Francesco Califano
Physics Department
University of Pisa, Italy

I plasmi nello spazio e in laboratorio: studio della dinamica di un sistema complesso


MASTER ITALO - FRANCESE DI FISICA INDIRIZZO PLASMI

Un doppio diploma e un'esperienza internazionale
Université Pierre et Marie Curie
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> di studiare per un anno in ciascuna delle due Università nell'ambito del Master Physique et Applications (UPMC) e della Laurea Magistrale in Fisica (UNIPI)
> di confrontarsi con due diverse culture accademiche
> di inserirsi nella rete di collaborazioni scientifiche italo - francesi

Importante!
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- Selezione su dossier

Per maggiori informazioni
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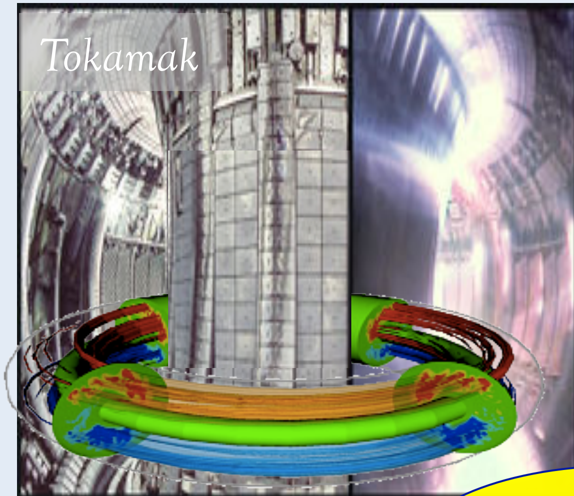
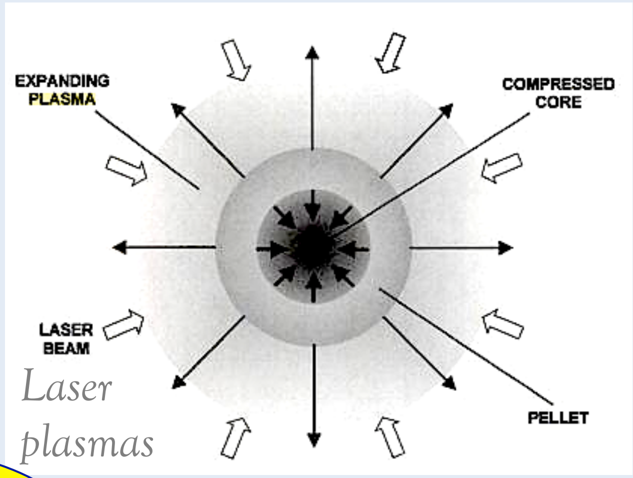
For many observed phenomenon *very similar physical mechanism*

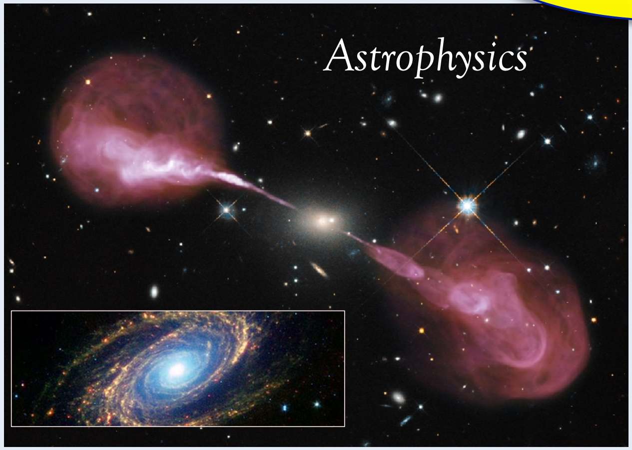
Plasmas are produced in the laboratory mainly for fusion purpose

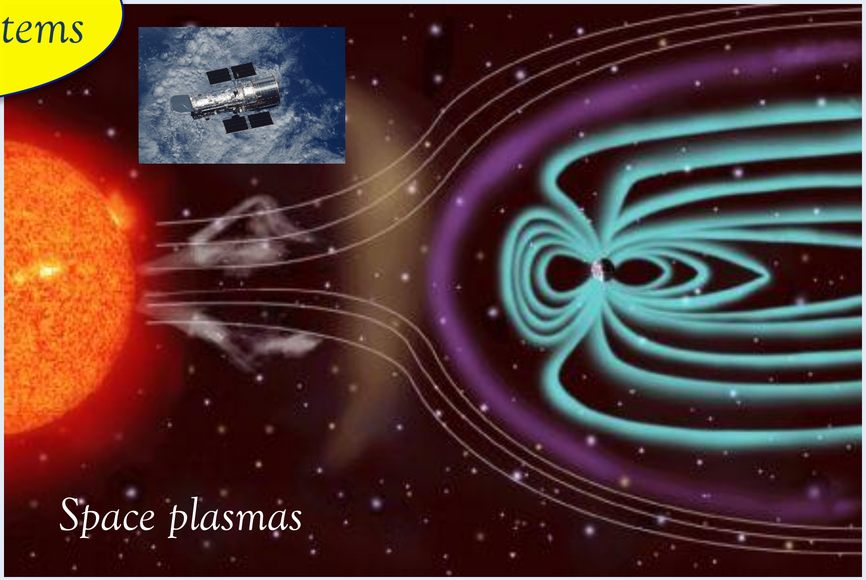
toroidal'naya kamera s magnitnymi katushkami
toroidal chamber with magnetic coils



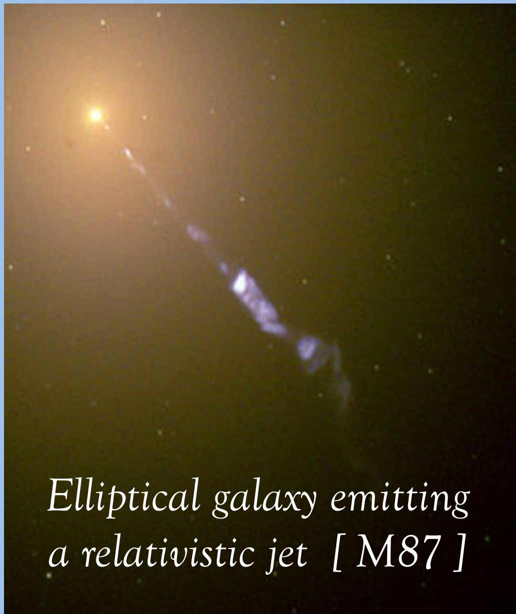


Complex and fascinating systems



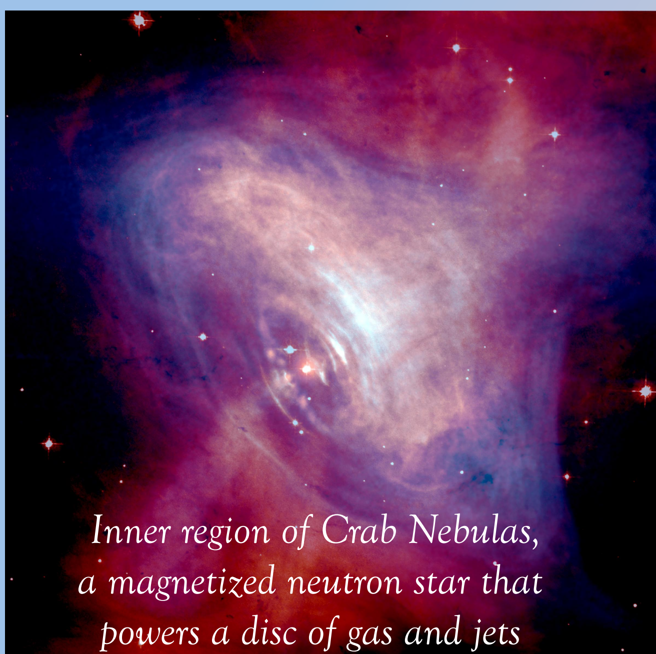


Astrophysics, very spectacular objects: accretion disk, stars, black-holes, jets, ...



Elliptical galaxy emitting a relativistic jet [M87]

Lagoon Nebula: a giant interstellar cloud in the constellation Sagittarius



Inner region of Crab Nebulas, a magnetized neutron star that powers a disc of gas and jets

Plasmas: hot and/or rarefied systems almost collisionless

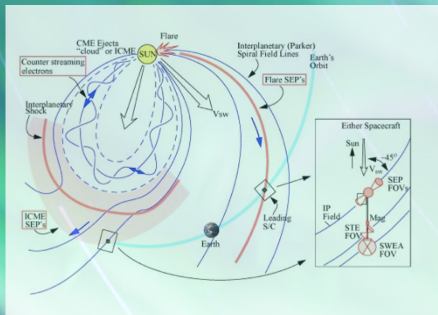
Why space plasmas are so important for plasma physics ?

Significant technical developments in space observations have offered the possibility to obtain ***measurements of electric and magnetic fields***, density, etc...with a sufficient resolution (in space and time) to reach the ***kinetic scales***, such as the Debye length and electron plasma frequency.

It is today possible to ***investigate the fine structuring of space plasmas*** and its role in converting the large-scale macroscopic motions in thermal energy, in particle acceleration as well as in the heat transport that drive the dynamics and/or the stability of space plasmas.

Space plasmas: a laboratory of excellence for collisionless plasma dynamics

Aurora: a beautiful phenomenon arising by the intrinsic coupling of the Earth – Magnetosphere – Sun system



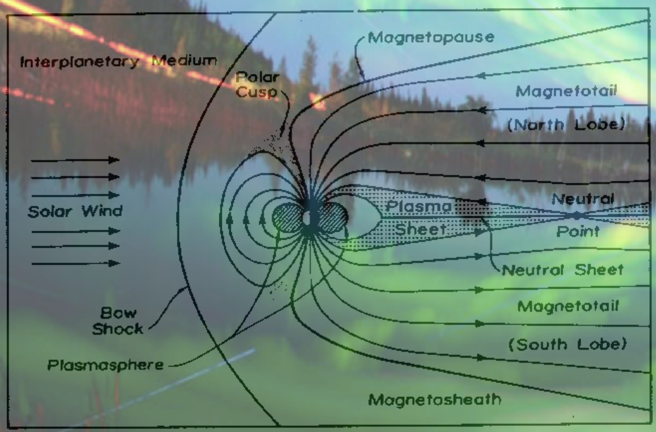
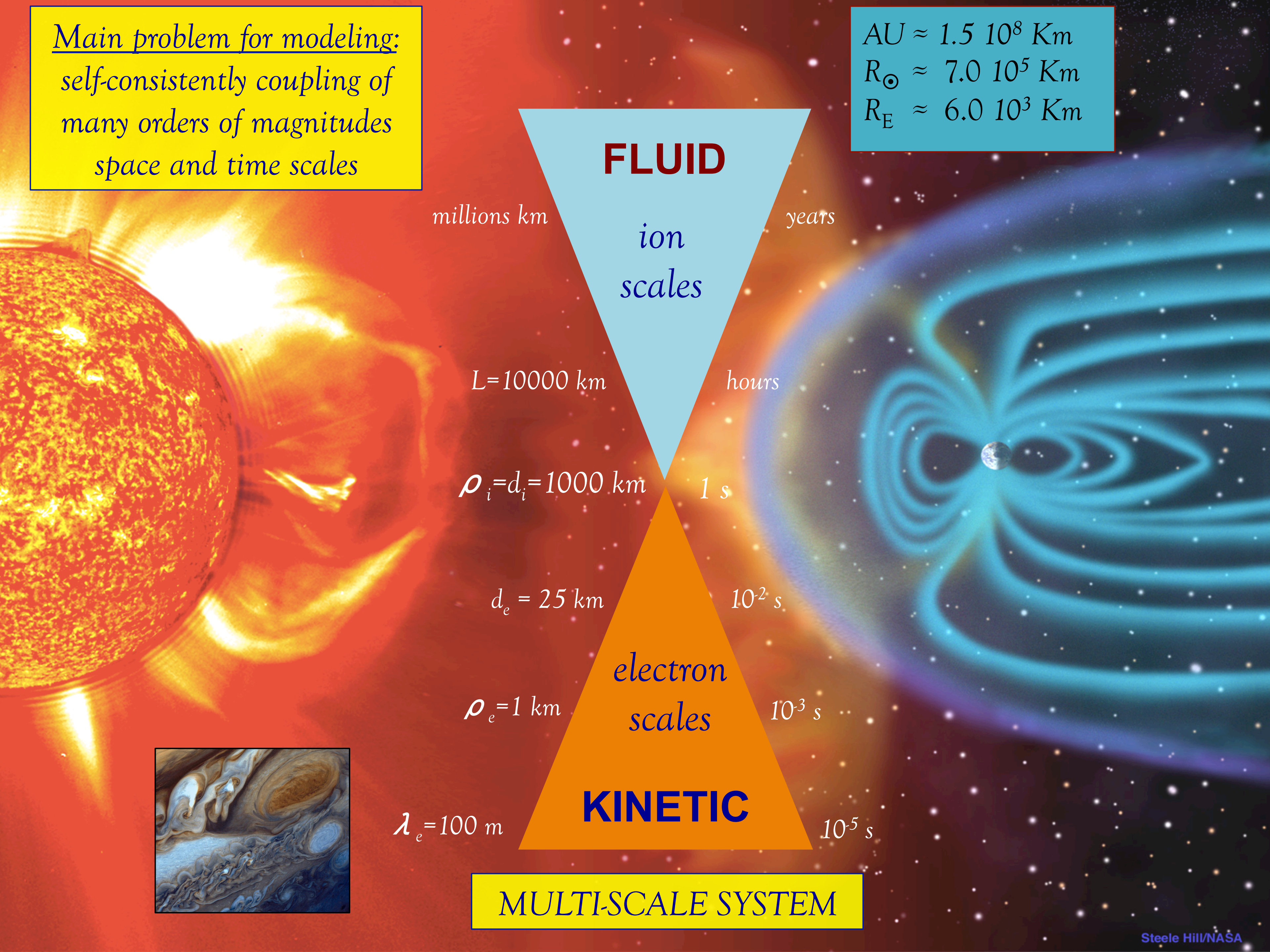
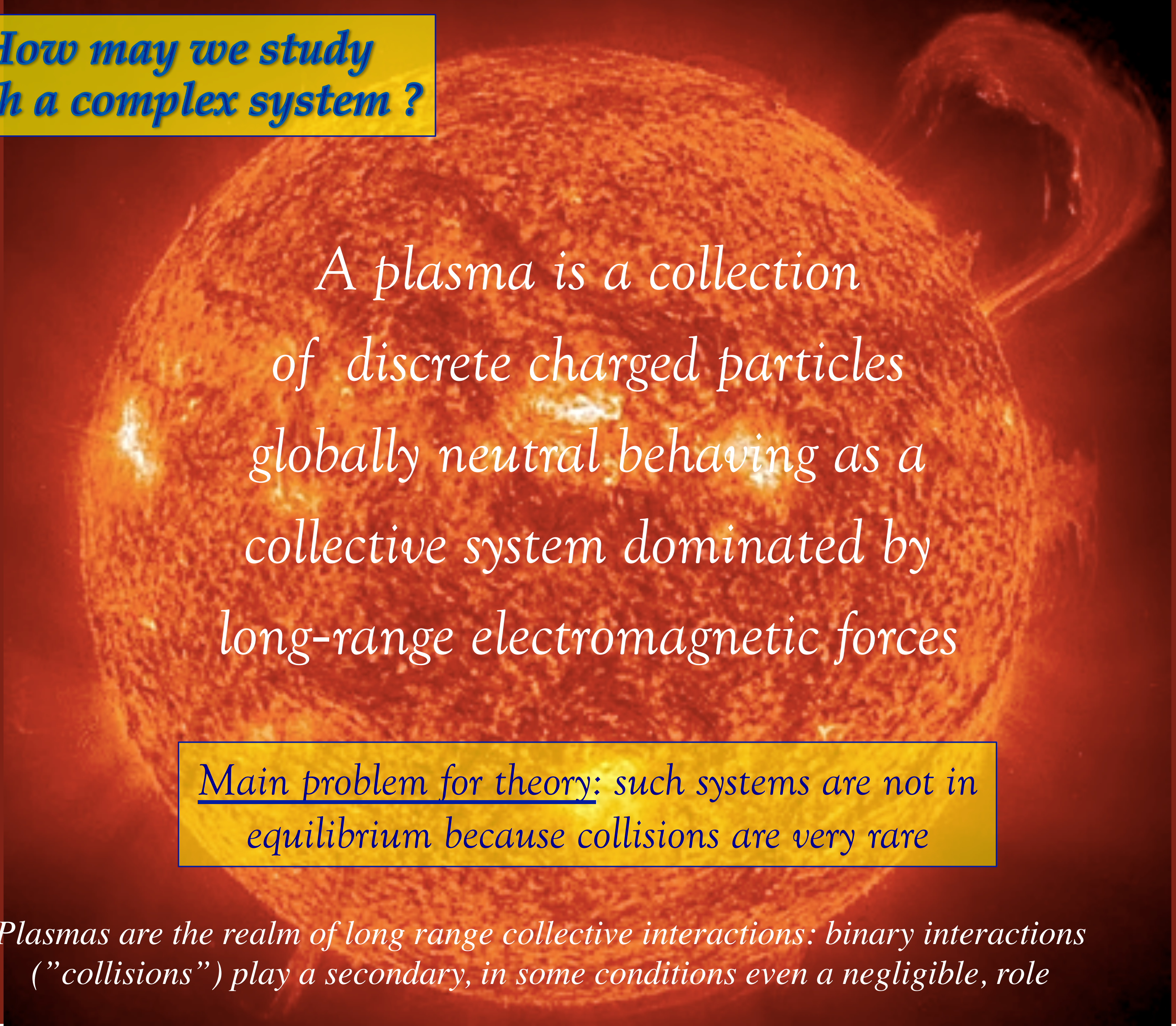


Figure 1


Main problem for modeling:
self-consistently coupling of
many orders of magnitudes
space and time scales
AU ≈ 1.5 10^8 Km
R⊙ ≈ 7.0 10^5 Km
R_E ≈ 6.0 10^3 Km
FLUID
ion
scales
millions km
years
L=10000 km
hours
ρ_i=d_i=1000 km
1 s
d_e = 25 km
10^-2 s
electron
scales
ρ_e=1 km
10^-3 s
KINETIC
λ_e=100 m
10^-5 s
MULTI-SCALE SYSTEM
Steele Hill/NASA



How may we study such a complex system ?

A plasma is a collection of discrete charged particles globally neutral behaving as a collective system dominated by long-range electromagnetic forces

<u>Main problem for theory:</u> such systems are not in equilibrium because collisions are very rare

Plasmas are the realm of long range collective interactions: binary interactions ("collisions") play a secondary, in some conditions even a negligible, role

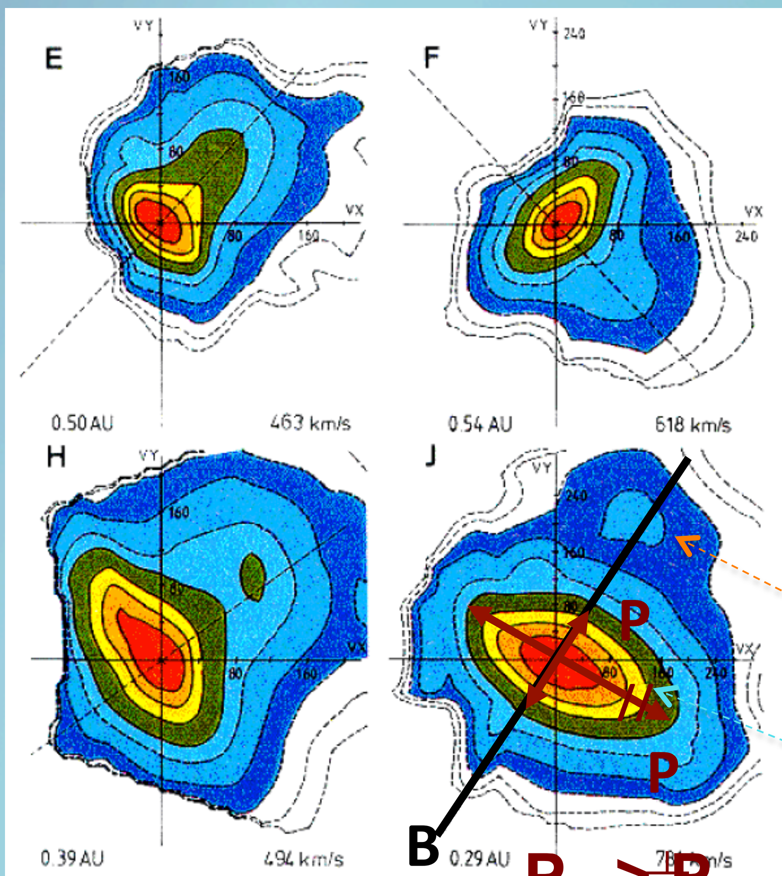
Lack of collisions observed in space

Neutral Gaz: $\nu_{coll} » \omega$

Plasma: $\omega » \nu_{coll}$

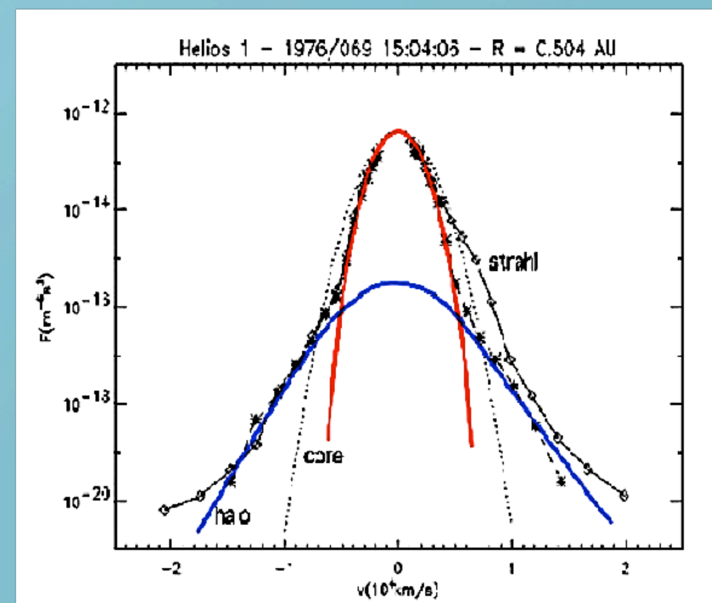
Proton velocity distribution functions in *velocity space*, as measured by Helios in the fast solar wind.

Problems for plasma thermodynamics!



$P_\perp > P_{//}$

Non-Maxwellian Distribution function routinely observed in the solar wind



particle beam

pressure anisotropy

We can see our plasma as a almost collisionless long range interactions MANY BODY SYSTEM

Plasmas are the realm of long range collective interactions: binary interactions ("collisions") play a secondary, in some conditions even a negligible, role

Too many particles for a N-body description even for the last generation of super-computers

WE NEED A CONTINUOUS DESCRIPTION!

The idea is to use statistical description of a N particles system 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.

By assuming the particle kinetic energy is much larger than the typical potential energy due to its nearest neighbor, $E_k << \Phi$, we can simplify by using the reduced probability function $f_s(x_1,..,x_s,v_1,...,v_s)$ by integrating the d.f. allover the particles except 1 to s:

$$f_s(x_{1,}..,x_s,v_1,..,v_s) = \int F_n(x_{1,}..,x_{n,}v_1,..,v_{n,})\, dx_{s+1,}...,x_{n,}v_{s+1,}...,v_{n,}$$

The probability density contains the effects of the interactions among particles. Each particle interacts at first with the whole system while we neglect interactions with nearby particles

We need to reduce s as small as possible, i.e. to have particles

"quasi non-correlated"

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

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.

$$F_2(x_1, x_2) = F_1(x_1)\, F_1(x_2)\, [1 + \cancel{P_{12}(x_1, x_2)} \quad \cancel{+ \ldots\ldots}\ ]$$

P_{12} : *two particle correlation function*

In general, single particle interactions are assumed as negligible

EACH PARTICLE INTERACTS WITH THE FULL SYSTEM

IN OTHER WORDS THE DISTRIBUTION FUNCTION EVOLVES UNDER THE ACTION OF THE E.M. FIELDS GENERATED BY ALL PARTICLES

IN CONCLUSION, Plasma collisionless dynamics is described by The Vlasov equation for the $f^1(x,v,t)$ (3D-3V phase space)

(neglecting collisions)

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

Liouville equation in phase space

Here f_a is the ***distribution function*** *of a-species,* **E** *and* **B** *the electromagnetic fields self-consistently generated by the whole system*

The ***Vlasov equation****, self-consistently coupled to the Maxwell equations is the* ***basic model for a collisonless plasma***

FROM VLASOV TO FLUID

Macroscopic equations and variables are obtained as velocity moments of the d.f.;

why? because it is very difficult to solve the Vlasov equation

$$\int \mathbf{v}^n \left[\frac{\partial f_a}{\partial t} + \mathbf{v} \cdot \frac{\partial f_a}{\partial \mathbf{x}} + \frac{q_a}{m} \left(\mathbf{E} + \frac{\mathbf{v} \times \mathbf{B}}{c} \right) \cdot \frac{\partial f_a}{\partial \mathbf{v}} \right] d\mathbf{v} = 0$$

Continuity (n=0), Momentum (n=1), *and so on equations are obtained by integrating the* v^n *moment of the Vlasov equation.*

Number of particles, m=0

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

Current density, m=1

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

Pressure tensor, scalar pressure

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

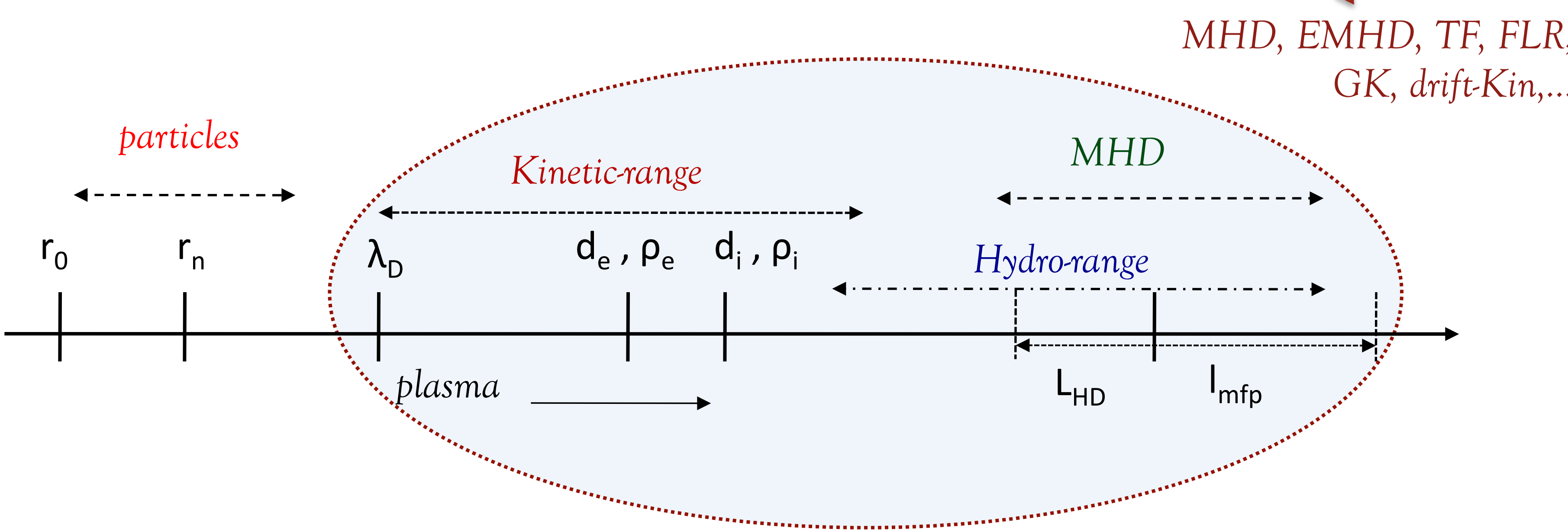
heat flux, ...

$$\mathbf{q}_a(\mathbf{x},t) = \frac{1}{2} m_a n_a \int |\mathbf{w}_a|^2 \mathbf{w}_a f_a(\mathbf{x},\mathbf{v},t)\; d\mathbf{v}$$

Even if a plasma is not a fluid !

.......closure problems.....

A plasma is a multi-scale (multi-frequency) system. Most of the models focus on a regime corresponding to a particular range of scales



$r_0 = e^2 / T$ [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 , ω_e = plasma freq.]

$\rho_{e/i} = v_{th,e/i}/\Omega_{ce,ci}$ [e/i Larmor radius, $\Omega_{ce,ci}$ = cycl. freq.]

L_{HD} ($\gg \lambda_D, \rho_{e/I}$) [hydro scale]

l_{mfp} [mean free path]

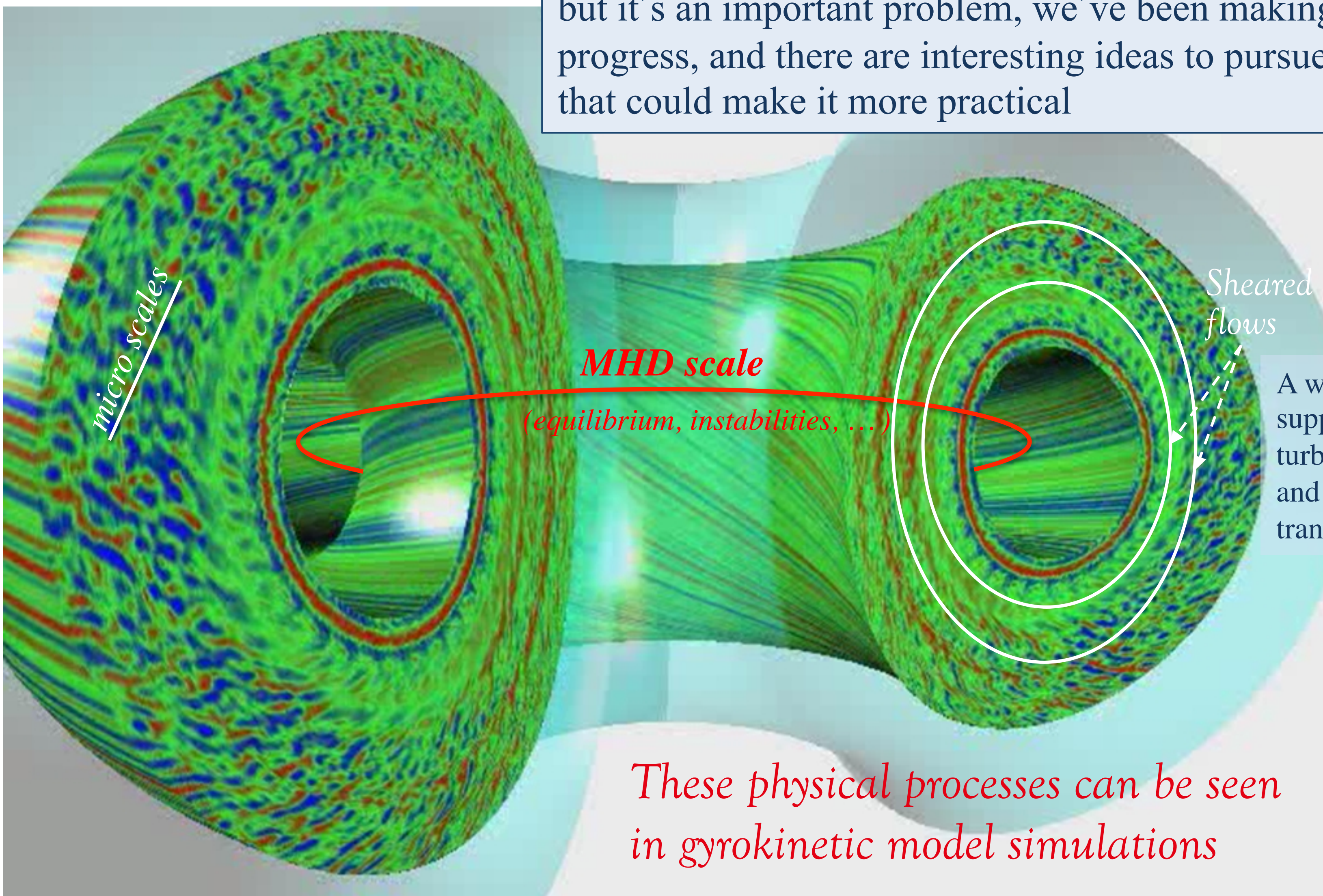
- $L \geq \lambda_D$

A plasma must be "larger" than the Debye lebgth (screening distance)

Turbulence, one of most important processes in plasmas, one of the best example of multi-scale physics

Here turbulence play a key role in transport

Fusion energy is hard and it will take a lot of time, but it's an important problem, we've been making progress, and there are interesting ideas to pursue that could make it more practical

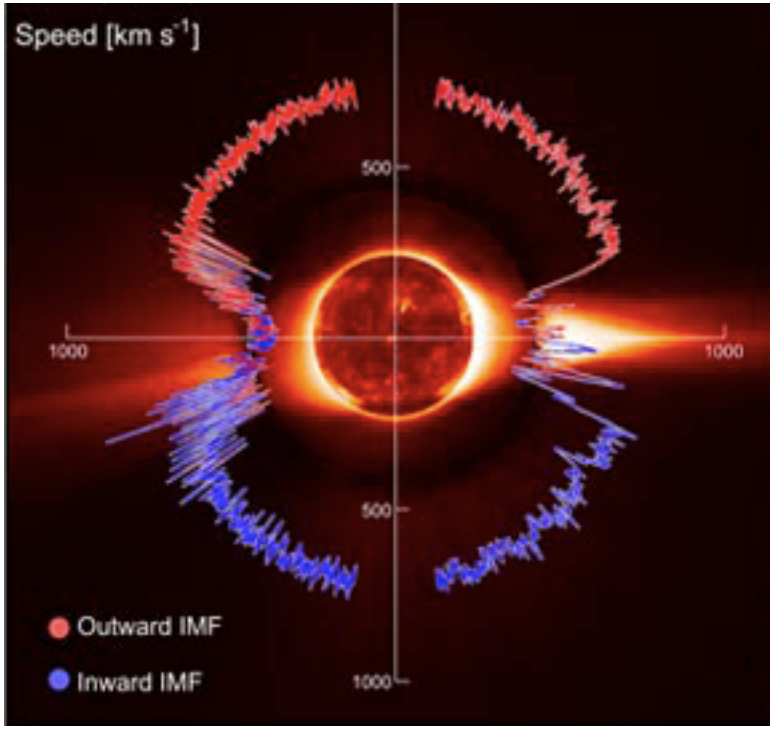


A way to suppress turbulence and so ion transport

These physical processes can be seen in gyrokinetic model simulations

Heating in space

The interplanetary plasma generated by the Sun and filling the Heliosphere, is known to be hotter than expected in an expanding plasma.

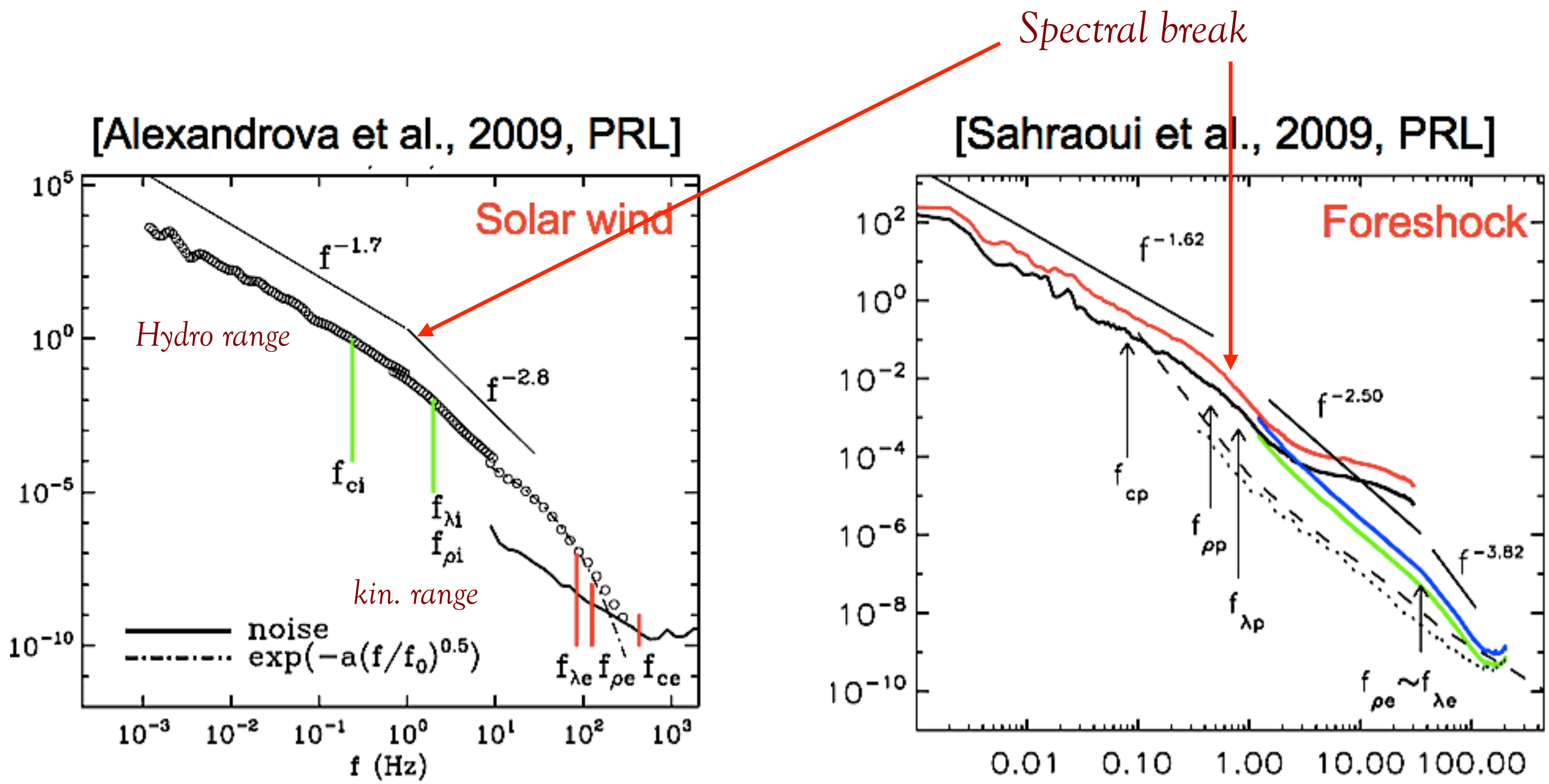


Solar Wind

Understanding how energy from the Sun can be "dissipated" into heat in such a collision-free system represents a top priority in space physics.

Here turbulence again play a key role

Turbulence at electron scales: Cluster observations

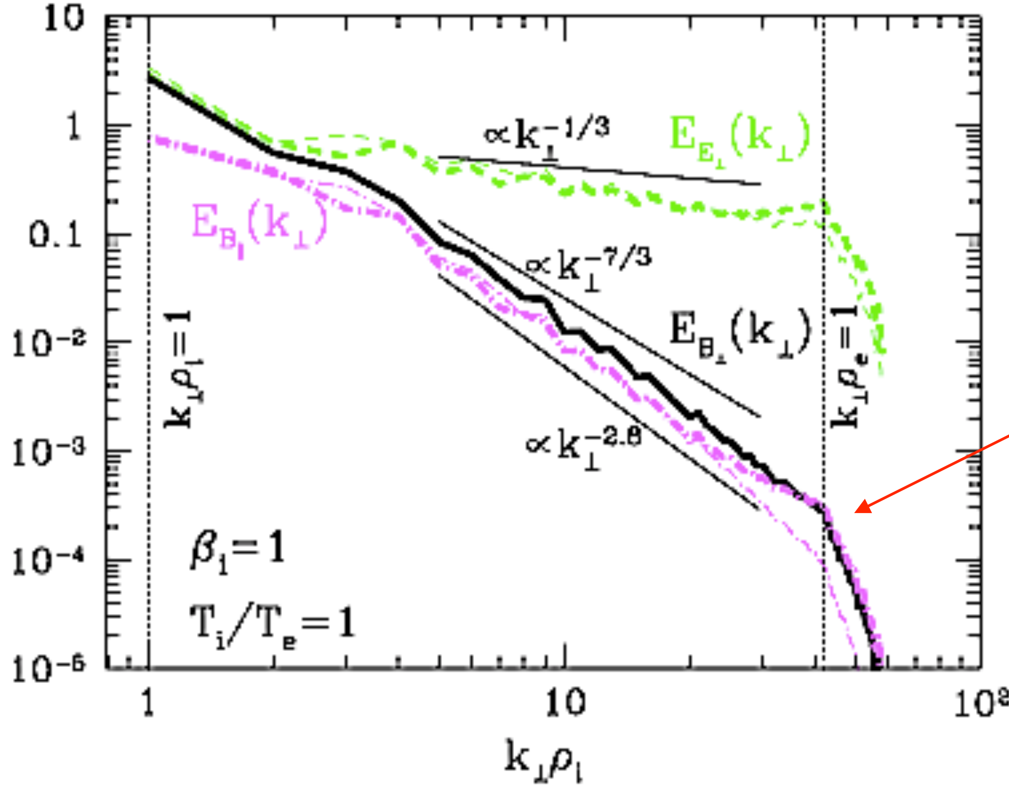


In the solar wind the energy cascade is supported primarily by Alfvén waves or Alfvénic fluctuations at MHD scales and by kinetic Alfvén waves (KAWs) at kinetic scales $k_\perp \rho_i \geq 1$.

Gyro-kinetic simulation of solar wind turbulence with correct mass ratio

(model developed in the laboratory context)

Howes et al., PRL, 2011



Kinetic Alfvén waves cascade can produce a nearly power-law behavior over the dissipation range.

Dissipation is due to resolved collisionless damping via Landau resonances.

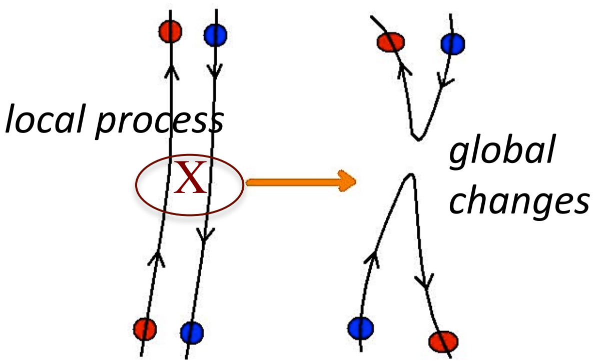
Thick lines: perpendicular and parallel magnetic (solid, dot-dashed), electric (dashed) energy spectra. Thin lines: perpendicular electric (dashed) and parallel magnetic (dot-dashed) energy spectra of the KAW model.

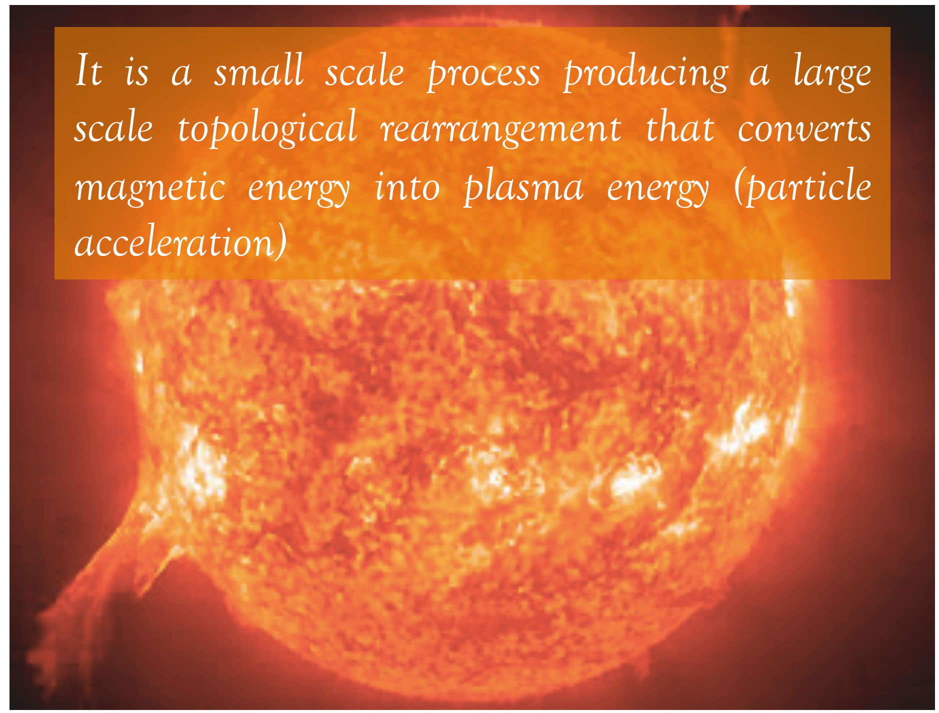
Magnetic Reconnection is also a multi-scale process

one of the most important processes in plasmas

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

reorganizes the ***large scale magnetic topology*** (laboratory)

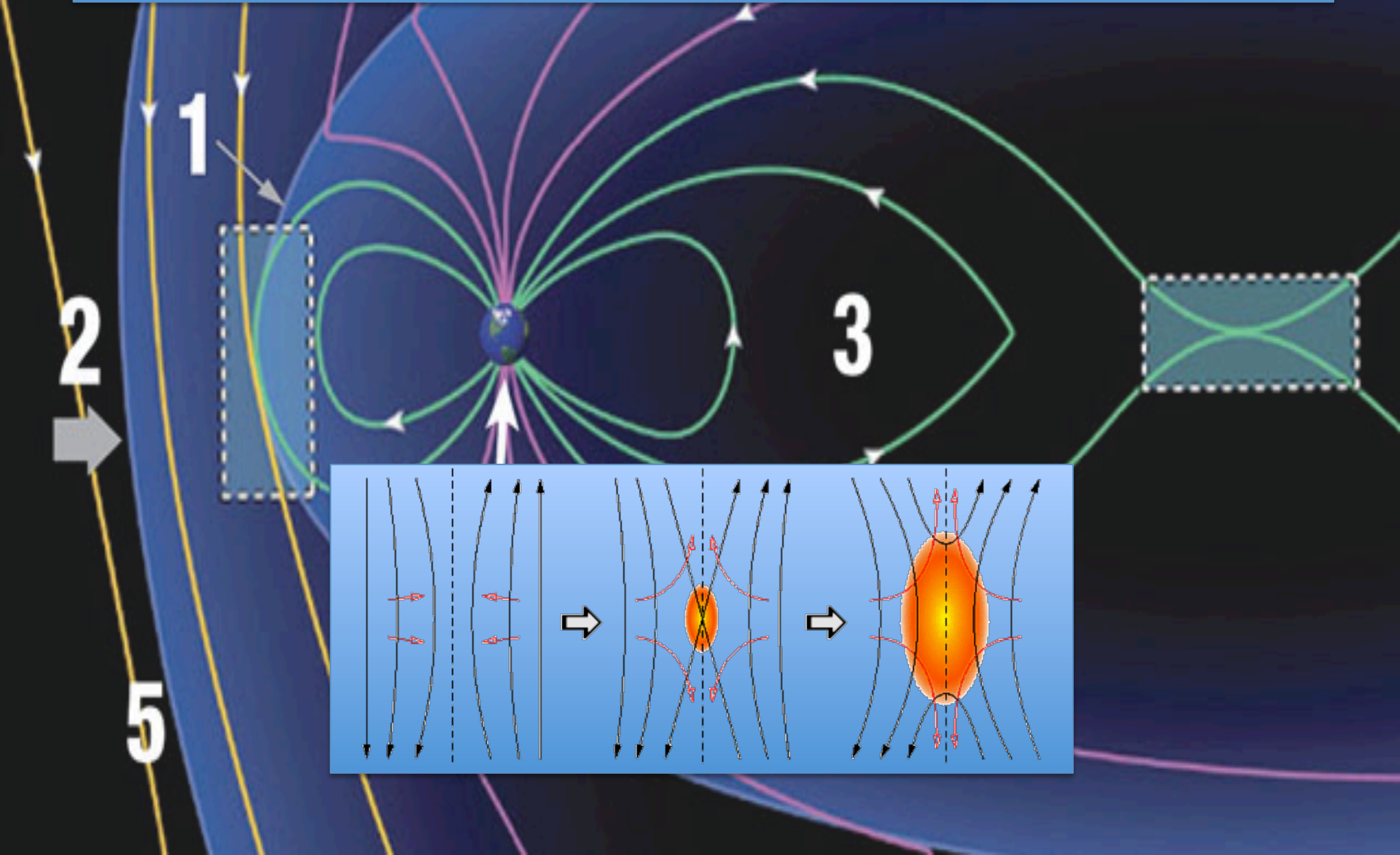




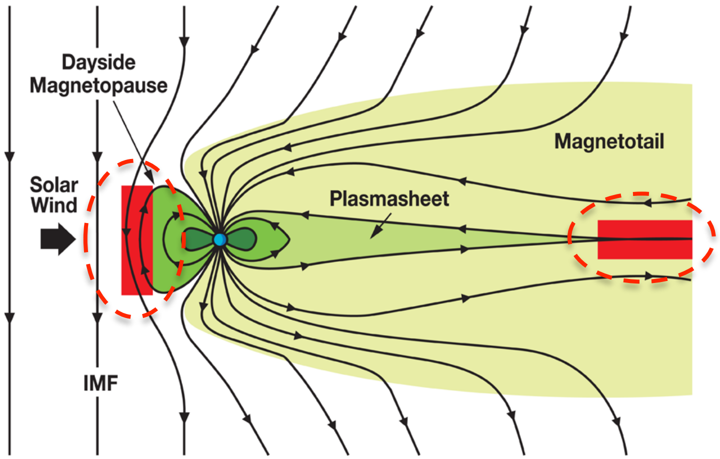
Release of the magnetic energy confined in the plasma can occur if the large-scale topological constraints get broken

Very strong and rapid energy release observed in space and laboratory

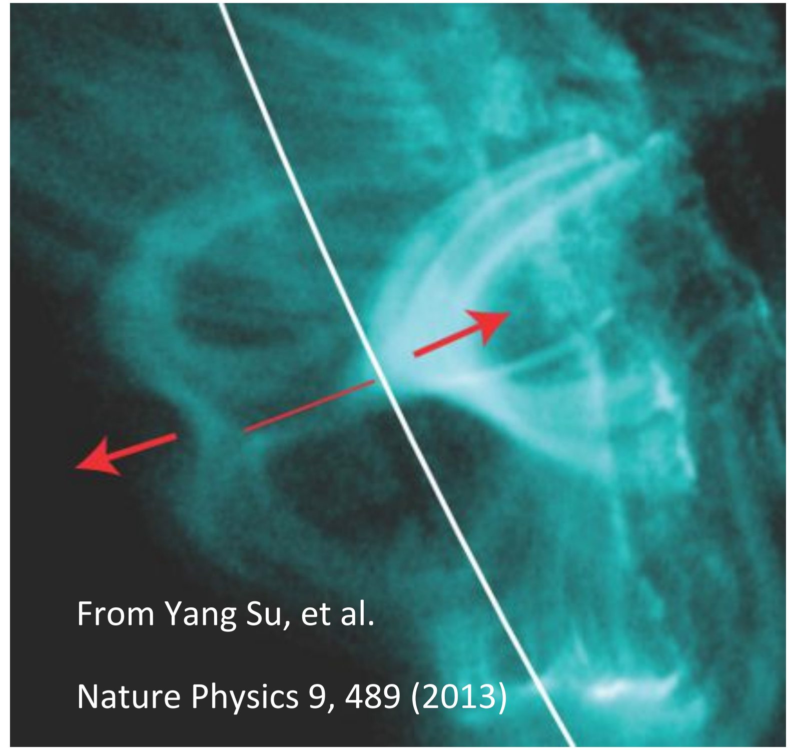
Magnetic reconnection is a physical process in highly conducting plasmas in which the magnetic topology is rearranged and magnetic energy is converted to kinetic energy, thermal energy, and particle acceleration.



Reconnection in space



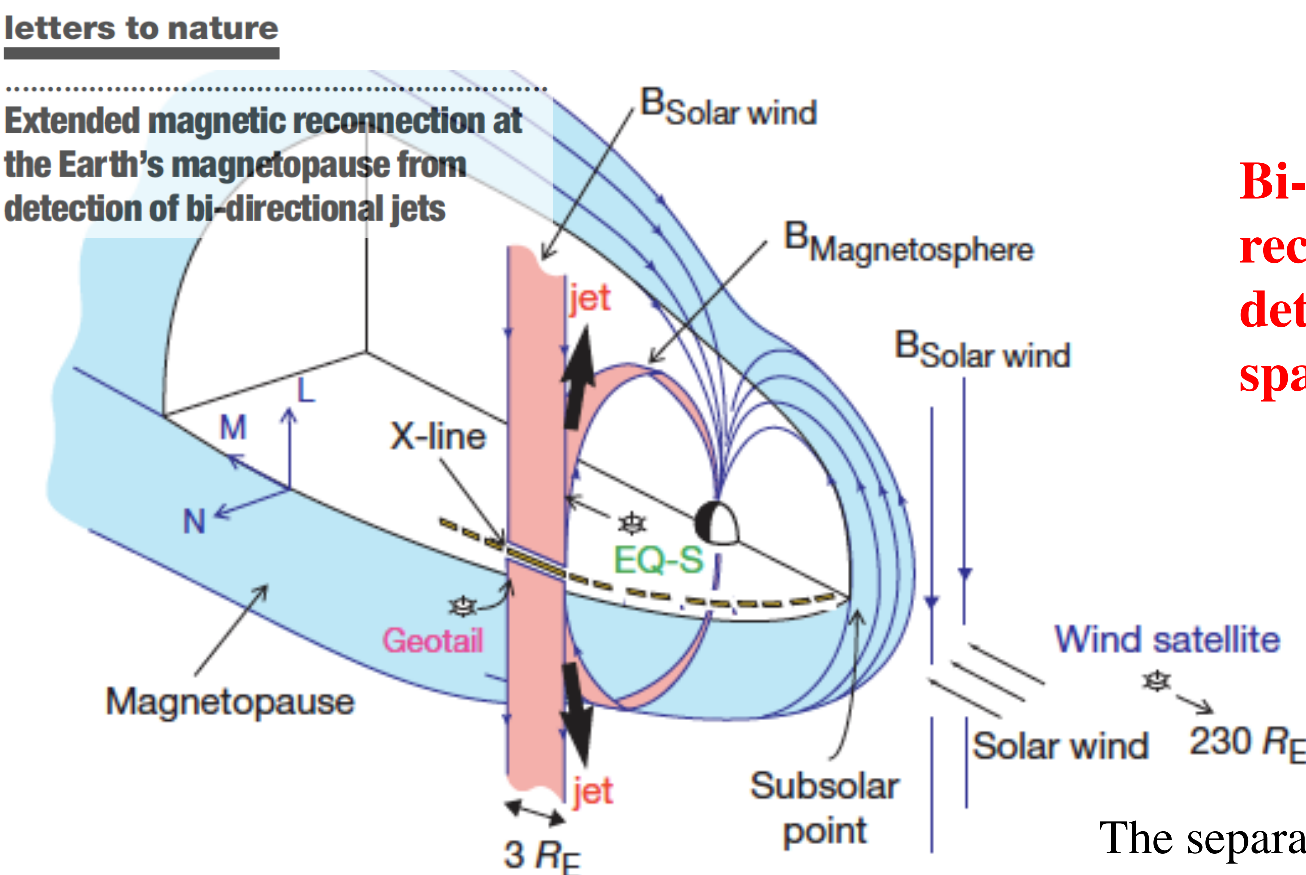
magnetic reconnection is responsible for solar wind plasma transfer into the magnetosphere, magnetic sub-storms, acceleration of beam particles, …



"The flare, which occurred on 17 August 2011 lasted about 20 minutes. It was ideally positioned at the edge of the visible solar disk (white curve). Loops of hot plasma pinned to magnetic field lines were seen to move from opposite sides toward the red line, reconnect, and flow outward in the directions of the red arrows.

Reconnection is believed to be the dominant process by which solar-wind energy enters the Earth's magnetosphere

This energy is subsequently dissipated by magnetic storms and aurorae



Three-dimensional cutaway view of the magnetosphere showing the spacecraft positions and the presence of an extended reconnection line.

Bi-directional reconnection jets detected at both spacecraft locations

The separation between the Geotail satellite and the Equator satellite was 4 R_E in the north-south And 3 R_E in the east-west direction.

Reconnection in laboratory

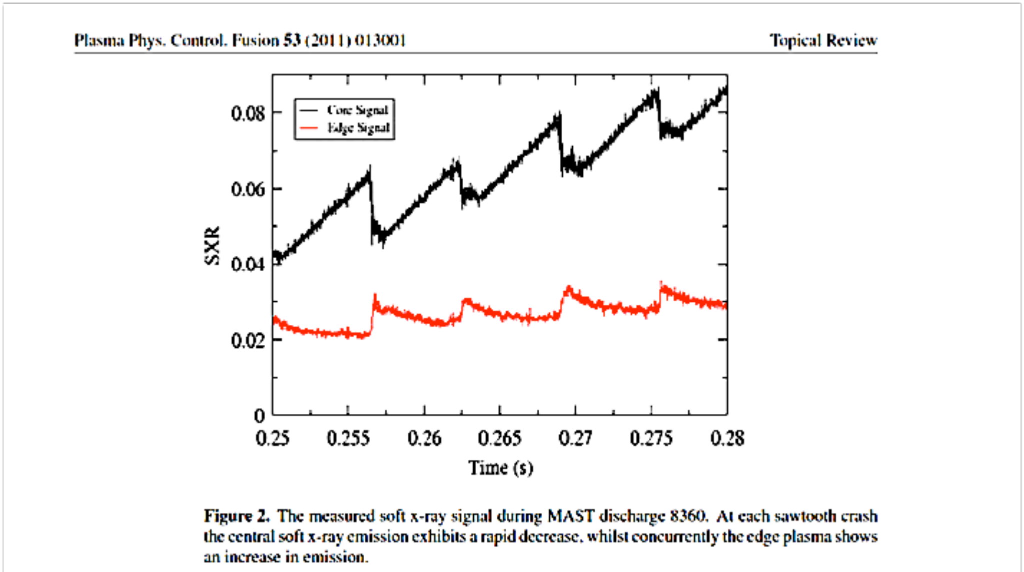
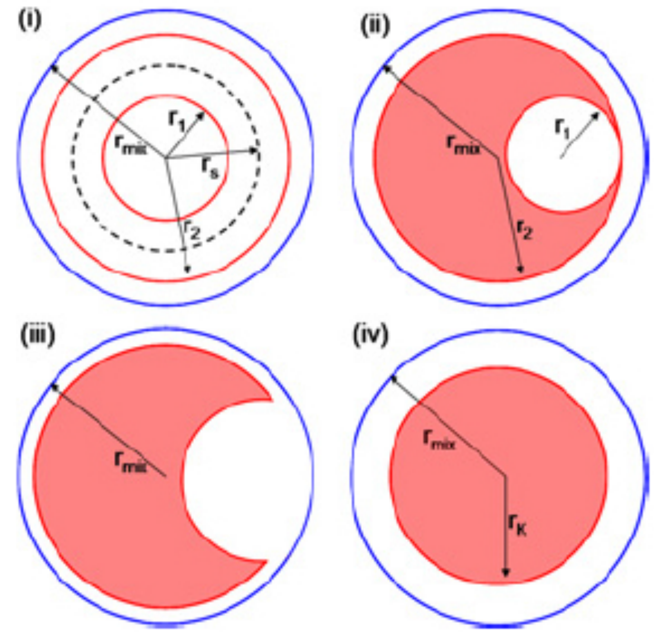

Plasma Phys. Control. Fusion 53 (2011) 013001 Topical Review

Figure 2. The measured soft x-ray signal during MAST discharge 8360. At each sawtooth crash the central soft x-ray emission exhibits a rapid decrease, whilst concurrently the edge plasma shows an increase in emission.

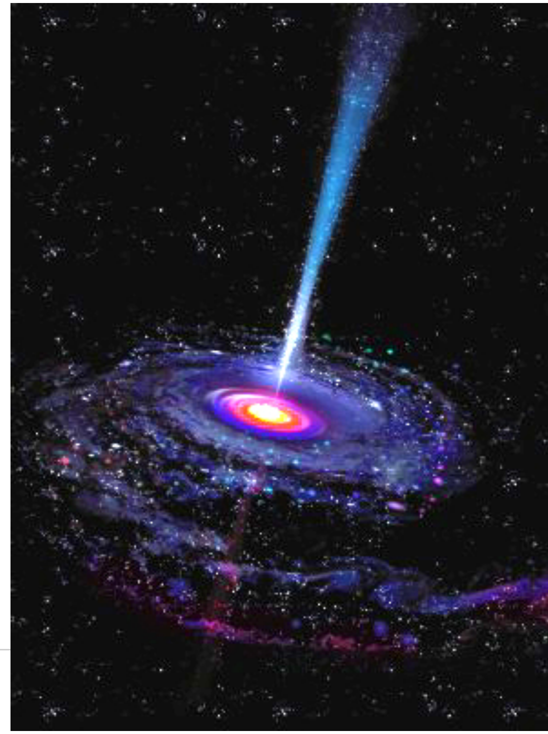


Magnetic and thermal energy release in a series of reconnection events in a toroidal fusion plasma. The change of magnetic topology makes a "punch" in the magnetic confinement. This allows the hotter central part of the plasma to escape towards the plasma boundaries.

A poloidal cross section of the plasma torus is shown at successive times. The magnetic field lines of the un-reconnected configuration follow helices that wind up on nested toroidal surfaces. The circles in frame i) are poloidal sections of such surfaces

Reconnection in Astrophysics

An accretion disc is a structure formed by diffuse material in orbital motion around a massive central body(typically a star). Gravity causes material in the disc to spiral inward towards the central body



Dynamo theory, based on small scale reconnection, describes the process through which a rotating, convecting, and electrically conducting fluid can maintain a magnetic field over astronomical time scales

THE ASTROPHYSICAL JOURNAL, 773:118 (16pp), 2013 August 20

637X/77

PARTICLE ACCELERATION DURING MAGNETOROTATIONAL INSTABILITY IN A COLLISIONLESS ACCRETION DISK

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Received 2013 May 16; accepted 2013 June 25; published 2013 August 1

ABSTRACT

Particle acceleration during the magnetorotational instability (MRI) in a collisionless accretion disk was investigated by using a particle-in-cell simulation. We discuss the important role that magnetic reconnection plays not only on the saturation of MRI but also on the relativistic particle generation. The plasma pressure anisotropy of $p_\perp > p_\parallel$ induced by the action of MRI dynamo leads to rapid growth in magnetic reconnection, resulting in the fast generation of nonthermal particles with a hard power-law spectrum. This efficient particle acceleration mechanism involved in a collisionless accretion disk may be a possible model to explain the origin of high-energy particles observed around massive black holes.


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> di confrontarsi con due diverse culture accademiche

> di inserirsi nella rete di collaborazioni scientifiche italo - francesi

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Per maggiori informazioni

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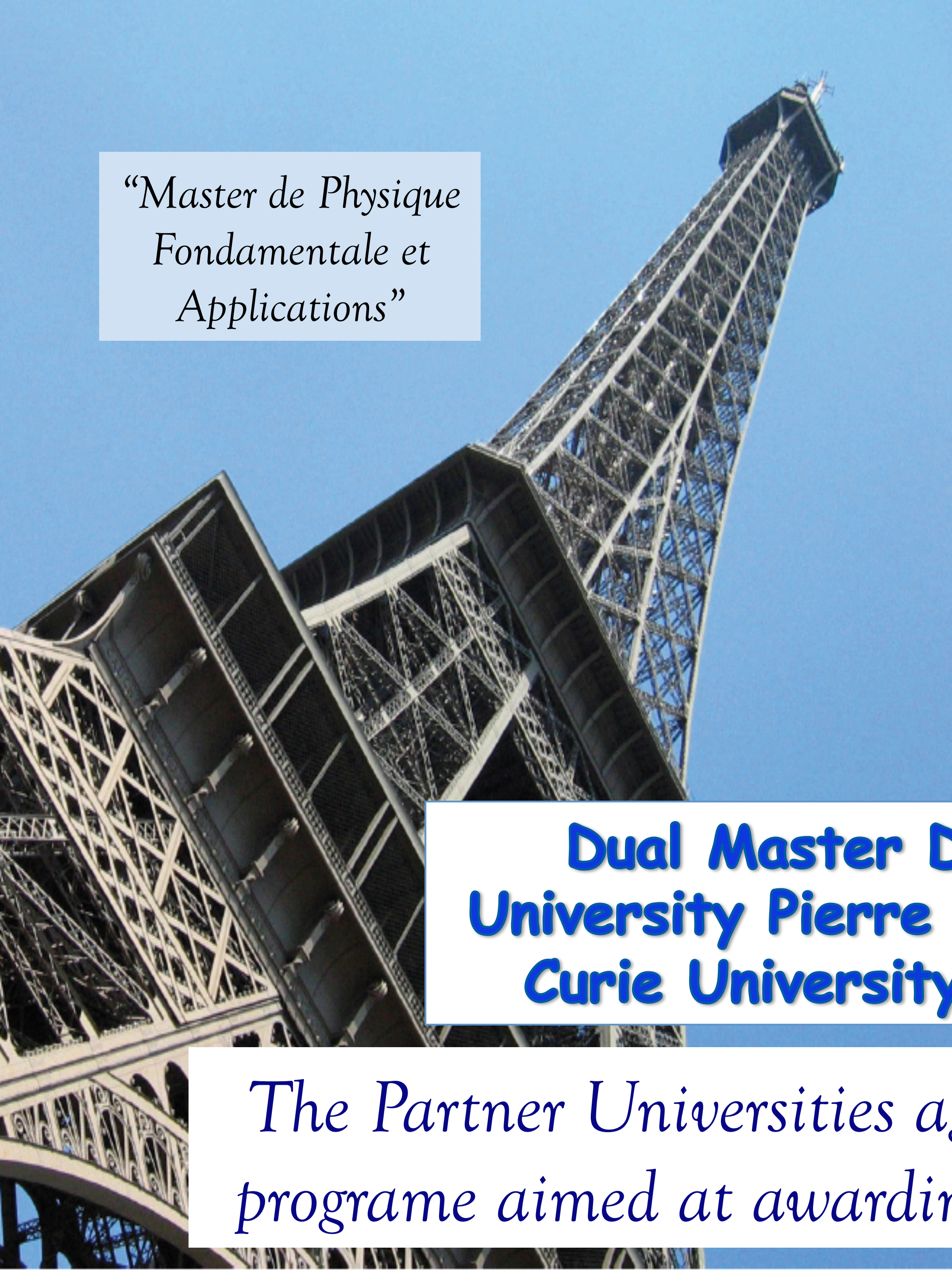
PLAS@PAR Plasmas à Paris

IN SUPREMÆ DIGNITATIS 1343 UNIVERSITÀ DI PISA

UPMC SORBONNE UNIVERSITÉS



"Master de Physique Fondamentale et Applications"

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Dual Master Diploma University Pierre and Marie Curie University of Pisa

The Partner Universities agree to start a joint programe aimed at awarding a ***Dual Degree***

Dual Master Diploma
Students of the University of Pisa

First year in Pisa (fundamental courses)

CURRICULUM Structure of Matter - Plasmas, M2 at UPMC (Paris) Pisa students				
ITALIAN STUDENT First year (PISA) 60 ECTS. At least 51 before departure (60 before February)				
Numero	**Denominazione**	**SSD**	**ECTS**	**CFU TOTALI**
COURSES (mandatory)				
1	Struttura della Materia 2	FIS 03	9	9
1	Laboratorio di Ottica Quantistica	FIS 01	12	12
1 at choice	Fisica Teorica 1	FIS 02	9	9
	Fisica Statistica	FIS 02	9	
1 at choice	Fisica dello Stato Solido	FIS 03	9	9
	Fluidodinamica	FIS 03	9	
4	**TOTAL ECTS**			**39**
COURSES at choice				
	TOTAL ECTS			**21**
TOTAL First year ECTS (at least 51 to leave)				60

I ANNO STUDENTE UNIPI (60 crediti)

Second year in Paris (Master Thesis in plasma physics)

I SEMESTER (mandatory) **24 ECTS**. Exams in december (if problems at max before May)				
2014	Introduction à la physique des Plasmas	UE1	3	
2015 and following year	Outils pour les Plasmas et la Fusion	TC1	3	
2014	Théorie cinétique	UE2	3	
2015 and following year	Théorie Cinétique	TC3	3	
2014	Modélisations fluides des plasmas	UE3	3	
2015 and following year	Modélisation et simulation	TC5	3	
2014	Magnétohydrodynamique	UE4	3	
2015 and following year	Magnétohydrodynamique	TC2	3	
2014	Plasmas spatiaux	UE5	3	
2015 and following year	Ondes et Instabilités	TC4	3	
2014	Concepts fondamentaux en physique des plasmas froids	UE6	3	
2015 and following year	Physique atomique, moléculaire et rayonnement	TC7	3	
2014	Instrumentation, diagnostics et analyse des plasmas	UE7	6	
2015 and following year	Instrumentation, diagnostics et analyse des plasmas	TC6	6	
	UE7 ou TC6 : 6 ECTS will be counted as Stage/Thesis preparation in the second semester		-6	
	Totale ECTS		18	
II SEMESTER - Stage/Thesis from January first to end of August				
	Stage (Master Thesis)	1 January	36	36
		-31 August		
	6 ECTS counted as Stage/Thesis preparation in the first semester		6	6
	Totale ECTS			**42**
TOTAL Second year ECTS				**60**

A Tutor from UNIPI will follow the student career at UPMC

II ANNO STUDENTE UNIPI (60 crediti)

GRAZIE!