Particle Acceleration at Merger Shocks in Galaxy Clusters

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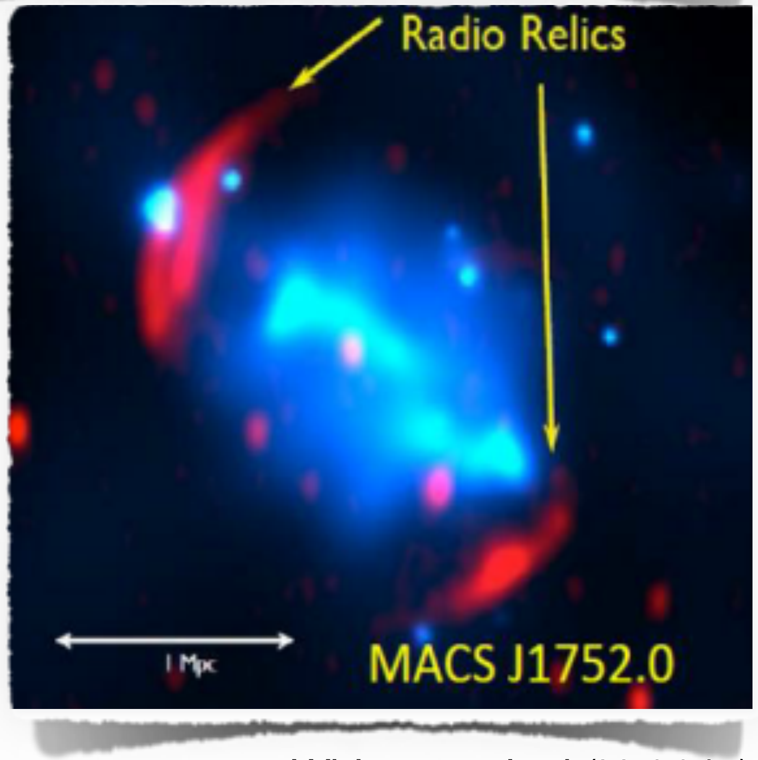
10th Int. Workshop on Air Shower Detection at High Altitudes, Nanjing, China, January 7-10, 2020

Introduction

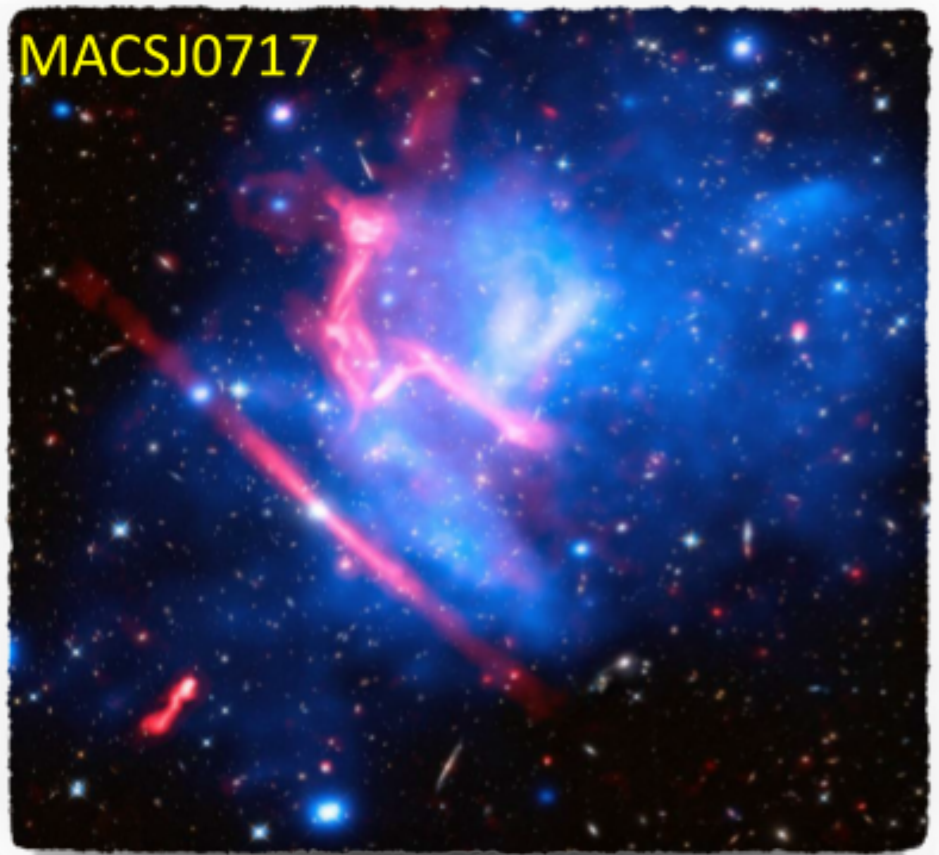
- supersonic flows of baryonic matter induced during large-scale formation of the universe produce shocks in hot intracluster (ICM) medium with high plasma beta ($\beta >> 1$)
- most energetic merger shocks have low Mach numbers ($M_s < 5$, $M_A < 10$)
- they are expected to accelerate cosmic-ray protons and electrons through Diffusive Shock Acceleration (DSA)
- merger shocks are observed in radio and X-rays as so-called radio relics; their synchrotron emission indicate CR electron acceleration to high energies
- CR protons accelerated at ICM shocks will be accumulated in galaxy clusters over cosmological lifetimes and should then produce cluster-wide γ-ray emission in interactions with thermal ions
- such emission has not been detected so far in either GeV (Fermi-LAT) or TeV (IACTs) range, suggesting that CR proton acceleration efficiency is very low

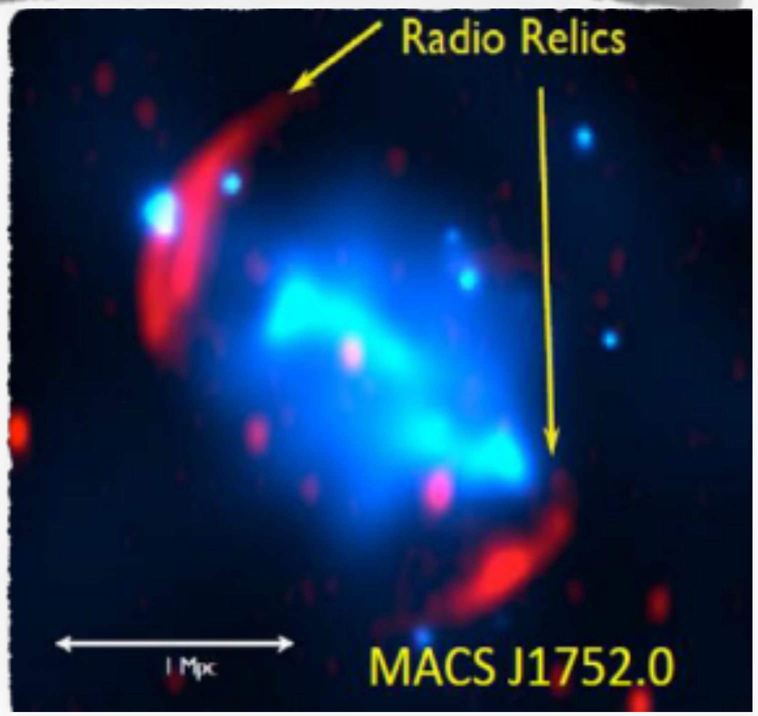


White – optical (Hubble)
Blue – X-ray (Chandra)
Red – radio (VLA)

Collisionless shocks in ICM

- ICM shocks are collisionless
- structure and particle acceleration at such shocks involve complex kinetic plasma processes, well beyond MHD description
- radiation emission is governed by the efficiency of CR acceleration, that is determined by the injection processes
- particle injection is poorly known for galaxy cluster conditions





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

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

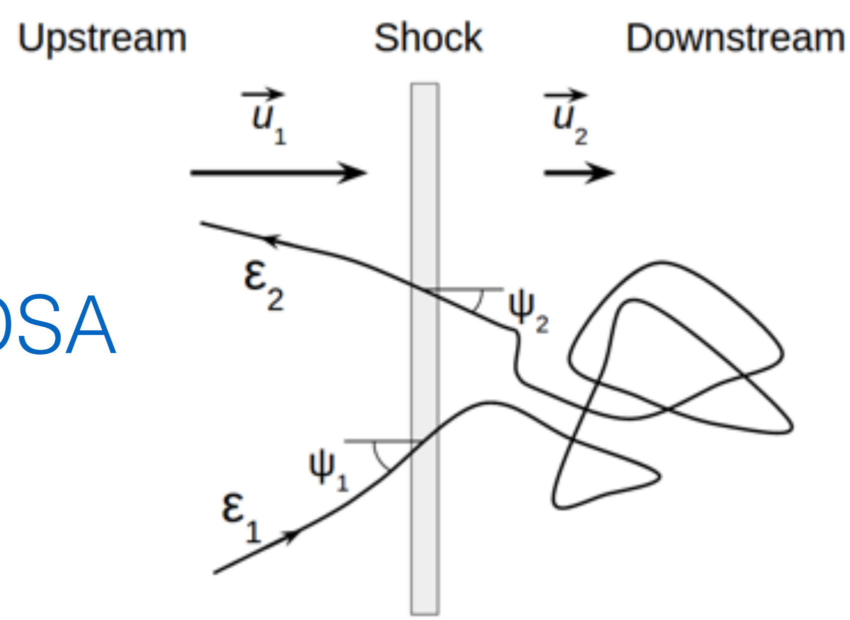
Plasma beta: $\beta = p_{\rm th}/p_{\rm mag}$

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

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

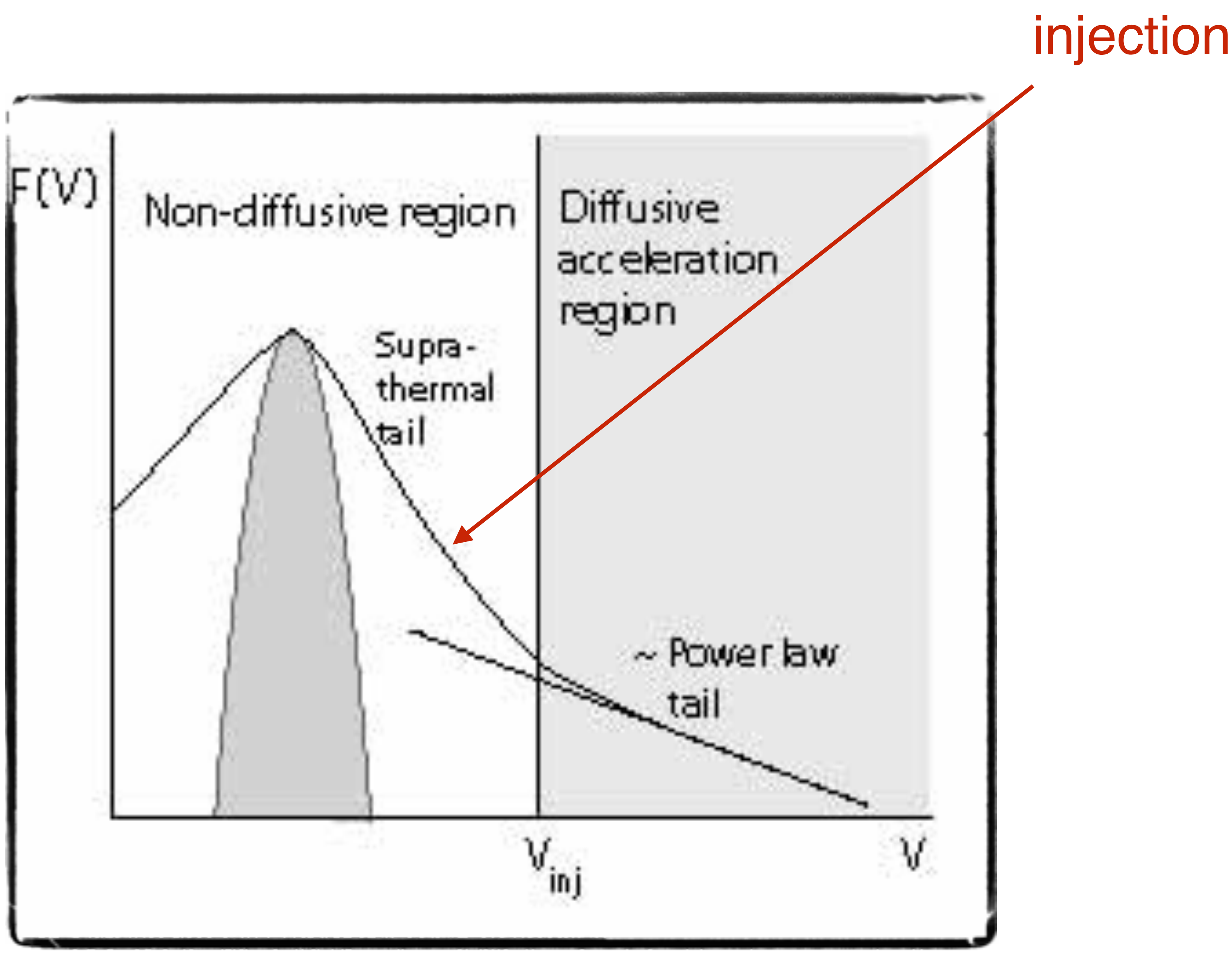
Particle injection to DSA

DSA



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

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



Outline

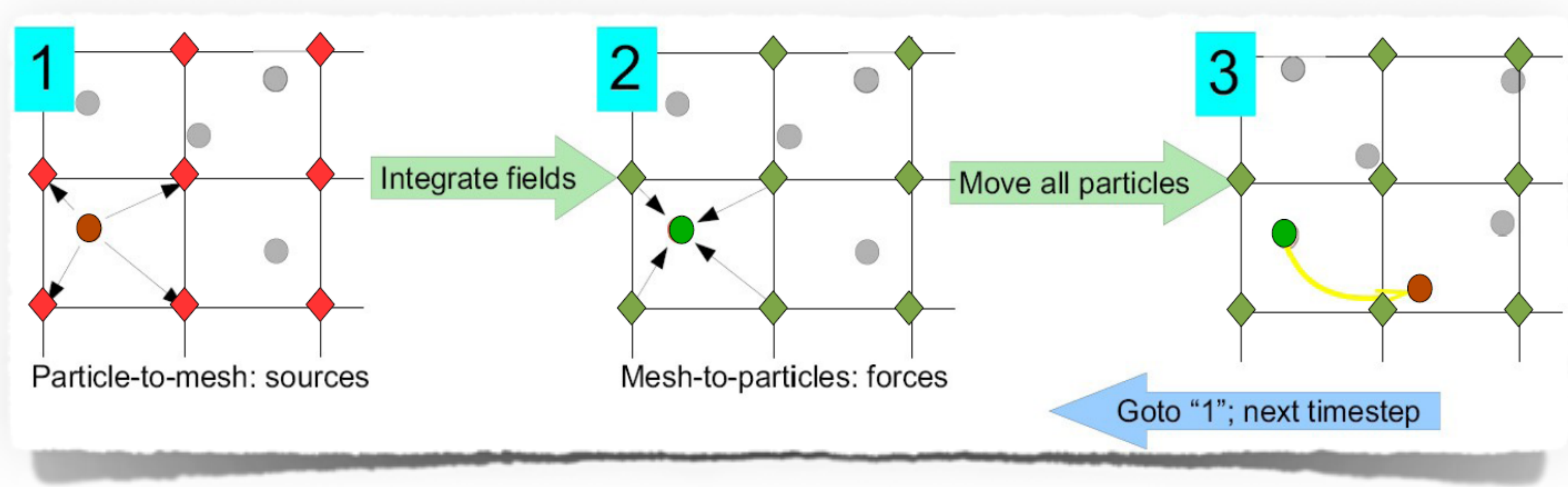
- Short review* of proton and electron acceleration in low Mach number shocks propagating in high-beta plasmas
- Electron injection in low M_s shocks with multi-scale turbulence

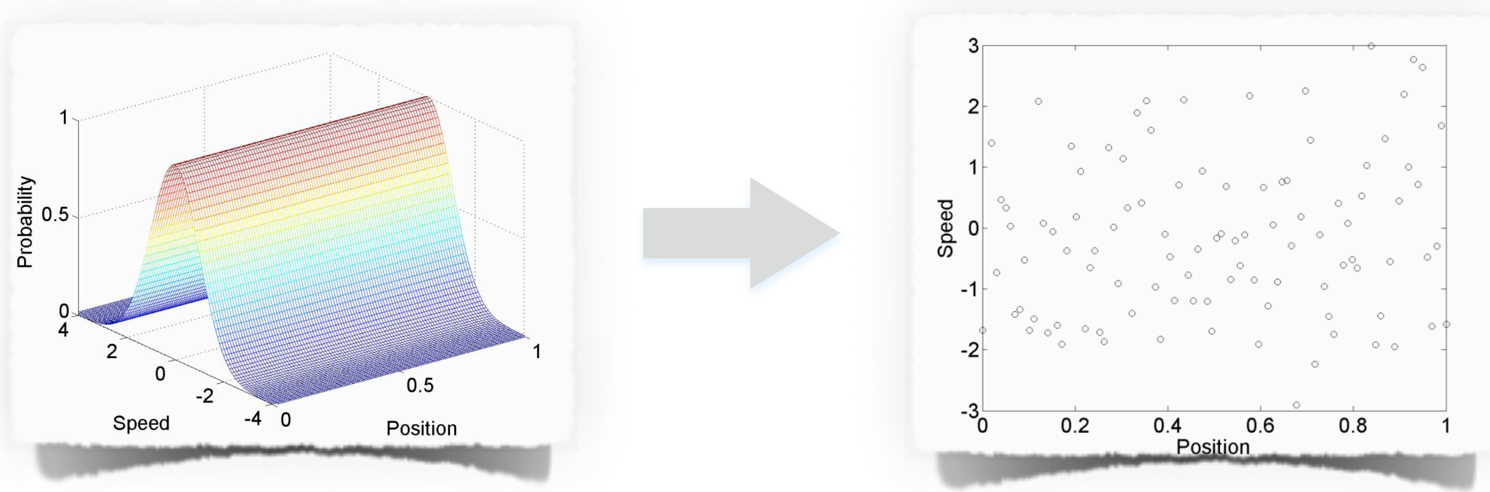
*Based on recent Particle-in-Cell simulations that cover both proton and electron micro-physics from injection through early DSA

Method of Particle-In-Cell Simulations

- Fully self-consistent description of collisionless plasma:
  - Vlasov equation (kinetic theory; time evolution of particle distribution function $f(\boldsymbol{x},\boldsymbol{v},t)$ 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

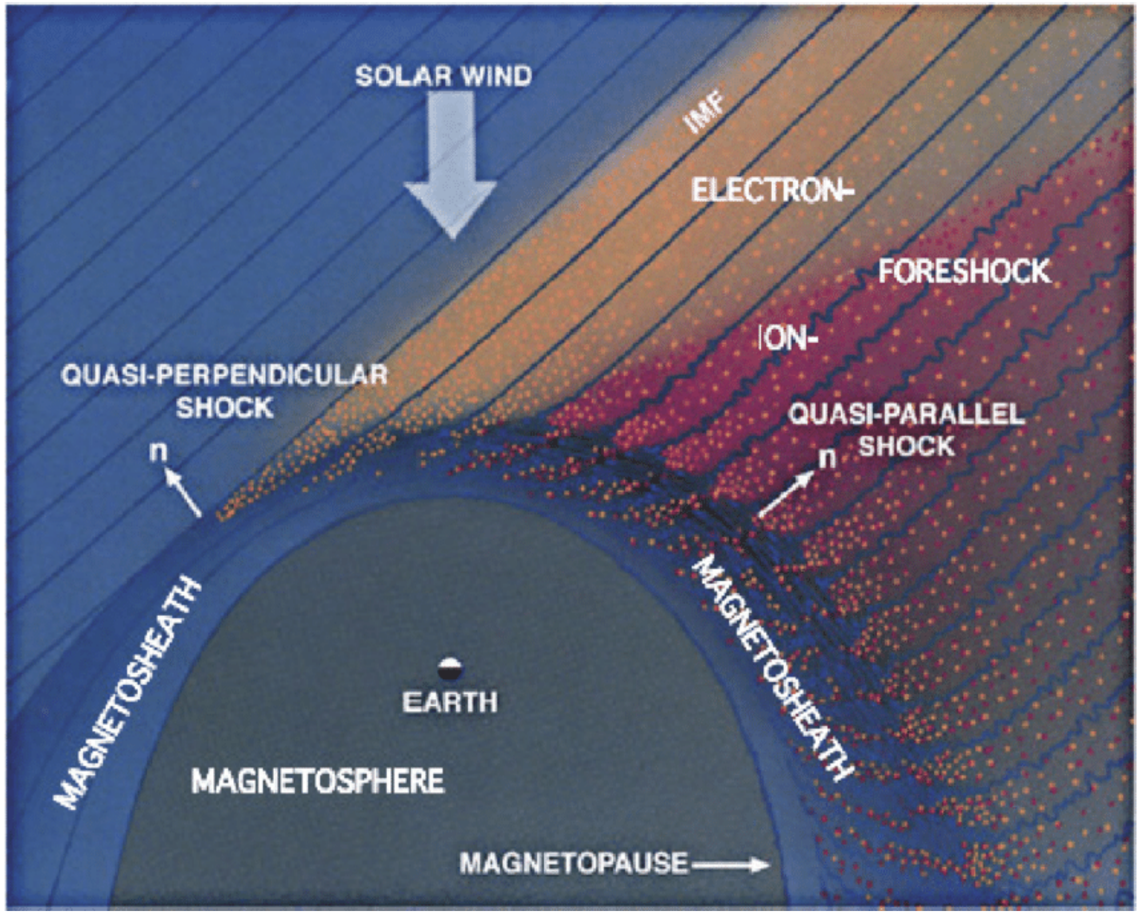




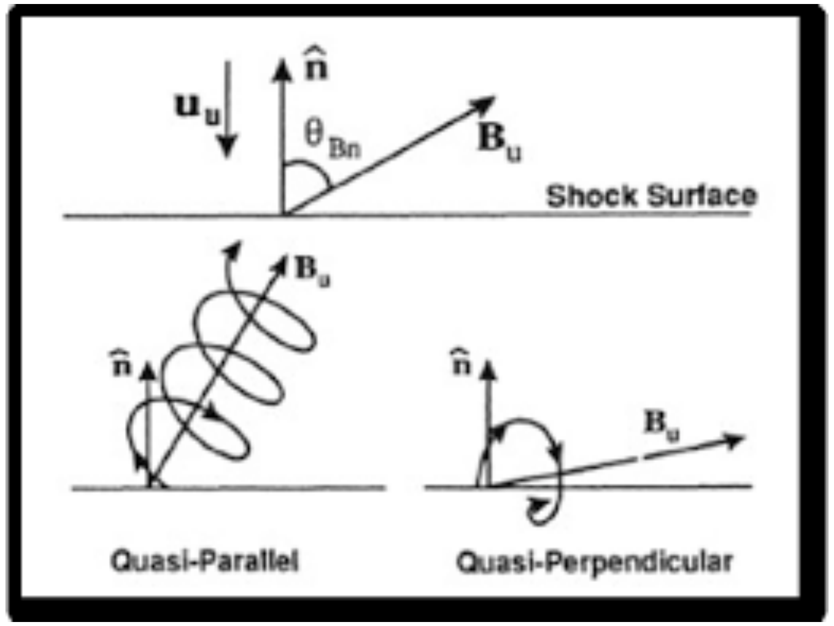
Particle distribution function represented by macroparticles on a numerical grid.
(Macroparticles represent a small volume of particle phase-space; equations of motion as for realistic particles)

Particle acceleration at shocks

- Particle acceleration at collisionless shocks depends on plasma parameters (sonic and Alfvenic Mach number, plasma beta, shock speed, shock obliquity,…)
- Most studies up to now concern low beta ($\beta < 1$) shocks (Earth's bow shock, interplanetary shocks, SNR shocks)
- Emerging picture:
  - supercritical - reflected ions drive plasma instabilities upstream
  - efficient proton acceleration at quasi-parallel ($Q_{\parallel}$) shocks
  - efficient electron acceleration at quasi-perpendicular ($Q_{\perp}$) shocks

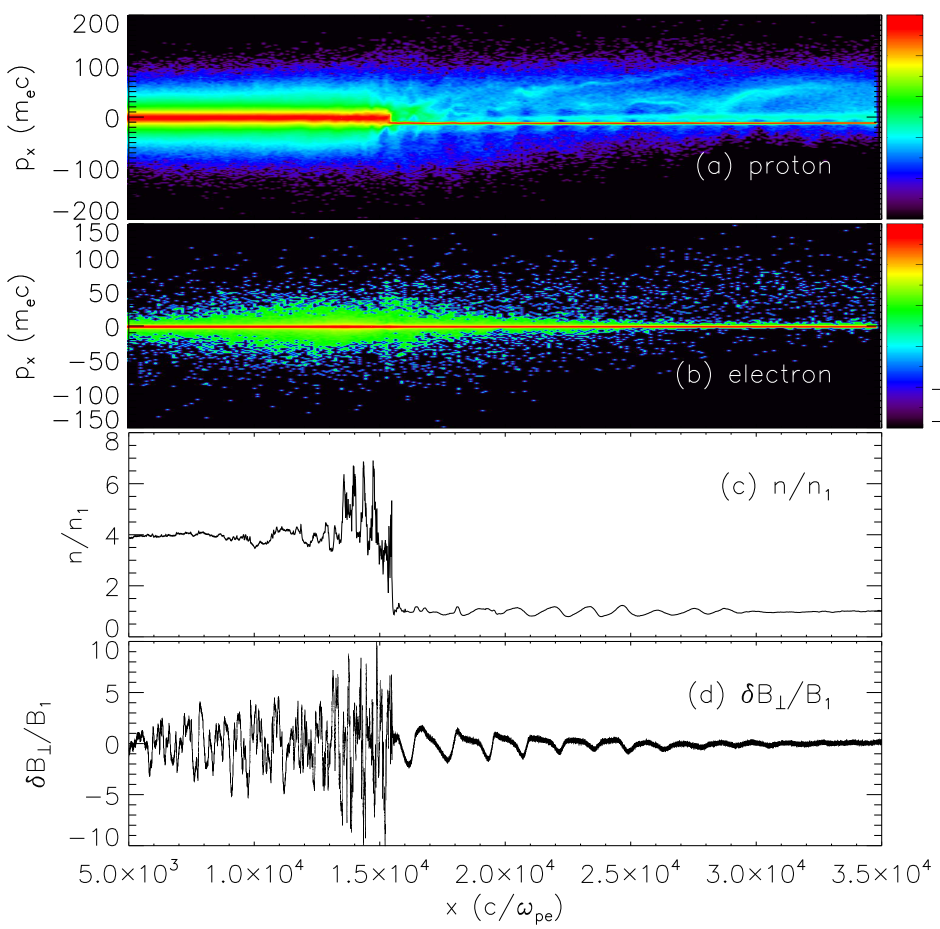


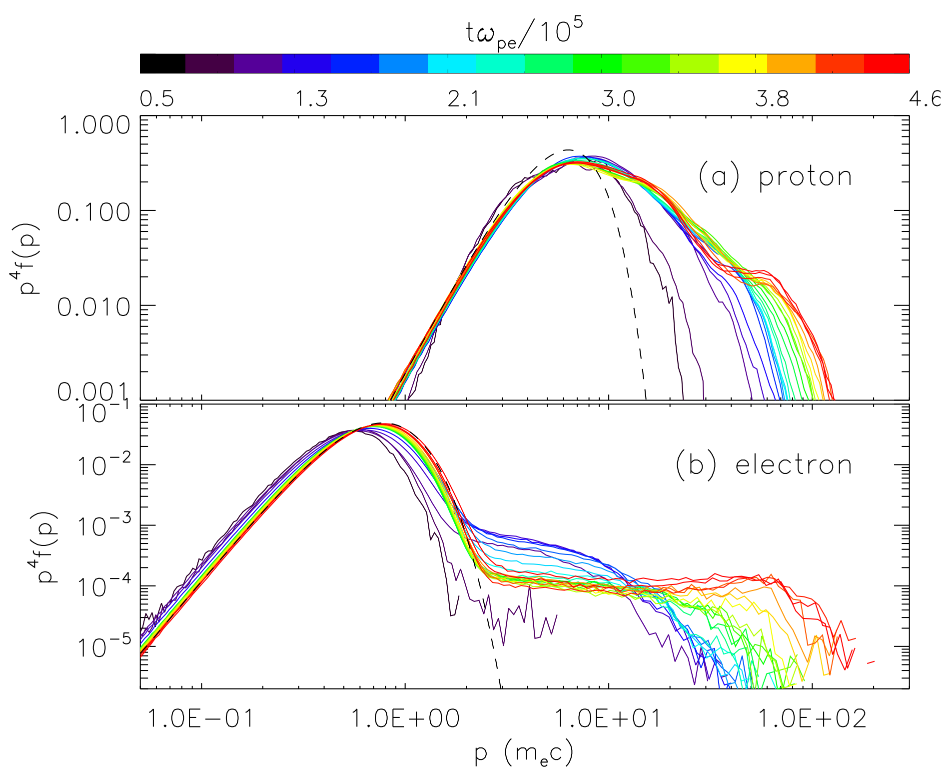
Shock obliquity

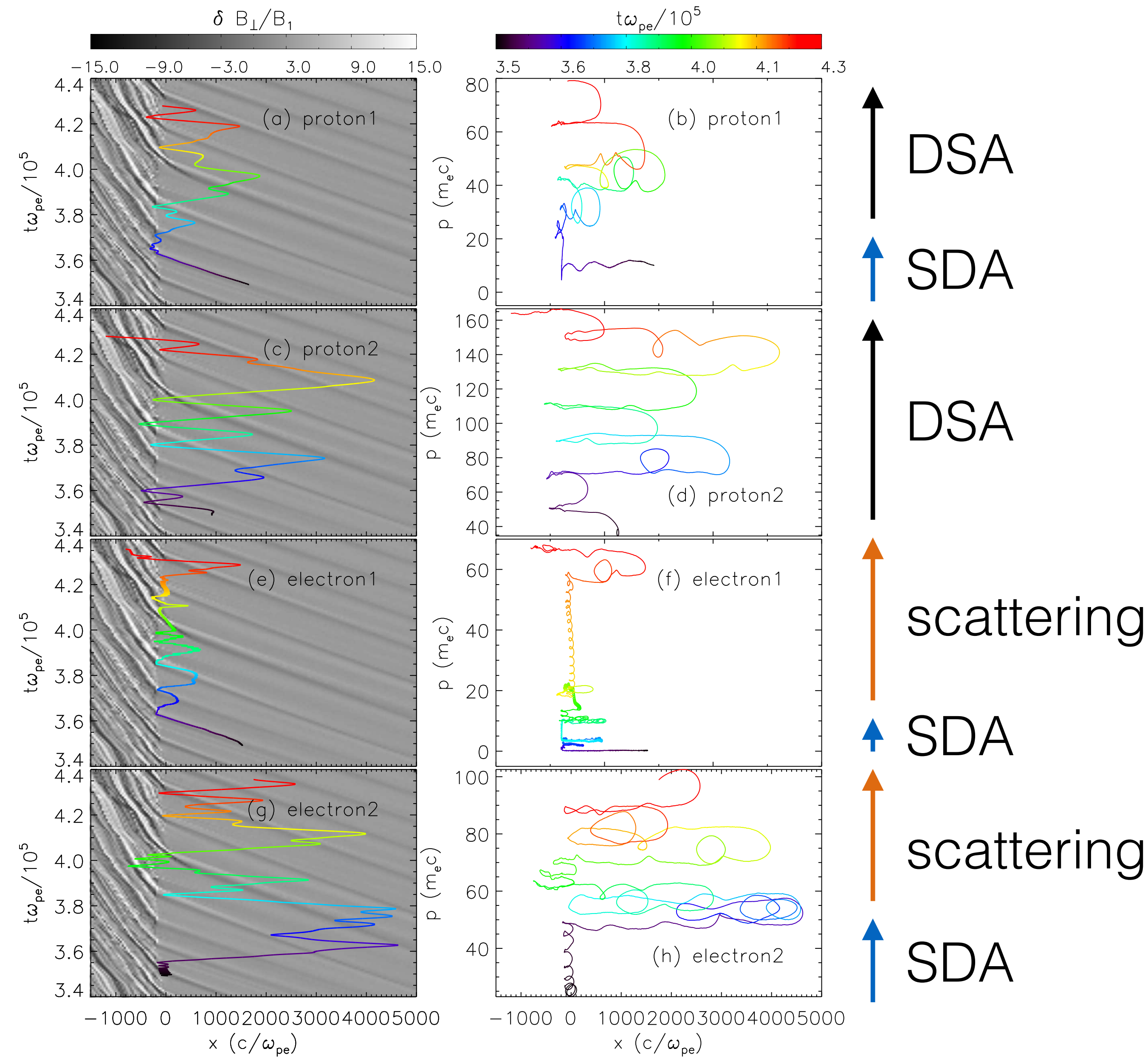


Proton injection

1D3V, $M_A=20$, $M_S=40$, $\vartheta=30^o$, $m_i/m_e=100$, $v_0=0.1c$; Park et al. 2015 Quasi-parallel shock



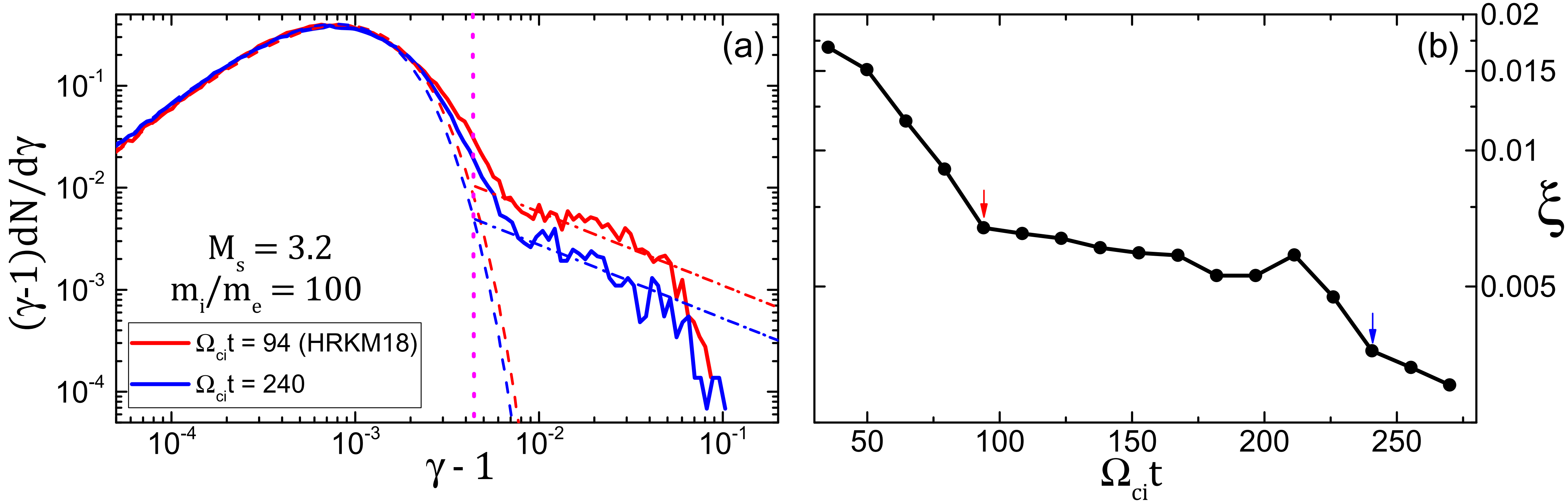




- ion and electron streaming upstream
- nonresonant (Bell) instability excited (ion-induced short-scale waves, $kr_{gi} \gg 1$).
- ion acceleration: SDA ⟶ DSA
- electron acceleration: SDA + scattering on Bell waves ($r_{ge}k_{max} \sim 1$) ⟶ DSA (?)

Proton acceleration in low M_s high beta $Q_{||}$ shocks

- only shocks with $M_s > M_s^* \sim 2.25$ are supercritical and can accelerate protons
- proton injection proceeds like in low-beta shocks for $M_s > M_s^*$ (no electron acceleration observed)
- Proton injection fraction decreases in time

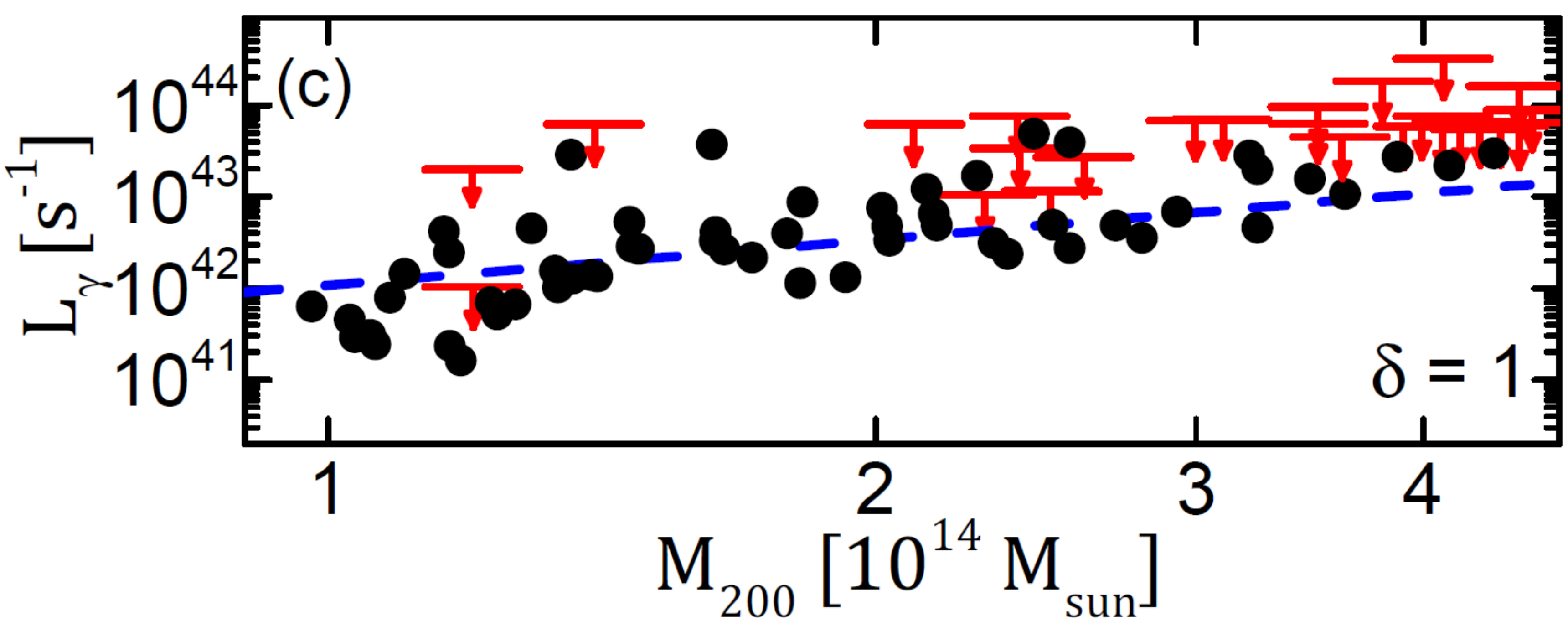


$$\xi = \frac{4\pi}{N_2}\int_{p_{min}}^{p_{max}} \langle f(p)\rangle\, p^2 dp$$

2D3V, M_A~18-36, M_s=2-4, ϑ=13°, m_i/m_e=100, v_0=0.027c-0.067c, β=(30)-100; Ha et al. 2019a

Proton acceleration in low M_s high beta $Q_{||}$ shocks

- cosmological structure formation simulations adopting Ha et al. 2019a results show that only ~30% of cluster shocks is $Q_{||}$, of which ~23% is supercritical
- only ~7% of the kinetic energy flux of entire shock population is dissipated at shocks able to accelerate protons
- average fraction of kinetic energy transferred to CR protons is ~10^{-4}
- Gamma-ray emission is thus below upper limits for clusters observed by Fermi-LAT (Ha et al. 2019b)



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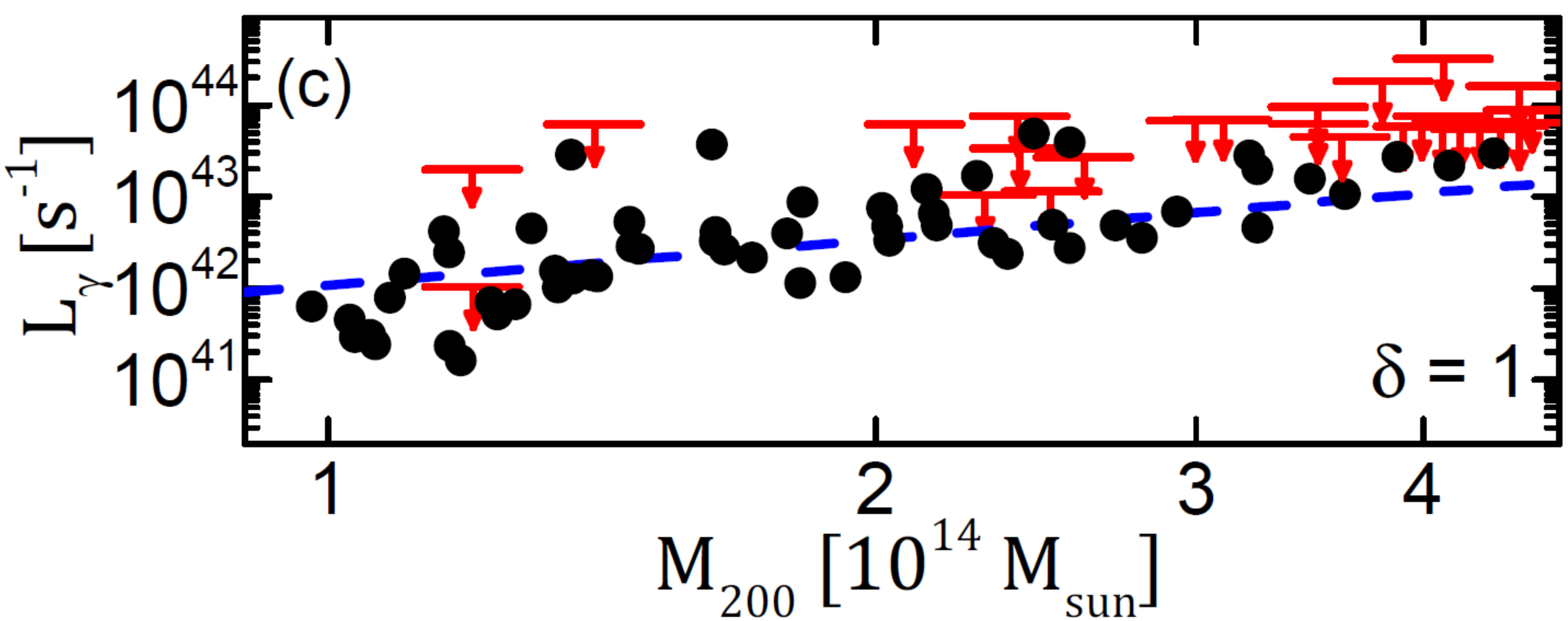
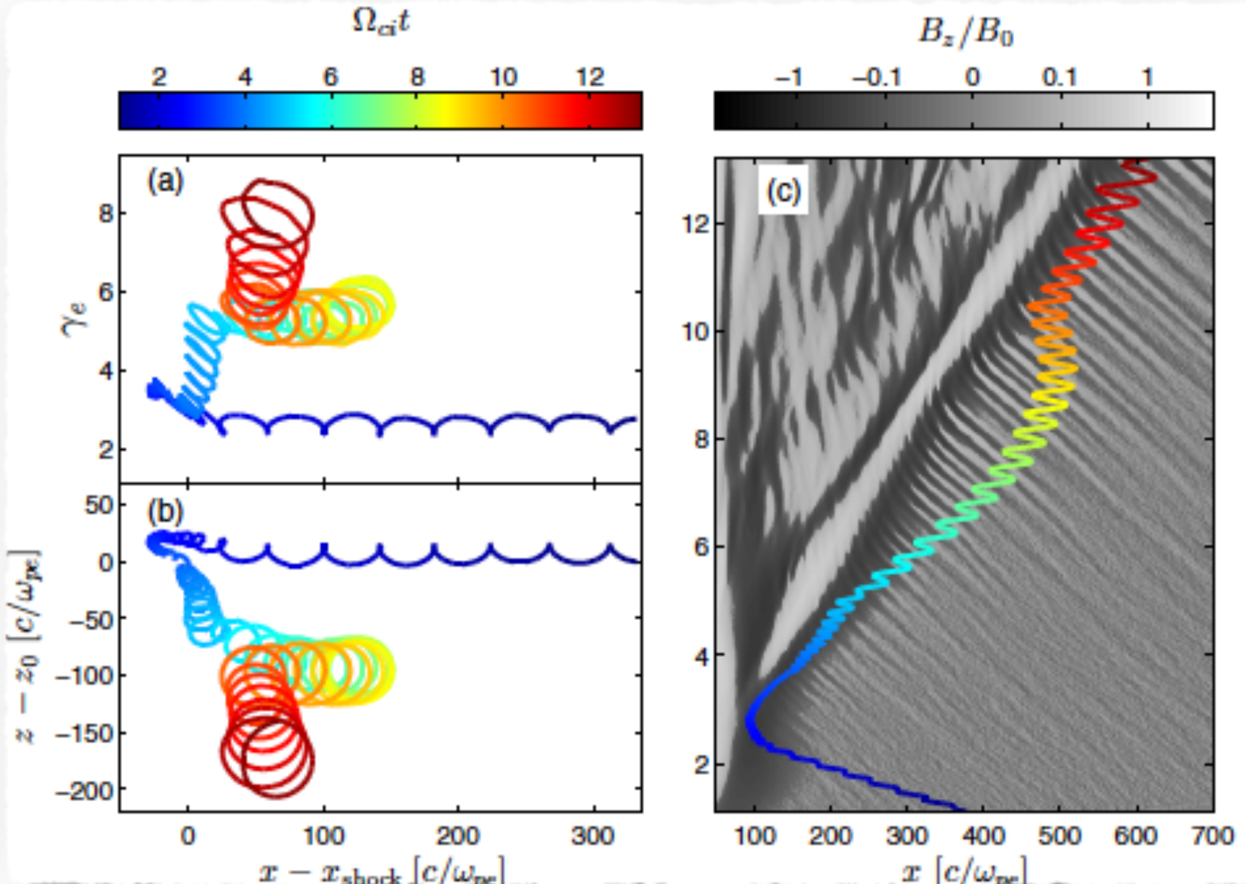


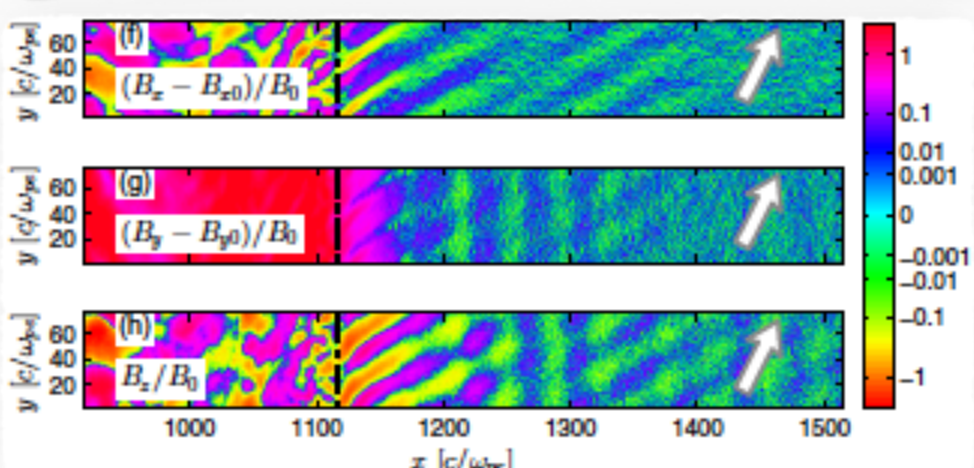
- Beware! - 2D (and 3D) simulations may reveal a different picture of shock structure and particle injection mechanism and efficiency.

Electron injection

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

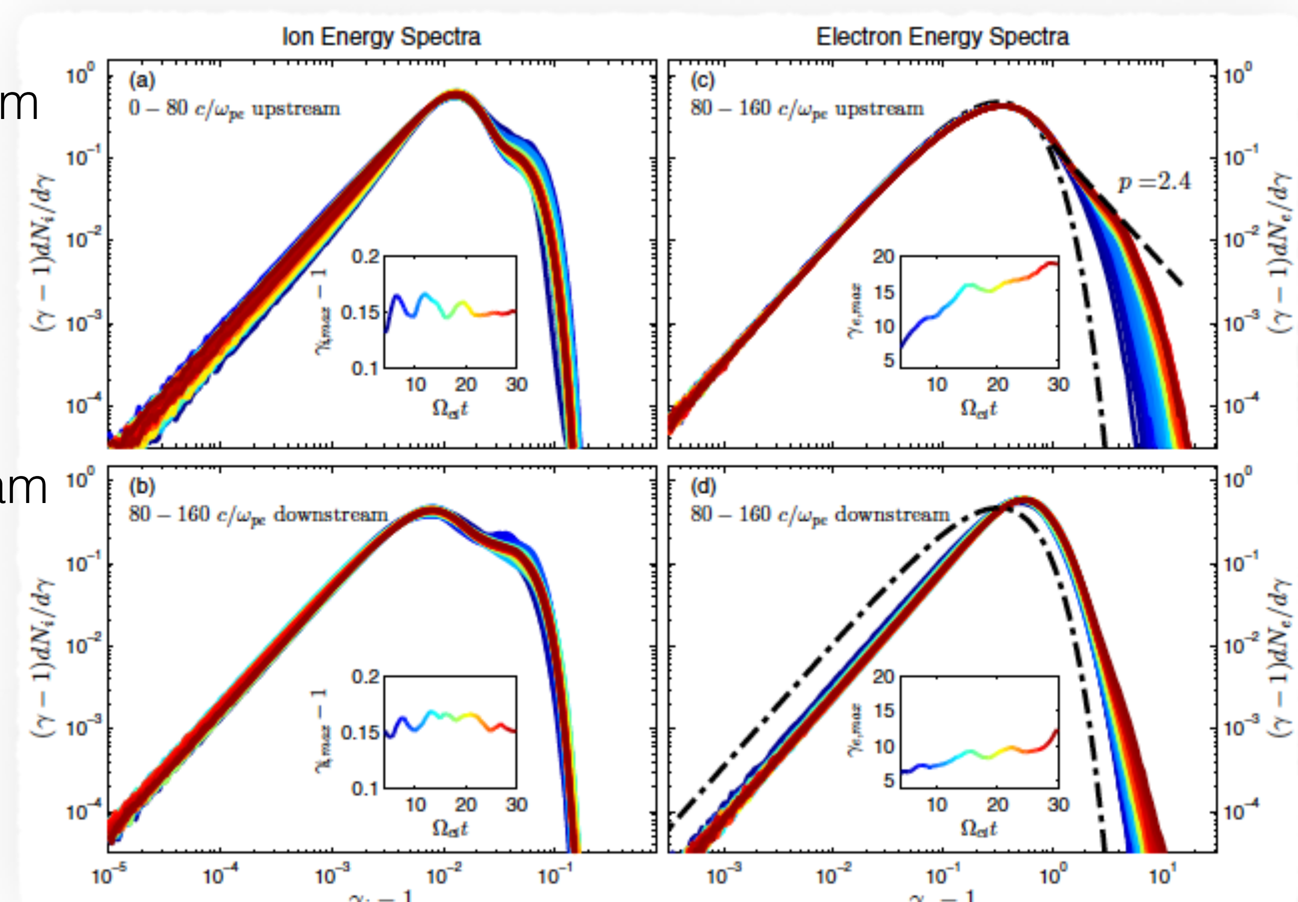


- SDA-reflected electrons scattered back towards shock by upstream self-generated waves - DSA-like process
- formation of upstream power-law spectra
- more effective at high β
- $\gamma_{max} \ll \gamma_{inj}$?

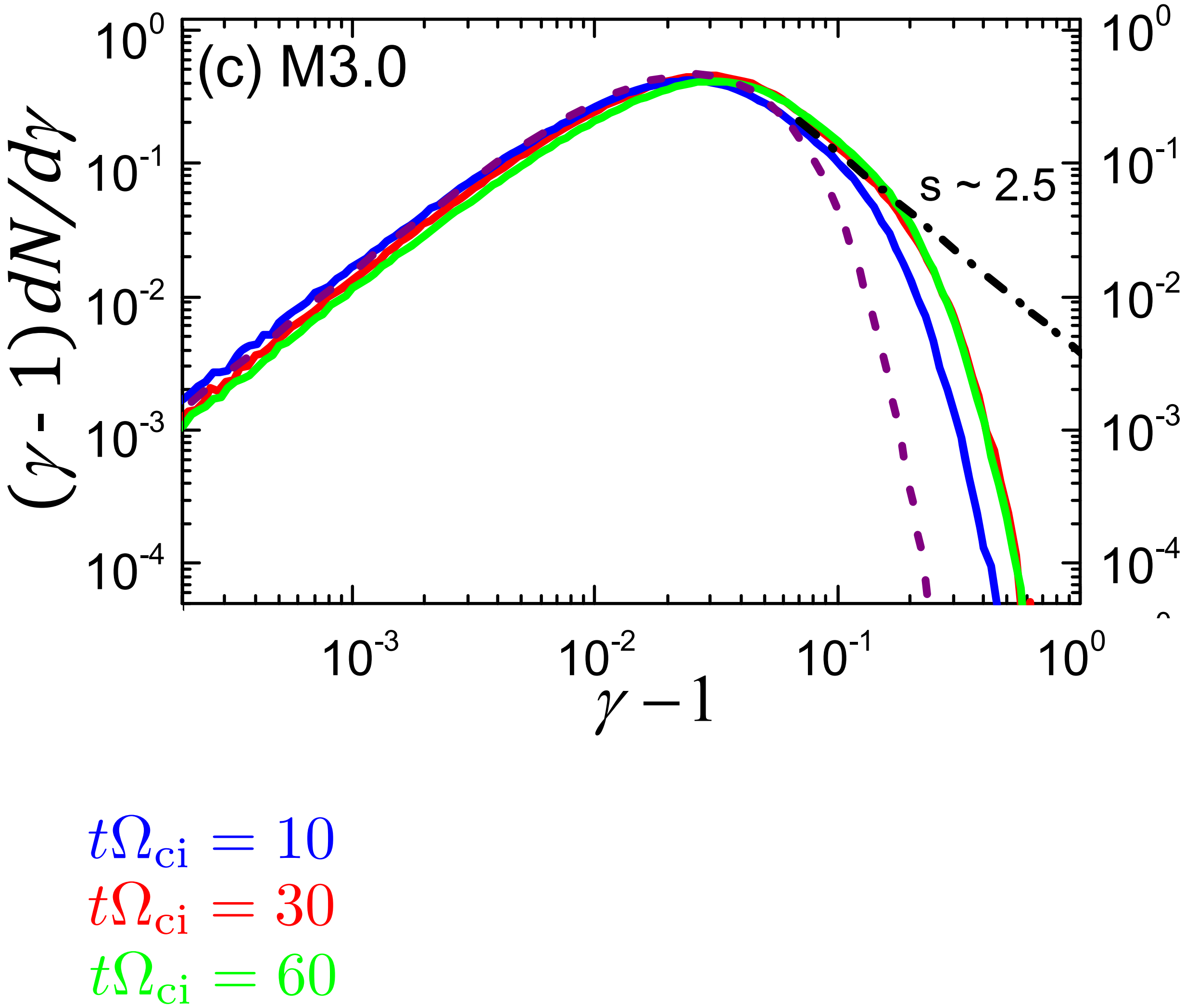


upstream

downstream



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

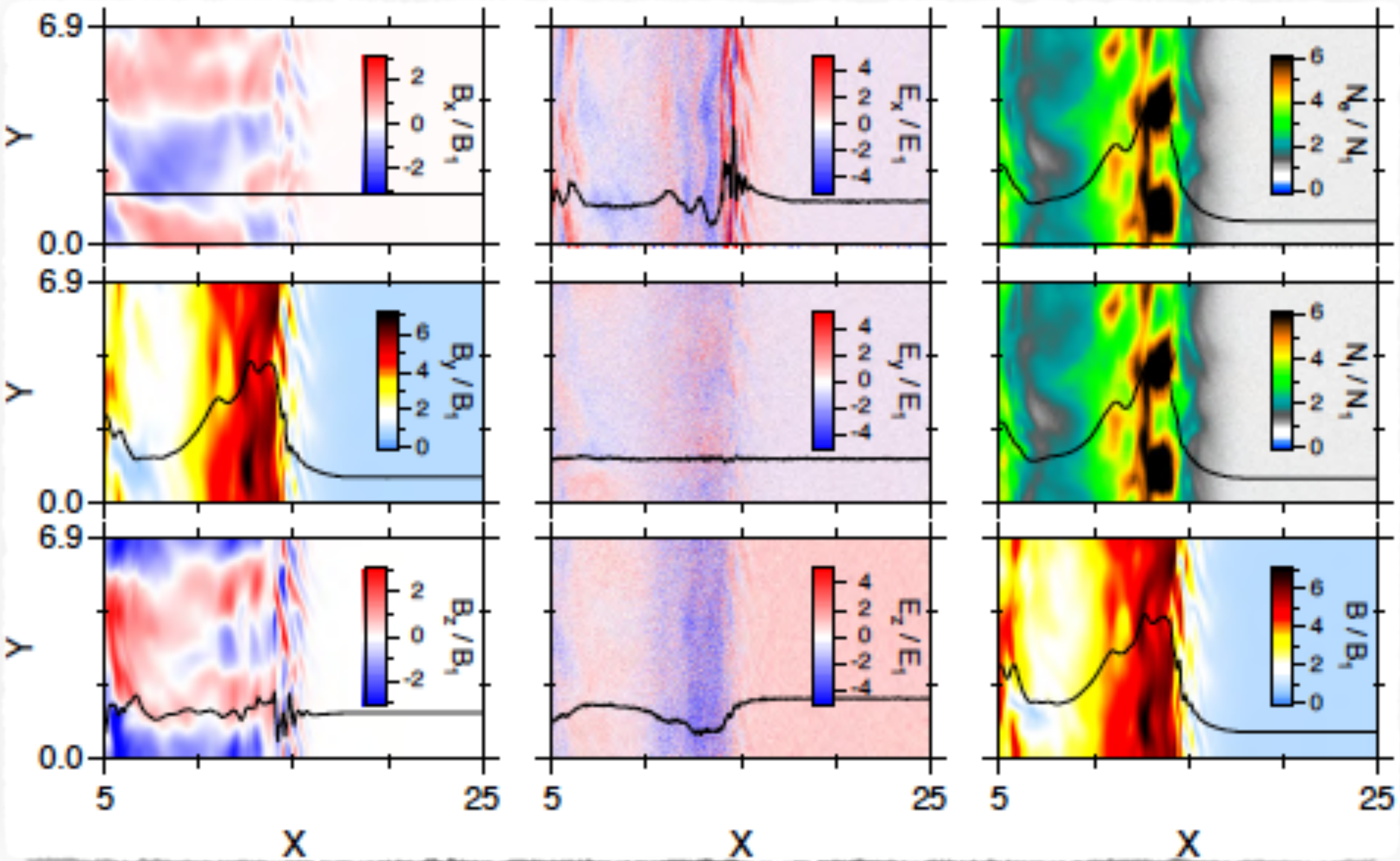


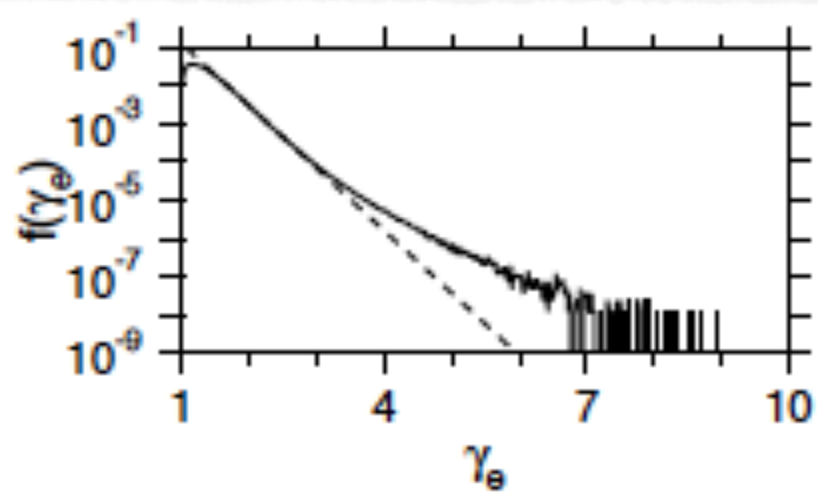
- multiple-cycle SDA shown to be effective only in shocks above a critical Mach number M_{EFI}~2.3, in which electron firehose instability (EFI) can be excited
- quasi-perpendicular shocks may not inject electrons to DSA because EFI saturates before long-wavelength modes develop
- re-acceleration of fossil electrons?

2D3V, M_{A}~18-28, M_{s}=2-3, ϑ=53-73°, m_i/m_e=100, v_0=0.027c-0.047c, β=(50)-100;

Kang et al. 2019

Effects of the shock rippling





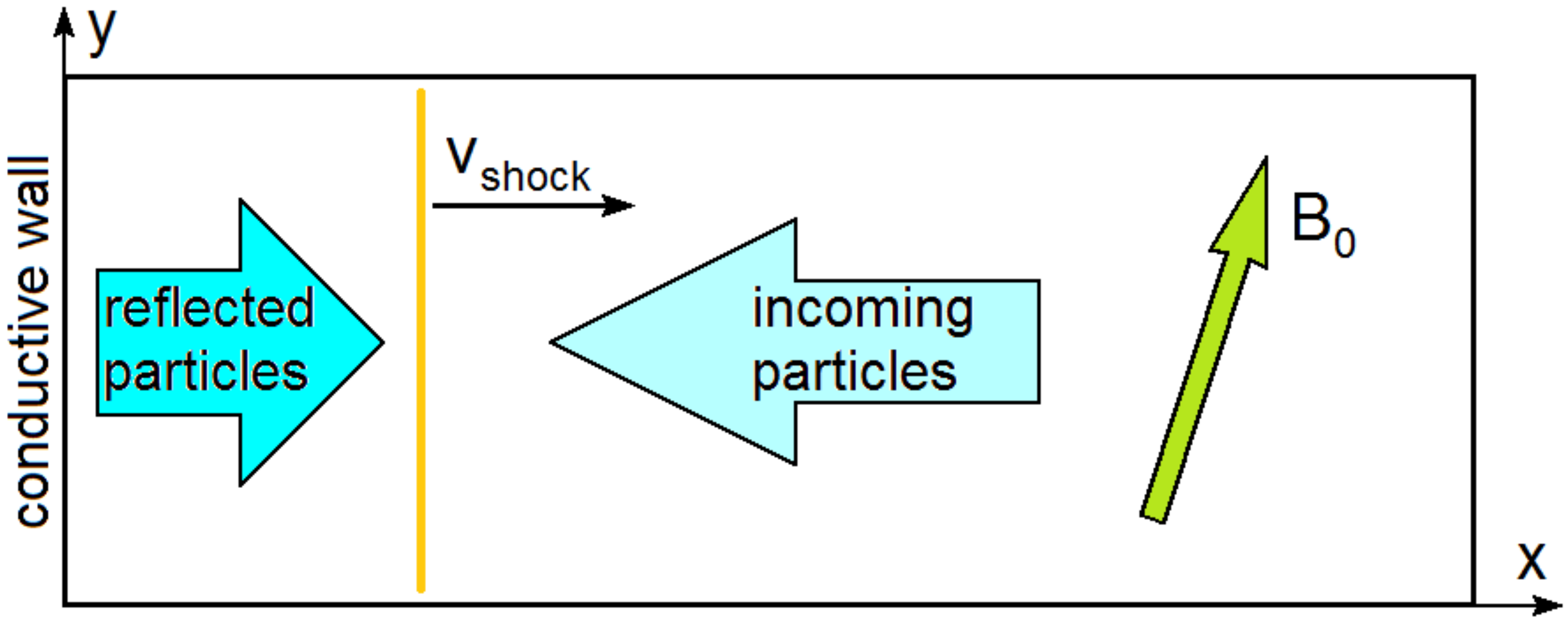
spectrum in overshoot

- 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

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

Kobzar et al., in preparation (2020)



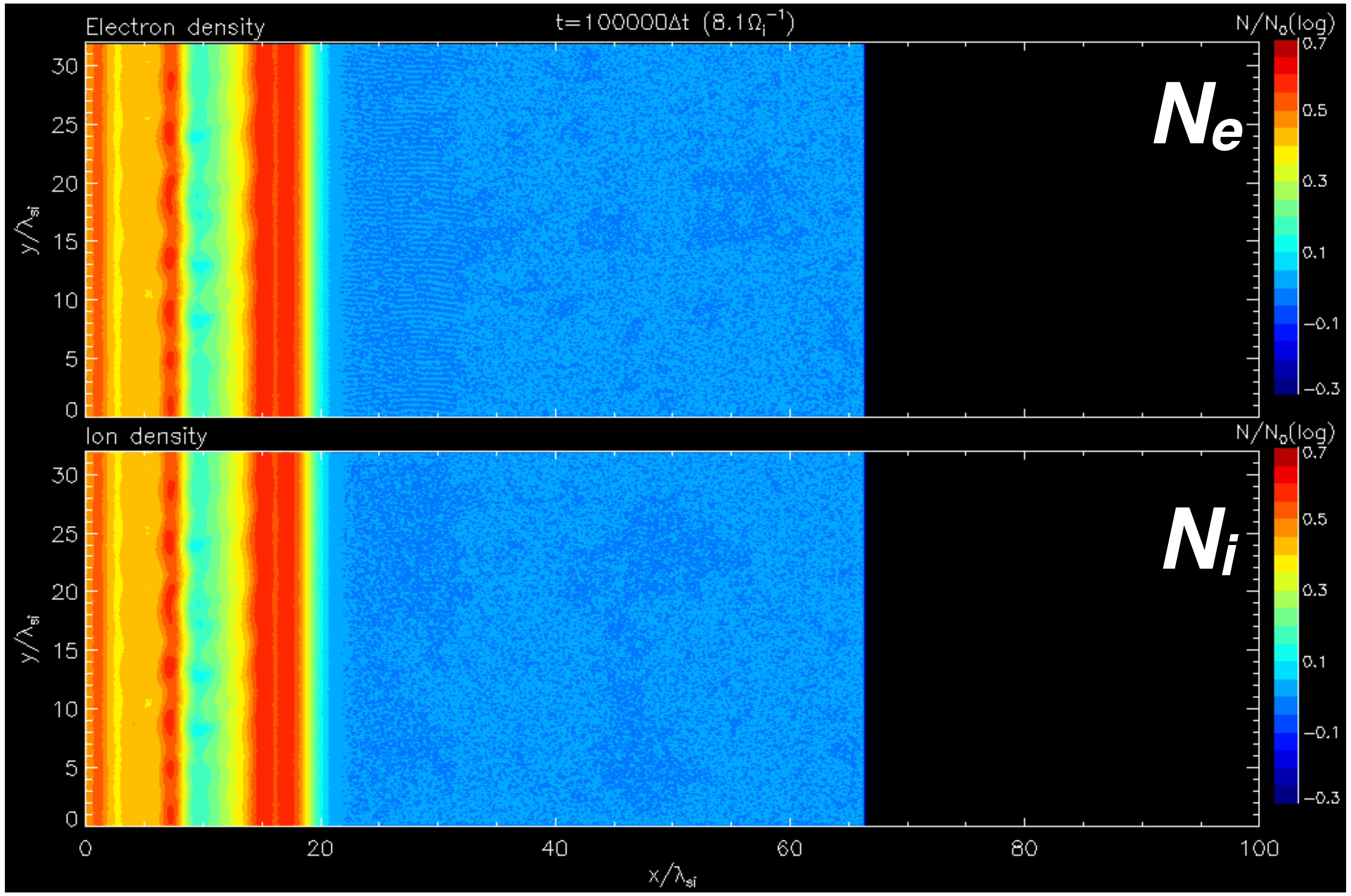
2D3V ($L_x \times L_y = 333\ \lambda_{si} \times 32\ \lambda_{si}$), $M_A=6.1$, $M_s=3$, $m_i/m_e=100$, $v_0=0.1c$, $\beta=5$ (plasma temperature $k_B T \approx 40$ keV)

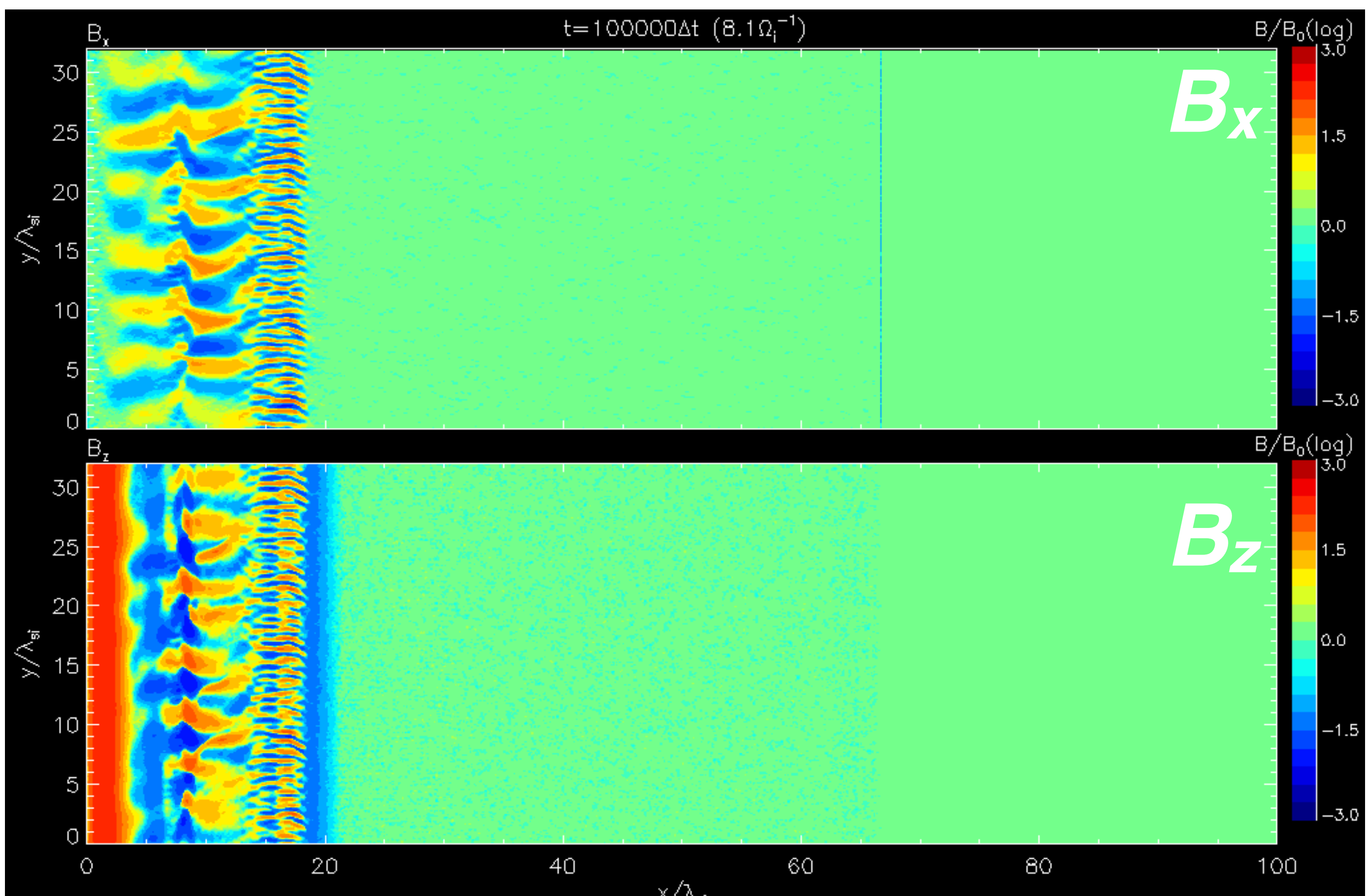
subluminal shock: $\vartheta=75^o$ ($\vartheta_{cr} \approx 81^o$)

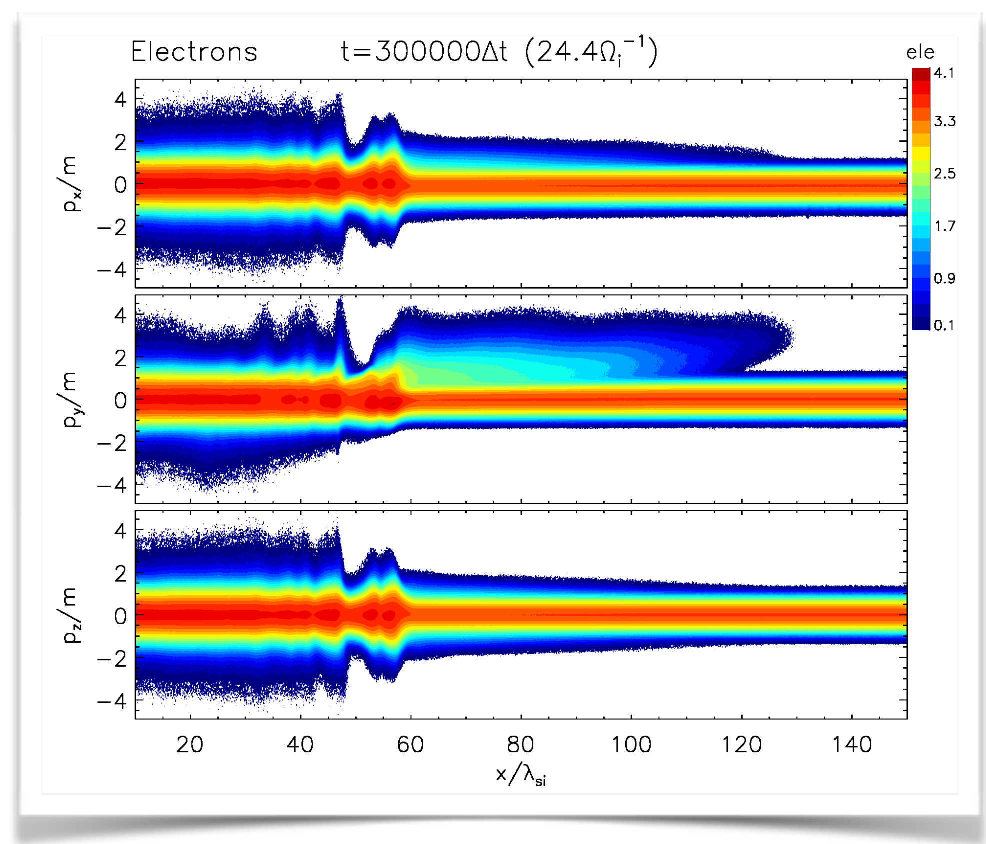
$$v_t \simeq 1.5\, v_{\rm th,e} > v_{\rm th,e} \quad (v_t = v_{\rm sh}^{\rm up} / \cos\vartheta)$$

Global shock structure: multi-scale turbulence

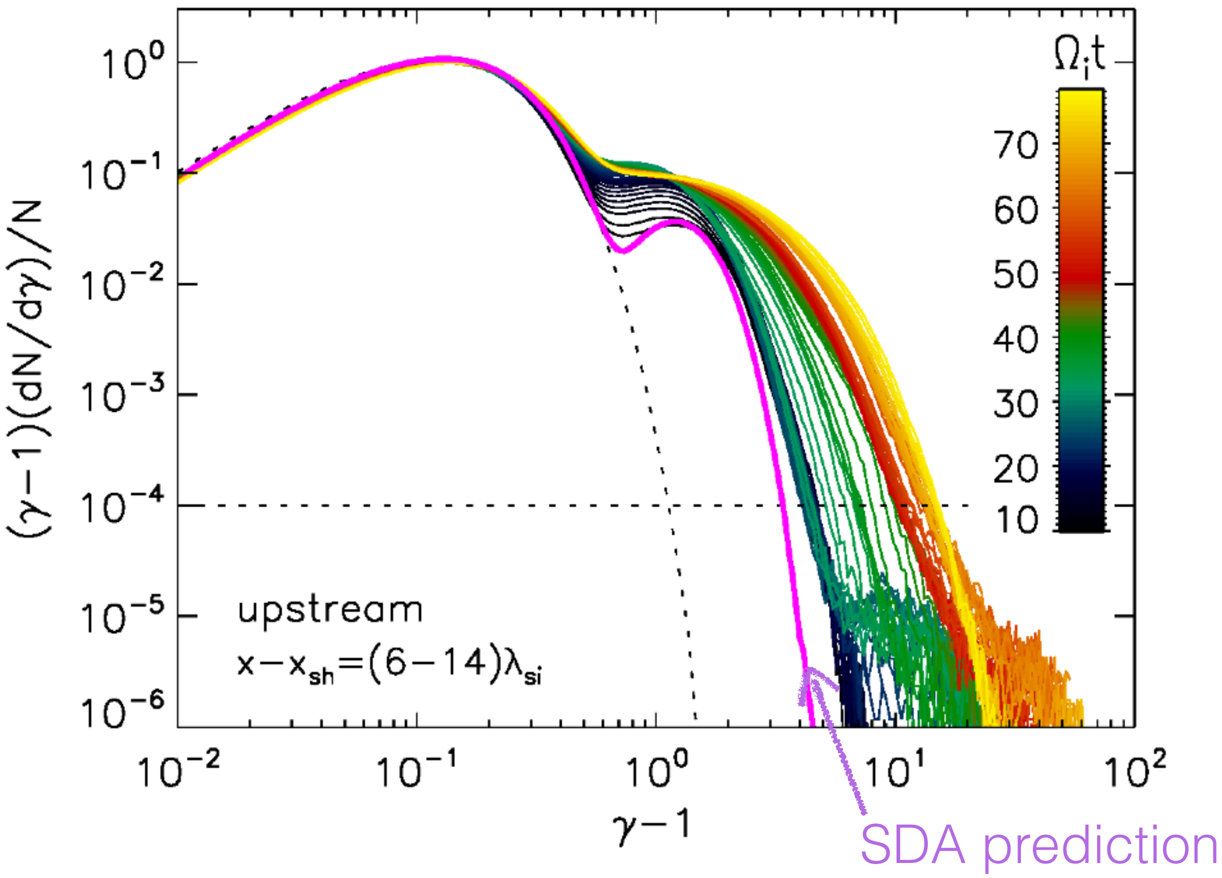
- rippling in the shock transition on different scales (overshoot-undershoot-2nd overshoot)
  - AIC and mirror modes
- short-scale whistler waves in the overshoot
- oblique and perpendicular modes of the electron firehose instability in the upstream, enhanced and modulated by the ripples

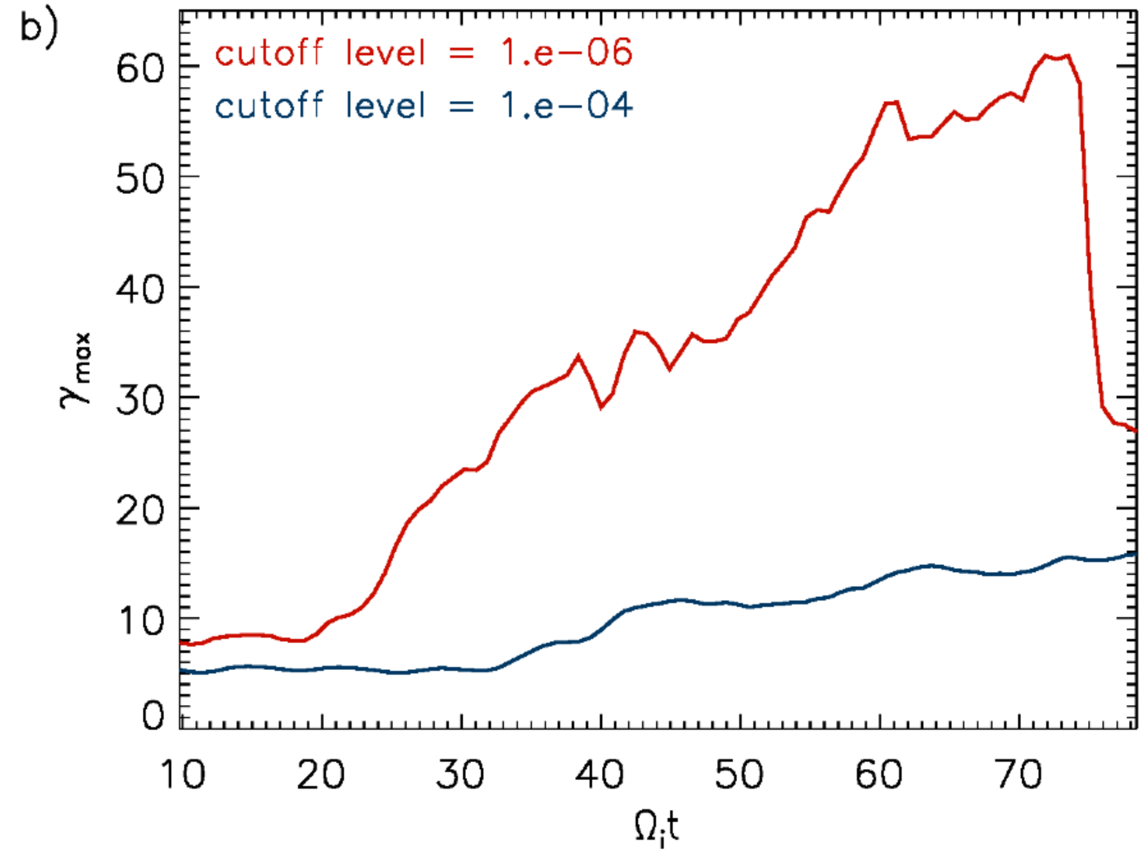


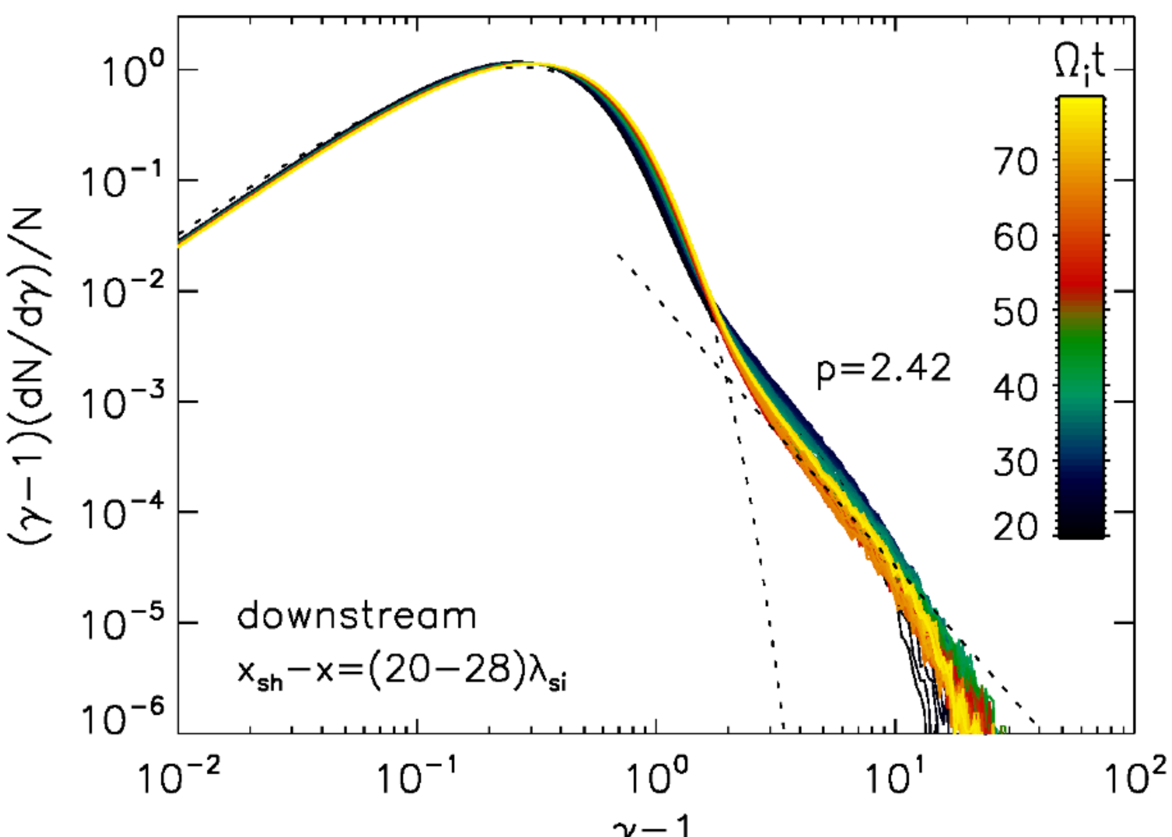




Electron spectra – time evolution

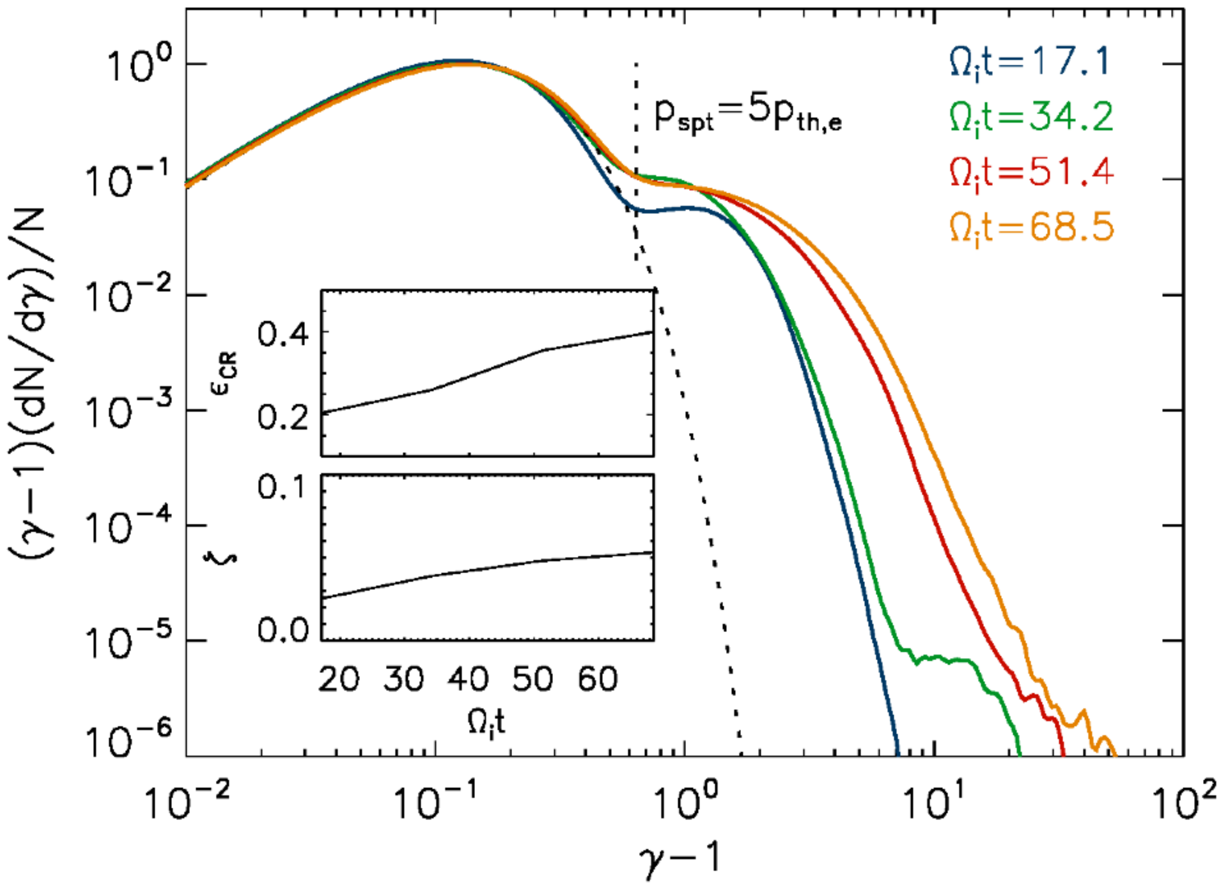


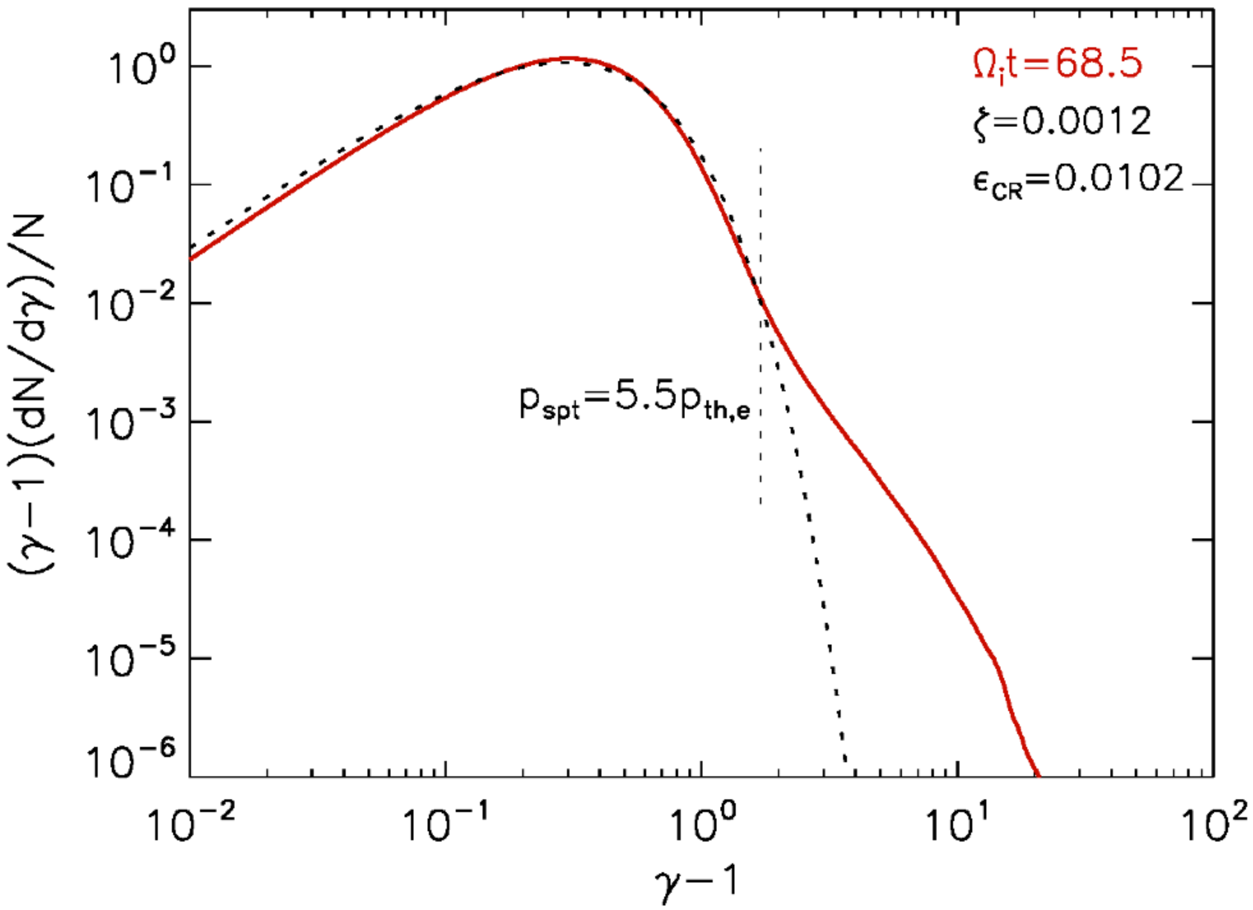




- substantial increase in non-thermal tail production efficiency coincident with the onset of the shock rippling at $\Omega_{ci} t \approx 20$
- power-law spectra downstream in agreement with observations

Electron spectra – injection efficiency





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

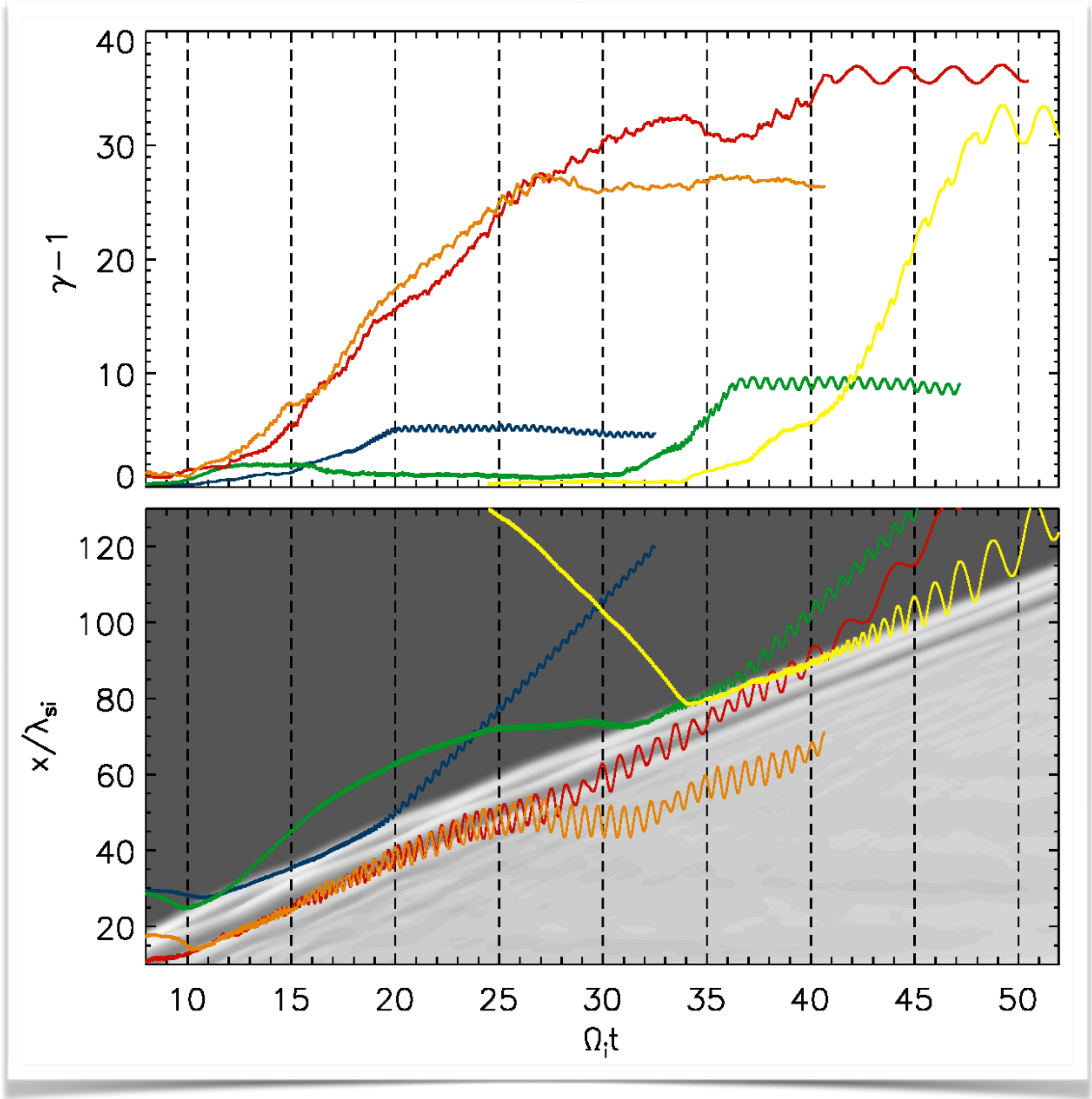
$\epsilon_{\rm CR}$ - corresponding energy density fraction

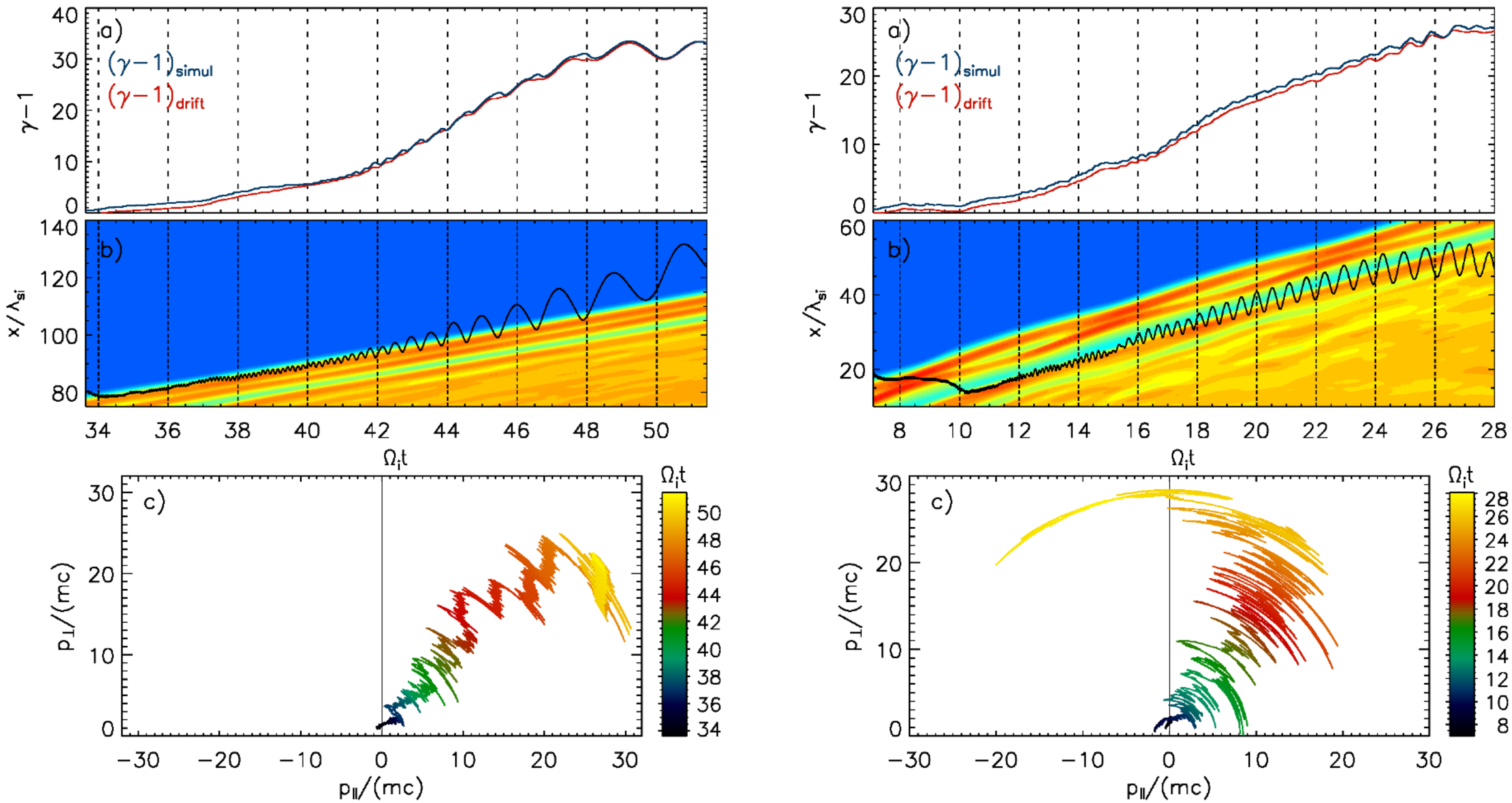
$$\zeta_{\rm max,up} \simeq 5\%, \;\; \epsilon_{\rm CRmax,up} \simeq 40\%$$

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

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





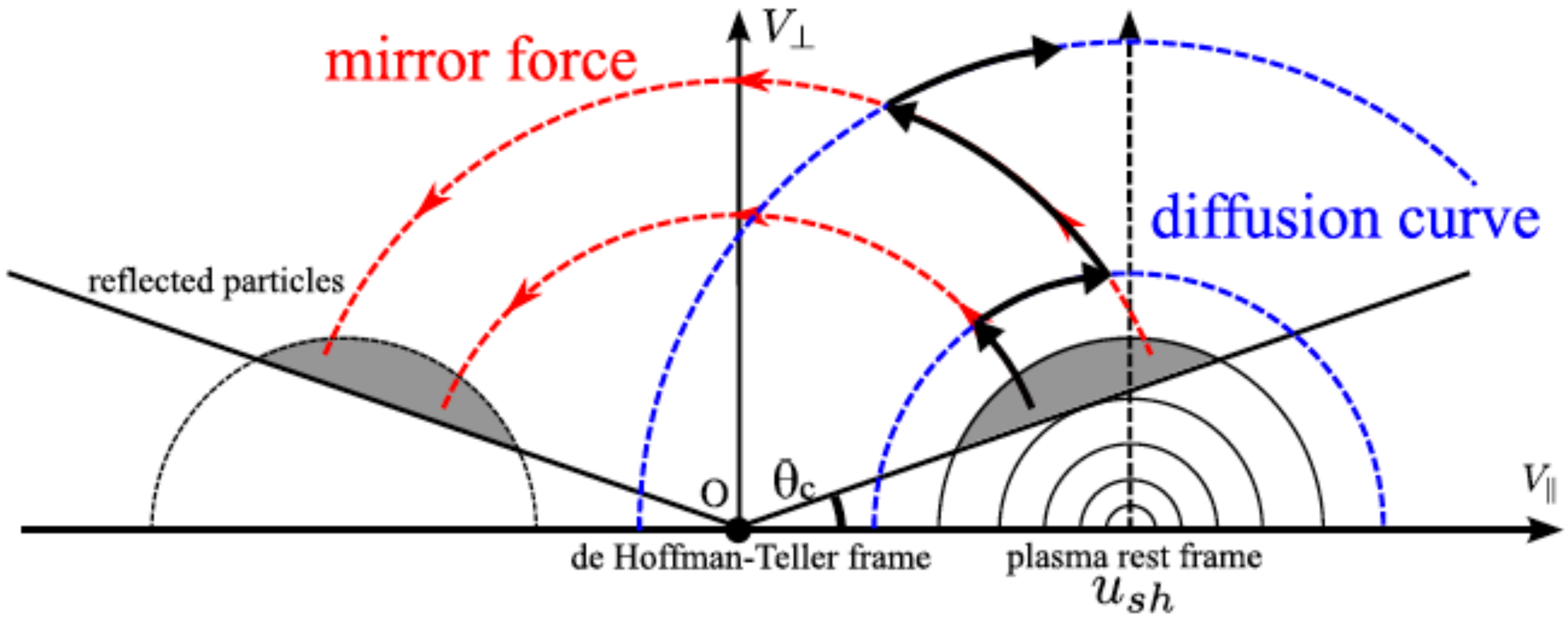
- most accelerations associated with an increase in $p_\perp$
- strong pitch-angle scattering (arcs in $p_\parallel$-$p_\perp$ momentum space)
- energy gain mostly through the drift along motional electric field:

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

➜ Stochastic Shock-Drift Acceleration (SSDA)

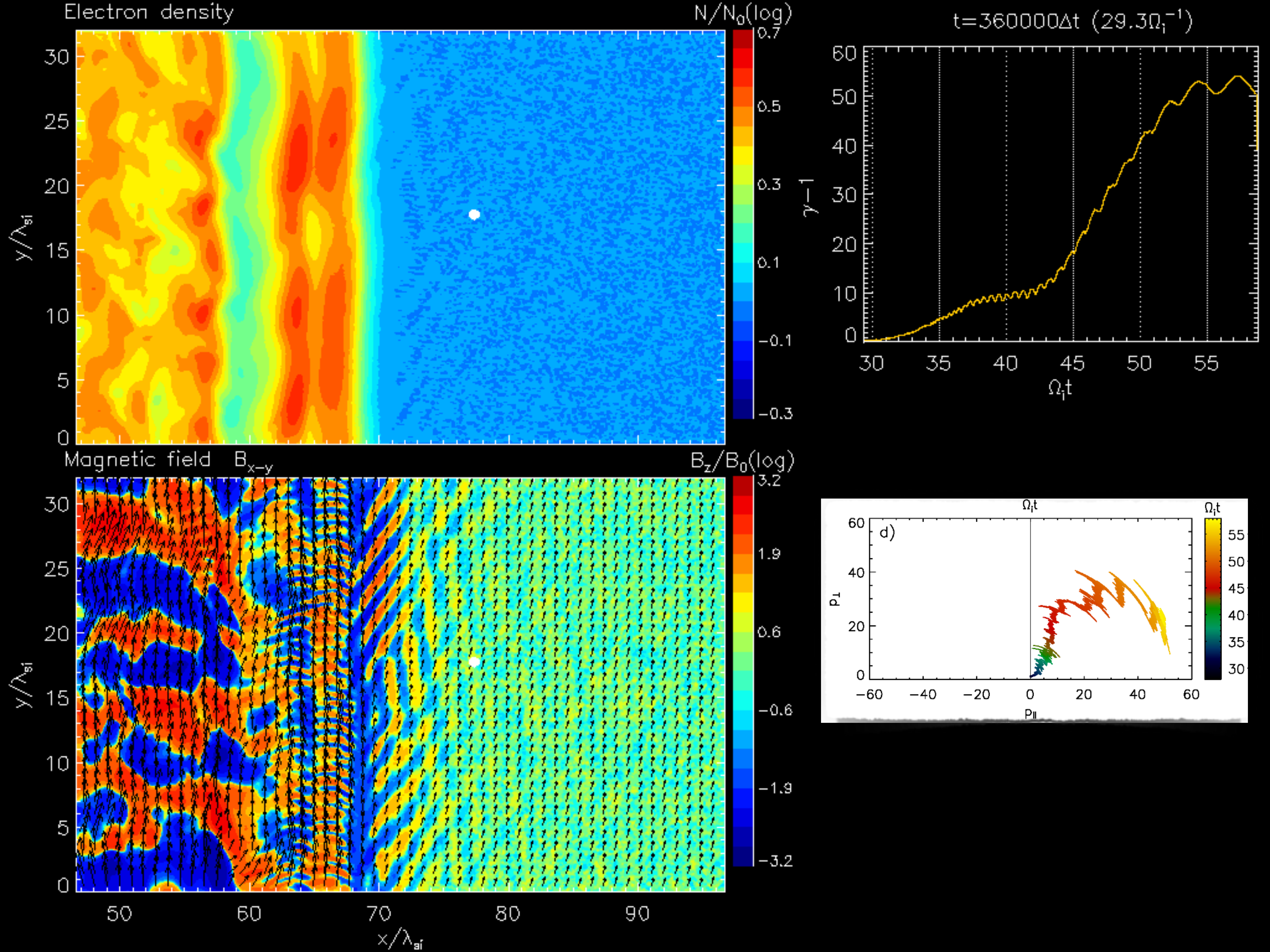
Stochastic Shock Drift Acceleration (SSDA)

Katou & Amano (2019)

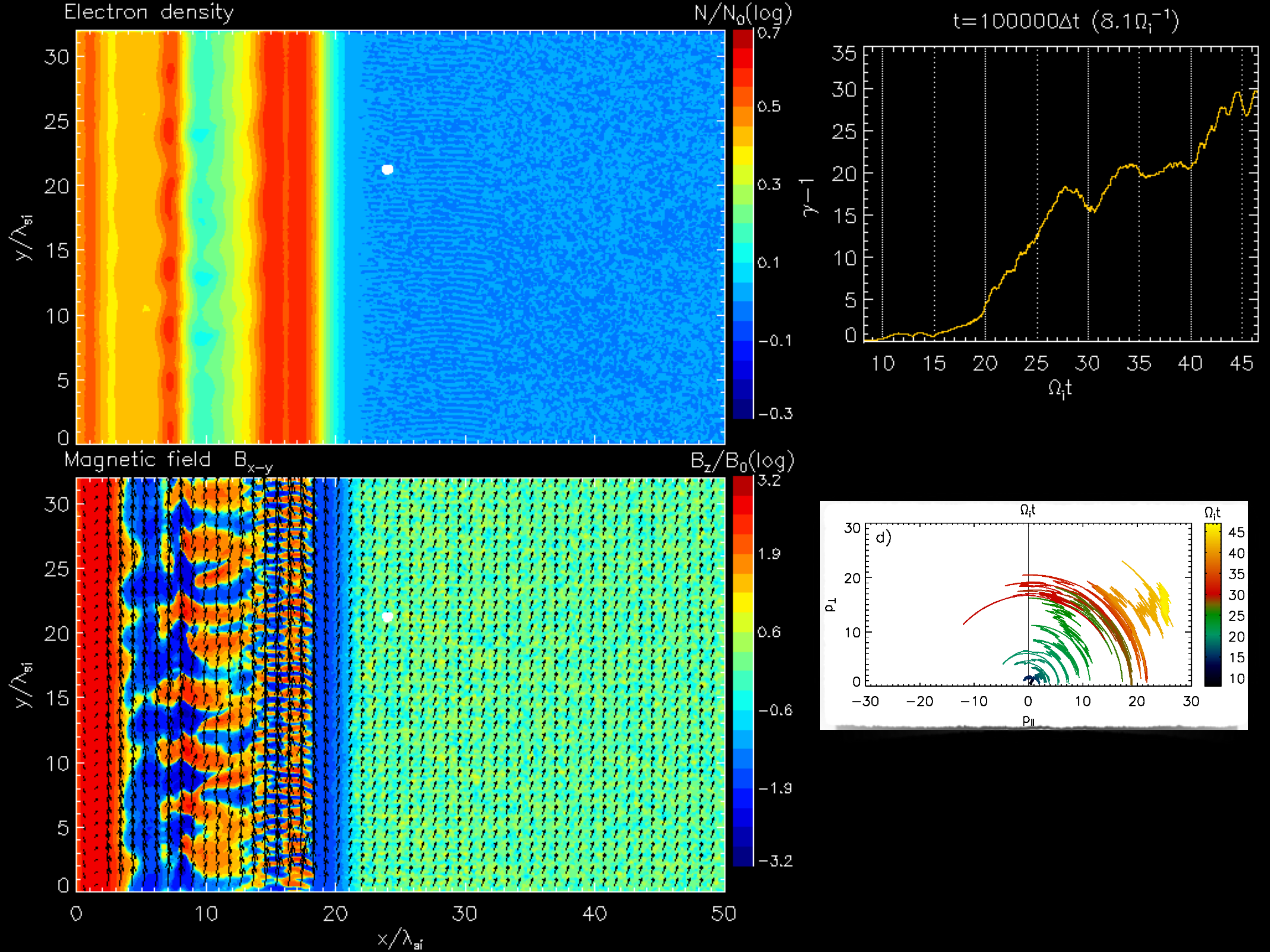


- adiabatic mirror reflection in the HTF
- elastic scattering (diffusion) in the plasma rest frame

- 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

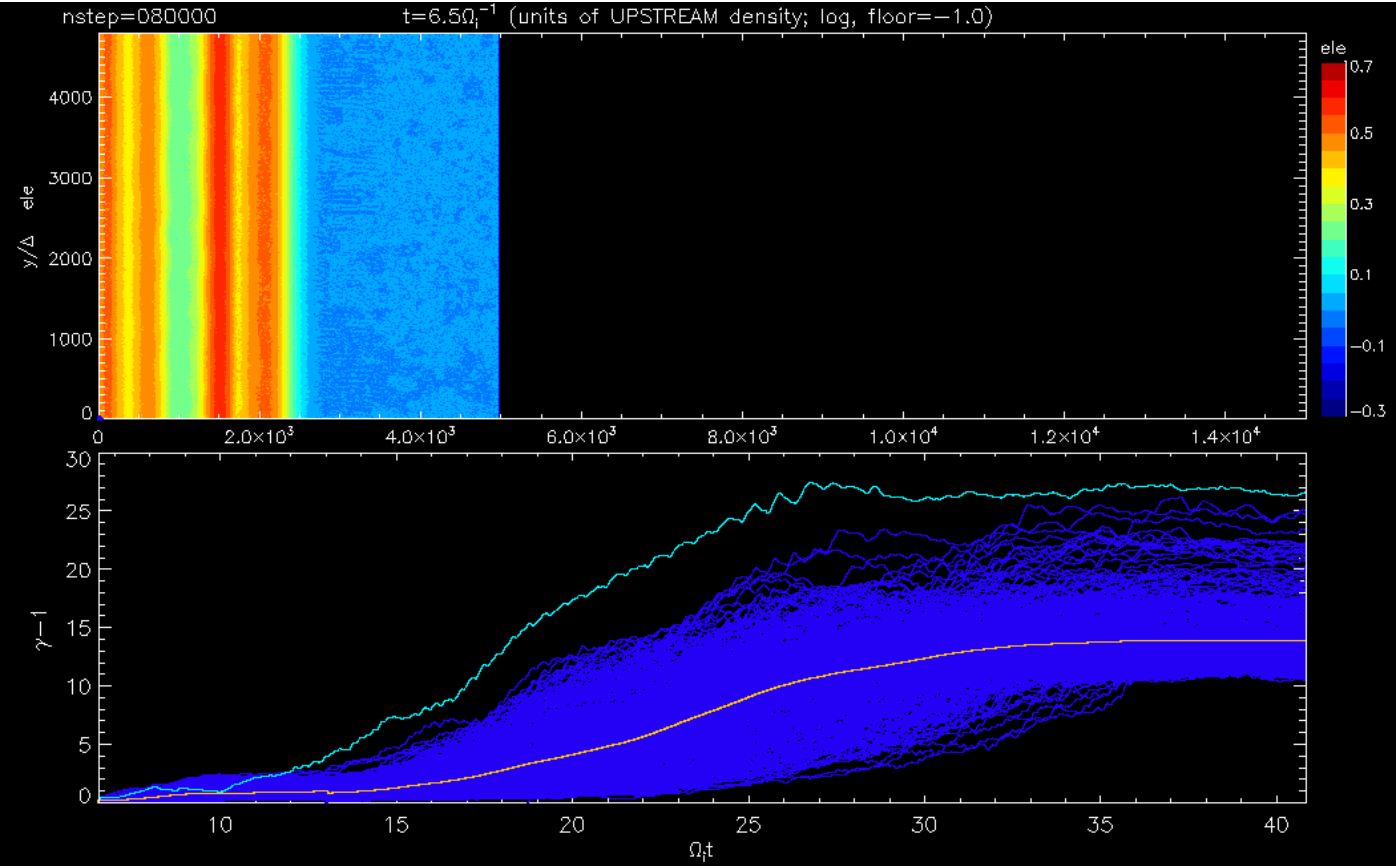


Electron density
N/N0(log)
y/λsi
Magnetic field Bx−y
Bz/B0(log)
x/λsi
t=360000Δt (29.3Ωi−1)
γ−1
Ωit
d)
p⊥
p∥



Electron density
N/N0(log)
0.7
0.5
0.3
0.1
−0.1
−0.3
y/λsi
Magnetic field Bx−y
Bz/B0(log)
3.2
1.9
0.6
−0.6
−1.9
−3.2
x/λsi
t=100000Δt (8.1Ωi−1)
γ−1
Ωit
d)
p⊥
p∥
Ωit

Downstream spectrum formation



- downstream particles accelerated in the shock through SSDA
- 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
- 1D studies of proton injection suggest proton acceleration efficiency at ICM shocks much lower than in low-β plasmas - detection of gamma-ray emission requires sensitive observations (LHAASO, CTA)
- protons injected only in supercritical quasi-parallel shocks with $M_s > 2.25$
- electrons are injected at quasi-perpendicular sub-luminal shocks
- 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