Nonadiabatic Ion Acceleration at Injection Fronts

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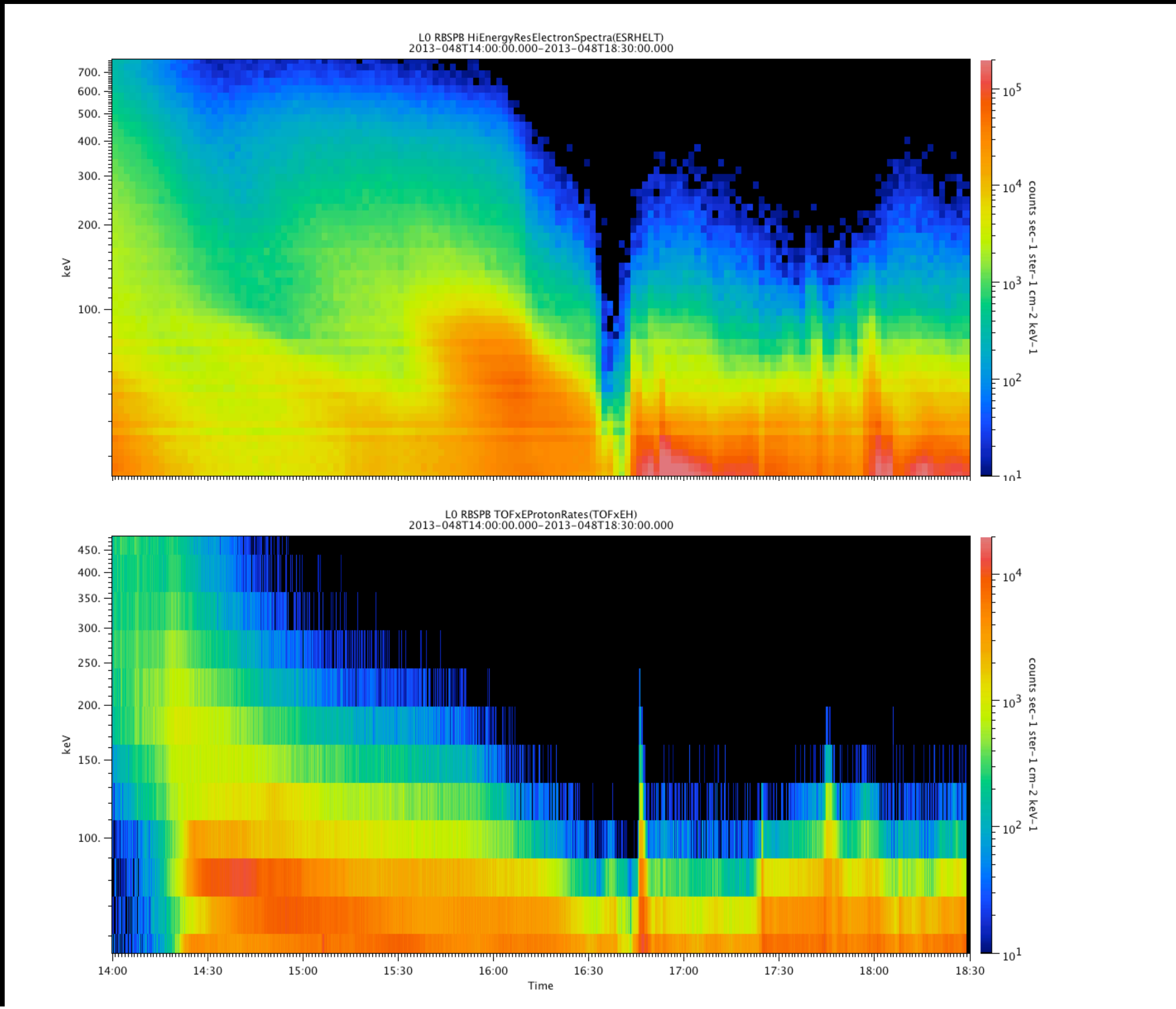
RBSPICE-B
Feb 17, 2013



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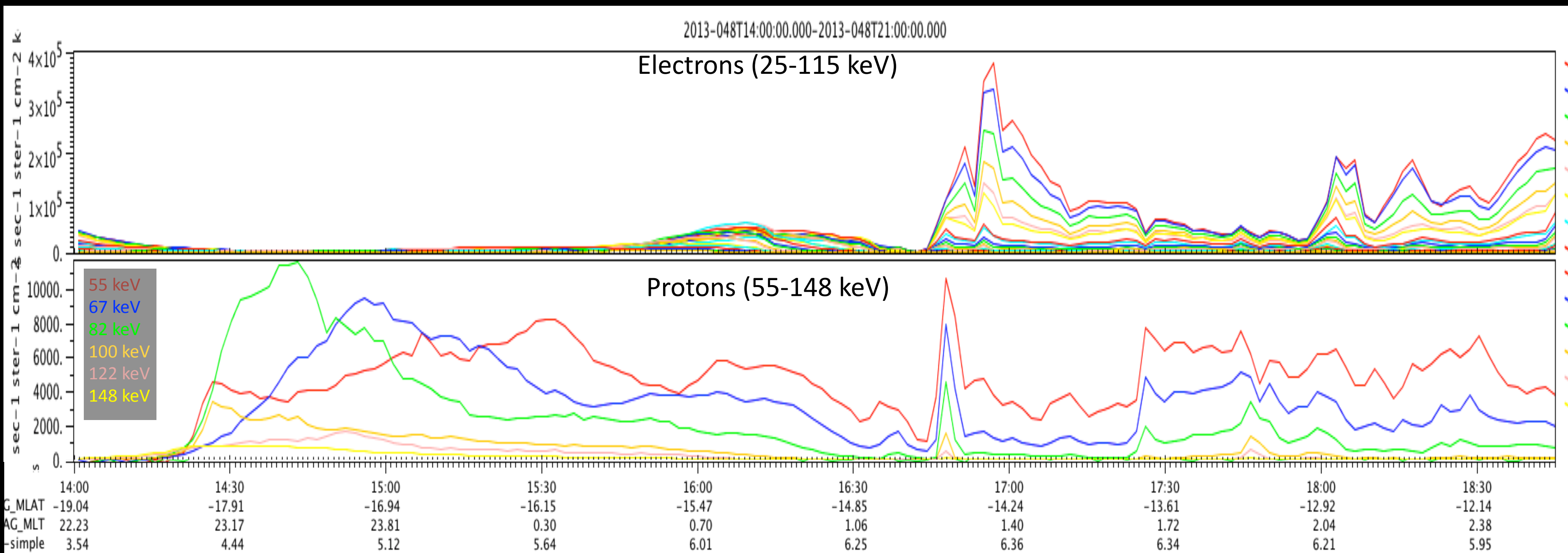
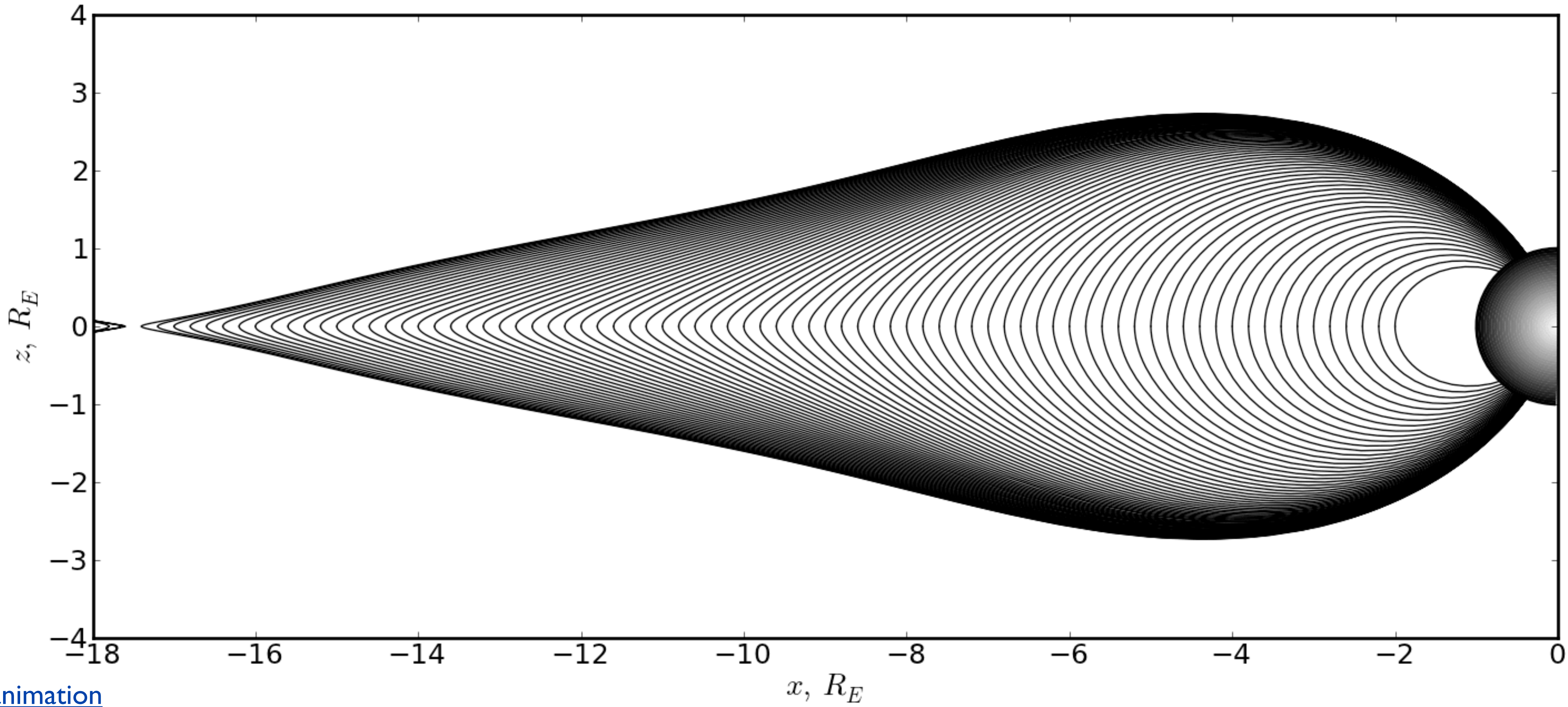


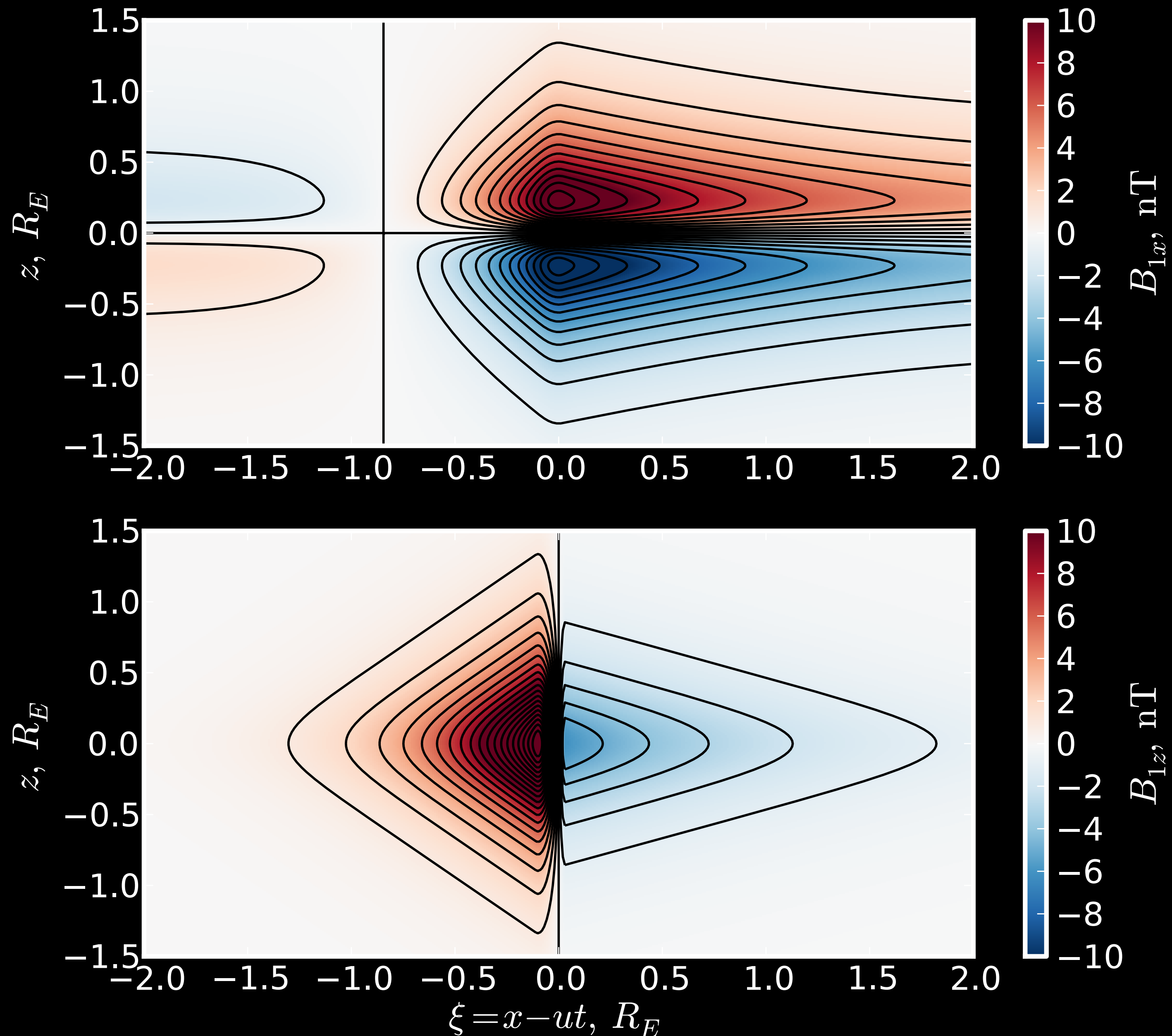
Modeled Propagation of DF



animation

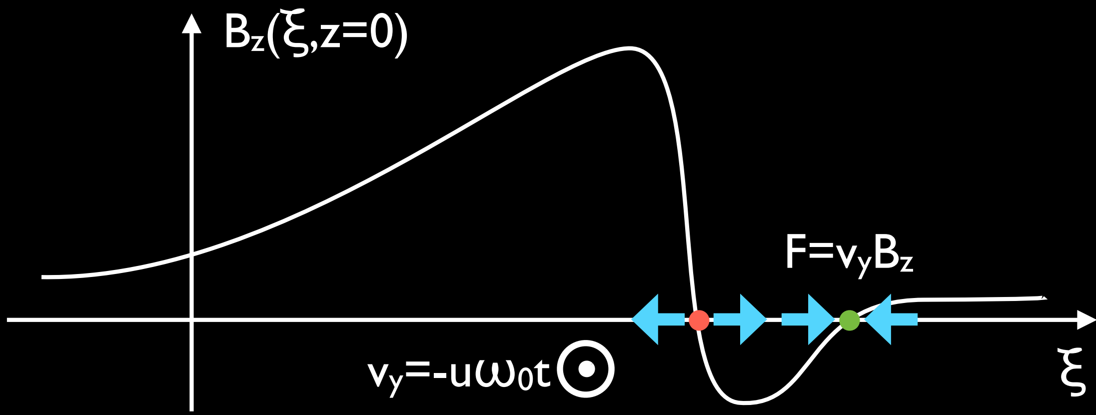
A self-similar DF $\mathbf{B}_1(x\text{-}ut,z)$ propagating from the tail towards Earth, is superimposed on the ambient magnetic field $\mathbf{B}_0(x,y,z)$, slowly varying in the x direction.

Analytical Model of DFs



Equatorial Proton Motion

$$e = m = c = 1$$



$$B_z(x,t) = B_0 + B_1(x - ut)$$

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

$$\begin{cases} \ddot{\xi} = (B_0 + B_1(\xi))v_y \\ \dot{v}_y = -uB_0 - (B_0 + B_1(\xi))\dot{\xi} \end{cases}$$

Motion along y: 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 (dξ/dt≈0), it gets linearly accelerated in the -y direction in the E-field $-uB_0$ due to the Lorentz transformation of the background B-field.

$$v_y = -uB_0 t$$

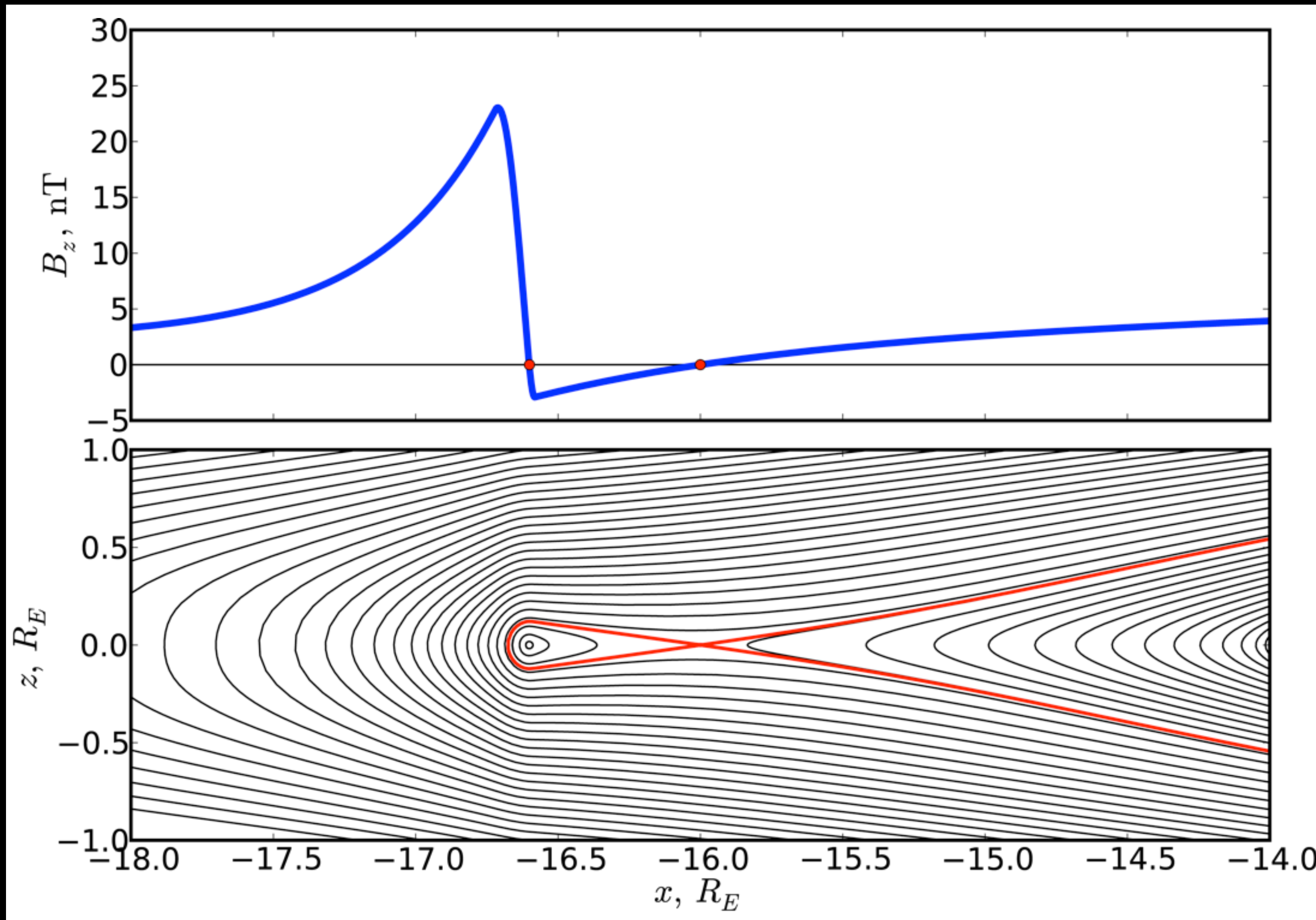
Motion along ξ: Can be described in terms of a 1D Hamiltonian: H=K+U

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

$$U_M(\xi, \xi_0, t) = uB_0 t[B_0(\xi - \xi_0) + A_1(\xi) - A_1(\xi_0)]$$

Total Magnetic Field

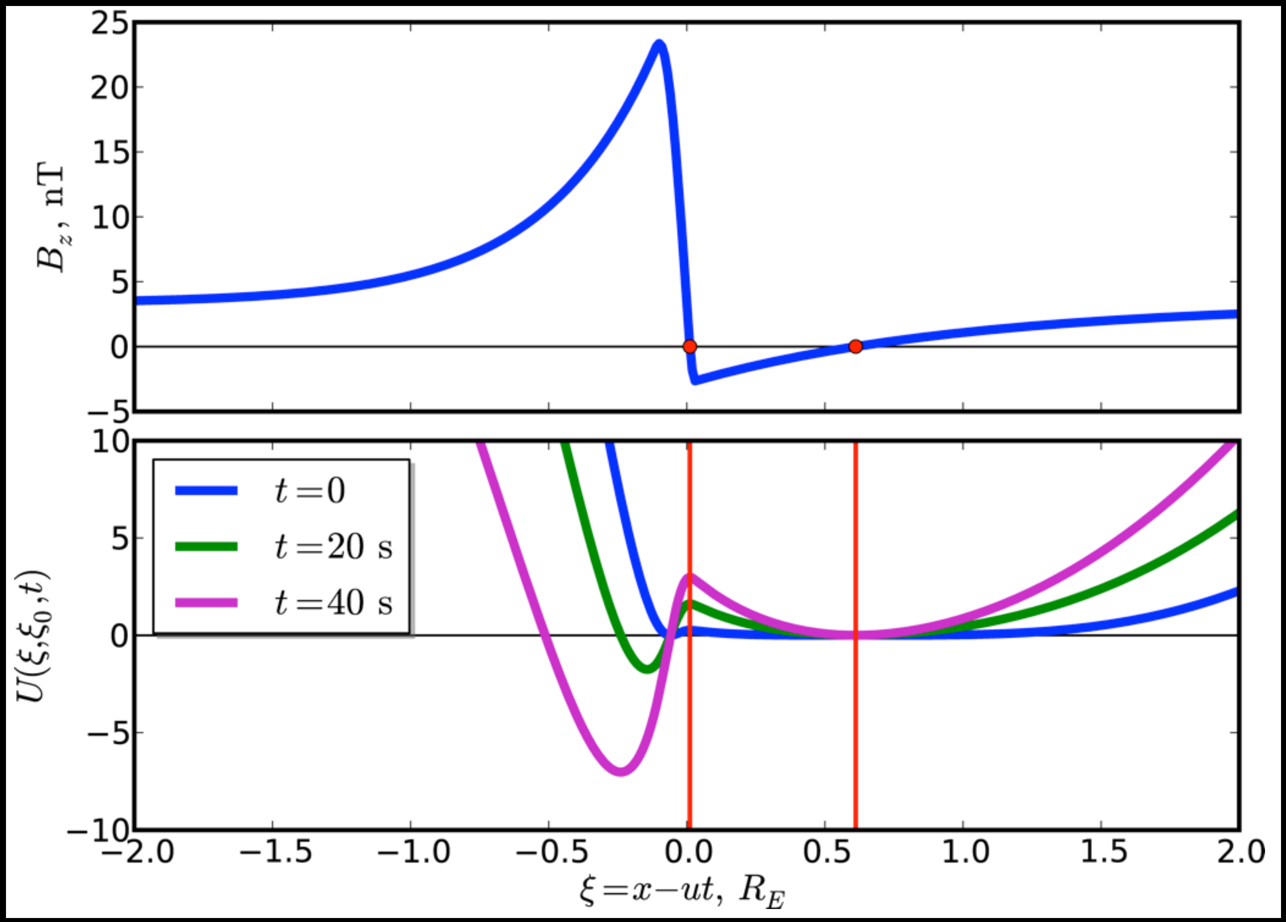
X=-16 R_E



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

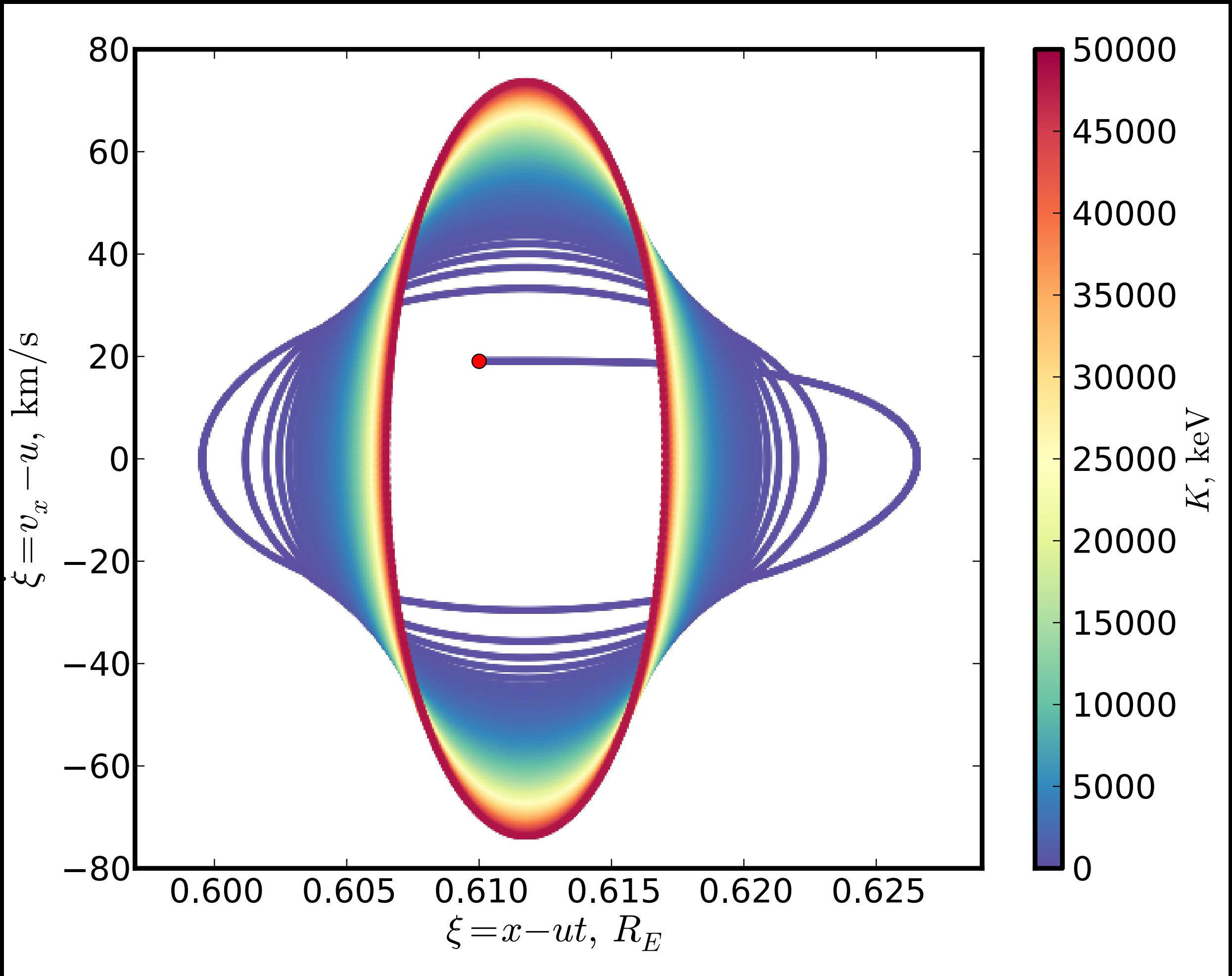
X=-16 R_E



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

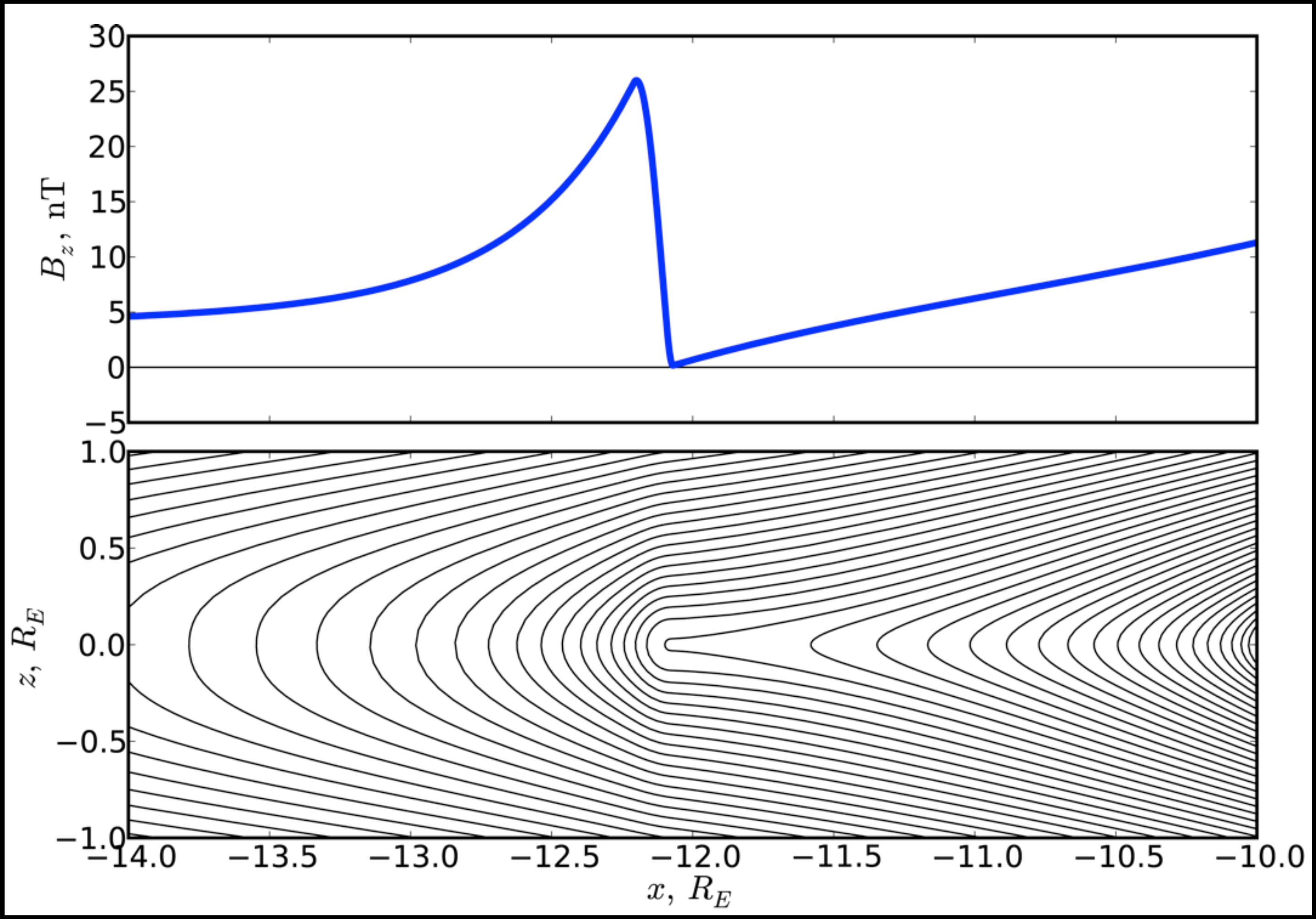
Initial Conditions: B_0=3.35 nT; V_ξ=600 km/s; ξ=0.61 R_E



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

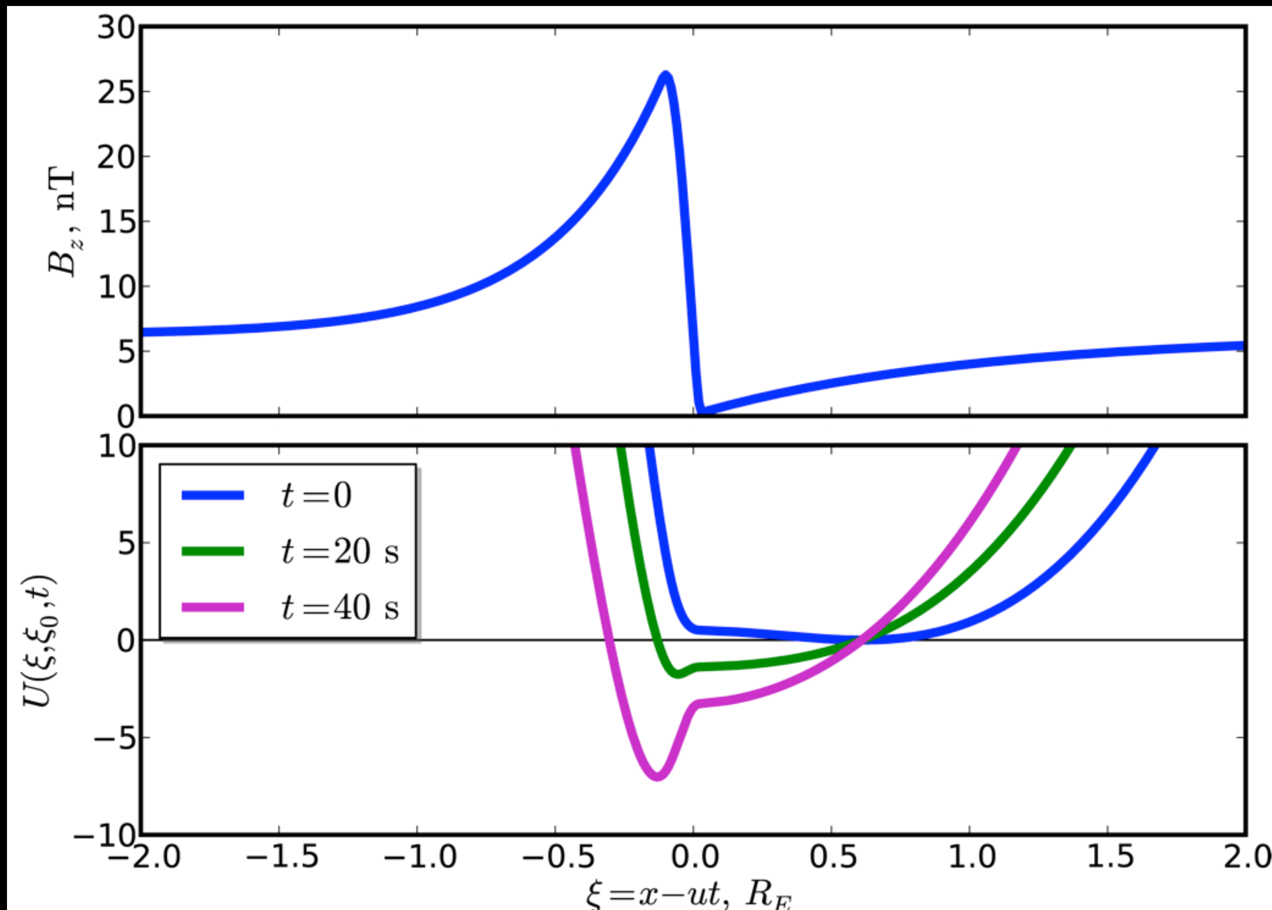
X=-12 R_E



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

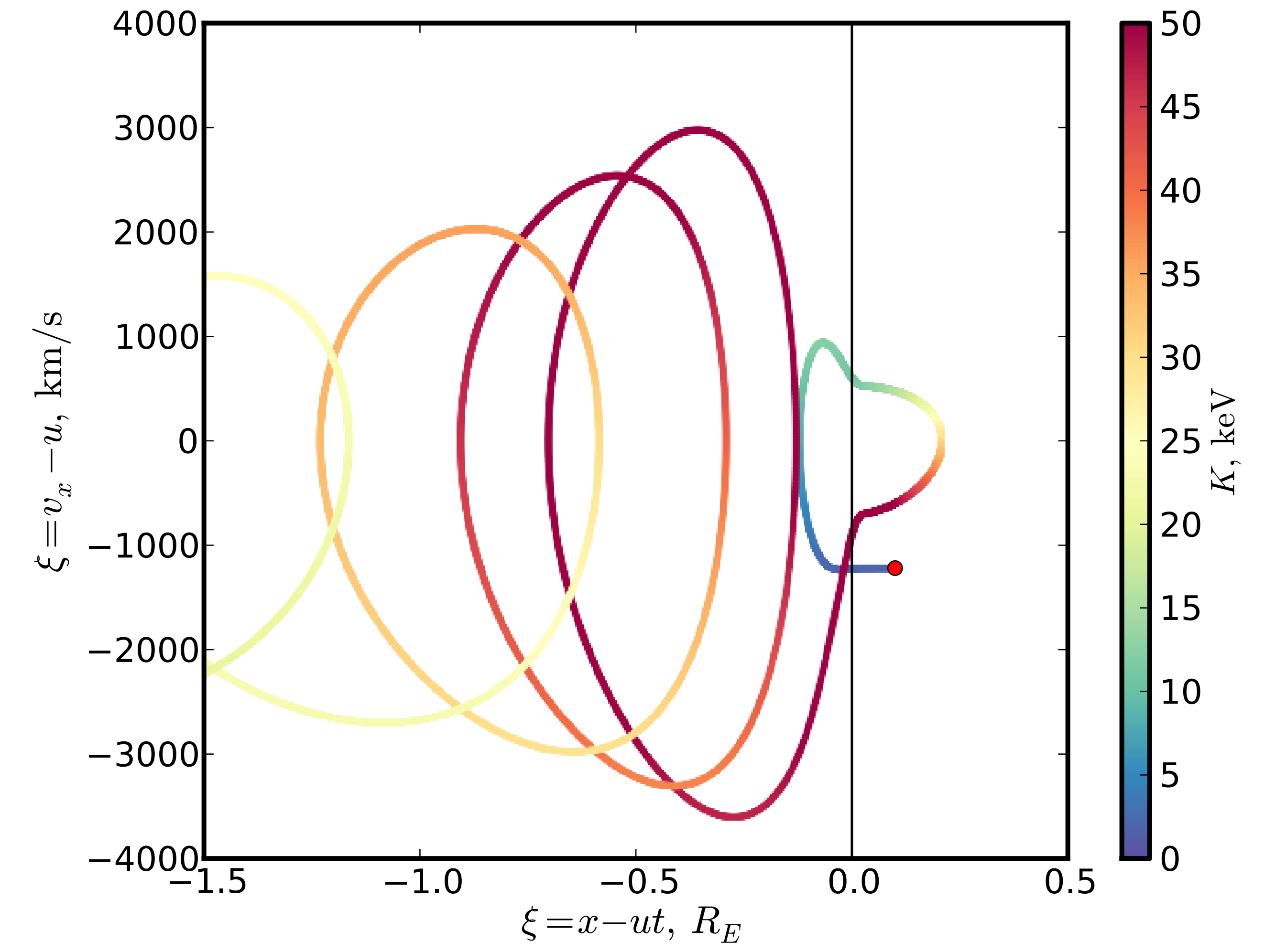
X=-12 R_E



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.

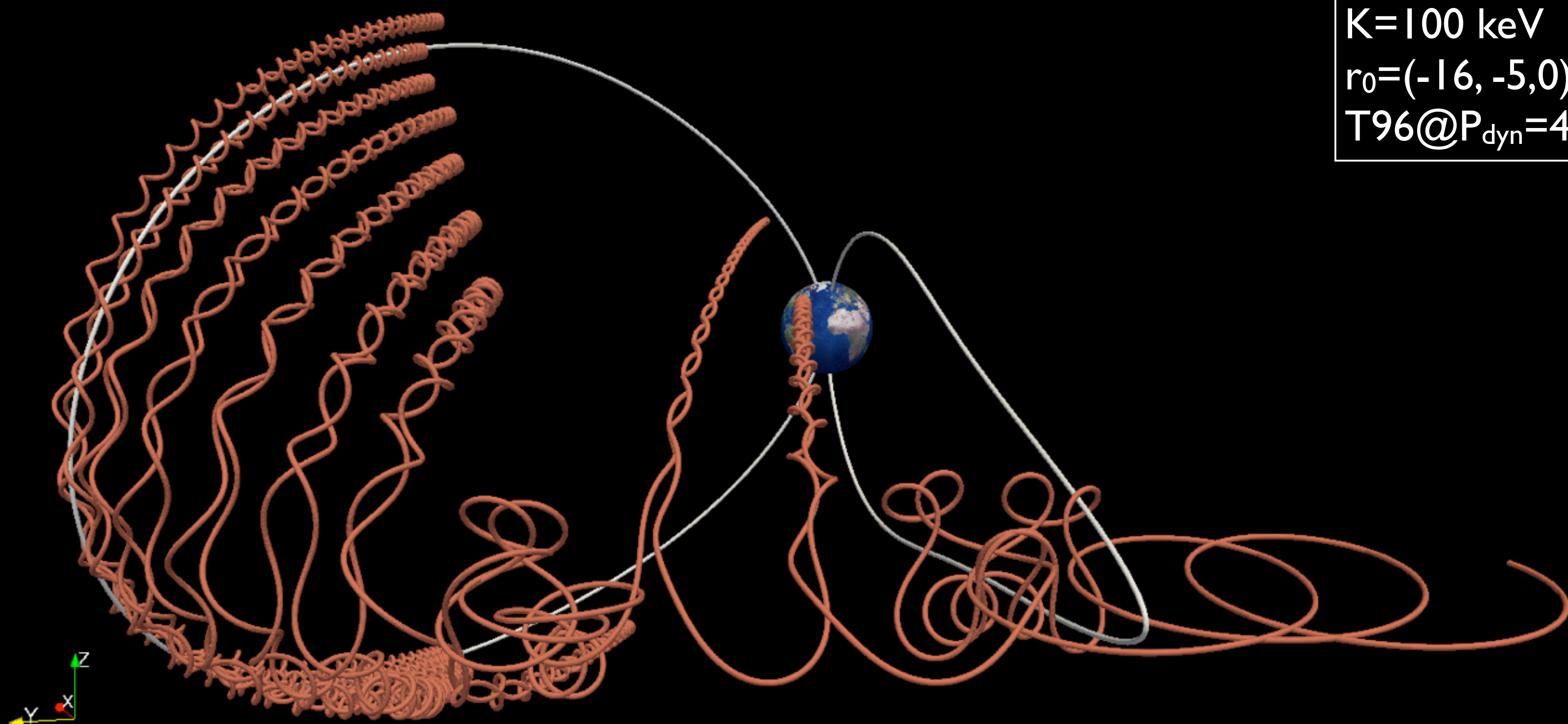
Acceleration in Idealized 2D Case

Initial Conditions: B_0=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.

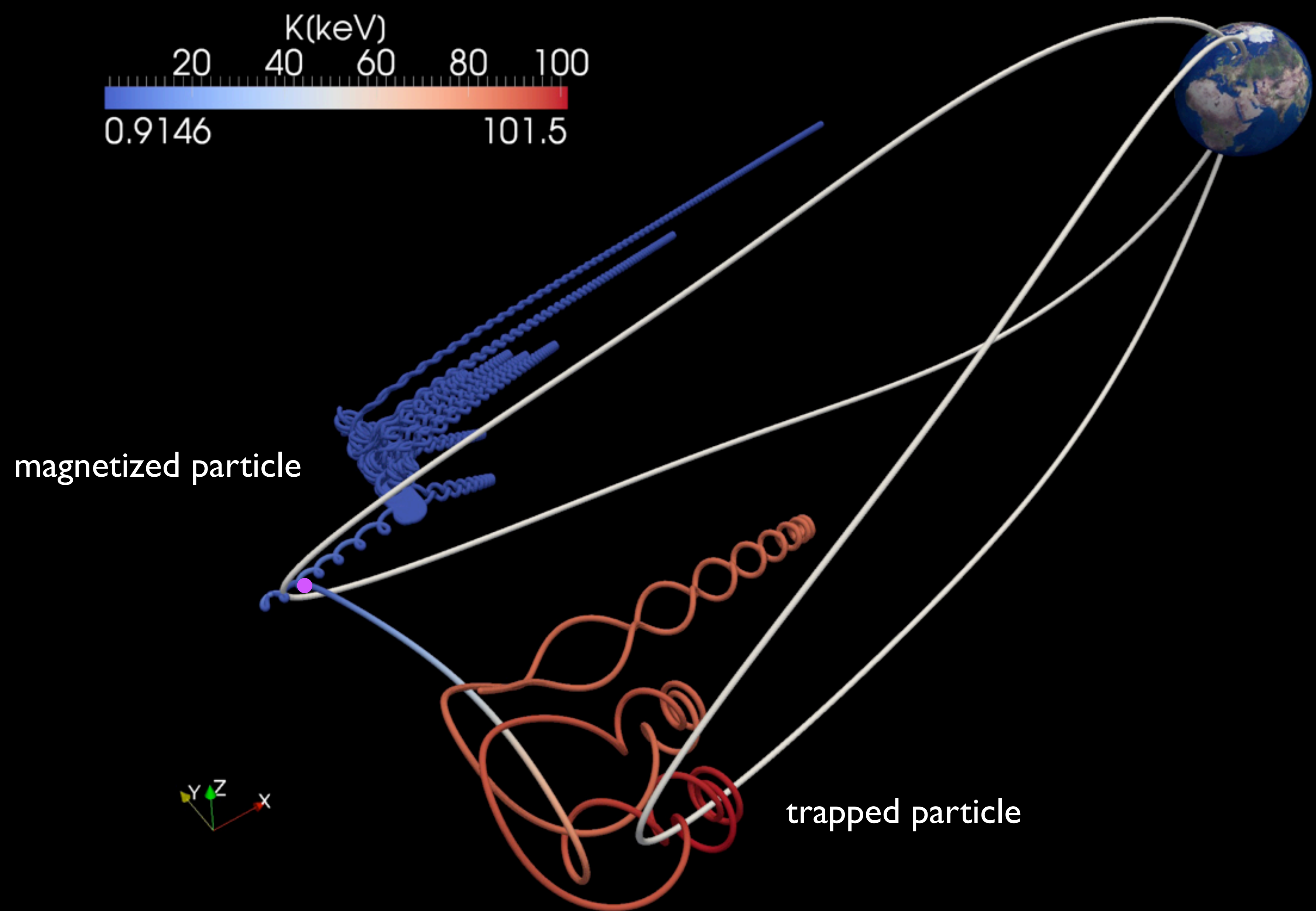
3D Numerical Simulations



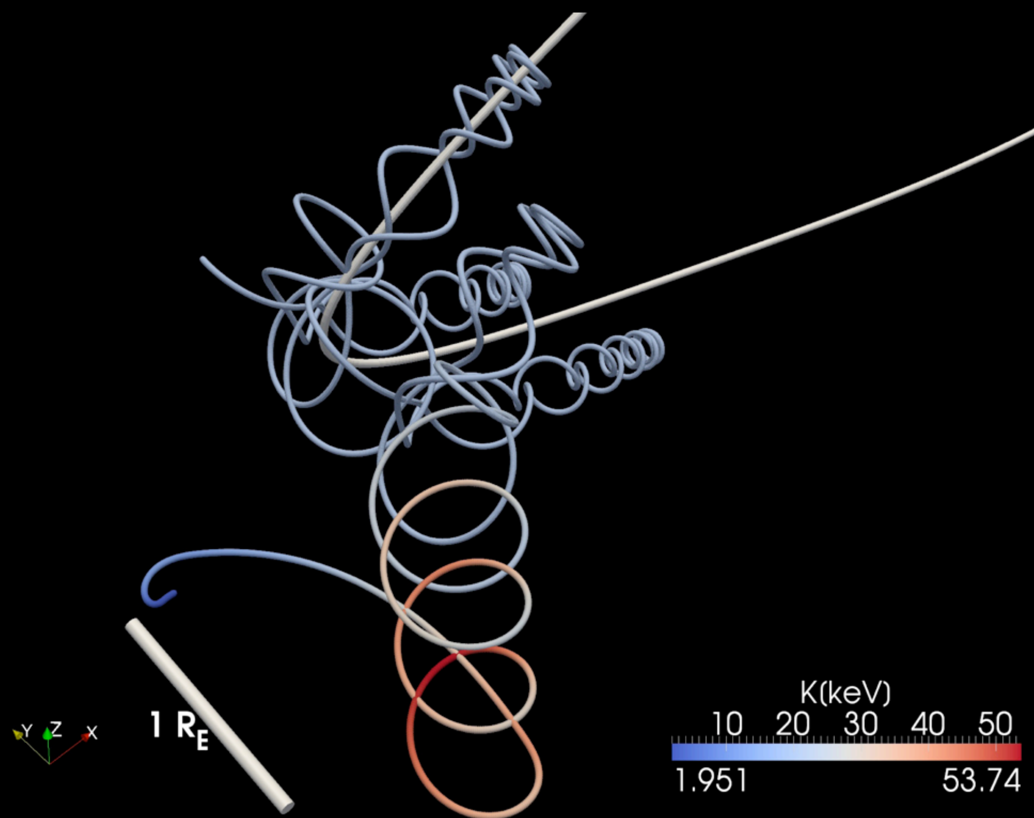
K=100 keV
r_0=(-16, -5,0)
T96@P_{dyn}=4 nPa

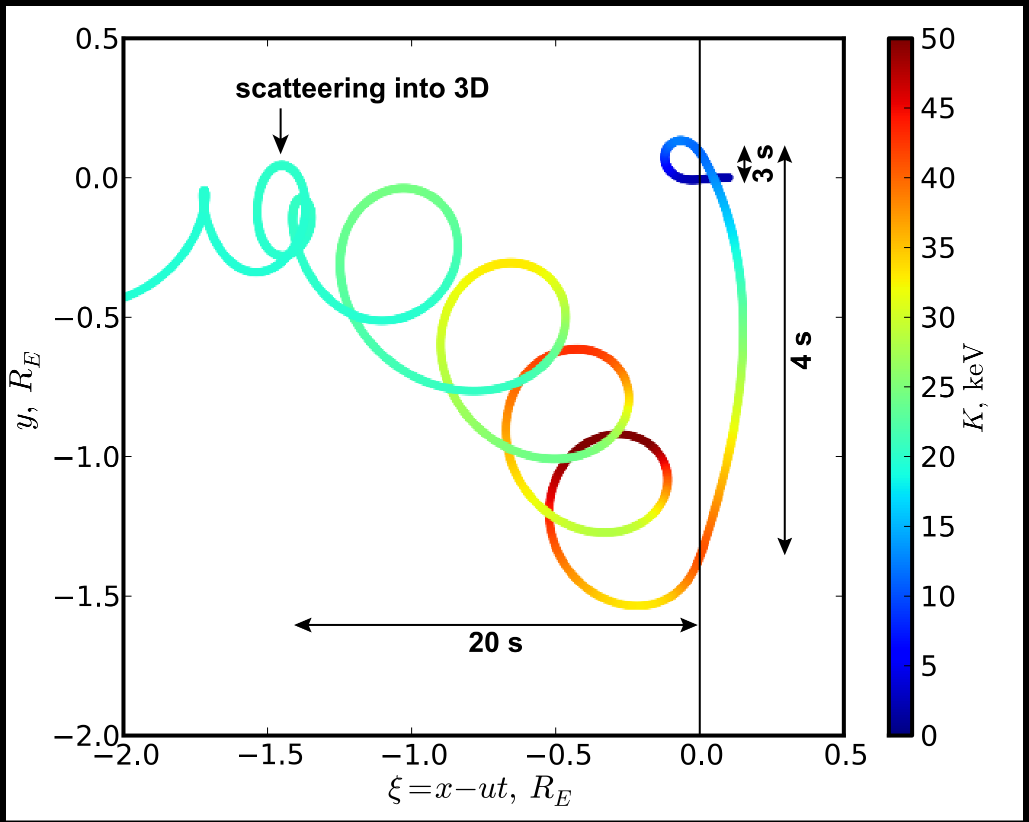
In the magnetotail energetic (>1 keV) protons exhibit complex quasi-adiabatic motion. Initially equatorial particles get eventually scattered to lower pitch-angles due to coupling of the gyro- and the bounce motions. It is therefore necessary to understand how this complexity affects particle interaction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

Case I: x_0=-16 R_E



Case II: x_0=-12 R_E



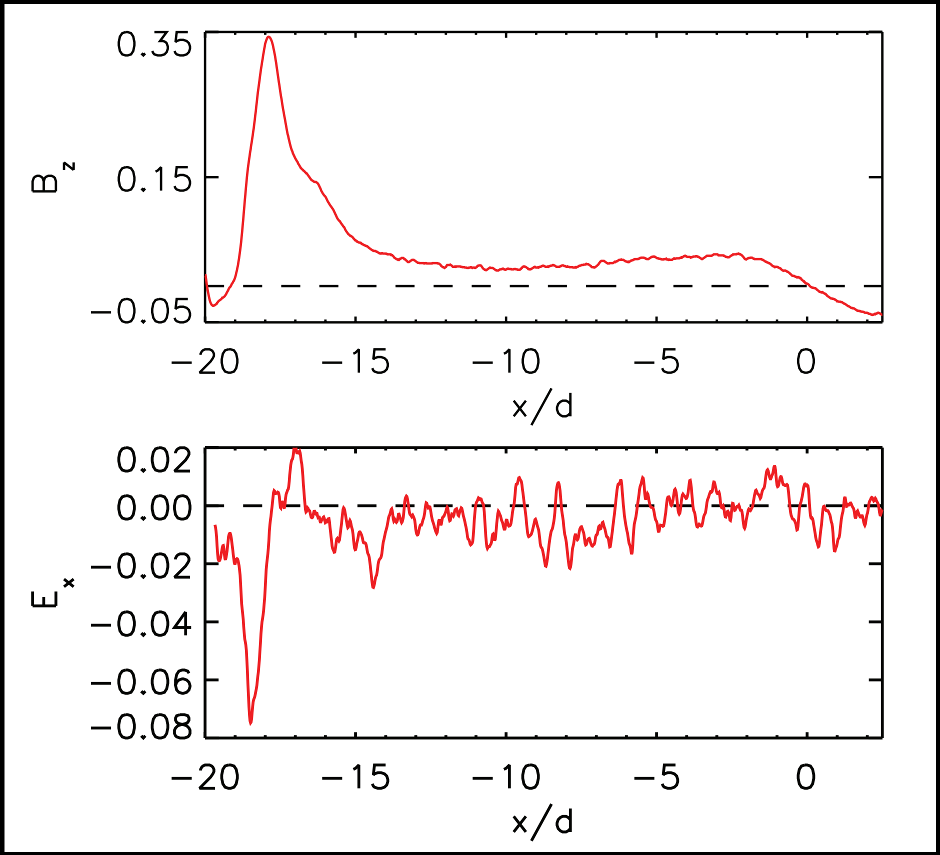


As expected from 2D simplified considerations particle acceleration is not as strong in the absence of negative B_z ahead of the front, when stable trapping is no longer possible. Nonetheless, quasi-trapped particles can still be accelerated to up to 20 keV (by order of magnitude).

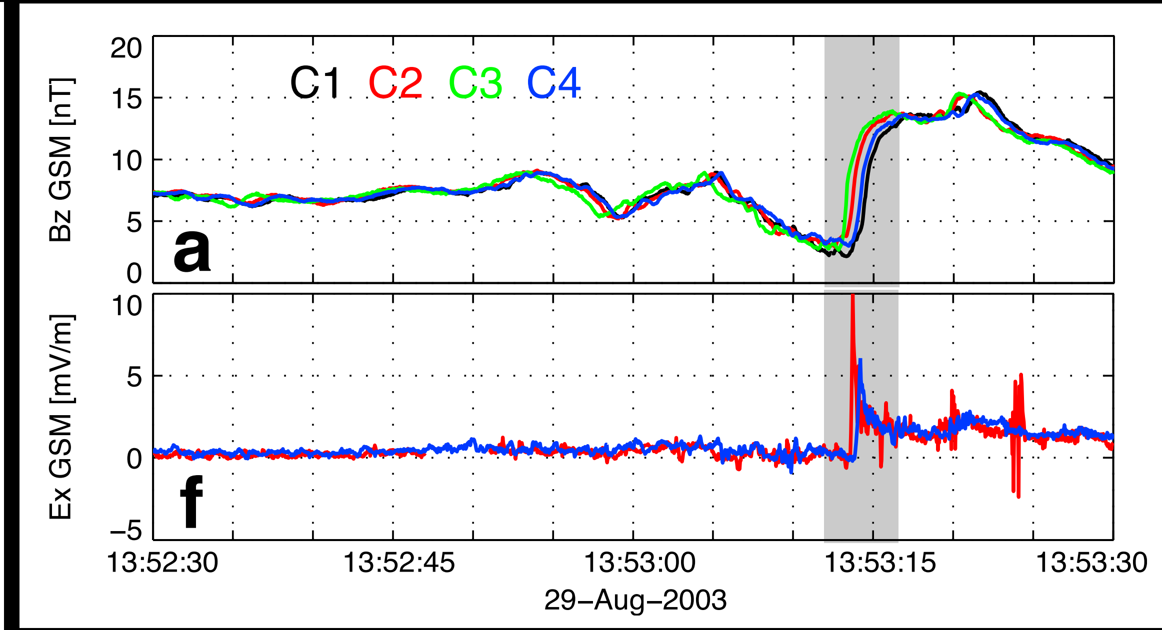
Can Protons be Stably Trapped without a Negative B_z?

Kinetic Structure of DFs

<u>PIC Simulations of Reconnection Onset</u>



<u>Cluster Observations of DFs</u>

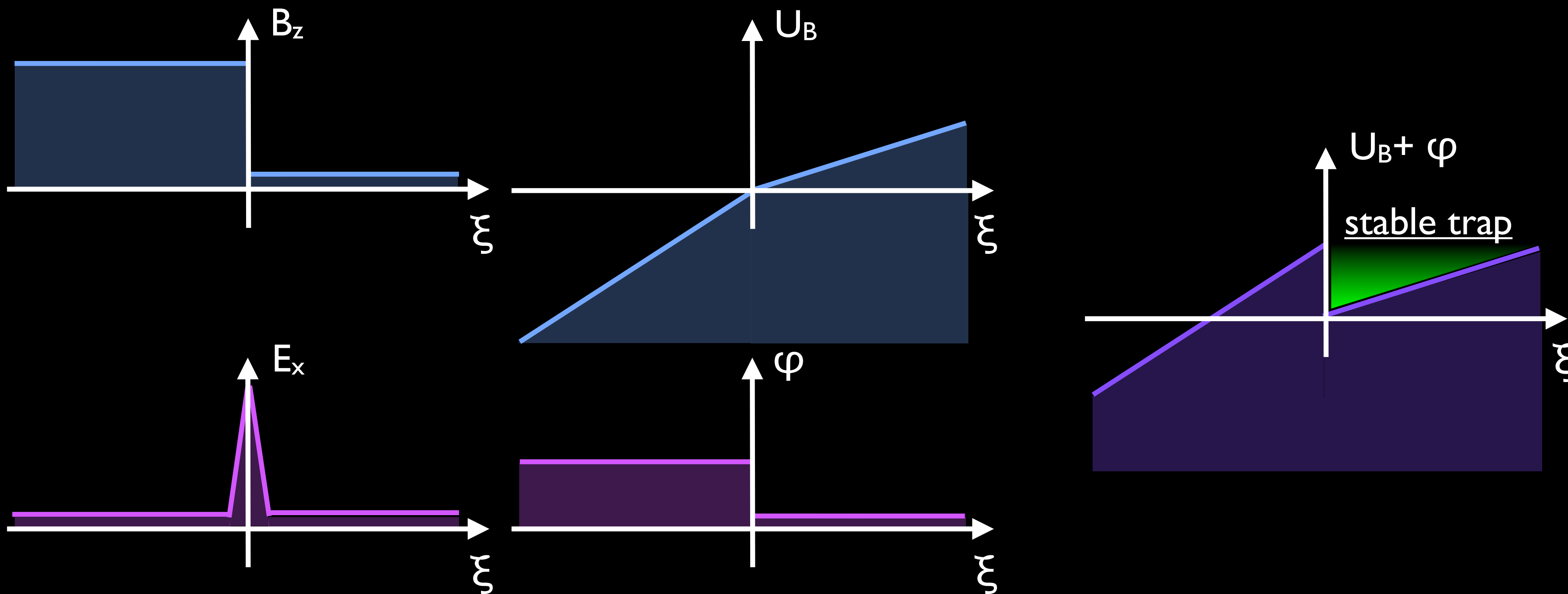


[Fu et al., 2012]

Kinetic simulations supported by in situ spacecraft measurements show that the difference in electron and proton motion in DFs produces large electrostatic fields in the direction of front propagation.

Stable Trapping due to E_x

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

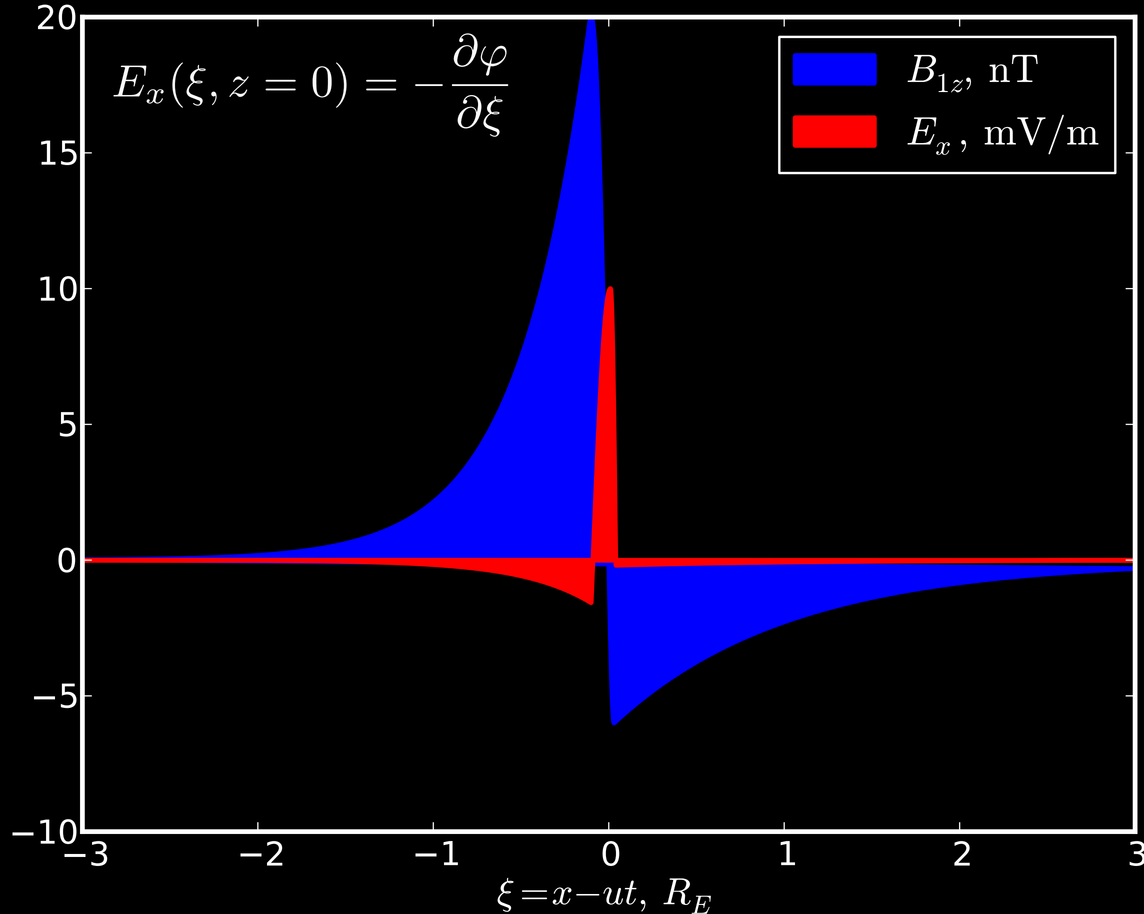


Trapping Limit: $\frac{e}{c} v_y B_z \geq e E_x$

Maximum Energy: $K[\mathrm{keV}] = \frac{m v_y^2}{2} \simeq 5 \left(\frac{E_x[\mathrm{mV/m}]}{B_z[\mathrm{nT}]} \right)^2$ >100 keV

Electrostatic Field Across DF

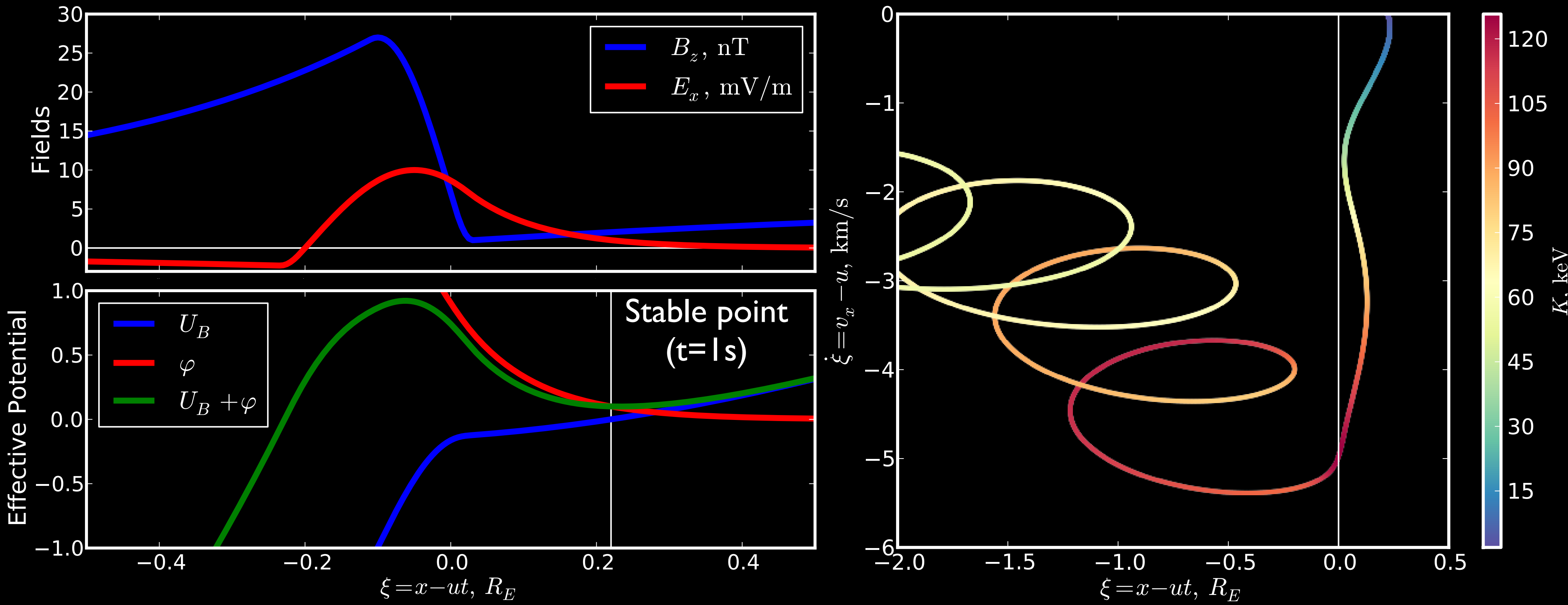
in the equatorial plane



Electrostatic field across the front is produced by the separation of electron and ion motion

2D Analysis of Stable Trapping

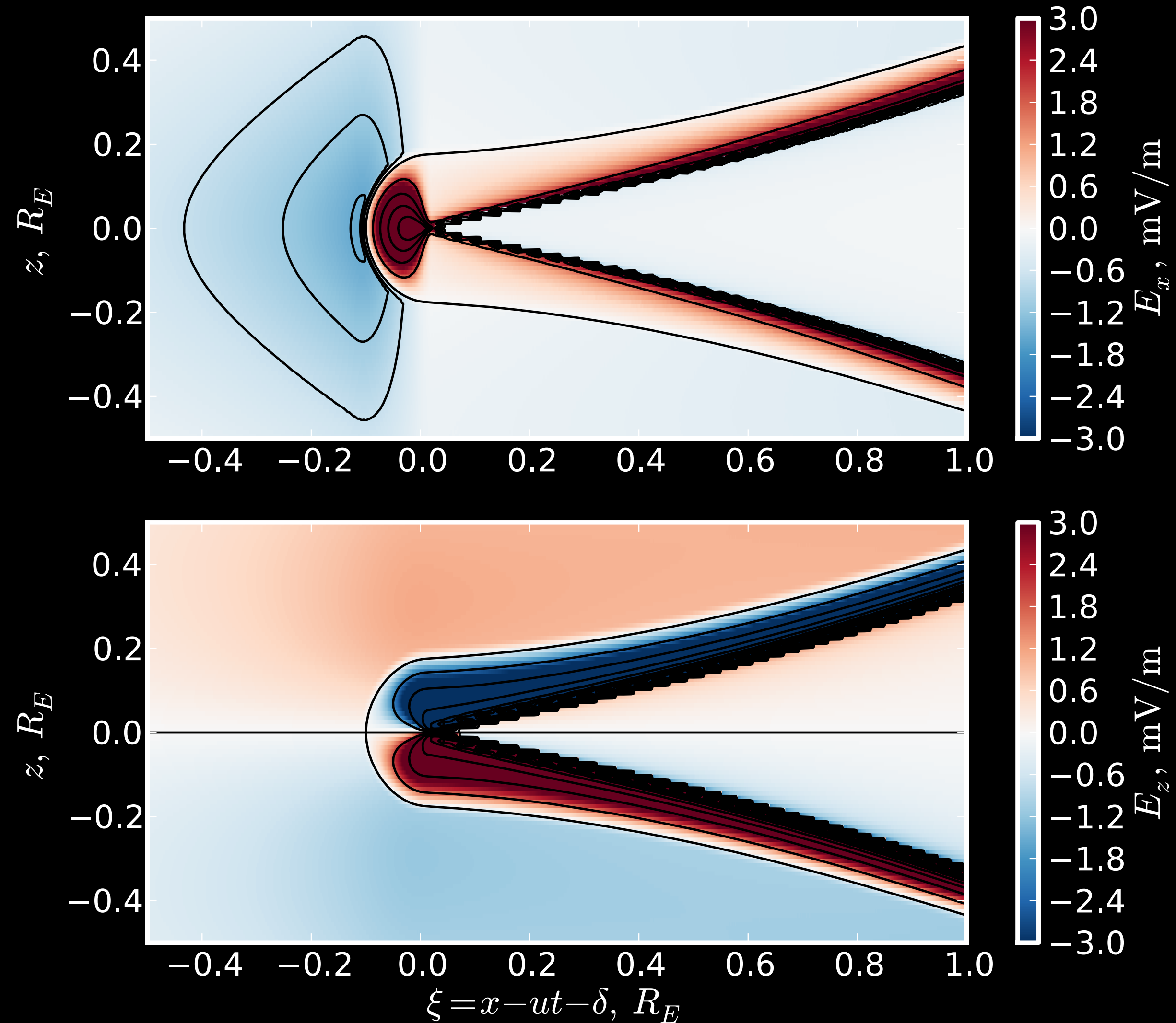
E_x=10 mV/m



In 2D with homogeneous ambient magnetic field particles launched from the vicinity of stable point of the effective potential U stay trapped ahead of the front for >10 s and are accelerated by >120 keV.

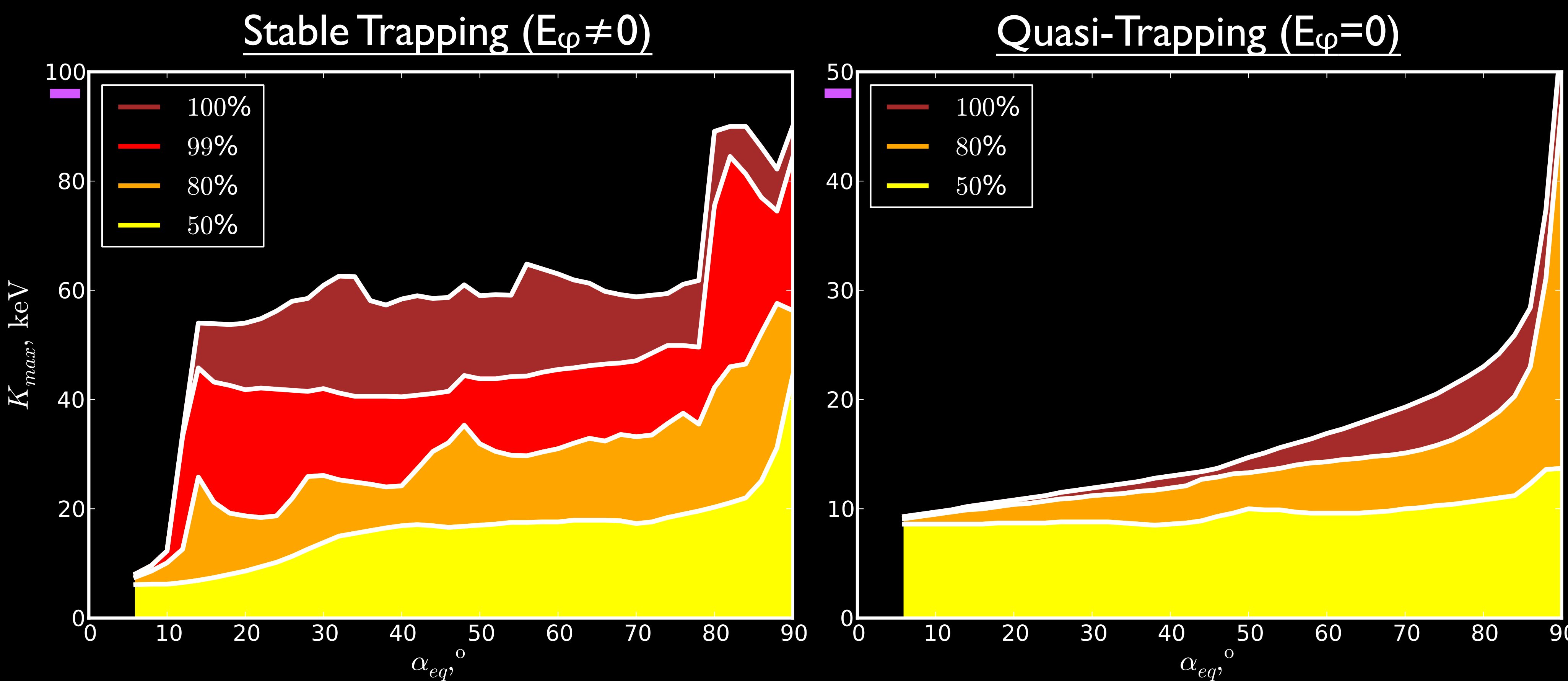
3D Electrostatic Field

separation of electron and ion motion across the front



$$E_{\parallel} = 0:\ \varphi(s) = \varphi(0) - \frac{u}{c}\int_0^s \hat{b}_y(s')B_{1z}(s')ds'$$

3D Analysis of Ion Acceleration at DFs



In the absence of E-field across the front, quasi-trapping is efficient only at near perpendicular equatorial pitch angles.

Electrostatic E-field enables stable trapping over the entire pitch-angel distribution up to the atmospheric loss cone. At chosen simulation parameters, protons at large (>75°) pitch-angles are accelerated up to 95 keV, and up to 60 keV at smaller pitch angle values.

3D Trajectories at DFs