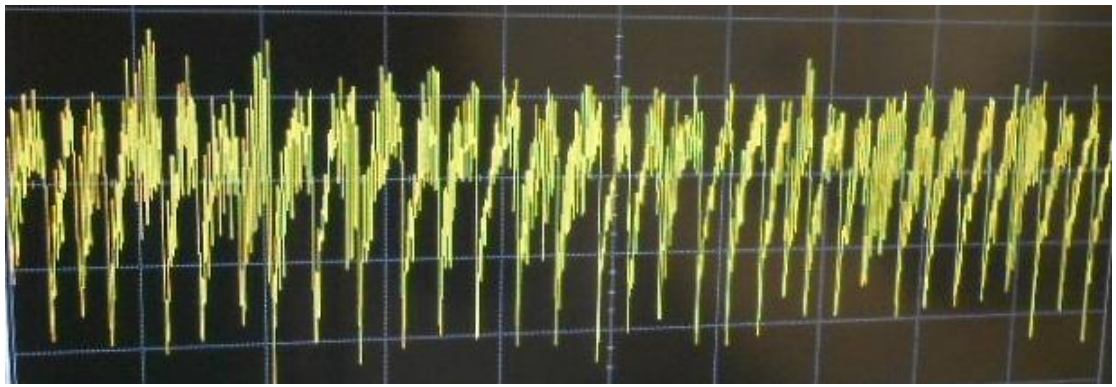

Symbolic patterns, clusters and hierarchies in spiking systems

Cristina Masoller

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UNIVERSITAT POLITÈCNICA DE CATALUNYA BARCELONATECH

Campus d'Excel·lència Internacional

Dynamics Days Asia Pacific 08
Chennai, July 2014

Collaborators

- Andres Aragoneses

- Taciano Sorrentino

- Carme Torrent

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Where are we?

1. Barcelona
2. Castelldefels
3. Igualada
4. Manresa
5. Mataró
6. Sant Cugat del Vallès
7. Terrassa
8. Vilanova i la Geltrú

Viernes, 25 de septiembre de 2009 **Diari de Terrassa**

El edificio Gaia centraliza grupos científicos consolidados y emergentes.

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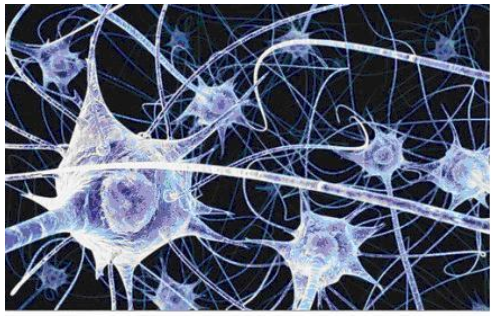
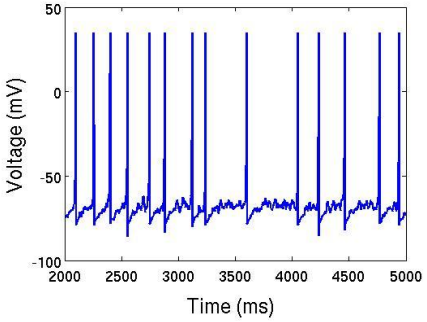
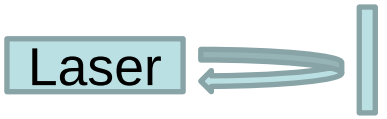
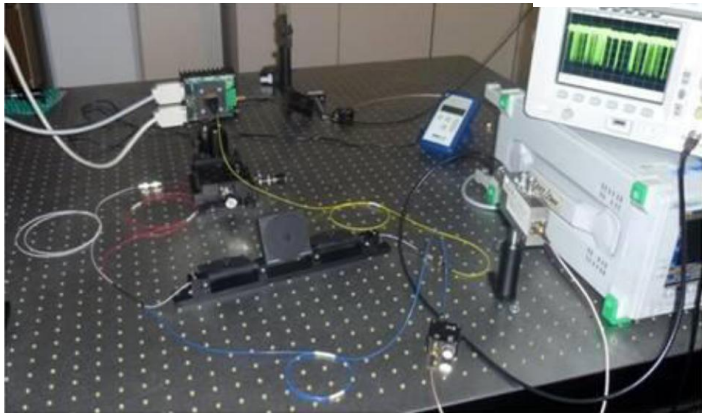
Research lab: nonlinear dynamics of semiconductor lasers



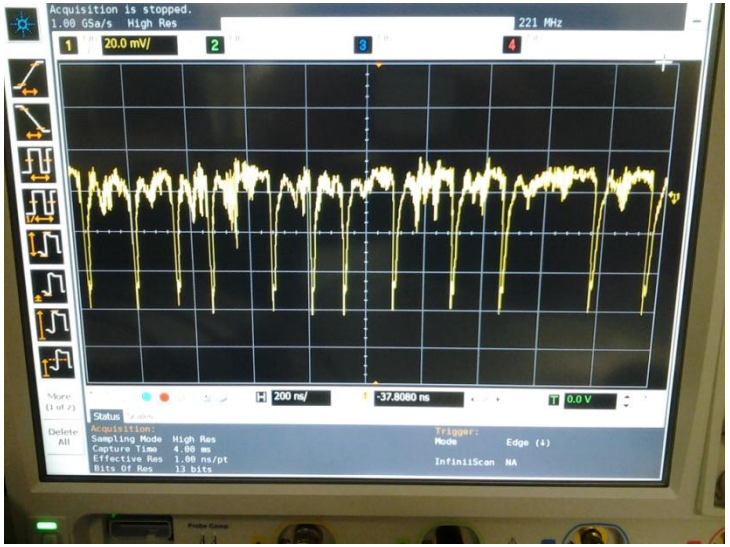






- Research goals: are optical spikes similar to neuronal spikes?

- Potential for ultra-fast optical, brain-inspired information processing?



Outline

- Introduction

  Semiconductor lasers with optical feedback: stochastic and high-dimensional dynamical systems

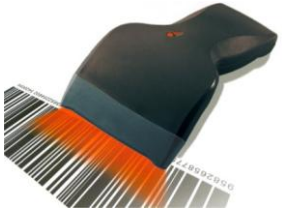
- Method of symbolic time-series analysis and experimental setup

- Results
  - Inferring signatures of determinism
  - Clusters in the symbolic dynamics
  - Response to external periodic forcing

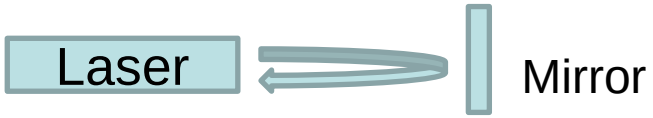
- Conclusions and take home message

Semiconductor lasers

- Used in:
  - Fiber-optics communications
  - Optical data storage (CDs, DVDs …)
  - Barcode scanners, laser printers, computer mice
  - Biomedical applications (imaging, sensing …)
  - etc

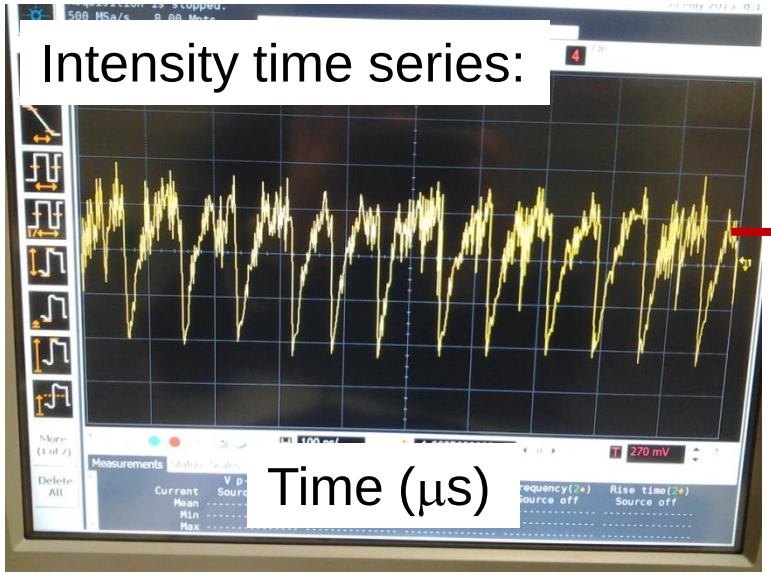


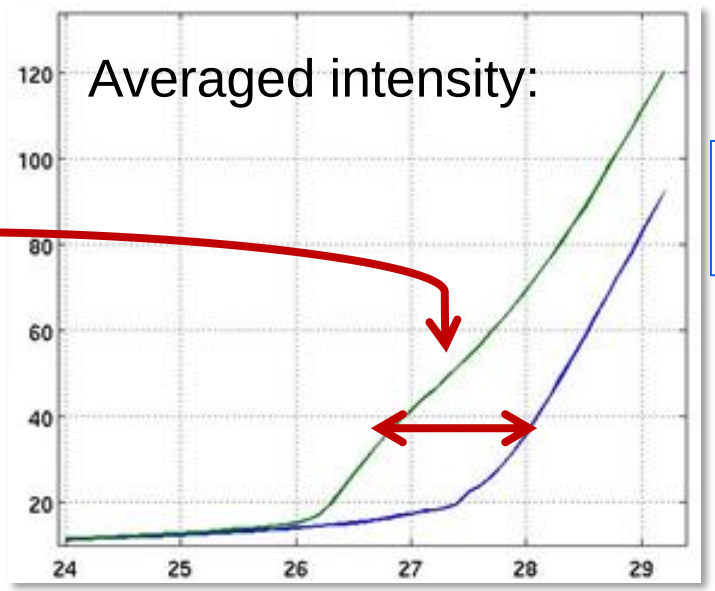
- Feedback induces nonlinear dynamics:
  - Multi-stability
  - Regular pulses
  - Extreme pulses
  - Intermittency
  - Chaos



Optical spikes

- The **intensity dropouts** resemble neuronal **spikes**





with feedback

without feedback

Pump current (mA)
(CONTROL PARAMETER)

- This spiking dynamics is referred as low-frequency fluctuations

Why intensity dropouts?

- Complex interplay of:
  - Feedback delay time
  - Various noise sources
  - Nonlinear light-matter interactions

$\Rightarrow$ Stochastic and high-dimensional system

- Over years a lot of work has been devoted to understand the laser spiking behavior and to identify simple models.

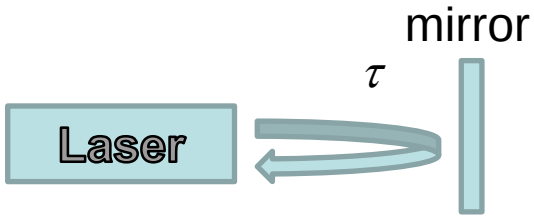
A. Prasad et al, *Low-frequency fluctuations in external cavity semiconductor lasers: understanding based on a simple dynamical model*, J. Opt. B: Quantum Semiclass. Opt. 3 242 (2001).

Goals

- To develop a method of time-series analysis for determining signatures of determinism;
- To extract new information;
- To compare model predictions with observations;
- To find a minimal model;
- To explore potential for building optical neurons.

Governing equations

R. Lang and K. Kobayashi, IEEE J. Quantum Electron. 16, 347 (1980)



$|E|^2$ ~ photon number (output intensity)

N ~ number of carriers (electron-holes)

$$\frac{dE}{dt} = \frac{1}{2\tau_p}(1+i\alpha)(G-1)E + \eta\, E(t-\tau)e^{-i\omega_0\tau} + \sqrt{\beta_{sp}}\,\xi$$

feedback noise

$$\frac{dN}{dt} = \frac{1}{\tau_N}\left(\mu - N - G|E|^2\right)$$

Gain: $G = N/(1+\varepsilon|E|^2)$

η = feedback strength

τ = feedback delay time

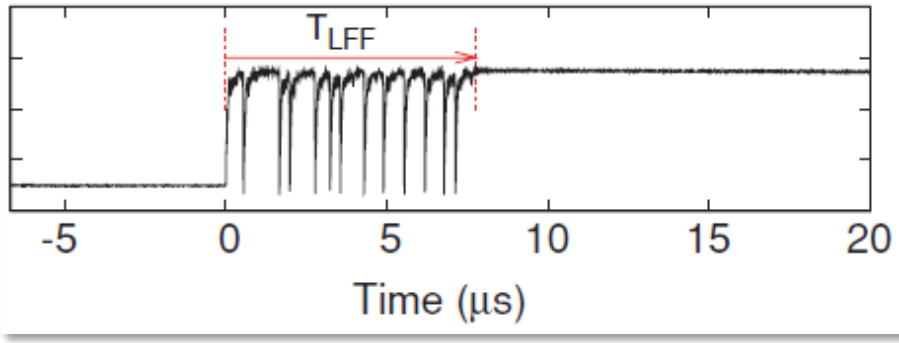
μ = pump current

(control parameter)

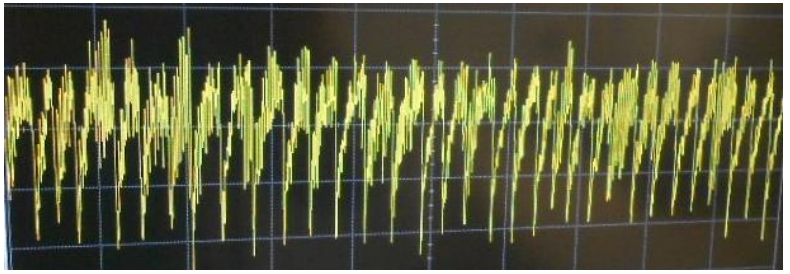
Model predictions

- In **deterministic** simulations: the spikes (dropouts) are **transient**.

Laser intensity



- But in **stochastic** model simulations: **bursts** of dropouts.
- In the experiments: which dropouts are triggered by **noise** and which ones are **deterministic**?

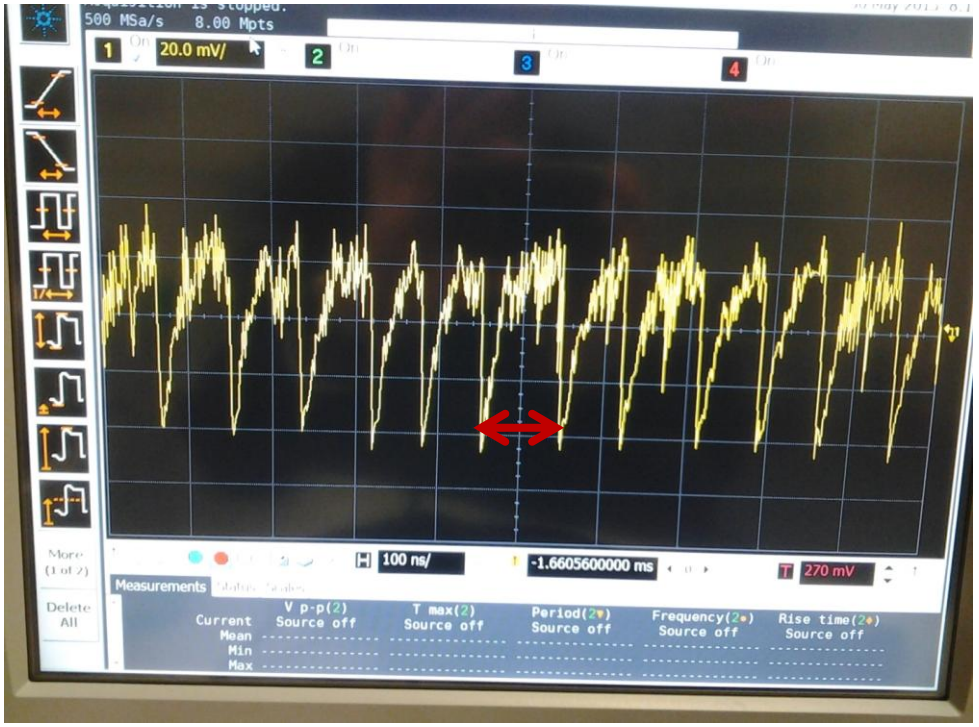


- **Information** in the spike sequence?

A. Torcini et al, Phys. Rev. A 74, 063801 (2006)
J. Zamora-Munt et al, Phys Rev A 81, 033820 (2010)

Problems and strategy

- Main problem: we can measure only one variable (the laser intensity)
- Also a problem: the detection system (photodiode, oscilloscope) has a finite *bandwidth* that gives limited temporal resolution.



- Our strategy: we analyze the sequence of **inter-dropout-intervals (IDIs)**:

$$\Delta T_i = t_{i+1} - t_i$$

Event level description of complex systems

- Examples of sequences of events:
  - **Intervals between threshold crossings, barrier crossings,**
  - **Neurons: inter-spike intervals (ISIs),**
  - **Human communication: inter-event user times (SMS, emails, Twitters).**
  - **Earth and climate: intervals between earthquakes, extreme events (tornados, rainfalls) etc.**

- The identification of patterns in the sequence of events allows for:
  - **Model verification**
  - **Parameter estimation**
  - **Classification of different types of dynamical behaviors**
  - **Predictability - forecasting**

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Symbolic Ordinal Analysis

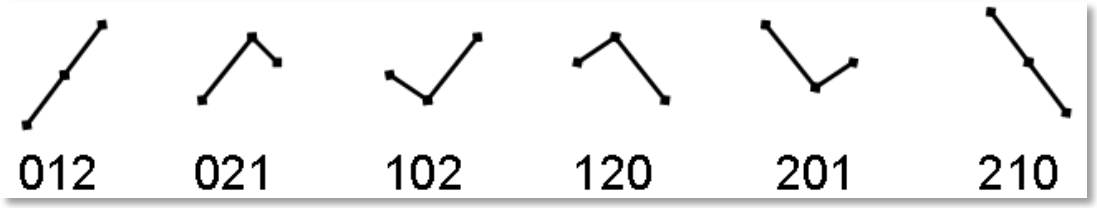
- Has been widely used to analyze data generated from complex systems
  - **Financial, economical**
  - **Biological, life sciences**
  - **Geosciences, climate**
  - **Physics, chemistry, etc**

- Able to:
  - **Distinguish stochasticity and determinism**
  - **Classify different types of dynamical behaviors (pathological, healthy)**
  - **Quantify complexity**
  - **Identify coupling and directionality.**

Brandt & Pompe, Phys. Rev. Lett. 88, 174102, (2002).

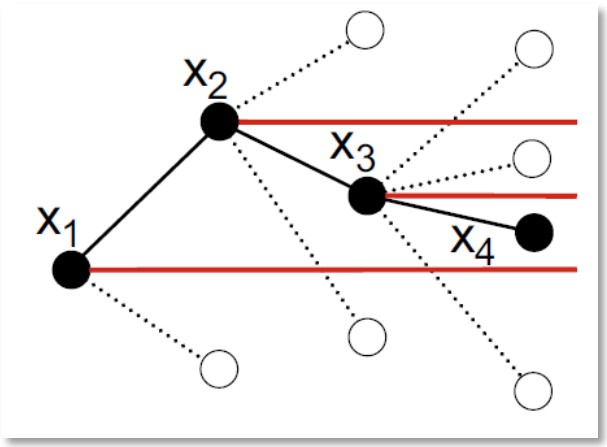
Ordinal Patterns ("words")

- "Words" of **D letters** can be formed by considering the **order relation** between sets of D values $\{\ldots x_i, x_{i+1}, x_{i+2}, \ldots\}$.
- For **D=3** there are 6 possible words



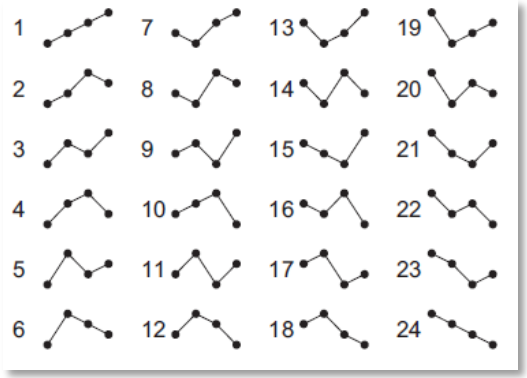
Example: the set (5, 1, 7) gives "102" because 1 < 5 < 7

- Advantage: the transformation keeps information about correlations in the time-series.
- Drawback: the set (5,1,100) also gives word "102".

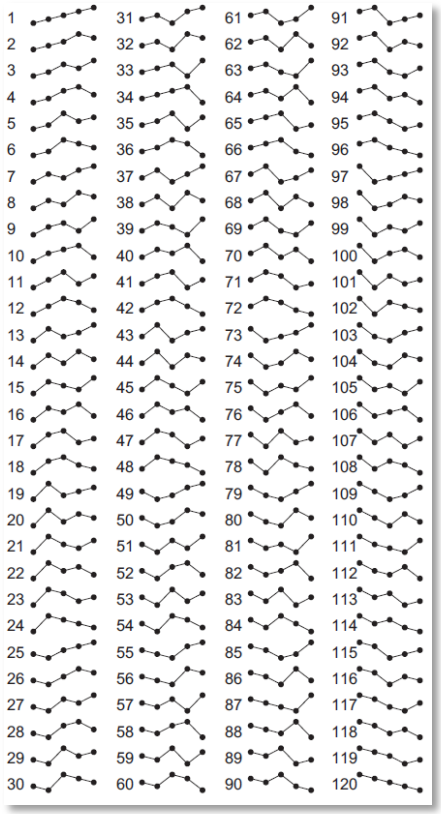


Number of possible ordinal patterns: D!

D=4

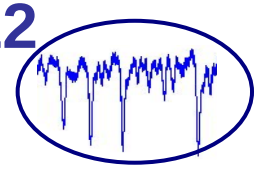


D=5



- The probabilities of the words unveil correlations between events.
- How to select D? Optimal D depends on:
  - The length of the time series.
  - The time scale of correlations.
- For optical spikes: D=2 (D=3) reveal correlations among 3 (4) spikes

012



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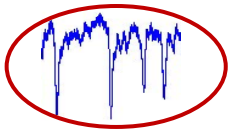
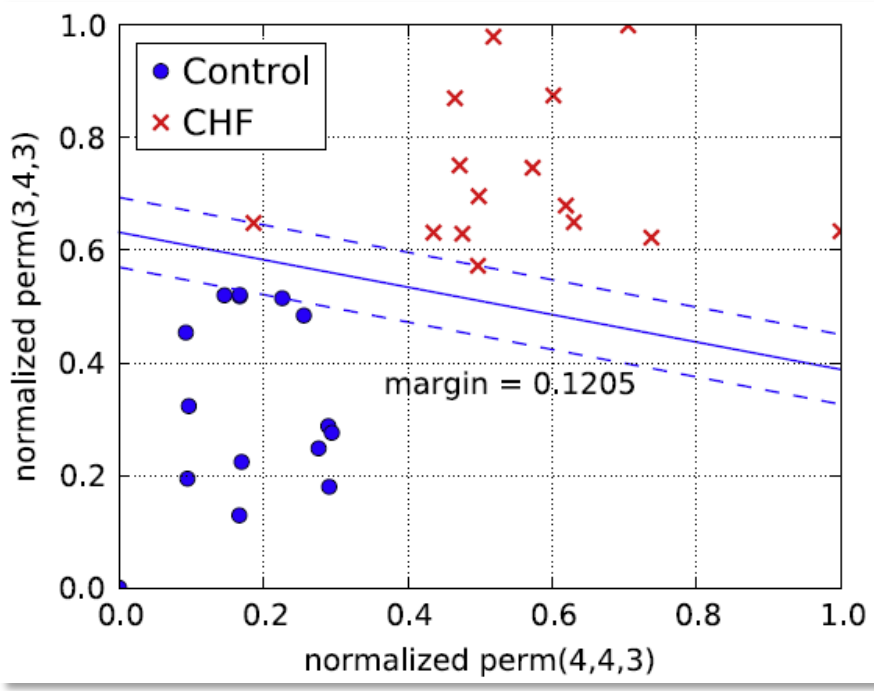


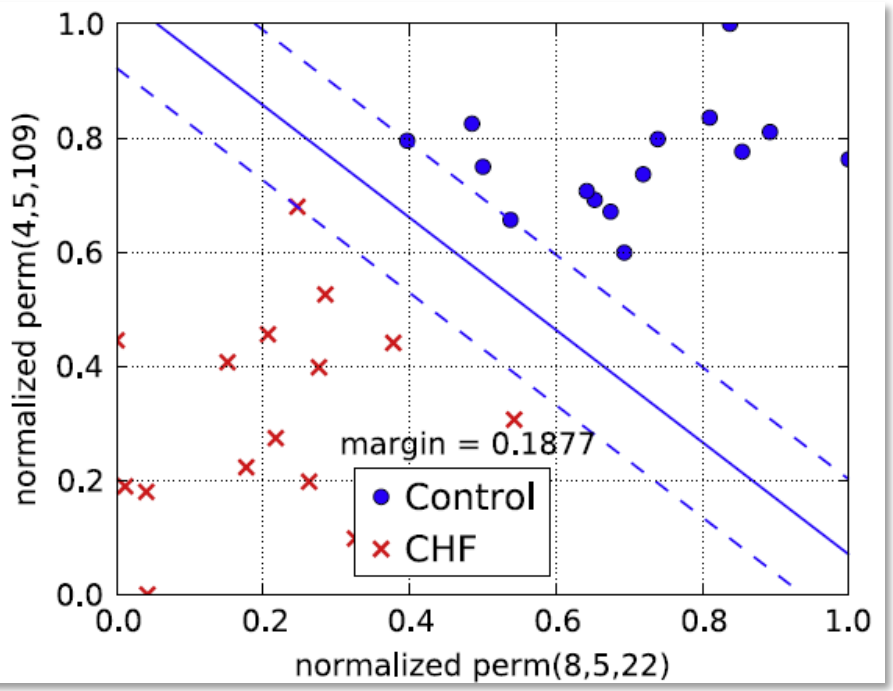
U. Parlitz et al. / Computers in Biology and Medicine 42 (2012) 319–327

An illustrative example

Classifying cardiac biosignals using ordinal pattern statistics

congestive heart failure (CHF) vs healthy subjects.





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

Outline

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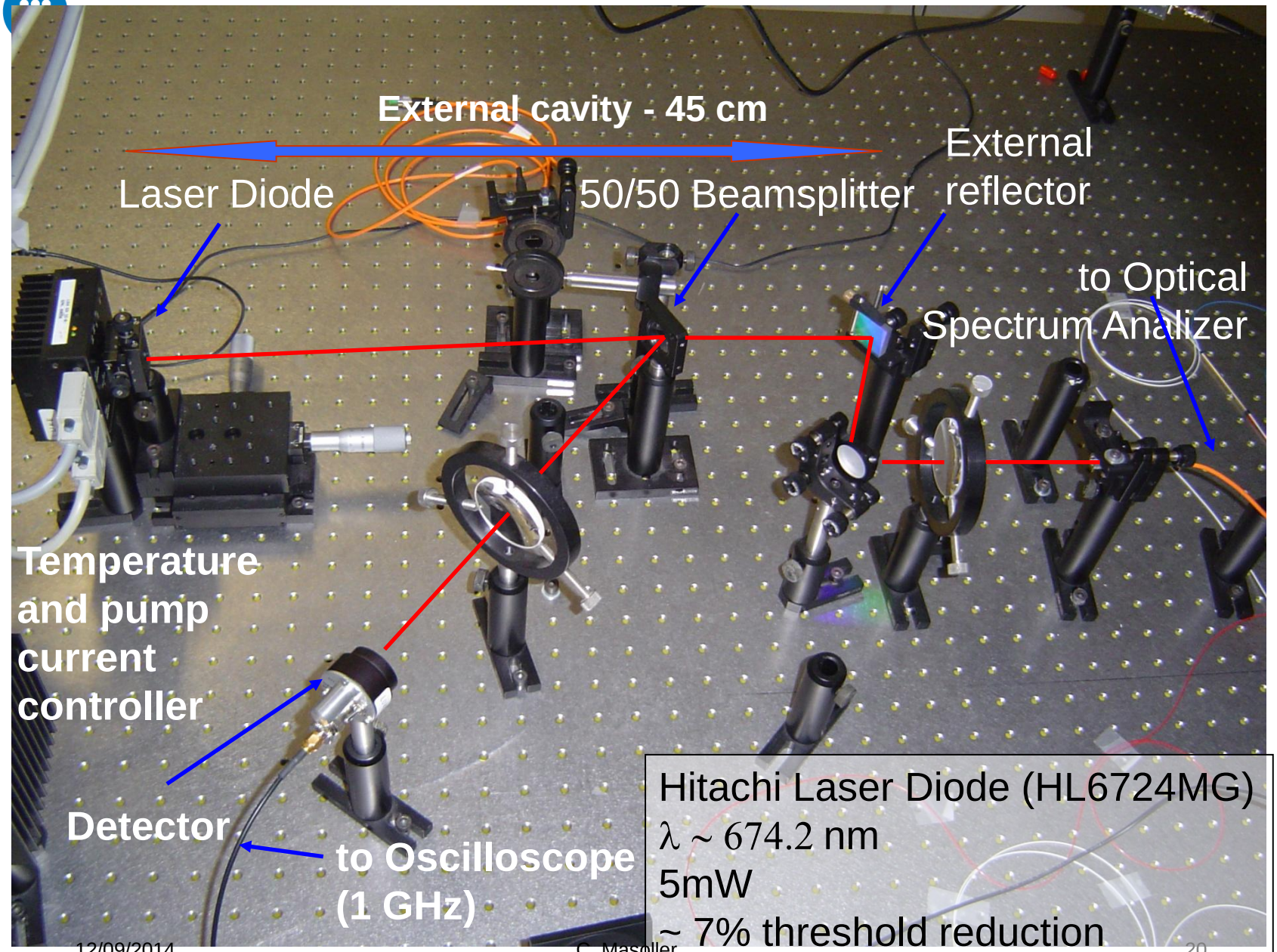
- Results
- Conclusions and take home message



Hitachi Laser Diode (HL6724MG)
$\lambda \sim 674.2$ nm
5mW
~ 7% threshold reduction

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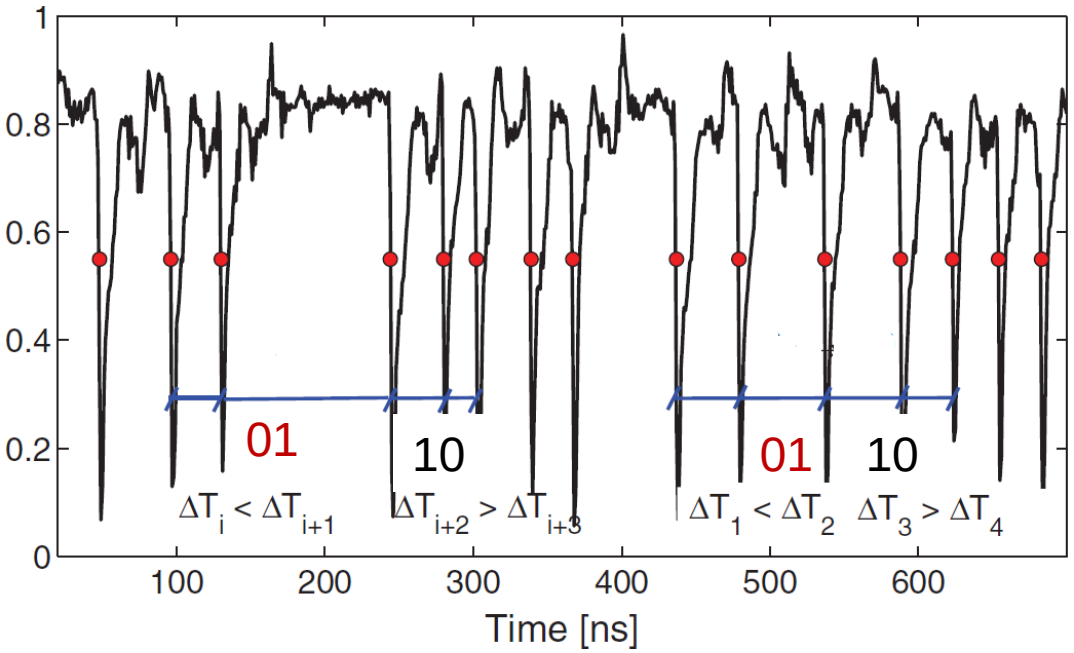
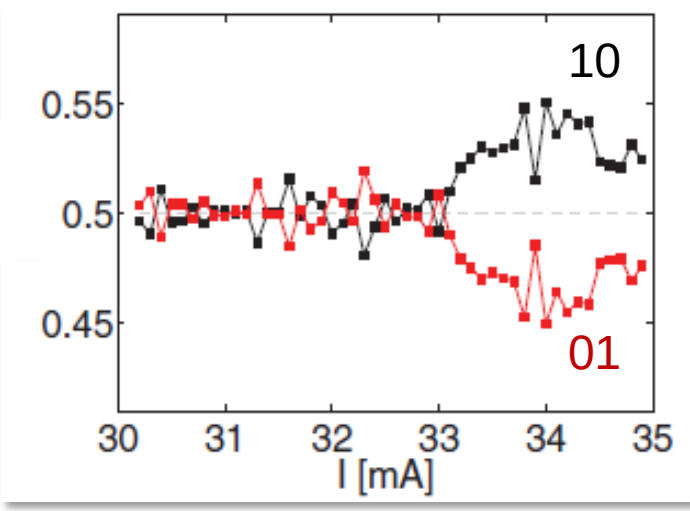
Correlations between 3 consecutive spikes



Word probabilities:

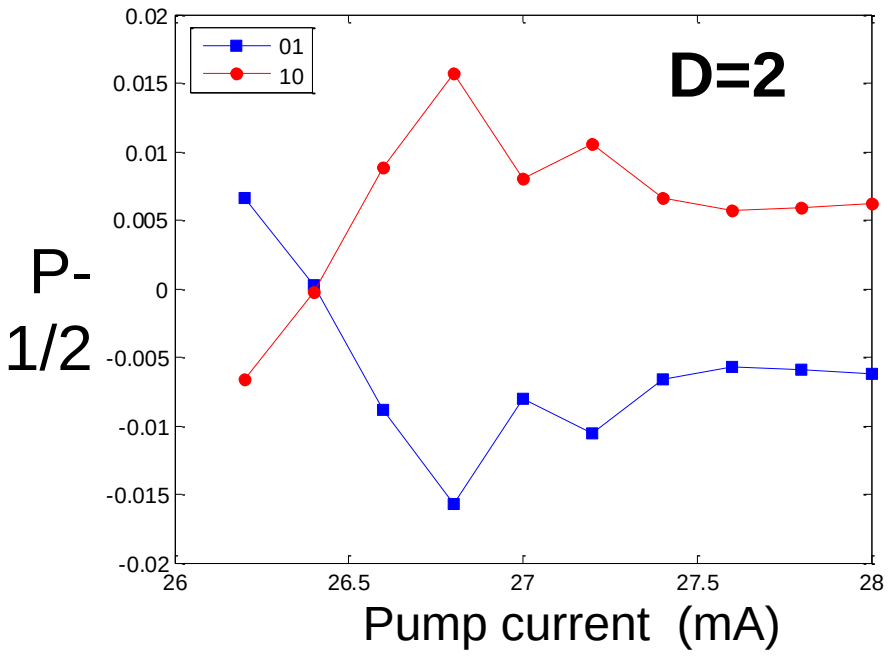


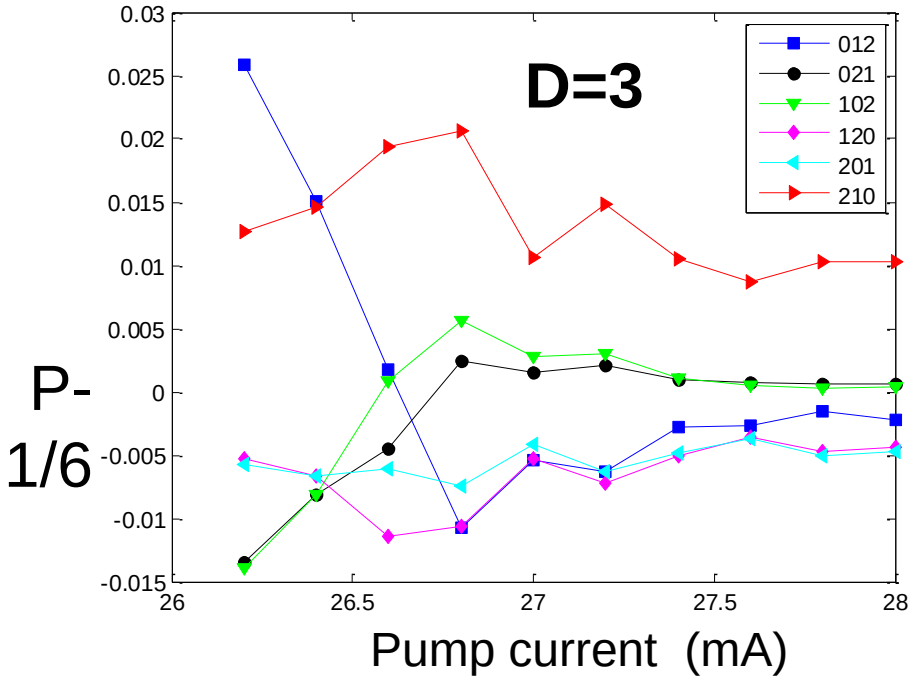
D=2: 3-spike correlations?
Null hypothesis: fully random sequence of spikes ⇒ P(01) = P(10)

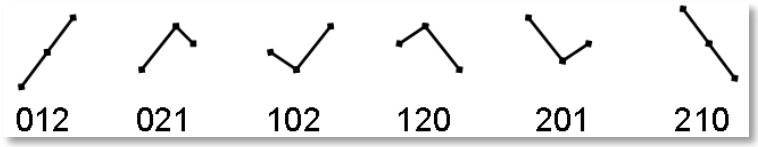
Consistent with stochastic at low pump current, but signatures of determinism at high pump current.

N. Rubido et al, Phys. Rev. E 84, 026202 (2011)

At low pump current: are the spikes fully random? New experiment

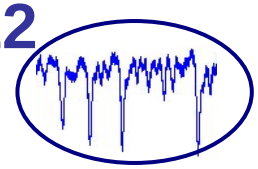




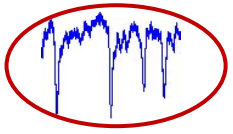


45000 - 220000 spikes

012

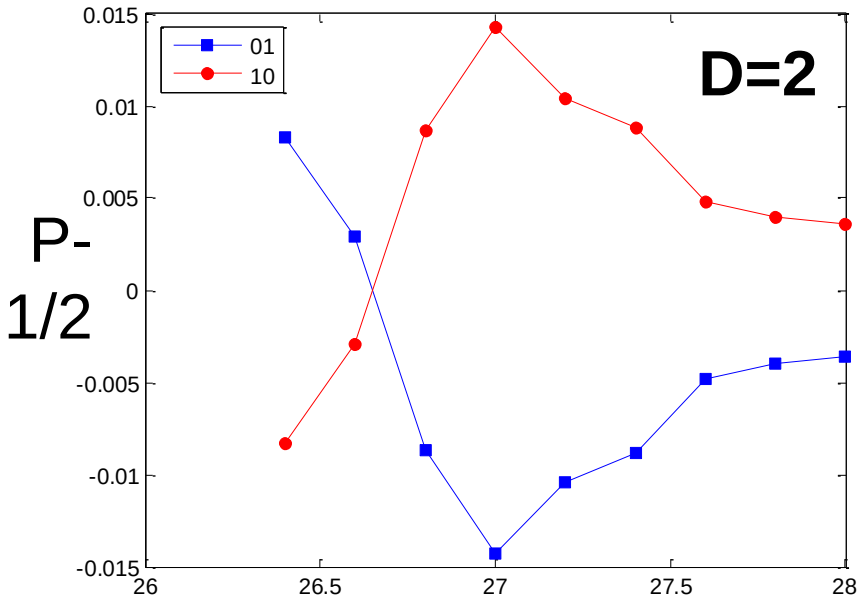


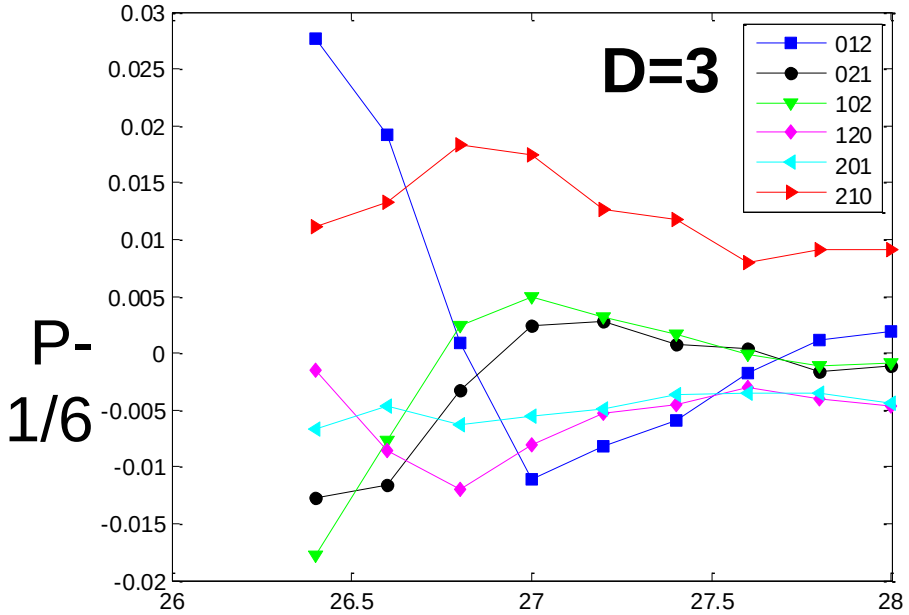
210

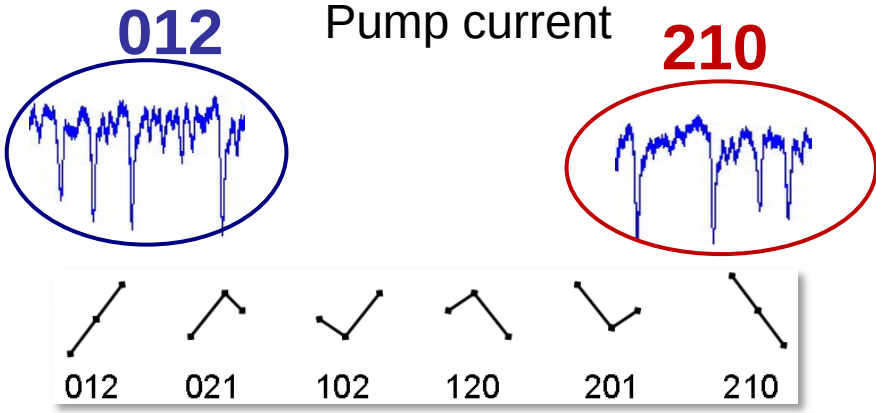


A. Aragoneses et al, Scientific Reports 3, 1778 (2013)

Also in another data set recorded at a different temperature (T=20 C)

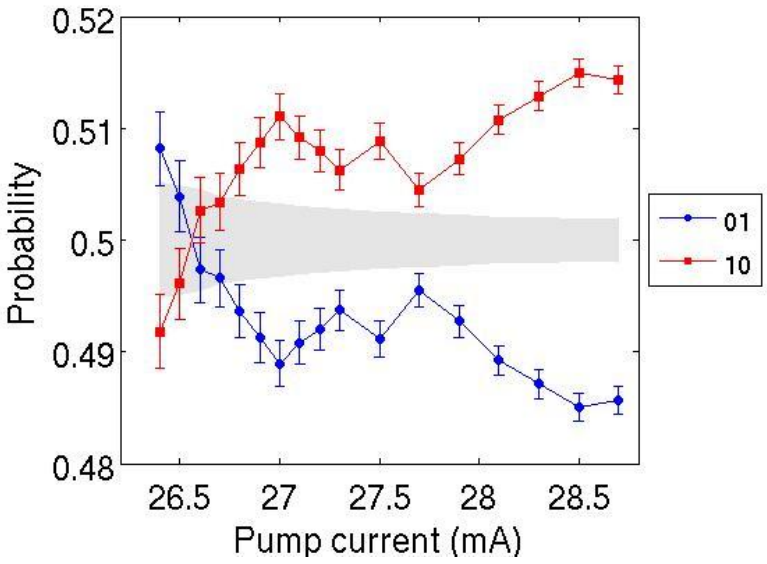




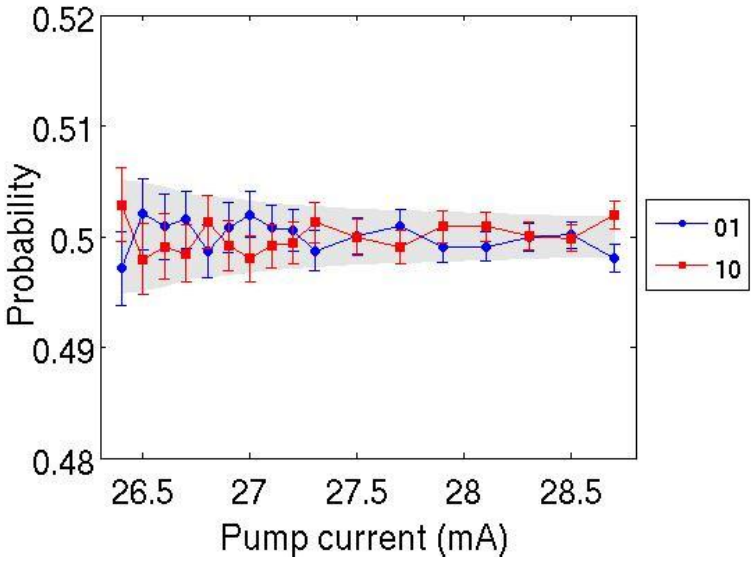


Are the deviations from the null hypothesis significant?

Recorded data



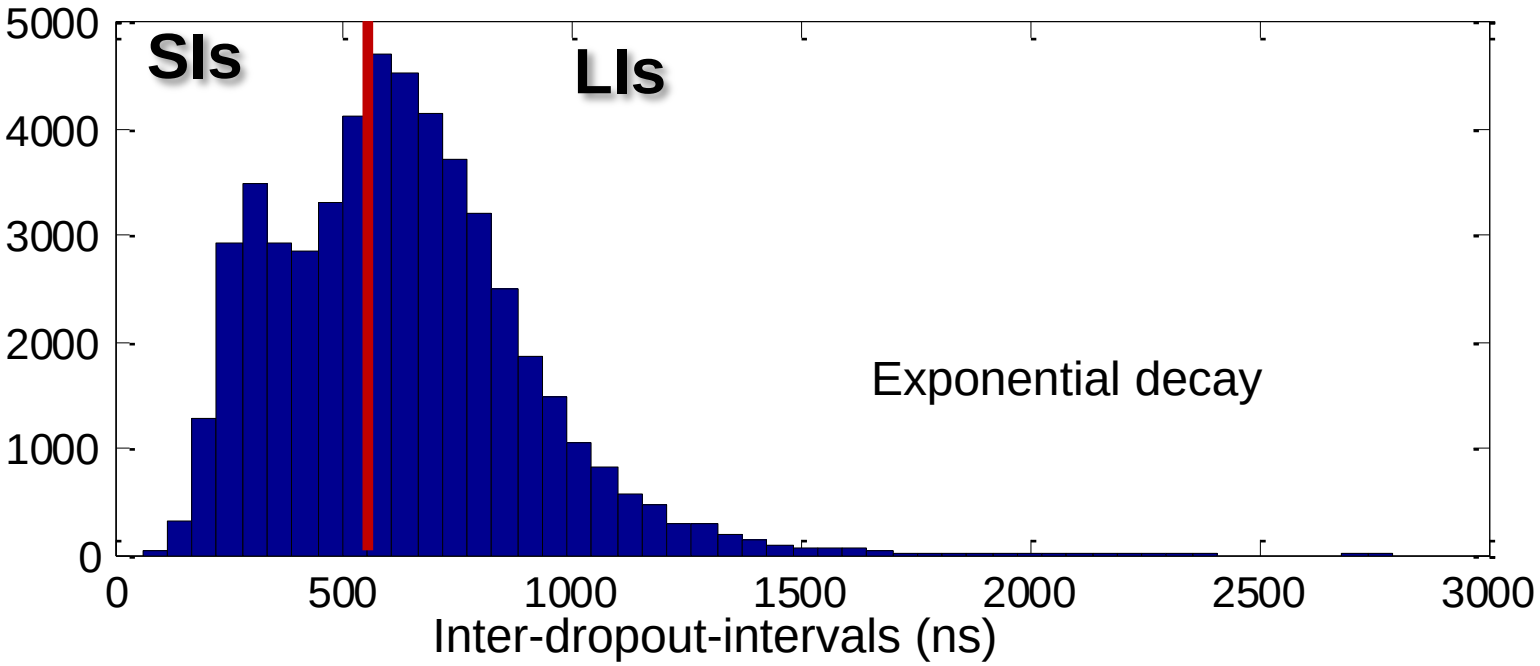
Surrogated data



Error bars computed with a binomial test, gray region is consistent with N.H.

Which dropouts are triggered by noise?

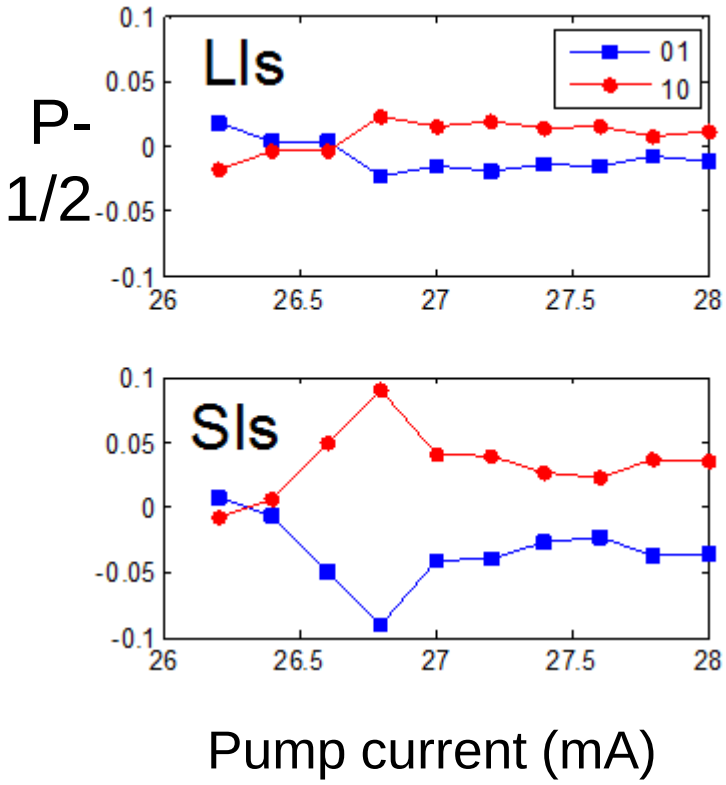
Histogram of Inter-dropout-intervals (IDIs)



We use a **threshold** to classify the inter-dropout-intervals as **short** and **long** intervals

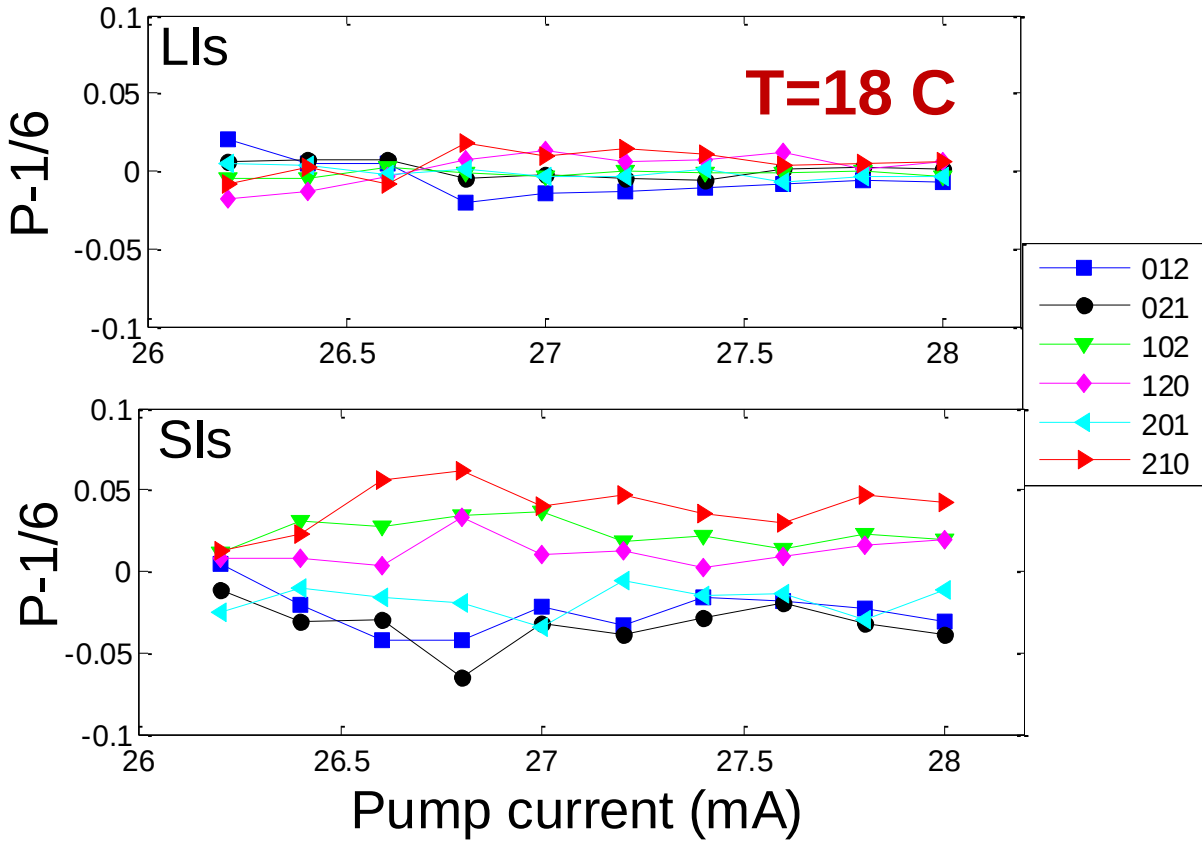
Constructing the words with 2 consecutive SIs or LIs

- At high currents: significant differences
  - LIs consistent with random events
  - SIs more deterministic.
- But at low currents, the spikes can not be classified in two types with significant differences.



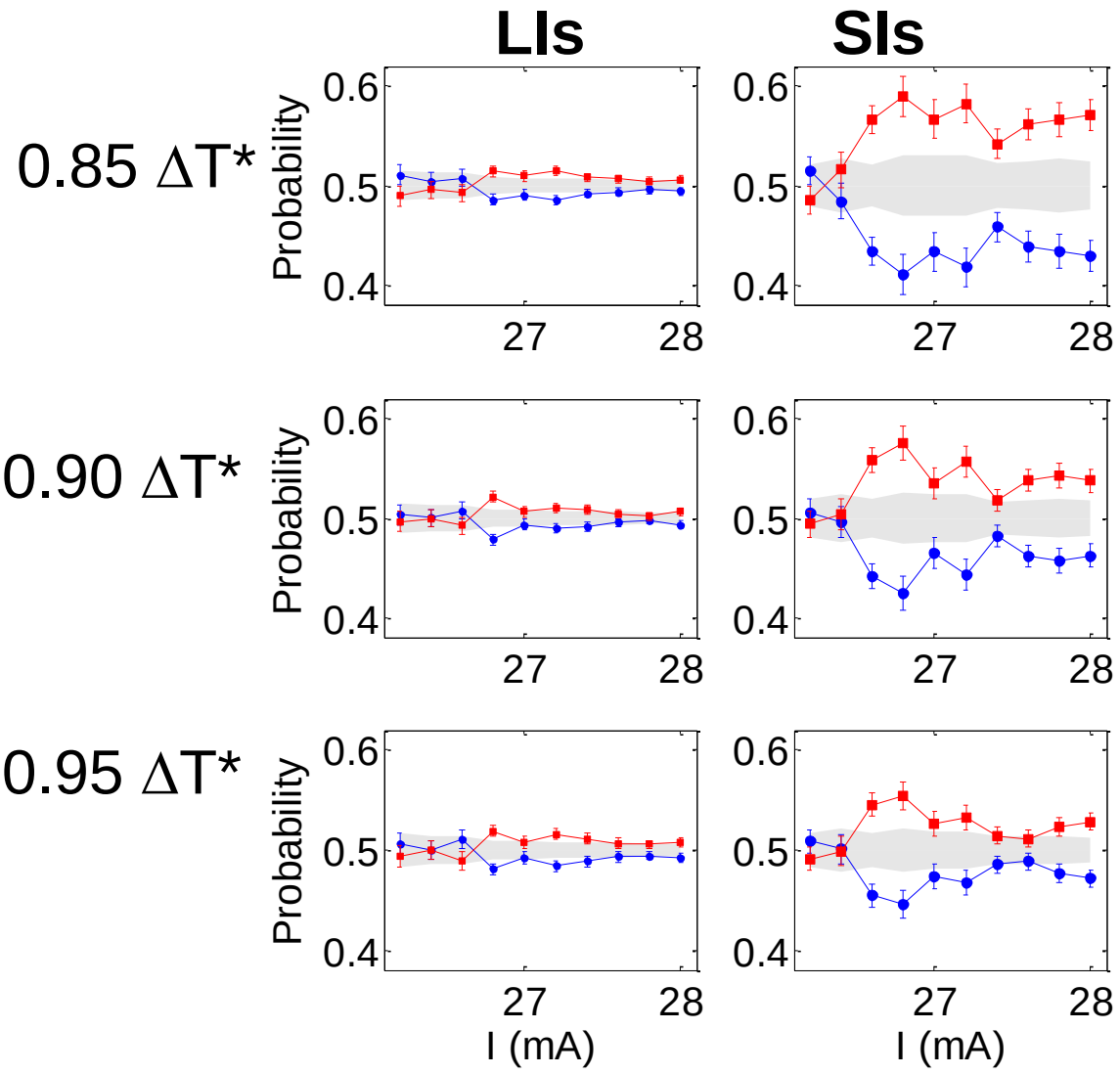
Constructing the words with 3 consecutive SIs or LIs

- At high currents: significant differences
- But at low currents, the spikes can not be classified.

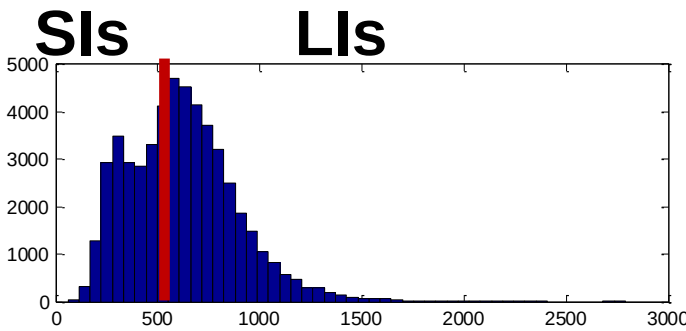


Similar results were obtained in the other dataset (**T=20 C**)

Influence of the threshold used to classify IDIs as LIs and SIs



ΔT*= most probable value



Error bars computed with a binomial test, gray region consistent with NH

Tips to chose a good threshold

- LIs have statistical features as close as possible to random events:
  - Exponential distribution of values
  - Uniform distribution of word probabilities

- Good statistics: there are enough consecutive LIs and SIs
  - The NH region is sufficiently narrow
  - For the LIs, the error bars are in the NH region
  - For the SIs, the error bars are out of the NH region.

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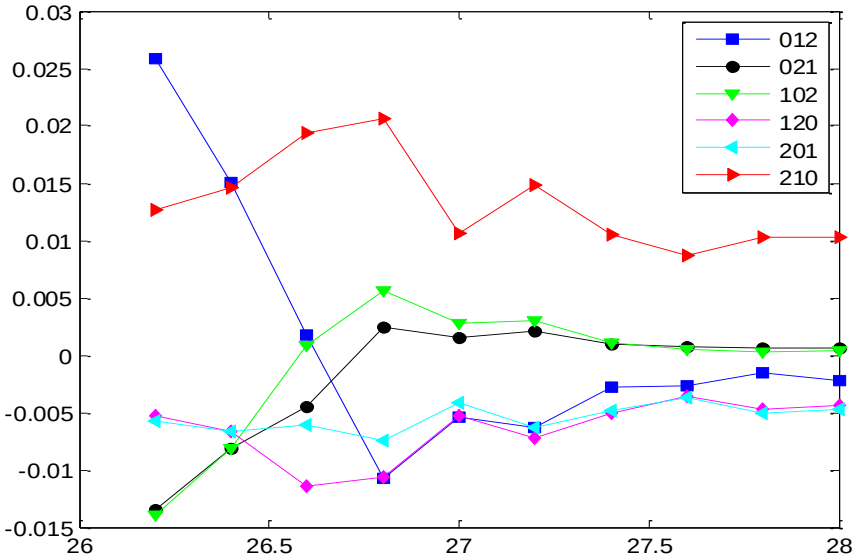
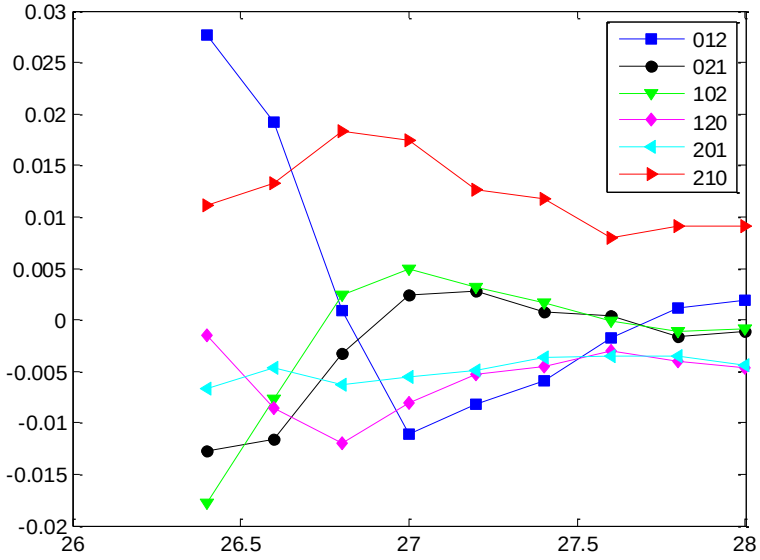
Ordinal analysis unveils new information

T=18 C



Pump current (mA)

T=20 C

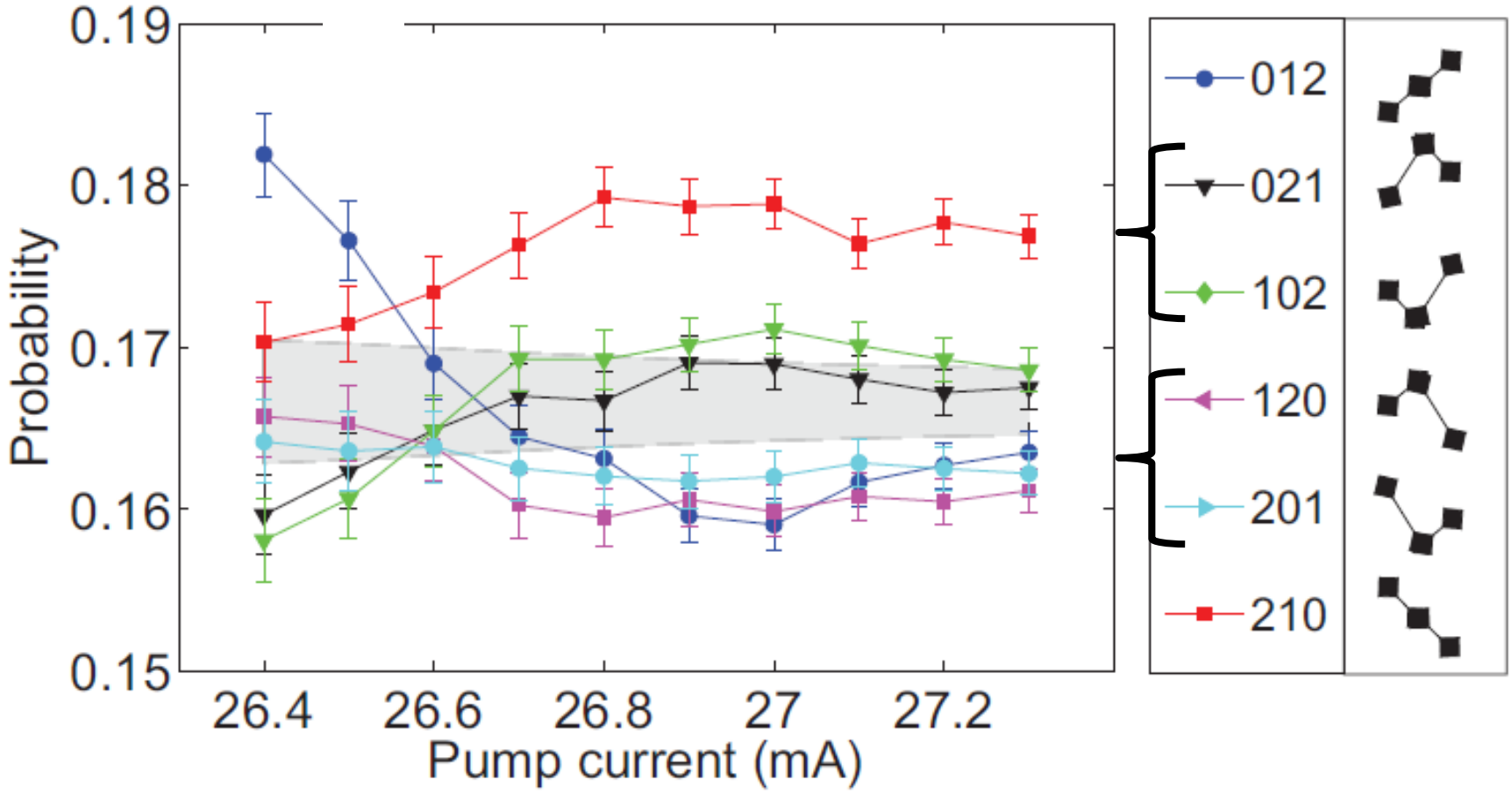


Pump current (mA)

P-1/6

There is a hierarchical and clustered organization of the probabilities of the words

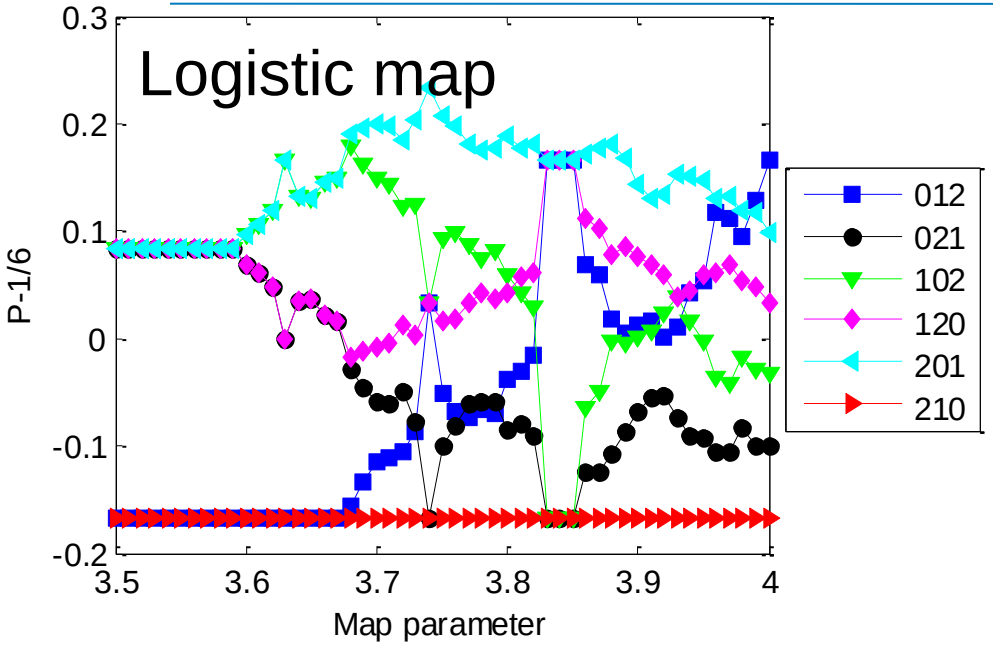
In another experiment: also the same hierarchy and the same 2 clusters

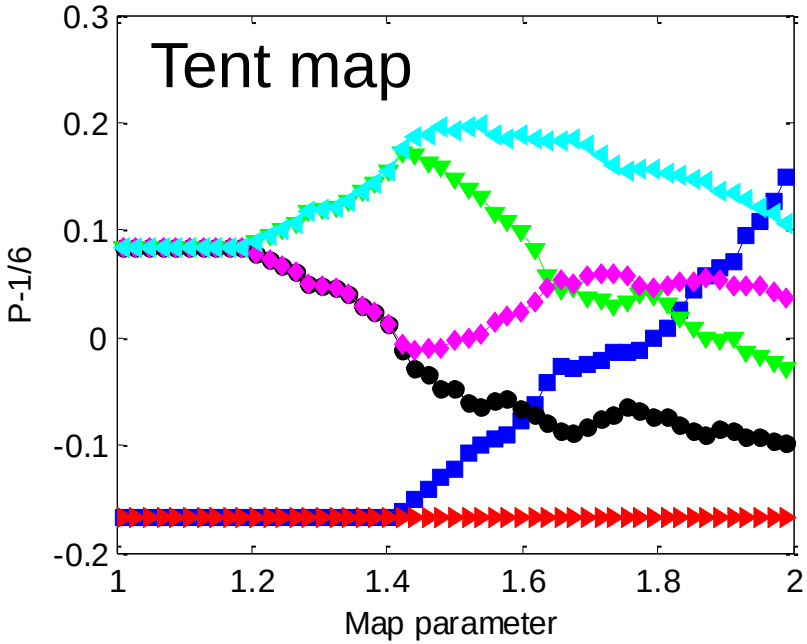


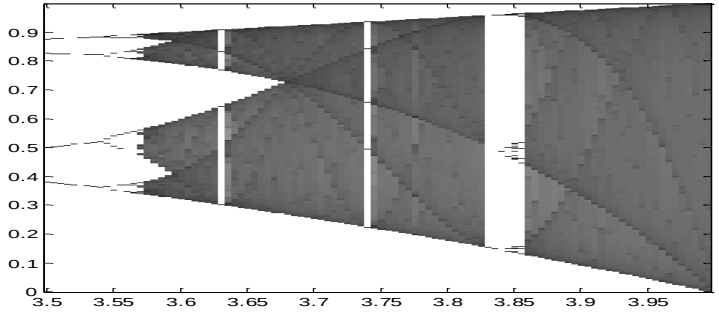
75,000 – 880,000 spikes
(different laser, new oscilloscope)

(Prof. Struzik't talk)

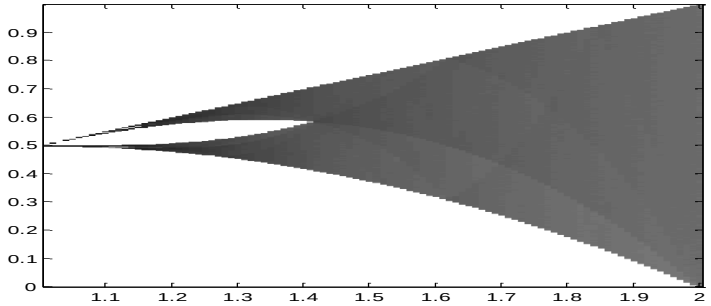
Can we find a minimal model that displays these features?







Map parameter



Map parameter

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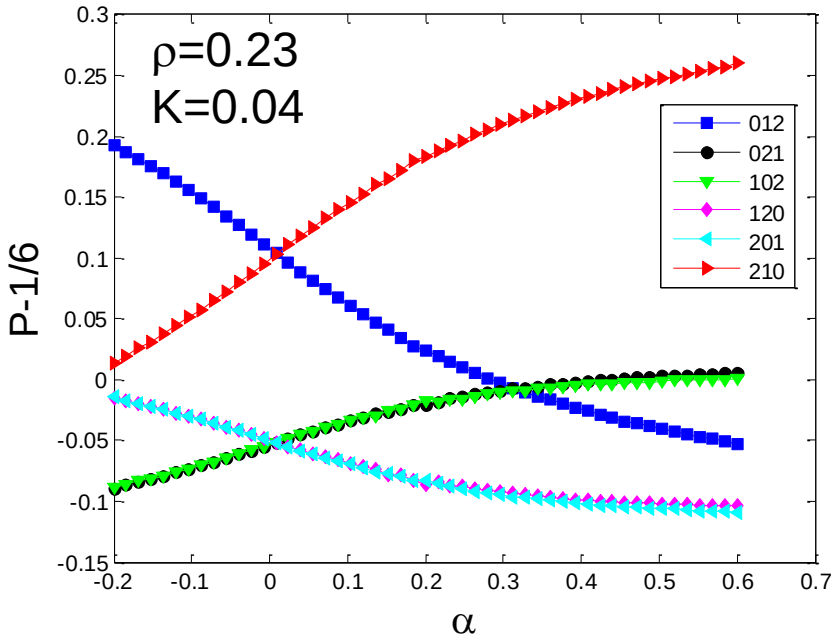
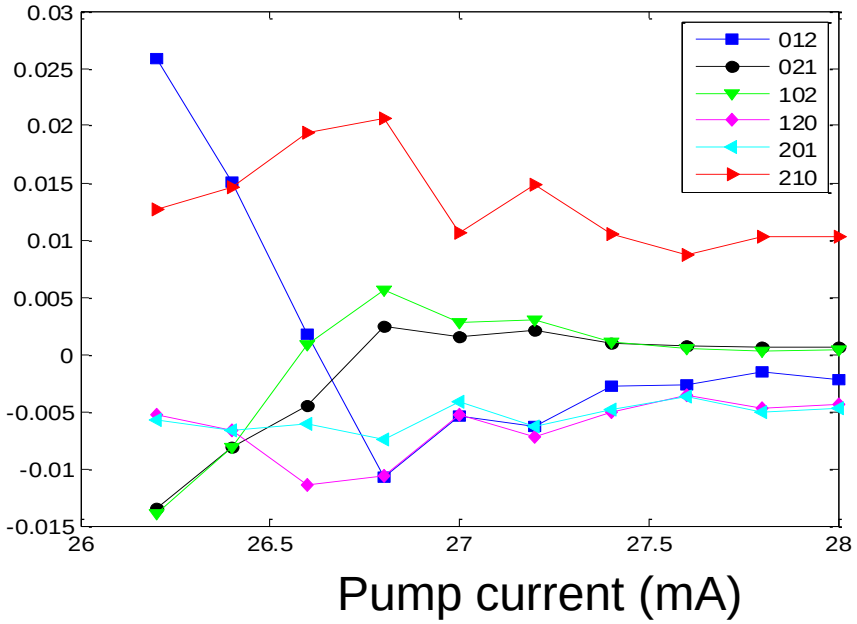
A modified circle map: minimal phenomenological model

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

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





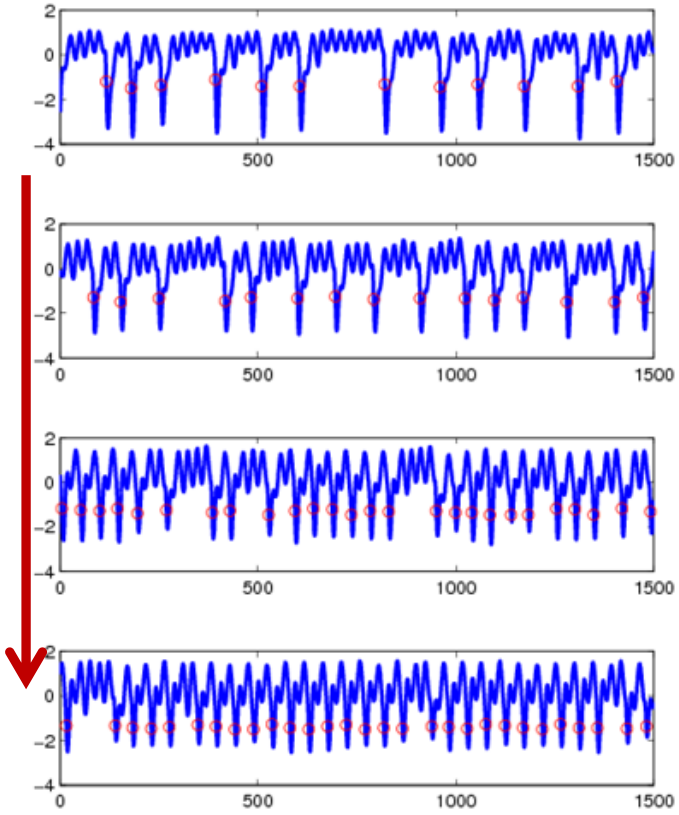
A. B. Neiman and D. F. Russell, *Minimal model for electroreceptors of paddlefish*, PRE 71, 061915 (2005)

Outline

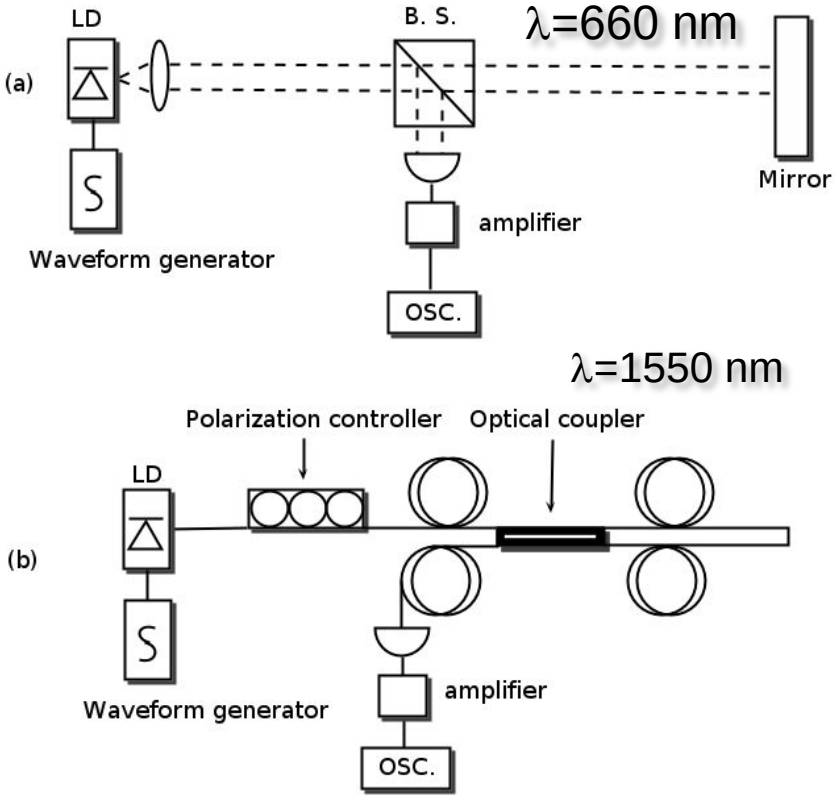
- Introduction
- Method of time-series analysis and experimental setup
- Results
  - Inferring signatures of determinism
  - Clusters in the symbolic dynamics
  - Response to external periodic forcing
- Conclusions and take home message

Response to external periodic modulation

Laser intensity:



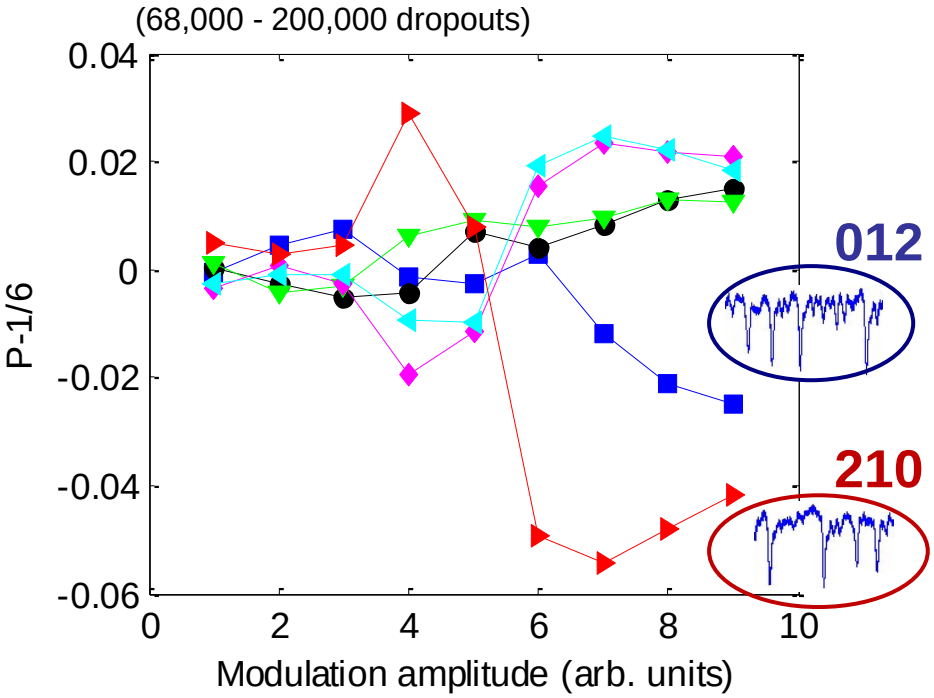
Two sets of experiments:



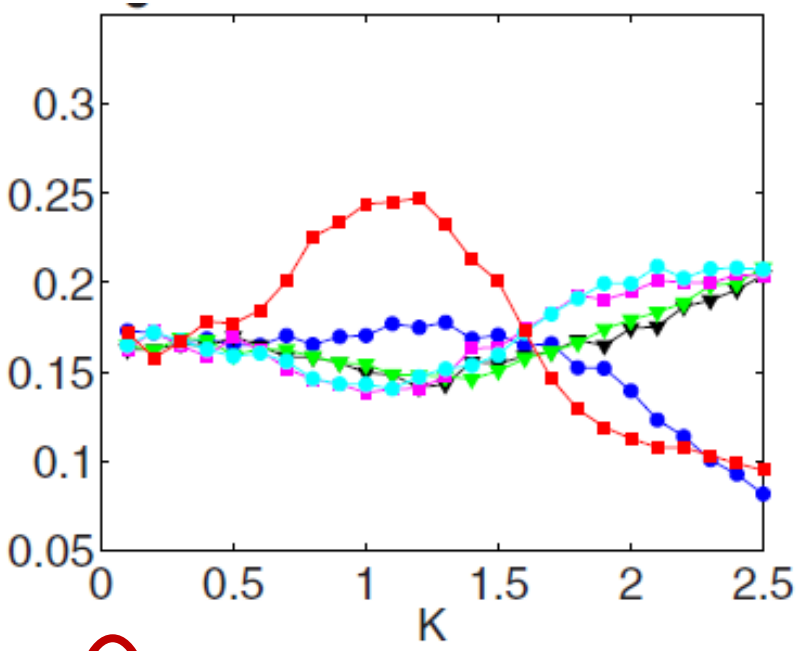
Relevant for understanding neuronal encoding of external stimuli

Experiment-model comparison

Experiments @ 660 nm



Minimal circle-map model



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

Similar observations @ 1550 nm

Interpretation: locking to external forcing

Outline

- Introduction
- Method of time-series analysis and experimental setup
- Results
- Conclusions and take home message

Conclusions

- Novel method for identifying signatures of determinism in complex time series.
- Spikes were classified in two categories: one stochastic; the other displaying signatures of determinism.

- We found new symbolic states with an hierarchical and clustered organization.
- We identified a minimal model. Robust under external forcing.

- Potential breakthrough: optical neurons for neuro-inspired information processing.
- Present work: towards understanding why the modified circle map is a good minimal model.

Take home message

- Ordinal analysis is a powerful method of symbolic time-series analysis

— useful for understanding data, uncovering patterns,

— for improving system modeling, model comparison, parameter estimation,

— for classifying data,

— for improving predictability and forecasting.

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Thanks to

You for your attention!

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Taciano Sorrentino

Carme Torrent

Papers @ www.fisica.edu.uy/~cris

- A. Aragoneses et al, Scientific Reports 3, 1778 (2013).
- A. Aragoneses et al, Scientific Reports 4, 4696 (2014).