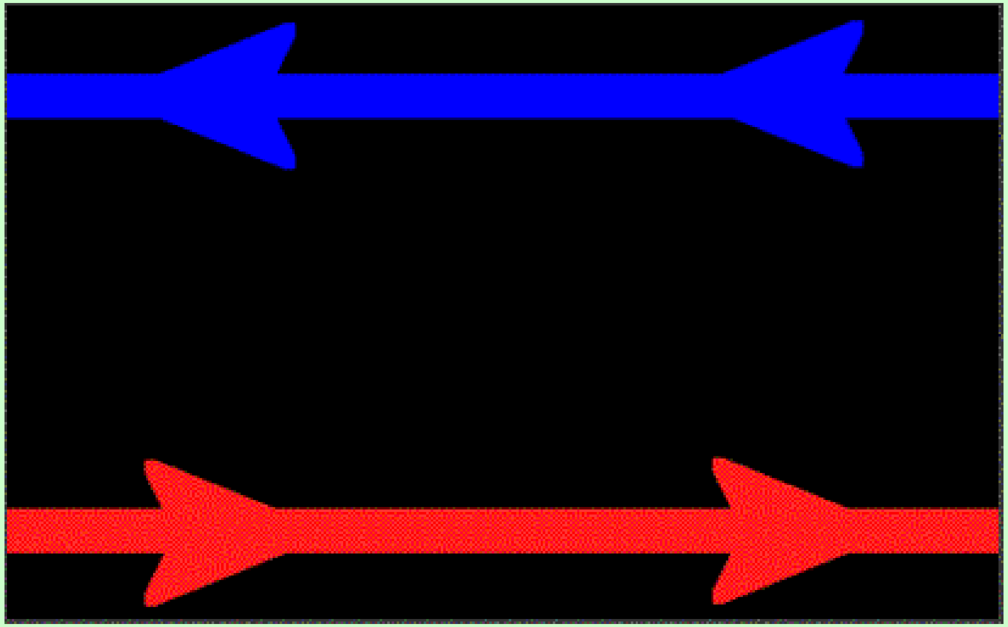
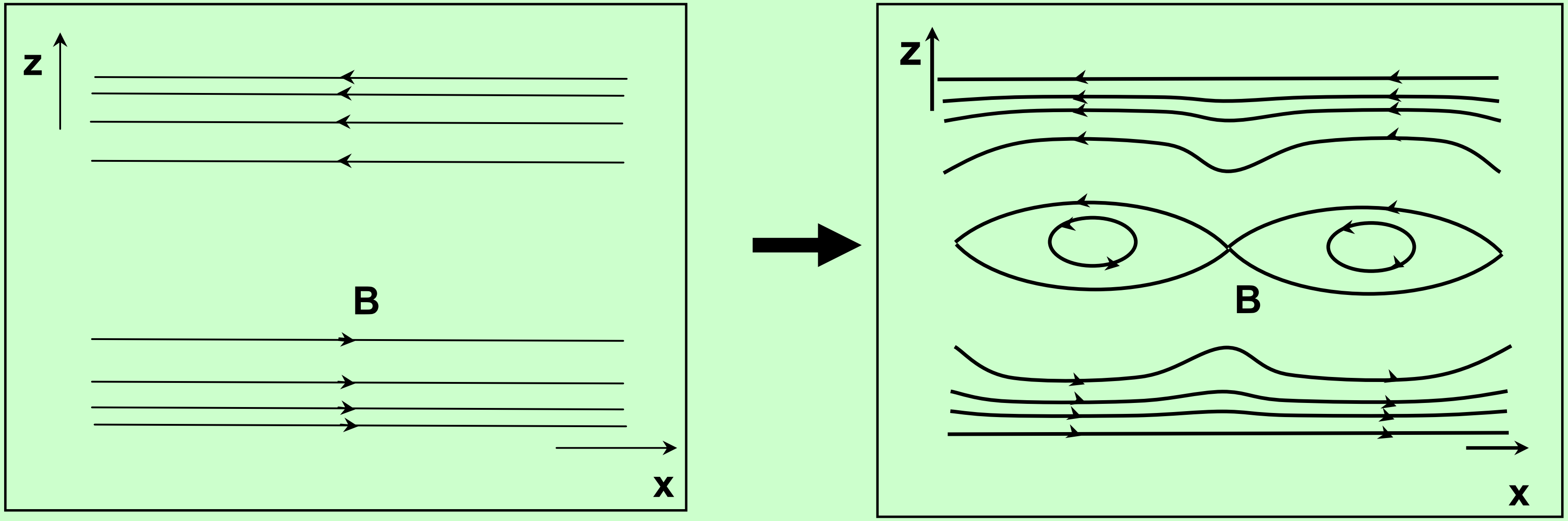
SPONTANEOUS RECONNECTION IN COLLISIONLESS PLASMA



FORCED RECONNECTION

Fourth International Sakharov Conference on Physics
MAY , 22, 2009

SPONTANEOUS RECONNECTION IN COLLISIONLESS PLASMA



Spontaneous Reconnection == **TEARING MODE**

Fourth International Sakharov Conference on Physics
MAY , 22, 2009

- **LEV ZELENYI**

- **ANTON ARTEMIEV**
- **HELMI MALOVA**
- **ANATOLYI PETRUKOVICH**
- **VICTOR POPOV**
- **SERGEI RUBALKO**

Fourth International Sakharov Conference on Physics
MAY , 22, 2009

LONG LASTING DRAMA OF IDEAS

Solar plasma

- **1946 - R.Giovanelli, A theory of chromospheric flares, Nature, 1946**

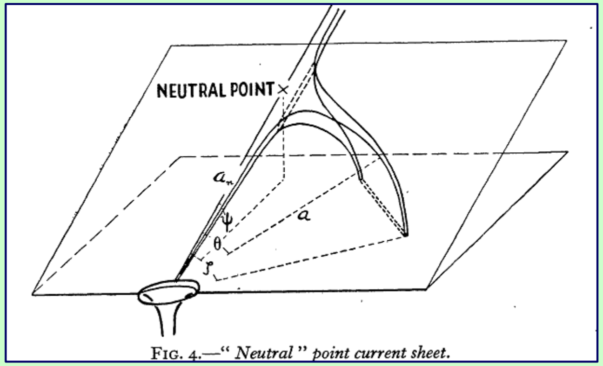
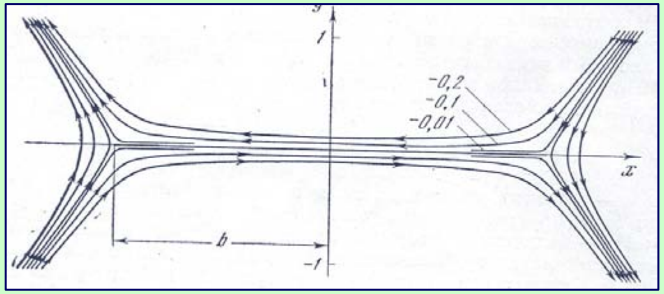
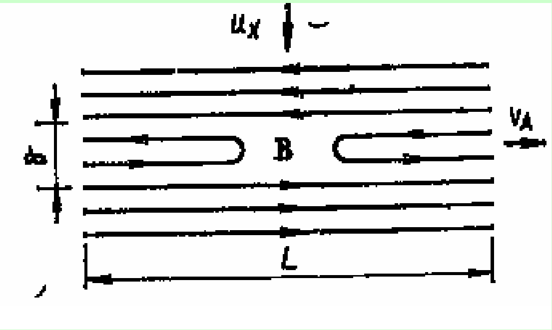


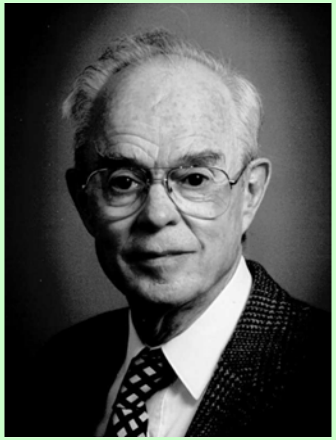
FIG. 4.—" *Neutral" point current sheet.*

- **1971-– S.Syrovatsky, MHD theory of thin current sheets in Solar corona**



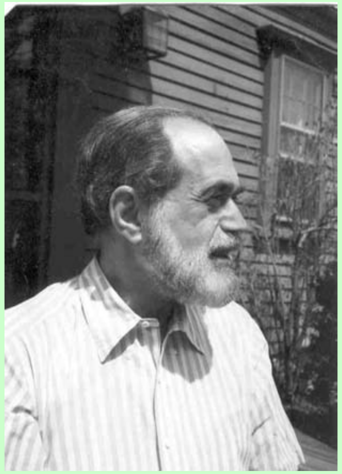
1957 – E. Parker, Sweet's mechanism for merging magnetic fields in conducting fluids, 1957

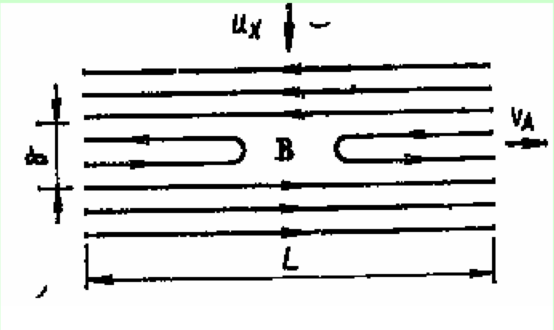




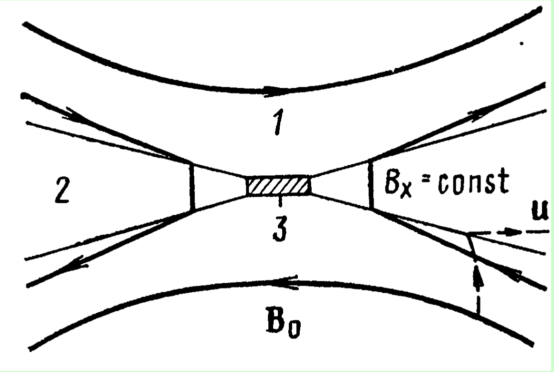
1958 – P. Sweet, The neutral point theory of solar flares,

STEADY STATE PLASMA FLOW WITH RECONNECTION



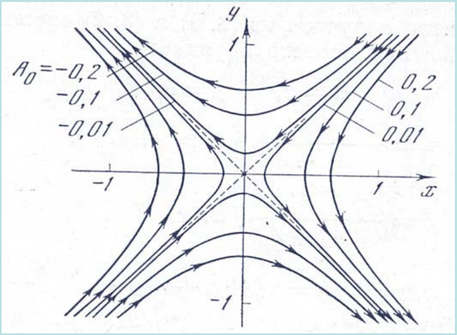


Sweet-Parker model

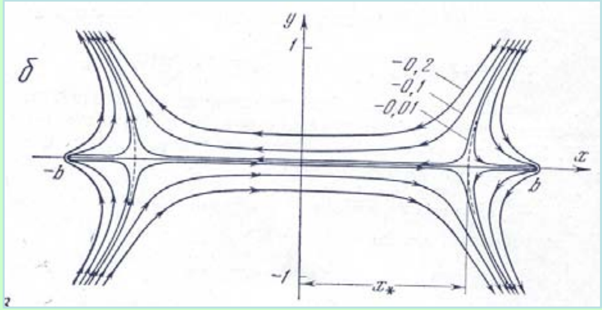


Petschek model

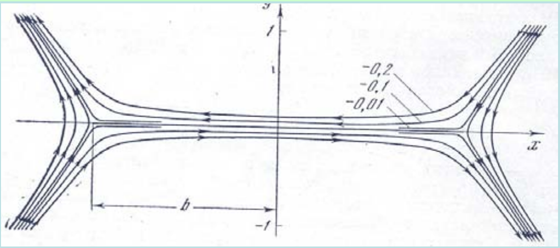
Petschek, H. E.
Magnetic field annihilation
NASA Spec. Pub., 1964.



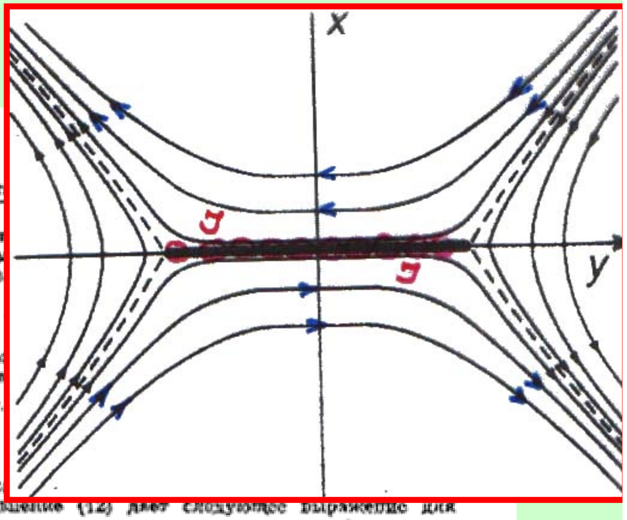
Dynamic thin current sheet

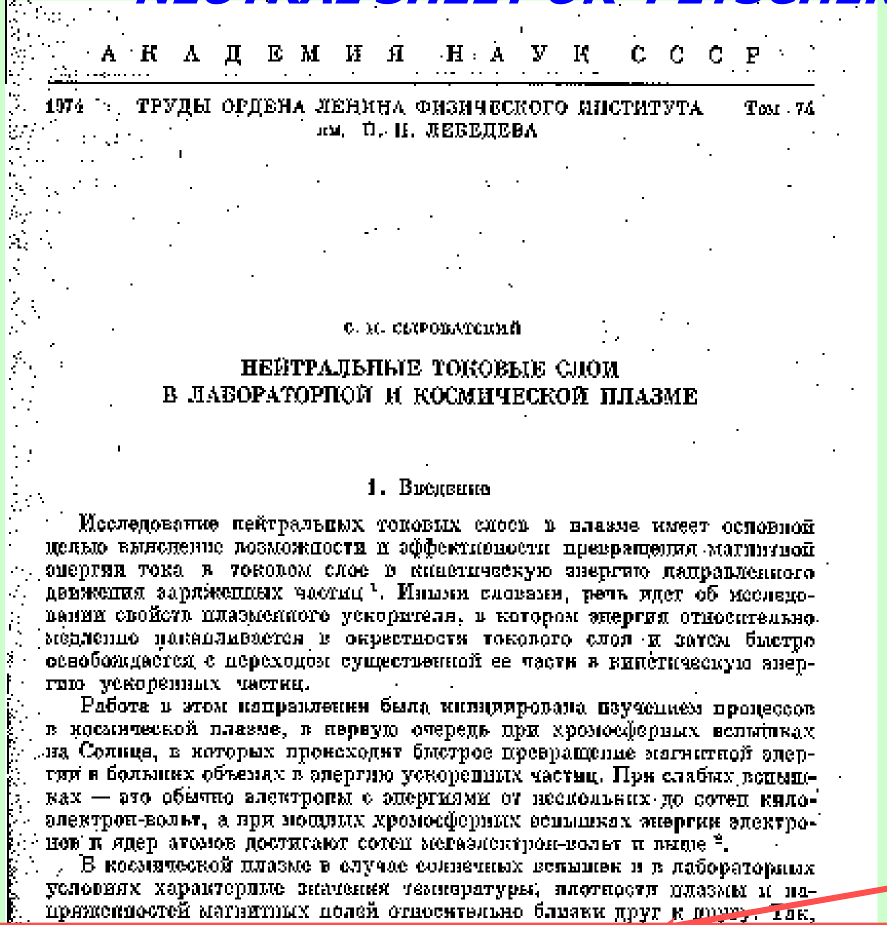


S.I.Syrovatsky



DILEMMA:
NEUTRAL SHEET OR PETSCHEK FLOW ?





АКАДЕМИЯ НАУК СССР

1974 ТРУДЫ ОРДЕНА ЛЕНИНА ФИЗИЧЕСКОГО ИНСТИТУТА Том 74
им. П. Н. ЛЕБЕДЕВА

С. И. СЫРОВАТСКИЙ

НЕЙТРАЛЬНЫЕ ТОКОВЫЕ СЛОИ В ЛАБОРАТОРНОЙ И КОСМИЧЕСКОЙ ПЛАЗМЕ

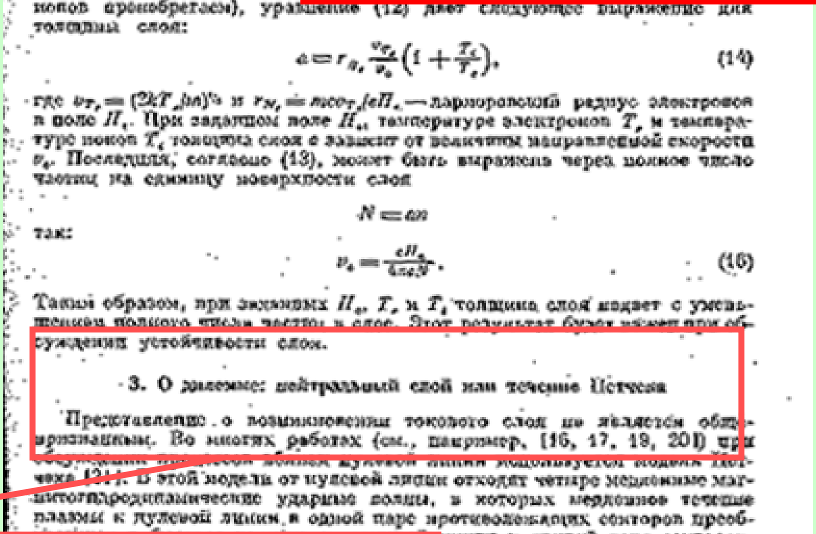
1. Введение

Исследование нейтральных токовых слоев в плазме имеет основной целью выяснение возможности и эффективности превращения магнитной энергии тока в токовом слое в кинетическую энергию направленного движения заряженных частиц [1]. Иными словами, речь идет об исследовании свойств плазменного ускорителя, в котором энергия относительно медленно накапливается в окрестности токового слоя и затем быстро освобождается с переходом существенной ее части в кинетическую энергию ускоренных частиц.

Работа в этом направлении была инициирована изучением процессов в космической плазме, в первую очередь при хромосферных вспышках на Солнце, в которых происходит быстрое превращение магнитной энергии в больших объемах в энергию ускоренных частиц. При слабых вспышках — это обычно электроны с энергиями от нескольких до сотен килоэлектрон-вольт, а при мощных хромосферных вспышках энергии электронов и ядер атомов достигают сотен мегаэлектрон-вольт и выше [2].

В космической плазме в случае солнечных вспышек и в лабораторных условиях характерные значения температуры, плотности плазмы и напряженностей магнитных полей относительно близки друг к другу. Так,

ров, а только порядковых соотношений между ними. Так, если какой-либо



нейт

Рассмотрим теперь толщ
вуем уравнение баланса д
дится к условию равенств

где n — концентрация плаз
электронов и ионов в нейтра
отношением $\mathrm{rot}\,\mathbf{H} = \frac{4\pi}{c}\,\mathbf{j}$, т.

где v_s — средняя токовая с
ионов пренебрегаем), уравнение (12) дает следующее выражение для толщины слоя:

$$a = r_{H_e}\frac{v_{T_e}}{v_s}\left(1+\frac{T_i}{T_e}\right), \qquad (14)$$

где $v_{T_e} = (2kT_e/m)^{1/2}$ и $r_{H_e} = mcv_{T_e}/eH_s$ — ларморовский радиус электронов в поле H_s. При заданном поле H_s, температуре электронов T_e и температуре ионов T_i толщина слоя a зависит от величины направленной скорости v_s. Последняя, согласно (13), может быть выражена через полное число частиц на единицу поверхности слоя

$$N = an$$

так:

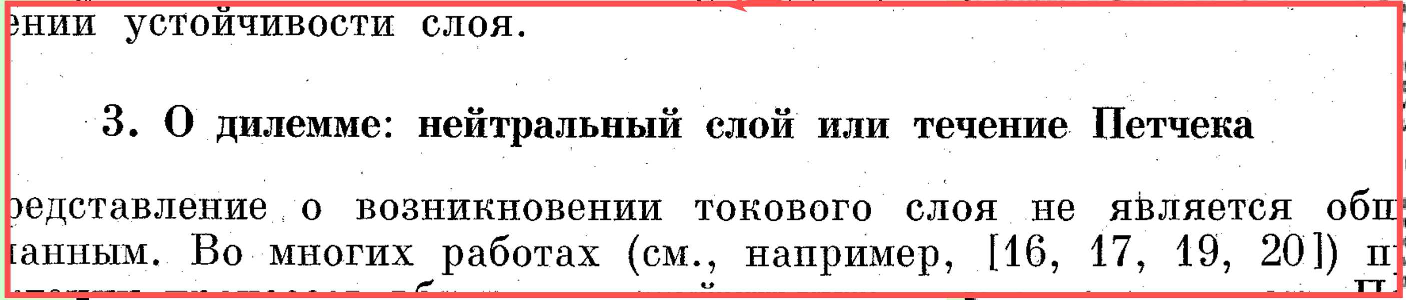
$$v_s = \frac{cH_s}{4\pi eN}. \qquad (15)$$

Таким образом, при заданных H_s, T_e и T_i толщина слоя падает с уменьшением полного числа частиц в слое. Этот результат будет важен при обсуждении устойчивости слоя.

3. О дилемме: нейтральный слой или течение Петчека

Представление о возникновении токового слоя не является общепризнанным. Во многих работах (см., например, [16, 17, 19, 20]) при обсуждении процессов вблизи нулевой линии используется модель Петчека [21]. В этой модели от нулевой линии отходят четыре медленные магнитогидродинамические ударные волны, в которых медленное течение плазмы к нулевой линии в одной паре противолежащих секторов преоб-

линии в другой паре секторов.
ти нулевой линии расположена
ней происходит пересоединение
ых потоков плазмы.
ется от нейтрального слоя в двух
тность тока минимальна, тогда
ь тока имеет максимум (см. (5)).
ширина диффузионной области
(20)), тогда как ширина квази-
(см. (9)).
ом ряд критических замечаний
ь по меньшей мере должна быть
полнительной системы волн [25].
возможности согласовать такую
шними граничными условиями,

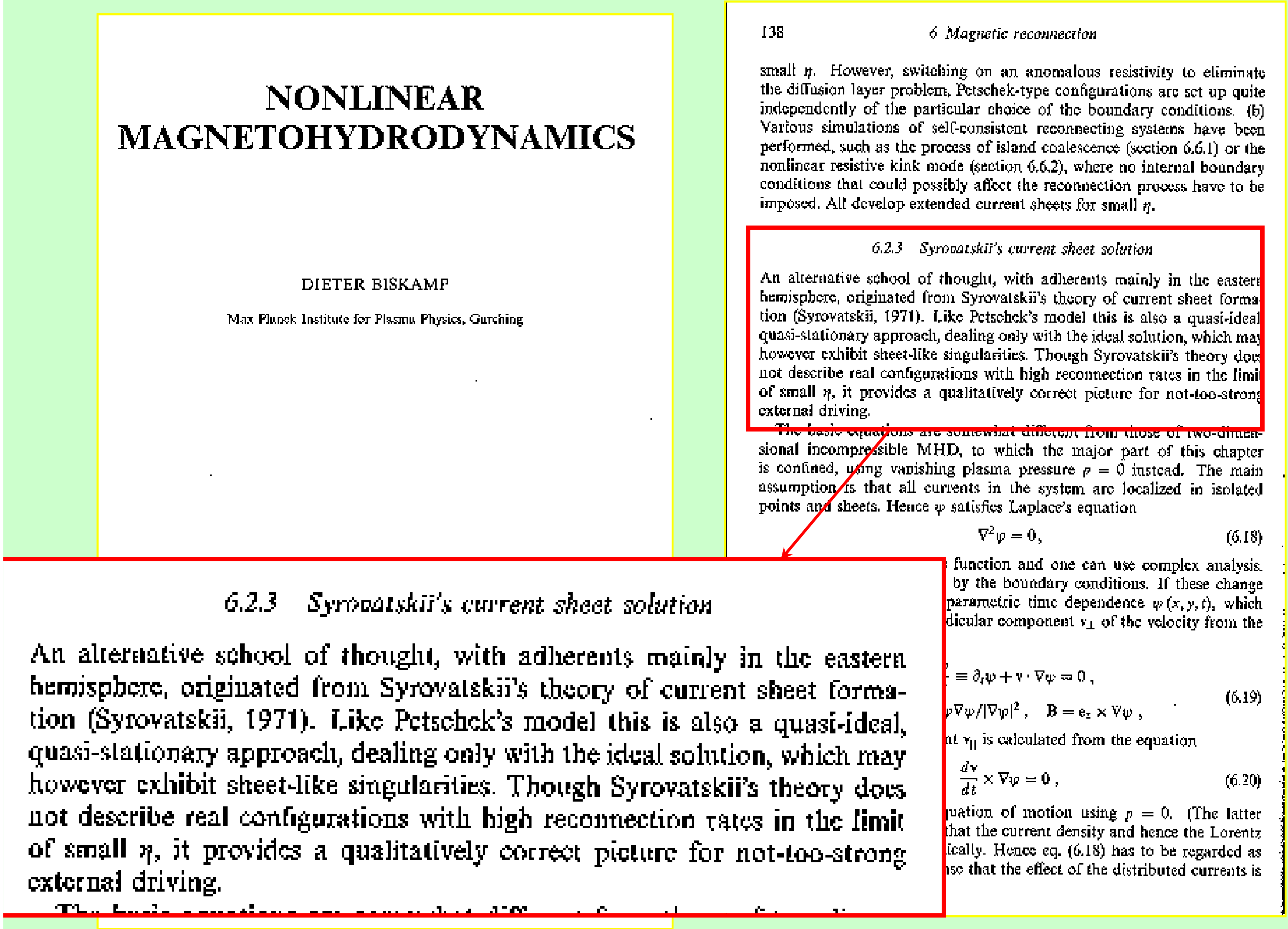


ении устойчивости слоя.

3. О дилемме: нейтральный слой или течение Петчека

едставление о возникновении токового слоя не является общ
анным. Во многих работах (см., например, [16, 17, 19, 20]) п

25 years after: *Biscamp comments*



NONLINEAR MAGNETOHYDRODYNAMICS

DIETER BISKAMP

Max Planck Institute for Plasma Physics, Garching

---

small η. However, switching on an anomalous resistivity to eliminate the diffusion layer problem, Petschek-type configurations are set up quite independently of the particular choice of the boundary conditions. (b) Various simulations of self-consistent reconnecting systems have been performed, such as the process of island coalescence (section 6.6.1) or the nonlinear resistive kink mode (section 6.6.2), where no internal boundary conditions that could possibly affect the reconnection process have to be imposed. All develop extended current sheets for small η.

6.2.3 Syrovatskii's current sheet solution

An alternative school of thought, with adherents mainly in the eastern hemisphere, originated from Syrovatskii's theory of current sheet formation (Syrovatskii, 1971). Like Petschek's model this is also a quasi-ideal, quasi-stationary approach, dealing only with the ideal solution, which may however exhibit sheet-like singularities. Though Syrovatskii's theory does not describe real configurations with high reconnection rates in the limit of small η, it provides a qualitatively correct picture for not-too-strong external driving.

The basic equations are somewhat different from those of two-dimensional incompressible MHD, to which the major part of this chapter is confined, using vanishing plasma pressure $p = 0$ instead. The main assumption is that all currents in the system are localized in isolated points and sheets. Hence ψ satisfies Laplace's equation

$$\nabla^2\psi = 0, \qquad (6.18)$$

function and one can use complex analysis.
by the boundary conditions. If these change
parametric time dependence $\psi(x,y,t)$, which
dicular component $v_\perp$ of the velocity from the

$$\equiv \partial_t\psi + \mathbf{v}\cdot\nabla\psi = 0\,,$$

$$\psi\nabla\psi/|\nabla\psi|^2\,, \quad \mathbf{B} = \mathbf{e}_z\times\nabla\psi\,, \qquad (6.19)$$

nt $v_\parallel$ is calculated from the equation

$$\frac{d\mathbf{v}}{dt}\times\nabla\psi = 0\,, \qquad (6.20)$$

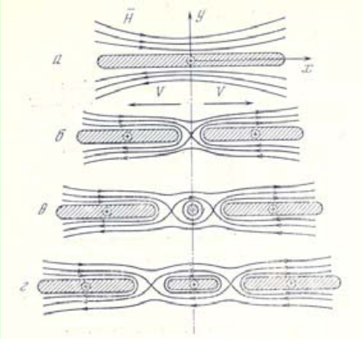
uation of motion using $p = 0$. (The latter
that the current density and hence the Lorentz
ically. Hence eq. (6.18) has to be regarded as
so that the effect of the distributed currents is

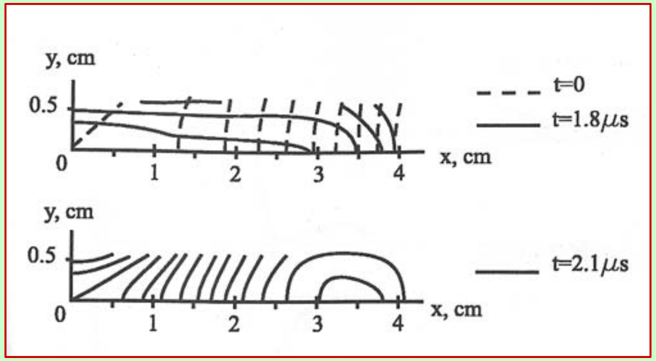
6.2.3 Syrovatskii's current sheet solution

An alternative school of thought, with adherents mainly in the eastern hemisphere, originated from Syrovatskii's theory of current sheet formation (Syrovatskii, 1971). Like Petschek's model this is also a quasi-ideal, quasi-stationary approach, dealing only with the ideal solution, which may however exhibit sheet-like singularities. Though Syrovatskii's theory does not describe real configurations with high reconnection rates in the limit of small η, it provides a qualitatively correct picture for not-too-strong external driving.

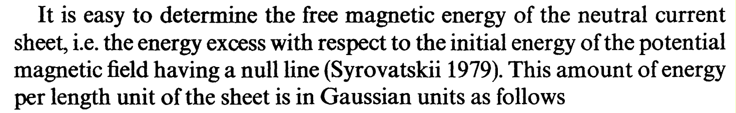
Energy storage in thin current sheets

A.FRANK
Laboratory Experiments

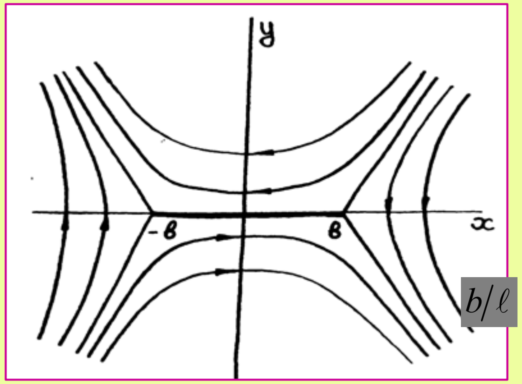




METASTABILITY !!

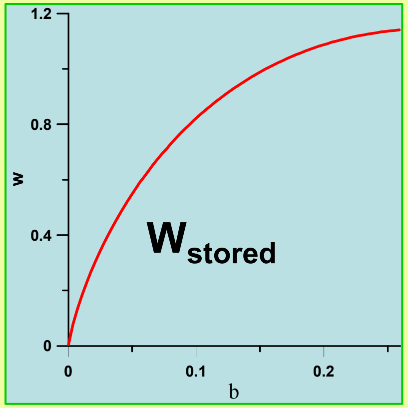


It is easy to determine the free magnetic energy of the neutral current sheet, i.e. the energy excess with respect to the initial energy of the potential magnetic field having a null line (Syrovatskii 1979). This amount of energy per length unit of the sheet is in Gaussian units as follows

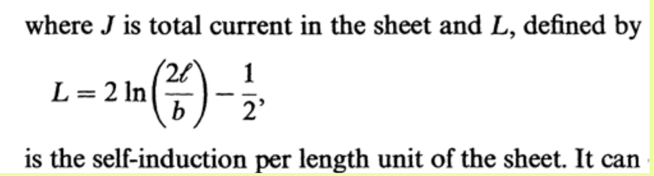


Syrovatsky, 1971

DYNAMIC
RECONNECTION
singular cut –
infinitely thin
metastable CS



$$w = \int (B^2 - h_0^2 r^2)\,\frac{dV}{8\pi} = \frac{h_0^2 b^4}{32}\left(\ln\frac{4\ell^2}{b^2} - \frac{1}{2}\right) = \frac{LJ^2}{2c^2}$$



where J is total current in the sheet and L, defined by

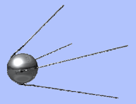
$$L = 2\ln\left(\frac{2\ell}{b}\right) - \frac{1}{2},$$

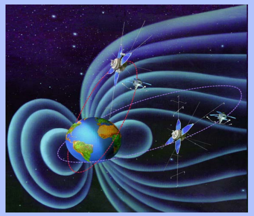
is the self-induction per length unit of the sheet. It can

Solar plasma

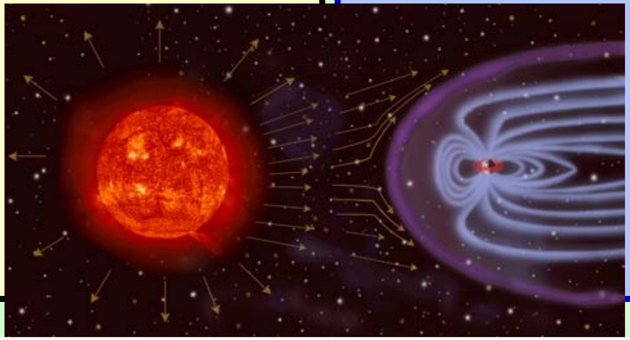
- 1946 - R.Giovanelly, A theory of chromospheric flares, Nature, 1946
- 1971-1979 – S.Syrovatsky, MHD theory of thin current sheets in Solar corona
- 1957 – E. Parker, Sweet's mechanism for merging magnetic fields in conducting fluids, 1957
- 1958 – P. Sweet, The neutral point theory of solar flares, 1958.

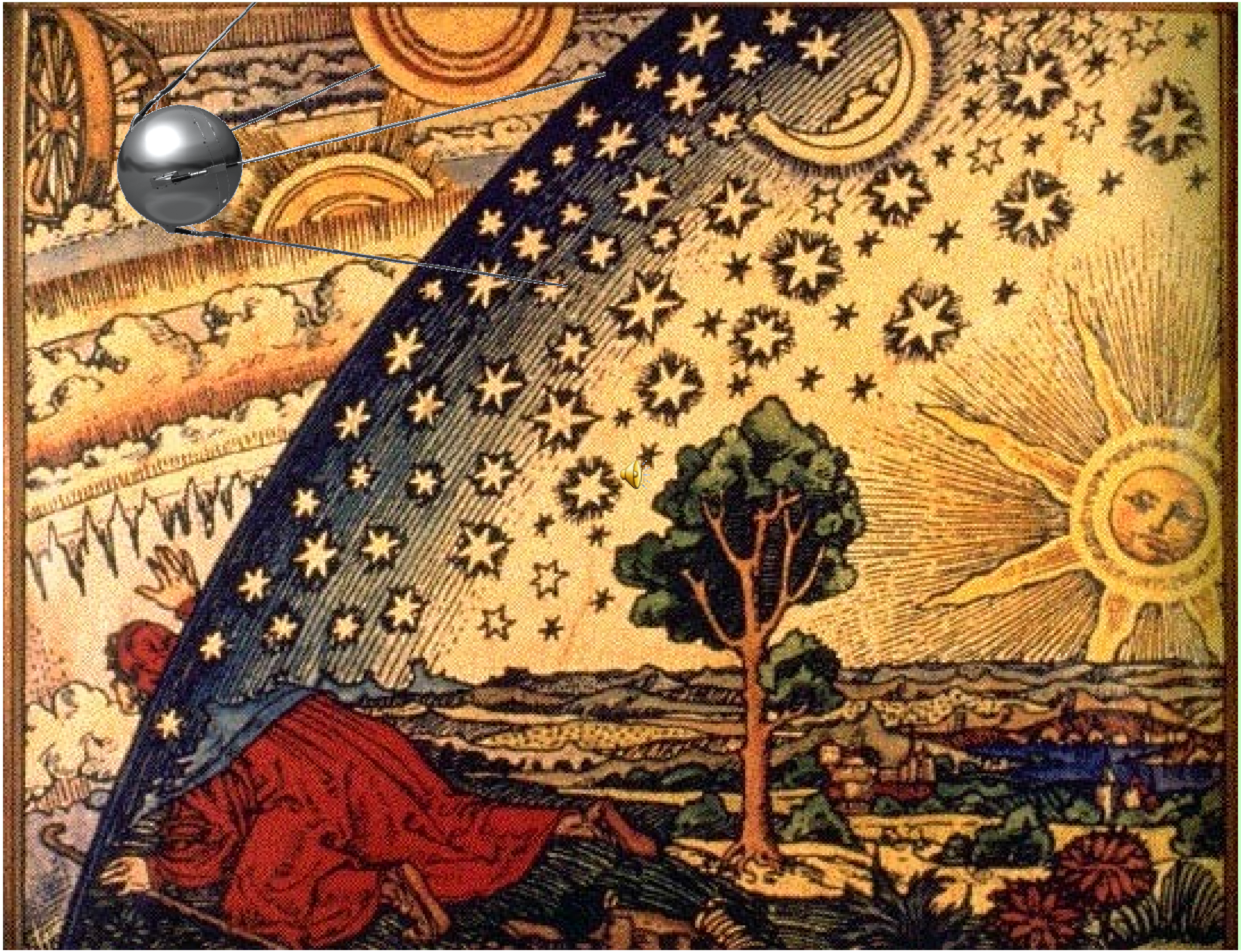
Magnetospheric plasma





- 1957 – Sputnik launch
- 1957-1958 – discovery of radiation belts by Van Allen (inner r.b.), S.Vernov and A.Chudakov (outer r.b)
- 1965 – discovery of the Earths' magnetotail - N.Ness, J. Geophys. Res.,





SAKHAROV LEGACY ::
Beginning of the Space Age

Intercontinental
Ballistic missile launcher
8K71
M=5500 kg
L=8000 km

FORTUITOUS FOR SPACE SCIENCE
SAKHAROV OVERESTIMATE
OF THE MASS REGUIRED FOR THE
THERMONUCLEAR EXPLOSIVE DEVICE

KOROLEV'S DESIGN OF 5 ENGINE
SUPERPOWERFUL R-7 LAUNCHER

- ***"Существенно, что вес заряда, а следовательно и весь масштаб ракеты, был принят на основе моей докладной записки. Это предопределило работу всей огромной конструкторско-производственной организации на многие годы. Именно эта ракета вывела на орбиту первый искусственный спутник Земли в 1957 году и космический корабль с Юрием Гагариным на борту в 1961 году. Тот заряд, под который все это делалось, много раньше, однако, успел "испариться", и на его место пришло нечто совсем иное..." .*** **А.Д. Сахаров. Воспоминания**

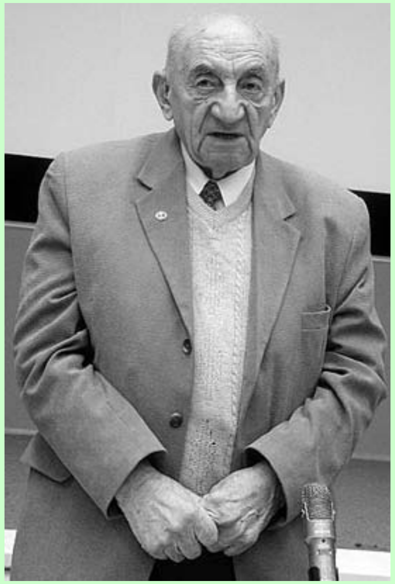
"It's significant to note, that the charge weight and consequently the size of the rocket were accepted according to my memorandum. This for many years has determined the activity of the whole rocket industry.

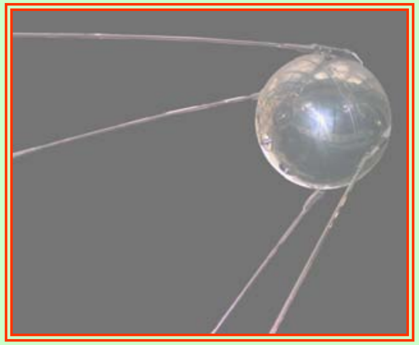
By means of this very rocket the First SPUTNIK was launched in 1957 and the spacecraft with Yury Gagarin onboard was put into orbit in 1961.

The charge, the whole activity was based on before, vanished into thin air, but something totally different appeared instead…". **ANDREI SAKHAROV MEMOIRS**

- … Я не могу судить, в какой мере Андрей Сахаров лично определил конструкцию и массу заряда, предназначенного для первой межконтинентальной ракеты. Но, безусловно, именно то, что делал Сахаров, потребовало создания такой ракеты, какую мы разработали под шифром Р-7. И имя Сахарова тоже должно упоминаться в истории космонавтики!

Б.Е.Черток, Ракеты и люди, 1994, ROCKET AND PEOPLE





BORIS CHERTOK
Korolev's DEPUTY

… I can't tell exactly, whether it was Andrei Sakharov who personally determined the construction and the charge weight for the intercontinental rocket. But, undoubtedly, Andrei Sakharov's activity had demanded such a rocket to be constructed, which was designed and called R-7. Therefore, the name of A. Sakharov should also be mentioned in the history of Soviet cosmonautics

Международные следствия запуска первого ИСЗ

International Dimensions of Sputnik Launch

“Mutual deterrence” regime

- **Глобализировал и перевел в плоскость науки и техники мирный аспект соревнования между социалистической и капиталистической системами**

  Contributed to globalization of peaceful competition between the socialistic and capitalistic systems and transferred it to the domain of science and technology

- **Запуск спутника «полностью изменил суть «Холодной войны».**

  “What Sputnik did… was to alter the nature of the Cold War….” ***Walter McDougall, The Heavens and The Earth***

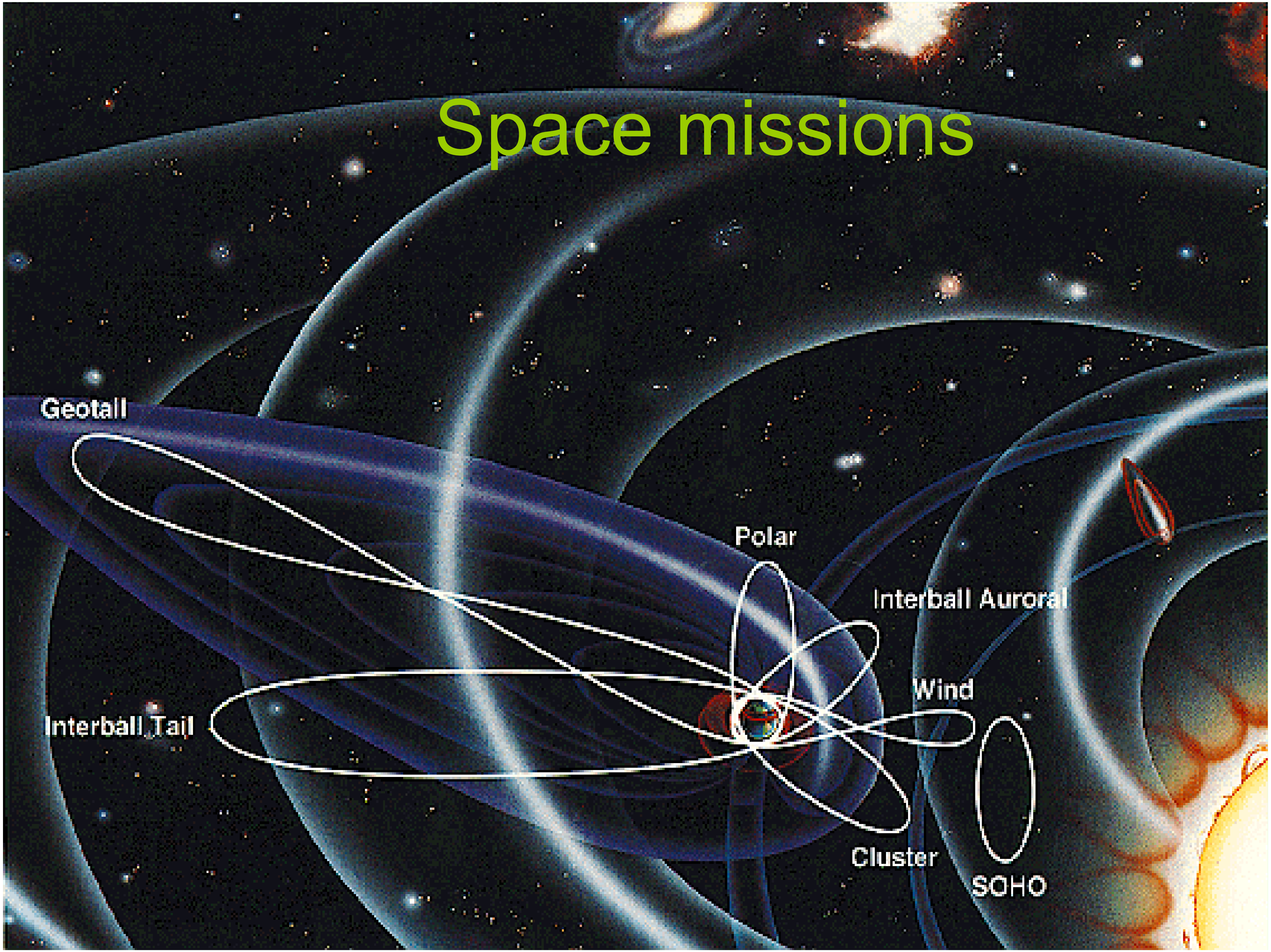
- **Президент АН СССР М.В. Келдыш :**

  «Еще неизвестно, что имело большее значение для обороны страны: боевая межконтинентальная ракета, или первый спутник»

  President of the USSR Academy of Sciences Mstislav Keldysh :

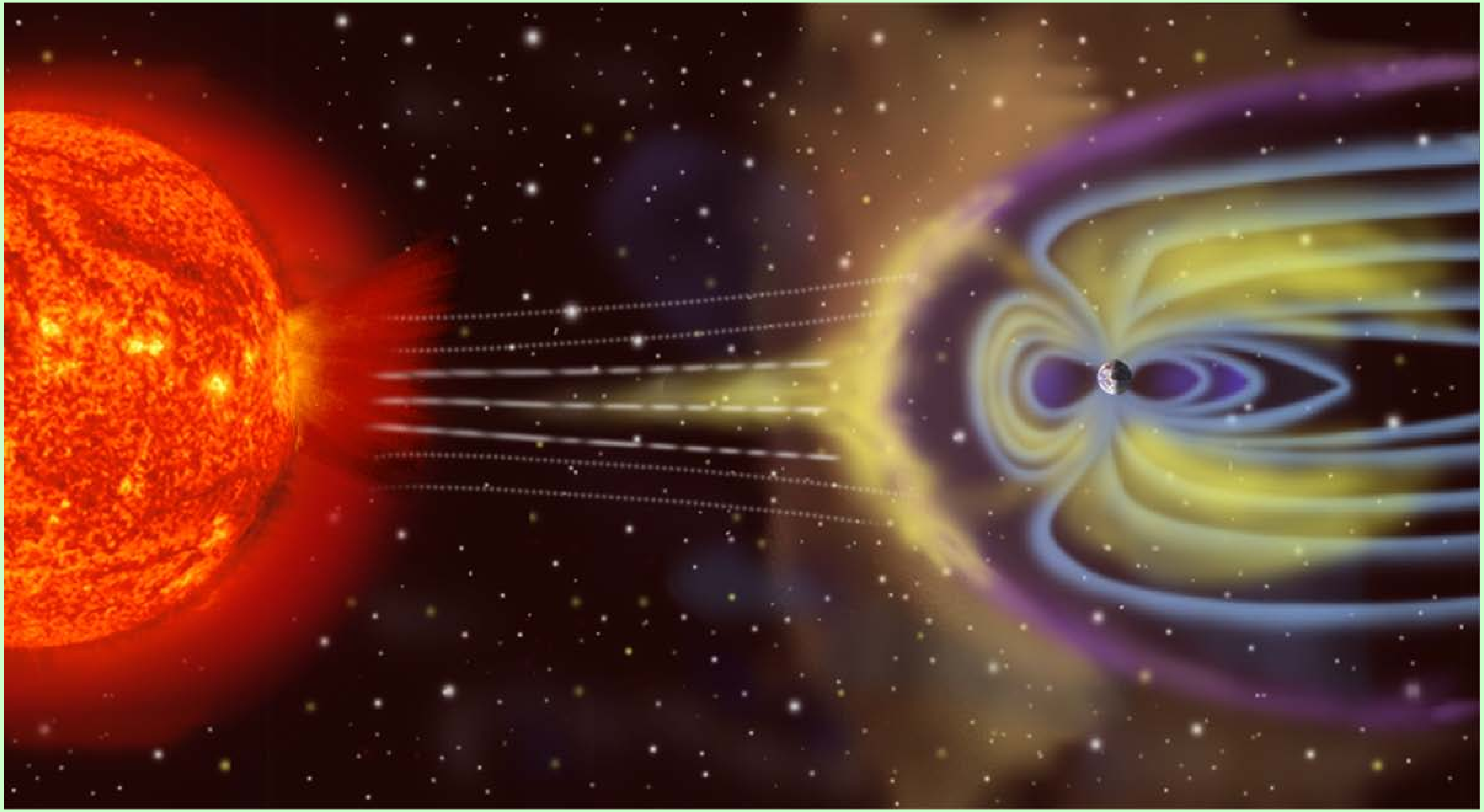
  “It is hard to say what strengthened the Soviet defense better – - the ICBM or the first Sputnik ?”.

Space missions



Earth’s Magnetosphere

The scene of dynamic interactions between the Sun and Earth’s Magnetic Field



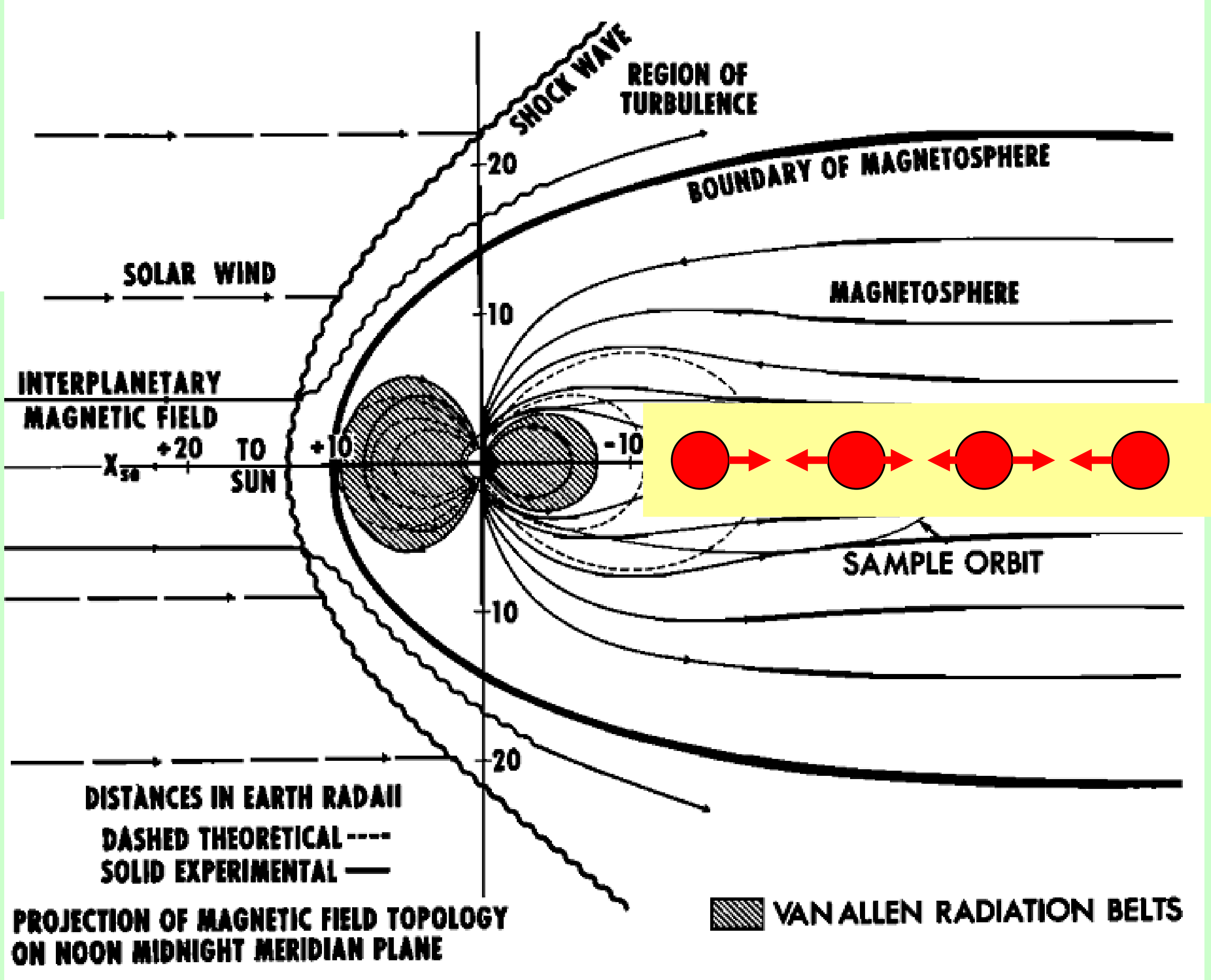
Earth Current sheet

Norman F. Ness

The Earth's Magnetic Tail[1]

Norman F. Ness

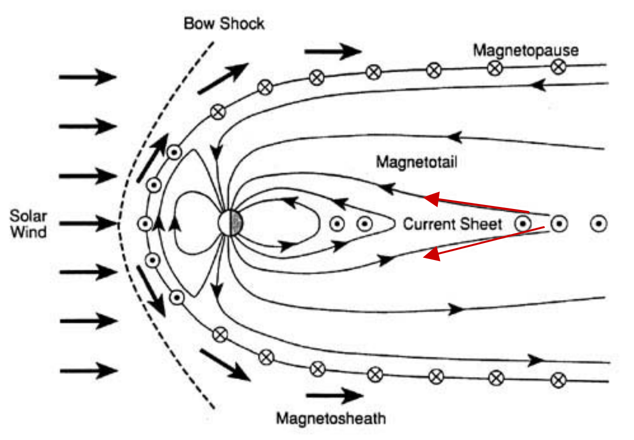
1965



PLASMA SHEET

CURRENT SHEET

PLASMA SHEET BOUNDARY LAYER



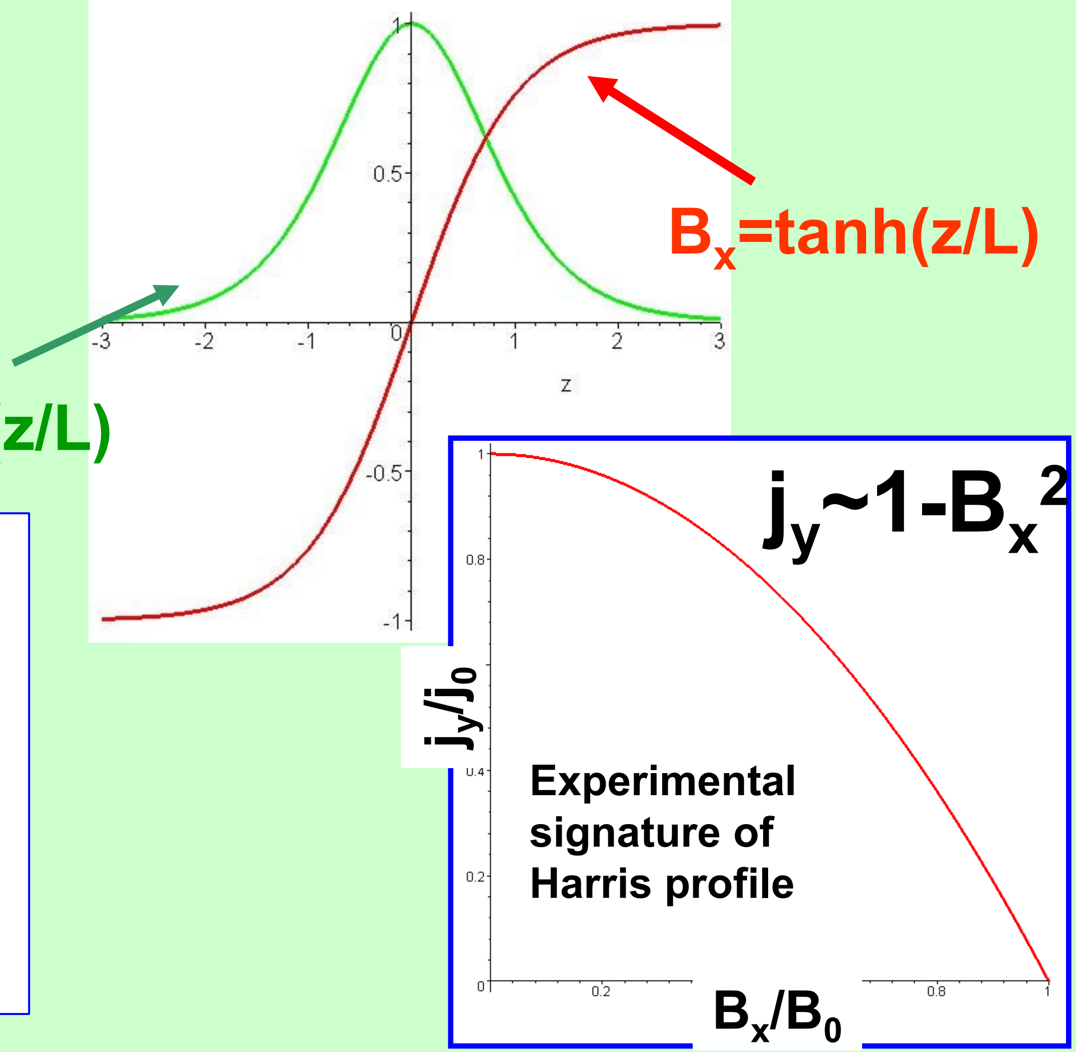
$\beta = 8\pi nkT/B^2$	2 - 6 (central) / 0.1 - 2 (outer)
Ion density	$0.25\ \mathrm{cm}^{-3}$
Ion temperature	~ 4 keV
Electron temperature	~ 0.5 keV
Magnetic field	< 10 nT
Plasma convection velocity	~ 20 km/s
Plasma beam velocity	~ 1500 km/s
Ion gyroradius	~ 300-1000 km
M.F.P. length	~ 1 a.u.

Harris model

On a plasma sheath separating regions of oppositely directed magnetic fields.

Harris E.G., Nuovo Chimento, 23, 115–119, 1962

MATHEMATICALLY ELEGANT
SIMPLE 1D KINETIC MODEL
Erroneously used
by everybody
and everywhere



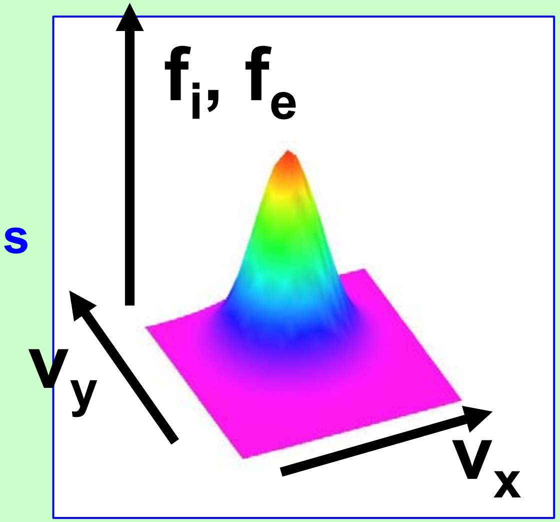
$B_x=\tanh(z/L)$

$j_y \sim n \sim \cosh^{-2}(z/L)$

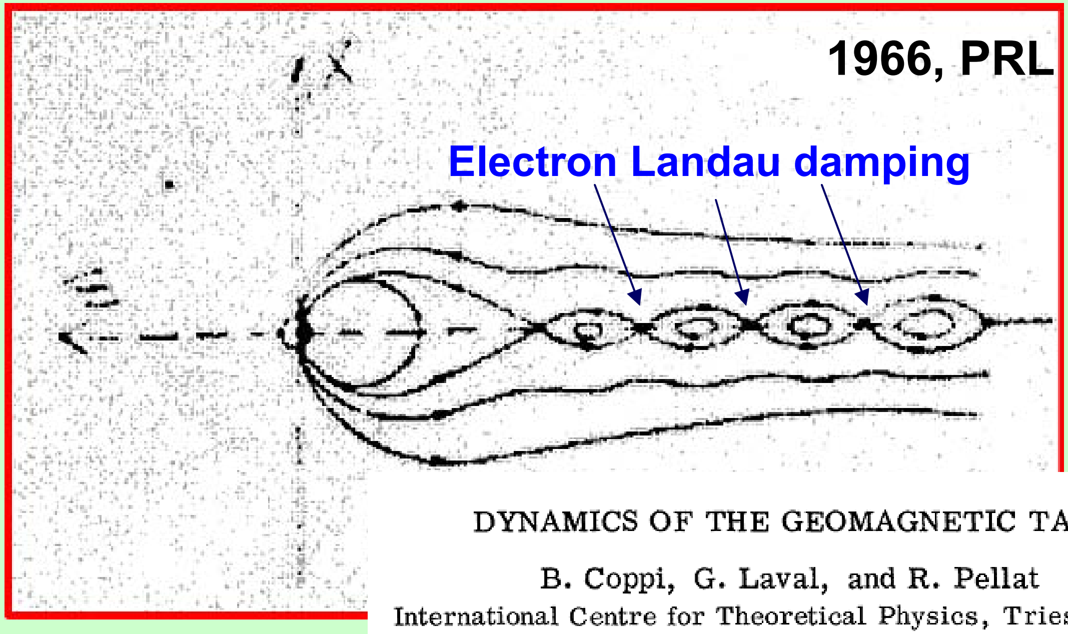
$j_y \sim 1-B_x^2$

Experimental signature of Harris profile

Shifted maxwellians



First steps in theory of CS stability.



DYNAMICS OF THE GEOMAGNETIC TAIL

B. Coppi, G. Laval, and R. Pellat
International Centre for Theoretical Physics, Trieste, Italy
(Received 13 January 1966)

The “Mirror Instability” for finite particle gyro-radius.
Harold P. Furth, Nuclear Fusion, 1962

$$f_0 = \frac{n_0}{(2\pi)^{3/2} a v^3} \exp\left[-\frac{v^2}{2}\left(\frac{v_x^2}{a^2} + v_y^2 + v_z^2\right)\right] \quad (1)$$

are subjected to the perturbation

$$B_z = b e^{\omega t} \sin k_{\parallel} x \sin k_{\perp} z \quad (2)$$

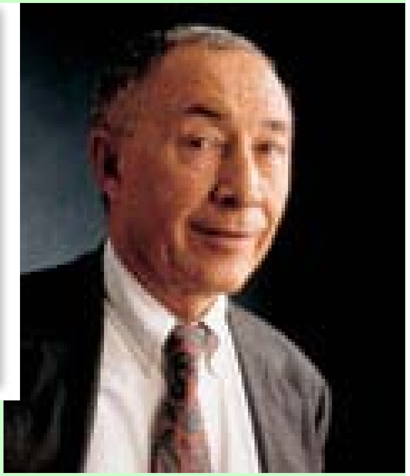
$$B_x = B + (k_{\perp}/k_{\parallel})\, b e^{\omega t} \cos k_{\parallel} x \cos k_{\perp} z \quad (3)$$

$$E_y = (\omega/c k_{\parallel})\, b e^{\omega t} \cos k_{\parallel} x \sin k_{\perp} z \quad (4)$$

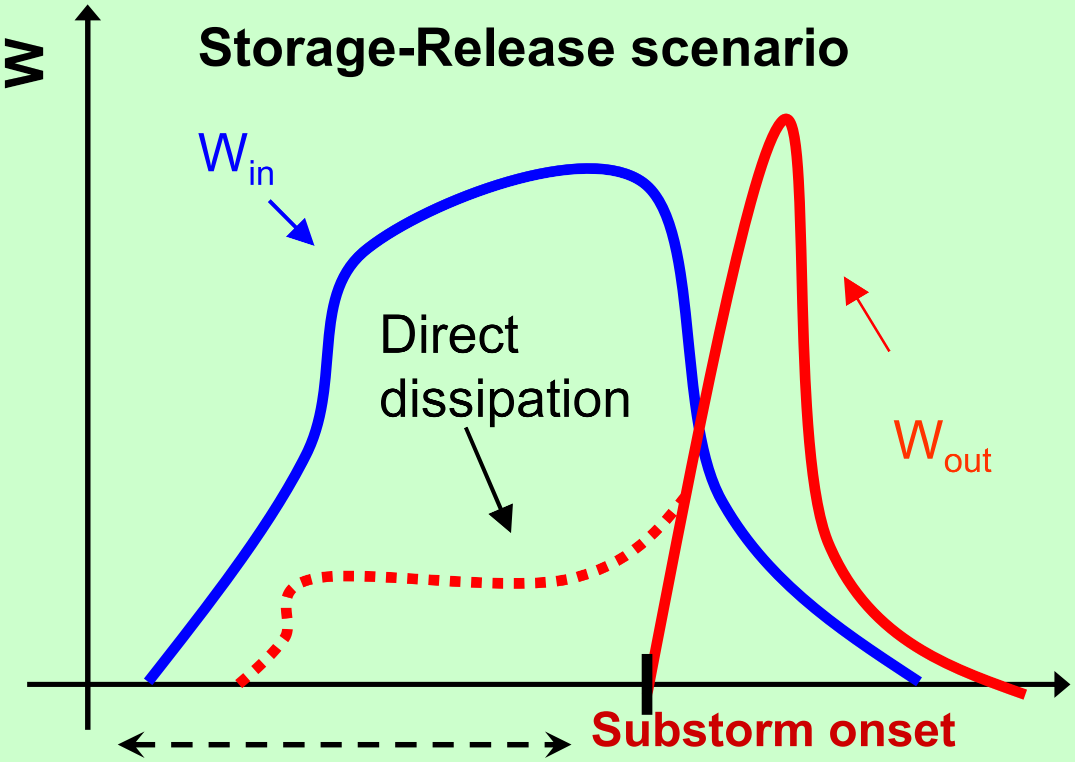
$$f = f_0 + f_1 e^{\omega t},$$


Bruno Coppi


Guy LavaL

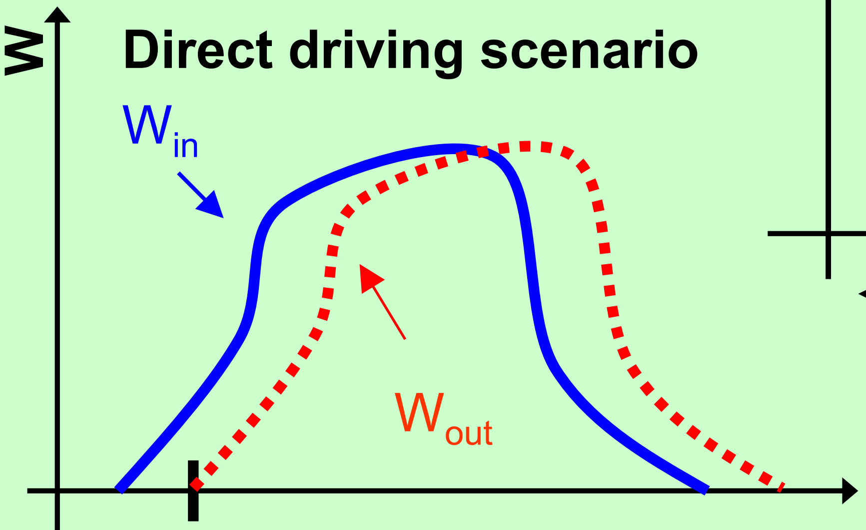

Rene Pellat

Two scenarios of magnetospheric activity



Energy Accumulation

METASTABILITY OF MAGNETOTAIL CONFIGURATION



Substorm onset

OUTLINE & MOTIVATIONS

- **SPONTANEOUS RECONNECTION::**

  CHANGE OF MAGNETIC TOPOLOGY (Formation of X/O lines)

  Non trivial problem in collisionless plasma

  (only LANDAU damping)

- **Observational constraints:**

  possibility to accumulate magnetic flux –

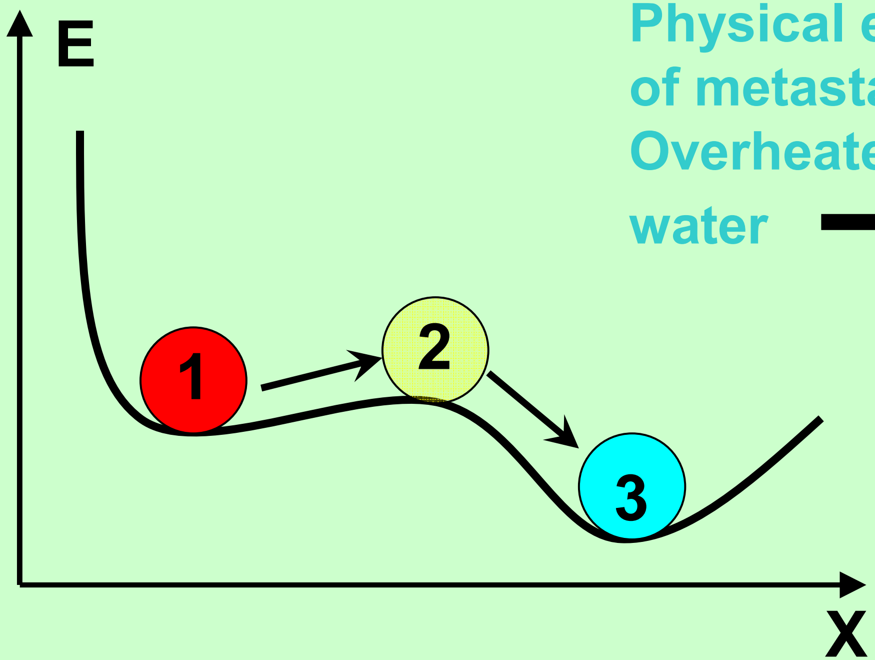
  possibility quickly release stored energy—

- **METASTABILITY**

  - **HARRIS SHEET PARADIGMA- OVERSTABILITY**
  - **Realistic models of CS – anisotropy , bifurcations , steepening**
  - **Stability properties of anisotropic CS- and their free energy reservoirs**
  - **Nonlinear effects and inverse cascade**
  - **Substorm implications**
  - **Overlapping of tearing/kink/sausage modes**
  - **Conclusions**

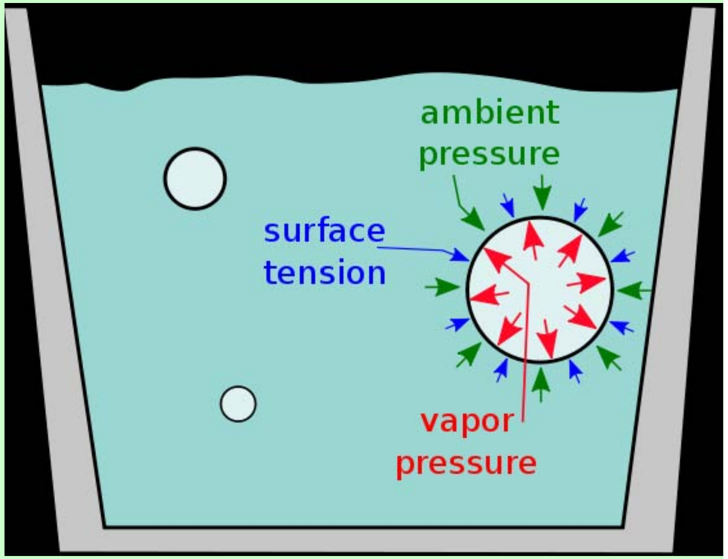
Metastability

Metastability is a general scientific concept which describes states of delicate equilibrium. A system is in a metastable state when it is in equilibrium (not changing with time) but is susceptible to fall into lower-energy states with only slight interaction.



A metastable system with a weakly stable state (1), an unstable transition state (2) and a strongly stable state (3)

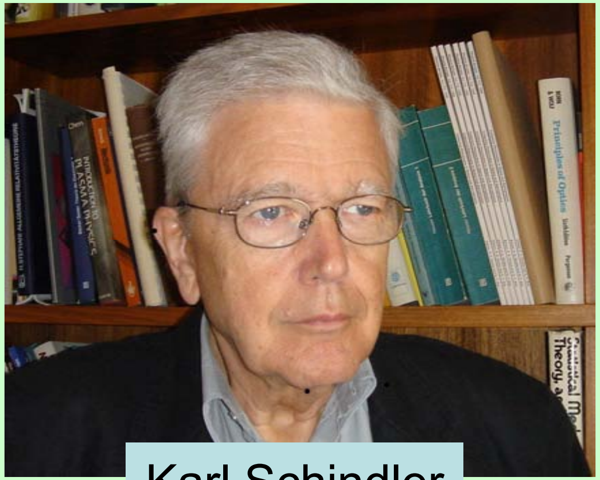
Physical example of metastability Overheated clean water



In order for boiling to occur, the vapor pressure must exceed the ambient pressure plus a small amount of pressure induced by the surface tension

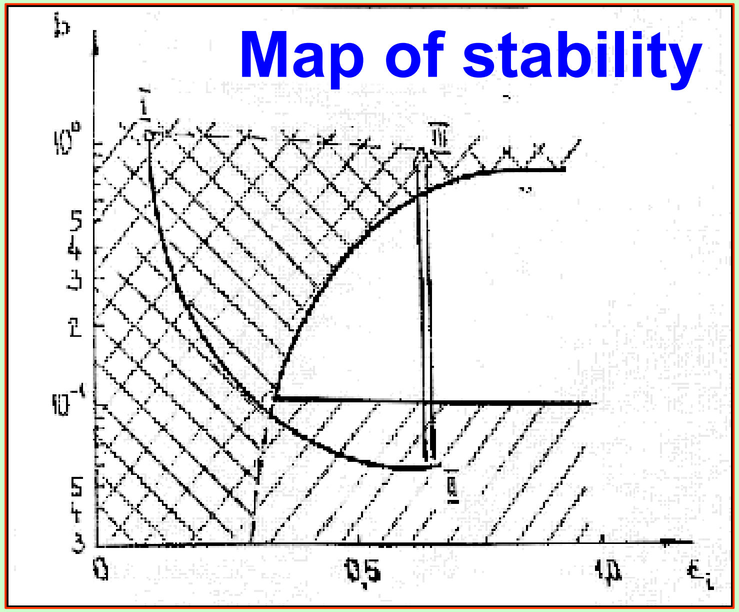
Bz - destruction of electron Landau damping.

Electron stabilization.



Karl Schindler

ION MODE



Map of stability

A Theory of the Substorm Mechanism

K. Schindler

1974, JGR

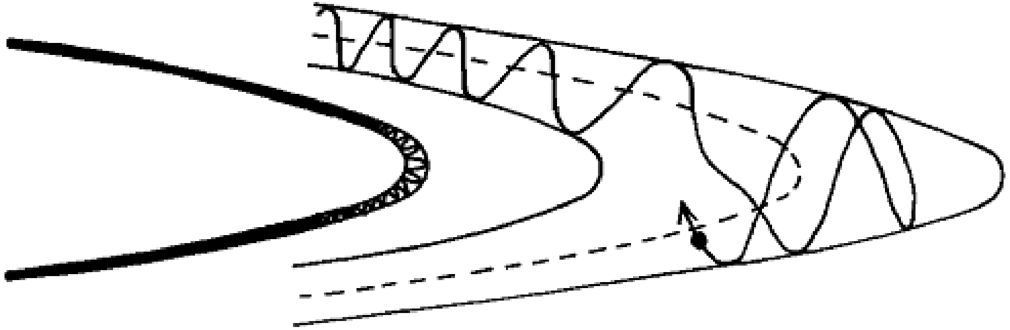


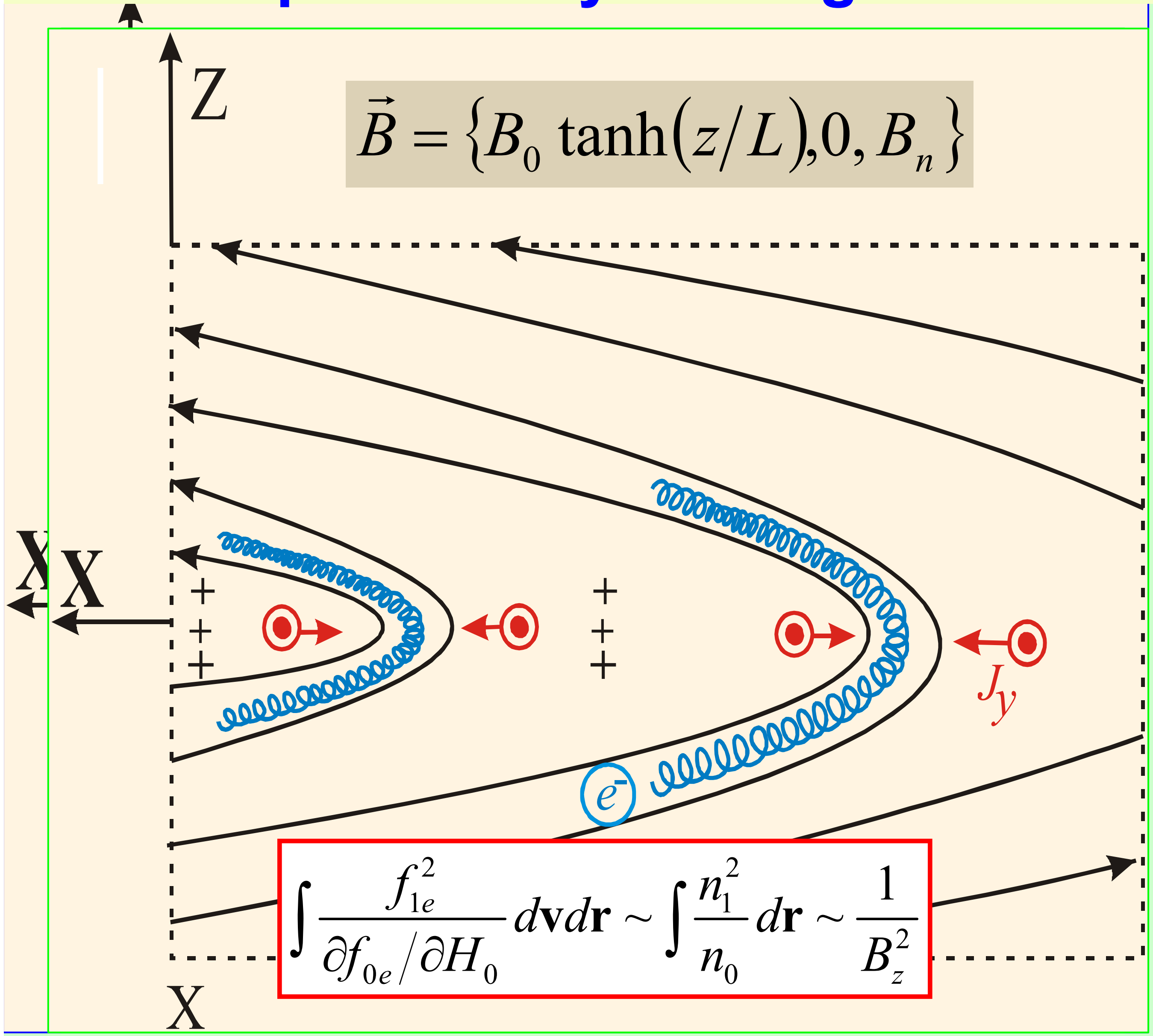
Fig. 4. Regime of ion tearing: the electrons are gyroscopic, and the ions see a neutral sheet. The ion motion perpendicular to the plane shown is unidirectional on either side of the broken line.

Tearing instability in plasma configurations

Galeev, A. A., Zelenyi, L. M. JETP, 1976

Albert Galeev

Stabilization of ion tearing mode by the compressibility of magnetized electron

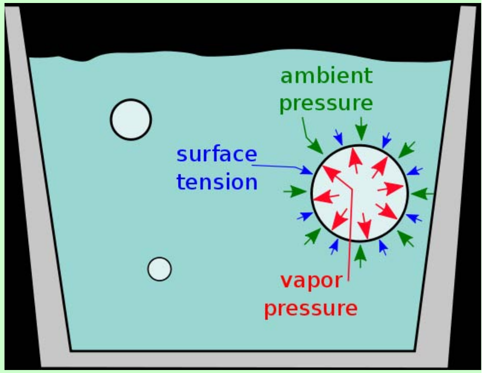


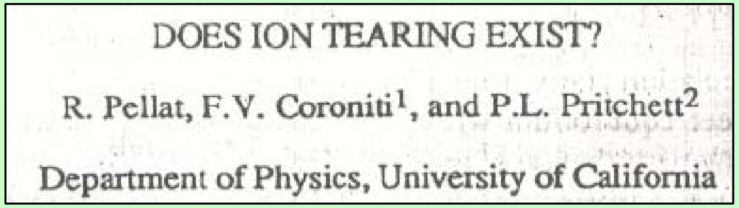
$$\vec{B} = \{B_0 \tanh(z/L), 0, B_n\}$$

$$\int \frac{f_{1e}^2}{\partial f_{0e}/\partial H_0} d\mathbf{v} d\mathbf{r} \sim \int \frac{n_1^2}{n_0} d\mathbf{r} \sim \frac{1}{B_z^2}$$

ABSOLUTE STABILITY OF HARRIS TYPE FIELD REVERSAL with $|B_z| >0$

B_z effects = Metastability



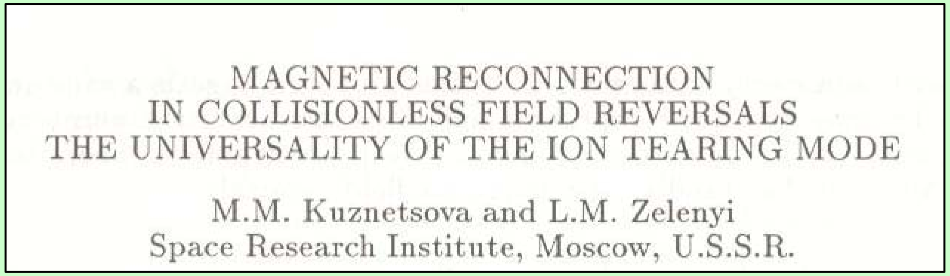


DOES ION TEARING EXIST?

R. Pellat, F.V. Coroniti[1], and P.L. Pritchett[2]

Department of Physics, University of California

In conclusion, neither pitch-angle diffusion nor stochastic orbit diffusion removes the stabilizing effect of electron compressibility. Cross-field spatial diffusion can result in an unstable electron tearing mode, but to reach the ion tearing regime requires diffusion rates which are inconsistent with the initial assumed equilibrium. Thus, within our present state of knowledge, there is no parameter space for an ion tearing mode.



MAGNETIC RECONNECTION
IN COLLISIONLESS FIELD REVERSALS
THE UNIVERSALITY OF THE ION TEARING MODE

M.M. Kuznetsova and L.M. Zelenyi
Space Research Institute, Moscow, U.S.S.R.

Concluding this paper we would like to summarize all possible mechanism of the destabilization of the tearing mode (spontaneous reconnection) which exists according to our present understanding of the problem:

1) Pitch angle diffusion (external or intrinsic), studied in this paper.
2) Magnetic shear (By field).
3) Collisions even very weak
4) Violation of the WKB approach for long-wavelength perturbations (kL<Bz/B0).

DEAD END !

For HARRIS CS MODEL

Very intense

discussions

Leaders of both

groups were

serious pipe smokers

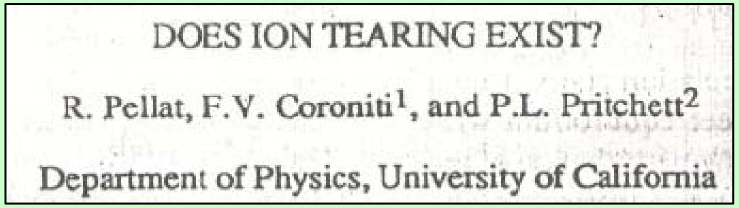
EXCHANGE

OF IDEAS

and CUBAN

TOBACCO

Alex GALEEV Rene PELLAT



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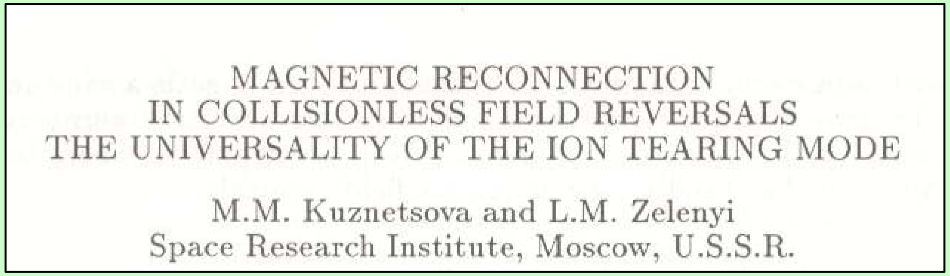

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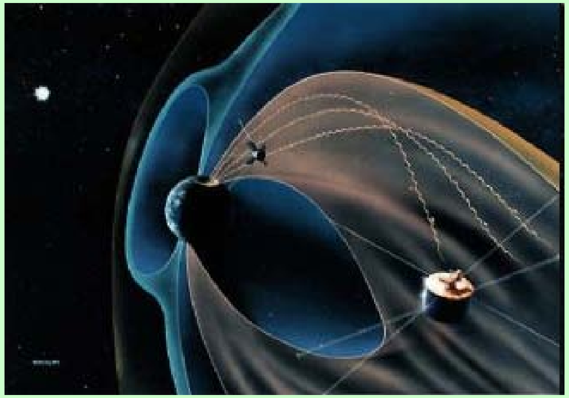
DEAD END !

For HARRIS CS MODEL

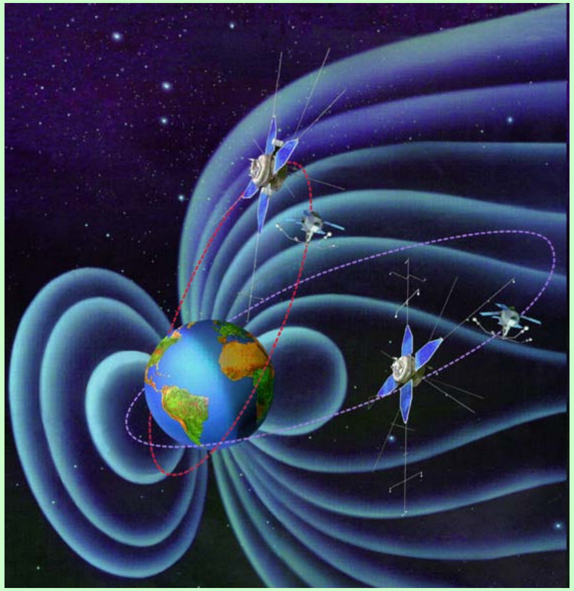
It is necessary to develop a new model of realistic current sheet compatible with 4-point CLUSTER observations of real current profiles and recalculate its stability properties

Spacecraft observations of magnetotail processes (1992-….)

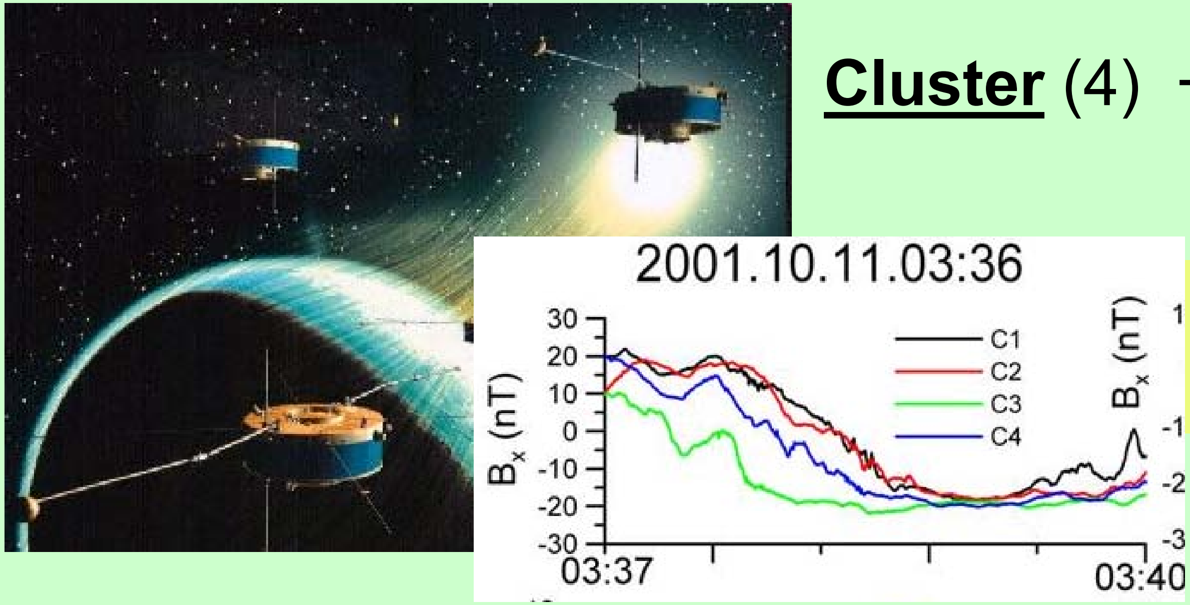
Geotail (1)



Interball (2+2)



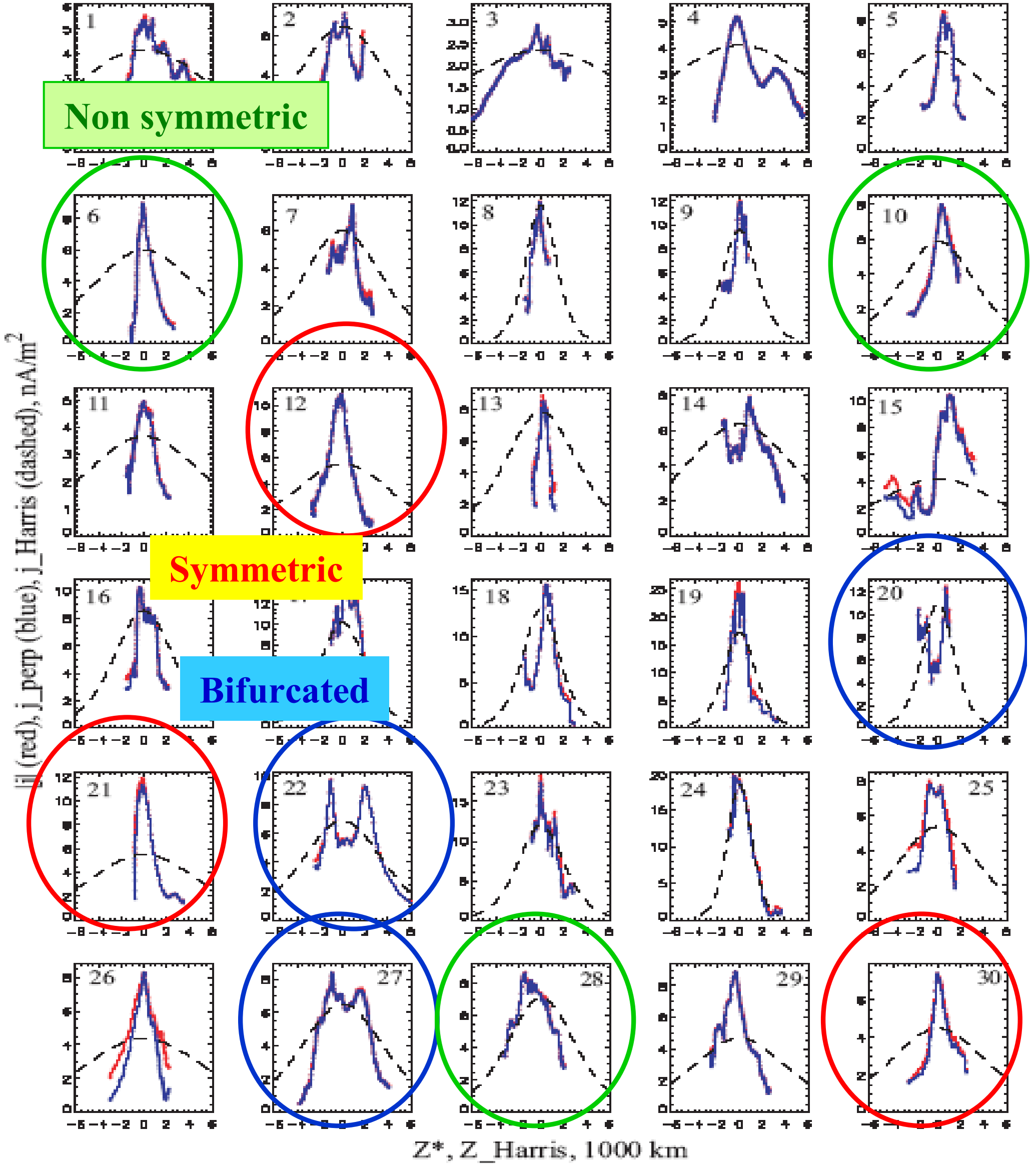
Cluster (4) + Double Star (2)



THEMIS(5)

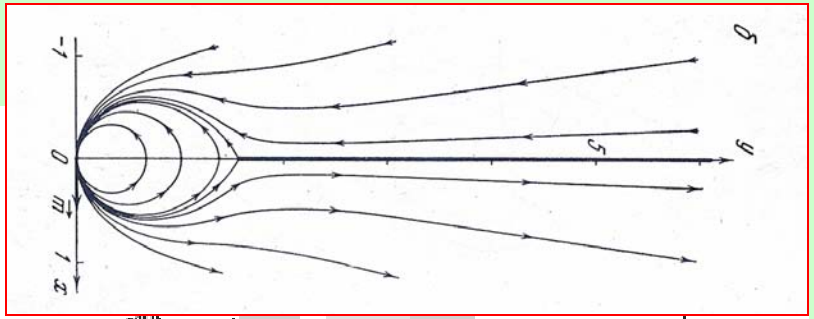
CLUSTER
CS OBSERVATIONS

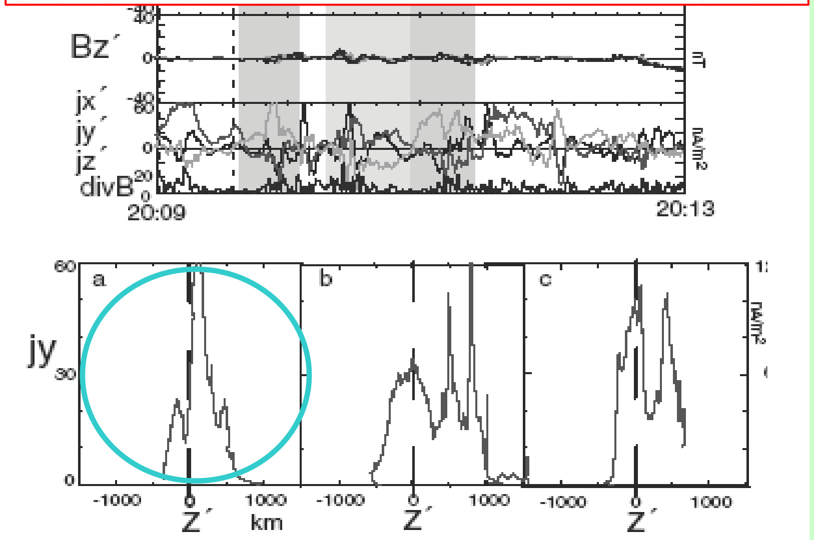
Runov et al., 2006 collection
Nakamura et al., 2006



Profiles of absolute values of the current densities j (blue) and $j_\perp$ (red) versus the effective vertical coordinate Z^*, calcula
Dashed lines show the corresponding Harris profiles.

Super thin (<1000km) current sheet predicted by Syrovatsky

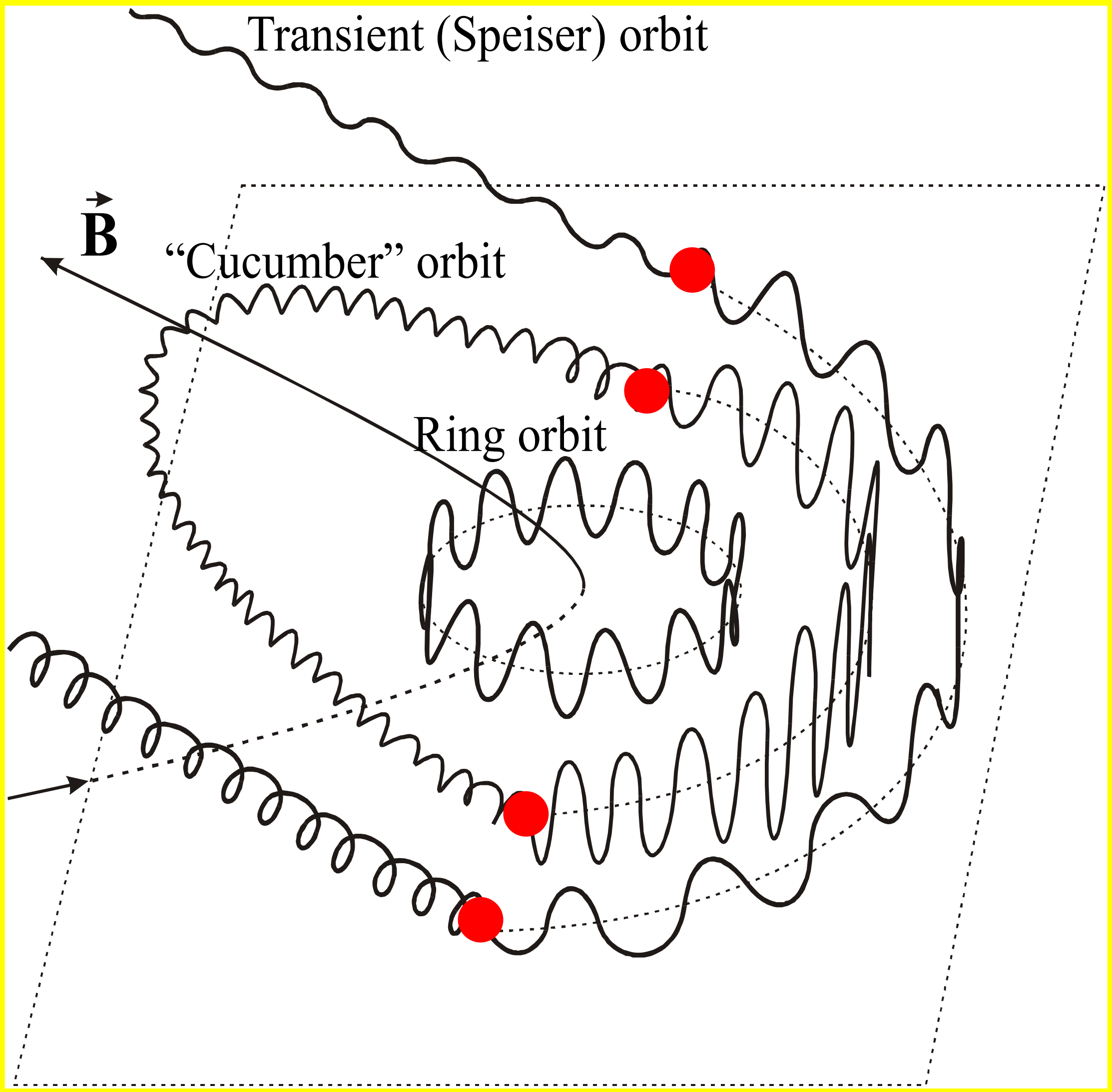




Nakamura et.al. SSR, 2006

Essence of nonadiabatic particle motion

Ion dynamics



Breaking of usual guiding center description

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

Quasiadiabatic integral of motion I_z is conserved during ion motion

Self-consistent equilibrium model of anisotropic CS

The quasi-adiabatic integral of motion (action integral Iz) is approximately conserved along ion trajectory

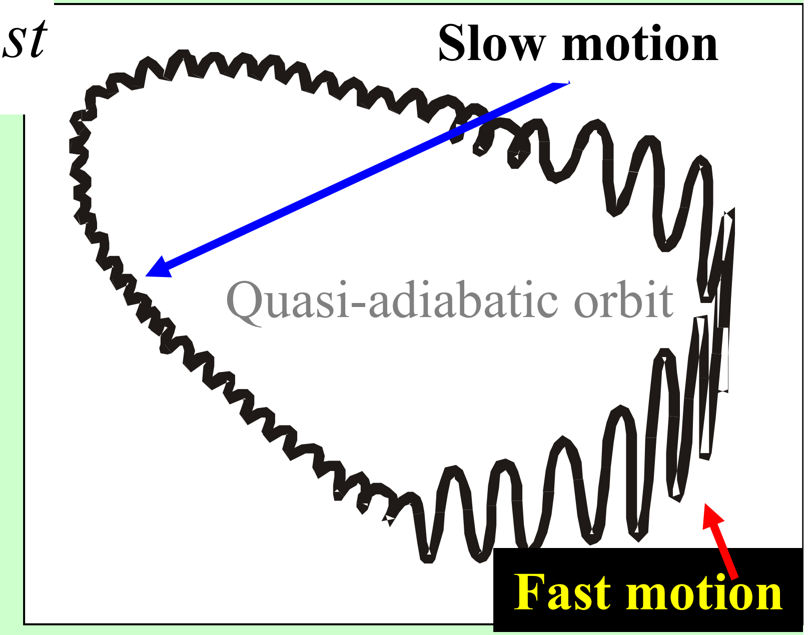
$$\kappa_i = \frac{\omega_{\mathrm{SLOW}}}{\omega_{\mathrm{FAST}}} << 1$$

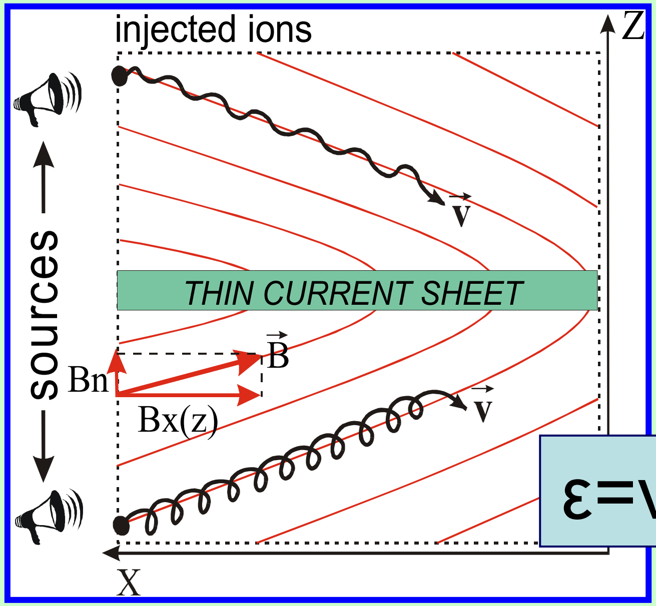
$$I_z \equiv \frac{1}{2\pi}\oint m v_z dz \approx const$$

Bz=const= Parameter

$$\Delta I_z \ll I_z$$

Action integral Iz over fast variable is approximately conserved

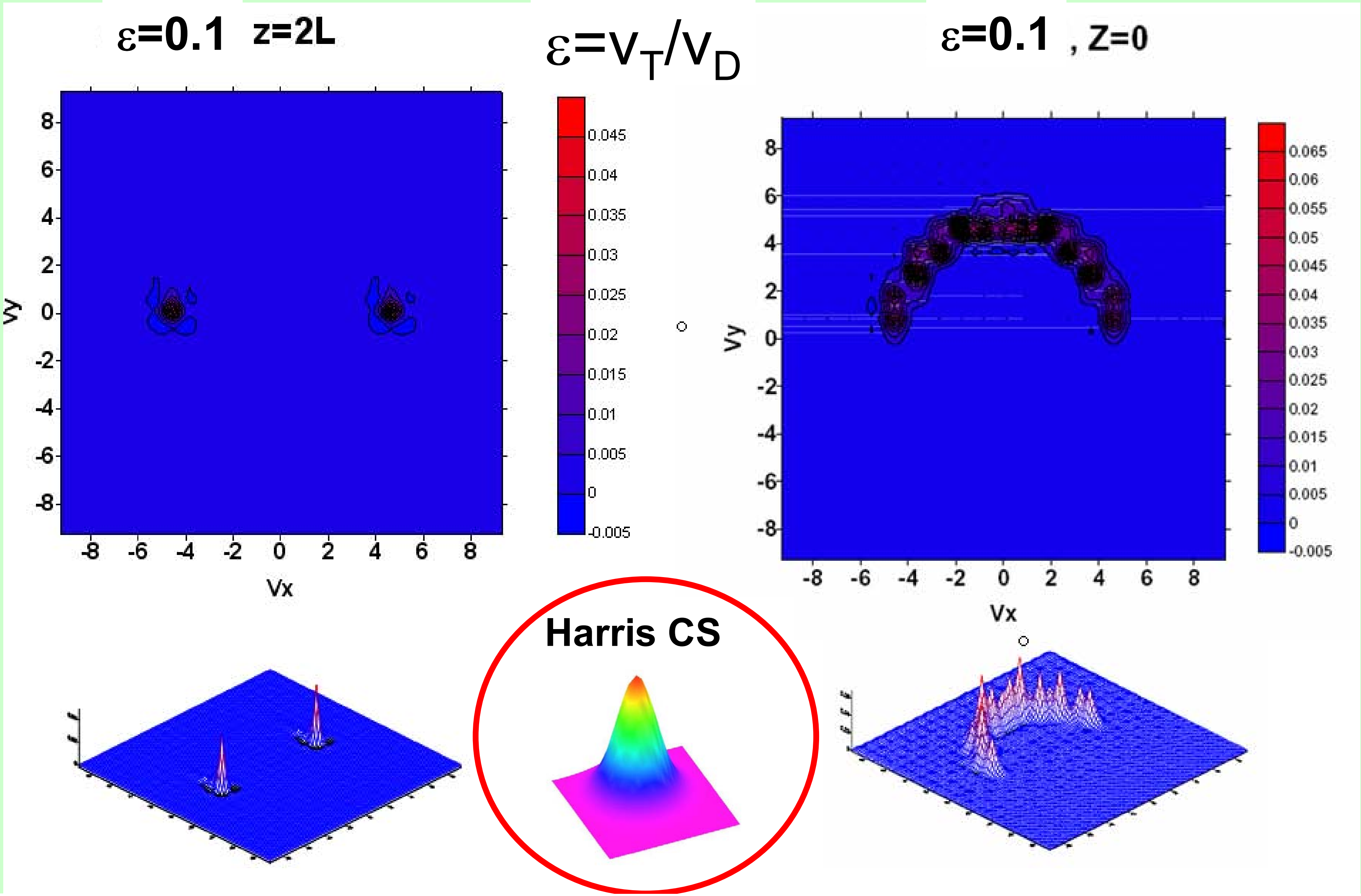




$\varepsilon = v_T / v_D$

Using approximate I_z~const makes the system integrable.

Map of distribution function of Speiser ions at the edges and in the center of CS



ε=0.1 z=2L

$\varepsilon = v_T / v_D$

ε=0.1 , Z=0

Harris CS

TCS Model

$$\varepsilon = v_T / v_D \qquad b_n = B_z / B_0$$

Current density in the drift approximation

$$\boxed{J_{e\perp} = -en_e c \frac{\left[\vec{E},\vec{B}\right]}{B^2} + \frac{c}{B^2}\left[\vec{B},\vec{\nabla}_\perp \tilde{p}_{\perp e}\right] + \frac{c}{B^4}\left(\tilde{p}_{IIe} - \tilde{p}_{\perp e}\right)\left[\vec{B},\left(\vec{B}\vec{\nabla}\right)\vec{B}\right]}$$

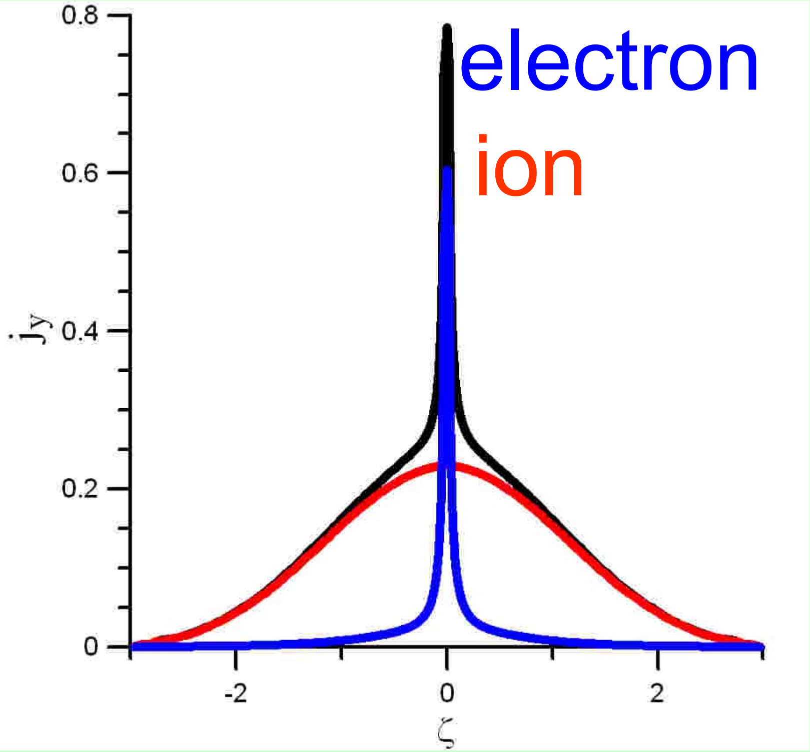
$$\boxed{j_e \sim \left(p_\parallel - p_\perp\right)\frac{\left[\mathbf{B}\times\left(\nabla\mathbf{B}\right)\mathbf{B}\right]}{\left|\mathbf{B}\right|^4}}$$

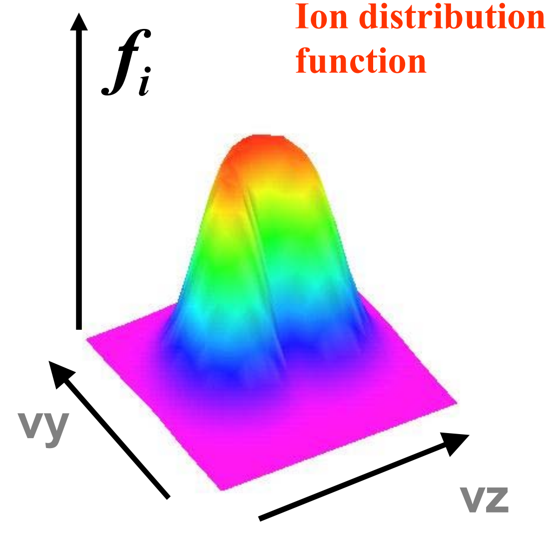
$$df / dt = 0$$

$$\frac{dB}{dz} = \frac{4\pi}{c}\left\{\sum_{j=H^+_{hot},H^+_{cold}} \int_{V^3} v_y f_j(\vec{v}) d^3 v + j_e\right\}$$

$$B\big|_{z=L} = B_0,\ \varphi\big|_{z=L} = 0$$

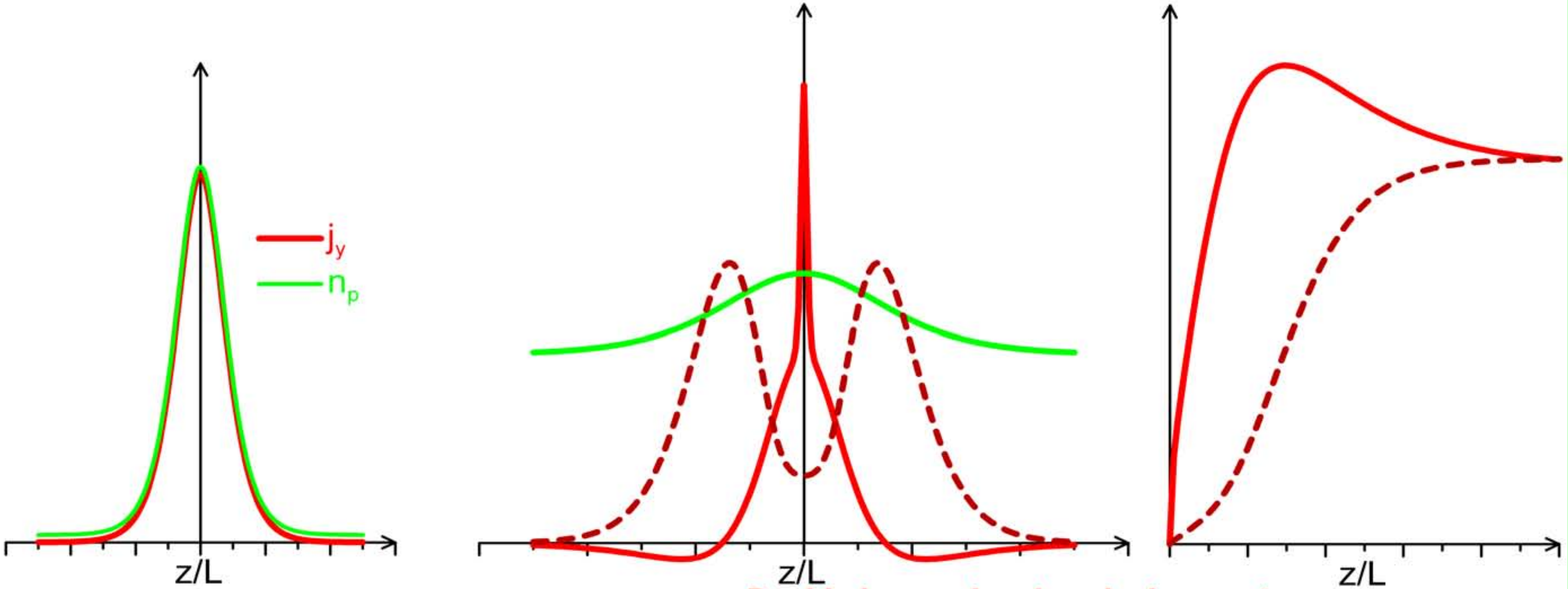
Grad- Shafranov system of Equations





Thin current sheets

ROLE OF ANISOTROPY



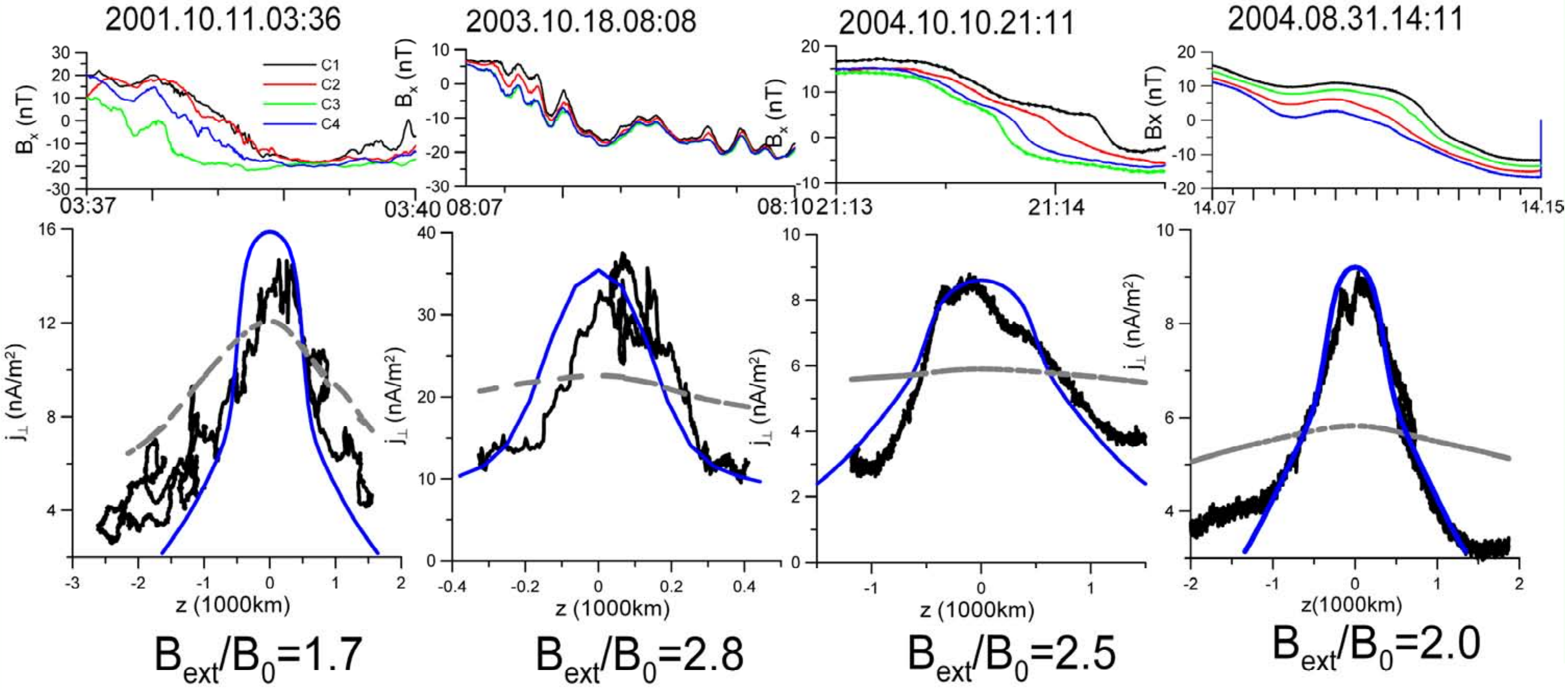
Harris-like current density profile coincides with plasma density profile

Double-humped and peaked current sheets are embedded inside plasma sheet

Realistic features of TCS: embedding, bifurcation, overshoots, steepening

Fast CS crossing and the model of thin current sheet

Observations approximated by Thin CS model and Harris CS



Artemyev et al. 2008

Difference between experimental N_p, T_p, B_L and TCS model parameters <30%

Spatial scale ~ 200 km

Spatial scale < 1000 km

Energy principle for tearing mode.

Marginal stability.

$$\int_{-\infty}^{\infty}\frac{\vec{B}_1^2+\vec{E}_1^2}{8\pi}d\tau = -\int_{-\infty}^{\infty}\left(\vec{j}_1\vec{E}_1\right)d\tau$$

$$f_j = \frac{\partial f_{0j}}{\partial A_0}A_1 + \tilde{f}_{1j}$$

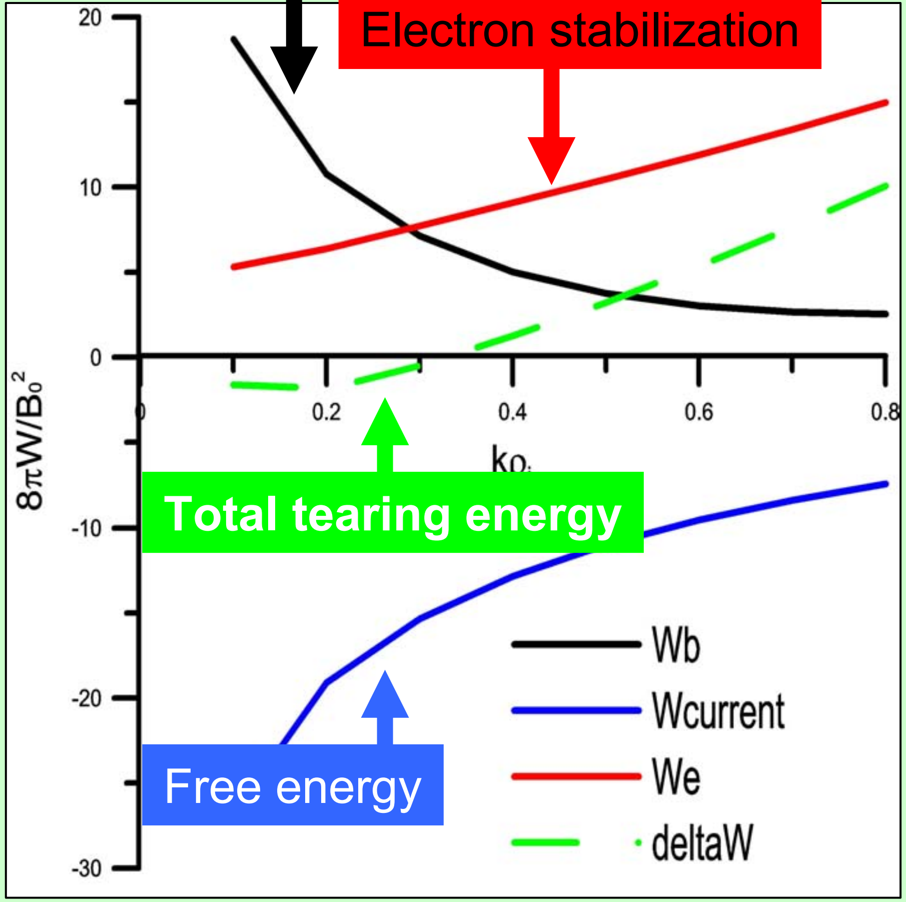
$$\overbrace{W_{tearing}}^{\text{deltaW}} = \int_{-\infty}^{\infty}\left\{\overbrace{\left|\nabla\times A_1\right|^2+\left|\nabla\varphi_1\right|^2}^{\text{Wb}} + \overbrace{\frac{4\pi}{c}\frac{\partial j_y}{\partial A_0}\left|A_1\right|^2}^{W_{\text{current}}\text{ = free energy}} + \overbrace{4\pi e\int_{-\infty}^{\infty}\frac{\tilde{f}_{1e}^2}{\partial\tilde{f}_{0e}/\partial\varphi_0}d\vec{v}}^{\text{We}}\right\}$$

$$\frac{1}{2}e\int_{-\infty}^{\infty}\frac{\tilde{f}_{1e}^2}{\partial\tilde{f}_{0e}/\partial\varphi_0}d\vec{v} \le \frac{1}{2}T_e\int_{-\infty}^{\infty}\tilde{f}_{1e}^2 d\vec{v}\Bigg/\int_{-\infty}^{\infty}f_0 d\vec{v} = \frac{1}{2}T_e n_{0e}\frac{k^2\left|A_1\right|^2}{B_z}, \qquad \frac{n_1}{n_0}=\frac{kA_1}{B_z}$$

Different components of tearing mode energy sufficient criteria of instability.

Perturbation of magnetic field

Electron stabilization



Total tearing energy

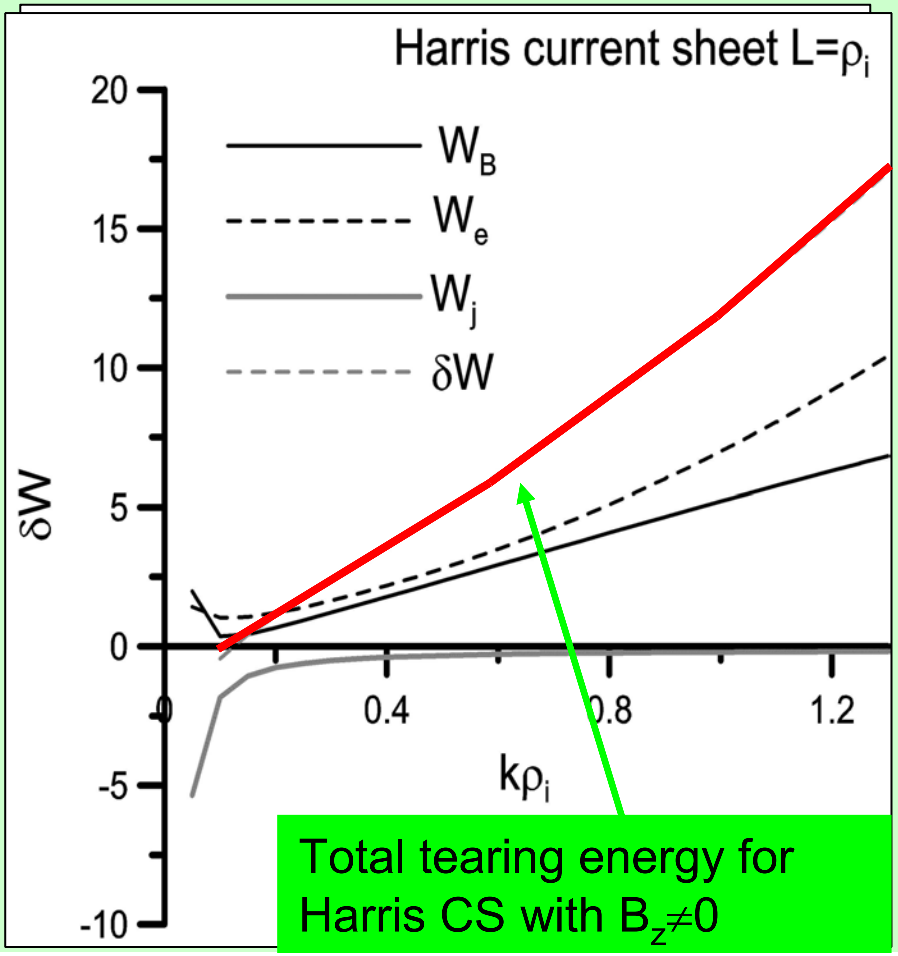
Free energy

components of energy $L = 0.7\rho_i \quad b_n = 0.1$

Ti/Te=3

$$\boxed{\delta W < 0}$$

total tearing mode energy



Total tearing energy for Harris CS with $B_z \neq 0$

Embedding of observed CS and their sources of Free energy

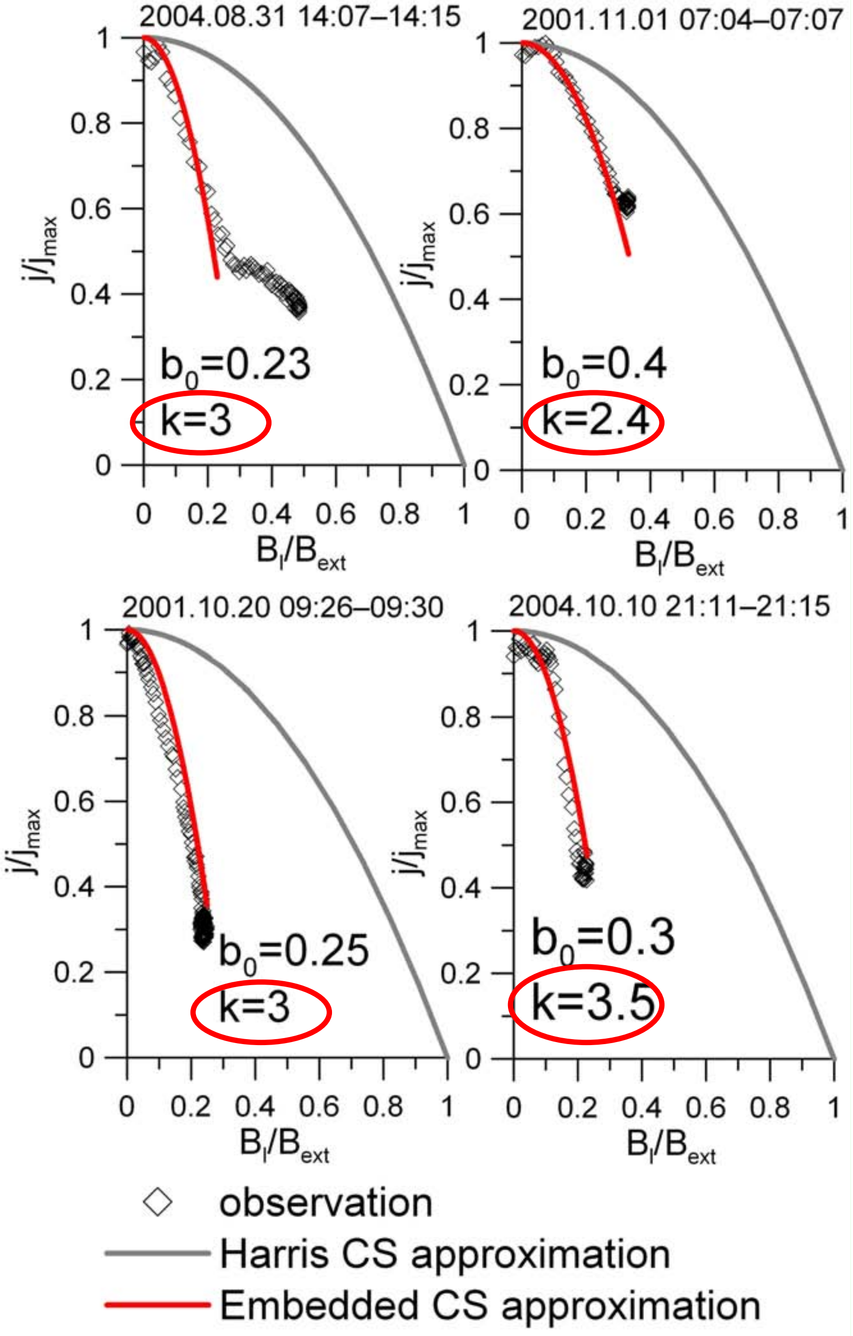
$k=W_{free}$(observed CS)/W_{free}(Harris CS)

$$\boxed{\begin{aligned} W_F &= \frac{1}{2c}\int_{-\infty}^{+\infty}\frac{\partial j}{\partial A_y}A_1^2\,dz \\ &= \frac{j_{\max}}{c}\int_0^{B_0}\frac{\partial\left(j/j_{\max}\right)}{\partial B_x}\frac{1}{B_x}A_1^2\,dB_x + \\ &\quad \frac{j_{\max}}{c}\int_{B_0}^{B_{ext}}\frac{\partial\left(j/j_{\max}\right)}{\partial B_x}\frac{1}{B_x}A_1^2\,dB_x \end{aligned}}$$

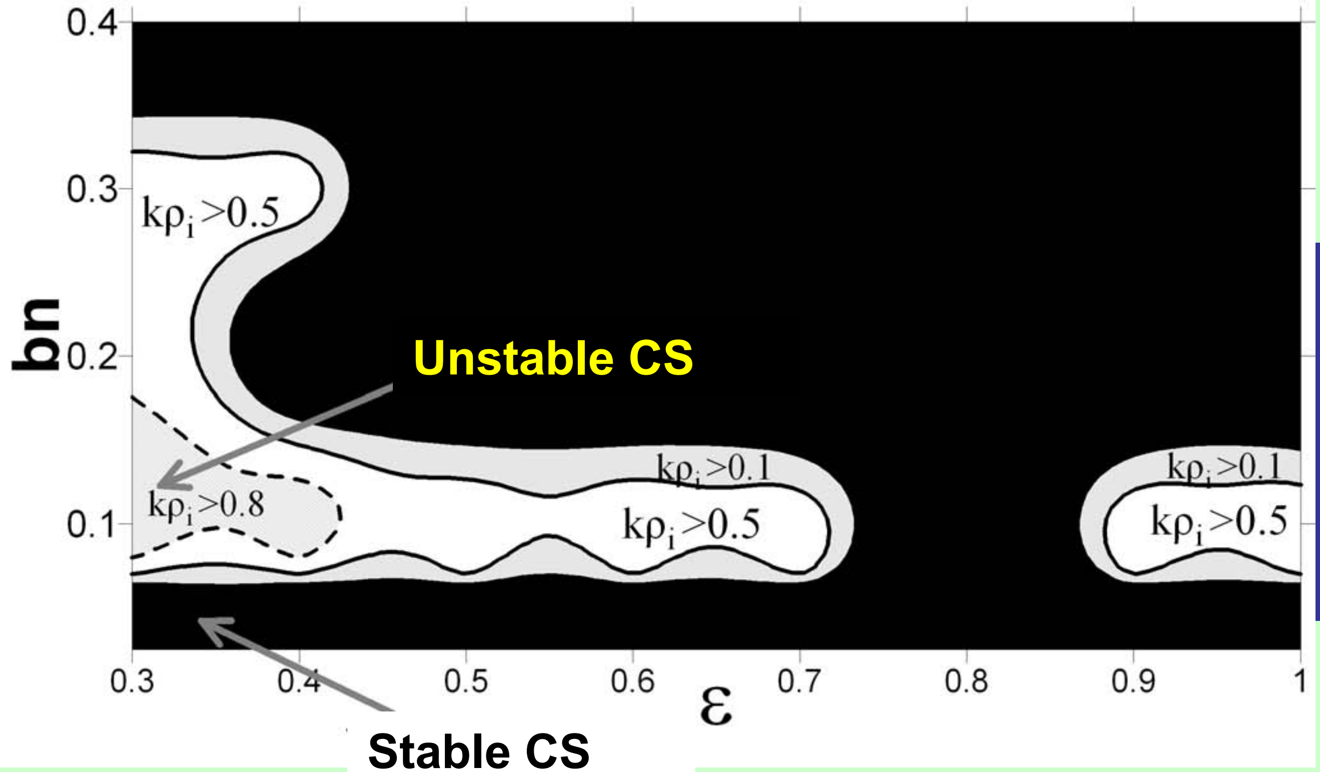
$$b_0 = B_0/B_{ext}\,,\quad \mu = j_{\min}/j_{\max}$$

$$k = (1-\mu)/b_0 + (1-b_0)$$

“Free” energy of observed CSs is 2-3 larger than the one of corresponding Harris sheet



Parameter space of TCS instability

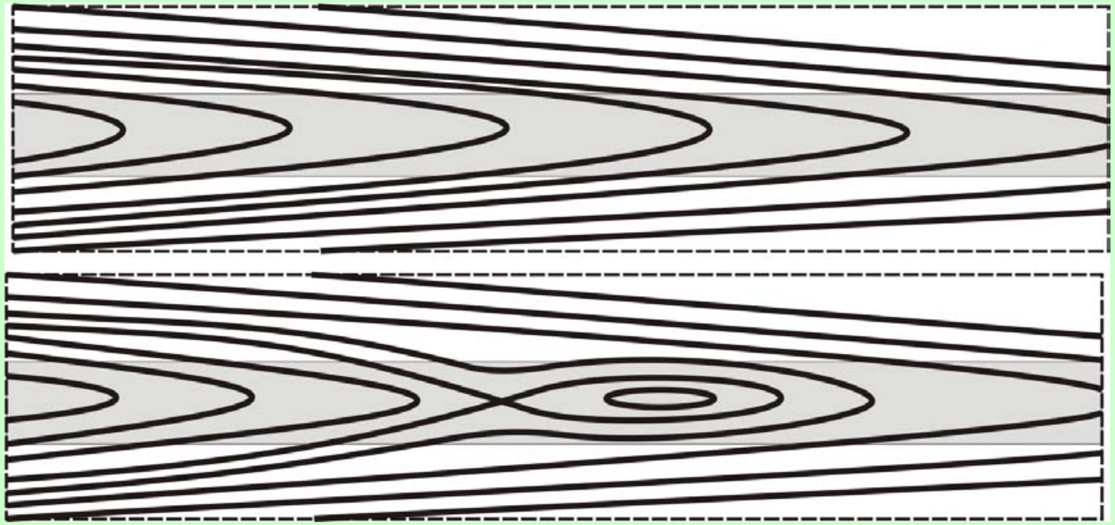


Unstable CS

Stable CS

$T_i/T_e=3$

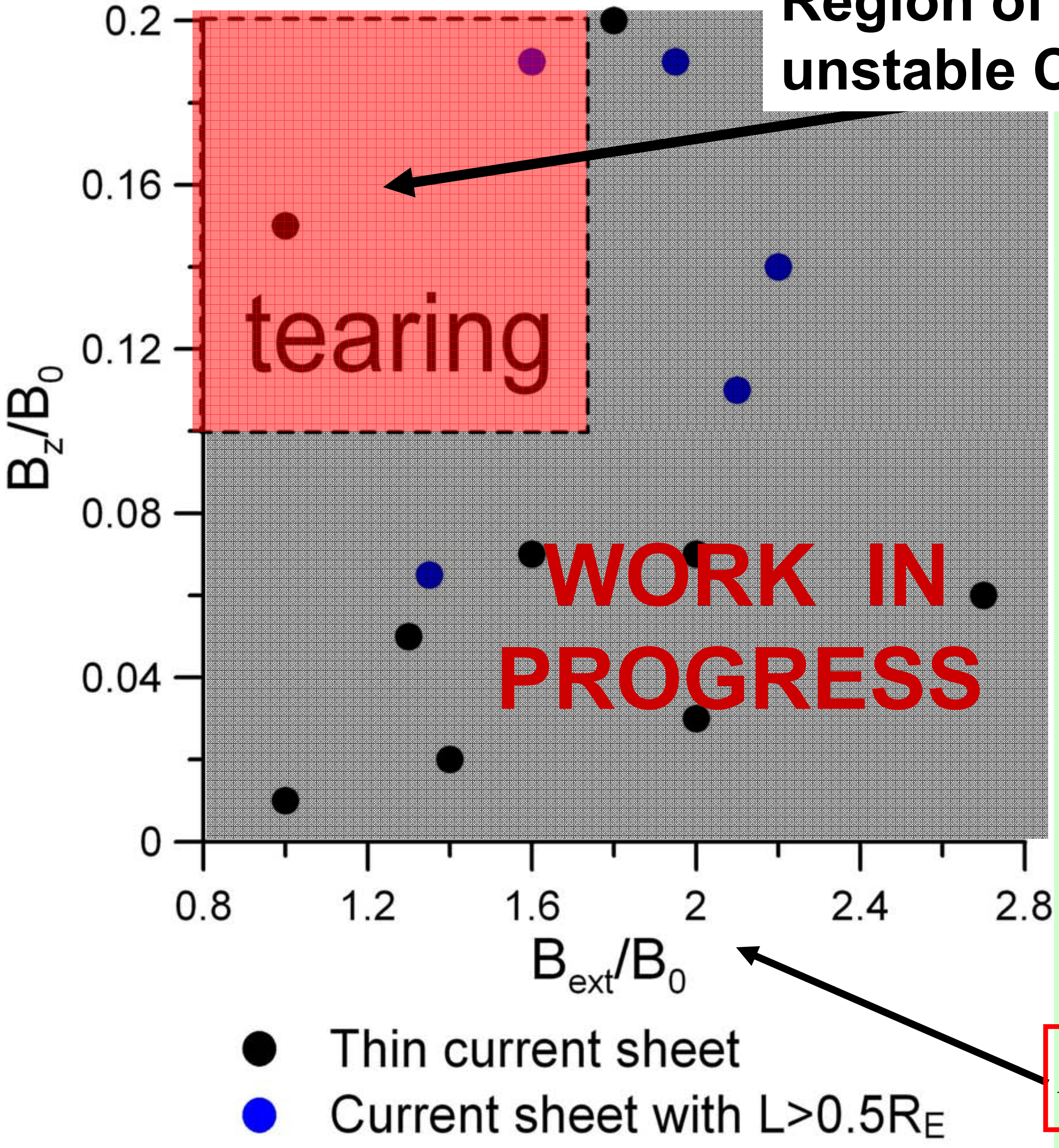
Integral instability window for all $0<kL<3$



Initial moment

NL mode growth

Linear theory and Cluster observations

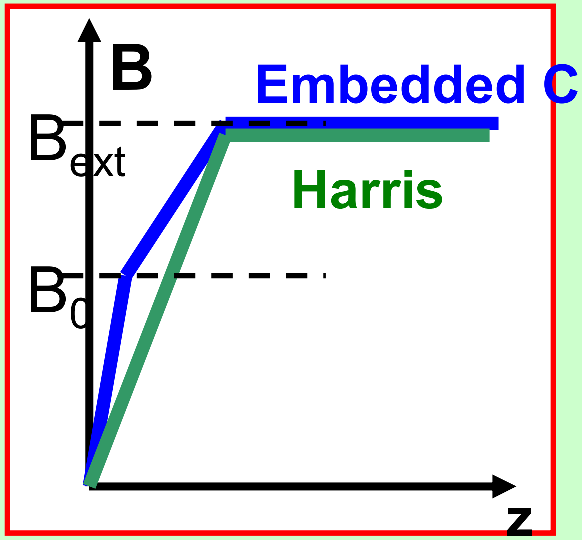


Region of unstable CS.

Measure of CS embedding can be presented as B_{ext}/B_0.

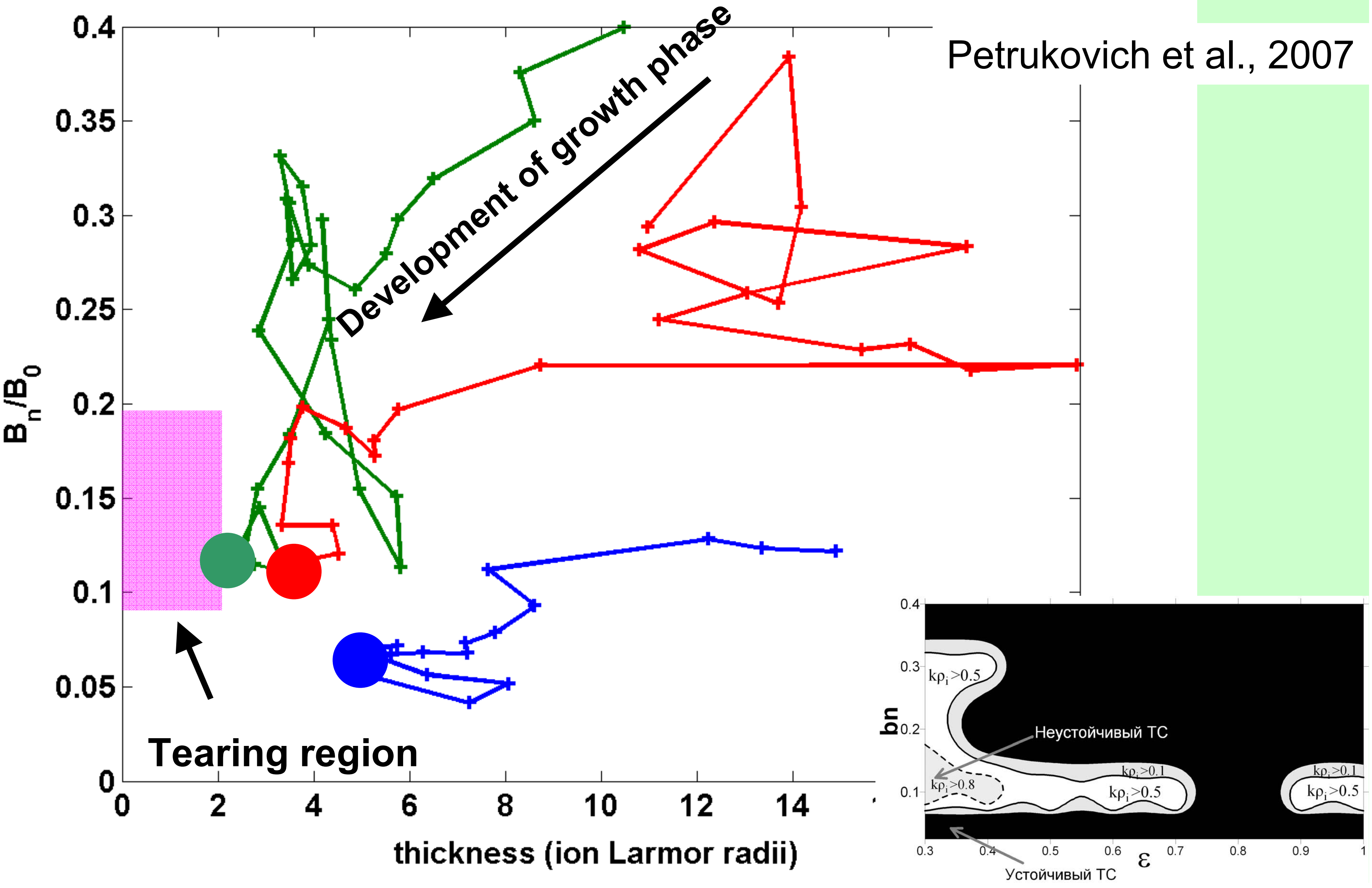
For Harris CS $B_{ext}/B_0=1$.

For TCS $B_{ext}/B_0>1$



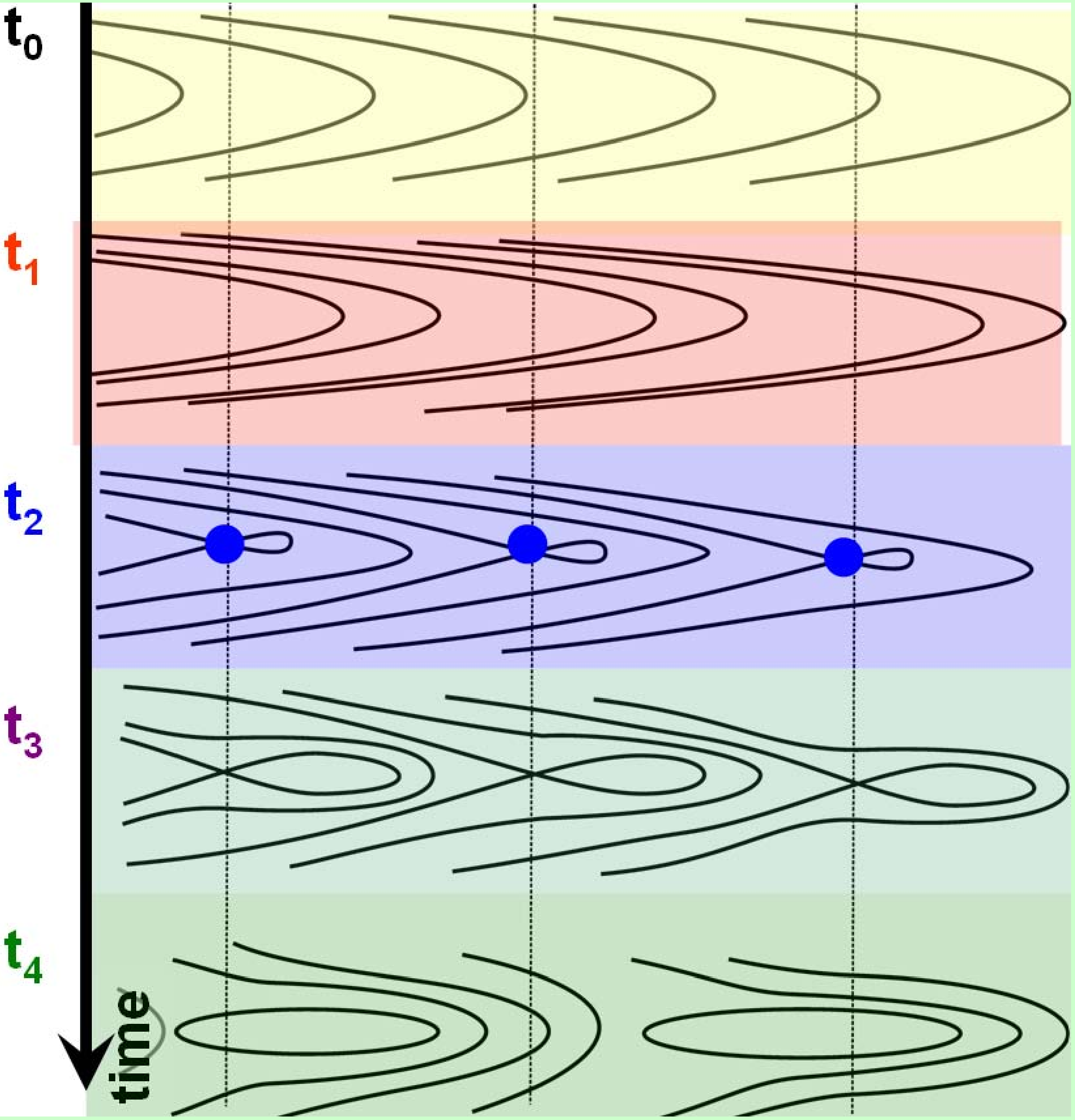
$$B_{ext}^2 = B_0^2 + \mu_0 p\left(z = L\right)$$

Evolution of metastable CS during the growth phase. Thinning & stretching towards instability.

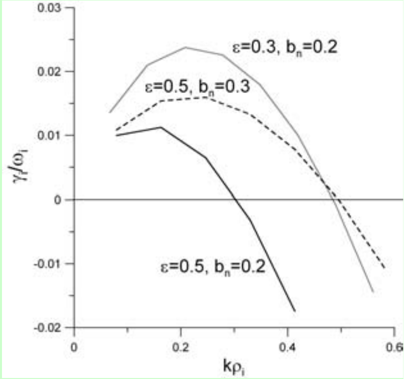


Petrukovich et al., 2007

Nonlinear evolution



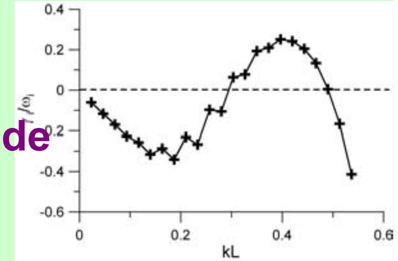
<u>Preonset CS.</u>
Ion T. mode.
Suppression of electron stabilization



Formation of x/o lines – electron mode growth

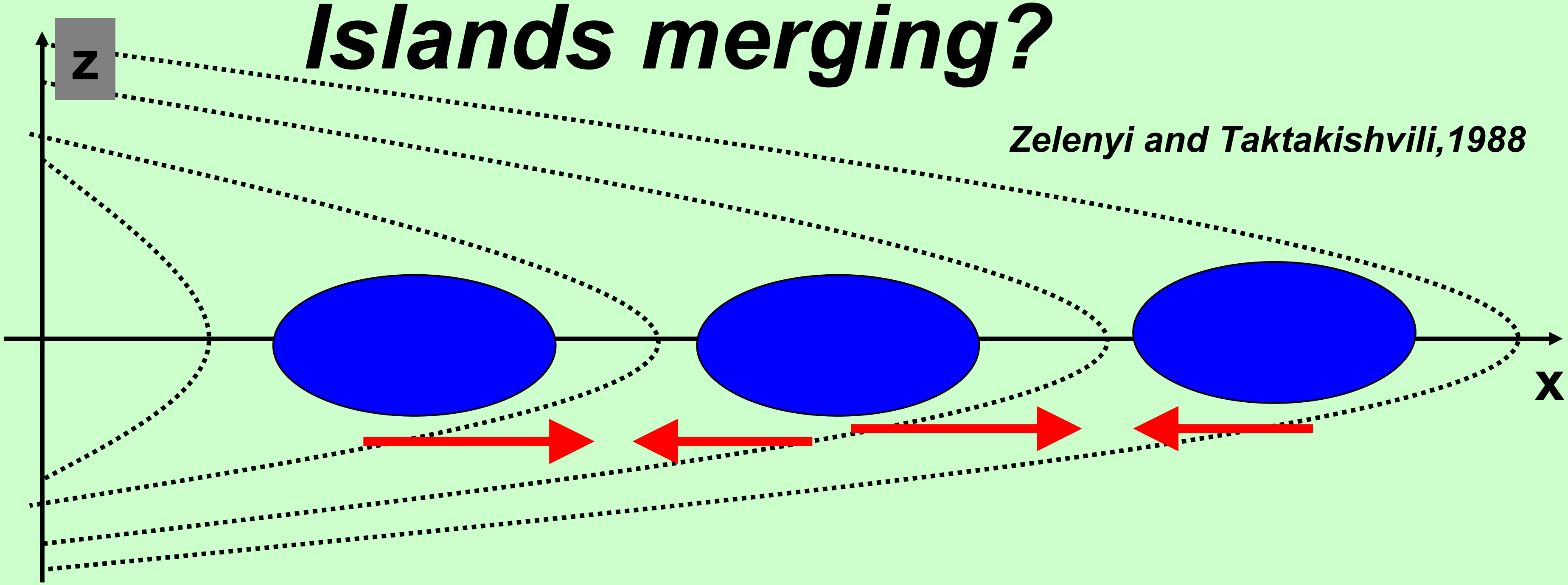
$$\gamma_e = \left(\frac{v_{Te}}{L}\right)\left(\frac{\rho_e}{L}\right)^{3/2} \times$$
$$\times \left(1+\frac{T_i}{T_e}\right)\left(1-k^2L^2\right)$$

Growth of ρ_i scale islands due ion T. mode



Merging of islands due to large scale (MHD) instability

Islands merging?



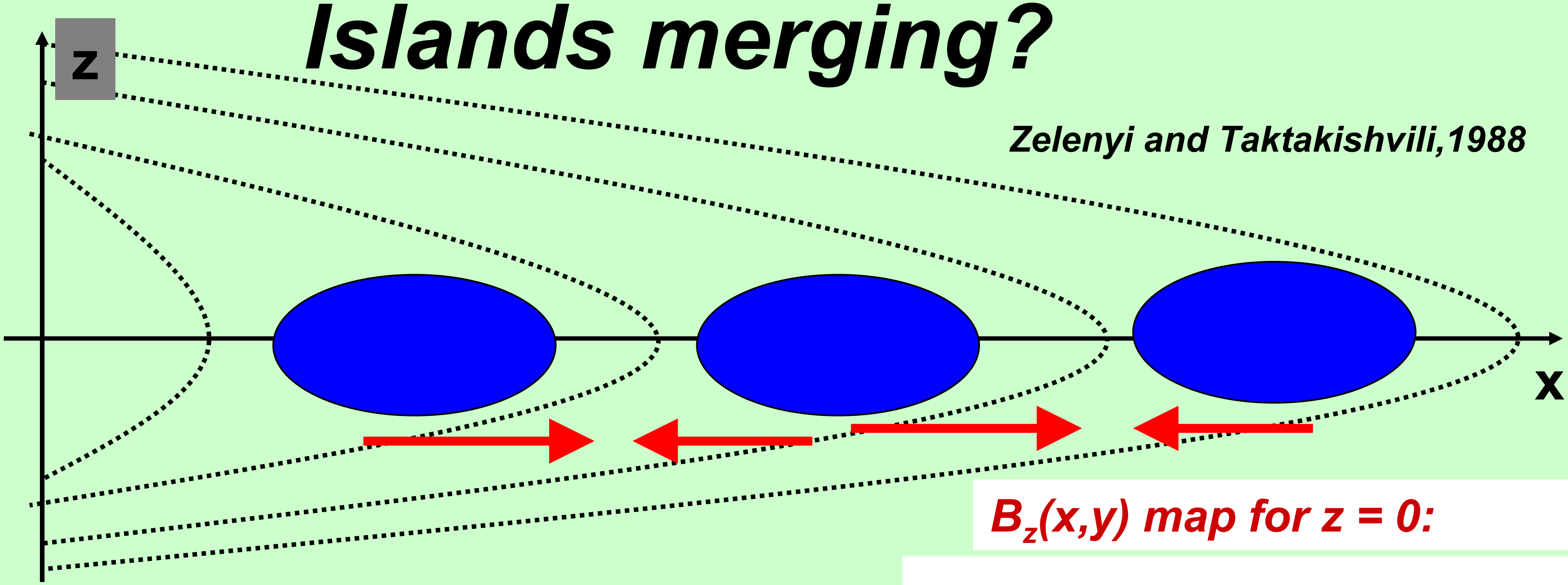
Zelenyi and Taktakishvili,1988

Pellat 1983

$$\frac{\gamma_{\mathrm{MHD}}}{\omega_{0i}} = (kL)^{1/4} \left(\frac{T_e}{T_i}\right)^{1/2} \left(\frac{\delta B_z}{B_0}\right)^{3/4}$$

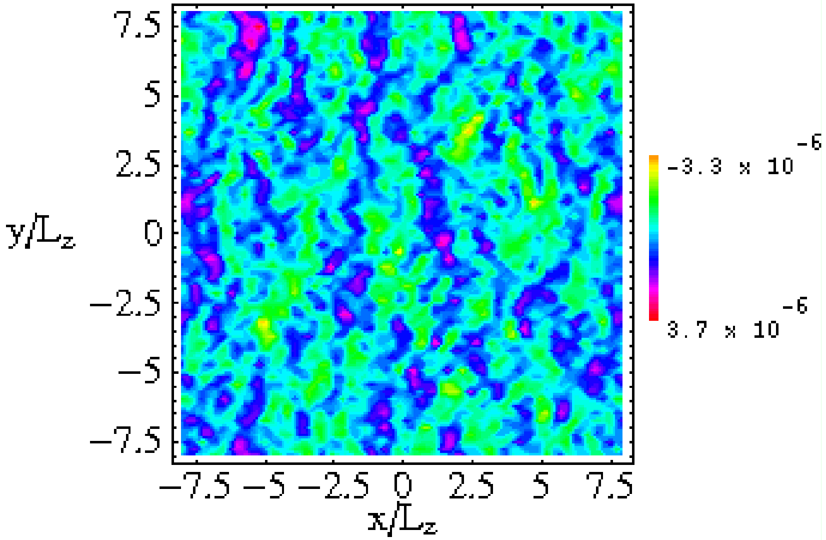
Formation of large scale plasmoid from small scale islands

Islands merging?



Zelenyi and Taktakishvili,1988

$B_z(x,y)$ map for $z = 0$:



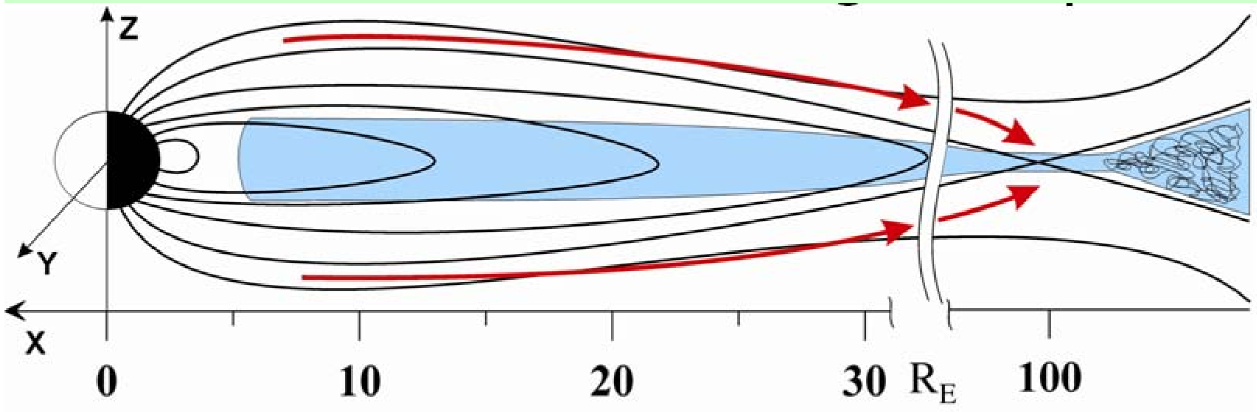
Pellat 1983

$$\frac{\gamma_{\mathrm{MHD}}}{\omega_{0i}} = (kL)^{1/4}\left(\frac{T_e}{T_i}\right)^{1/2}\left(\frac{\delta B_z}{B_0}\right)^{3/4}$$

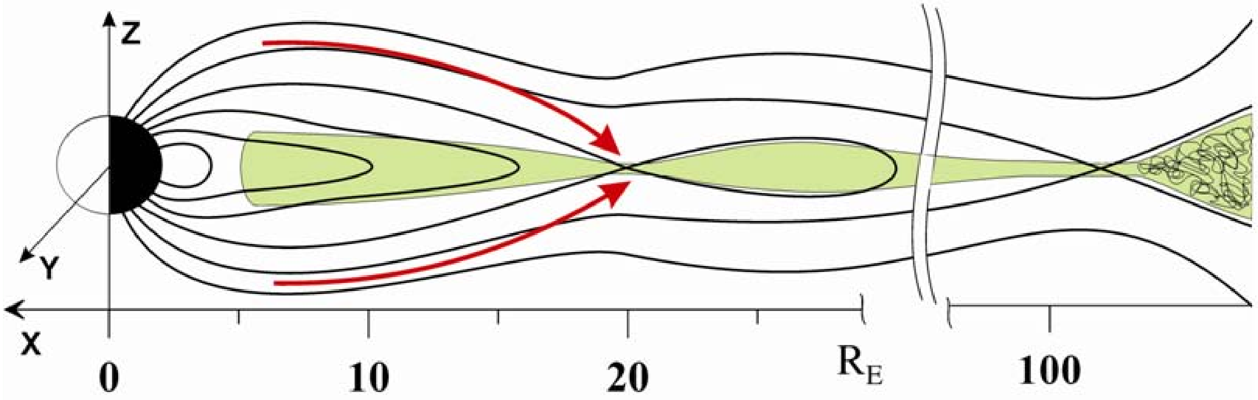
Formation of large scale plasmoid from small scale islands

J.BUECHNER, 2004

Where reconnection could occur in the Earth's magnetosphere ?

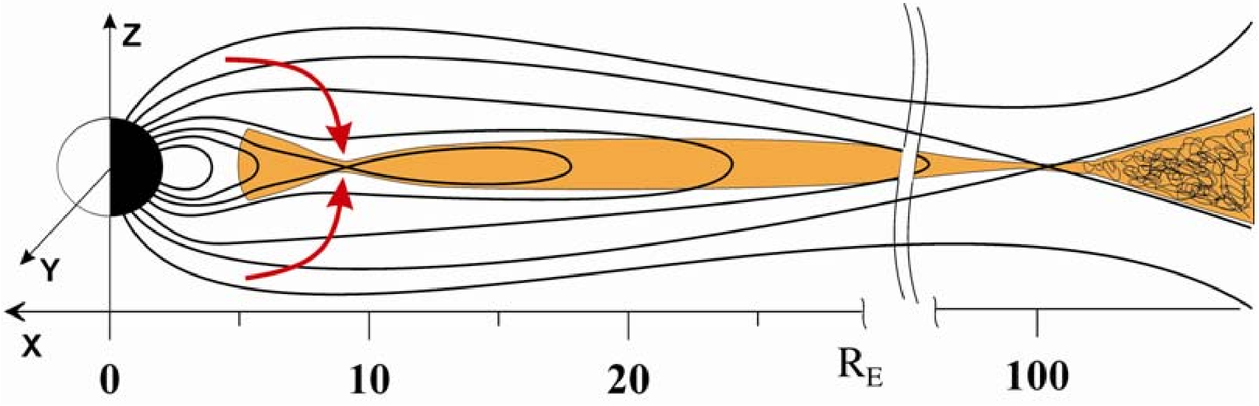


Quiet conditions
Topological distant
tail reconnection



Middle tail
reconnection

Baker et al. 1996
Petrukovich et al. 1998
Phan et al. 2000



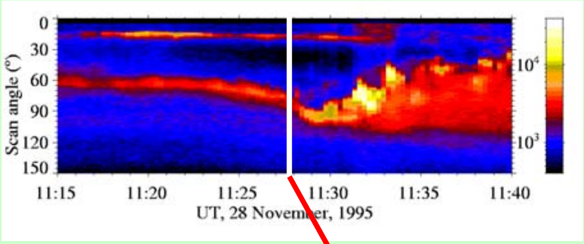
Near Earth
initiation

Lui 1991
Kan 1998

Localization of the substorm onset

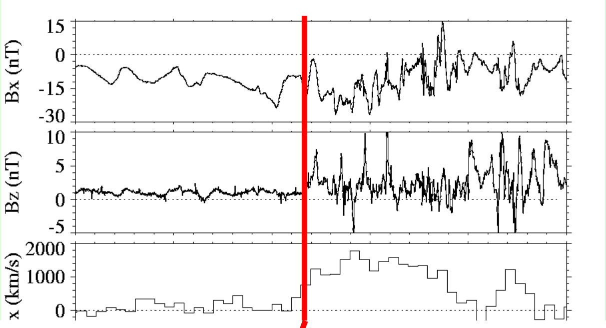
Ground auroral breakup (Poker Flat MSP)

11:27:30 UT



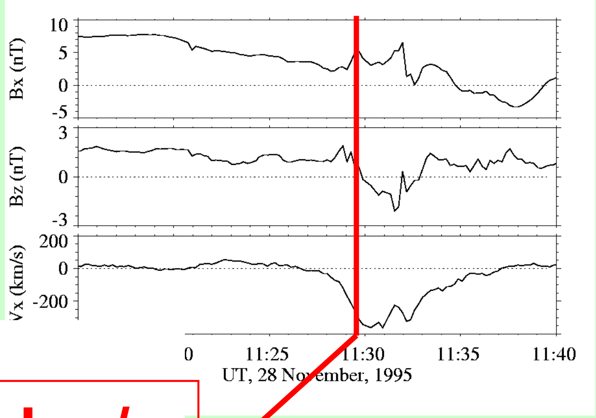
Injection in the inner part (Interball-1 X=-11.5 R_E)

11:26:30 UT



Tailward plasmoid (Geotail X=-28.5 R_E)

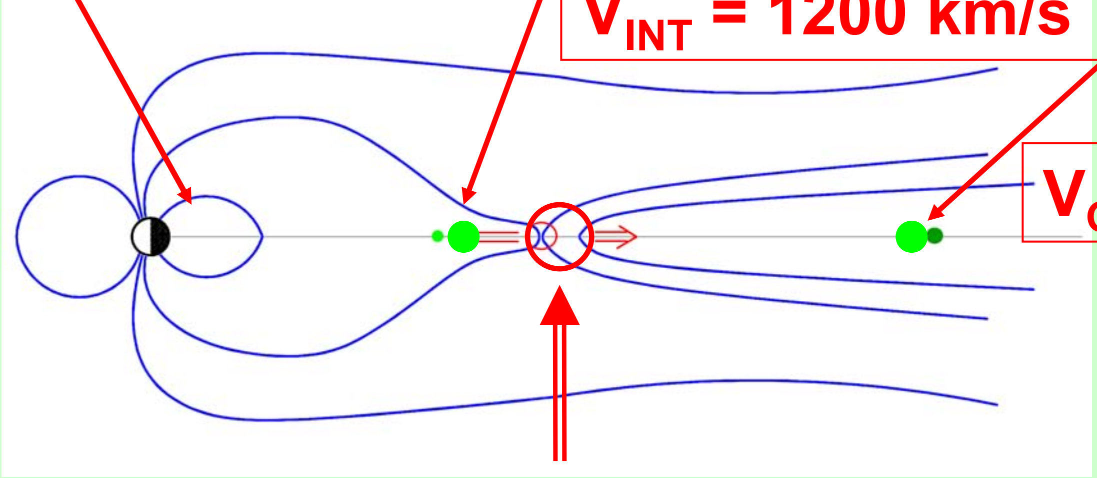
11:29:50 UT



V_{INT} = 1200 km/s

V_{GTL}= -350 km/s

IACG Campaign 1 on magnetotail energy flow



Substorm onset at X=-15.5 R_E, 11:26:10 UT

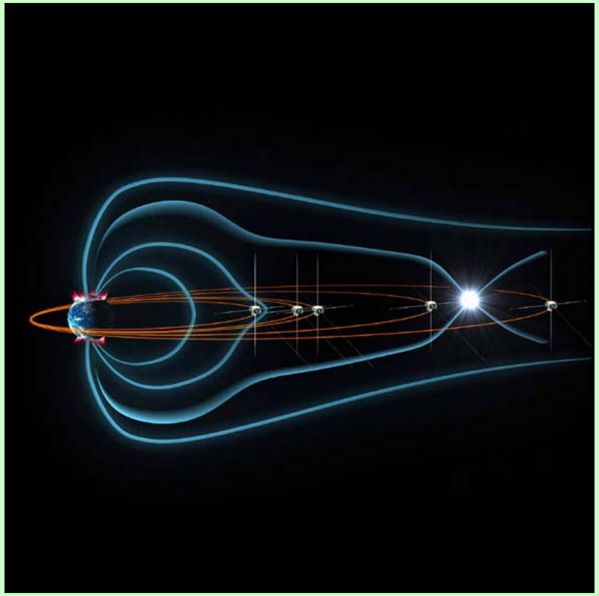
Tail Reconnection Triggering Substorm Onset

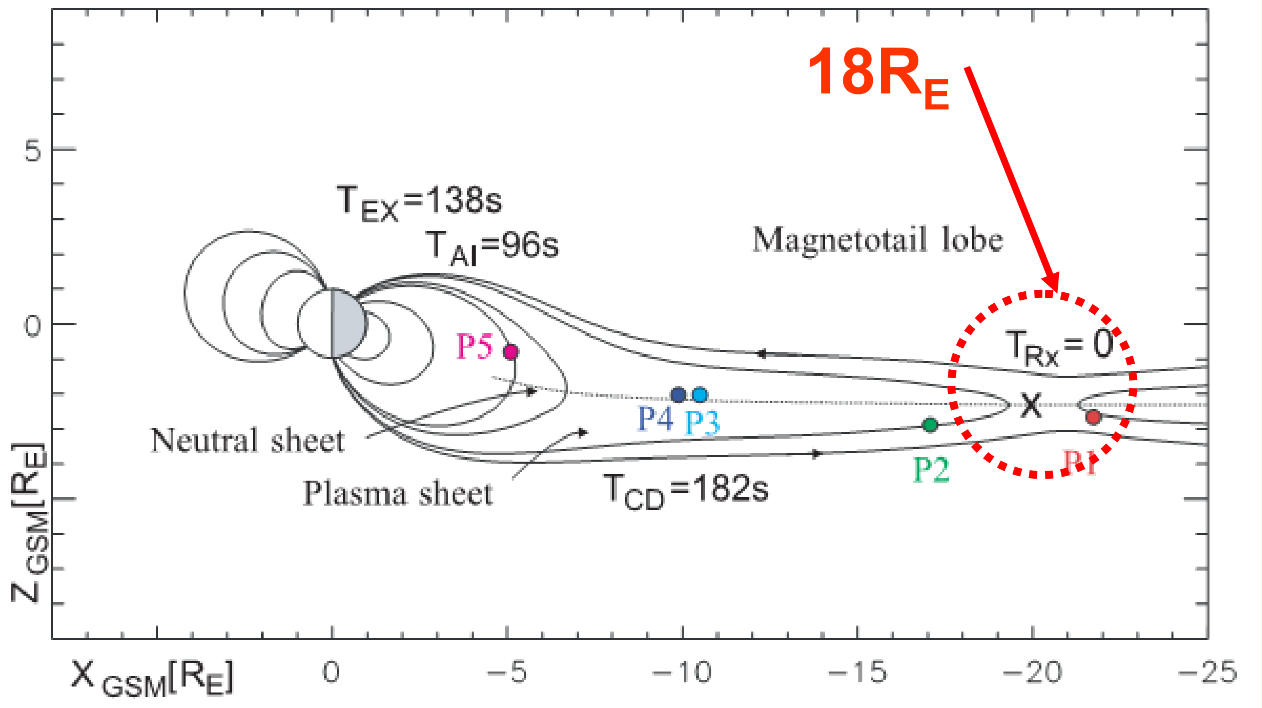
Science 2008

Vassilis Angelopoulos,[1*] James P. McFadden,[2] Davin Larson,[2] Charles W. Carlson,[2] Stephen B. Mende,[2] Harald Frey,[2] Tai Phan,[2] David G. Sibeck,[3] Karl-Heinz Glassmeier,[4] Uli Auster,[4] Eric Donovan,[5] Ian R. Mann,[6] I. Jonathan Rae,[6] Christopher T. Russell,[1] Andrei Runov,[1] Xu-Zhi Zhou,[1] Larry Kepko[7]

5 spacecraft

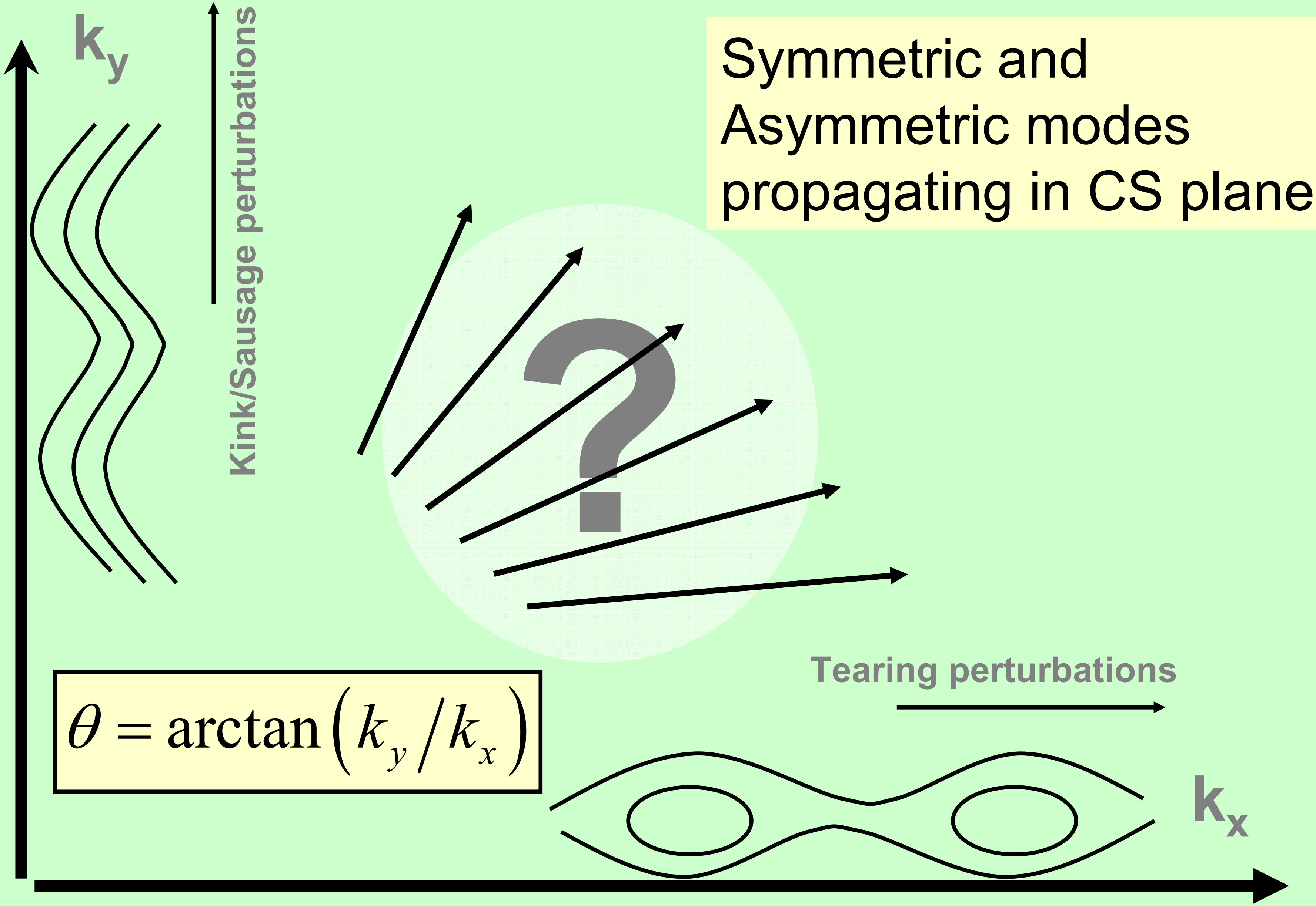
THEMIS PROJECT





Hopes for breakthrough in understanding substorm initiations

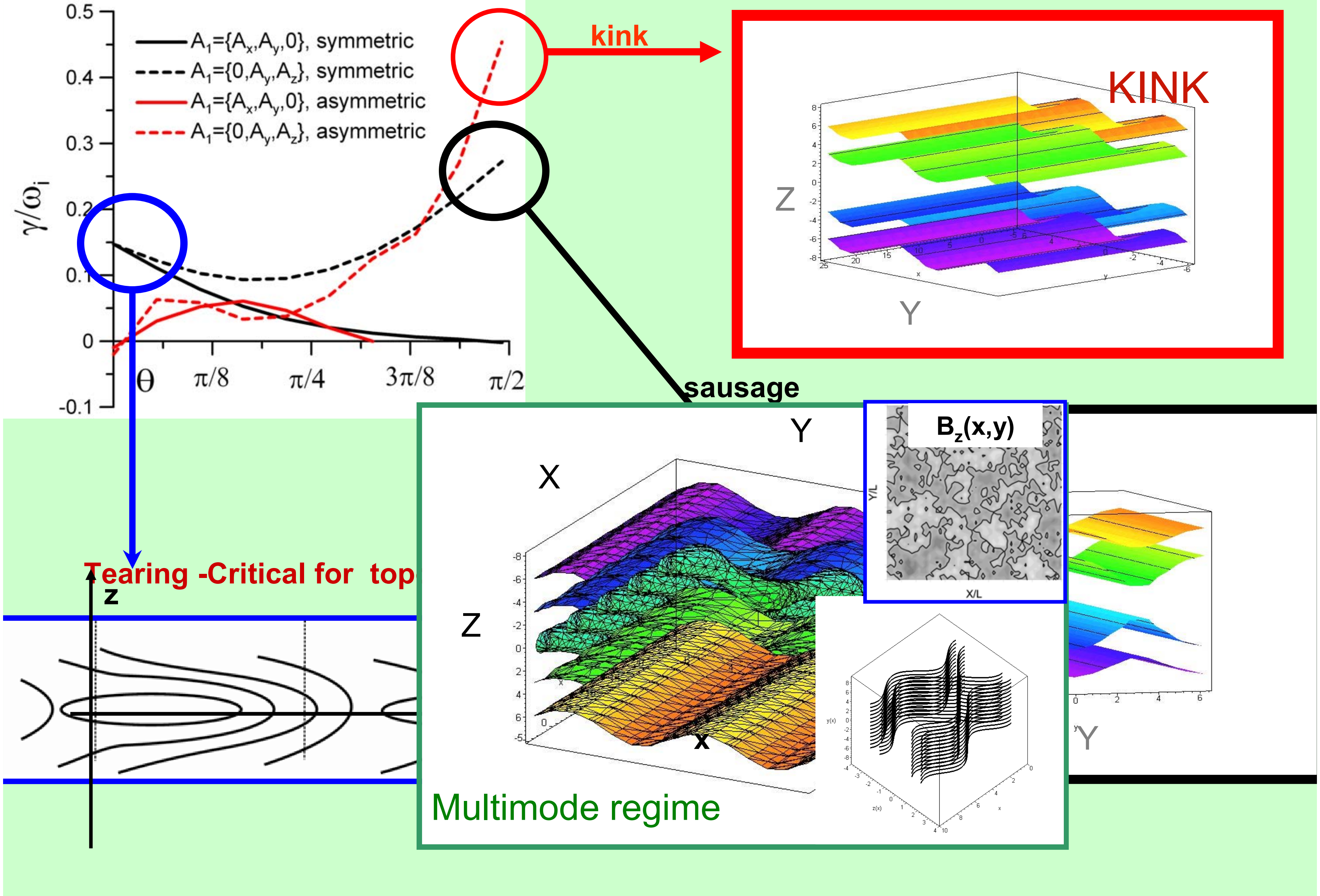
Eigenmodes of TCS



Symmetric and Asymmetric modes propagating in CS plane.

$$\theta = \arctan\left(k_y / k_x\right)$$

Multimode structure of TCS perturbations



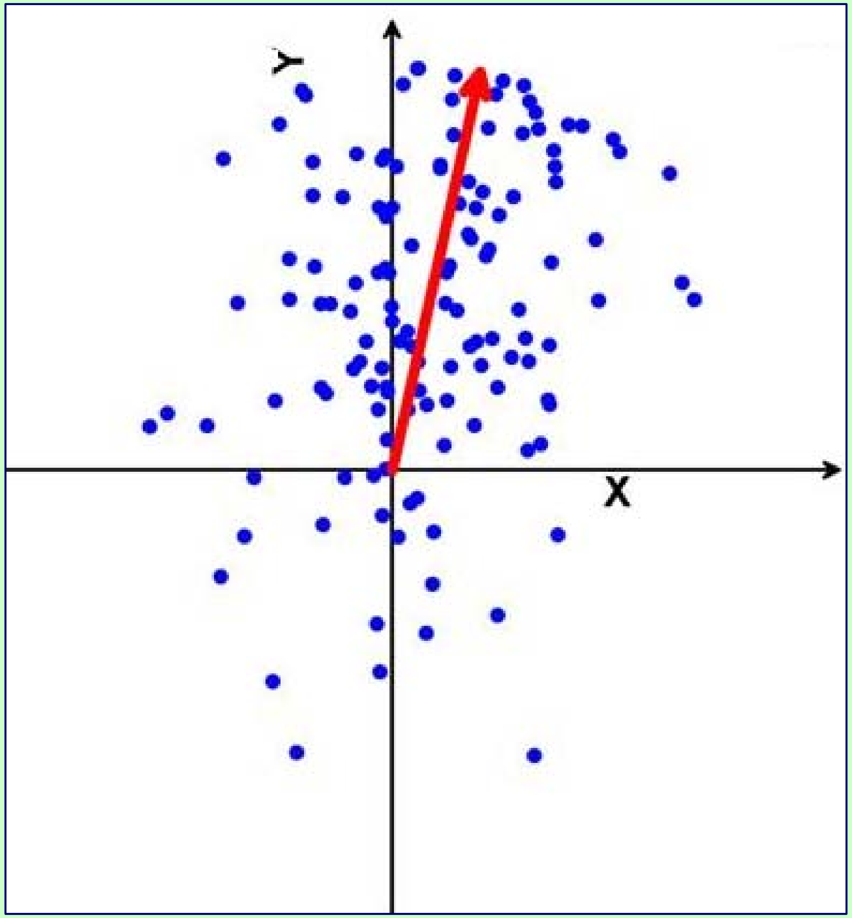
kink

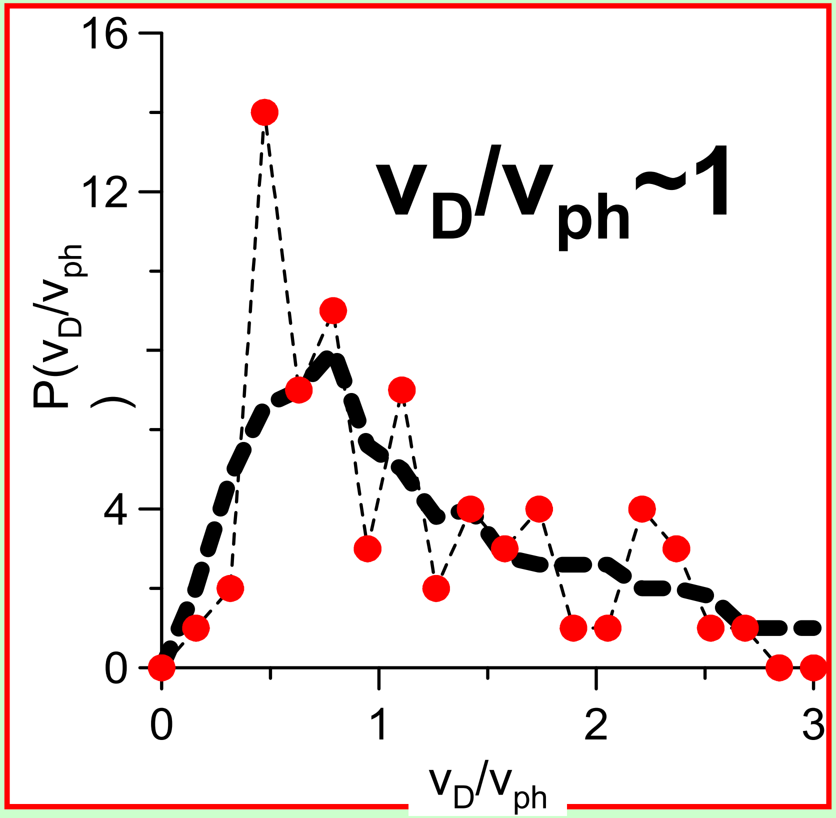
sausage

Tearing -Critical for top

Multimode regime

Propagation of oblique drift waves in the CS



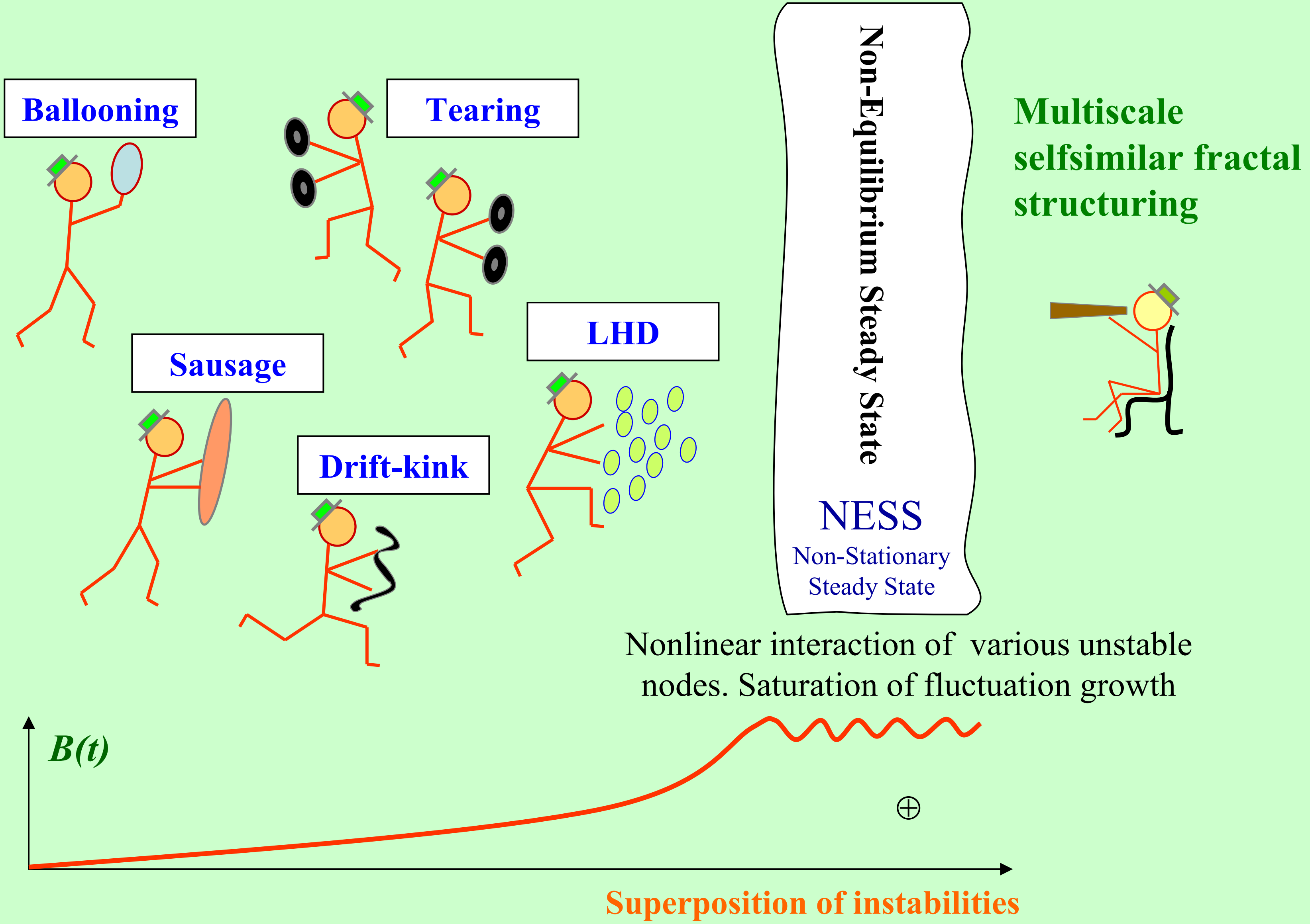


v_D/v_{ph}~1

Statistics of wave direction (120 cases)

Standing tearing modes for $k=k_x$
Propagating oblique modes $\omega=k_y v_D$

Nonlinear interaction of numerous wave modes existing in the magnetotail- Non-Equilibrium Steady State (NESS)



Multiscale selfsimilar fractal structuring

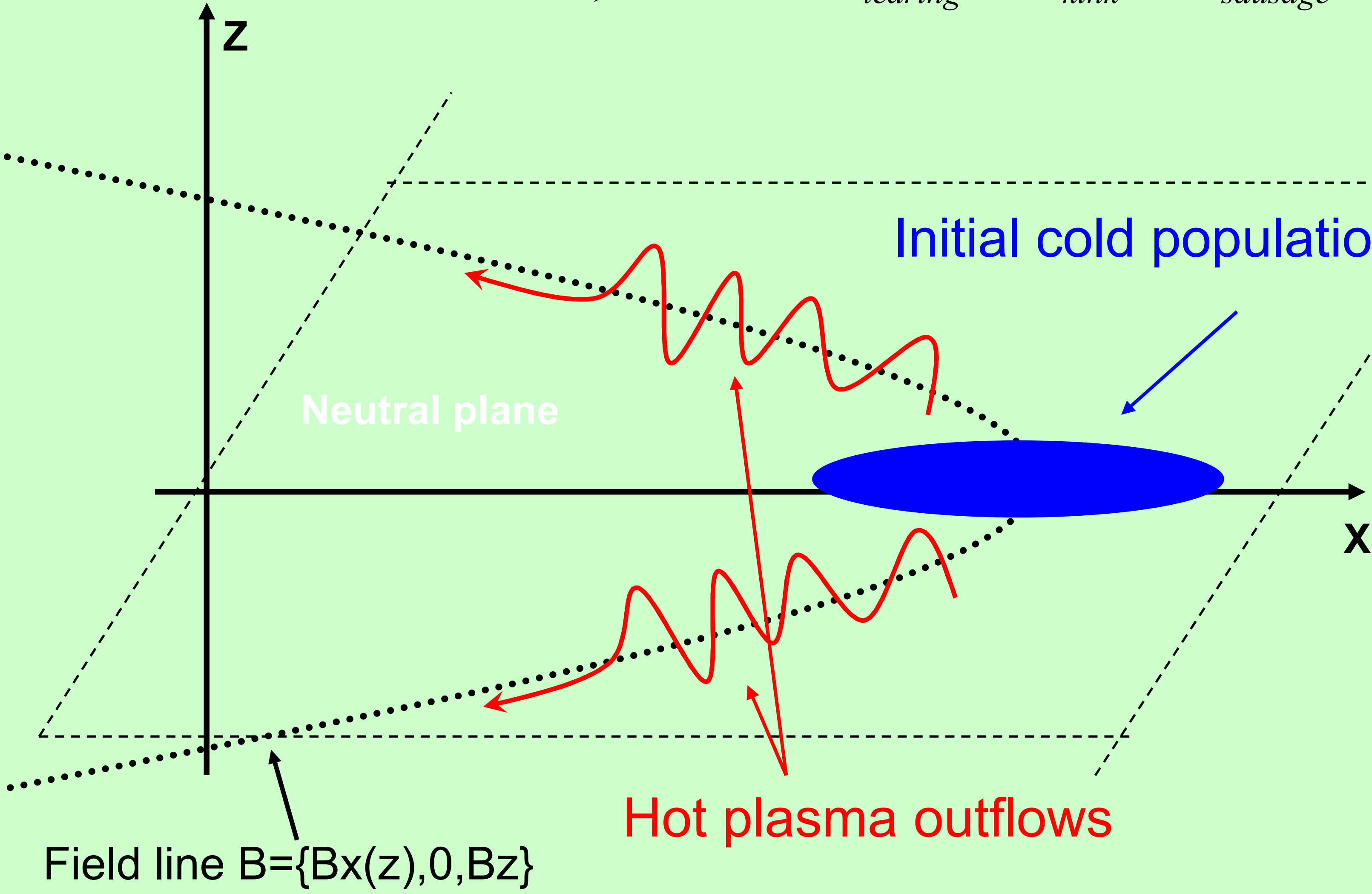
Nonlinear interaction of various unstable nodes. Saturation of fluctuation growth

Superposition of instabilities

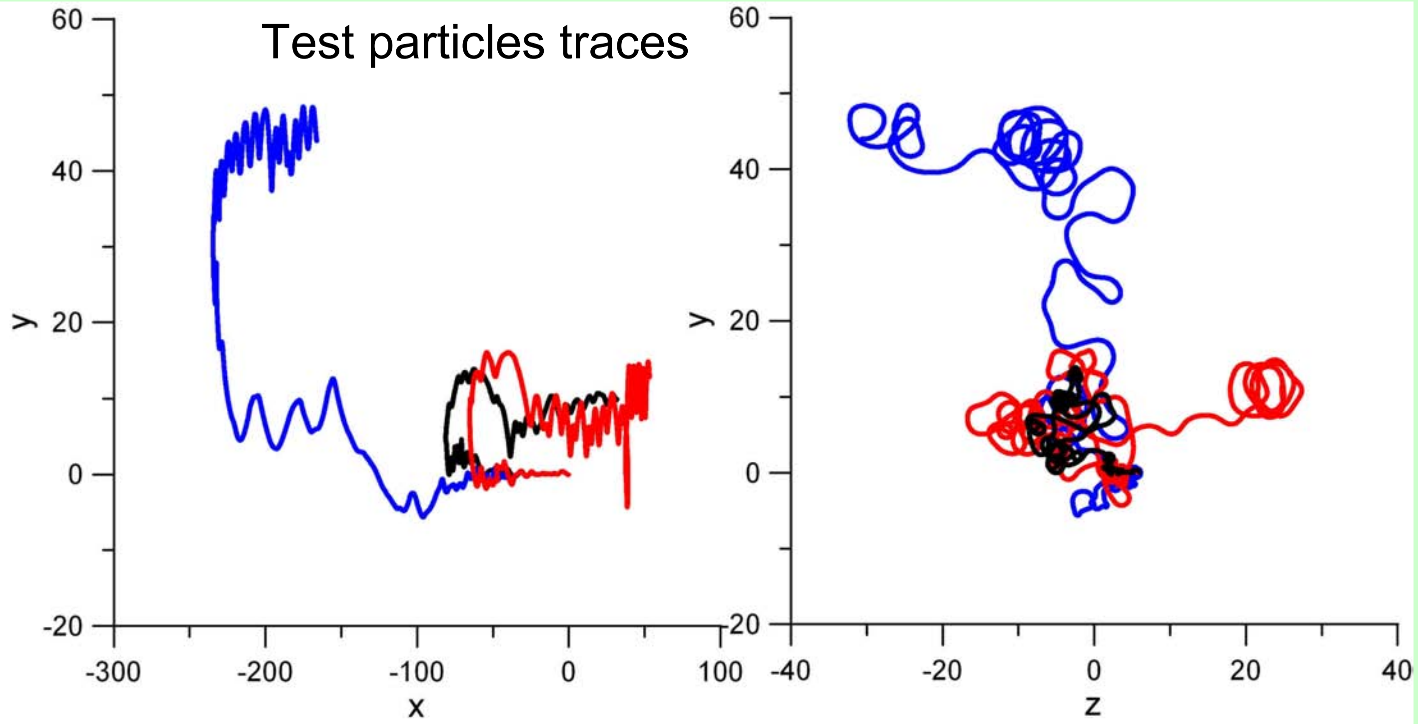
Geometry of the system

Stationary field → $\mathbf{B}_0 = B_0 \tanh\left(z/L\right)\mathbf{e}_x + B_n\mathbf{e}_z$

Turbulent field → $\delta\mathbf{B} = \mathbf{B}_{tearing} + \mathbf{B}_{kink} + \mathbf{B}_{sausage}$



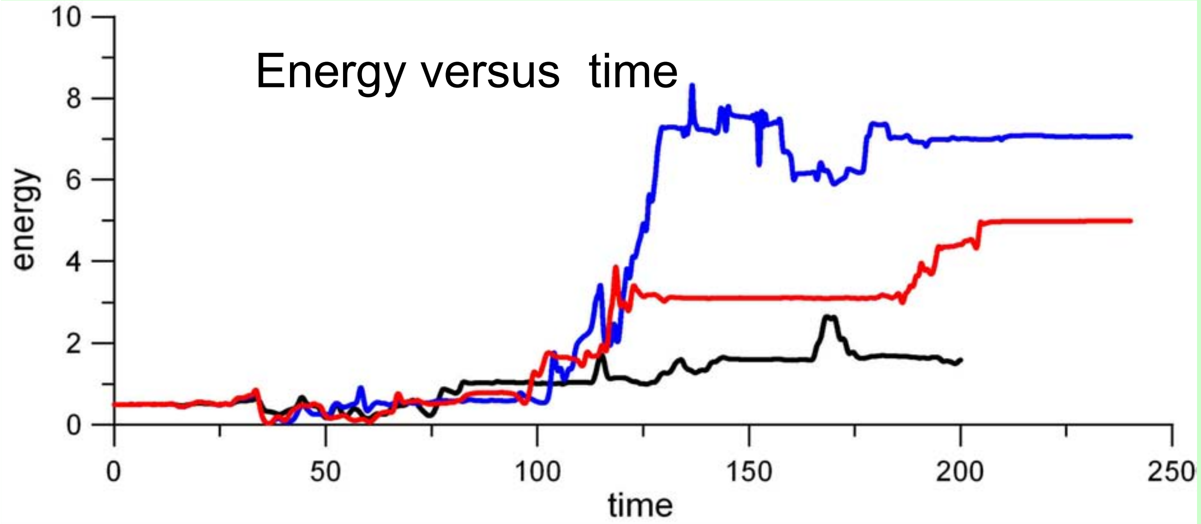
Particle dynamics

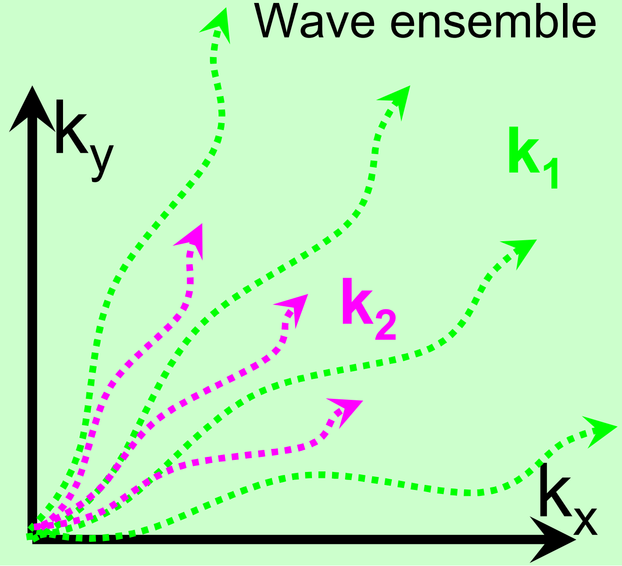

Test particles traces

$\delta\mathbf{B}/B_0=0.3$

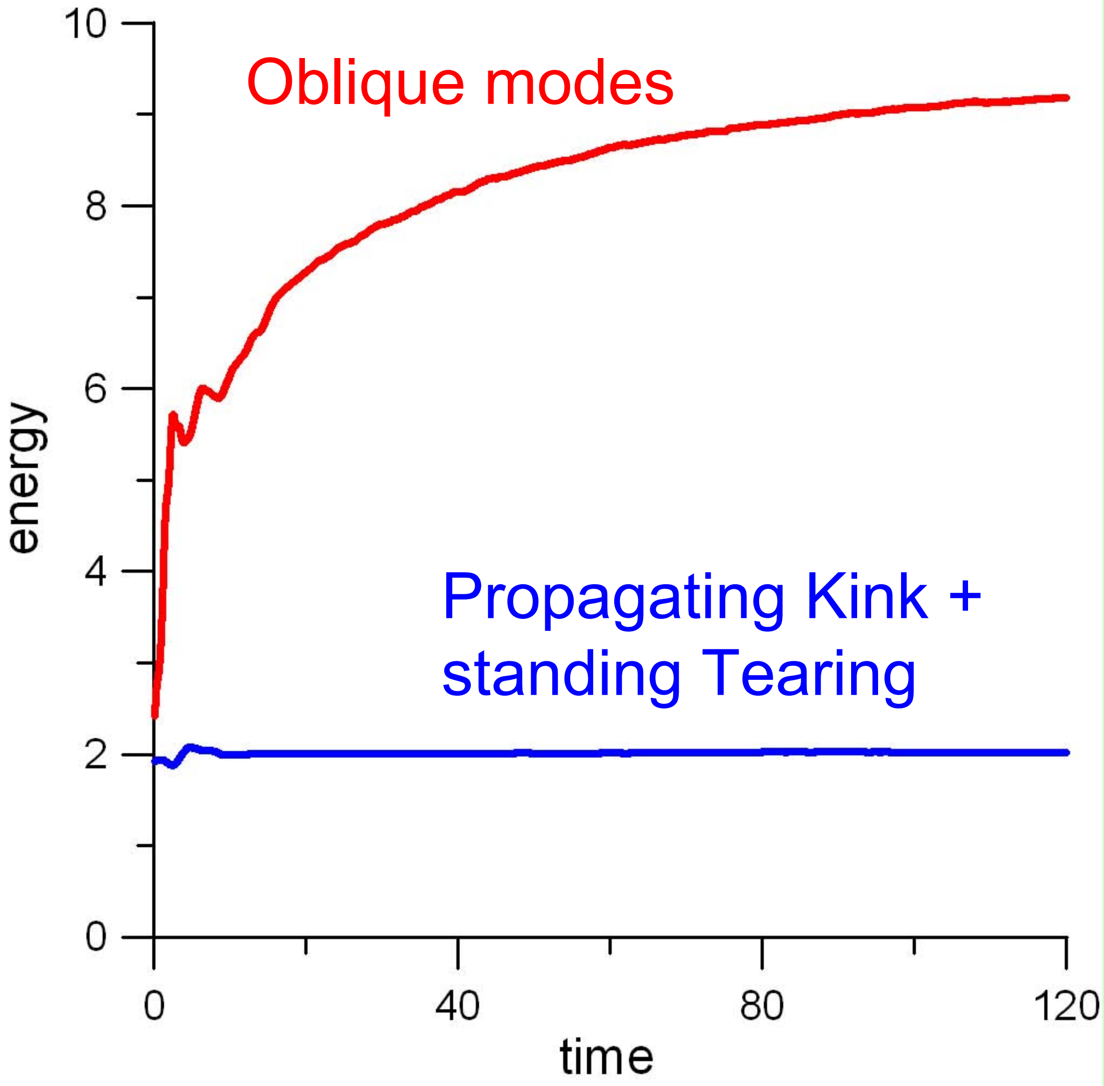
$\delta\mathbf{B}/B_0=0.5$

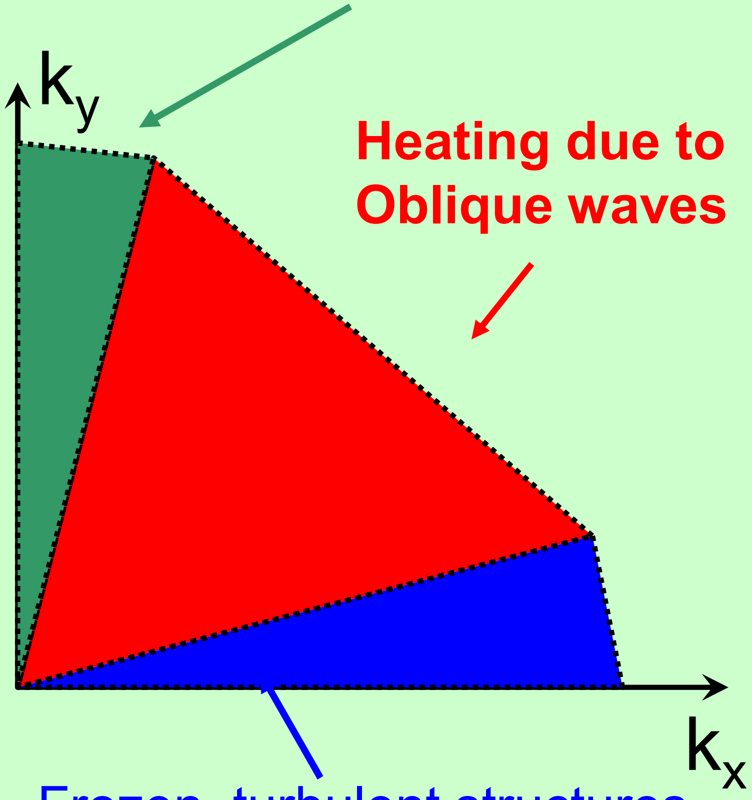
$\delta\mathbf{B}/B_0=0.7$


Energy versus time


Wave ensemble

Oblique propagation



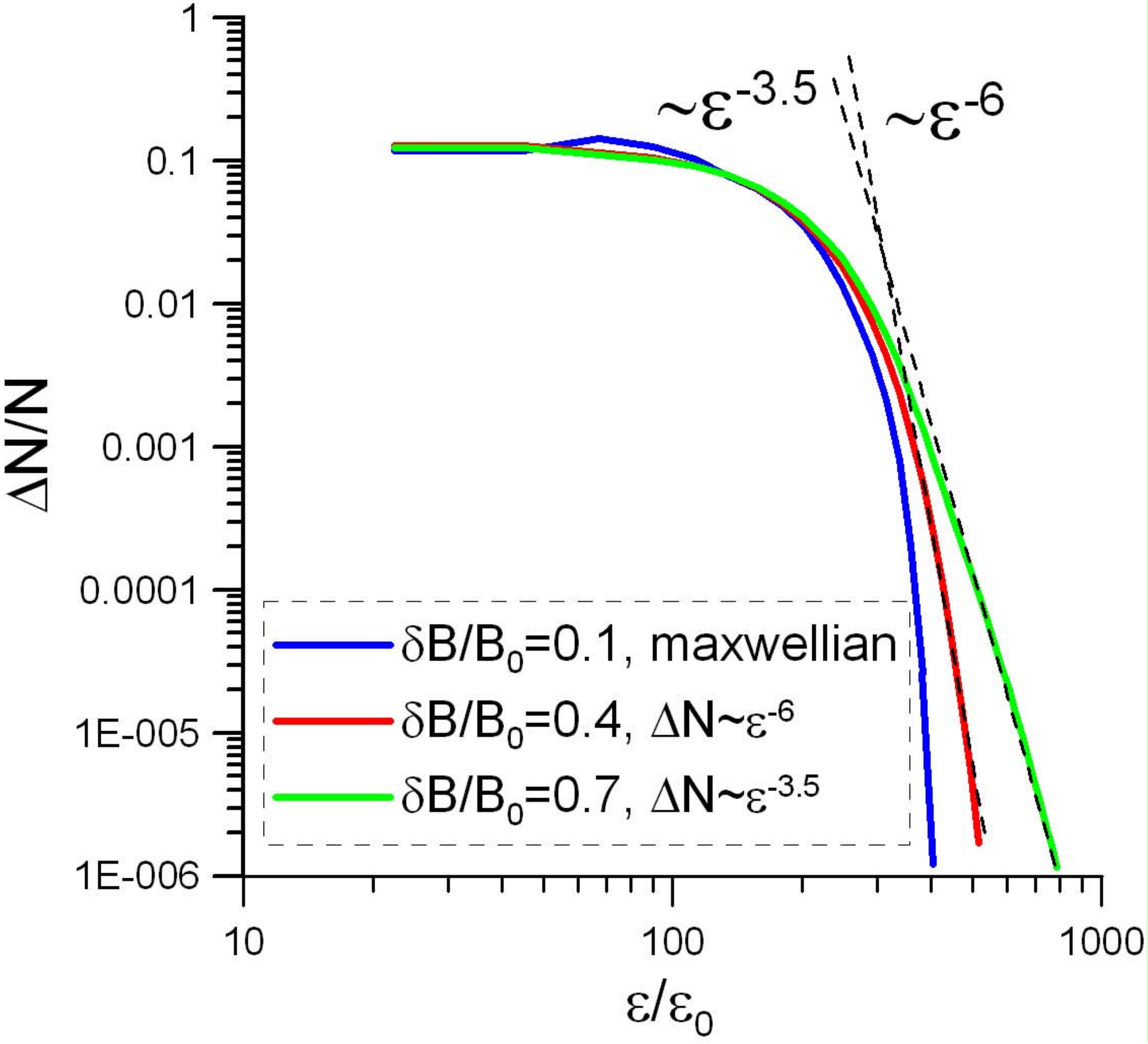


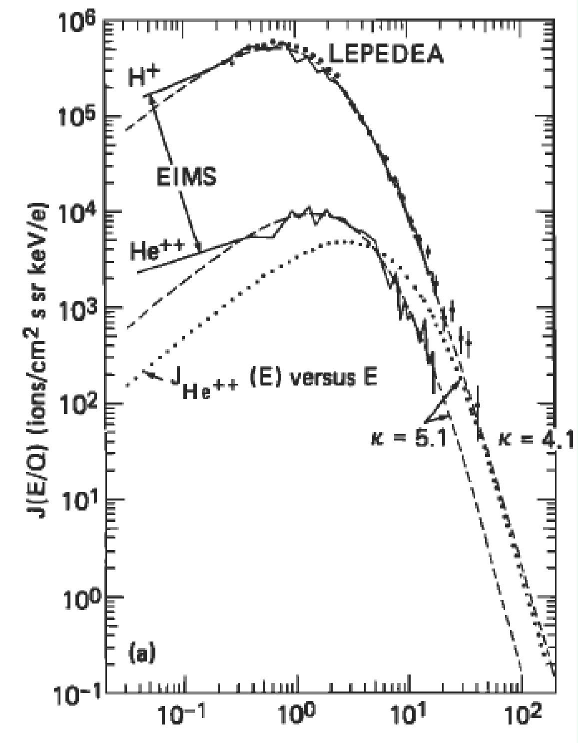
Absence of magnetic field nulls

Heating due to Oblique waves

Frozen turbulent structures

Formation of nonmaxwellian spectra

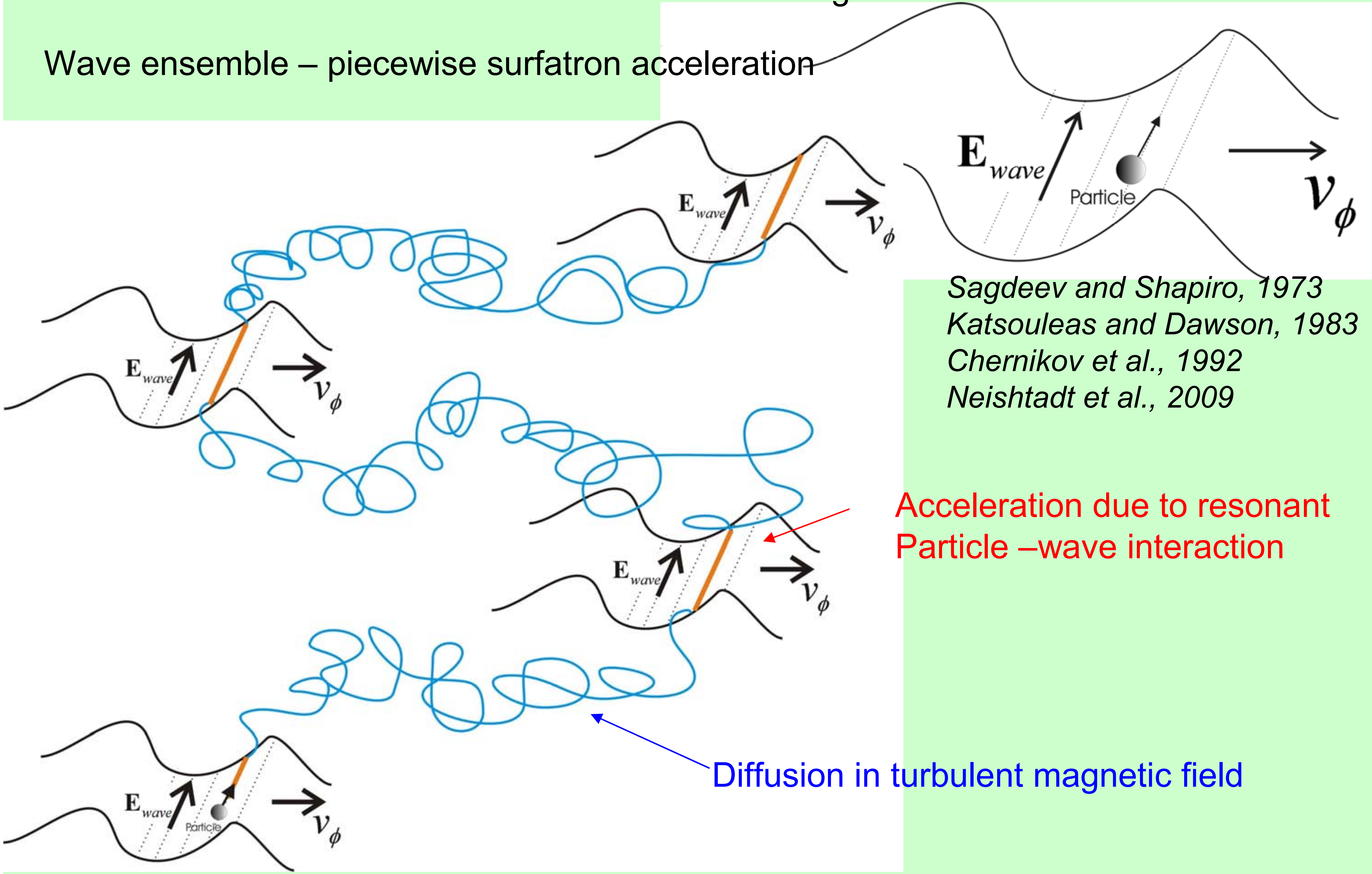




Christon 1989,JGR

Average spectra of energetic ions in the plasma sheet

Acceleration mechanism



Single wave – surfacton acceleration

Wave ensemble – piecewise surfatron acceleration

Sagdeev and Shapiro, 1973
Katsouleas and Dawson, 1983
Chernikov et al., 1992
Neishtadt et al., 2009

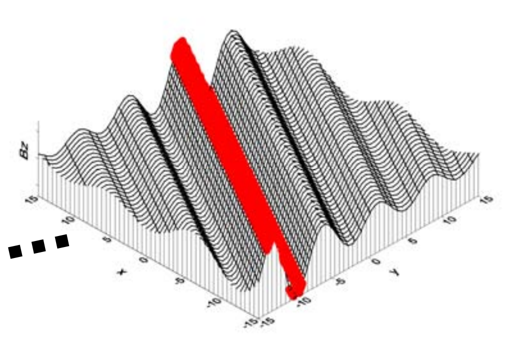
Acceleration due to resonant
Particle –wave interaction

Diffusion in turbulent magnetic field

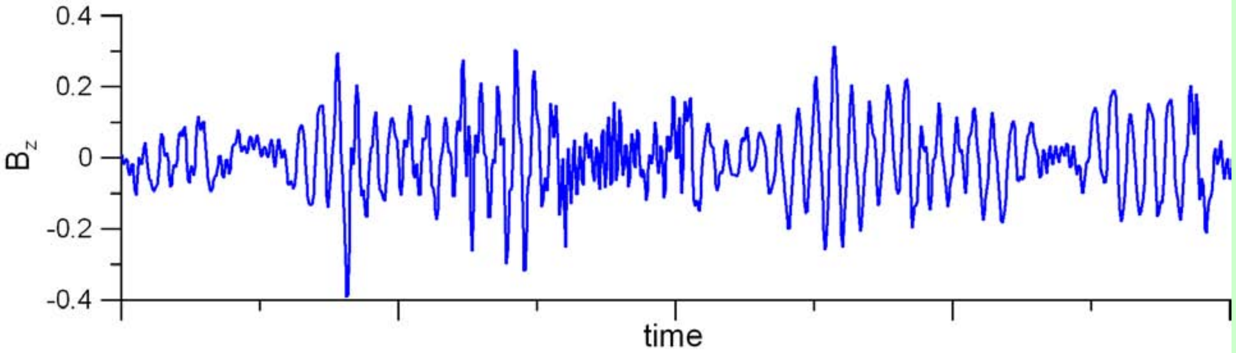
Intermittent wave structure

$$A \sim J_0\left(k_x x + k_y y - t\omega\right) \Rightarrow \delta B \sim J_1$$

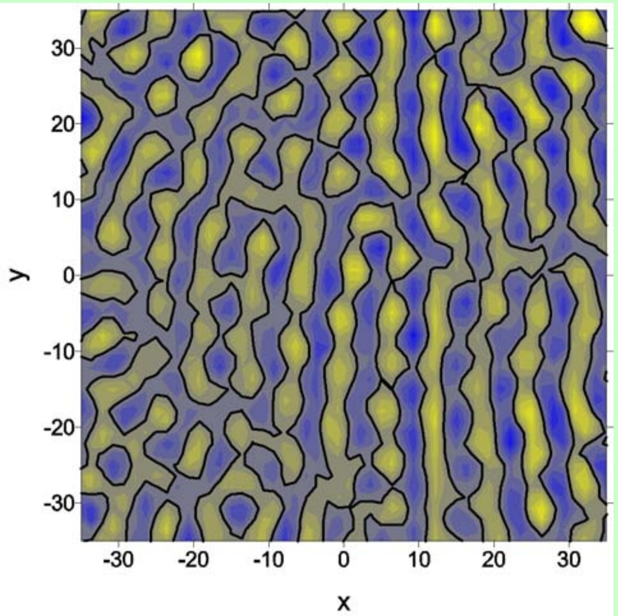
elementary wave mode



Ensemble of propagating NL structures



B_z field at z=0



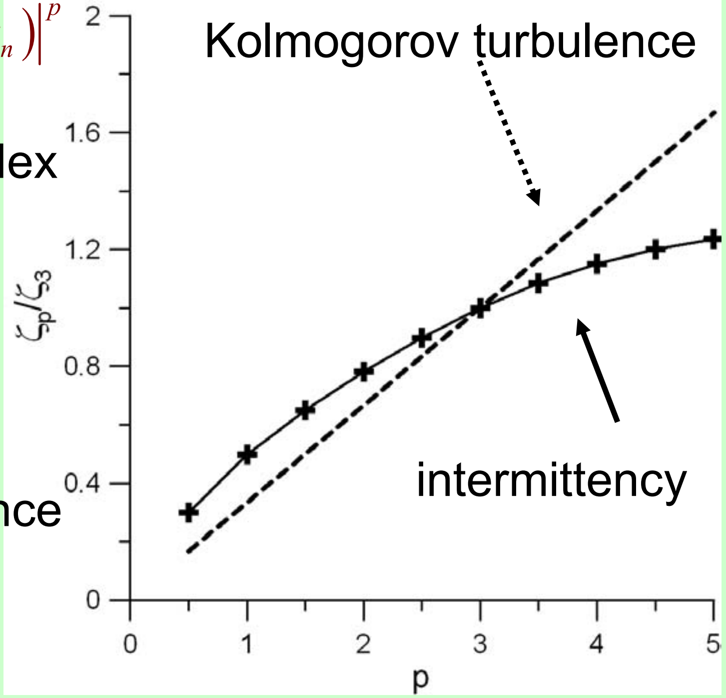
$$S_p\left(\Delta\right) = \sum_n \left|B\left(x_n + \Delta\right) - B\left(x_n\right)\right|^p$$

Structure function index

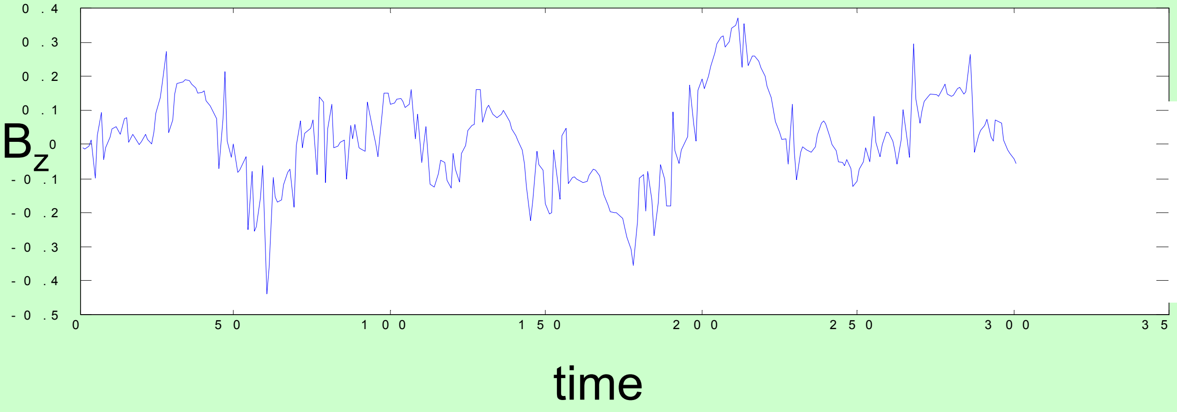
$$\zeta_p : \; S_p\left(\Delta\right) \sim \Delta^{\zeta_p}$$

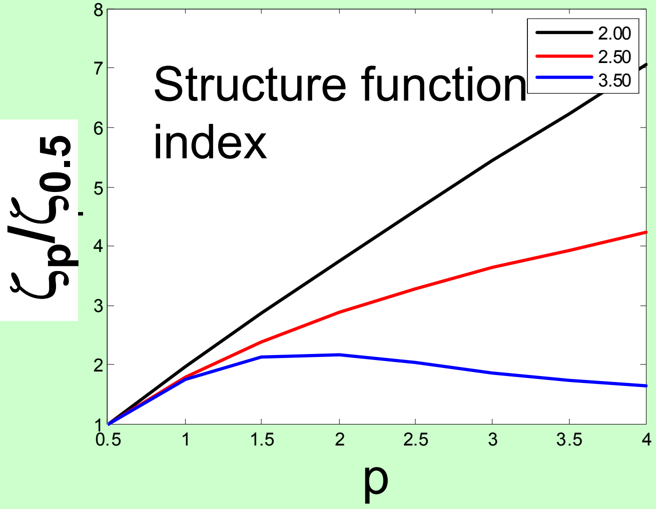
Kolmogorov turbulence

$$\zeta_p = p/3$$

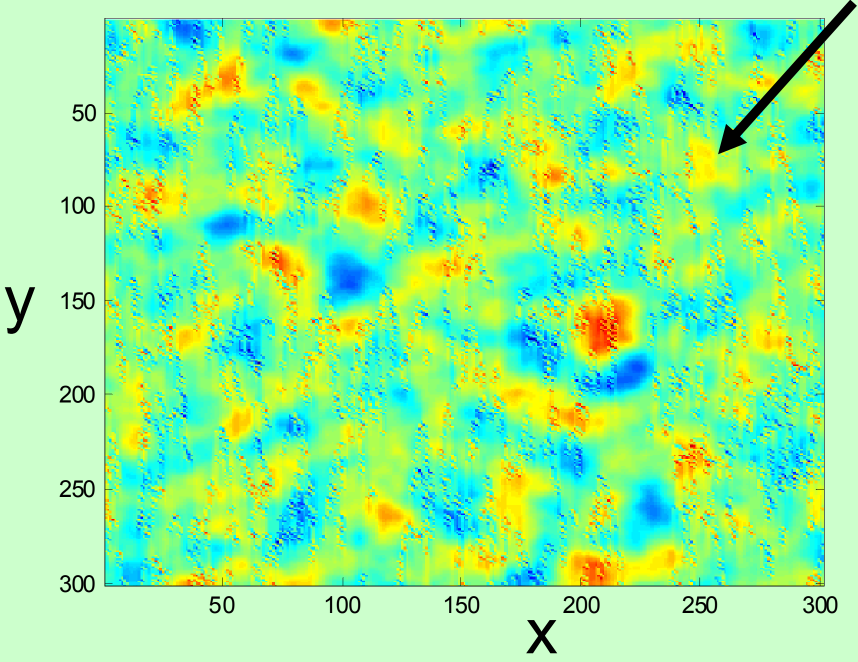


Intermittency

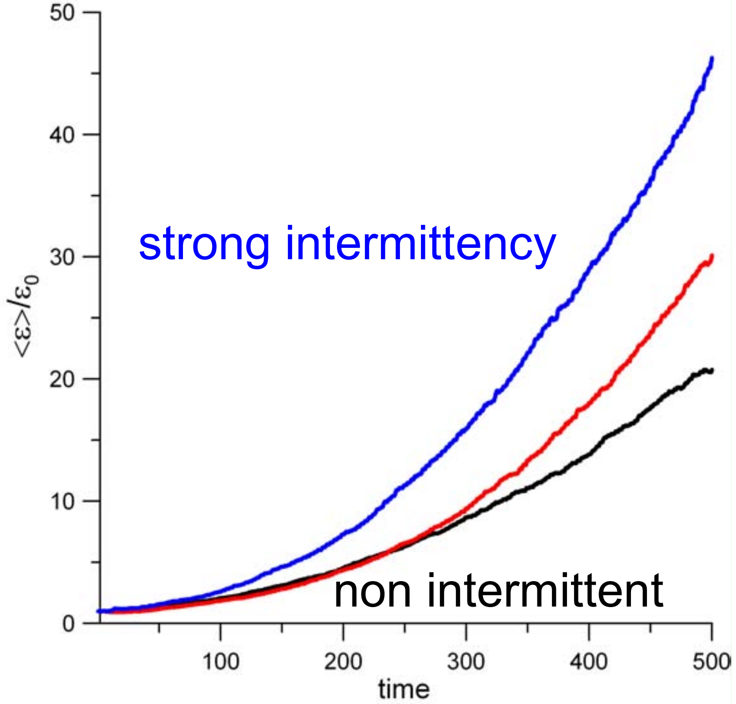




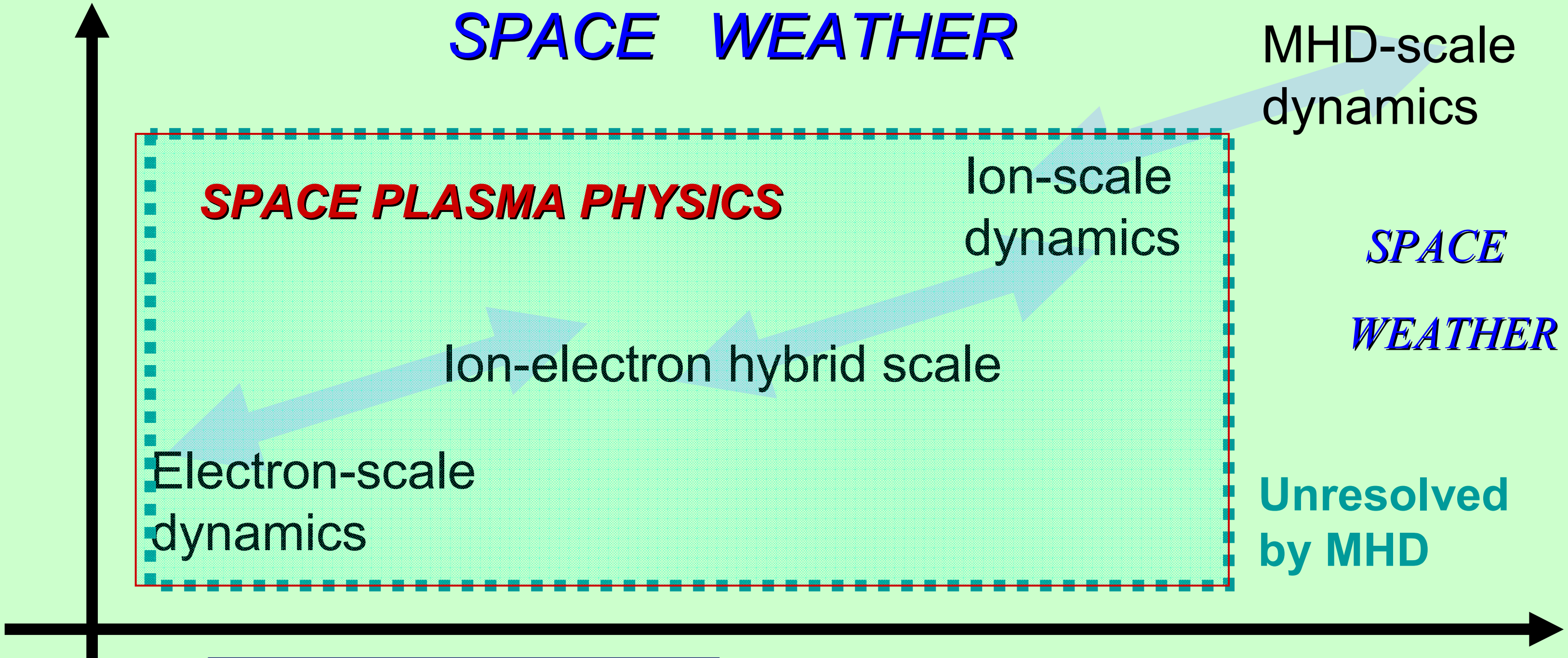
B_z field at $z = 0$



Nonlinear structures can be localized and form intermittent magnetic field affecting particle acceleration



Cross-Scale Coupling



Slow in time

SPACE WEATHER

MHD-scale
dynamics

SPACE PLASMA PHYSICS

Ion-scale
dynamics

SPACE

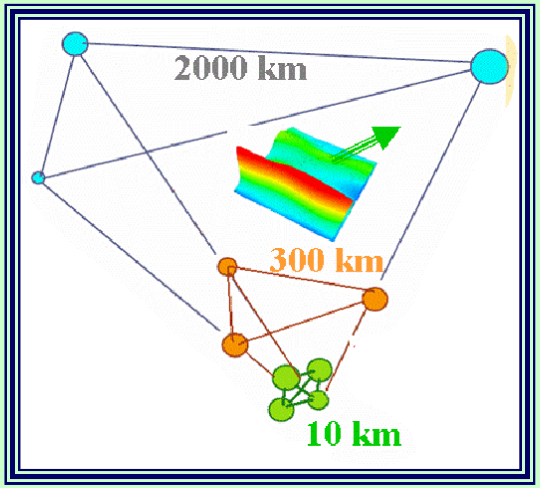
WEATHER

Ion-electron hybrid scale

Electron-scale
dynamics

**Unresolved
by MHD**

Large in space



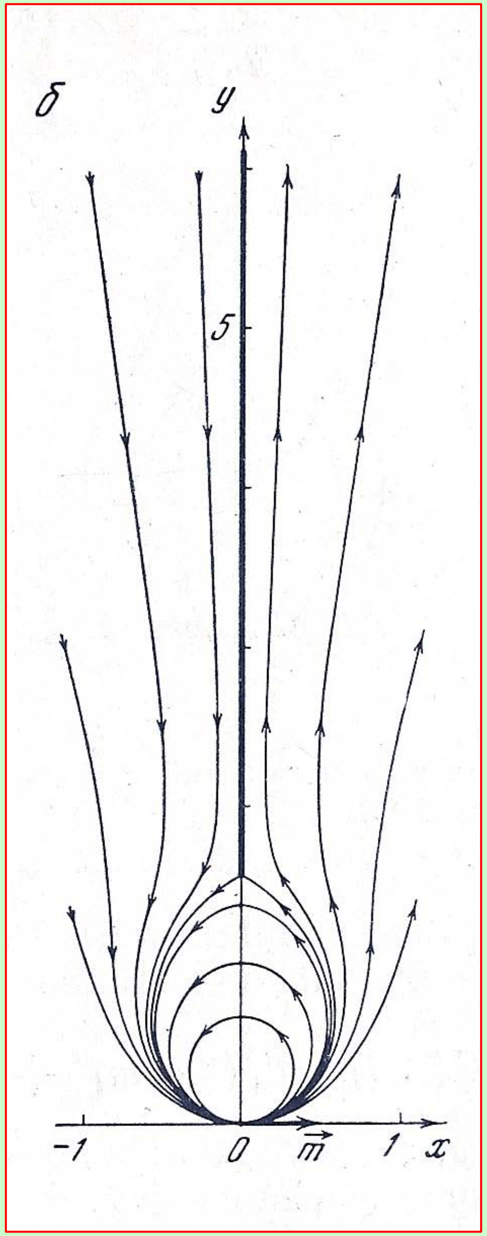
**MULTISCALE SPACECRAFT SYSTEM
JAXA – ESA - RSA**

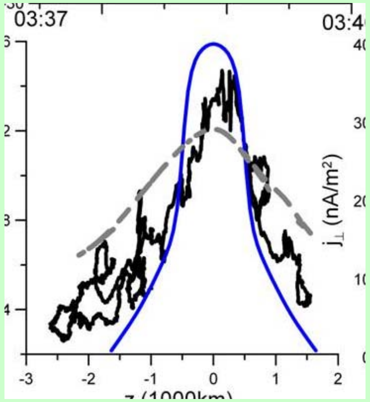
Conclusions:

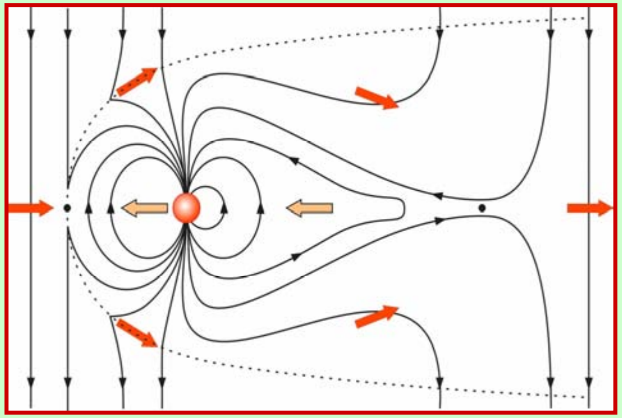
- Configurations with magnetic field reversals (current sheets) are intrinsically metastable.
- For certain (quite narrow narrow region of parameters L, Bn) TCS can become unstable to tearing perturbation (contrary to the Harris one), which drives the spontaneous reconnection
- CS wave modes are effective particle accelerators by “piecewise surfatron” mechanism
- Tearing mode ingredient is necessary for particle acceleration. Importance of oblique modes

•More data (CrossScale+Scope+ROI) are needed

• Electron scales are still not resolved







THANKS FOR YOUR ATTENTION !