Cracow University
of Technology

Electron acceleration at rippled low-Mach-number shocks in high-beta cosmic plasmas:

role of the pre-shock conditions

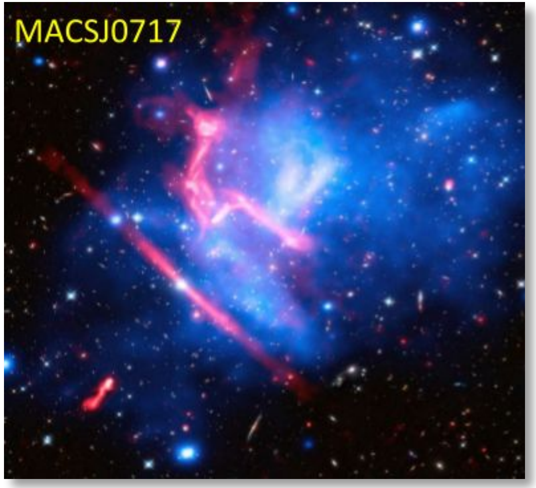
Oleh Kobzar

Faculty of Materials Engineering and Physics
Cracow University of Technology

XXVIII Cracow EPIPHANY Conference, 10 – 14 January 2022

Shocks in the astrophysical objects

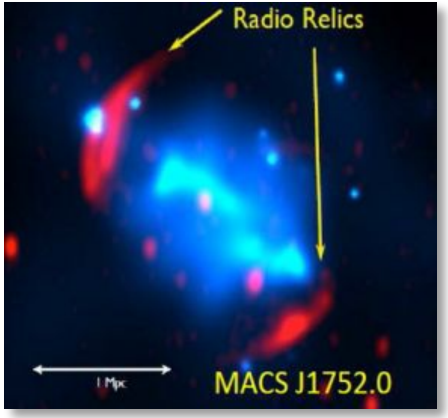
- Earth's bow shock
- Solar wind termination shock
- Supernova remnant (SNR) shocks
- Active galactic nuclei (AGN) shocks
- Large-scale shocks in the galaxy clusters:
  - turbulence shocks
  - infall shocks
  - merger shocks



In the latter case, low-Mach-number (***M<<10***) shocks are found to propagate in high-beta (***β>>1***) plasmas.

X-ray and radio emission show the electron acceleration to non-thermal energies.

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

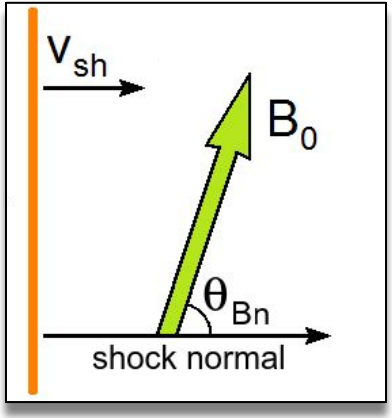


Shock forming and particle acceleration

The electron injection problem:

The diffusive shock acceleration (DSA) does not work for thermal electrons. Other mechanisms of the electrons (pre-)acceleration are required for their injection to DSA.

Shock drift acceleration (SDA)*



Electrons are energized via motional electric field:

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

Conditions of the SDA reflection:

$$v_{i\parallel}^{\rm up} < u_t \qquad v_{i\perp}^{\rm up} \geqslant \gamma_t\left(u_t - v_{i\parallel}^{\rm up}\right)\tan\alpha_0$$

$$u_t = u_{\rm sh}^{\rm up}\sec\theta_B$$

$u_t \leqslant c$ **subluminal**

$u_t > c$ **superluminal**

SDA reflection is possible only at the subluminal shocks.

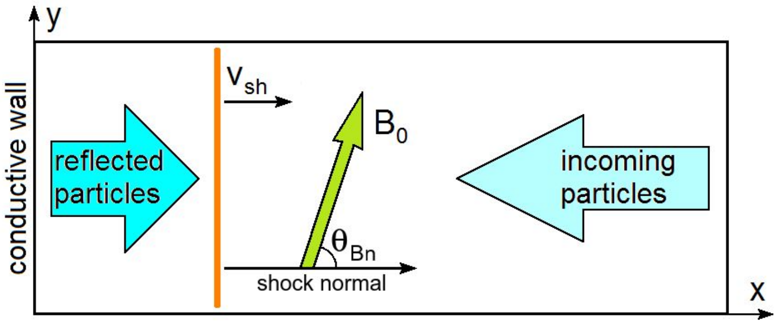
Particle energization at SDA reflection:

$$\frac{\Delta\gamma}{\gamma_i^{\rm up}} \equiv \frac{\gamma_r^{\rm up} - \gamma_i^{\rm up}}{\gamma_i^{\rm up}} = \frac{2u_t\left(u_t - v_{i\parallel}^{\rm up}\right)}{c^2 - u_t^2}$$

* *The formulas are taken from the article by **X.Guo, L.Sironi and R.Narayan** (ApJ, 2014)*

Simulation setup and parameters

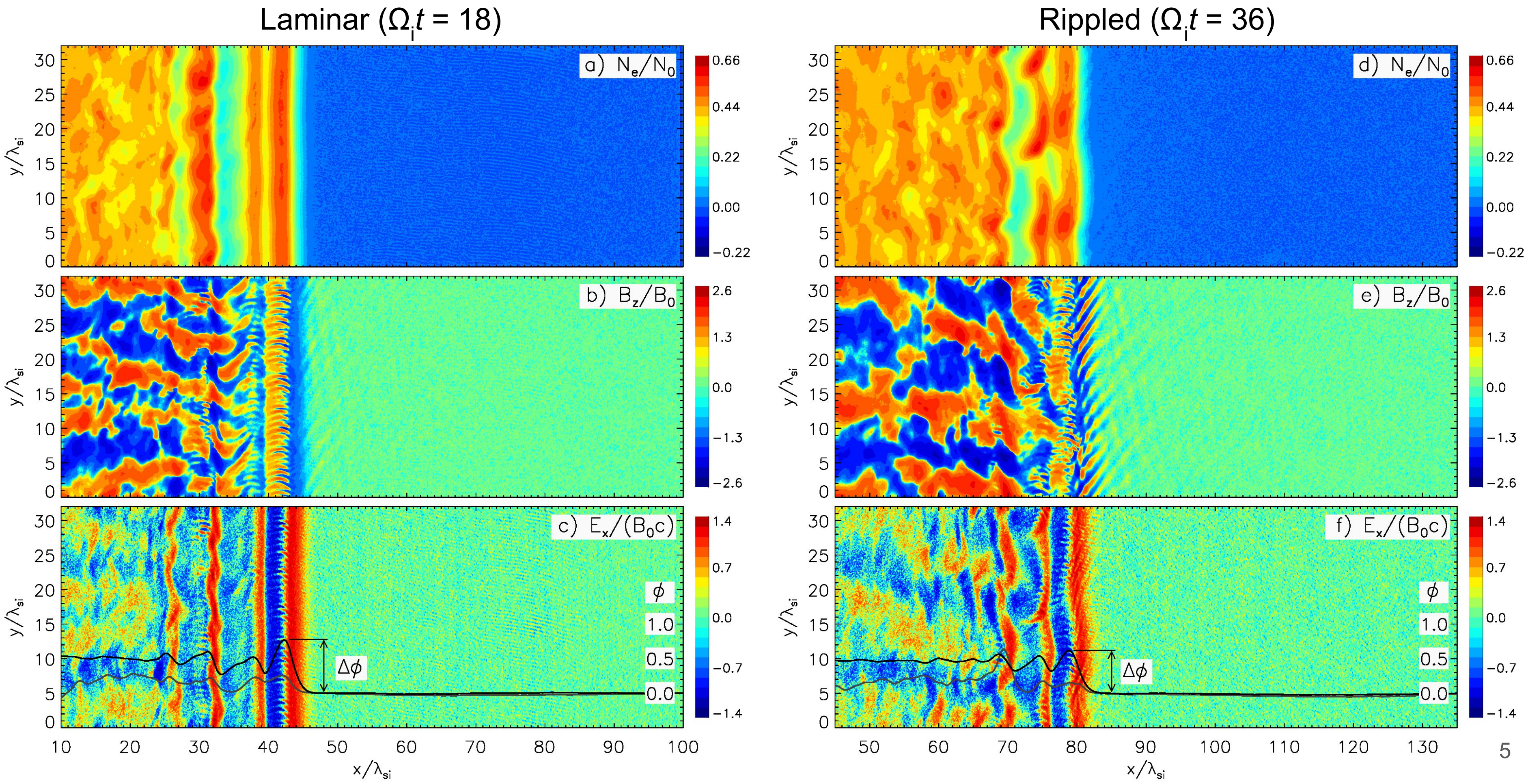
2D-3V Particle-In-Cell (PIC) simulations in rectangular box with reflecting wall



* *published by*
O.Kobzar, J.Niemiec, T.Amano, M.Hoshino, S.Matsukiyo, Y.Matsumoto & M.Pohl
(*ApJ, 2021, v.919, p.97*)

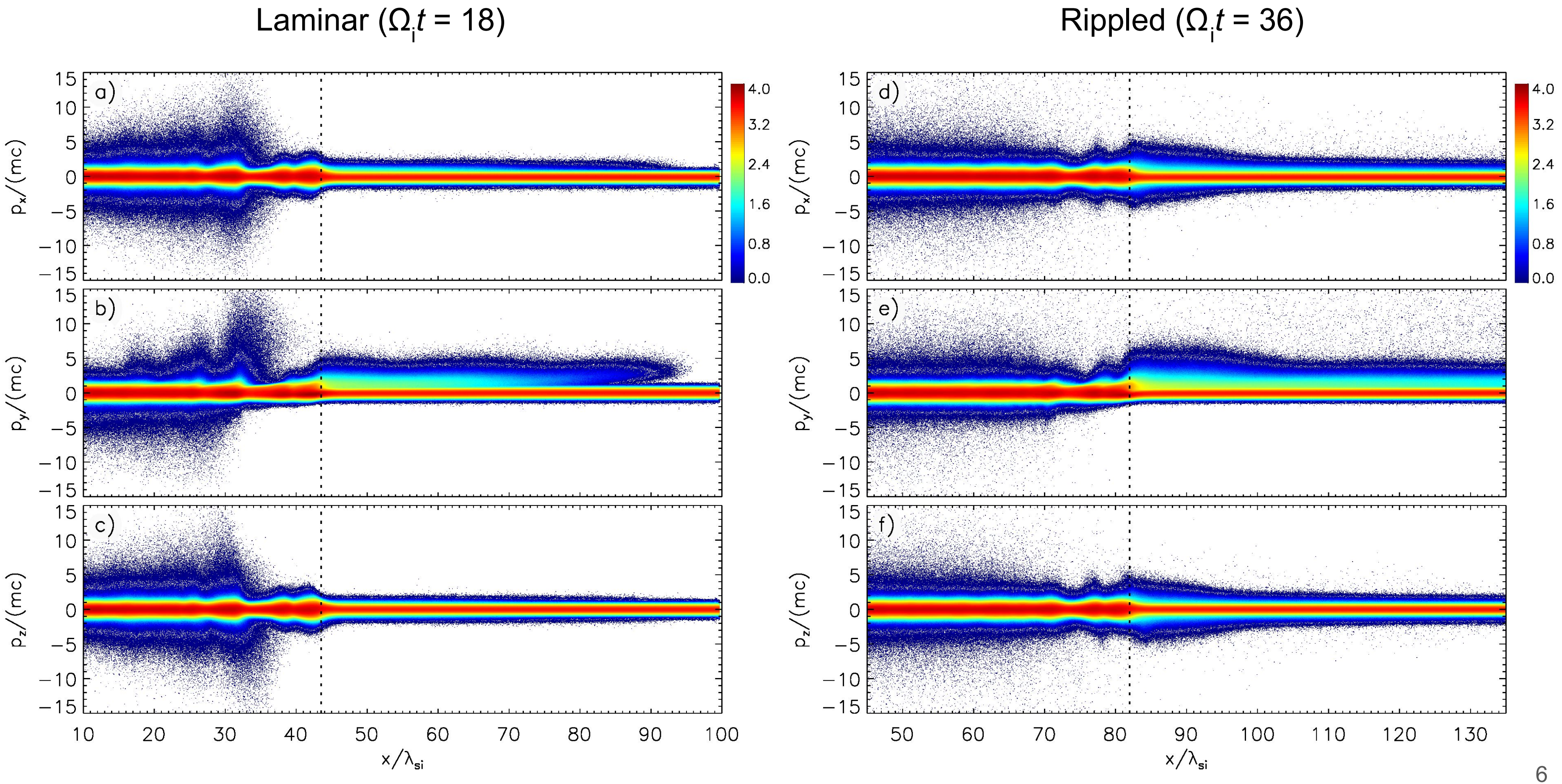
	Run A (reference*)	**Run B**
Magnetic field obliquity, θ_{Bn}	**75^{o}**	**78^{o}**
Mass ratio, m_i/m_e	**100**	
Upstream plasma beam velocity, v_0/c	**0.1**	
Shock velocity, v_{sh}/c, in simulation (upstream) frame	**0.05 (0,149)**	
Thermal velocity, $v_{e,th}/c$ ($v_{i,th}/c$)	**0.387 (0.0387)**	
Sonic Mach number, M_s	**3**	
Plasma beta, $\beta = p_{th}/p_B$	**5**	

Run A



Laminar ($\Omega_i t$ = 18)
Rippled ($\Omega_i t$ = 36)
a) N_e/N_0
b) B_z/B_0
c) $E_x/(B_0 c)$
d) N_e/N_0
e) B_z/B_0
f) $E_x/(B_0 c)$
ϕ
$\Delta\phi$
y/λ_{si}
x/λ_{si}

Run A

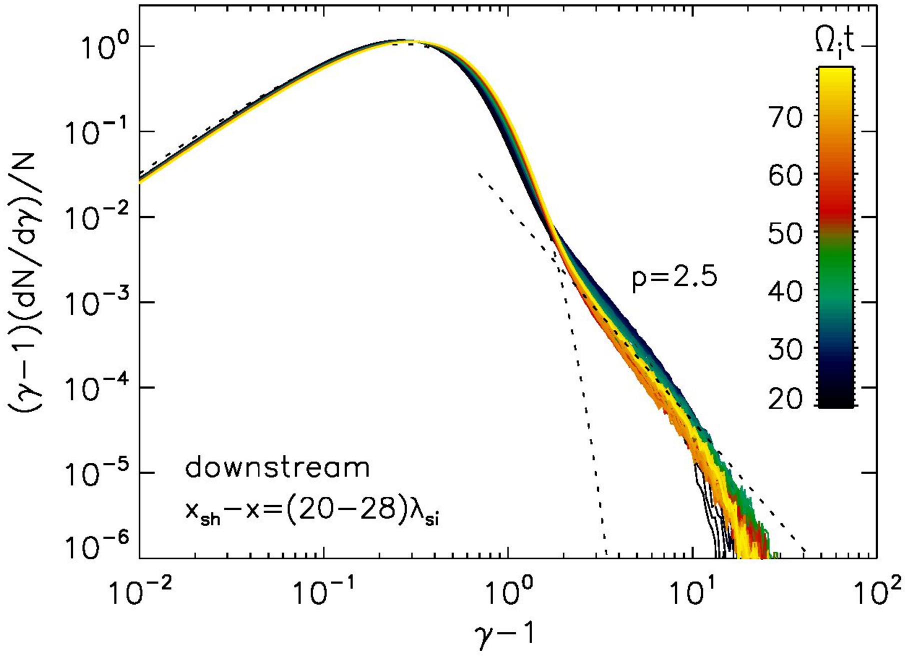


Laminar ($\Omega_i t$ = 18)
Rippled ($\Omega_i t$ = 36)
a)
b)
c)
d)
e)
f)
$p_x/(mc)$
$p_y/(mc)$
$p_z/(mc)$
x/λ_{si}

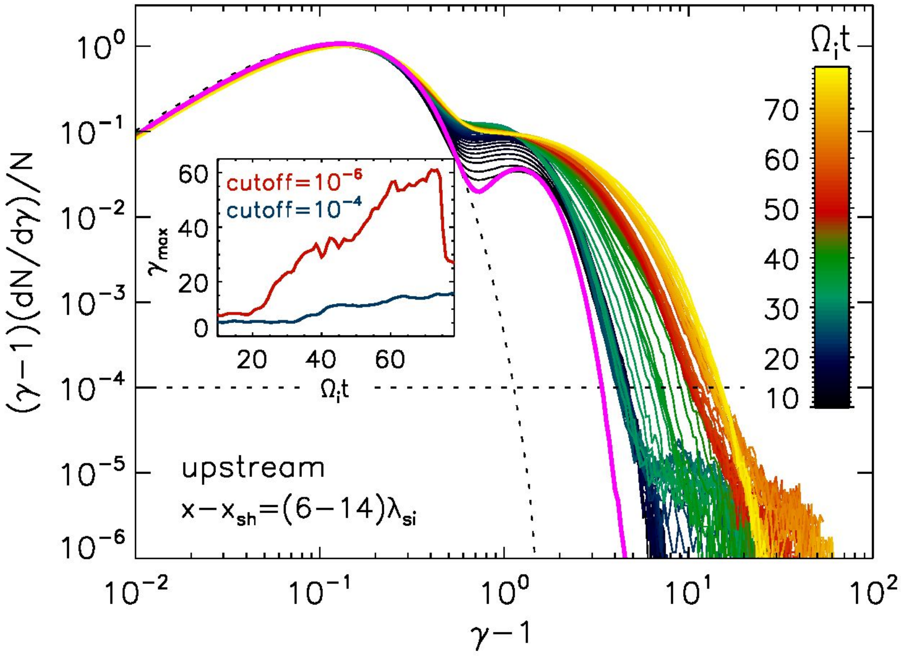
Run A

Evolution of the electron energy spectra

Downstream distributions

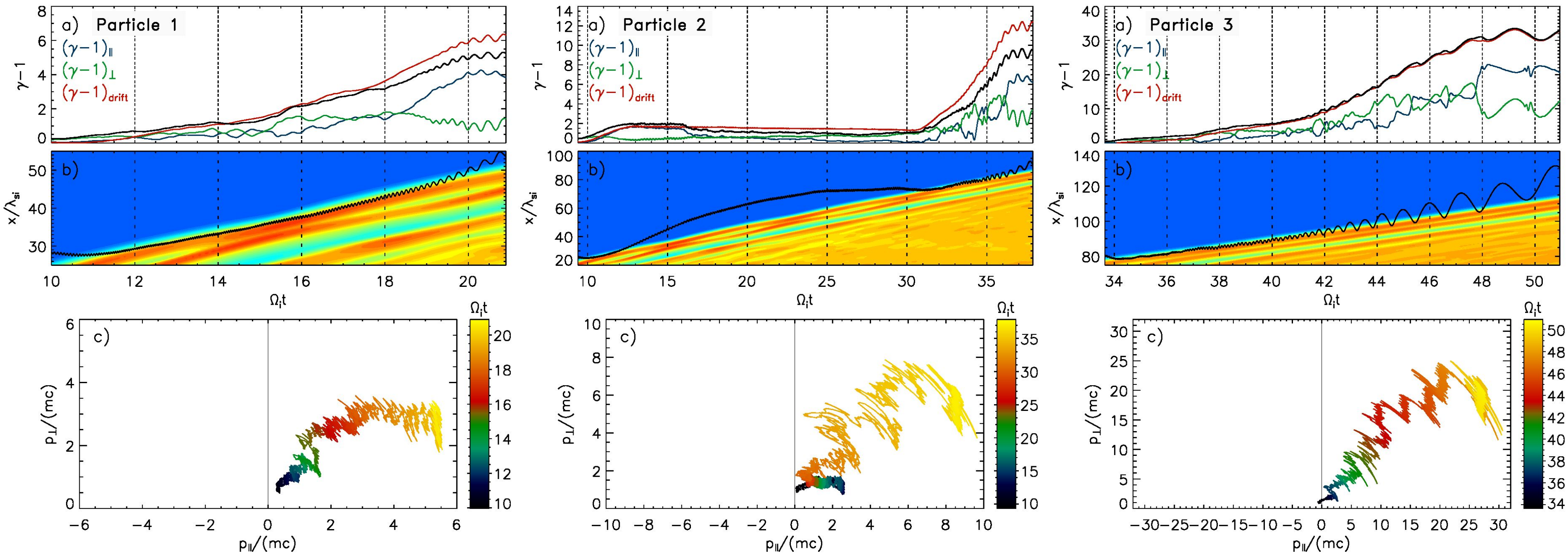


Upstream distributions



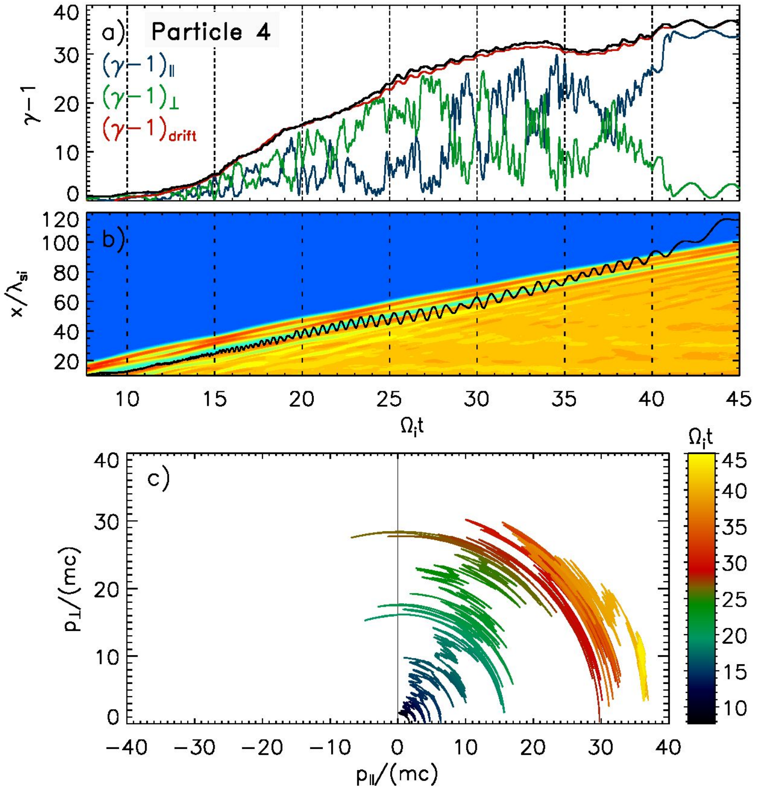
Run A

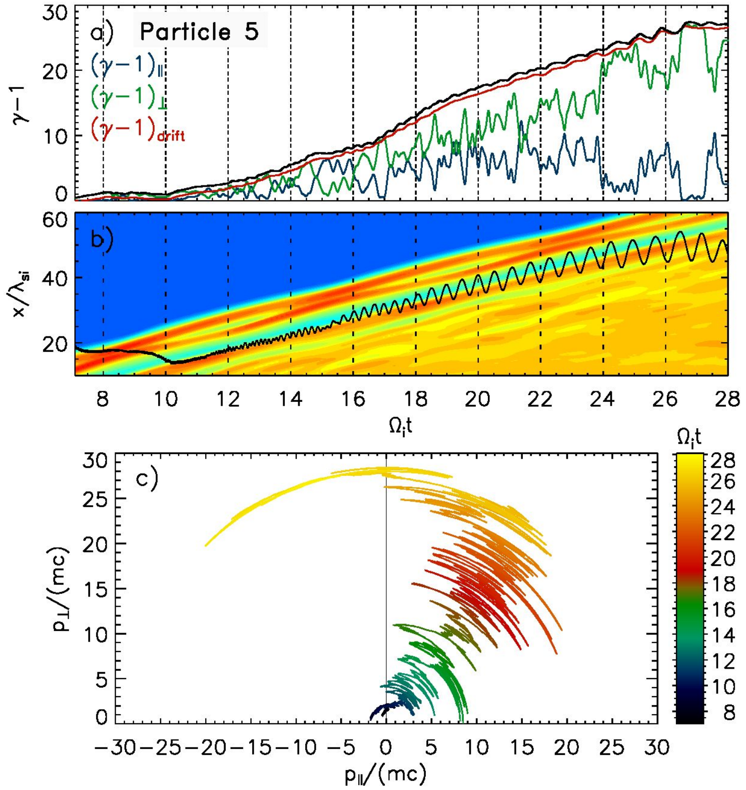
Possible types of the electron acceleration at the rippled shock



Run A

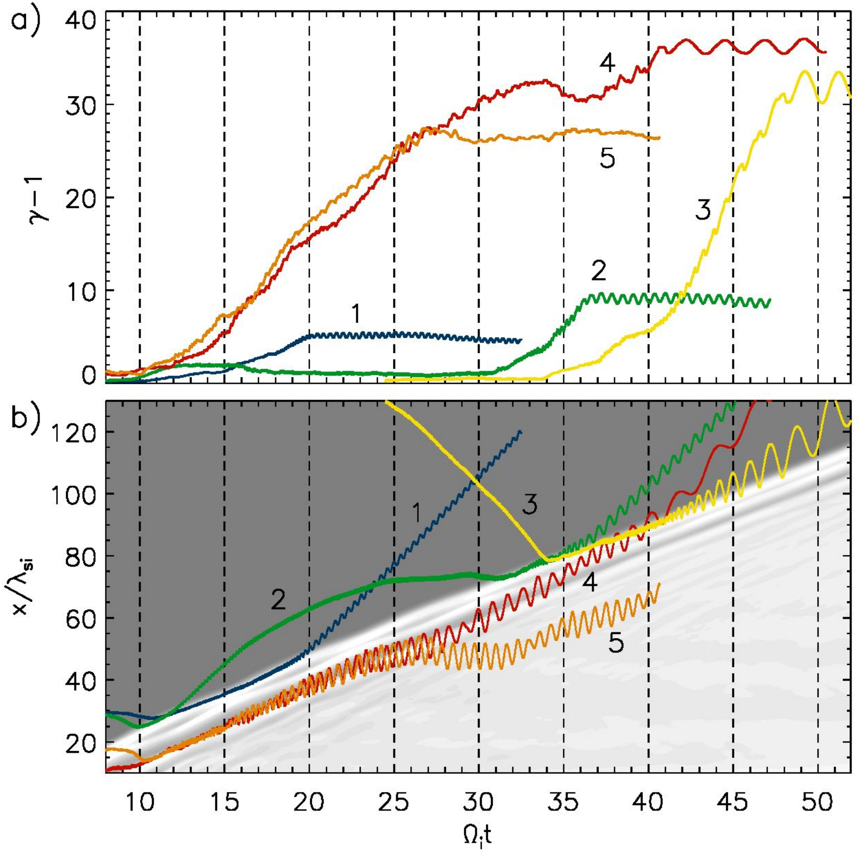
Possible types of the electron acceleration at the rippled shock





Run A

Possible types of the electron acceleration at the rippled shock



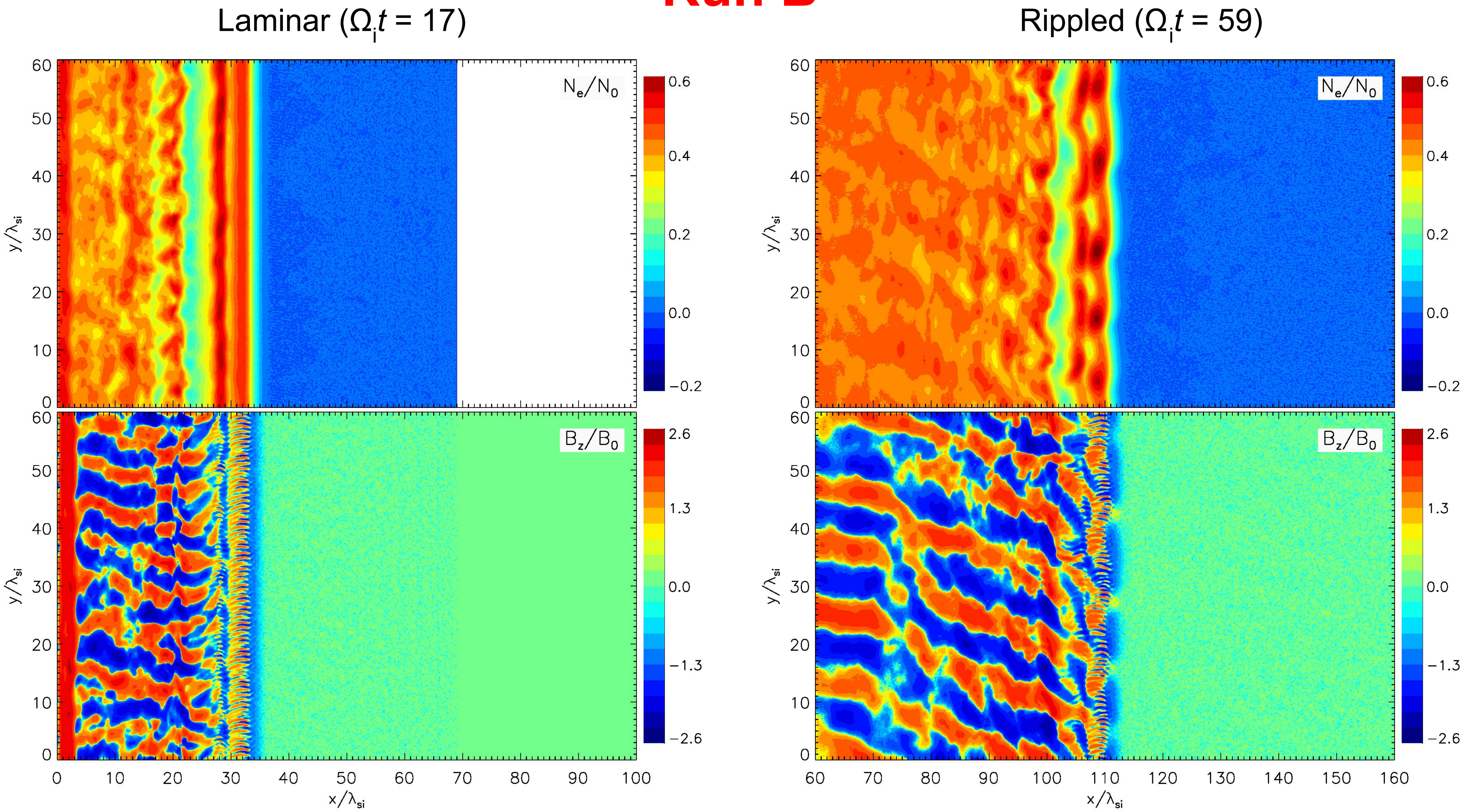
1. Single-cycle SDA process.
2. Double-cycle SDA proces.
   Rare, second cycle occurs at already rippled shock.
3. Single-cycle SSDA process,
   occurring at **rippled** shock.
4. Accelerated in the undershoot
   and **scattered to the upstream**.
5. Accelerated in the undershoot
   and **scattered to the downstream**.

The main acceleration mechanism is **SSDA**.

Increase of the magnetic wave turbulence scale:
whistlers → EFI-waves → rippling modes

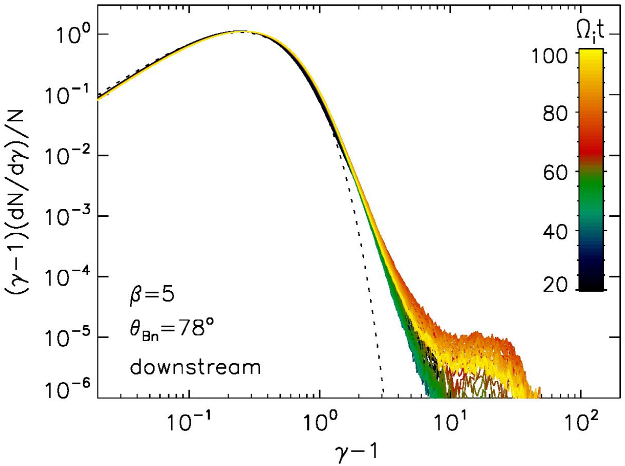
Gradual growth of the scattering field wavelength:
is it necessary for acceleration to high energies?

Run B


Laminar ($\Omega_i t$ = 17)
Rippled ($\Omega_i t$ = 59)
N_e/N_0
B_z/B_0
y/λ_{si}
x/λ_{si}
0.6
0.4
0.2
0.0
−0.2
2.6
1.3
0.0
−1.3
−2.6

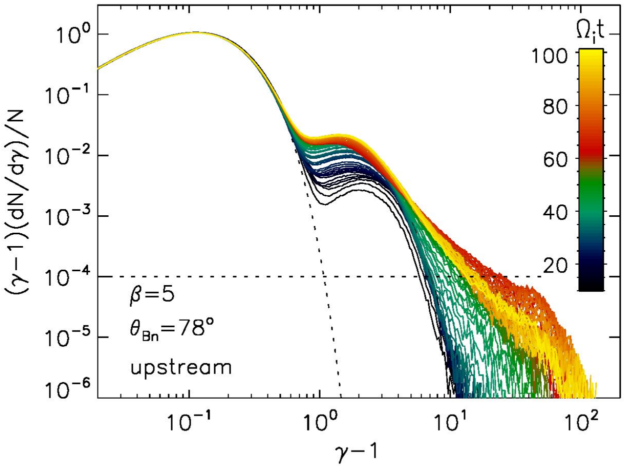
Run B

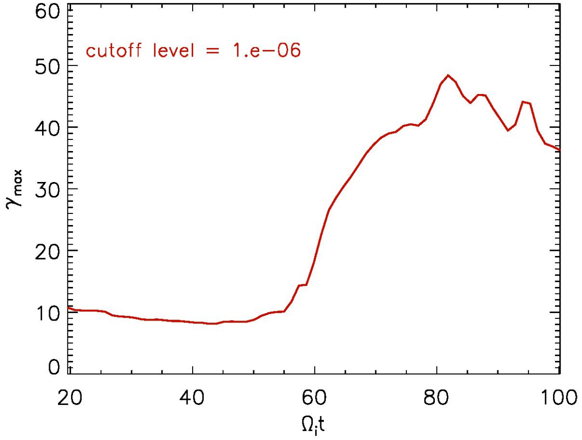
Evolution of the electron energy spectra

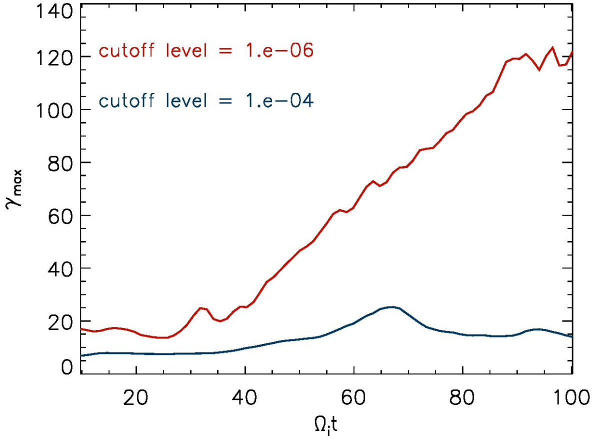


← **downstream**

upstream →

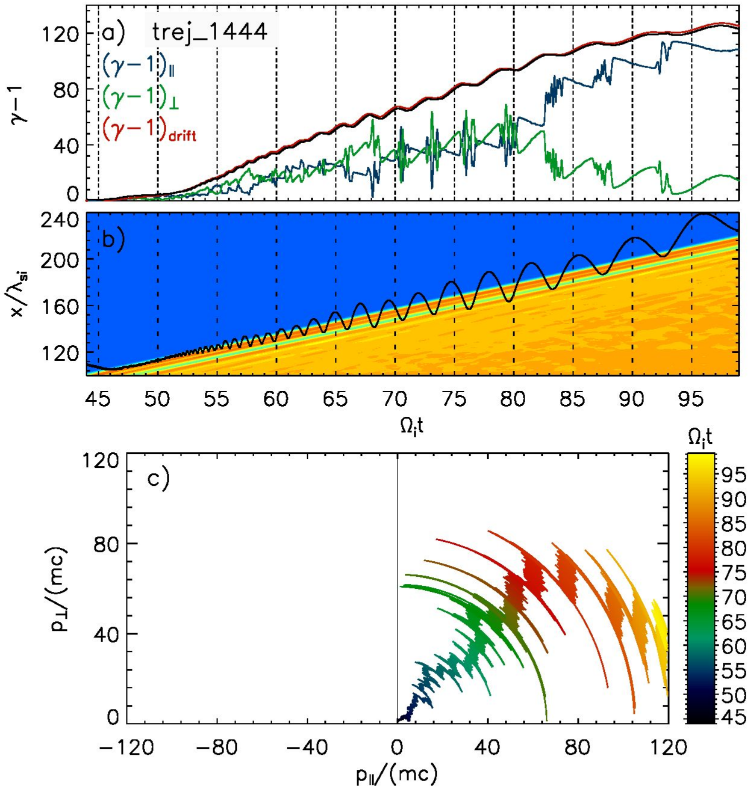


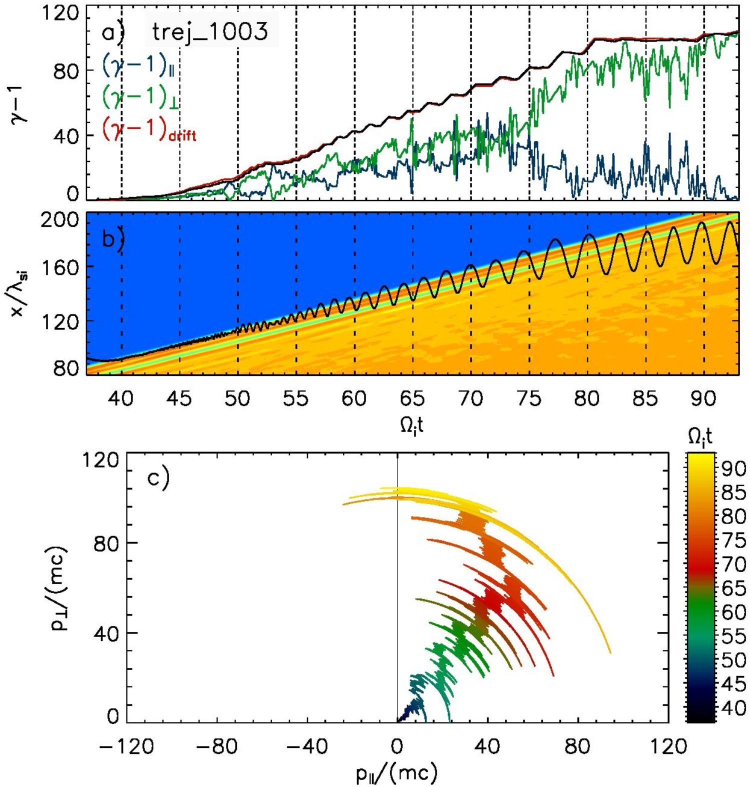




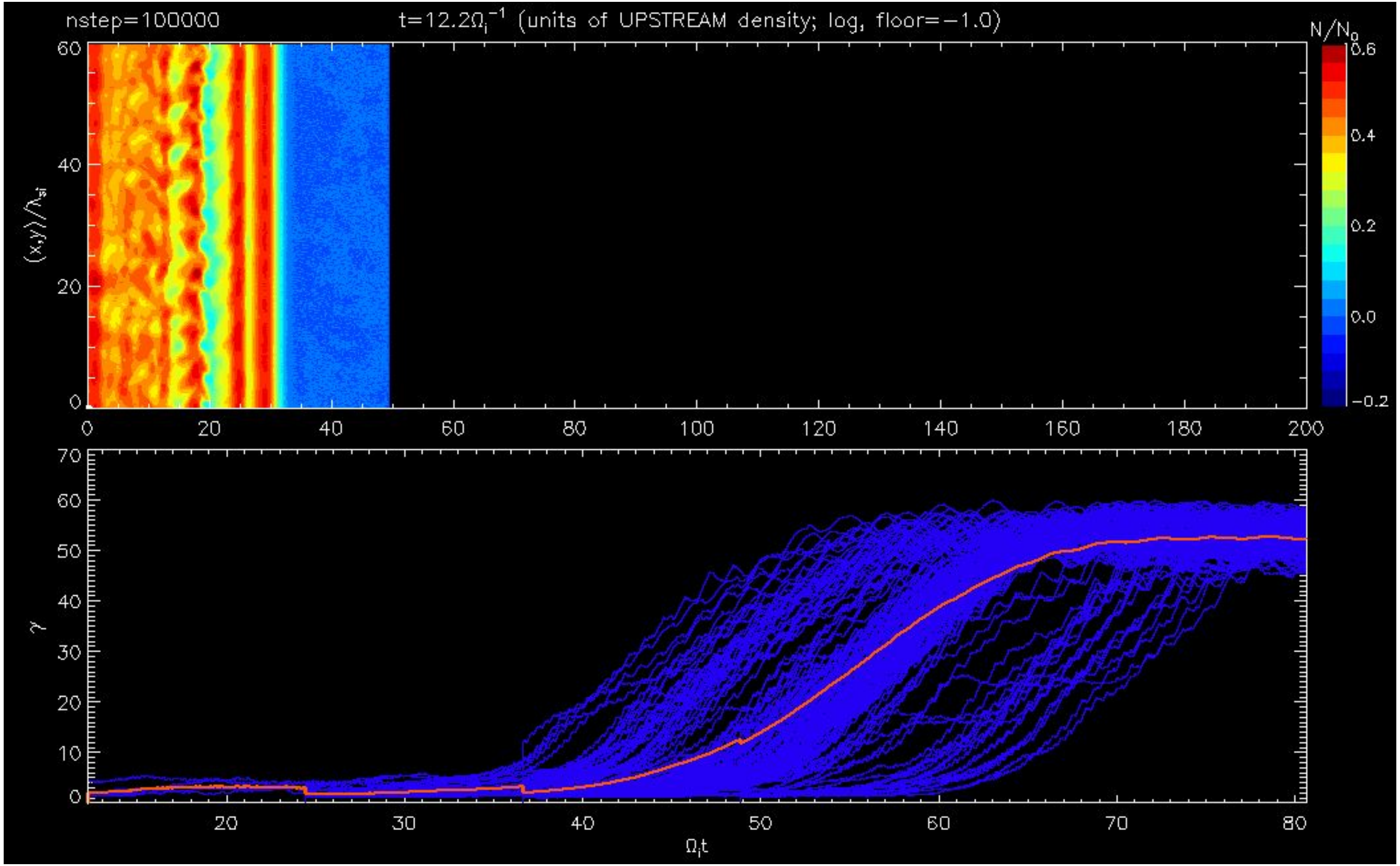
Run B

Electron acceleration at the rippled shock front





Run B Tracing of the accelerated electrons



Conclusions

- Shock rippling facilitates the electron acceleration to much higher energies, than typically observer at regular SDA reflection.
- Acceleration at the rippled shocks is much more complex than regular SDA process.
  It is strongly affected by the different waves: 1) **whistlers** in the overshoot, 2) **EFI**-induced upstream waves, 3) **rippling** wave modes in the main and next overshoots.
- Being accompanied by the pitch-angle scattering off turbulence, the main **acceleration process is SSDA**.
- Internal shock structure can play a role. The efficient electron acceleration at the second and/or third overschoots is also observed.
- Generation of the upstream EFI modes is driven by the electron temperature anisotropy, that in turn strongly depends on the shock obliquity.
- EFI may play a role for the efficient gradual particle energization, however rippling modes by themselves are found to ensure the scattering, necessary for electron acceleration to highest energies, both in upstream and downstream.