



Convection Processes in Astrophysics, Fusion and Laboratory plasmas

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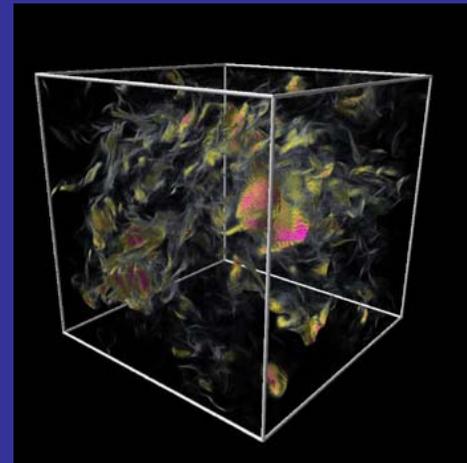
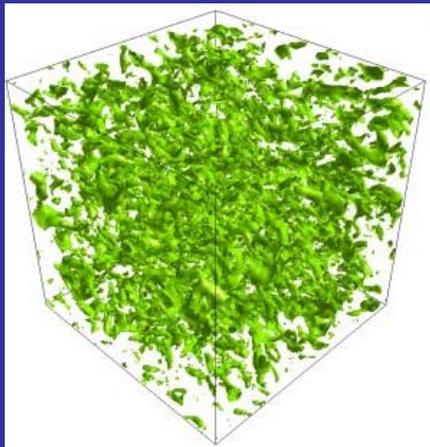
American University of Beirut



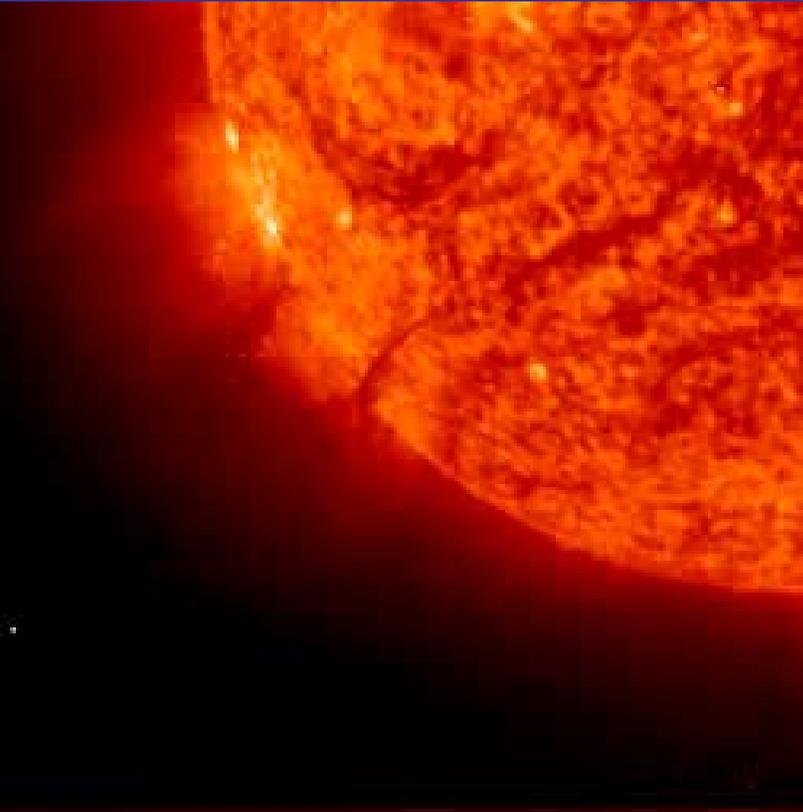
- Convection and intermittency in space plasmas
- Convection and intermittency in Laboratory Plasmas
- Convection and intermittency in Magnetic Fusion Plasmas

Definitions: Convection and Intermittency

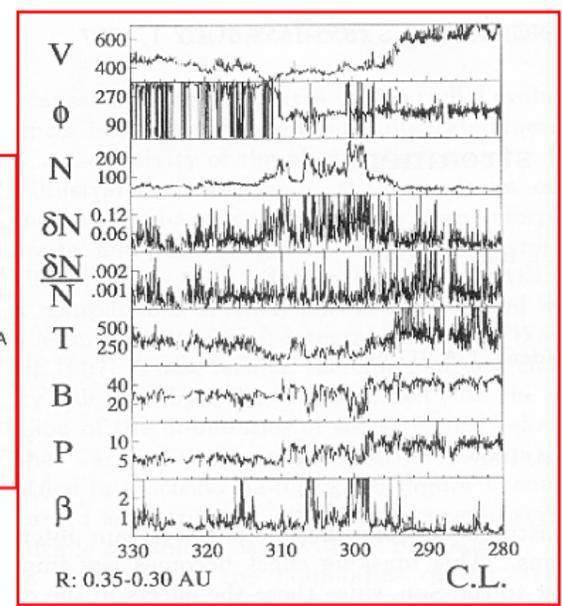
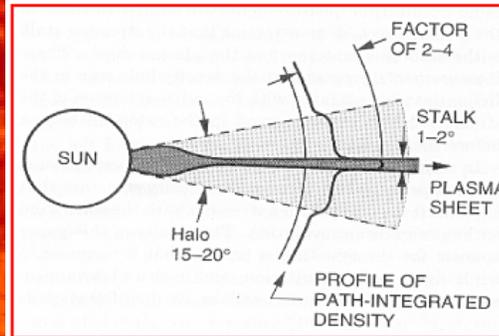
- Convective events denote here structures with large velocities with respect to the background, therefore, the Galilean transformation, $\mathbf{r} \rightarrow \mathbf{r} + \mathbf{v}t$ does **not** hold.
- Intermittency is a term that describes phenomena with dynamics deviate from a Gaussian random process.



Large Twisting Prominence in the Sun: Events that are intermittent and Convective



The configuration of a helmet streamer and the density profile across this structure

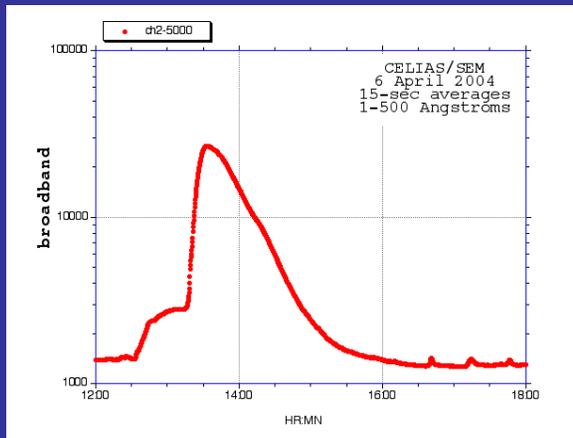
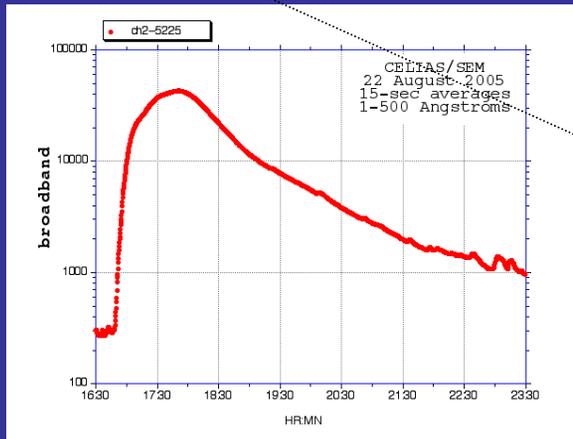


From top to bottom: wind speed, magnetic field azimuthal angle, proton number density, density fluctuations and normalized density fluctuations, proton temperature, magnetic field magnitude, total pressure, and plasma beta, respectively

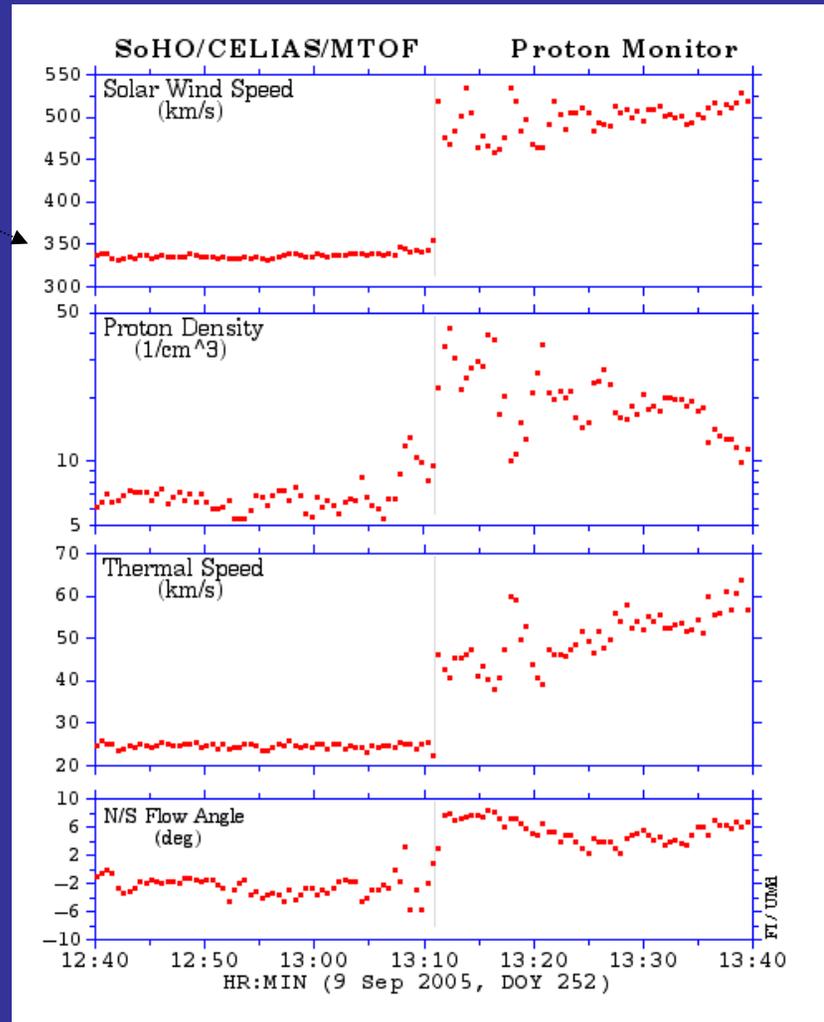


Solar Flares temporal signature and shocks

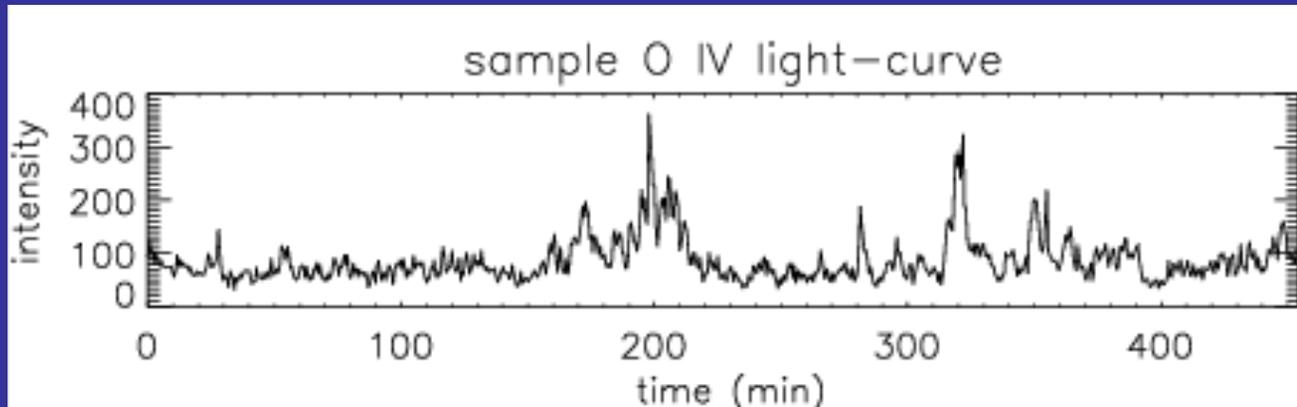
X17.0 x-ray flare in AR0810 with a 3B optical flare at S06E89, leading to a shock 43.5 hours later on 09 Sep 2005 (DOY 252) at 1310 UT.



M2.4 x-ray flare in AR0588 and a sub optical flare at S18E15



Intermittency seems to occur inside and outside the sun

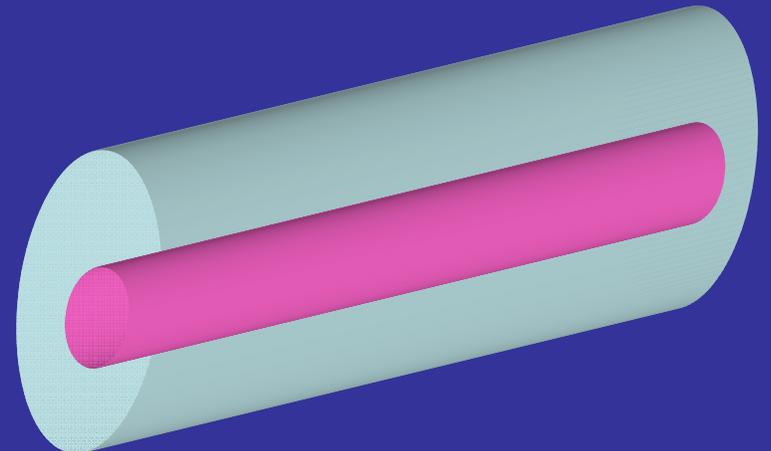
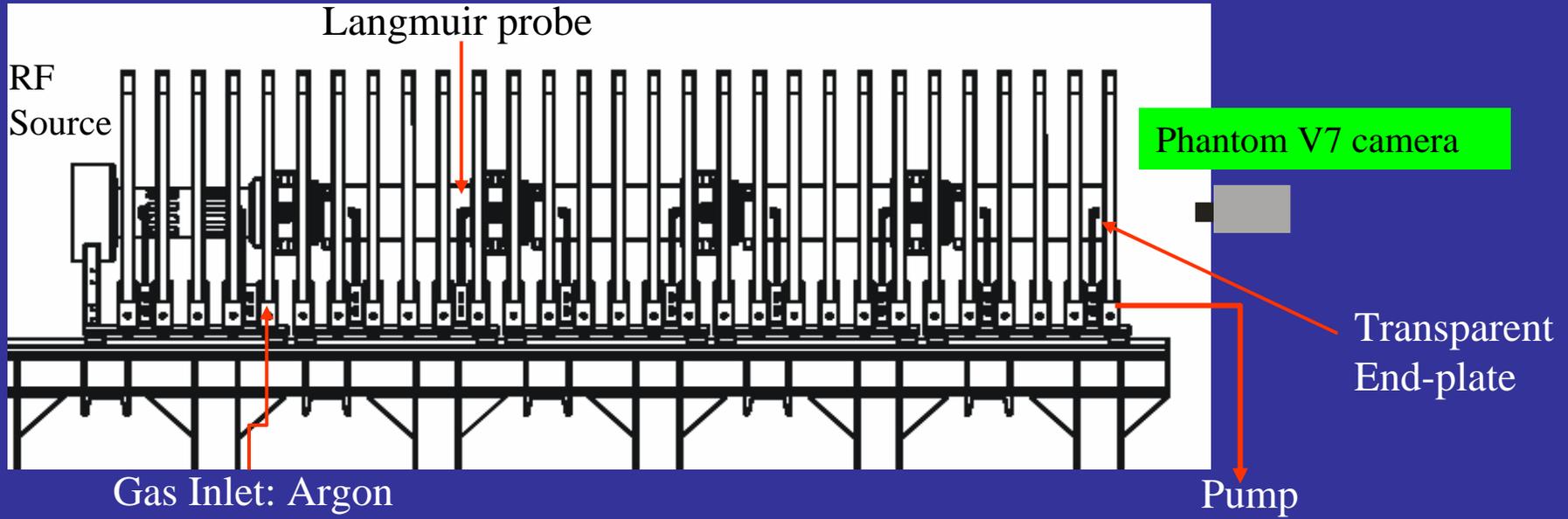


O IV transition region recorded in a quiet Sun region by SUMER/SOHO.

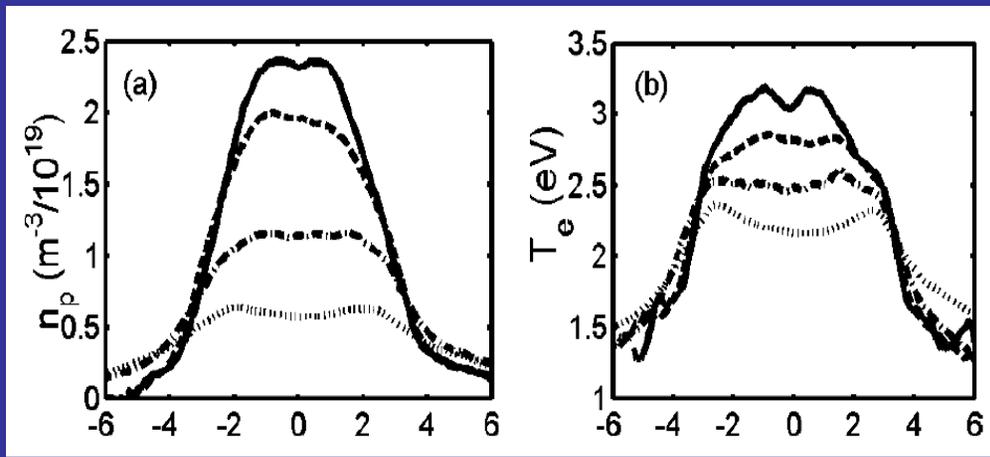
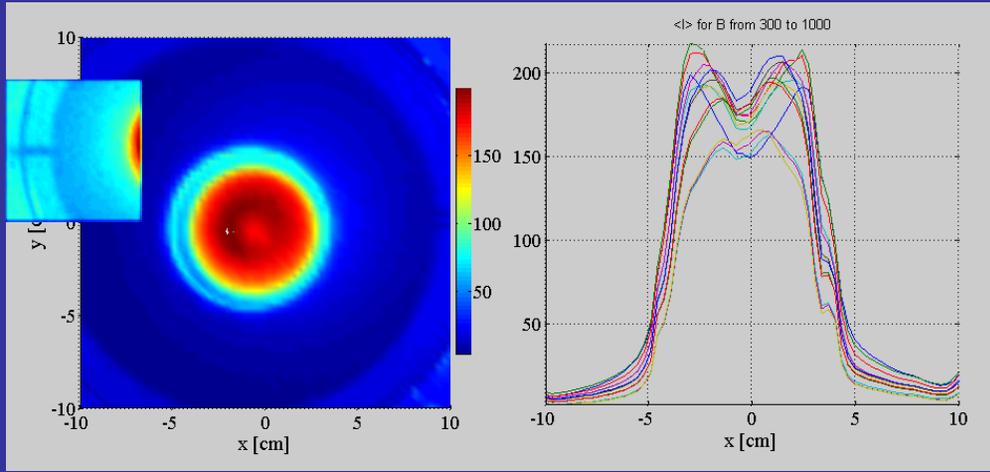
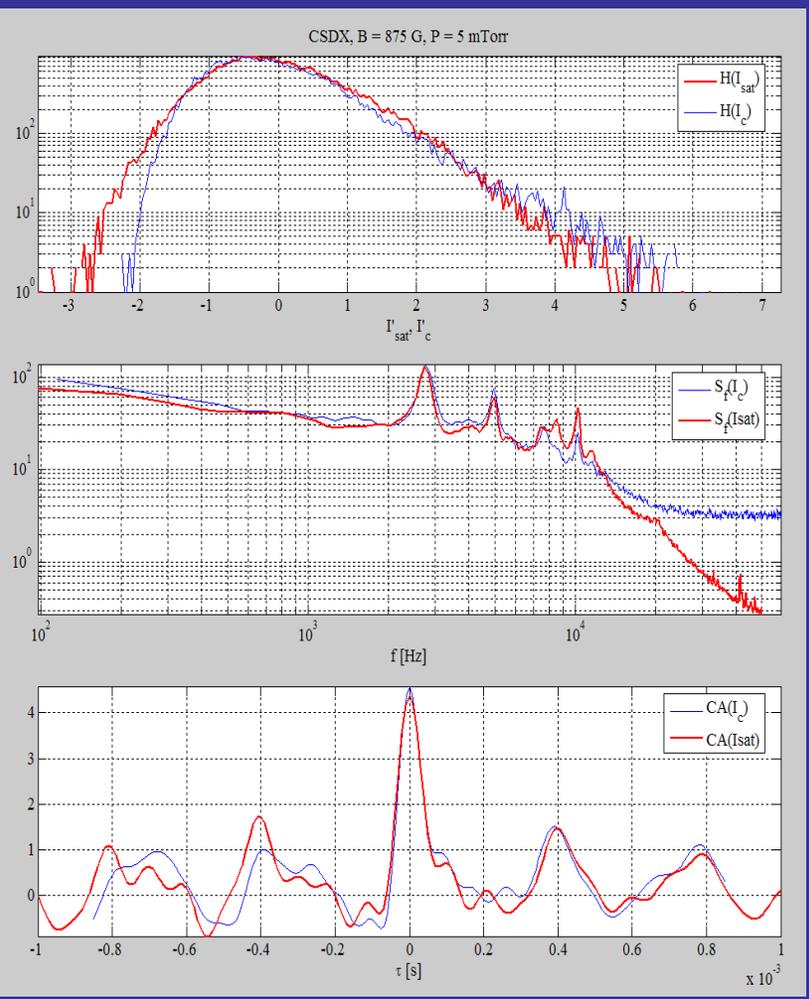
It was found that a significant proportion of points in the observed area exhibit clear indications of intermittency, irrespectively of their intrinsic intensity.

S. Patsourakos - J.-C. Vial, *Astronomy & Astrophysics*, 2002

Linear Plasma Devices (CSDX, PISCES)



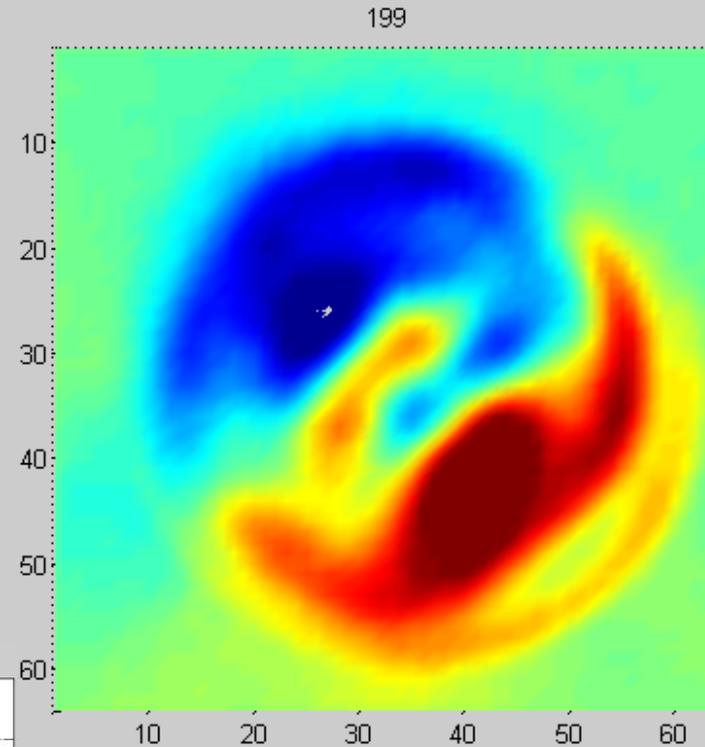
Good agreement between the images profiles and fluctuations and those done using Langmuir probe for scales above 3 mm



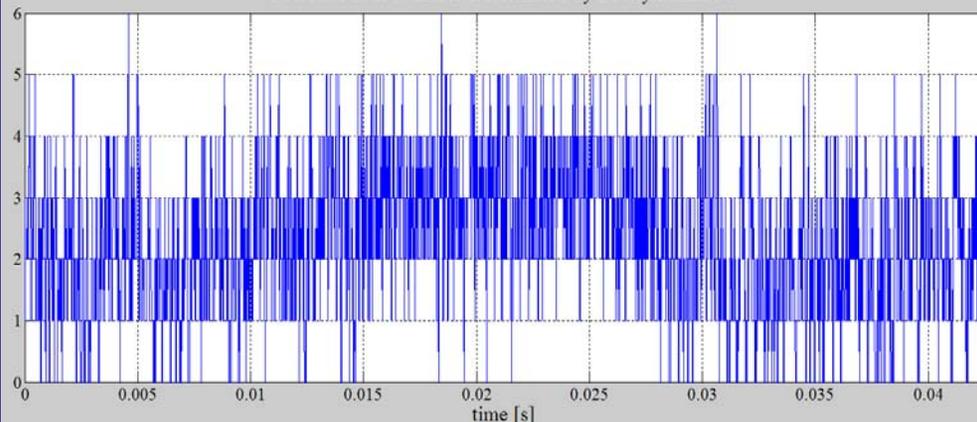
M. Burin et al PoP 2004

Inside the main plasma column

- The system transits from low to high mode number fluctuations in time and can remain in one of the modes for relatively long time.
- One can no longer speak of “stationary turbulence”...
- No evidence of zonal flows were observed in the movies.



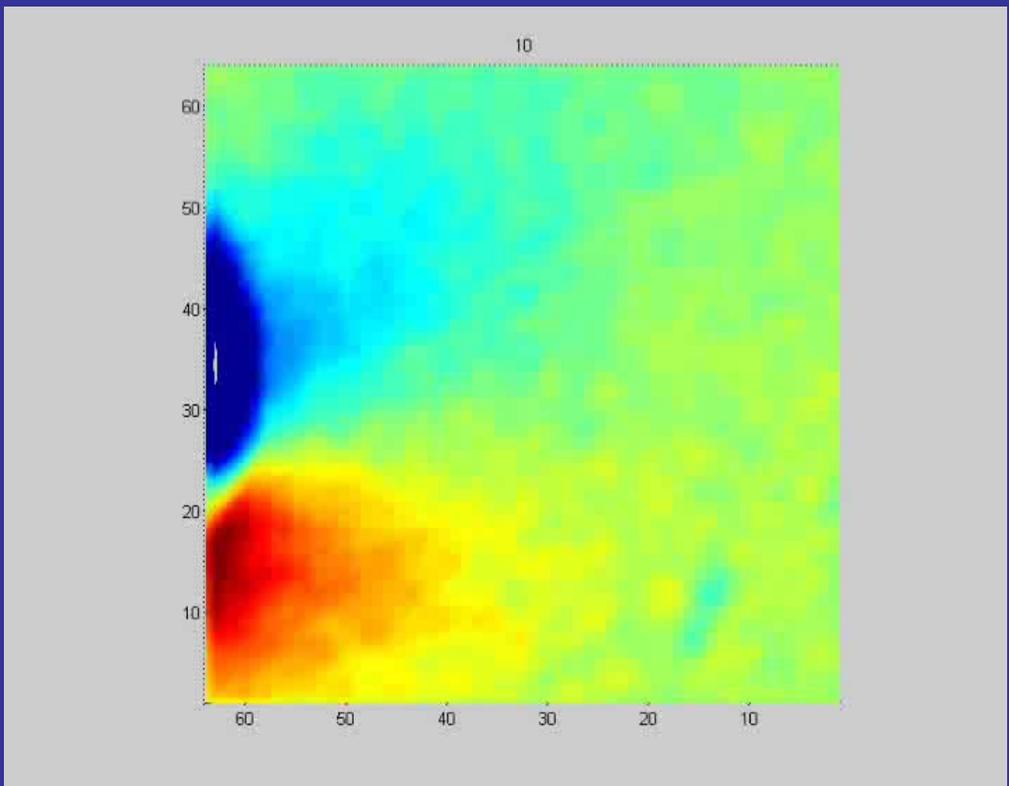
Poloida Mode Number Determined by a Polynomial Fit



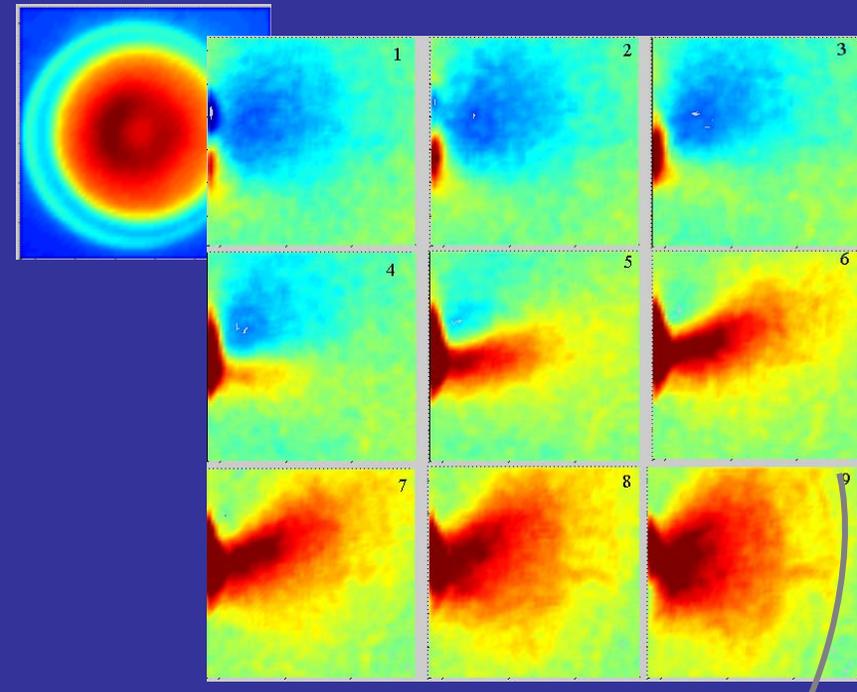
Camera settings:
Integration time 1 μ s
Time between frames 15 μ s
32x32 pixels

Fast Imaging allows the observation of the growth of avaloids, their scale lengths and velocities

No detachment of the structure, hence, it is not a “blob” but rather has a finger-like shape



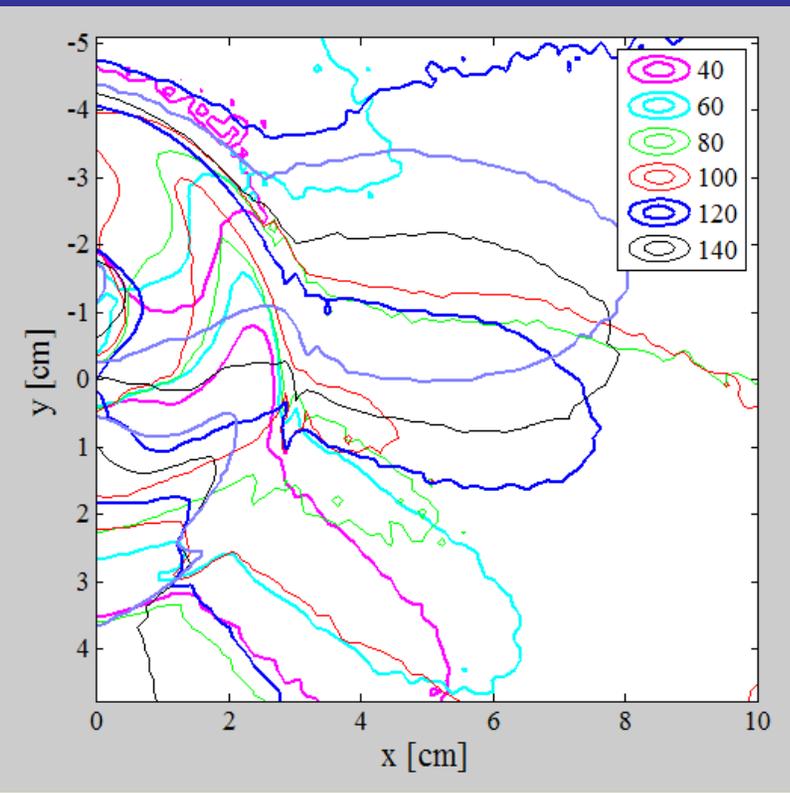
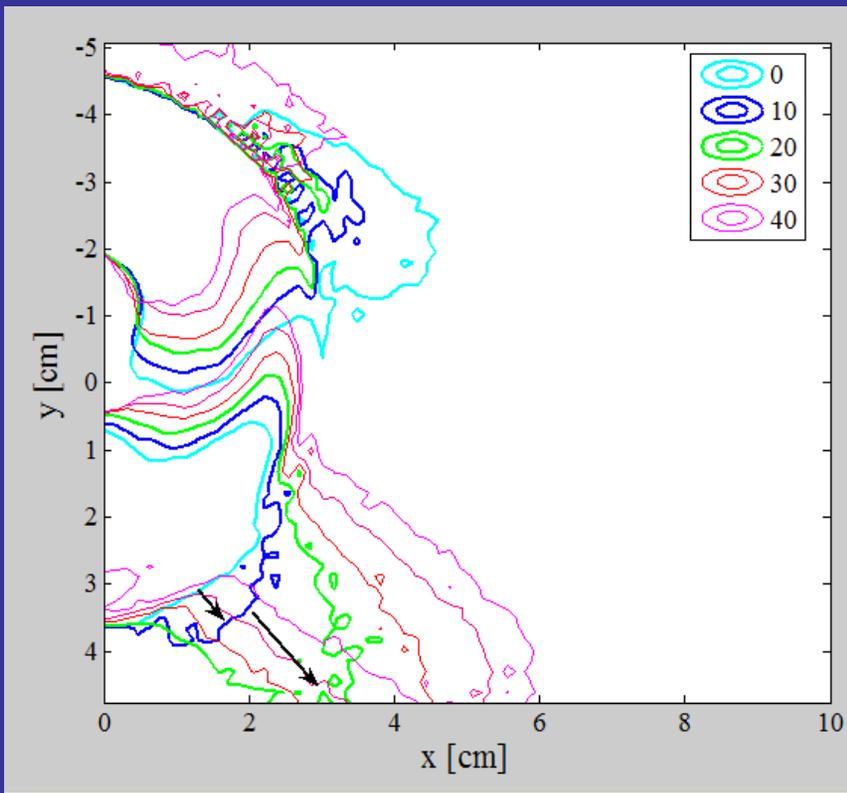
Camera setting:
Integration time 1 μ s
Time between frames 15 μ s
32x32 pixels



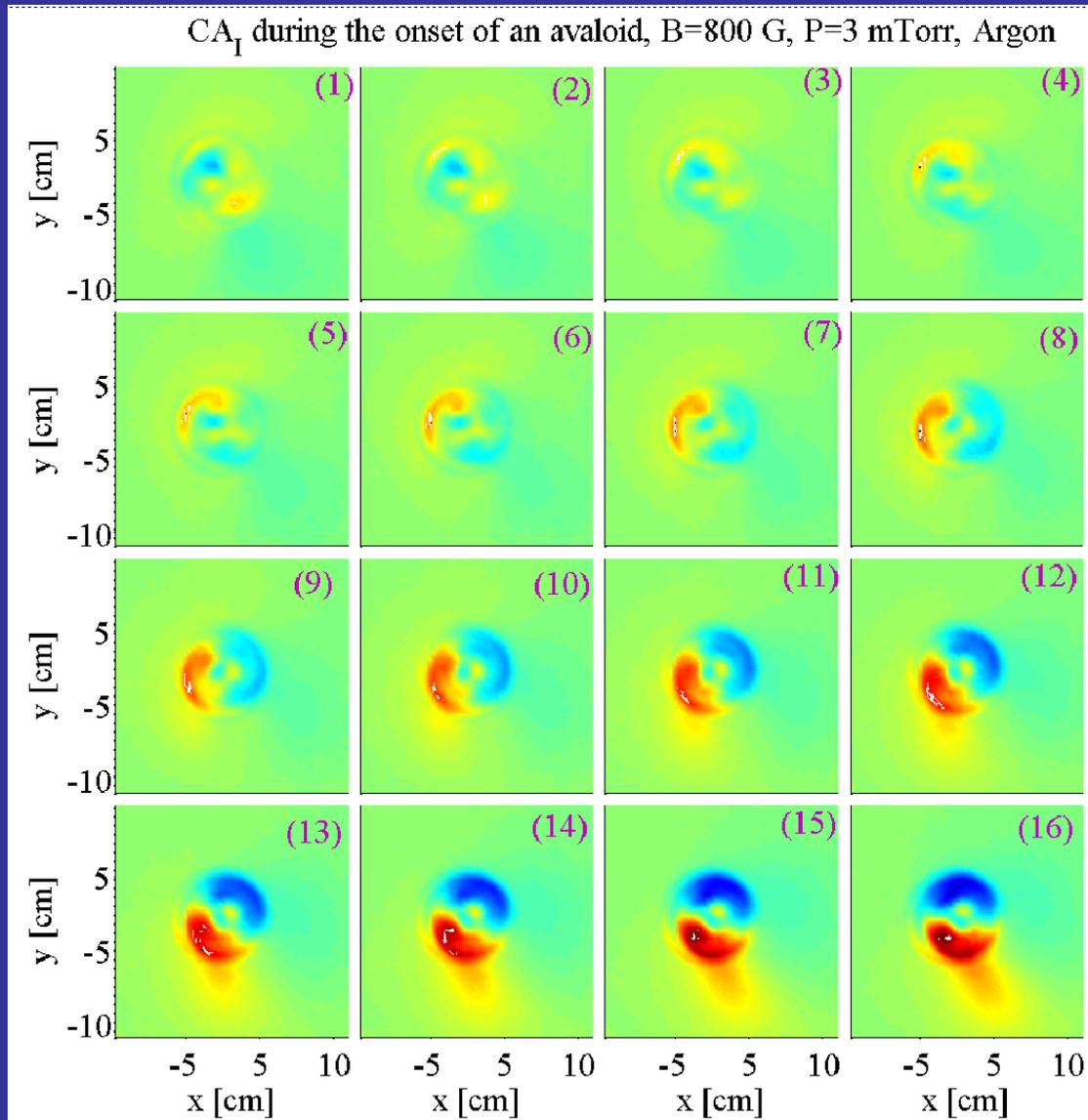
The vessel wall

From an “average movie” imaging half the main plasma column and the SOL, the convective structures properties are:

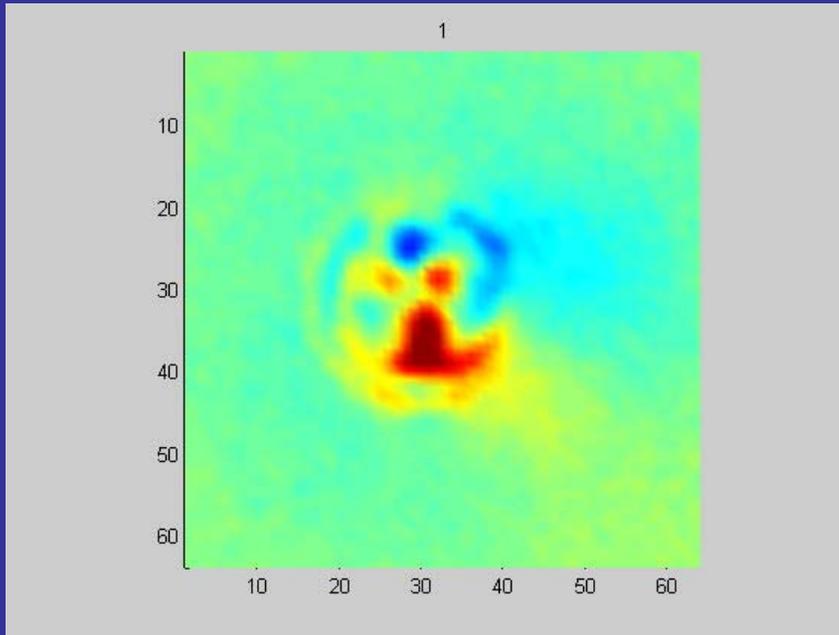
- Life-time $\sim 60 \mu\text{s}$;
- $L_{r,\text{avaloid}} \sim 5 \text{ cm}$;
- $L_{\theta,\text{avaloid}} \sim 2 \text{ cm}$; $V_{r,\text{avaloid}} \sim 10^5 \text{ cm/s}$
- $V_{\theta, \text{main plasma}} \sim 4.5 \times 10^4 \text{ cm/s}$
- $V_{\theta,\text{avaloids}} \sim 4.5 \times 10^4 \text{ cm/s}$



The conditionally averaged movie reveals that the onset of avaloids is associated with the non-linear evolution of the poloidal number $m=1$ instability.



Comparing Laboratory Plasma to SOHO



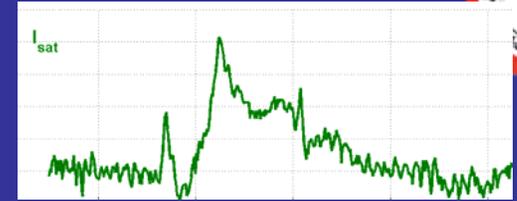
Linear plasma device: Plasma in the far SOL exists during and because of avaloids



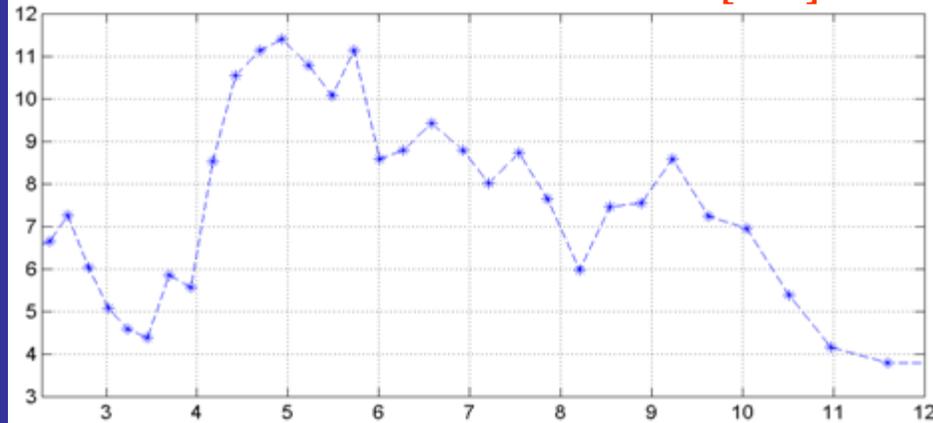
The sun: Plasma in far space exists during and because of the solar flares

Furthermore: Because of the flat profiles and damping caused by the connection to the target plates, turbulence around the separatrix is the main cause of turbulence in the SOL

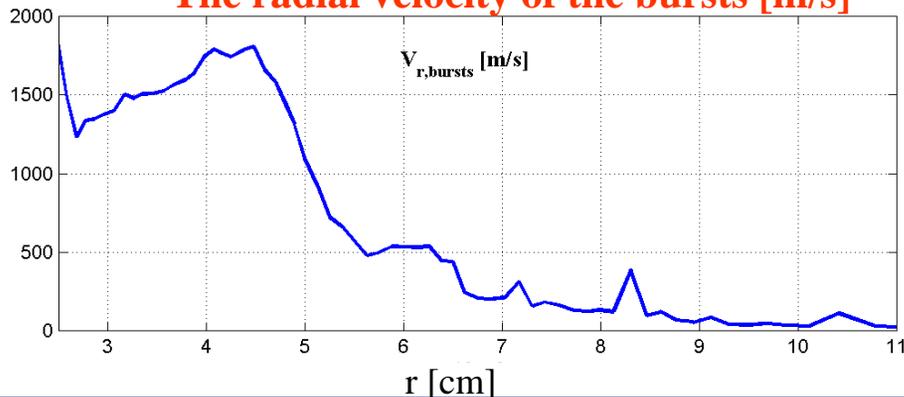
The bursts radial velocity is far from being negligible reaching 1/10th of the sound speed. The radial scale of the bursts is about 1 cm



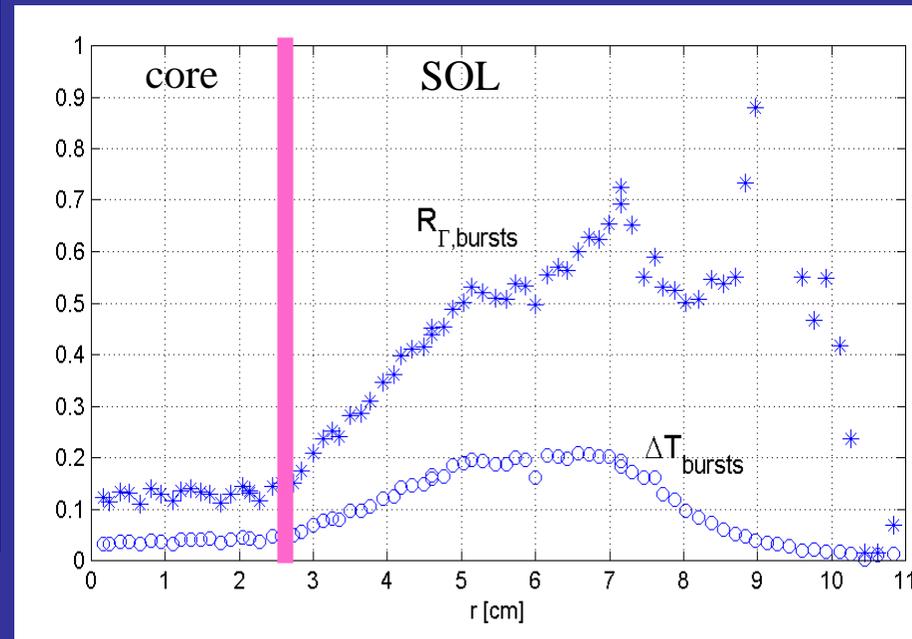
The radial scale of the bursts [mm]



The radial velocity of the bursts [m/s]



Intermittent Bursts Contribute to about 50% of the total radial transport while occupying only 20% of the total duration of the signals

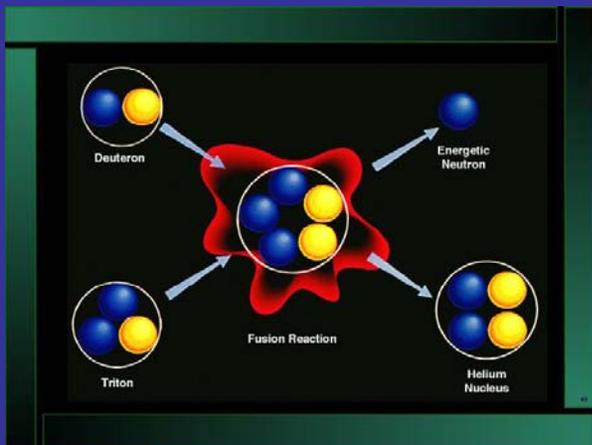


AVALOIDS are defined as large-scale concentration of density with high radial velocity encountered intermittently in the scrape-off layer

Fusion for energy production



Numbers to keep in mind



Reaction		Ignition Temperature		Output Energy
Fuel	Product	(millions of °C)	(keV)	(keV)
D + T	$^4\text{He} + n$	45	4	17,600

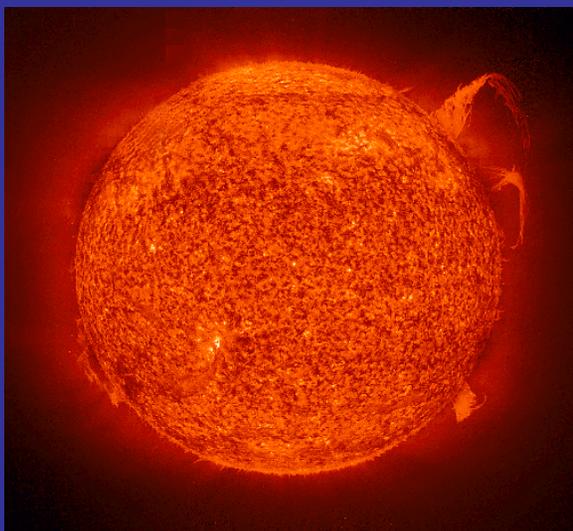
Abundant Energy From Sea Water

50 Cups Sea Water = 2 Tons of Coal

or

Thimble of ^2H (D) Deuterium = 20 Tons of Coal

Magnetic fusion



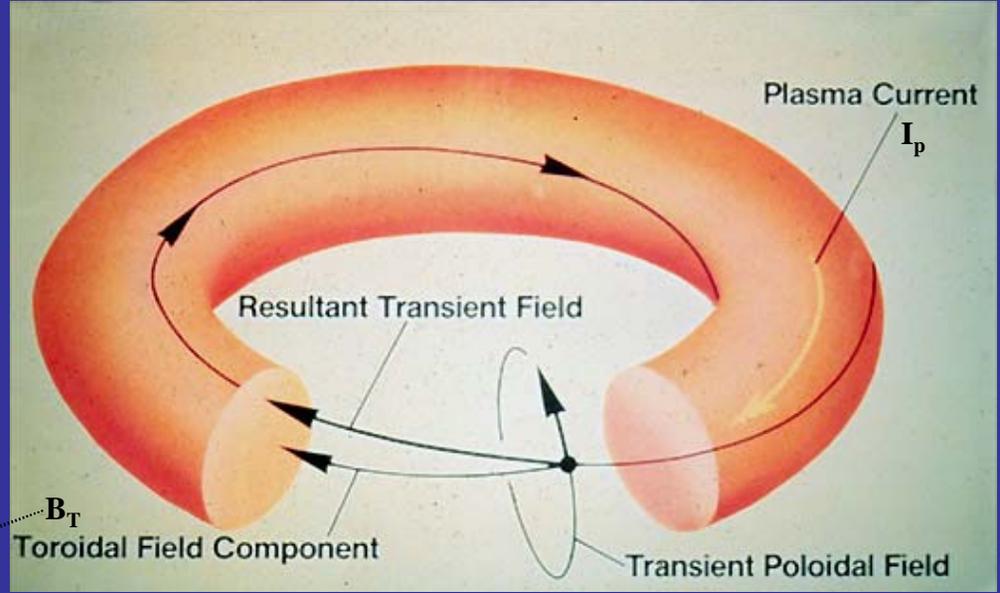
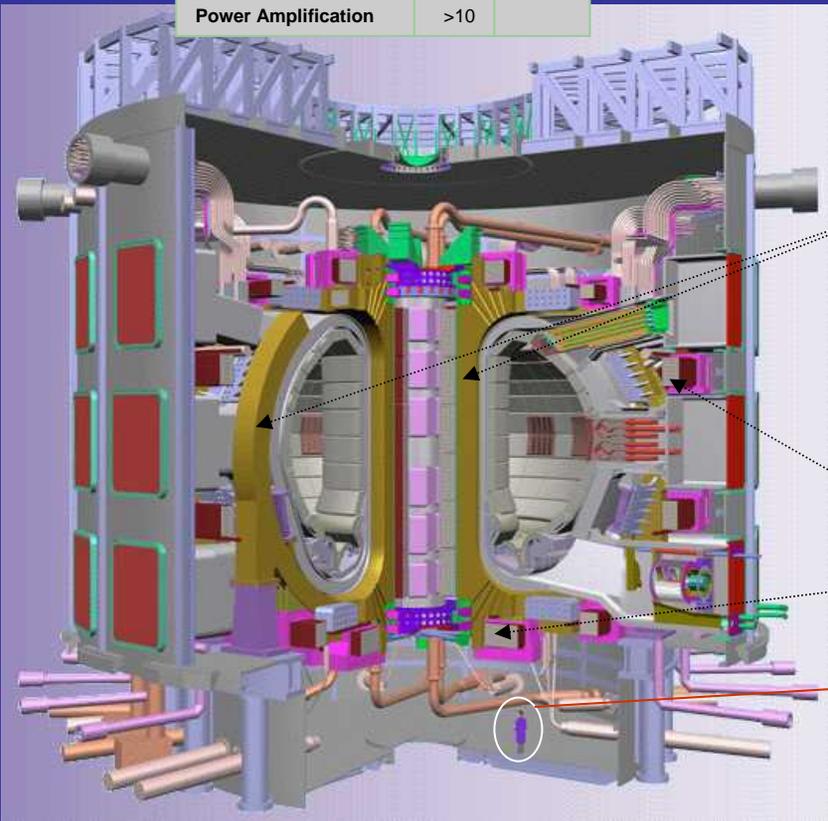
Inertial fusion



Magnetic Fusion: the Tokamak Configuration

THE ITER PROJECT

Plasma Major Radius	6.2	m
Plasma Minor Radius	2.0	m
Plasma Volume	840	m ³
Plasma Current	15.0	MA
Toroidal Field on Axis	5.3	T
Fusion Power	500	MW
Burn Flat Top	>400	s
Power Amplification	>10	



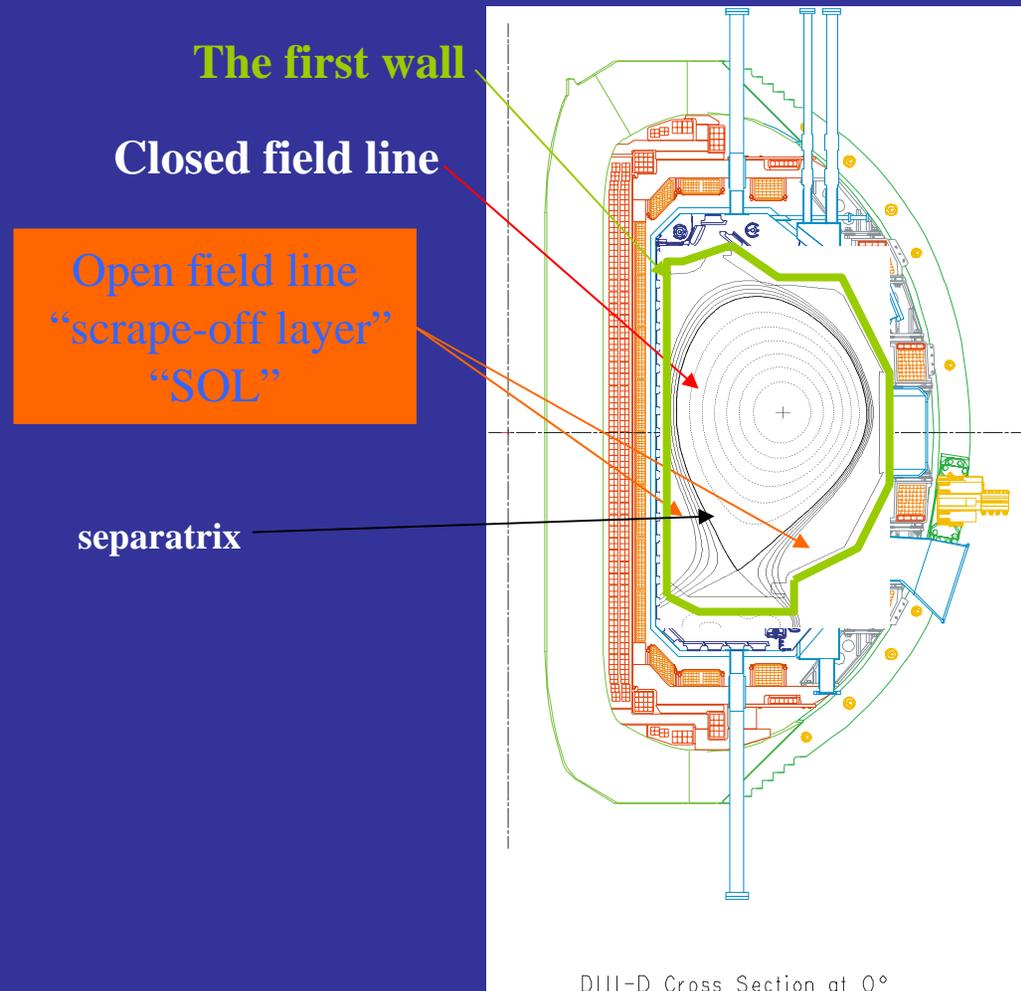
Particle trajectory inside a Tokamak are said to be **CLOSED** as they return to their initial position after a number of toroidal rounds.

B_p

Human dimension

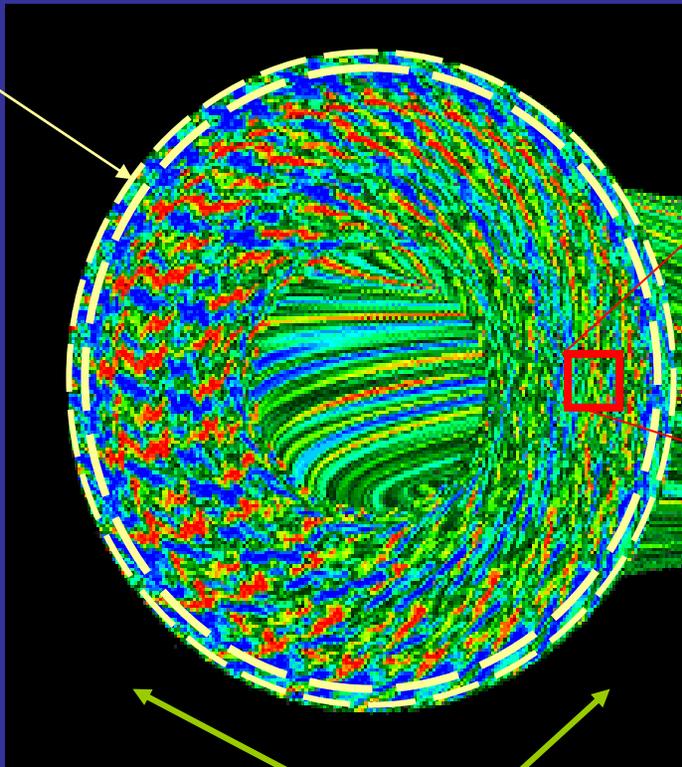
The Scrape-off Layer (SOL) is a region in the tokamak where the field lines are “OPEN” as they are connected to the first wall

- The SOURCE of plasma in the SOL is mainly **turbulence**.
- In H-mode, plasma in the SOL is caused by turbulence and Edge Localized Modes (ELMs).
- The plasma-wall interactions leads to the first wall deterioration via sputtering. This limits the life-time of the confinement device.
- Impurities that come from the wall finds its way back into the plasma core and deteriorate the confinement.

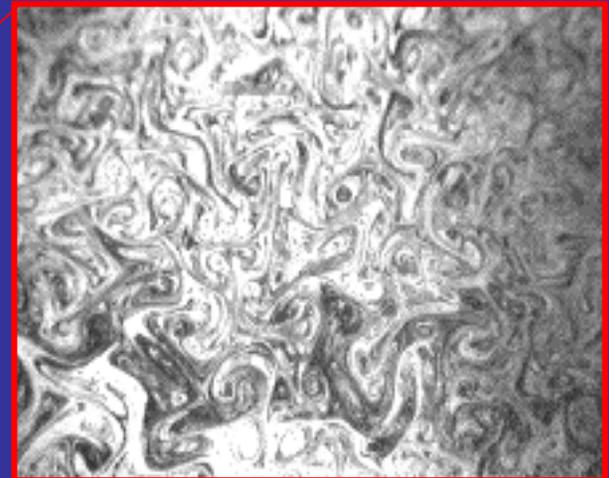


Turbulence and radial Transport in tokamaks

Turbulence in this region, around the separatrix, determines the particle confinement time in a tokamak.



Turbulence in the core can be described as “diffusive”



Turbulent transport in the SOL has two components:

1) Diffusive Transport:
Small radial velocity with respect to the sound speed

2) Convective Transport:
Significant radial velocity up to the order of the sound speed (1/10th)

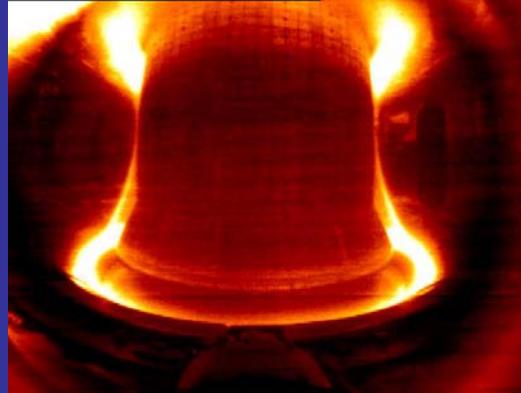
Universality of avaloids by Comparing : the Tore Supra, Alcator C-MOD, MAST tokamaks and the PISCES linear device

Tore Supra tokamak



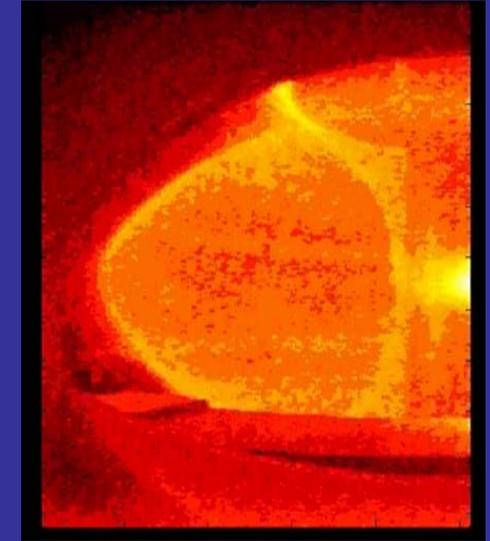
- $a = 76 \text{ cm}$, $R = 2.32 \text{ m}$
- $B_T = 3.5 \text{ T}$, $I_p = 1 \text{ MA}$
- limiter machine

Alcator C-MOD tokamak



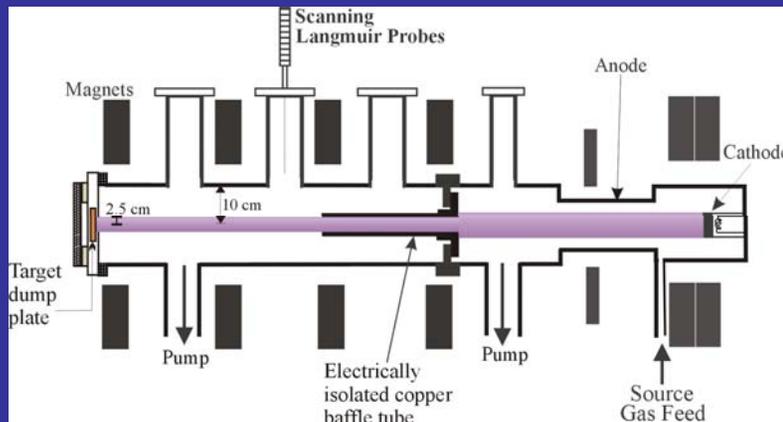
- $a = 21 \text{ cm}$, $R = 70 \text{ cm}$
- $B_T = 5.3 \text{ T}$, $I_p \sim 0.8 \text{ MA}$
- divertor machine

MAST Spherical tokamak



- $a = 52 \text{ cm}$, $R = 73 \text{ cm}$
- $B_T = 0.6 \text{ T}$, $I_p = 700 \text{ kA}$
- First wall far from the LCFS

PISCES



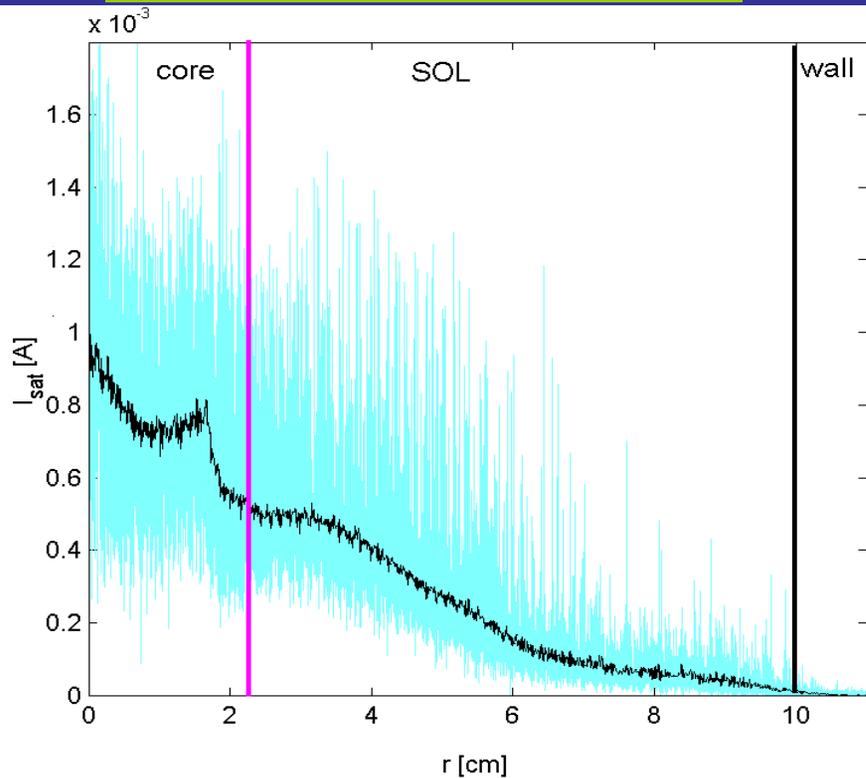
$n_e \sim 10^{17} \text{ m}^{-3}$, $T_e \sim 10 \text{ eV}$,
 $B = 0.12\text{-}0.24 \text{ T}$

- Plasma radius = 2.5 cm
- Vessel radius = 10 cm

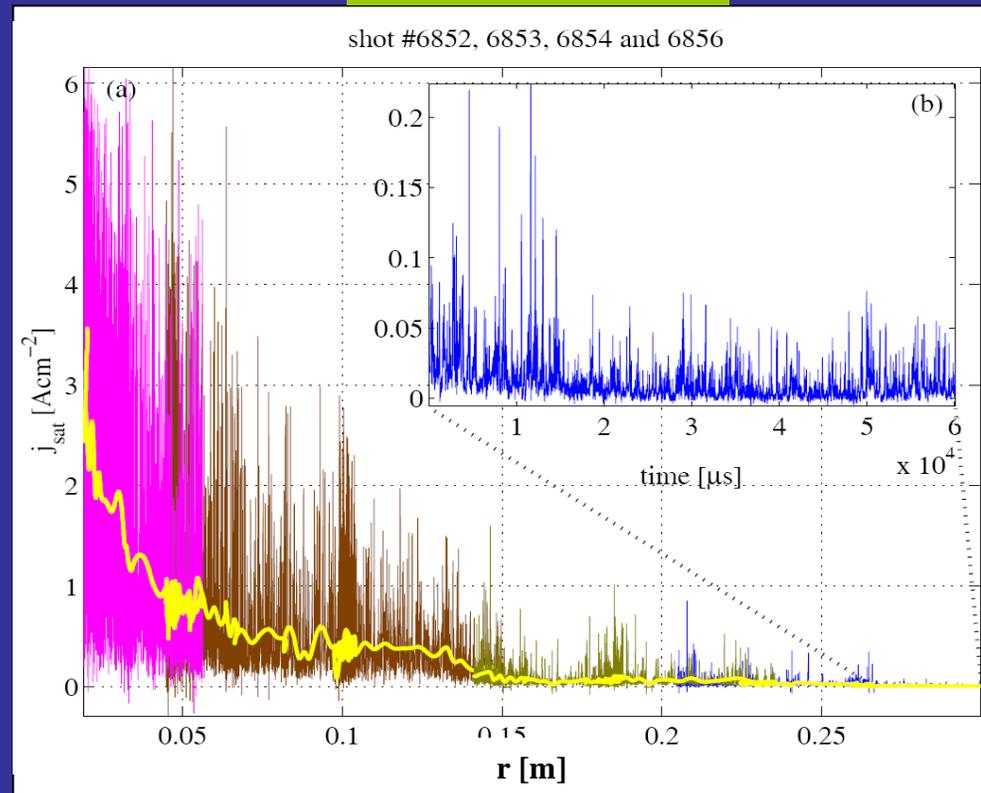
Plasma Far from the Last Closed Flux Surface in PISCES and MAST exists in form of intermittent bursts



PISCES Linear Plasma Device



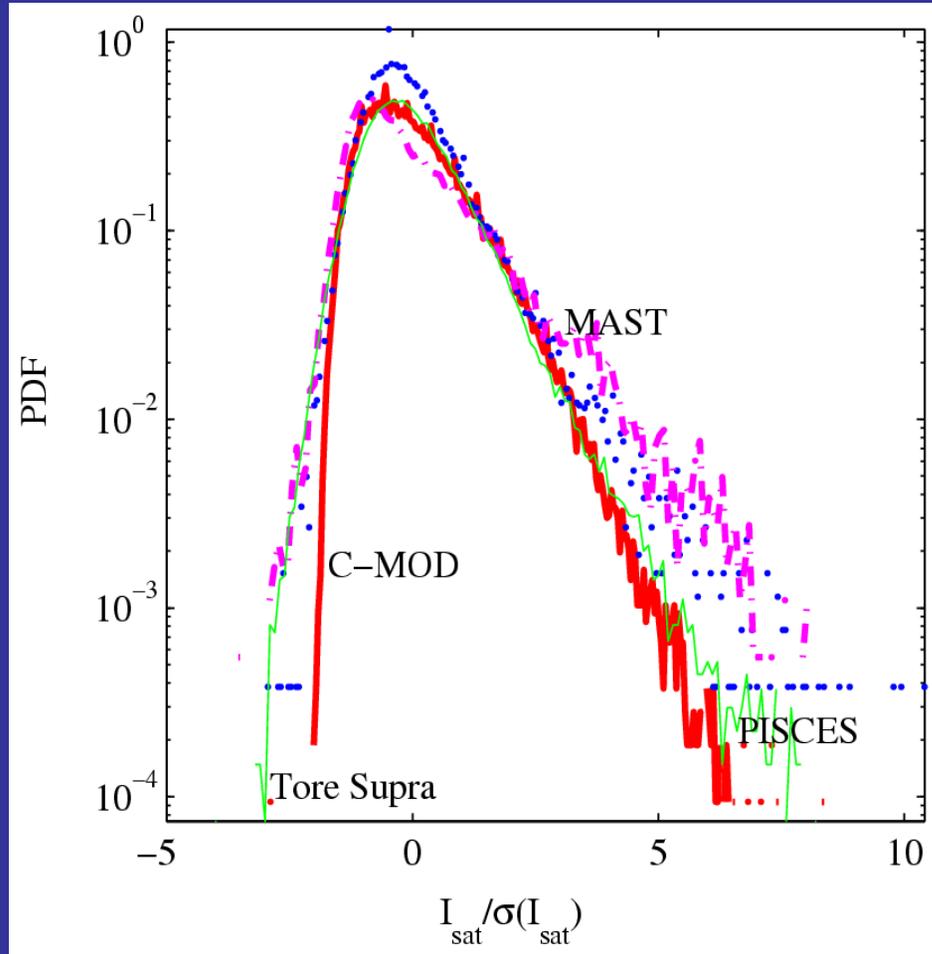
MAST tokamak





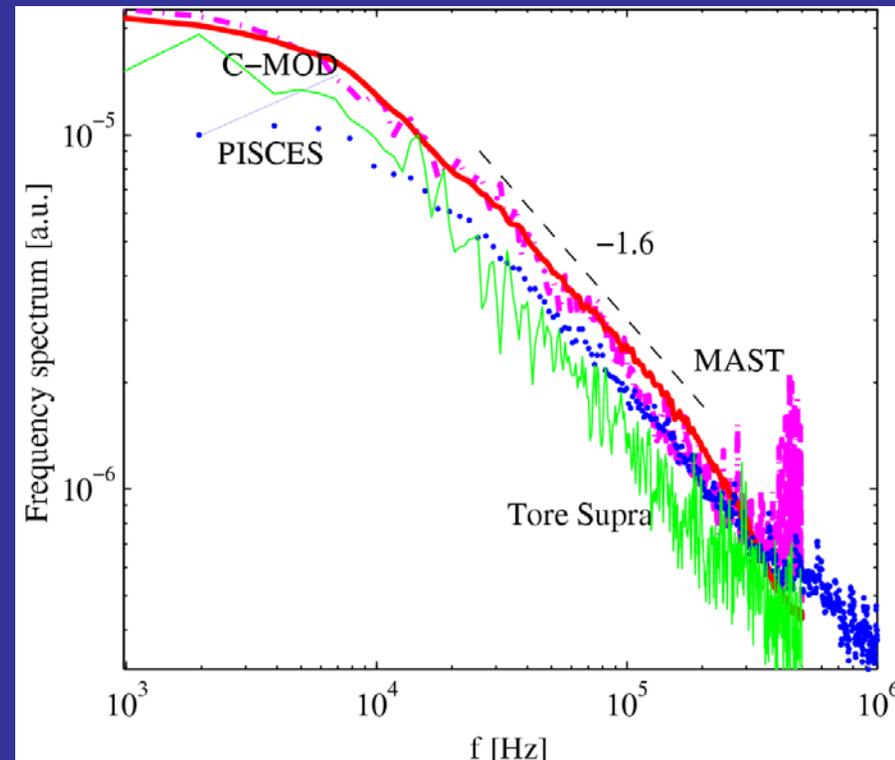
Similarity of the PDF of I_{sat} fluctuations

- Gaussian for negative fluctuations
- Strongly Skewed for positive fluctuations



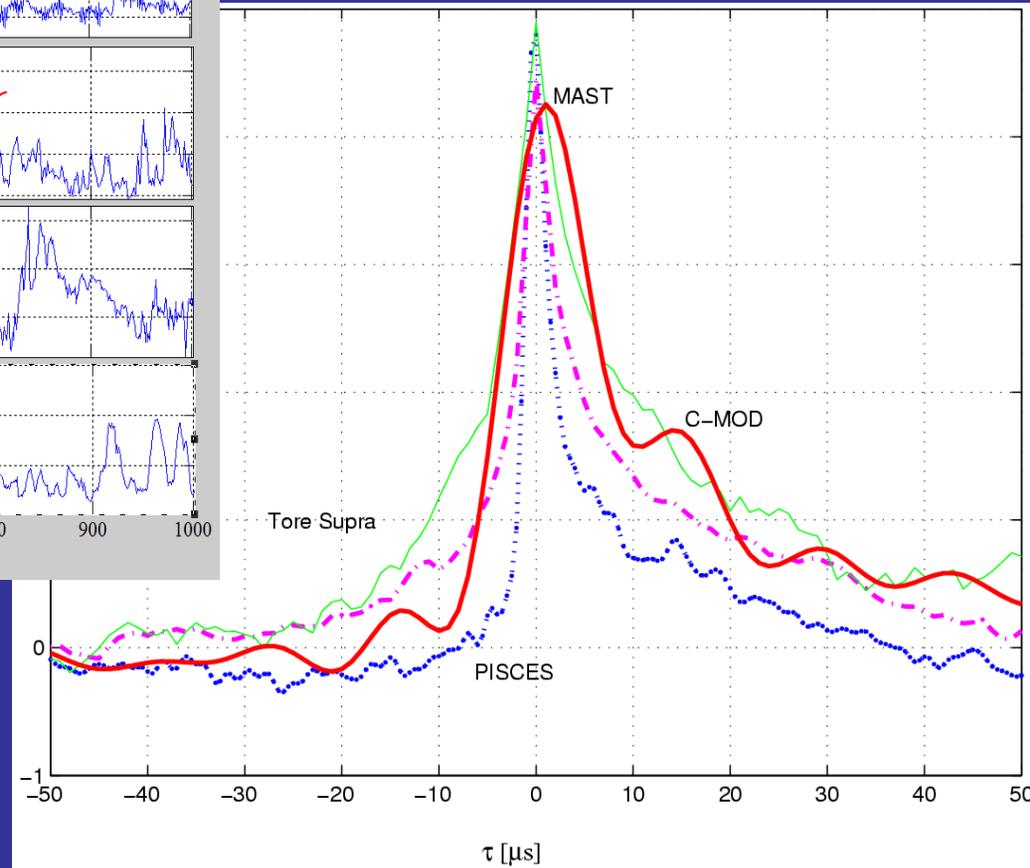
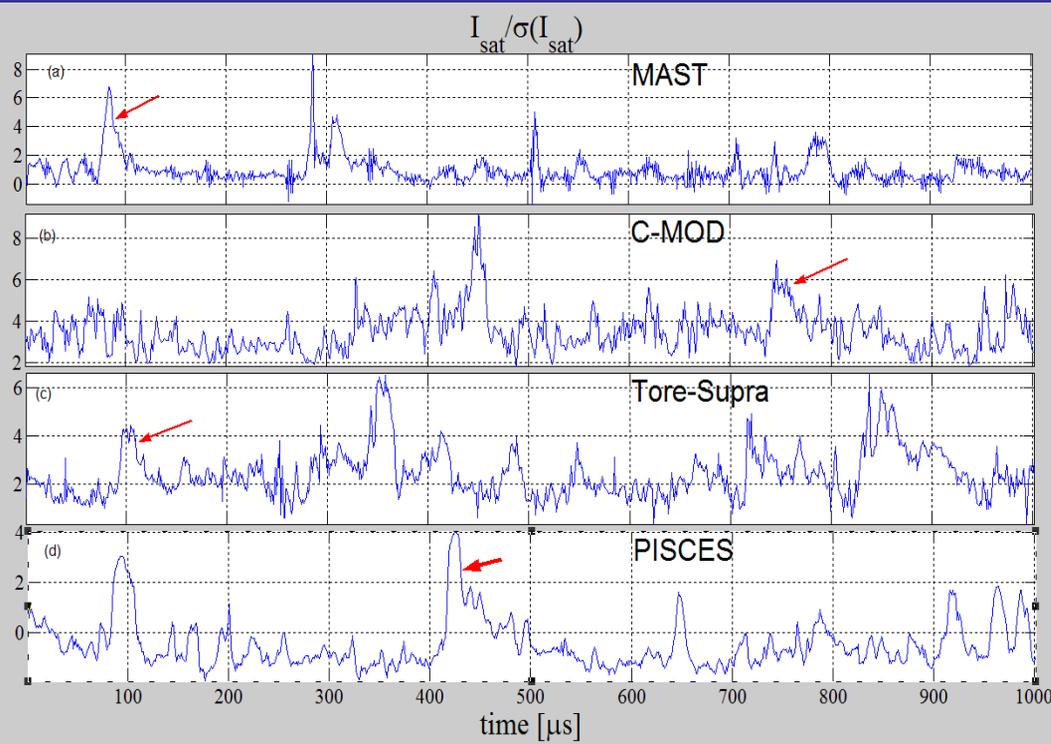
Similarity of the power spectra of I_{sat}

- One scaling region
- approximately the same scaling exponent -1.6
- Large scales

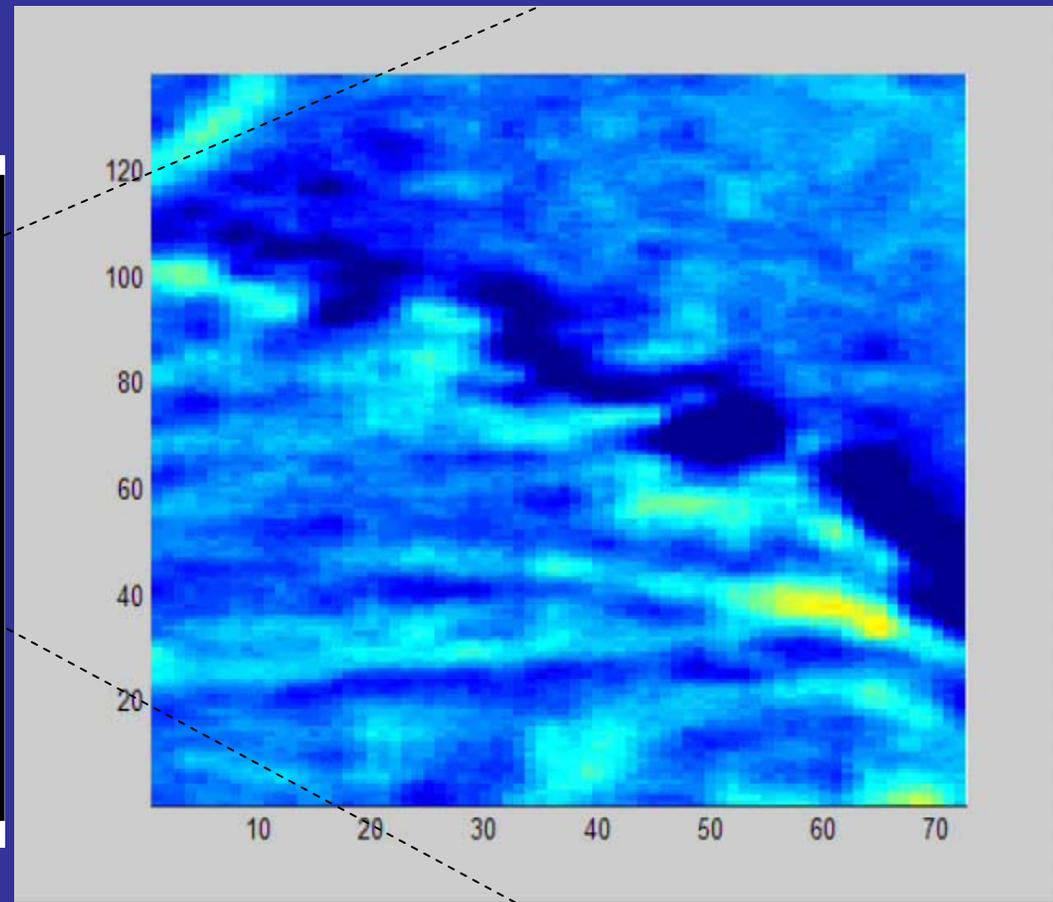
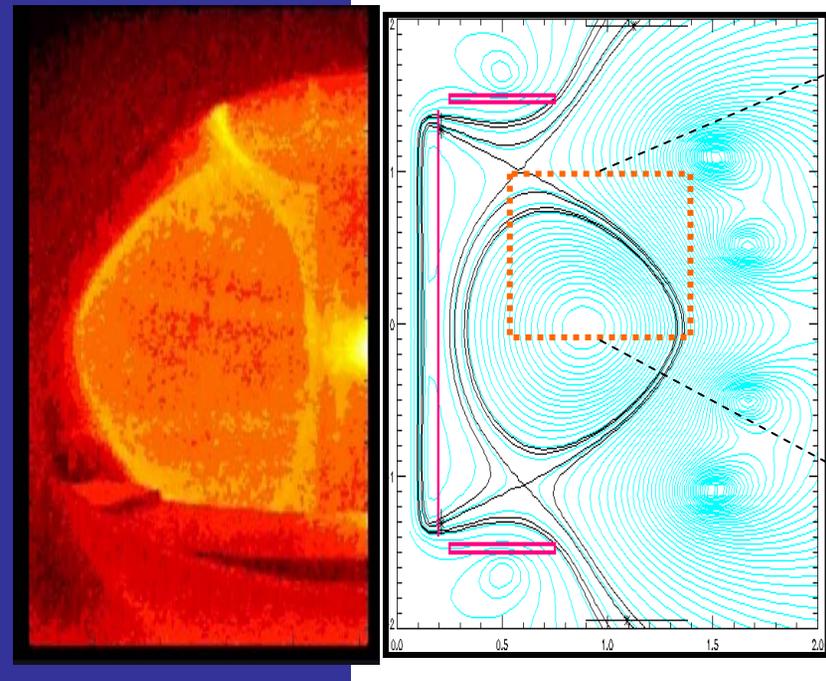


Similarity of the avaloid temporal signature

- Non-conservation of mass
- Asymmetric shape (like ELM's or saw teeth)



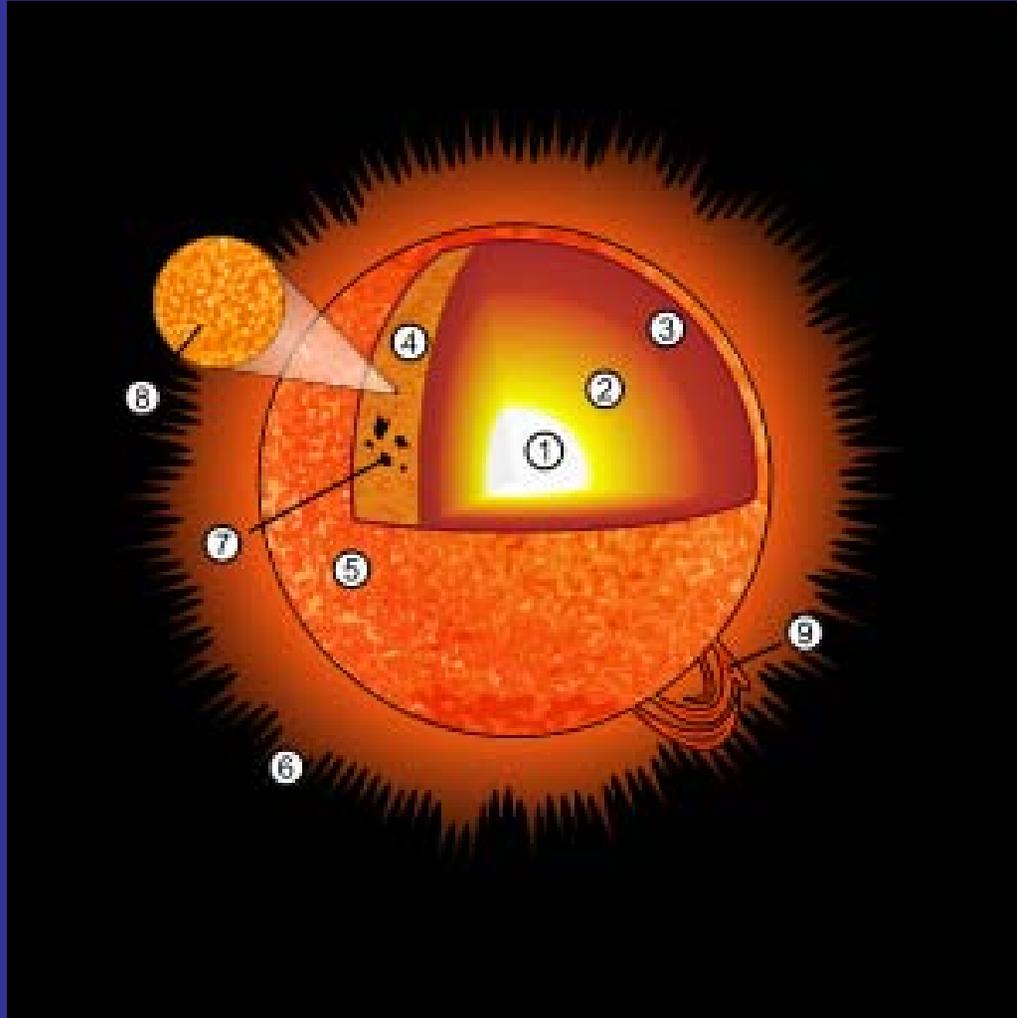
- Imaging of avaloids on MAST using the Phantom V4 camera with $50 \mu\text{s}$ exposure time and $500 \mu\text{s}$ between frames (No correlation between two consecutive frames).
- Avaloids, as in CSDX and PISCES, are ‘observed’ to remain attached to the main plasma.
- Avaloids extend radially far from the separatrix with elongated structures.



(Recent) Progress in understanding turbulence and radial transport in the SOL of magnetic fusion devices



- Intermittency in the SOL of magnetic fusion devices is caused by large-scale structures with large radial velocities that we call avaloids.
- Avaloids result from the non-linear evolution of a low poloidal number edge instability.
- Universality: Avaloids have the same properties on different magnetic fusion devices.



An illustration of the sun structure:

1. Core
2. Radiative zone
3. Convective zone
4. Photosphere
5. Chromosphere
6. Corona
7. Sunspot
8. Granules
9. Prominence