Solar Flare Particle Heating via low-beta Reconnection

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Observational Constraints

- e^- acceleration to 20 – 50keV and above
- large (prompt, hard) x-ray flux → bulk heating rather than acceleration
- related to reconnection, but diffusion region has insignificantly small volume
- "slow shocks" usually dismissed, not expected to heat much. MHD fluid assumed to be close to isothermal…

…but what are the characteristics in a kinetic plasma?

Outline

- kinetic results of low beta reconnection outflow:
  ~1/2 of available energy goes into ion heating
  $v_{th} \sim v_A$; $\sim 1/\beta$
  - → all of inflow plasma is affected; 20 to 40 keV
  - → large pool of heated ions as seed particles

- ion distribution: bi-directional beams
  - → free energy for bi-directional waves
  - → generation of energetic ion tails
  - → fast electron heating and acceleration

We address several outstanding questions:

(i) what process can heat the entire reconnecting plasma to the known energies?

(ii) what provides the free energy for wave-particle interactions?

We propose a process in which initially the ions are heated and also provide the free energy for electron heating and tail formation

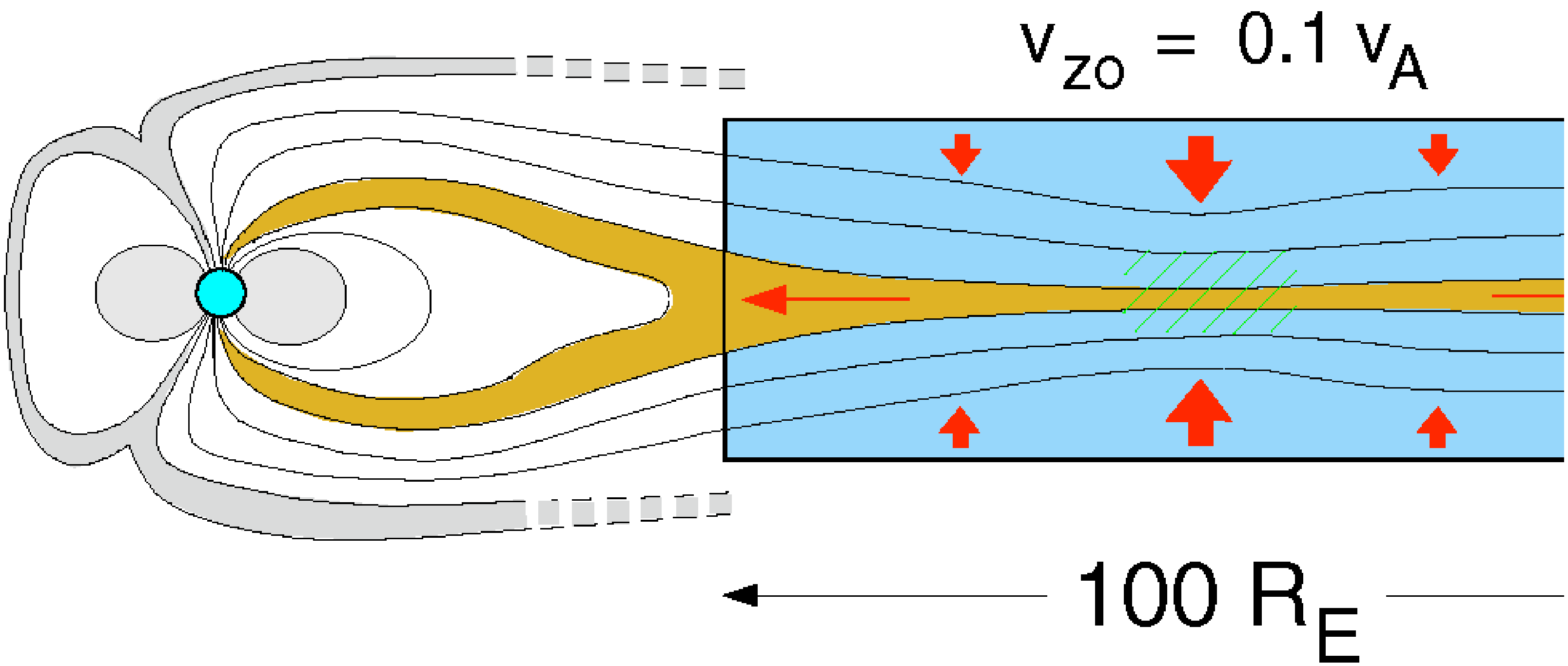
[*Krauss-Varban & Welsch, 2006*].

Overview

- role of low beta reconnection, parallels:
  - magnetotail and solar wind
- new hybrid code simulation results (kinetic ions, electron fluid)
- discussion of wave modes and electron acceleration

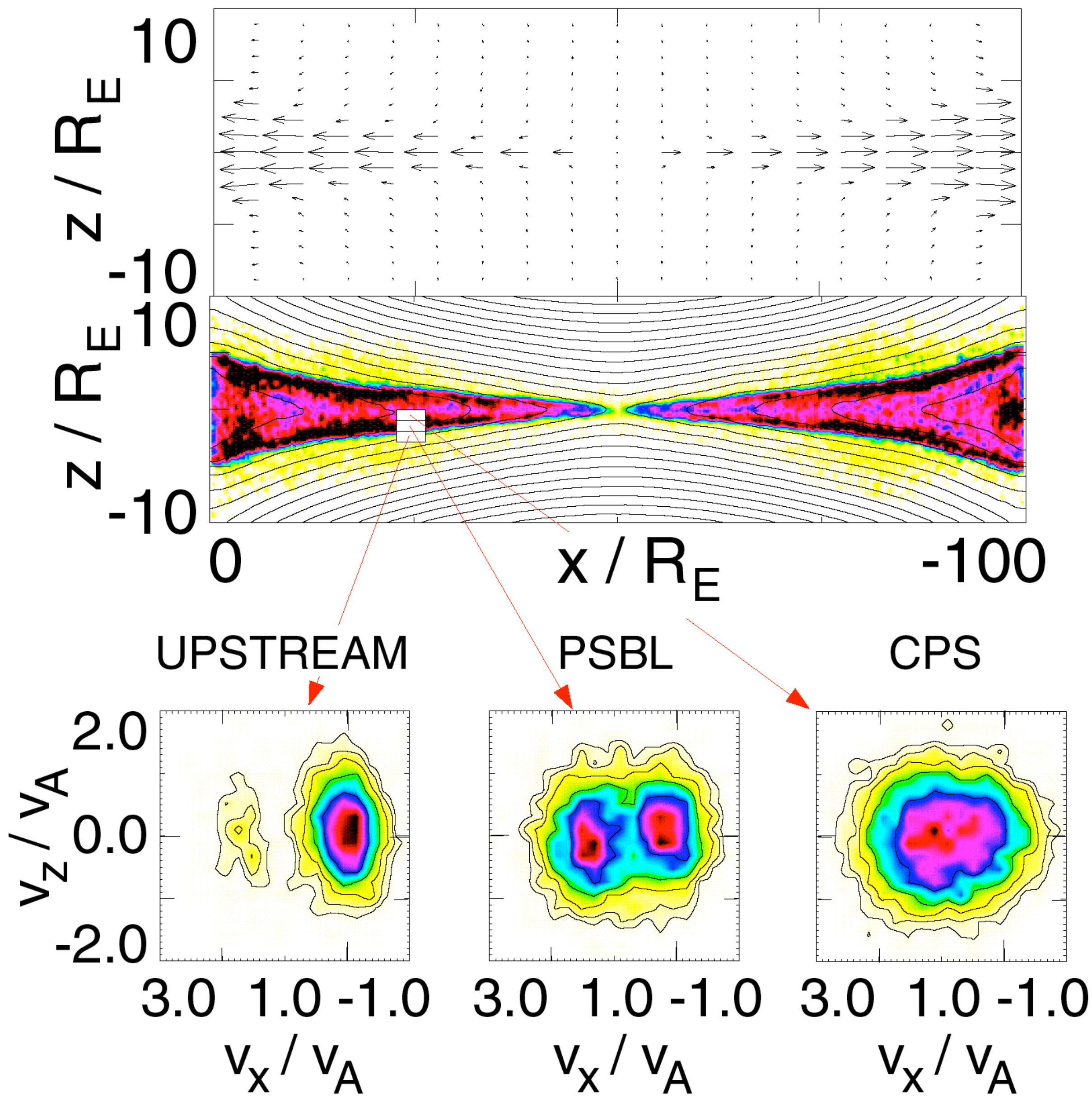
Magnetotail

Hybrid Simulations (kinetic ions, electron fluid)

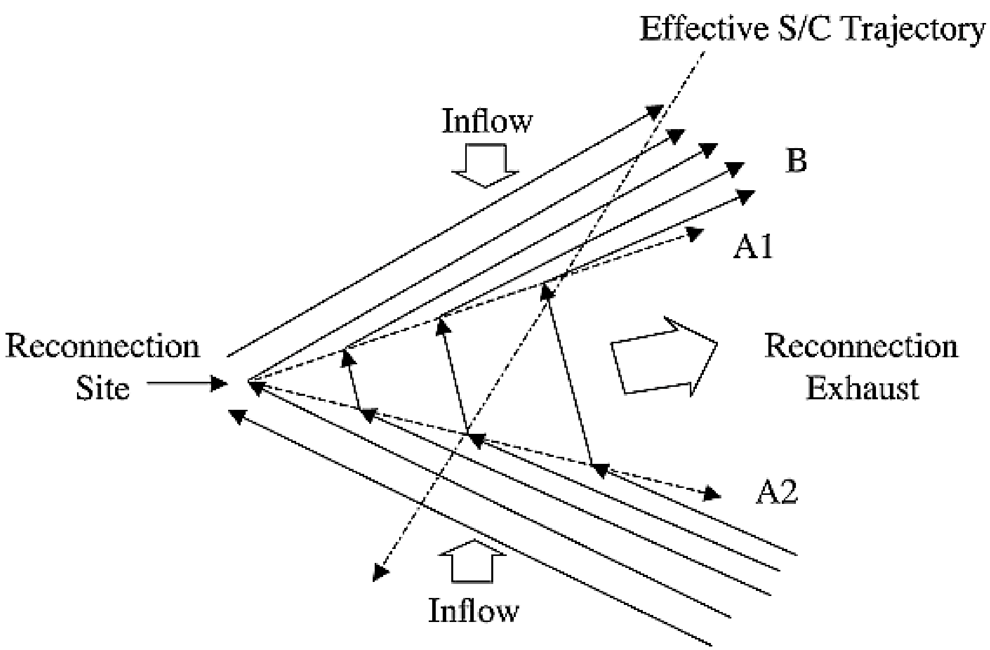


Krauss-Varban and Omidi, Geophys. Res. Let., 22, 3271-3274, 1995

Magnetotail



Reconnection in Solar Wind

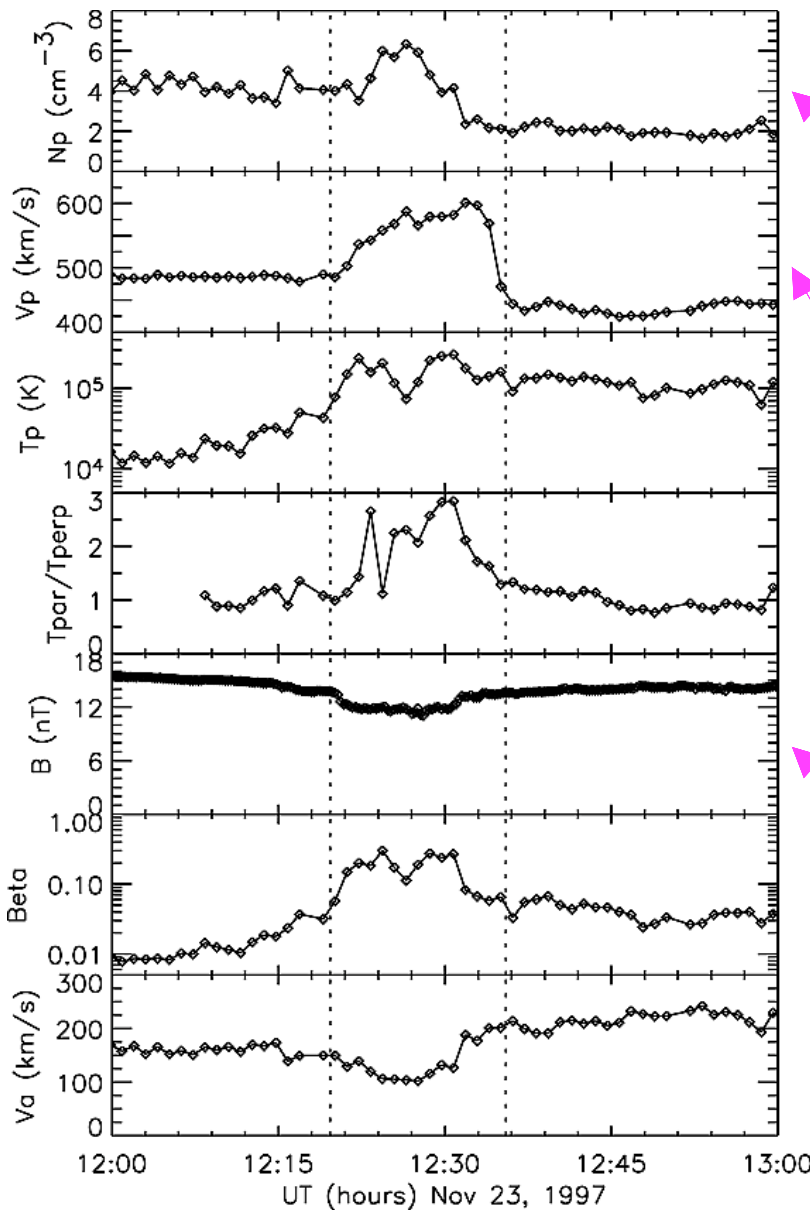


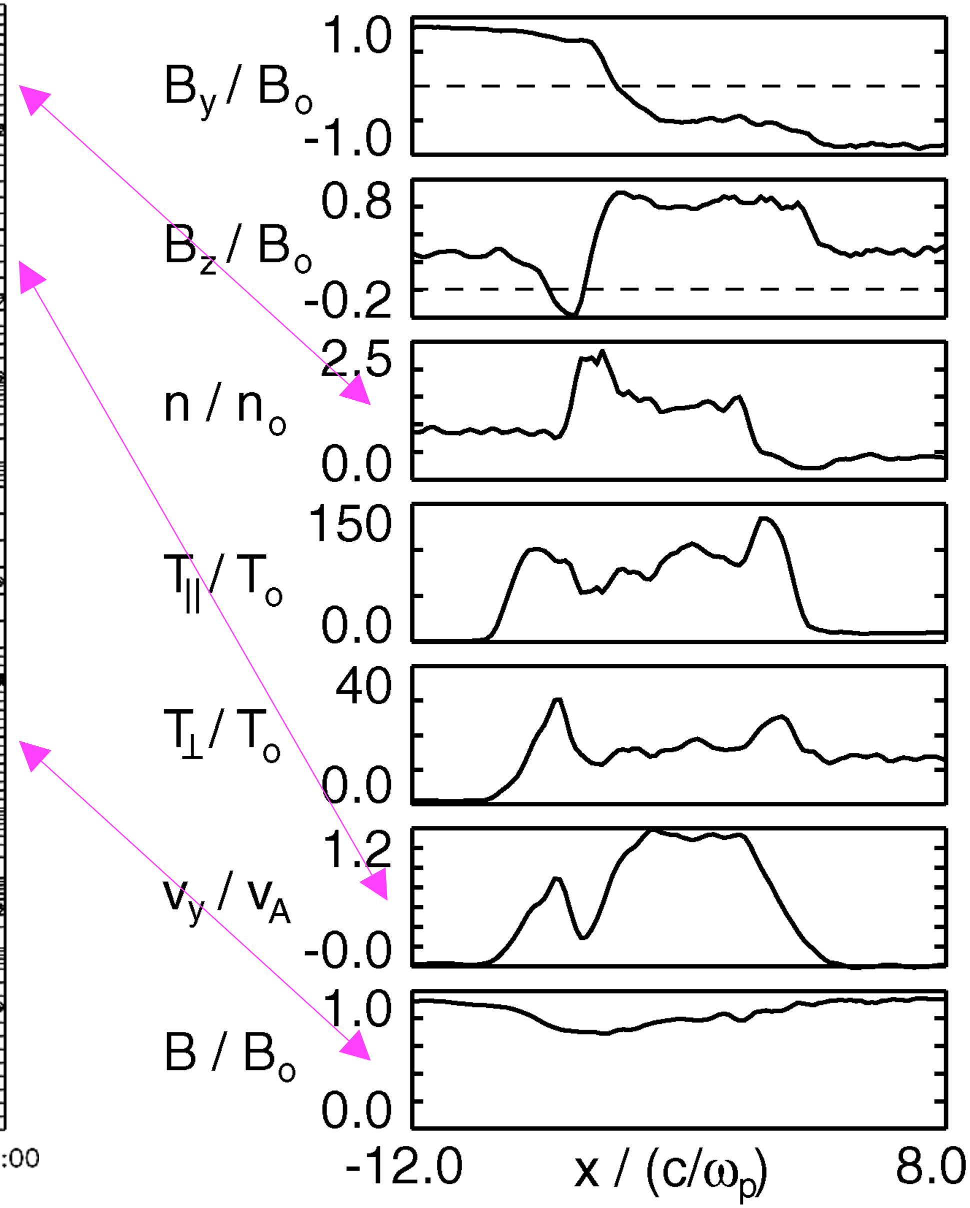
Gosling et al., 2005

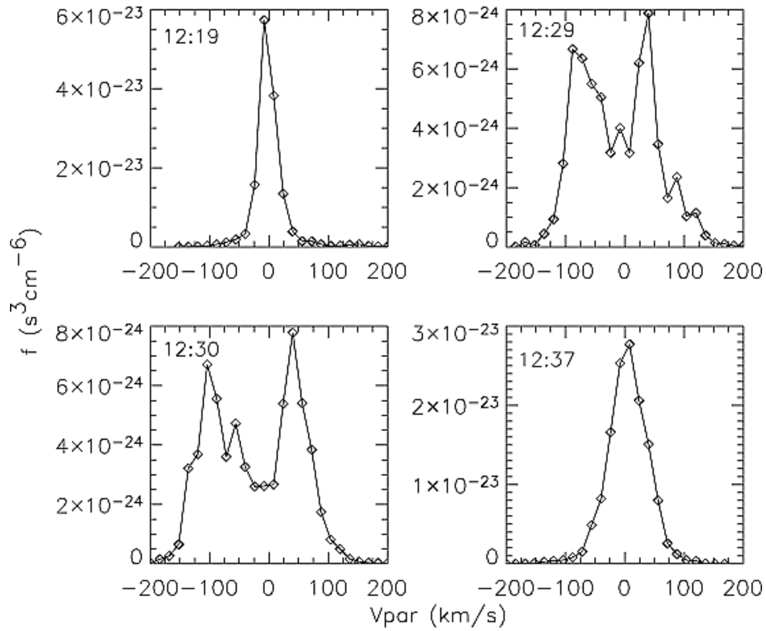
- Many 10s of cases observed
- Generally asymmetric, finite shear flow, **low β_i (e.g., 0.008)**
- Multi-spacecraft observations → x-line can extend for 100s of R_E (*Phan et al.,* 2005)

Gosling et al., 2005

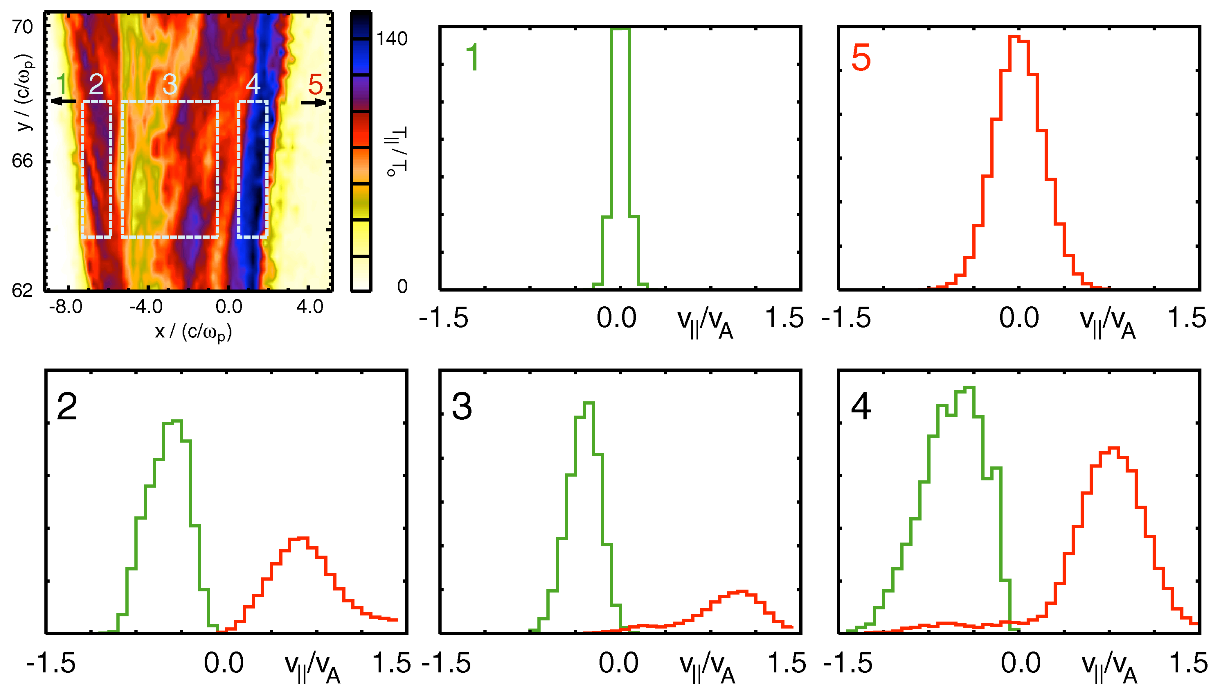
hybrid simulations





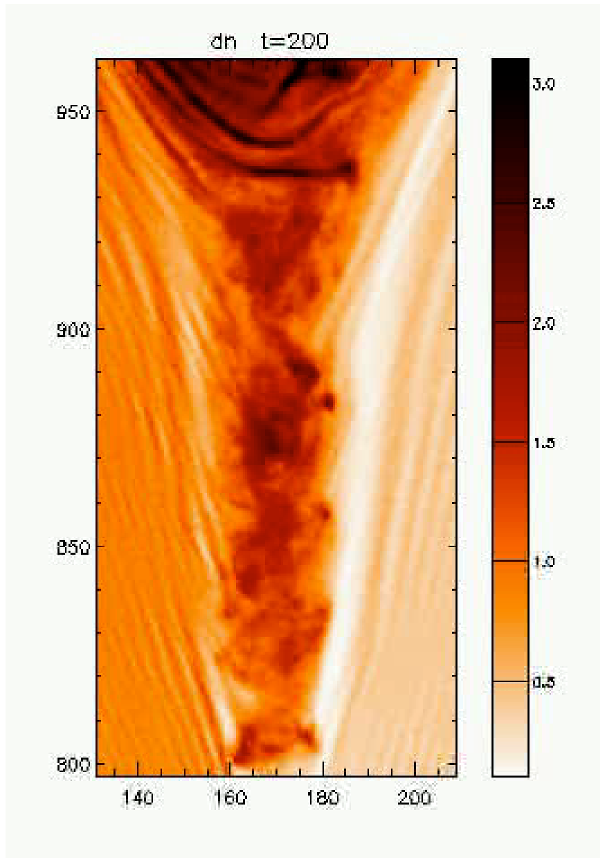


Gosling, 2005



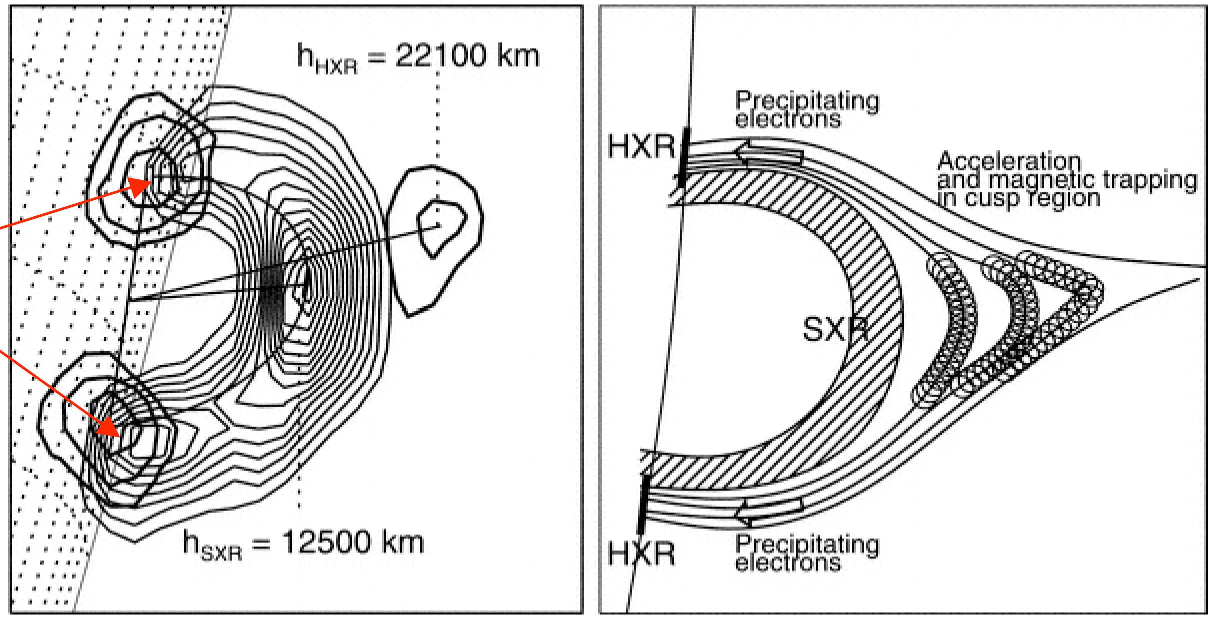
hybrid simulations

Turbulent Outflow



Flare Loop Reconnection Geometry

X-rays
highly
correlated

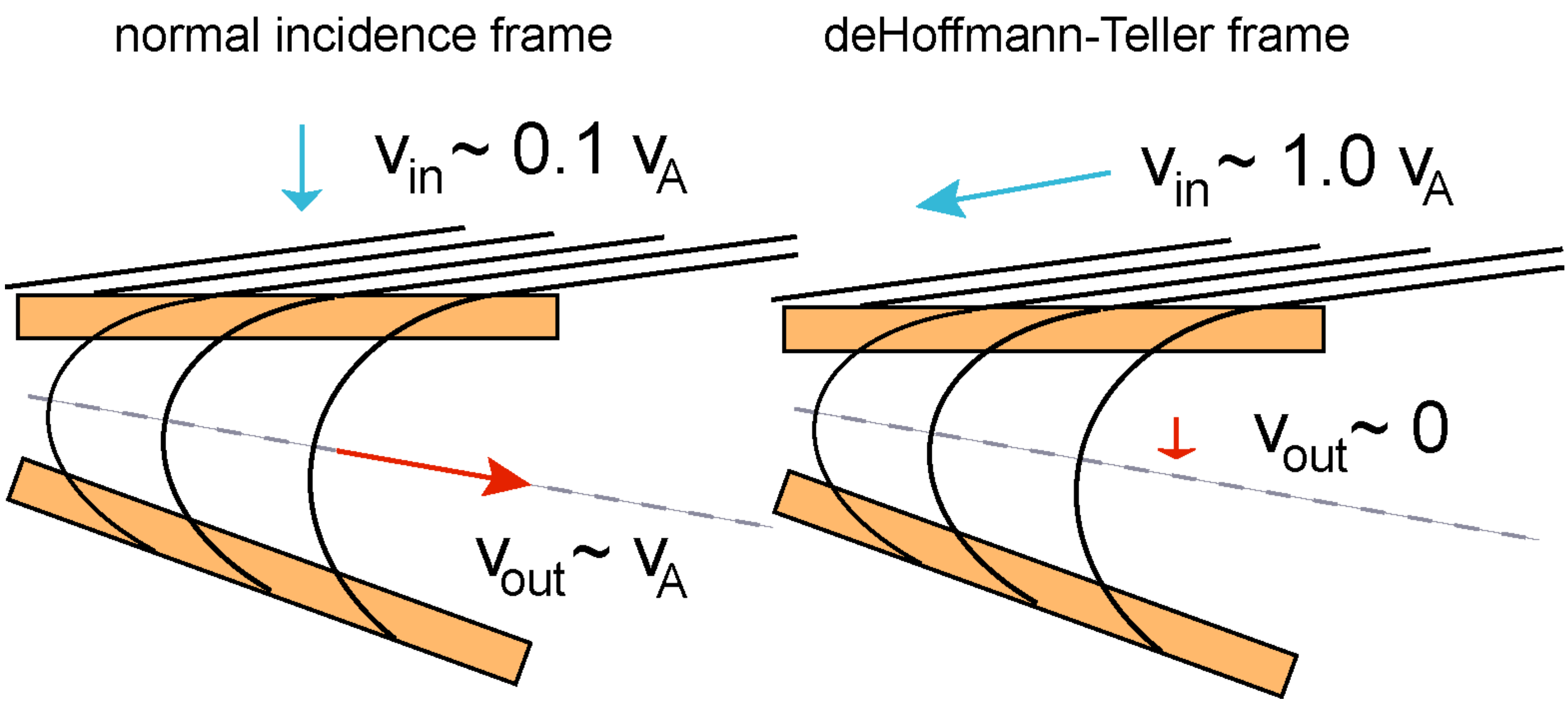


reconnection
outflow

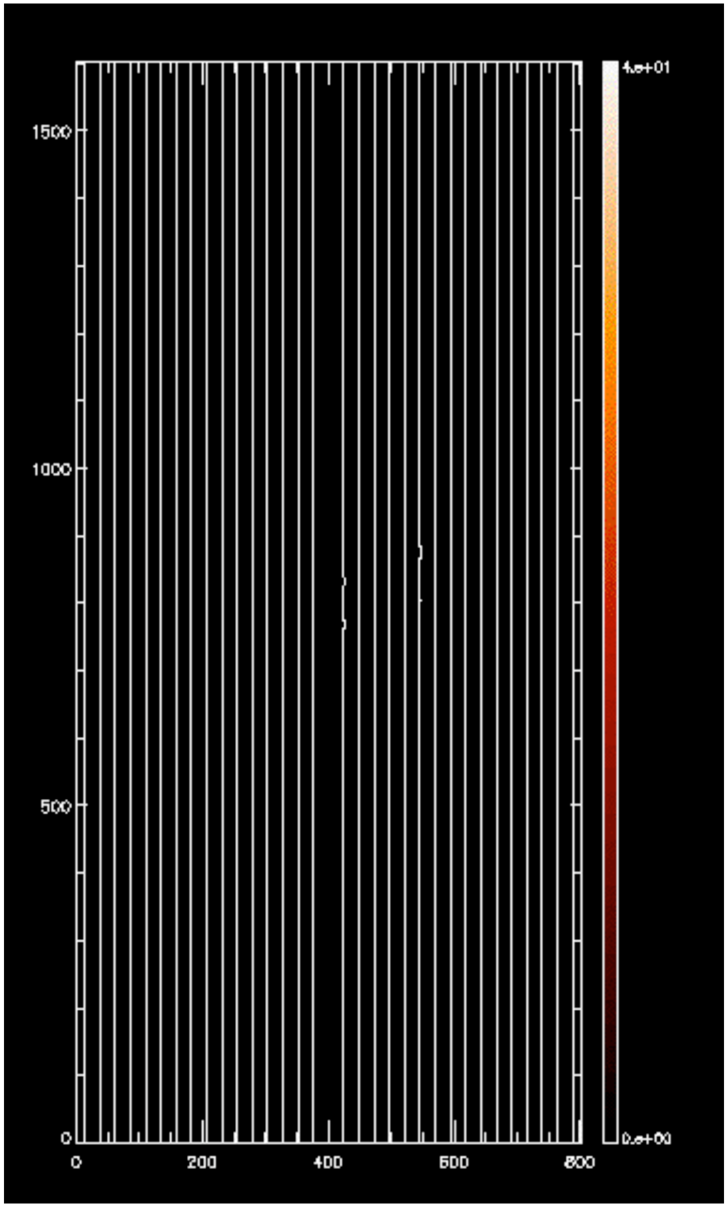
flare loop (after Aschwanden 2005)

…but applicable to other geometries as well, since simulation dimensions much smaller, here.

Ion Beam Generation



→ when $\beta << 1$ (I.e., $v_{th} << v_A$), result is interpenetrating ion beams with beam speed of $\sim v_A$



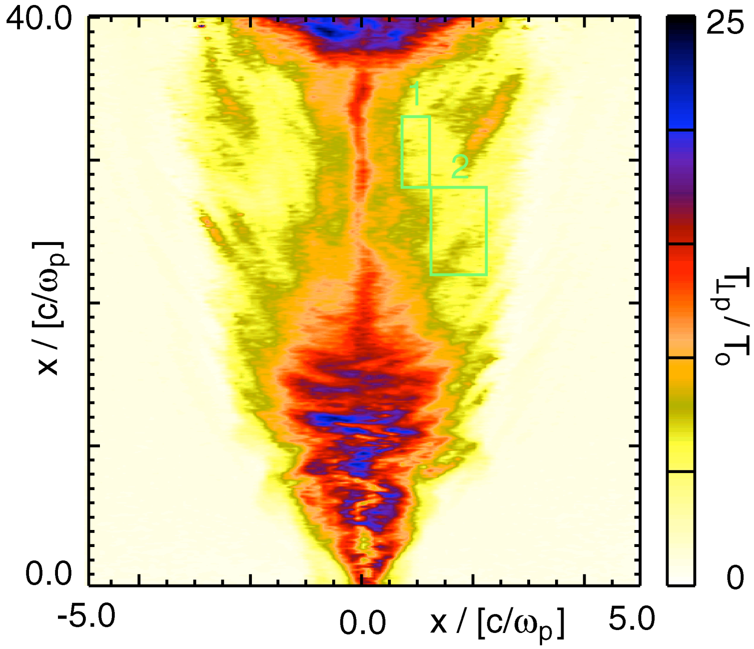
$T_{||}$

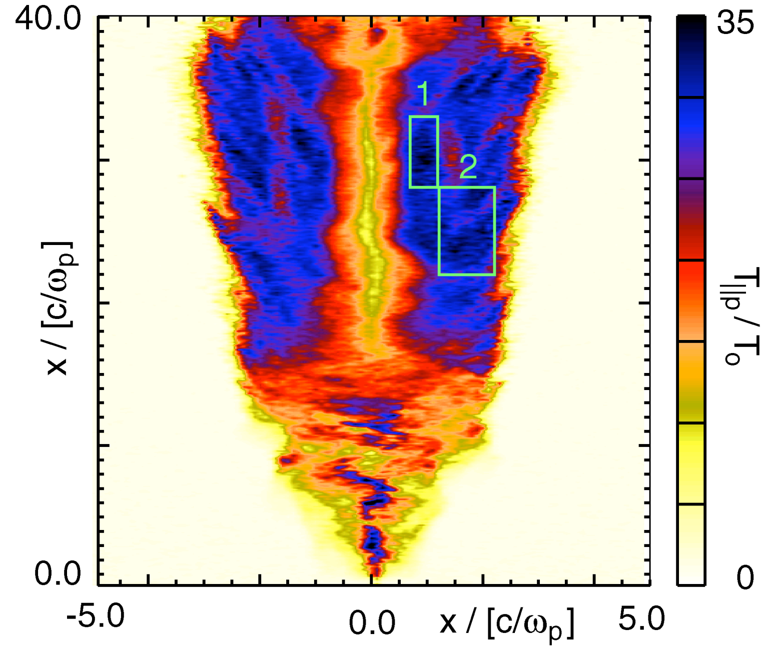
scale: 0 to 40 T_o

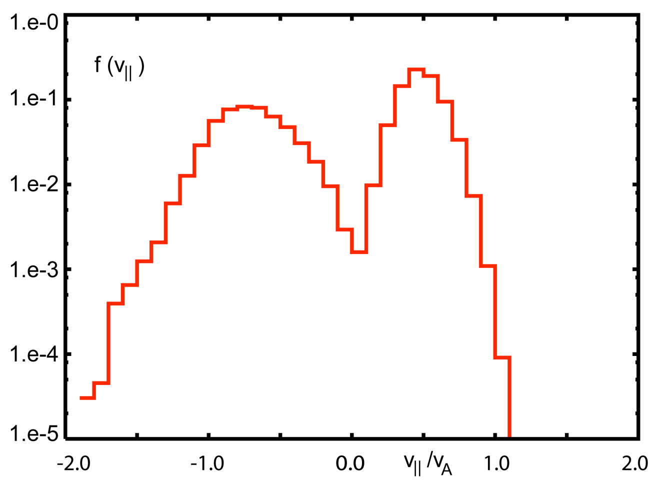
β_{pi} = 0.025

t = 0 to 128Ω_c^{-1}

Ion Beam Generation in Flare Loops



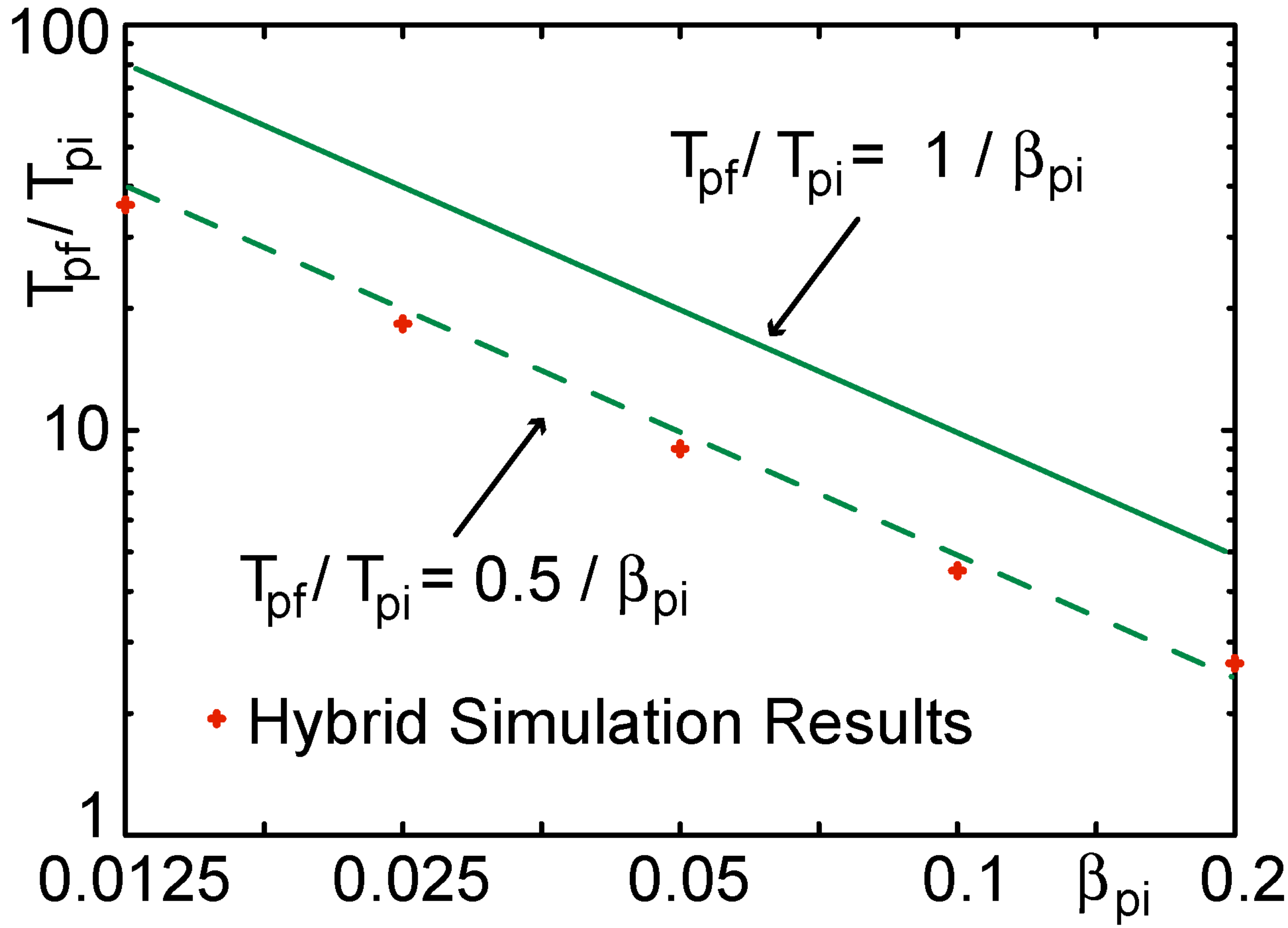




$\beta_i = \beta_e = 0.025$

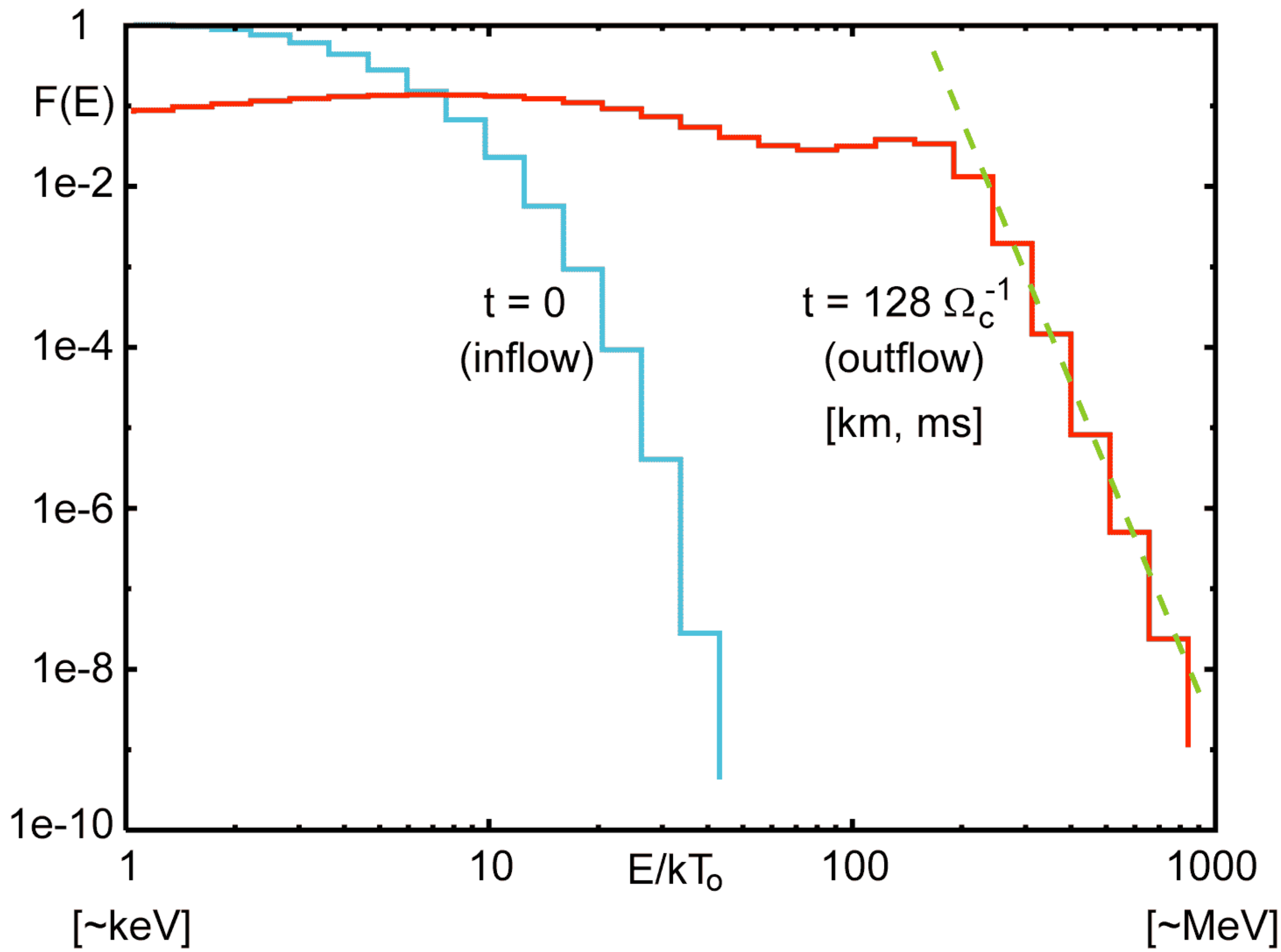
Ion beam generation is similar over wide range of betas: →

Scaling of Ion Heating with Upstream β_{pi}



…using effective temperature

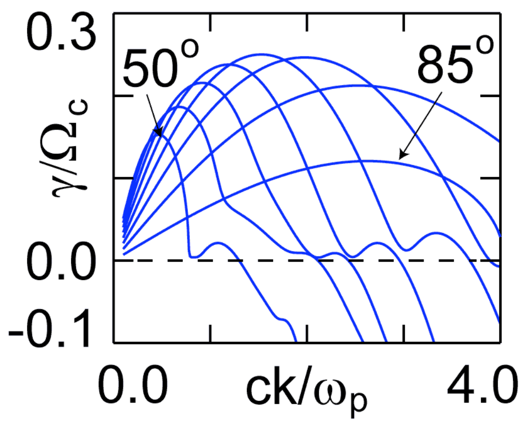
Ion Tail Generation



- bulk heating
- thermal pool, ~ 20keV seed particles
- energetic tail generation
- MeV protons within ms
- $E \propto m$

(energy in solar/upstream/inflow frame)

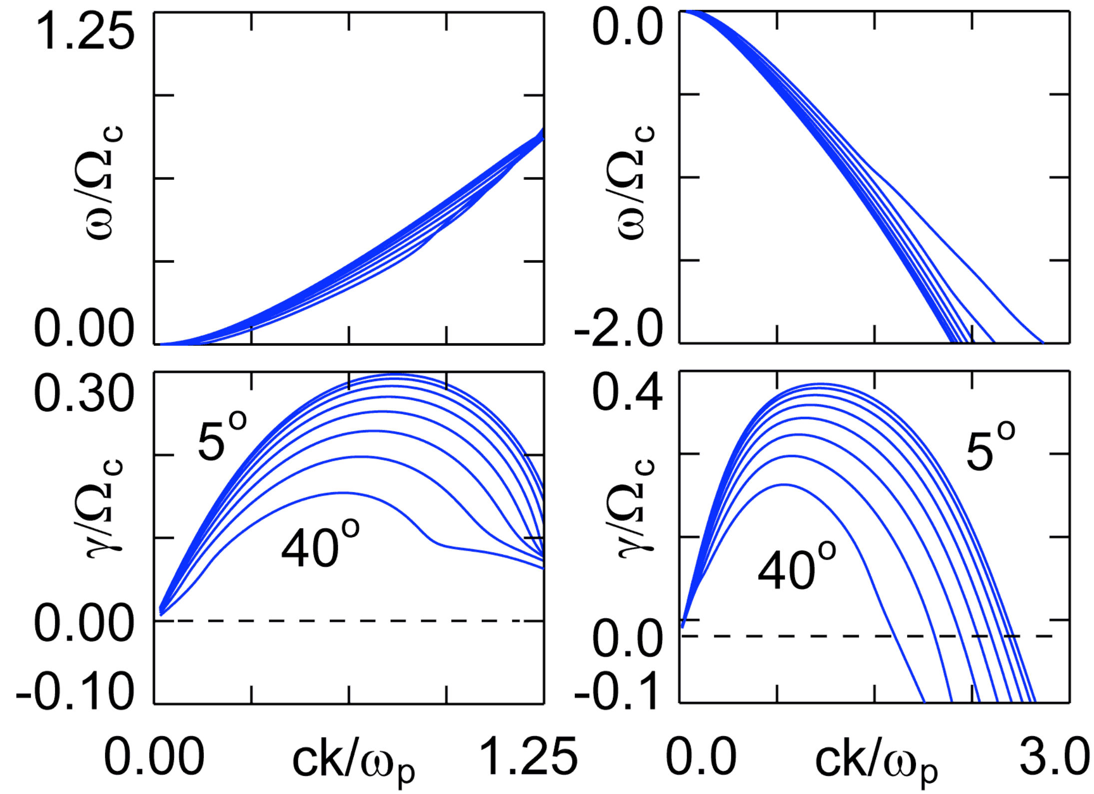
Linear Theory



EMIIC (slow shocks)

- e.s & e.m. A/IC -

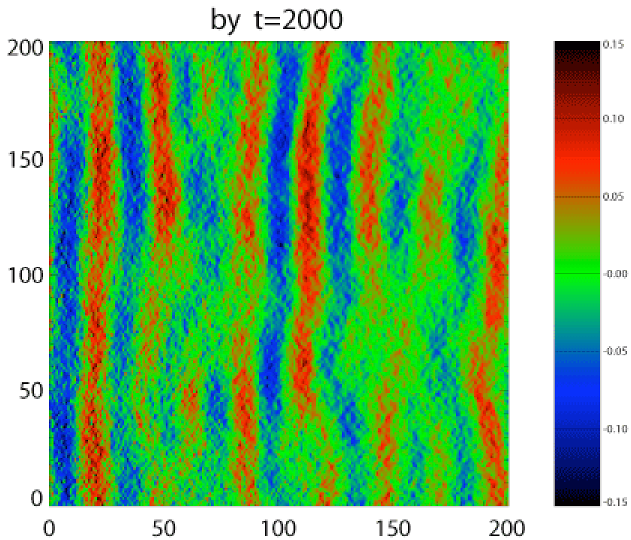
Winske & Omidi '92

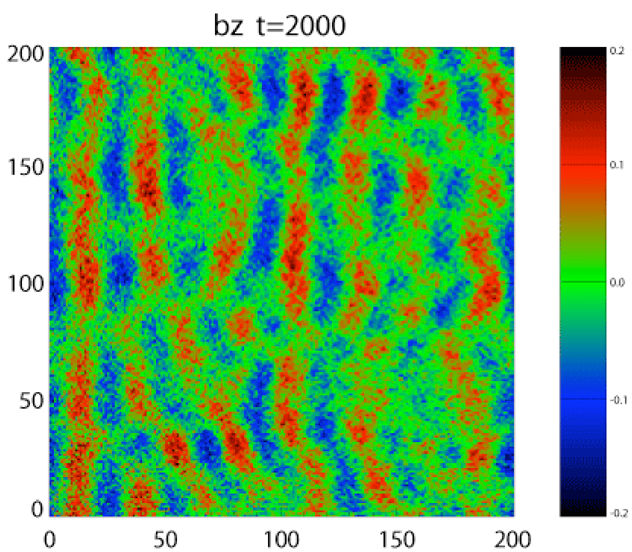


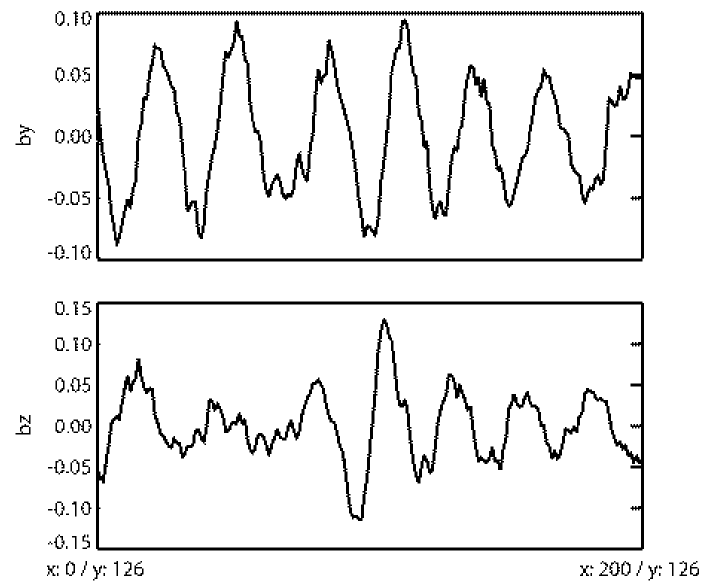
bi-directionally propagating
fast/magnetosonic waves

…using dual beam distributions from simulations

2-D periodic simulations







- both ~ parallel and oblique waves
- $ck/\omega_{pi} \sim 1$ as in linear theory
- $\Delta B/B \sim 0.1$

Electron Heating/Acceleration

Wave-particle interactions:

- slow shocks: oblique (kinetic) Alfvén waves (*Lin and Winske*)
- here: bi-directional fast magnetosonic waves and whistlers

Time scales: 1000km "source region" corresponds to 10^5 - 10^6 ion inertial lengths; traversed in 10ms by 20keV electrons

Currently executing 2-D full-particle simulations to address effectiveness

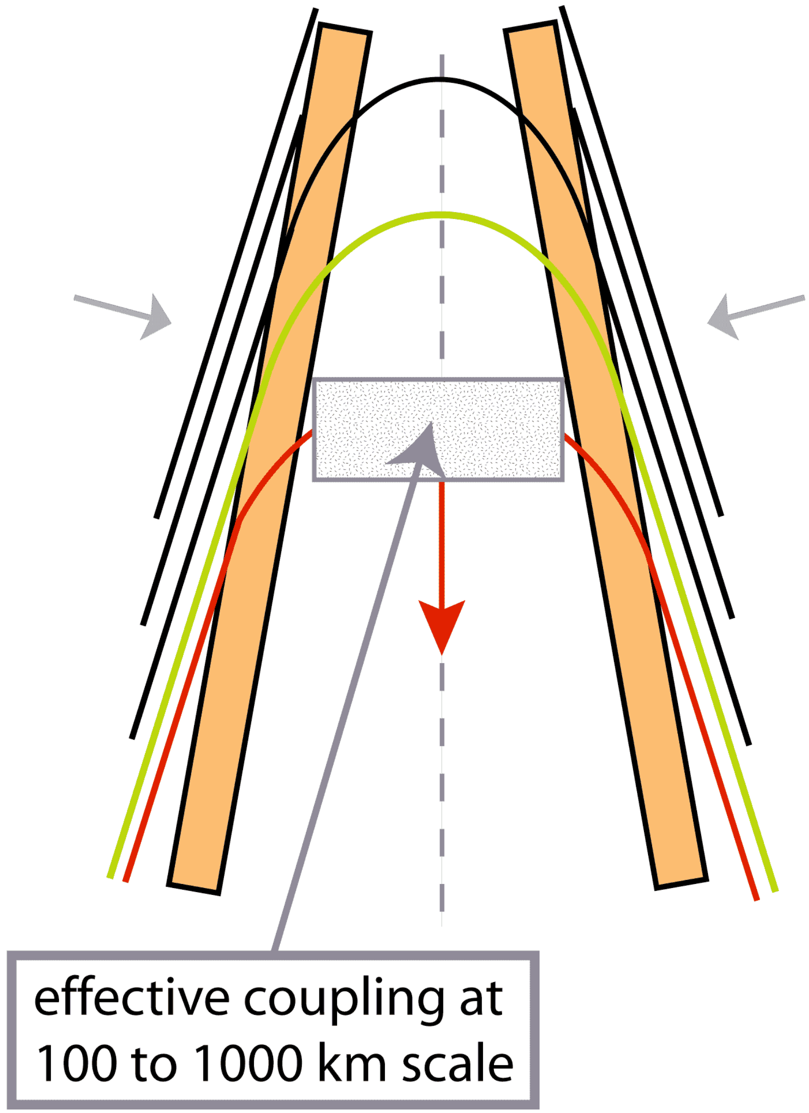
Separation of Scales

Argument is that simulations can be reasonably divided into:

(i) ion-kinetic reconnection/outflow,

(ii) local/periodic ion-ion beam with electron test particles, and

(iii) local/periodic full particle simulations of transit-time damping, perpendicular heating, and scattering in ion-ion wave fields.



Summary

Low beta kinetic reconnection leads to:

- bulk heating of the ions (scaling: $\propto \_{pi}^{-1}$, $\propto m$)
- bi-directional ion beams
- bi-directional fast/magnetosonic waves
- energetic ion tails
- presumably, efficient electron heating and acceleration due to transit-time damping (e.g., Lee & Völk, 1975, Miller et al., 1996)