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Electron Injection in Merger Shocks of Galaxy Clusters

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Introduction

- radio and X-ray observations of so-called radio relics indicate electron acceleration at merger shocks in galaxy clusters
- these large-scale shocks are also candidate sites for ultra-high-energy cosmic ray production
- most energetic merger shocks have low Mach numbers ($M_s < 4$, $M_A < 10$) and propagate in high beta ($\beta \gg 1$) plasmas.
- Diffusive Shock Acceleration (DSA) assumed to operate at merger shocks but mechanism of **electron injection** is poorly known for galaxy cluster conditions

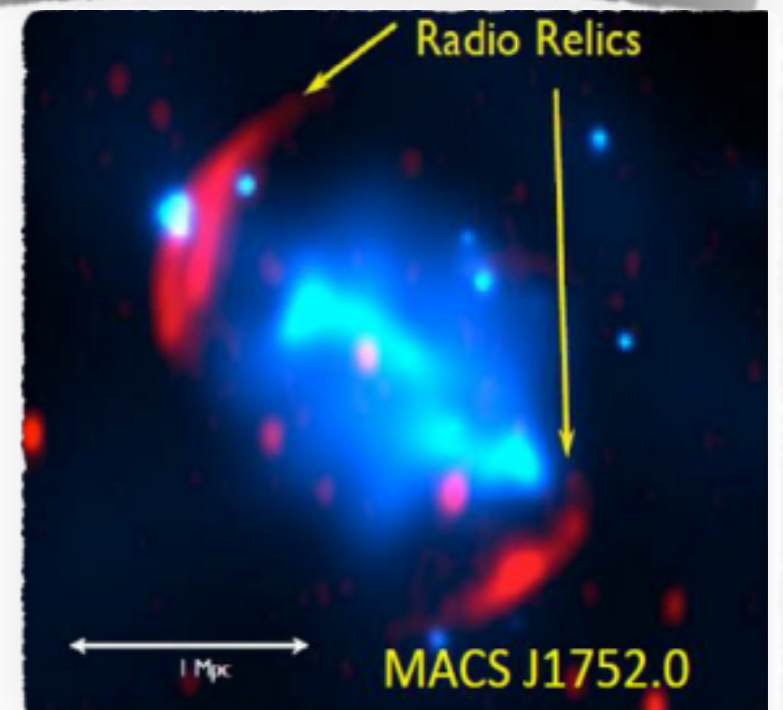
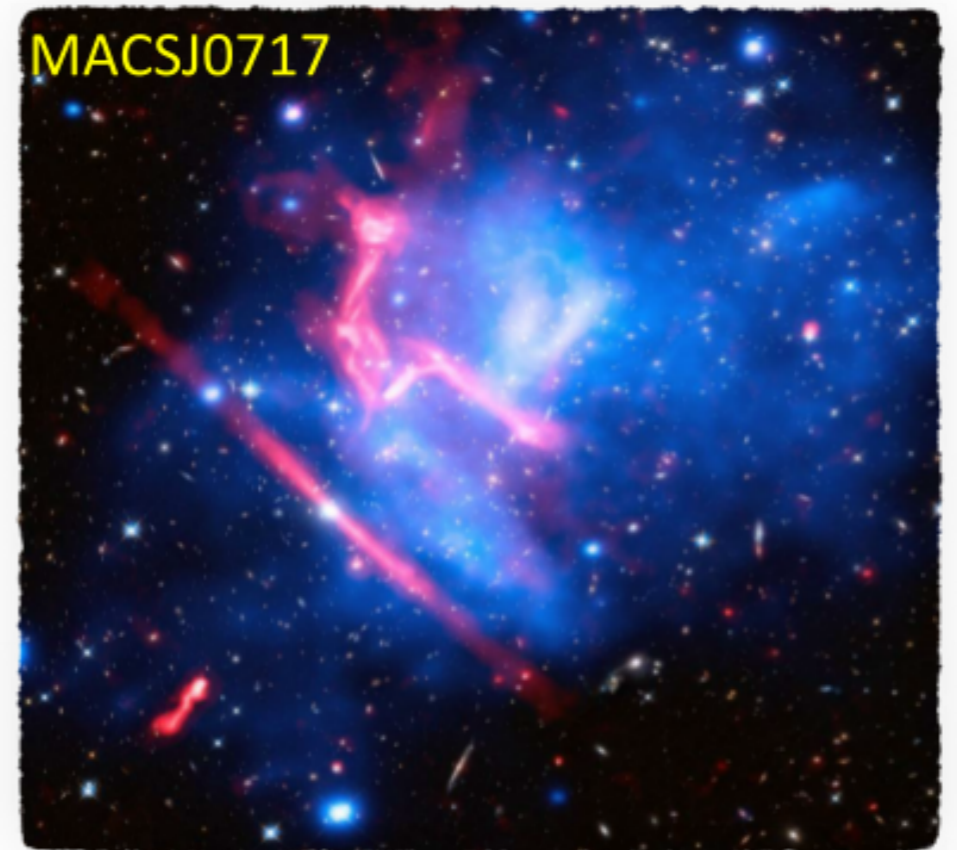
Alfvenic Mach number: $M_A = \frac{v_{sh}}{v_A}$

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

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

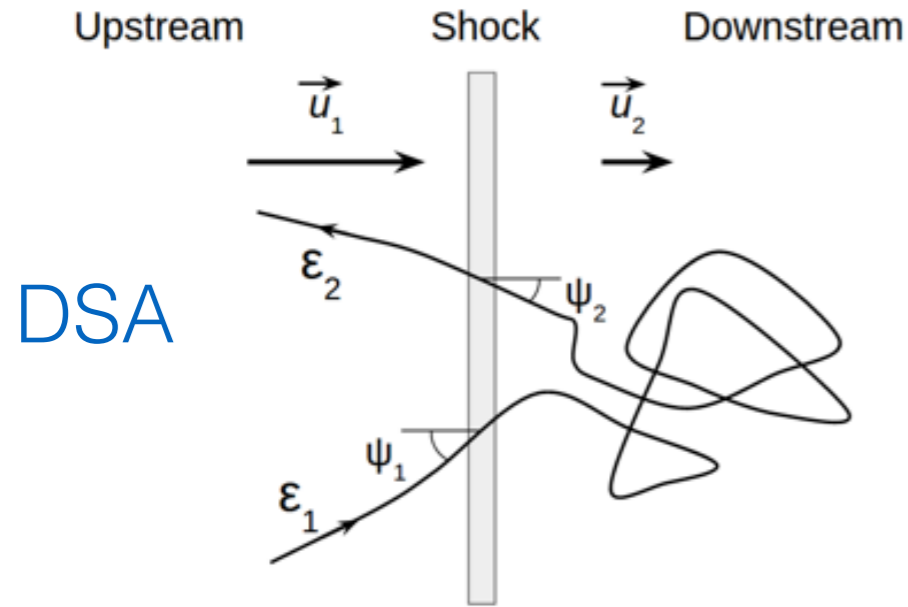
$$v_A = \frac{B_0}{\sqrt{\mu_0(N_e m_e + N_i m_i)}}$$

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



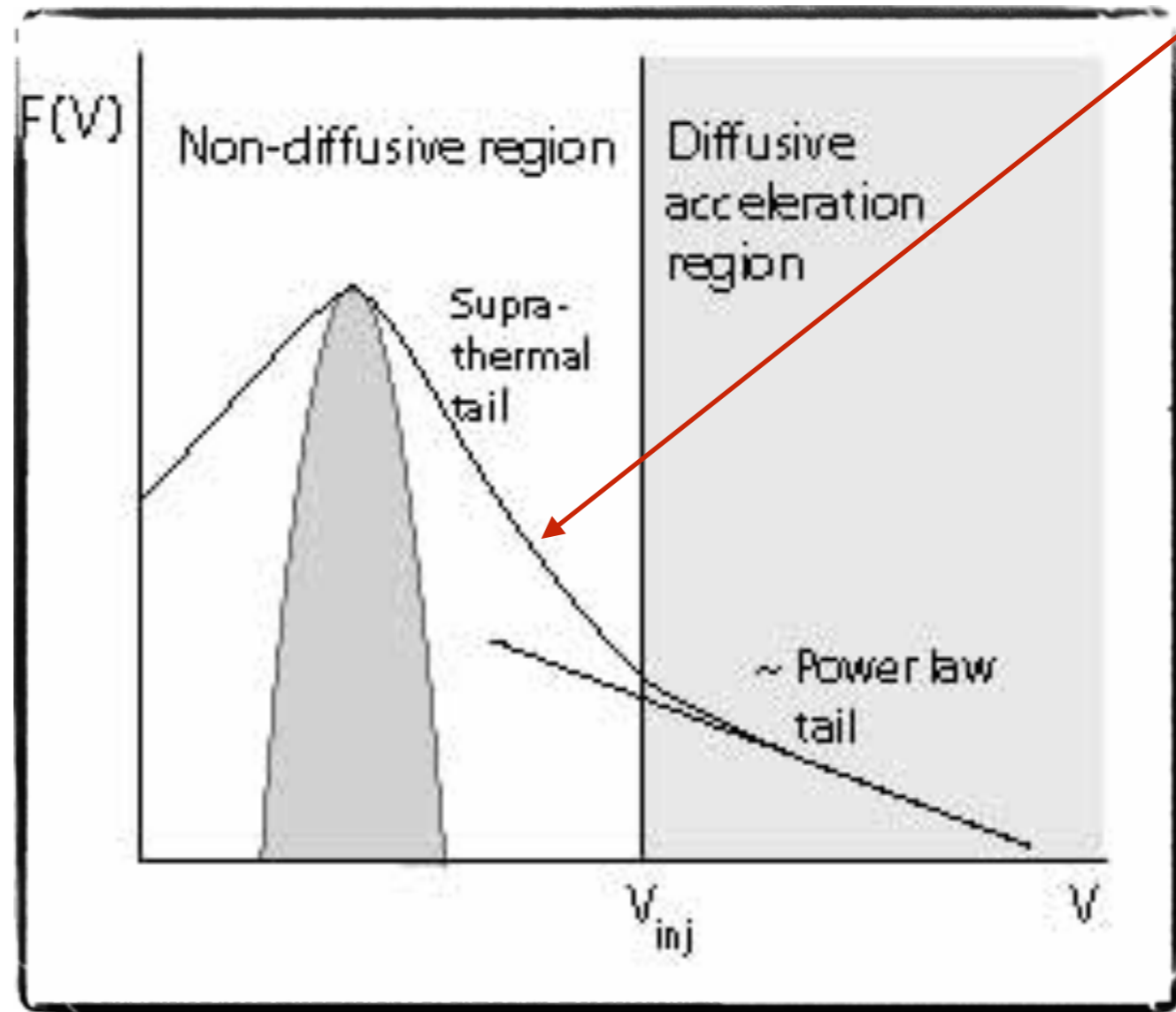
White – optical (Hubble)
 Blue – X-ray (Chandra)
 Red – radio (VLA)

Particle injection to DSA

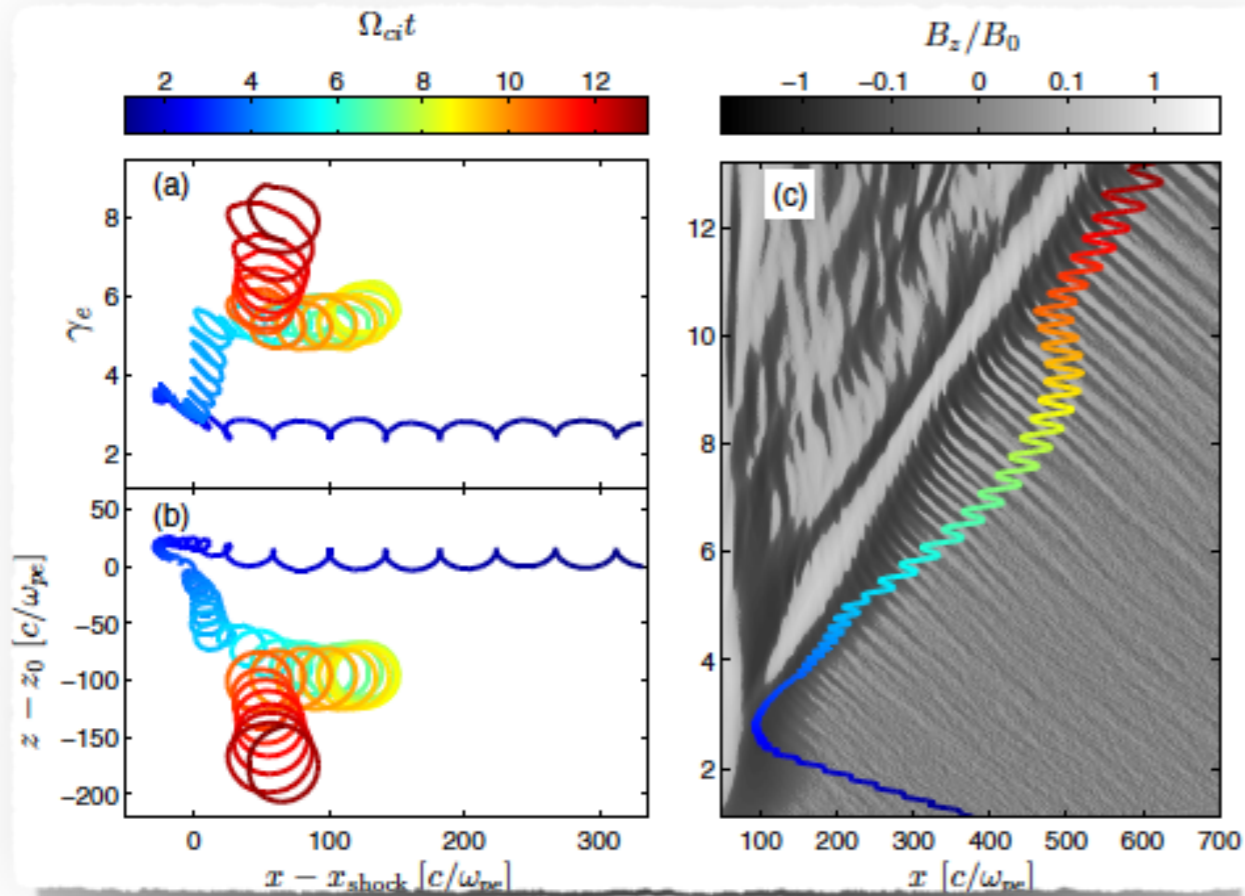


$$d_{sh} \sim (1-100) \lambda_{gi}$$

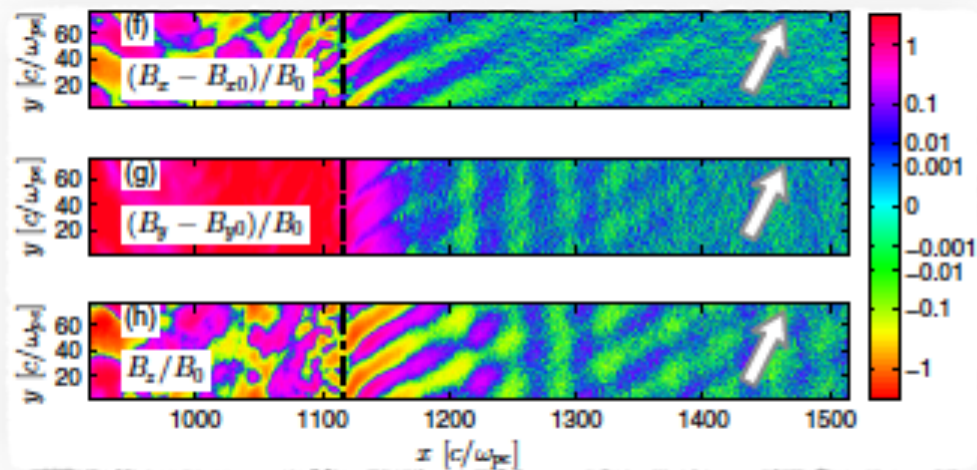
$$r_g(\epsilon_{inj}) > d_{sh}$$



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

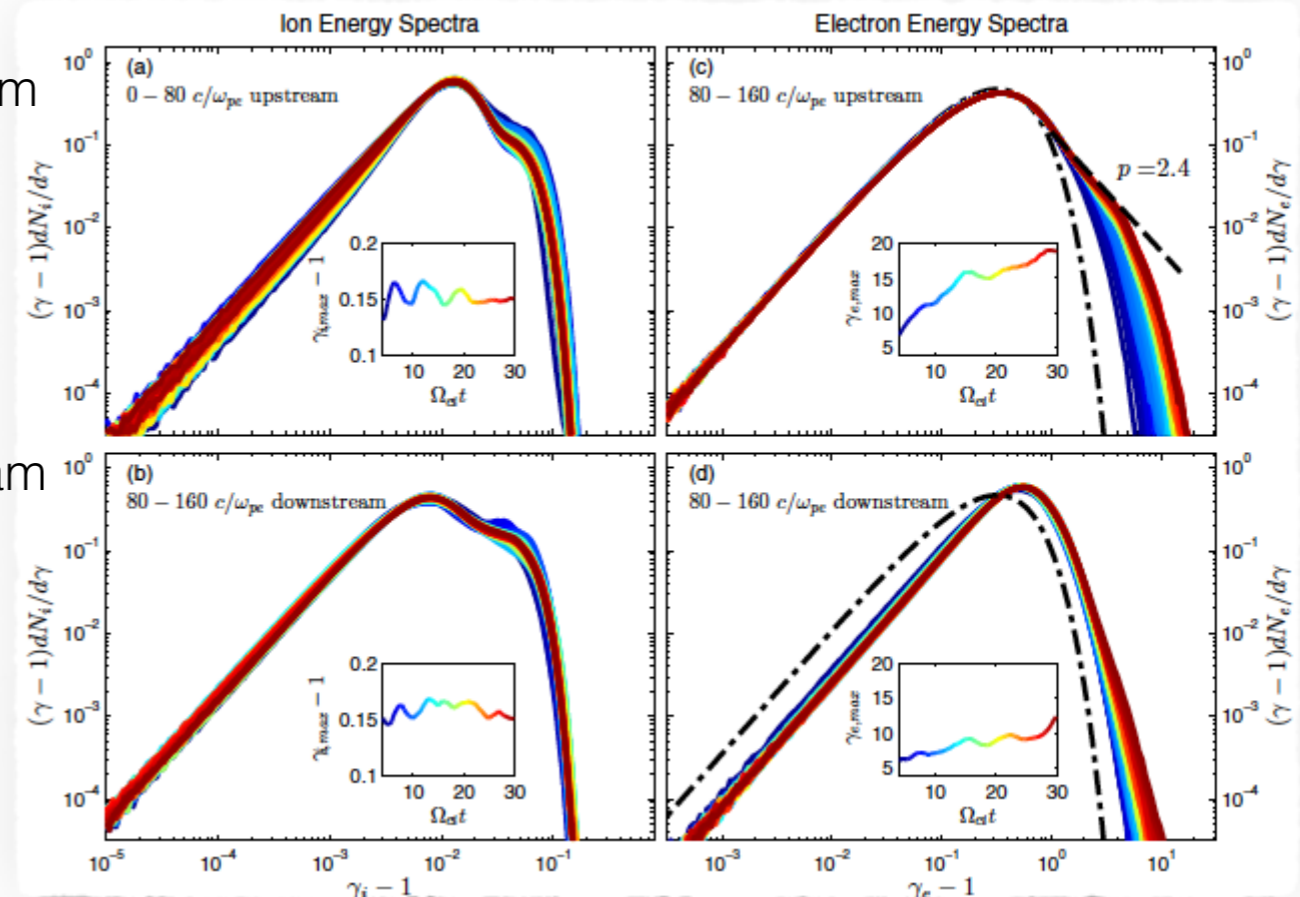


- SDA-reflected electrons scattered back towards shock by upstream self-generated waves - **DSA-like process**
- formation of **upstream** power-law spectra
- more effective at high β
- $\gamma_{\text{max}} \ll \gamma_{\text{inj}}$?



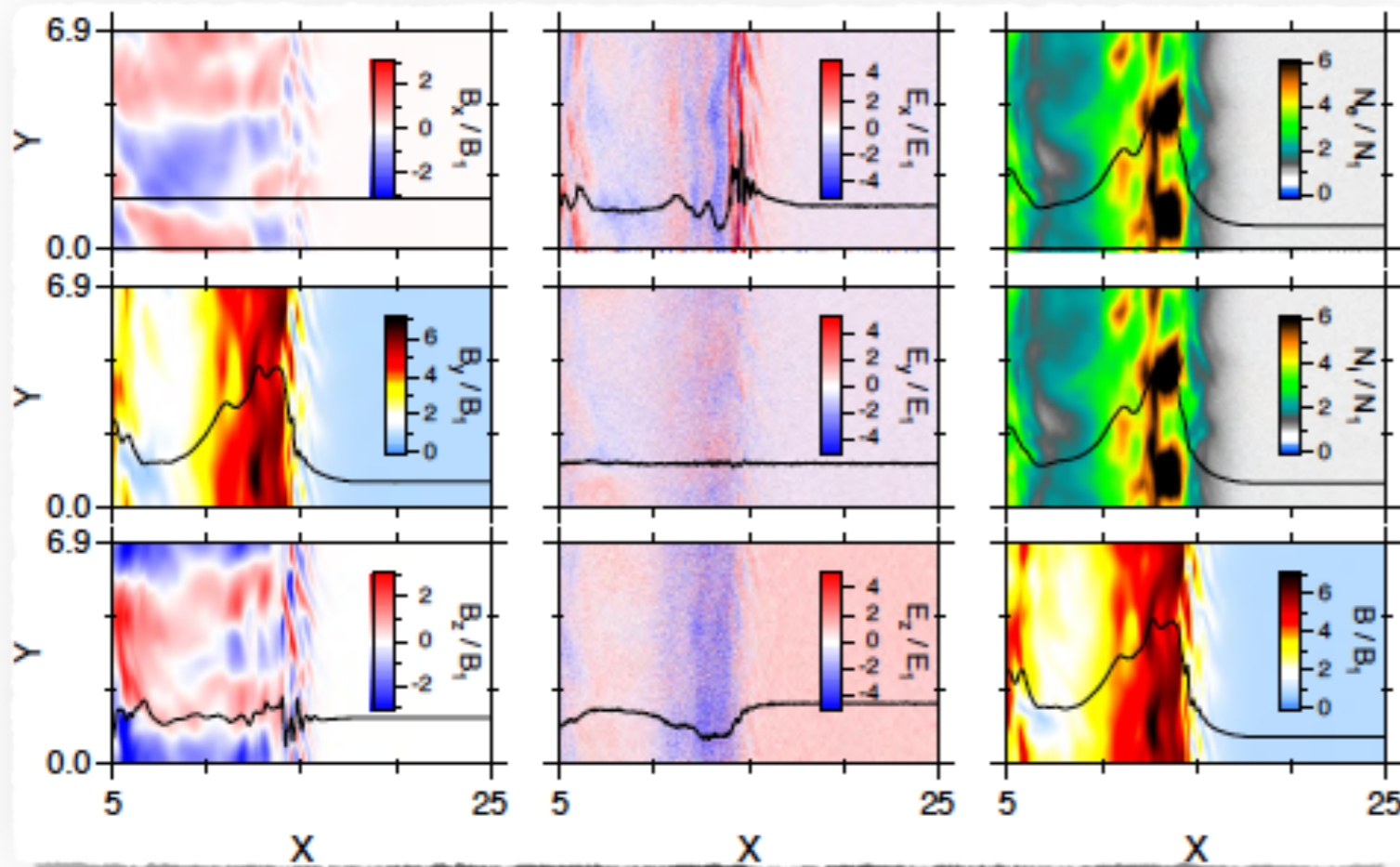
upstream

downstream

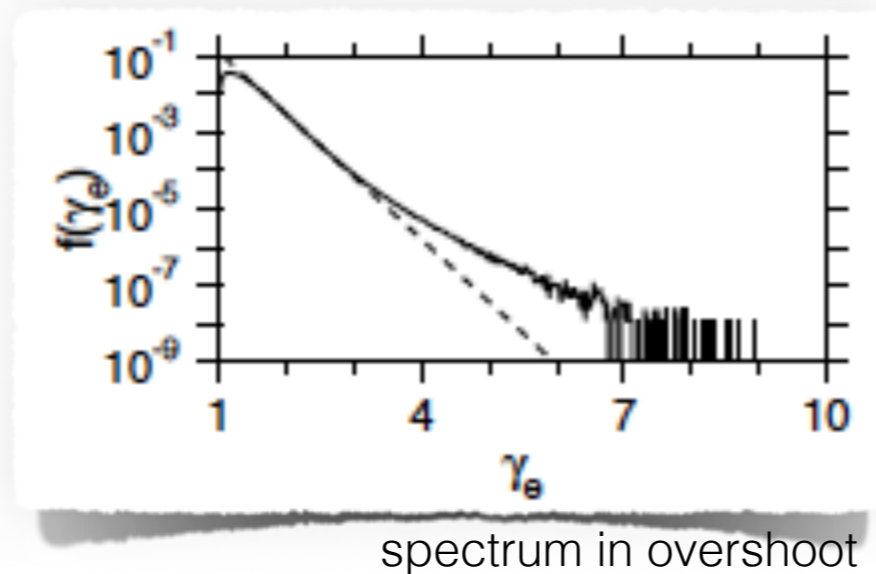


Matsukiyo et al. 2011 (1D)
 Guo et al. 2014 (2D)
 Kang et al. 2019 (2D)

Effects of the shock rippling



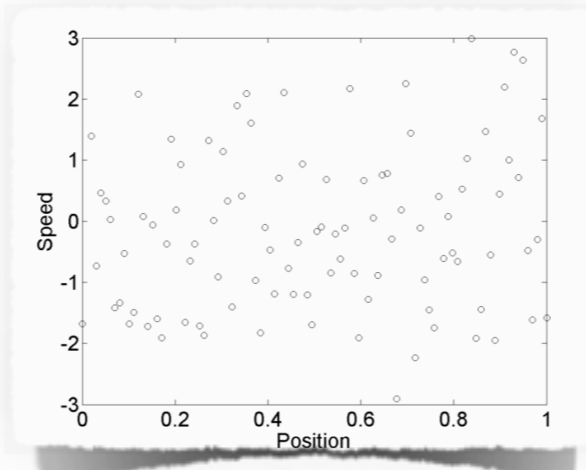
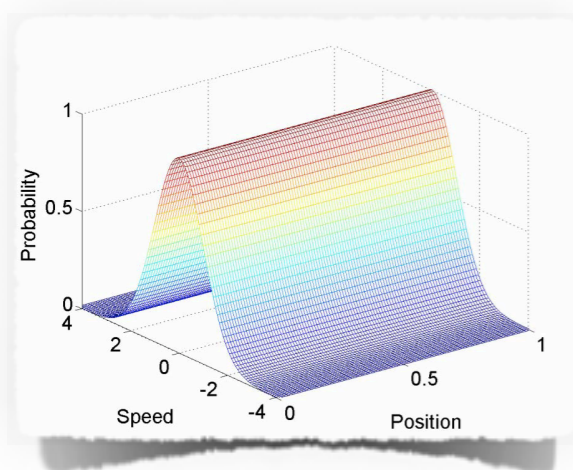
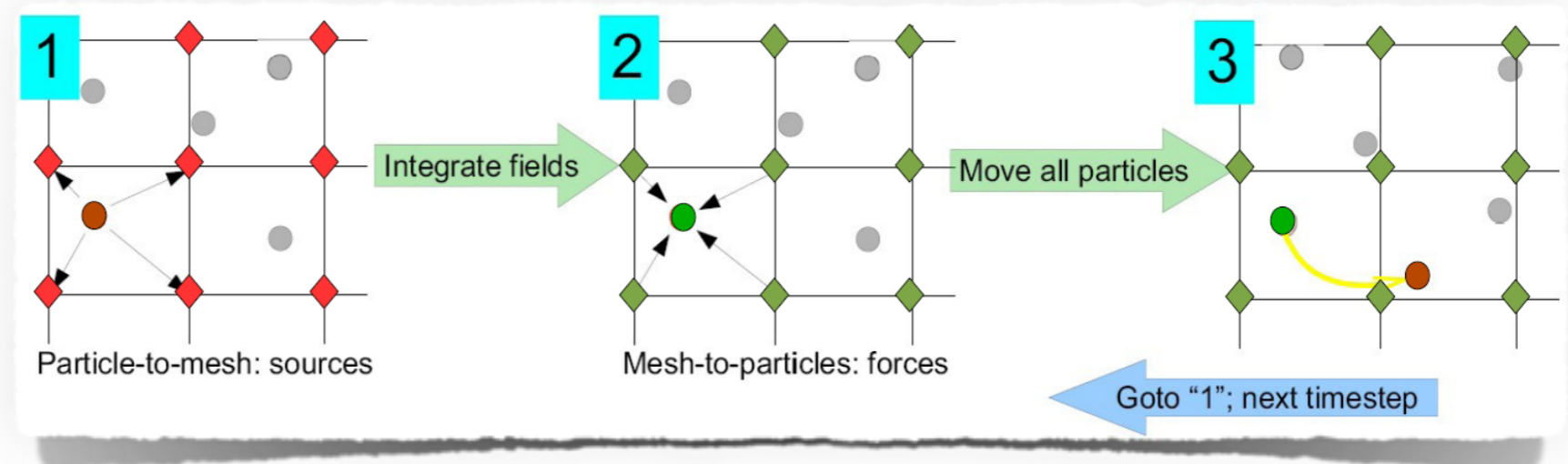
- no reflected electrons because of ion-scale shock ripples
- SDA **does not** work
- acceleration by scattering on the waves in the shock transition instead
- if the same shock rippling mechanism operates for conditions assumed in Guo et al. 2014 and Kang et al. 2019, then their simulations might have not been able to resolve it



relatively low $\beta=3$, Matsukiyo & Matsumoto 2015

Method of Particle-In-Cell Simulations

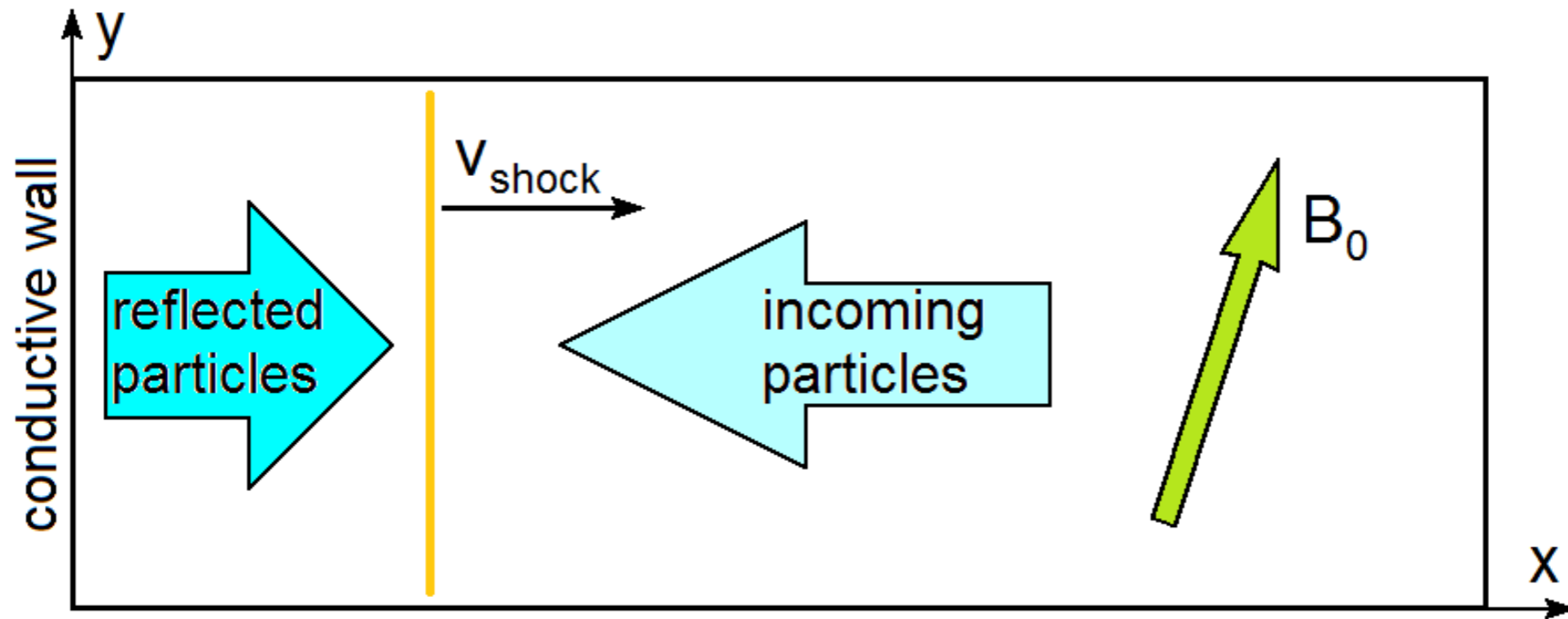
- Fully self-consistent description of collisionless plasma:
 - Vlasov equation (kinetic theory; time evolution of particle distribution function $f(\mathbf{x}, \mathbf{v}, t)$ in phase-space) + Maxwell's equations
- Particle-In-Cell modeling - an *ab-initio* method of Vlasov equation solution through:
 - 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)

Our current work: investigate multi-scale electron acceleration physics
with large-scale 2D Particle-In-Cell simulations

Kobzar et al., in preparation (2020)



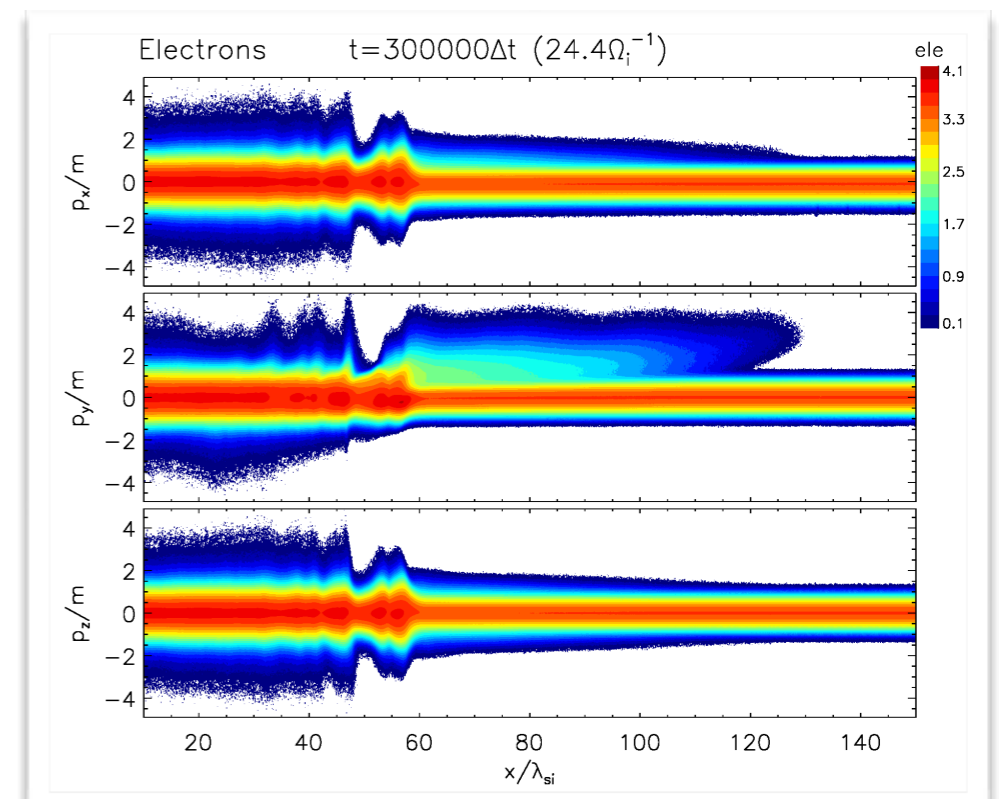
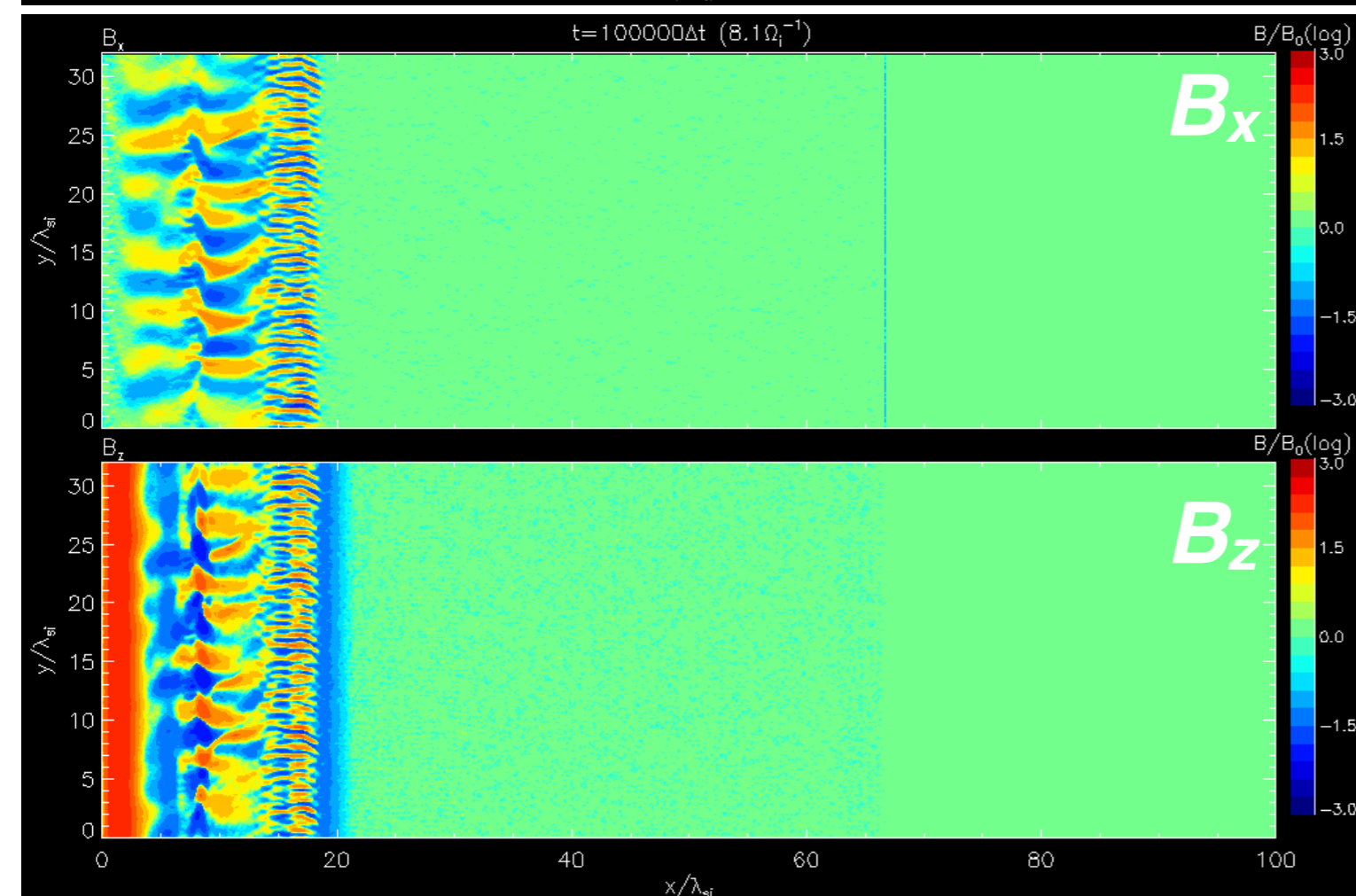
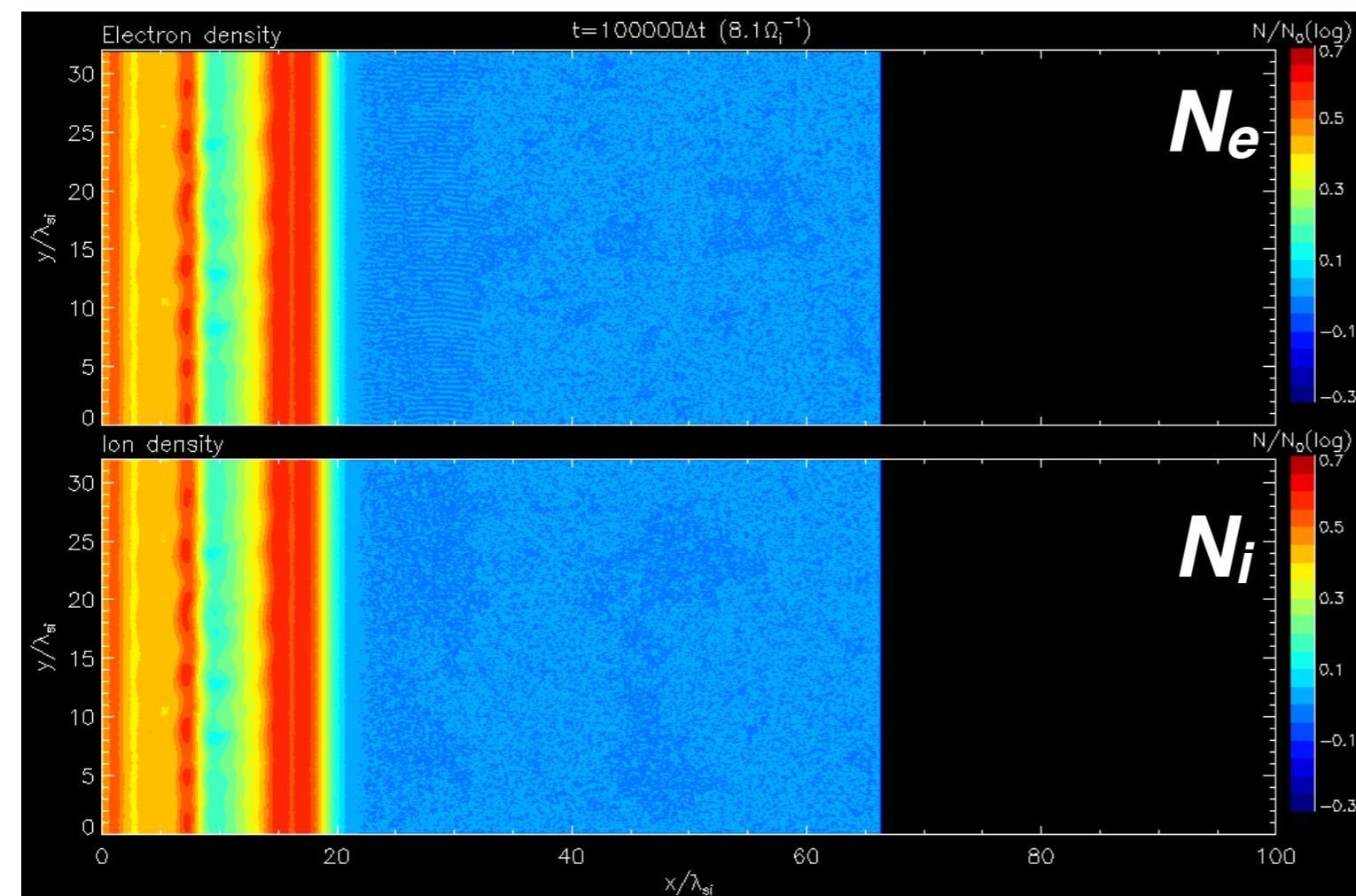
2D3V ($L_x \times L_y = 333 \lambda_{\text{si}} \times 32 \lambda_{\text{si}}$), $M_A=6.1$, $M_s=3$,
 $m_i/m_e=100$, $v_0=0.1c$, $\beta=5$ (plasma temperature $k_B T \approx 40 \text{ keV}$)

subluminal shock: $\vartheta=75^\circ$ ($\vartheta_{\text{cr}} \approx 81^\circ$)

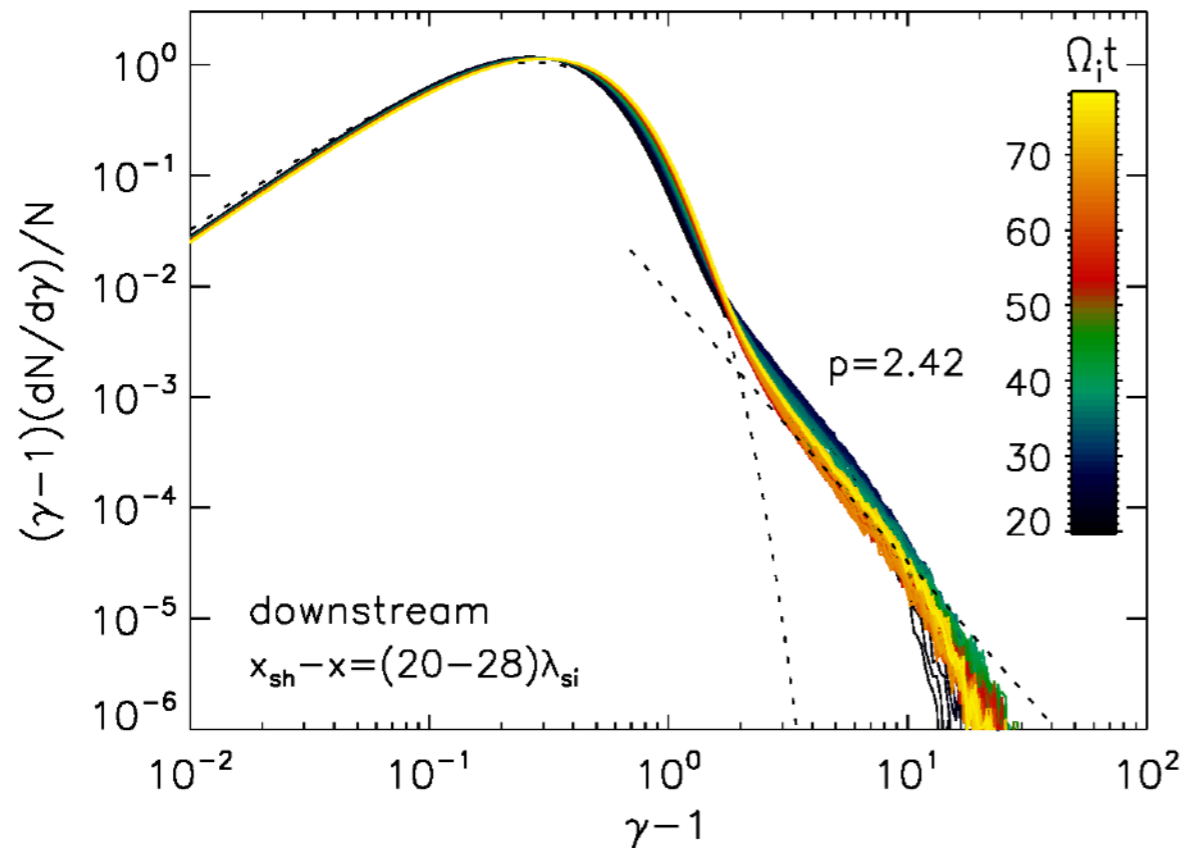
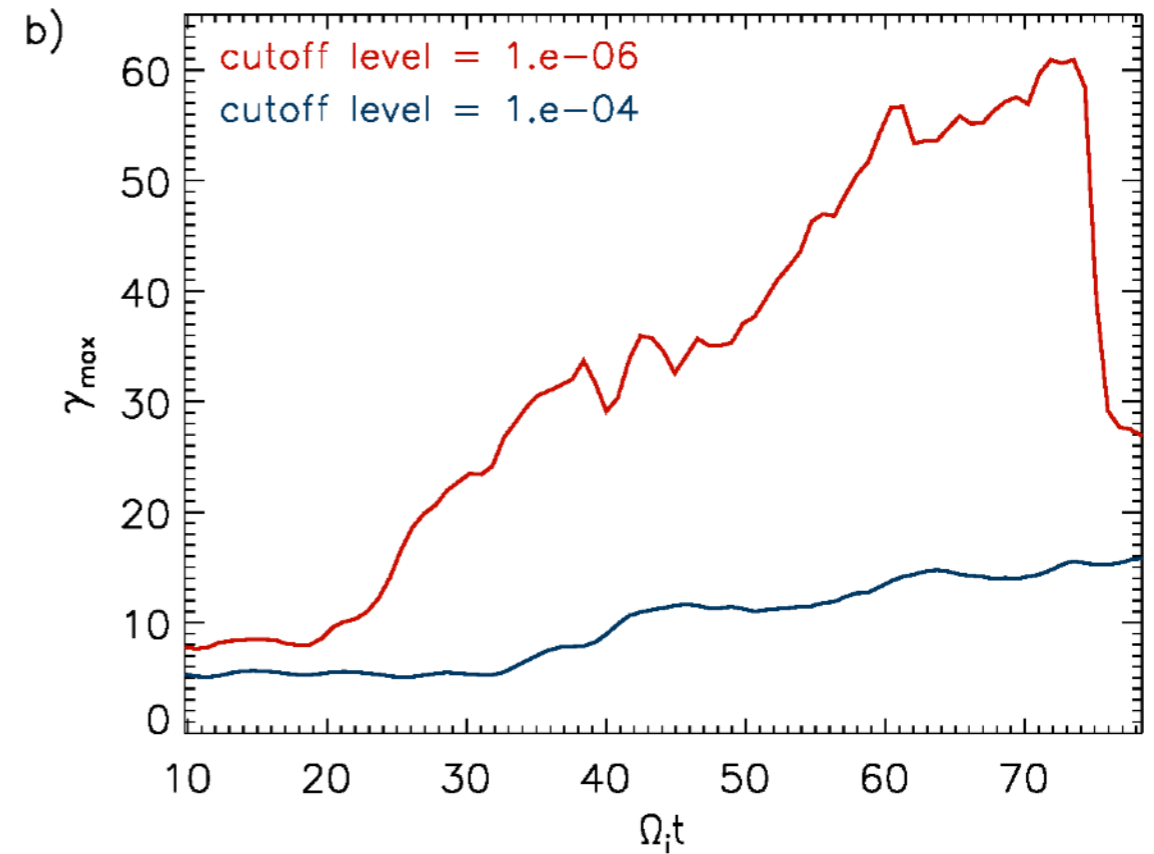
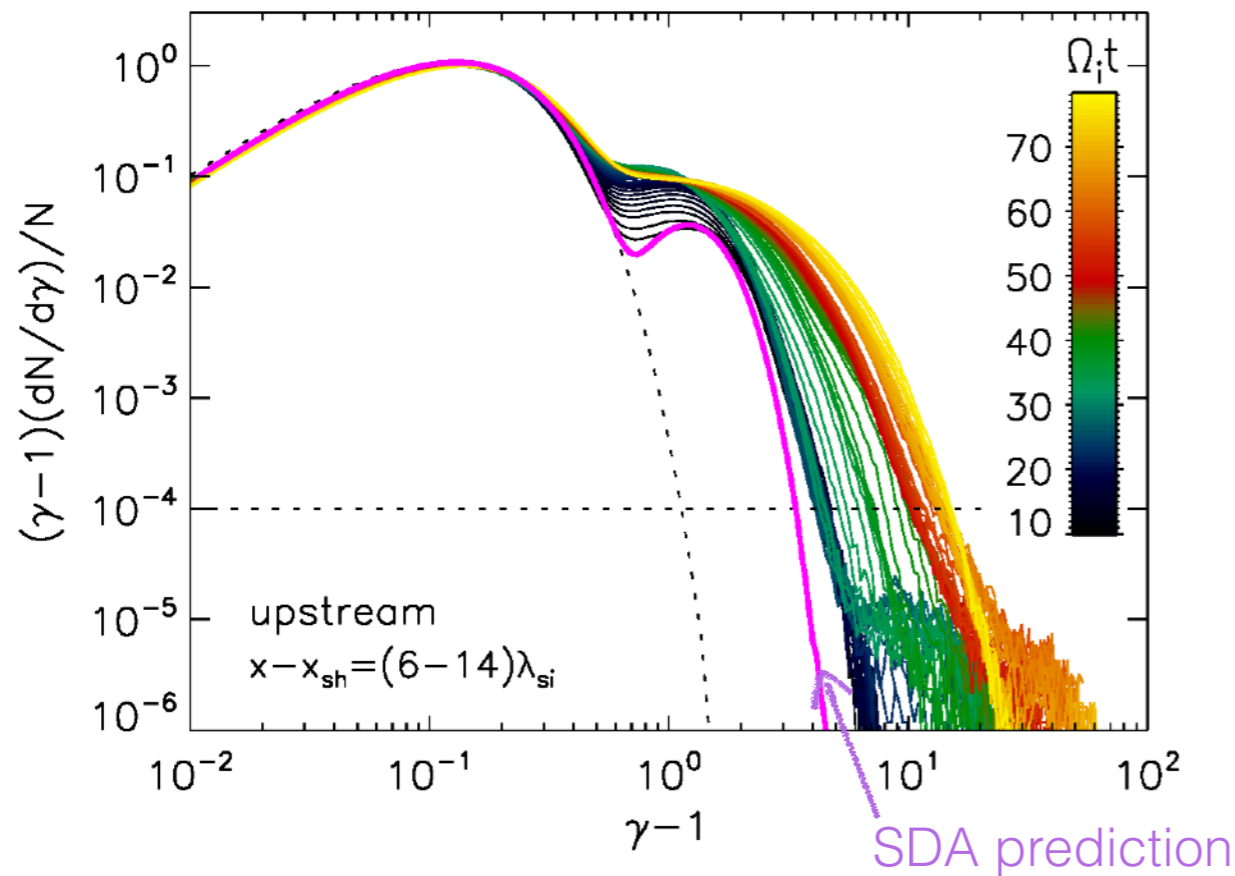
$$v_t \simeq 1.5 v_{\text{th},e} > v_{\text{th},e} \quad (v_t = v_{\text{sh}}^{\text{up}} / \cos \vartheta)$$

Global shock structure: multi-scale turbulence

- **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**

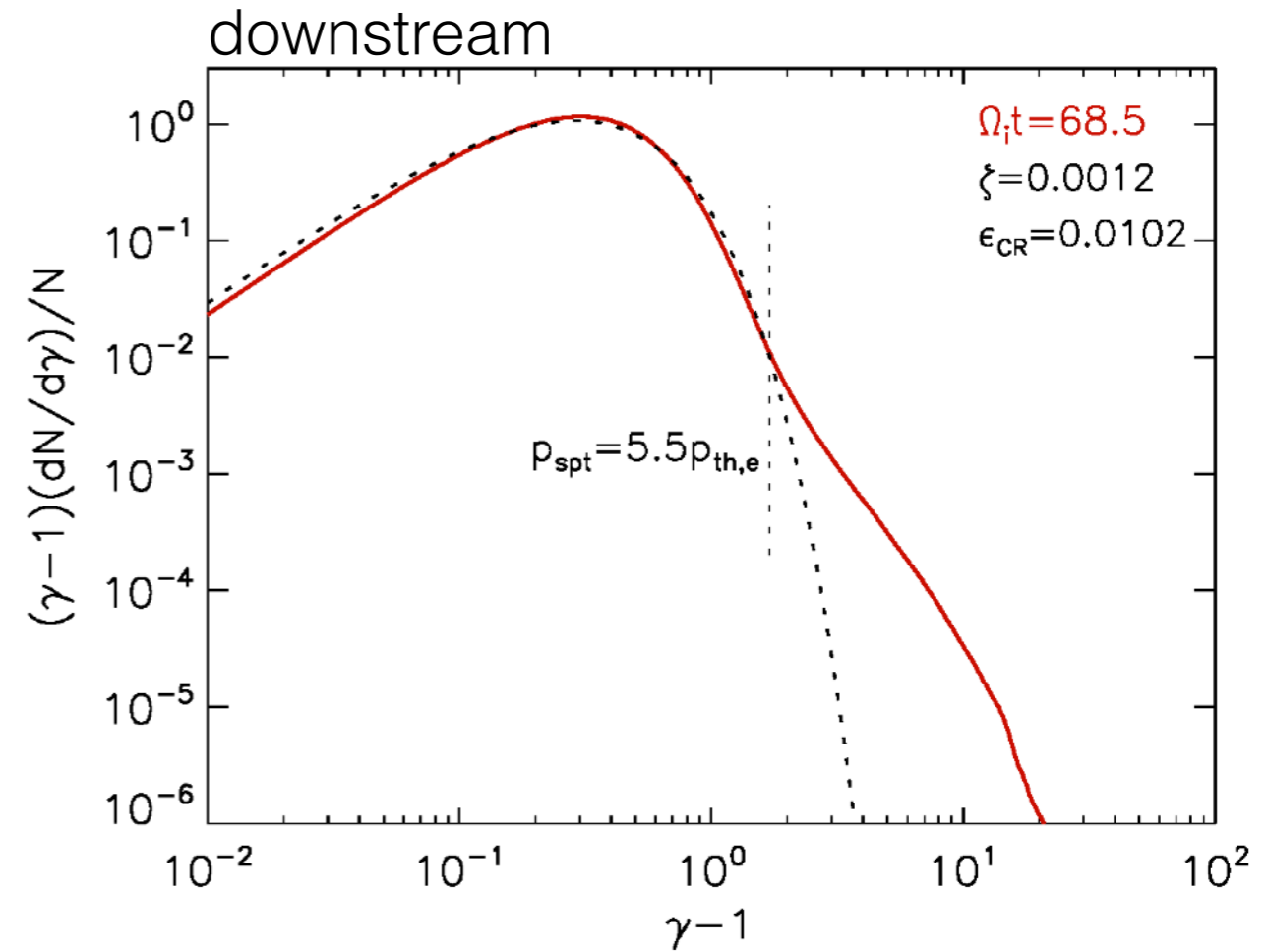
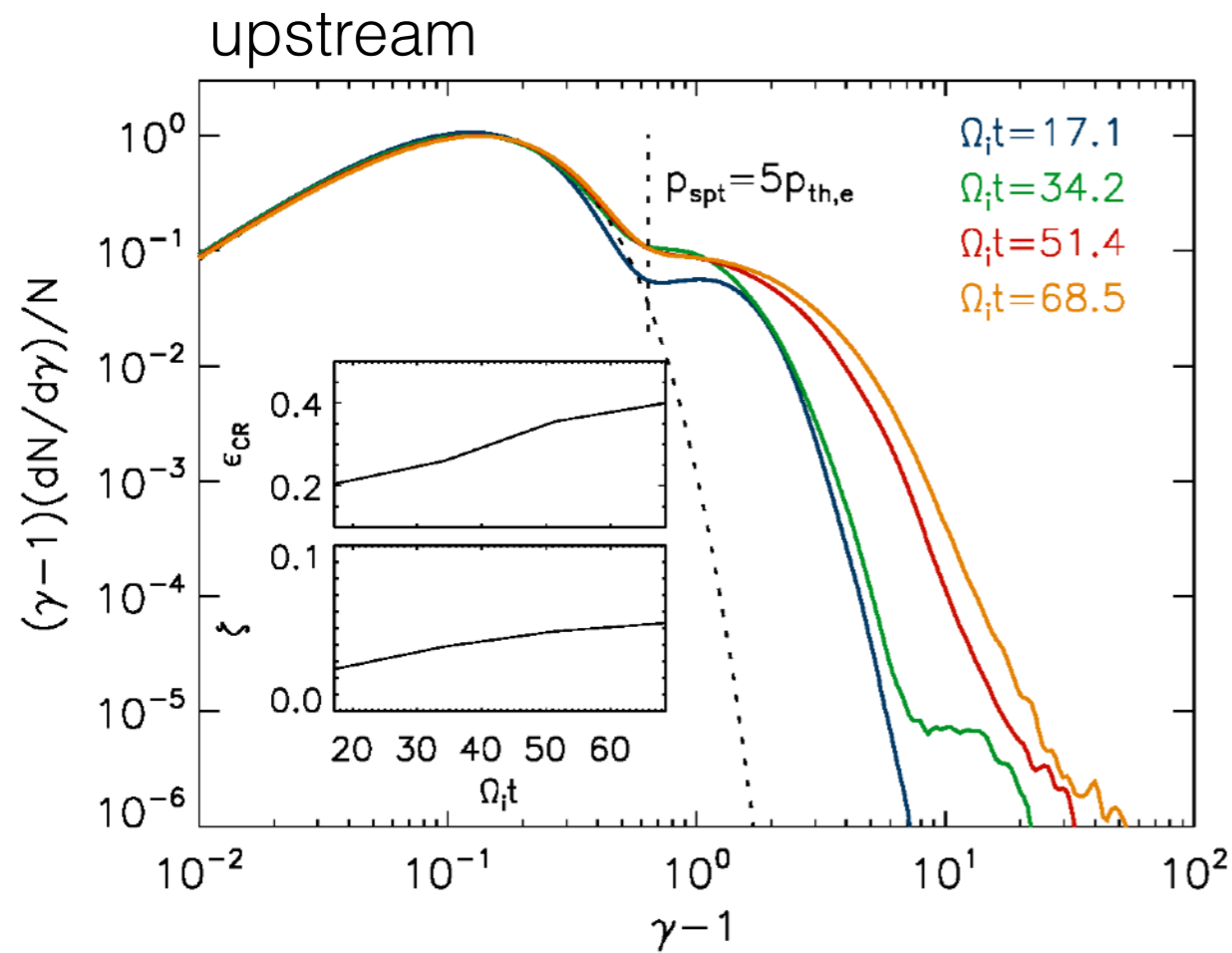


Electron spectra – time evolution



- substantial increase in non-thermal tail production efficiency coincident with the onset of the shock rippling at $\Omega_{ci}t \approx 20$
- power-law spectra **downstream** in agreement with observations

Electron spectra – injection efficiency



$$\zeta = \frac{4\pi}{N_2} \int_{p_{\text{spt}}}^{p_{\text{max}}} \langle f(p) \rangle p^2 dp \quad - \text{fraction of supra-thermal electrons}$$

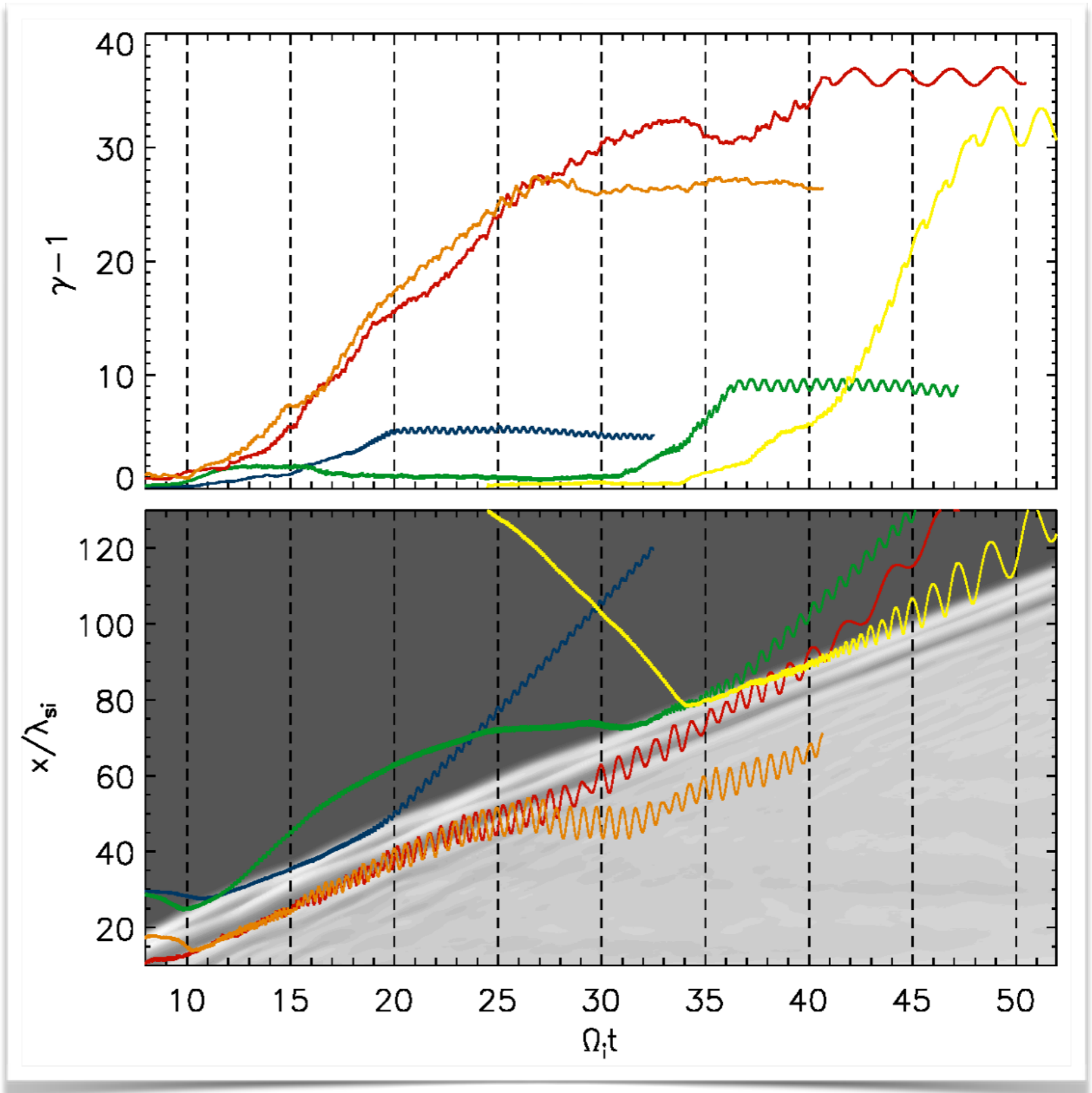
ϵ_{CR} - corresponding energy density fraction

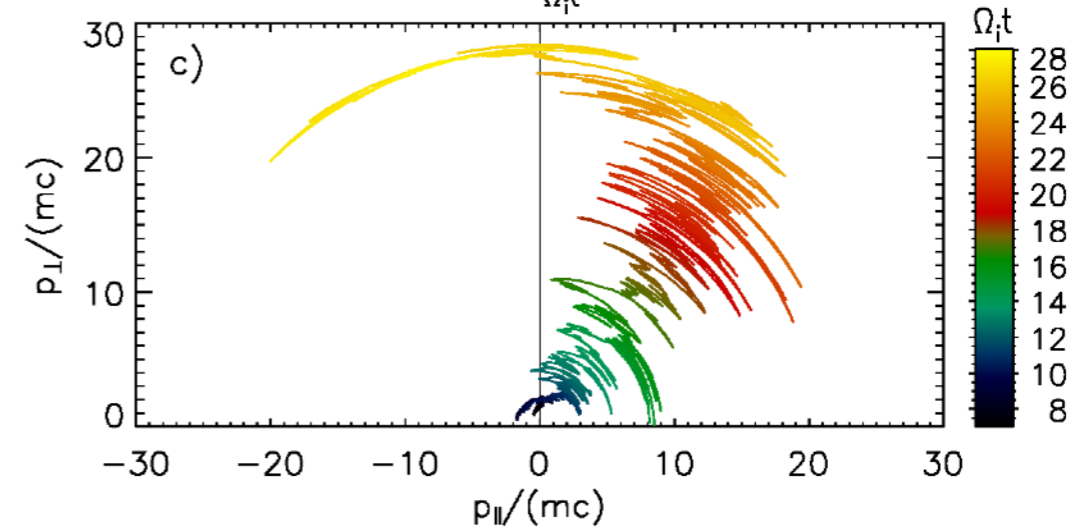
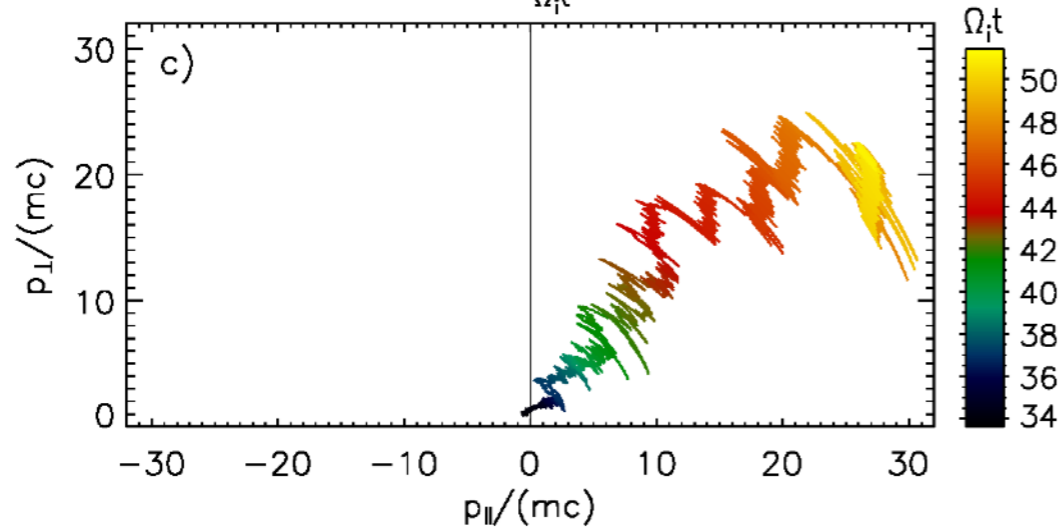
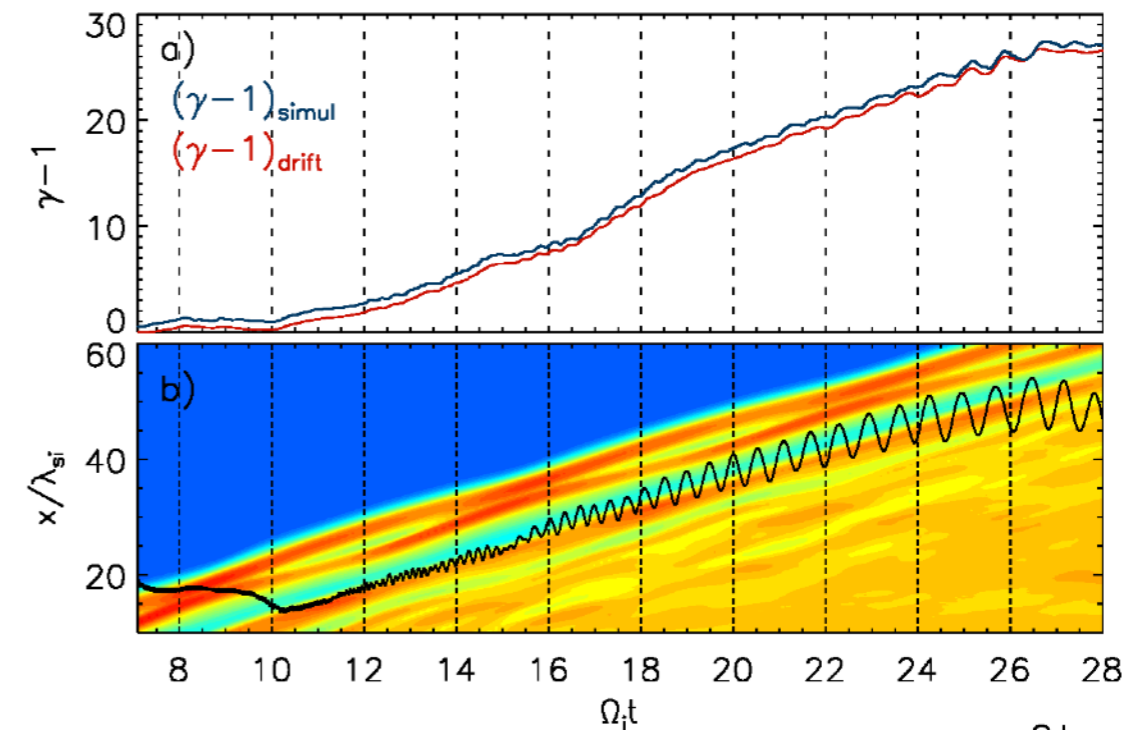
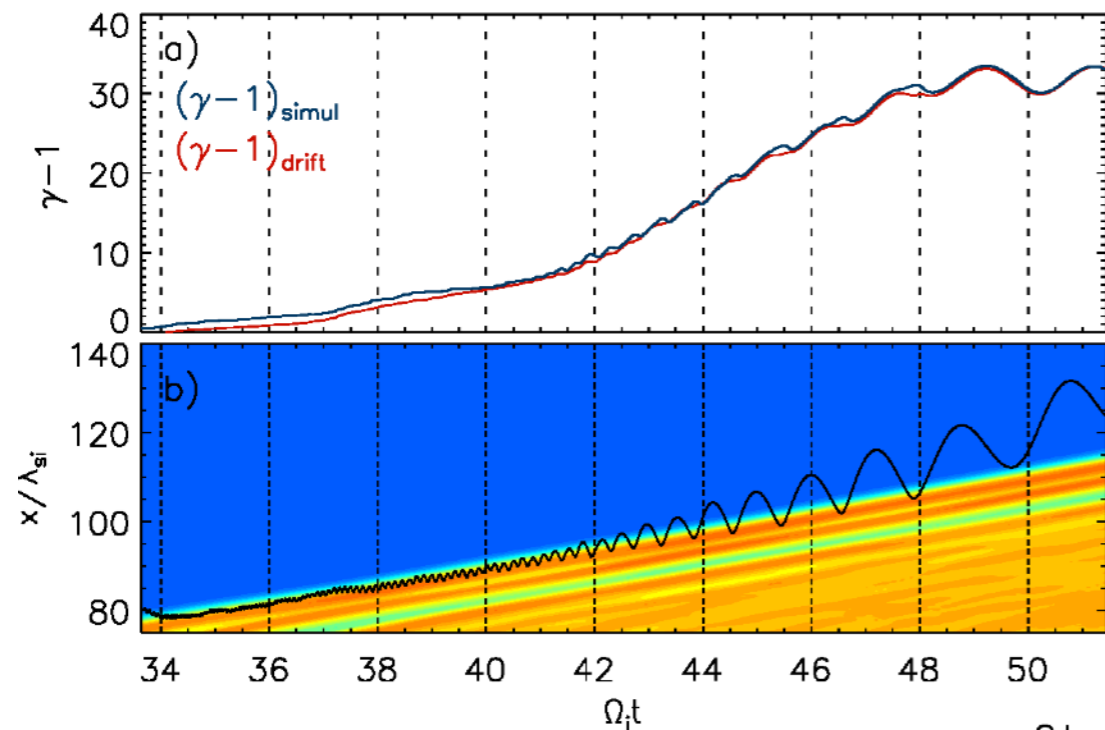
$$\zeta_{\text{max,up}} \simeq 5\%, \quad \epsilon_{\text{CRmax,up}} \simeq 40\%$$

$$\gamma_{\text{max,up}} \approx 40 - 60 \quad \leftarrow \gamma_{\text{inj}} \approx 25 \quad (p_{\text{inj}} \sim 3 p_{\text{th,i}})$$

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 ($\sim 1/\Omega_i$)
- acceleration takes place also deep in the shock transition





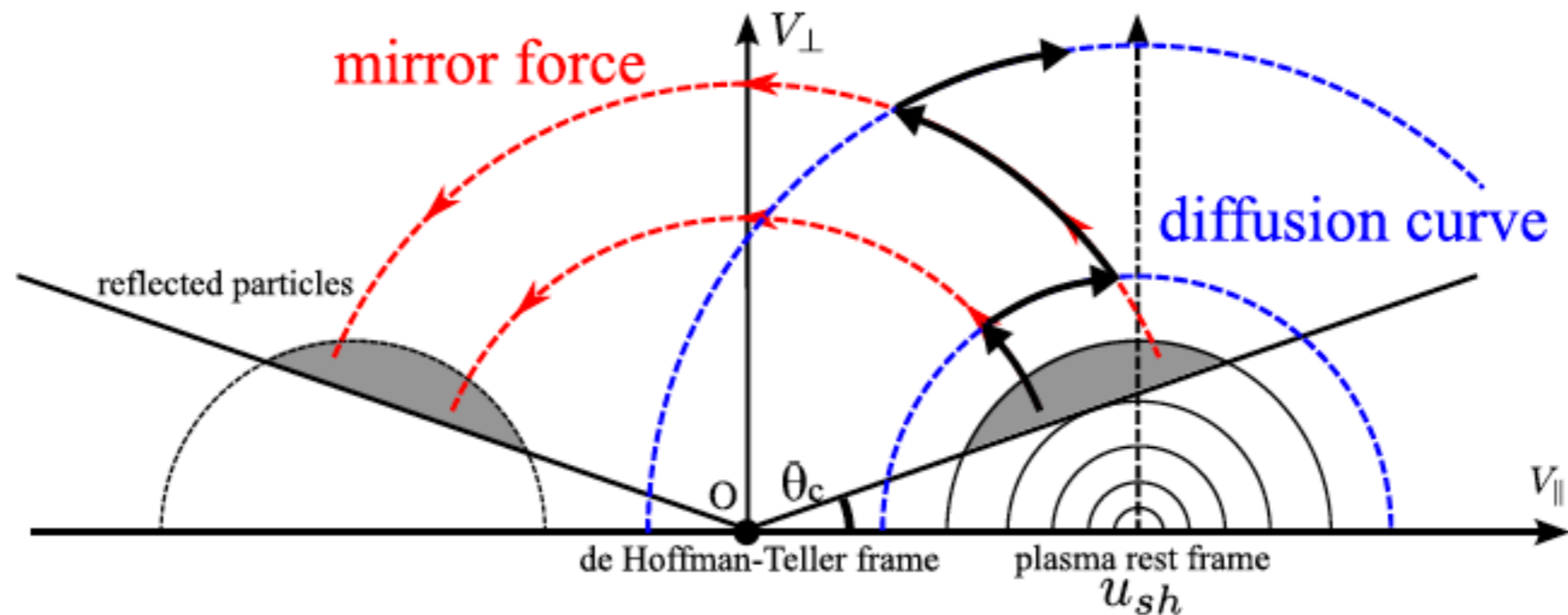
- most accelerations associated with an increase in p_{\perp}
- strong **pitch-angle scattering** (arcs in p_{\parallel} - p_{\perp} momentum space)
- energy gain mostly through the drift along motional electric field:

$$\Delta\gamma_{\text{drift}} = (-e/m_e c^2) \int E_z dz$$

→ Stochastic Shock-Drift Acceleration (SSDA)

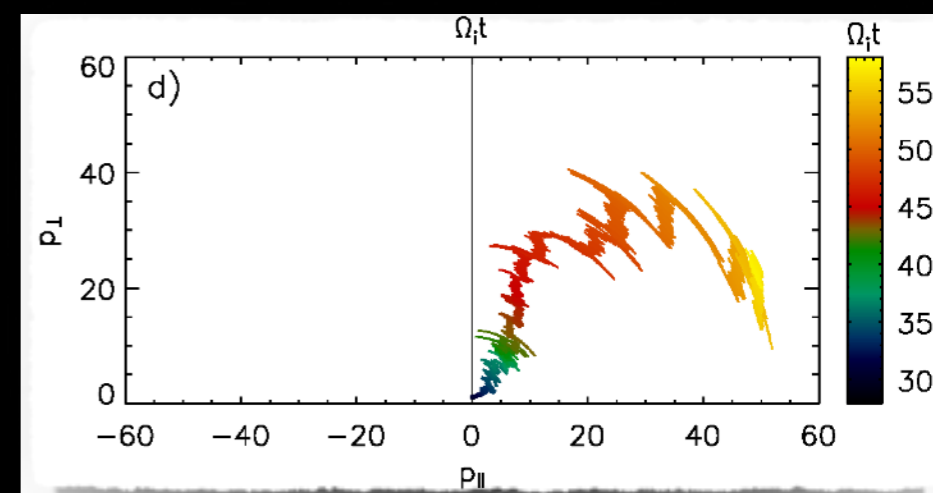
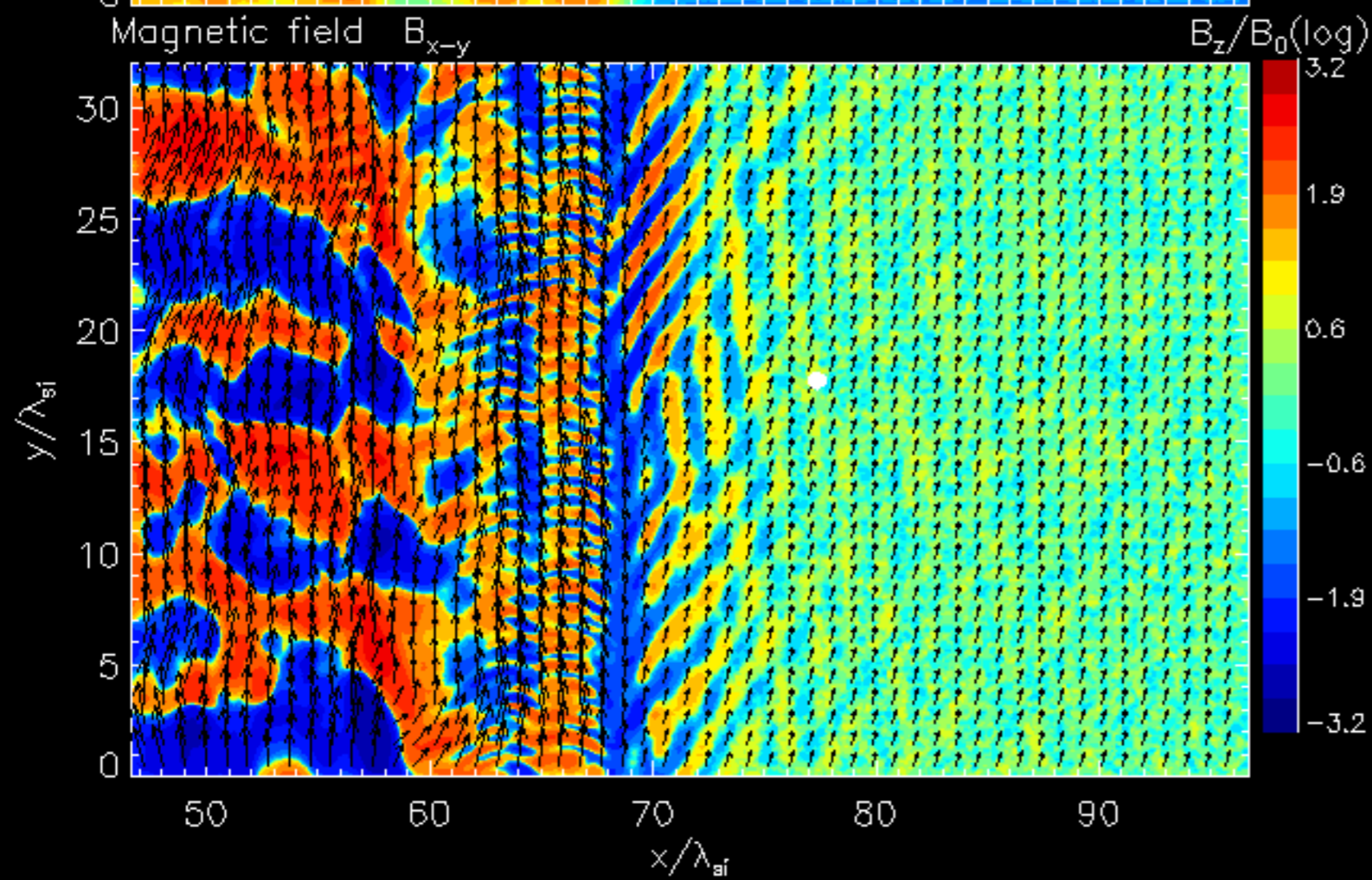
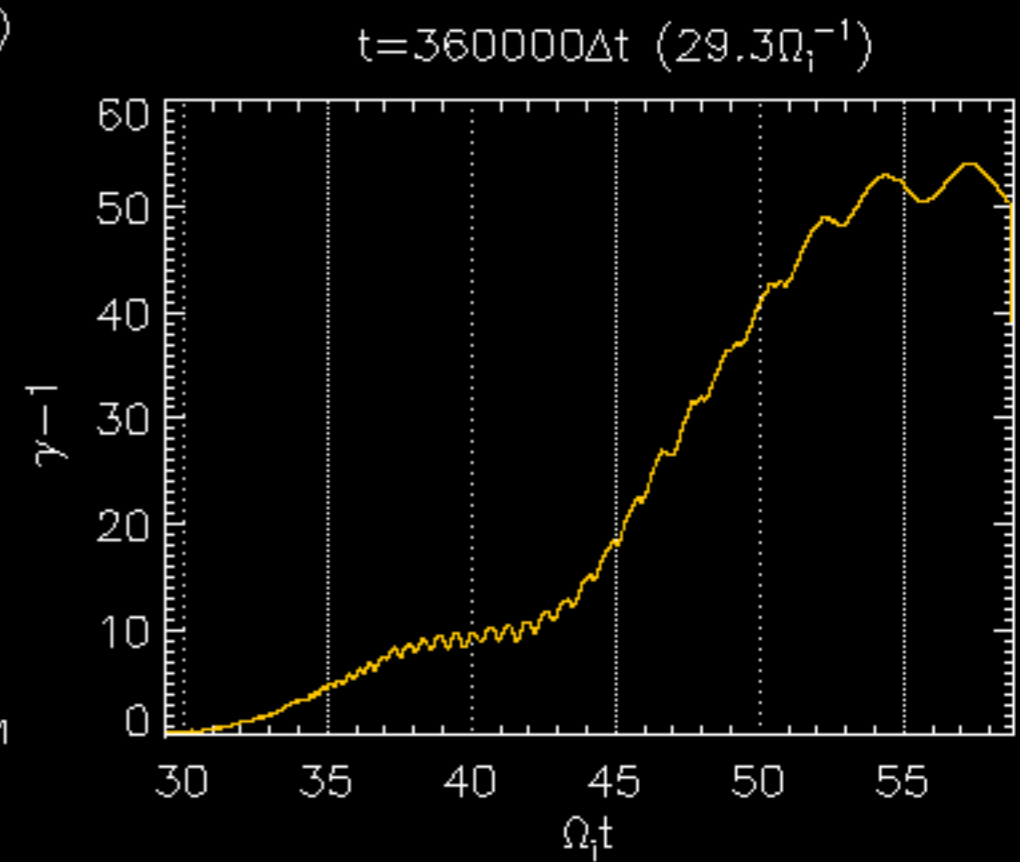
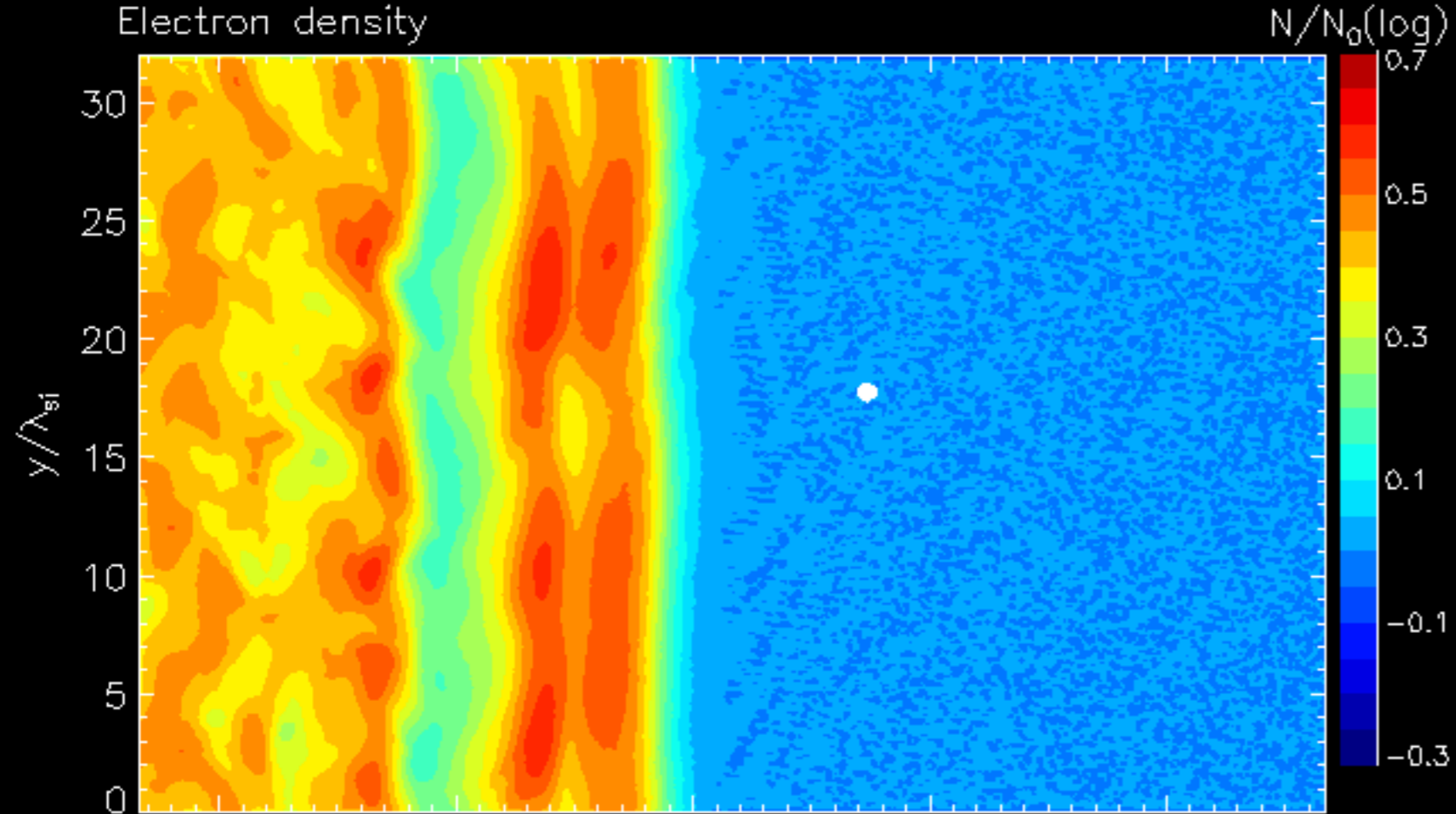
Stochastic Shock Drift Acceleration (SSDA)

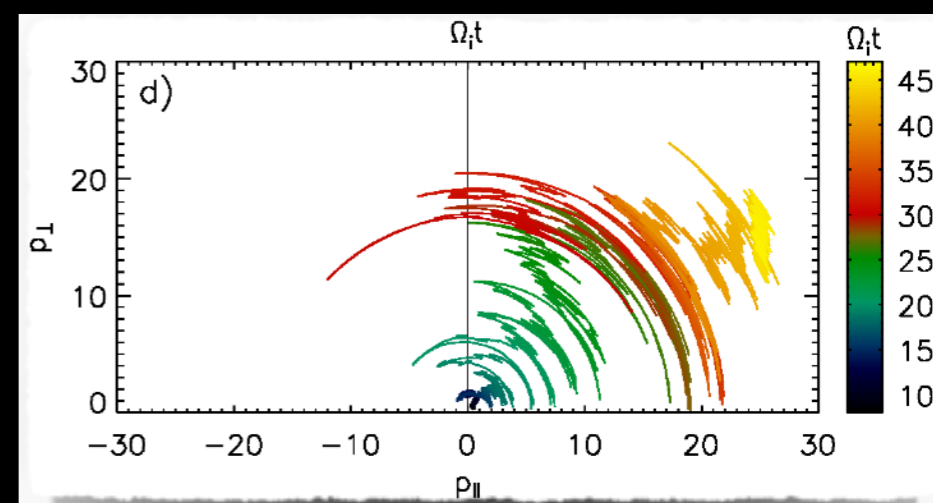
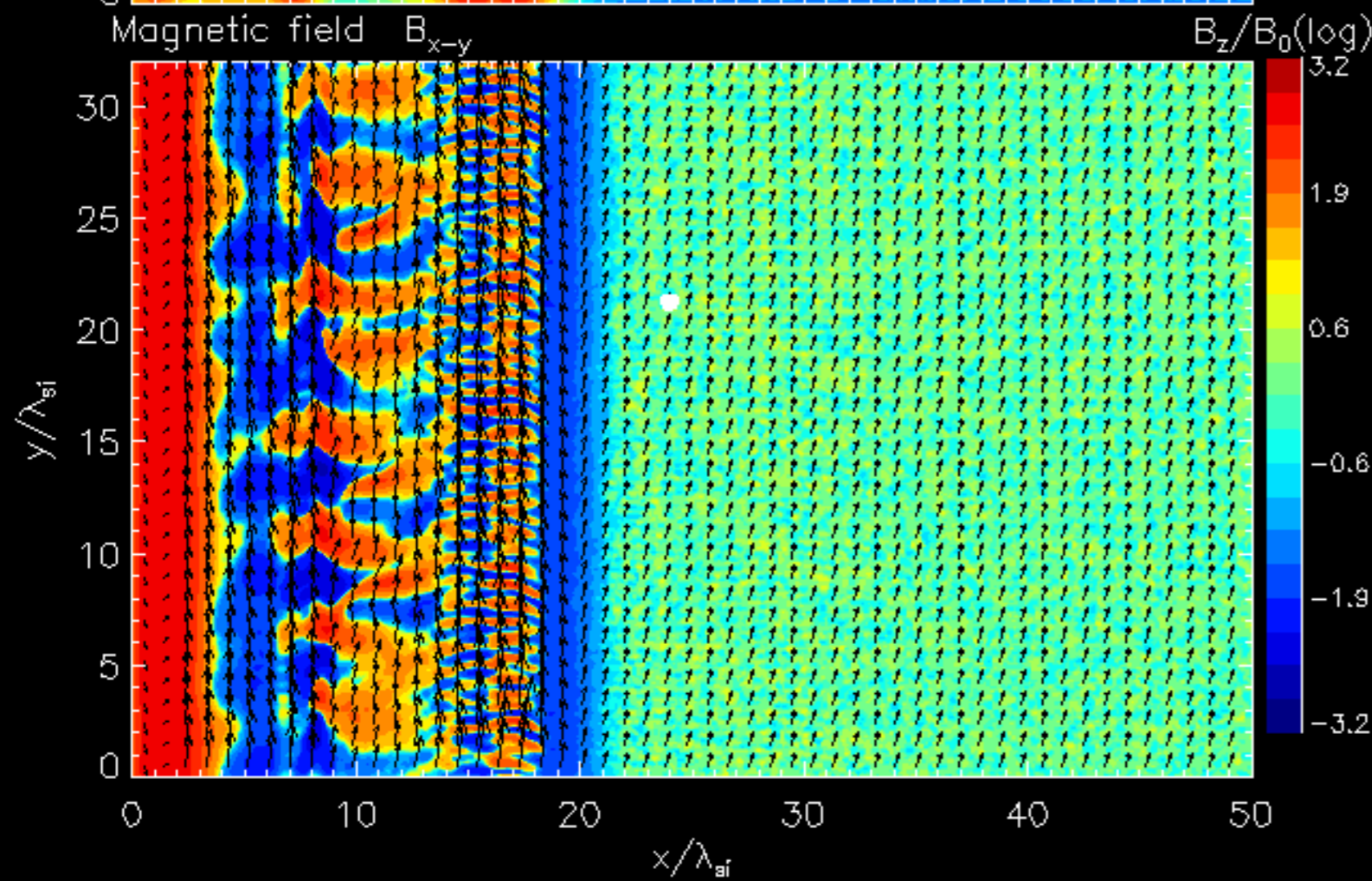
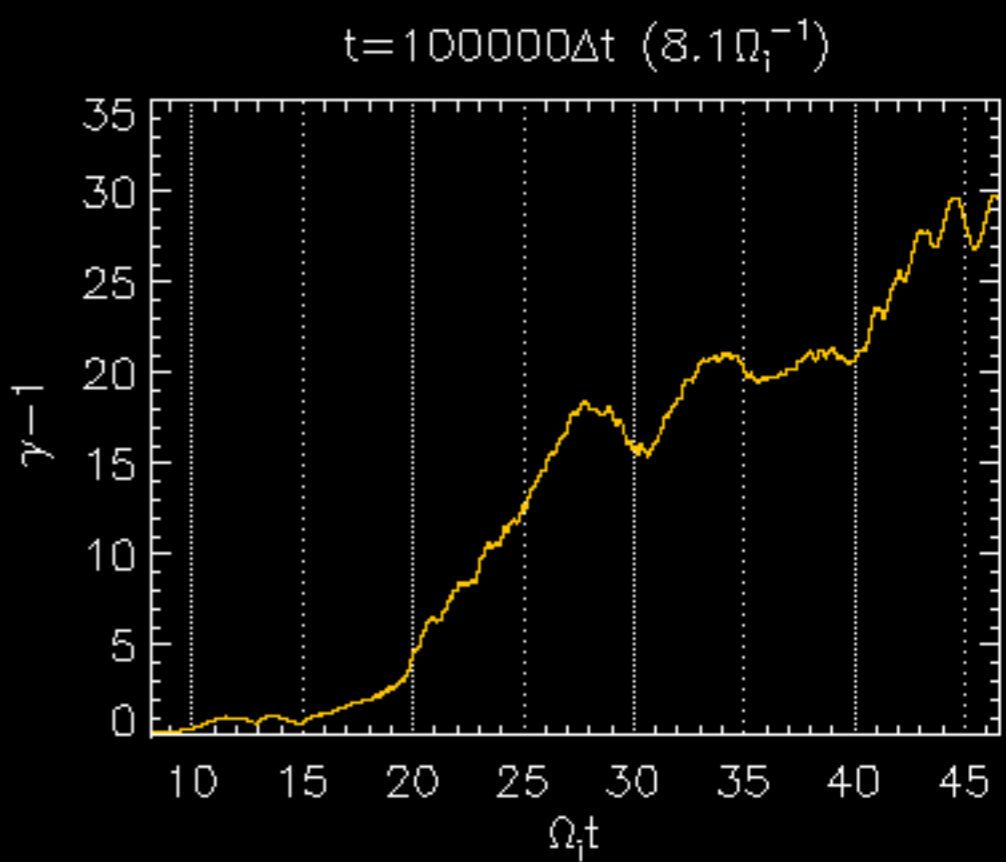
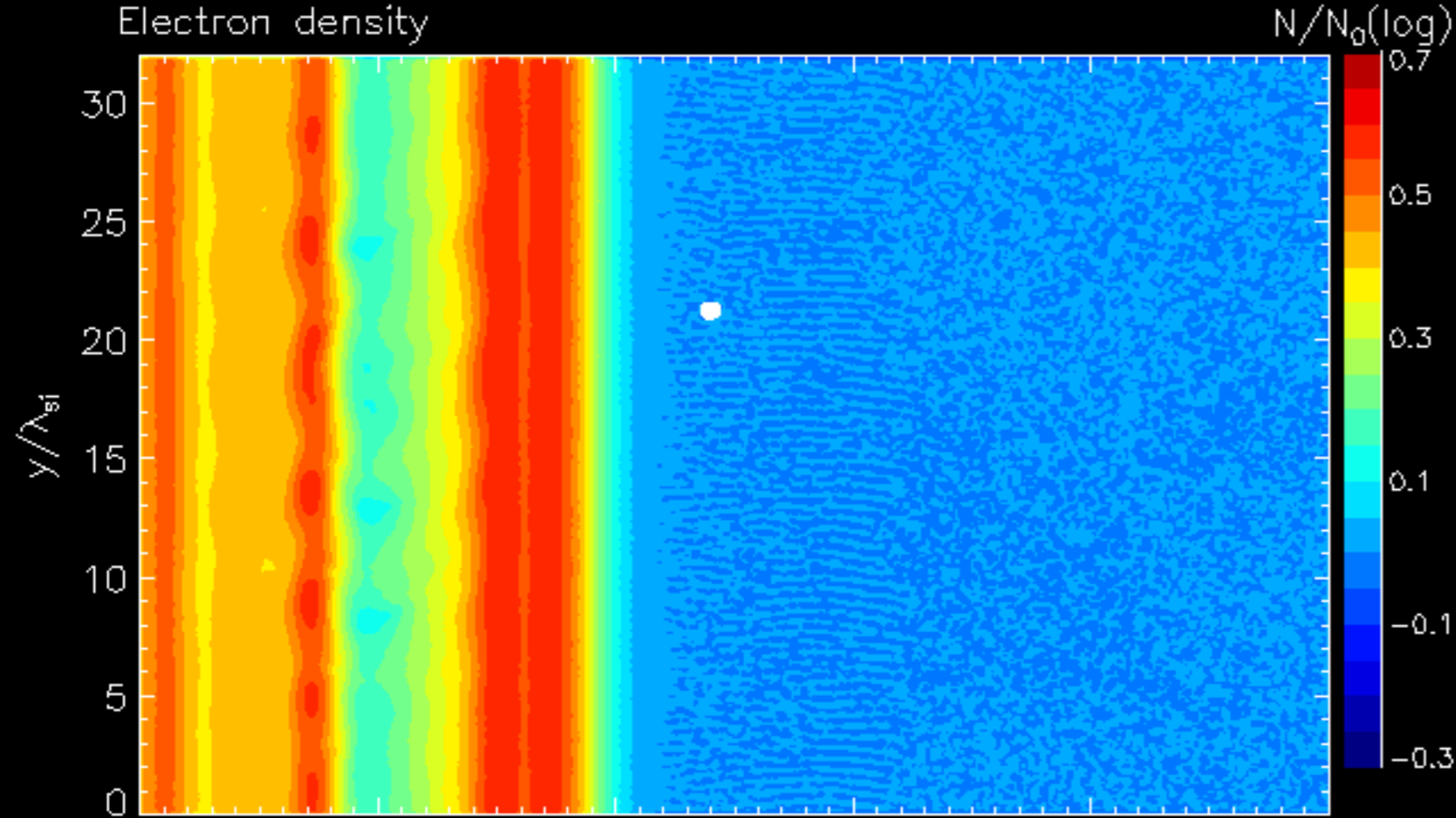
Katou & Amano (2019)



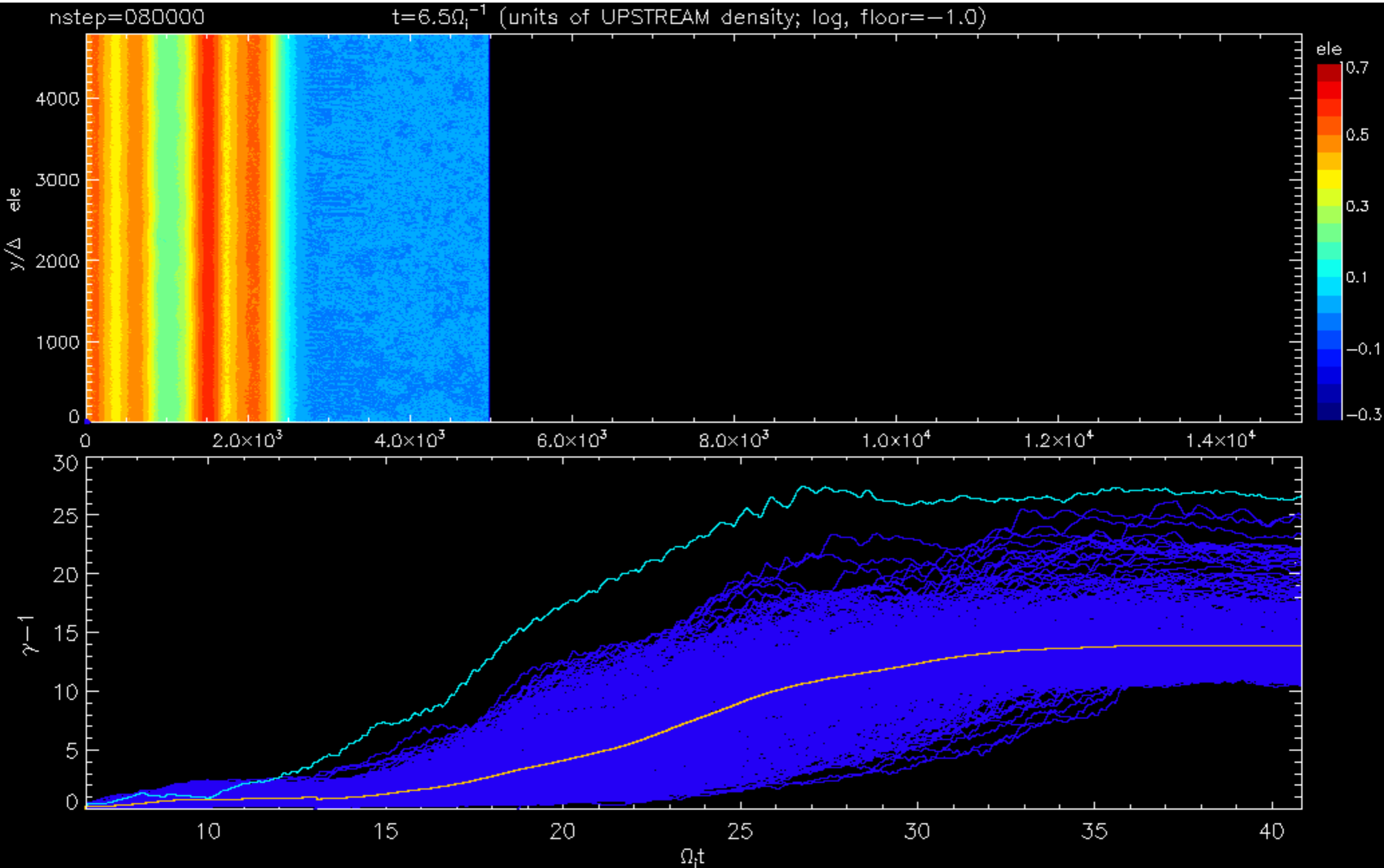
- adiabatic mirror reflection in the HTF
- elastic scattering (diffusion) in the plasma rest frame

- 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





Downstream spectrum formation



- downstream particles accelerated in the shock through SSSDA
- advection of upstream-reflected particles plays minor role

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
- for parameters analysed in this work we find the presence of multi-scale turbulence, including ion-scale shock rippling modes, to be critical for efficient electron acceleration
- electron injection proceeds mainly through the stochastic SDA process, effects of multi-SDA cycles are also observed
- acceleration to very high energies occurs that should lead to electron injection to DSA in the presence of long-wave (MHD) upstream turbulence
- *work to be continued*