## Modern Challenges in Nonlinear Plasma Physics
## A Conference Honouring the Career of Dennis Papadopoulos

# Progress in Plasma Physics by Numerical Simulation: Collisionless Shocks

Manfred Scholer

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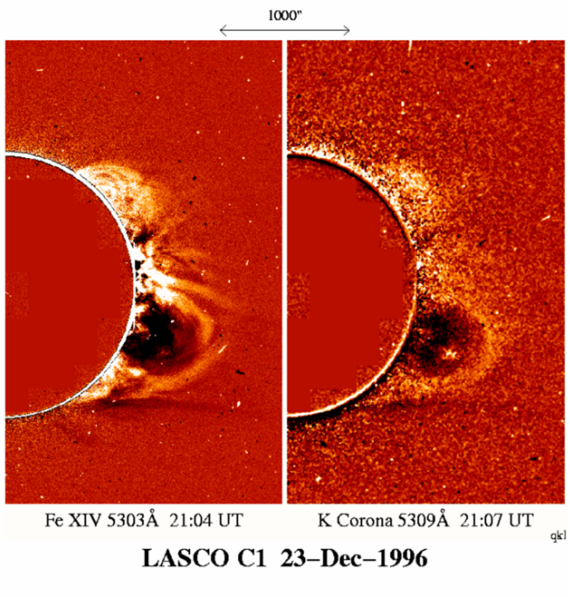
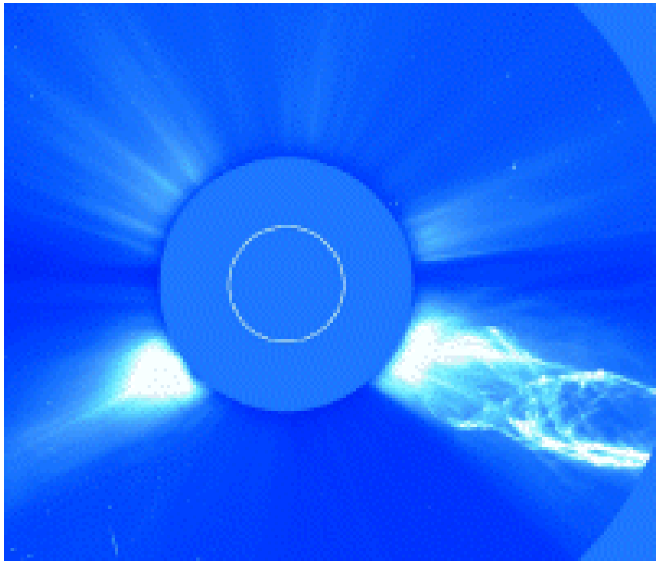
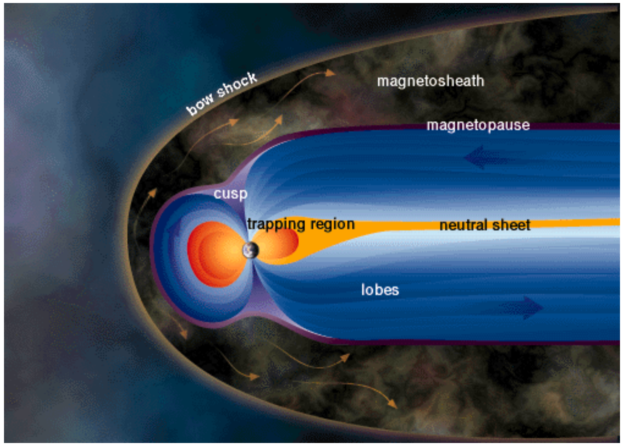
# Examples of Collisionless Shocks I




Coronal Mass Ejection (SOHO-LASCO) in forbidden Fe line

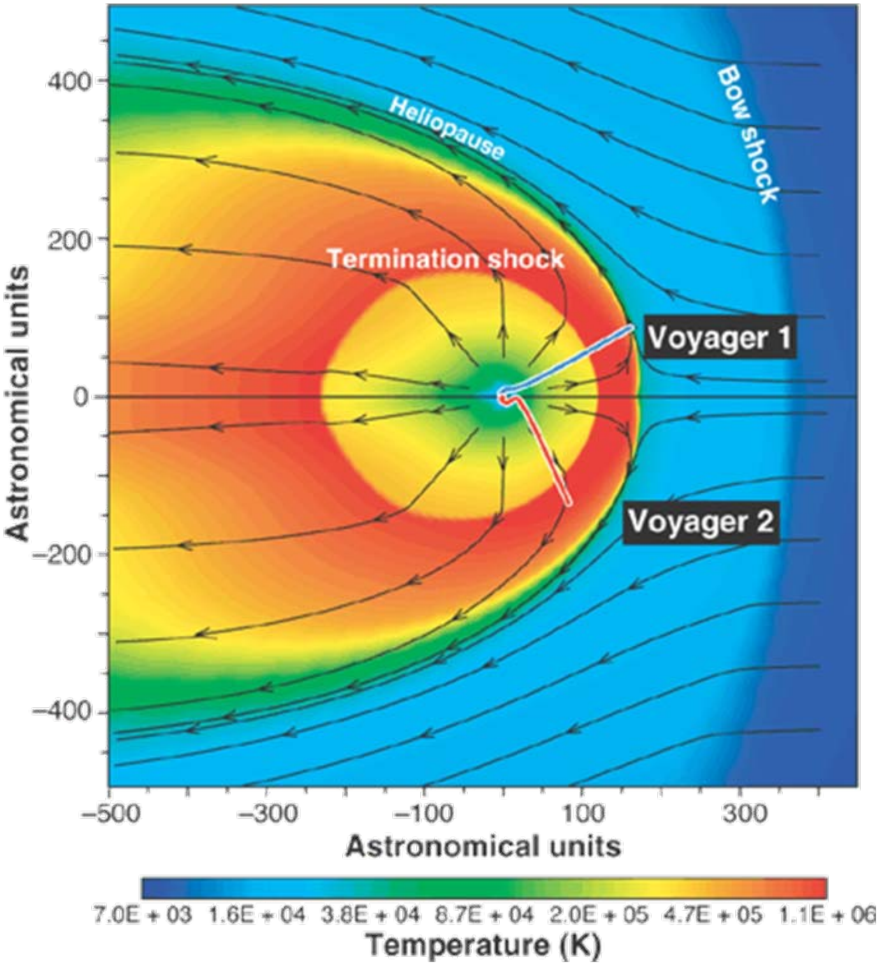


Large CME observed with SOHO coronograph

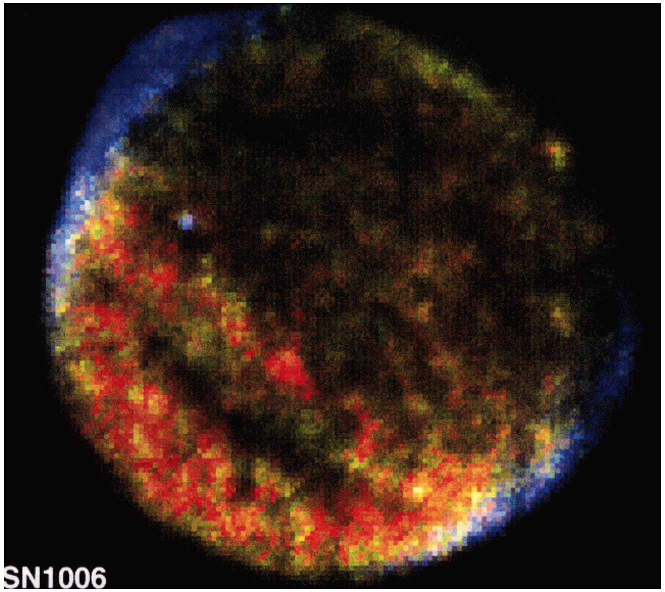



Schematic of Earth‘s bow shock

# Examples of Collisionless Shocks II




Schematic of the heliosphere showing the heliospheric termination shock and the bow shock in front of the heliosphere.




Supernova SN 1006 – ROSAT PSPC image. Blue caps: hard non-thermal X-ray spectrum due to energetic electrons.

THE PHYSICS OF FLUIDS VOLUME 14, NUMBER 4 APRIL 1971

* **Heating of Counterstreaming Ion Beams in an External Magnetic Field**

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(Received 23 June 1970)

VOL. 76, NO. 16 JOURNAL OF GEOPHYSICAL RESEARCH JUNE 1, 1971

* Ion Thermalization in the Earth's Bow Shock

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*Naval Research Laboratory, Washington, D. C.*

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 87, NO. A7, PAGES 5081–5094, JULY 1, 1982

* **The Structure of Perpendicular Bow Shocks**

M. M. LEROY,[1] D. WINSKE, C. C. GOODRICH, C. S. WU, AND K. PAPADOPOULOS

*University of Maryland, College Park, Maryland 20742*

# LETTERS

*The purpose of this Letters section is to provide rapid dissemination of important new results in the fields regularly covered by The Physics of Fluids. Results of extended research should not be presented as a series of letters in place of comprehensive articles. Letters cannot exceed three printed pages in length, including space allowed for title, figures, tables, references and an abstract limited to about 100 words.*

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* **Creation of high-energy electron tails by means of the modified two-stream instability**

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(Received 11 February 1983; accepted 11 April 1983)

## ELECTRON HEATING IN SUPERHIGH MACH NUMBER SHOCKS*

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(Received 15 July, 1987)

THE ASTROPHYSICAL JOURNAL, **329**: L29–L32, 1988 June 1


* A MECHANISM FOR STRONG SHOCK ELECTRON HEATING IN SUPERNOVA REMNANTS

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Department of Physics and Astronomy, University of Maryland, College Park
*Received 1987 October 26; accepted 1988 March 9*

## Subcritical shock

Dissipation is sufficient to account for temperature jump required by RH relations

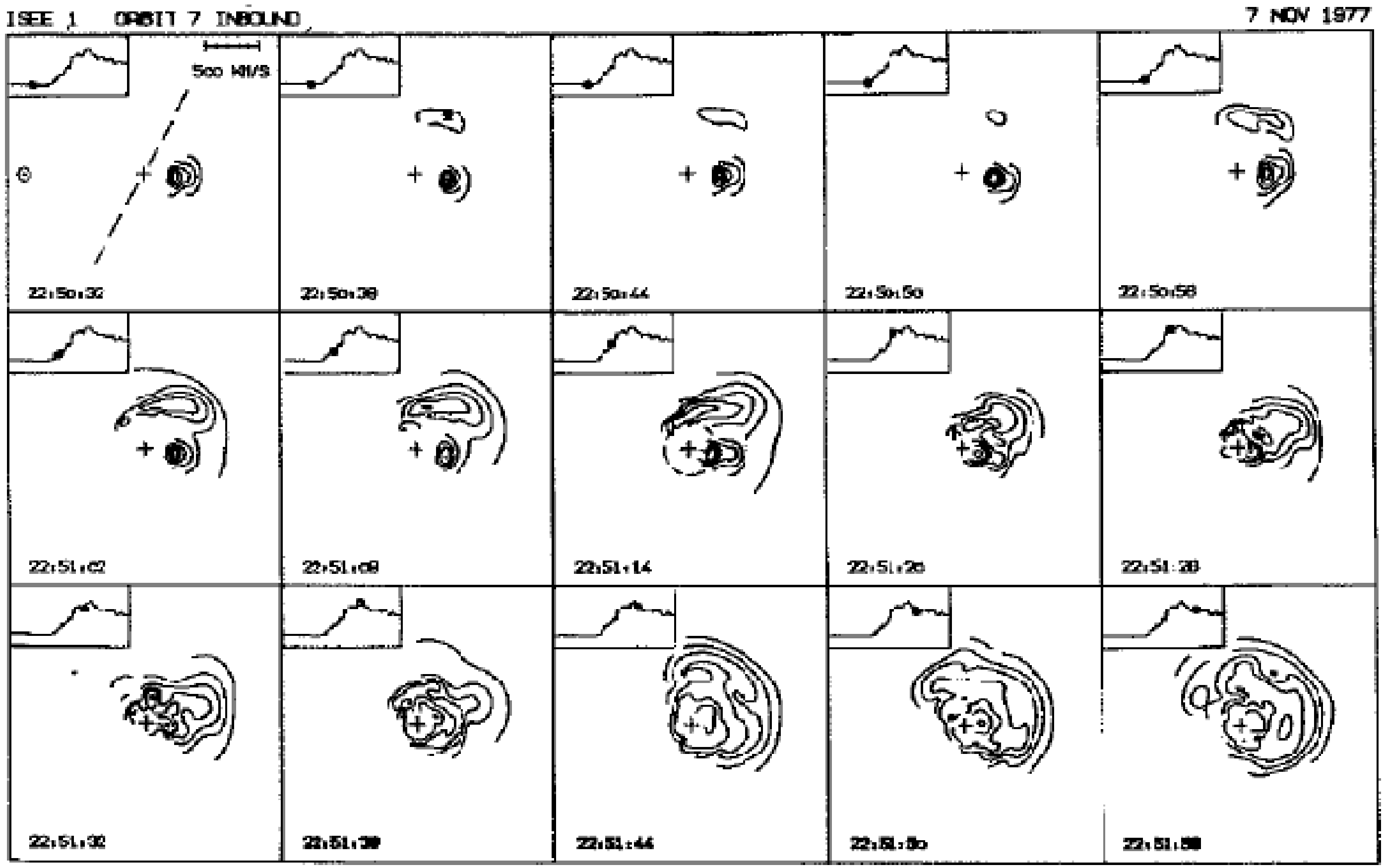
## Supercritical shock

Additional process of reflection of part of incident ions is needed

(First critical Mach number: fast magnetosonic Mach number at which downstream flow speed equals flow speed)

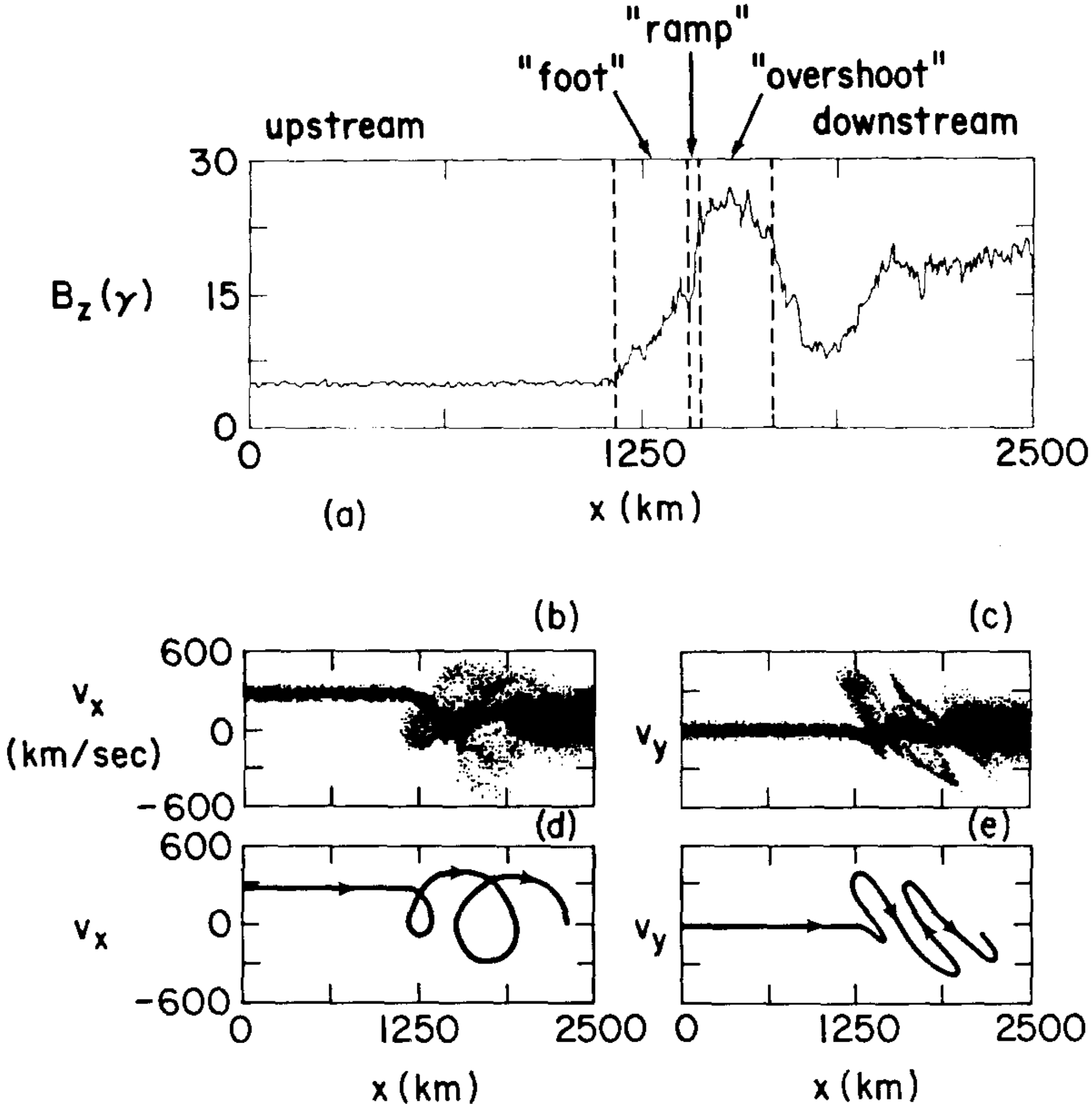
# Specularly reflected ions in the foot of the quasi-perpendicular bow shock – in situ observations (ISEE)

Sckopke et al. 1983



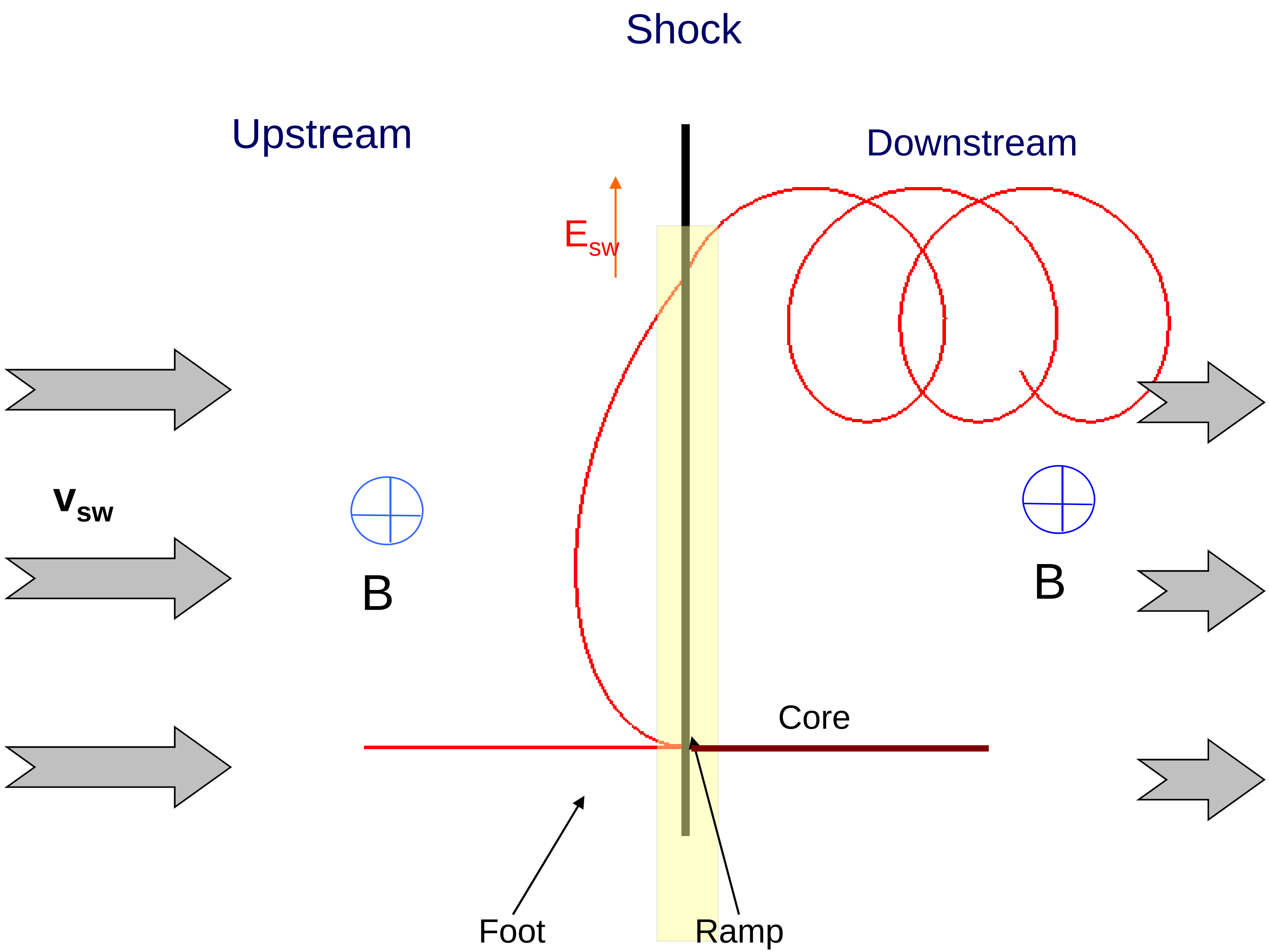

Ion velocity space distributions for an inbound bow shock crossing. The position of the measurement is shown by dots on the density profile. Phase space density is shown in the ecliptic plane with sunward flow to the left.

Papadopoulos 1985

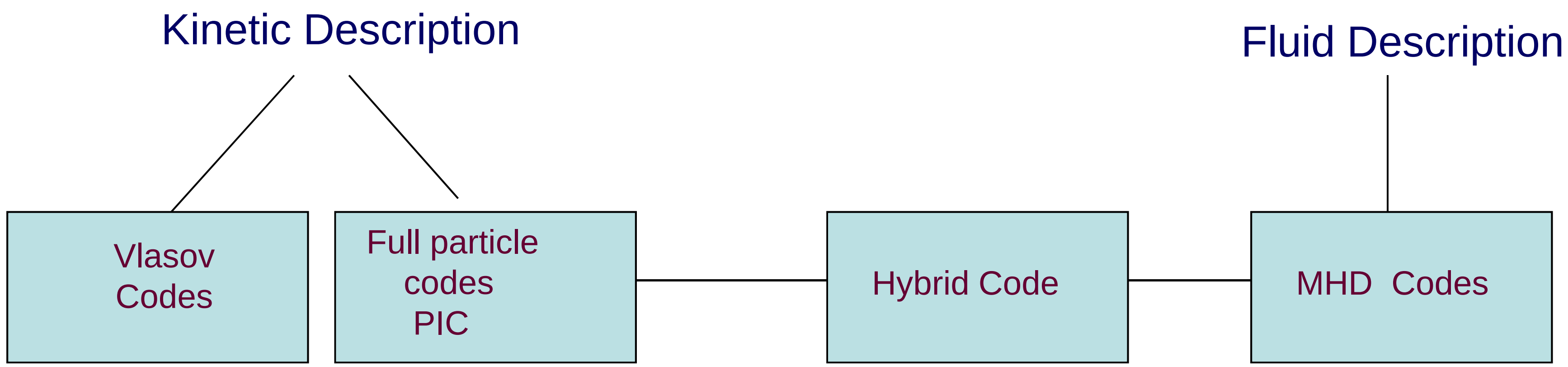



Hybrid simulation of a perpendicular shock by the Maryland group (Papadopoulos, Leroy, Goodrich, Winske, Wu)

## Schematic of ion reflection and downstream thermalization at supercritical perpendicular shocks



# Classification of Computer Simulation Models of Plasmas



## Simulation Methods

### 1. Hybrid Method

Ions are (macro) particles
Electrons are represented as a charge-neutralizing fluid

Electric field is determined from the momentum equation of the electron fluid

$$nm_e \frac{d\vec{V}_e}{dt} = -en(\vec{E} + \frac{\vec{V}_e \times \vec{B}}{c}) - \nabla p_e$$

## 2. Particle-In-Cell (PIC) Method

Both species, ions and electrons, are represented as particles

Poisson‘s equation has to be solved

Spatial and temporal scales of the electrons
(gyration, Debye length) have to be resolved

Disadventage:

Needs huge computational resources

Adventage:

Gives information about processes on electron scales
Describes self-consistently electron heating and acceleration

# Parameters in PIC Simulations of Collsionless Shocks

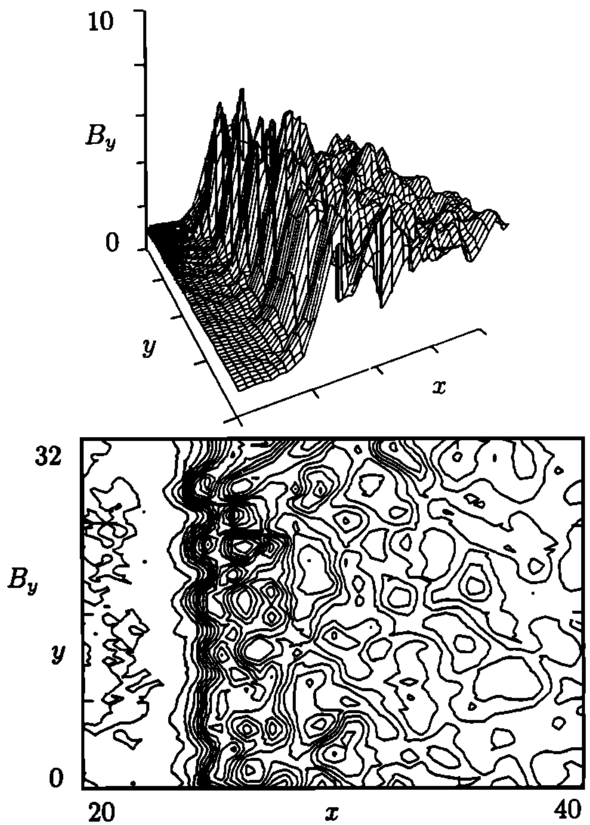
1. Mass ratio $m_i / m_e$

2. Ratio of electron plasma to gyrofrequency $\nu = \dfrac{\omega_{pe}}{\Omega_{ce}} = \dfrac{c}{V_A}\sqrt{\dfrac{m_e}{m_i}}$

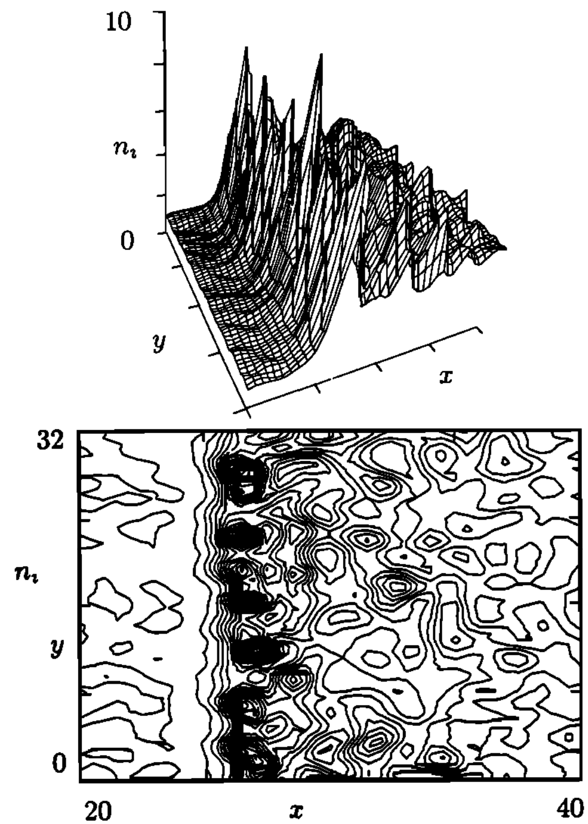
| | $m_i / m_e$ | $\omega_{pe} / \omega_{ce}$ | | $c / V_A$ |
|---|---|---|---|---|
| Solar Wind | 1836 | 100 – 200 | | (5000) |
| Biskamp and Welter, 1973 | 124 | 5 | 1-D | |
| Lembege and Dawson, 1987 | 100 | 2 | 1-D | |
| Liewer et al., 1991 | 1836 | 1-4 | 1-D | |
| Savoini and Lembege, 1994 | 42 | 2 | 2-D | |
| Shimada and Hoshino, 2000,2003,2005 | 20 | 20 | 1-D | (90) |
| Lembege and Savoini, 2002 | 42 | 2 | 2-D | |
| Krasnoselskikh et al., 2002 | 200 | - | 1-D | |
| Hada, Oonishi. Lembege, Savoini 2003 | 84 | 2 | 1-D | (18) |
| Scholer, Shinohara, Matsukiyo, 2003 | 1840 | 2 | 1-D | (95) |
| Scholer, Matsukiyo, 2004 | 1840 | 2 | 1-D | |
| Muschietti and Lembege, 2005 | 100 | 2 | 1-D | ( 20) |
| Matsukiyo, Scholer, 2006 | 1860 | 2 | 2-D | |
| Scholer, Comisel, Matsukiyo, 2007 | 1000 | 5 | 1-D | (150) |

# 2-D Hybrid Simulation of Perendicular Shock  - B in Simulation (x-y) Plane

Winske and Quest  1988




$B_y$ magnetic field in x-y plane

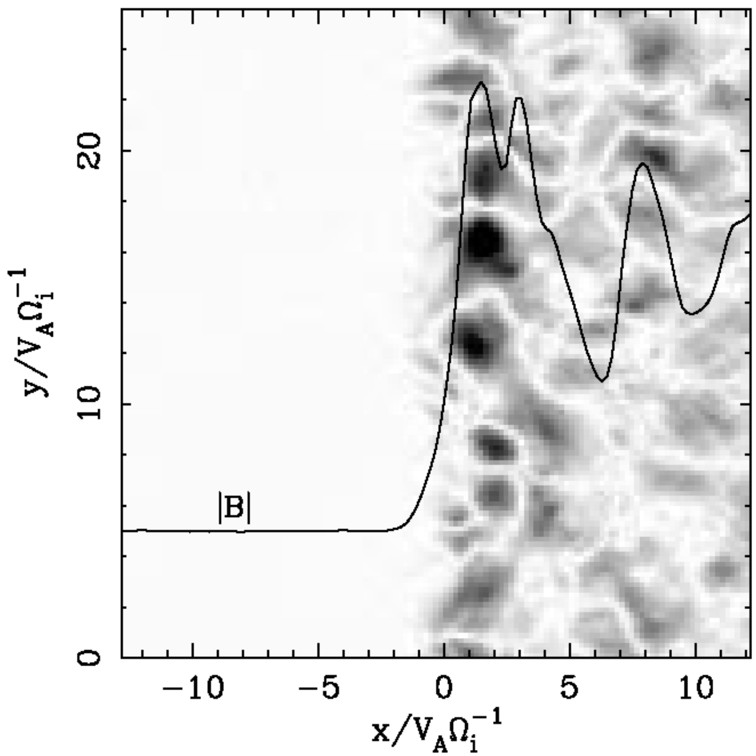



Density in x-y plane

Oblique propagating Alfven Ion Cyclotron waves produced
by the perpendicular/parallel temperature anisotropgy
(large perp temperature due to reflected gyrating ions)

# Shock Ripples

Lowe and Burgess 2003

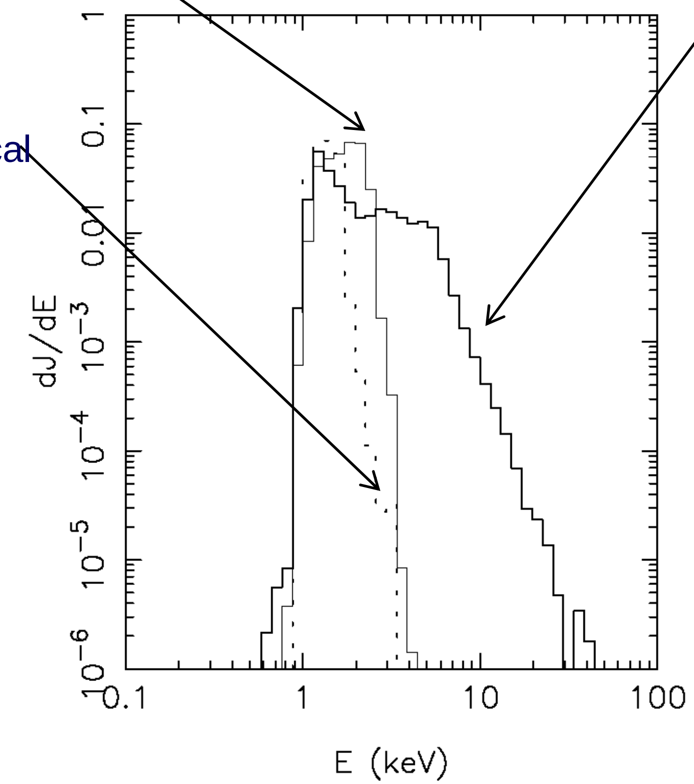



Burgess 2006

Shocks without ripples
B perp to simulation plane

Shock with ripples

Subcritical



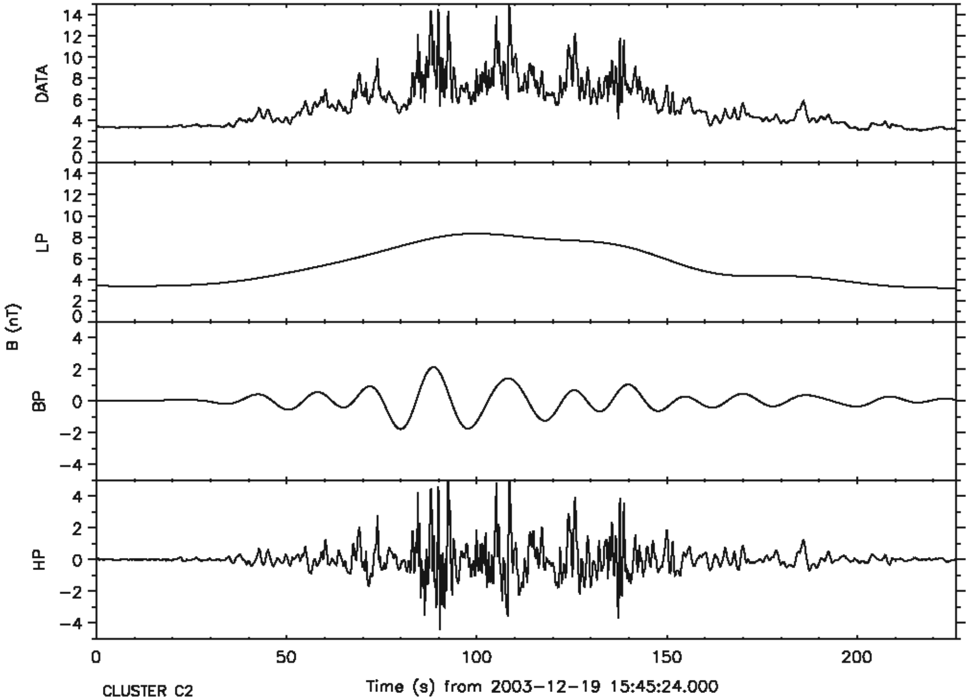

Gray-shaded: magnetic field $B_x$ component

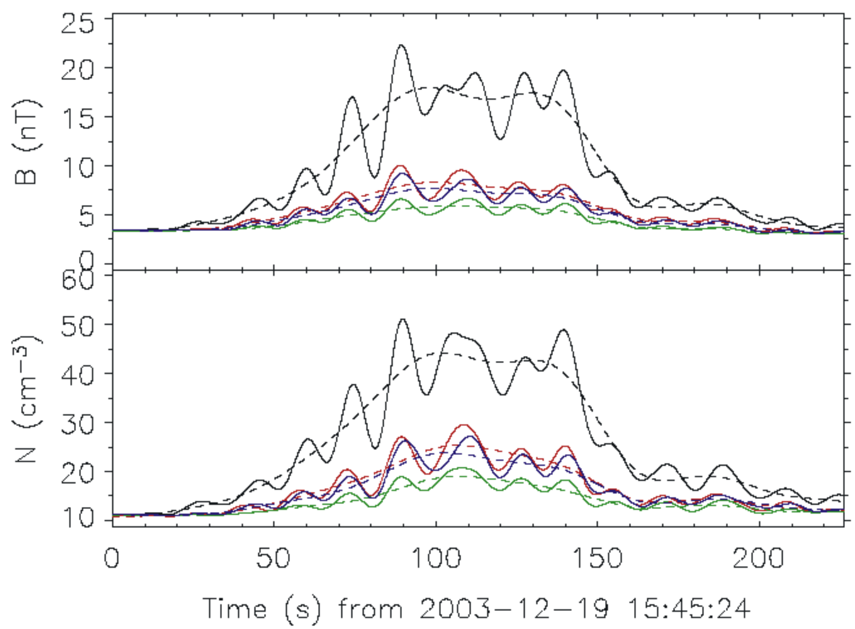
Ripples are surface waves on shock front
Move along shock surface with Alfven velocity given by magnetic field in overshoot

Ion scale structures produce efficient electron scattering $\longrightarrow$
Electron acceleration (test particle electrons in hybrid code shock)

# Cluster Observations of Bow Shock Ripples

Moullard et al. 2006

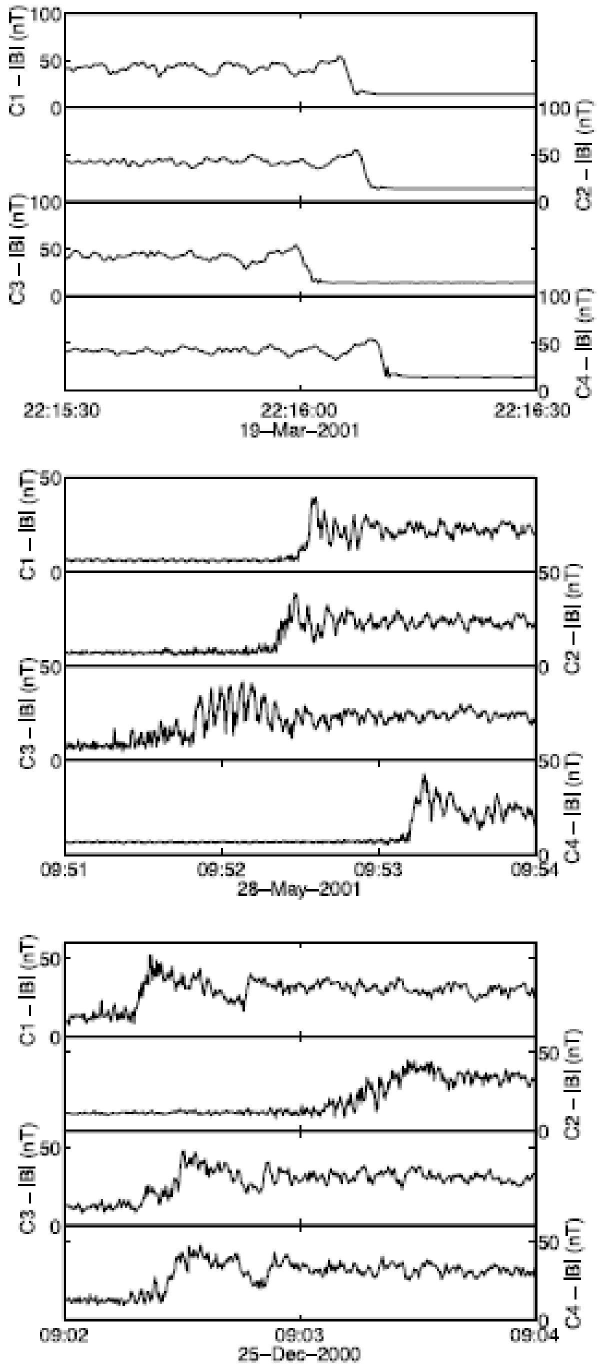



From Top: Magnetic field magnitude, low pass, band pass (0.025-0.83 Hz), and high pass filter

16 sec fluctuations - ripples with wavelengths of about 30 ion inertial lengths

Low pass + band pass filtered magnetic field (top) and density (bottom) at the four S/C




# Nonstationary Shocks (Self-Reformation)

Four- spacecraft Cluster observations of three quasi-perpendicular bow shock crossings

Horbury et al. 2002

# Oblique Shocks and Whistler Precursor

Whistler critical Mach number

$$M_w = \frac{|\cos\Theta_{Bn}|}{2(m_e/m_i)^{1/2}}$$

Condition:

(1) Phase velocity = shock velocity (phase standing)
(2) Wave length = electron inertial length (smallest wave length)

Below $M_w$ exists phase standing small amplitude upstream whistler with upstream directed group velocity

Biskamp and Welter 1972

## 1. Whistler excited nonlinear instability beween incoming solar wind and reflected ions

Incoming and reflected ion beams are stable when velocity difference large

A nonlinear beam-instability between incoming and reflected ions is triggered by the electric field of the upstream whistler and results in dissipation

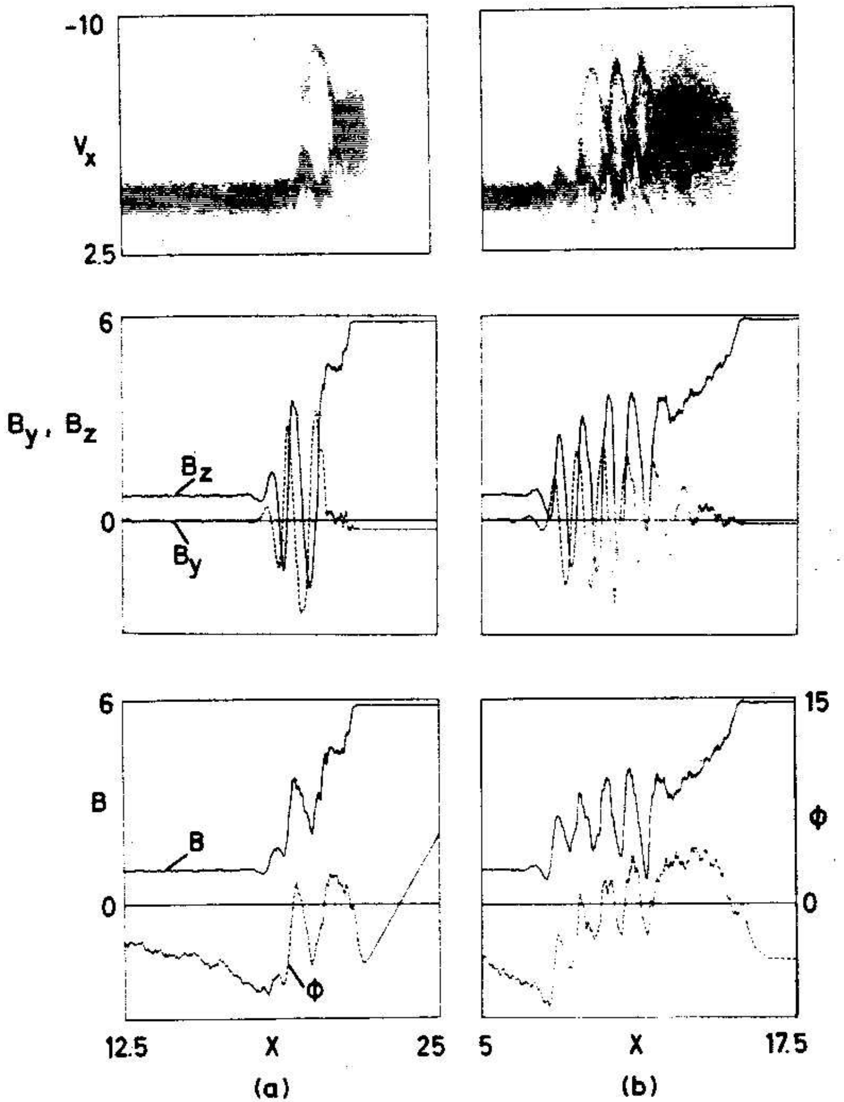



Fig. 2. Ion phase space $x$ and $v_x$, magnetic field components $B_y$ and $B_z$, total magnetic field $B$, and electric potential $\phi$ of a magnetic shock at $(a)$ $t = 1.25/\Omega_i$ and $(b)$ $t = 3.25/\Omega_i$. The mass ratio is $m_i/m_e = 128$.

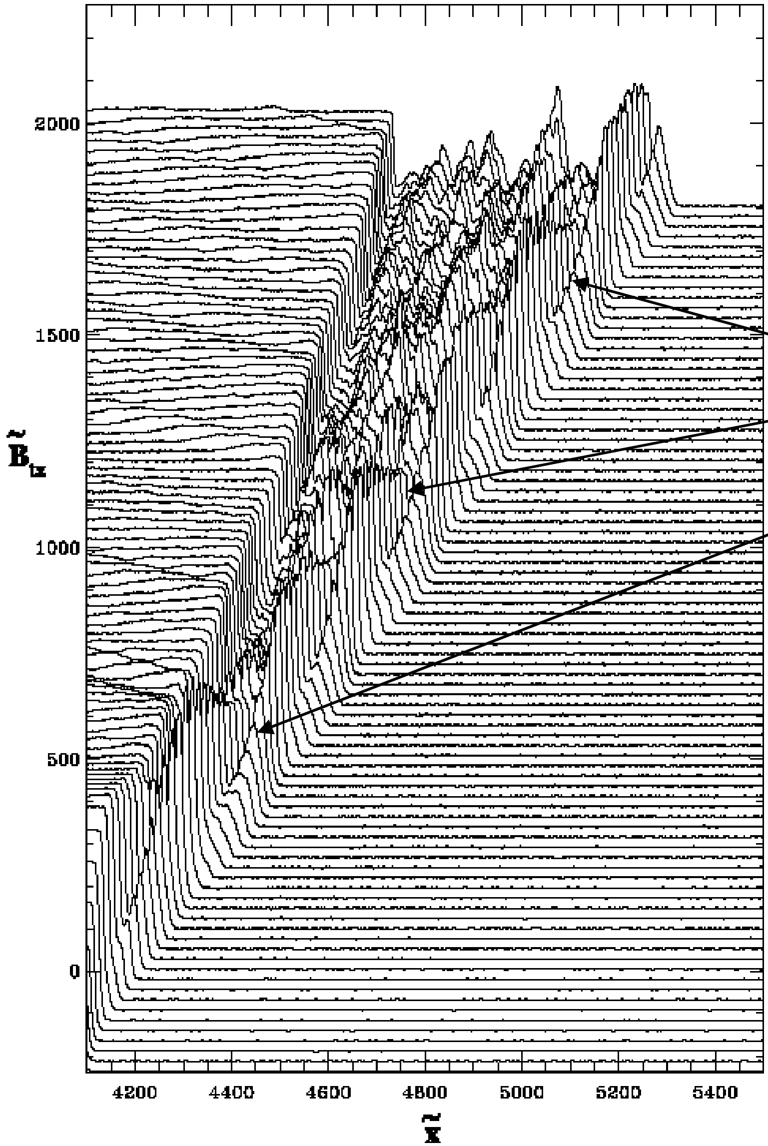
$M_A = 5.0$

45

$$M_w = \frac{|\cos\Theta_{Bn}|}{2(m_e/m_i)^{1/2}} = 4.0$$

# PIC simulation of a $\Theta_{Bn}$ = $90^o$ shock

($m_i$ / $m_e$ = 84)

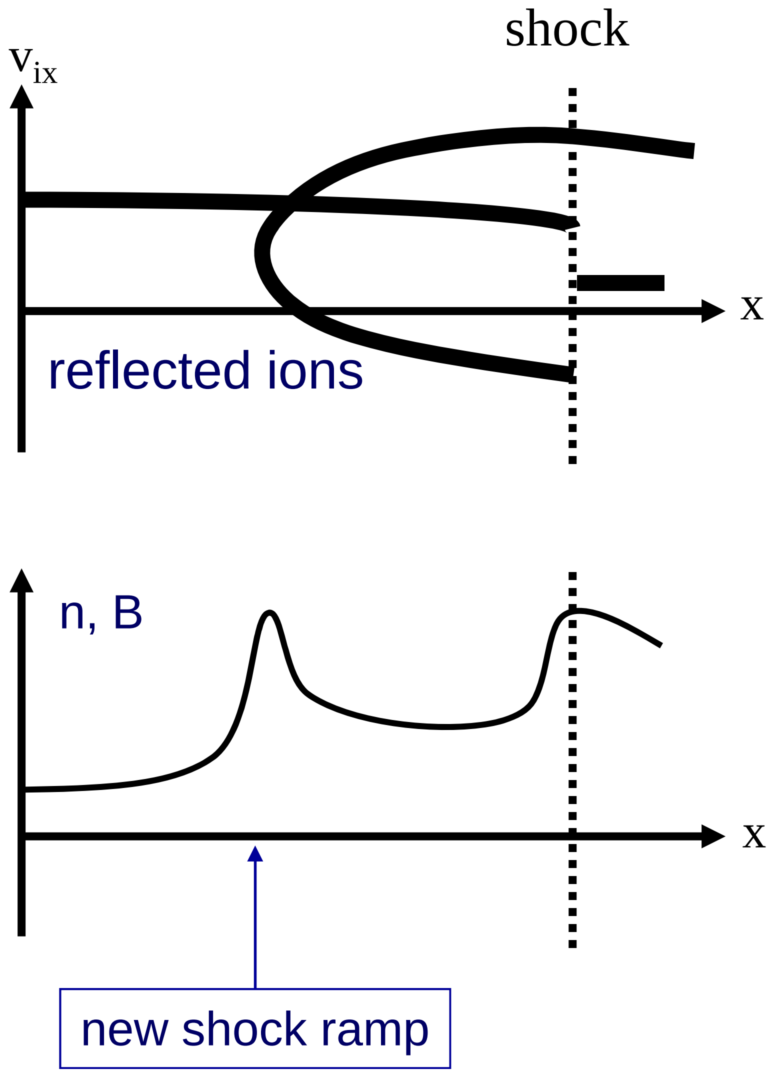



Shock reformation on time scale of about 300 inverse electron gyrofrequencies (about 3 inverse ion gyrofrequencies)

Lembege and Savoini 2002
Hada et al. 2003

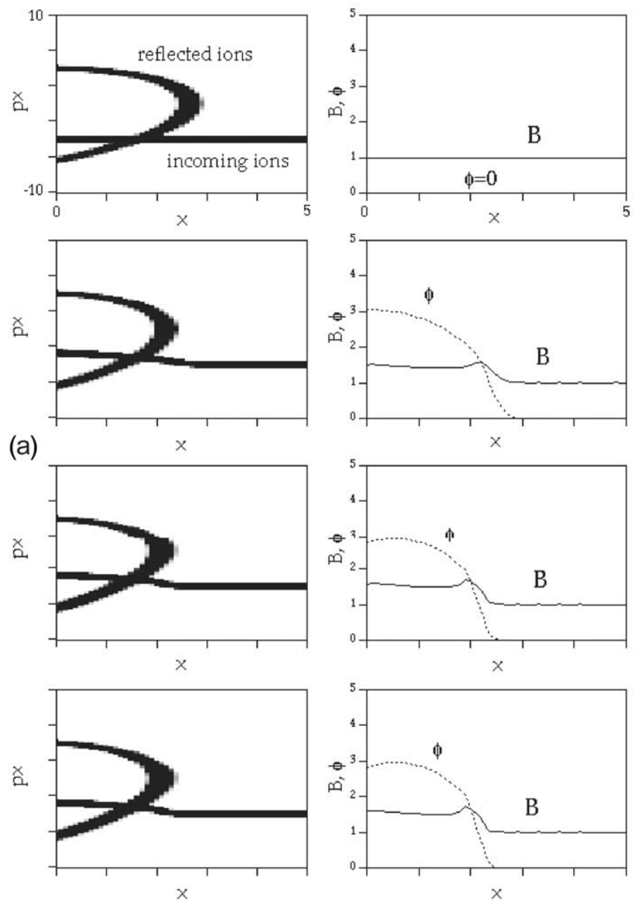
Hada et al. 2003

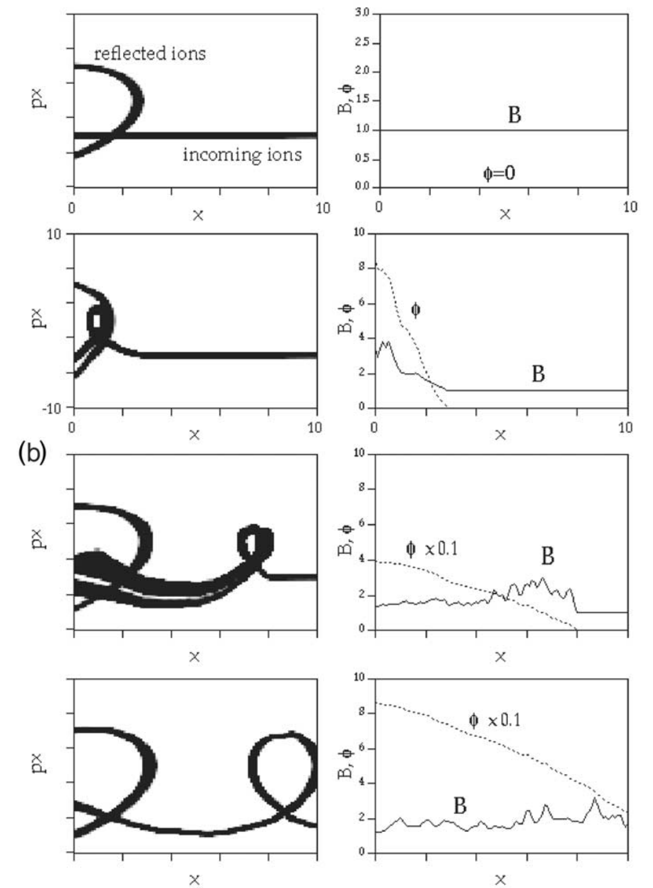
2. Self-reformation by ion accumulation at the upstream edge of the foot



Iteration of time-dependent hybrid equations (ions kinetic, electrons as fluid) for intial state with constant magnetic field, zero potential, incoming ions and reflected (gyrating) ions.

Ion phase space and field variables as number of iterations increases



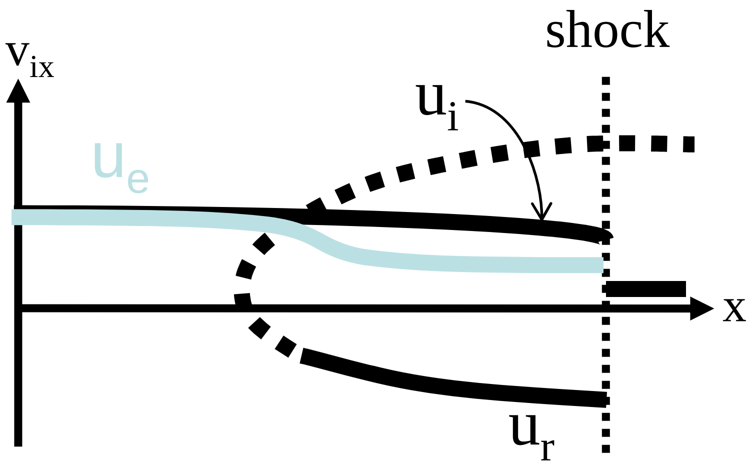

10% reflected ions:
time-stationary configuration

20% reflected ions:
Itertations do not converge

non-stationary

Scholer et al. 2003

# 3. Instabilities in the foot

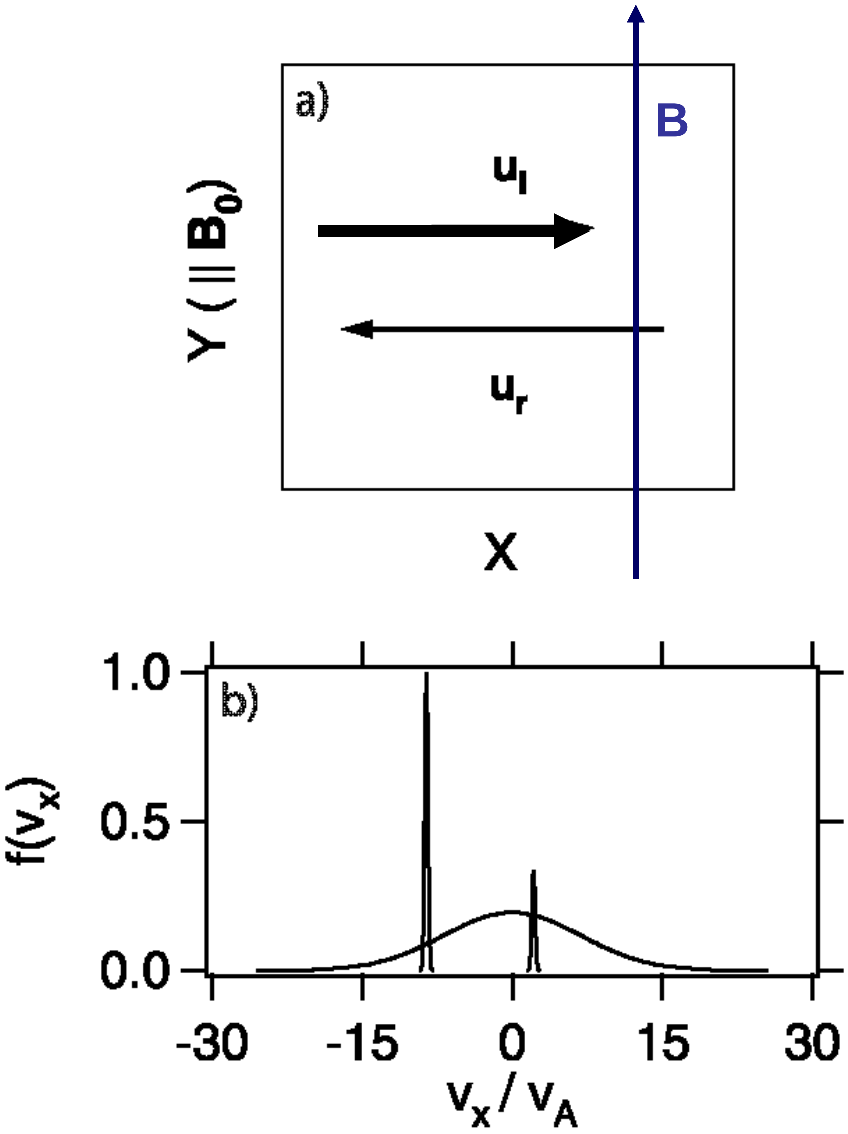



Source of instabilities

$$u_r \neq u_e$$

$$u_i \neq u_e$$

# Situation in the foot region of a perpendicular shock



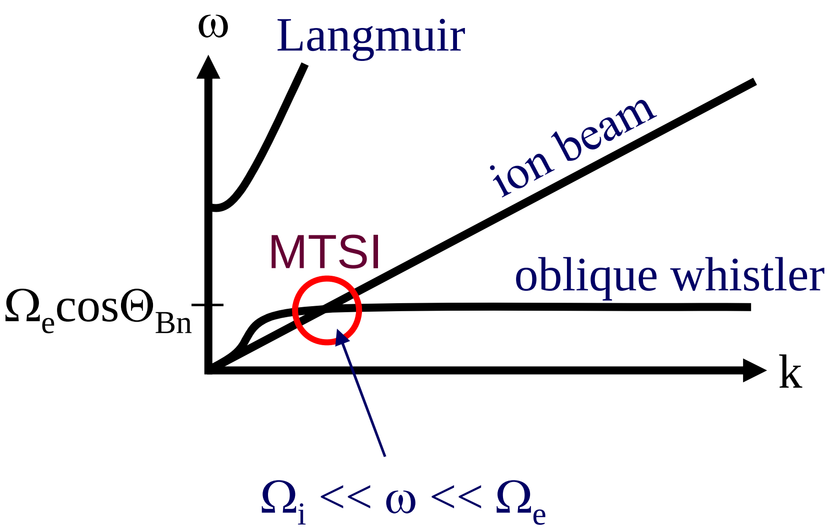

Ion and electron distributions in the foot

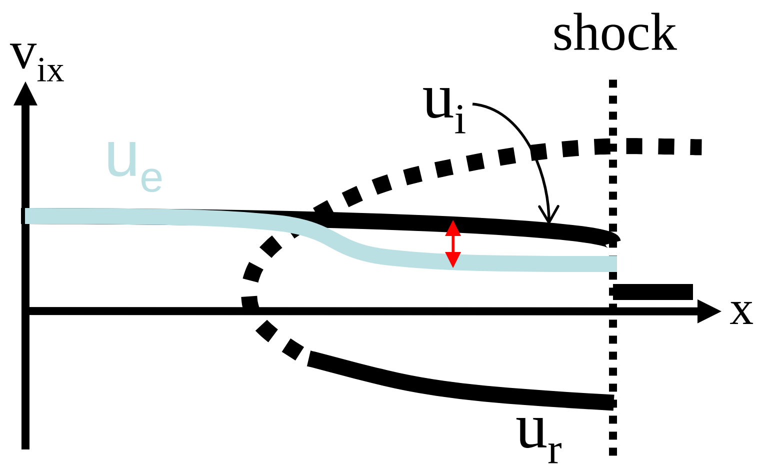
Ions: unmagnetized
Electrons: magnetized

# Microinstabilities in the Foot Region of Quasi-Perpendicular Shocks

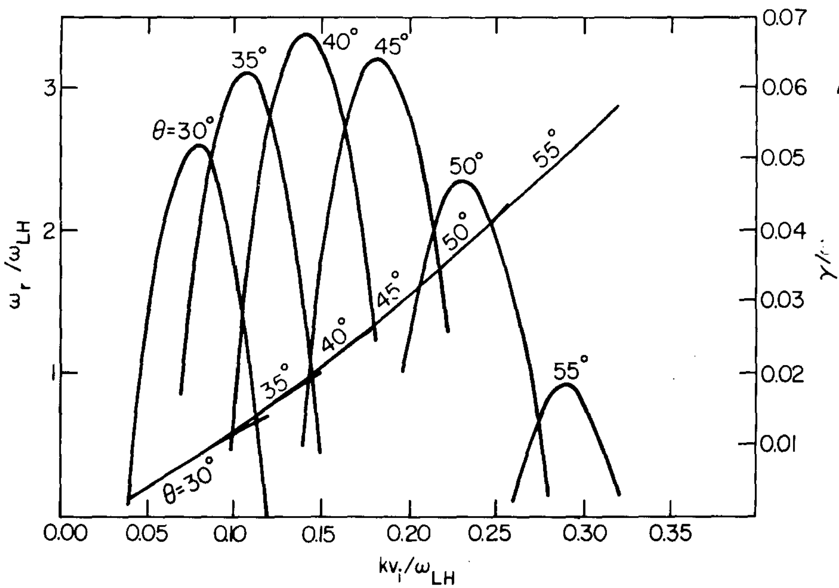
| | Wave type | Necessary condition |
|---|---|---|
| Buneman inst. | Upper hybrid (Langmuir) | $\Delta u \gg v_{te}$ |
| Ion acoustic inst. | Ion acoustic | $T_e \gg T_i$ |
| Bernstein inst. | Cyclotron harmonics | $\Delta u > v_{te}$ |
| Modified two-stream inst. | Oblique whistler | $\Delta u/\cos\theta > v_{te}$ |

# Modified Two-Stream Instability

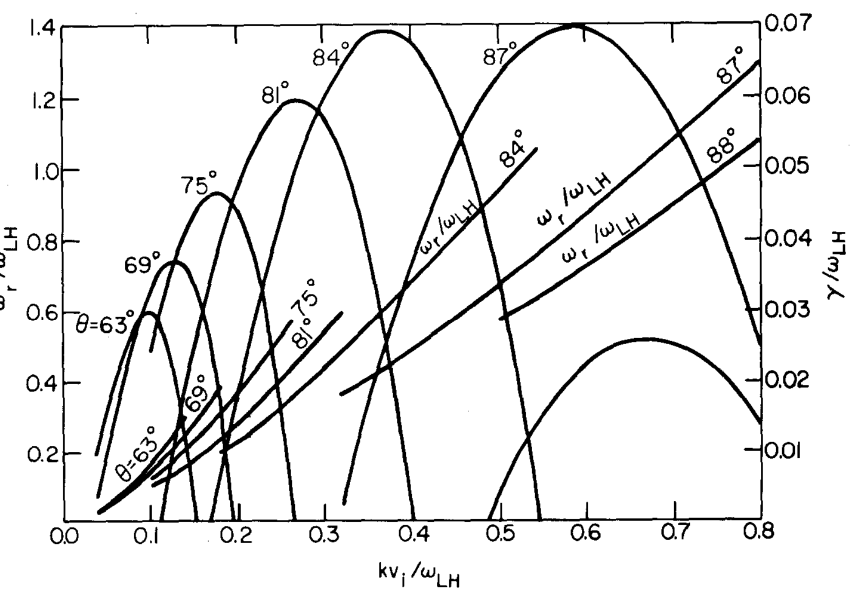



- unmagnetized ions ⟶ perpendicular trapping
- strongly magnetized electrons ⟶ parallel trapping




(a)




(b)

1983

# A kinetic cross-field streaming instability


C. S. Wu, Y. M. Zhou,[a] S. T. Tsai,[a] and S. C. Guo[a]
*Institute for Physical Science and Technology, University of Maryland, College Park, Maryland 20742*
D. Winske and K. Papadopoulos
*Department of Physics and Astronomy, University of Maryland, College Park, Maryland 20742*


1983

# MICROINSTABILITIES ASSOCIATED WITH A HIGH MACH NUMBER, PERPENDICULAR BOW SHOCK


C. S. WU[1], D. WINSKE[2], Y. M. ZHOU[1,3], S. T. TSAI[1,3], P. RODRIGUEZ[4], M. TANAKA[1], K. PAPADOPOULOS[2], K. AKIMOTO[2], C. S. LIN[5], M. M. LEROY[1,6], and C. C. GOODRICH[2]


Growth rate and real frequency of the modified two-stream instability for

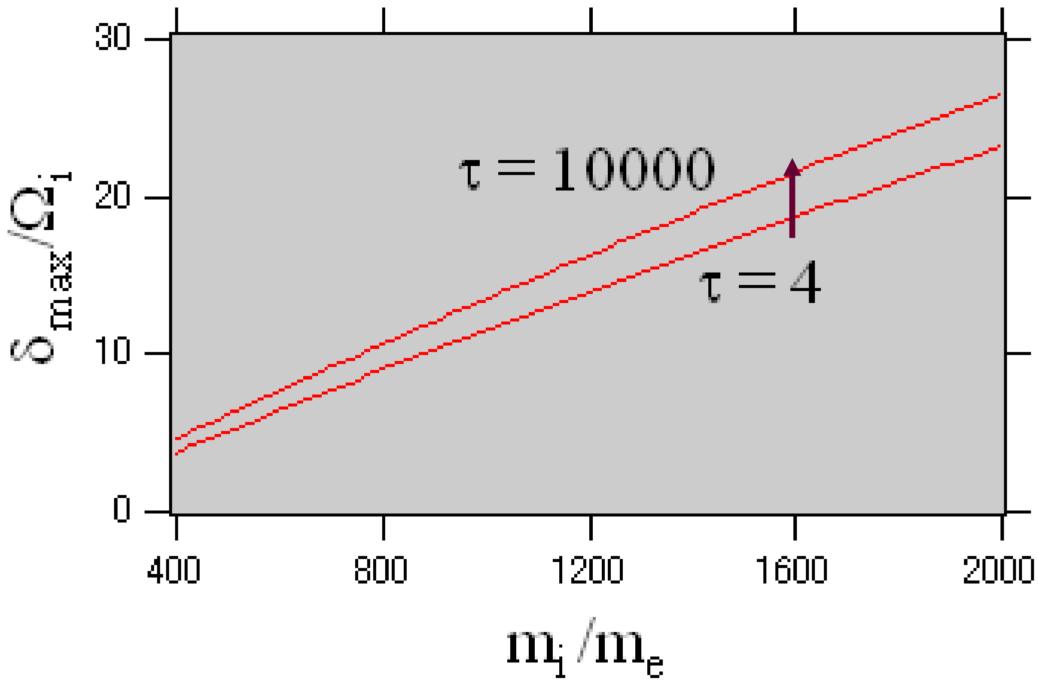
(a) reflected ions

(b) transmitted ions

for various angles $\Theta_{Bk}$

# Mass dependence of the maximum linear growth rate of MTSI

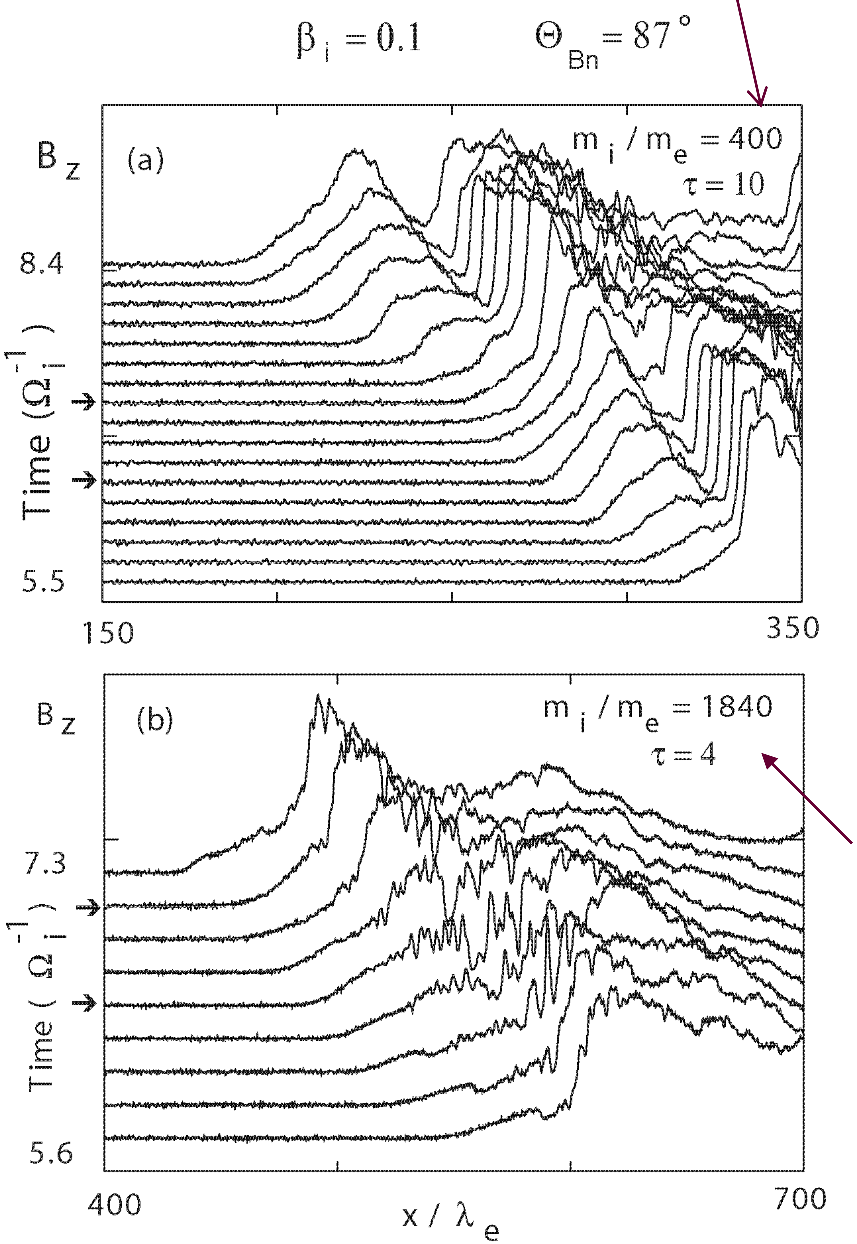
(Cold plasma dispersion relation)

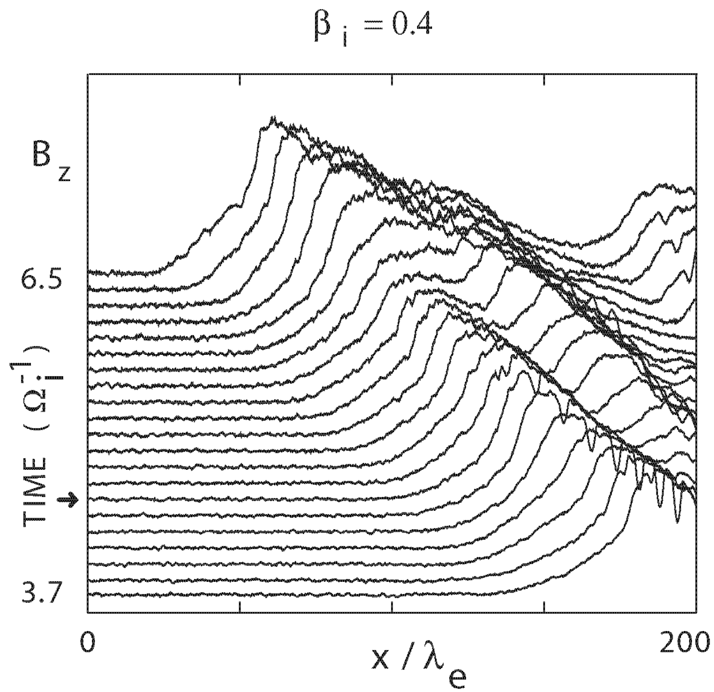



$\tau = \omega^2_{pe} / \Omega^2_{ce}$

Matsukiyo and Scholer 2003

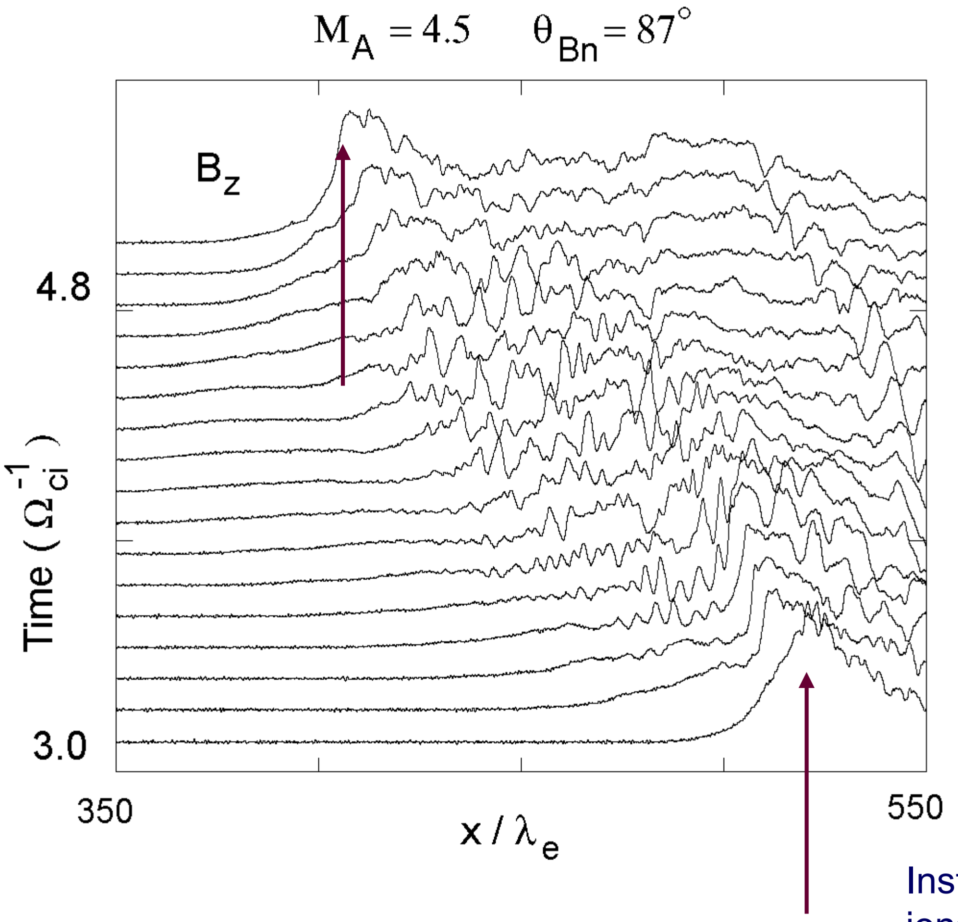
# Reformation of almost perpendicular medium Mach number shocks: Mass ratio and ion beta effect

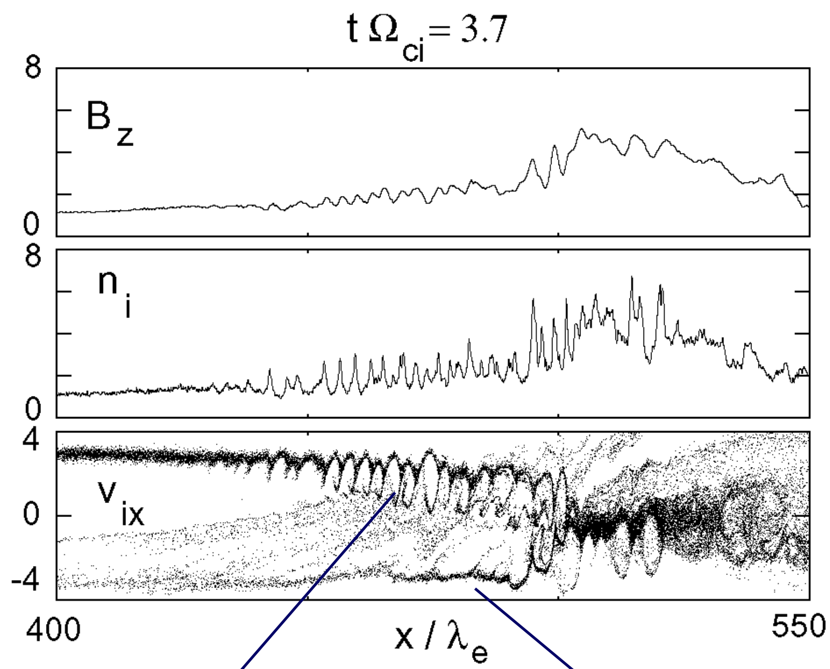



Higher beta: electron & ion Landau damping stabilizes

$$\beta_i = \beta_e = 0.05$$

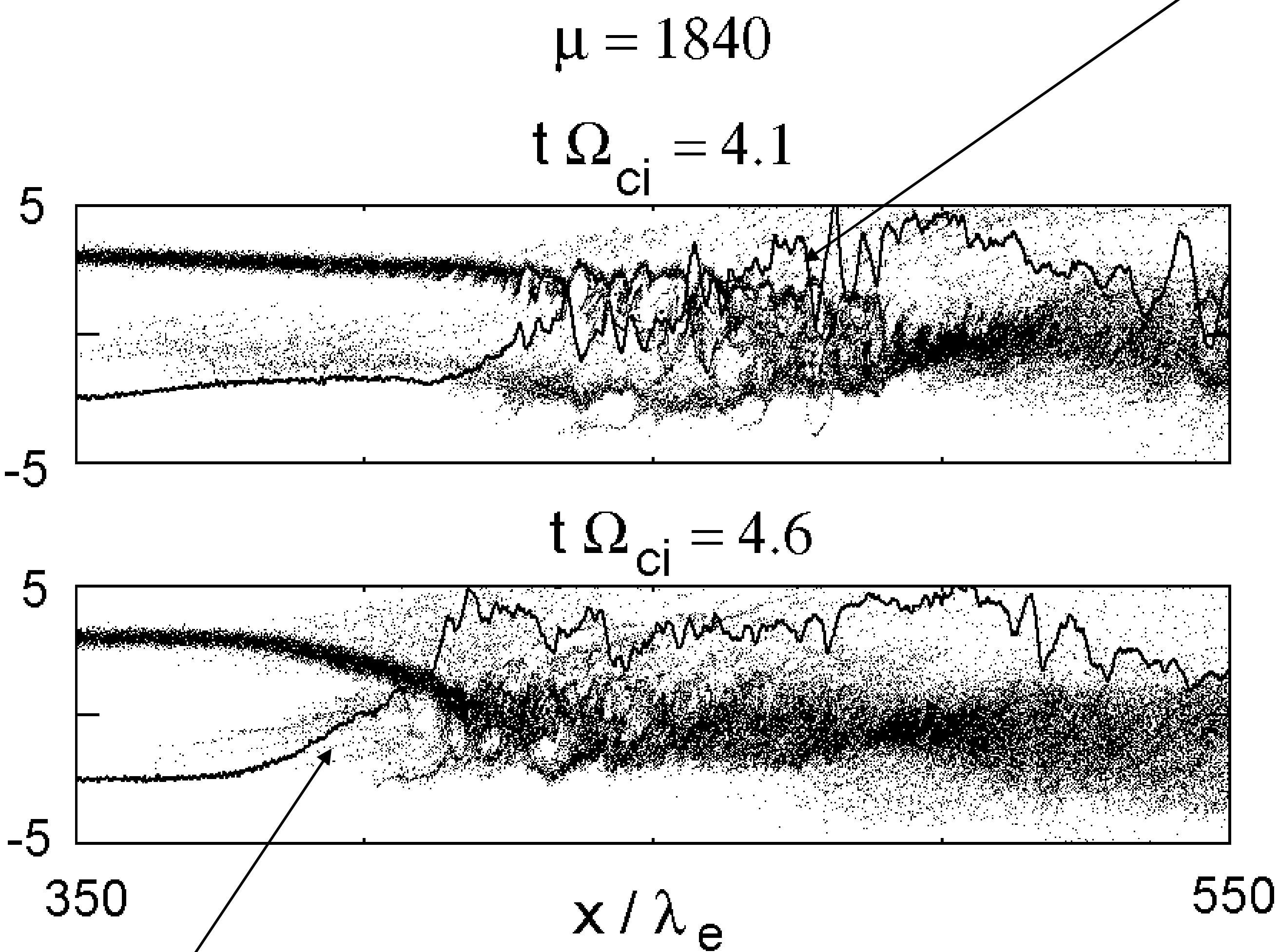



Instability between incoming ions and incoming electrons leads to perpendicular ion trapping

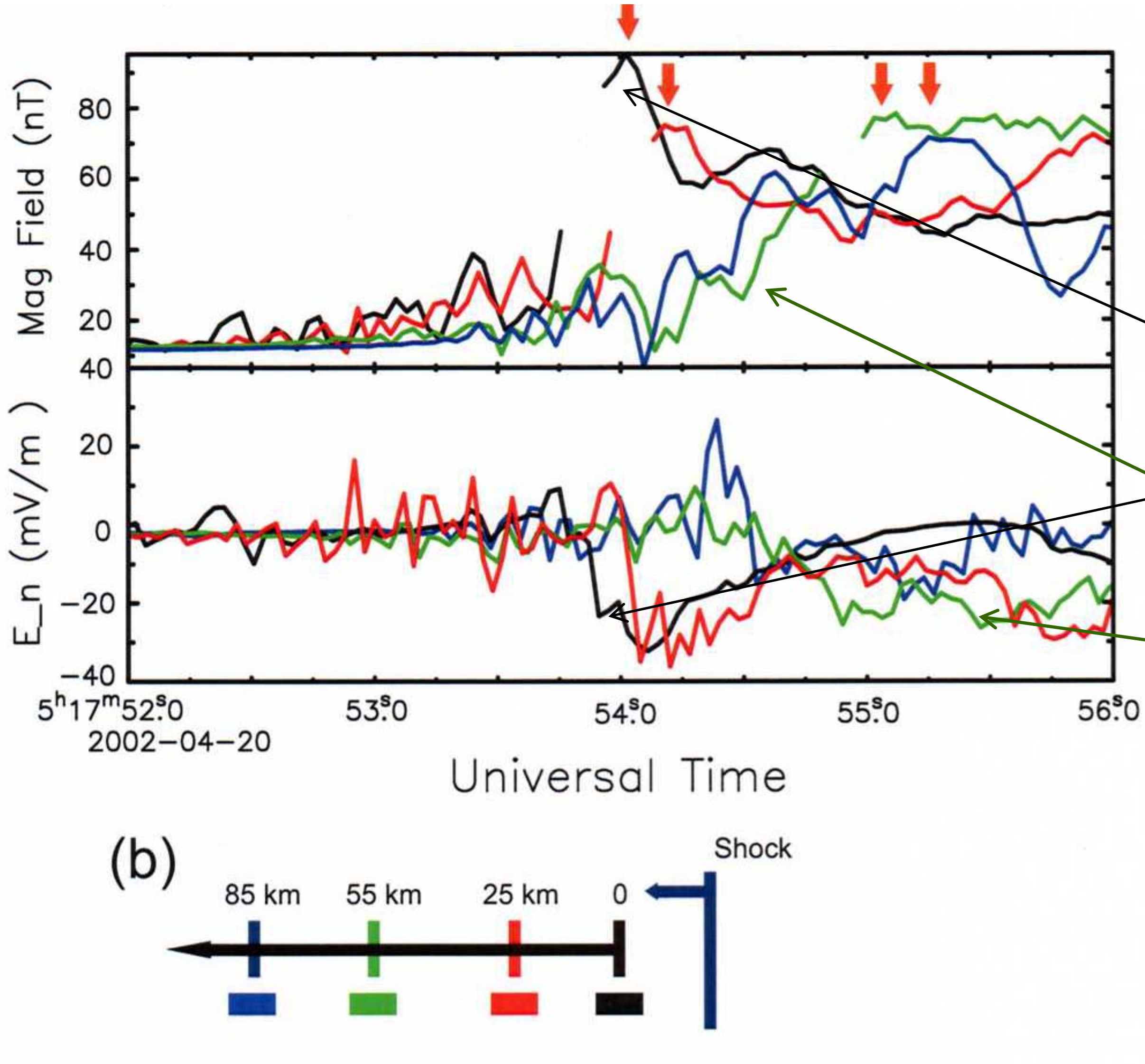
Reflected ions not effected

Phase-mixing – Ion thermalization




Shock reformation

$M_A = 8$ $\beta_\iota = 0.5$




Cluster magnetic and electric field observations of shock reformation

Steepend magnetic field and large electric field spike

Seki et al. in press 2009

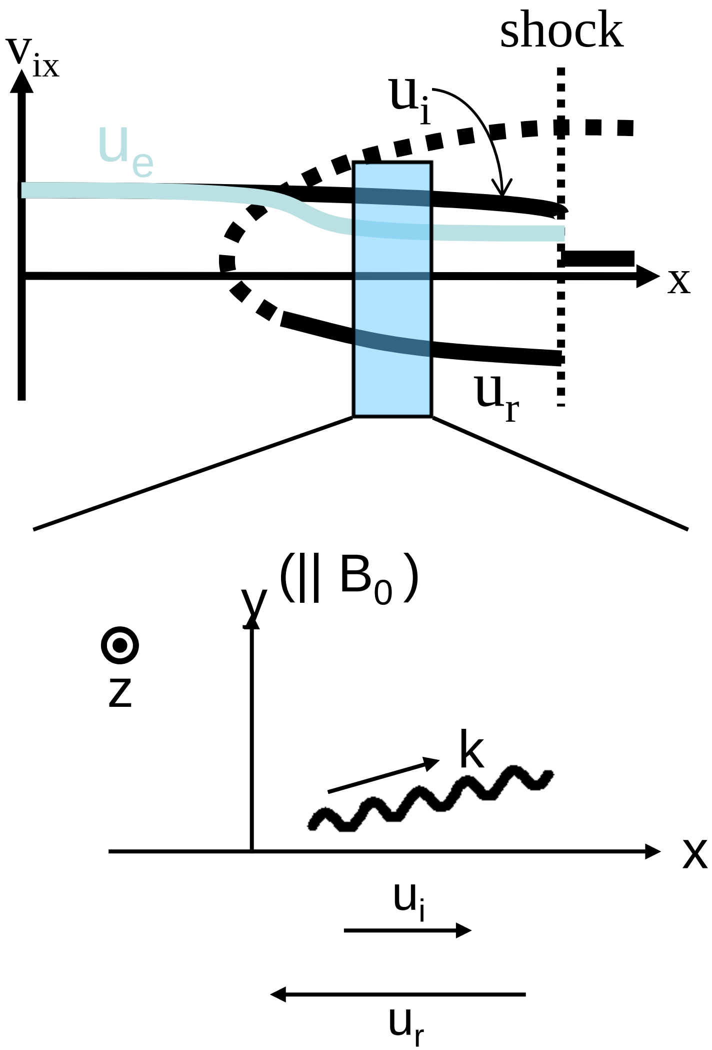
# Future of Shock Simulations

2-D PIC Simulations of Shocks  -  Instability-Induced Nonstationarity

2-D, 3-D (Hybrid) Global Bow Shock Simulations

Very High Mach Number Shock PIC Simulations – Electron acceleration

# 1. 2-D PIC Simulations of Ion/Ion Beams in a Periodic System




| | |
|---|---|
| Number of grids | 1,024 × 1,024 |
| Number of particles | 100 /cell |
| Time step | $0.02\ \omega_{pe}^{-1}$ |
| System length | $40.96\ c/\omega_{pe}$ |

$\omega_{pe}^2/\omega_{ce}^2 = 4$

$m_i/m_e = 1836$

$\beta_i = \beta_r = 0.05$

$\beta_e = 0.05$

$M_A \sim 10$

Matsukiyo and Scholer 2006

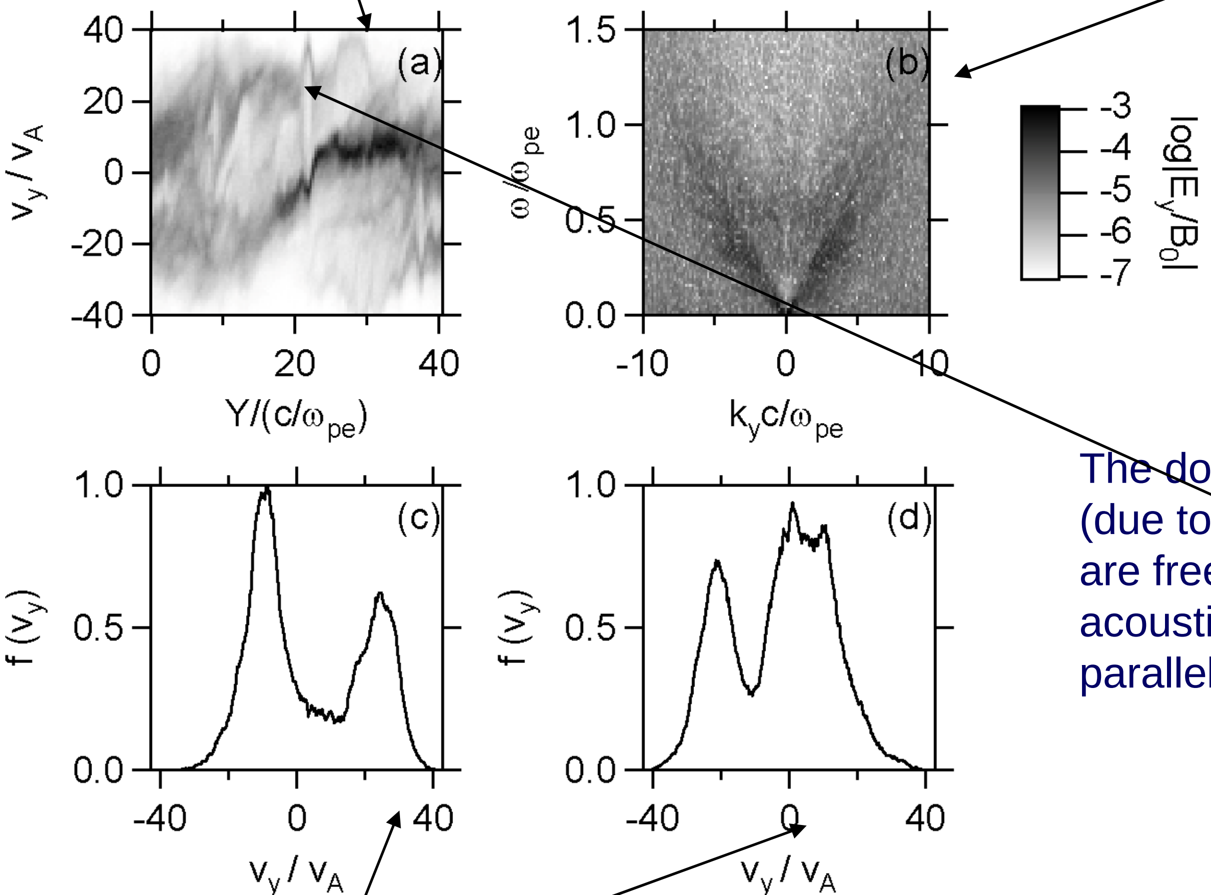
# Two-Step Instabilities

1. MTSI between reflected /transmitted ions and electrons → Parallel electron acceleration

2. Electron acoustic instability – electron heating

Electron phase space $v_y$ at a certain x

Power spectrum of $E_y$ electric field component (broad-band fluctuations typical for EAI)

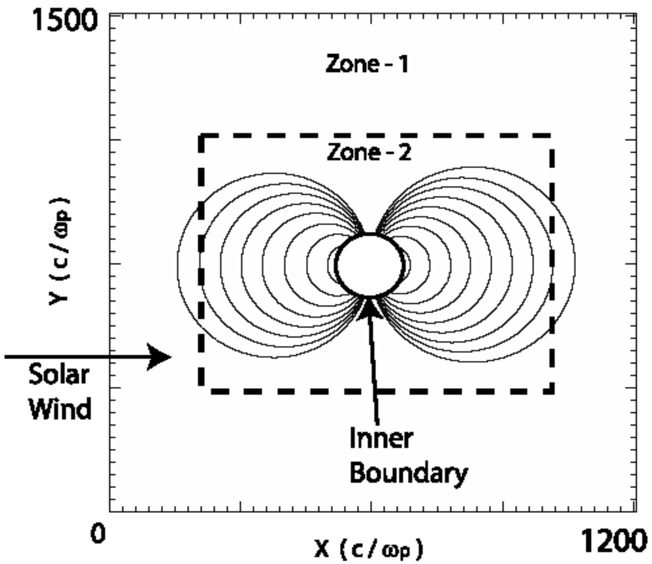


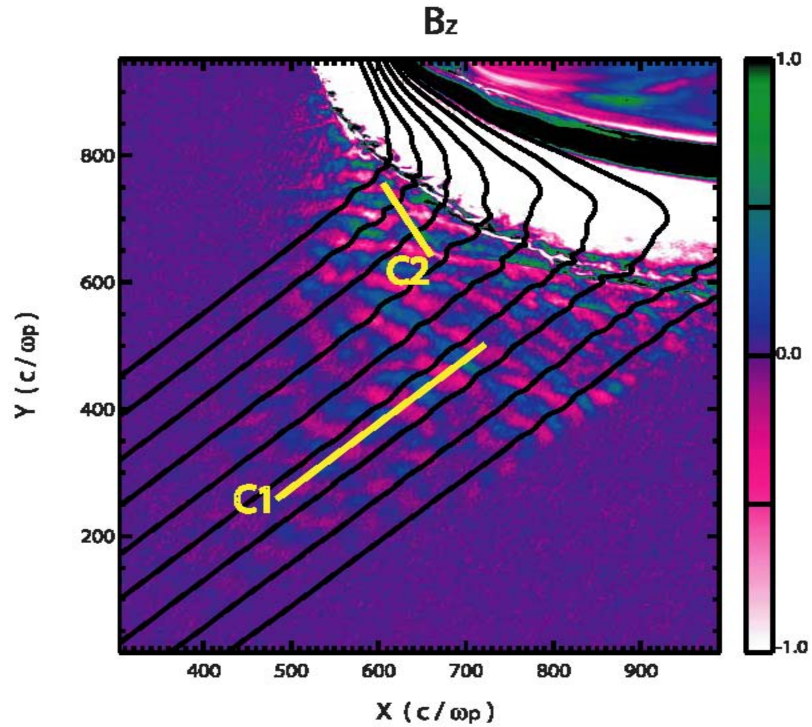

The double peaked electron distributions (due to the modified two-stream instab.) are free energy source for electron acoustic instability. Small scale vortices – parallel electron heating.

Two local distribution functions

# 2. 2-D Global Hybrid Simulation

Omidi, Blanco-Cano, Russell 2005

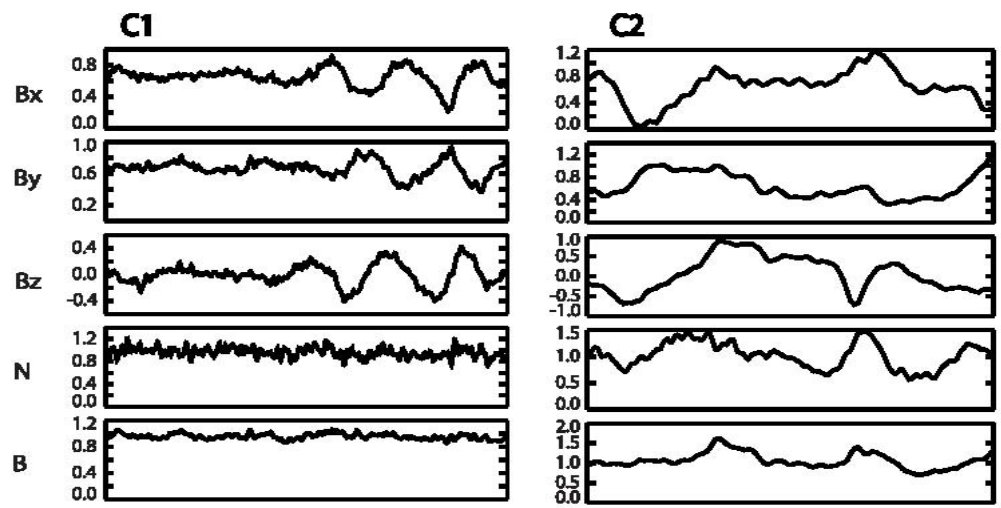



$D_p$= 64

$D_p$ = magnetopause standoff distance/
ion inertial length

(at 1 AU inertial length is about 100 km)



# 3. Very High Mach Number Shocks - SNRS

**ELECTRON HEATING IN SUPERHIGH MACH NUMBER SHOCKS***

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*Department of Physics and Astronomy, University of Maryland, College Park, MD, U.S.A.*

(Received 15 July, 1987)

1. Excitation of the Buneman Instability in the foot $\longrightarrow$ Electron heating

2. Excitation of Ion-Acoustic Instability $\longrightarrow$ Further strong electron heating

Cargill and Papadopoulos 1988: hybrid simulation of a Mach number $M_A = 50$ shock with phenomenological resistivity

# Buneman Instability

$\Delta u \gg v_{the}$

Suppressed when

$\beta_e > 4 (1 - \alpha) M_A^2 / \mu$ where $\mu$ = ion/electron mass ratio
$\alpha$ ratio of reflected ions

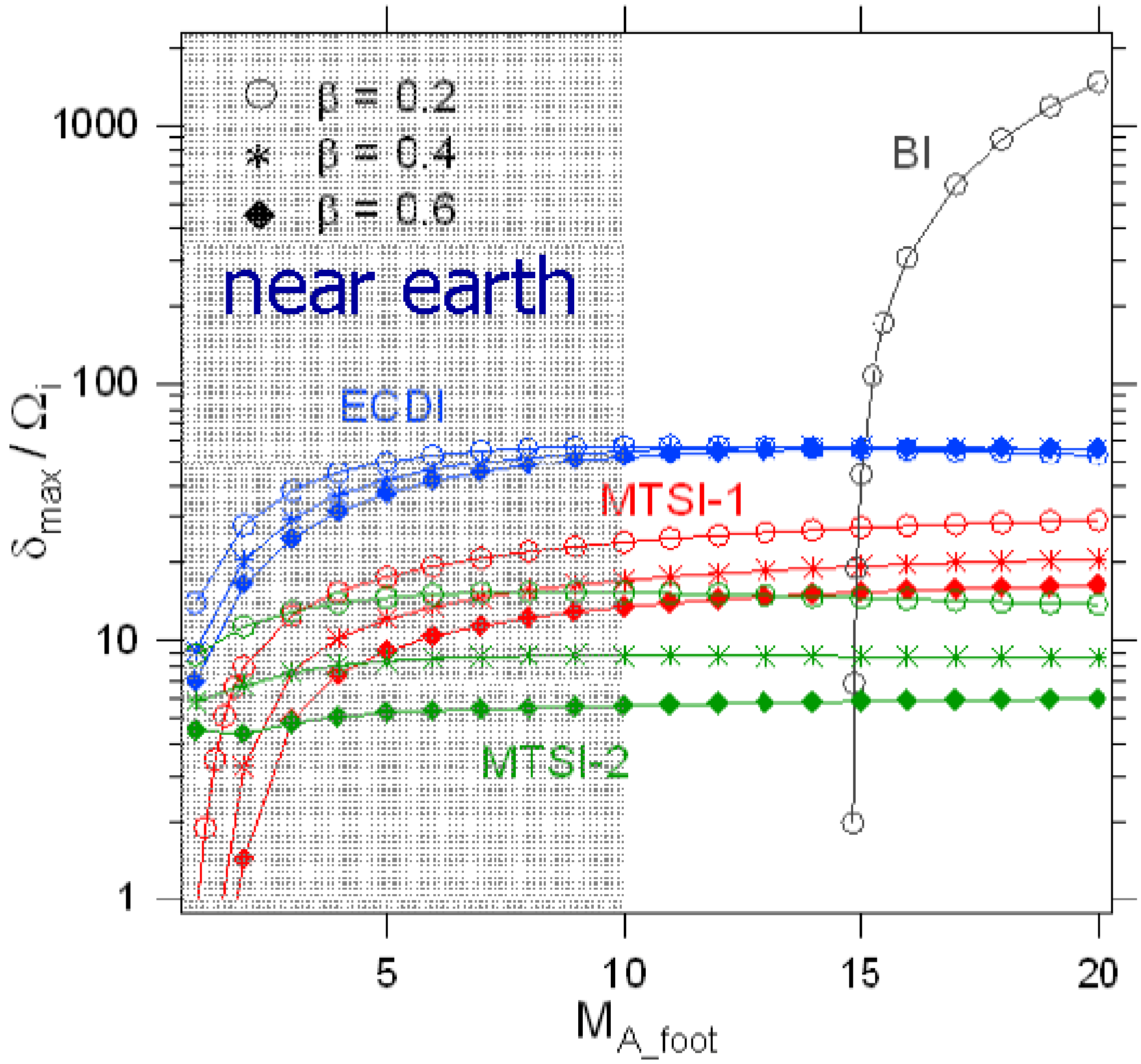
with $\mu = 1836$, $\alpha = 0.2$ this results in

$$\boxed{\beta_e > M_A^2 / 720}$$

(always fullfilled at Earth‘s bow shock)

But: when using in PIC simulationssmall mass ratio $\mu$ the Buneman Instability can get excited at smaller Mach number

$(\omega_{pe}/\Omega_e = 50,\ m_i/m_e = 1836,\ \Theta_{Bn} = 90^o)$



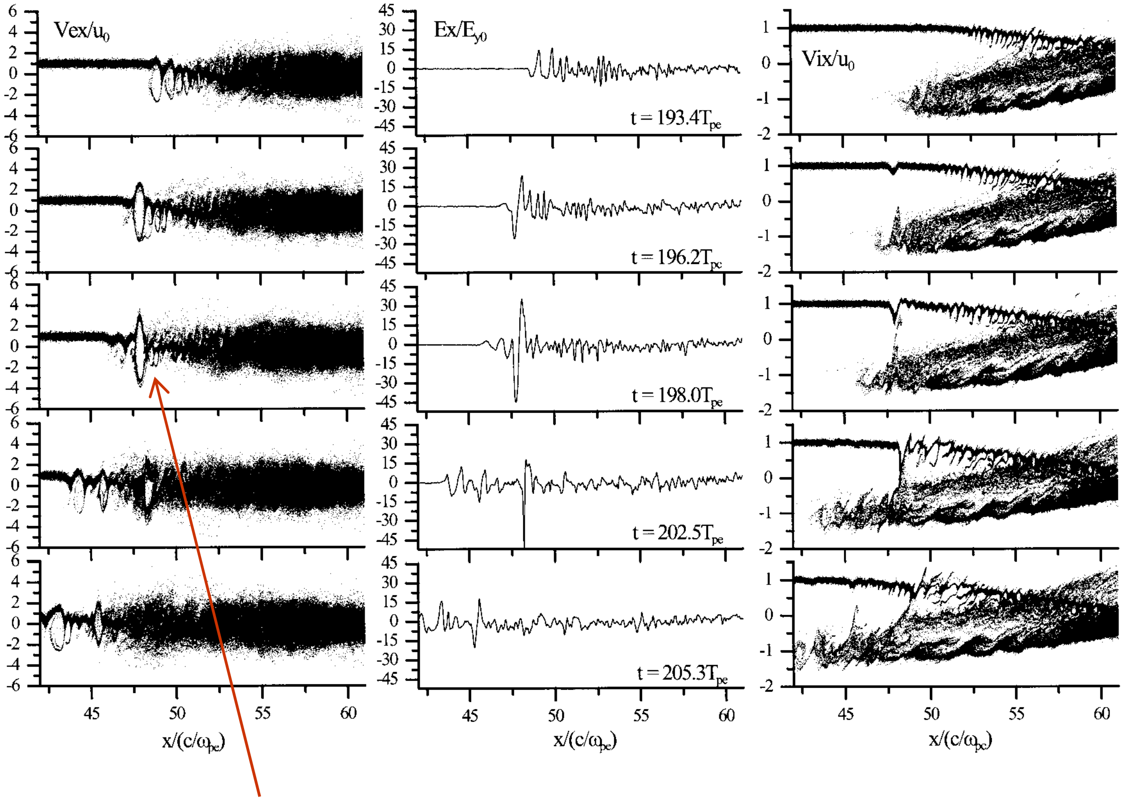

Matsukiyo 2009

# PIC Simulations: Buneman-Instability (BI) in the Foot and Electron Acceleration

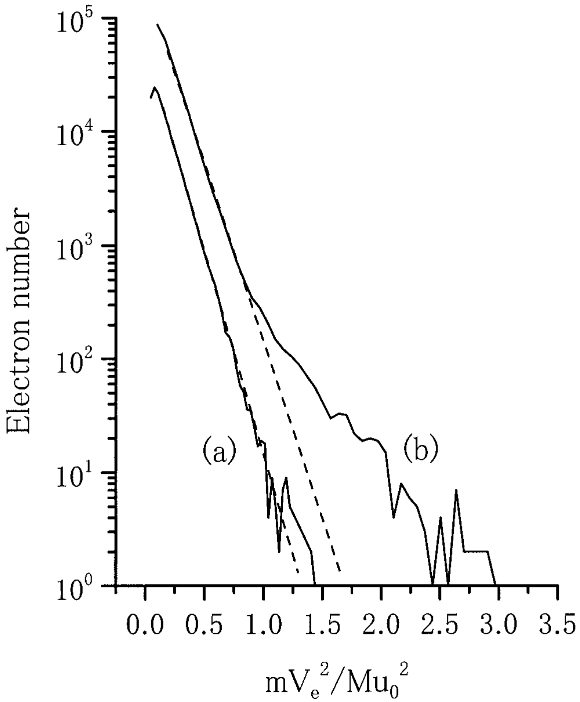
Shimada and Hoshino 2000

$M_A = 10.5$ $m_i / m_e = 20$

$$\nu = \frac{\omega_{pe}}{\Omega_{ce}} = \frac{c}{V_A}\sqrt{\frac{m_e}{m_i}} = 20$$



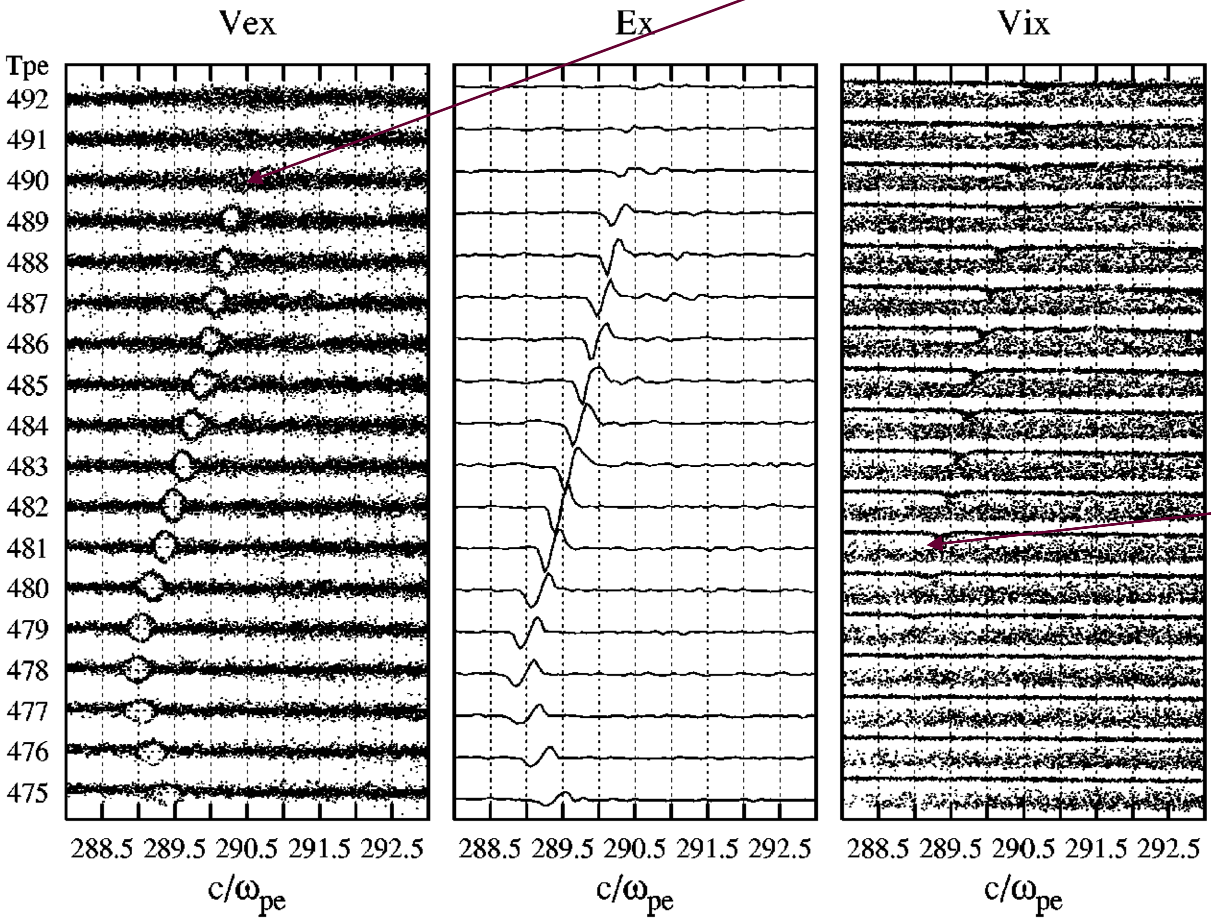

Nonlinear state of the BI: electron holes




Downstream electron energy spectra for (a) low and (b) high Mach Number run

Large-amplitude electron hole couples to ions via ion acoustic fluctuations.
Decelerates incoming and reflected ions and leads to further potential increase in the hole.

Hole disappears and electrons are heated and accelerated




Coupling of hole to the incoming ions

Numerical simulations have led to better understanding of features observed in situ at Earth‘s bow shock (ISEE).

Simulations have predicted new features/processes at shocks which have subsequently been verified by in situ observations at Earth‘s bow shock (Cluster).

Comparison of simulation and in situ observations allows verification of the validity of the simulation model/method.

Simulations allow access to parameter regimes (in astrophysical settings) not directly accessable by observations.