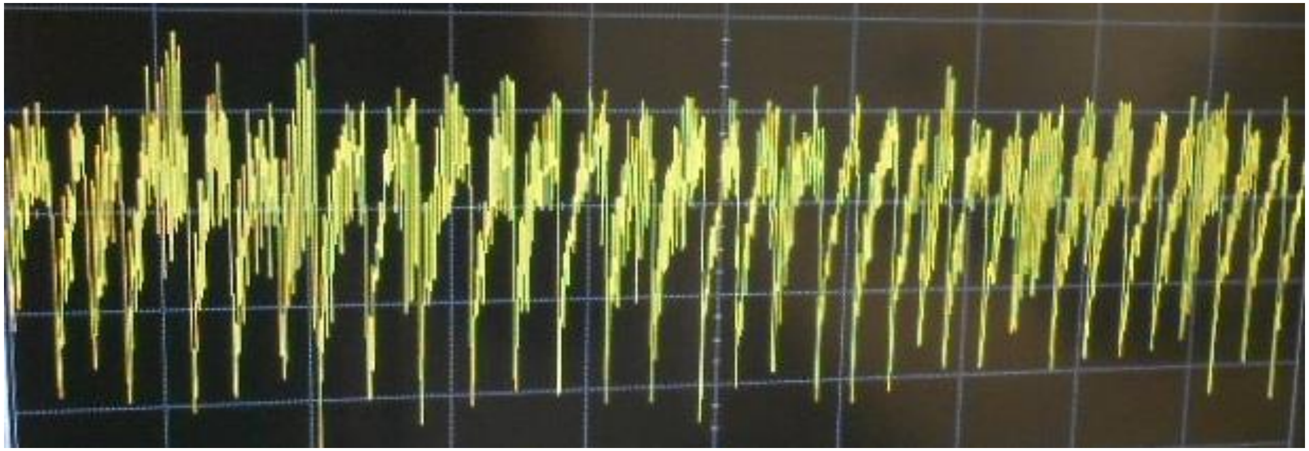

Exploring experimental optical complexity with big data nonlinear analysis tools

Cristina Masoller

Cristina.masoller@upc.edu

www.fisica.edu.uy/~cris

UNIVERSITAT POLITÈCNICA DE CATALUNYA
BARCELONATECH

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**4th International Conference on Complex Dynamical Systems & Applications
Durgapur, India, February 2016**

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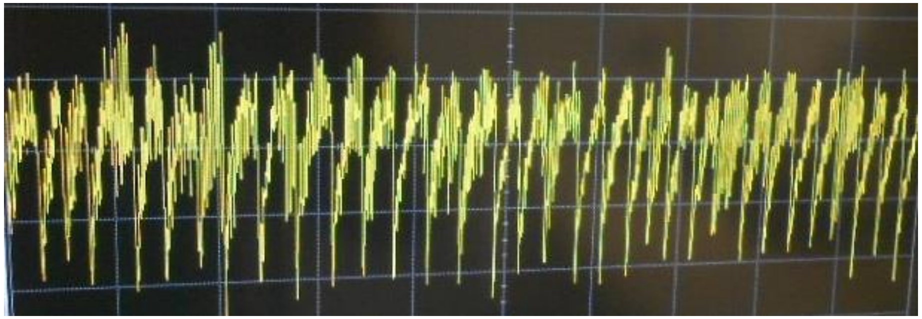
MINISTERIO DE CIENCIA E INNOVACIÓN

Dynamical optical complexity

- Optical spikes

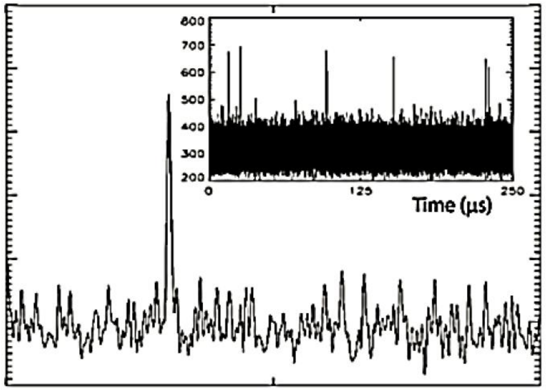
Semiconductor laser with optical feedback



Time

- Extreme optical pulses

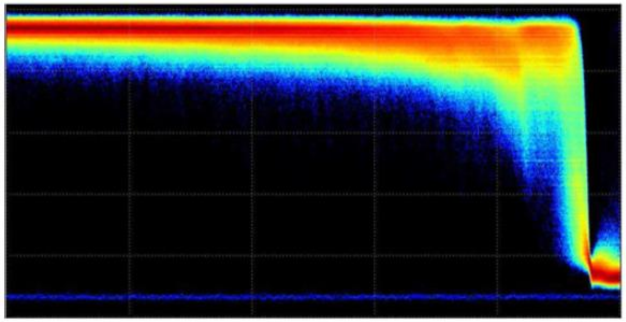
Semiconductor laser with injection



Time

- Polarization switching

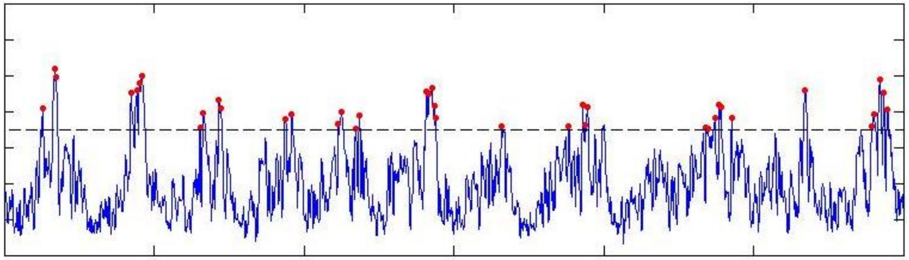
VCSELs



Time

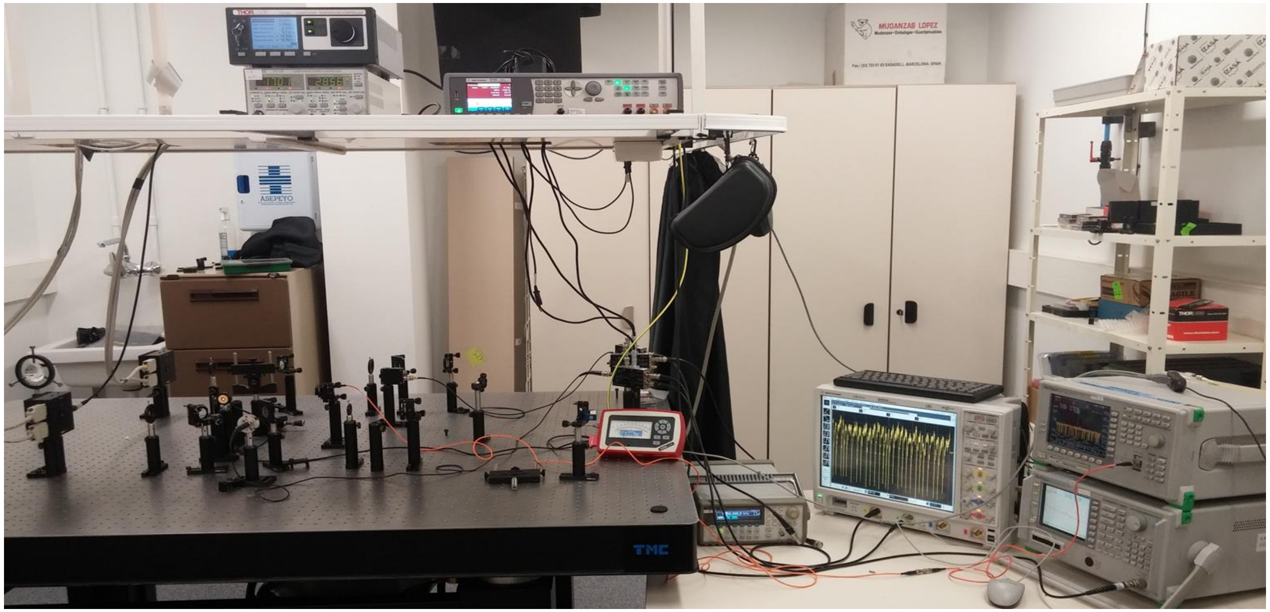
- Optical turbulence

Fibre laser



Time

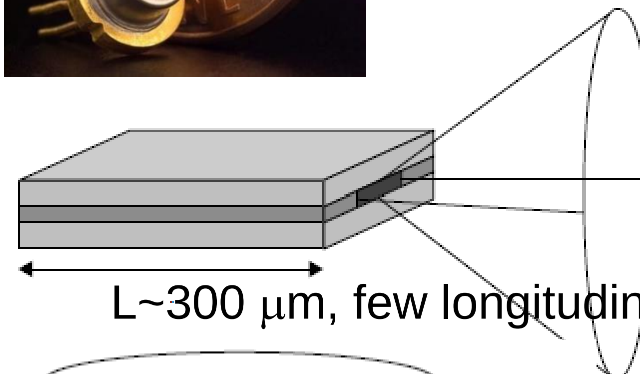
Big data approach



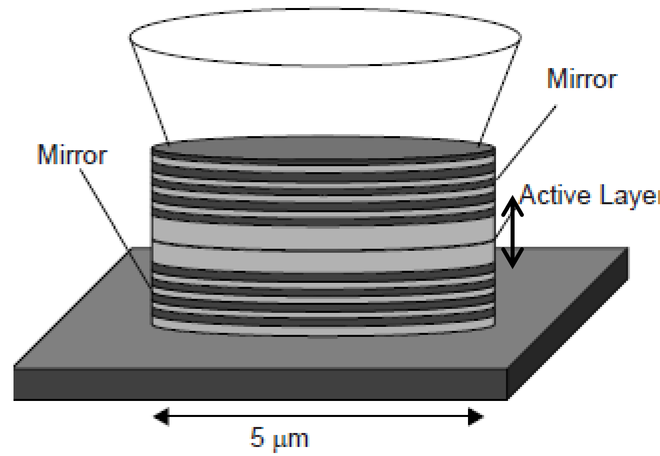
- Optical systems allow recording long time-series under controlled conditions.
- With this "optical big data" we can
  - test novel analysis tools (prediction, control).
  - capture relevant features in the data (classification, model verification, parameter estimation).

Optical systems: three types of lasers

- Semiconductor lasers
  - Edge-emitting lasers (EELs)
  - Vertical-cavity (VCSELs)

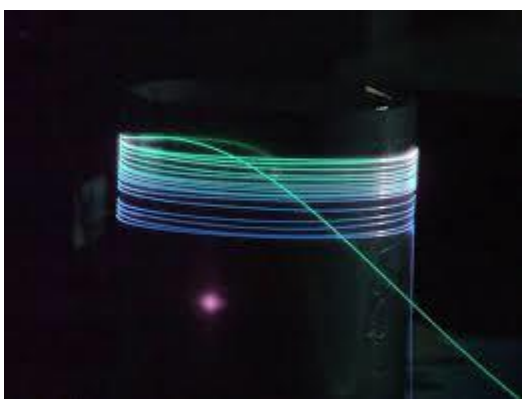


L~300 μm, few longitudinal modes



L=1-10μm, single longitudinal mode

- Fibre laser

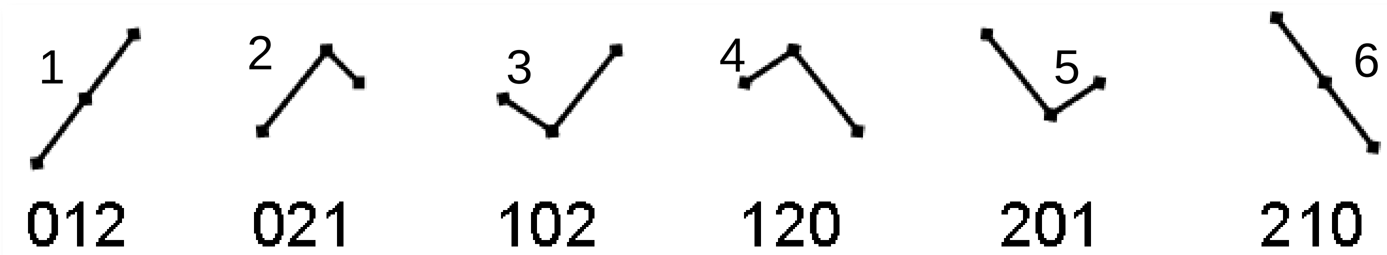


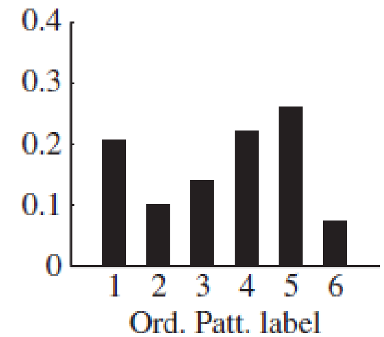
L=1 km, millions of longitudinal modes

Method of symbolic time-series analysis: ordinal patterns

- $X = \{\ldots x_i, x_{i+1}, x_{i+2}, \ldots\}$

Brandt & Pompe, PRL 88, 174102 (2002)





Random data $\Rightarrow$ OPs are equally probable

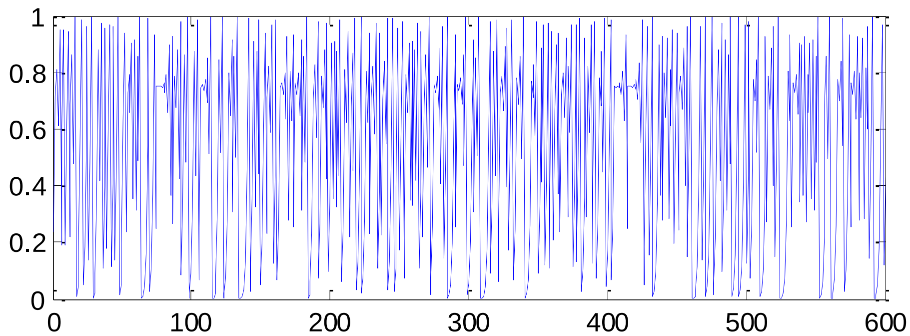
The OP probabilities allow to identify frequent patterns in the *ordering* of the data points

– Advantage: the probabilities uncover temporal correlations.

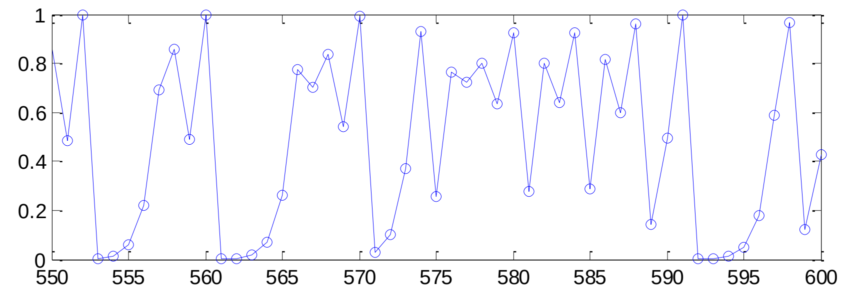
– Drawback: we lose information about the actual values.

Example: the logistic map $x(i+1)=4x(i)[1-x(i)]$

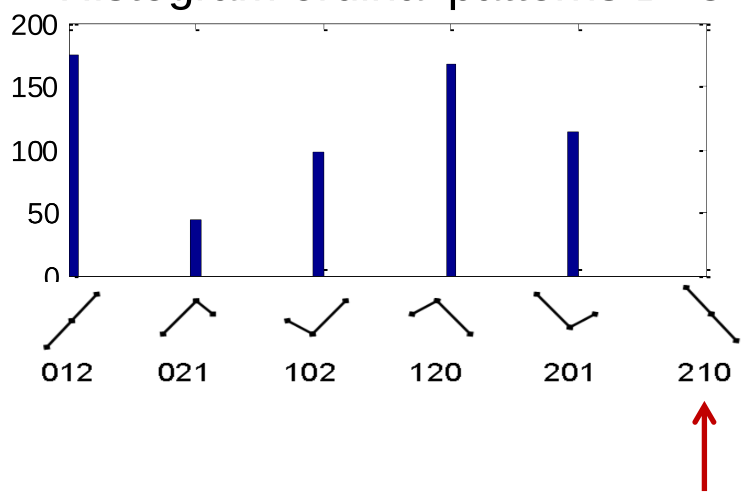
Time series



Detail

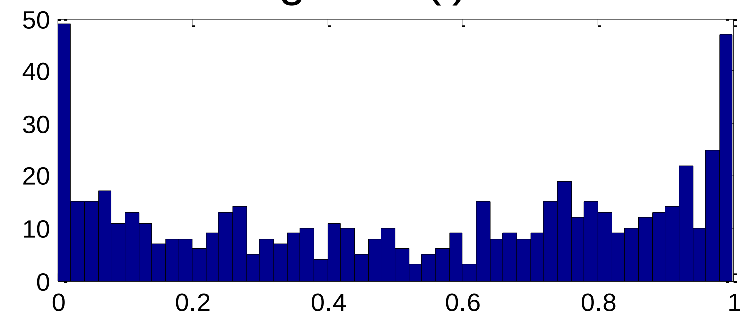


Histogram ordinal patterns D=3



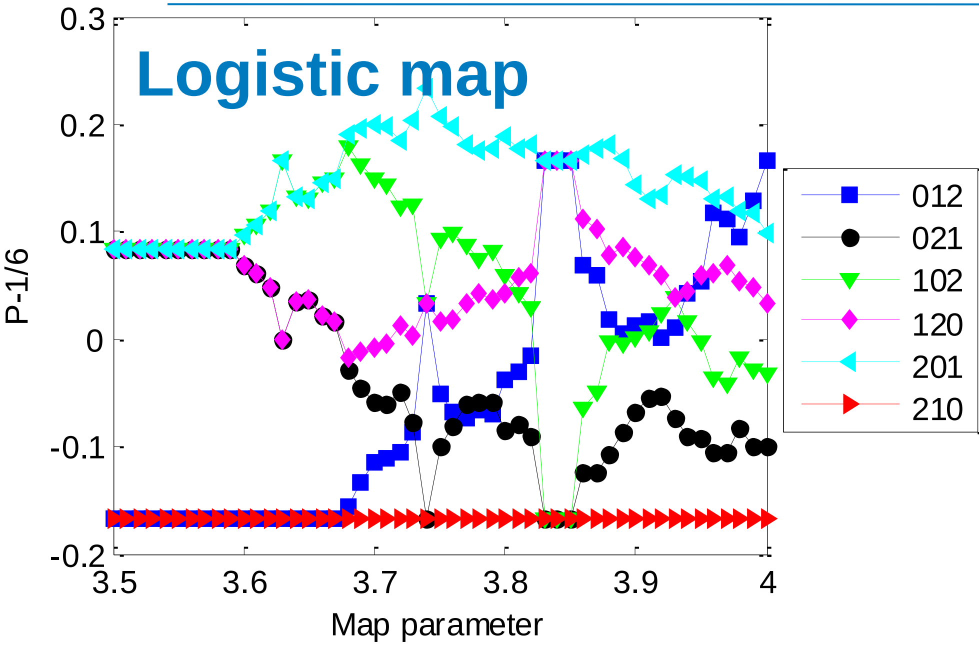
Forbidden pattern

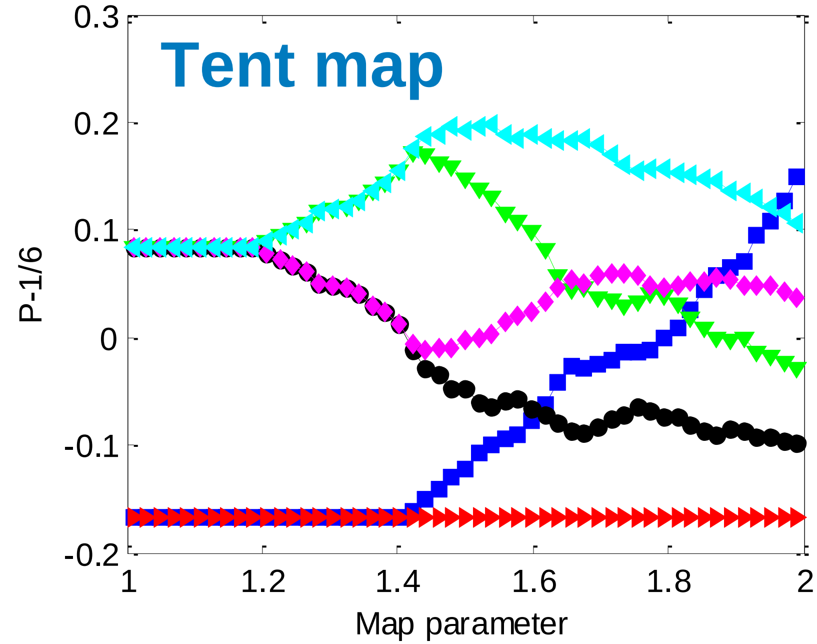
Histogram x(i)

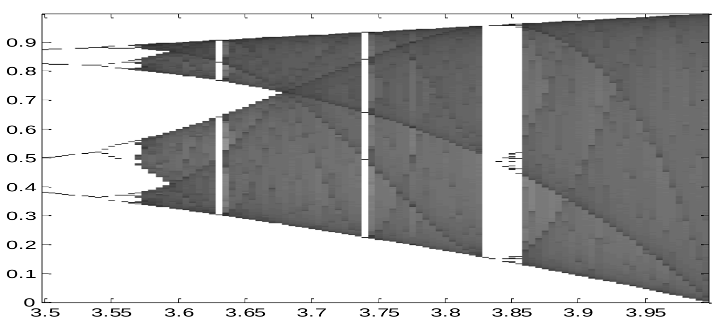


Ordinal analysis provides complementary information.

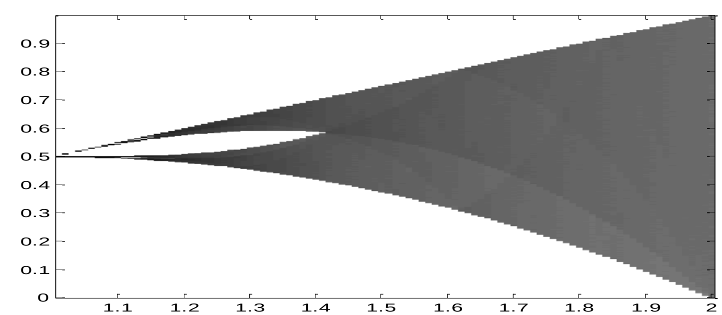
Ordinal bifurcation diagrams







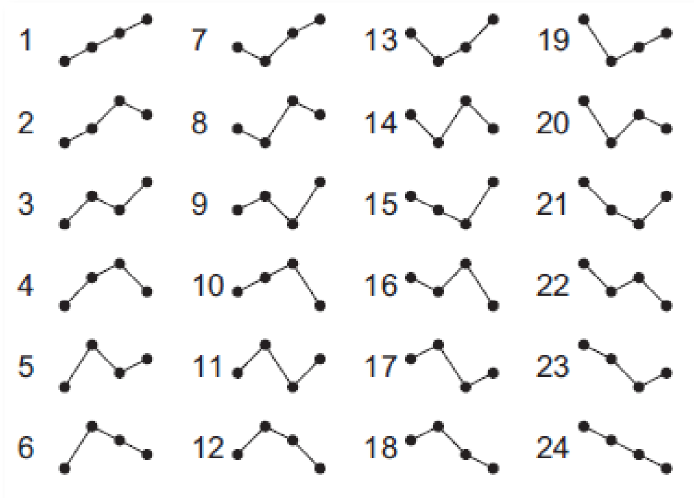
Map parameter



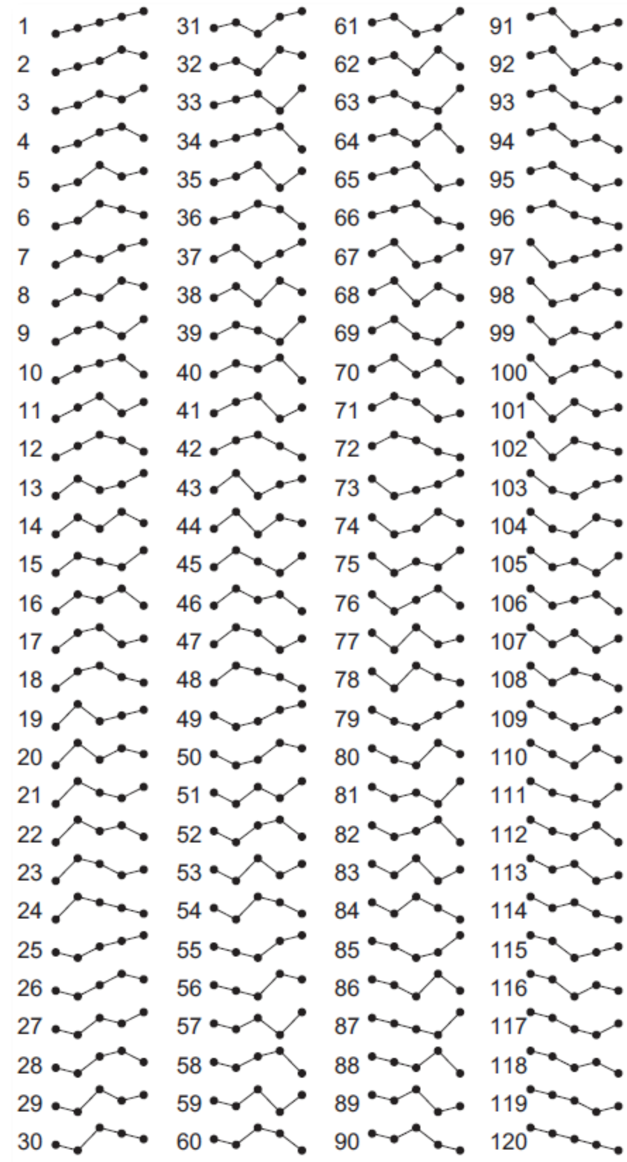
Map parameter

Number of possible ordinal patterns: D!

D=4



D=5



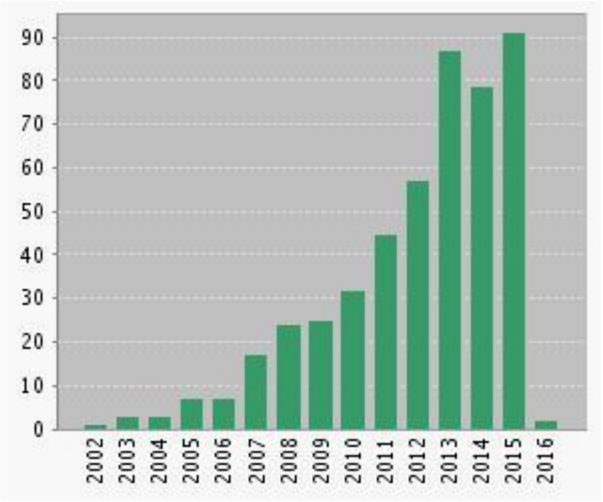
- How to select D?

  depends on:
  - The length of the data.
  - The length of correlations in the data.

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

- Ordinal analysis has been widely used to study the output signals of complex systems
  - Financial, economical
  - Biological, life sciences
  - Geosciences, climate
  - Physics, chemistry, etc
- It has been shown to be able to:
  - Distinguish stochasticity and determinism
  - Classify different types of behaviors
  - Quantify complexity
  - Identify coupling and directionality.

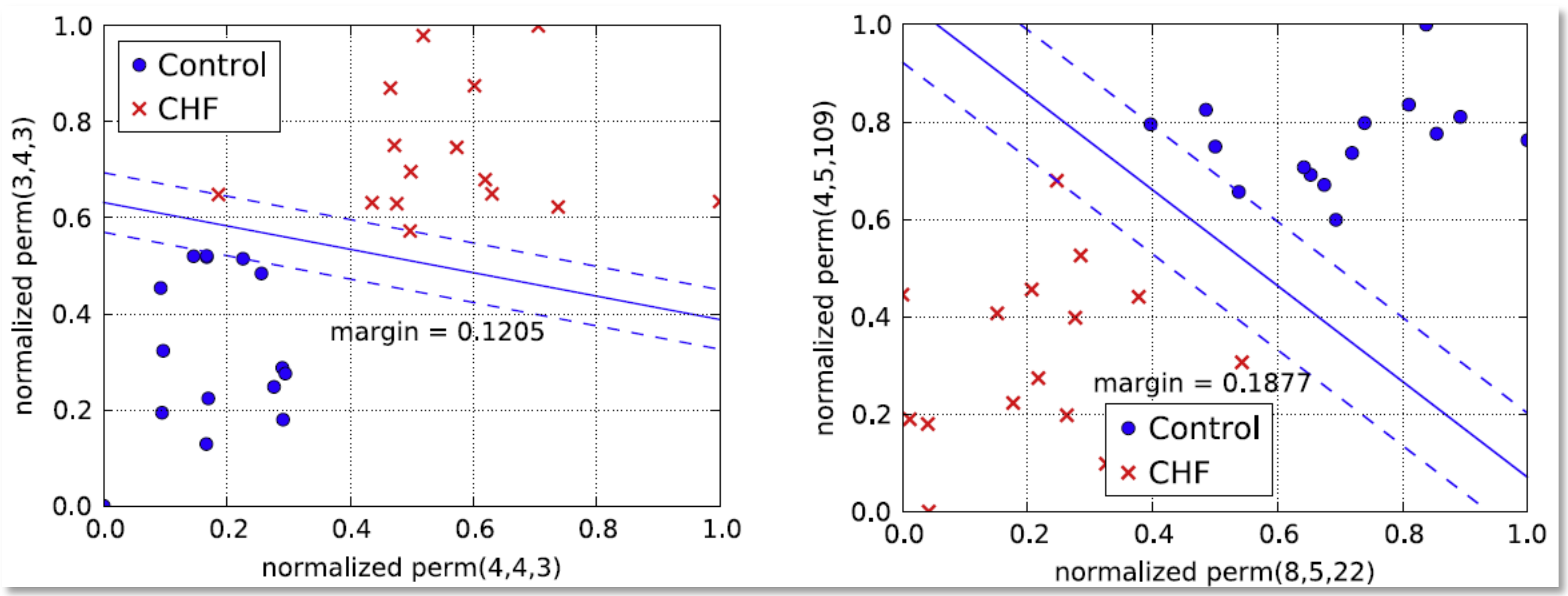
Number of papers citing PRL 2002



Review: Zanin, Rosso et al, Entropy 14, 1553 (2012)

Example of application: classification of electrocardiography signals

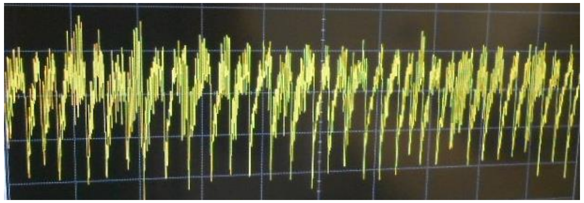
- Distinguishing patients suffering from congestive heart failure (CHF) from a (healthy) control group by analyzing **inter-beat time intervals**.



(the probabilities are normalized with respect to the smallest and the largest value occurring in the data set)

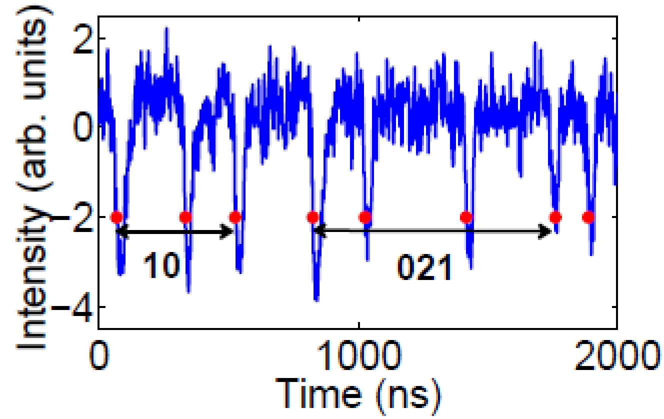
U. Parlitz et al. / Computers in Biology and Medicine 42 (2012) 319–327

Optical complexity, first example: spikes induced by optical feedback

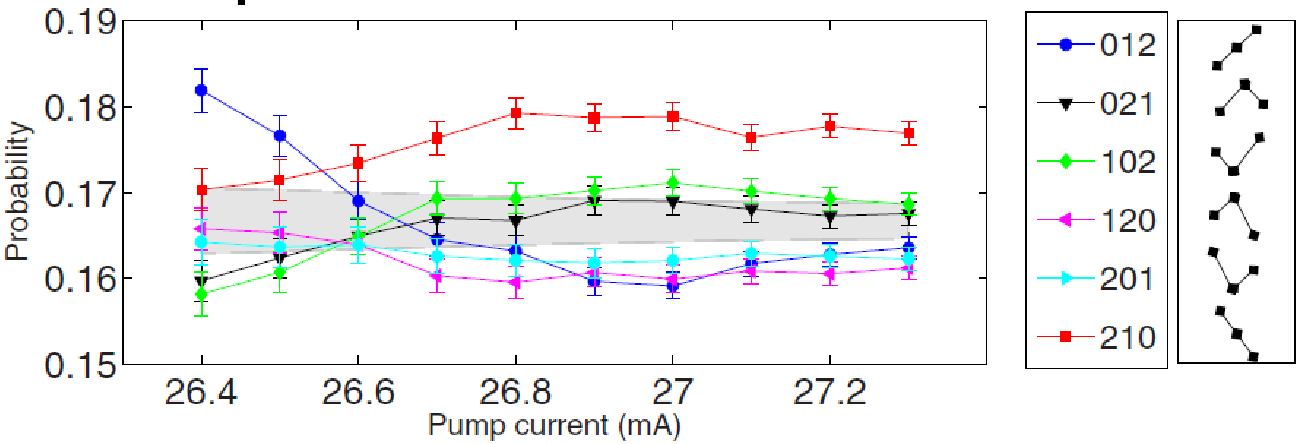


$X = \{\ldots \Delta T_i, \Delta T_{i+1}, \Delta T_{i+2}, \ldots\}$

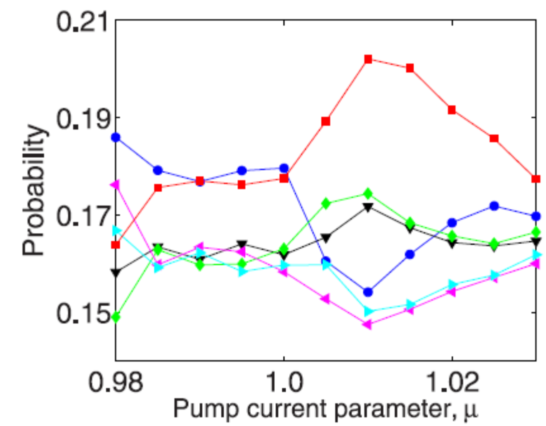
Time intervals between spikes



Empirical data



LK Model



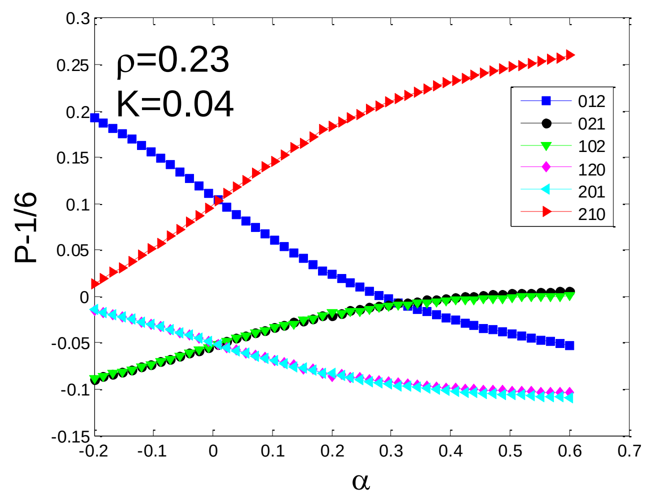
Error bars computed with a binomial test, gray region is consistent with $p_i = 1/6\ \forall\ i$.

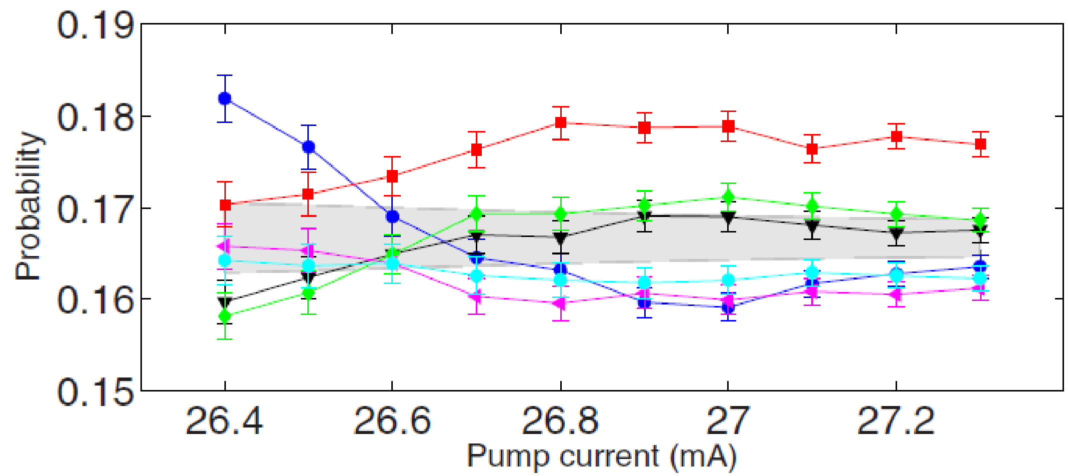
A. Aragoneses et al, Sci. Rep. 4, 4696 (2014)

Minimal model for temporal correlations: modified circle map

$$\varphi_{i+1} = \varphi_i + \rho + \frac{K}{2\pi}\left[\sin(2\pi\varphi_i) + \alpha\sin(4\pi\varphi_i)\right]$$

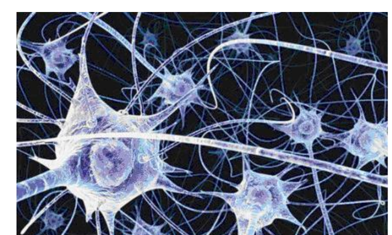
$$X_i = \varphi_{i+1} - \varphi_i$$





- The circle map describes many excitable systems
- The modified circle map has been used to describe correlations in the spikes of biological neurons.

  Neiman and Russell, *Models of stochastic biperiodic oscillations and extended serial correlations in electroreceptors of paddlefish*, PRE 71, 061915 (2005)



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How similar temporal correlations in optical spikes and in neuronal spikes are?

Neuron Interspike interval (ISI) histogram

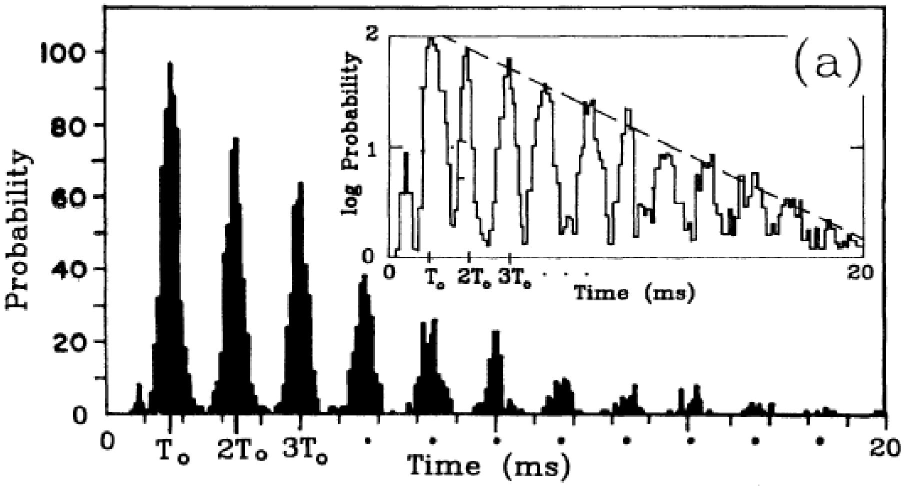
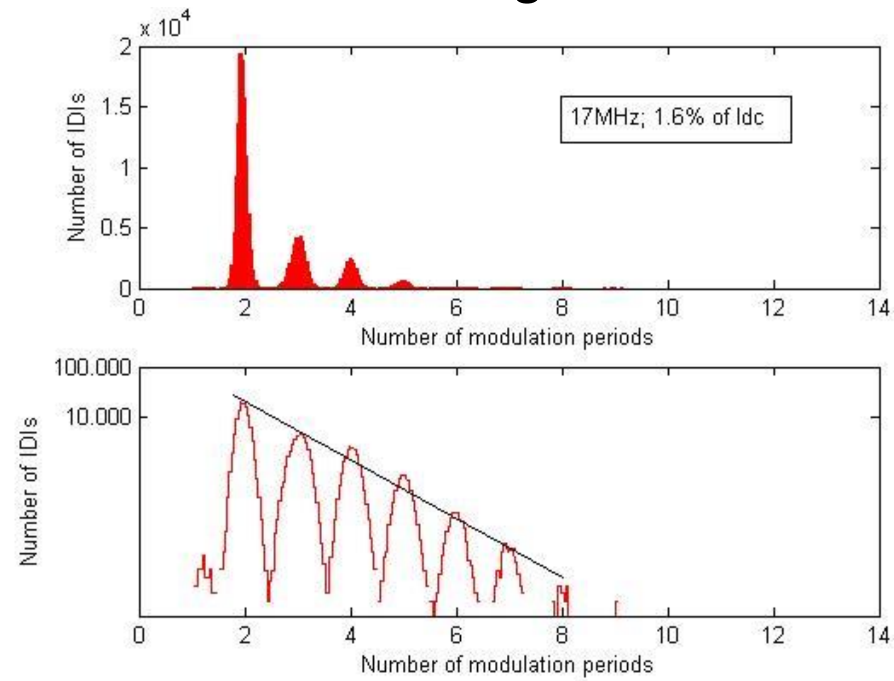


FIG. 1. (a) An experimental ISIH obtained from a single auditory nerve fiber of a squirrel monkey with a sinusoidal 80-dB sound-pressure-level stimulus of period $T_0 = 1.66$ ms applied at the ear. Note the modes at integer multiples of T_0. Inset:

Laser ISI histogram



With current modulation, data recorded in our lab

A. Longtin et al, PRL 67 (1991) 656.

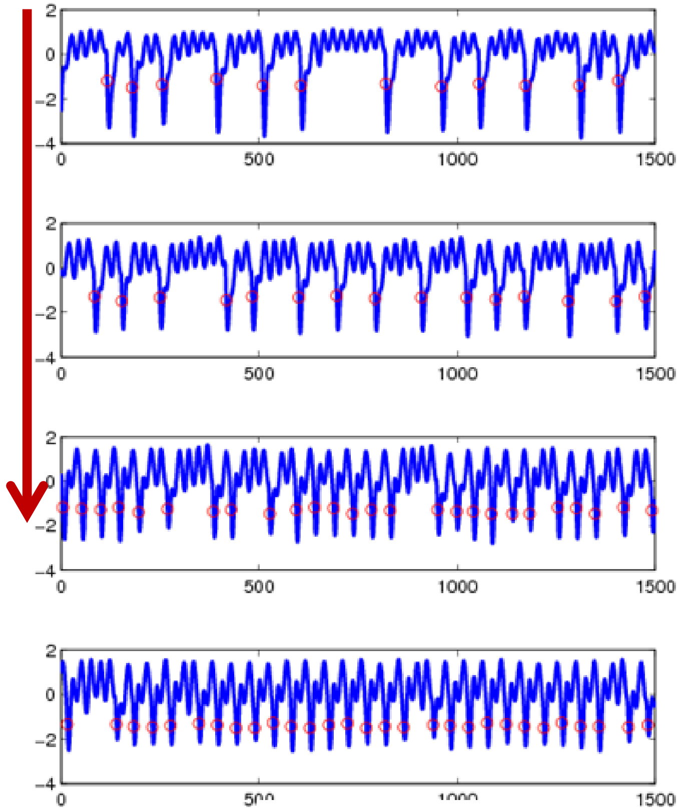
Response to periodic modulation

Relevant for understanding neuronal encoding of external stimuli

Laser intensity:

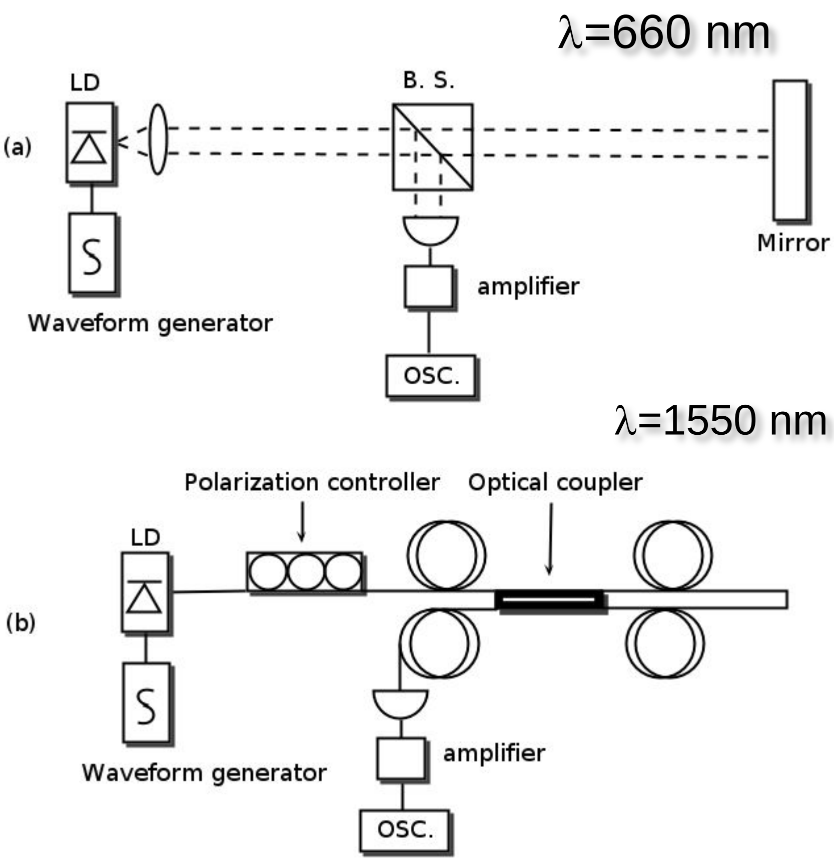
Increasing modulation amplitude

Tendency to lock



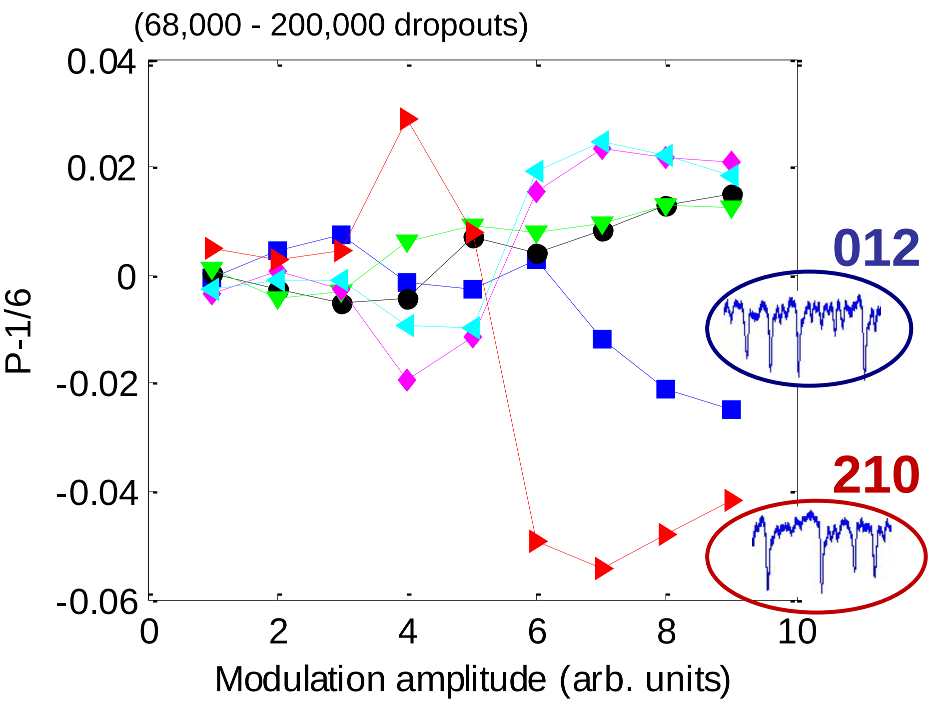
Time (ns)

Two experiments:

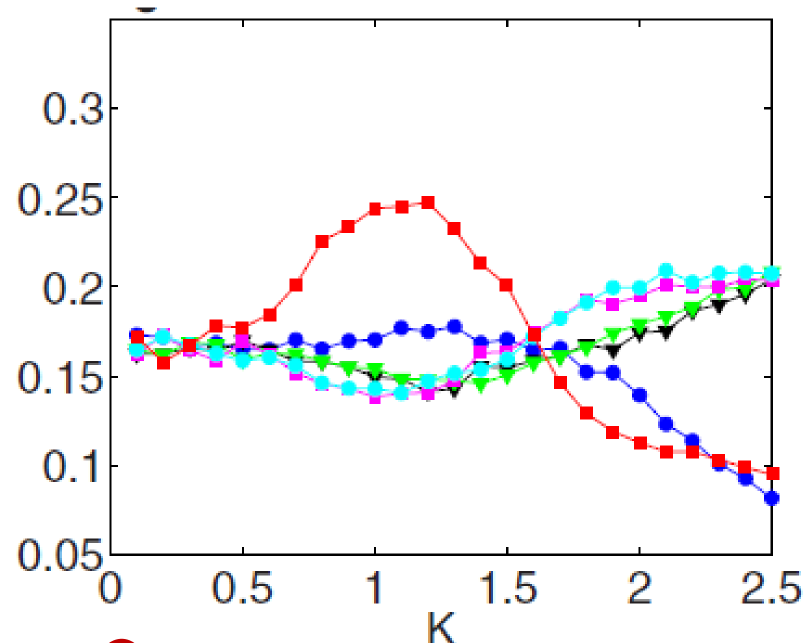


Varying the modulation amplitude: experiments - minimal model comparison

Experiments @ 660 nm



Modified circle map



$$\varphi_{i+1} = \varphi_i + \rho + \frac{K}{2\pi}\left[\sin(2\pi\varphi_i) + \alpha \sin(4\pi\varphi_i)\right] + D\zeta$$

Similar observations @ 1550 nm

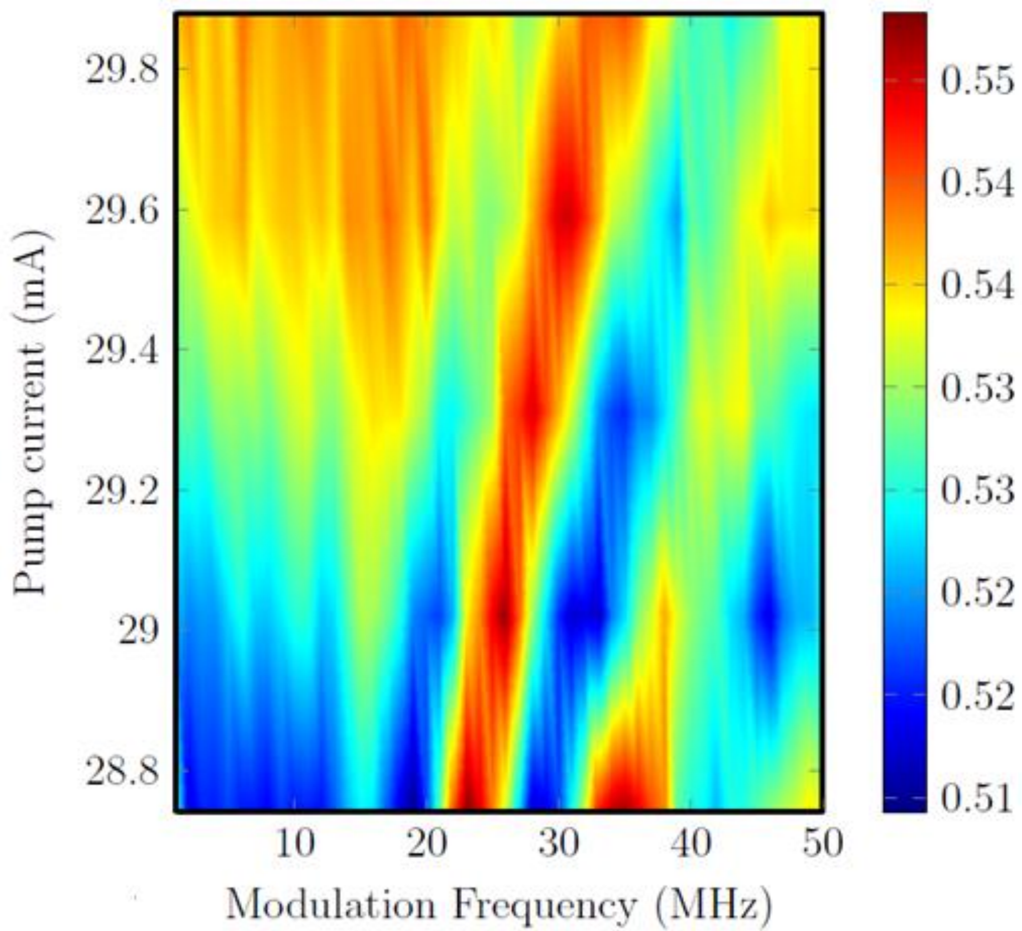
Interpretation: locking to external forcing

A. Aragoneses et al, Sci. Rep. 4, 4696 (2014)

Varying the natural frequency and the forcing frequency

Probability of **"10"** computed from experimental data.

modifies the natural spike rate →



T. Sorrentino et al,
Optics Express **23**, 5571 (2015).

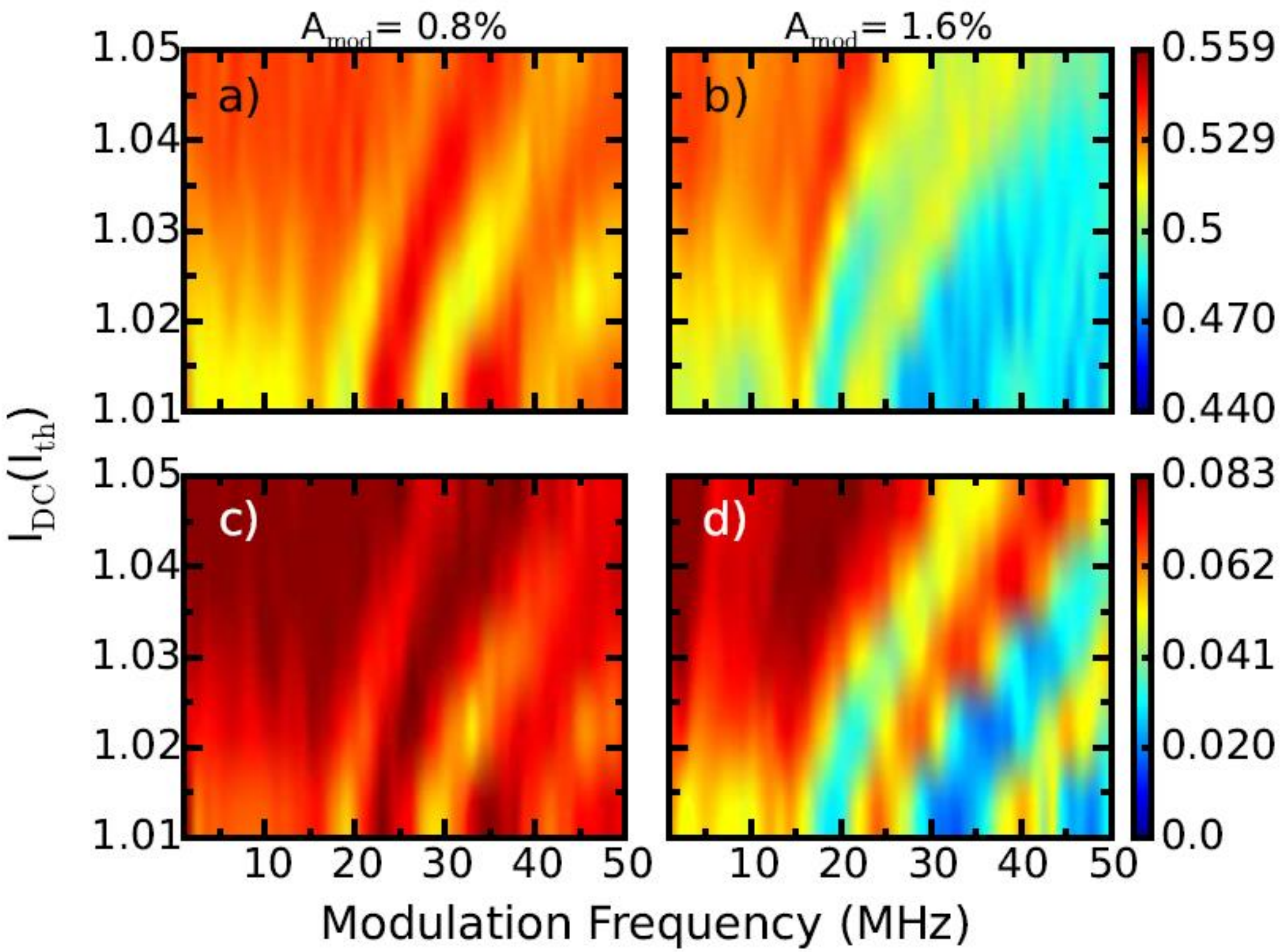
IEEE J. Sel. Top. Quantum Electron. **21**, 1801107 (2015).

$\Rightarrow$ useful tool for identifying noisy locking

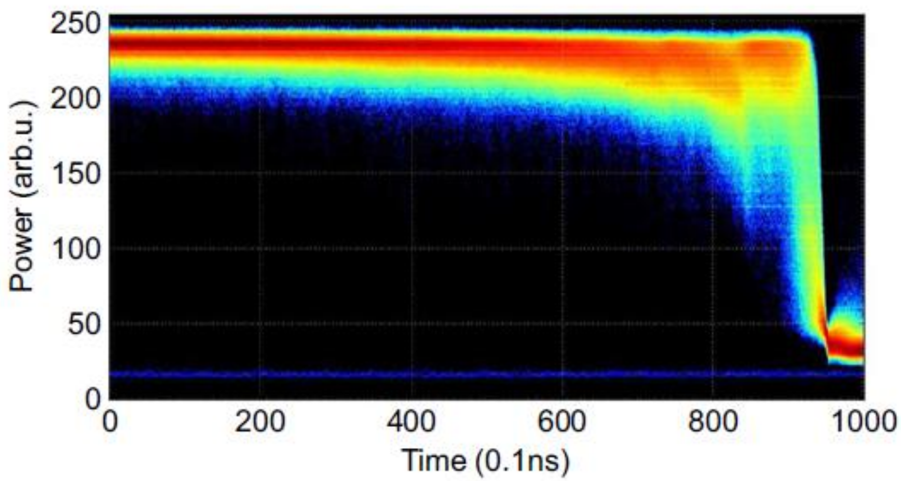
Ordinal analysis allows uncovering longer temporal correlations

Probability of **"10"**

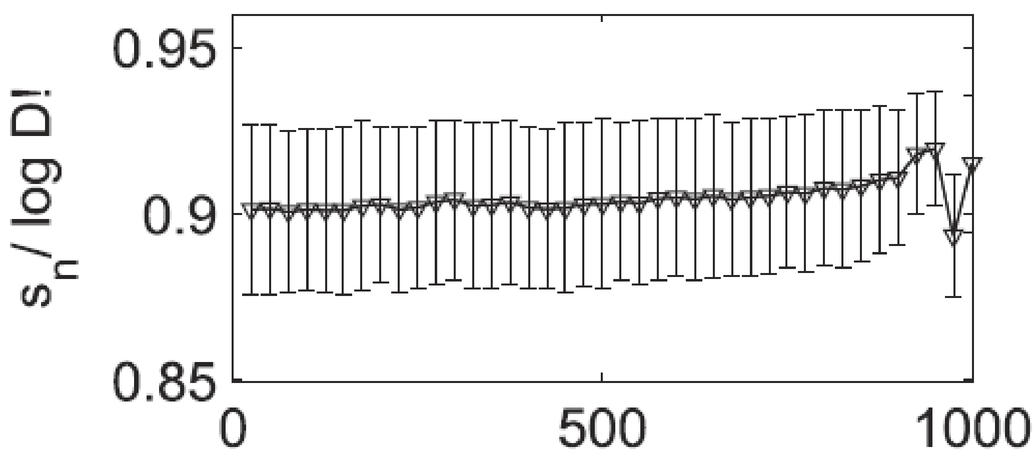
Probability of **"3210"**



Example 2: early warning of an abrupt transition



VCSEL polarization-resolved intensity when a control parameter varies (pump current)



Entropy computed from transition probabilities (‘012’→ ‘012’, etc.) in a sliding window of 500 data points.

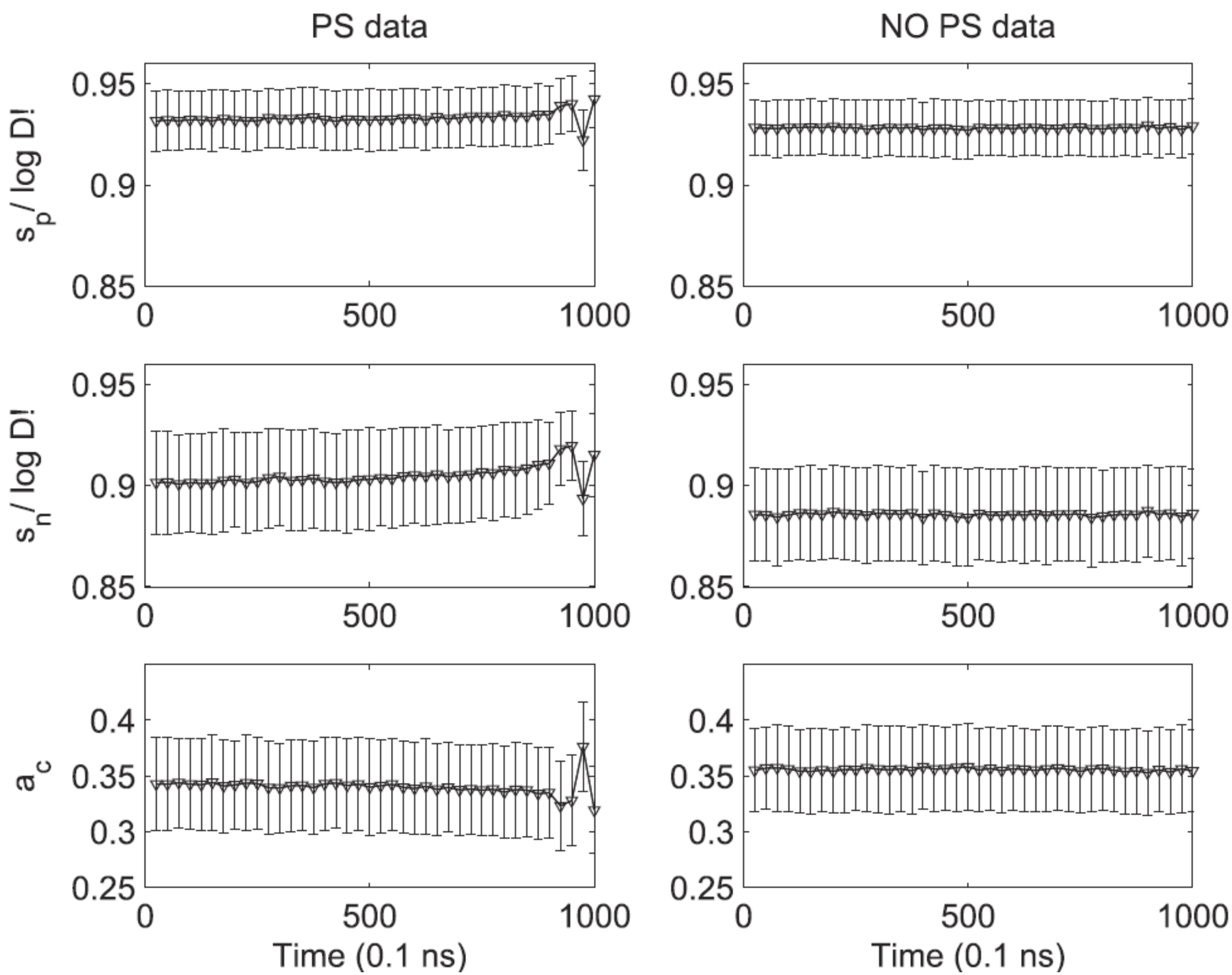
C. Masoller et al, New J. Phys. 17 (2015) 023068

Three early-warning indicators

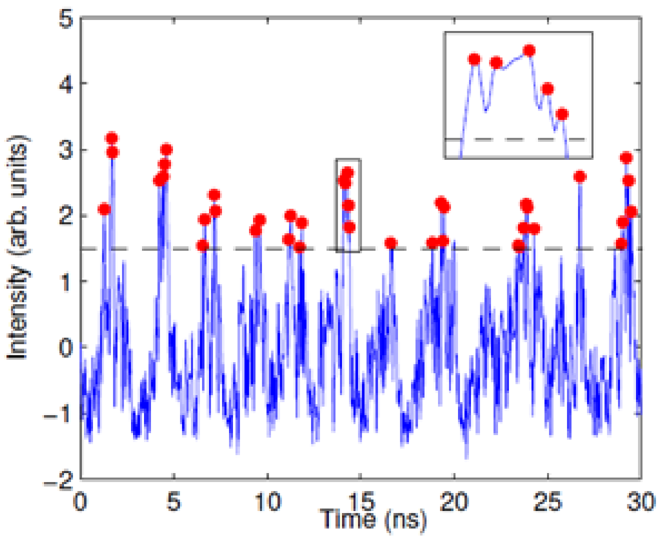
Entropy computed from the probabilities of the ordinal patterns

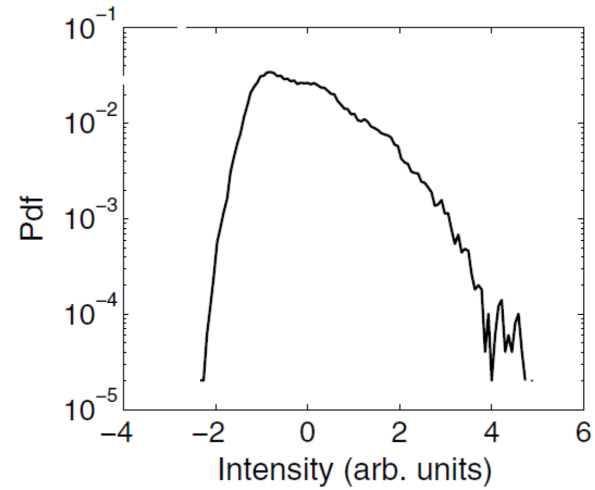
Entropy computed from the transition probabilities (TPs)

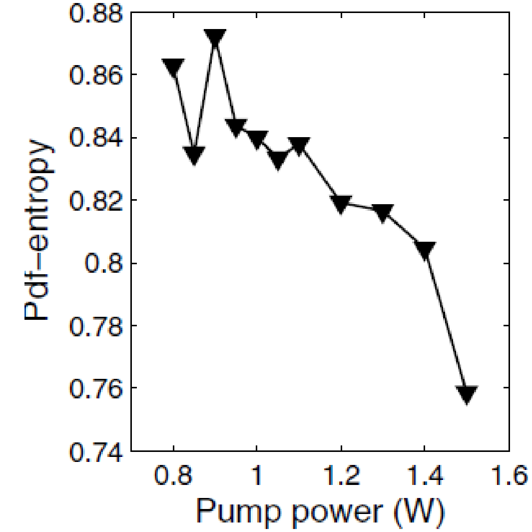
Asymmetry coefficient computed from TPs

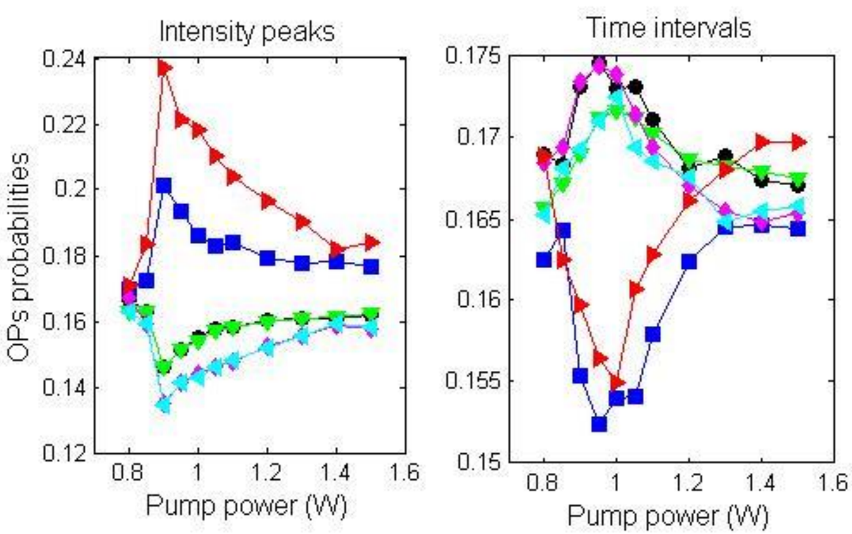


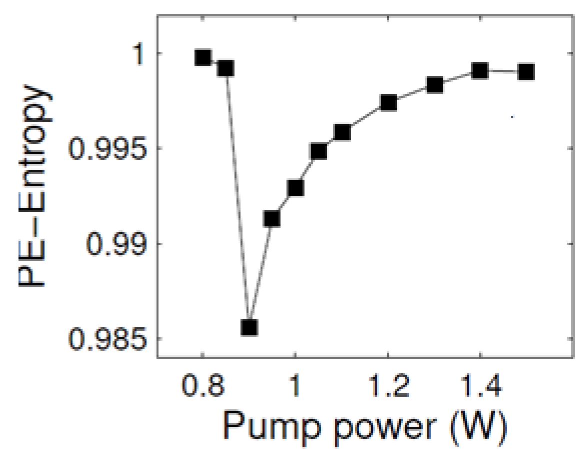
Example 3: laminar– turbulence regime transition in a fiber laser









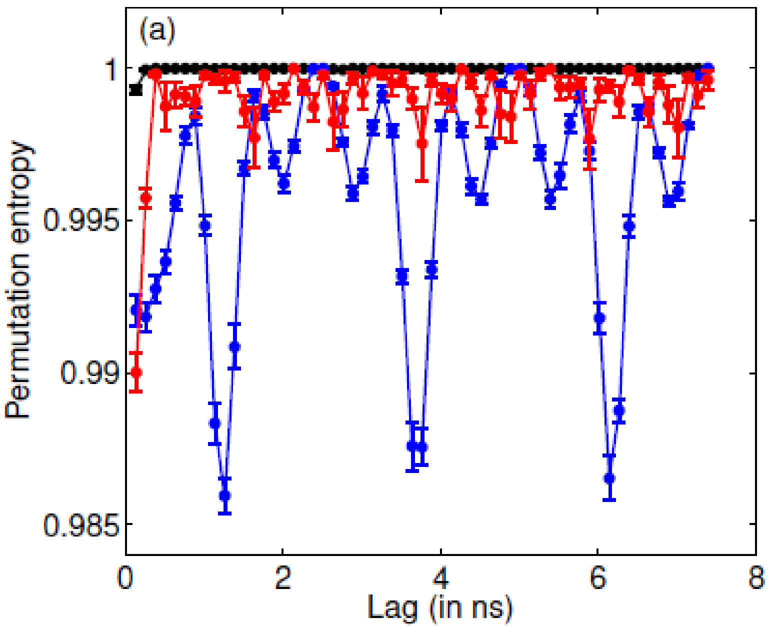


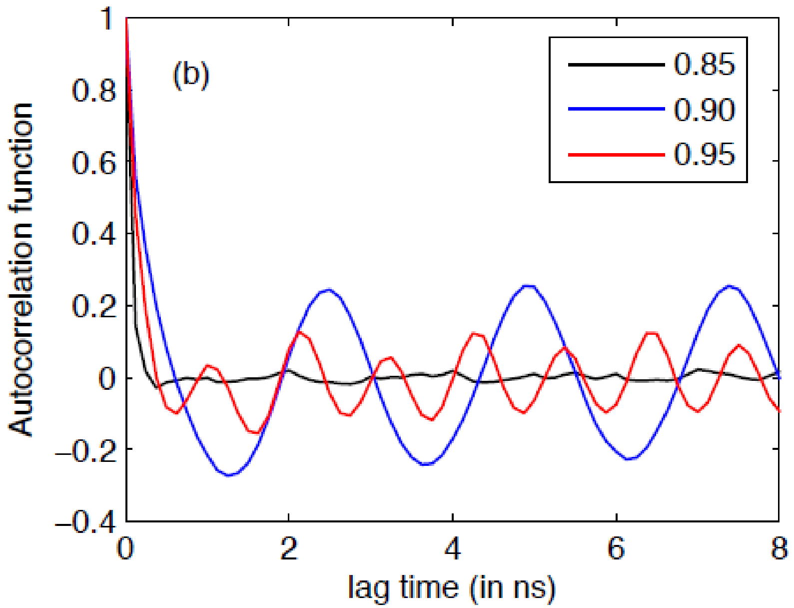
Aragoneses et al, PRL 116, 033902 (2016)

Ordinal analysis allows to unveil "hidden" intrinsic time-scales

Ordinal patterns constructed with lagged data points (all data points, no threshold used)

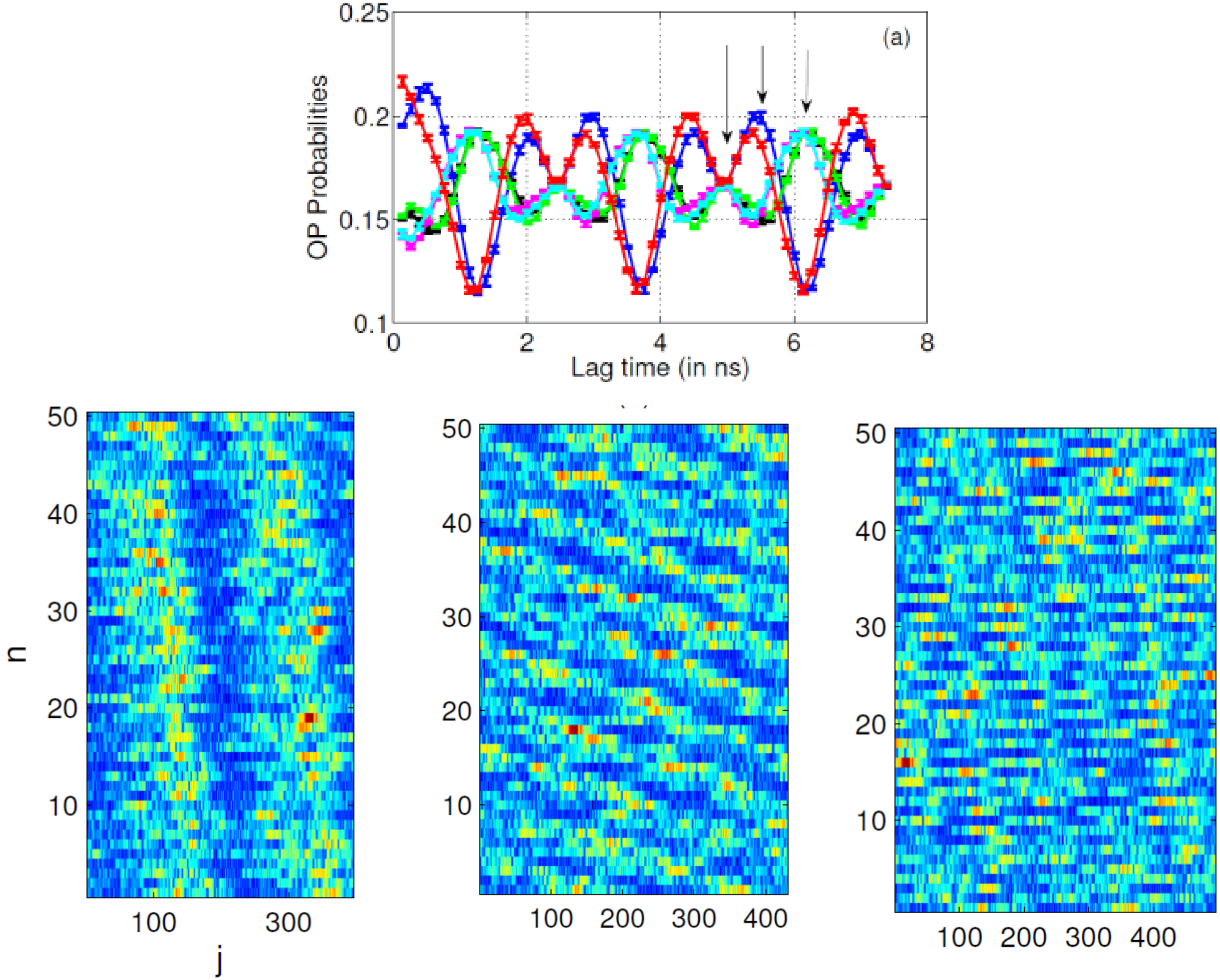
$$\{I_i, I_{i+\tau}, I_{i+2\tau}, \ldots\}$$





Aragoneses et al, PRL 116, 033902 (2016)

Uncovering spatio-temporal coherent structures



Take home message and ongoing work

- What have we learnt:
  - When observing complex optical output signals, nonlinear tools might capture hidden relevant features in the data.
  - Optics provides "big data" for testing novel analysis tools.
- A few specific conclusions:
  - In VCSELs ,"early warnings" of PS were inferred from data.
  - In fiber lasers, long-range temporal correlations during the laminar-turbulence transition.
  - Spikes induced by optical feedback, noisy locking detected; minimal model for temporal correlations identified.
- Ongoing and future work:

  Characterizing the performance of these tools for
  - Anticipating extreme pulses, abrupt transitions.
  - Analysis of complex 2D patterns: going from 1D time-series to biomedical images

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Collaborators & funding

Taciano Sorrentino

Carlos Quintero

Andres Aragoneses

Laura Carpi

Carme Torrent

Experimental data from:

- VCSEL polarization-switching
  - Y. Hong (Bangor University, UK)
  - S. Barland (INLN, Nice, France)

- Fibre laser data: Prof. Turitsyn' group (Aston University, UK)

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THANK YOU FOR YOUR ATTENTION !

<cristina.masoller@upc.edu>
http://www.fisica.edu.uy/~cris/

Publications:

- A. Aragoneses et al, Sci. Rep. 4, 4696 (2014)
- T. Sorrentino et al, Optics Express **23**, 5571 (2015)
- T. Sorrentino et al, IEEE J. Sel. Top. Quantum Electron. **21**, 1801107 (2015)
- C. Masoller et al, New J. Phys. 17, 023068 (2015)
- Aragoneses et al, PRL 116, 033902 (2016)