Solar Flare Physics
and
Solar Cosmic Ray Problem

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A large solar flare is the first link in the long complicated chain of physical phemomena that we call the problem of solar cosmic rays

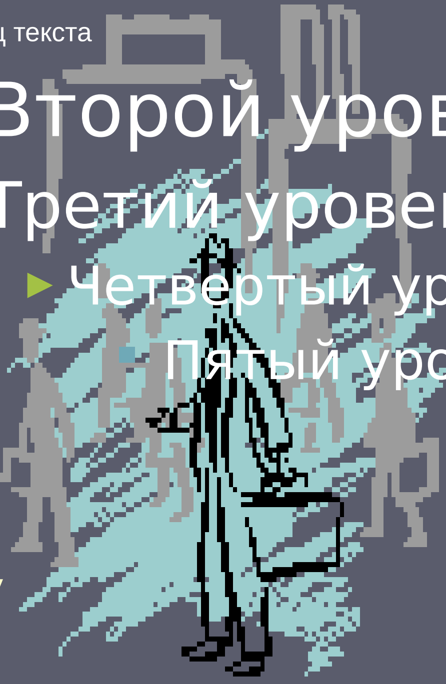
- Modern space experiments:

How are charged particles accelerated in a solar flare to highest energies ?

- Solar flare physics:

... in two steps ...

More specifically ?



- Образец текста
  - Второй уровен
  - Третий уровень
    - Четвертый уровен
      - Пятый уровен

The first step and the first problem!

Why?

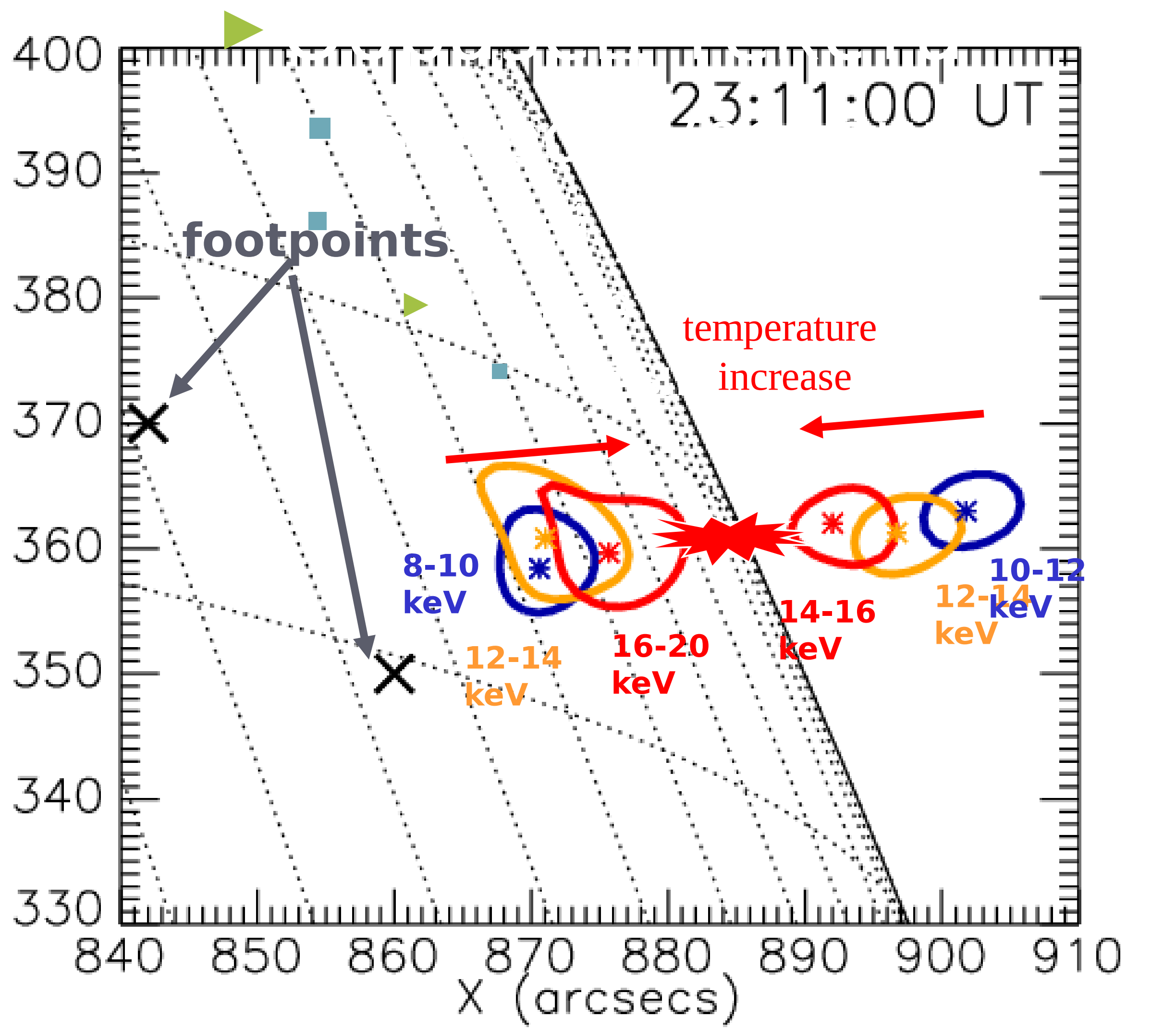
The first step and the first problem

Observational problem
No. 1

We do not see
the primary source of
energy
in a solar flare.

What do you see, indeed?

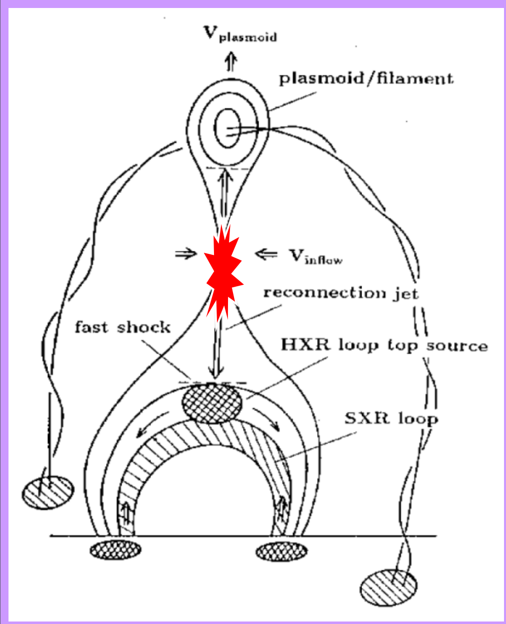
For example: Temperature distribution near the source of energy



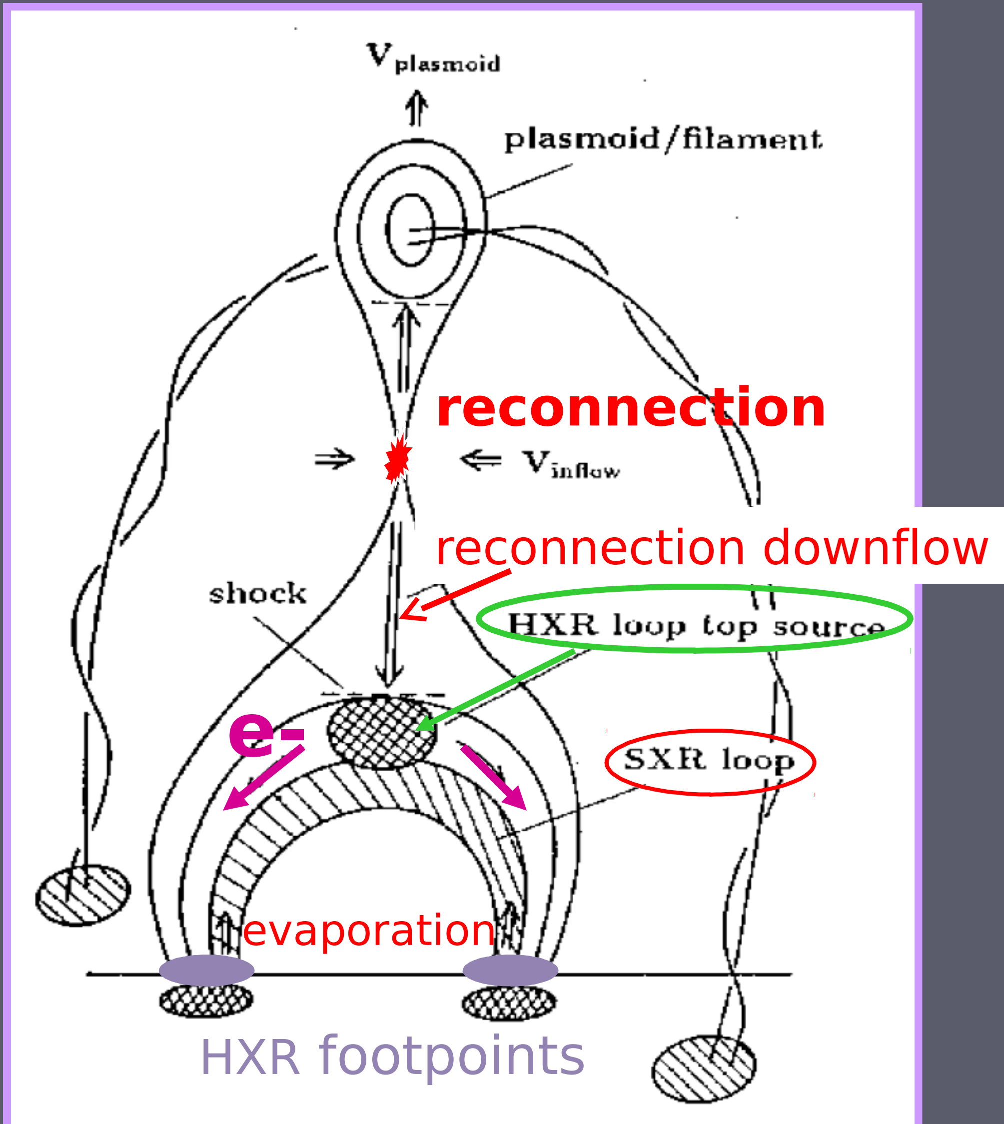
Sui, Holman,

Thanks to S. Krucker

How can we observe the **super-hot turbulent-current layer** (**SHTCL**, Somov, 2013) ?



Magnetic reconnection interpretation

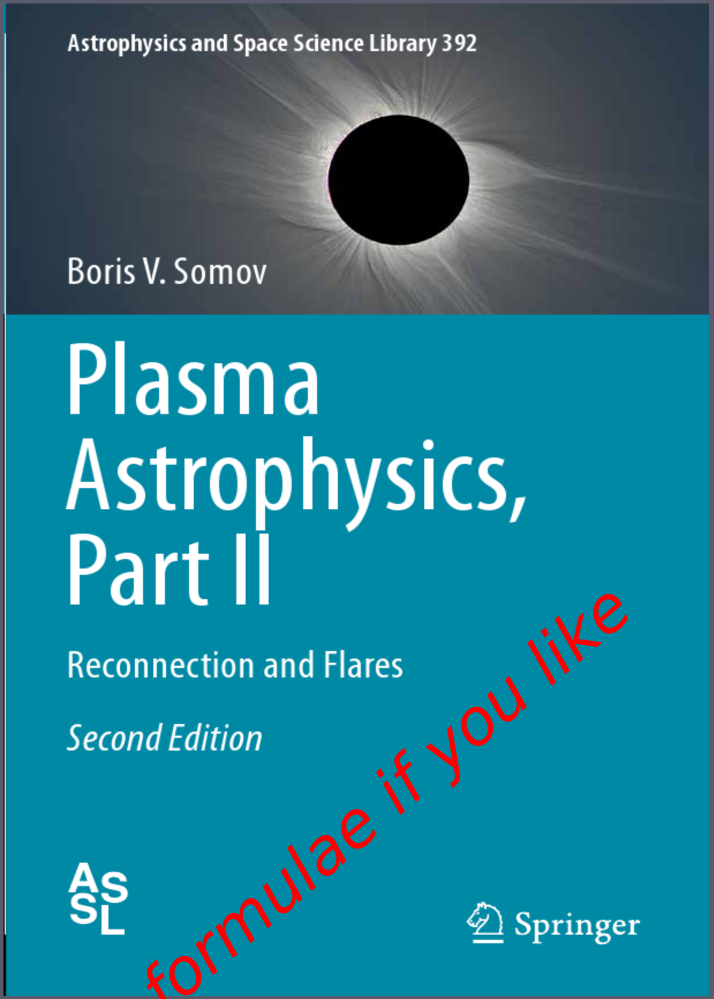


1) Release of magnetic energy
2) Accelerated electrons produce HXRs and heat plasma
3) RHESSI provides the first pieces of quantitative evidence for reconnection in flares.

Не всё так плохо, как кажется. Видим всё, кроме источника Энергии.

What does follow from the theory?

Thermal and non-thermal XR emissions from the corona can be interpreted involving a reconnecting super-hot turbulent-current layer as the source of flare energy



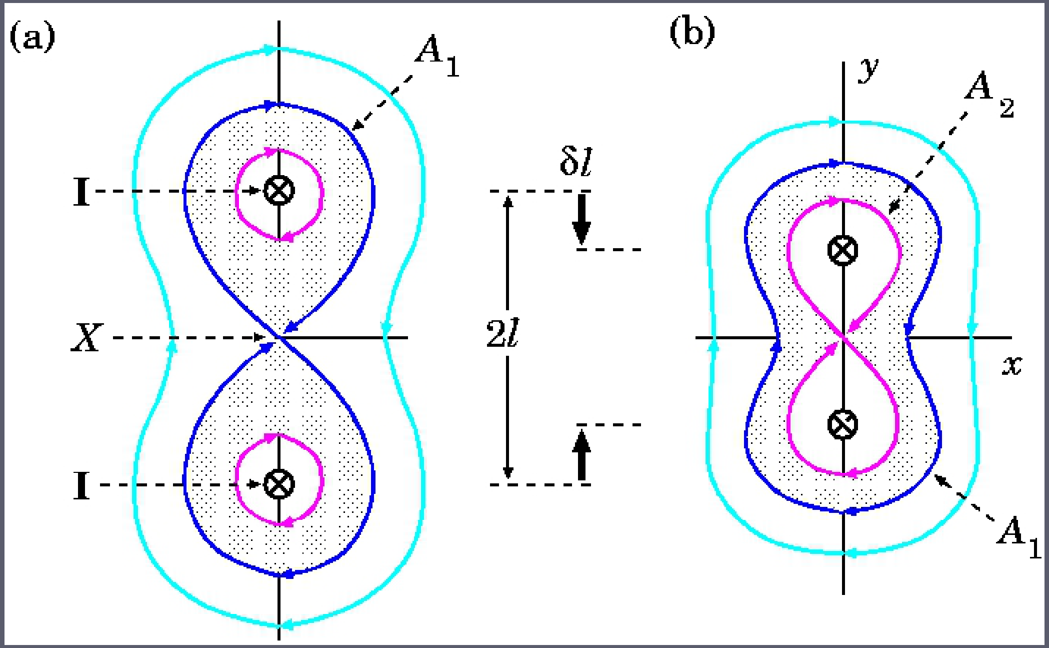
Many formulae if you like them

Somov B.V., *Plasma Astrophysics, Part II, Reconnection and Flares, Second Edition,*

Springer SBM, New York, 2013

What is reconnection?
Why and how?

What is reconnection in vacuum ?



The magnetic field of two parallel currents I

- (a) An initial state, *2l* is a distance between the currents
- (b) The final state after the currents have been drawn nearer by a dispacement *δl*

Reconnection in vacuum is a real physical process

Reconnection is inevitably associated with electric field

$$\mathbf{E} = -\frac{1}{c}\frac{\partial \mathbf{A}}{\partial t}\,, \qquad (1)$$

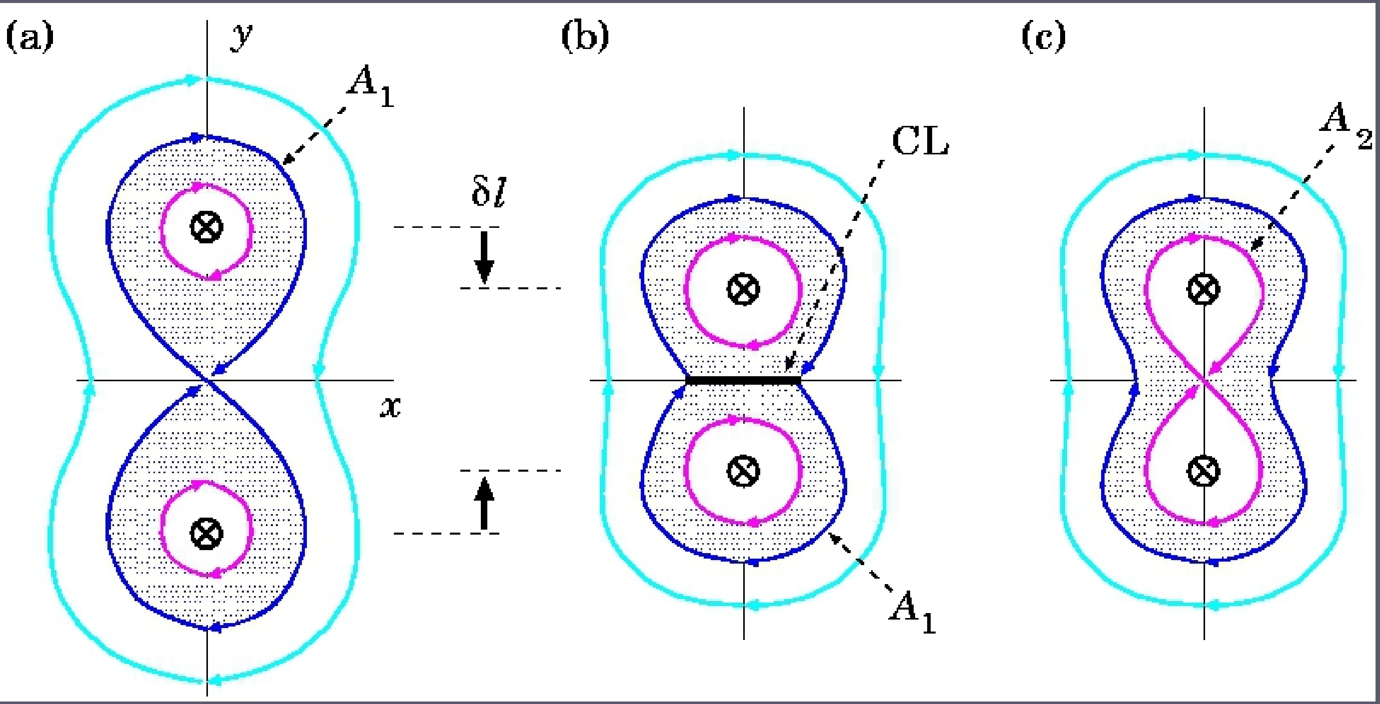
where $\mathbf{A}$ is the vector potential, $\mathbf{B} = \mathrm{curl}\,\mathbf{A}$.

If δt is the characteristic time of reconnection, then

$$E \approx \frac{1}{c}\frac{\delta A}{\delta t} \approx \frac{1}{c}\frac{A_2 - A_1}{\delta t}\,. \qquad (2)$$

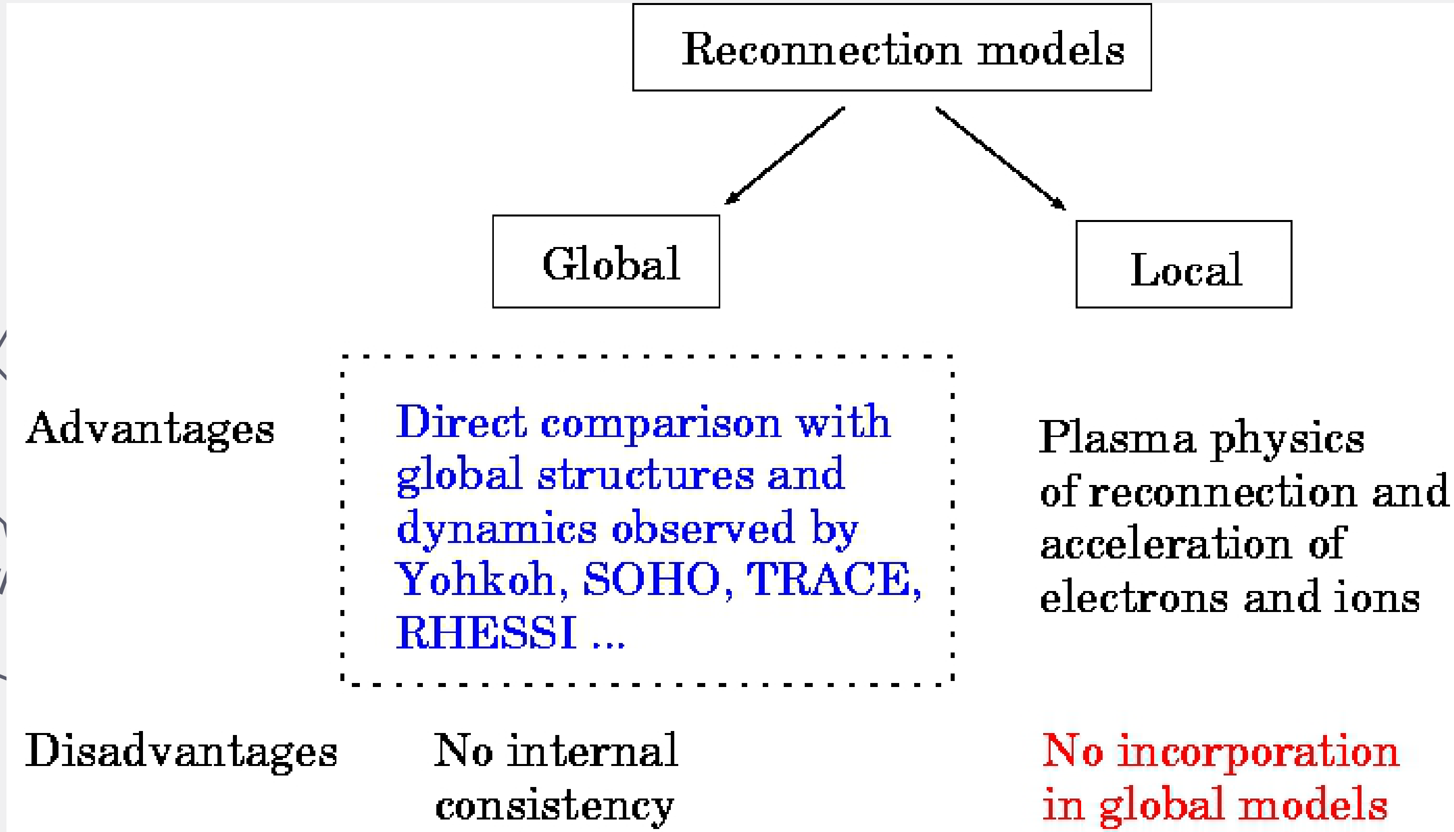
- Magnetic field lines move to the X-type neutral point
- The electric field is induced and accelerates particles

What about Reconnection in Plasma?



- (a) The initial state
- (b) The pre-reconnection state with a current layer (CL)
- (c) The final state after reconnection

Flare Reconnection Models

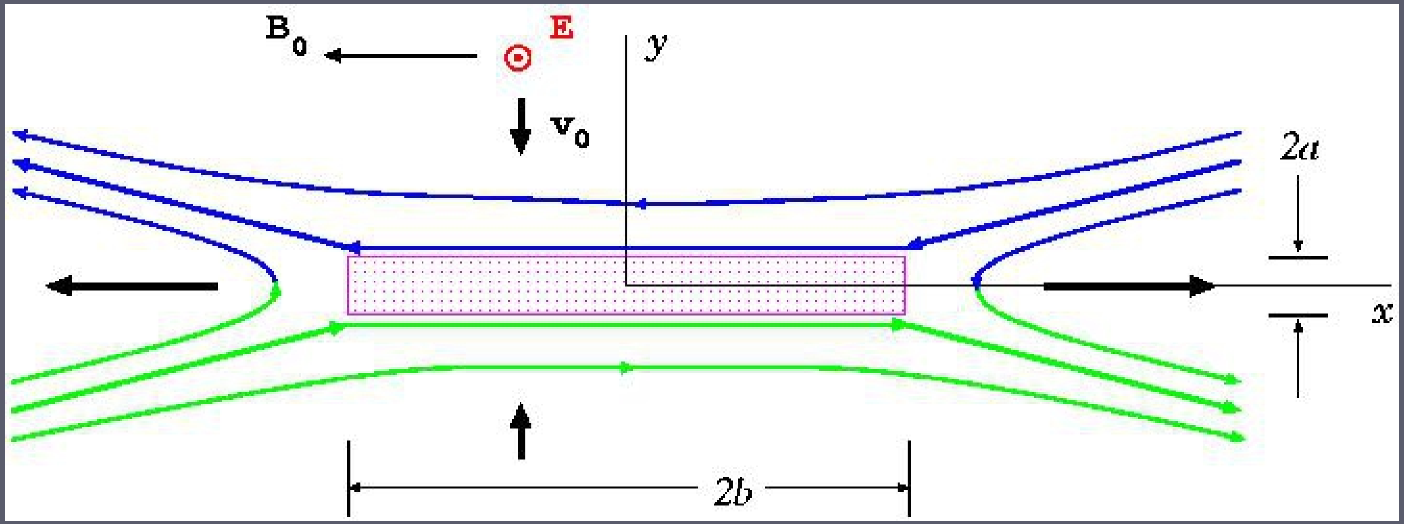


- Future models should join global and local properties of reconnection in the flares

Local Models

- Reconnecting Current Layer (RCL; Sweet, Parker, Syrovatskii)
- Super-Hot Turbulent-Current Layer (SHTCL; SAI of the MSU)

Reconnecting Current Layer (RCL)



- RCL is at least two-dimensional and two-scale formation
- The wider the RCL, the larger the magnetic energy accumulated
- A small thickness *2a* is responsible for high rate of dissipation

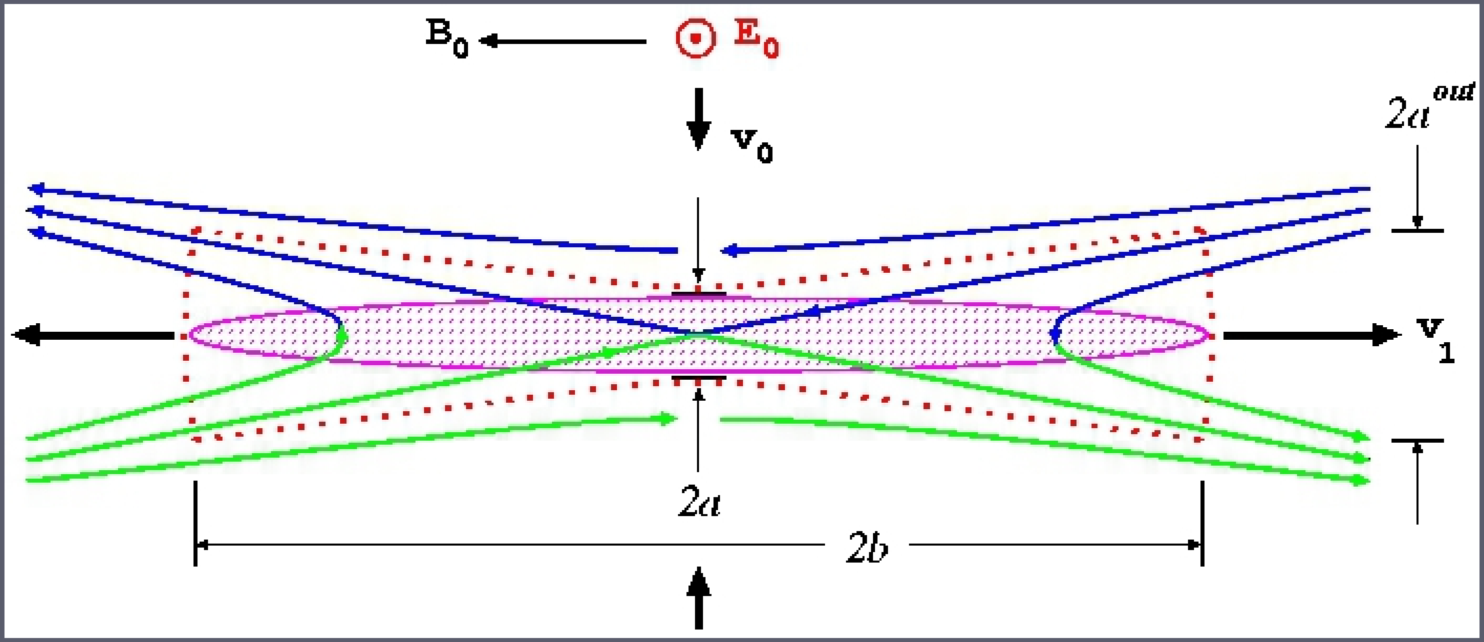
Super-Hot Turbulent-Current Layer (SHTCL)

- Coulomb collisions do not play any role because of a super-high temperature
- Collisionless reconnection (dynamical dissipation; Syrovatskii, 1966) is a primary effect
- Fast conversion from field energy to particle energy (acceleration)

Somov B.V., 2013, *Plasma Astrophysics*, *Part II, Reconnection and Flares, Second Edition,* Springer SBM, New York

Super-Hot Turbulent-Current Layer (SHTCL)

Магнитно не-нейтральный !



- Powerful heating of electrons and ions results from wave-particle interactions

Somov, 2013, *Plasma Astrophysics, Part II*, Springer

Electrons and ions are heated in a different way:

$$\chi_{\rm ef}\,\mathcal{E}^{in}_{mag} + \mathcal{E}^{in}_{th,e} = \mathcal{E}^{out}_{th,e} + \mathcal{C}^{an}_{\parallel}\,, \qquad (1)$$

$$(1-\chi_{\rm ef})\,\mathcal{E}^{in}_{mag} + \mathcal{E}^{in}_{th,i} = \mathcal{E}^{out}_{th,i} + \mathcal{K}^{out}_{i}\,. \qquad (2)$$

Here the magnetic energy flux

$$\mathcal{E}^{in}_{mag} = \frac{B_0^2}{4\pi}\,v_0\,b\,, \qquad (3)$$

A relative fraction $\chi_{\rm ef}$ of the heating is consumed by electrons, while the remaining fraction $(1-\chi_{\rm ef})$ goes to the ions.

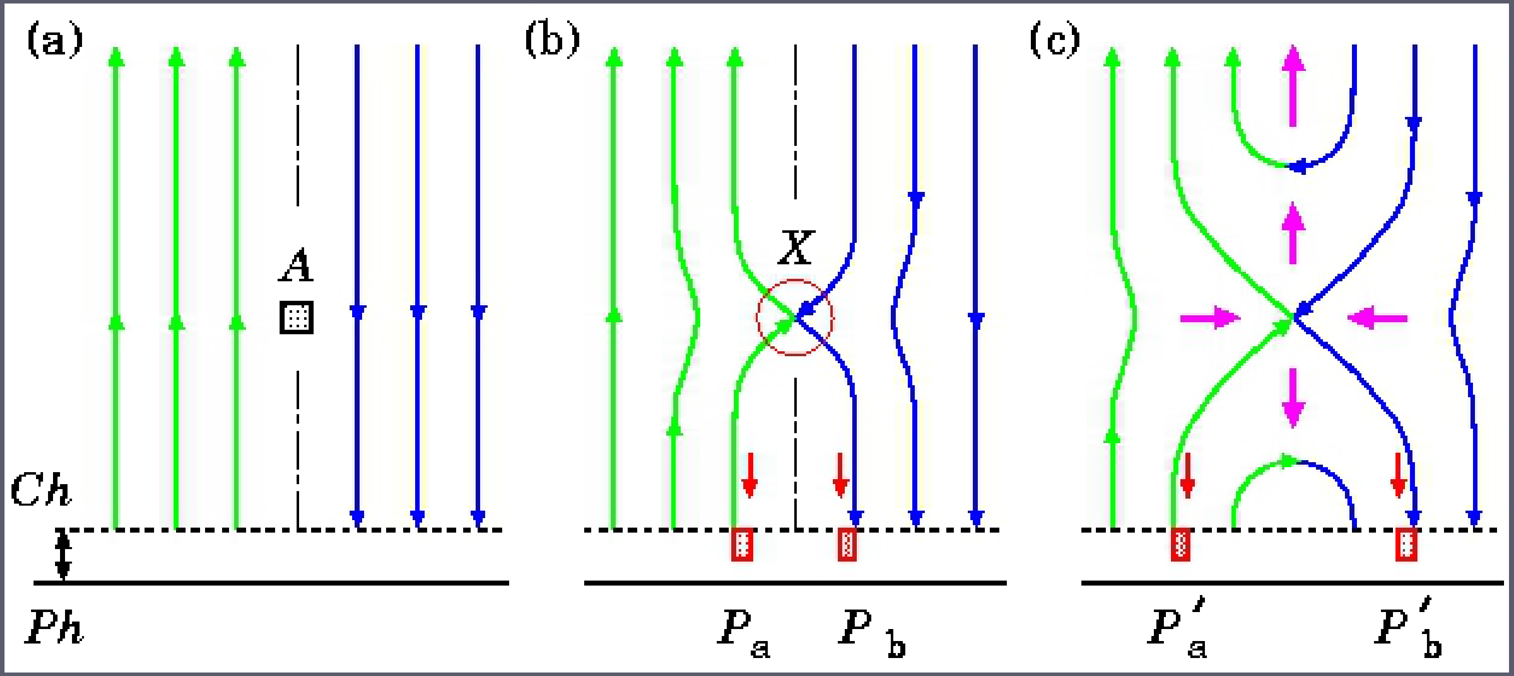
The SHTCL provides:

- Quasi-thermal super-hot plasma
- Supra-thermal accelerated particles

Global Models

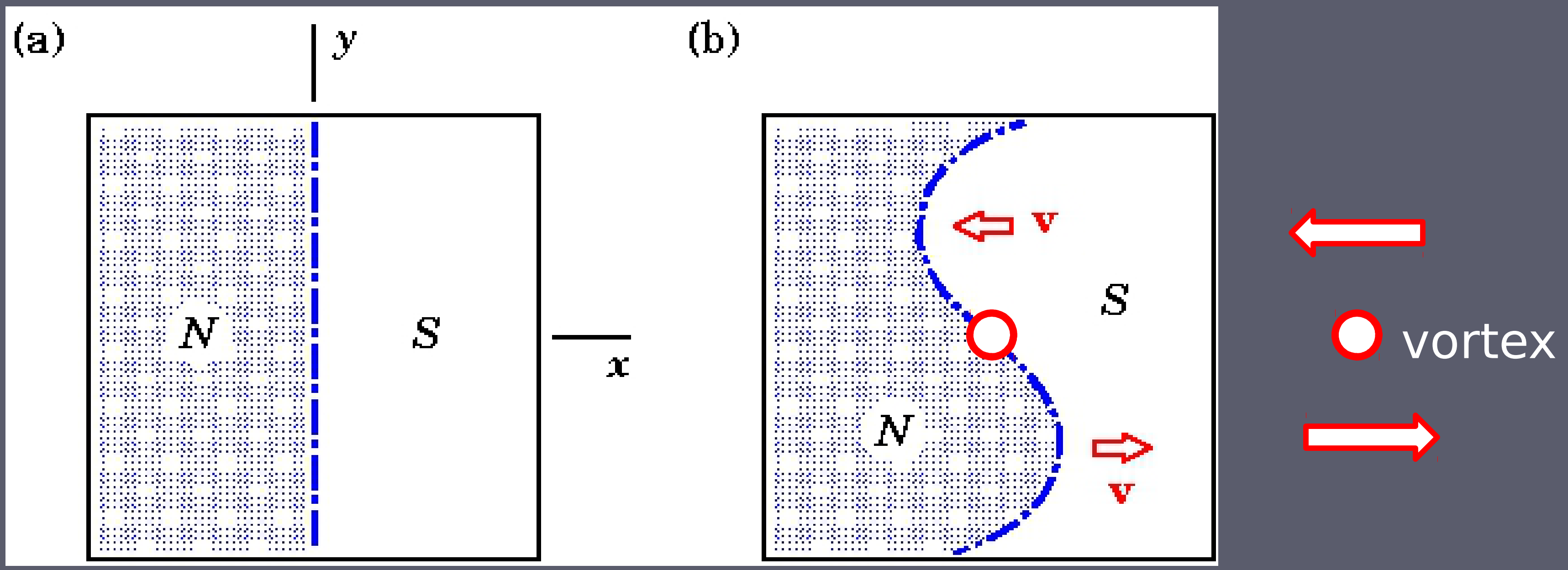
- Standard model (Carmichael, 1964; Sturrock, 1966; Kopp and Pneuman, 1976)
- Topological models (SAI of the MSU)

Basic Standard Model of a Two-ribbon Flare



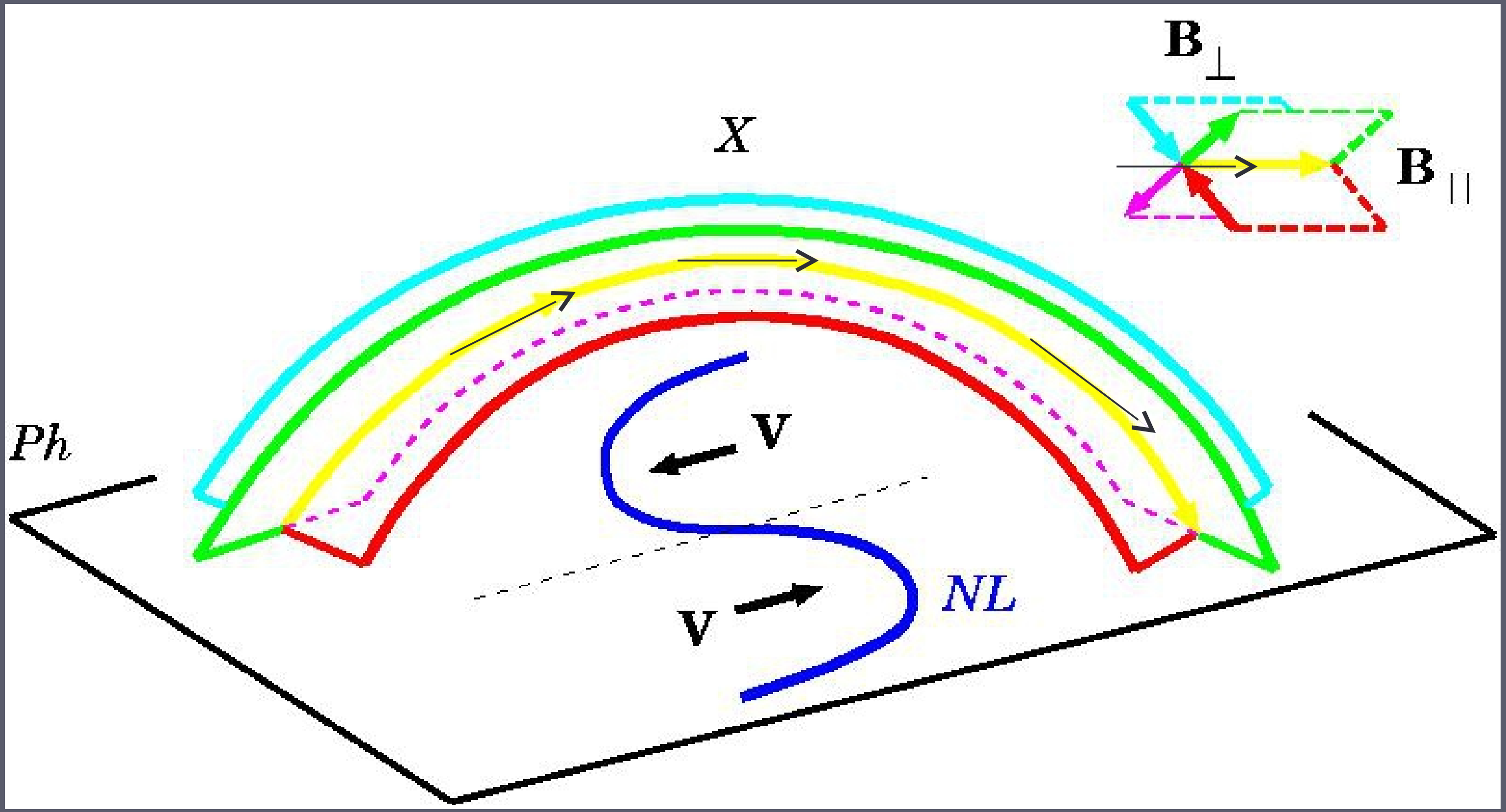
- (a) An initial state: a region *A* of a high resistivity
- (b) Reconnection at the *X*-point
- (c) Footpoint separation increases as new field lines reconnect

Rainbow Reconnection Model



- (a) A model distribution of magnetic field in the photosphere
- (b) A vortex flow distorts the neutral line so that it takes the shape of the letter *S*

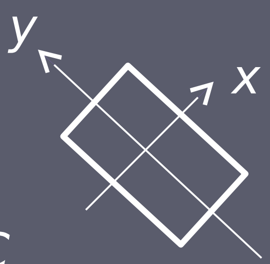
Rainbow Reconnection in the Corona



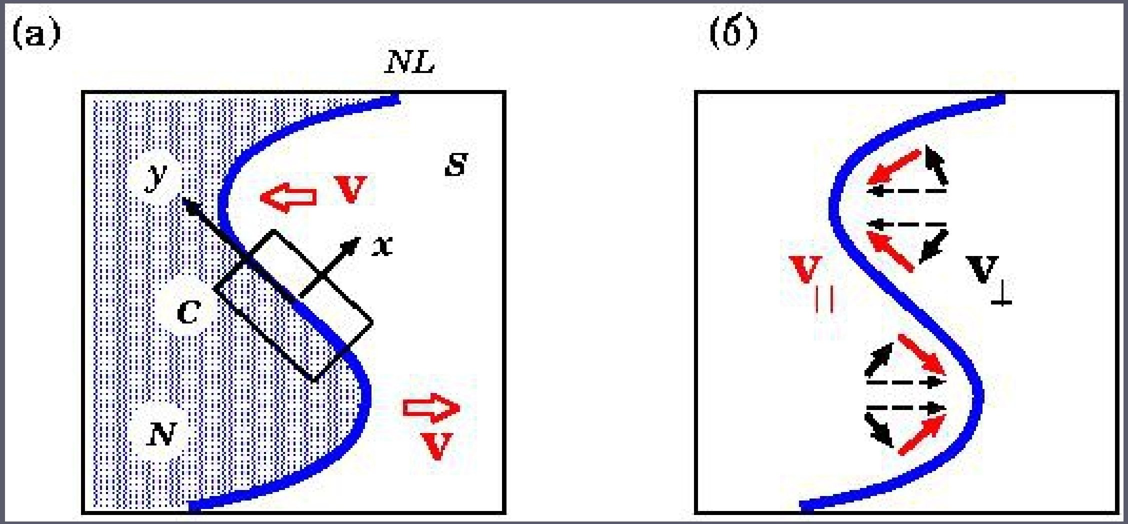
- A separator *X* appears above the *S* -bend of the photospheric neutral line *NL*

Somov B.V.: 1985, *Soviet Physics Usp.* **28**, 271

Vortex flow generates two components of the velocity field in the photoshere

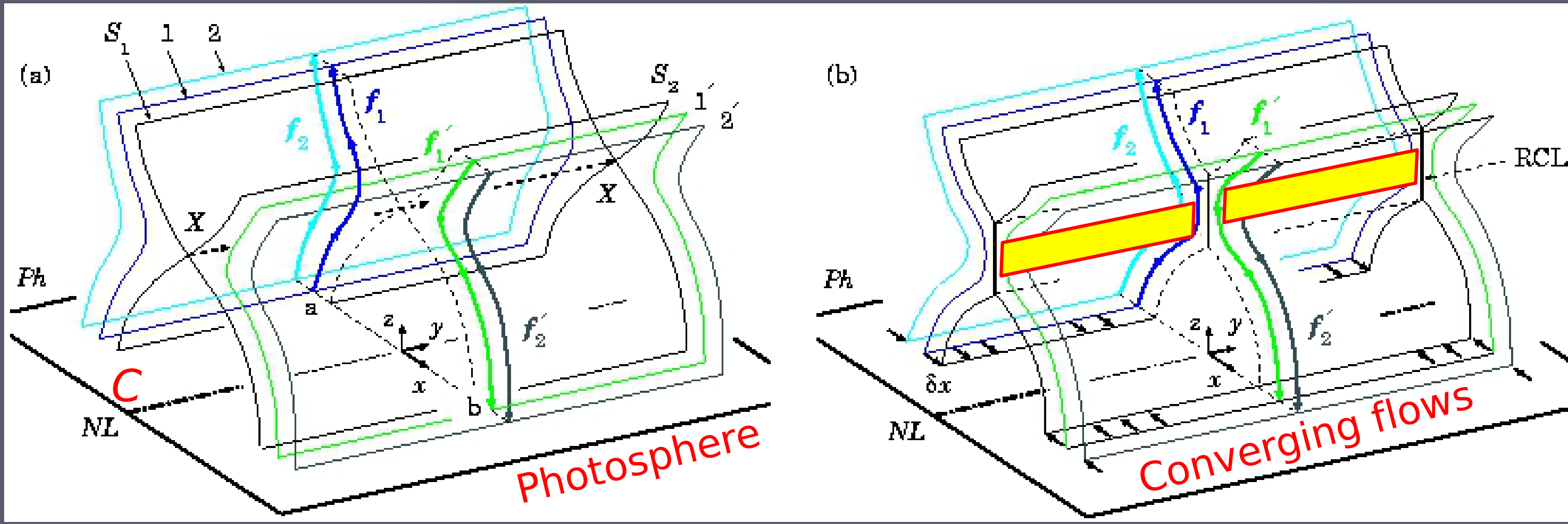


C
– central part



- The perpendicular component of velocity drives reconnection in the corona
- The parallel component provides a shear of magnetic field above the photospheric *NL*

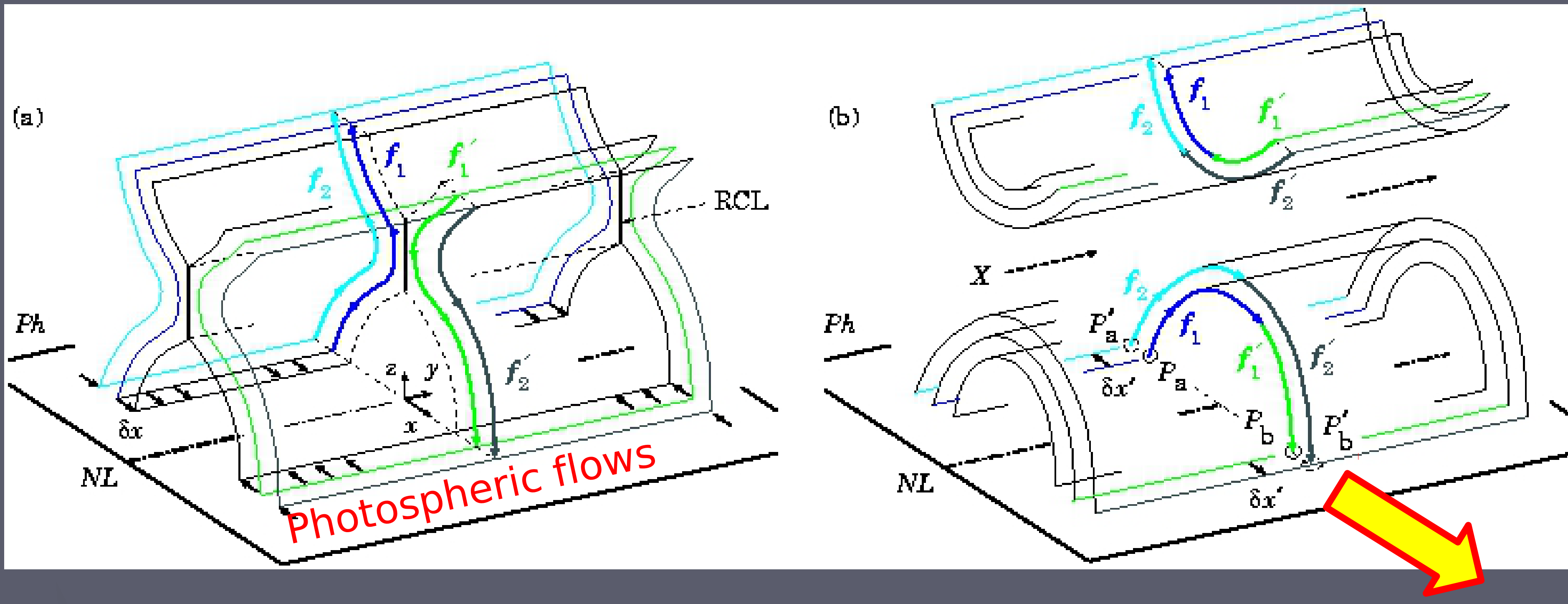
Pre-flare Energy Accumulation



- (a) An initial configuration in a central part *C*
- (b) Converging flows induce a slowly reconnecting current layer (RCL)
- An excess energy is stored as magnetic energy of the RCL

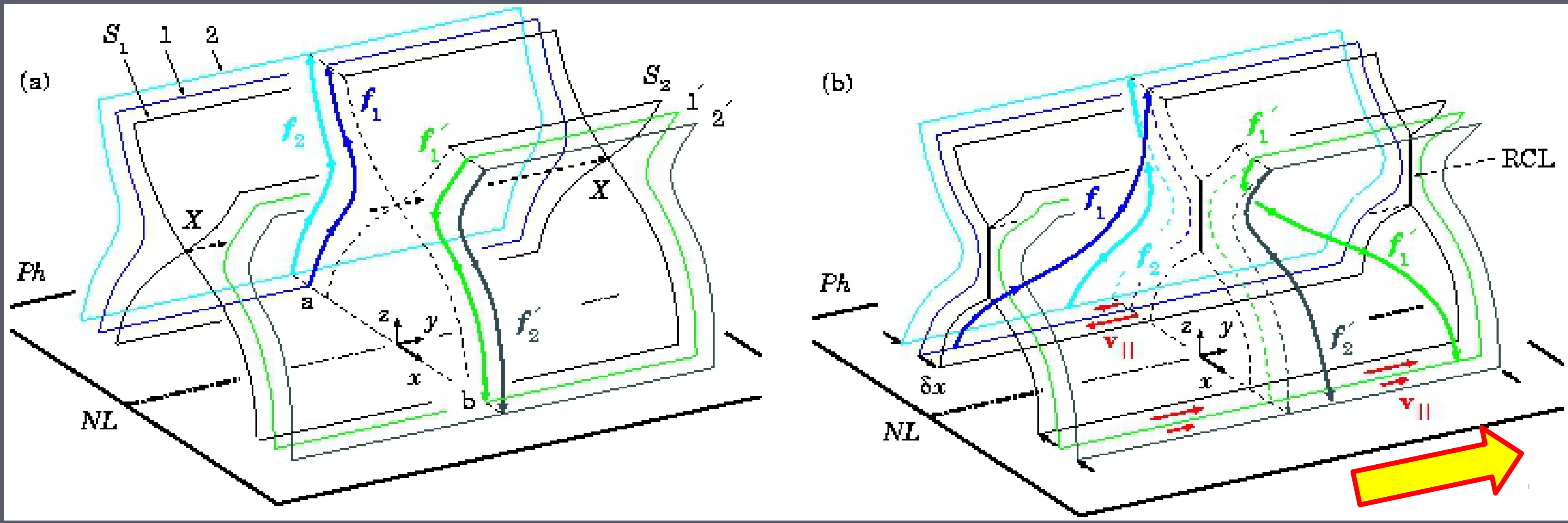
Somov, Kosugi, Hudson et al., ApJ **579**, 863, 200

Reconnection and Energy Release



- The apparent motion ➡ of the footpoints due to reconnection
- Footpoint separation increases with time
- The apparent displacement is proportional to a reconnected flux Электрическое поле

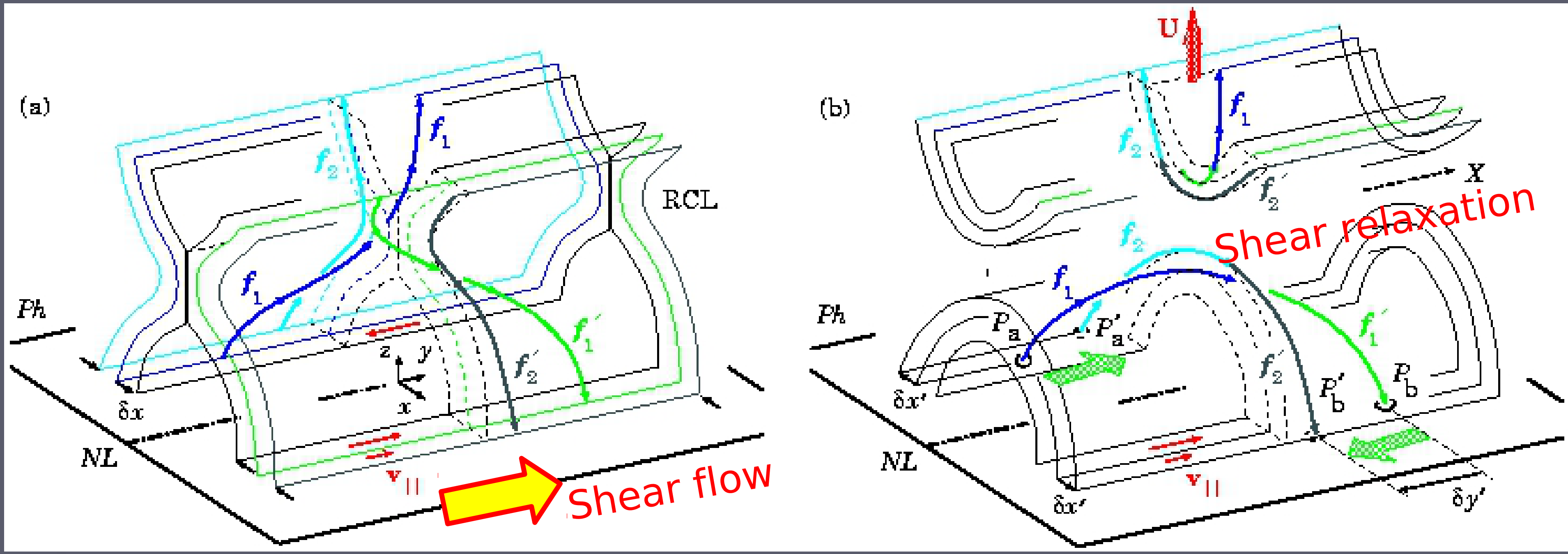
Pre-flare Structure with Shear



- (a) The initial configuration
- (b) The converging flows creates the RCL
- Shear flows make the field lines longer, increasing the energy in magnetic field

Motion of HXR Footpoints

Upward motion of plasma



- (a) Pre-reconnection state of the magnetic field with the converging and shear flows
- (b) Rapidly decreasing footpoint separation because of shear relaxation

Somov, Kosugi, Hudson et al., ApJ, 579, 863, 2002

The rainbow reconnection model predicts two types of motions of the HXR kernels

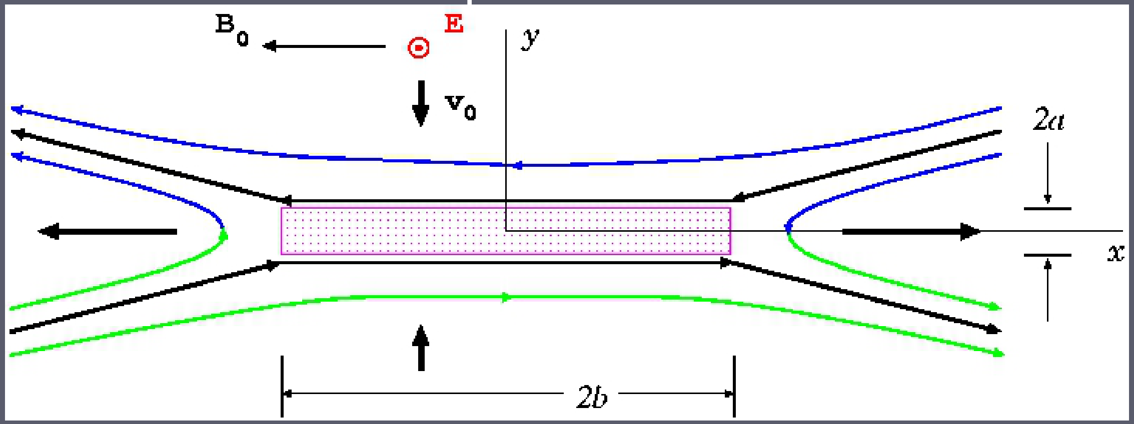
- An increase of a distance between the ribbons, in that the HXR kernels appear, because of reconnection in the RCLs
- A decrease of the distance between the kernels because of the shear relaxation

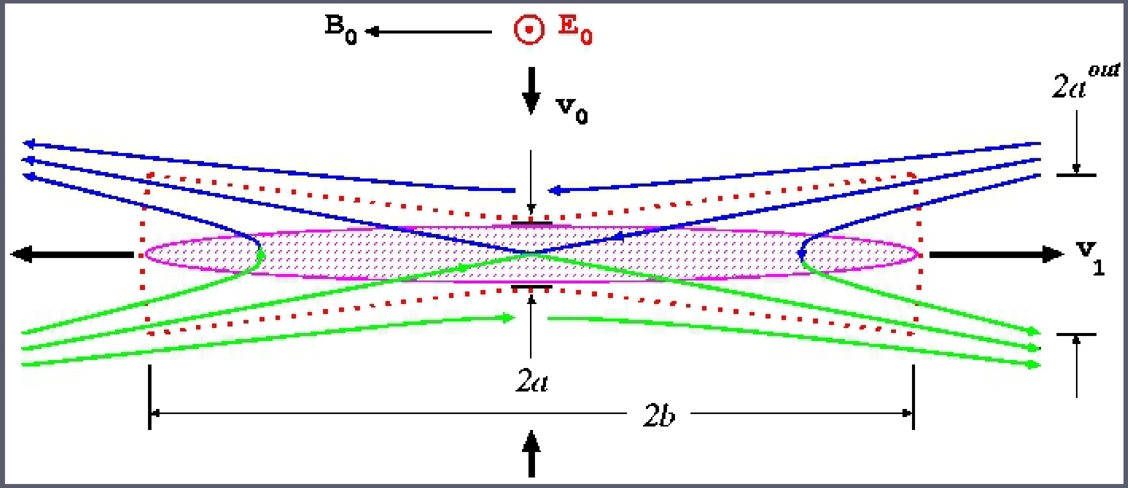
First Step
of
Particle Acceleration

- Acceleration by DC electric field in Reconnecting Current Layer

Acceleration in RCL

Нейтральный





Не-нейтральный

- A particle spends an infinite time and takes an infinite energy from the electric field
- A particle leaves the RCL with a small transversal field after a finite time

Speiser T.W., *J. Geophys. Res*. **70**, 4219, 1965

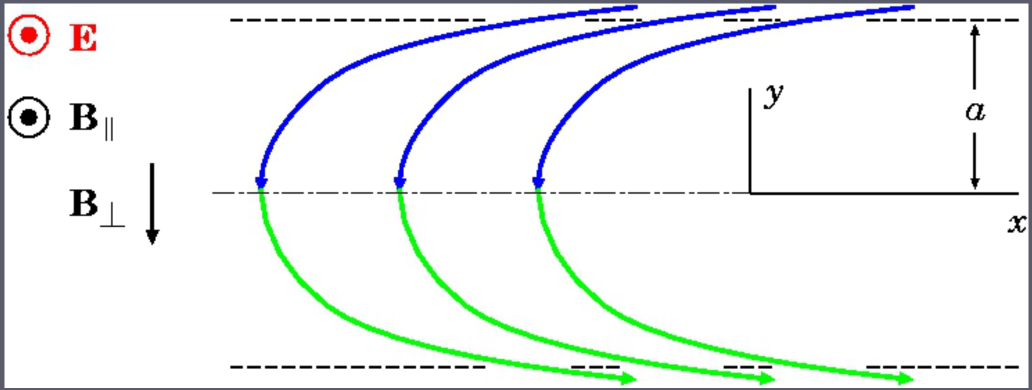
Approximate Analytical Solutions

of non-relativistic
equation of motion of
a particle in SHTCL *

*) See Somov B.V., Plasma Astrophysics, Part II, Reconnection and Flares, Second Edition, Springer SBM, New York, 2013, Chapter 11

Acceleration in a 3-component RCL

(An asymptotic solution)



The stabilization condition

$$\left(\frac{B_{\parallel}}{B_0}\right)^2 > \frac{mc^2 E_0}{aq\, B_{\perp} B_0} \,. \qquad (1)$$

The maximum energy of accelerated electrons

$$\mathcal{E}_{\max} = \frac{1}{2m}\left(\frac{qa\, B_{\parallel}}{c}\right)^2 . \qquad (2)$$

In the Super-Hot Turbulent-Current Layer (SHTCL), $\mathcal{E}_{\max} \approx 100\,\mathrm{keV}$.

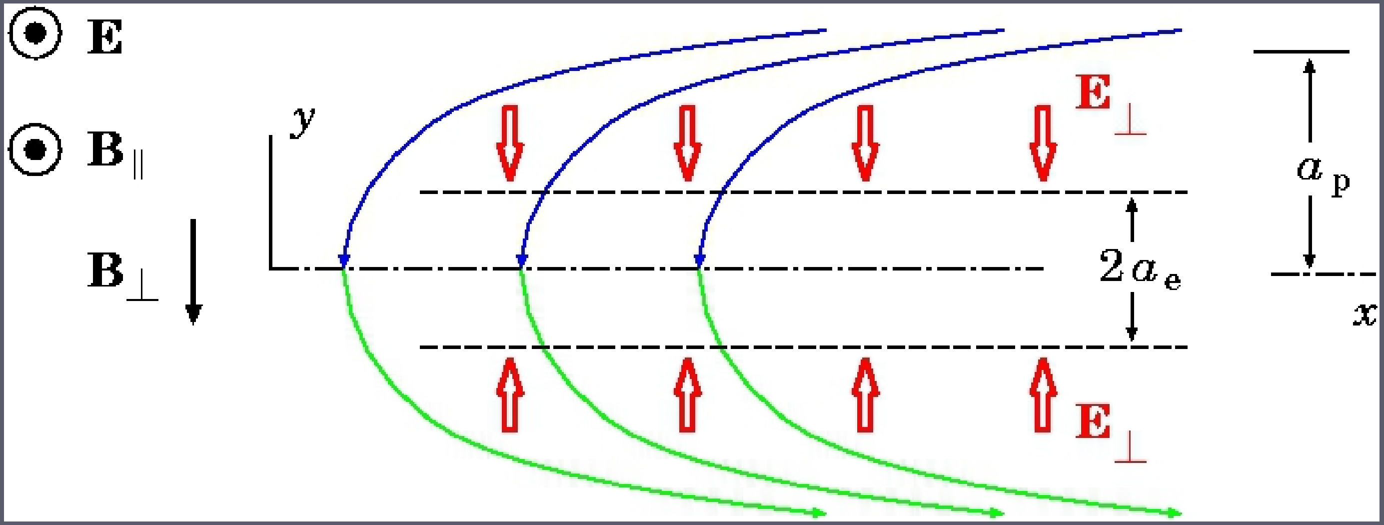
Litvinenko Yu.E. and Somov B.V., *Solar Phys*. **146**, 127, 1993

Electron Acceleration in a 3-component SHTCL

- The longitudinal magnetic field at the separator increases an efficiency of acceleration
- The Super-Hot Turbulent-Current Layer (SHTCL) model allows us to interpret the first step of electron acceleration without any problem *

*) Somov B.V. and Litvinenko Yu.E., in *Physics of Solar and Stellar Coronae*, Kluwer Acad., 603, 1993

Ion acceleration in an electrically non-neutral RCL



Electron current layer

- The charge-separation electric field detains the protons and ions in the vicinity of the electron current layer, thus increasing the acceleration efficiency for ions

Litvinenko Yu.E. and Somov B.V., *Solar Phys*. **158**, 317,1995

Non-relativistic and Relativistic Particle Acceleration in a RCL by a Strong Electric Field

Exact solutions *

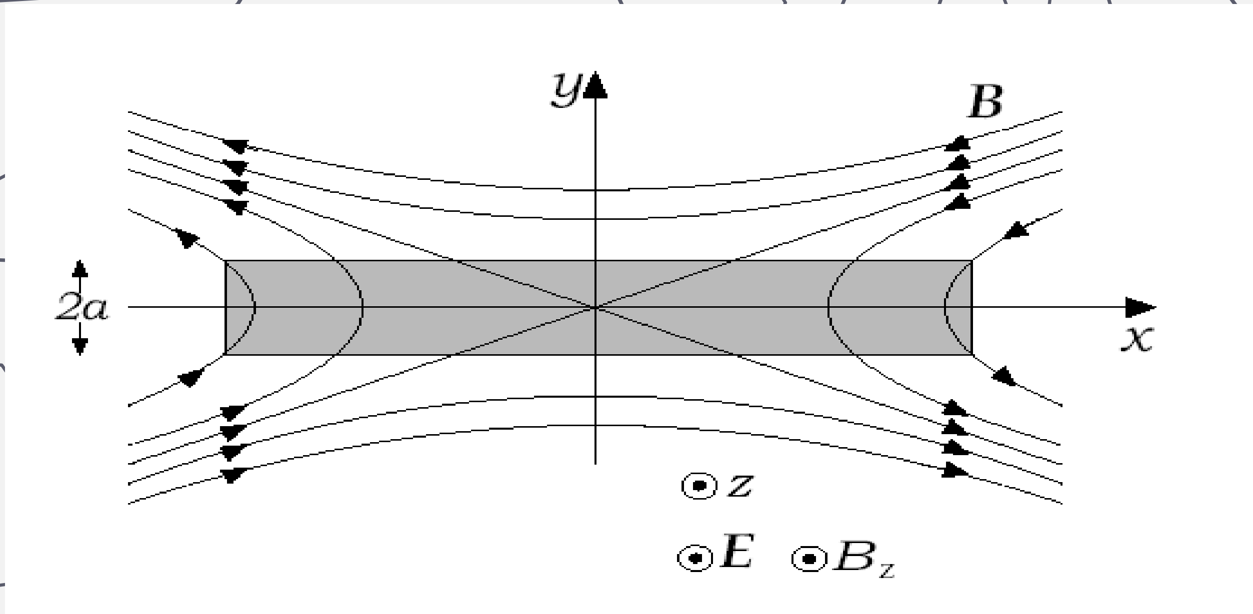
*) Oreshina A.V. and Somov B.V., Astronomical and Astrophysical Transactions **25**, No. 4, 261, 2006;
Astronomy Letters **35**, 195, 2009

“Simple” Model

The equation of motion

$$\frac{d\vec{p}}{dt} = q\left(\vec{E} + \frac{1}{c}[\vec{v}\times\vec{B}]\right), \quad \vec{p} = \frac{m\vec{v}}{\sqrt{1 - v^2/c^2}}$$

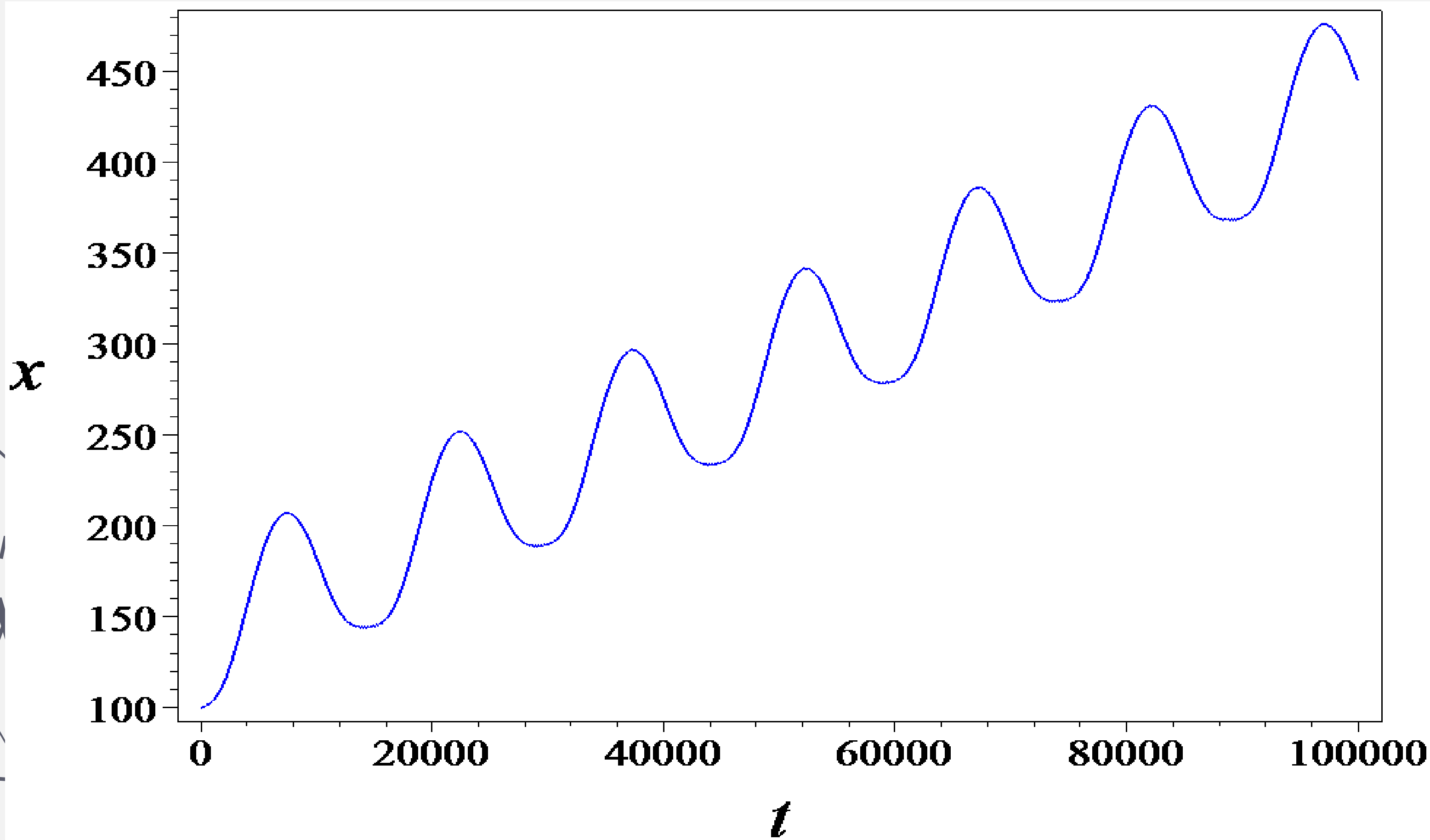
Reconnecting current layer



Electric and magnetic fields inside the layer

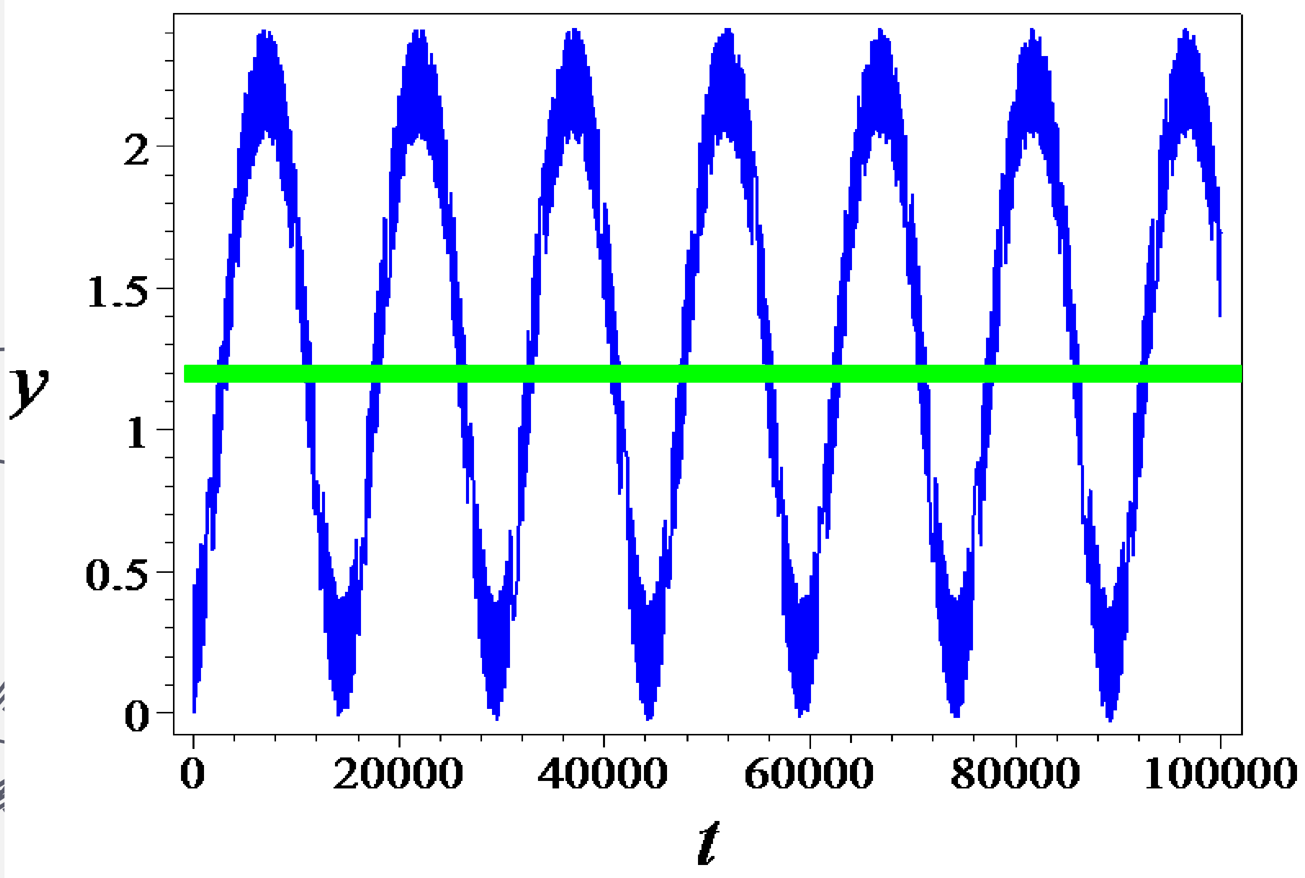
$$\vec{E} = (0, 0, E), \; \vec{B} = B_0\,(-y/a, -\xi_\perp \operatorname{sign} x, \xi_\parallel)$$

1. Non-relativistic acceleration ($v<<c$)



Along the x -axis, particles drift with a constant average velocity

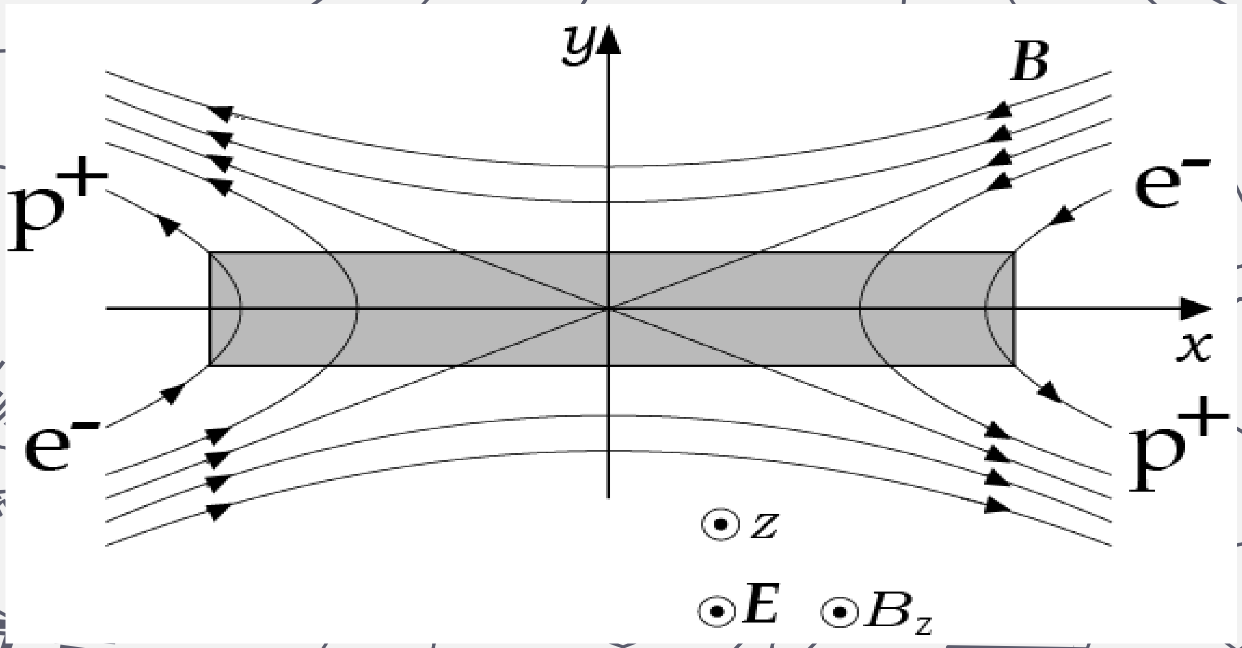
$$v_x = \frac{\varepsilon}{\xi_\perp} \operatorname{sign} x.$$



Along the *y* -axis, particles oscillate inside
the current layer near some average value.

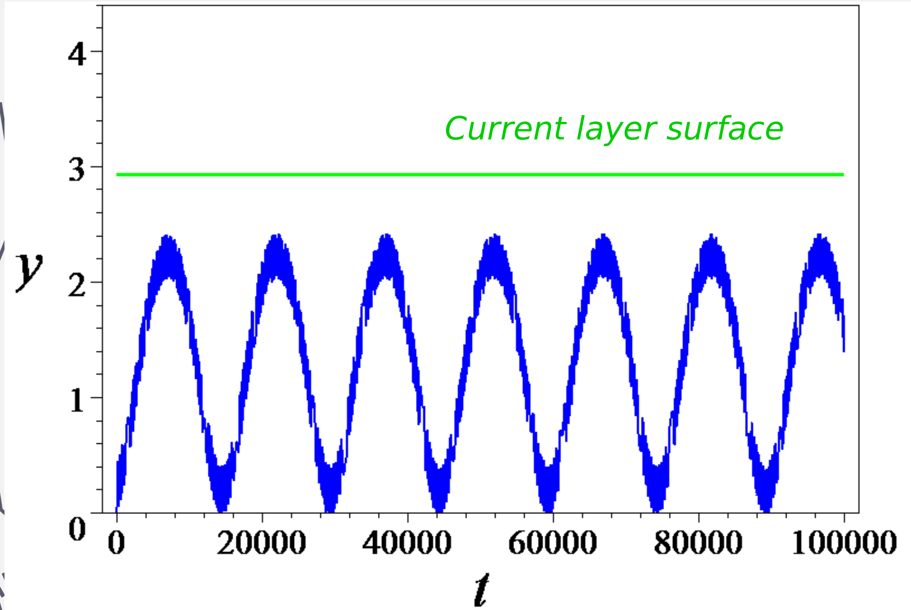
Charge separation in the RCL

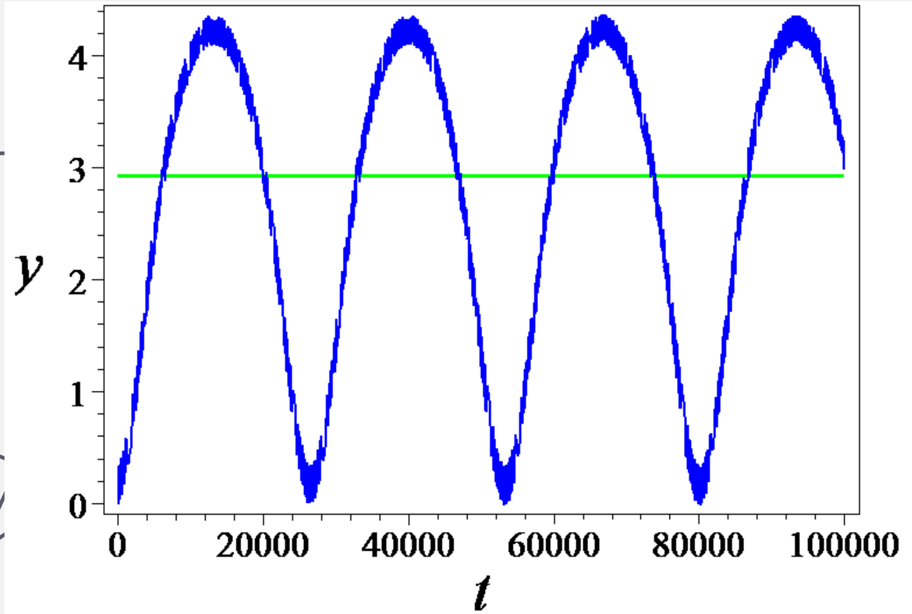
$$\bar{Y} = -\frac{1}{\delta} \cdot sign(q) \cdot sign(x) \cdot \frac{\varepsilon\xi_{\parallel}}{\delta\xi_{\perp}} \cdot \frac{W + sign(q) \cdot \varepsilon \cdot K}{M^2 - (\varepsilon\xi_{\parallel} / \delta\xi_{\perp})^2},$$



Oppositely charged particles are localized mostly in different parts of the layer.

Stable and unstable trajectories





Stable trajectory

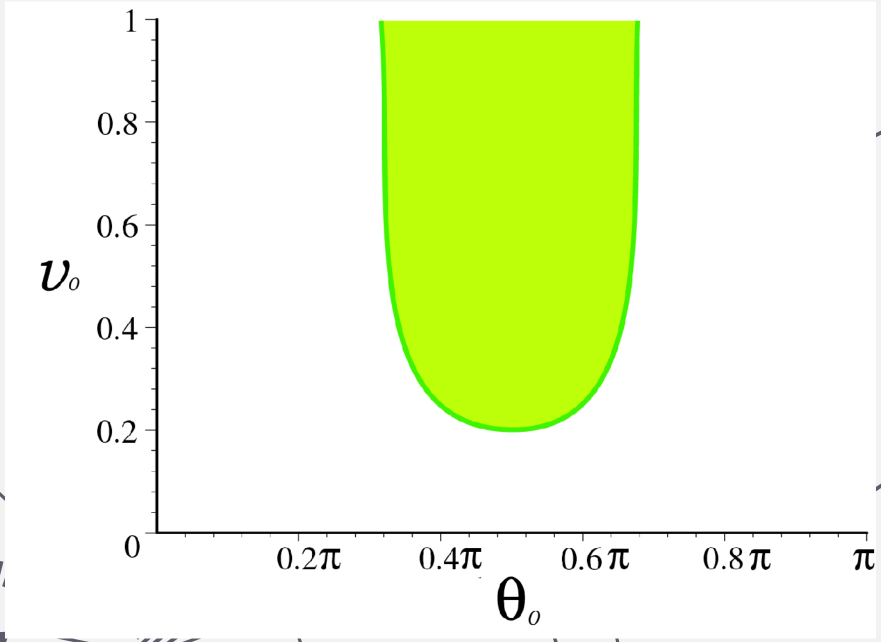
$(v_{x0} = 0.22)$

Unstable trajectory

$(v_{x0} = 0.18)$

Trajectory stability depends on initial velocity of particles.

Conditions of the trajectory stability



Domain of stable trajectories

1. A minimum initial velocity exists below which there are no stable trajectories.
2. For a given initial velocity, the stable trajectories take place only in a certain range of directions.

2. Relativistic Particle Acceleration

Particle trajectories are stable in the strong electric field, if

$$E^2 >> B_y^2 \quad \text{and} \quad E^2 >> \left(\frac{B_y B_z}{B_0}\right)^2.$$

Velocity in the x - direction is small and do not depend on the particle charge:

$$v_x = c\,\frac{\xi_\perp}{\varepsilon}\,\text{sign}\,x\,, \qquad |v_x| << c.$$

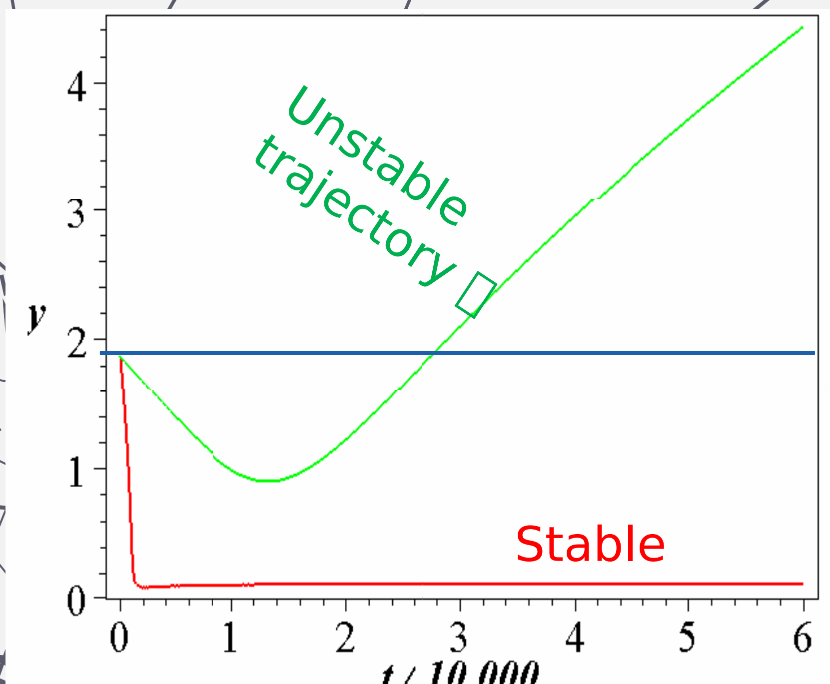
Particles gyrate in the vicinity of the plane y0=cons

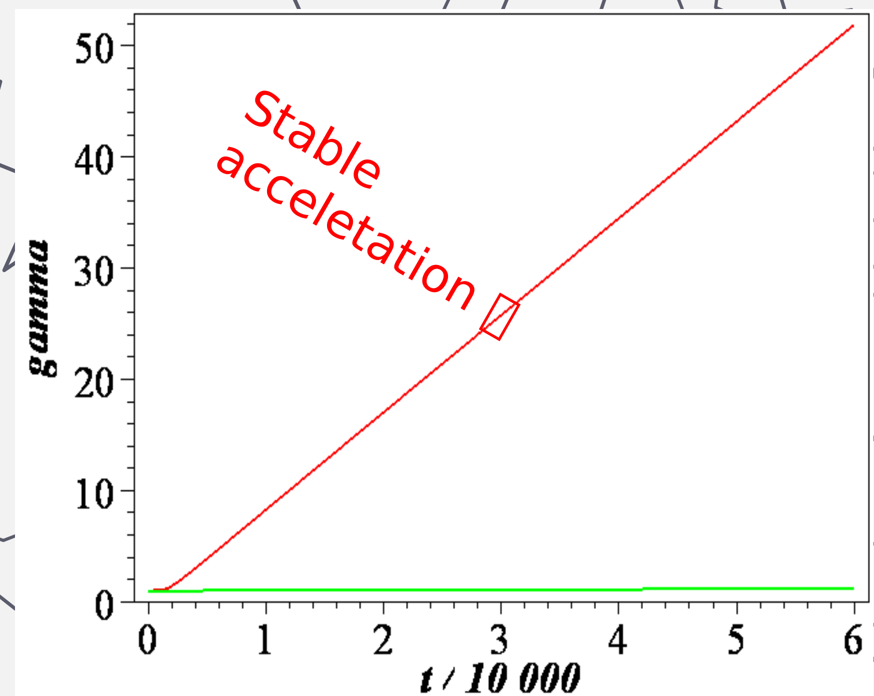
inside the current layer:

$$y_0 = -a\,\frac{\xi_\perp \xi_\parallel}{\varepsilon}\,(\text{sign}\,x)\,(\text{sign}\,q).$$

Velocity in the electric field direction (the *z* -axis) is close to the light speed *c* . Particles with different signs of charges move in opposite directions along the *z* -axis:

$$v_z = c\frac{\varepsilon t}{\sqrt{1+\varepsilon^2 t^2}}\,\mathrm{sign}\,q \to c\,\mathrm{sign}\,q.$$





Well consistent with asymptotic solution by Litvinenko and Somov (1993)

According to our model $\gamma = \varepsilon t = (E / B_0)t = 10^{-3} t.$

Thus, the observed values γ for relativistic electrons acquire the acceleration time ~ $1.1\cdot 10^{-6} - 1.2\cdot 10^{-3}$ s.

During this time, relativistic electrons come a distance ~ $3.4\cdot 10^{2} - 3.6\cdot 10^{7}$ cm.

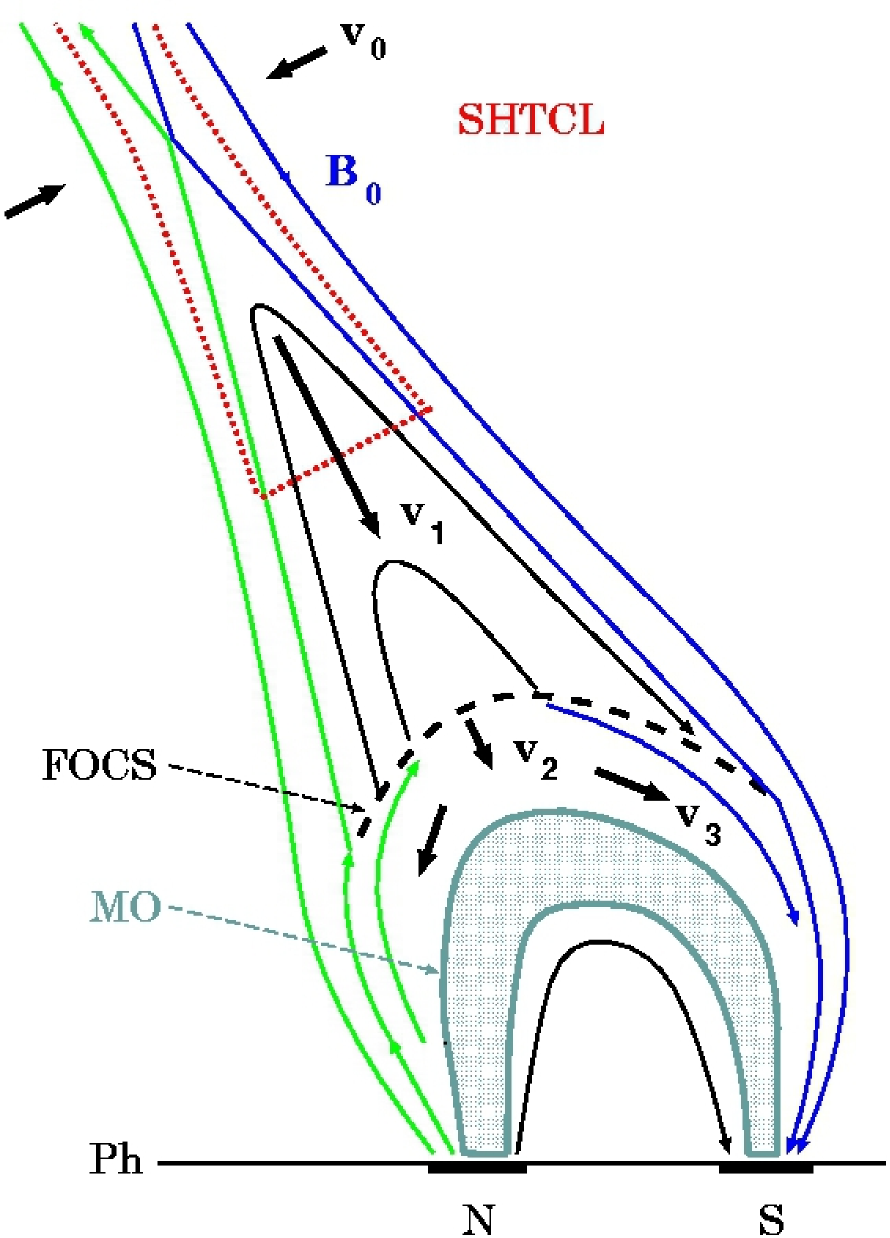
For protons, the acceleration time ~ $2.0\cdot 10^{-3} - 1.2\cdot 10^{-2}$ s.

The corresponding length ~ $6.0\cdot 10^{7} - 3.6\cdot 10^{8}$ cm.

These values do not contradict our knowledge about characteristic times and scales of flares.

Second Step
of
Particle Acceleration
in Flares

Collapsing magnetic trap

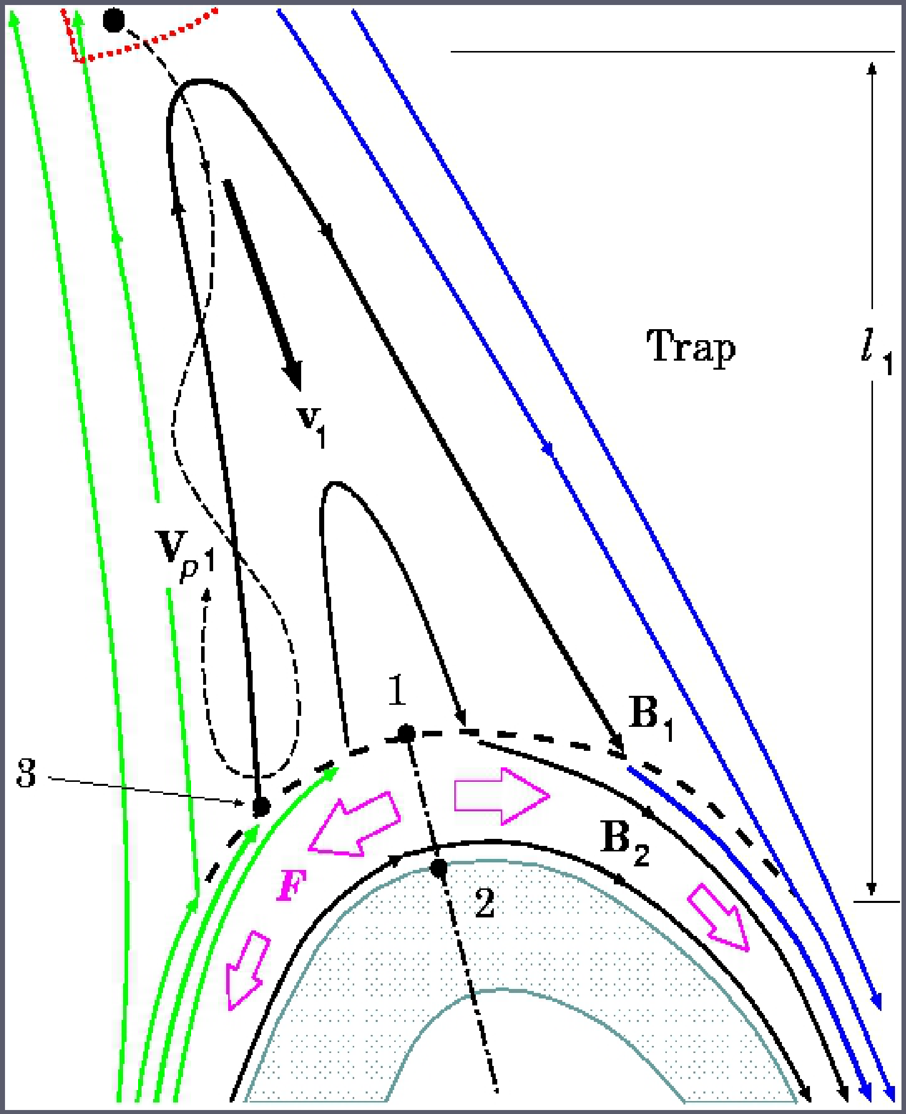


Acceleration in a Collapsing Trap

- A magnetic trap between the Super-Hot Turbulent-Current Layer (SHTCL) and a Fast Oblique Collisionless Shock (FOCS) above magnetic obstacle (MO)

Somov B.V. and Kosugi T., ApJ **485**, 859, 1997

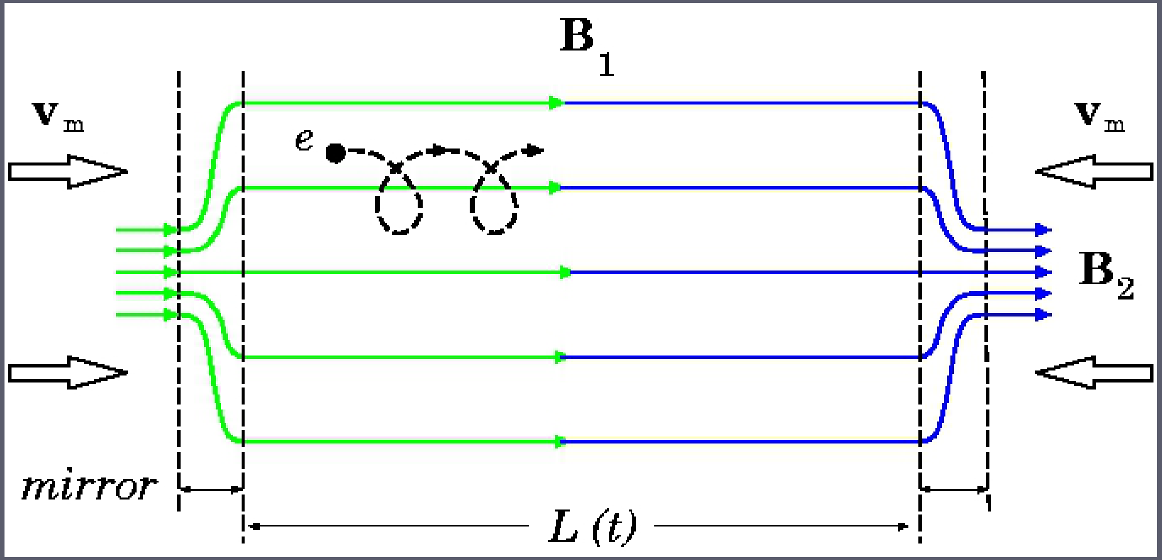
Fermi-type Acceleration as a Second-step Mechanism



- Decrease of the field line length (collapse of the trap) provides an increase of the longitudinal momentum of a particle

Somov B.V. and Kosugi T., ApJ **485**, 859, 1997

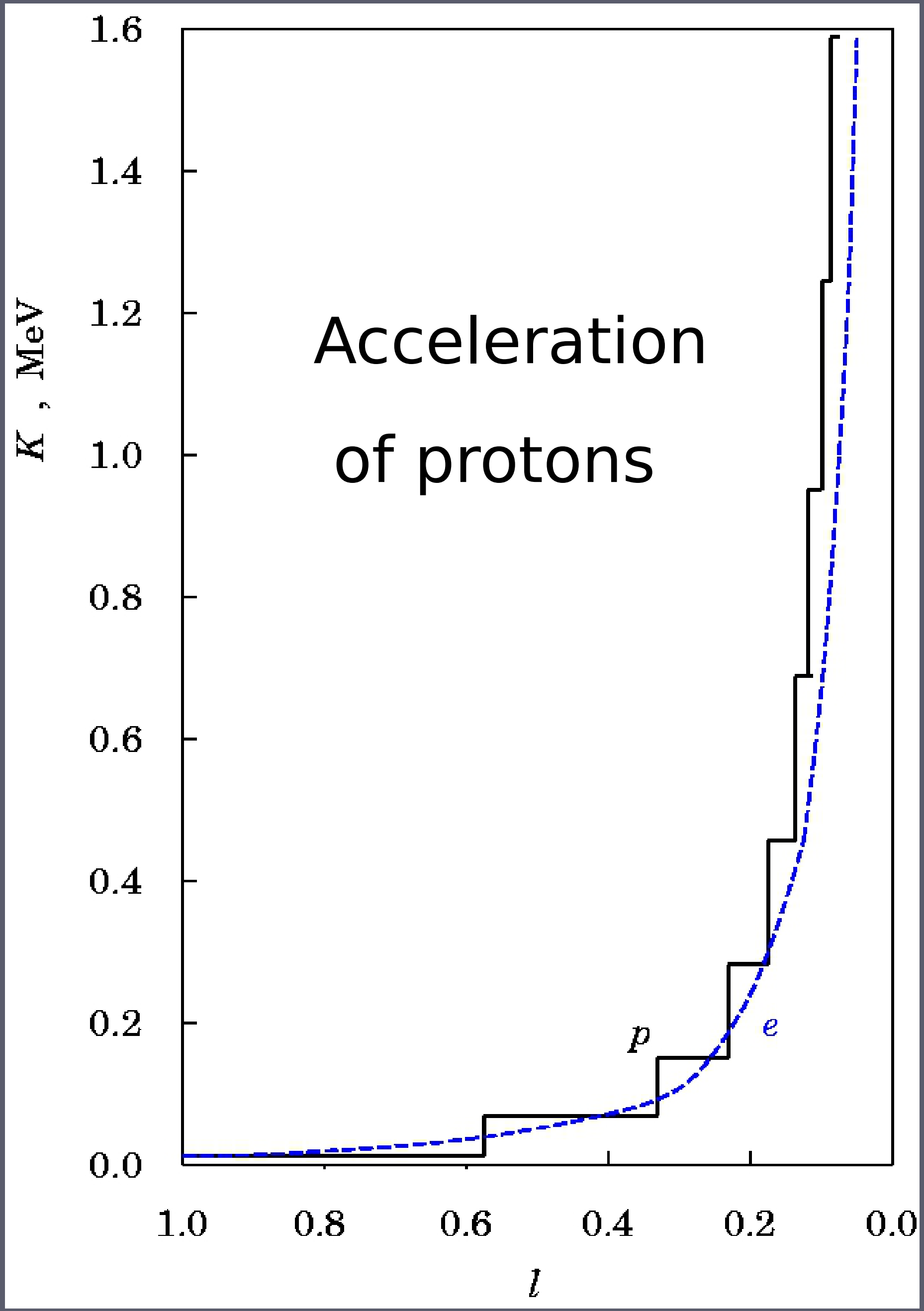
Acceleration of Electrons



pL=const

The second adiabatic invariant is valid. Therefore, the parallel momentum of electrons

$$p_{\|}(t) = \frac{p_{\|}(0)}{l(t)}, \quad \text{where } \; l(t) = \frac{L(t)}{L(0)} \; .$$

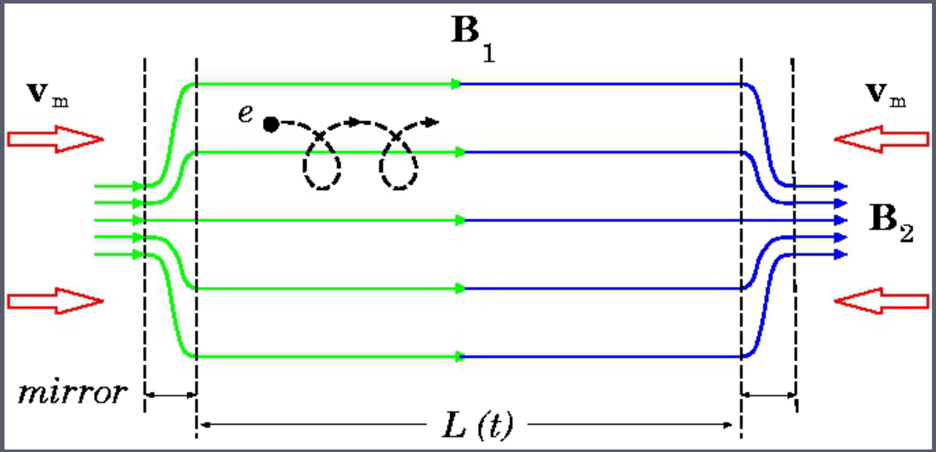


Ion Acceleration

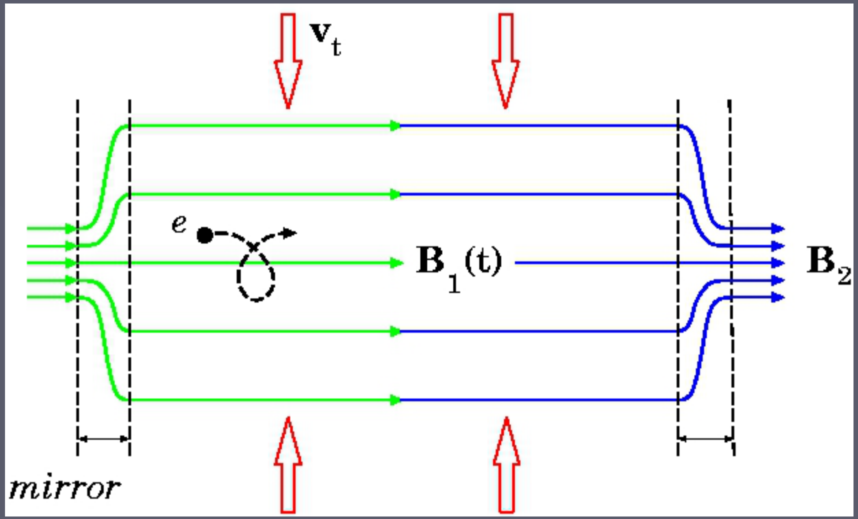
- Each reflection of an ion on a moving mirror leads to a jumpy increase of parallel velocity
- Protons are easily accelerated from thermal energies

Somov B.V., Henoux J.C., Bogachev S.A., *Adv. Space Res.* **30**, 55, 2002

Two Effects in Collapsing Trap



► Decrease of the field line length provides the first-order Fermi acceleration



► Compression of the magnetic field lines provides betatron acceleration

Both Effects Together

If the thickness of a collapsing trap decreases, the energy of a particle

$$\mathcal{K}(l) = \frac{1}{2m}\left(\frac{p_{0\parallel}^2}{l^2} + \frac{p_{0\perp}^2\,B(l)}{B_1}\right) \qquad (1)$$

increases faster than that without compression.

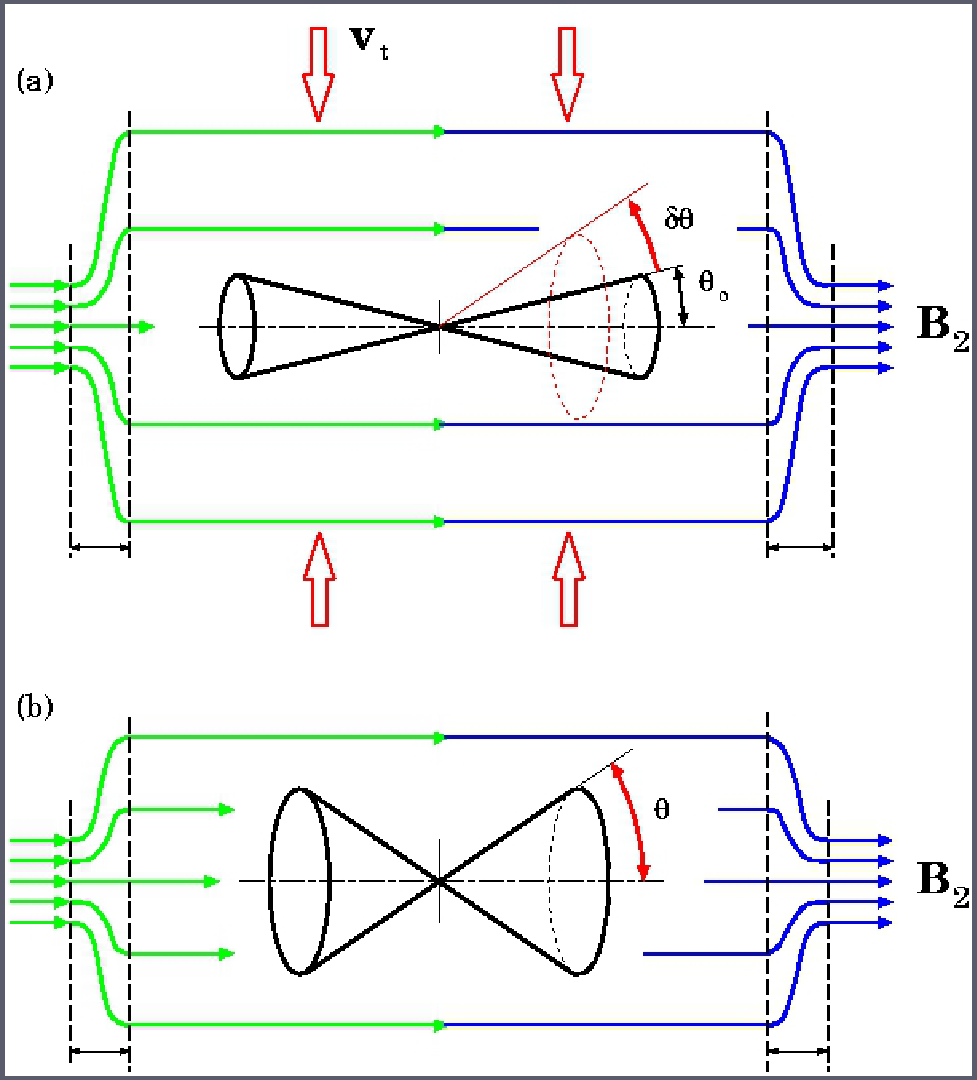
However, at the time of particle's escape from the trap,

$$\mathcal{K} = \mathcal{K}_{\max} = \frac{p_{0\perp}^2}{2m}\,\frac{B_2}{B_1}\,. \qquad (2)$$

is the same as without compression.

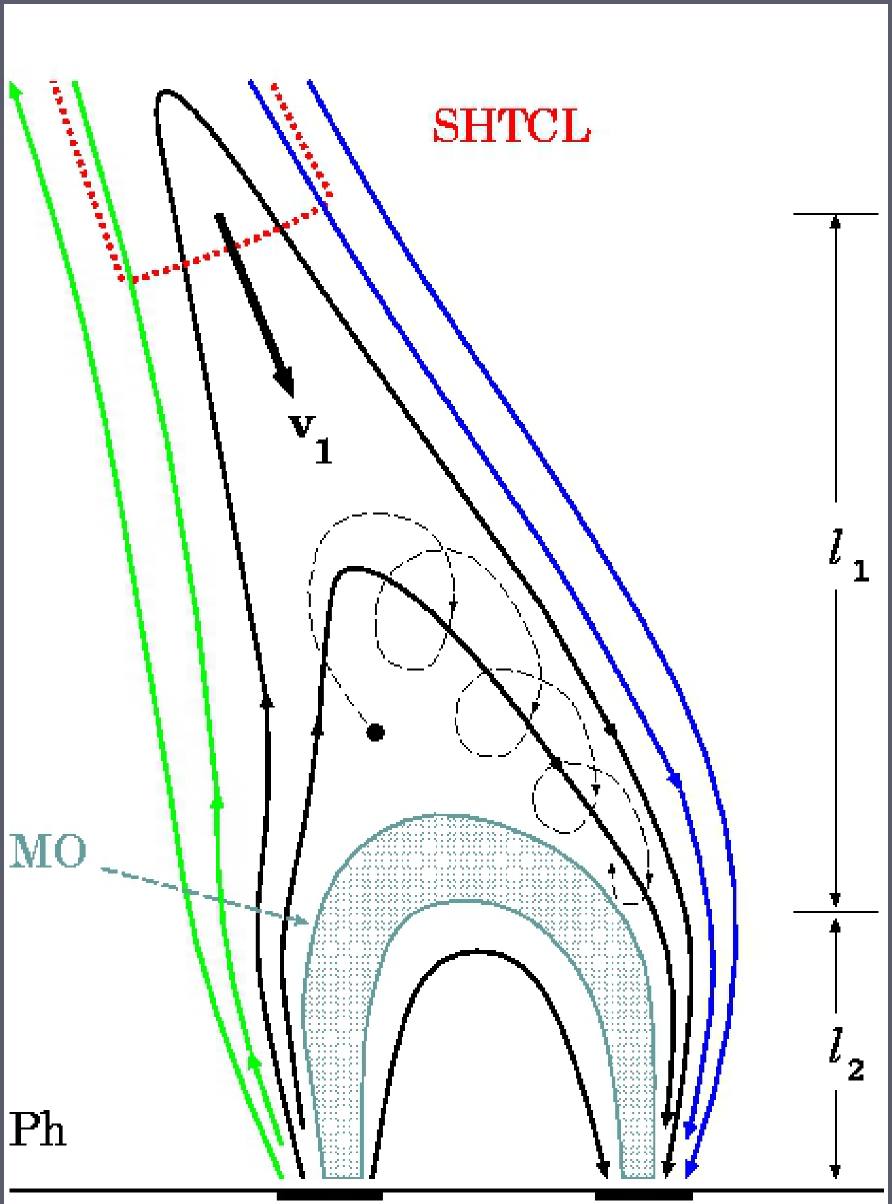
Somov B.V. and Bogachev S.A., *Astronomy Letters* **29**, 621, 2003

The Betatron Effect in a Collapsing Trap



- As the trap is compressed, the loss cone becomes larger
- Particles escape from the trap earlier
- An additional energy increase by betatron acceleration is exactly offset by the decrease in a confinement time

Somov B.V. and Bogachev S.A., *Astronomy Letters* **29**, 621, 2003

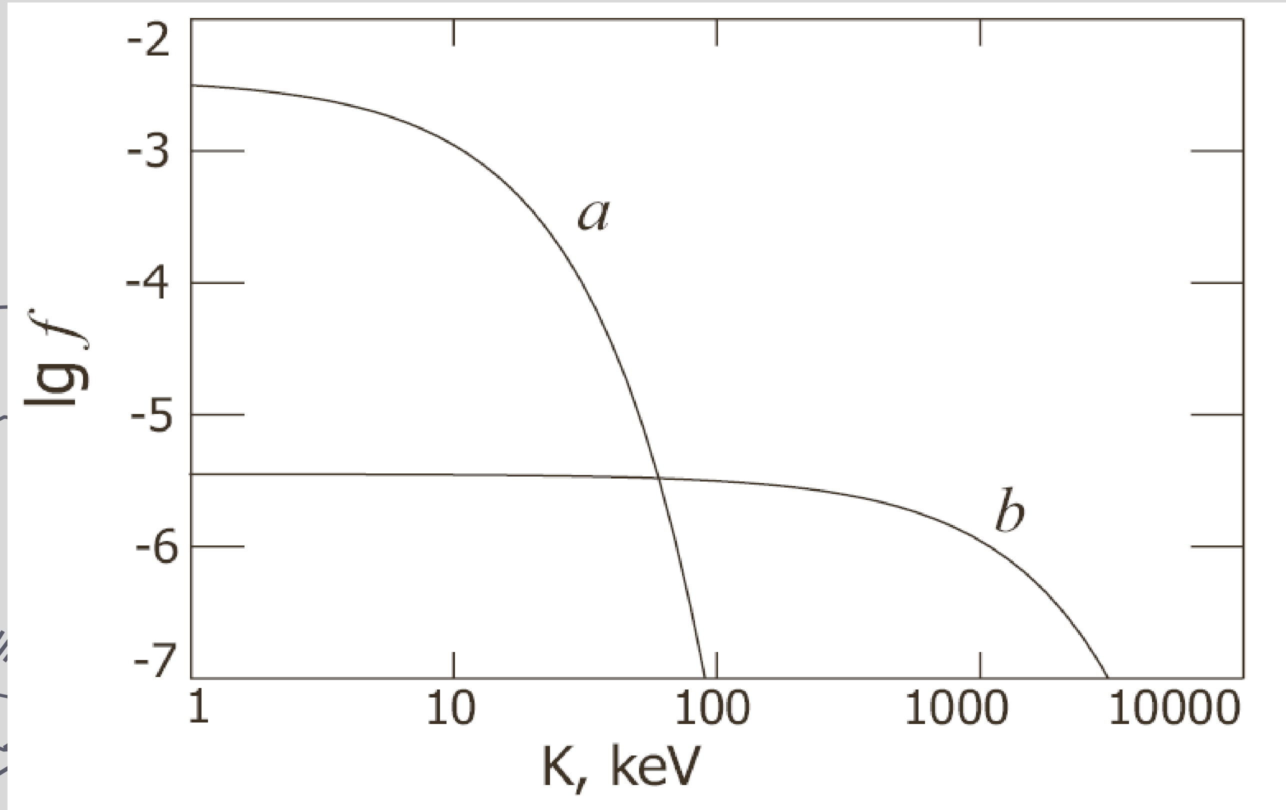


- The betatron effect increases the efficiency of the first-order Fermi acceleration because an acceleration time becomes shorter.
- Collapsing traps with a residual length (without shock) accelerate protons and ions well

Somov B.V. and Bogachev S.A., *Astronomy Letters* **29**, 621, 2003

Spectra of Accelerated Particles

Betatron Acceleration

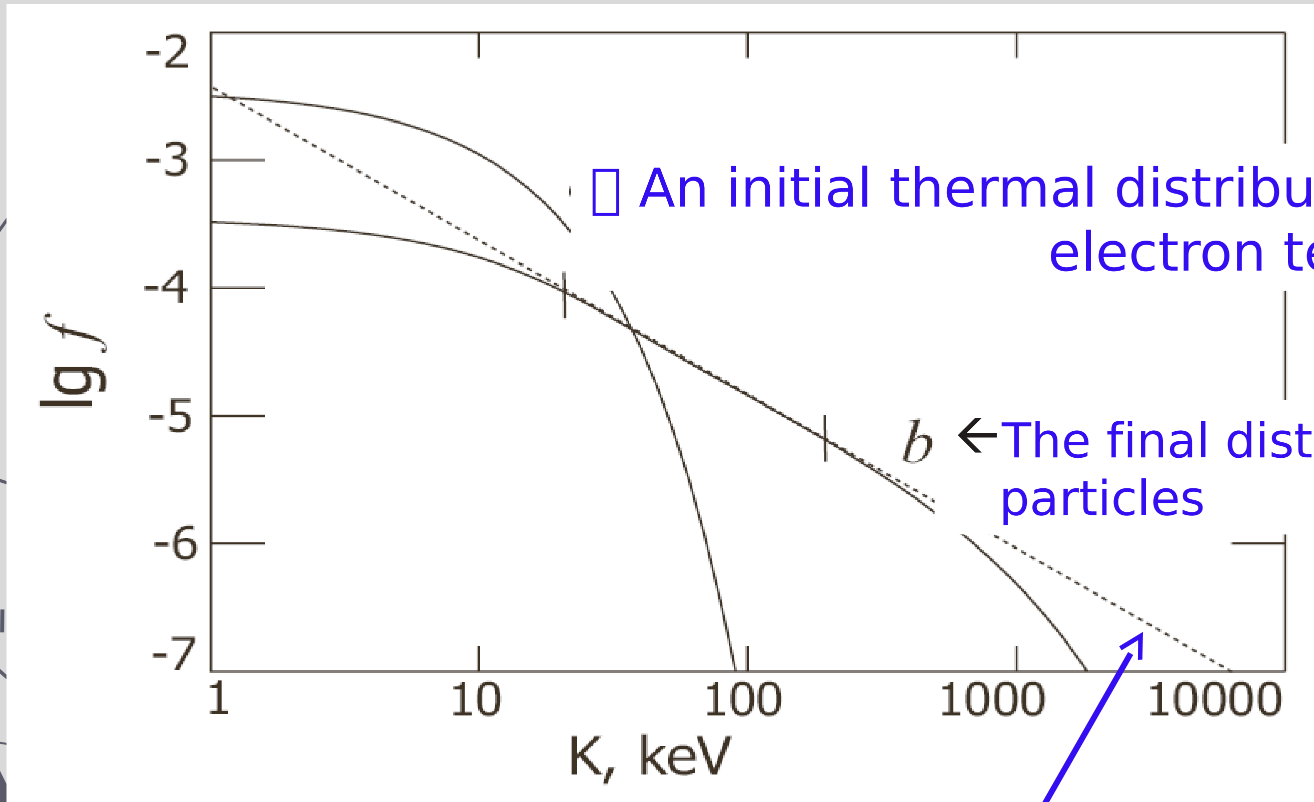


Betatron mechanism makes the super-hot particles
l

$$\lim_{b\to b_m} f(K) = \frac{\ldots}{4\pi}\frac{\ldots}{\sqrt{\pi k^3 (b_m T_0)^3}} \exp\left(-\frac{\ldots}{k(b_m T_0)}\right).$$

Bogachev and Somov, Astronomy Lett. **33**, 54, 2007.

Fermi acceleration



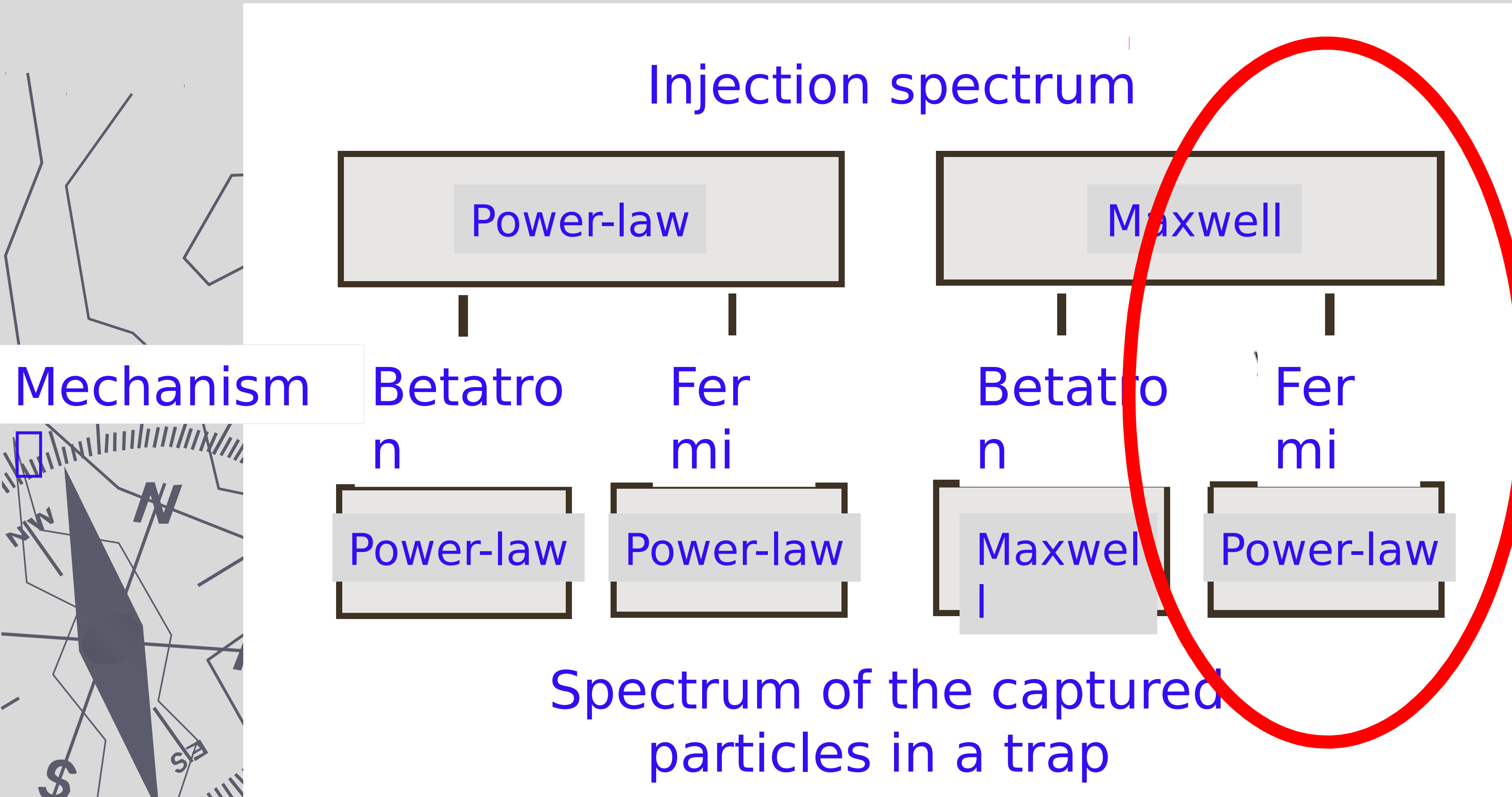
 An initial thermal distribution with electron temperature 10^8 K

← The final distribution of particles

The dashed straight line indicates the slope of the power-law segment of the

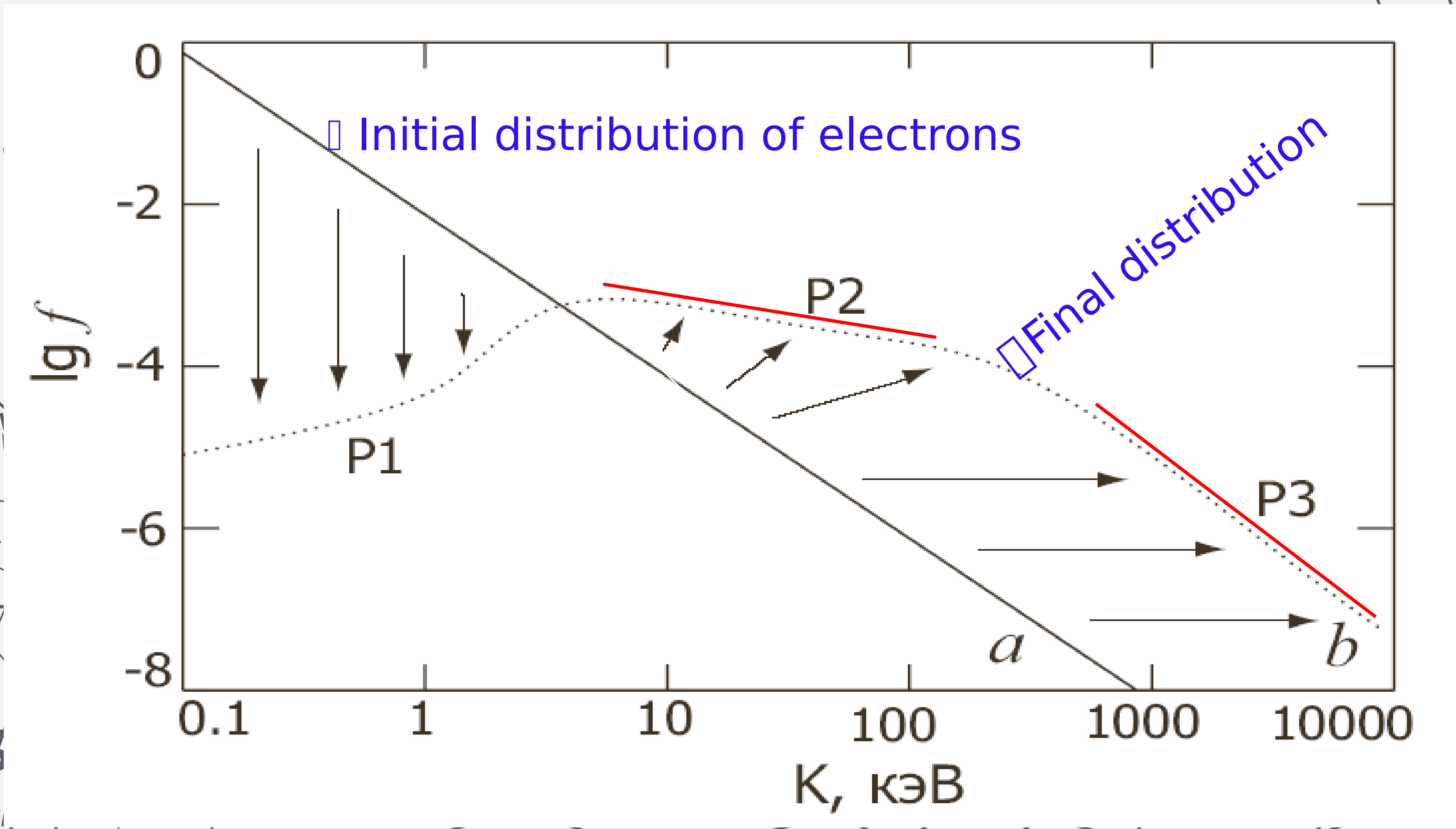
Bogachev and Somov, Astronomy Lett. **33**, 54,2007.

Transformation of Spectra in a Collapsing Trap



Bogachev and Somov, Astronomy Lett. **33**, 54, 2007

Formation of a double-power-law spectrum in a Collapsing Trap with Coulomb collisions

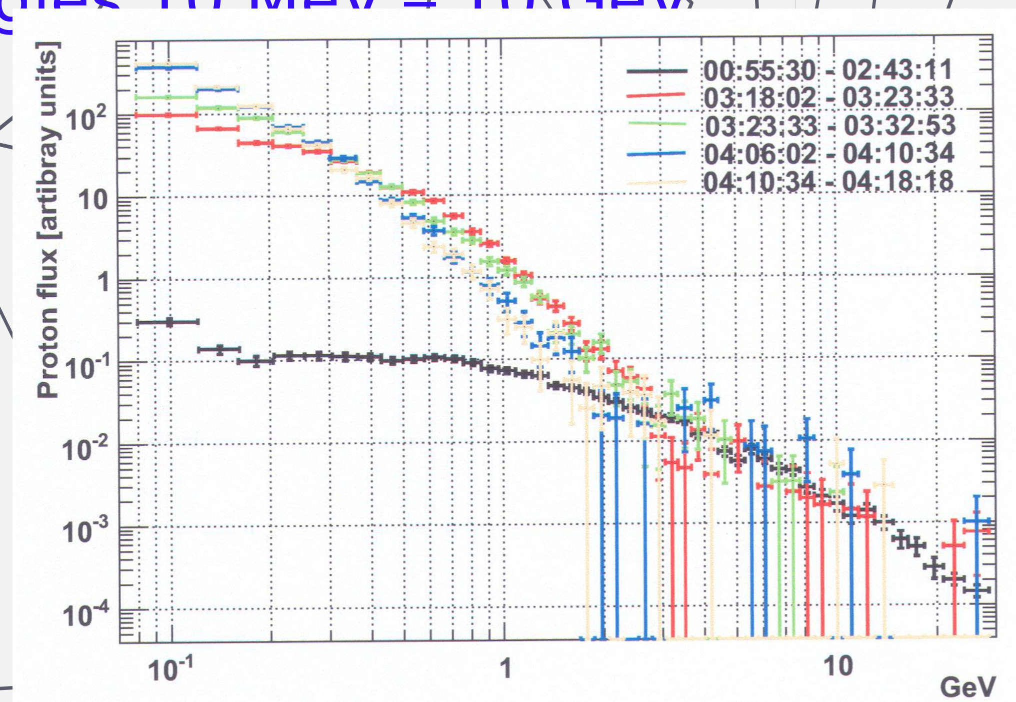


Bogachev and Somov, Astronomy Lett. **35**, 57, 2009

According to hard X-ray and gamma-ray observations, flares generate

- electrons with kinetic energies 20 keV - 1 GeV and
- protons with energies 10 MeV – 10 GeV

The large Solar Particle Event on 13th December 2006

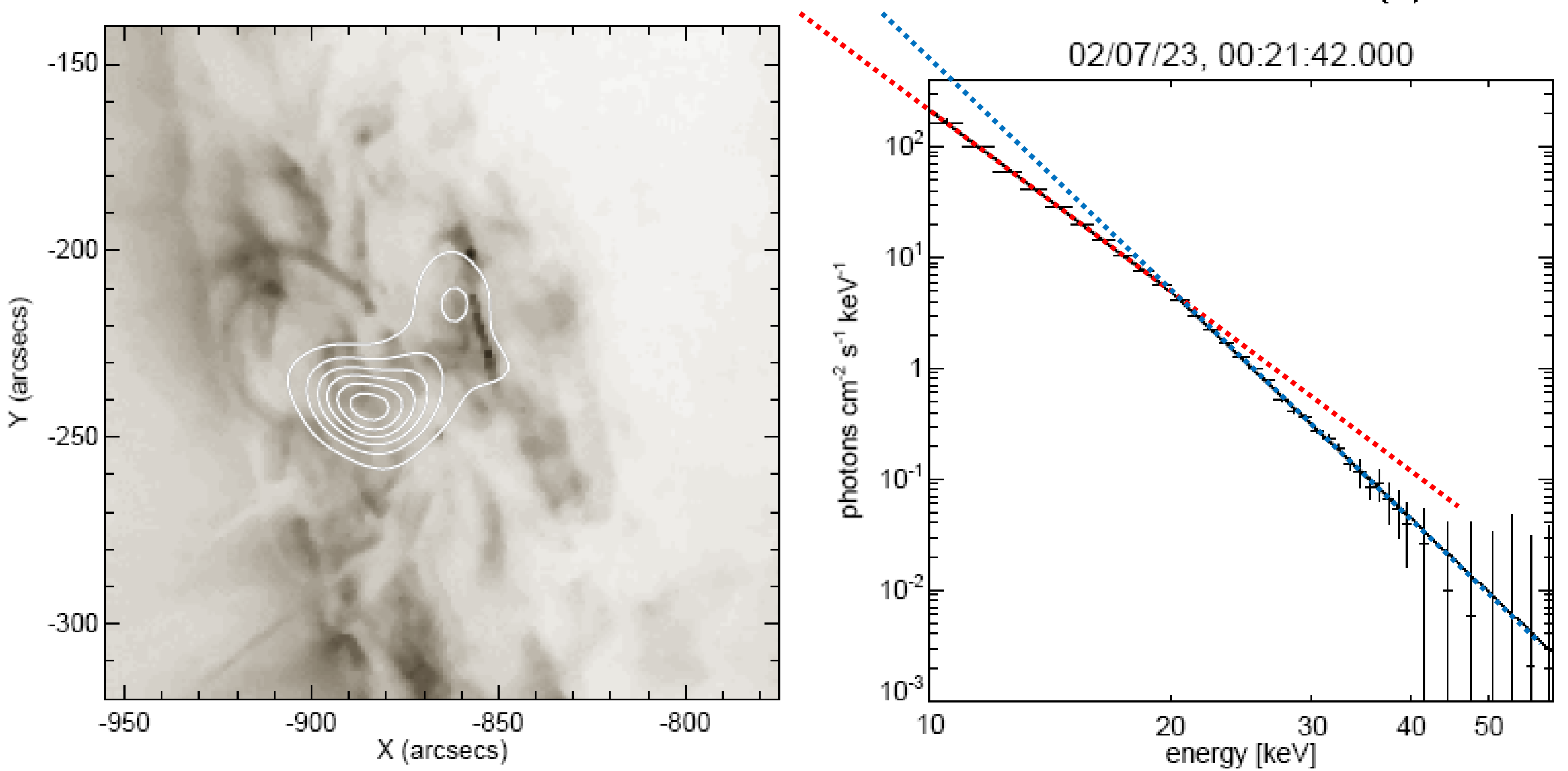


Differential energy spectra of protons in different time intervals.

Casolino M. et al., 2009, arXiv:0904.4692v1 [astro-ph.HE] 29 April 2009

The most interesting range of energies

Double-power-low spectrum of a coronal hard X-ray source in the flare on 23 July 2002 (RHESSI)



Instead of Conclusions

- In fact, we may proceed with confidence from simplified models to constructing the more quantitative theory of particle acceleration by magnetic reconnection and collapsing trap in flares.
- Open issues of the theory: spectra and composition of accelerated ions as they detected by different space missions.

Thanks for your attention

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