# Dipolarization fronts from observations and simulations

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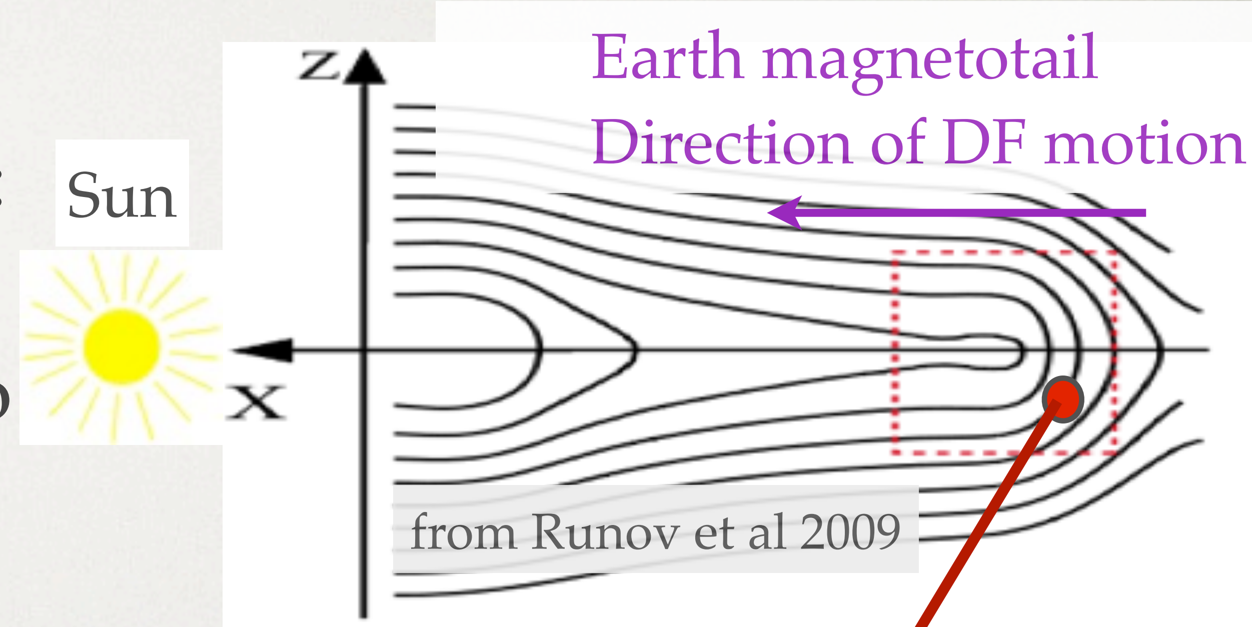
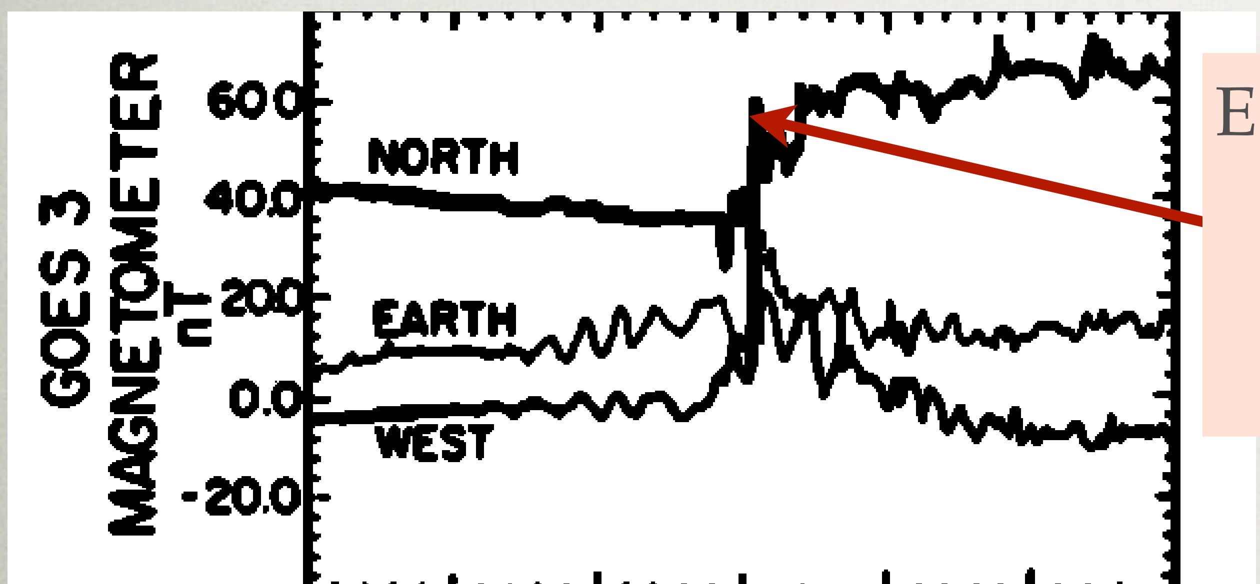
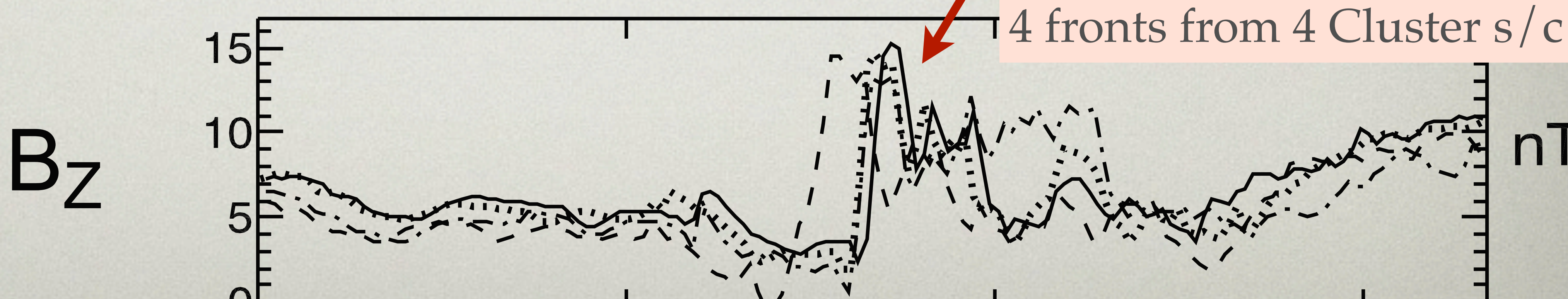
# ‘Dipolarization Front’ is derivative from ‘Dipole’

DF is a sharp moving B-field structure: Bz component (normal to the neutral plane) changes shape from stretched to more ‘relaxed’ dipole field




Early observations of DFs
Moore et al., 1981:
Substorm injection
and reconnection




Nakamura et al., 2002:
4 fronts from 4 Cluster s/c

DFs are different from plasmoids

# Observations of DFs

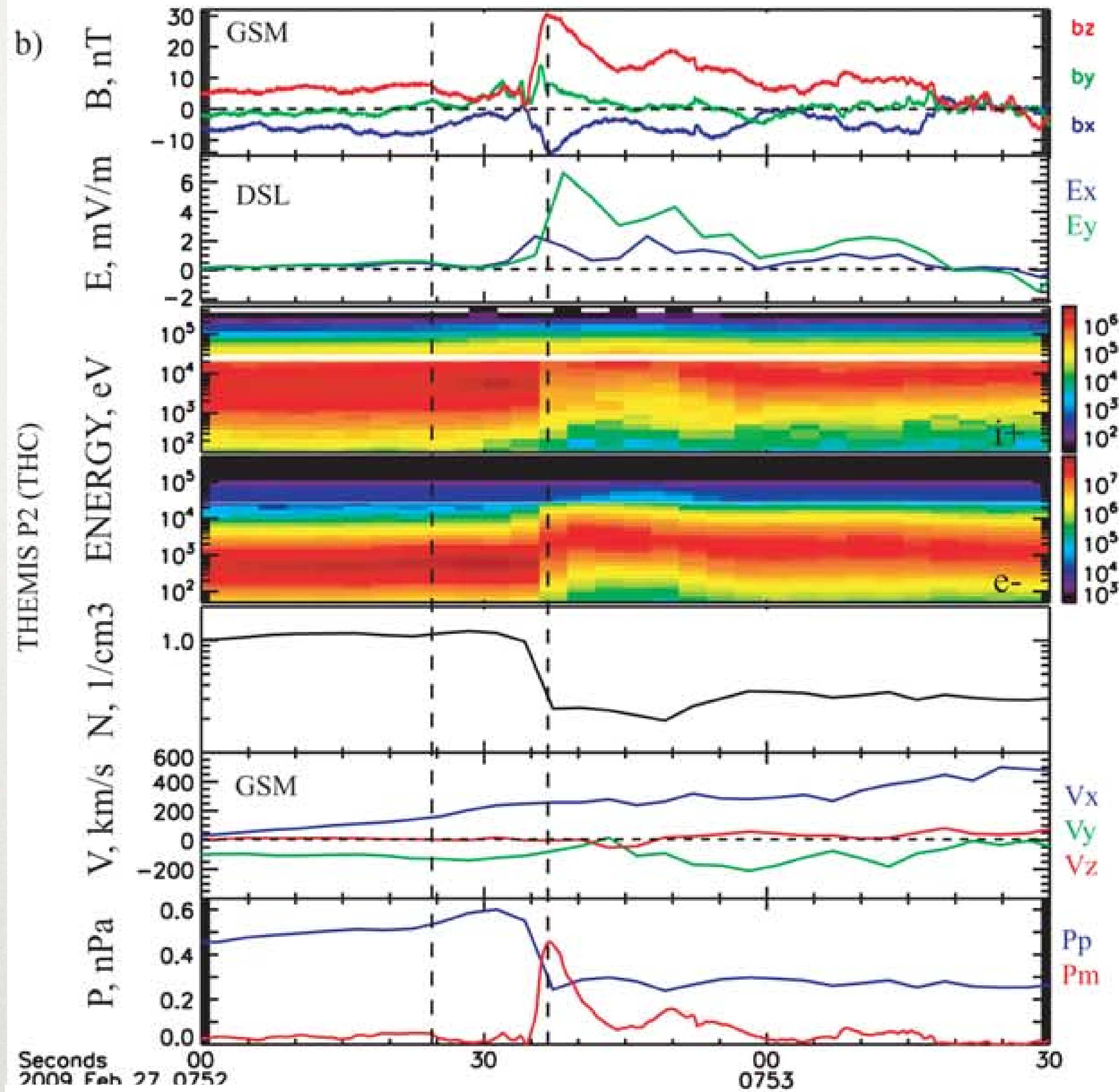
Kinetic structures with size
~ di (ϱi) propagate over tens di

DFs separate newly injected hot tenuous population from cold dense population

Related to reconnection; accelerate particles effectively

Embedded into regions of sporadic fast flows, main mechanism for plasma and energy transfer

Observed routinely in the Earth magnetotail by Geotail, Cluster, THEMIS s/cs




THEMIS observed DF

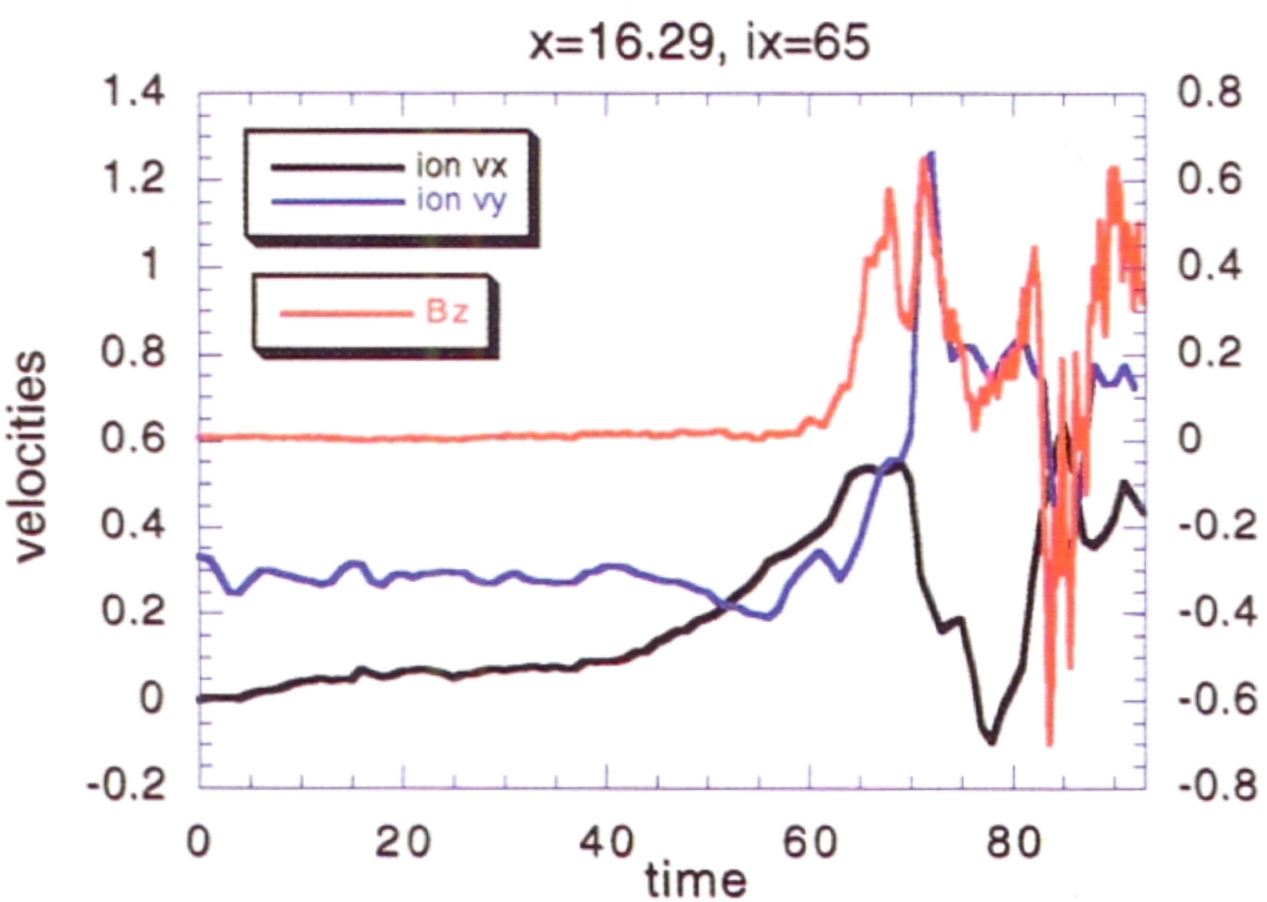
After Runov et al., 2009

Fairfield et al. (1999), Tu et al.(2000), Slavin et al. (2003), Ohtani et al. (2004), Nakamura et al. (2002, 2005), Eastwood et al. 2005 (2005), Runov et al., 2009, Sergeev et al., 2009, ...

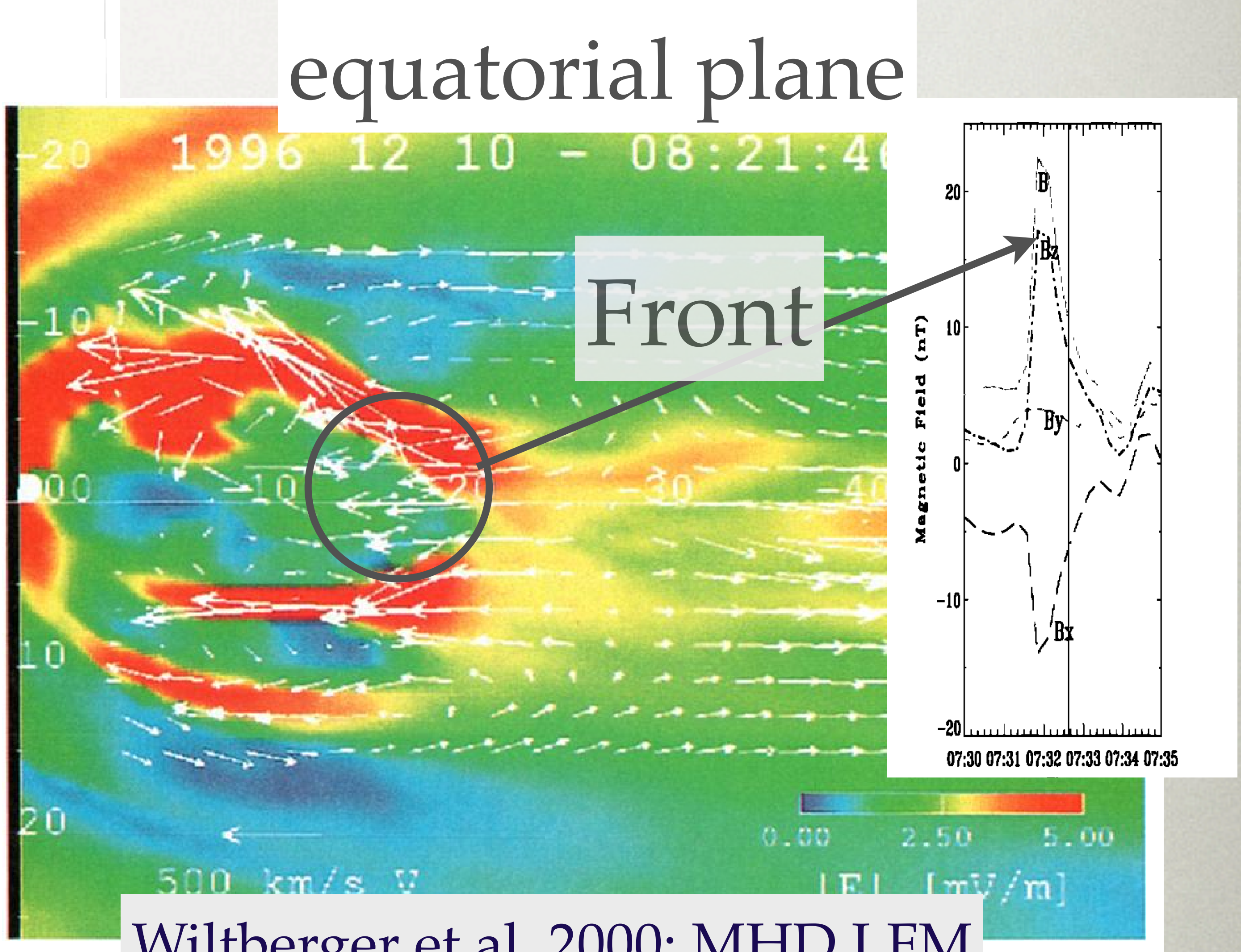
Since 2009, tens of publications on DFs...

# DFs are reproduced in hybrid and MHD simulations of reconnection

(Fujimoto et al., 1996; Hesse et al., 1998; Wiltberger et al., 2000; Nakamura et al., 2002; Krauss-Varban and Karimabadi, 2003; Ashour-Abdalla et al., 2010; Birn et al, 2011)




Hesse et al. (1998)




Wiltberger et al, 2000: MHD LFM

**Plate 4.** Frames from the visualizations showing $|E|$ in an $XY$ ($z = -4$) cut planes with velocity vectors (white arrows) overlaid.

Challenges: (1) For hybrid simulations, local resistivity is needed to trigger reconnection

(2) MHD apparently can not address kinetic nature of DF

# DFs are also reproduced in 2D Particle -In-Cell codes

with open boundary conditions or in very large simulation box (Daughton et al. 2006; Sitnov et al. 2009; Klimas et al., 2010; Wu and Shay, 2012)

Challenges:

(1) DF should propagate freely through boundary: Open boundaries are needed.

(2) Most of DF simulations start from GEM challenge:
1D Harris + external disturbance
GEM reconnection always has transient phase

(3) DFs are by nature transient processes.
It's hard to convince that DF in GEM reconnection is not an artificial transient process.

(5) Next step: Reconnection in 2.5 D equilibria with open boundaries

Sitnov et al., 2009: GEM challenge
Open boundaries

SITNOV ET AL.: DIPOLARIZATION FRONT

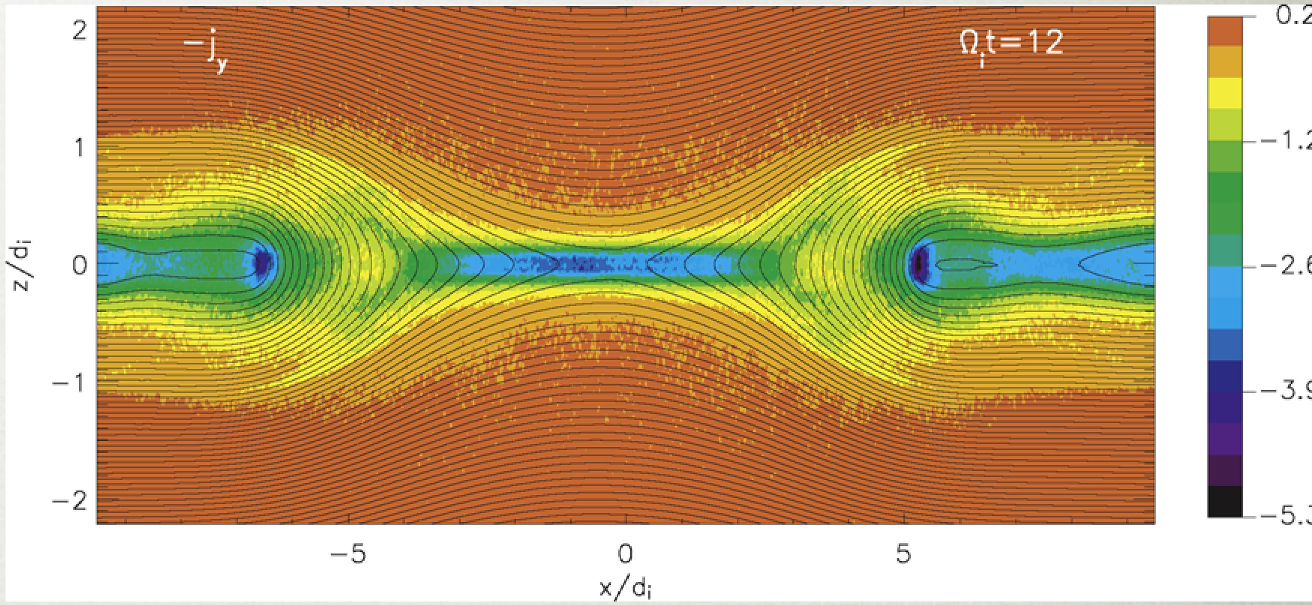
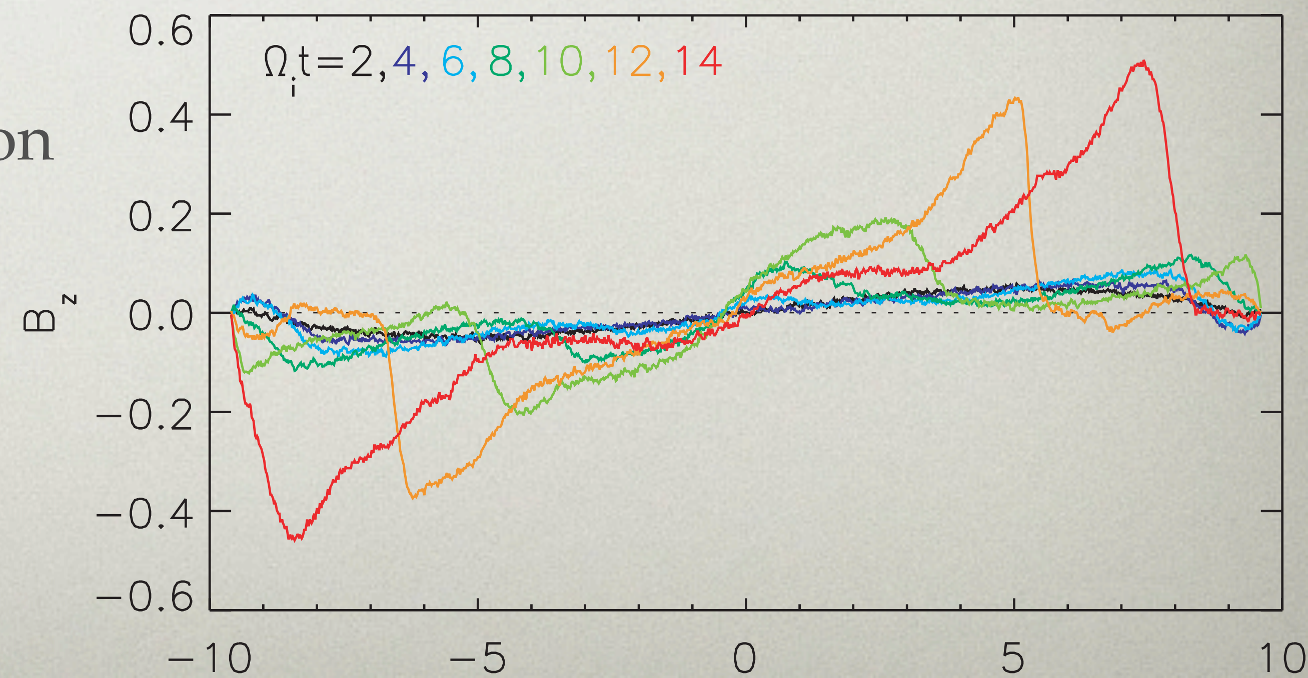


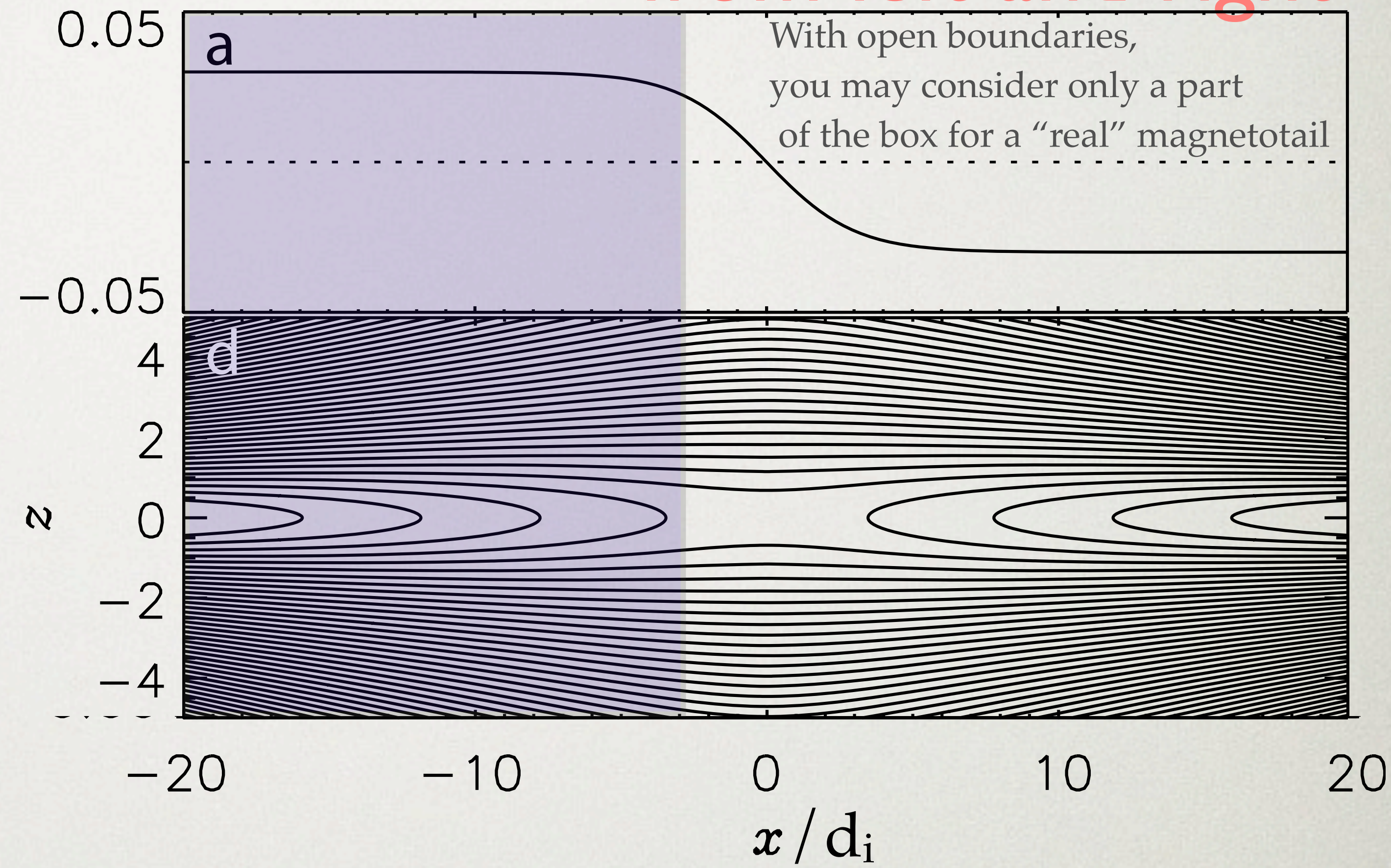

**Figure 2.** Magnetic field lines and the color-coded current density component $-J_y$ for Run 1 at the moment $\Omega_i t = 12$.



# PIC simulation of reconnection and DFs in 2D equilibrium: P3D code with Open boundary conditions from left and right

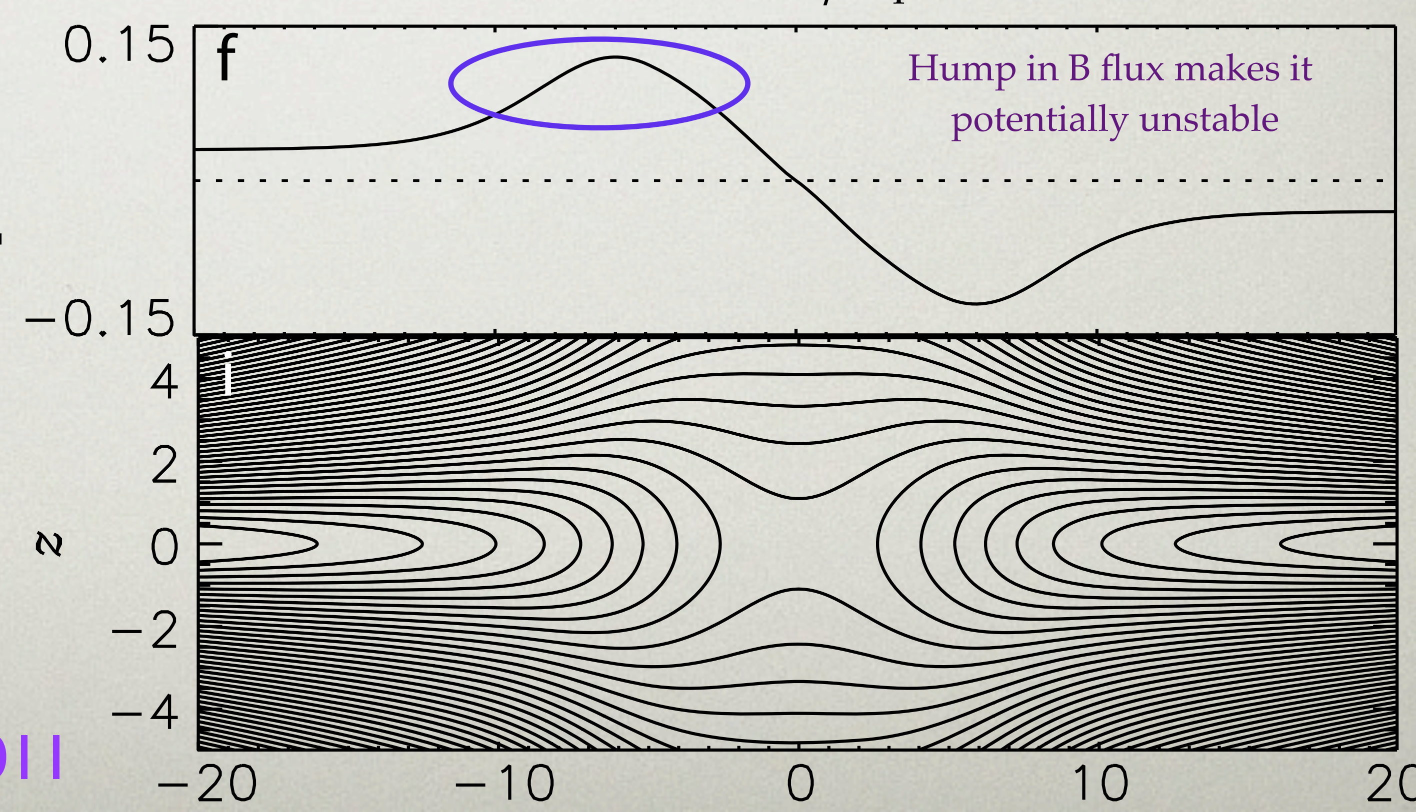
Case I: 2D equilibrium monotonic Bz profile

Lembege-Pellat magnetotail LP-1982
(Schindler, 1972; Lembege&Pellat, 1982)
weak driving Ey=0.05



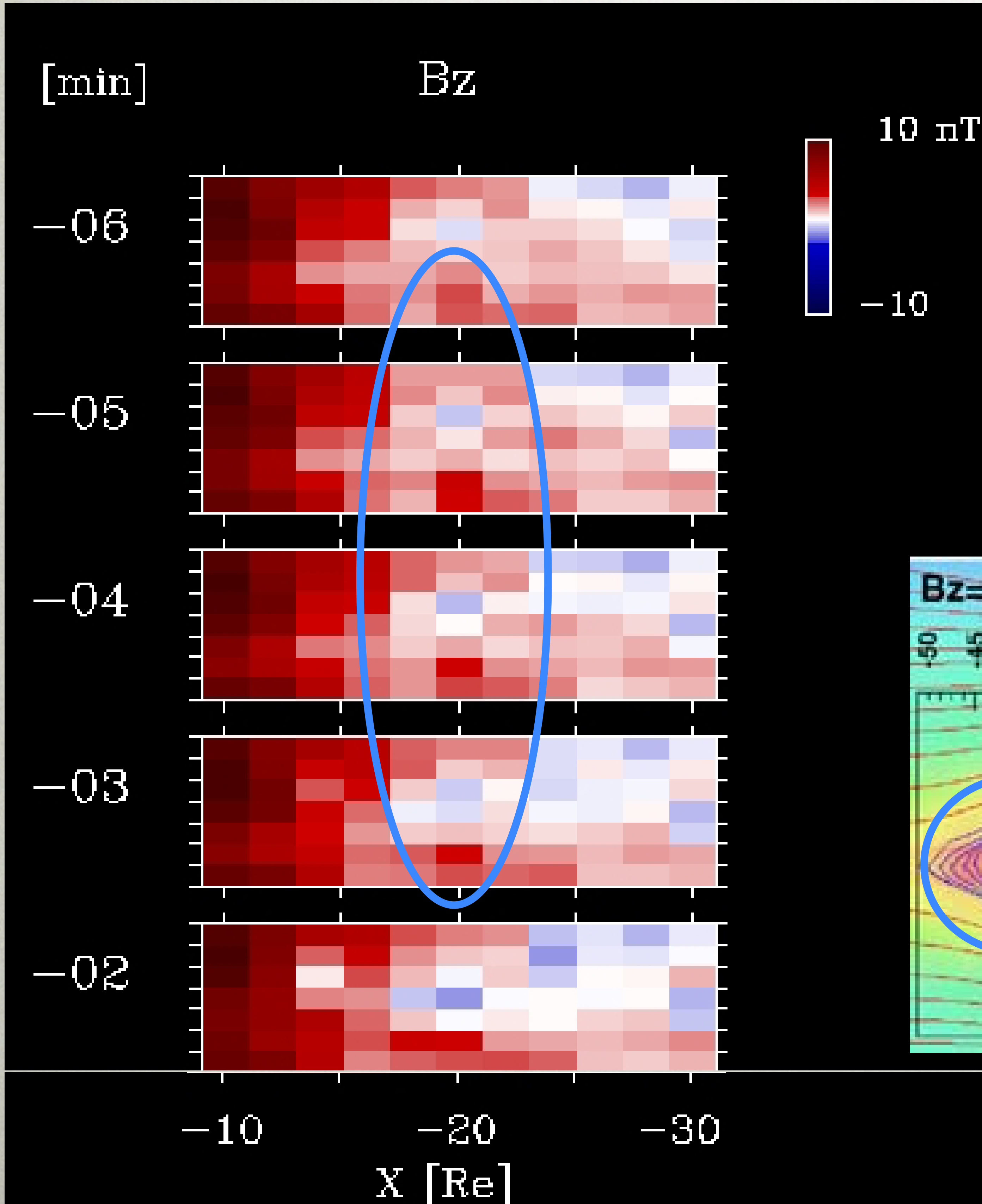

Case II: 2D equilibrium with accumulated flux (Bz has max)

Sitnov-Schindler magnetotail SS-2010
This equilibrium is potentially unstable against ion tearing mode
(Sitnov&Schindler, 2010;
Sitnov&Swisdak, 2011)
weak driving Ey=0.05



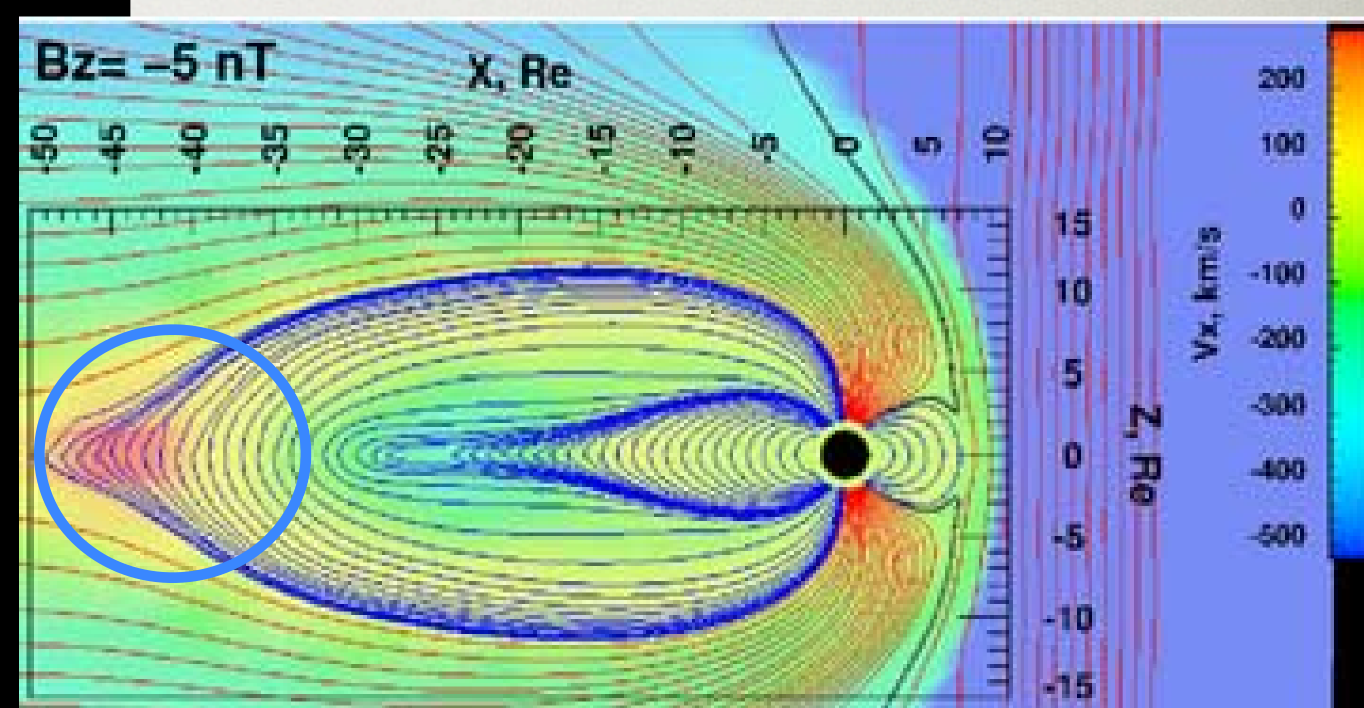

Runs are taken from Sitnov&Swisdak, 2011

Machida et al., 2009:
statistical picture of substorm from Geotail X axis is along magnetotail
Y axis is inversed plasma beta

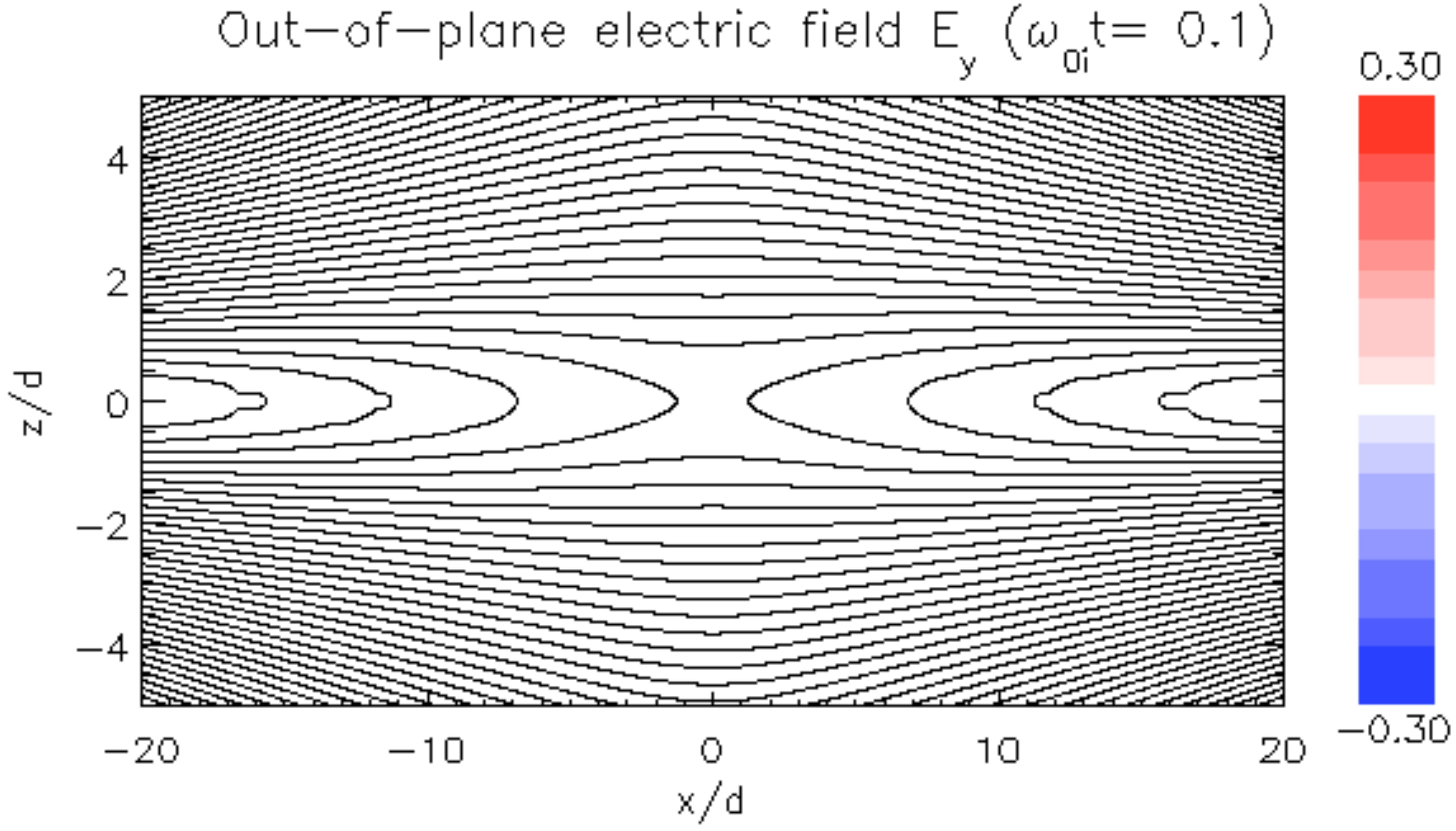



# Magnetic field hump from observations and global MHD simulations

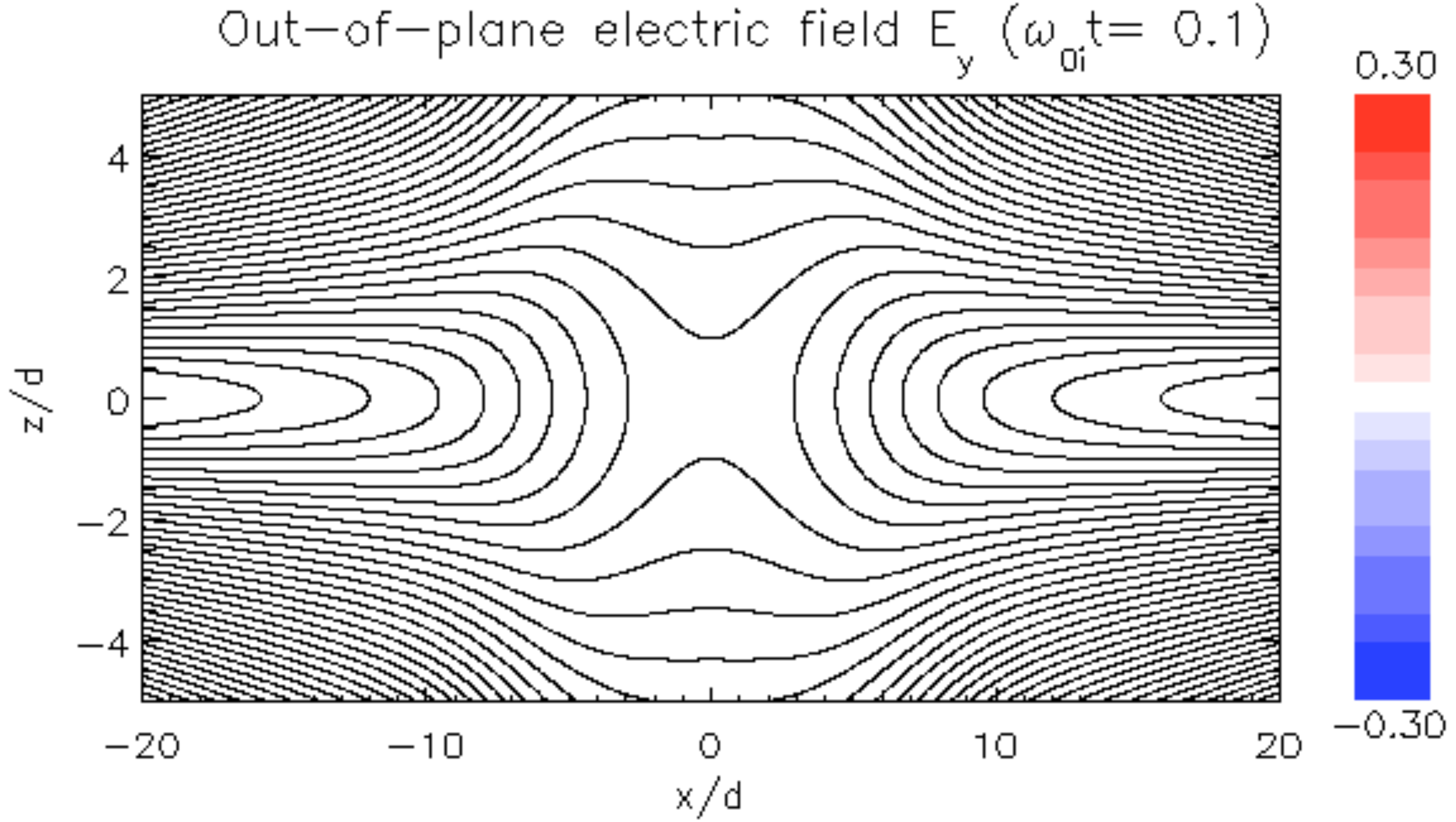
Merkin&Goodrich, 2007:
Global MHD LFM



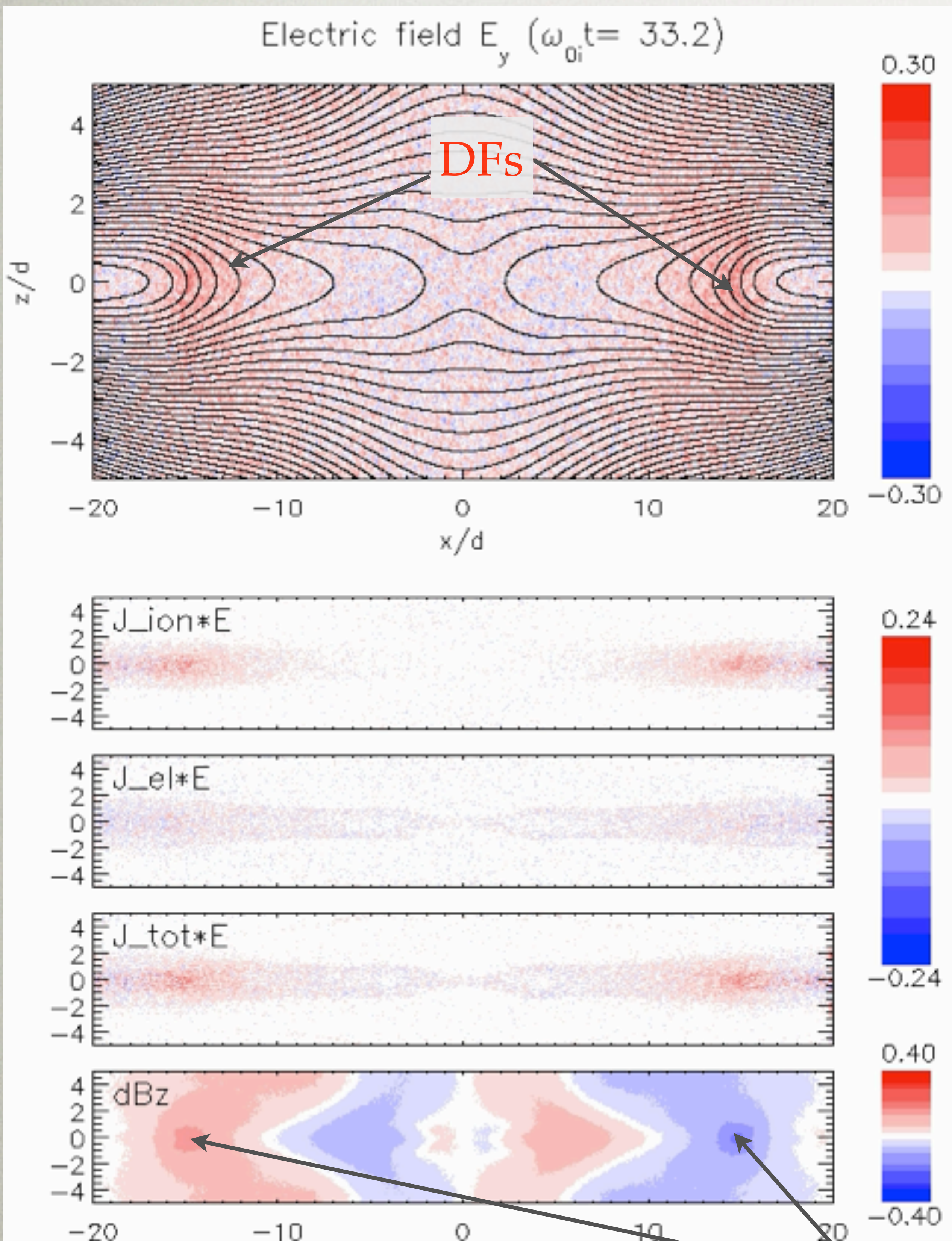
# B-field lines and reconnection electric field (color) in equilibria with monotonic Bz: Reconnection triggers DF motion



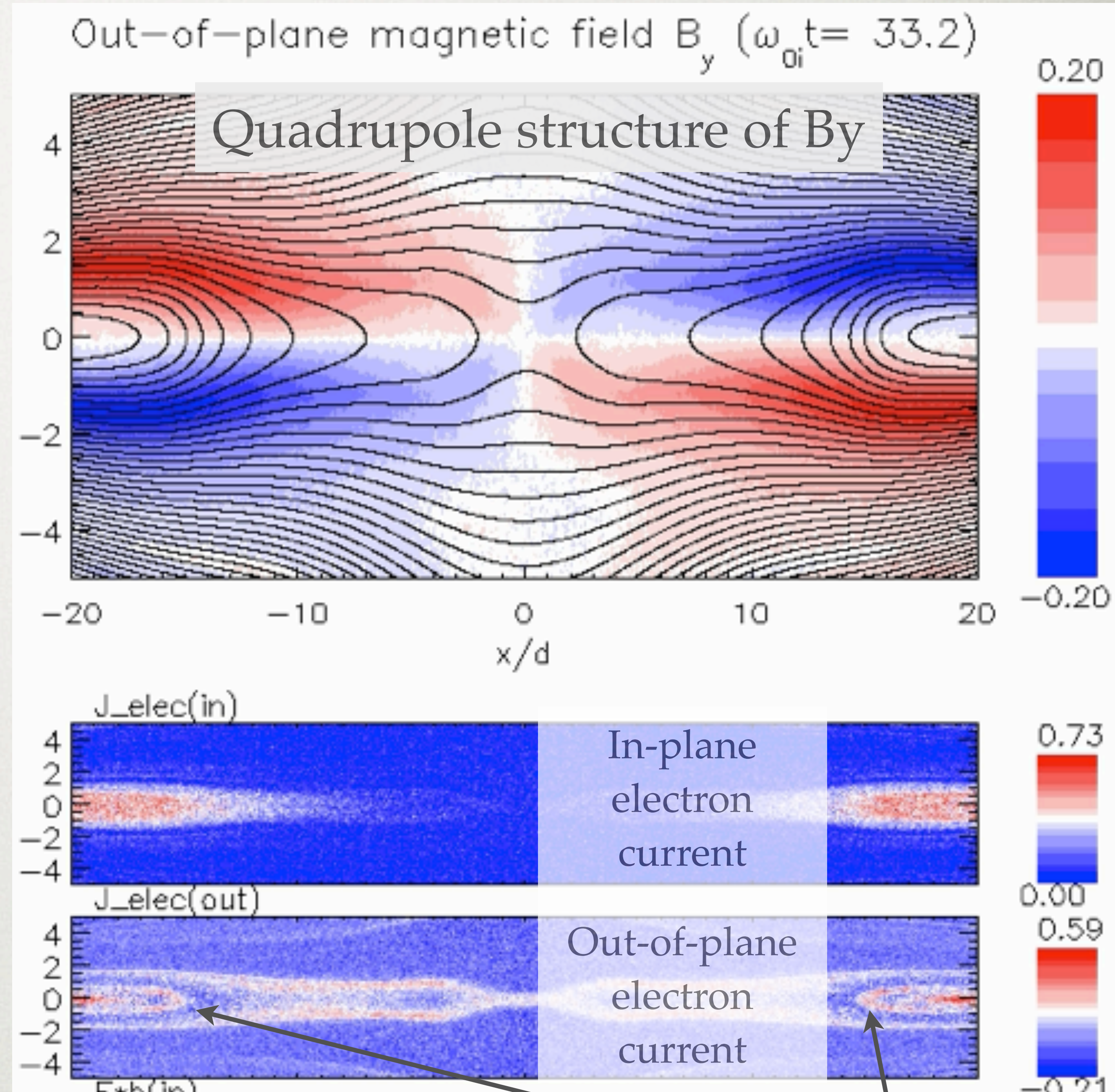
# B-field lines and reconnection electric field (color) in magnetotail with initial Bz-hump



# Run with ‘Bz-hump’ equilibria: reconnection onset and formation of DFs

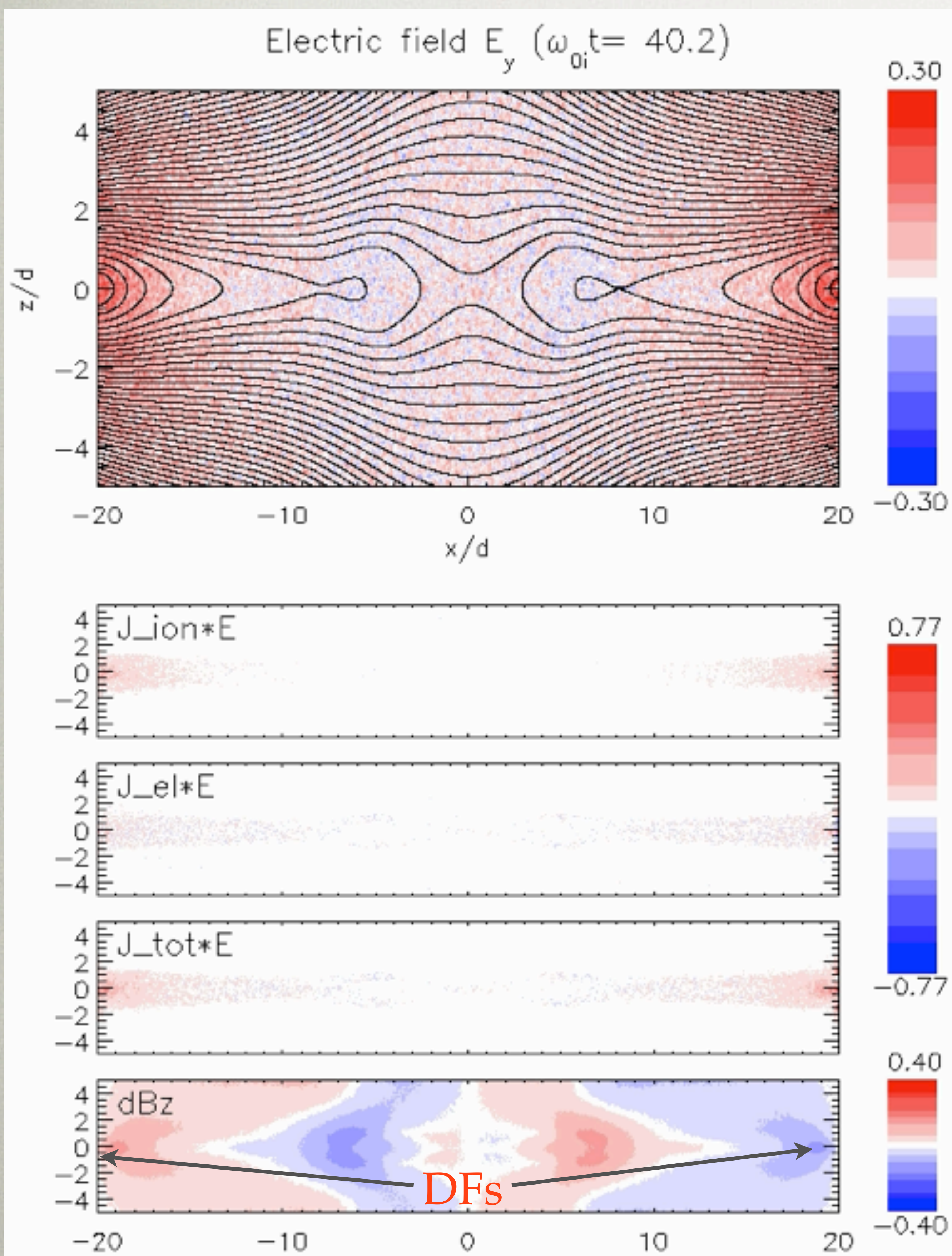



dBz=Bz(t0)-Bz(t) - visualization of DFs

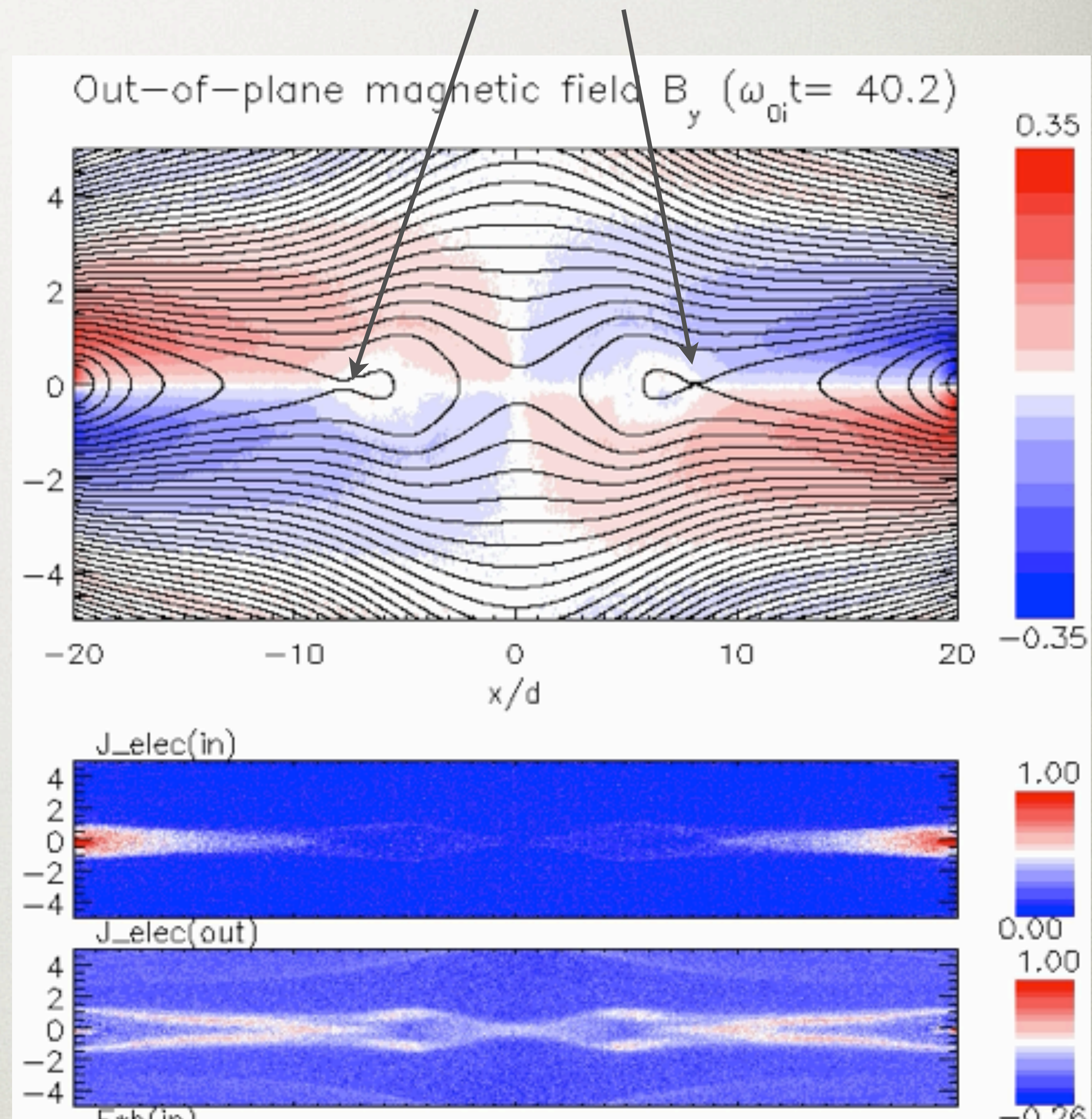



**Interpretation:**
**Ion tearing instability**
(Sitnov&Shindler, 2010;
Sitnov&Swisdak, 2011)

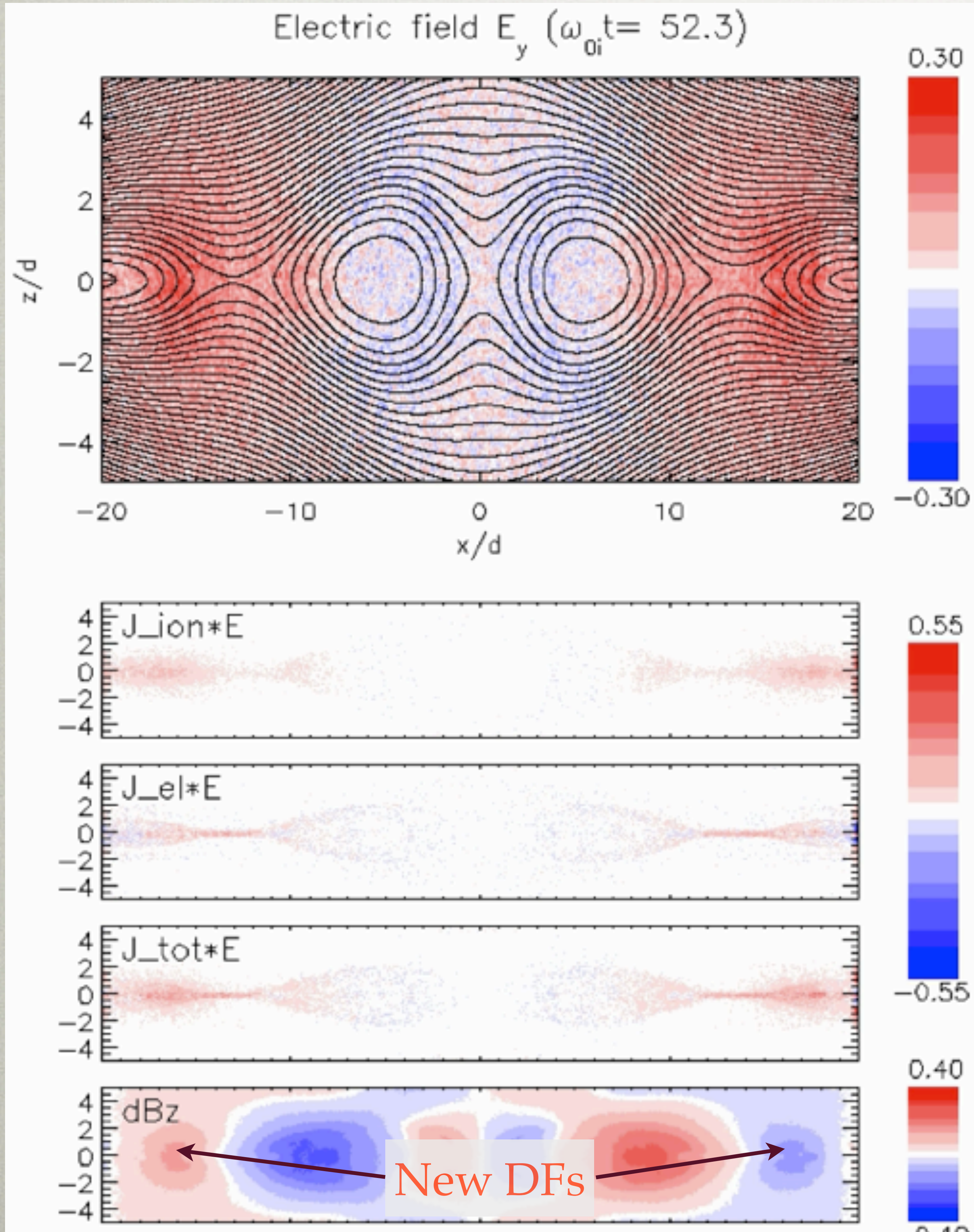
# Reconnection in SS2010 run: Formation of an inactive X-points



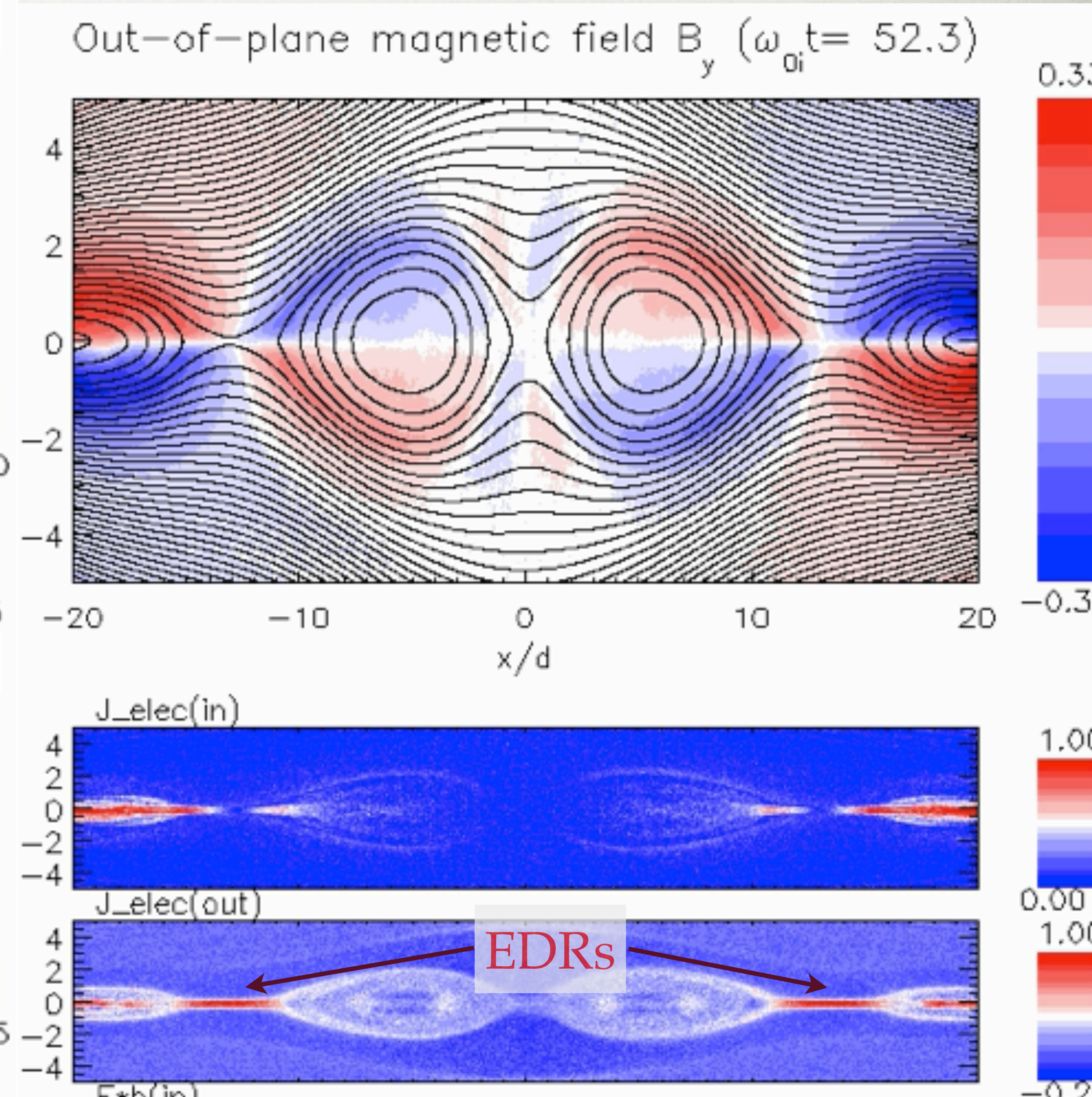

Inactive X-points



# Activation of X-points and formation of electron diffusion regions (EDRs) with new DFs

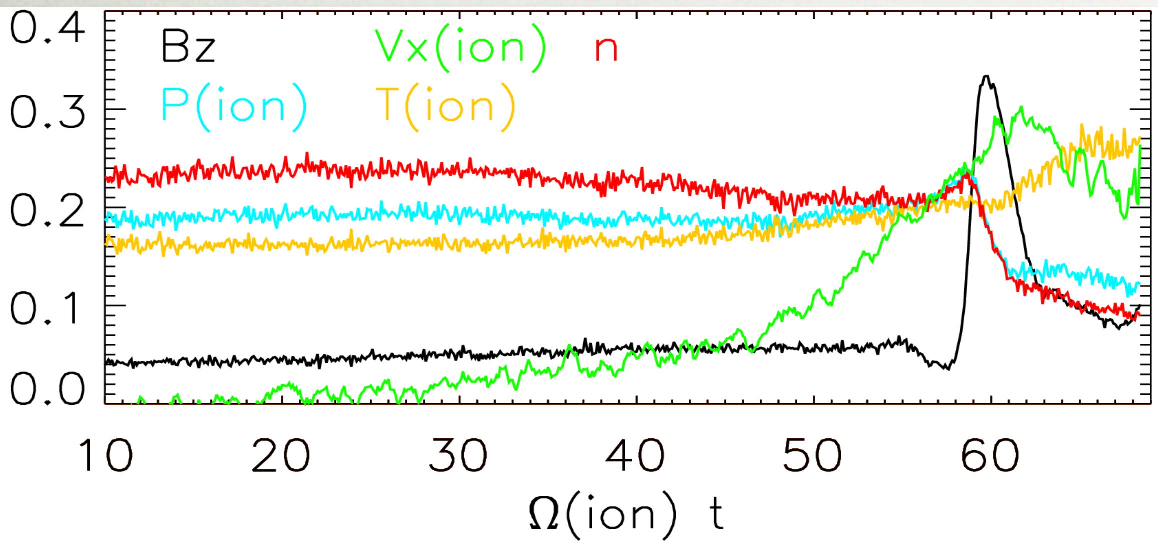



By-quadrupole structure is doubled

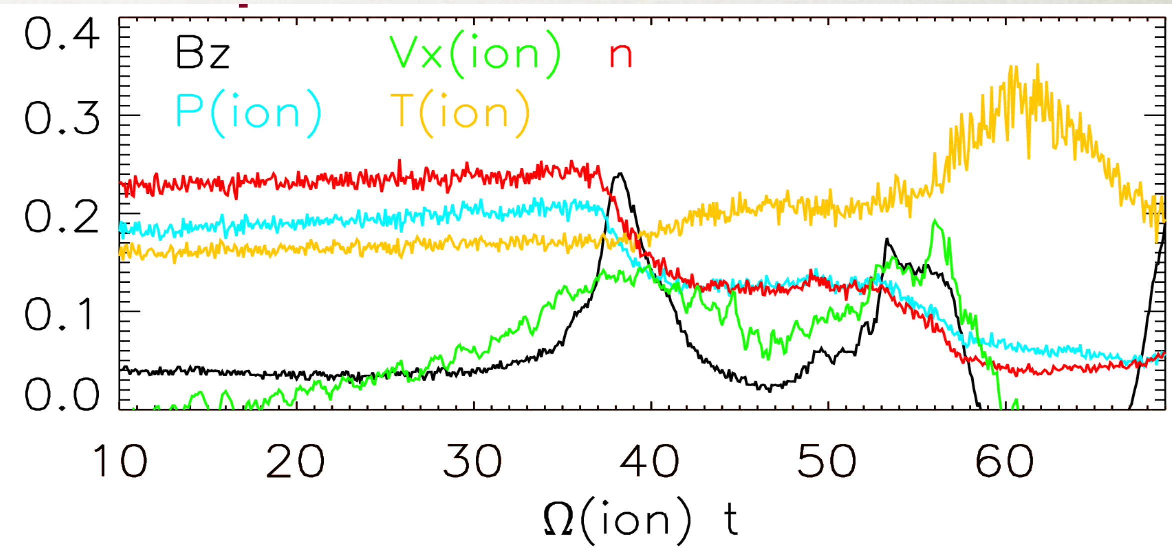


# Virtual s/c observations of DFs for two cases of equilibrium

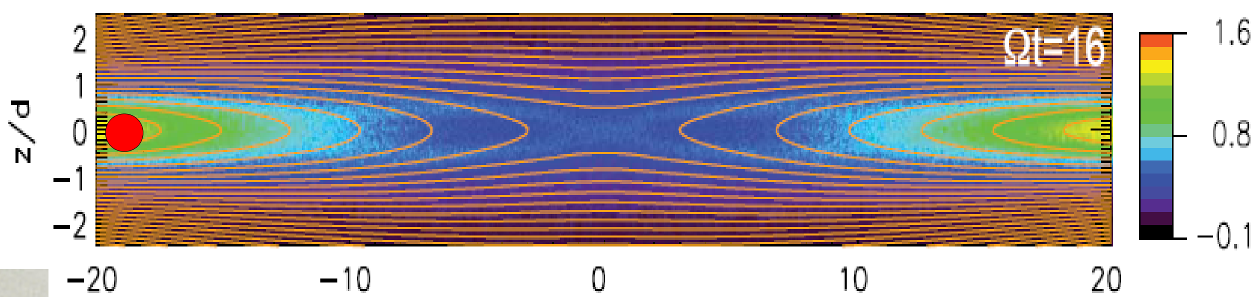
## Monotonic Bz-profile

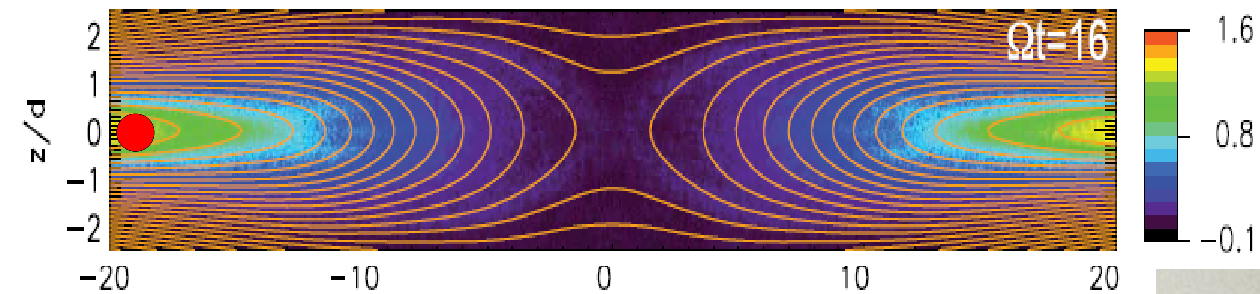



## Bz with hump - multiple DFs




(1) Sign of Vx is inverted to match GSM;
(2) Y scale is linear for all variables but Ymax is different for different variables

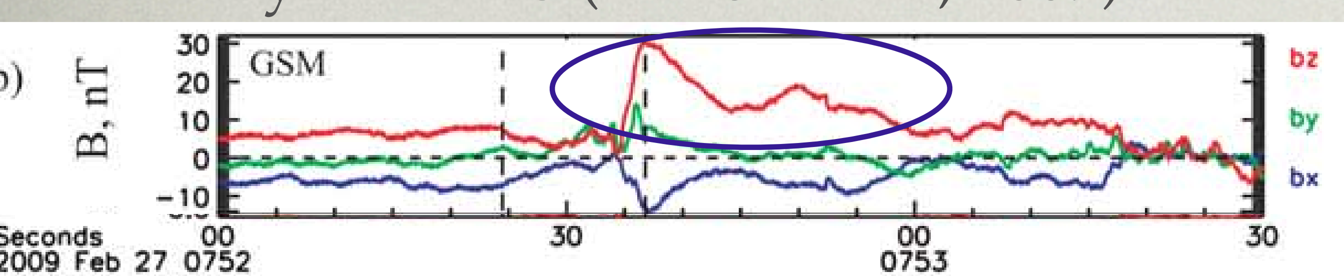


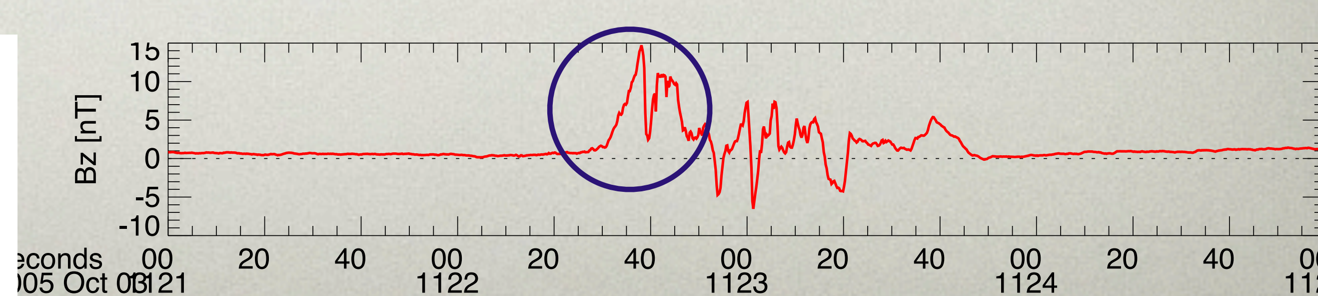

$E_0=0.05$; $Lx=40$; $n_b=0.2$;

● location of virtual s/c

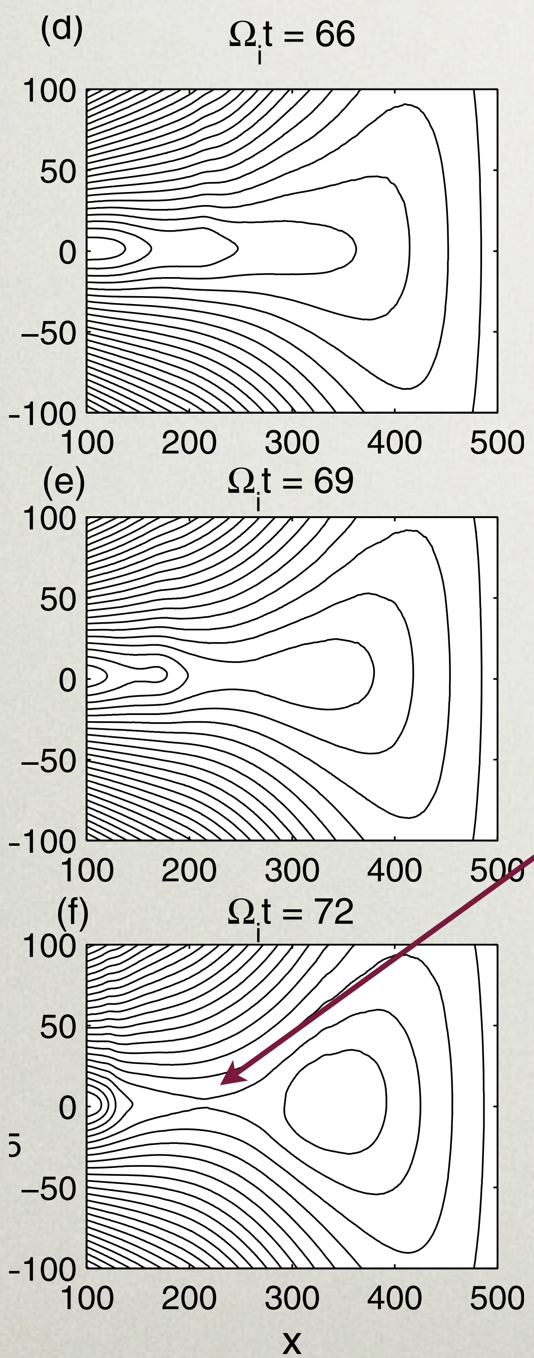
Multiple fronts are observed by THEMIS (Runov et al., 2009)




and by Cluster (Chen et al., 2011)



# 3D PICture
# New player: Interchange mode
# (Pritchett and Coroniti, 2011)




Reconnection is created by interchange (buoyancy) motion: Bz hump is unstable agains interchange in 3D

Difference between this case and our results:

Buoyancy vs tearing

Similarity:

Plasma motion (DF) creates X-point

# Conclusions

- There are lot of observations for dipolarization fronts (DFs):

  a good opportunity to learn about collisionless reconnection in the Earth magnetotail

- We found reconnection  and DF formation are sensitive to initial equilibrium

- Open boundary conditions seem critical

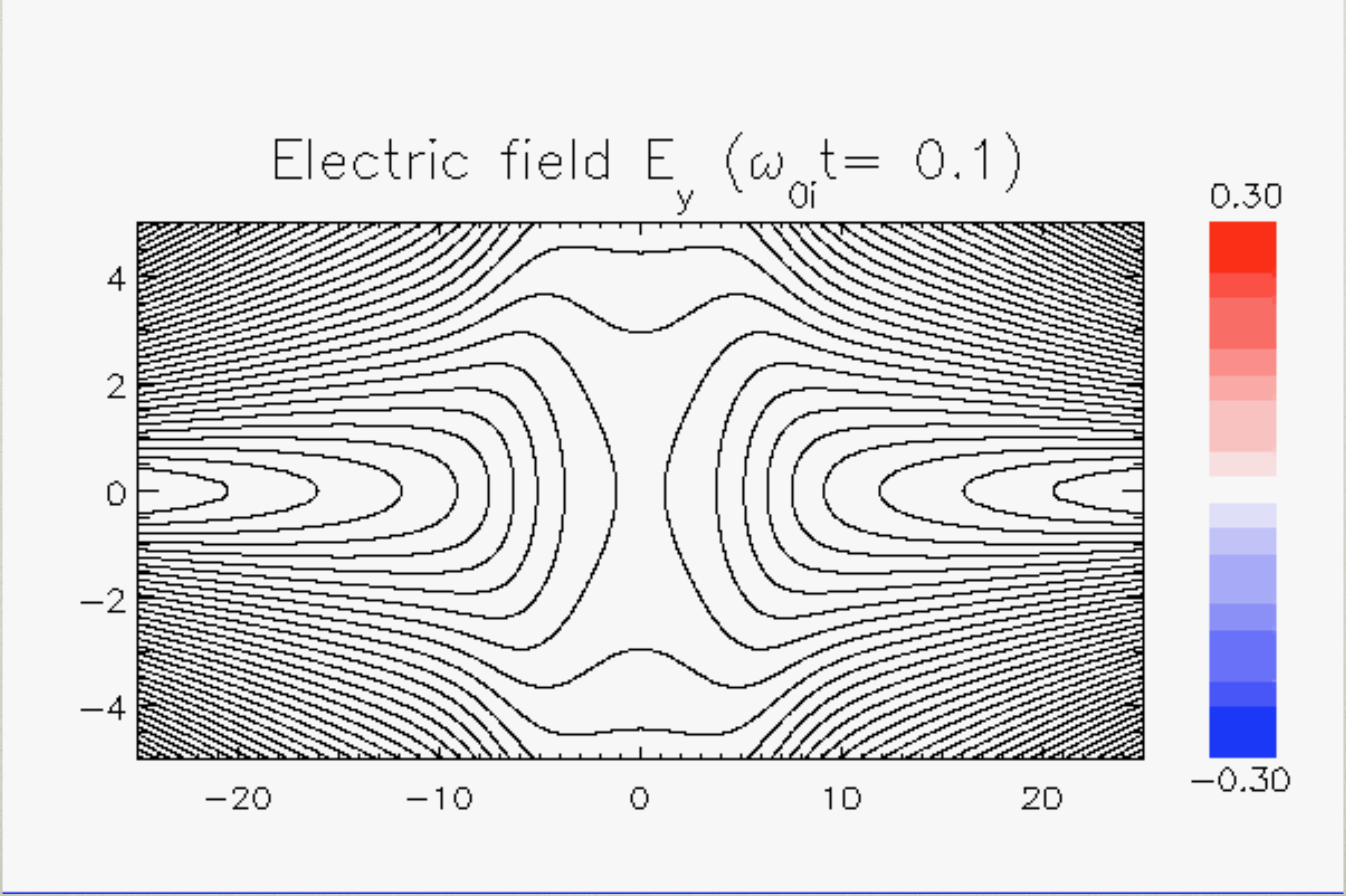
- 2D and 3D PIC simulations reveal that in the Earth magnetotail, reconnection may be a consequence of plasma motion due to instabilities

- Hence, it is DF that generate X-point in these regimes

- CLUSTER and THEMIS observations confirm this PICture at least for some cases

- We hope to apply these results for future NASA MMS mission

# Run with extended box (50di vs 40di in X direction)
# Initial equilibrium with Bz humps



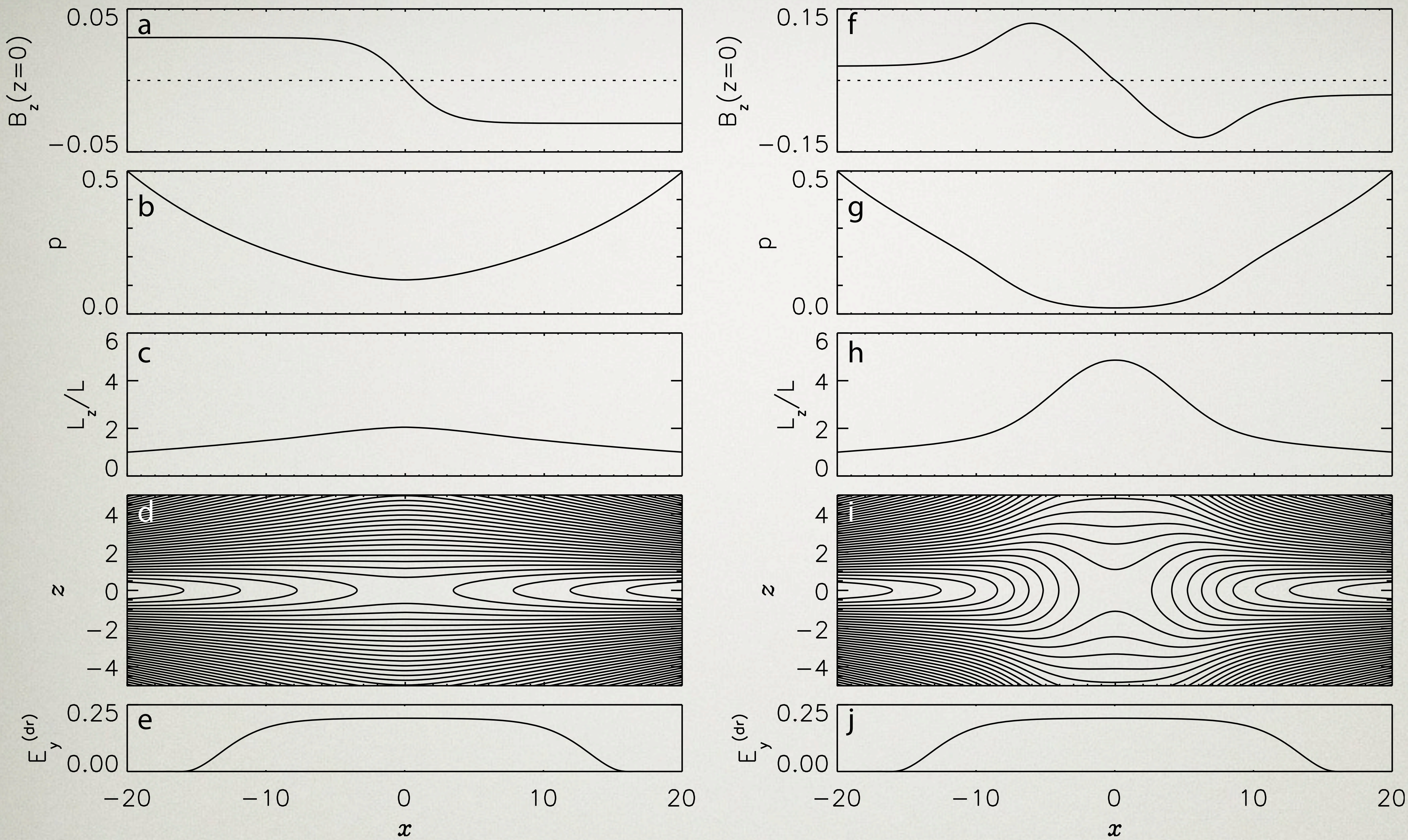



**Figure 1.** Two basic types of current sheet equilibria used in simulations. Run 1: (a) normal magnetic field $B_z$ at the neutral plane $z = 0$, (b) dimensionless plasma pressure parameter $p = 1/(2\beta^2)$, (c) current sheet half thickness $L_z/L = \beta(x)$, (d) magnetic field lines for the equilibrium with the magnetotails similar to the *Lembege and Pellat* [1982] model, and (e) the driving electric field $E_y^{(dr)}$ at top and bottom boundaries $z = \pm 10$. Run 5 differs from run 1 by the reduced value of the driving field $E_0^{(dr)} = 0.05$. Run 2: (f–j) parameters similar to those of run 1 for the multiscale equilibrium investigated by *Sitnov and Schindler* [2010] with the same driving field $E_0^{(dr)} = 0.2$ as in run 1. The strength of the driving field is reduced to $E_0^{(dr)} = 0.05$ in runs 3 and 4. The latter run differs from runs 2 and 3 by the increased size of the simulation box along the X direction: $-25 < x < 25$.

## Boundary conditions: Particles

Open boundaries are needed [Daughton et al., 2006]

- to allow the elongation and disruption of the electron diffusion region
- to avoid cutting the flux tube integral, which plays the key role in the tearing stability

$$\frac{\partial n^{(\alpha)}}{\partial x} = 0 \qquad \frac{\partial \mathbf{V}^{(\alpha)}}{\partial x} = 0 \qquad T^{(\alpha)} = T^{(\alpha)}(t = 0), \quad \alpha = e,i$$

Contradicts force balance across the boundary for 2D equilibria

$$j_y B_z \neq 0$$

Additional particle injection:

$$\delta n^{(\alpha)} \propto (\partial / \partial x) n^{(\alpha)}(t = 0)$$

## Boundary conditions: Fields

Outflow (X)

$$\frac{\partial E_x}{\partial x} = 0 \qquad \frac{\partial E_y}{\partial x} = 0 \qquad E_z = 0 \qquad \frac{\partial B_x}{\partial x} = -\frac{\partial B_z}{\partial z} \qquad \frac{\partial B_y}{\partial x} = 0 \qquad B_z = B_z(t = 0)$$

Provide free propagation of magnetic flux [Pritchett, 2001]

Inflow (Z) $\quad E_y^{(dr)} = 0.2$