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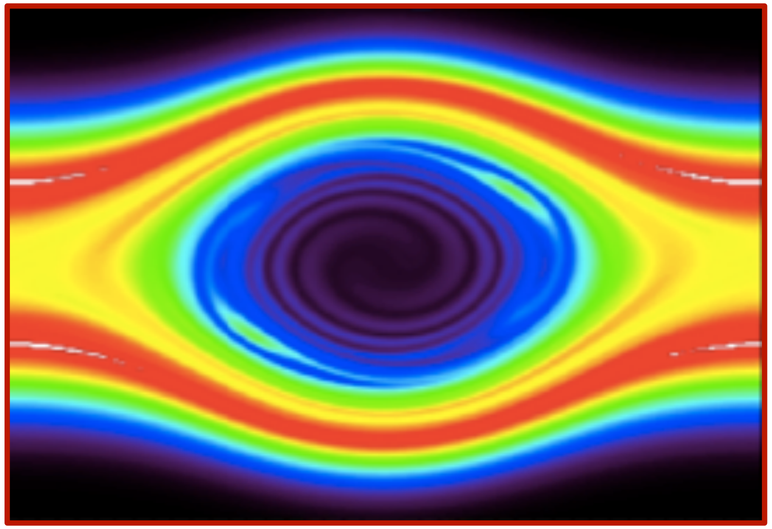
Processus fondamentaux dans les plasmas de l'environnement de la Terre et besoin d'un modèle incluant les effets cinétiques



PhD Doctoral School

A plasma is a

collection of discrete charged particles

globally neutral,

behaving as a collective system,

dominated by electromagnetic forces

Collective response of the plasma at the

PLASMA FREQUENCY

$$\omega_{pe} = \sqrt{4\pi n e^2 / m_e}$$

Systems described by plasma physics

Astrophysics; space plasmas

Laboratory plasmas (fusion, ...)

Laser plasmas interaction - new physics!:

(strongly non linear, relativistic effects, ...)

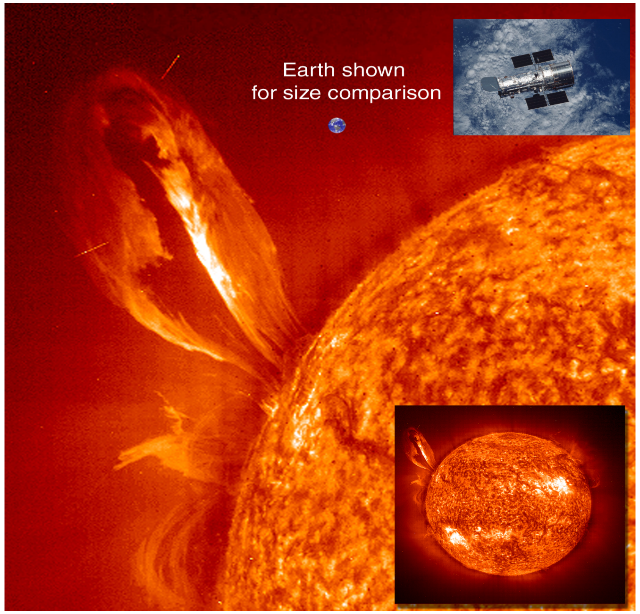
Furthermore: the study of the nonlinear electrostatic and electromagnetic collisionless plasma dynamics provides a paradigm for the *analysis of dynamical systems*.

Natural and laboratory plasmas

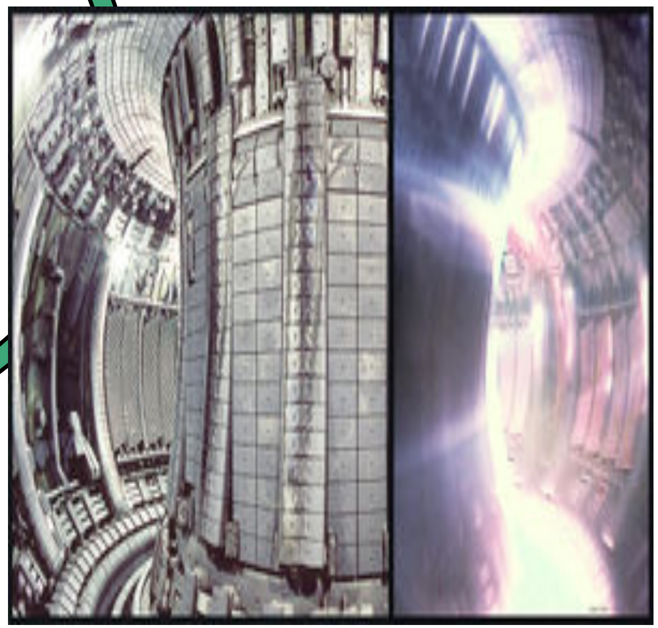
Complex and fascinating systems

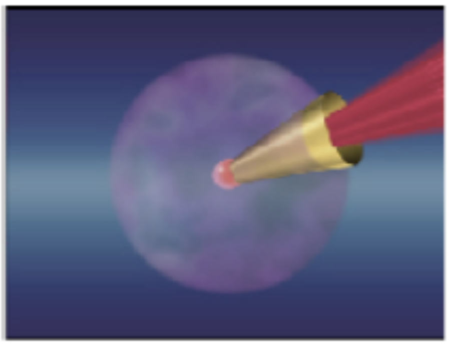
For many observed phenomenon

same physical mechanism



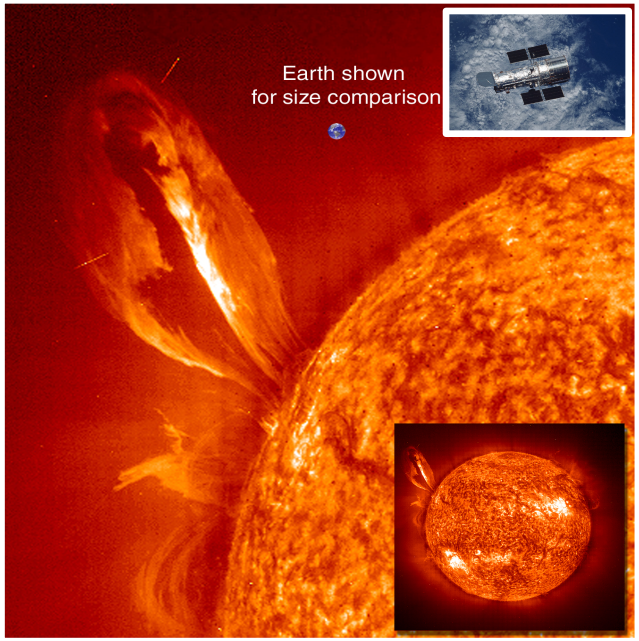
Differences and Similarities

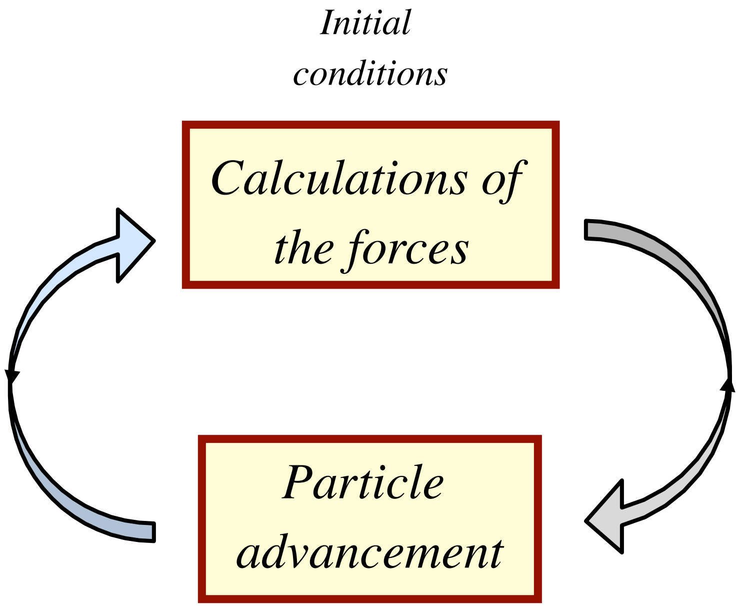




Problem: how to model a plasma ?

Too many particles for a N-body description even for modern super-computing systems



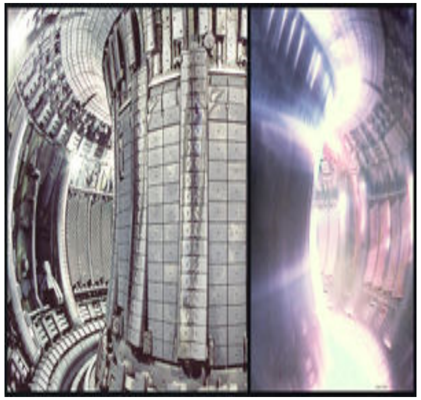


Computationally too heavy !

NEEDS FOR A CONTINUOUS DESCRIPTION

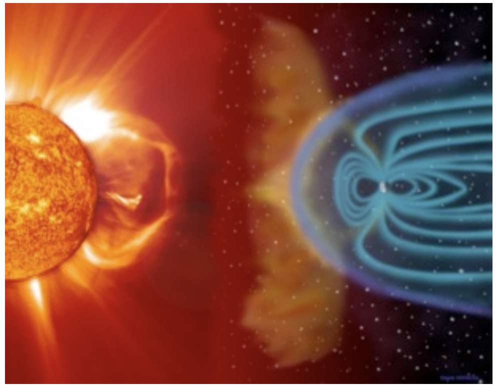
High temperature, tenuous plasmas usually found in space and in the laboratory can be considered as collisionless

Typically, the diffusive time scale is many orders of magnitude larger than any dynamical or kinetic time scale:



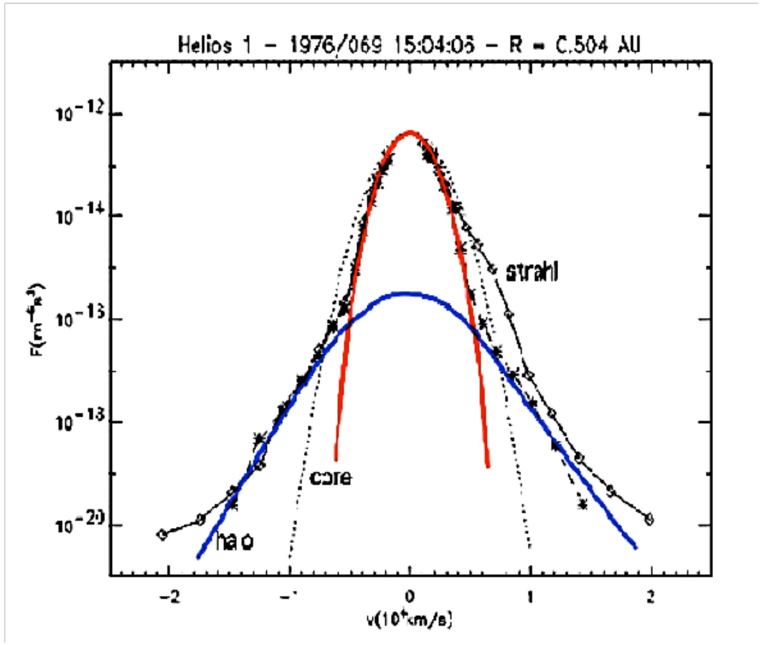
Magnetic Reynolds number

$$10^6 \leq R = \frac{\tau_{diff}}{\tau_{dyn}} \leq 10^{12}$$



non-Maxwellian distribution functions are often observed.

An example, the Solar Wind: no time to reach thermodynamical equilibrium: Temperature means "average energy"



Non-Maxwellian particle distribution function (electrons)

Neutral Gaz: $\nu_{coll} \gg \omega$

Plasma: $\omega \gg \nu_{coll}$

Problems for plasma thermodynamics!

But we can do something….

Free charges with kinetic (thermal) energy much larger than the typical potential energy due to its nearest neighbor (ex. e^- and p^+)

$$E_k >> \Phi \quad or \quad n_0^{1/3} e^2 << m v_{th}^2$$

where $n_0^{1/3}$ is the mean particle distance

We need:

$$\Lambda_D = n \lambda_D^3 >> 1$$

$\lambda_D = \sqrt{T / 4\pi n e^2}$

Very large number of particles in a Debye sphere

where

λ_D = Debye length,

Λ_D = number of particles in a Debye sphere

In other words, particles must be

"quasi non-correlated"

free charges with kinetic (thermal) energy much larger than the potential energy due to its nearest neighbor: $E_k >> V$

$r_0 = e^2 / T$ [distance of min. approach ($E_k \sim \Phi_C$)]

$r_n = n^{-1/3}$ [mean particle distance]

$\lambda_D = \sqrt{T / 4\pi n e^2}$ [Debye length]

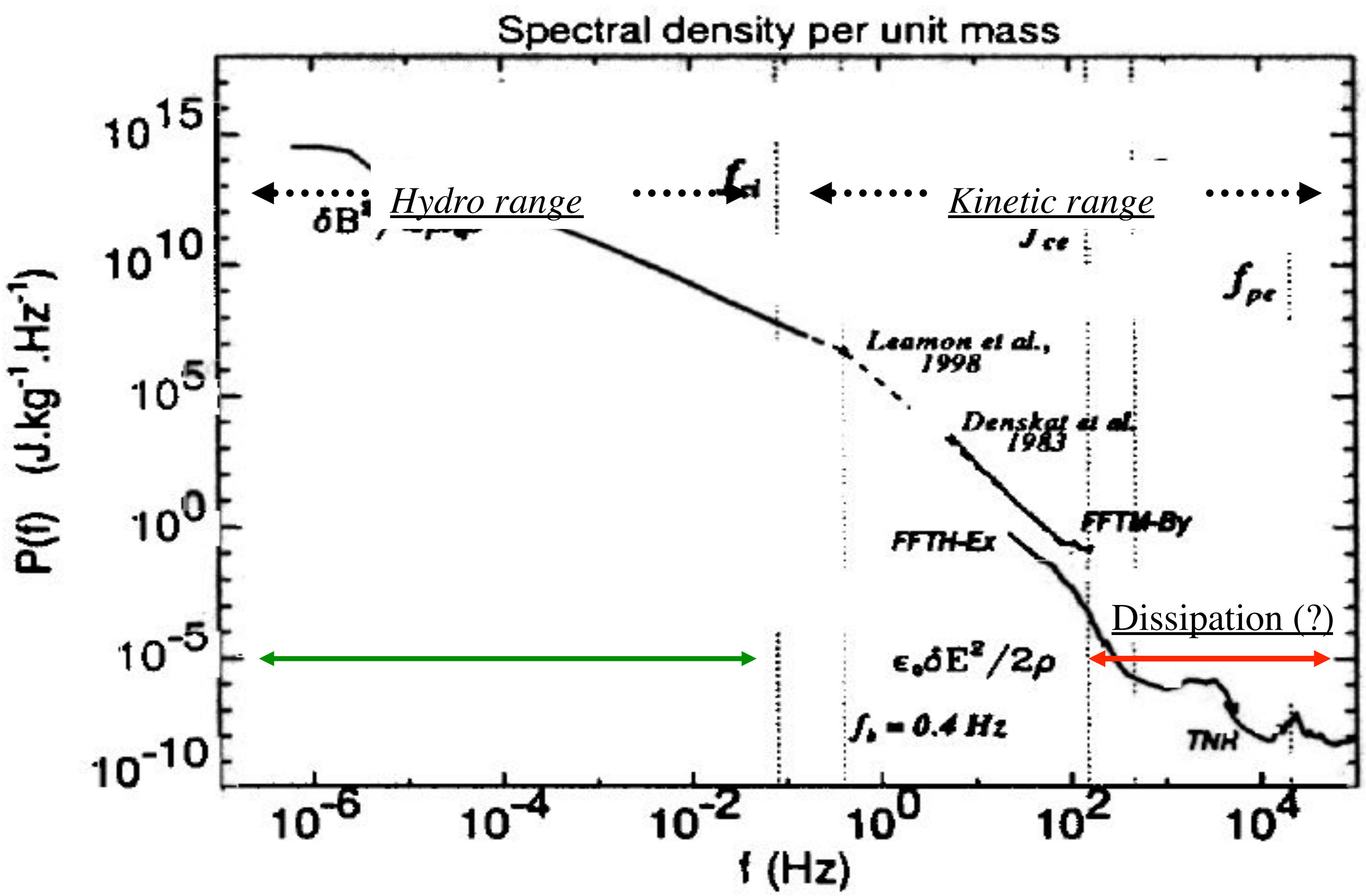
$d_{e/i} = c / \omega_{e/i}$ [e/i inertial length]

L_{HD} [hydro scale]

l_{mfp} [mean free path]

$g = 1/n \lambda_D^3$ plasma parameter [$g \sim \nu_c / \omega_{pe}$]

Many frequencies and scale lengths at play self-consistently coupled



*The **statistical description** of a N particles plasma is based on the probability densities F giving the probability of finding simultaneously the particles at locations (x_1, x_2, ..., x_N) in phase space [Gibbs distribution at equilibrium].*

The probability F_1 of finding particle 1 at location x_1 is given by integrating the d.f. allover the particles except 1. In general, the probability F_s to have simultaneously particle 1 in x_1,., particle s in x_s , is given by the integral over the other N-s particles

The probability density contains the effects of the interactions among particles

When the interaction potential can be neglected, the particles can be considered as ***statistically independent***:

$$\mathbf{F}_2(\mathbf{x}_1 , \mathbf{x}_2) = \mathbf{F}_1(\mathbf{x}_1)\, \mathbf{F}_1 (\mathbf{x}_2)$$

When instead the interaction potential among particles is present, the probability densities can be written trough a cluster expansion:

$$\mathbf{F}_2(\mathbf{x}_1 , \mathbf{x}_2) = \mathbf{F}_1(\mathbf{x}_1)\, \mathbf{F}_1 (\mathbf{x}_2)\, [1 + \mathbf{P}_{12} (\mathbf{x}_1 , \mathbf{x}_2)]$$

and so on for $\mathbf{F}_i$, $\mathbf{i} > 2$

$\mathbf{P}_{12}$ **:** *two particle correlation function*

In general, single particle interactions are assumed as negligible

$$\mathbf{P}_{12} \ll 1 \text{ (and so on)}$$

Neglecting single particle interactions, one make use of the ***probability*** $f^{(1)}(x_1)$ *of finding particle 1 at location* $\mathbf{x}_1$ *in phase space* - ***mean field theory***

In summary, a plasma is described in a reduced way in terms of the

$$f^{(1)}(\mathbf{x}_1, \mathbf{v}_1)\, \mathrm{d}\mathbf{x}_1 \mathrm{d}\mathbf{v}_1$$

CONTINUUM approach

One particle distribution function

Moments of the distribution function

Inter-particle forces can be dived into:

1. mean force ("many" distant particles)

2. Force due to nearest neighbor particles

Forces that do not depend on the exact location of all particles have the appearance of external forces.

Plasma collisionless dynamics is described by the

In a low density system the mean force due to many distant particles far exceeds the inter-particle forces:

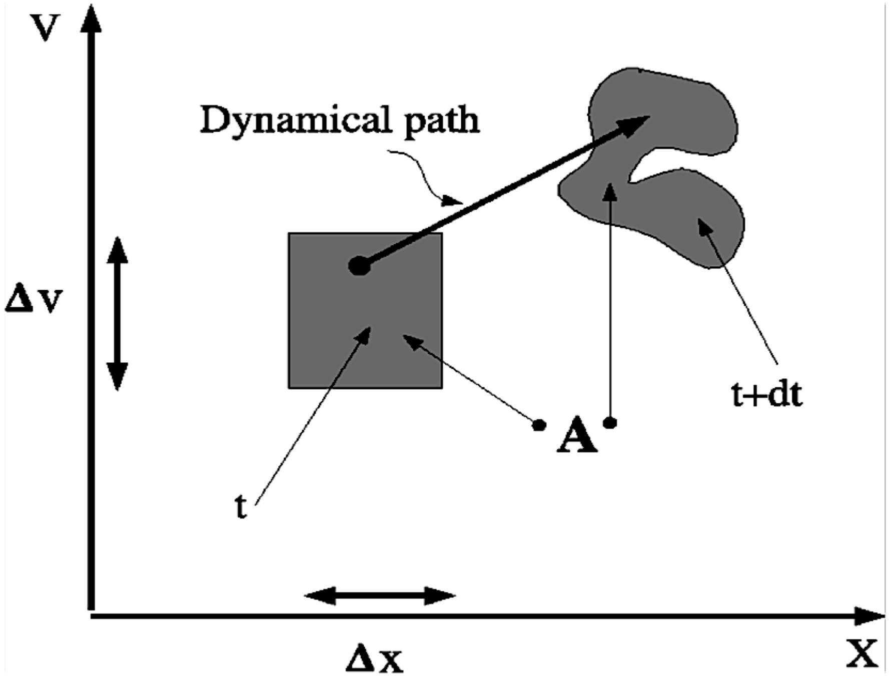
$a = a_{ext} + < a_{int} > \simeq a_{ext}$

Vlasov equation

$$\frac{\partial f_a}{\partial t} + \mathbf{v} \cdot \frac{\partial f_a}{\partial \mathbf{x}} + \frac{q_a}{m_a}\left(\mathbf{E} + \frac{\mathbf{v} \times \mathbf{B}}{c}\right) \cdot \frac{\partial f_a}{\partial \mathbf{v}} = 0$$

(neglecting collisions.)

The Vlasov equation is basically an advection equation in phase space:



Liouville's theorem:
The phase space volume can be deformed but its density is not changed during the dynamical evolution of the plasma.

It can be considered as a "transport" equation in phase space.

Invariants of the Vlasov equation:

A fundamental feature is that the d.f. is subjected to strong topological constraints, provided by the existence of invariants

$$\frac{\mathrm{d}}{\mathrm{dt}} \int \mathrm{d}\mathbf{x}\,\mathrm{d}\mathbf{v}\ \mathrm{H}(f_{\mathrm{a}}) = 0$$ *for any function H*

This reduces the (infinite) number degrees of freedom of the system: *the d.f. can be transported and roll up in a complex way* in phase space, but *different d.f. iso-lines can never be broken and reconnect*.

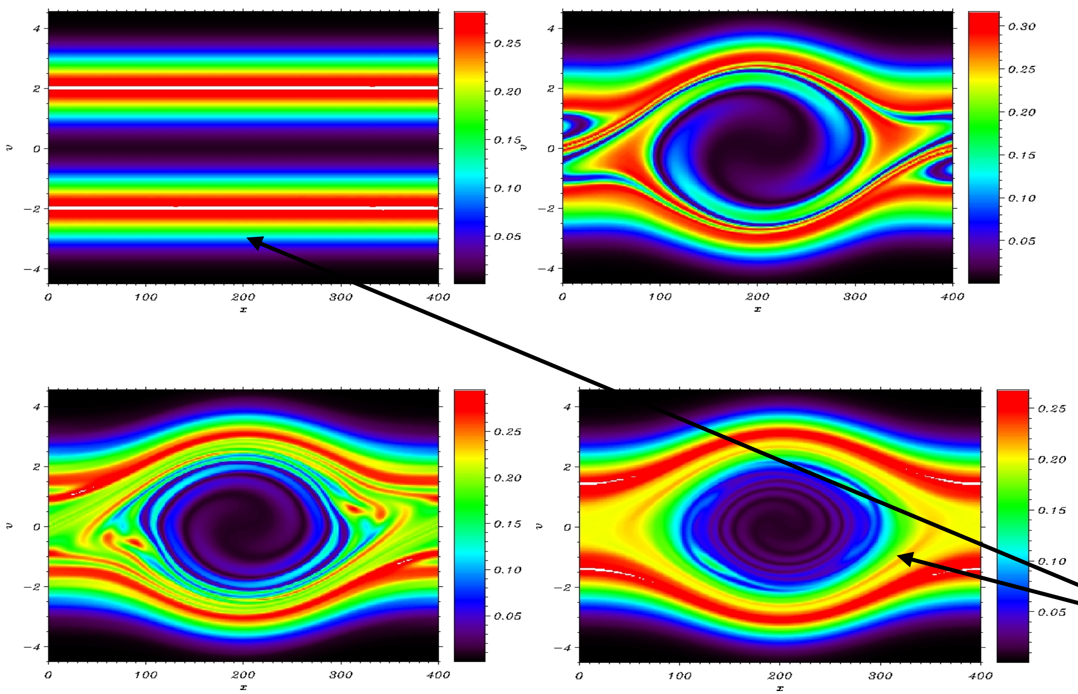
Transitions from "*unconnected states*" in phase space are forbidden, as for example from a laminar type state (free-streaming) to a vortex type state (particle trapping).

Vlasov: fundamental **physical model** for many **space and laboratory plasmas.** In particular, for the interpretation of **coherent e.s. structures observed in plasmas.**

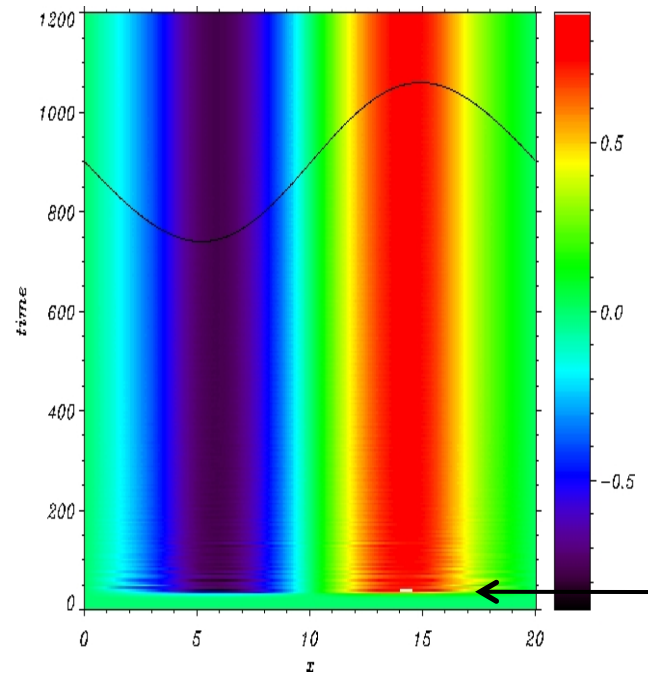
An example: *dipolar electric field associated to phase space vortices* generated by the two stream instability

The *(dipolar) electric field.* For $t > 50$ it becomes $\sim$ *constant in time*

The **d.f.** in the (x, v) phase space, t=0, 50, 100, 250



t



x

Transition forbidden by Vlasov !

From Vlasov to a fluid approach

Kinetic
3D-3V

Fluid
3D

Macroscopic variables of a plasma

The macroscopically observable quantities are found from the velocity moments of the *d.f.* :

Number of particles, Current density:

$$n_a(\mathbf{x}, t) = \int f_a(\mathbf{x}, \mathbf{v}, t)\, d\mathbf{v}$$

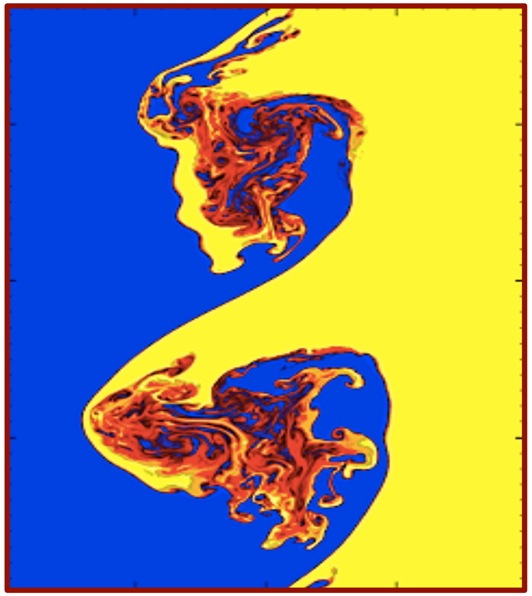
$$\mathbf{J}_a(\mathbf{x}, t) = q_a n_a(\mathbf{x}, t)\mathbf{V}_a(\mathbf{x}, t) = q_a \int \mathbf{v} f_a(\mathbf{x}, \mathbf{v}, t)\, d\mathbf{v}$$

Pressure tensor, Scalar pressure:

$$P_a(\mathbf{x}, t) = m_a \int (\mathbf{v} - \mathbf{V}_a)(\mathbf{v} - \mathbf{V}_a) f_a(\mathbf{x}, \mathbf{v}, t)\, d\mathbf{v}$$

$$p_a = \frac{1}{3}(p_{xx} + p_{yy} + p_{zz}) = n_a T_a$$

A space plasma research problem: Nonlinear dynamics at the interface between the Solar wind and the Earth's Magnetosphere

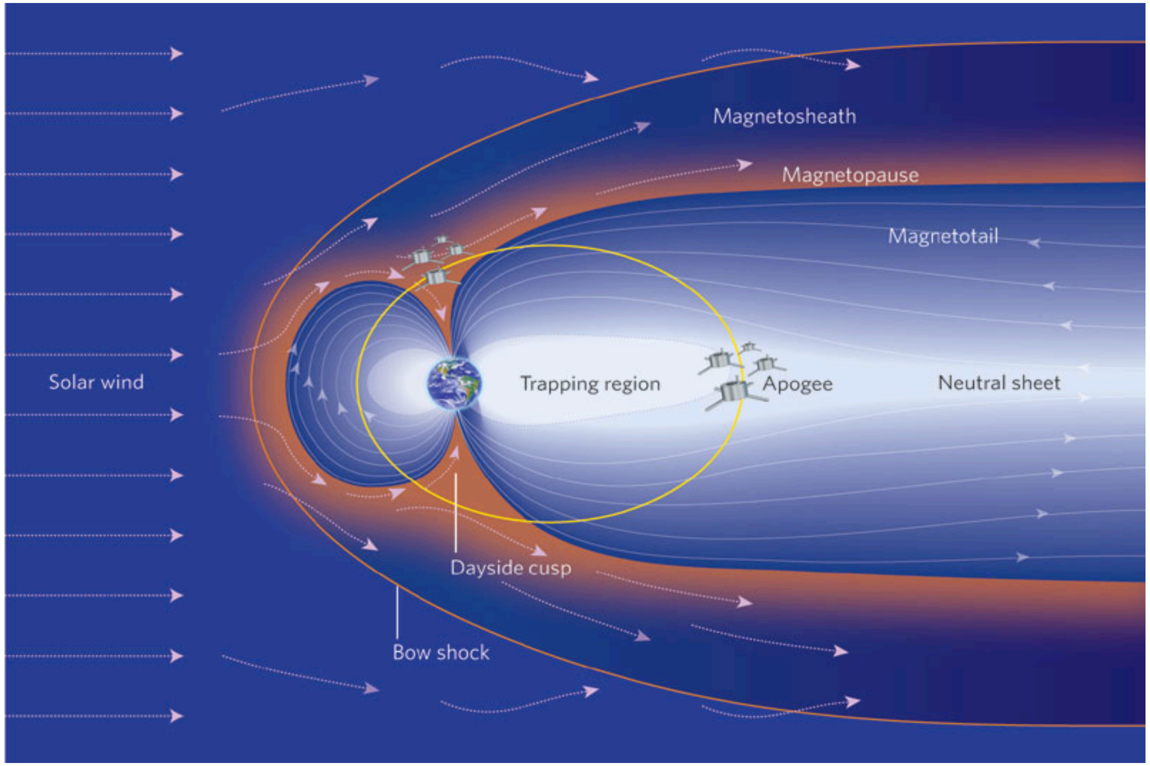


Funded by the European Commission's FP7 programme, grant agreement SWIFF (n. 26334)

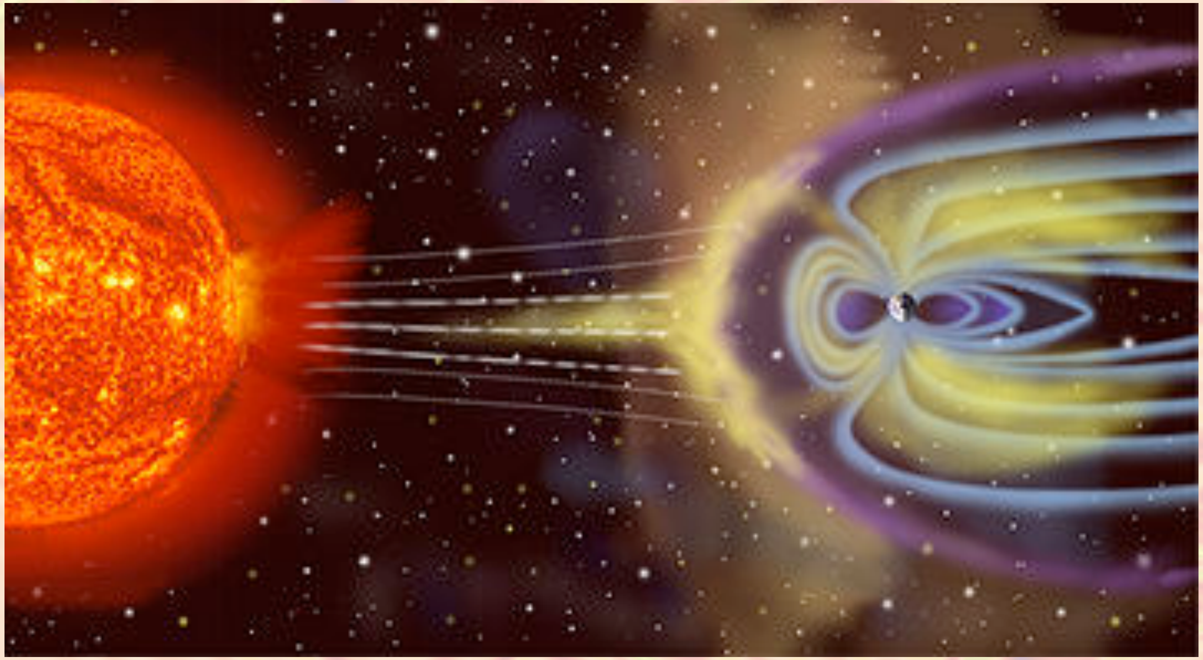
Part of the ***Space-Weather Integrated Forecasting Framework*** *programme*

The physical system: Solar Wind - Magnetosphere

The connection between the solar wind and the Earth's magnetosphere is mediated through the magnetosheath and magnetopause boundaries.



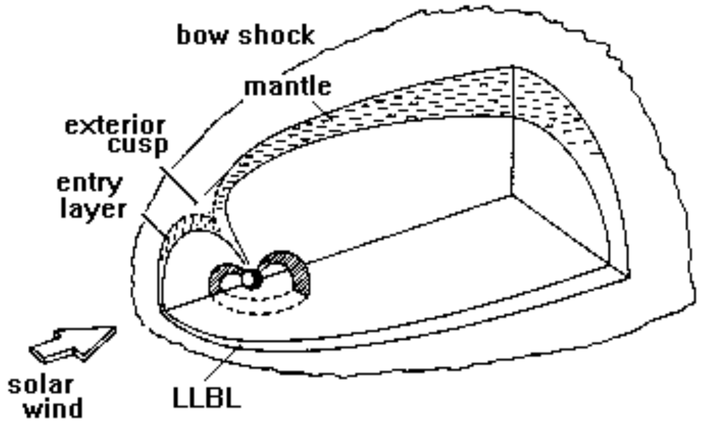
The solar wind-magnetosphere coupling strongly depends on solar wind properties and their variability, as the density and velocity value or the ***Interplanetary Magnetic Field orientation*** *with respect to the Earth's dipole.*



The **great interest in the analysis of the processes** at play is:

i) Importance in the shaping and dynamics of the system

ii) A wealth of in-situ diagnostics of improving quality (electromagnetic profiles and particle distribution functions)



Questions:

- *how can we represent the 3D large scale field ?*
- *Is it a true equilibrium in the MHD sense?*
- *Can satellite data help us ?*

At low latitude, when the IMF is mostly southward: *magnetic reconnection dominates the transport*

If reconnection at low latitude would be the only relevant phenomena for mixing, the northward periods (IMF and geomagnetic field parallel) should be relatively quiet and the flank regions should be dominated by the tenuous and hot plasma of the Earth plasma sheet

On the contrary, during **northward periods** the near-Earth plasma sheet becomes denser and colder near the flanks suggesting an **enhancement of the plasma transport** across the magnetopause

[Terasawa et al., Geophys. Res. Lett. 24, 935, 1997]

Two *main processes* have been proposed in order to explain this efficient transport

*1) High−latitude **magnetic reconnection** in both hemispheres converts northward magnetosheath field lines into closed geomagnetic field lines allowing for the entry of the magnetosheath plasma into the magnetosphere*

McFadden et al., 2008 and refs. therein

2) Development of ***Kelvin-Helmholtz instability*** at low−latitude magnetopause. Several nonlinear processes efficient for the formation of a mixing layer :

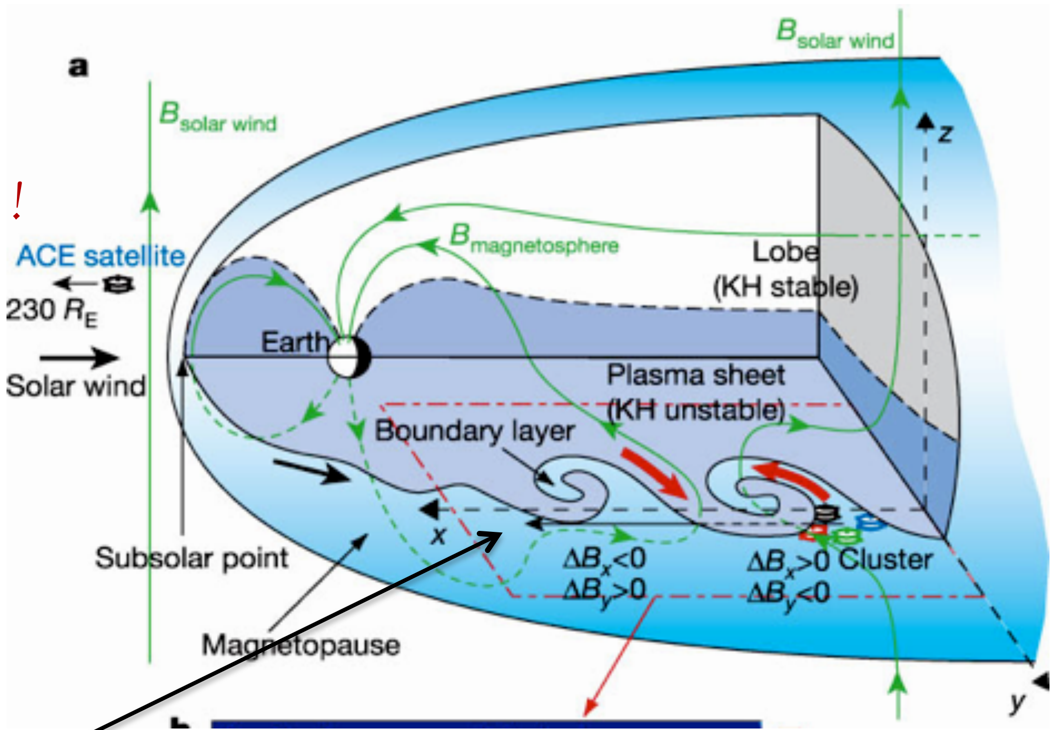
vortex pairing (standard HD non linear process)
twists up magnetic field lines leading to magnetic reconnection
secondary fluid and magnetic instabilities (on the shoulder of the vortices)

Belmont and Chanteur, 1989; Fairfield et al. , 2000; Nakamura and Fujimoto, 2005; Miura, 1997

Miura, Matsumoto, Hoshino, Hashimoto, Otto, Faganello, …

The solar wind flow provides an important source of "free energy" generating large-scale vortices driven by the development of **shear-flow** instability

Mixing efficiency strongly increased !



Complex non linear phenomenology induced by the K-H vortices

Quasi periodic perturbations often observed near the flank magnetopause

Hasegawa et al., Nature, 2004

The Kelvin - Helmholtz instability

*It has been proposed[1,2] that the **shear flow** between the solar wind and the magnetosphere **drives** the formation of Kelvin - Helmholtz vortices that tend to pair in the non-linear phase.*

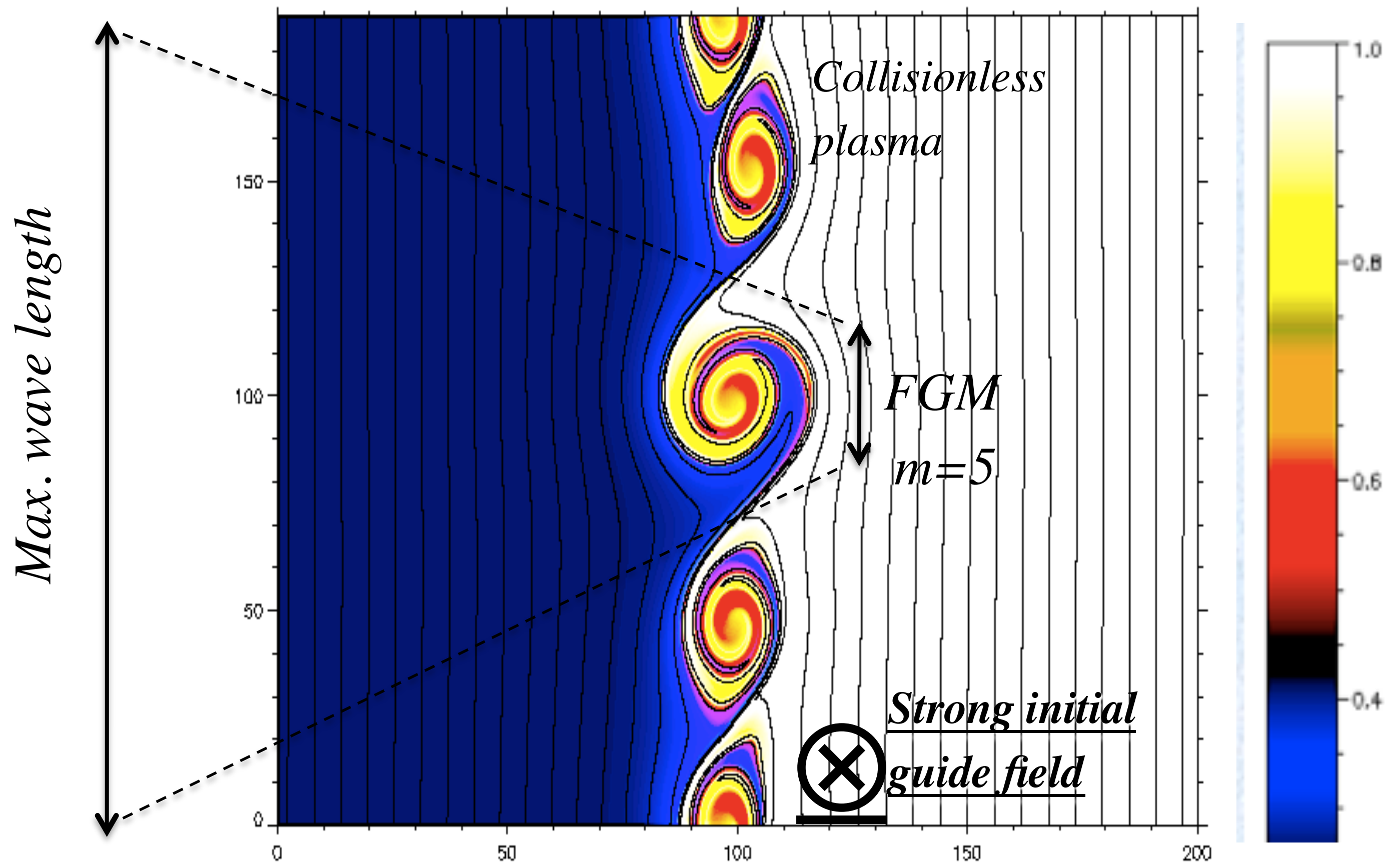
*At low latitude **the magnetic field is nearly perpendicular*** to the plane of the flow direction and of its transverse variation and does not inhibit the ***development of a "quasi-2D" Kelvin - Helmholtz instability.***

[1] G. Belmont, G., Chanteur, in "Turbulence and Nonlinear Dynamics in MHD Flows", 1989

[2] A. Miura, Phys. Plasmas 4, 2871, 1997

This provides an efficient mechanism for the formation of a mixing layer

Vortex chain generated by the KH instability



In-plane magnetic field advected by the rolled-up vortices, thus increasingly stretched and compressed

KHI: Fast Growing Mode and vortex pairing

Net transport of momentum across the initial velocity shear occurs both when the Fast Growing Mode and its sub-harmonics (paired vortices) grow, and when the vortex pairing process takes place.

In a homogeneous density system, the momentum transport caused by vortex pairing process is much larger than that due to the growth of the FGM[1] thus leading to a faster relaxation of the velocity shear.

Vortex pairing is therefore expected to be an efficient process in the nearly two-dimensional external region of the magnetopause at low latitude[1].

[1] A. Otto et al., J. Geophys. Res. 105, 21175 (2000)

EQUATIONS

$$\frac{\partial(n\mathbf{U})}{\partial t} + \nabla\left[n(\mathbf{u}_i\mathbf{u}_i + \varepsilon\mathbf{u}_e\mathbf{u}_e)\right] = -\frac{1}{m_i}\nabla\cdot(\mathbb{P}_i + \mathbb{P}_e) + \frac{\mathbf{J}\times\mathbf{B}}{m_i c}$$

$$\frac{\partial n_a}{\partial t} + \frac{\partial}{\partial x_i}(n_a u_{a_i}) = 0$$

$\mathbf{U} = \mathbf{u}_i + \varepsilon\, \mathbf{u}_e$; $\varepsilon = m_e / m_i$

$$\frac{d}{dt}\left(P_a \cdot n_a^{-\gamma_a}\right) = 0$$

$$\left[1 + \varepsilon(1 - d_e^2\nabla^2)\right]\mathbf{E} = -\frac{(\mathbf{u}_e + \varepsilon\mathbf{u}_i)\times\mathbf{B}}{c} - \frac{1}{en}\nabla\left[\mathbb{P}_e - \varepsilon\mathbb{P}_i - \varepsilon m_i n(\mathbf{u}_i\mathbf{u}_i - \mathbf{u}_e\mathbf{u}_e)\right]$$

$$\mathbf{J} = \frac{c}{4\pi}(\nabla\times\mathbf{B}) + \frac{1}{4\pi}\frac{\partial\mathbf{E}}{\partial t} \simeq \frac{c}{4\pi}(\nabla\times\mathbf{B})$$

$$\frac{\partial\mathbf{B}}{\partial t} = -c\,\nabla\times\mathbf{E}$$

Pressure Tensor

$$\frac{\partial \Pi_{a_{ij}}}{\partial t} + \frac{\partial}{\partial x_k}\left(\Pi_{a_{ij}} u_{a_k} + Q_{a_{ijk}}\right) + \left(\Pi_{a_{ik}} \frac{\partial u_{a_j}}{\partial x_k} + \Pi_{a_{jk}} \frac{\partial u_{a_i}}{\partial x_k}\right) =$$

$$= \frac{e_a}{m_a c}\left(\epsilon_{ilm} \Pi_{a_{lj}} + \epsilon_{jlm} \Pi_{a_{li}}\right) B_m$$

Gyrotropic pressure equations, ϱ/L << 1

$$\frac{\partial p_{a_\perp}}{\partial t} + \frac{\partial}{\partial x_l}(p_{a_\perp} u_{a_l}) = -\, p_{a_\perp} \frac{\partial u_{a_l}}{\partial x_l} + p_{a_\perp} b_l b_j \frac{\partial u_{a_l}}{\partial x_j} - \frac{\partial}{\partial x_l}(q_{a_\perp} b_l) - q_{a_\perp} \frac{\partial b_l}{\partial x_l}$$

$$\frac{\partial p_{a_\parallel}}{\partial t} + \frac{\partial}{\partial x_l}(p_{a_\parallel} u_{a_l}) = -\, 2\, p_{a_\perp} b_l b_j \frac{\partial u_{a_l}}{\partial x_j} - \frac{\partial}{\partial x_l}(q_{a_\parallel} b_l) + 2\, q_{a_\perp} \frac{\partial b_l}{\partial x_l}$$

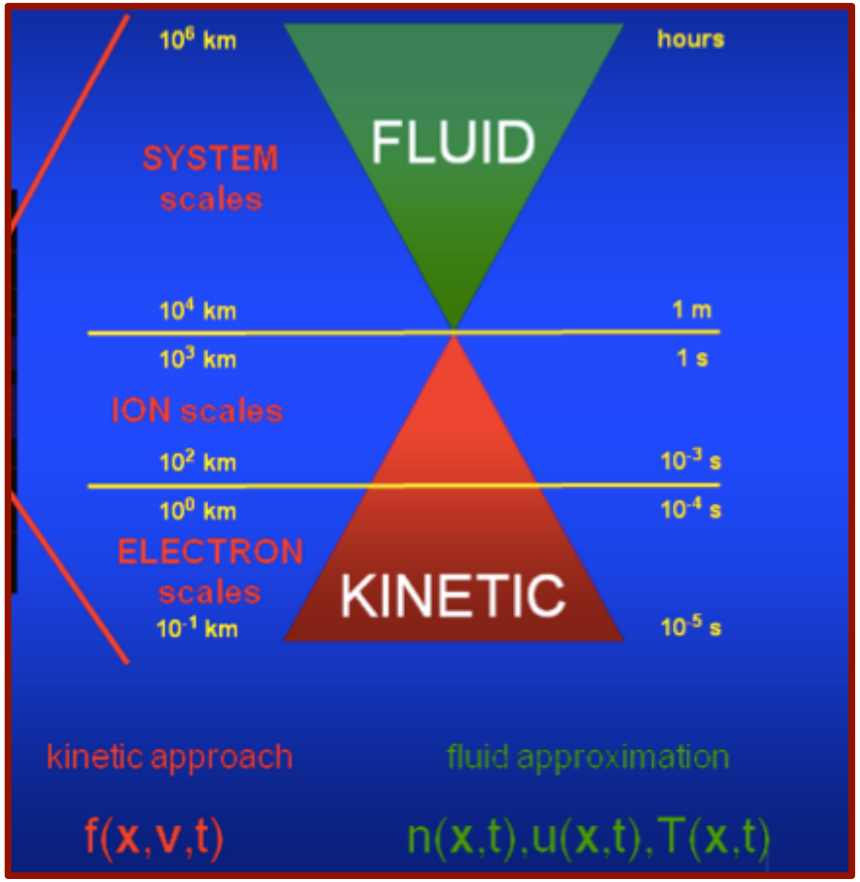
+ FLR in motion equation (first order development)

Chew-Goldberger-Low equations, q=0, (par and perp. energy transport along **B***)*

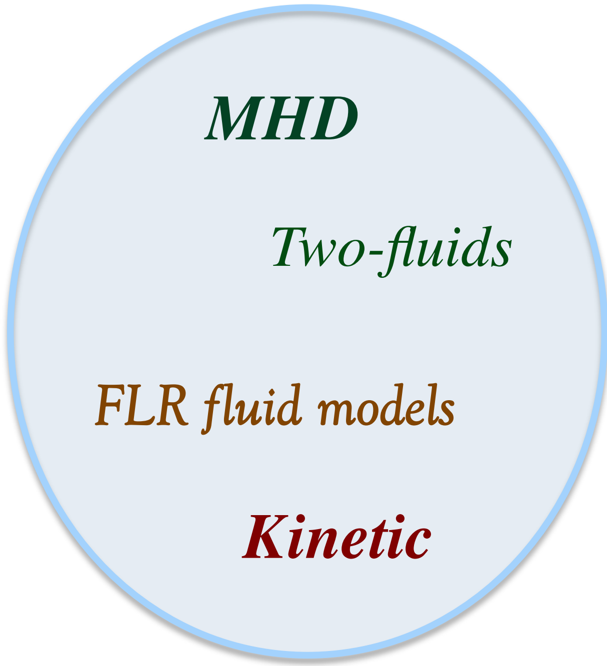
$$\frac{d}{dt}\left(\frac{p_{a_\perp}}{nB}\right) = 0 \quad \text{and} \quad \frac{d}{dt}\left(\frac{p_{a_\parallel} B^2}{n^3}\right) = 0$$

A posteriori equivalent to $Y_{par} = 1$ (i.e. isoth. Along B), $Y_{perp} = 2$

How to model such a multi-scale system ?



Shear flows: Pressure tensor ?



Problems:

$\rho_i \approx d_i$ (≈ 1000 Km) » $\rho_e \approx d_e$ » l_{coll} ; $\Pi_{I,j}$ terms important !

1. Kinetic model ? But how to initialize $U(x)\, e_y$? Computationally heavy.

2. Fluid modeling of $\Pi_{I,j}$? But then $Q_{i,j,k}$?

Problems with: MHD equilibrium modeling; Kinetic simulations, …

The equation: from MHD to EMHD regime

We adopt a "**simple**"
fluid approach

$$B_0(x) = \left[B_{0,R}^2 + 2\left(P_{0,R} - P_0(x)\right)\right]^{1/2}$$

$P_o \equiv$ *total thermal pressure*

$$\frac{\partial n}{\partial t} + \nabla \cdot (n\mathbf{U}) = 0$$ *Quasi neutrality*

$$\frac{\partial (nS_{e,i})}{\partial t} + \nabla \cdot (nS_{e,i}\mathbf{u}_{e,i}) = 0 \qquad S_{e,i} = P_{e,i} n^{-\gamma}$$

Isothermal or
Adiabatic closure

$$\frac{\partial (n\mathbf{U})}{\partial t} + \nabla \cdot \left[n(\mathbf{u}_i\mathbf{u}_i + d_e^2\mathbf{u}_e\mathbf{u}_e) + P\bar{\bar{\mathbf{I}}} - \mathbf{B}\mathbf{B}\right] = 0$$

$$(1 - d_e^2\nabla^2)\mathbf{E} = -\mathbf{u}_e \times \mathbf{B} - \frac{1}{n}\nabla P_e \qquad \partial B/\partial t = -\nabla \times E$$

Why so interesting this study ?

non linear, multi-scale collisionless dynamics

Typically: $L \gg d_i , \rho_i \rightarrow d_i , \rho_i \gg \lambda \gg \lambda_{coll}$

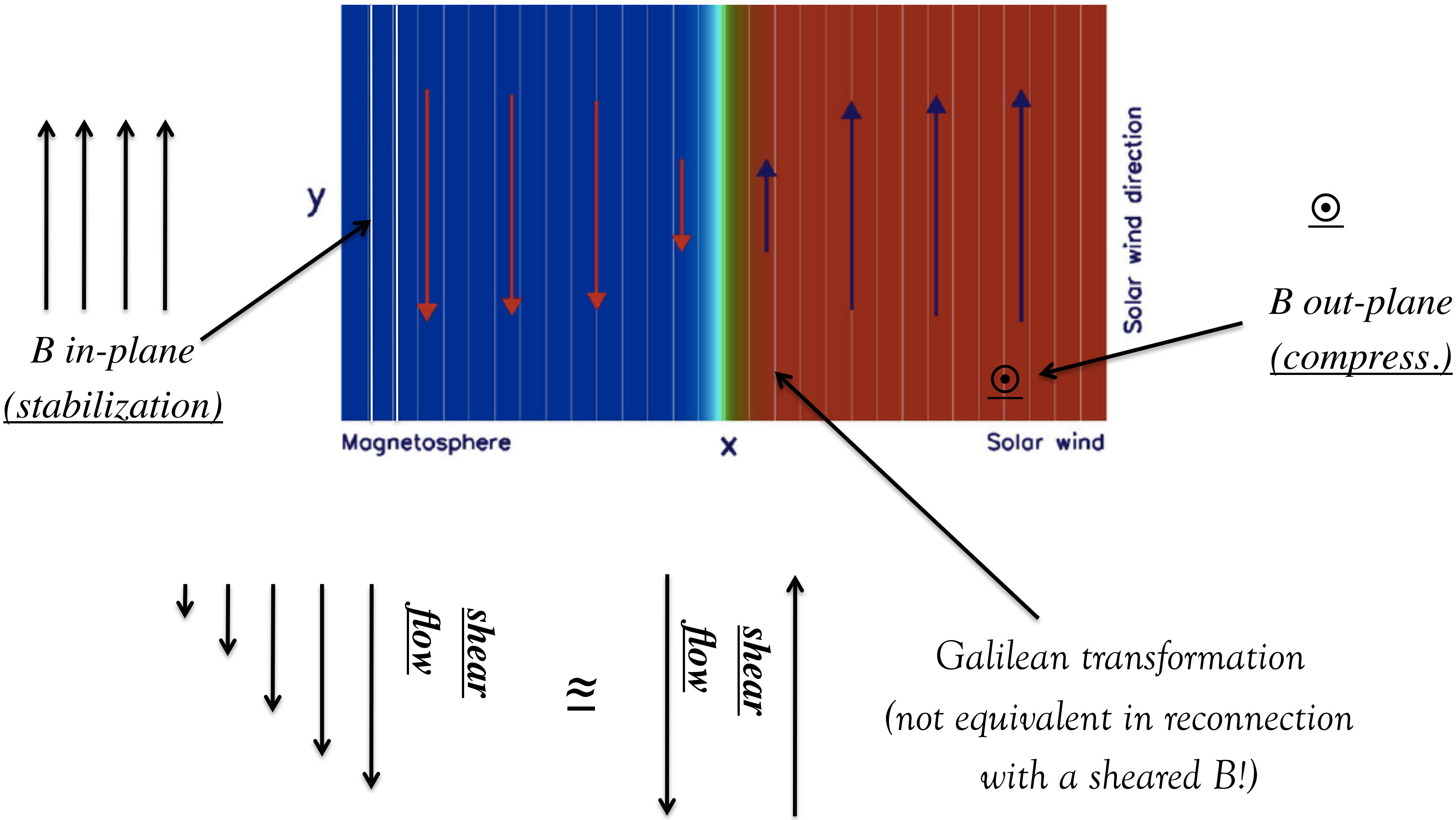
(same for frequencies…)

MHD → two-fluids → kinetic

See next slides

Very rich Physics: Hydrodynamics vortices, Fluid instabilities, magnetic reconnection, shocks structures, turbulence

The Kelvin – Helmholtz instability



Dispersion relation *(linear analysis)*

$$\gamma = -\frac{k_y}{\rho_1+\rho_2}(\rho_1 U_1 + \rho_2 U_2) \pm \left[\frac{k_y^2 B^2}{2\pi(\rho_1+\rho_2)} - k_y^2 \frac{\rho_1\rho_2}{(\rho_1+\rho_2)^2}(U_1-U_2)^2\right]^{\frac{1}{2}}$$

Important Parameters*: Mach sonic, Mach Alfvenic, Mach magnetosonic*

$$M_s = \Delta U / c_s$$

$$M_A = \Delta U / V_A$$

$$M_f = \Delta U / \sqrt{c_s^2 + V_A^2}$$

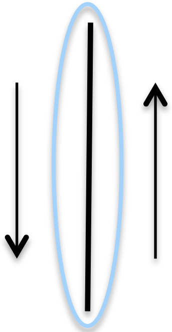
$M_s << 1$ (incompr.)

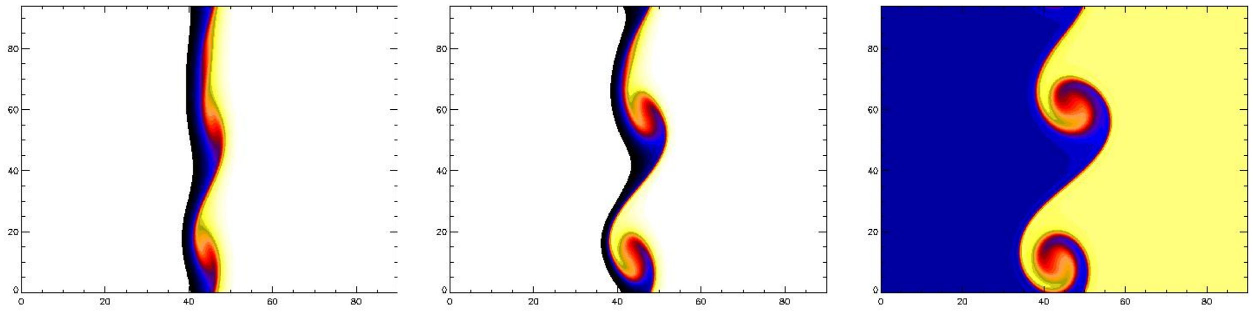
Magnetic stabilization of B_{parall}

$$\rho_1\rho_2(U_1-U_2)^2/(\rho_1+\rho_2)^2 \leqslant V_A^2.$$

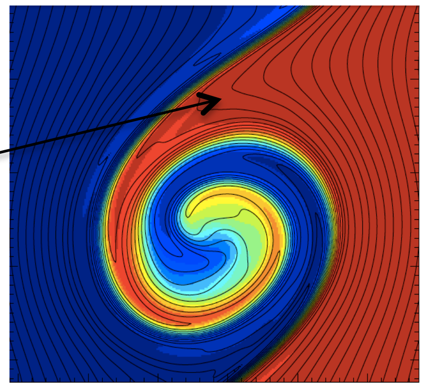
S. Chandrasekhar. Hydrodynamic and Hydromagnetic Stability, Oxford University Press, 1961.

Non linear regime: Generation of fully rolled-up vortices





advection, stretching and compression of B field lines



Fast Growing Mode and vortex pairing

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In a homogeneous density system, the momentum transport caused by ***vortex pairing*** *process is much larger than that due to the growth of the FGM*[1]*, thus leading to a faster relaxation of the velocity shear.*

[1] Winant and Browand, J. Fluid Mech., 63, 237, 1974
A. Miura Phys. Plasmas 4, 2871 (1997)
A. Otto et al., J. Geophys. Res. 105, 21175 (2000)

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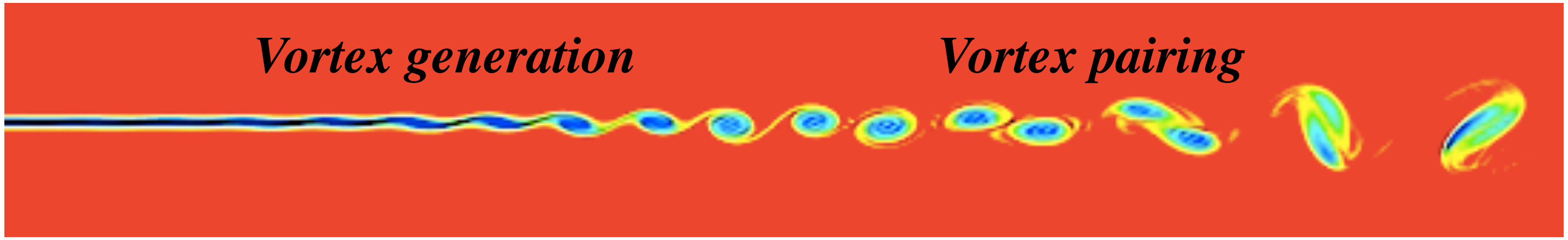
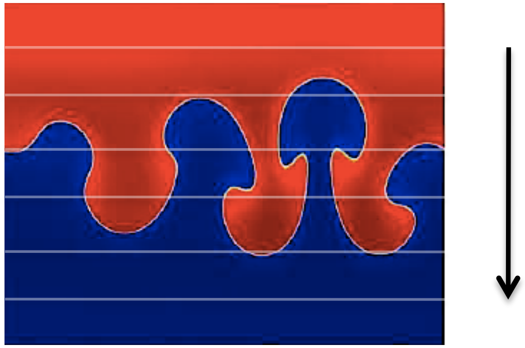


The Rayleigh – Taylor instability



Hydrodynamic instability of an heavy fluid accelerated over a light fluid

Very important in laser plasma interaction

$$\overline{V}_{A}^{2} > V_{g}^{2}(\rho_1 - \rho_2)/(\rho_1 + \rho_2)$$

Stability condition ($V_g = \sqrt{g/k}$)

$$\gamma = \pm\sqrt{gk\left(\frac{B^2 k}{2\pi g(\rho_1+\rho_2)} + \frac{\rho_1-\rho_2}{\rho_2+\rho_1}\right)}.$$

Magnetic stabilization

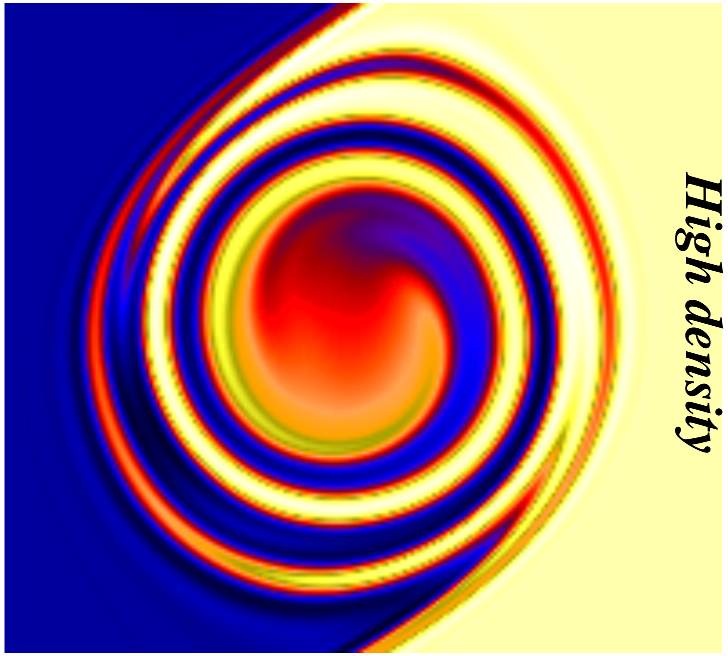
S. Chandrasekhar. Hydrodynamic and Hydromagnetic Stability, Oxford University Press, 1961.

Density jump between solar wind and magnetosphere:

the rolled-up K-H vortices are characterized by

alternating density layers in the vortex arms

The centrifugal acceleration of the rotating K-H vortices acts as an "effective" gravity force on the plasma.



[1]W.D. Smyth, J. Fluid Mech. 497, 67 (2003)
Y. Matsumoto et al., Geophys. Res. Lett. 31, 2807 (2004)
Faganello *et al*., Phys. Rev. Lett., 100, 015001, 2008

Theory on the onset of the secondary instabilities

We consider each vortex separately and to be stationary

We model the vortex as an "equilibrium". Inside two nearby vortex arms:

n_1, u_1 more dense ; n_2, u_2 less dense => density and velocity values of *two superposed fluid plasmas* in slab geometry.

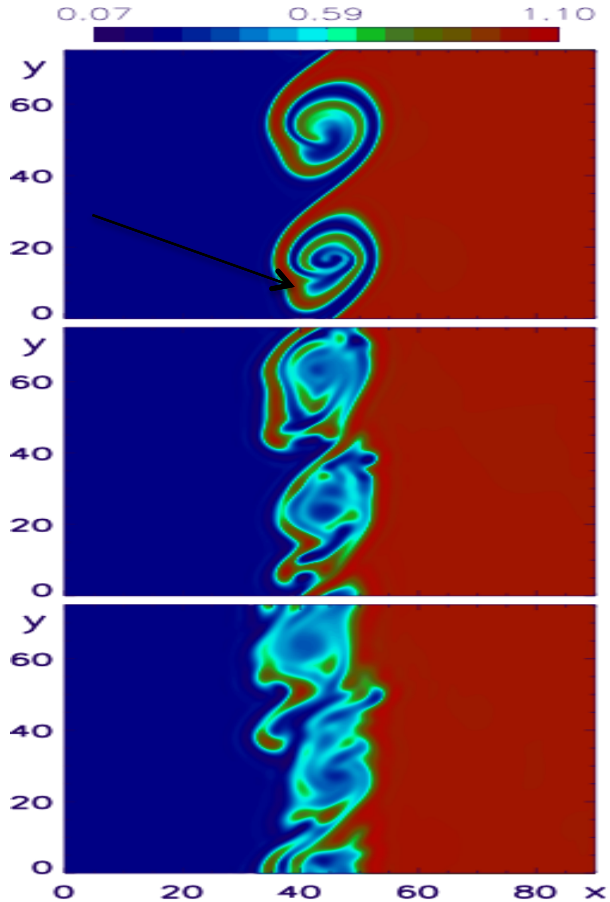
*The plasma slabs are subjected to an "**effective gravity**" which corresponds to the centripetal acceleration arising from the arms curvature*

ℓ_u ℓ_n $\equiv$ scale length of the velocity and density gradient between the two arms;
$\lambda \equiv$ wave length along the vortex arm associated to the observed R-T.

Typical values: $\ell_u \sim \ell_n \sim 1$; $1 \leq \lambda \leq 10$ (dimensionless)

Onset of R-T. Linear analysis

If the density variation is large enough, the *Rayleigh-Taylor* *instability can grow along the vortex arms.*



The R-T growth rate is compatible with simulations

We model the system by a step-like configuration since the R-T instability is not affected by the finite value of the length l_n , at least when $\lambda \geq l_n$

$$\gamma_{RT} \approx [\, g_{eff}\, k\, (\alpha_1 - \alpha_2\,)]^{1/2}$$

where $\alpha_1 = \rho_1/(\rho_1+\rho_2)$, $\alpha_2 = \rho_2/(\rho_1+\rho_2)$

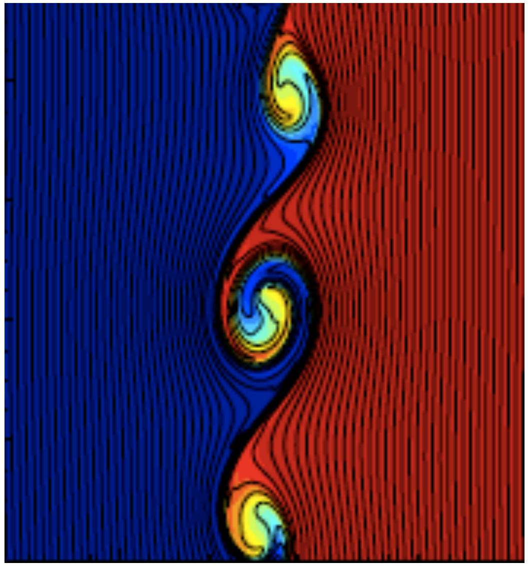
$g_{eff} \approx 0.1$ estimated using the Ω_{vortex} and r_{arms}

For $\lambda = 10, 4, 1$ we get $\gamma_{RT} = 0.2, 0.3, 0.6$

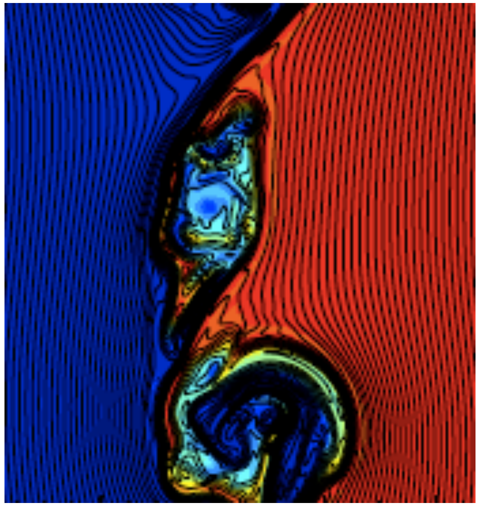
Mixing layer

***Strong density jump**, Δn = 0.8*

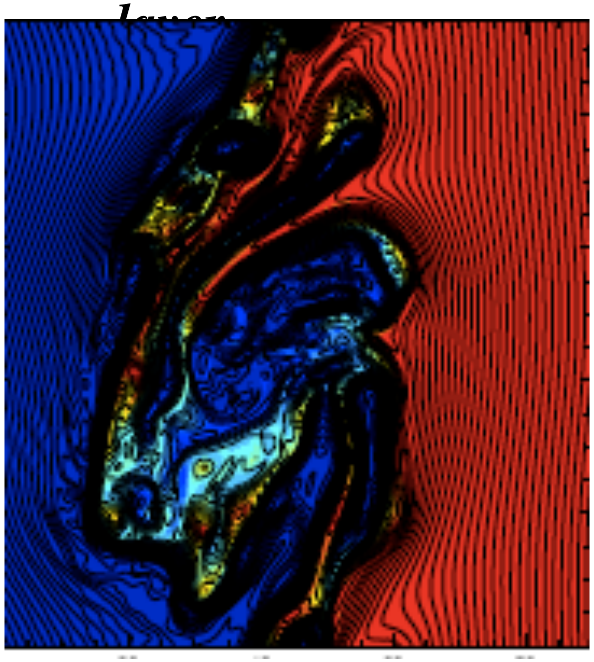
KHI



Development of** **fluid instabilities** **in the vortex



formation of a turbulent layer



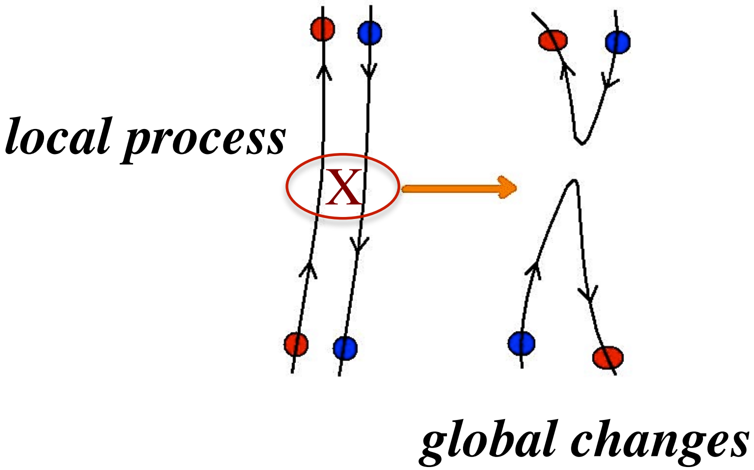
M. Faganello, F. Califano, F. Pegoraro, Phys. Rev. Lett. 100, 015001 2008

Importance of magnetic field

In a plasma the process of ***Magnetic Reconnection*** play a fundamental role in the dynamics by violating (locally) the "ideal" Ohm law thus allowing the system to access ideally forbidden energetic states.

The only process capable of violating the linking condition is known as

Magnetic Reconnection

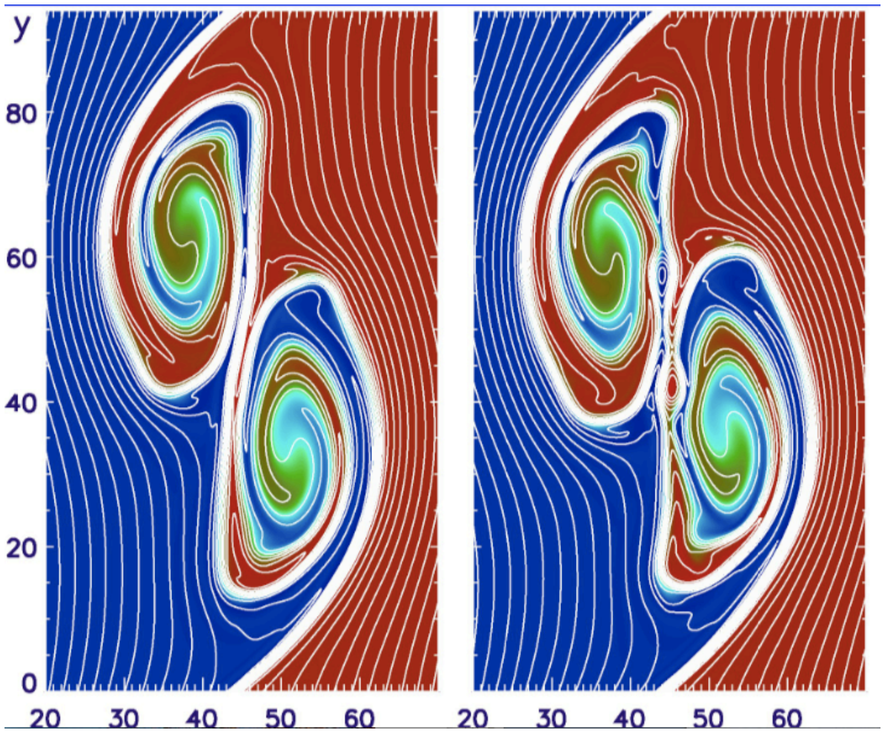


Magnetic Reconnection:

affects the *global energy balance of the system* (astrophysics)

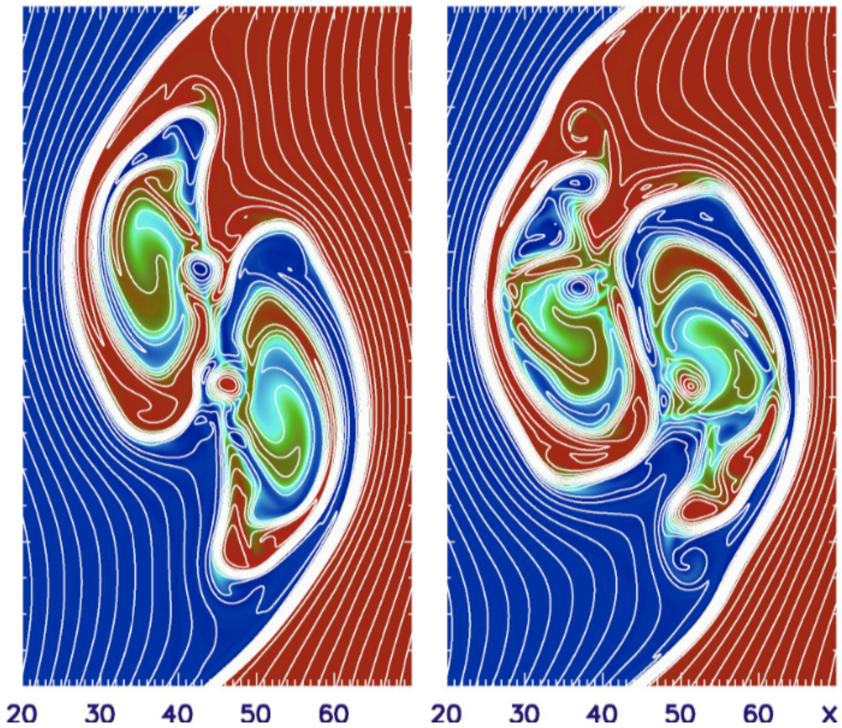
reorganizes the large scale magnetic topology (laboratory)

Spontaneous development of reconnection
(plasma passive tracer and magnetic field lines)

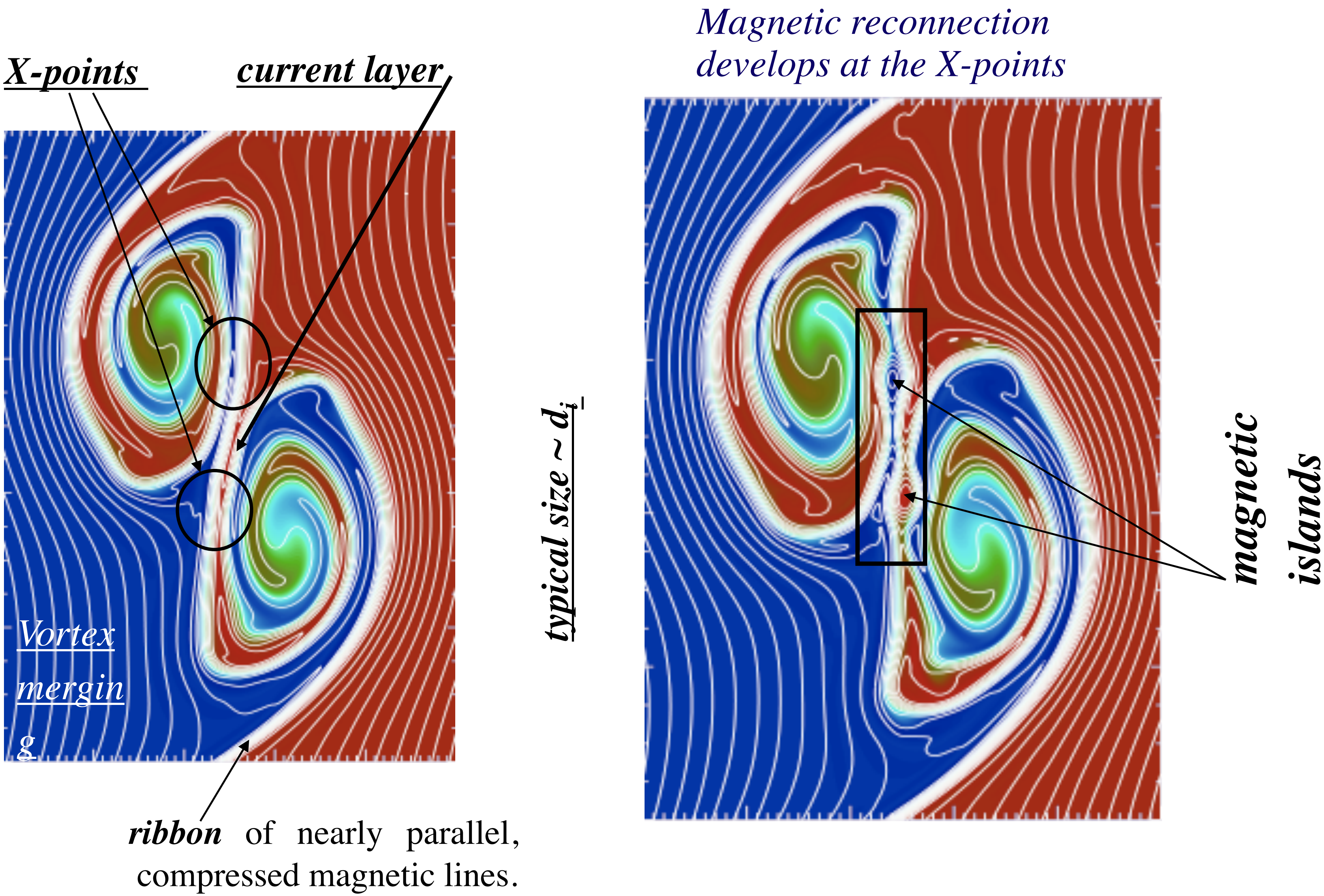


"Spontaneous" formation of magnetic islands

Magnetic reconnection changes the global connection thus stopping vortex pairing

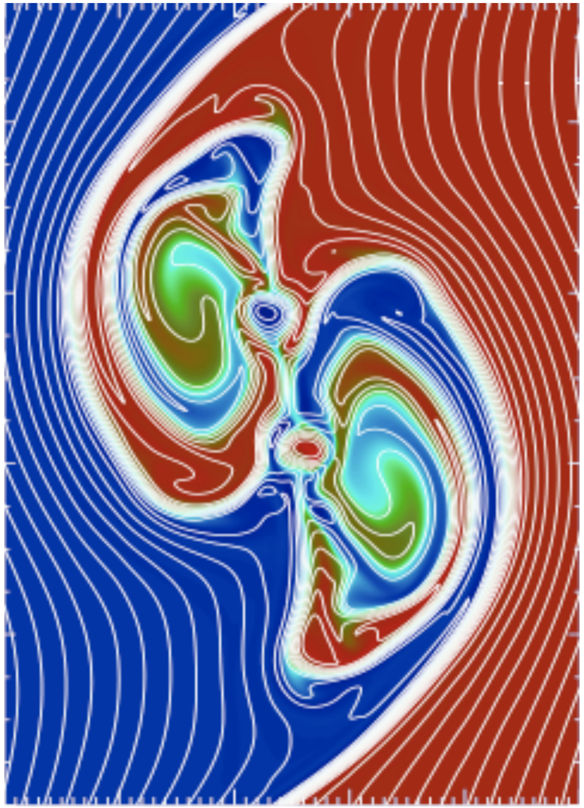


Current sheet generation by the fully rolled-up vortex dynamics



The inflow plasma velocity at the X-points is $\sim 0.1\ c_{A,\,local}$ (as expected for *fast magnetic reconnection**) $\Rightarrow$ $\gamma \sim 0.1\ c_A / L_{B,\,local} \sim 0.15$ compatible with $d\ln E_z / dt$ at the X-point.

$\gamma \sim 0.15$



"fast" reconnection

In the time interval of a few growth times the two vortices can only rotate by a few degrees

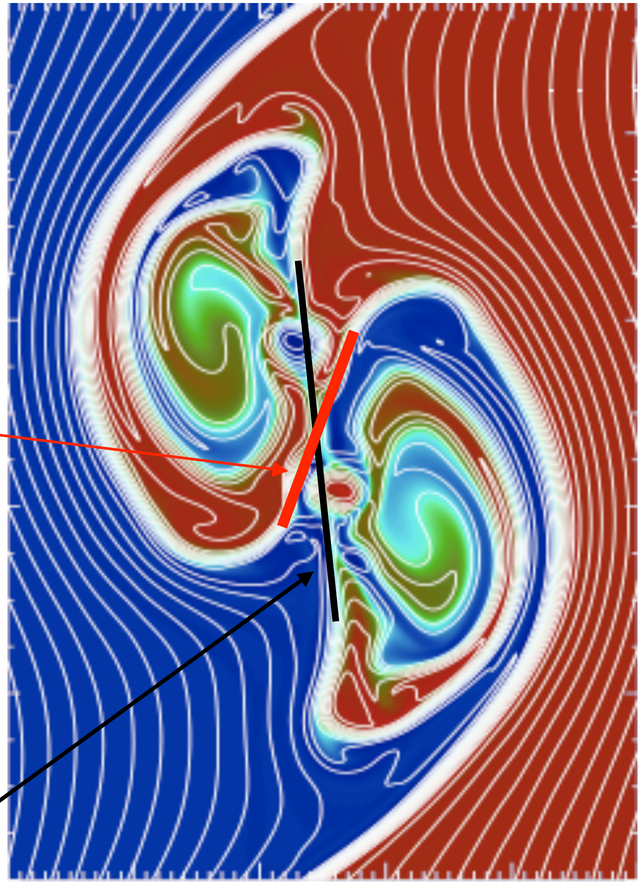
The plasma displacement and the current rearrangement due to vortex rotation are

not sufficient rapid to interfere with the reconnection process.

M.A. Shay et al., J. Geophys. Res. 103, 9165 (1998)

Change in large scale magnetic field topology

The field line ribbon shrinks and finally opens up



A new ribbon of field lines appears which no longer separates the red and the blue plasma regions

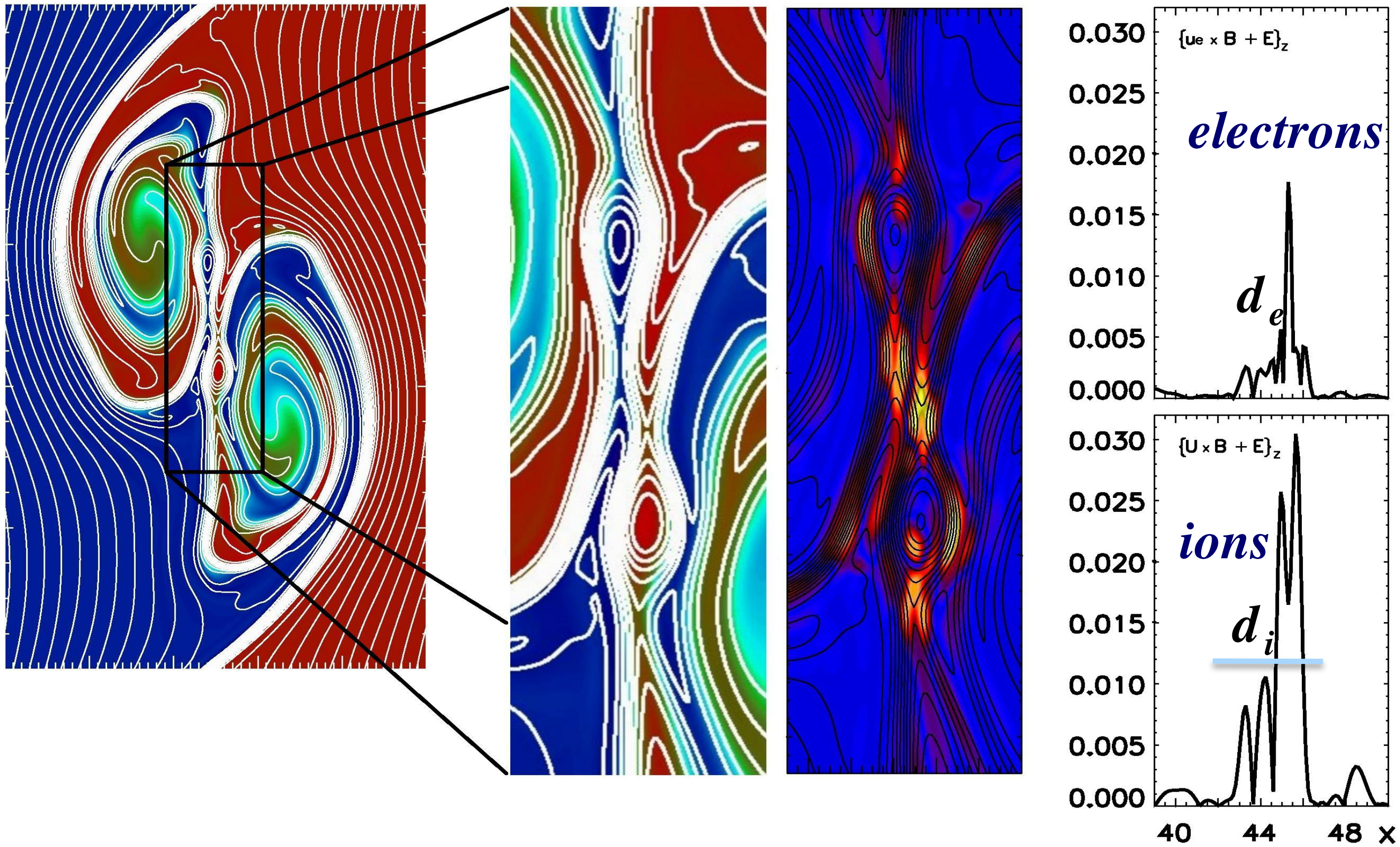
old ribbon

Significant portions of the red plasma have been engulfed in the form of "blobs" into the blue plasma region and viceversa.

The ribbon indicates nearly parallel, compressed magnetic lines.

Field lines rolled-up by the two vortices form two sub-d_i current layers (local magnetic inversion, two-fluid behavior).

Fast magnetic reconnection develops spontaneously leading to the cut of the central ribbon

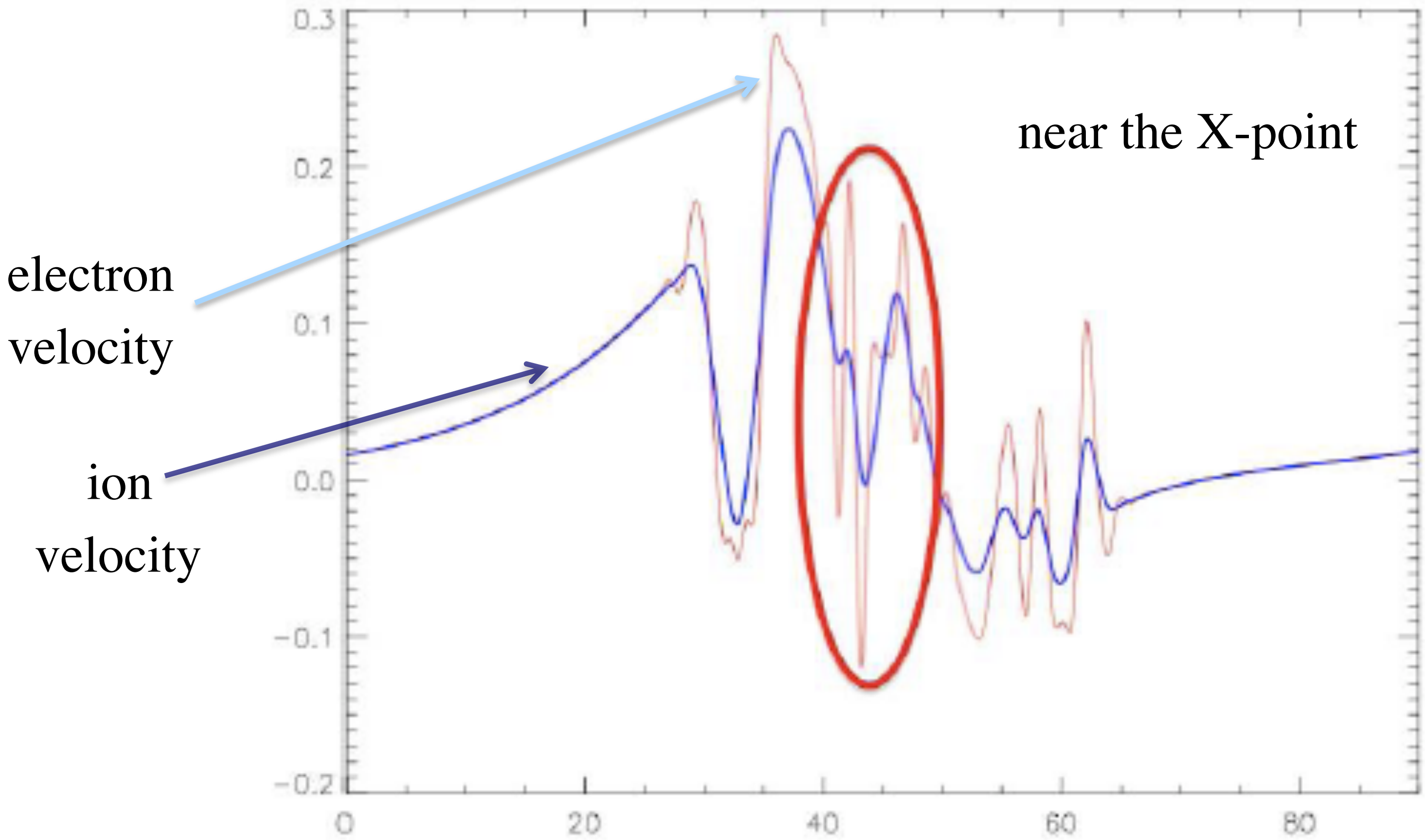


Reconnection does not destroy the vortices before they coalesce, but acts during the pairing process.

Correlation between plasma and magnetic structures: the magnetic field is mainly advected by the fluid velocity

The Hall term

Local decoupling between the electron and the ion Motion: a signature of the role of the Hall term



From sub-sonic to super-magnetosonic regimes

The physical properties of the solar wind change crossing the Earth's bow shock moving tail-ward inside the magnetosheath where, according to the *Rankine-Hugoniot* relations, the plasma density and temperature increases, thus leading to subsonic velocities.

However, at larger distances the shocked solar wind regains a fraction of its initial speed as it flows past the magnetosphere while the plasma temperature decreases more and more. Near the magnetopause flanks, the velocity of the magnetosheath plasma is increasingly accelerated as the distance from the Earth increases:

we can expect a transition to a supersonic regime for the KHI in the tail region of the magnetopause

Fairfield et al., J. Geophys. Res., 105, 21.159 (2000)

Sreiter et al., Planet. Space Sci., 14, 223 (1966)

Super-magnetosonic regimes

We study this regime by ***increasing*** V_0

Transition towards magnetosonic Mach numbers ≥ 1: the **vortex** acts as an **obstacle** leading to the *formation of shocks structures* extending far from the transition region.

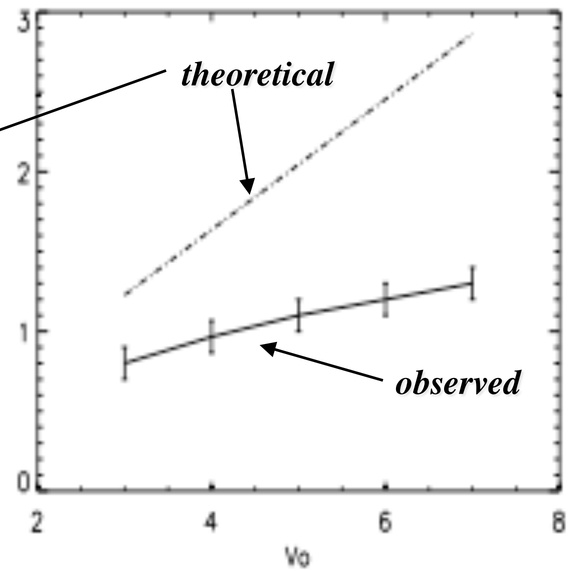
In this regime, *rarefaction and compression effects* play a key role. In particular the **vortices** are now of **low density** thus *modifying the non linear dynamics* (pairing, secondary instabilities) observed in the "low” Mach number regime.

Vortex propagation due to density variations

The most important effect with respect to the uniform density regime is that the vortices propagate in the same direction of the flow where the plasma density is larger (but less rapid than expected).

$$V_{theor}^{vort} = \frac{V_0}{2}(n_{0,R} - n_{0,L})/(n_{0,R} + n_{0,L})$$

(incompressible plasma with density discontinuity)



Vortex propagation due to density variations

*We define the **Fast magneto-sonic Mach***

$$M_f^{sw} = V^{sw}/c_f \; ; \quad c_f = \left(c_s^2 + c_A^2\right)^{1/2}$$

The vortex velocity vs. the flow velocity V_0 in the simulation reference frame)

The transition occurs before reaching a Magnetosheath vortex Mach number equal to one: $M_f^{vort} < 1$

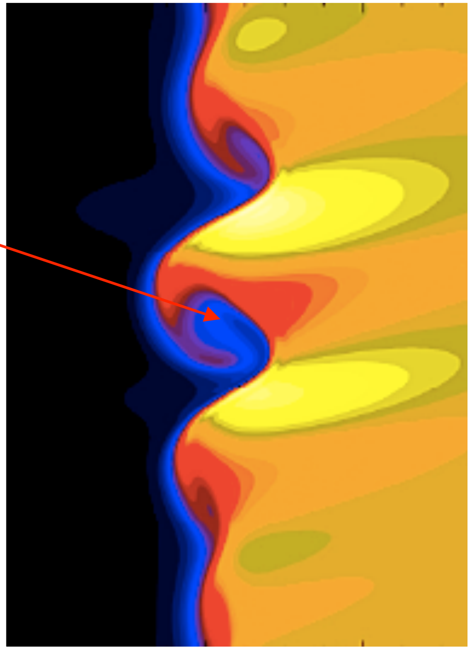
Vortex (Convective) Mach number

$$M_{f,L/R}^{vort} = U_{L/R}/c_{f,L/R} \; ; \quad U_{L/R} = \| V_0/2 \mp V_{vort} \|$$

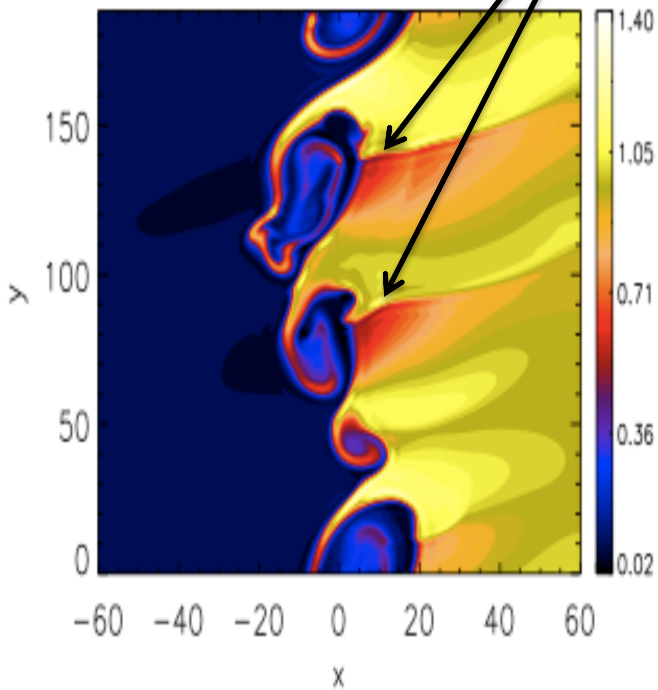
Vortex induced shock formation. $(V_0 = 5)$

Shocks

low density,
nearly uniform
vortices



plasma density



plasma density

Palermo et al., J. Geophys. Res. 116, A04223 (2011)

Palermo et al., Ann. Geophys., 29, 1169 (2011)

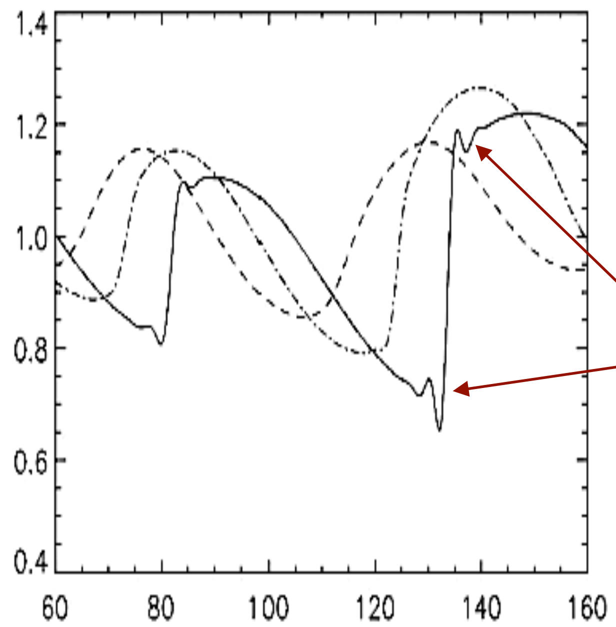
The shocks

The perpendicular magnetic fluctuations δB_z are practically superposed to the density fluctuations δn thus identifying the shock as a ***perpendicular magneto -sonic shock****, in agreement with the fact that it propagates, with respect to the magnetic field, at an angle $\pi/2$ - θ where $\theta < (m_e/m_i)^{1/2}$*

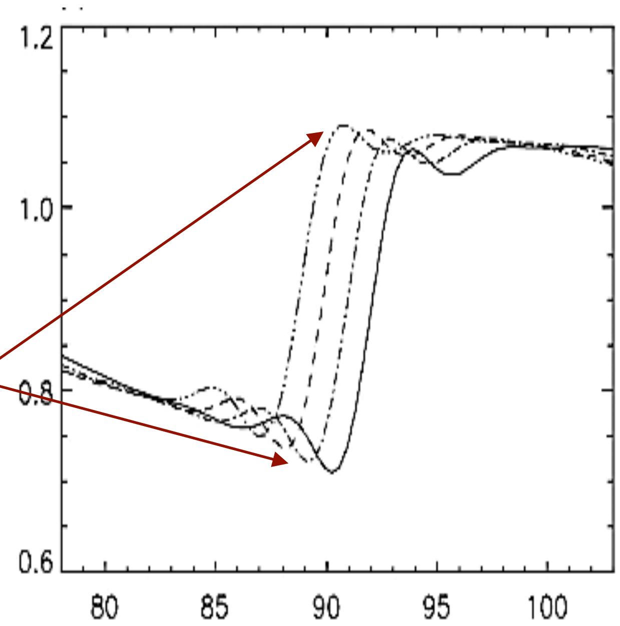
Formally "collisionless shocks"

In the shock frame of reference, the **Rankine - Hugoniot** conditions for a fast magnetosonic shock are satisfied.

$n_2 / n_1 \approx B_2 / B_1 \approx u_{y,1} / u_{y,2}$



Numerical dissipation



The upstream (downstream) plasma velocity is > (<) than the magnetosonic velocity

Importance of the shocks

1) The shocks could provide an ***efficient mechanism for particle acceleration***

Usually the existence of super-thermal ions and electrons observed in the cold magnetosheath has been explained as a product of magnetic reconnection and/or a hot magnetospheric plasma injection[1]. The particle acceleration associated with the, vortex induced, shocks could instead provide a different explanation.

2) Periodic shock structures observed away from the magnetopause could provide an indirect signature of fully developed KH vortices at the magnetopause in supersonic conditions.

[1] Fujimoto et al., J. Geophys. Res. 103, 2297 (1998)
Lavraud et al., J. Geophys. Res. 110, A062109 (2005)

Conclusions

The Solar wind - Magnetosphere low latitude boundary layer:

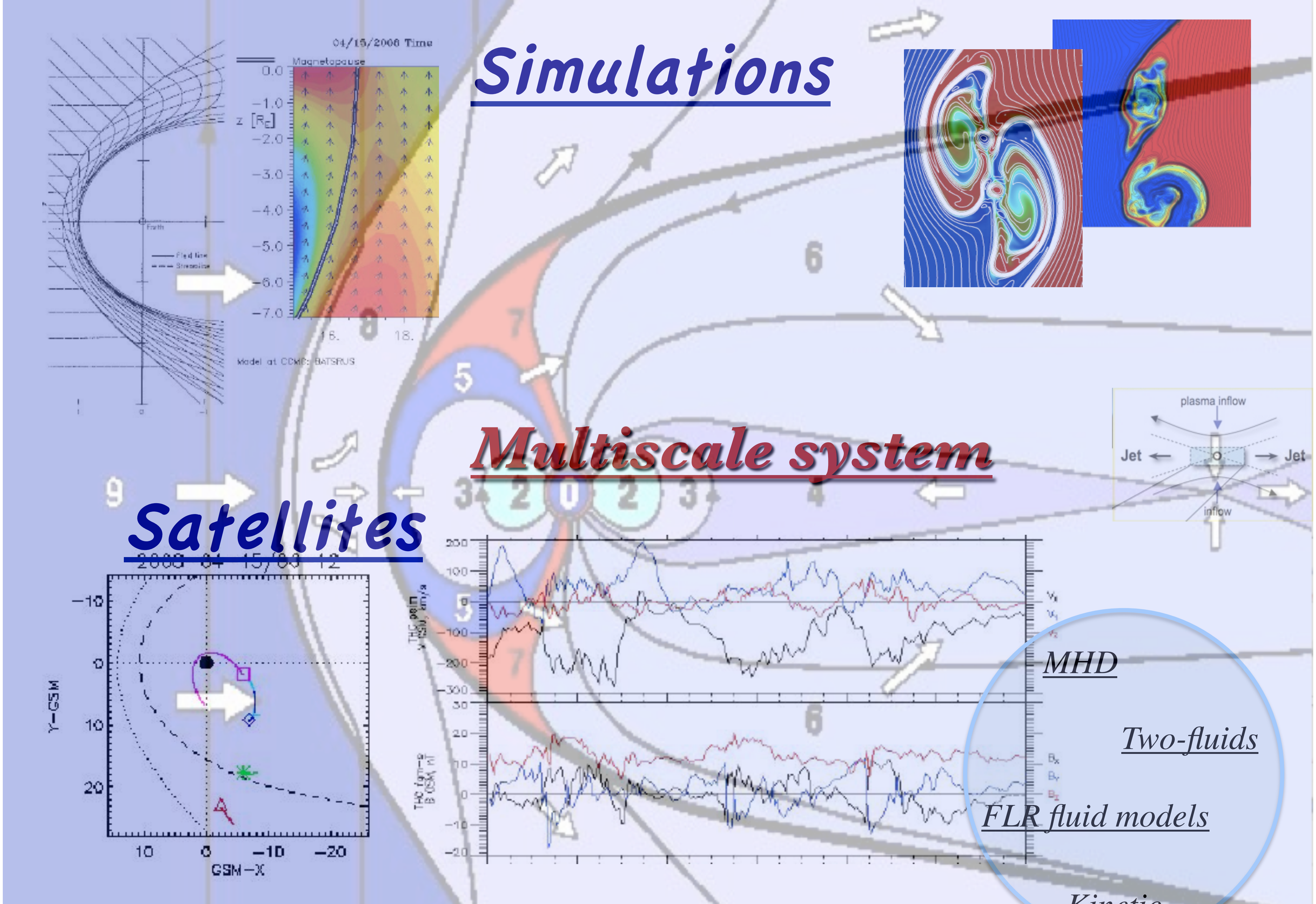
i) Play a key role for the entry of solar wind plasma in the Magnetosphere
ii) It is a laboratory of excellence for basic processes in plasmas
iii) It is one of the best example of multi-scale plasma dynamics

Results

We have understood many key processes at play in the dynamics

Problems and future work

i) Need for satellite data analysis in the transition region: large scale fields
ii) Need of a 3D initial configuration (MHD equilibrium ?)
iii) Need of kinetic simulations


Simulations
Multiscale system
Satellites
04/15/2008 Time
Magnetopause
z [RE]
Model at CCMC: BATSRUS
plasma inflow
Jet
Jet
inflow
Y-GSM
GSM-X
MHD
Two-fluids
FLR fluid models
Kinetic

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