The structure of the magnetic reconnection exhaust boundary

Yi-Hsin Liu @ LANL

Collaborators/PhD Advisors:
Jim Drake @ University of Maryland
Marc Swisdak @ University of Maryland

Current collaborators:
Bill Daughton @ LANL
Hui Li @ LANL

UNIVERSITY OF MARYLAND 18 56
DEPARTMENT OF PHYSICS UNIVERSITY OF MARYLAND

Los Alamos NATIONAL LABORATORY EST. 1943

What controls the acceleration of the plasma crossing into the reconnection exhaust?

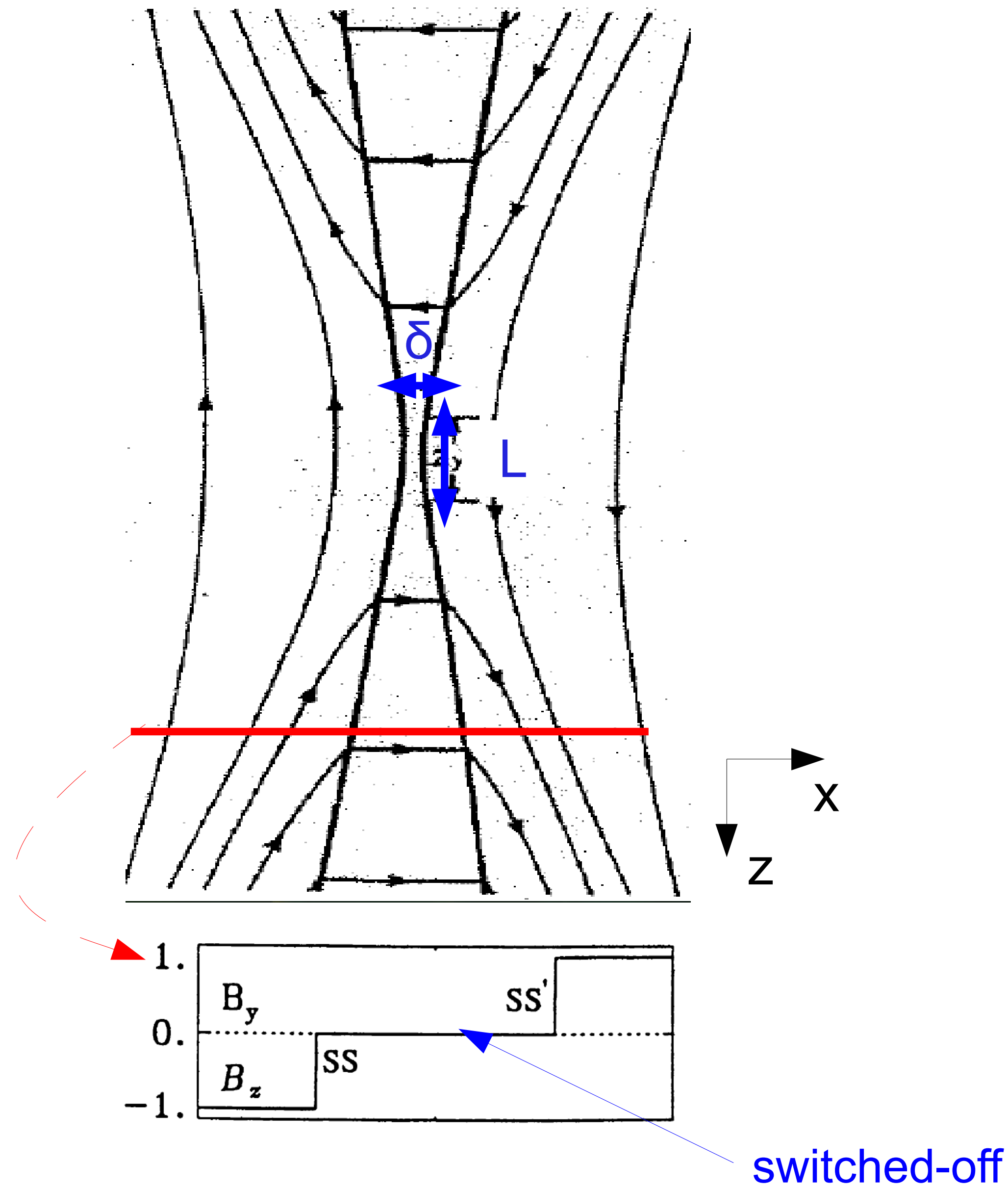
- Standing Switch-off Slow Shocks are the key to Petscheck's model.
  (Petschek 1964)
- X-ray emissions at solar flares are related to these slow shocks.
  (Tsuneta 1996, Longcope & Guidoni 2011)

What happens in collisionless plasmas?

- In-situ observations of Switch-off Slow Shocks are rare.
  (Seon et al. 1996)
- No Switch-off Slow Shocks seen in kinetic reconnection simulations (hybrid & PIC).
  (Lottermoser, Scholer & Matthews 1998, Lin & Swift 1996)
- Strong firehose-sense temperature anisotropy ($T_{||} > T_{per}$) due to the counter-streaming ions.
  (Gosling et al. 2005, Hoshino et al. 1998)

→ Q: if not Switch-off Slow Shocks, what is bounding the reconnection exhausts?

Petscheck 101



Structure of the reconnection exhaust

- Petschek-like open exhaust
- NO Switch-off Slow Shocks

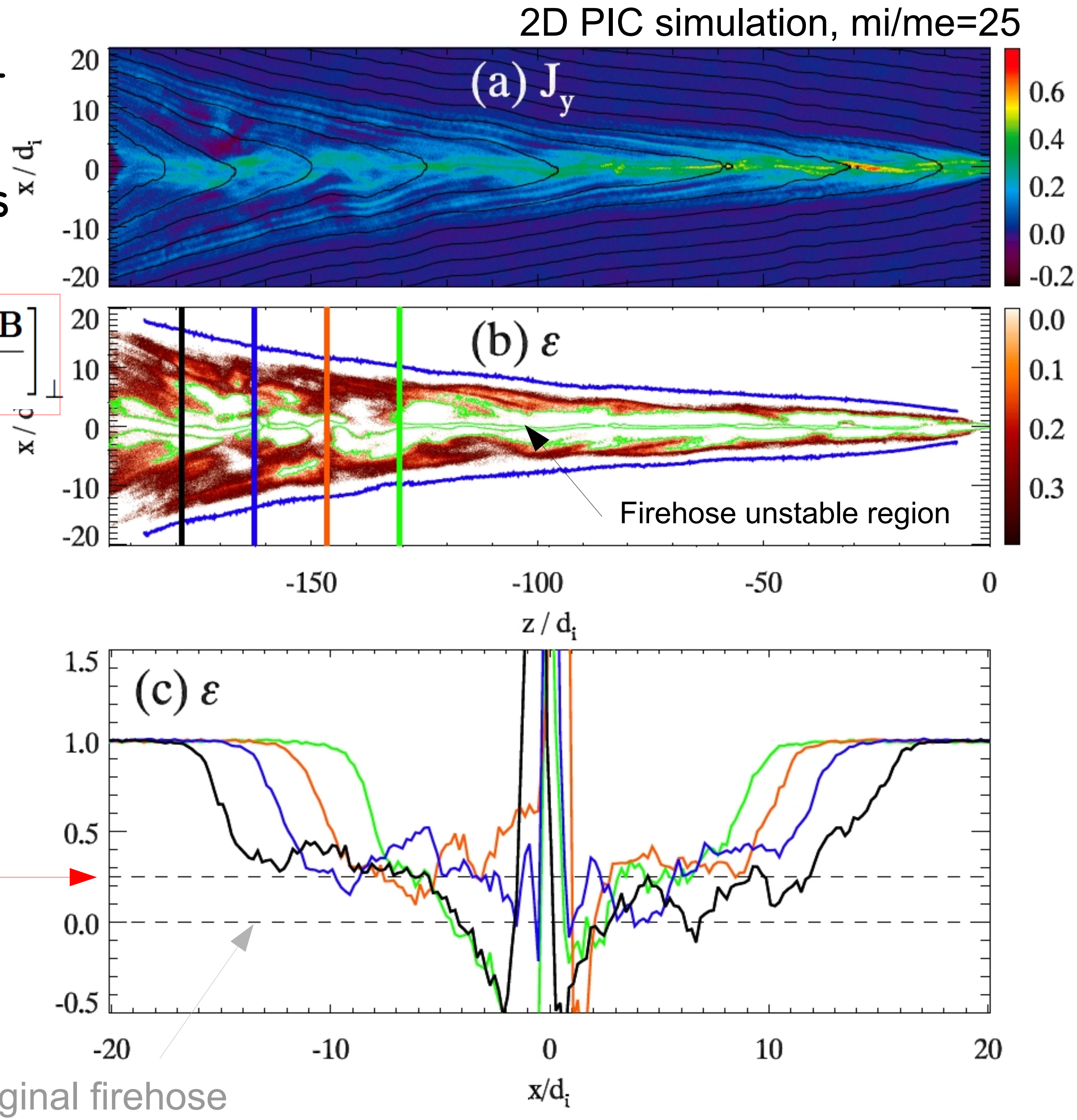
ε weakens the magnetic tension

$$\rho\left(\frac{d\mathbf{V}}{dt}\right)_{\perp}+\nabla_{\perp}\left(p_{\perp}+\frac{B^2}{2\mu_0}\right)=\varepsilon\left[\frac{(\mathbf{B}\cdot\nabla)\mathbf{B}}{\mu_0}\right]_{\perp}$$

- Firehose unstable near the symmetry line
- Outflow exhibits plateau formation around

$$\varepsilon\equiv 1-\frac{P_{\parallel}-P_{\perp}}{B^2/\mu_0}=0.25$$

WHY??

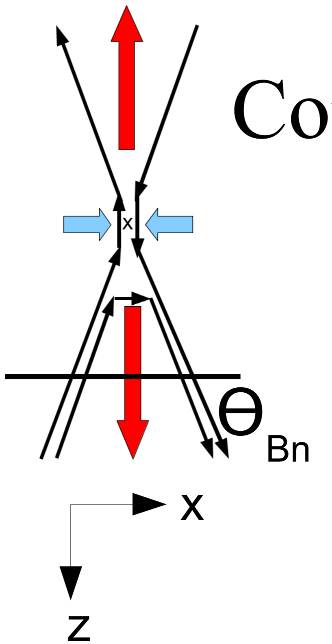


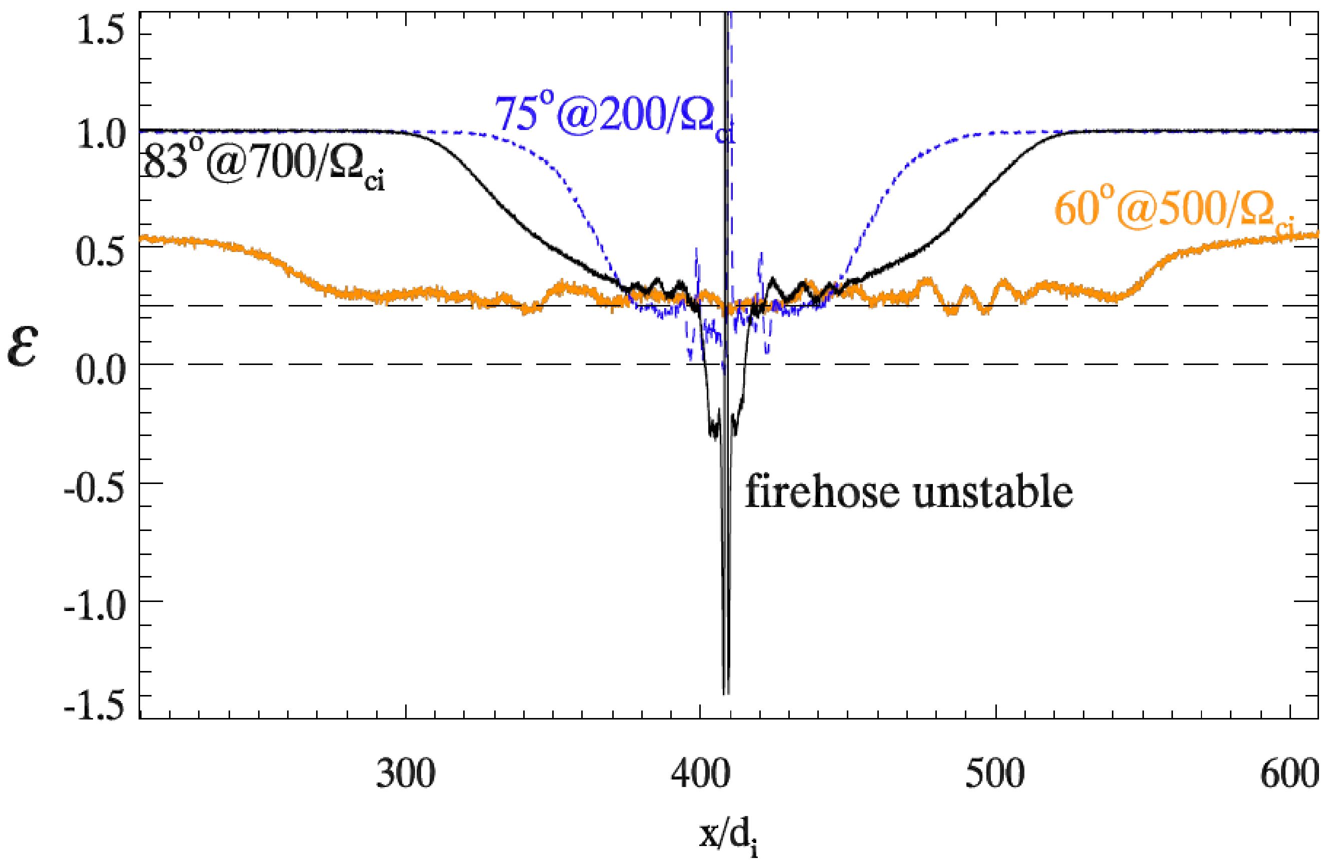
Development of long reconnection exhaust

mi/me=25

- Long Petschek-like open exhaust.
- Short (di) scale waves are radiated from the center.

Companion Riemann Problems show similar plateaus





0.25 !

- ε plateaus at 0.25 when shock is oblique enough.
- ε = 0.25 is always associated with the onset of rotational waves behind a slow shock! Why?

$$\varepsilon \equiv 1 - \frac{P_{\|} - P_{\perp}}{B^2/\mu_0}$$

Anisotropic Rankine-Hugoniot Jump Conditions

(Chao 1970, Hudson 1970)

Continuity:

$$[\rho V_x]_d^u = 0$$

Momentum:
(normal)

$$\left[\rho V_x^2 + P + \frac{1}{3}\left(\varepsilon + \frac{1}{2}\right)\frac{B^2}{\mu_0} - \varepsilon\frac{B_x^2}{\mu_0}\right]_d^u = 0$$

Momentum:
(transverse)

$$\left[\rho V_x \mathbf{V}_t - \varepsilon\frac{B_x \mathbf{B}_t}{\mu_0}\right]_d^u = 0$$

Energy:

$$\left[\left(\frac{1}{2}\rho V^2 + \frac{5}{2}P + \frac{1}{3}(\varepsilon - 1)\frac{B^2}{\mu_0}\right)V_x - (\varepsilon - 1)\frac{B_x\mathbf{B}_t}{\mu_0}\cdot\mathbf{V}_t - (\varepsilon - 1)\frac{B_x^2}{\mu_0}V_x + Q_x\right]_d^u = 0$$

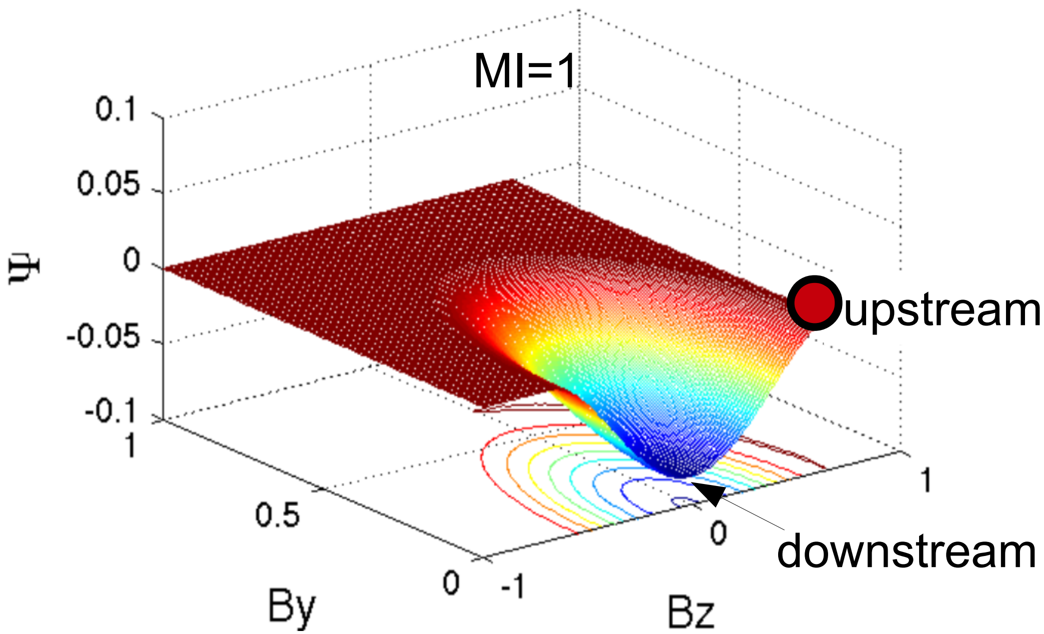
Heat flux

@ DeHoffmann-Teller frame

$$\varepsilon \equiv 1 - \frac{P_\parallel - P_\perp}{B^2/\mu_0}$$

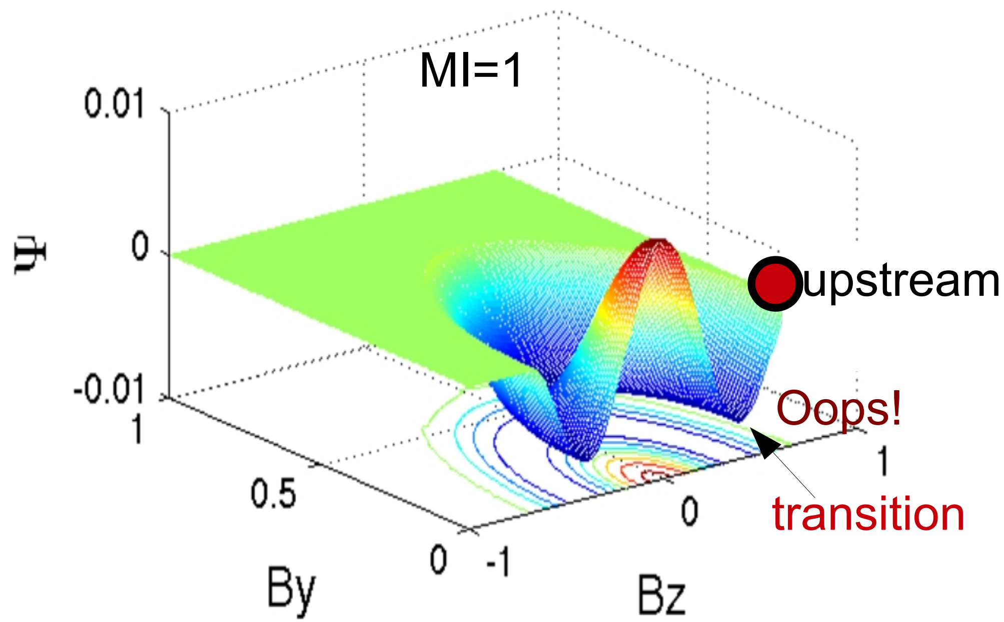
The analysis of shock Pseudo-Potential
(From Switch-off Slow Shocks to compound SS/RD waves)

Isotropic fluid theory



→ Switch-off Slow Shock (SSS)

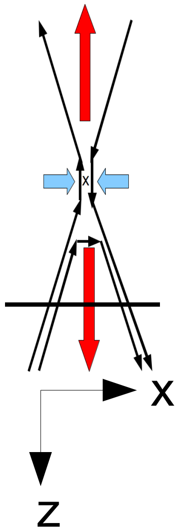
Anisotropic fluid theory
(when anisotropy is strong enough...)



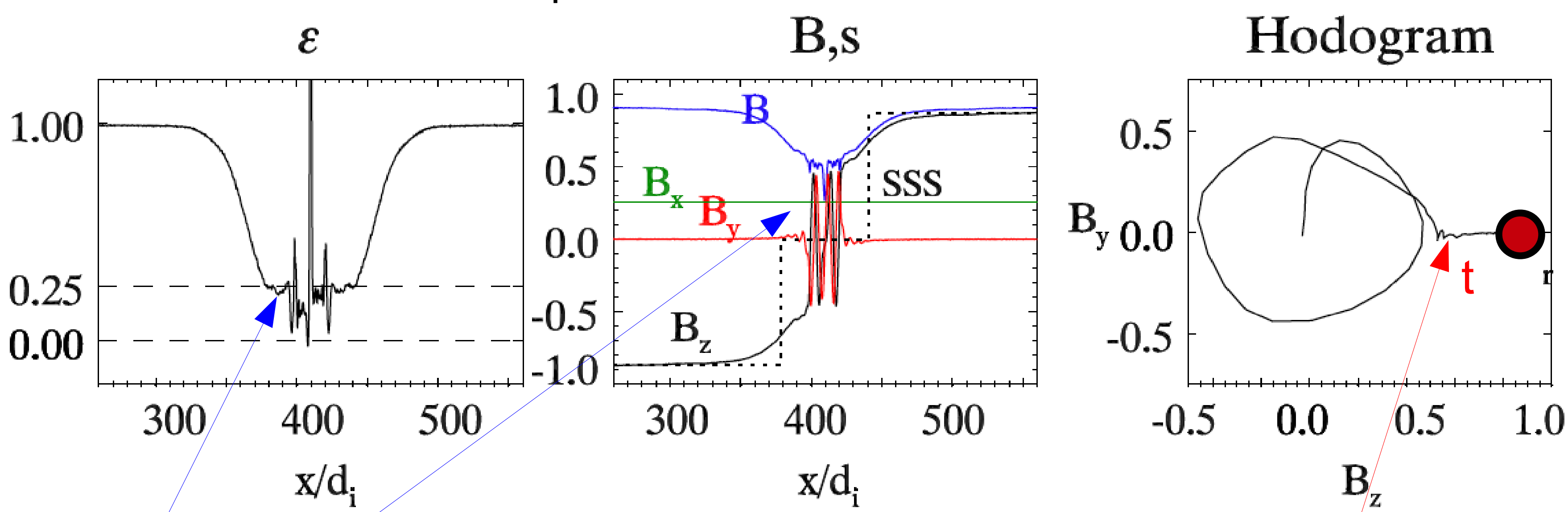
→ compound SS/RD wave

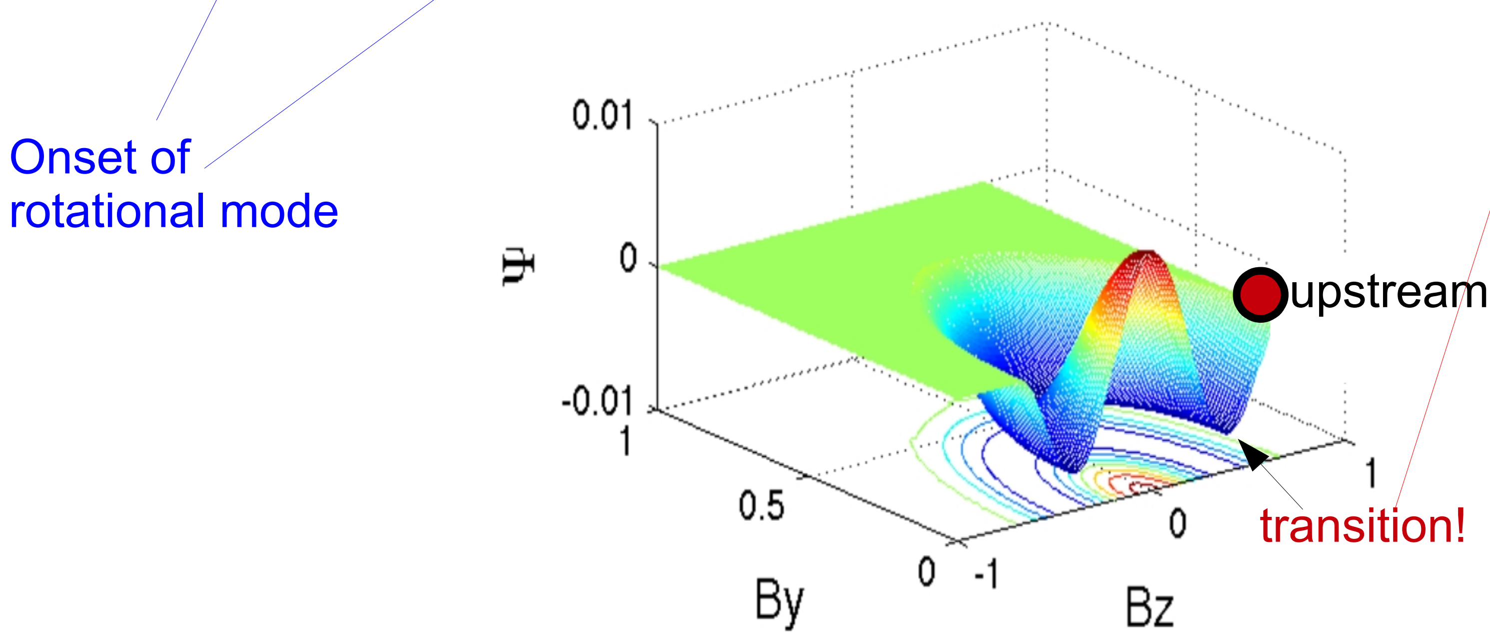
- Pseudo-particle cannot access to the origin and cannot form SSS
  → Instead, a **compound Slow/Intermediate wave forms.**
- Underline physics: intermediate mode becomes slower than slow mode.
  → Linear modes analysis: Abrham-Shrauner 1967; Hau & Sonnerup 1993; Walthour et al. 1997

Compare with simulation



Companion 1D Riemann Problem

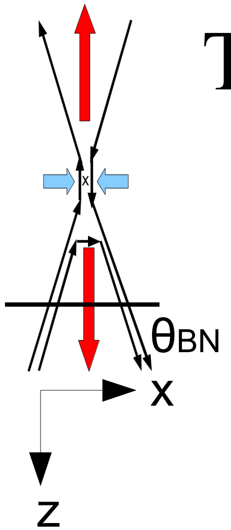




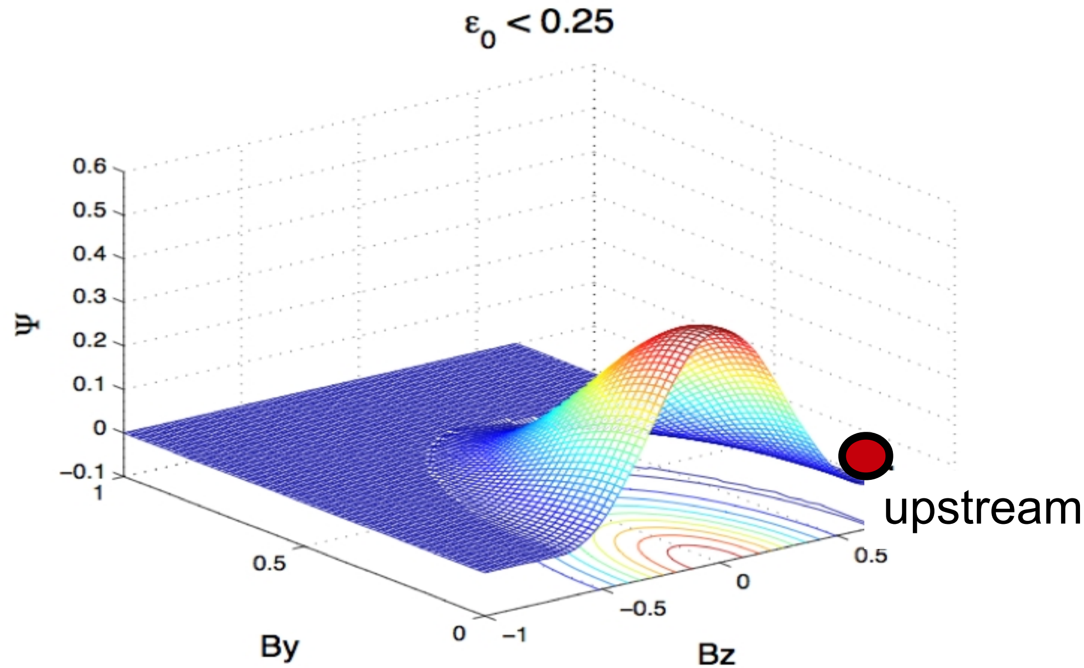
- Similar coplanar to non-coplanar transition is seen!

$$\varepsilon \equiv 1 - \frac{P_{\parallel} - P_{\perp}}{B^2/\mu_0}$$

The significance of 0.25 in anisotropic fluid theory



$$\varepsilon \equiv 1 - \frac{P_{\|} - P_{\perp}}{B^2/\mu_0}$$



γ=5/3 for monatomic plasmas

From a simplified equation

- If $\varepsilon_0 < (3\gamma-4)/(3\gamma-1) = 0.25$,

→ nonlinearity "$\alpha \sim (3\gamma-1)\varepsilon_0-(3\gamma-4)$ " changes sign

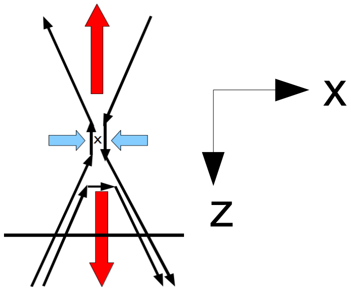
→ Slow mode becomes fast-mode-like.

→ there is no slow mode transition!

Independent of β_u, ε_u & θ_{BN}

- ε = 0.25 is an "absolute" barrier that a SSS cannot cross.
- In the oblique limit, a general critical ε that a SSS cannot reach,

$$\varepsilon_{cr} = \frac{-2\varepsilon_u^2 + (15\beta_u + 8)\varepsilon_u}{10\varepsilon_u + 15\beta_u + 5}$$

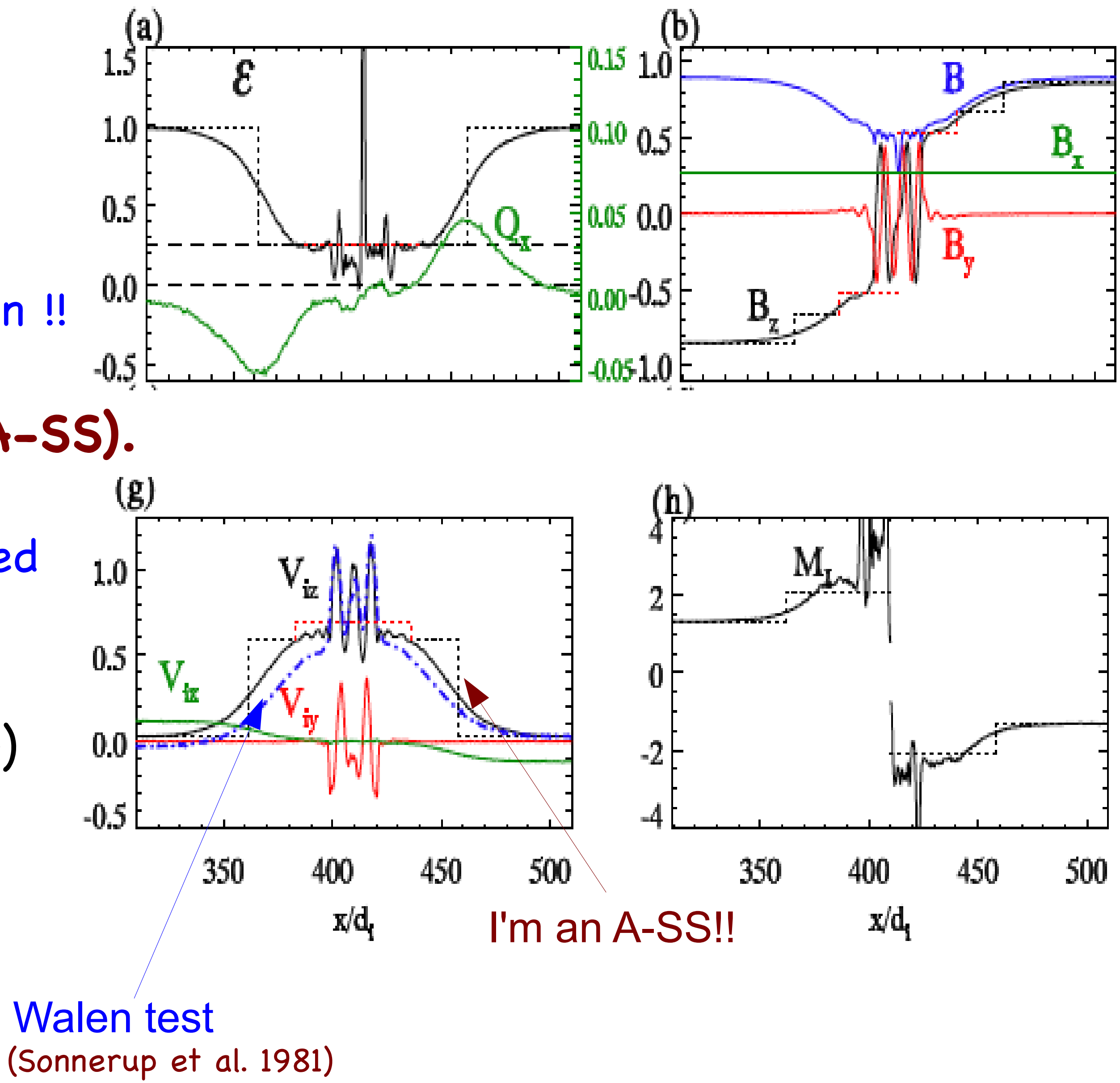


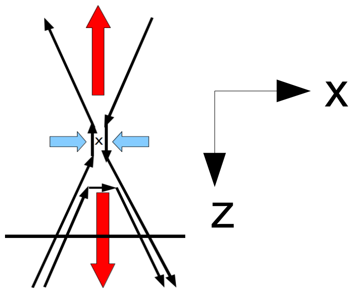
Rankine-Hugoniot Jumps vs. 1D Riemann structure

- Slow shock upstream
  → Super intermediate to super intermediate transition !! (super slow to sub slow)
  → **Anomalous slow shock (A-SS).** (Karimabadi et al 1995)
  → Dotted lines are the predicted jumps of A-SS.

- Transition to a left-hand (LH) rotational wave downstream at Ɛ = 0.25

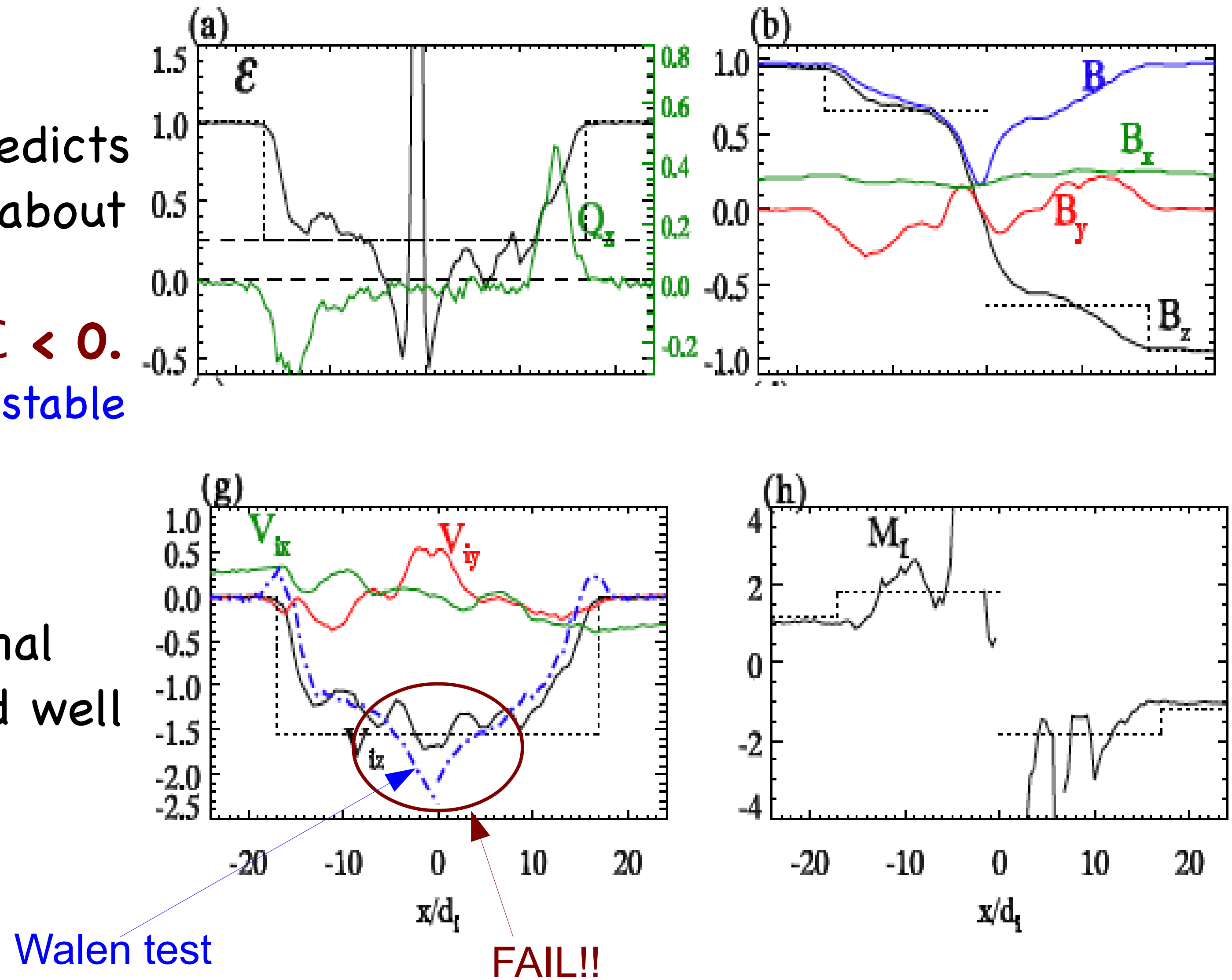
$$\varepsilon \equiv 1 - \frac{P_\parallel - P_\perp}{B^2/\mu_0}$$





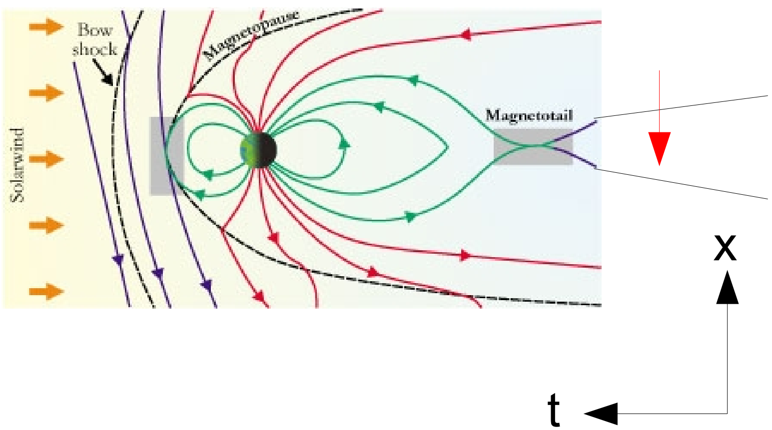
Rankine-Hugoniot Jumps vs. reconnection exhaust structure

- The Walen test over predicts the ouflow velocity by about 40% .
  - → **Walen test fails at ε < 0.**
  - → which is the firehose unstable Regime.
  - → most outflow driven by A-SS
- Downstream LH rotational wave has not developed well yet.

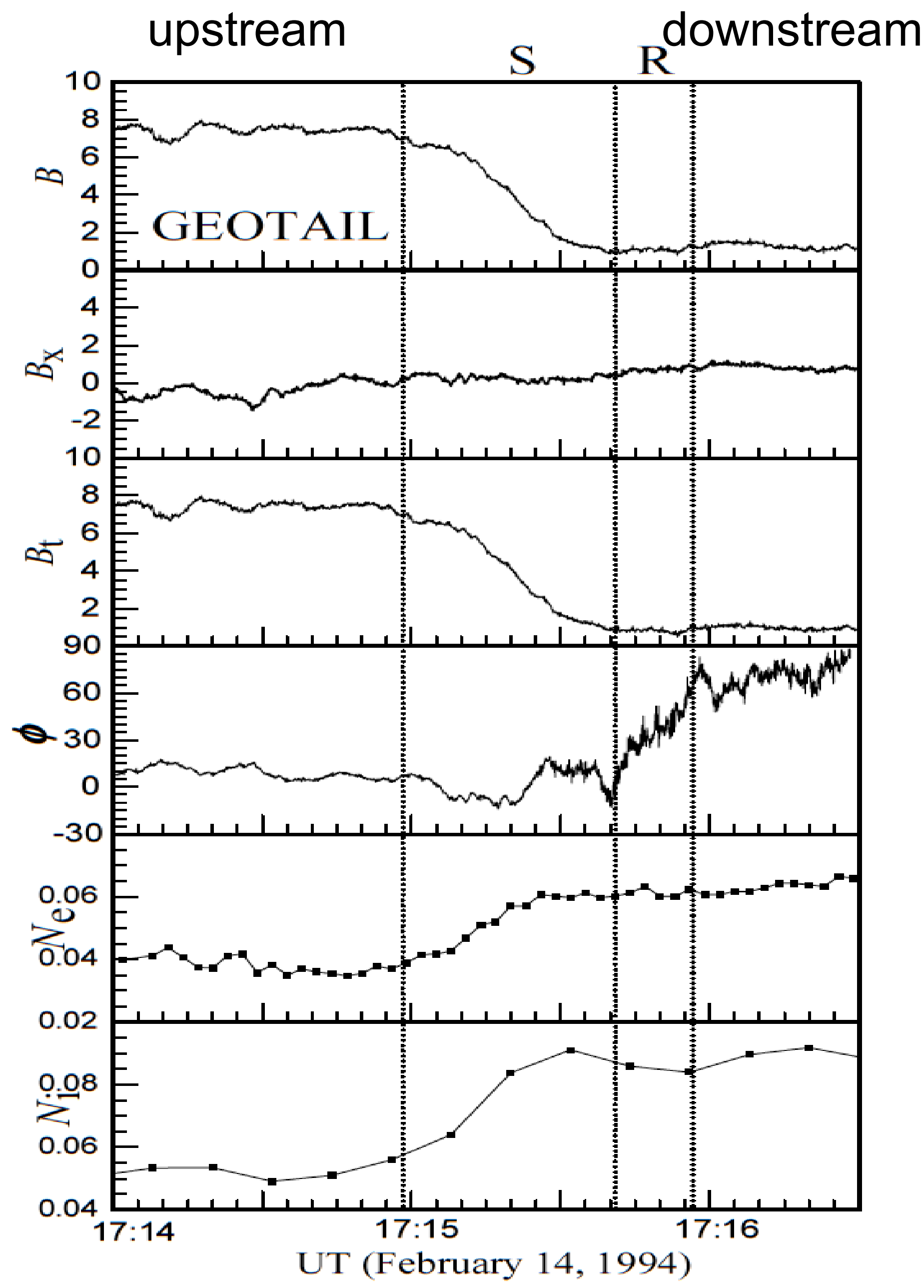


$$\varepsilon \equiv 1 - \frac{P_\parallel - P_\perp}{B^2/\mu_0}$$

Observation: Reconnection exhaust crossing

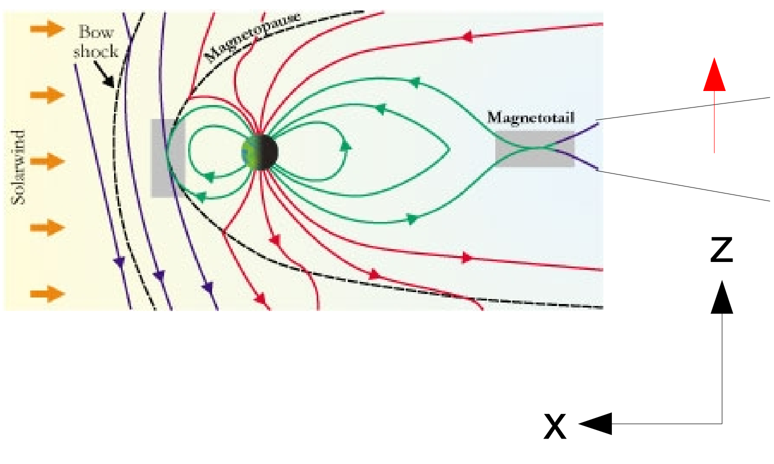


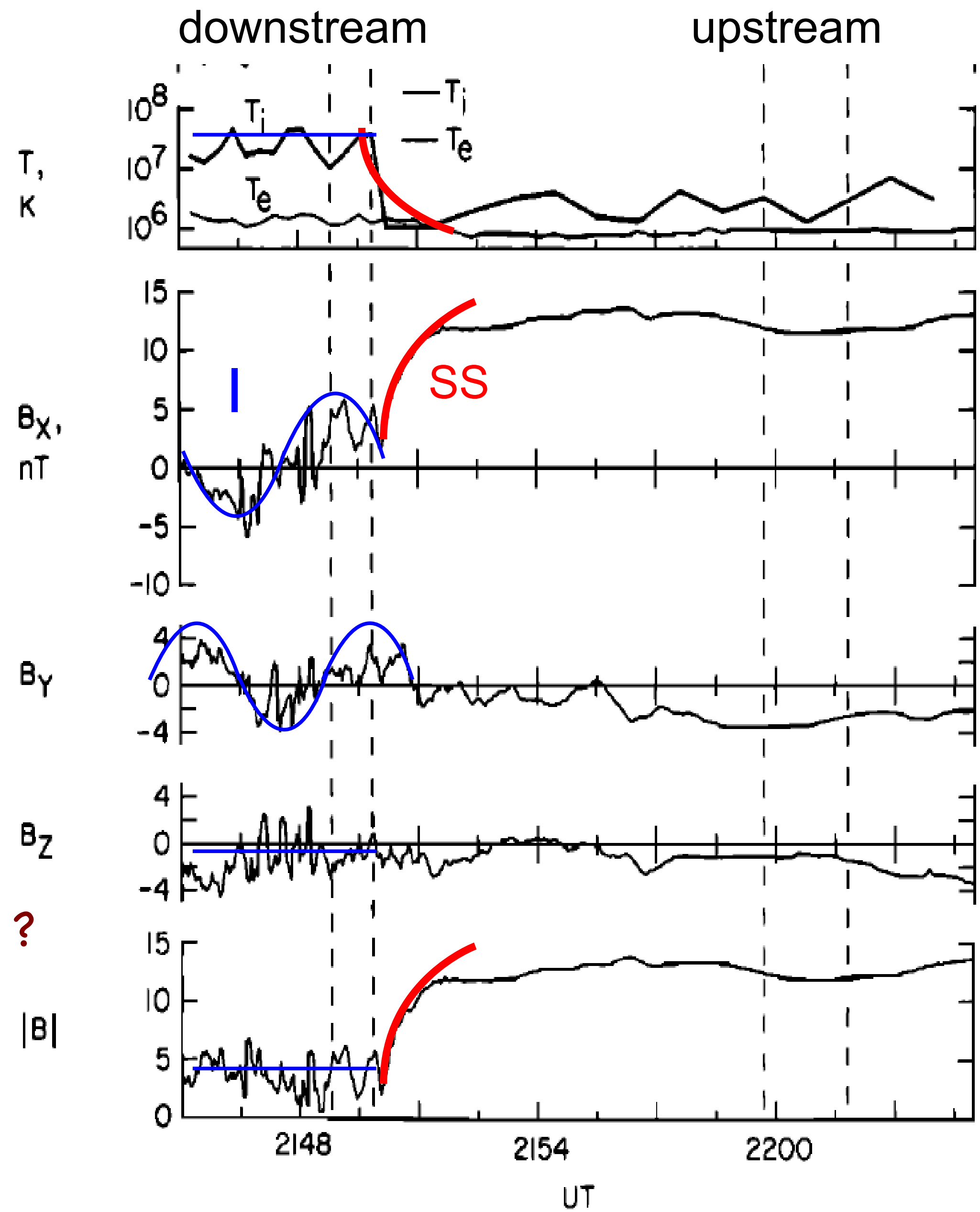
- High temporal resolution. (60 millisecond VS. 3 seconds)
- LH polarized.
- It was called a "Double Discontinuity"
- Evidence of compound Slow/Intermediate waves?



GEOTAIL @ X_{GSM}=-54R_E. (Whang, 2004)

Observation: Reconnection exhaust crossing- 2





- LH polarized.
- Evidence of compound Slow/Intermediate waves ?

GEOTAIL @ X_{GSM}=-181.8 R_E. (Seon et al. 1996)

Summary

- ε = 0.25 plateau forms at reconnection exhaust boundary.

- ε = 0.25 is a special point in RH jump conditions.
  → It is closely related to the degenerate behavior of slow & intermediate modes due to the temperature anisotropy.

- Switch-off Slow Shocks cannot transition to $\varepsilon < 0.25$,
  → therefore Petschek's Switch-off Slow Shocks cannot be realized.
  → this explains the rareness of SSSs in space.
  → Overall, a compound Anomalous Slow Shock/Intermediate wave forms.

- The reconnection outflow speed is usually slower than expected.
  → due to the firehose unstable region
  → reconnection outflow is driven by A-SS

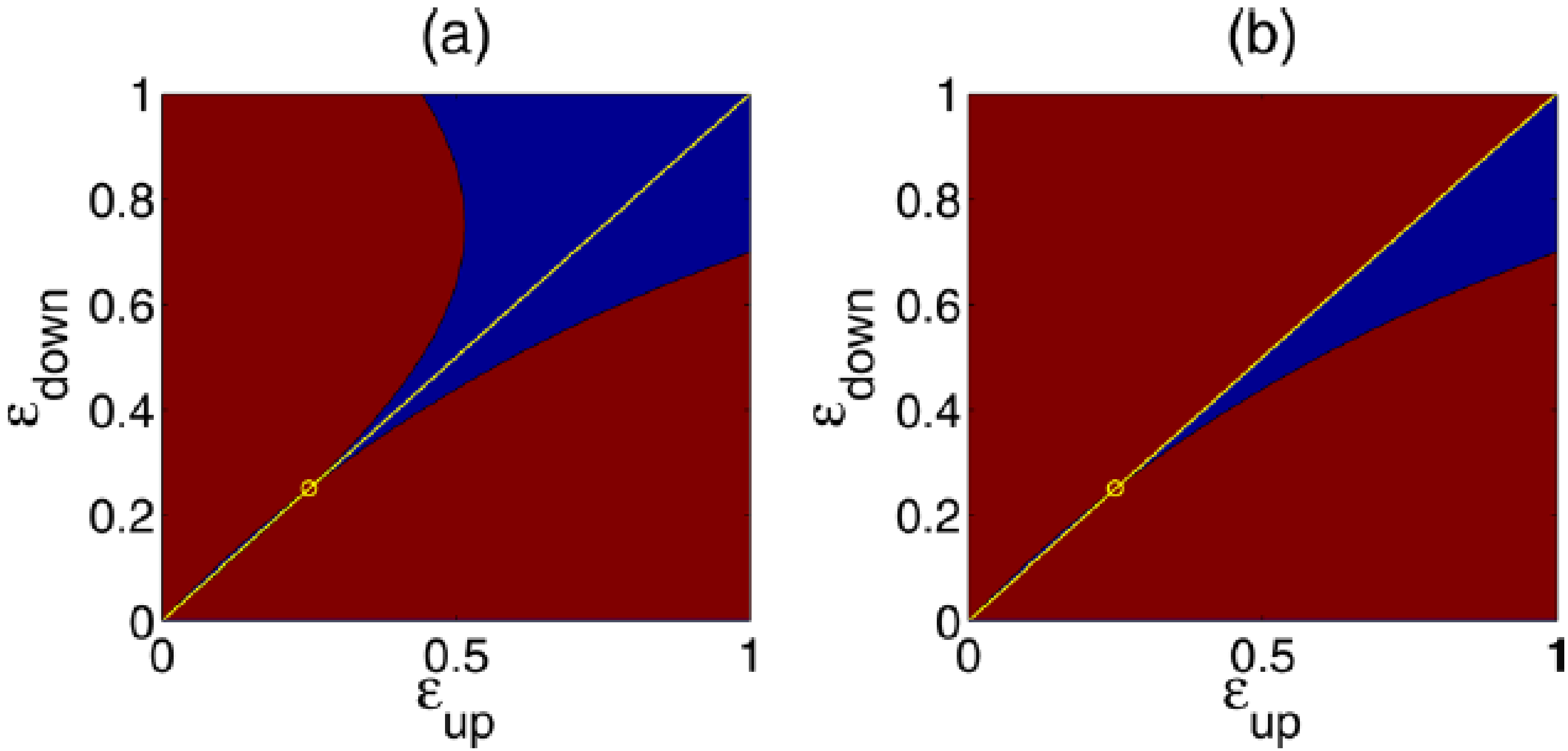
- ε = 0.25 should be an in-situ observable signature in tail reconnection.

Yi-Hsin Liu, J. F. Drake and M. Swisdak, POP **18**, 062110 (2011)
Yi-Hsin Liu, J. F. Drake and M. Swisdak, POP **18**, 092102 (2011)
Yi-Hsin Liu, J. F. Drake and M. Swisdak, POP **19**, 022110 (2012)
C. C. Hung, L. -N. Hau and M. Hoshino, GRL **38**, L18106, 5pp. (2011)
K. Higashimori and M. Hoshino, JGR **117**, A01220 (2012)

Anisotropic Rotational Discontinuity

(Hudson 1970)

Consider entropy condition

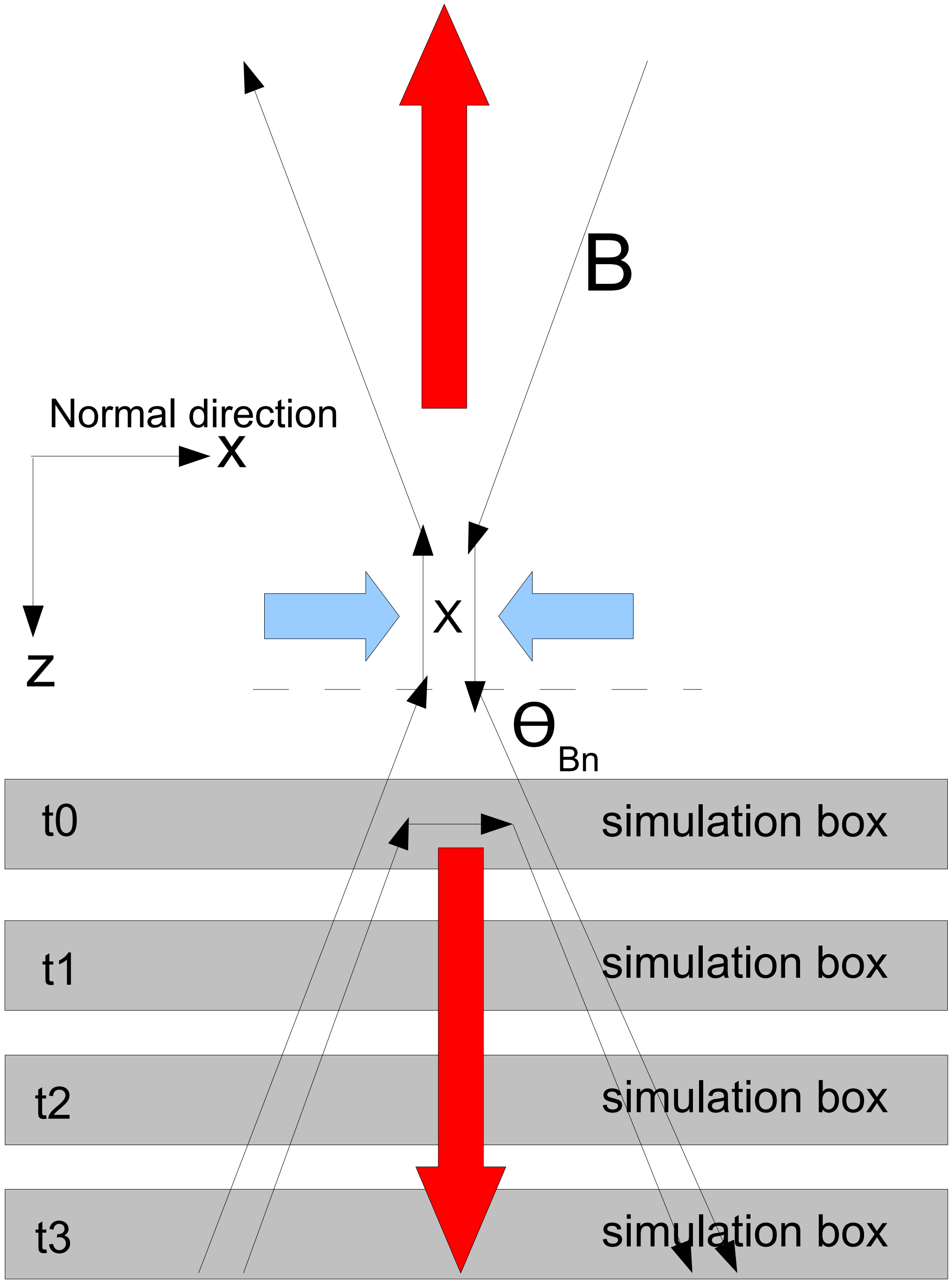


- Hudson thinks although 0.25 is special, but not important in space.
- Out of Hudson's surprise,

  → We find a place to reveal the specialty of 0.25.

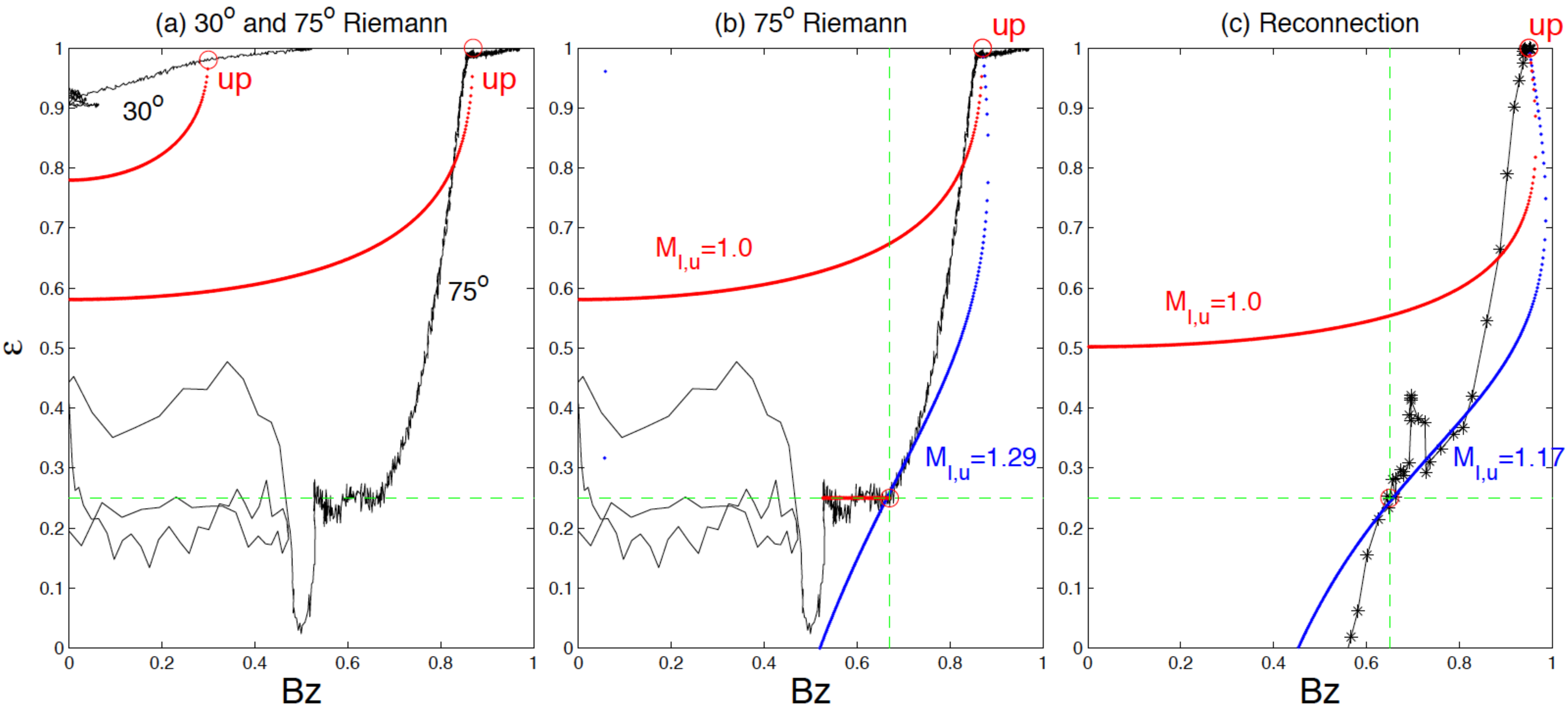
  → it is inside the reconnection exhaust!!

The setup of our PIC Riemann simulations



- Initial profile:
  Harris Sheet[$B_z = B_0 \tanh(x/w)$] + B_x
- Driven by the unbalanced magnetic tension force.
- It is a Riemann problem.
  (Scholer & Lottermoser et al. 1998, Lin & Lee et al. 1993)
- Use time as a proxy of space
- A much longer domain in the normal direction. (~ 800 di)
- θ_{BN} is one of the key parameters that controls the propagation angle.

The way of determining the Mach number

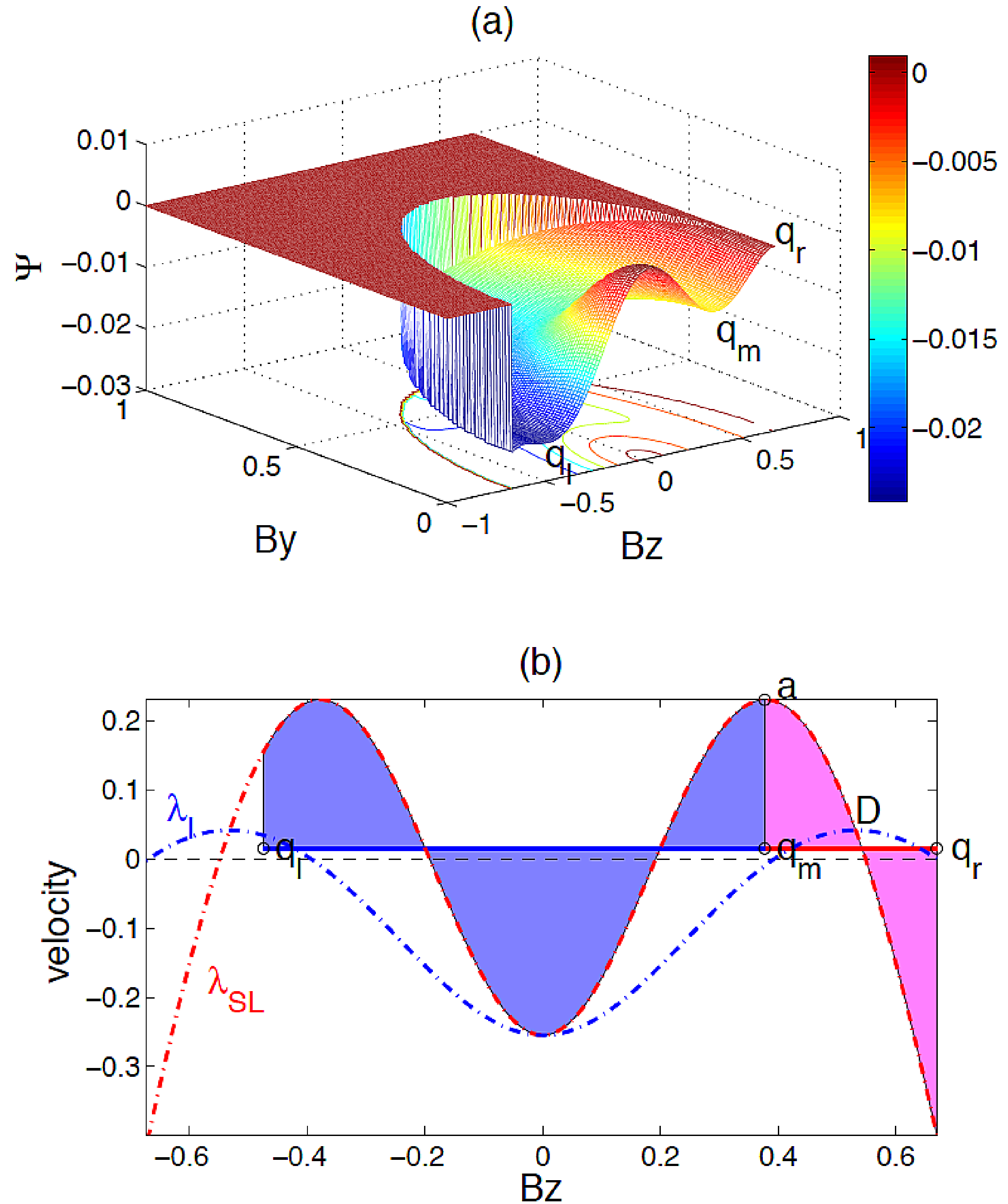


→ Increase $M_{I,u}$ till the SS solution curve intersects with the data curve at ε=0.25

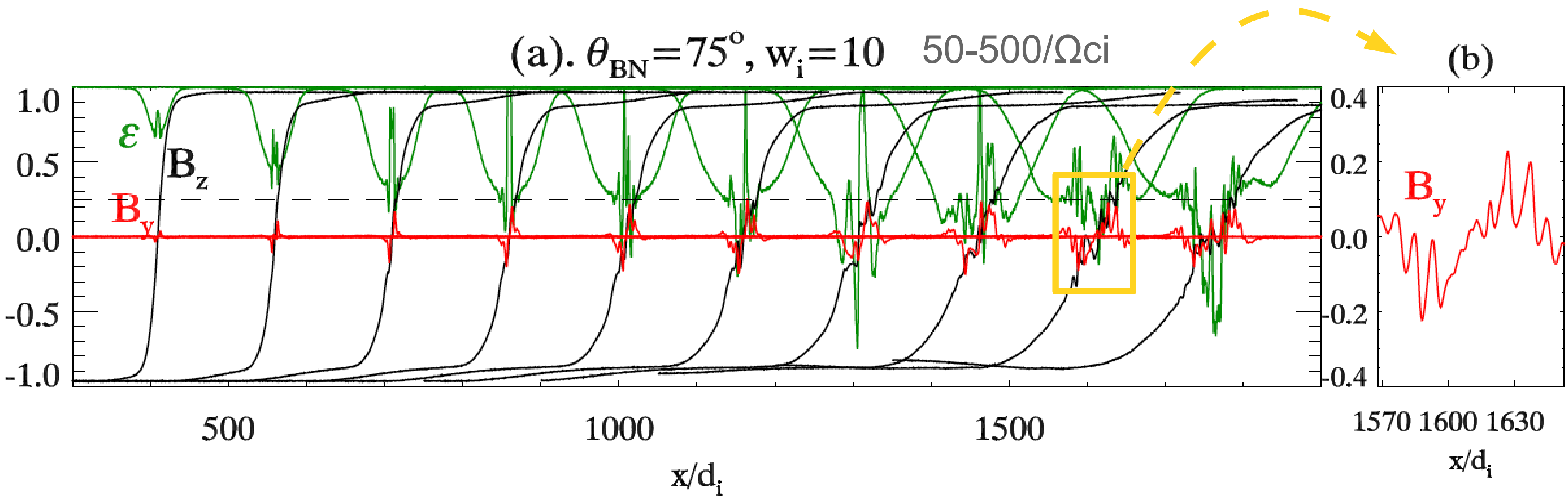
Being slightly super-intermediate...

- The analysis of slow and intermediate characteristics shows the formation of compound A-SS/IS wave

(Liu et al 2011)

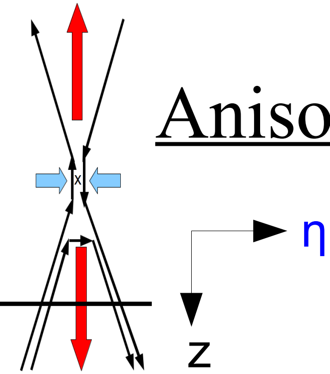


The rotational part of the SS/RD is not stable!



- The rotational part of SS/RD tends to break into ion inertial scale waves!
  → spatially modulated rotational wave radiates dispersive waves.
- Ɛ is raised by scattering from these di-scale waves.

$$\varepsilon \equiv 1 - \frac{P_{\parallel} - P_{\perp}}{B^2/\mu_0}$$



Anisotropic Derivative NonLinear Schrodinger-Burgers equation

Extend the work of Kennel et al. 1990

$$\partial_\tau \mathbf{b}_t + \partial_\eta[\alpha \mathbf{b}_t(b_t^2 - b_{t0}^2) + \Omega \mathbf{b}_t(\varepsilon - \varepsilon_0)] = \partial_\eta(R\partial_\eta \mathbf{b}_t) - \frac{1}{2\sqrt{\varepsilon_0}} d_i \partial_\eta^2(\hat{\mathbf{e}}_x \times \mathbf{b}_t)$$

Nonlinear steepening — Dissipation — Dispersion

$$\alpha \propto (3\gamma - 1)\varepsilon_0 - (3\gamma - 4)$$

b_t: transverse magnetic field

The difference between the slow and intermediate characteristic speeds is:

$$\lambda_{SL} - \lambda_I = 2\alpha b_t^2 + \Omega \delta\varepsilon_{b_t} b_t$$

Therefore, the slow and intermediate modes degenerate (i.e., have the same speed) at:

$$b_t = 0.$$

The traditional degeneracy point

$$2\alpha b_t + \Omega \delta\varepsilon_{b_t} = 0$$

New degeneracy points due to the temperature anisotropy!!

$$\varepsilon \equiv 1 - \frac{P_\parallel - P_\perp}{B^2/\mu_0}$$

Calculate the pseudo-potential (Sagdeev potential)

Looking for stationary solutions: $\mathbf{b}_t = \mathbf{b}_t[\xi(\eta - V_S\tau)]$

Shock speed

$$\int ...d\xi$$

ξ → time

bt → spatial coordinate

$$\rightarrow \quad R\partial_\xi \mathbf{b}_t - \frac{1}{2\sqrt{\varepsilon_0}} d_i \partial_\xi (\hat{\mathbf{e}}_x \times \mathbf{b}_t) = -V_S(\mathbf{b}_t - \mathbf{b}_{t0}) + \alpha_{\text{eff}}(b_t)\mathbf{b}_t(b_t^2 - b_{t0}^2) \equiv \partial_{\mathbf{b}_t}\Psi(b_y, b_z)$$

Friction

Coriolis force

Nonlinear term

Potential gradient force

$$\int (...) \cdot \partial_\xi \mathbf{b}_t d\xi$$

$$\rightarrow \quad \Psi|_{\text{up}}^{\text{down}} = R\int_{\text{up}}^{\text{down}} (\partial_\xi \mathbf{b}_t)^2 d\xi < 0$$

- The pseudo-potential characterizes the nonlinearity of this wave system.
- Resistivity sinks pseudo-particles to the potential low → shock transition