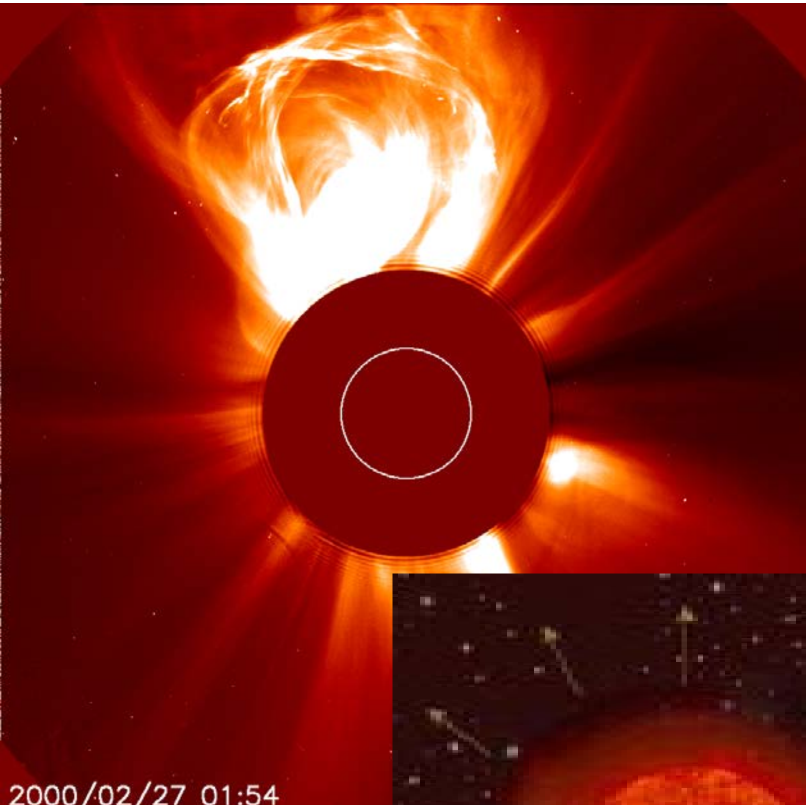
Hybrid Simulation Techniques for Space Plasmas

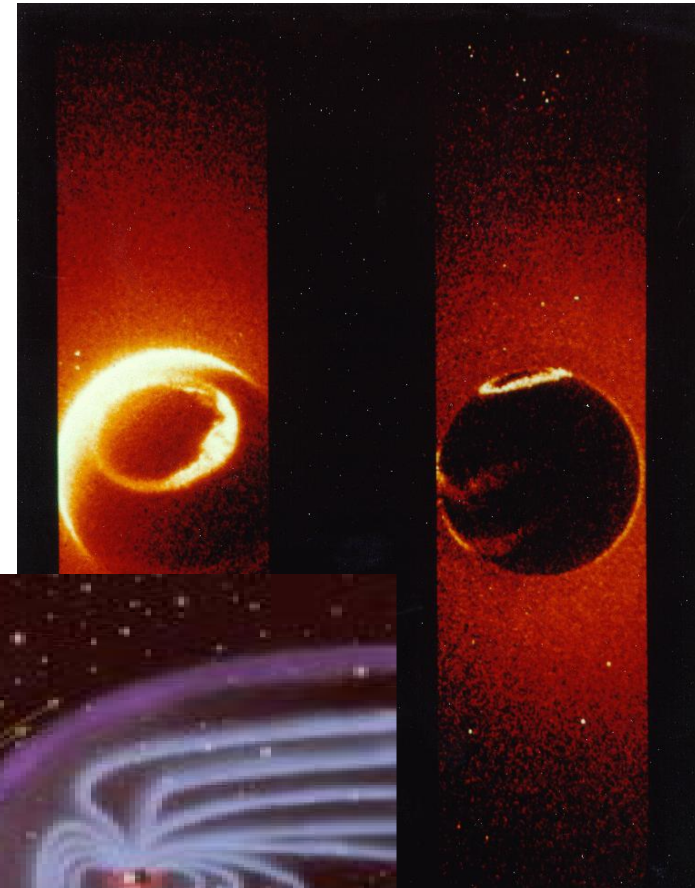
Fundamental processes in space weather, 2012

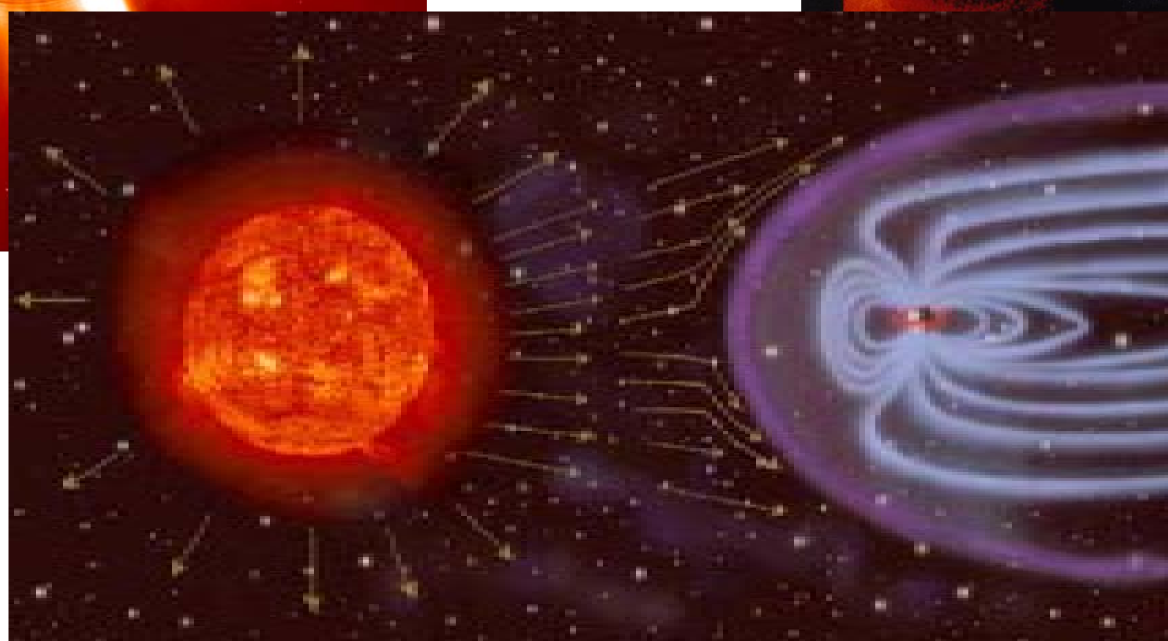
David Burgess
Astronomy Unit
Queen Mary University of London

With thanks to Dietmar Krauss-Varban

Space Plasmas: From Sun to Earth







Space Plasma

- Plasma is (mostly) electrons and protons
- Plasma is (mostly) fully ionized
- Plasma is (mostly) collisionless
- Plasma is (mostly) magnetized

- Collisionless → Vlasov-Maxwell system
- Magnetized → Fluid (MHD) system

The Problem: Plasma = Particles

- Problem:
  - Vlasov-Maxwell system in terms of phase space density function $f(x,v,t)$ which depends on $x_i(t)$, $v_i(t)$ of particles $i=1..N$ where N enormously large

- Dimensionality of psd $f(x,v,t)$ makes simulation difficult in terms of resources
  - Vlasov simulations, usually just 1d in space

- Kinetic effects are vital to explain collisionless plasmas

Solution 1: Fluid Simulation

Compute moments – use equations for macroscopic moments density, velocity

Plus fields => MHD

All quantities function time, can use grid based methods, etc as for ordinary fluid. (Or alternative methods.)

Solution 2: Particle Simulation

Follow ion and electron macro-particles – compute moments on grid (PIC) for density, currents etc

Calculate field evolution on grid based on particle moments

Vlasov-Maxwell system with Lagrangian particles and Eulerian fields.

Kinetic scales

	Ions	Electrons
Cyclotron frequency	$\Omega_{ci} = eB/m_p$ $\tau_{ci} \sim 0.5 - 10\text{s}$	$\Omega_{ce} = 1836\Omega_{ci}$
Plasma frequency	$\omega_{pi} = \left(\frac{ne^2}{\epsilon_0 m_i}\right)^{1/2}$ $\omega_{pi}/\Omega ci \sim 100 - 10,000$	$\omega_{pe} = 40\omega_{pi}$
Thermal gyro-radius	$\rho_i = v_{th,i}/\Omega_{ci}$ $\rho_i \sim 20 - 200\text{km}$	$\rho_e = \rho_i/40\ (T_e = T_i)$
Inertial length (skin depth)	$\lambda_i = c/\omega_{pi}$ $(\rho_i/\lambda_i)^2 = \beta \sim 0.5 - 10$	$\lambda_e = \lambda_i/40$

Plasma Kinetic Scales

- Electron time scales
  - much shorter than for ions

- Electron lengths scales
  - much smaller than for ions

(At least for Solar Wind at 1AU)

Solution 3: Hybrid Methods

The BIG idea ... to get around scales problem

- Some of plasma = particles
- Some of plasma = fluid

- PIC method for one particle type
- Fluid (grid) methods for other species
- Fields on grid

Separation of scales required

- fluid-like at one of scales
- capture kinetic behaviour at different scale

Scales Again ...

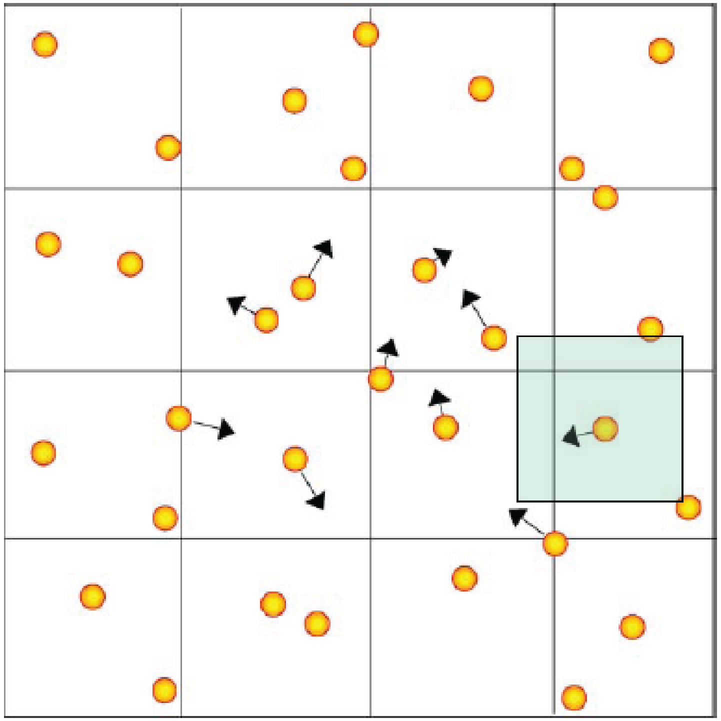
Thought experiment...

- Energy at large scales
  - Cascade to smaller scales eg by steepening
    - Reaches ion scales
      - But electrons still behaving as a fluid

- Hybrid with particle ions and electron fluid
- Valid for certain range of scales
- There are other kinds of hybrid

Hybrid Codes: Ion PIC Method

- "Finite size" ion particles
- Follow motion in E,B on grid
- Collect & interpolate moments onto grid
- Solve E.M. fields on grid



Where have the electrons gone?

Hybrid Method: System Equations

- Electrons
  - massless, charge neutralizing fluid

$$en_e = q_i n_i$$

  - Momentum equation

$$\frac{d}{dt}(n_e m_e \vec{v}_e) = 0 = -en_e(\vec{E} + \vec{v}_e \times \vec{B}) - \nabla P_e$$

  -Closure relation for electron pressure:
    - scalar pressure with constant temperature,
    - scalar pressure with adiabatic law
    - pressure tensor
    - etc.
  - Other types of electron fluid equation (eg with mass)

Hybrid Method: System Equations

- Particle ions

$$
\begin{aligned}
m_i \frac{d\vec{v}_i}{dt} &= q_i(\vec{E} + \vec{v}_i \times \vec{B}) \\
\frac{d\vec{x}_i}{dt} &= \vec{v}_i
\end{aligned}
$$

- Solve with standard PIC leap frog
  - position and velocity out of synchronization by half time step
- Collect moments on to grid

Hybrid Method: System Equations

- Electromagnetic Fields
  - Faraday's Law

$$\frac{\partial \vec{B}}{\partial t} = -\nabla \times \vec{E}$$

  - Ampere's Law

$$\nabla \times \vec{B} = \mu_0 \vec{J} = \mu_0 n_i q_i (\vec{V}_i - \vec{V}_e)$$

  - Electron momentum equation

$$\vec{E} = -\vec{V}_i \times \vec{B} - \frac{1}{n_i q_i} \nabla P_e - \frac{1}{\mu_0 n_i q_i} \vec{B} \times (\nabla \times \vec{B})$$

  - Electric field is a "state" quantity

Hybrid Method

- Faraday Law to advance B field

- State equation for E field

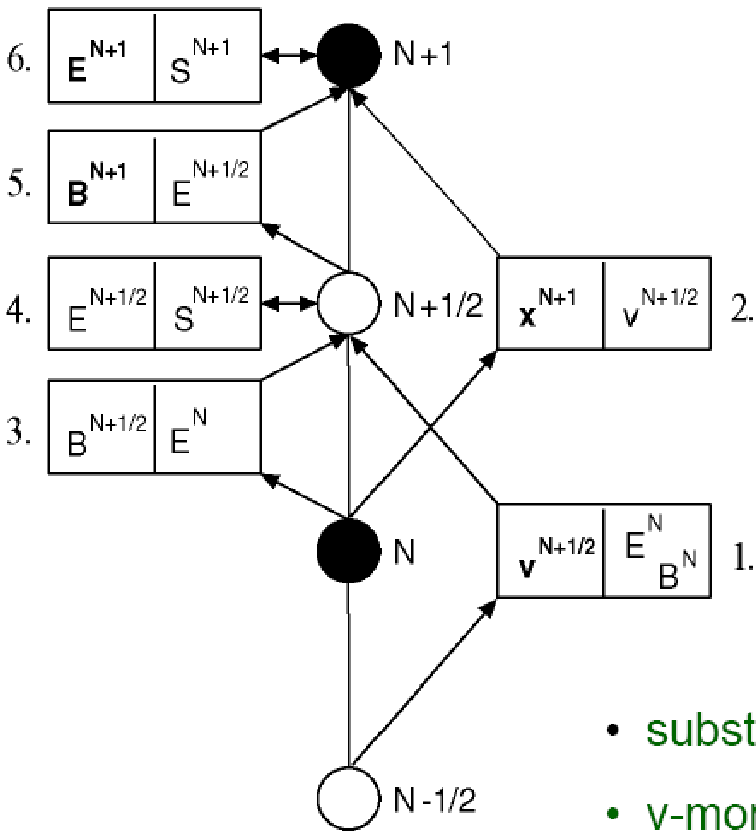
- Leapfrog for ion particle position and velocity
    - Information not necessarily available at “right” time

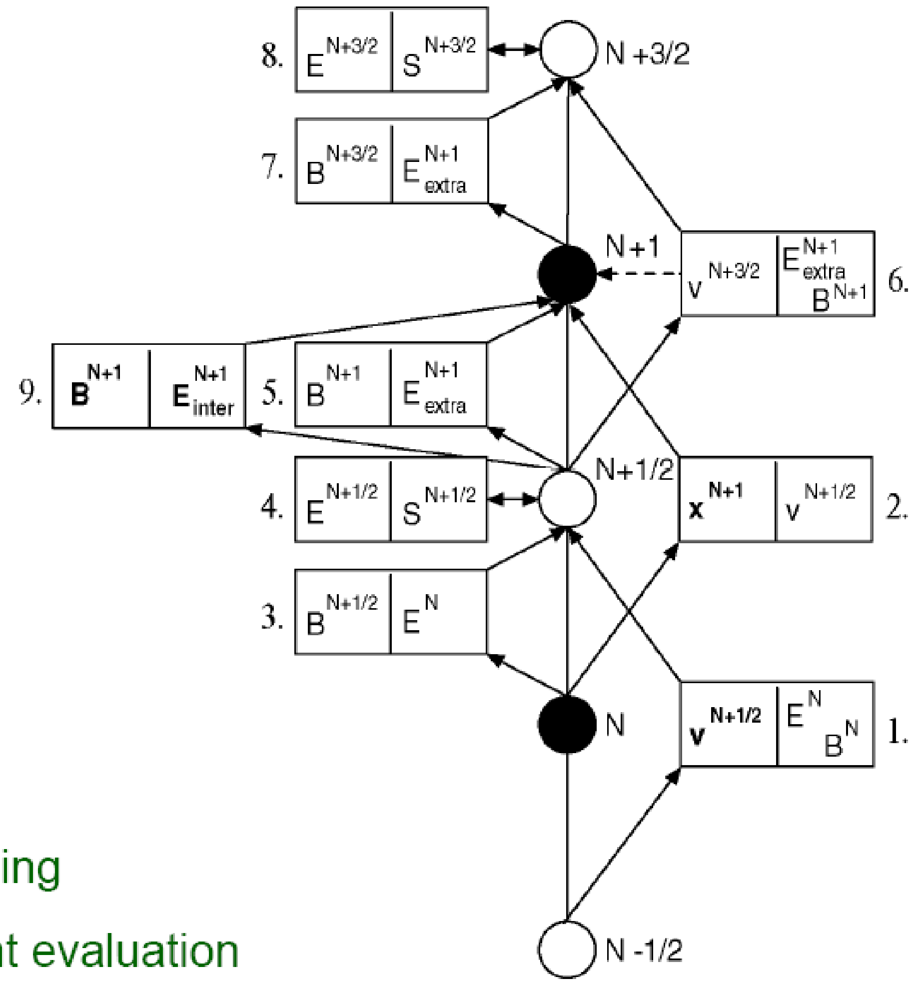
- Different algorithms:

  - Predictor-corrector
  - Moment method (CAM-CL)
  - One-pass
  - Variations: Resistivity, finite electron mass, full electron pressure tensor, model electron energy equation, etc.

Flow Charts:

Simple Explicit Method vs. Predictor-Corrector





- substepping
- v-moment evaluation

Moment Methods (CAM-CL)

- Use moment method to advance unknown velocity or current density ½ step ahead
- Faster than additional particle push required in P-C
- Collect appropriate moments and apply a separate equation of motion
- CAM-CL:

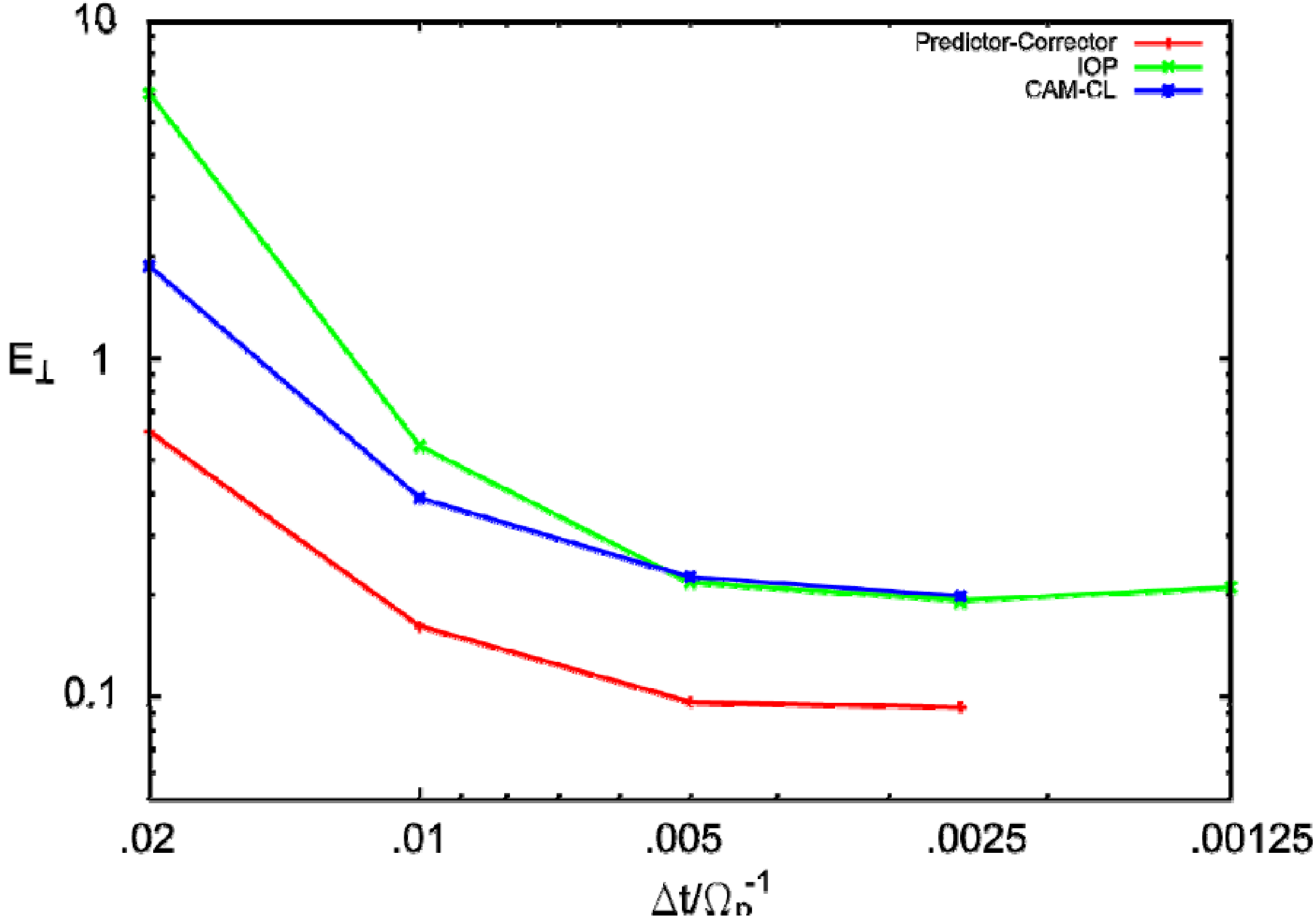
  - current density → easier to include multiple species

  - advective term absent (included via time centering)

  - no ion pressure tensor required

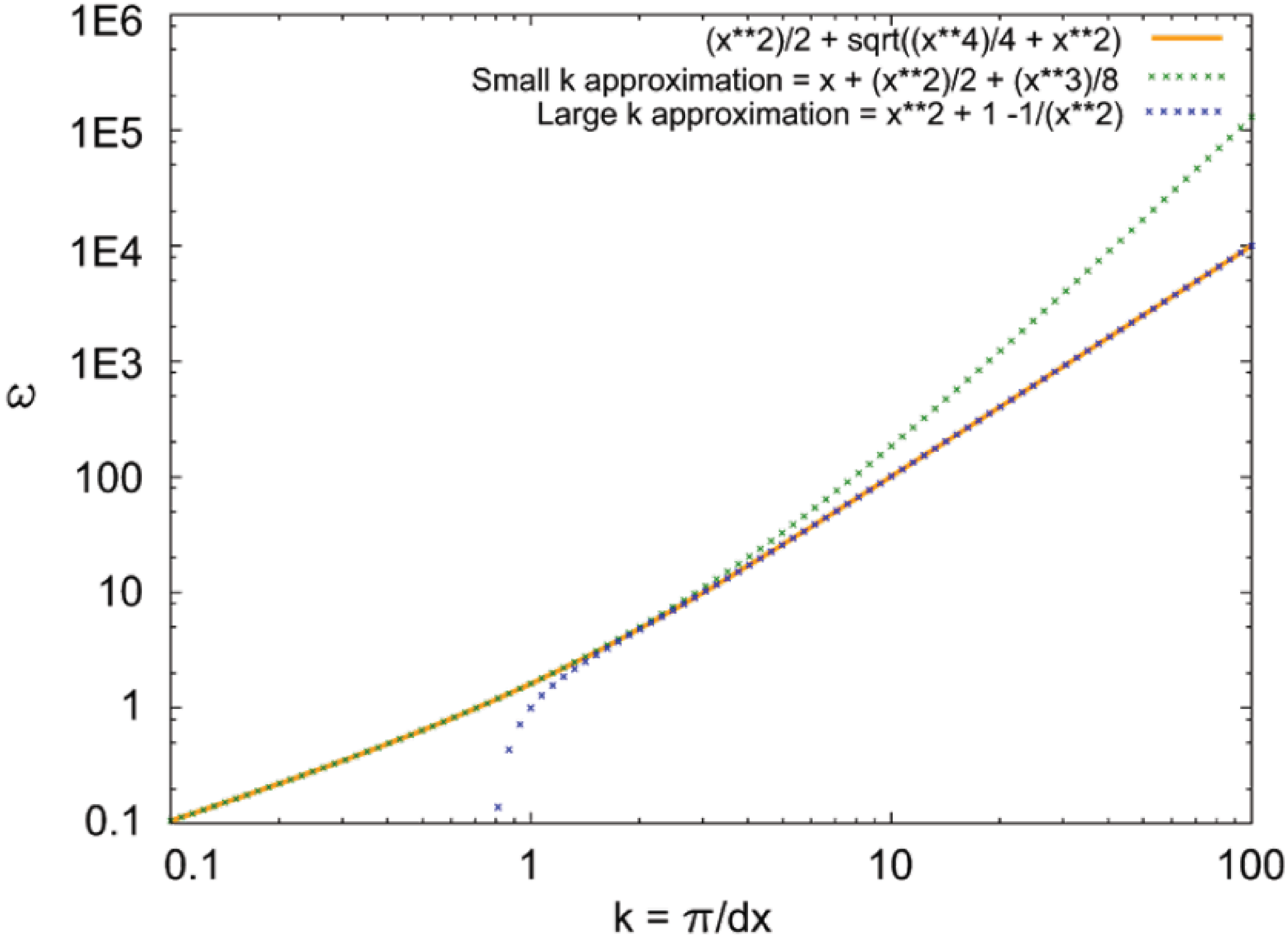
Matthews, 1994

Numerical Properties:
Drifting Plasma Regions with Anti-Parallel Fields



Numerical Properties:

Dispersion Relation of Parallel Whistlers



Numerical Properties:

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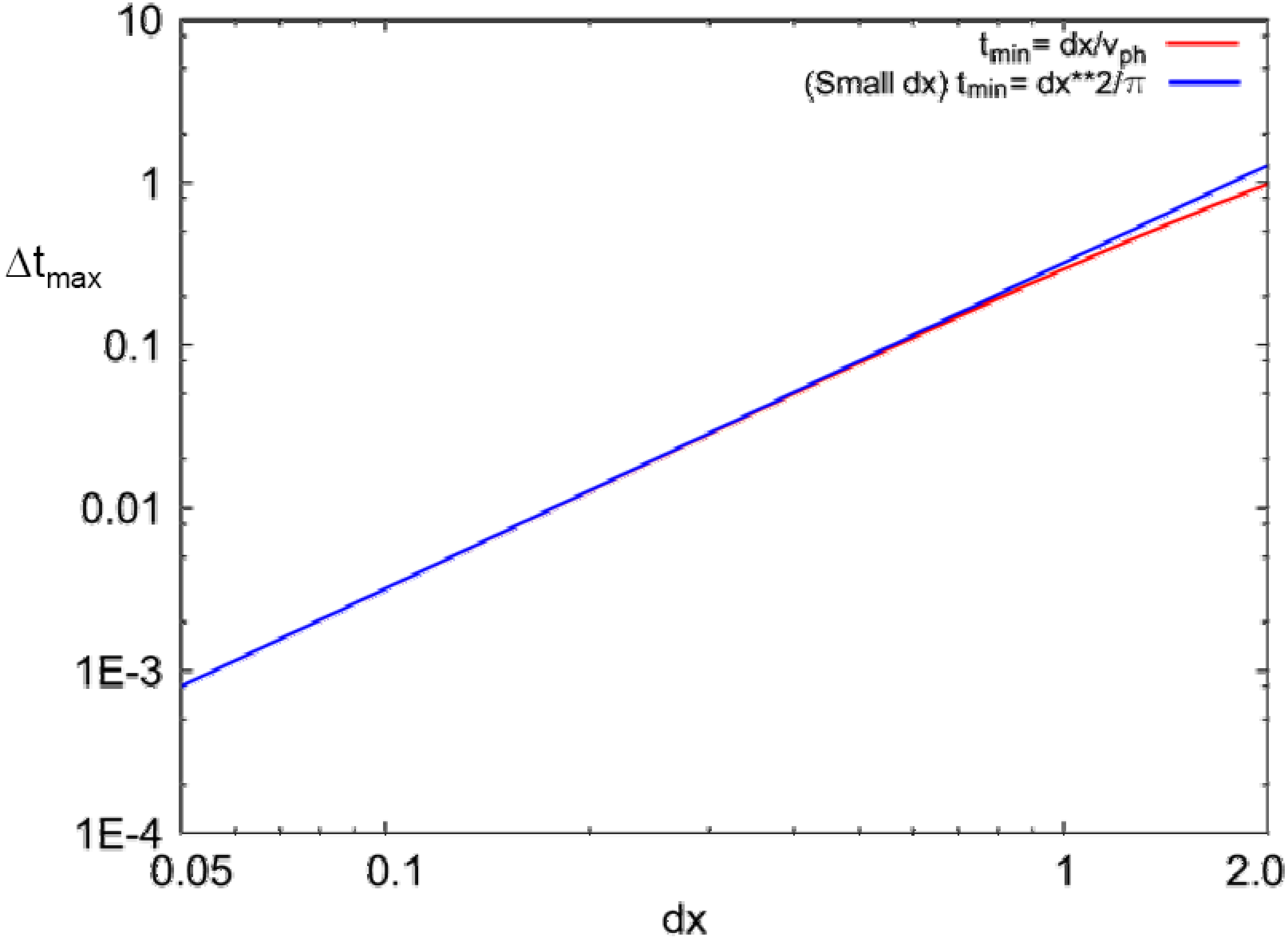
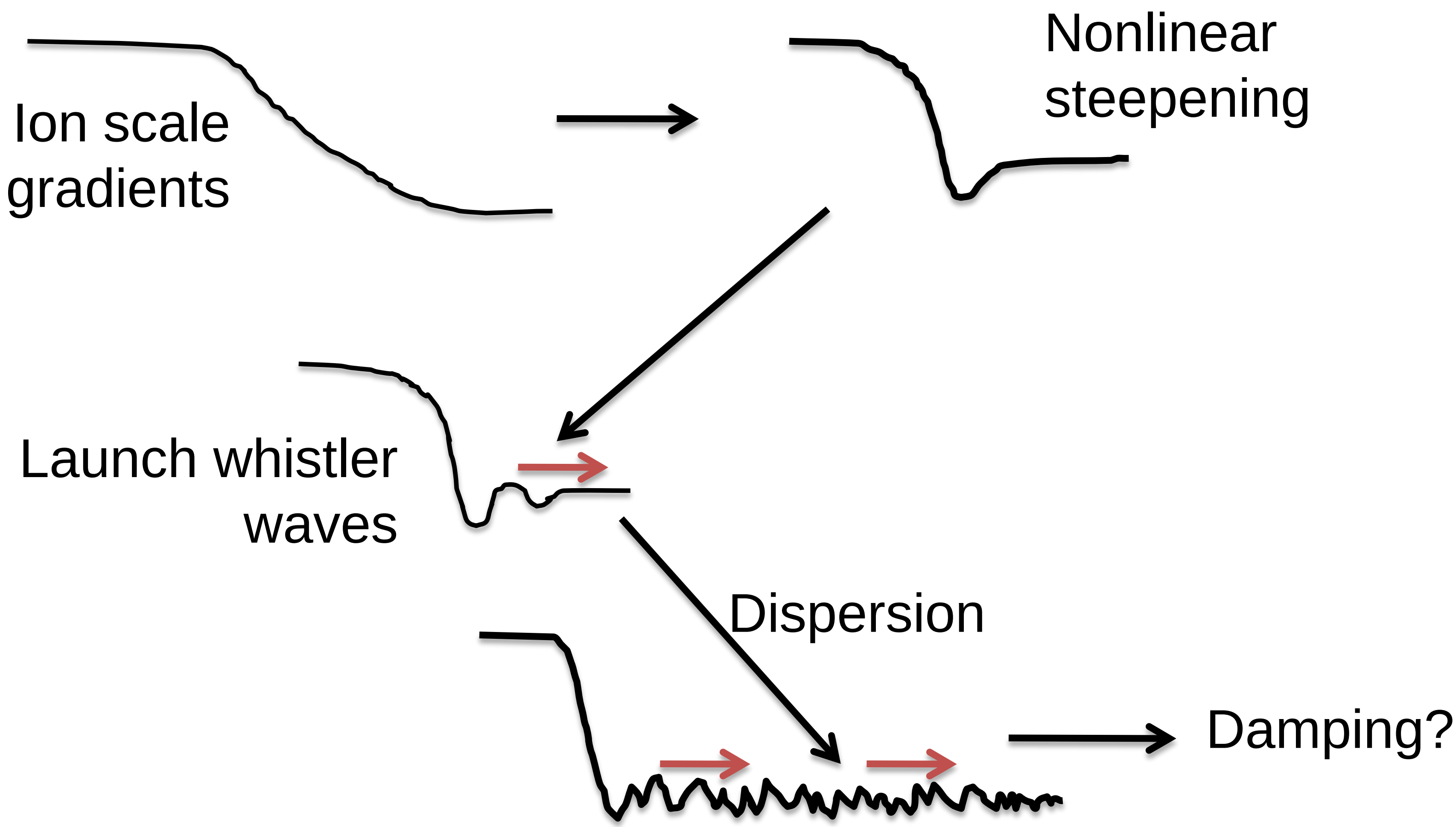


The (not such spoken about) problem with hybrid codes



Hybrid methods and dispersive whistler waves

PROBLEM

- Hybrid codes lack electron kinetics
  - Damping at “electron” scales is wrong
- Steepening gives large amplitude changes at small scales with fast propagation speed (via dispersion)
  - Good conditions for error build-up

SOLUTION(S)

- Don’t make cell size too small
- “Improve” electron fluid, eg finite mass, explicit resistivity (what value?!)
- Hope(!) that numerical scheme has enough intrinsic diffusion/damping at small scales
- Help the numerical scheme with additional smoothing or filtering

Hybrid codes and low density regions

- Alfven speed is a characteristic speed
- V_A increases as density decreases
- Errors larger as density decreases
- “Explosive” failures associated with low density regions

“Solution”

- Force density “floor” to maintain “finite” electric field
- OK ... Provided low density region not too large

Plasma-vacuum boundaries are difficult in hybrid method

Historical Example

- Leroy et al., 1982, "The Structure of Perpendicular Bow Shocks"

- Based on earlier PIC codes (normalizations!)

- Explained bow shock observations of reflected ions, magnetic foot & overshoot structure

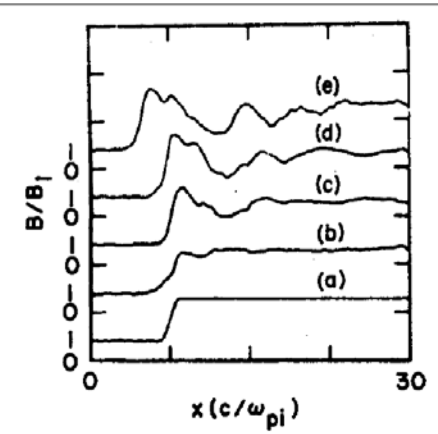


Fig. 2. Magnetic field profiles for $M_A = 6$, $\beta_{e1} = \beta_{i1} = 1$ at the times as in Figure 1.

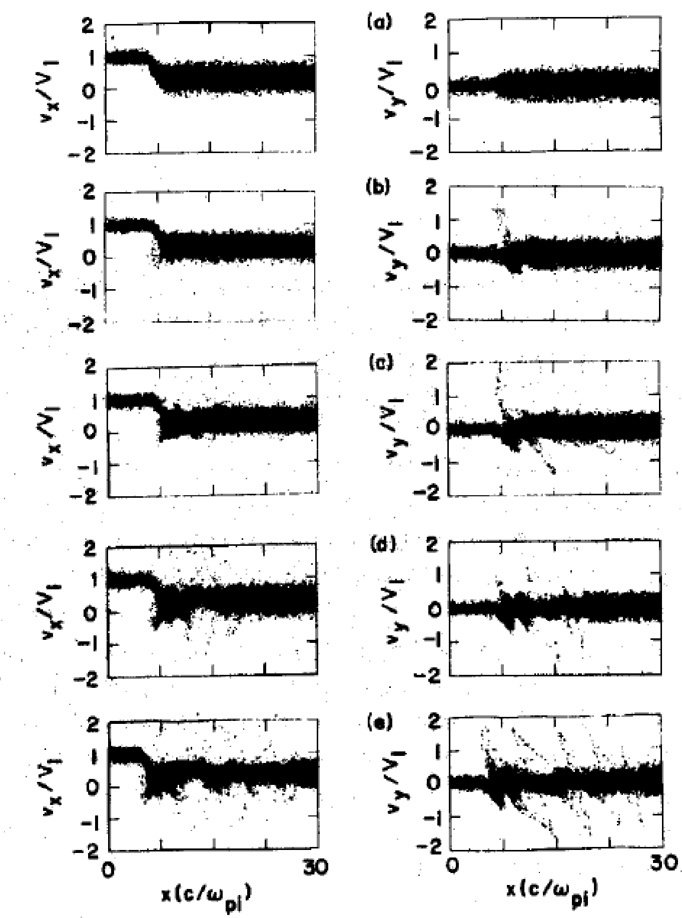


Fig. 1. v_x versus x and v_y versus x phase space for $M_A = 6$, $\beta_{e1} = \beta_{i1} = 1$ at (*a*) $t = 0$, (*b*) 1.3 ω_{ci}^{-1}, (*c*) 2.6 ω_{ci}^{-1}, (*d*) 5.2 ω_{ci}^{-1}, and (*e*) 9.6 ω_{ci}^{-1}.

1980's Hybrid Code

- Reasons for success
  - Implicit field solver possible in 1D (always stable!)
  - Separation of scales

  - Ion reflection ensures ion kinetic scale dominant

  - Bow shock in parameter regime where electron heating is not large ie electron kinetic effects not dominant

  - Characteristic large scale to small scale steepening, so ion kinetic effects play a role before electron kinetics

- And not so successful ...

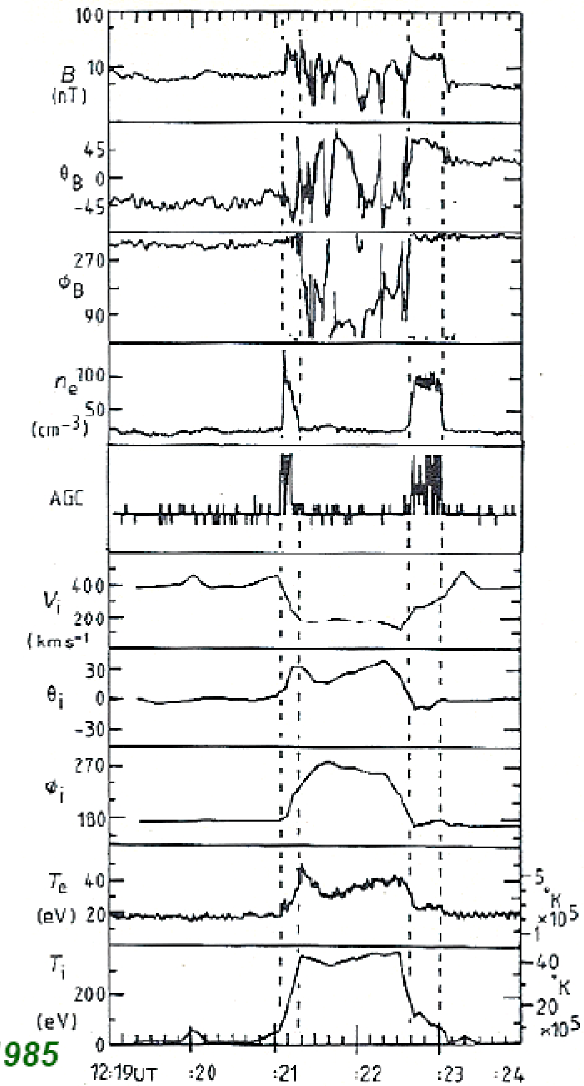
- One-dimensional (space) simulation means no parallel heating of ions

- But ... observations could not show ion parallel temperature accurately!

Hot flow anomalies at the heliospheric termination shock

- Schwartz et al (1985) discovered "active current sheets" in the solar wind near 1AU
  - large plasma temperature regions associated with rotations in the magnetic field
  - also known as "hot diagmagnetic cavities" and "hot flow anomalies" in the literature

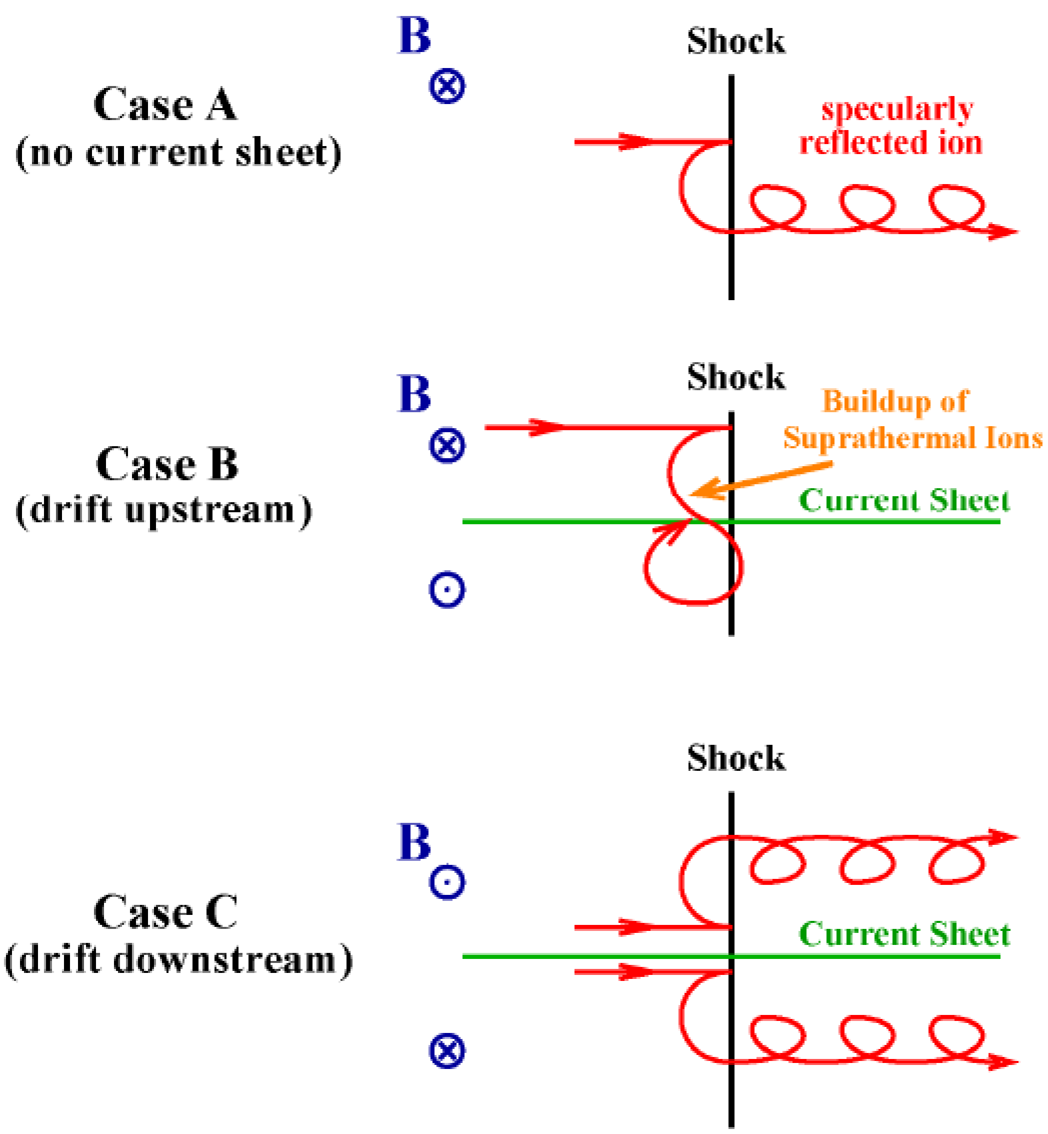
- They are formed when a tangential discontinuity of a certain polarity interacts with Earth's bow shock
  - The particle drift is directed away from the shock



Schwartz et al, Nature, 1985

The physics of hot flow anomalies

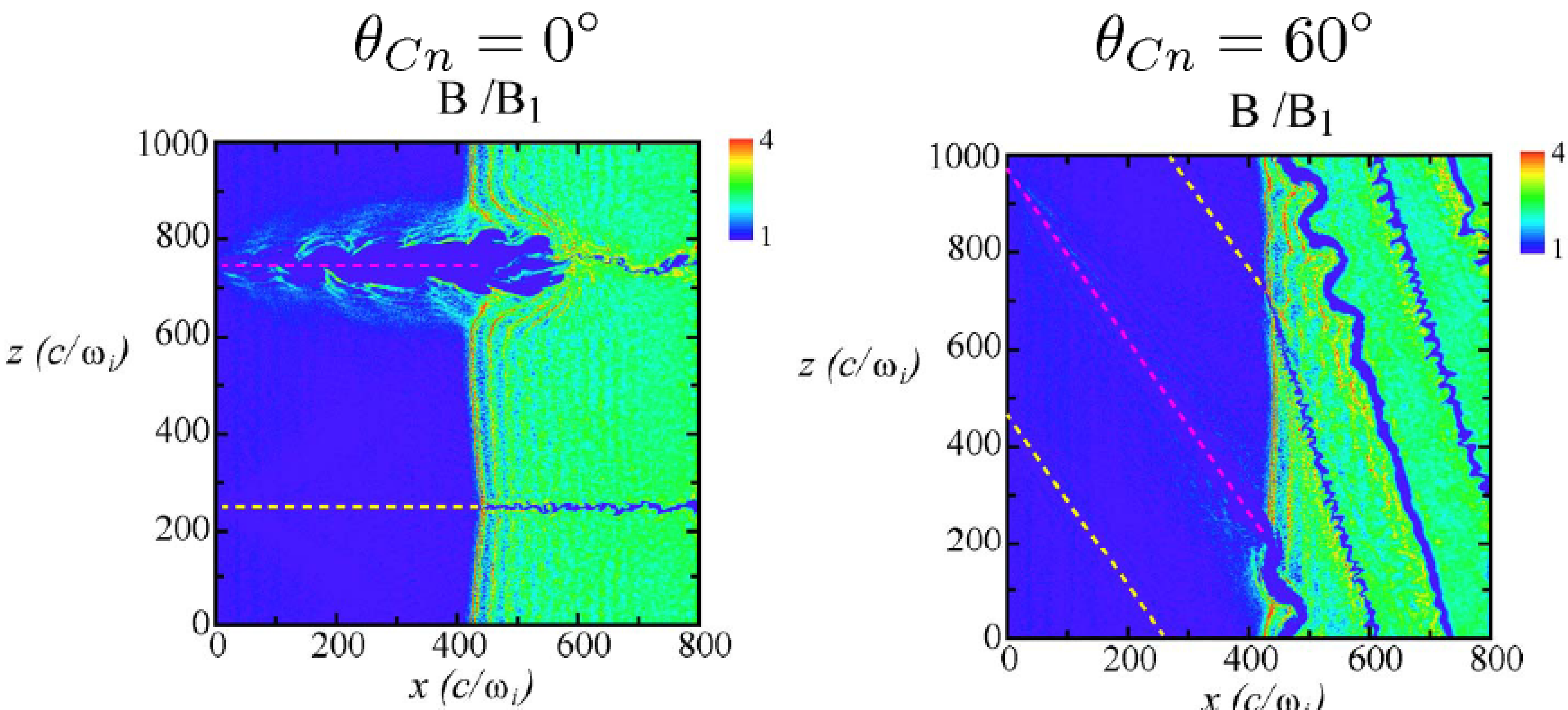
- <u>Case B</u> the region in front of the shock contains many suprathermal protons
  - High temperature
  - High pressure region expands, leading to a decrease in density
  - Weak shocks can form upstream of the shock



After Burgess (1989) and Thomas et al. (1993)

Effect of Current-Sheet Inclination on HFA structure

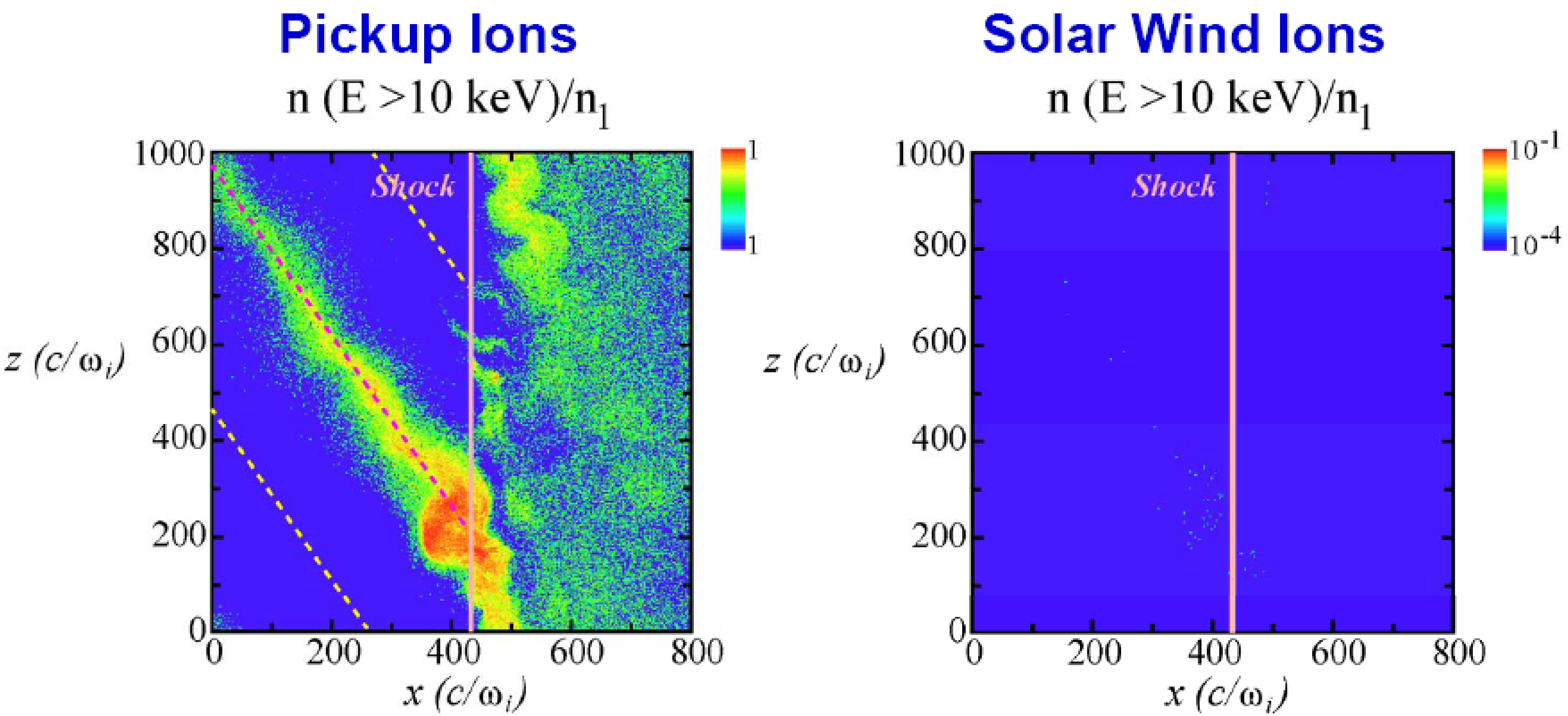
- The morphology of the HFA is much different for highly inclined shocks because the intersection point of the CS and shock moves along the shock very rapidly
- It is unlikely that a HFAs, like those observed near Earth, exist near the termination shock, except for transient ones



[With Joe Giacalone, Arizona, GRL 2010]

Dynamics of pick-up ions at Hot Flow Anomaly

- Large number of upstream energetic particles are produced by the interaction of the "active" current sheet with the shock.
- They are nearly ALL pickup ions (not thermal solar wind ions).

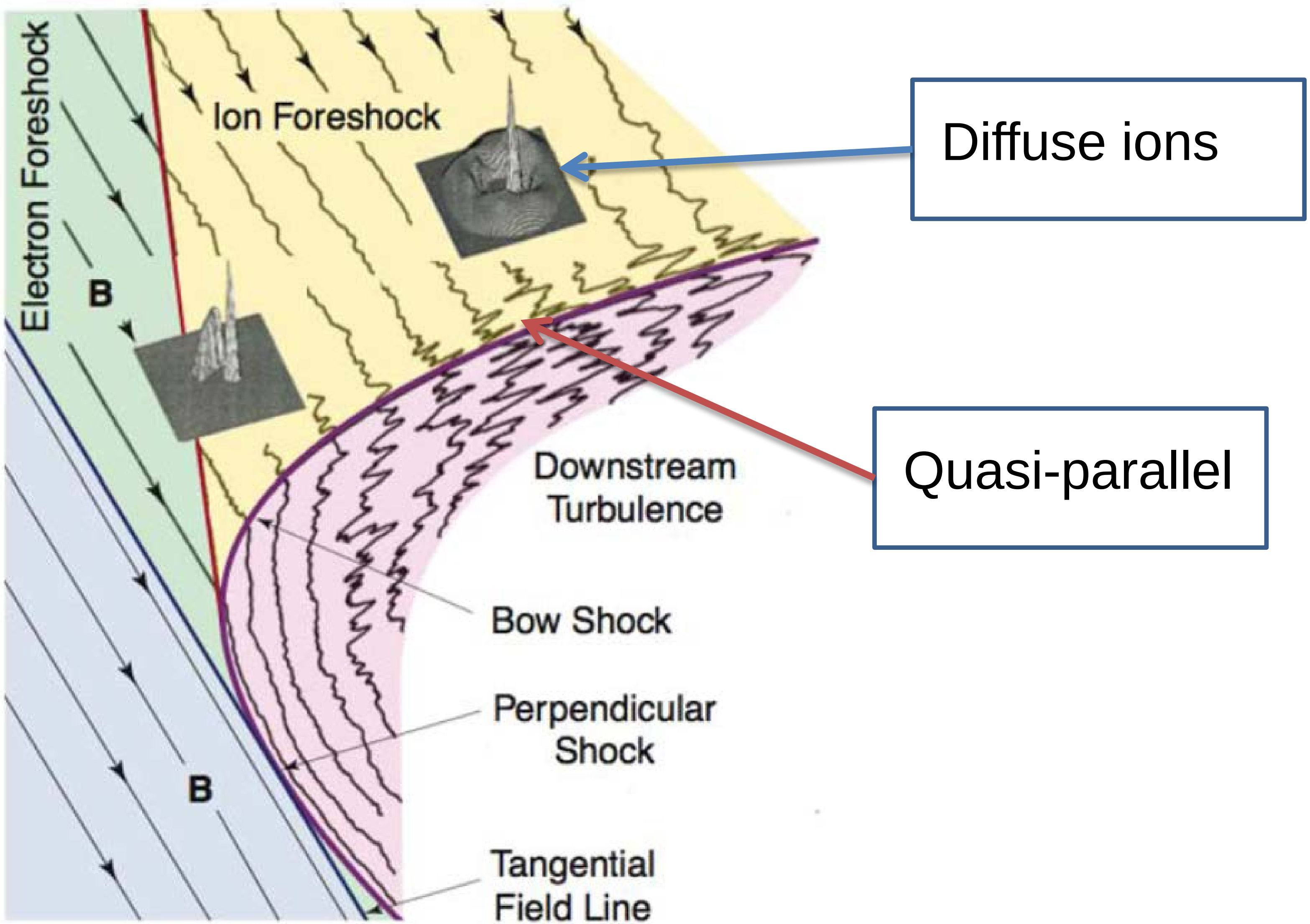


Microphysics at the Quasi-parallel Shock

An Example of Hybrid Simulation

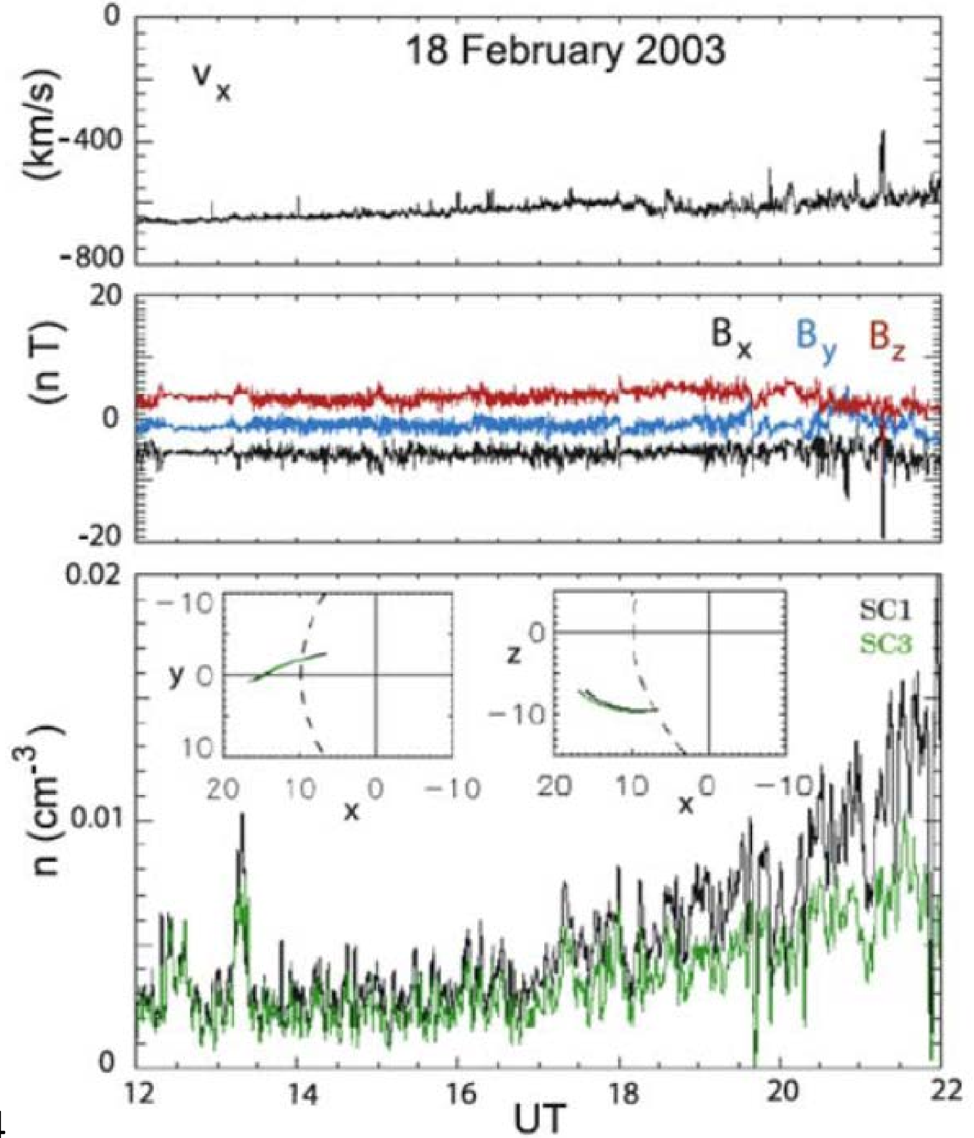
Space Weather connections:
- *Particle acceleration at CME and IP shocks*
- *Transmission of solar wind disturbances through bow shock*

Terrestrial Bow Shock



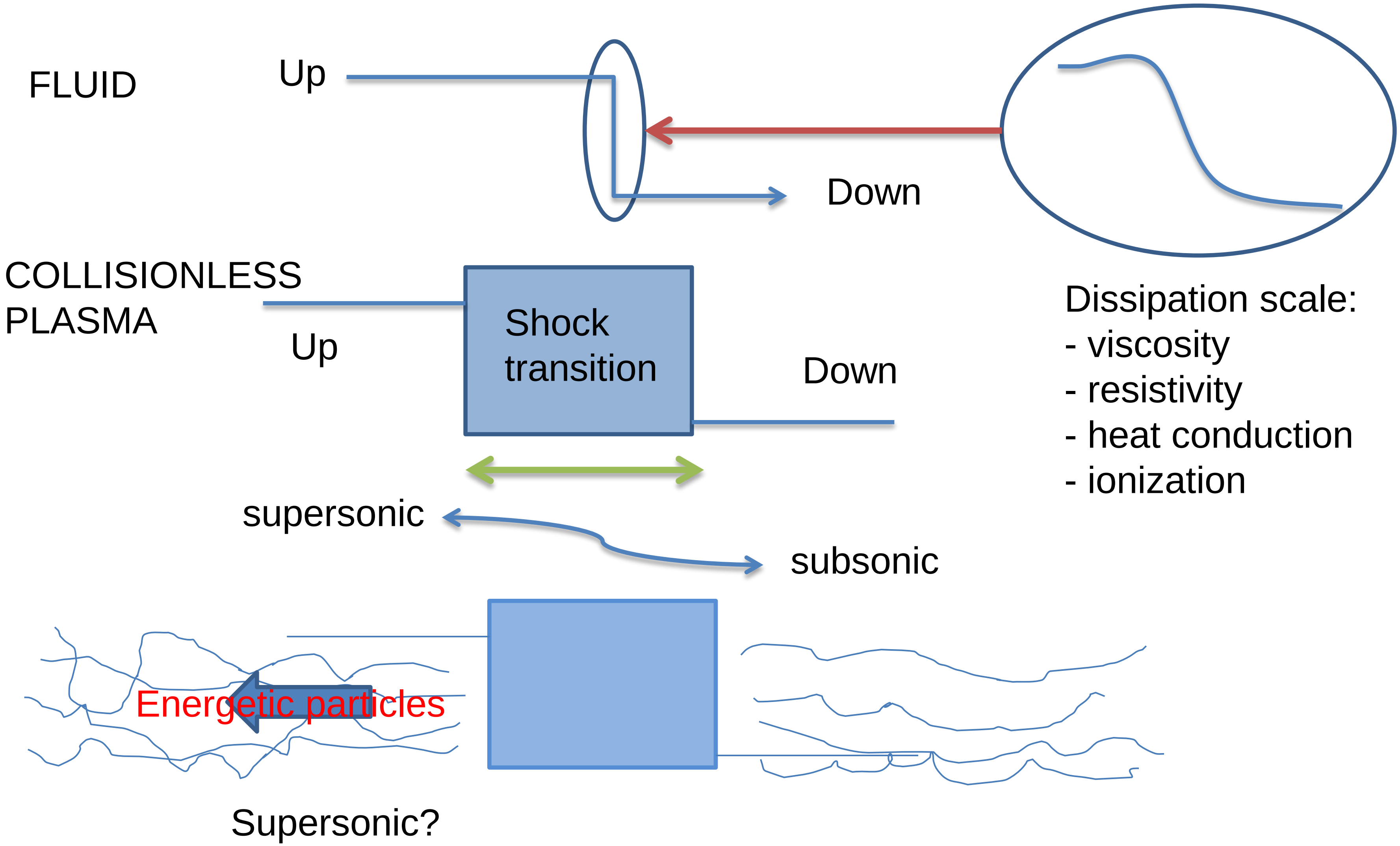
Diffuse Ions

- Isotropic (on average) close to shock
- Spectra above 30keV exponentials in E/q
- e-folding distance increases with energy
- Anisotropic far from shock



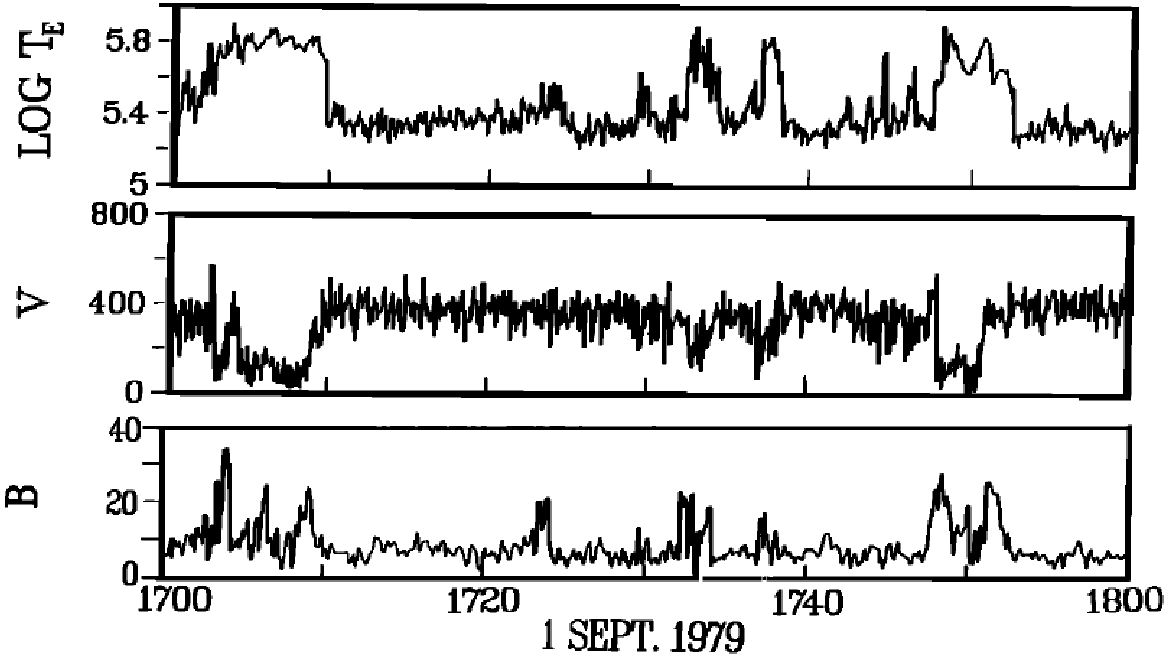
Kis et al, 2004

Shock Transition

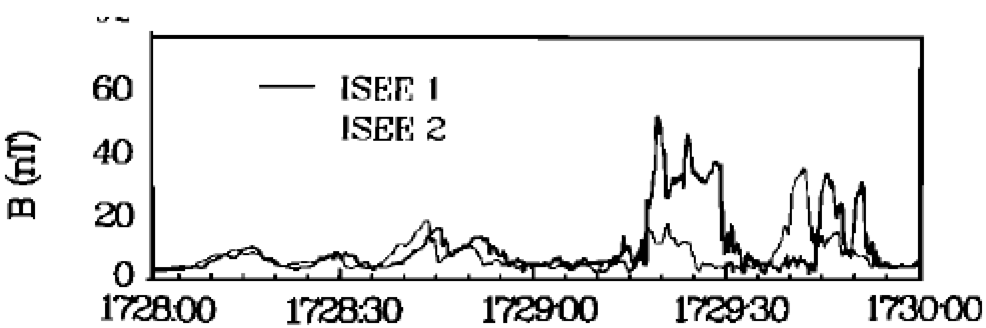


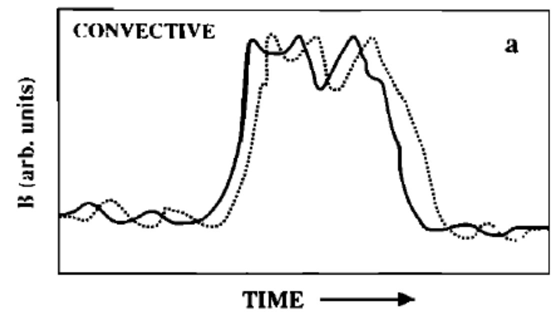
Dissipation scale:
- viscosity
- resistivity
- heat conduction
- ionization

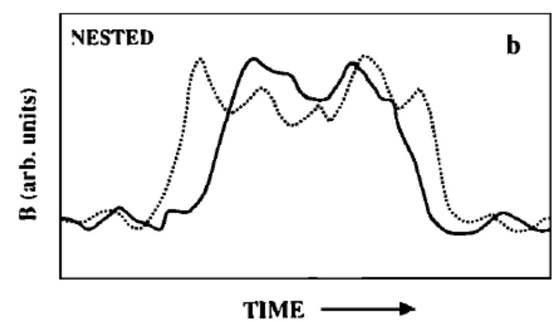
Quasi-parallel Shock Observations



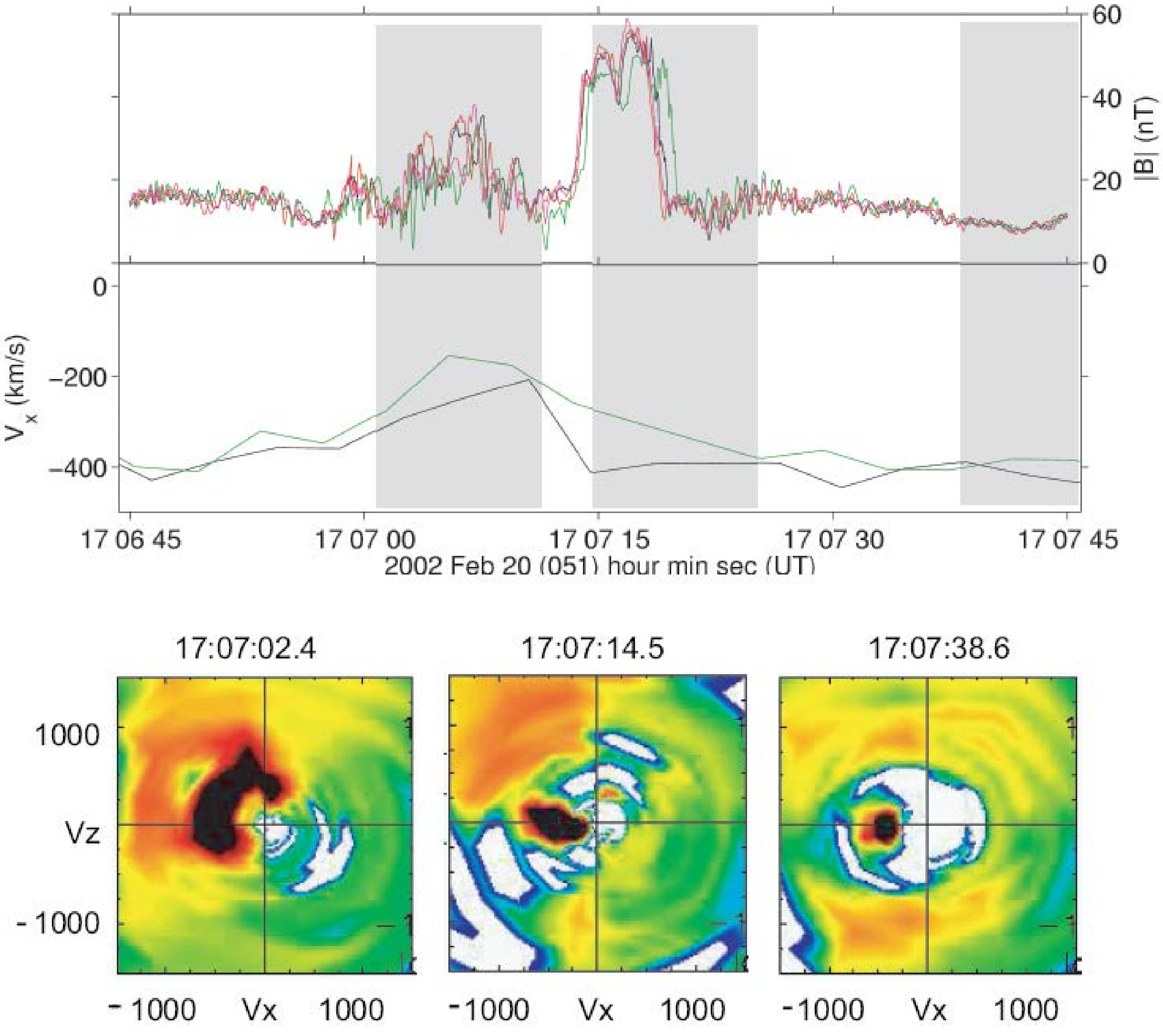
Gosling et al 1989,
Thomsen et al 1990







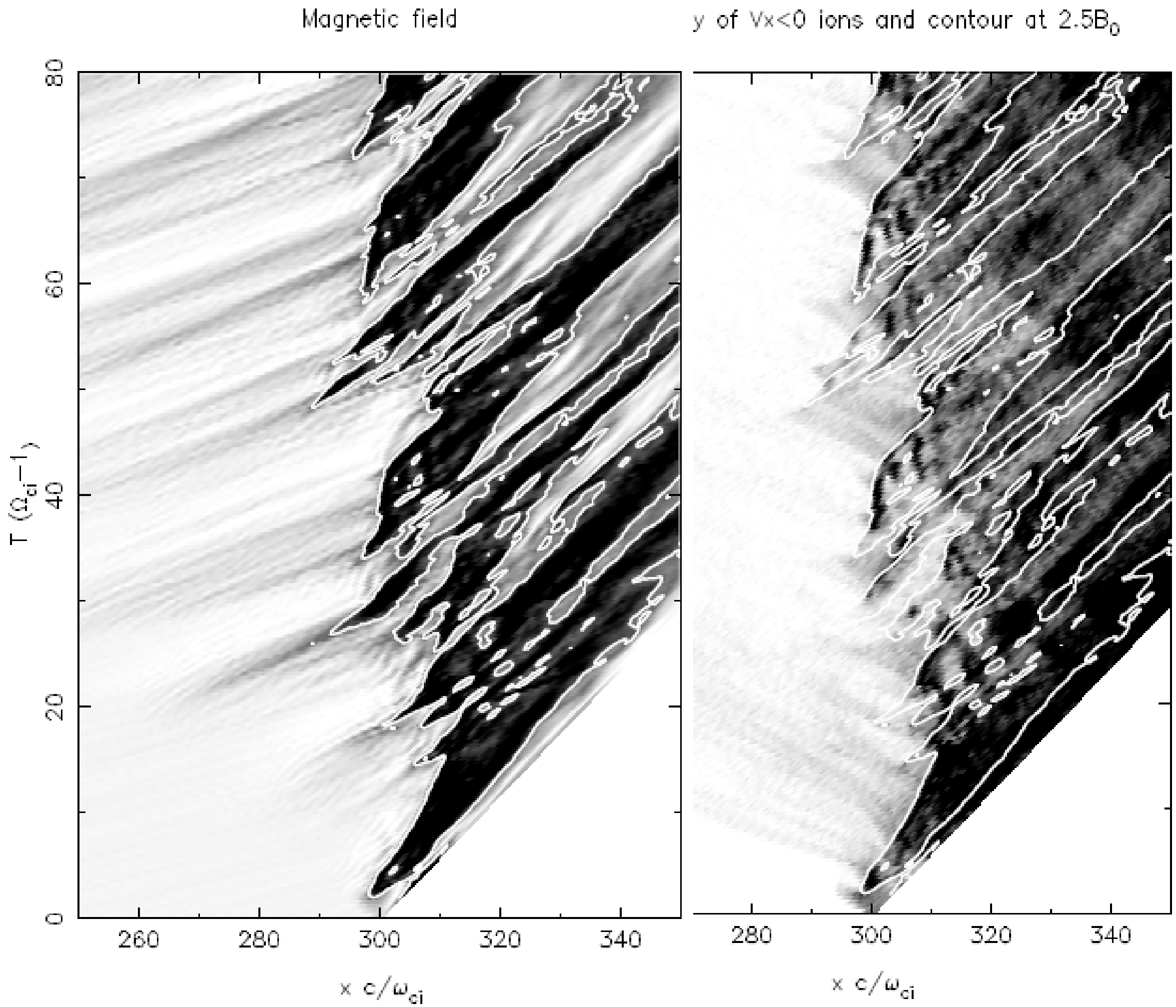
Pulsations and Ion Distributions



Burgess et al
SSR 2005

Quasi-parallel Simulations

- "Reformation" of shock front associated with upstream pulsations convecting into shock
- Bursts of upstream directed ions linked to incident waves

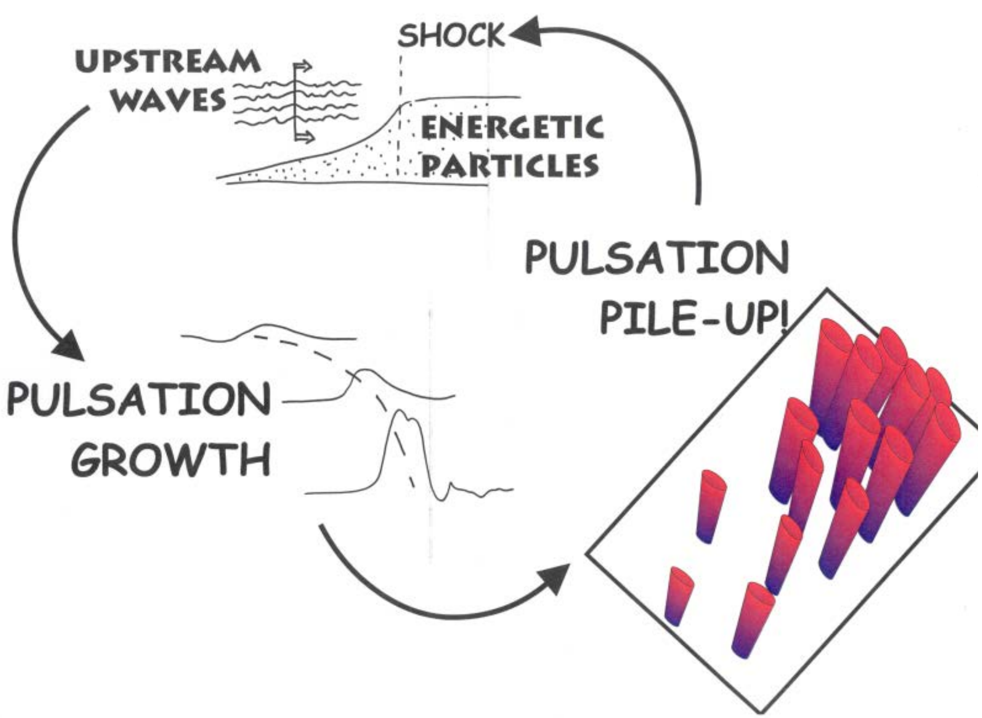


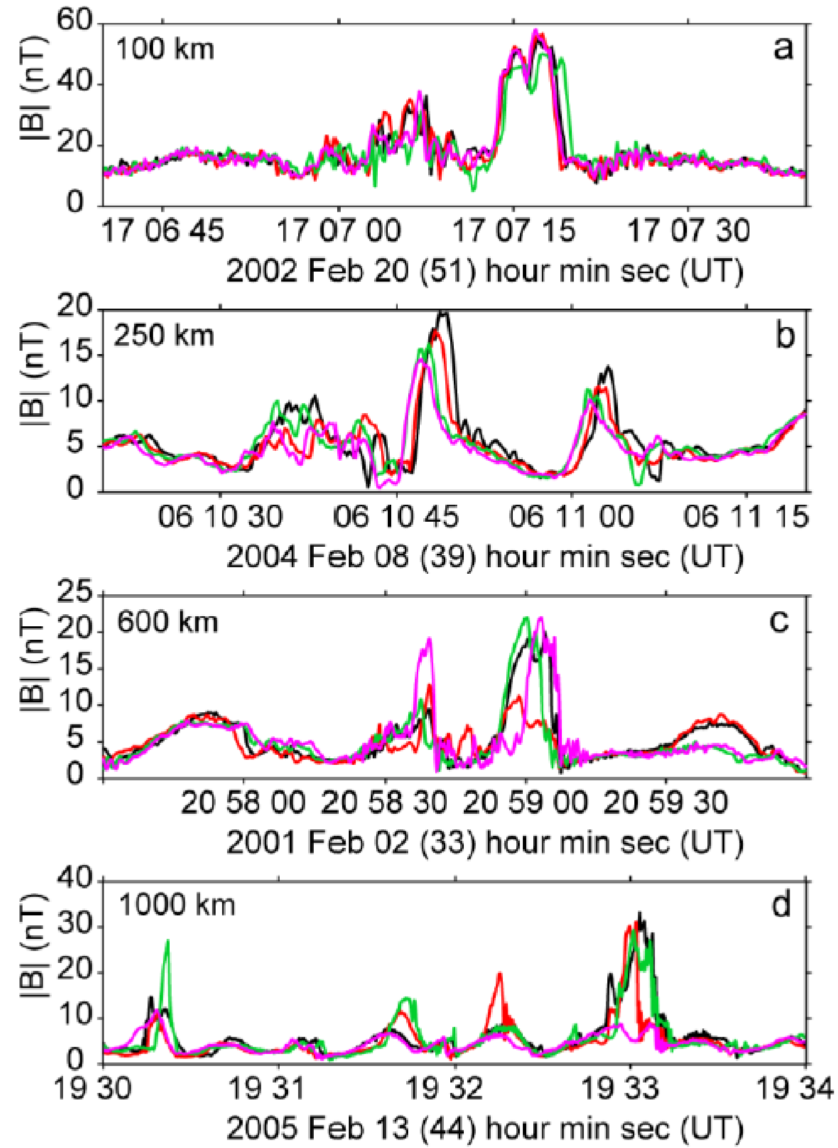
Burgess, 1995

Quasiparallel shock structure

- Large amplitude magnetic pulsations are central to quasi-parallel structure

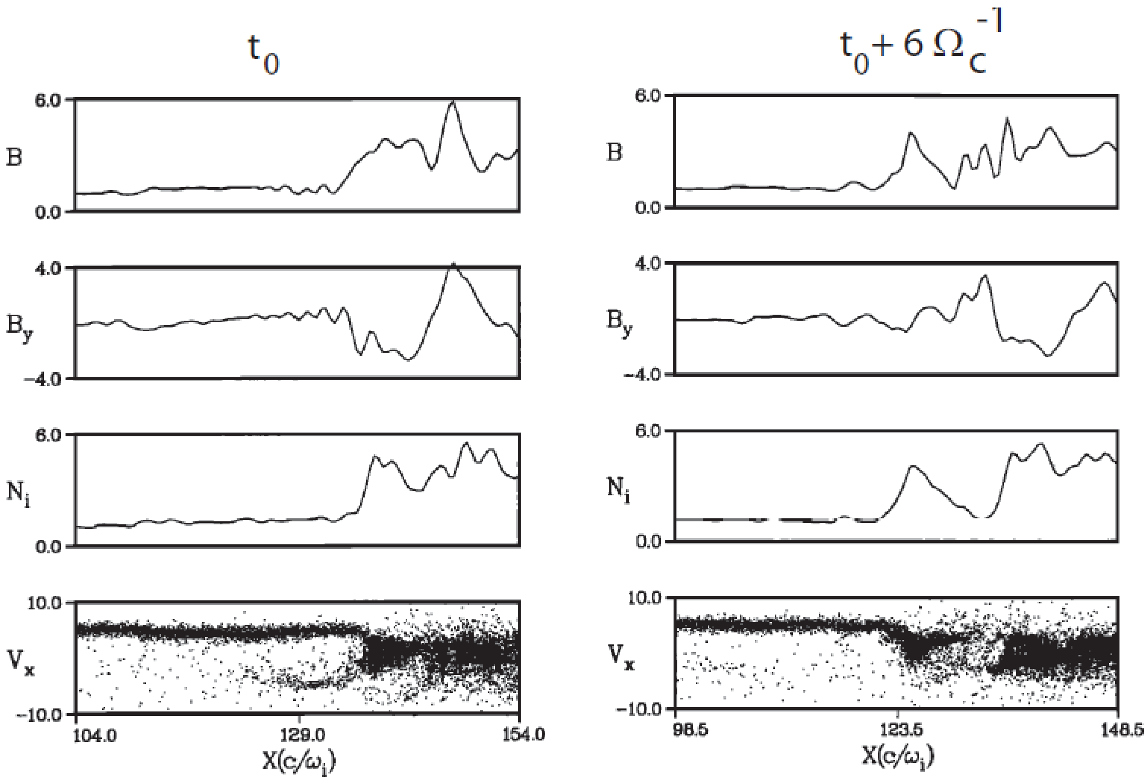
- Strong variations on short scales





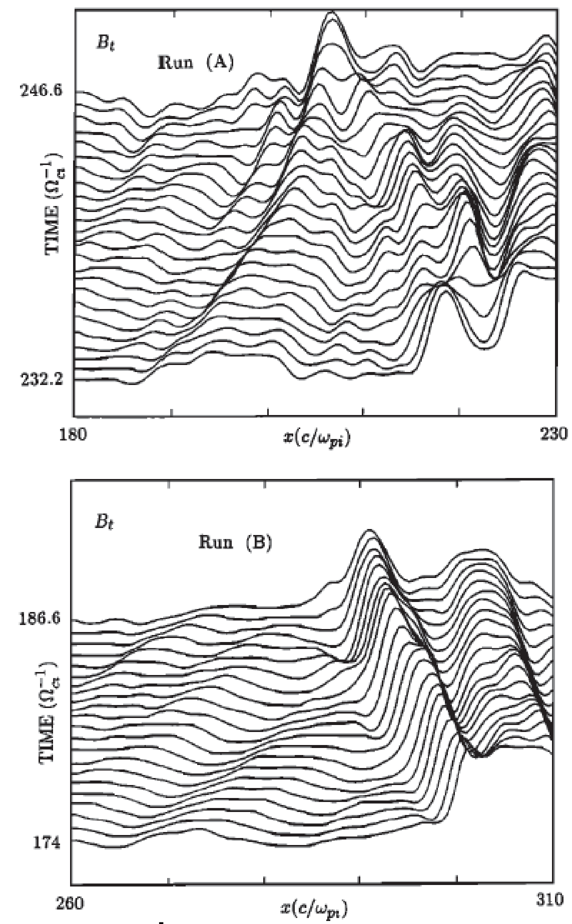
Lucek et al 2008

Pulsation growth and shock “reformation”



Backstreaming ions removed far(ish) away from shock

Thomas et al 1990

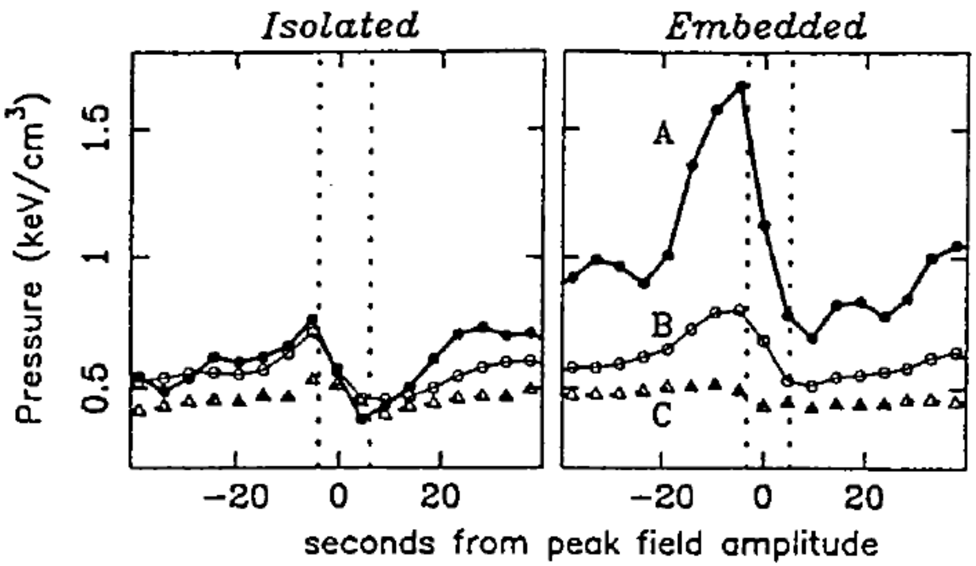


Run B: Backstreaming ions removed near shock

Scholer and Burgess 1992

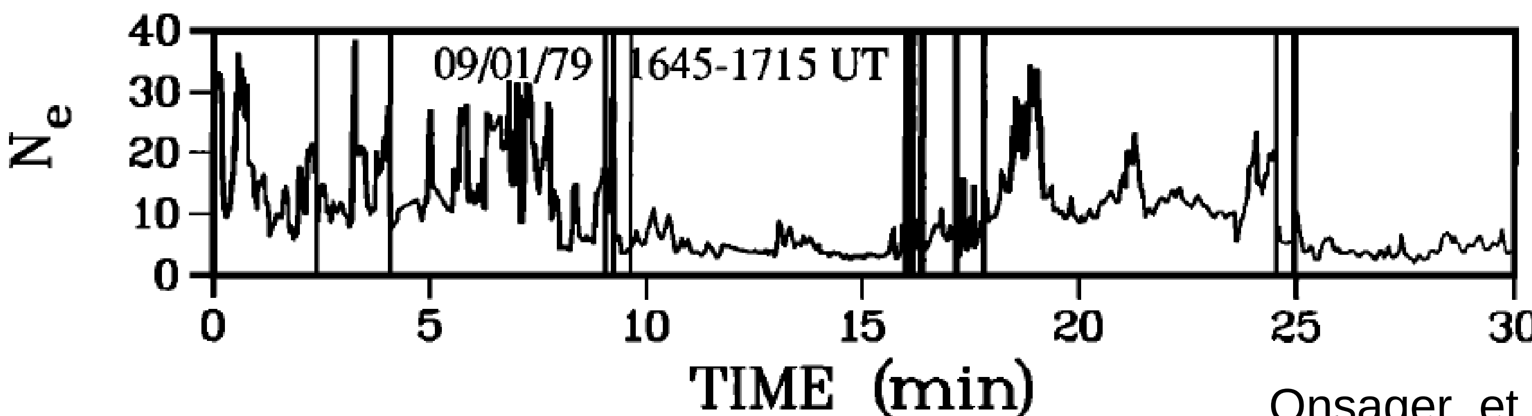
Pulsation Growth: Diffuse Ions or Specular reflection?

Correlation pulsations and diffuse ion pressure



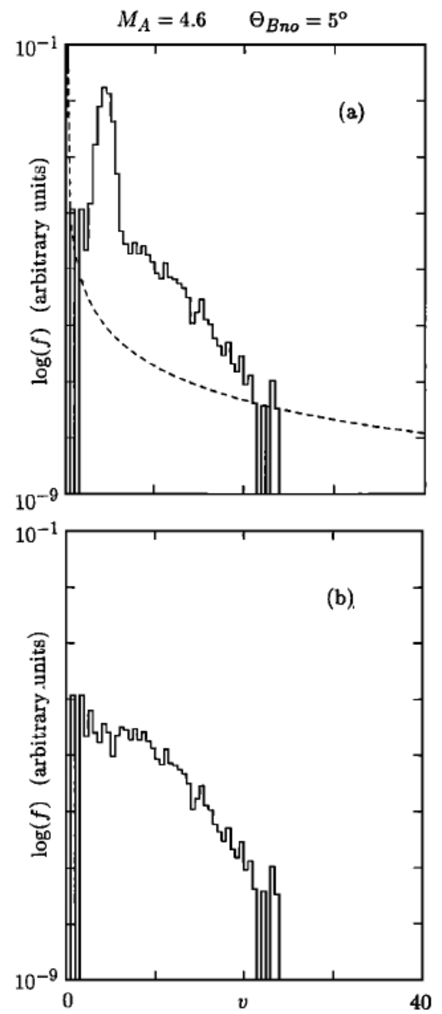
Giacalone et al. 1993

Cold reflected ion events

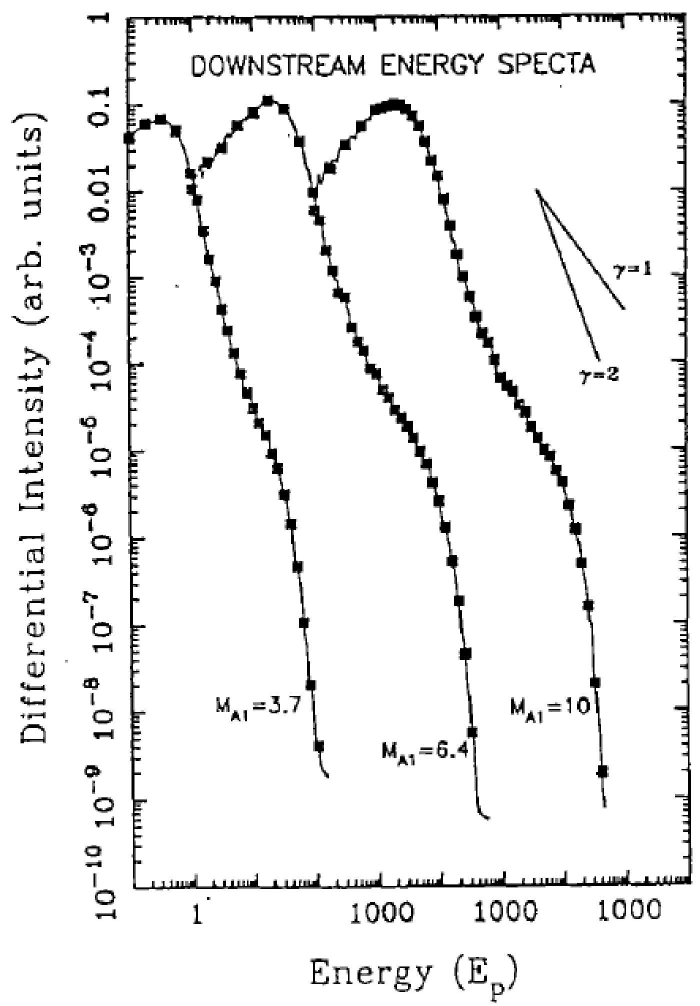


Onsager et al 1990

Hybrid Simulations of Diffuse Ions

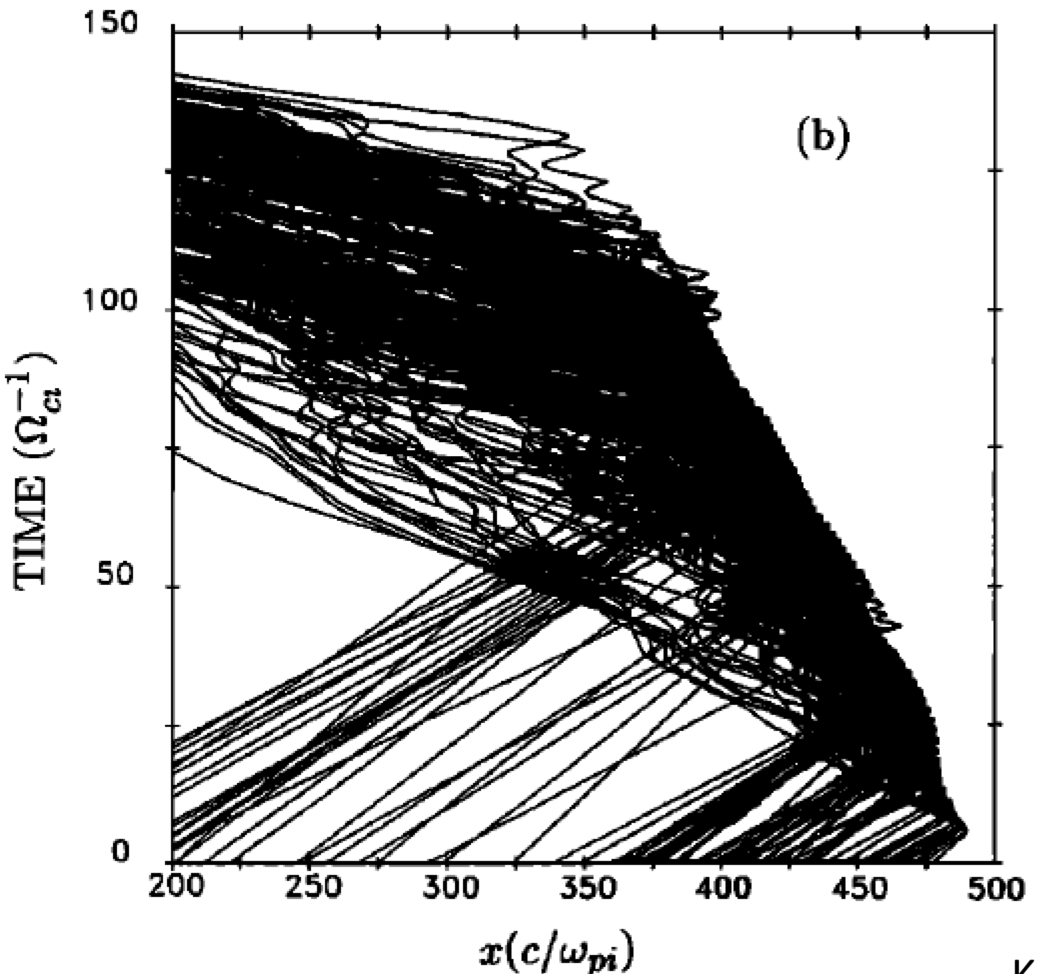


Kucharek and Scholer, JGR 1991



Giacalone et al ApJ 1993

Origin of Diffuse Ions - Hybrid

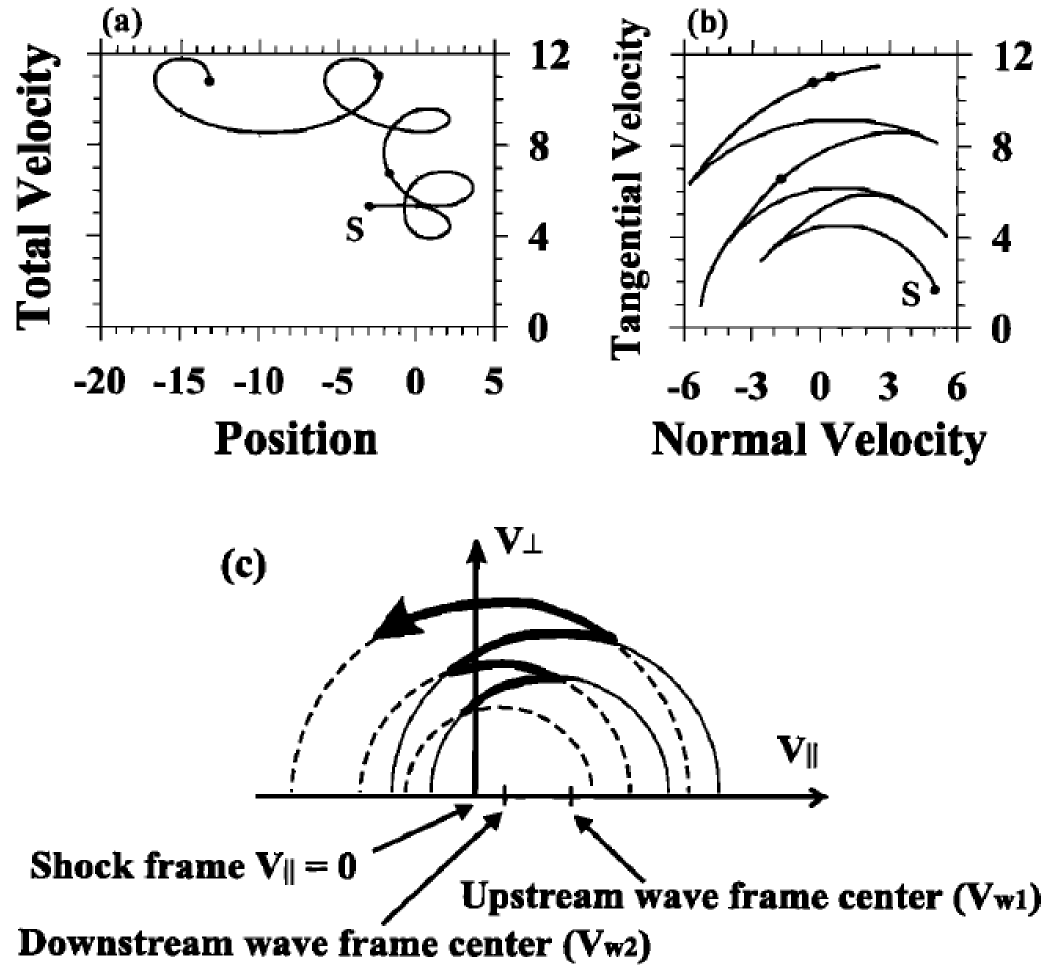


No evidence of leakage of hot ions from downstream

Kucharek and Scholer, JGR 1991

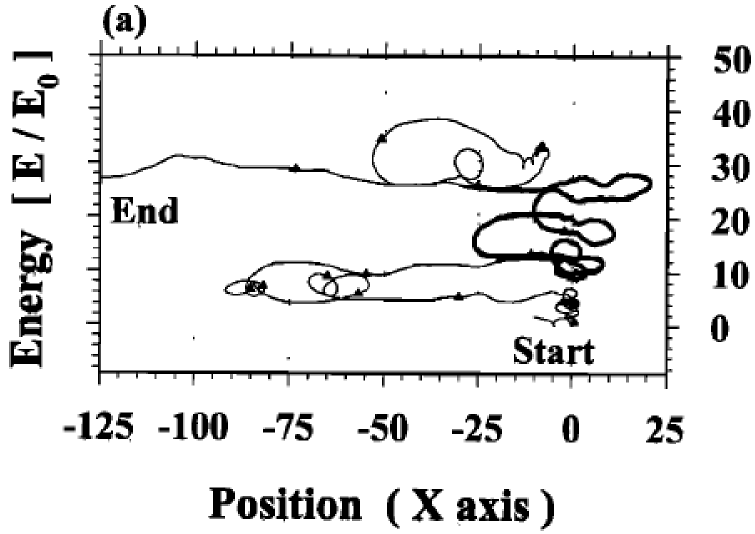
Quick Ion Acceleration/Injection

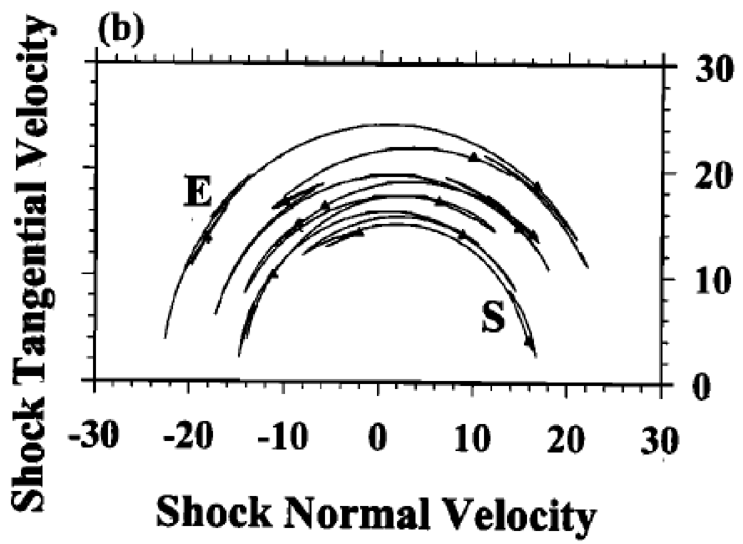
- Particles have phase trapping motion in convecting waves
- Deceleration of wave phase speed at shock leads to energy gain from "bouncing" between upstream wave and wave at shock front



Sugiyama and Terasawa, 1999

Quick Ion Acceleration/Injection

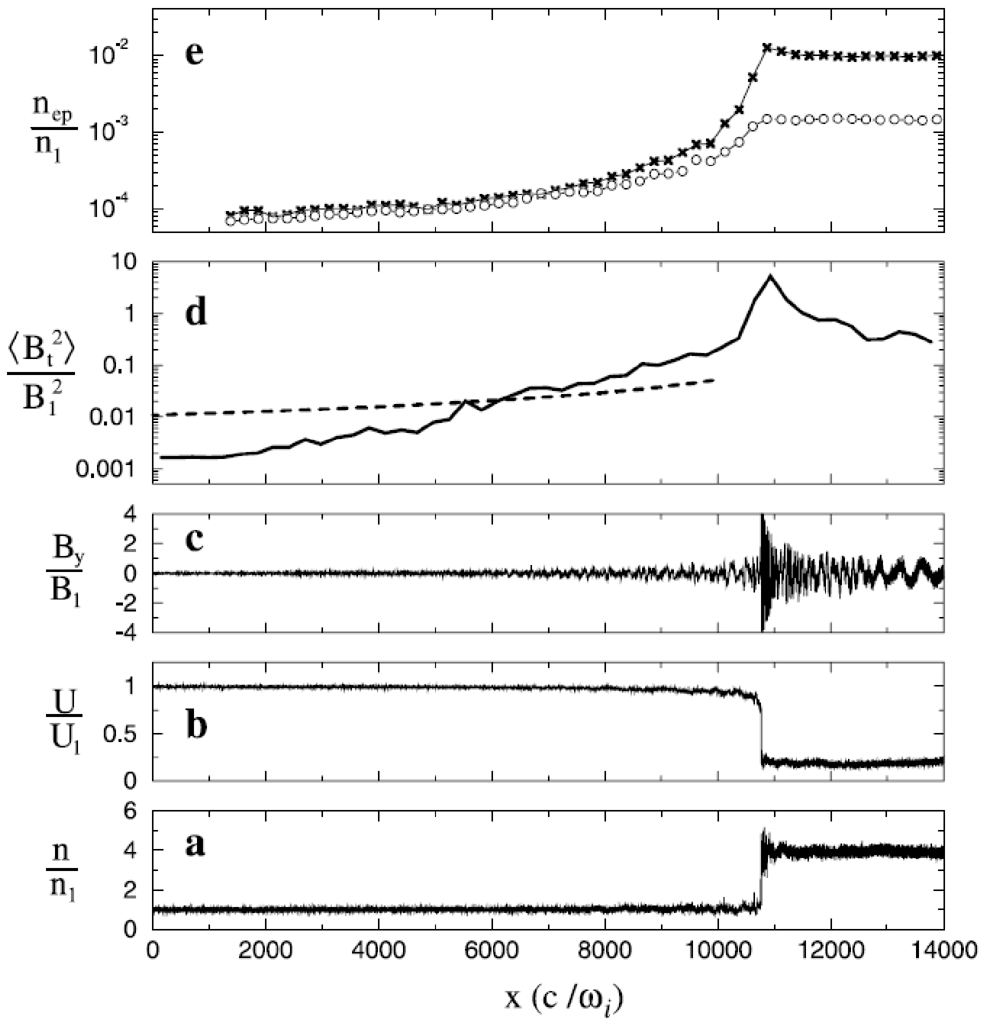


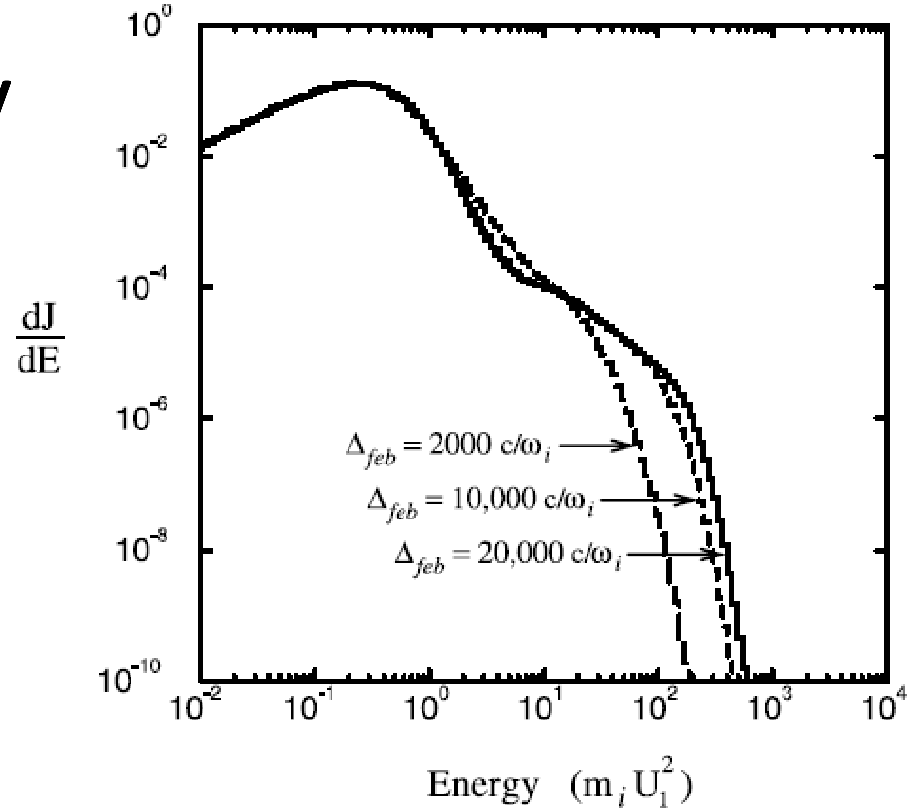


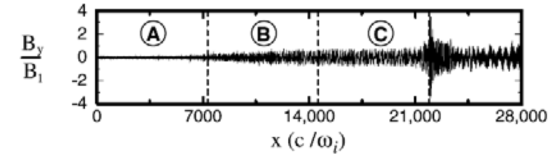
Sugiyama et al 2001

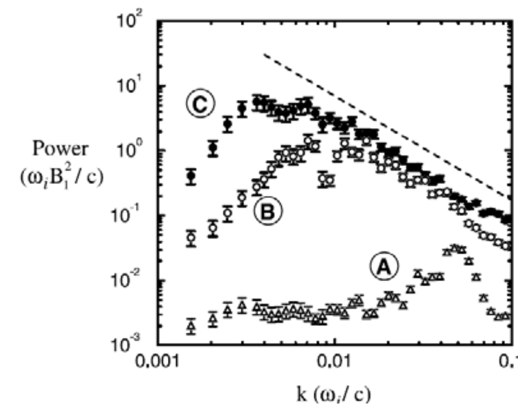
Free Escape Boundary

Giacalone 2004

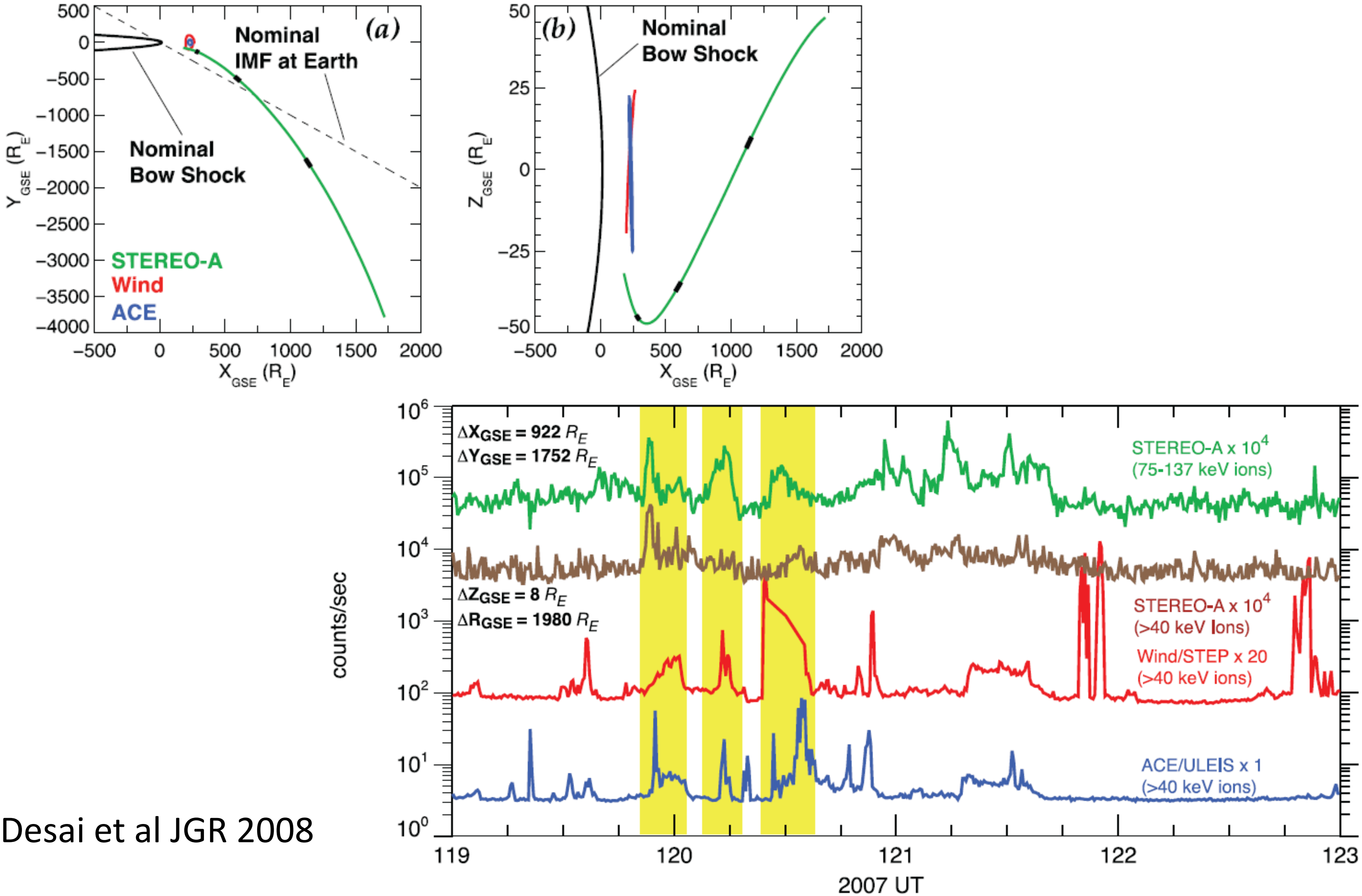






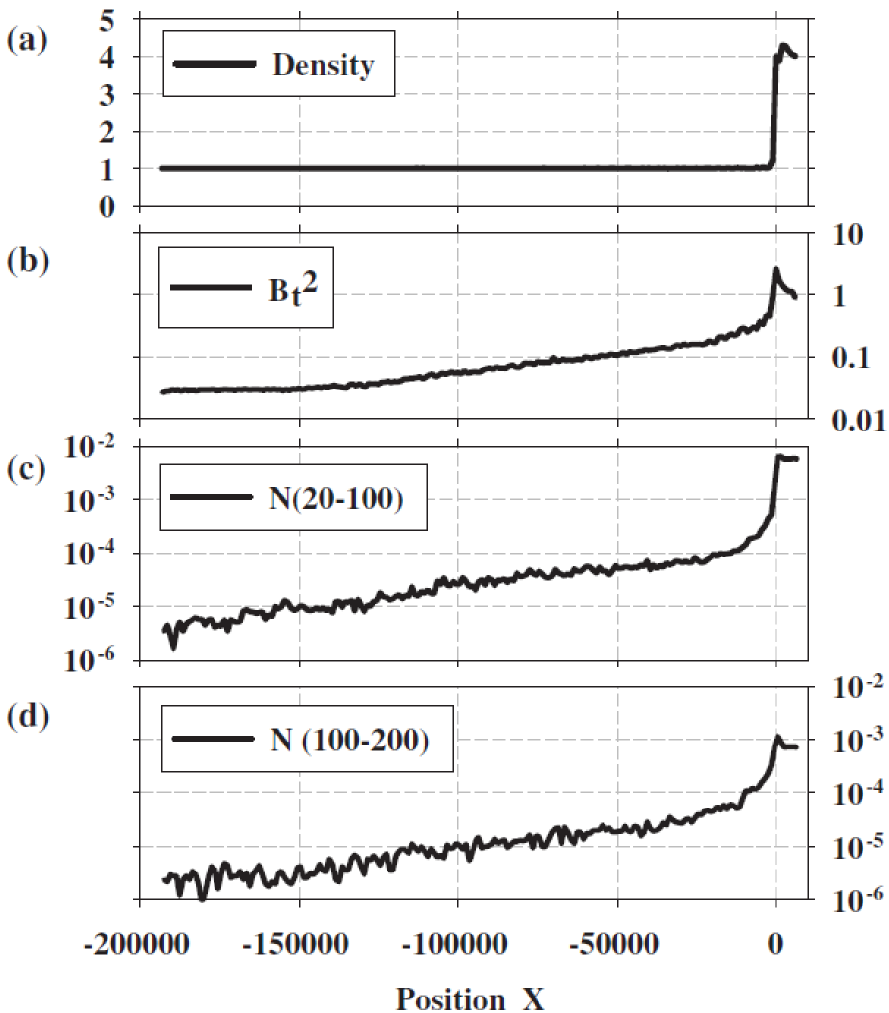


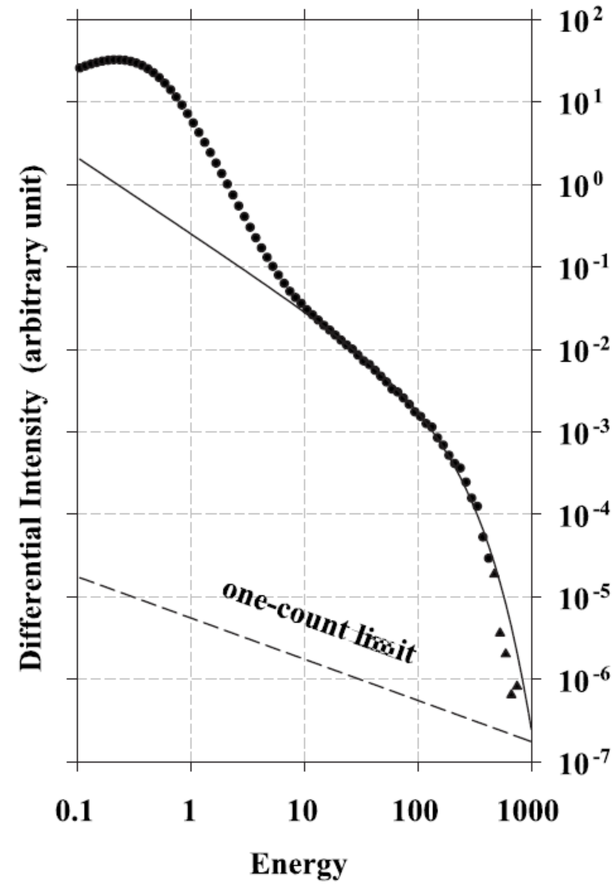
Diffuse Ions Far Upstream



Desai et al JGR 2008

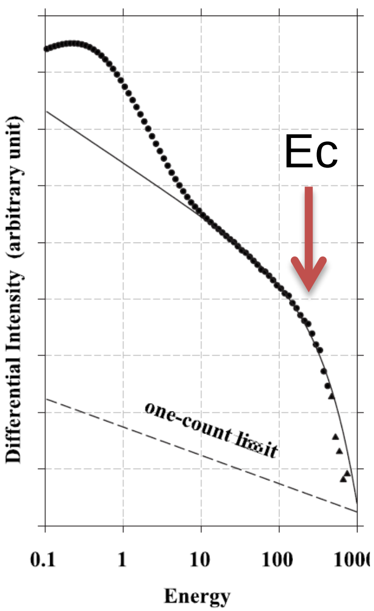
Free Escape Boundary 2

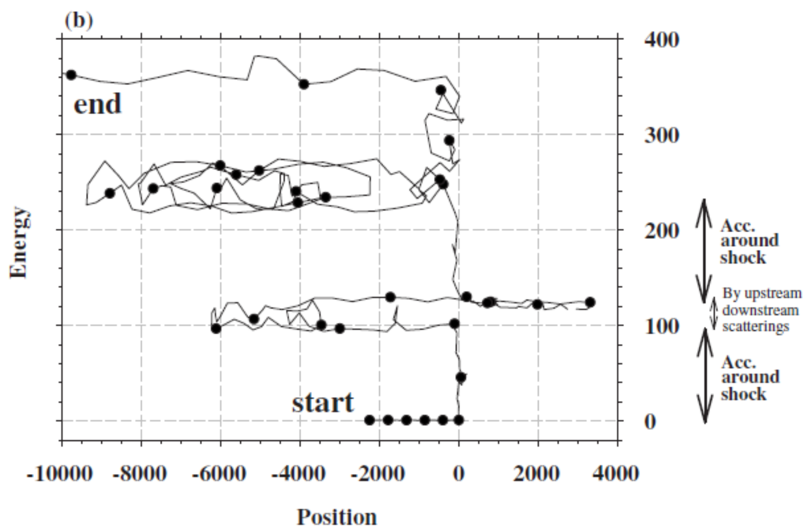


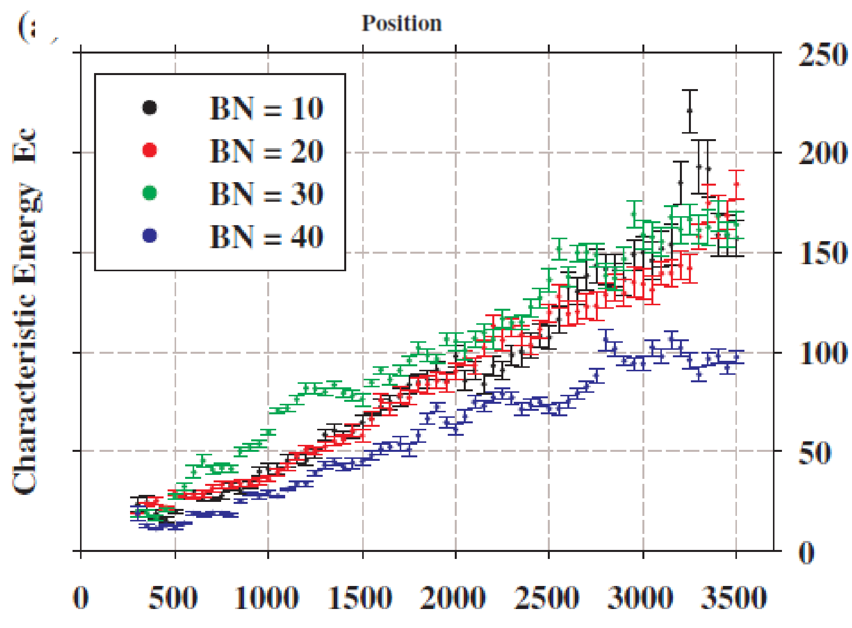


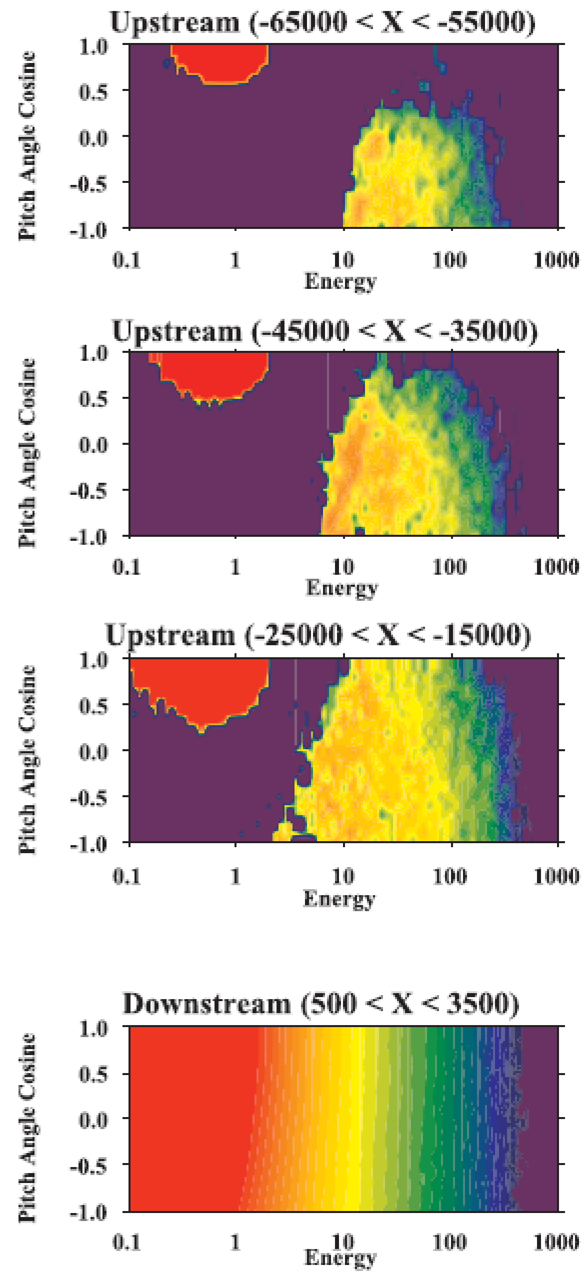
Sugiyama 2011

Large Scale 1D Hybrid

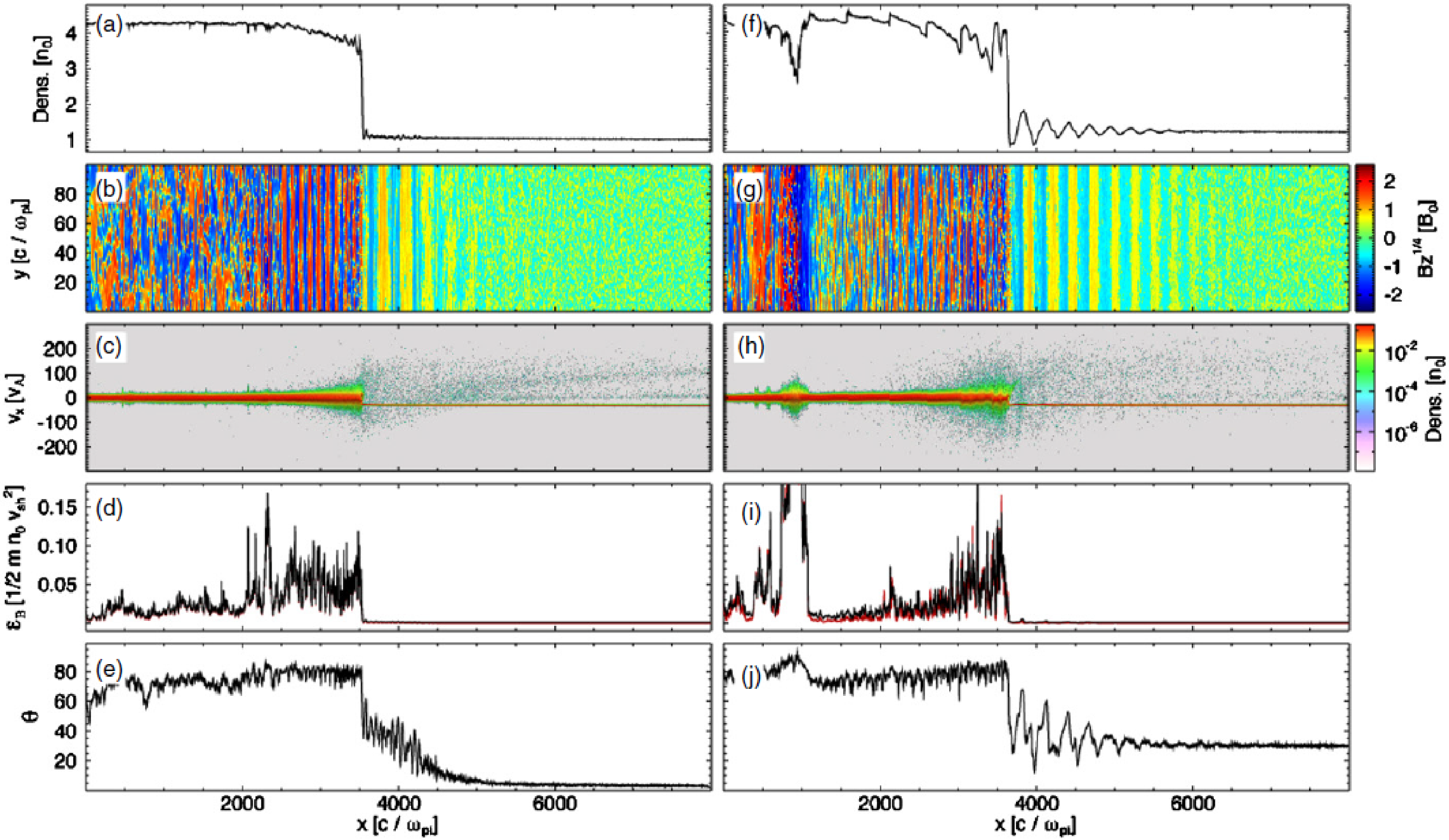








High Mach Number Quasiparallel

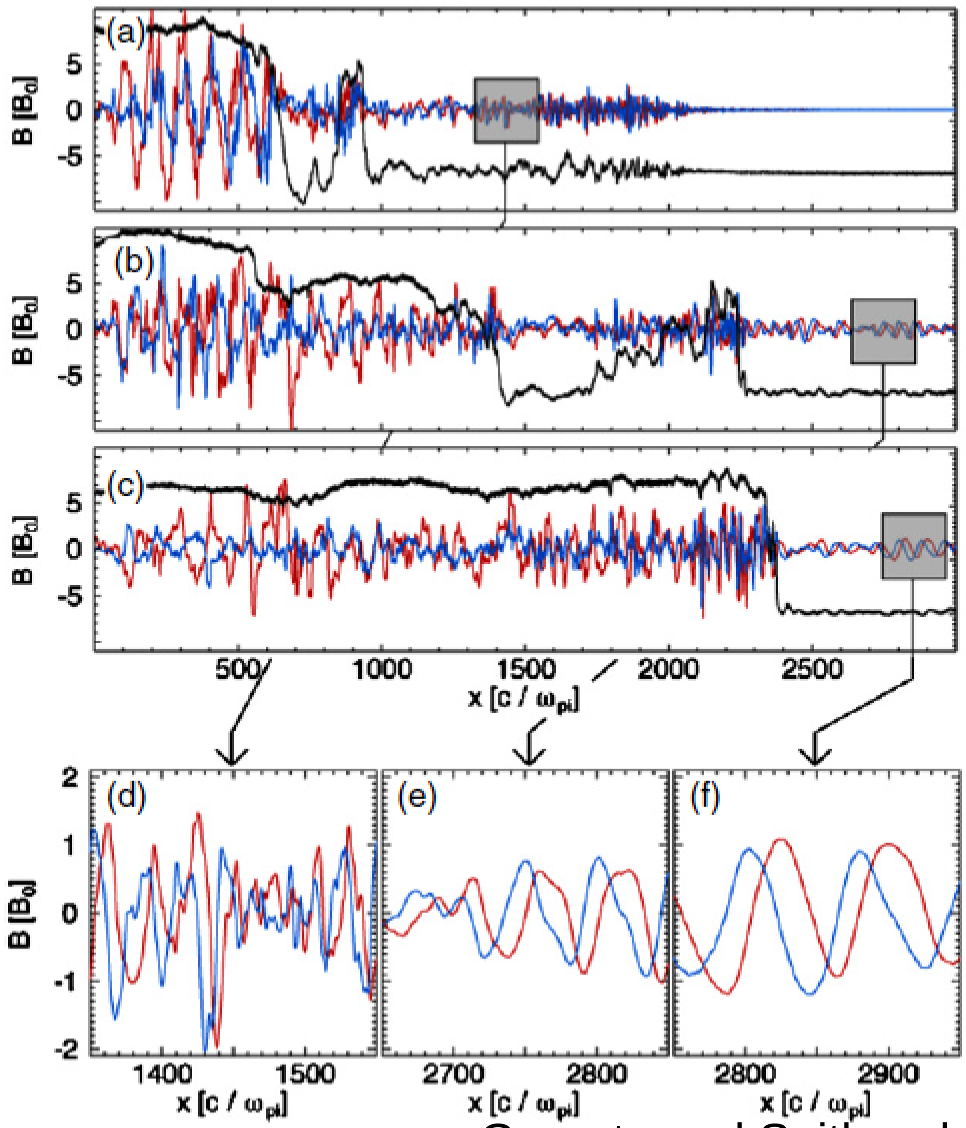


M_A=31

Gargate and Spitkovsky 2012

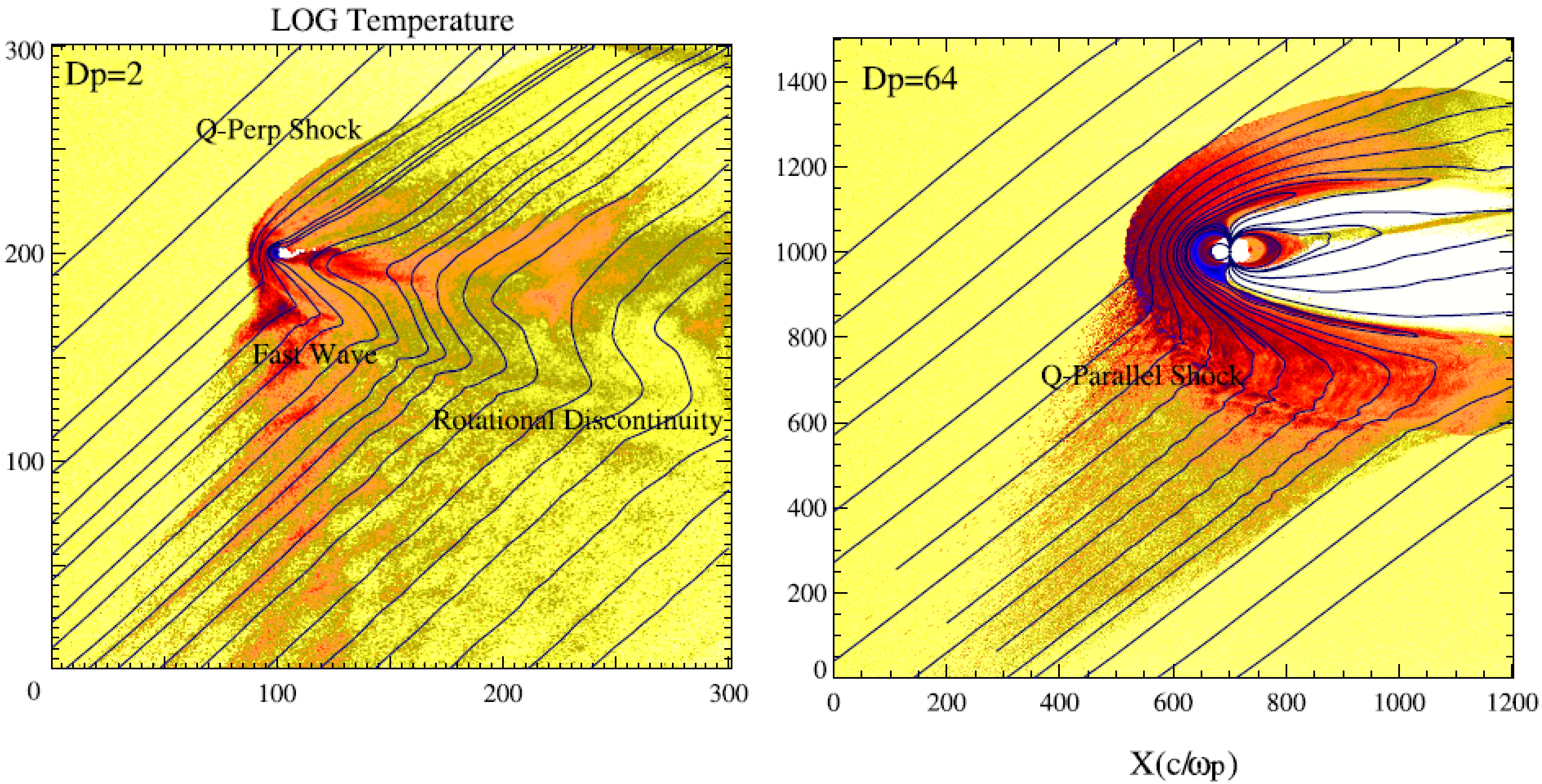
High Mach Number Quasiparallel

M_A=31
Large scale “reformation”



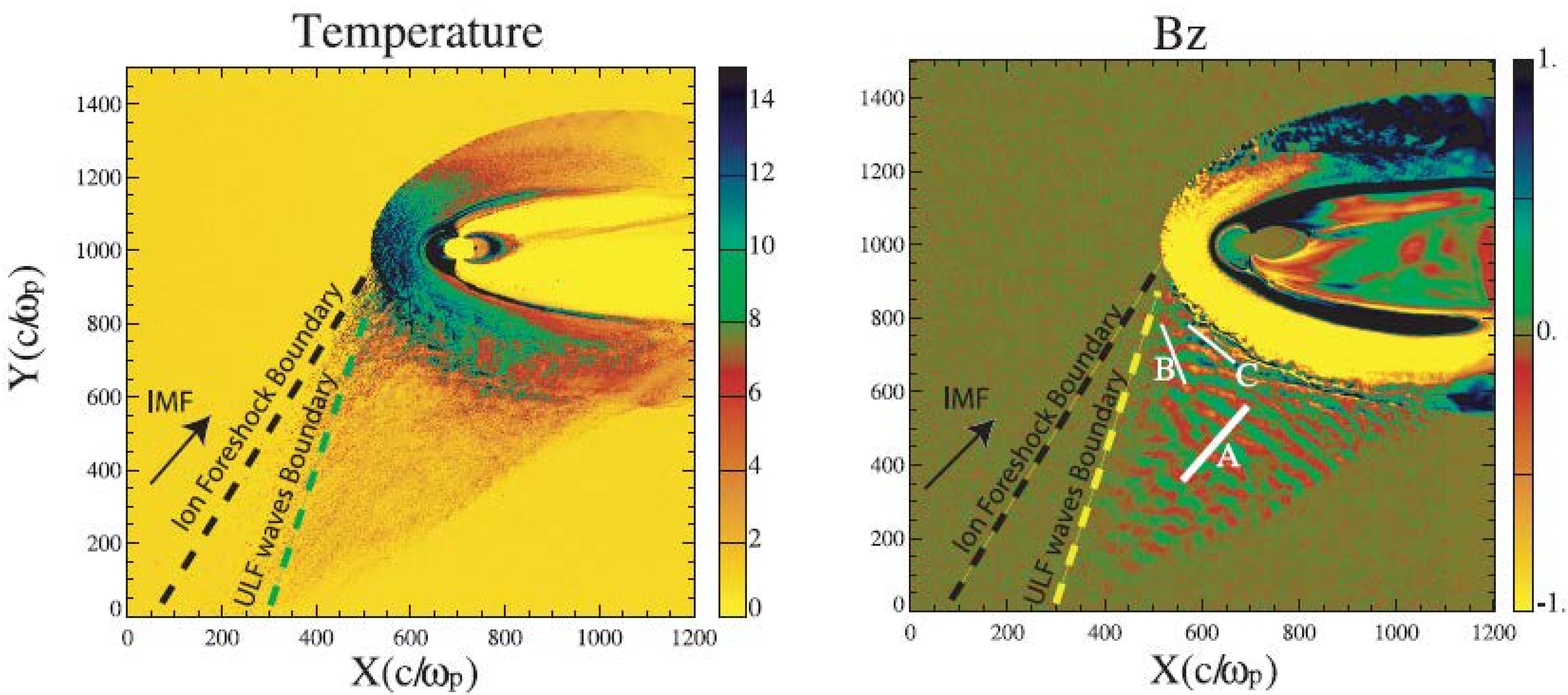
Gargate and Spitkovsky 2012

2D Global Hybrid Simulations



Blanco-Cano et al 2006

Global Hybrid Simulations

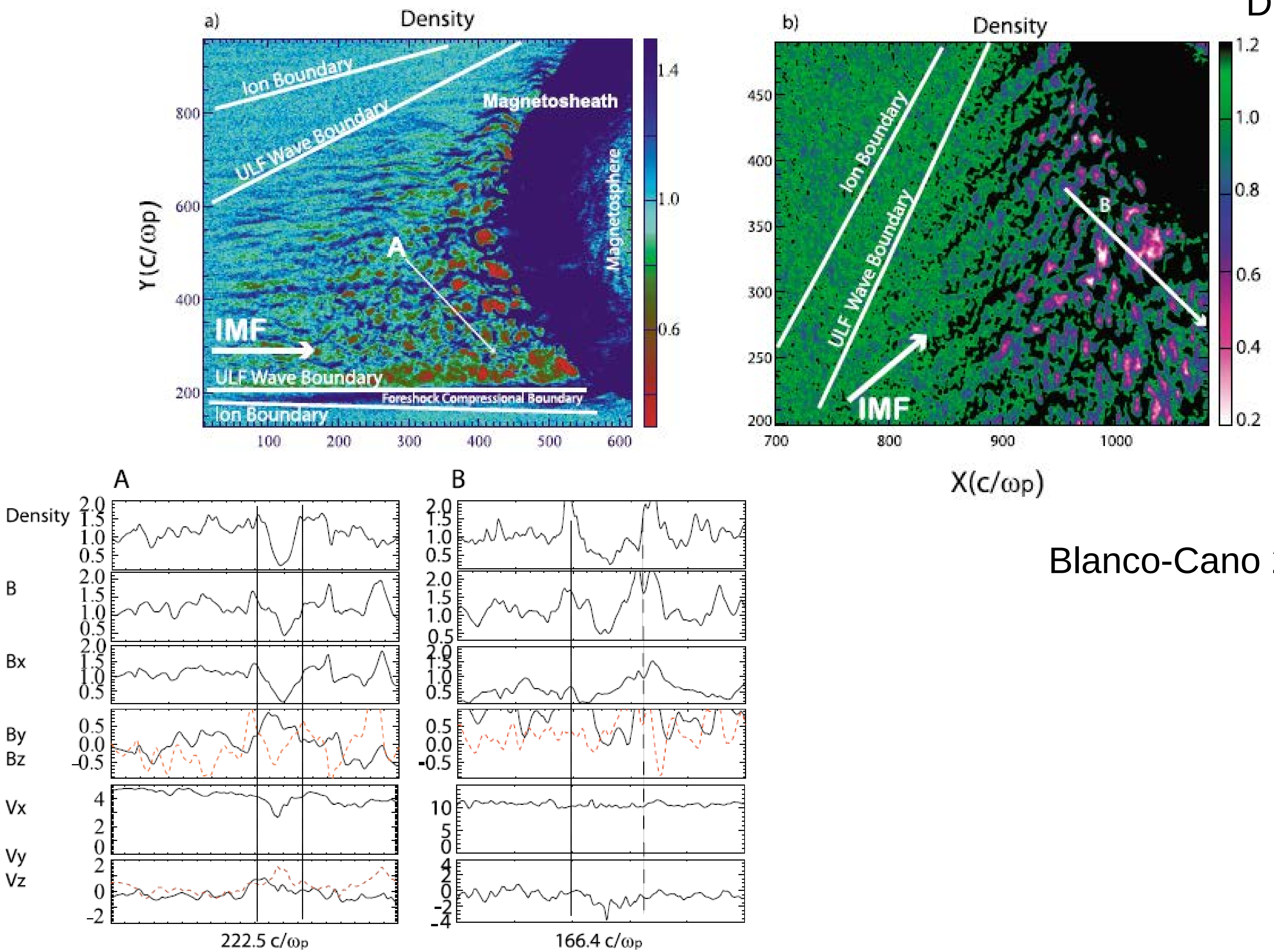


- Obstacle size Dp = 64
- But note that Dp = 640 for Earth
- and not 2D...

Blanco-Cano et al 2006

Global Foreshock Simulations

Dp=128



Blanco-Cano 2011

Microphysics at Quasi-parallel Shock

- Ion coupling and shock “reformation”, pulsation growth
- Links between ion microphysics and energetic particle acceleration
- Bigger and better simulations – detailed analysis

- Electron microphysics ... What heats the electrons?

Hybrid Space Plasma Simulations

- Successful for space plasmas where there is appropriate separation of ion and electron scales
- A powerful method bridging MHD and full particle PIC
- History of successful application to space plasmas – shocks, instabilities, etc.