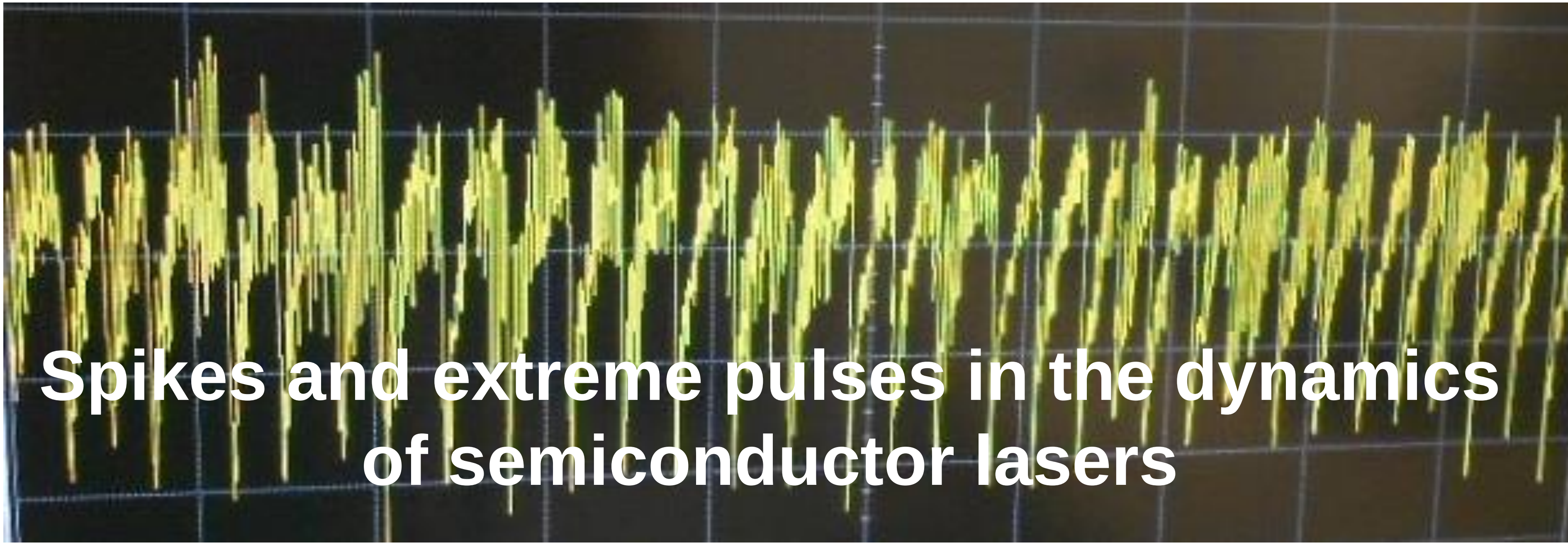

Spikes and extreme pulses in the dynamics of semiconductor lasers

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International Year of Light 2015

Workshop on Advanced Computational and Experimental Techniques in Nonlinear Dynamics

Cusco, Peru, July 2015

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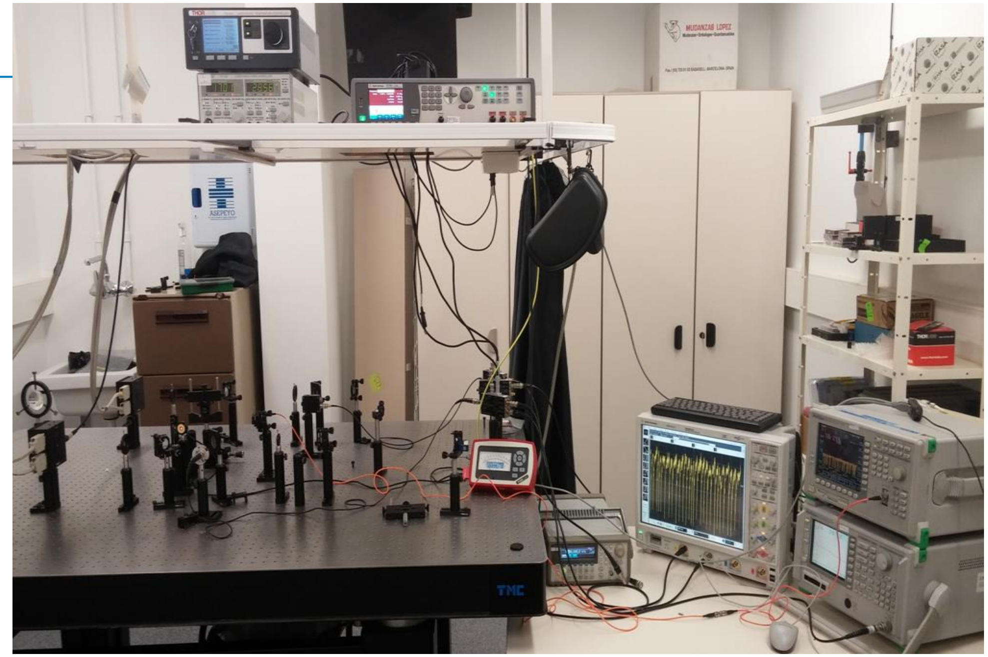
Where are we?


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

El edificio Gaia centraliza grupos científicos consolidados y emergentes.

People and lab



12 senior researchers,
2 posdoctoral researchers
10 phd students

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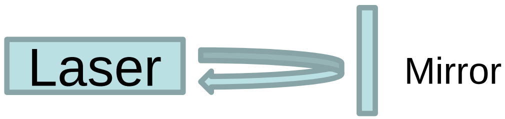
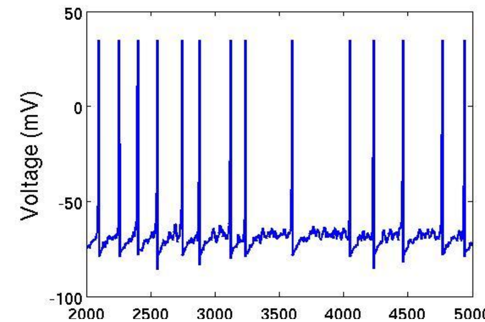
What do we study?
Nonlinear dynamics of semiconductor lasers

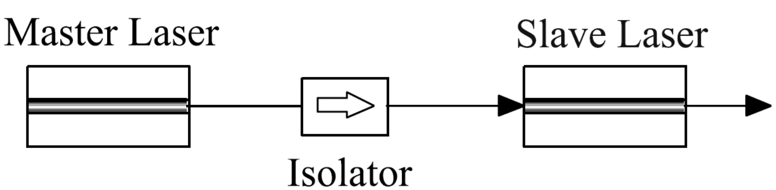
- Optical feedback

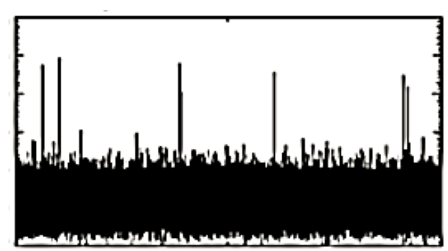




  - Are optical spikes similar to neuronal spikes ?

- Optical injection

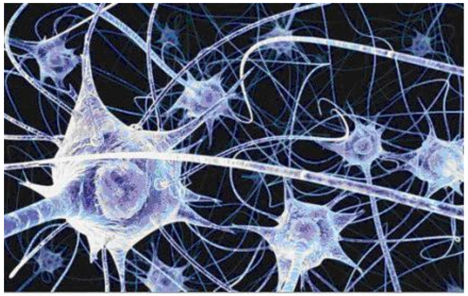




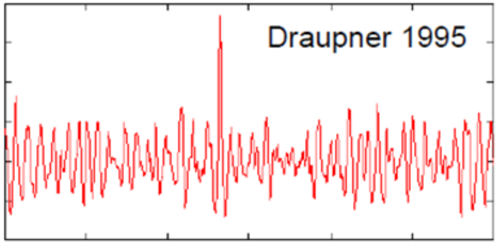
  - Extreme pulses
    - Can they be predicted?
    - Can they be controlled?

Motivation

- Optical Neurons open the possibility of developing novel photonic neuro-inspired information processing systems: ultrafast (**ms vs ns-μs**).



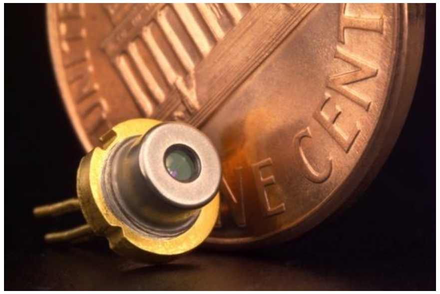
- Extreme events occur in many complex systems
  - "big data" approach: the laser setup allows for recording large amounts of data,
  - Useful for testing methods of prediction ("early warning signals") and control.



Outline

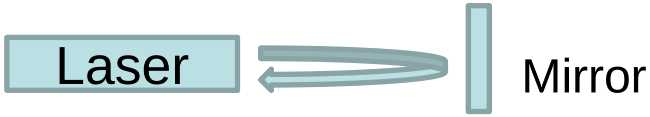
- Introduction
  - Nonlinear dynamics of semiconductor lasers
  - Method of time series analysis
- Part 1: optical neurons
- Part 2: extreme pulses

Semiconductor lasers



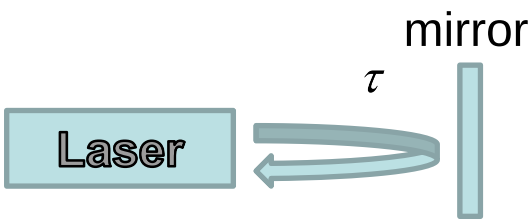
- Widely used in:
  - Communications
  - Data storage (CDs, DVDs …)
  - Barcode scanners, laser printers, computer mice
  - Life sciences (imaging, sensing …)
  - Etc.

- Optical feedback can improve the emission characteristics but it can also induce nonlinear dynamics:
  - Irregular power dropouts
  - Chaotic emission



Governing equations

R. Lang and K. Kobayashi, IEEE J. Quantum Electron. 16, 347 (1980)



$|E|^2 \sim$ photon number (output intensity)

$N \sim$ number of carriers (electron-holes)

$$\frac{dE}{dt} = \frac{1}{2\tau_p}(1+i\alpha)(G-1)E + \underbrace{\eta\, E(t-\tau)e^{-i\omega_0\tau}}_{\text{feedback}} + \underbrace{\sqrt{\beta_{sp}}\,\xi}_{\text{noise}}$$

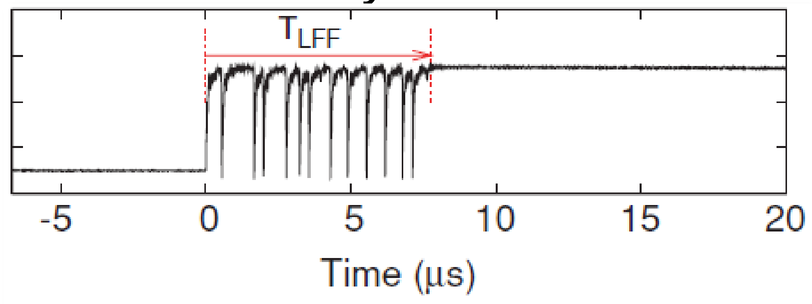
$$\frac{dN}{dt} = \frac{1}{\tau_N}\left(\mu - N - G|E|^2\right)$$

Gain: $G = N/(1+\varepsilon|E|^2)$

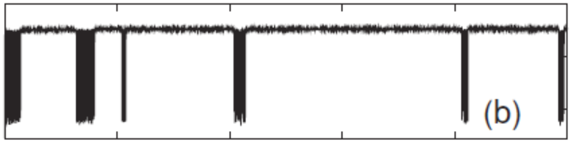
η = feedback strength
τ = feedback delay time
μ = pump current **(control parameter)**

Model predictions

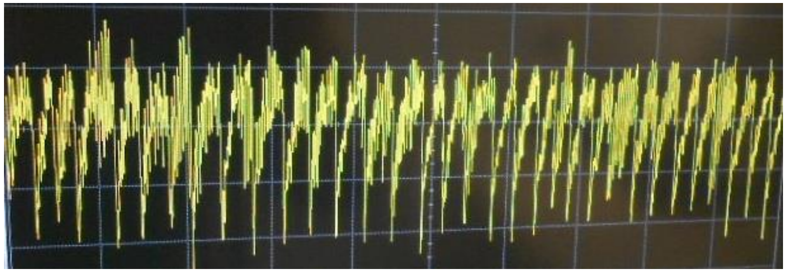
- In **deterministic** simulations: the spikes are **transient**.

Laser intensity


- But in **stochastic** simulations: **bursts** of spikes.



- In the experiments: which spikes are **noise-induced** and which ones are **deterministic**?

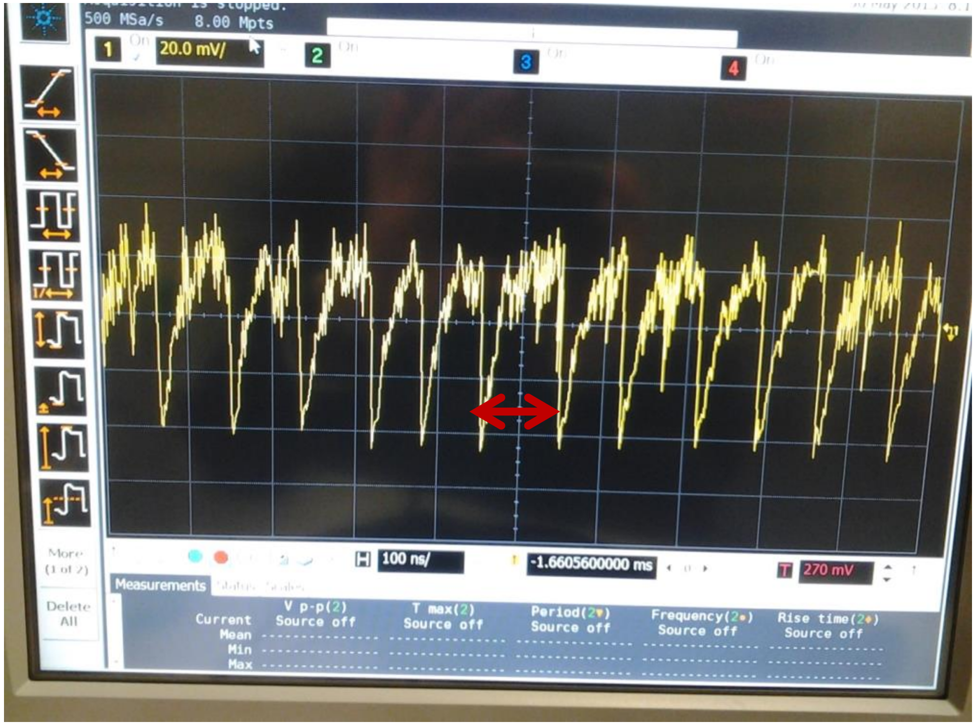


- Can we infer signatures of determinism?
- Is there any **information** in the spike sequence?

A. Torcini et al, Phys. Rev. A 74, 063801 (2006)
J. Zamora-Munt et al, Phys Rev A 81, 033820 (2010)

How to extract information from optical spikes?

- Problem: we can measure only one variable (the laser output intensity).
- Also a problem: the detection system (photodiode, oscilloscope) has a finite *bandwidth* that gives limited temporal resolution.



- Solution: **event-level description**. We analyze the sequence of **inter-spike-intervals (ISIs)**:

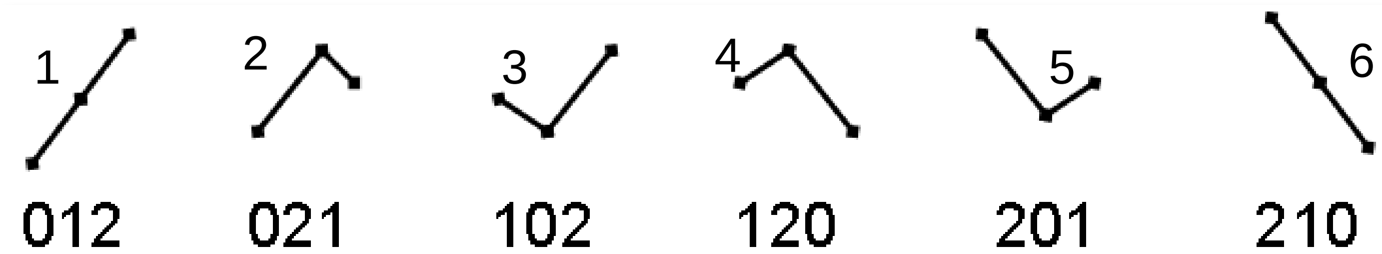
$$\boxed{\Delta T_i = t_{i+1} - t_i}$$

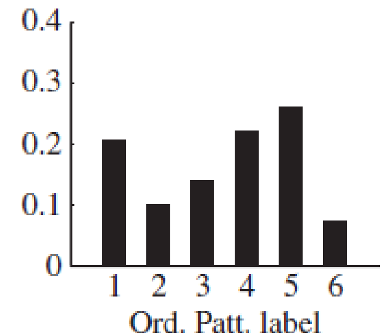
- Method of analysis: symbolic ordinal analysis

Ordinal Patterns (OPs)

Brandt & Pompe, PRL 88, 174102 (2002)

- $X = \{\ldots \Delta T_i, \Delta T_{i+1}, \Delta T_{i+2}, \ldots\}$ (**inter-spike-intervals**)

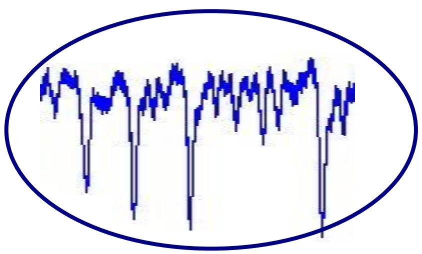




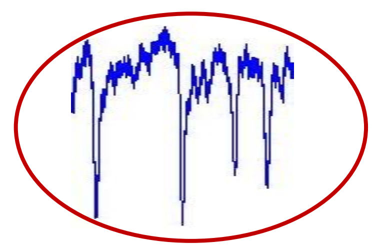
Example: (5, 1, 7) gives "102" because 1 < 5 < 7

Random spikes $\Rightarrow$ all patterns are equally probable

012



210



– Advantage: the OP **probabilities** uncover spike correlations.

– Drawback: we lose information (5,1,100) also gives "102".

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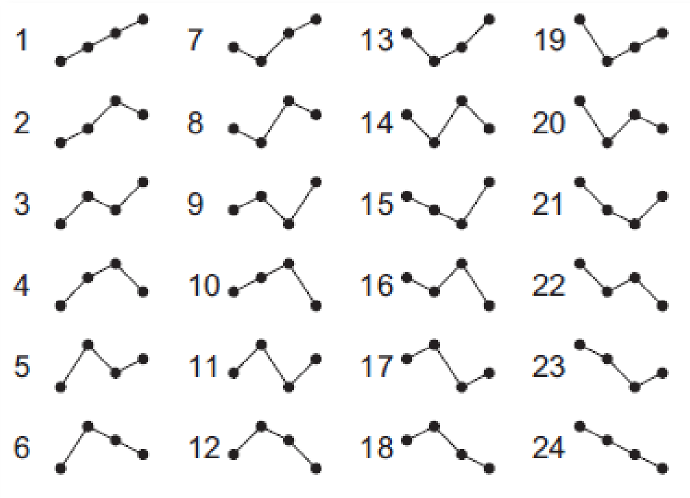
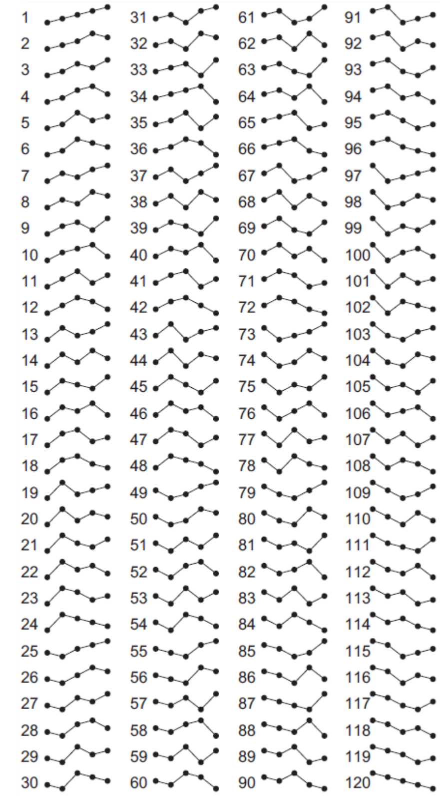
Number of possible ordinal patterns: D!

D=4



D=5



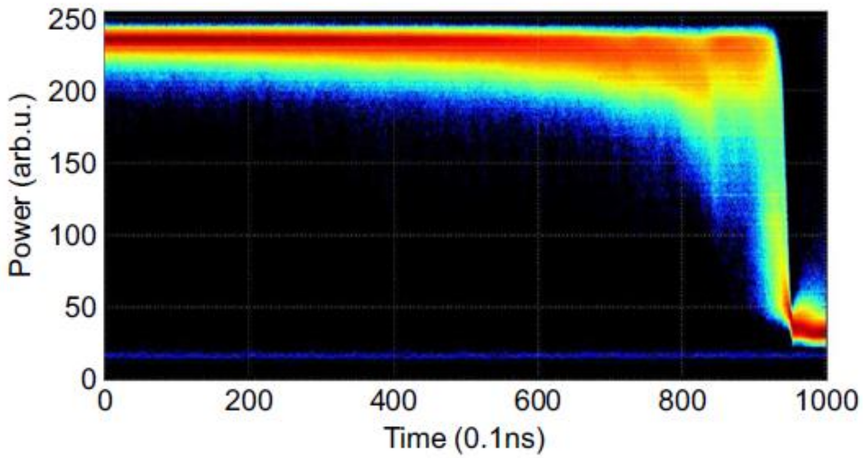
- How to select optimal D?

  depends on:
  - The length of the data.
  - The length of correlations in the data.

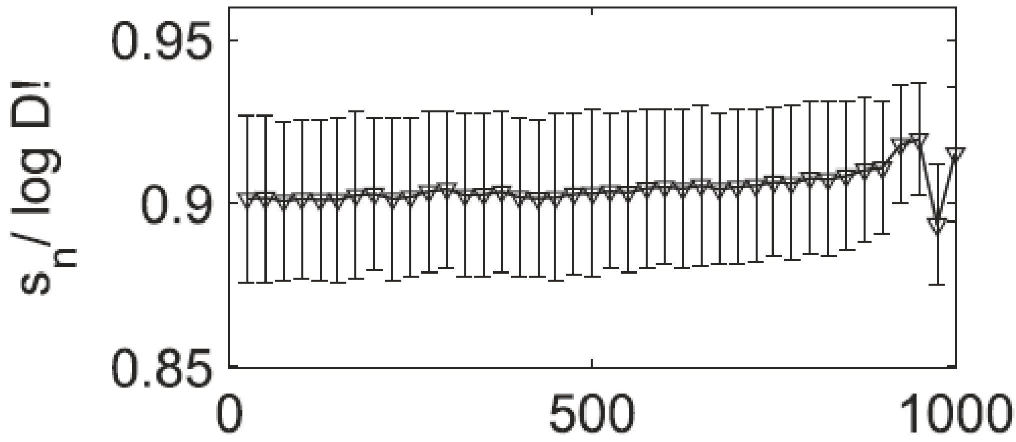
U. Parlitz et al. / Computers in Biology and Medicine 42 (2012) 319–327

Ordinal analysis has been widely used to analyze the observed output signals of complex systems

- Example: abrupt polarization switching.



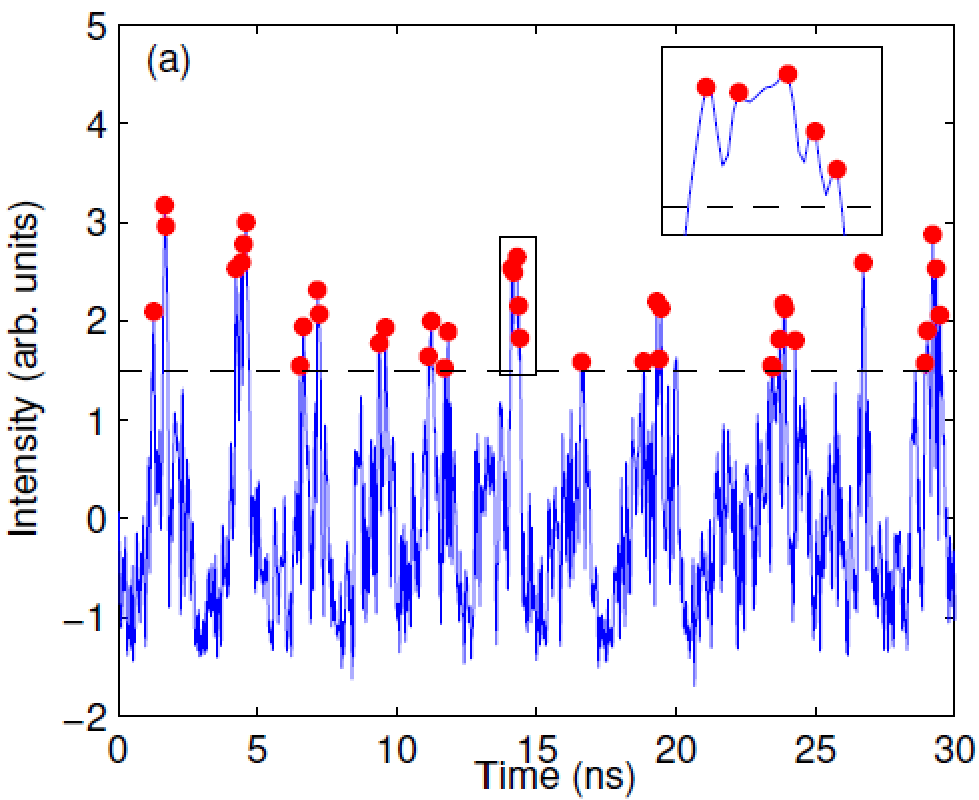
- An entropy measure provides an **early warning** of the transition.

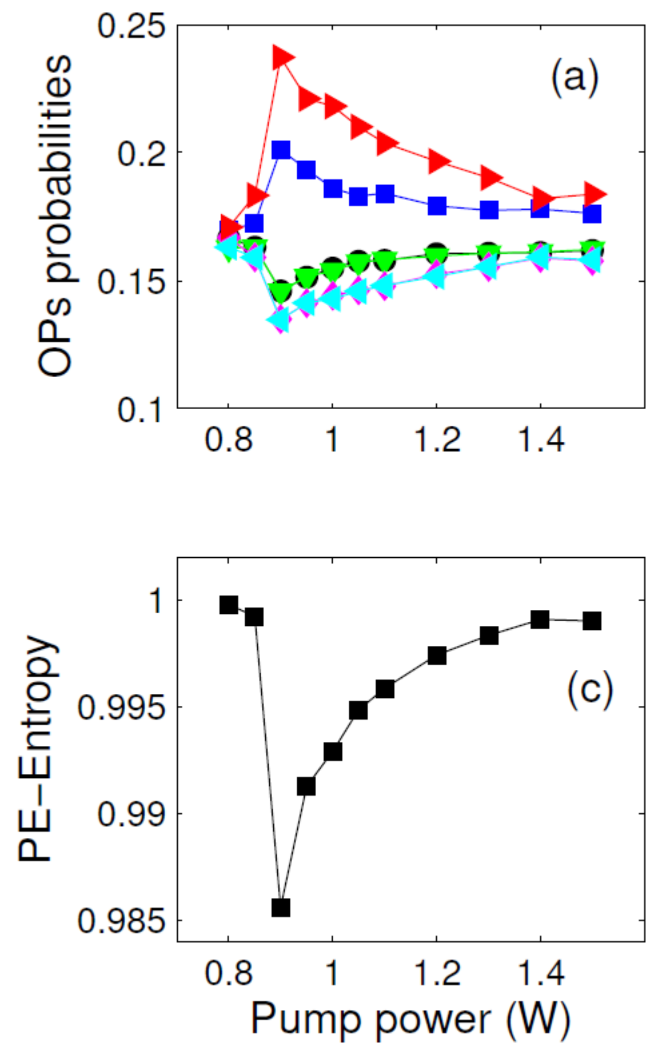


C. Masoller et al, New J. Phys. 17 (2015) 023068

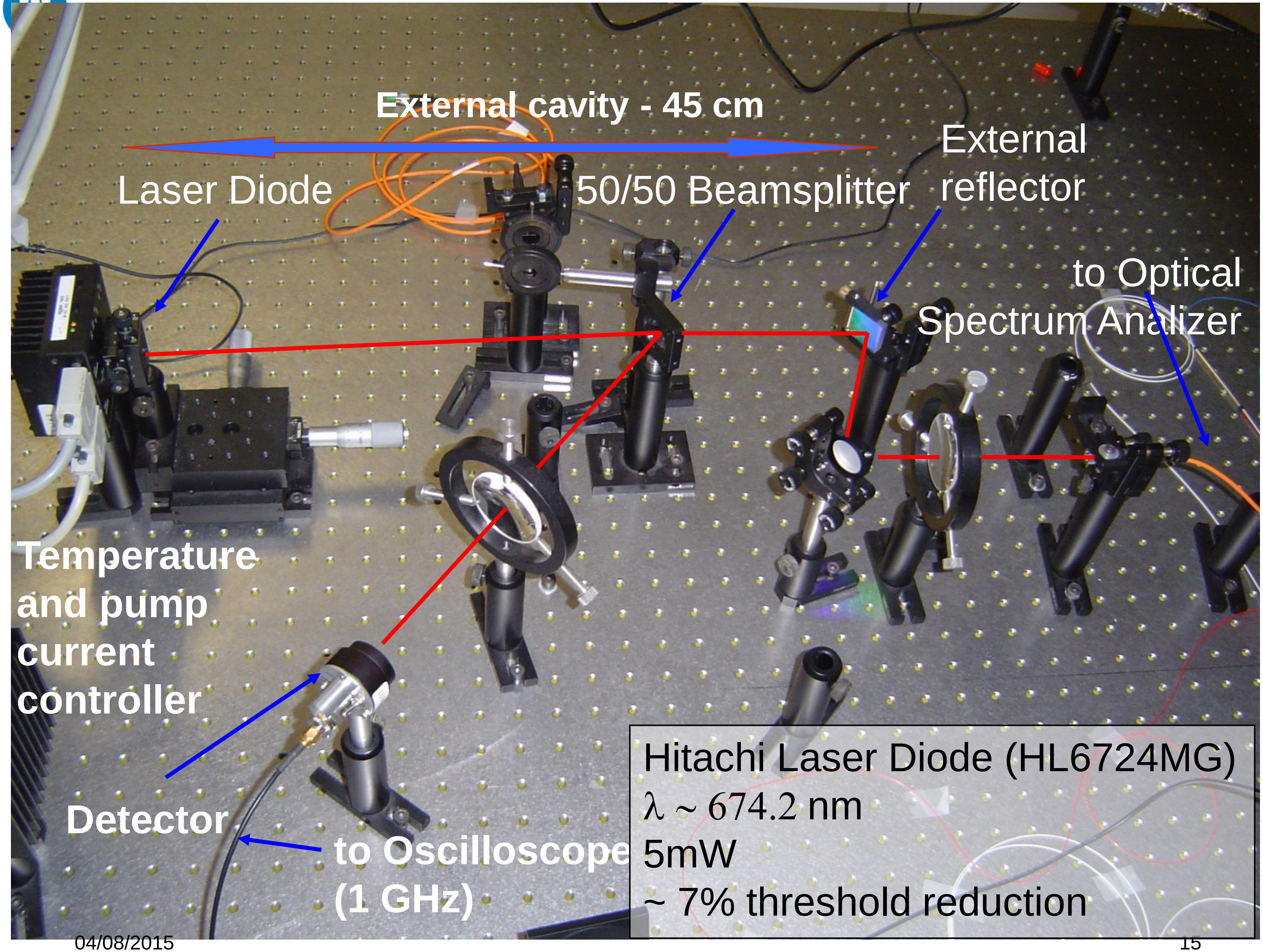
Another example

- Transition laminar - turbulence in a fiber laser





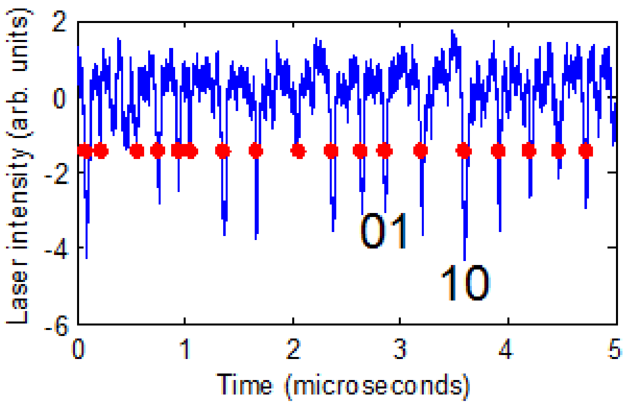
A. Aragoneses et al, submitted (2015)



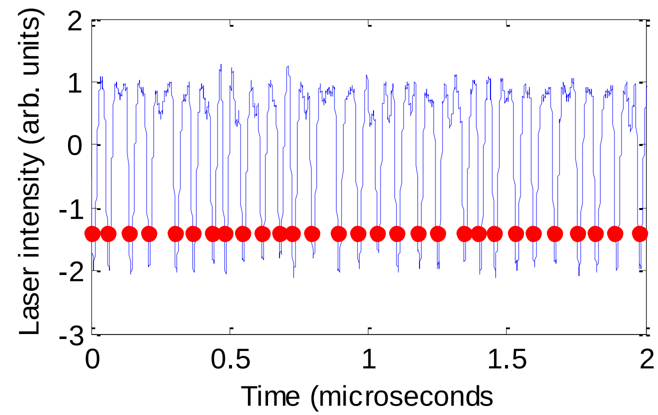
Hitachi Laser Diode (HL6724MG)
$\lambda \sim 674.2$ nm
5mW
~ 7% threshold reduction

Spiking dynamics

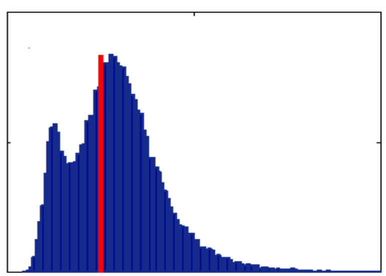
Low pump current

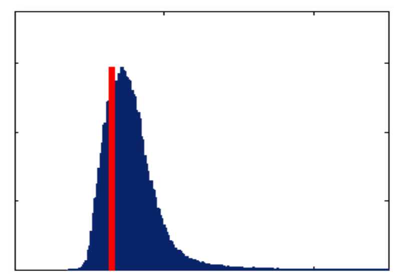


Higher pump current



ISI
Histograms

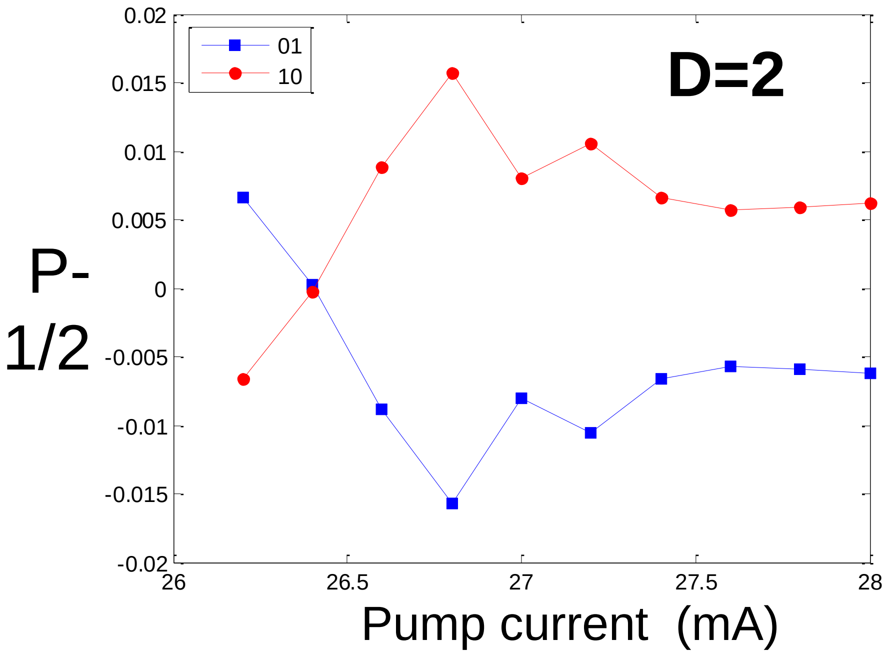


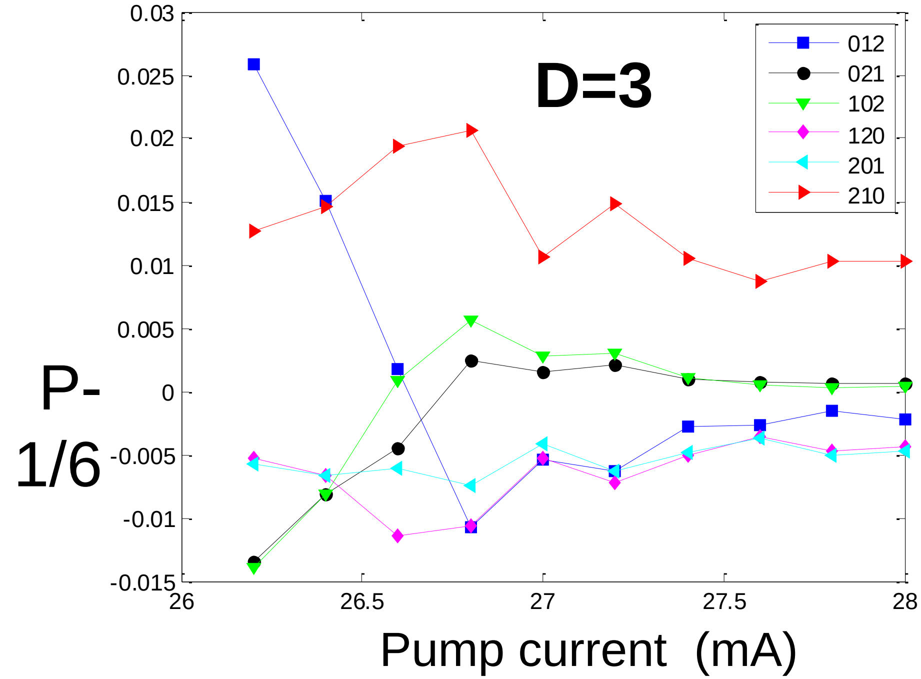


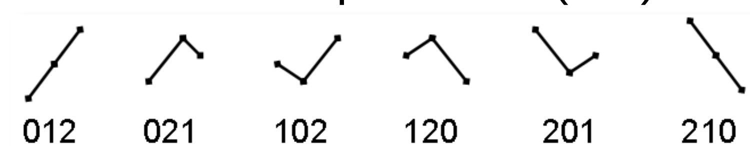
Probabilities of (**01**) and (**10**) uncover 3-spike correlations

Null Hypothesis: random spikes $\Rightarrow$ P(01) = P(10)

Are optical spikes random?

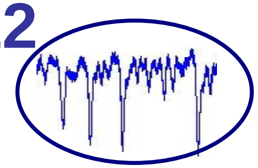






45000 - 220000 spikes

012



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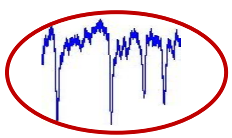

A. Aragoneses et al, Scientific Reports 3, 1778 (2013)

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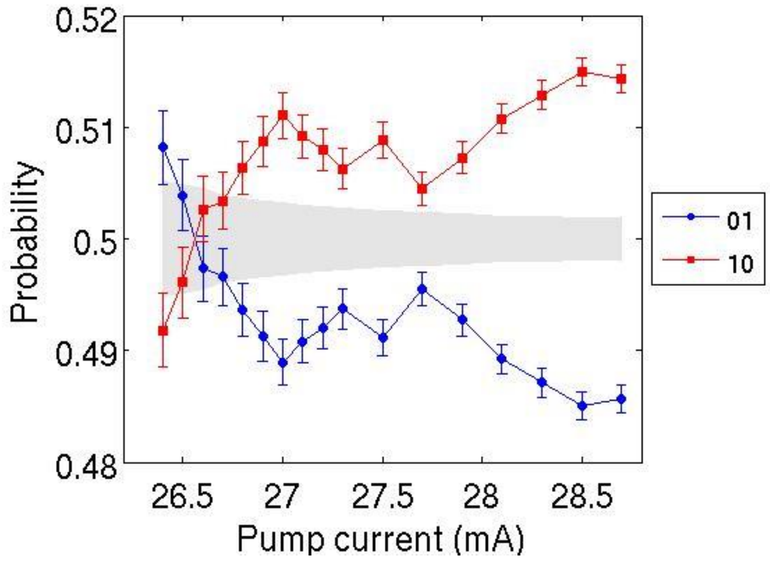
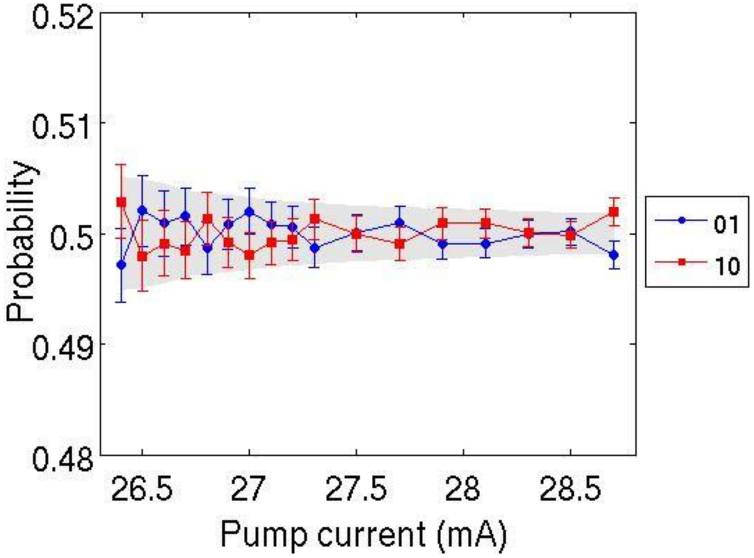
Are the results significant?

Recorded data



Surrogated data



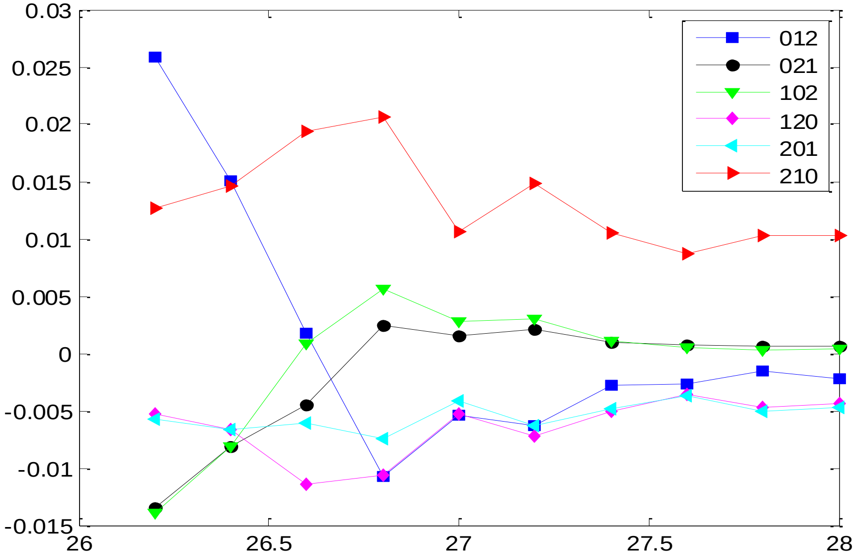
Error bars computed with a binomial test, gray region is consistent with N.H.

A. Aragoneses et al, Scientific Reports 3, 1778 (2013)

Ordinal analysis unveils new information

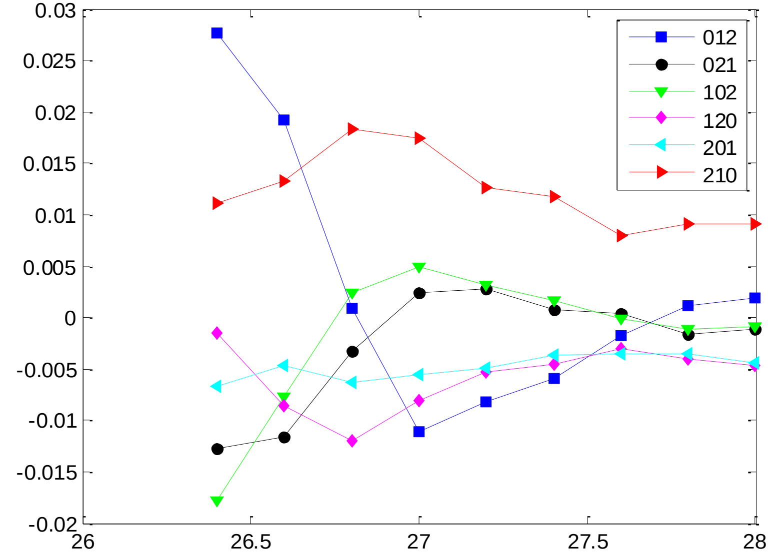
P-1/6

T=18 C



Pump current (mA)

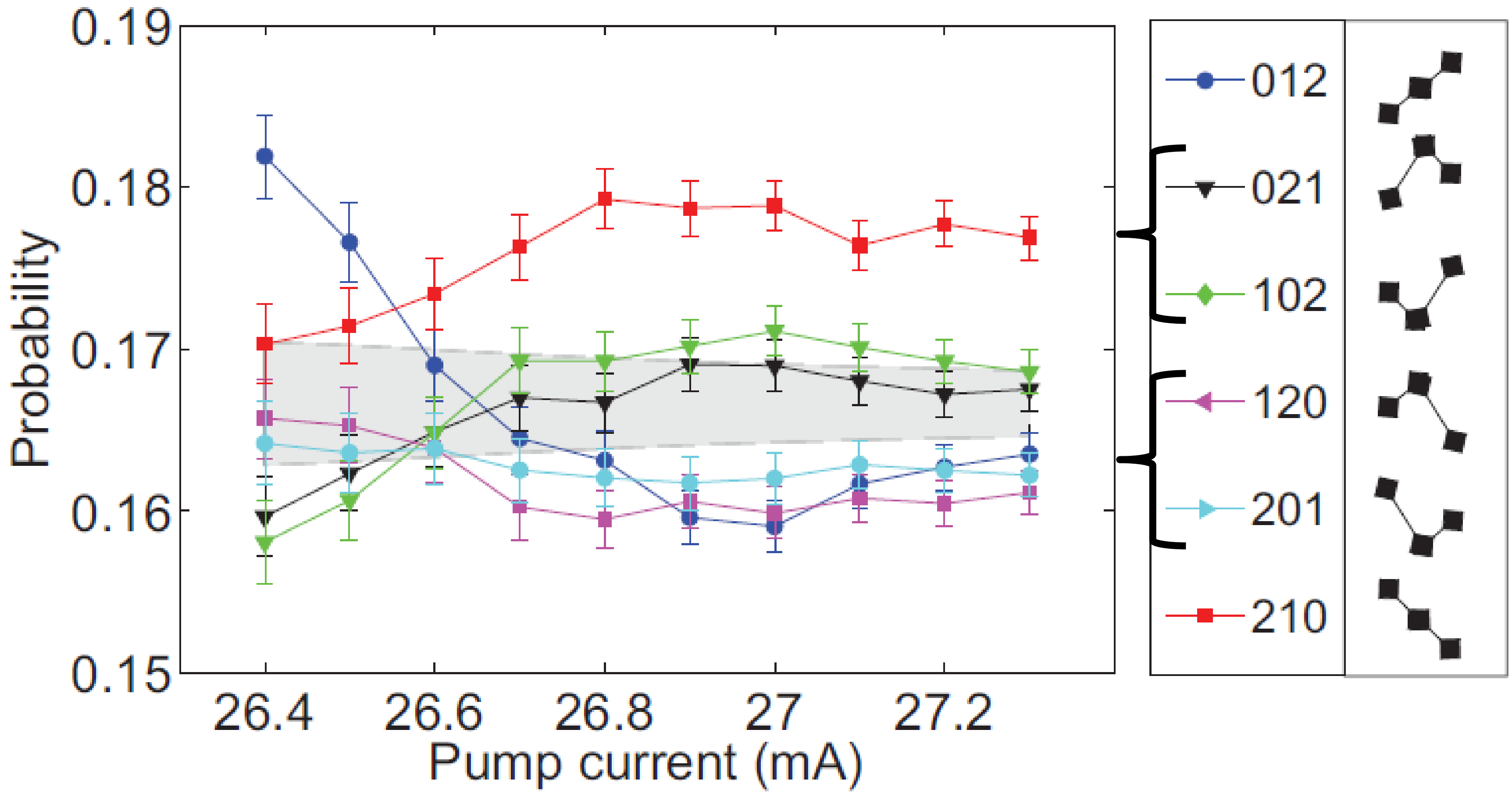
T=20 C



Pump current (mA)

Same transition, hierarchical and clustered organization of the pattern probabilities

In another experiment: the same transition, hierarchy and clusters



75,000 – 880,000 spikes
(different laser, new oscilloscope)

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

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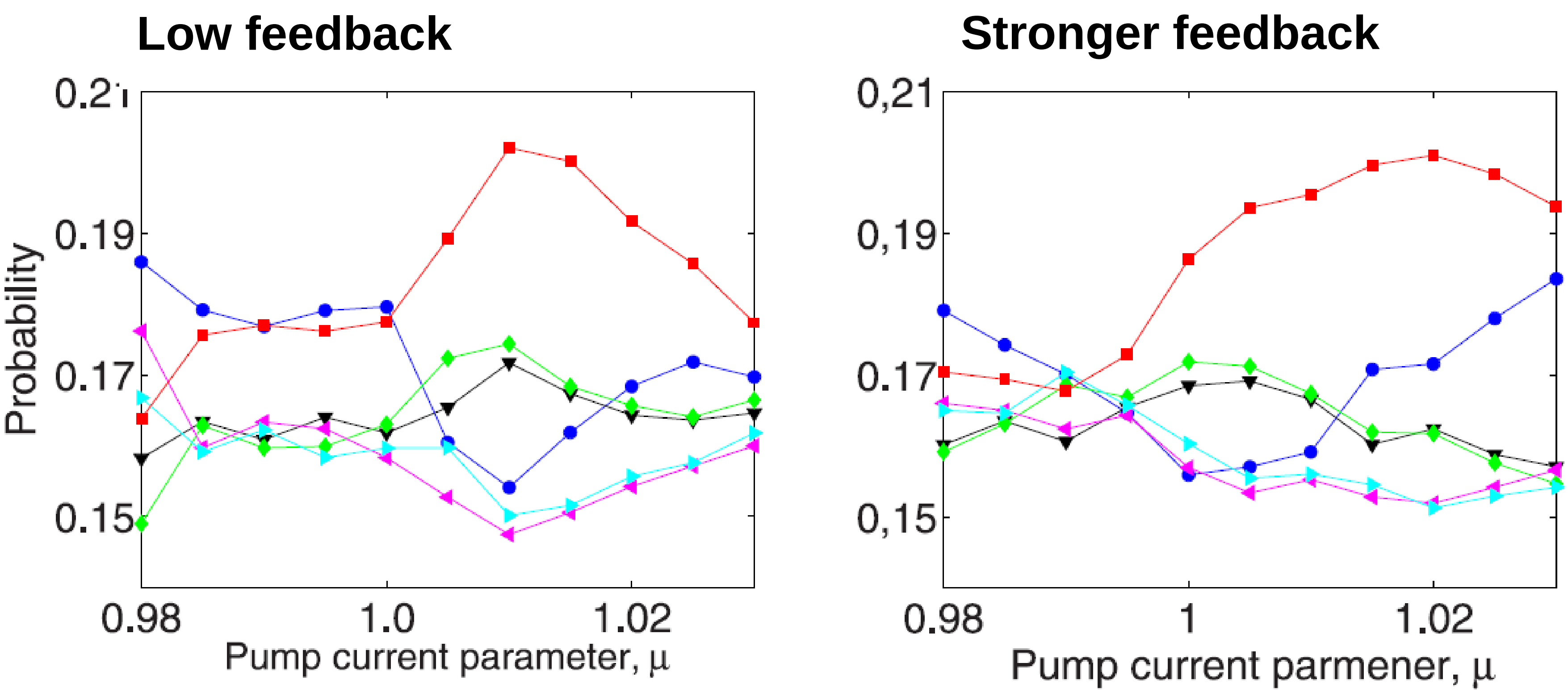
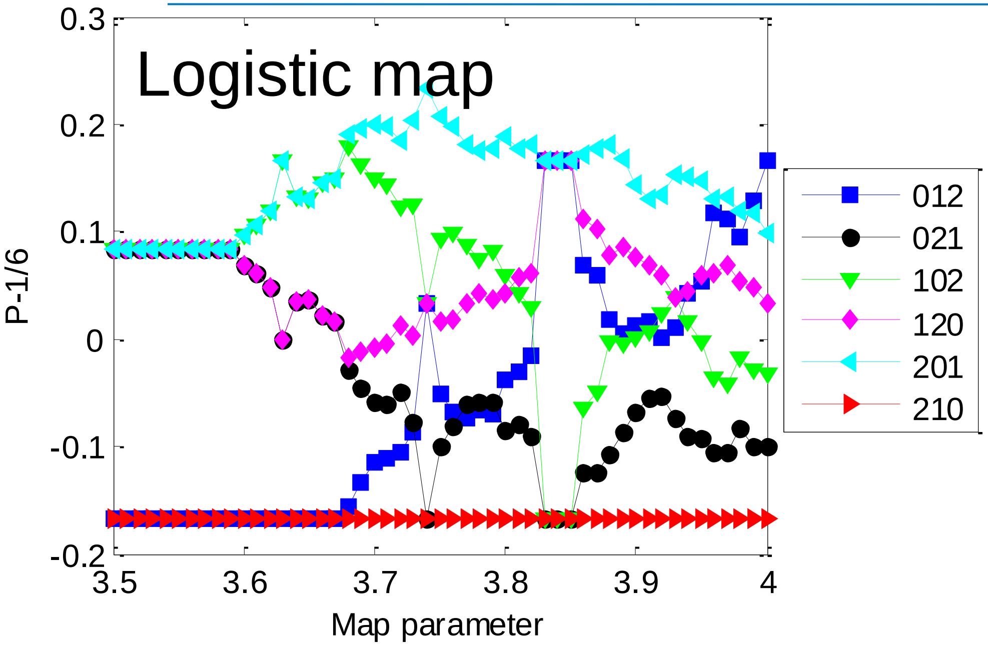
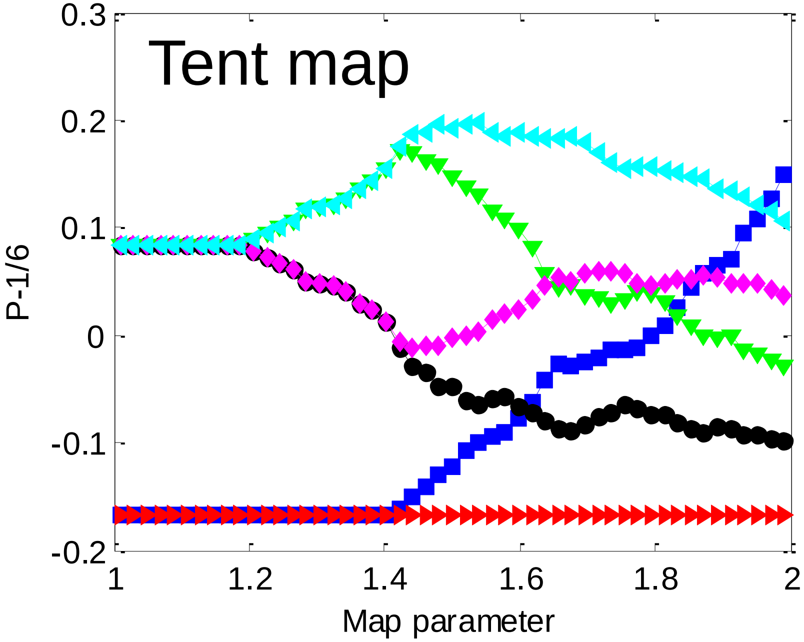
LK model in good agreement with observations

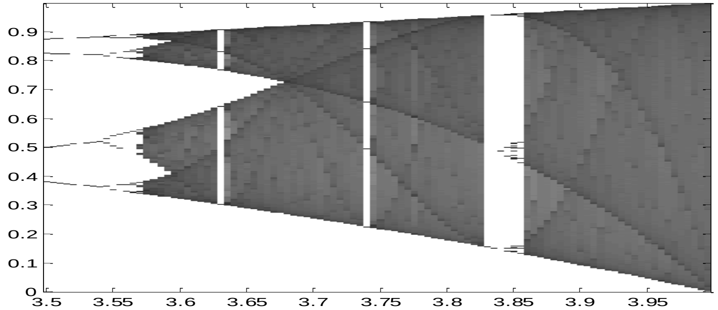


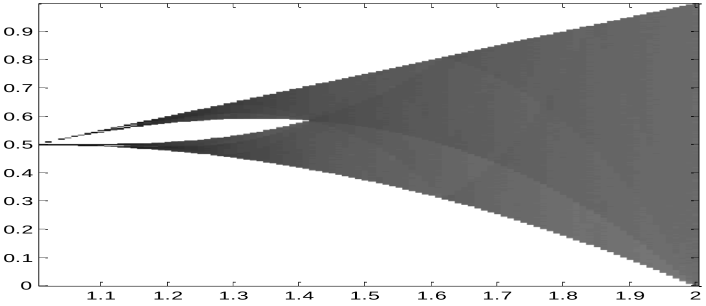
A. Aragoneses et al, Sci. Rep. 4, 4696 (2014)

Can we find a minimal model that displays these features?





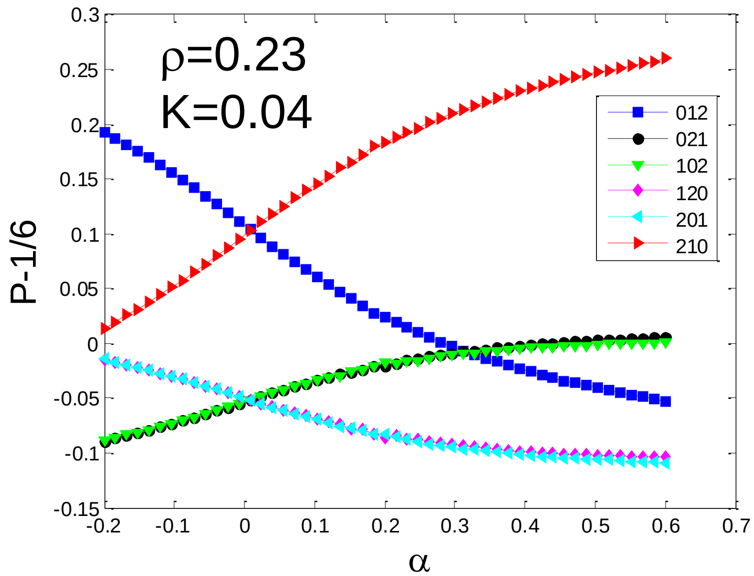


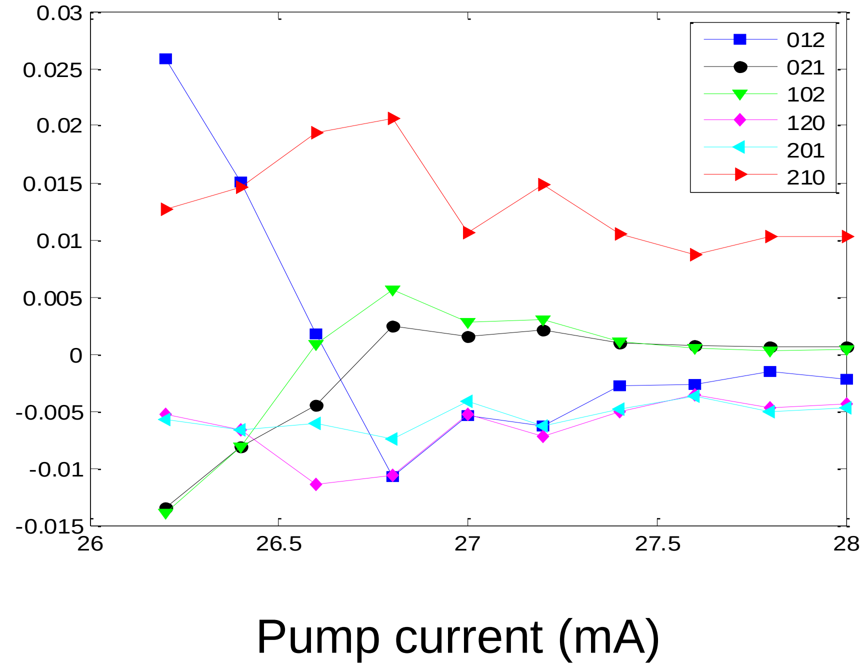


Modified circle map

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

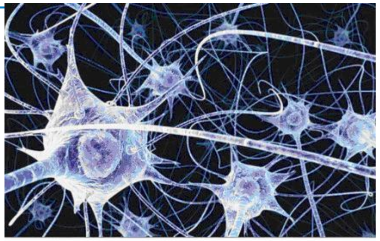
$$X_i = \varphi_{i+1} - \varphi_i$$





Minimal phenomenological model

Connection with neurons



- The circle map describes many excitable systems (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 71, 061915 (2005)

How similar the spikes of lasers and neurons are?

Neuron Interspike Interval (ISI) histogram

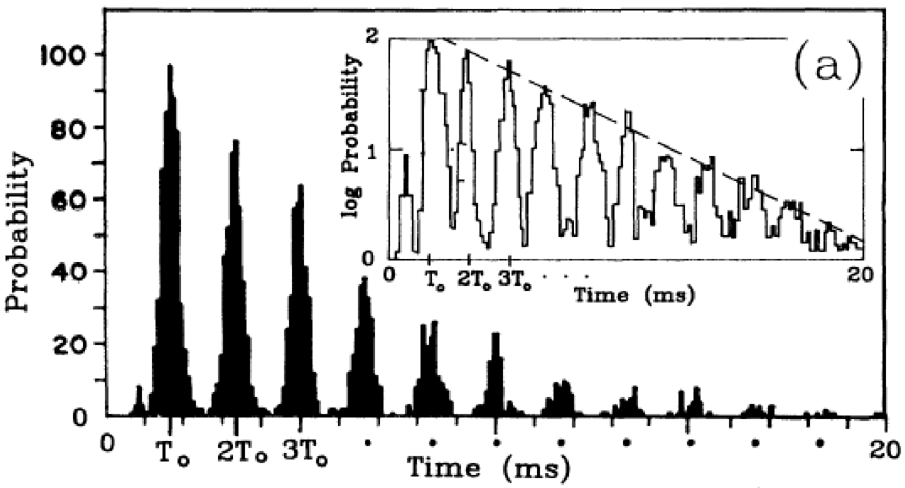
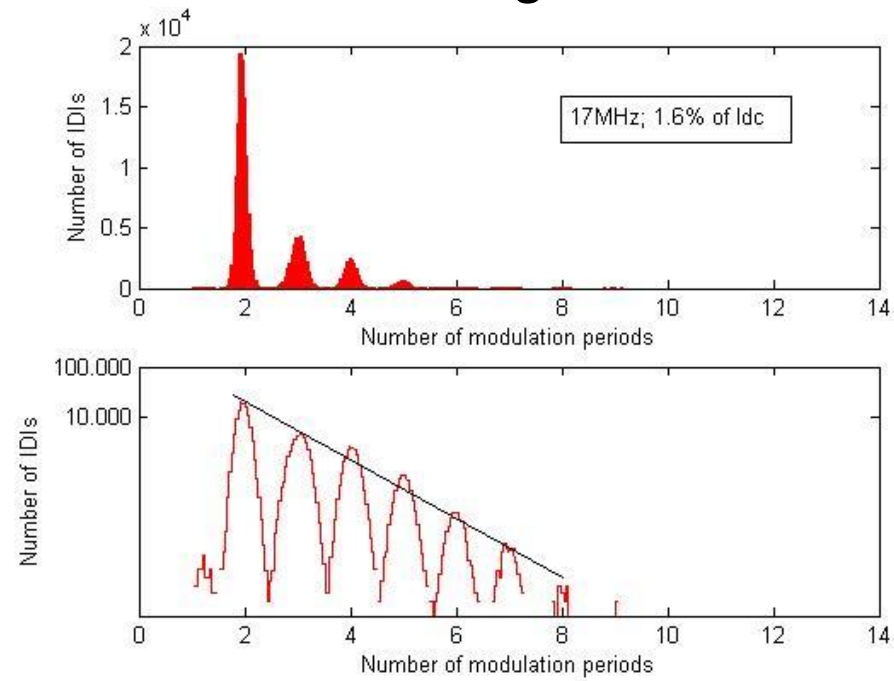


FIG. 1. (a) An experimental ISIH obtained from a single auditory nerve fiber of a squirrel monkey with a sinusoidal 80-dB sound-pressure-level stimulus of period $T_0 = 1.66$ ms applied at the ear. Note the modes at integer multiples of T_0. Inset:

Laser ISI histogram



With direct current modulation, data recorded in our lab

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

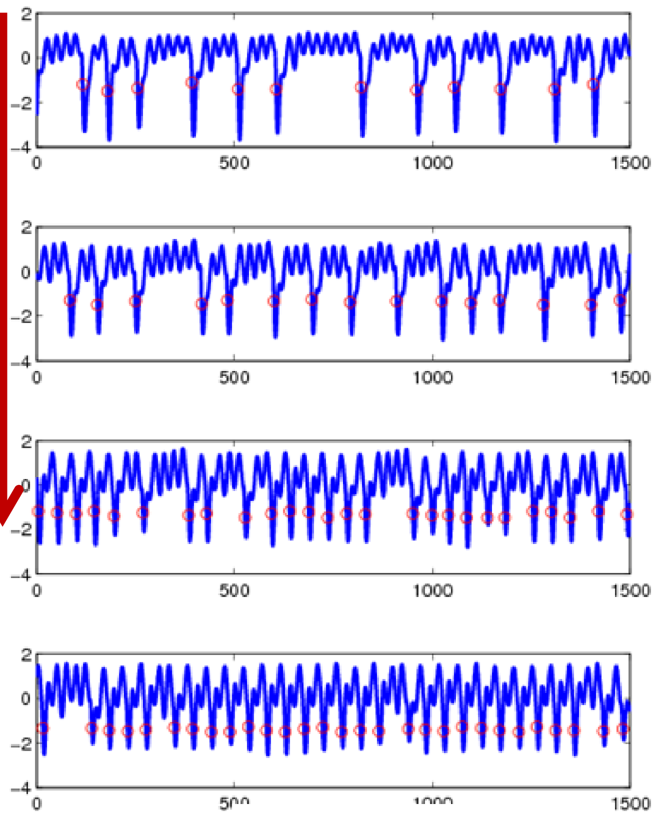
Response to periodic modulation

Relevant for understanding neuronal encoding of external stimuli

Laser intensity:

Increasing modulation amplitude

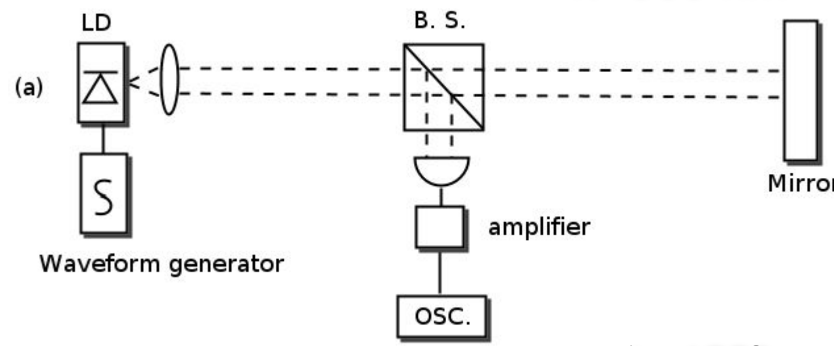
Tendency to lock



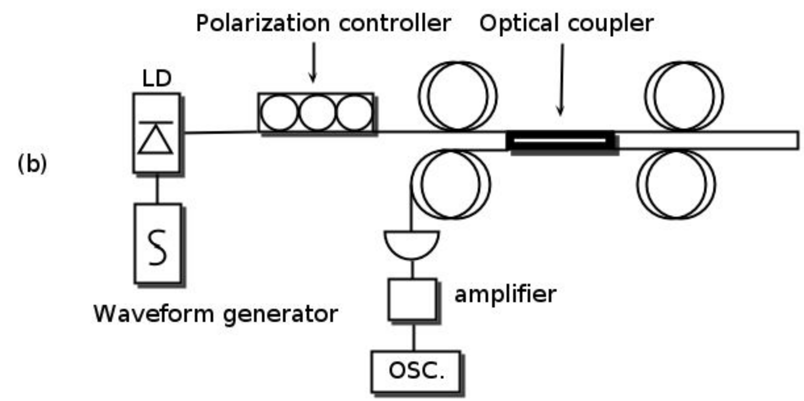
Time (ns)

Two experiments:

λ=660 nm

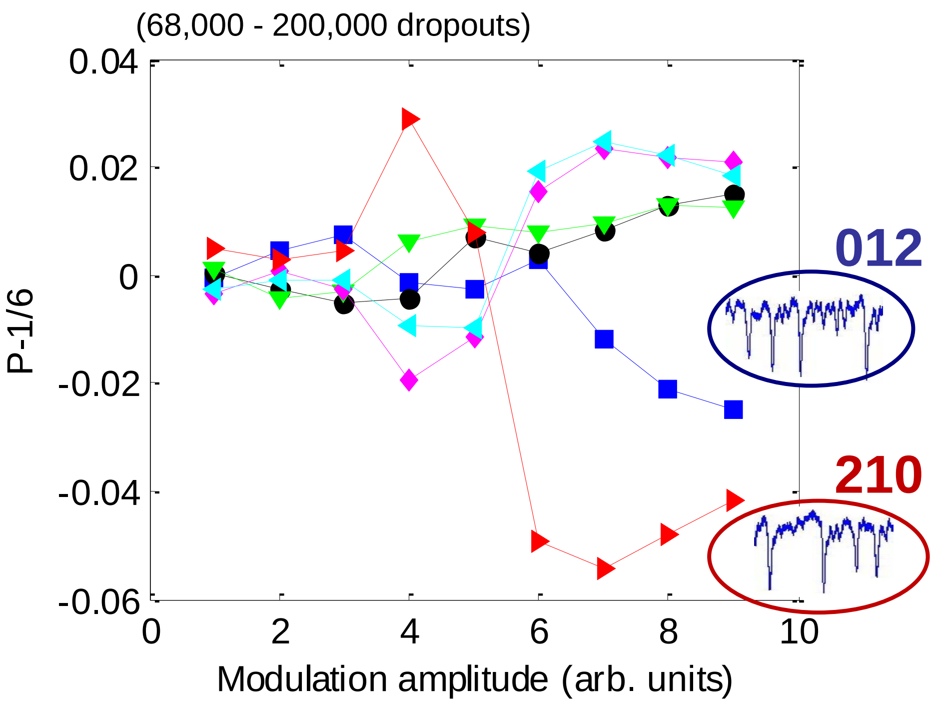


λ=1550 nm

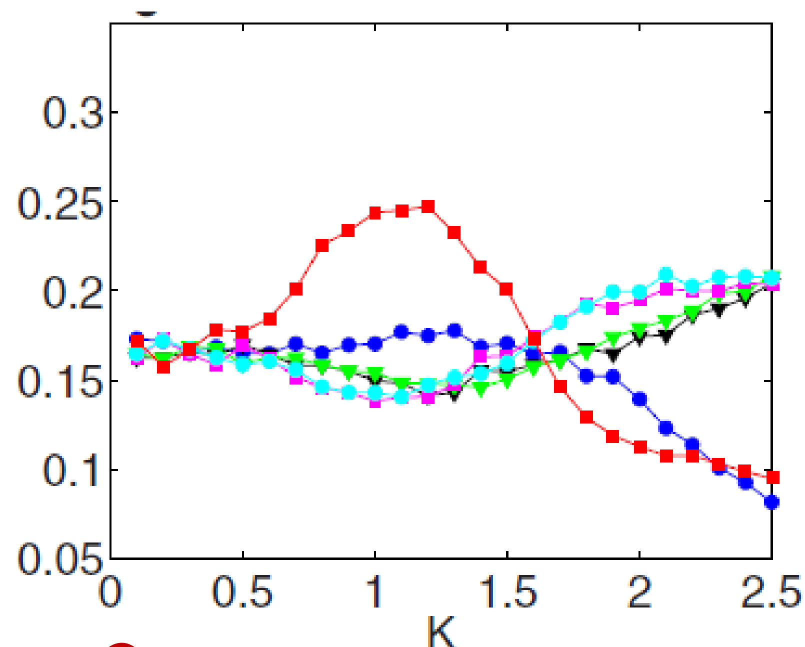


Experiments - minimal model comparison

Experiments @ 660 nm



Circle map



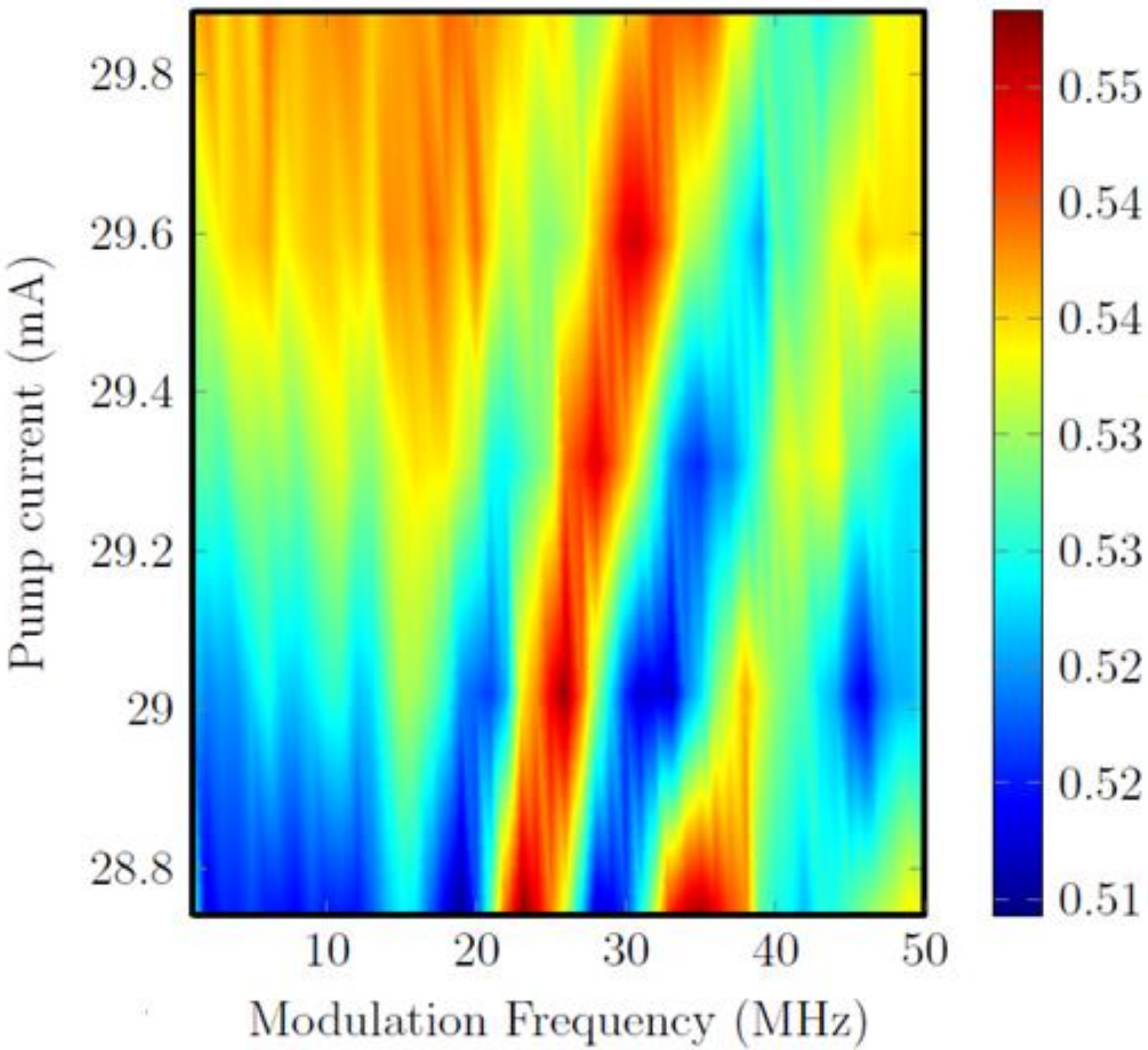
$$\varphi_{i+1} = \varphi_i + \rho + \frac{K}{2\pi}\left[\sin(2\pi\varphi_i) + \alpha\sin(4\pi\varphi_i)\right] + D\zeta$$

Similar observations @ 1550 nm

Interpretation: locking to external forcing

A valuable tool for identifying noisy locking

Probability of "10" from empirical data.



Pump current: modifies the natural (unmodulated) spike rate

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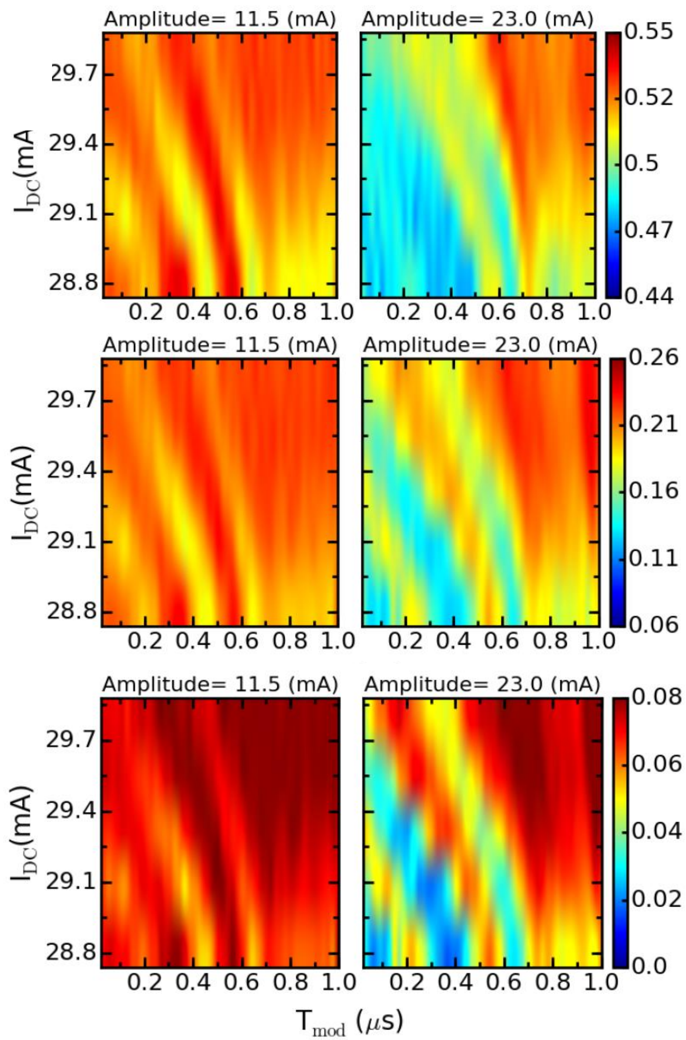
Uncovering longer correlations

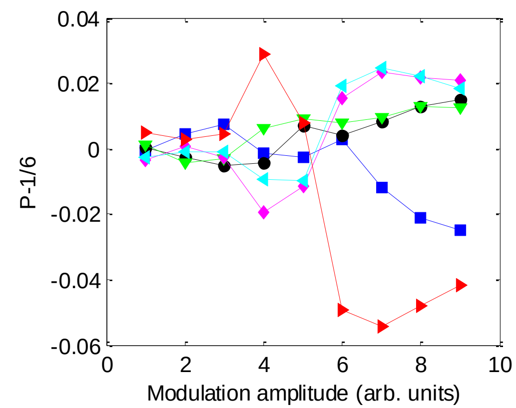
Weak modulation   Stronger modulation

Probability of "10"

Probability of "210"

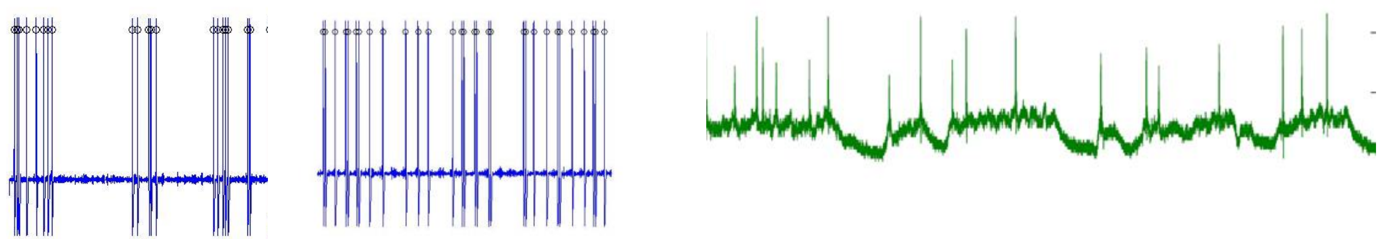
Probability of "3210"





Part 1: Conclusions

- Underlying transition (012→210) in the spiking laser output.
- Hierarchical and clustered organization of pattern probabilities.
- Good agreement with LK model.
- Minimal model identified. Robust under external forcing.
- Present work: can the laser be an "optical neuron"? Detailed comparison with neuronal models & real data.



What is a Rogue Wave?

A “monster wave”, a “freak wave”, an ultra-high wave.

(a) Hokusai's Great Wave

(b) Breaking Wave in the Southern Ocean

Can develop suddenly even in calm and apparently safe seas.

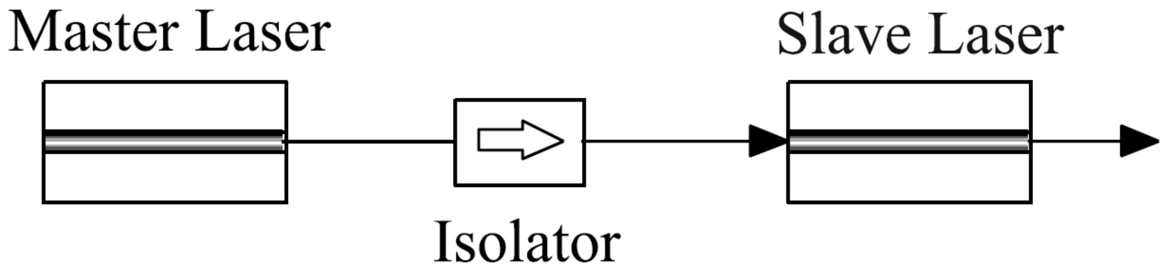
Adapted from F. Dias (Dublin, Ireland)

RWs appear suddenly and vanish without a trace

A challenge for boats and also, for the oil and gas industry, for the design of safe off-shore platforms.

Source: National Geographic

Optically injected semiconductor lasers provide a controllable setup for the study of RWs



- Parameters:
  - Injection ratio
  - Frequency detuning

- Regimes:
  - Stable emission
  - Periodic oscillations
  - Chaos

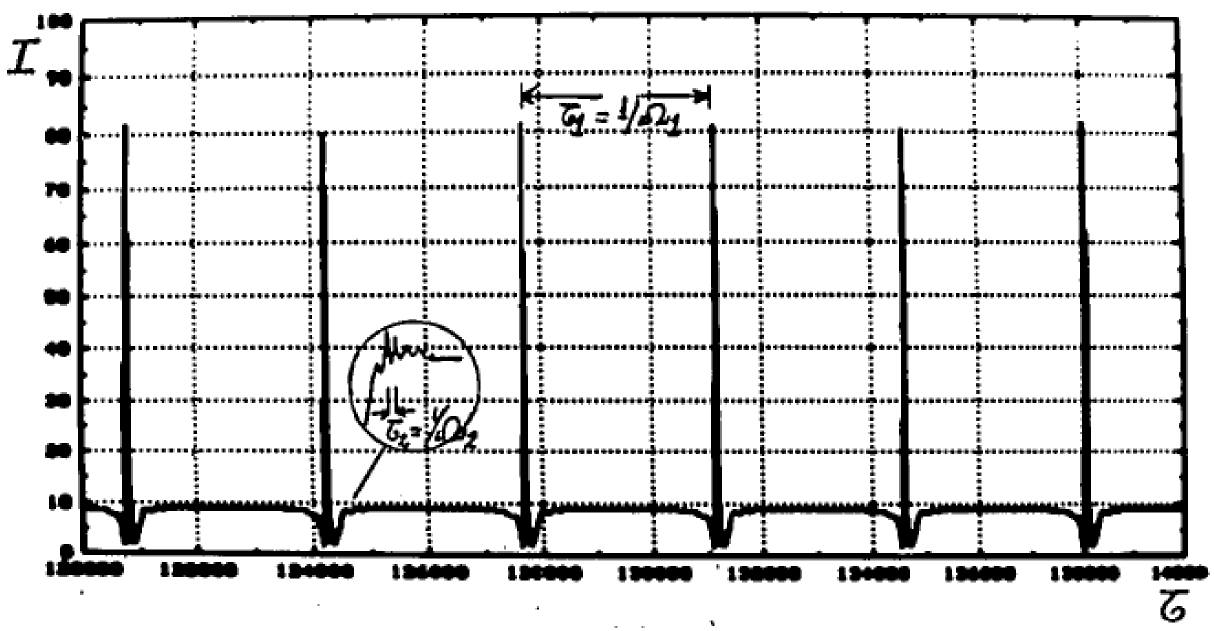
S. Wieczorek, B. Krauskopf, T. B. Simpson, and D. Lenstra, “The dynamical complexity of optically injected semiconductor lasers,” Phys. Rep. 216 (2005).

Motivation

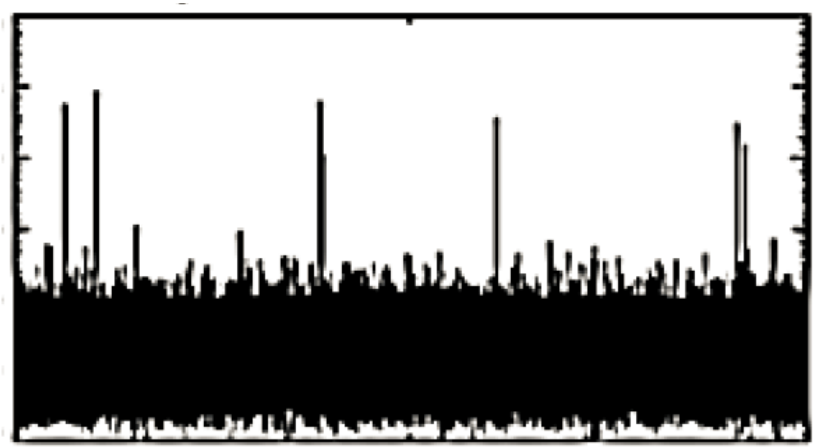
Instabilities in lasers with an injected signal

J. R. Tredicce, F. T. Arecchi, G. L. Lippi, and G. P. Puccioni

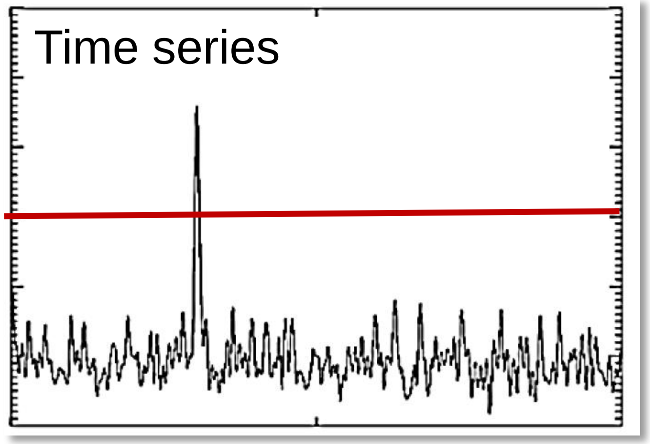
178 J. Opt. Soc. Am. B/Vol. 2, No. 1/January 1985

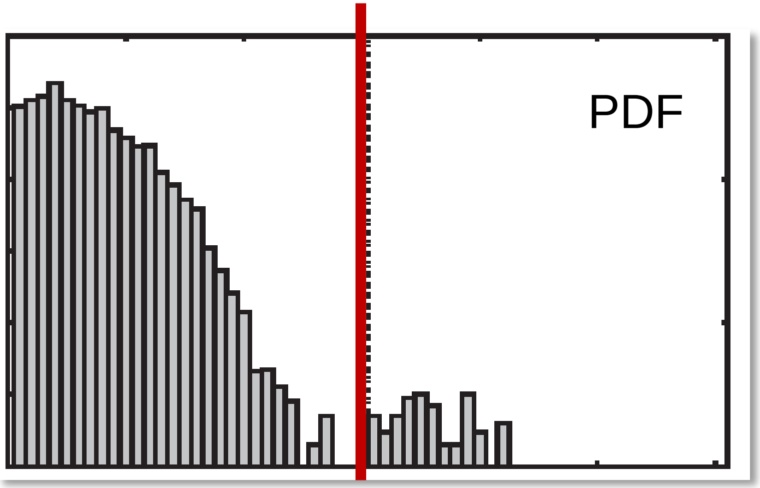


Experimental observation of extreme pulses in the laser output



- RW definition: pulse above a <u>threshold</u> (<H> + **4-8** σ)





C. Bonatto et al, PRL 107, 053901 (2011).

What we have learned

- RWs can be **deterministic**, generated by a crisis-like process.
- RWs can be **predicted** with a certain anticipation time.
- RWs can be **controlled** via noise and/or modulation.

- C. Bonatto et al, *Deterministic optical rogue waves*, PRL 107, 053901 (2011).
- J. Zamora-Munt et al, *Rogue waves in optically injected lasers: origin, predictability and suppression,* PRA 87, 035802 (2013).
- S. Perrone et al, *Controlling the likelihood of RWs in an optically injected semiconductor laser via direct current modulation*, PRA 89, 033804 (2014).
- J. Ahuja et al, *Rogue waves in injected semiconductor lasers with current modulation: role of the modulation phase*, Optics Express 22, 28377 (2014).

Governing equations

- Complex field, **E**
- Carrier density, **N**

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

$$\underbrace{\frac{dN}{dt} = \frac{1}{\tau_N}\left(\mu\text{-}N\text{-}N|E|^2\right)}_{\text{Solitary laser parameters: } \alpha\ \tau_p\ \tau_N\ \mu}$$

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

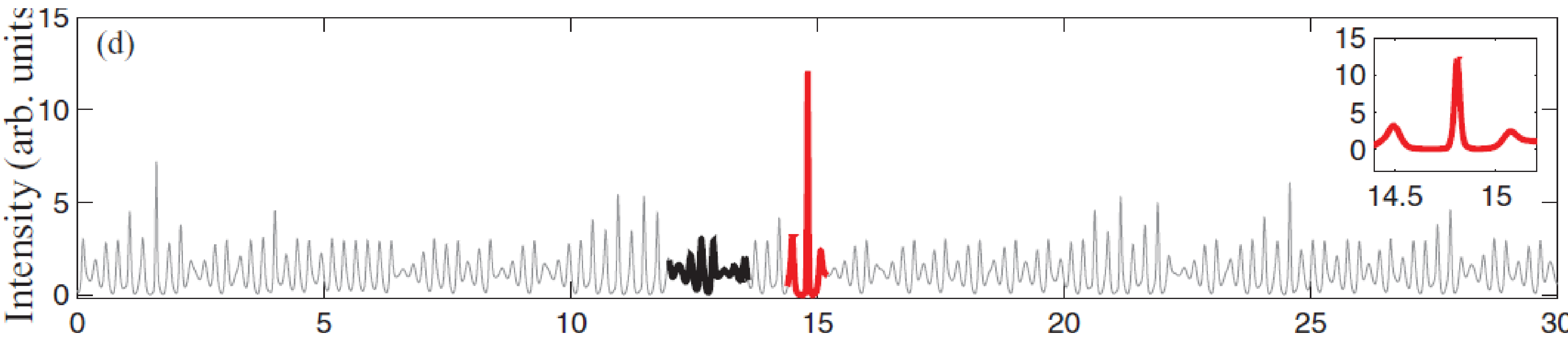
spontaneous emission noise

Solitary laser parameters: **α τ_p τ_N μ**

Typical parameter values:
$\alpha = 3$, $\tau_p = 1$ ps, $\tau_N = 1$ ns

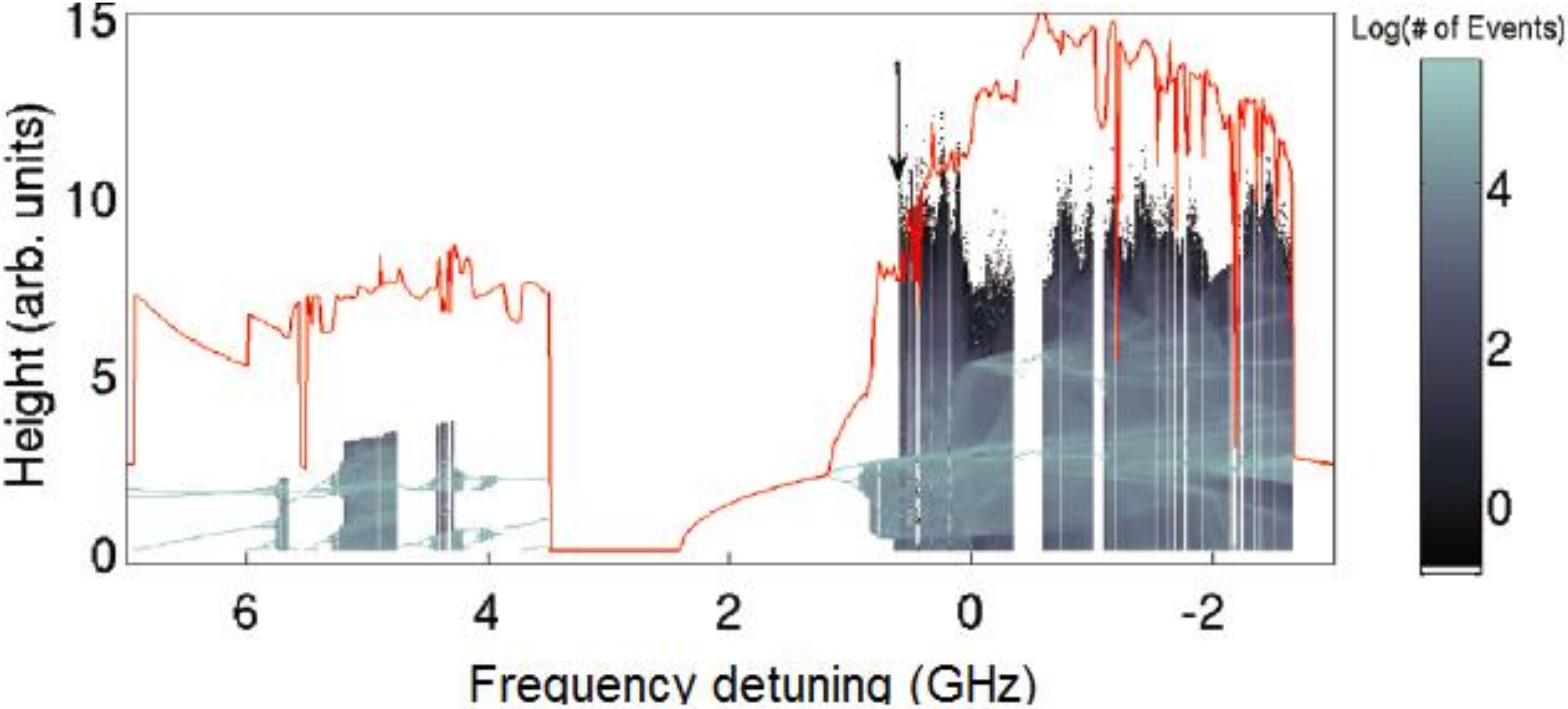
μ: normalized pump current parameter

A simulated RW



Bifurcation diagram

Threshold: <H> + 8σ



$\Delta\omega = \omega_s - \omega_m$

A narrow channel: the RW "door"

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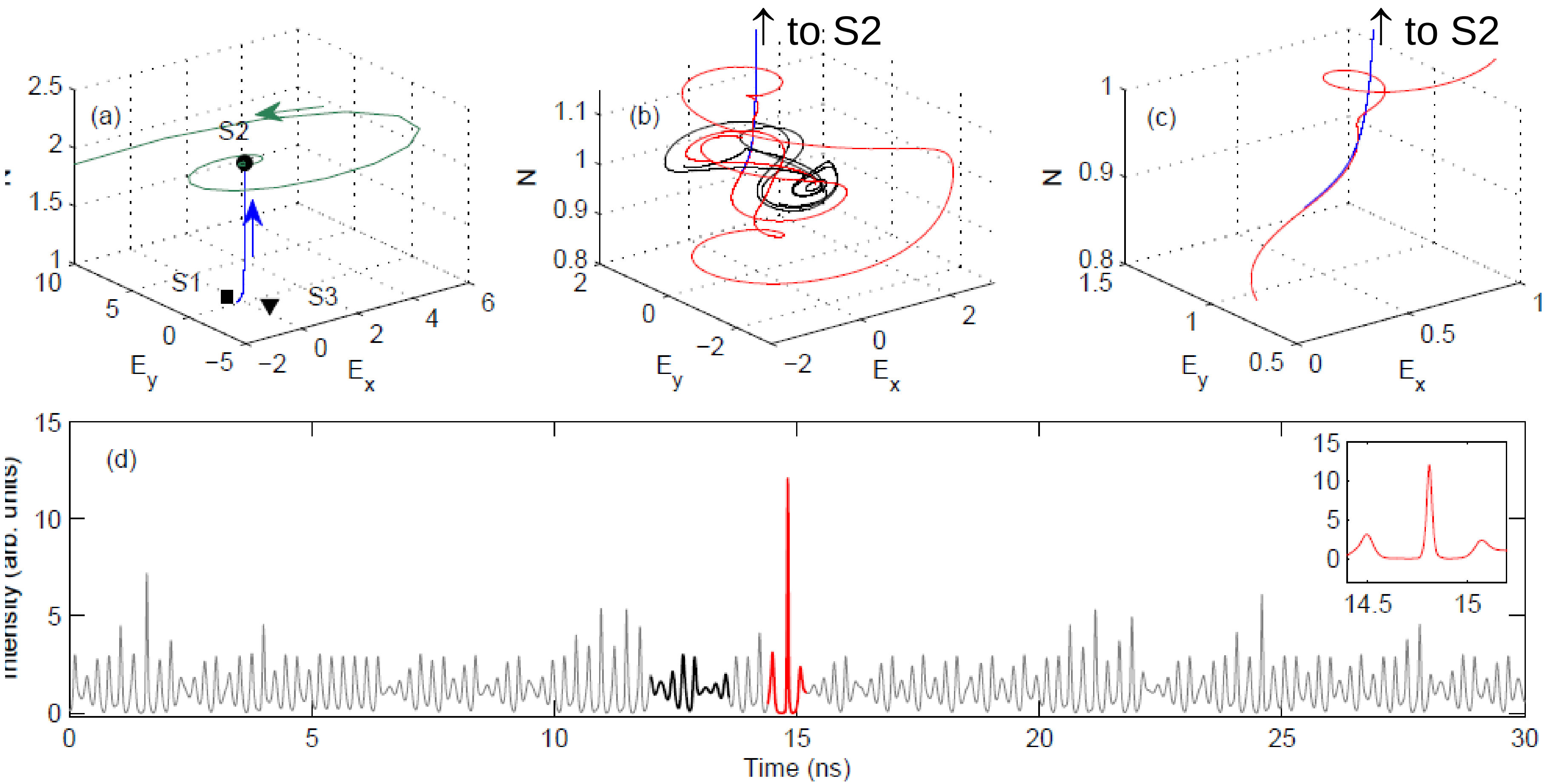
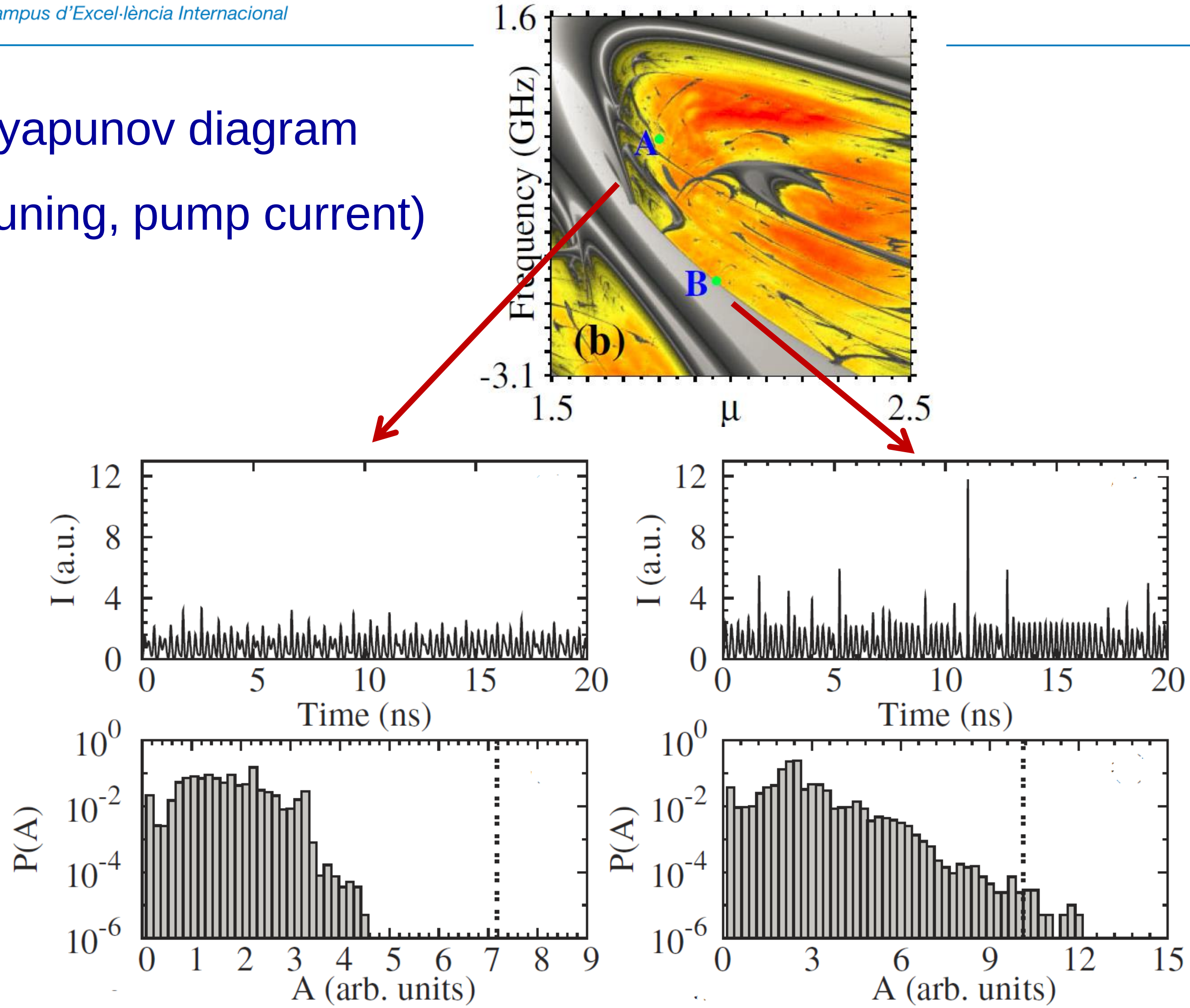


A RW is triggered whenever the trajectory closely approaches the stable manifold of S2

Deterministic simulations

Lyapunov diagram

(detuning, pump current)



Chaos without RWs

Chaos with RWs

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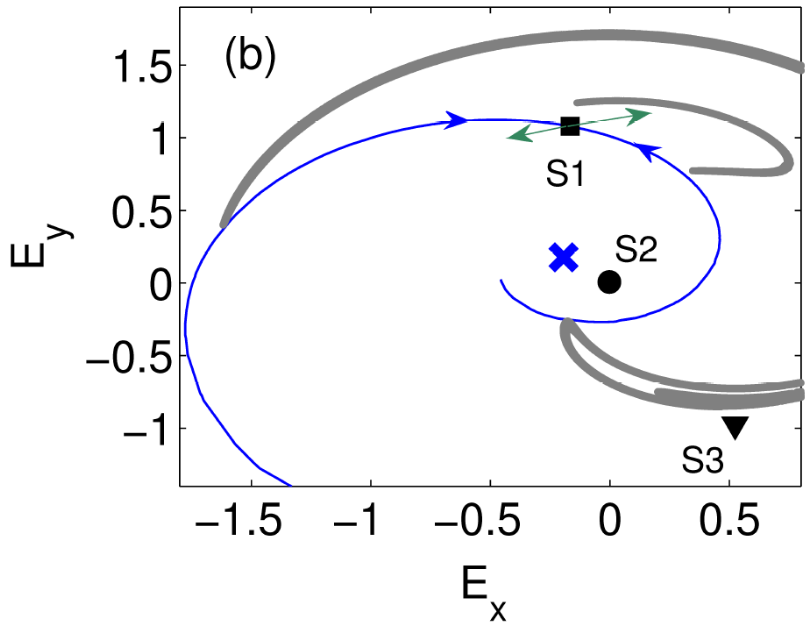
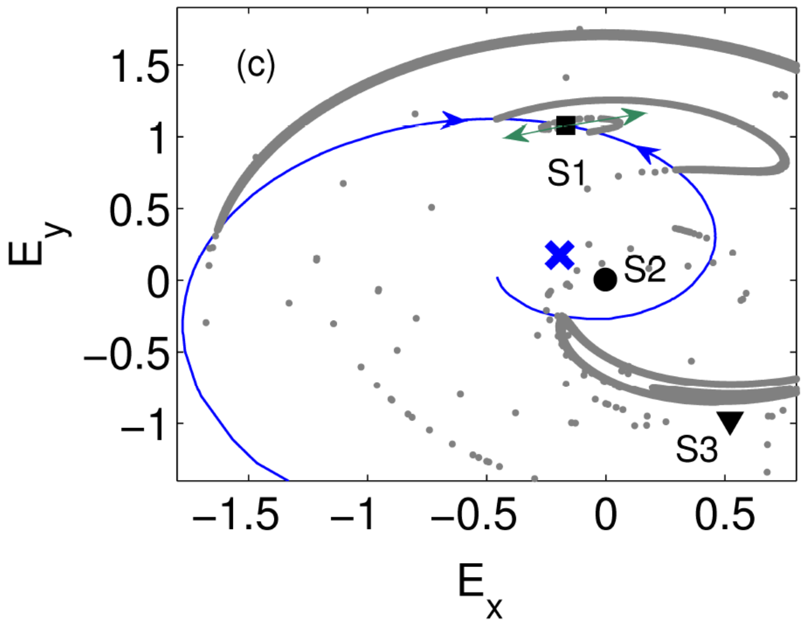
Why chaos with RWs and chaos without them?

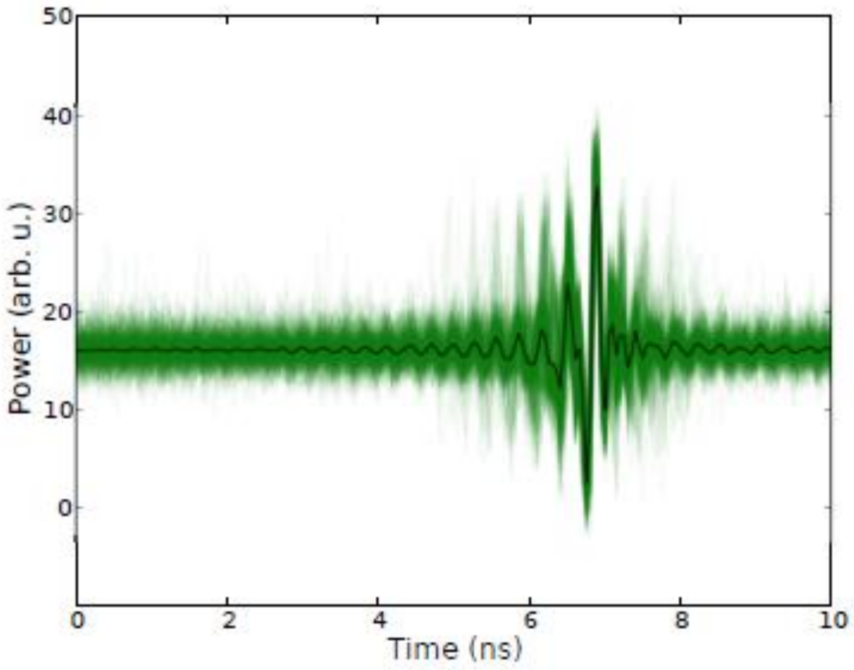




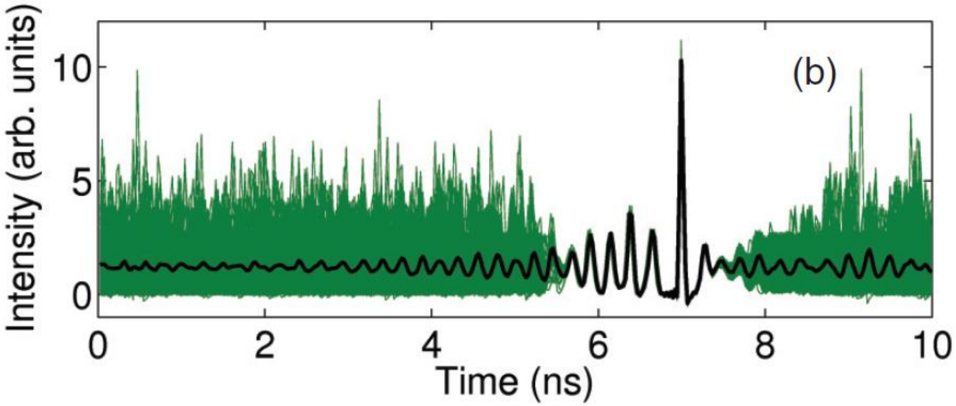
An external crises-like process enables access to the region of phase space where the stable manifold of S2 (x) is.

RW predictability

Experiments



Simulations

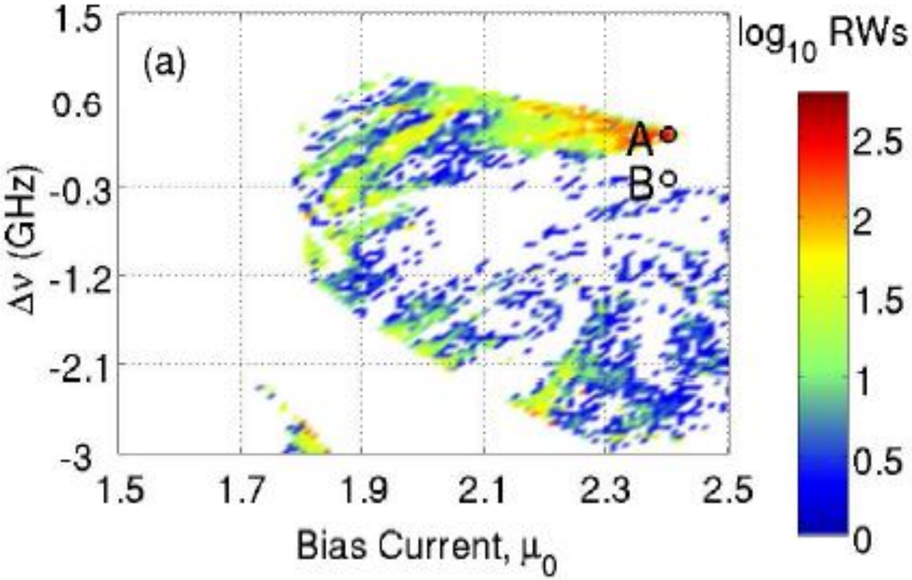


Superposition of 500 time series at the RW peak

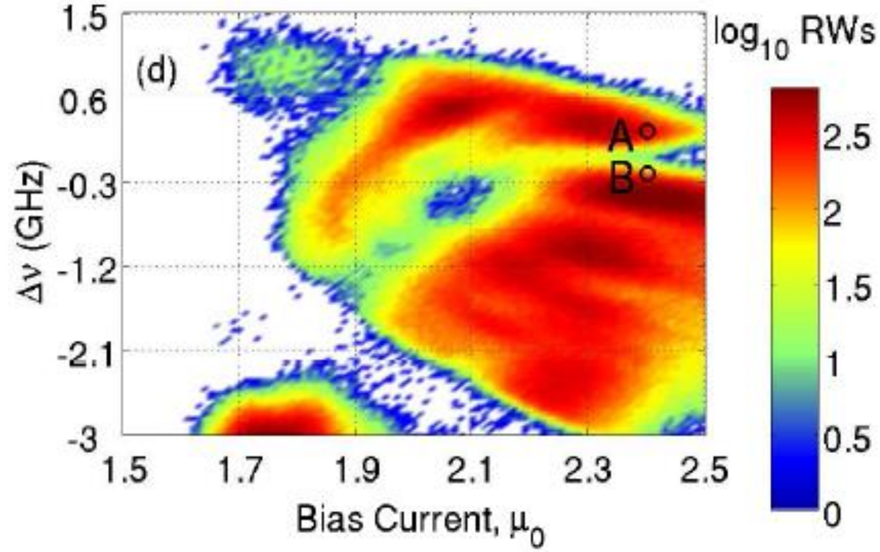
J. Zamora-Munt et al, PRA 87, 035802 (2013)

Role of noise: number of RWs vs (pump current, detuning)

Deterministic RWs (β_{sp}=0)



Stochastic simulations (β_{sp}=0.01)



White = No RWs

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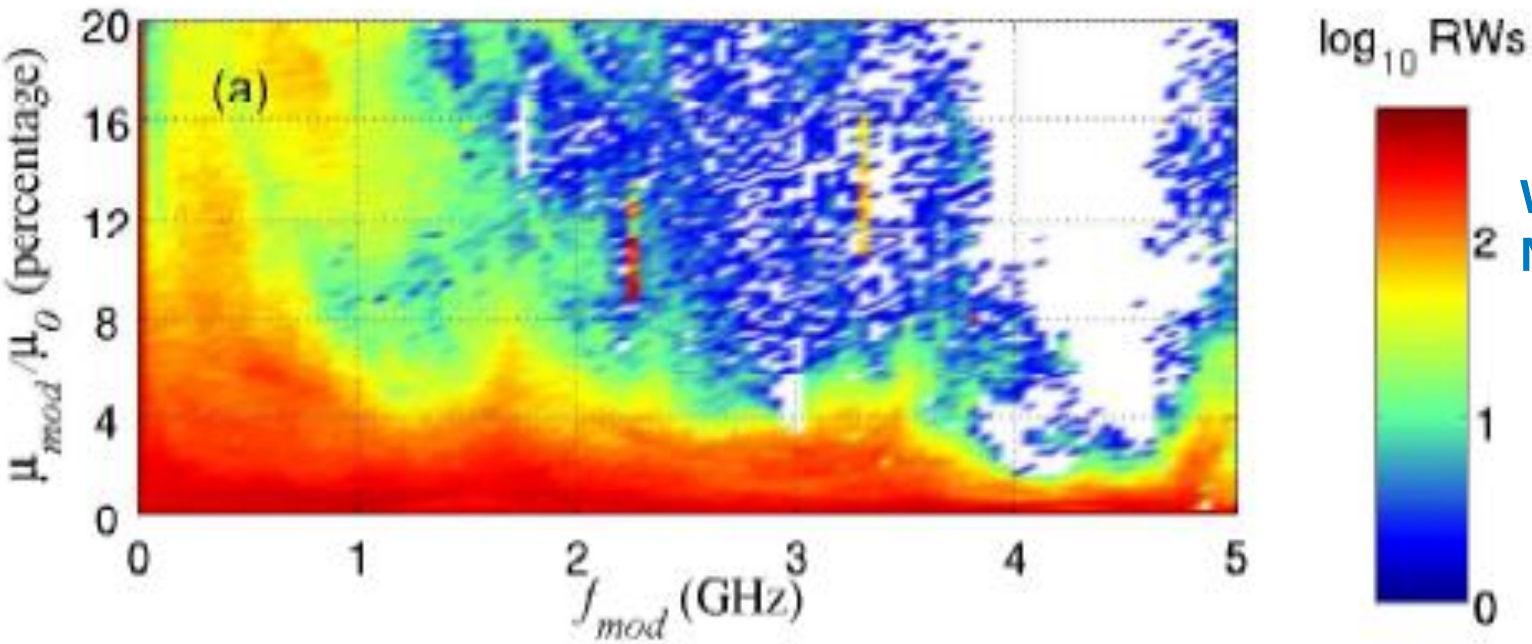
RW control in Point A (deterministic RWs)

$$\mu = \mu_0 + \mu_{mod} \sin(2\pi \ f_{mod} \ t)$$



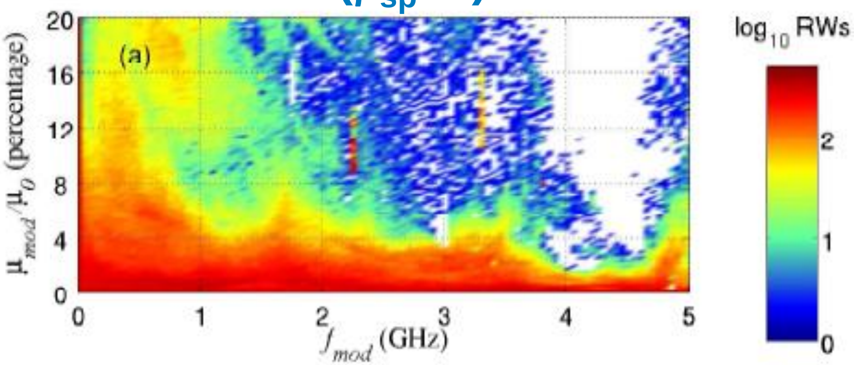
Current modulation with appropriated amplitude and frequency completely suppresses RWs.

S. Perrone et al, PRA 89, 033804 (2014)

RW control in Point A: influence of noise

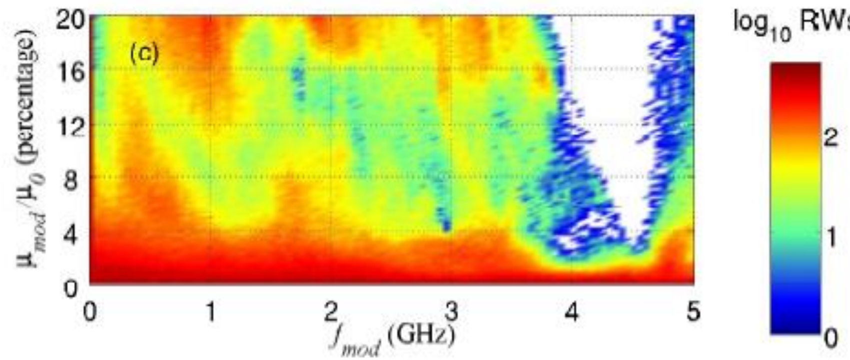
$$\boxed{\mu = \mu_0 + \mu_{\mathrm{mod}} \sin(2\pi\ f_{\mathrm{mod}}\ t)}$$

No noise (β_{sp}=0)



White = No RWs

Stochastic simulations (β_{sp}=0.01)

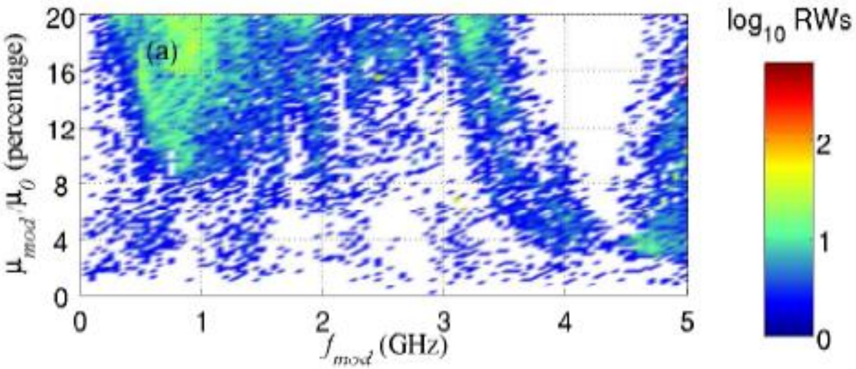


White = No RWs

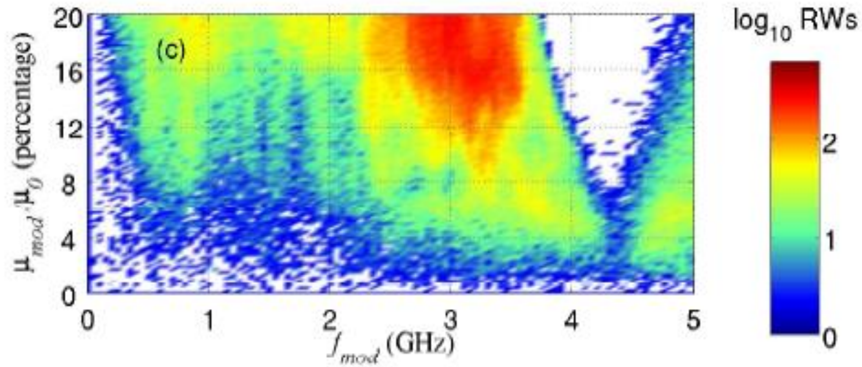
"safe parameter region" is robust to the presence of noise.

in Point B (no deterministic RWs)

β_{sp}=0



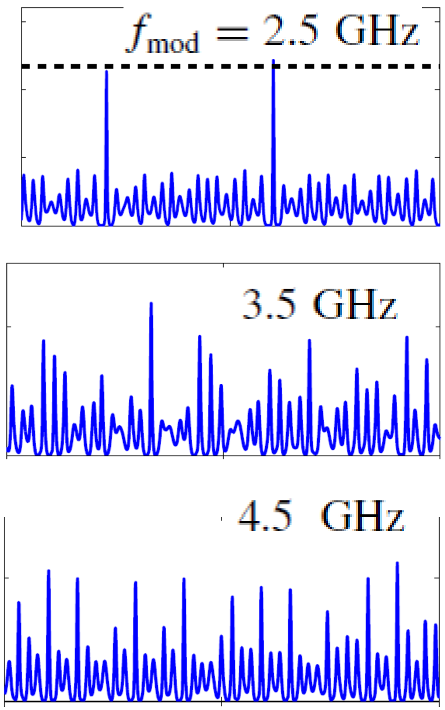
β_{sp}=0.01

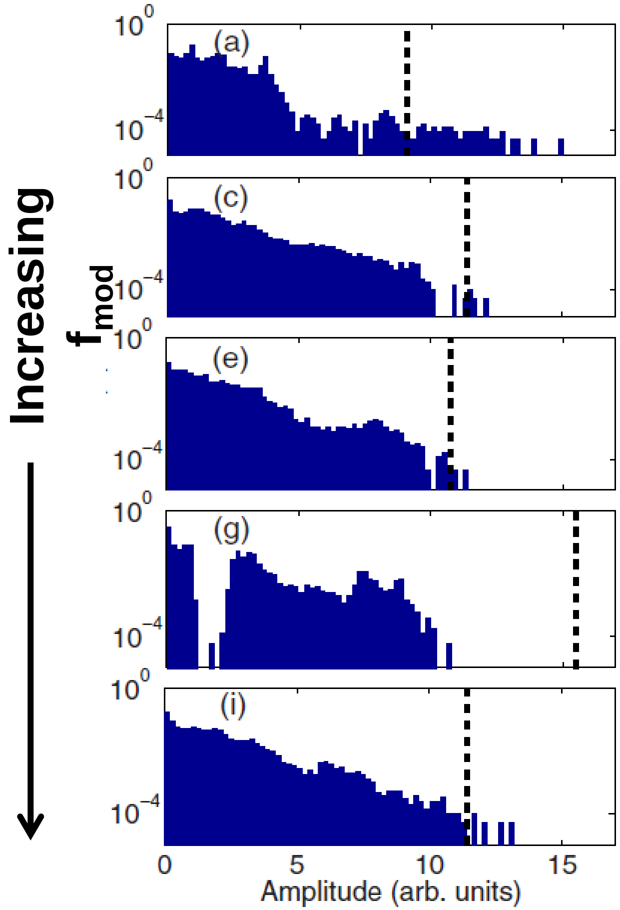


White = No RWs

"safe parameter region" also in point B, also robust to noise

Modulation suppressed RWs





Analogy: avalanche risk

Triggering controlled small avalanches avoids a large and dangerous avalanche.

When RWs are not suppressed: role of the modulation phase

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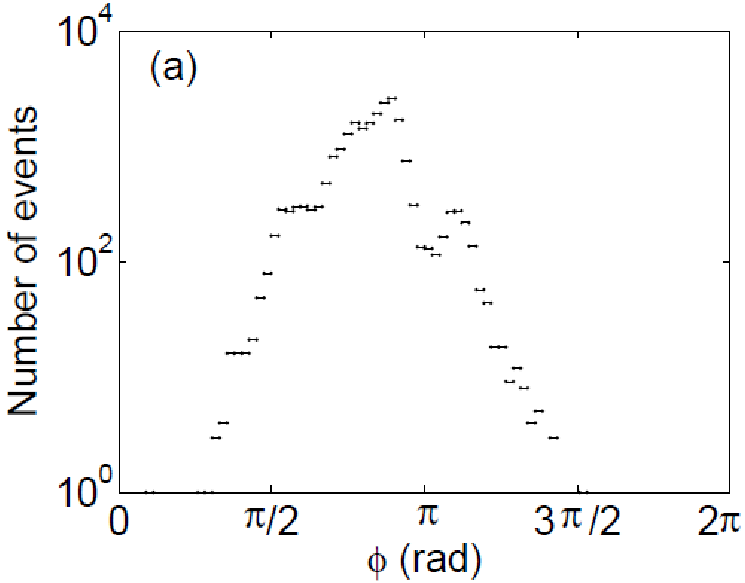
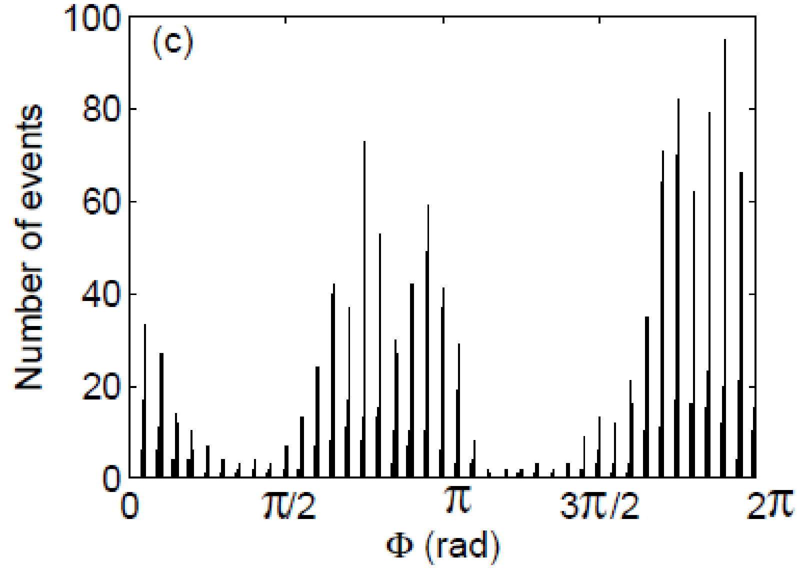
Slow modulation



Fast modulation



RWs occur during the first ¾ of the modulation cycle.

J. Ahuja et al, Optics Express 22, 28377 (2014)

Summary part II

- **RW Control**: noise and modulation strongly affect the likelihood of RWs.
- **RW Predictability**:
  - RWs can be predicted with some anticipation.
  - with modulation, they occur at certain values of the modulation phase.

Papers @ **www.fisica.edu.uy/~cris**

- C. Bonatto et al, PRL 107, 053901 (2011).
- J. Zamora-Munt et al, PRA 87, 035802 (2013).
- S. Perrone et al, Phys. Rev. A 89, 033804 (2014).
- J. Ahuja et al, Optics Express 22, 28377 (2014).

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