



# The Origin of Intermittency in Magnetically Confined Plasma Devices

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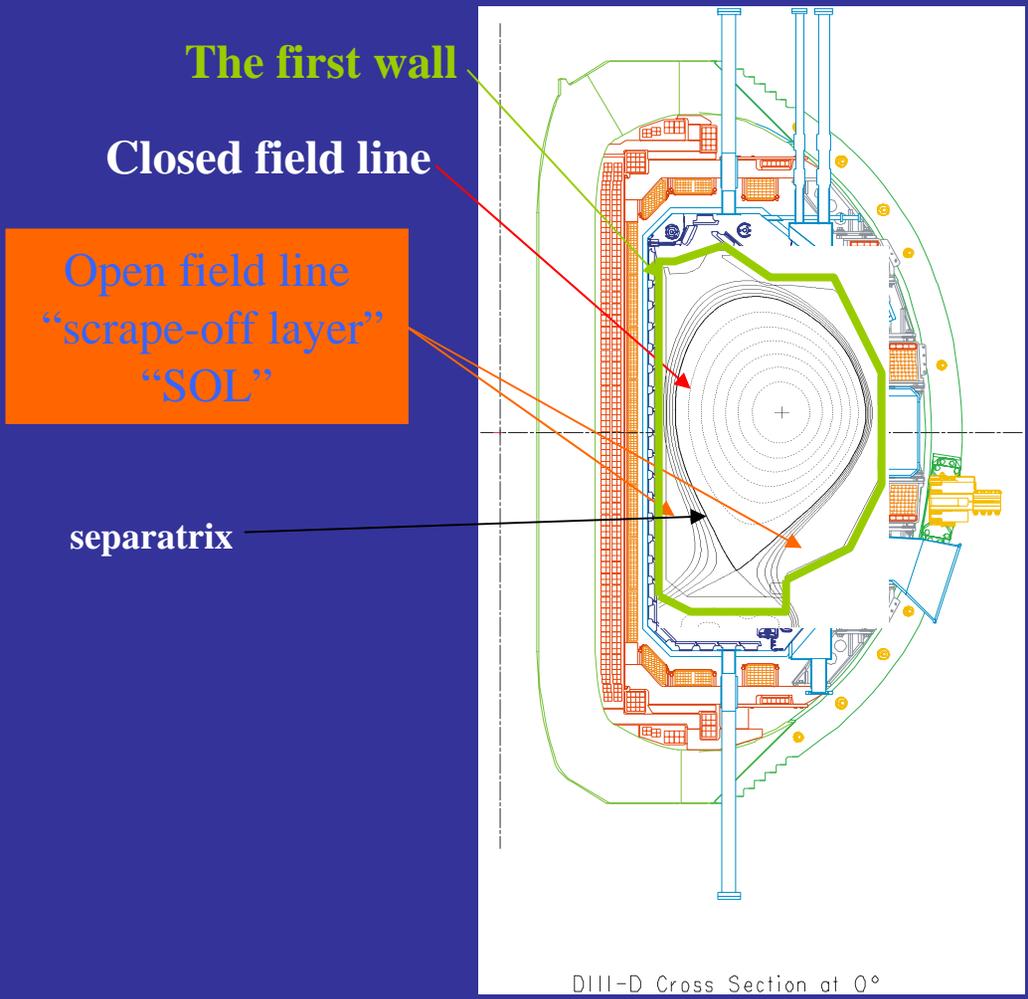
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In collaboration with G. Tynan (UCSD),  
the MAST and the ASDEX-Upgrade teams

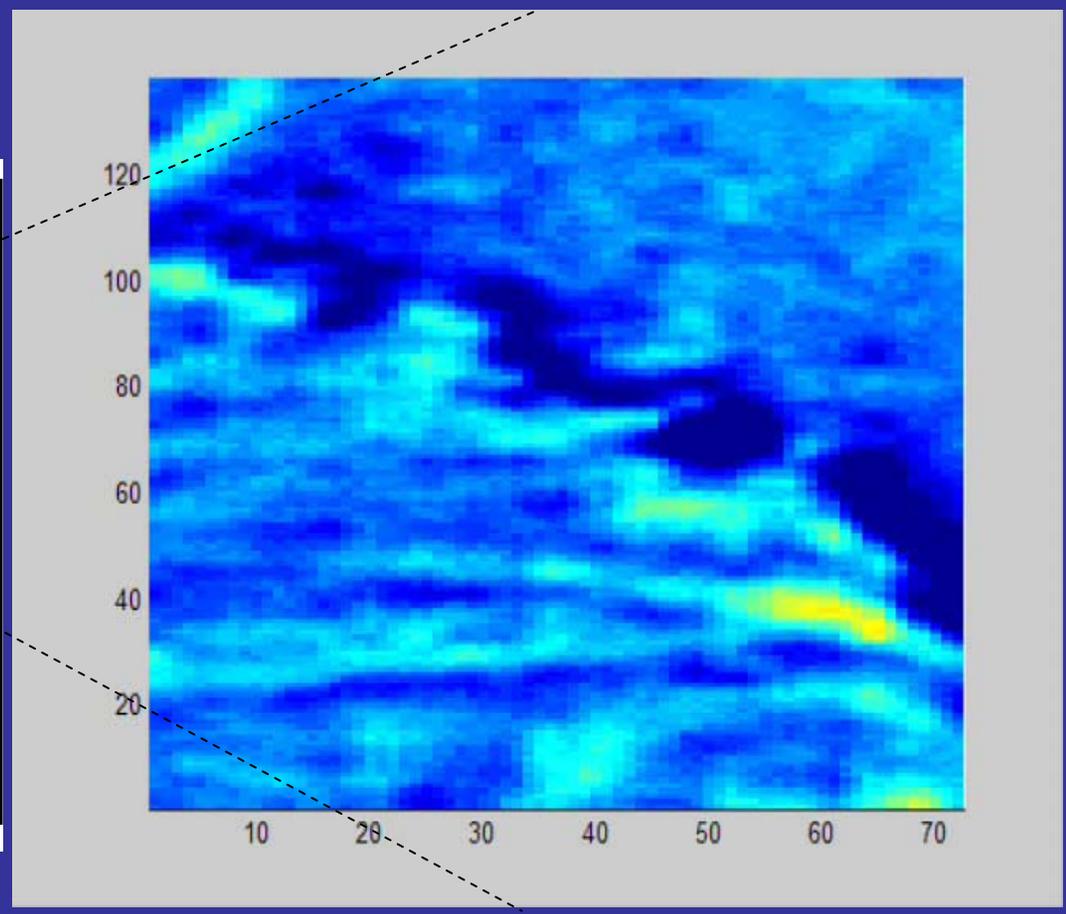
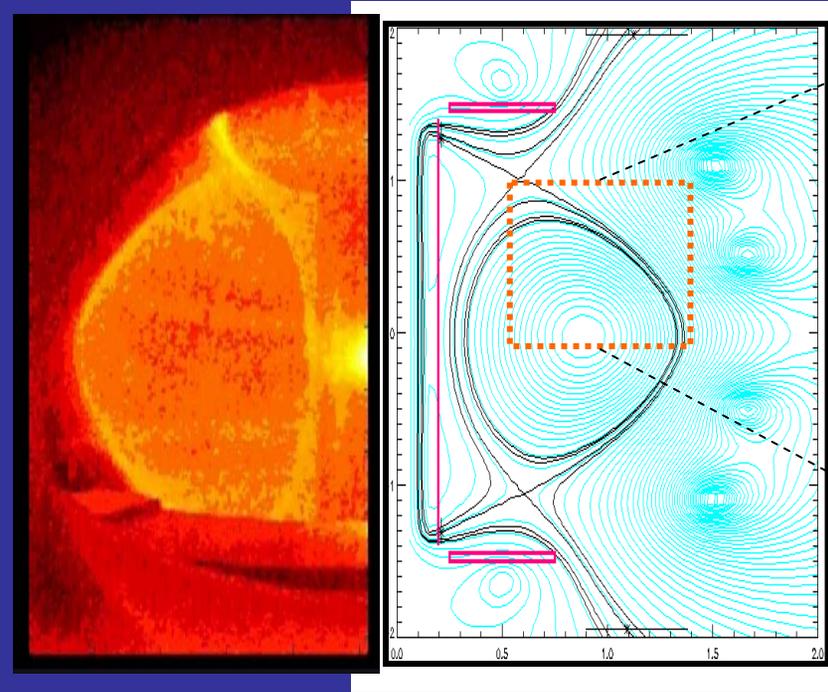


# The Scrape-off Layer (SOL) is a region in the tokamak where the field lines are “OPEN” as they are connected to the first wall

- The SOURCE of plasma in the SOL is mainly turbulence.
- Hence, by looking in this region, we are able to understand the radial transport processes.
- 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.



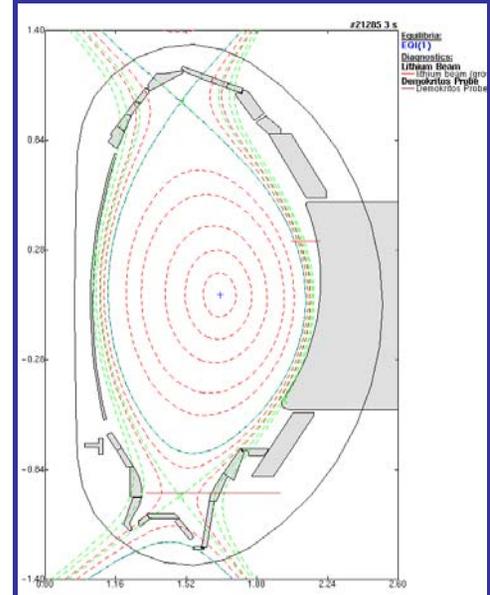
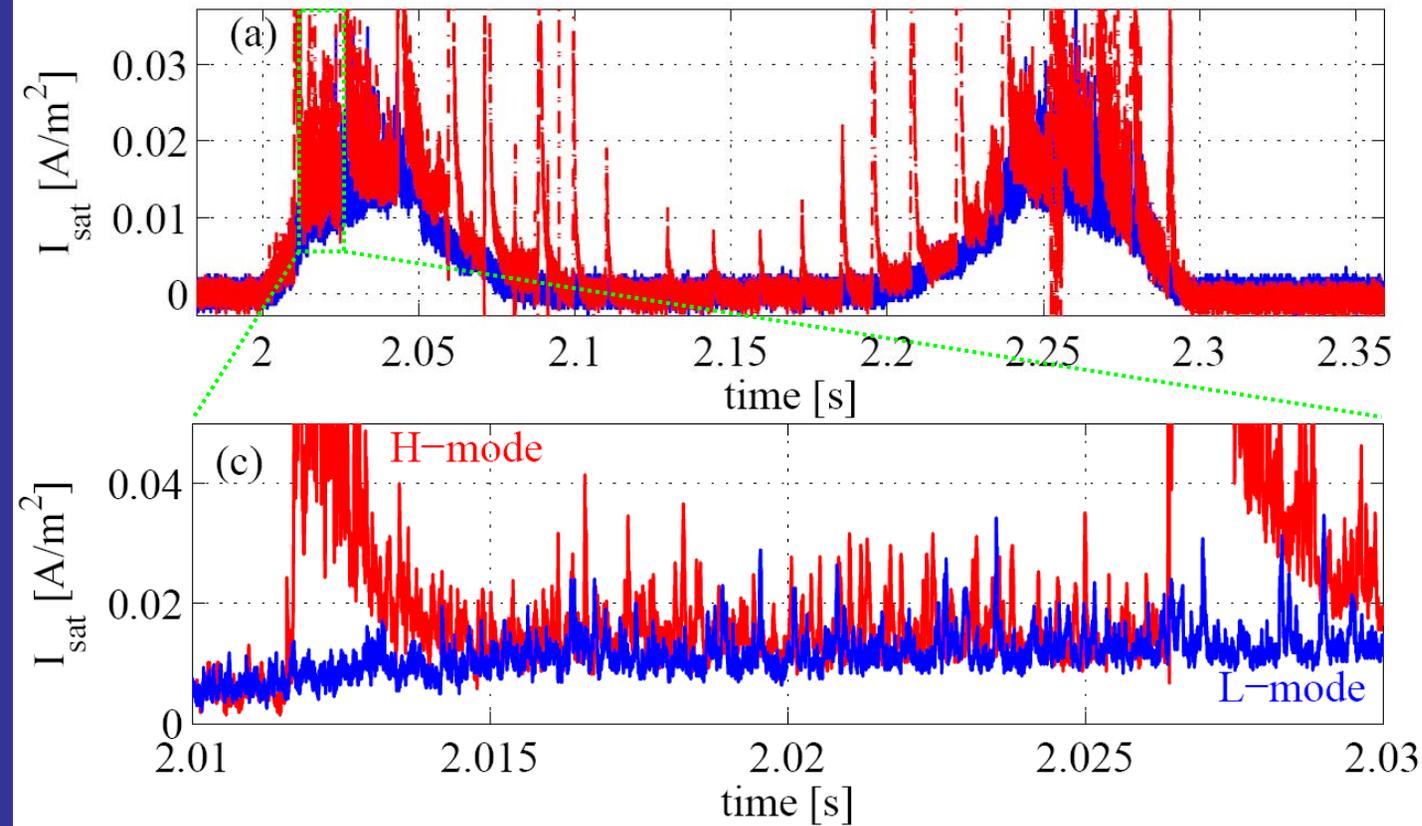
- Intermittent large-scale large-velocity structures extend radially far from the separatrix with elongated shapes.
- Imaging of avaloids on MAST using the Phantom V4 camera with 50  $\mu$ s exposure time and 500  $\mu$ s between frames
- No correlation between two consecutive frames.



# Avaloids exist not only in L-mode but also in H-mode!

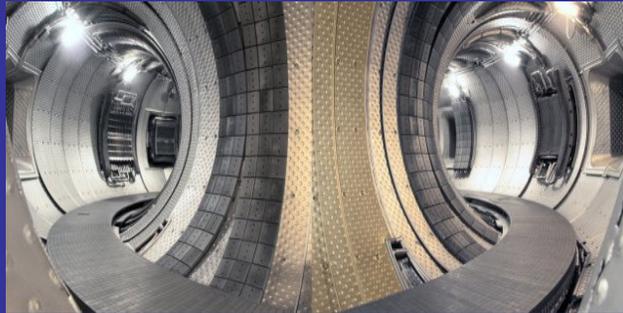
Reciprocating probe position

L-mode 21284 (—), H-mode 21285 (---)



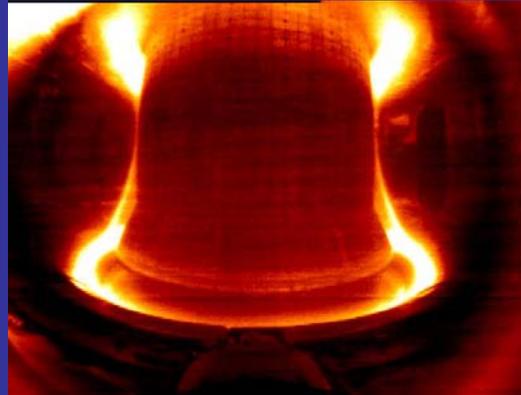
# Universality of avaloids is demonstrated by Comparing the Tore Supra, Alcator C-MOD, MAST tokamaks and the PISCES linear device

Tore Supra tokamak



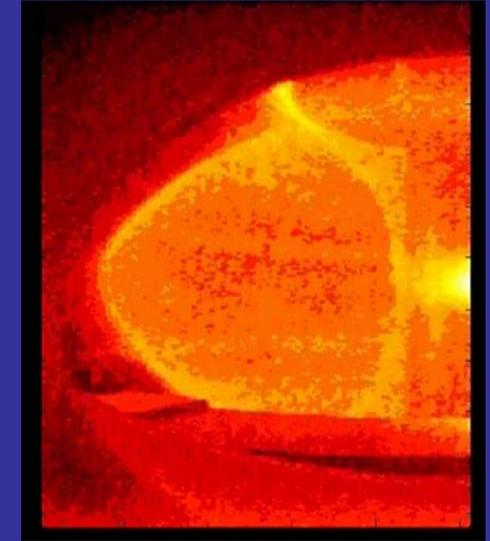
- $a = 76 \text{ cm}$ ,  $R = 2.32 \text{ m}$
- $B_T = 3.5 \text{ T}$ ,  $I_p = 1 \text{ MA}$
- limiter machine

Alcator C-MOD tokamak



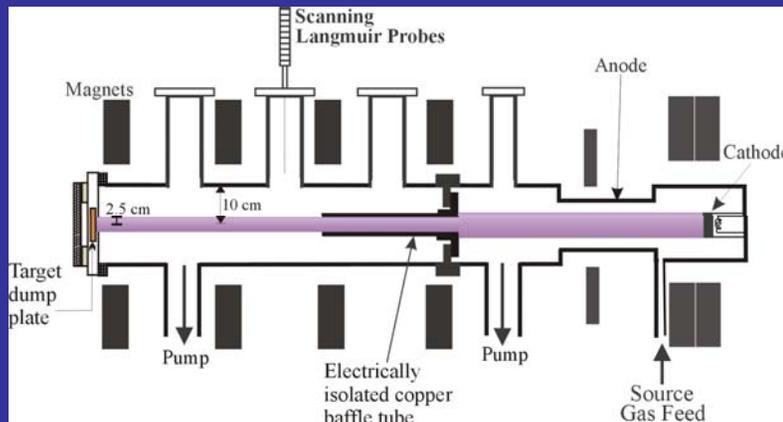
- $a = 21 \text{ cm}$ ,  $R = 70 \text{ cm}$
- $B_T = 5.3 \text{ T}$ ,  $I_p \sim 0.8 \text{ MA}$
- divertor machine

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

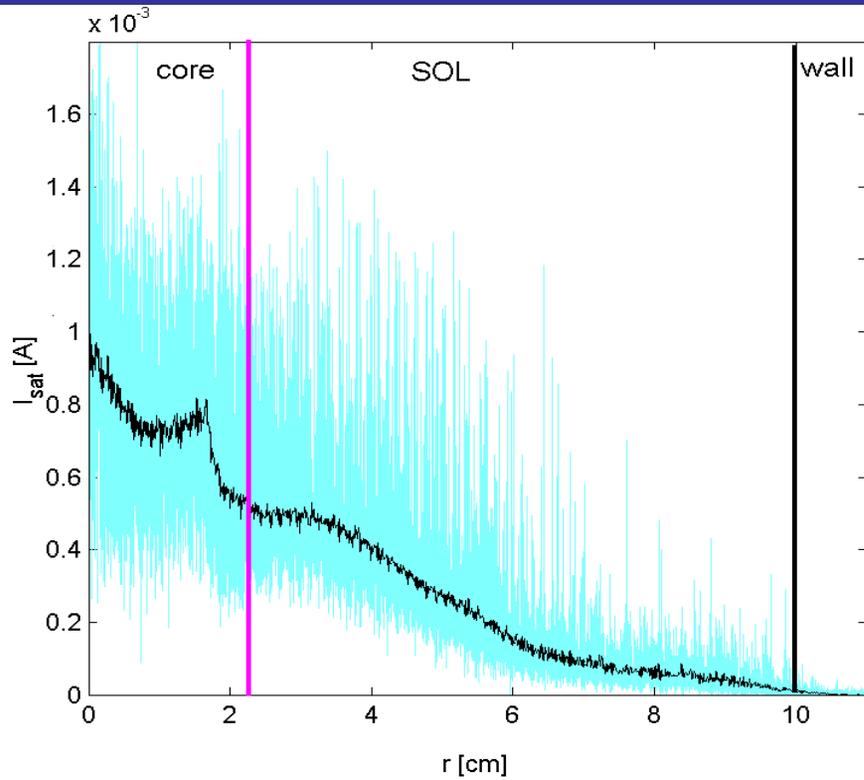


$n_e \sim 10^{17} \text{ m}^{-3}$ ,  $T_e \sim 10 \text{ eV}$ ,  
 $B = 0.12\text{-}0.24 \text{ T}$

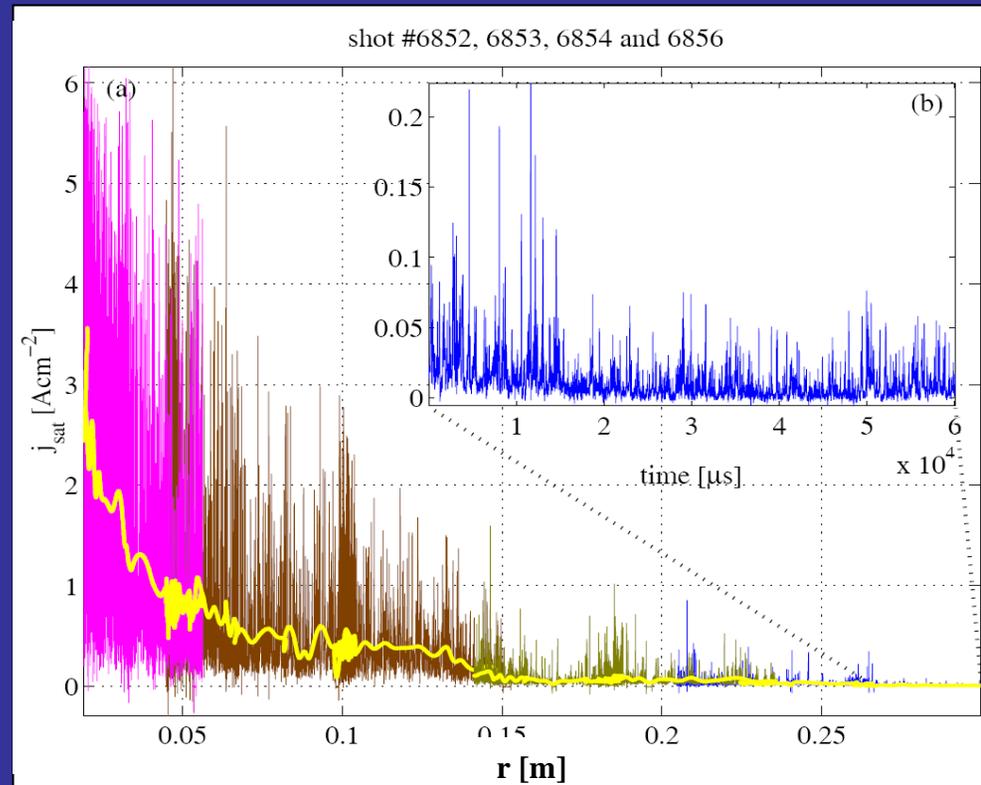
- Plasma radius = 2.5 cm
- Vessel radius = 10 cm

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

PISCES



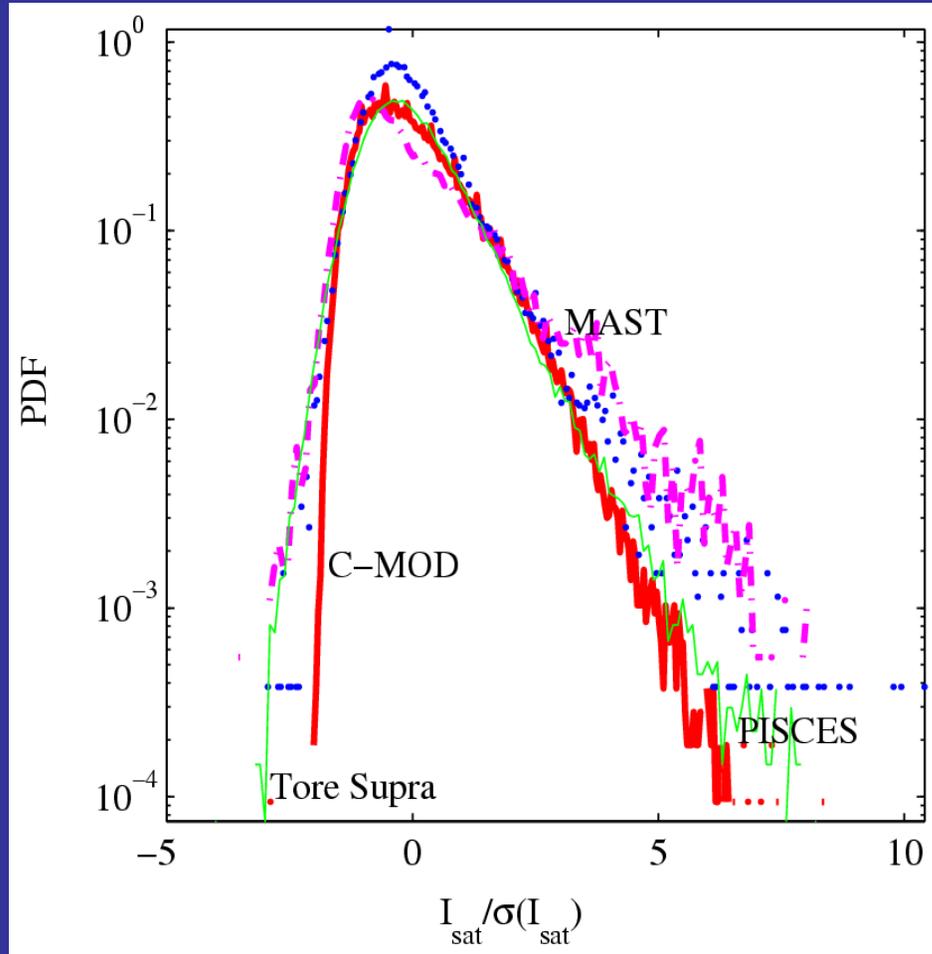
MAST





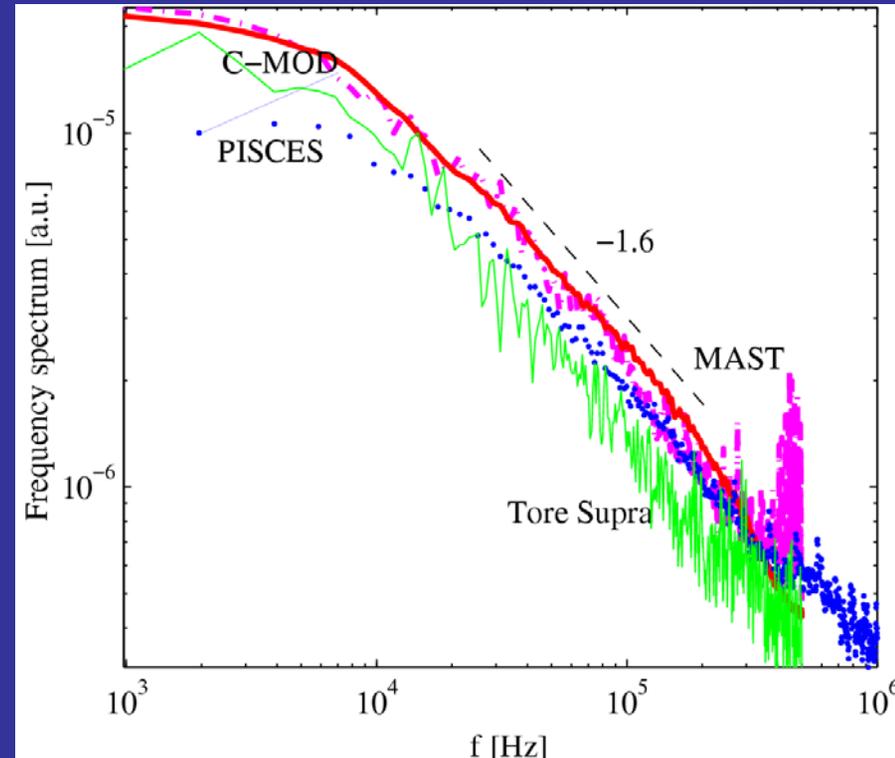
## Similarity of the PDF of $I_{sat}$ fluctuations

- Gaussian for negative fluctuations
- Strongly Skewed for positive fluctuations



## Similarity of the power spectra of $I_{sat}$

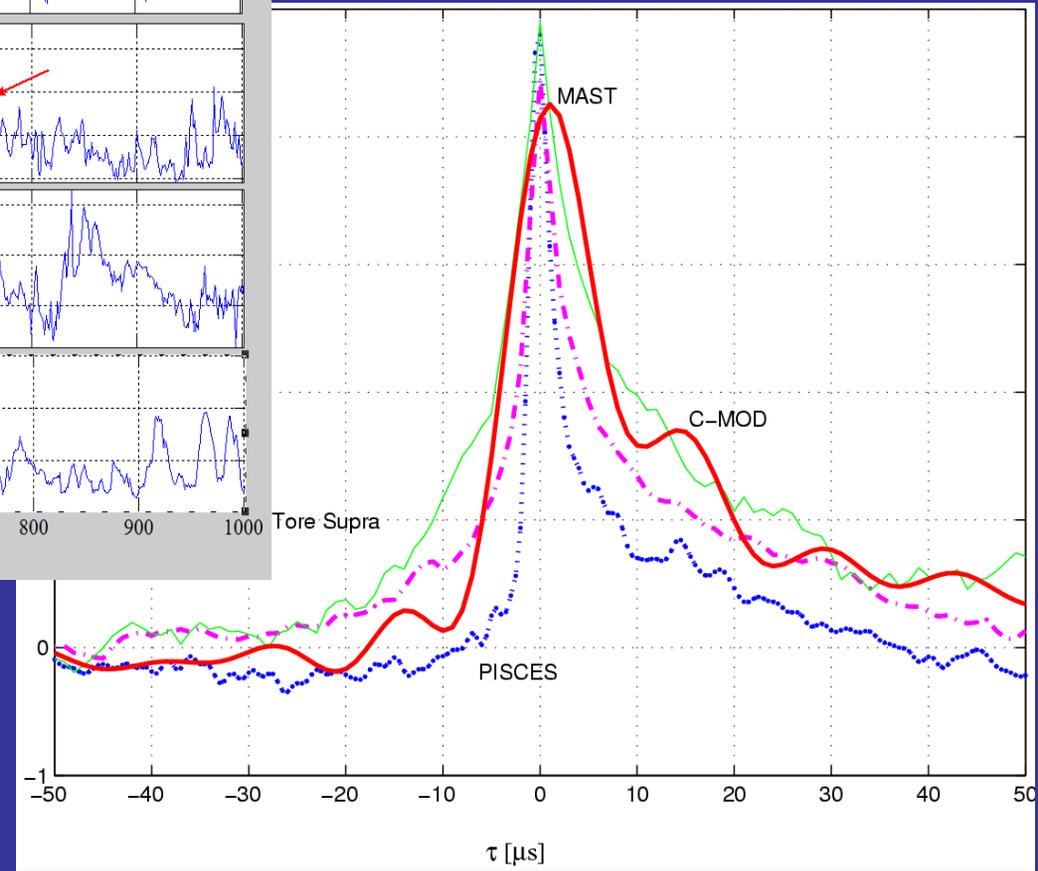
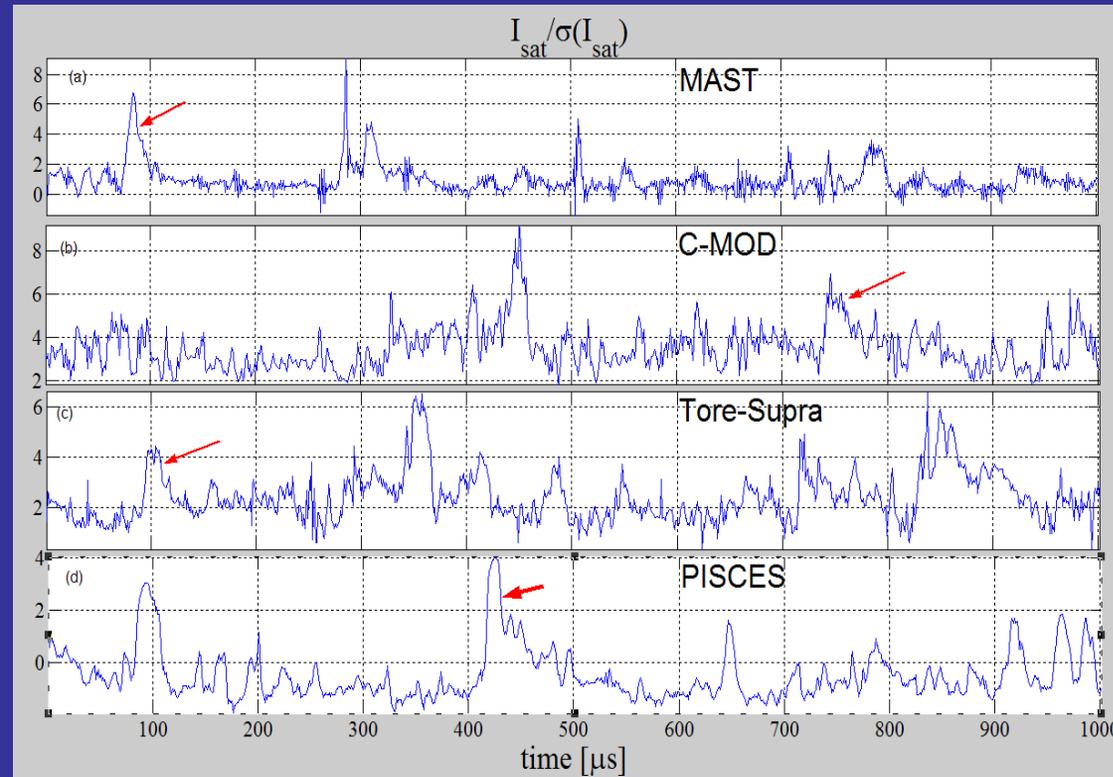
- One scaling region
- approximately the same scaling exponent -1.6
- Large scales





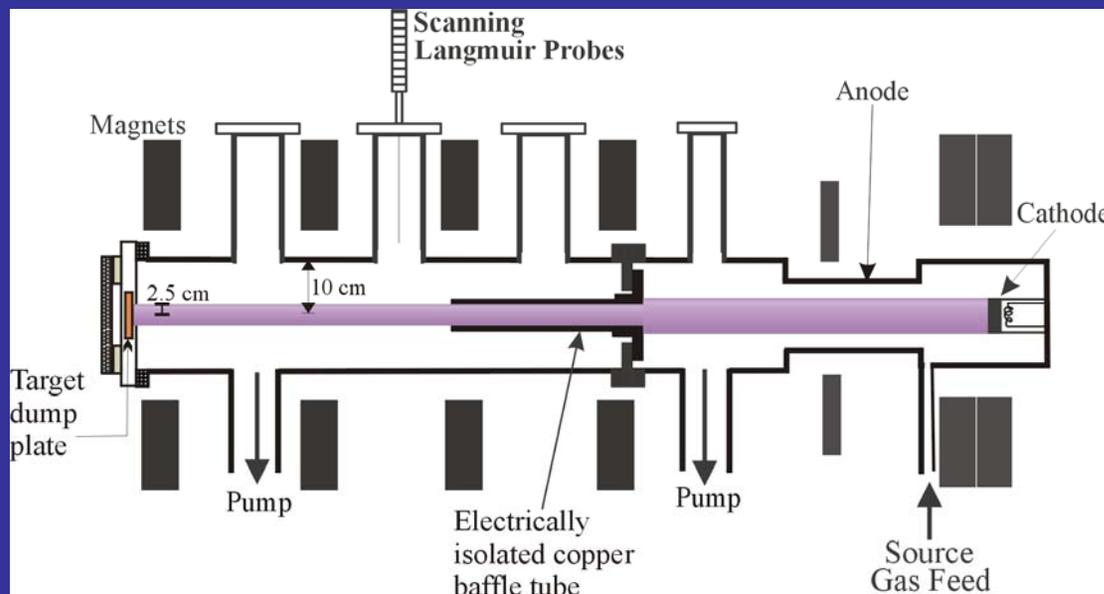
# Similarity of the avaloid temporal signature

- Non-conservation of mass
- Asymmetric shape



# Convective Transport in Linear Magnetic Fusion Devices

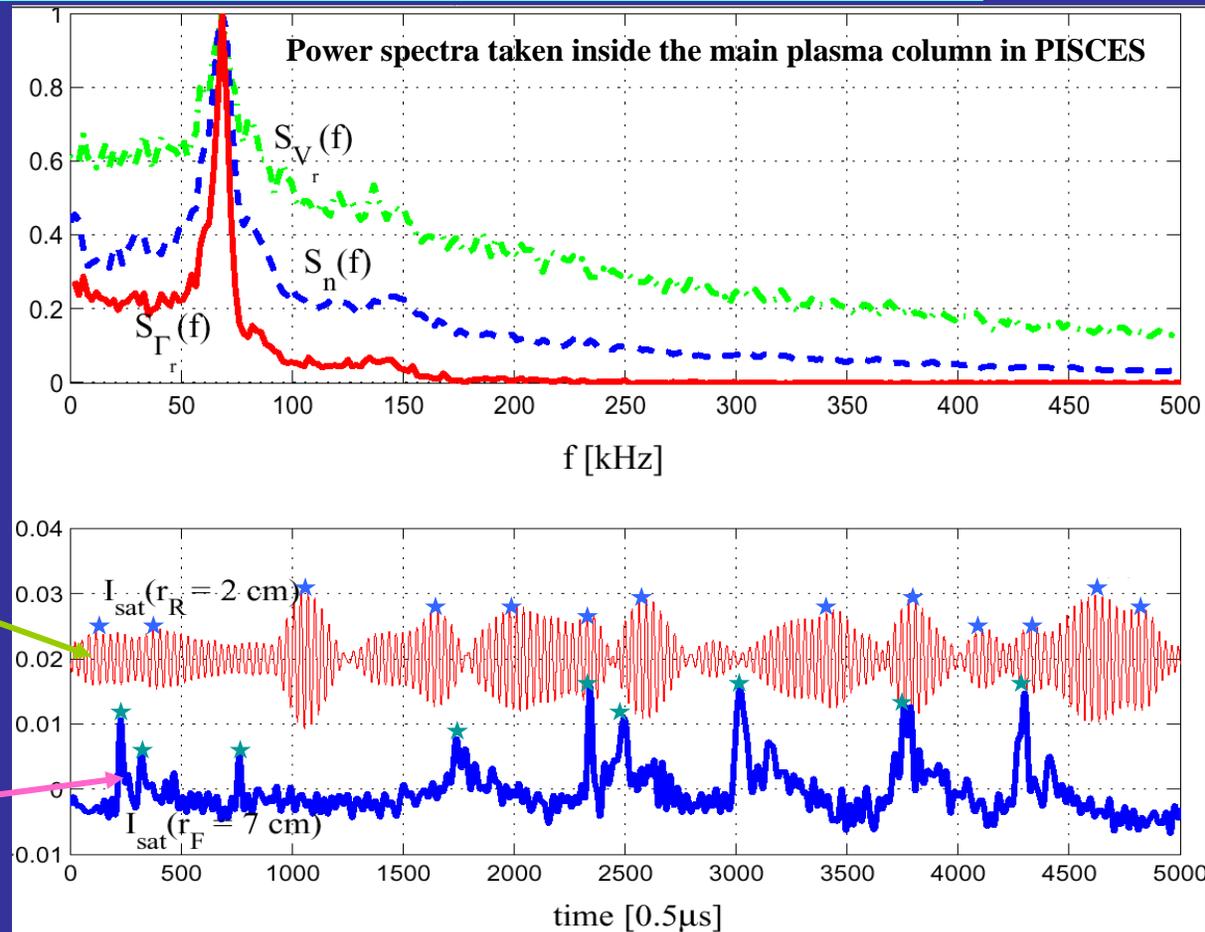
Turbulence is studied in linear devices such as PISCES described below and CSDX (later) where the magnetic geometry is simpler and the plasma is better diagnosed



## Plasma Parameters:

- $n_e \sim 5 \times 10^{17} \text{ m}^{-3}$
- $T_e \sim 15 \text{ eV}$
- $B = 0.12\text{-}0.2 \text{ T}$
- Gaz type: Hydrogen, Argon ...
- Plasma radius = 2.5 cm
- Length = 1 m
- Vessel radius = 10 cm

- In addition to broad-band turbulence there exist a coherent mode inside the main plasma column that also leads to radial transport.
- When filtering around the coherent mode, the fluctuations appear in form of wave-packets.
- This may reflect the cycle “growth-saturation-decay...”
- At the same time bursts are recorded in the SOL as in tokamaks



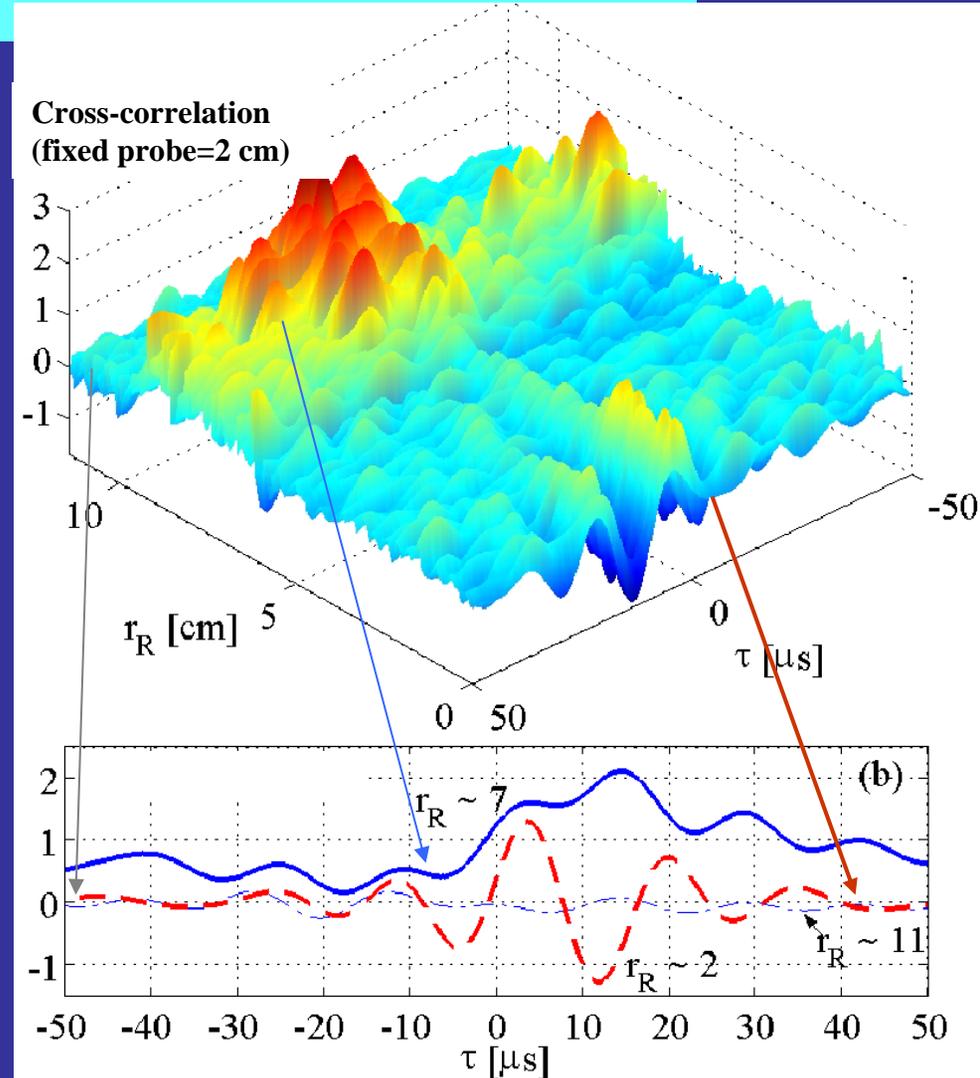
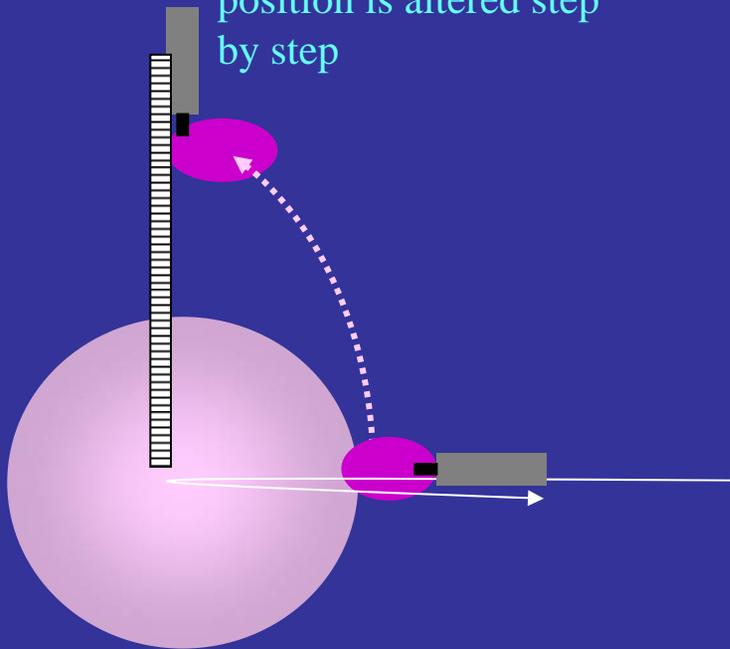
The  $I_{sat}$  signal  
@  $r = 2 \text{ cm}$   
**(INSIDE)**  
filtered around  
70 kHz

The  $I_{sat}$  signal  
@  $r = 7 \text{ cm}$   
**(OUTSIDE)**

- The Bursts in the far SOL are correlated To Wave-packets inside the main plasma column.
- The 70 kHz coherent mode is responsible for the generation of avaloids

### Experimental Setup using two probes

The vertical probe position is altered step by step



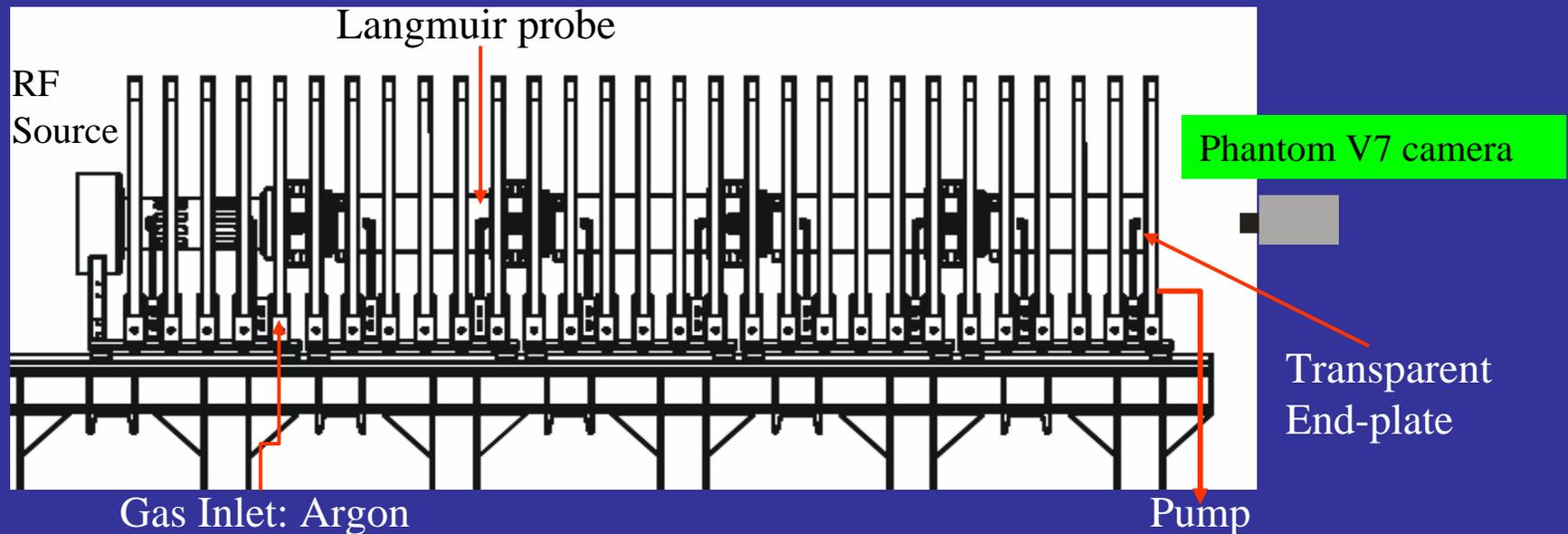
Avaloids (or blobs) result from a non-linear saturation of an instability at the plasma edge

Recall: Universality results when comparing the different magnetic confinement devices

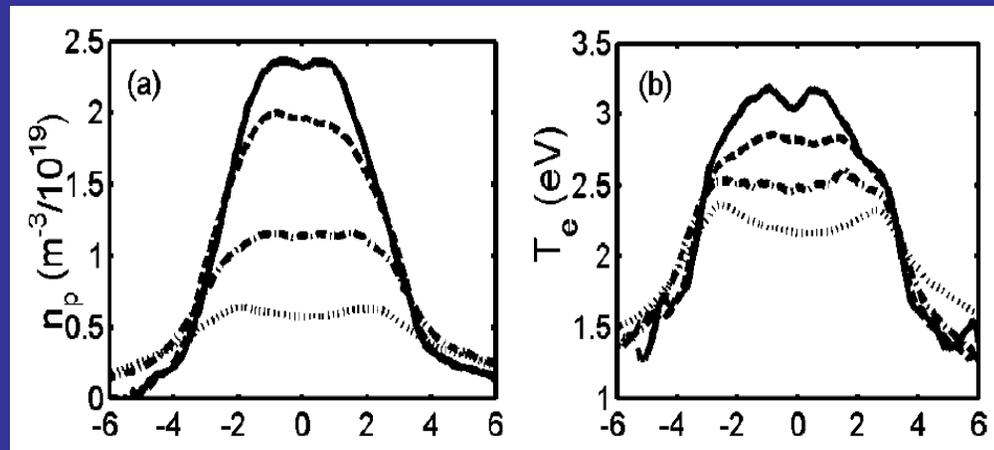
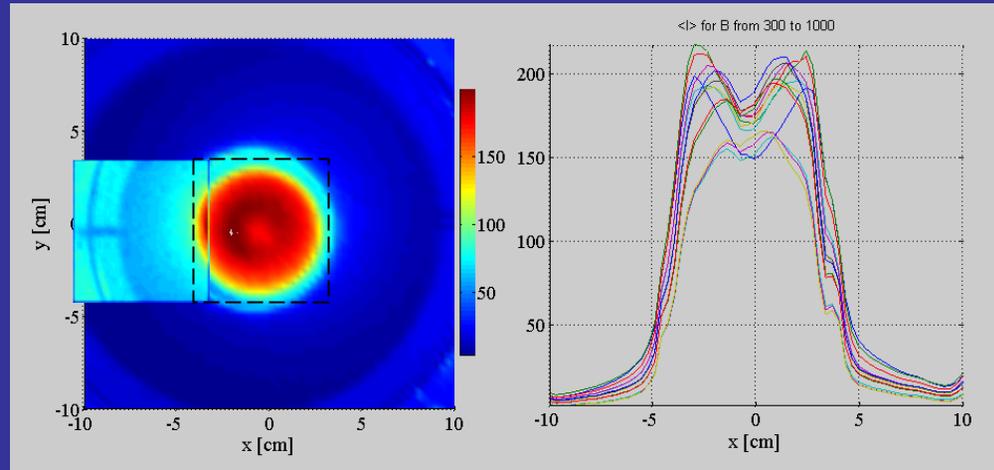
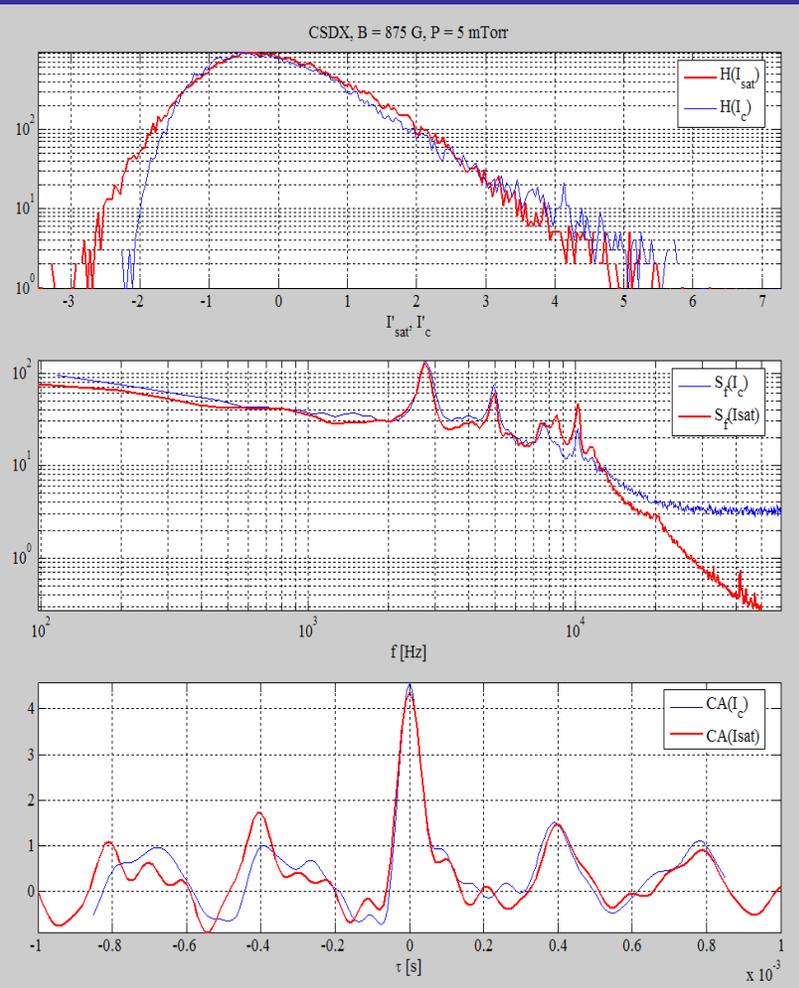


**Confirmation and more using high-speed imaging**

The CSDX linear plasma device



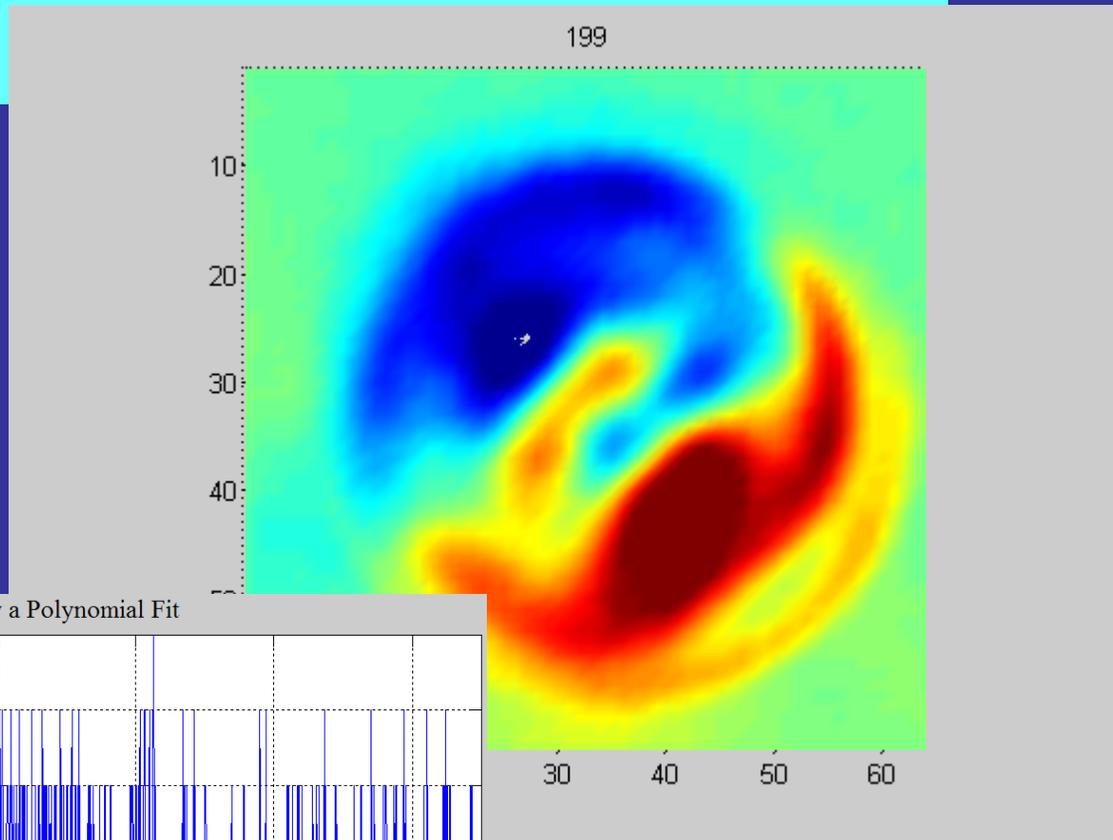
# Good agreement between the images profiles and fluctuations and those done using Langmuir probe for scales above 3 mm set by the view line integration.



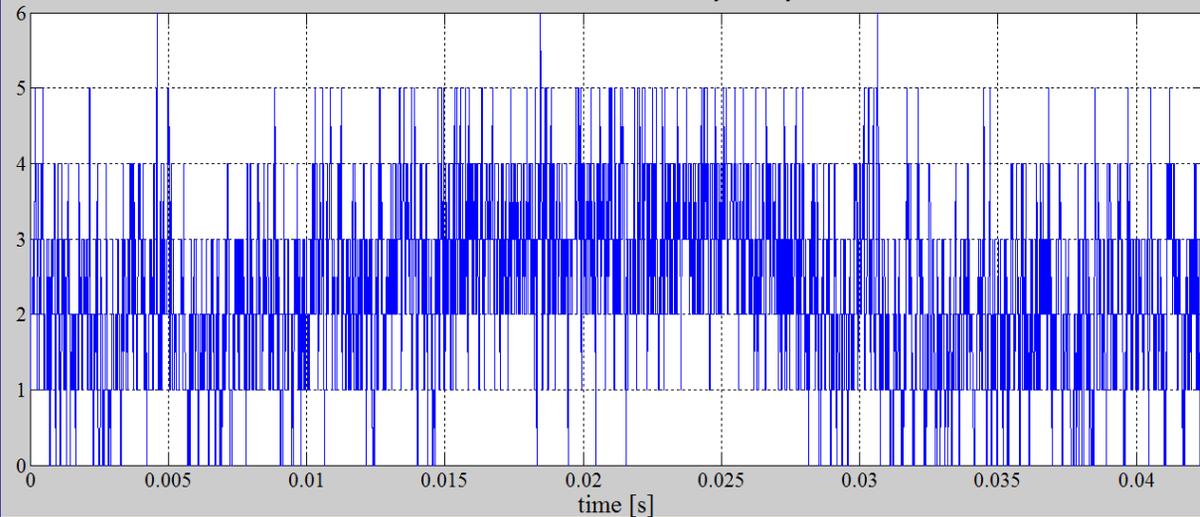
M. Burin et al PoP 2004

# 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”...



Poloidal Mode Number Determined by a Polynomial Fit

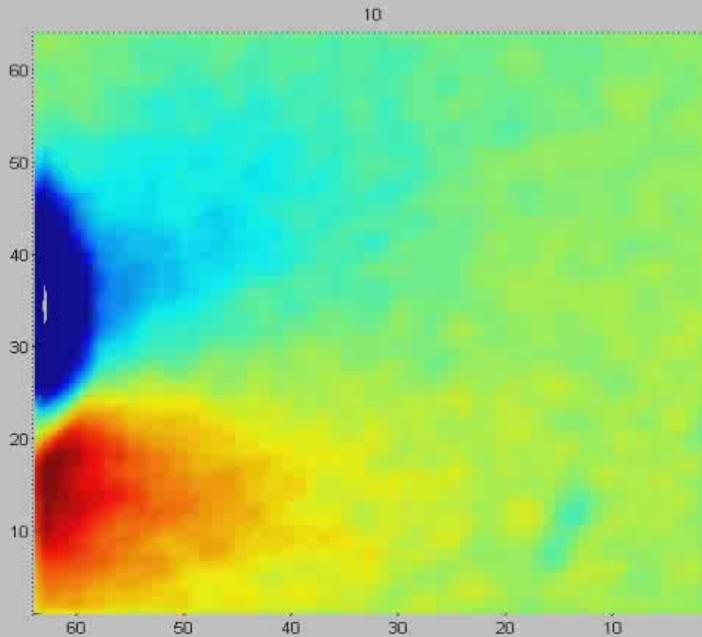


**Camera settings:**  
**Integration time 1  $\mu$ s**  
**Time between frames 15  $\mu$ s**  
**32x32 pixels**

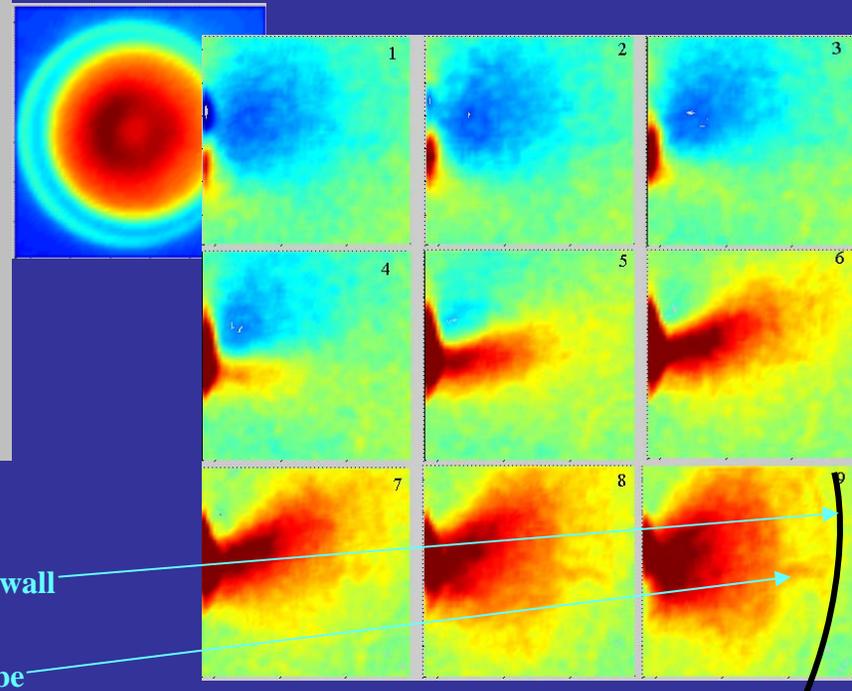
# Shifting the viewed area to outside the main plasma

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  $1 \mu\text{s}$   
Time between frames  $15 \mu\text{s}$   
32x32 pixels



The vessel wall

The probe

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

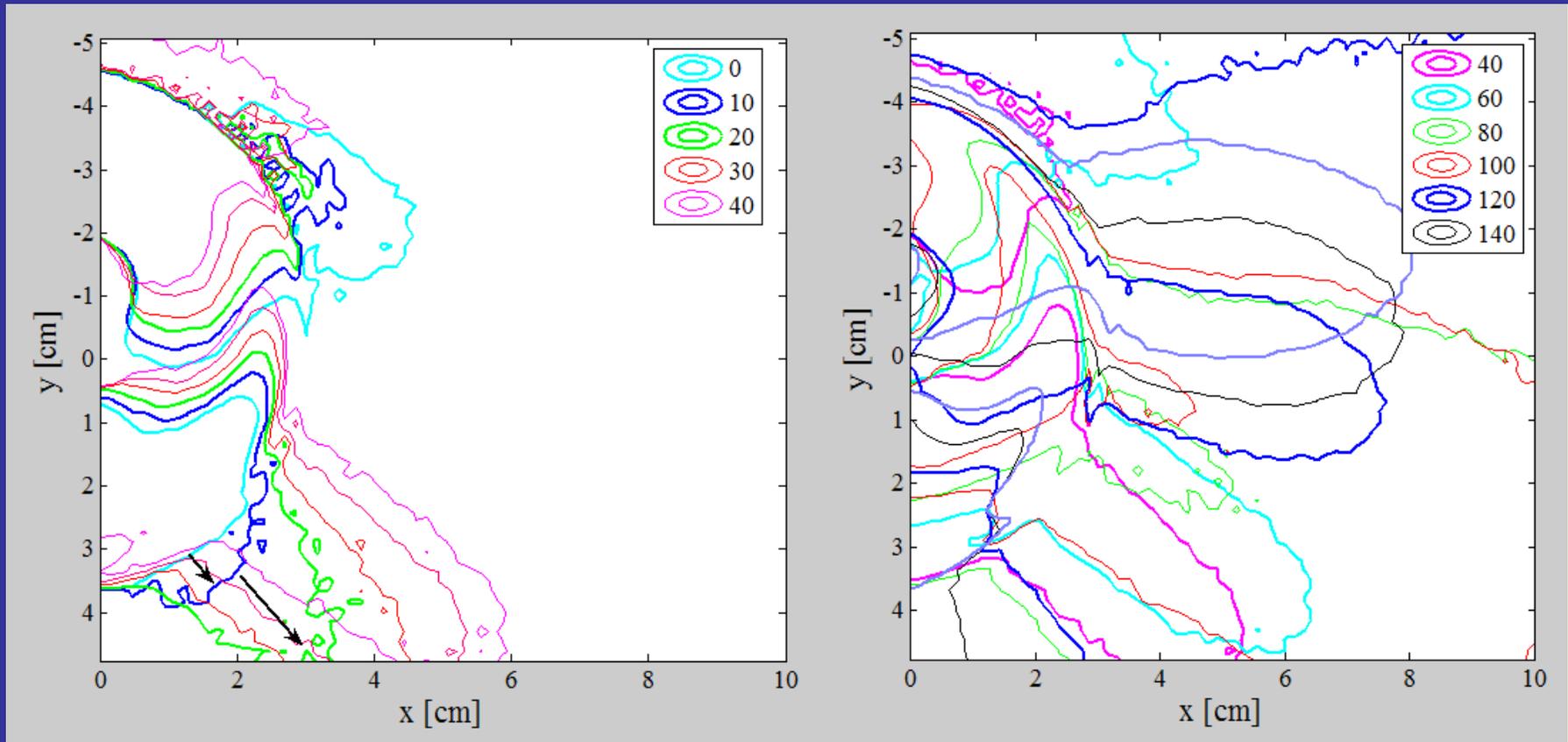
**Life-time  $\sim 60 \mu\text{s}$ ;**

**$L_{r,avaloid} \sim 6 \text{ cm}$ ;**

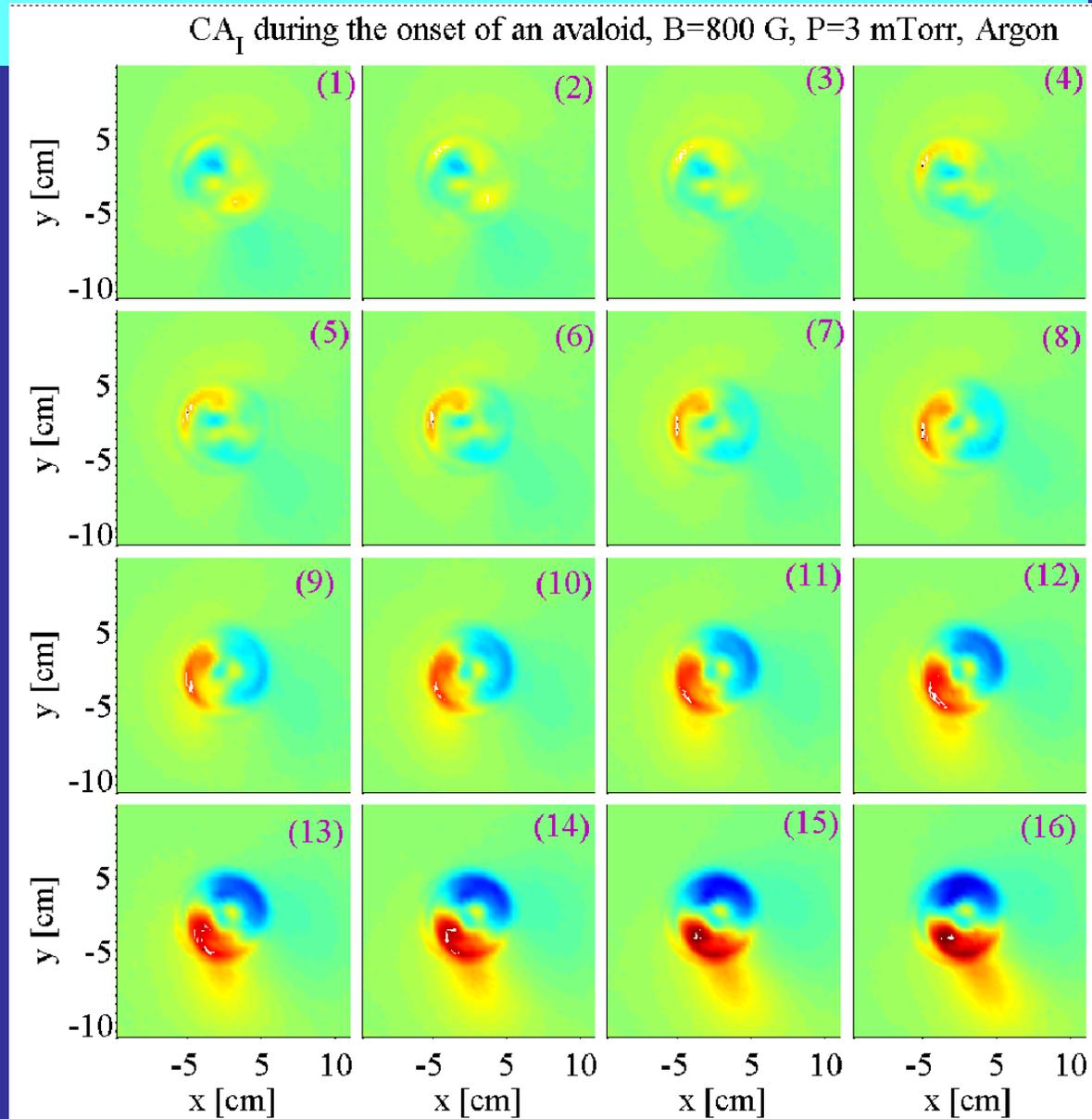
**$L_{\theta,avaloid} \sim 2 \text{ cm}$ ;  $V_{r,avaloid} \sim 10^5 \text{ cm/s}$**

**$V_{\theta, \text{main plasma}} \sim 5 \times 10^4 \text{ cm/s}$**

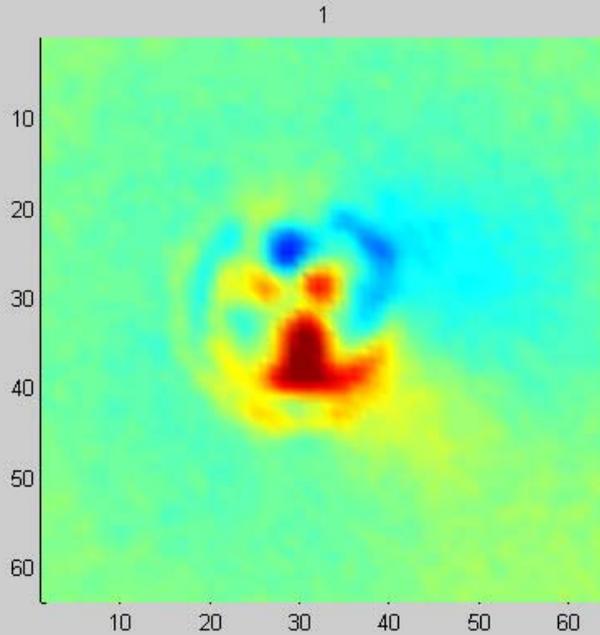
**$V_{\theta,avaloids} \sim 4.5 \times 10^4 \text{ cm/s}$**



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 movies from CSDX & 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

# Conclusion



- Intermittency in the SOL of magnetic fusion devices is caused by large-scale structures with large radial velocities that we call avaloids.
- Universality: Avaloids have the same properties on different magnetic fusion devices.
- Avaloids result from the non-linear evolution of a low poloidal number edge instability occurring inside the plasma. More precisely, on the average, it is the mode number  $m = 1$ .
- Inside the main plasma, turbulence is NOT stationary
- Avaloids are elongated structure that does NOT necessarily detach from the main plasma