# Surfing and Drift Acceleration of Electrons at High Mach Number Quasi-Perpendicular Shocks

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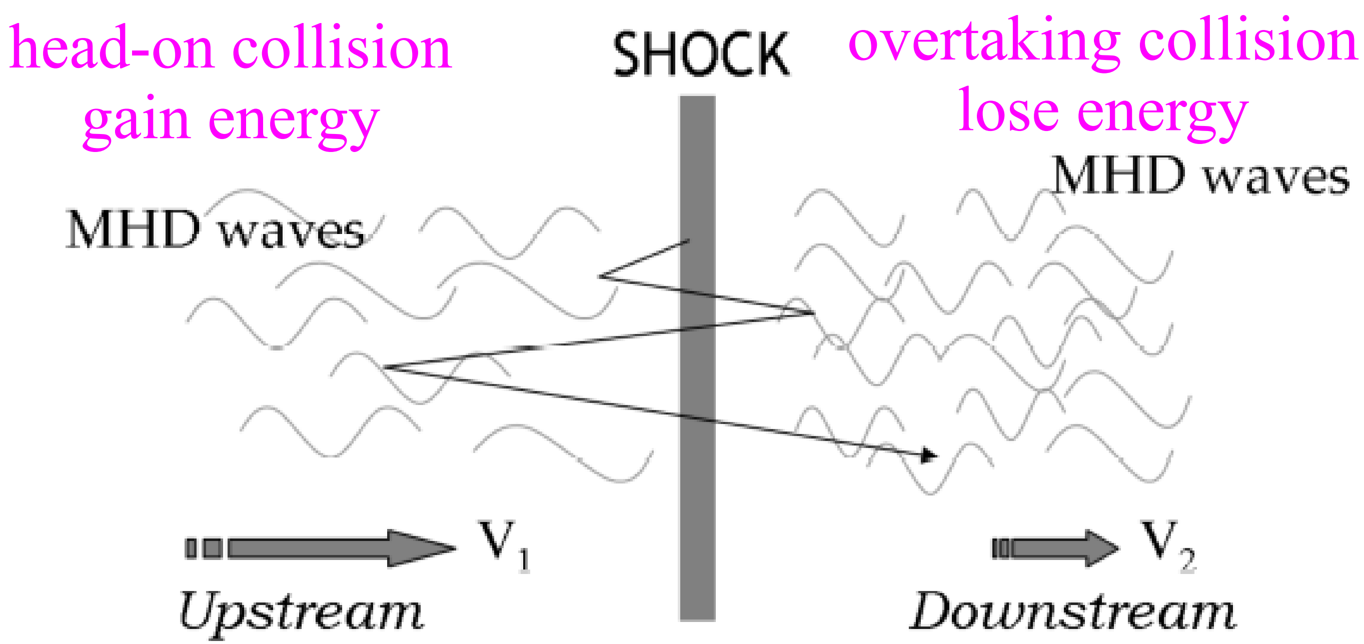
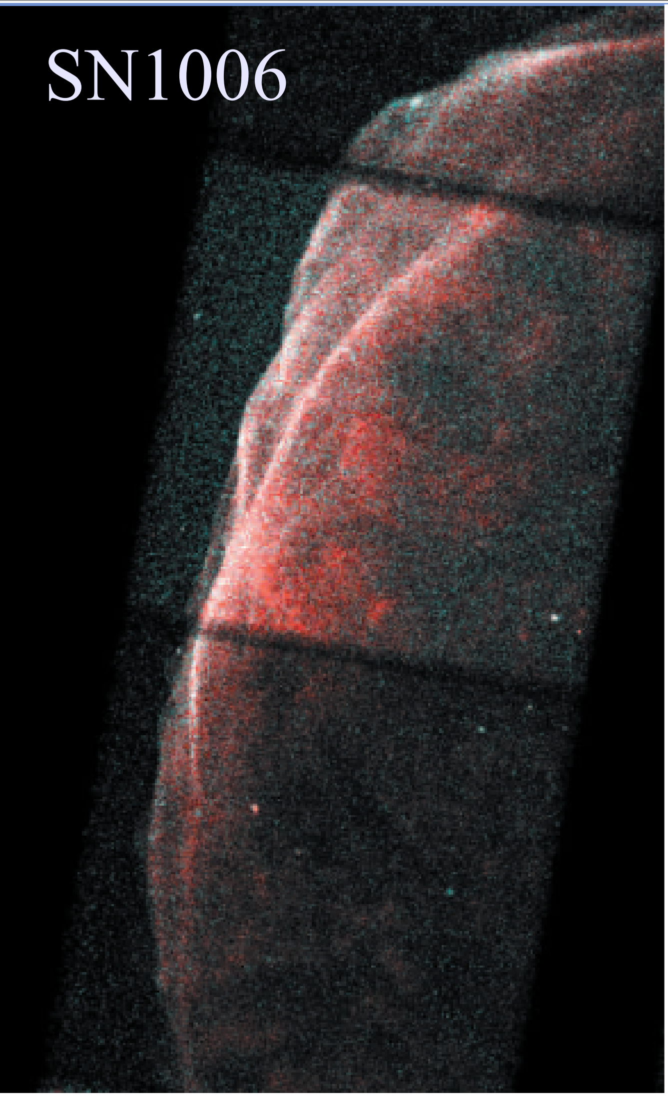
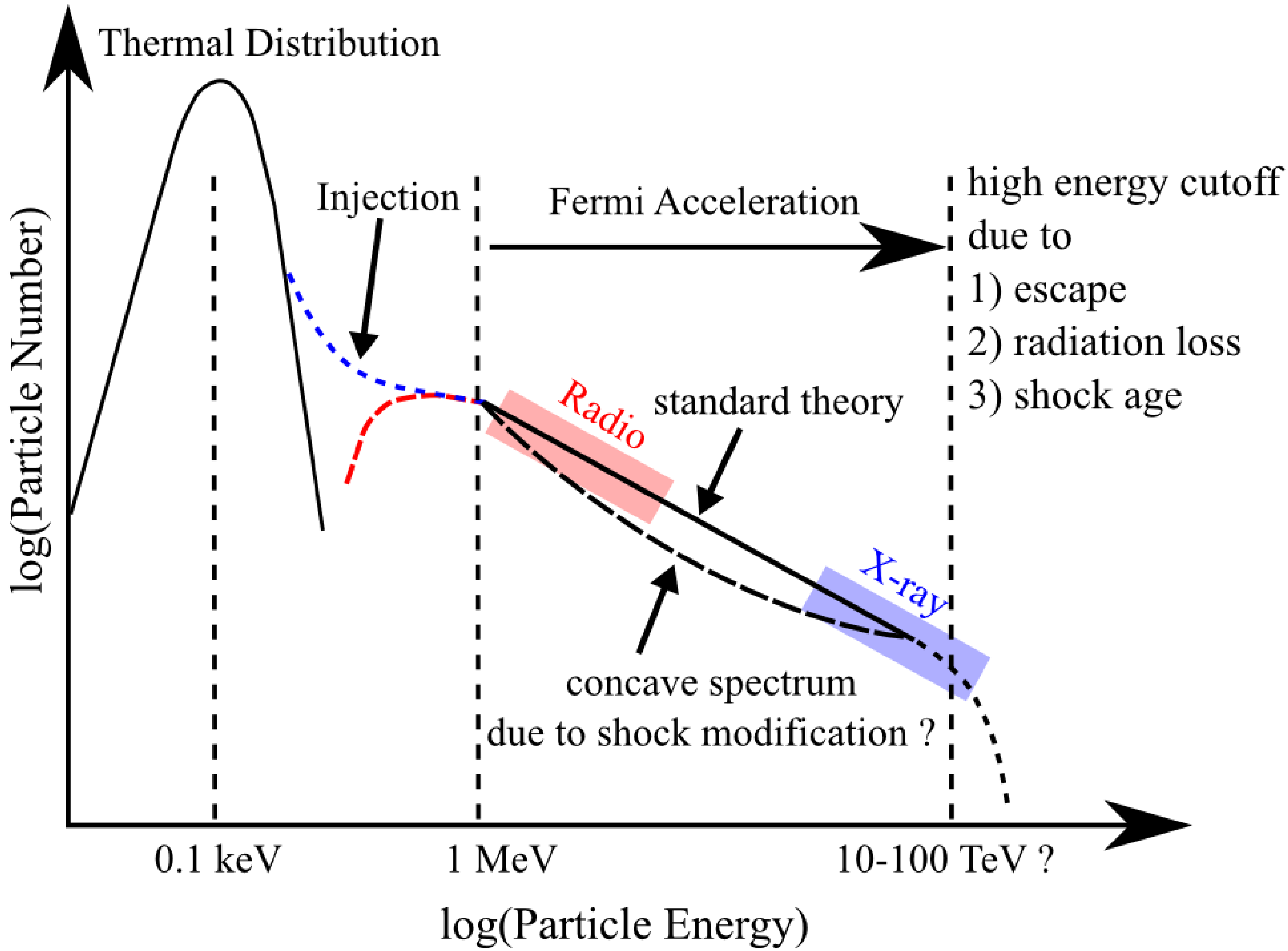
# Diffusive Shock Acceleration and the Injection Problem
[e.g., Bell 1978, Blandford & Ostriker 1978]

- DSA
  - particles gain energy by diffusively cross the shock front many times
- Injection Problem
  - escape condition : escape from downstream to upstream
  - resonance condition : resonantly scattered by MHD waves



# Evidence for Ultra-relativistic Electrons at SNR Shocks




Electron acceleration is typically efficient at SNRs (> TeV) while it is not at shocks in the heliosphere probably because of the difference in Mach numbers

# Electron Injection via Surfing and Drift Acceleration in Quasi-perpendicular Shocks [Amano & Hoshino ApJ, 2007]

- Does kinetic 1D PIC simulations can account for the electron injection to DSA ?
- Can we explain the observed injection efficiency at SNRs ?

# Quasi-Perpendicular Shock ($\theta_{Bn}$=80)
[Amano & Hoshino, 2007]

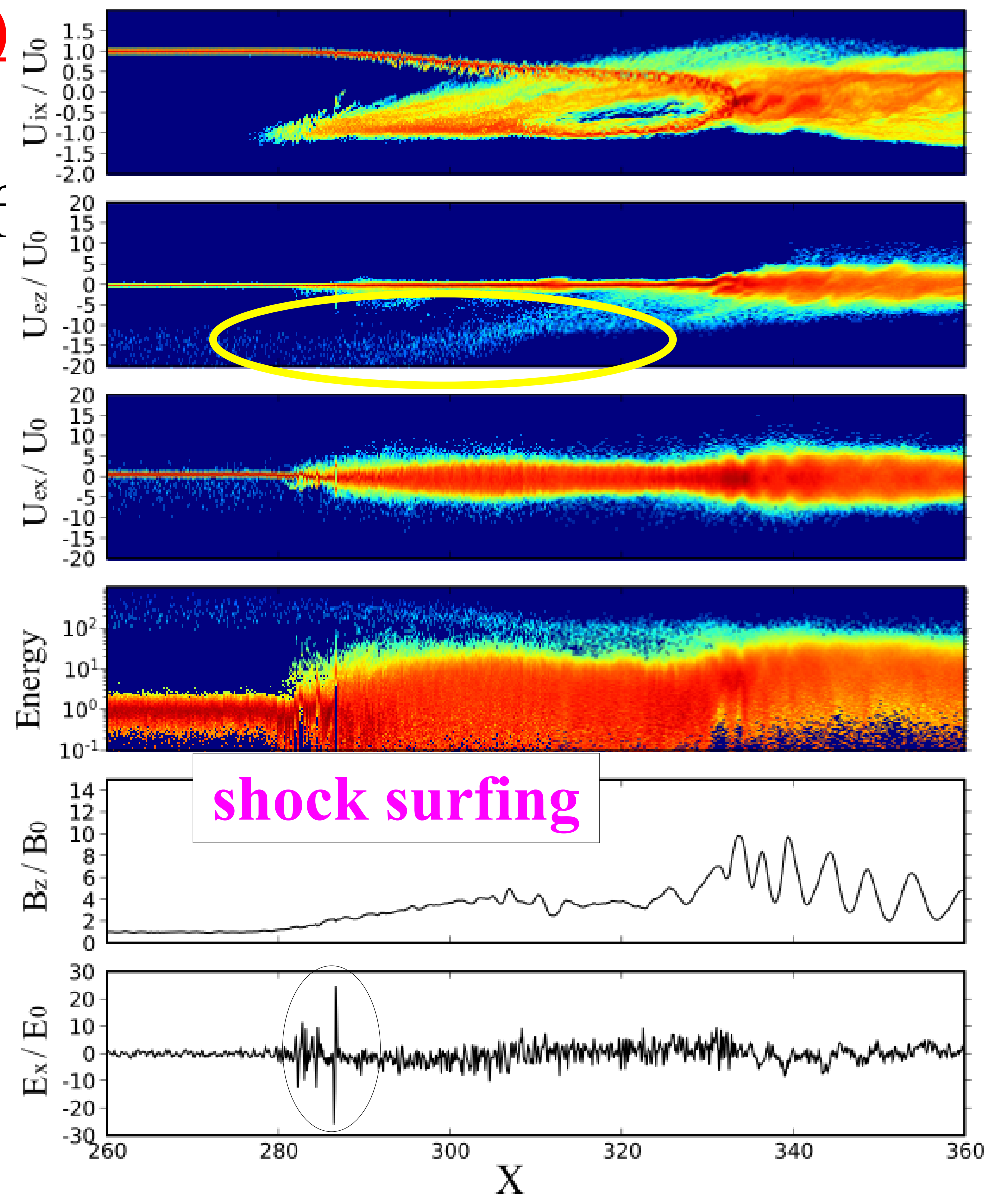
- Shock Surfing Acceleration (SSA)
  - Energetic electrons are generated at the leading edge of the foot

  [e.g., Hoshino & Shimada 2002]
- Shock Drift Acceleration (SDA)
  - further accelerated by the magnetic mirror reflection

  [Wu et al., 1984, Leroy & Mangeney 1984]

**Shock Parameter**

- $m_i/m_e$ = 100
- $\omega_{pe}/\Omega_{ce}$ = 20
- $\beta_i = \beta_e$ = 0.08
- $M_A$ ~ 15



# Trajectory of Energetic Electron

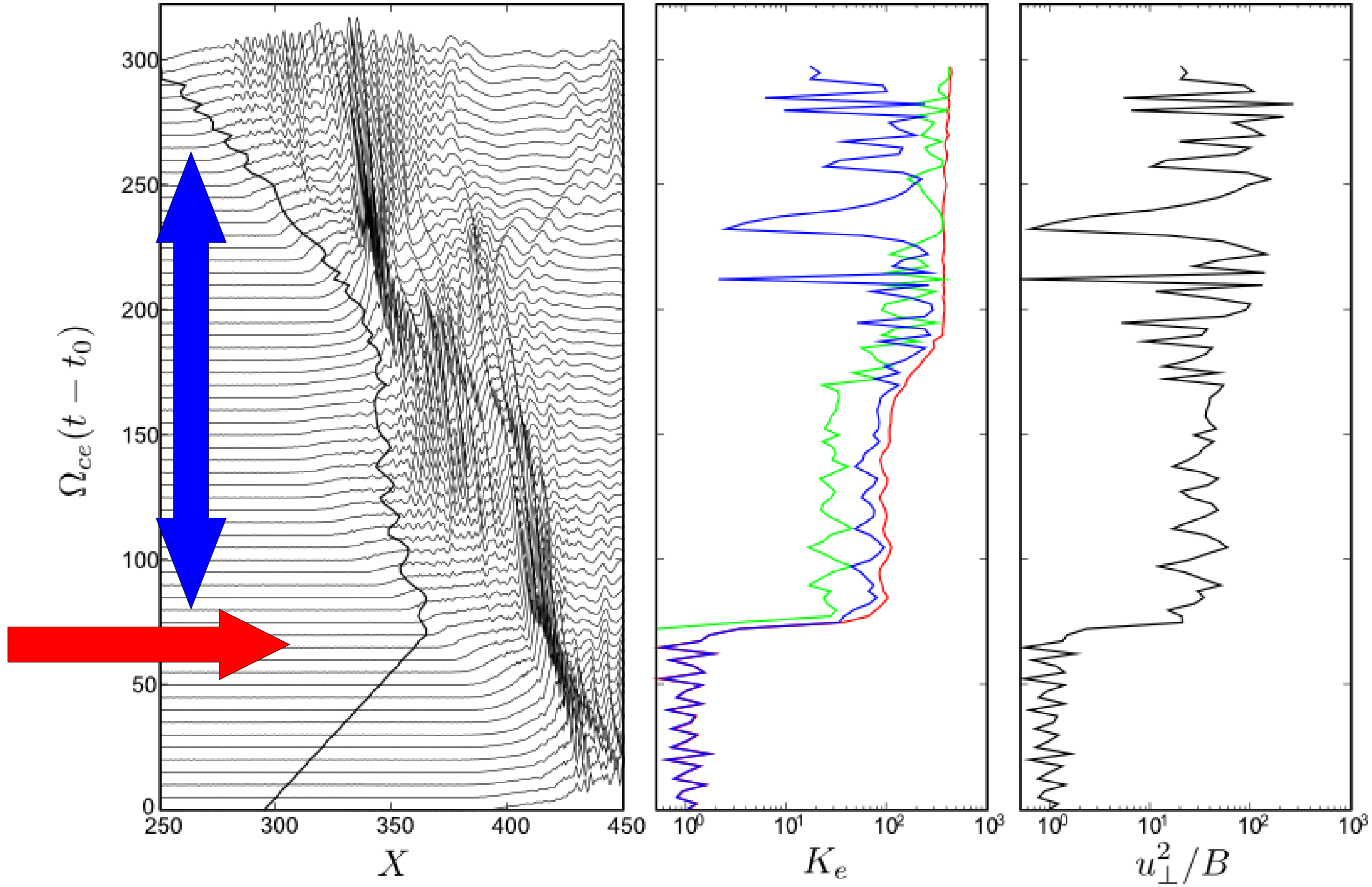
total,perp,para energy history

**Shock Drift**

(para. and slow ~ $\Omega_{ci}^{-1}$)

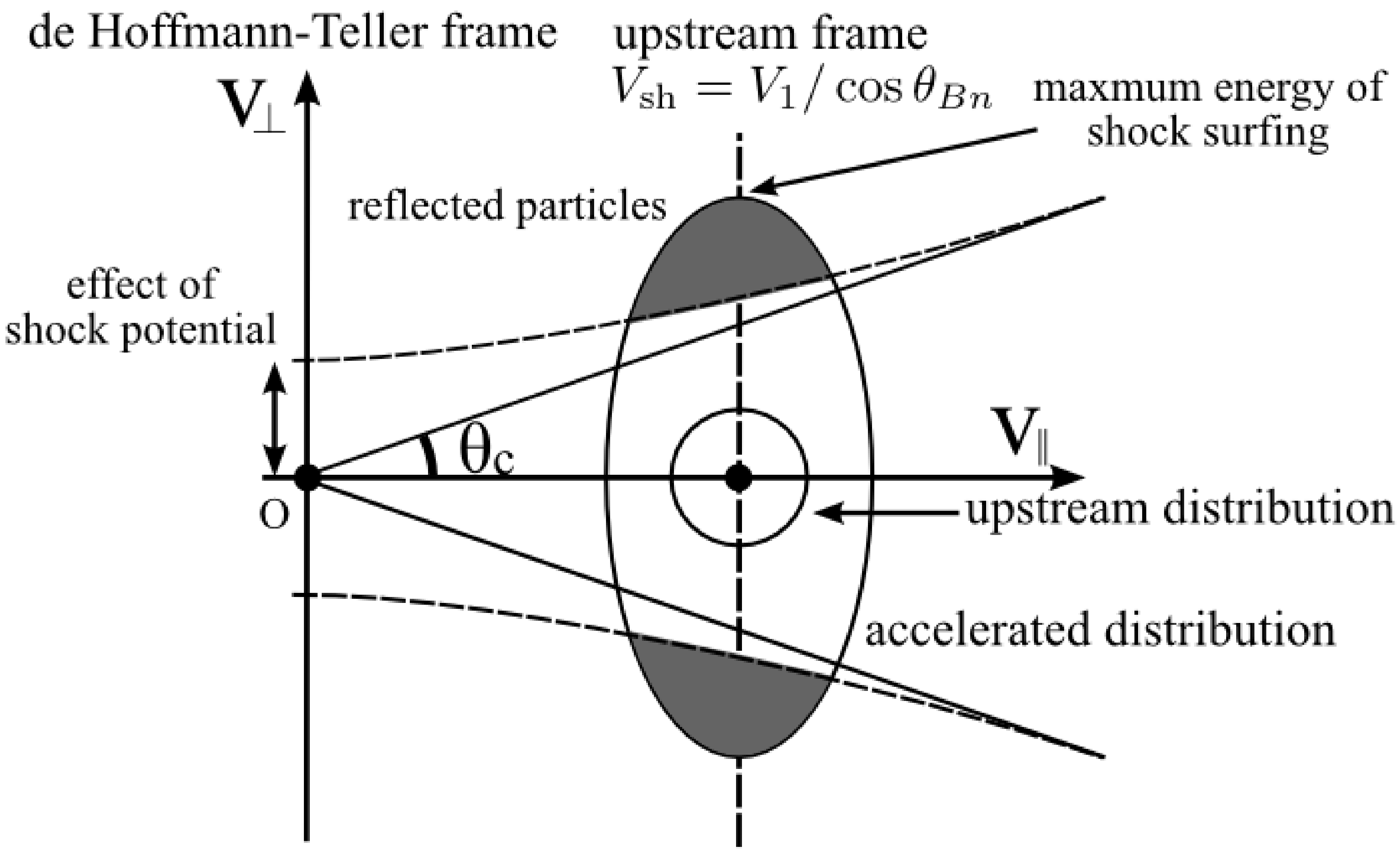
**Shock Surfing**

(perp. and fast ~ $\Omega_{ce}^{-1}$)




**The energy of reflected electrons is large enough for the injection when the Ma > 100 (depends on shock angle)**

# Interpretation: Surfing and Drift Acceleration

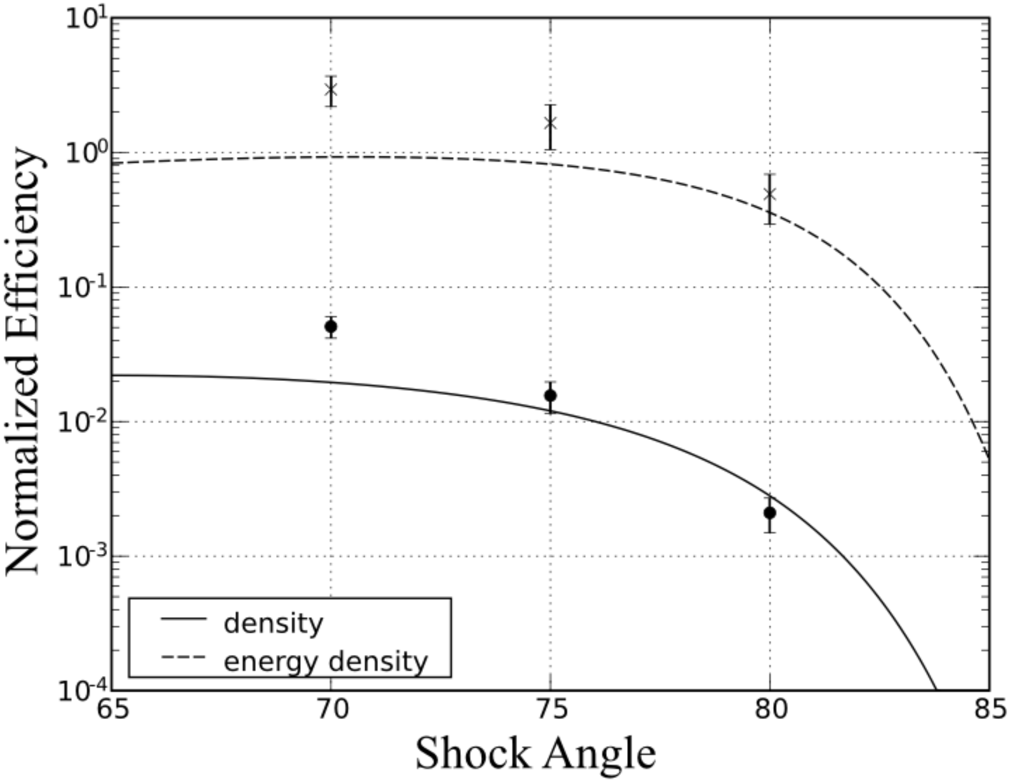



- non-adiabatic acceleration by SSA initiates SDA
- assuming the pre-accelerated distribution function, we can estimate the fraction of reflected electrons

# Electron Injection Model
## comparison with simulation

- free parameter
  - spectral index = 3.5
  - shock potential = 0.4 $K_{i0}$
- corrections
  - escape probability

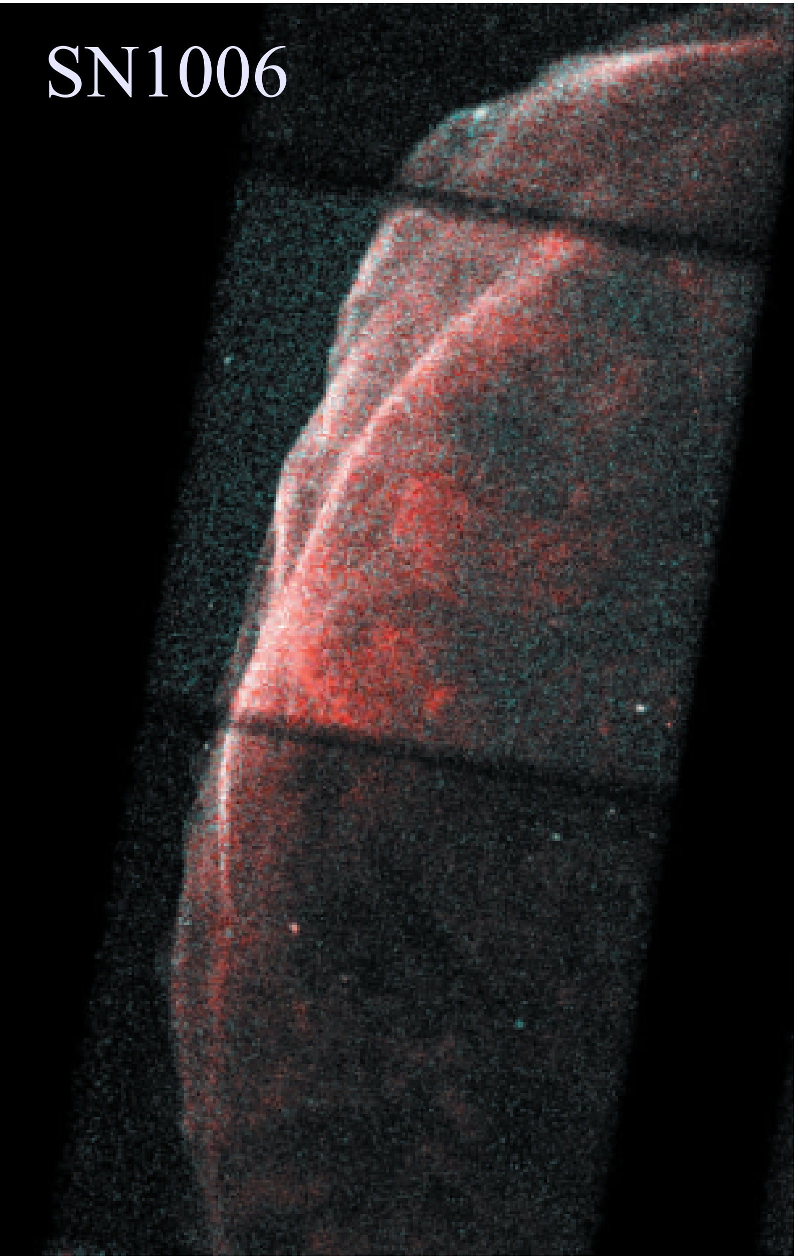
  probably related to the nonstationarity of the shock front
  - maximum energy of SSA (minor correction)




**units**

| | |
|---|---|
| density | : upstream density |
| energy density | : bulk energy density (ele) |
| $K_{i0}$ | : bulk ion energy |
| $K_{e0}$ | : bulk electron energy |

# Application to SNR Shocks
## comparison between model and observation



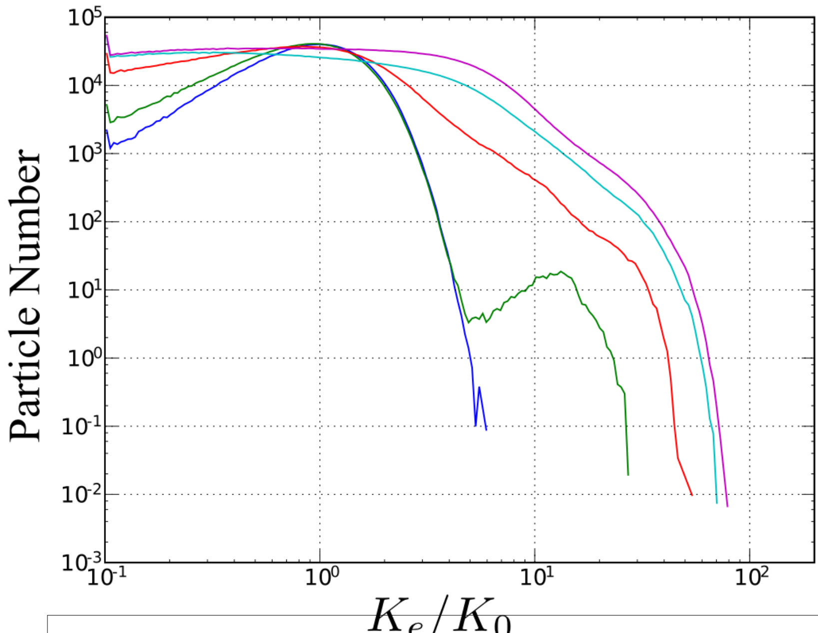

- Observation [e.g., Bamba et al. 2003]
  – injection efficiency ~ $10^{-4}$-$10^{-3}$
  – non-thermal / thermal energy ~ 30%
- Injection Model [Amano & Hoshino 2007]
  – injection efficiency ~ $2 \times 10^{-4}$ (peak)
  – non-thermal / thermal energy ~ 10%
  – peak appears at $75 \leq \theta_{Bn} \leq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

# Strong Electron Acceleration in 2D Perpendicular Shocks: Surfing Acceleration in Multidimensions [Amano & Hoshino ApJ, in press]

- Can the strong electron non-adiabatic energization (required for the injection) observed in 1D actually occur in multidimensions ? We here consider purely perpendicular shocks for simplicity.

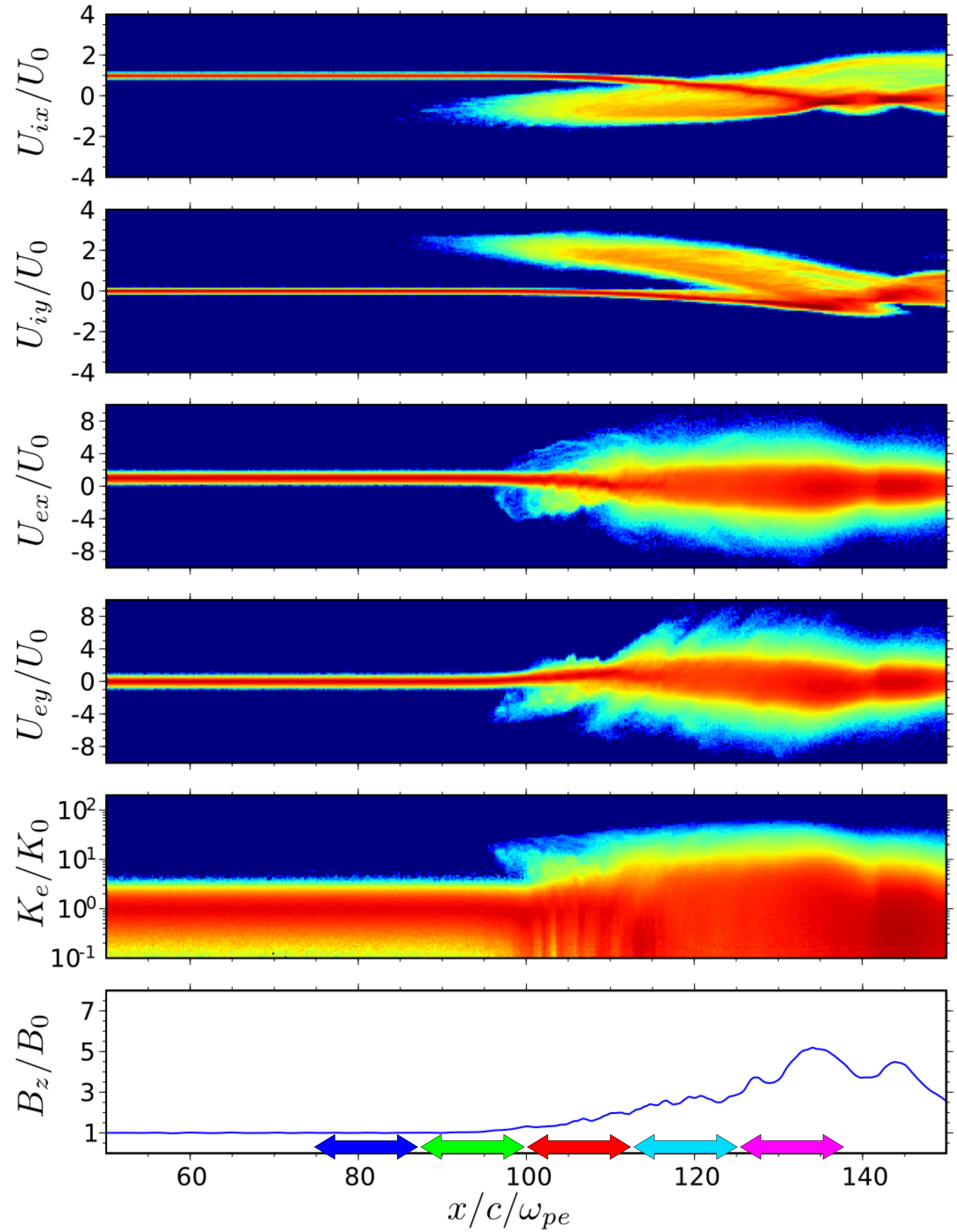
# Electron Acceleration

- strong electron acceleration is observed in the foot



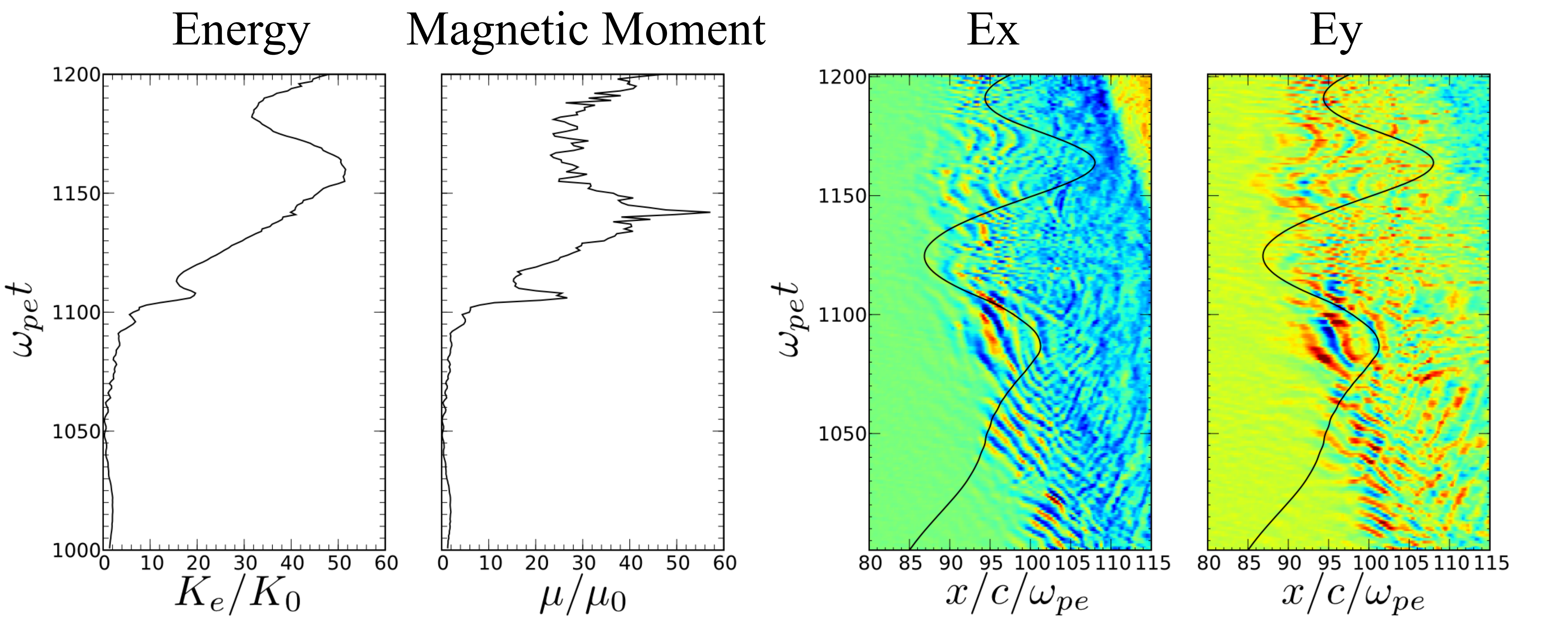

Shock Parameter

- $m_i/m_e$ = 25
- $\omega_{pe}/\Omega_{ce}$ = 10
- $\beta_i = \beta_e$ = 0.5
- $M_A$ ~ 14



# Trajectory Analysis

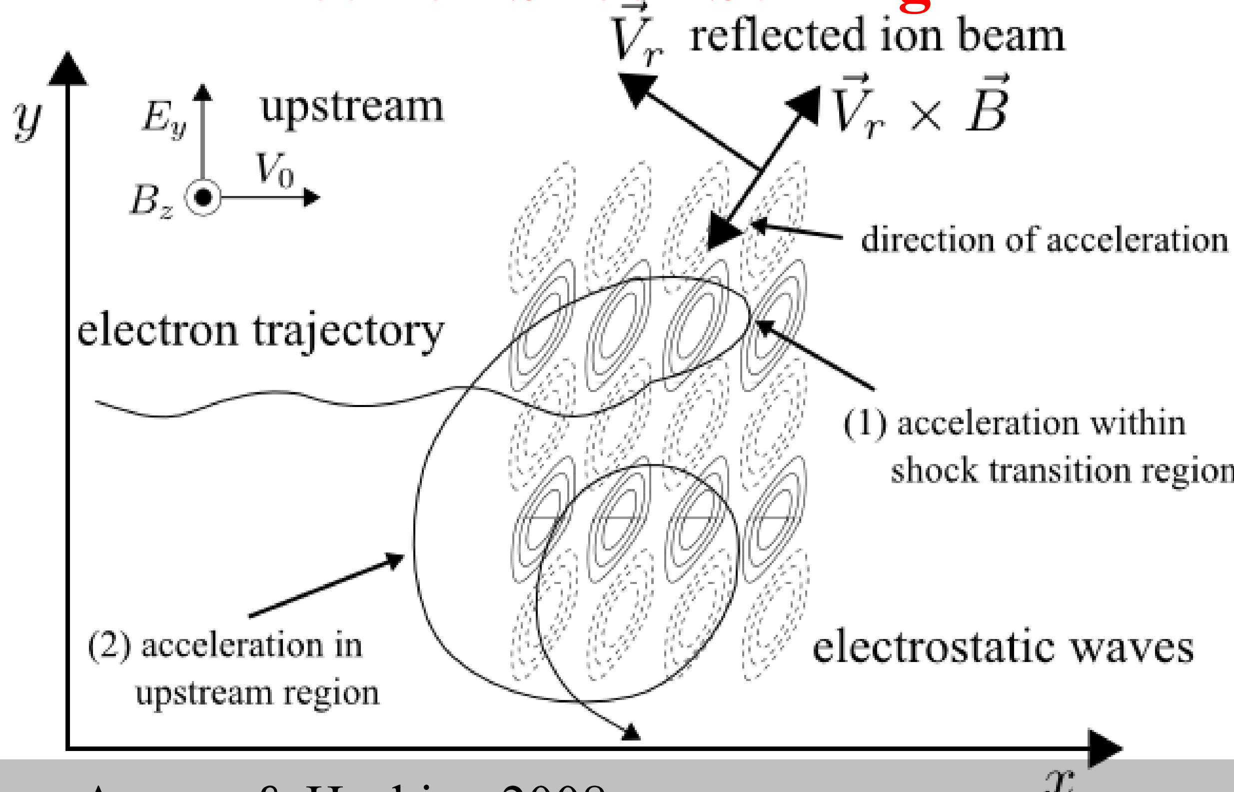
1. energized in the shock transition region, then reflected back upstream
2. accelerated by the constant motional E-field in the upstream



# Acceleration Mechanism

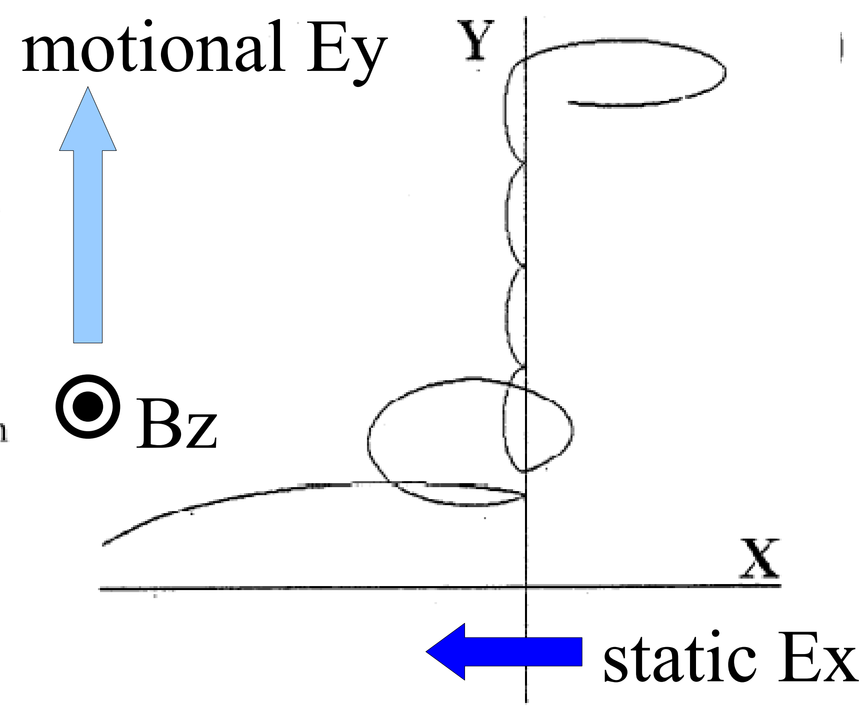
- electrons are reflected by turbulent, large amplitude ES waves excited by Buneman instability
- the mechanism is similar to the shock surfing of ions that are reflected by the macroscopic shock potential

**Electron Shock Surfing**




Amano & Hoshino 2008

**Ion Shock Surfing**




Zank et al. 1996

# Summary

- the problem of electron injection is still under active investigation, but will be revealed in near future
  - kinetic shock microphysics is actually of great importance
  - multidimensionality should be taken into account for the quantitative estimates of the injection efficiency
- the injection (of both protons and electrons) is a key ingredient for understanding of the nonlinear shock evolution in the presence of energetic particles
  - nonlinear evolution (or magnetic field amplification) will strongly depend on the number and energy densities of the injected energetic particles
  - interaction with upstream turbulence and the shock may also enhance the injection efficiency