Proton Acceleration Properties at Dipolarization Fronts

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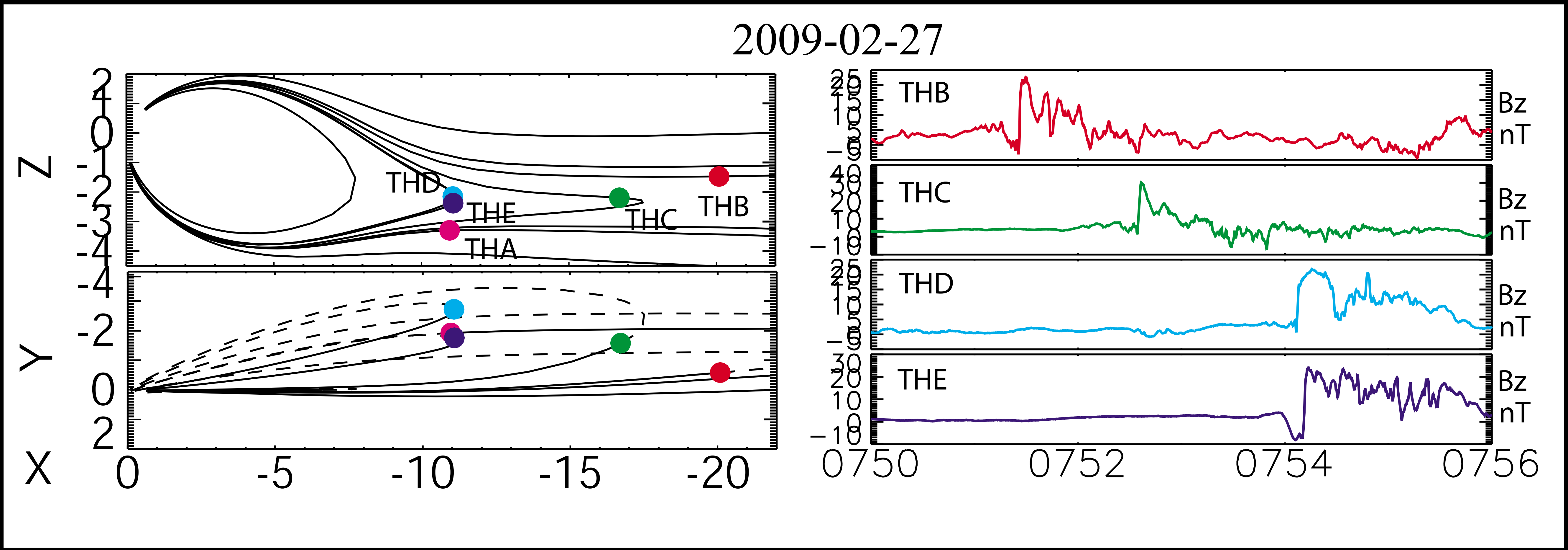
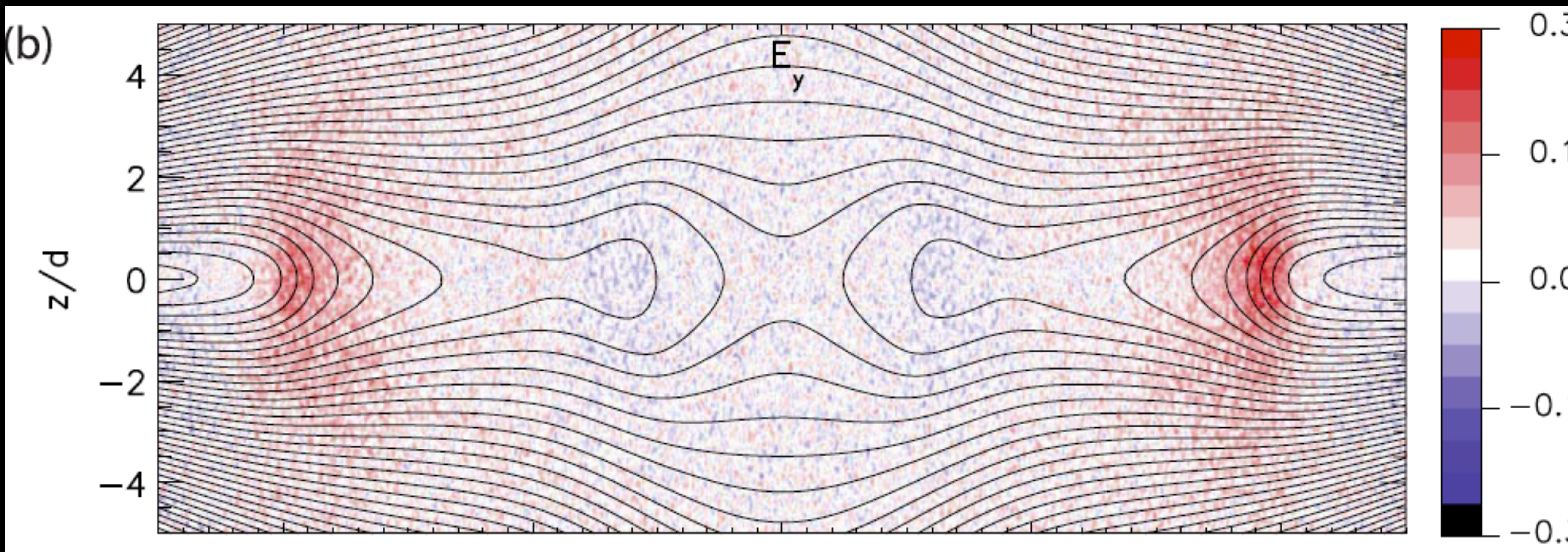
Spacecraft Observations of Dipolarization Fronts (DFs)



[Runov et al., 2011]

DFs are routinely observed by spacecraft from the tail to the inner magnetosphere. Figure shows THEMIS observations of DFs between -20 and -11 R_E. Sharp increase in B_z inherent to the fronts is preceded by sometimes negative depletion of the field [Runov et al., 2011]. Some events described in the paper propagate earthward with U_x as hight as 600 km/s.

DFs in Kinetic Simulation of Reconnection Onset



[Sitnov and Swisdak 2011]

Kinetic PIC simulations of reconnection onset show formation of DFs with thickness on the order of the ion inertial length propagating away from the X-point.

Analytical 2D Model of DFs

$$\mathbf{A}_1(\xi, z) = \hat{\mathbf{y}} X(\xi) Z(z); \;\; \mathbf{B}_1 = -\hat{\mathbf{x}} X(\xi) Z'(z) + \hat{\mathbf{z}} X'(\xi) Z(z)$$

$$\xi = x - ut \qquad\qquad Z(z) = \frac{1}{\sqrt{\cosh\left(z/L_z\right)}}$$

X'(x) is a continuous function selected to mimic observed $B_z(t)$ profiles of DFs from the in situ spacecraft measurements with the (+) parameters corresponding to the B_z depletion ahead of, and the (-) parameters to the B_z enhancement behind the front:

(1) min B^+_z=-6 nT; max B^+_z=20 nT;

(2) The front width $\xi^+ - \xi^-$=0.1 $R_E \approx \rho_H$;

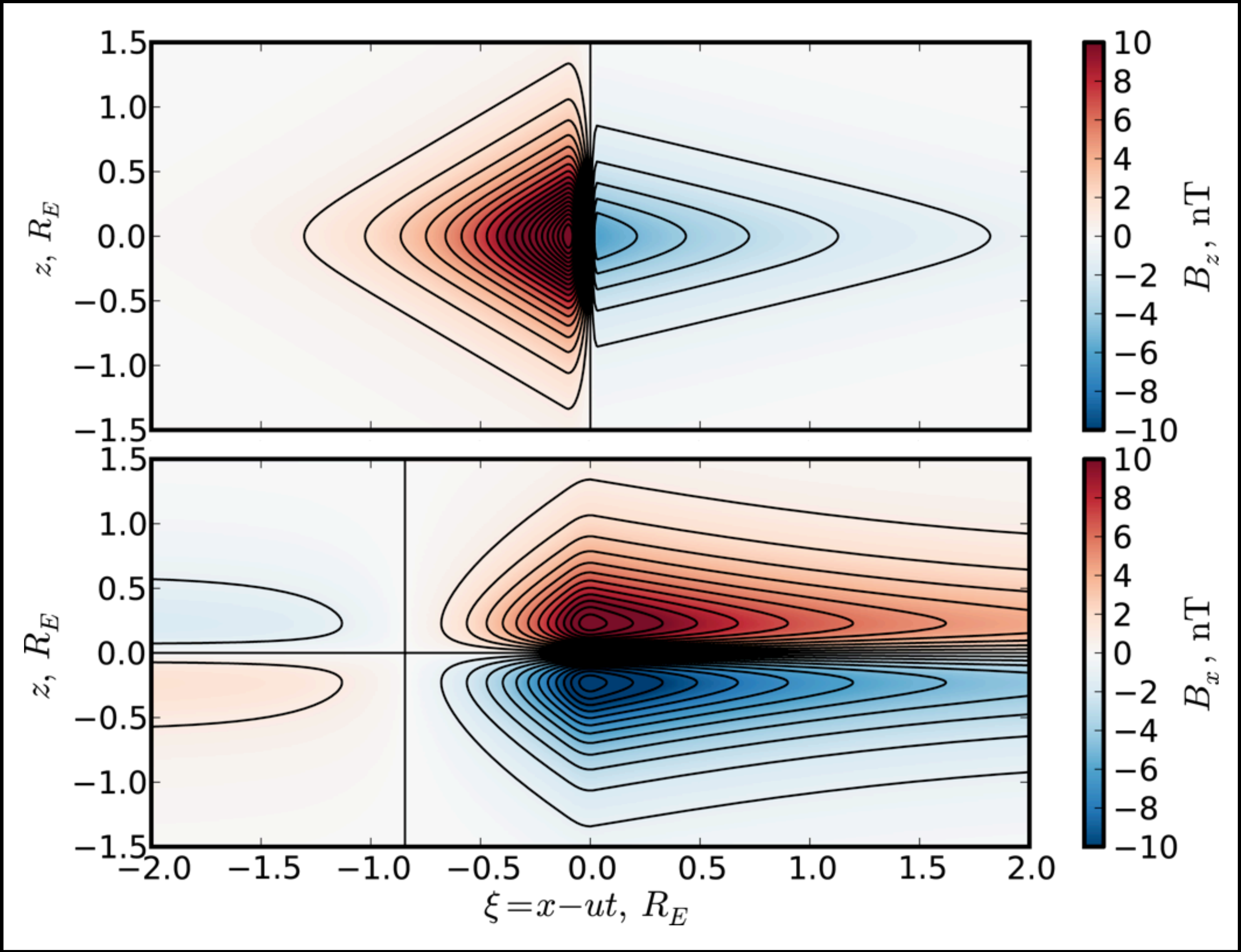
(3) Behind the front $B(\xi)=B_0 \exp[-\alpha^- |\xi - \xi_1|]$, where $1/\alpha^- \approx$ 1 R_E;

(4) $X(+\infty)$=2 nT·R_E, which increases the curvature of plasmasheet ahead of the front to:

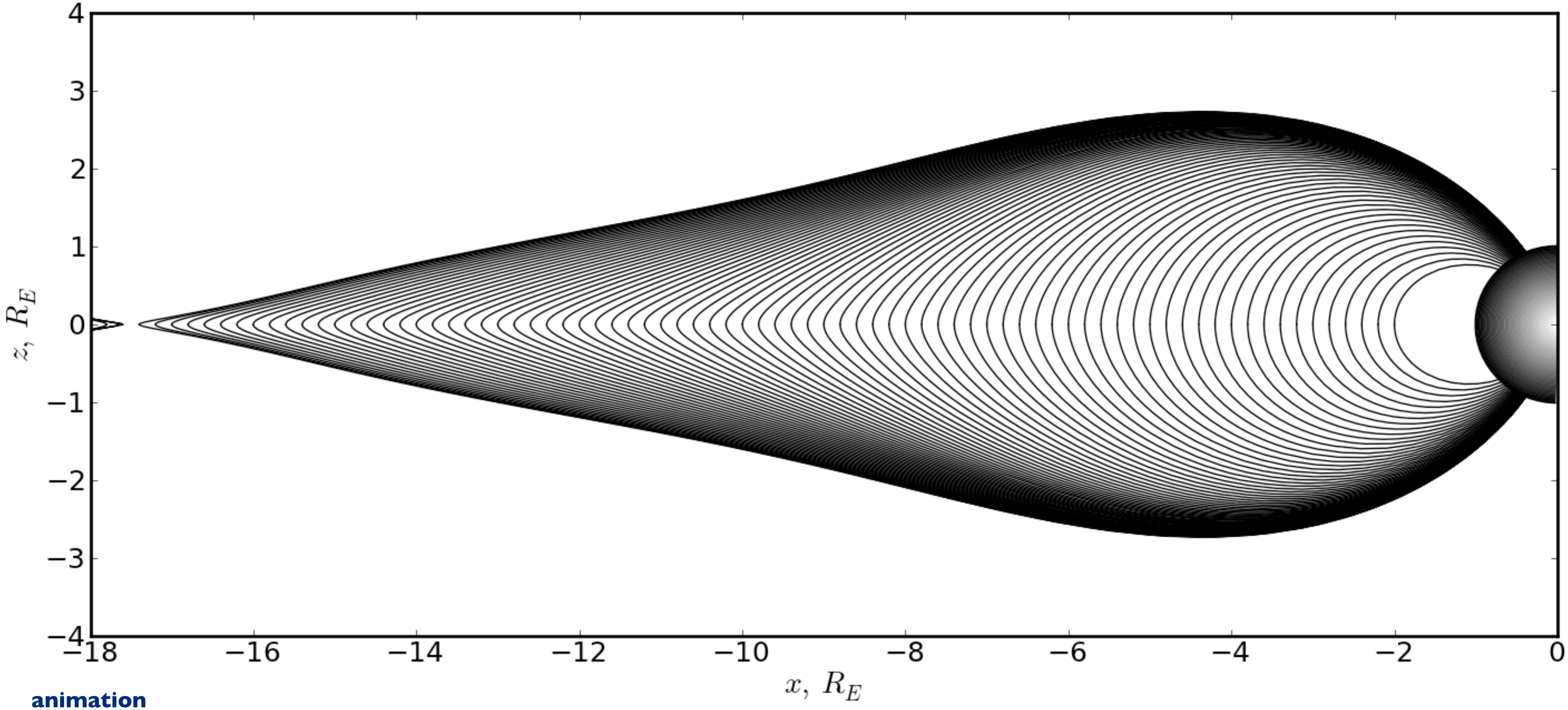
$\kappa = \partial_z b_x|_{z=0}$; $1/\kappa$=0.25 R_E (@x=-16 R_E)consistent with Runov [2005] (500-10000 km)

Z(z) function describes localization of the fronts in the z direction (L_z=0.2 R_E) [Sitnov and Swisdak, 2011].

Analytical Model of DFs



Modeled Propagation of DF



animation

A self-similar DF $\mathbf{B}_1(x\text{-}ut,z)$ propagating from the tail towards Earth, is superimposed on the ambient magnetic field $\mathbf{B}_0(x,y,z)$, slowly varying in the x direction.

Simpleminded Considerations

DF parameters:

u_x=600 km/s

max ΔB_z=20 nT

min ΔB_z=-6 nT

Larmor radius (non-relativistic):

$\rho=c(2Km)^{1/2}/eB$, $\rho_H/R_E \approx 0.7(K[keV])^{1/2}/B[nT]$

Reflection criterium:

$L>\rho_{in}$ and $\rho_{in}<<\rho_{out}$

For chosen initial conditions (K_{H+}=2 keV; x_0=-16 to -12 R_E, B=3-6 nT):

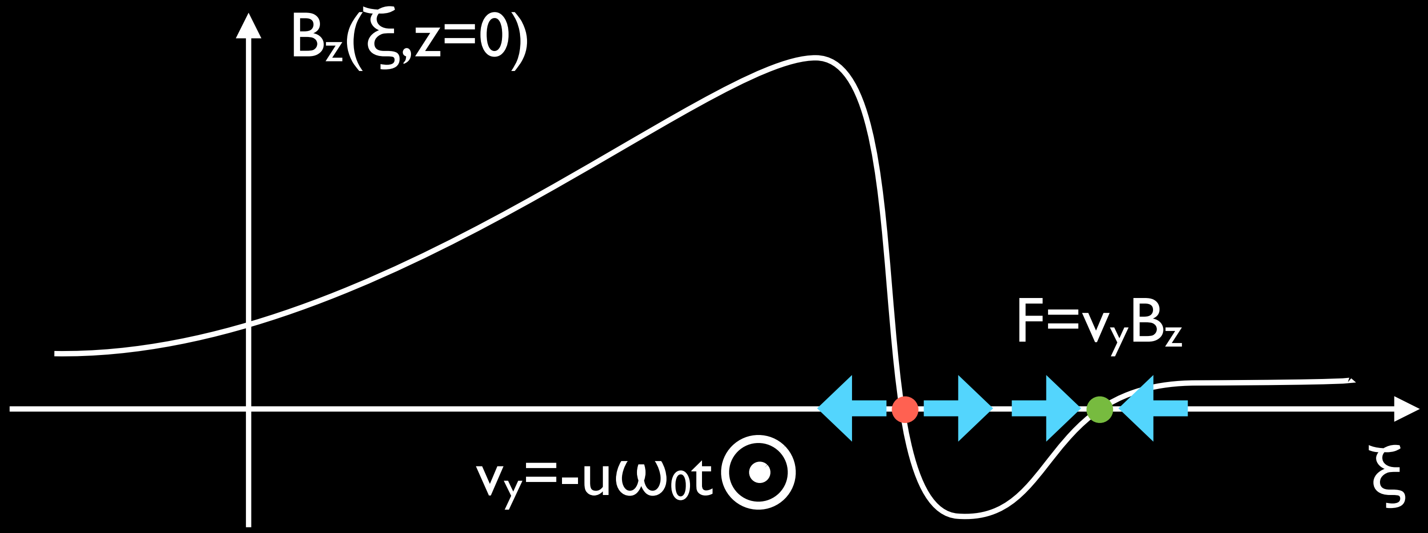
$\rho_H \approx 0.3$-$0.6\ R_E$; $\rho_{in}/\rho_{out}<0.1$

Energization due to reflection from the front $\Delta K=mu_x^2/2$:

$\Delta K_H \approx 1.8$ keV

Single reflection from the front gives only factor of ~2 increase in energy

Exact Solution for Equatorial Protons



$$\begin{cases} \dot{v}_x = [\omega_0 + \omega_1(x - ut)]v_y \\ \dot{v}_y = \omega_1 u - [\omega_0 + \omega_1(x - ut)]v_x \end{cases}$$

$$\xi = x - ut;\; v_x = \dot{\xi} + u$$

<u>Motion along y:</u> If a particle is trapped by the front, i.e. travels in the +x direction without significantly changing its ξ position relative to the front, it gets linearly accelerated in the -y direction in the E-field $-uB_0$ due to the Lorentz transformation of the background B-field.

$$\dot{v}_y = -\omega_0 u - (\omega_0 + \omega_1(\xi))\dot{\xi} \qquad v_y = -\omega_0 ut - \int_{\xi_0}^{\xi} (\omega_0 + \omega_1(\xi'))\xi'$$

<u>Motion along x:</u> Can be described in terms of a 1D Hamiltonian: H=K+U

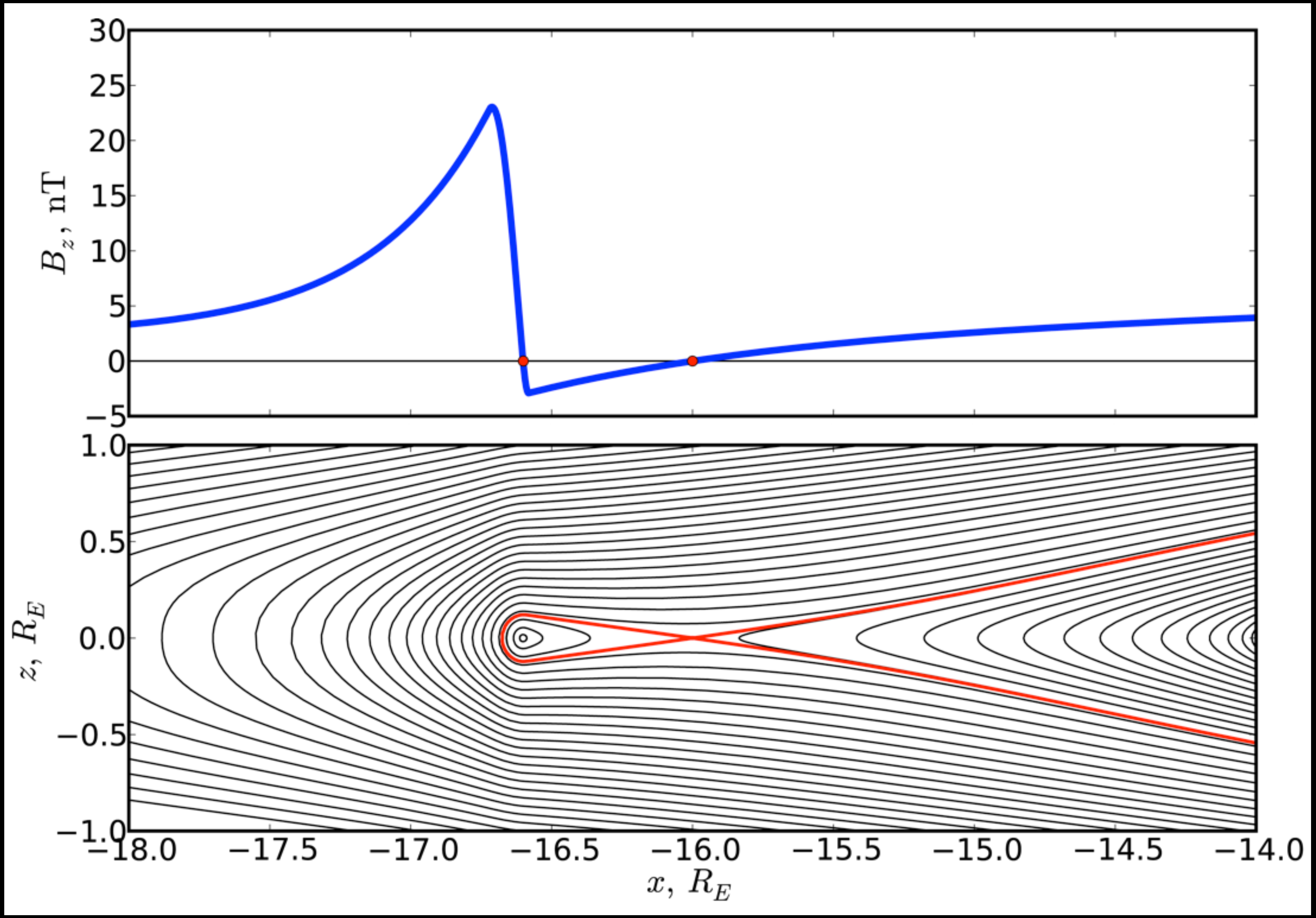
$$\ddot{\xi} = -(\omega_0 + \omega_1(\xi))[\omega_0 ut + \int_{\xi_0}^{\xi} (\omega_0 + \omega_1(\xi'))\xi']$$

$$\ddot{\xi} = -\frac{\partial}{\partial \xi} U(\xi, \xi_0, t)$$

$$\frac{m}{e} U(\xi, \xi_0, t) = B_0 ut[B_0(\xi - \xi_0) + A_1(\xi) - A_1(\xi_0)] + \frac{1}{2}[B_0(\xi - \xi_0) + A_1(\xi) - A_1(\xi_0)]^2$$

Total Magnetic Field

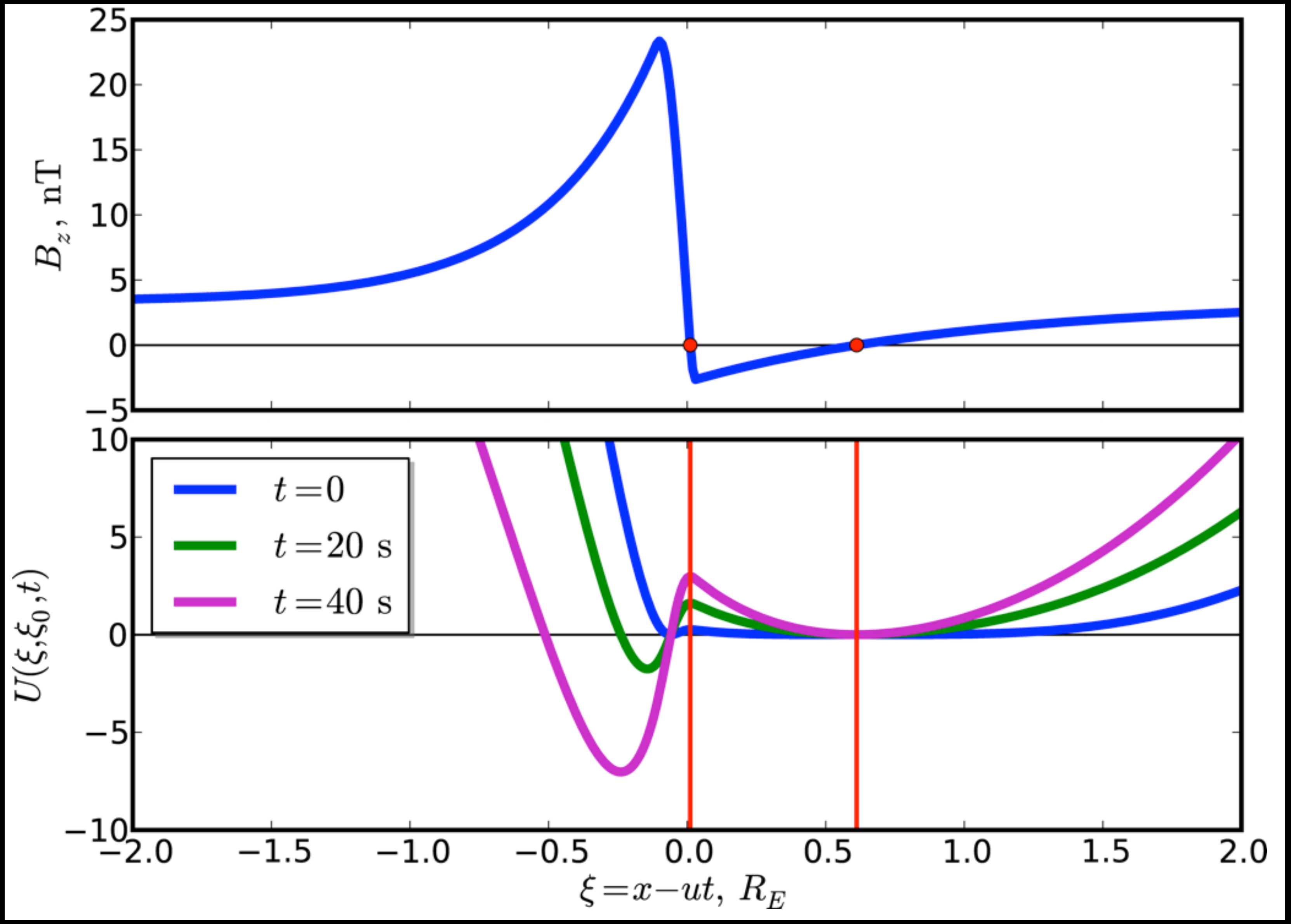
X=-16 R_E



In the tail regions where the magnetic field is the weakest, the depletion ahead of the front can be greater than the ambient magnetic field. The total B_z, in this case, is negative ahead of the front, being separated from positive B_z values by a reconnection point moving earthward with the front.

Time-Dependent Effective Potential

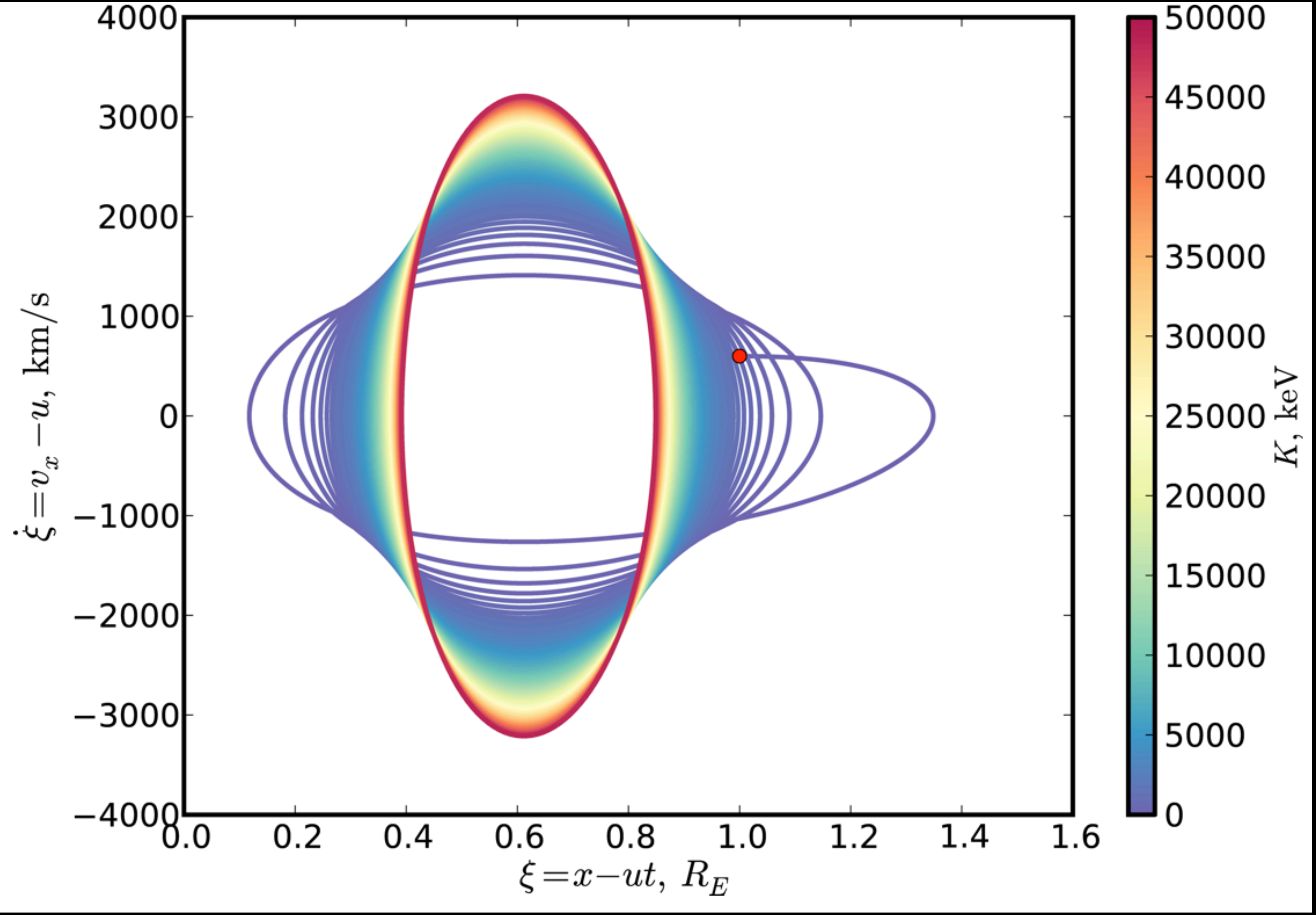
X=-16 R_E



Local maximum of U at the unstable fixed point enables particle trapping ahead of the front. The concave profile of U(ξ>0) is steepening with time pushing trapped particle population towards the stable fixed point. Trapping does not require particles to be in resonance with the front (V_ξ=0), suggesting that this acceleration mechanism can affect a substantial region of proton phase space.

Acceleration in Idealized 2D Case

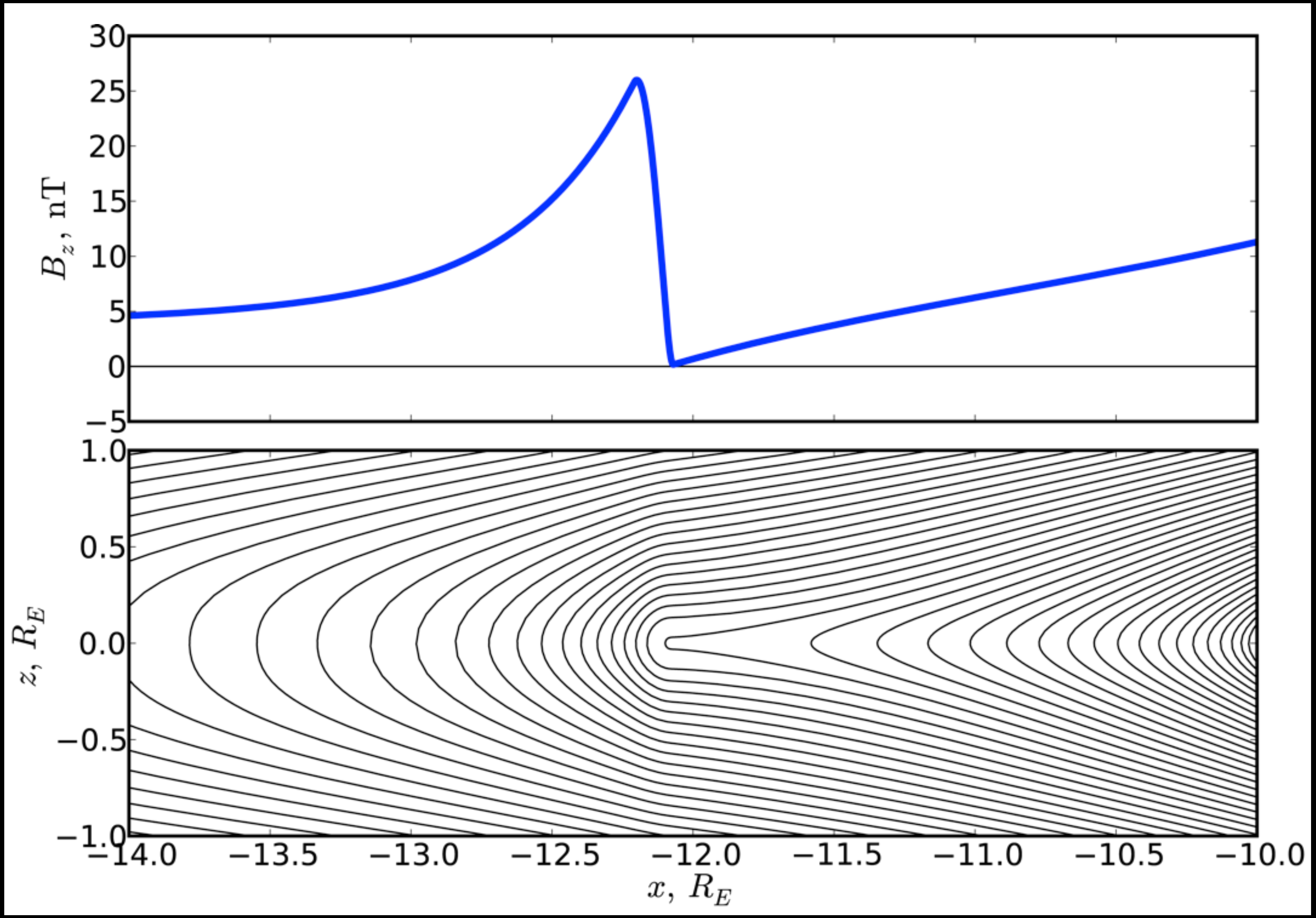
Initial Conditions: B0=3.35 nT; V_ξ=600 km/s; ξ=1 R_E



In idealized 2D case of a constant background magnetic field and a front unbounded in the y direction, particles are stably trapped ahead of the front and their acceleration is limited only by relativistic effects.

Total Magnetic Field

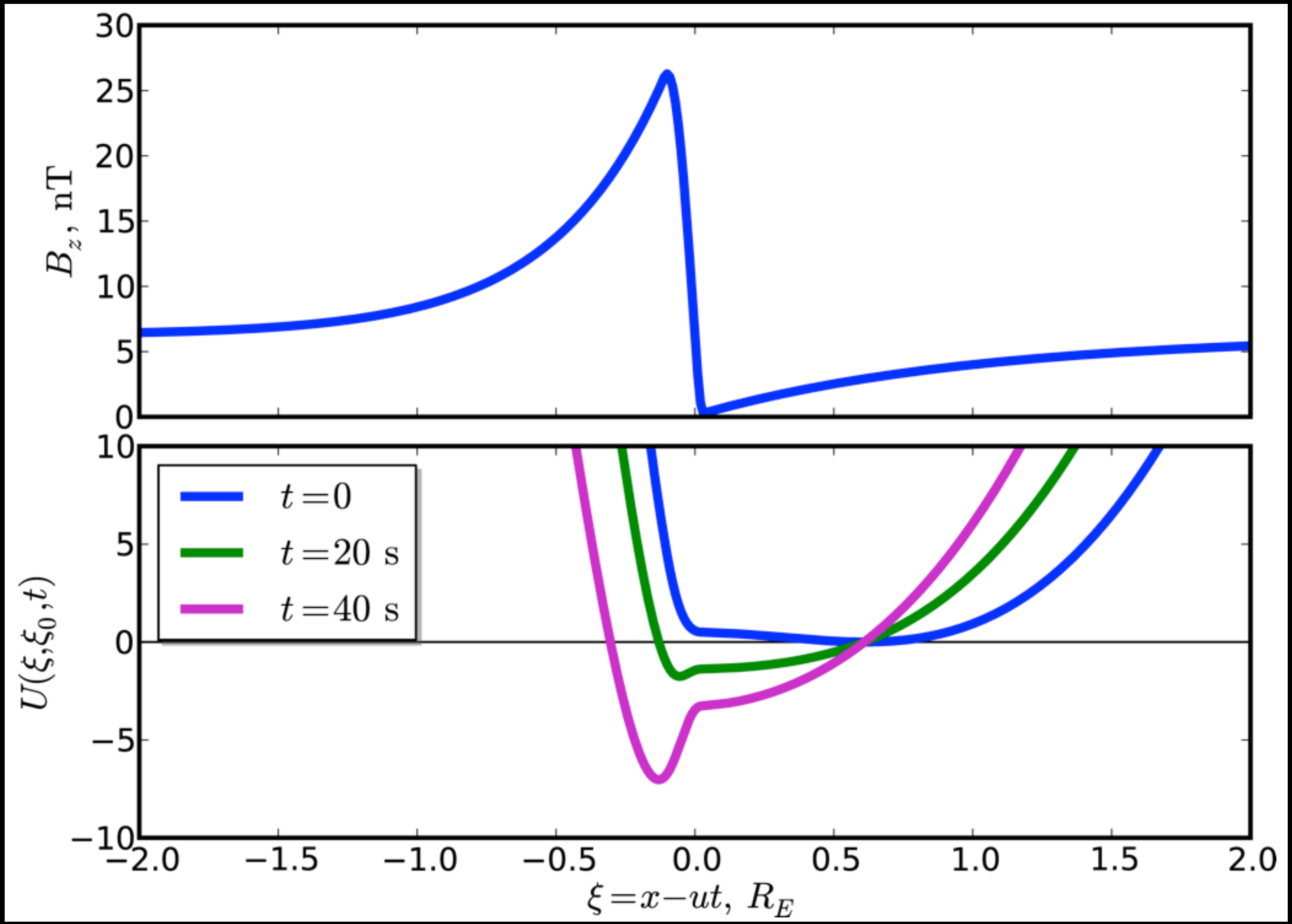
X=-12 R_E



Closer to Earth, where ambient B_z is stronger, field depletion ahead of the front causes weakening of the field without changing its sign.

Time-Dependent Effective Potential

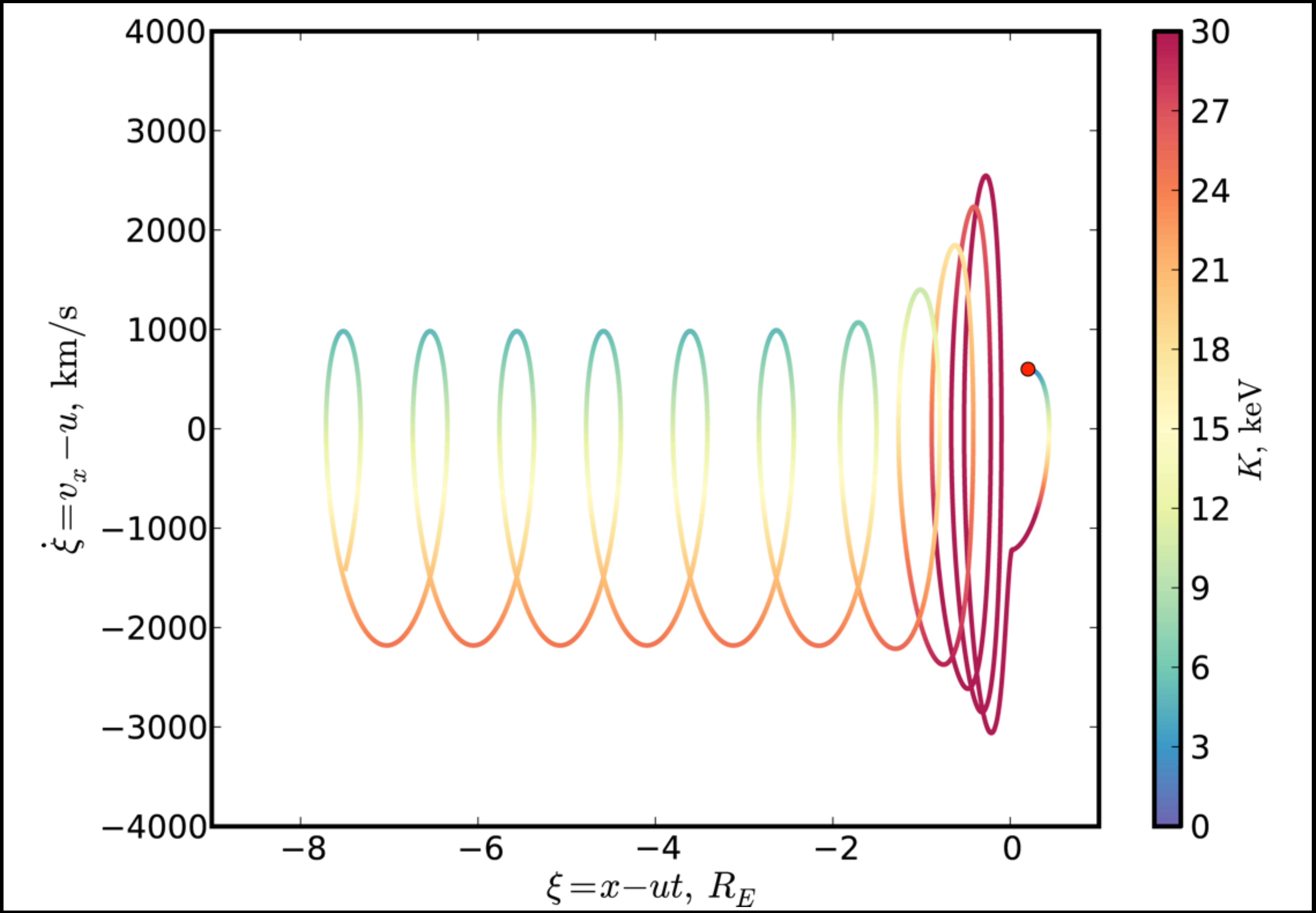
X=-12 R_E



Effective potential in this case does not have a local maximum ahead of the front. Consequently particles cannot be stably trapped. With each oscillation particle penetrate deeper and deeper behind the front, eventually falling behind and resuming gyromotion in the background magnetic field.

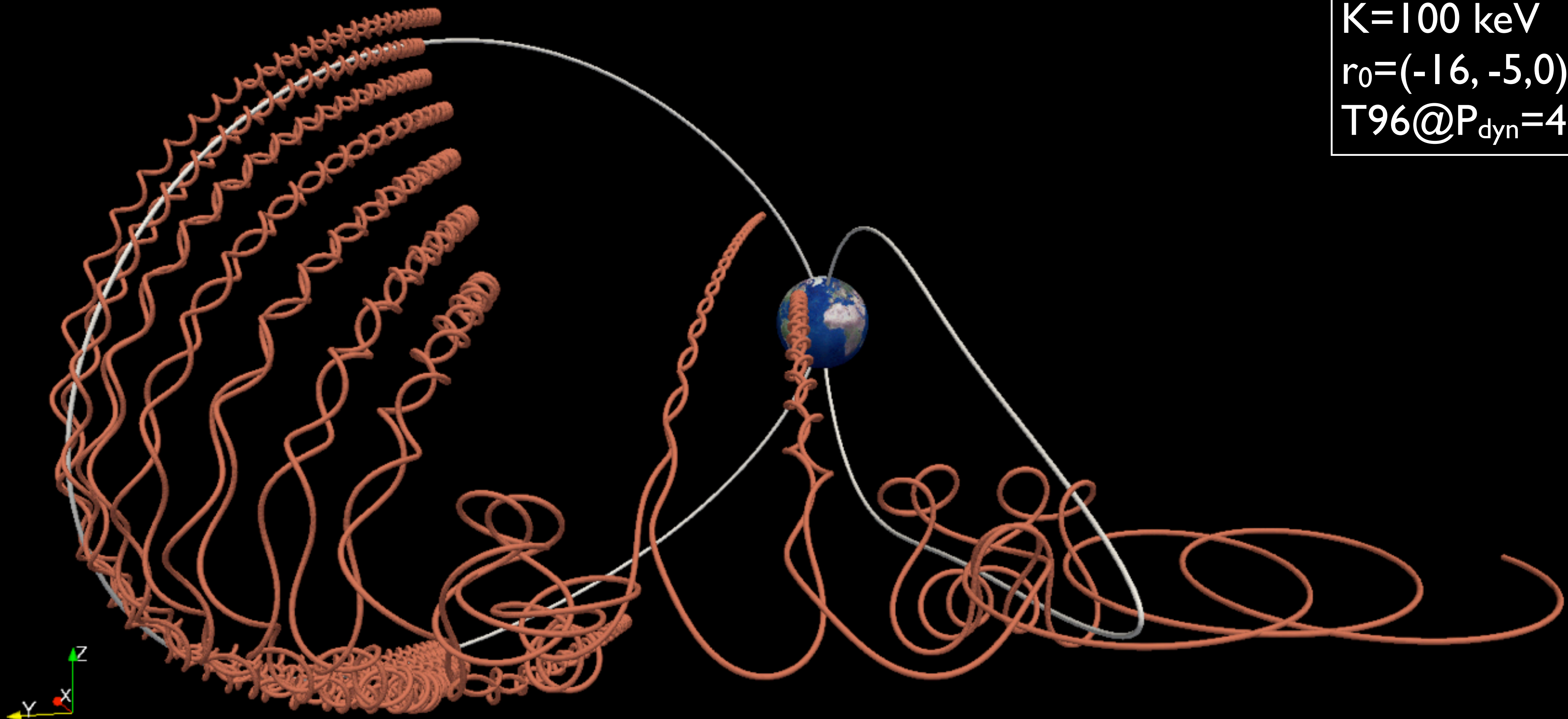
Acceleration in Idealized 2D Case

Initial Conditions: B0=6.28 nT; V_ξ=600 km/s; ξ=0.2 R_E



Particle energization in the -y direction is limited to the time while the particle is quasi-trapped by the front.

3D Numerical Simulations



K=100 keV
r_0=(-16, -5,0)
T96@P_{dyn}=4 nPa

In the magnetotail energetic (>1 keV) protons exhibit complex quasi-adiabatic motion. Initially equatorial particles get eventually scattered to lower pitch-angles due to coupling of the gyro- and the bounce motions. It is therefore necessary to understand how this complexity affects particle interaction with DFs.

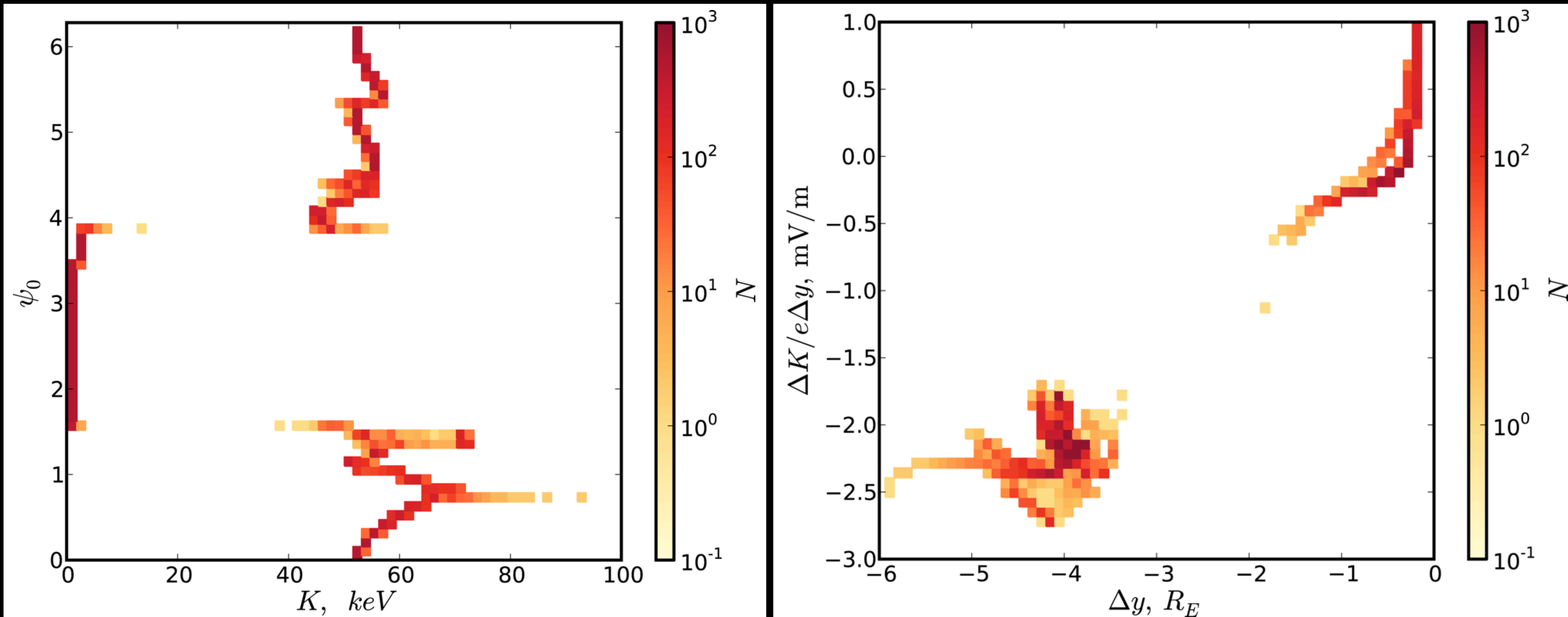
Simulation Setup

1) Two initial locations along the tail were selected: x_0=-16 R_E, where total B_z<0 ahead of the front, and x_0=-12 R_E, where B_z>0 ahead of the front

2) In each location ensembles of $3 \cdot 10^4$ particles were initiated at z_0=y_0=0 with the gyrophase evenly distributed between 0 and 2π, with the equatorial pitch angle of 90°, and with kinetic energy of 2 keV

3) In the first case the front was launched at x_{DF}=-16.61 R_E, such that x_0=-16 R_E is the stable fixed point (B_z=0) ahead of the front, in the second simulation the front was launched at x_{DF}=-12.1 R_E.

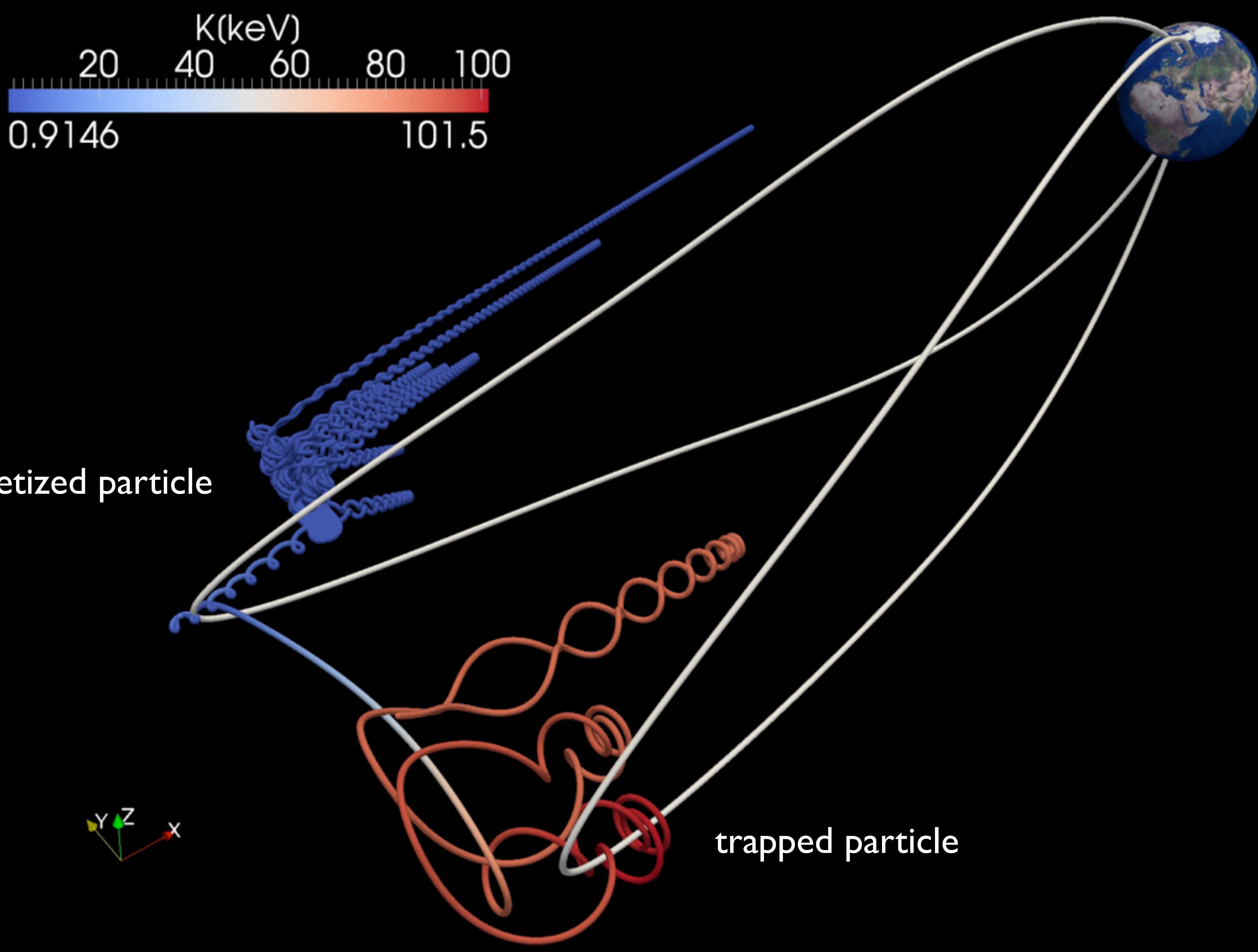
Case 1: x_0=-16 R_E



There are two groups of particles - (1) particles with gyrophase ψ_0 centered around π (i.e. initially move in the direction opposite of the front). These particles get magnetized behind the front and drift earthward due to ExB lagging behind due to the difference in u and $uB_1/(B_0+B_1)$ until E drops to 0, at which point they resume quasi-periodic motion. These particles exhibit only weak acceleration;

(2) 63 % of particles exhibit substantial acceleration (by >40 keV) associated with trapping. Particle acceleration is well ordered by their negative Δy displacement. The effective E-field accelerating particles in the -y direction, $\langle \Delta K/q\Delta y \rangle$=2.10 mV/m, well agrees with the field in the reference frame moving with the front, $-uB_0$=-2.01 mV/m, due to Lorentz transformation of the background B-field.

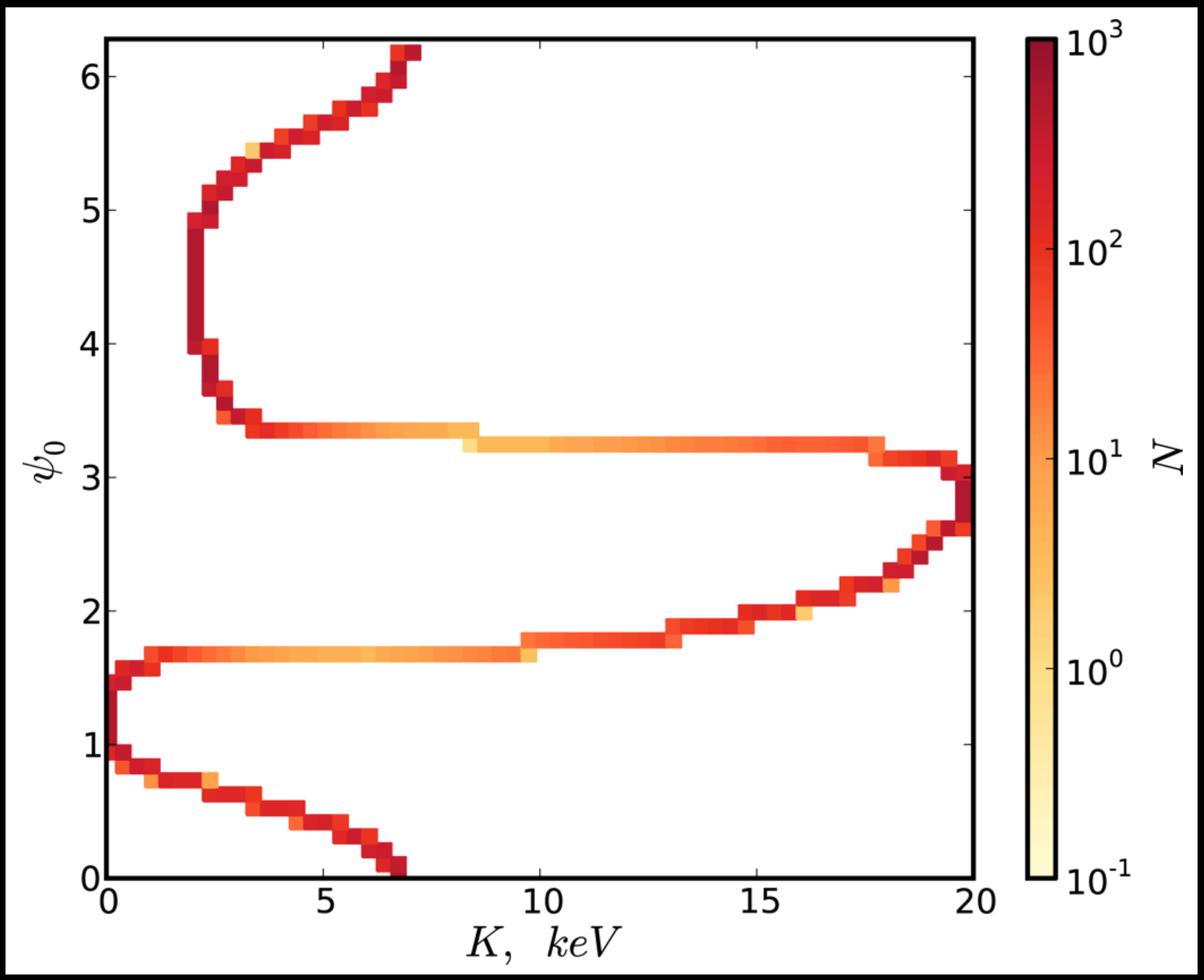
Examples of Particle Trajectories

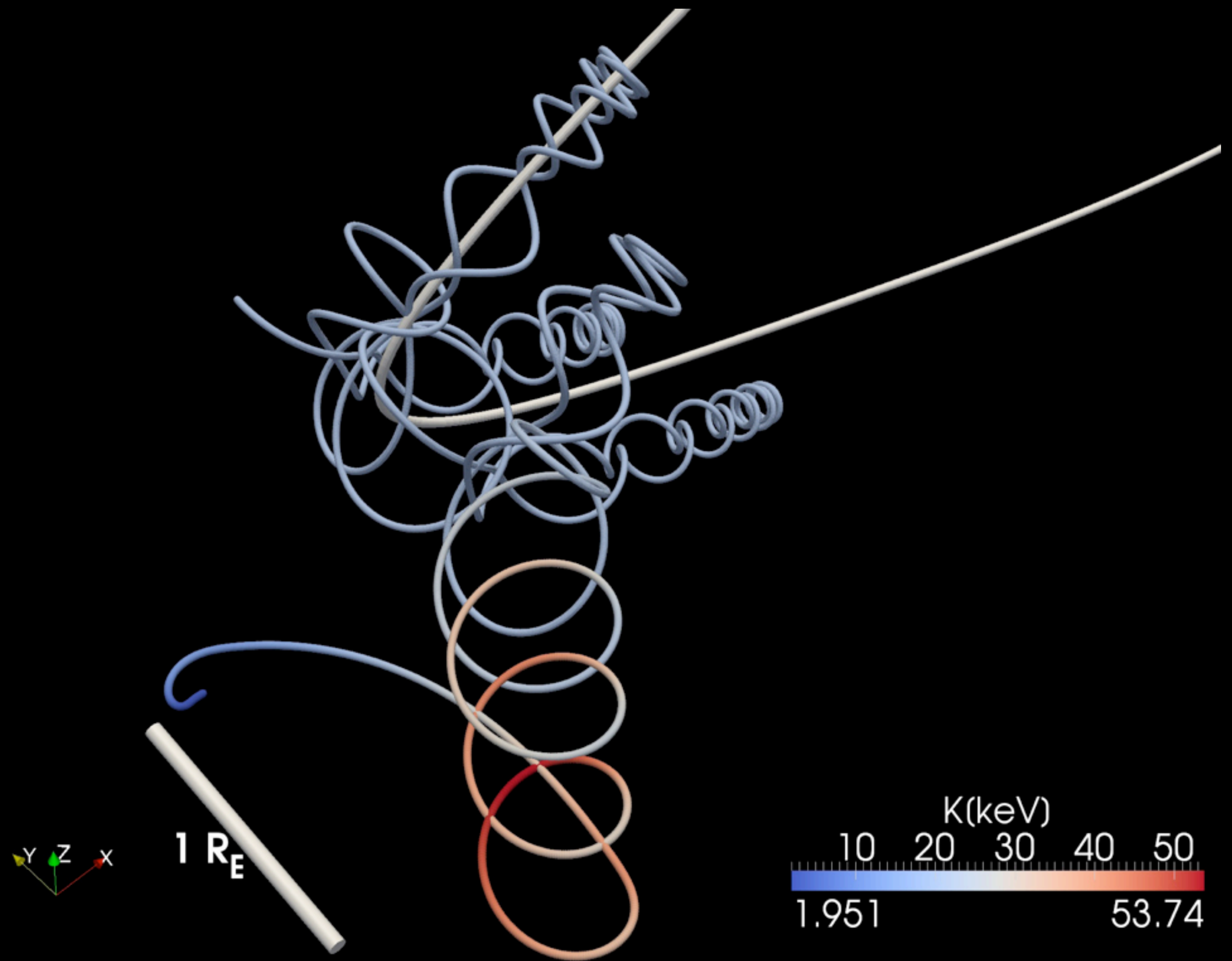


magnetized particle

trapped particle

Case II: x_0=-12 R_E





As expected from 2D simplified considerations particle acceleration is not as strong in the absence of negative B_z ahead of the front, when stable trapping is no longer possible. Nonetheless, quasi-trapped particles can still be accelerated to up to 20 keV (by order of magnitude).

Conclusions

Protons in the magnetotail can be rapidly accelerated by up to ~100 keV due to interaction with earthward propagating dipolarization fronts.

The level of particle energization depends on how long the particle can stay in phase with the front moving earthward in the equatorial plane and being accelerated by the negative E_y due to the Lorentz transformation of the background magnetic field.

The energization is more efficient in the tail regions where the magnetic field does not vary rapidly in the x direction and is weaker than the negative depletion of B_z ahead of the front, such that there is a region of zero magnetic field moving earthward with the front. Particles in this case can be stably trapped by the front. The level of acceleration is limited by the width of the front and the curvature of the background B-field. The higher is the curvature, the faster particles get scattered out of the equatorial plane

Closer to Earth where the background magnetic field is high enough to prevent reconnection due to the negative field depletion ahead of the front, particles can be quasi-trapped. For the chosen field parameters quasi-trapping can lead to particle acceleration to ~20 keV.