SELF-ORGANIZED CRITICALITY vs. LOW-DIMENSIONAL CHAOS FOR THE UNDERSTANDING OF FUSION EDGE PLASMA TURBULENCE

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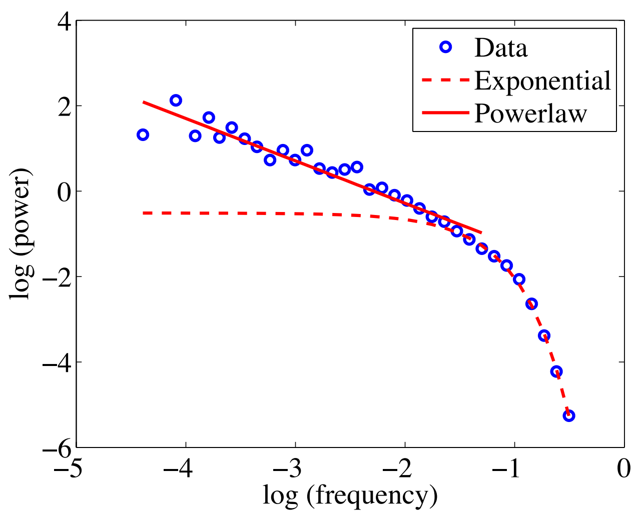

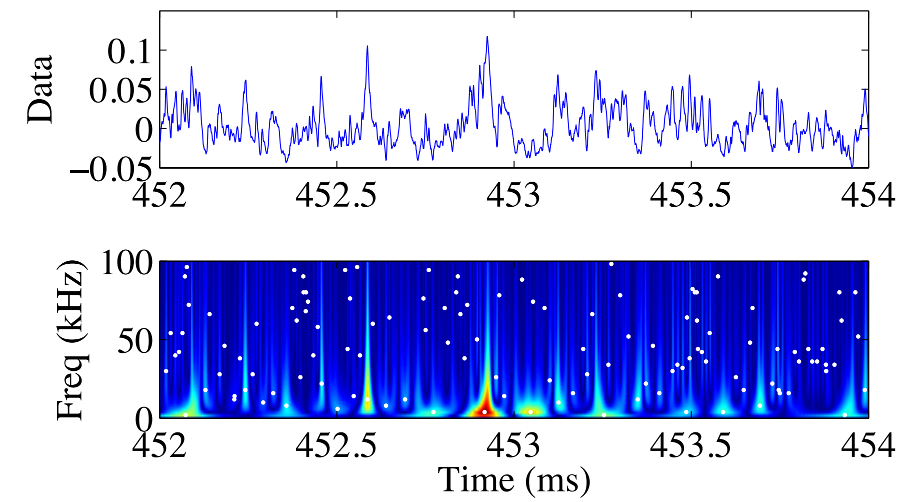

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SELF-ORGANIZED CRITICALITY

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SELF-ORGANIZED CRITICALITY: concept introduced by P. Bak in 1987 to attempt to explain 1/f noise in many natural systems.

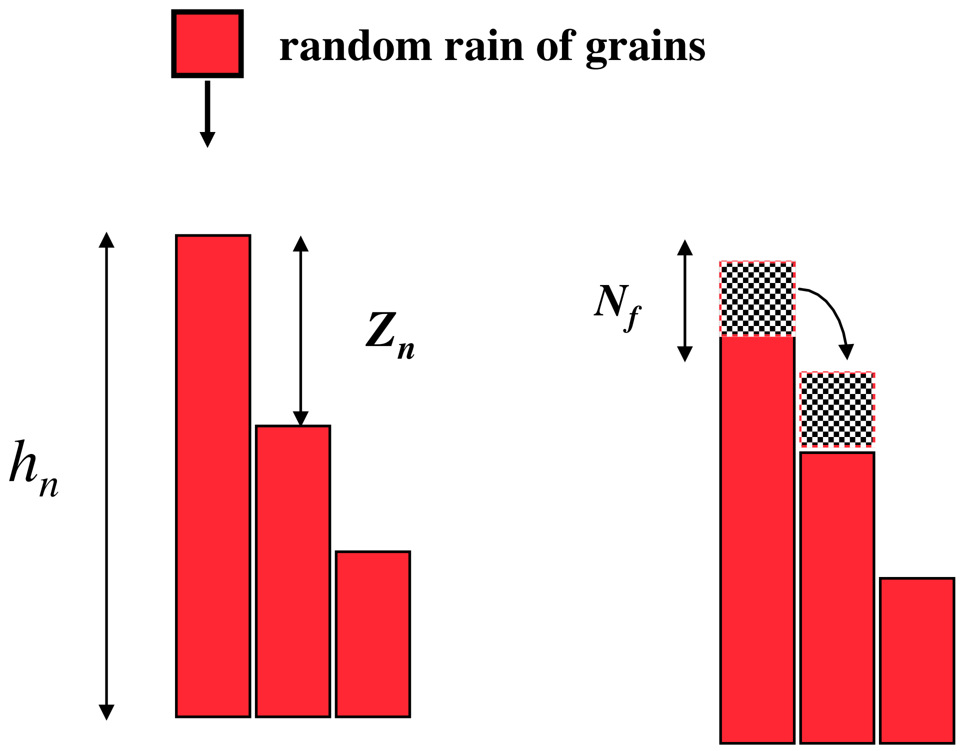
- Typically, requires the existence of a threshold that separates a quiescent phase from an active phase in which fast transport/redistribution takes place.

- It also requires a certain randomness/unpredictability in the system.

Bak's paradigmatic toy-model: the sandpile.

- Grains of sand dropped on a sandpile whose cells can go critical and turn when a certain local threshold condition is overcome.

Bak's original model was driven infinitely slow, with sand-addition being stopped as soon as an avalanche starts, and restarted when it stops.



Steady-state (SOC state) exhibits self-similarity, long-term correlations and other properties typical of equilibrium critical states but without the need of external tuning.

DIRECTED RUNNING SANDPILE

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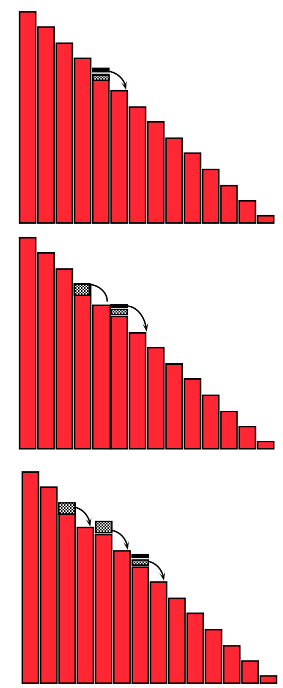
The directed running sandpile (DRS), using as the critical threshold the local slope, is much closer in spirit to the real situation that turbulent fusion plasmas experience. It <u>does not stop the external drive while avalanches take place</u>.

[See: T. Hwa and M. Kardar, Phys. Rev. A 45, 7002 (1992)]

SOC-state exhibits self-similar, scale-free statistics of avalanche sizes and energies

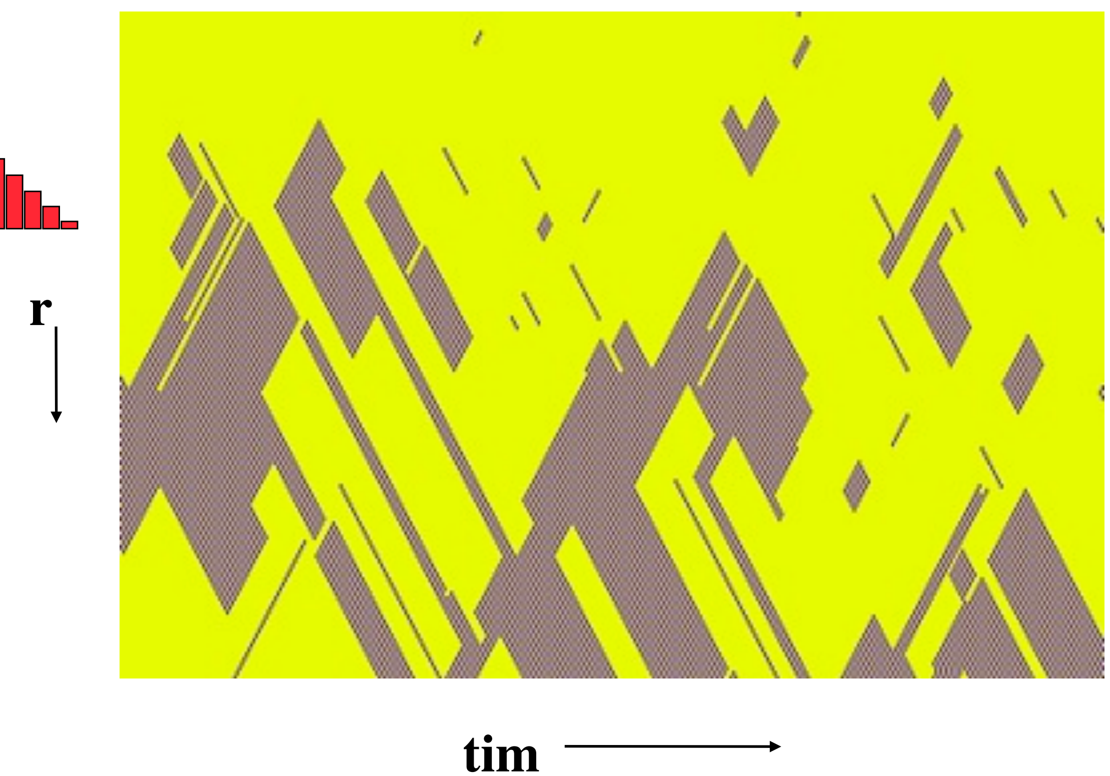
It can maintain a net non-zero outflux in spite of being submarginal on average

Intermittent transport is strongly correlated in time via shaping of the height profile



The shape of the height profile at the SOC-state is rather insensitive to the location of the source as long as the system is not overdriven

Avalanche overlapping is a real issue (invoked to explain the 1/f spectrum by HK)



FUSION TOROIDAL PLASMAS

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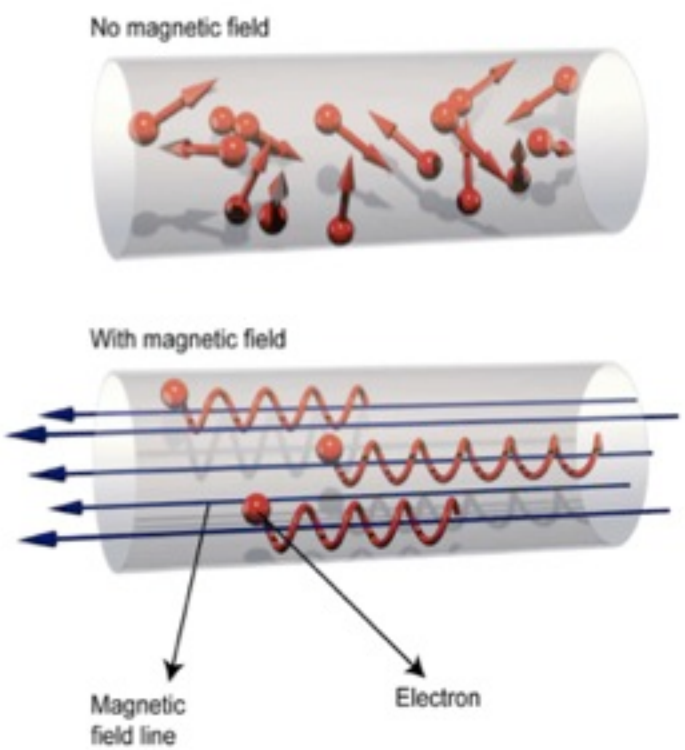
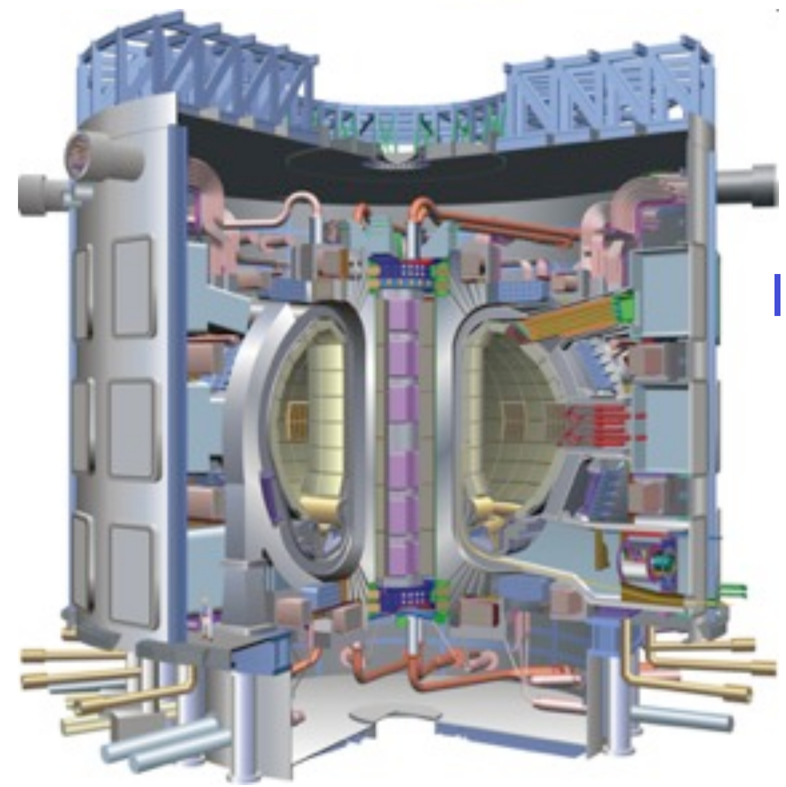


Helical magnetic fields can be used to confine hot plasmas long enough to produce energy



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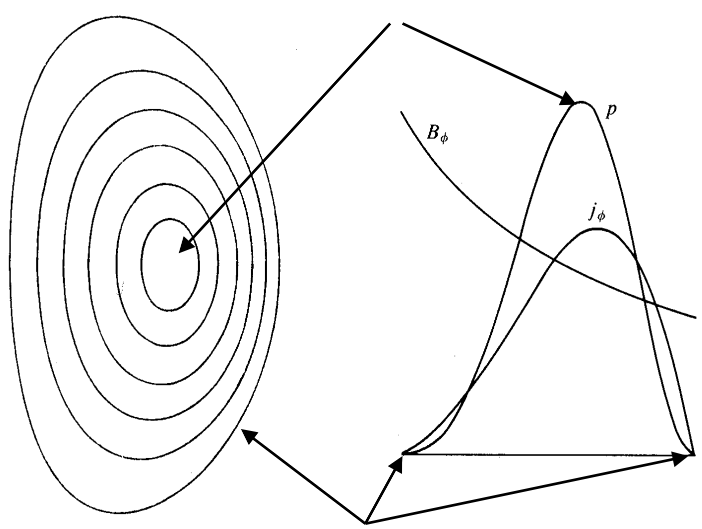
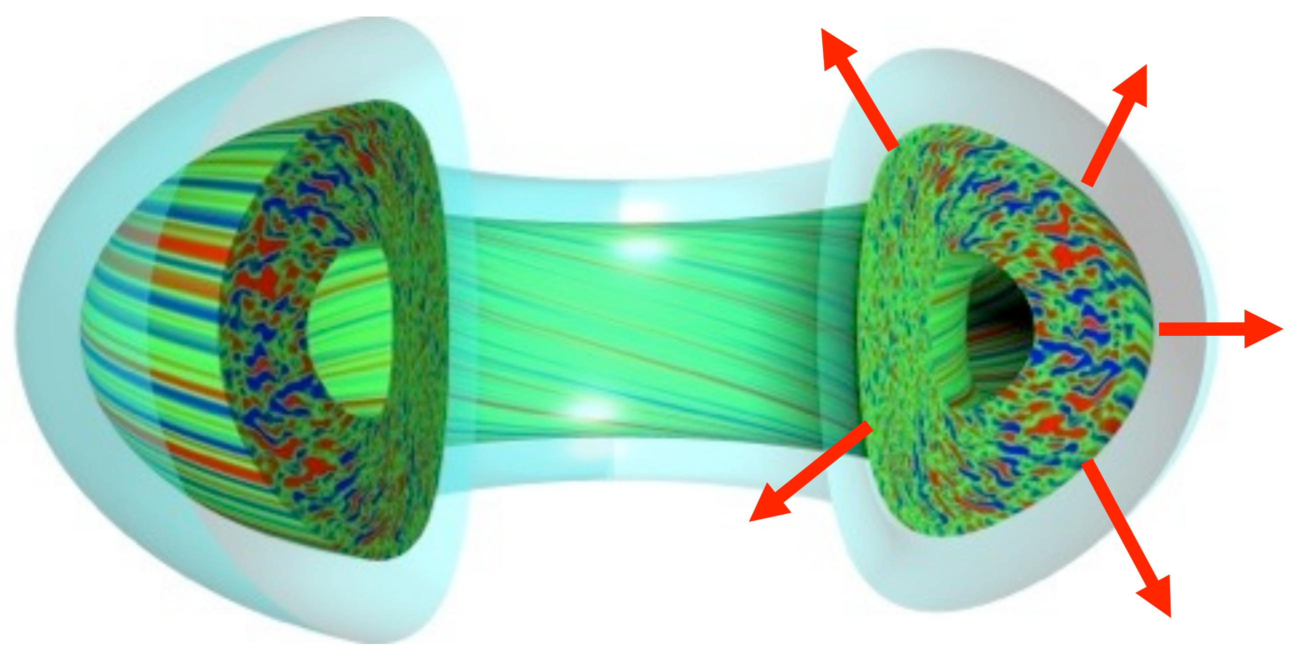


Turbulence dominates radial losses of energy and particles



GYRO, General Atomics

First EVIDENCE FOR SOC: Power spectra

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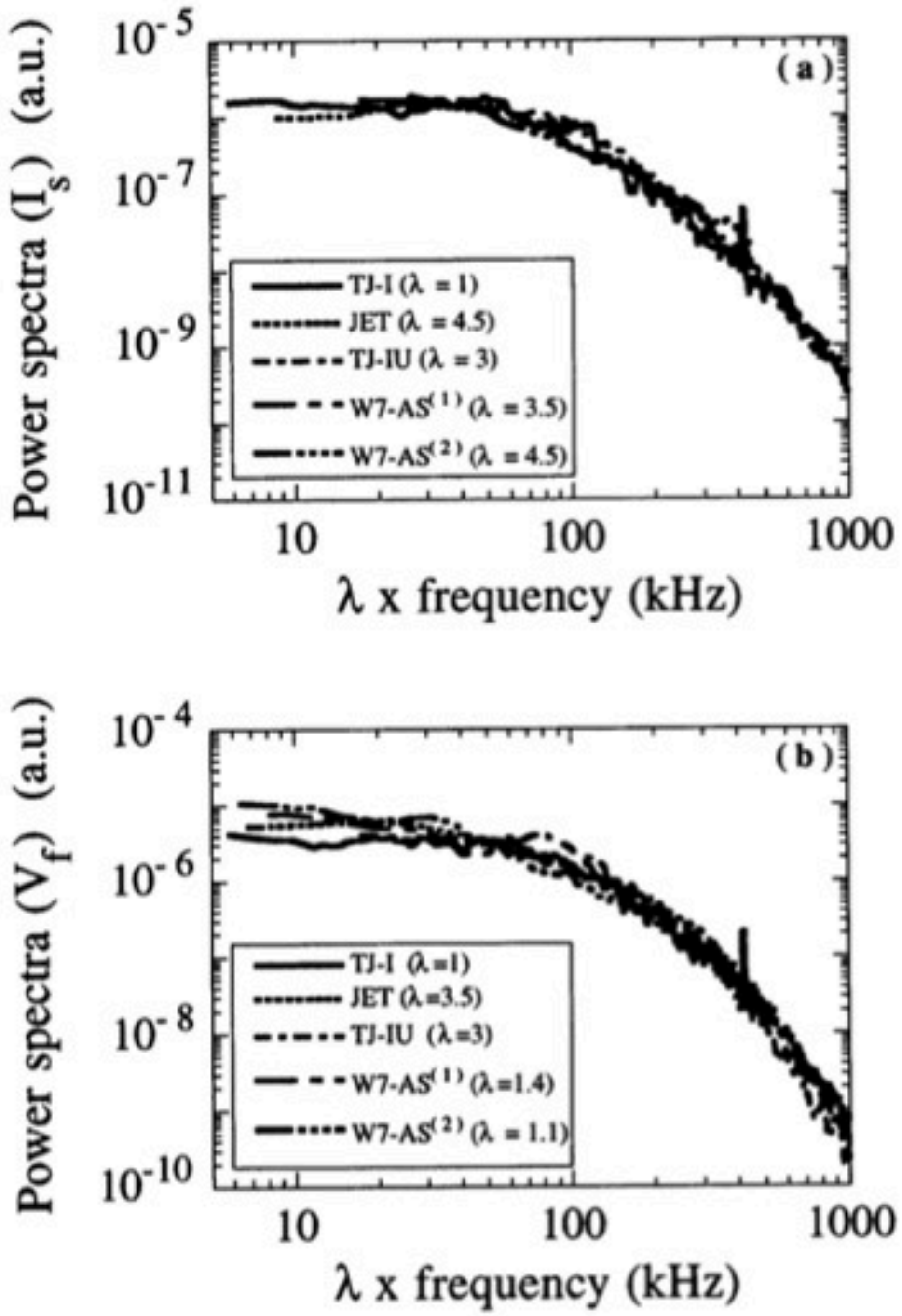

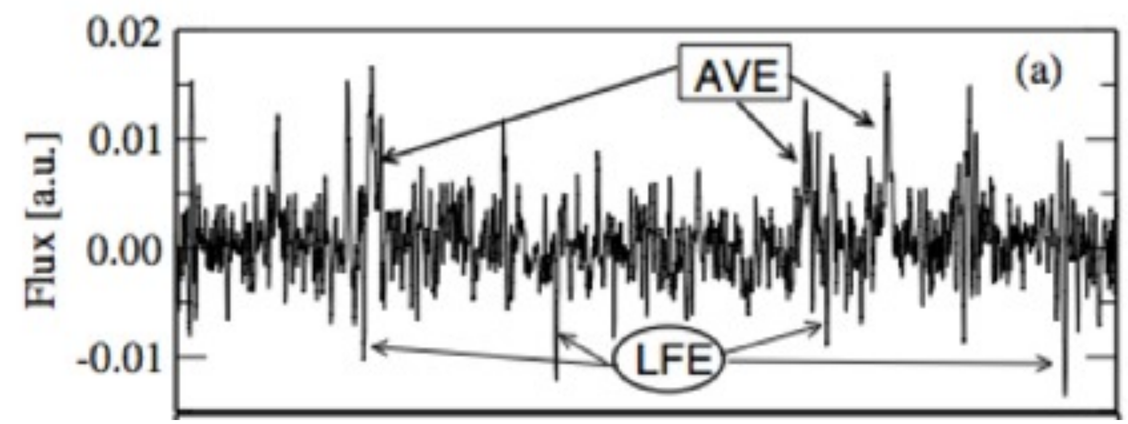

1/f regions in power spectra such as those exhibited by DRS were considered a trademark of SOC then.

1/f regions were sought for in fusion experiments, both tokamaks and stellarators.

Mainly, using edge fluctuation data measured with Langmuir probes. From these, time series of the turbulent fluctuations and turbulent fluxes can be obtained at a single radial location.

Self-similarity of power-spectra and power-laws close to 1/f were indeed reported.

[See: M.A. Pedrosa et al, Phys. Rev. Lett. 82, 3621 (1999)]

L-MODE TOKAMAK PLASMAS

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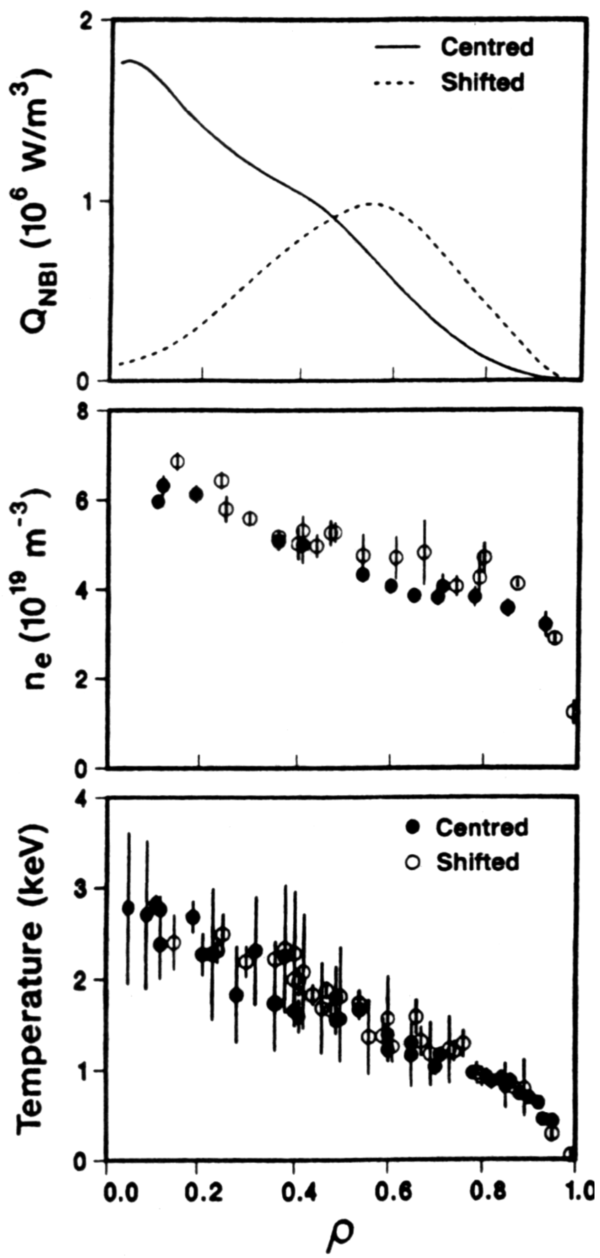
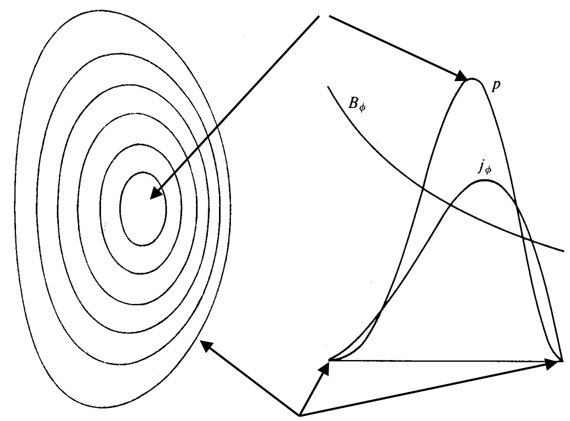
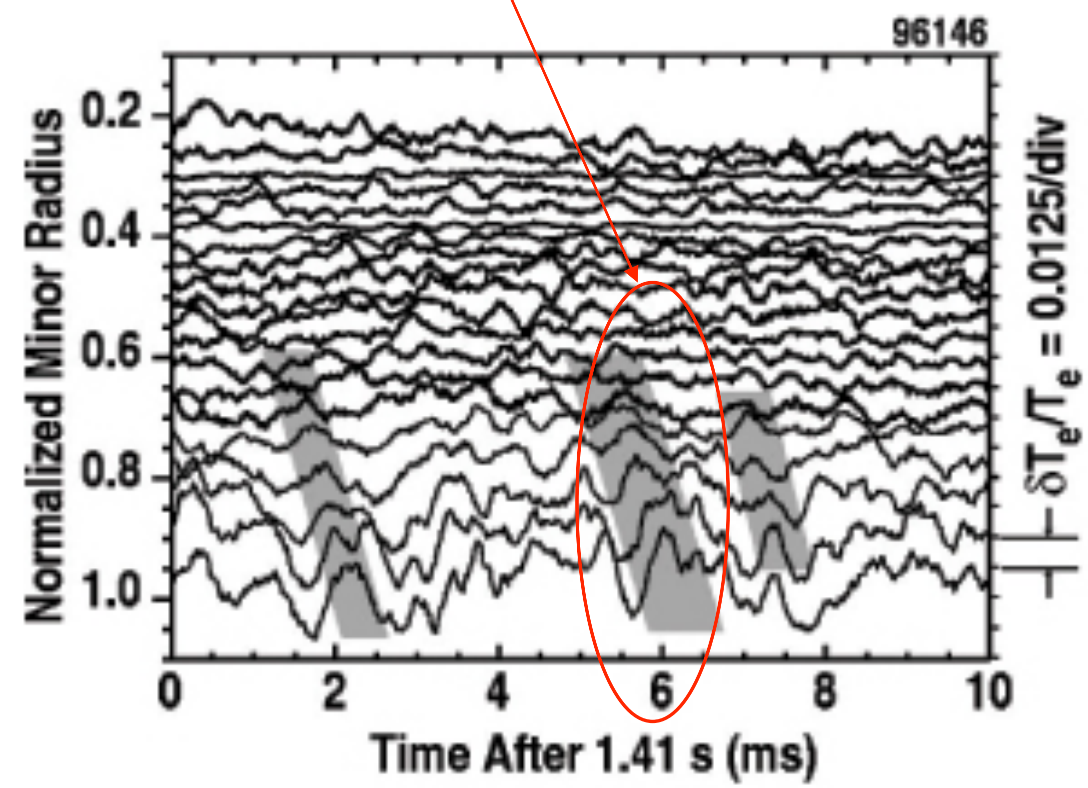
Profiles insensitive to external drive location

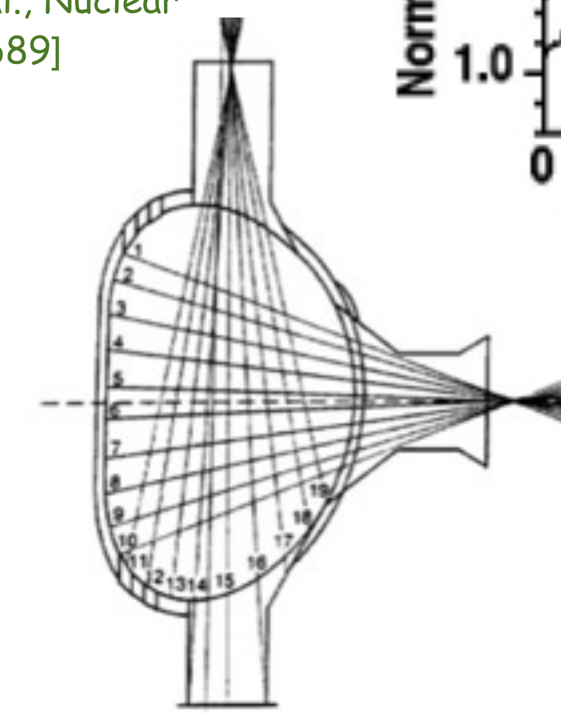




[See: Schissel et al., Nuclear Fusion **32** (1992) 689]

Radial avalanches seen in ECE diagnostic





[P.Politzer et al, Phys.Plasmas **9** (2002) 1962]

SOC hypothesis suggested as an explanation?

NEAR-MARGINAL TURBULENCE

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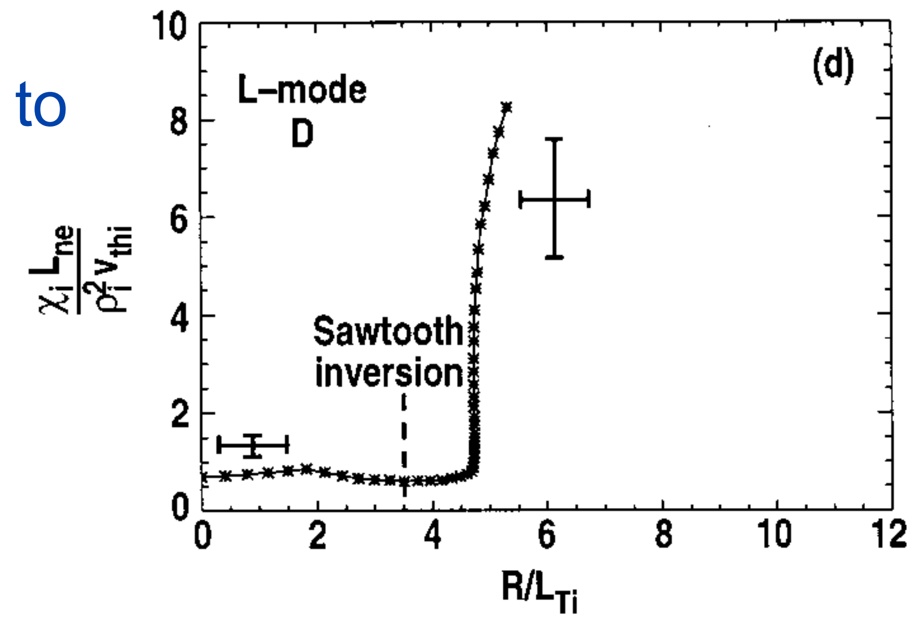
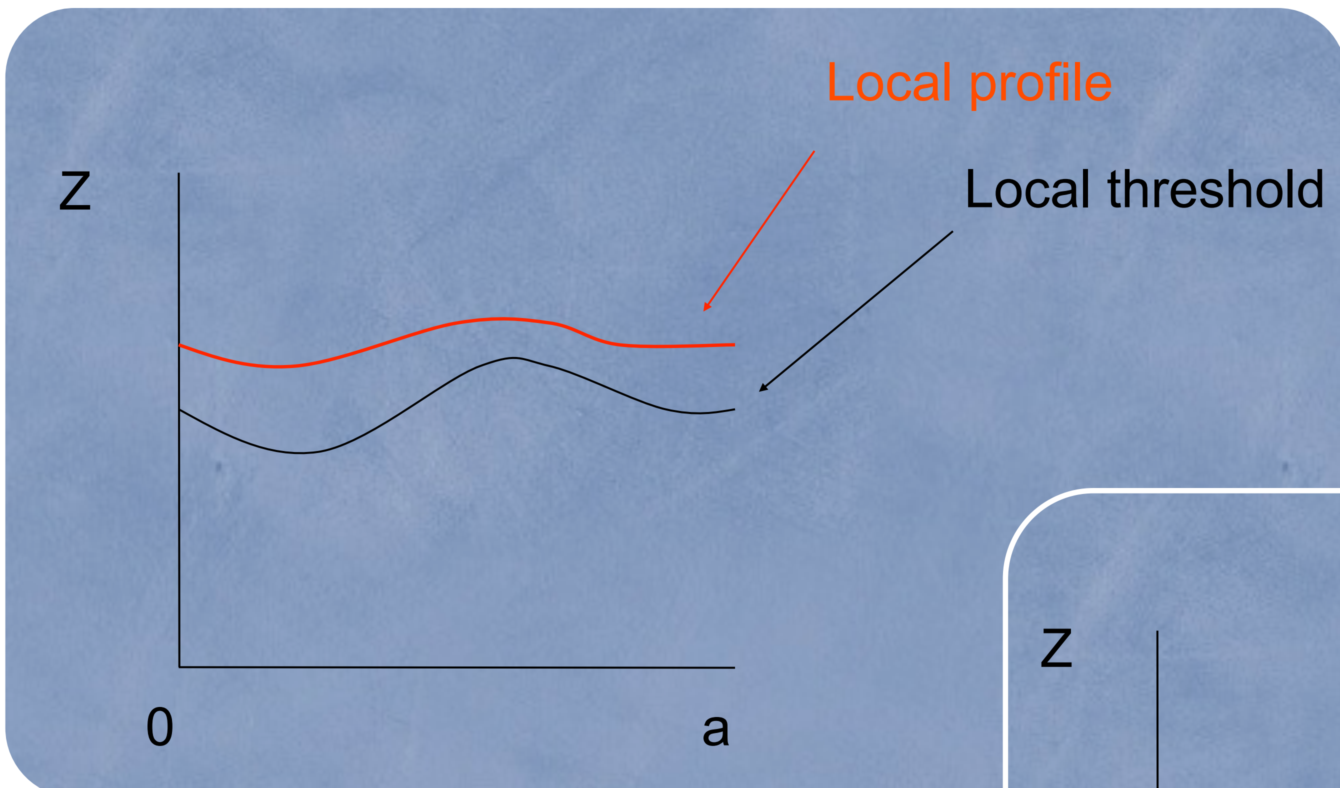
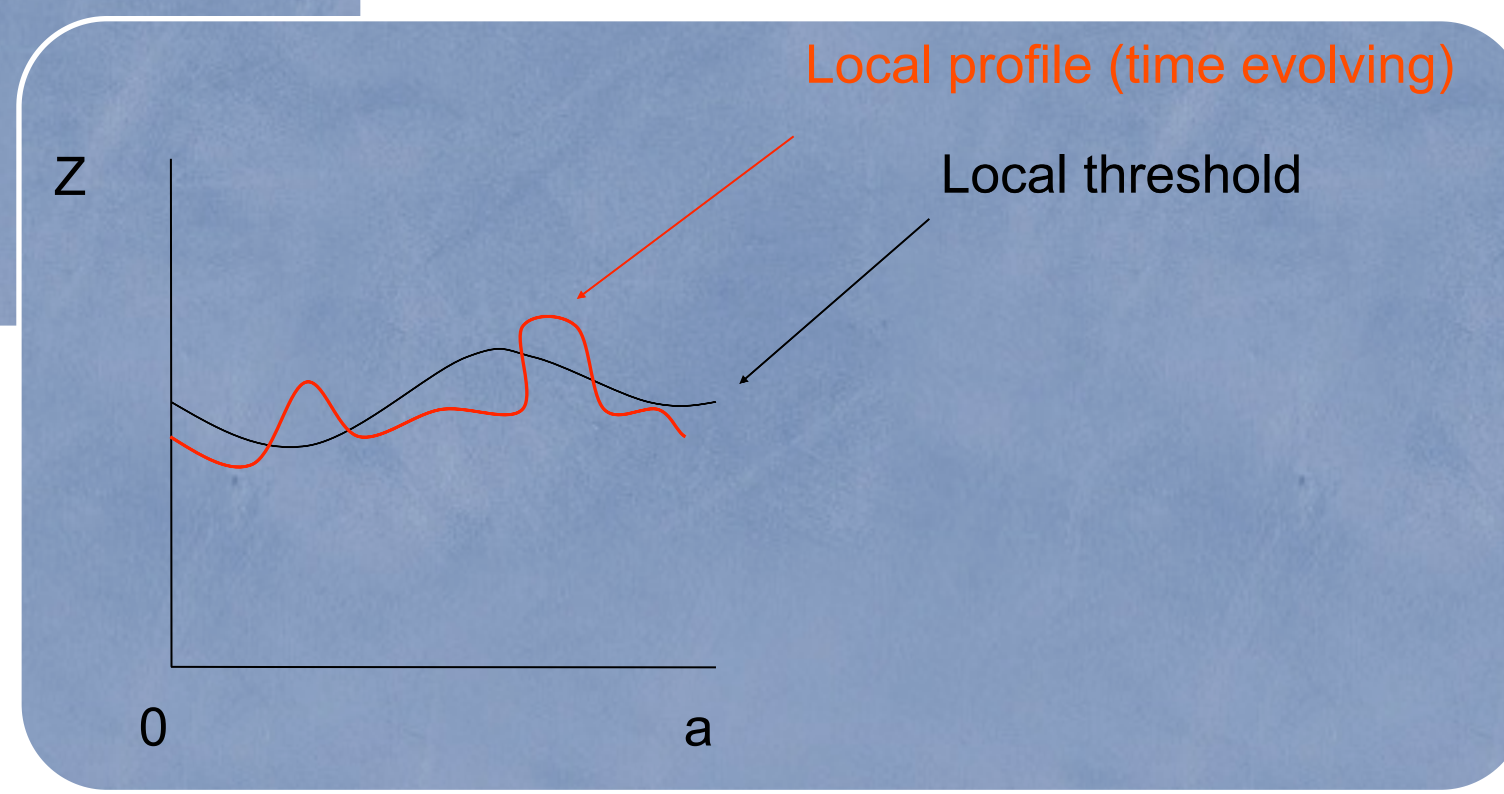
Some of the aforementioned phenomenology could be understood if the confined plasma has its profiles close to marginal values for the onset of turbulence.

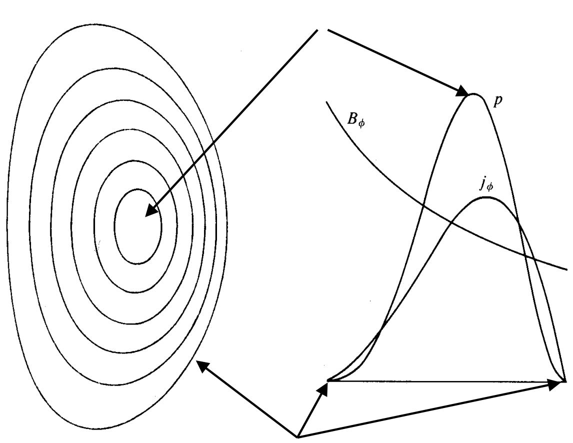


[See: D.R. Baker et al, Physics of Plasmas 8, 4138 (2001)]





[See: P.H. Diamond and T.S. Hahm, Physics of Plasmas 3640, (1995)]



SOC AND TOKAMAK PLASMAS

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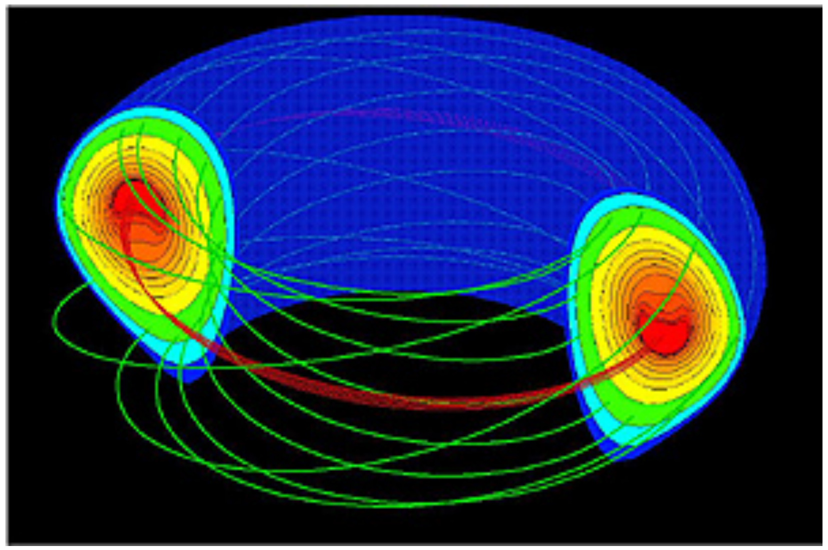
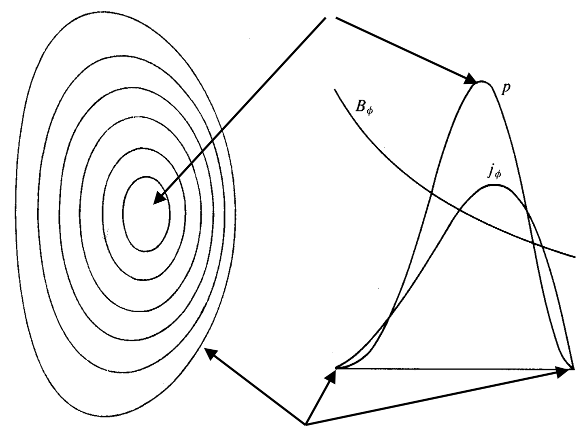
An analogy between HK's sandpile an a magnetically confined toroidal fusion plasma can be easily done if it is near-marginal conditions.





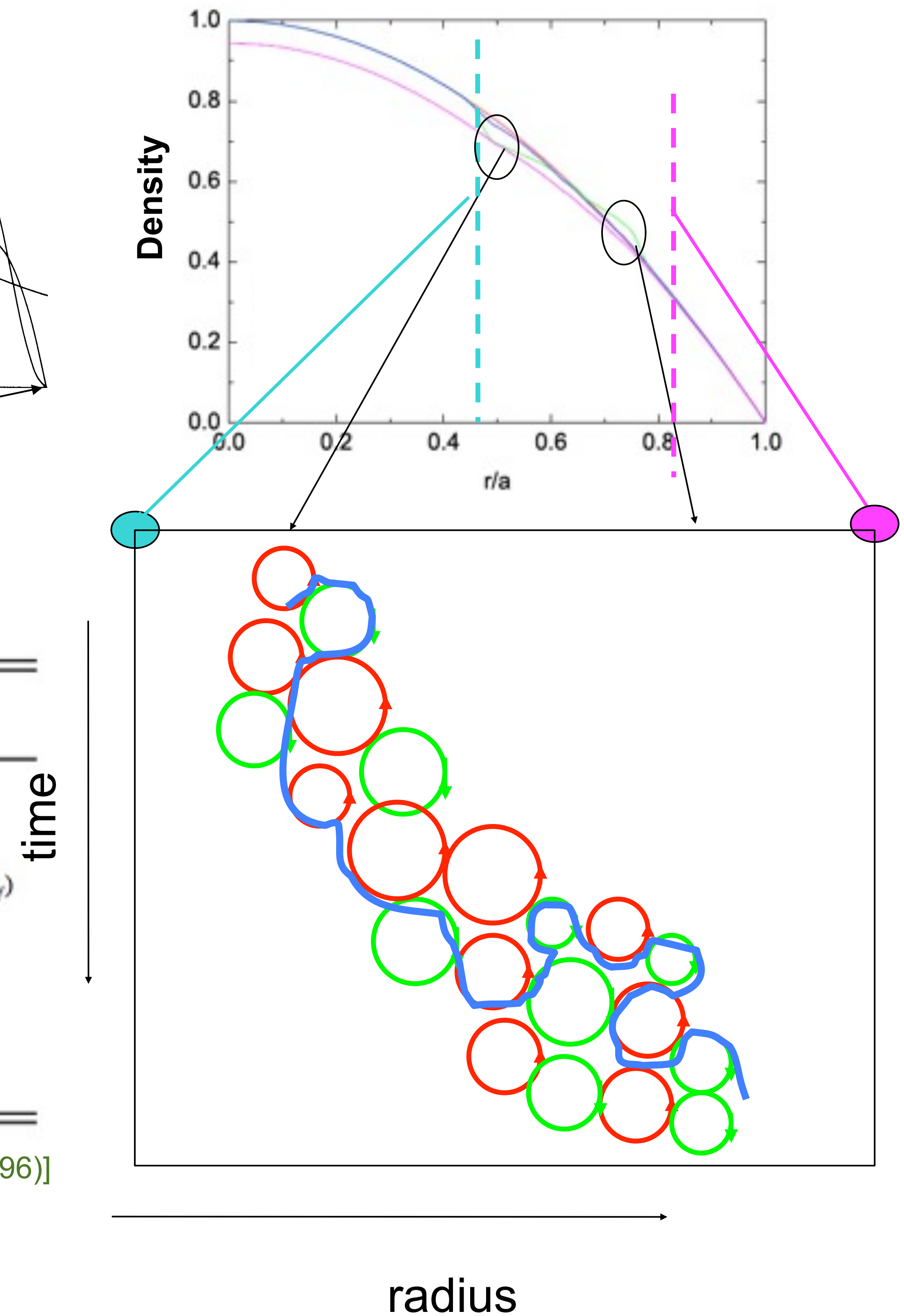


TABLE I. Analogies between the sandpile transport model and a turbulent transport model.

Turbulent transport in toroidal plasmas	Sandpile model
Localized fluctuation (eddy)	Grid site (cell)
Local turbulence mechanism:	*Automata rules*:
Critical gradient for local instability	Critical sandpile slope (Z_{crit})
Local eddy-induced transport	Number of grains moved if unstable (N_f)
Total energy/particle content	Total number of grains (total mass)
Heating noise/background fluctuations	Random rain of grains
Energy/particle flux	Sand flux
Mean temperature/density profiles	Average slope of sandpile
Transport event	Avalanche
Sheared electric field	Sheared flow (sheared wind)

[See: D.E. Newman et al, Phys. Plasmas 3, 1858 (1996)]

Lots of activity (not comprehensive...)

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P.H. Diamond et al, Phys. Plasmas 2, 3640 (1995)	– Theory, PDE
D.E. Newman et al, Phys. Plasmas 3, 1858 (1996)	– Sandpile, near-marginal dyns, shear flow effects
B.A. Carreras et al, Phys. Plasmas 3, 2904 (1996)	– Simulation (Interch. fluid), near marginal, avalanches
R. Dendy et al, Pl. Phys. Contr. Fusion 39, 1947(1997)	– Sandpile, near-marginal dyns
X. Garbet et al, Phys. Plasmas 5, 2836 (1998)	– Simulation (gyrofluid, DTEM), near marginal, flux-driven
Y. Sarazin et al, Phys. Plasmas 5, 4214 (1998)	– Simulation (gyrofluid, ITG), near marginal, flux-driven
T. Rhodes et al., Phys. Lett. A 253, 181 (1998)	– Experimental, tokamak, fluctuation statistics
B.A. Carreras et al., Phys. Rev. Lett. 80, 4438 (1998)	– Experimental, Hurst exponents, edge fluctuations
M.A. Pedrosa et al., Phys. Rev. Lett. 82, 3621 (1999)	– Experimental, power spectra, edge fluctuations
B.A. Carreras et al., Phys. Rev. Lett. 83, 3653 (1999)	– Experimental, self-similarity, edge fluctuations
P. Beyer et al, Pl. Phys. Contr. Fusion 41, A757 (1999)	– Experimental, tokamak, edge fluctuations
B. A. Carreras et al, Phys. Rev. E 60, 4770 (1999)	– Sandpile, Effective Tr. Model (CTRWs)
B. A. Carreras et al., Phys. Plasmas 8, 5096 (2001)	– Simulation (Interch., fluid), Eff. Tr. Model (CTRWs)
R. Sanchez et al., Nucl. Fusion 41, 247 (2001)	– Sandpile, diffusion effects, ELMs
S. Chapman et al, Phys. Rev. Lett. 86, 2814 (2001)	– Sandpile, ELMs
E. Spada et al, Phys. Rev. Lett. 86, 3032 (2001)	– Experimental (against) – W. times, No s-similarity
R. Sanchez et al, Phys. Rev. Lett. 88, 068302 (2002)	– Sandpile, Wait. times
P.A. Politzer et al, Phys. Plasmas 9, 1962 (2002)	– Experimental, avalanche viz., ECE, tokamak
L. García et al, Phys. Plasmas 9, 841 (2002)	– Theory, PDE (continuum sandpile)
R. Sanchez et al, Phys. Rev. Lett. 90, 185005 (2003)	– Experimental – W. times, Response to Spada's PRL
I Gruzinov et al, Phys. Plasmas 10, 569 (2003)	– Sandpile, ELMs
V. Tangri et al, Phys. Rev. Lett. 91, 025011 (2003)	– Theory, PDE (continuum sandpile)
Y Xu et al, Phys. Plasmas 11, 5413 (2004)	– Experimental, Tokamak, edge fluctuations
B.Ph. van Milligen et al, Phys. Plasmas 11, 2272 (2004)	– Theory, Effective Tr. Model (CTRWs/Master Eqs.)
D. del-Castillo-Negrete et al, Phys. Plasmas (2004)	– Simulation (Interch., fluid), Eff. Tr. Model (Fract. Diff. Eqs)
B. Dudson et al, Pl. Phys. Contr. Fusion 47, 885 (2005)	– Experimental, spherical tokamak
L. Marrelli et al, Phys. Plasmas 12, 030701 (2005)	– Experimental, reverse field pinch
R. Sanchez et al, Phys. Rev. E 74, 016305 (2006)	– Theory, Eff. Tr. Models (FBM/FLM -> FDEs)
J.A. Mier et al, Phys. Plasmas 13, 102308 (2006)	– Simulation (DTEM, fluid), effect of diffusion
F. Sattin et al, Phys. Rev. Lett. 96, 105005 (2006)	– Sandpile, include WTs
J. A. Mier et al, Phys. Rev. Lett. 101, 165001 (2008)	– Simulation (DTEM, fluid), Eff. Tr. Model (Lagr. Diag.)
Y. Sarazin et al, Nucl. Fusion 50, 054004 (2010)	– Simulation (ITG, gyrokinetics), near-marg., avalanches
H. Isliker et al, Phys. Plasmas 17, 082303 (2010)	– Sandpile, ITG-like
J. Maggs et al, Phys. Rev. Lett. 107, 185003 (2011)	– Experimental (against) – Lorenzian, random pulses
S. Tokunaga et al, Phys. Plasmas 19, 092303 (2012)	– Experimental, tokamak, enhanced modes
B. van Milligen et al, Phys. Rev. Lett. 109, 105001 (2012)	– Experimental – Response to Magg's PRL
GZ dos Santos et al, Phys. Lett. A 376, 753 (2012)	– Experimental, tokamak

Motivation of this work

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PRL 107, 185003 (2011) PHYSICAL REVIEW LETTERS week ending 28 OCTOBER 2011

Generality of Deterministic Chaos, Exponential Spectra, and Lorentzian Pulses in Magnetically Confined Plasmas

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(Received 15 August 2011; published 28 October 2011)

The dynamics of transport at the edge of magnetized plasmas is deterministic chaos. The connection is made by a previous survey [M. A. Pedrosa *et al.*, Phys. Rev. Lett. **82**, 3621 (1999)] of measurements of fluctuations that is shown to exhibit power spectra with exponential frequency dependence over a broad range, which is the signature of deterministic chaos. The exponential character arises from Lorentzian pulses. The results suggest that the generalization to complex times used in studies of deterministic chaos is a representation of Lorentzian pulses emerging from the chaotic dynamics.

DOI: 10.1103/PhysRevLett.107.185003 PACS numbers: 52.25.Fi, 05.45.Ac, 52.25.Gj, 52.25.Xz

Recently, it has been proposed that edge turbulent fluctuations could be better described as an uncorrelated superposition of Lorentzian pulses with a narrow distribution of widths.

Original data from the LAPD linear device (*Pace et al, 2008*). Then, from cold plasmas inside the TJ-K stellarator (*Hornung et al, 2011*).

If correct, fluctuations would exhibit an exponential power spectrum, that of the Lorentzian pulse.

Secondly, a connection with low-dimensional chaotic dynamics might exist, in contrast to previous interpretations from edge data from tokamaks and stellarators based on near-marginal, correlated dynamics (*Carreras et al, 1998, Pedrosa et al, 1999, Carreras et al, 2000, Sanchez et al, 2003*).

How <u>universal</u> are the LAPD/TJK results and their conclusions?

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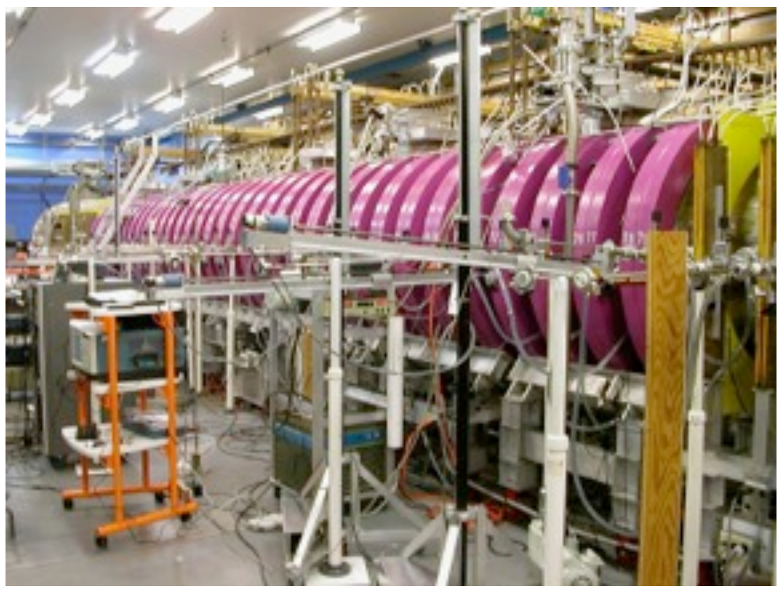
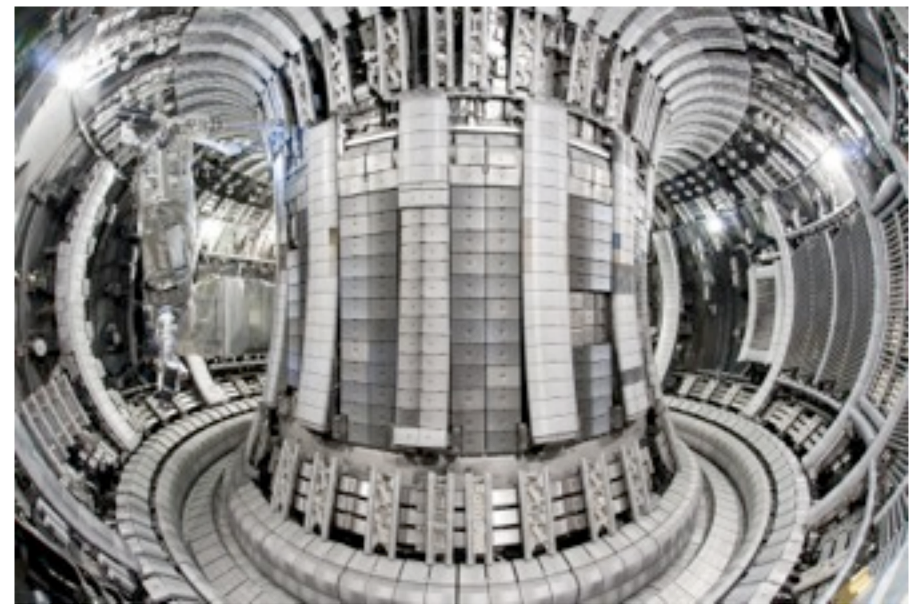
Outline

Our plasmas (in both tokamaks and stellarators) are quite different from LAPD and TJ-K:

1. closed magnetic surfaces, not open field lines like in LAPD





2. very hot plasmas (~0.5 KeV). TJ-K and LAPD are very cold (~10-20 eV).

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Outline (cont'd)

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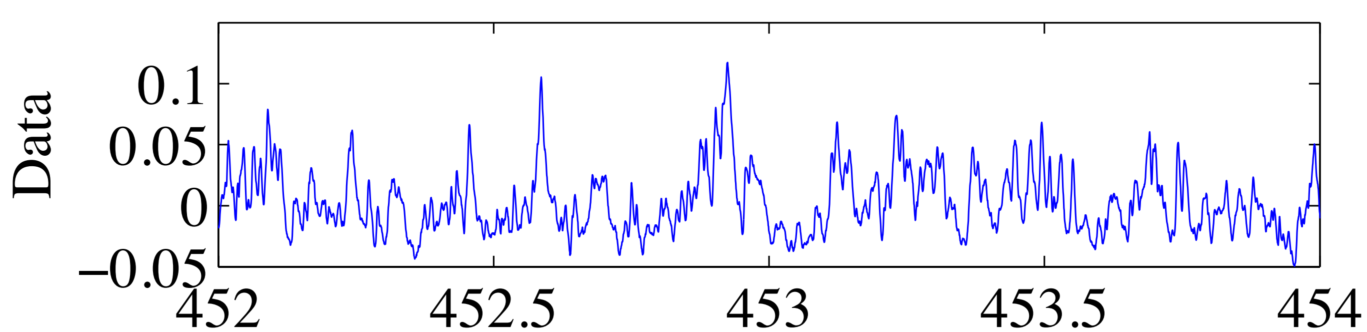
So, the question is whether the Lorentzian model interpretation describes our data or not. In particular, we want to answer the questions?

1. Are the power spectra of our tokamak/stellarator data exponential?
2. Are the pulses Lorentzians in shape, and their widths narrowly-distributed?
3. Are the pulses randomly triggered or correlated in time?

We have reexamined two sets of data, one from the edge of the JET tokamak, one from the edge of the W7-AS stellarator, just inside the LCFS.



See: B.Ph. van Milligen, R. Sanchez and C. Hidalgo, Phys. Rev. Lett. 109, 105001 (2012)

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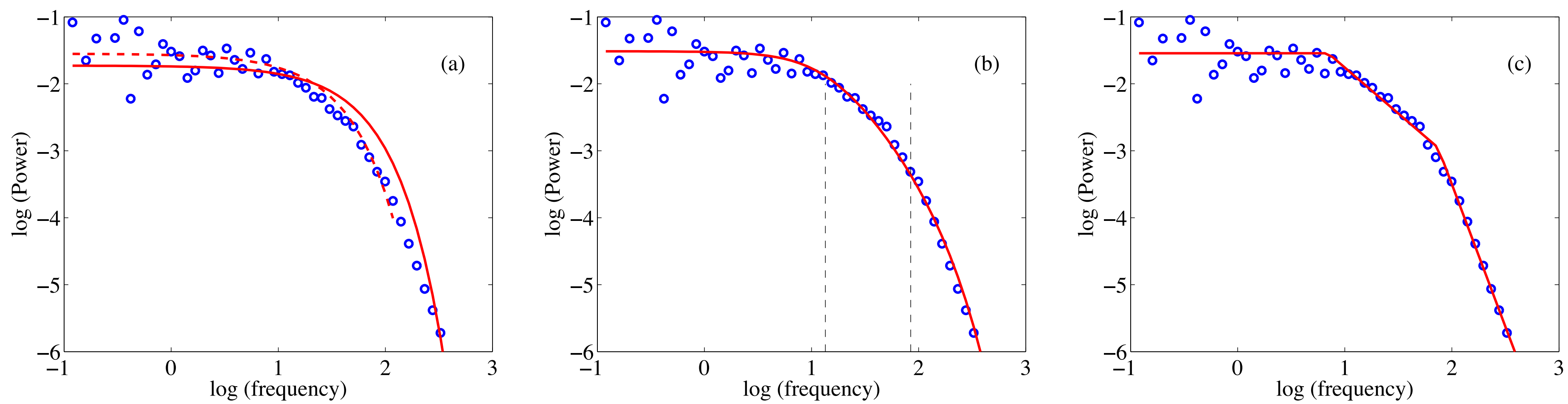
Are our spectra exponential?

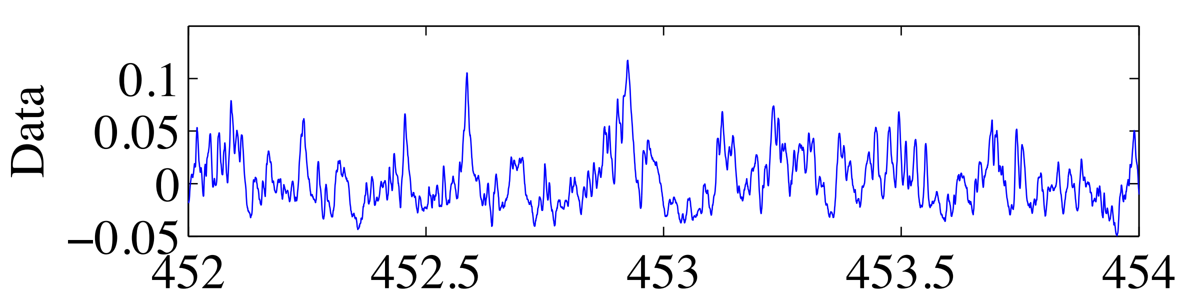
Spectral shape analysis

Are spectra truly exponential? To test this, we fit an actual spectrum (W7-AS) to various alternative shapes.



Case	Expression	R^2
a	$A\exp(-f/f_1)$	0.9146
b	$A\exp(-f/f_2)/(1+(f/f_1)^\beta)$	0.9716
c	three connected power-law lines	0.9716

At least in this case, the exponential fit is worse than alternatives based on power laws.

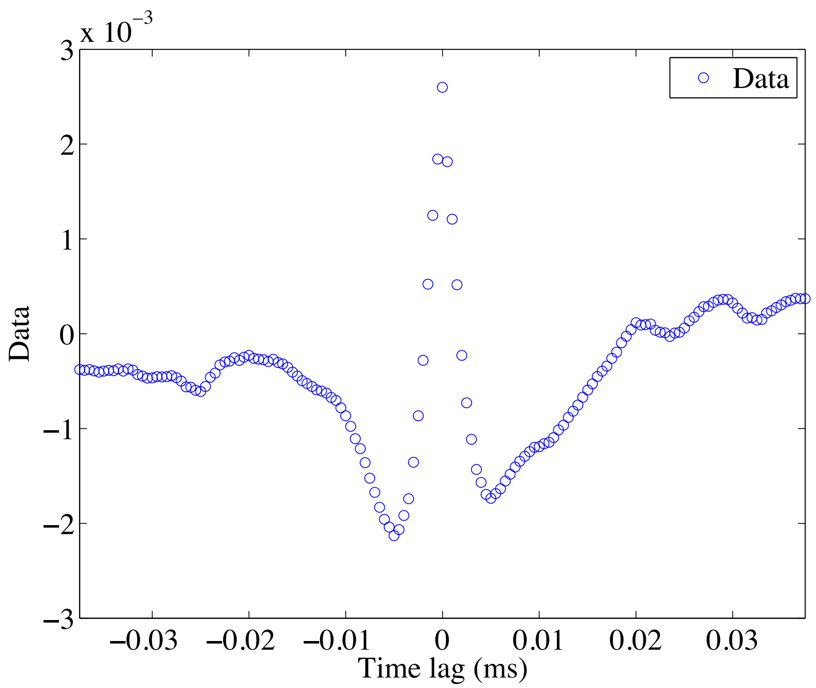


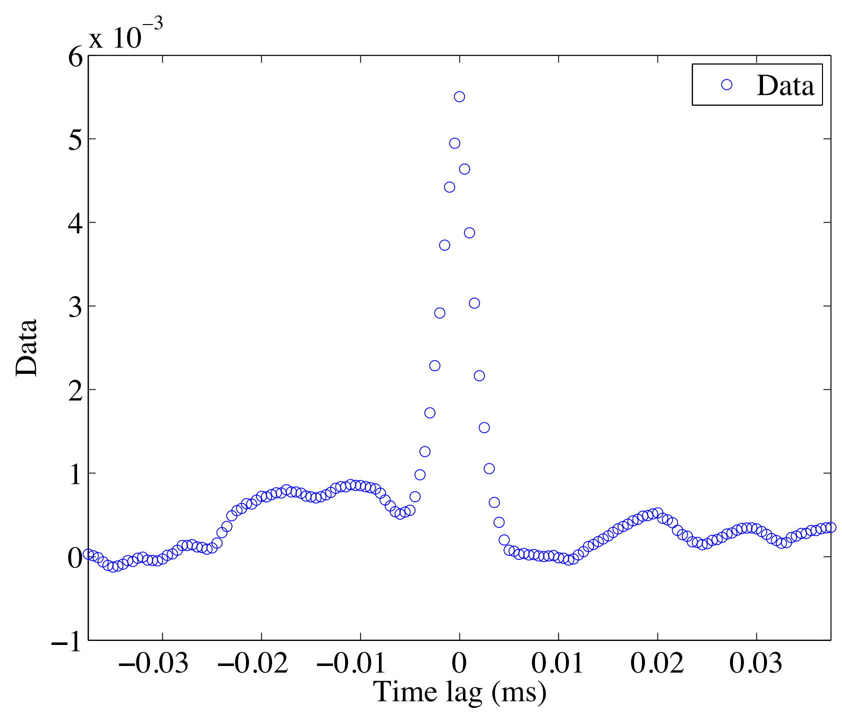
Are our pulses Lorentzian?

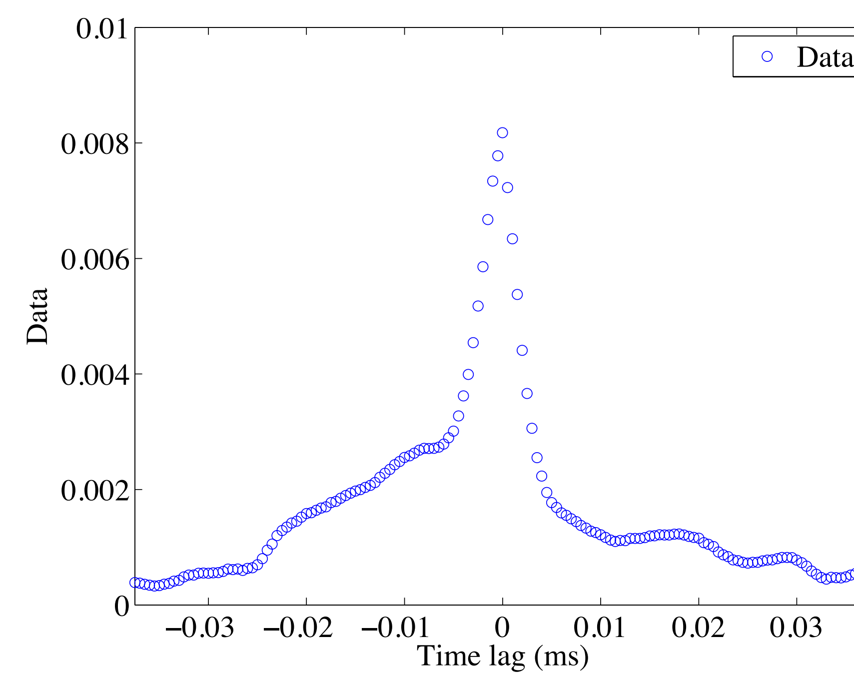
Pulse shape from conditional averaging

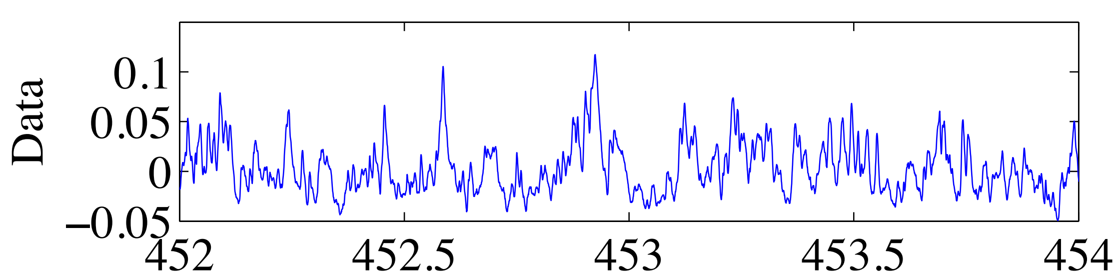
Depending on threshold, the pulse shape varies (W7-AS data).

I.e., it is difficult to determine “the” shape of the pulses.









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Hurst exponents: R/S analysis

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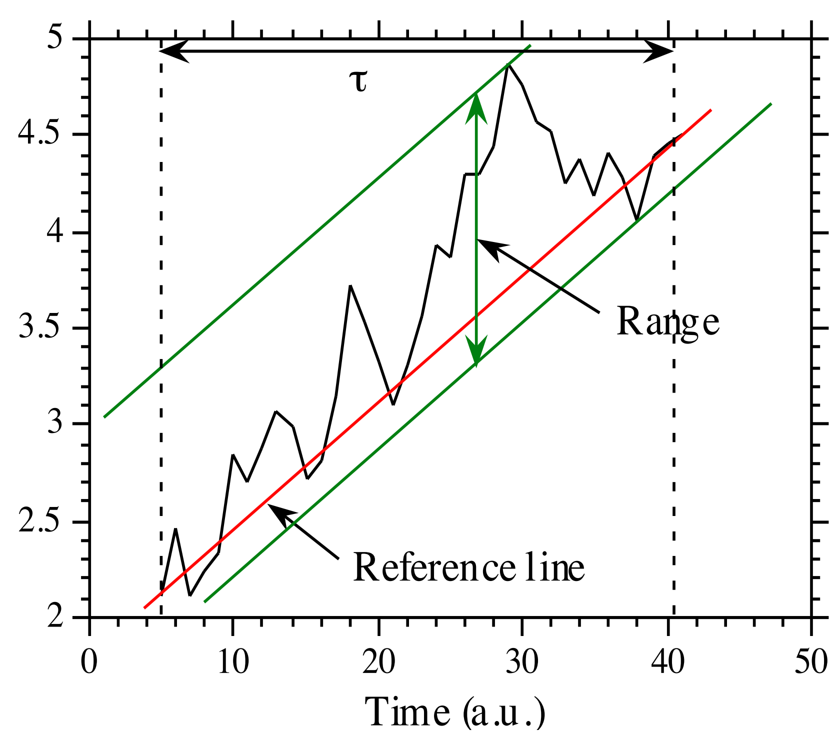
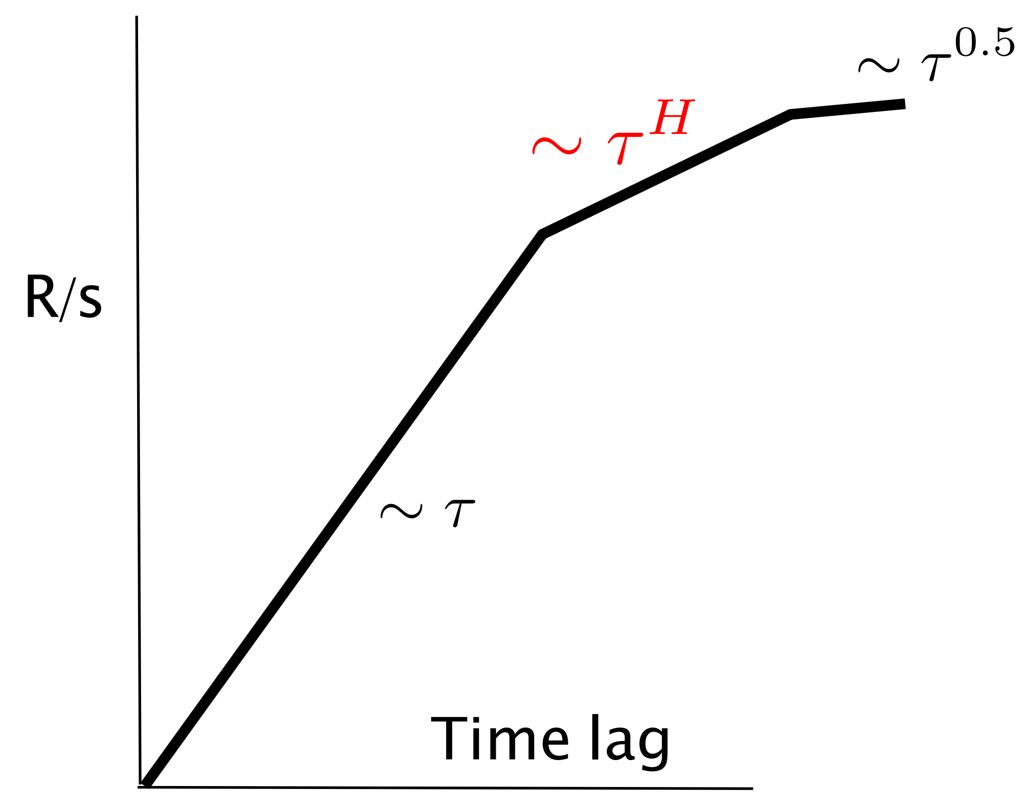
The Hurst exponent was introduced by Hurst (1952) to quantify correlation in time series.

He assumed that any stationary signal can be thought of as the ordered sequence of displacements of a particle. If the signal is random, the motion of such a particle will be that of a random walk, and the distance from its initial position will grow on average as $t^{1/2}$.

If the signal contains positive correlations between successive displacement, such distance will grow with a stronger exponent, t^H, $H > 1/2$. Similarly, if negative correlations exist, it will grow with $H < 1/2$.

H, the Hurst exponent, can be determined in many ways. One of the most popular ones is the R/S method, which is one of the more un-sensitive to noises.





Are our pulses uncorrelated?

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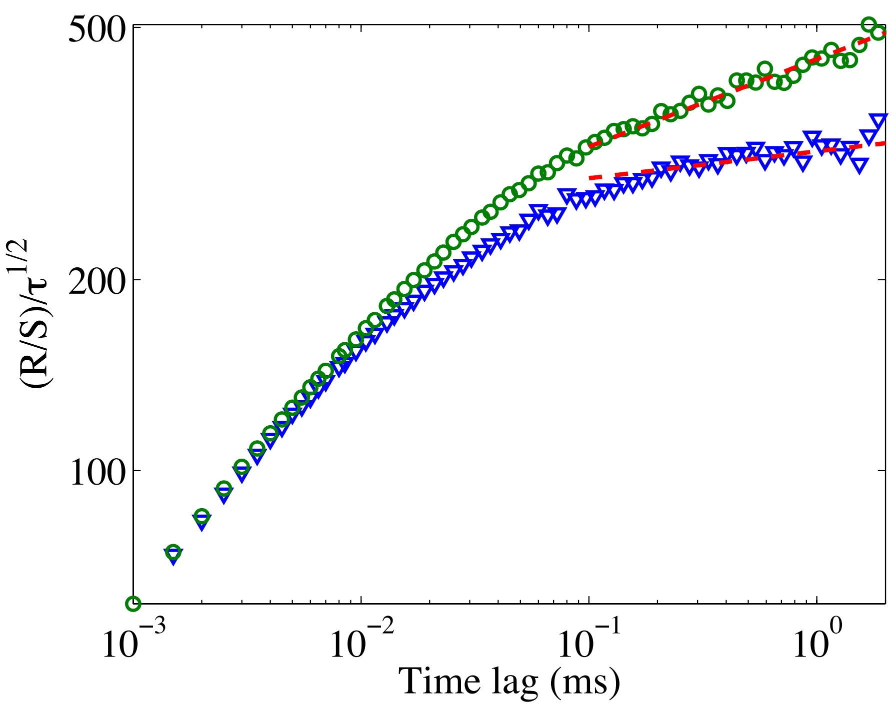
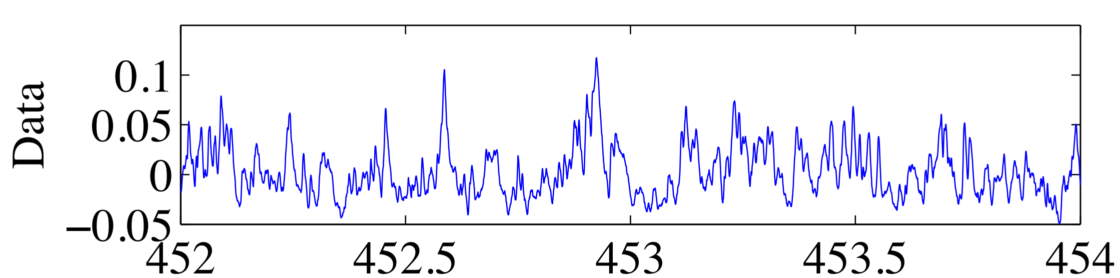
Hurst analysis



Rescaled Range analysis for W7-AS I_{sat} data. Top curve (green circles): original data. Slope of fitted line: H=0.64 ± 0.02. Bottom curve (blue triangles): shuffled data, T_{shuf} =0.02 ms. Slope of fitted line: H=0.54 ± 0.02.
Thus, the data contain significant temporal correlations.



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Wavelet analysis: identification of pulses

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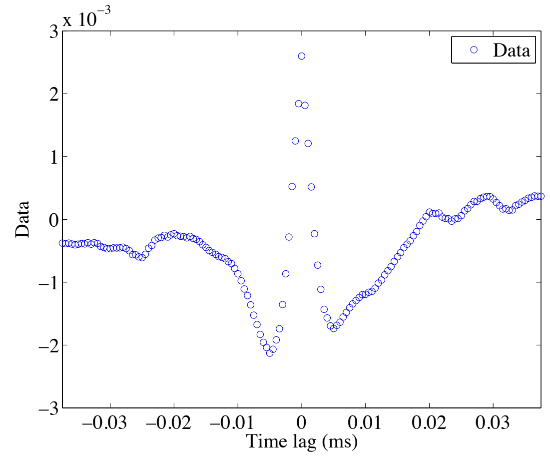

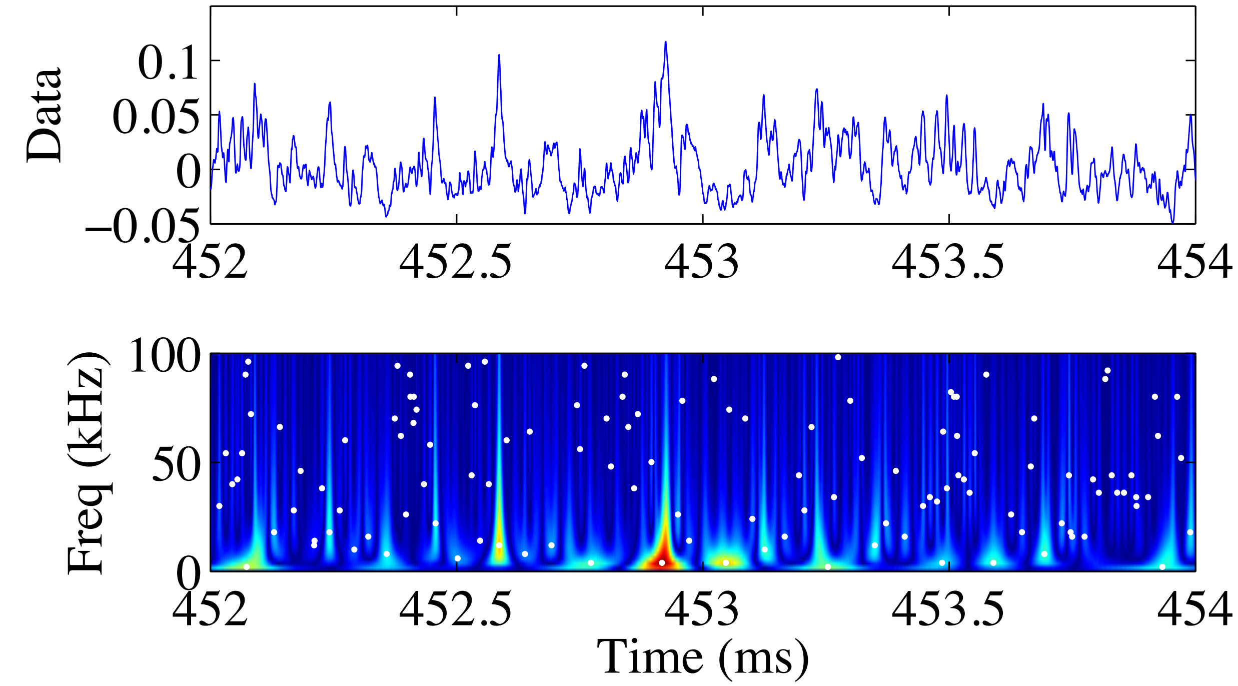

Wavelet analysis

Define a "Difference of Lorentzians" mother wavelet

Standard wavelet analysis follows: wavelet

Transform and inverse transform:

$$a(t,\tau) = \int s(t')\psi_\tau(t-t')dt',$$

$$s'(t) = \frac{1}{C_\psi}\iint a(t',\tau)\psi^*_\tau(t-t')\frac{d\tau dt'}{\tau^2}$$

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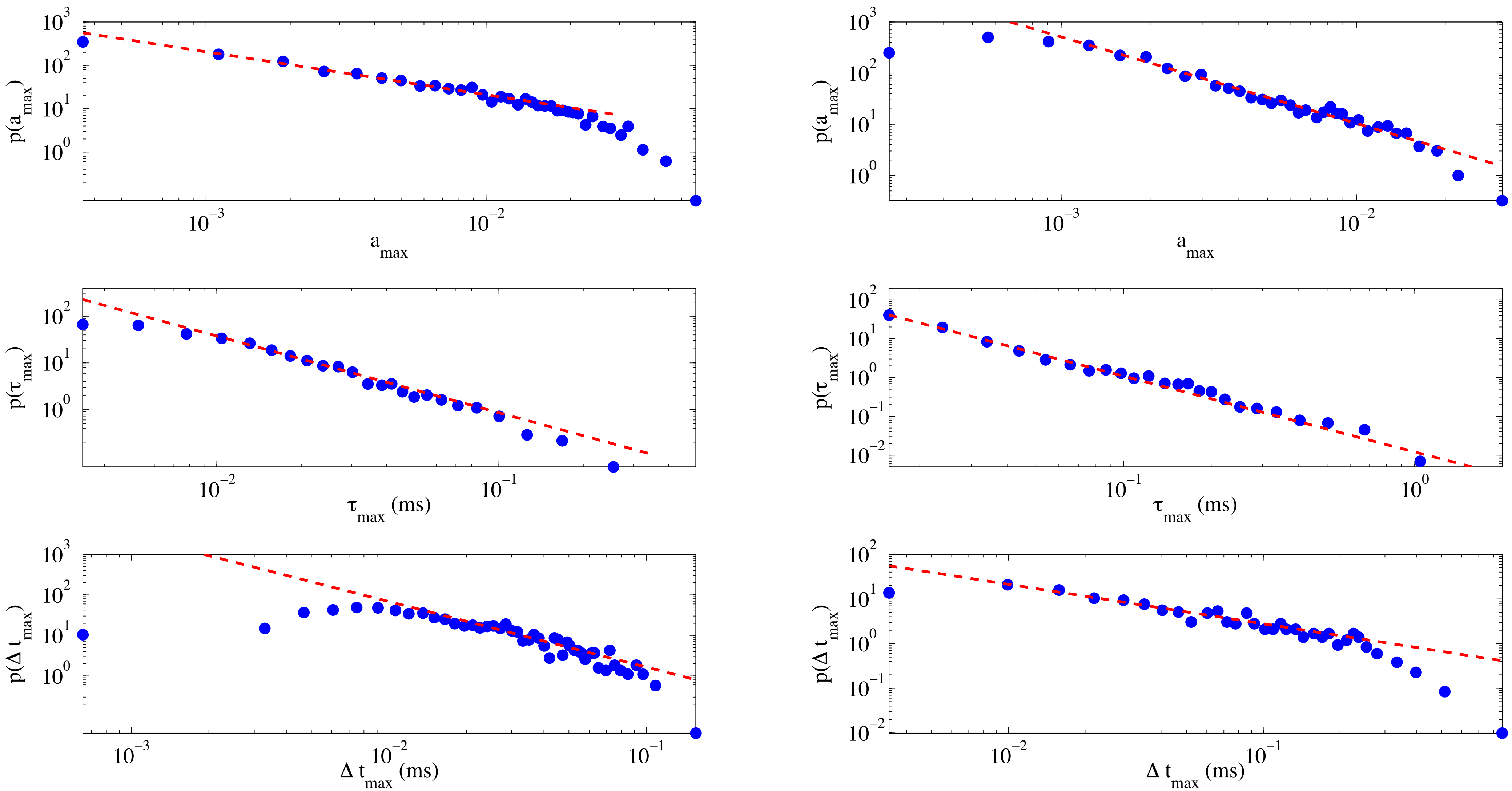
Do pulses have narrowly distributed widths?



W7-AS **JET**

For waiting time distribution, only consider "energetic" pulses

$$E = (a_{\max}/\tau_{\max})^2 > E_\theta$$

Conclusion: fusion edge data are power-law distributed

Waiting times in SOC systems

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In the late-90s, it was suggested that the statistics of waiting-times between avalanches could be used as a test for SOC.

In the original Bak sandpile and in DRS, waiting-times followed Poisson (exponential) statistics, due to the randomness of the drive.

This statement must be made more precise, though. When sufficiently large avalanches are considered, correlations are indeed apparent, and power-laws appear.

Furthermore, for non-random drives, power-laws may appear with no thresholding. These, however, are a reflection of drive correlations, not dynamical ones. Via thresholding, the SAME power-law can be made to appear as in the random drive case!

[See: R. Sanchez et al, Phys. Rev. Lett.88, 068302 (2002)]

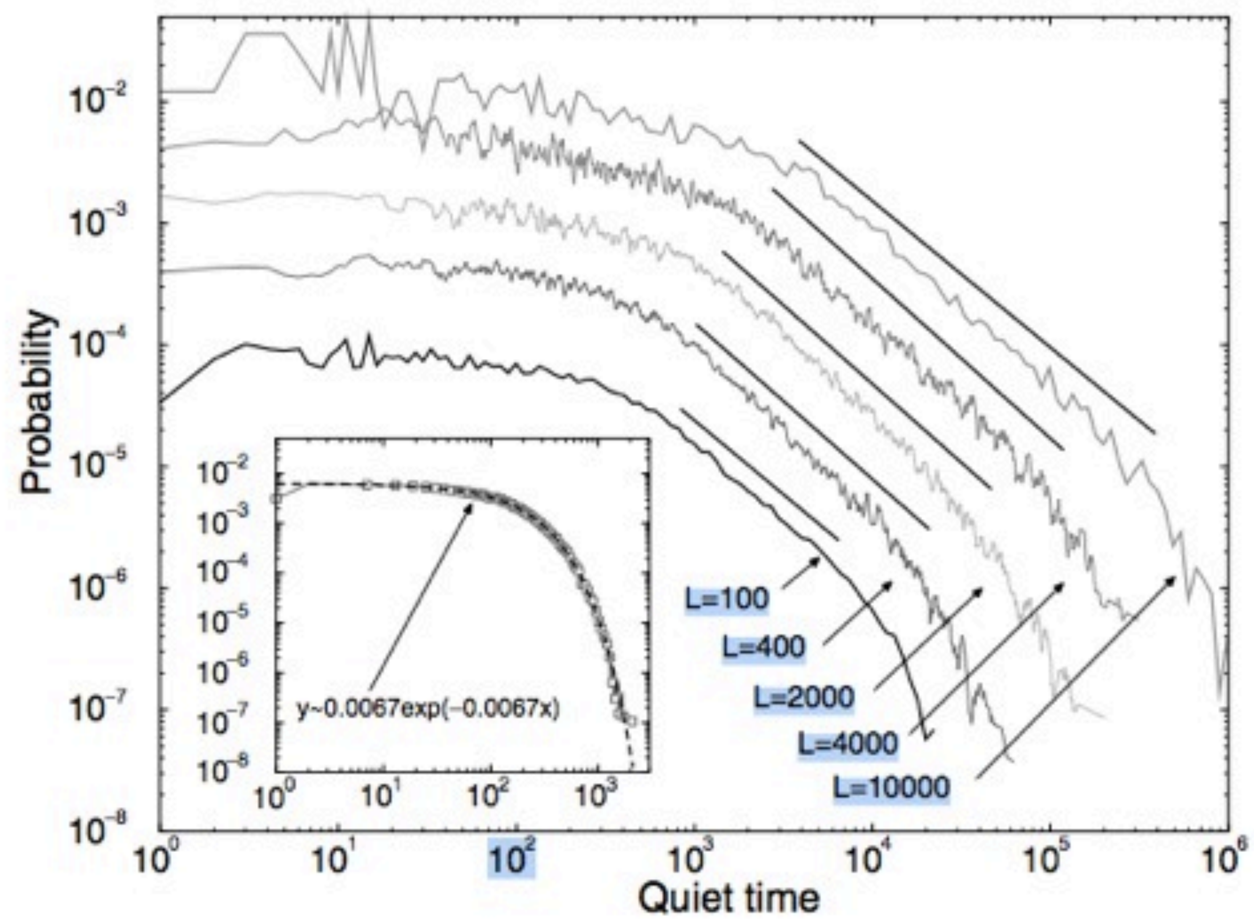

FIG. 2. Quiet times PDFs, for sandpiles with $L = 100, 400, 2000, 4000$, and $10\,000$, respectively thresholded using $d_t = 30, 75, 200, 400$, and 800. The two upper and two lower PDFs have been, respectively, shifted up and down by a half and a full decade to allow for easier comparison. In the inset, the PDF is shown without thresholding.

CONCLUSIONS

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Relevance of Uncorrelated Lorentzian Pulses for the Interpretation of Turbulence in the Edge of Magnetically Confined Toroidal Plasmas

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Recently, it has been proposed that the turbulent fluctuations measured in a linear plasma device could be described as a superposition of uncorrelated Lorentzian pulses with a narrow distribution of durations, which would provide an explanation for the reported quasiexponential power spectra. Here, we study the applicability of this proposal to edge fluctuations in toroidal magnetic confinement fusion plasmas. For the purpose of this analysis, we introduce a novel wavelet-based pulse-detection technique that offers important advantages over existing techniques. This technique allows for extracting the properties of individual pulses from the experimental time series, and for quantifying the distribution of pulse duration and energy as well as temporal correlations. We apply the wavelet technique to edge turbulent fluctuation data from the W7-AS stellarator and the JET tokamak, and find that the pulses detected in the data do not have a narrow distribution of durations and are not uncorrelated. Instead, the distributions are of the power-law type, exhibiting temporal correlations over scales much longer than the typical pulse duration. These results suggest that turbulence in open and closed field line systems may be distinct, and cast doubts on the proposed ubiquity of exponential power spectra in this context.

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- Edge fluctuation data at the edge of hot fusion plasmas from JET and W7-AS DO NOT follow the uncorrelated, narrowly-distributed width Lorentzian model.

- Instead, time correlations are present. Pulse durations and sizes are power-law distributed, their triggerings are correlated and their shape is difficult to determine uniquely.

- Power spectra of fluctuations ARE NOT well-fit by exponential law. Compound expressions containing power-laws over certain ranges of frequencies seem better.

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CONCLUSIONS

- Why LAPD/TJK data are so different from JET/W7AS data?

  Critical dynamics requires near-marginality and that any subdominant transport mechanism competing with the near-marginal channel be weak.

  Parallel transport at LAPD can disable critical dynamics due to open field lines

  Low temperature at both LAPD and TJK can make collisional transport dominant; or not drive instabilities enough to keep profiles close to marginal.