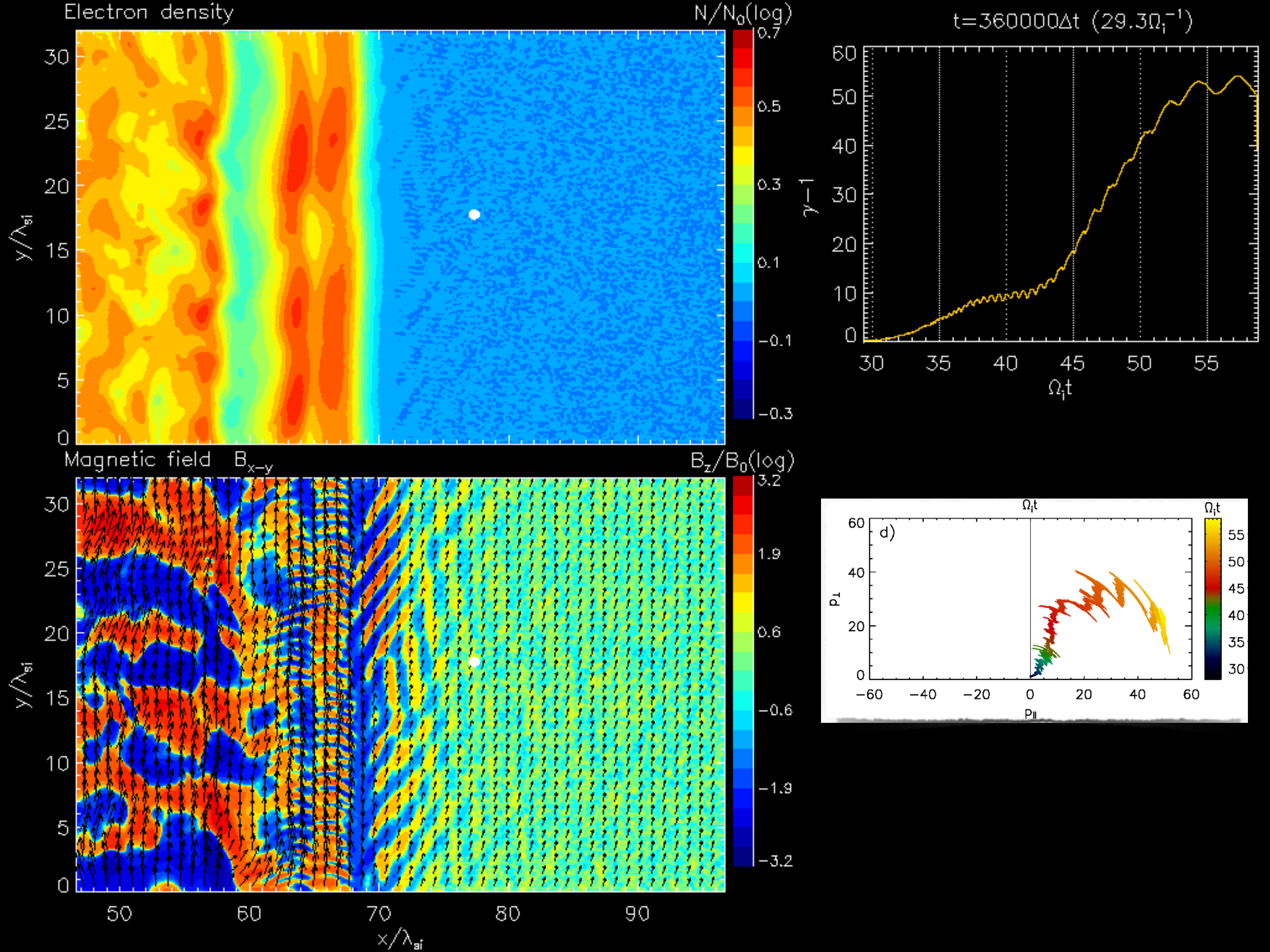
- also observed in hybrid PIC and test-particle studies of solar wind shocks (M_s=6.6, β=1; Trotta & Burgess 2019) - shock-surface fluctuations



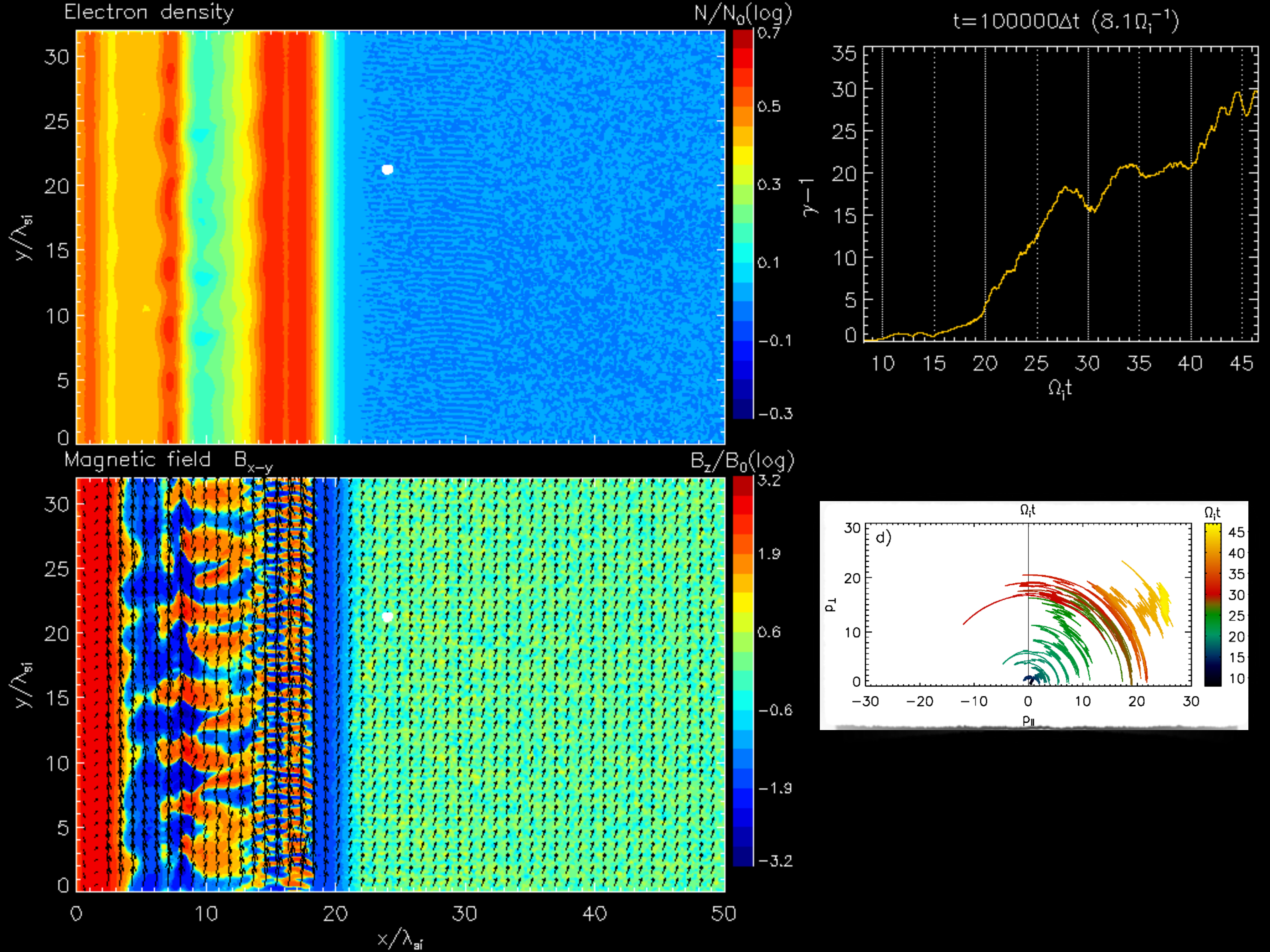
Matsumoto et al. (2017)

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

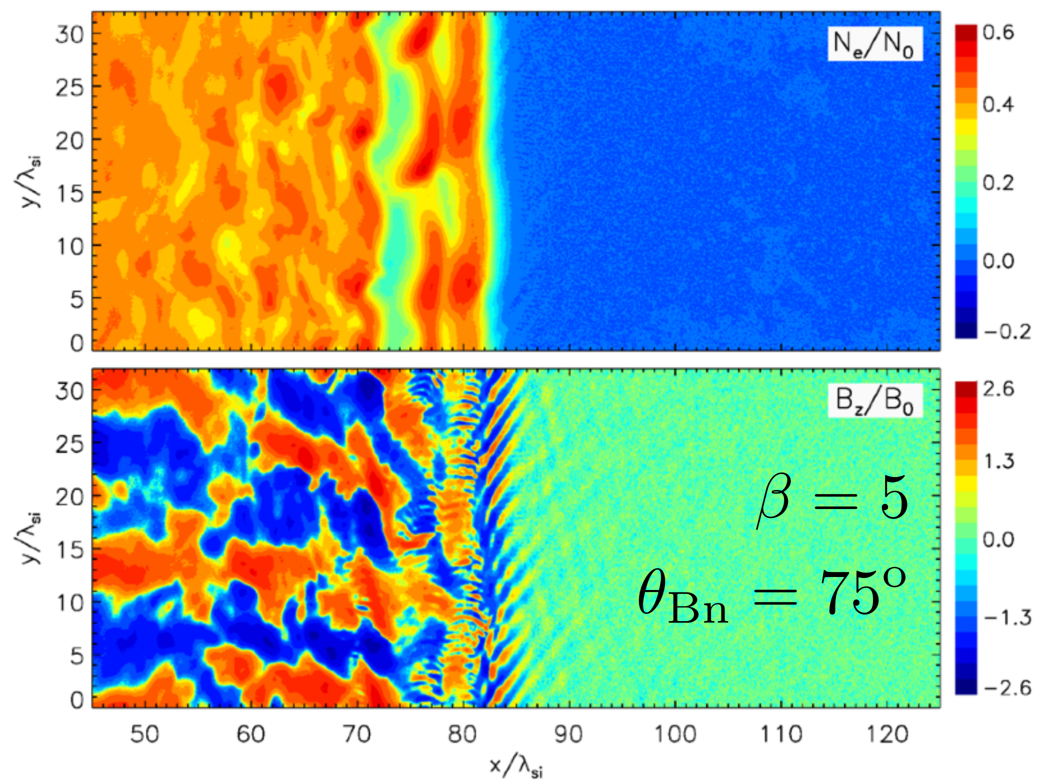
- results for shocks with β=5 and ϑ_{Bn}=75° show that the electron scattering can be due to multi-scale (broad-band) turbulence in the entire shock transition

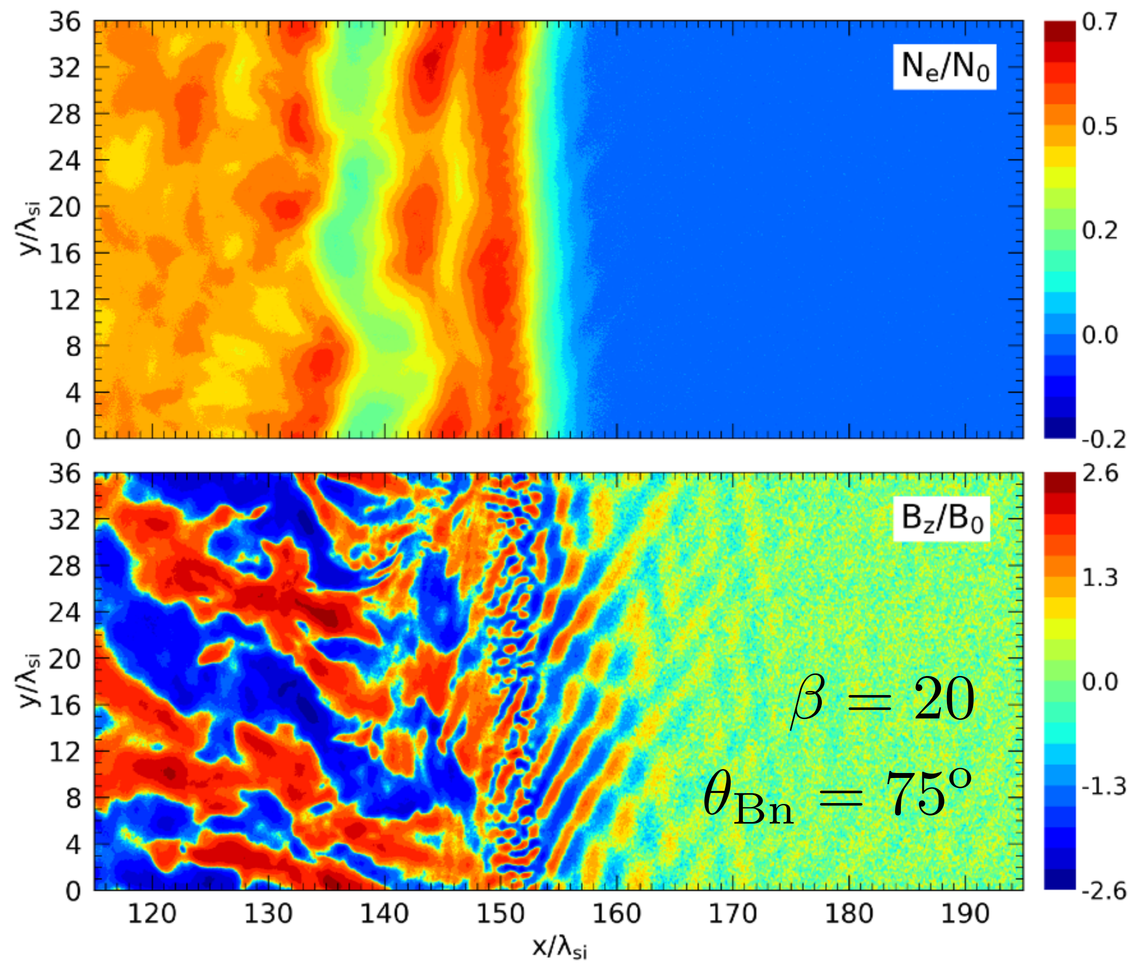


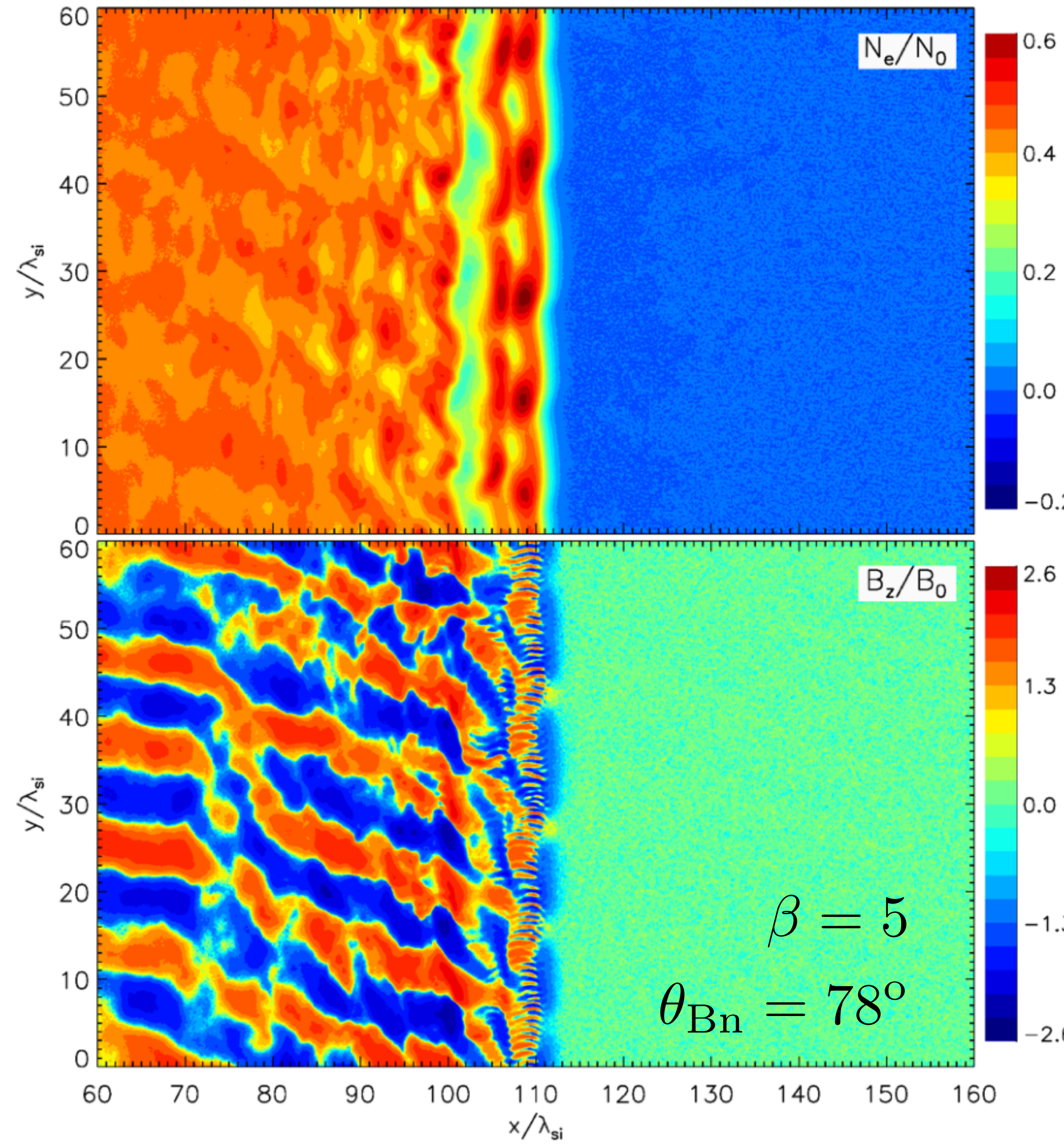
Electron density
N/N$_0$(log)
0.7
0.5
0.3
0.1
−0.1
−0.3
y/λ$_{si}$
Magnetic field B$_{x-y}$
B$_z$/B$_0$(log)
3.2
1.9
0.6
−0.6
−1.9
−3.2
x/λ$_{si}$
t=360000Δt (29.3Ω$_i^{-1}$)
γ−1
Ω$_i$t
d)
p$_\perp$
p$_\parallel$


Electron density
N/N$_0$(log)
0.7
0.5
0.3
0.1
−0.1
−0.3
y/λ$_{si}$
t=100000Δt (8.1Ω$_i^{-1}$)
γ−1
Ω$_i$t
Magnetic field B$_{x-y}$
B$_z$/B$_0$(log)
3.2
1.9
0.6
−0.6
−1.9
−3.2
x/λ$_{si}$
d)
Ω$_i$t
p$_\perp$
p$_\parallel$

Parameter dependence - multi-scale turbulence

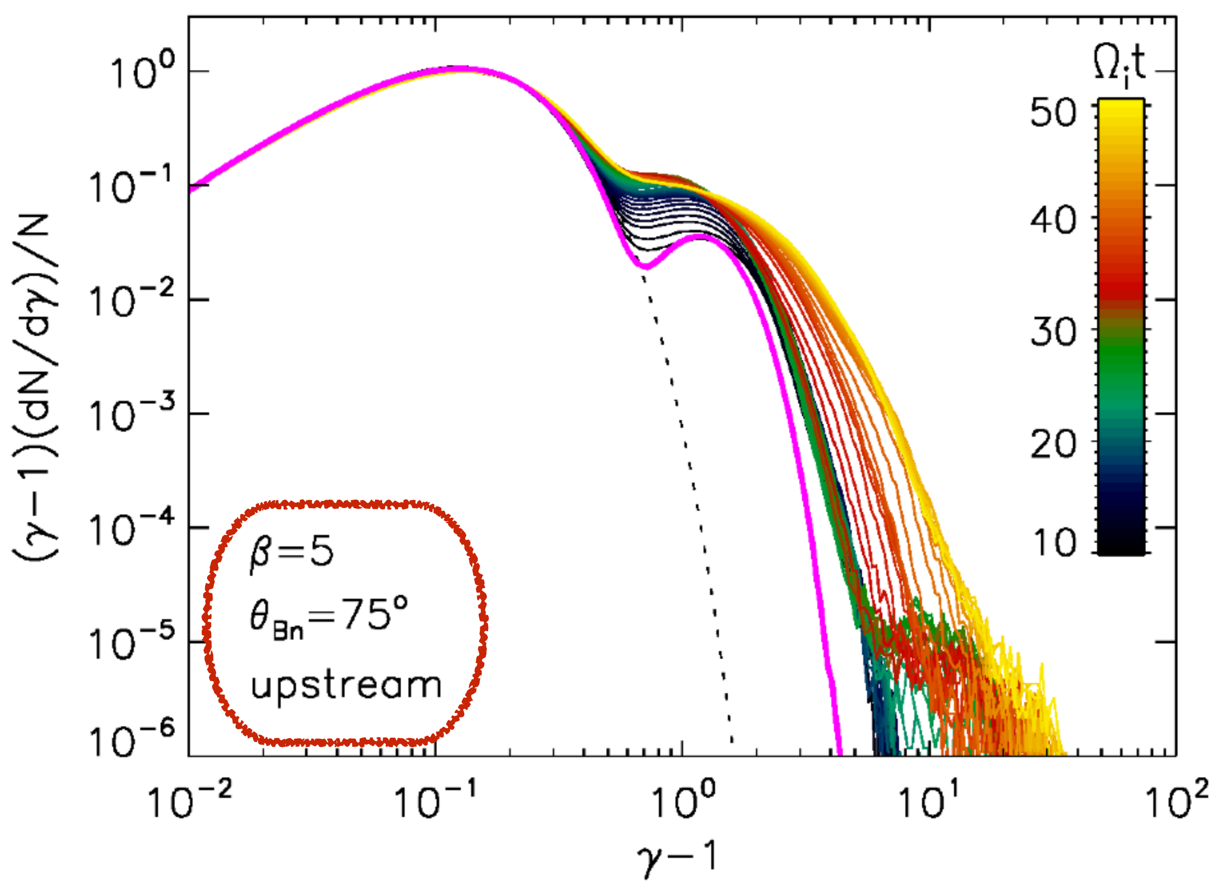


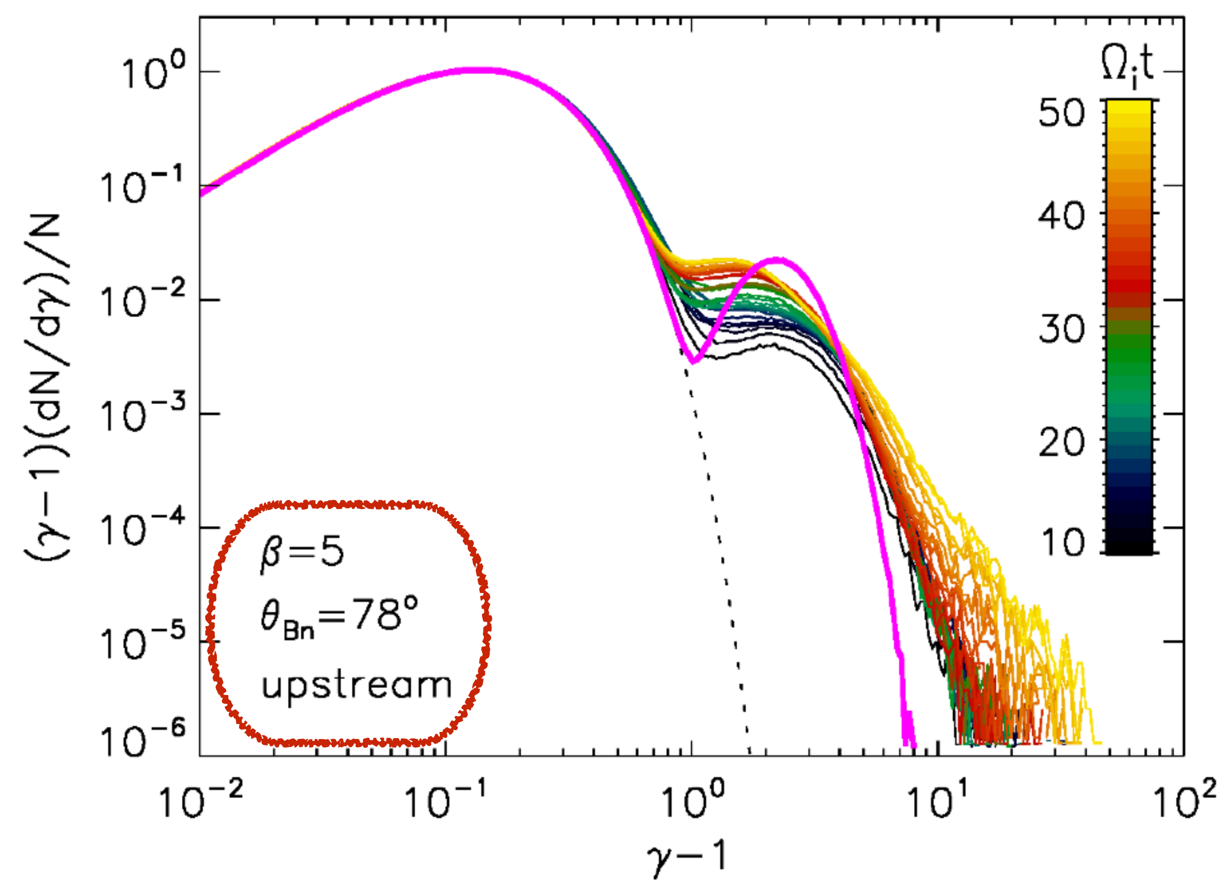


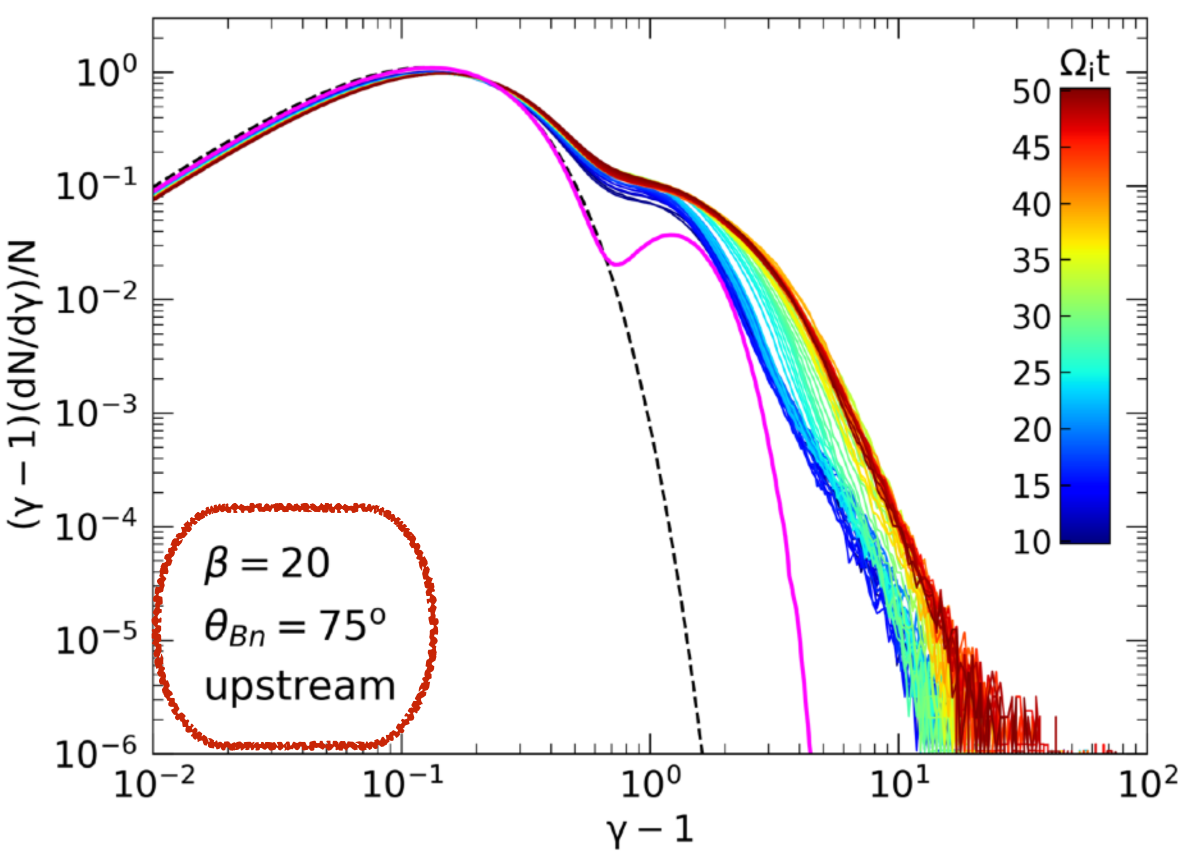


- features of multi-scale turbulence similar in all cases
- longer-wavelength ripples with growing β
- absence of EFI waves for higher θ_{Bn}
- stronger and longer-wavelength EFI modes with increasing β (after amplification in rippled shocks)

Parameter dependence - upstream spectra

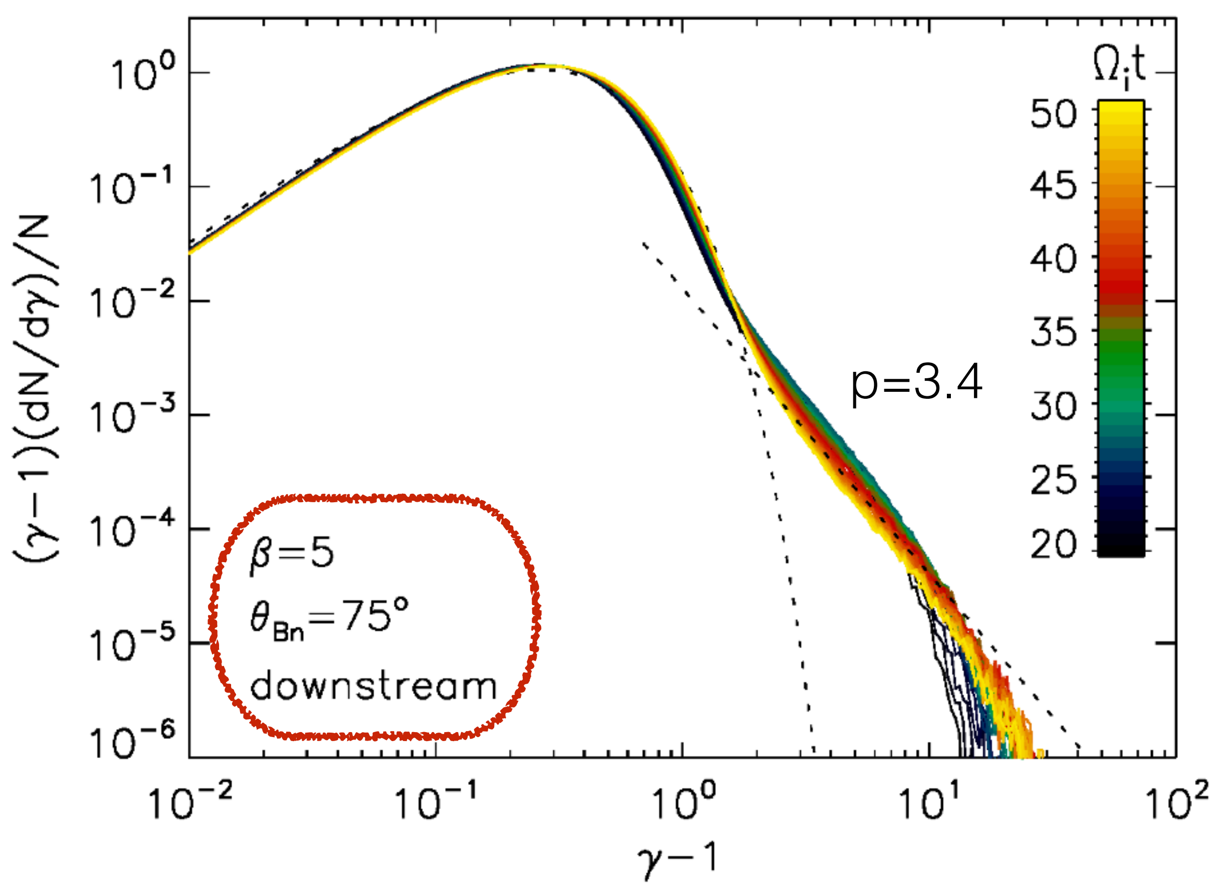


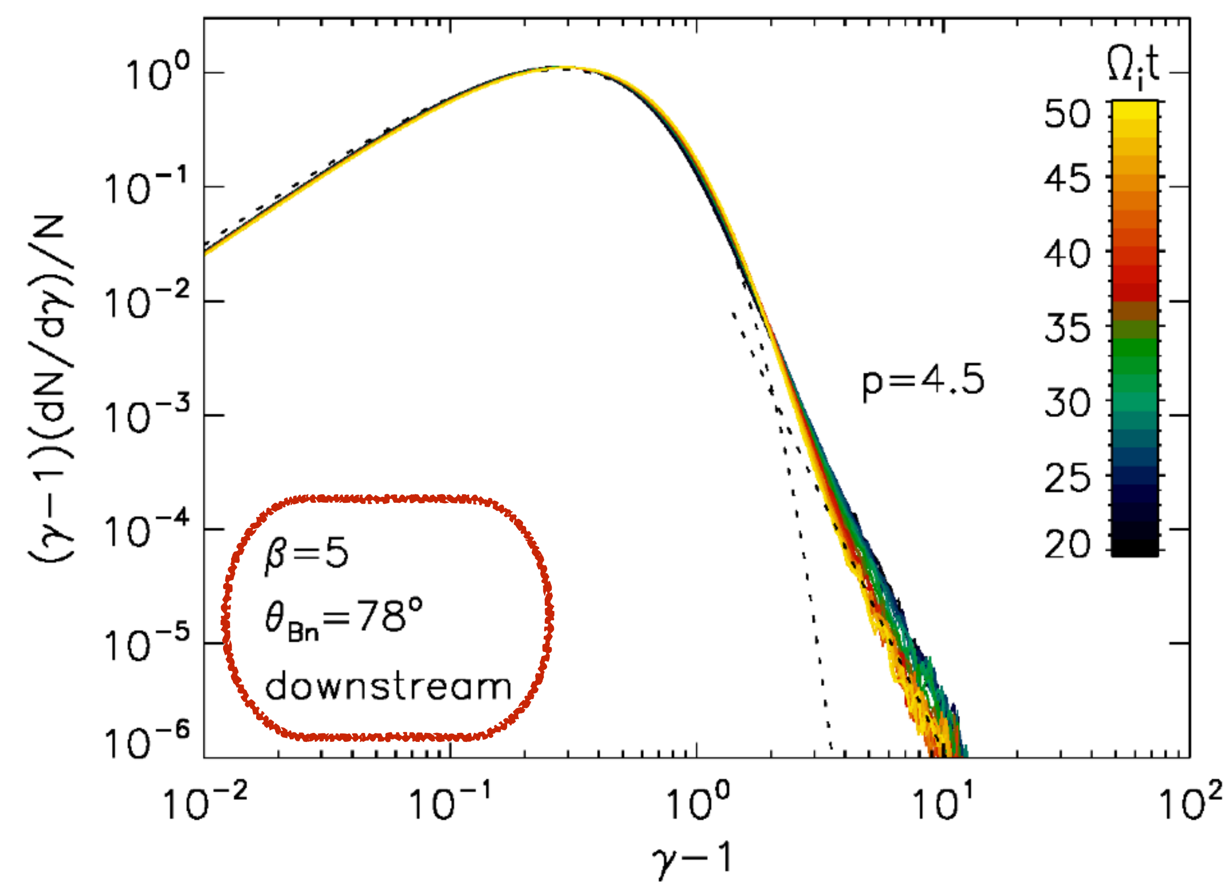


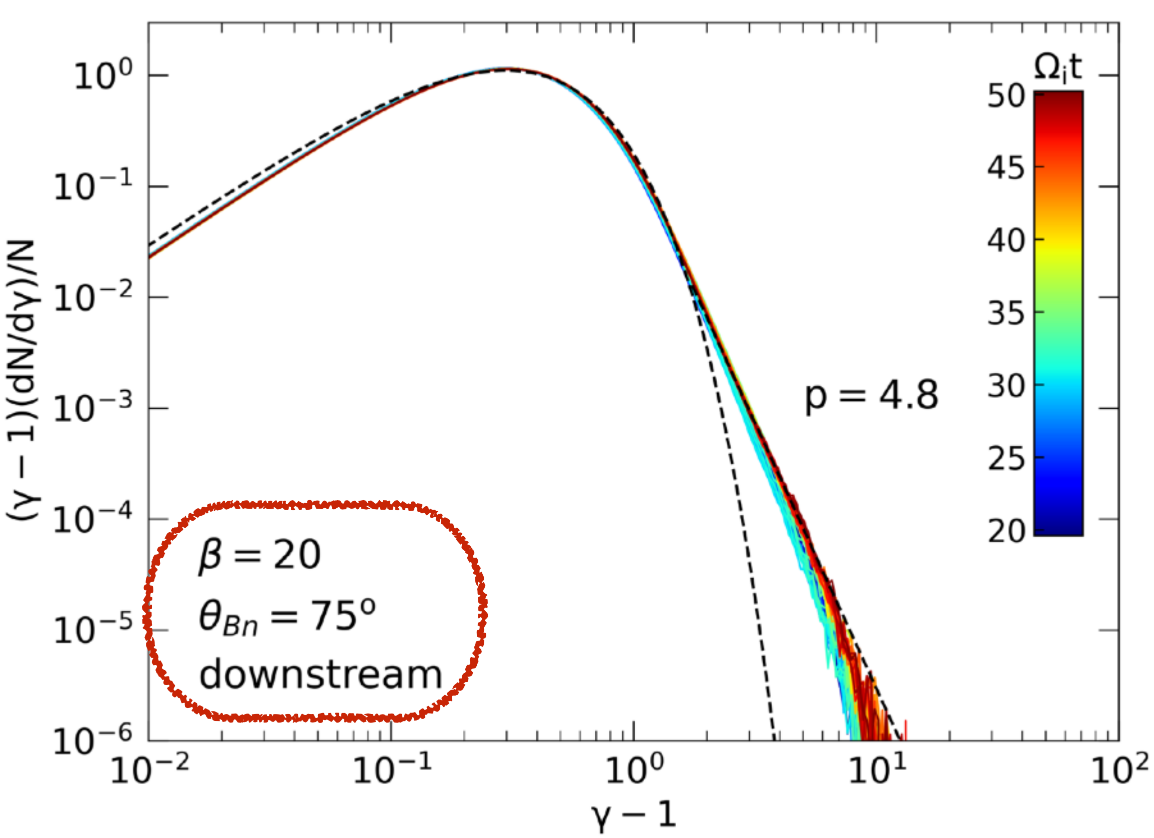


- SSDA in rippled shocks provides electron acceleration also for higher β=10-30 (up to β=100 - Ha et al. 2021)
- upstream spectra depend weakly on β
- maximum energies γ_{max}~30-40 > γ_{inj}
- multiple-cycle SDA is not critical for injection but may contribute to electron acceleration in high-β plasmas

Parameter dependence - downstream spectra

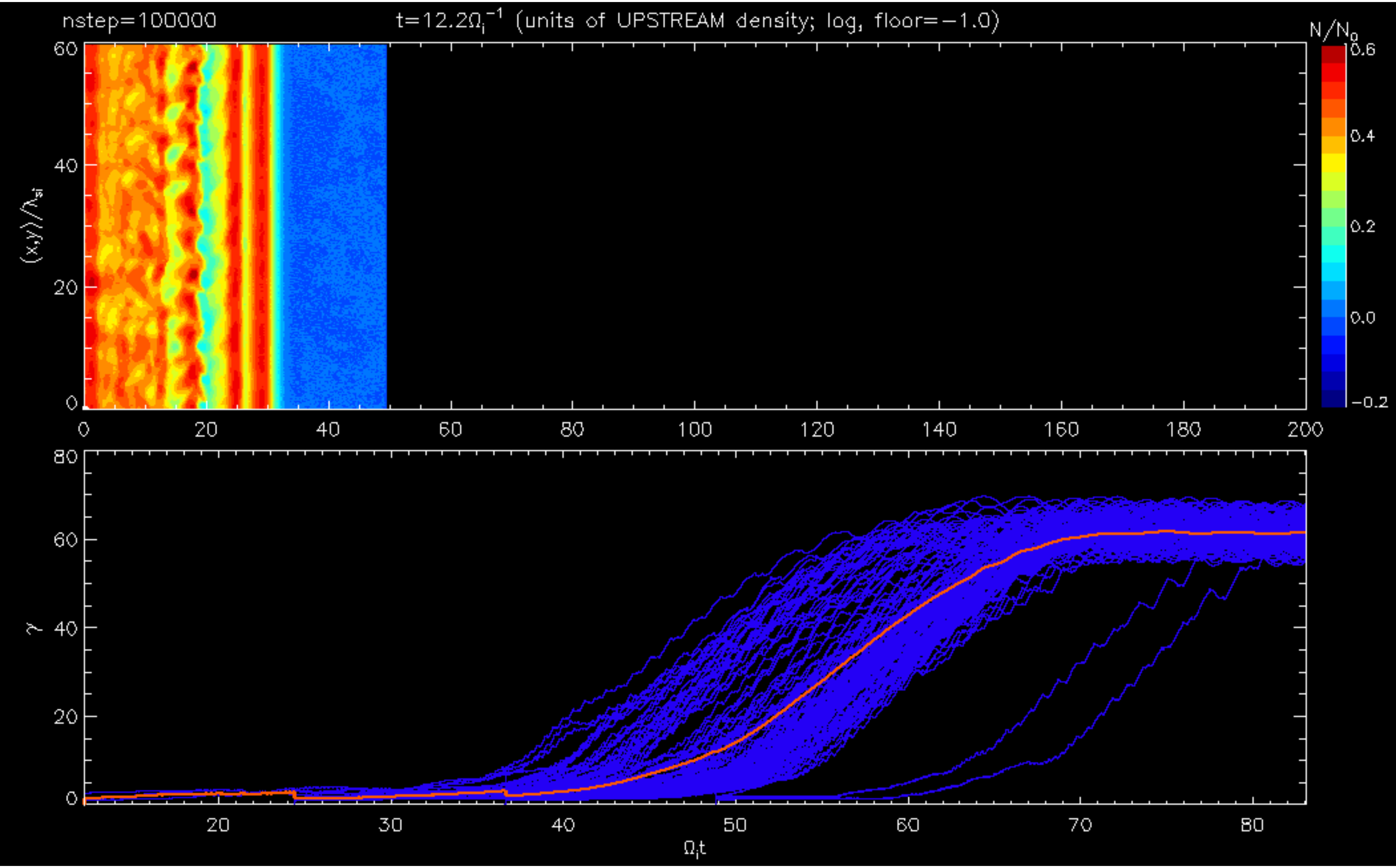






- downstream spectra steepen with increasing β and ϑ_{Bn}

Sample trajectories of electrons with γ_{max}~55-70; ϑ_{Bn}=78°



- gradual formation of supra-thermal tails
- electrons accelerated exclusively at the shock front - superluminal cond. at 2nd overshoot
- some of them diffuse downstream

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