Are the spikes emitted by a semiconductor laser with feedback similar to neuronal spikes?

C. Quintero-Quiroz, T. Sorrentino, A. Aragoneses,
J. Tiana, M. C. Torrent and Cristina Masoller

Universitat Politecnica de Catalunya

Cristina.masoller@upc.edu

www.fisica.edu.uy/~cris

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ICTON, Girona, July 2017

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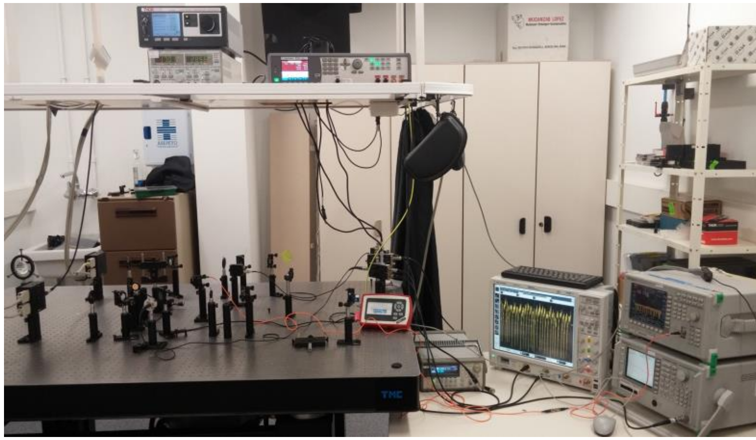
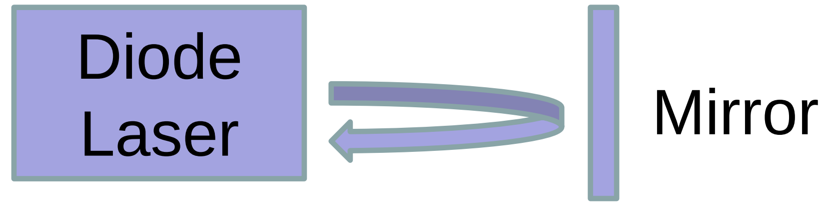
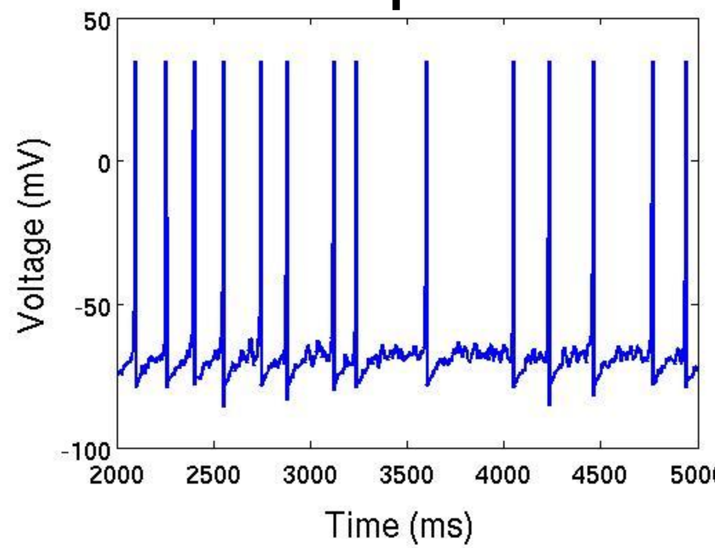


Low Frequency Fluctuations



Optical spikes

Neuronal spikes



Similar statistical properties?

Outline

- Introduction
  - Motivation: spiking lasers that mimic neuronal behavior
  - Method of time-series analysis
- Results:
  - Analysis of optical spikes
  - Contrasting with neuronal spikes
- Summary

MOTIVATION

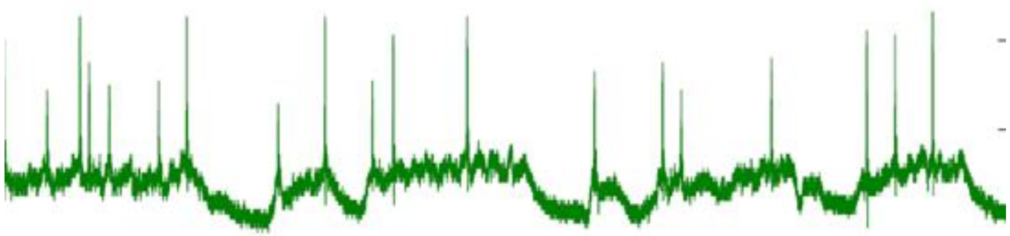
Science 345, 668 (2014)

"a computer that is **inspired** by the brain."

Neuro-synaptic architecture allows to do things like image classification at a very low power consumption.

- Spiking lasers: photonic neurons?
- potential building blocks of brain-inspired computers.
- Ultra fast ! (micro-sec vs. mili-sec)

How neurons encode information?

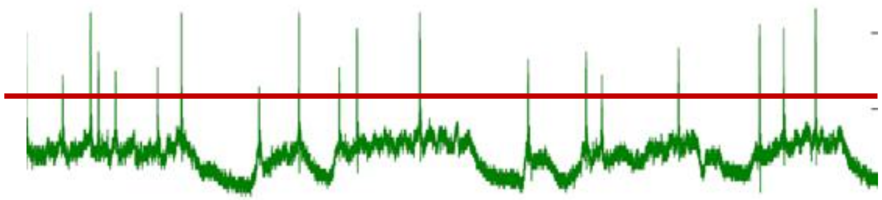


- In the spike rate?
- In the relative **timing** of the spikes?
- How temporal correlations can be detected and quantified?
- Our goal: try to understand how a weak periodic signal is encoded in the sequence of spikes.

Inter-spike-intervals

$$\{\ldots I_{i-1}, I_i, I_{i+1} \ldots\}$$

inter-spike-intervals $I_i = t_{i+1} - t_i$



HOW TO INDENTIFY TEMPORAL STRUCTURES?
RECURRENT / INFREQUENT PATTERNS?

Comparison of empirical data: neuronal & optical spikes

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Neuron inter-spike interval (ISI) distribution

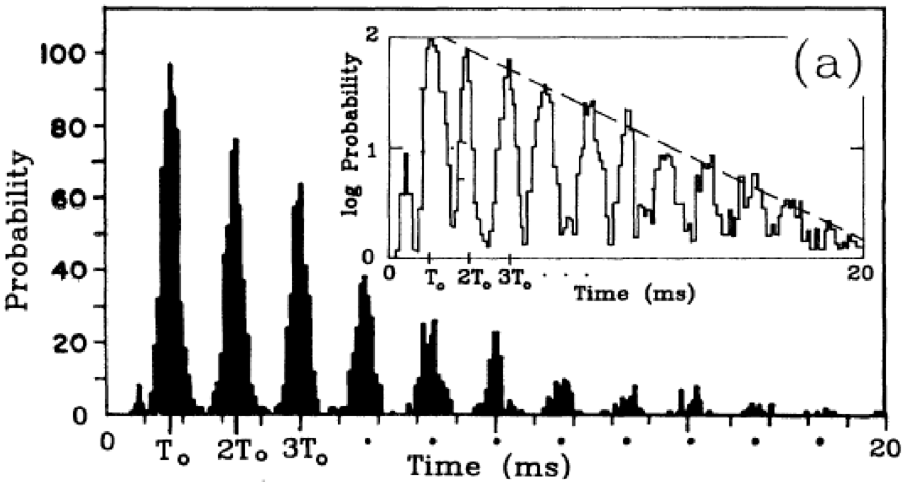
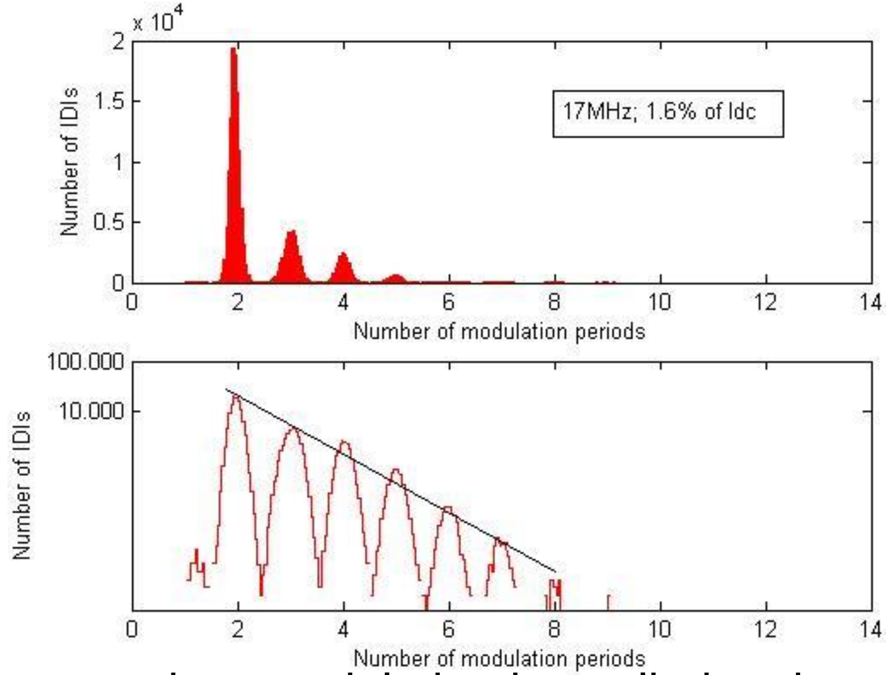


FIG. 1. (a) An experimental ISIH obtained from a single auditory nerve fiber of a squirrel monkey with a sinusoidal 80-dB sound-pressure-level stimulus of period $T_0 = 1.66$ ms applied at the ear. Note the modes at integer multiples of T_0. Inset:

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

Optical ISI distribution



when modulation is applied to the laser current

Neuronal ISIs

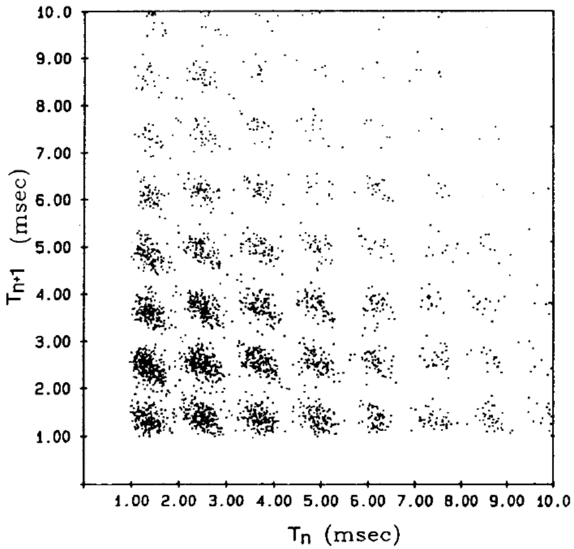
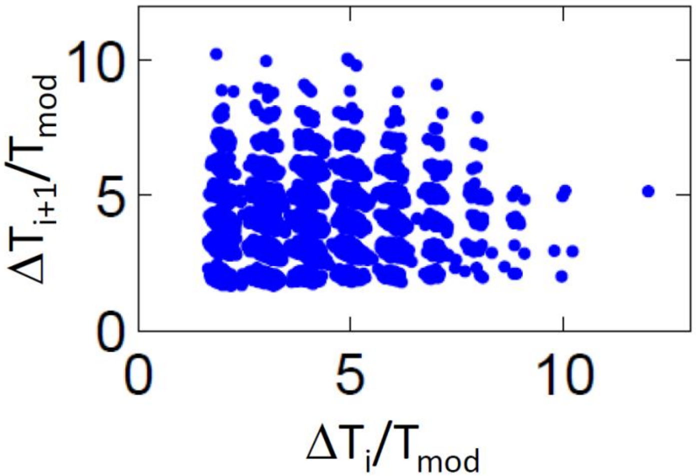
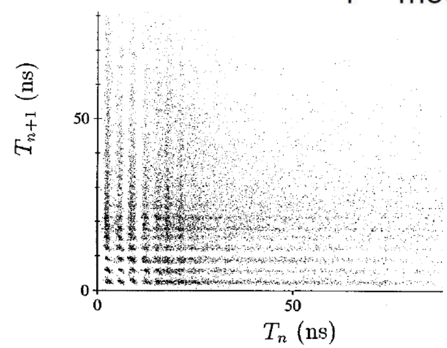


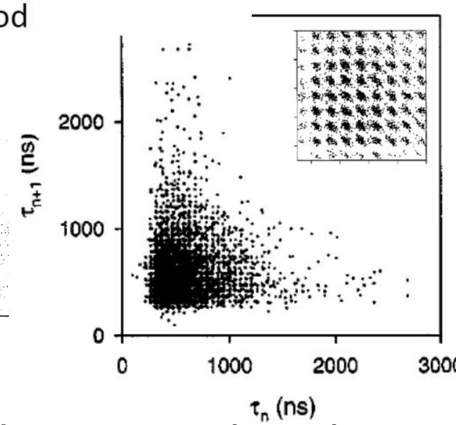
Fig. 4. Scatter plot of spike train data obtained from extracellular measurements of cat auditory fiber activity in response to an 800 Hz 60 dB sound pressure level pure tone presented to the outer ear. The stimulus is discontinuous (see

A. Longtin IJBC 3 (1993) 651

Optical ISIs







A. Aragoneses et al, Opt. Exp. (2014)
M. Giudici et al, PRE 55, 6414 (1997)
D. Sukow and D. Gautheir, JQE (2000)

Symbolic method of time-series analysis

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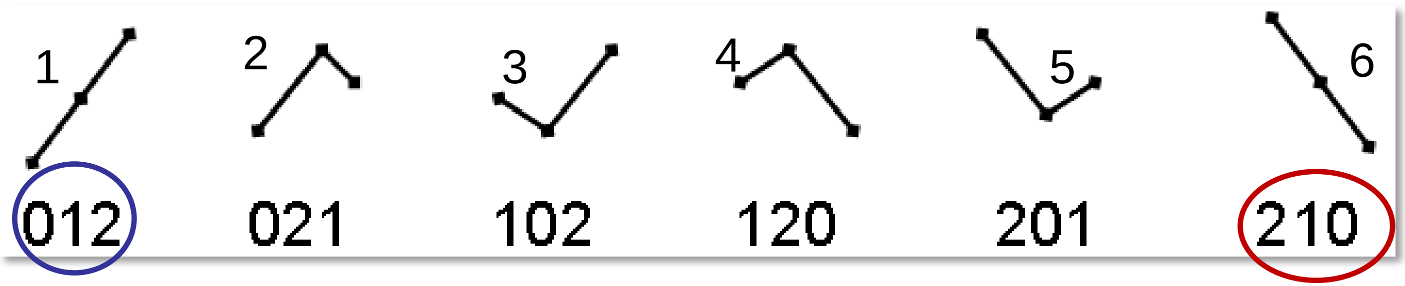
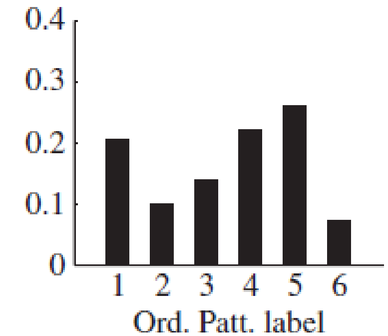
Symbolic method of time-series analysis

Sequence of inter-spike-intervals $\{\ldots \mathbf{I}_i, \mathbf{I}_{i+1}, \mathbf{I}_{i+2}, \ldots\}$

D=3



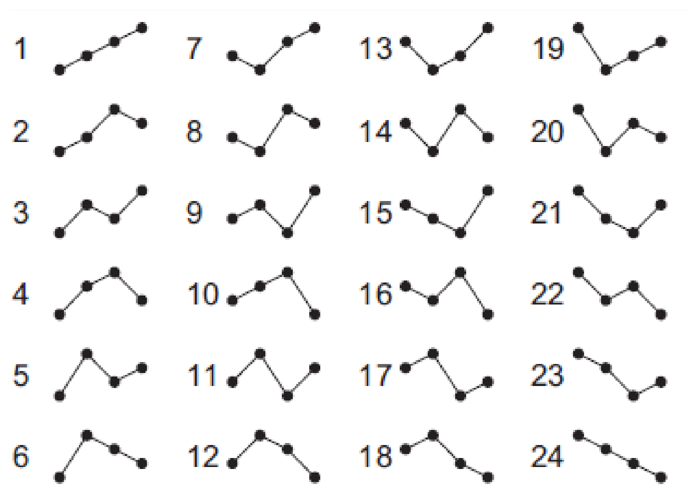
Ordinal probabilities



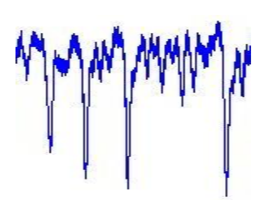
Example: (5, 1, 7) gives "102" because 1 < 5 < 7

D=4: 24

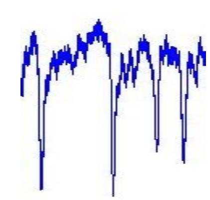
D=5: 120



We limit the analysis to D ≤ 4 consecutive intervals because: noisy dynamics ⇒ short-range correlations.



⇒012



⇒210

Brandt & Pompe, PRL 88, 174102 (2002)

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

Results

- analysis of experimental optical spikes
-comparison with synthetic sequences generated by a simple neuron model

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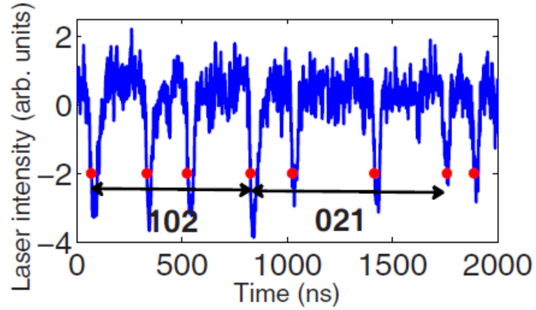
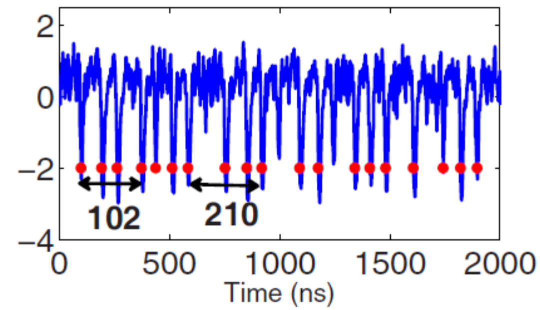
Experimental control parameter: the pump current of the semiconductor laser

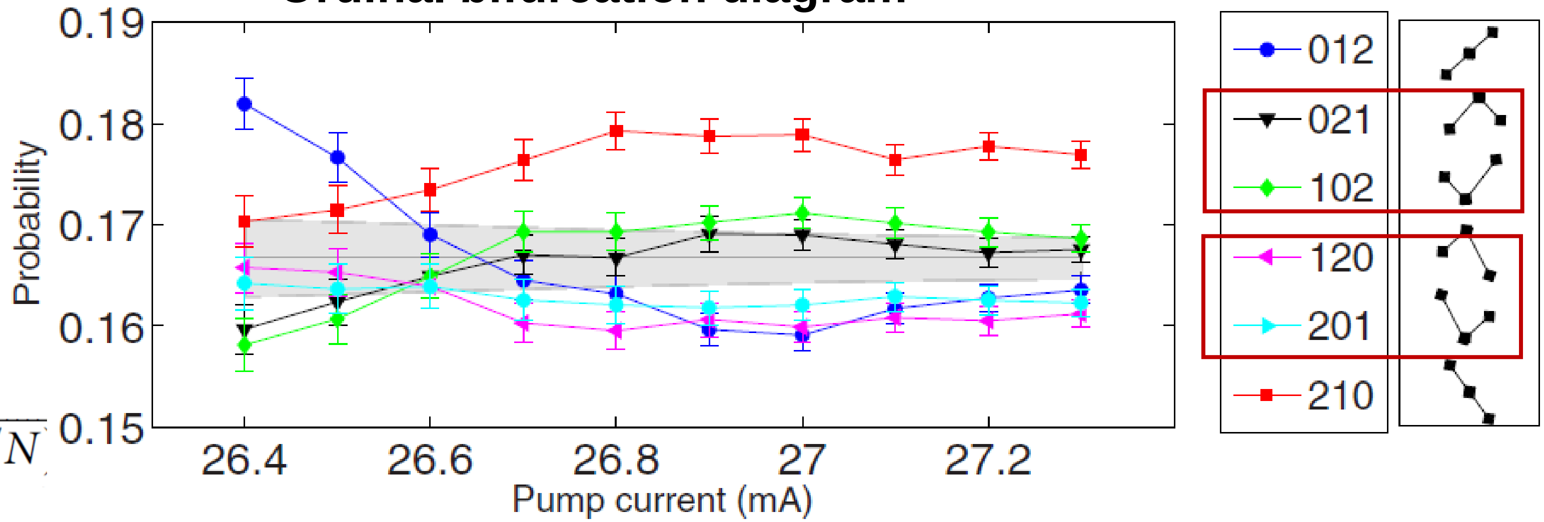
Close to threshold



Higher pump current



Ordinal bifurcation diagram



Grey region 99.7% confidence level.

$$p \pm 3\sigma_p$$

$$\sigma_p = \sqrt{(p(1-p)/N)}$$

P =1 /6; ***N* > 10,000 ISIs**

A. Aragoneses, S. Perrone, T. Sorrentino, M. C. Torrent and C. Masoller, Sci. Rep. **4**, 4696 (2014)

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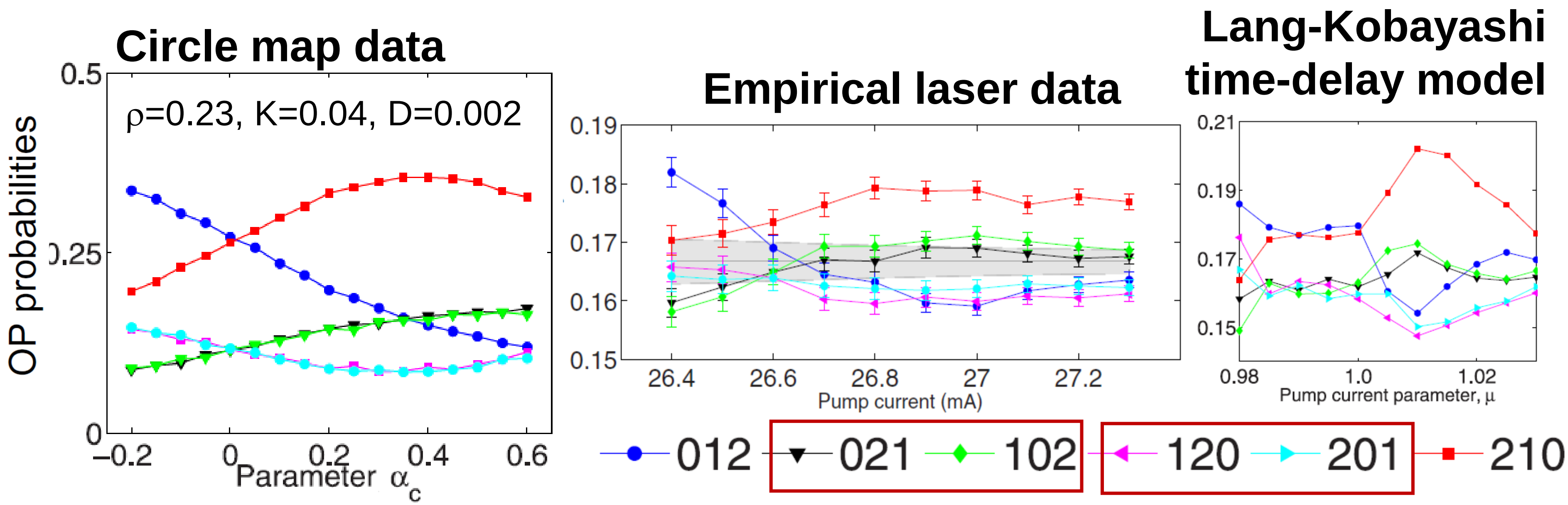
Minimal model of ISI nonlinear correlations: modified circle map

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

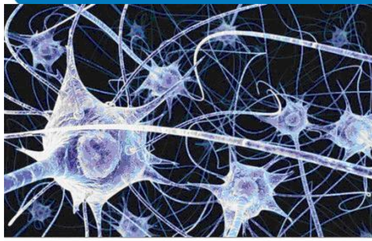
$$X_i = \varphi_{i+1} - \varphi_i$$

ρ = natural frequency / forcing frequency
K = forcing amplitude
D = noise strength



- Same "clusters" & same hierarchical structure.
- Modified circle map: minimal model for ordinal correlations.
- Same qualitative behavior found with other lasers & feedback conditions.

Model equations and parameters: A. Aragoneses et al, Sci. Rep. **4**, 4696 (2014)



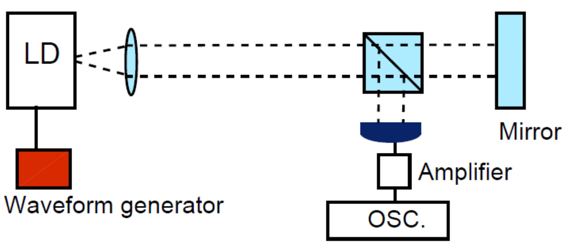
Connection with neurons

- The modified circle map has been used to describe spike correlations in biological neurons.

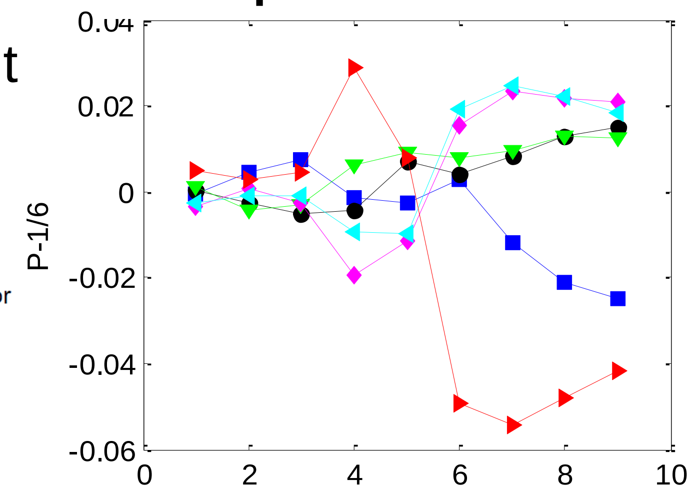
  Neiman and Russell, *Models of stochastic biperiodic oscillations and extended serial correlations in electroreceptors of paddlefish*, PRE 2005

How to test the model?

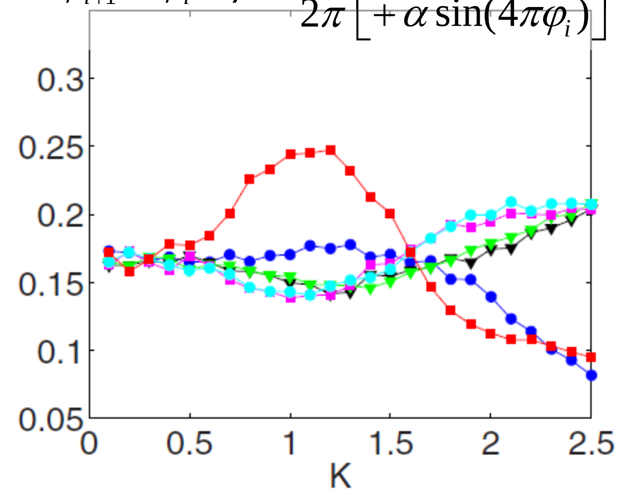
Apply external forcing: direct sinusoidal current modulation



Empirical laser data



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



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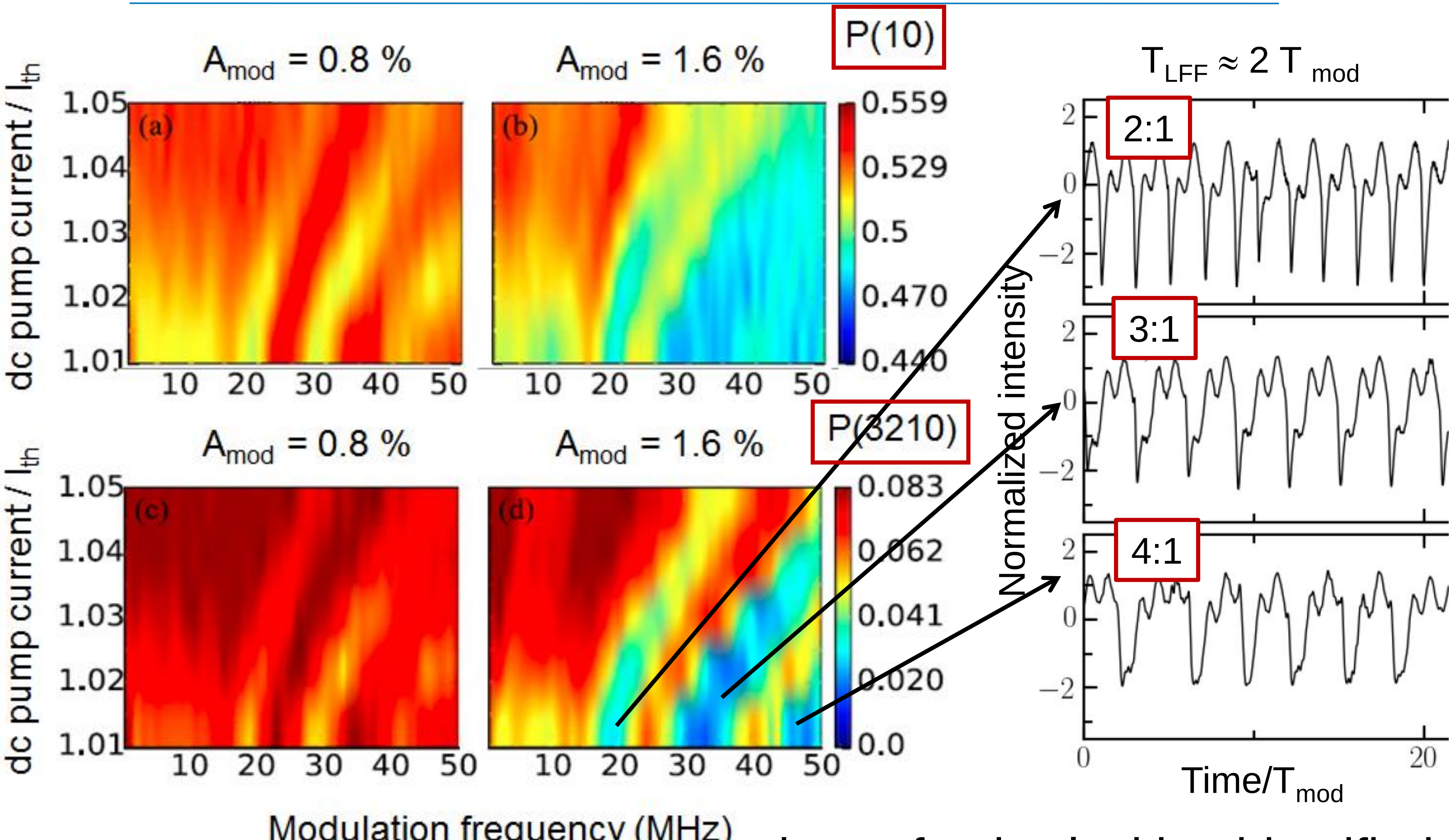
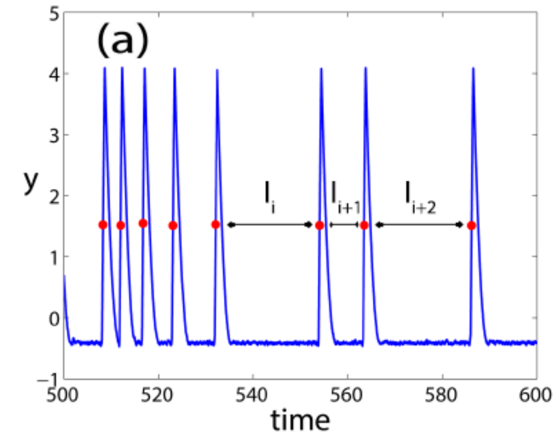


⇒ regions of noisy locking identified

T. Sorrentino et al, JSTQE 21, 1801107 (2015)

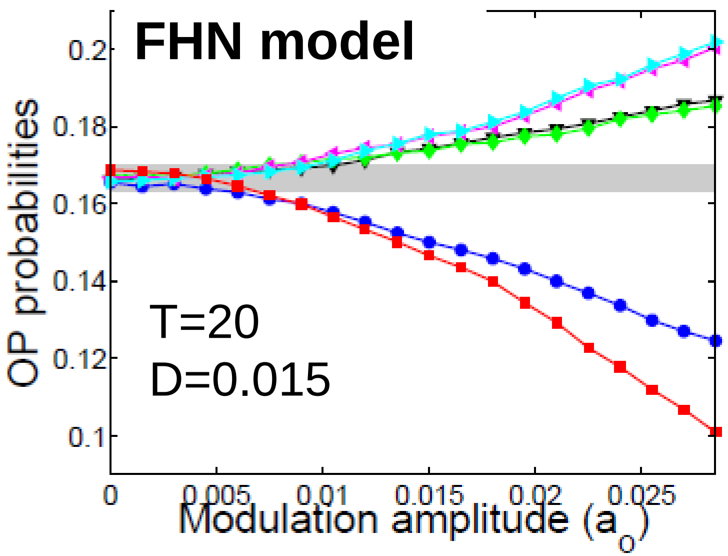
FHN neuron model

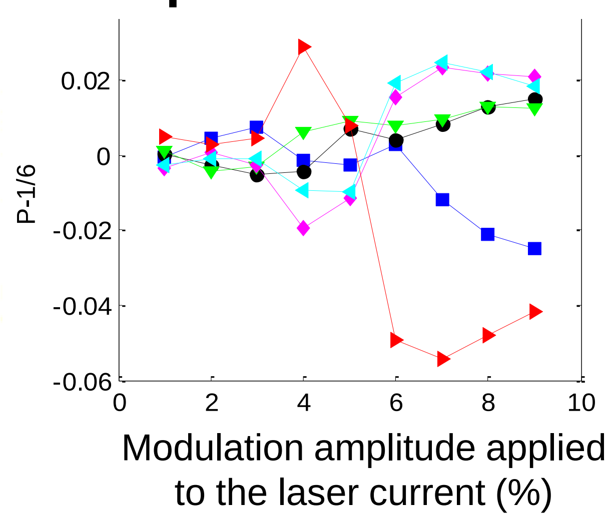
$$\epsilon \frac{dx}{dt} = x - \frac{x^3}{3} - y,$$
$$\frac{dy}{dt} = x + a + \boxed{a_o \cos(2\pi t/T)} + D\xi(t),$$



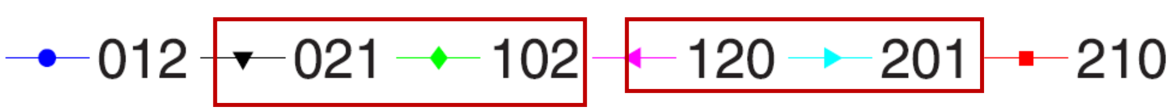
Gaussian white noise and <u>subthreshold</u> (weak) modulation: $\mathbf{a_0}$ and **T** such that spikes are only noise-induced.

Time series with 100,000 ISIs simulated.





$\Rightarrow$ Good qualitative agreement.



J. M. Aparicio-Reinoso et al, PRE 94, 032218 (2016).

Conclusions

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What did we learn?

- Take home message:
  - ordinal analysis is useful for uncovering patterns, model comparison, parameter estimation, etc.
  - robust to noise and artifacts in the data.
- Main conclusions
  - Optical & neuronal spikes compared: good *qualitative* agreement.
  - Minimal model for optical spikes identified: a modified circle map.
- Ongoing and future work:
  - Mathematical insight: can we calculate the probabilities analytically?
  - Compare with empirical data (single-neuron ISI sequences)

THANK YOU FOR YOUR ATTENTION !

<cristina.masoller@upc.edu>

Papers at: **http://www.fisica.edu.uy/~cris/**

- *Unveiling the complex organization of recurrent patterns in spiking dynamical systems*

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

- *Analysis of the spike rate and spike correlations in modulated semiconductor lasers with optical feedback*

  T. Sorrentino et al., IEEE J. Sel. Top. Quantum Electron. 21, 1801107 (2015).

- *Emergence of spike correlations in periodically forced excitable systems*

  J. A. Reinoso et al. Phys. Rev. E. 94, 032218 (2016).

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