Characterisation of emergent properties during the transition to optical turbulence in a fibre laser

Laura Carpi and <u>Cristina Masoller</u>

Universitat Politecnica de Catalunya, Barcelona, Spain

Cristina.masoller@upc.edu

www.fisica.edu.uy/~cris

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CLEO EUROPE
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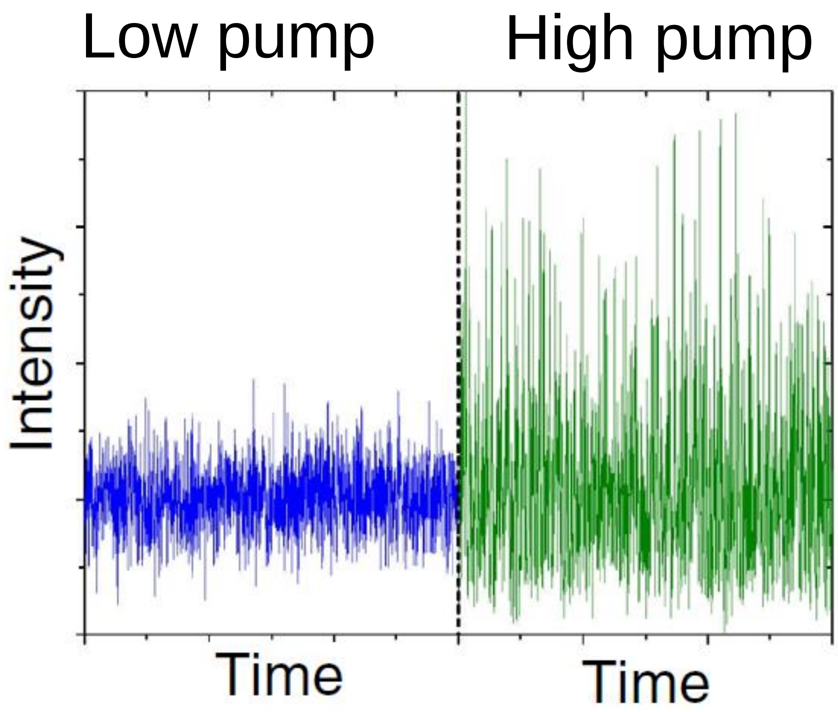
Motivation

E. G. Turitsyna et al Nat. Phot. 7, 783 (2013)

- Transition to optical turbulence in a quasi-cw Raman fiber laser
- 1 km of normal dispersion fiber placed between two fiber Bragg gratings acting as cavity mirrors



Motivation

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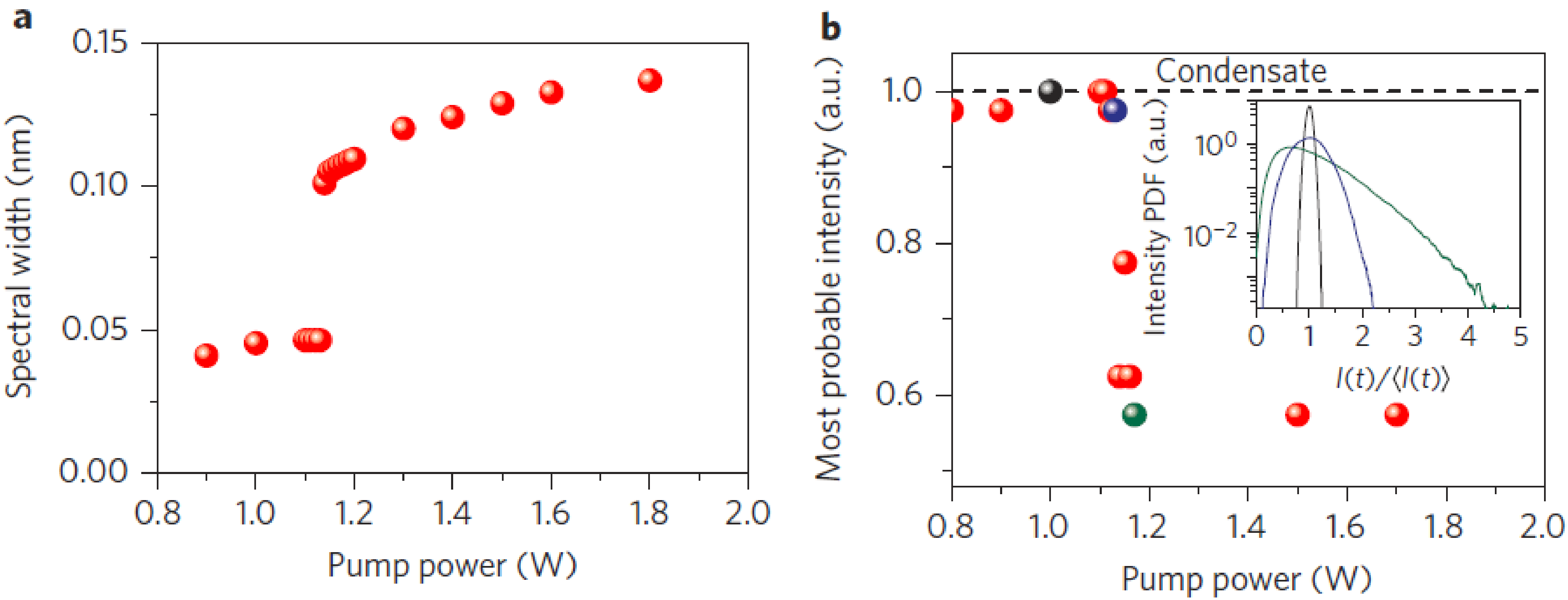


Sharp increase of the number of excited modes.

Sharpe decrease of the most probable intensity

TEMPORAL CORRELATIONS?

Scope and outline

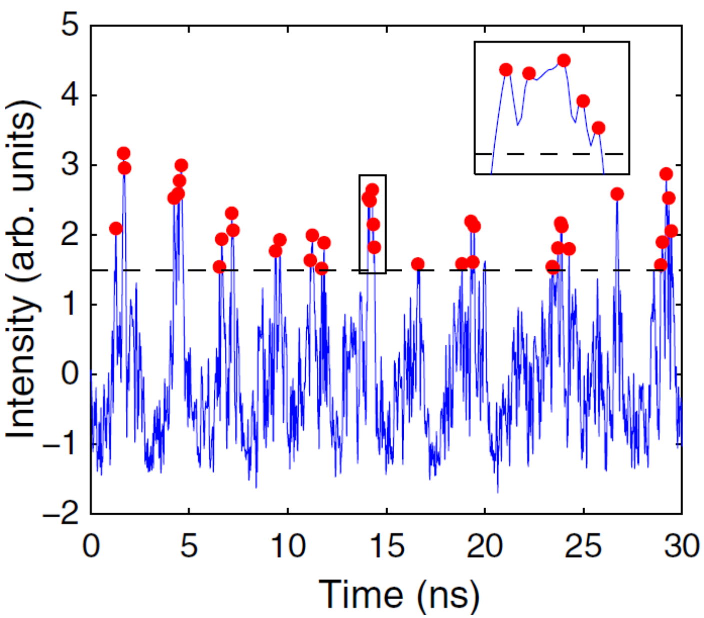
- "Big data": novel diagnostic tools for the analysis of output signals of complex systems.

- These tools can provide new insight into optical instabilities and complex dynamics.

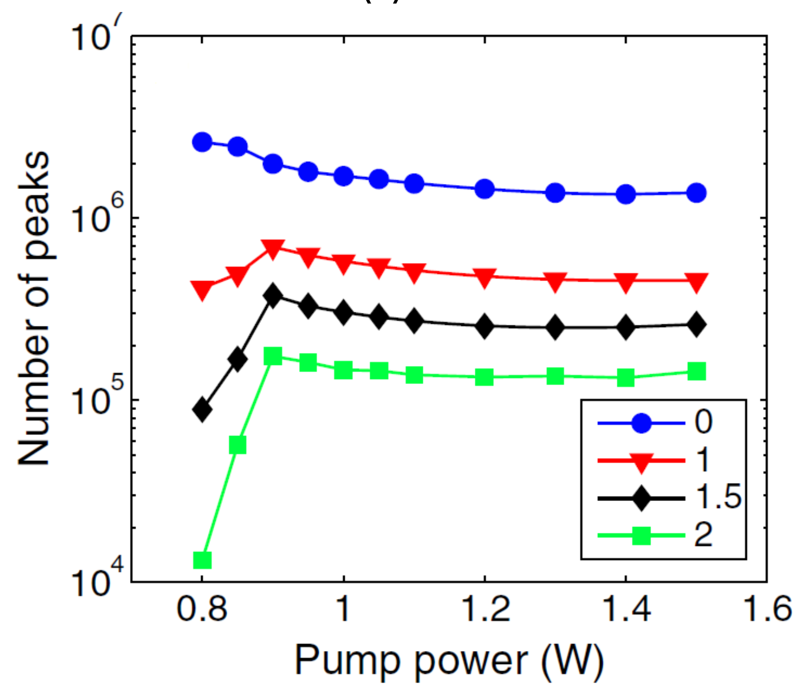
- Outline
  - Methods
  - Results
  - Summary

Analysis of the intensity dynamics

Preprocessing: each time series is normalized to ⟨I⟩=0 and σ=1



$$\{I_{\max,i}\}$$



time series with 5×10^7 data points, 12.5 ps resolution

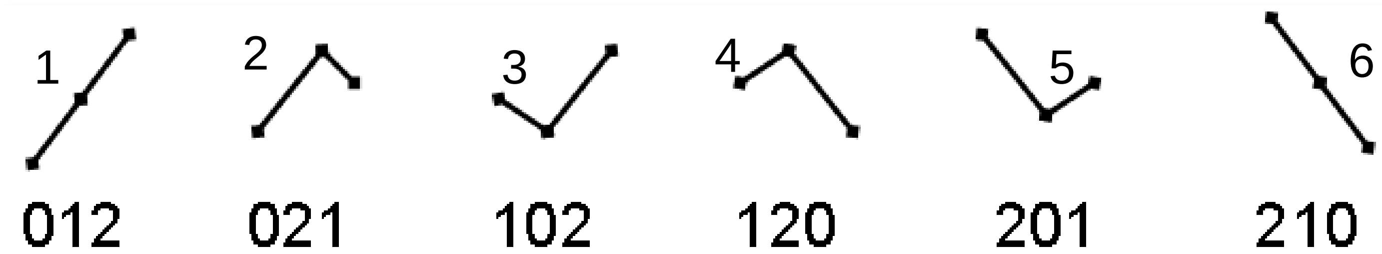
number of pulses above **2σ**: larger than 10^4 for all pump powers

Experimental data from Prof. Turitsyn' group, Aston Univ., UK.

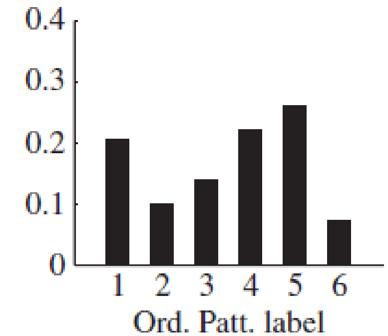
Symbolic method of time-series analysis: ordinal Patterns

$X = \{\ldots \mathbf{x}_i, \mathbf{x}_{i+1}, \mathbf{x}_{i+2}, \ldots\}$

D=3



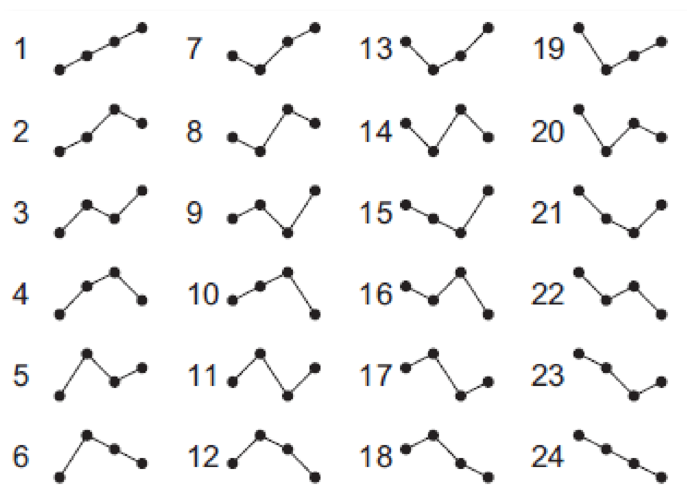
Ordinal probabilities



Example: (5, 1, 7) gives "102" because 1 < 5 < 7

D=4:

D=5, 120



<u>Permutation entropy</u>

$$s_p = -\sum p_i \log p_i$$

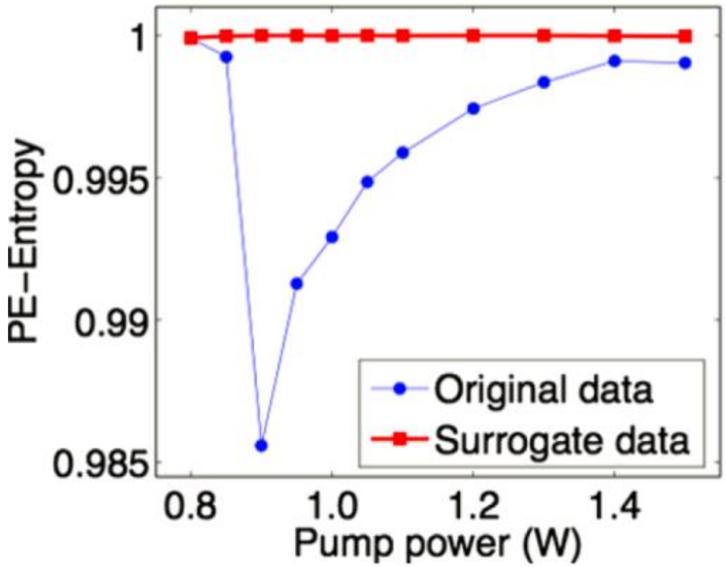
We will also use a <u>lag</u>

$\{\ldots \mathbf{x}_i, x_{i+1}, \mathbf{x}_{i+2}, x_{i+3}, \mathbf{x}_{i+4}, x_{i+5} \ldots\}$

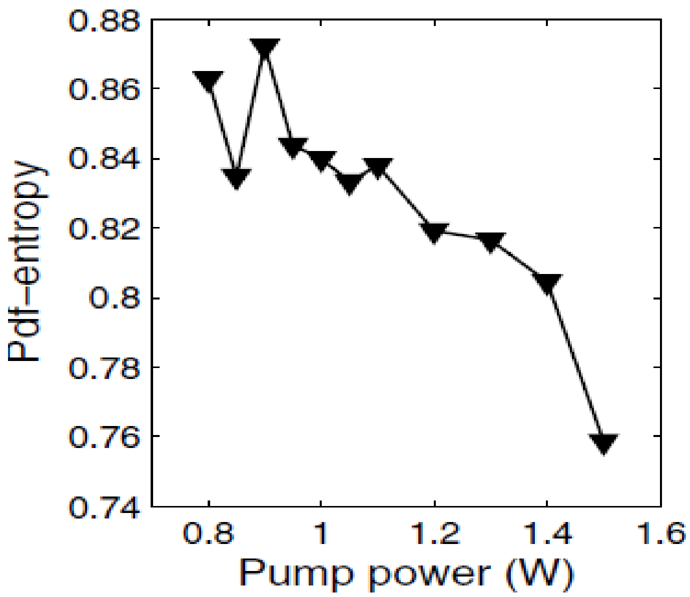
Brandt & Pompe, PRL 88, 174102 (2002)

U. Parlitz et al. / Computers in Biology and Medicine 42 (2012) 319–327

Entropy from the pattern probabilities, intensity pulses > 2σ



Entropy from pdf of intensity values



- Sharp transition is <u>not captured</u> when the entropy is calculated from the intensity pdf.
- Different entropy behavior.

A. Aragoneses, L. Carpi, N. Tarasov, D. V. Churkin, M. C. Torrent, C. Masoller, and S. K. Turitsyn, Phys. Rev. Lett. 116, 033902 (2016).

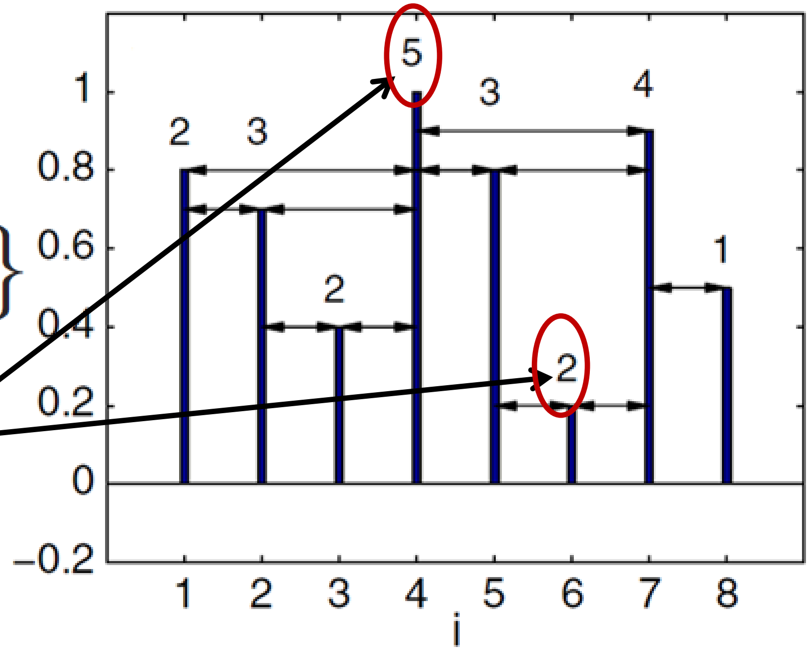
Second diagnostic tool: time-series is represented as a graph

B. Luque et al, PRE 80, 046103 (2009)

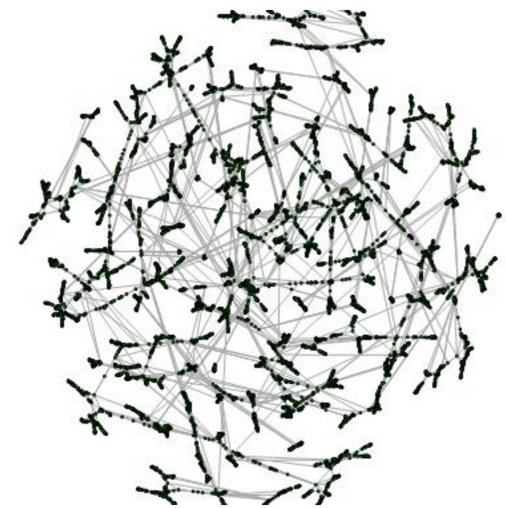
intensity pulses >2σ

$$\{I_{\max,i}\}$$

Number of links



Horizontal Visibility Graph (HVG)

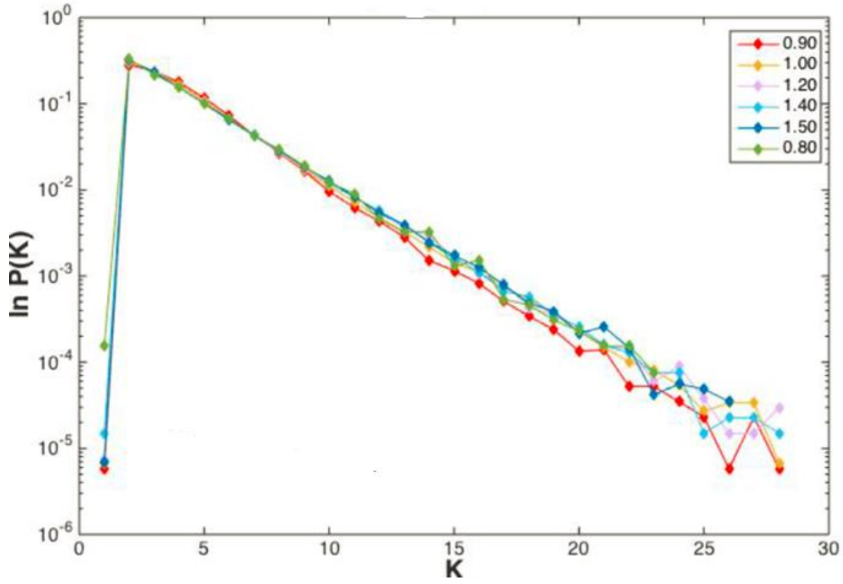


- Rule: pulses *i* and *j* are connected if there is "**horizontal visibility**" between them: $I_{\mathrm{max},i}$ and $I_{\mathrm{max},j} > I_{max,n}$ for all *n*, $i<n<j$
- The sequence { … 2, 3, 2, 5, 3, 2, 4, 1 …} contains information about the pulses **relative heights** $\{\ldots I_{\mathrm{max},i} \ldots\}$

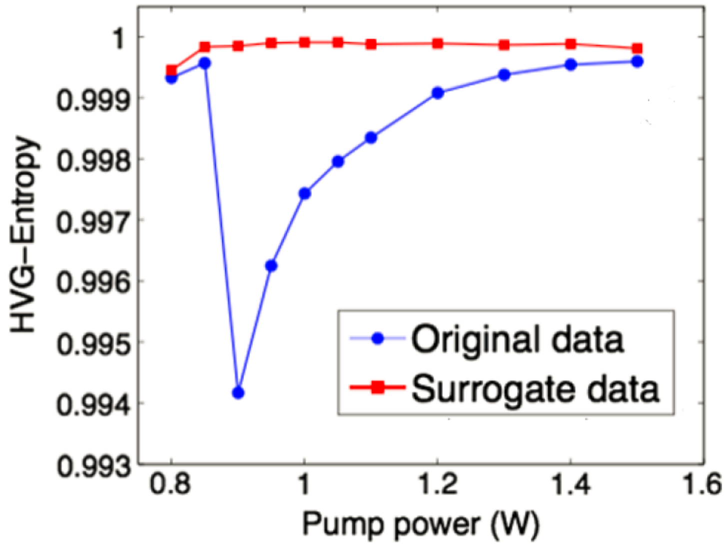
HVG analysis

How to characterize the graph obtained?
⇒ Distribution of the number of links (degree distribution)

- P(k) = degree distribution various pump powers



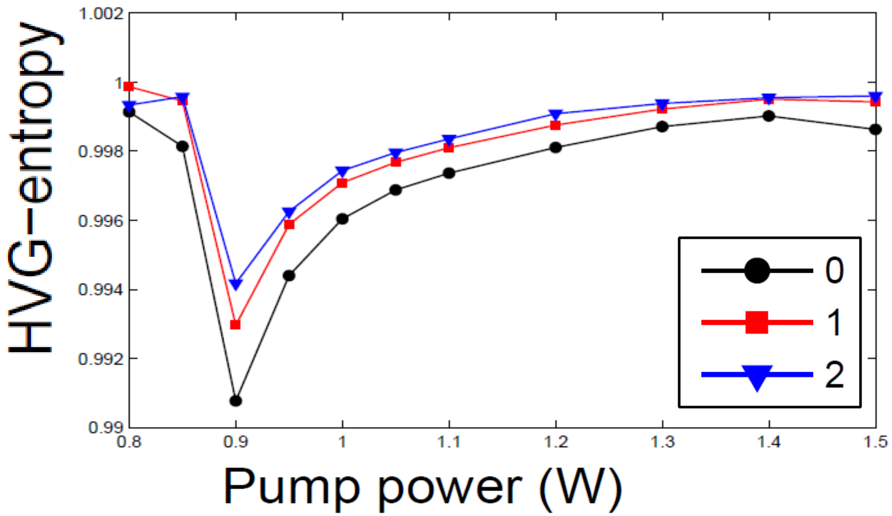
- Entropy of P(k) (normalized to the entropy of Gaussian white noise)



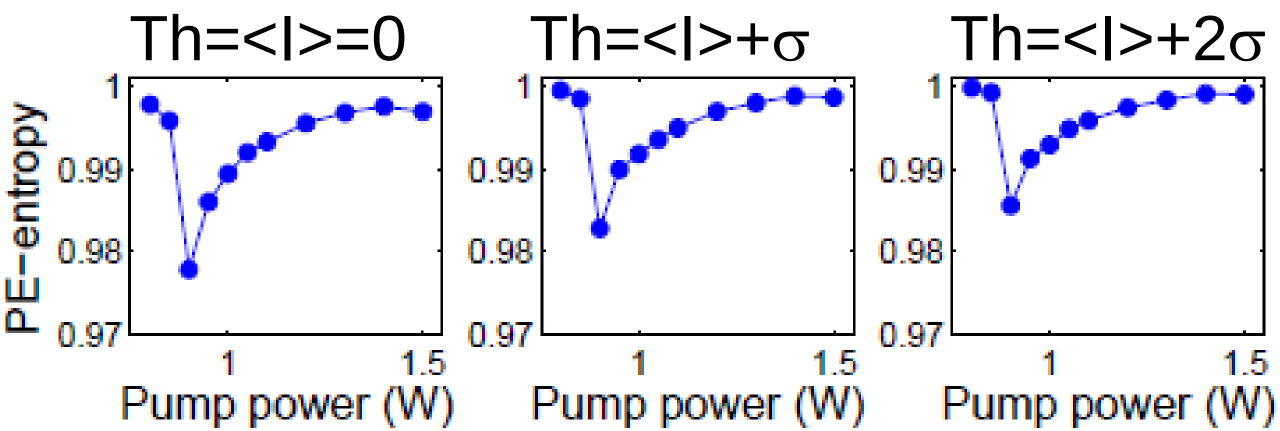
⇒ sharp transition detected, entropy decreases at the transition.

Influence of the threshold

Raw data $\{\ldots I_i \ldots\} \Rightarrow$ Th $\Rightarrow \{\ldots I_{max,i} \ldots\}$



$\Rightarrow$ sharp transition detected with different thresholds.



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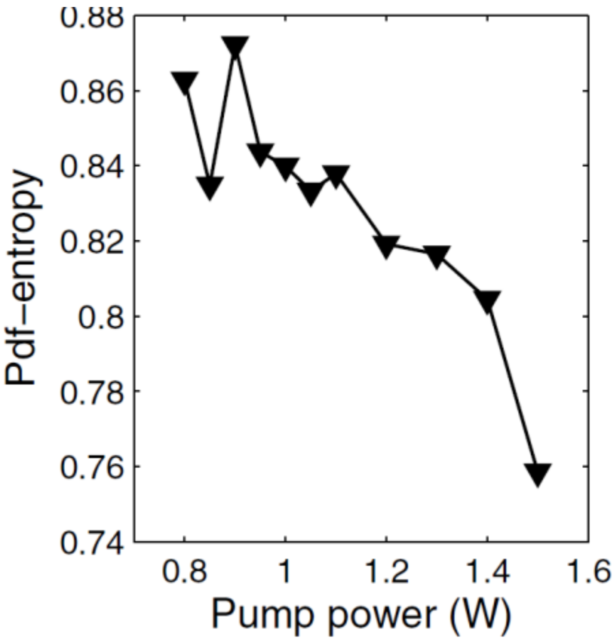
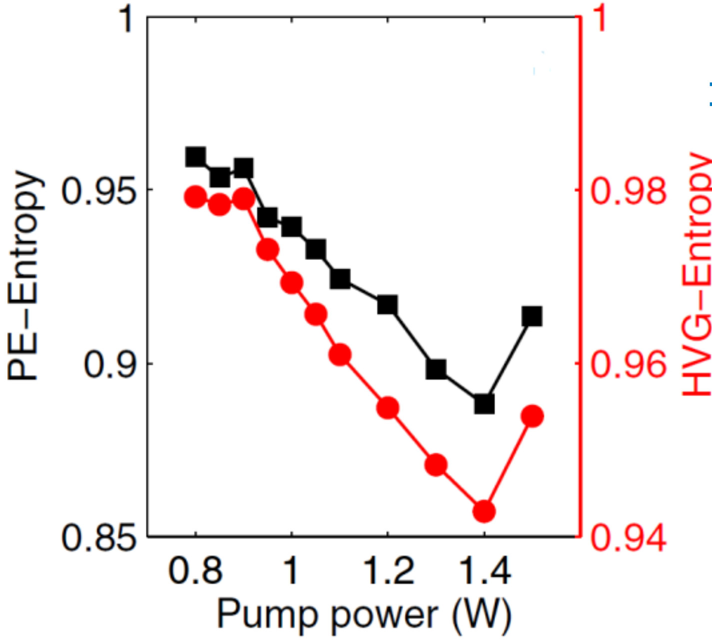
Influence of the threshold

Raw data $\{\ldots I_i \ldots\} \Rightarrow$ Th $\Rightarrow \{\ldots I_{max,i} \ldots\}$

With the raw data





⇒ sharp transition not detected.

Can we obtain more information from the raw data?

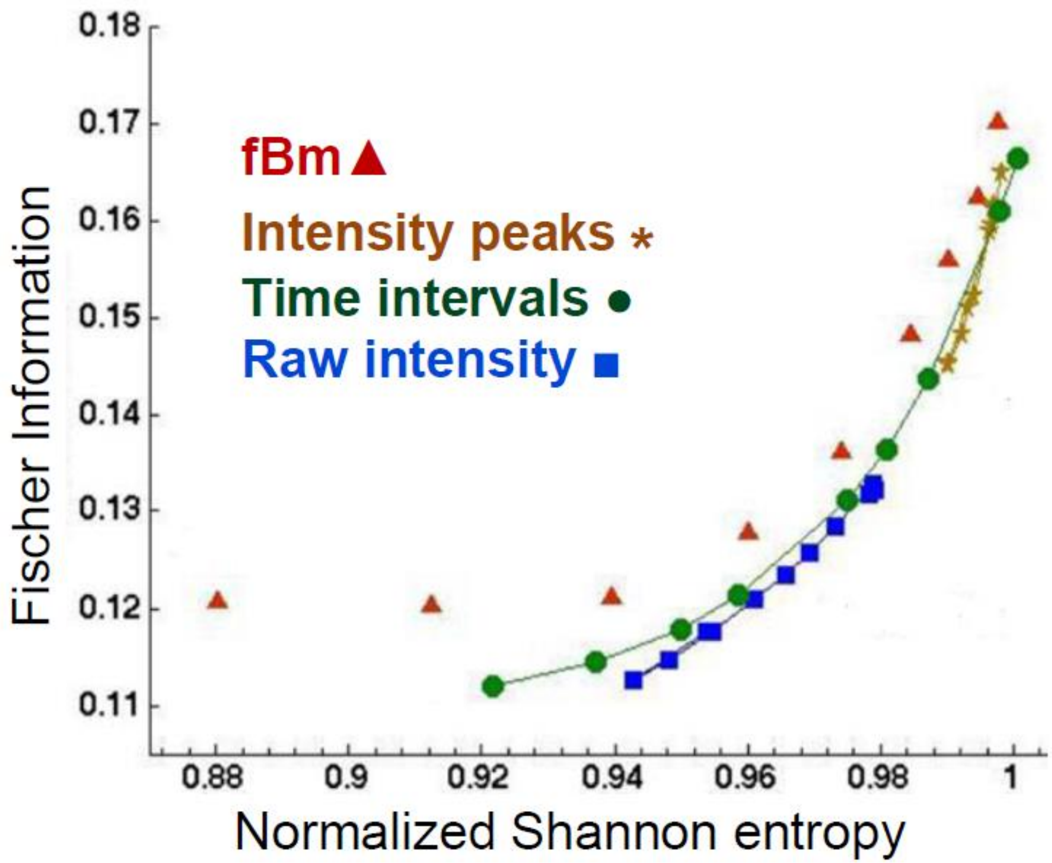
Comparison with synthetic data: fractional Brownian motion (fBm)

Gaussian stochastic process with a control parameter (the Hurst exponent H) that allows to vary temporal correlations

- $H > 0.5$, consecutive increments $(x_{i+1}-x_i)$, $(x_{i+2}-x_{i+1})$ tend to have the same sign $\Rightarrow$ the process is **persistent**.
- $H < 0.5$, consecutive increments tend to have opposite signs $\Rightarrow$ the process is **anti-persistent**.
- $H = 0.5$, consecutive increments are **uncorrelated**

  $\Rightarrow$ Gaussian white noise.

Information-theory approach: the Shannon-Fischer plane



weaker correlations

stronger correlations

⇒ At all pump powers the intensity dynamics is highly stochastic, very close to the noise "frontier".

Can we extract more information from the data?

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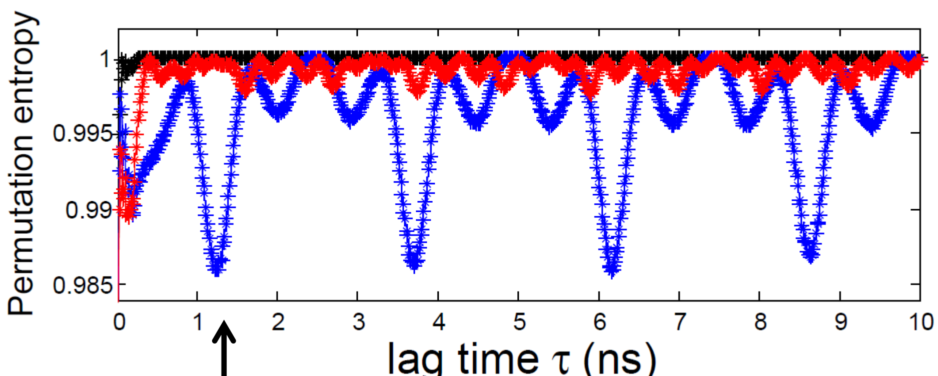
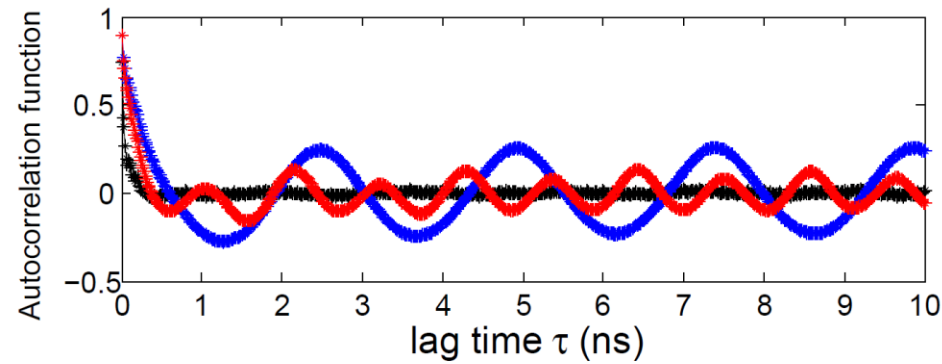
Ordinal analysis of lagged raw data

$\{I_i, I_{i+\tau}, I_{i+2\tau}, \ldots\}$; all data points, no threshold used

0.85
0.90
0.95

Pump power below, at, and above the transition.





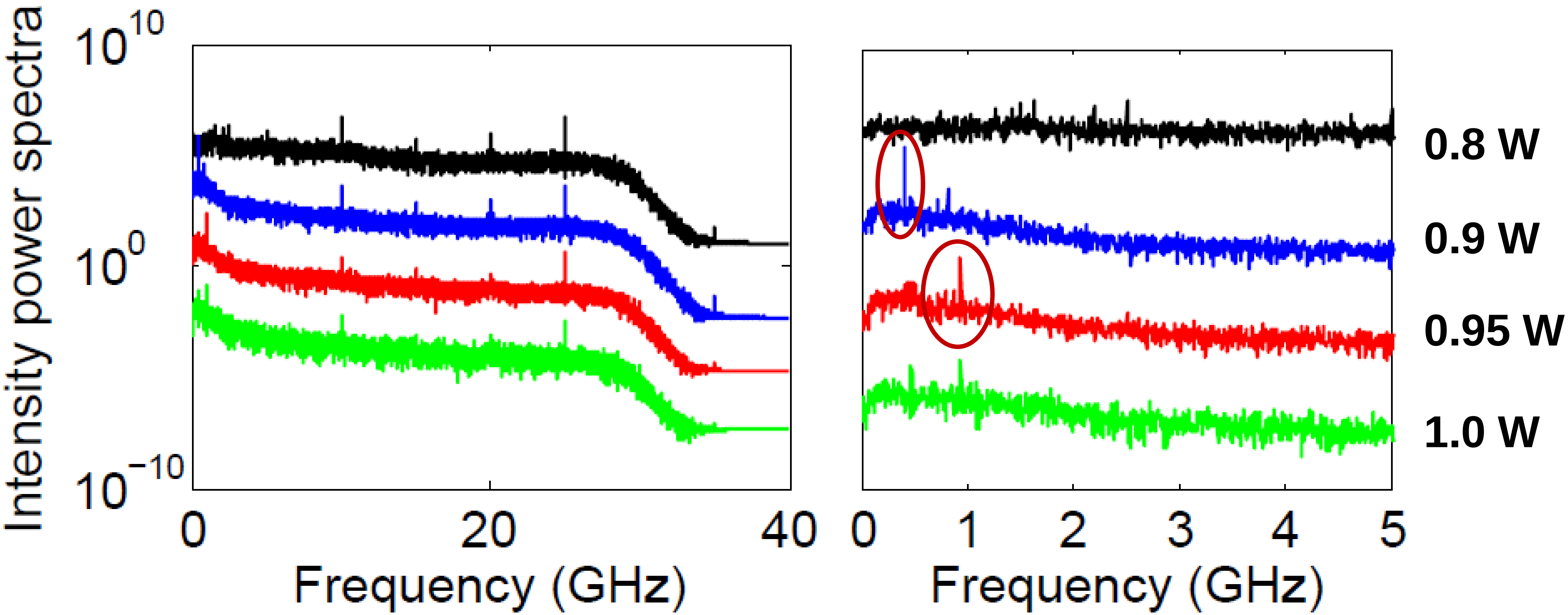
1.23 ns

2.5 ns

$\Rightarrow$ Sharp variation not captured by correlation analysis.

Aragoneses et al, PRL 116, 033902 (2016)

Intensity power spectra
(displaced vertically for clarity)



At 0.9 W: ν_0 = 0.4 GHz (T_0=2.5 ns)
0.81 GHz →1.23 ns

At 0.95W: 0.93 GHz

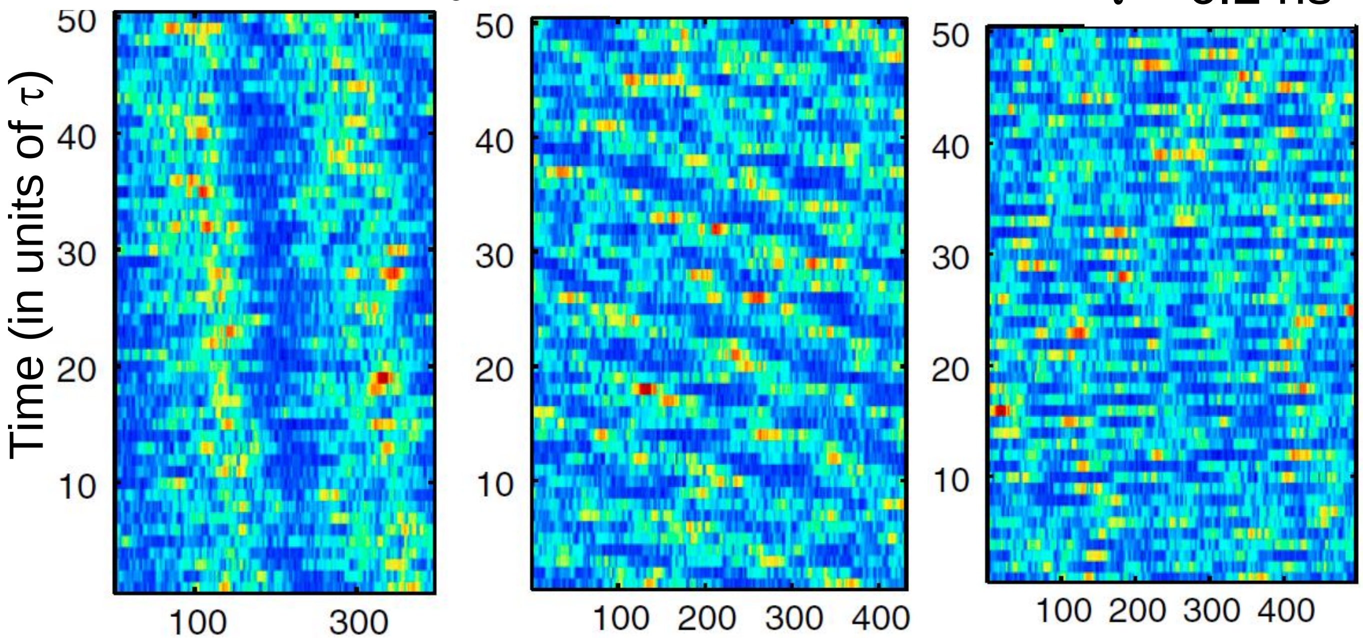
Space time representation

τ, 2τ, 3τ

$$\{I_1, I_2, I_3 \ldots, \; I_\tau, I_{\tau+1}, \ldots, \; I_{2\tau}, I_{2\tau+1}, \ldots\} \Rightarrow \begin{bmatrix} \ldots & \ldots & \ldots & \ldots \\ I_{2\tau+1} & I_{2\tau+2} & \ldots & I_{3\tau} \\ I_{\tau+1} & I_{\tau+2} & \ldots & I_{2\tau} \\ I_1 & I_2 & \ldots & I_\tau \end{bmatrix}$$

Color: I_i

τ = 4.95 ns = $2T_0$ τ = 5.39 ns τ = 6.2 ns



Time (in units of dt)

⇒ Different structures uncovered with different lags (sampling times).

Aragoneses et al, PRL 116, 033902 (2016)

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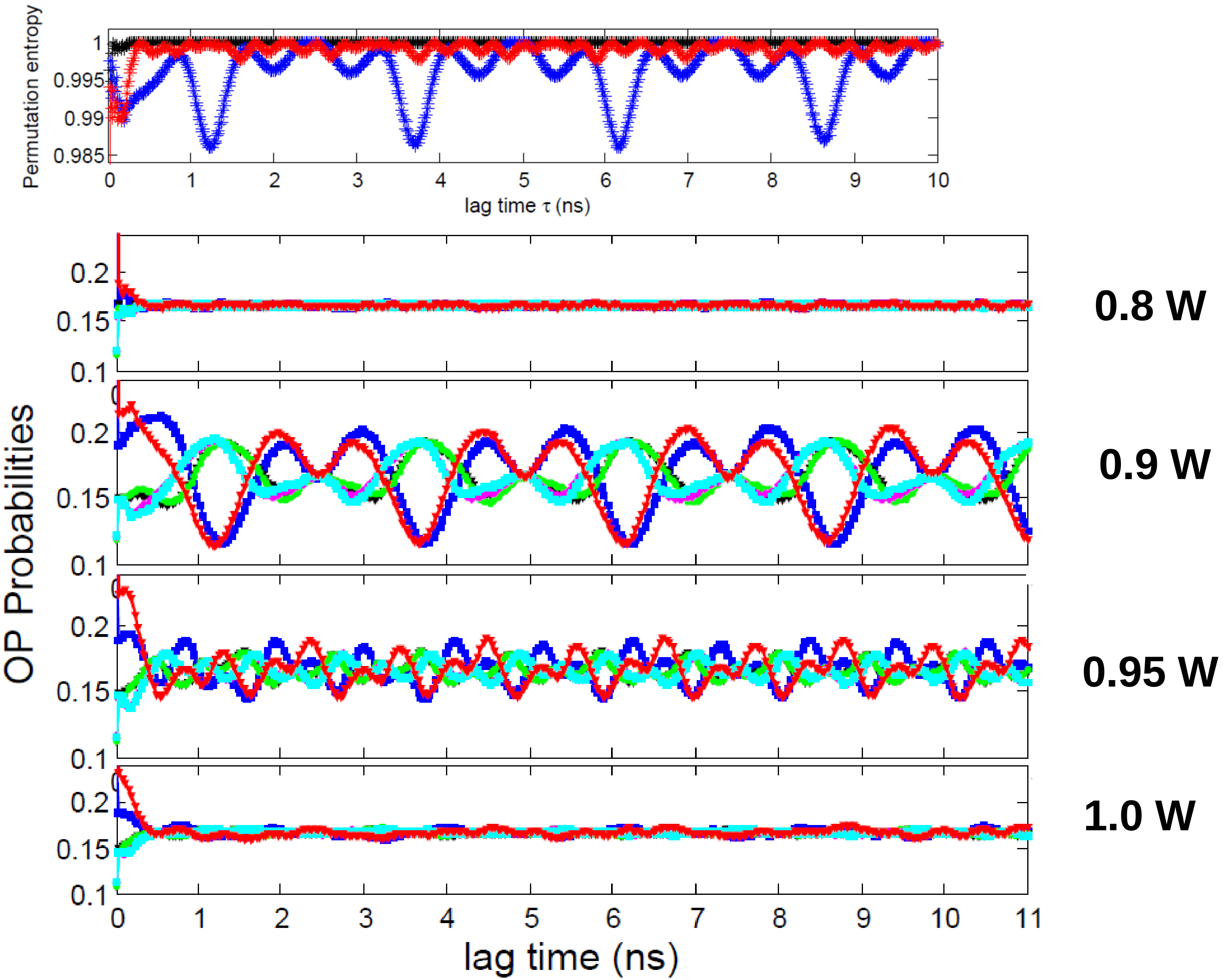
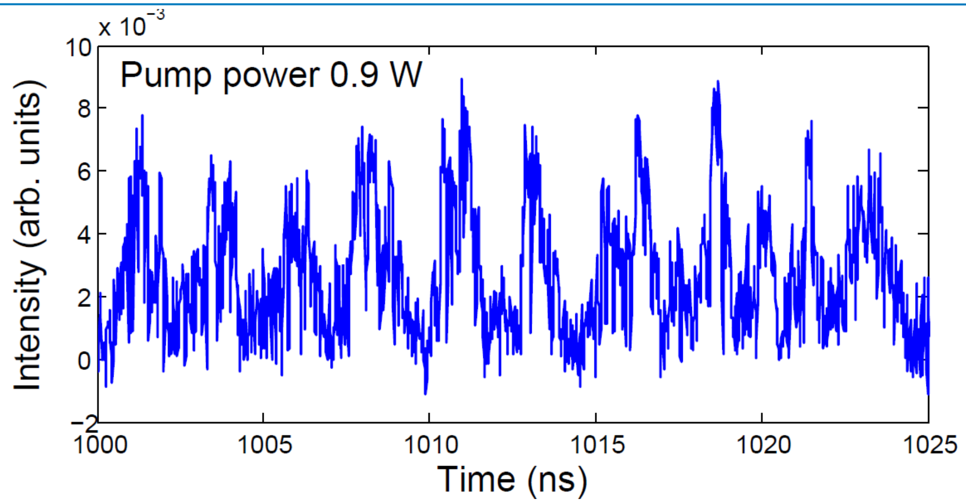
Ordinal probabilities vs. lag



Minimal model that represents ordinal probabilities at the transition



Stochastic limit cycle: phase rate equation

$$\frac{d\varphi}{dt} = \omega_0 + f(\varphi, t) + \xi$$

Stroboscopic sampling at time-interval τ

$$\varphi(t_0 + \tau) = \varphi(t_0) + \omega_0\tau + F(\varphi(t_0)) + \xi$$

$$\varphi_{i+1} = \varphi_i + \rho + \frac{K}{2\pi}\sin(2\pi\varphi_i) + D\xi$$

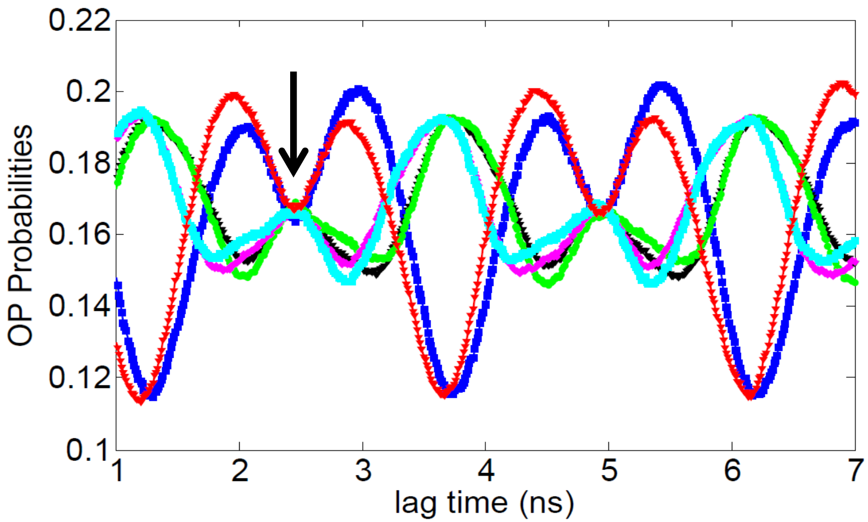
Circle map: minimal model of ordinal probabilities at the transition

$$\varphi_{i+1} = \varphi_i + \rho + \frac{K}{2\pi}\sin(2\pi\varphi_i) + D\xi$$

$$\{X_i, X_{i+1}, X_{i+2}, \ldots\}$$
$$X_i = \varphi_{i+1} - \varphi_i$$

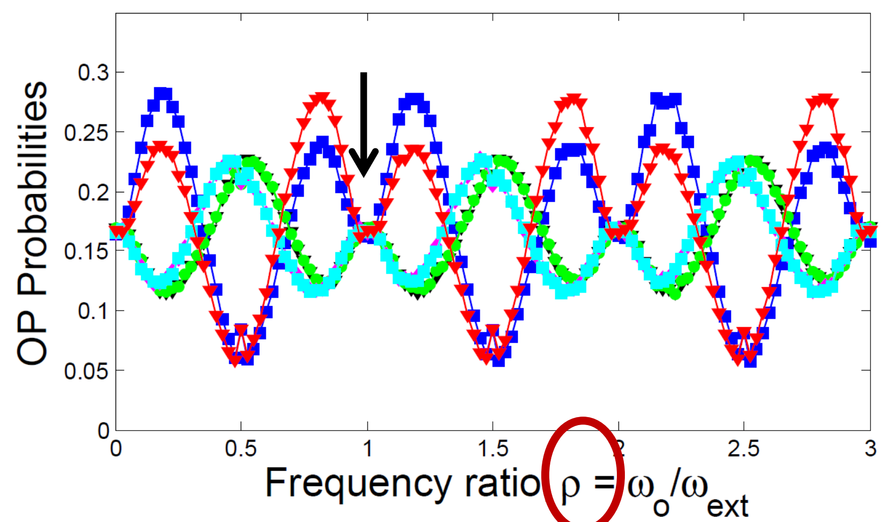
Fiber laser data $\{I_i, I_{i+\tau}, I_{i+2\tau}, \ldots\}$

(at the transition, pump power 0.9 W)



Synthetic data (phase increments)

(K=0.23 & D=0.02)



τ = 2.5 ns $\Leftrightarrow$ $\rho = 1 = \nu_0 \tau$ $\Rightarrow$ $\nu_0 = 1/\tau$ = 0.4 GHz

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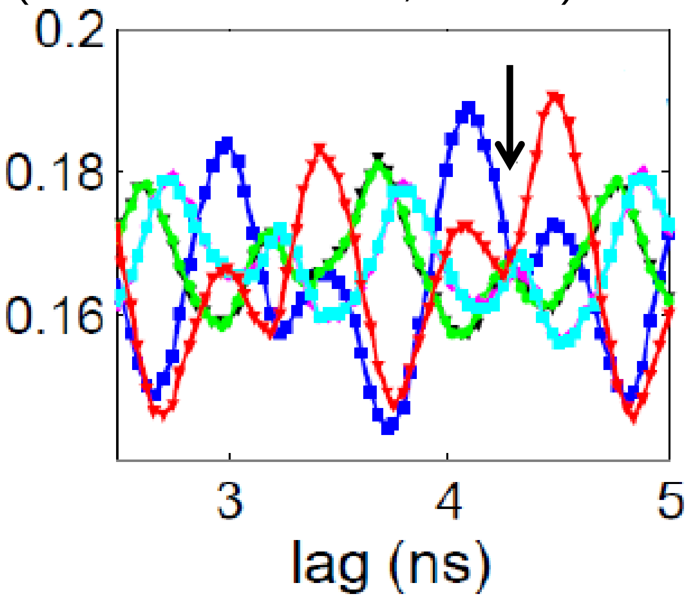
Good agreement also at higher pump power

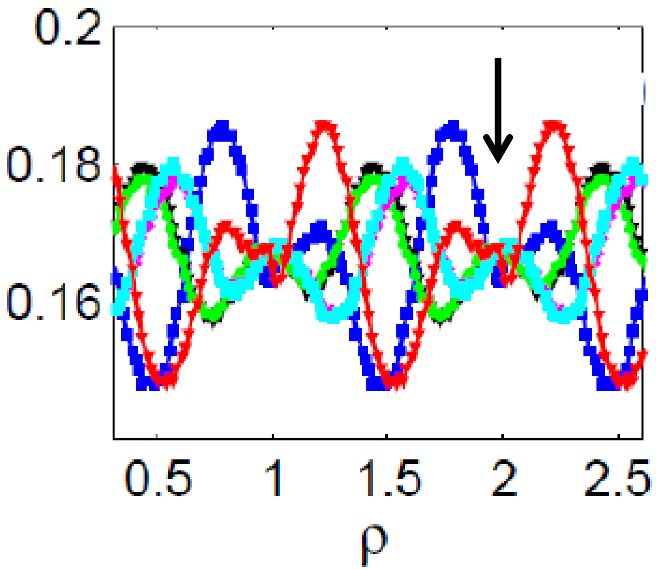
$$\phi_{i+1} = \phi_i + \epsilon\rho + (K/2\pi)\sin(2\pi\phi_i) + D\xi_i$$

Fiber laser data

(above the transition, 0.95 W)



$K = 0.25,\ D = 0.075,\ \epsilon = -1$



$\tau = 4.3$ ns $\Leftrightarrow \rho = 2 = \nu_0\,\tau \;\Rightarrow \nu_0 = 1/(2\tau) = 0.46$ GHz

The intensity spectrum has a peak at about 0.93 GHz, consistent with $2\nu_0$.

Summary

- Nonlinear data analysis tools were applied to study the intensity dynamics during the transition to turbulence in a quasi-cw Raman fiber laser (normal dispersion fiber).
- Sharp transition seen in thresholded data but not in raw data.
- Specific time-scales detected at the transition, not captured by linear analysis.
- At the transition, minimal model identified: stochastic limit cycle dynamics.

THANK YOU FOR YOUR ATTENTION !

Experimental data from Prof. Turitsyn (Aston University, UK)

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