Investigating complex dynamics in laser systems: a symbolic data analysis perspective

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Workshop on
Nonlinear Dynamics in Semiconductor Lasers
WIAS Berlin, June 2016

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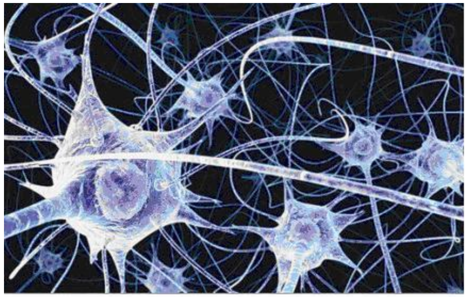
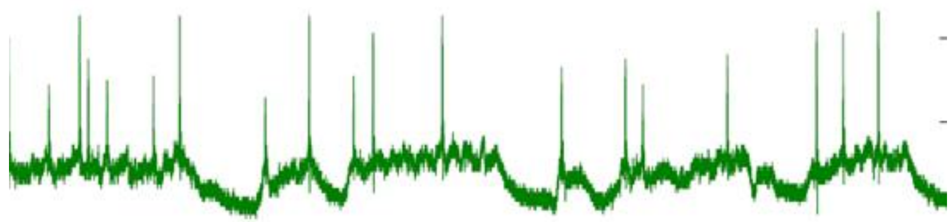
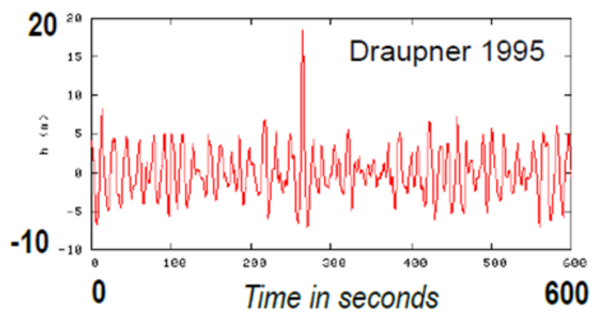
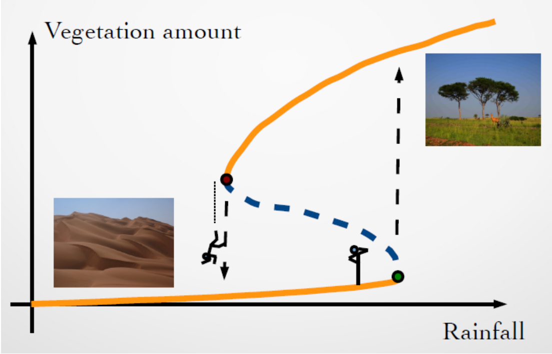
Nonlinear phenomena in complex systems







Elevation of the sea surface (in meters)

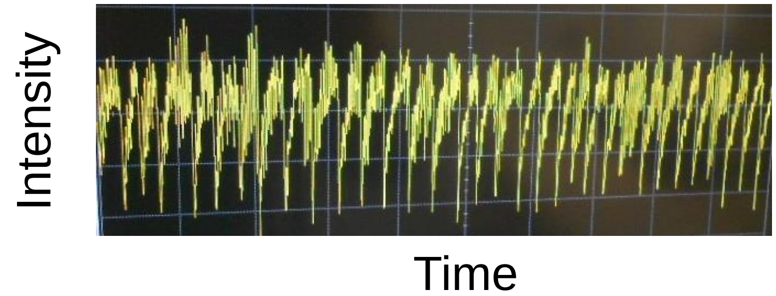


Bangladesh, Nature 2014

Semiconductor lasers provide an opportunity to study similar phenomena

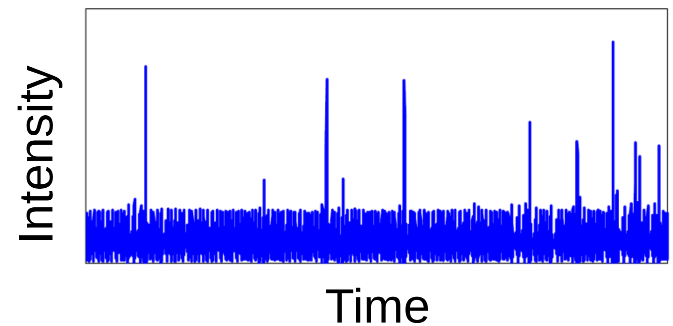
- Low frequency fluctuations –LFFs (optical spikes)

  induced by optical feedback



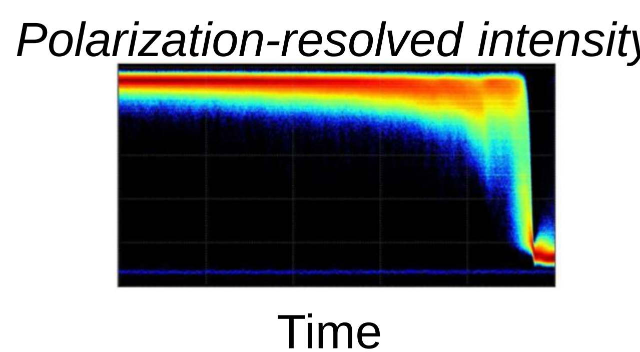
- Extreme pulses (optical rogue waves –RWs)

  induced by optical injection



- VCSEL polarization switching

  induced by noise and/or by the variation of a control parameter –typically the pump current



Outline

- Extreme intensity pulses (rogue waves)

- Characterization of regime transition
  - Symbolic method of time-series analysis
  - Applications
    - LFF noisy entrainment via weak modulation
    - Early indicators of VCSEL polarization switching
    - Quantifying the onset of LFF and Coherence Collapse regimes

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Physics Reports 416 (2005) 1–128

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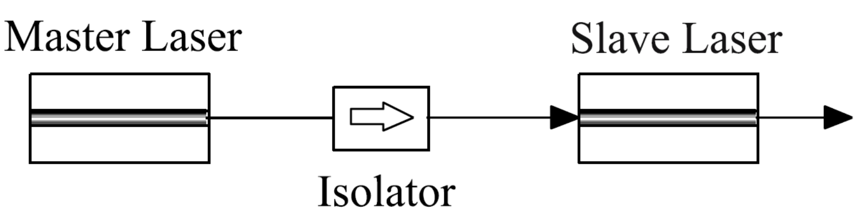
The dynamical complexity of optically injected semiconductor lasers

S. Wieczorek[a,*], B. Krauskopf[b,d], T.B. Simpson[c], D. Lenstra[d,e]

Dynamical regimes

- Injection locking (cw output)
- Periodic oscillations
- Excitable pulses
- Chaos



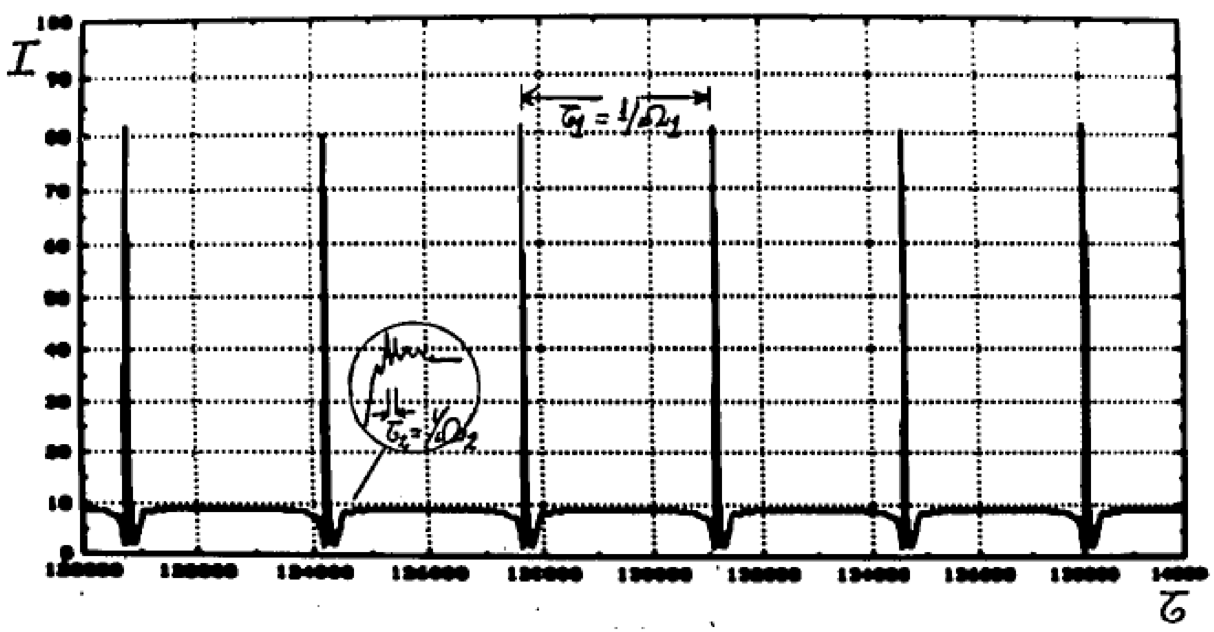
Also rogue waves?

Instabilities in lasers with an injected signal

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

Istituto Nazionale di Ottica, Largo E. Fermi 6, I50125 Firenze, Italy

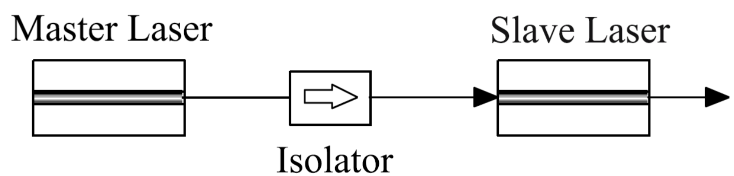
178 J. Opt. Soc. Am. B/Vol. 2, No. 1/January 1985



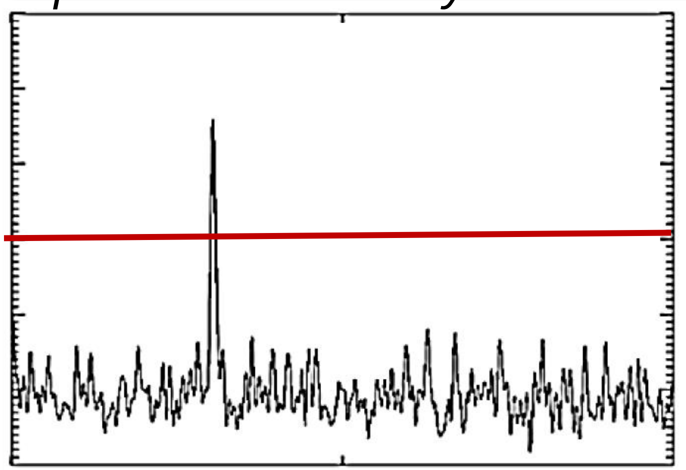
PRL **107,** 053901 (2011) PHYSICAL REVIEW LETTERS week ending 29 JULY 2011

Deterministic Optical Rogue Waves

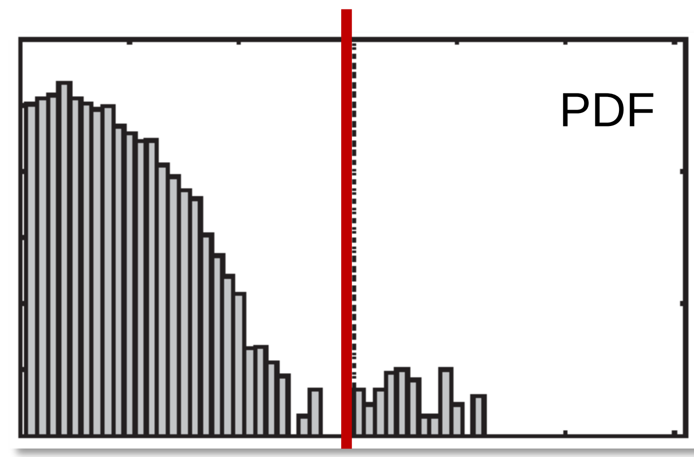
Cristian Bonatto,[1] Michael Feyereisen,[2] Stéphane Barland,[2] Massimo Giudici,[2] Cristina Masoller,[1]
José R. Rios Leite,[2,3] and Jorge R. Tredicce[2,3]



Experimental intensity time series



Time



ORW: pulse above

<A> + **6-8** σ

What we have learned

In our system optical rogue waves

- **can be deterministic**, generated by a crisis-like process (but they can also be induced by noise).
- **can be fully suppressed** via appropriate current modulation (but they can also be induced by modulation).
- have a certain degree of **predictability**.

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).

CW optically injected laser: governing equations

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

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

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

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

Spatial & multimode effects are not taken into account.

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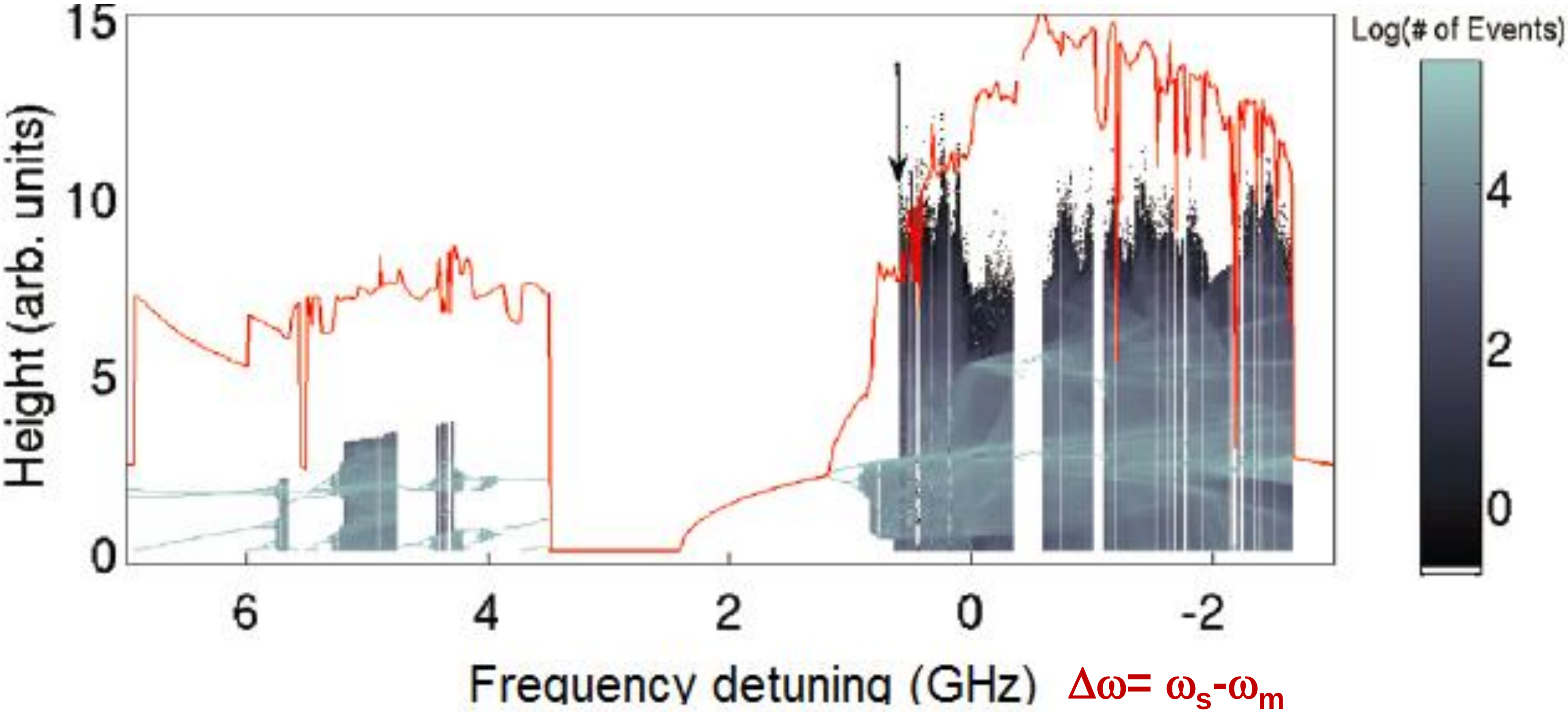
With optical feedback: Lang-Kobayashi (LK) model

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

$$\frac{dE}{dt} = \frac{1}{2\tau_p}(1+i\alpha)(N-1)E + \underbrace{\eta E(t-\tau)e^{-i\omega_0\tau}}_{\substack{\text{optical feedback} \\ \eta\text{: feedback strength} \\ \tau\text{: delay time}}} + \underbrace{\sqrt{2\beta_{sp}/\tau_N}\,\xi(t)}_{\substack{\text{spontaneous} \\ \text{emission} \\ \text{noise}}}$$

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

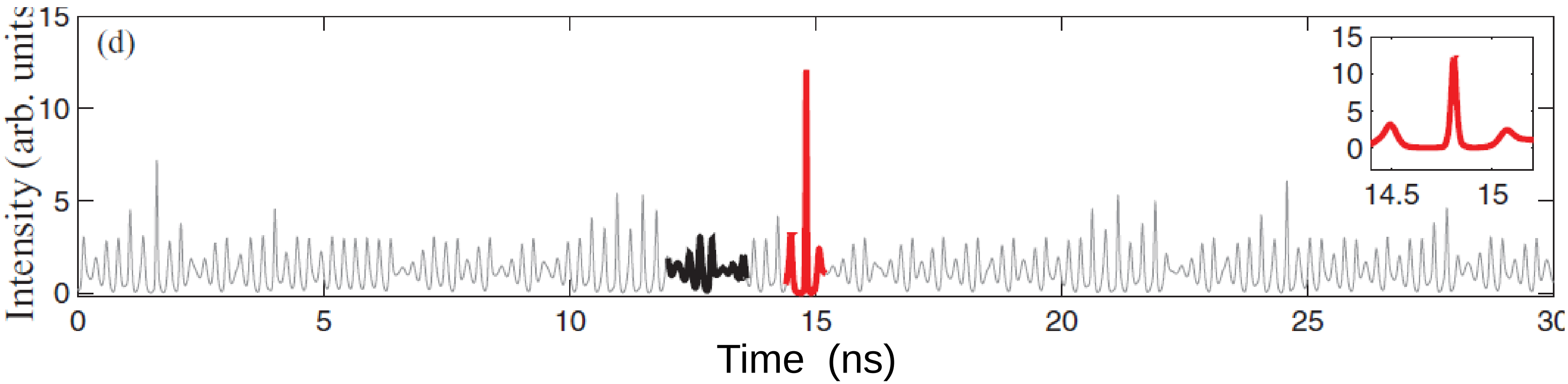
Optically injected laser: bifurcation diagram

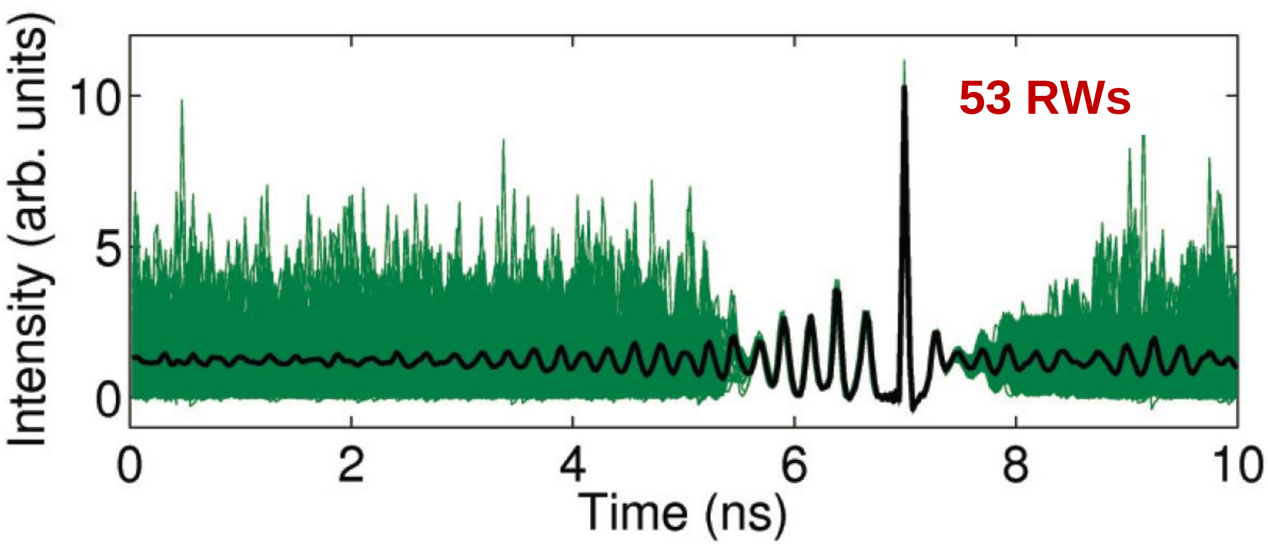


$\Delta\omega = \omega_s - \omega_m$

Threshold: <H> + 8σ

Deterministic simulations (β_{sp}=0)

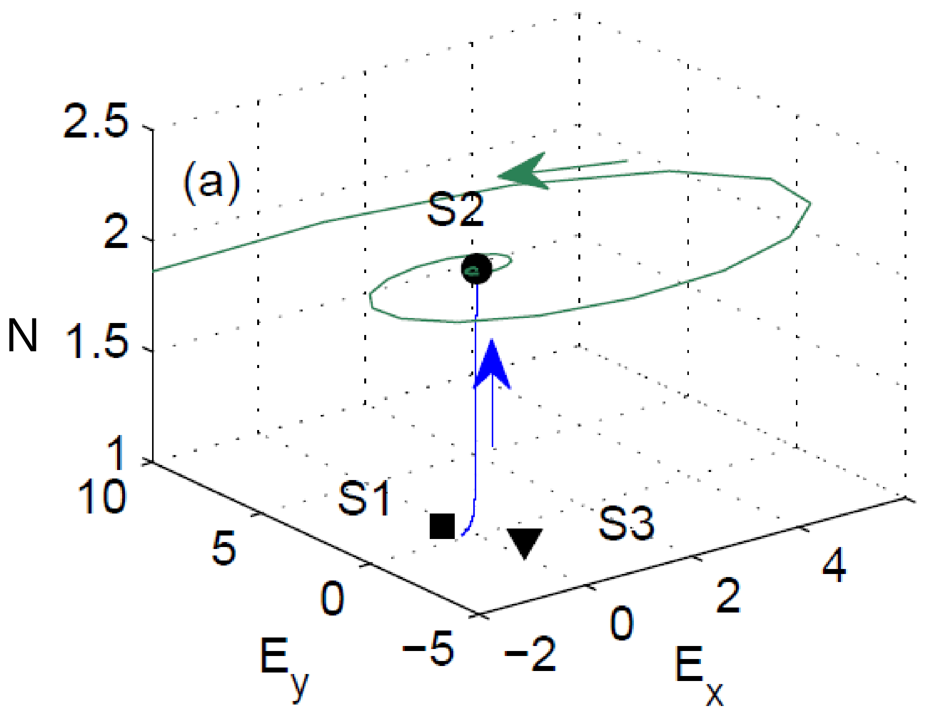


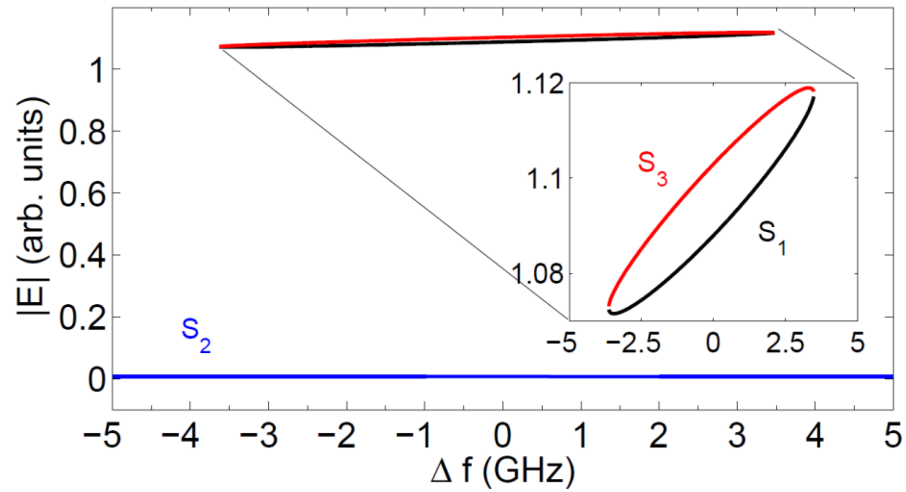


J. Zamora-Munt et al, PRA 87, 035802 (2013)

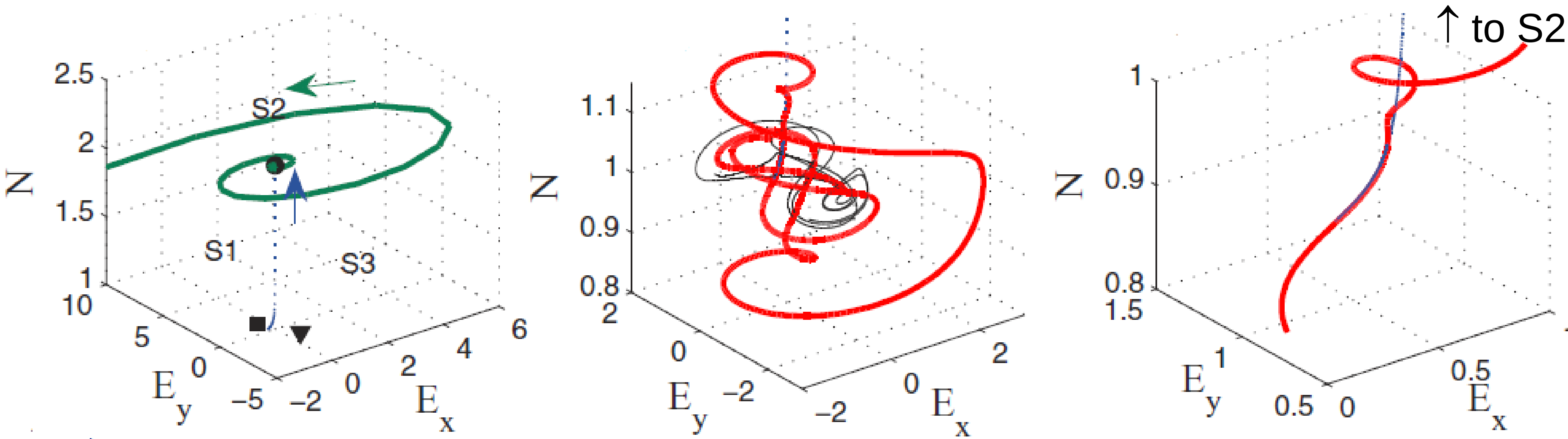
What triggers a RW?

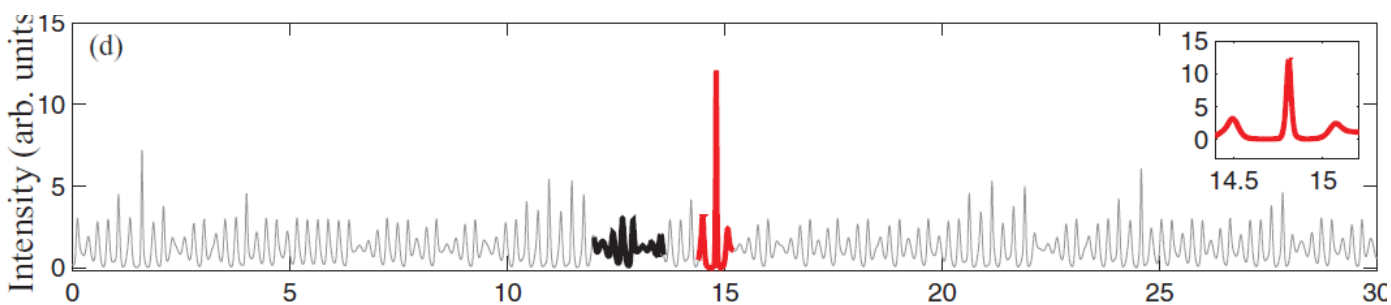
Three fixed points in the phase space





Plot of the trajectory during an extreme pulse

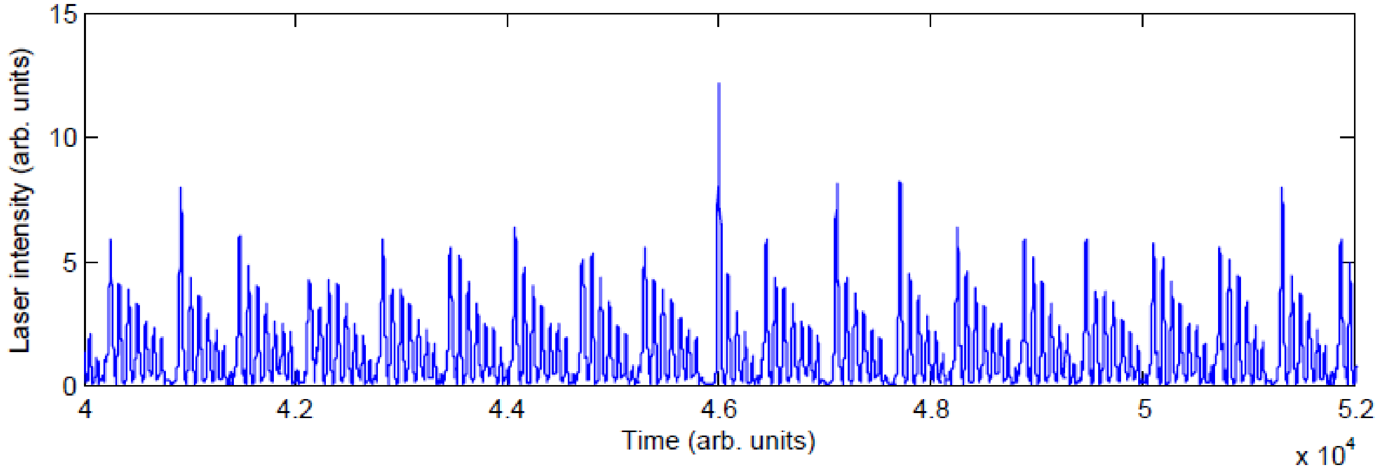


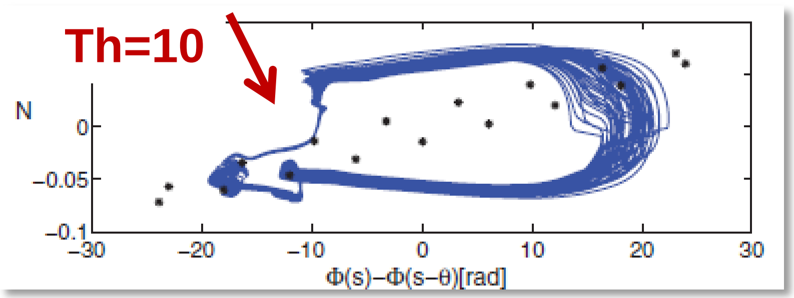


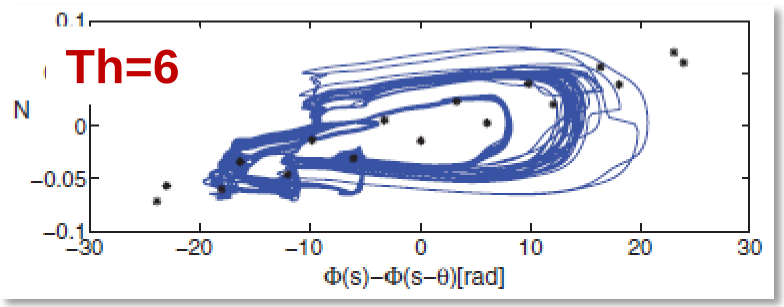
A RW is triggered whenever the trajectory closely approaches the stable manifold of S2 (the “RW door”)

With optical feedback (LK model simulations)

A similar mechanism generates extreme pulses







Superposition of 50 pulses

J. A. Reinoso et al, PRE 87, 062913 (2013)

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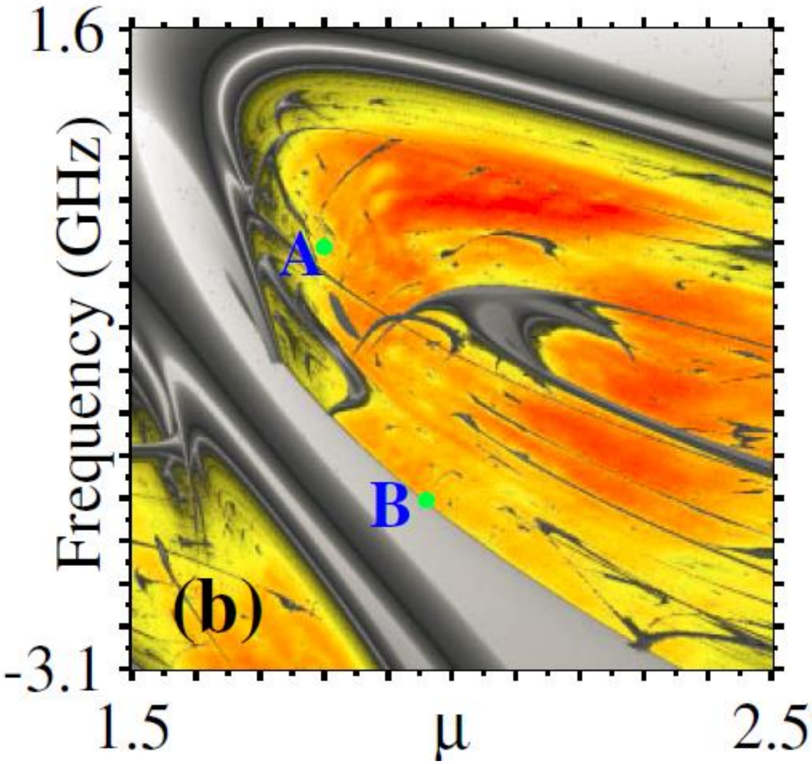
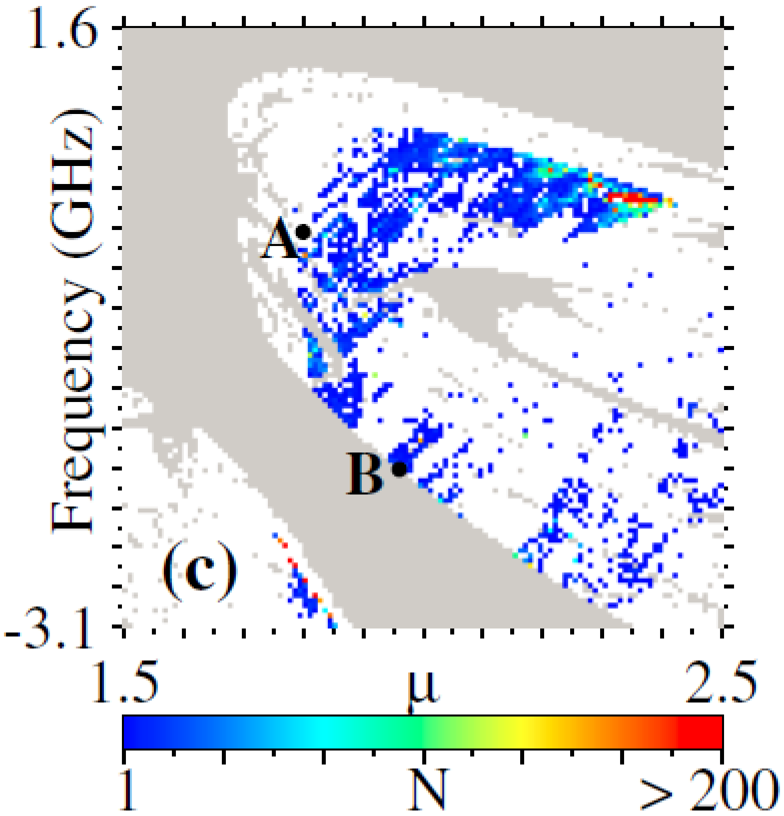
Back to optically injected laser: the Lyapunov exponent and the number of RWs

Lyapunov exponent

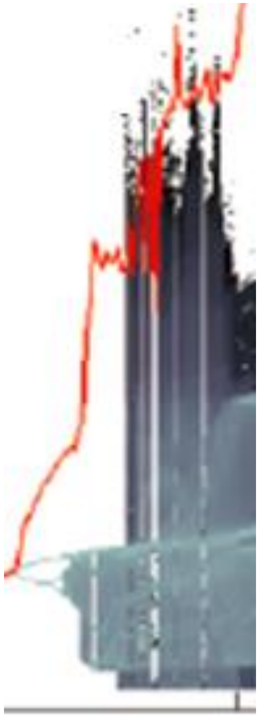


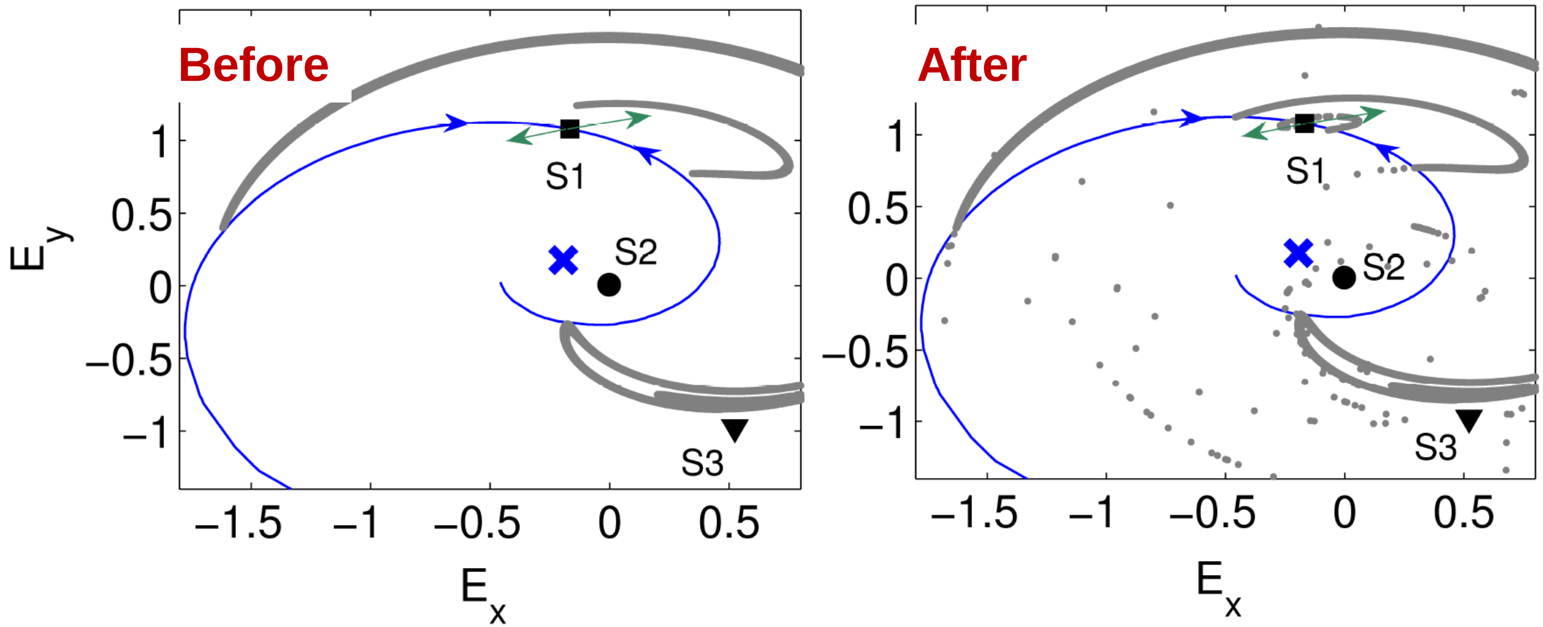
Number of rogue waves (10 μs)



Why chaos with RWs and chaos without them?

Poincare map and projections of the three fixed points

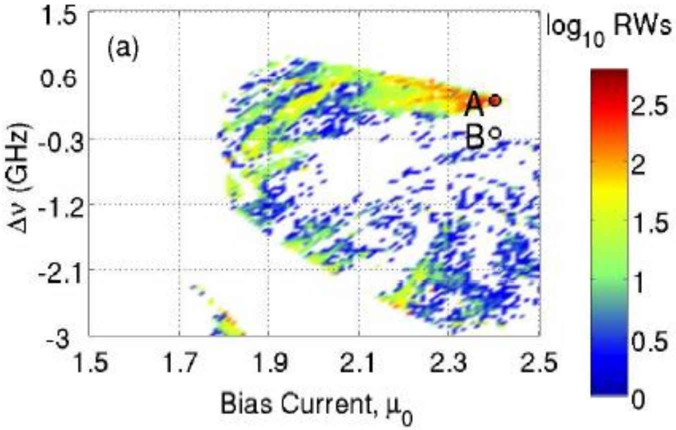




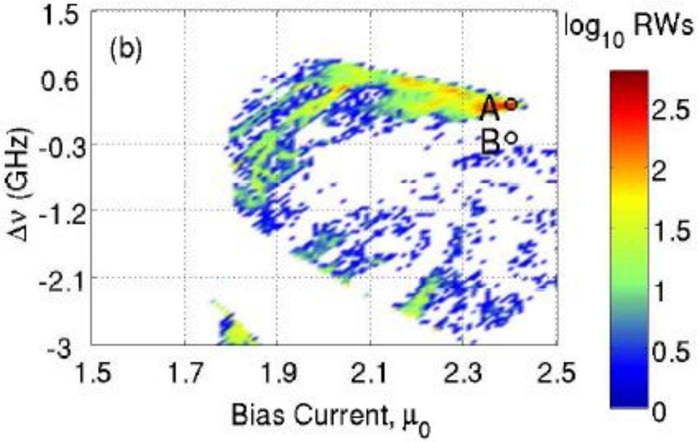
An **external crises-like** process enables access to the region of phase space where the **stable manifold of S2 (x)** is.

Impact of noise

Deterministic RWs (β_{sp}=0)

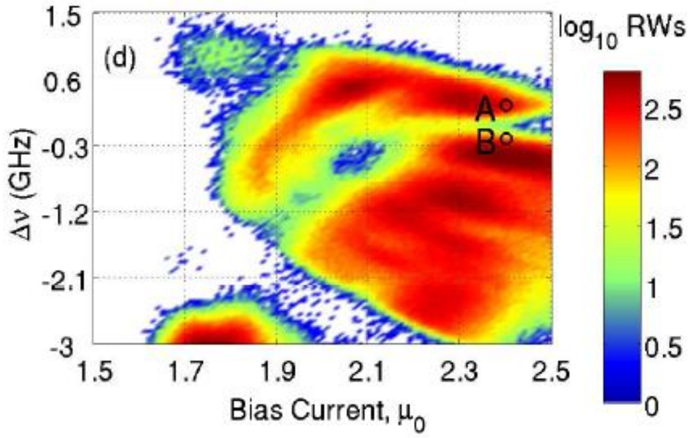


Weak noise (β_{sp}=0.0001)



White = No RWs

Stronger noise (β_{sp}=0.01)



Strong noise can induce RWs

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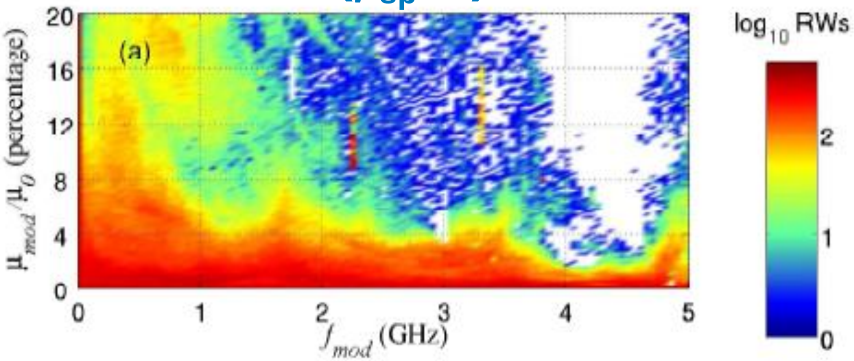
Role of current modulation in Point A (deterministic RWs)

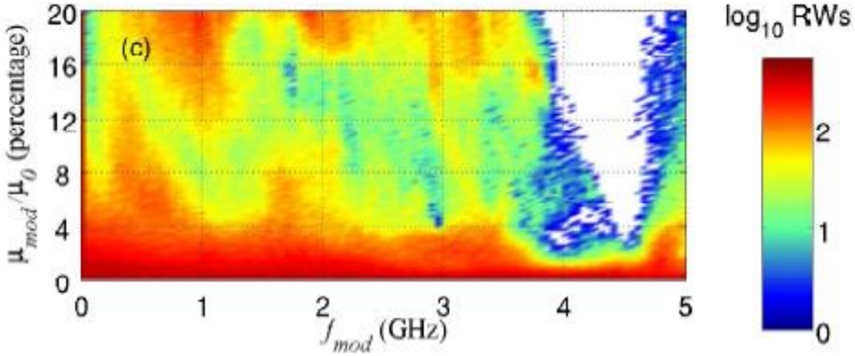
$$\boxed{\mu = \mu_0 + \mu_{\text{mod}} \sin(2\pi\ f_{\text{mod}}\ t)}$$

No noise (β_{sp}=0)



White = No RWs

Stochastic simulations (β_{sp}=0.01)



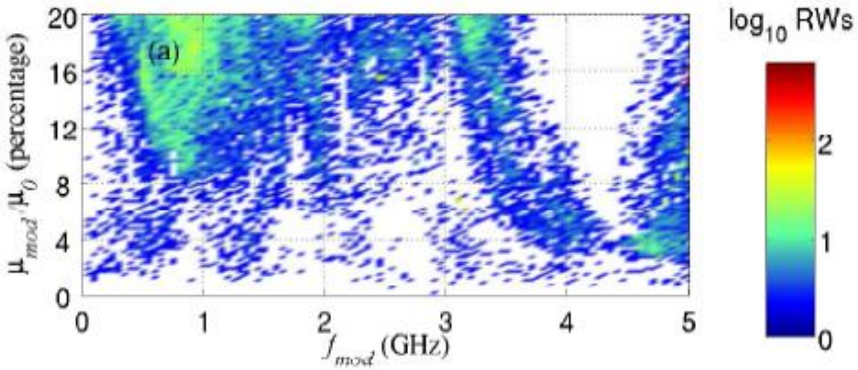
White = No RWs

- Current modulation with appropriated amplitude and frequency can fully suppress the RWs.
- "safe parameter region" is robust to the presence of noise.

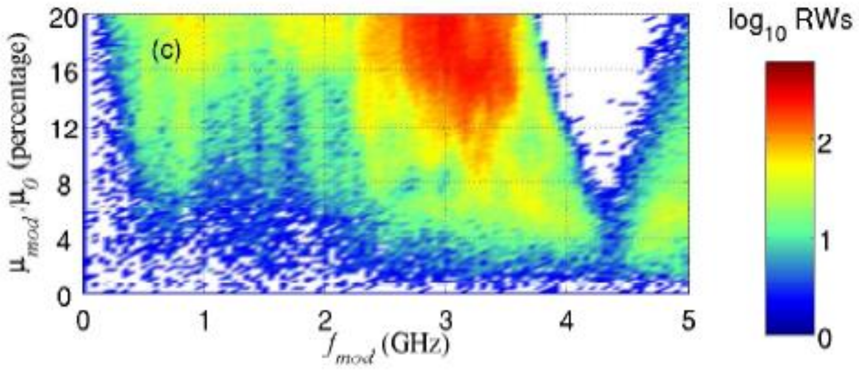
S. Perrone, J. Zamora Munt, R. Vilaseca and C. Masoller, PRA 89, 033804 (2014)

Role of current modulation in Point B (no deterministic RWs)

β_{sp}=0



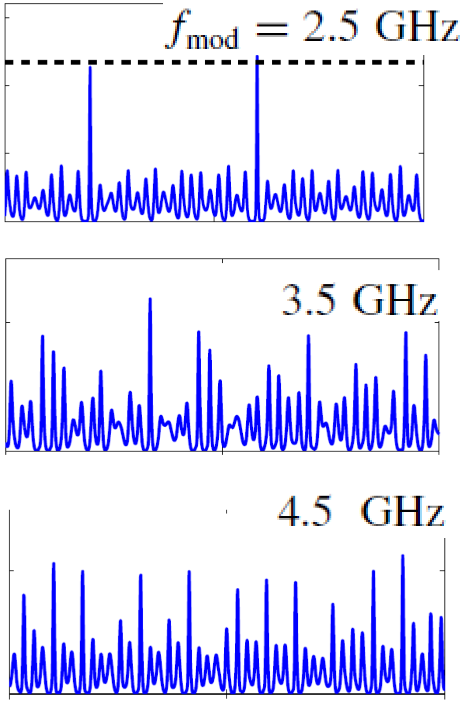
β_{sp}=0.01



White = No RWs

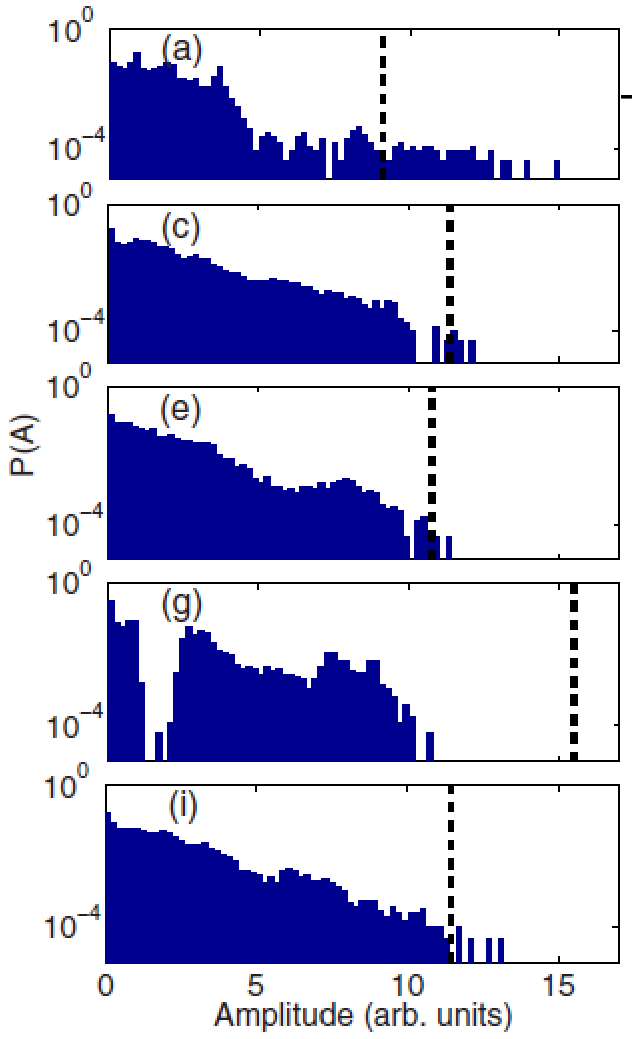
- Current modulation can induce RWs
- "safe parameter region" is also robust to noise

Why RWs are suppressed?



Increasing mod. freq.

Histograms of pulse amplitudes



Threshold = <A> + **6** σ

High pulses are not rare.

Characterizing regime transitions

- Symbolic ordinal analysis
- LFF entrainment
- Early indicators of polarization switching
- Noise-LFFs-CC transition

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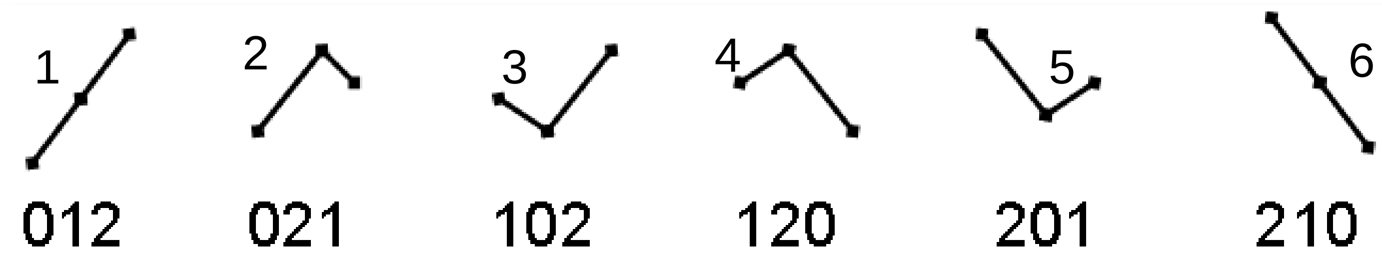
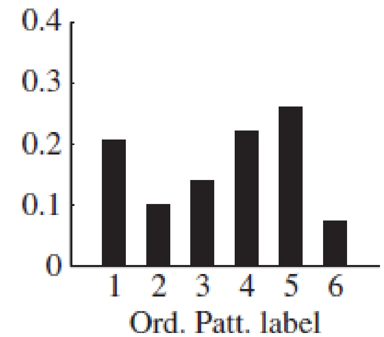
Method of symbolic time-series analysis: ordinal patterns

- $X = \{\ldots x_i, x_{i+1}, x_{i+2}, \ldots\}$

Brandt & Pompe, PRL 88, 174102 (2002)





Random data $\Rightarrow$ OPs are equally probable

The OP probabilities allow to identify frequent patterns in the *ordering* of the data points

– Advantage: the probabilities uncover temporal correlations.

– Drawback: we lose information about the actual values.

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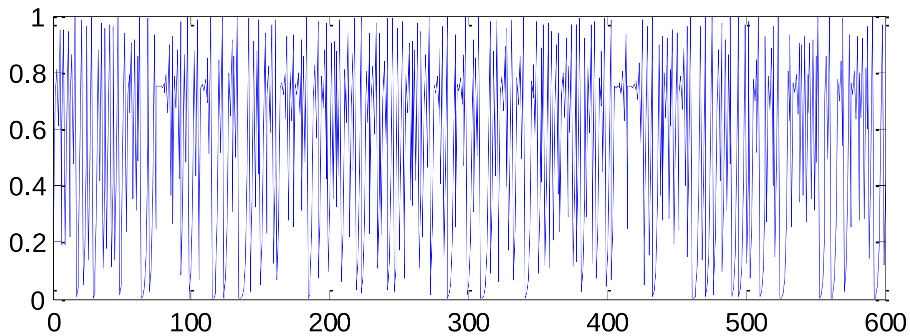
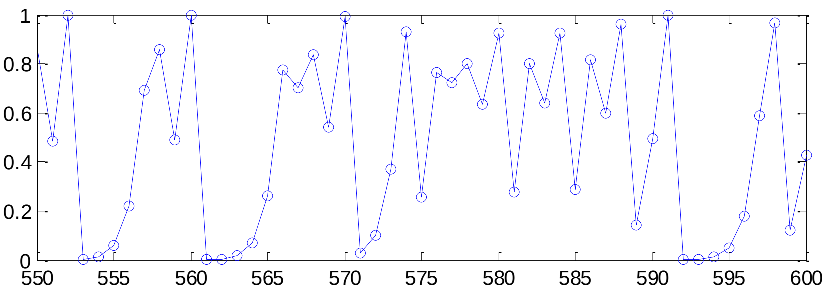
To fix ideas: the logistic map $x(i+1)=4x(i)[1-x(i)]$

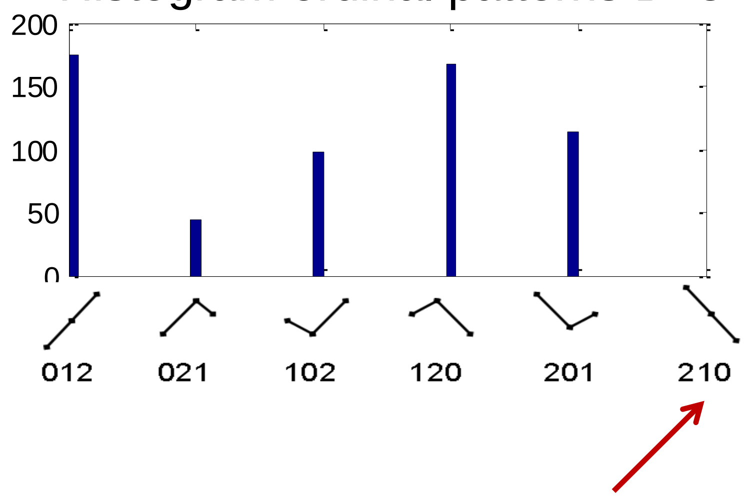
Time series



Detail

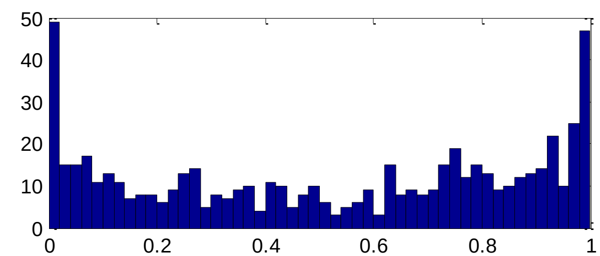


Histogram ordinal patterns D=3



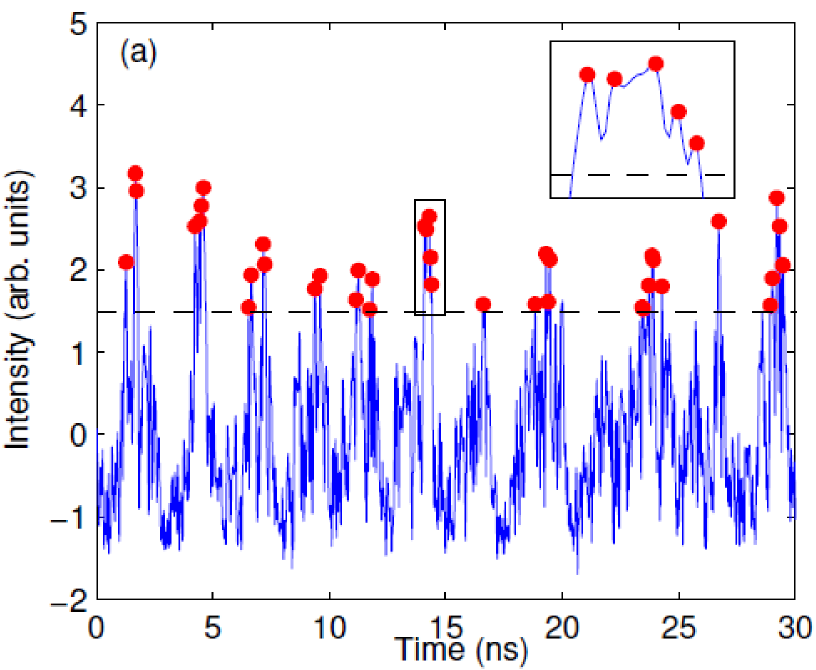
Forbidden pattern

Histogram x(i)

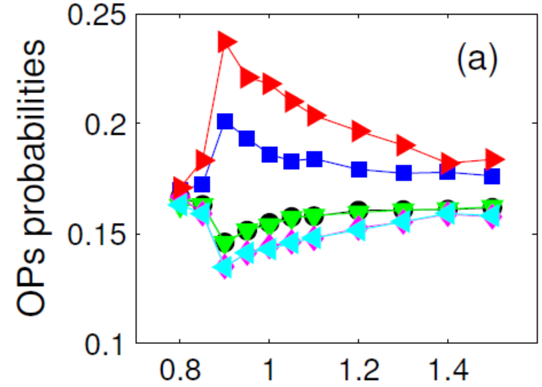


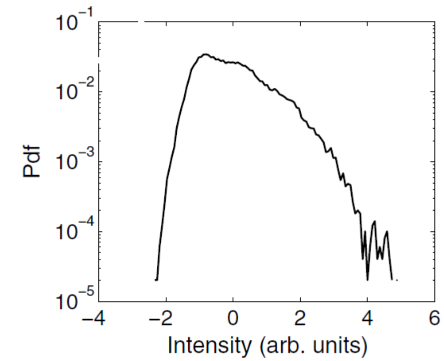
- Ordinal analysis provides complementary information.
- Useful for model verification, parameter estimation, classification, etc.

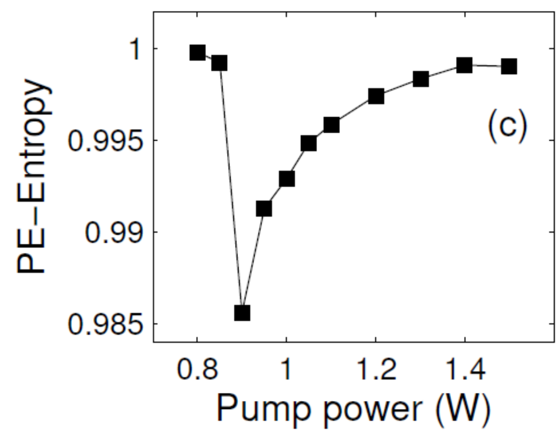
Application to the laminar – turbulent transition in a fiber laser

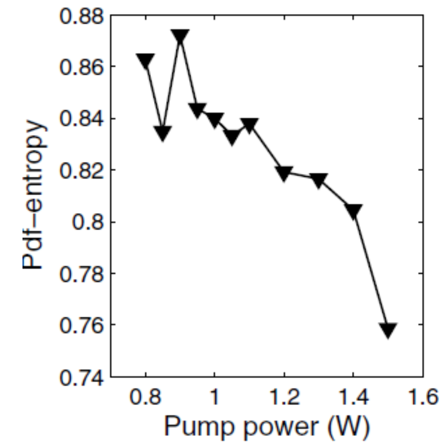


$$s_p = -\sum_{i=1}^{M} p_i \log p_i$$





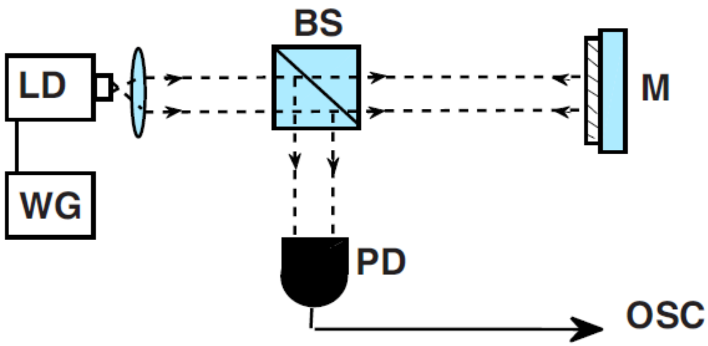




A. Aragoneses et al, PRL 116, 033902 (2016)

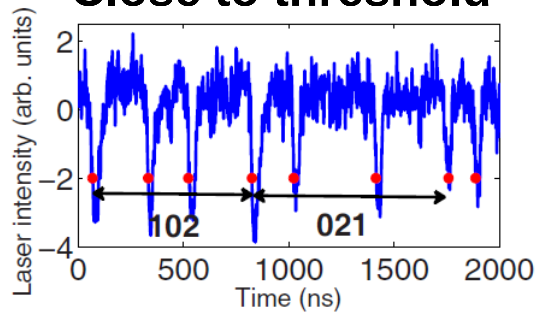
E. G. Turitsyna et al, "*The laminar–turbulent transition in a fibre laser*", Nat. Phot. 7, 783 (2013)

First example of application to semiconductor laser nonlinear dynamics: ordinal analysis of LFFs

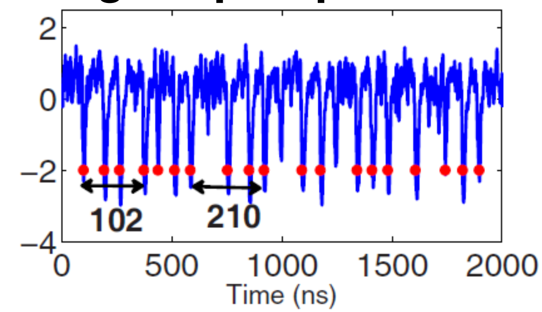


Low-pass filtered intensity

Close to threshold



Higher pump current

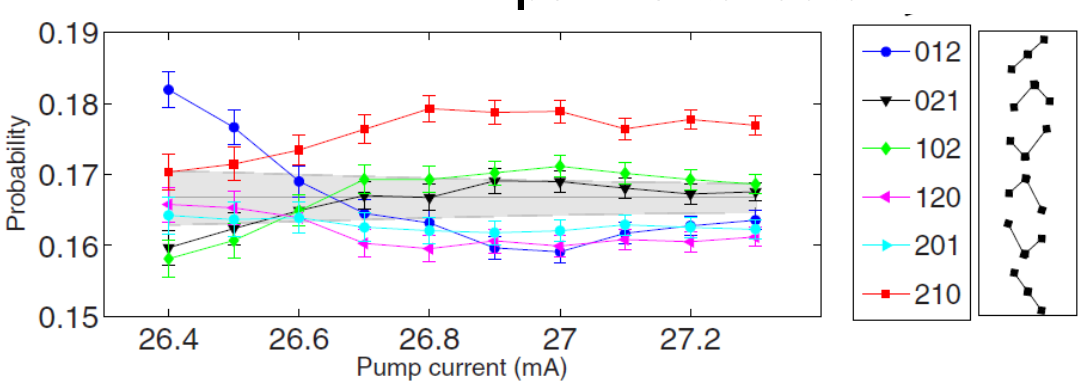


We consider the time-intervals between consecutive dropouts.

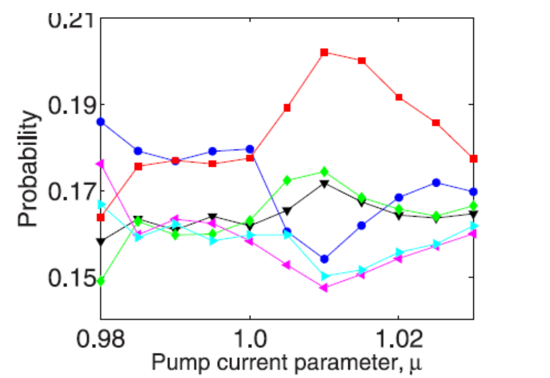
10: $\Delta T_i > \Delta T_{i+1}$

01: $\Delta T_i < \Delta T_{i+1}$

Experimental data



LK model simulations



A. Aragoneses, S. Perrone, T. Sorrentino, M. C. Torrent and C. Masoller, Sci. Rep. **4**, 4696 (2014).

With weak current modulation ordinal probabilities allow identifying regions of noisy locking

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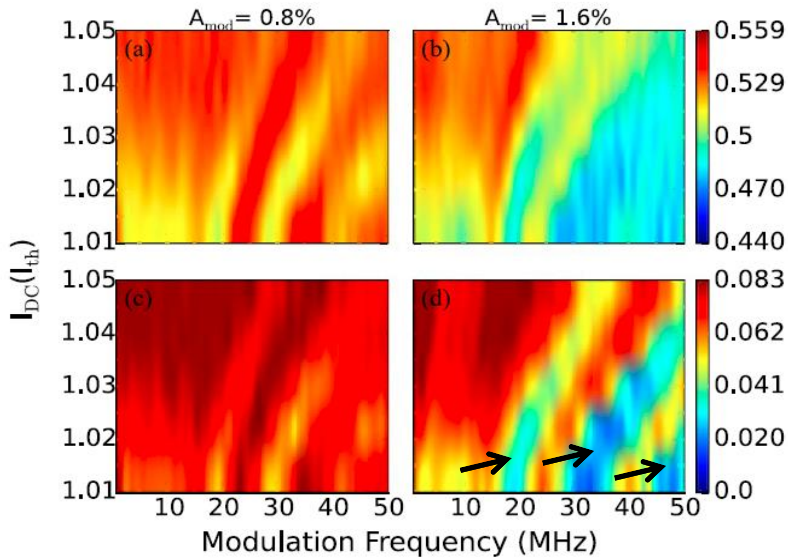
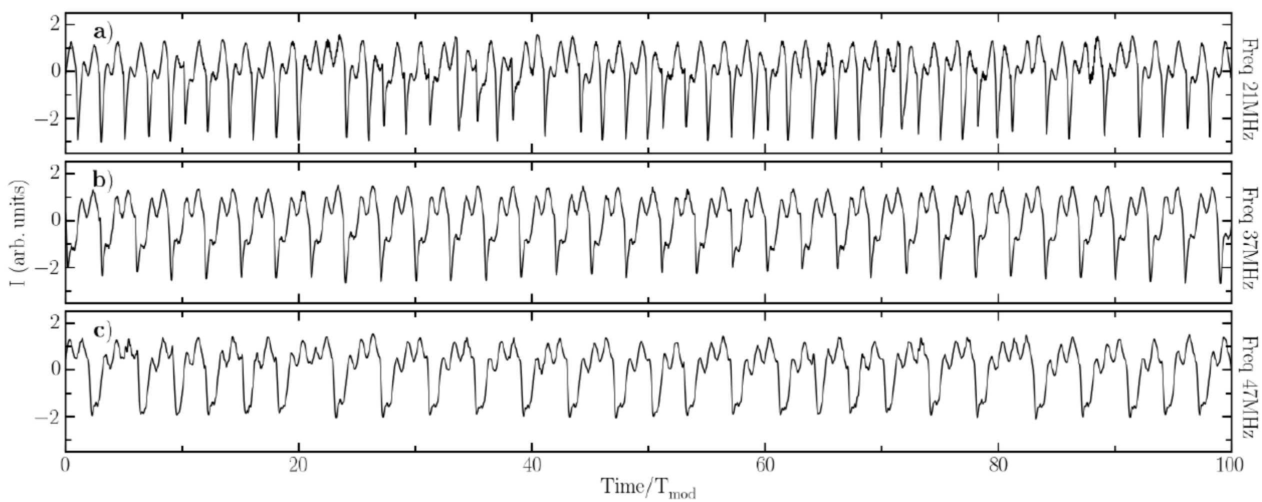


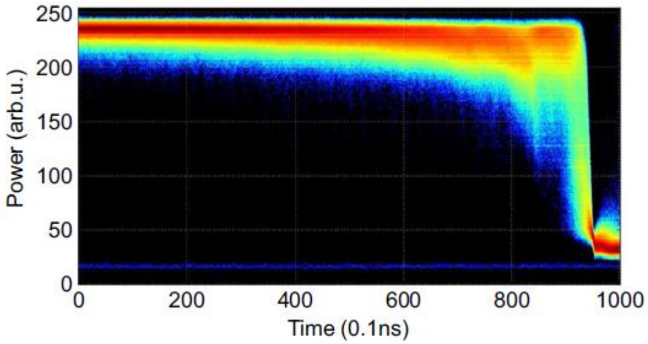
P(10)

P(3210)

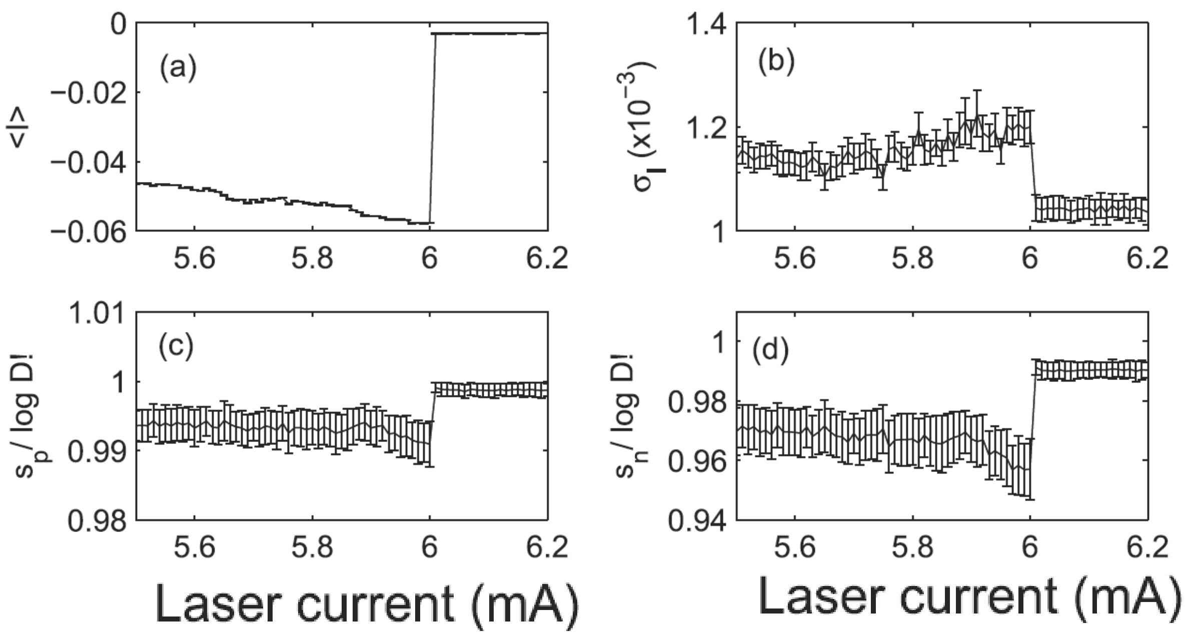


T. Sorrentino et al, IEEE JSTQE 21, 1801107 (2015).

Second example: inferring early indicators of an abrupt transition



VCSEL polarization-resolved intensity when the pump current is linearly increased.



$$s_p = -\sum_{i=1}^{M} p_i \log p_i$$

Entropy computed from pattern probabilities and also from transition probabilities ('012'→ '012', etc.).

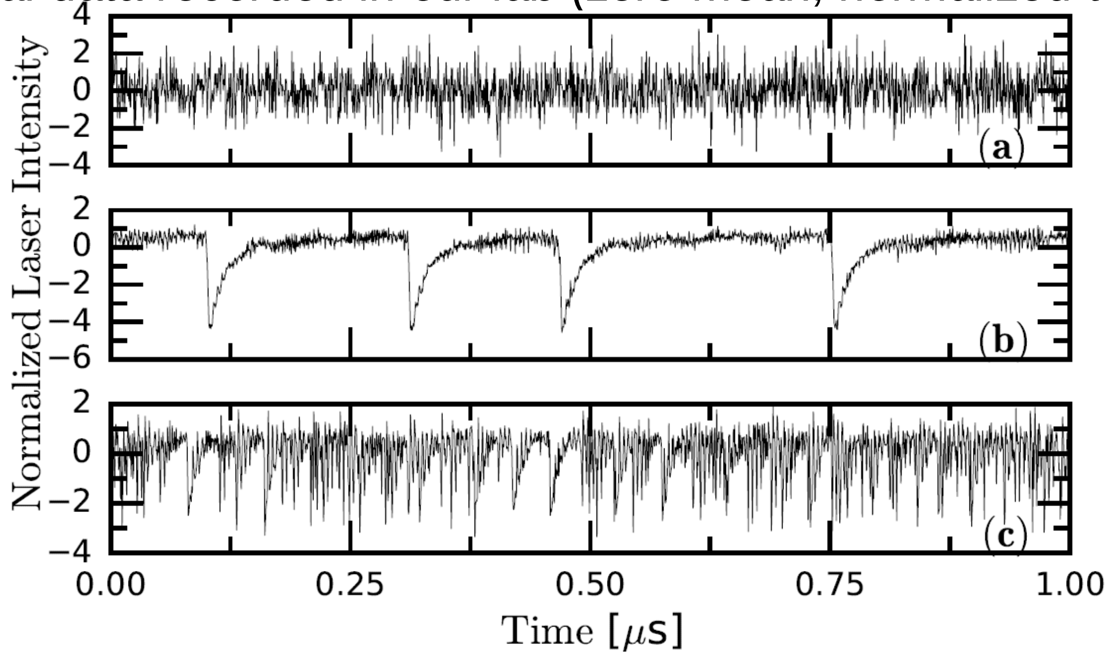
C. Masoller et al, New J. Phys. 17 (2015) 023068

Third example: Noise-LFFs-CC transition

The low-frequency fluctuations (LFFs) and the coherence collapse (CC) regimes induced by optical feedback have been intensively studied in the last three decades.

Experimental data recorded in our lab (zero mean, normalized to σ=1)

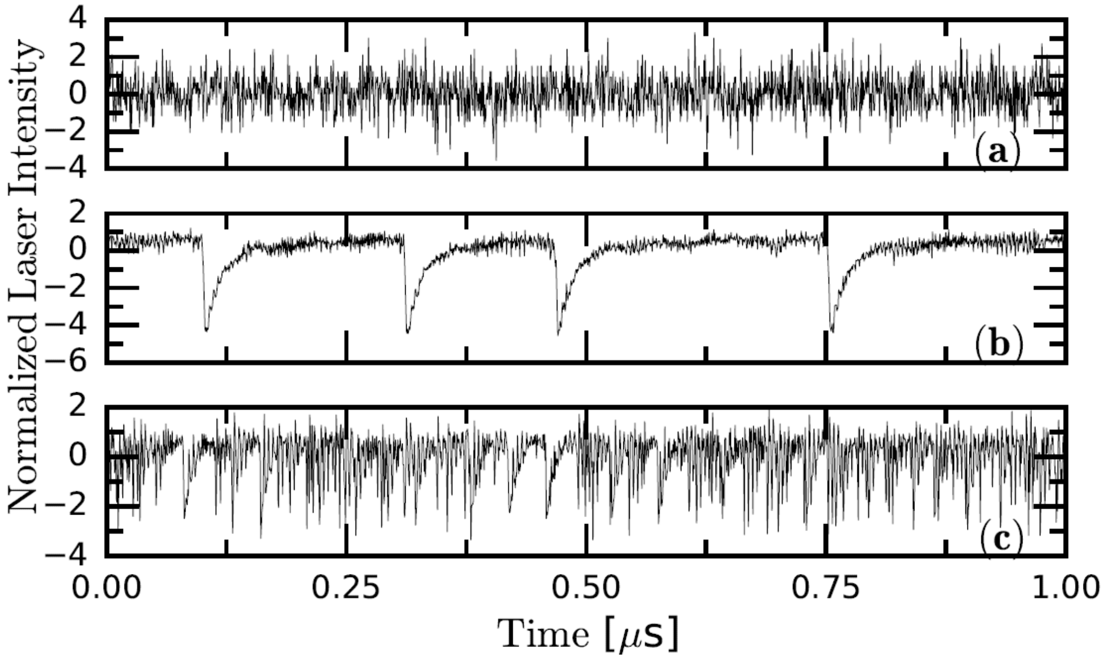
Increasing pump current



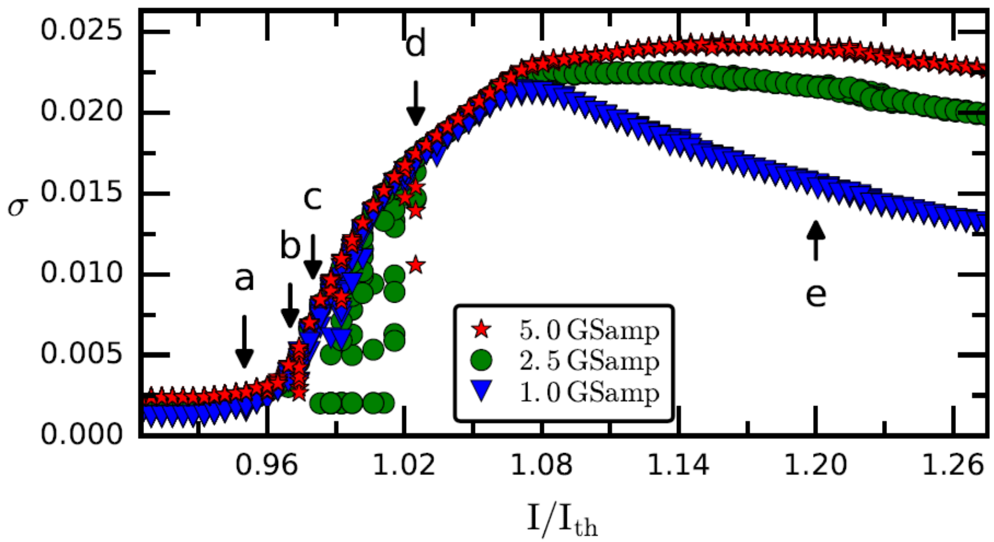
D. Lenstra, B. Verbeek and A. Den Boef, IEEE J. Quantum Electron. 21, 674 (1985)

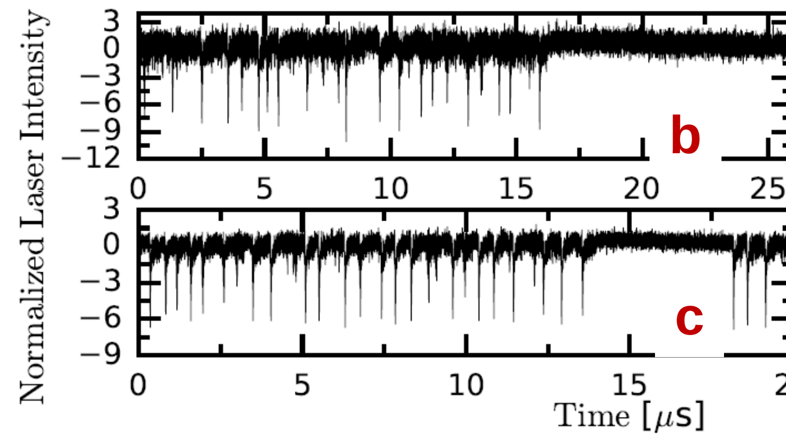
- Can we quantitatively identify the onset of LFFs and CC regimes?

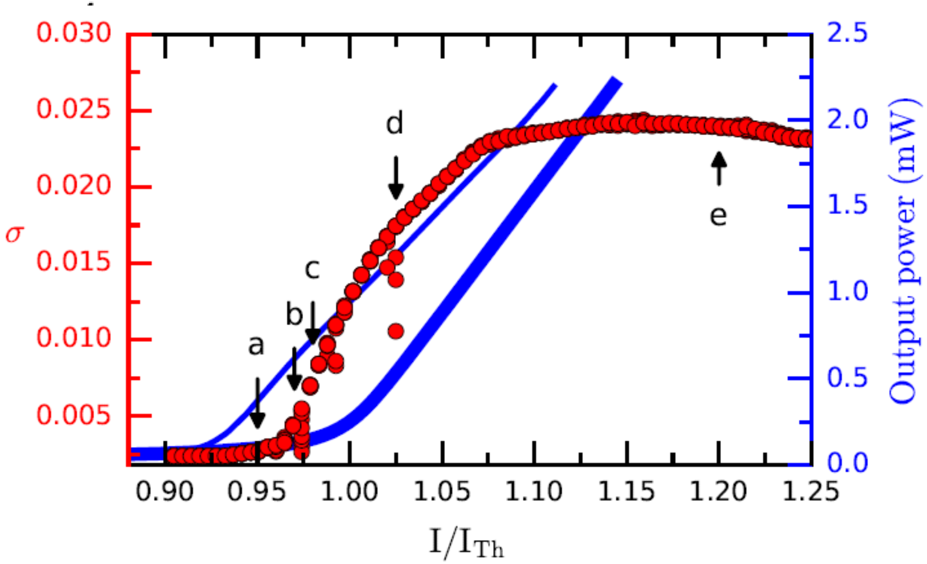
- Can we quantify their different properties?

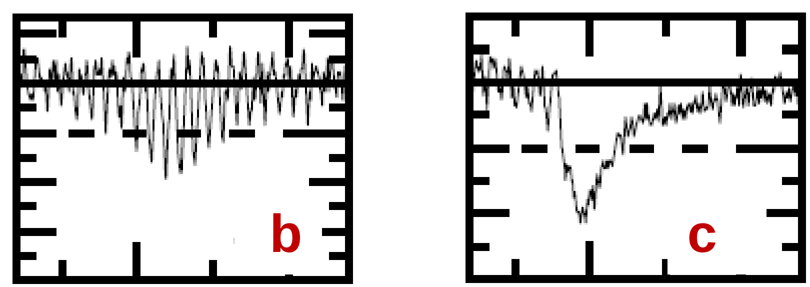


LFF slow-fast dynamics: intensity PDF depends on the oscilloscope sampling time



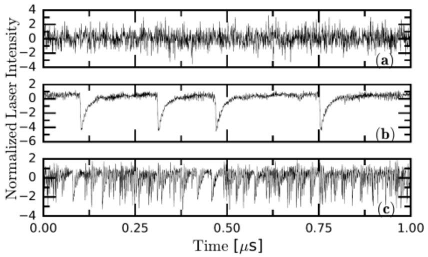


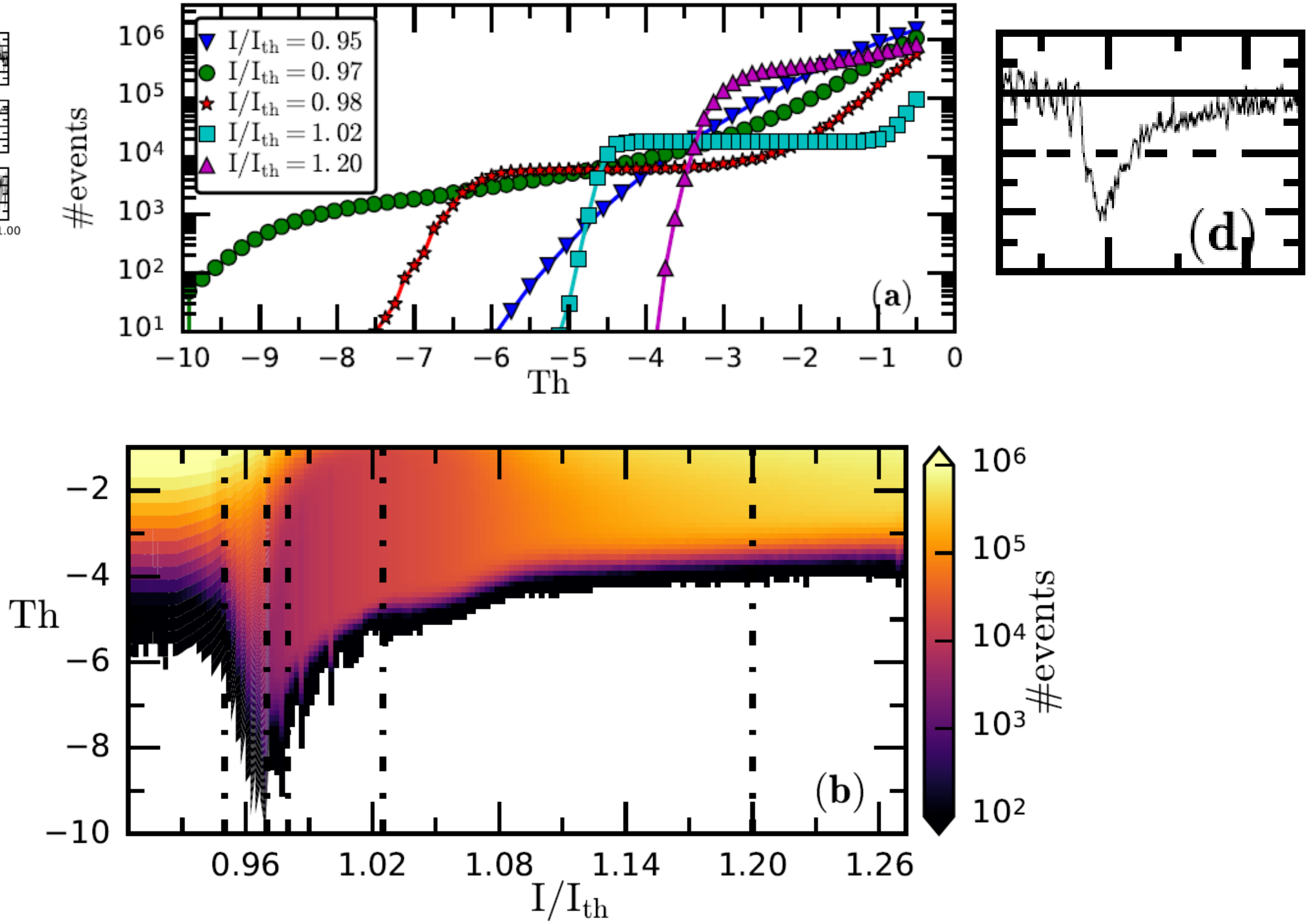




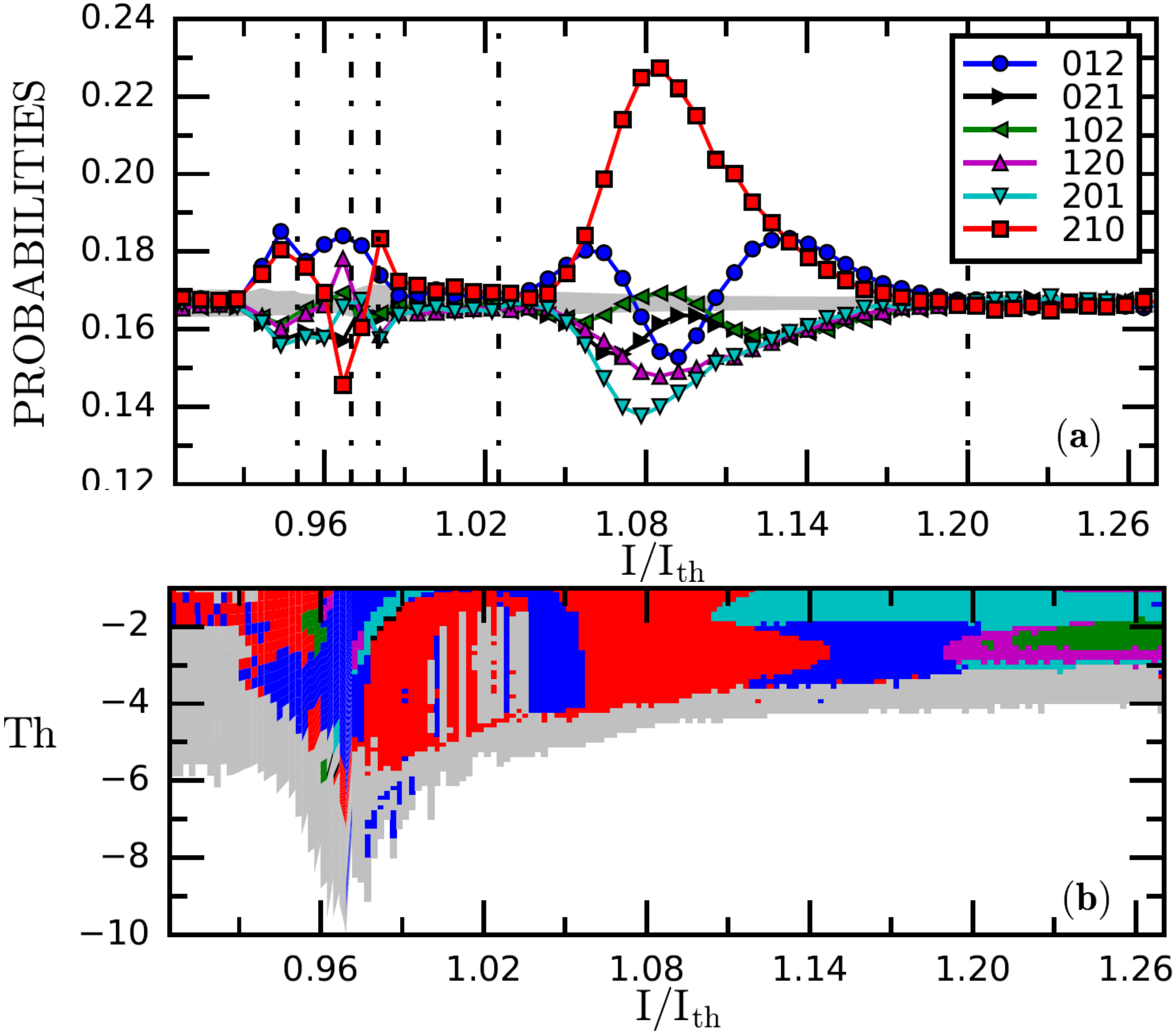
C. Quintero-Quiroz et al, submitted (2016)

Number of threshold-crossing events

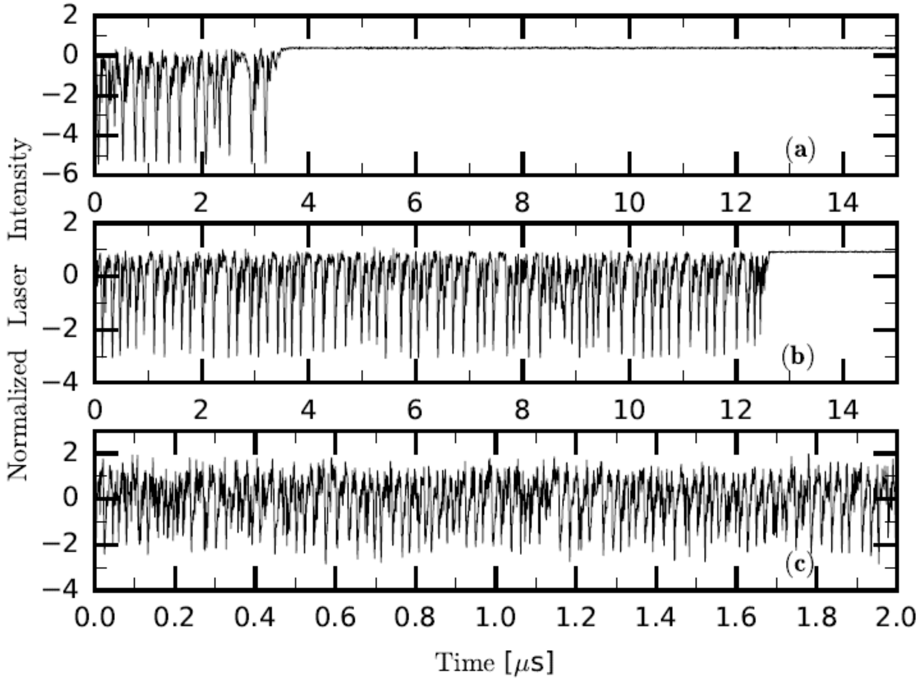


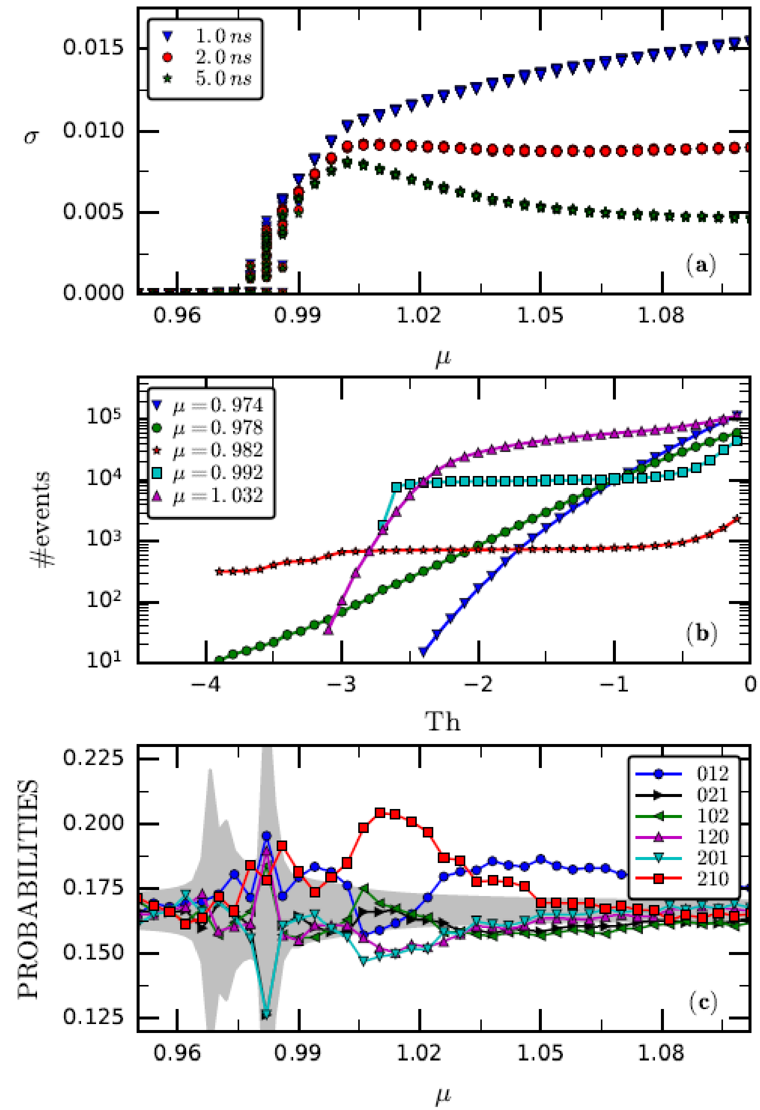


Ordinal probabilities



LK model simulations





Good *qualitative* agreement with experimental observations

Conclusions

- Take home message:
  - Semiconductor lasers with optical feedback / injection provide "big data" for testing novel analysis tools.
  - Nonlinear tools capture patterns and new features in the data.

- A few specific conclusions:
  - RWs are generated when the trajectory closely approaches a narrow channel ("RW door"); a crises-like mechanism allows access to the phase space region where the "RW door" is.
  - VCSEL PS: opportunity to test novel early warning indicators of abrupt transitions.
  - LFFs with weak current modulation: OP probabilities detect noisy locking.
  - Noisy-LFF-CC transition: quantitative identification of the onset of each regime.

Collaborators

UPC

- Nuria Martinez, Jordi Roma
- Carlos Quintero-Quiroz
- Andres Aragoneses, Taciano Sorrentino
- Jordi Tiana
- Carme Torrent

VCSEL experimental data from:

- S. Barland and M. Giudici (INLN, Nice, France)
- Y. Hong (Bangor University, UK)

Fiber laser experimental data from:

- S. Turitsyn (Aston University, UK)

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THANK YOU FOR YOUR ATTENTION !

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Papers at **http://www.fisica.edu.uy/~cris/**

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- J. A. Reinoso et al, PRE 87, 062913 (2013).
- 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).
- A. Aragoneses et al, Sci. Rep. 4, 4696 (2014).
- C. Masoller et al, New J. Phys. 17, 023068 (2015).
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- A. Aragoneses et al, PRL 116, 033902 (2016).
- C. Quintero-Quiroz et al, submitted (2016).

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