Particle Acceleration and Injection in Magnetosonic Shocks

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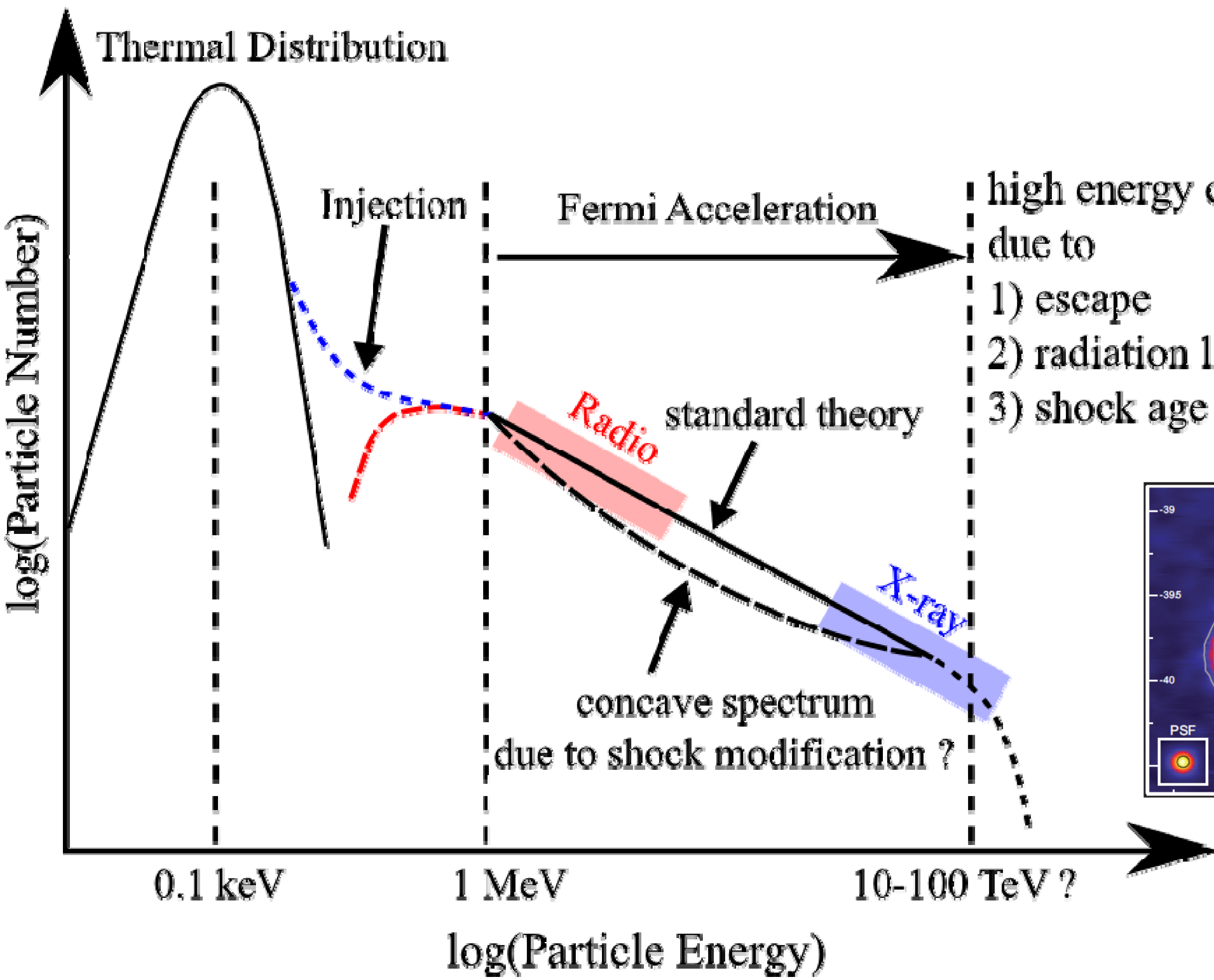
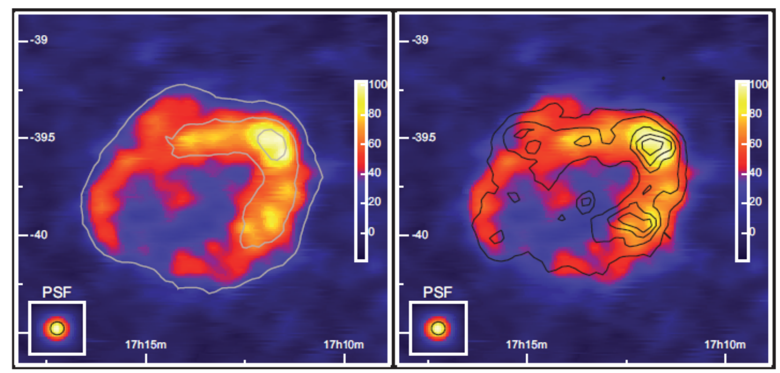
Electron Energy Spectrum at SNR Shocks



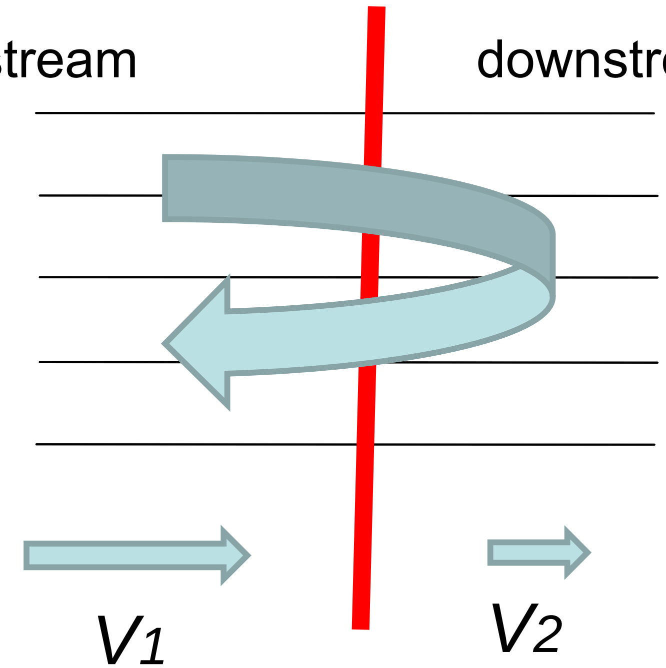
SN1006, Chandra X-ray
Bamba et al. 2003;
Long et al. 2003



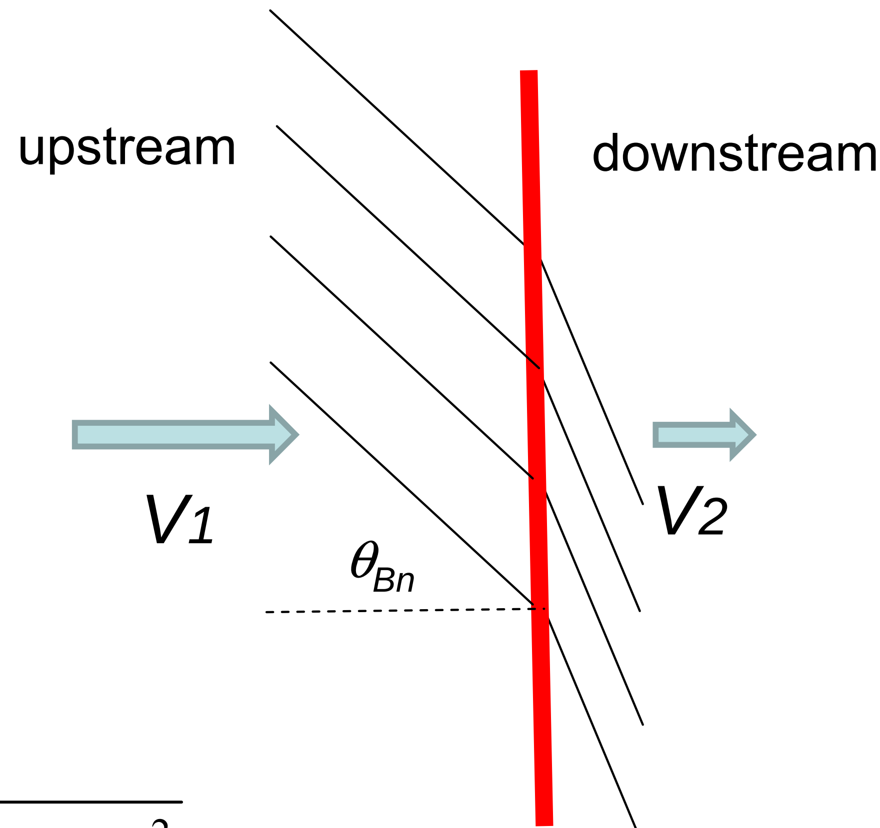
RX J1713.7-3946, HESS
TeV gamma ray image +
ASCA X ray contour (right)
Aharonian et al. 2007

Injection

(Quasi-) Parallel Shock



Quasi-Perpendicular Shock

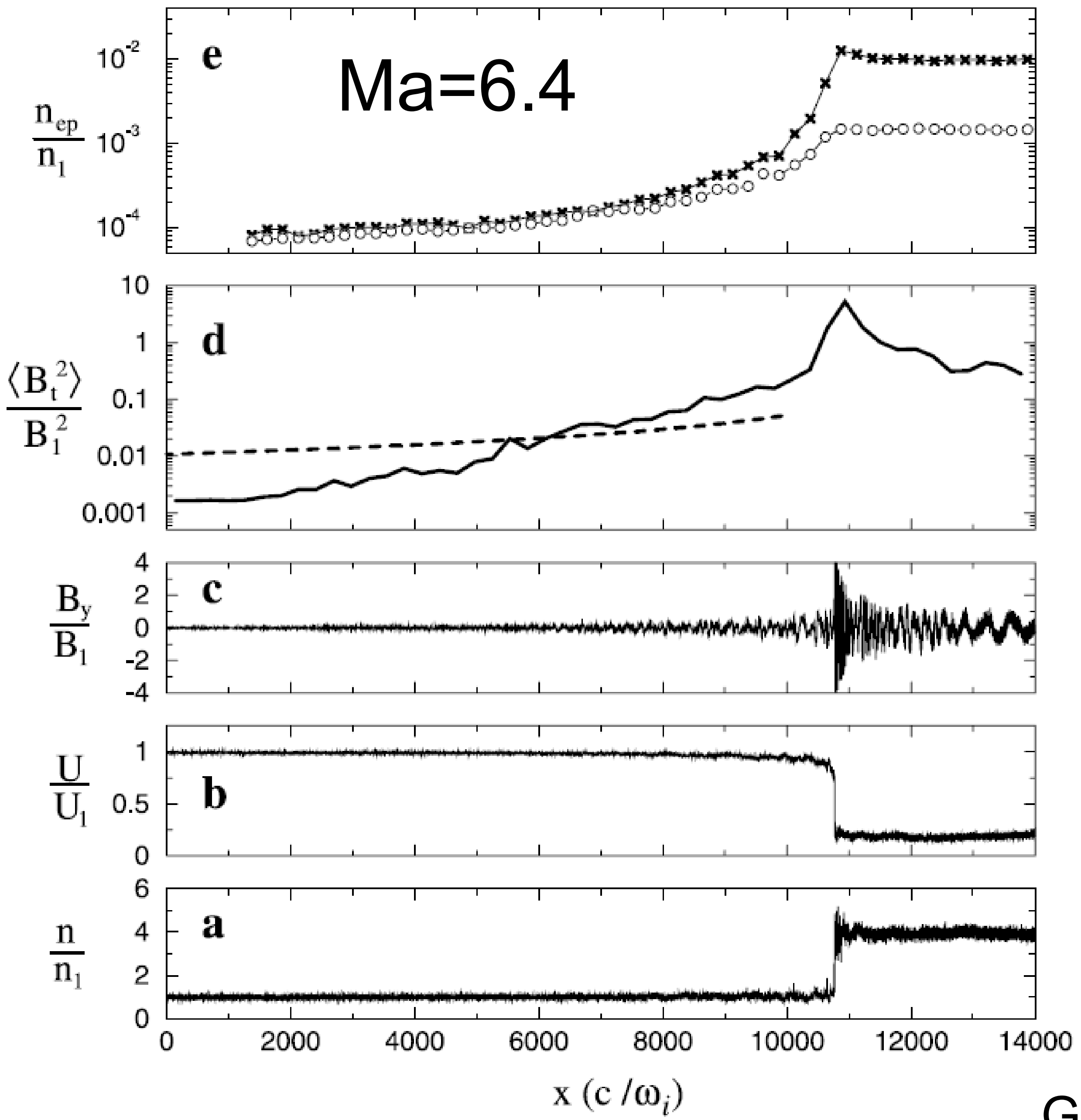


$$v_{inject} > V_1 \sqrt{\tan^2 \theta_{Bn} + (V_2 / V_1)^2} \approx V_1 \tan \theta_{Bn}$$

easy

difficult

Parallel Shock in Hybrid Simulation

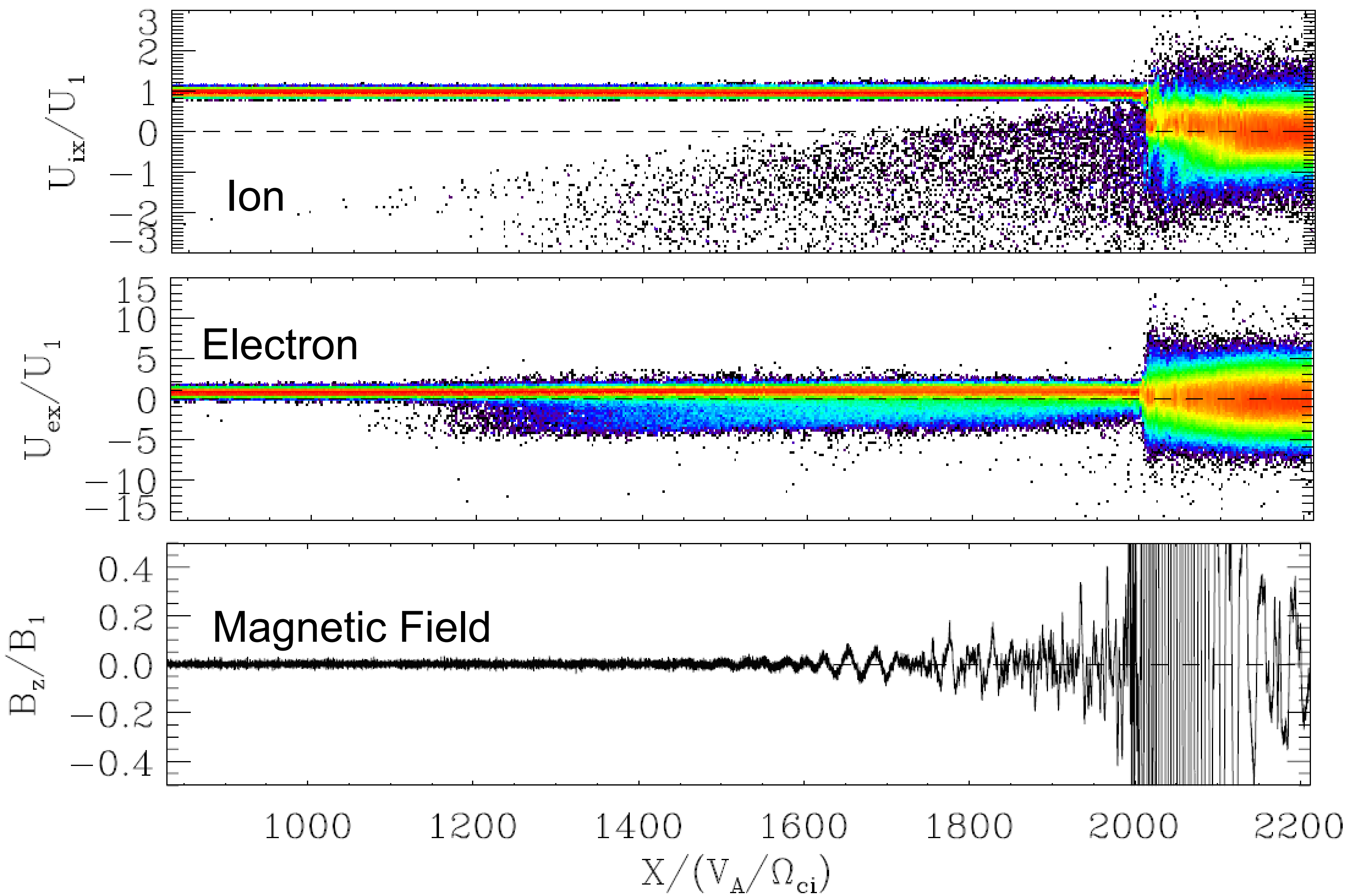


Ion Fermi Acceleration

Alfvenic Turbulence

Giacalone, ApJ, 2004

Parallel Shock in PIC (early stage)



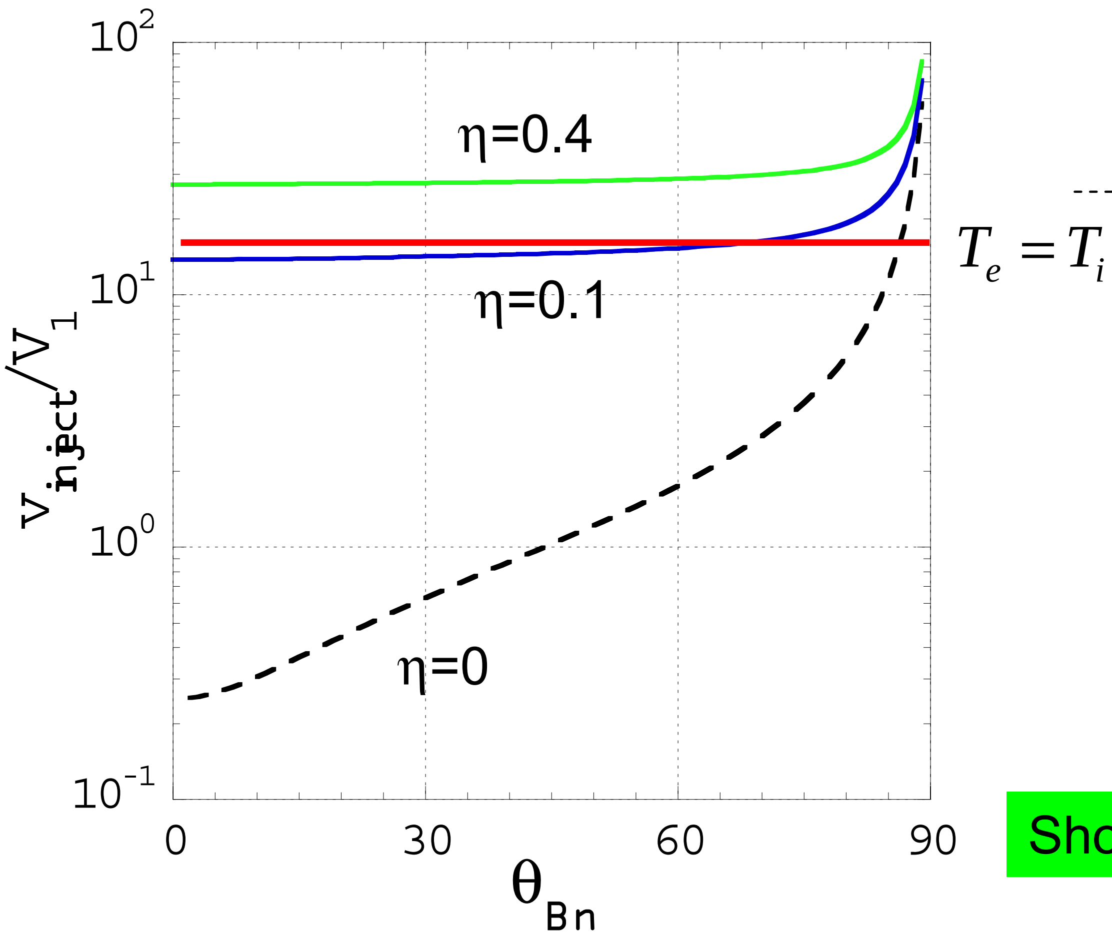
Ma=3
Mi/me=25

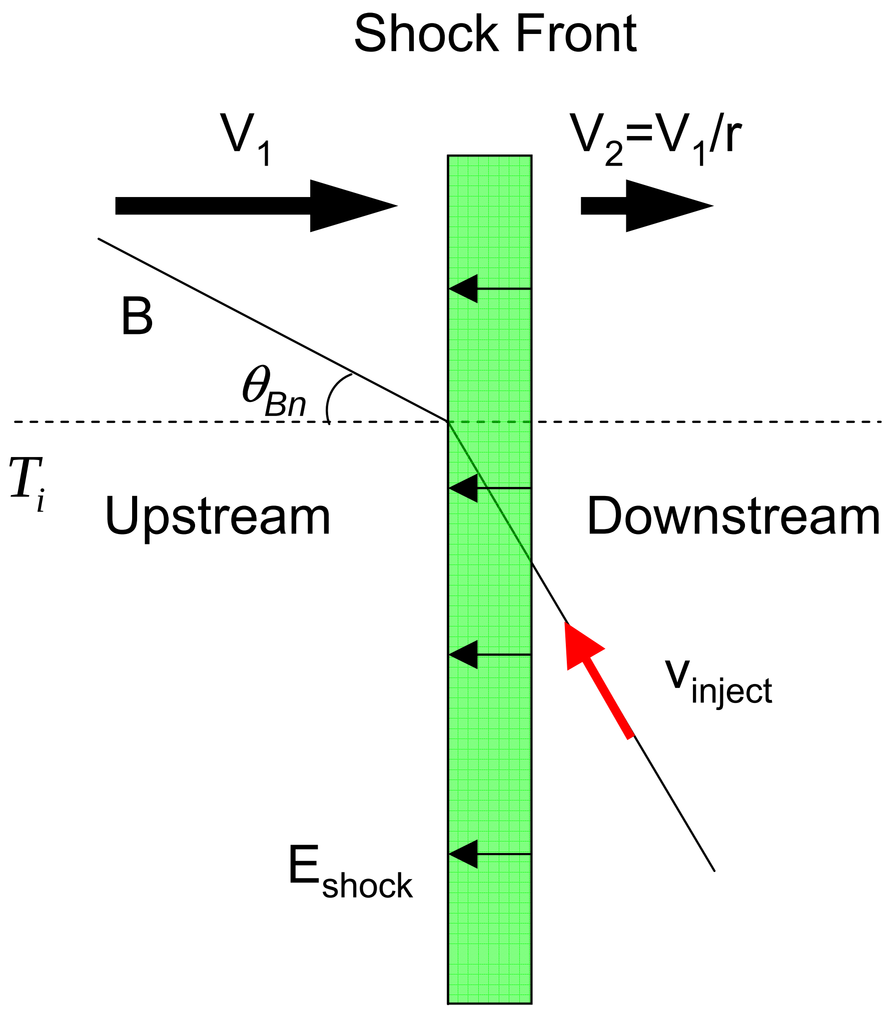
Electron Injection

Alfven Wave Precursor

Electron Injection Problem

$$\frac{v_{inject}}{V_1} > \tan\theta_{Bn} + \sqrt{\frac{2e\phi_{shock}}{m_{ele}V_1^2}}$$





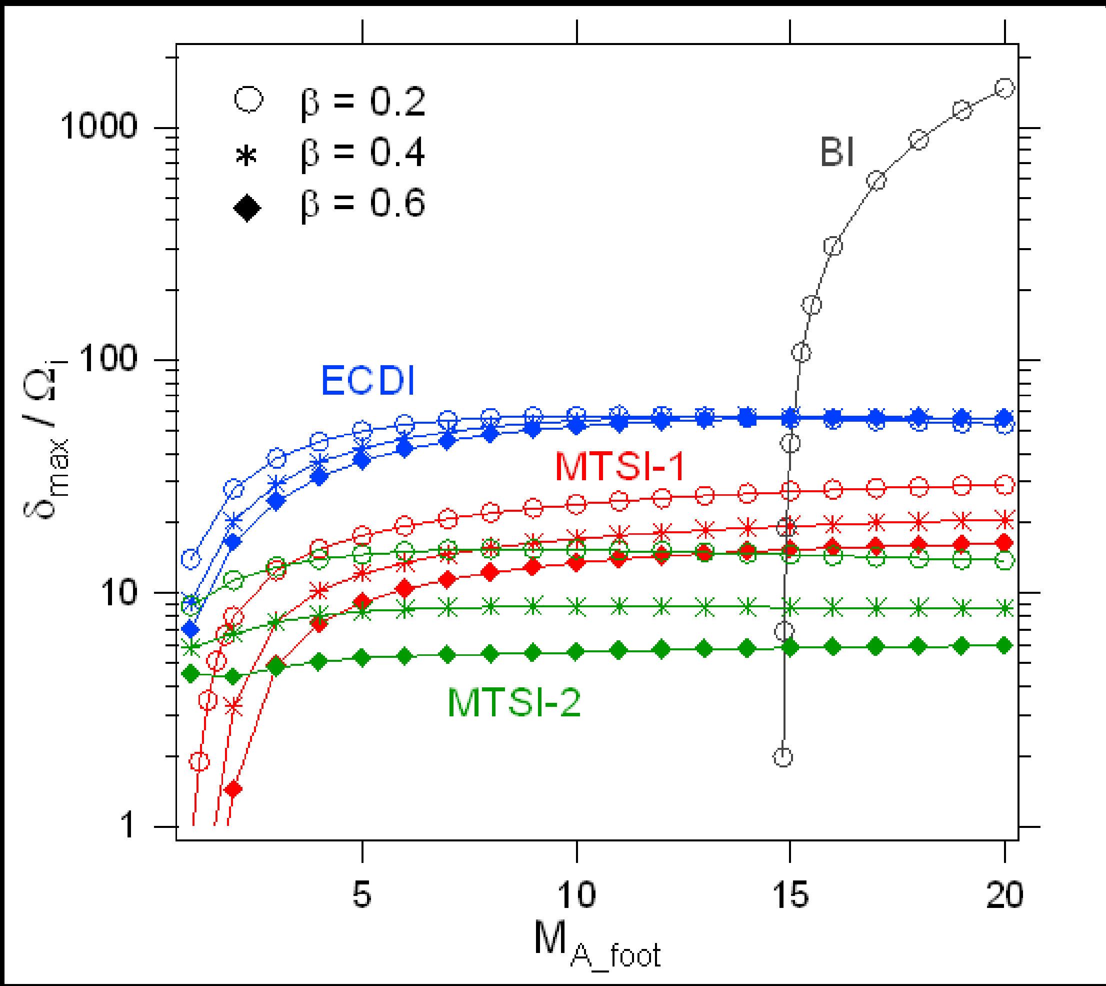
Shock Potential Φ_{shock} (E_{shock}=-□ Φ_{shock} □

$$\eta \equiv \frac{2e\phi_{shock}}{m_{ion}V_1^2} \approx 0.1-0.4$$

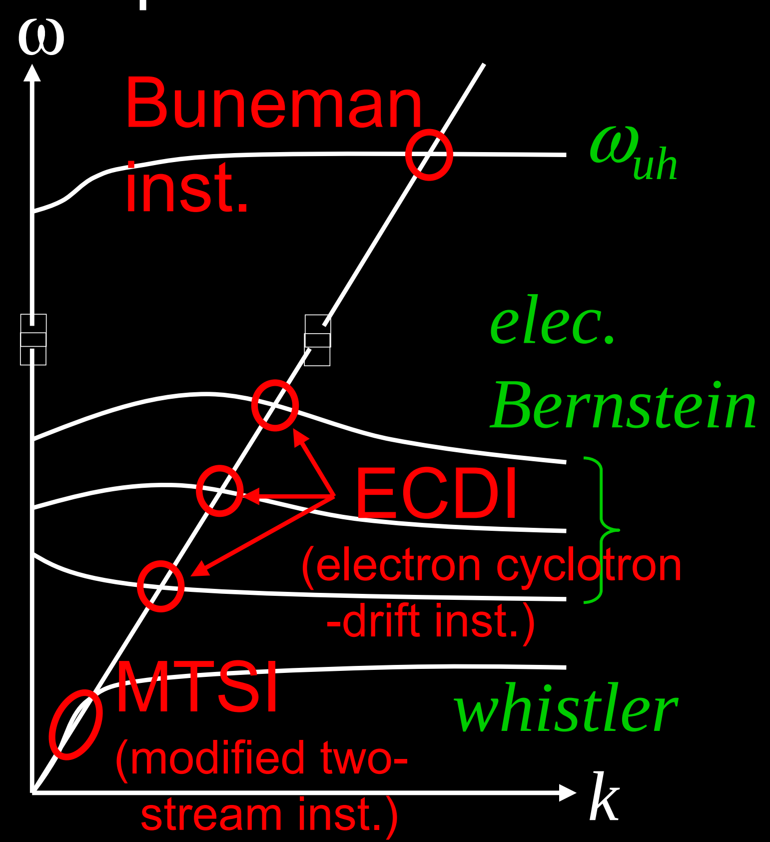
Injection is Difficult for θ_{BN} > 60

Plasma Instabilities in Quasi-□ Shock

$(\omega_{pe}/\Omega_e = 50, m_i / m_e = 1836)$



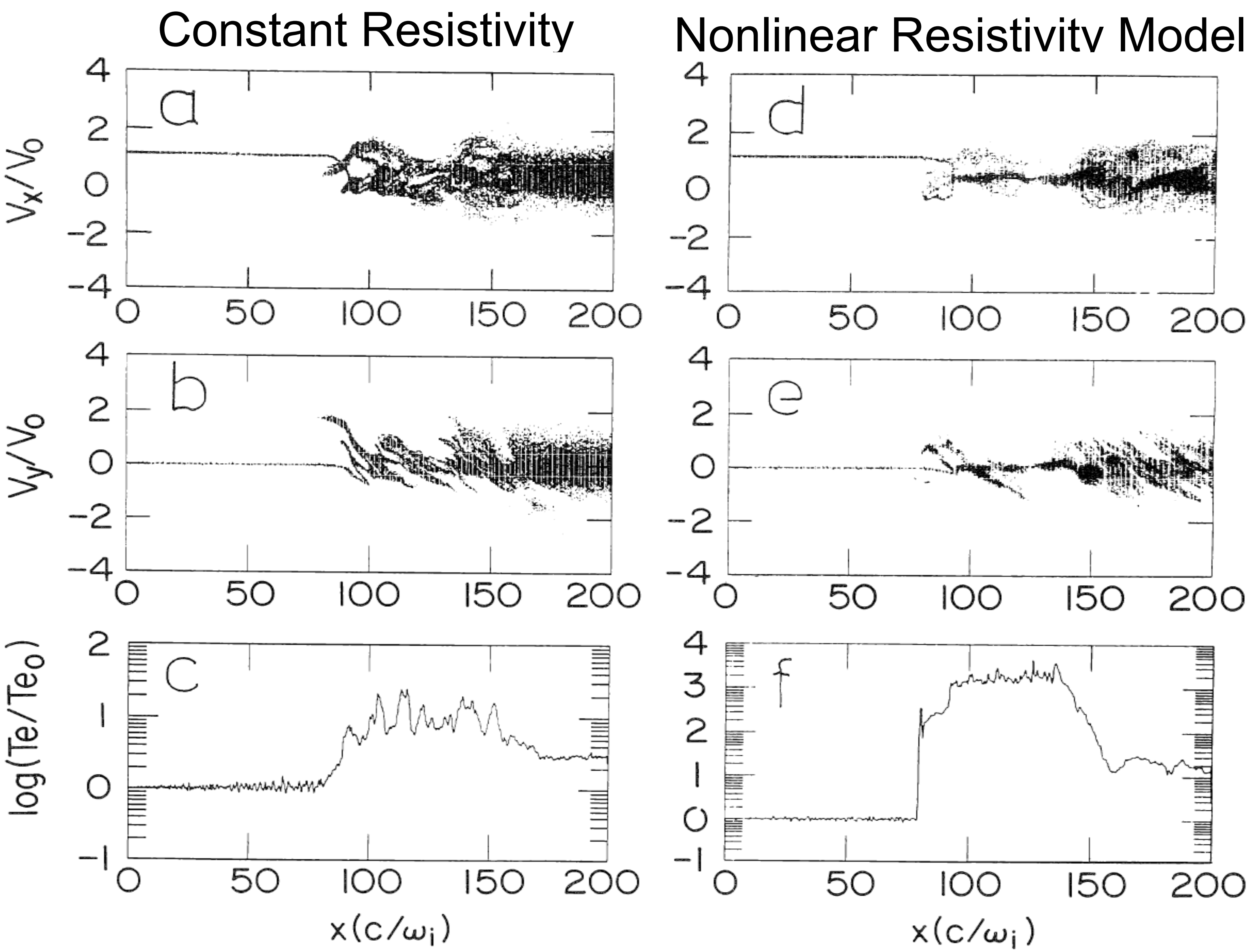
Dispersion relation



Matsukiyo and Scholer, JGR 2003; Scholer et al., JGR 2004; Muschietti & Lembege, ASR 2006

Electron Heating in Hybrid Simulation

Buneman Instability & Ion-Acoustic Instability



Ma=50

Cargill and Papadopoulos ApJ 1988

2D Perpendicular Shock in PIC (Ma=15)

upstream downstream

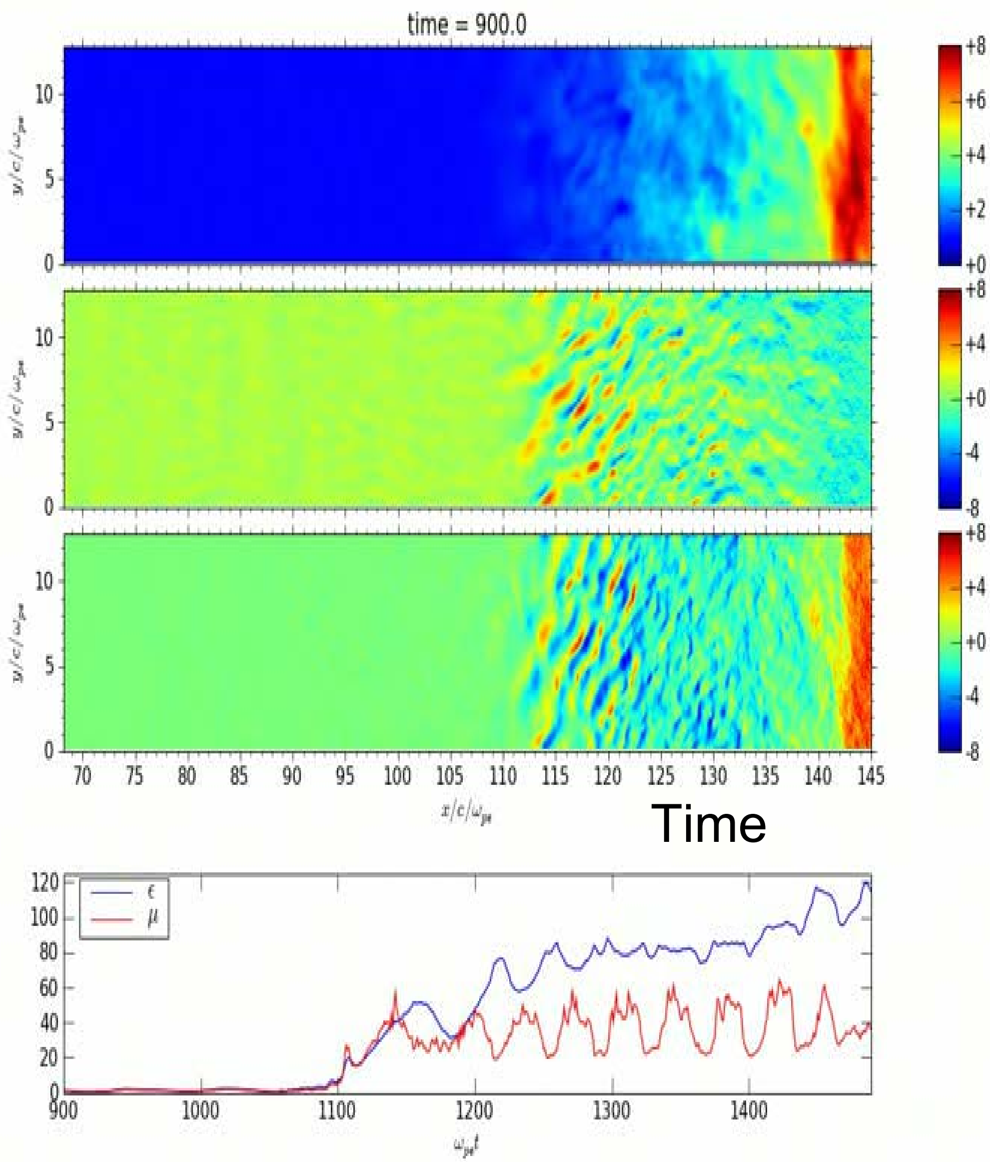
Mi/me=25

Bz

Ey

Ex

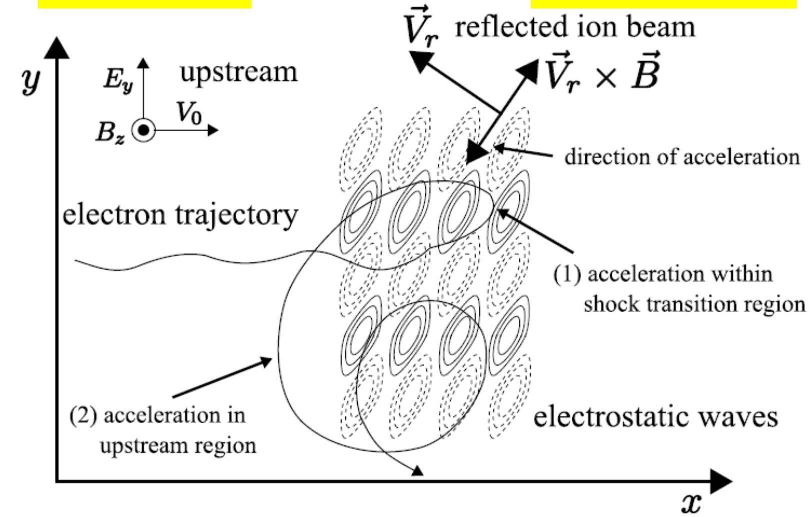
Kinetic Energy



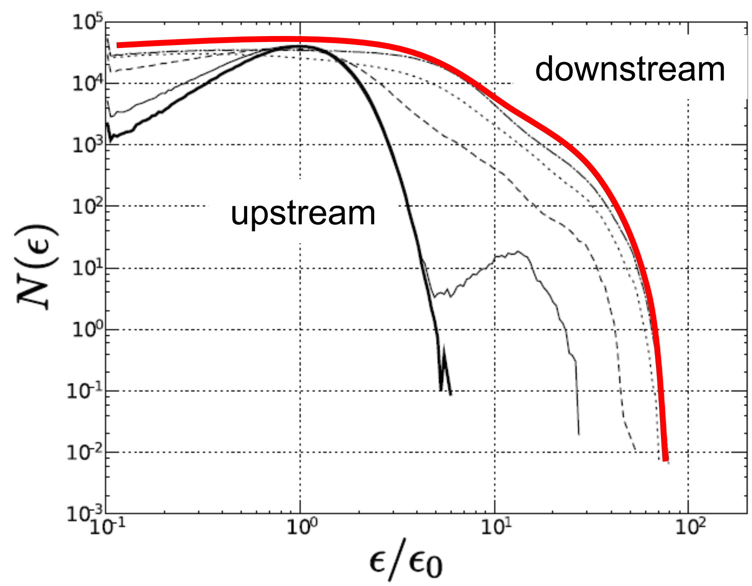
Time

Time

upstream downstream



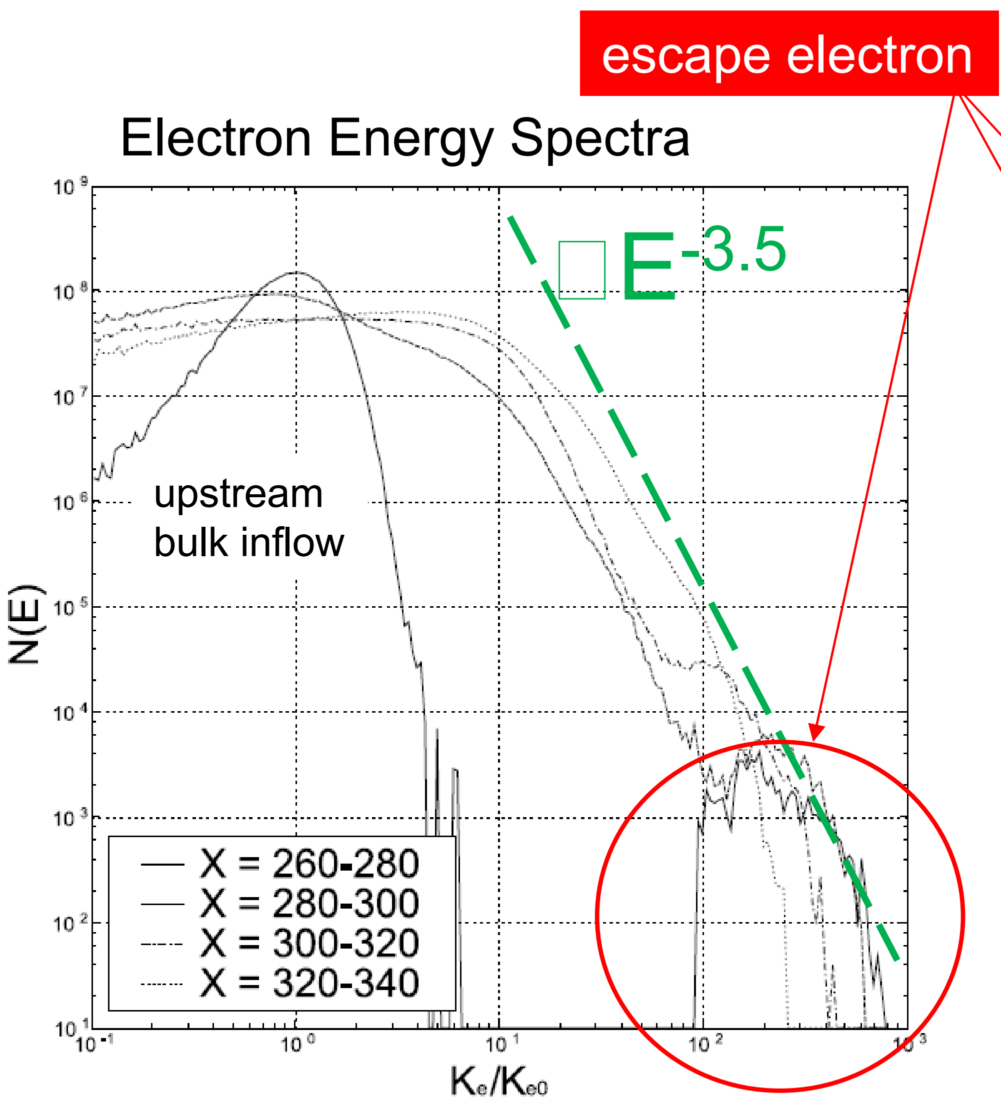
Electron Energy Spectra

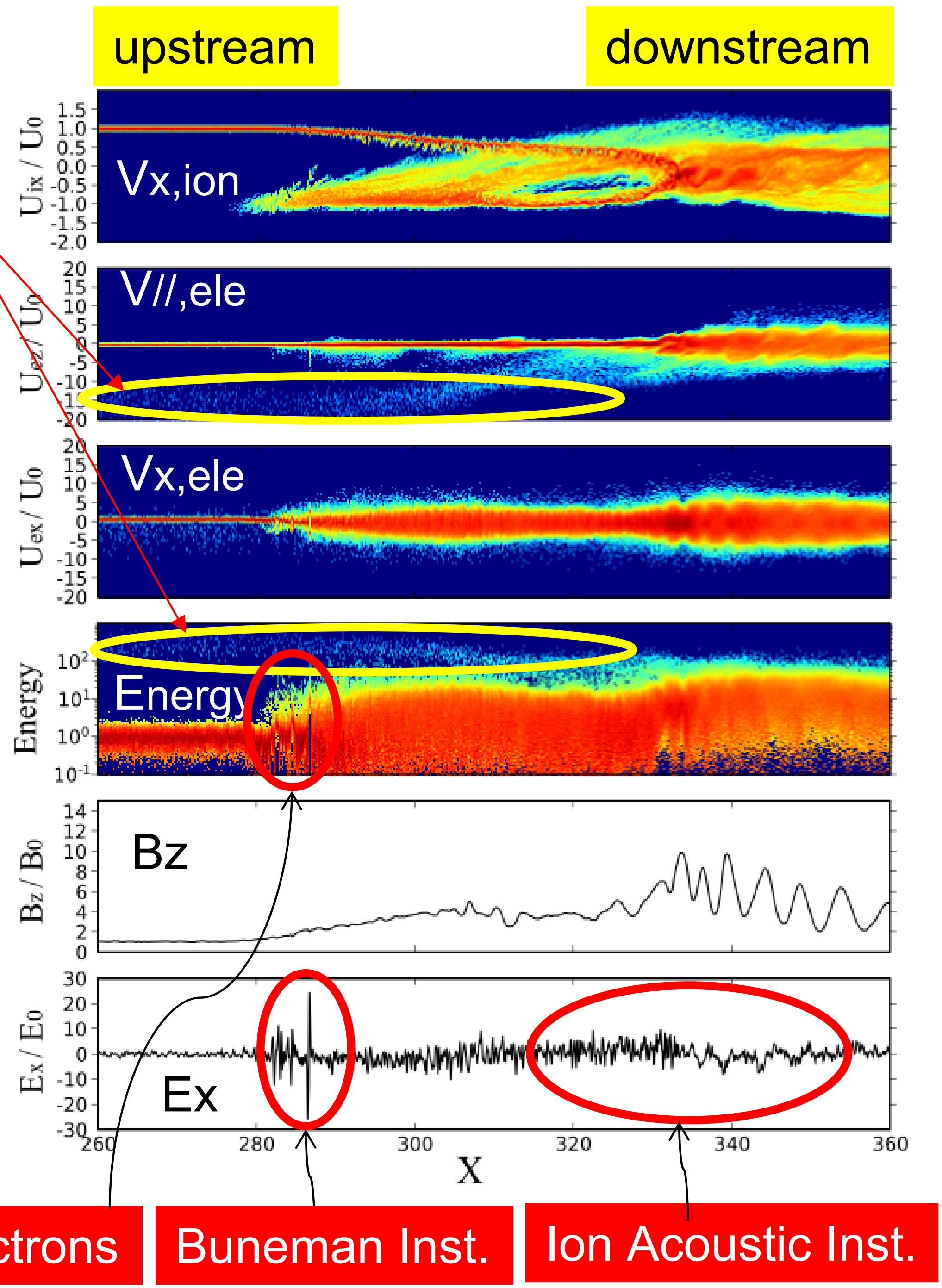


Amano & MH, ApJ 2009

Quasi-⊥ Shock (θ_{Bn}=80) & Injection

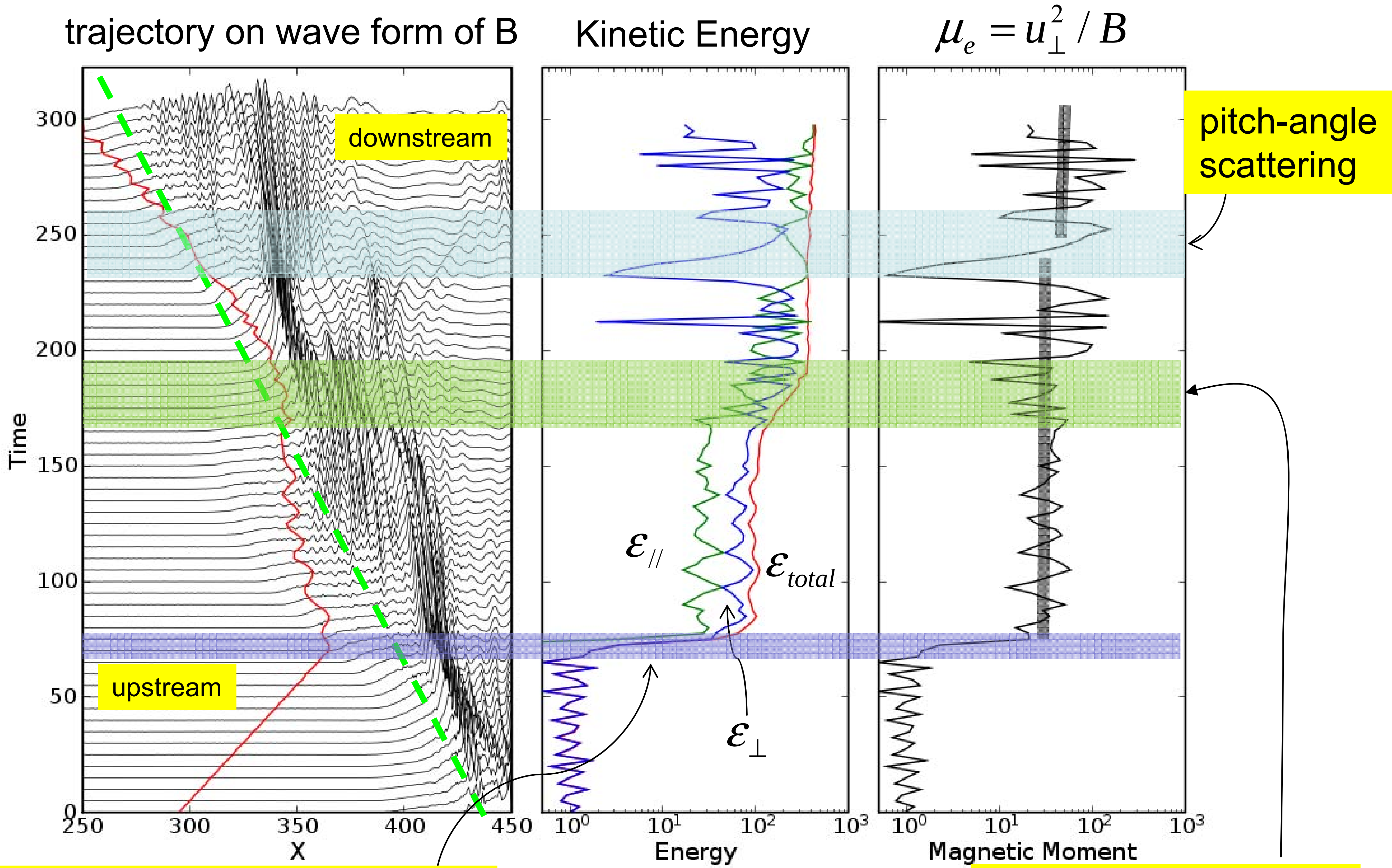
(M_a=15, ω_{pe}/ω_{ce}=20, m_i/m_e=100)





Amano & MH, ApJ 2007

Electron Trajectory near Shock Front



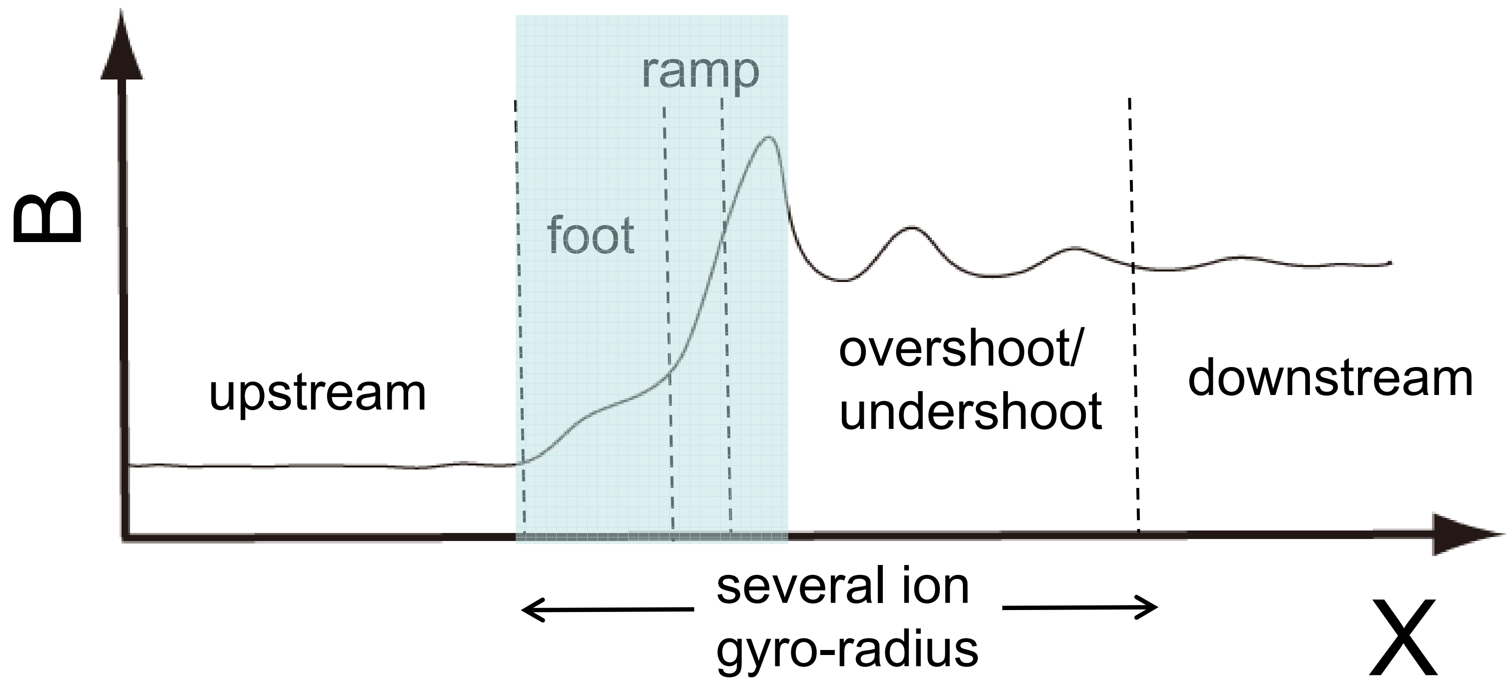
shock surfing (non-adiabatic)

MH & Shimada 2002

shock drift (adiabatic)

Wu et al., 1984, Leroy & Mangeney 1984

Electron Heating/Acceleration in High Mach Number, Quasi-   Shock

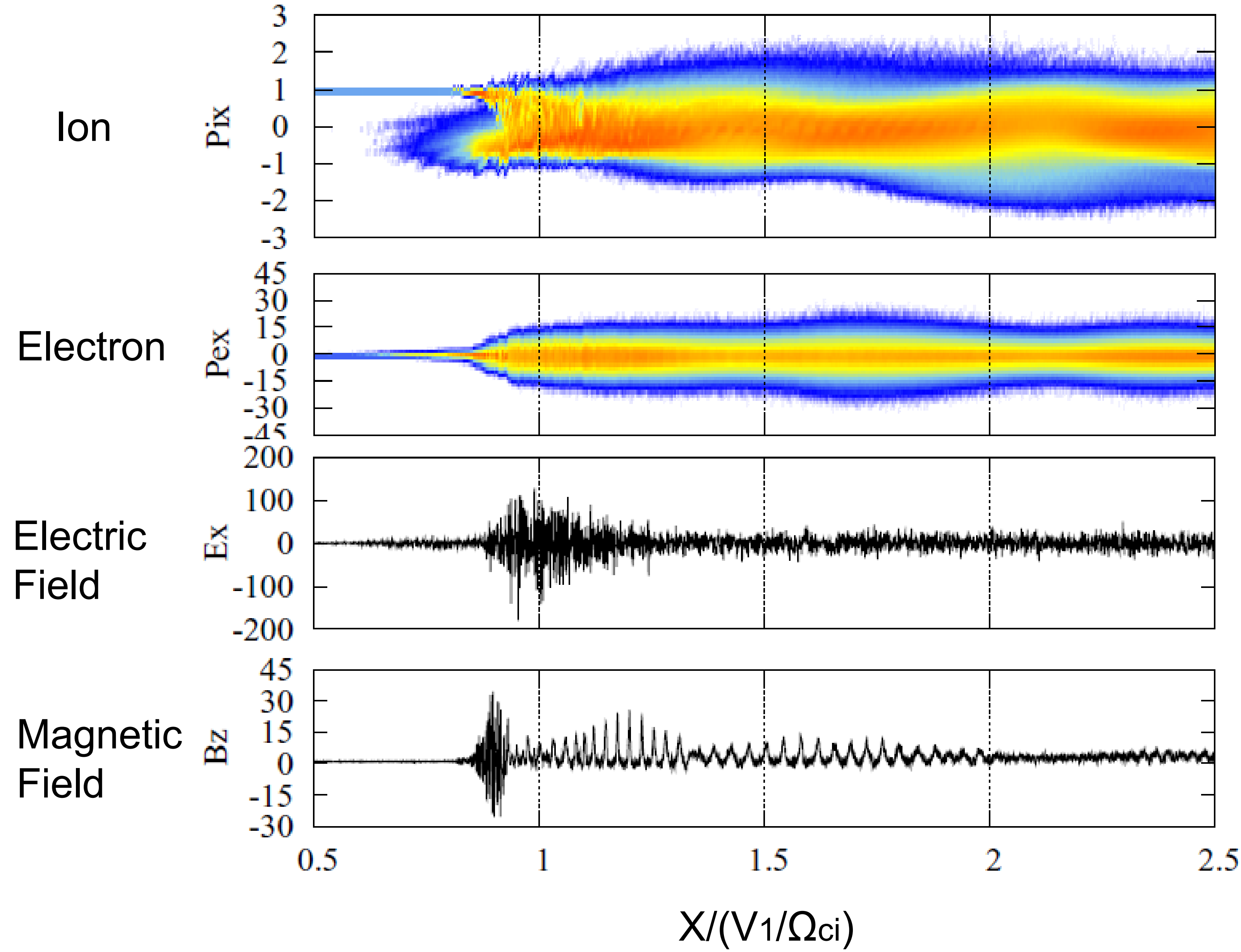


- Buneman Instability (BI) → Ion Acoustic Instability (IA) (with shock surfing and shock drift processes)

Very High Mach Number Shock (Ma=137)

$m_i V_1^2 \approx m_e c^2$ or $V_1 \approx 5000\text{km/s}$

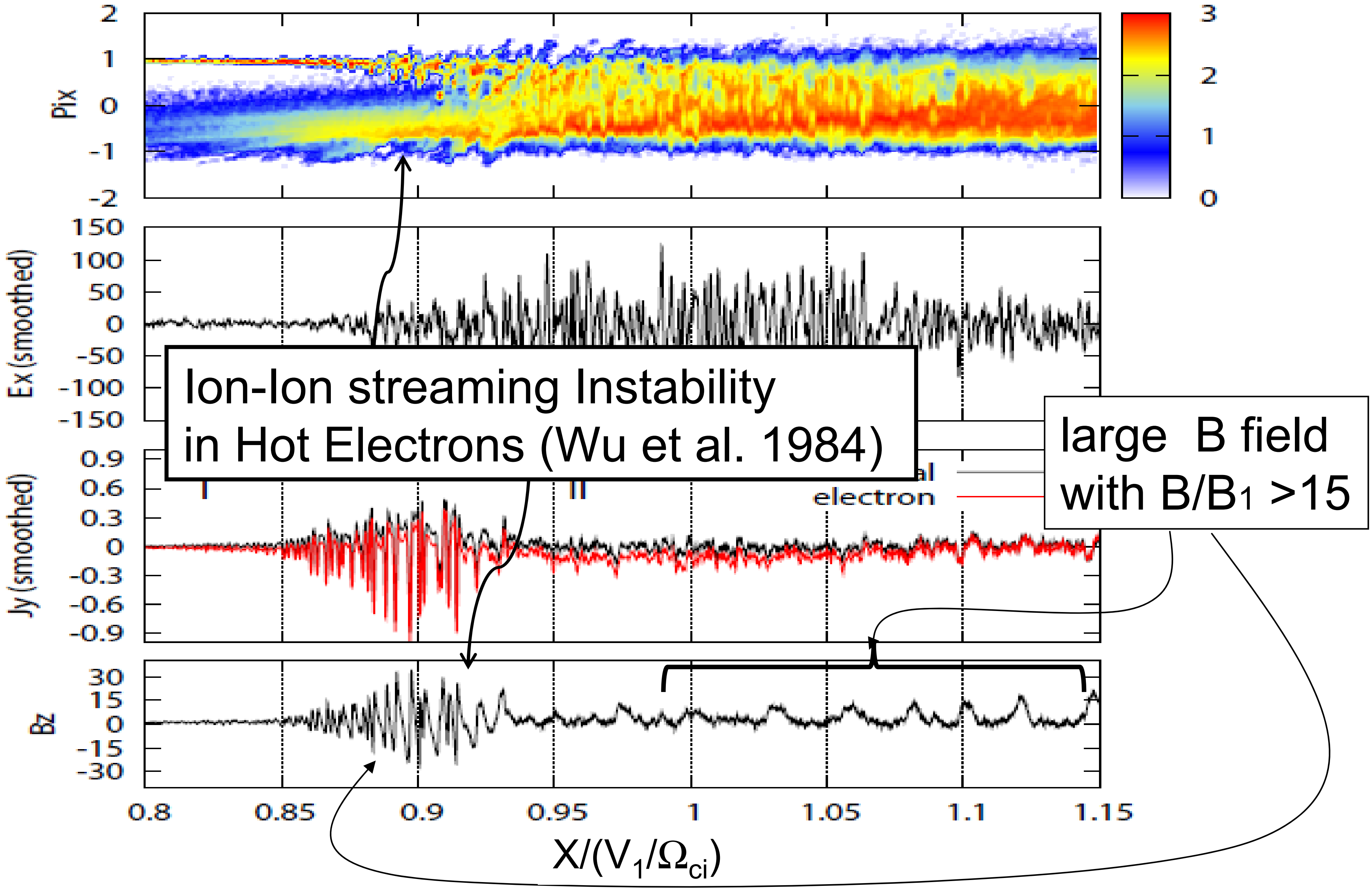
$\omega_{pe}/\omega_{ce}=100$, $m_i/m_e=100$



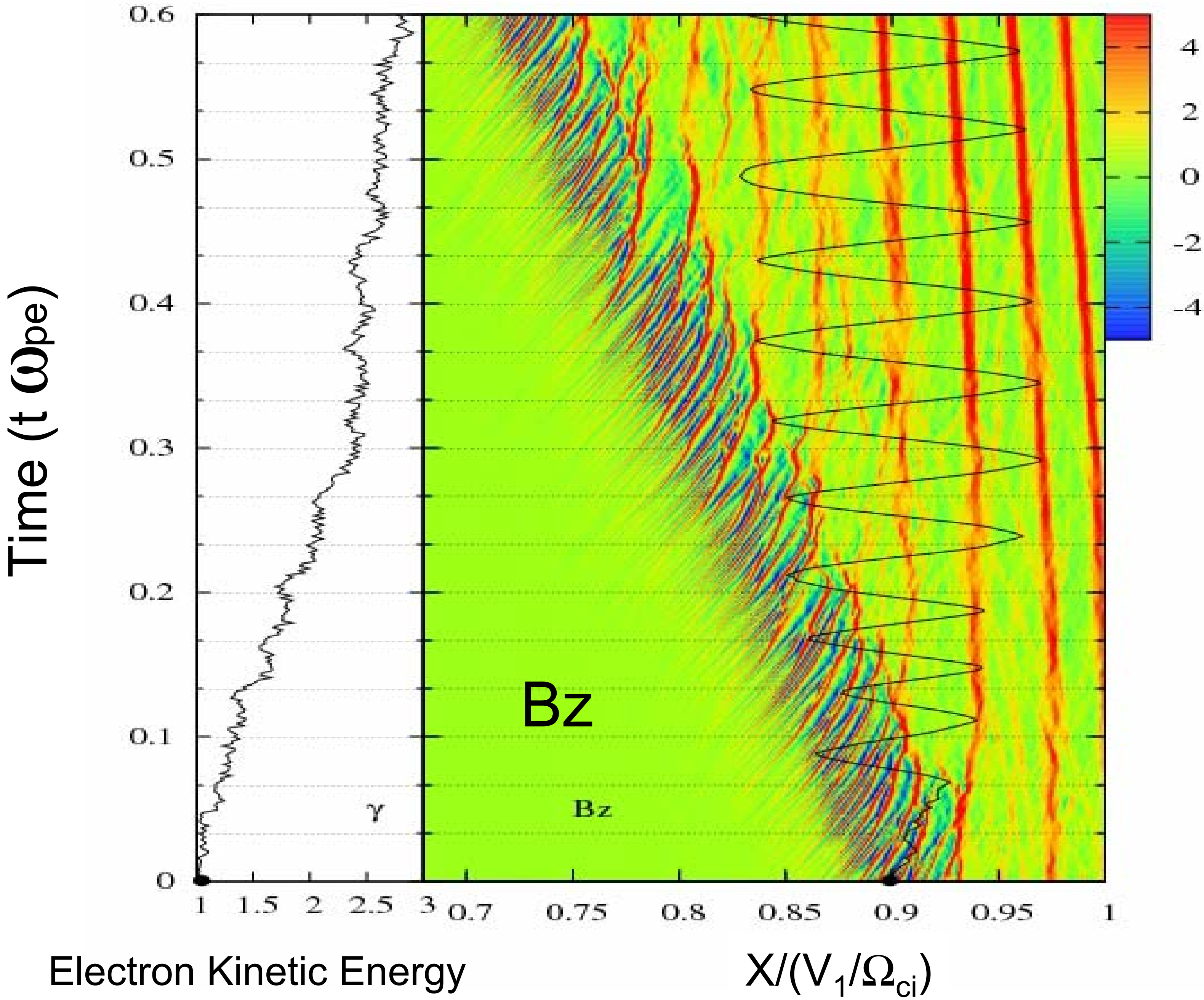
Strong Electron Heating (Te ~ Ti)

Large Amplitude Magnetic Fields

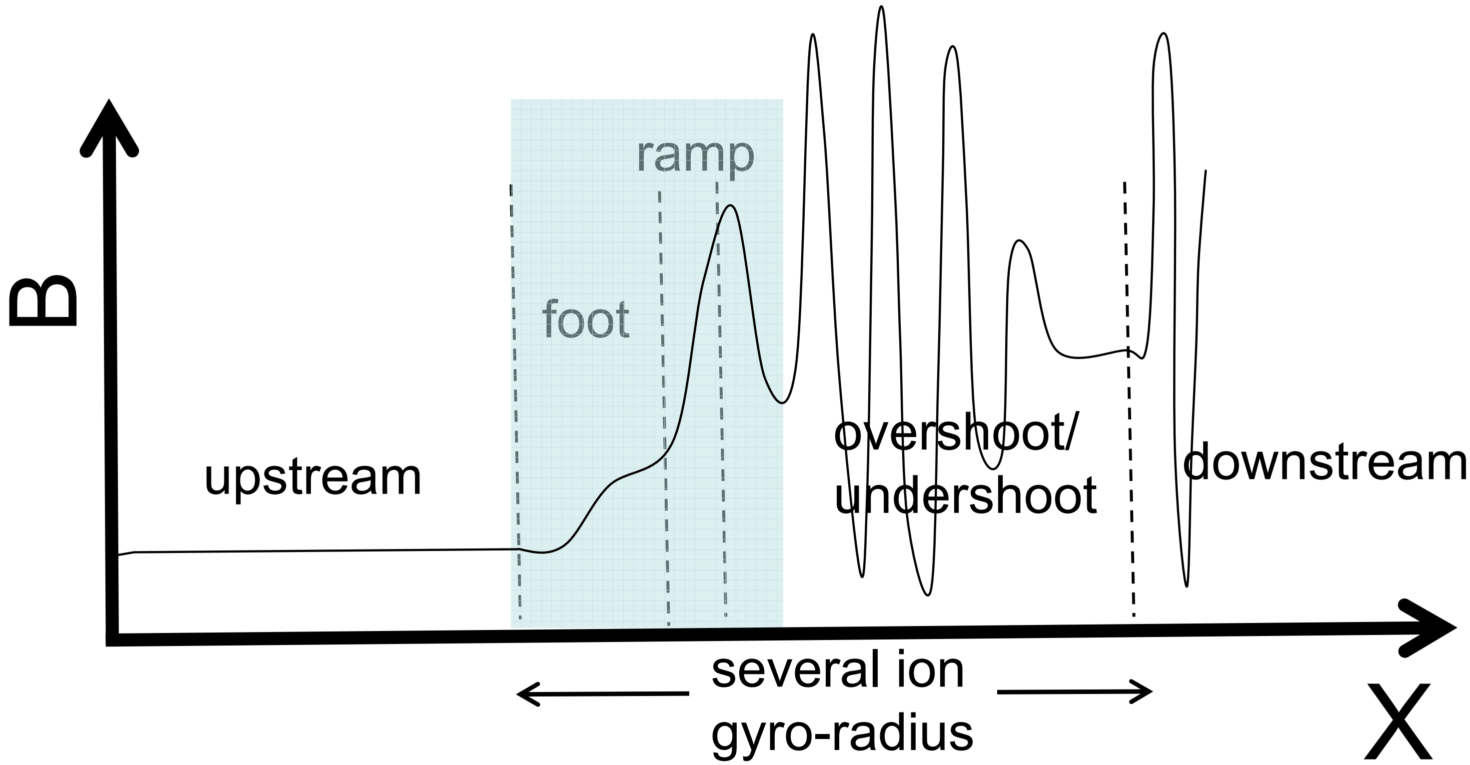
Magnetic Field Amplification



Fermi-like Acceleration



Electron Heating/Acceleration in Very High Mach Number Shock



- If $m_i V_1^2 \approx m_e c^2$ $(V_1 \approx 5000\mathrm{km/s})$,

  $\mathrm{BI} \rightarrow \mathrm{IA} \rightarrow$ Ion - Ion Streaming Inst. (with Fermi - like process)

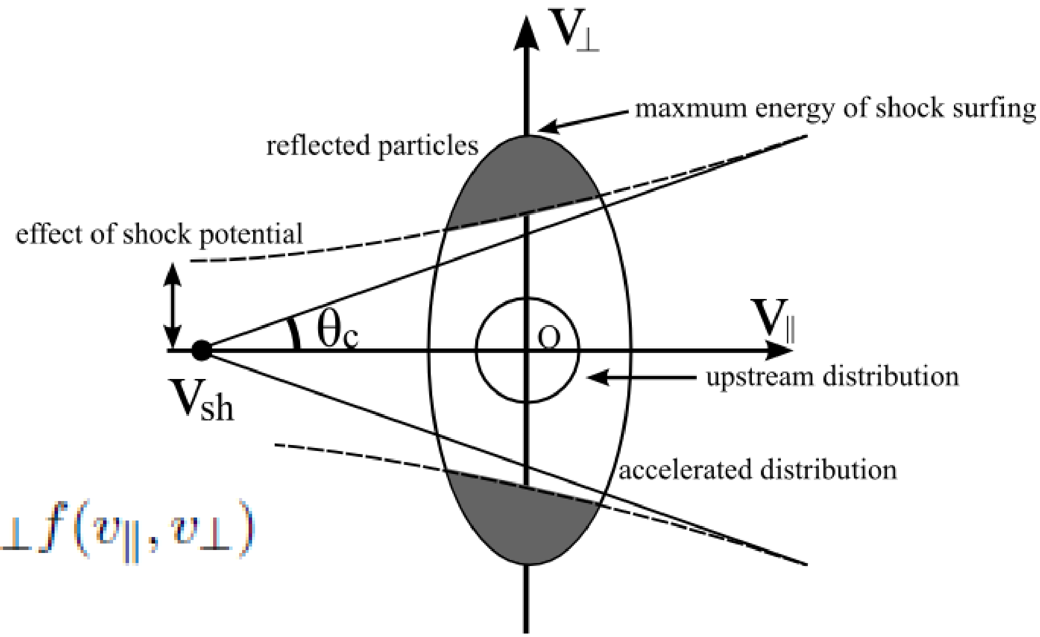
Electron Injection Model

- Shock Surfing & Drift Acceleration
  - thermal electron heating□ $T_e \sim m_e V_1^2$ [Papadopoulos 1988]
  - non-thermal electron: power law index = 3.5

  □ <u>bi-kappa distribution is assumed at overshoot</u>

$$f(v_\parallel, v_\perp) = \frac{n_{\rm foot}}{v_{e,\perp}^2 v_{e,\parallel}} \frac{\Gamma(\kappa+1)}{(\pi\kappa)^{3/2}\Gamma(\kappa-1/2)} \left[1 + \frac{1}{\kappa}\left(\frac{v_\perp^2}{v_{e,\perp}^2} + \frac{(v_\parallel - V_{sh})^2}{v_{e,\parallel}^2}\right)\right]^{-\kappa-1}$$

- Integrate distribution functior outside the loss cone (adiabatic approx.)



$$n_r = 2\pi \int_0^\infty dv_\parallel \int_{\sqrt{v_\parallel^2 + \frac{2e}{m_e}\phi^{HT}}\tan\theta_c}^\infty v_\perp dv_\perp f(v_\parallel, v_\perp)$$

Electron Injection Model
comparison with simulation

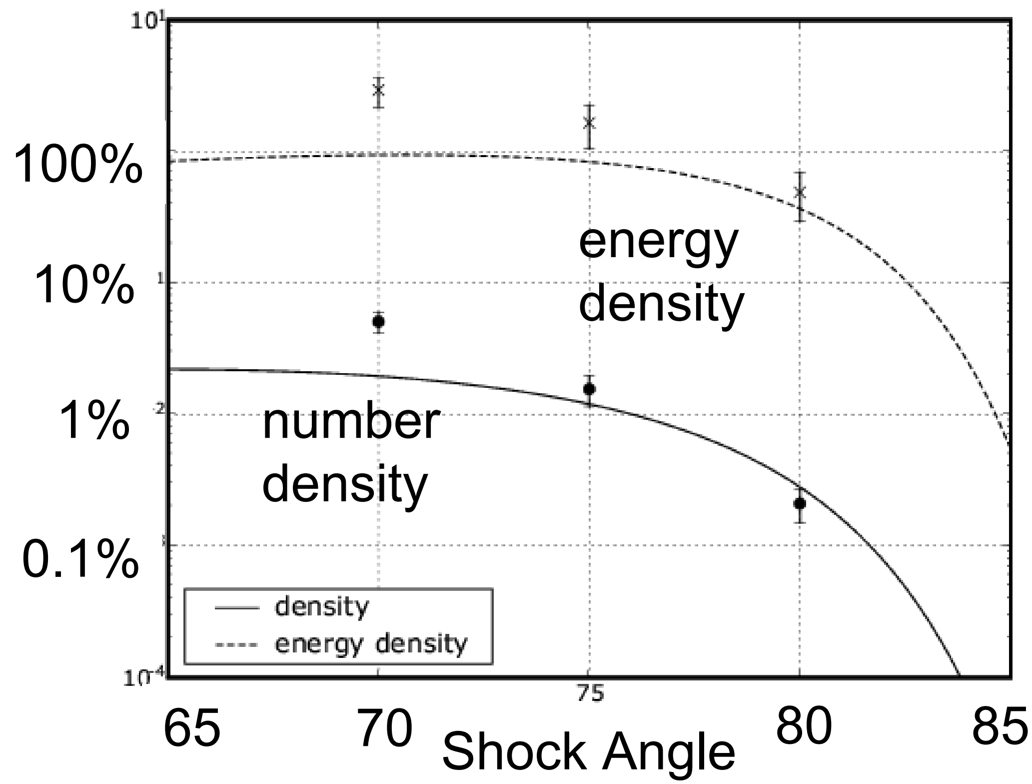
- free parameter
  - shock potential=0.4 K_{i0}
- minor corrections
  - escape probability

    probably related to

    (1) turbulence

    (2) shock non-stationarity
  - maximum energy of SSA

$m_i/m_e=100$



units

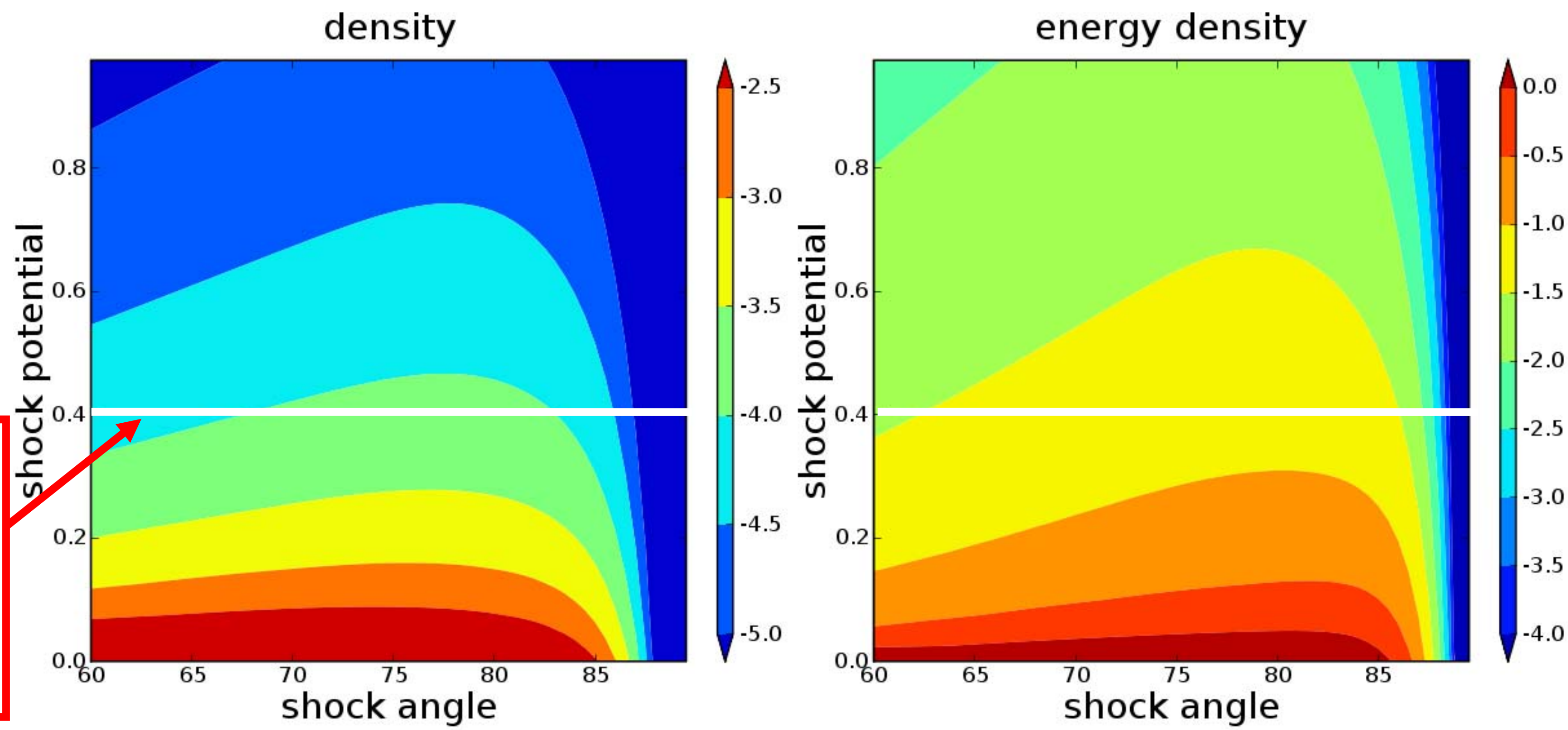
density : upstream density

energy density : bulk electron energy density

Application to SNR Shocks

- Real mass ratio shocks
  - shock potential, 40% of ion bulk flow energy
  - $60 \leq \theta_{Bn} \leq 85$
- Injection efficiency of ~ 10^{-4}
- Non-thermal/thermal energy of ~ 10^{-1}

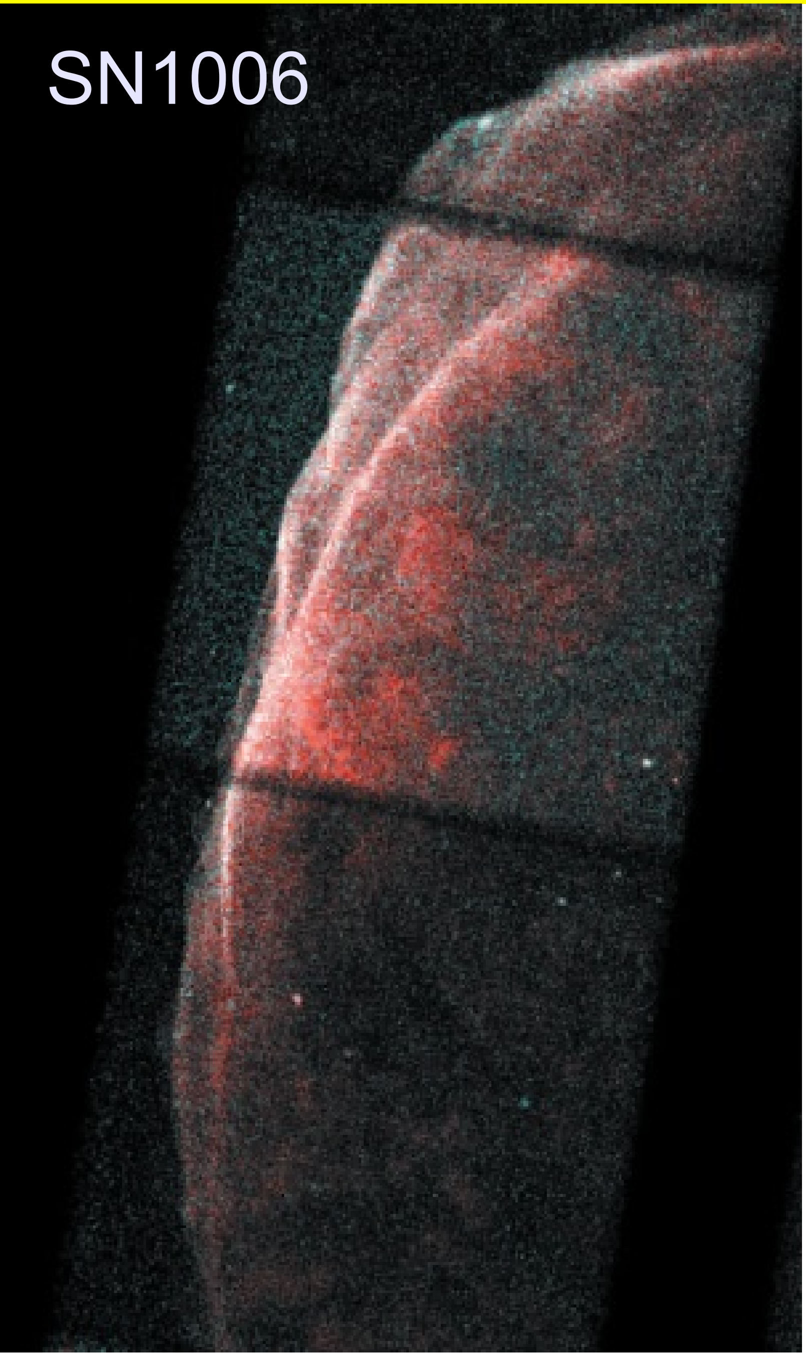
shock potential 40% of bulk ion energy



Amano & MH, ApJ 2007

Application to SNR Shocks

comparison between model and observation



- Observation [e.g. Bamba et al. 2003]
  - injection efficiency ~ 10^{-4}-10^{-3}
  - non-thermal / thermal energy ~ 30%
  - shock angle dependence $\theta_{Bn} \geq 80$
- Injection Model [Amano & MH 2007]
  - injection efficiency ~ 2×10^{-4} (peak)
  - non-thermal / thermal energy ~ 10%
  - peak appears at $75 \leq \theta_{Bn} \leq 80$

Summary

Injection of Electron Fermi Acceleration
for quasi-perpendicular shocks ($60 \leq \theta_{Bn} \leq 85$)

- injection efficiency ~ 10^{-4}
- non-thermal/thermal energy ~ 10^{-1}

Very High Mach Number Shock ($m_i V_1^2 > 500$keV)

- localized, amplified magnetic fields
- Fermi-like electron heating/acceleration
- effective temperature Te ~ Ti