Proton Trapping and Acceleration at Dipolarization Fronts: High-Resolution MHD & Test-Particle Simulations

APL/SRP
SPACE PHYSICS GROUP

CHIMP
Conservative Hamiltonian Integrator for Magnetospheric Particles

$\partial_t f + \{f, H\} = 0$

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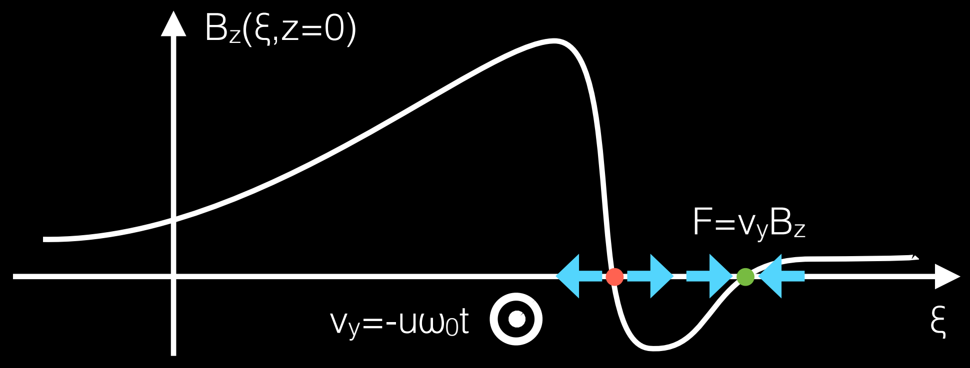
Acceleration Mechanisms at Dipolarization Fronts

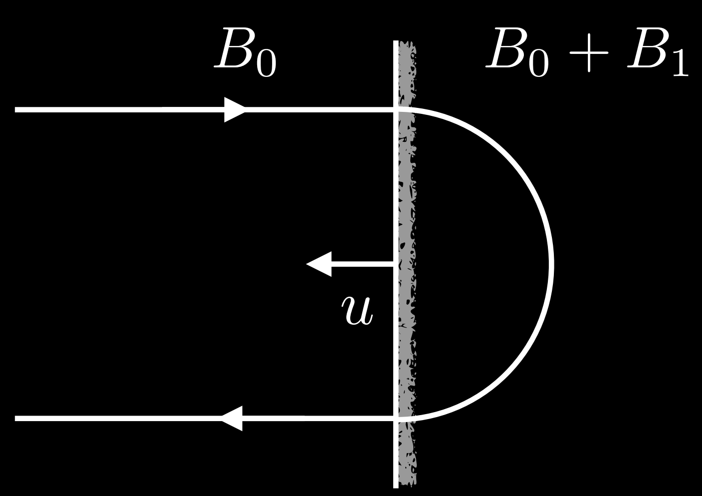


[Artemyev et al., 2012; Ukhorskiy et al., 2013]

Surfatron acceleration

Magnetic reconnection
ahead of a propagating front

$$B_z \sim 0$$

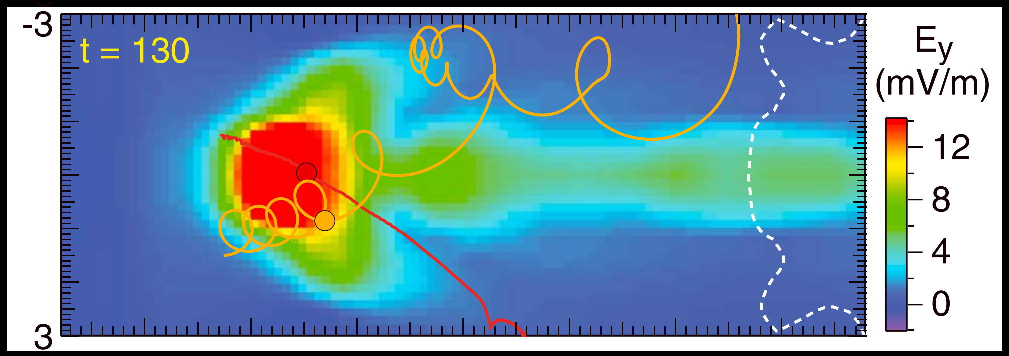


[Zhou et al., 2010; 2011]

Reflection

$$\Delta K = 2mu(u - v_x)$$

requires $B_0 \ll B_1$



[see review, Birn et al., 2012]

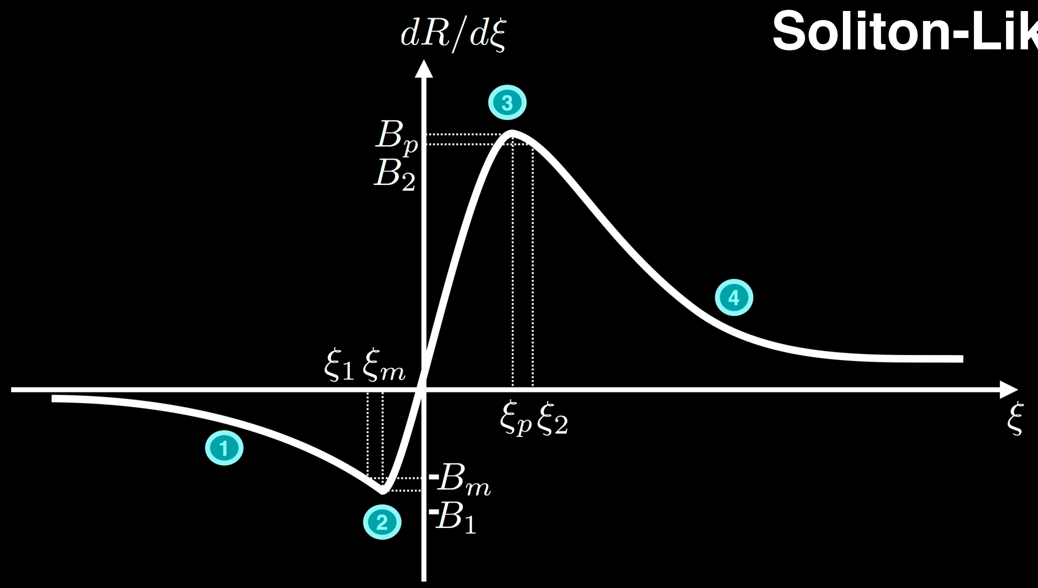
'Betatron' acceleration

$$E_y[\mathrm{mV/m}] = 10^{-3}u[\mathrm{km/s}]B_1[\mathrm{nT}]$$

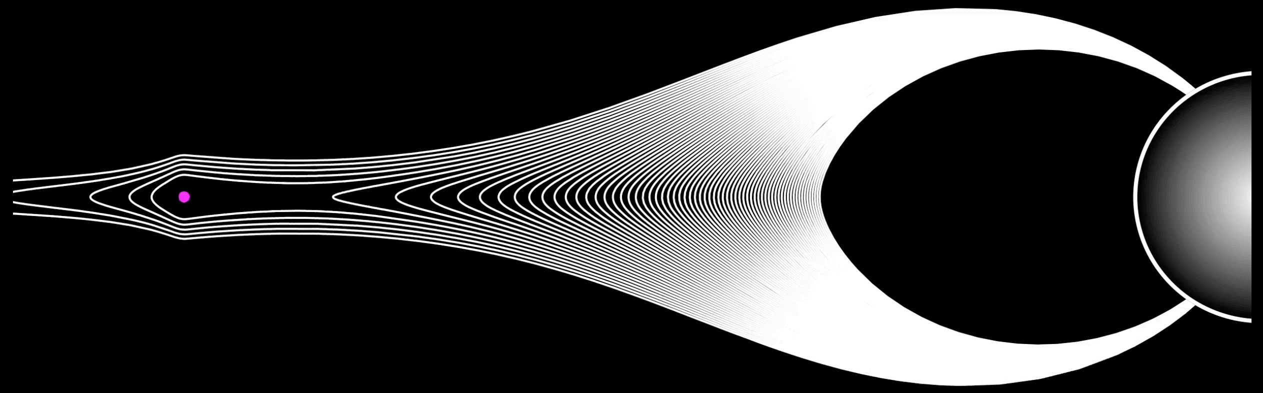
$$u \sim 10^3\ \mathrm{km/s};\ B_1 \gtrsim 10\ \mathrm{nT}$$

$$E_y \gtrsim 10\ \mathrm{mV/m}$$

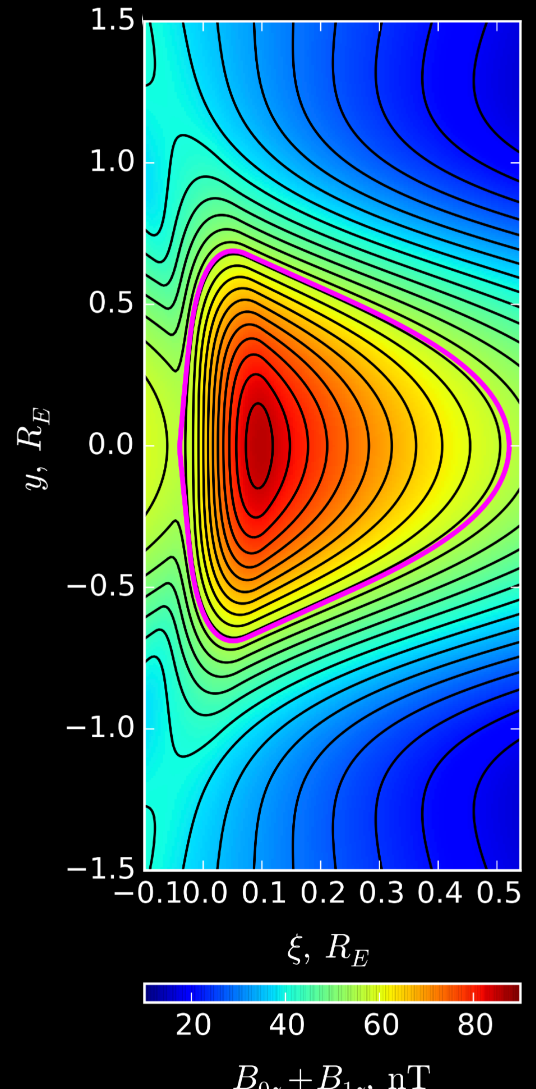
Magnetic Trapping at Dipolarization Fronts



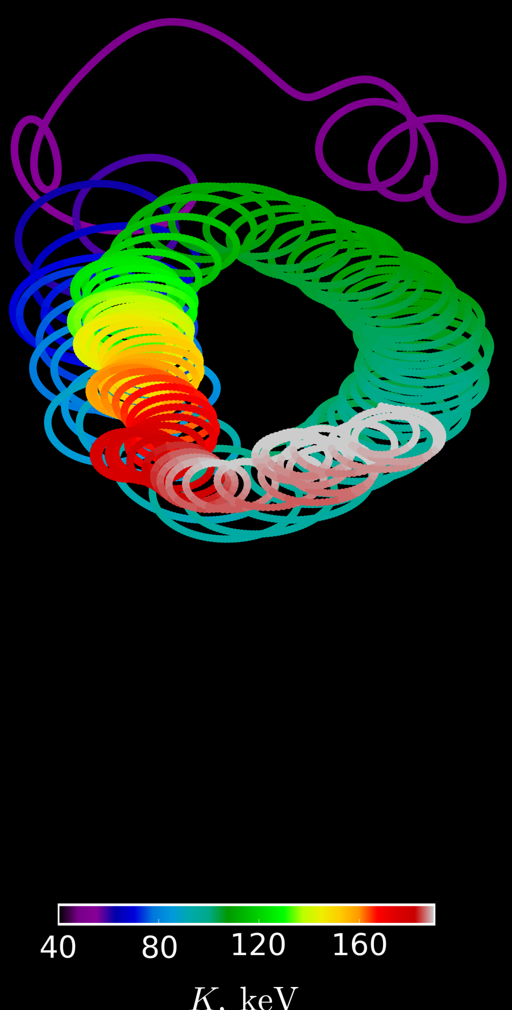
Soliton-Like Propagating Dipolarization Front



Magnetic Island



Stable Trapping



Enhanced Acceleration

Inverse magnetic field gradient associated with azimuthally localized dipolarization structures can stably trap energetic ions.

Trapping enables persistent interaction of ions with electric field induced by the front motion producing large acceleration: the intensities of keV ions increase by a factor of 10.

[Ukhorskiy et al., 2017]

Some Questions we Had..

- Does magnetic trapping exist under realistic dynamical conditions, when the structure of dipolarization fronts can significantly vary on the course of their earthward propagation? How does it depend on particle energy?

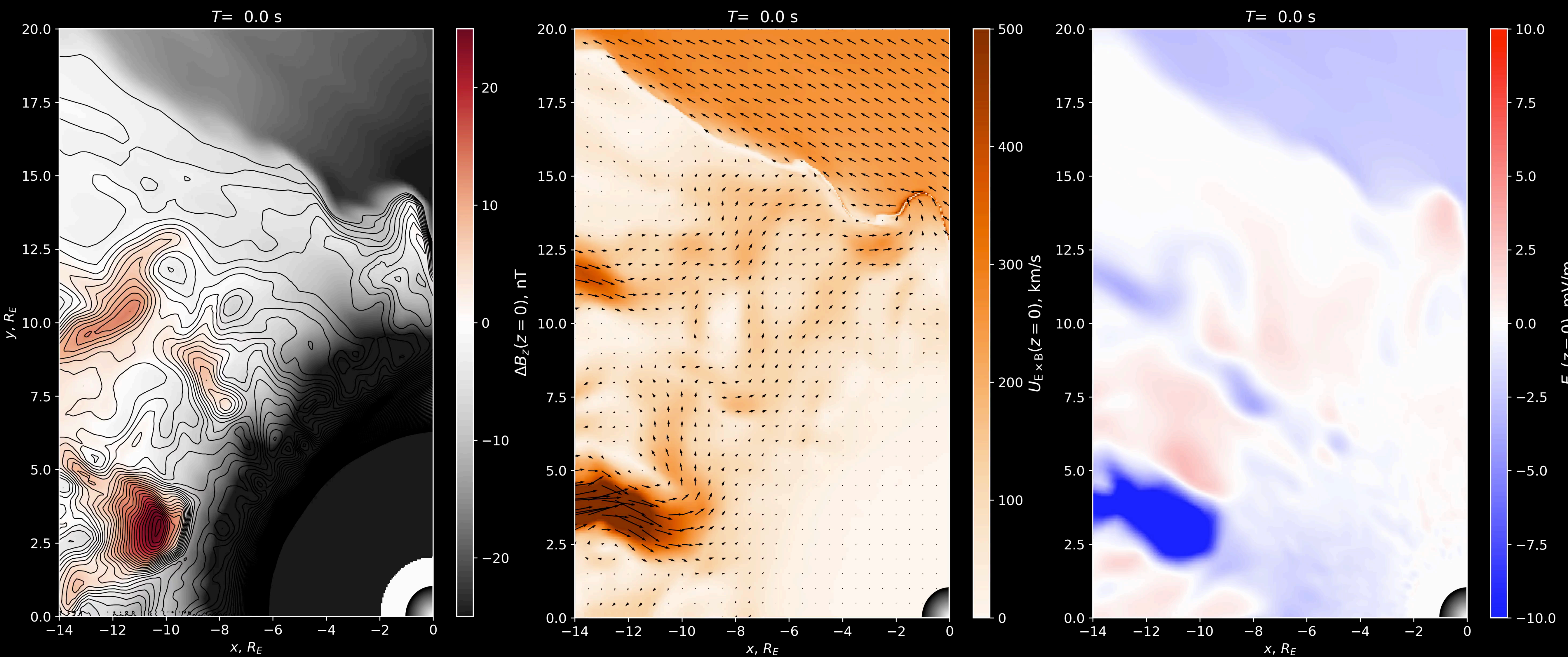
- What role does the trapping play on the buildup of proton pressure in the inner magnetosphere?

- Are proton transport/energization adiabatic (in terms of the first invariant)?

Dipolarizations in High-Resolution MHD (LFM)

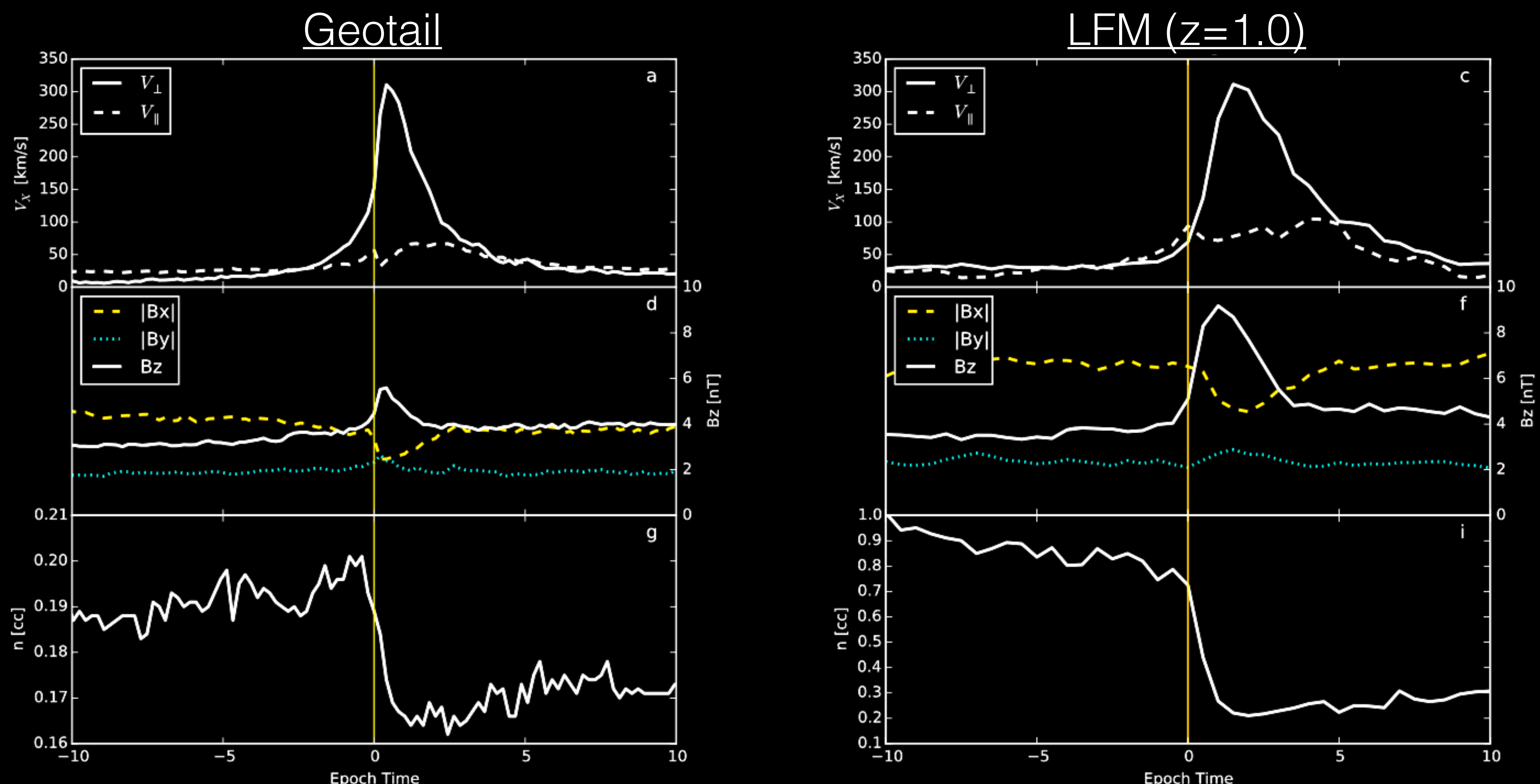
n_{sw}=5 cm^{-3}, V_x=400 km/s IMF B_z=-5 nT

[Wiltberger et al., 2015]



- “Magnetic islands”, i.e., closed constant B contours with ΔB_z~10-30 nT
- u≲500km/s; Eϕ≲10 mV/m

Data-Model Comparison



[Witberger et al., 2015]

A superposed epoch analysis of dipolarization flows in the high-resolution MHD simulations, used the event selection criteria of [Ohtani et al., 2004] statistical study of BBFs measured by Geotail. It shows a very good qualitative agreement between simulated and observed dipolarization flows.

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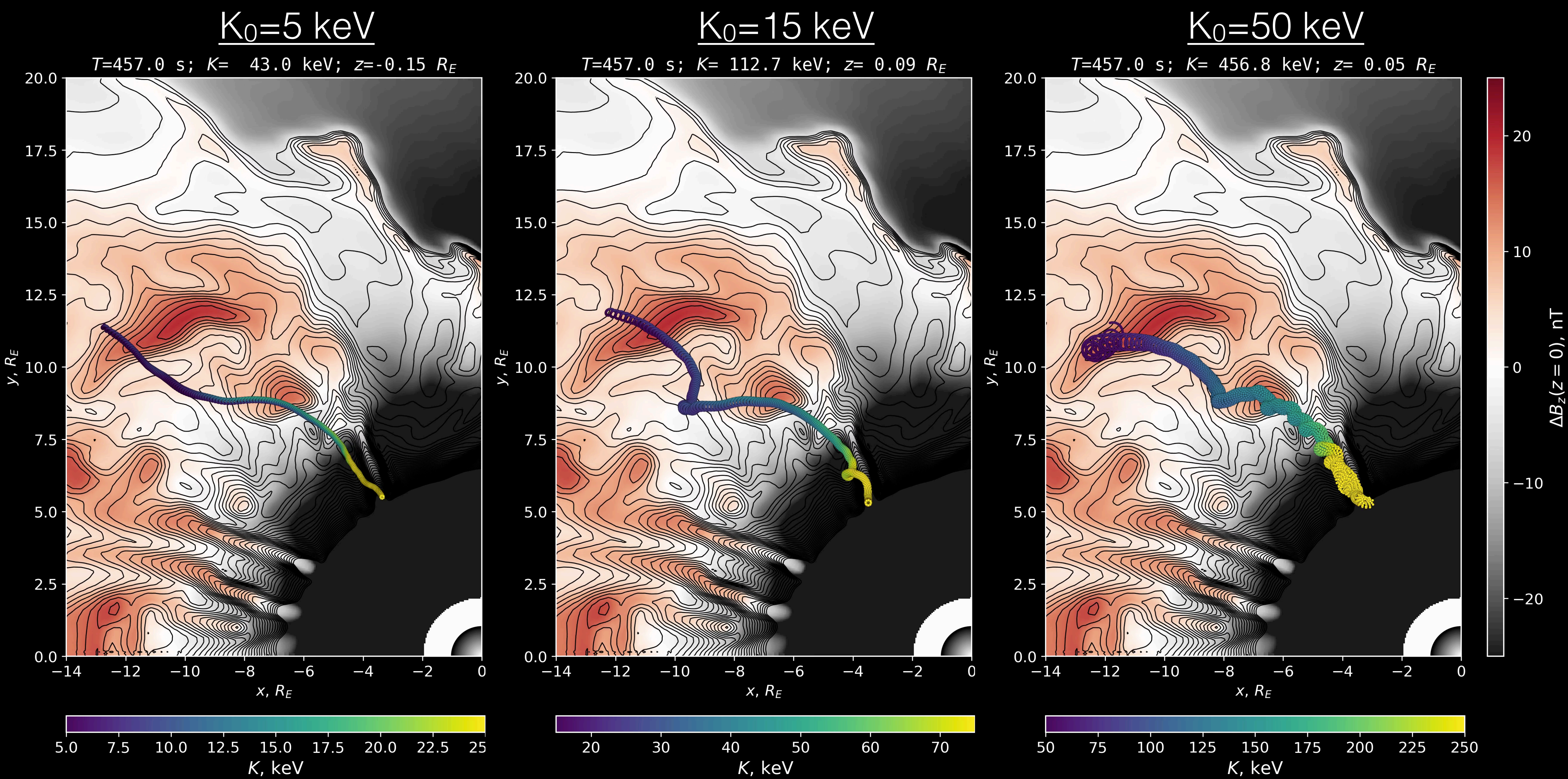
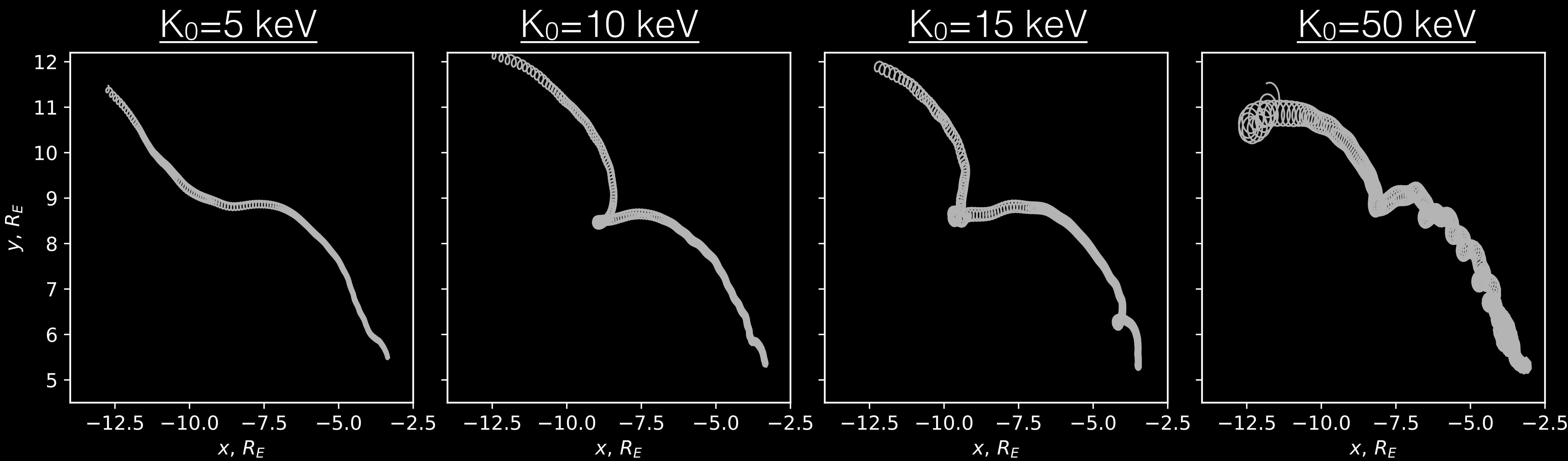
Trapping at a Dipolarization Front



Dynamics of protons with initial energy above ≲10 keV exhibit clear signature of trapping: on the course of the earthward ExB motion, particles guiding centers circle around magnetic islands.

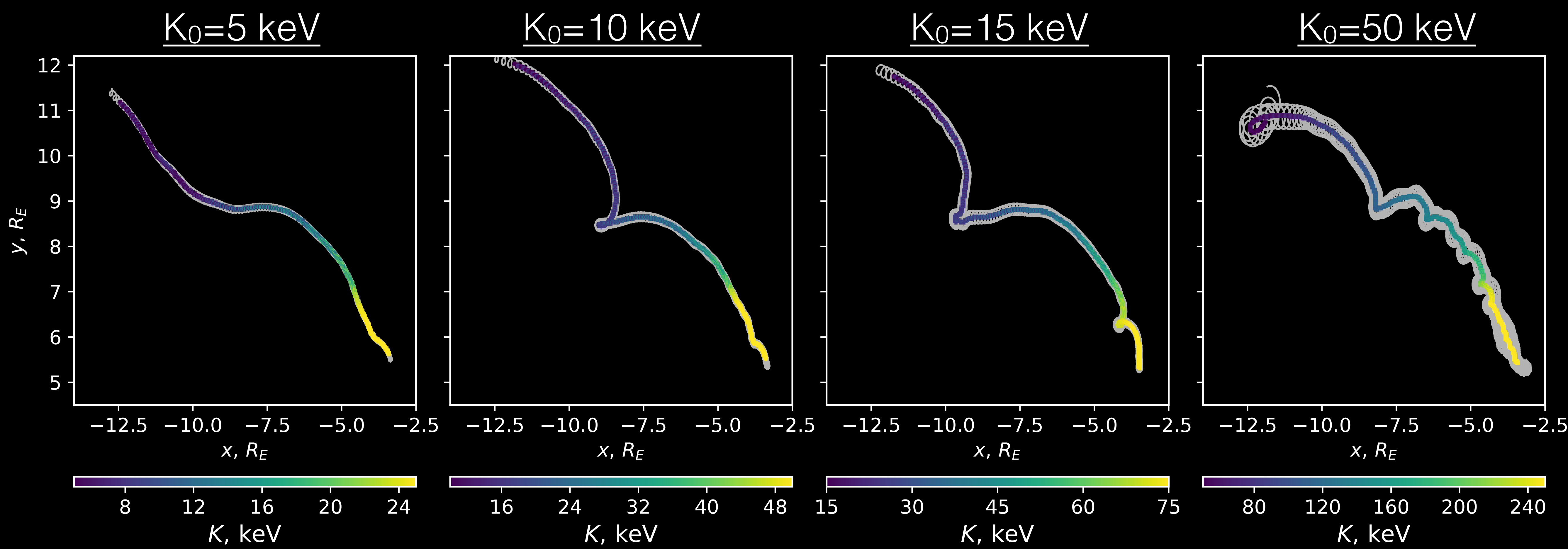
Trapping at a Dipolarization Front

"Dragon" Diagrams



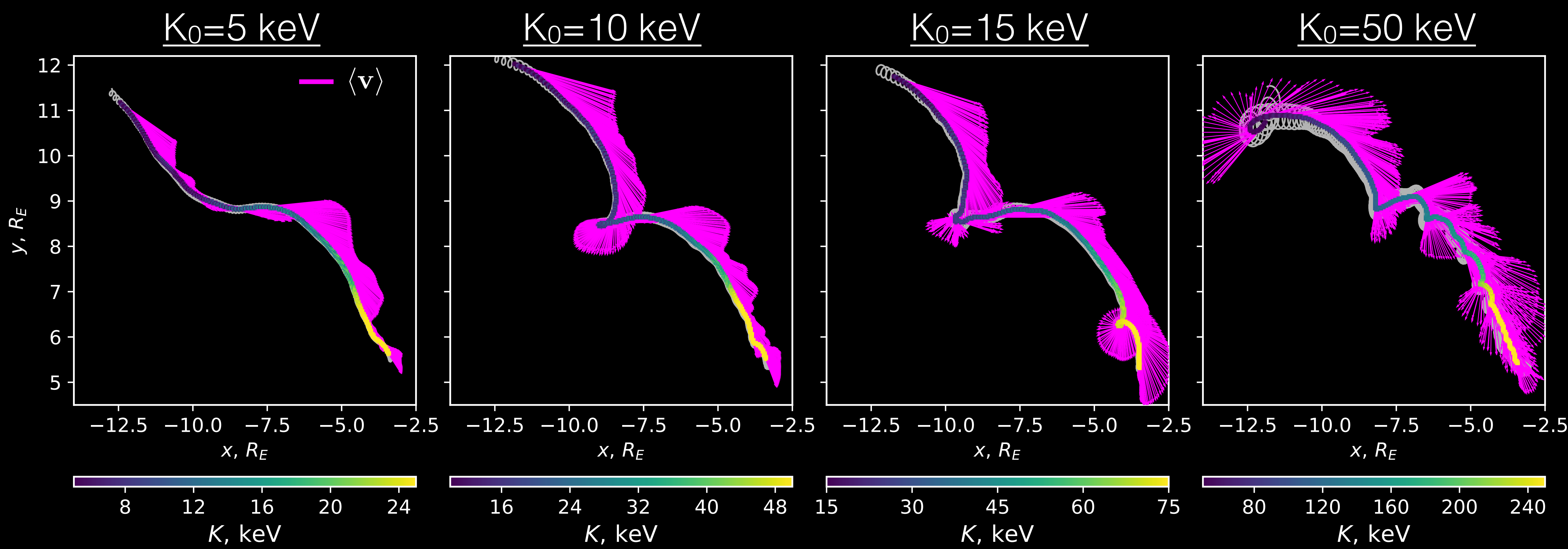
Trapping at a Dipolarization Front

“Dragon” Diagrams



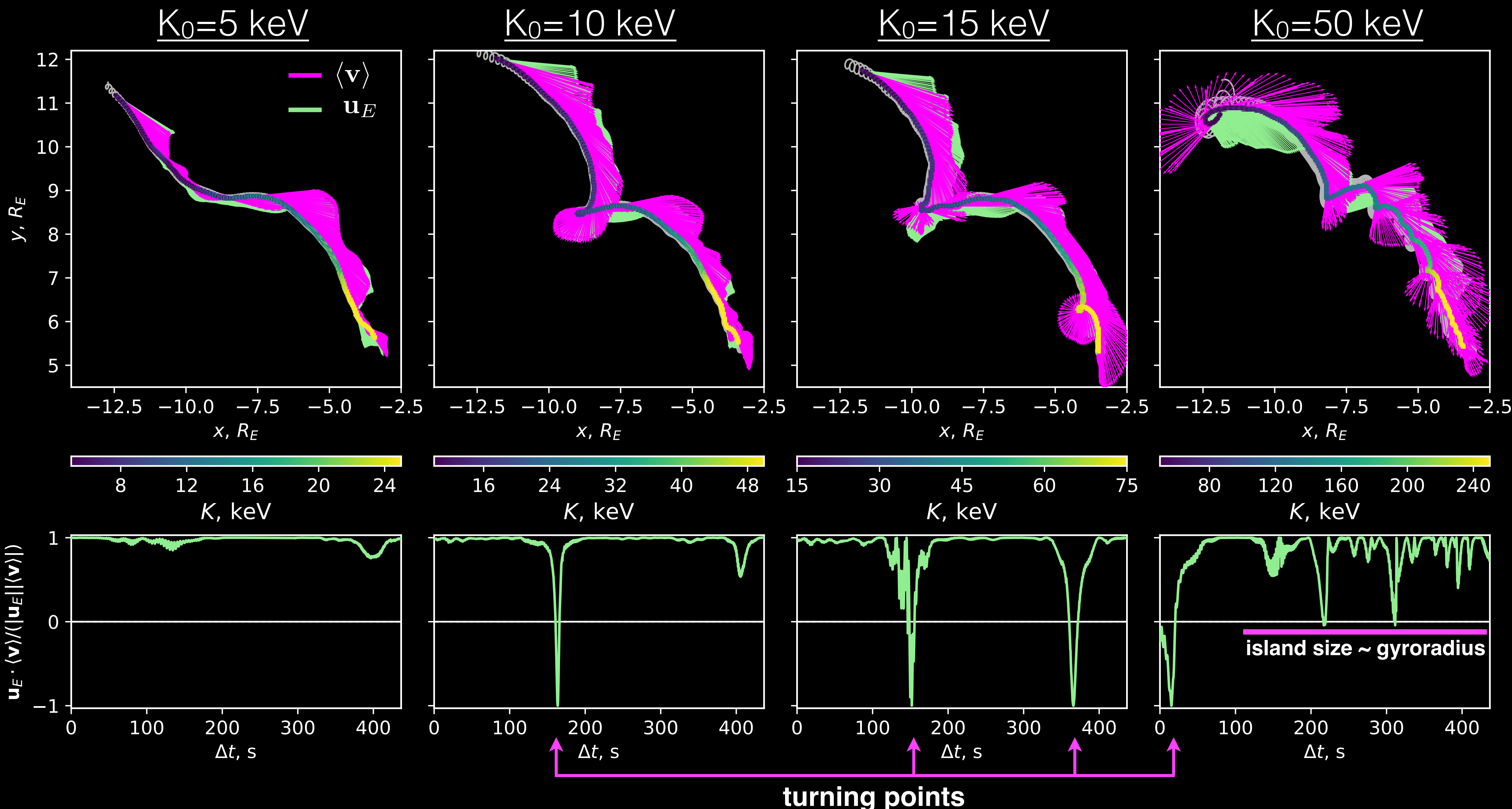
Trapping at a Dipolarization Front

“Dragon” Diagrams



Trapping at a Dipolarization Front

"Dragon" Diagrams



To identify turning points we compute the cosine of the angle between the ExB drift velocity, $\mathbf{u}_E$, and the guiding center velocity, estimated from a moving average of the full particle velocity vector, $\langle \mathbf{v} \rangle$.

Some Questions we Had..

- Does magnetic trapping exist under realistic dynamical conditions, when the structure of dipolarization fronts can significantly vary on the course of their earthward propagation? How does it depend on particle energy?

- What role does th ton pressure in the inner magnetosph

It does. Starting at ≳10 keV.

- Are proton transport/energization adiabatic (in terms of the first invariant)?

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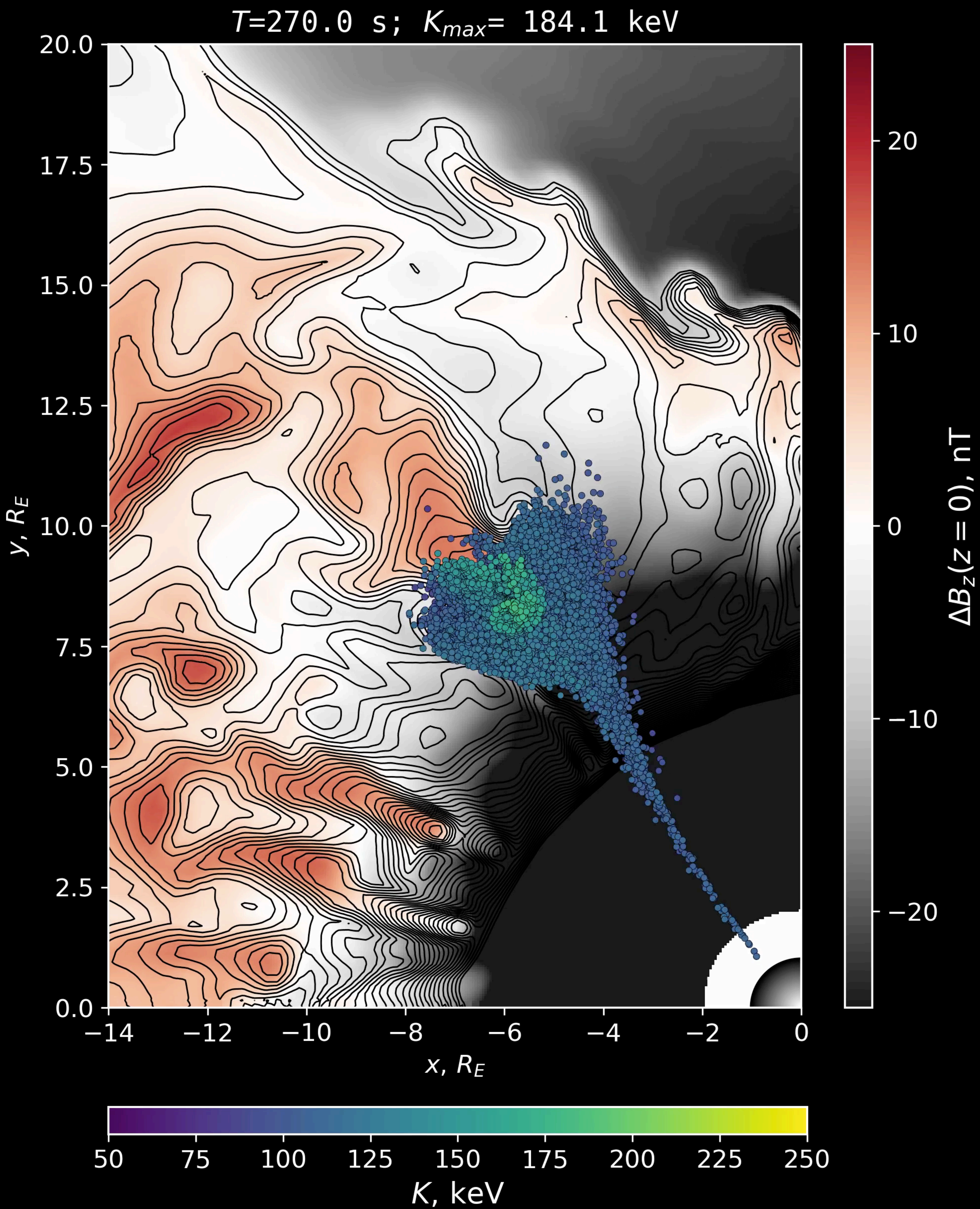
- What role does the trapping play on the buildup of proton pressure in the inner magnetosphere?

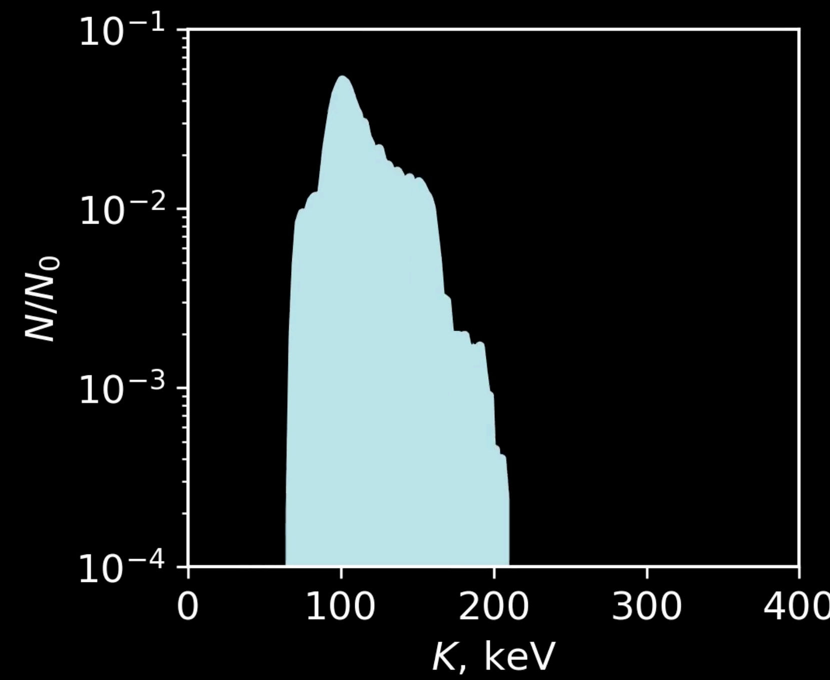
- Are proton transport/energization adiabatic (in terms of the first invariant)?

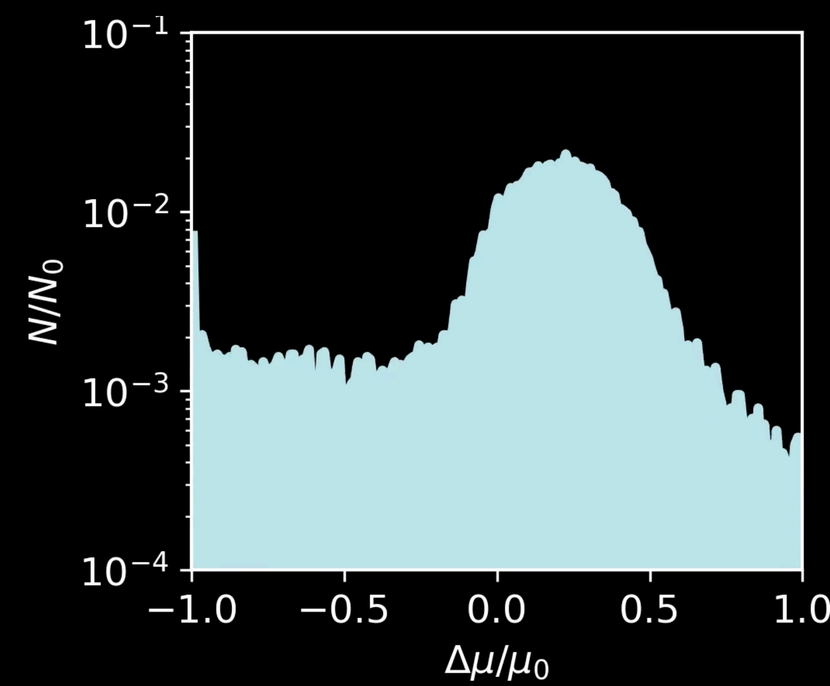
Large Ensemble Run



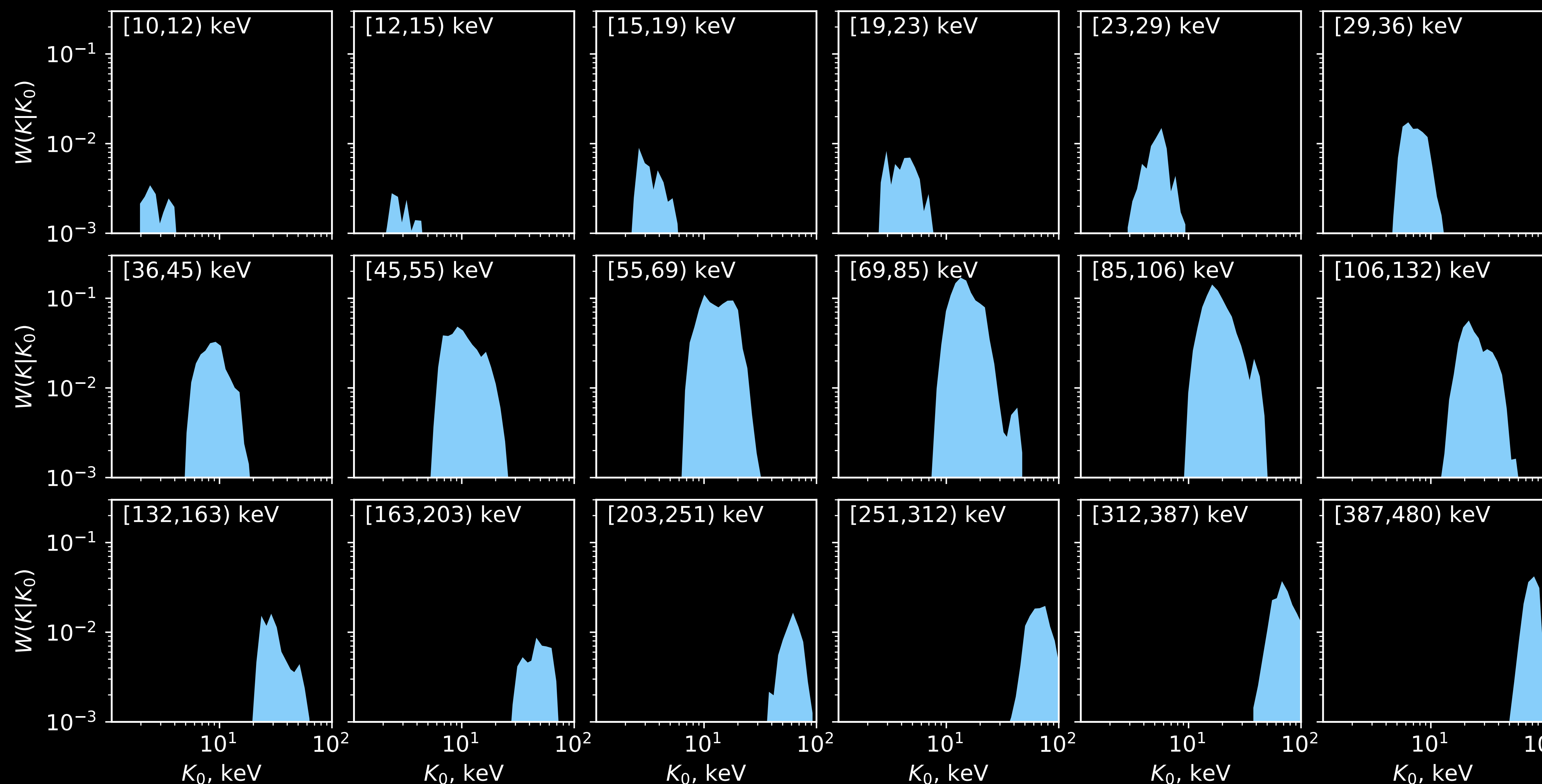
2.5·10^5 particles; 20 runs with:

K_0	:2 - 100 keV;	N_K=25
L	:16.5 - 17.4;	N_L=10
ϕ	:135° - 138°;	N_ϕ=10
α_{eq}	:10° - 90°;	N_α=5





Green's Function



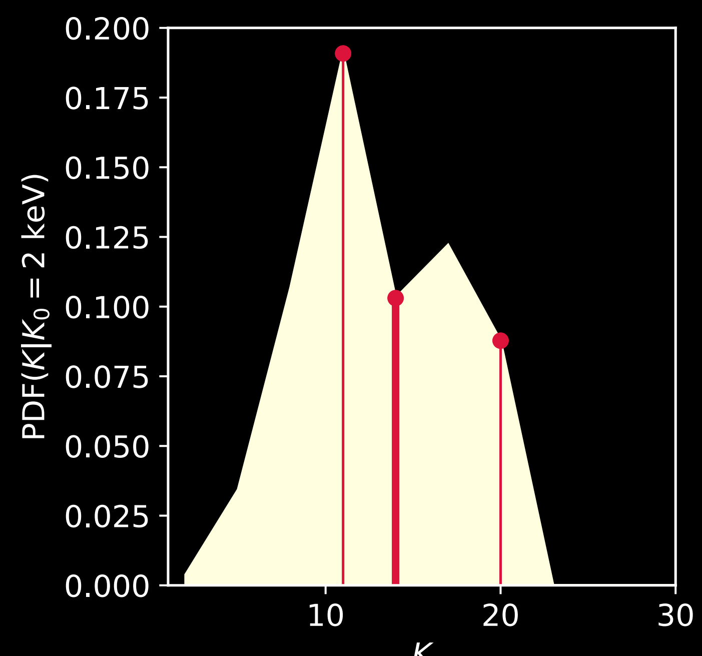
W(K|K_0) - the probability of a particle with initial energy K_0 at L=17 behind the dipolarization front to be transported to L<7 with energy K

Relative Contribution to Plasma Pressure

$$W(K|K_0): \qquad f(K) = \int_0^{\infty} W(K|K_0) f(K_0) dK_0$$

$$P(> K_0) = A \int_0^{\infty} K^{3/2} dK \int_{K_0}^{\infty} W(K|K_0') f(K_0') dK_0'$$

Most of ring current plasma pressure in the inner magnetosphere is associated with proton energies above 10 keV, which corresponds to the seed population energies of >2 keV at L=17.



	P(>10 keV)/P(>2 keV)		
	T=1.5 keV	T=3.0 keV	T=5.0 keV
κ =3	0.35	0.51	0.61
κ =4	0.27	0.43	0.55
κ =5	0.22	0.38	0.60
κ =6	0.19	0.34	0.58

Protons with initial energy of 10 keV and above, that exhibit trapping, provide an important source population of plasma pressure in the inner magnetosphere (L<7).

Some Questions we Had..

- Does magnetic trapping exist under realistic dynamical conditions, when the structure of dipolarization fronts can significantly vary on the course of their earthward propagation? How does it depend on particle energy?

- What role does the trapping play on the buildup of proton pressure in the inner magnetosphere?

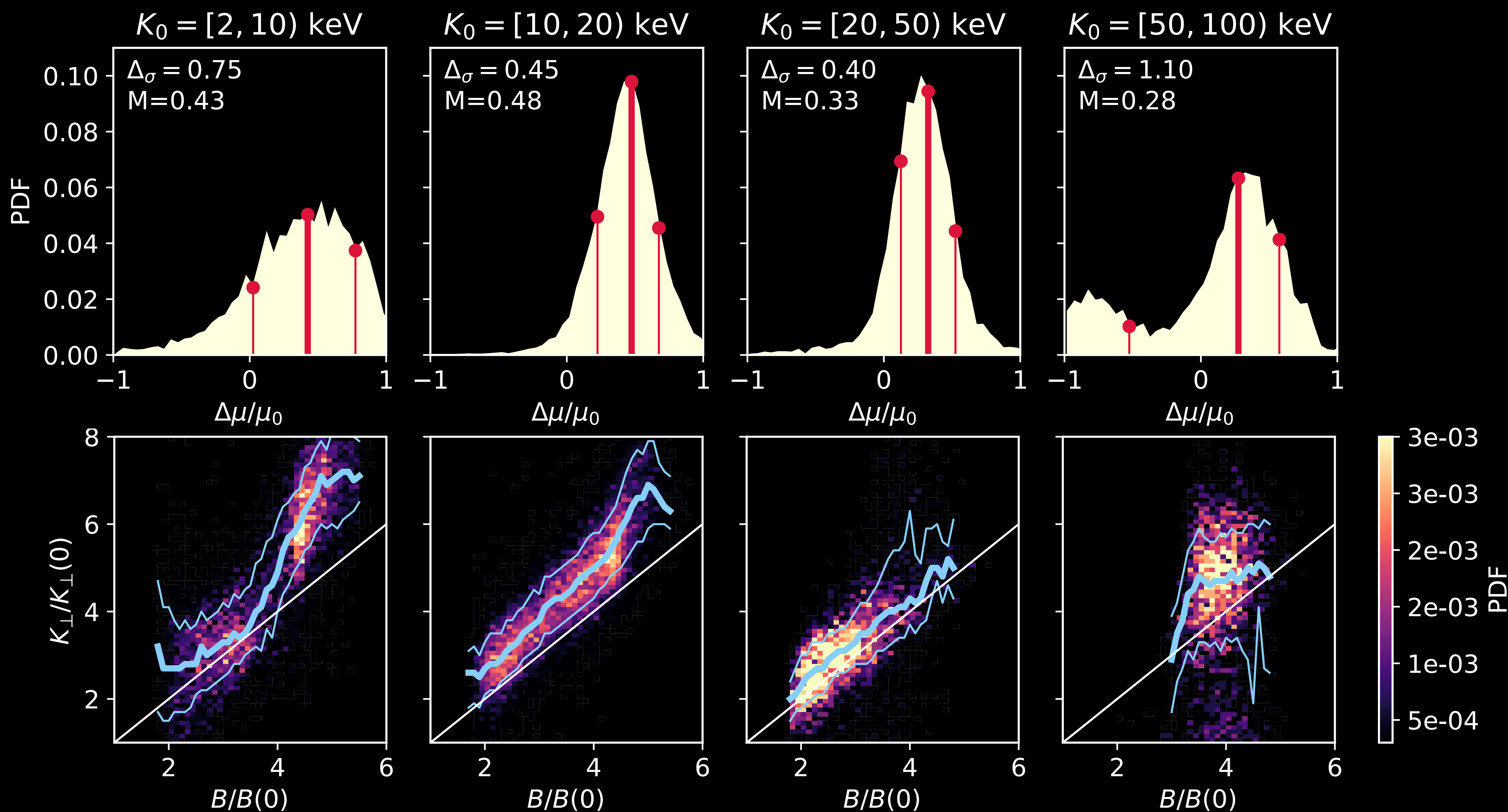
- Are proton transp … he first invariant)?

Important. Can contribute to 20-60% of ring current pressure.

Some Questions we Had..

- Does magnetic trapping exist under realistic dynamical conditions, when the structure of dipolarization fronts can significantly vary on the course of their earthward propagation? How does it depend on particle energy?
- What role does the trapping play on the buildup of proton pressure in the inner magnetosphere?
- Are proton transport/energization adiabatic (in terms of the first invariant)?

How Adiabatic are Transport/Acceleration?



While being well ordered by B/B(0), transport and acceleration exhibit substantial deviations from adiabaticity; measured by the relative change of the magnetic moment it varies between M=0.3-0.5 and Δ_σ=0.4-1.1

Some Questions we Had..

- Does magnetic trapping exist under realistic dynamical conditions, when the structure of dipolarization fronts can significantly vary on the course of their earthward propagation? How does it depend on particle energy?

- What role does the trapping play on the buildup of proton pressure in the inner magnetosphere?

- Are proton transport/energization adiabatic (in terms of the first invariant)?

Not really…

Conclusions

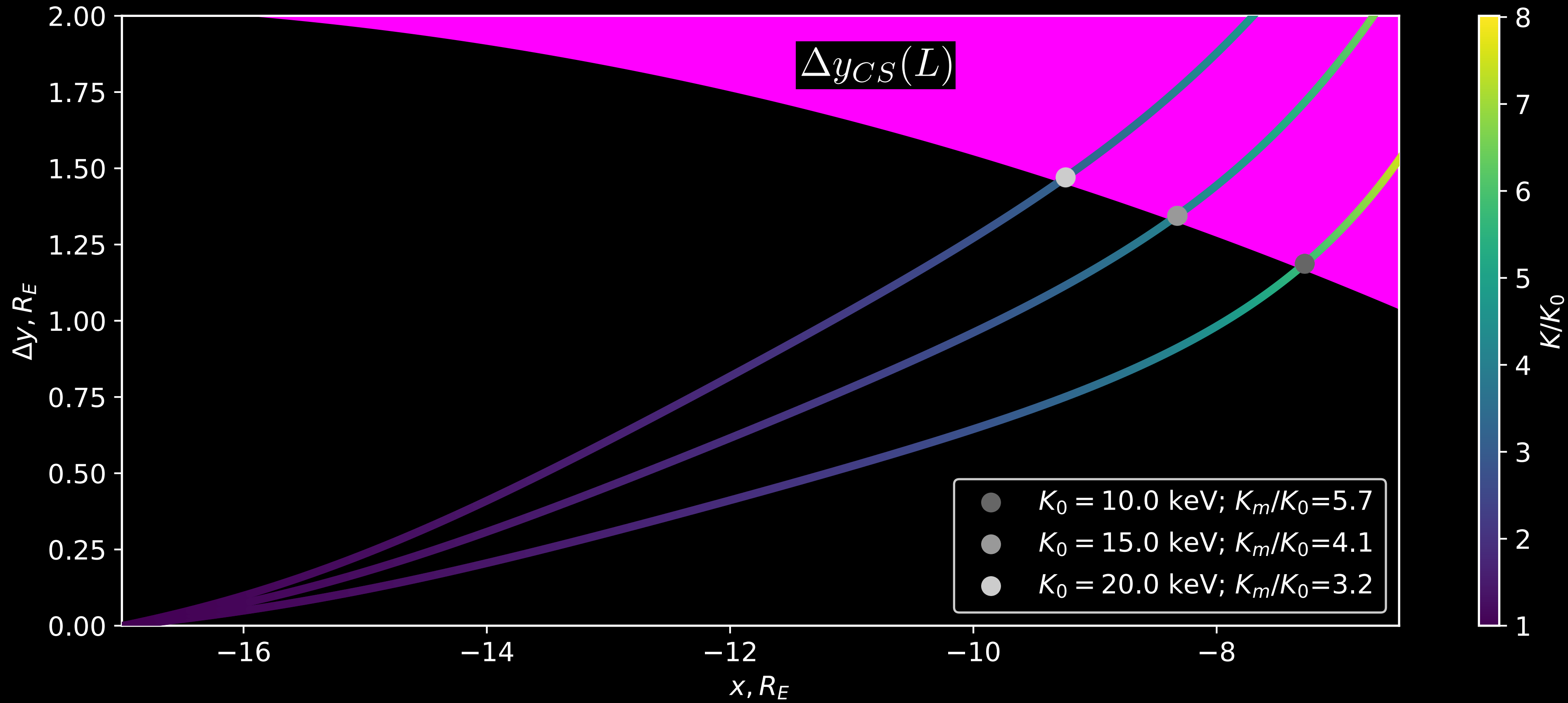
- Protons with initial energies above $\lesssim$10 keV exhibit magnetic trapping. In the absence of trapping particles would traverse the entire azimuthal extent of the front at higher L (then observed in the simulations) and consequently would not achieve full energization.

- Trapping is important for the buildup of ion pressure in the inner magnetosphere; depending on the assumptions on the initial particle energy spectrum trapped particles can contribute between 20% and 60% of ring current plasma pressure $>$10 keV.

- Proton transport/acceleration exhibit significant deviations from purely betatron acceleration. Violation of the magnetic moment is most noticeable for lowest and highest energy particles.

EXTRAS

Convection Surge Escape Distance

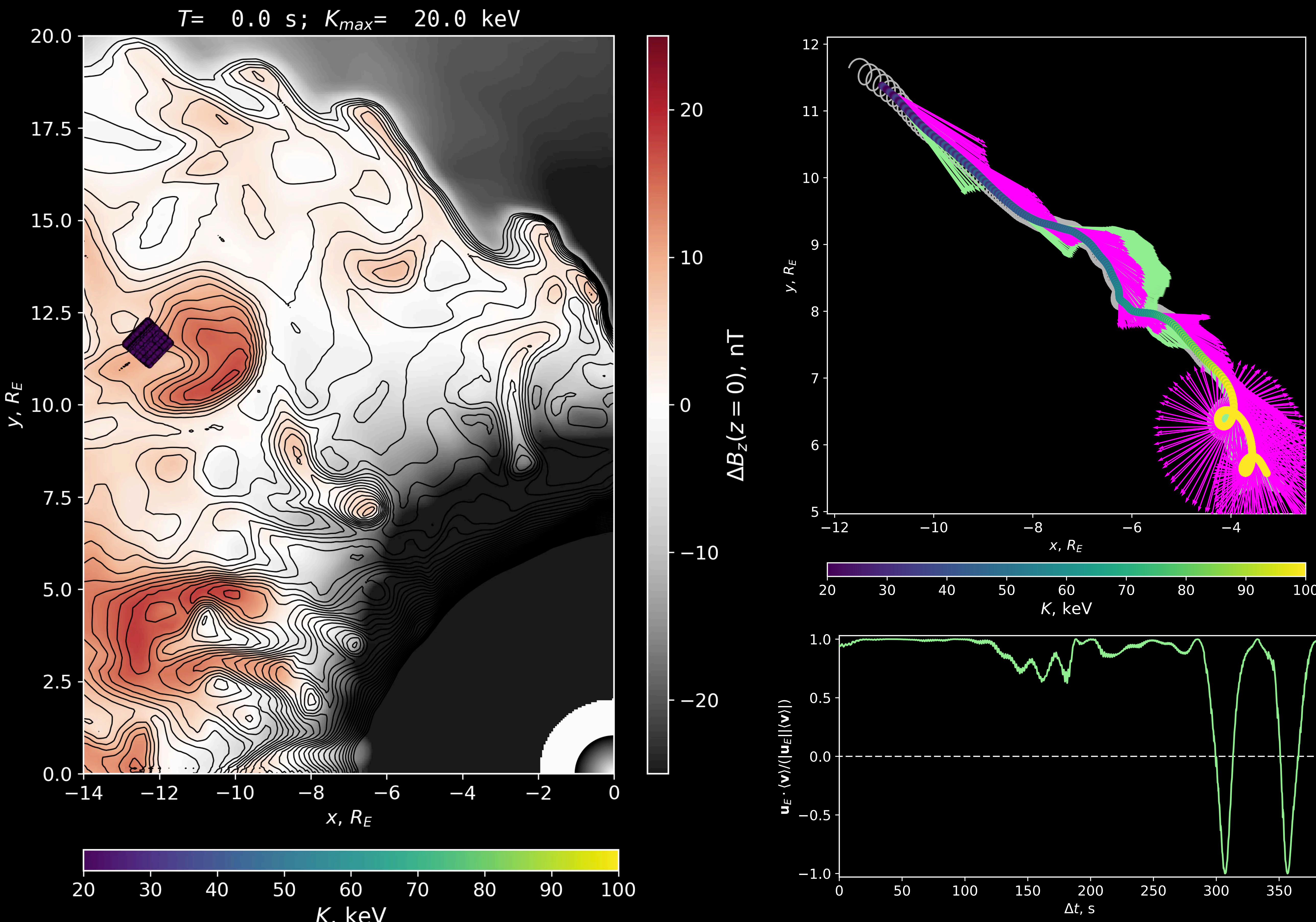


$$\frac{d\varphi}{dL} = \frac{\mu c}{e R_E} \frac{1}{L u_E(L)} \frac{d}{dL} \ln B(L)$$

$u_E(L)$: the radial component of the ExB drift along particle trajectories

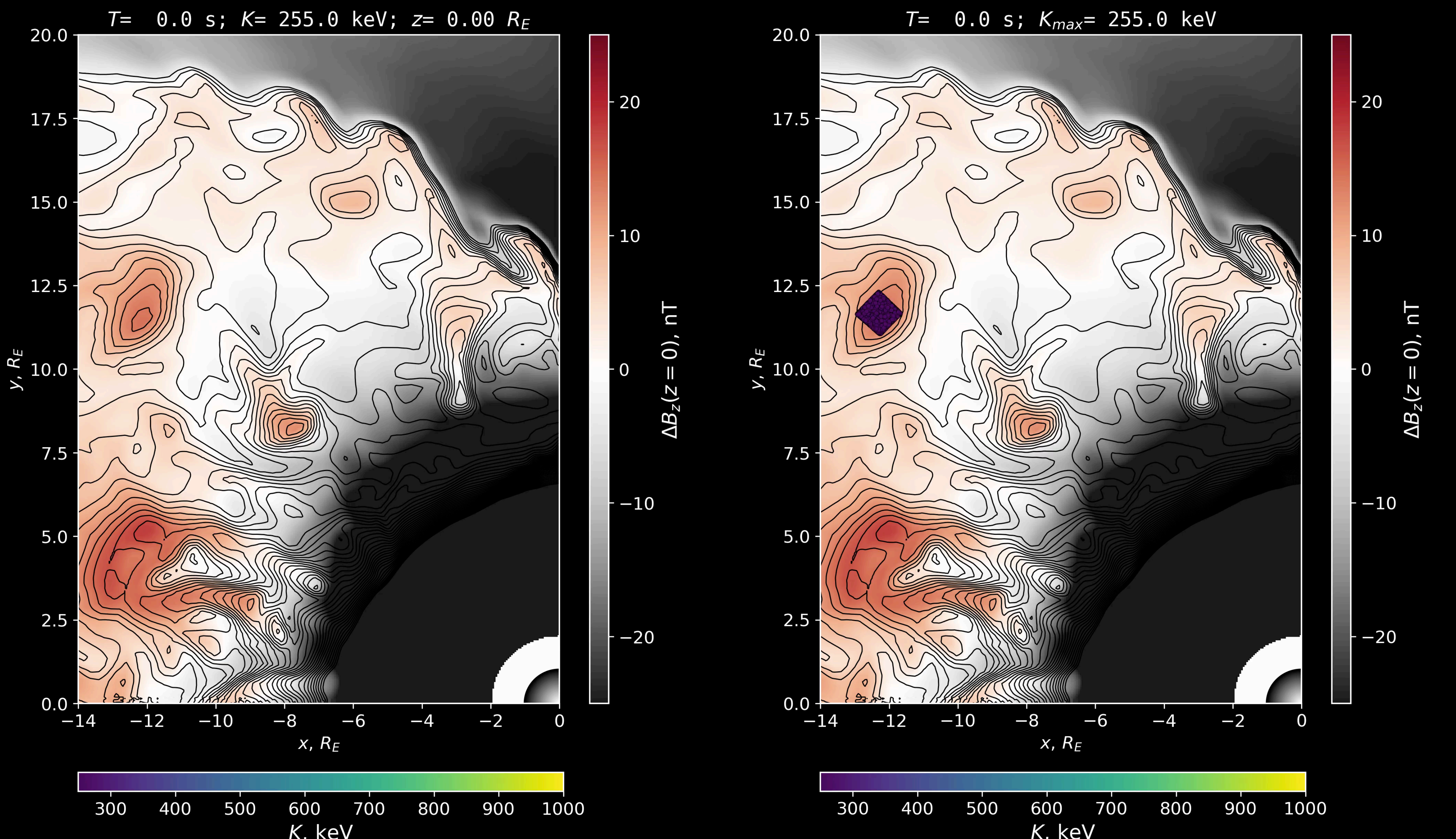
$B(L)$: smooth fit into the average equatorial magnetic field amplitude (removes dipolarization fronts)

$\Delta y_{CS}(L)$: the width of the convection surge determined locally at the half peak of the radial flow velocity



T= 0.0 s; Kmax= 20.0 keV
y, RE
x, RE
ΔBz(z=0), nT
K, keV
y, RE
x, RE
K, keV
uE · ⟨v⟩/(|uE||⟨v⟩|)
Δt, s

How do Mesoscale Flows Transport/Accelerate Electrons?



Azimuthally localized (~1 R_E) 100s km/s flows ($E\phi \lesssim 10$ mV/m) can stably trap 100s keV seed population electrons and transport them from the tail to the inner magnetosphere, across >10 R_E leading to energization to MeV energies of the core radiation belt population.

PSD to Test Particles and Back

We follow dynamics in the hyperplane corresponding to the z=0 plane:

$$\mathbf{X} = (K, \alpha, L, \varphi)$$

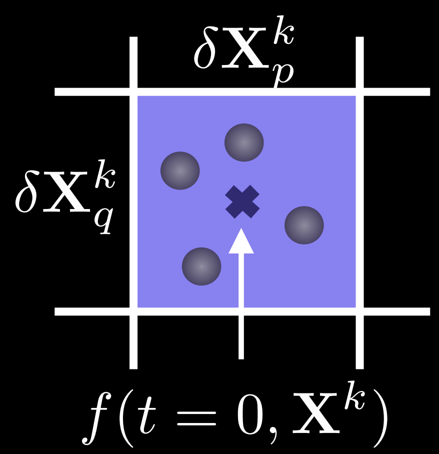
Injected electron PSD is assumed to be an isotropic kappa distribution:

$$f(K) = A_\kappa \left(1 + \frac{K}{\kappa K_0}\right)^{-\kappa-1} \quad A_\kappa = n\frac{1}{\sqrt{\kappa}(2m\pi K_0)^{3/2}}\frac{\Gamma(\kappa)}{\Gamma(\kappa-1/2)} \qquad K_0 = T\frac{\kappa - 3/2}{\kappa}$$

Particles initially located in a k^th cell of the phase space grid are assigned the weight based on the ratio of the number of "physical" particles in the grid cell to the number N_i of test particles in this grid cell:

$$w_i = \frac{1}{N_k} f(t=0, \mathbf{X}^k)\delta\Gamma(\mathbf{X}^k),\ N_k = \#\mathcal{I}$$

$$\mathcal{I} = \{\mathbf{X}_i(t=0) | \mathbf{X}_i \in [\mathbf{X}^k, \mathbf{X}^k + \delta\mathbf{X})\}$$

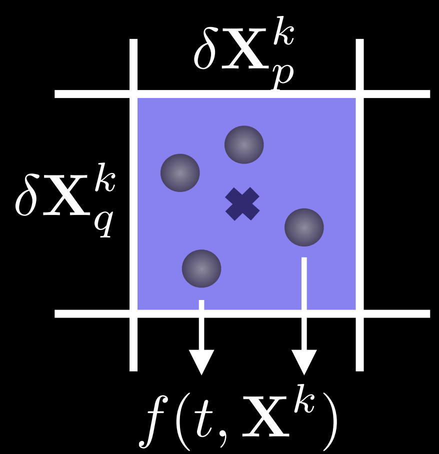


$$\delta\Gamma = \delta\Gamma_p V_\Phi \qquad V_\Phi = \Phi\int_m^{m'}\frac{ds}{B(s)} \qquad \delta\Gamma_p = 2\pi m^2 c\gamma\sqrt{\gamma^2-1}\sin\alpha\delta\alpha\delta K$$

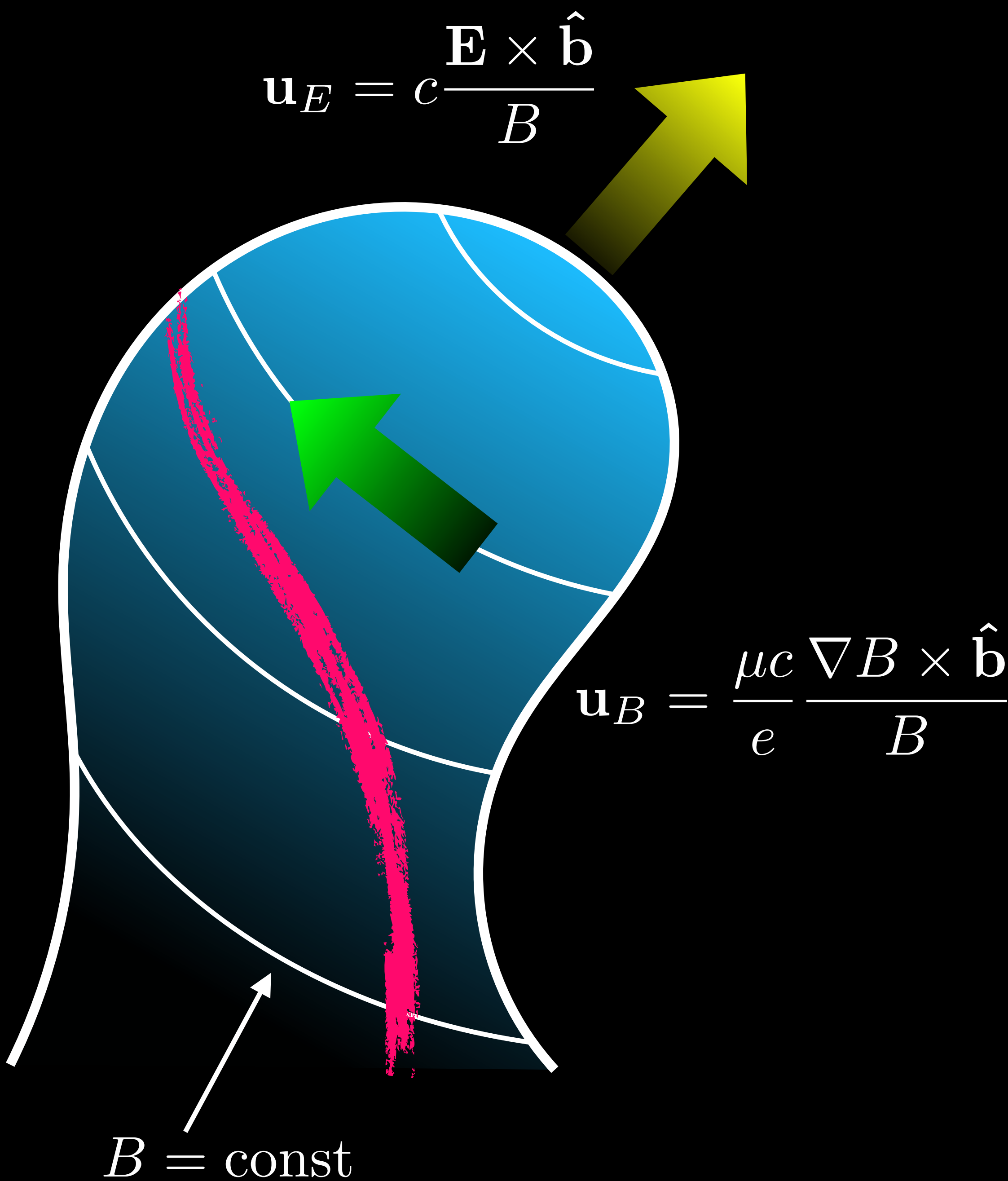
The PSD at a given moment of time is computed from the weights:

$$f(t, \mathbf{X}^k) = \frac{1}{\delta\Gamma(\mathbf{X}^k)}\sum_{j=1}^{N_k} w_j,\ N_k = \#\mathcal{J}$$

$$\mathcal{J} = \{\mathbf{X}_j(t) | \mathbf{X}_j \in [\mathbf{X}^k, \mathbf{X}^k + \delta\mathbf{X})\}$$



Convection Surge



Convection Surge - an increase in the earthward flow/azimuthal E-field

Thermal ions ExB drift towards Earth and adiabatically accelerated due to an increase in the ambient magnetic field

Acceleration/transport continues until ions drift out of the flow due to the gradient-curvature drift

Trapping at Dipolarization Fronts

Inverse magnetic field gradients associated with a dipolarization front form magnetic islands that can trap ions on the guiding center trajectories circling the front

Trapping enables ions to propagate with the front earthward over multiple Earth radii producing efficient ion acceleration