Experimental study of the entrainment phenomenon using a semiconductor laser with optical feedback

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NOLTA 2018, Tarragona, Spain

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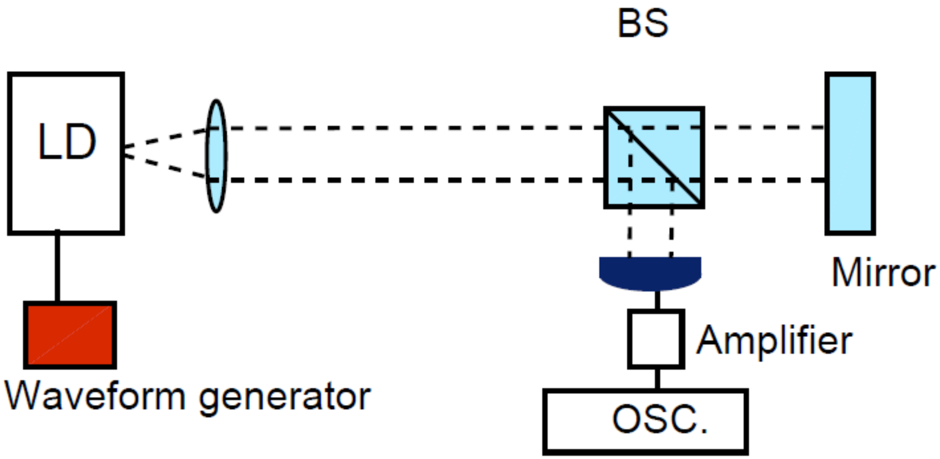
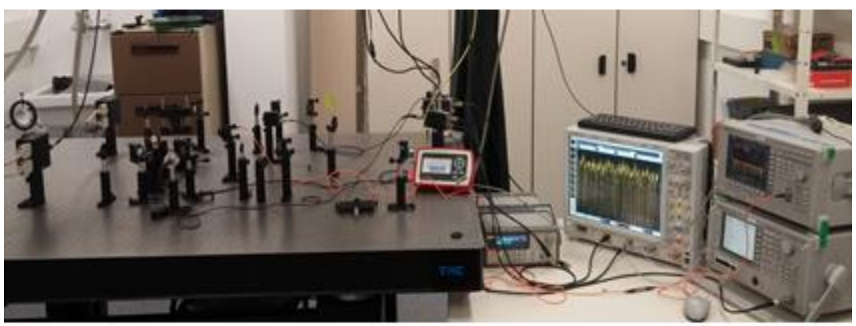
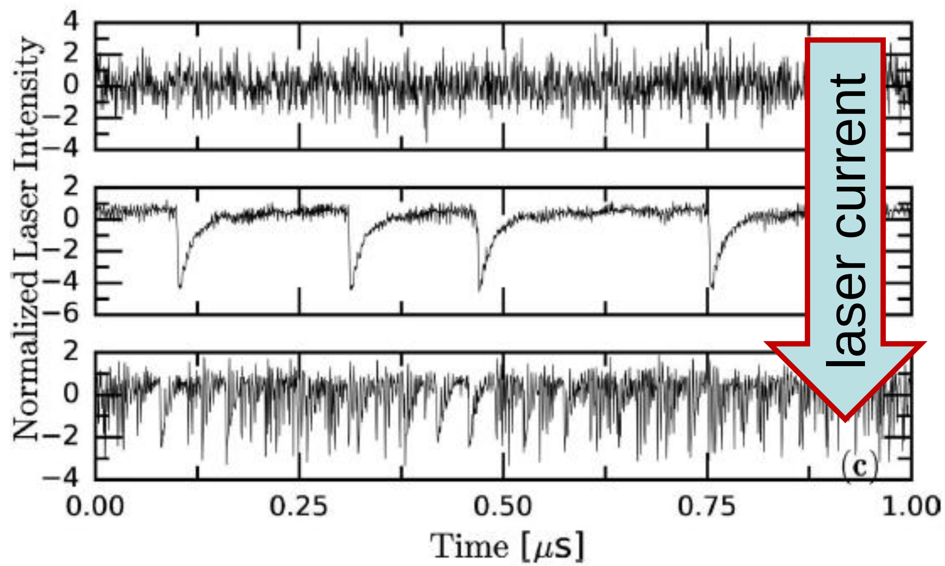
- Characterization of the spiking feedback-induced dynamics
- Entrainment: spike control via small electric perturbations

Dynamics of a semiconductor laser with optical feedback

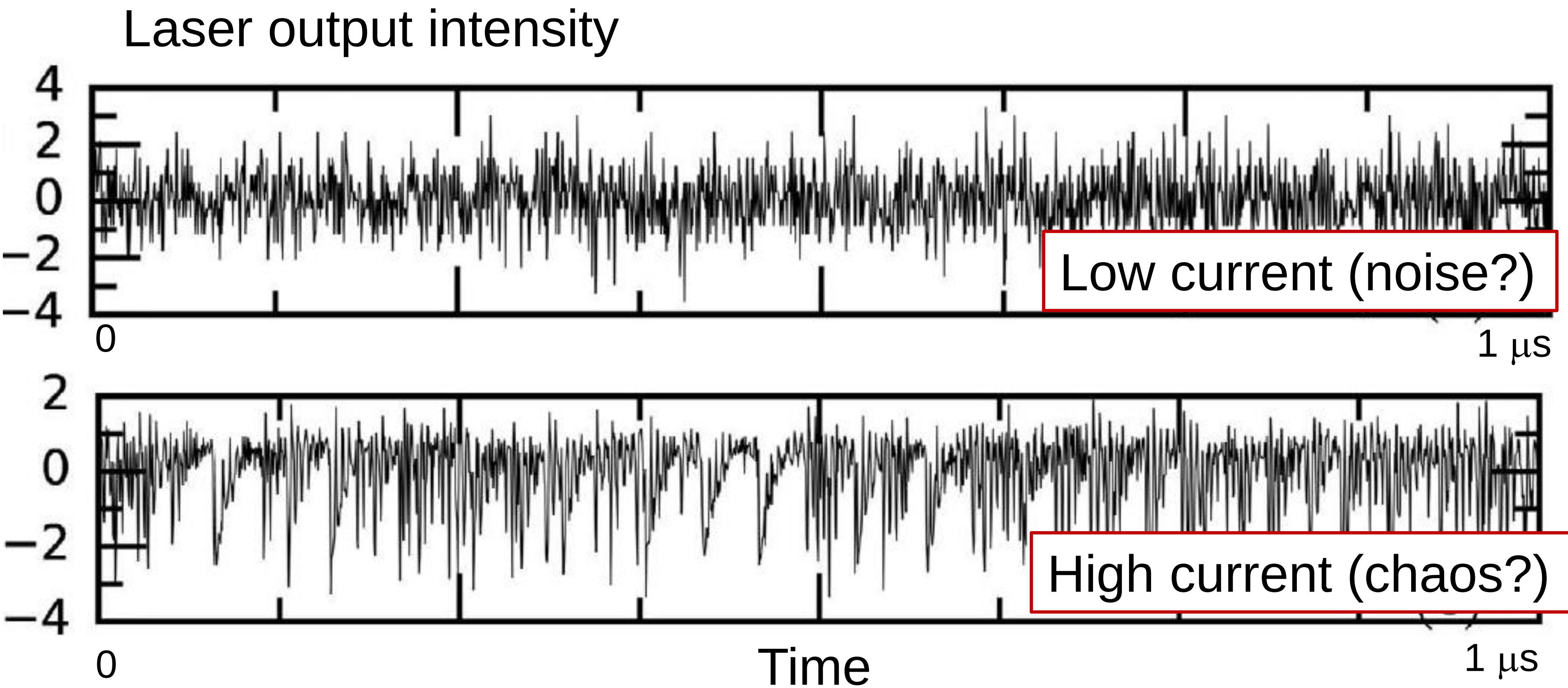






Video: how complex signals emerge from optical noise

Different dynamical regimes are difficult to distinguish.



Can differences be quantified? With what reliability?

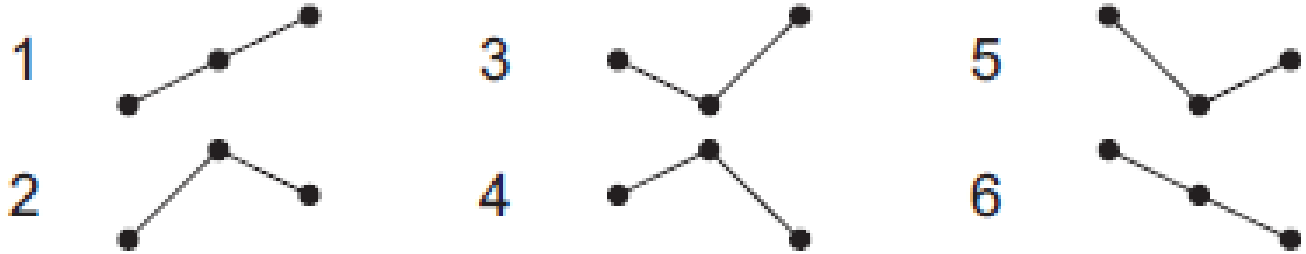
Different methods of time series analysis provide complementary information

- 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.

Ordinal analysis: a tool to look for patterns in data

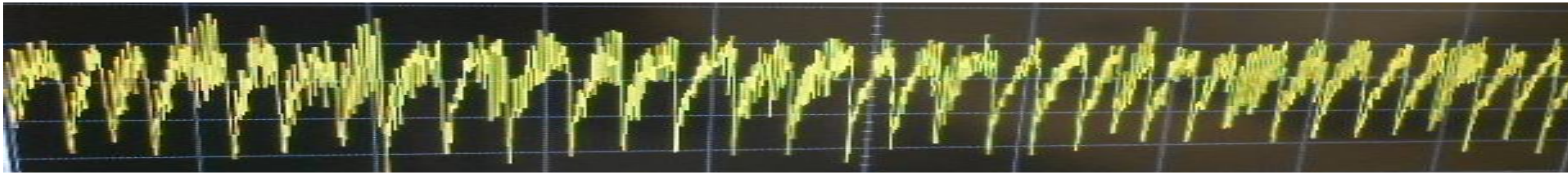
- Consider a time series $x(t)=\{\ldots x_i, x_{i+1}, x_{i+2}, \ldots\}$
- Which are the possible order relations among three data points?

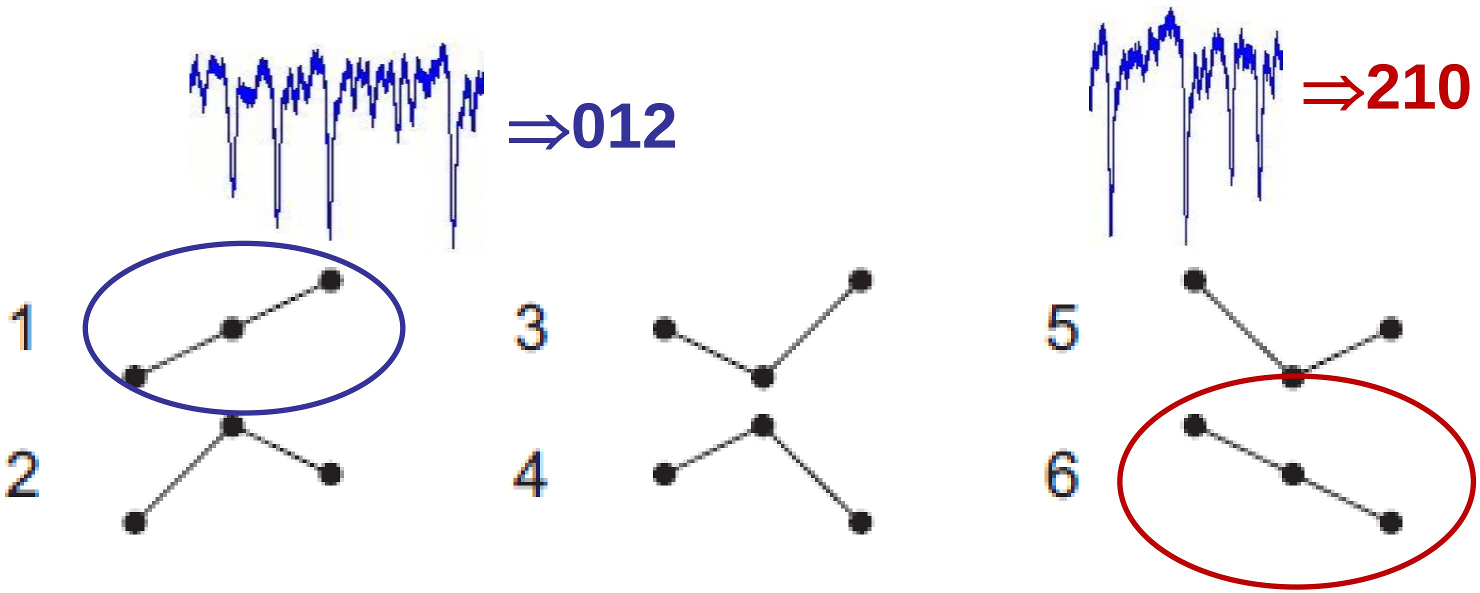


- Count how many times each "ordinal pattern" appears.
- Advantages: allows to identify temporal structures & is robust to noise.
- Drawback: information about actual data values is lost.

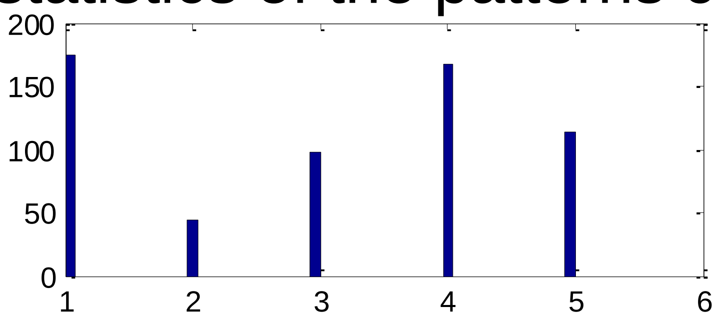
Bandt and Pompe PRL (2002)

Ordinal analysis of time intervals between spikes

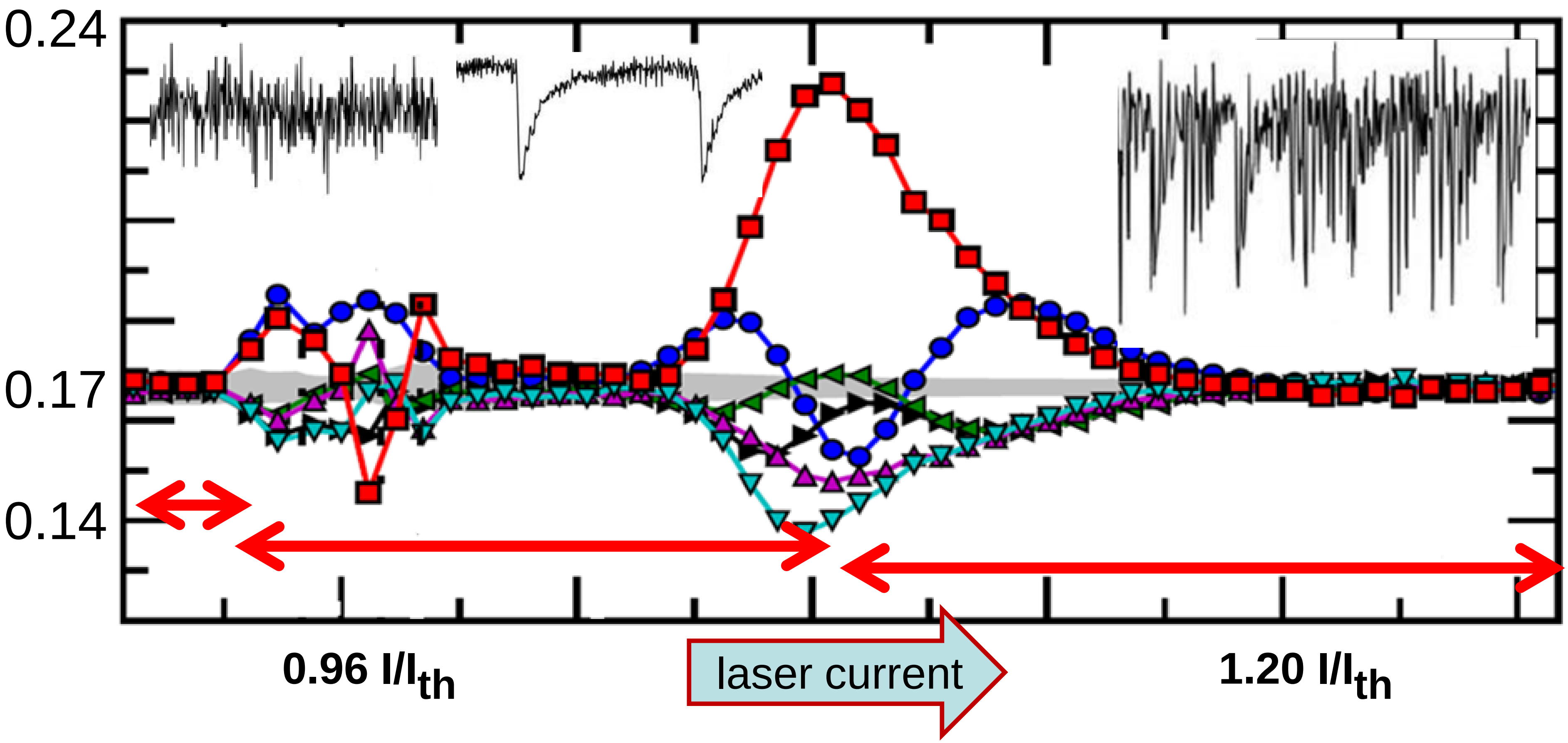




The statistics of the patterns characterizes the dynamics



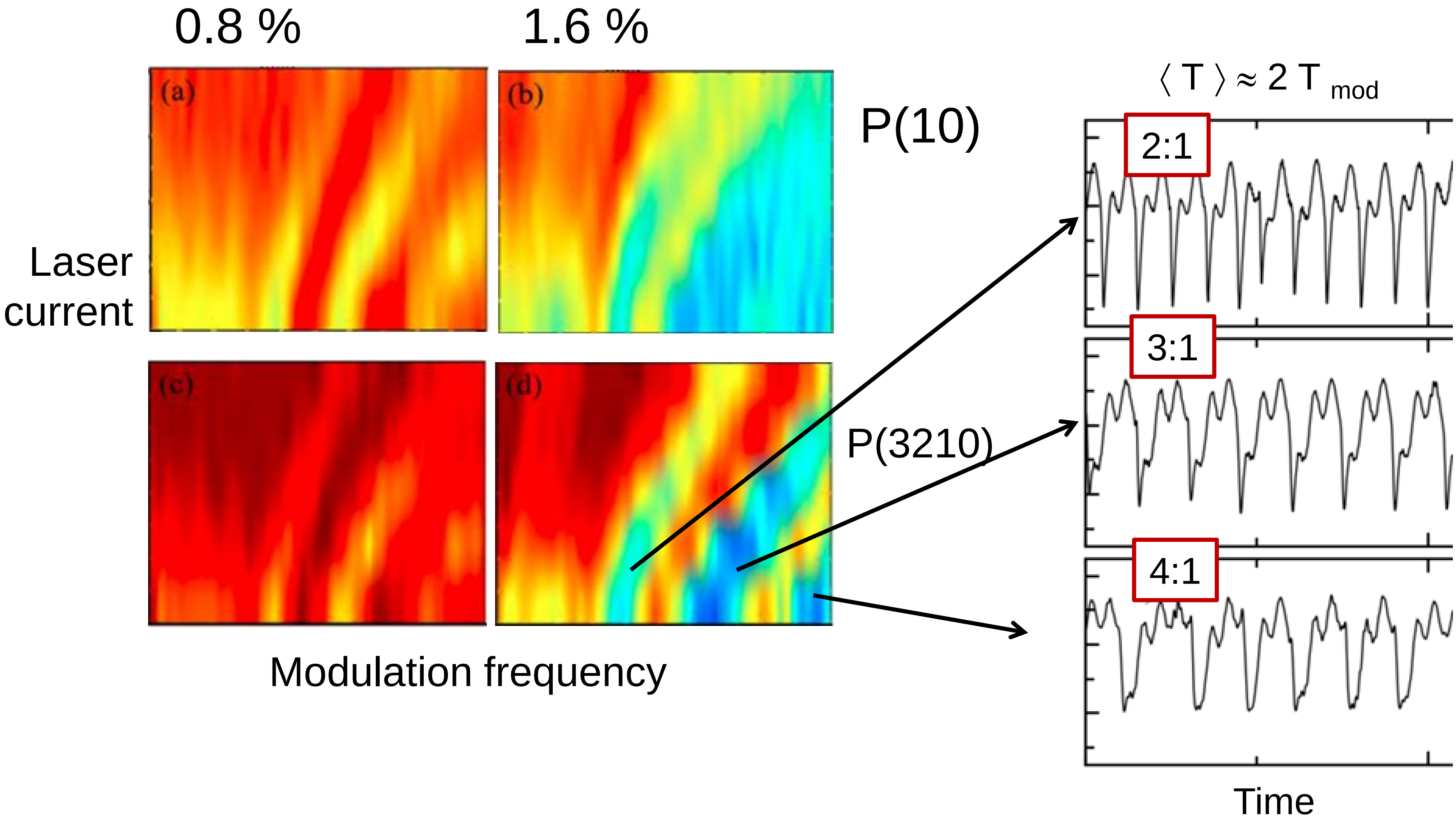
Ordinal analysis identifies the onset of different dynamical regimes, but does not distinguish "noise" and "chaos"



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)

With small-amplitude sinusoidal current modulation, 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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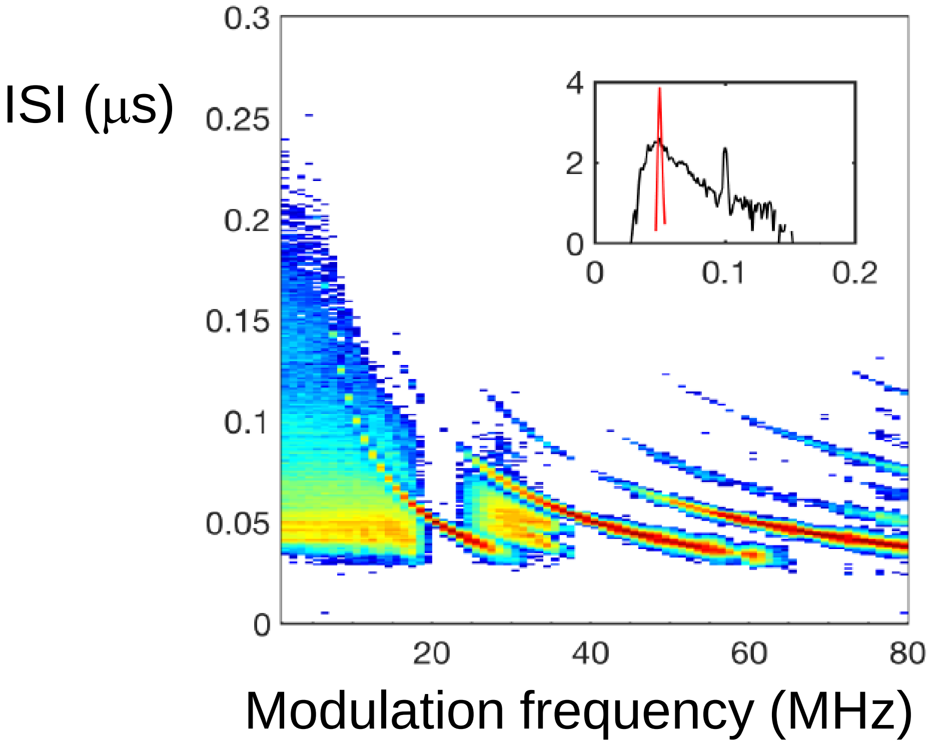
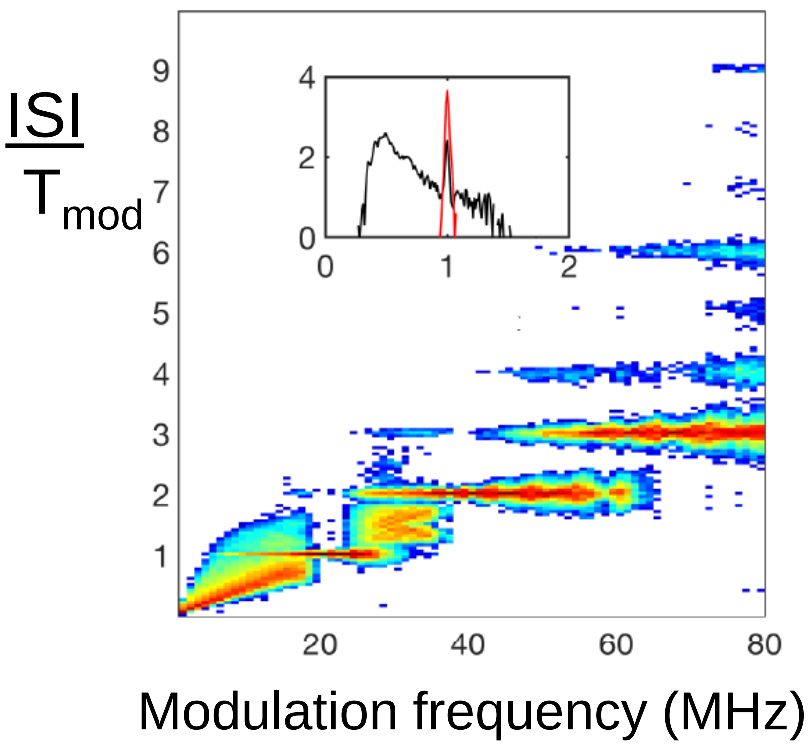
Inter-spike time interval distribution as a function of the frequency of the current modulation

$I_{th,sol} = 26.62$ mA

$I_{th} = 24.70$ mA

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

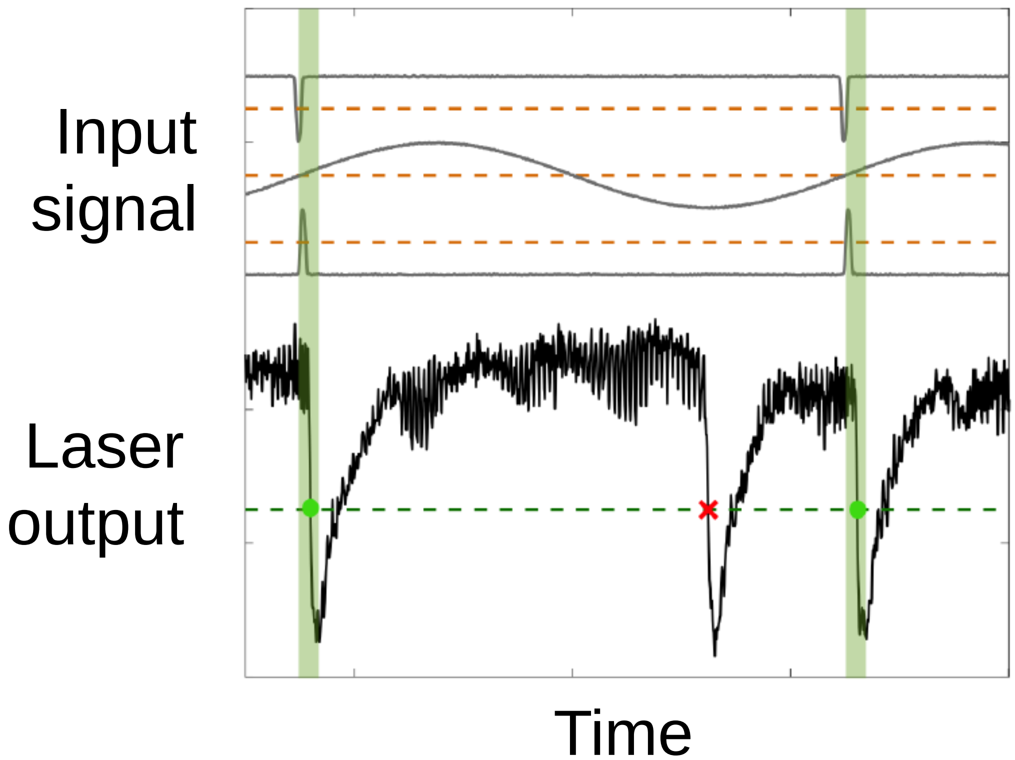




⇒ "refractory time" clear

⇒ "locking" horizontal

We test three modulation waveforms and quantify locking with the success rate and the false positive rate

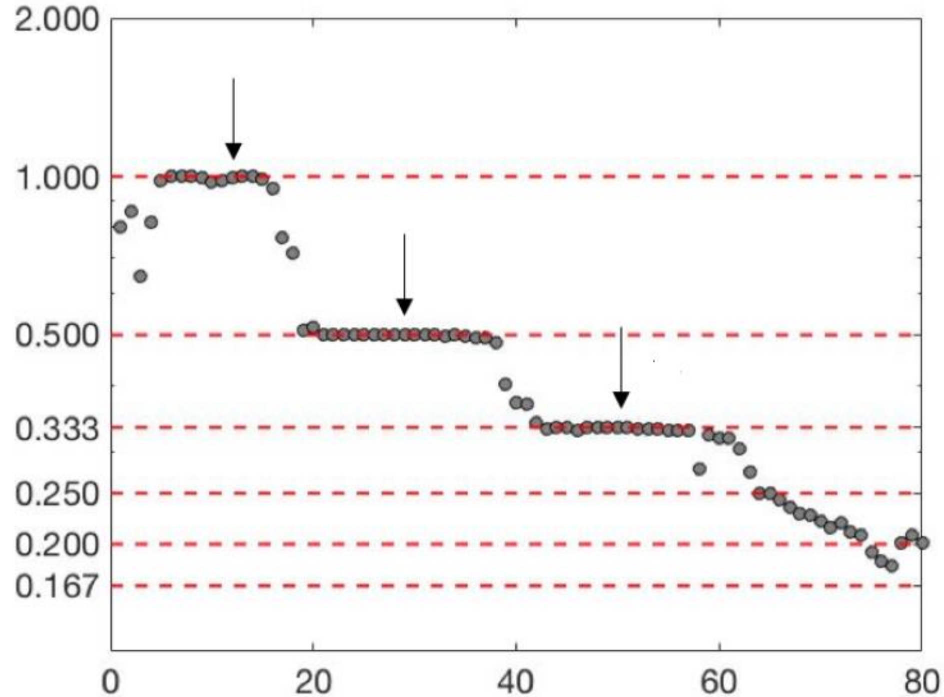


$$SR(\tau) = \frac{\text{\# of spikes emitted in the interval } \tau}{\text{\# of modulation cycles}}$$

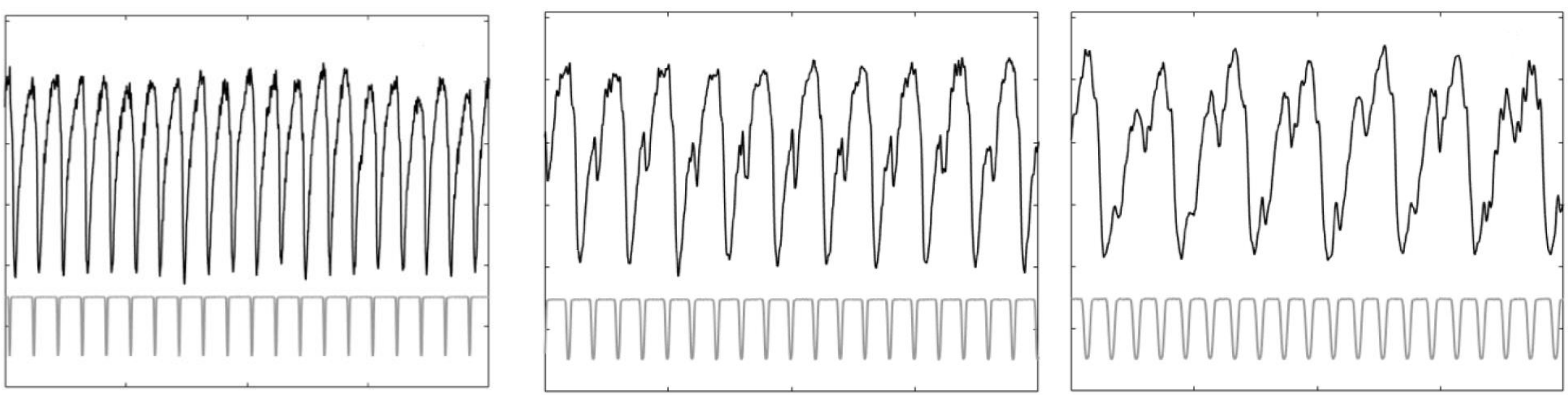
$$FPR(\tau) = \frac{\text{\# spikes that are not emitted in the time interval } \tau}{\text{Total \# of spikes}}$$

Quantification

Success rate

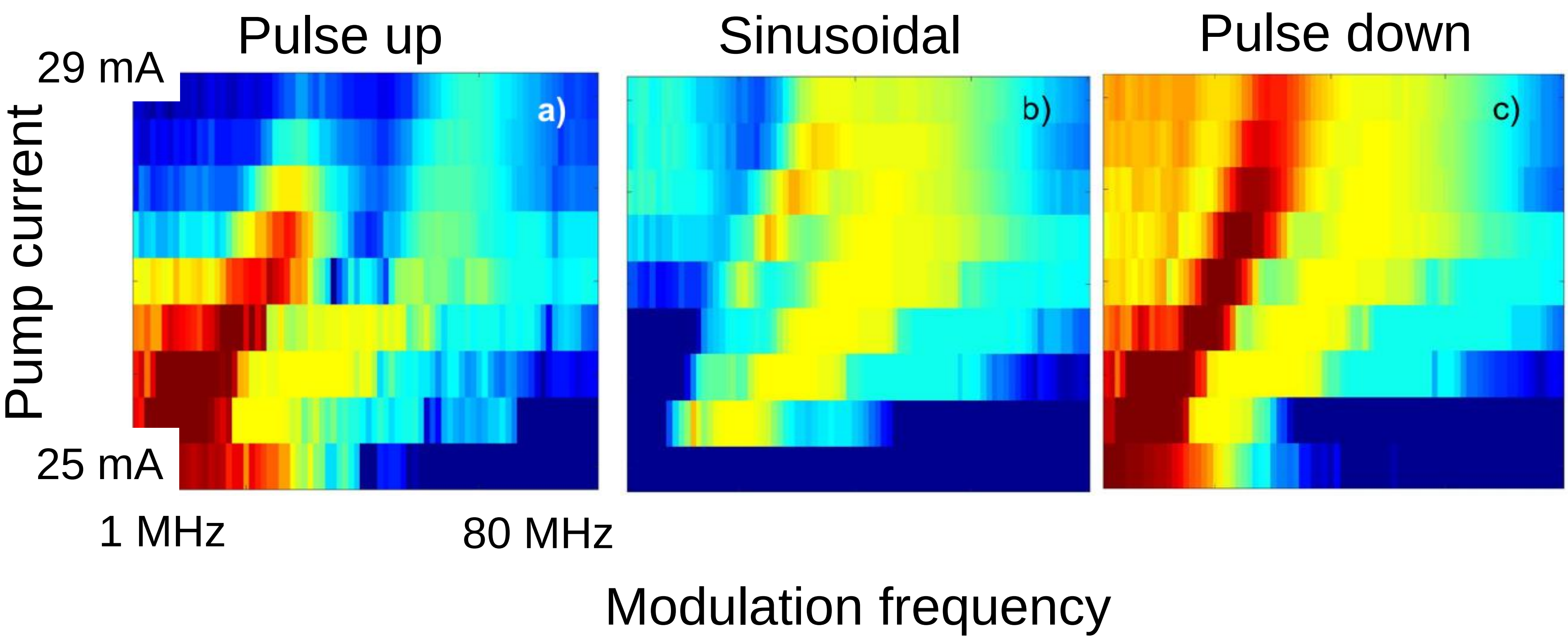


Modulation frequency (MHz)



Time/T_{mod}

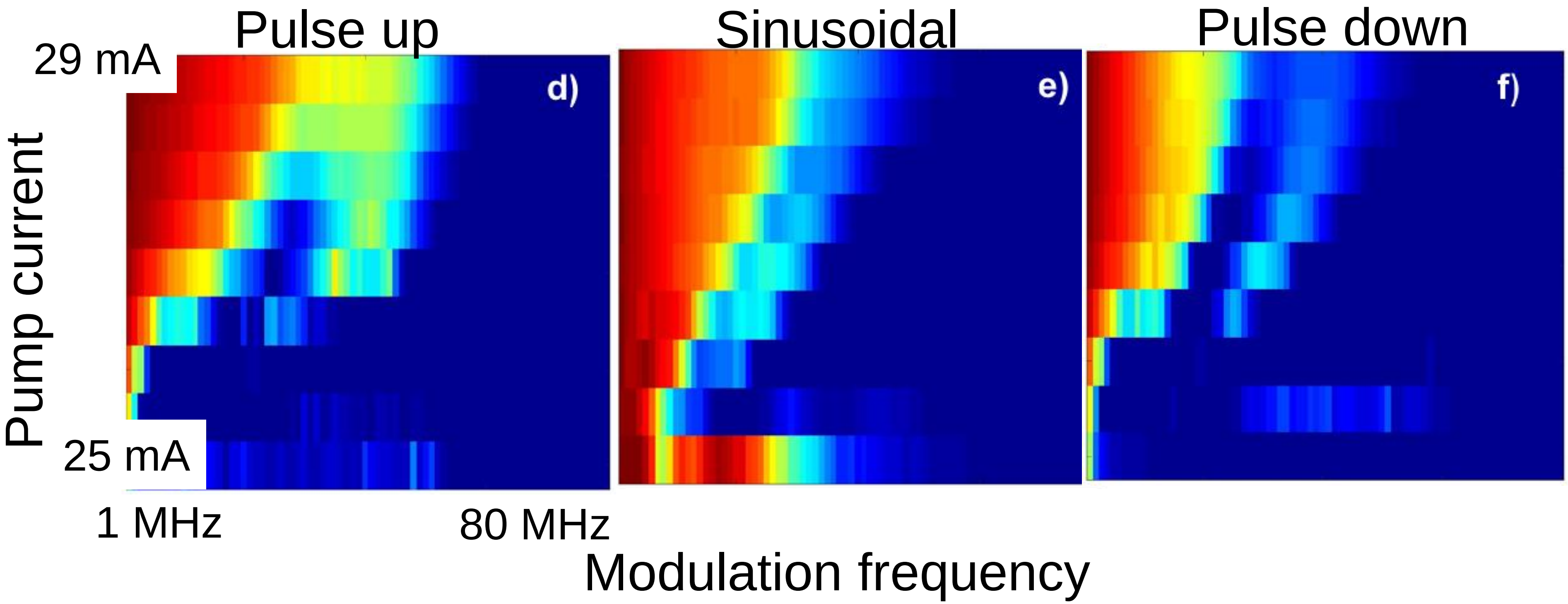
Waveform comparison: in color code the success rate (red SR=1)



⇒ pulse-down waveform produces a wider locking region

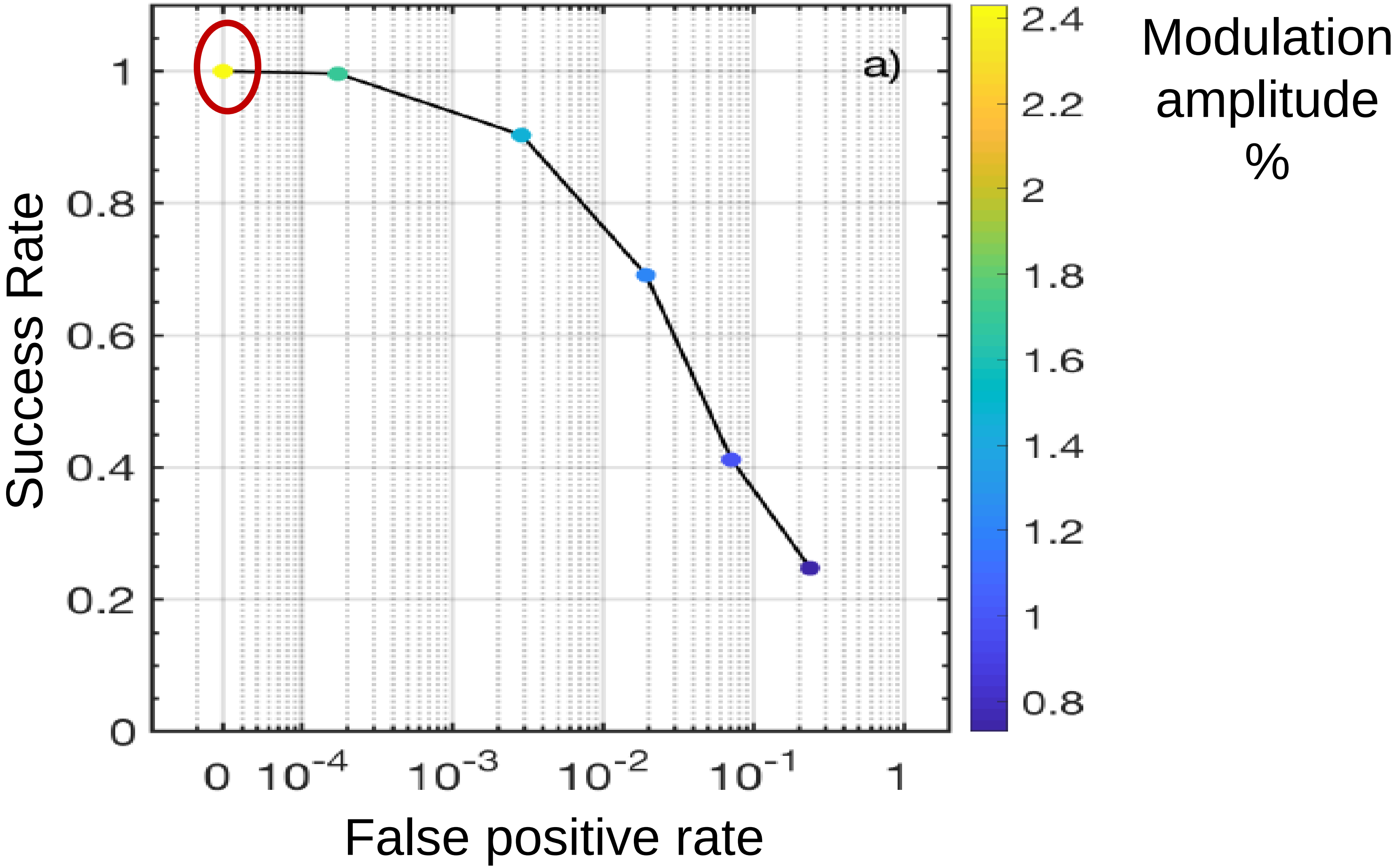
J. Tiana et al., Opt. Express 26 9298 (2018)

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



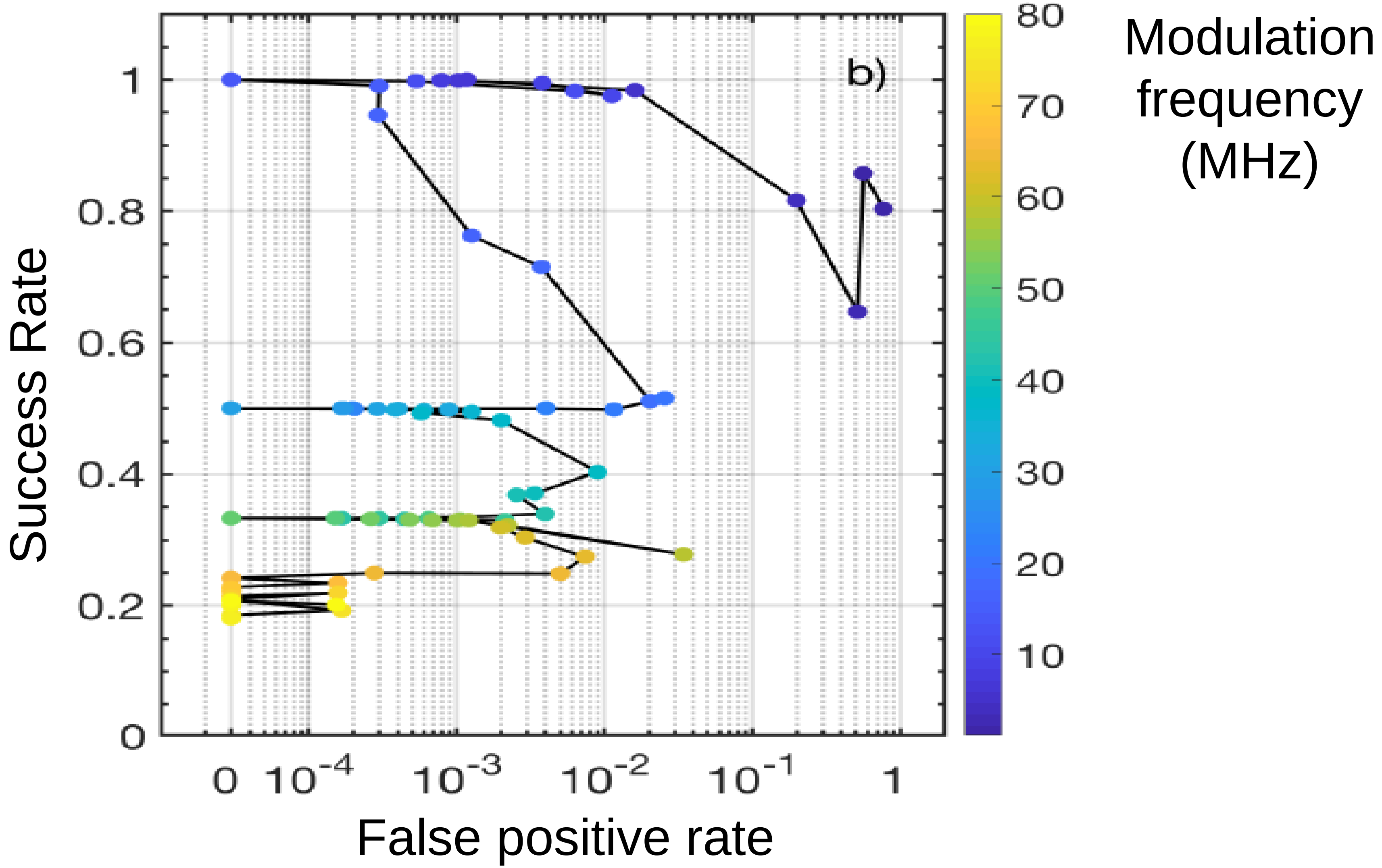
J. Tiana et al., Opt. Express 26, 9298 (2018)

Receiver operating characteristic (ROC) curves



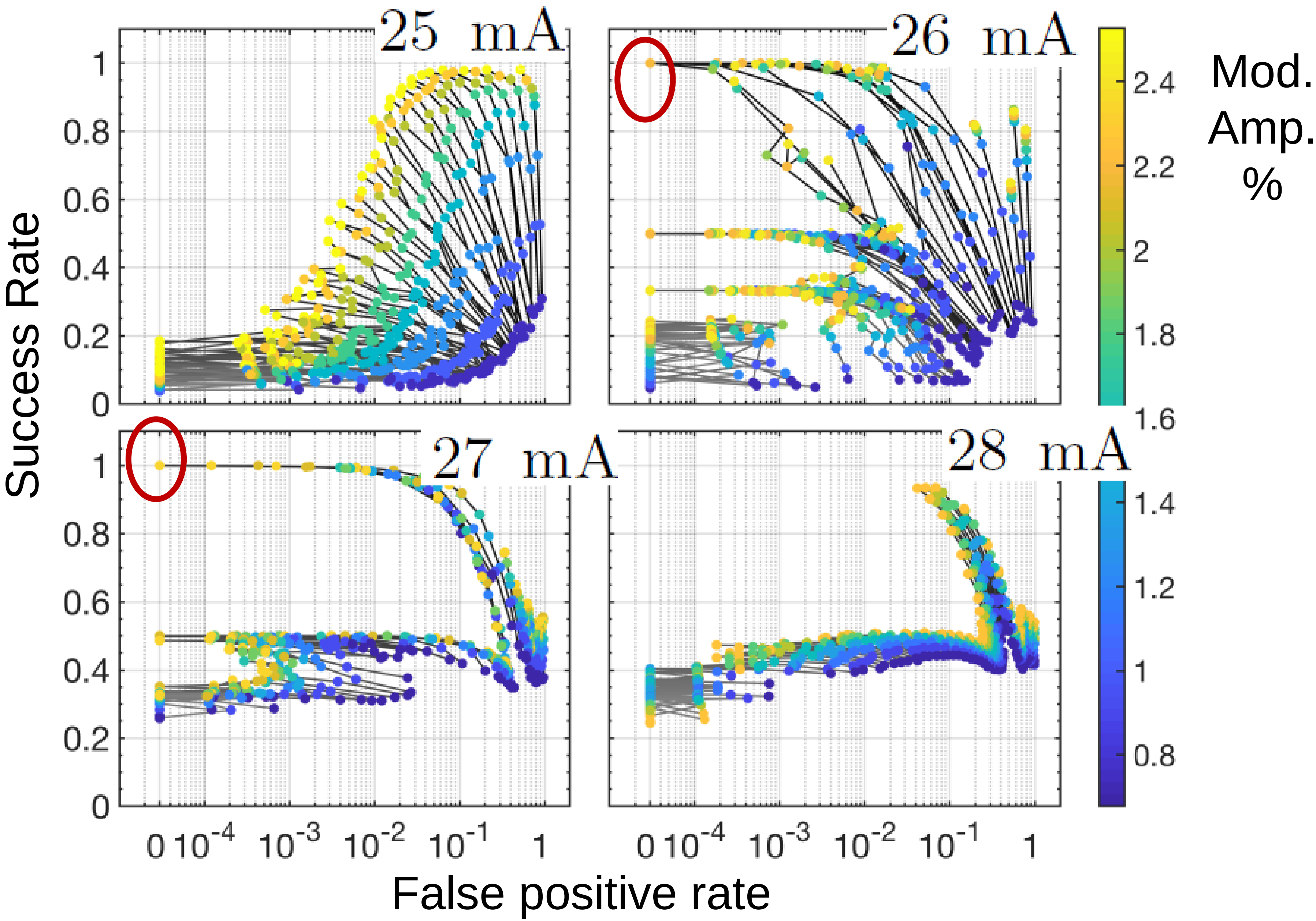
J. Tiana et al., arXiv:1806.08950v1 (2018)

Locked-unlocked transitions when the modulation frequency increases



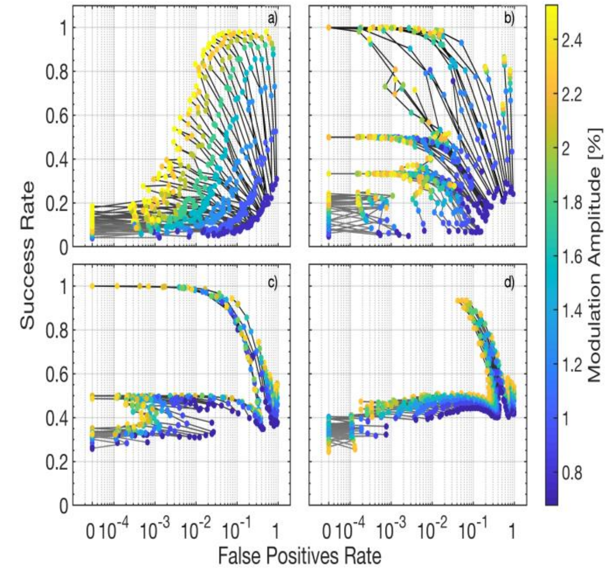
J. Tiana et al., arXiv:1806.08950v1 (2018)

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

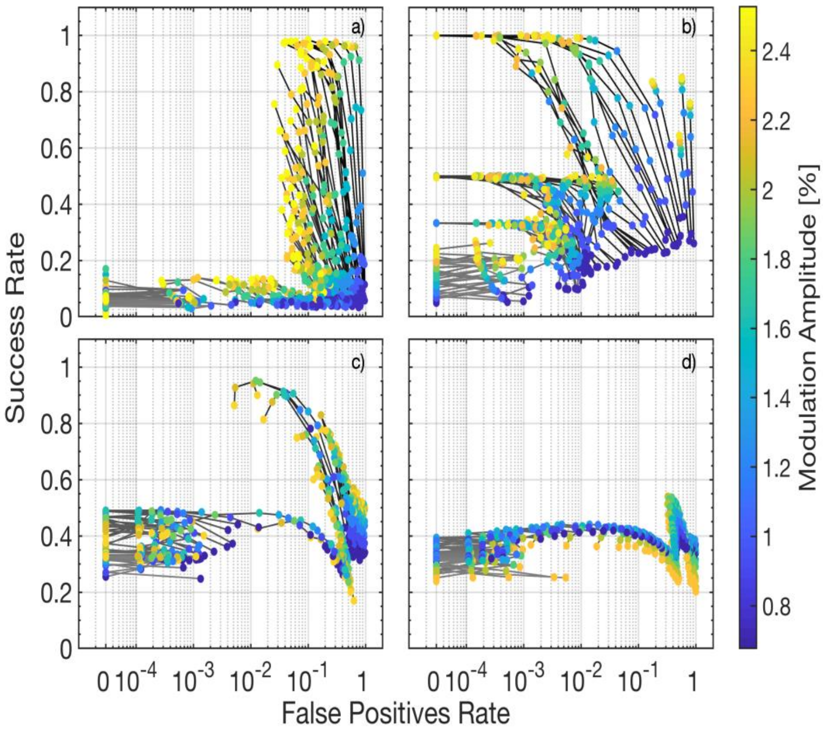


Influence of the modulation waveform

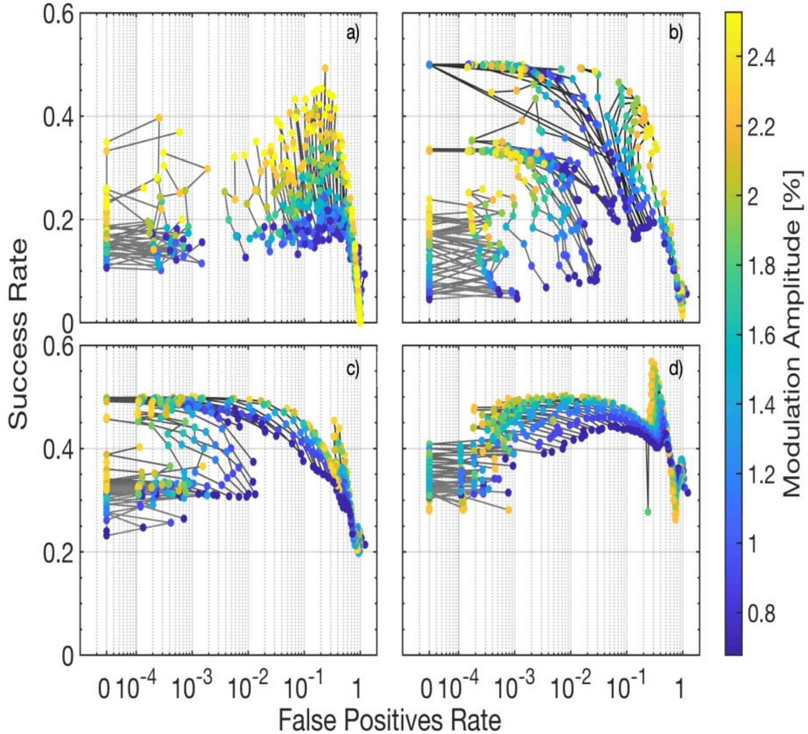
Pulsed-down



Pulsed-up



Sinusoidal



What did we learn?

- Transition to optical chaos: ordinal analysis distinguishes different regimes.

- Optical spikes can be entrained to a small-amplitude electrical signal.

- ROC curves allow to quantify the entrainment quality.

- Regions of perfect 1:1 locking identified.

Ongoing work: potential for sensing applications?

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Thank you for your attention

http://www.fisica.edu.uy/~cris

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

C. Quintero-Quiroz et al., Sci. Rep. 6, 37510 (2016)

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

J. Tiana et al., arXiv:1806.08950v1 (2018)

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