Peculiarities of quasi-adiabatic dynamics of charged particles in current sheets with a magnetic shear

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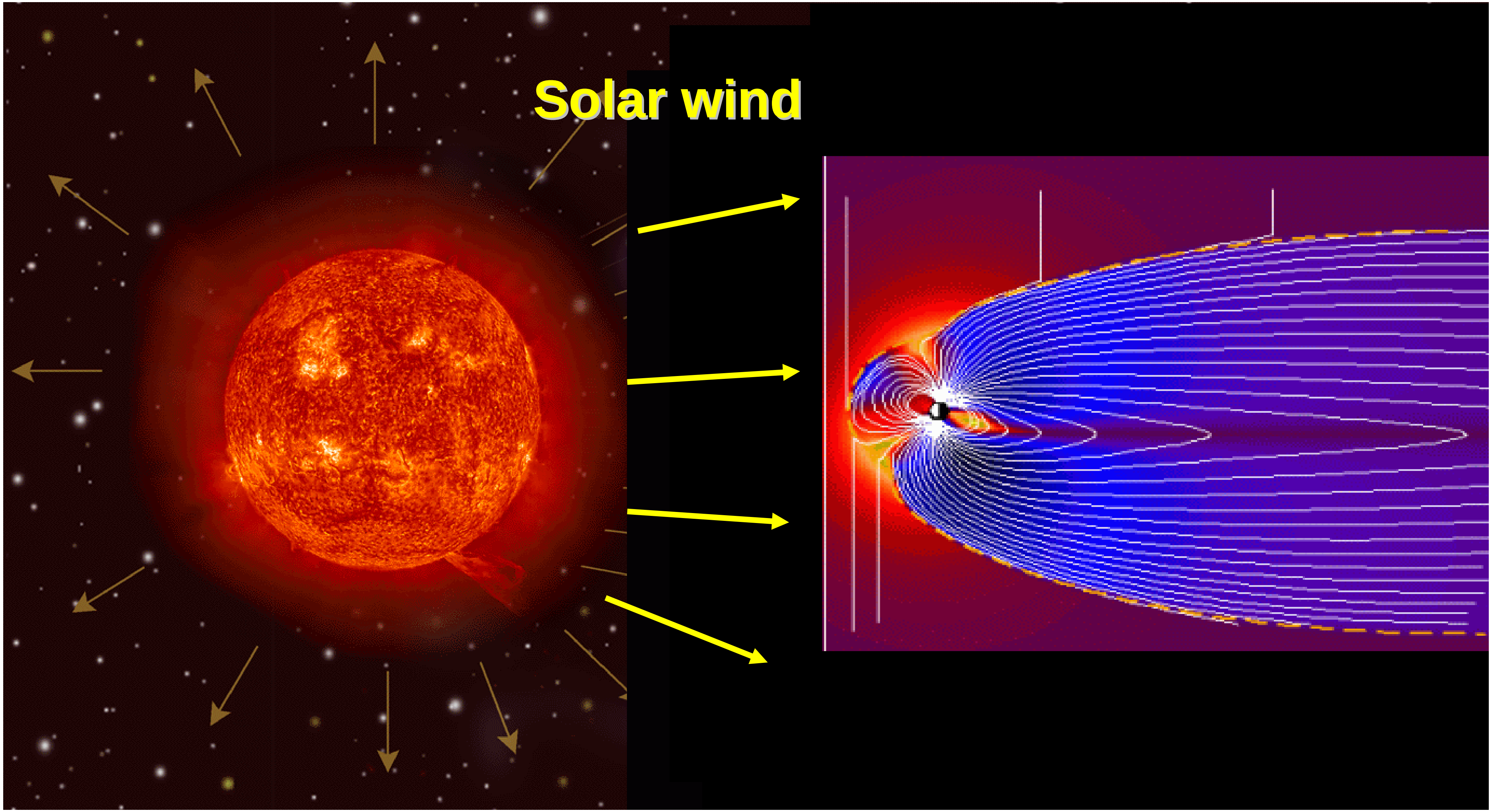
with the participation of Marina Belyalova (IKI RAS)

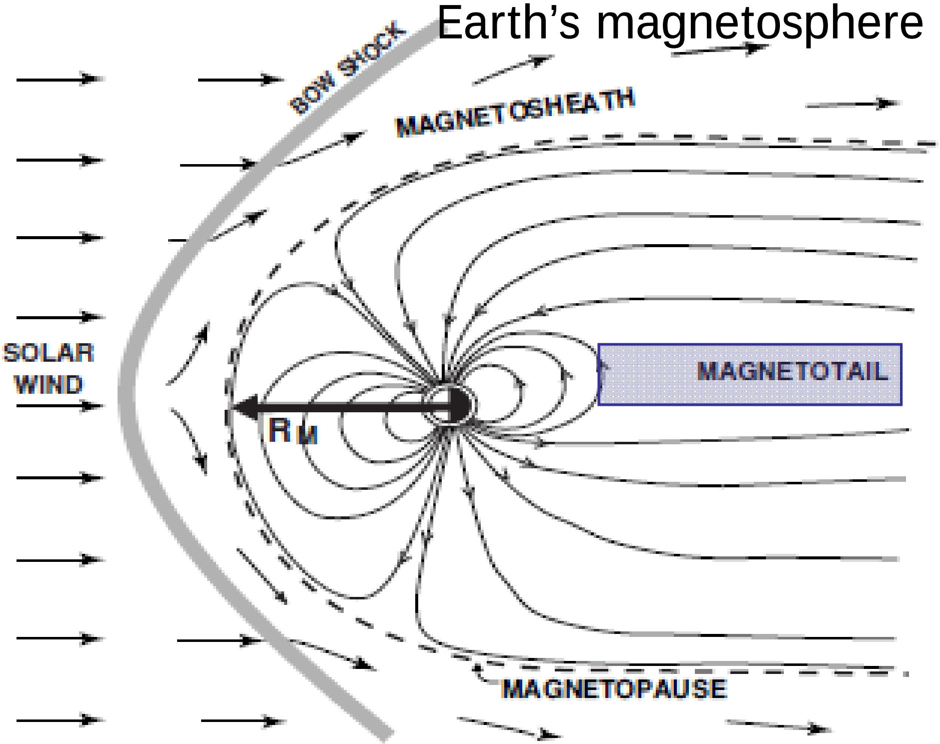
Dynamical interaction of solar wind and planetary magnetospheres leads to the formation of thin current sheets in the magnetotails with thicknesses about one to several Larmor radii ρ_L



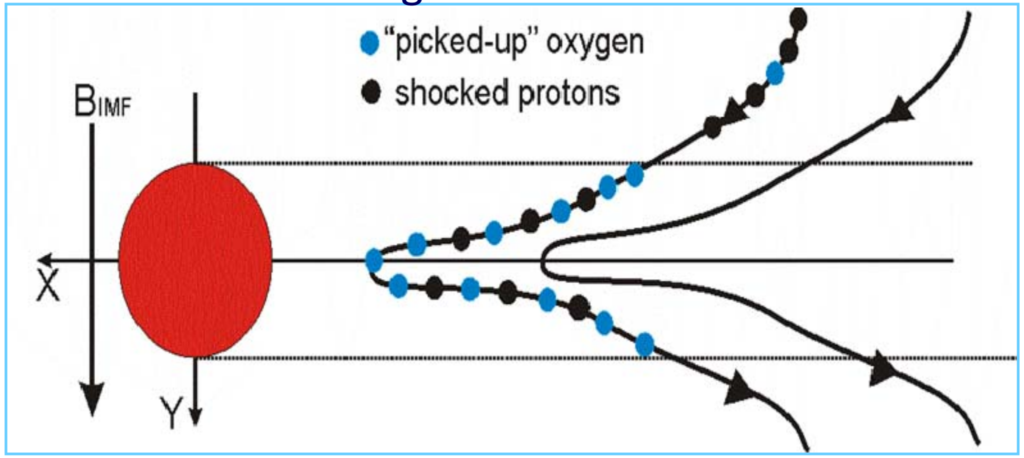
Magnetotail current sheets

It is shown that not only the Earth, but Mercury, Venus and other planets can have magnetospheres
with thin current sheets in their magnetotails

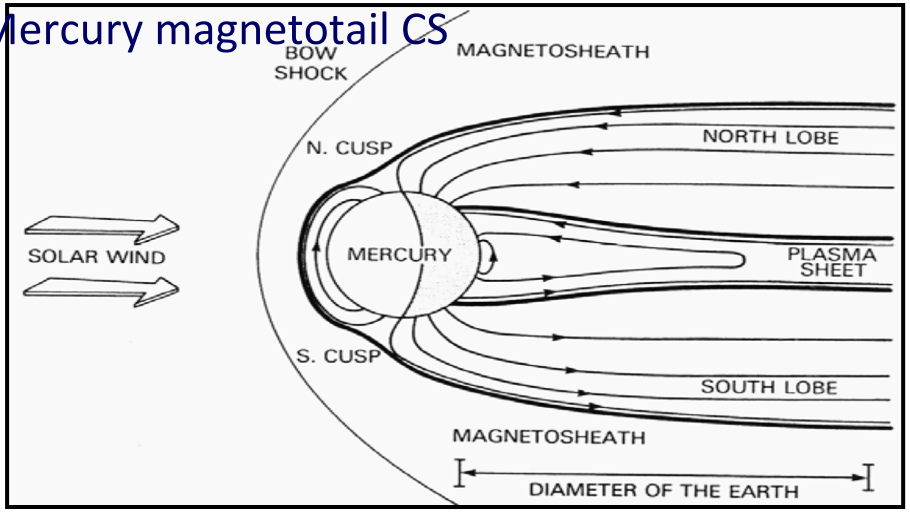
Earth's magnetosphere



Venus magnetotail CS



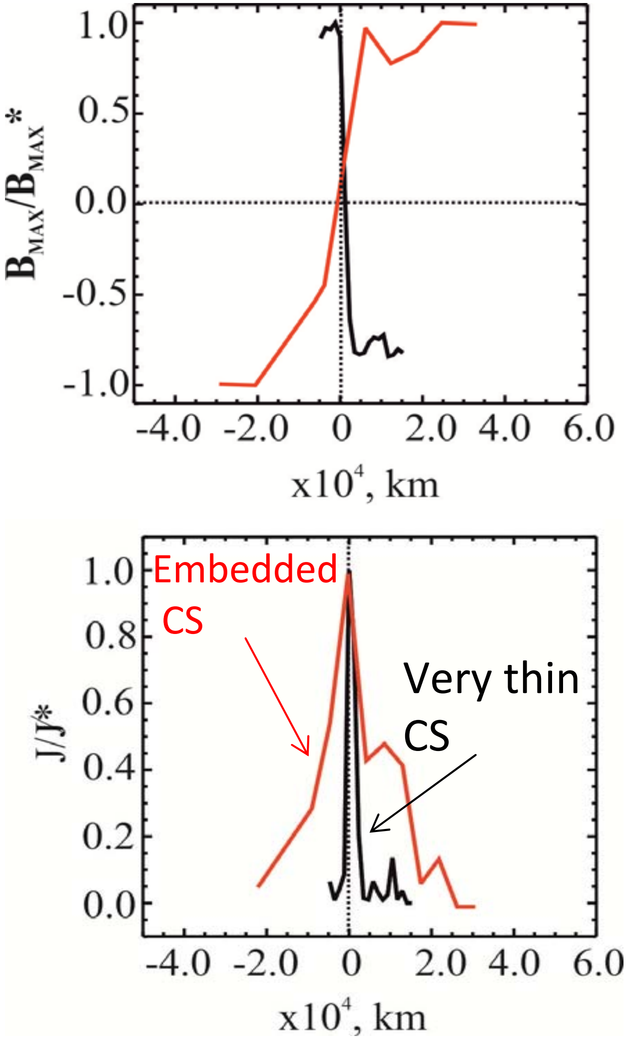
Mercury magnetotail CS



The similar features are observed also in current sheets in:

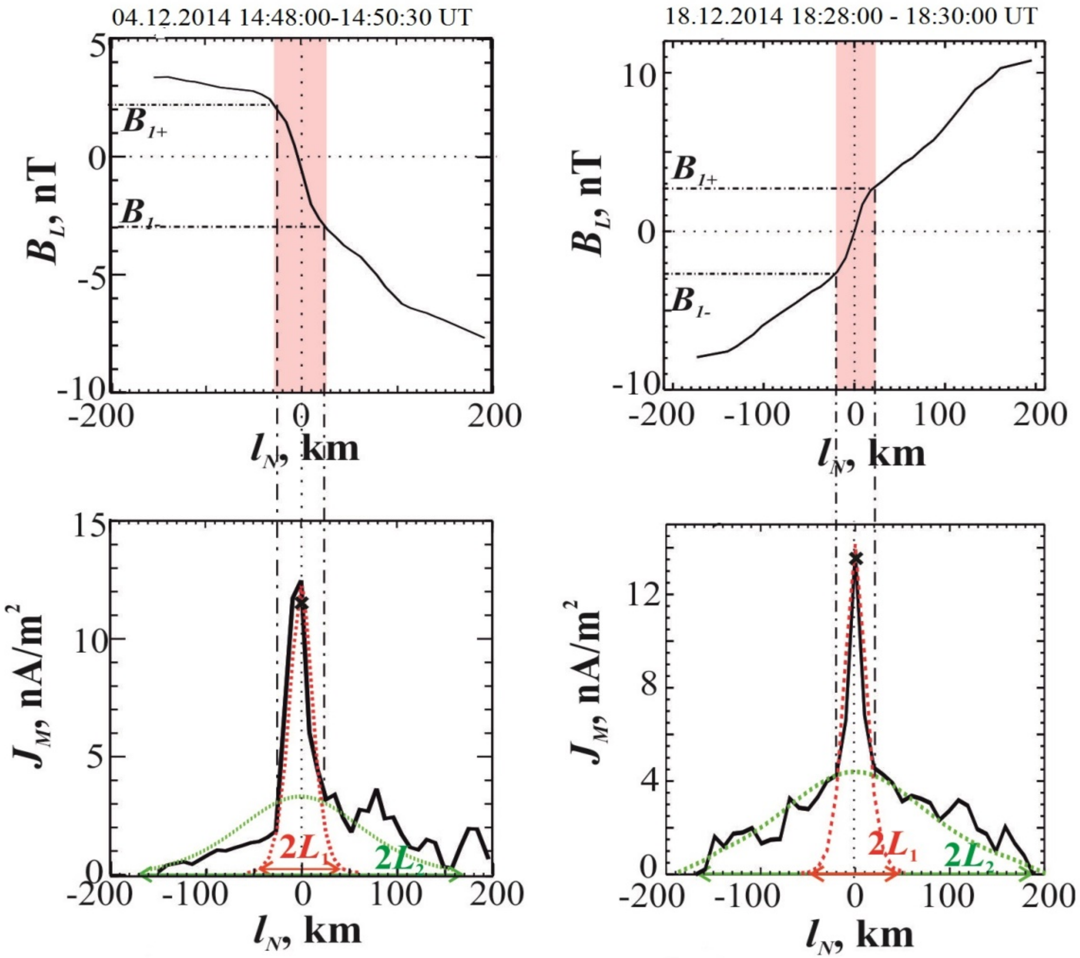
the Solar Wind

STEREO-A observations of two CS crossings



In the Martian magnetotail

MAVEN observations of two CS crossings

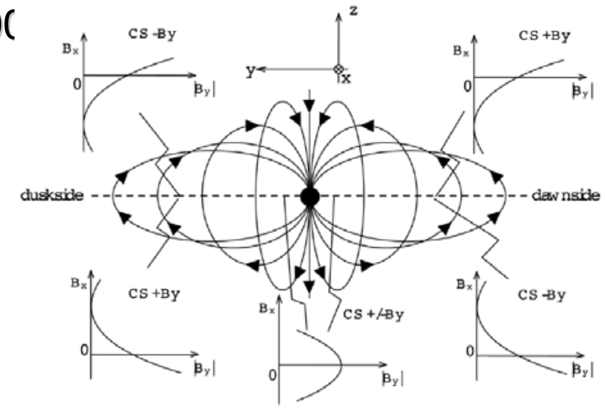


A thin embedded layer has a thickness L_1 less than gyroradius of thermal protons

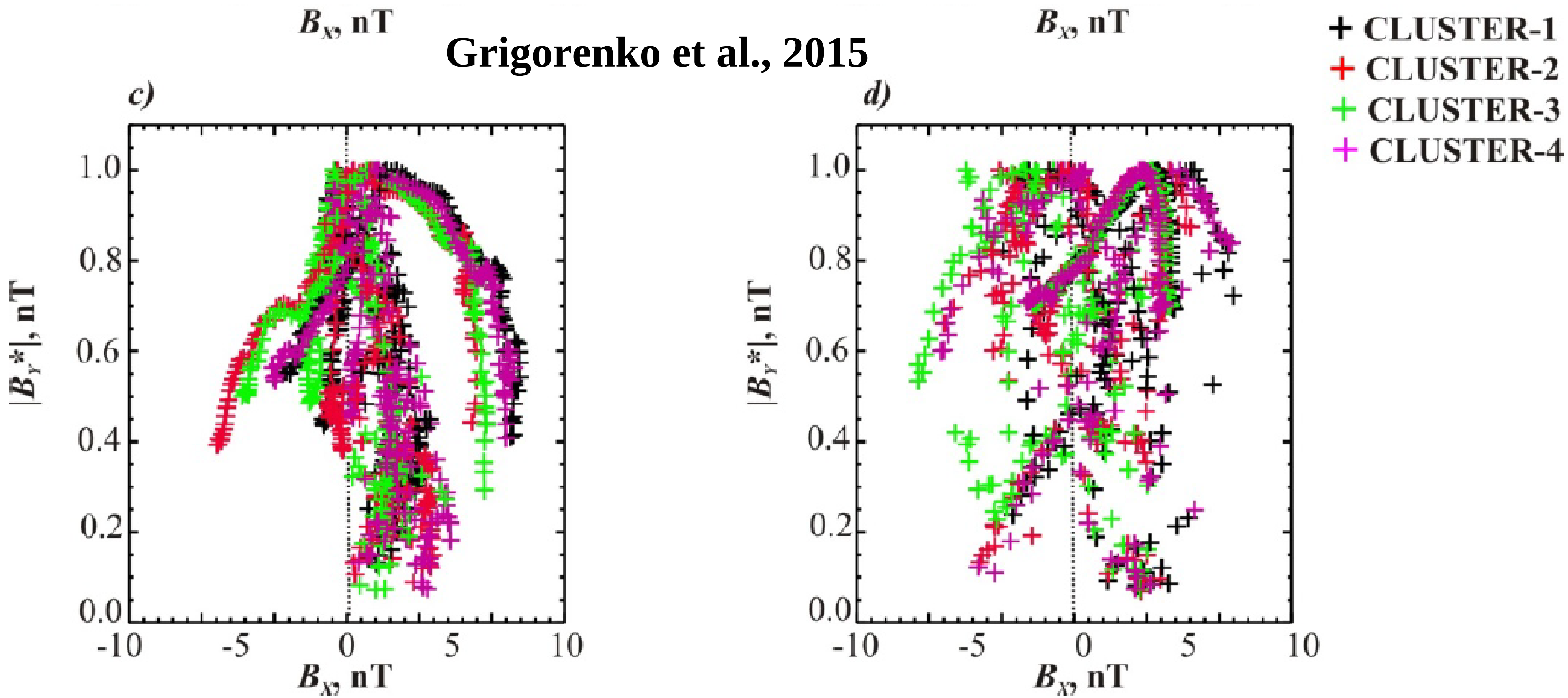
(Grigorenko et al., JGR, 2017)

(Malova et al., ApJ, 2017)

After subtracting the flaring effect, a bell-shaped magnetic field By is demonstrated in TCS (Rong, 20



Sometimes observations of By component in magnetotail current sheet do not correlate with the global magnetic shear in the solar wind (Petrukovich, 2011; Rong et al., 2012).



Grigorenko et al., 2015

Questions

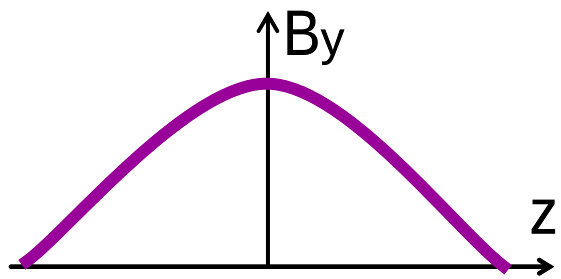
- **What is the particle dynamics in thin current sheet with different shapes of magnetic shear components?**
- **How particle dynamics influence the structure and evolution of thin current sheet?**

The aim of this work is to investigate a quasi-adiabatic particle dynamics in thin current sheet with a guiding field and to understand its influence to the current sheet structure

Three possible shapes of the shear magnetic component in thin current sheet

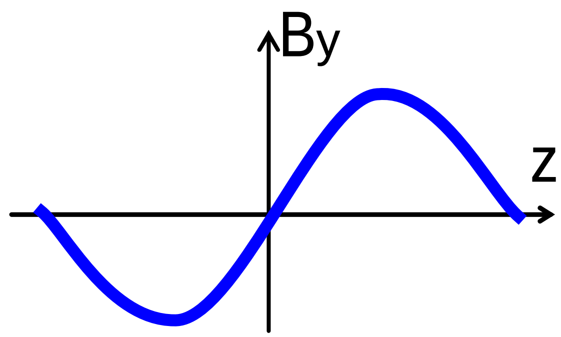
1) Symmetric By(z)

(planetary magnetotails)



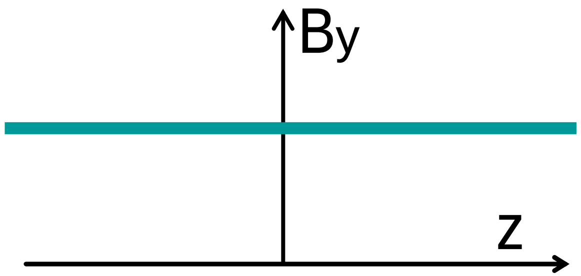
2) Antisymmetric By(z)

(Heliospheric and strong current sheets, planetary magnetotails)



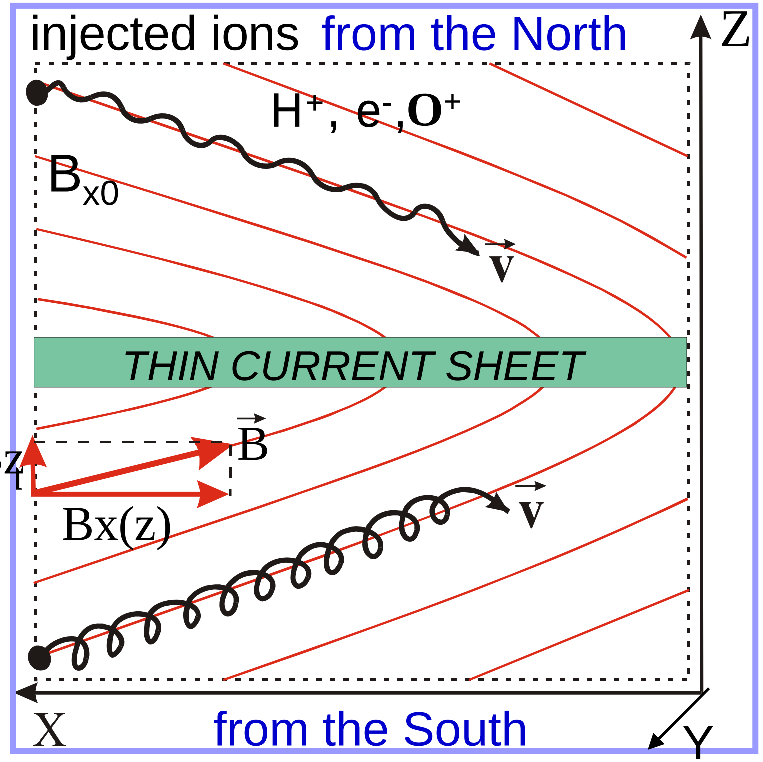
3) By=const

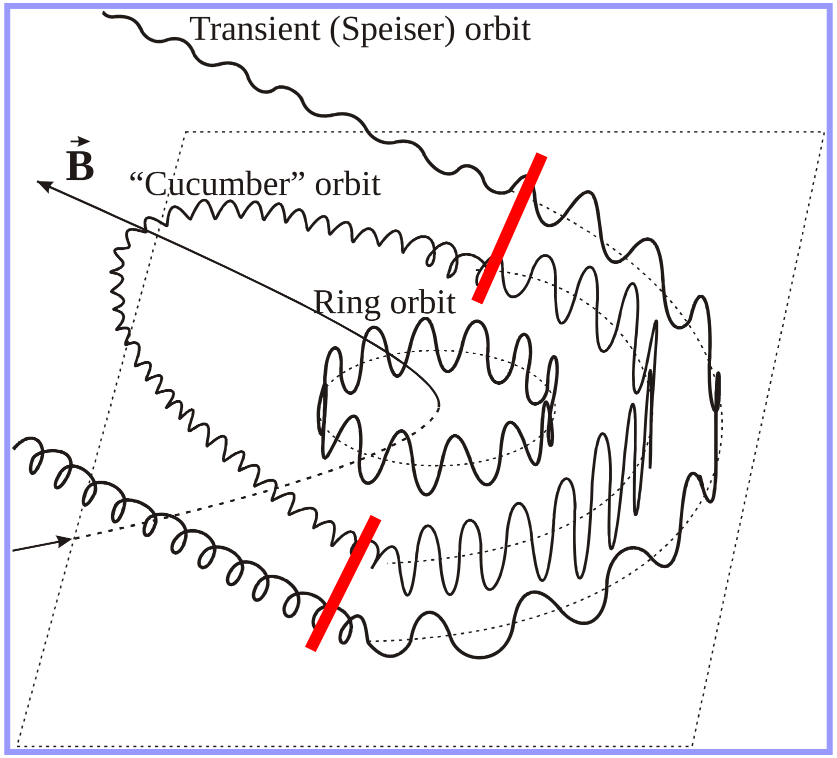
(planetary magnetotails, magnetopauses, Current structures in the solar wind)



Remark: In the case of a different sign of the shear component By(z) all results presented below have mirror symmetry relatively the neutral plane Z=0

Quasi-adiabatic (QA) ion dynamics in the field $\mathbf{B} = \{B_{x0}(z/L), B_y(z), B_z\}$





$$m\frac{d^2\vec{\mathbf{R}}}{dT^2} = \frac{e}{c}[\vec{\mathbf{V}} \times \vec{\mathbf{B}}] + e\vec{\mathbf{E}}$$

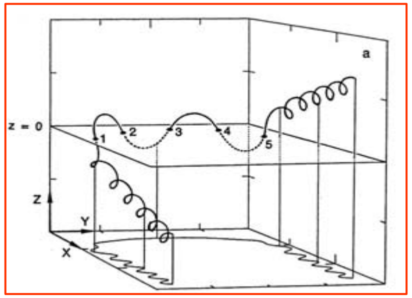
$$I_z \equiv \frac{1}{2\pi}\oint m v_z dz \approx const,\ E = const,\ P_y = const$$

The quasi-adiabatic integral Iz is approximately conserved during ion motion. Its jumps during separatrix crossing are much smaller than the value of the QA integral itself

$$\Delta I_z \ll I_z$$

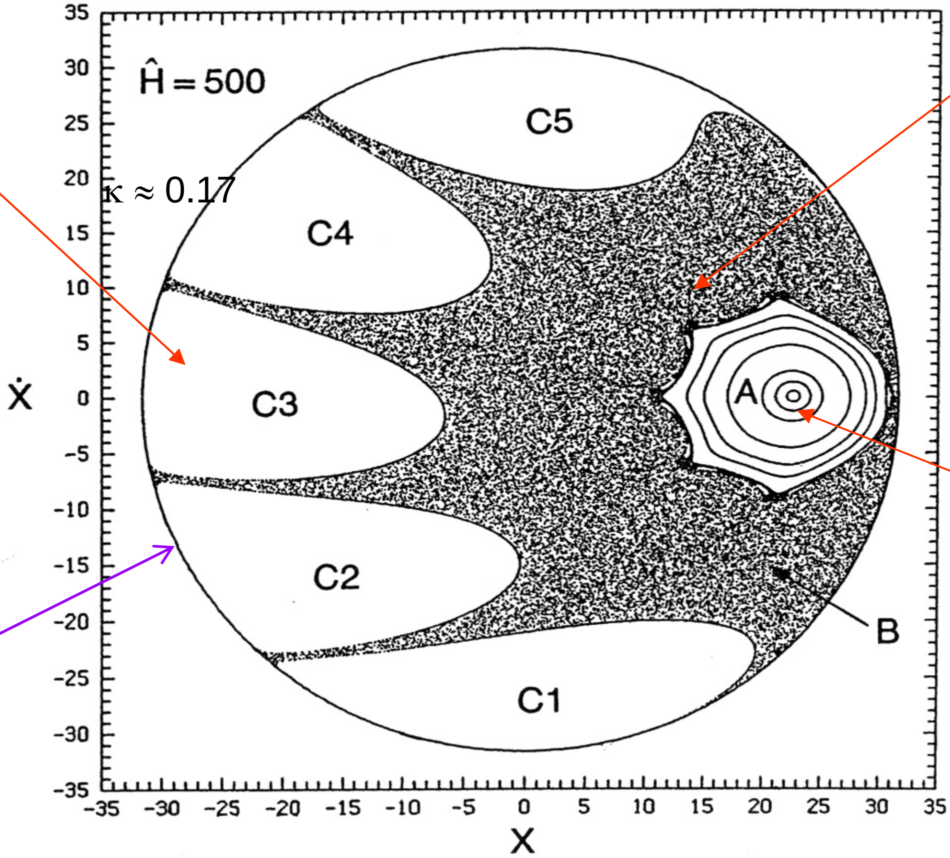
Poincaré map: partitioning of a phase space for quasi-adiabatic ion dynamics in thin current sheets

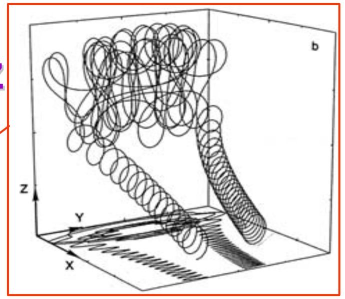
$$I_z \equiv \frac{1}{2\pi}\oint m v_z dz \approx const$$



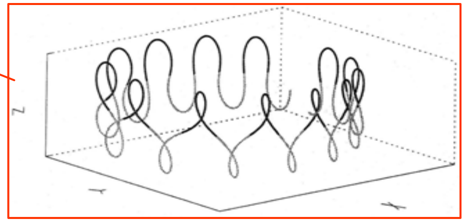
transient particle ("Speiser")

Approximate quasi-adiabatic integral of motion Iz





quasi-trapped trajectory ("cucumber")

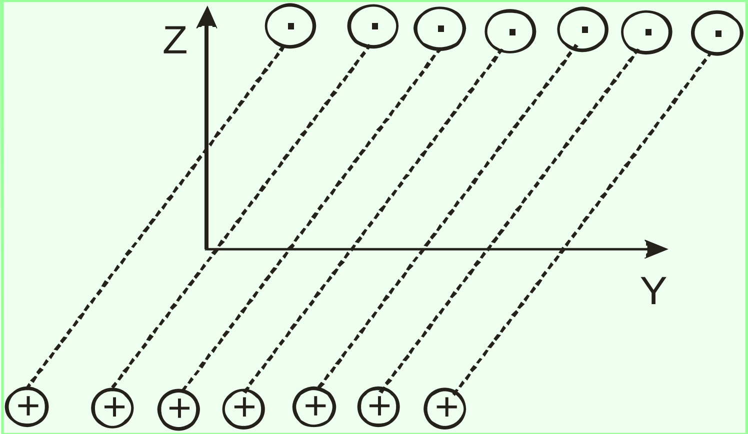


Trapped ion trajectory

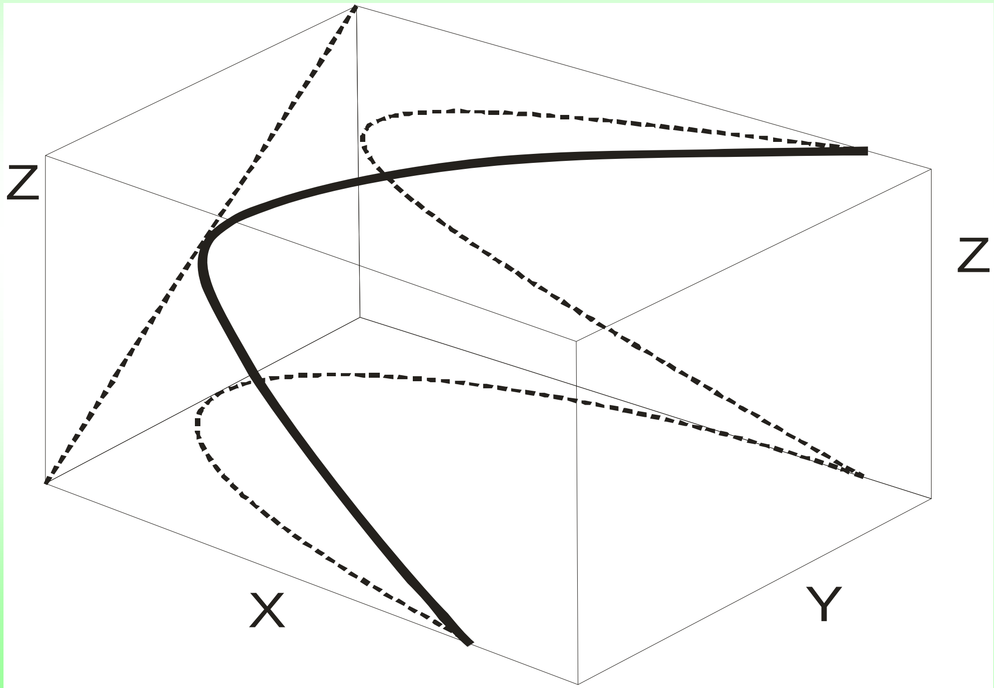
Surface of Section Plot (Poincaré map is the set of normalized crossing points of CS plane z=0)

Chen, 1992
Buchner and Zelenyi, JGR, 1989

Magnetic field lines configuration at the constant By

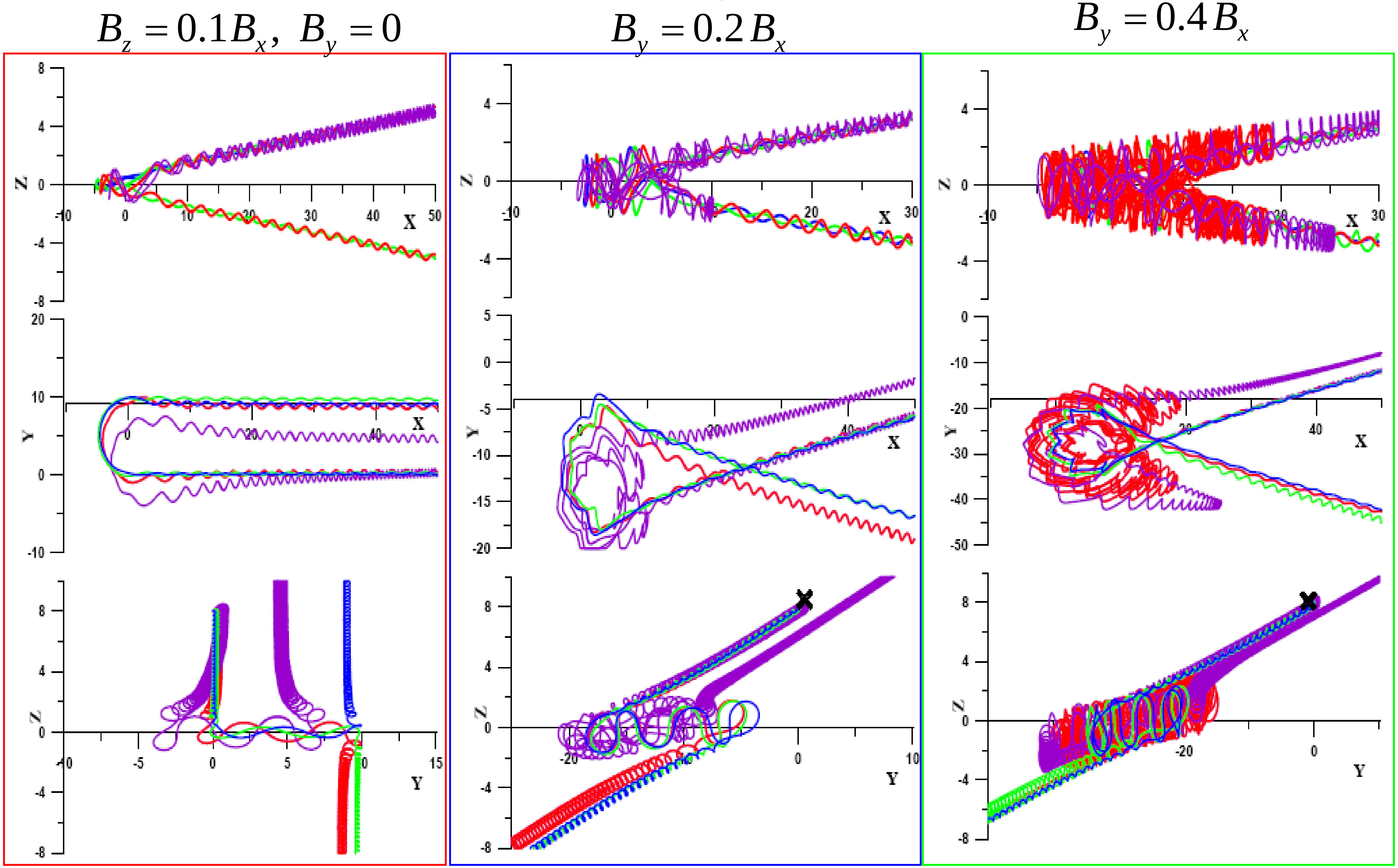


$$By = const$$



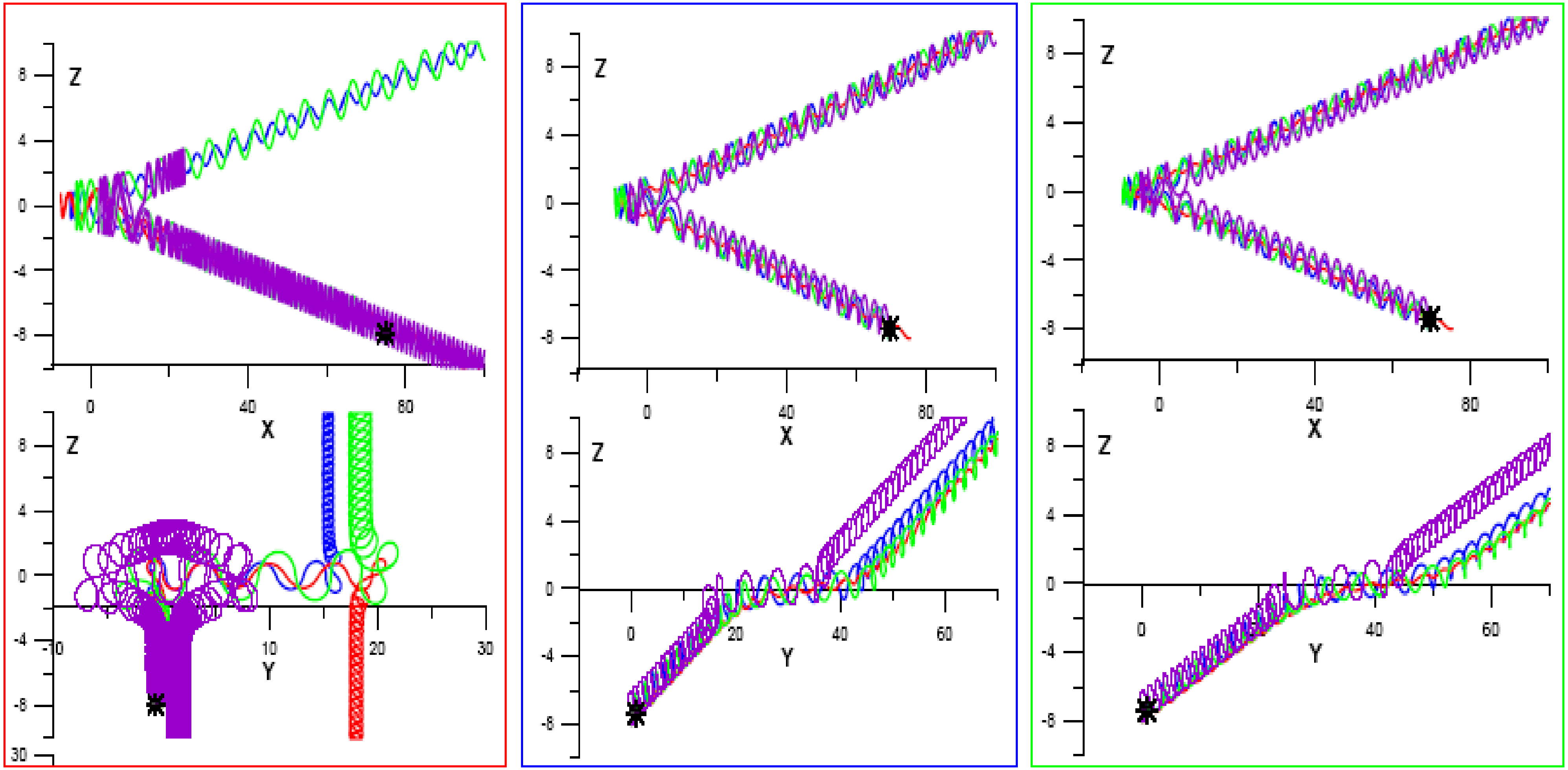
During numerical experiment protons were traced from the Northern to the Southern (marked as N -> S) hemisphere toward the current sheet and from the Southern to the Northern hemisphere (S -> N)

Trajectories of 4 particles launched from the North hemisphere (N->S) at different By values

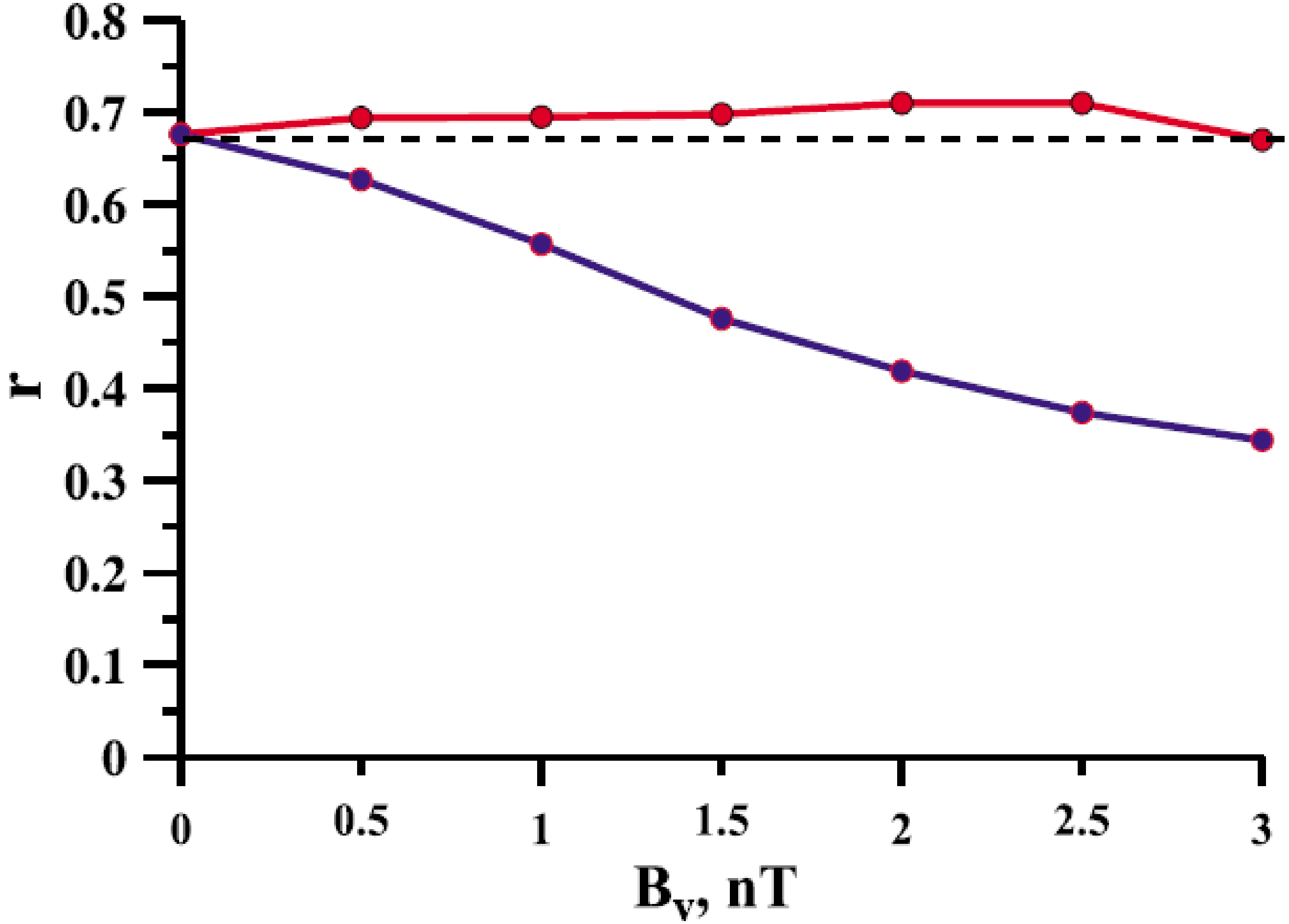


Scattering of 4 particles launched from the Southern hemisphere (S->N) at different By values

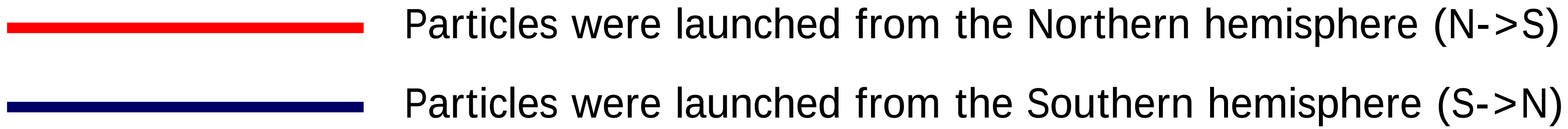
$B_z = 0.1 B_x, \; B_y = 0$ | $B_y = 0.2 B_x$ | $B_y = 0.4 B_x$



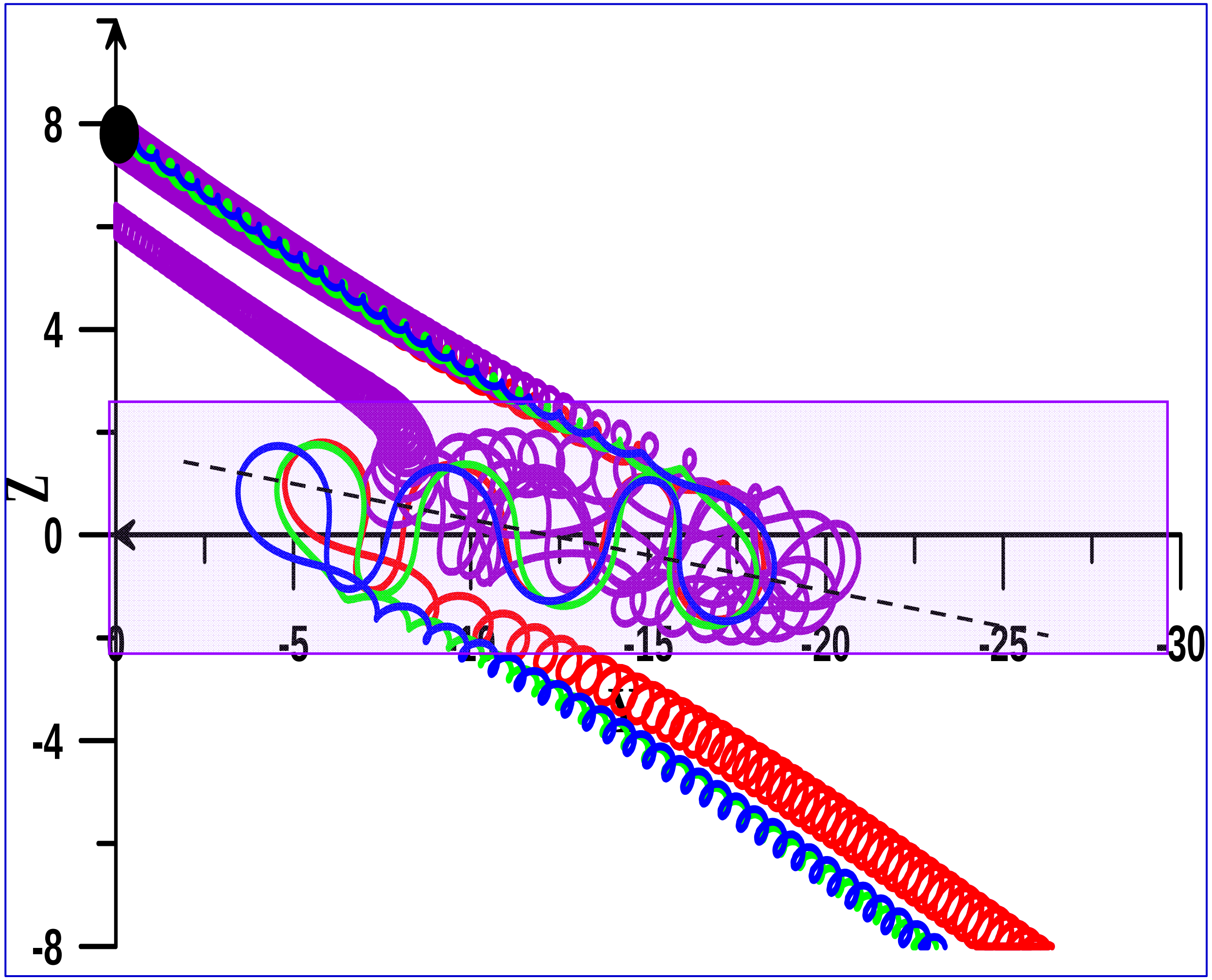
Asymmetry of particle scattering at By-const
Coefficient of plasma reflection $r=n_{ref}/n_0$ as a function of the value of magnetic component By

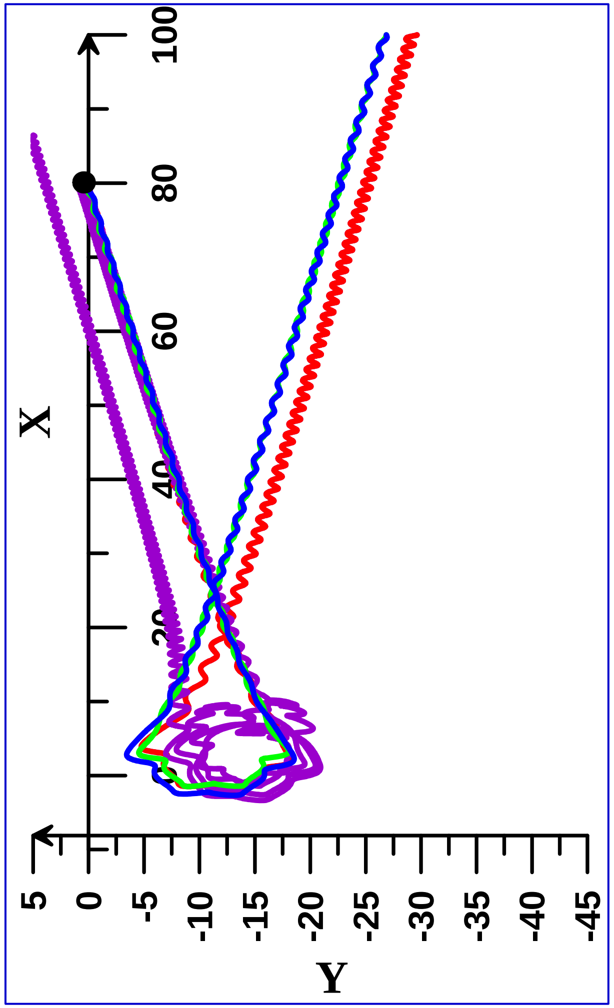


Coefficient $r=n_{ref}/n_0$ is the relative density of ions n_{ref} reflected from the neutral plane relatively the total density n_0



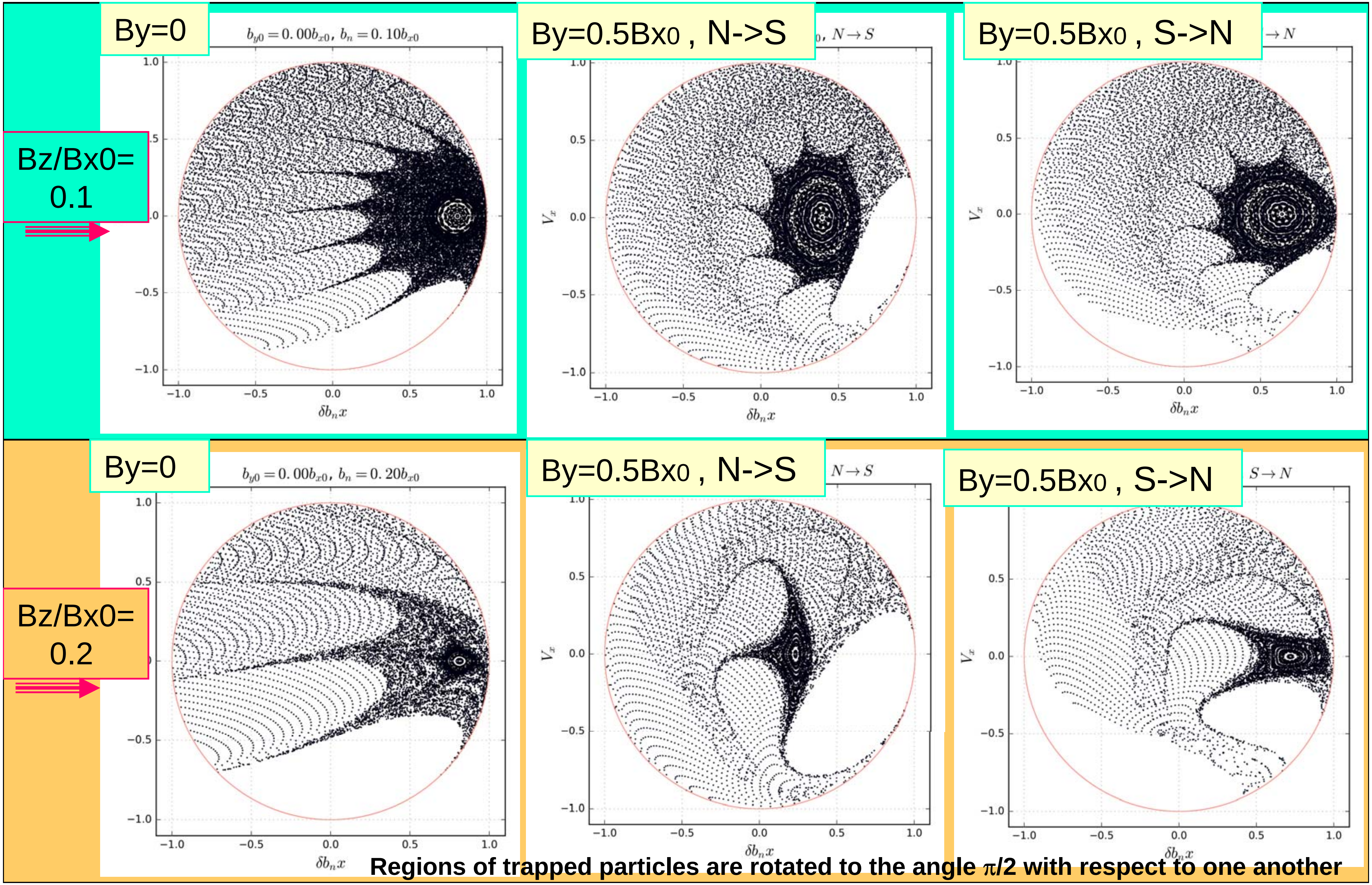
Particle dynamics at B_Y/B_{x0}=const: Current sheet is thickened due to the geometric effect (tilting of the meandering plane)





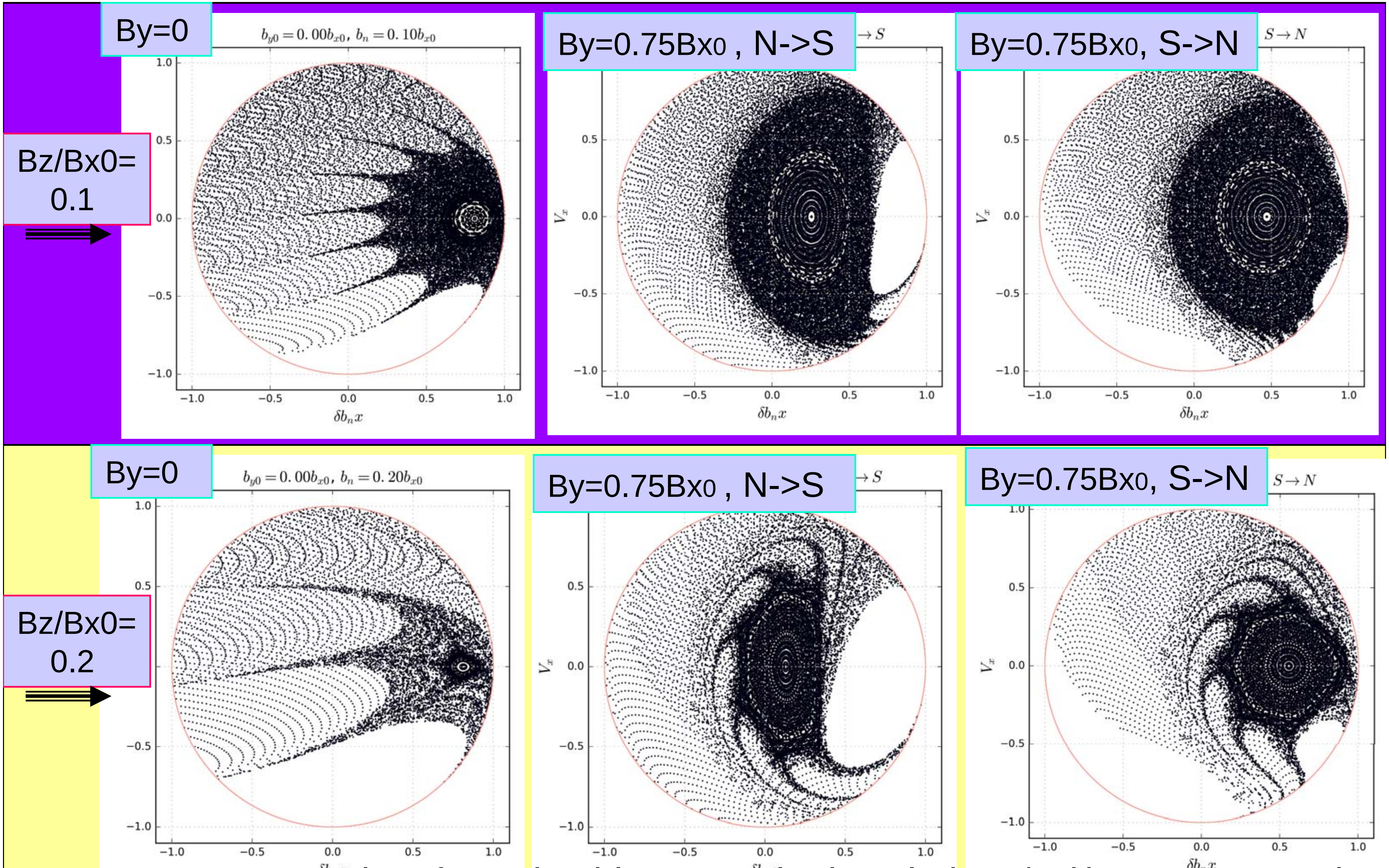
B_{x0} is the tangential magnetic field value at the edges of current sheet

Poincaré sections of quasi-adiabatic particle motion (By=const)



Regions of trapped particles are rotated to the angle $\pi/2$ with respect to one another

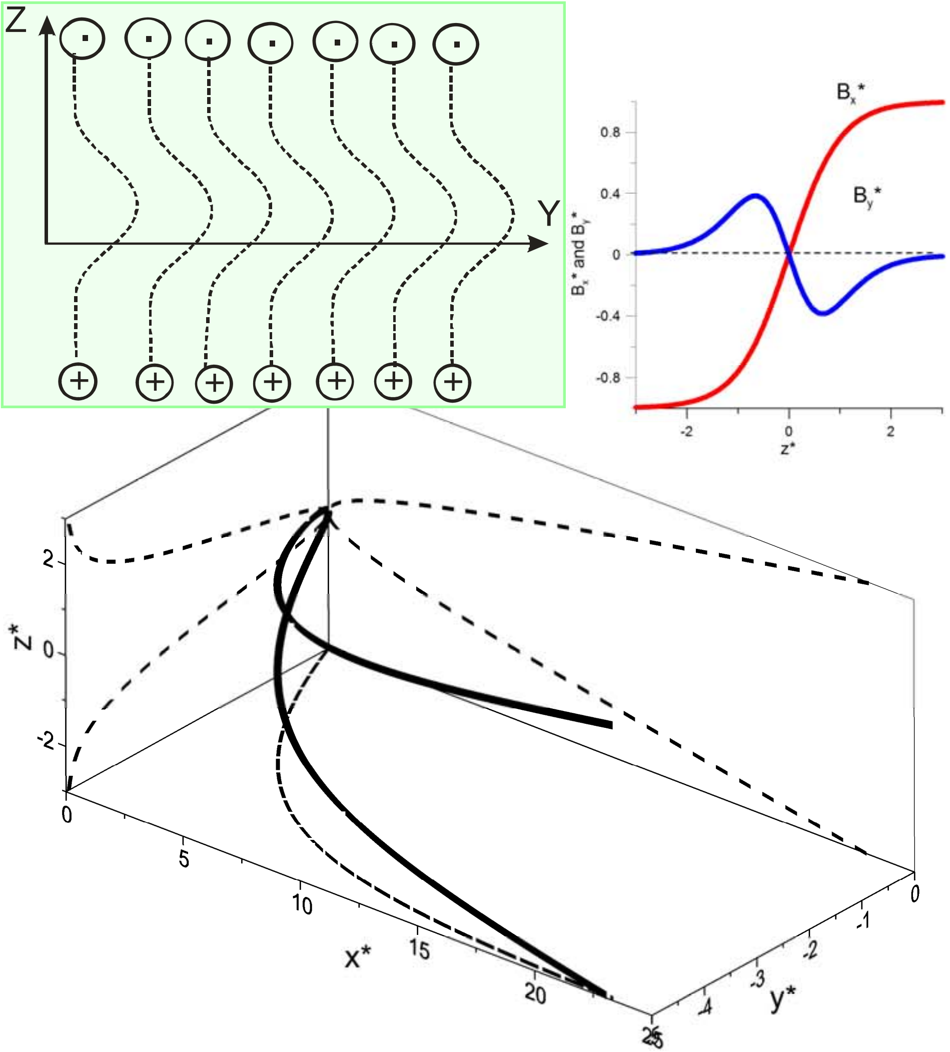
Poincaré sections of quasi-adiabatic particle motion (By=const)



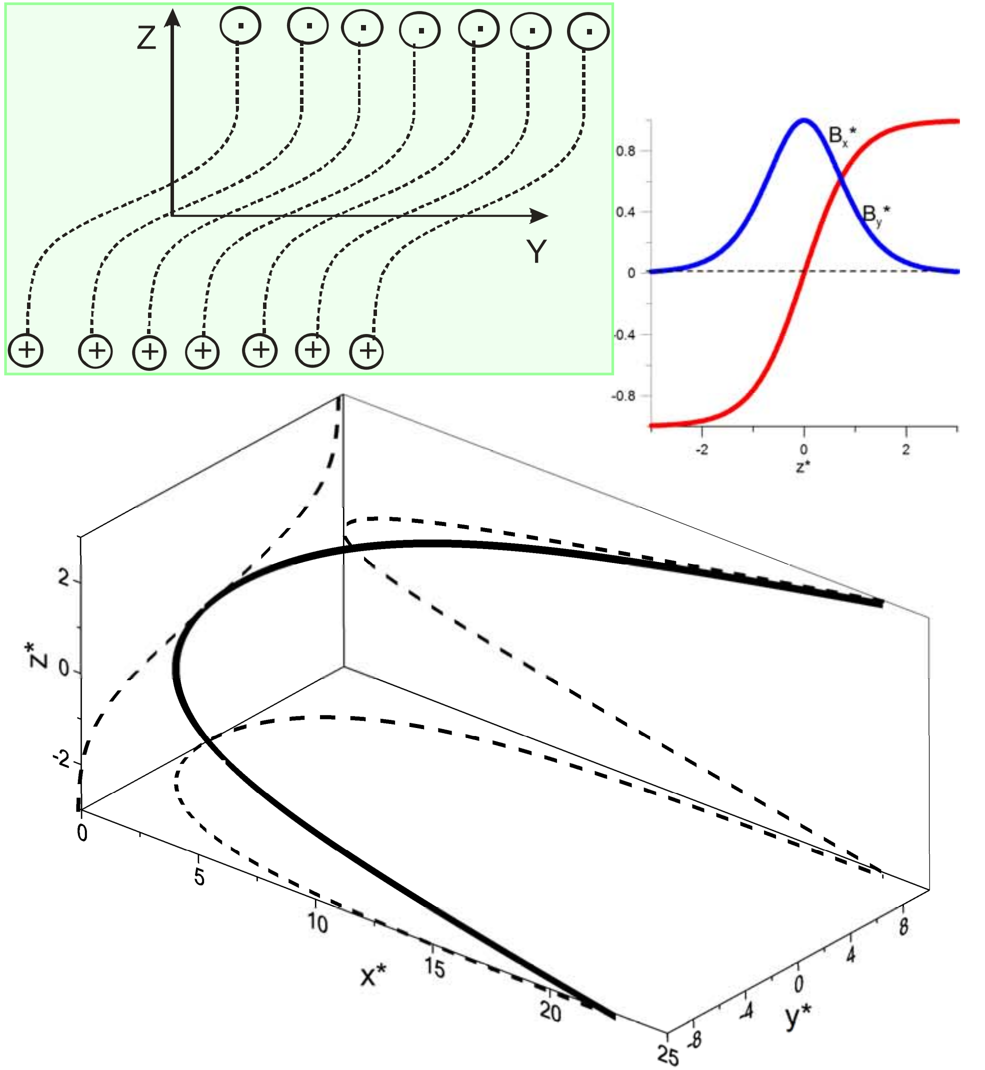
Regions of trapped particles are rotated to the angle about $\pi/2$ with respect to one another

Two magnetic field lines configurations By(z)

$B_y = B_y(z)$ *antisymmetric*

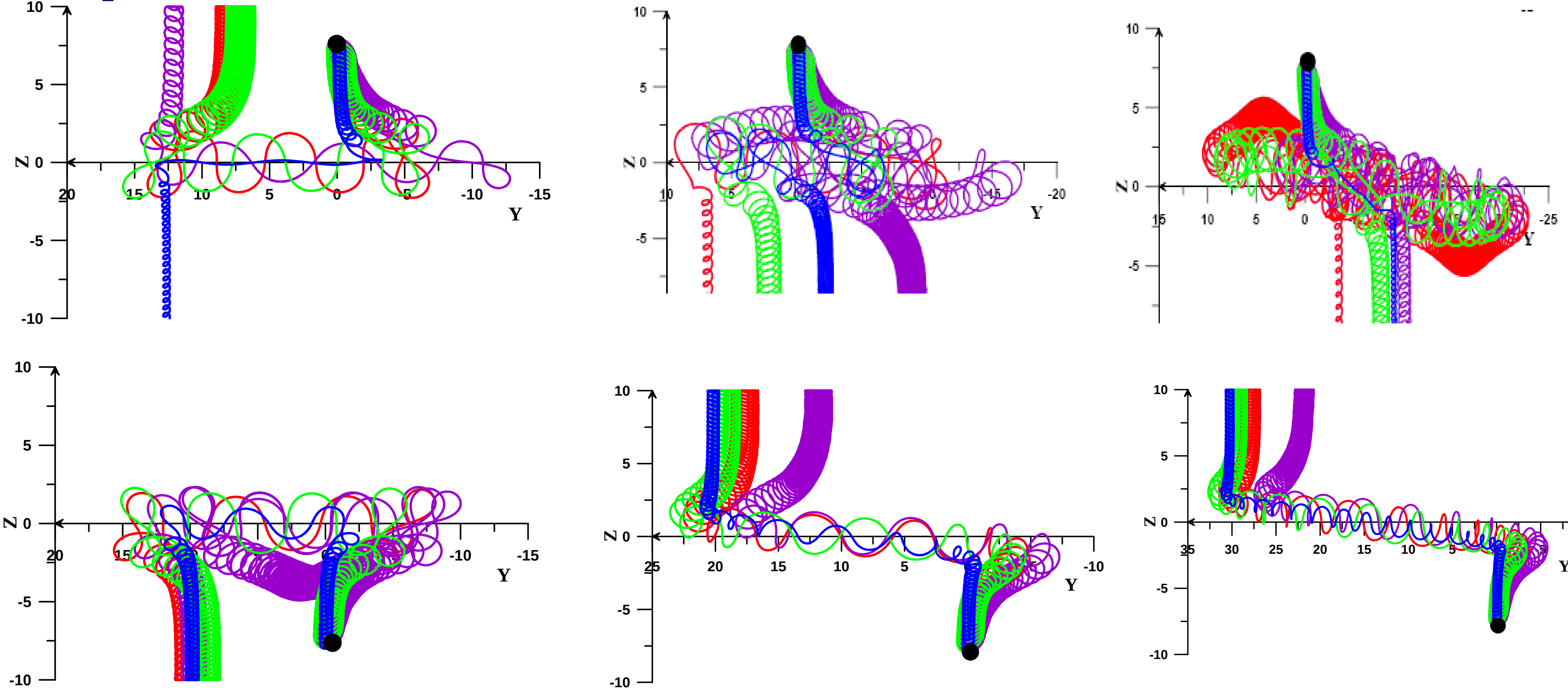


$B_y = B_y(z)$ *symmetric*



Particle trajectories in thin current sheet with bell-shape (symmetric) By(z)

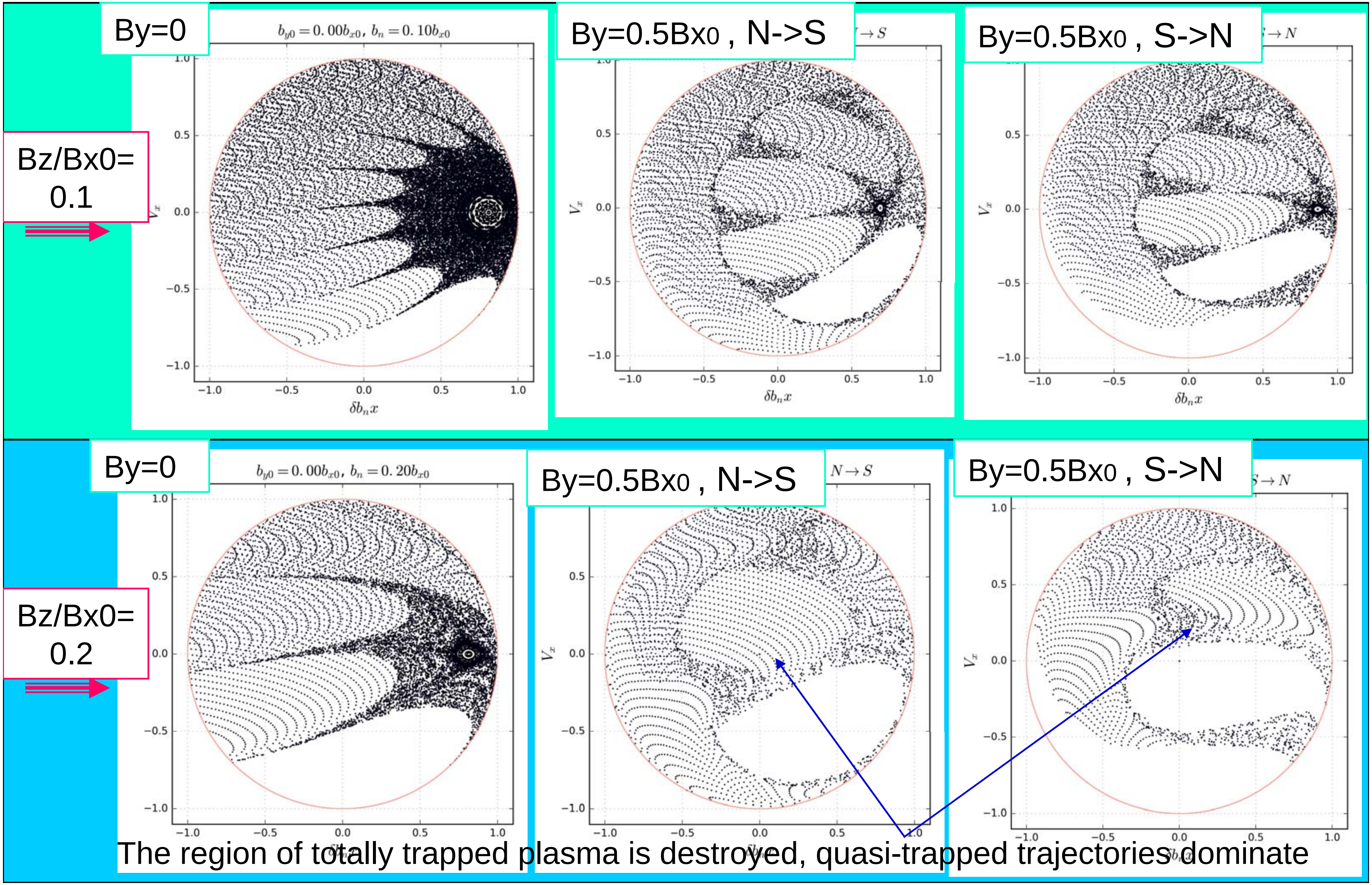
Amplitude of By(z) increases from the left to the right: By0/Bx0=0; 0.4; 0.8. The upper set of trajectories corresponds to the Northern source, the bottom set corresponds to the Southern one.



By0/Bx0= 0; 0.4; 0.8

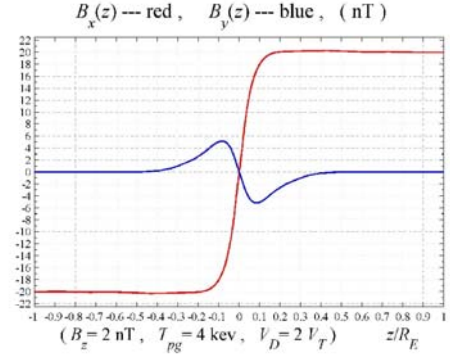
General effect: TCS is thickened due to the tilt of meandering plane relatively the neutral plane

Poincaré sections of quasi-adiabatic particle motion (By is bell-shaped)

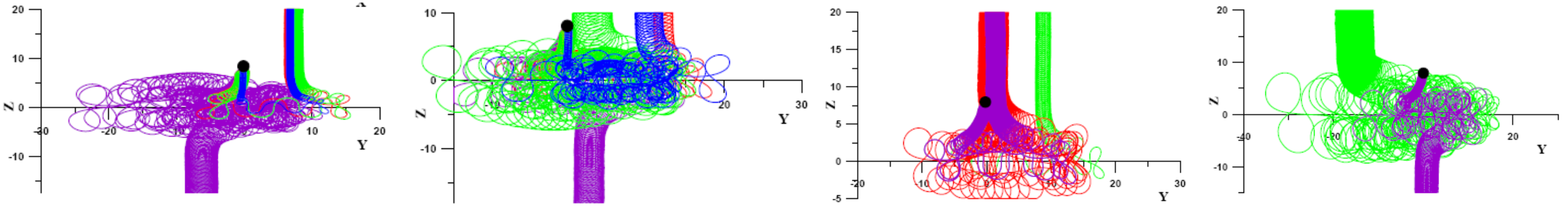


Particle motion in the presence of the asymmetric By(z) component

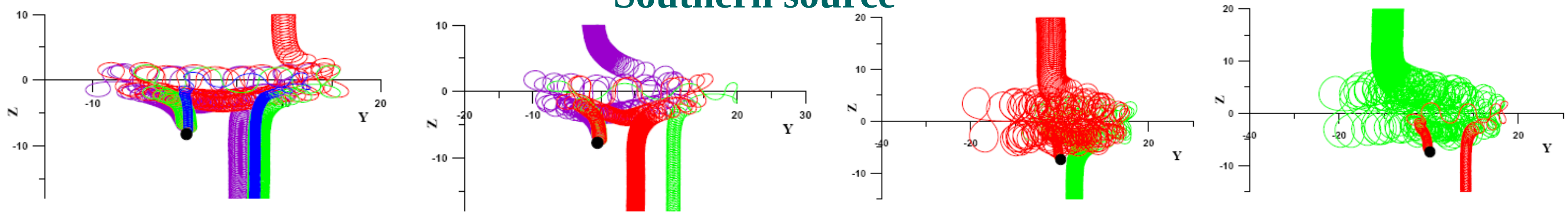
In the presence of asymmetrical By shear component the characteristic changes of By~sin(z/L) are less than the transverse scale of meandering motion $\rho \sim L$. As a result most of particles with large Larmor radii almost do not feel the changes of magnetic field and their motion is not influenced strongly by the shear magnetic component. As a result the QA character of motion is conserved and the general part of current in thin current sheet is carried by ions in meandering (serpentine-like) orbits



Northern source



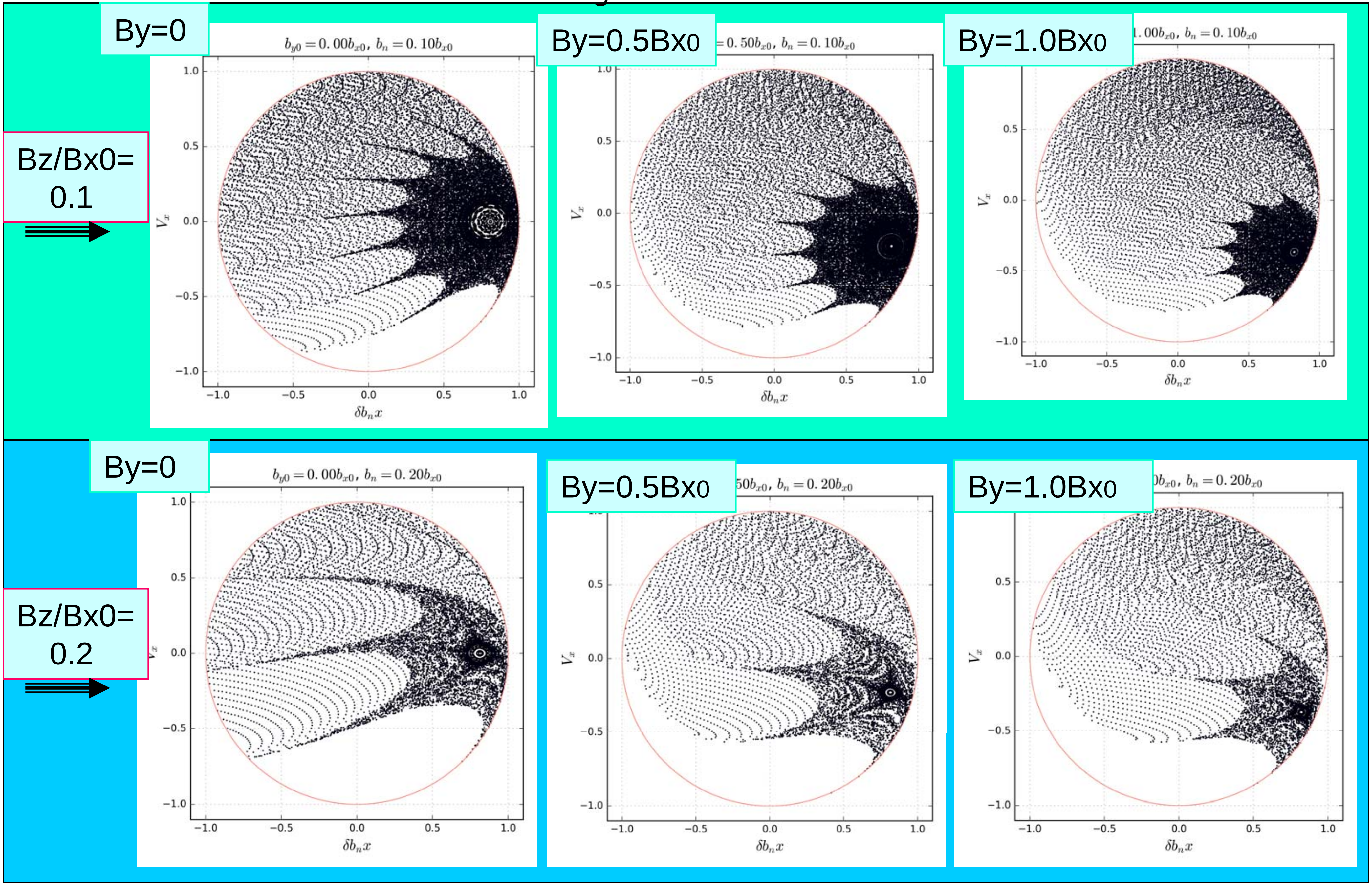
Southern source



B_y/B_{x0} = 0.1, 0.2, 0.3 0.4

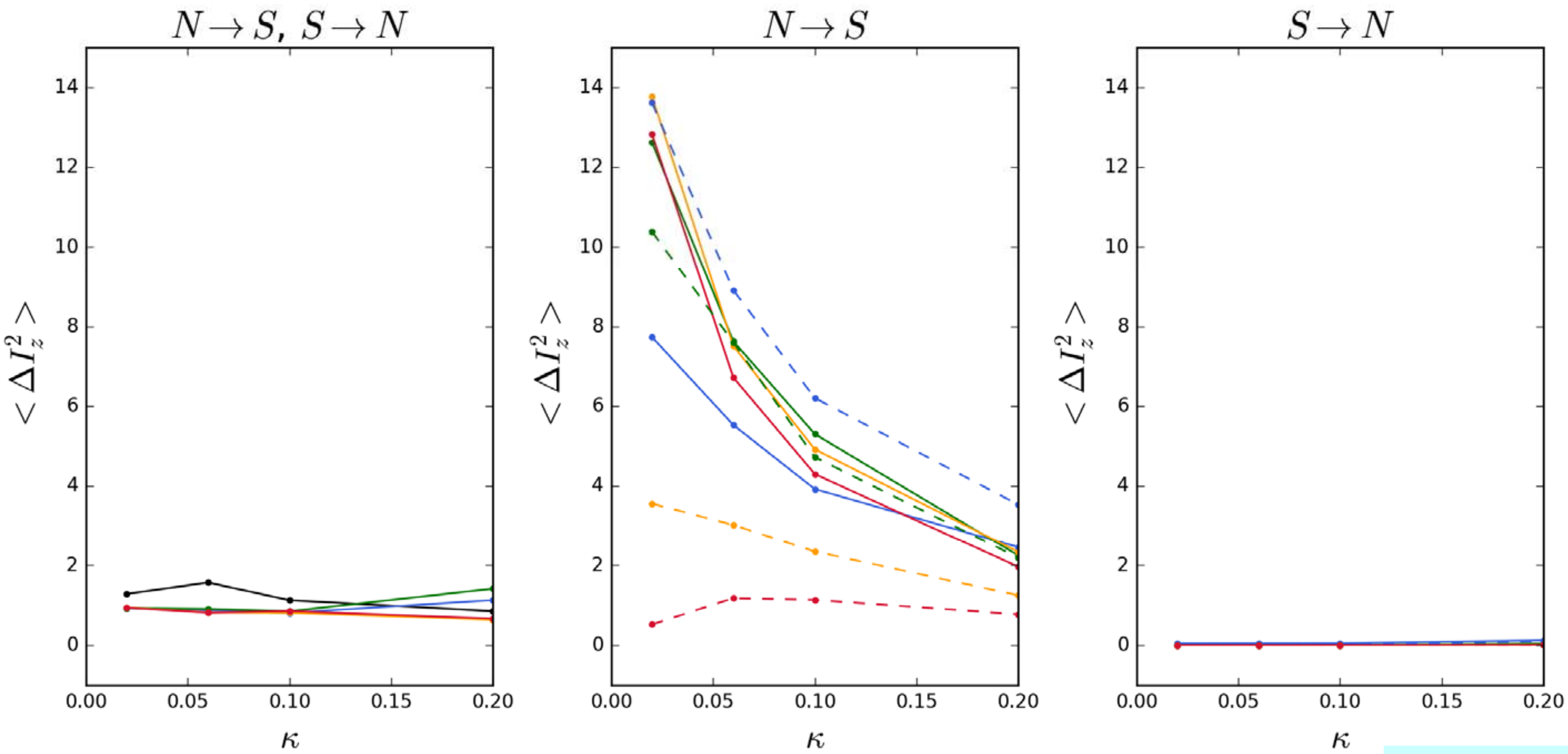
Poincaré sections of quasi-adiabatic particle motion (By is antisymmetric)

Particle scattering is the same in N->S and S->N directions



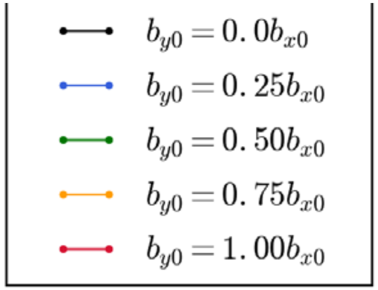
The squares of the values of adiabatic invariant Iz jumps

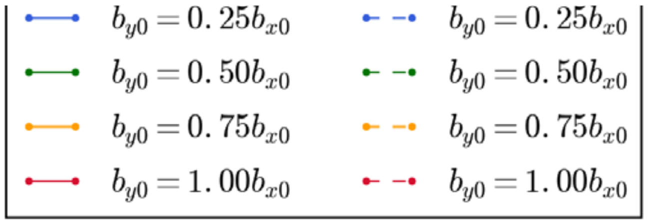
as functions of parameter of adiabaticity kappa



Shearless and antisymmetric By

Bell-shaped constant By





parameter of adiabaticity

$$\kappa = \sqrt{\frac{R_{\min}}{\rho_{\max}}}$$

$$R_{\min} = \frac{b_n}{db/dz}\Big|_{z=0}$$

Conclusions:

Numerical analysis of particle dynamic in thin current sheets (TCSs) taking (or do not taking) into account the magnetic shear component has shown that:

1) Particle dynamics is different in TCSs having three general shapes of magnetic shear component: (A) constant; (B) symmetric; (C) antisymmetric relatively neutral plane; and in (D) shearless configuration.

2) In the cases (A) and (B) particle scattering near the neutral plane is asymmetric and depends on the location of the plasma source in Northern or Southern hemispheres. Ions originated from the Northern hemisphere are scattered stronger in comparison with particles from the Southern hemisphere, their jumps of quasi-adiabatic invariants Iz tends to small value proportional to the value of By component. The direction of scattering depends on the sign of By (and has mirror symmetry relatively z=0 plane). As a result the plasma density from both sides of CS plane can be different.

3) In the cases (C) and (D) particle scattering does not depend on plasma source location, and there is no difference between the jumps of particles going from the North or the South toward current sheet. The Poincaré sections and Iz jumps are identical for particles with the same parameters going in N->S and S->N directions.

4) Current sheet thickness is larger in configurations (A) and (B) due to geometric effect (the tilting of a meandering plane of ions). CS thickness does not change in the configuration (C) in comparison with (D).

Thank you for your attention!