Experimental study and control of optical pulses emitted by semiconductor lasers with feedback

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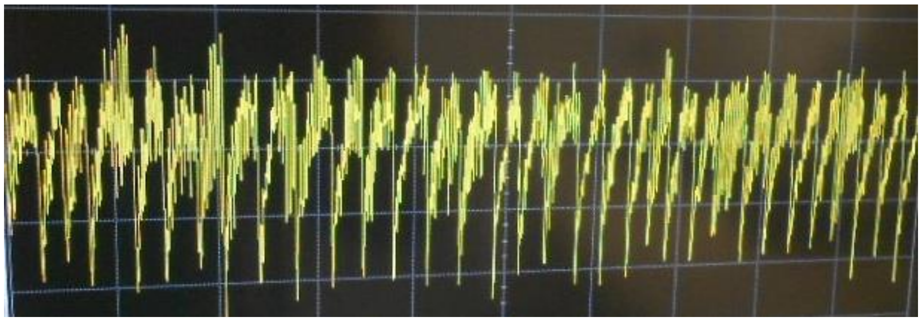
Campus d'Excel·lència Internacional

- Characterization of optical spikes
- Control via small electric perturbations

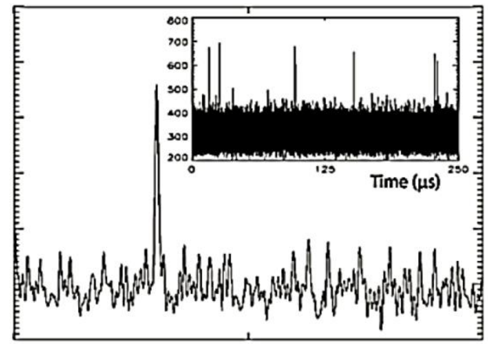
Lasers provide "big data" for testing analysis tools and can be "toy models" for testing control strategies

- Diode laser with time-delayed optical feedback



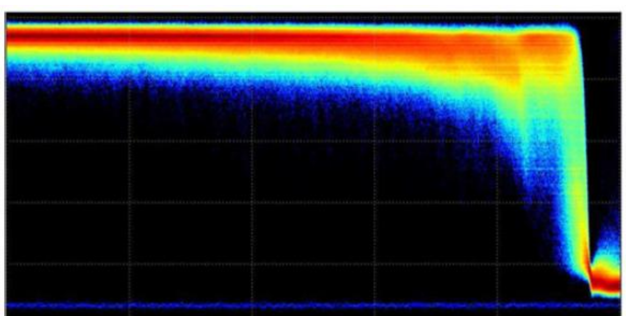
Time

- Extreme pulses
  (diode laser with injection)



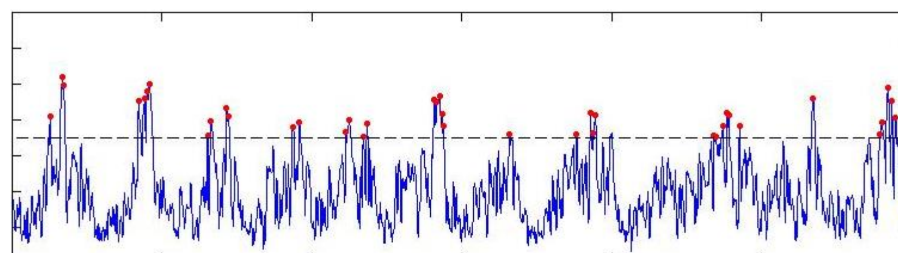
Time

- Polarization switching
  VCSEL



Time

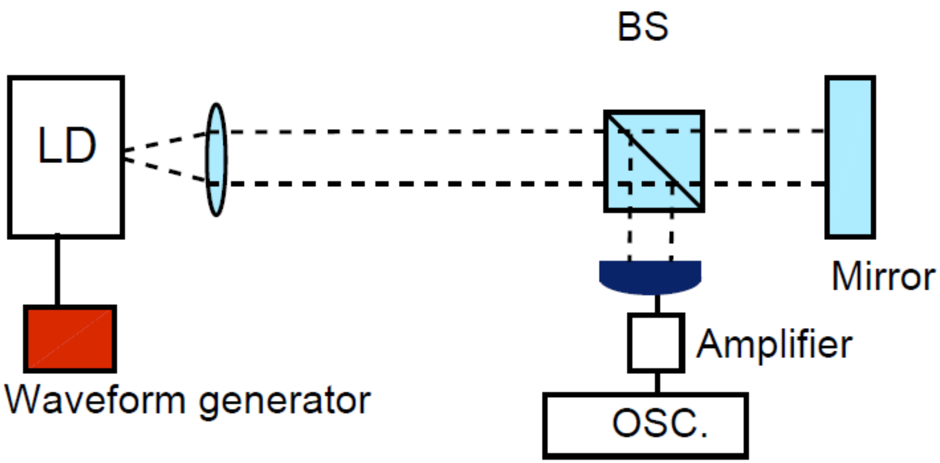
- Transition to optical turbulence
  Fiber laser

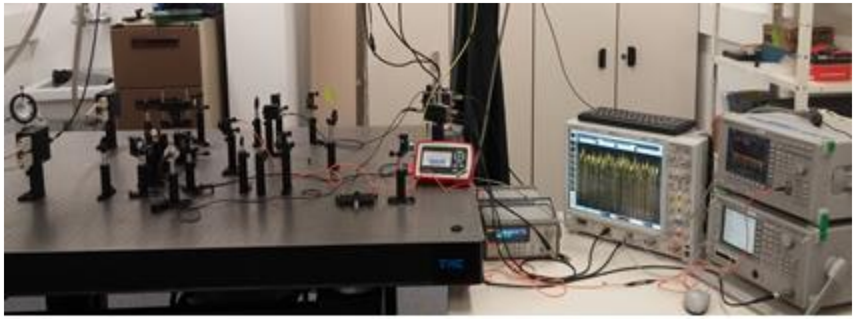


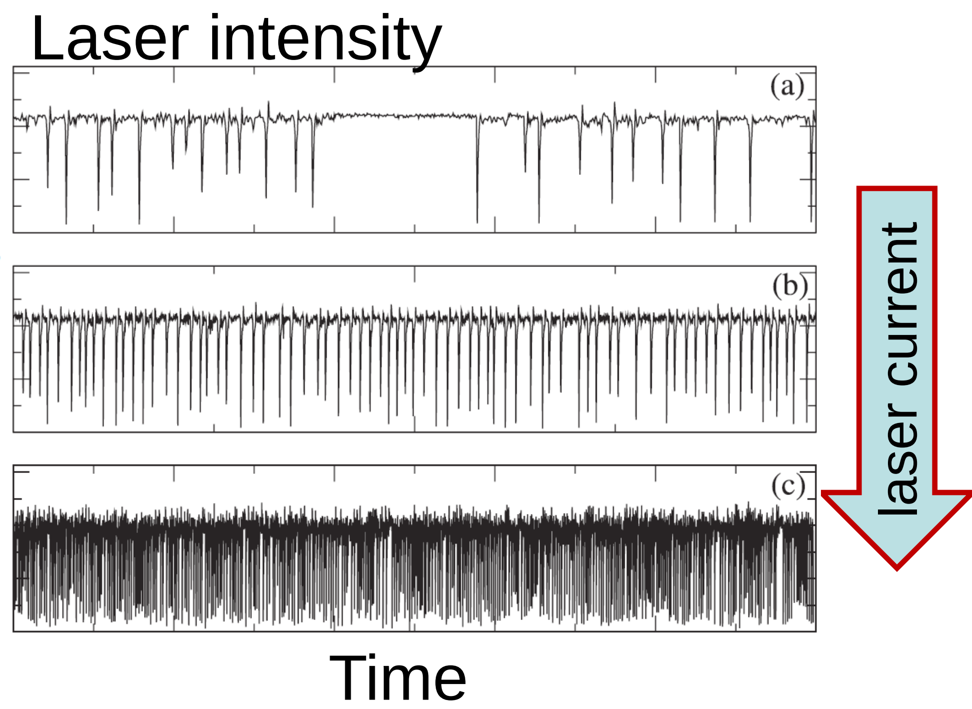
Time

Dynamical transitions are often difficult to identify and to characterize.

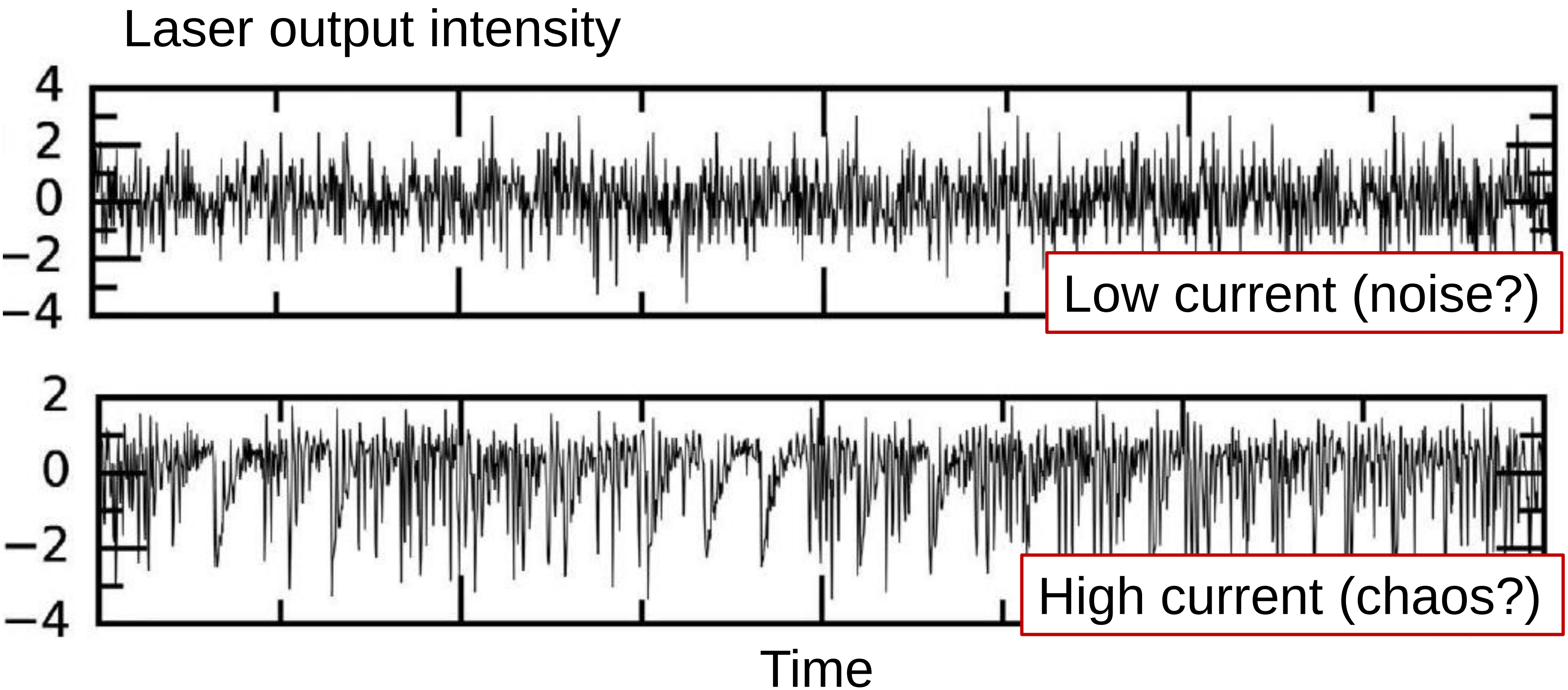
Example: diode laser with time delayed optical feedback







Video: [how complex signals emerge from optical noise]()



Can differences be quantified? With what reliability?

Different methods provide complementary information

- Many methods
  - Correlation analysis
  - Fourier analysis
  - Lyapunov & fractal analysis
  - Symbolic analysis
  - Wavelet analysis
  - Etc. etc.

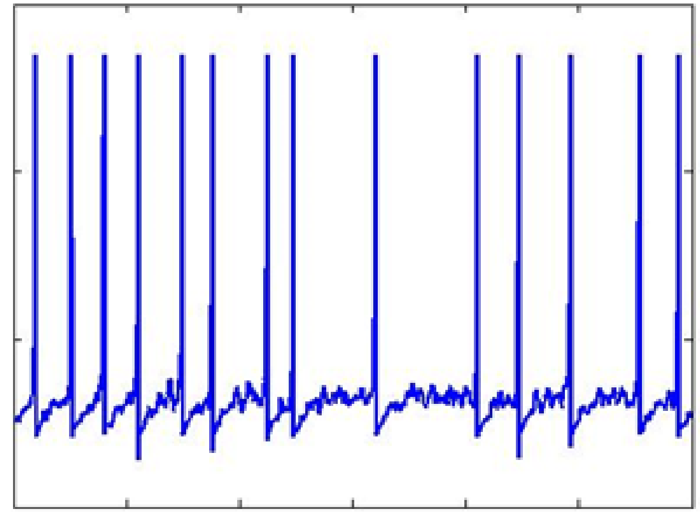
- The method to be used depends on the data
  - Length
  - Noise
  - Resolution
  - Etc.

How similar these time series are?

Optical spikes

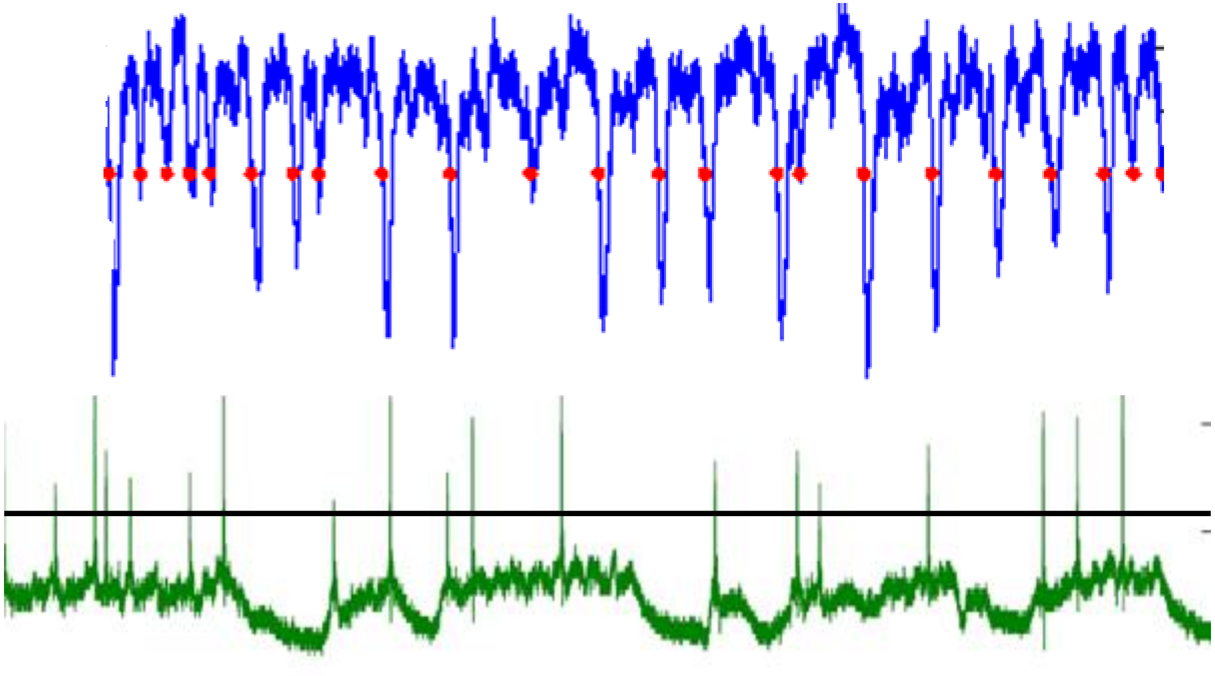
Time

Neuronal spikes



Time

Threshold crossings define ``events'' in a time series

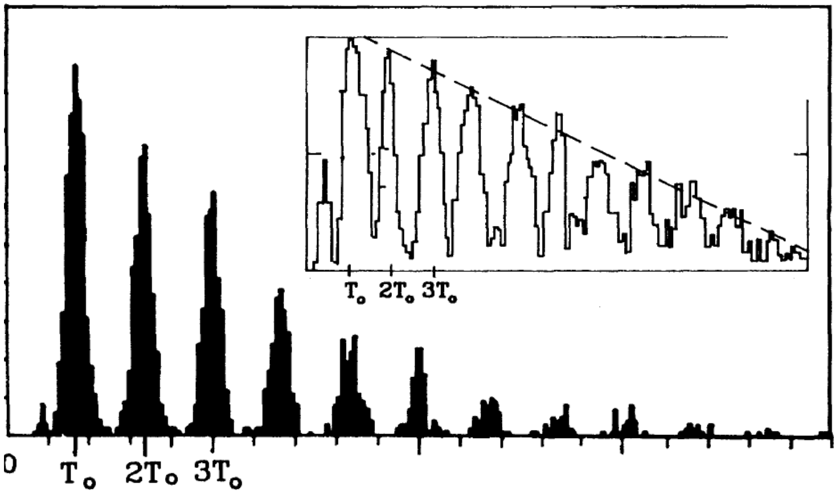


- Problems:
  - How to select the threshold?
  - Threshold dependent results?

inter-spike-intervals (ISIs): $\Delta T_i = t_{i+1} - t_i$

ISI distribution indicates that neurons and lasers have a similar response to external periodic forcing

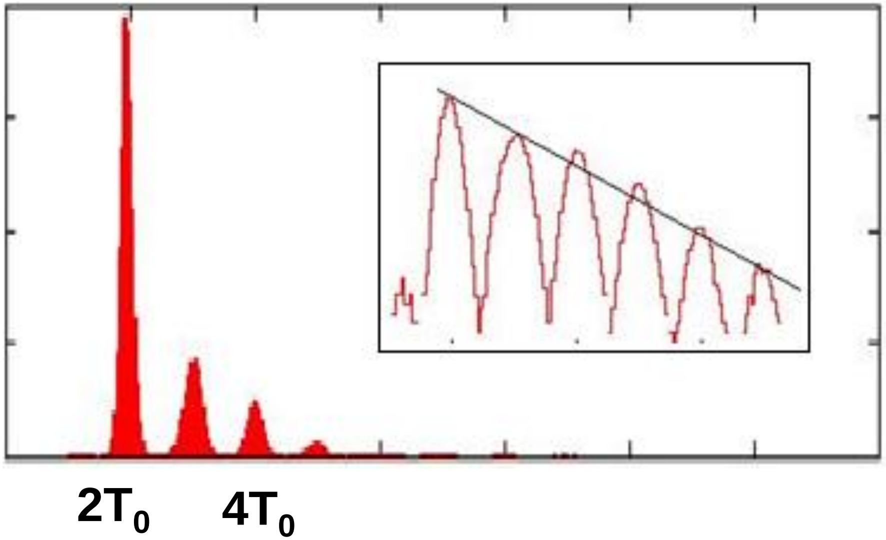
Neuron data



Single auditory nerve fiber of a squirrel monkey with a sinusoidal sound stimulus applied at the ear.

A. Longtin et al PRL (1991)

Laser data

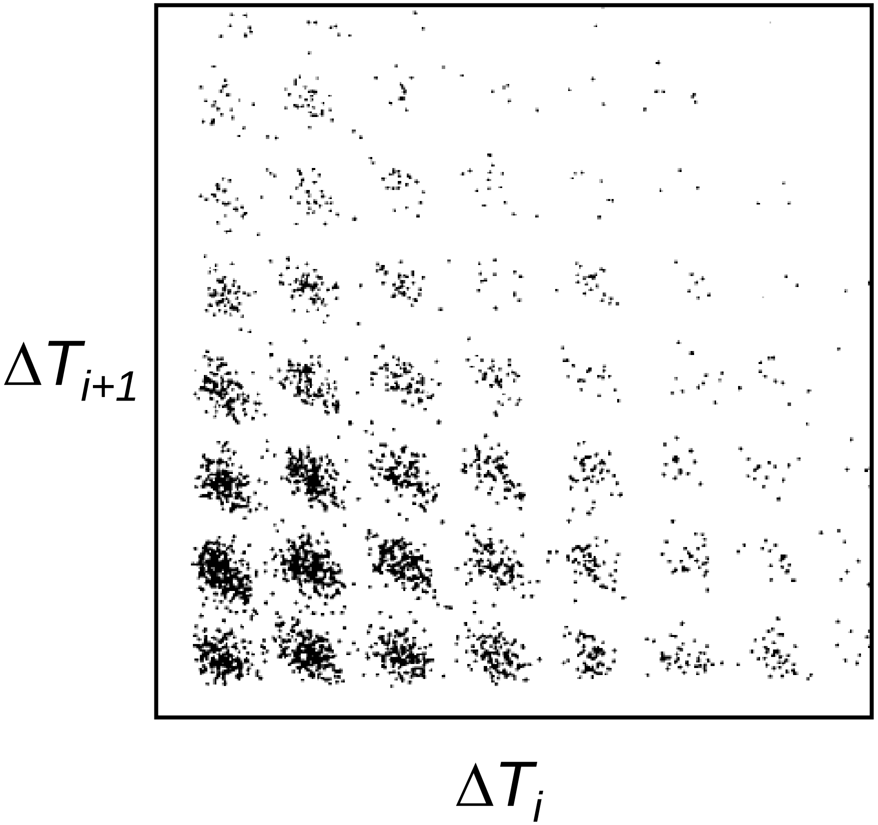


Data recorded in our lab when a sinusoidal signal is applied to the laser current.

A. Aragoneses et al Optics Express (2014)

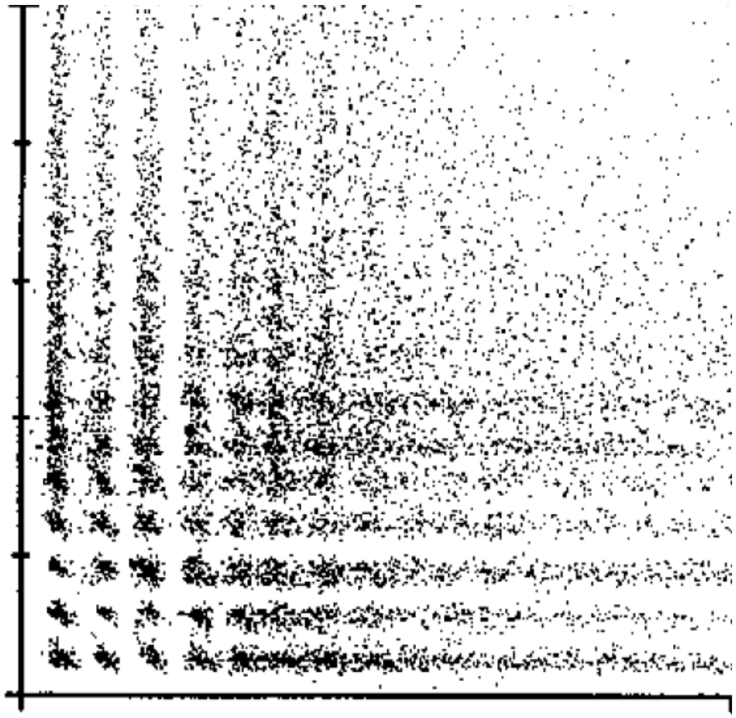
Return maps also suggest that neurons and lasers have similar response to external periodic forcing

Neuronal ISIs



A. Longtin
Int. J. Bif. Chaos (1993)

Laser ISIs



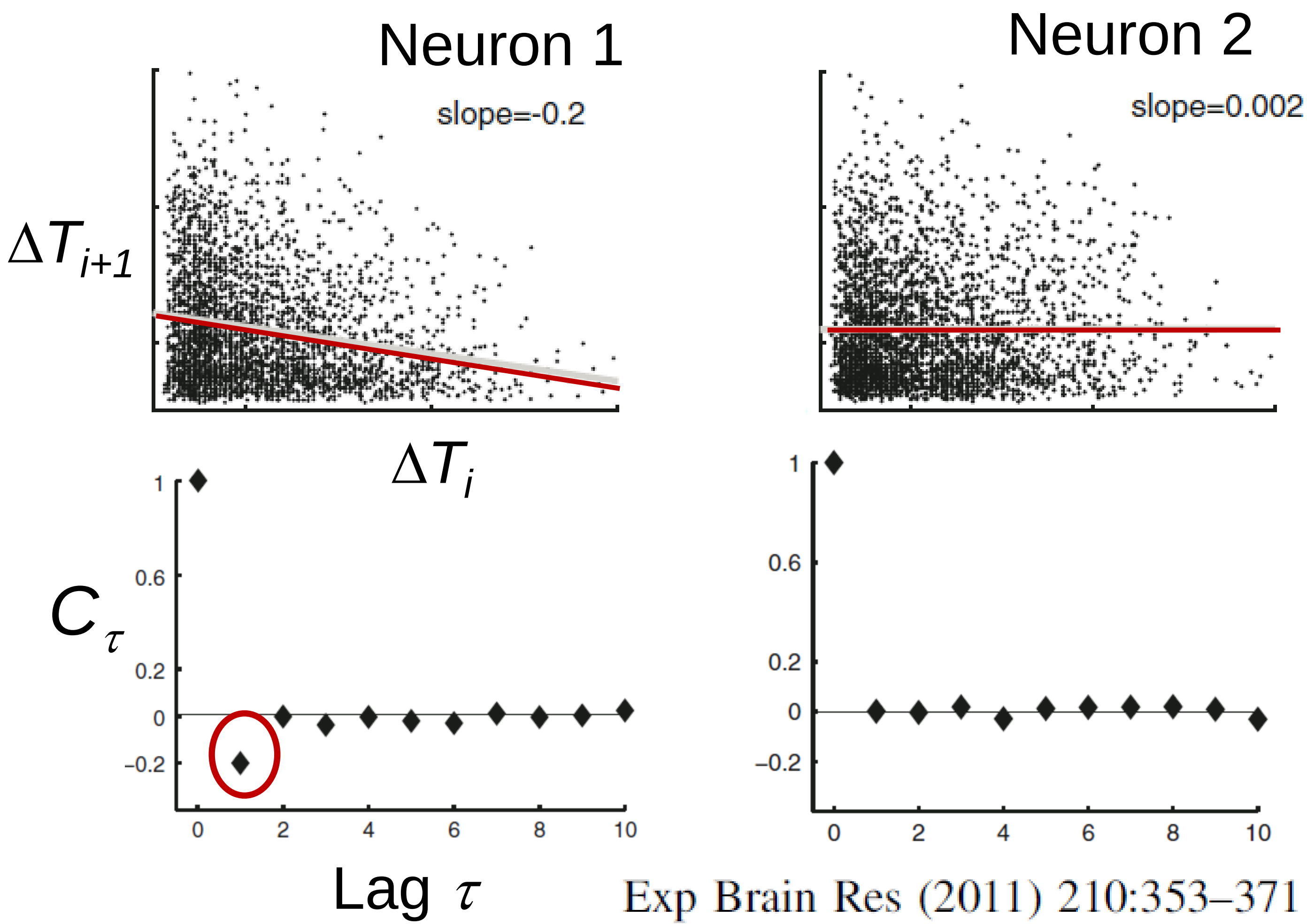
M. Giudici et al PRE (1997)
A. Aragoneses et al
Optics Express (2014)

ISI correlations uncover memory in neuron's firing activity

$$\{\ldots \Delta T_{i-\tau} \ldots \Delta T_i \ldots\}$$

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

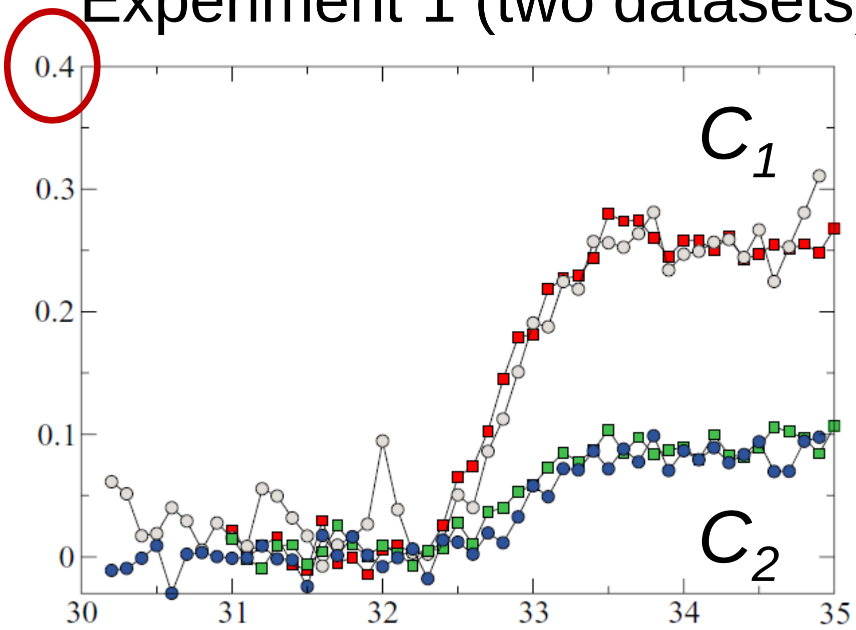
Also positive and alternating ISI correlations have been reported.



Exp Brain Res (2011) 210:353–371

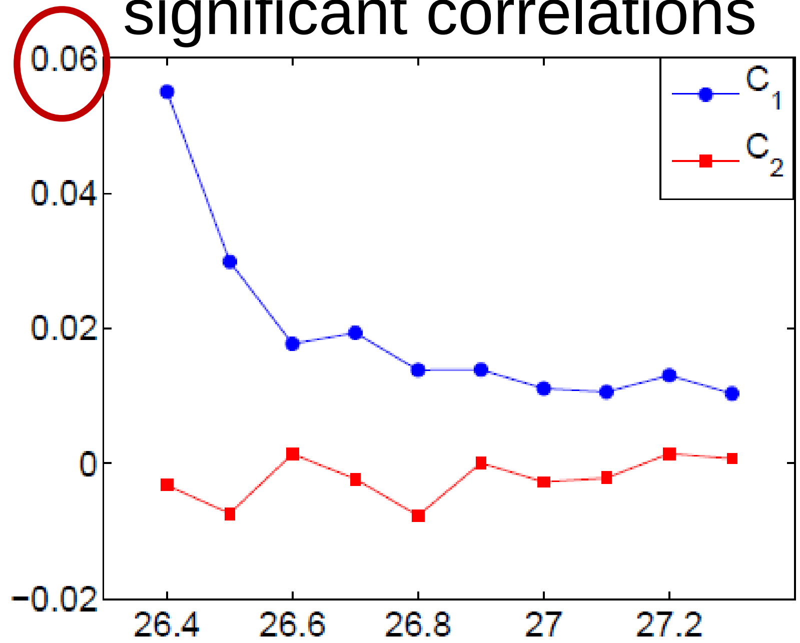
In the laser data, ISI correlations uncover transitions

Experiment 1 (two datasets)



Laser current

Experiment 2: no significant correlations



Laser current

- How to identify temporal order in the laser spikes?
- Are there more or less expressed spike patterns?

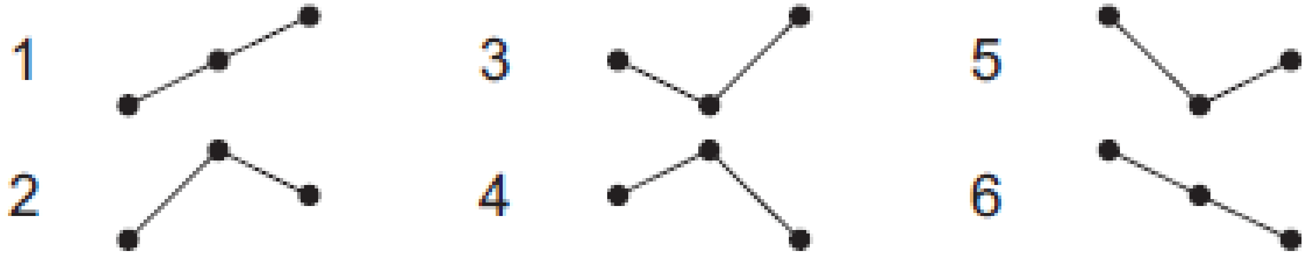
J. Tiana et al PRA (2010)

A. Aragoneses et al Sci. Rep. (2014)

Symbolic ordinal analysis

Ordinal analysis: a tool to look for 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?

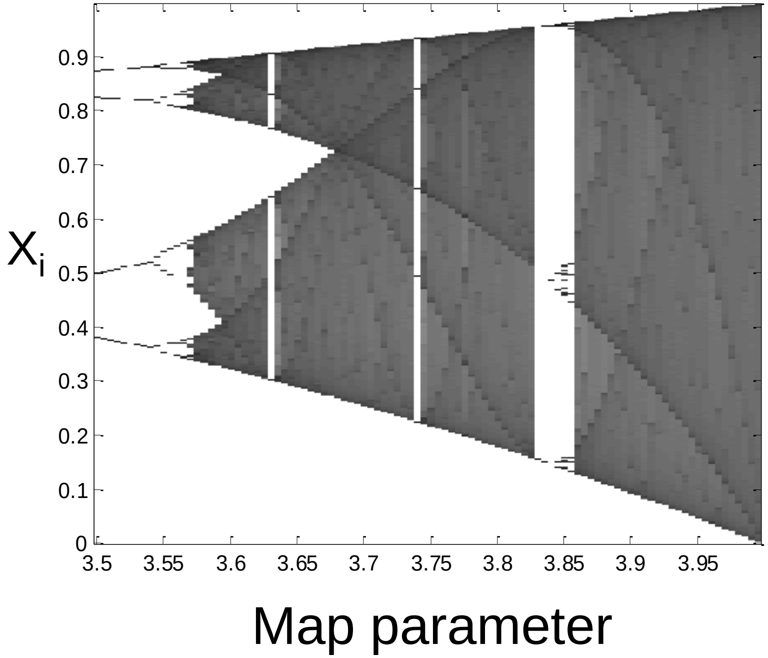


- Count how many times each “ordinal pattern” appears.
- Advantages: allows to identify temporal structures & is robust to noise.
- Drawback: information about actual data values is lost.

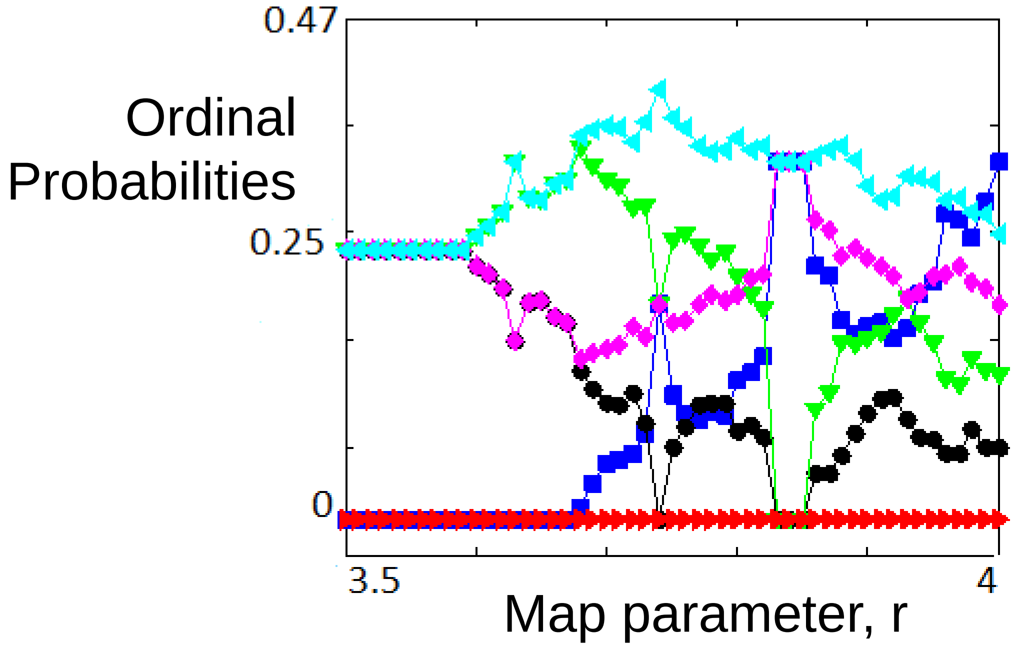
Bandt and Pompe PRL (2002)

Ordinal analysis yields complementary information

Normal bifurcation diagram

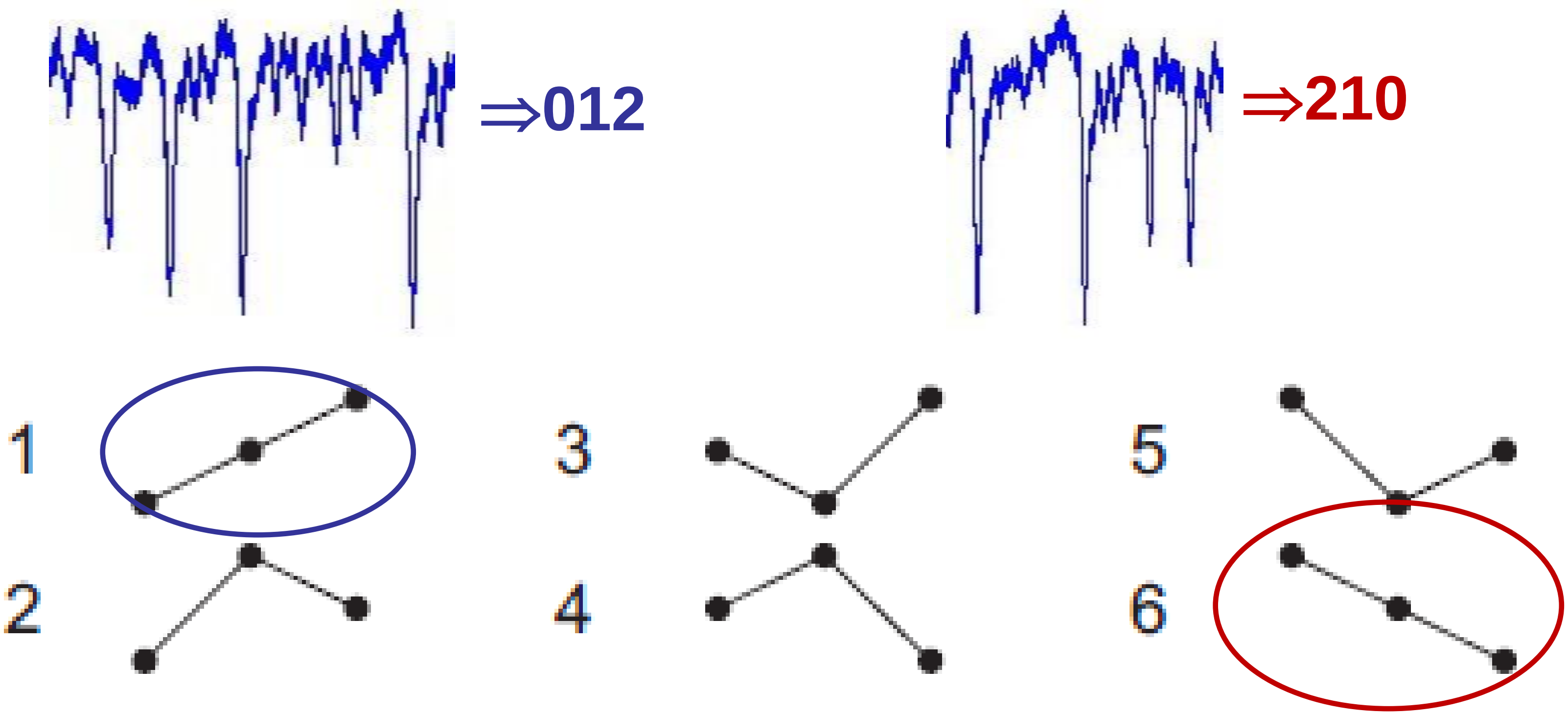


Ordinal bifurcation diagram



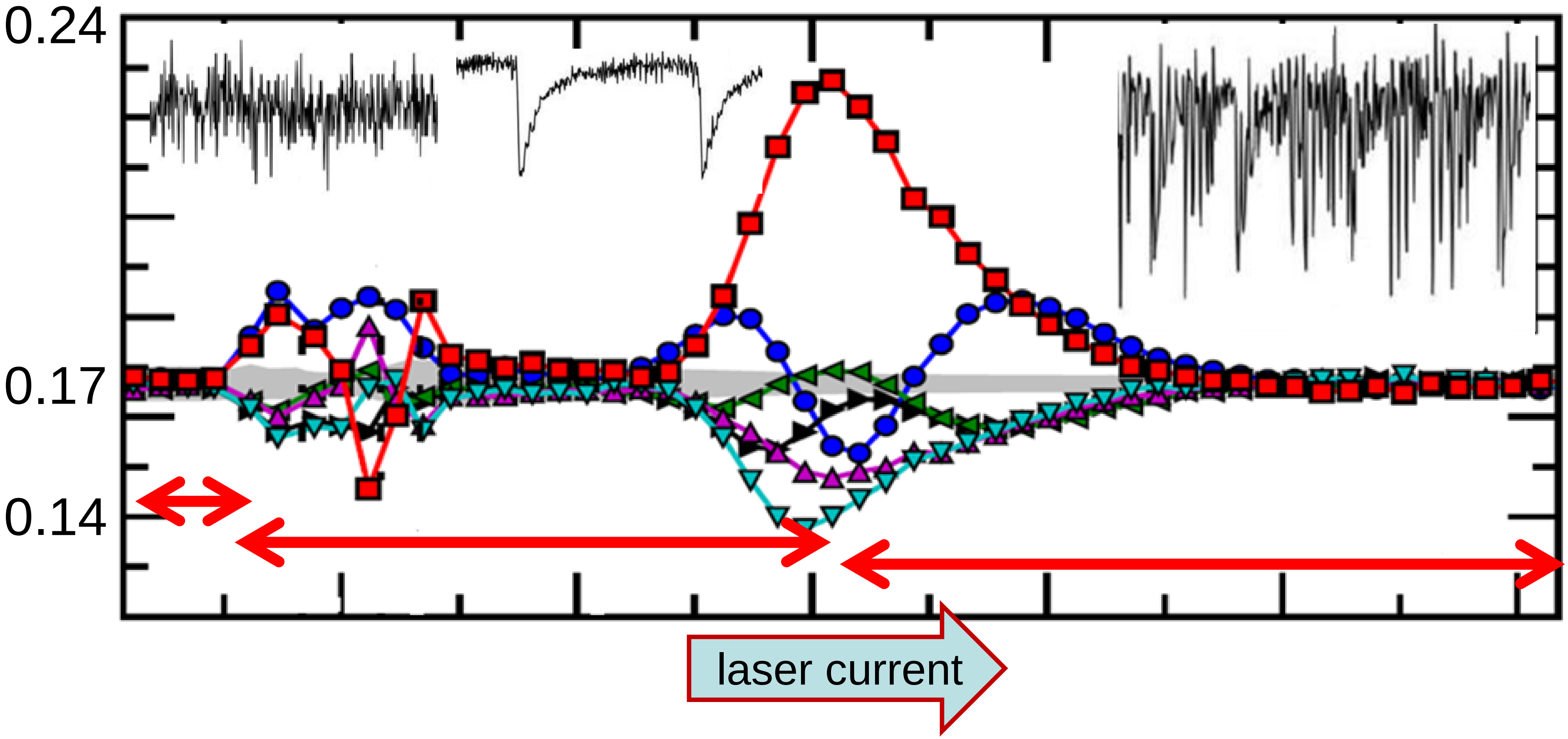
Pattern **6 (210)** is always forbidden; pattern **1 (012)** is more frequently expressed as r increases

Ordinal analysis of inter-spike intervals



Example of application:
How optical chaos emerges from noise?

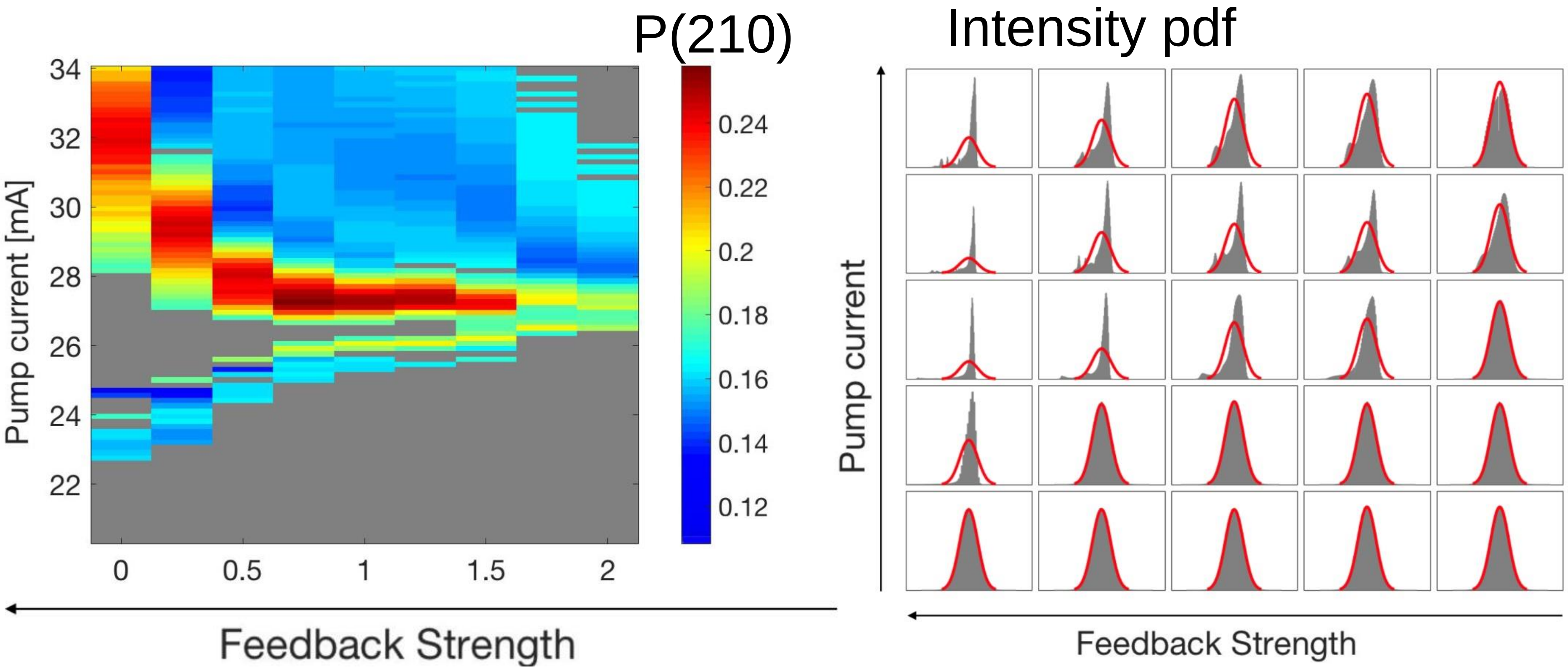
Ordinal analysis identifies the onset of different dynamical regimes, but does not distinguish "noise" and "chaos"



Grey region: probabilities are consistent with the uniform distribution ($P_i = 1/6 \cong 0.17\ \forall$ i) with 99.7% confidence level

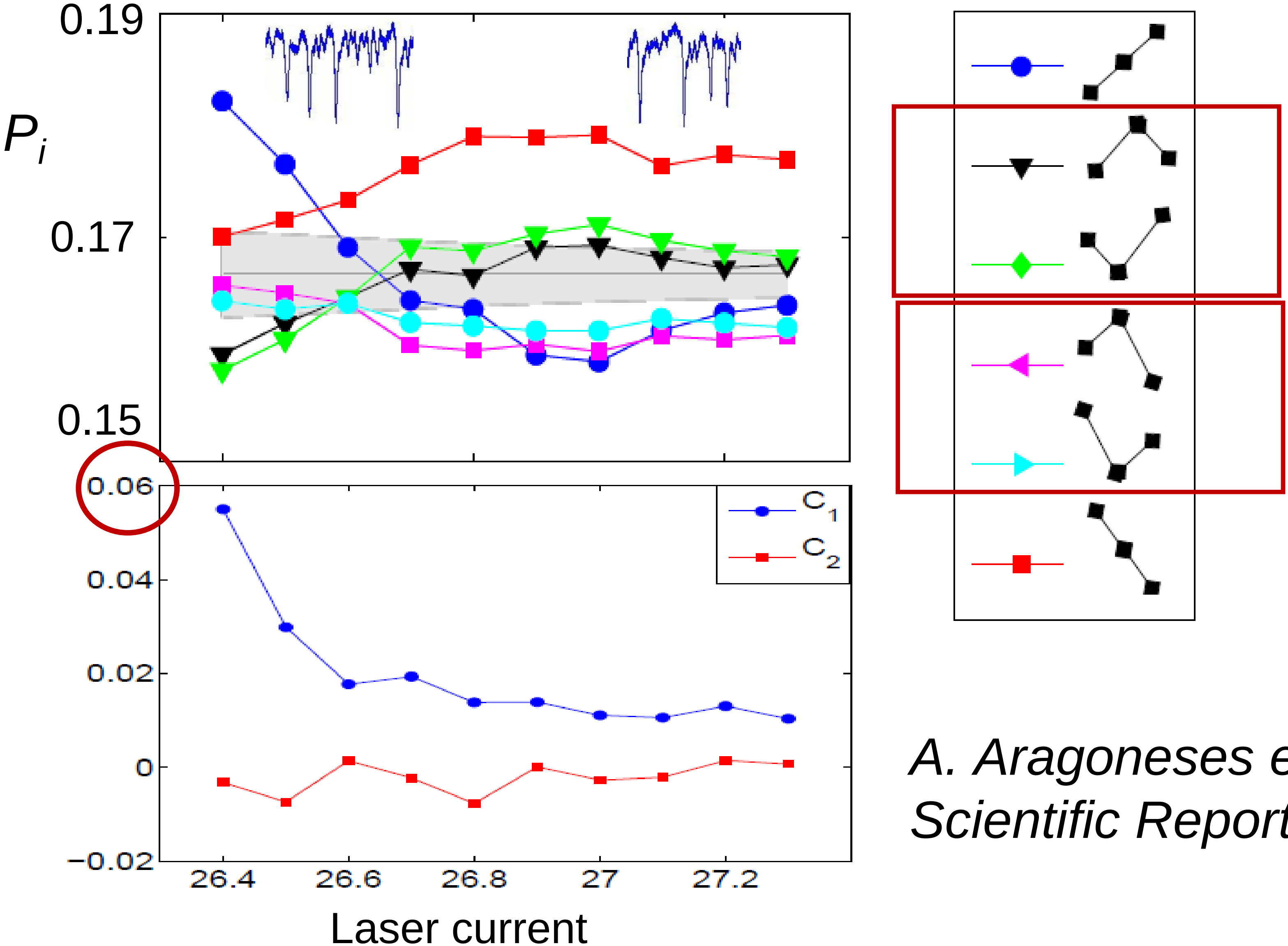
C. Quintero-Quiroz et al, Scientific Reports (2016)

P(210) identifies dynamical regimes in parameter space (pump current, feedback strength)



M. Panozzo et al, Chaos (2017)

Zooming into the region where spikes are well-defined, a transition is detected (not captured by correlation analysis)



A. Aragoneses et al
Scientific Reports (2014)

A modified circle map: simple minimal model

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

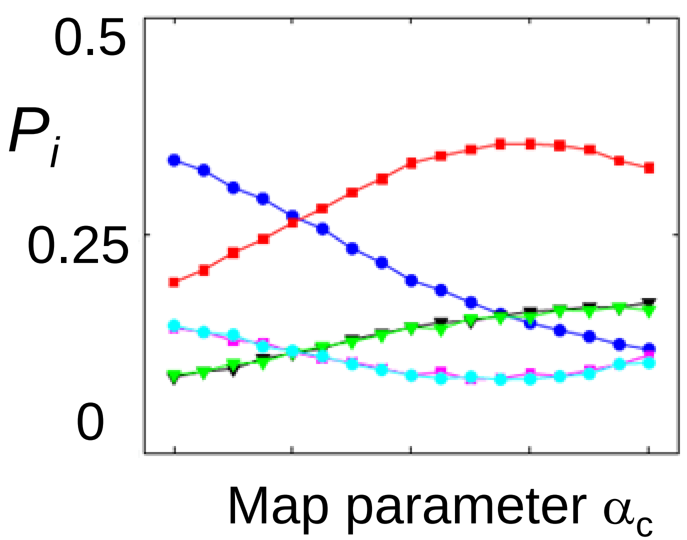
$$X_i = \varphi_{i+1} - \varphi_i$$

$\rho = \dfrac{\text{natural frequency}}{\text{forcing frequency}}$

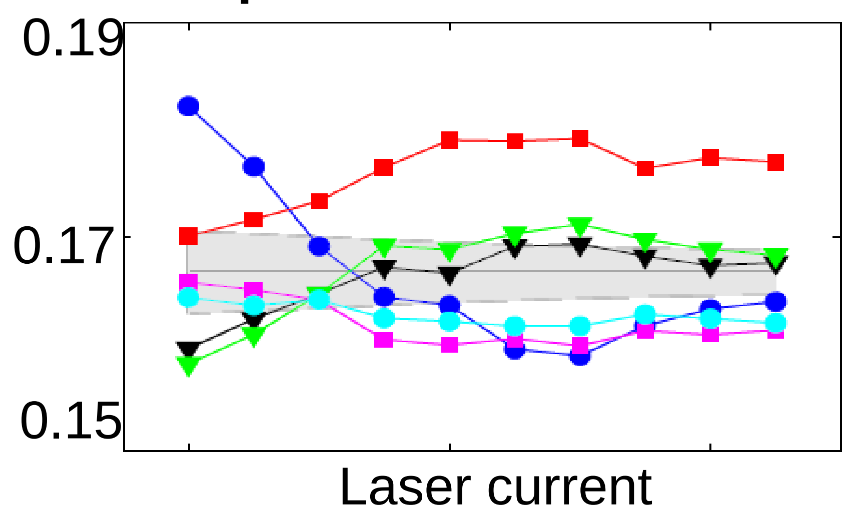
K = forcing amplitude

D = noise strength

Circle map data



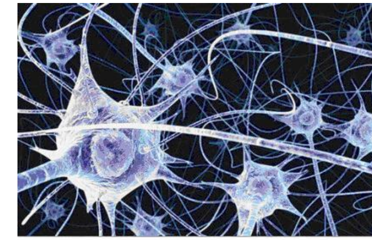
Empirical laser data



Same “clusters” & same hierarchical structure

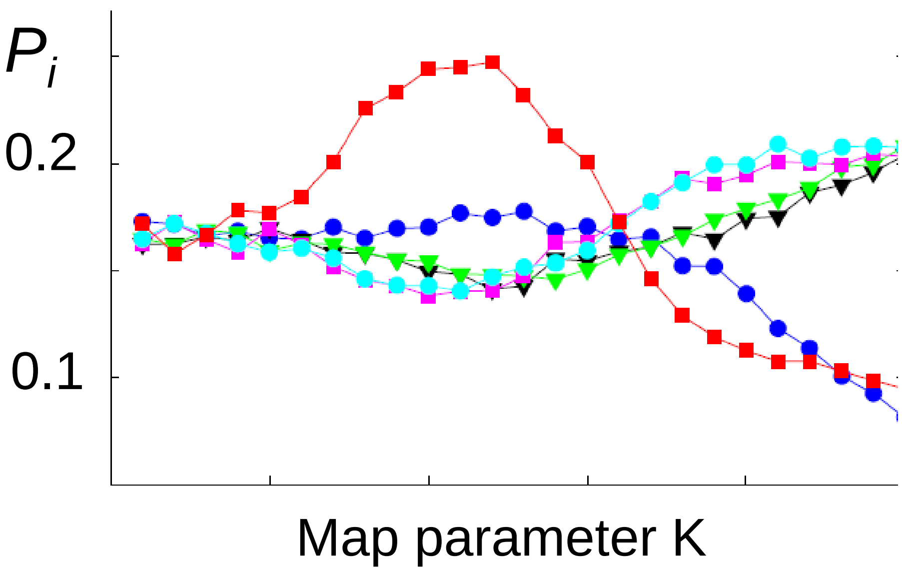
A. Aragoneses et al Scientific Reports (2014)

Connection with neurons: the circle map describes many excitable systems

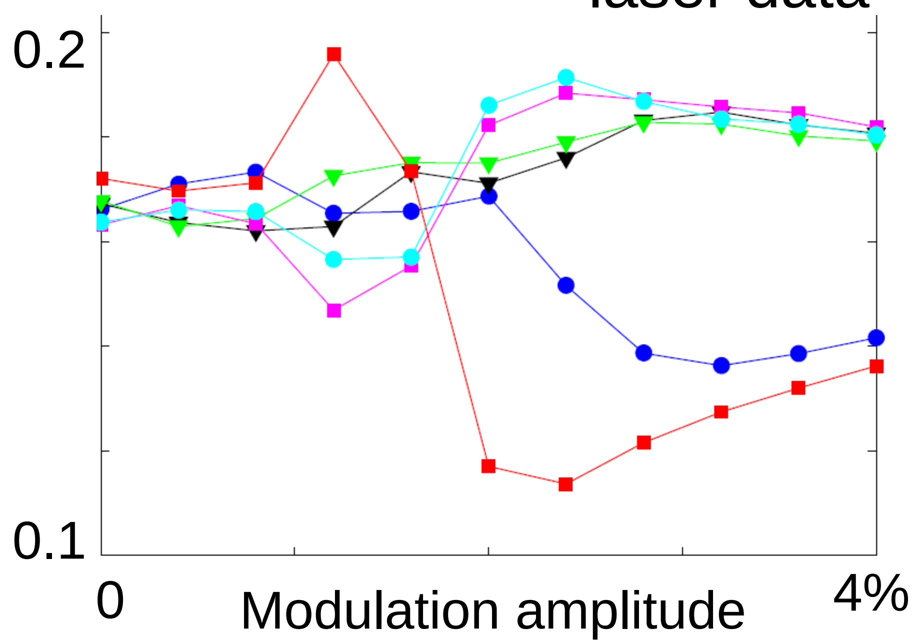


- The modified map describes spike correlations in sensory neurons (Neiman and Russell, PRE 2005)
- Can we test its validity as a minimal model for the laser spikes?

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



laser data

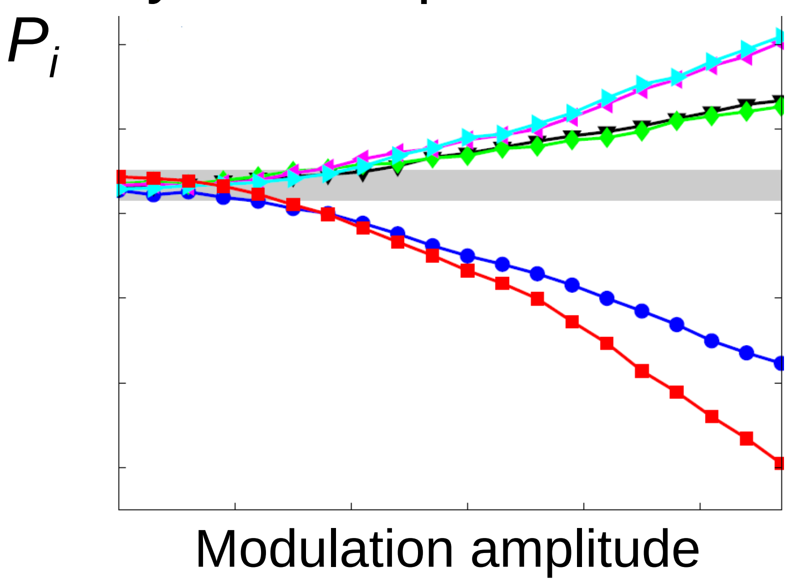


Comparing with synthetic neuronal spikes: good agreement

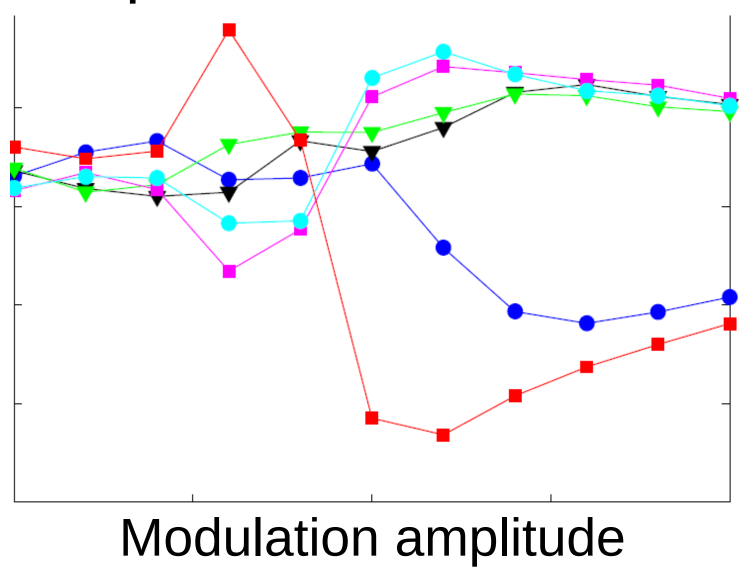
FHN model with Gaussian white noise and **weak** sinusoidal input: spikes are noise-induced

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

Synthetic spikes

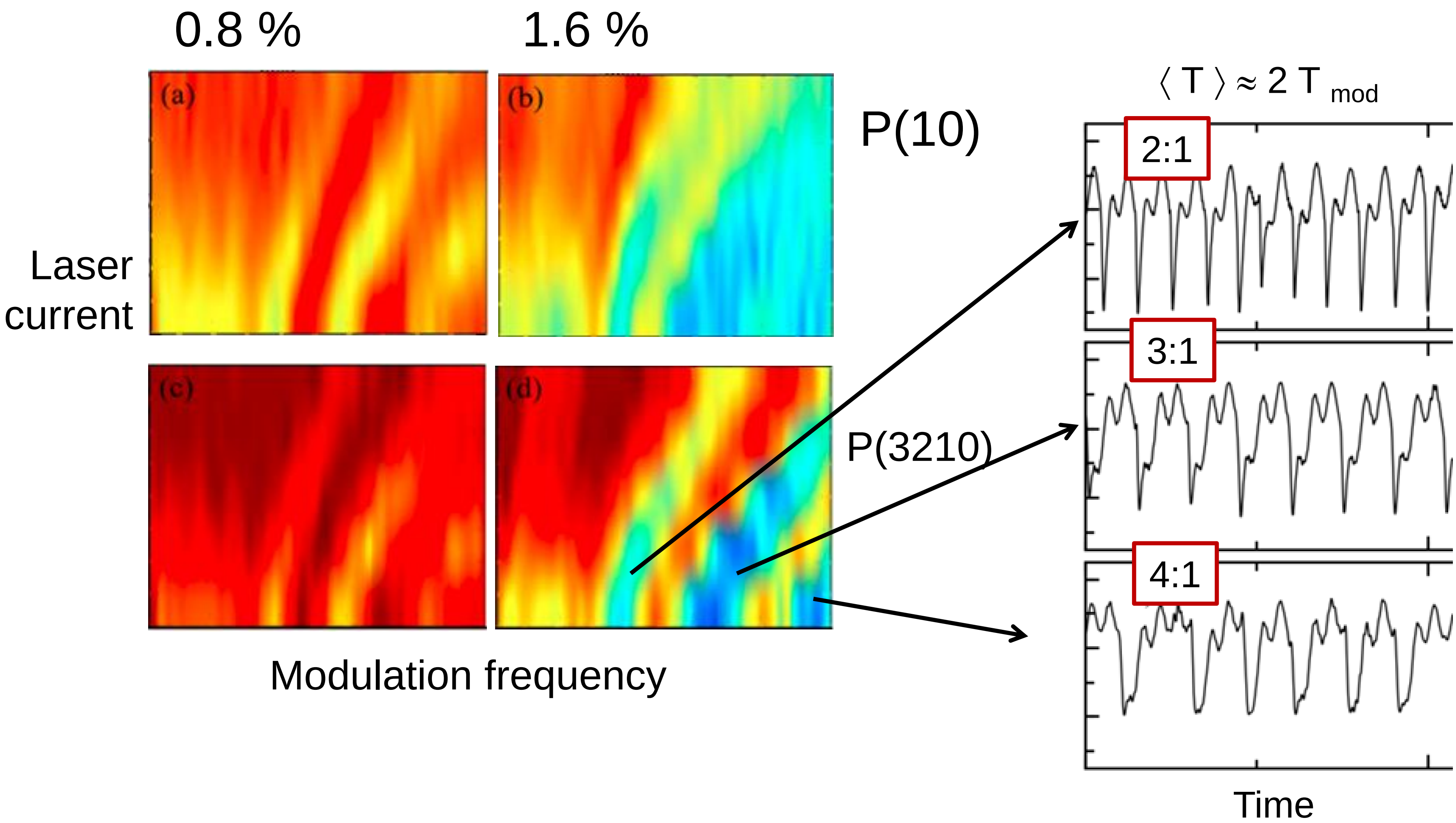


Empirical laser data



Aparicio-Reinoso et al, PRE (2016)

Ordinal probabilities uncover the regions of noisy locking



T. Sorrentino et al, JSTQE (2015)

How to *control* the laser spikes? How to *quantify* the degree of entrainment?

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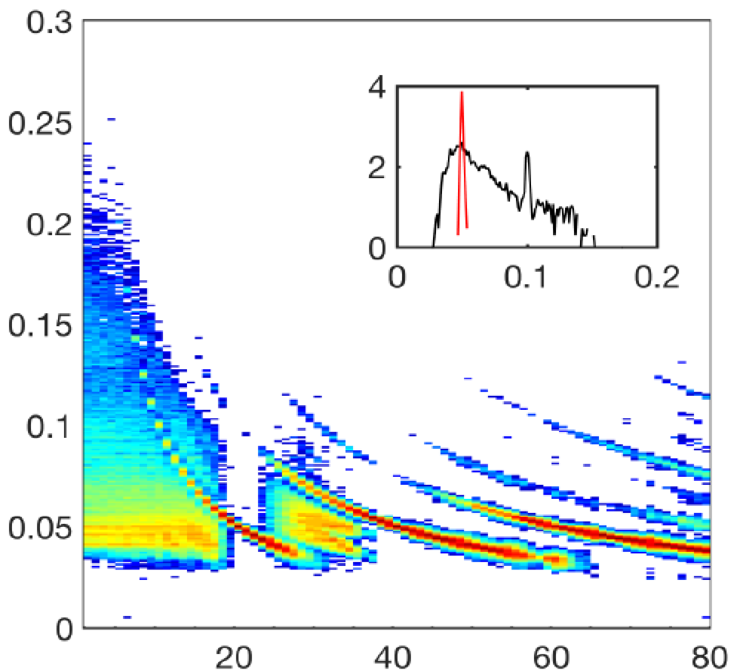
Gaining insight into the locking regions: the inter-spike time interval (ISI) distribution as a function of the frequency of the external forcing

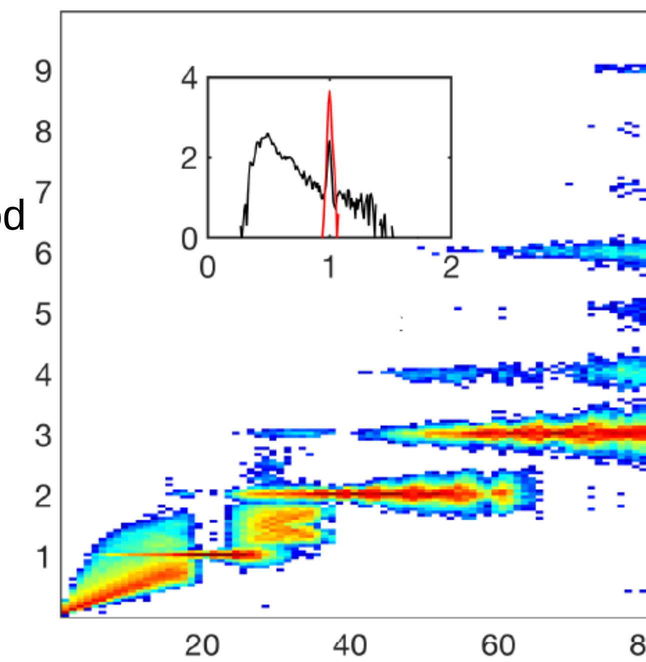
$A_{mod} = 2.3\%$ of I_{dc}

ISI (μs)



Modulation frequency (MHz)

$\frac{ISI}{T_{mod}}$

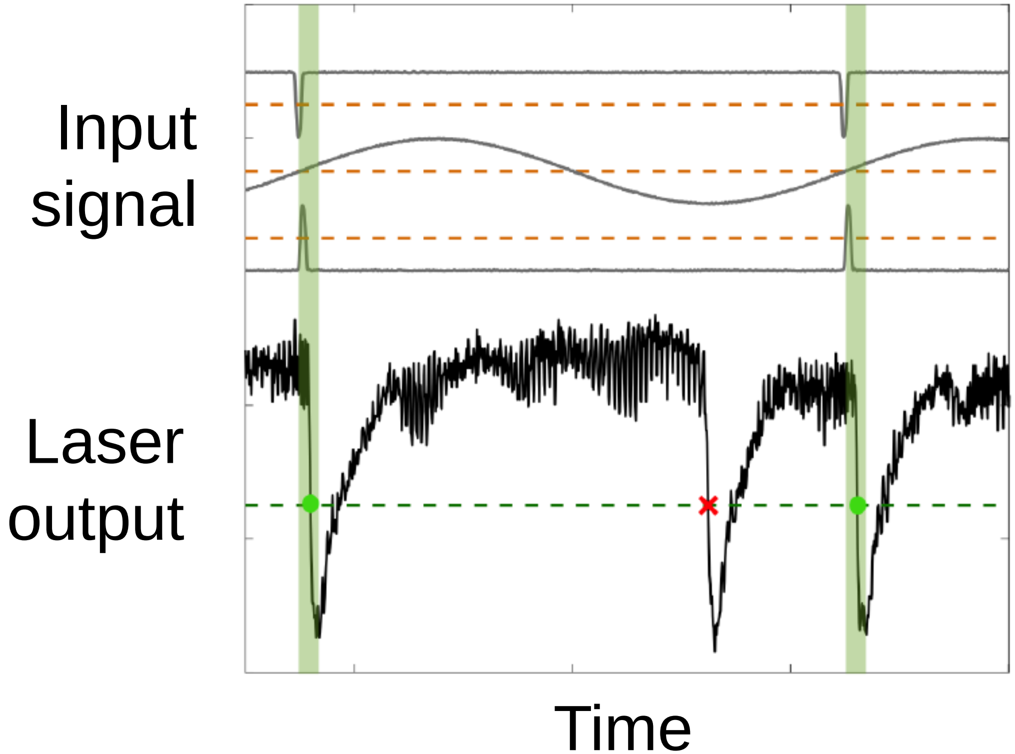


Modulation frequency (MHz)

⇒ "refractory time" clear

⇒ "locking" horizontal

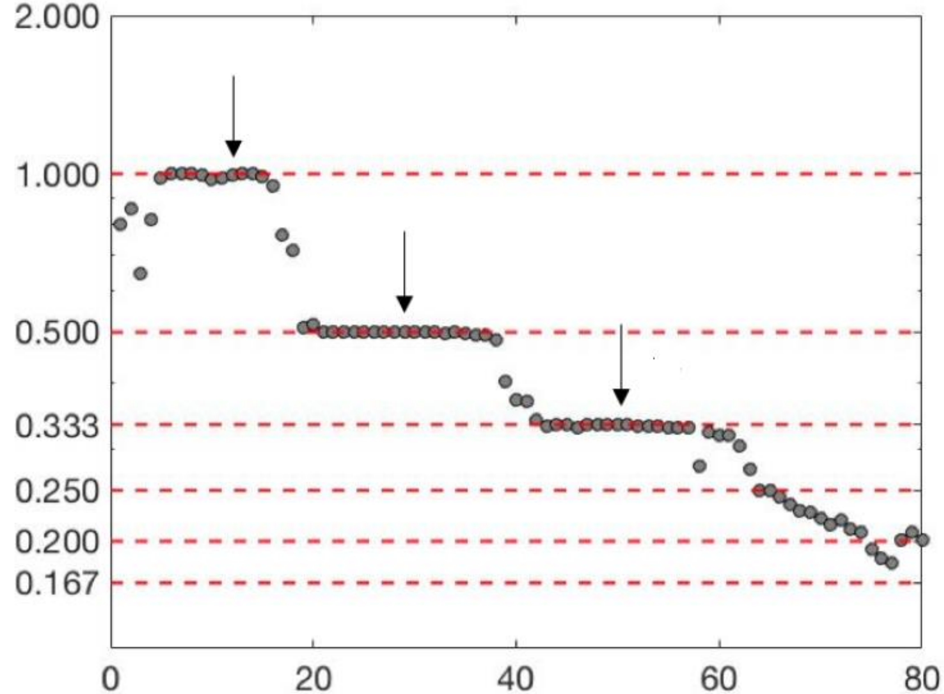
We test three modulation waveforms and quantify locking with the <u>success rate</u> and the <u>false positive rate</u>

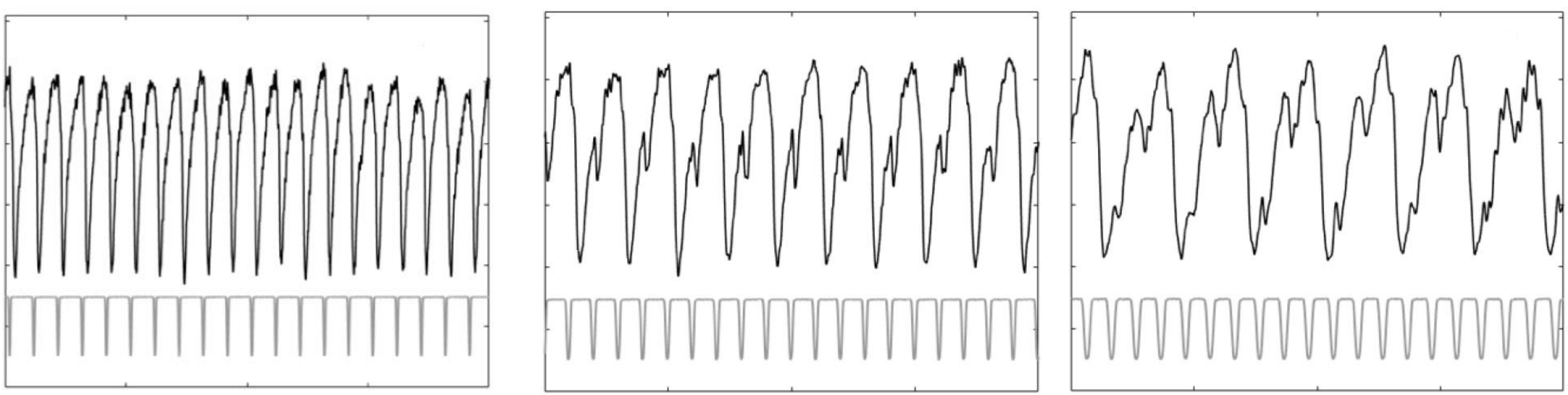


$$\mathrm{SR}(\tau) = \frac{\text{\# of spikes emitted in the interval } \tau}{\text{\# of modulation cycles}}$$

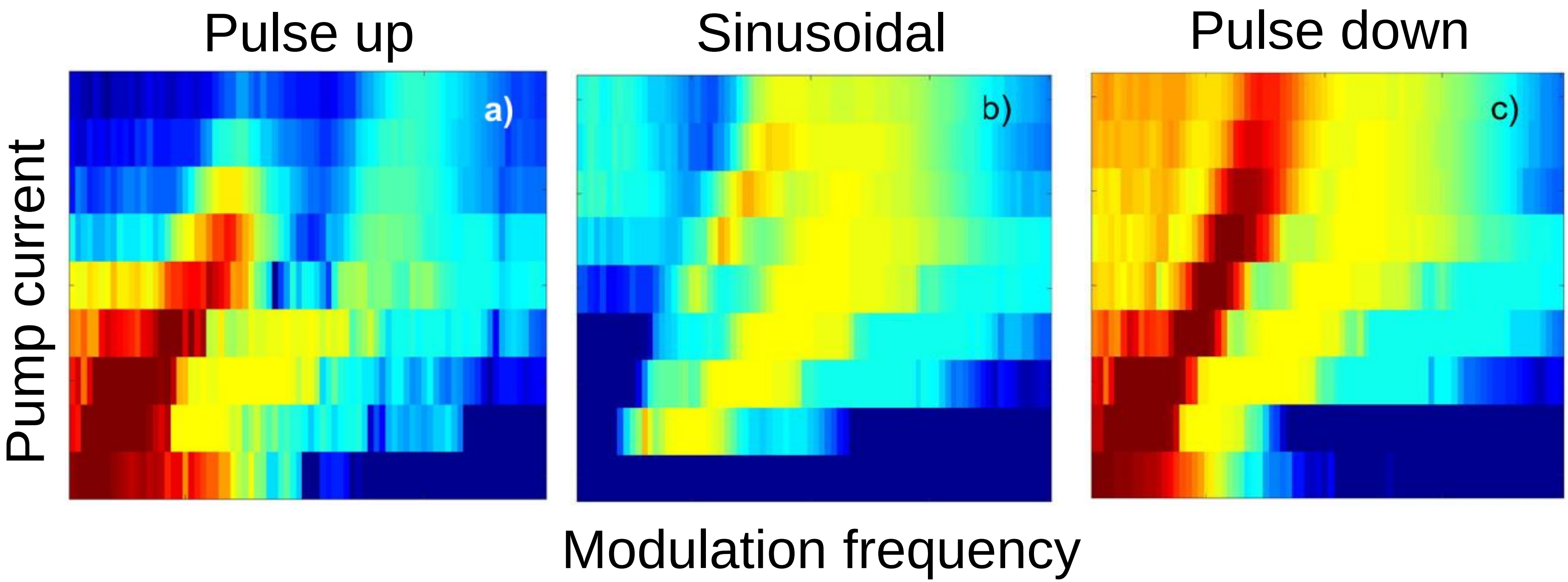
$$\mathrm{FPR}(\tau) = \frac{\text{\# spikes that are not emitted in the time interval } \tau}{\text{Total \# of spikes}}$$

Quantification





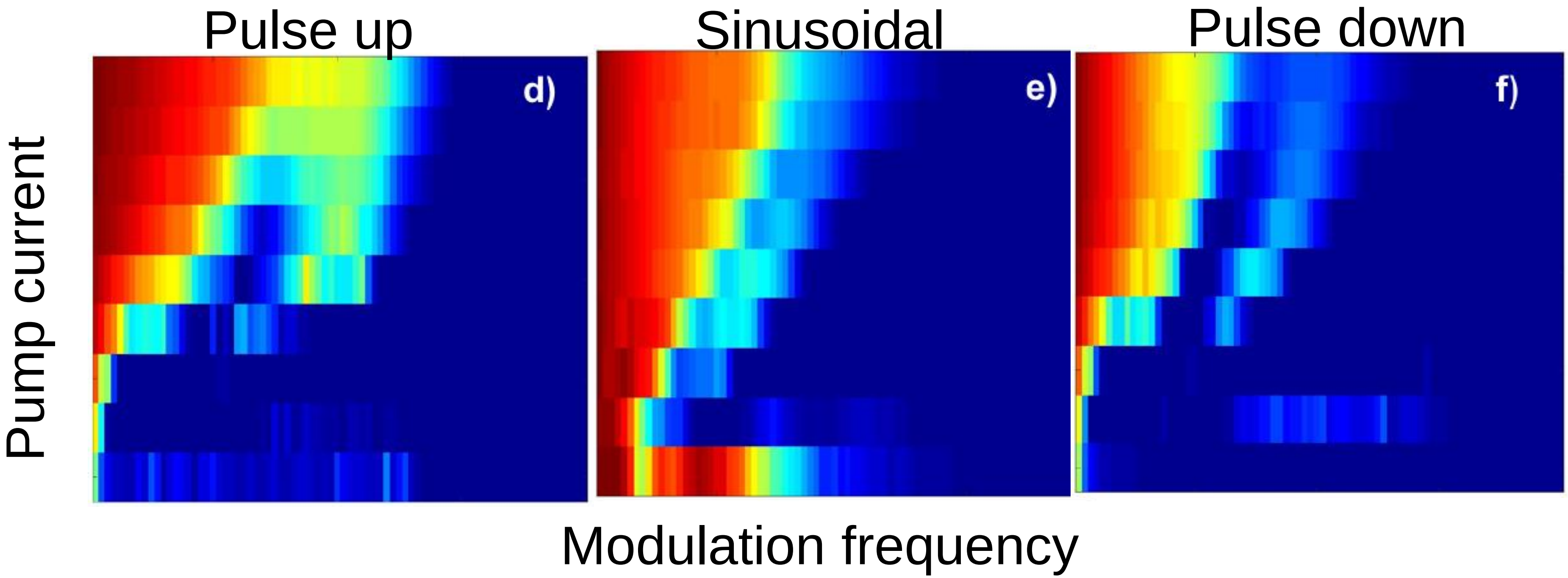
Waveform comparison: in color code the success rate (red SR=1)



⇒ wider locking with pulse-down waveform

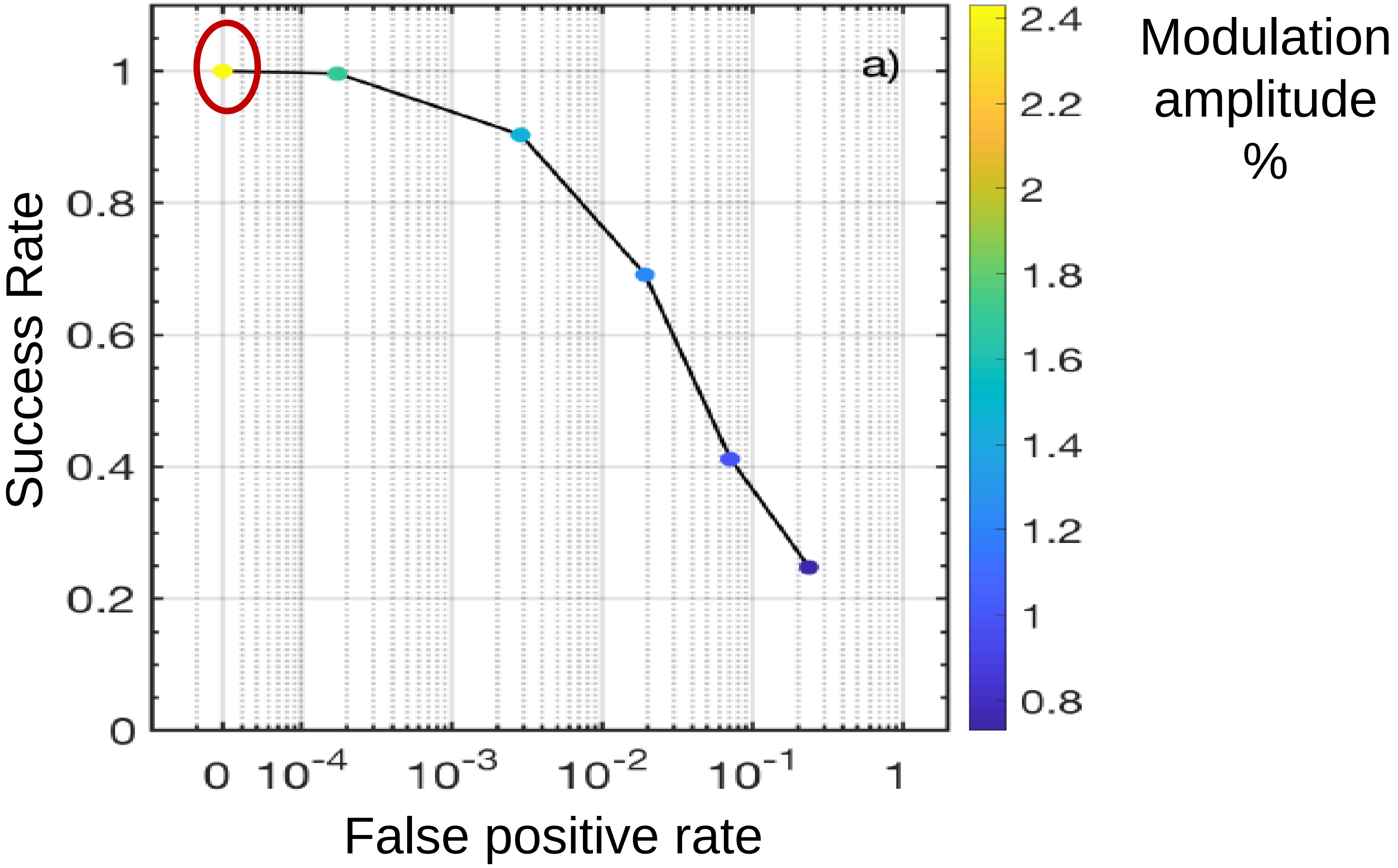
J. Tiana et al, Opt. Express 26 9298 (2018)

And the false positives? (the natural, uncontrolled spikes)

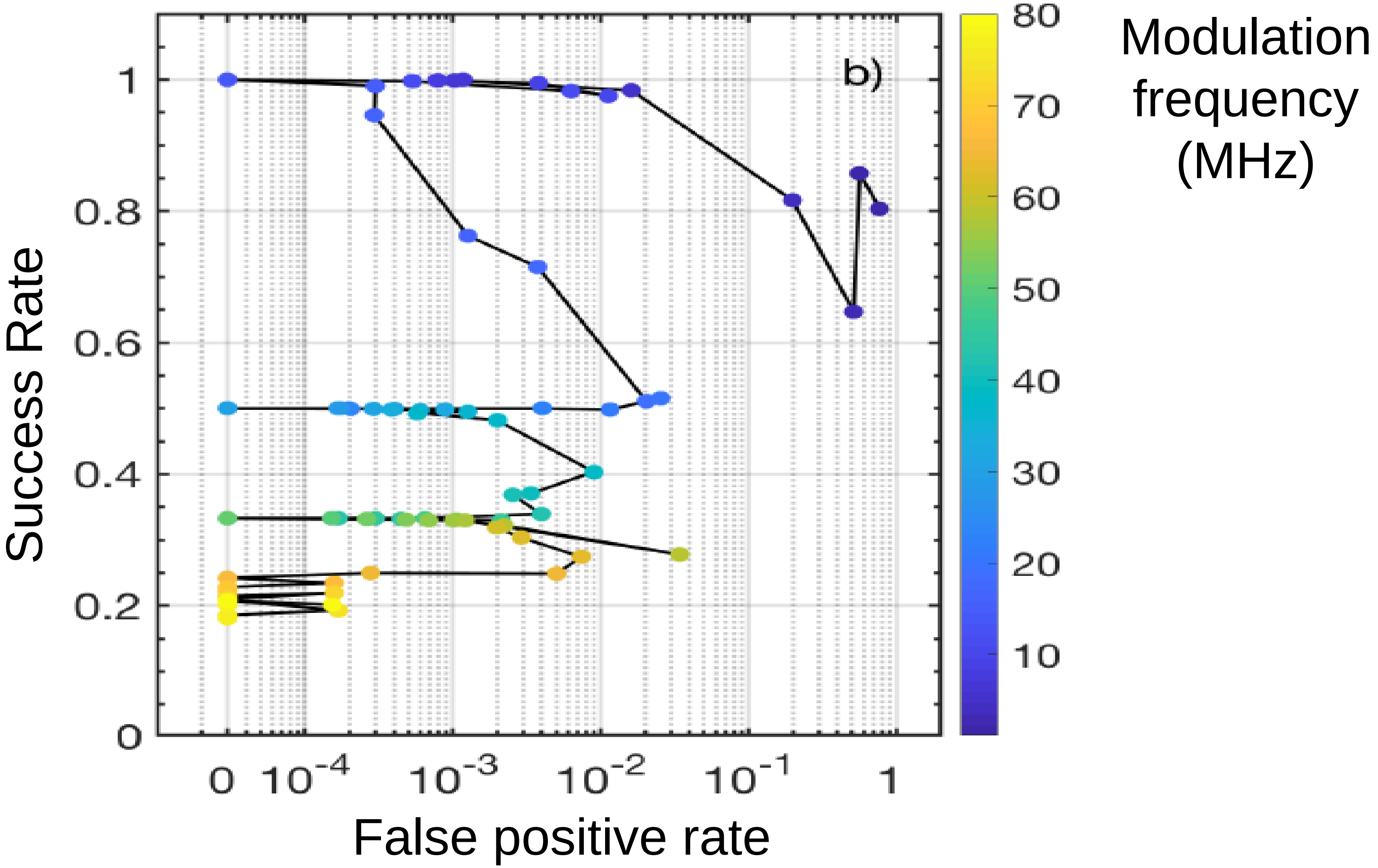


J. Tiana et al, Opt. Express 26, 9298 (2018)

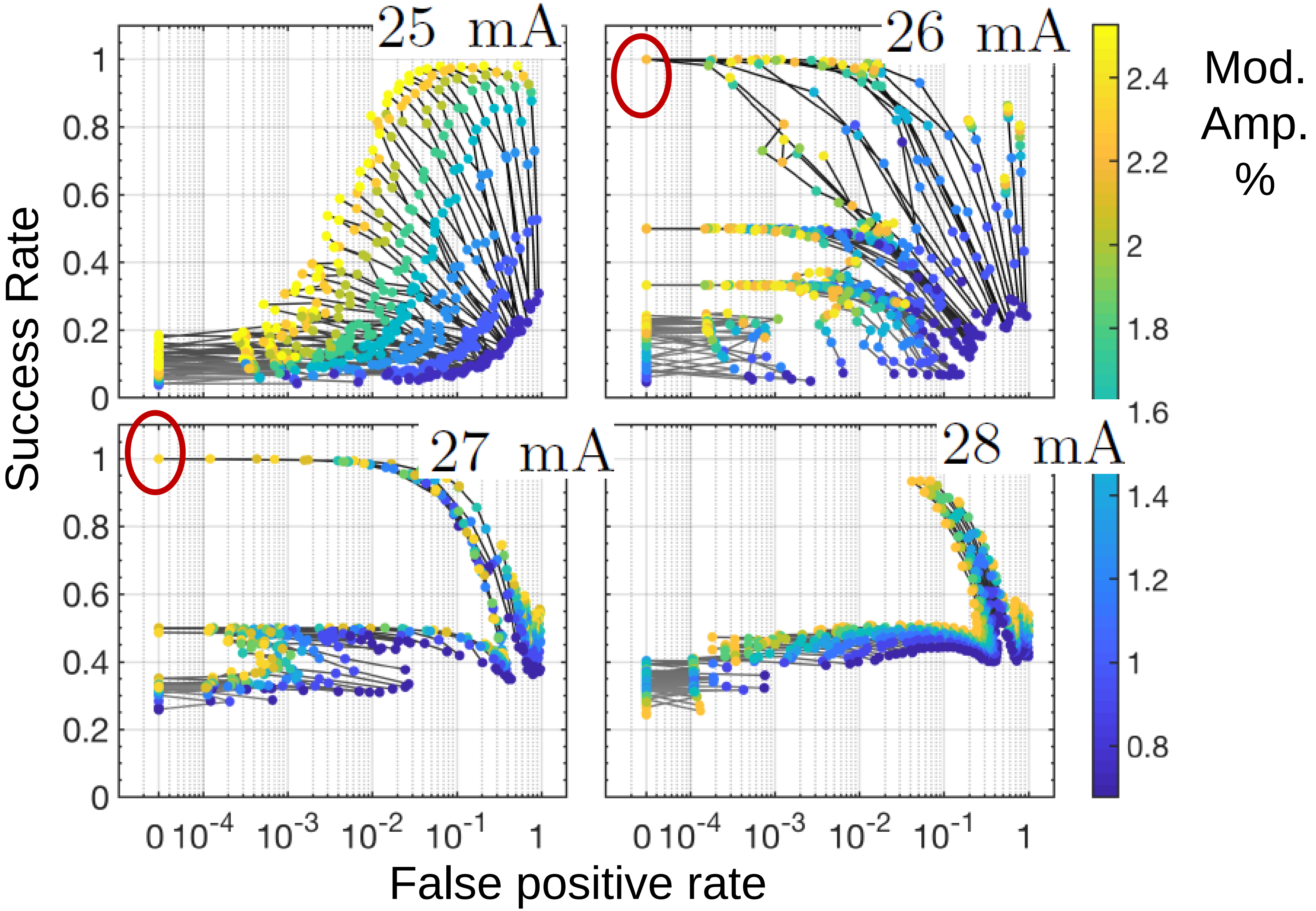
Receiver operating characteristic (ROC) curves



Locked-unlocked transitions when the modulation frequency increases



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



What did we learn?

- Transition to optical chaos: ordinal analysis distinguishes different regimes.
- Spike patterns that are more/less expressed are not always detected by correlation analysis.
- 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: potential for sensing applications?

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

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Acknowledgments





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J. Tiana et al., Opt. Express 26, 9298 (2018)

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