Proton Injection & Acceleration in Weal shocks in high beta Intracluster Medium

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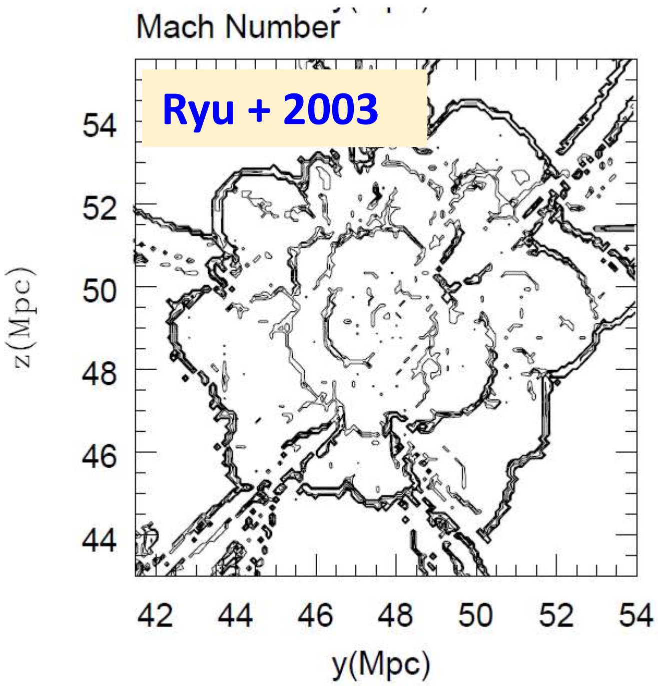
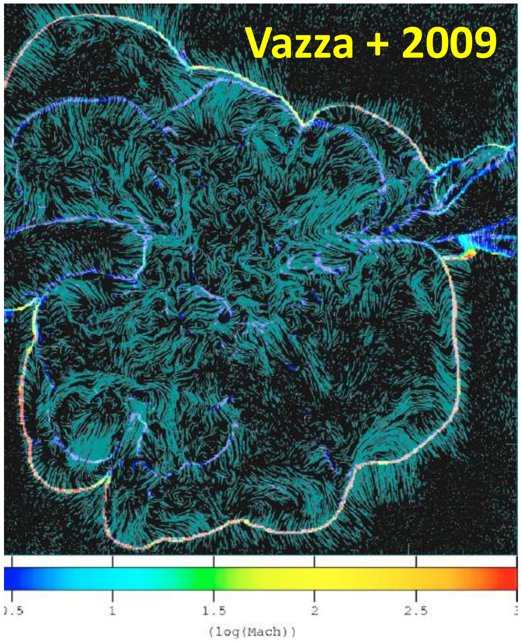
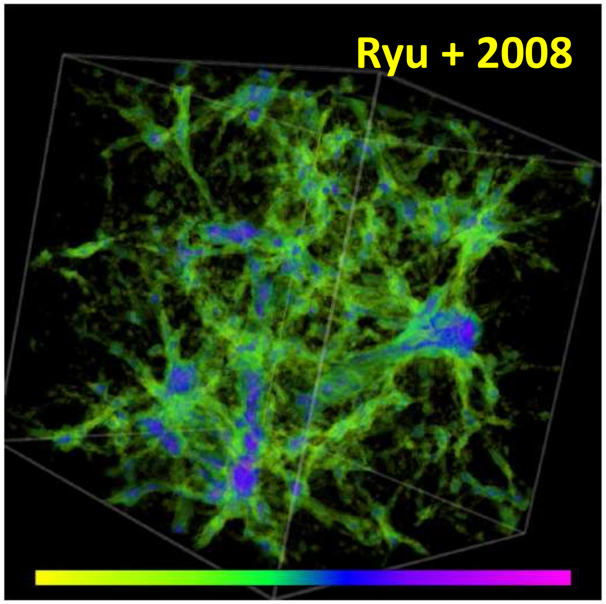


Shocks

+ CR Particle acceleration



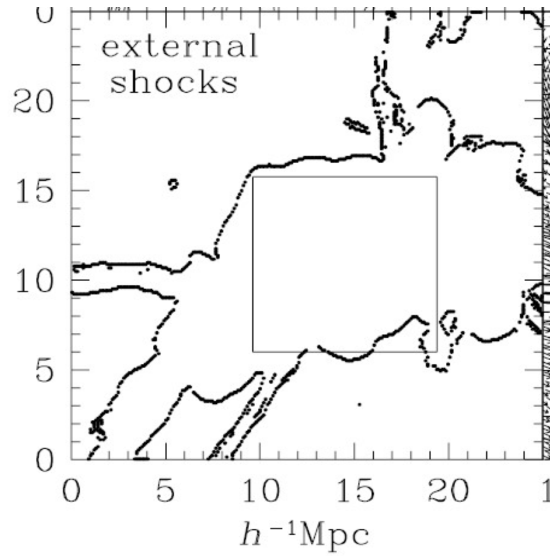
Turbulence



Magnetic Fields

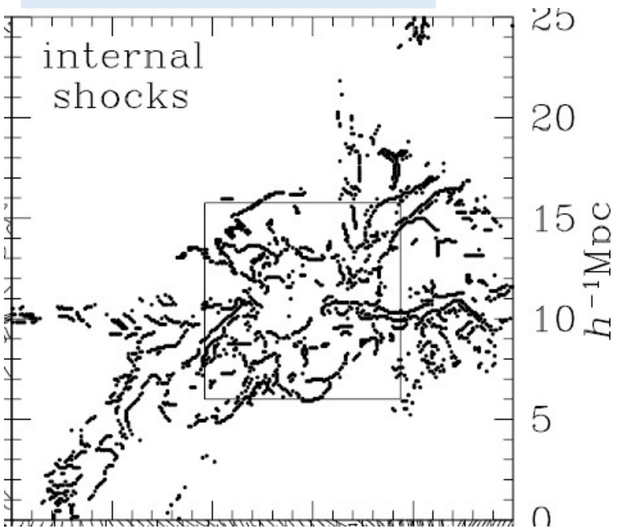
Shocks in Structure Formation Simulations (Ryu et al 2003)

Accretion Shocks



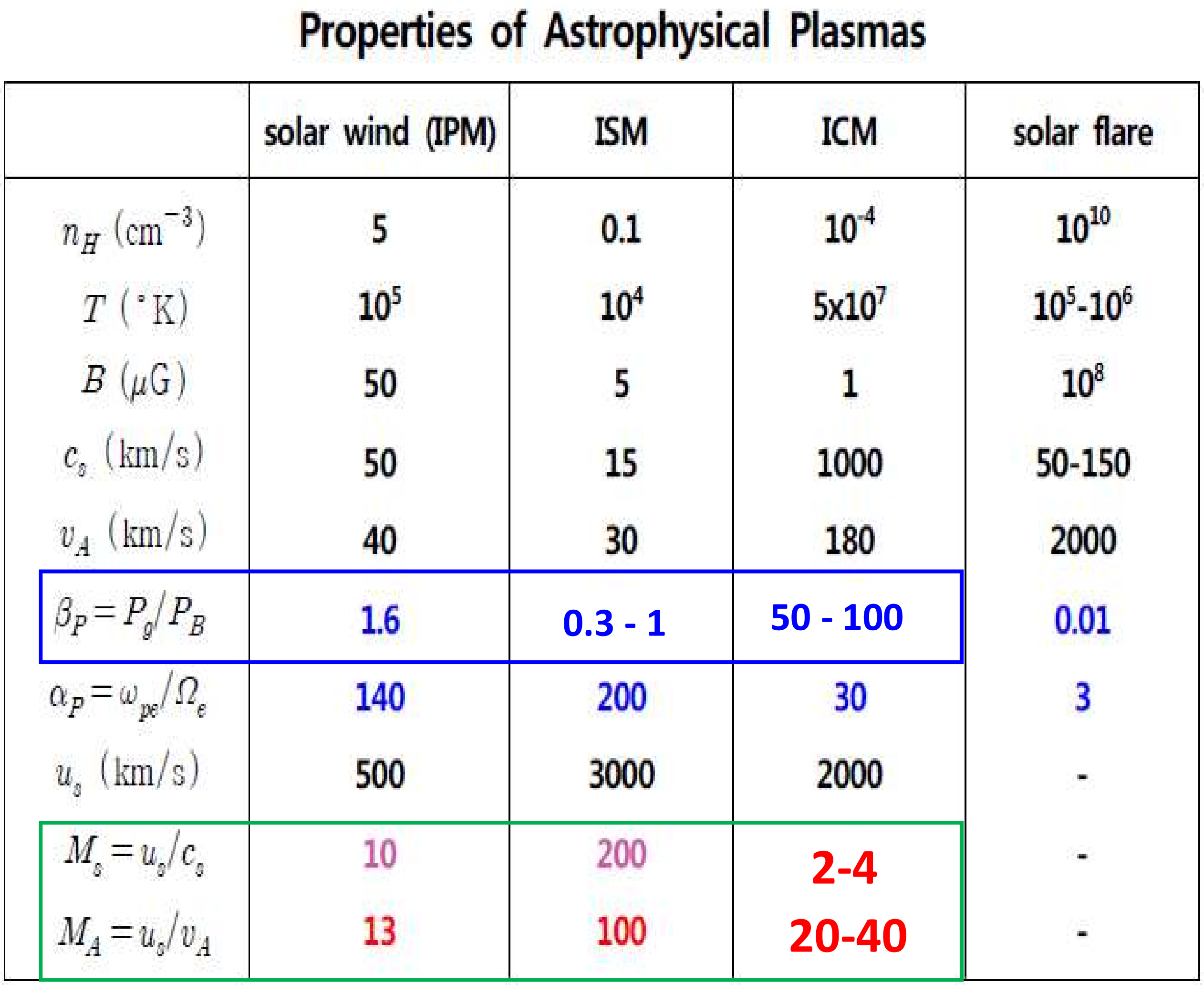
Strong accretion shocks have low kinetic energy flux, so they may not have detectable signatures.

Shocks in ICM



Weak internal shocks with M_s<4 are dominant and energetically important inside high beta ICM plasma.

intracluster medium (ICM): low density, high temperature



Properties of Astrophysical Plasmas

	solar wind (IPM)	ISM	ICM	solar flare
n_H (cm^{-3})	5	0.1	10^{-4}	10^{10}
T (°K)	10^5	10^4	5×10^7	10^5-10^6
B (μG)	50	5	1	10^8
c_s (km/s)	50	15	1000	50-150
v_A (km/s)	40	30	180	2000
$\beta_P = P_g/P_B$	1.6	0.3 - 1	50 - 100	0.01
$\alpha_P = \omega_{pe}/\Omega_e$	140	200	30	3
u_s (km/s)	500	3000	2000	-
$M_s = u_s/c_s$	10	200	2-4	-
$M_A = u_s/v_A$	13	100	20-40	-

IPM
=InterPlanetary Medium

ISM
=InterStellar Medium

ICM
=IntraCluster Medium

$$\beta_p = \frac{P_{gas}}{P_B} \propto \frac{n_H T}{B^2}$$

$$\alpha_p = \frac{\omega_{p,e}}{\Omega_{c,e}} \propto \frac{\sqrt{n_e}}{B}$$

$$M_A \approx \beta_p^{1/2} M_s$$

θ_{Bn} : obliquity angle

ICM (cluster shocks) vs ISM (SNR shocks)

higher β_p : B pressure is dynamically less important in ICM

particle acceleration at collisionless shocks depend on $M_s, M_A, \theta_{\mathrm{Bn}}, \beta_p$

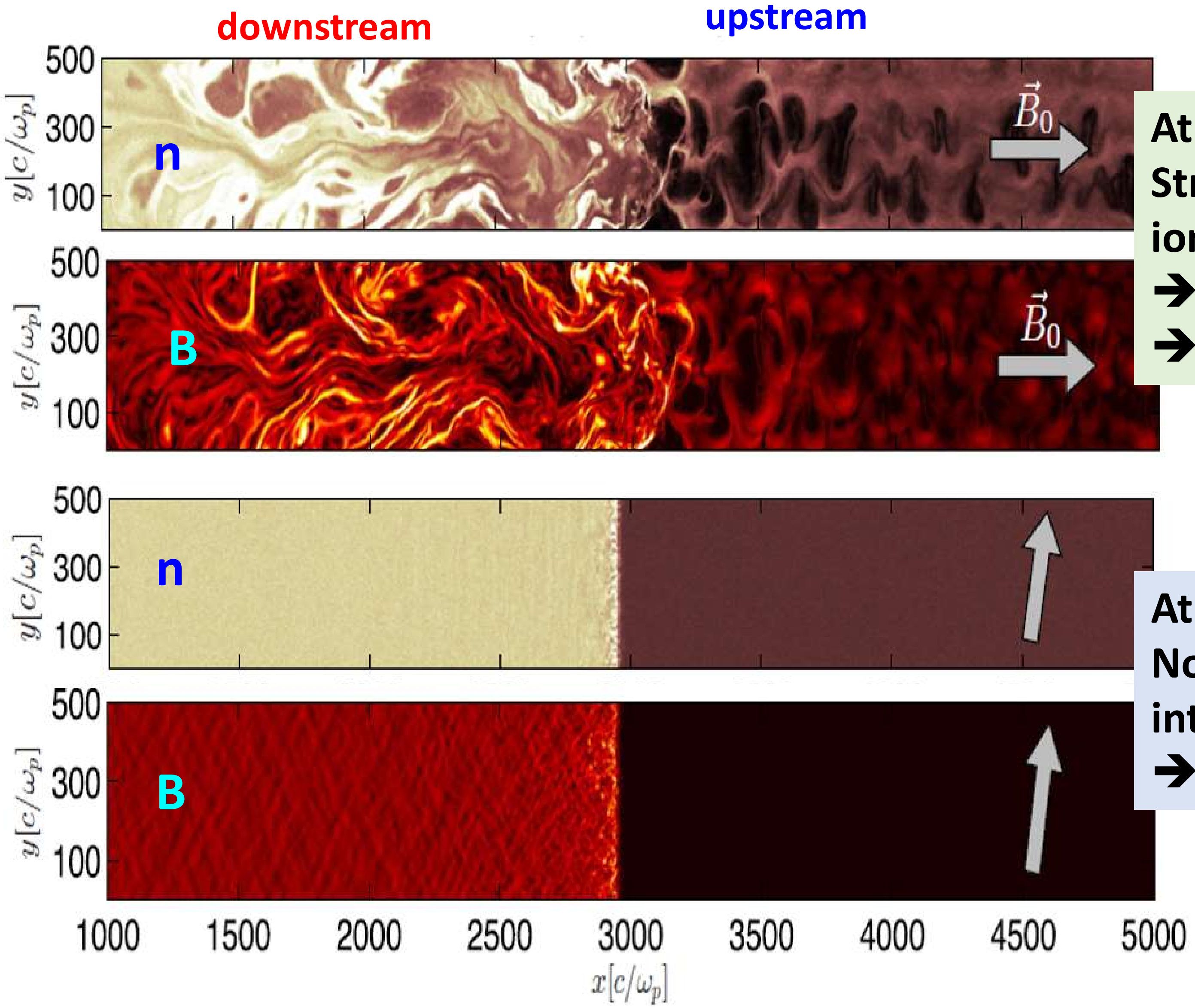
Proton acceleration in beta=1 shocks

Caprioli & Sptikovsky 2014

Hybrid simulation

$$\boxed{M_A \approx \beta_p^{1/2} M_s}$$

$$\beta = \beta_e + \beta_p \approx 1,\ M_A \sim M_s = 20$$

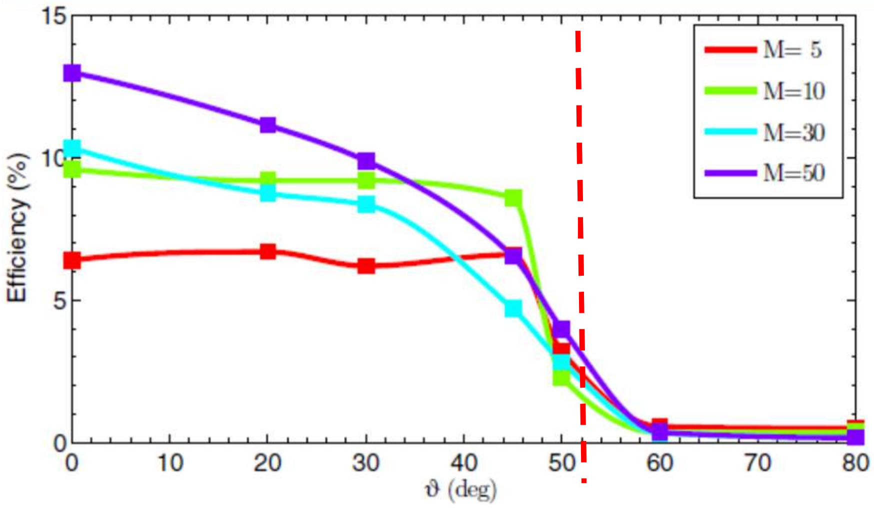


At parallel shocks
Stream of accelerated ions into upstream
➔self-generated waves
➔B amplification

At Q-perp shocks
No backstreaming ions into upstream
➔No turbulent waves

CR proton acceleration efficiency from Hybrid simulations

Caprioli & Spitkovsky 2014



$$\beta_p = \frac{P_{gas}}{P_B} \approx 1$$

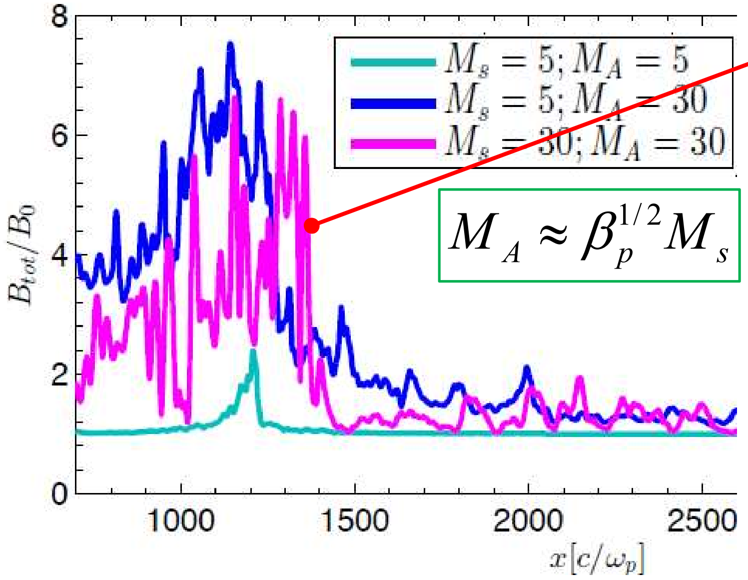
$$\boxed{\eta \equiv \frac{E_{CR} u_2}{1/2 \rho V_s^3}}$$

$$\eta \approx 0.05 \text{ for } M_s = 5$$

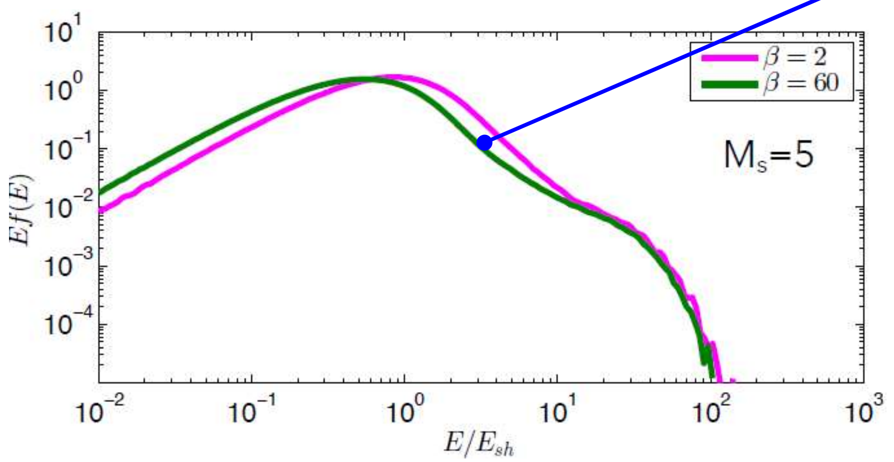
$$\text{at quasi-parallel shocks}$$

High beta cases

- $\eta \sim M_s (\%)$ for $M_s < 5$
- B amplification is controlled by M_A
- CR acceleration is governed by M_s



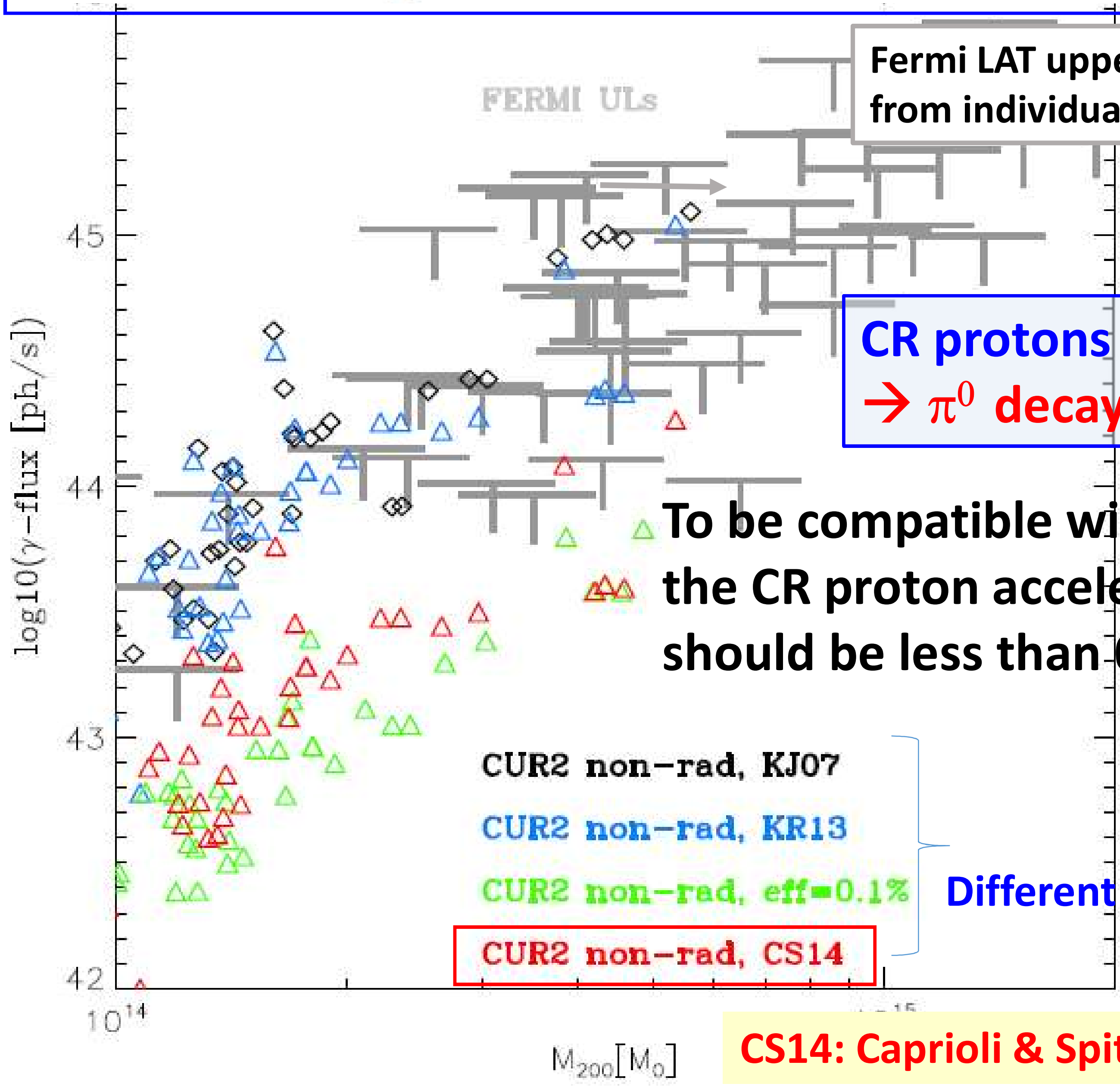
$$\boxed{M_A \approx \beta_p^{1/2} M_s}$$



Caprioli 2017 (KAW9)

Constraining the efficiency of cosmic ray acceleration by cluster shocks

F. Vazza,[1]★ M. Brüggen,[1] D. Wittor,[1] C. Gheller,[2] D. Eckert[3] and M. Stubbe[1] **2016**



Fermi LAT upper limits on gamma-ray flux from individual clusters

CR protons + ICM p→ π^0 , π^+, π^-

→ π^0 decay γ rays (not detected)

To be compatible with Fermi upper limits, the CR proton acceleration efficiency should be less than 0.1% for 2<M_s<5.

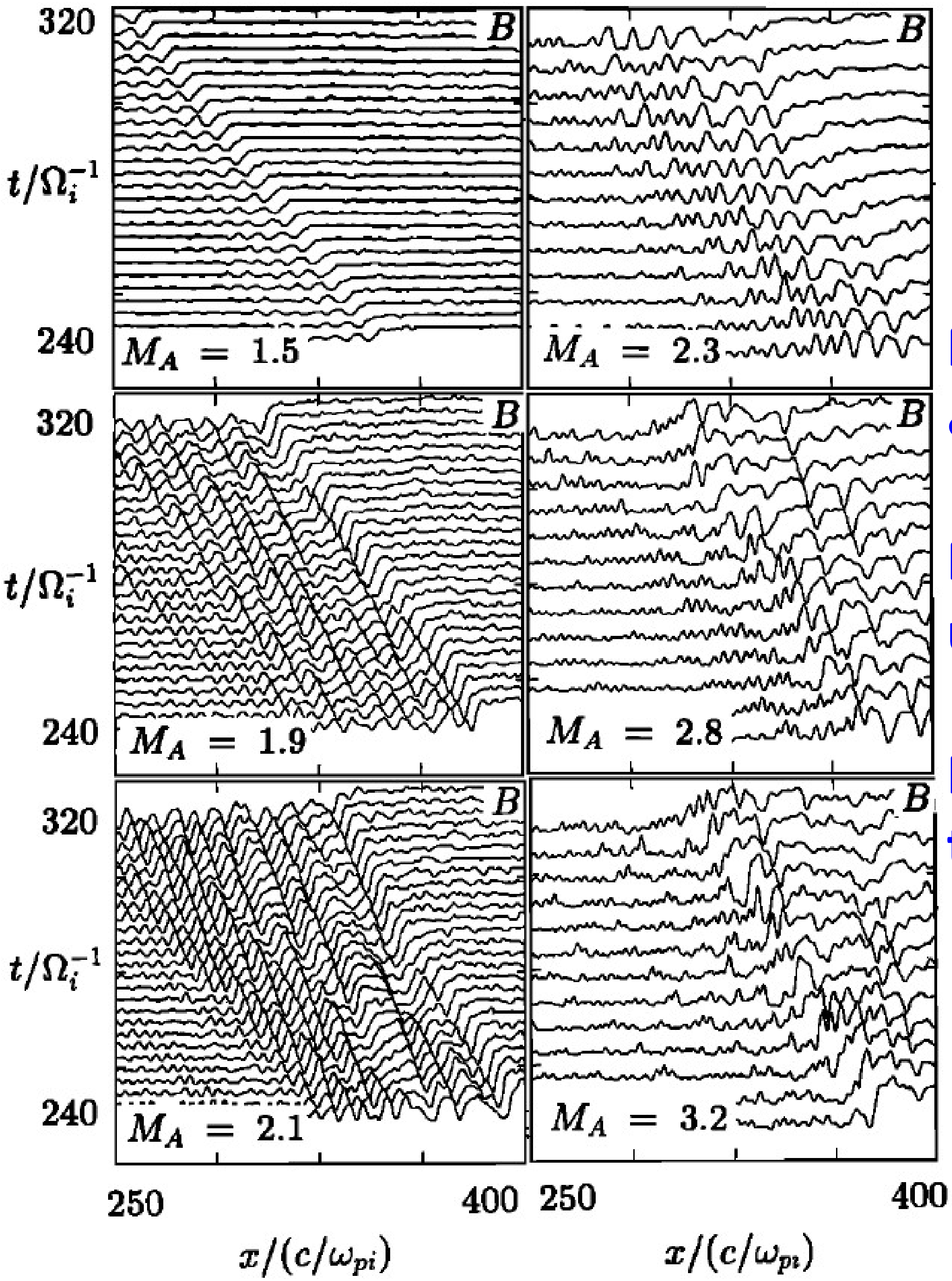
Different DSA efficiency models

CS14: Caprioli & Spitkovsky 2014

Low M_A Q-par shocks

1D hybrid simulations

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



M_A= 1.5 the shock is steady & smooth.

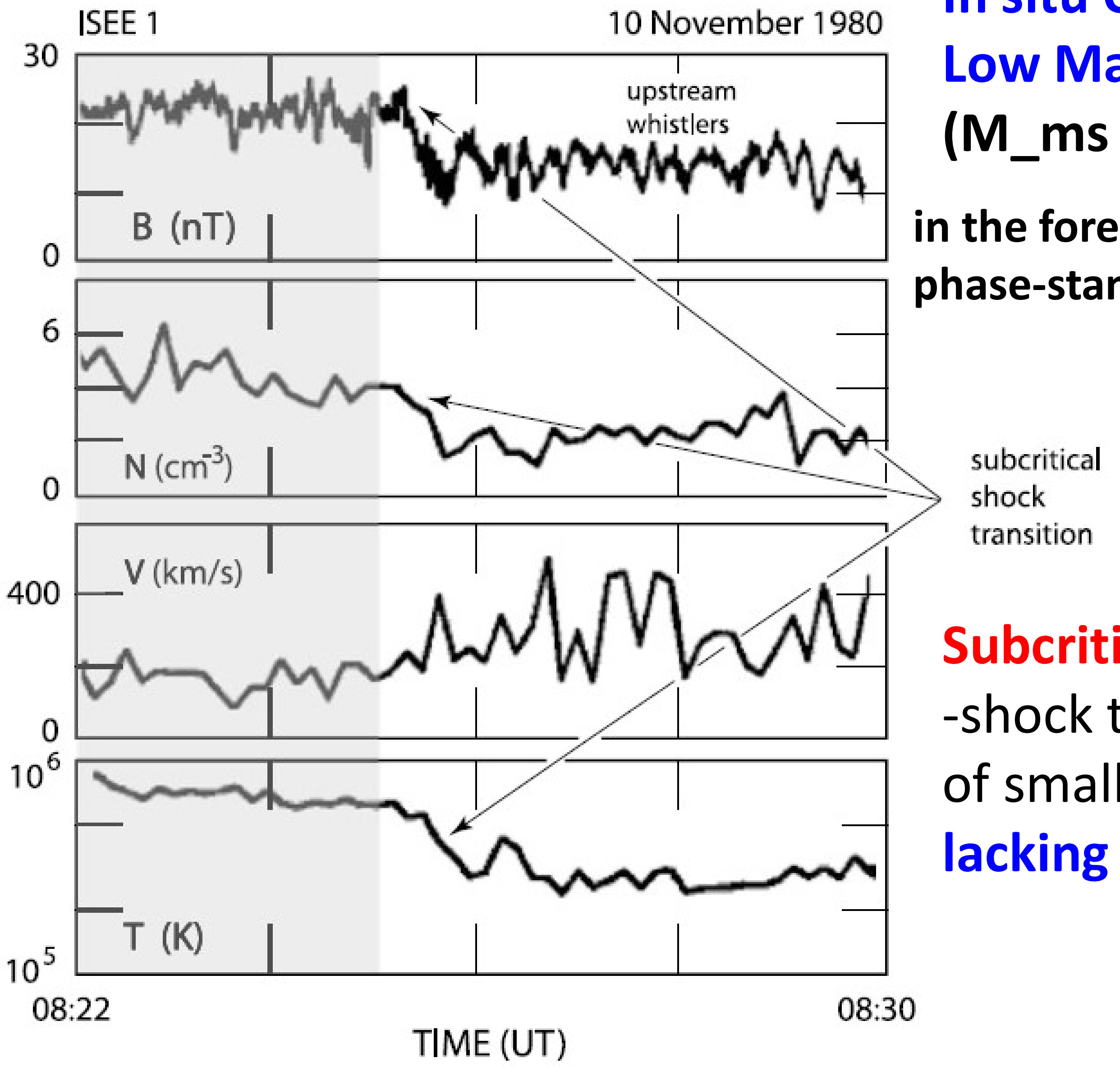
M_A>2.3 the shock becomes unsteady.

For M_A> 2.8 the shock starts to reform.

Omidi + 1994

SOURCES OF MAGNETOSHEATH WAVES
AND TURBULENCE

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



In situ Observations of Low Mach bowshocks

(M_ms ~ 2)

in the foreshock region

phase-standing whistlers

Subcritical bow shock

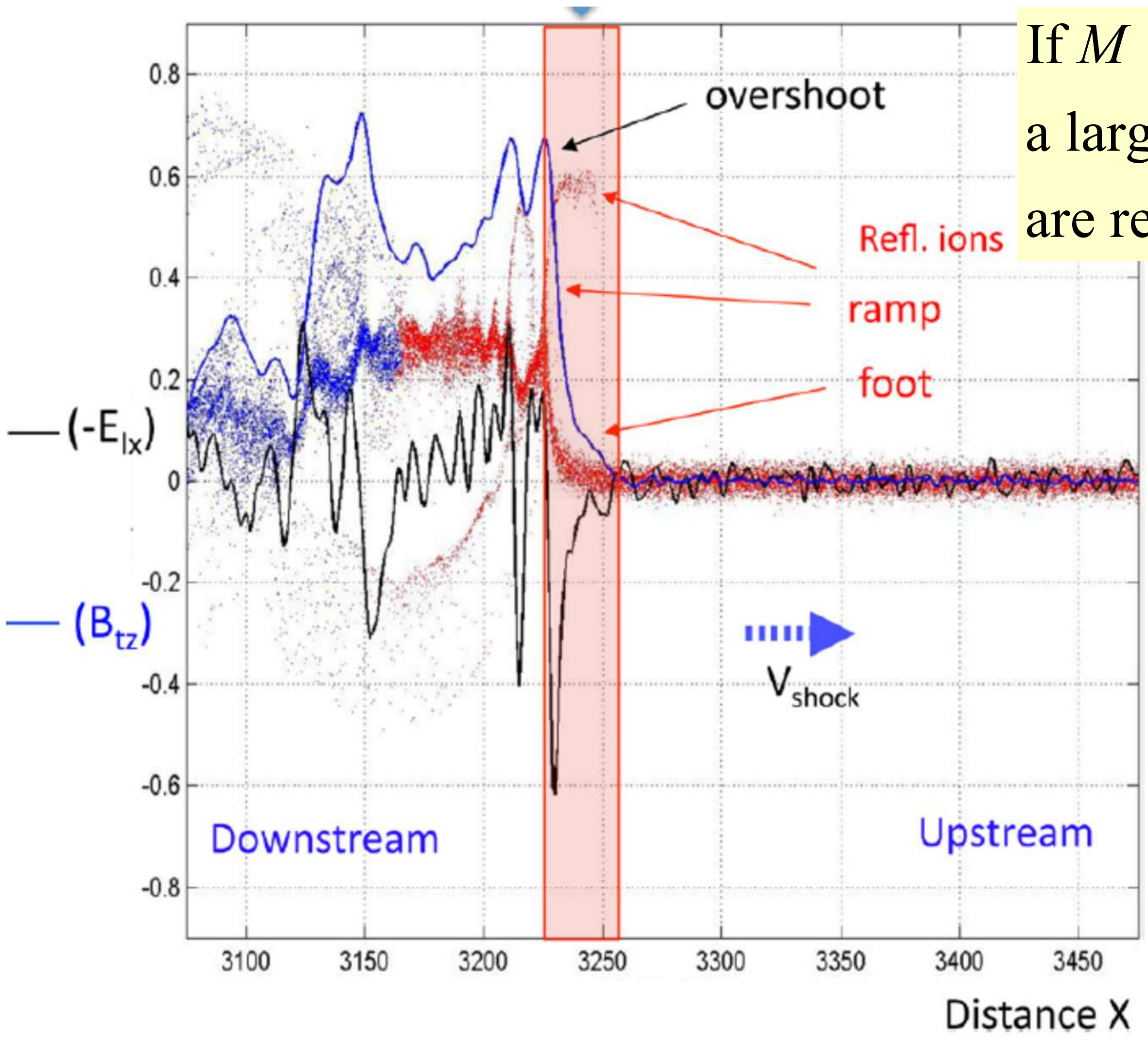
-shock transition is smooth,

of small compression ratio,

lacking an overshoot.

Farris et al 1994

Structure of supercritical perpendicular shock



If $M > M_{crit}$ (supercritical),
a large fraction of incoming ions
are reflected back to upstream.

-generate the overshoot in electric potential $\Delta\Phi$

-generated locally perp B → magnetic mirrors

-RIs excite various micro-instabilities in the shock foot.

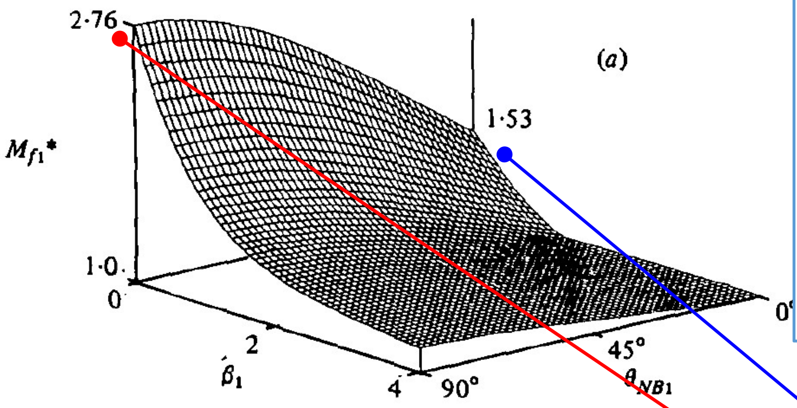
→ amplification of transverse B

-gain energy via SDA

Shock criticality is well known in space physics community, but relatively new to astrophysics community.

First fast critical Mach number: $U_{2x} = c_{s2}$ for ion reflection

Edmiston & Kennel 1984



Number flux:

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

Momentum flux:

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

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

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

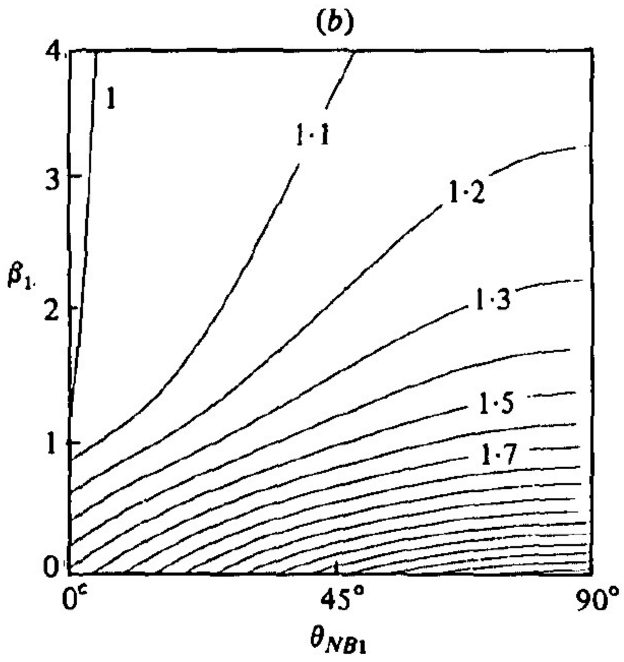
Energy flux:

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

$\beta = 0$ limit

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

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



$\beta \sim 1$ regime: $M_f^* \sim M_A^* \sim M_s^*$

Alfven critical Mach number is often used.

$\beta >> 1$ limit

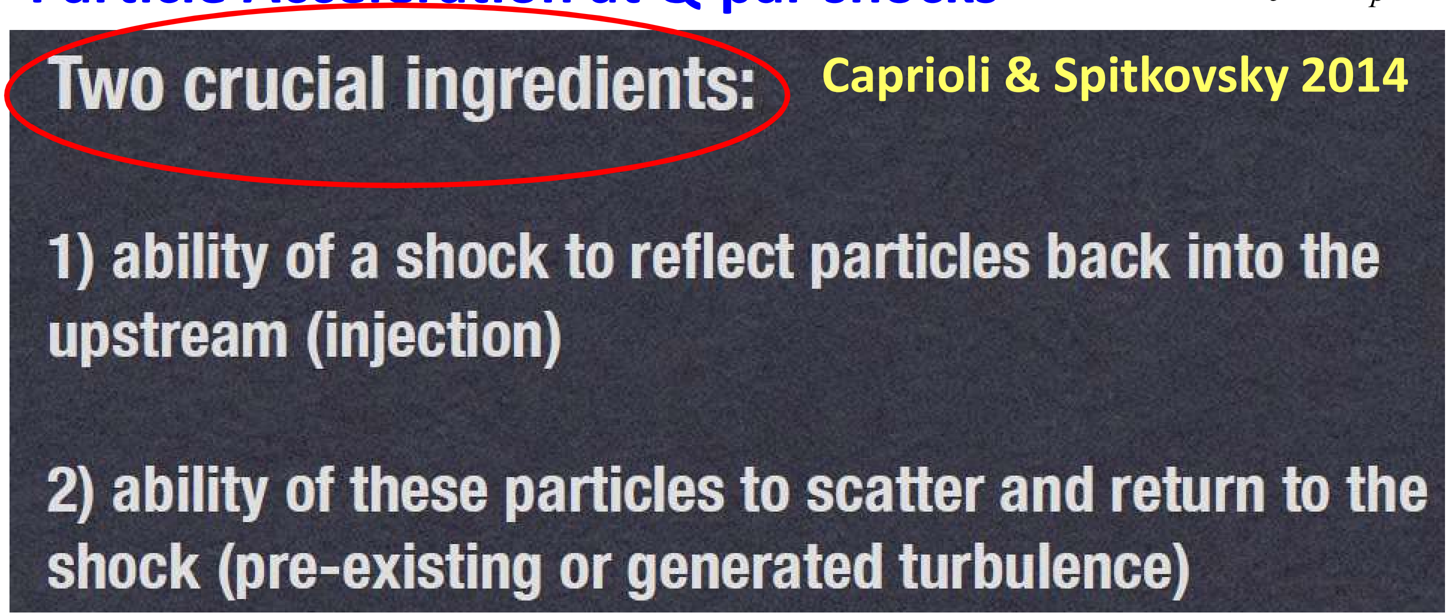
$M_f^* \sim 1.0 - 1.1$ for $\theta_{Bn} < 45^\circ$ **Q-par shocks**

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

All ICM shocks are supercritical ?

Particle Acceleration at Q-par shocks

$$\beta = \beta_e + \beta_p \approx 1,\ M_A \sim M_s = 20$$



Two crucial ingredients:

Caprioli & Spitkovsky 2014

1) ability of a shock to reflect particles back into the upstream (injection)

2) ability of these particles to scatter and return to the shock (pre-existing or generated turbulence)

2D hybrid simulations

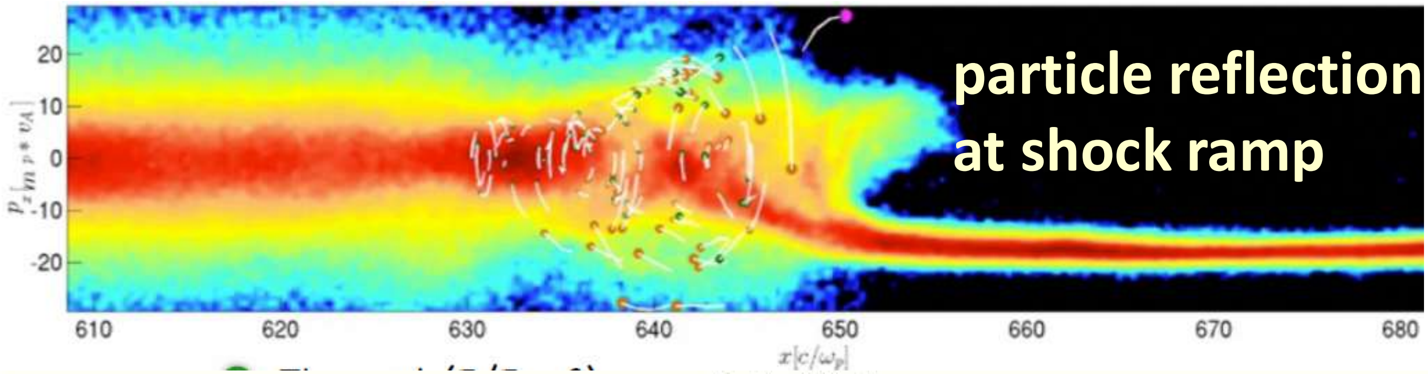
Ion reflection at the shock ramp (SDA)

+

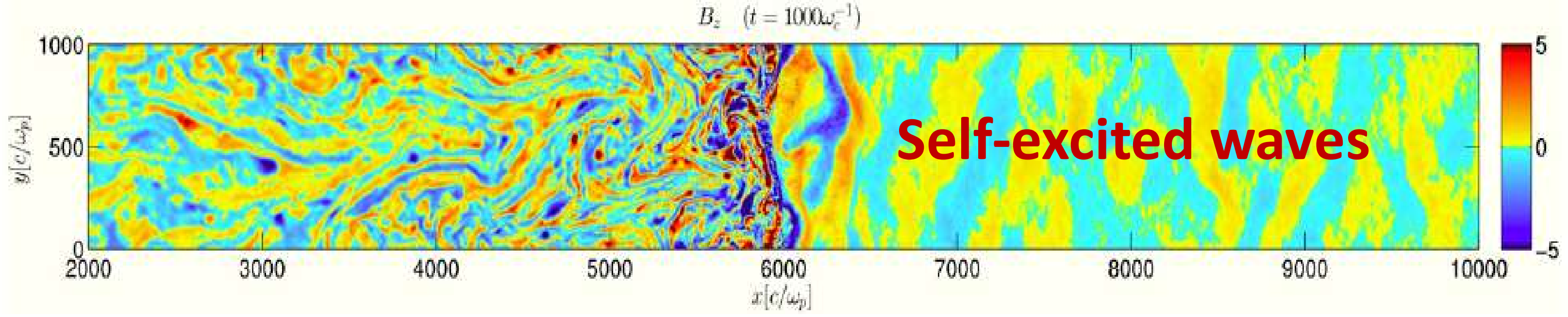
Self-generation of waves

↓

Ion Injection to DSA

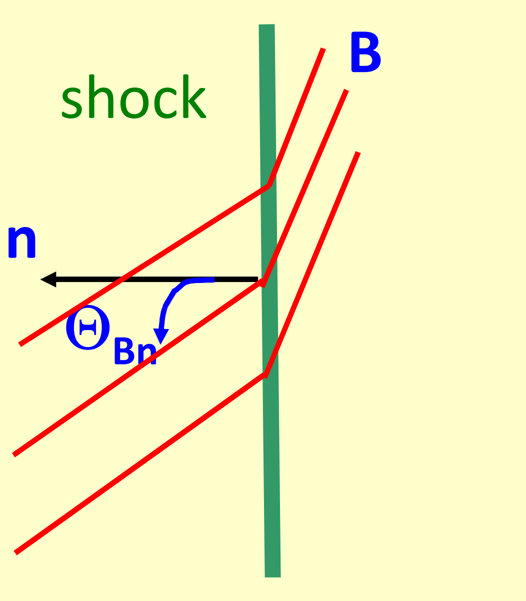


particle reflection at shock ramp



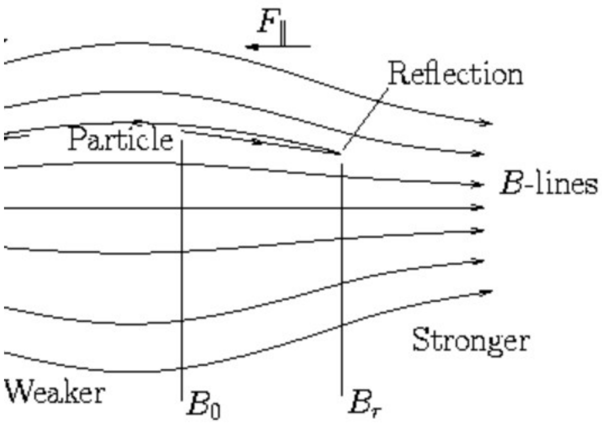
Self-excited waves

(1) magnetic mirror reflection due to compressed magnetic field lines



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

mirror force due to gradient of B



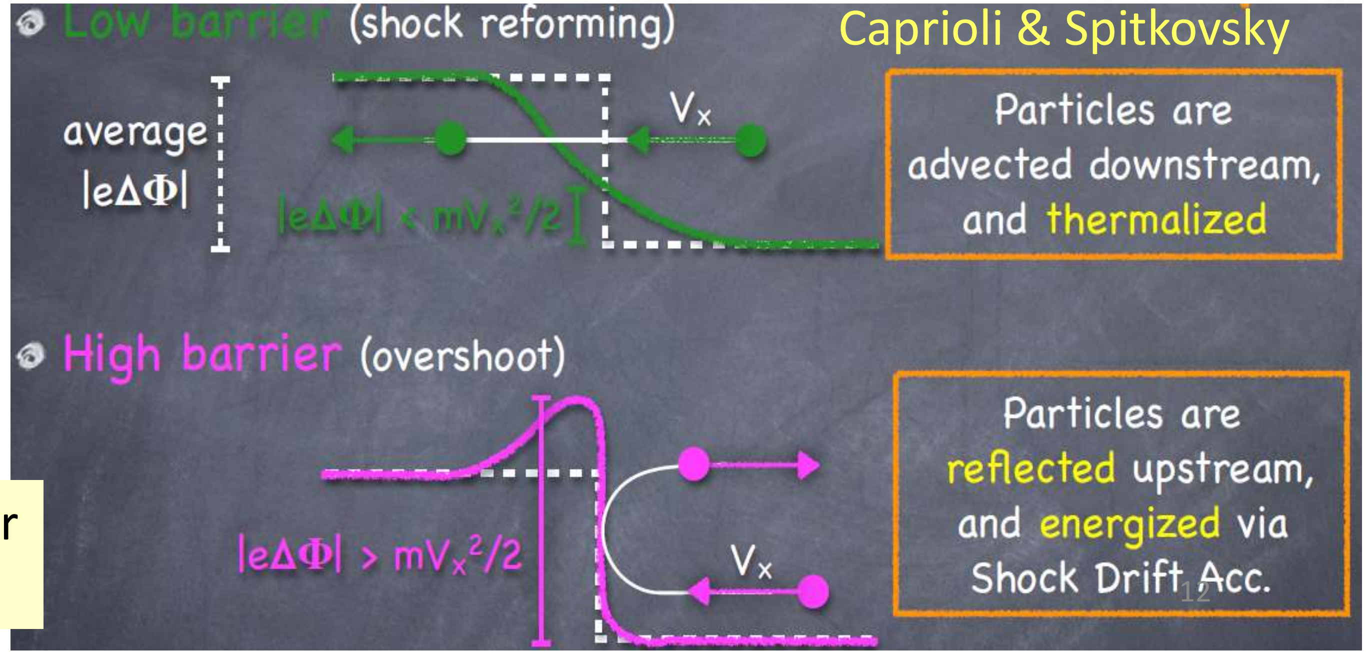
Both protons & electrons can be reflected.

More important in Q-perp shocks

(2) Cyclic shock reformation

Shock potential barrier decelerates ions

More important in Q-par shocks



Caprioli & Spitkovsky

- Low barrier (shock reforming)

Particles are advected downstream, and thermalized

- High barrier (overshoot)

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

Q: Low M_s shocks in high beta ICM are supercritical (ion reflection)?

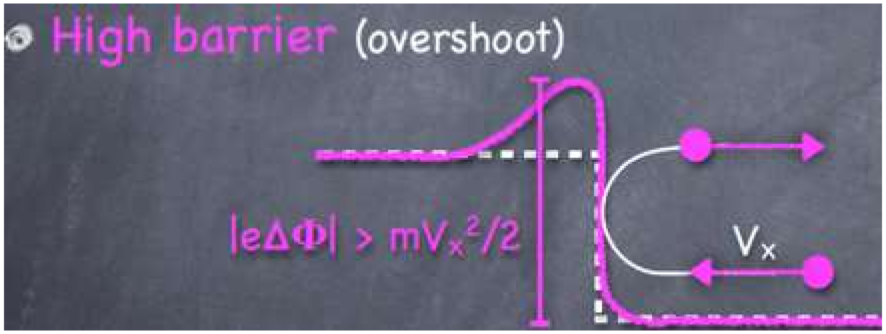
$$M_{\mathrm{s}} \equiv \frac{v_{\mathrm{sh}}}{c_{\mathrm{s}}} \approx 2 - 4$$

$$M_{\mathrm{A}} \equiv \frac{v_{\mathrm{sh}}}{v_{\mathrm{A}}} \approx \sqrt{\beta} \cdot M_s = 20 - 40$$

Key Ingredients for ion reflection at shock ramp: depend on the shock compression

$$\boxed{e\Delta\phi \approx \alpha(M_{\mathrm{s}}, t)\frac{m_i v_{\mathrm{sh}}^2}{2},}$$

α ~1: but smaller for smaller M_s



$\boxed{B_1 / B_2}$ **Smaller for smaller M_s → weaker magnetic mirror**

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

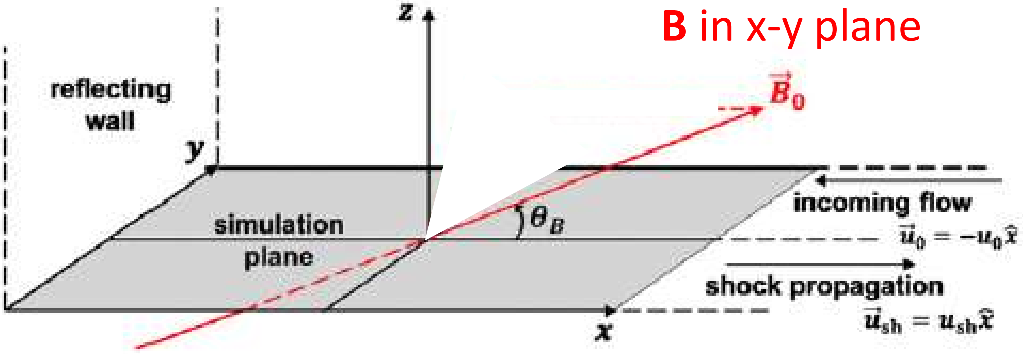
JI-HOON HA,[1] DONGSU RYU,[1] HYESUNG KANG,[2] AND ALLARD JAN VAN MARLE[1]

2018

Table 1. Model Parameters for the Simulations

1D+ 2D PIC 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



B in x-y plane

Figure 1. Simulation setup.

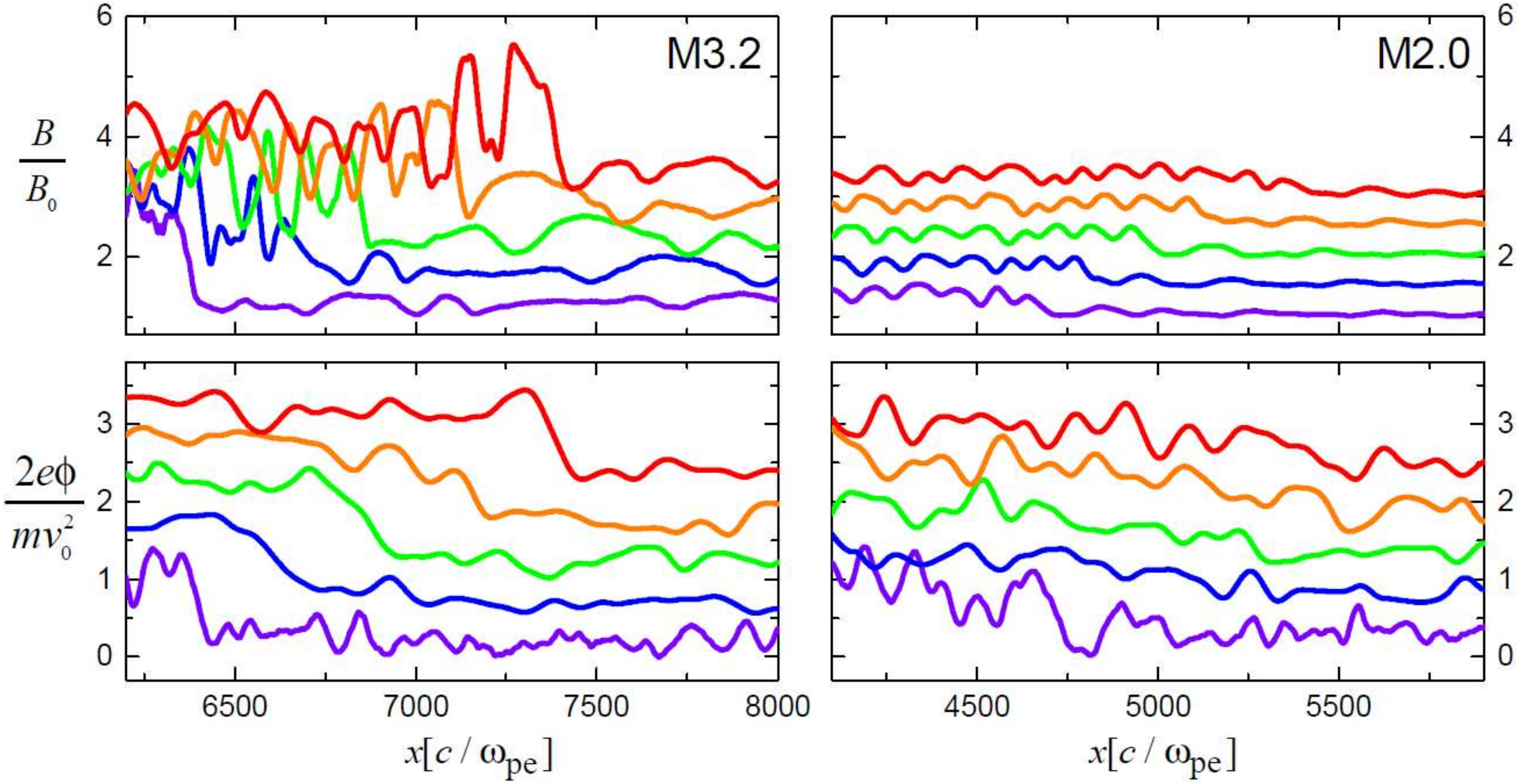
$$M_0 \equiv \frac{v_0}{c_s} = \frac{v_0}{\sqrt{2\Gamma k_B T_i/m_i}},$$

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

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

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

M_s=3.2 Supercritical **M_s=2.0** subcritical



-Time-varying overshoot in eΦ & B

-cyclic reformation of the shock

-No overshoot, but smooth transition

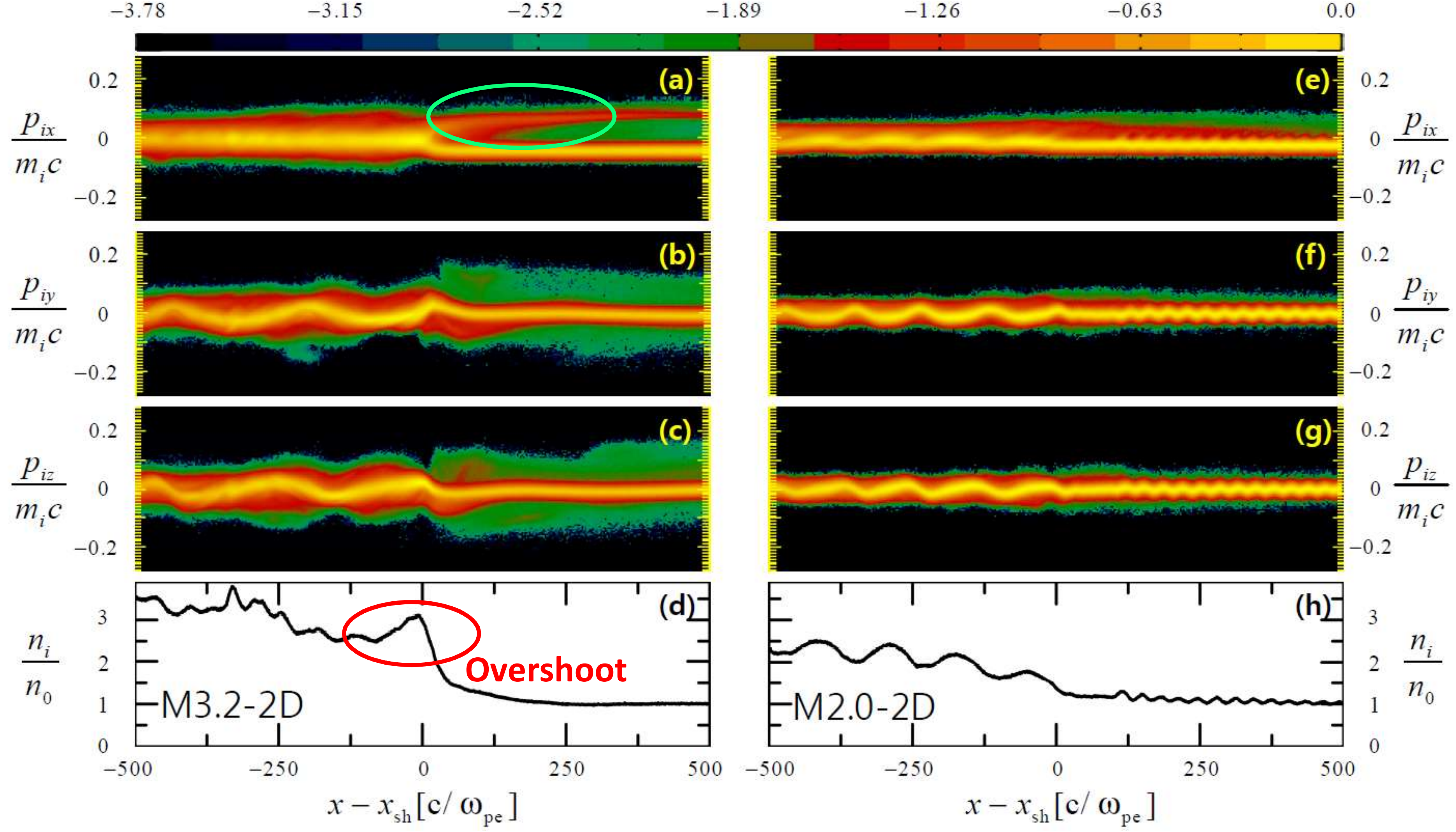
-Low frequency waves in upstream

Ha + 2018

Ms=3.2 supercritical with a beam of reflected ions

Ms=2.0 subcritical without reflected ions

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

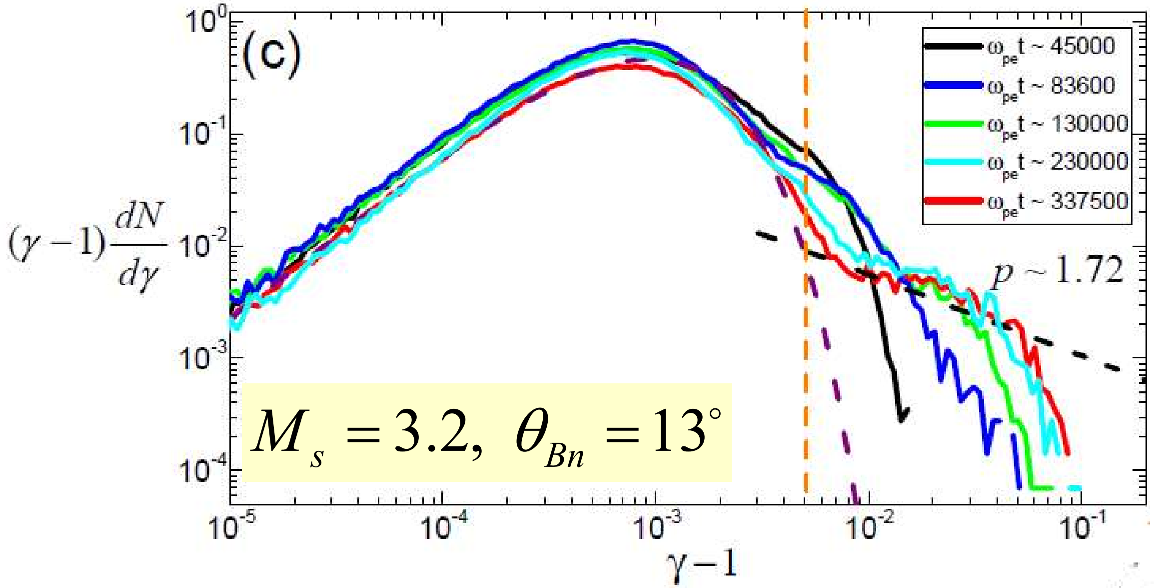


Overshoot

$$r_{\mathrm{L,i}} \equiv \frac{m_i v_0 c}{e B_0} = M_{\mathrm{A},0}\sqrt{\frac{m_i}{m_e}}\frac{c}{w_{\mathrm{pe}}} \sim 200\,\frac{c}{w_{\mathrm{pe}}}$$

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

Time Evolution of energy spectrum

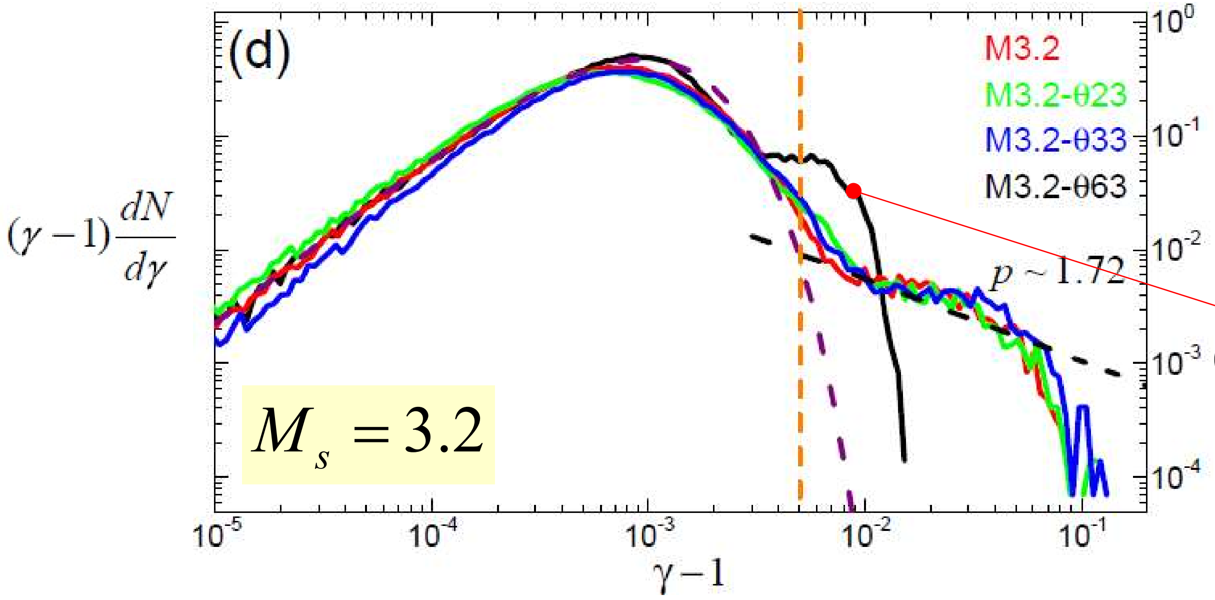


"Injection to DSA"
(Fermi I acceleration)

DSA power-law spectrum extends to higher energy in time.

$$w_{\mathrm{pe}}t \approx 3.4 \times 10^5 \ (\Omega_{\mathrm{ci}}t \approx 90)$$

Obliquity dependence



Early stage of DSA in Q-par shocks

Only SDA (no DSA) in Q-perp shocks

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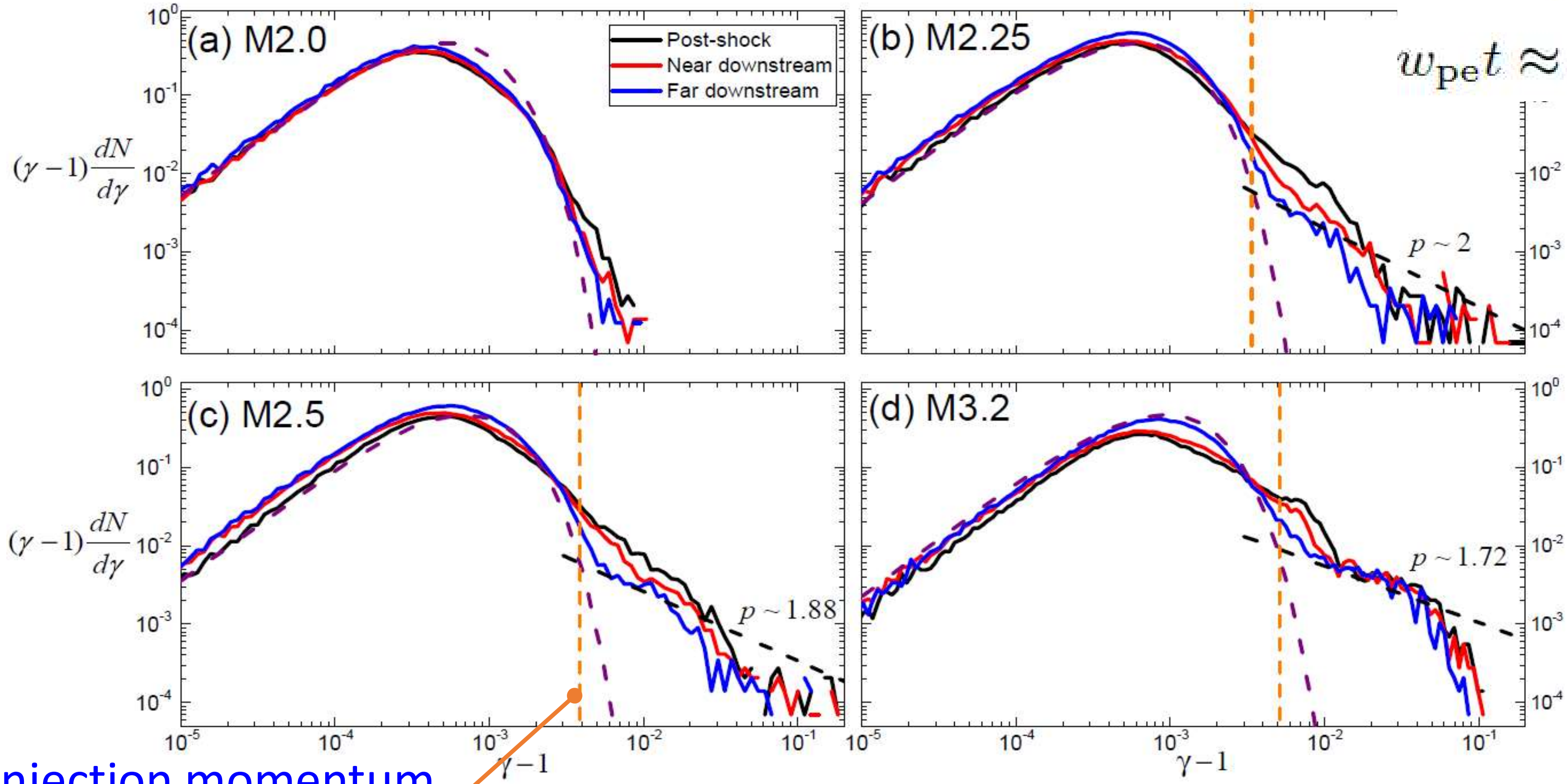
Mach number dependence

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

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



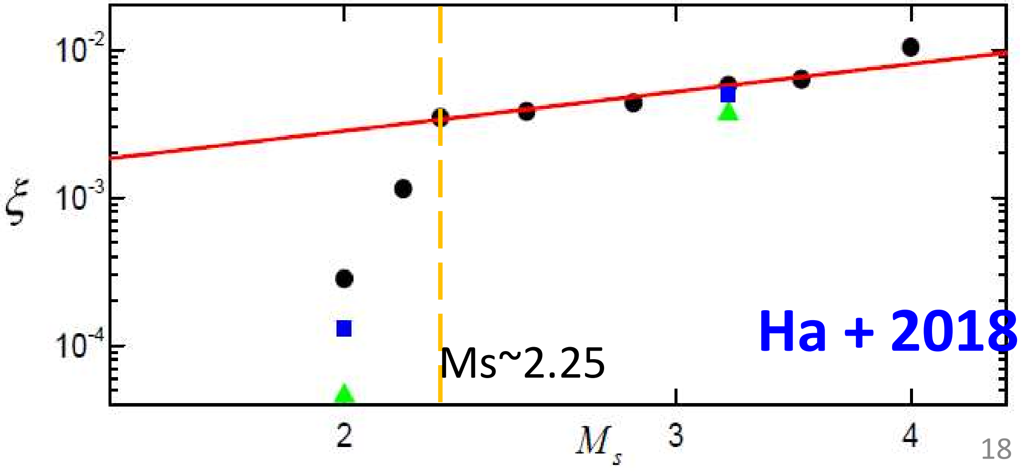
Injection momentum

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

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



Ms~2.25

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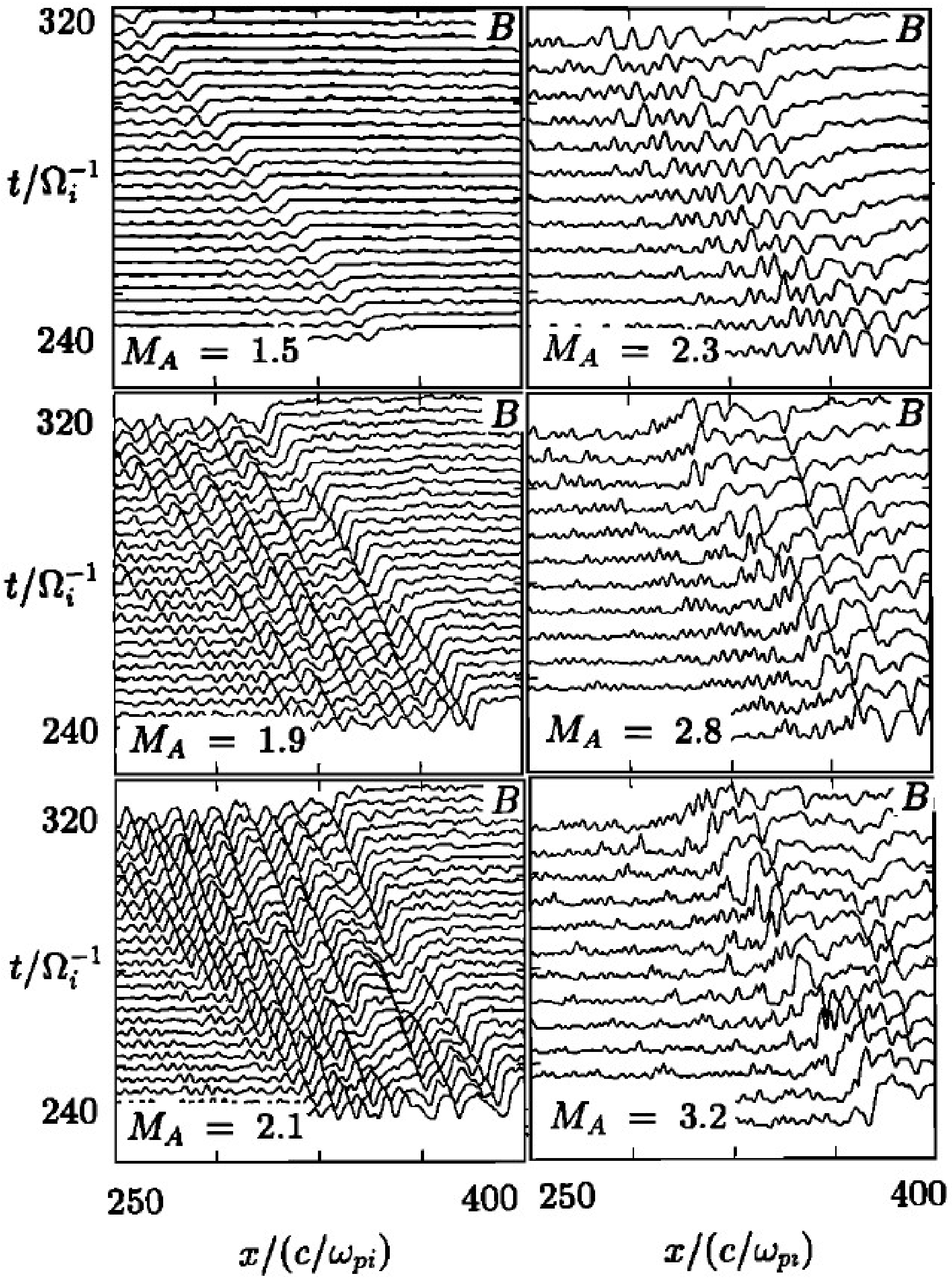


Low M_A Q-par shocks

1D hybrid simulations

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

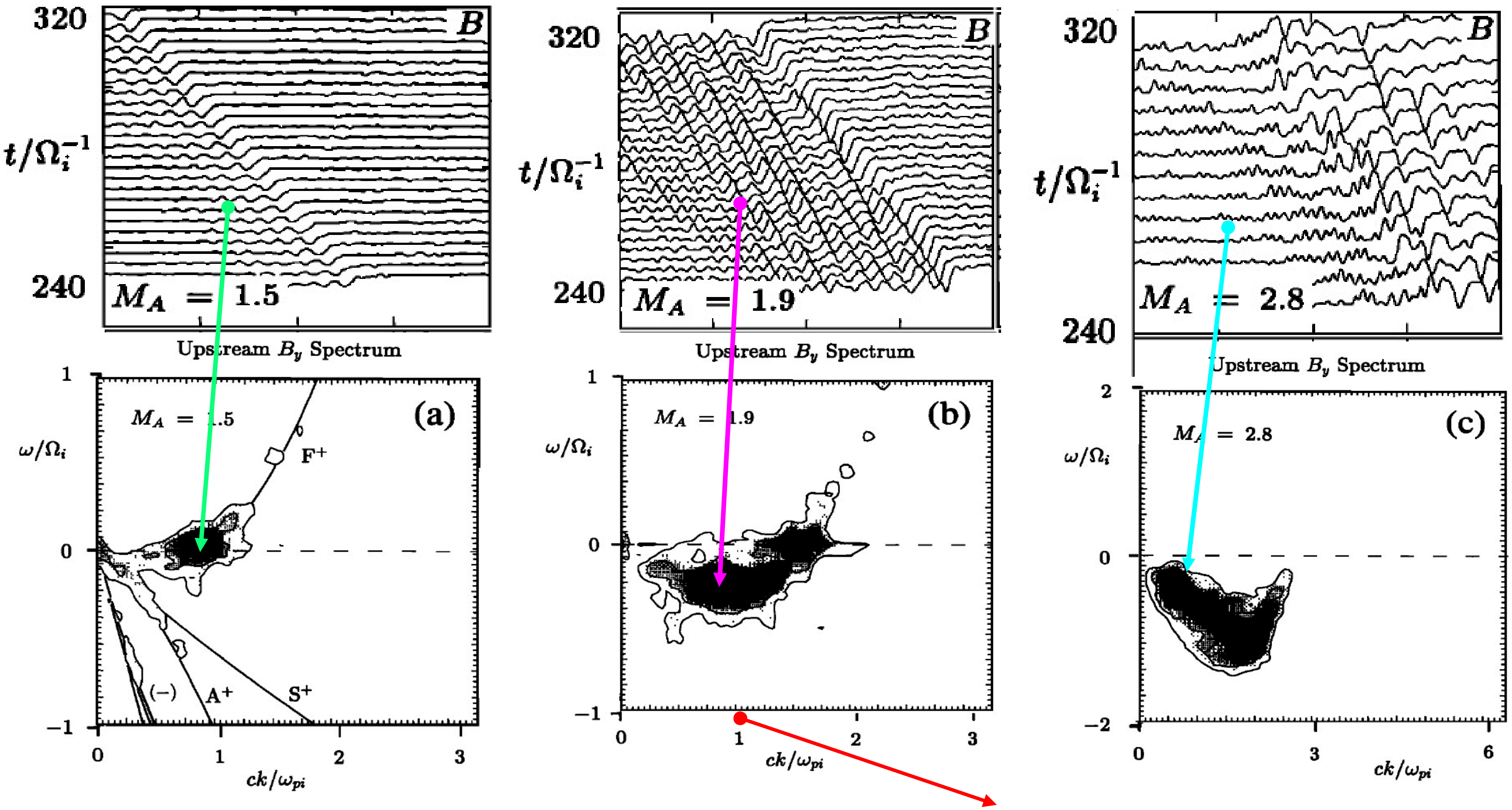
Self-excited Waves in the foreshock region

Omidi + 1994

magnetosonic whistler waves in foreshock

$\theta_{Bn} = 30^\circ$, β_i=0.5

Omidi + 1994



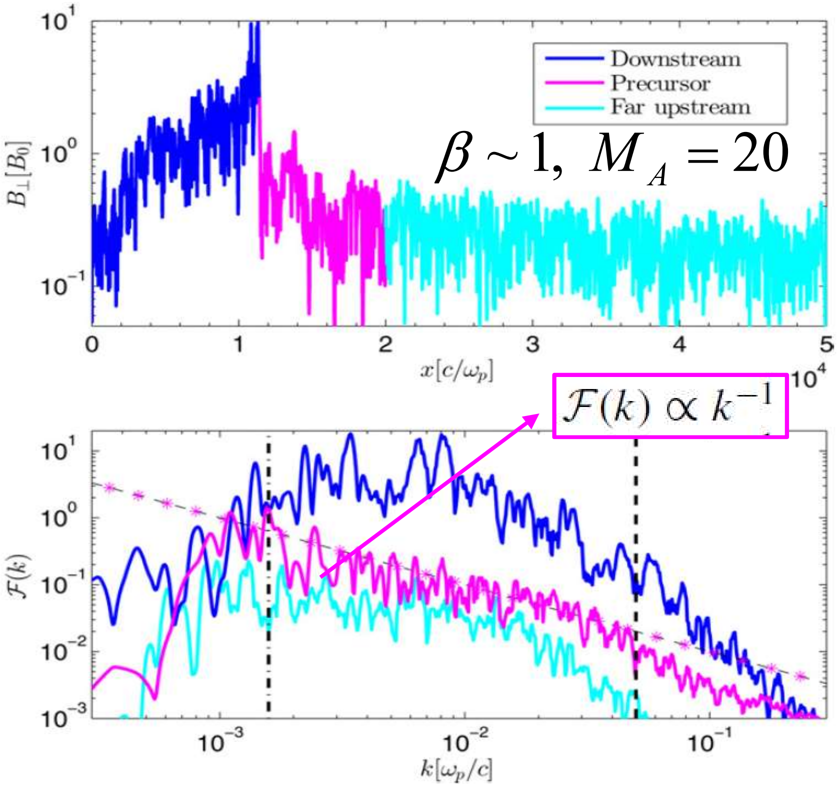
-fast magnetosonic whistler waves (right handed): c k / w_pi < 1
excited by the reflected ions via the resonant ion/ion beam instability

-With increasing M_A, the dominant waves change from phase standing whistlers → group standing whistlers → longer wavelength waves with downstream directed group velocity

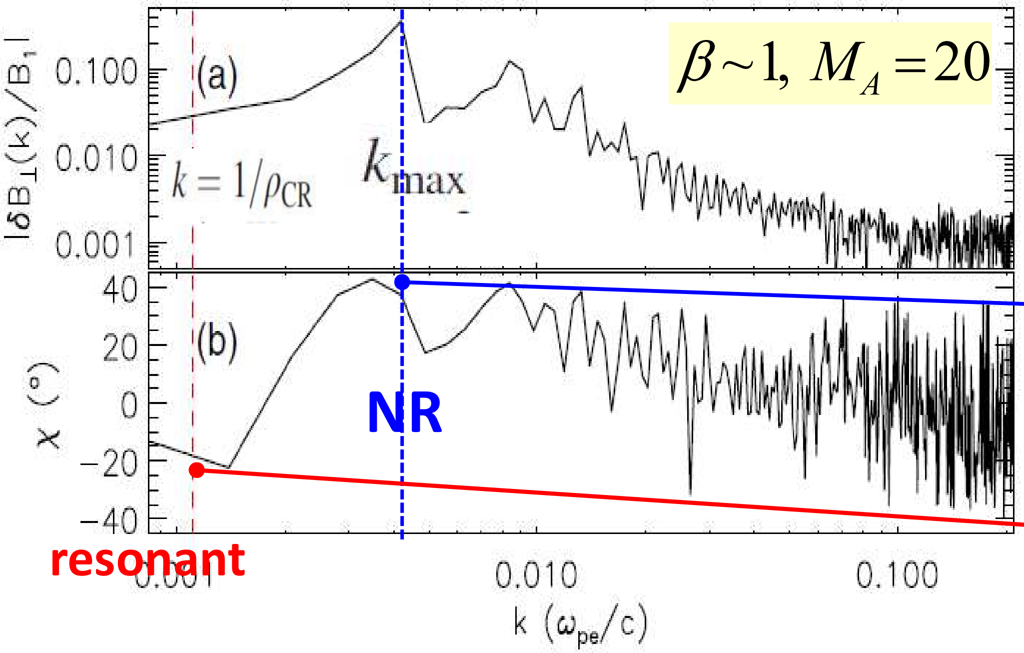
Resonant vs. Nonresonant Bell instabilities by streaming CRs

2D Hybrid simulations (CS2014)
-For M_A<30, resonant streaming instability dominates over NR Bell instability.
→ excite mainly left-handed CP waves.

power spectrum of $B_\perp$ in the precursor consistent with resonant instab



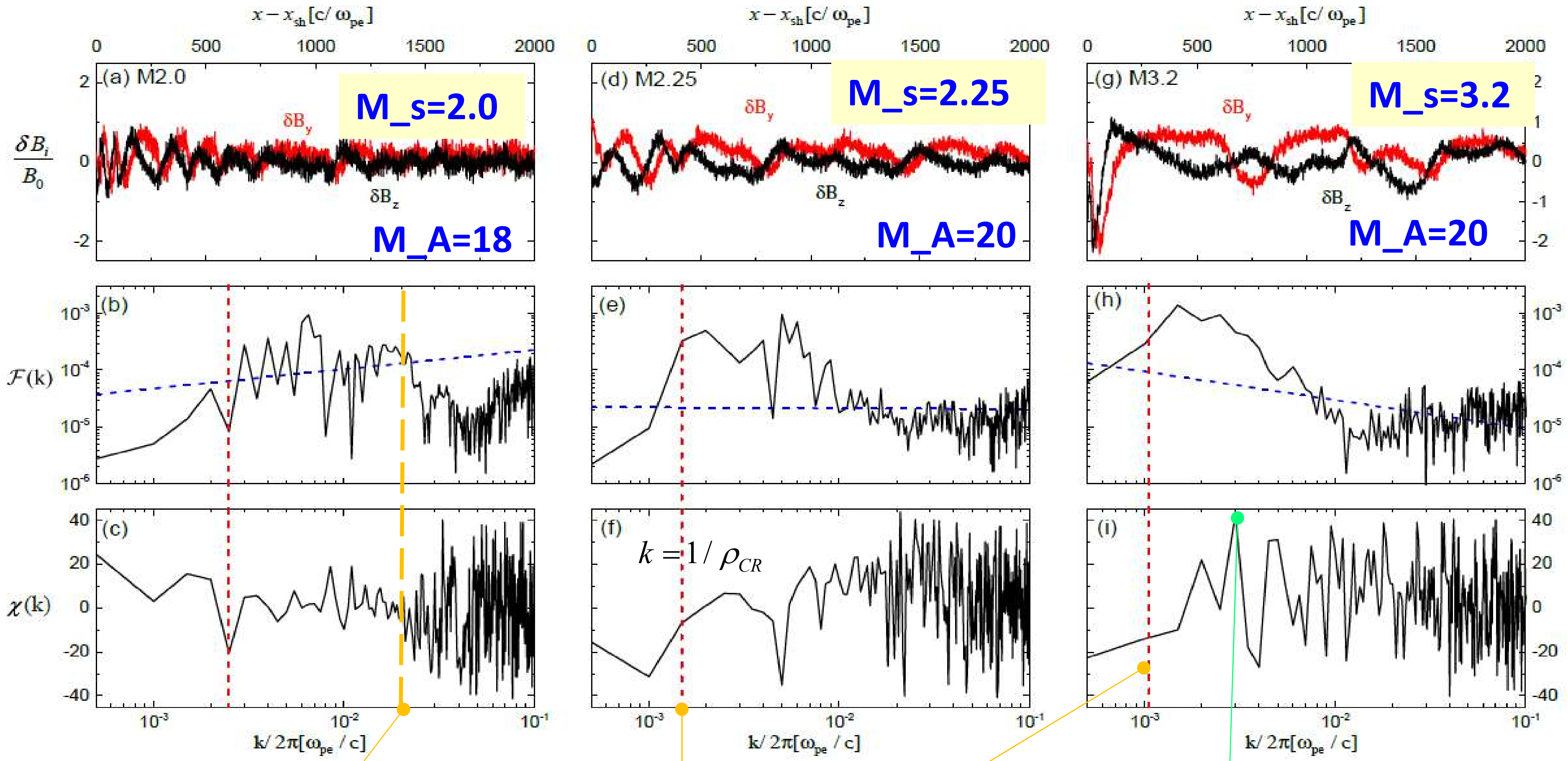
Park et al. 2015 **1D PIC sim**



$\chi = +45$: right-handed

$\chi = -45$: left-handed

Upstream waves: Transverse components of B $\delta B / B \sim 1$



M_s=2.0

M_A=18

M_s=2.25

M_A=20

M_s=3.2

M_A=20

$k = 1/\rho_{CR}$

magnetosonic whistlers: $\frac{ck}{\omega_{pi}} \le 1$

$\frac{ck}{\omega_{pe}} \le 0.1$ with $m_i / m_e = 100$

Resonant mode (left-handed pol, χ=−45)

Non-resonant (right-handed pol, χ=+45)

$$\mathcal{F}(k) \propto k \left(\frac{\delta B}{B_0}\right)^2 \propto k^{q-5},$$

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

Ha + 2018

SUMMARY

1. fast critical Mach number for ion reflection is M_f* ~2.25
   for Q-par shocks in high beta~100 plasma.

2. Only supercritical Q-par shocks with M_s > 2.25 may inject & accelerate CR protons via Fermi I acceleration.

3. The injection fraction, $\xi(t)$, decreases with time.
   Long-term evolution of $\xi(t)$ can be studied with other methods.

4. A clue to the mystery of non-detection of gamma-rays from
   galaxy clusters.