Particle injection at weak ICM shocks

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Ha et al. 2018

Proton Acceleration in Weak Quasi-parallel Intracluster Shocks: Injection and Early Acceleration

$$M_s \leq 4,\ M_A \leq 40,$$
$$\beta \approx 50 - 100$$

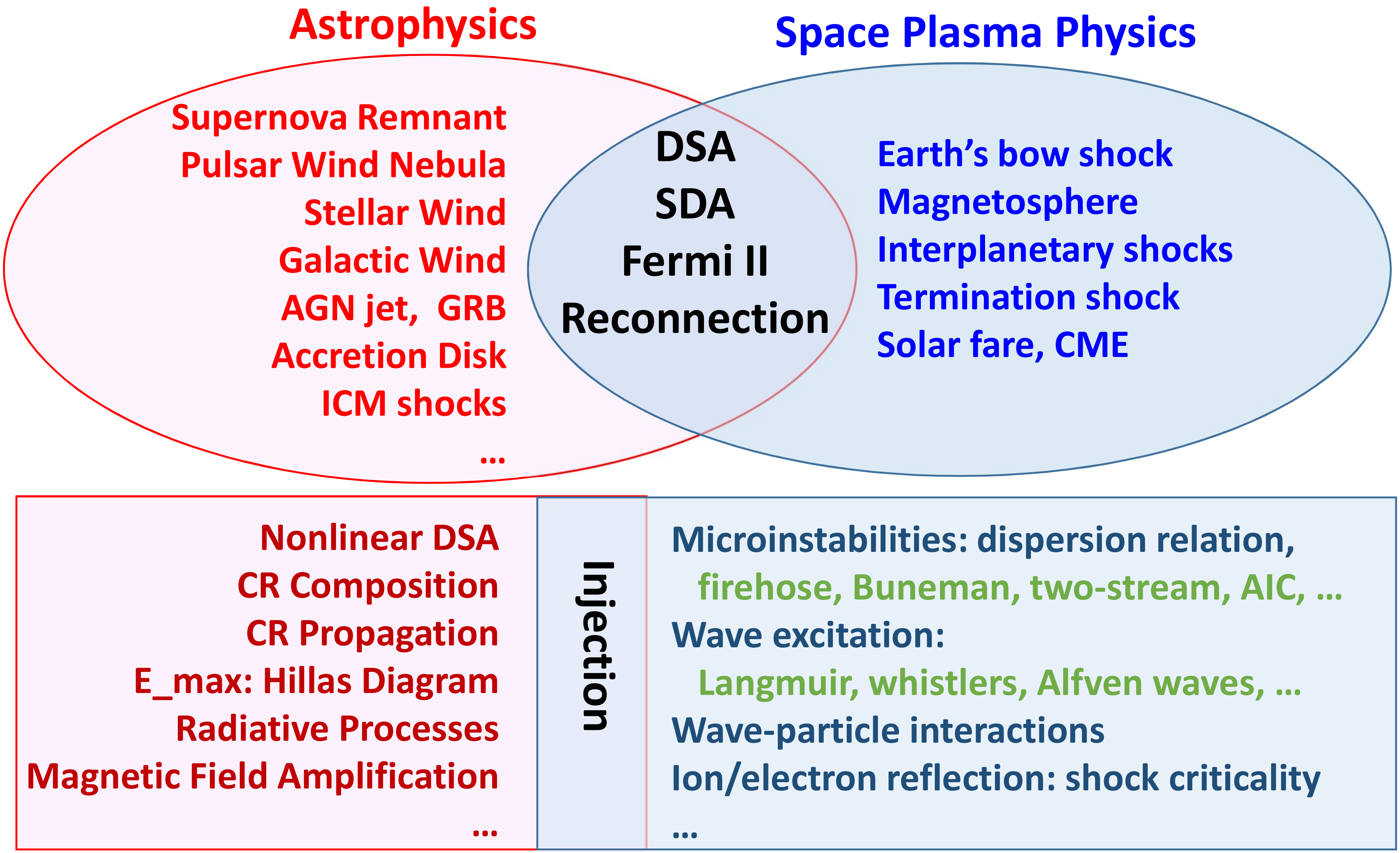
Kang et al. 2019

Electron Preacceleration in Weak Quasi-perpendicular Shocks in High-beta Intracluster Medium

Ryu et al. 2019

A Diffusive Shock Acceleration Model for Protons in Weak Quasi-parallel Intracluster Shocks

Physics of Collisionless shocks



Astrophysics

Supernova Remnant
Pulsar Wind Nebula
Stellar Wind
Galactic Wind
AGN jet, GRB
Accretion Disk
ICM shocks
…

DSA
SDA
Fermi II
Reconnection

Space Plasma Physics

Earth's bow shock
Magnetosphere
Interplanetary shocks
Termination shock
Solar fare, CME

Nonlinear DSA
CR Composition
CR Propagation
E_max: Hillas Diagram
Radiative Processes
Magnetic Field Amplification
…

Injection

Microinstabilities: dispersion relation,
firehose, Buneman, two-stream, AIC, …
Wave excitation:
Langmuir, whistlers, Alfven waves, …
Wave-particle interactions
Ion/electron reflection: shock criticality
…

CR transport EQ (Fokker Planck), Hybrid, PIC, MHD-PIC simulations

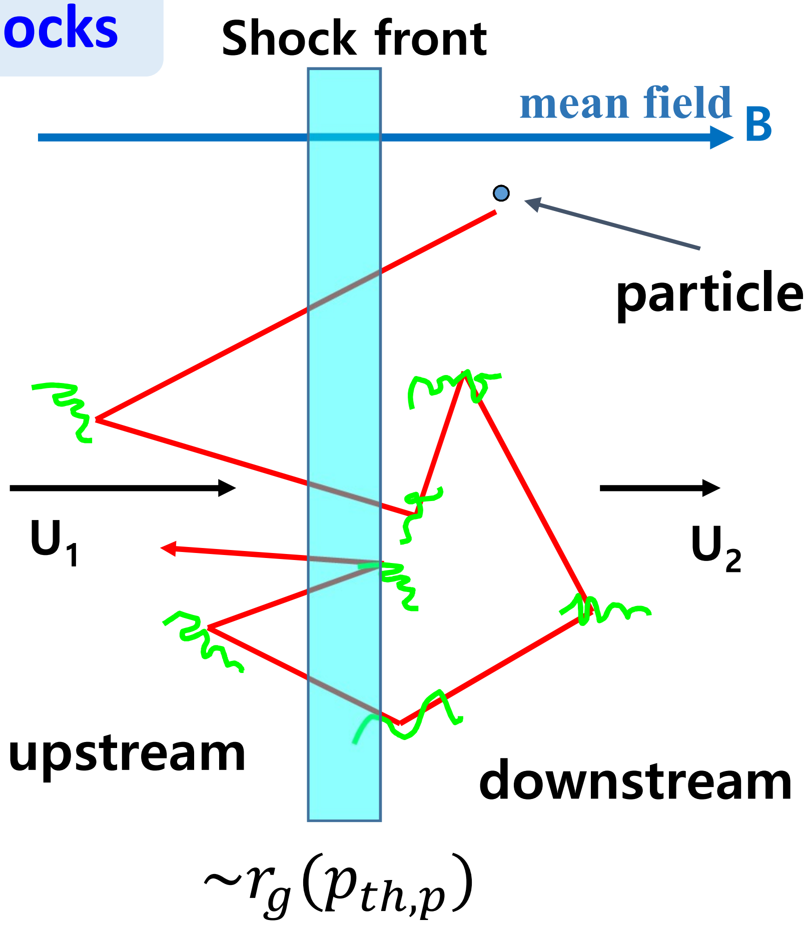
Outline

For non-shock-experts

1. **What is the injection problem ?**
2. **Thermal leakage injection recipe**
3. **Ion injection: reflection + SDA + wave generation**
4. **Electron injection: reflection + SDA + wave generation**
5. **Summary (slide # 35)**

DSA: Fermi first order process at $Q_{\parallel}$ shocks

$$\frac{\Delta \mathrm{p}}{\mathrm{p}} \sim \frac{\mathrm{u}_1 - \mathrm{u}_2}{\mathrm{v}} \text{ at each shock crossing}$$



Simple prediction:

test-particle limit solution

$$f_{\text{test}}(p) \propto p^{-q_{\text{test}}} \quad \text{:power-law}$$

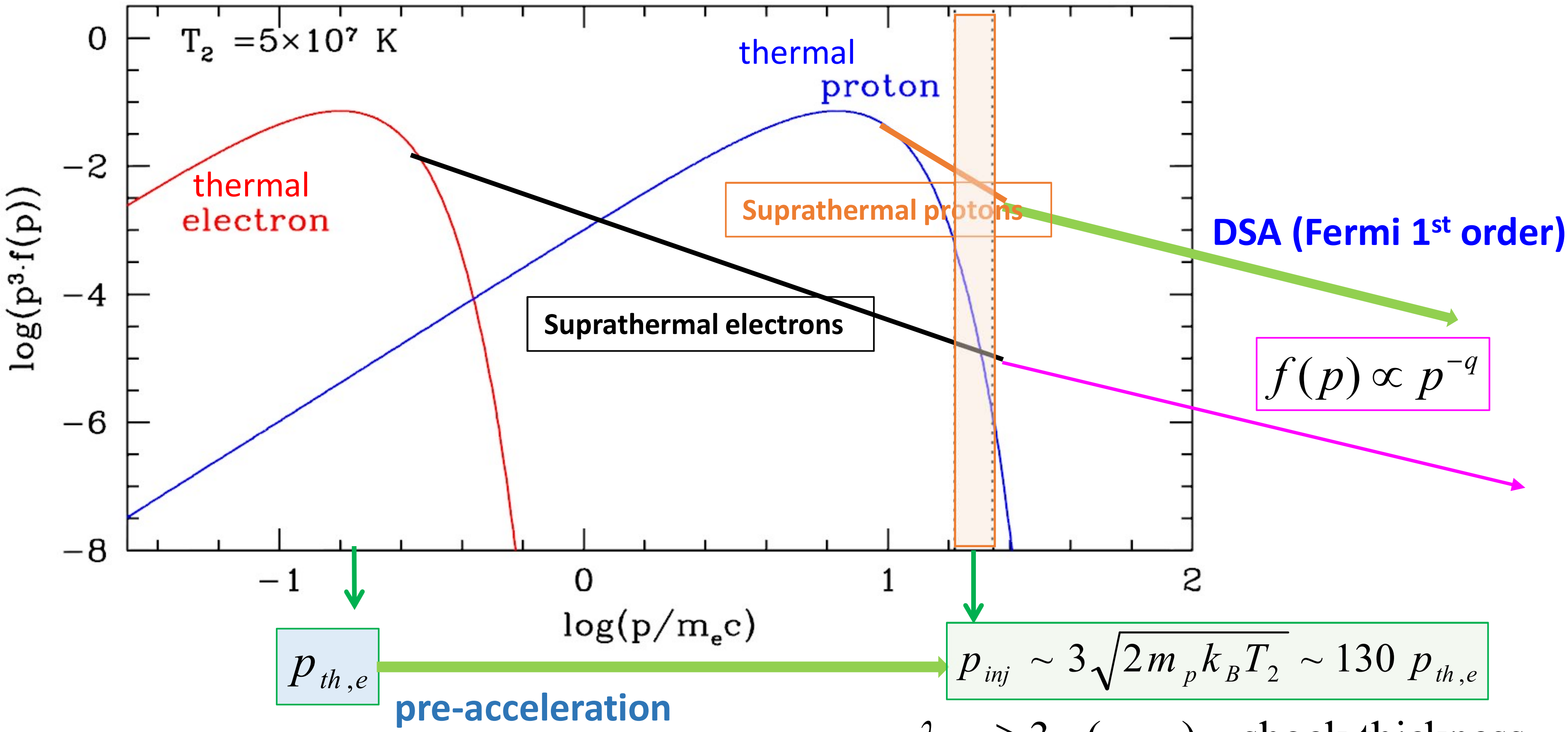
$$q_{\text{test}} = \frac{3u_1}{(u_1 - u_2)}$$

Requirement for shock crossing

$$\text{shock thickness} \sim \lambda_{mpf} > 3r_g(p_{th,p})$$

$\Rightarrow$ preacceleration & injection of particles into DSA needs to be investigated.

Proton &Electron pre-acceleration to be injected to DSA ?



$$f(p) \propto p^{-q}$$

$$p_{th,e}$$

$$p_{inj} \sim 3\sqrt{2m_p k_B T_2} \sim 130\ p_{th,e}$$

$$\lambda_{mpf} \geq 3r_g(p_{th,p}) \sim \text{shock thickness}$$

Protons (electrons) need to be pre-accelerated from $p_{th,p}$ ($p_{th,e}$) to p_{inj} in order to get injected into DSA process.

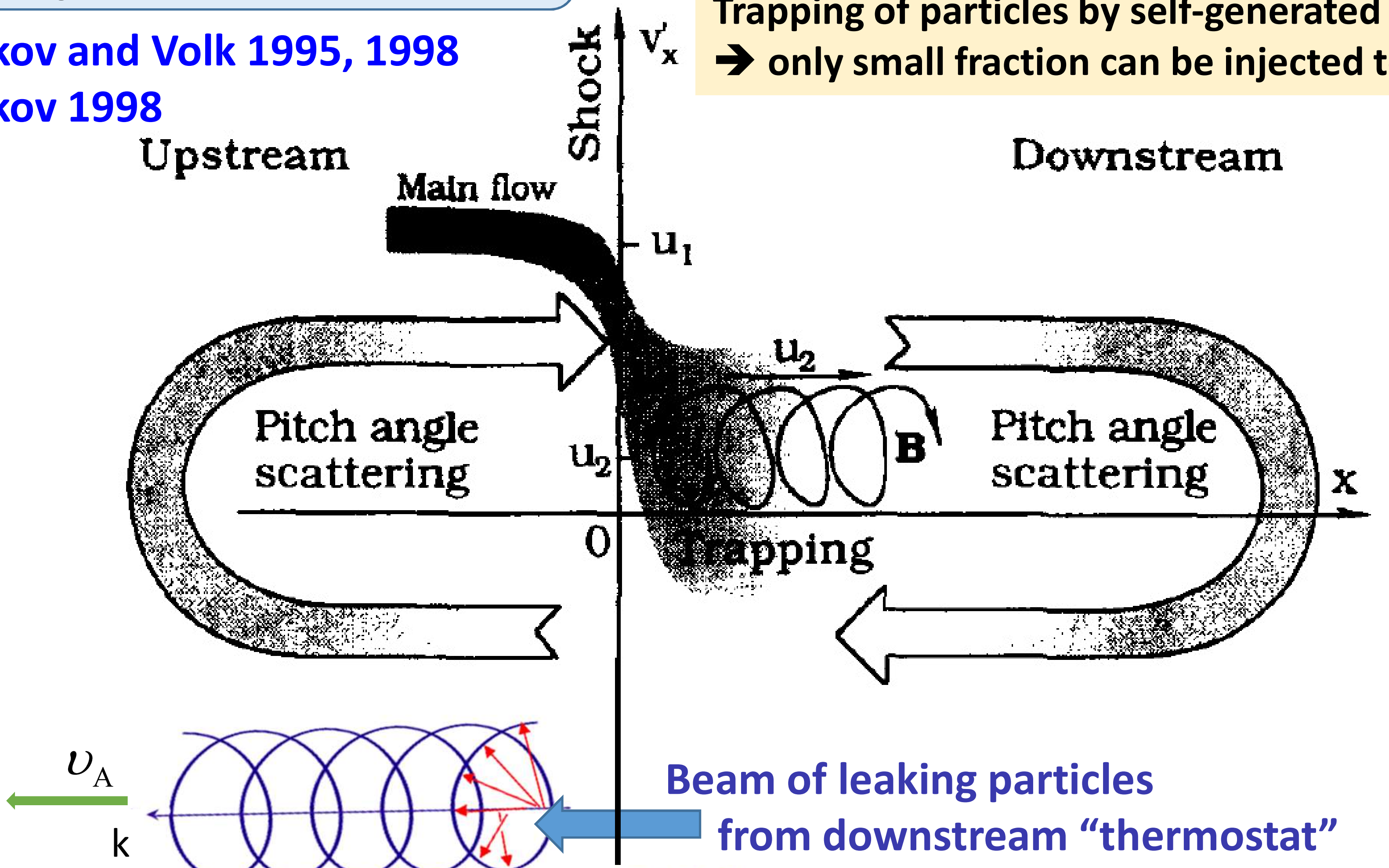
Understanding kinetic plasma processes in the shock front is important.

→ PIC or Hybrid simulations are required.

Thermal Leakage Injection for Q-par shocks

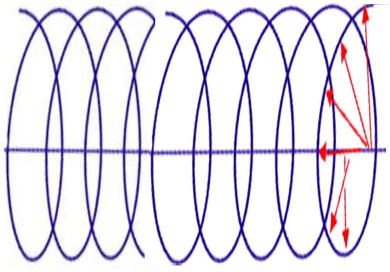
Malkov and Volk 1995, 1998
Malkov 1998

Trapping of particles by self-generated waves
➔ only small fraction can be injected to DSA



Beam of leaking particles from downstream "thermostat"

LH circularly polarized Alfven wave (self-generated)



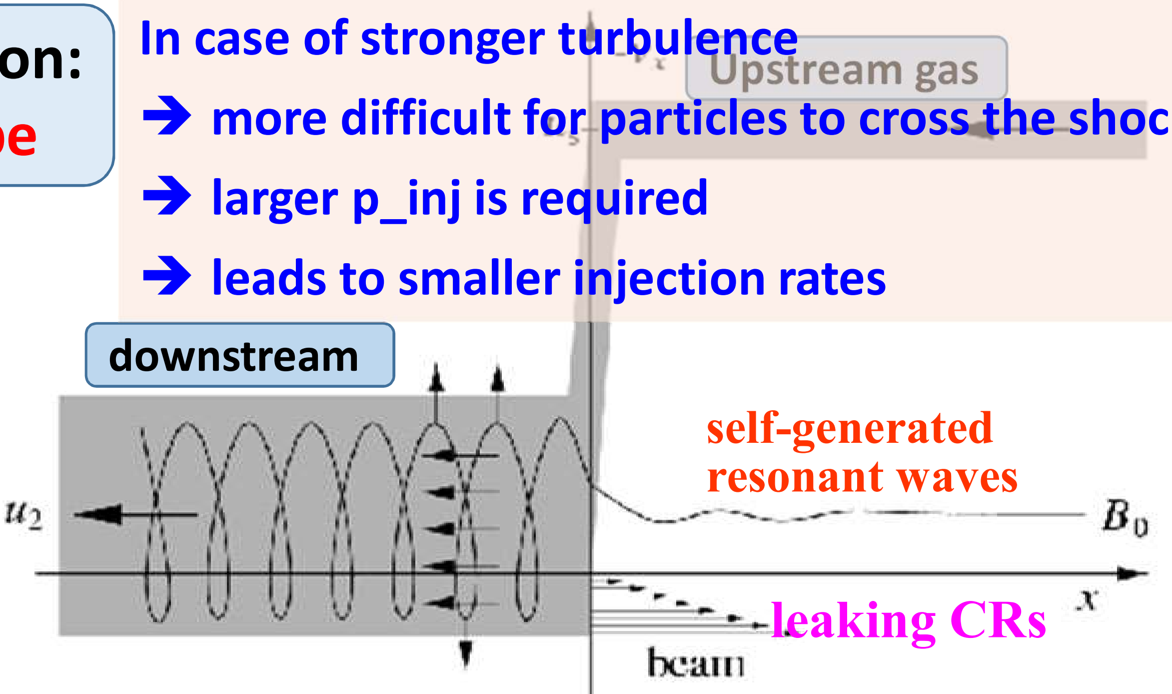
compressed & transmitted waves with $\delta B / B_0 \approx 3-4$ at strong shock

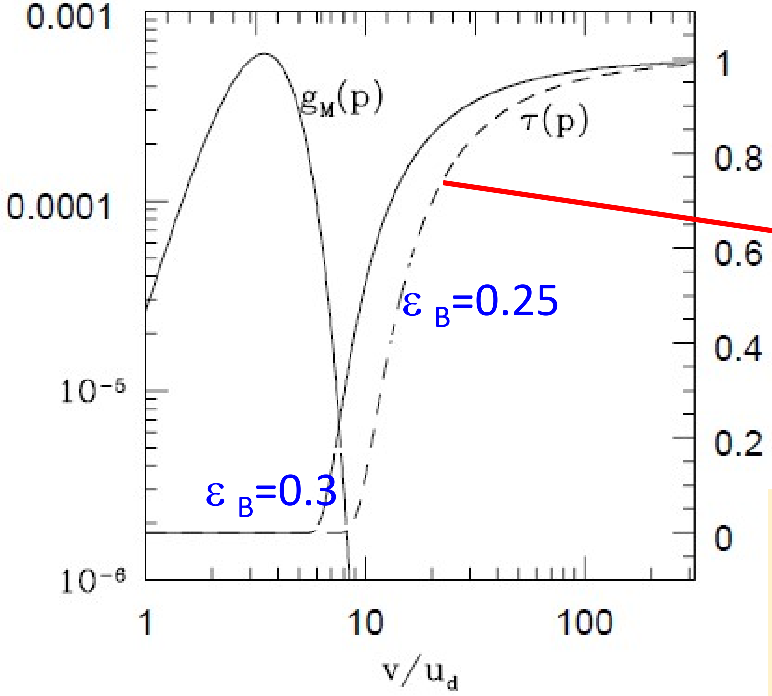
Thermal Leakage Injection:
Phenomenological recipe

Gieseler, Jones, Kang 2000

“Transparency function”:
probability that particles at a given velocity can swim through turbulence and leak from dnstream to upstream.

In case of stronger turbulence
➔ more difficult for particles to cross the shock
➔ larger p_inj is required
➔ leads to smaller injection rates





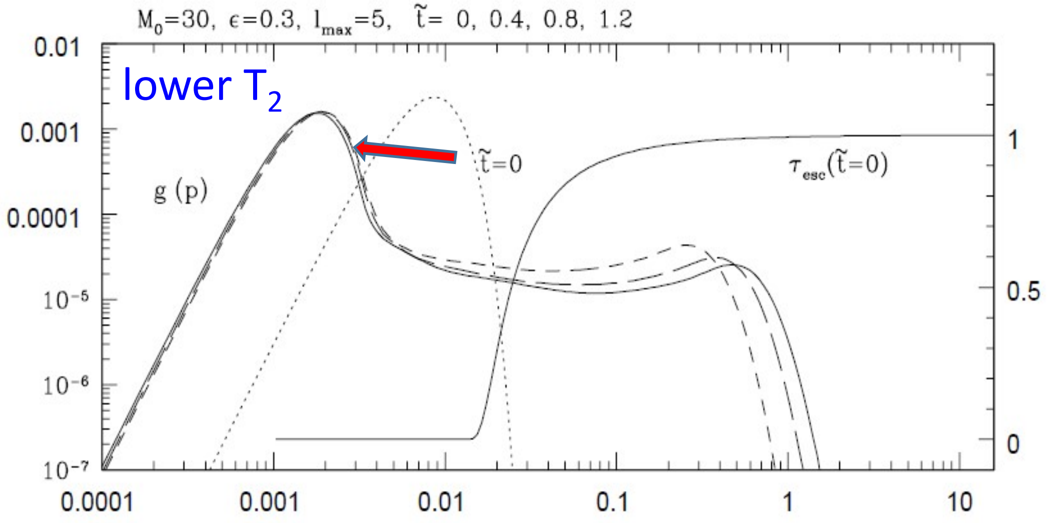
$$\tau_{esc}(\varepsilon_B, \frac{\upsilon}{u_d}) = H\left[\frac{\varepsilon_B \upsilon}{u_d} - (1+\varepsilon_B)\right]\left(1-\frac{u_d}{\upsilon}\right)^{-1}\left(1-\frac{u_d}{\varepsilon_B \upsilon}\right) \times \exp\left\{-\left[\frac{\varepsilon_B \upsilon}{u_d} - (1+\varepsilon_B)\right]^{-2}\right\}$$

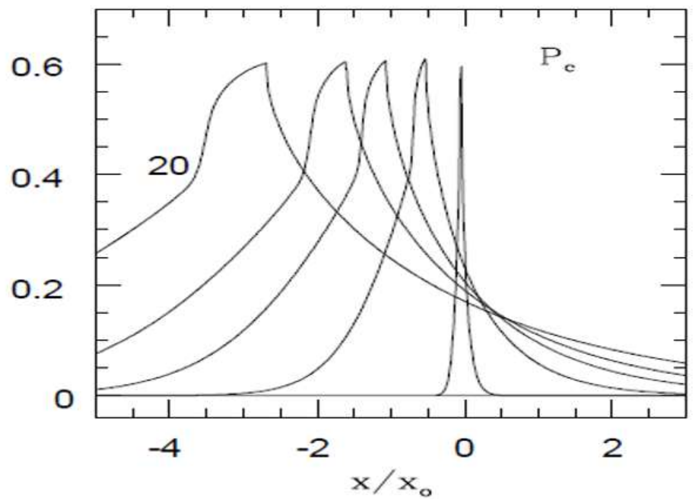
$$u_d(M) = \text{downstream flow speed}$$

$$\varepsilon_B = \frac{B_0}{B_\perp} = \frac{\text{mean field}}{\text{turbulent field}} \approx 0.25 - 0.35 \text{ for strong shocks}$$

NUMERICAL STUDIES OF COSMIC-RAY INJECTION AND ACCELERATION

Kang, Jones, Gieseler, 2002

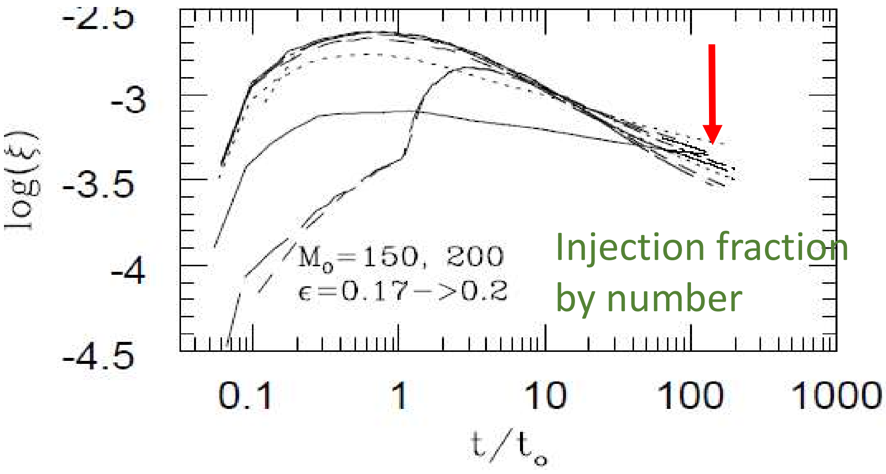


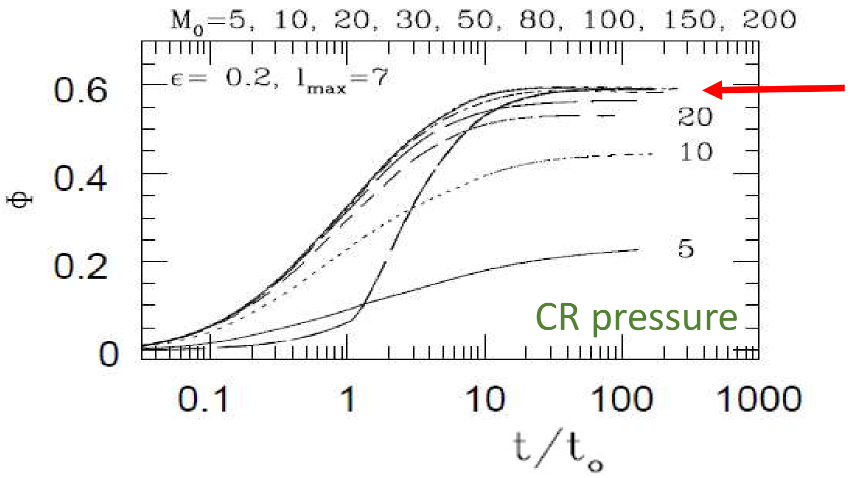


As the CR pressure increases,

1. **Posthshock temperature decreases (T_2 ↓)**
2. **The subshock weakens and the injection rate decreases accordingly.**
3. **The postshock CR pressure reaches an approximate time-asymptotic value.**

$$\Phi(t) = \frac{\int dx E_{CR}(x,t)}{0.5\rho_0 V_s^3 t}$$





Kang, Jones, Gieseler, 2002

In “fluid” simulations

Instead of following individual particle trajectories and evolution of fields

→ diffusion approximation (isotropy in local fluid frame is required)

→ **Diffusion-convection equation** for *f(p)* = isotropic part

$$\frac{\partial f}{\partial t} + (u+u_w)\frac{\partial f}{\partial x} = \frac{1}{3}\frac{\partial}{\partial x}(u+u_w)\cdot p\frac{\partial f}{\partial p} \;+\; \frac{\partial}{\partial x}[\kappa(x,p)\frac{\partial f}{\partial x}] \;+\; Q(x,p)$$

$$u_w \approx \text{wave drift speed} \approx V_A(x) = B(x)/\sqrt{4\pi\rho} : \quad \text{MFA}$$

$$\kappa(x,p) \approx \kappa^* p \propto B(x)^{-1} \quad : \text{Bohm - like diffusion}$$

$$Q(x,p) = \text{ injection of suprathermal ptls into Fermi process}$$

DIFFUSIVE SHOCK ACCELERATION IN TEST-PARTICLE REGIME

Kang & Ryu 2010

$$f_{\rm tp}(x_s, p) \approx f_{\rm inj} \cdot \left(\frac{p}{p_{\rm inj}} \right)^{-q_{\rm tp}}$$

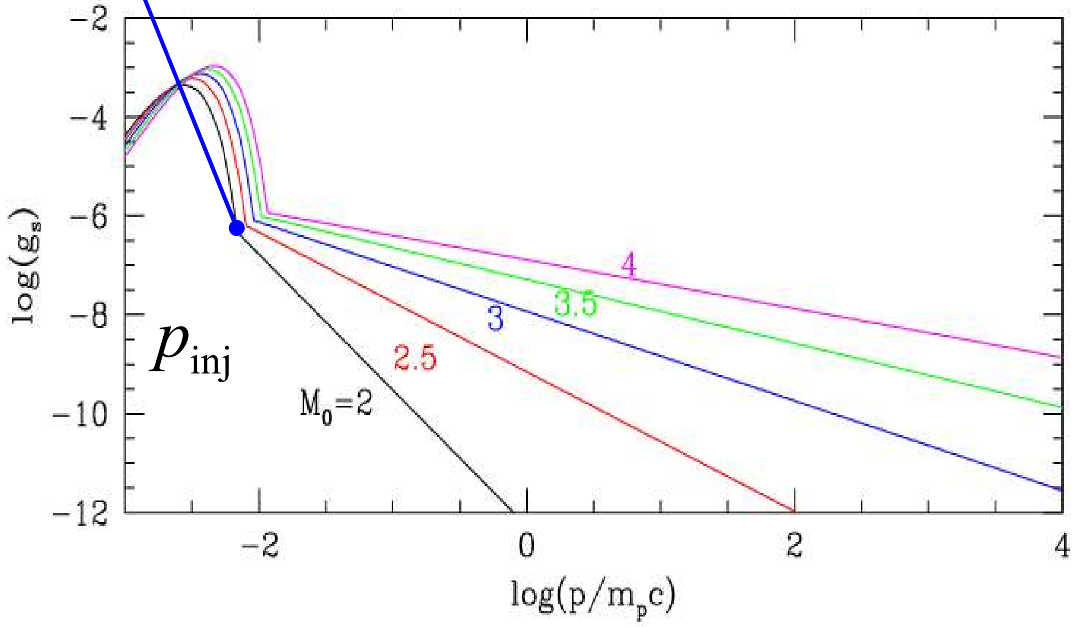
For weak ICM shocks

$$f_{\rm inj} = f(p_{\rm inj}) = \frac{n_2}{\pi^{1.5}} p_{\rm th}^{-3} \exp\left(-Q_{\rm inj}^2\right),$$

Q_{inj} determines the normalization.

$$p_{\rm inj} \approx 1.17 m_p u_2 \left(1 + \frac{1.07}{\epsilon_B} \right) \equiv Q_{\rm inj}(M, \epsilon_B) p_{\rm th},$$

Analytic solution depends on Q_{inj}



CR injection fraction

$$\xi_{\rm M} = \frac{4}{\sqrt{\pi}} \frac{Q_{\rm inj}^3}{(q-3)} \exp\left(-Q_{\rm inj}^2\right)$$

depends only on $Q_{\rm inj}$

Caprioli & Spitkovsky 2014
(Hybrid simulations)

$$Q_{\rm inj} \approx 3 - 3.5$$

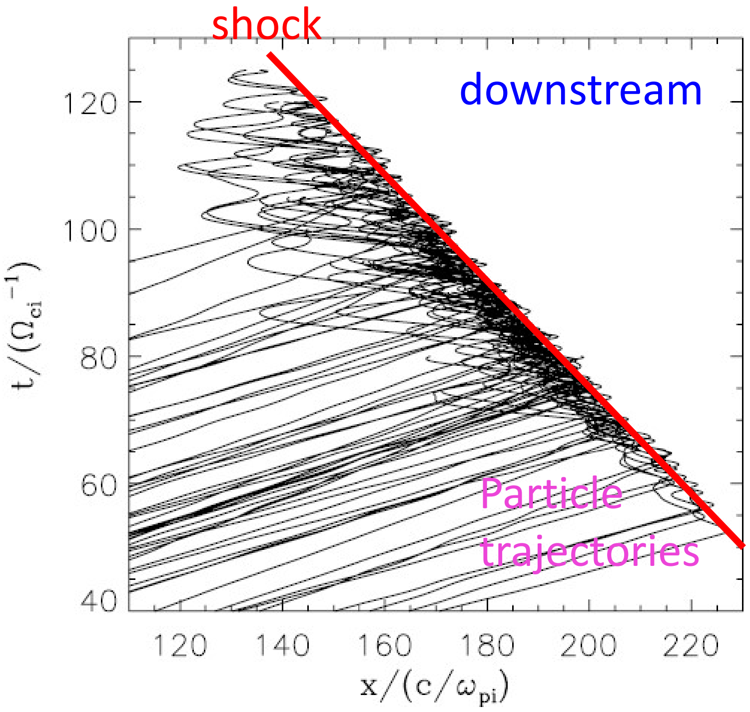
$$\xi \approx 10^{-4} - 10^{-3}$$

$$\Rightarrow \varepsilon_B \approx 0.23 - 0.27$$

$Q_{inj} > 3.8$ to be in test-particle regime

THE ACCELERATION OF THERMAL PROTONS AT PARALLEL COLLISIONLESS SHOCKS: THREE-DIMENSIONAL HYBRID SIMULATIONS

Guo & Giacalone 2013



Locations of 50 accelerated protons.

They gain their initial energy at the first reflection off the shock.

$$M_{A0} = V_x/V_{A0} = 4.0$$

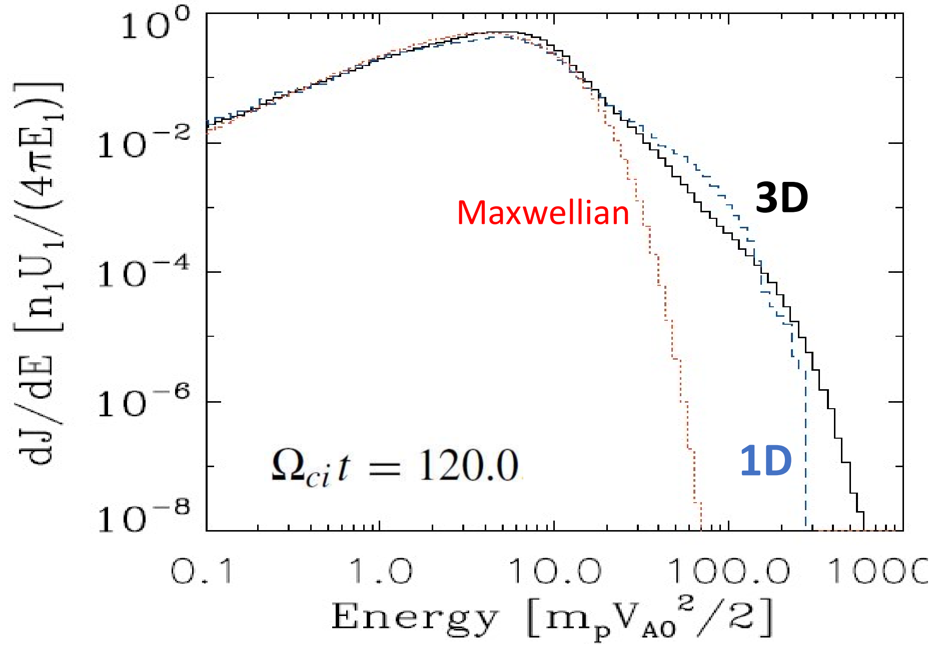
$$\theta_{Bn} = 0^{\circ},\ \beta \approx 1$$

Turbulent B fields can be locally Q-perp even for Q-par shocks.

➔ Protons go through SDA at shock transition zone.

➔ They are reflected upstream at the shock

Not consistent with thermal leakage



Well established in space physics community, Scholer 1990, Scholer & Terasawa 1990, Giacalone et al. 1992

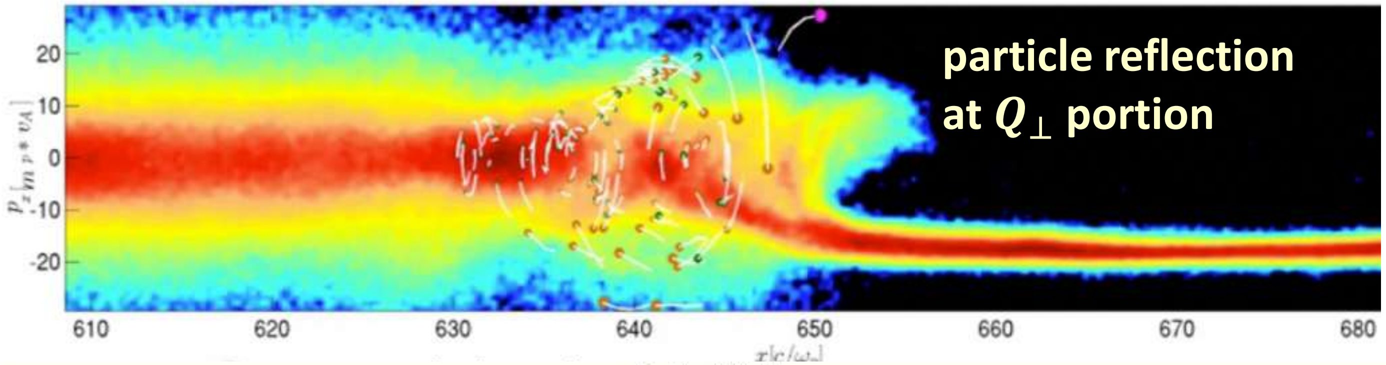
2D & 3D hybrid simulations by Caprioli & Spitkovsky 2014a, b, c

+ Minimal model for ion injection by Caprioli et al 2015.

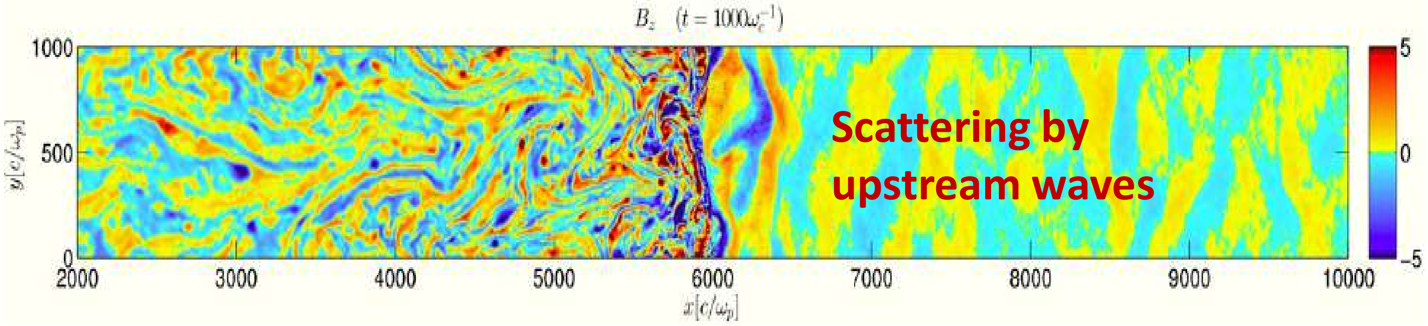
Two crucial ingredients for Proton Acceleration at $Q_{\parallel}$ shocks

1) **Injection: multiple cycles of [reflection + SDA]**
2) **Scattering by upstream waves (pre-existing or self-generated)**

   ➔ return back to the shock ➔ DSA



particle reflection at $Q_{\perp}$ portion



Scattering by upstream waves

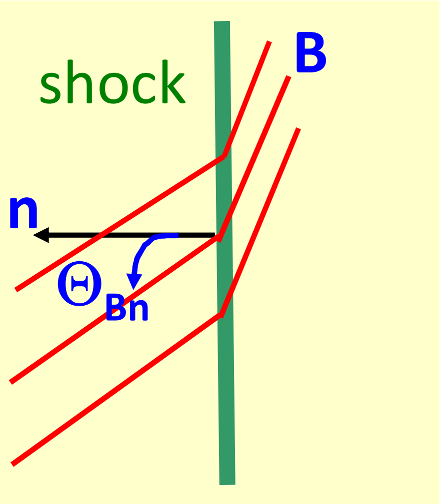
Ion reflection at the shock ramp (SDA)

+

Self-generation of upstream waves

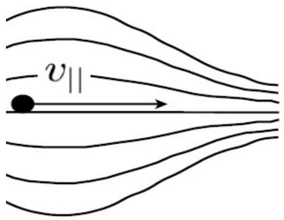
Two ways to reflect protons/electrons at the shock

(1) magnetic mirror reflection due to compression of transverse magnetic fields



$$m\frac{d\upsilon_{\parallel}}{dt} = -\frac{m\upsilon_{\perp}^{2}}{2B}\nabla_{\parallel}B$$

mirror force due to gradient of B



- **dominant at $Q_{\perp}$ shock**
- **more important at low β shock**

(2) Shock potential barrier:

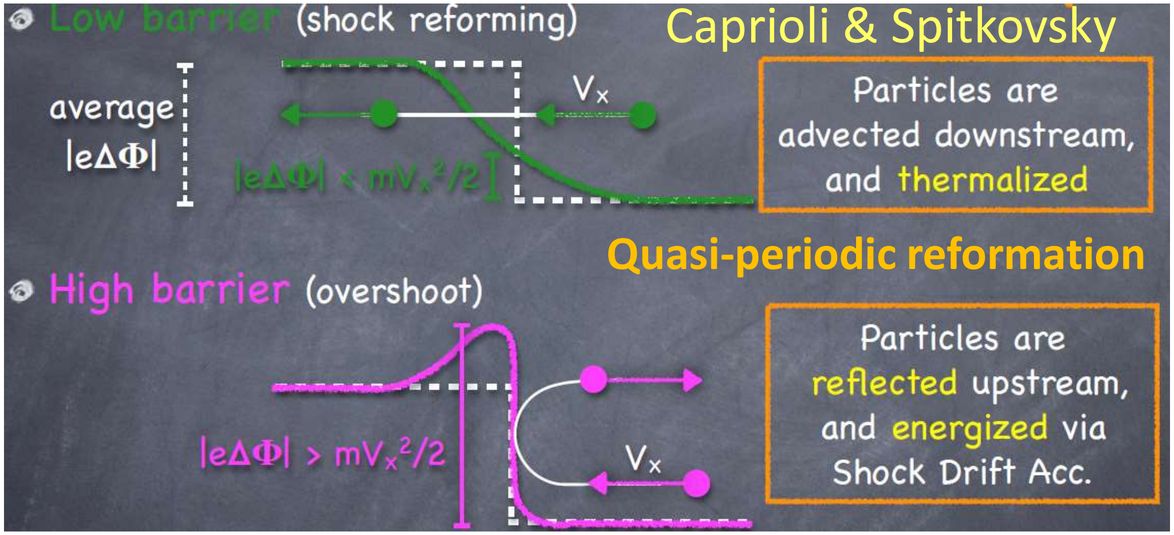
-decelerates ions

but accelerates electrons

-ions are reflected by overshoot

$$e\Delta\phi \approx \alpha(M_s, t)\frac{m_i v_{\rm sh}^2}{2},$$

- **dominant at $Q_{\parallel}$ shock**



Caprioli & Spitkovsky

Particles are advected downstream, and thermalized

Quasi-periodic reformation

Particles are reflected upstream, and energized via Shock Drift Acc.

Both magnetic field compression & shock potential drop depends on M_s

→ Reflection fraction decreases with decreasing M_s

Key elements for proton injection to DSA at $Q_{\parallel}$ shocks

(1) **Reflection** at the shock & energy gain near the front via **SDA**

(2) **Backstreaming** of ions upstream along B_0

→relative drift between reflected ions & incoming particles: free E source

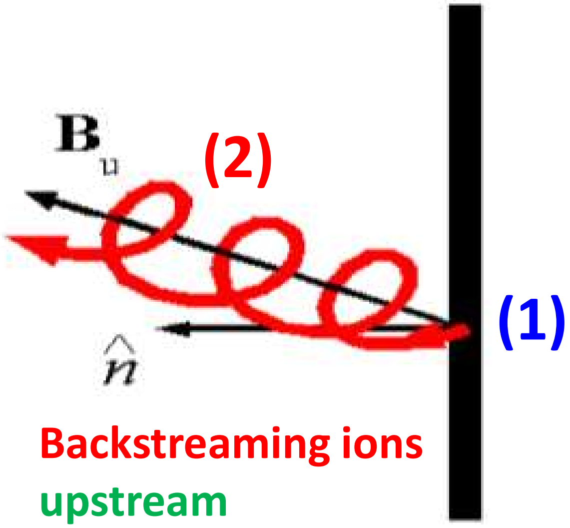
(3) **Self-excitation** of upstream waves: e.g. whistlers & Alfven waves

→ Scattering back to the shock → **Injection to Fermi I acceleration**

(3) Excitation of waves

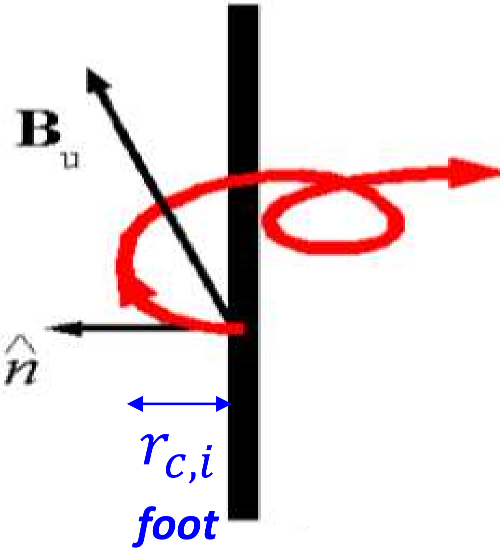
Scattering back to the shock by upstream waves

Q-par shock



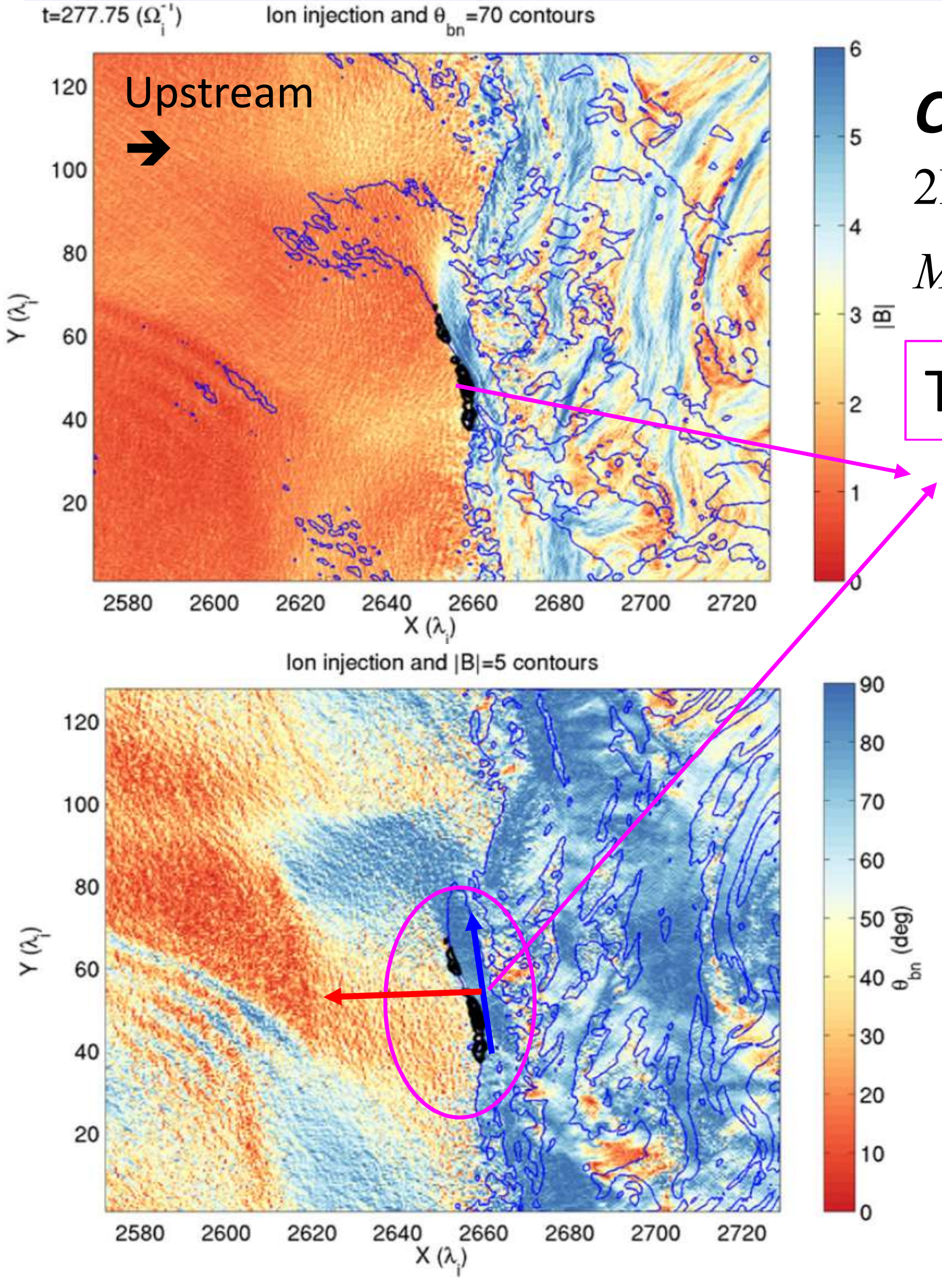
Backstreaming ions upstream

after a few gyro-orbit, advect downstream



Q-perp shock

ION ACCELERATION AT THE QUASI-PARALLEL BOW SHOCK: DECODING THE SIGNATURE OF INJECTION



Sundberg et al. 2016

***Cluster* mission data**

2D Hybrid simulations:

$$M_A = 8.1, \quad \theta_{\mathrm{Bn}} = 30^{\circ}, \beta_{\mathrm{i}} = 0.5$$

Transition from $Q_{\parallel}$ to $Q_{\perp}$ obliquity

Ion injection occurs

- at sharp B field gradient

- Θ_{Bn} changes from perp to parallel

At the trailing edge of a ULF wave

➔specular reflection off a shock potential at locally perp. field orientation.

➔ escape upstream at parallel orientation

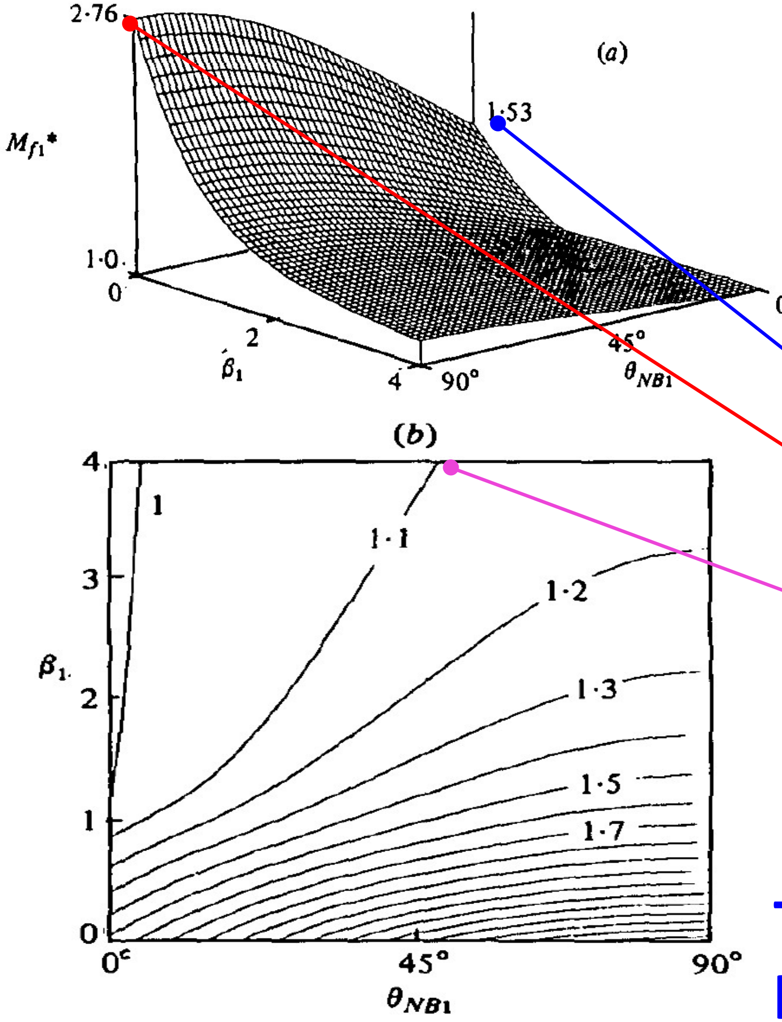
Ion Injection=
specular reflection at $Q_{\perp}$ portion
+ upstream streaming at $Q_{\parallel}$ portion

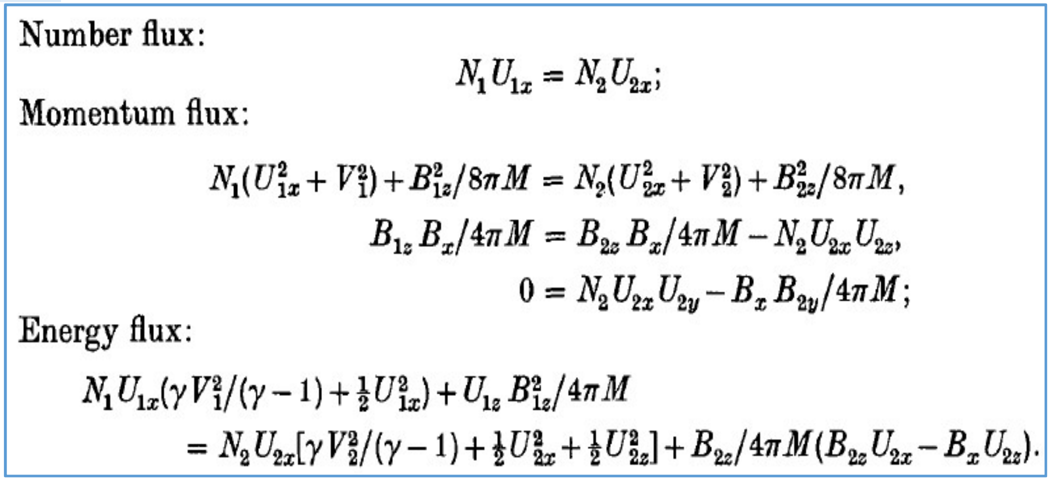
Shock Criticality: ion reflection

Edmiston & Kennel 1984

First fast critical Mach number:

$U_{2x} = c_{s2}$ for ion reflection





Number flux:

$$N_1 U_{1x} = N_2 U_{2x};$$

Momentum flux:

$$N_1(U_{1x}^2 + V_1^2) + B_{1z}^2/8\pi M = N_2(U_{2x}^2 + V_2^2) + B_{2z}^2/8\pi M,$$

$$B_{1z} B_x/4\pi M = B_{2z} B_x/4\pi M - N_2 U_{2x} U_{2z},$$

$$0 = N_2 U_{2x} U_{2y} - B_x B_{2y}/4\pi M;$$

Energy flux:

$$N_1 U_{1x}(\gamma V_1^2/(\gamma - 1) + \tfrac{1}{2}U_{1x}^2) + U_{1z} B_{1z}^2/4\pi M$$
$$= N_2 U_{2x}[\gamma V_2^2/(\gamma-1) + \tfrac{1}{2}U_{2x}^2 + \tfrac{1}{2}U_{2z}^2] + B_{2z}/4\pi M(B_{2z}U_{2x} - B_x U_{2z}).$$

$\beta = 0$ limit

$M_f^* = 1.53$ for $\theta_{Bn} = 0^\circ$ Parallel shocks

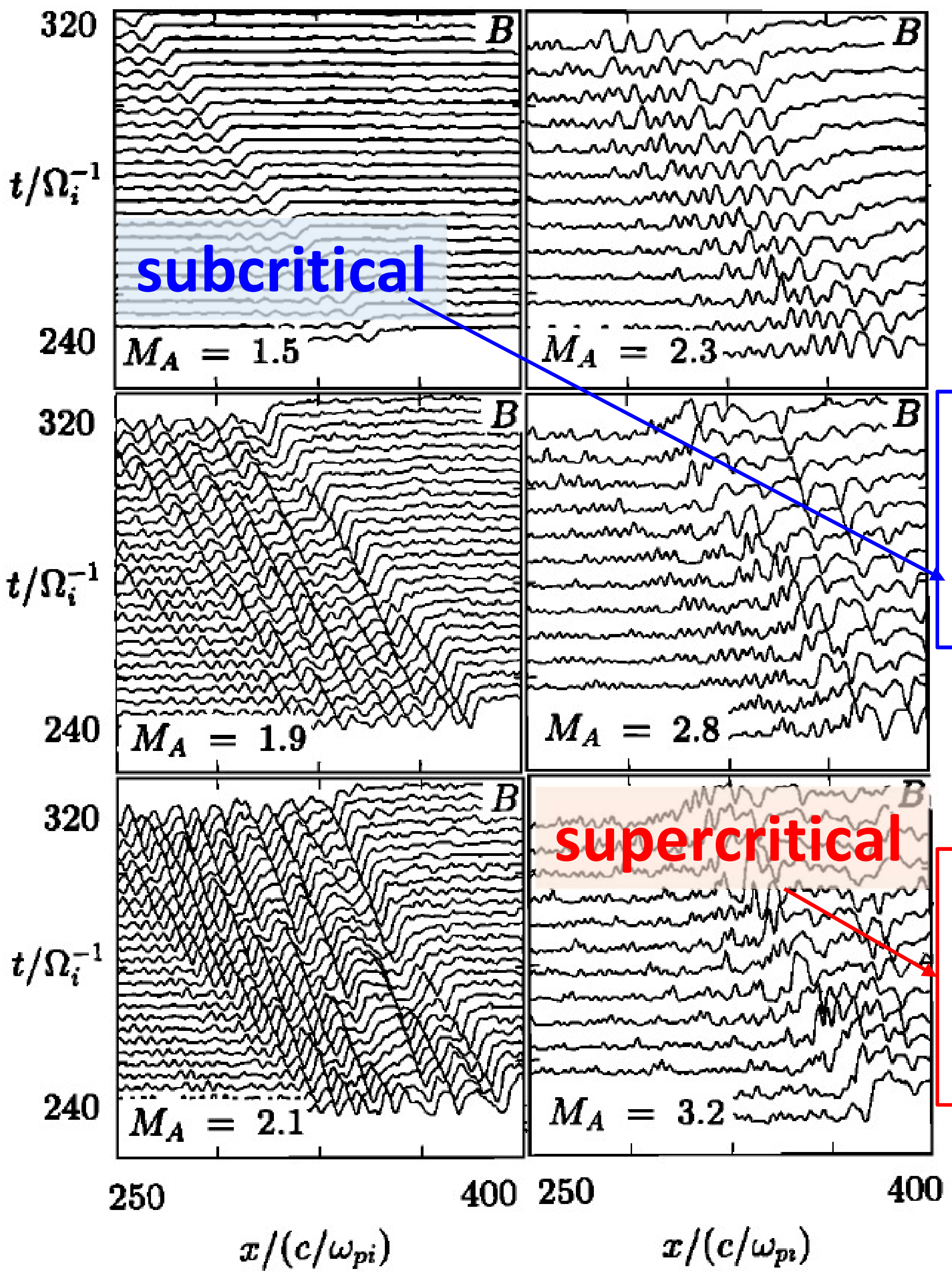
$M_f^* = 2.76$ for $\theta_{Bn} = 90^\circ$ Perp. shocks

$\beta >> 1$ limit,

$M_f^* \sim 1.0 - 1.1$ for $\theta_{Bn} < 45^\circ$ **$Q_\parallel$ shocks**

$M_f^* \sim 1.1 - 1.2$ for $\theta_{Bn} > 45^\circ$ **$Q_\perp$ shocks**

This fluid approach does not account for kinetic processes in shock transition.



SOURCES OF MAGNETOSHEATH WAVES
AND TURBULENCE

Omidi + 1994

N. Omidi,* A. O'Farrell** and D. Krauss-Varban***

1D hybrid simulations

Low M_A $Q_{\|}$ shocks

$$\theta_{Bn} = 30^\circ, \quad \beta_i = 0.5$$

M_A= 1.5 : shock is steady & smooth, lacking an overshoot.
→ Ion reflection is inefficient, maybe little particle acceleration

M_A= 3.2 : shock is unsteady & undergoes self-reformation.
→ Efficient ion reflection & particle acceleration

1D PIC simulations for $Q_{\parallel}$ high β shocks (proton injection to DSA)

Ha, Ryu, Kang + 2018

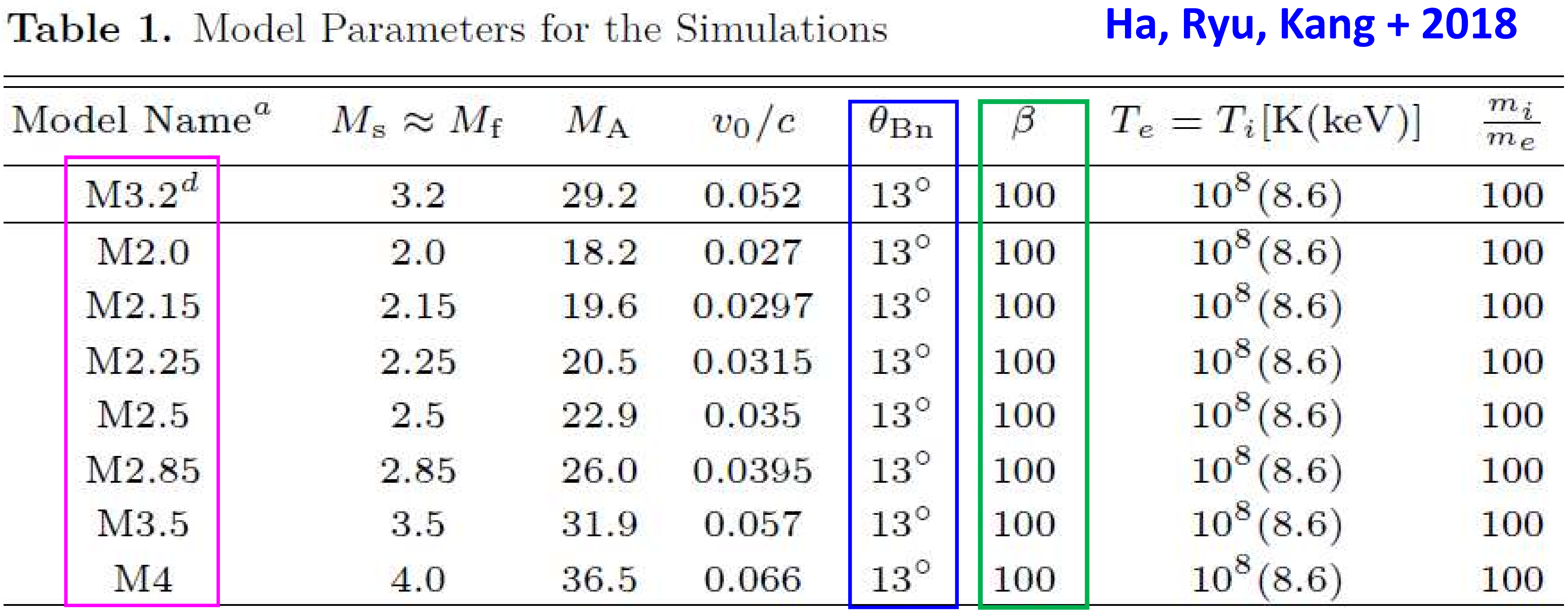
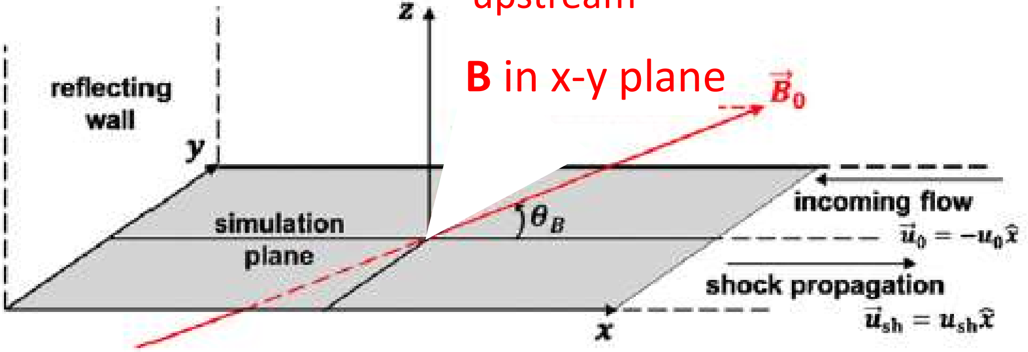


Table 1. Model Parameters for the Simulations

Model Name[a]	$M_s \approx M_f$	M_A	v_0/c	θ_{Bn}	β	$T_e = T_i$[K(keV)]	$\frac{m_i}{m_e}$
M3.2[d]	3.2	29.2	0.052	13°	100	10^8(8.6)	100
M2.0	2.0	18.2	0.027	13°	100	10^8(8.6)	100
M2.15	2.15	19.6	0.0297	13°	100	10^8(8.6)	100
M2.25	2.25	20.5	0.0315	13°	100	10^8(8.6)	100
M2.5	2.5	22.9	0.035	13°	100	10^8(8.6)	100
M2.85	2.85	26.0	0.0395	13°	100	10^8(8.6)	100
M3.5	3.5	31.9	0.057	13°	100	10^8(8.6)	100
M4	4.0	36.5	0.066	13°	100	10^8(8.6)	100



downstream

upstream

B in x-y plane

$$M_0 \equiv \frac{u_0}{c_s} = \frac{u_0}{\sqrt{2\Gamma k_B T_i/m_i}},$$

$$M_s \equiv \frac{u_{sh}}{c_s} \approx M_0 \frac{r}{r-1}$$

$$M_A \equiv \frac{v_{sh}}{v_A} \approx \sqrt{\beta} \cdot M_s$$

$$\Omega_{ci} \propto \frac{\omega_{pe}}{\sqrt{\beta}}$$

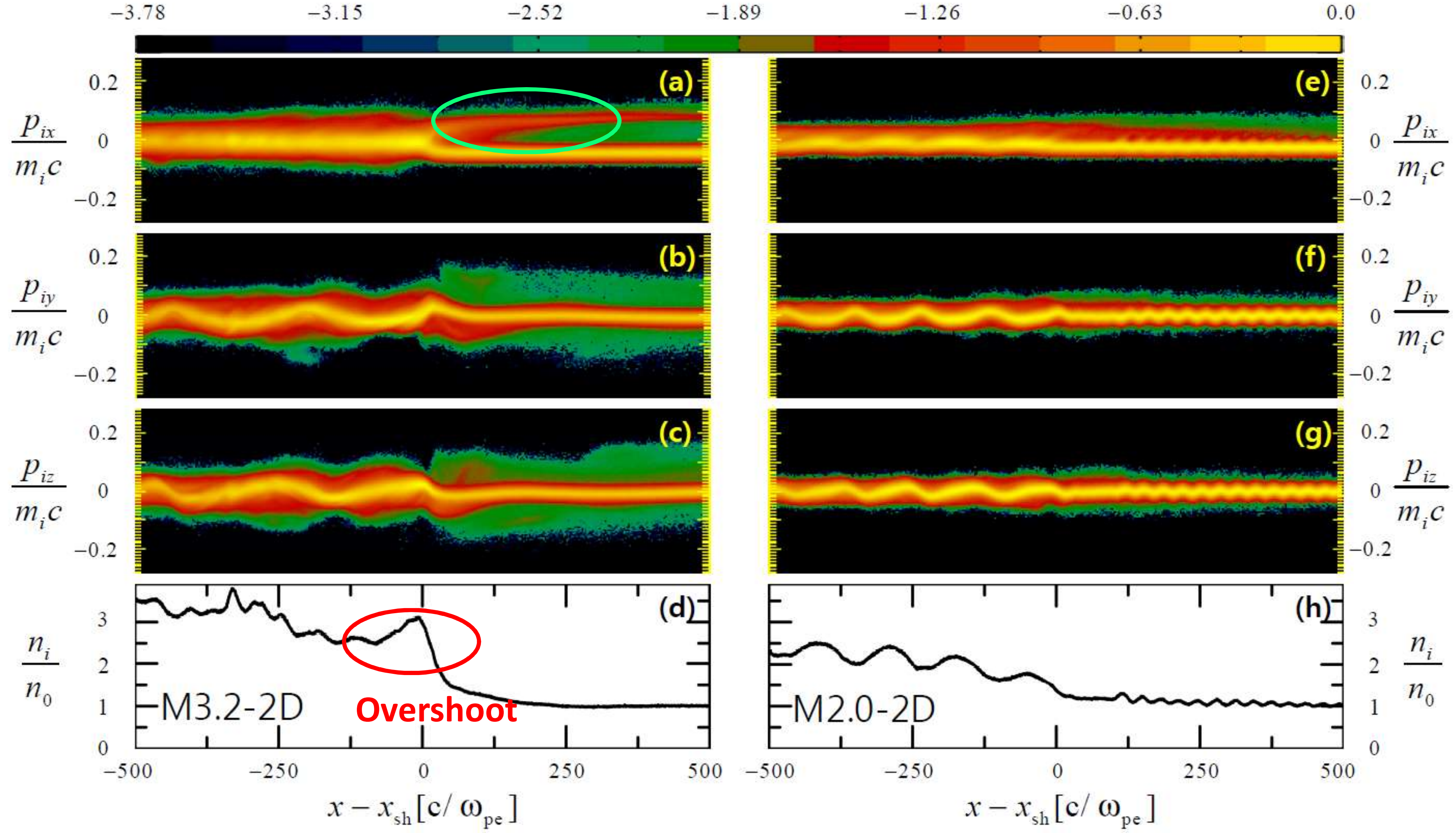
2D Run:	$L_x[c/w_{pe}]$	$L_y[c/w_{pe}]$
	2×10^4	60

Simulation frame = downstream rest frame

$\theta_{Bn} = 13^\circ$

M_s= 3.2 supercritical with a beam of reflected ions

M_s= 2.0 subcritical with a small amount of reflected ions



Time-varying overshoot in eΦ & B & cyclic reformation of the shock

$r_{\rm L,i} \equiv \frac{m_i v_0 c}{eB_0} = M_{\rm A,0}\sqrt{\frac{m_i}{m_e}}\frac{c}{\omega_{\rm pe}}$ ~ 200 $\frac{c}{\omega_{\rm pe}}$

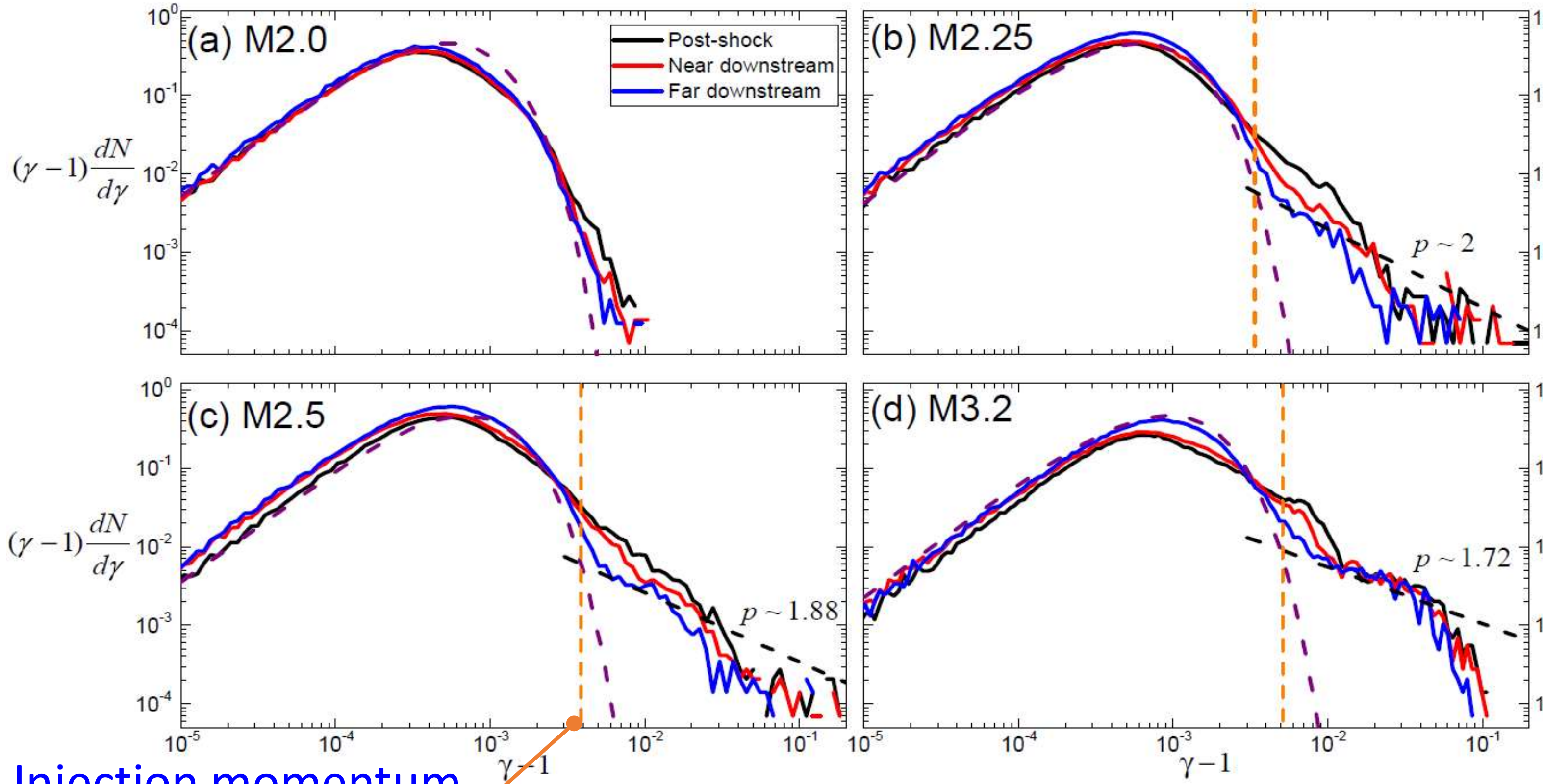
Mach number dependence

$\theta_{Bn} = 13^\circ$

$(0-1)r_{L,i}$, $(1-2)r_{L,i}$ and $(5-6)r_{L,i}$

$w_{pe}t \approx 3.4\times10^5$

$(\Omega_{ci}t \approx 90)$



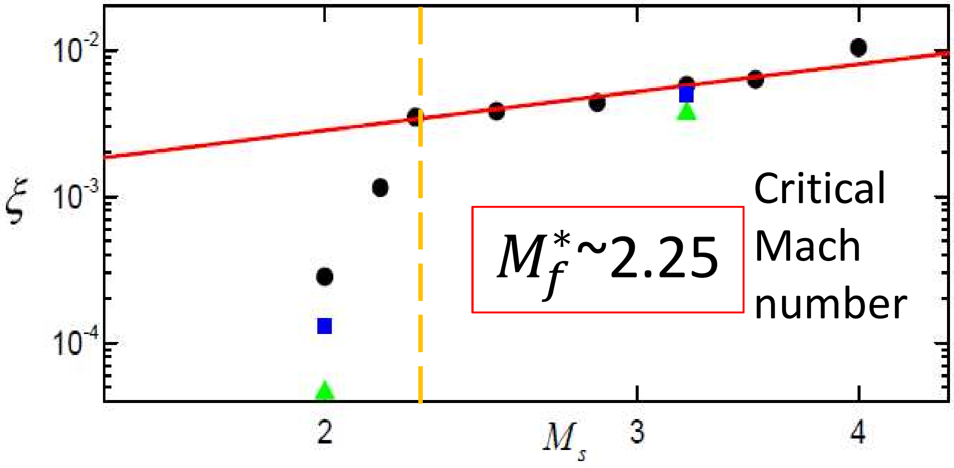
Injection momentum

$$p_{inj} \approx 2.7\,p_{th},\quad \text{where } p_{th} = \sqrt{2m_i k_B T_2}$$

Injection fraction

$$\xi \equiv \frac{1}{n_2}\int_{p_{\min}}^{p_{\max}} 4\pi f(p)p^2\,dp,$$

$$p_{min} = \sqrt{2}\,p_{inj}$$



M_f^*~2.25

Critical Mach number

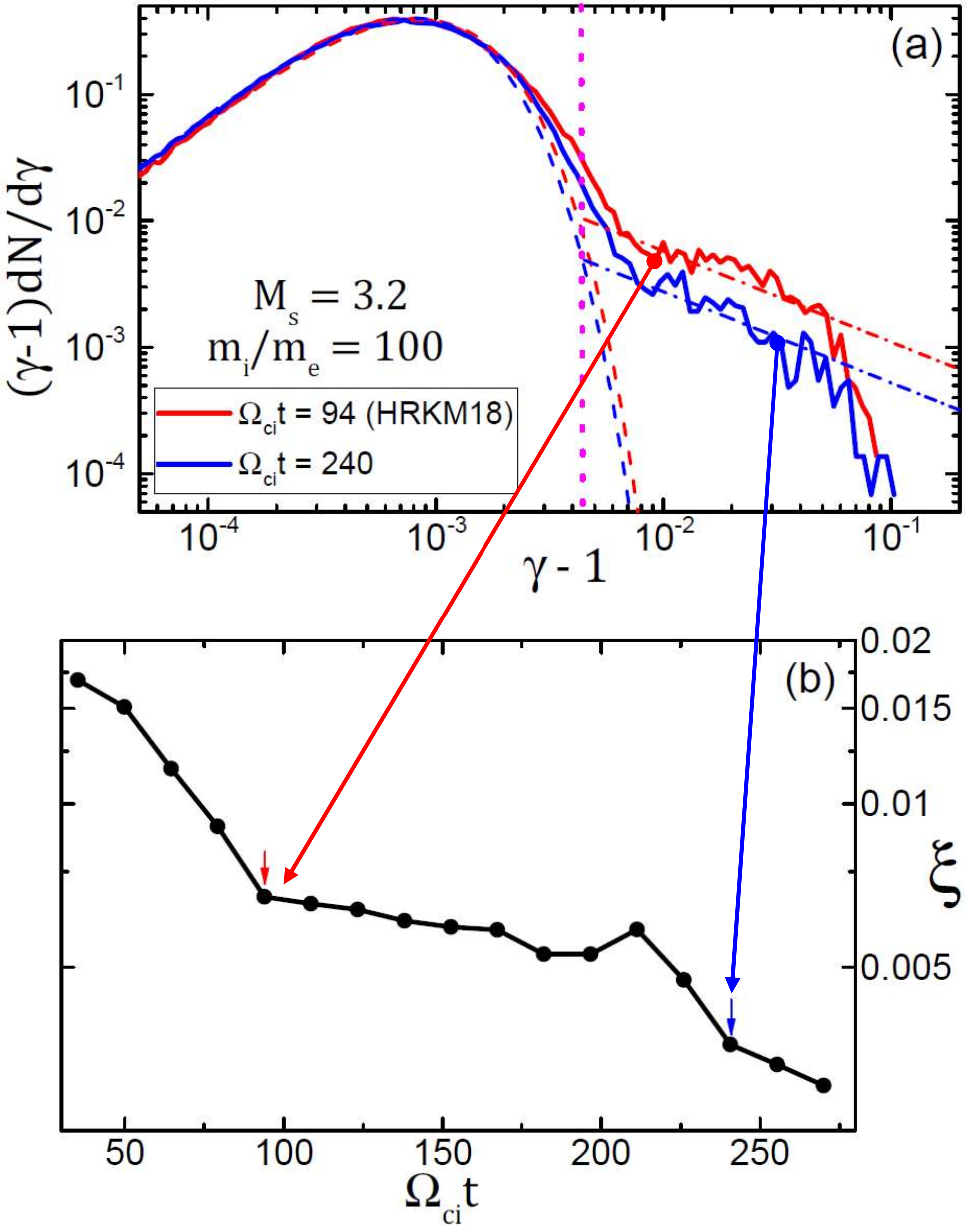
DSA beyond injection ?

We attempted to perform longer 1D PIC simulations.

$M_s = 3.2, \ \theta_{Bn} = 13^\circ$

$p_{\rm inj} = Q_{\rm i} \cdot p_{\rm th,p}$

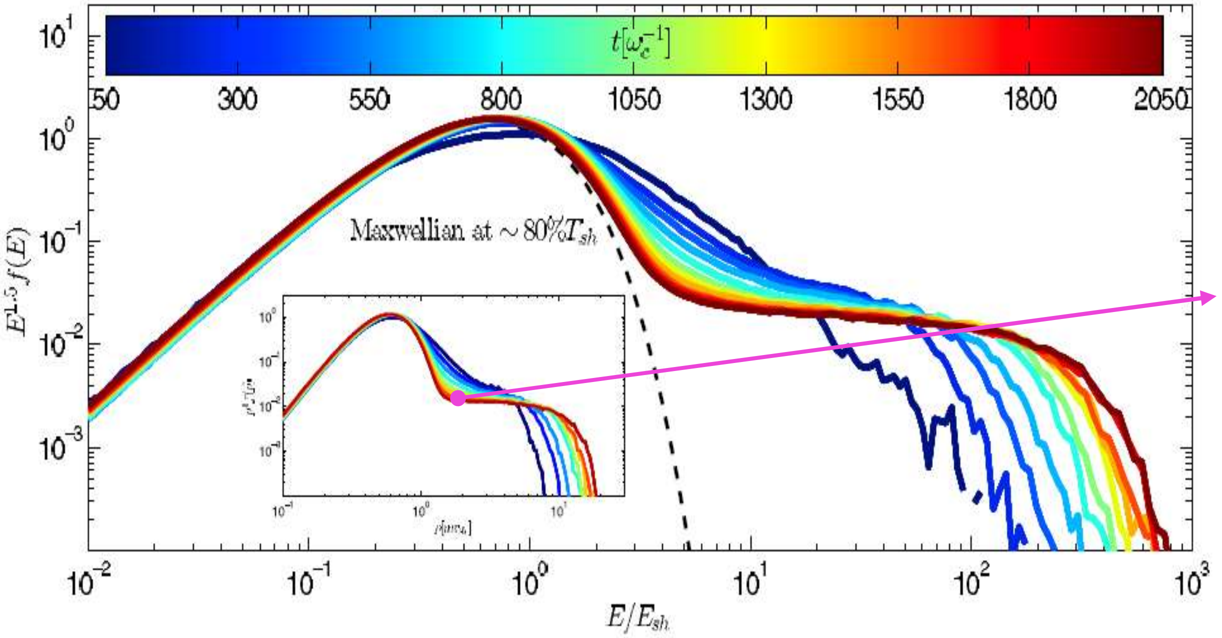
$Q_i = 2.7 \rightarrow 3.0$



The injection fraction, ξ(t), indeed decreases with time. However, long-term evolution of ξ(t) can be studied with other methods such as hybrid simulations.

Time evolution of downstream spectrum

Caprioli & Sptikovsky 2014

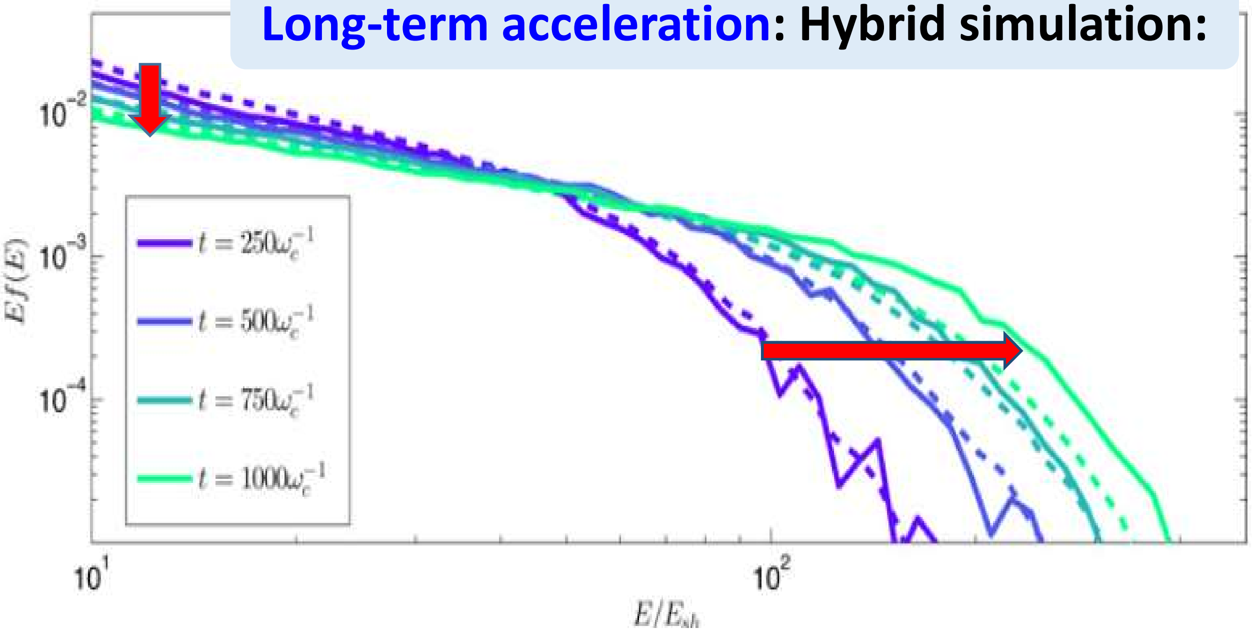


$$\boxed{\frac{E_{CR,2}}{E_{CR,2}+E_{th,2}} \approx 0.01-0.1}$$

Cooled Maxwellian
+ DSA power-law
above p_{inj}

***Hybrid*: $Q_i \sim 3 - 3.5$**

Long-term acceleration: Hybrid simulation:



As the spectrum extends to higher p_{max} in time, amplitude of f(p_{inj}) decreases.

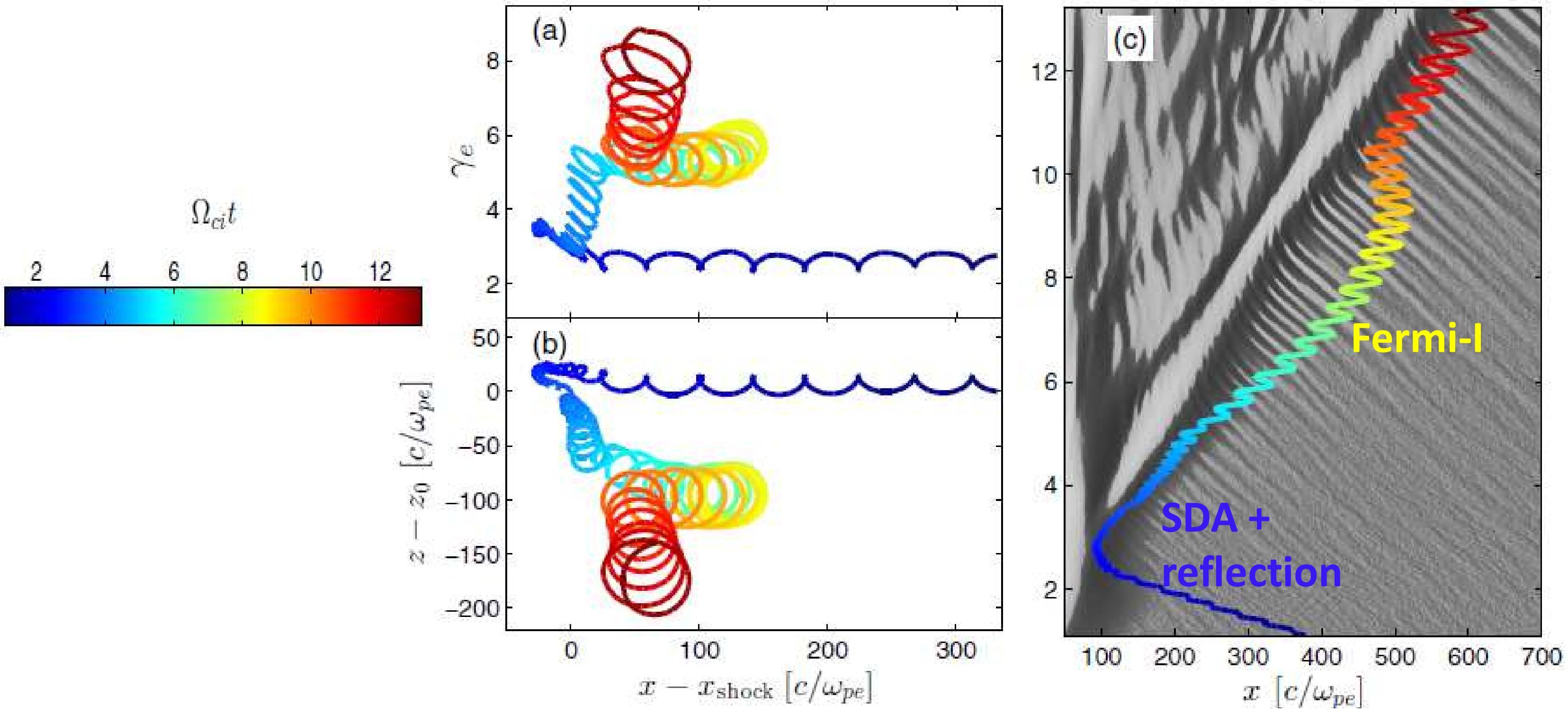
$$\Rightarrow \eta \equiv \frac{E_{CR} u_2}{1/2 \rho V_s^3} \quad ??$$

Dongsu' talk tomorrow

Electron pre-acceleration in weak Q-perp shocks in high beta ICM

cf. Guo et al. 2014a, b

1. Reflection by magnetic deflection (mirror) at the shock ramp
2. Shock Drift Acceleration (SDA) along the shock surface
3. T anisotropy ($T_{e_\parallel} > T_{e\perp}$) due to backstreaming electrons
4. Generation of waves via the Electron Firehose Instability (EFI)
5. Fermi-like acceleration bwt the shock and upstream waves

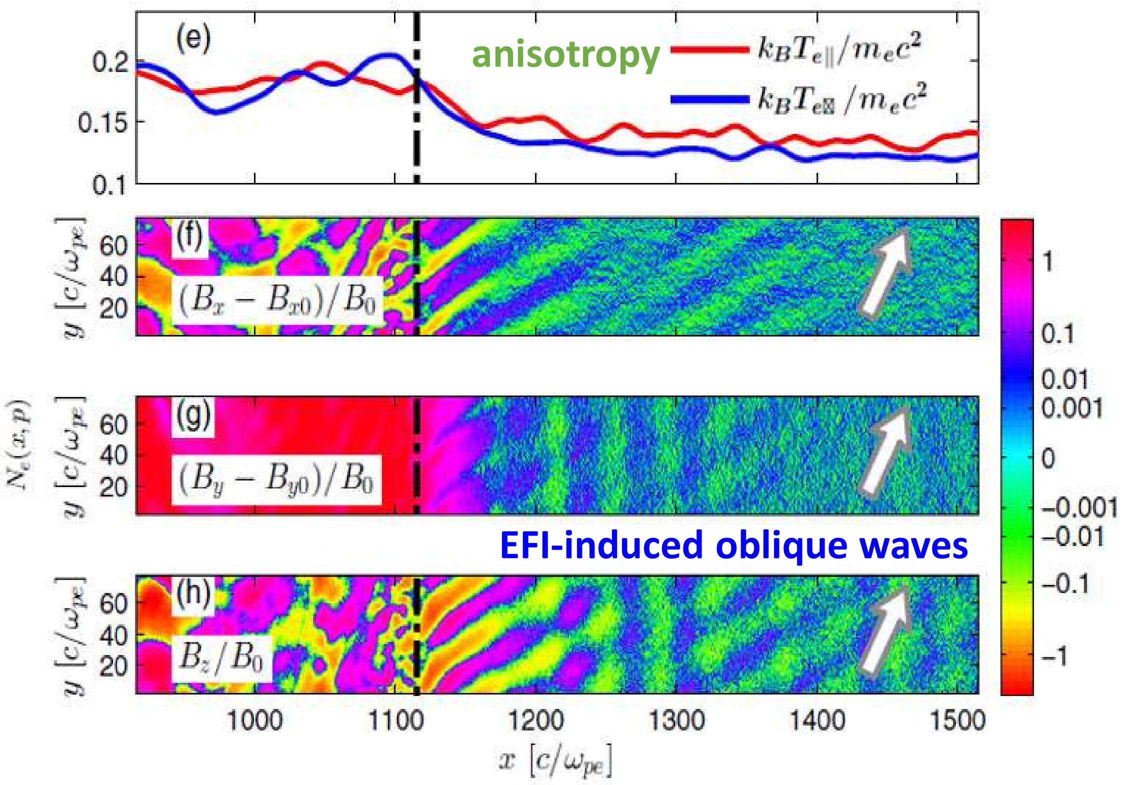


Electron pre-acceleration in weak ICM shock

Guo et al. 2014a, b

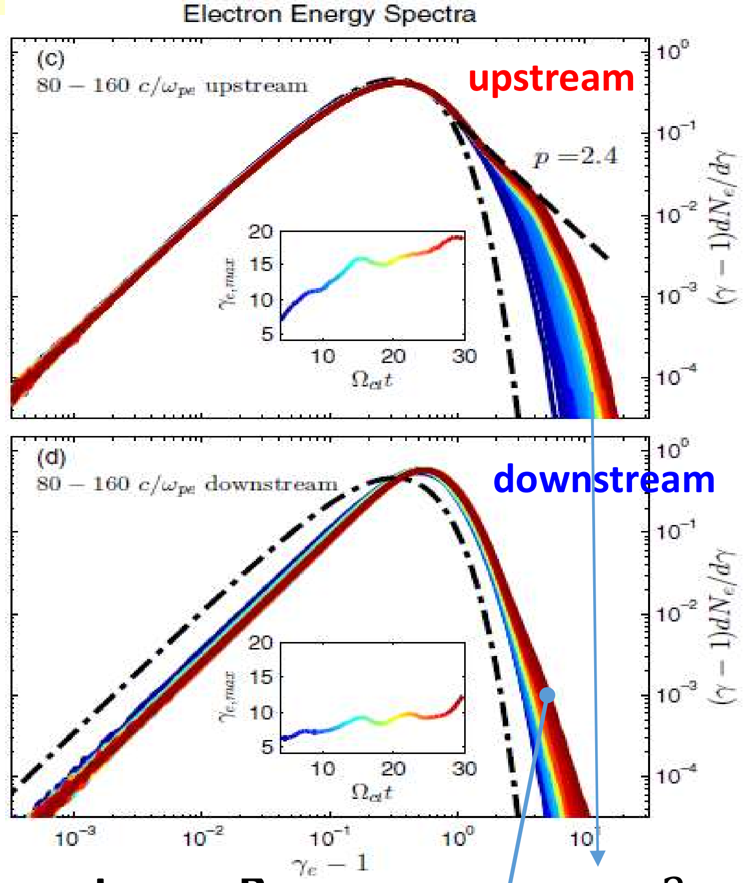
2D PIC (TRISTAN-MP)

$$\frac{m_i}{m_e} = 100, \theta_{Bn} = 63^o, T = 10^9 K\ (86keV), M_s = 3\ (M_A \sim 12), \beta = 20$$



anisotropy

EFI-induced oblique waves



upstream

downstream

$\gamma \sim 2$

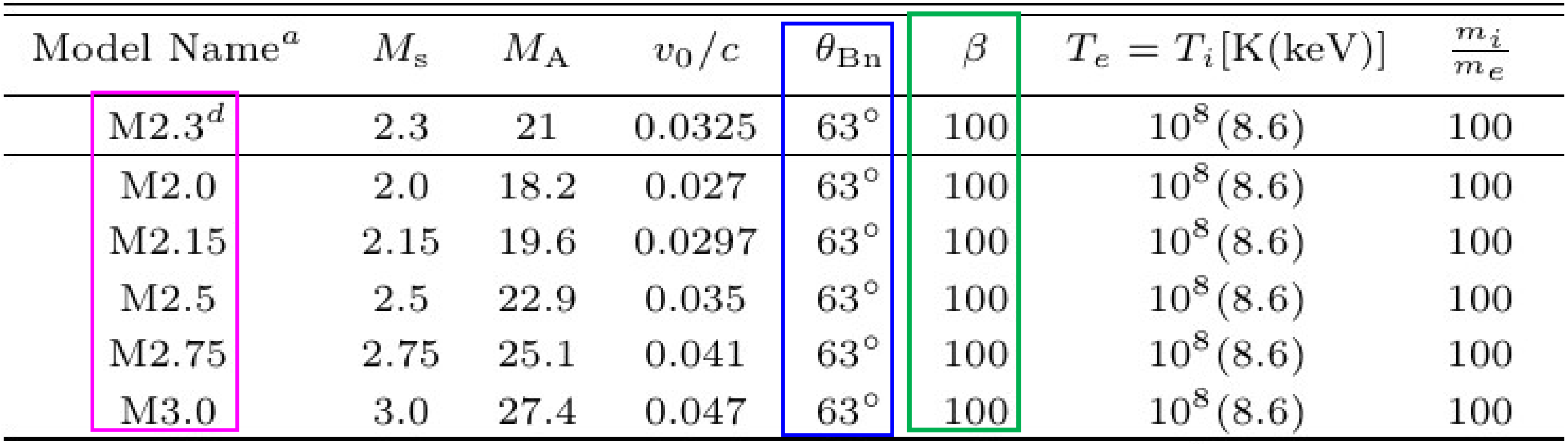
No CRs yet !

- **Reflected electrons preferentially move along the upstream B**
- **EFI induced by electron T anisotropy.**
- **Upstream electrons are efficiently accelerated**
  (SDA+Fermi-I process by upstream waves).

2D PIC simulations for Q-pep shocks (electron pre-acceleration)

Kang, Ryu, Ha 2019

Table 1. Model Parameters for the Simulations



Model Name[a]	M_s	M_A	v_0/c	θ_{Bn}	β	$T_e = T_i$[K(keV)]	$\frac{m_i}{m_e}$
M2.3[d]	2.3	21	0.0325	63°	100	10^8(8.6)	100
M2.0	2.0	18.2	0.027	63°	100	10^8(8.6)	100
M2.15	2.15	19.6	0.0297	63°	100	10^8(8.6)	100
M2.5	2.5	22.9	0.035	63°	100	10^8(8.6)	100
M2.75	2.75	25.1	0.041	63°	100	10^8(8.6)	100
M3.0	3.0	27.4	0.047	63°	100	10^8(8.6)	100

Guo et al. 2014ab

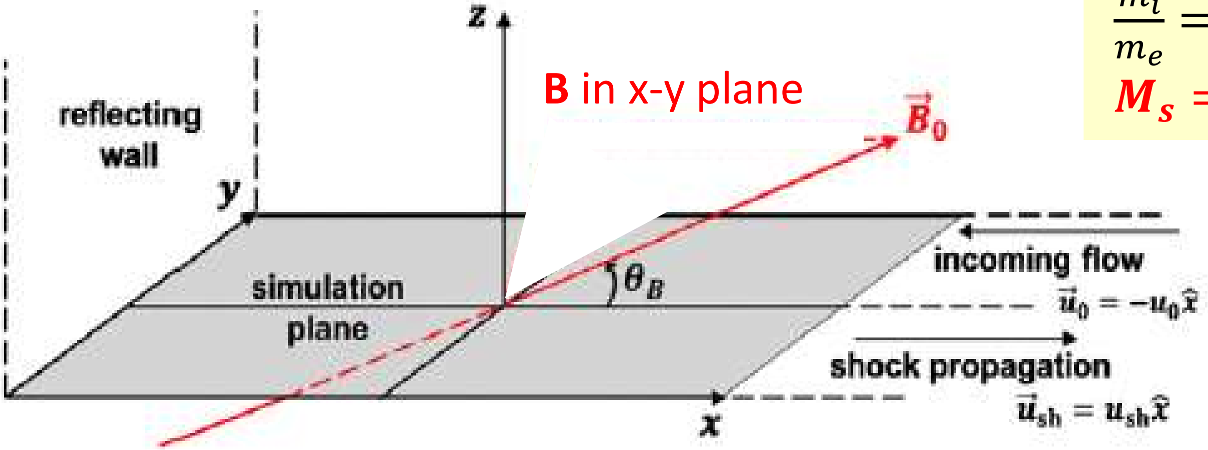
$$\frac{m_i}{m_e} = 100, \theta_{Bn} = 63^o, \boldsymbol{T = 10^9 K},$$

$$\boldsymbol{M_s = 3}\ (M_A \sim 12), \boldsymbol{\beta_p = 20}$$

downstream

upstream

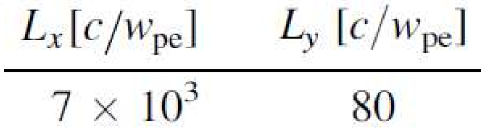
B in x-y plane



$T = T_i = T_e$ $n = n_i = n_e$

$$\Omega_{ci} \propto \frac{\omega_{pe}}{\sqrt{\beta}}$$

2D:

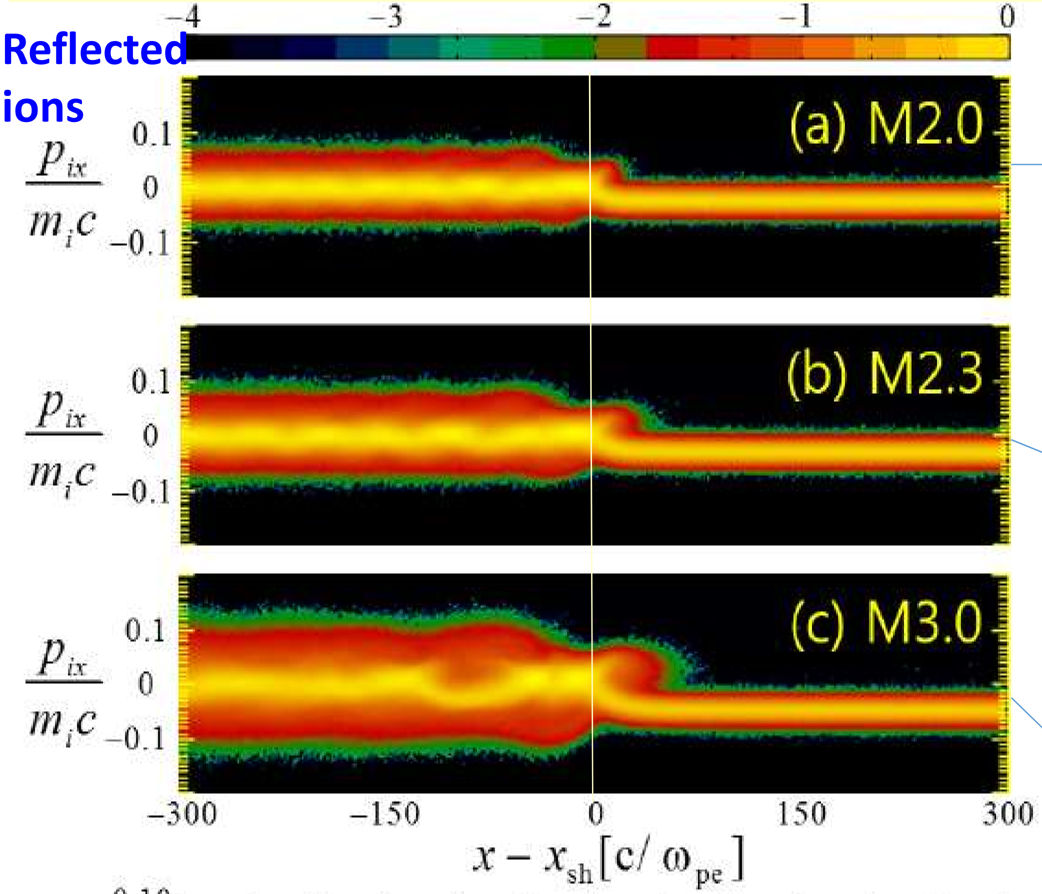


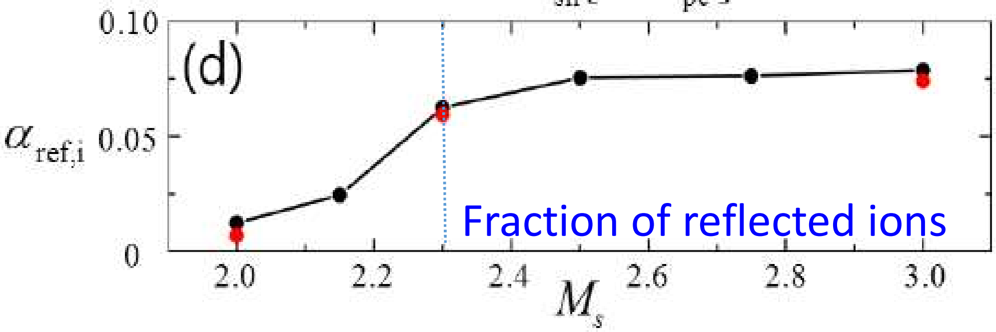
$L_x [c/w_{pe}]$	$L_y\ [c/w_{pe}]$
7×10^3	80

Shock structures governed by dynamics of reflected ions:

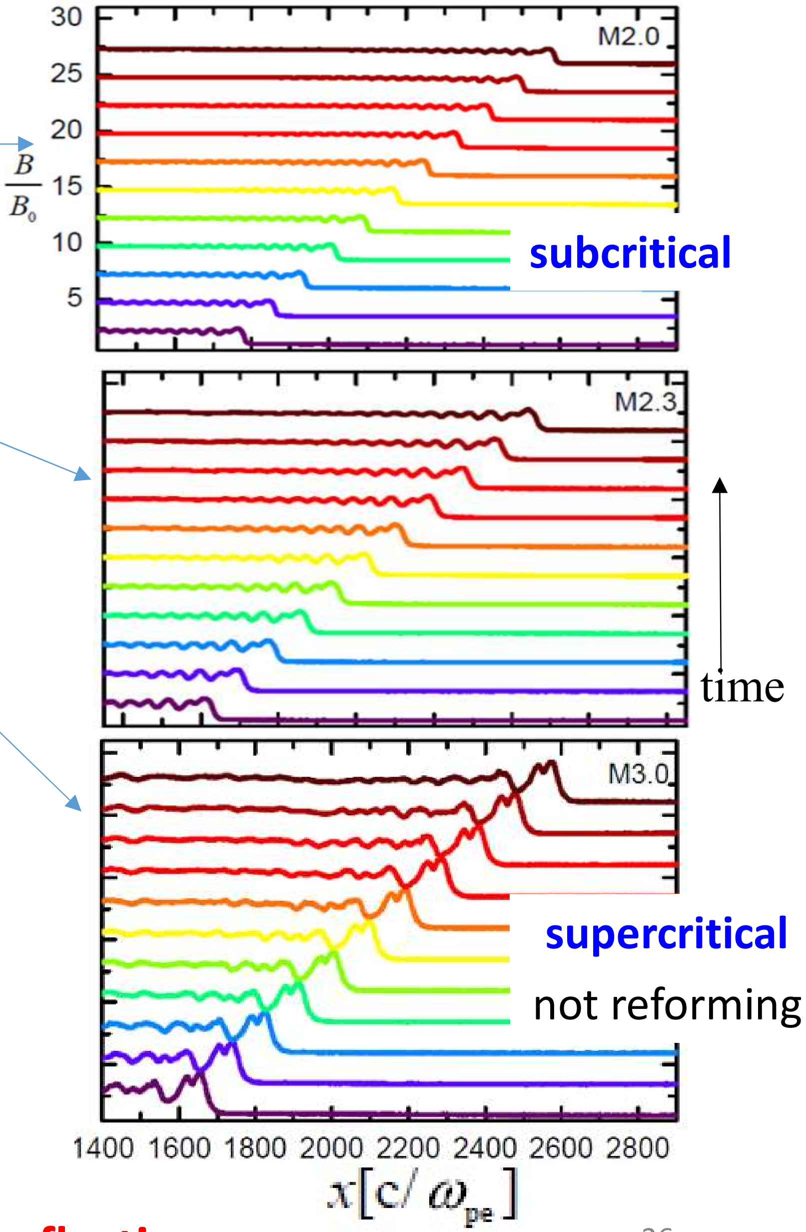
$\theta_{Bn} = 63^o$

Reflected ions





Fraction of reflected ions



subcritical

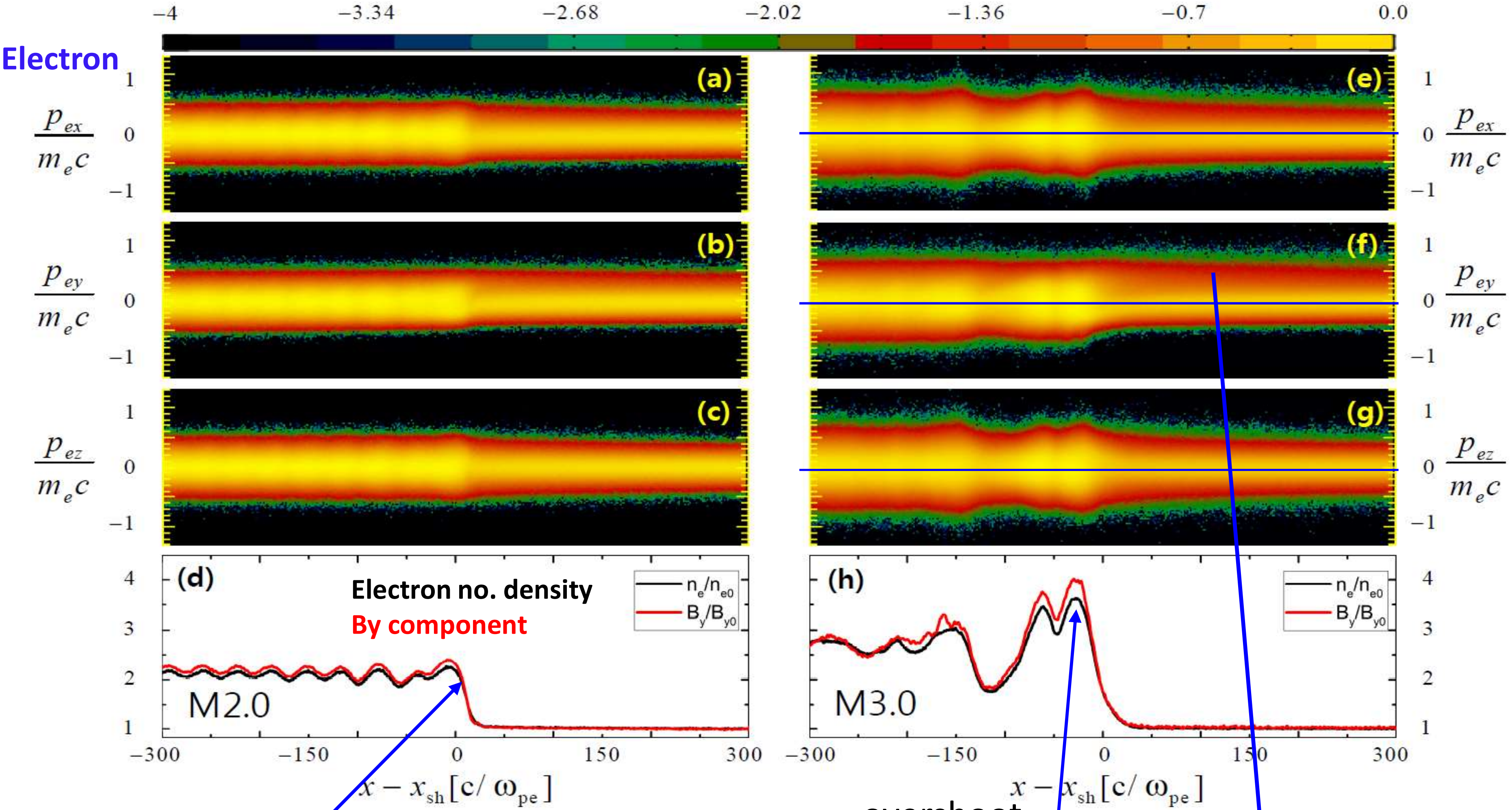
time

supercritical

not reforming

$M_f^* \sim 2.3$: First critical Mach number due to ion reflection

Ms = 2.0 (subcritical shock) **Ms = 3.0** (supercritical shock)



overshoot

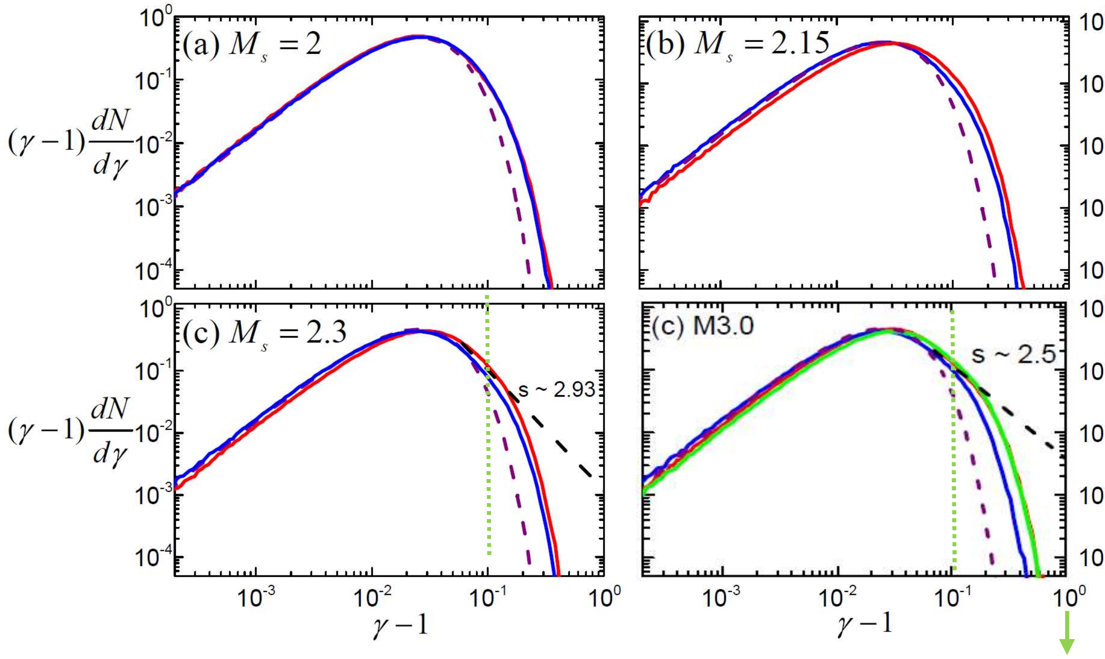
relatively smooth structure

Backstreaming along B

$M_f^* \sim 2.3$: First critical Mach number due to ion reflection

Evolution of upstream electron energy spectra

Blue: $\Omega_{ci}t = 10$, Red: $\Omega_{ci}t = 30$, Green: $\Omega_{ci}t = 60$

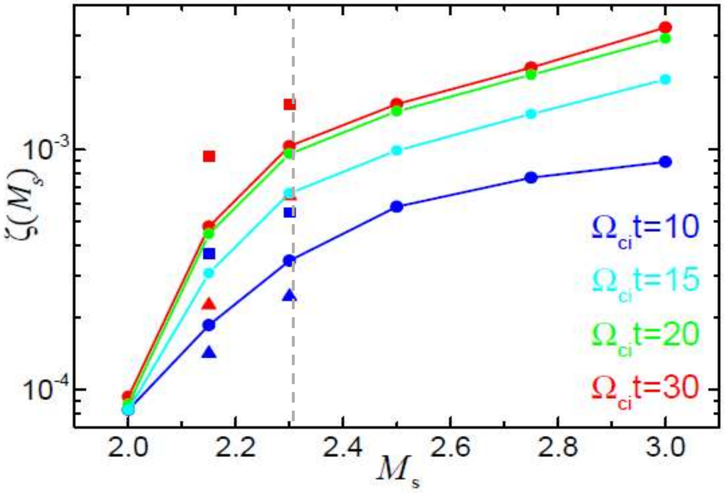


Suprathermal fraction

$$\zeta \equiv \frac{1}{n_2}\int_{p_{\rm spt}}^{p_{\max}} 4\pi \langle f(p,t)\rangle p^2 dp,$$

$p_{spt} \sim 3.3 p_{th,e}$: suprathermal

$p_{inj} \sim 3.3 p_{th,p}$: injection



- suprathermal fraction increases with Ms
- but saturates Ω_{ci}t>20

$M_{ef}^{*} \sim 2.3$

-Subcritical shocks: only single SDA

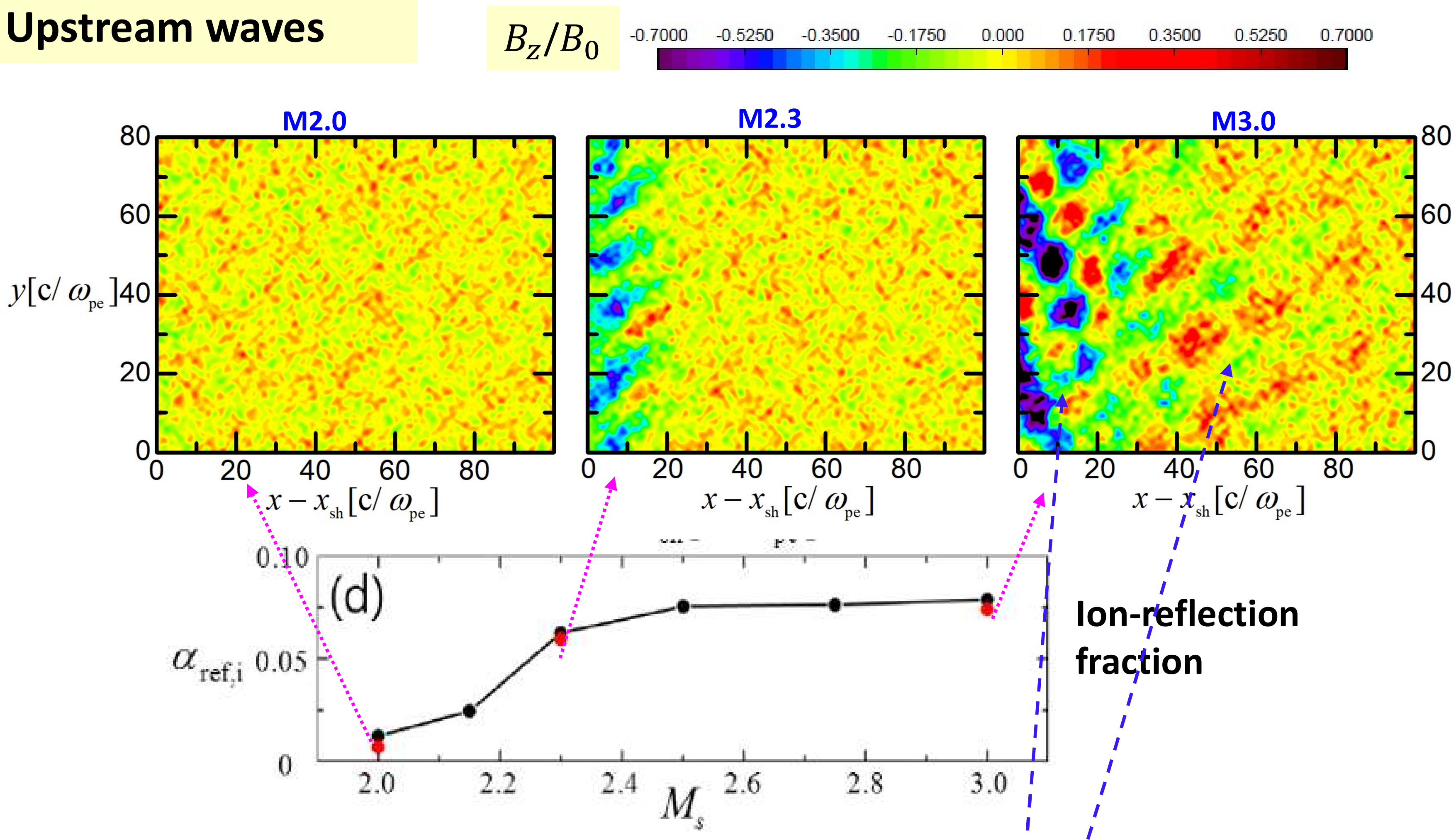
-Supercritical shocks: multiple cycles of SDA

suprathermal tail via Fermi-like acceleration

-Pre-acceleration is saturated due to lack of power in longer λ

-Pre-acceleration may not go all the way to injection to DSA

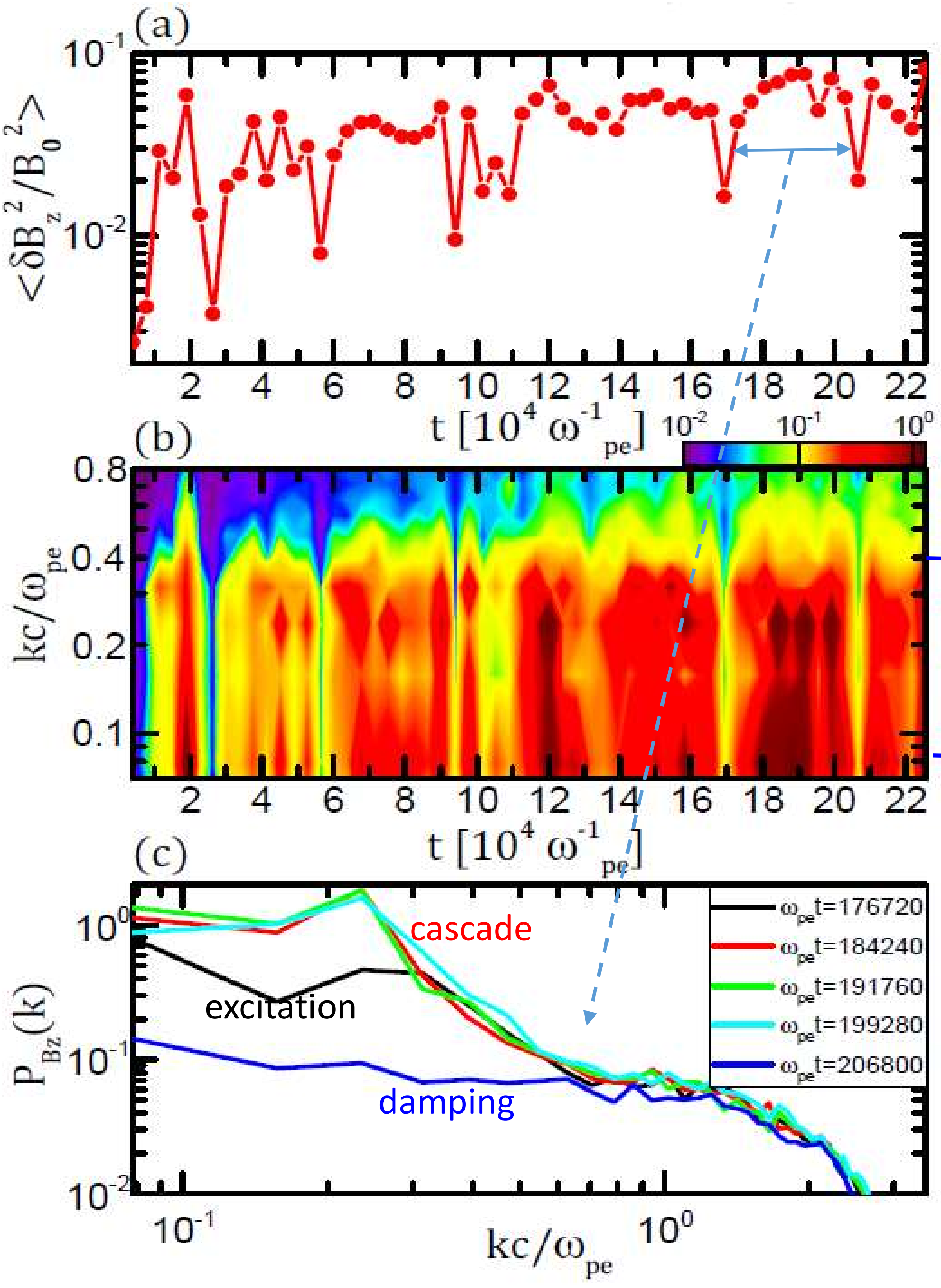
Upstream waves



Ion-reflection fraction

Three kinds of waves are expected:

1. **phase-standing whistlers excited by reflected ions** $kc/\omega_{\mathrm{pi}} \sim 1$
2. **Non-propagating ($\omega_r = 0$) oblique waves by EFI** $kc/\omega_{\mathrm{pe}} \sim 0.4$
3. **Propagating ($\omega_r \neq 0$) oblique waves by EFI : weak**



Quasi-periodic bursts of reflection:

$$t w_{\rm pe} \sim 2\times10^4 - 4\times10^4$$
$$t\Omega_{\rm ce} \sim 500-1000$$
$$t\Omega_{\rm ci} \sim 5-10$$

(but shock is steady, not self-refoming)

EFI-induced oblique waves

$$kc/\omega_{\rm pe} \sim 0.4$$

Whistlers induced by reflected ions

$$kc/\omega_{\rm pi} \sim 1$$

Burst of reflection

→ Growth of T anisotropy

→ Excitation of the EFI

→ Growth of oblique waves

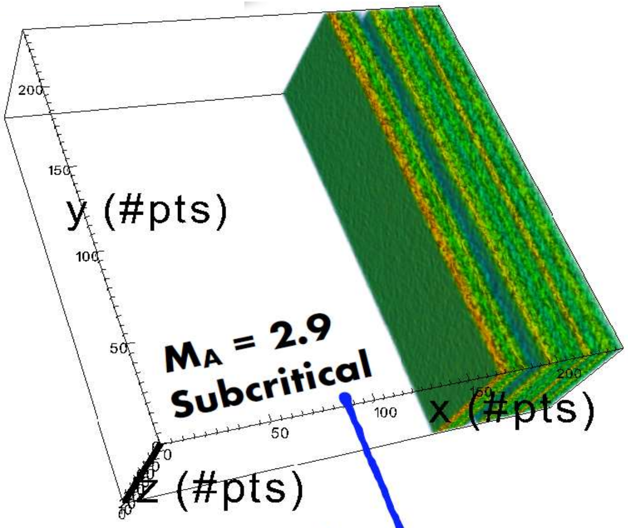
→ Inverse cascade to smaller k

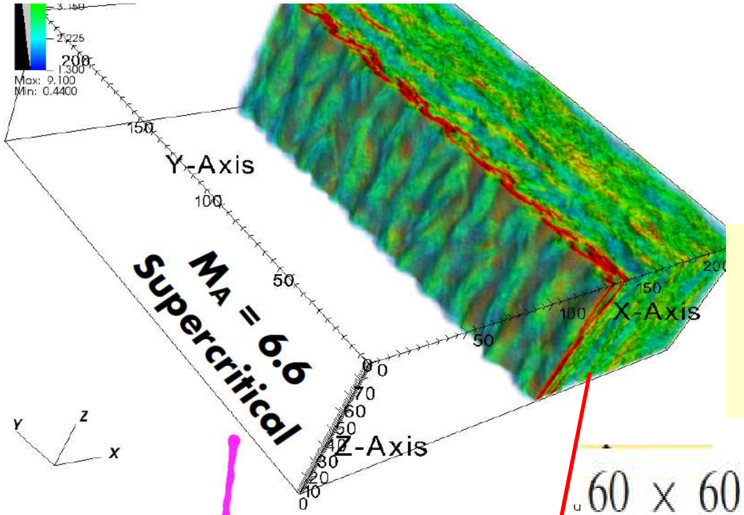
→ Damping of waves

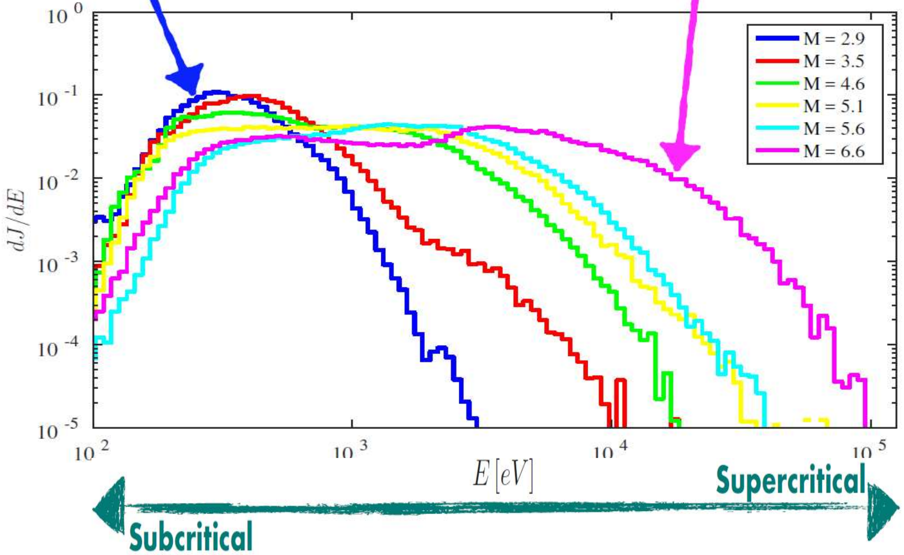
Electron acceleration at quasi-perpendicular shocks in sub- and supercritical regimes: 2D and 3D simulations

Hybrid + test-particle electrons

Domenico Trotta & David Burgess 2019







$\beta_i \approx \beta_e \approx 0.5$

$\frac{v_A}{c} = 2 \times 10^{-4}$

$\boldsymbol{\kappa = 4}$

electron distribution for solar wind

$60 \times 60 \times 20\ d_i$ in the 3D

Supercritcal shocks

→ Reflected ions

→ Field-aligned propagating ripples on shock surface

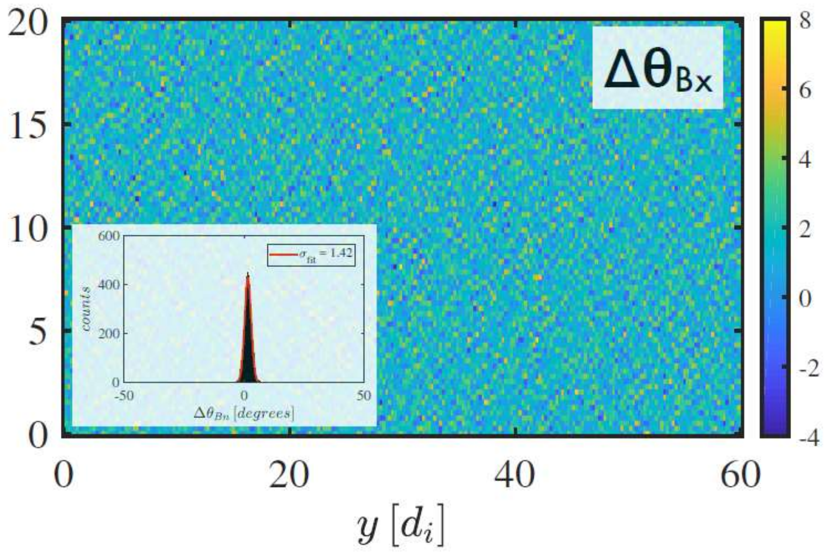
→ ion-scale fluctuations

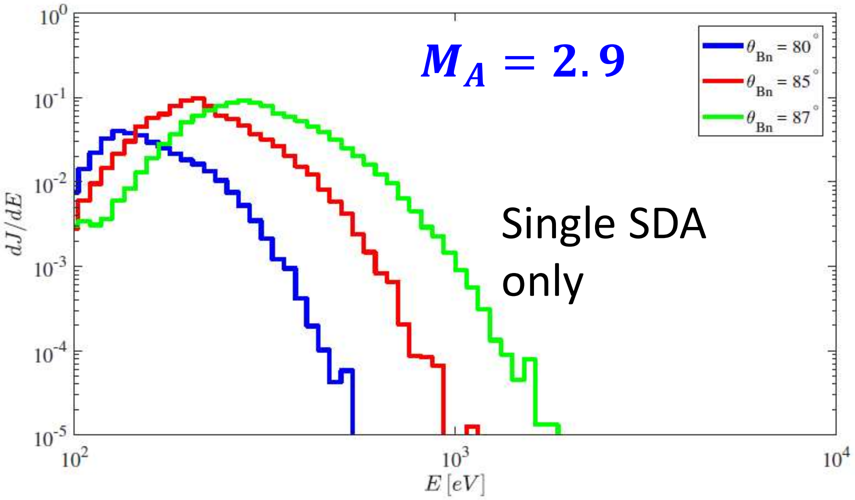
→ Efficient electron acceleration

Acceleration efficiency with θ_{Bn}

Domenico Trotta & David Burgess 2019

Subcritical





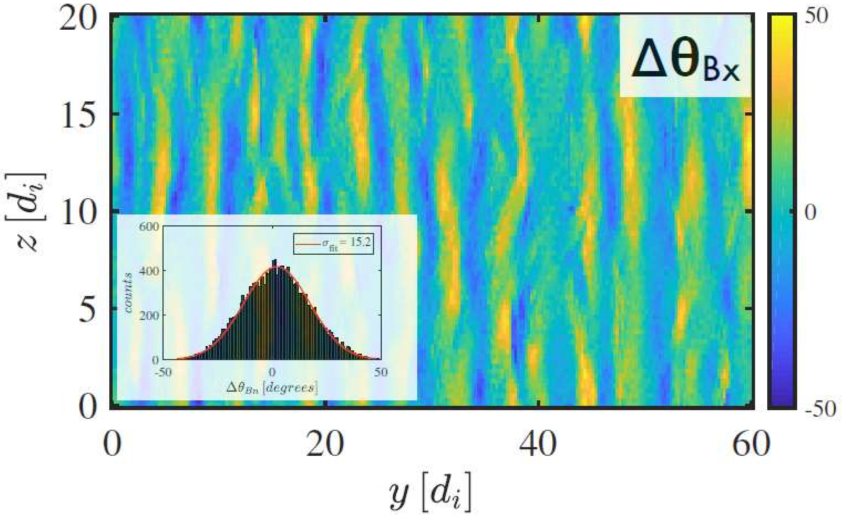
$M_A = 2.9$

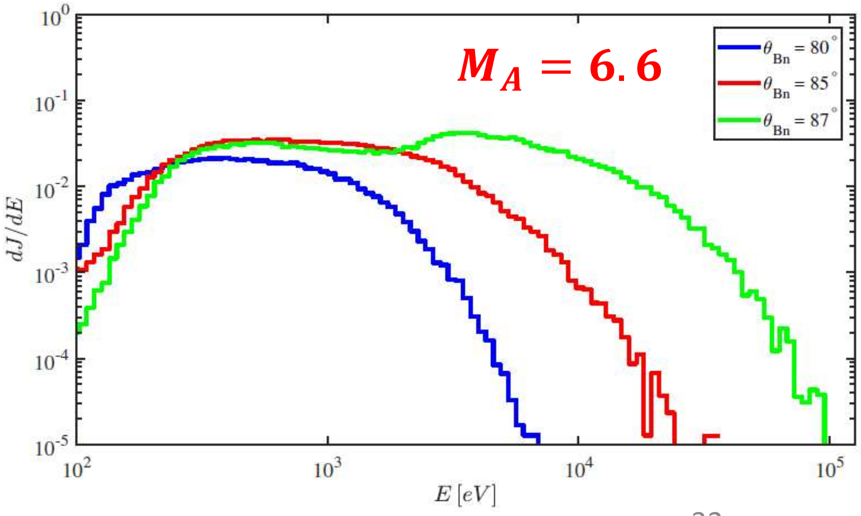
Single SDA only

critical Mach number: $M_{A,c} \approx 3.5$

Shock surface fluctuations on ion scales ➔ lead to higher energization of electrons

Supercritical

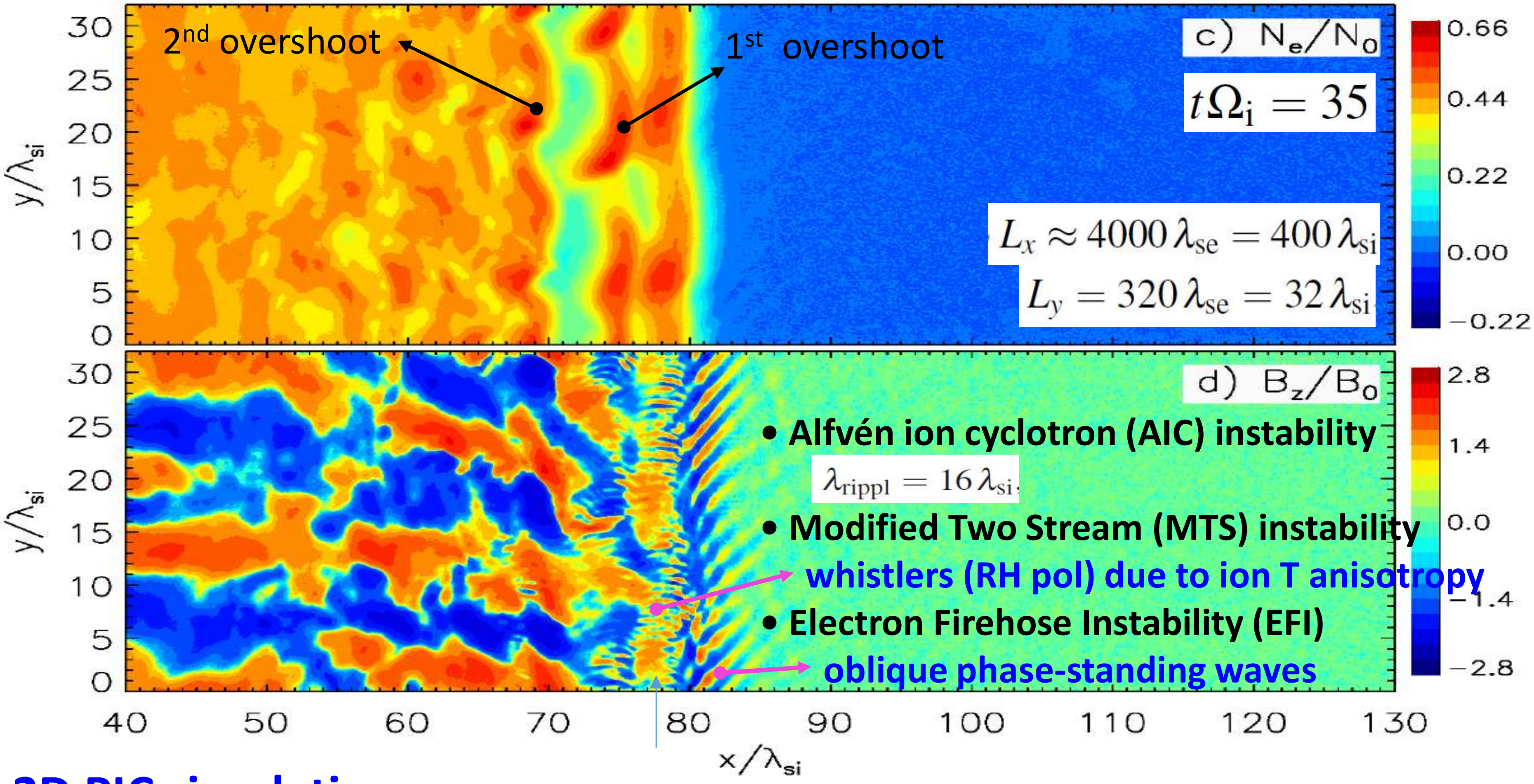




$M_A = 6.6$

Electron Acceleration at Rippled Low Mach Number Shocks

Oleh Kobzar et al. , @ICRC2019 & Jacek Niemiec et al. @KAW10



$t\Omega_i = 35$

$L_x \approx 4000\,\lambda_{se} = 400\,\lambda_{si}$

$L_y = 320\,\lambda_{se} = 32\,\lambda_{si}$

- **Alfvén ion cyclotron (AIC) instability**

$\lambda_{rippl} = 16\,\lambda_{si}$

- **Modified Two Stream (MTS) instability**

whistlers (RH pol) due to ion T anisotropy

- **Electron Firehose Instability (EFI)**

oblique phase-standing waves

2D PIC simulations

$$T_e = T_i \approx 5 \cdot 10^8\,\mathrm{K} = 43\,\mathrm{keV}/k_B$$

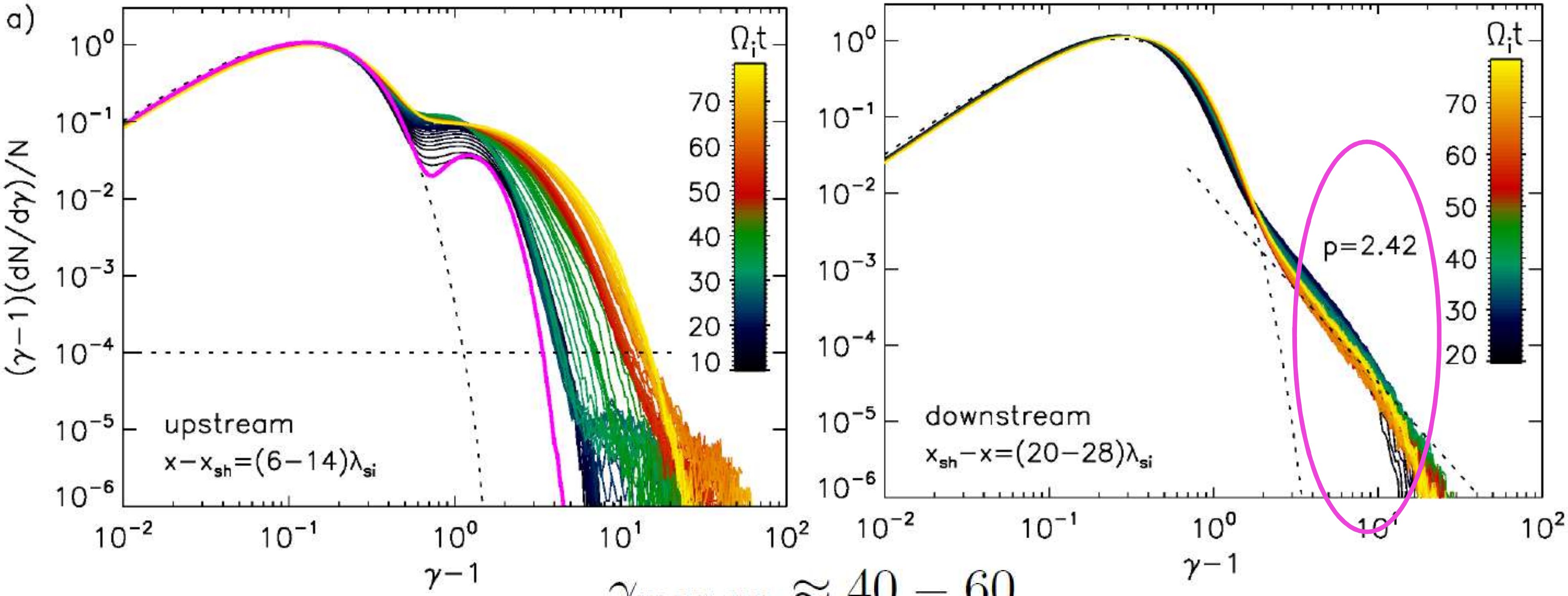
$$M_s \equiv v_{sh}/c_s = 3 \qquad M_A = v_{sh}/v_A \simeq 6.1$$

$$\beta = 5\ (\beta_e = \beta_i = 2.5) \qquad m_i/m_e = 100$$

Stochastic SDA:

electrons are confined in the shock transition region by pitch-angle scattering off magnetic turbulence and gain energy from motional electric field

Oleh Kobzar et al. , @ICRC2019 & Jacek Niemiec et al. @KAW10



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

$$\gamma_{\mathrm{inj}} \approx 25 \quad (p_{\mathrm{inj}} \sim 3\, p_{\mathrm{th,i}})$$

$$\frac{m_i}{m_e} = 100$$

- the presence of multi-scale turbulence, including ion-scale shock rippling modes,

➔lead to efficient electron acceleration & injection to DSA in the presence of long-wave upstream turbulence

➔ energy gain mainly through the stochastic SDA process

- electron downstream spectrum: $E^{-2.4}$

Summary: Particle injection at weak ICM shocks

- In high β ICM, only supercritical $Q_\parallel$ shocks with $M_s \geq 2.3$ may inject suprathermal protons to DSA and accelerate CR protons (Ha et al. 2018).

- In high β $Q_\perp$ shocks, upstream waves are generated via Electron Firehose instability (Guo et al. 2014a,b).

- Only supercritical $Q_\perp$ shocks with $M_s \geq 2.3$ may pre-accelerate suprathermal electrons via Fermi-I like process. Due to wave damping, electrons may not be injected to DSA (Kang et al. 2019).

- Ion-scale shock rippling at supercritical $Q_\perp$ shocks generates multi-scale turbulence, leading to electron injection to DSA (Trotta & Burgess 2019, Niemiec et al. 2019).

What is next ? DSA power-law for downstream spectrum, pre-existing turbulence, kappa-distribution, long-term evolution, …

Acceleration processes - typical particle trajectories

Niemiec + @KAW10

- single-cycle SSDA most common; acceleration either at the shock front (blue) or in the shock transition (pink)
- multiple-cycle SDA not common; upstream scattering of SDA-reflected particles typically followed by an SSDA event (green)
- particles accelerated in the shock can escape downstream (dashed arrow)
- some particles accelerated in the shock can be picked-up from local plasma (dotted arrow)