Magnetic Reconnection in Plasmas, Nordita, Stockholm, August 11, 2015

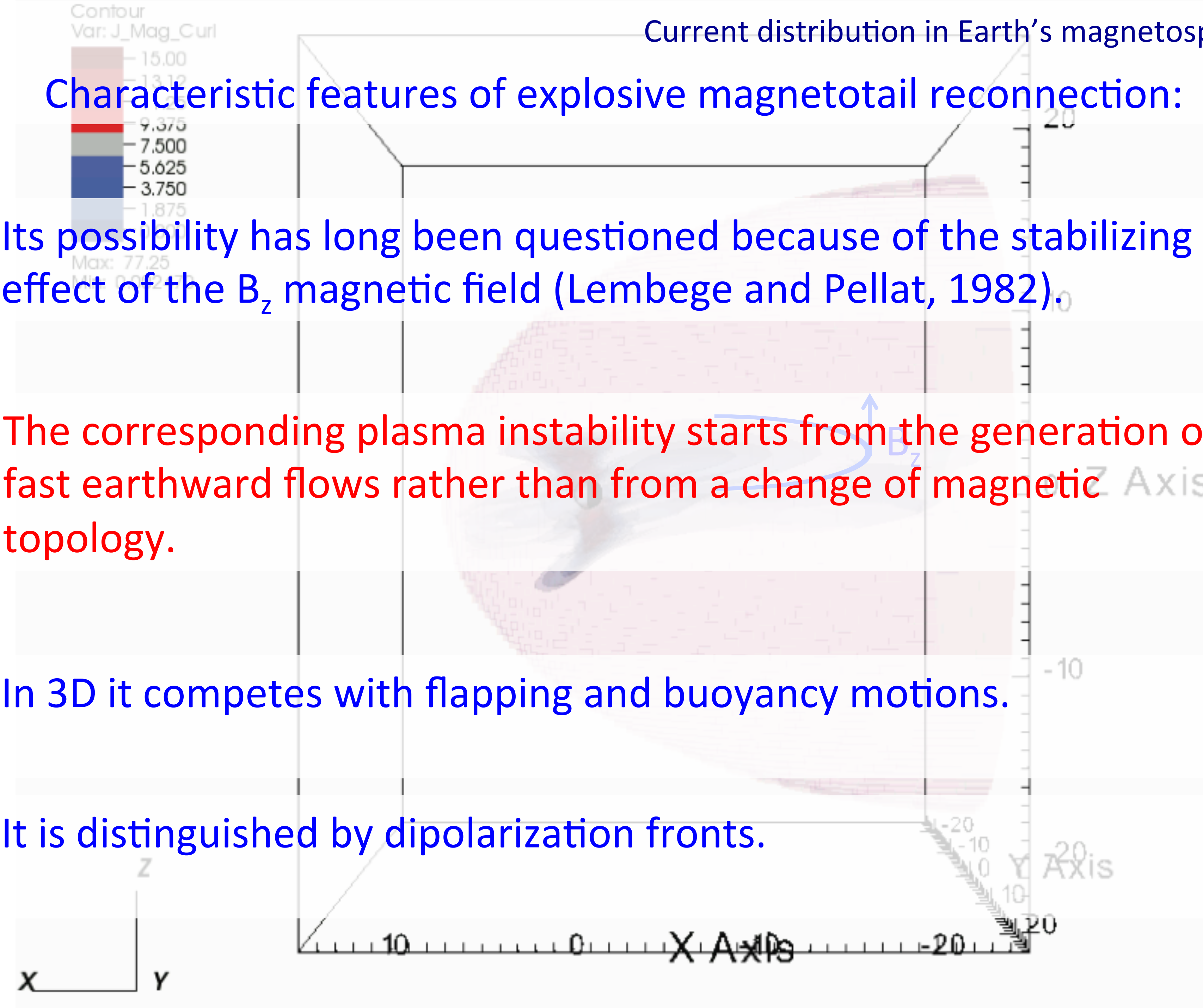
Three-dimensional kinetic picture of magnetic reconnection, buoyancy and flapping motions in the magnetotail

Collaborators: Slava Merkin, Marc Swisdak, Natasha Buzulukova, Tetsuo Motoba, Tom Moore, Barry Mauk, Shin Ohtani

Mikhail Sitnov

JOHNS HOPKINS
APPLIED PHYSICS LABORATORY

Current distribution in Earth's magnetosphere

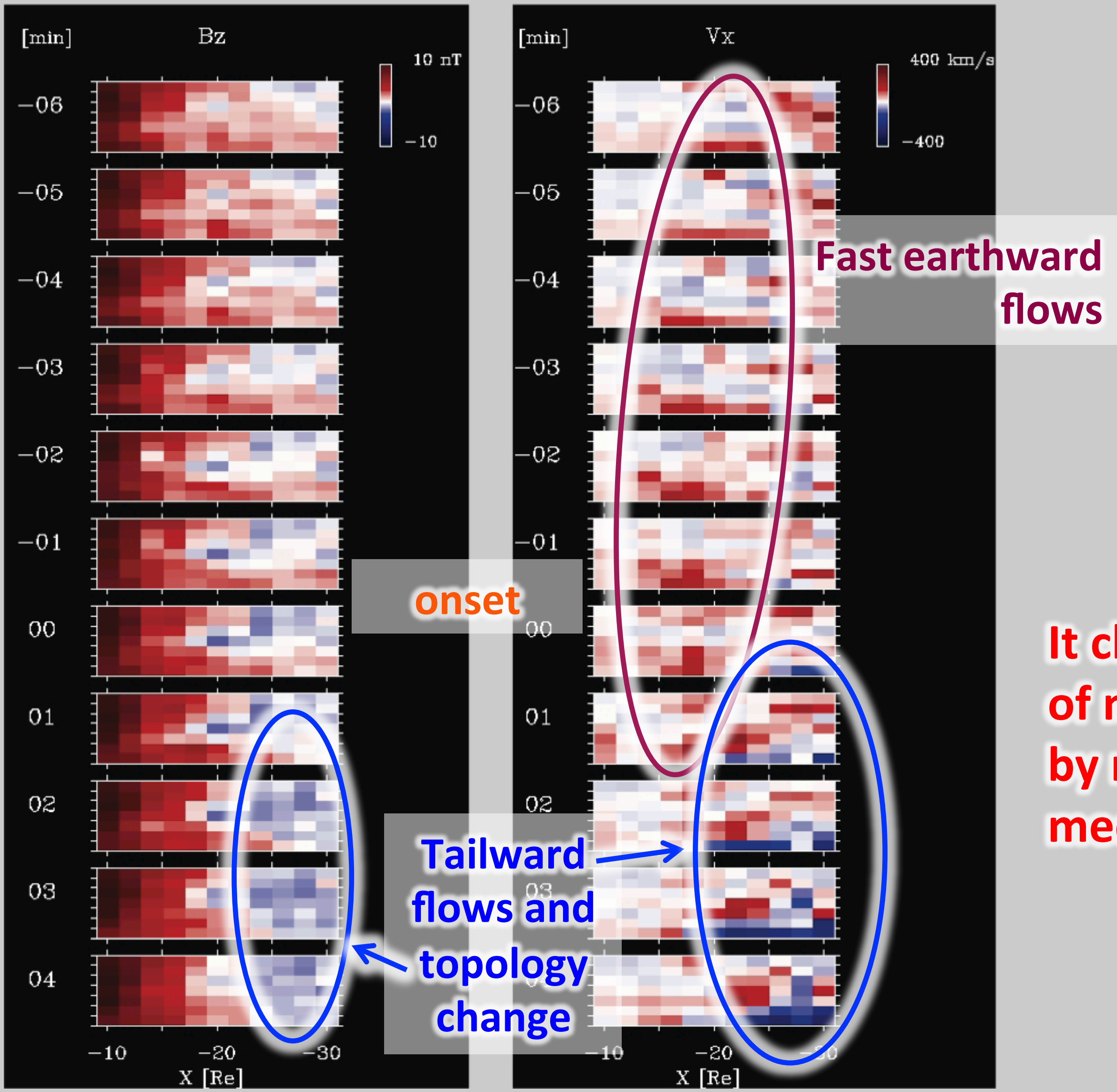


Characteristic features of explosive magnetotail reconnection:

- Its possibility has long been questioned because of the stabilizing effect of the B_z magnetic field (Lembege and Pellat, 1982).
- The corresponding plasma instability starts from the generation of fast earthward flows rather than from a change of magnetic topology.
- In 3D it competes with flapping and buoyancy motions.
- It is distinguished by dipolarization fronts.

Magnetotail explosion (substorm) starts from the generation of fast earthward flows rather than from a change of magnetic topology

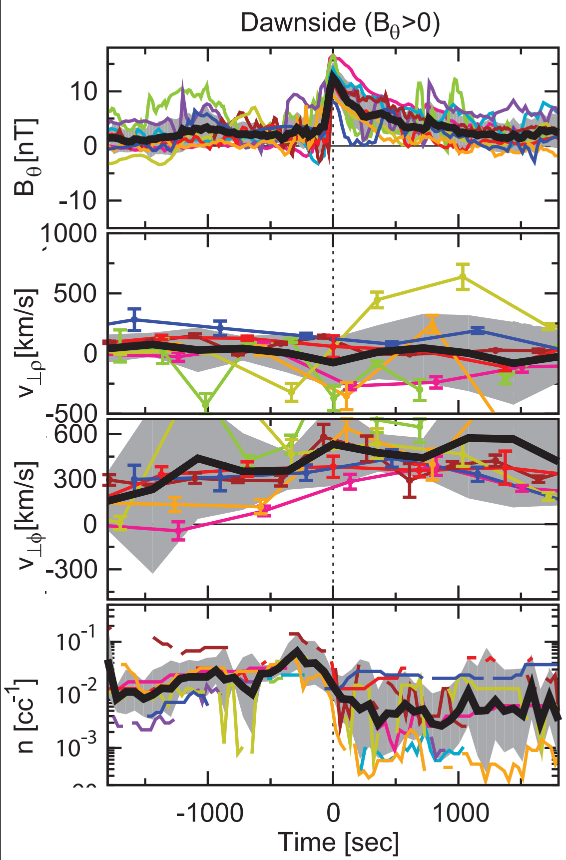
Machida et al. [2009]



It challenges explanation of magnetotail explosions by magnetic reconnection mechanism

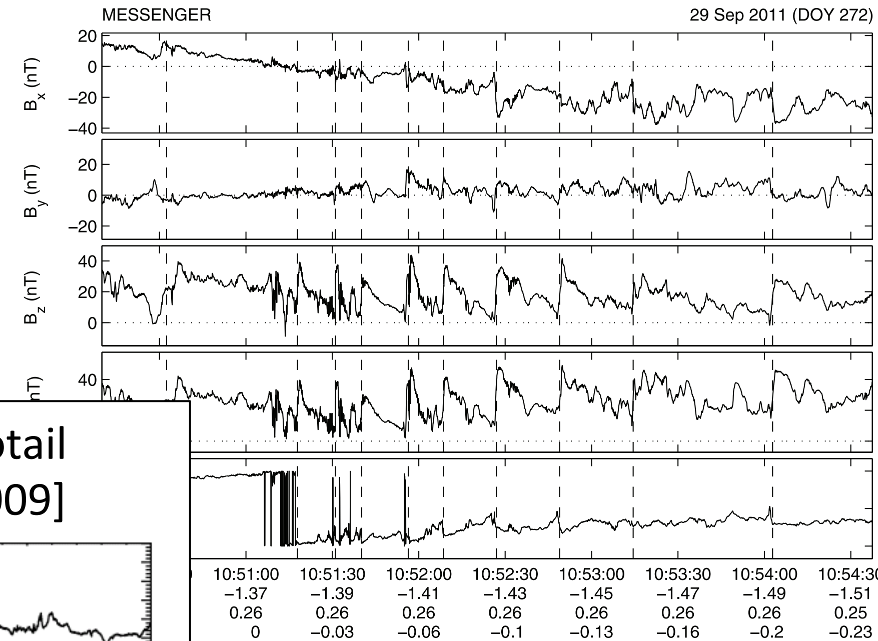
Dipolarization fronts challenge conventional reconnection picture

Jupiter's magnetotail [Kasahara et al., 2013]

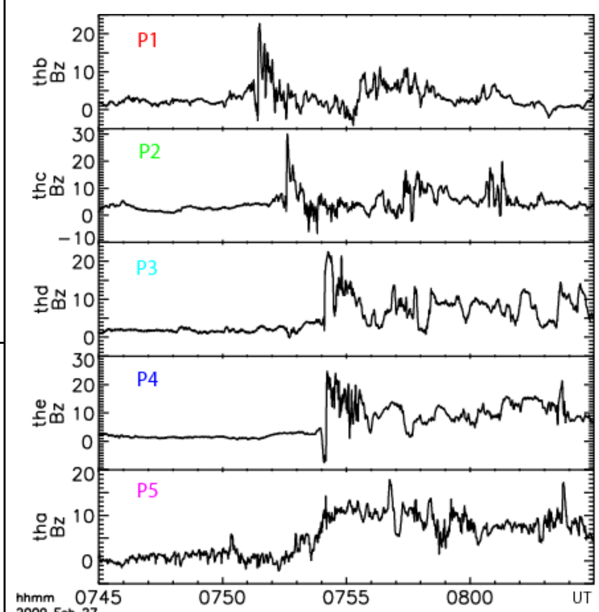


Conventional reconnection picture implies bipolar Bz perturbations!

Mercury's magnetotail [Sundberg et al., 2012]

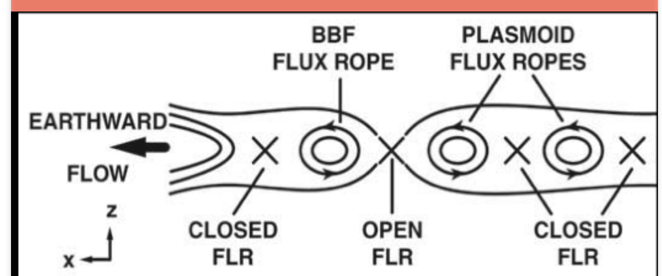


Earth's magnetotail [Runov et al., 2009]



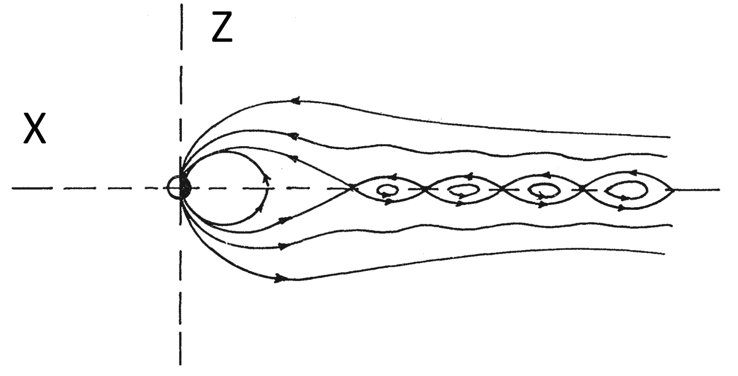
No room for multiple plasmoids!

Slavin et al. [2002]



Tearing linear stability theory

Coppi, Laval and Pellat [1966]: Electron tearing instability of 1D current sheet



Fairfield and Ness [1970]: Bz≠0

Schindler [1974]: Ion tearing instability

Lembege and Pellat [1982]:

$$\frac{kL_z B_0}{B_z} > \frac{4}{\pi}$$

Sufficient stability criterion for the ion tearing mode coincides with WKB approximation condition, which means that spontaneous reconnection is not possible in the magnetotail

Sitnov and Schindler [2010]: L&P stability criterion revisited

$$\frac{kL_z B_0}{\pi B_z} > \left(\frac{VB_z}{\pi L_z}\right)^2 \equiv C_d^2$$

Lembege and Pellat:

$$V = \int \frac{dl}{B} \approx \frac{2L_z}{B_z}$$

$C_d \leq 1$ - Stable

$C_d > 1$ - Potentially unstable

For equilibria [*Schindler*, 1972] $\psi = LB_0 \ln\left[\beta(x)\cosh\left(z/[L\beta(x)]\right)\right]$ $\beta'_x/\beta = B_z/B_0$

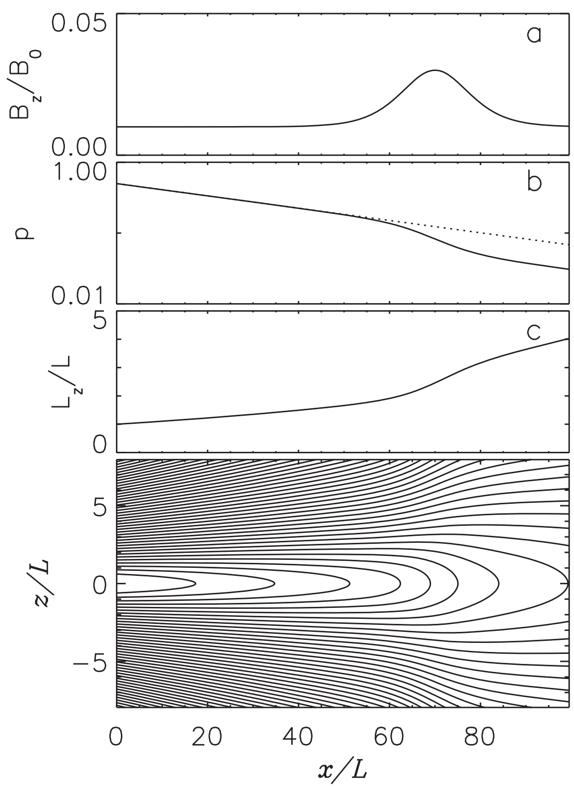
The destabilization factor C_d can be presented in the form: $C_d = \frac{\beta'_x(x)}{\pi\beta(x)} \int_0^\infty \frac{\beta(x(u))}{\beta'_x(x(u))} \frac{du}{\sqrt{e^u - 1}}$, $u = 2\psi/LB_0 - 2\ln\beta$

Tail configuration prior to onset

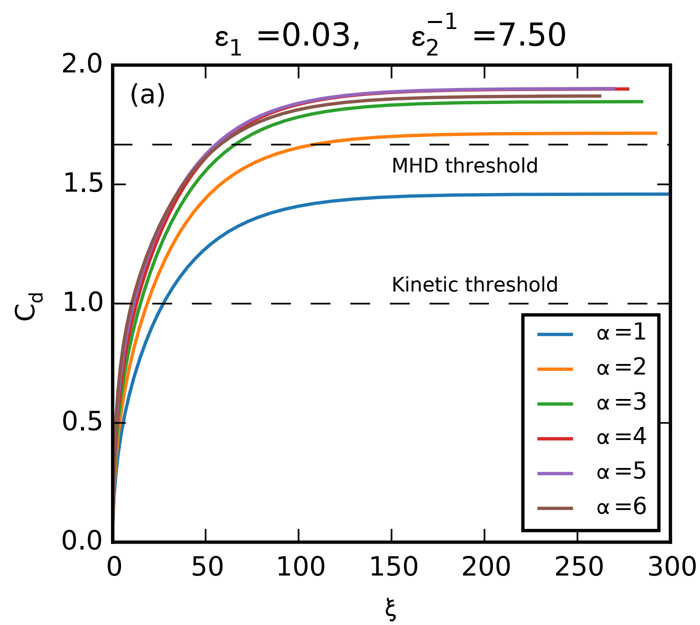
The only class of tail equilibria which have a potential for spontaneous reconnection onset must have a region of the tailward Bz gradient

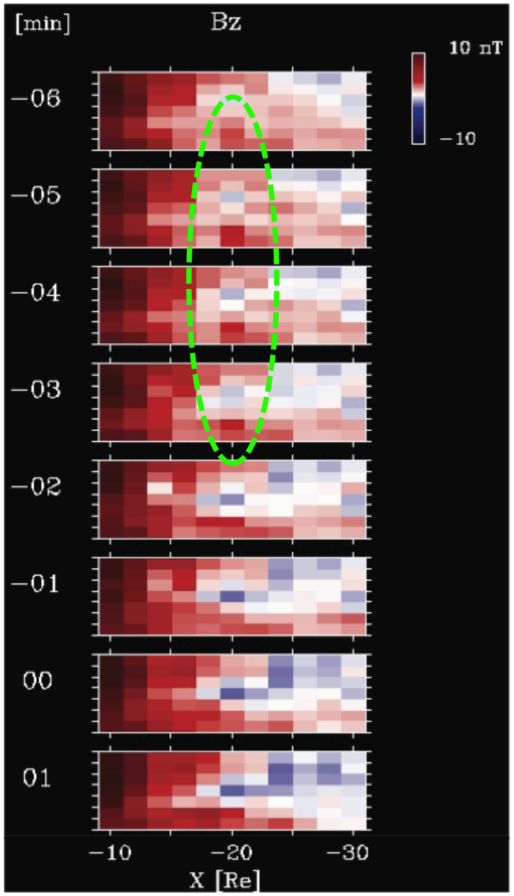
$$B_z = \varepsilon_1 B_0 \left[1 + \frac{\alpha}{\cosh^2\left(\varepsilon_2\left(\xi - \xi_0\right)\right)} \right] \qquad \xi = x/L, \quad \varepsilon_1 << \varepsilon_2 << 1$$

Machida et al. [2009]



Merkin [2015]





And it must be located sufficiently far from the planet

Sufficient instability condition

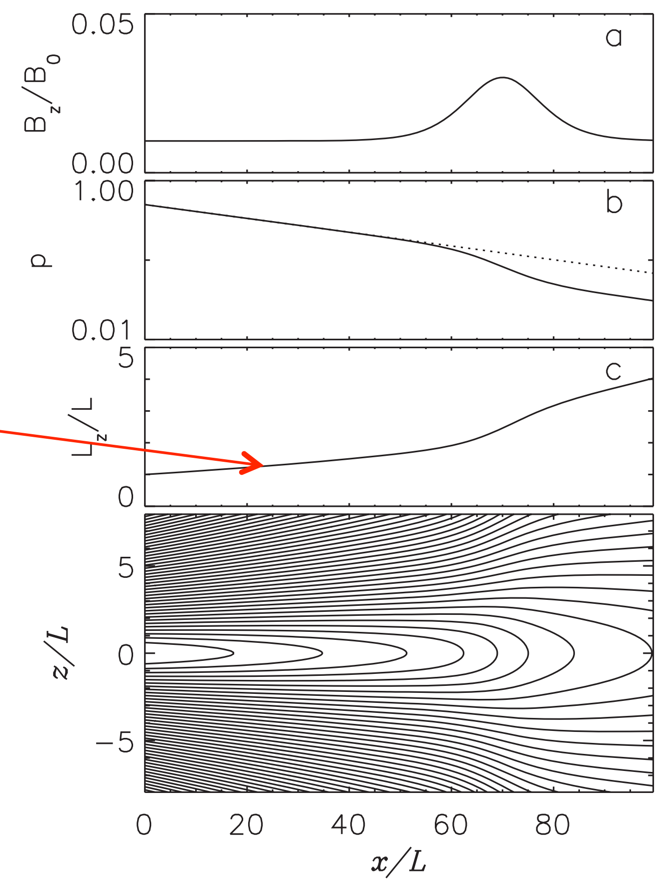
To be unstable the tail current sheet must also be sufficiently thin [Biskamp et al., 1970; Schindler, 1974; Pritchett et al, 1991; Brittnacher et al., 1995]:

$$L_z \le \rho_{0i} \left(B_0 / B_z \right)^{1/\nu}$$

ν=5/2 for $L_z >> \rho_{0i}$ and ν=3 for $L_z < \rho_{0i}$

Here is a problem:

For 1972 Schindler-class magnetotail equilibria L_z is increasing tailward because $\frac{\partial(\log L_z)}{\partial x} = \frac{B_z}{L B_0}$



To be more precise: $L_z \propto \rho_{0i} \propto 1 / B_0$

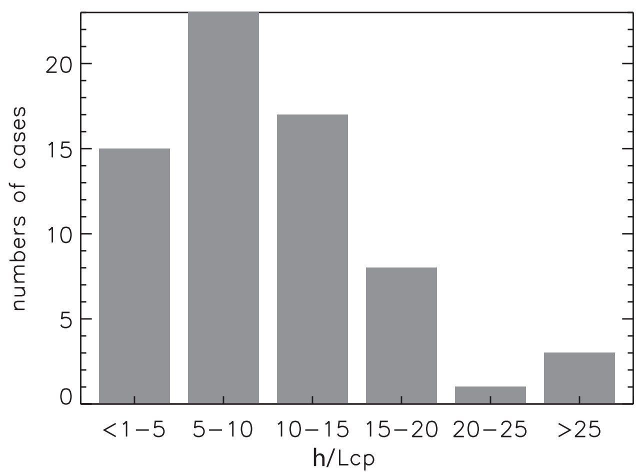
Thus, the instability window shrinks with the distance from Earth

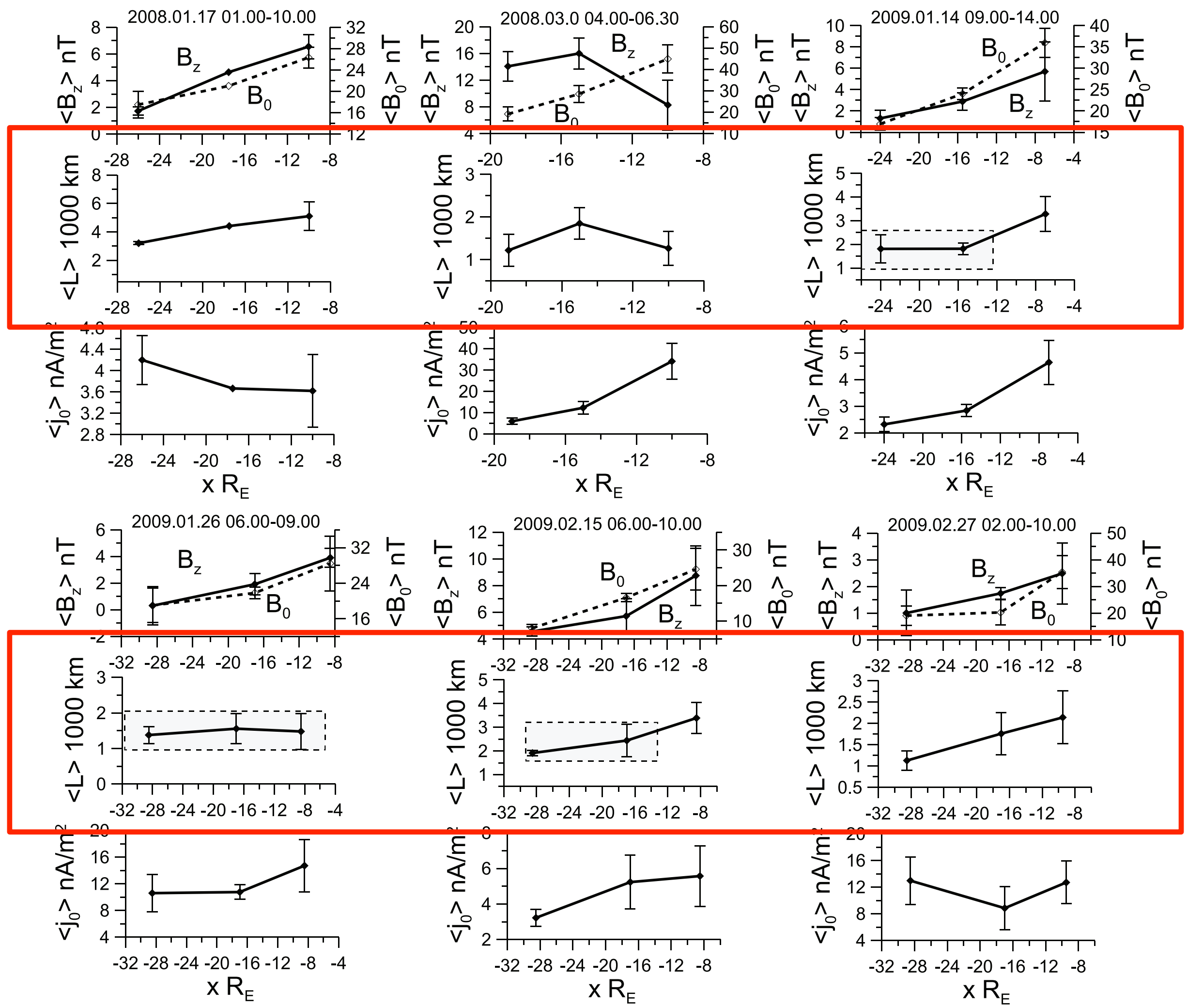
How can one explain sufficiently thin current sheets far from the planet?

Observations

THEMIS [Artemyev et al., 2015]

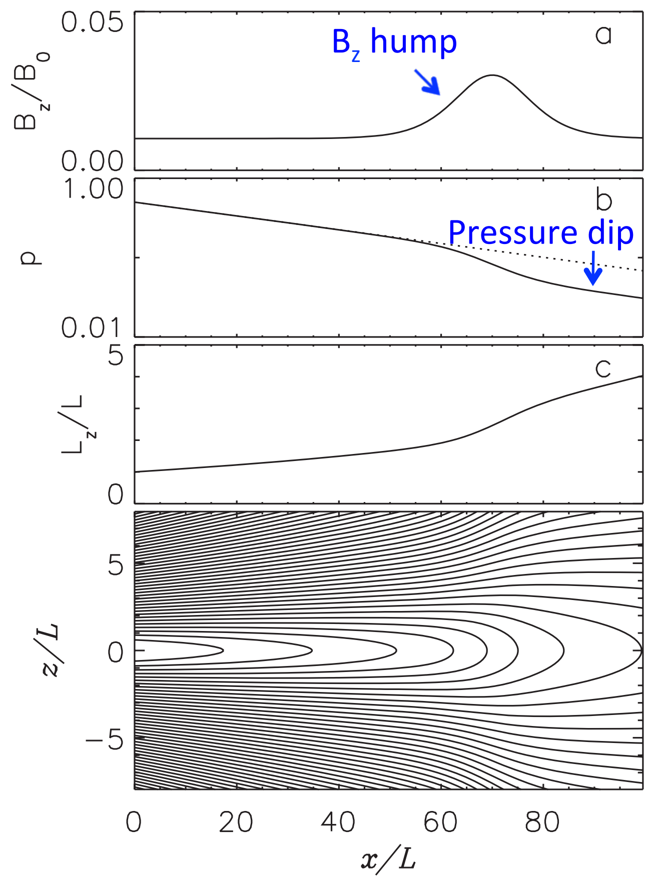
Cluster [Runov et al., 2005]



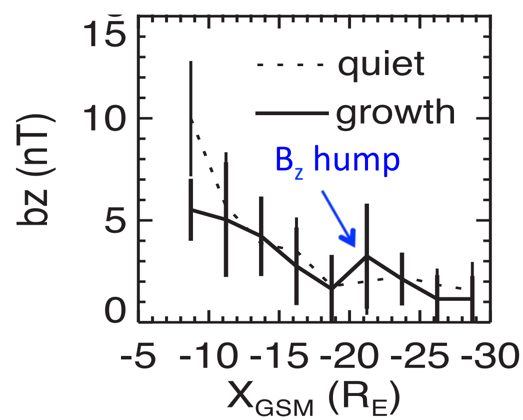


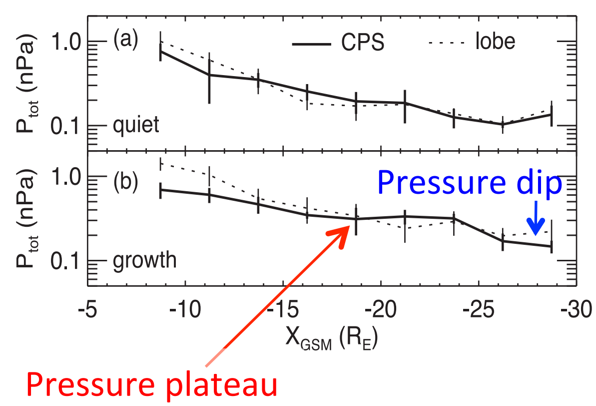
2D current sheet equilibrium taking into account the dipole field

2010 tail equilibrium

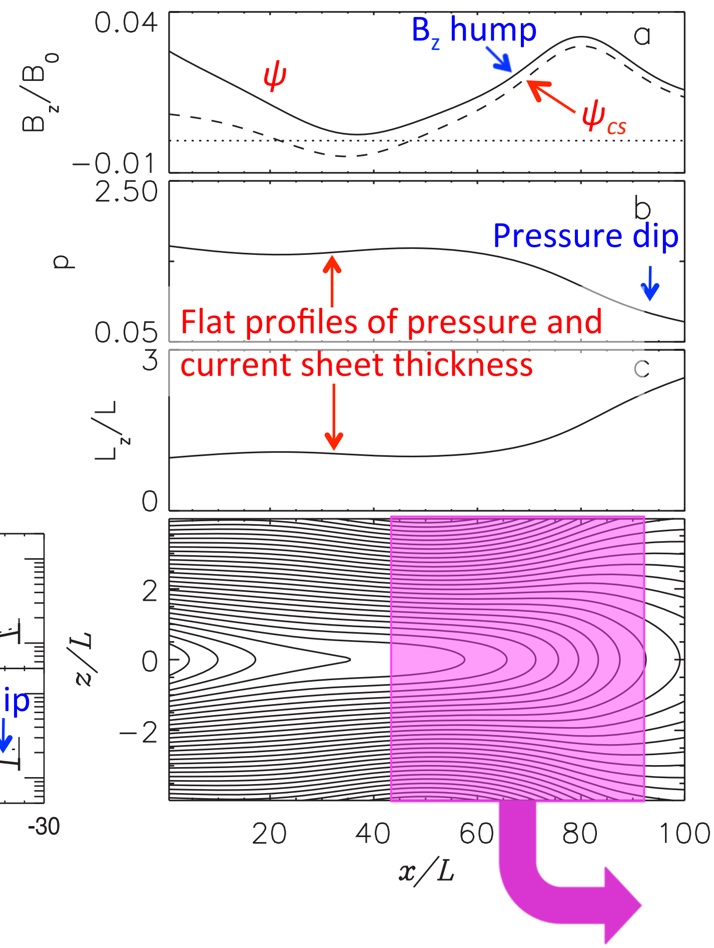


Wang et al. [2004]





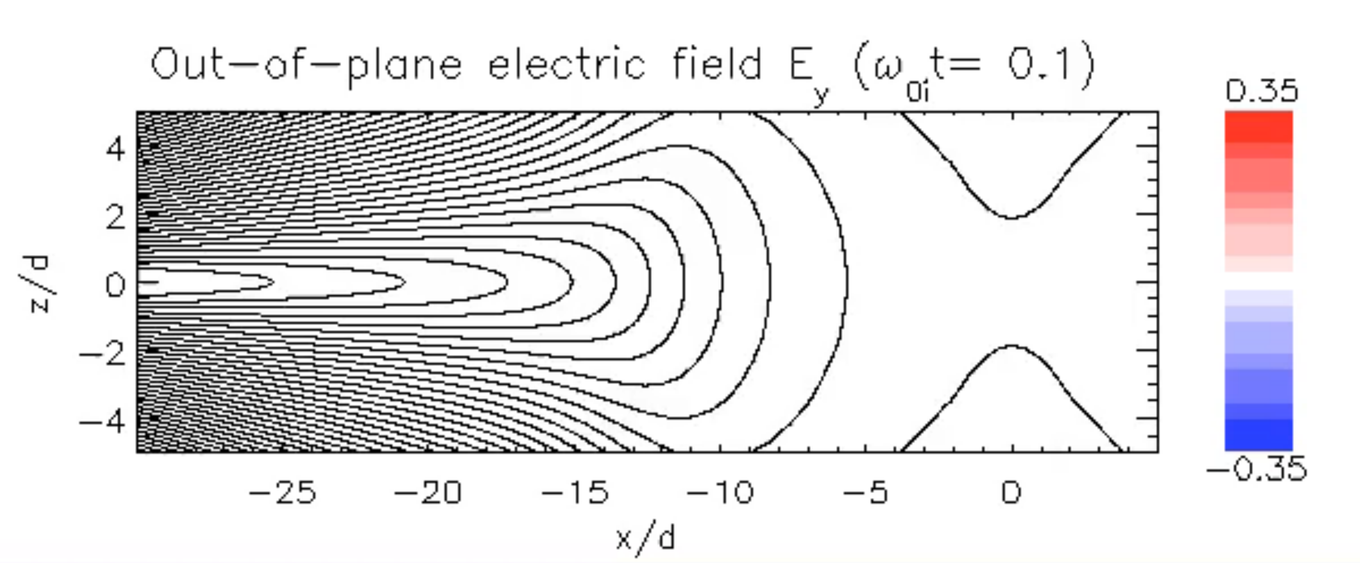
B_z hump with dipole field



Smaller box with open boundaries

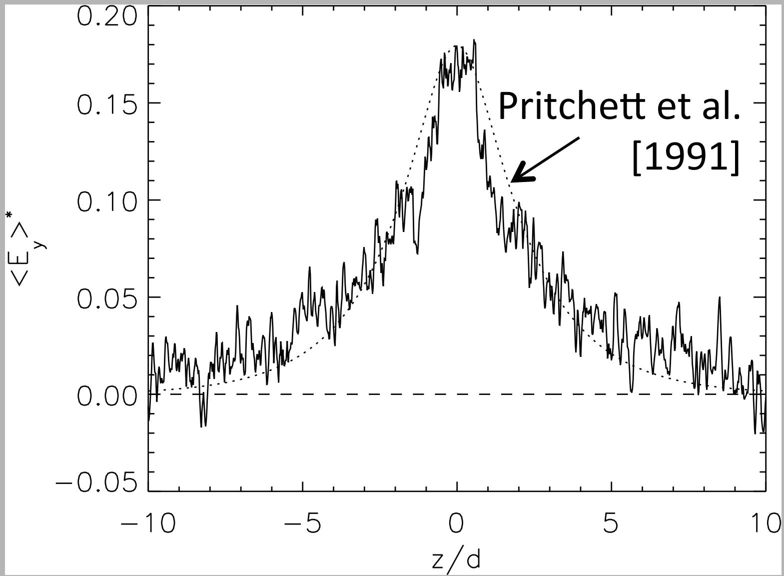
New class of 2D equilibria describes flat profiles of pressure and current and it helps explain why the current sheet may be sufficiently thin far fro

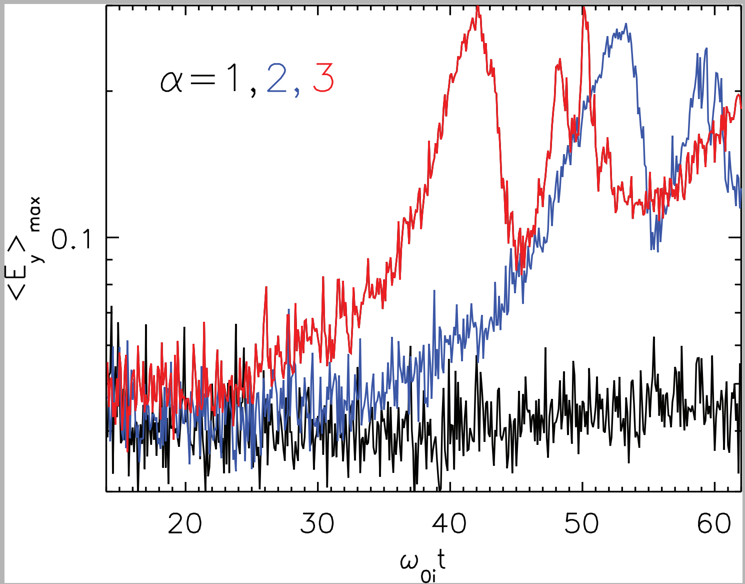
2D PIC simulations with open boundaries



$d=d_i=c/\omega_{pi}$

Looks more like slingshot/slippage than tearing

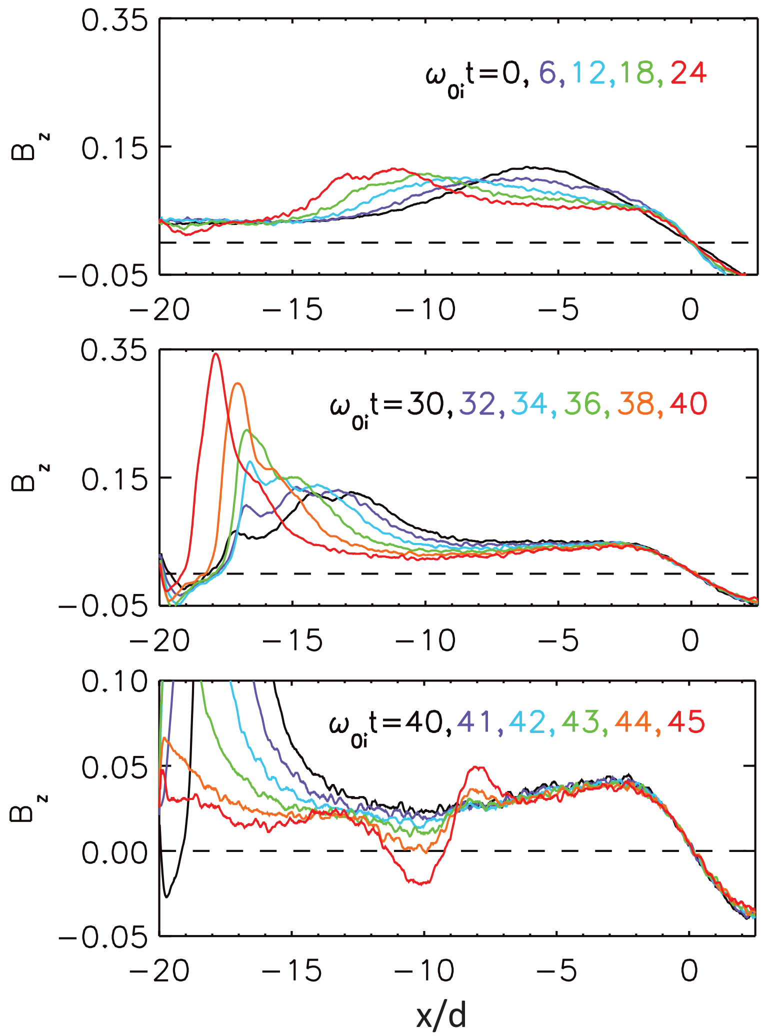


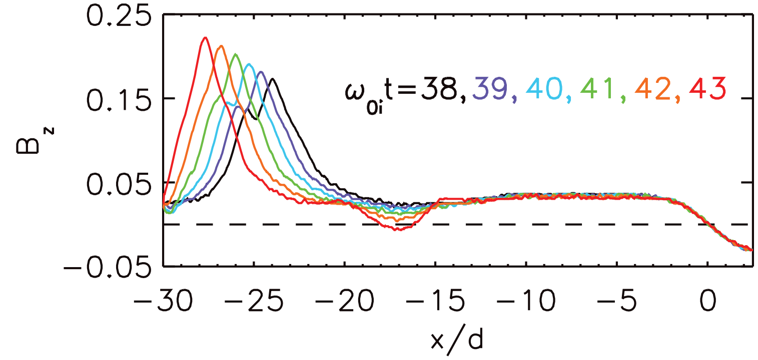


Instability has formal signatures of the ion tearing

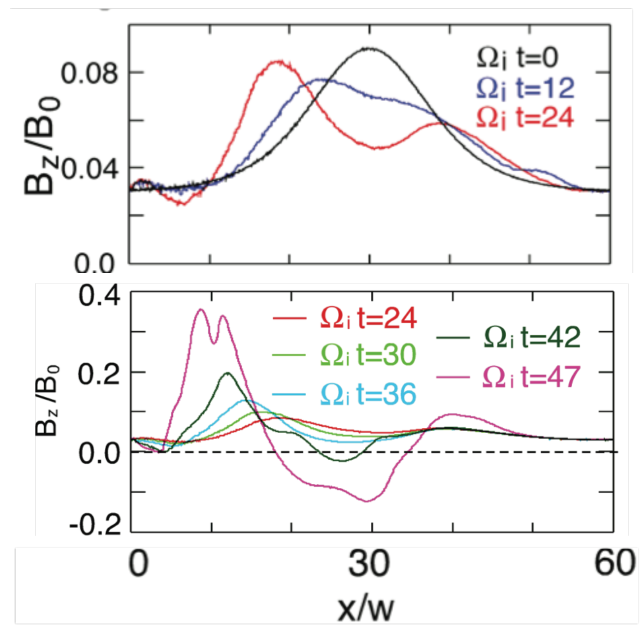
Dipolarization front as a reconnection trigger

Sitnov, Buzulukova, Swisdak, Merkin, Moore [2013]





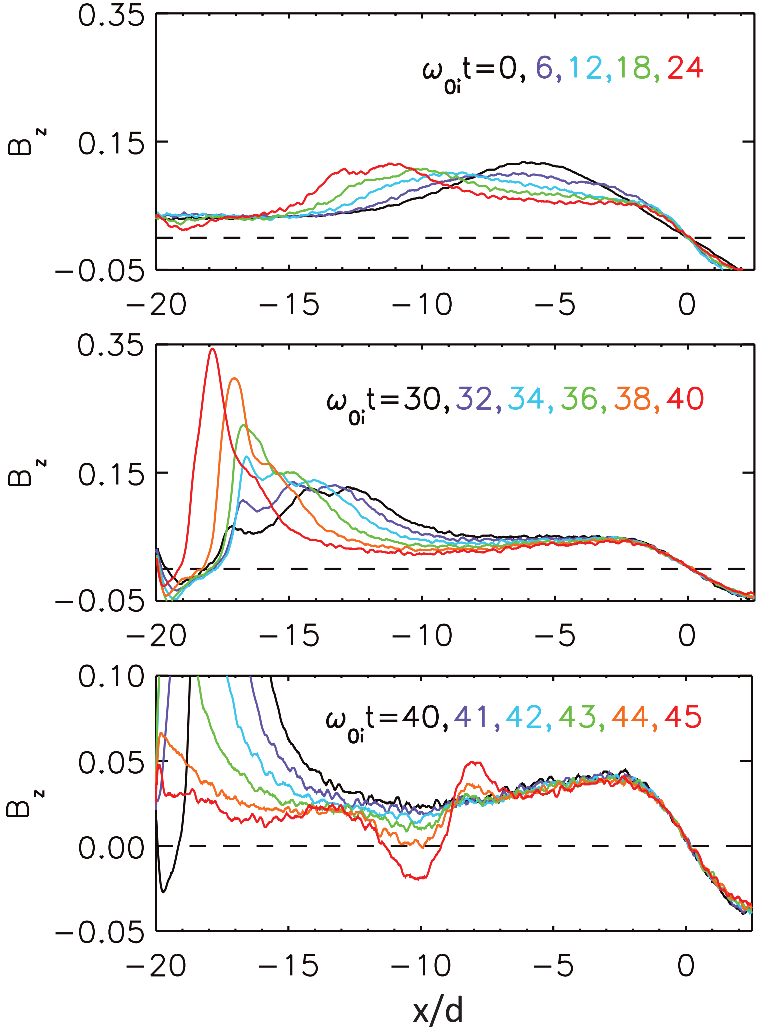
Bessho and Bhattacharjee [2014]



Spontaneous tail reconnection onset is possible, but it is manifested primarily by the formation of fast earthward flows and dipolarization fronts

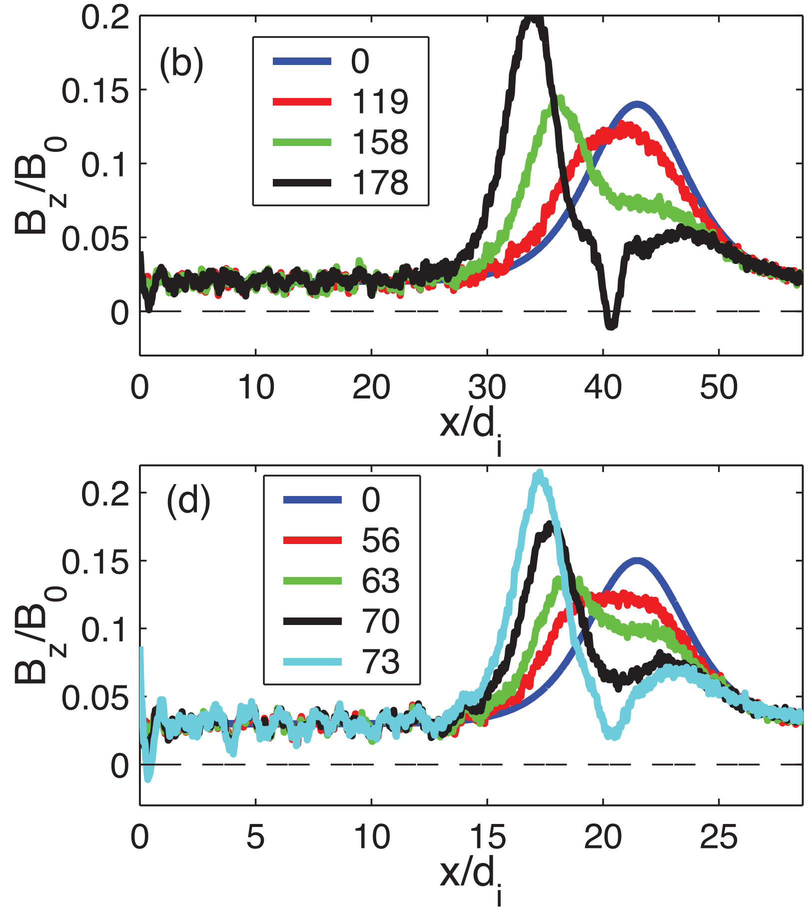
Different 2D PIC simulations compared

Sitnov, Buzulukova, Swisdak, Merkin, Moore [2013]

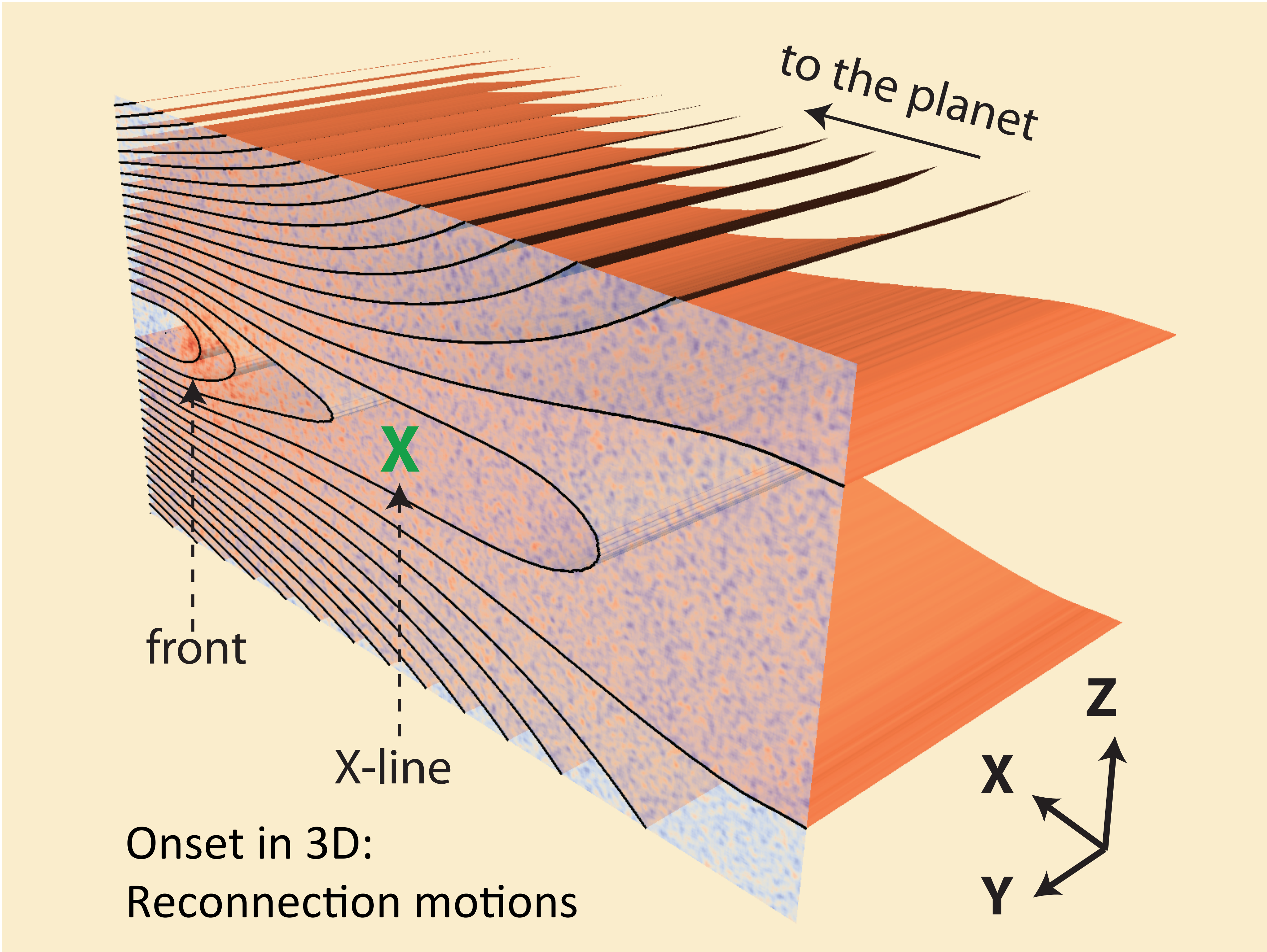


Open boundaries

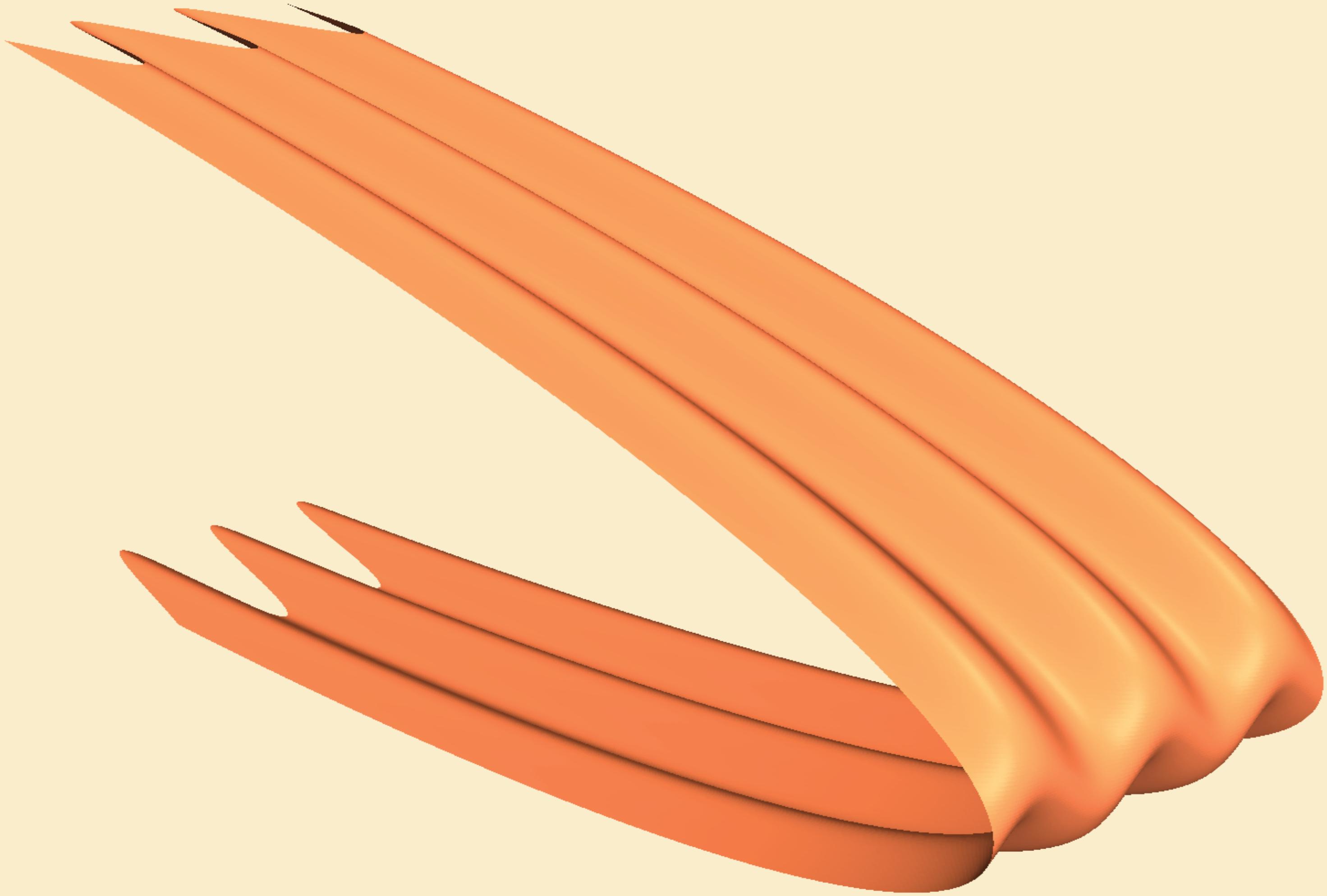
Pritchett [2015]



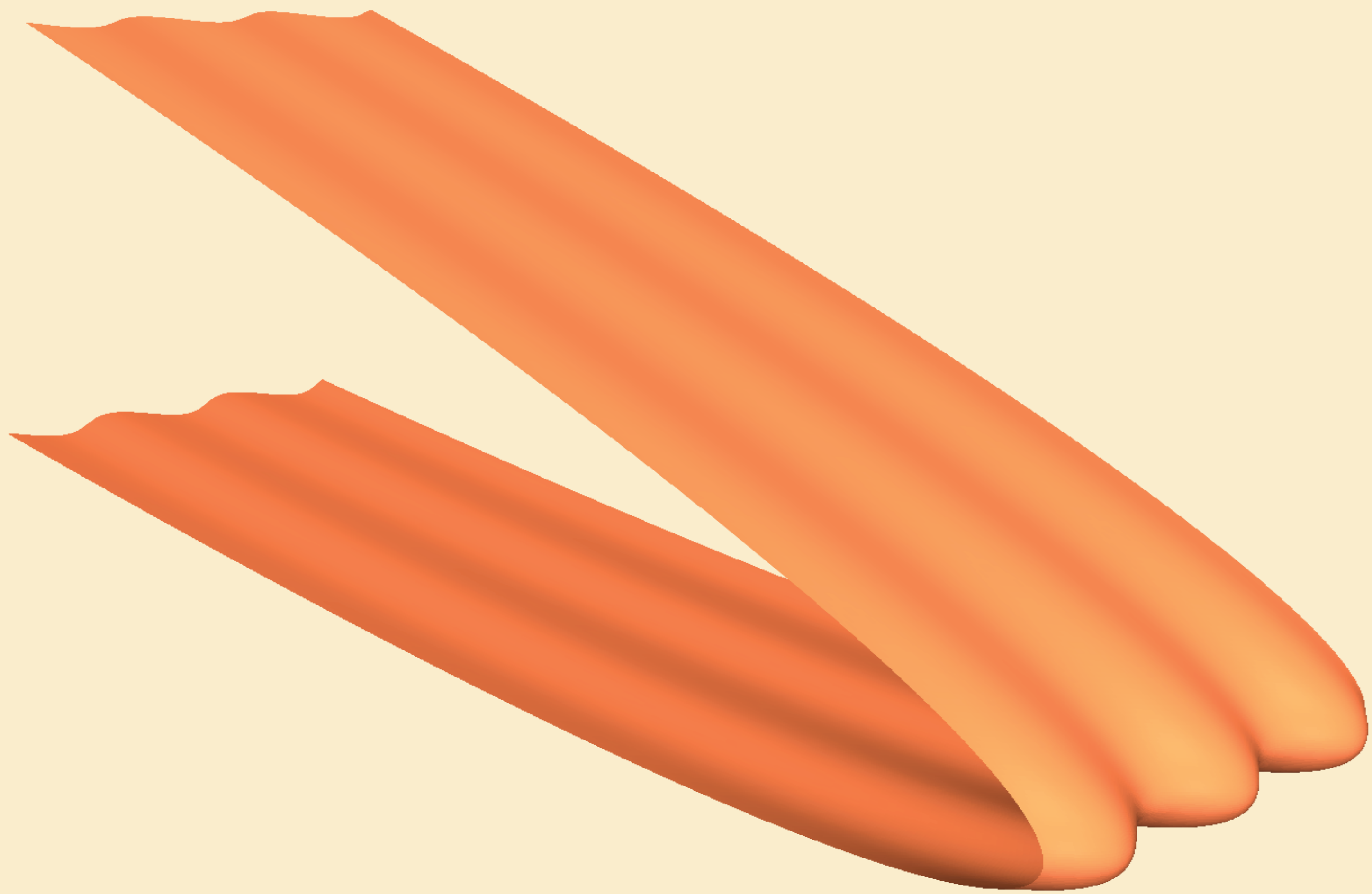
Closed boundaries



to the planet
X
front
X-line
Z
X
Y
Onset in 3D:
Reconnection motions



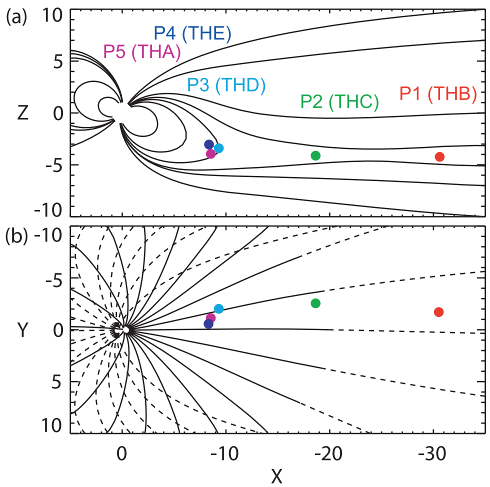
Onset in 3D:
Flapping motions

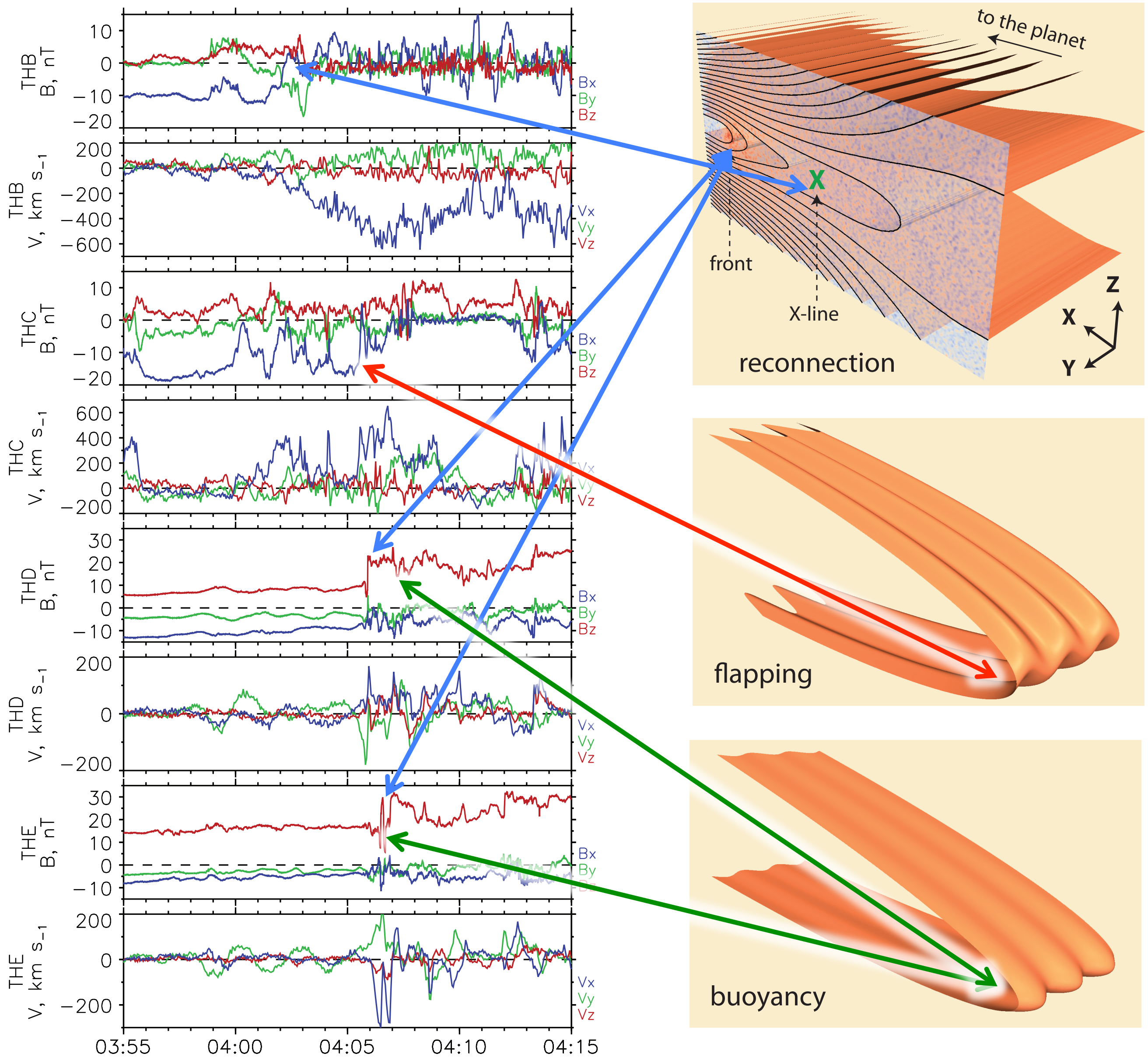


Onset in 3D:
Buoyancy motions

Observations of magnetotail explosions

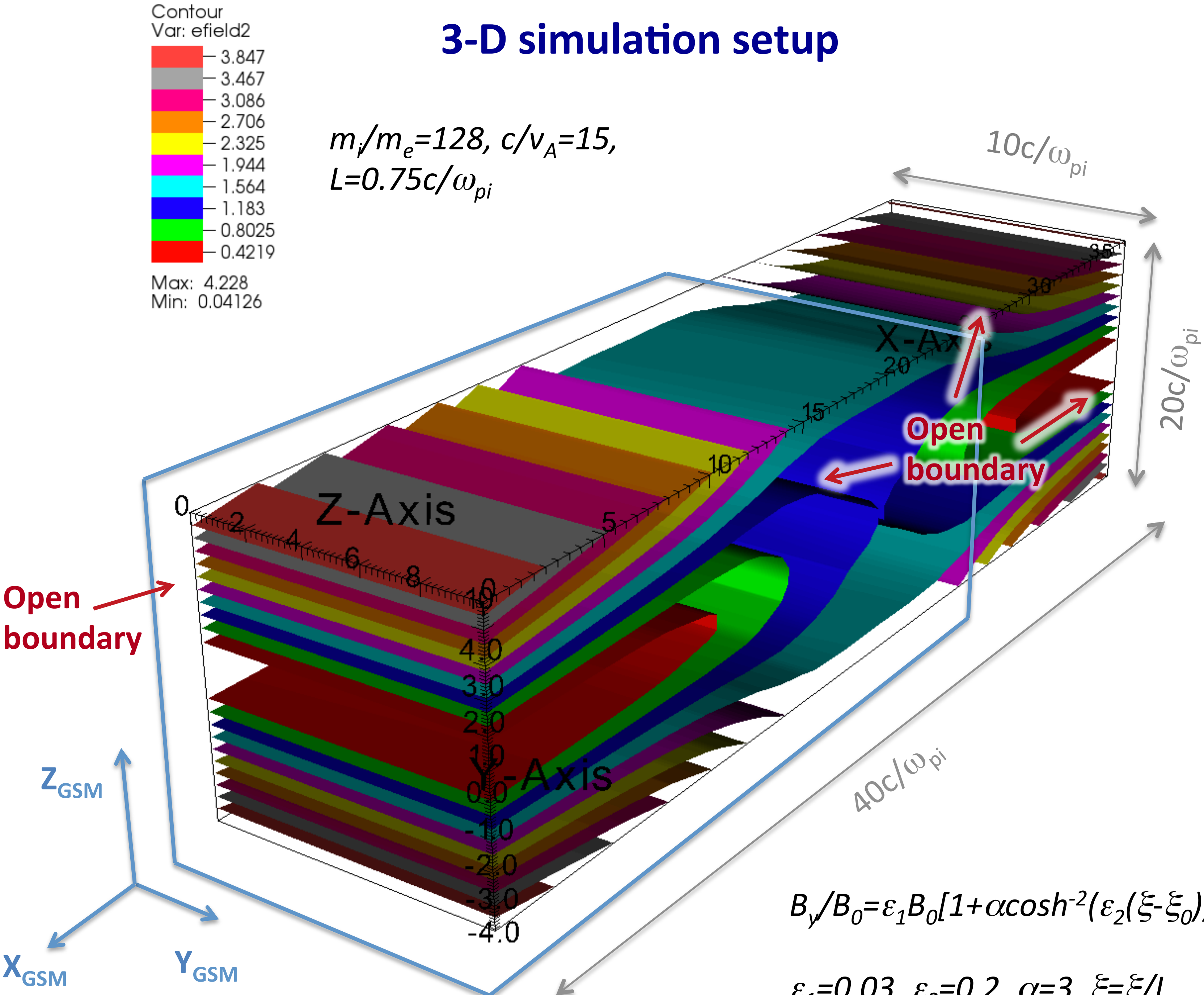
THEMIS
02/07 2009
[Oka et al., 2011]





3-D simulation setup

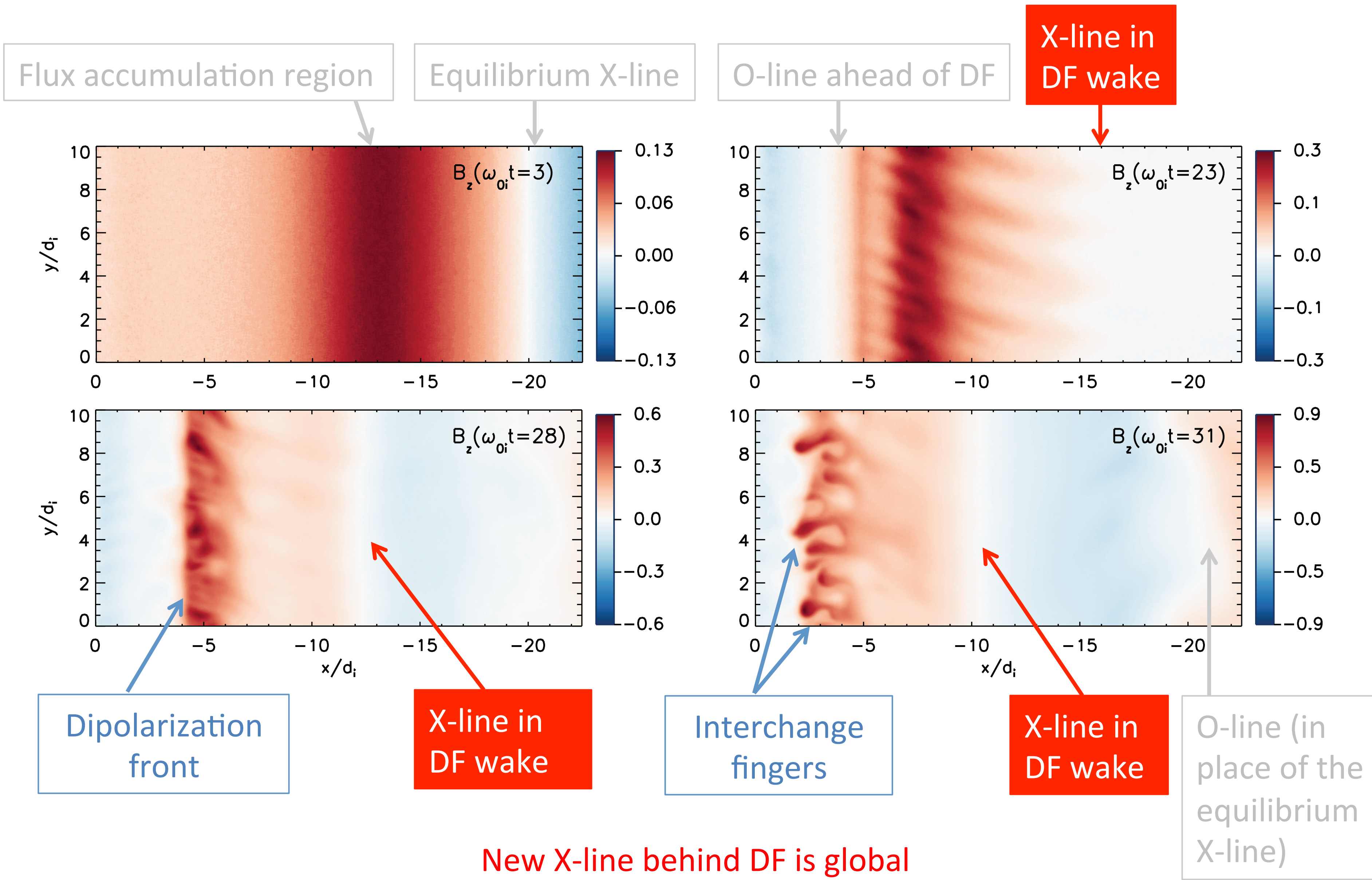
$m_i/m_e=128,\ c/v_A=15,$
$L=0.75c/\omega_{pi}$



$B_y/B_0=\varepsilon_1 B_0[1+\alpha \cosh^{-2}(\varepsilon_2(\xi-\xi_0))],$

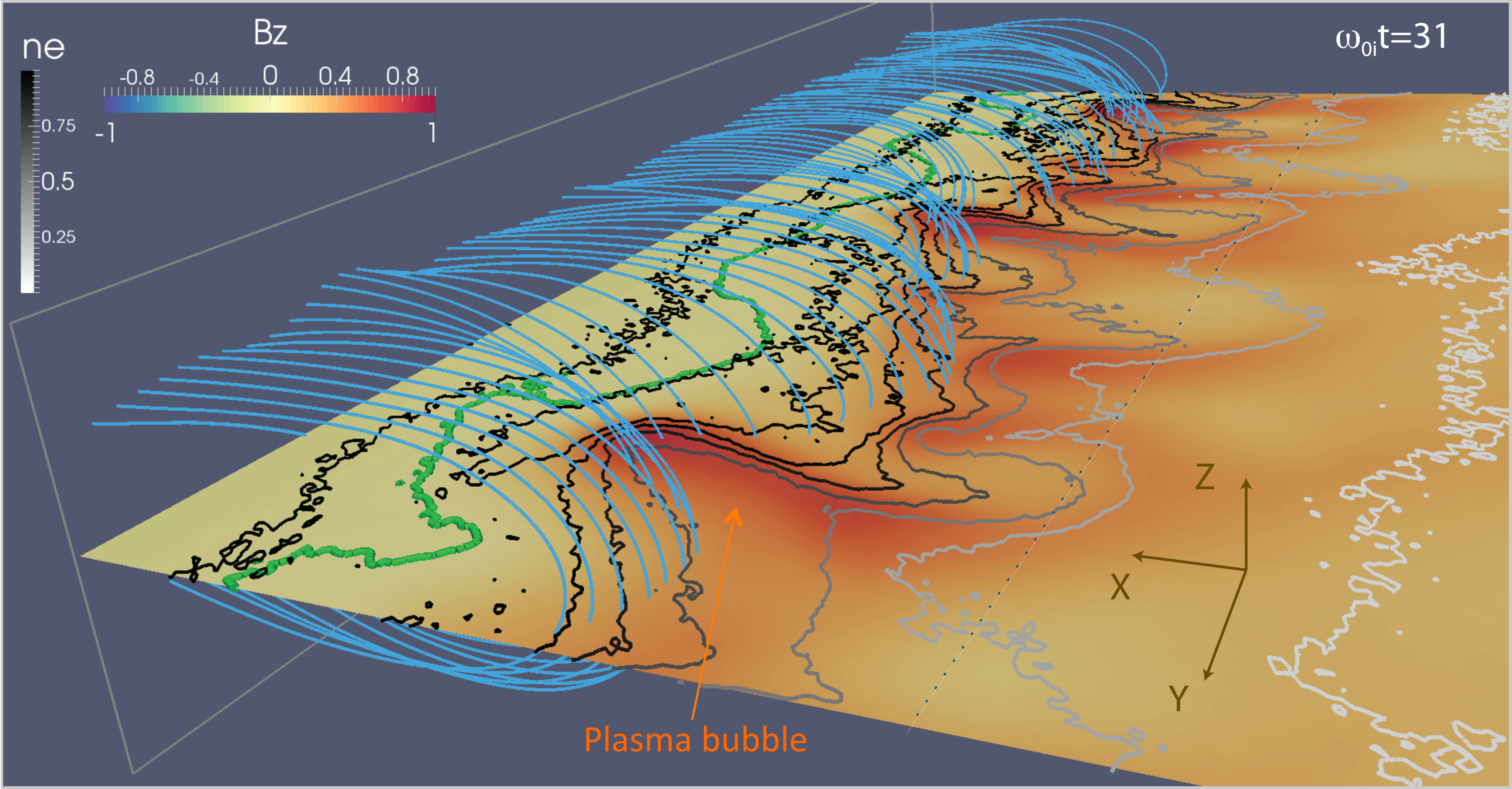
$\varepsilon_1=0.03,\ \varepsilon_2=0.2,\ \alpha=3,\ \xi=\xi/L$

Reconnection and buoyancy motions



New X-line behind DF is global

Reconnection front and plasma bubbles

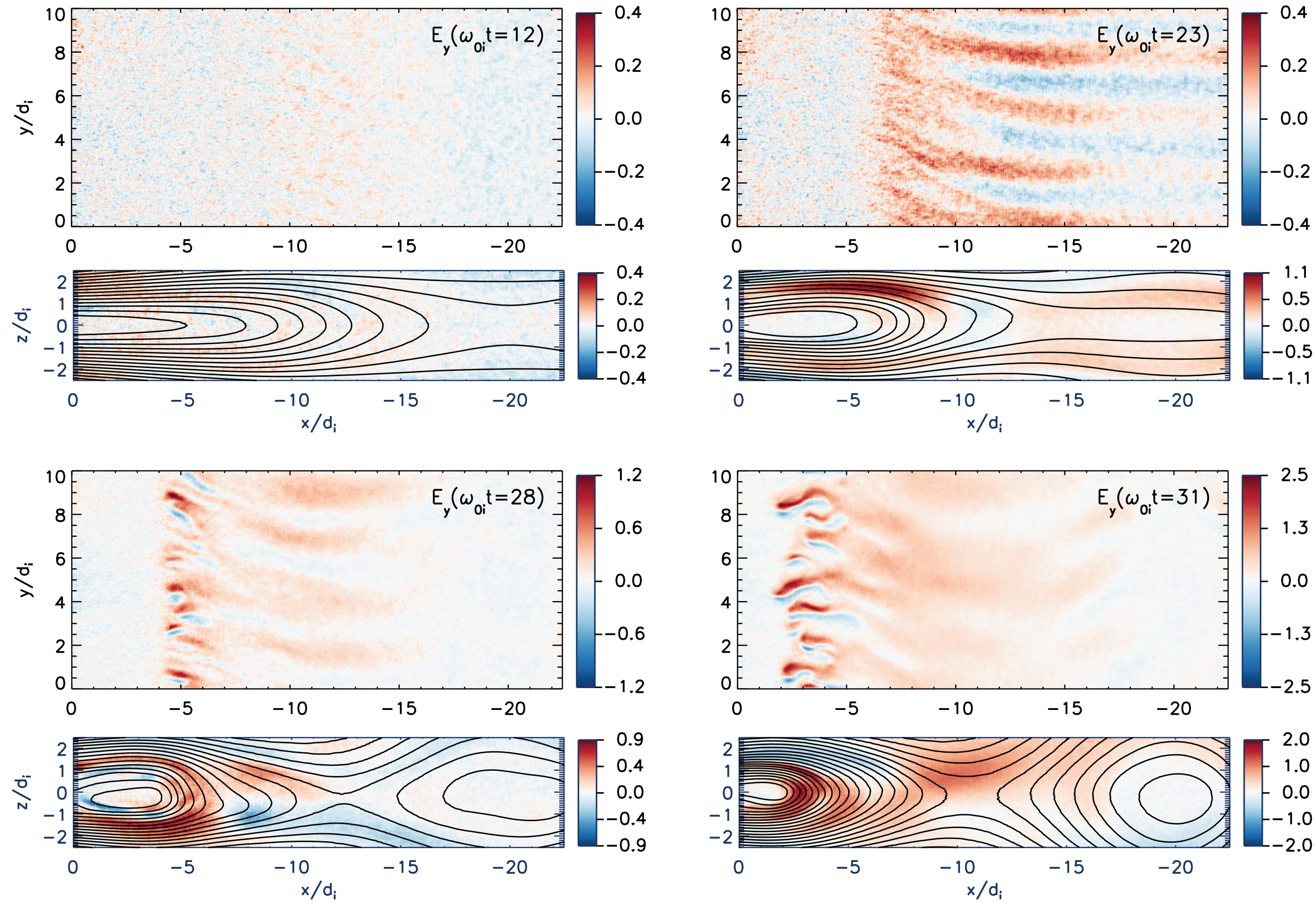


Buoyancy motions substantially perturb the dipolarization front but neither destroy it nor even change it critically

Dawn-dusk electric field

Distinctive features:

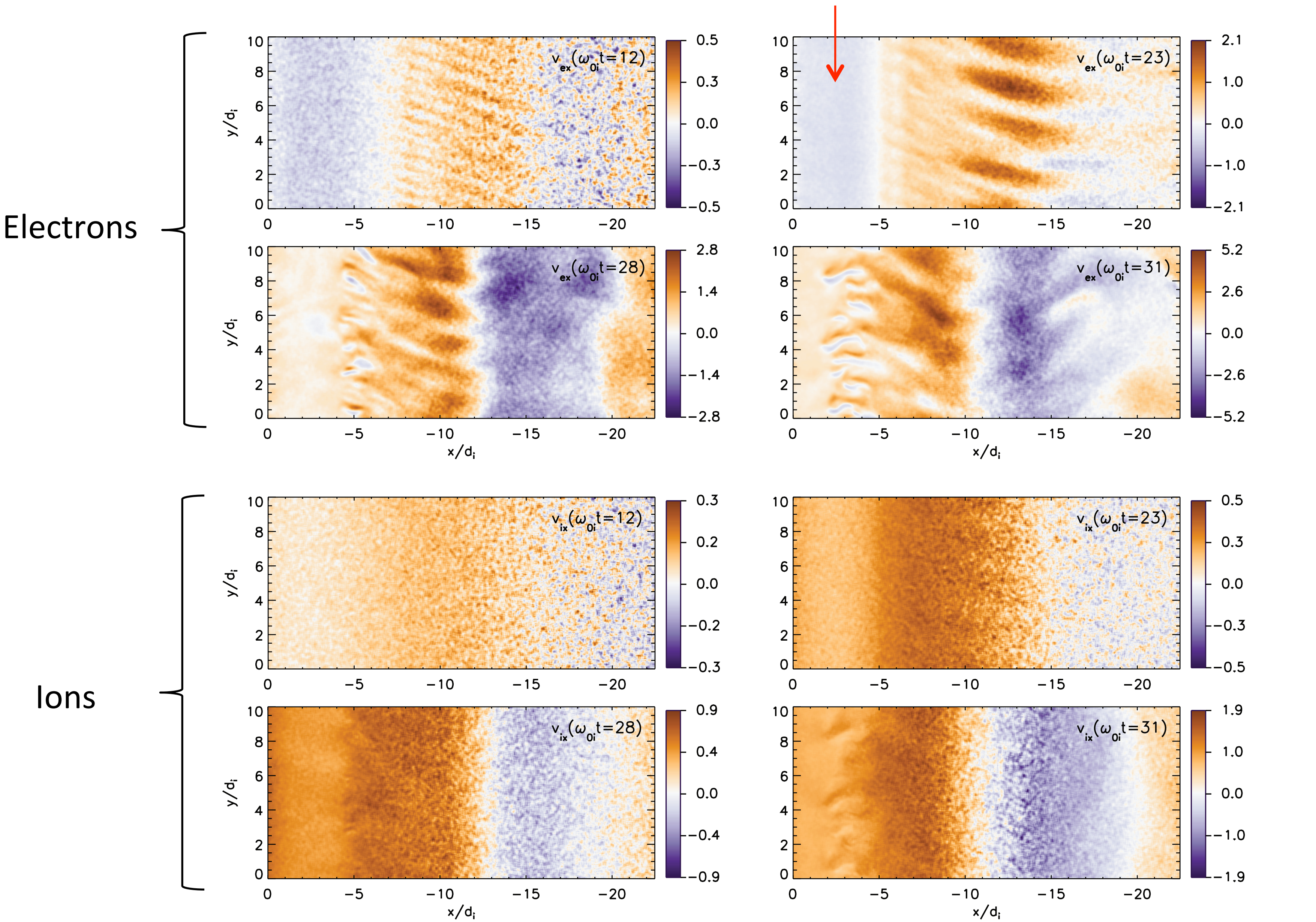
1. Strong reconnection field ($\langle E_y(z=0)\rangle_y \neq 0$) at **DFs**
2. Dawn-dusk modulation – **buoyancy effect**
3. North-south asymmetry of the dawn-dusk electric field – **flapping effect**



Plasma flows

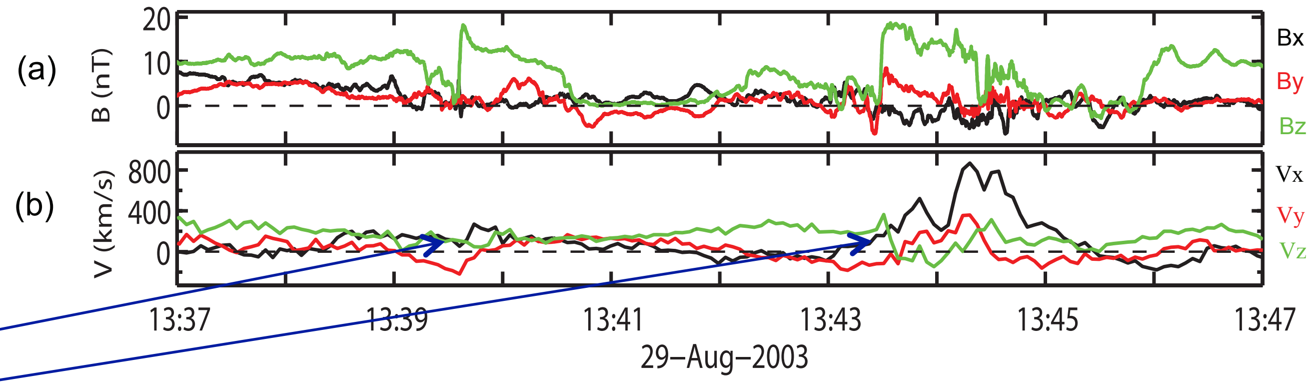
Different motions of electron and ions species

tsunami drawback effect ahead of DF

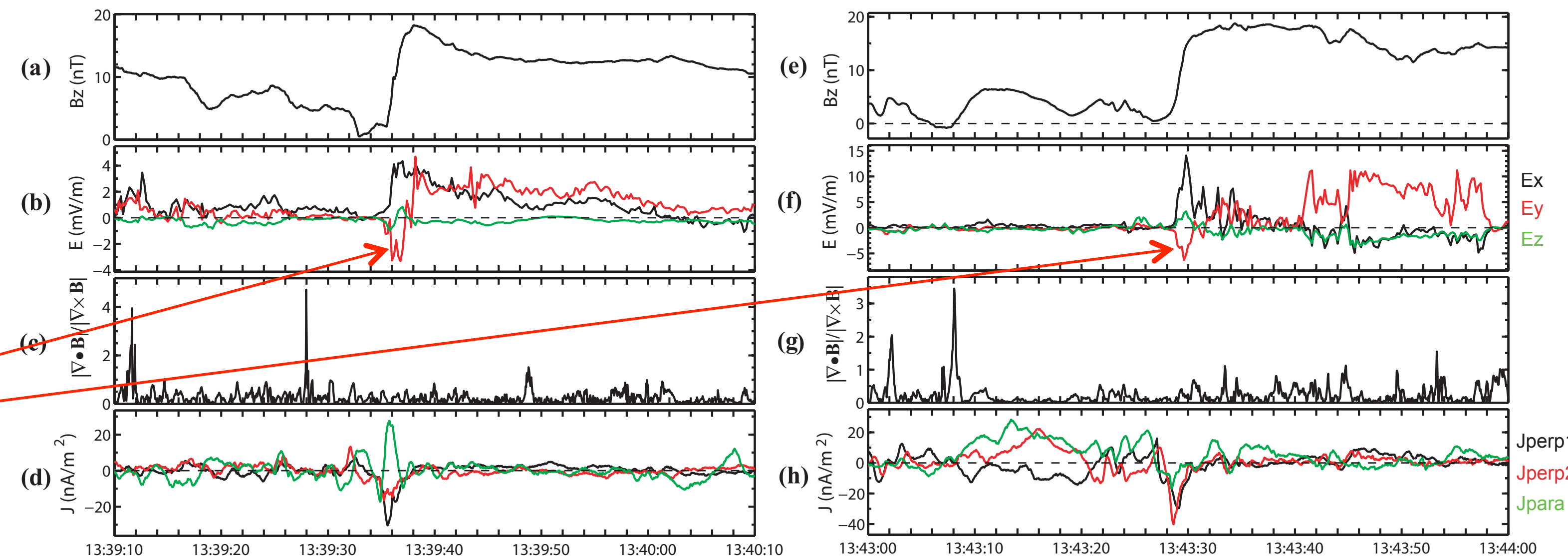


DF tsunami drawback effect: observational signatures

Cluster observations
[Huang et al., 2012]

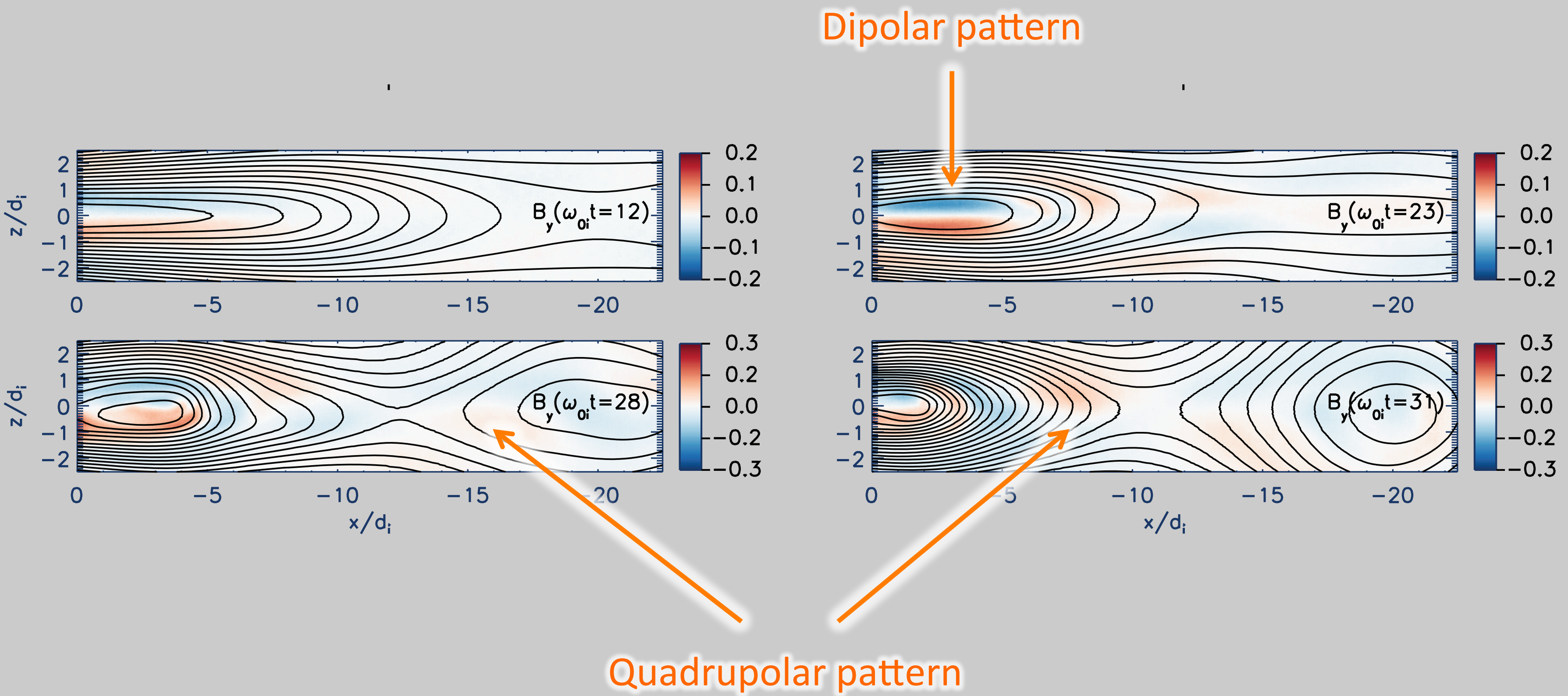


Earthward
ion motion



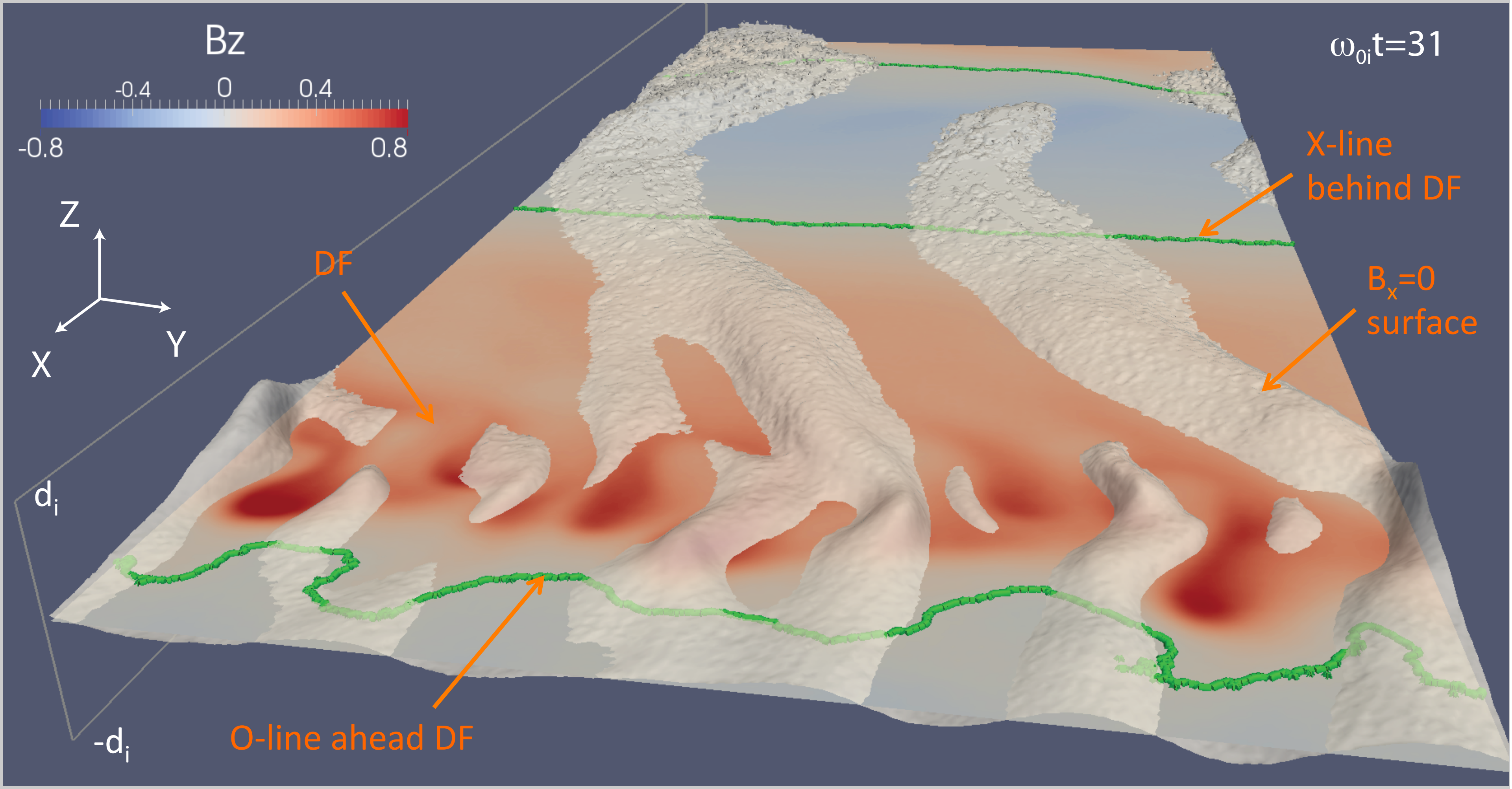
Tailward
electron
motion

Hall magnetic field



In contrast to the classical quadrupolar B_y structure near the X-line, DFs have dipolar B_y structure

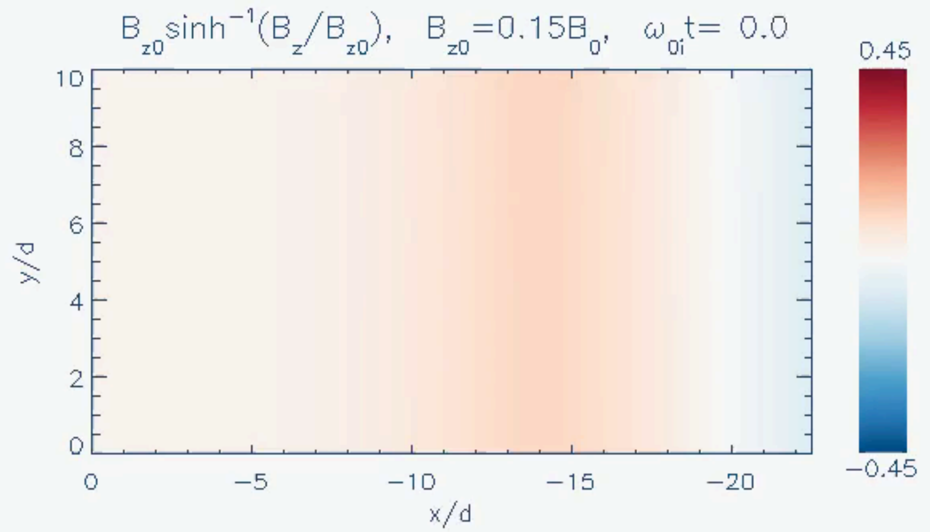
Flapping motions and global X-line behind DF



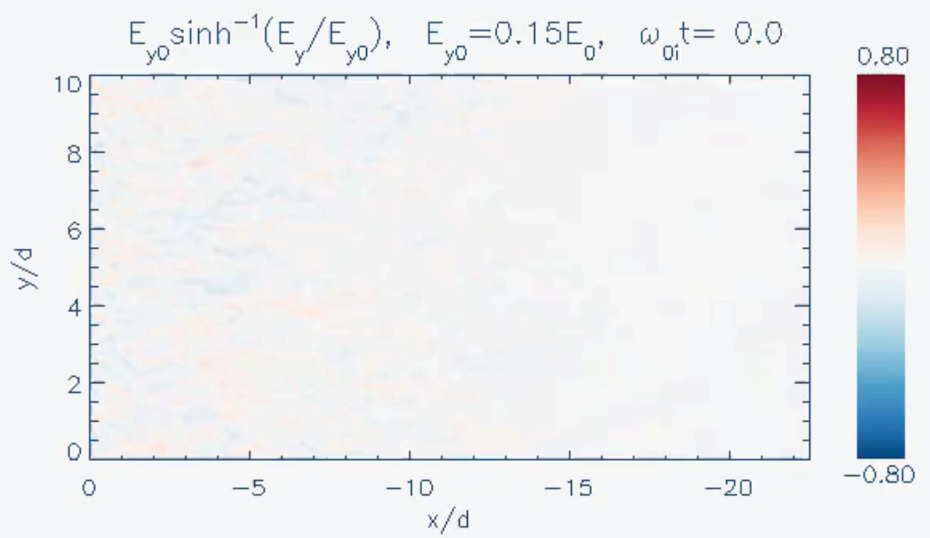
Flapping motions are strong but they do not affect DF or new X-line in its wake

Coherent growth of reconnection, buoyancy and flapping motions

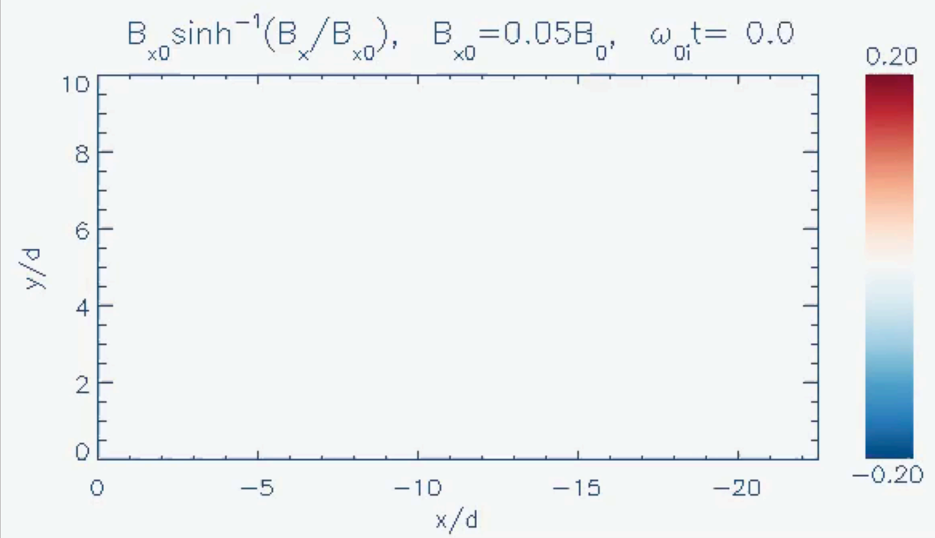
reconnection and buoyancy (B_z)



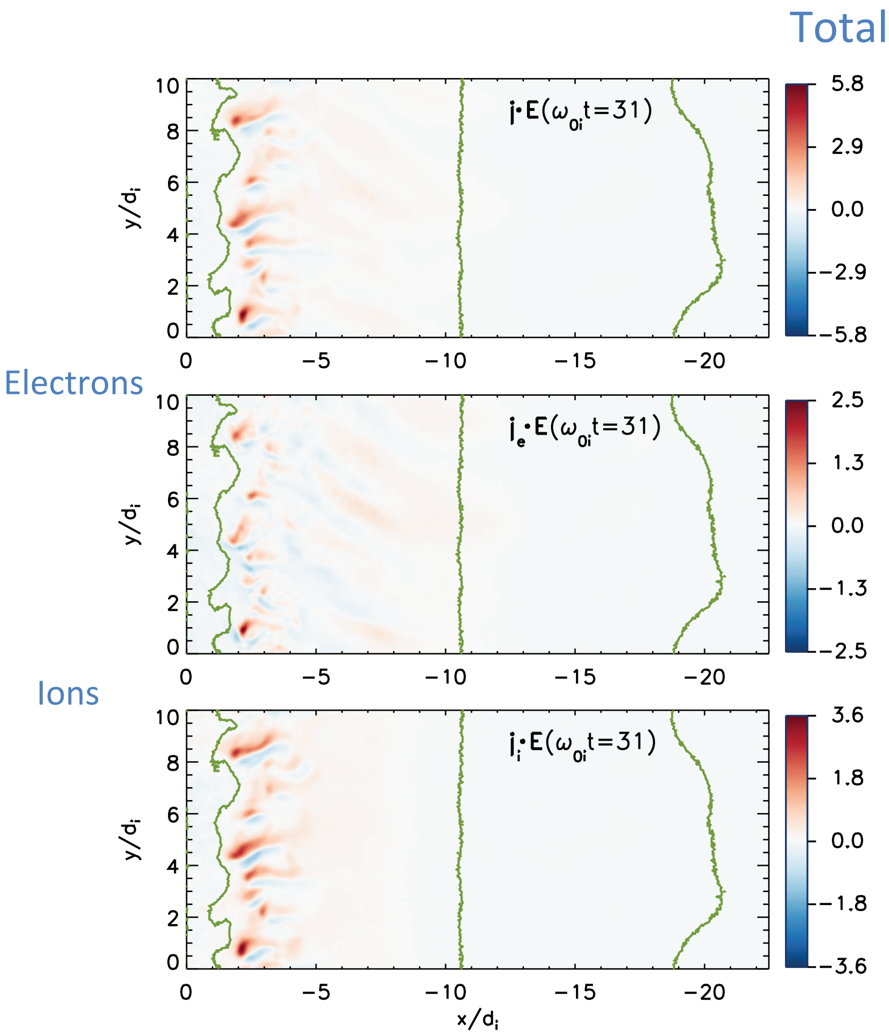
reconnection and buoyancy (E_y)

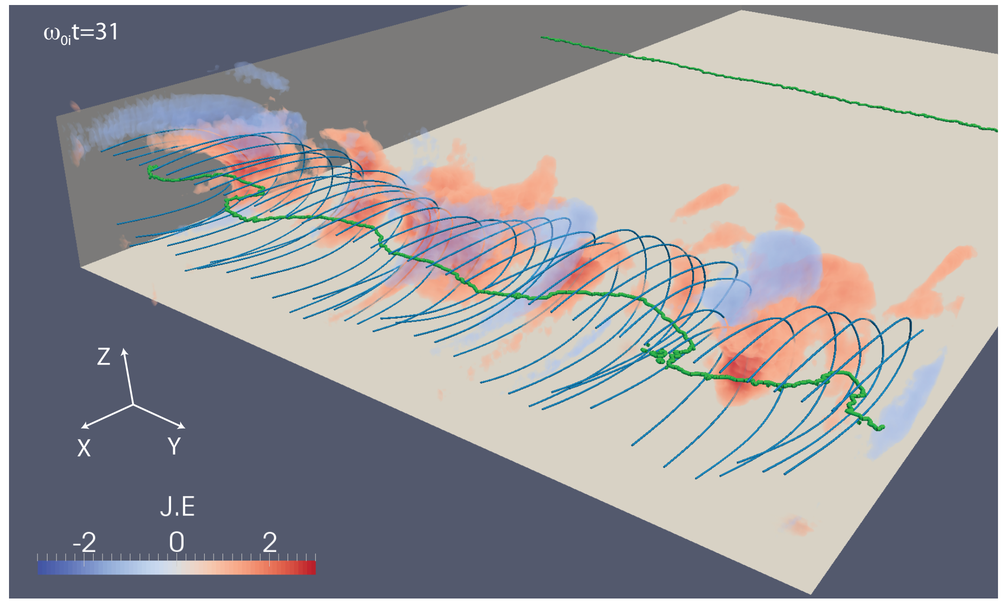


flapping (B_x)



Energy conversion





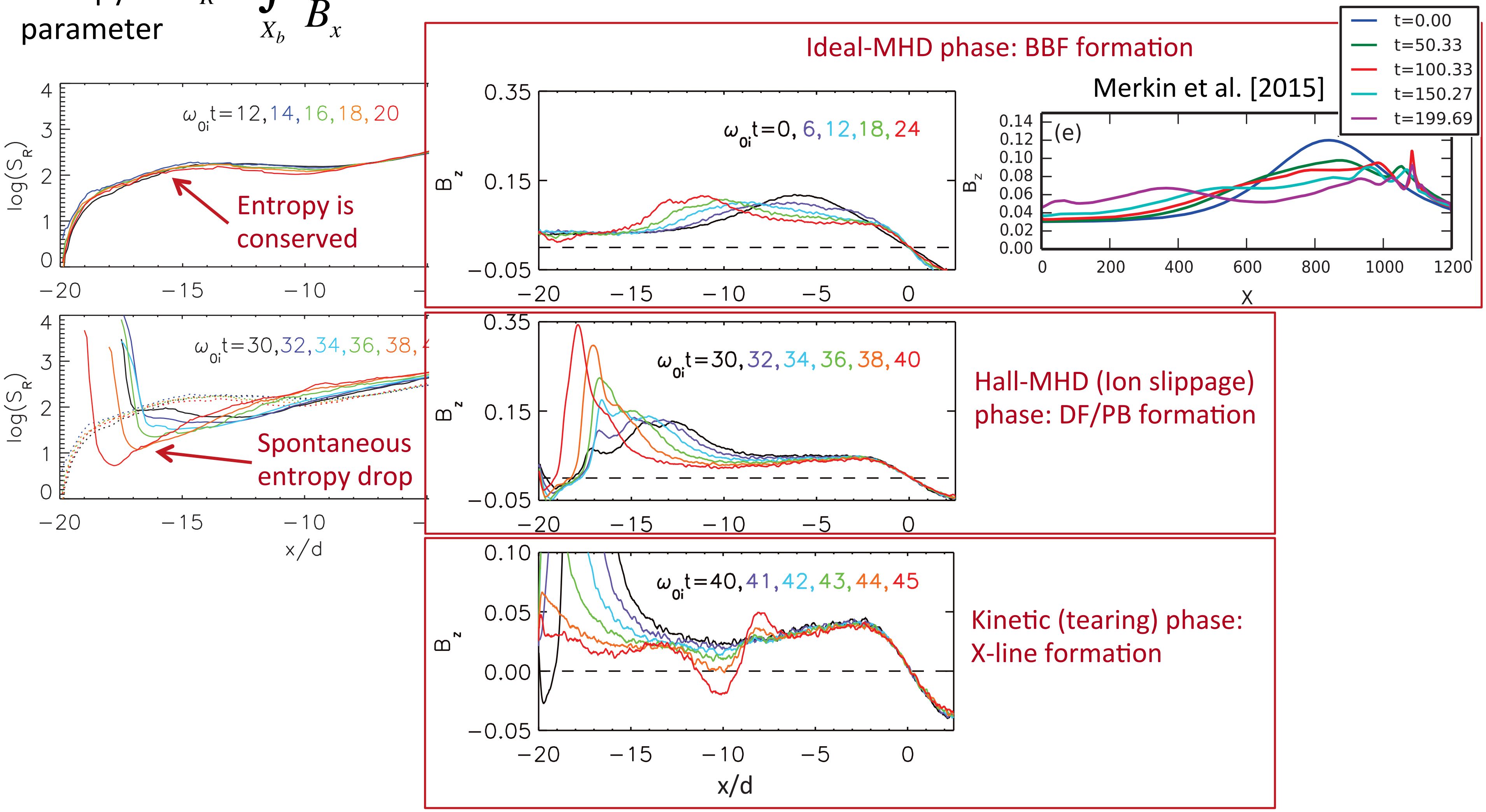
Consistent with THEMIS observations [Angelopoulos et al., 2013] the energy conversion takes place at DFs, **away from X- and O-lines**, and it involves scales less than the ion inertial length d_i.

Key phases of the magnetotail reconnection onset

Reduced entropy parameter $S_R = \int_{X_b}^{X_0} \frac{p^{1/\gamma}}{B_x} dx$

PIC simulations

MHD simulations

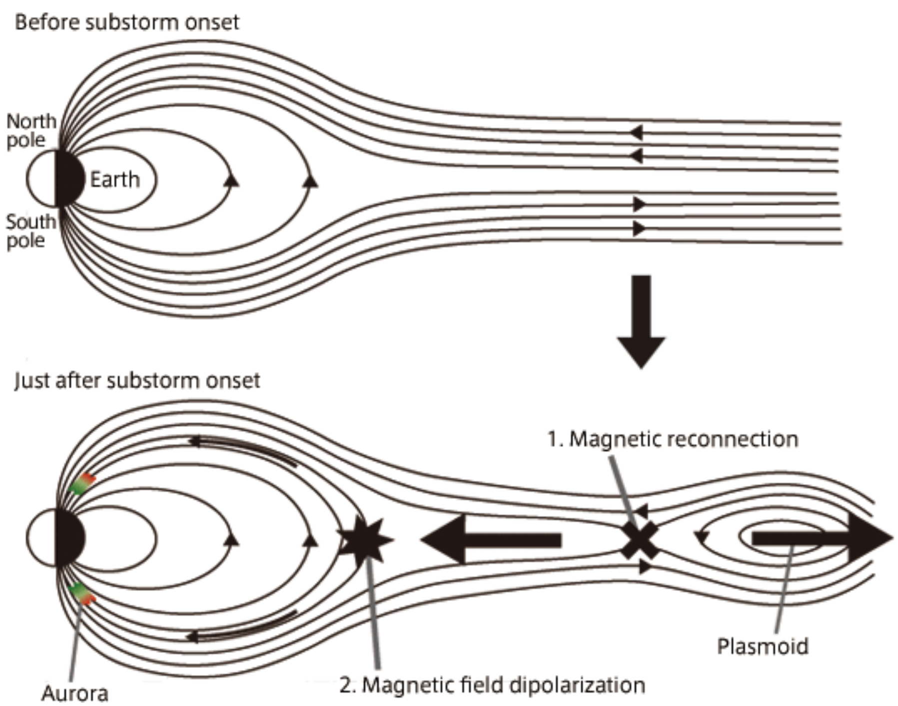


Tail reconnection onset has MHD, Hall-MHD and kinetic phases

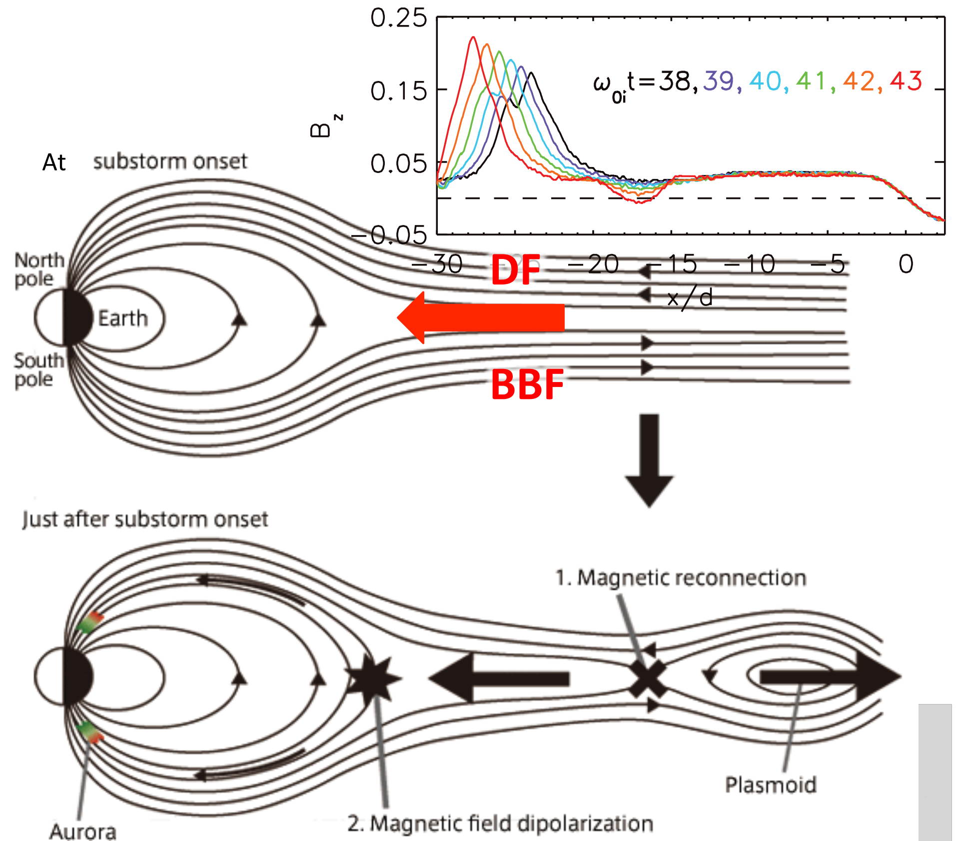
Conclusion

- Spontaneous reconnection is possible in the magnetotail in case of the tailward B_z gradient; but it is manifested primarily by the formation of fast plasma flows (BBFs) and dipolarization fronts.
- BBFs and fronts are accompanied by buoyancy and flapping motions; the latter substantially perturb the dipolarization front but neither destroy it nor even change it critically.
- Magnetotail reconnection instability(ies?) has MHD (BBF, snowplow, DF) , Hall-MHD (bubble-blob formation) and fully kinetic (magnetic topology change) phases.
- Magnetotail reconnection instability starts before a magnetic topology change

Traditional understanding of magnetic reconnection: topology change causes fast plasma flows



New picture of magnetotail reconnection: fast plasma flows cause the magnetic topology change



Tail wagging the dog!

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JOHNS HOPKINS

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