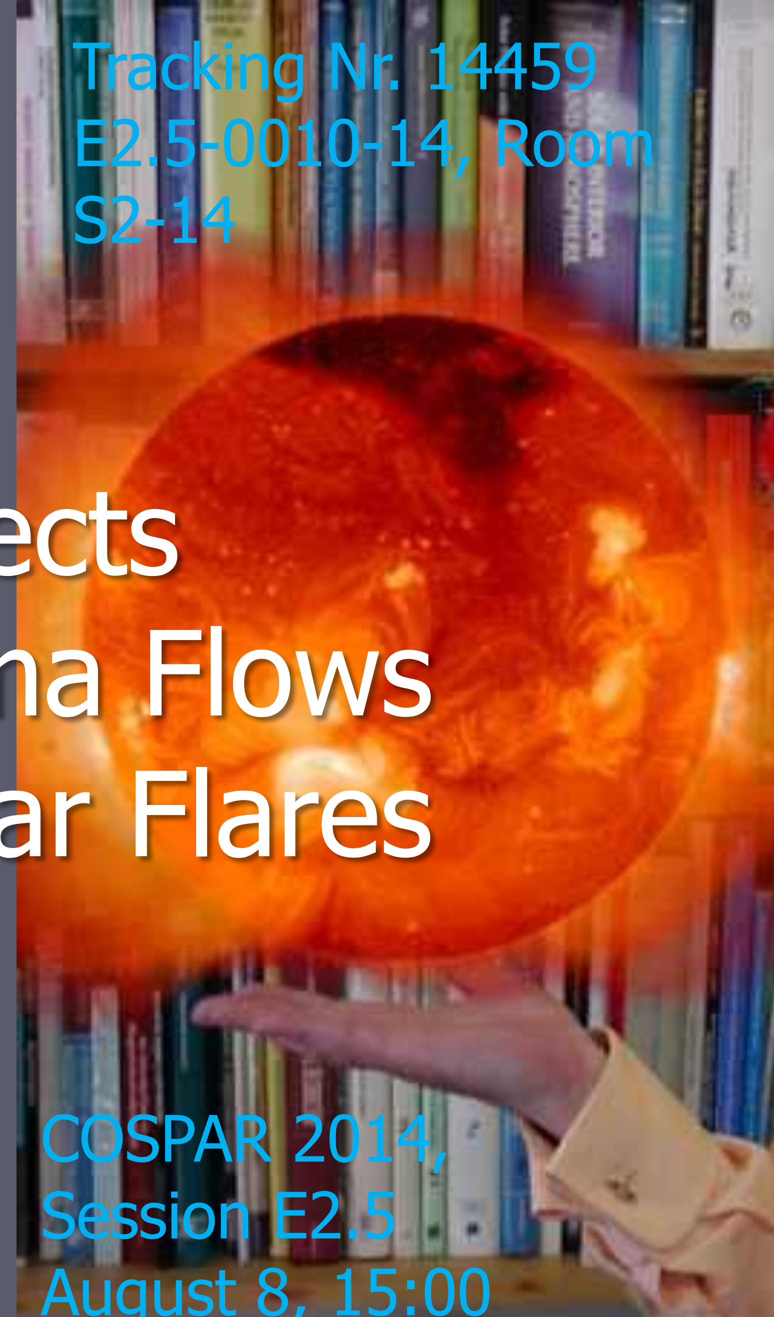


Tracking Nr. 14459
E2.5-0010-14, Room S2-14

Theoretical Aspects Related to Plasma Flows Observed in Solar Flares

Boris V. Somov
Solar Physics Department
Astronomical Institute
Moscow State University

COSPAR 2014,
Session E2.5
August 8, 15:00

Logic of the talk

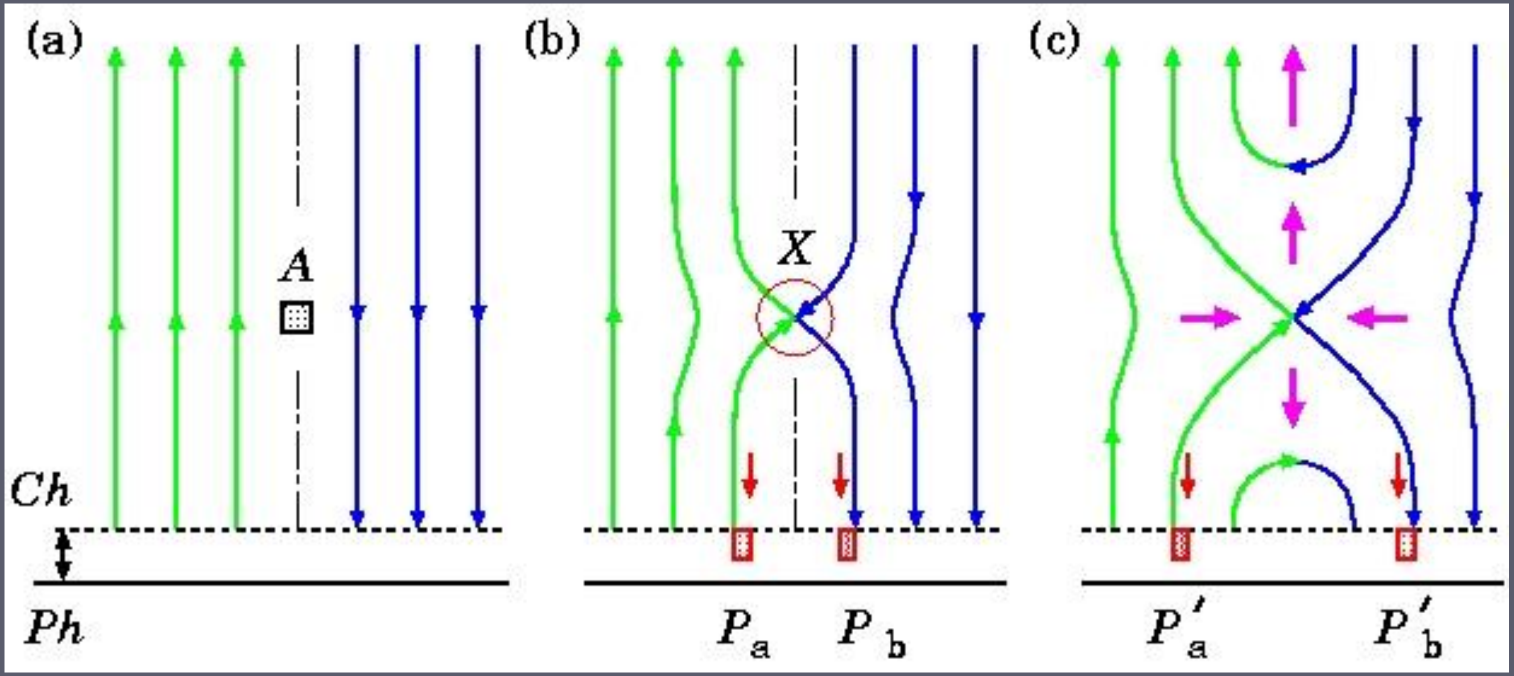
- Apparent motions and real flows of plasma
- Plasma flows in a flare energy source
- Flows in a surrounding plasma

Two Classical Models of Solar Flares

- Standard models (Carmichael, 1964; Sturrock, 1966; …)
- Topological models (Sweet, 1969; … Gorbachev and Somov *, 1989; …)

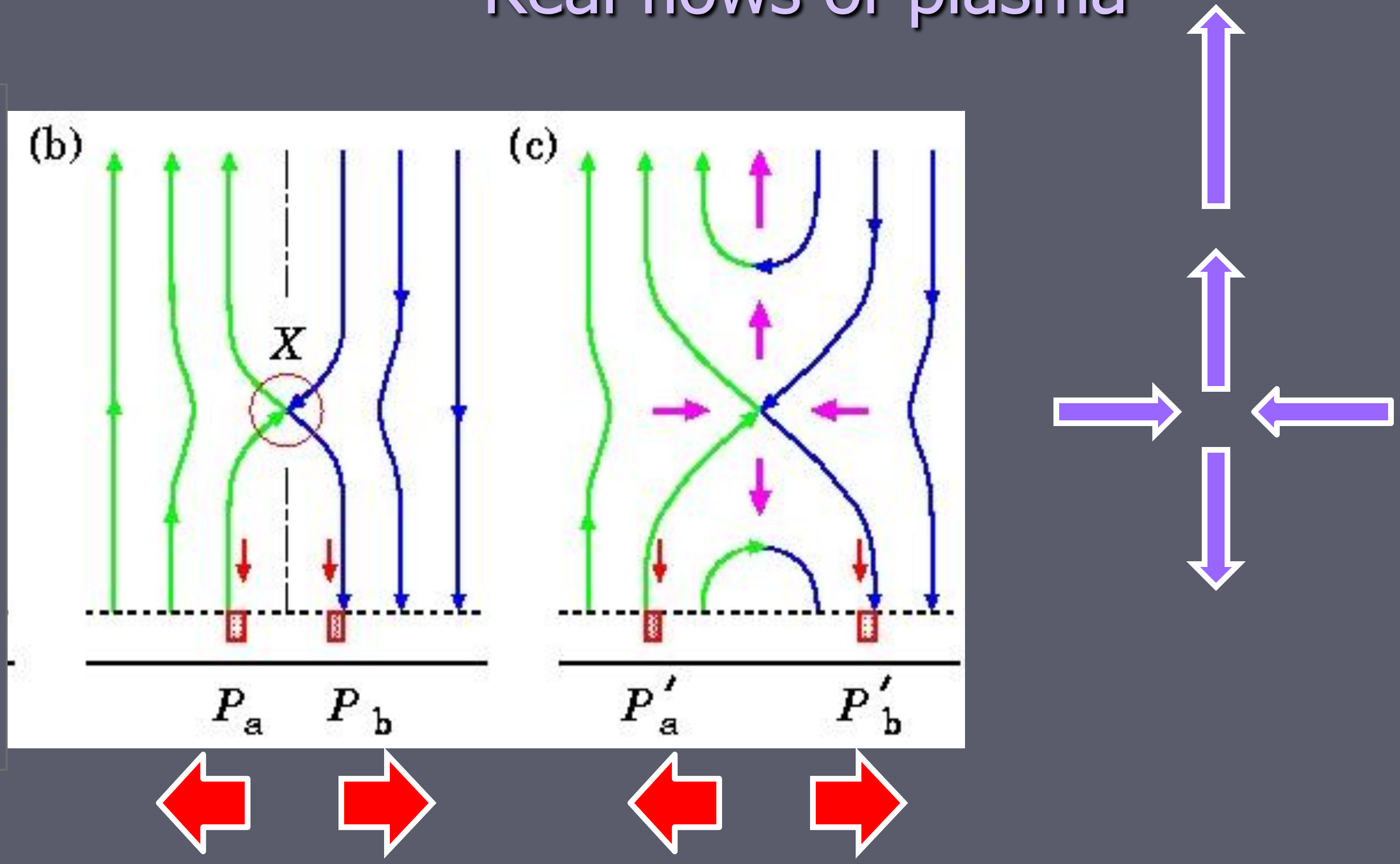
* Gorbachev V.S., Somov B.V., Soviet Astron. -- AJ, **33**, 57, 1989

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) Separation of footpoints P_a and P_b increases as new field lines reconnect

Real flows of plasma



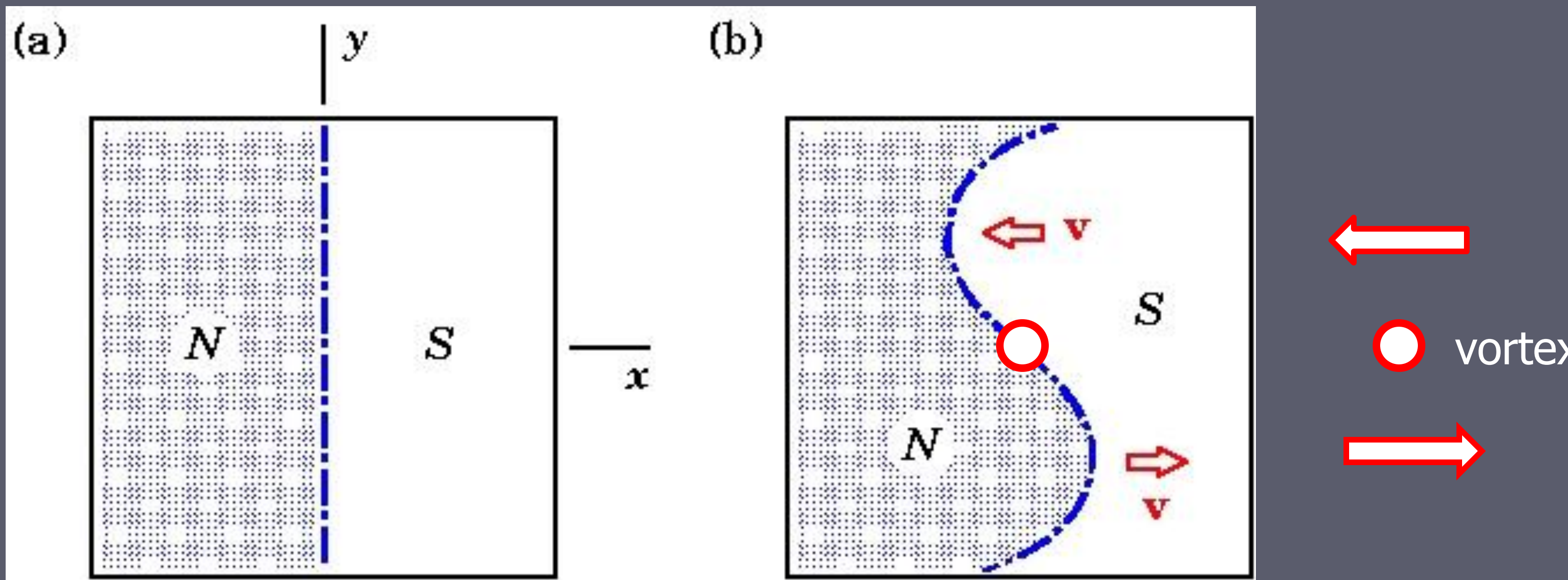
Apparent displacements of reconnected loop footpoints

Topological models *

- Rainbow reconnection model
- Photospheric plasma flows
- Pre-flare energy accumulation
- Reconnection and energy release
- Apparent and real motions
- Downward motion of coronal plasma

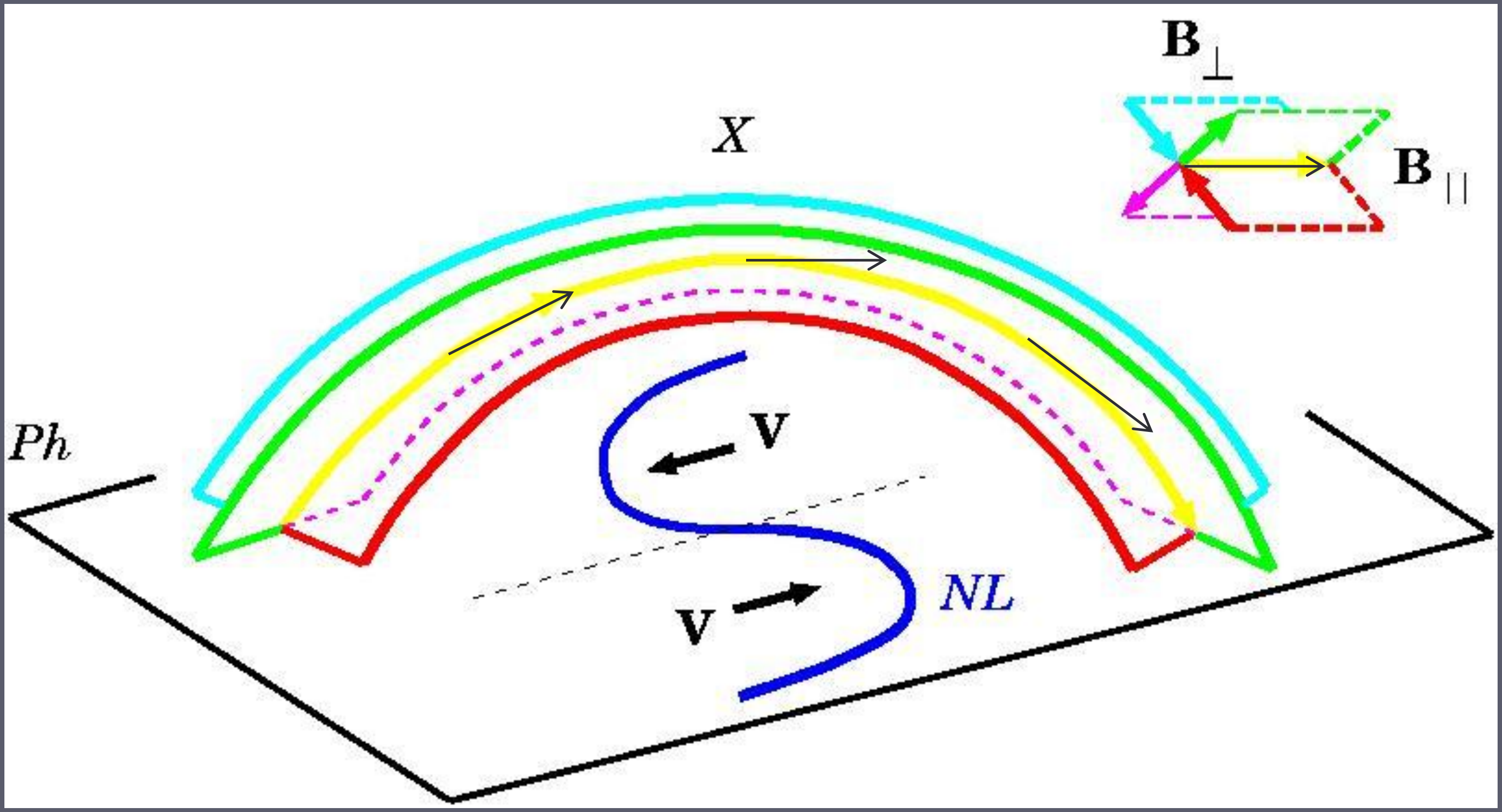
*) Reviewed in
Somov B.V., Plasma Astrophysics, Part II, Reconnection and Flares, Second Edition, Springer SBM, New York, 2013, Chapters 4 - 7

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*

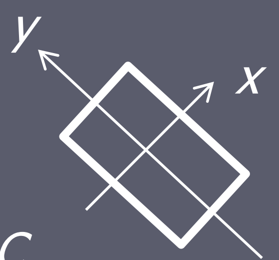
Rainbow Reconnection in the Corona



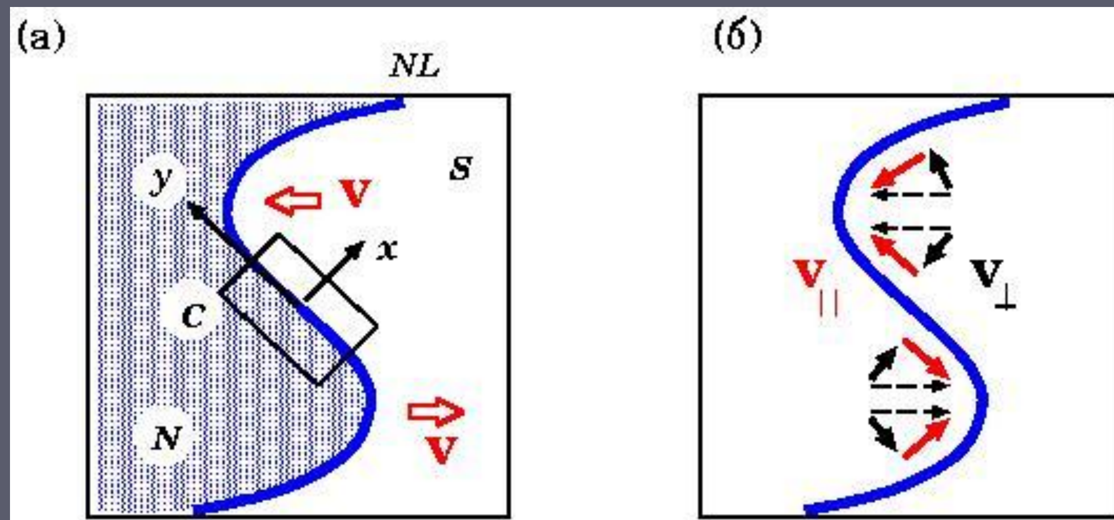
► A separator *X* appears above the *S*-bend of the photospheric neutral line *NL*

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

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

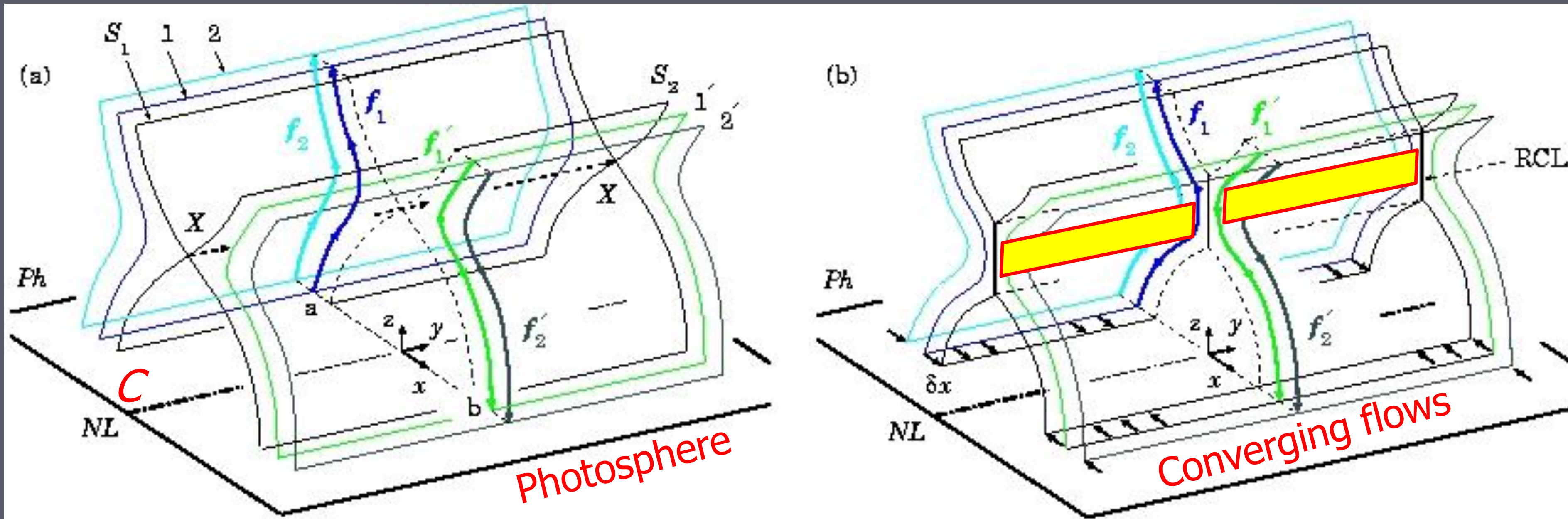


C – central part



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

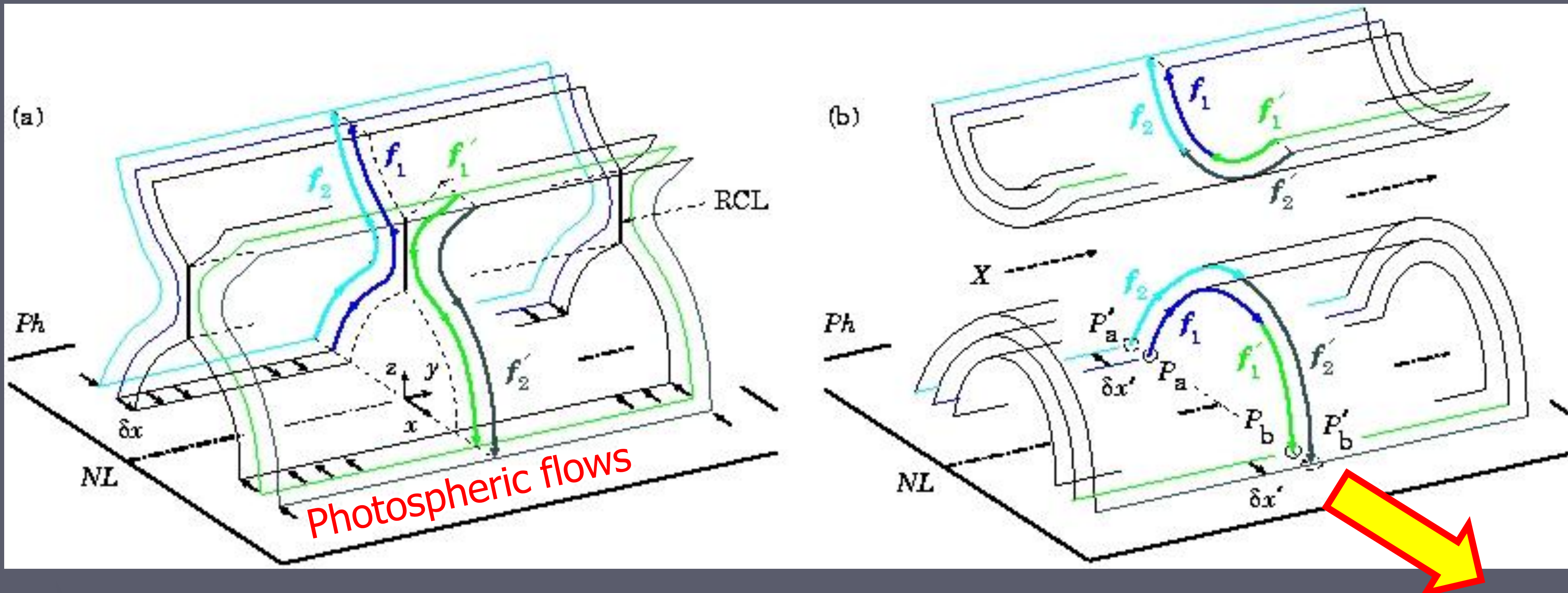
Pre-flare Energy Accumulation



- (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

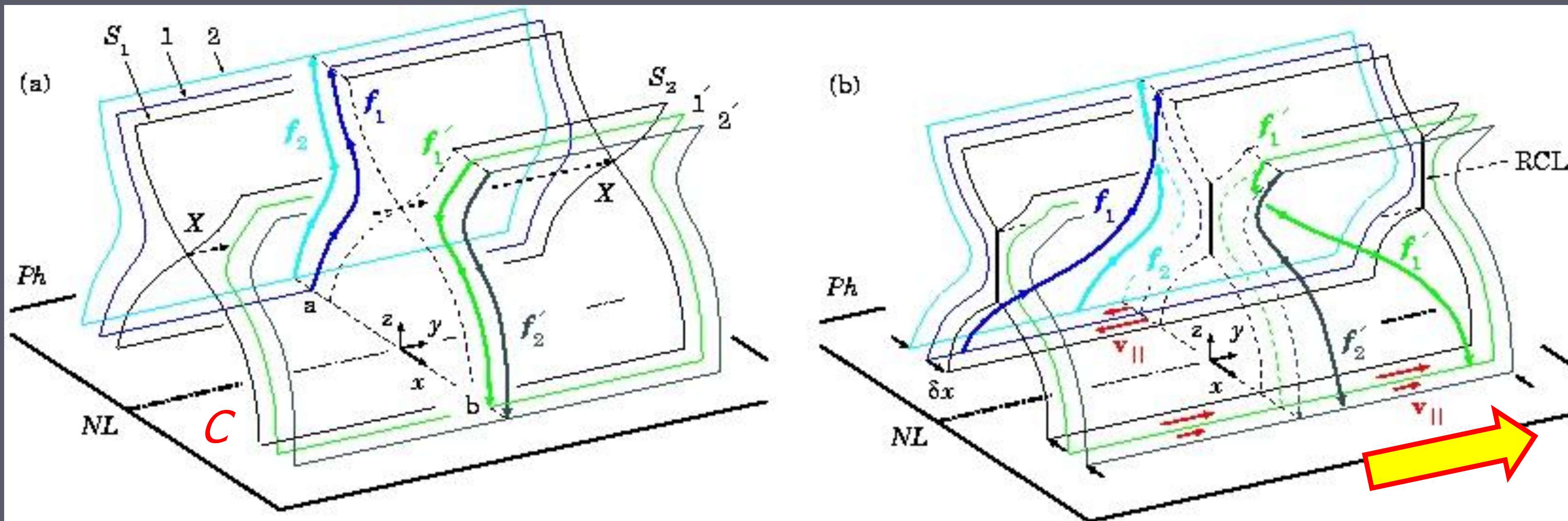
Somov, Kosugi, Hudson et al., ApJ **579**, 863, 2002

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

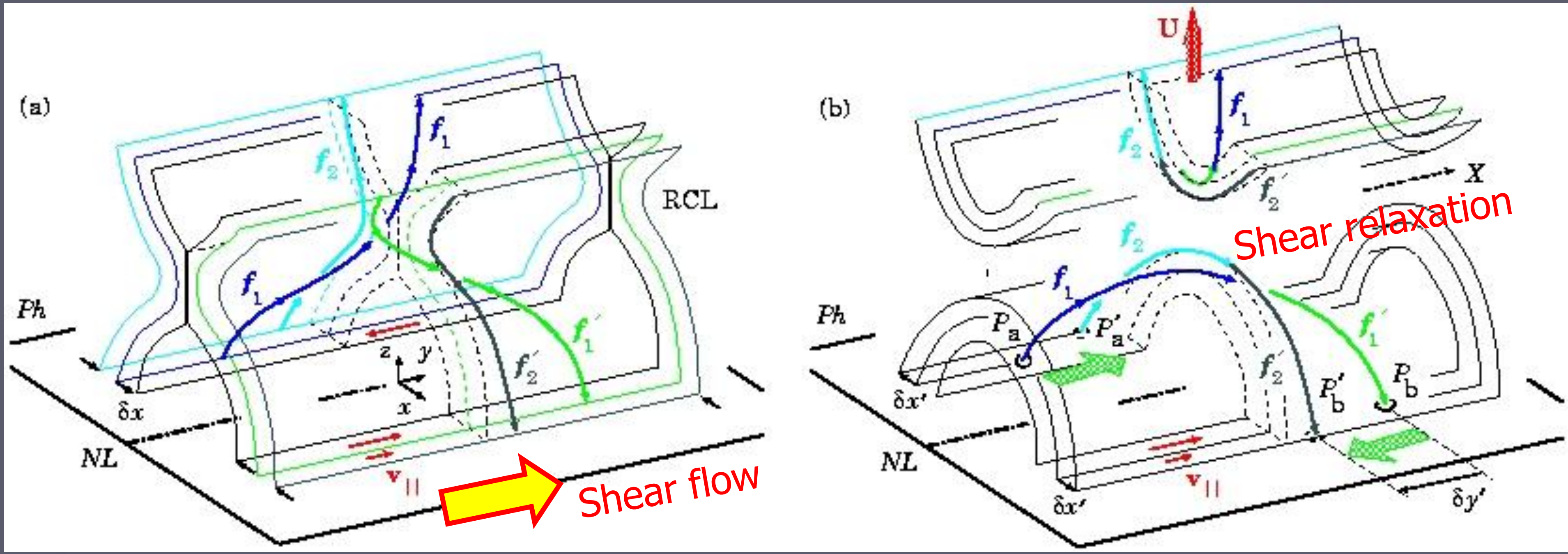
Pre-flare Structure with Shear



- (a) The initial configuration
- (b) 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

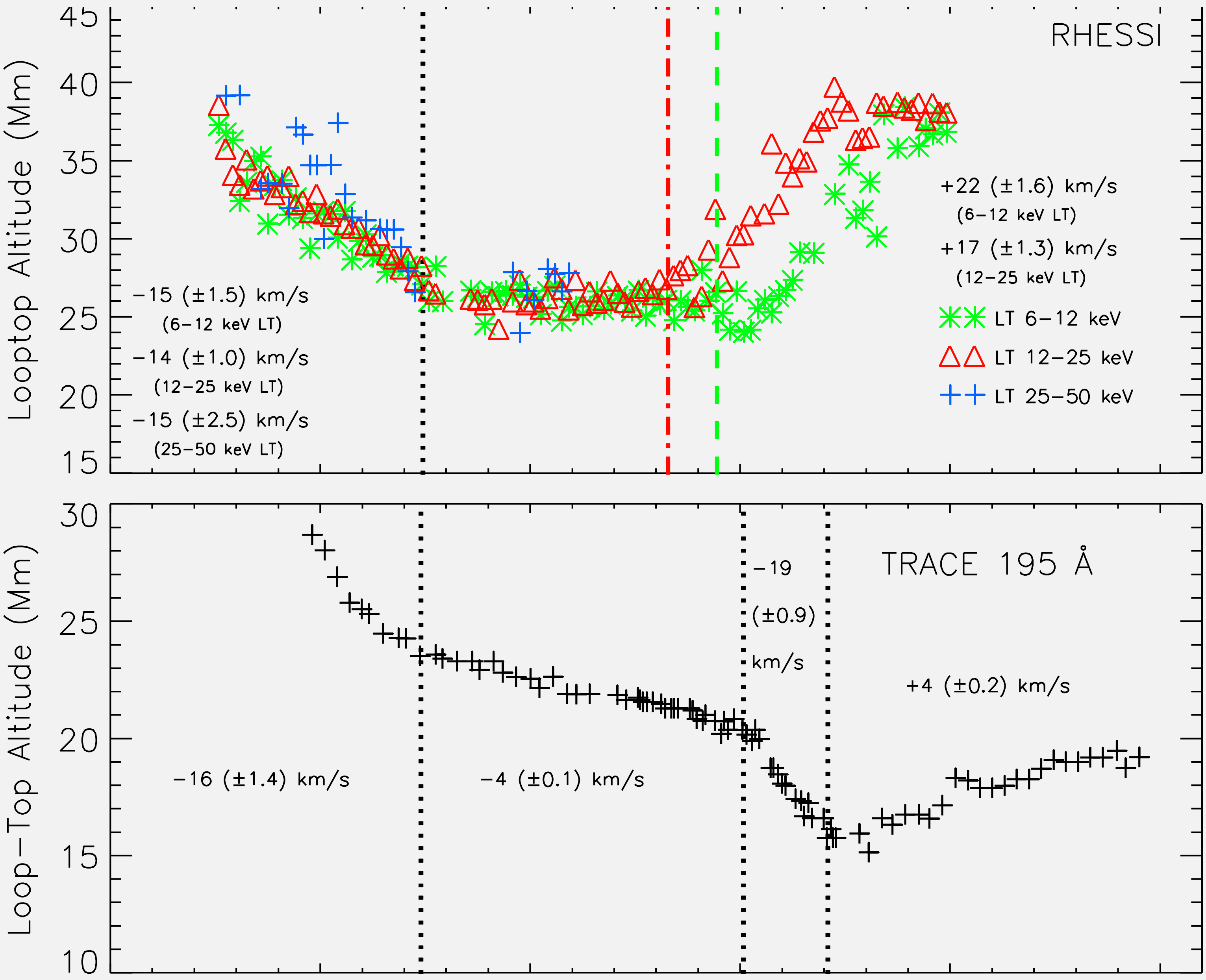
The rainbow reconnection model predicts two types of motions of chromospheric footpoints (kernels)

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

The rainbow reconnection also explains the descending motion of coronal plasma during the early phase of a flare

- A decrease of the distance between the kernels because of the shear relaxation
- Downward motion of coronal plasma

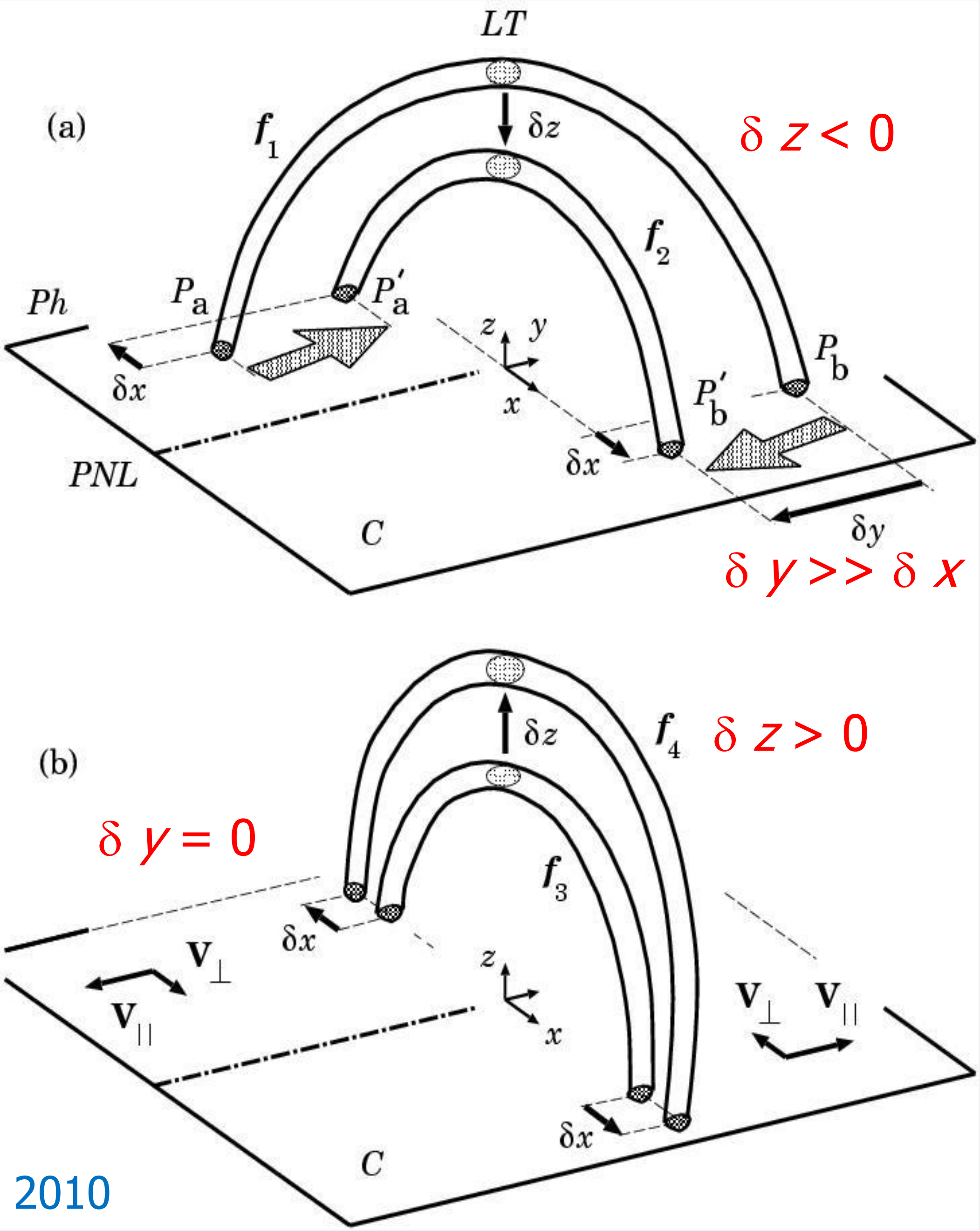
Somov, Astronomy Lett. **36**, No. 7, 2010



RHESSI
Looptop Altitude (Mm)
45
40
35
30
25
20
15
−15 (±1.5) km/s
(6−12 keV LT)
−14 (±1.0) km/s
(12−25 keV LT)
−15 (±2.5) km/s
(25−50 keV LT)
+22 (±1.6) km/s
(6−12 keV LT)
+17 (±1.3) km/s
(12−25 keV LT)
LT 6−12 keV
LT 12−25 keV
LT 25−50 keV
TRACE 195 Å
Loop−Top Altitude (Mm)
30
25
20
15
10
−16 (±1.4) km/s
−4 (±0.1) km/s
−19
(±0.9)
km/s
+4 (±0.2) km/s

Rapid decrease of FP separation dominates an increase of distance between flare ribbons

FPs separate in opposite directions from PNL and from each other



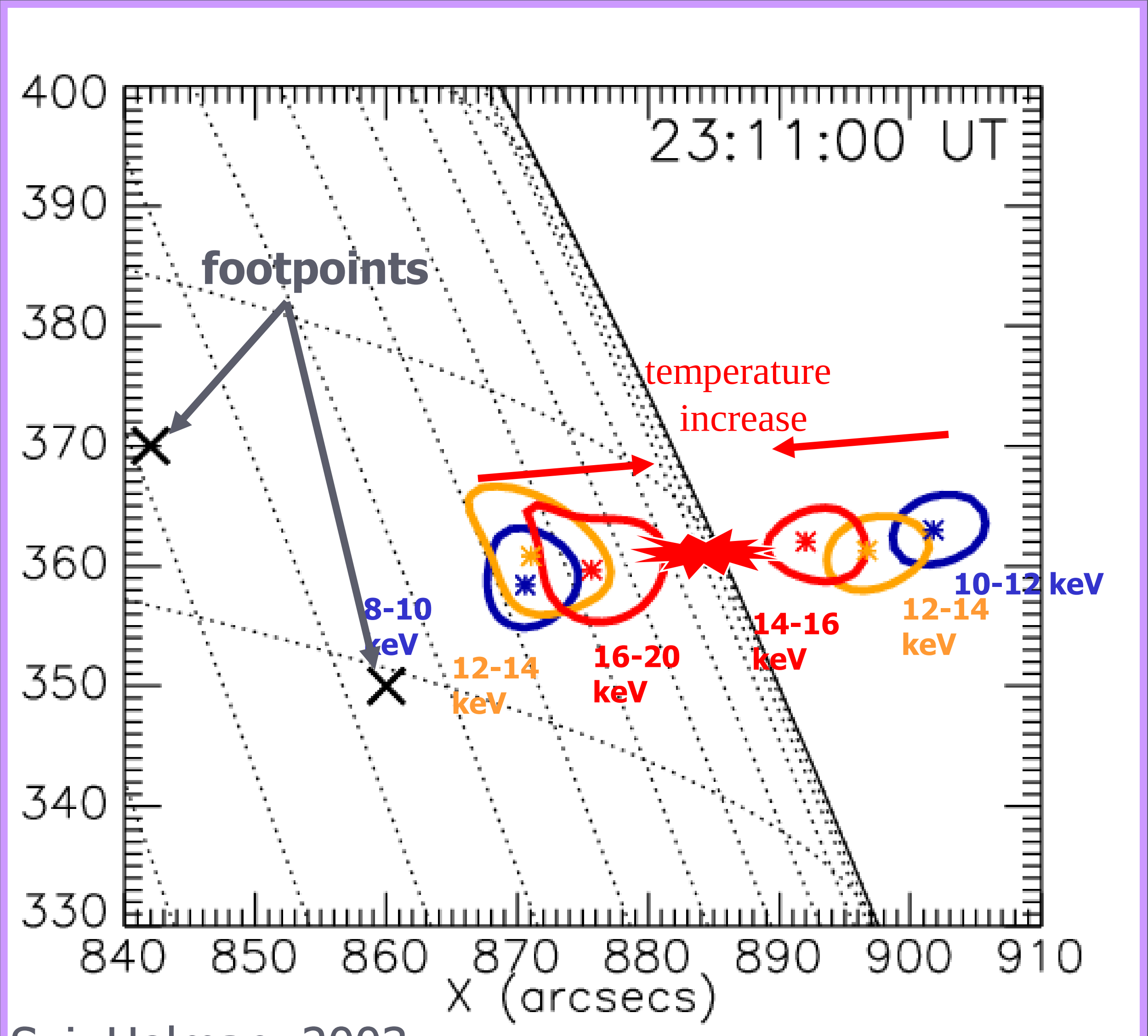
Somov , Astronomy Lett. **36**, 514, 2010

Plasma flows in the source of energy

Observational problem
No. 1

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

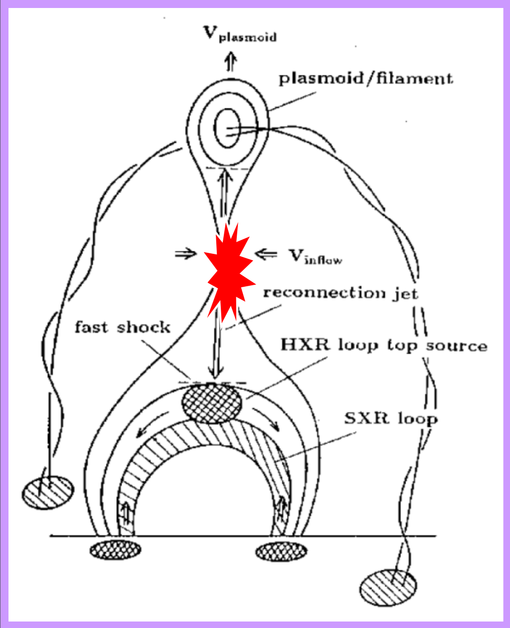
RHESSI: Temperature distribution near the source of energy



Sui, Holman, 2003

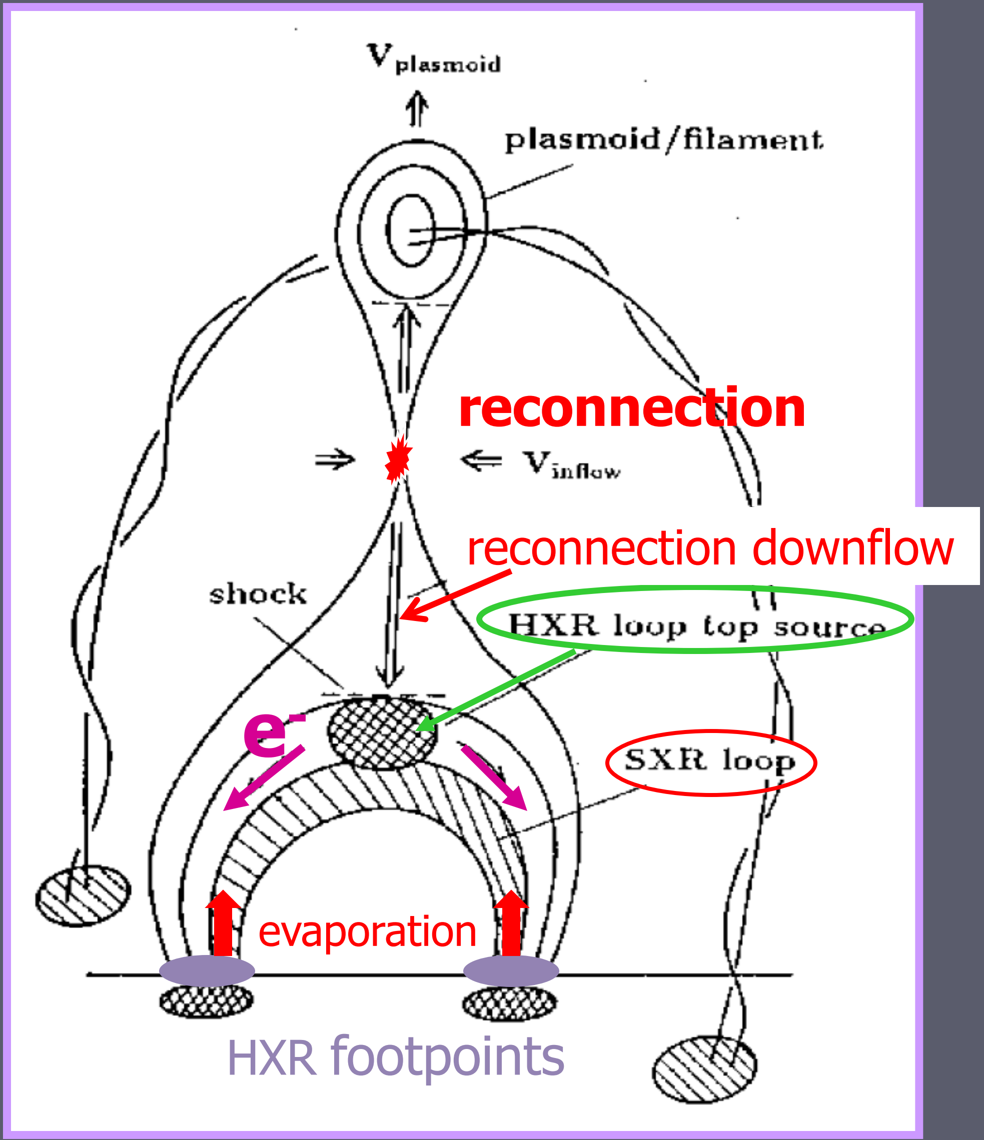
Thanks to S. Krucker

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



Shibata 1998

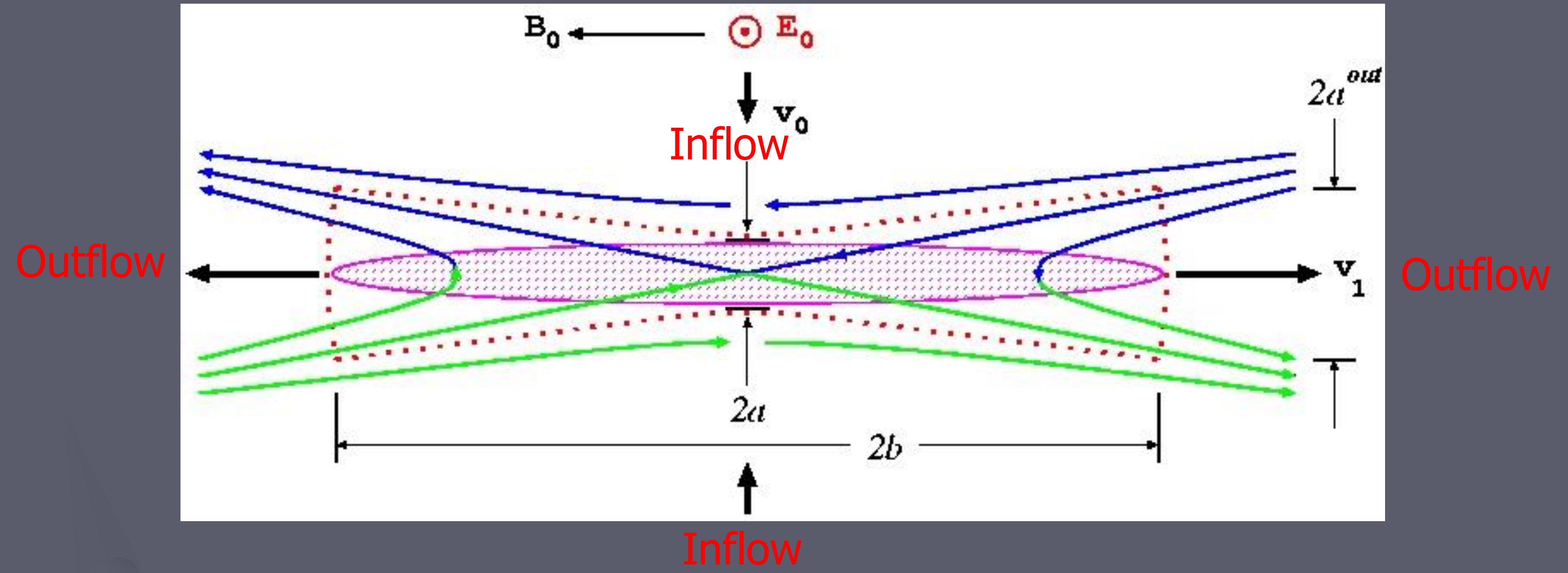
Magnetic reconnection interpretation



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

Shibata 1998

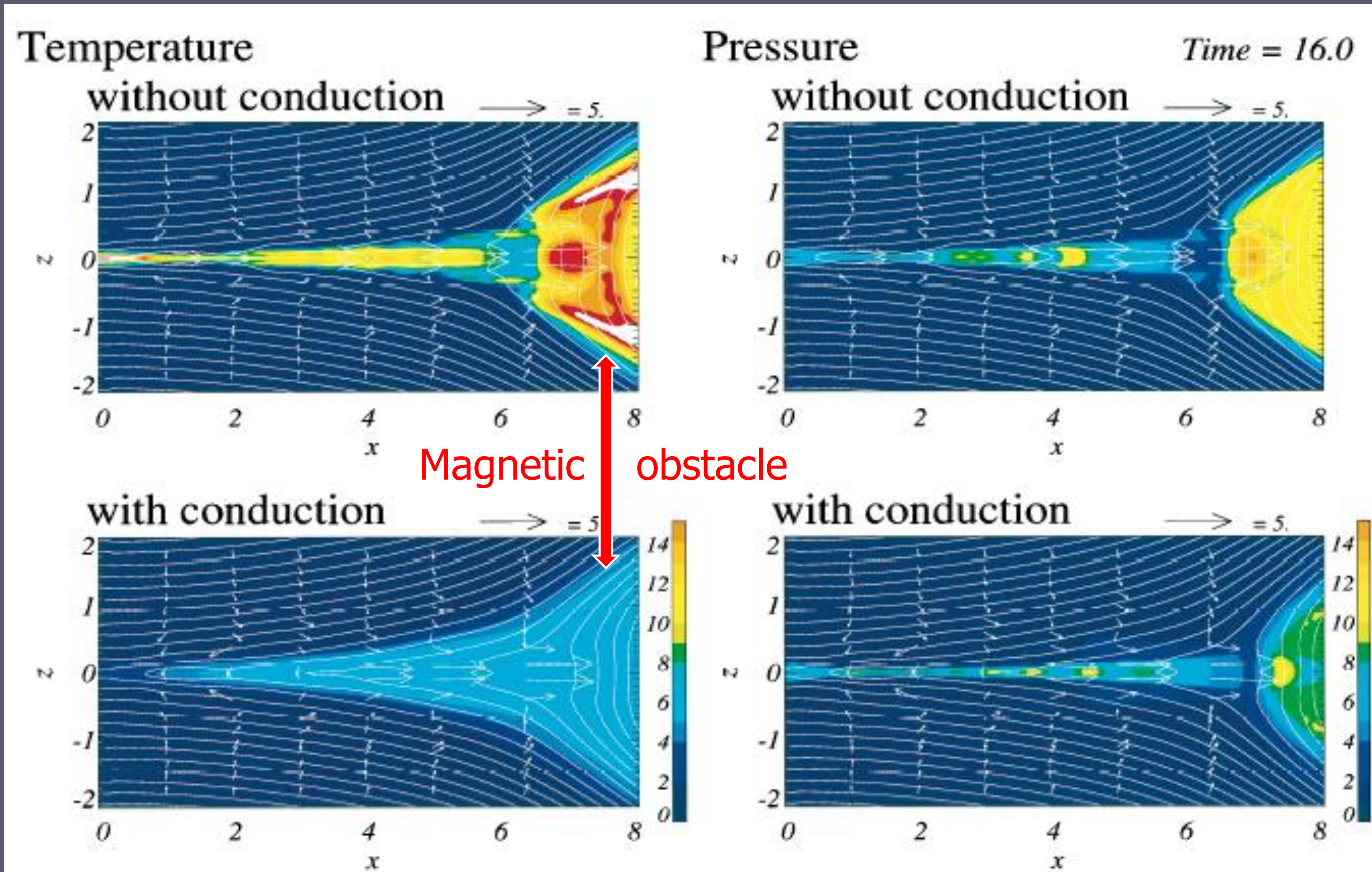
Plasma flows near a Super-Hot (Te > or ~ 100 MK) Turbulent-Current Layer (SHTCL)



Powerful heating of electrons results from wave-particle interactions

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

Dissipative MHD numerical modeling downflow



Yokoyama, Shibata, ApJ, 474, L61

Numerical experiment

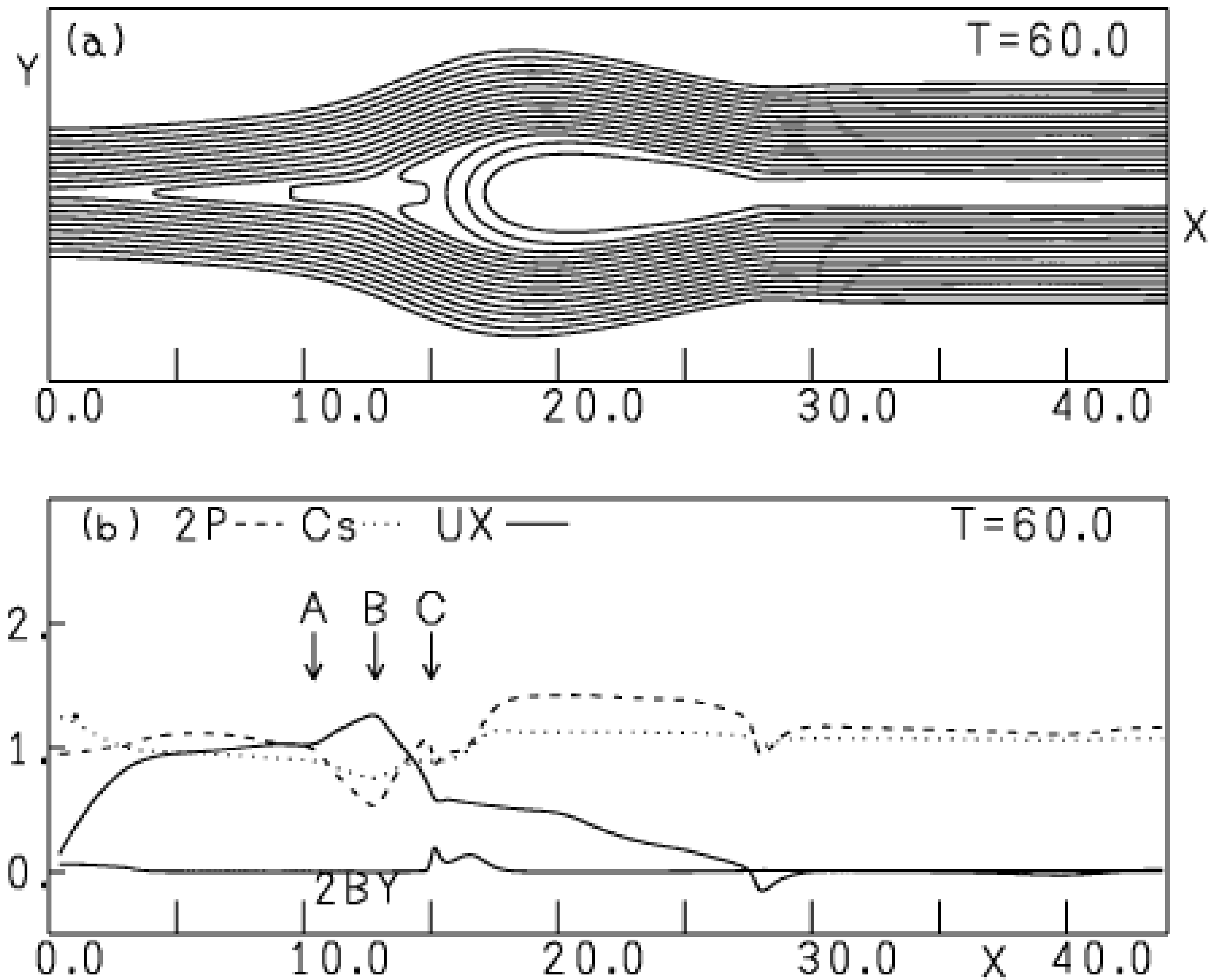
MHD shock wave structure in supersonic reconnection

Upward Flow

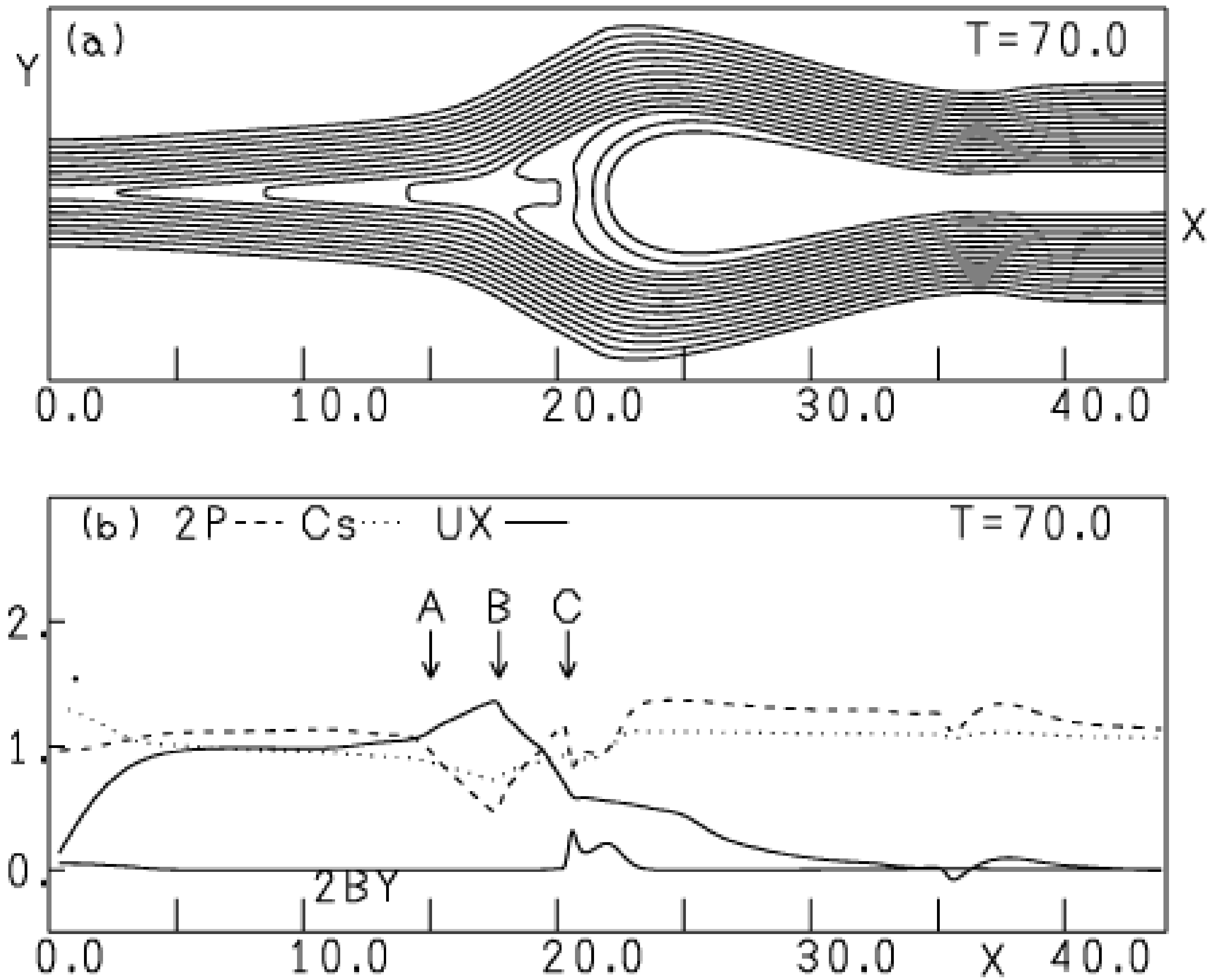
Shimisu, Kondo, Ugai. 2005

T=60, (a) Magnetic field lines (b) x-directional profiles along the x-axis. Arrow B is fast shock

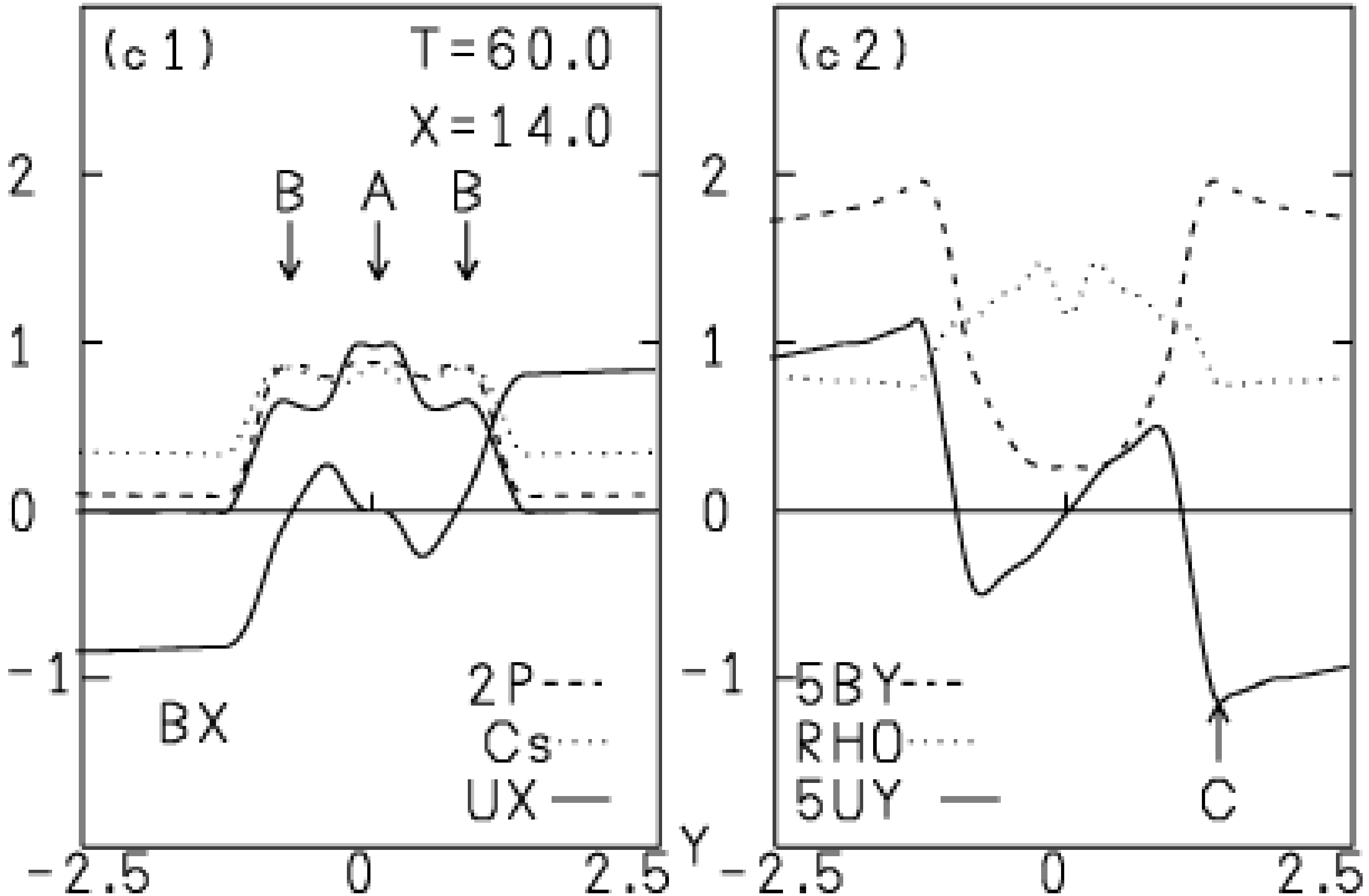
Upward direction →



T=70, (a) Magnetic field lines (b) x-directional profiles along the x-axis. Arrow B is fast shock



T=60, y-directional profiles at x=14

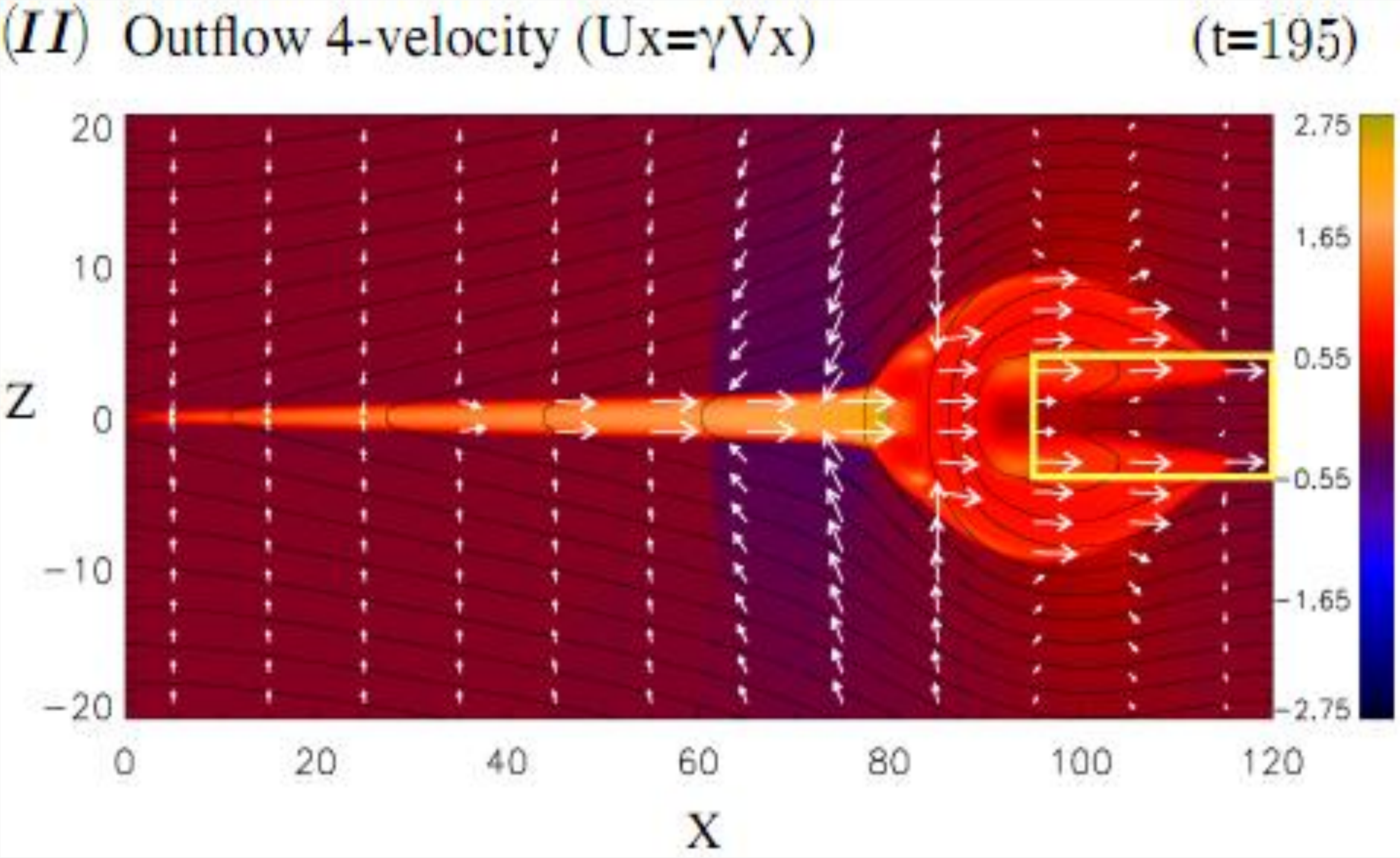


Resistive MHD Simulations of Reconnection

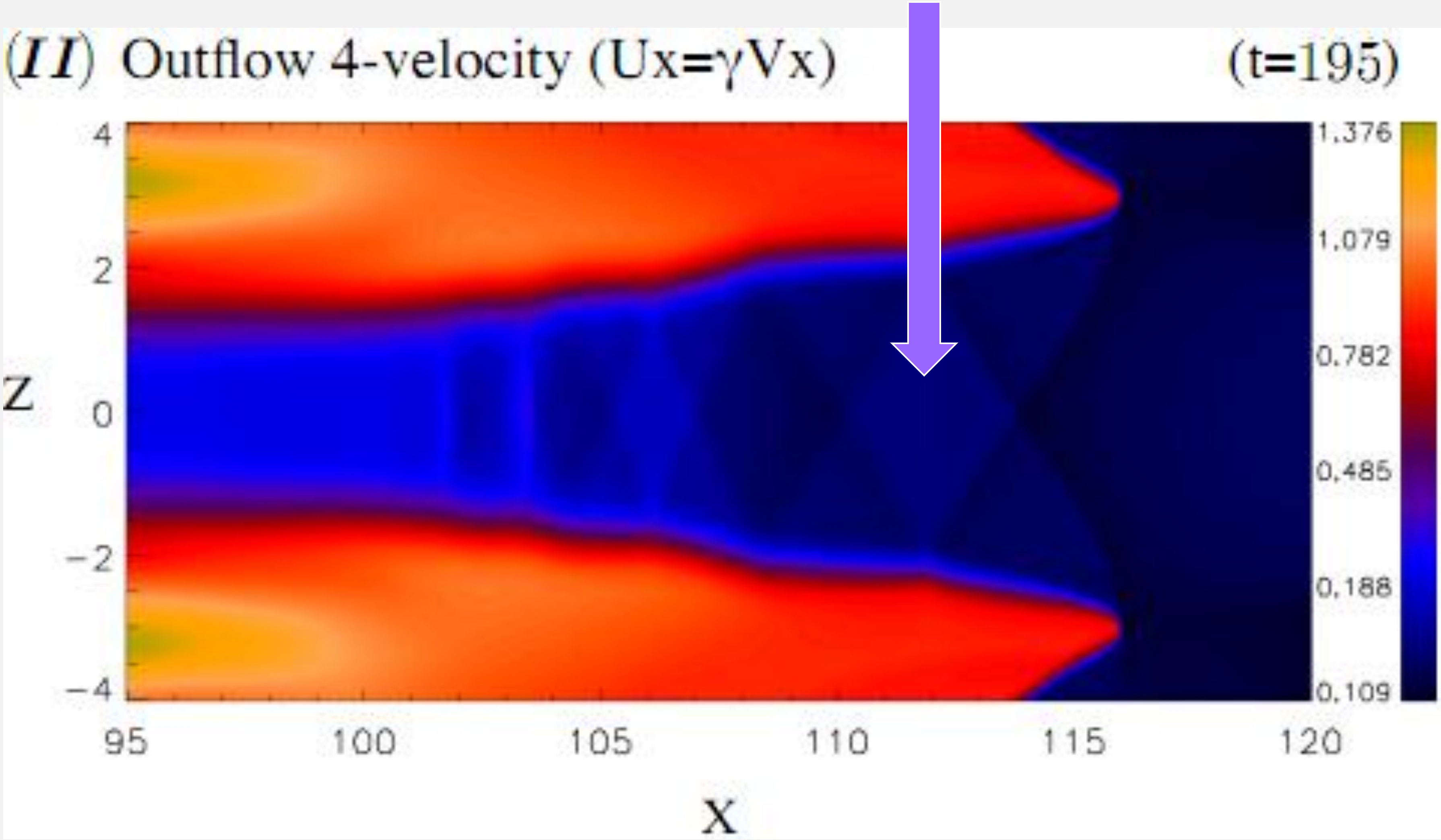
Upward Flows

Zenitani, Hesse, Klimas, 2010

Reconnection of open magnetic field lines upward



Diamond-chain structure related to excitation of TAS-Waves

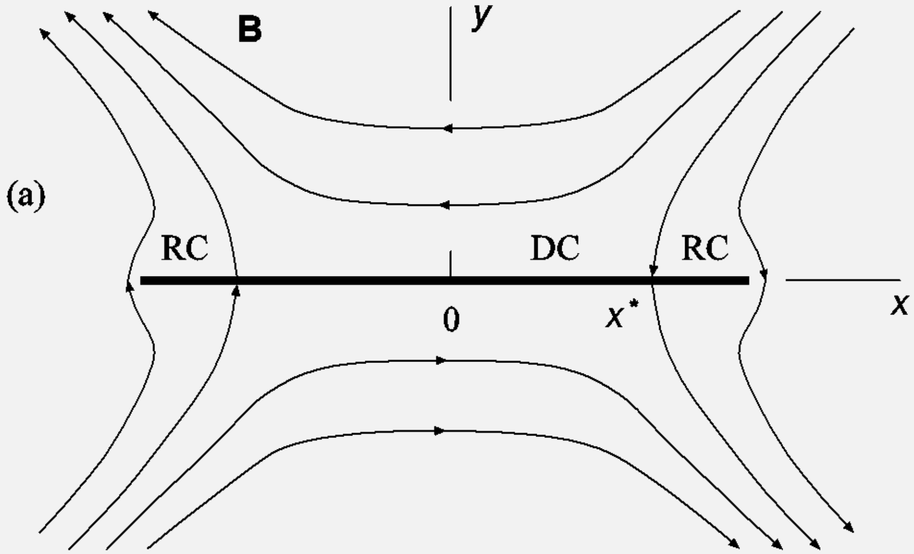


- The post-plasmoid vertical shocks and the diamond-chain structure are discovered.
- Different resistivity models are examined, which showed different system evolutions.
- However …

Old and New *
Analytical Models
of
Magnetic Reconnection

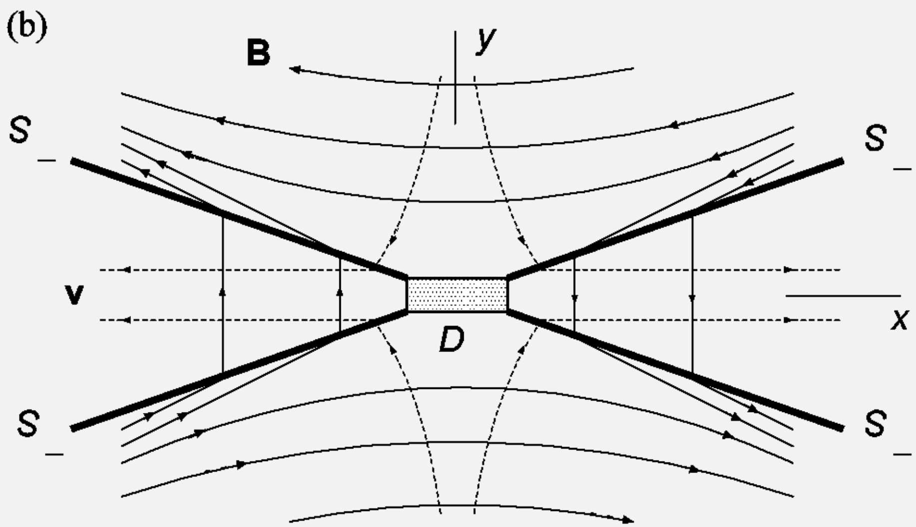
*) Bezrodnykh, Vlasov, Somov, Astronomy Lett. 37, 113, 2011.
Ledentsov, Somov, Astronomy Lett. 37, 131, 2011

Two classic models of reconnection



Thin current layer by Syrovatskii:

direct current (DC) and return currents (RC) inside the current layer



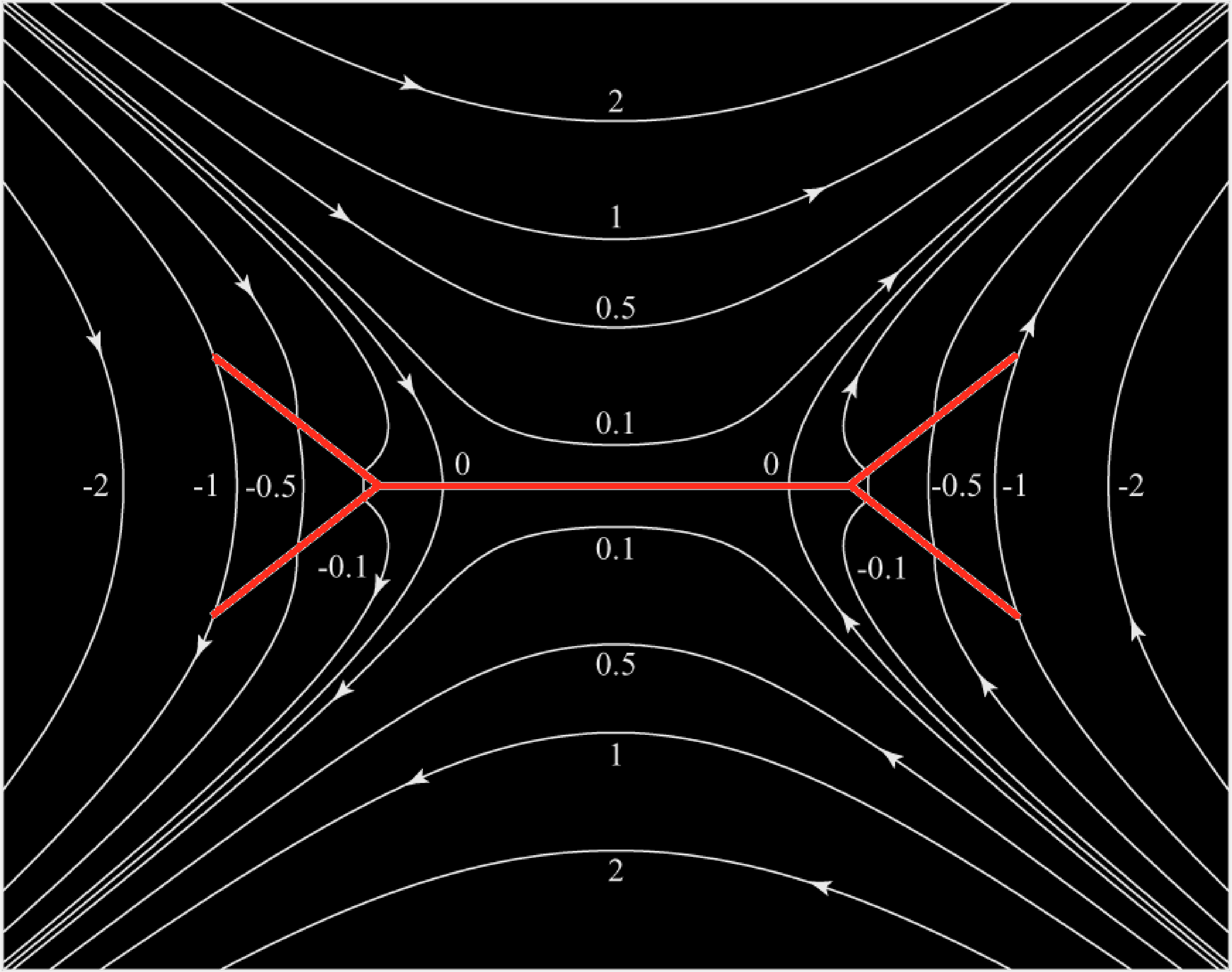
Petschek Flow:

compact diffusion region *D* and 4 attached MHD slow shock waves of infinite length

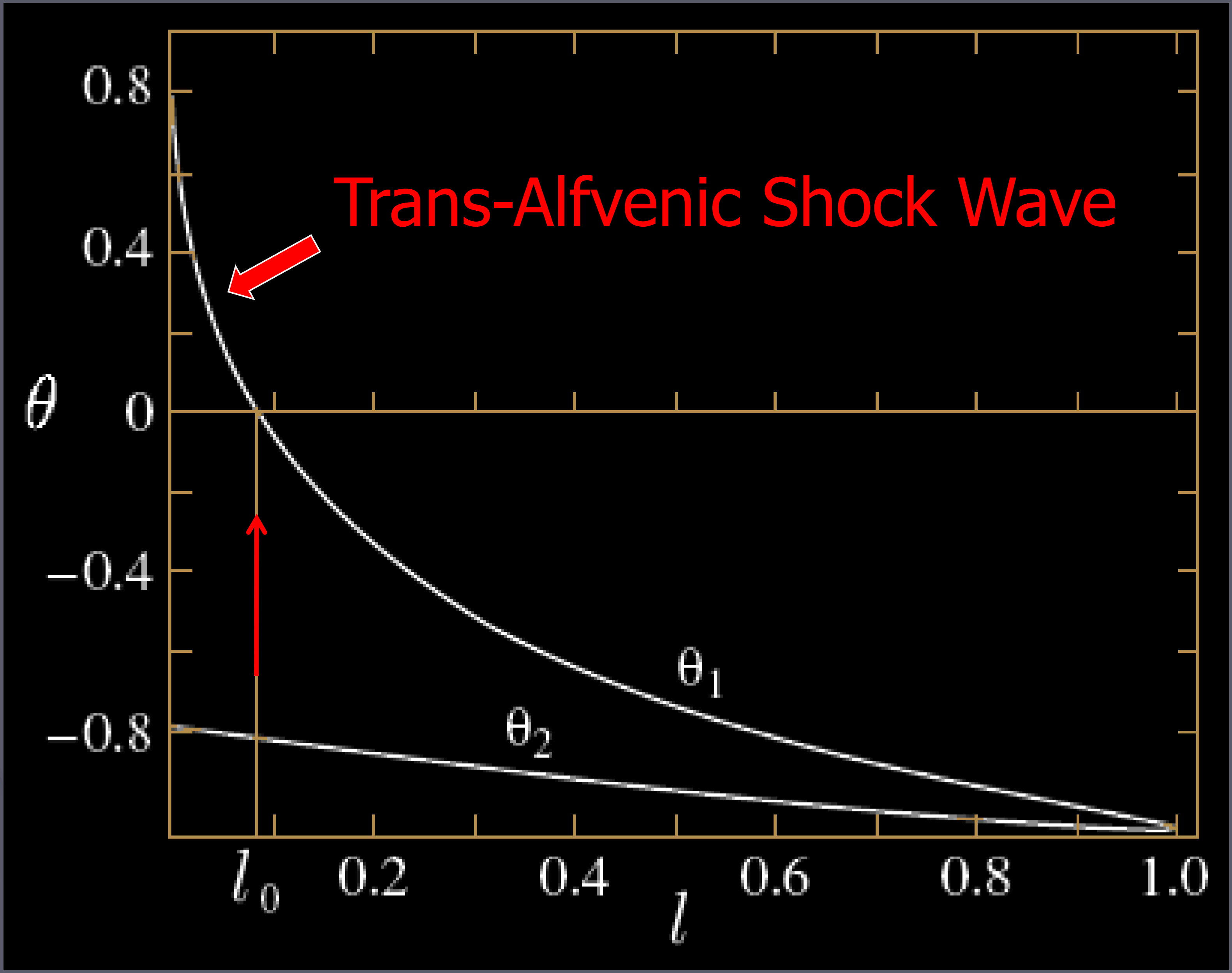
New analytical models

- Thin current layer of the Syrovatskii type and attached discontinuous MHD flows of finite length
- A character of flows is not prescribed but determined from a self-consistent solution
- Global structure of magnetic field and local properties of the field near current layer and discontinuities

Bezrodnykh, Vlasov, Somov, Astronomy Lett. 37, 113, 2011



Magnetic field lines



Angles θ_1 and θ_2 as a function of l

New features of reconnection

- Despite the expectations that follow from the Petschek model, the attached discontinuities appear to be not the slow MHD but Trans-Alfvenic shock waves (TASW)
- This is typical for the fast reconnection with return currents inside the current layer
- TASW are non-evolutionary *

*) MHD discontinuities in solar flares: Continuous transitions and plasma heating. Ledentsov, today 18:00

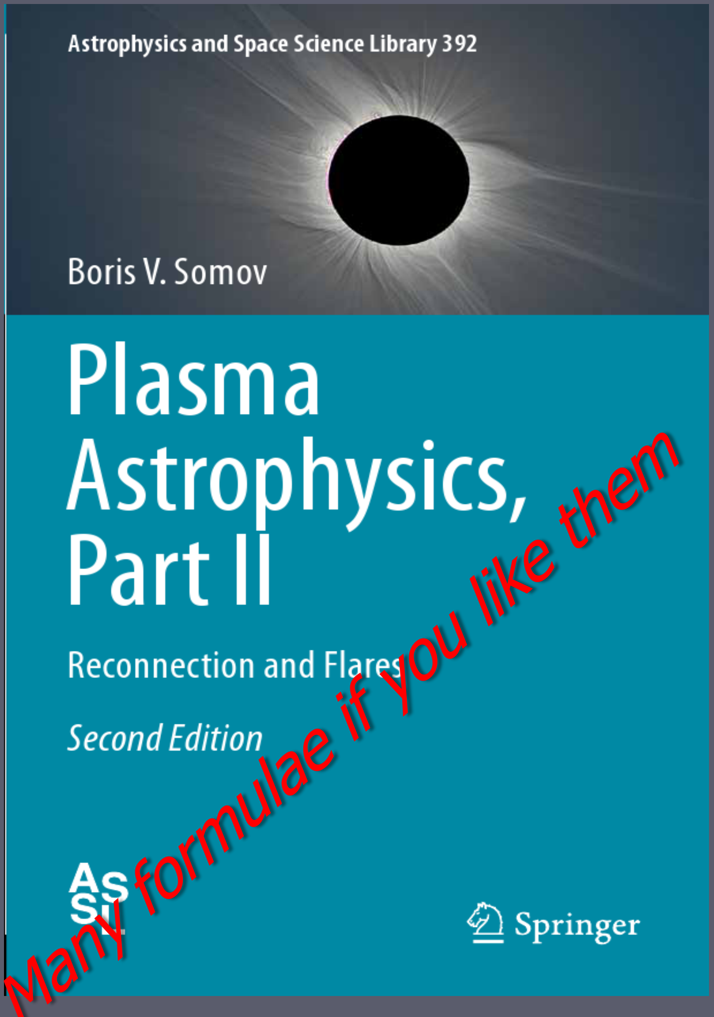
New consequences for physics of solar flares

- Two types of transition from non-evolutionary shock waves (TASW) to evolutionary ones exist depending on geometrical parameters of reconnection region
- New possibilities to interpret results of numerical and laboratory experiments on reconnection in the dissipative MHD and collisionless plasmas

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

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



What has to be understood?

Heat-transfer problem → Predictions for observations (Classical and relaxed heat conduction)

Flows in a surrounding plasma

- Plasma flows near a Reconnecting Current Layer (RCL): Strong magnetic field approximation (Kolesnikov and Bezrodnykh, today 16:15)

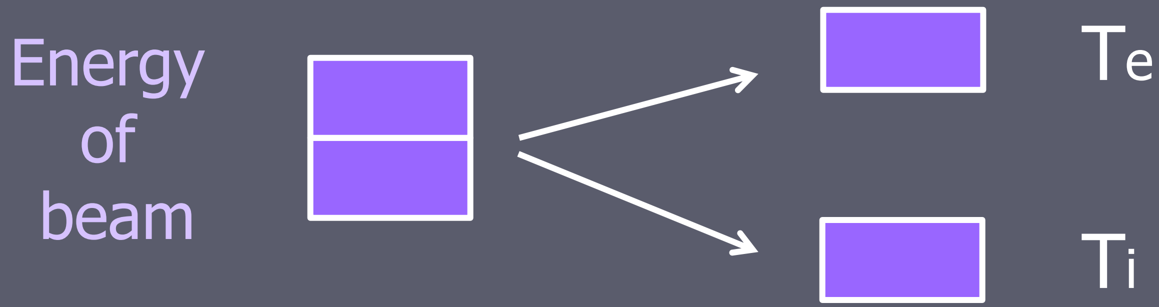
*) Kolesnikov et all, E2.5-0014-14

Chromospheric evaporation

Impulsive heating of plasma
by
energetic electrons

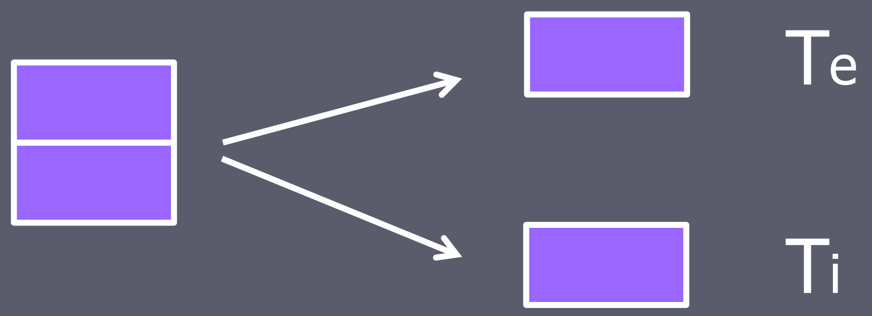
! $T_e >> T_p$!

- "Lazy" models – Beam heats electrons and ions



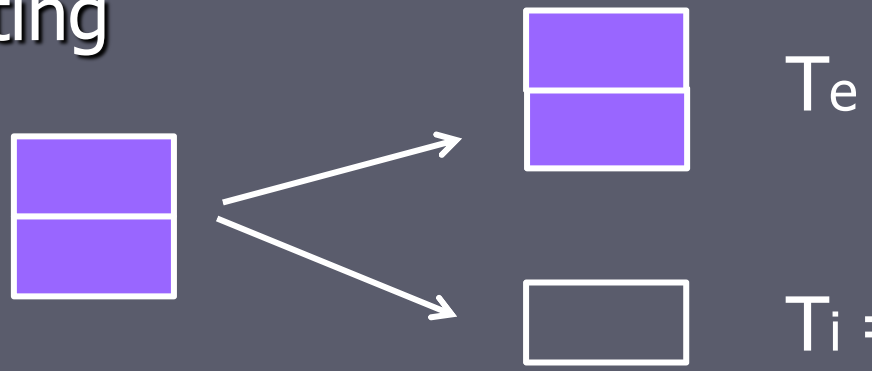
$T_e = T_i = T$

- "Lazy" model – Beam heats electrons and ions



$T_e = T_i = T$

- Real heating



$$F_{real} = \kappa_e \nabla T_e \sim T_e^{5/2} \times T_e \sim T_e^{7/2} \sim \underline{2^{7/2}}\, T^{7/2} \sim \underline{10}\, F_{lazy}$$

The “lazy” one-temperature models
of chromospheric evaporation
are less (10 times) dynamic then
the realistic two-temperature models

Instead of Conclusion

In fact, we may proceed with confidence from simplified models to constructing the more quantitative theory of magnetic reconnection, particle acceleration by reconnection and collapsing traps, to prediction of large flares.

Thanks for your attention

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