Experimental characterization of dynamical regimes, entrainment and complex phenomena in laser systems

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Hong Kong, December 2018

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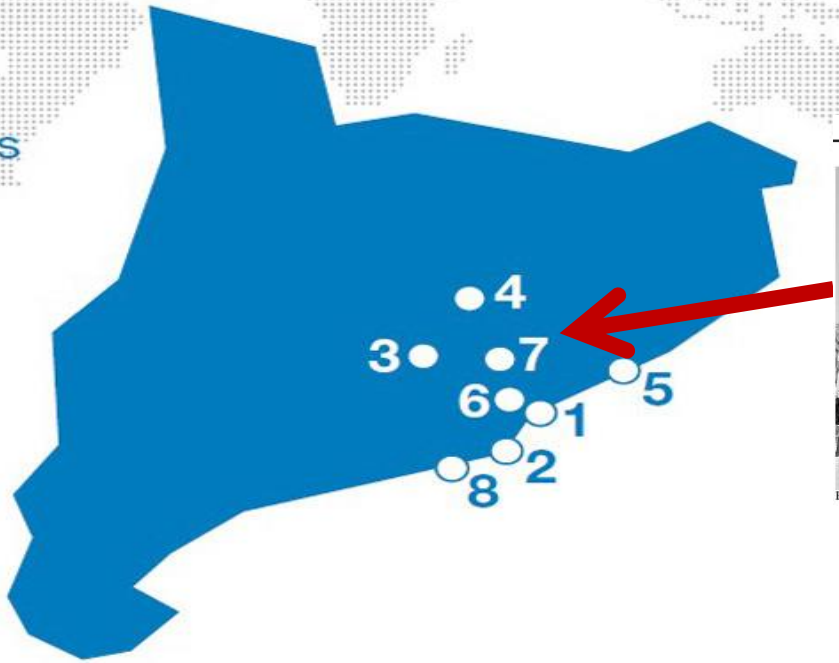


Viernes, 25 de septiembre de 2009 **Diari de Terrassa**

El edificio Gaia centraliza grupos científicos consolidados y emergentes.

Nonlinear / complex dynamics of semiconductor lasers

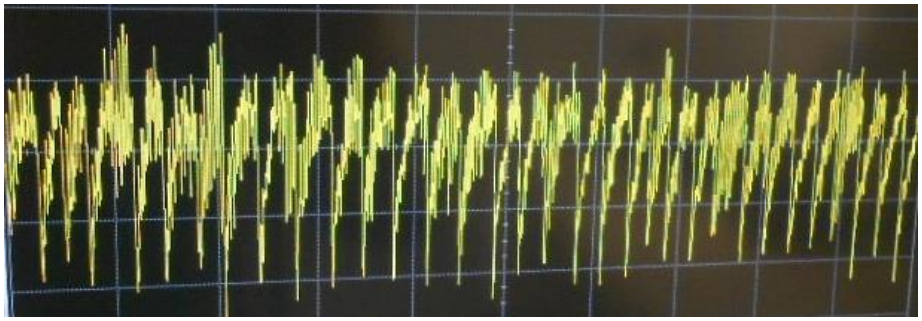
Not only has important applications (random number generation, chaotic lidar, optical computing, etc.)…

- Also provides “big data” for testing novel analysis tools

- And can advance our understanding of the physics underlying complex real-world signals.

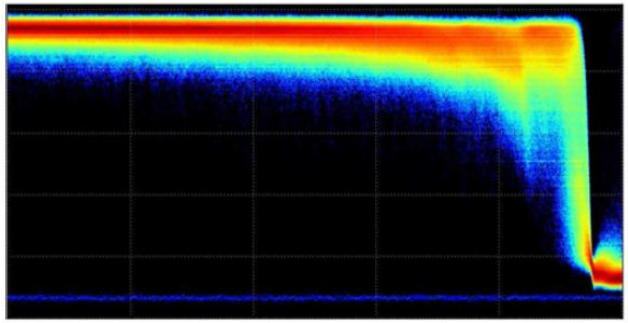
A few examples

- Spikes emitted by a semiconductor laser with optical feedback



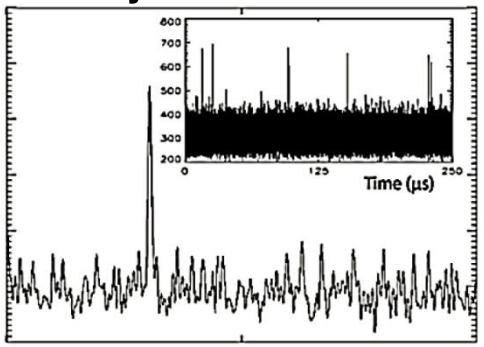
Time

- VCSEL polarization switching



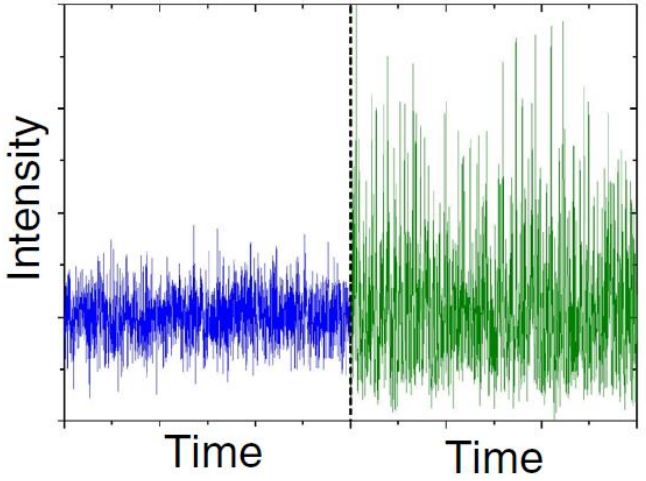
Time

- Extreme pulses emitted by a cw injected semiconductor



Time

- Transition to optical turbulence in a fiber laser



Entrainment

Circadian rhythm

Zeitgeber ("time giver" in German): environmental cyclic variable

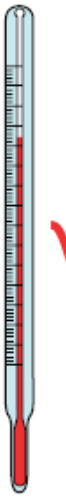
e.g., L:D cycle

Entrainment (input)

Circadian clock (oscillator)

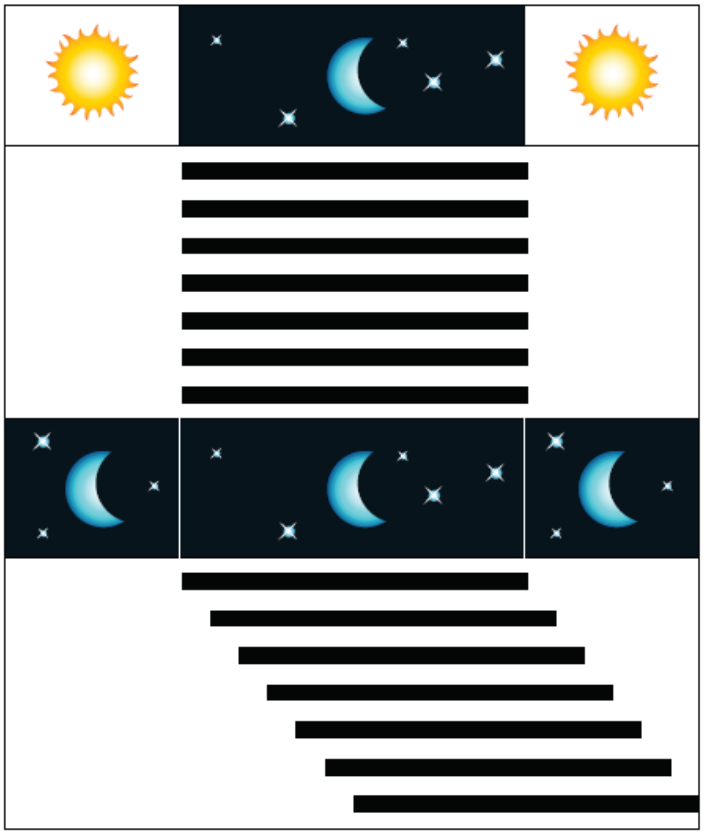
e.g

Coupling (output)



Circadian rhythm

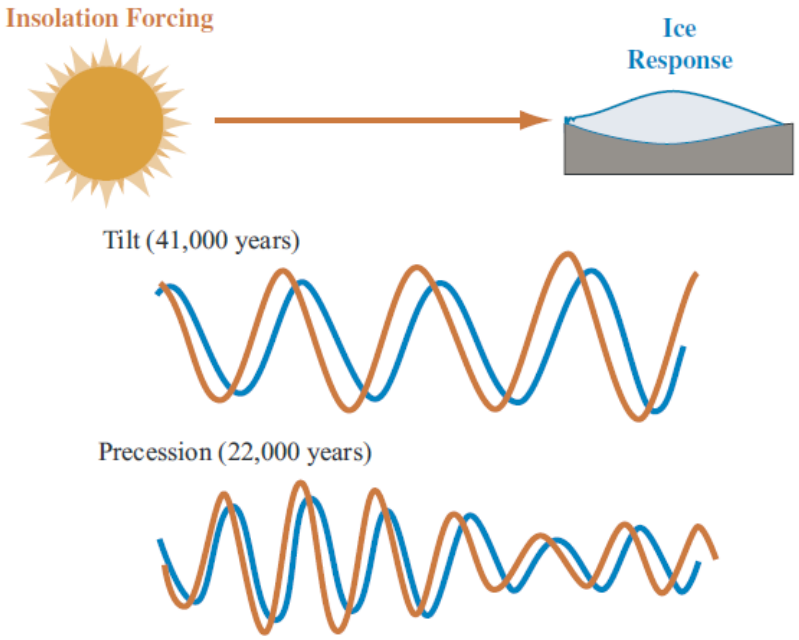
e.g., Body temperature rhythm



Neurons in the suprachiasmatic nucleus (SCN) are part of a central timing circuit that drives behavior and physiology

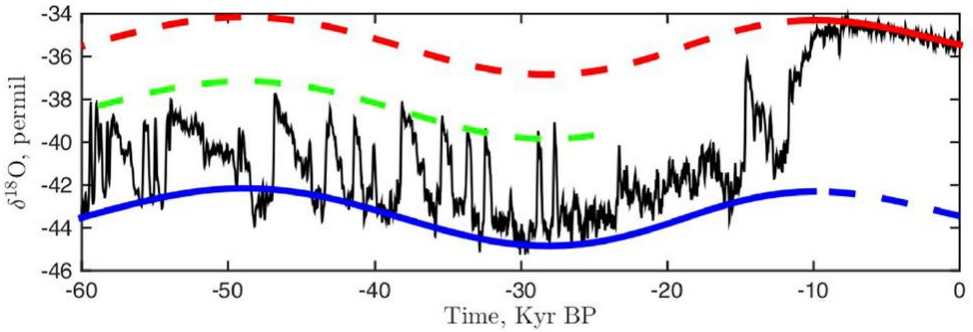
Golombek and Rosenstein, Physiol Rev 90, 1063 (2010)

In our climate: entrainment to astronomical forcing



Changes in solar radiation force lagged ice-volume responses at the periods of tilt and precession.

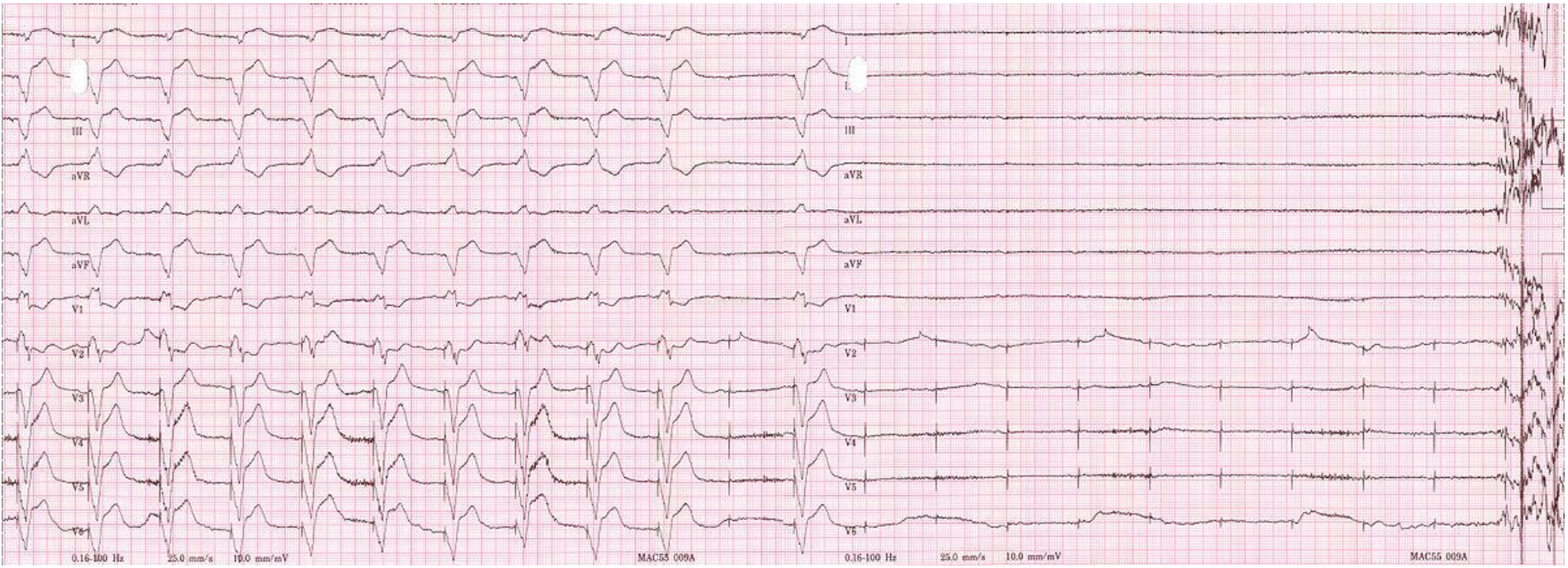
Ruddiman, Quaternary Science Reviews 25, 3092 (2006)



The NGRIP isotope record for the past 60 kyr is a proxy for temperature.
The red, green and blue curves are the summer insolation at 65N fitted to the climate record.

Ditlevsen and Ashwin, Frontiers in Phys. 6, 62 (2018)

Entrainment of the heart beats by a pacemaker

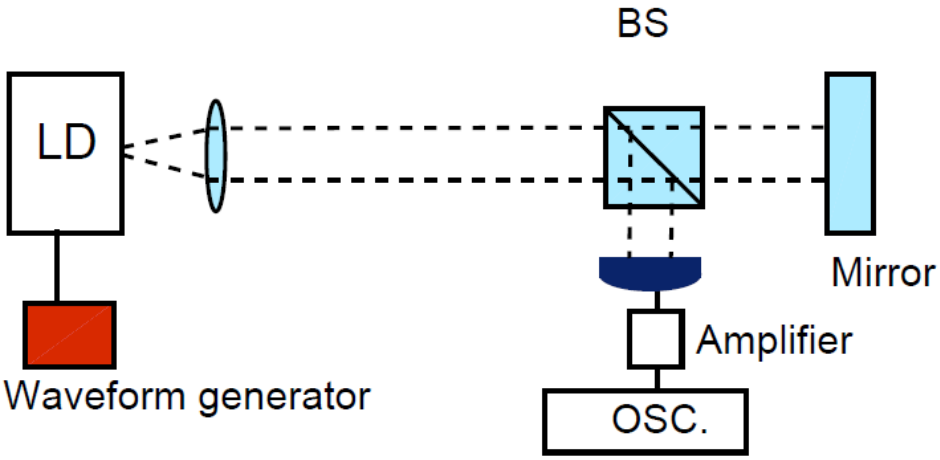


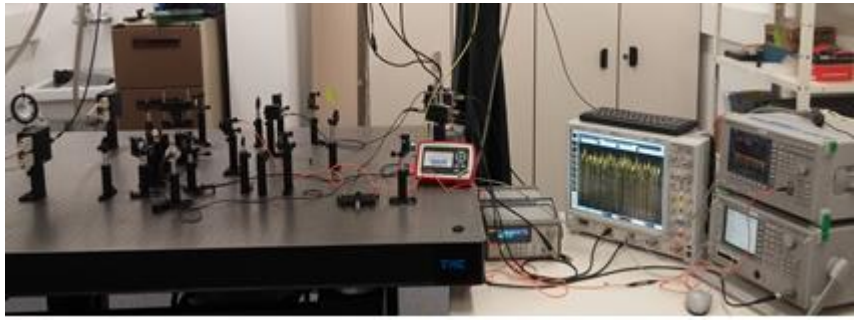
Source: S. Fruitsmaak, wikipedia

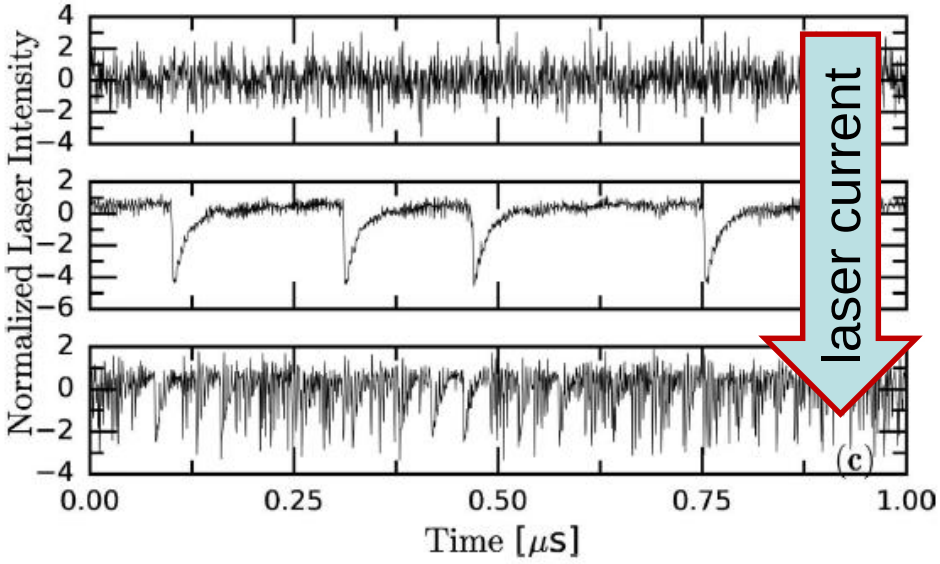
Outline

- Characterization of transitions between dynamical regimes (diode laser with feedback)
- Entraining the laser spikes (diode laser with feedback)
- Predictability and on-demand generation of extreme pulses (cw injected diode laser)
- Characterization of the laminar-turbulence transition (fiber laser)

Dynamics of a semiconductor laser with optical feedback



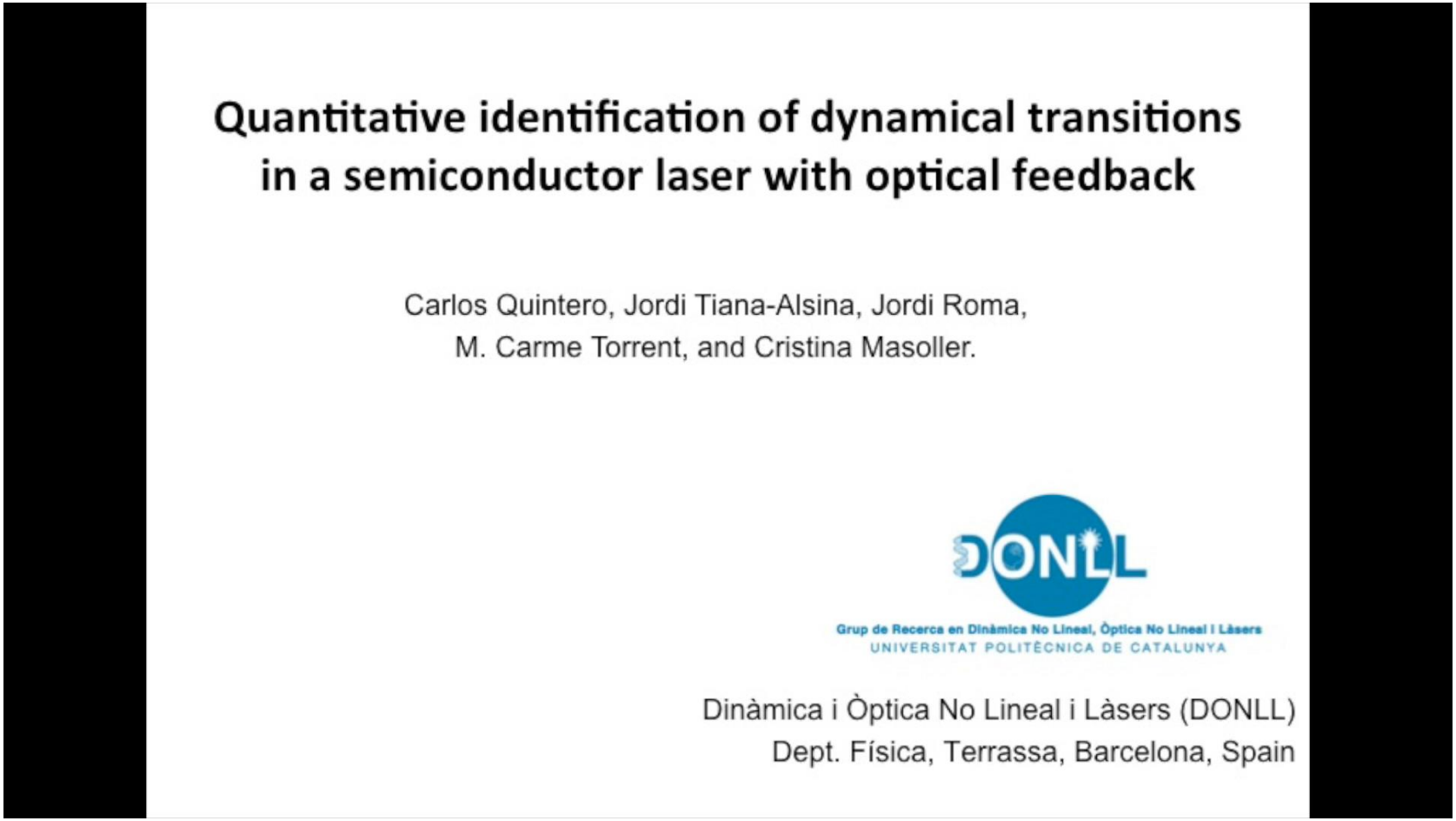




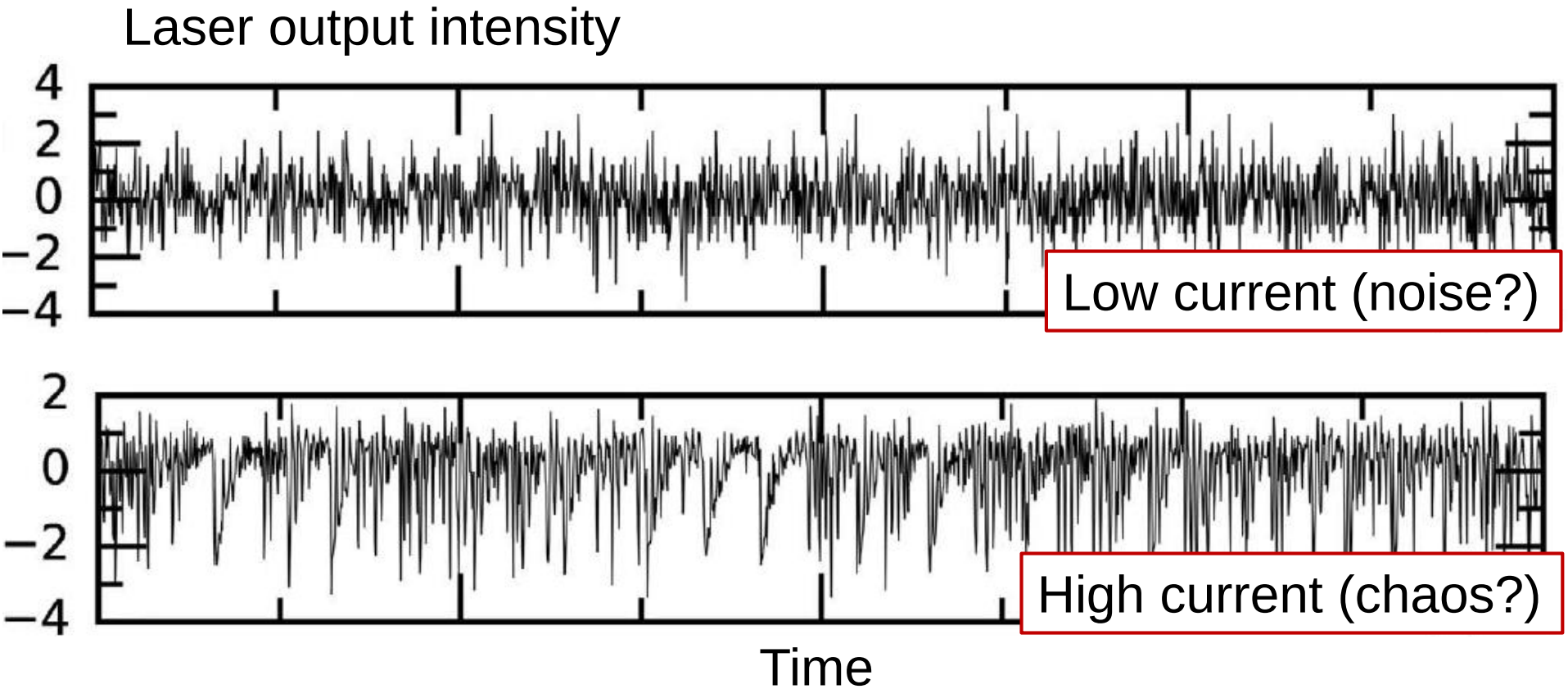
(Slow “envelope” of very fast fluctuations)

D. Lenstra et al, “Coherence collapse in single-mode semiconductor lasers due to optical feedback”, IEEE J. Quantum Electron. 21, 674-679 (1985)

Video: how complex signals emerge from optical noise

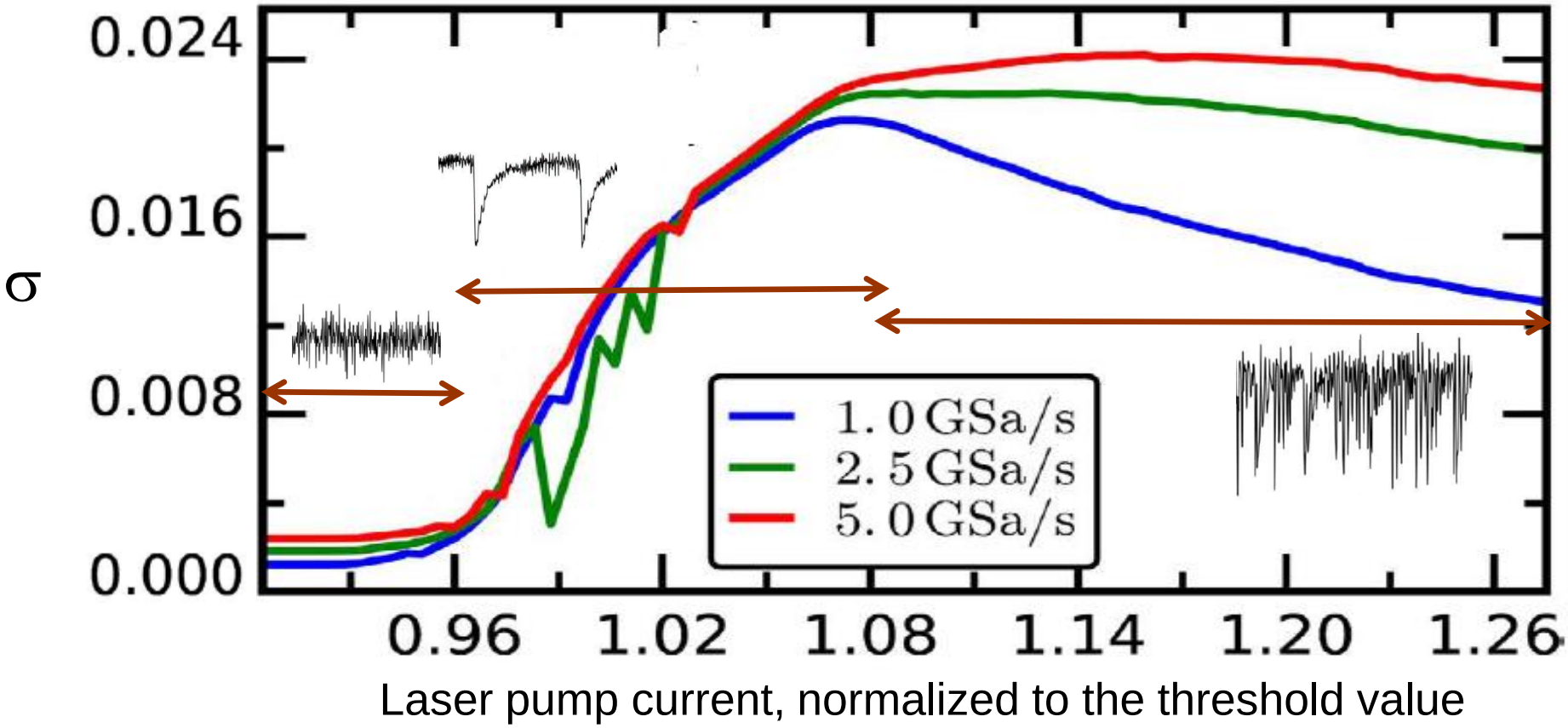


Different regimes are difficult to distinguish, quantitatively
The onset of different regimes is difficult to identify



Can differences be quantified? With what reliability?

Standard deviation of the intensity time series, recorded using three different sampling rates

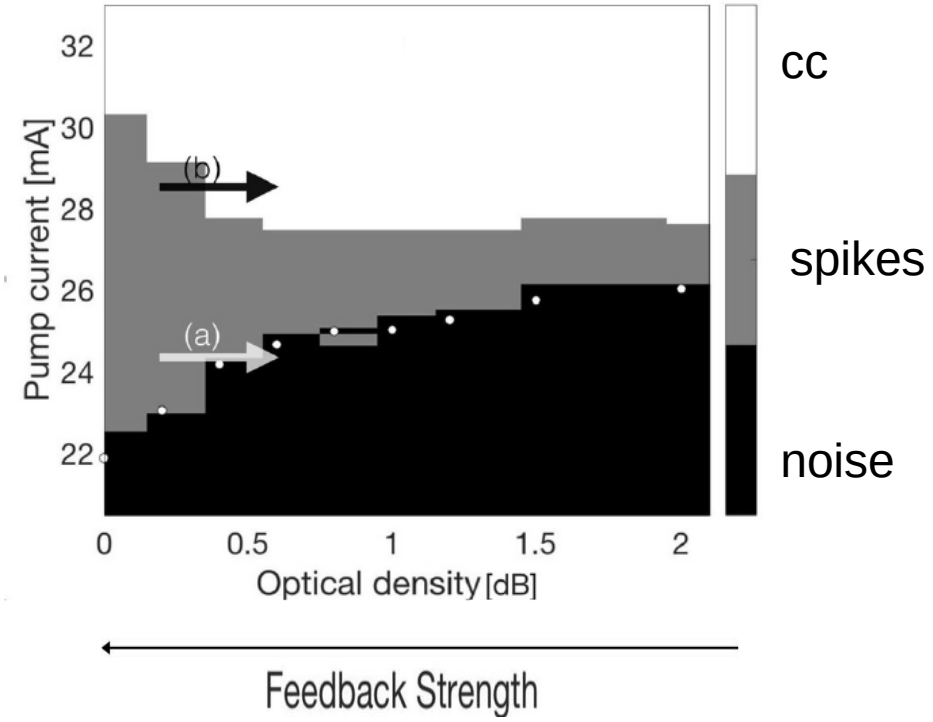


C. Quintero-Quiroz et al., "*Characterizing how complex optical signals emerge from noisy intensity fluctuations*", Scientific Reports 6 37510 (2016)

Classification criteria

$I = \{i_1, i_2, \ldots i_N\}$ laser *"raw"* intensity recorded for different pump currents and feedback strengths

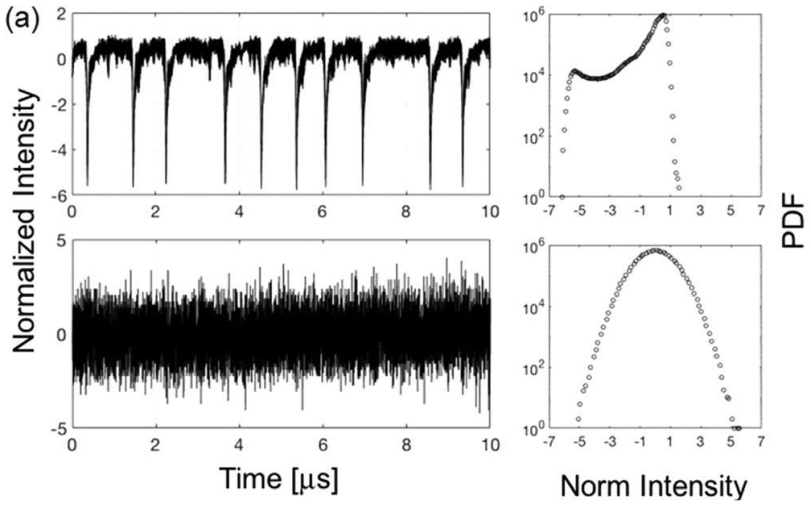
- If the skewness and kurtosis of the distribution of values are "consistent" with a Gaussian → noise
- Else, if σ increases with the pump current → spikes
- Else → coherence collapse



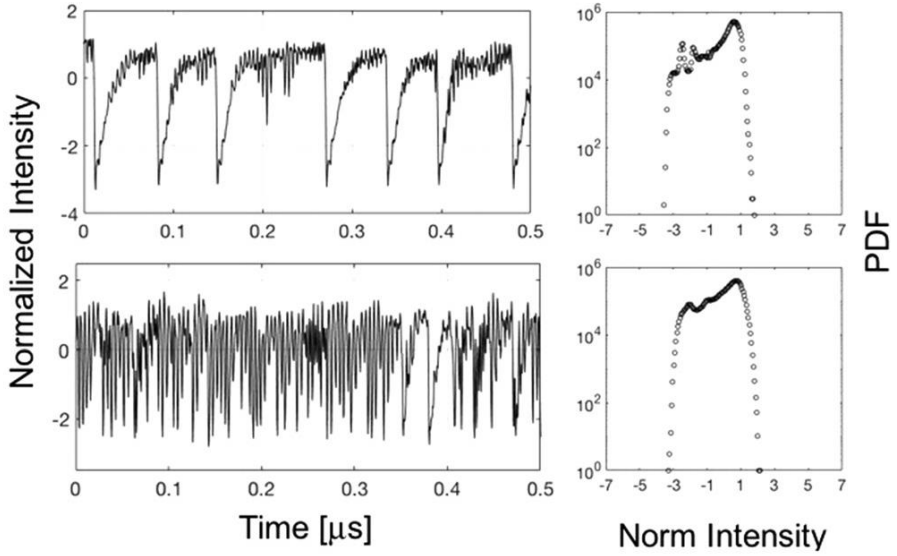
M. Panozzo et al., "*Experimental characterization of the transition to coherence collapse in a semiconductor laser with optical feedback*", Chaos 27, 114315 (2017)

Transitions when decreasing the feedback level

Low pump current: LFF → Noise

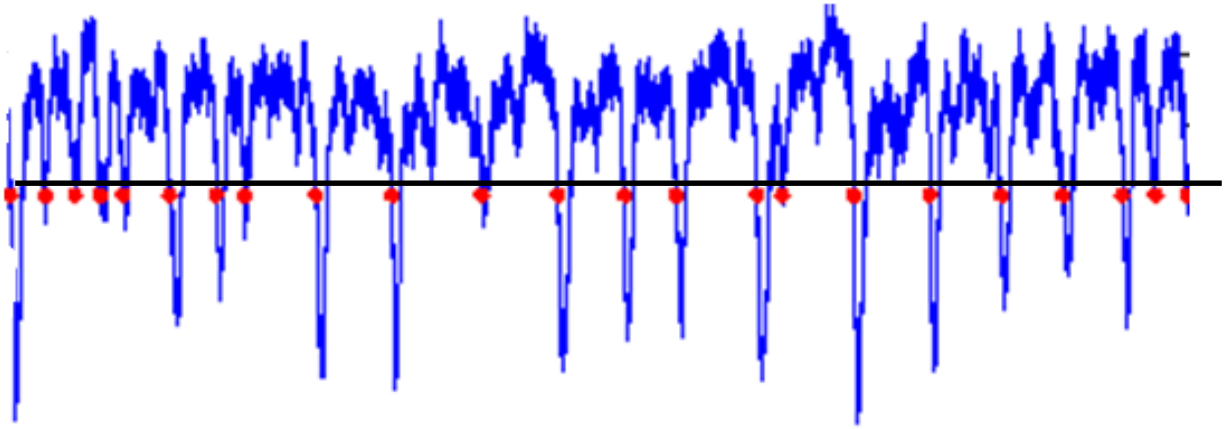


(b) Higher pump current: LFF→ CC



From intensity time series to sequence of events

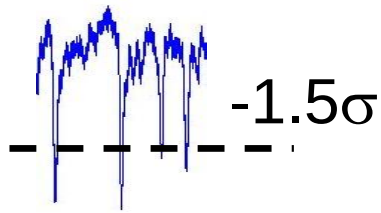
Threshold crossing ``events''

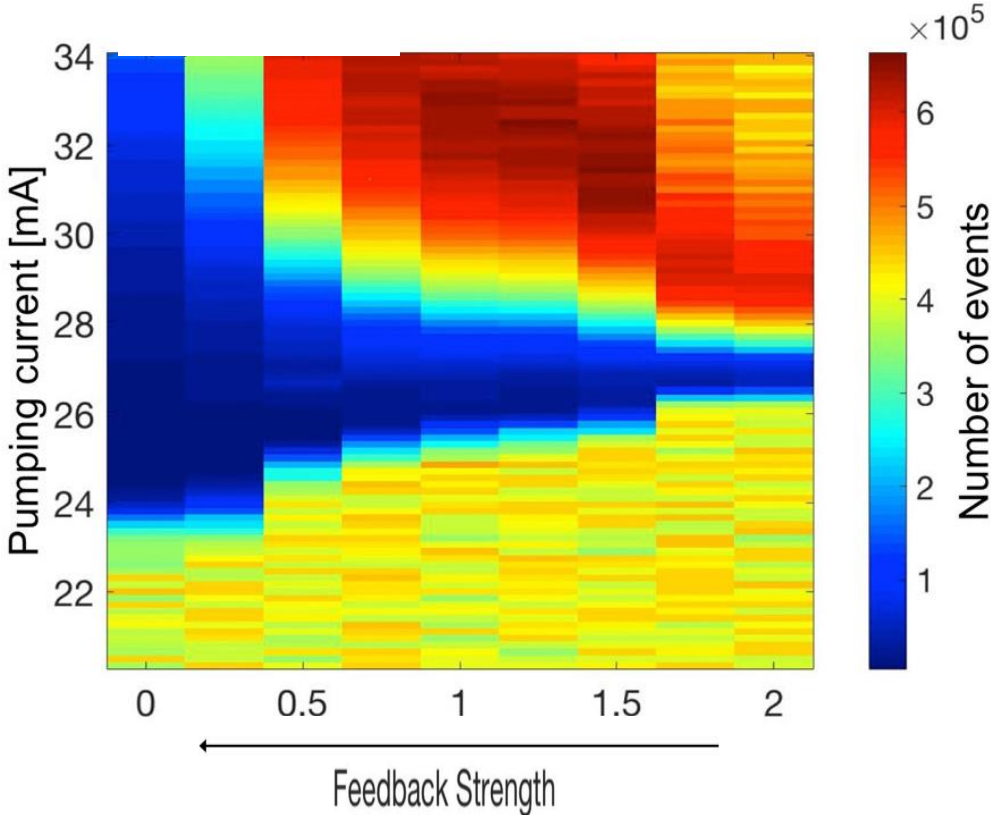


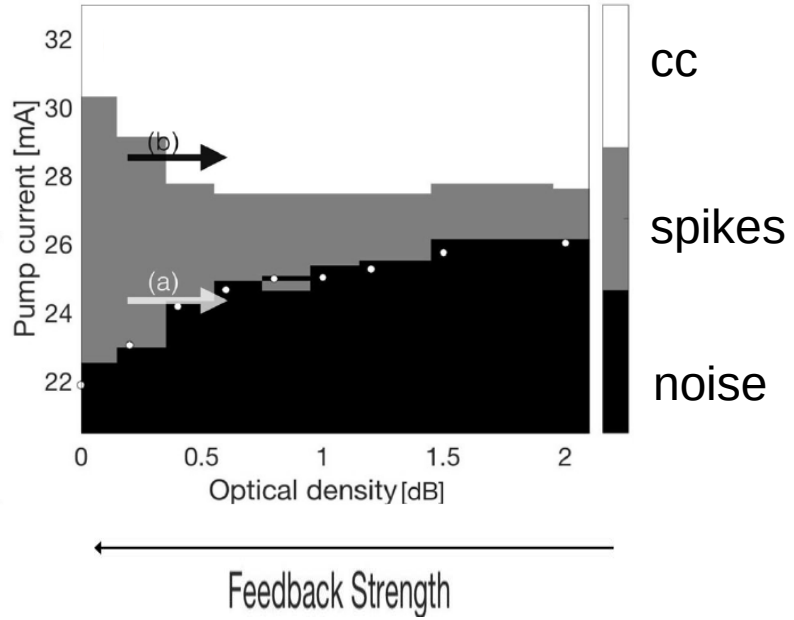
inter-spike-intervals (ISIs): $\Delta T_i = t_{i+1} - t_i$

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

Counting the number of threshold-crossing events we can distinguish three regions







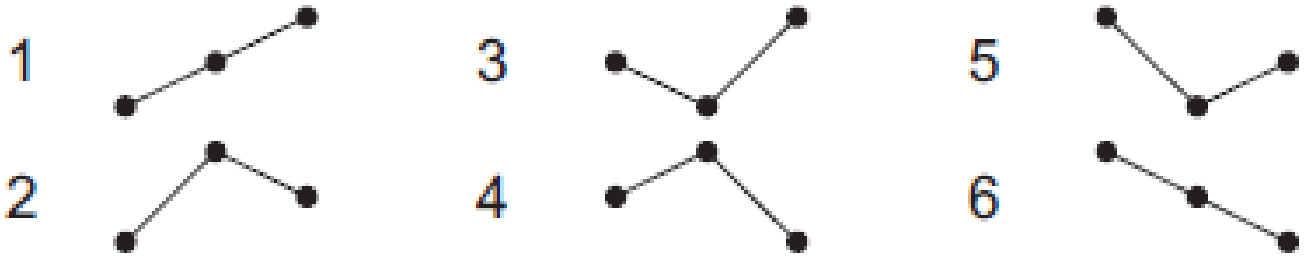
Different temporal correlations?

M. Panozzo et al., "*Experimental characterization of the transition to coherence collapse in a semiconductor laser with optical feedback*", Chaos 27, 114315 (2017)

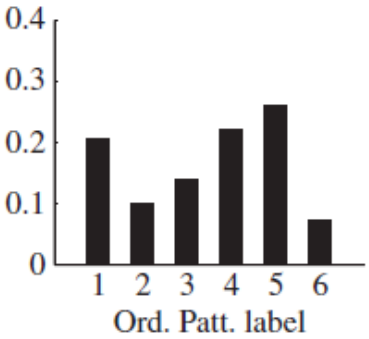
Symbolic ordinal analysis

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?

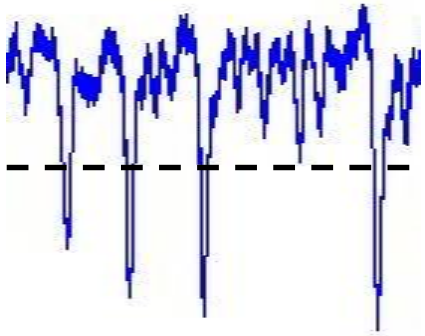


- Count how many times each “ordinal pattern” appears.
- Advantages: allows to identify temporal structures & is robust to noise.
- Drawback: information about actual data values is lost.

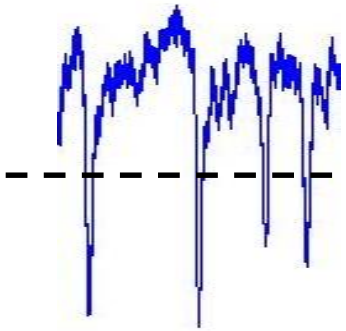


Bandt and Pompe PRL (2002)

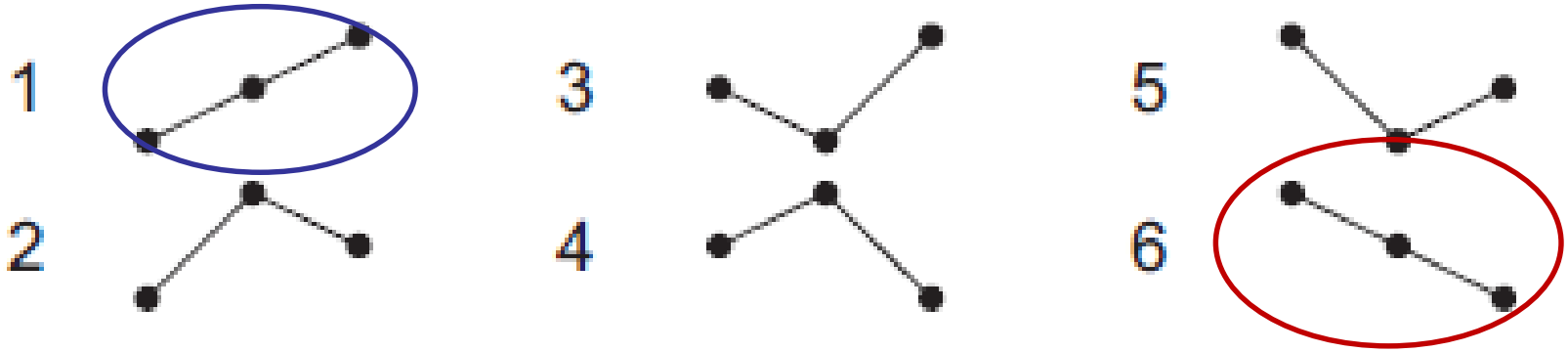
Ordinal analysis of inter-spike intervals



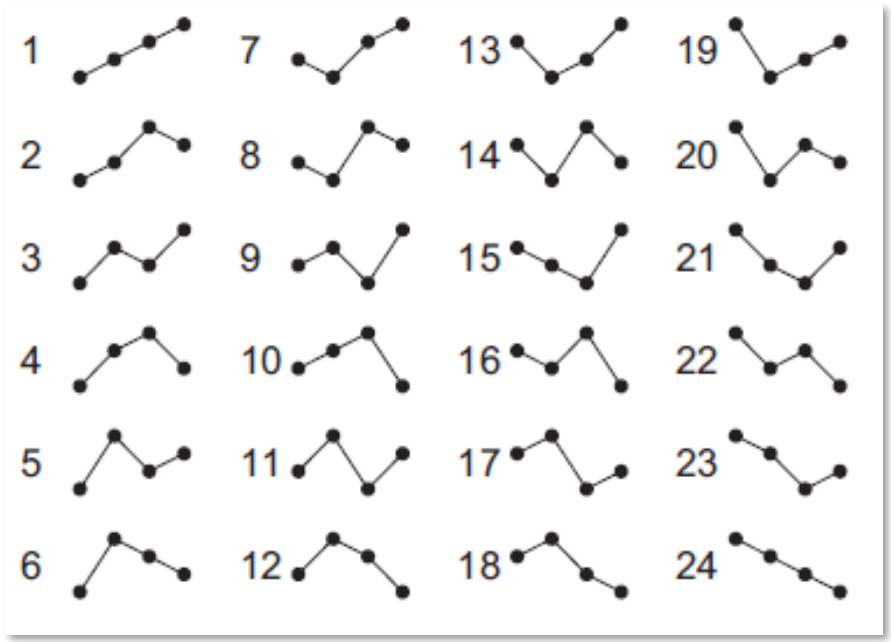
⇒012

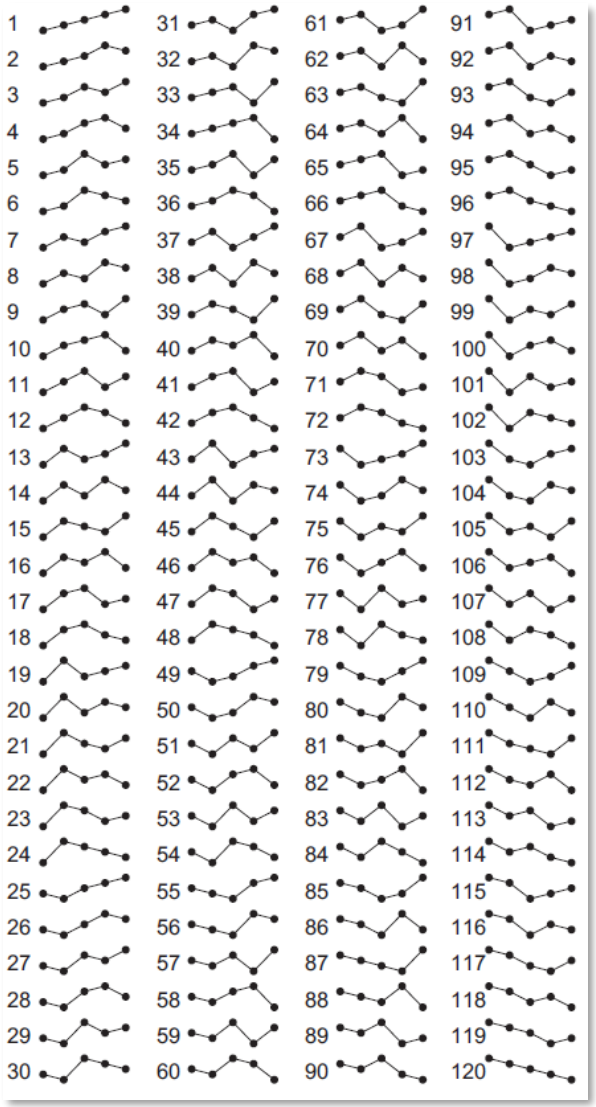


⇒210



The number of patterns increases with the number of data points as *D*!



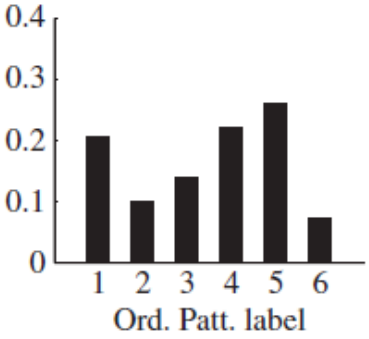


- A problem for short datasets
- How to select the optimal *D*?

  it depends on:
  - The length of the data
  - The length of the correlations

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

Are the *D*! ordinal patterns equally probable?



- **Null hypothesis**:

  $p_i = p = 1/D!$ for all $i = 1 \ldots D!$

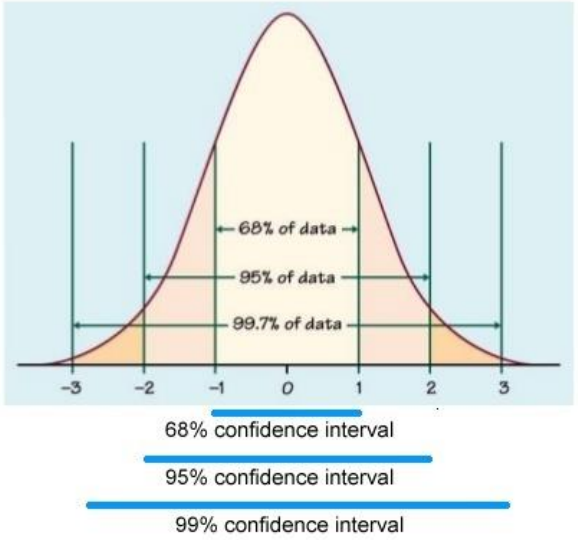
- If at least one probability **is not** in the interval $p \pm 3\sigma$ with $\sigma = \sqrt{p(1-p)/N}$

  and N the number of ordinal patterns:

  We **reject** the NH (with 99.7% confidence level).

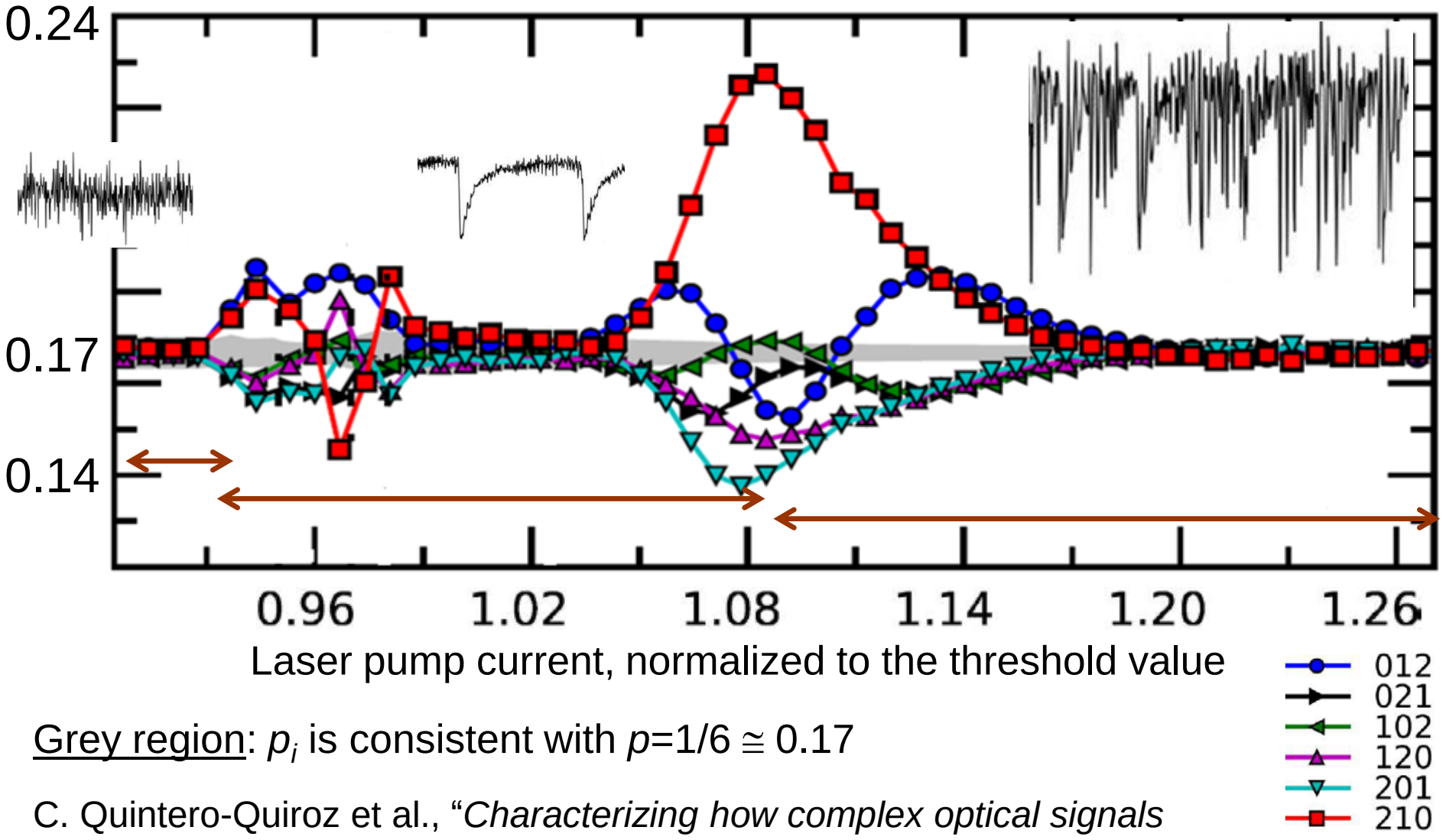
- Else

  We **fail to reject** the NH.



Ordinal analysis of the noise-LFF-CC transition

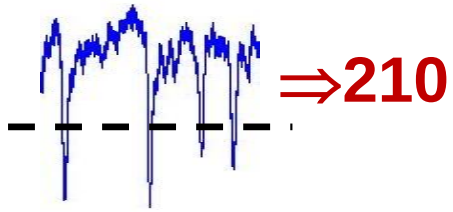
Ordinal analysis identifies the onset of different dynamical regimes, but fails to distinguish “noise” and “chaos”



Grey region: p_i is consistent with p=1/6 ≅ 0.17

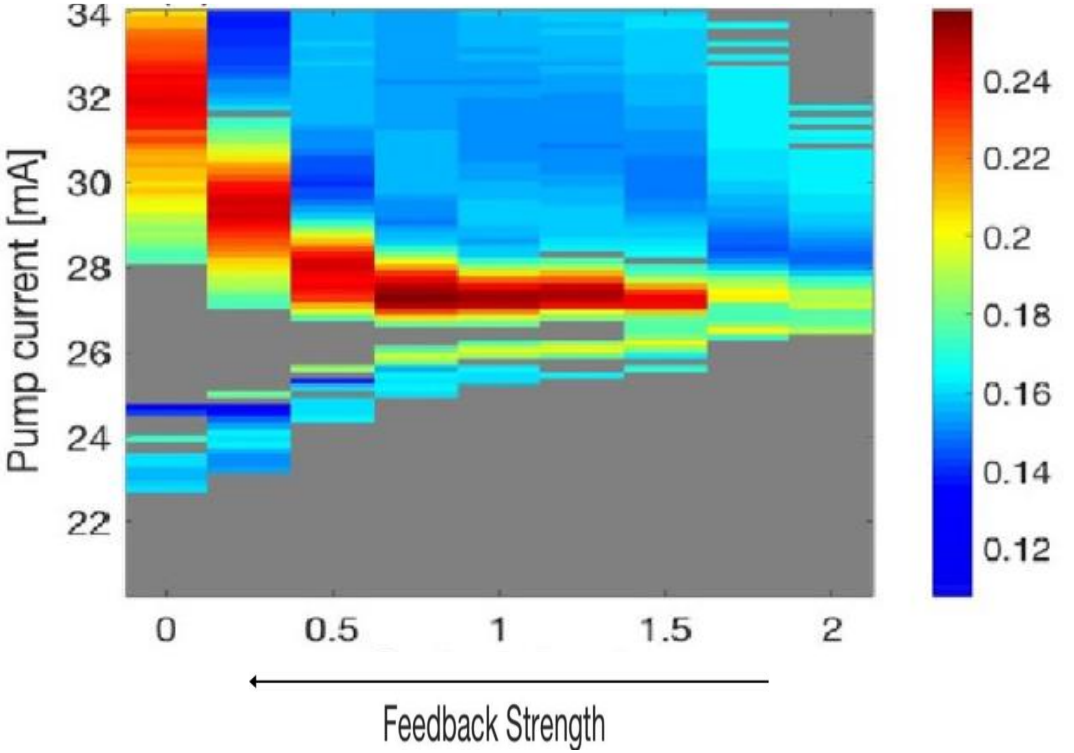
C. Quintero-Quiroz et al., “*Characterizing how complex optical signals emerge from noisy intensity fluctuations*”, Scientific Reports 6, 37510 (2016)

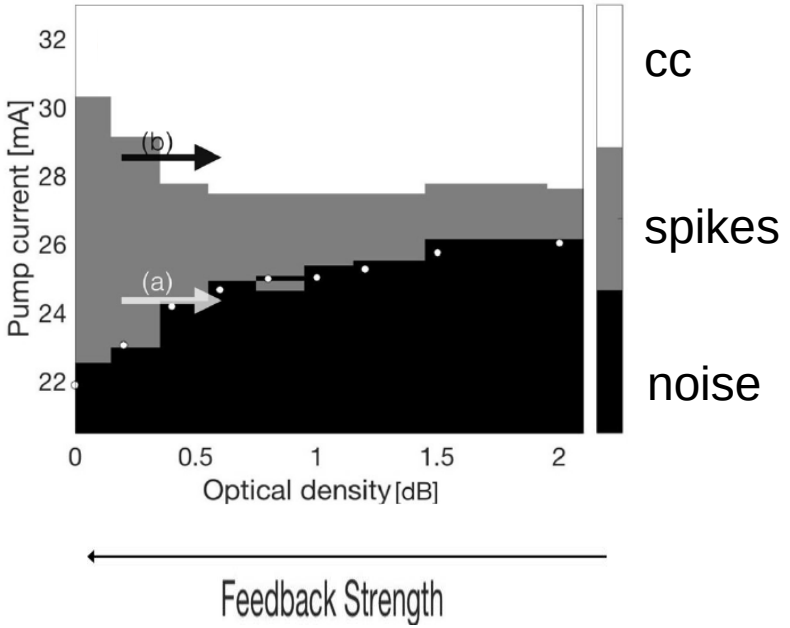
Another way to “classify” the intensity time series as noise, spikes or coherence collapse



⇒210

P(210)





Gray region: P(210) is consistent with 1/6 with 3σ confidence level.

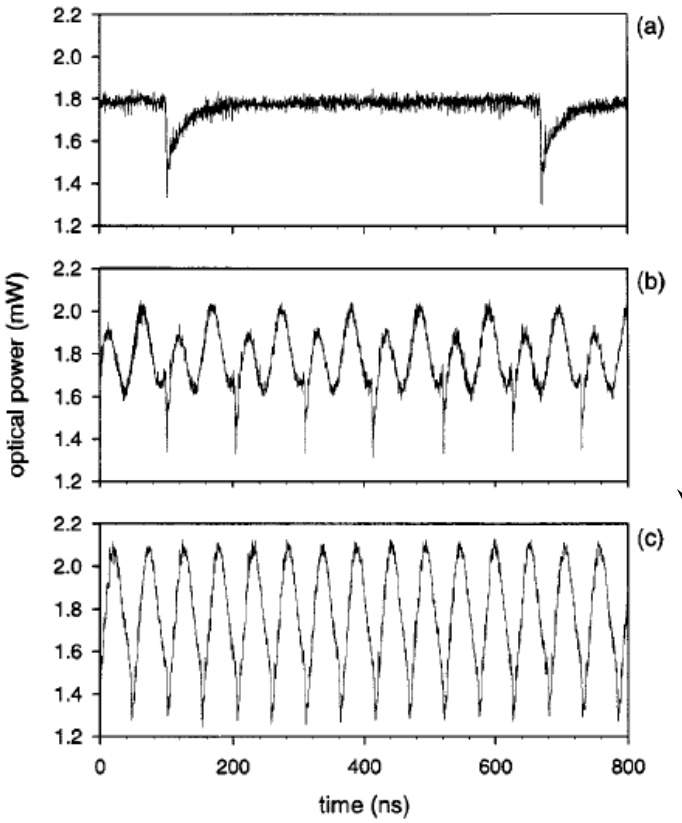
M. Panozzo et al., “*Experimental characterization of the transition to coherence collapse in a semiconductor laser with optical feedback*”, Chaos 27, 114315 (2017)

Can we *entrain* the laser spikes?

Where?

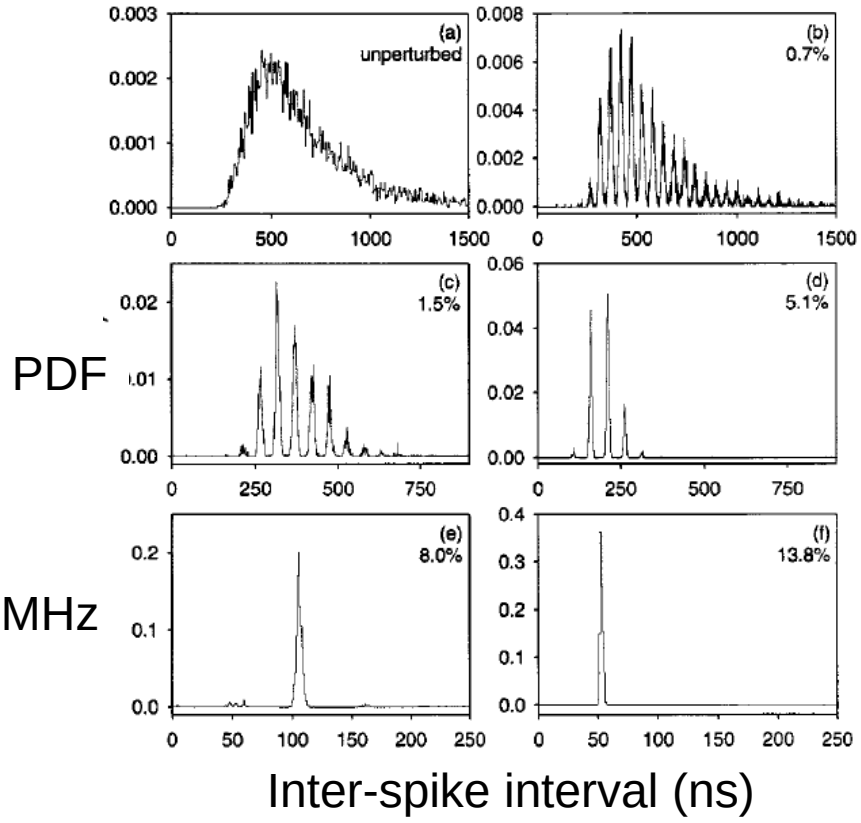
How to *quantify* the degree of entrainment?

Direct modulation of the laser pump current



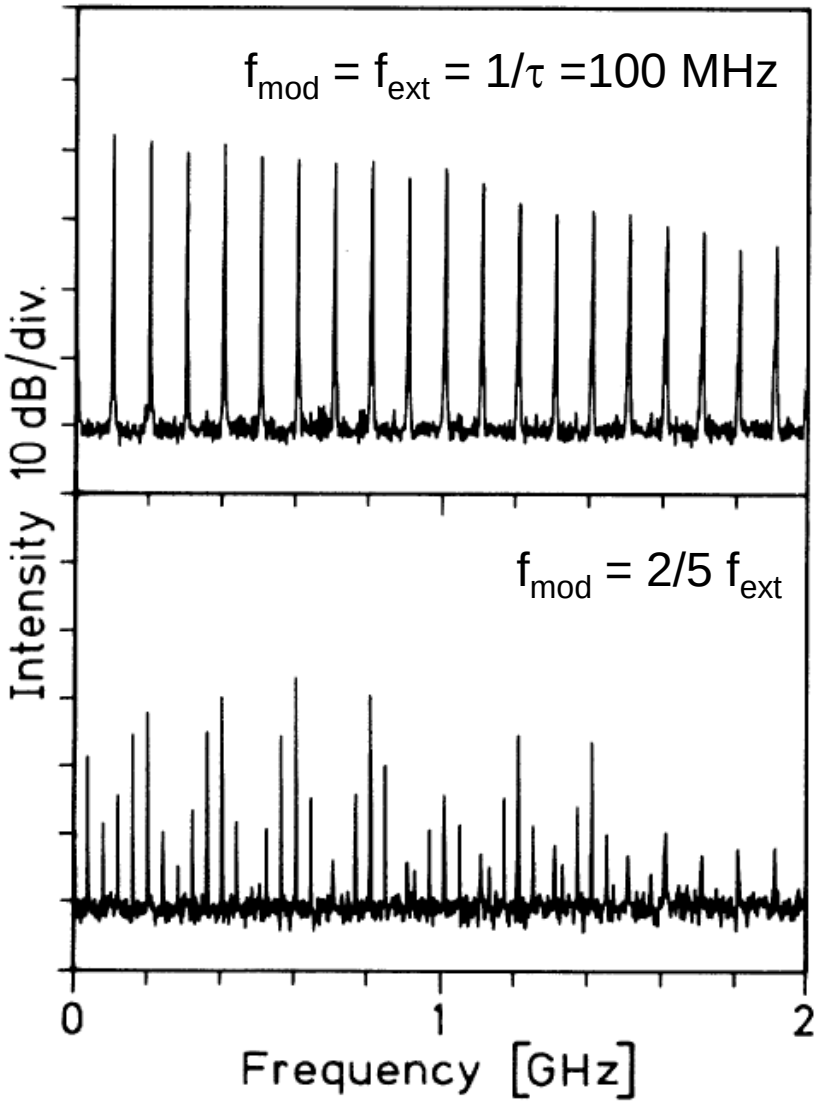
Mod. amplitude

f_{mod} = 19 MHz



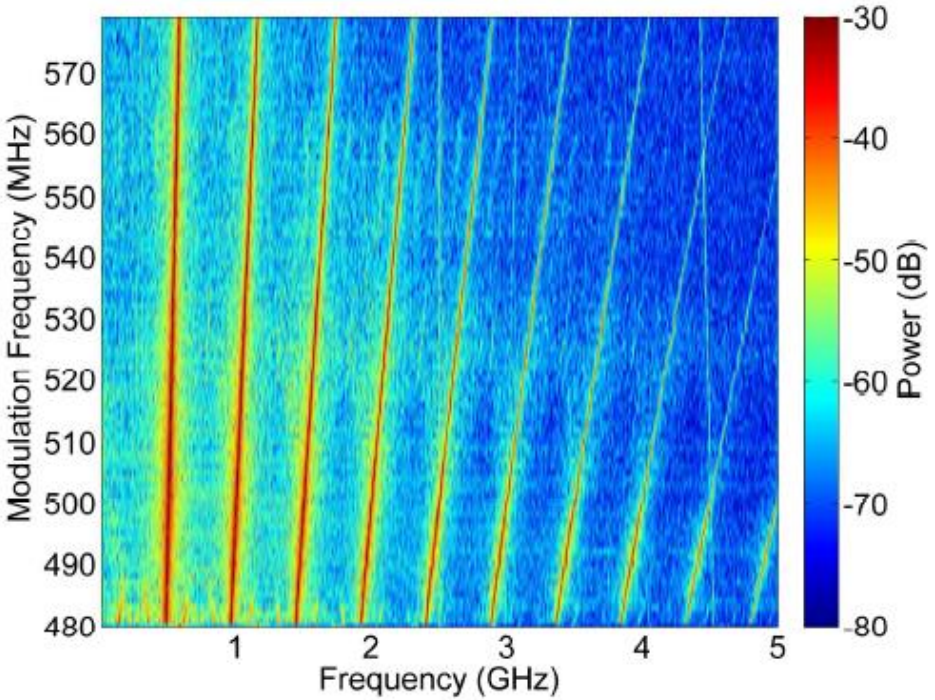
Sukow and Gauthier, "Entraining Power-Dropout Events in an External-Cavity Semiconductor Laser Using Weak Modulation of the Injection Current", IEEE J. Quantum Electron. 36 175 (2000).

Locking to the external-cavity frequency: Fourier analysis



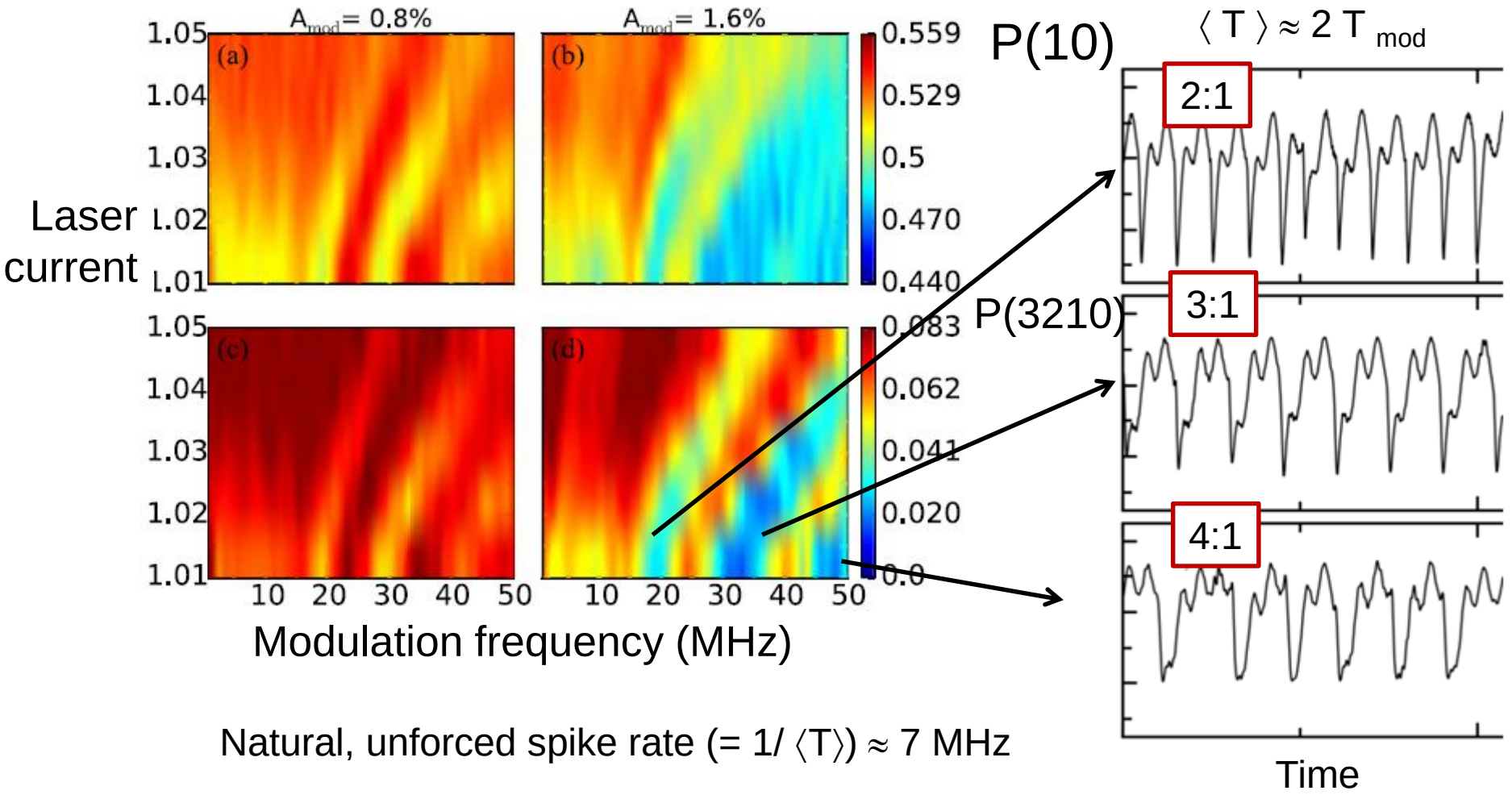
Baums, Elsasser and Gobel, PRL 63, 155 (1989)

f_{ext} = 500 MHz



Toomey et al, Opt. Express 18, 16955 (2010)

Ordinal probabilities uncover regions of noisy locking

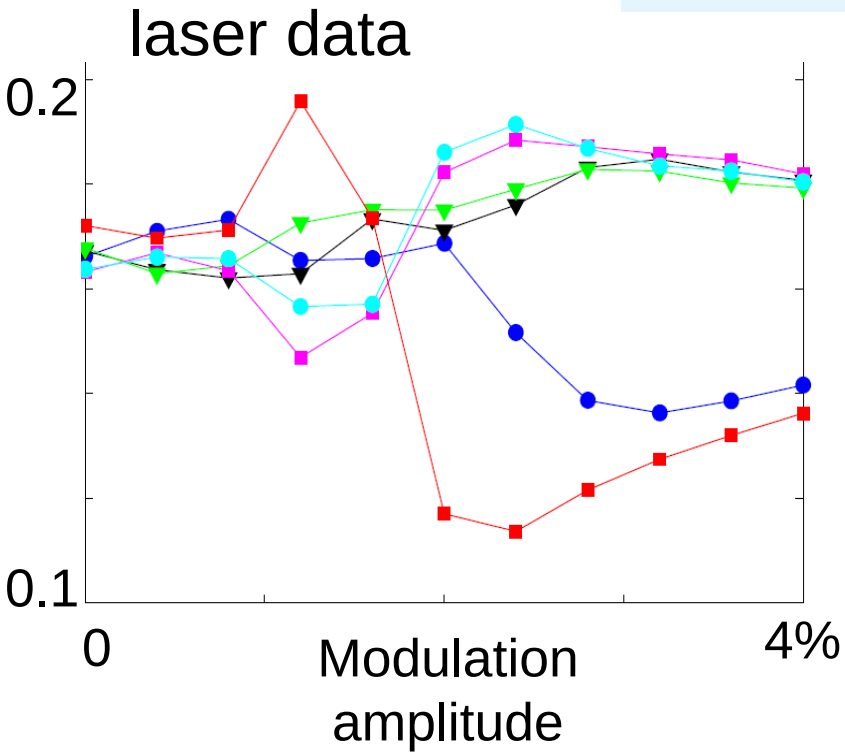


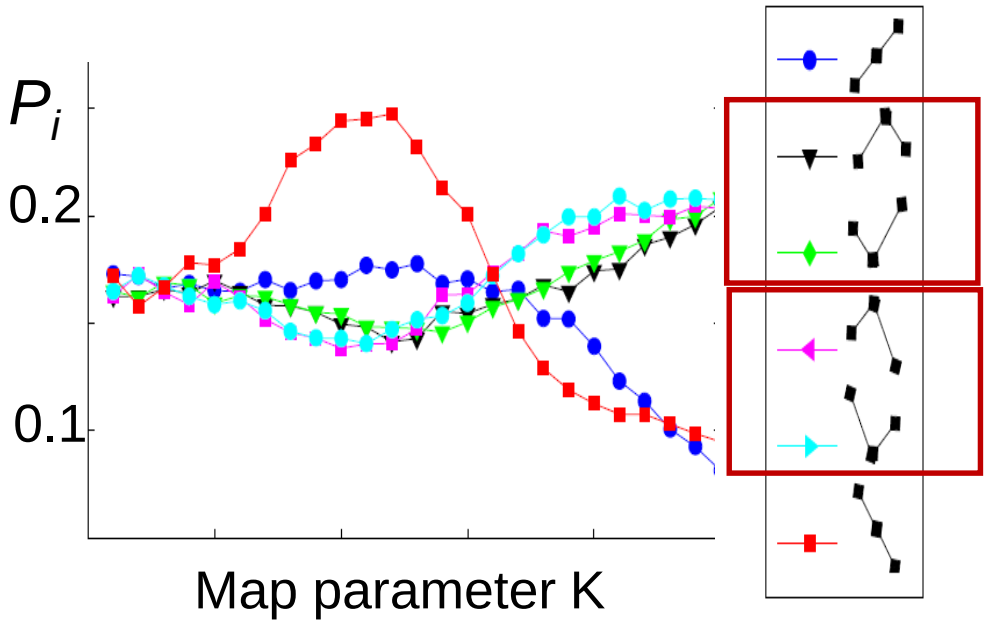
Natural, unforced spike rate (= 1/ ⟨T⟩) ≈ 7 MHz

T. Sorrentino et al, "*Analysis of the spike rate and spike correlations in modulated semiconductor lasers with optical feedback*" JSTQE 21, 1801107 (2015)

A simple model qualitatively describes the variation of the ordinal probabilities with the modulation amplitude

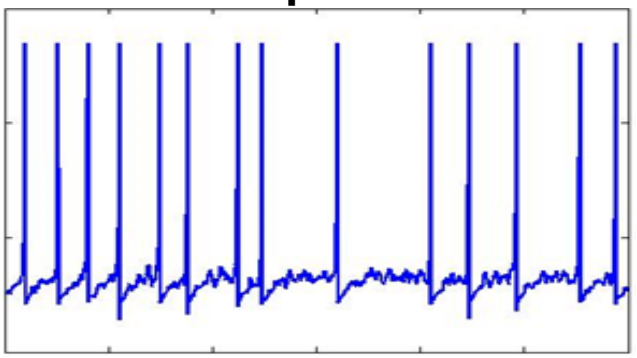
$$\varphi_{i+1} = \varphi_i + \rho + \frac{K}{2\pi}\left[\sin(2\pi\varphi_i) + \alpha_c \sin(4\pi\varphi_i)\right] + D\zeta$$



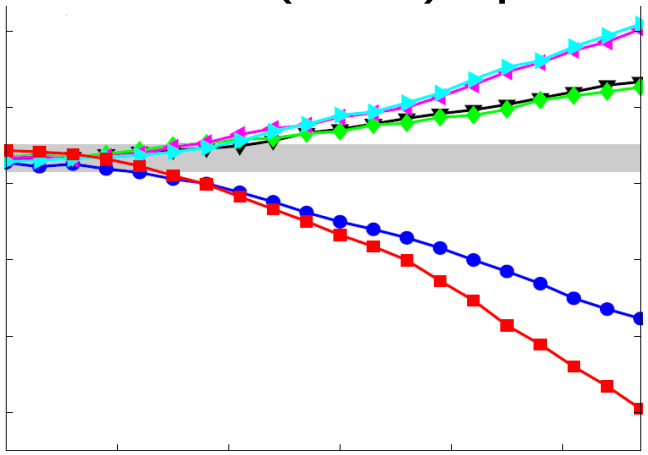


A. Aragoneses et al, "*Unveiling the complex organization of recurrent patterns in spiking dynamical systems*", Sci. Rep. **4**, 4696 (2014).

Side note: comparison with the spikes generated with FitzHugh-Nagumo neuron model

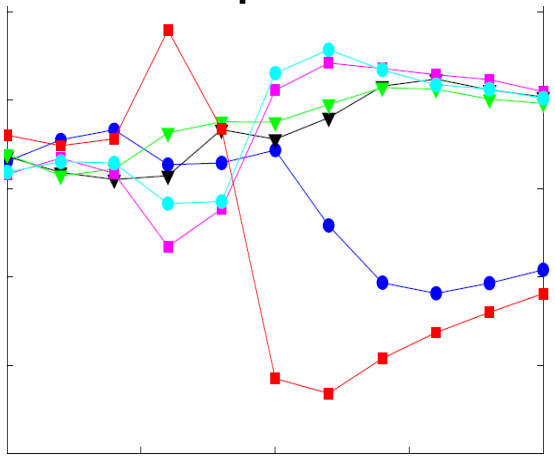


Neuronal (FHN) spikes

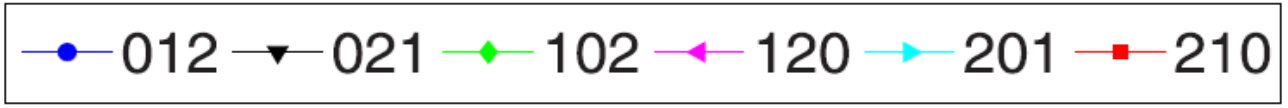


J. M. Aparicio-Reinoso, M. C. Torrent and C. Masoller, PRE 94, 032218 (2016).

Laser spikes



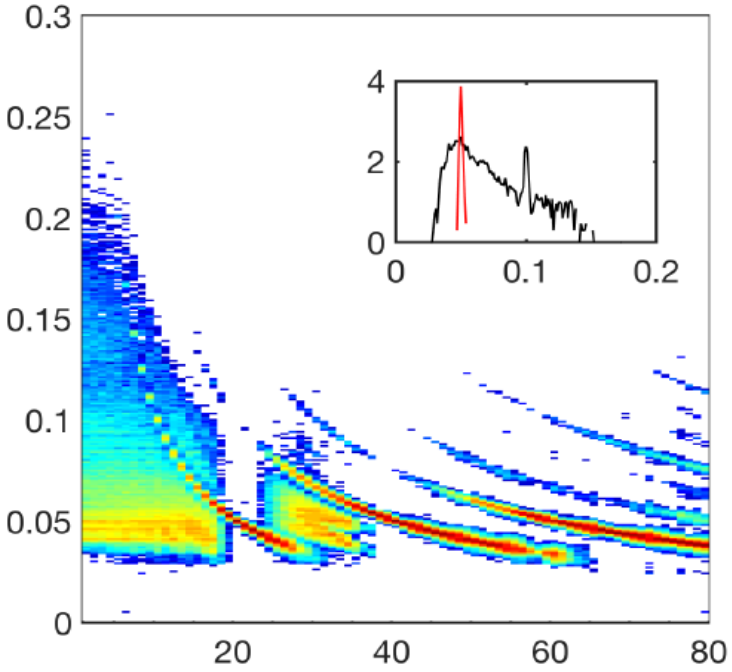
A. Aragoneses et al, Sci. Rep. **4**, 4696 (2014).



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

A_{mod} = 2.3% of I_{dc} ; I_{dc}/I_{th}=1.01 – 1.17

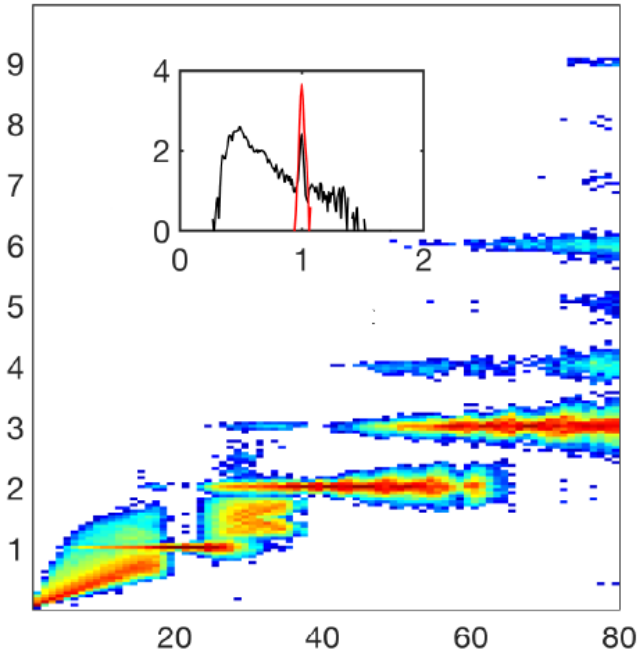
ISI (μs)



Modulation frequency (MHz)

⇒ "refractory time" clear

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

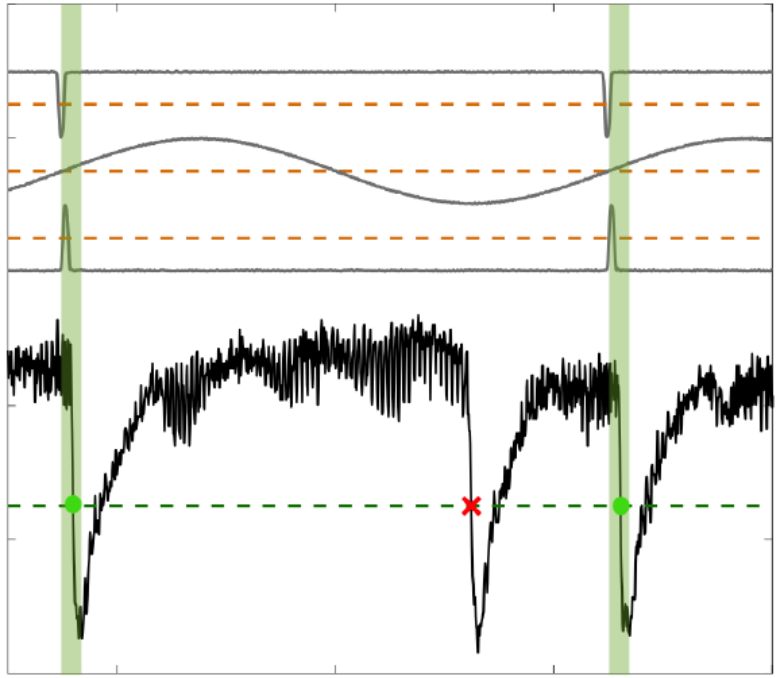


Modulation frequency (MHz)

⇒ "locking" horizontal

J. Tiana-Alsina et al., "*Experimental characterization of transitions between locking regimes in a laser system with weak periodic forcing*", arxiv.org:1806.08950 (2018)

How to quantify the degree of locking?



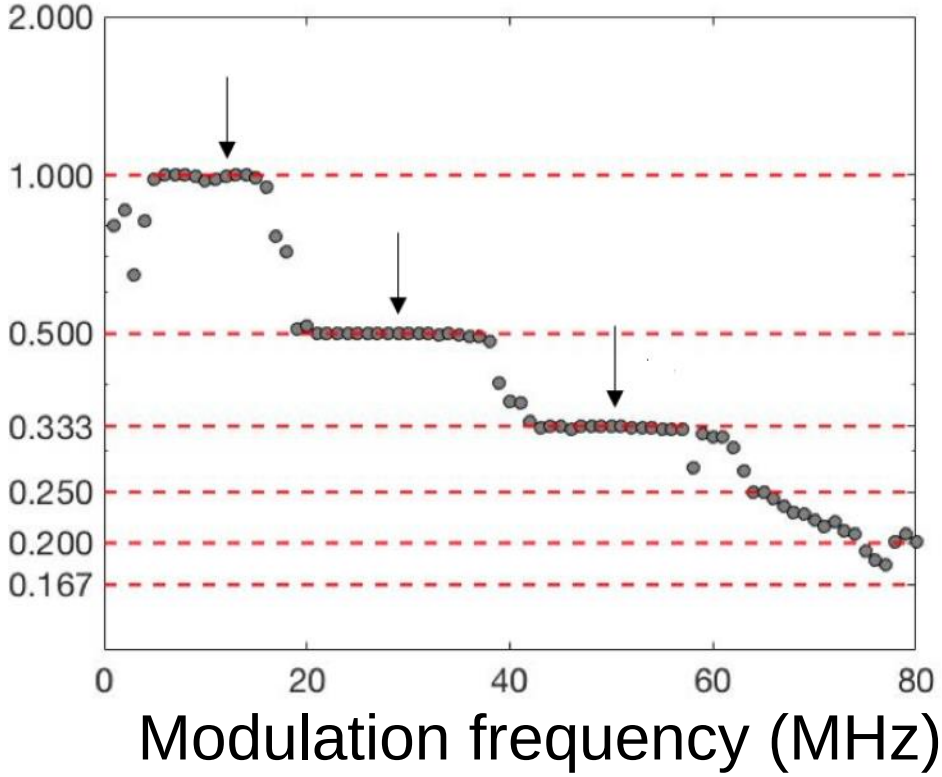
We test three modulation waveforms

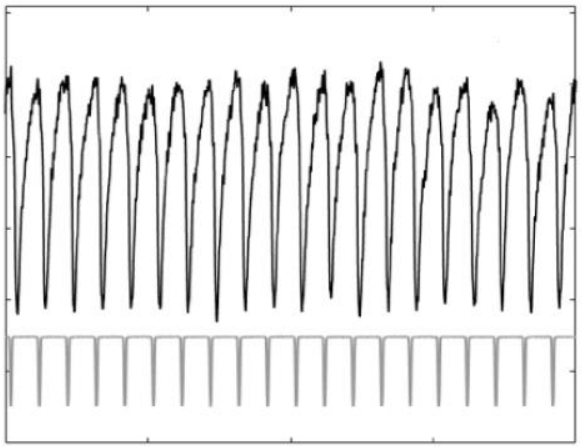
success rate $$\mathrm{SR}(\tau) = \frac{\#\text{ of spikes emitted in the interval } \tau}{\#\text{ of modulation cycles}}$$

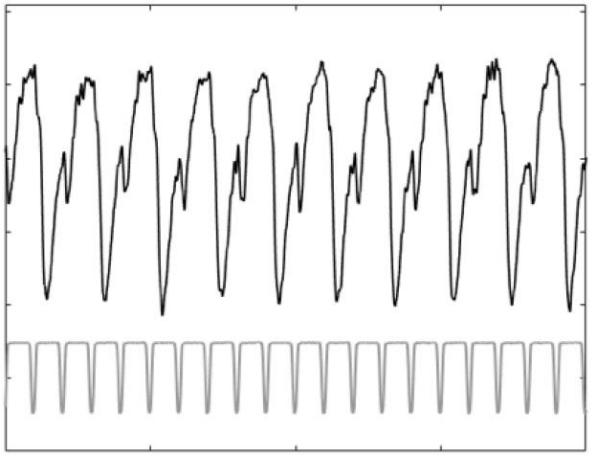
false positive rate $$\mathrm{FPR}(\tau) = \frac{\#\text{ spikes that are not emitted in the time interval } \tau}{\text{Total }\#\text{ of spikes}}$$

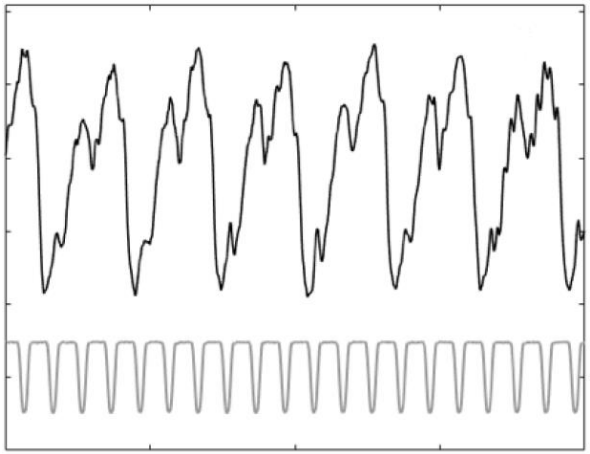
Results

Success rate



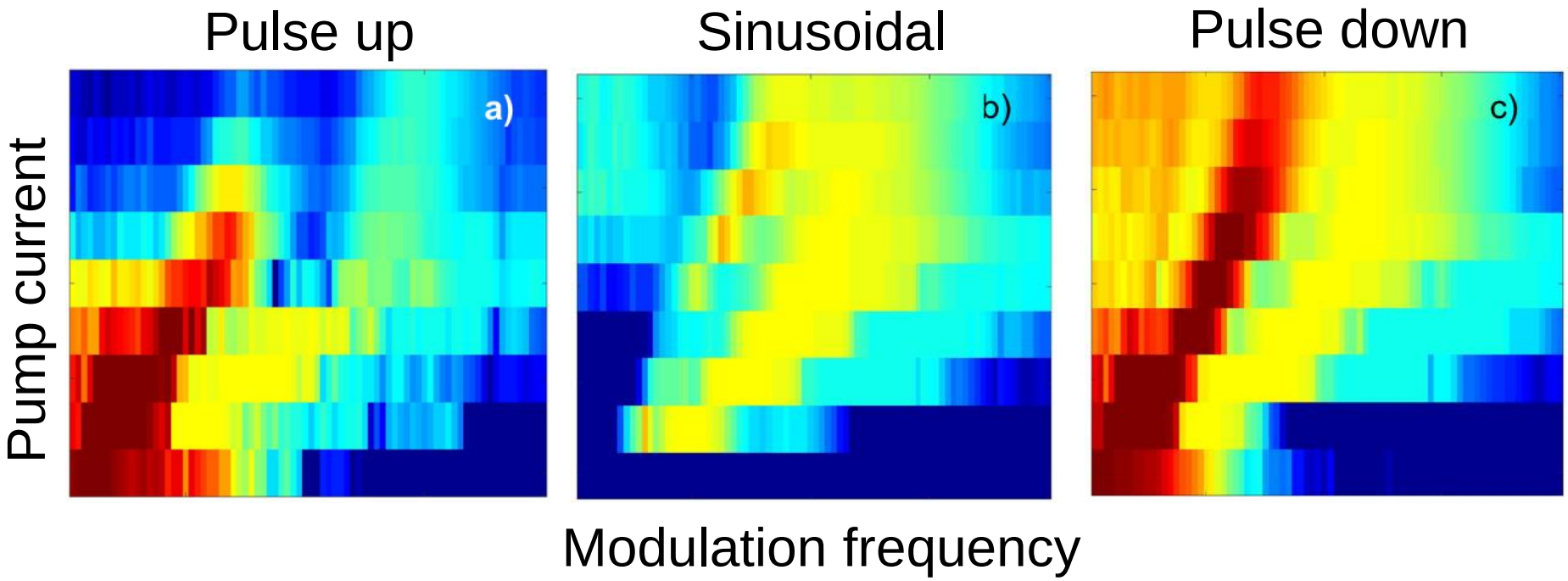






Time/T_{mod}

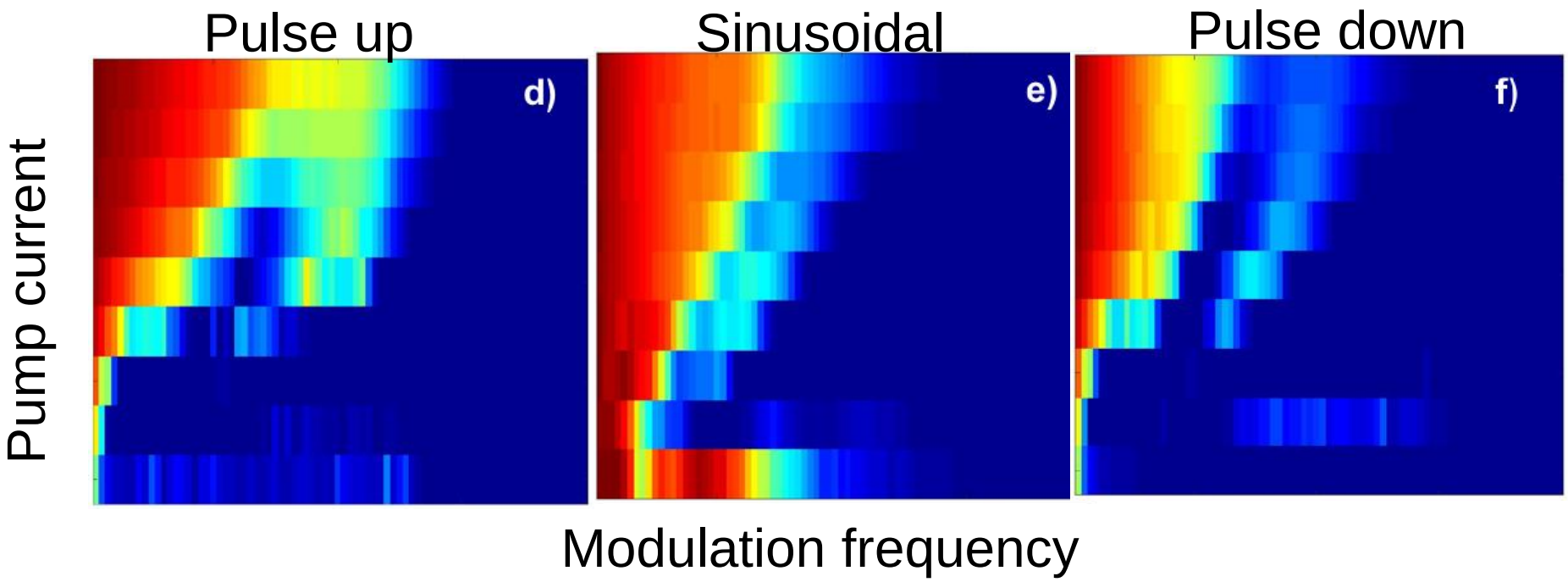
Waveform comparison: in color code the success rate (red SR=1)



$\Rightarrow$ wider locking with pulse-down waveform

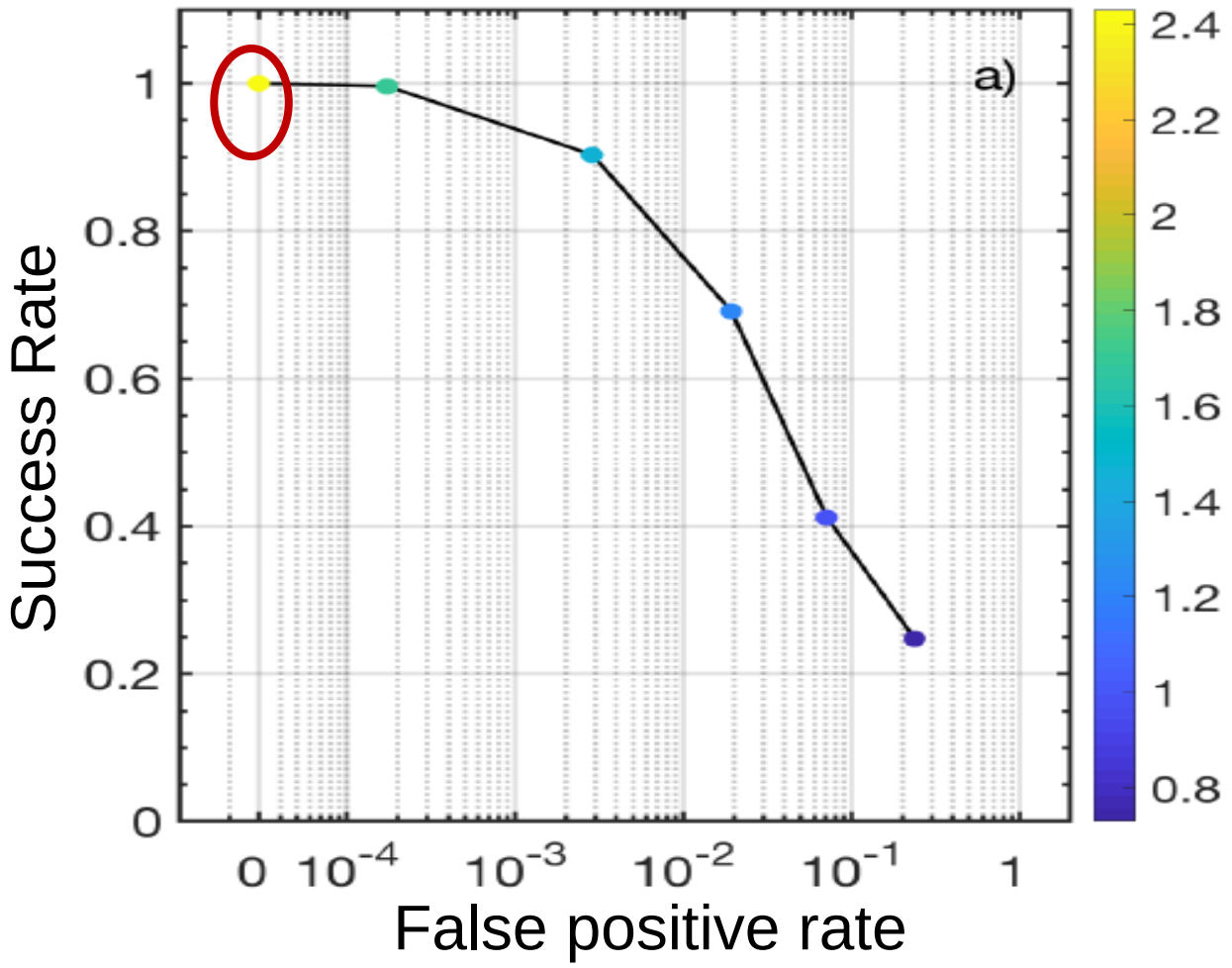
J. Tiana et al, "*Experimental study of modulation waveforms for entraining the spikes emitted by a semiconductor laser with optical feedback*", Opt. Express 26 9298 (2018)

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



J. Tiana et al, "*Experimental study of modulation waveforms for entraining the spikes emitted by a semiconductor laser with optical feedback*", Opt. Express 26 9298 (2018)

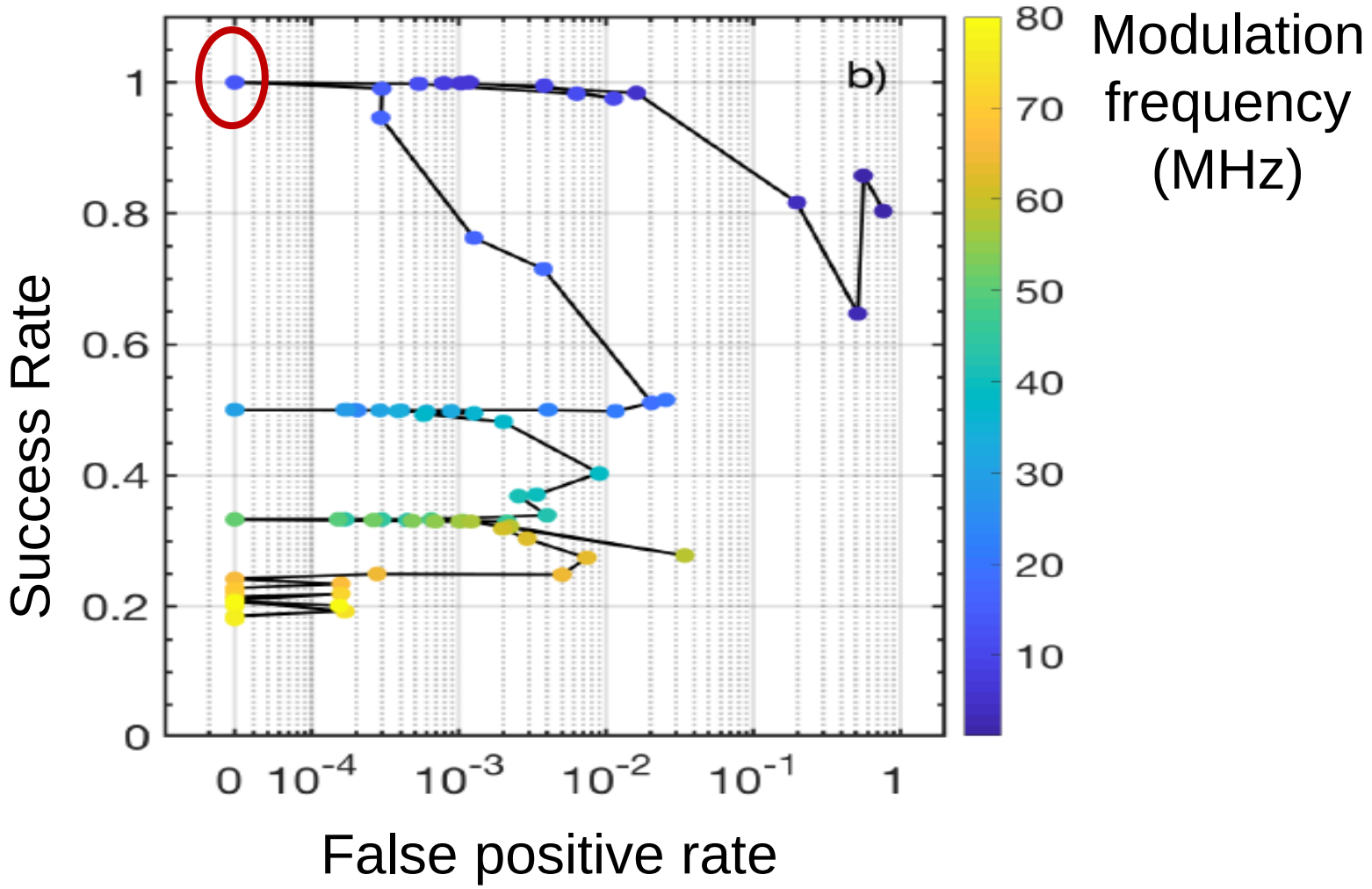
Receiver operating characteristic (ROC) curve



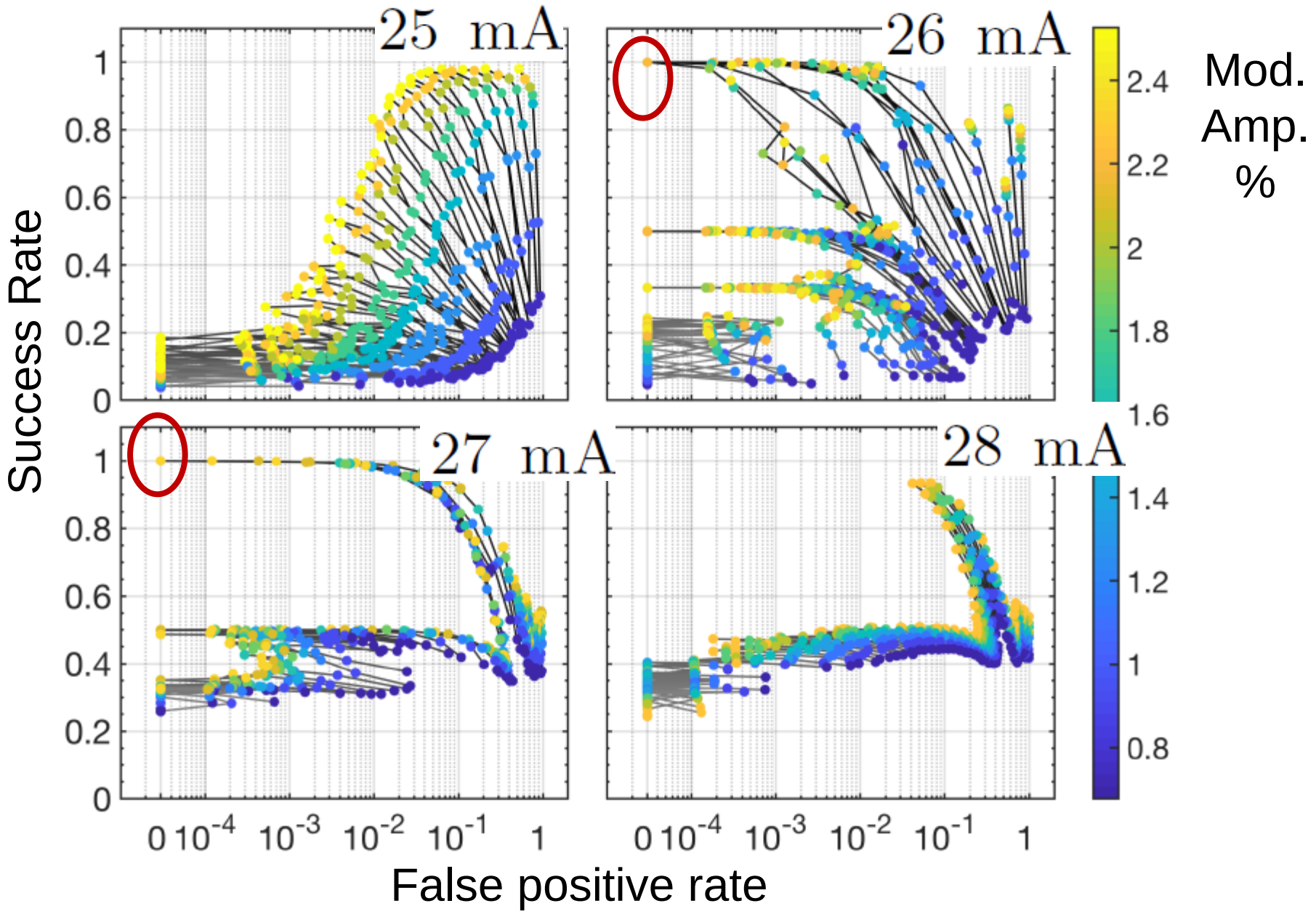
Modulation amplitude % of I_{dc}

J. Tiana-Alsina et al., "*Experimental characterization of transitions between locking regimes in a laser system with weak periodic forcing*", arxiv.org:1806.08950 (2018)

Locked-unlocked transitions when the modulation frequency increases



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



Summary part 1

- Ordinal analysis identifies the onset of the LFF-CC transition but fails to distinguish between noise and CC regimes.

- ROC curves allow to quantify the degree of locking.

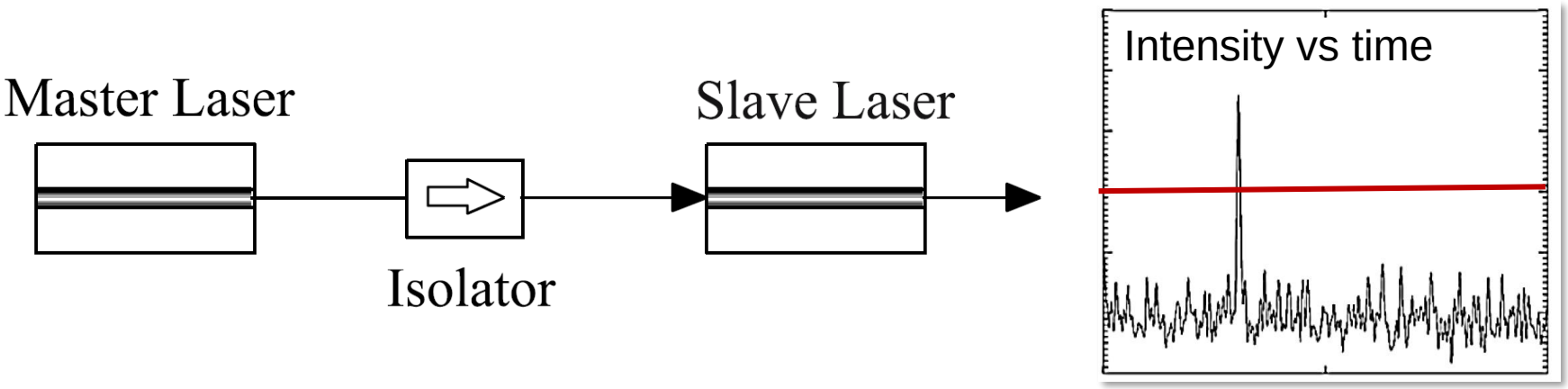
- Regions of perfect 1:1 locking identified (SR=1, FPR=0).

C. Quintero-Quiroz et al., "*Characterizing how complex optical signals emerge from noisy intensity fluctuations*", Scientific Reports 6 37510 (2016).

J. Tiana et al, "*Experimental study of modulation waveforms for entraining the spikes emitted by a semiconductor laser with optical feedback*", Opt. Express 26 9298 (2018).

J. Tiana-Alsina et al., "*Experimental characterization of transitions between locking regimes in a laser system with weak periodic forcing*", arxiv.org:1806.08950 (2018).

Extreme pulses in a cw optically injected laser



- Which mechanism triggers ultra-high pulses?
- Role of noise?
- Can they be suppressed?
- Can they be predicted ?
- Can they be generated “on demand”?

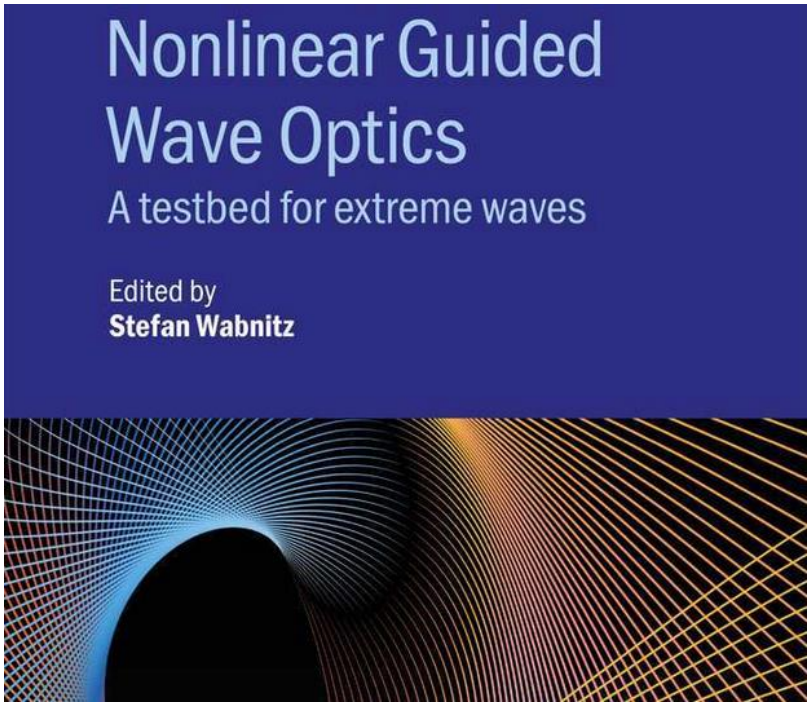
December 2017

⇐ **Open access**

Chapter 1

Extreme events in forced oscillatory media in zero, one and two dimensions

S Barland, M Brambilla, L Columbo, B Garbin, C J Gibson, M Giudici, F Gustave, C Masoller, G L Oppo, F Prati, C Rimoldi, J R Rios, J R Tredicce, G Tissoni, P Walczak, A M Yao and J Zamora-Munt



-0D
-1D
-2D

J. Opt. **18** (2016) 063001 (37pp)

Roadmap on optical rogue waves and extreme events

Nail Akhmediev[1,22], Bertrand Kibler[2], Fabio Baronio[3], Milivoj Belić[4], Wei-Ping Zhong[5], Yiqi Zhang[6], Wonkeun Chang[1], Jose M Soto-Crespo[7], Peter Vouzas[1], Philippe Grelu[2], Caroline Lecaplain[8], K Hammani[2], S Rica[9], A Picozzi[2], Mustapha Tlidi[10], Krassimir Panajotov[11], Arnaud Mussot[12], Abdelkrim Bendahmane[12], Pascal Szriftgiser[12], Goery Genty[13], John Dudley[14], Alexandre Kudlinski[12], Ayhan Demircan[15], Uwe Morgner[15], Shalva Amiraranashvili[16], Carsten Bree[16], Günter Steinmeyer[17], C Masoller[18], Neil G R Broderick[19], Antoine F J Runge[19], Miro Erkintalo[19], S Residori[20], U Bortolozzo[20], F T Arecchi[21], Stefan Wabnitz[3], C G Tiofack[12], S Coulibaly[12] and M Taki[12]

Governing equations

Complex field, **E –Laser intensity ~ $|E|^2$**

Carrier density, **N**

$$\frac{dE}{dt} = \frac{1}{2\tau_p}(1+i\alpha)(N-1)E + i\Delta\omega + \sqrt{P_{\text{inj}}} + \sqrt{2\beta_{sp}/\tau_N}\,\xi(t)$$

$$\frac{dN}{dt} = \frac{1}{\tau_N}\left(\mu - N - N|E|^2\right)$$

optical injection
η: injection strength
$\Delta\omega = \omega_s - \omega_m$: detuning

spontaneous emission noise

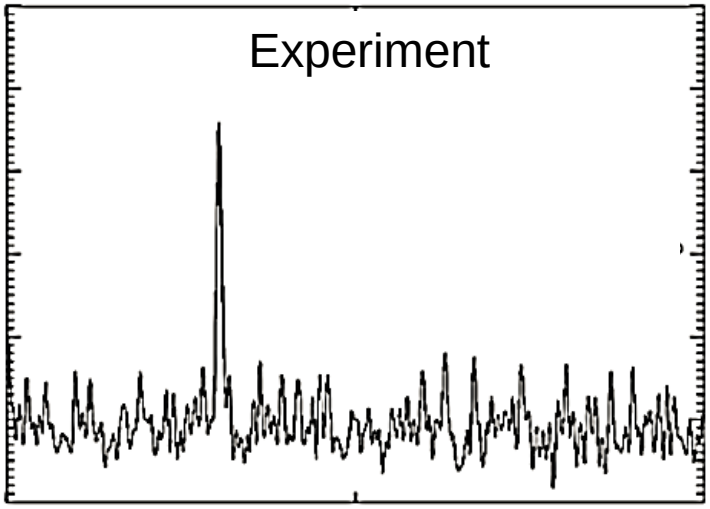
Solitary laser parameters: α τ_p τ_N μ

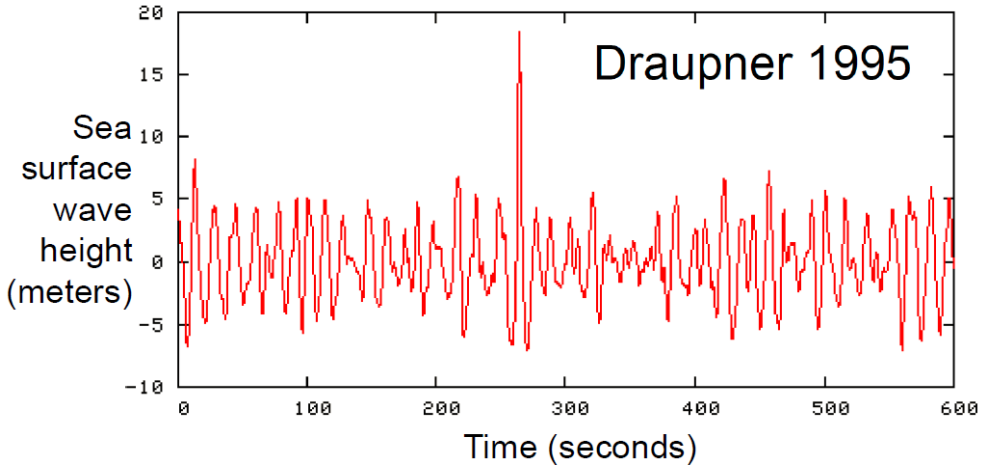
μ: normalized pump current parameter

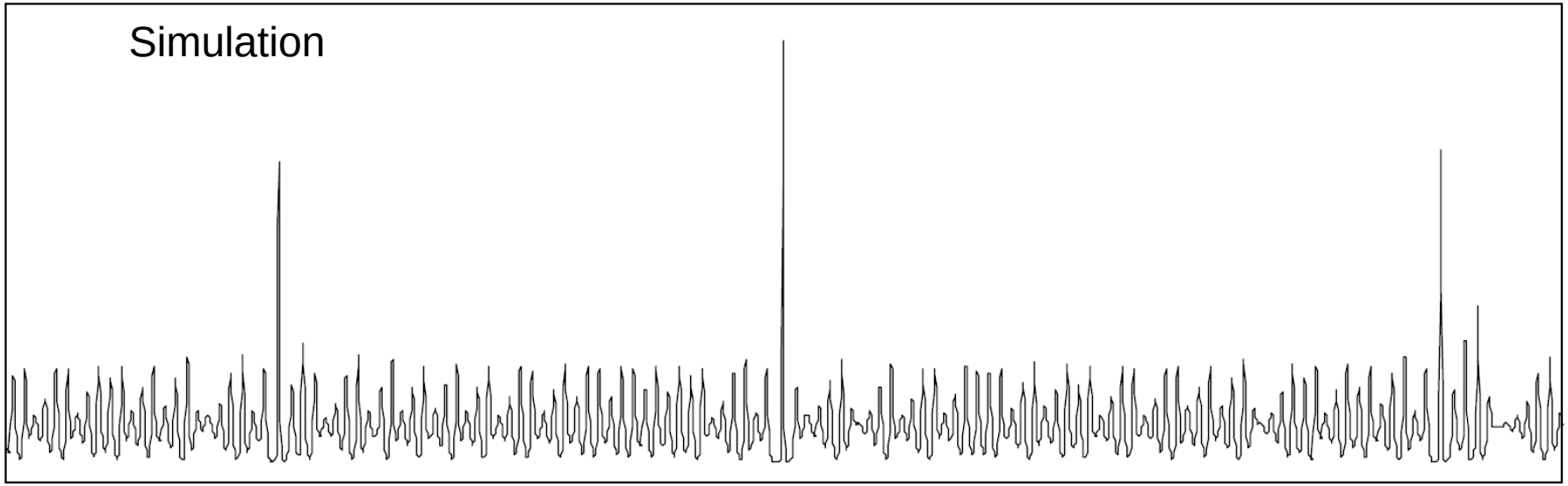
Typical parameter values:

$\alpha = 3$, $\tau_p = 1$ ps, $\tau_N = 1$ ns

These 0D rate-equations provide good qualitative agreement with the experimentally observed intensity dynamics.


Experiment

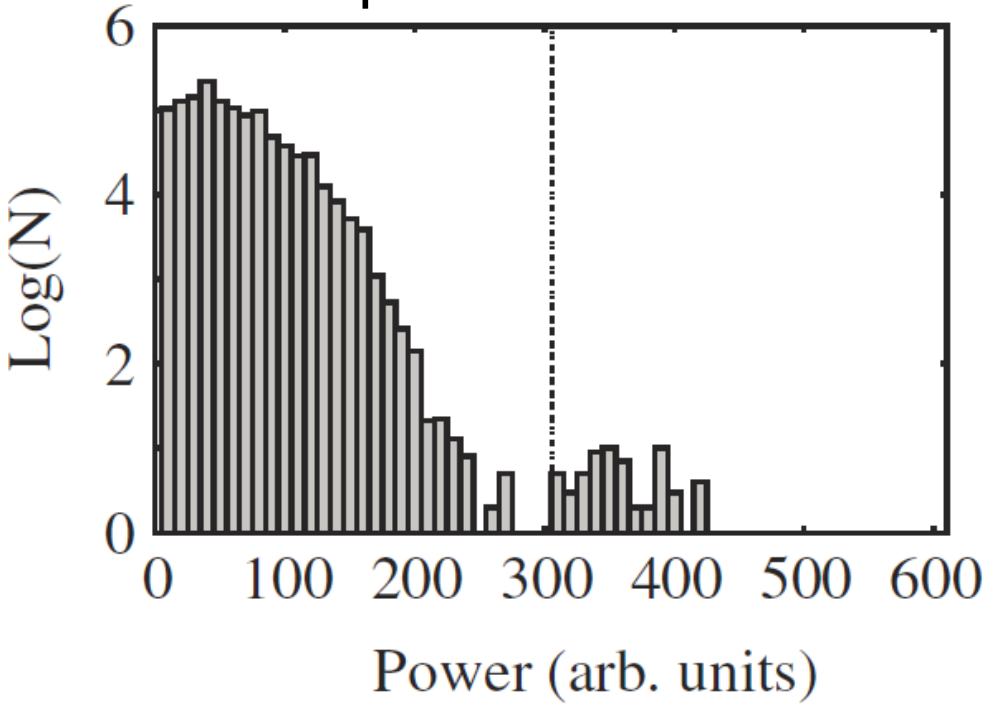

Draupner 1995
Sea surface wave height (meters)
20
15
10
5
0
-5
-10
0
100
200
300
400
500
600
Time (seconds)


Simulation

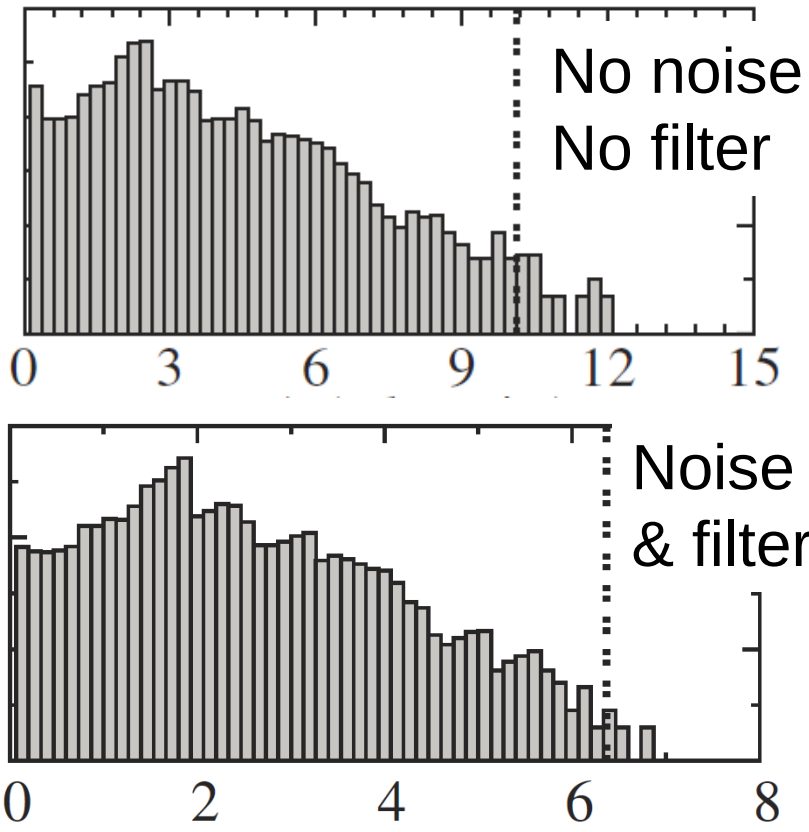
Time

Distribution of pulse amplitudes

Experiments



Simulations



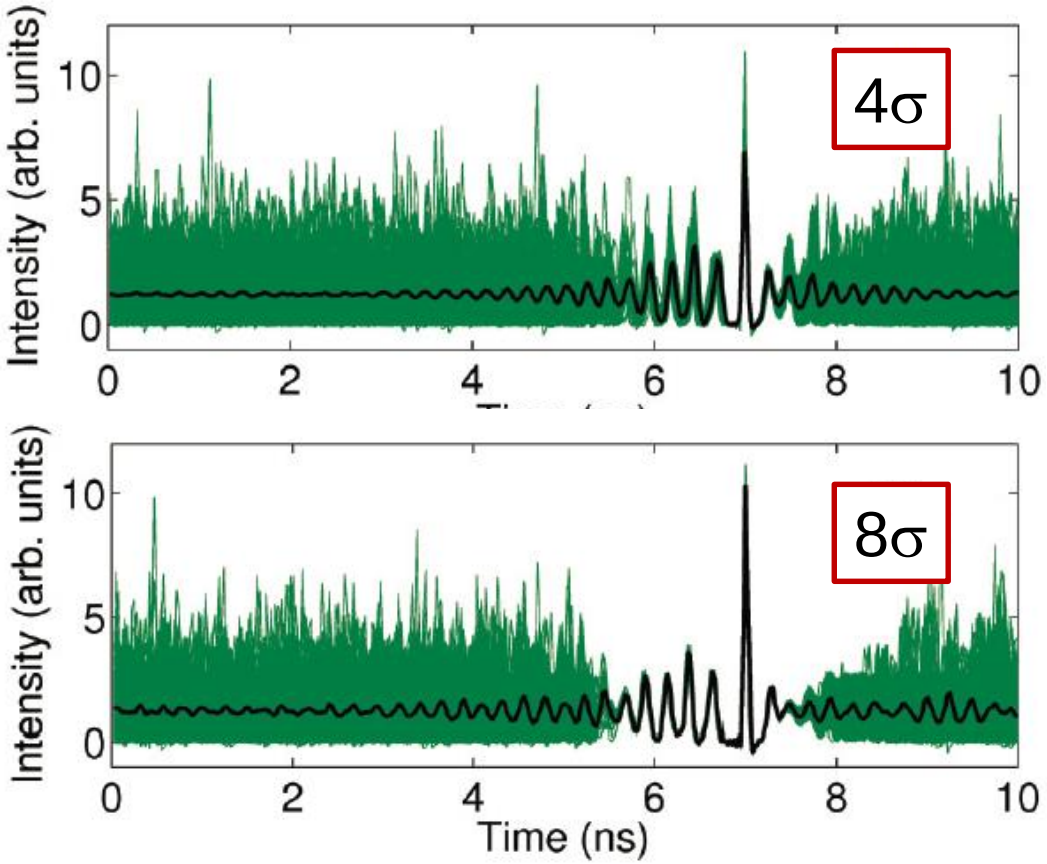
Optical rogue wave:

pulse higher than <A> + **6-8** σ

Bonatto et al, "*Deterministic optical rogue waves*", PRL 107, 053901 (2011)

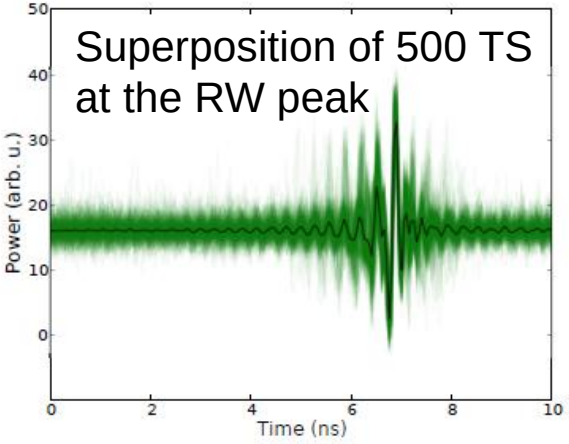
Predictability?

Deterministic simulations



Superposition of 50 time-series at the RW peak

Experiments

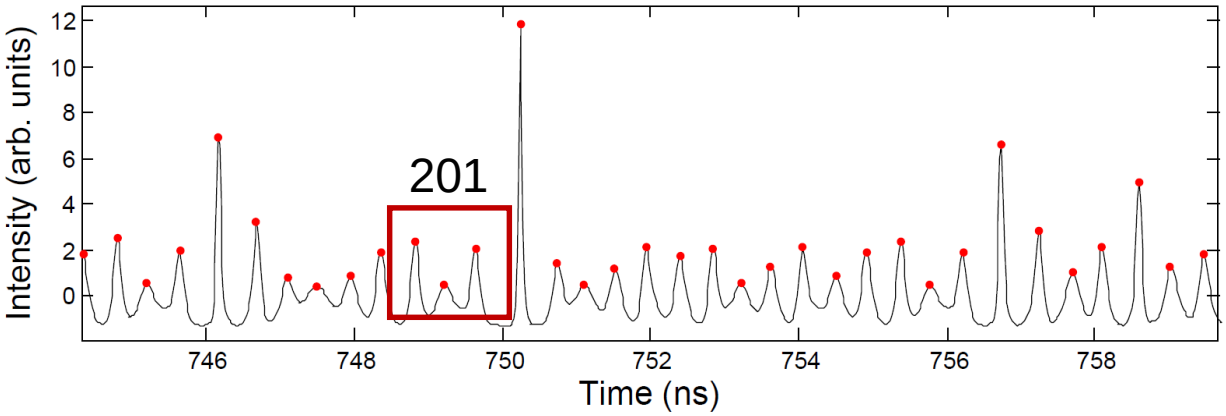


⇒ Well-defined oscillation pattern anticipates extreme pulses.

How can this effect be quantified?

J. Zamora-Munt et al. "*Rogue waves in optically injected lasers: origin, predictability, and suppression*", Phys. Rev. A 87, 035802 (2013)

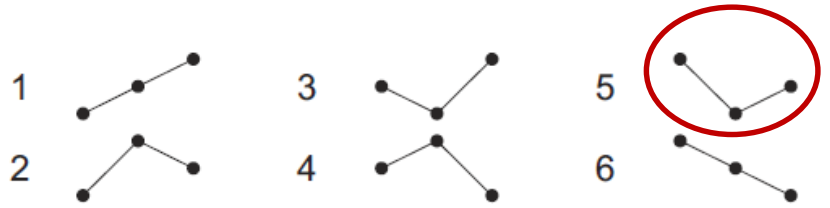
Identifying the pattern that tends to occur before the pulse



- Consider the sequence of intensity peak heights (red dots):

  $\{\ldots I_i, I_{i+1}, I_{i+2}, \ldots\}$

- Possible order relations of three consecutive values:

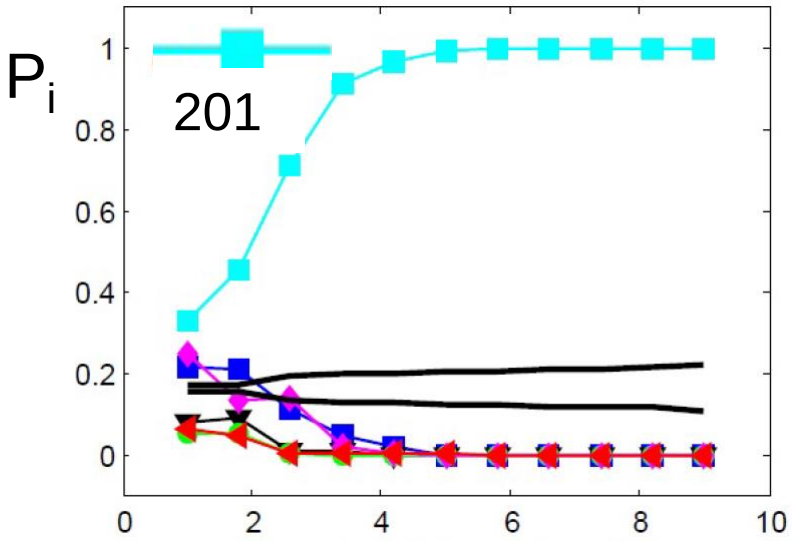


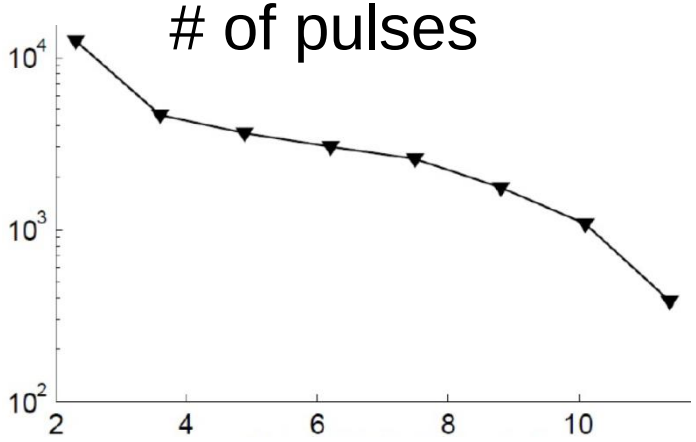
We calculate the probability of the pattern that occurs before each high pulse:

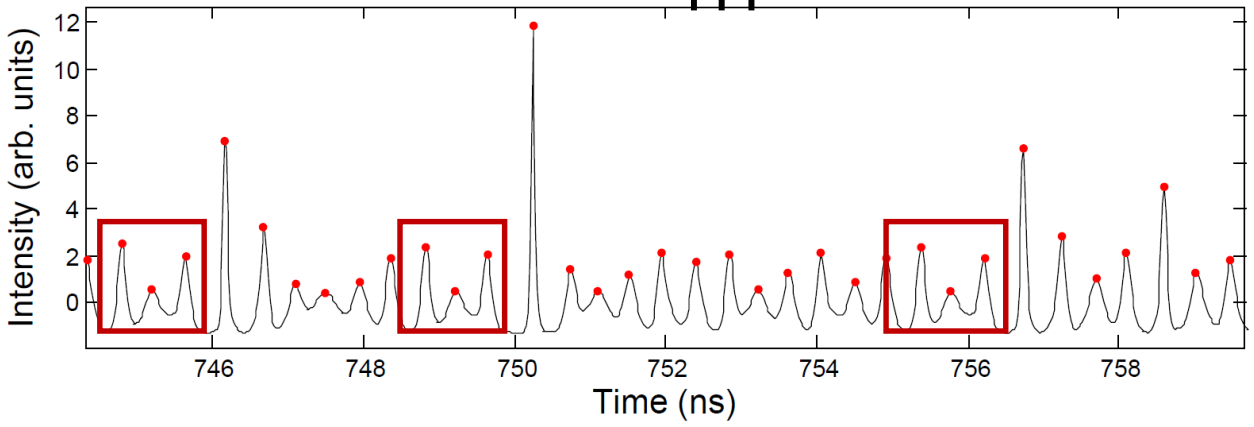
If $I_i >$ **TH**, we analyze the pattern defined by $(I_{i-3}, I_{i-2}, I_{i-1})$

“Good” result in deterministic simulations: P(201)=1 if TH >6

Black lines: probabilities consistent with p_i=1/6





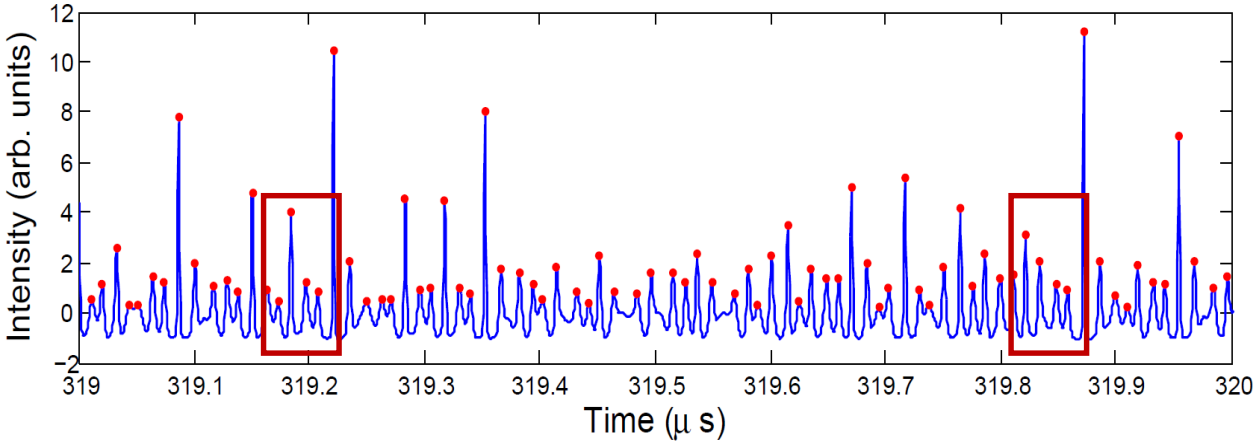


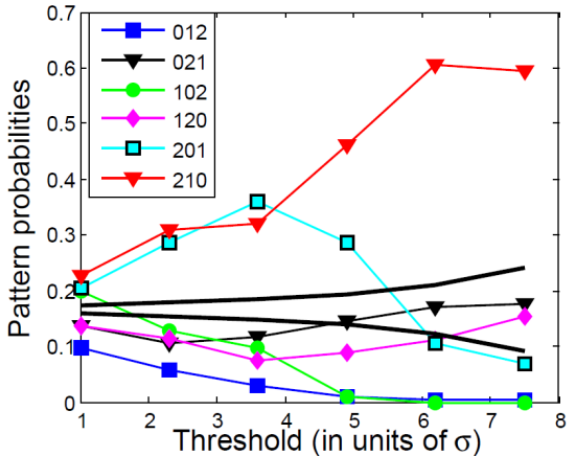
Problem: P(201)≠0 if TH <6 (pattern 201 also anticipates small pulses) ⇒ false positives

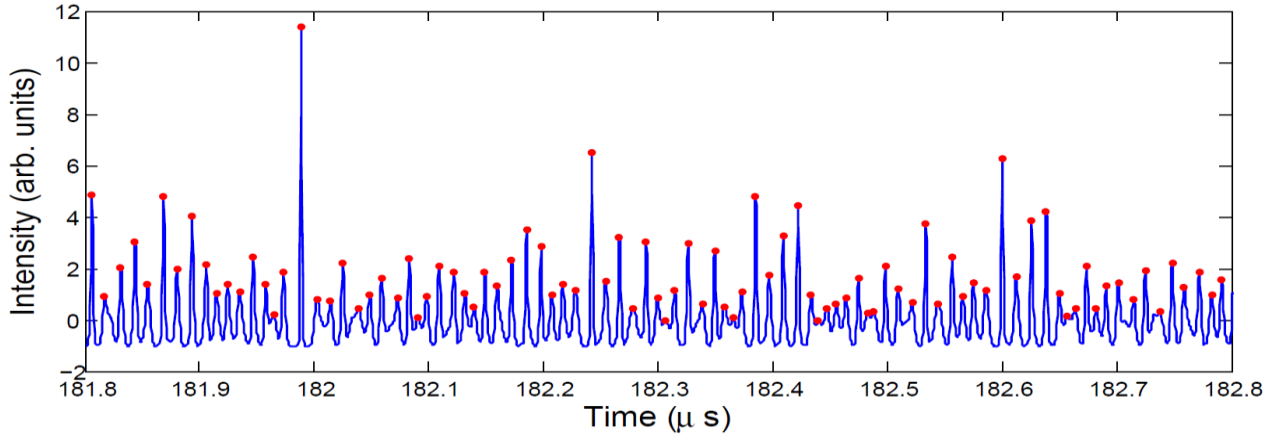
N. Martinez Alvarez et al, “*Predictability of extreme intensity pulses in optically injected semiconductor lasers*”, Eur. Phys. J. Spec. Top. 226, 1971 (2017)

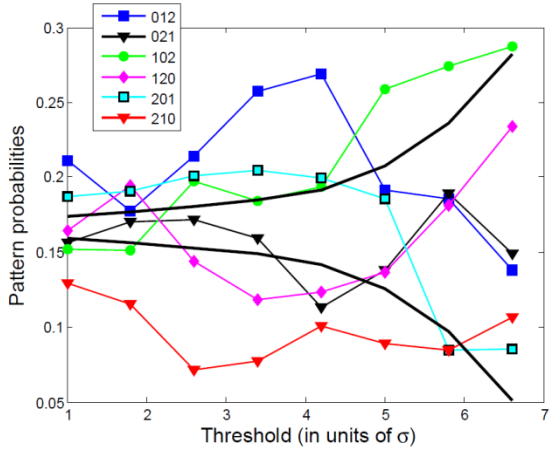
The “early warning pattern” varies with the parameters and might not exist.

Including noise and current modulation, with different modulation frequencies.

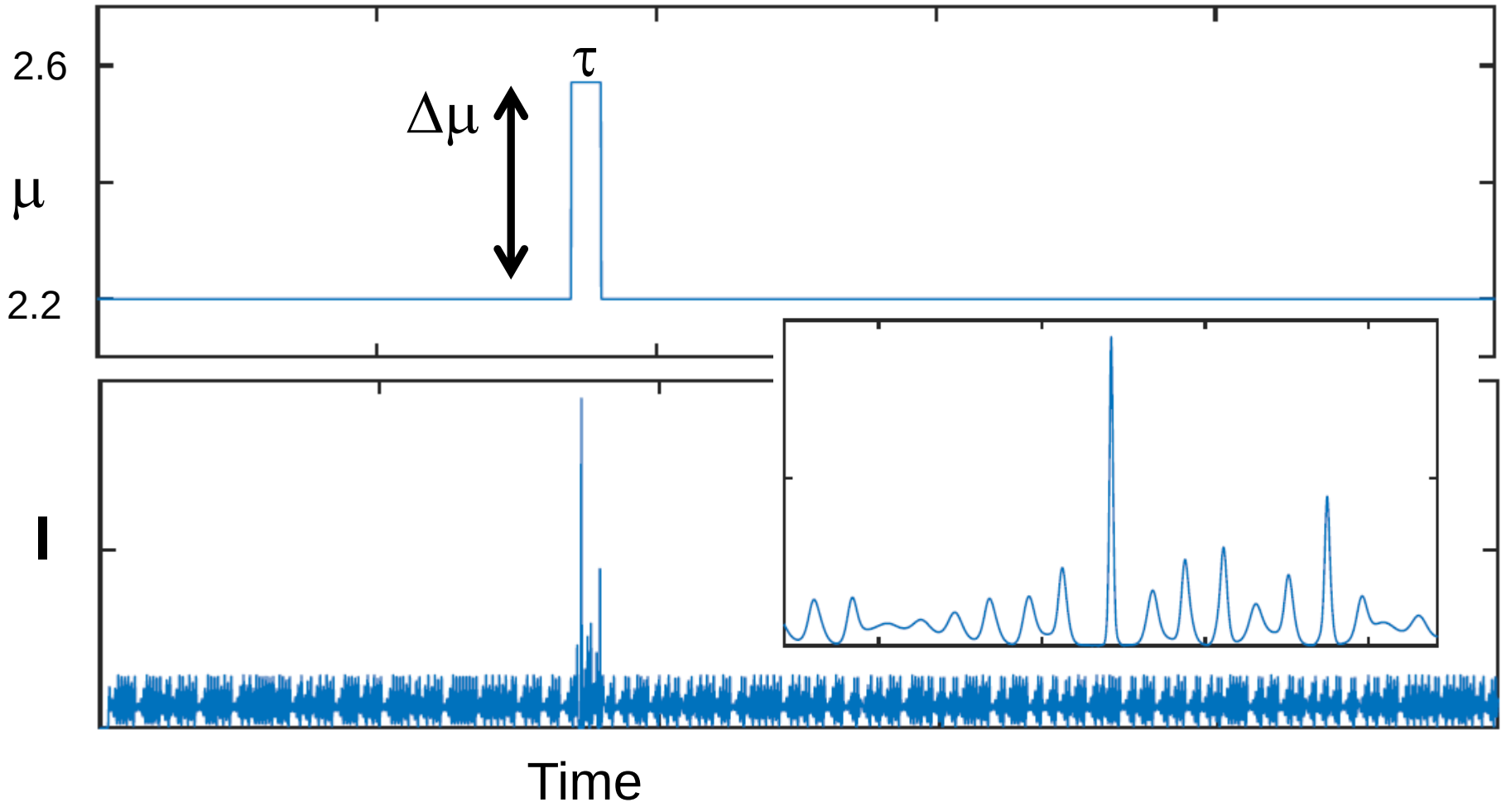






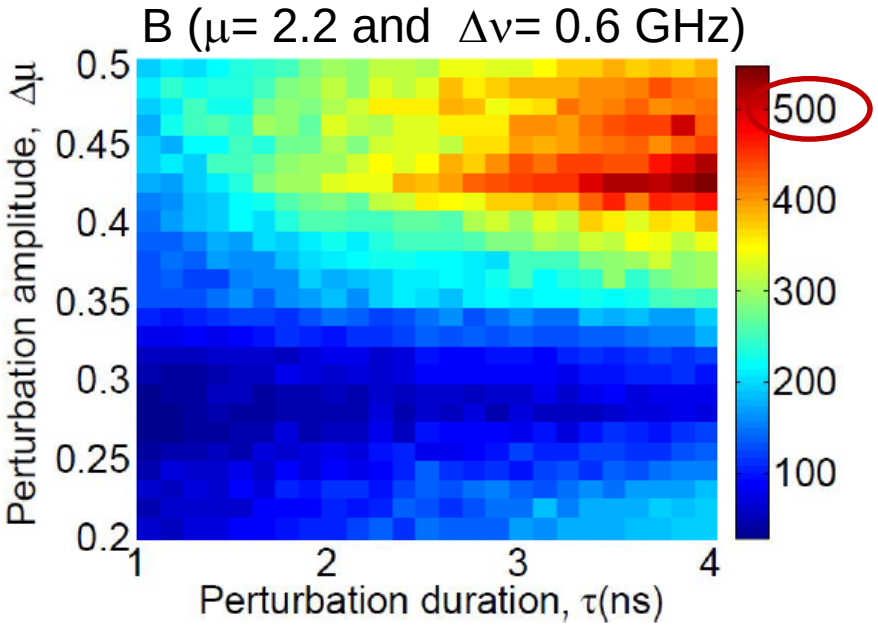


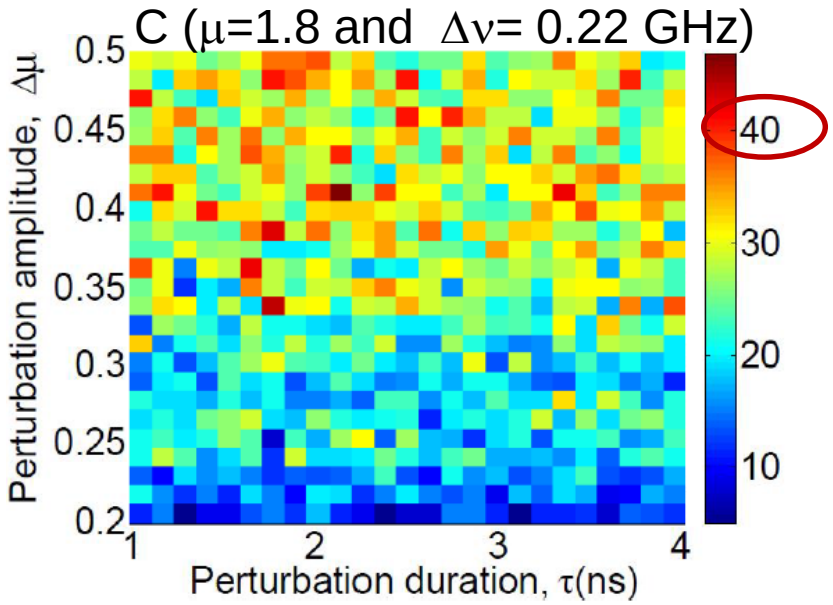
On demand generation via small step-up current perturbation (a step down perturbation does not work)



Reliability?

Plot the number of high pulses generated after 1000 perturbations, a function of the perturbation parameters.



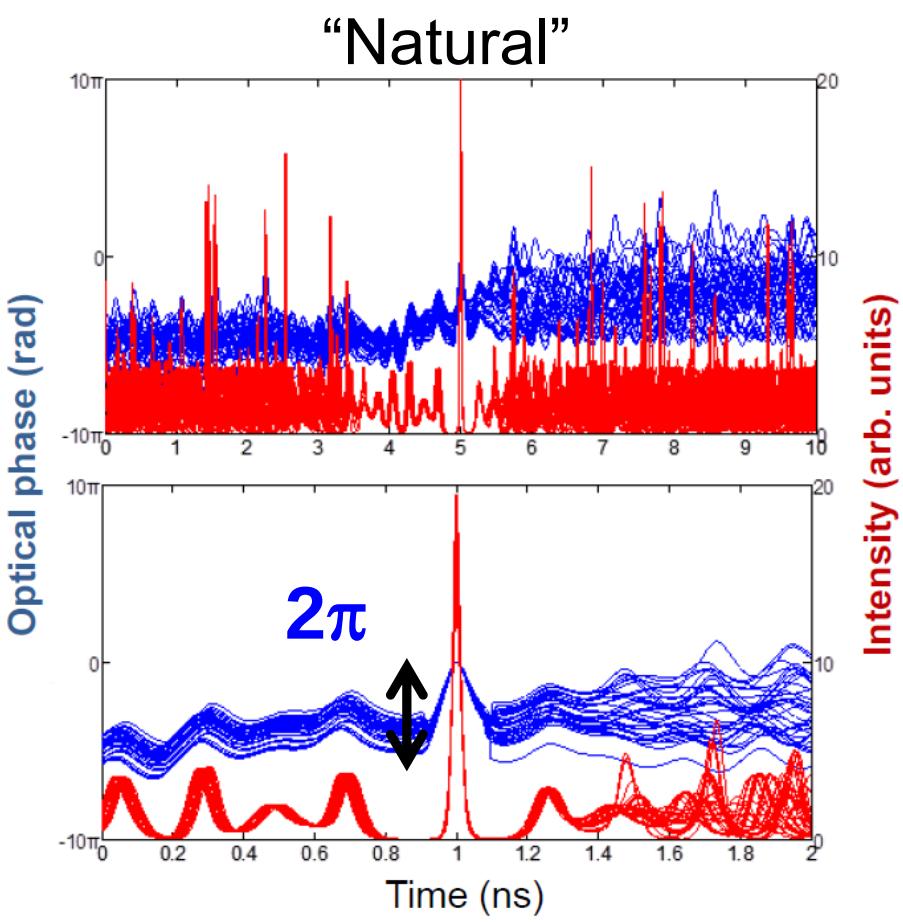


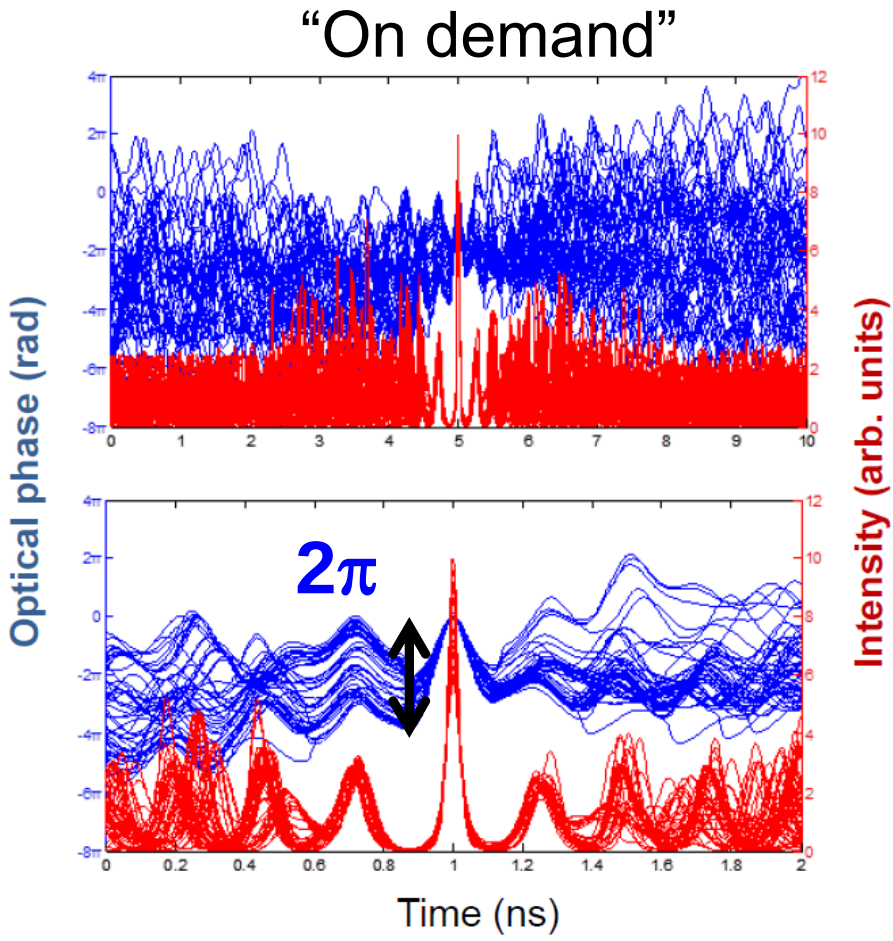
The “success rate” strongly depends on the laser parameters and on the perturbation parameters.

Excitability?

T. Jin, C. Siyu and C. Masoller, “*Generation of extreme pulses on demand in semiconductor lasers with optical injection*”, Opt. Express 25, 031326 (2017)

Are the generated pulses similar to the “natural” ones?

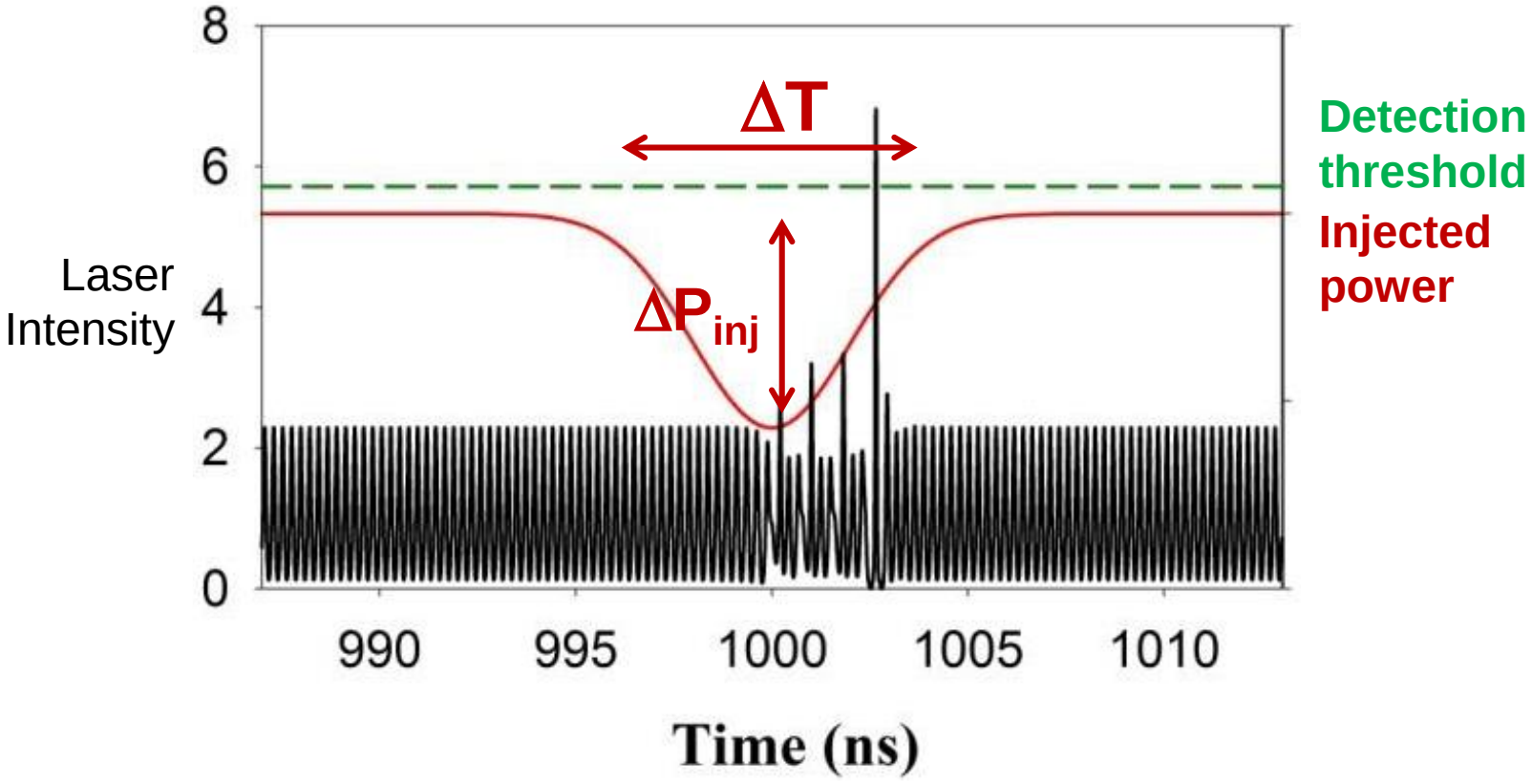




T. Jin, C. Siyu and C. Masoller, “*Generation of extreme pulses on demand in semiconductor lasers with optical injection*”, Opt. Express 25, 031326 (2017)

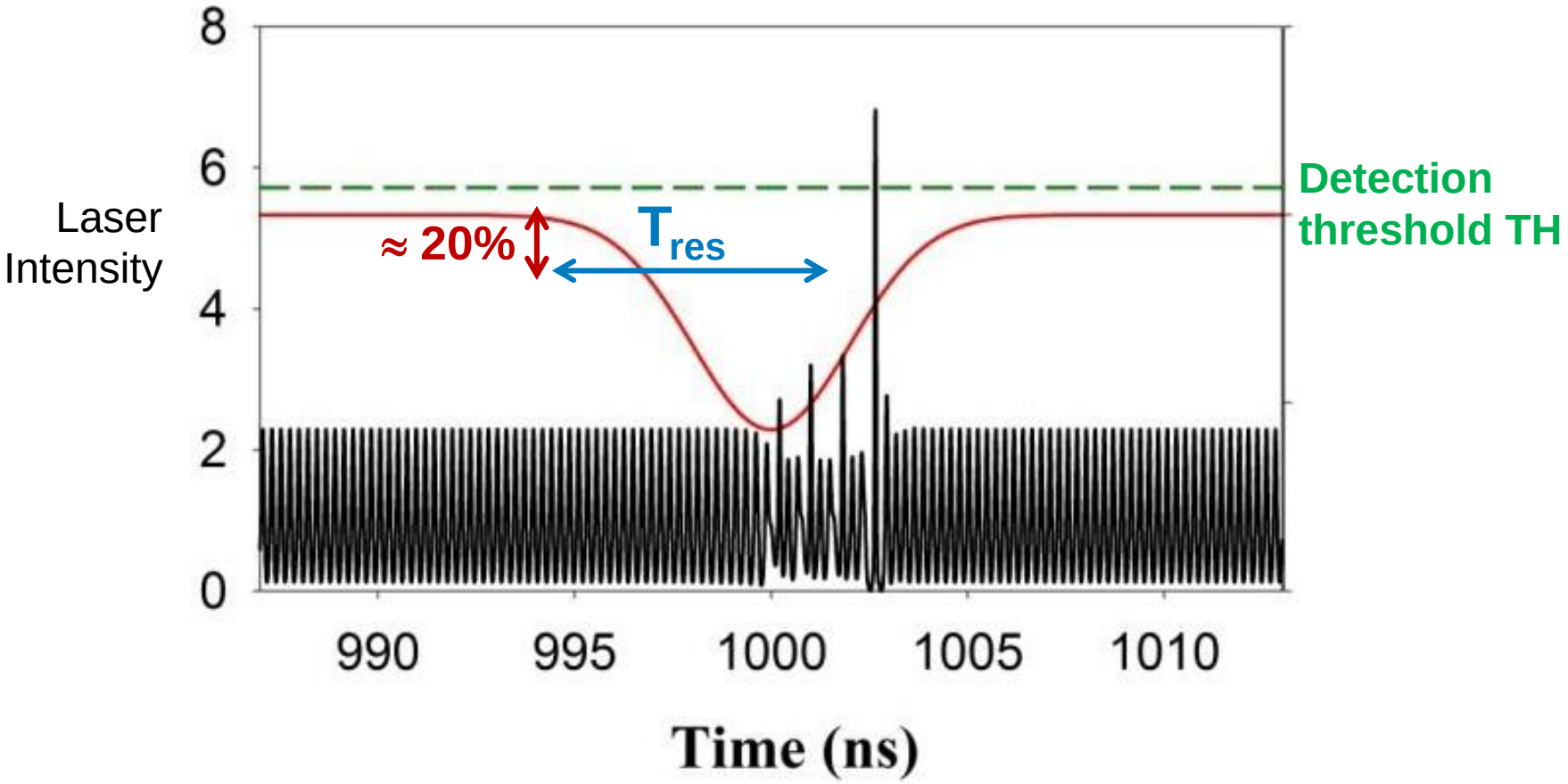
Sensing with extreme pulses?

We consider parameters such that there are no “natural” RWs and a Gaussian variation of the injected power



M. S. Torre and C. Masoller, in preparation

Response time

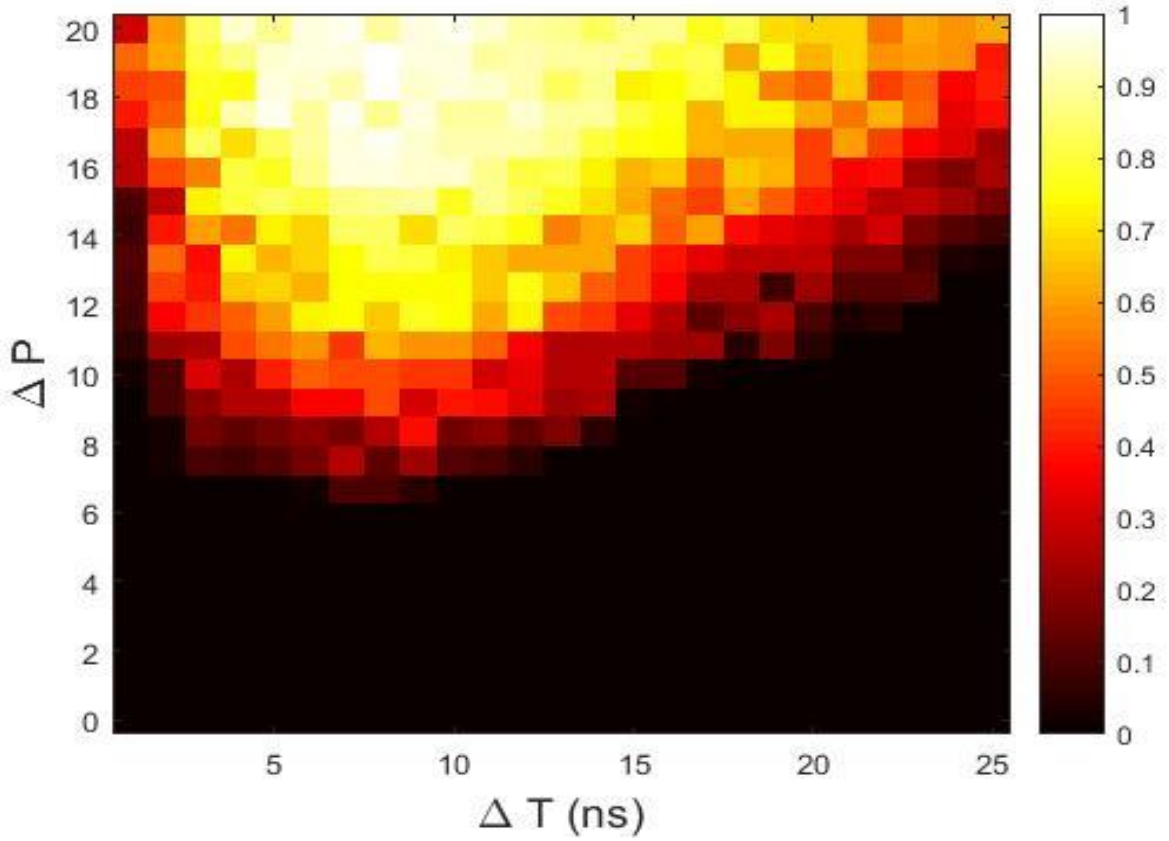


If one (or more) high pulses (**>TH**) are emitted in a given time interval (response time, T_{res}) $\Rightarrow$ successful detection, else, the perturbation is not detected.

M. S. Torre and C. Masoller, in preparation

Preliminary results

50 noise-free simulations with parameters P_{inj} = 50, μ= 1.75, $\Delta\nu$= -1.31 GHz. **T_{res} = 20 ns**

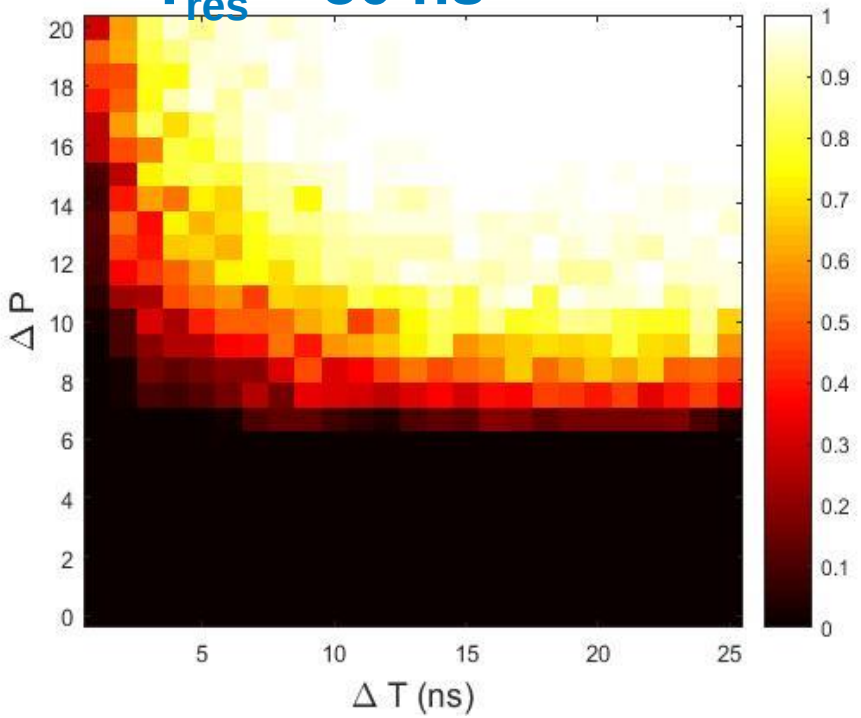


Probability of high-pulse detection

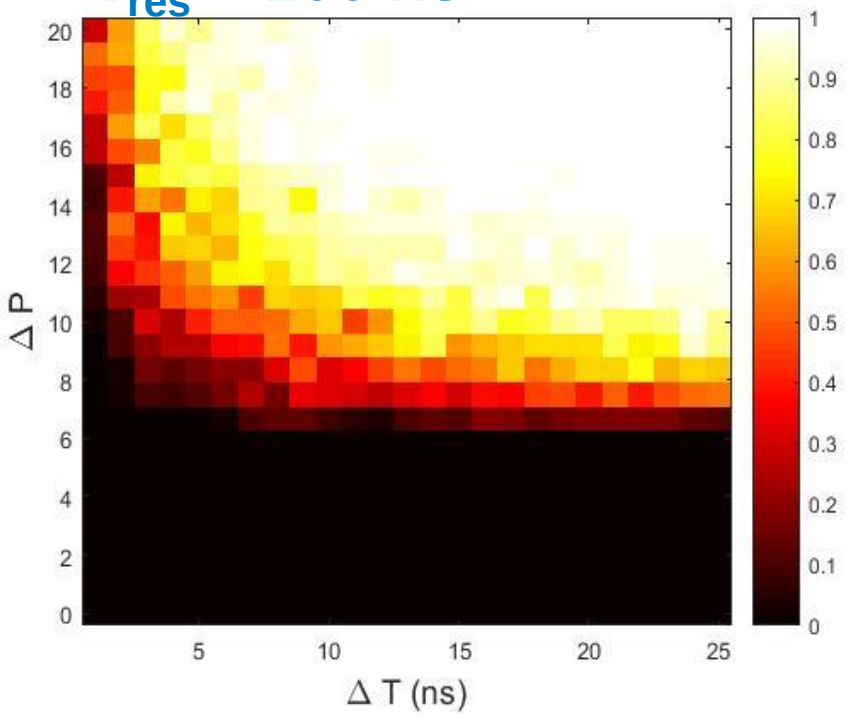
M. S. Torre and C. Masoller, in preparation

Influence of the response time

T_{res} = 50 ns



T_{res} = 100 ns



M. S. Torre and C. Masoller, in preparation

Summary part 2

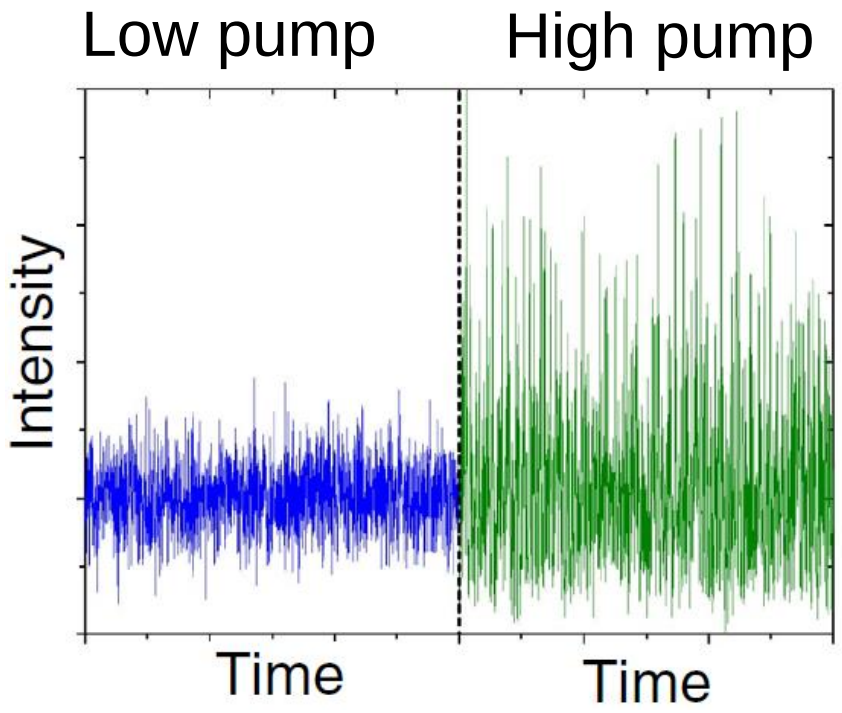
- Certain patterns of oscillations can be more (or less) likely to occur before the extreme pulses.
- Extreme pulses can be generated “on demand” by appropriate perturbation of a control parameter (step up perturbation of the pump current).
- Ongoing work: exploring potential for sensing.

N. Martinez Alvarez, S. Borkar and C. Masoller, “*Predictability of extreme intensity pulses in optically injected semiconductor lasers*”, Eur. Phys. J. Spec. Top. 226, 1971 (2017).

T. Jin, C. Siyu and C. Masoller, “*Generation of extreme pulses on demand in semiconductor lasers with optical injection*”, Opt. Express 25, 031326 (2017).

Transition to optical turbulence in a quasi-cw Raman fiber laser

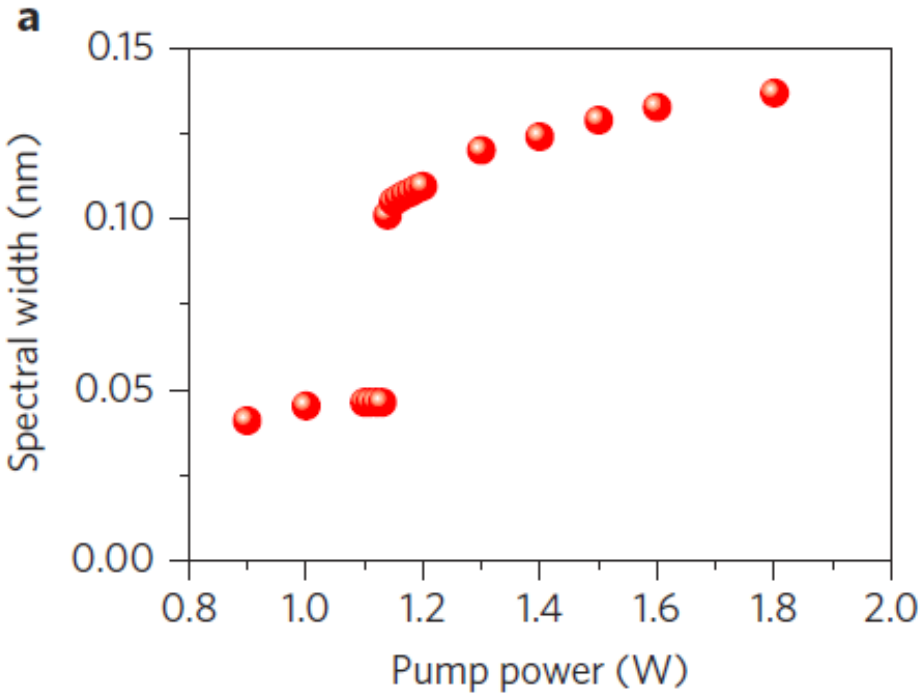
1 km of normal dispersion fiber placed between two fiber Bragg gratings acting as cavity mirrors.



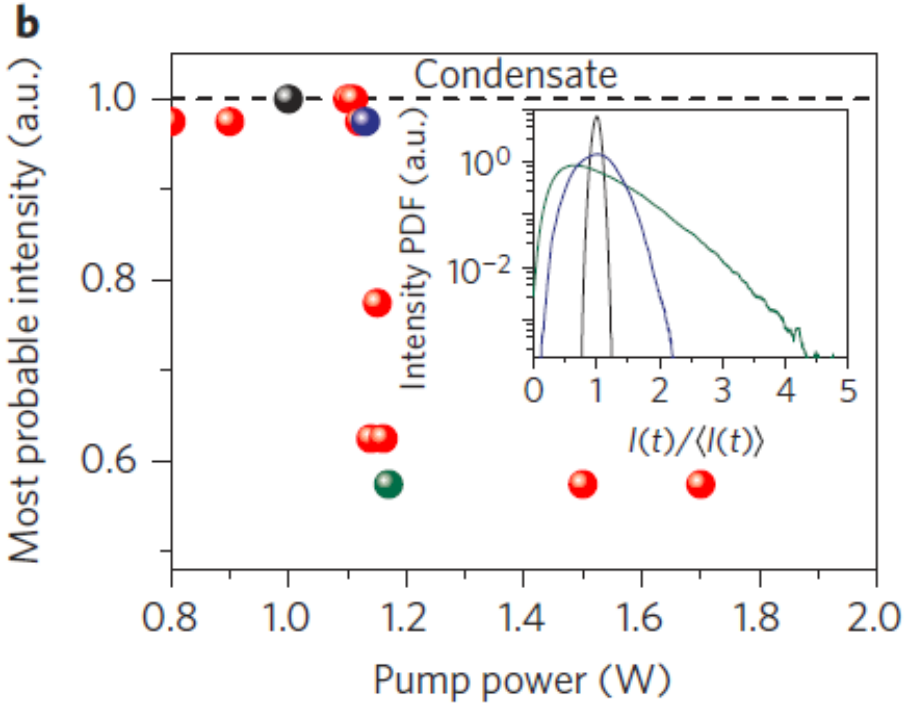
Experimental data from Prof. Turitsyn' group, Aston Univ., UK.

E. G. Turitsyna et al Nat. Phot. 7, 783 (2013)

Abrupt transition to optical turbulence



Sharp increase of the number of excited modes.

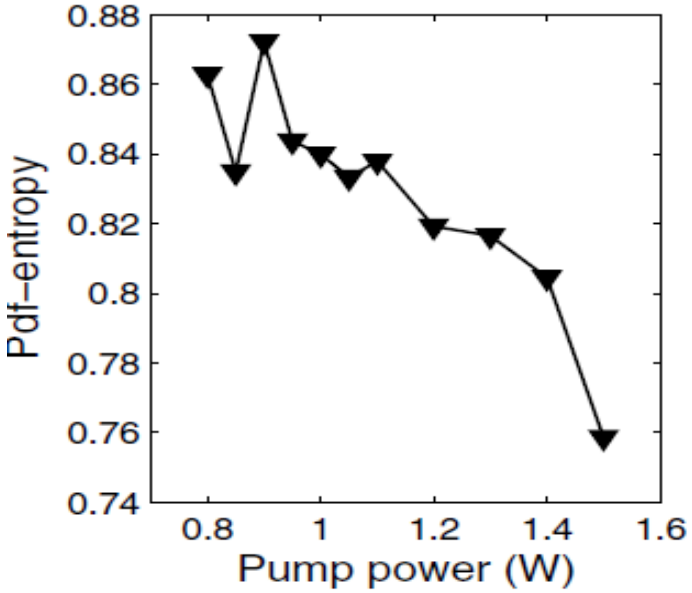


Sharp decrease of the most probable intensity

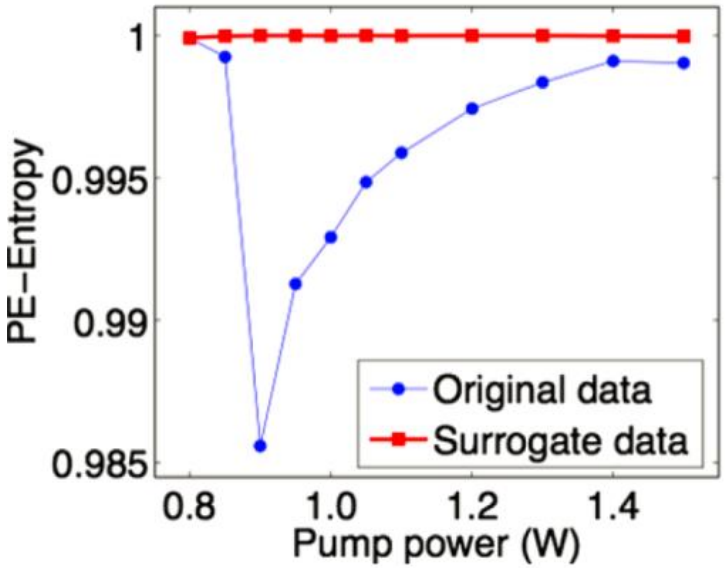
Temporal correlations?

E. G. Turitsyna et al Nat. Phot. 7, 783 (2013)

Entropy from pdf of intensity values



Permutation entropy, from pdf of intensity pulses > 2σ



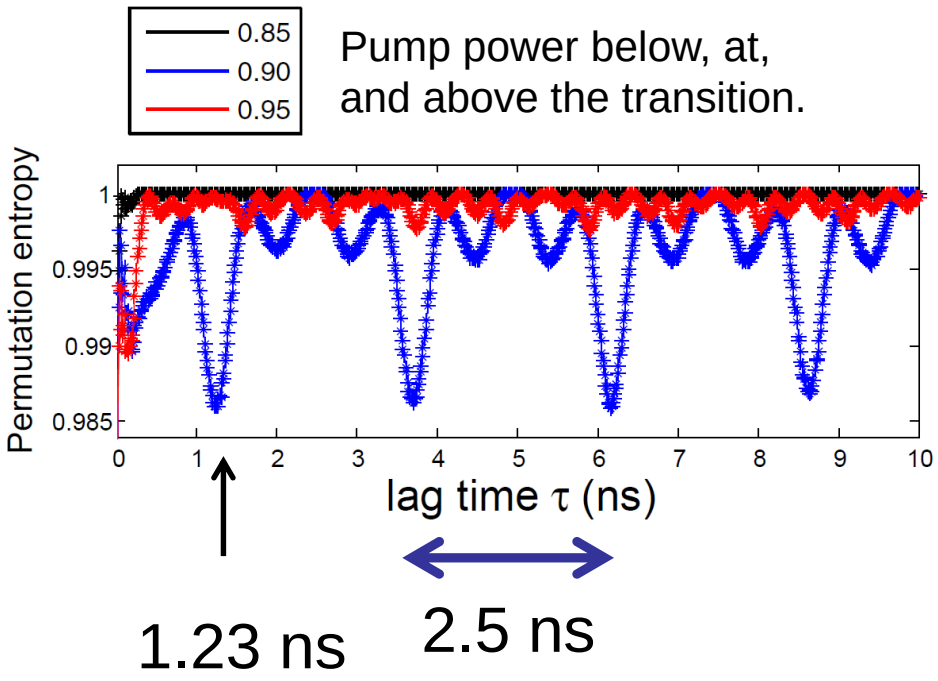
- The sharp transition is <u>not captured</u> when the entropy is calculated from the intensity pdf.
- But it is captured by the permutation entropy (entropy of the ordinal patterns) computed from intensity peak heights.

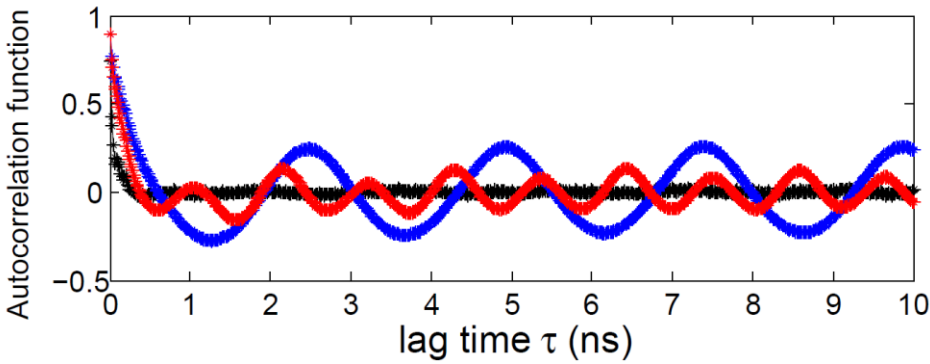
A. Aragoneses et al., "*Unveiling temporal correlations characteristic to phase transition in the intensity of fibre laser radiation*", PRL 116, 033902 (2016)

Ordinal analysis of lagged intensity time series

$$\{I_i, I_{i+\tau}, I_{i+2\tau}, \ldots\}$$

all data points, no threshold used

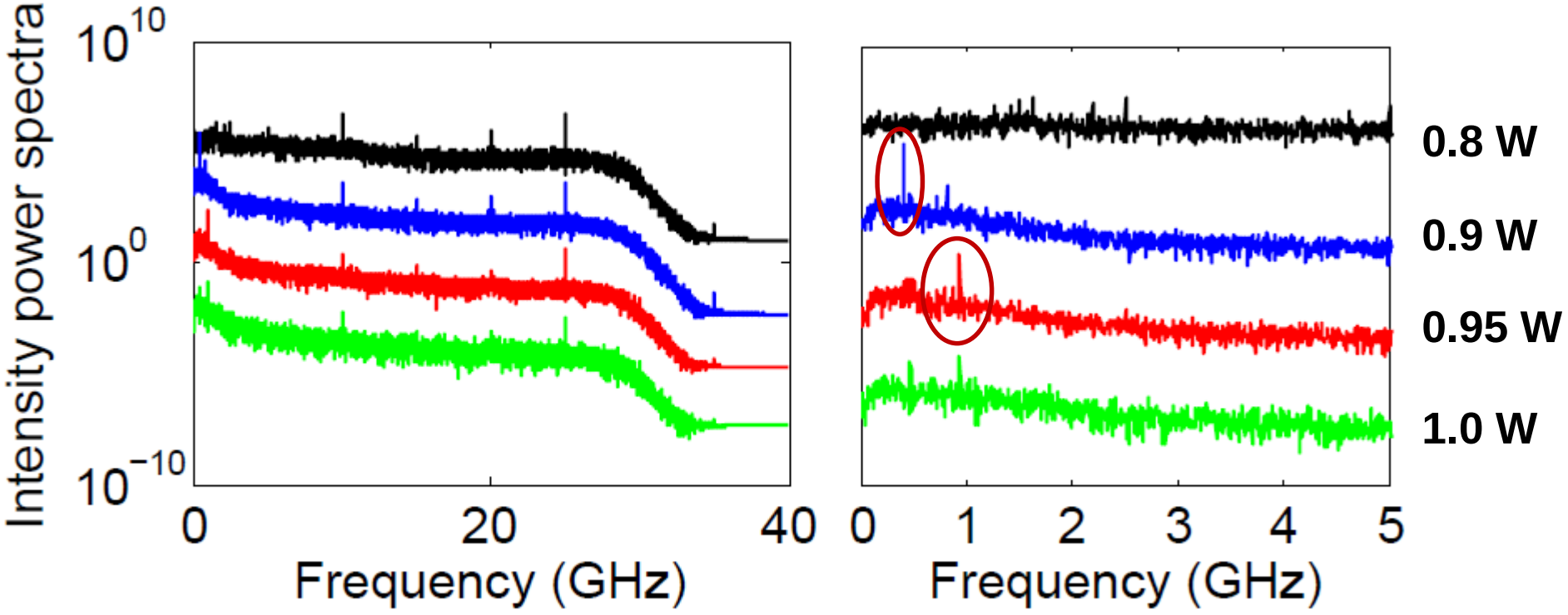




$\Rightarrow$ Sharp variation not captured by correlation analysis.

A. Aragoneses et al., "*Unveiling temporal correlations characteristic to phase transition in the intensity of fibre laser radiation*", PRL 116, 033902 (2016)

Intensity power spectra
(displaced vertically for clarity)



At 0.9 W: ν_0 = 0.4 GHz (T_0=2.5 ns)
0.81 GHz →1.23 ns

At 0.95W: 0.93 GHz

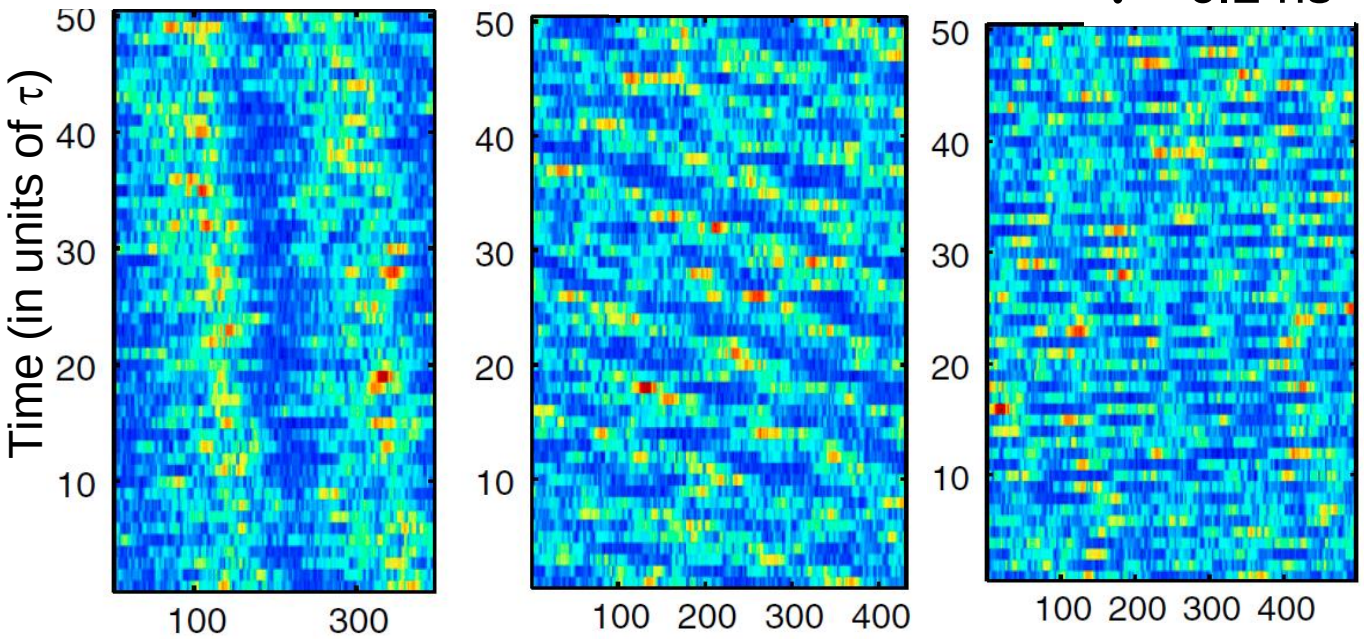
Space time representation

τ 2τ 3τ

$$\{I_1, I_2, I_3 \ldots, \; I_\tau, I_{\tau+1}, \ldots, \; I_{2\tau}, I_{2\tau+1}, \ldots\} \Rightarrow \begin{bmatrix} \ldots & \ldots & \ldots & \ldots \\ I_{2\tau+1} & I_{2\tau+2} & \ldots & I_{3\tau} \\ I_{\tau+1} & I_{\tau+2} & \ldots & I_{2\tau} \\ I_1 & I_2 & \ldots & I_\tau \end{bmatrix}$$

Color: I_i

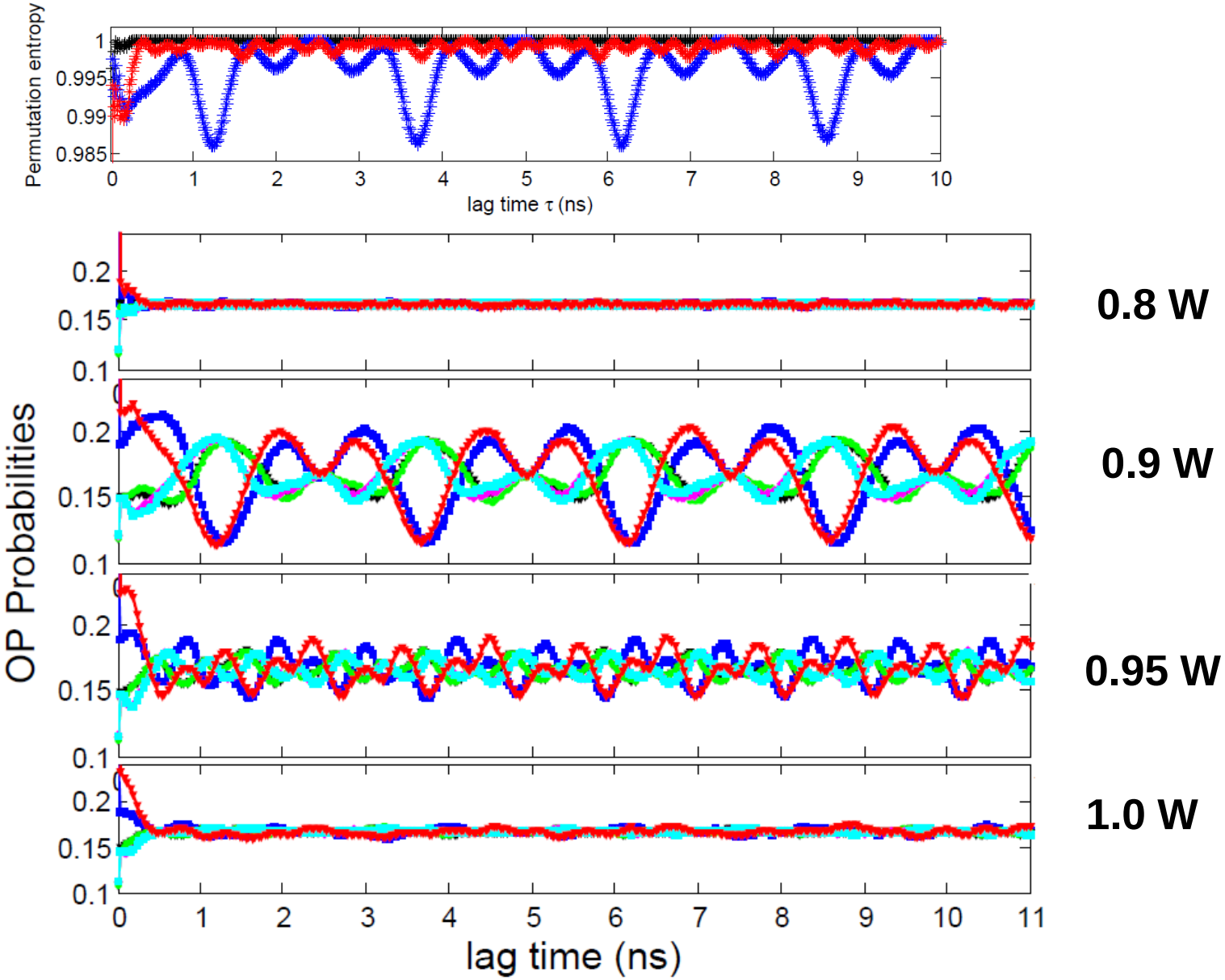
τ = 4.95 ns = $2T_0$ τ = 5.39 ns τ = 6.2 ns



⇒ Different structures uncovered with different lags (sampling times).

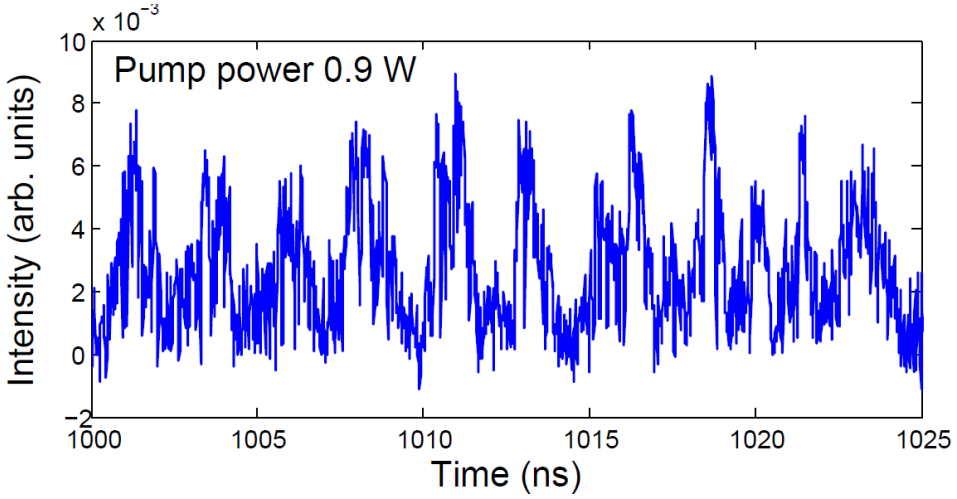
Aragoneses et al, PRL 116, 033902 (2016)

Ordinal probabilities vs. lag



A minimal model can explain the variation of the ordinal probabilities with the lag

At the transition:



Stochastic limit cycle: phase rate equation

$$\frac{d\varphi}{dt} = \omega_0 + f(\varphi, t) + \xi$$

Stroboscopic sampling at time-interval τ

$$\varphi(t_0 + \tau) = \varphi(t_0) + \omega_0 \tau + F(\varphi(t_0)) + \xi$$

$$\varphi_{i+1} = \varphi_i + \rho + \frac{K}{2\pi}\sin(2\pi\varphi_i) + D\xi$$

Minimal model: circle map

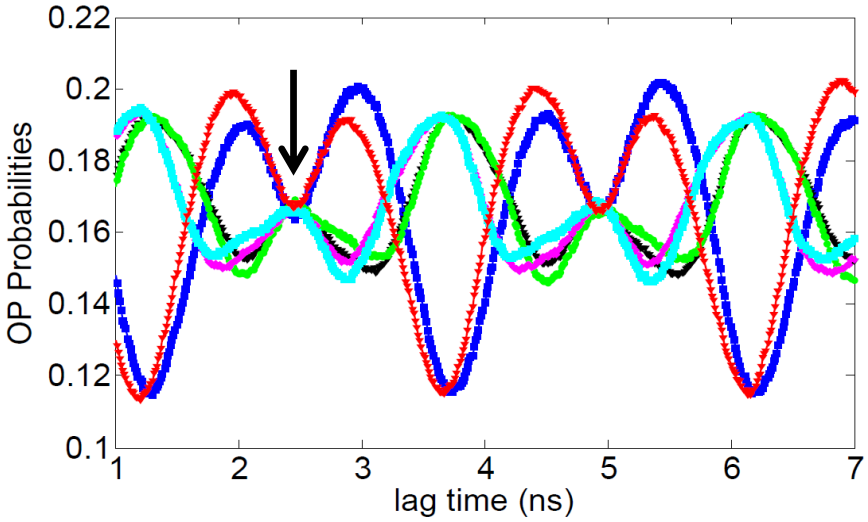
$$\varphi_{i+1} = \varphi_i + \rho + \frac{K}{2\pi}\sin(2\pi\varphi_i) + D\xi$$

$$\{X_i, X_{i+1}, X_{i+2}, \ldots\}$$

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

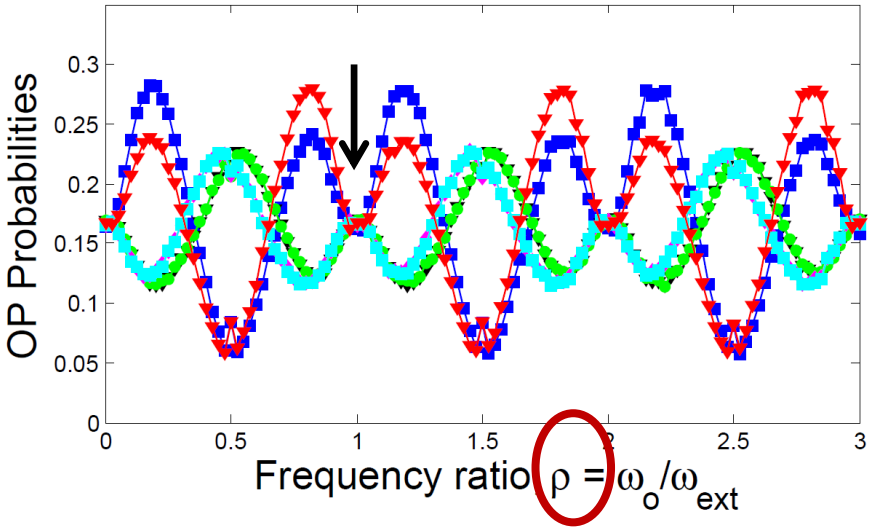
Fiber laser data $\{I_i, I_{i+\tau}, I_{i+2\tau}, \ldots\}$

(at the transition, pump power 0.9 W)



Synthetic data (phase increments)

(K=0.23 & D=0.02)



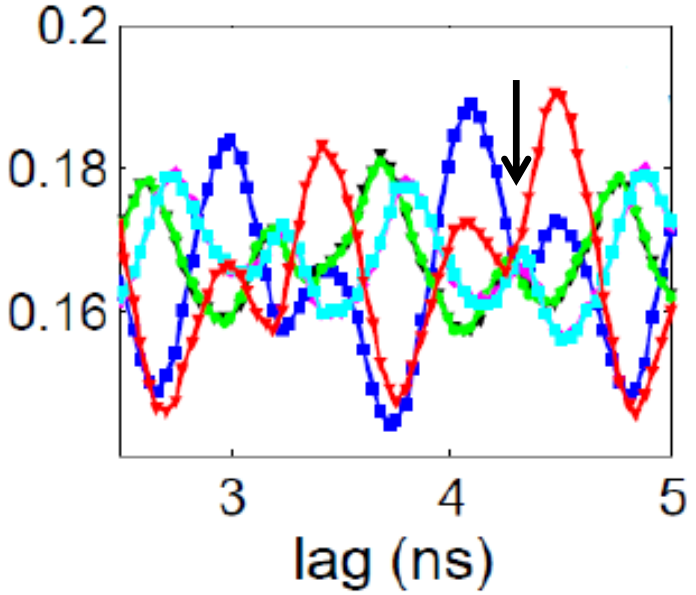
τ = 2.5 ns $\Leftrightarrow$ ρ = 1 = ν_0 τ $\Rightarrow$ ν_0 = 1/τ = 0.4 GHz

Carpi and Masoller, "*Persistence and stochastic periodicity in the intensity dynamics of a fiber laser during the transition to optical turbulence*", Phys. Rev. A 97, 023842 (2018)

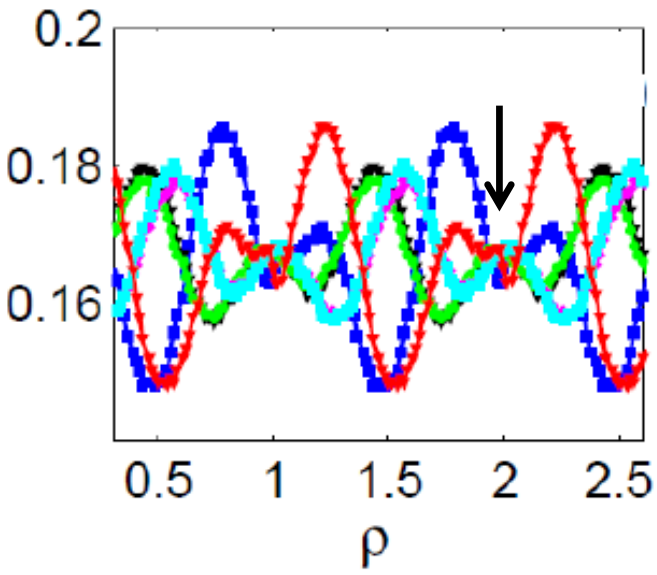
Qualitative agreement also at higher pump power

$$\phi_{i+1} = \phi_i + \epsilon\rho + (K/2\pi)\sin(2\pi\phi_i) + D\xi_i$$

Fiber laser data
(above the transition, 0.95 W)



Synthetic data
(circle map with ε=-1, K=0.25 & D=0.075)



τ = 4.3 ns $\Leftrightarrow$ $\rho = 2 = \nu_0\,\tau$ $\Rightarrow$ $\nu_0 = 1/(2\tau)$ = 0.46 GHz

The intensity spectrum has a peak ≈0.93 GHz, consistent with $2\nu_0$

Carpi and Masoller, "*Persistence and stochastic periodicity in the intensity dynamics of a fiber laser during the transition to optical turbulence*", Phys. Rev. A 97, 023842 (2018)

Summary of part 3

- During the transition to optical turbulence of a fiber laser, ordinal analysis detects well-defined characteristic times.
- The circle map (representing an stochastic limit cycle) is a minimal model to understand, at the transition, the variation of the ordinal probabilities with the lag.

A. Aragoneses et al., "*Unveiling temporal correlations characteristic to phase transition in the intensity of fibre laser radiation*", PRL 116, 033902 (2016).

L. Carpi and C. Masoller, "*Persistence and stochastic periodicity in the intensity dynamics of a fiber laser during the transition to optical turbulence*", Phys. Rev. A 97, 023842 (2018).

THANK YOU FOR YOUR ATTENTION !

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