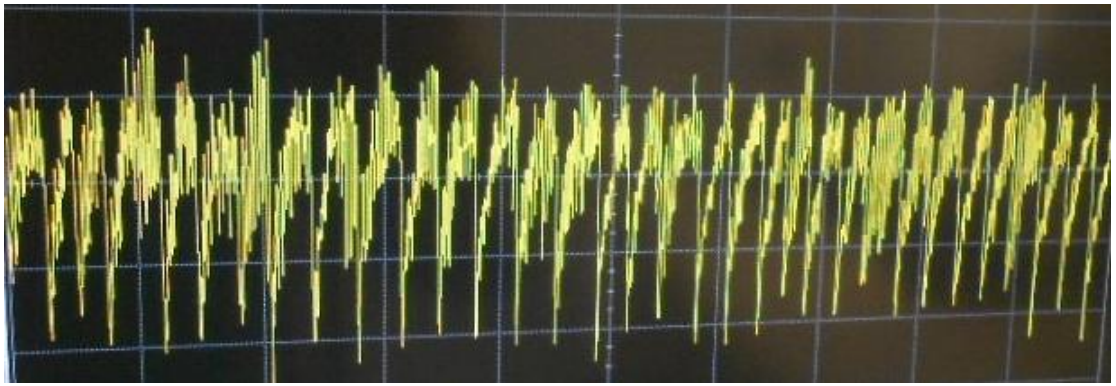

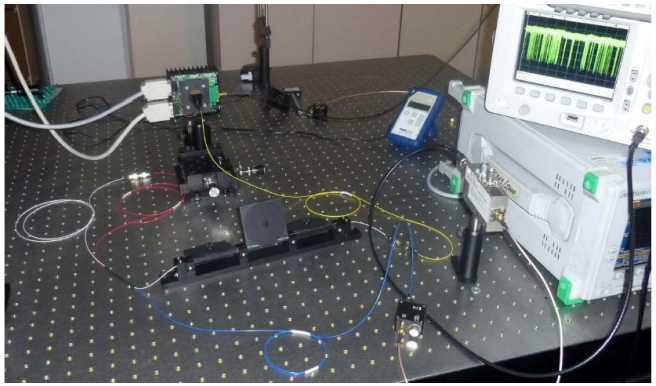

Inferring signatures of determinism in the LFF regime of semiconductor lasers with optical feedback

Cristina Masoller

www.fisica.edu.uy/~cris

UNIVERSITAT POLITÈCNICA DE CATALUNYA BARCELONATECH

Campus d'Excel·lència Internacional

VI Rio de la Plata Workshop on Laser Dynamics and Nonlinear Photonics, Montevideo, Uruguay, December 2013

Collaborators

- Andres Aragoneses

- Taciano Sorrentino

- Carme Torrent

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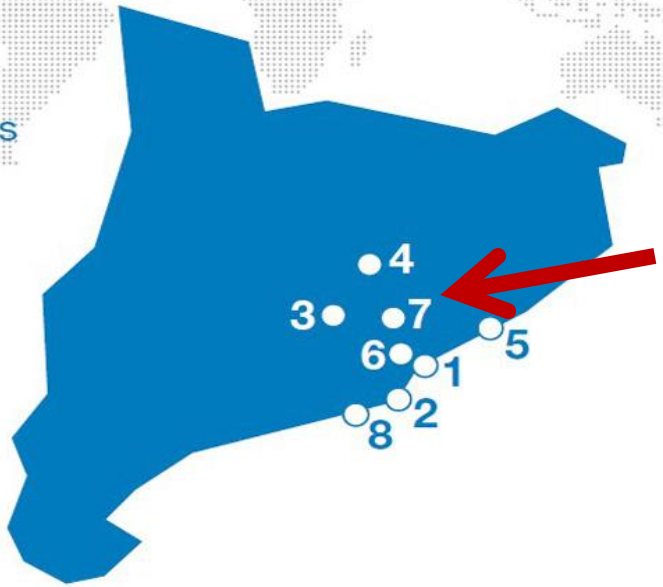
Where are we?

UPC Campus Terrassa

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



Gaia research Building

Viernes, 25 de septiembre de 2009 Diari de Terrassa

El edificio Gaia centraliza grupos científicos consolidados y emergentes.

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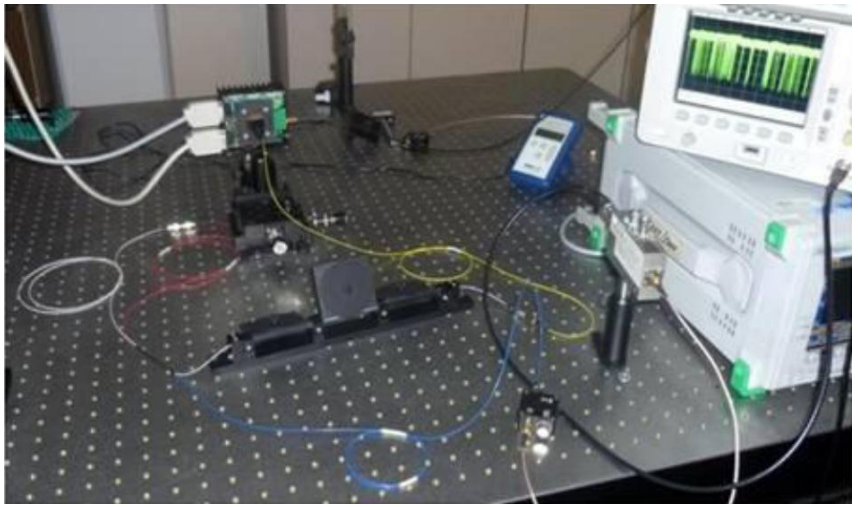
Nonlinear optics and laser dynamics research labs



Event level description of dynamical complex systems

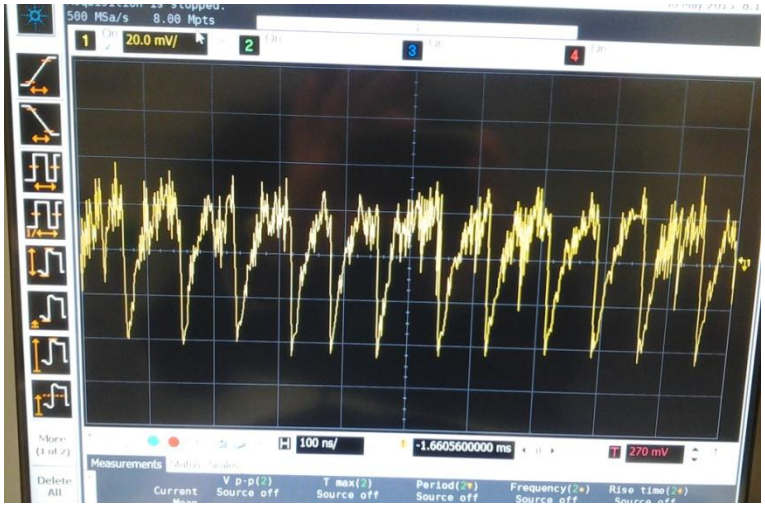
- Sequences of events generated by complex systems
  - **Intervals between threshold crossings and barrier crossings,**
  - **Neurons: inter-spike intervals (ISIs),**
  - **Human communication: inter-event user times (SMS, emails, Twitters).**
  - **Earth and climate: earthquakes, extreme events (tornados, rainfalls), etc.**
- Interplay of
  - **Different time scales, memory**
  - **Nonlinear, high dimensional & stochastic effects**
- The identification of patterns in the sequence of events can allow for
  - **Model verification, parameter estimation**
  - **Classification of different types of dynamical behaviors**
  - **Improving predictability and forecasting**

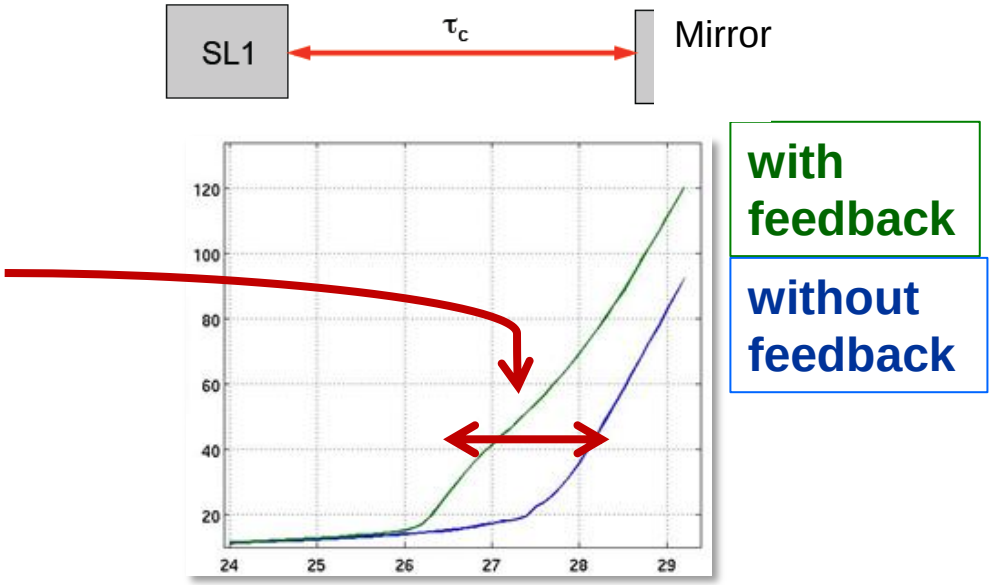
Outline

- Introduction: semiconductor lasers with feedback as high-dimensional & stochastic dynamical systems
- Method of time-series analysis and experimental setup
- Results. Experimental and model observations: inferring signatures of determinism + response to periodic forcing
- Conclusions and take home message

Semiconductor laser with optical feedback: optical spikes

- With optical feedback the laser **intensity** displays LFF dropouts similar to neuronal **spikes**.





- Complex interplay of:
  - Feedback delay time
  - Noise
  - Nonlineary

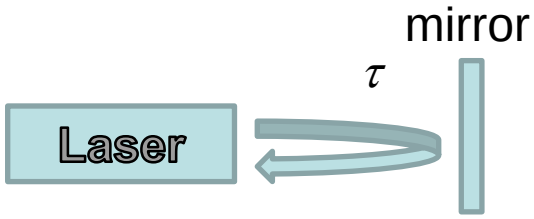
$\Rightarrow$ Stochastic and high-dimensional system

Goals

- To develop a method of time-series analysis that allows inferring signatures of determinism in the sequence of optical spikes;
- To extract new information;
- To compare model predictions with observations;
- 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

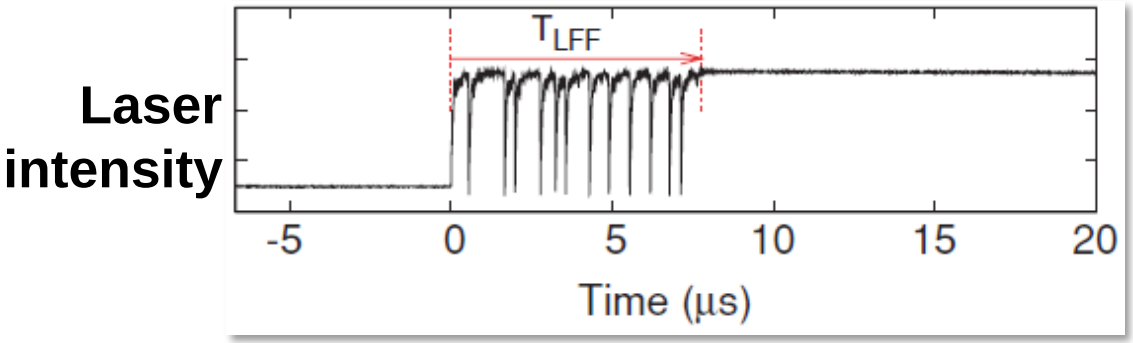
τ = feedback delay time

μ = pump current

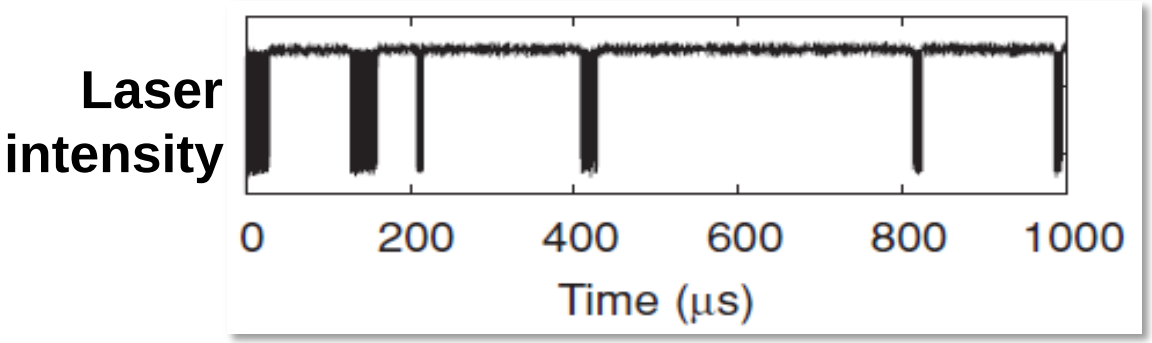
(control parameter)

Model predictions

- The dropouts are a **transient** dynamics.



- Burst of dropouts are triggered by **noise**.

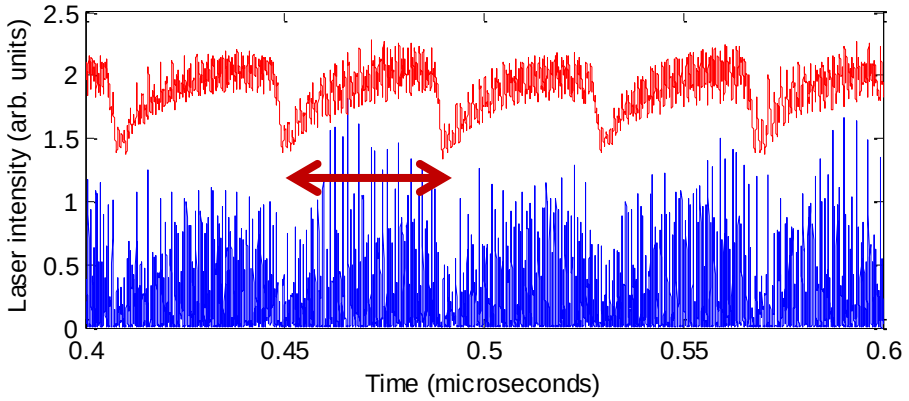


- In experimental sequences of dropouts: which ones are **deterministic** and which ones are **stochastic**?

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

Problems

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



- Approach: event-level description. We study the sequence of **inter-dropout-intervals**: $\Delta T_i = t_{i+1} - t_i$

Outline

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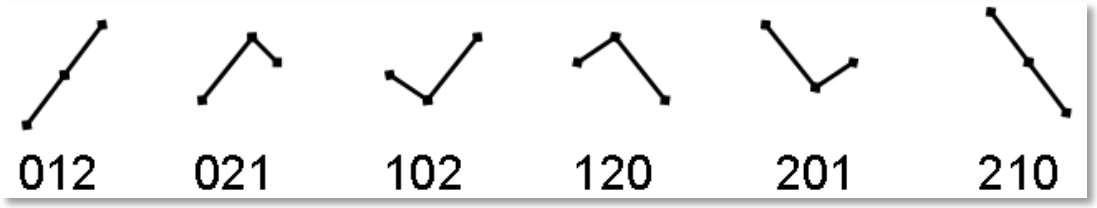
Symbolic ordinal analysis

- It has been used to analyze data generated from 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 dynamical behaviors (pathological, healthy)**
  - **Quantify complexity**
  - **Identify coupling and directionality.**

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

Ordinal Patterns (or "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 orders

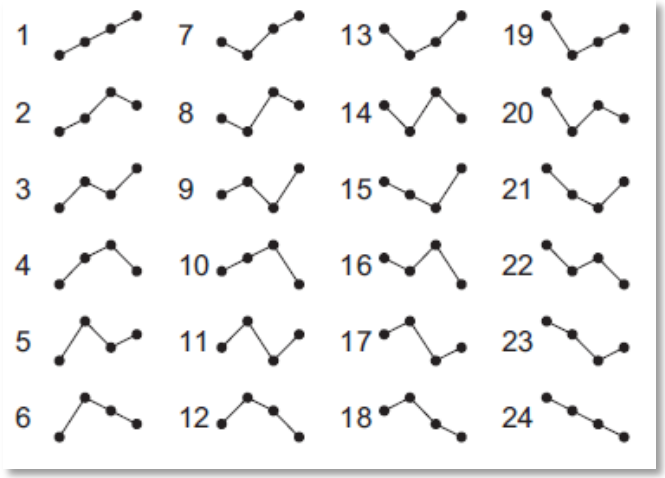


Example: the set (5, 1, 7) gives "102" because 1 < 5 < 7

- Advantage: the transformation keeps information about correlations in the time-series & does not need a threshold
- Drawback: it does not keep information about the values, the set (5,1,100) also gives word "102".

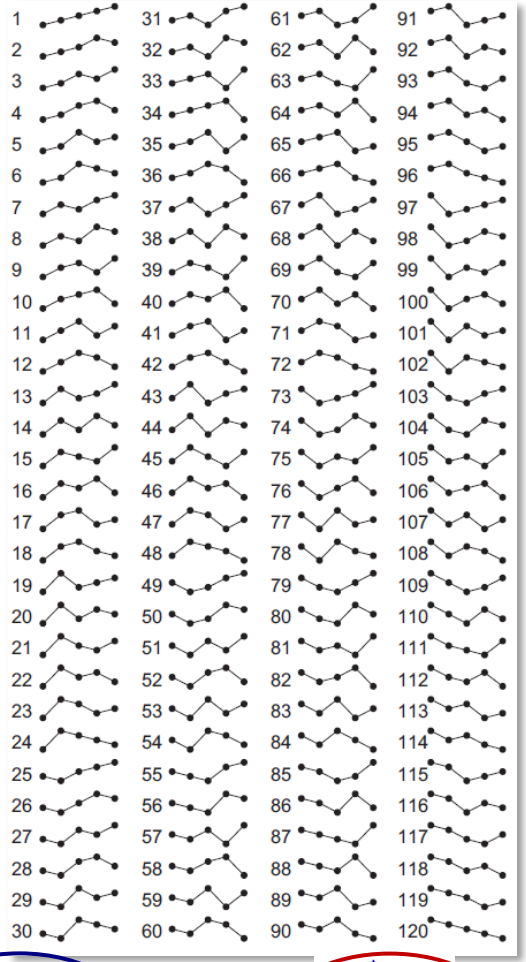
Number of possible ordinal patterns: D!

D=4

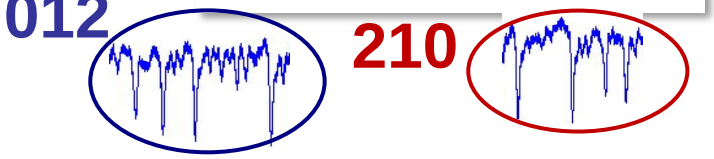


U. Parlitz et al. / Computers in Biology and Medicine 42 (2012) 319–327

D=5



- 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) unveil correlations of 3 (4) spikes



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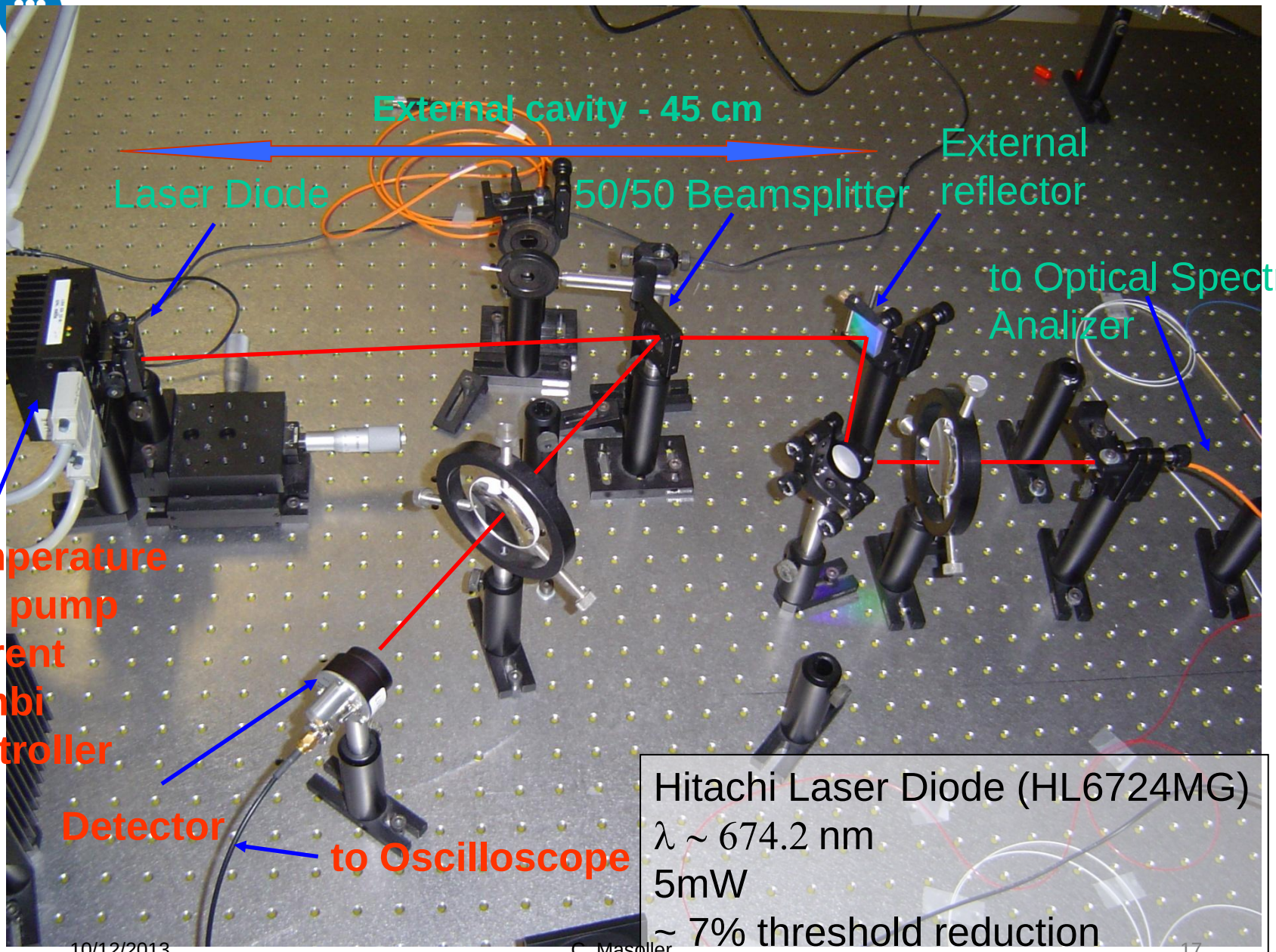


Hitachi Laser Diode (HL6724MG)
$\lambda \sim 674.2$ nm
5mW
~ 7% threshold reduction

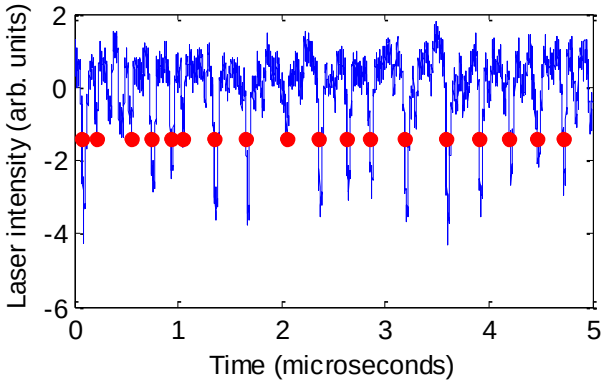
Experimental inter-dropout-intervals (IDIs in lasers – ISIs neurons)

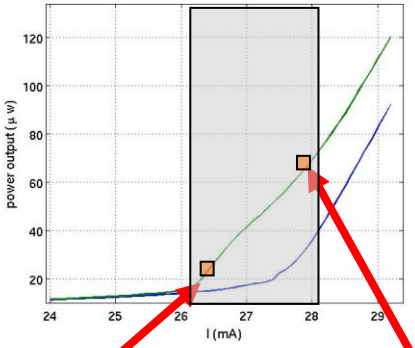
Laser output → (1 GHz oscilloscope)

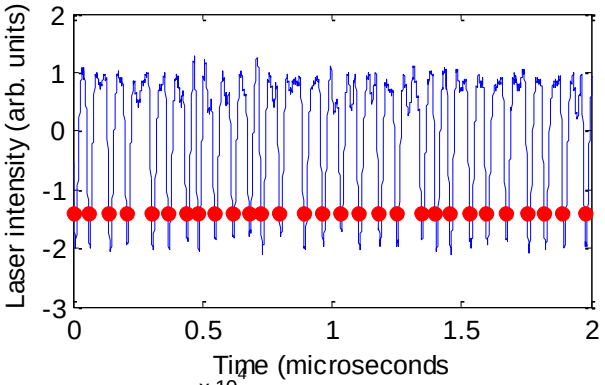
$\langle \Delta T \rangle$ = 100-200 ns
$\tau \sim$ 5 ns

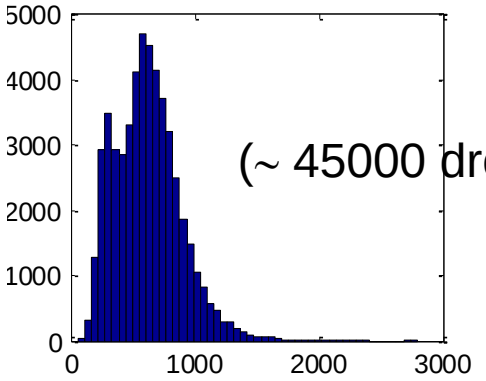
# of IDIs recorded
45,000 - 220000

IDI distributions



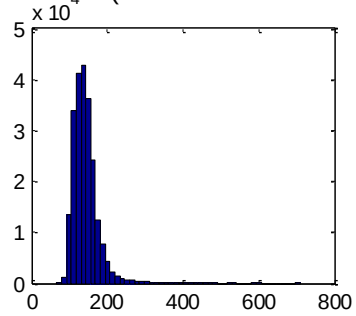






(~ 45000 dropouts)

(~ 225000 dropouts)



Is there any **information** in the 'spike' sequence?

Analogous to deciphering a foreign text.

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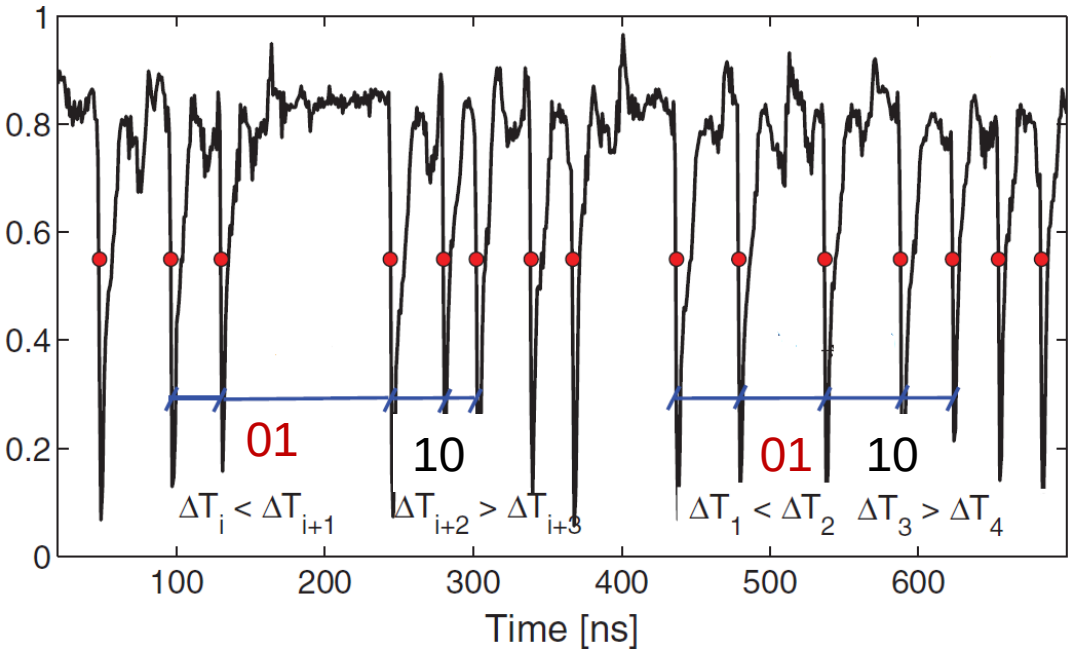
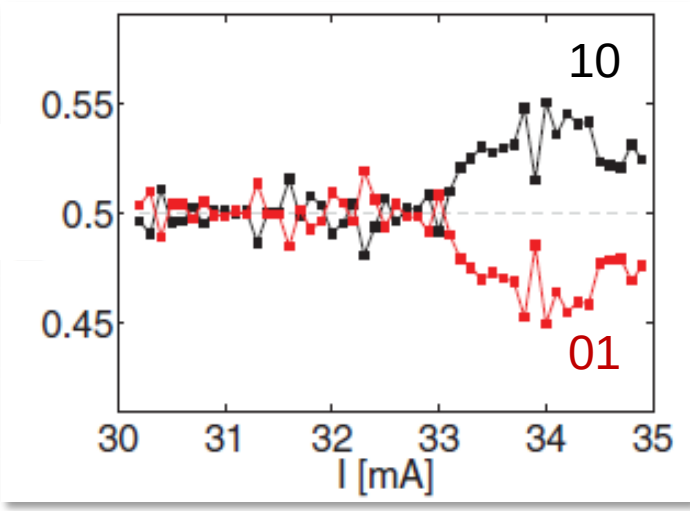
Correlations between 3 consecutive spikes: probabilities of 01 & 10



Probabilities:



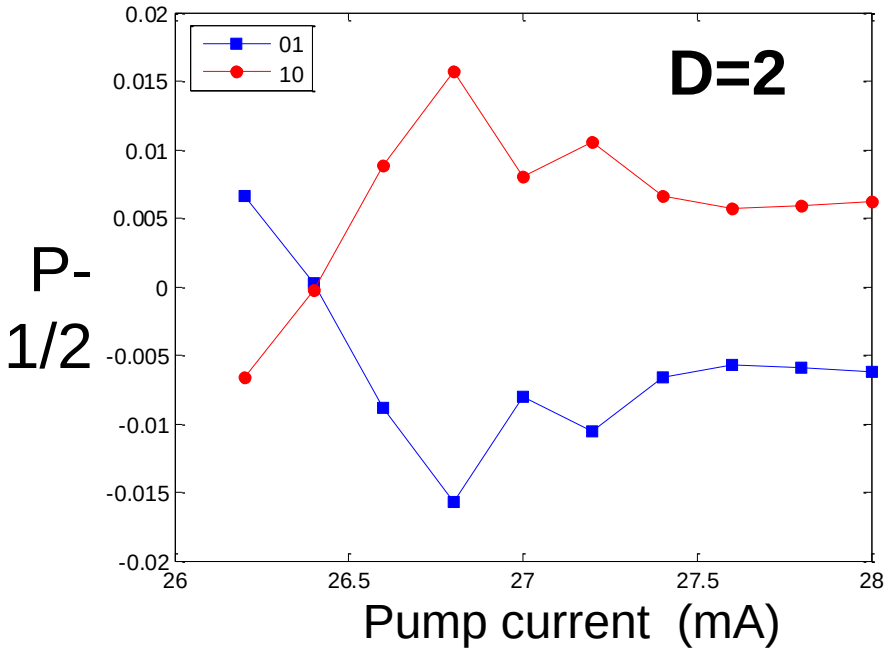
D=2: 3-spike correlations?

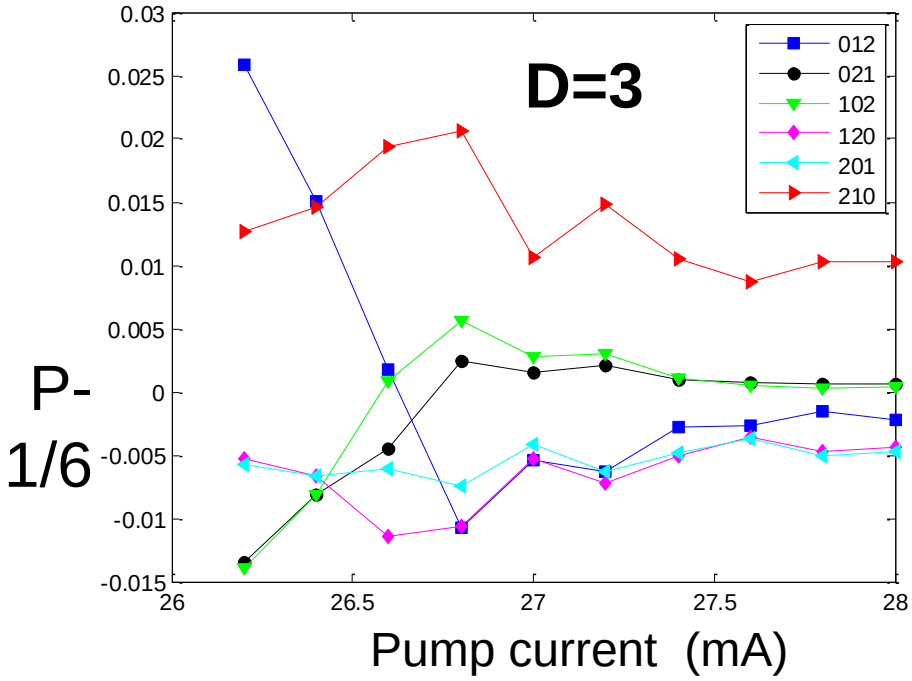
Null hypothesis: fully random sequence of spikes $\Rightarrow$ P(01) = P(10)

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

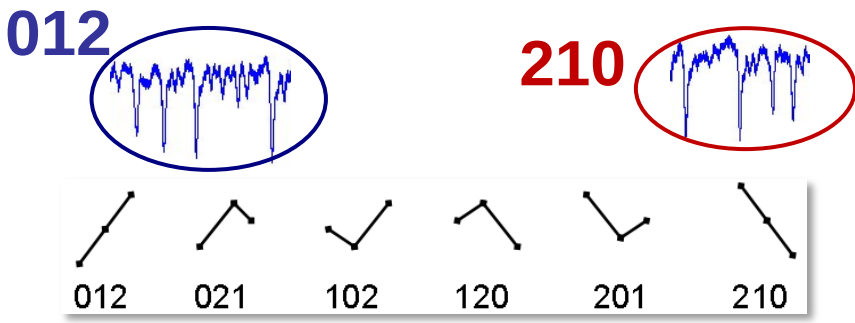
N. Rubido et al, Phys. Rev. E 84, 026202 (2011)

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



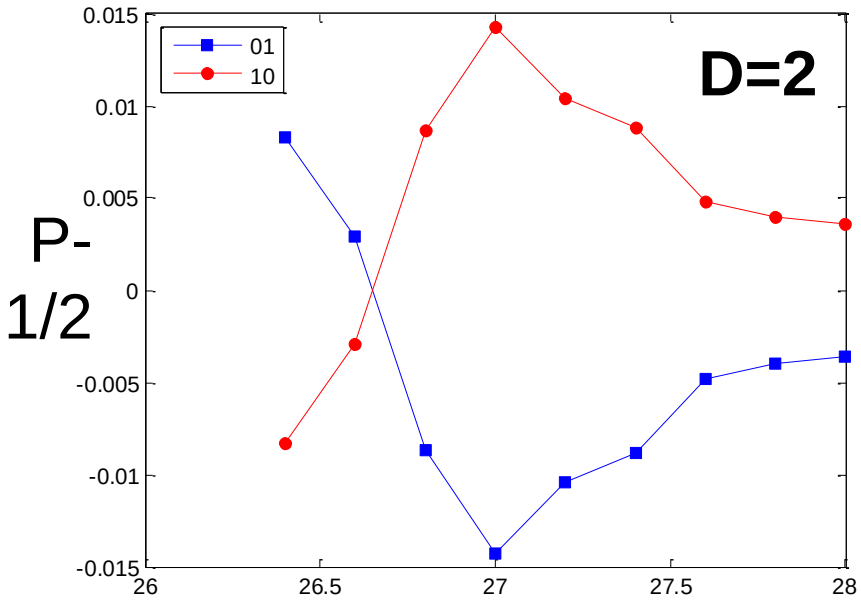


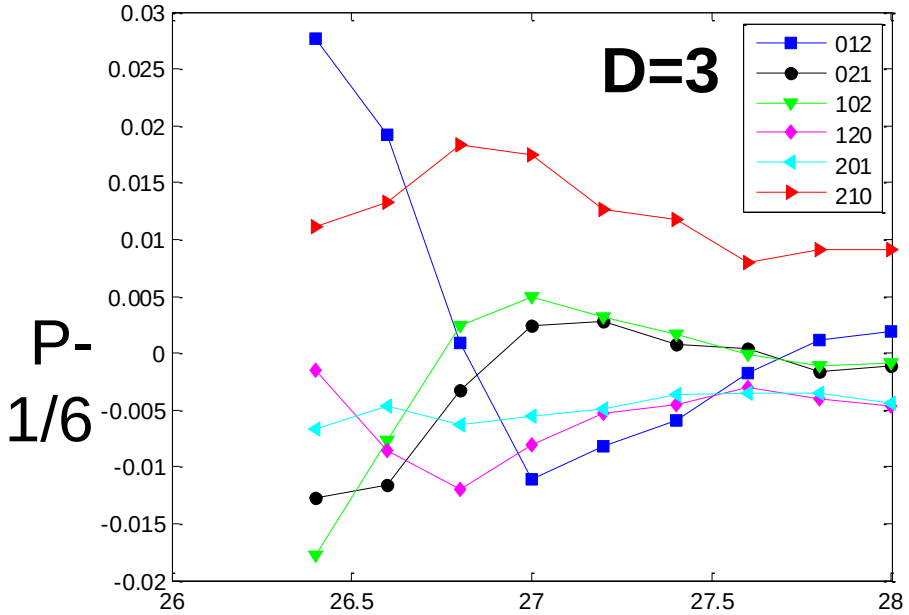
45000 - 220000 IDIs

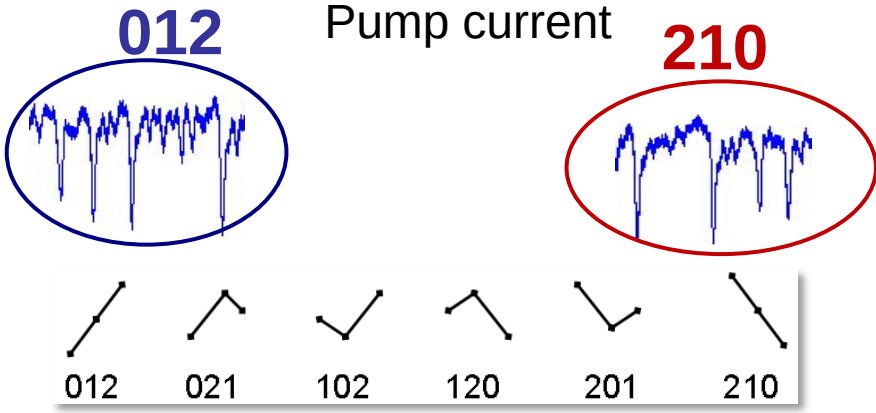


A. Aragoneses, N. Rubido, J. Tiana, M. C. Torrent and C. Masoller, Scientific Reports (2013)

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

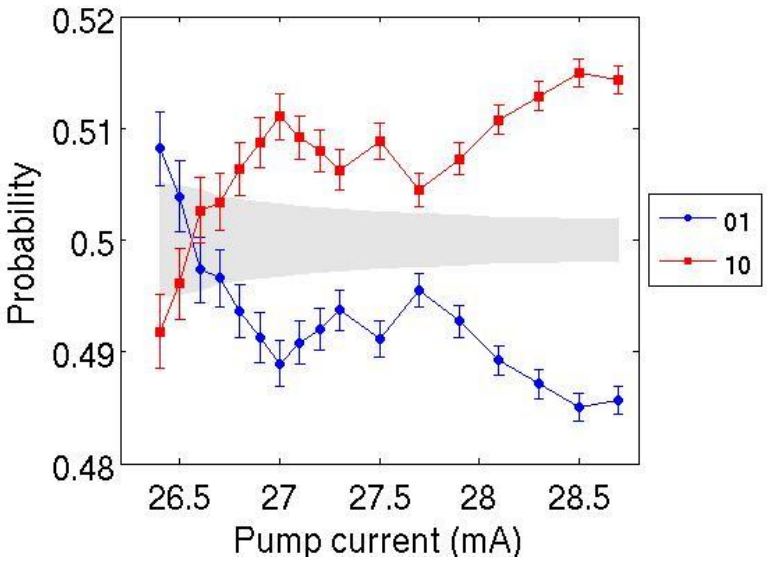




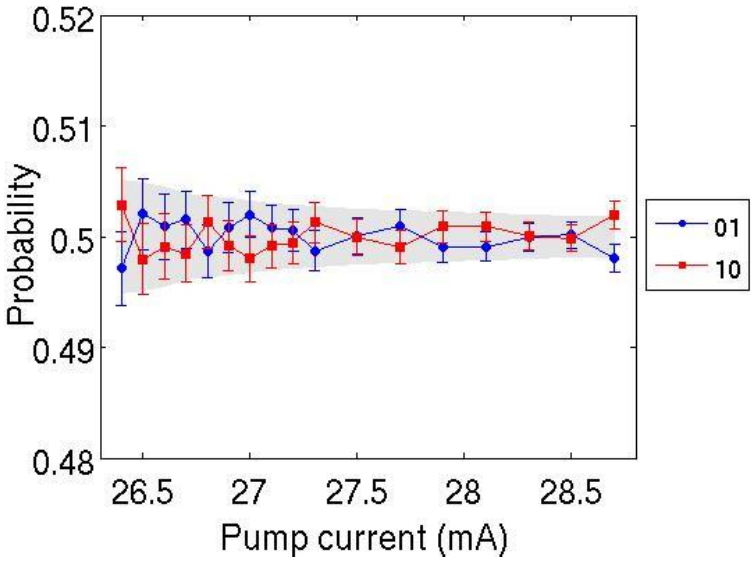


Are the deviations from the null hypothesis significant?

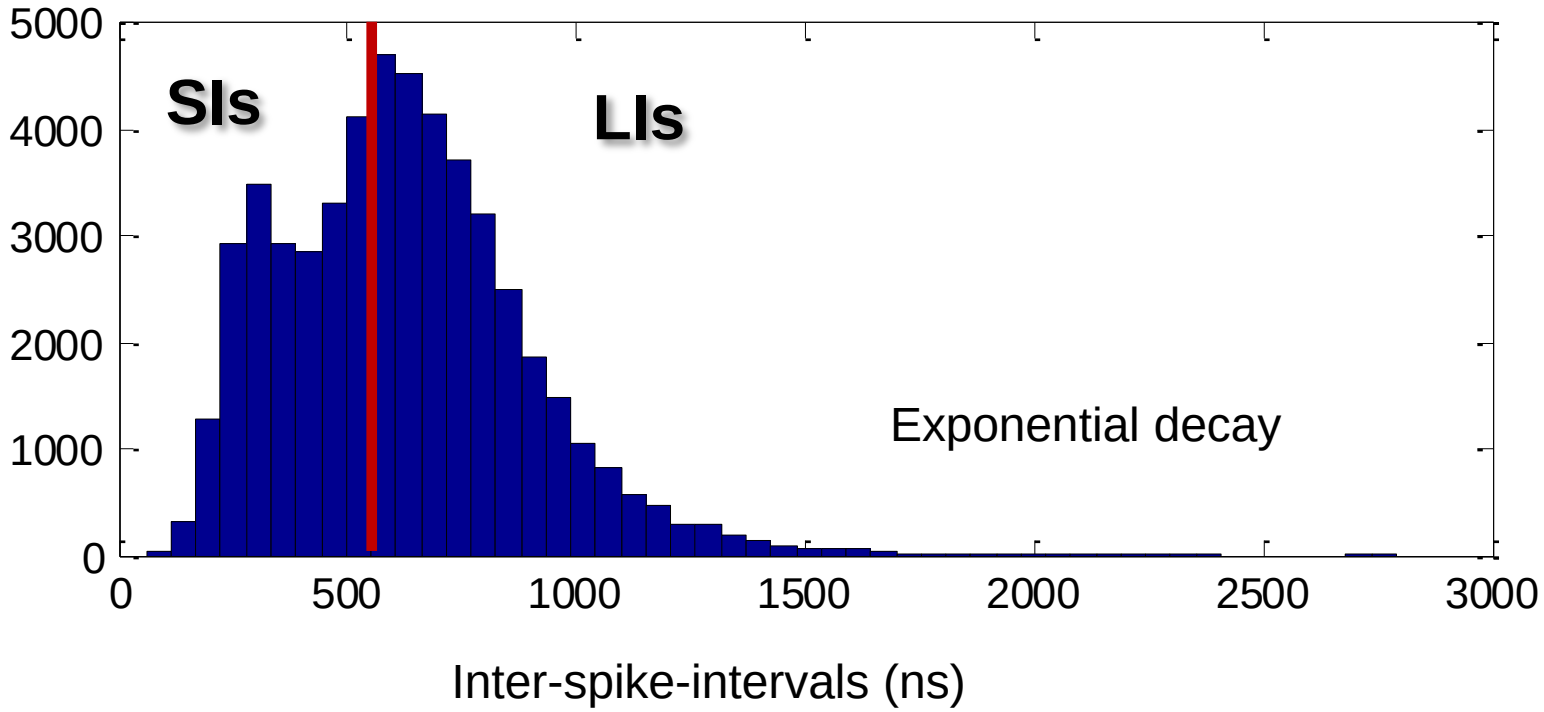
Recorded data



Surrogated data



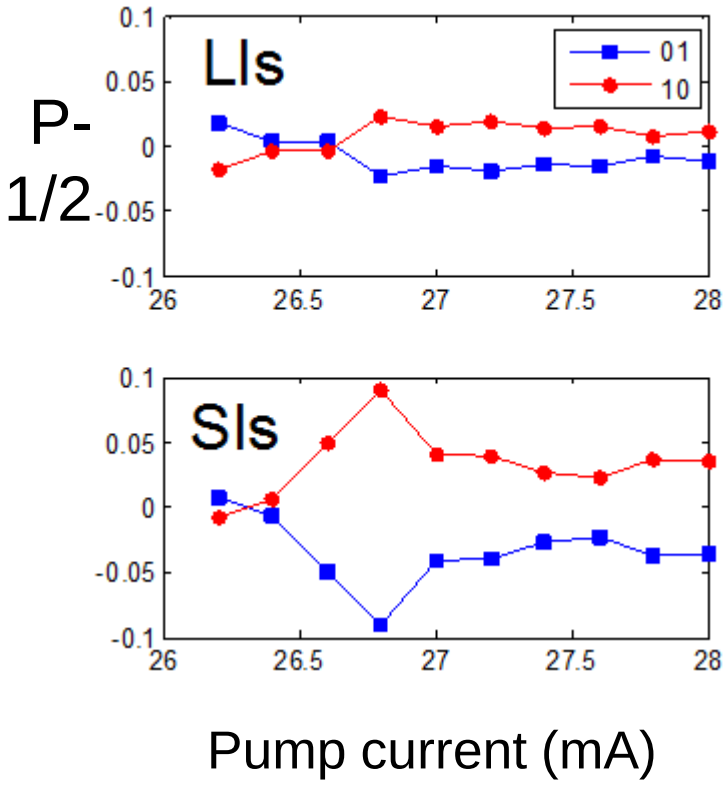
Which dropouts are noise-induced and which ones are deterministic?



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

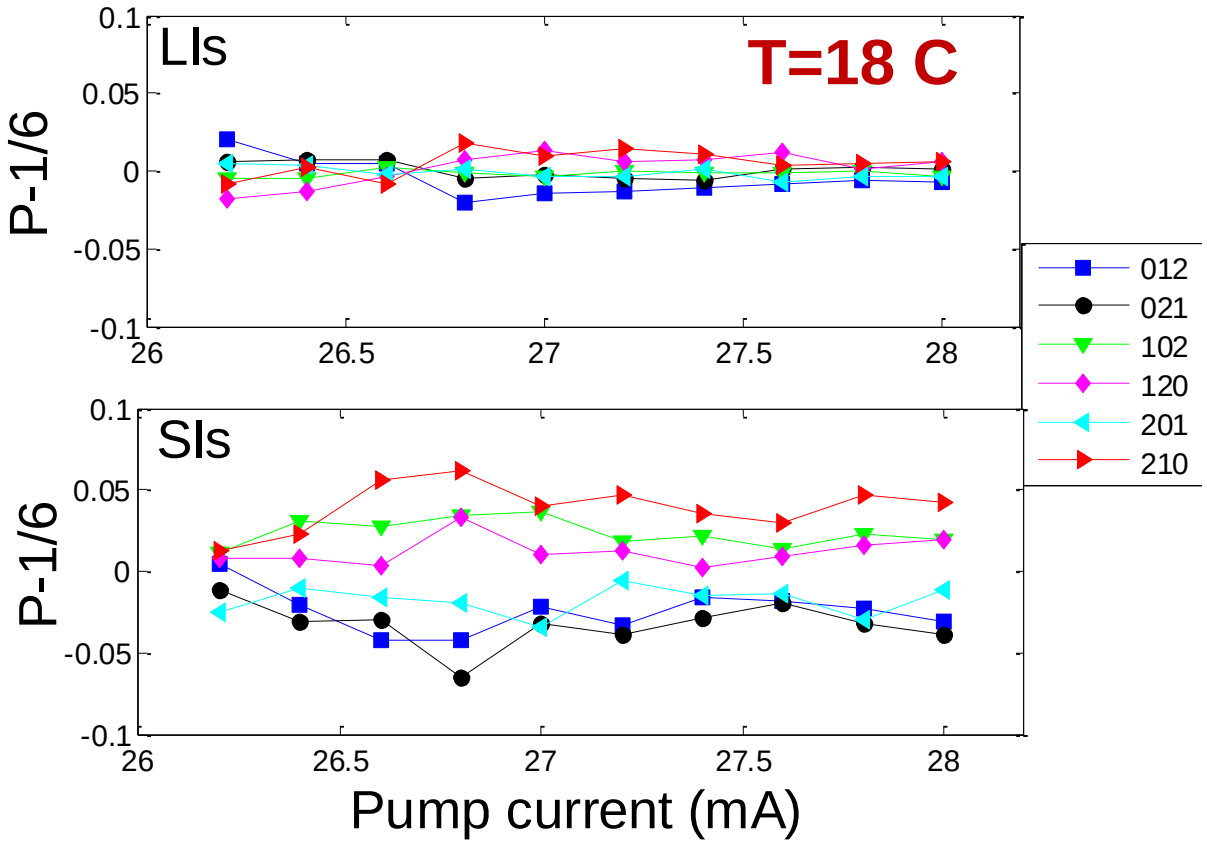
Constructing the words with 2 consecutive SIs or LIs

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

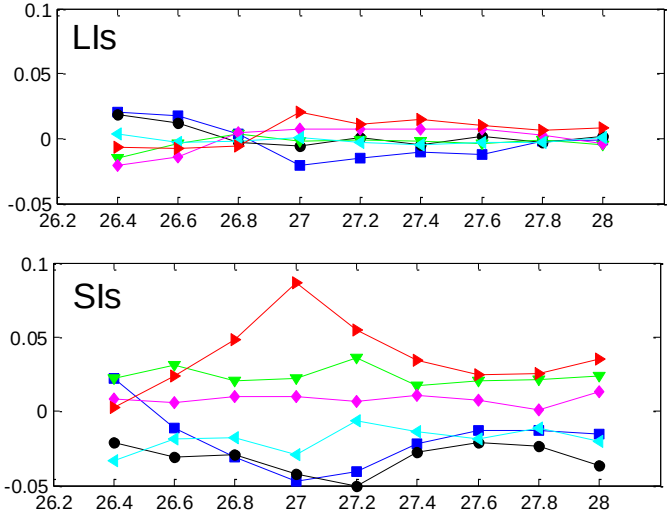


A. Aragoneses, N. Rubido, J. Tiana, M. C. Torrent and C. Masoller, Scientific Reports (2013)

Constructing the words with 3 consecutive SIs or LIs



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



At high pump currents an adequate threshold allows classifying the events in two distinct categories

Press attention

ÚLTIMA HORA **España se medirá con Holanda, Chile y Australia en el Mundial**

Investigadores de la UPC de Terrassa crean un nuevo método para identificar el orden dentro de sistemas caóticos complejos

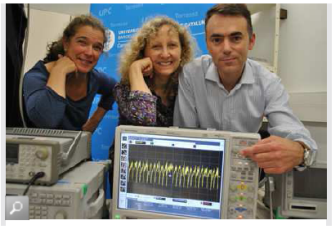
La técnica se podría utilizar para estudiar el comportamiento de las redes sociales, los terremotos o de la actividad neuronal

Miércoles, 26 de junio del 2013 - 13:58h.

Comentarios (2) Votos: +5 -0 Like 34 Twittear 4 Seguir +1 0

J. S. / Terrassa

En la película **'Contact'** (1997), protagonizada por **Jodie Foster**, el **equipo** de **científicos** que averiguan el origen y el significado de unas **señales acústicas** extraterrestres acaban por **descubrir** que detrás del **ruido** y de la frecuencia temporal de los **sonidos** escondían camufladas, entre un supuesto **caos**, imágenes de la Historia Contemporánea y los planos de una misteriosa esfera.



Cristina Masoller, Carme Torrent y Andrés Aragoneses, parte del equipo de la UPC de Terrassa que ha creado un nuevo método para identificar el orden dentro de sistema caóticos complejos UPC TERRASSA

Recientemente, y en la ciencia real, un equipo de investigadores del grupo de investigación Dinámica no Lineal, Óptica no Lineal y Láseres (DONLL) de la **Universitat Politècnica de Catalunya·BarcelonaTech** (UPC) en el Campus de **Terrassa** y de la **Universidad de Aberdeen** han conseguido con una nueva metodología mucho más sencilla que las que se utilizaban hasta ahora, separar el orden del caos. El trabajo se ha publicado en la prestigiosa revista **'Scientific Reports'**.

Los investigadores han desarrollado un método muy accesible, tanto desde el punto de vista conceptual

La UPC crea un sistema para distinguir el orden del caos

La técnica podría ser útil en medicina y redes sociales

Redacción

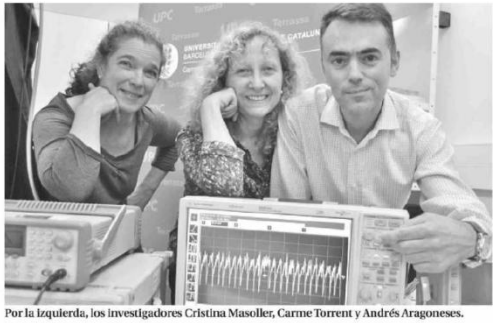
Un equipo de investigadores del campus de la Universitat Politècnica de Catalunya (UPC), junto con científicos de la Universidad de Aberdeen de Escocia, han desarrollado un nuevo método, basado en la escala temporal, con el que se puede distinguir comportamientos ordenados dentro de secuencias caóticas. El trabajo se ha publicado en la revista de referencia "Scientific Reports".

Los científicos han conseguitificado el grupo de inestabilidades que se manifiesta con una distribución aleatoria y de otro, el grupo de inestabilidades con una fase de secuencias y una estructura nítida.

Los investigadores de la UPC que han llevado a cabo el trabajo son Andrés Aragoneses, Cristina Masoller y María Carme Torrent, del grupo de Dinàmica no Lineal, Óptica no Lineal y Làsers (DONLL); y Jordi Tiana-Alsina, del departamento de Teoria del Señal y Comunicaciones. Ambos han minar unas estabilidades de las obras se basa en la escala temporal. El orden escondido provoca que las inestabilidades inducidas estén más juntas que las que están producidas de forma aleatoria por el ruido. De hecho, nuestro método puede predecir que alteraciones están producidas por el ruido y cuáles inducidas".

EJEMPLOS PRÁCTICOS

Sobre ello ha explicado que "es lo mismo que detectar una melodía suave y tenue en medio

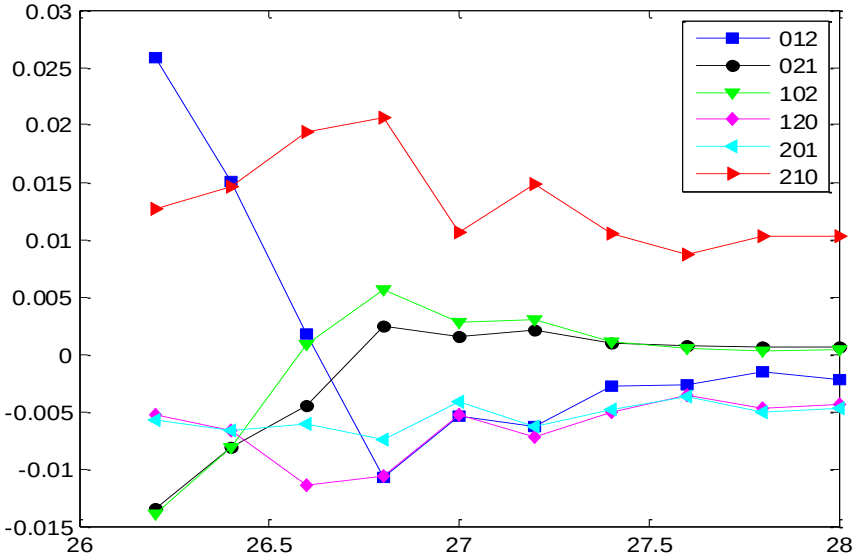


Por la izquierda, los investigadores Cristina Masoller, Carme Torrent y Andrés Aragoneses.

FP_BI_noticia_canal_terrassaa.wmv

Ordinal analysis unveils new information

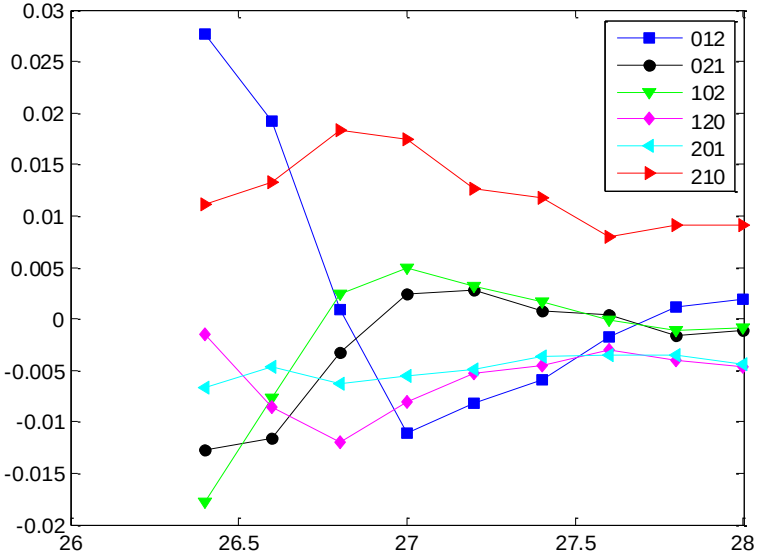
T=18 C



P-1/6

Pump current (mA)

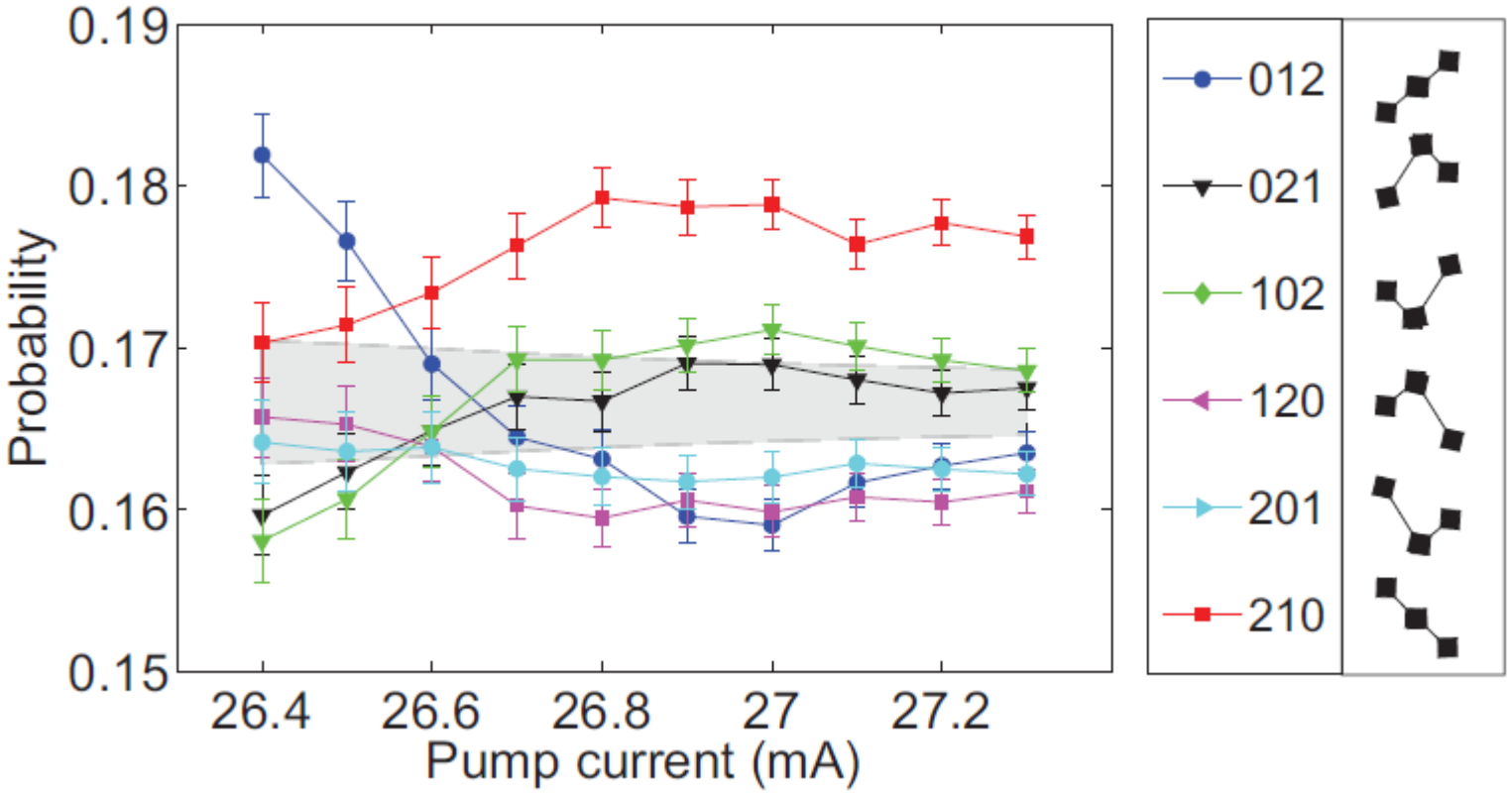
T=20 C



Pump current (mA)

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

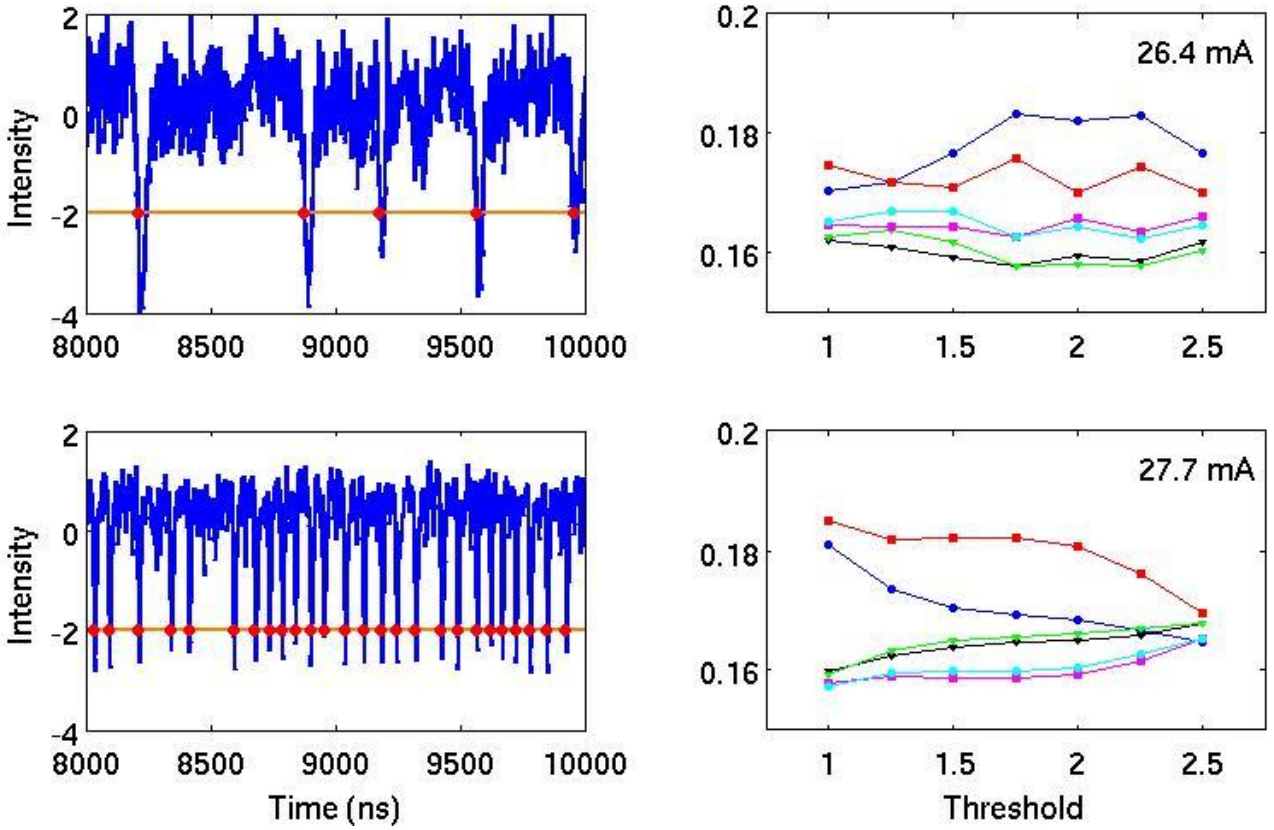
In another experiment: also the same hierarchy and the same 2 clusters



75,000 – 880,000 dropouts

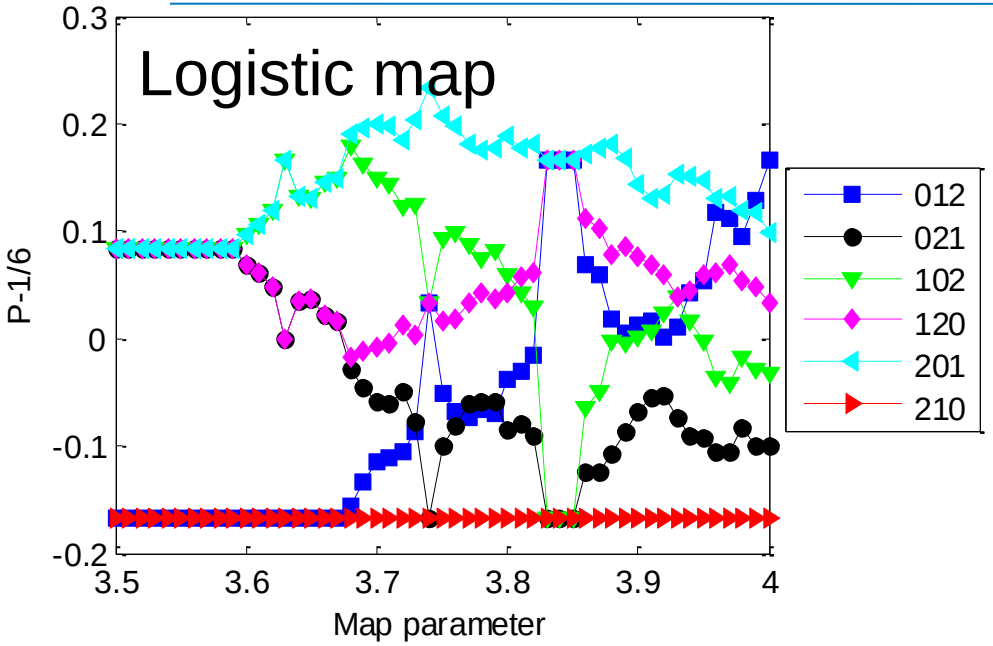
(different laser, new oscilloscope)

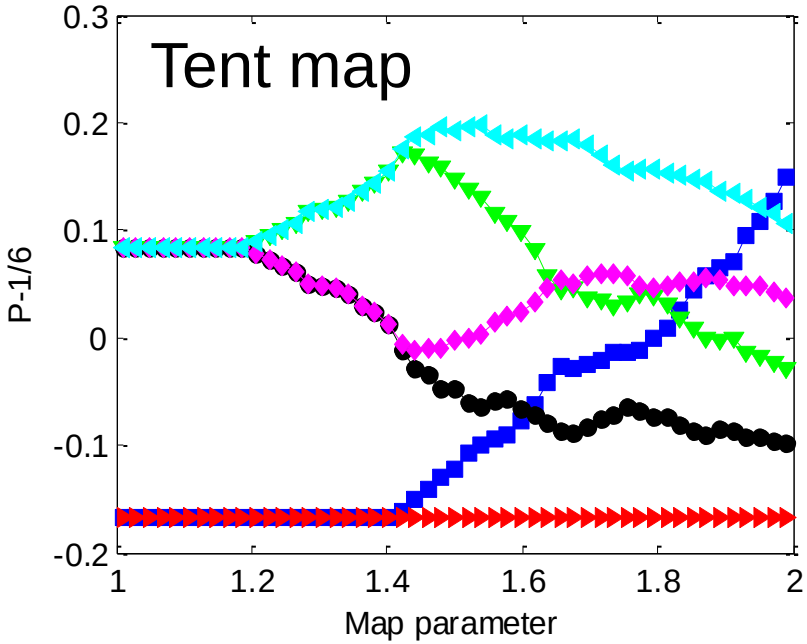
Sensitivity to the threshold that defines the event times?

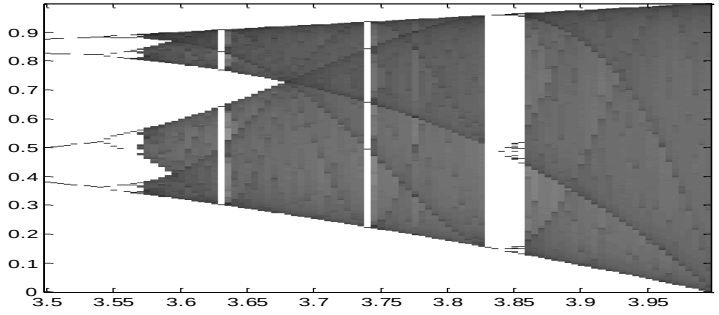


The hierarchy and the clusters are robust to the threshold chosen to define the spike times

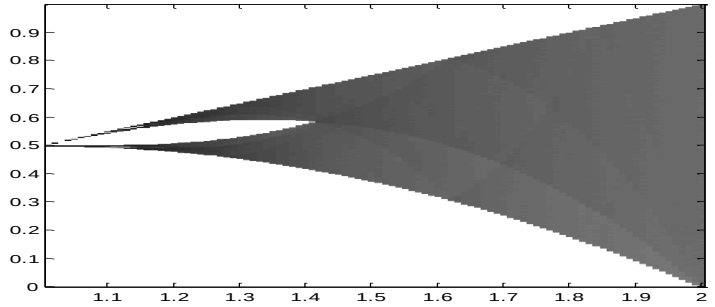
Can we find a minimal model that displays these features?







Map parameter

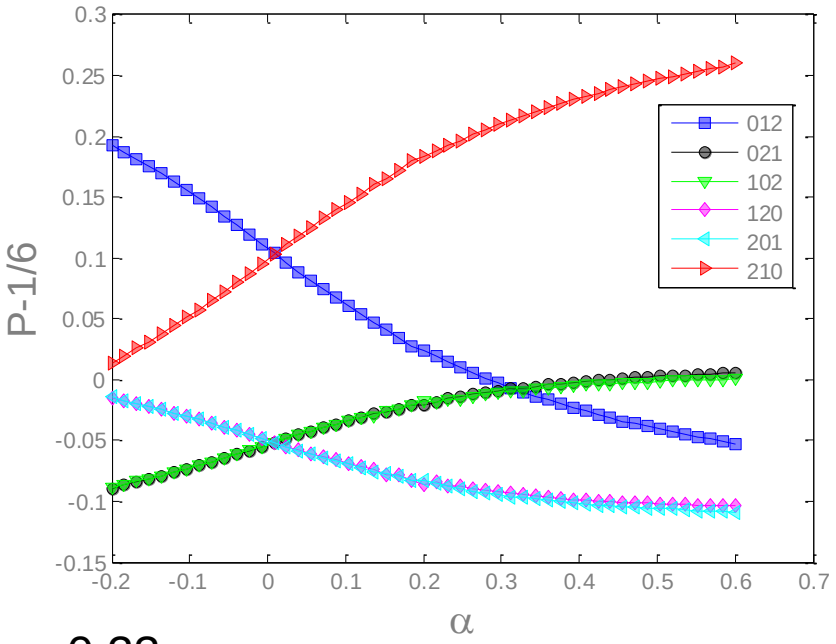


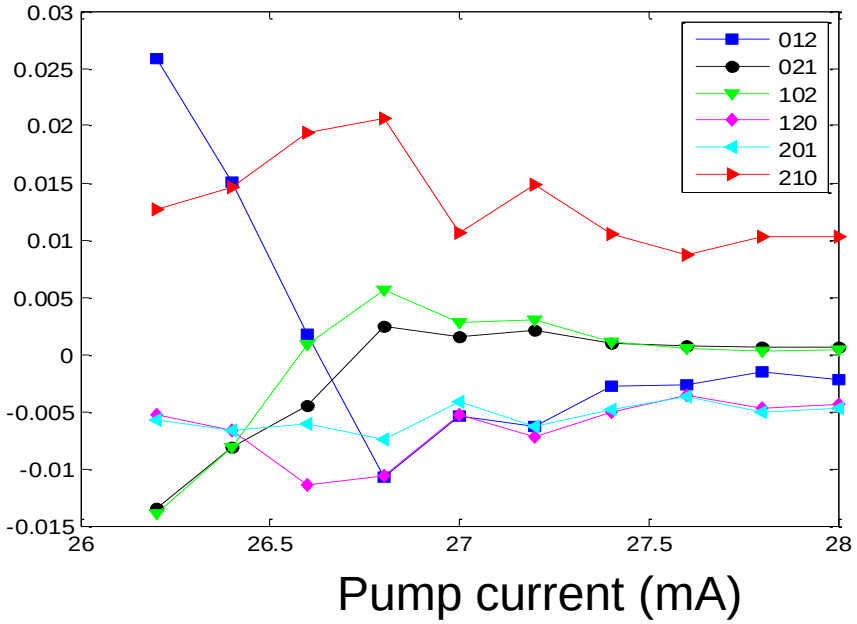
Map parameter

A modified circle map: minimal phenomenological model

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

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





ρ=0.23
K=0.04

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

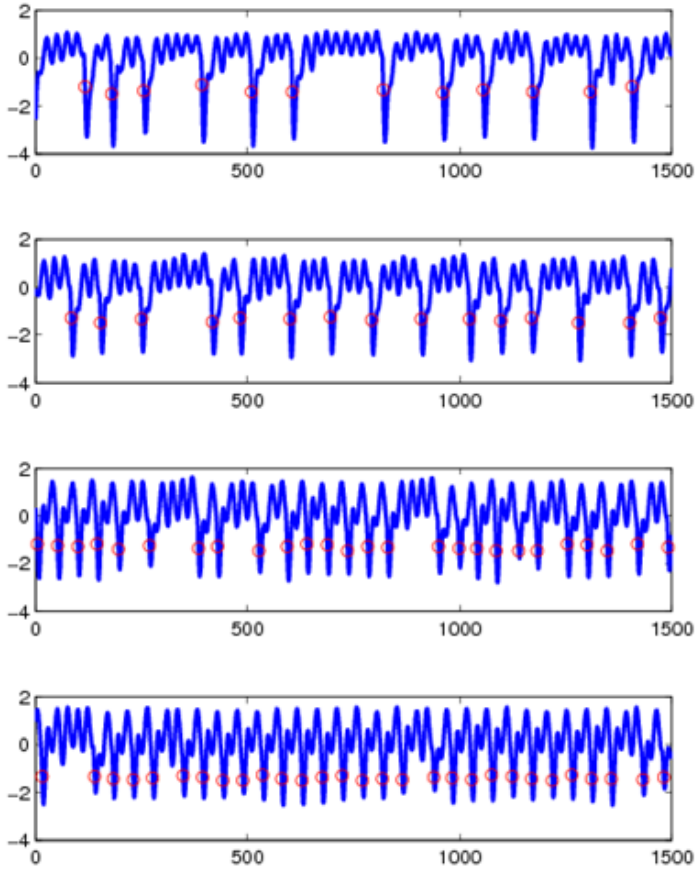
Outline

- Introduction: semiconductor lasers with feedback as high-dimensional & stochastic dynamical systems
- Method of time-series analysis and experimental setup
- Results. Experimental and model observations: inferring signatures of determinism + response to periodic forcing
- Conclusions and take home message

Periodic modulation of the laser current

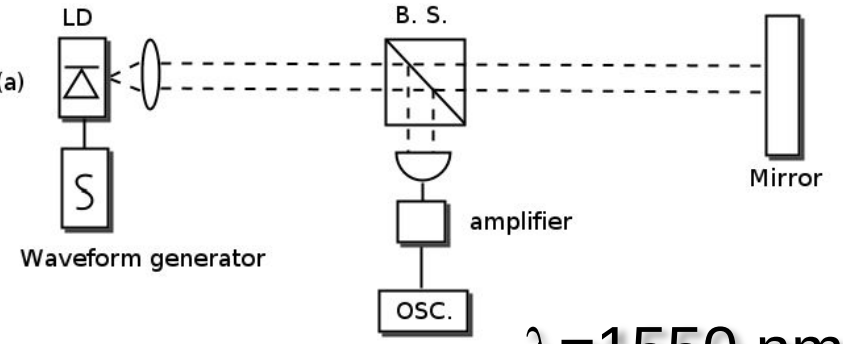
Laser intensity:

Increasing the modulation amplitude

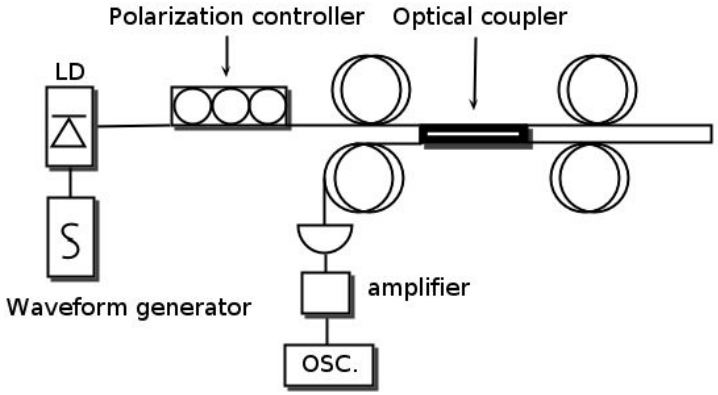


Time (ns)

λ=660 nm

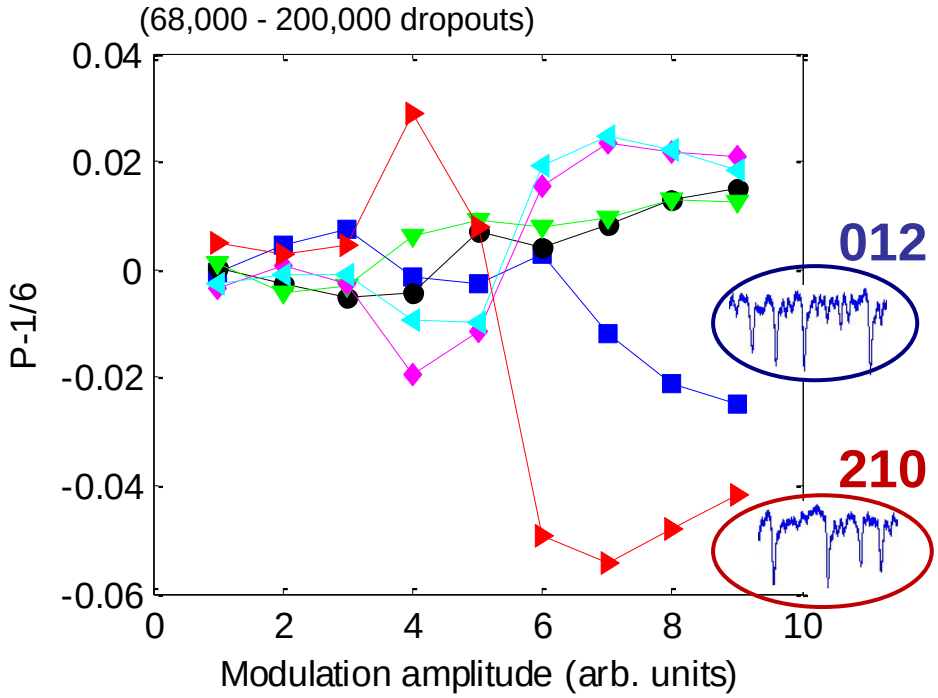


λ=1550 nm

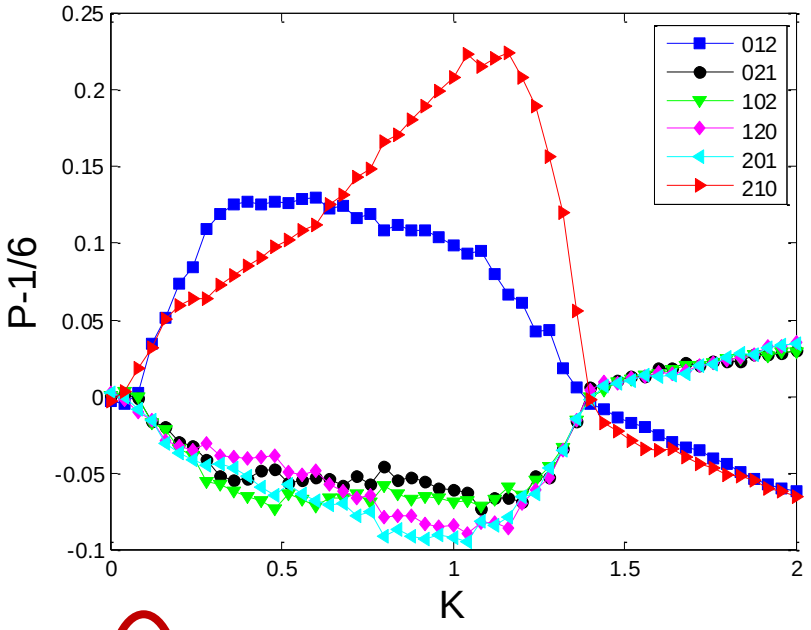


Experiment-model comparison

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

ρ=-0.23
α=0.2
D=0.02

Outline

- Introduction: semiconductor lasers with feedback as high-dimensional & stochastic dynamical systems
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Conclusions

- We proposed a novel method to infer signatures of determinism in sequences of events in dynamical complex systems.
- Adequate for high-dimensional & stochastic systems displaying noise or deterministically induced events.

- We found new symbolic states with an hierarchical and clustered organization of the probabilities of the patterns.
- We identified a minimal phenomenological model.
- LK model is in good agreement with observations (not shown)
- Potential breakthrough: optical neurons for neuro-inspired information processing.

Take home message

- Ordinal analysis is a powerful technique for the event-level description of complex systems

— useful for data understanding and uncovering patterns in the sequence of events,

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

— useful for classifying different types of behaviors,

— potential for improving event predictability and forecasting.

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Campus d'Excel·lència Internacional

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You for your attention!

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

- J. Zamora-Munt et al, PRA 2010
- N. Rubido et al, PRE 2011
- A. Aragoneses et al, http://www.nature.com/srep/2013/130507/srep01778/full/srep01778.html