Neural coding of weak periodic signals in symbolic spike patterns

Cristina Masoller
Departament de Física
Universitat Politècnica de Catalunya
Campus Terrassa

www.fisica.edu.uy/~cris

Institut non linéaire de Nice
SOPHIA ANTIPOLIS

Where I meet Valentin
(1999, Villeneuve-Loubet)

UNIVERSITAT POLITÈCNICA DE CATALUNYA
BARCELONATECH
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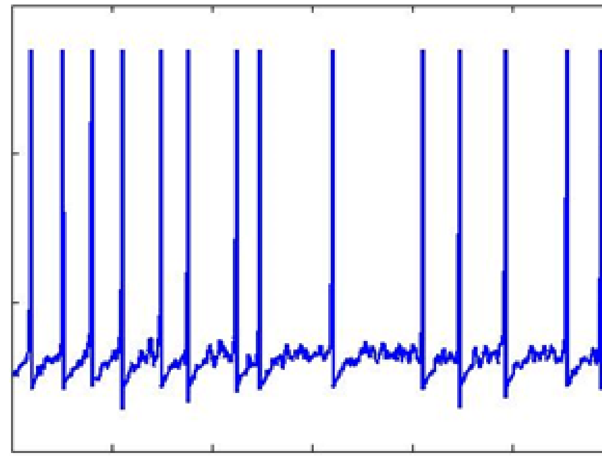
50 Years of Excitable Media
June 30, 2019, Gottingen, Germany

Motivation: How excitable systems respond to weak external forcing in noisy environments?

Laser intensity

Time 10^{-6} s

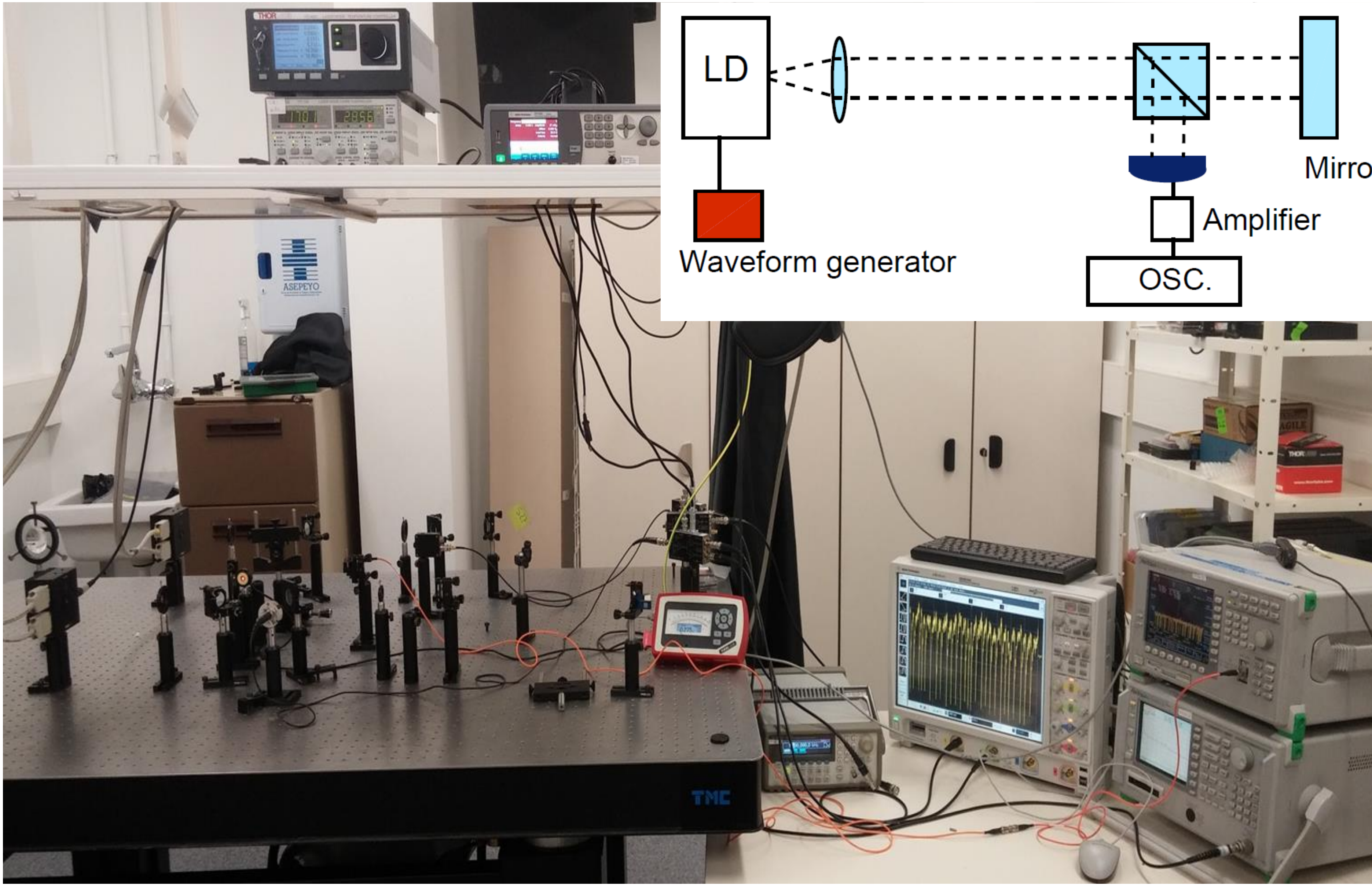
Neuron model



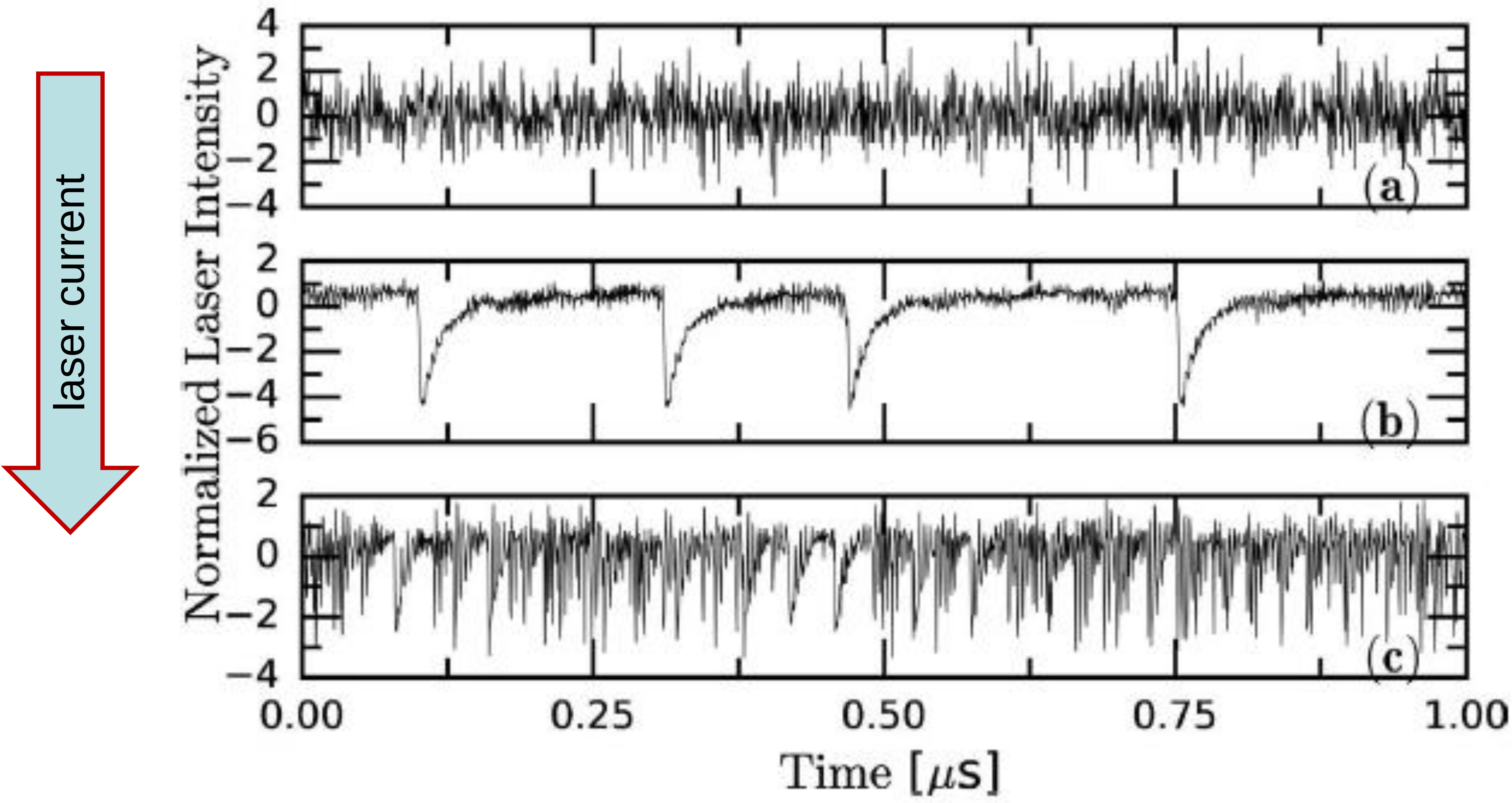
Time 10^{-3} s

Can lasers mimic real neurons?

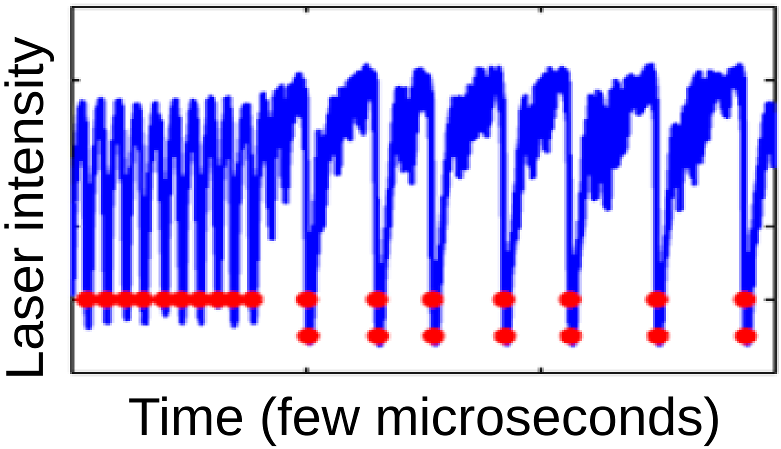
How can a neuron (or a laser) “encode”, in a sequence of spikes, the information of a weak signal, in the presence of noise?

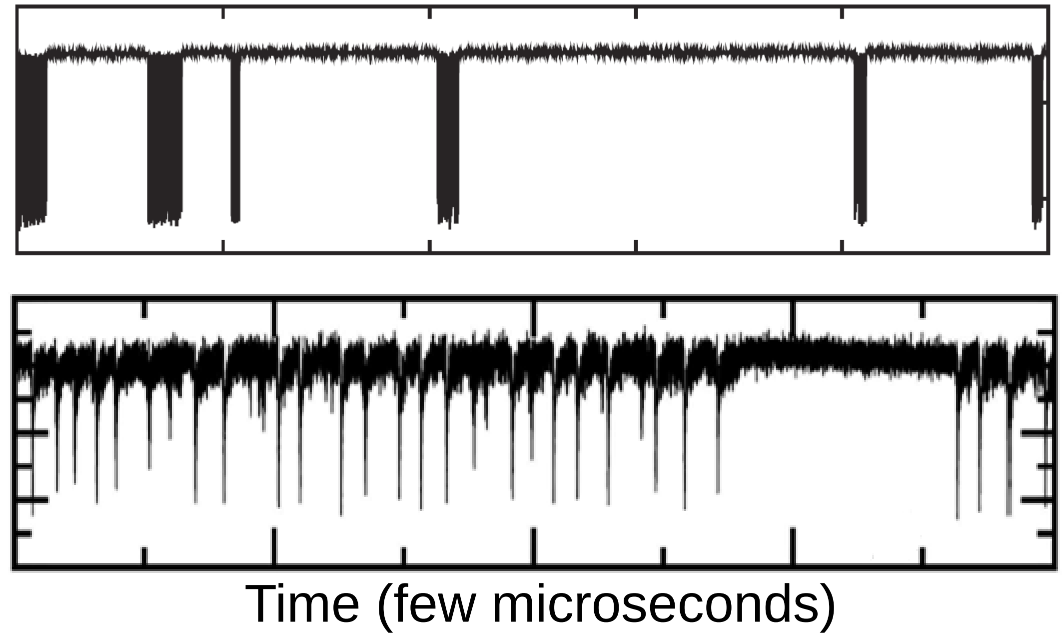

LD
Waveform generator
Mirror
Amplifier
OSC.

Optical noise ⇒ spikes ⇒ chaos



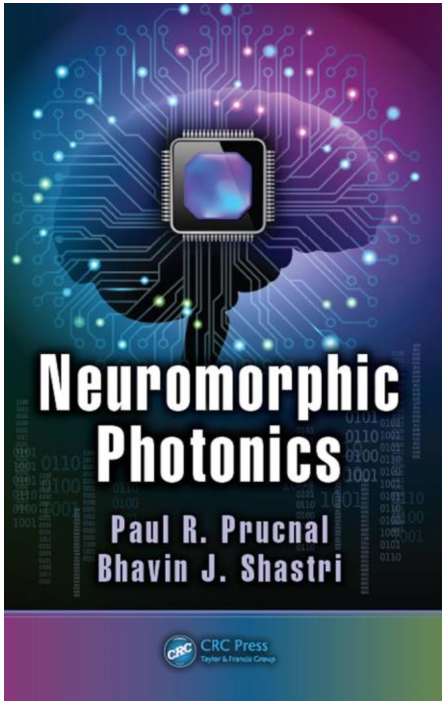
In the spike region: tonic spikes and bursting
Similar to real neurons?





A. Aragoneses et al., Sci. Rep. ***4****, 4696 (2014).*
C. Quintero-Quiroz et al., Sci. Rep. ***6*** *37510 (2016).*

Uncovering similarities can be interesting. But useful? Maybe…



- Excitable lasers: building blocks of **photonic neurons**.
- Diode lasers: very very low cost, highly energy efficient.
- Very very fast.
- Main challenge: understand how lasers and neurons encode a **weak periodic** signal in the presence of **noise**.

Inter-spike-interval (ISI) distribution with sinusoidal forcing

Neuron empirical data

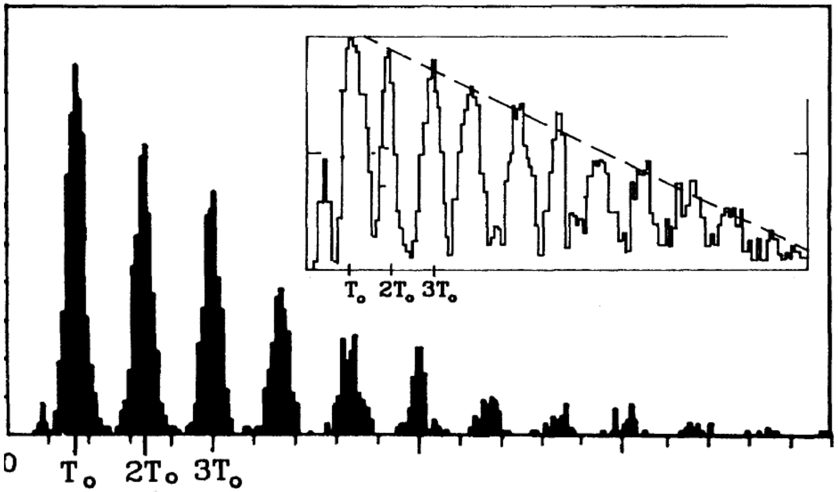
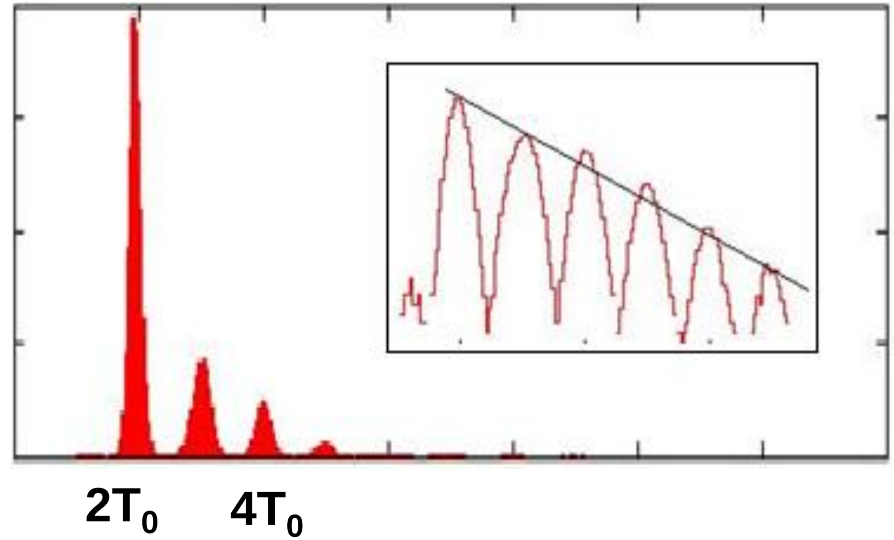


FIG. 1. (a) An experimental ISIH obtained from a single auditory nerve fiber of a squirrel monkey with a sinusoidal 80-dB sound-pressure-level stimulus of period $T_0 = 1.66$ ms applied at the ear. Note the modes at integer multiples of T_0. Inset:

A. Longtin et al. PRL (1991)

Laser empirical data



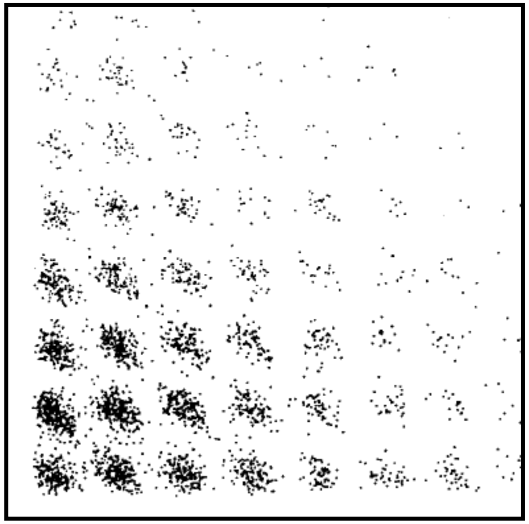
Experimental data when the laser current is modulated with a sinusoidal signal of period T_0.

Aragoneses et al. Opt. Express (2014)

Return maps of inter-spike-intervals (ISIs)

Neuronal ISIs

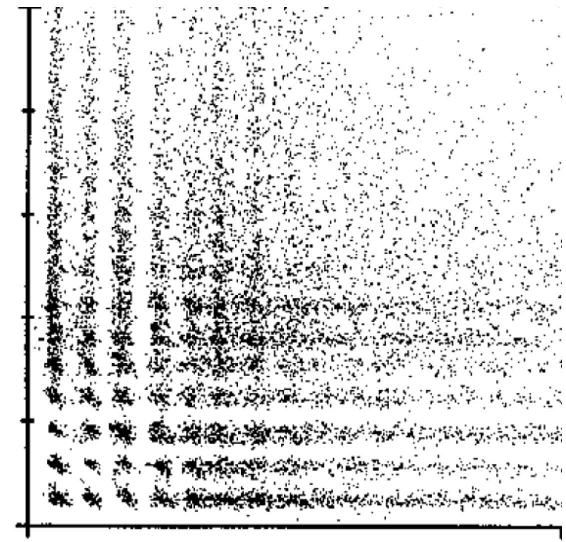
ΔT_{i+1}



ΔT_i

A. Longtin, IJBC 1993

Laser ISIs

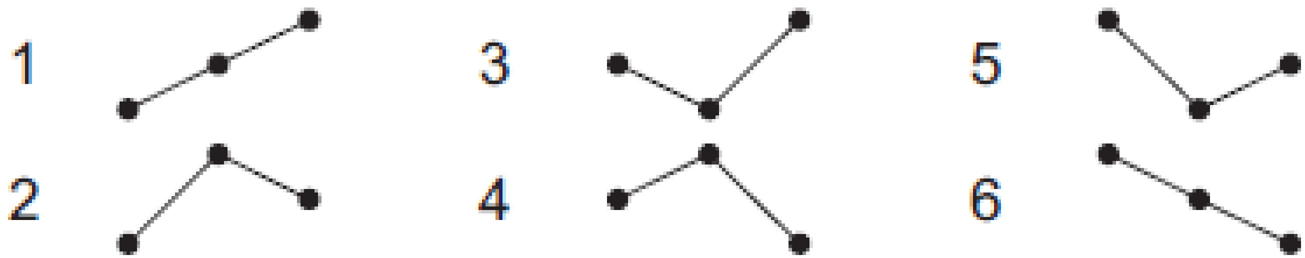


M. Giudici et al PRE 1997
A. Aragoneses et al., Opt. Exp. 2014

Similar temporal structure in the spike sequences?

Ordinal analysis: a method to find patterns in data

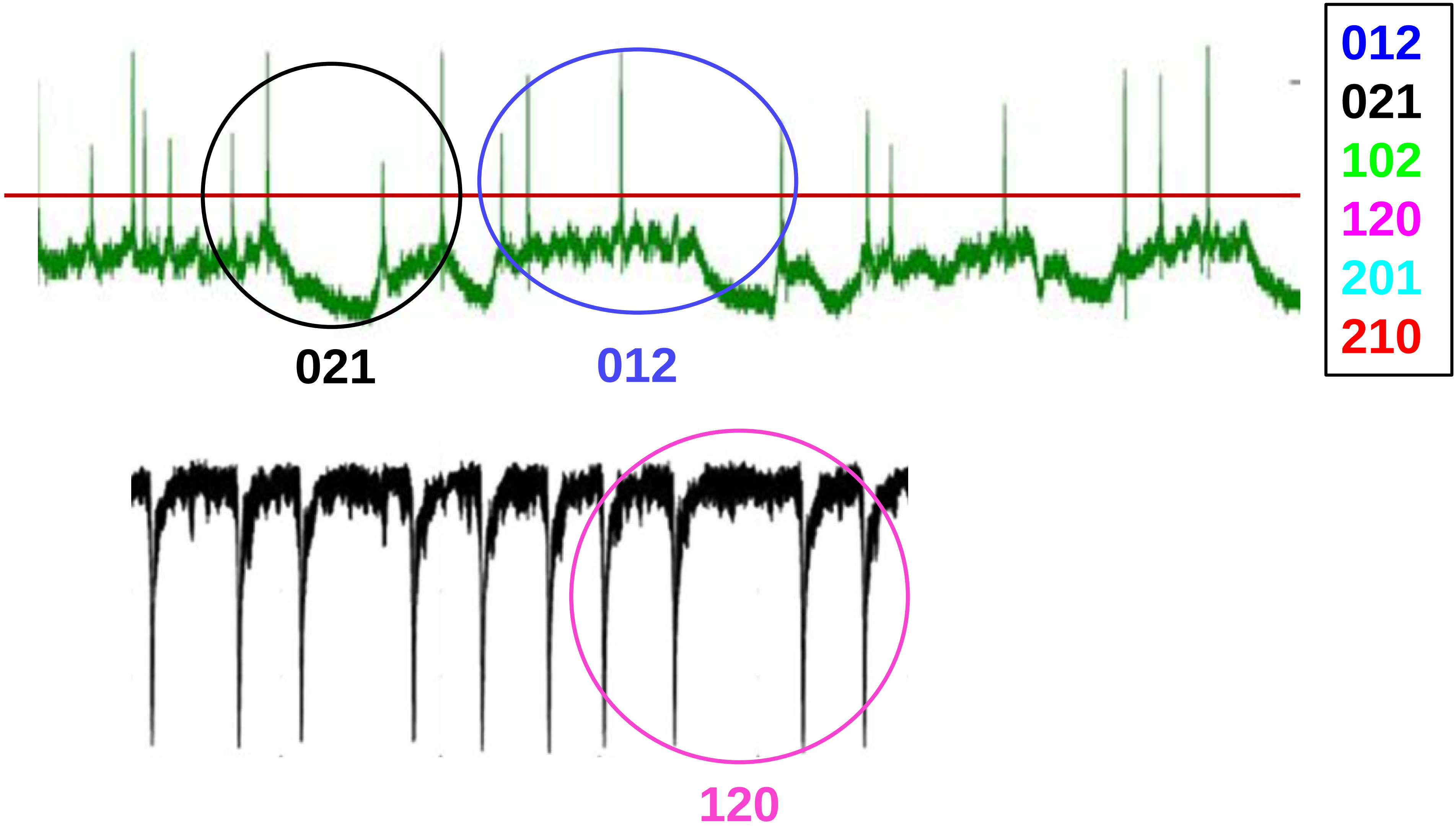
- Consider a time series $x(t)=\{\ldots x_i, x_{i+1}, x_{i+2}, \ldots\}$
- Which are the possible order relations among three data points?



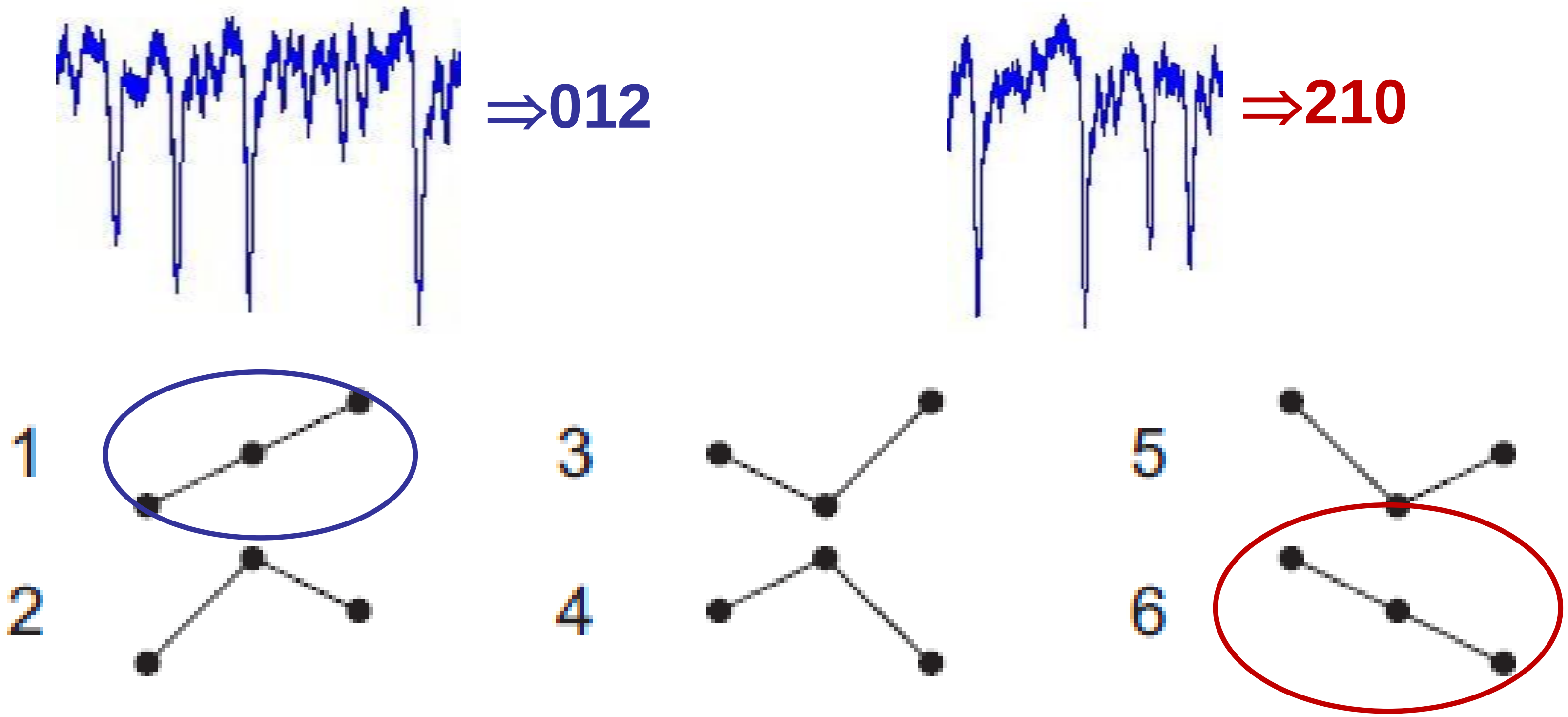
- Count how many times each “ordinal pattern” appears.
- Advantages: allows to identify temporal structures & is robust to noise.
- Drawback: information about actual data values is lost.

Bandt and Pompe PRL 88, 174102 (2002)

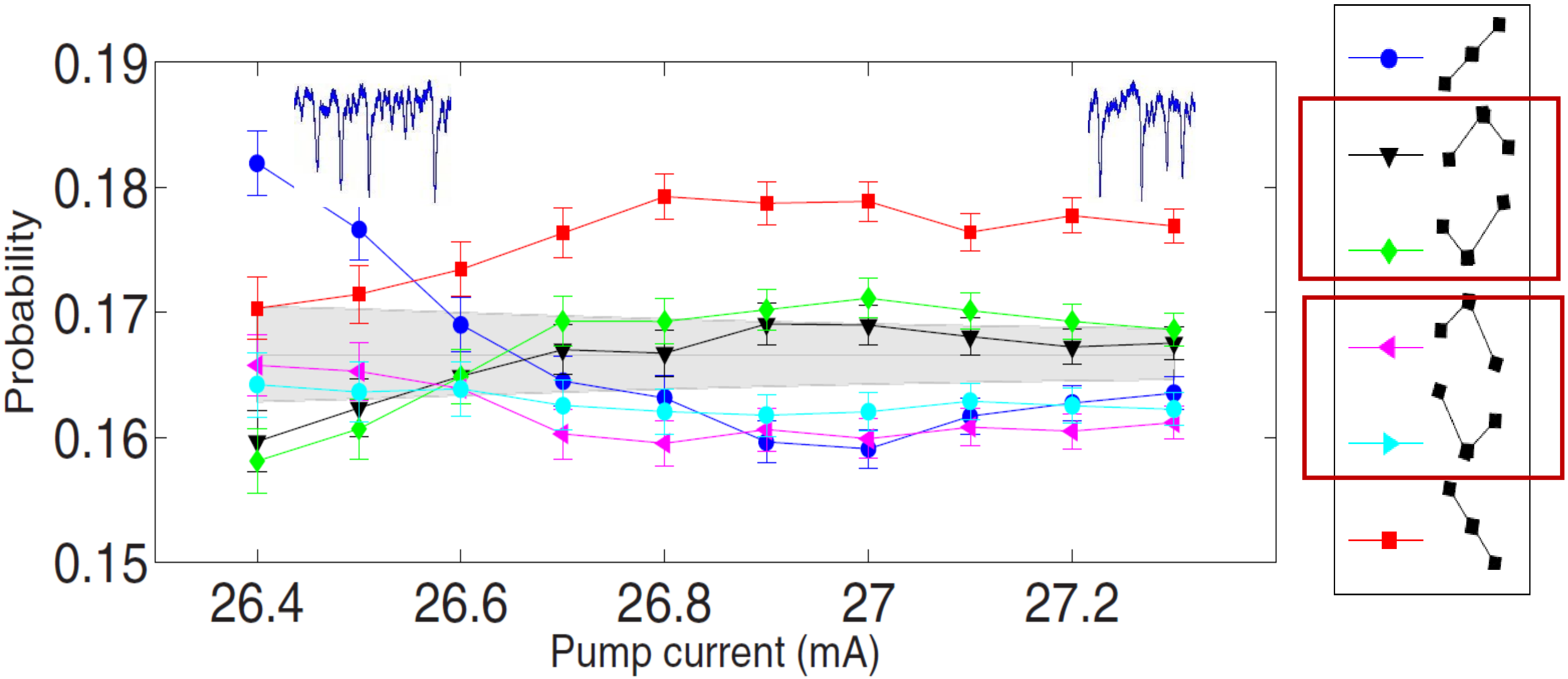
Analysis of D=3 patterns in spike sequences



Ordinal analysis of inter-spike intervals



More probable pattern varies with the laser pump current

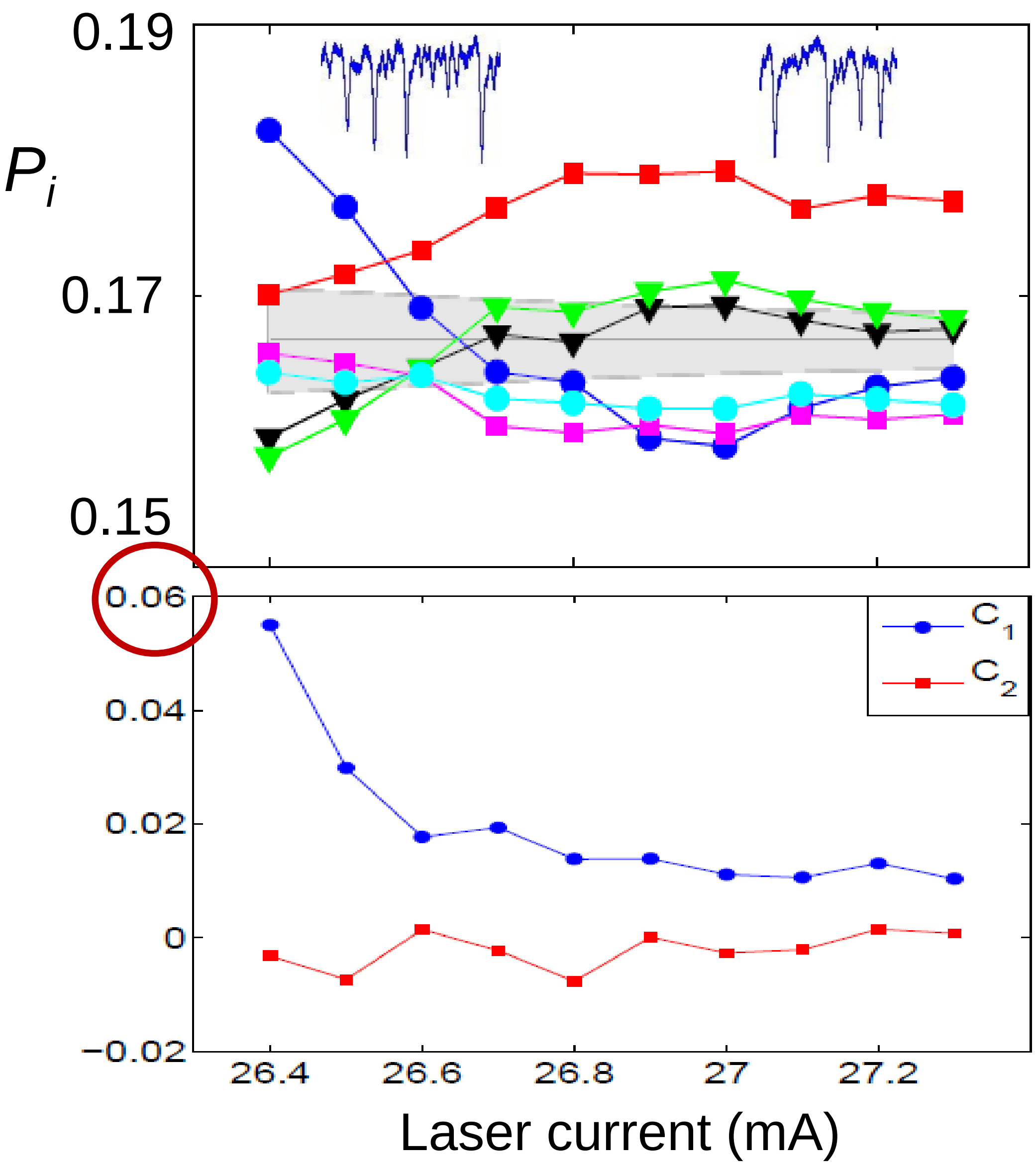


75,000 – 880,000 spikes

Gray region: probabilities consistent with 1/6

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

The variation is not captured by linear correlation analysis



$$C_\tau = \frac{\langle (\Delta T_i - \langle \Delta T \rangle)(\Delta T_{i-\tau} - \langle \Delta T \rangle) \rangle}{\sigma^2}$$

Minimal model? A modified circle map

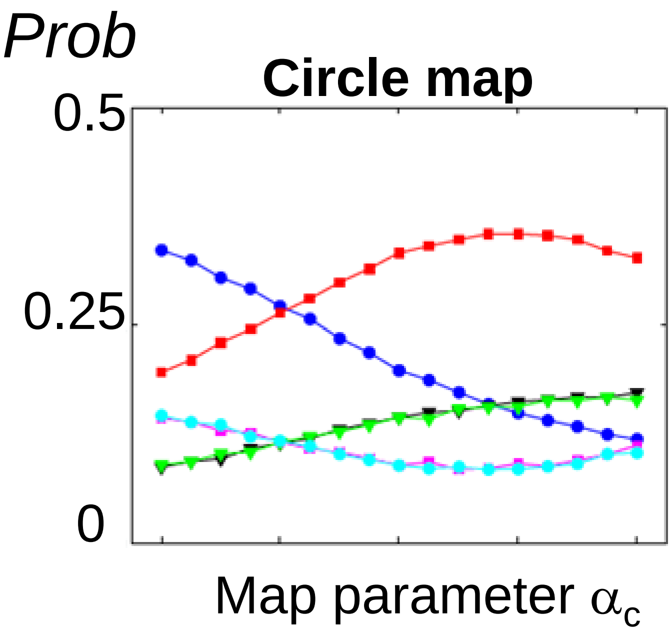
$$\varphi_{i+1} = \varphi_i + \rho + \frac{K}{2\pi}\left[\sin(2\pi\varphi_i) + \alpha_c \sin(4\pi\varphi_i)\right] + D\zeta$$

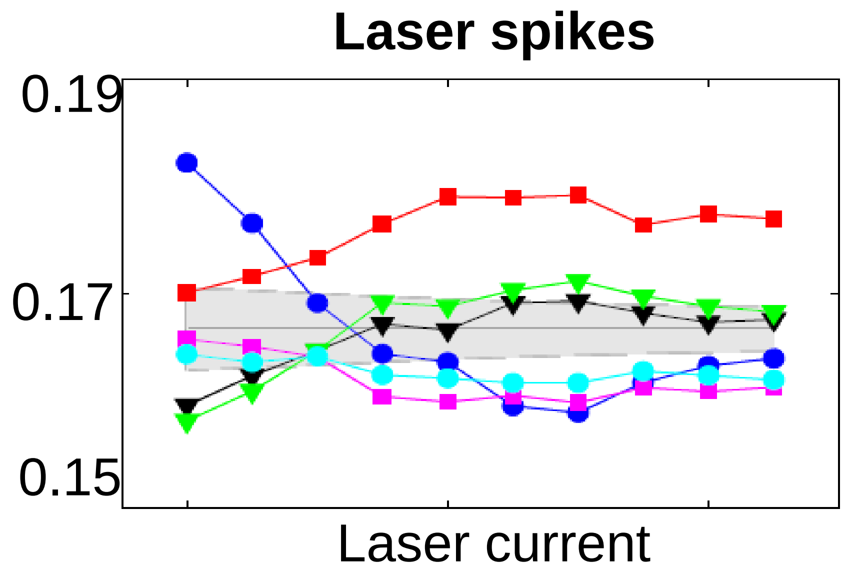
$$X_i = \varphi_{i+1} - \varphi_i$$

ρ = natural frequency / forcing frequency

K = forcing amplitude

D = noise strength

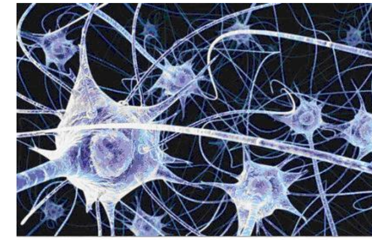




Same "clusters" & same hierarchical structure

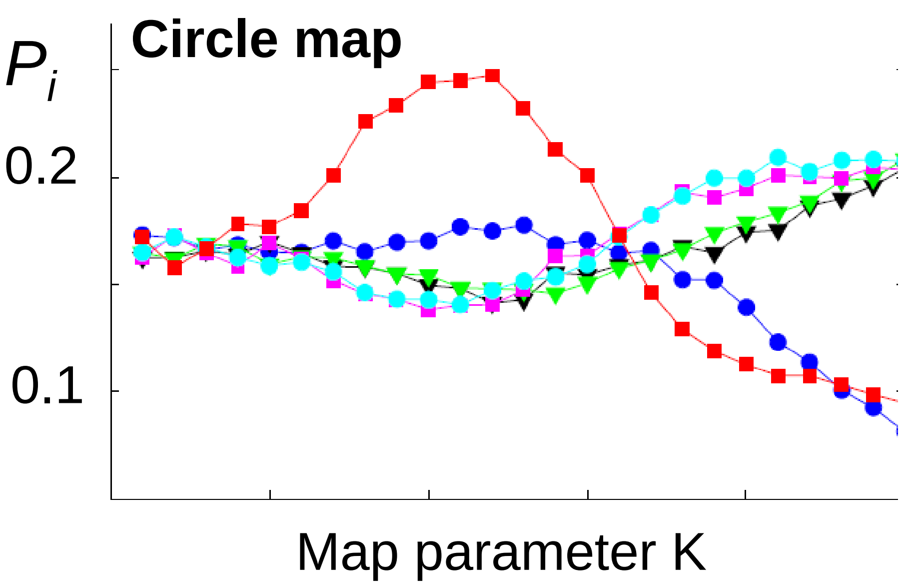
A. Aragoneses et al, Sci. Rep. 4, 4696 (2014)

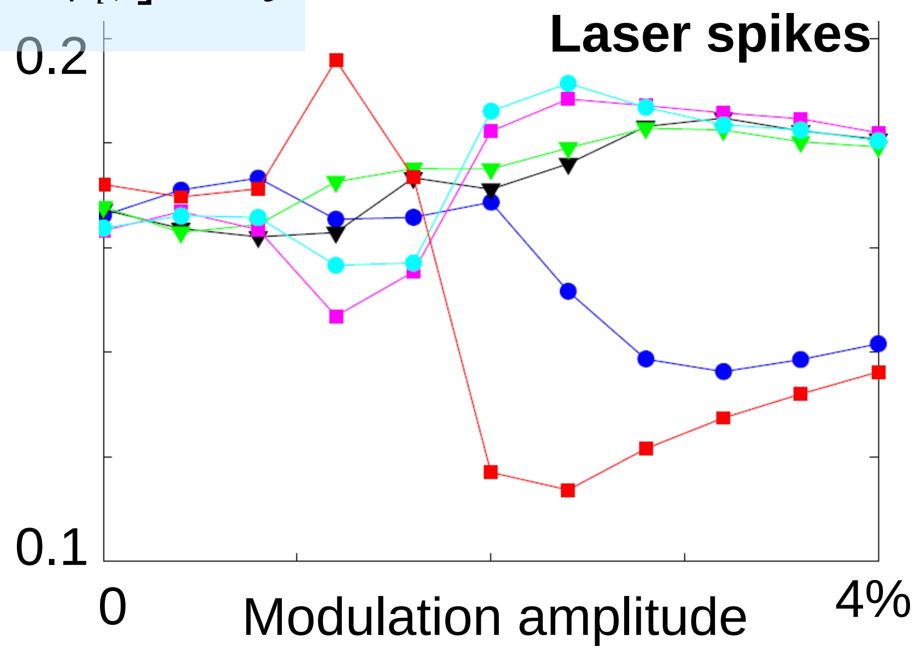
Connection with neurons: the circle map describes many excitable systems



- Spike correlations in sensory neurons (Neiman and Russell, PRE 2005)
- Can we test its validity as a minimal model for the laser spikes?

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



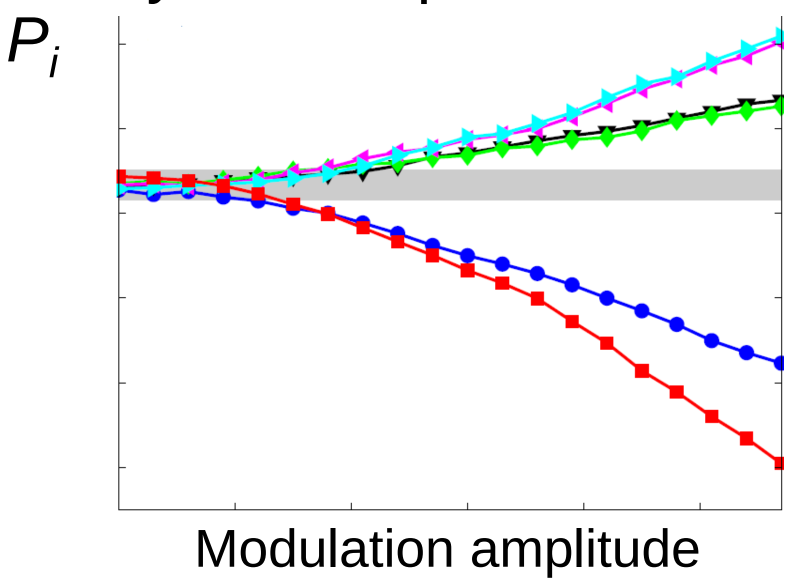


Comparing with synthetic neuronal spikes: good agreement

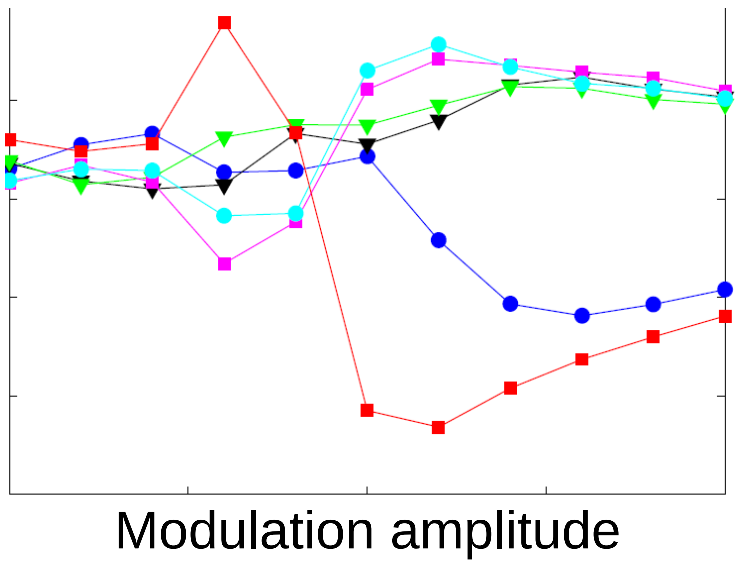
FHN model with Gaussian white noise and **weak** sinusoidal input: spikes are noise-induced

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

Synthetic spikes

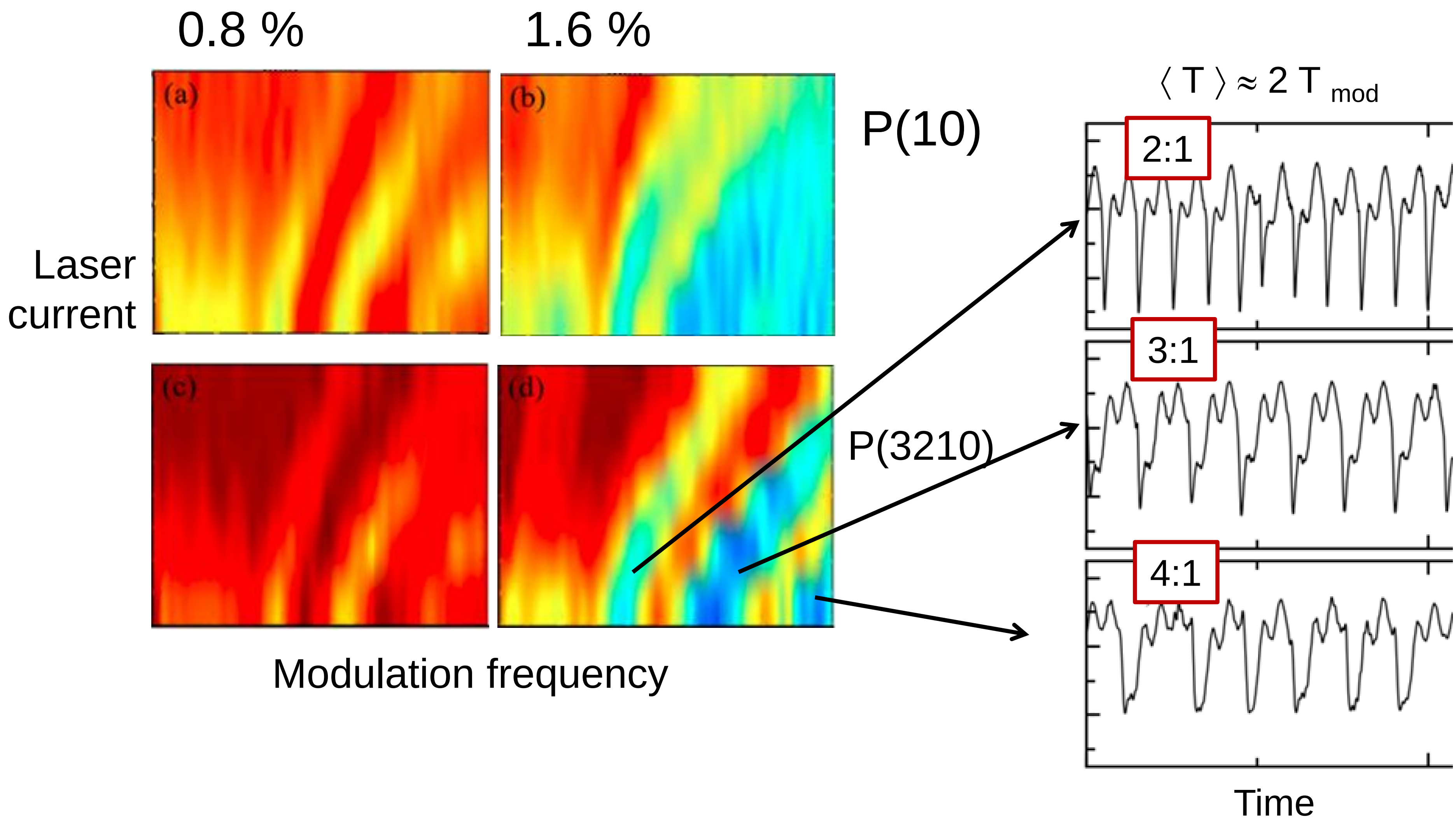


Empirical laser data



J. M. Aparicio-Reinoso, M. C. Torrent and C. Masoller, PRE 94, 032218 (2016)

Ordinal probabilities uncover the regions of noisy locking



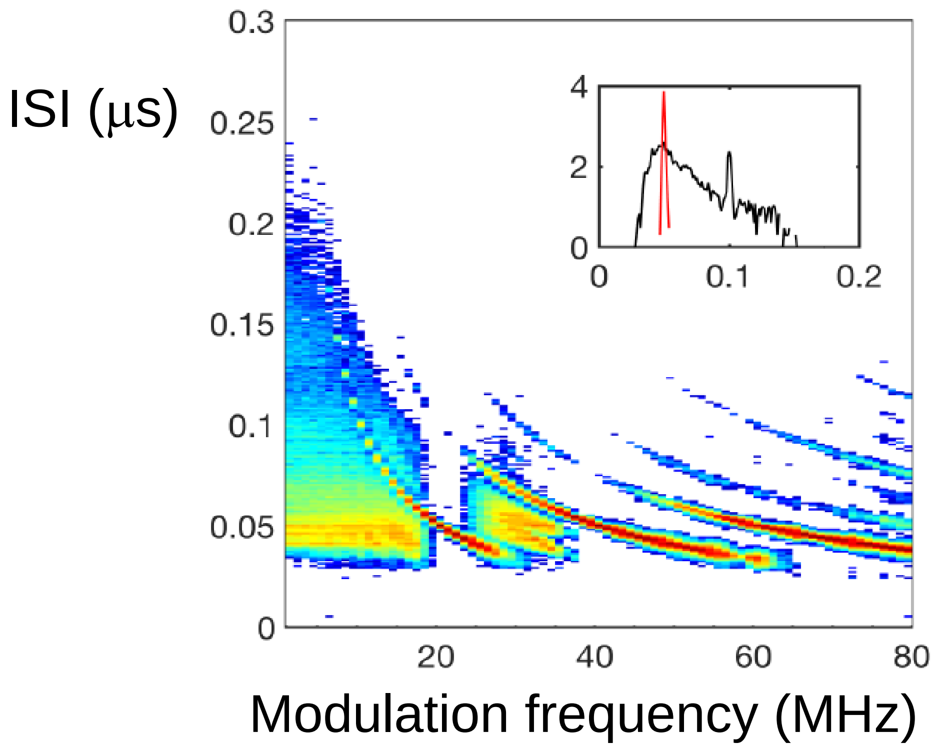
T. Sorrentino et al., JSTQE 21, 1801107 (2015)

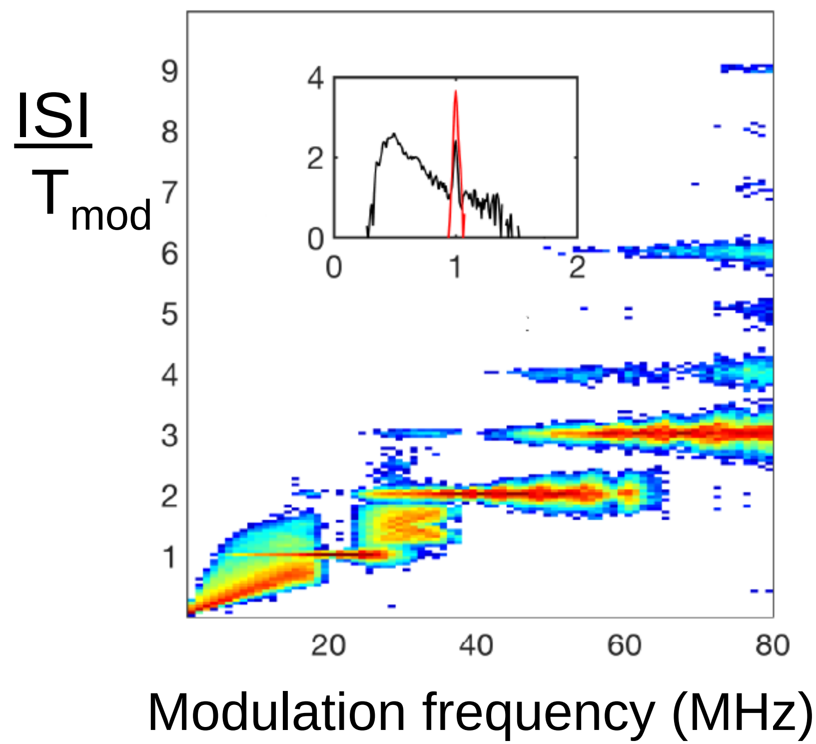
How to *control* the laser spikes?

How to *quantify* the degree of entrainment?

Inter-spike time interval distribution as a function of the frequency of the current modulation

I_{dc}= 27 mA (f_0=15 MHz), A_{mod} = 2.3% of I_{dc}

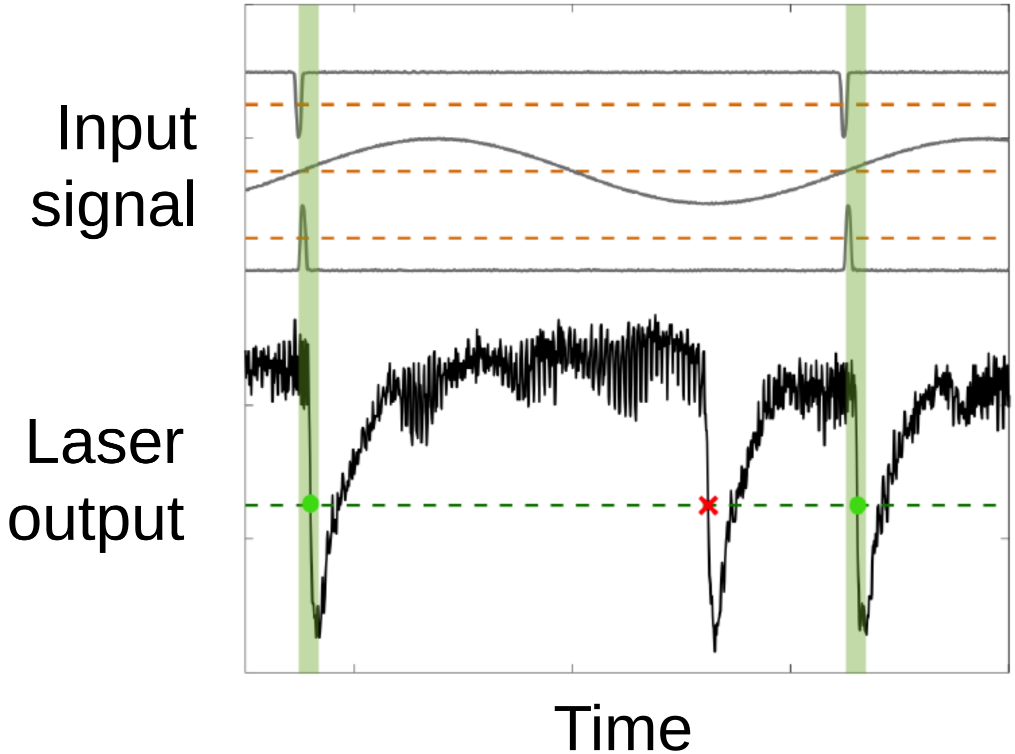




⇒ “refractory time” clear

⇒ “locking” horizontal

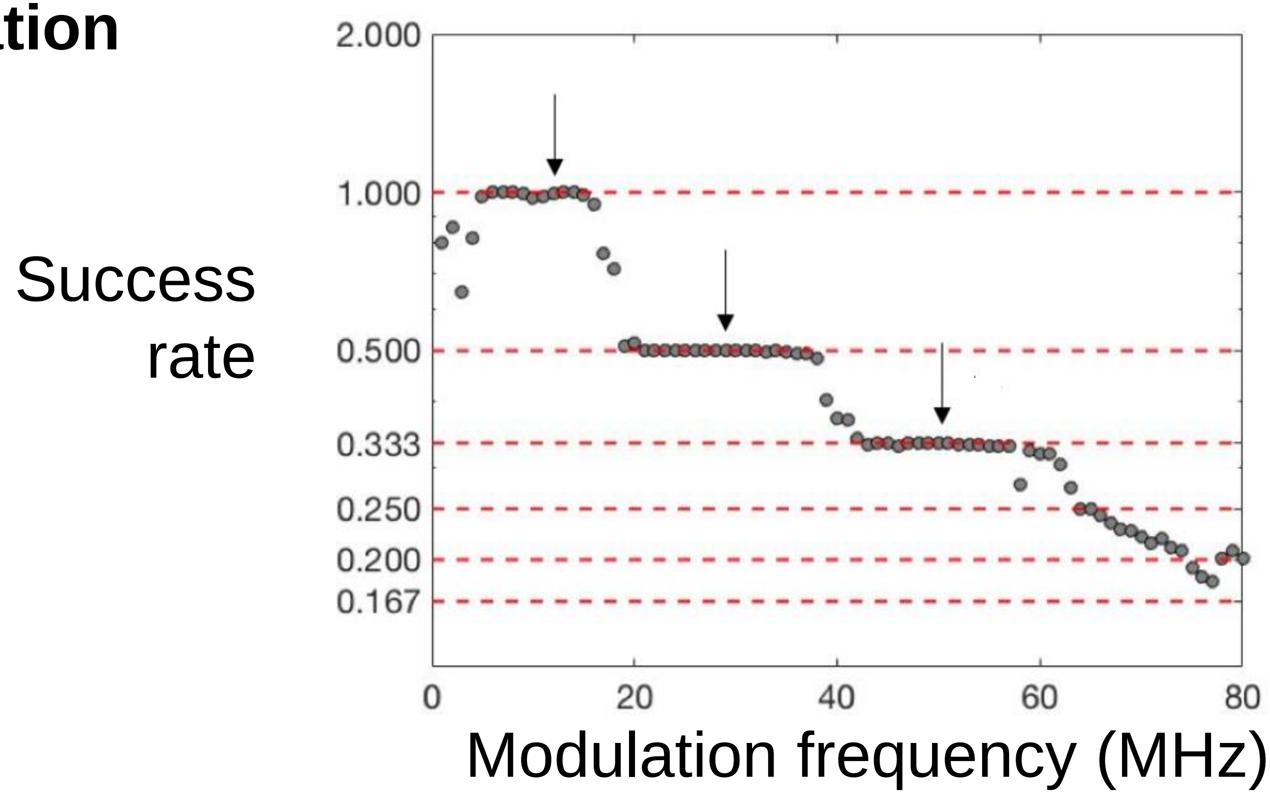
We test three modulation waveforms and quantify locking with the <u>success rate</u> and the <u>false positive rate</u>

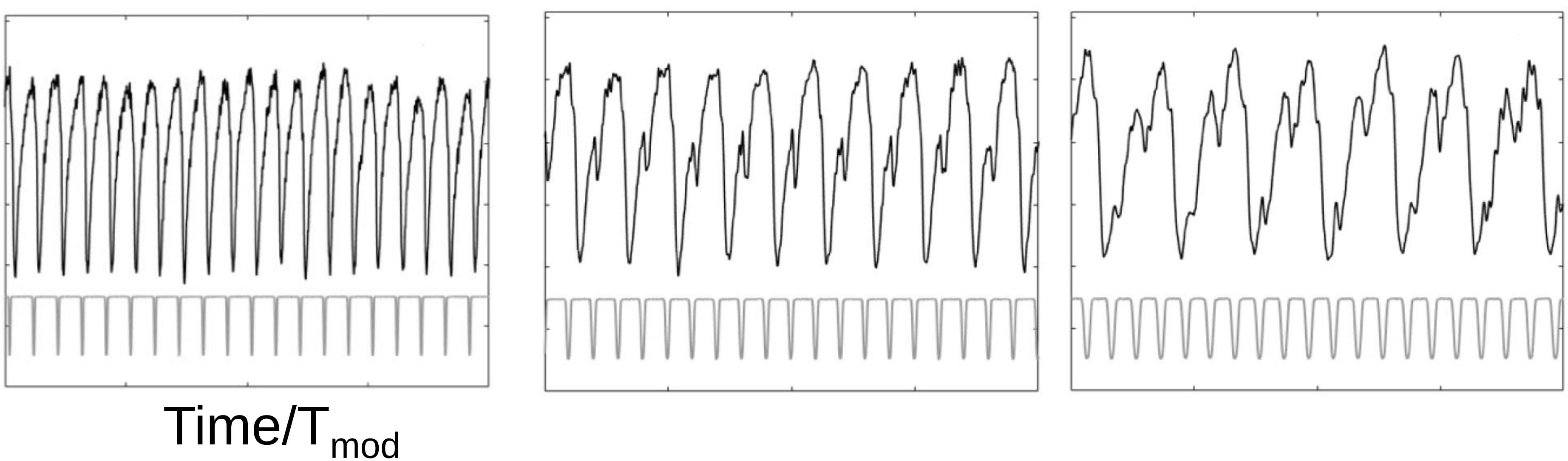


$$\mathrm{SR}(\tau) = \frac{\#\text{ of spikes emitted in the interval }\tau}{\#\text{ of modulation cycles}}$$

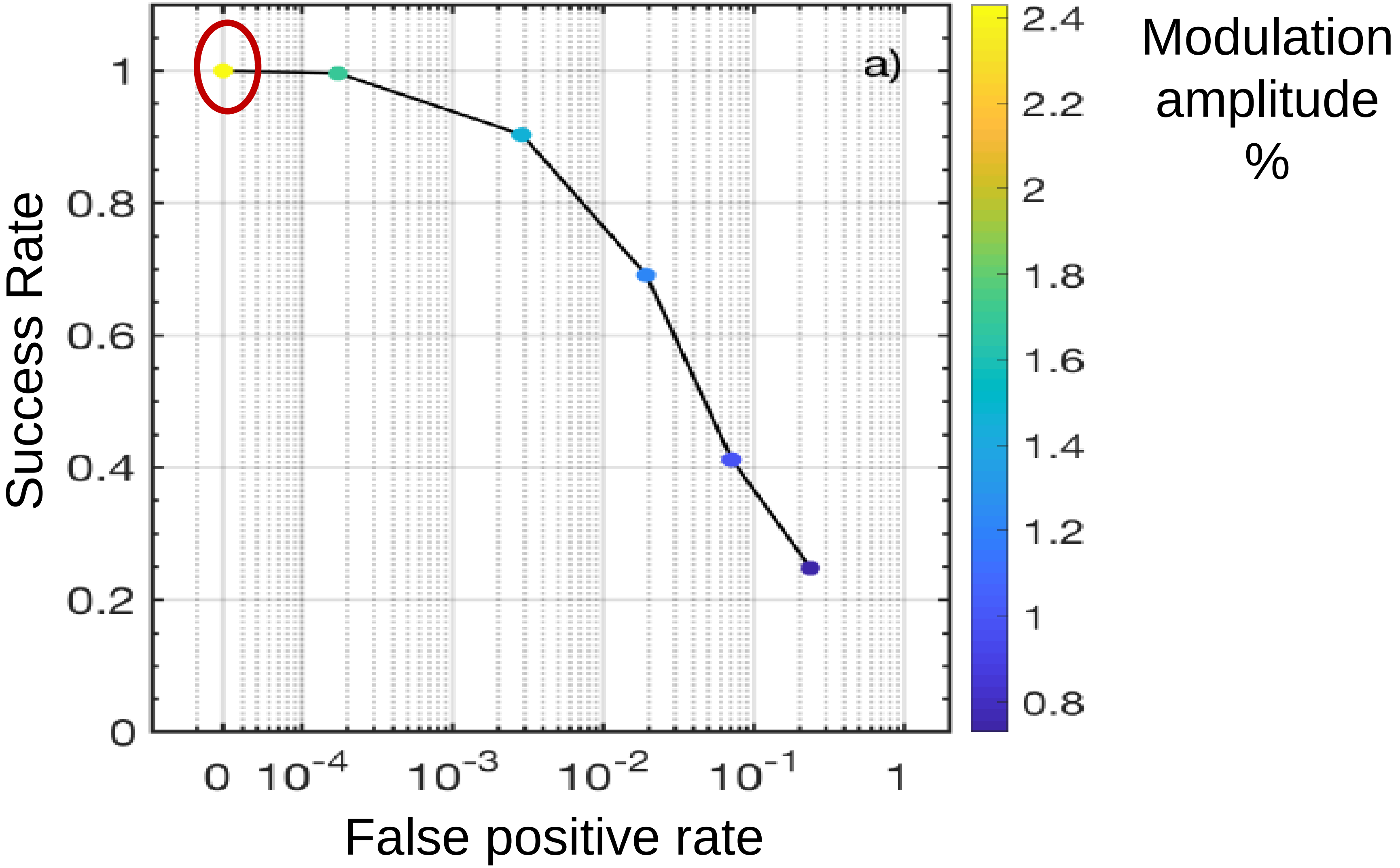
$$\mathrm{FPR}(\tau) = \frac{\#\text{ spikes that are not emitted in the time interval }\tau}{\text{Total }\#\text{ of spikes}}$$

Quantification



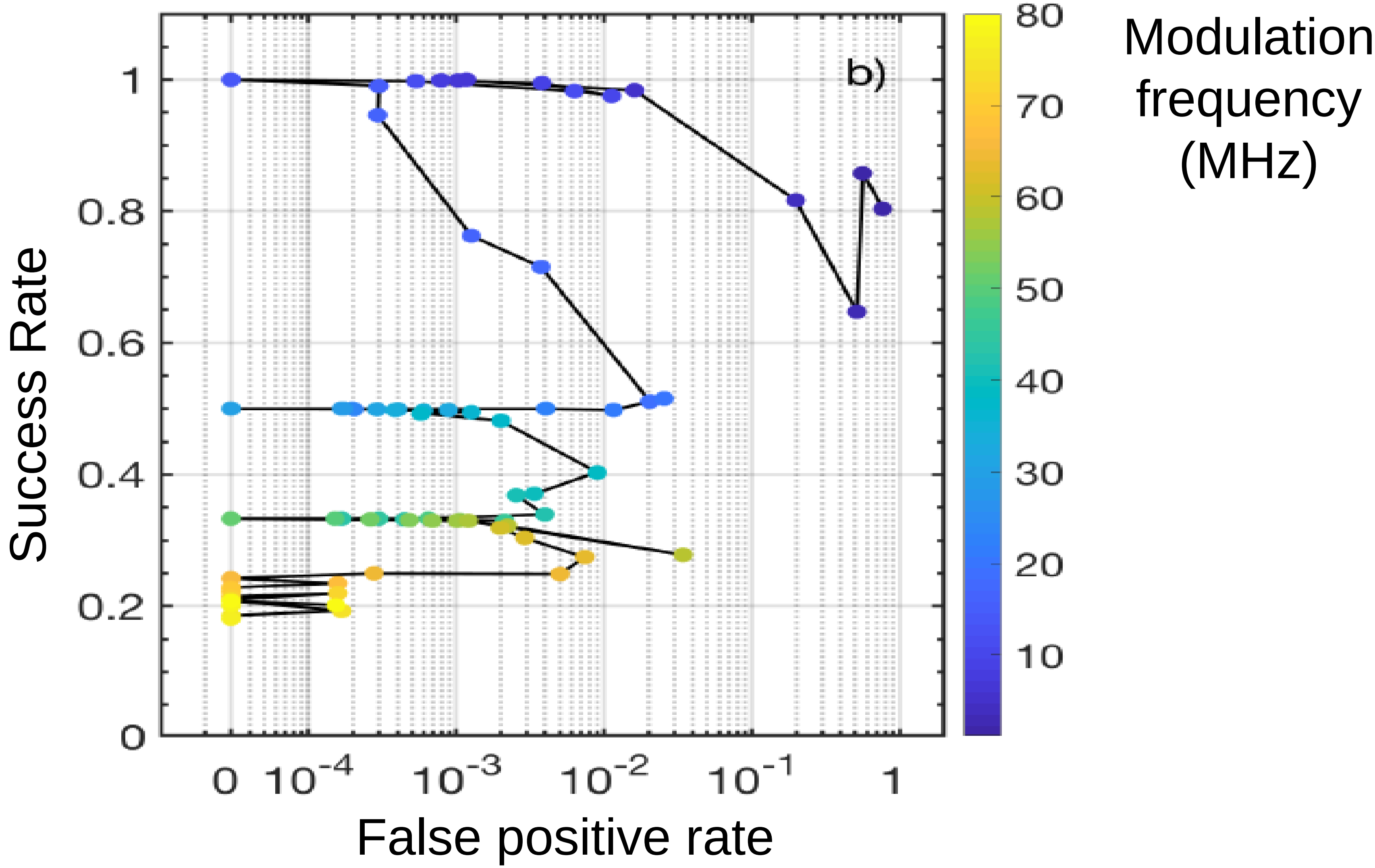


Receiver operating characteristic (ROC) curves



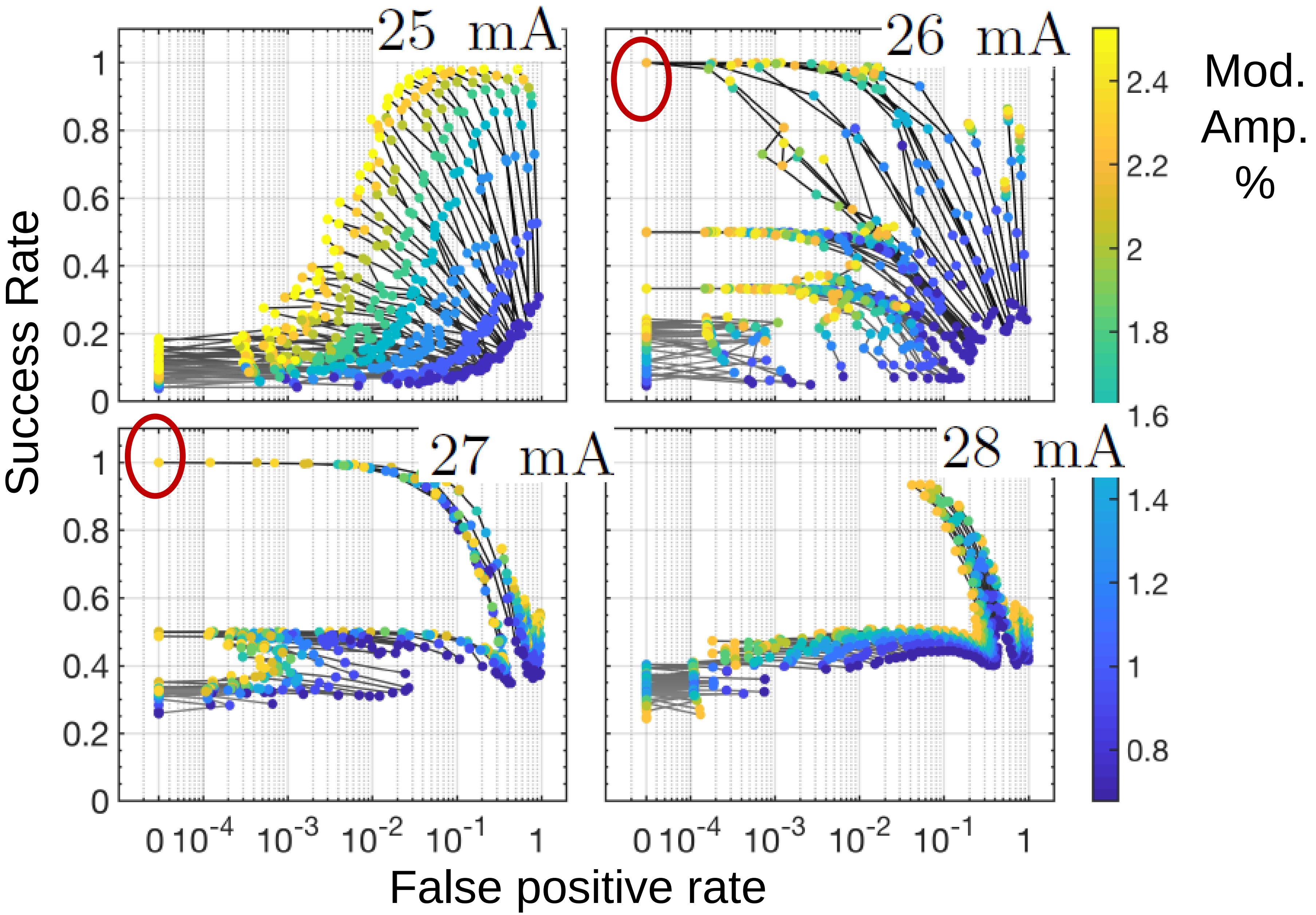
J. Tiana et al, PRE 99, 022207 (2019)

Locked-unlocked transitions when the modulation frequency increases



J. Tiana et al, PRE 99, 022207 (2019)

Role of the laser current (controls the natural spike rate)



What did we learn?

- Symbolic analysis of inter-spike-intervals uncovered preferred and infrequent spike patterns.
- Minimal model identified (a modified circle map).
- Good agreement between optical & neuron (synthetic) spikes.
- ROC curves allow to quantify the entrainment quality.
- Regions of perfect 1:1 locking identified.

Ongoing work: exploring the potential of the laser spikes for sensing applications (mechanical vibrations?)

To do in the future: The connection with the circle map needs to be explored.

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THANK YOU FOR YOUR ATTENTION !

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

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

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