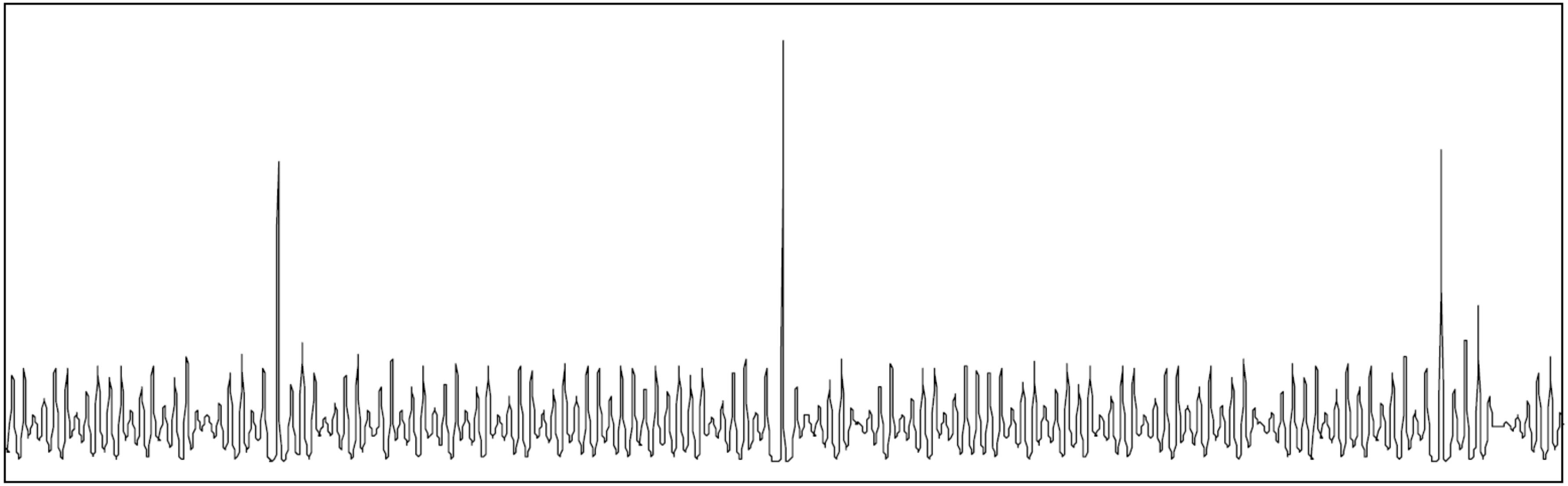


Investigating extreme pulses in laser systems with nonlinear analysis tools

Cristina Masoller

Cristina.masoller@upc.edu

www.fisica.edu.uy/~cris

UNIVERSITAT POLITÈCNICA DE CATALUNYA BARCELONATECH

Campus d'Excel·lència Internacional

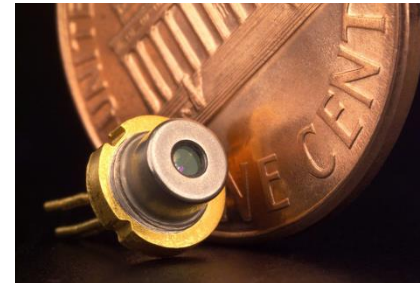
ICREA

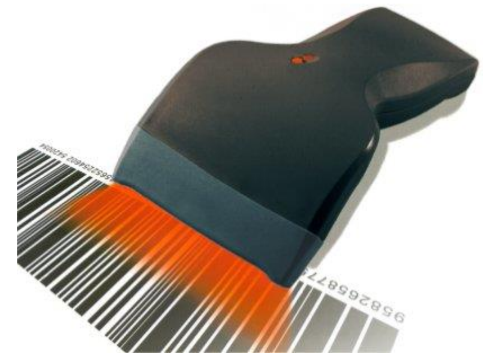
GOBIERNO DE ESPAÑA MINISTERIO DE CIENCIA E INNOVACIÓN

Workshop on Extreme Events and Rogue Waves, Bad Honnef, Germany, May 2016

Semiconductor lasers (diode lasers)

- Nowadays are widely used in:
  - Telecom & datacom
  - Optical data storage (CDs, DVDs, Blu rays)
  - Barcode scanners, printers, mouse
  - Biomedical applications (imaging, sensing, etc)





- They emit a very stable output… if they are not optically perturbed.

- Optically perturbed semiconductor lasers provide an inexpensive setup to study chaos and nonlinear dynamics.

Available online at www.sciencedirect.com

SCIENCE DIRECT®

ELSEVIER

PHYSICS REPORTS

Physics Reports 416 (2005) 1–128

www.elsevier.com/locate/physrep

The dynamical complexity of optically injected semiconductor lasers

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

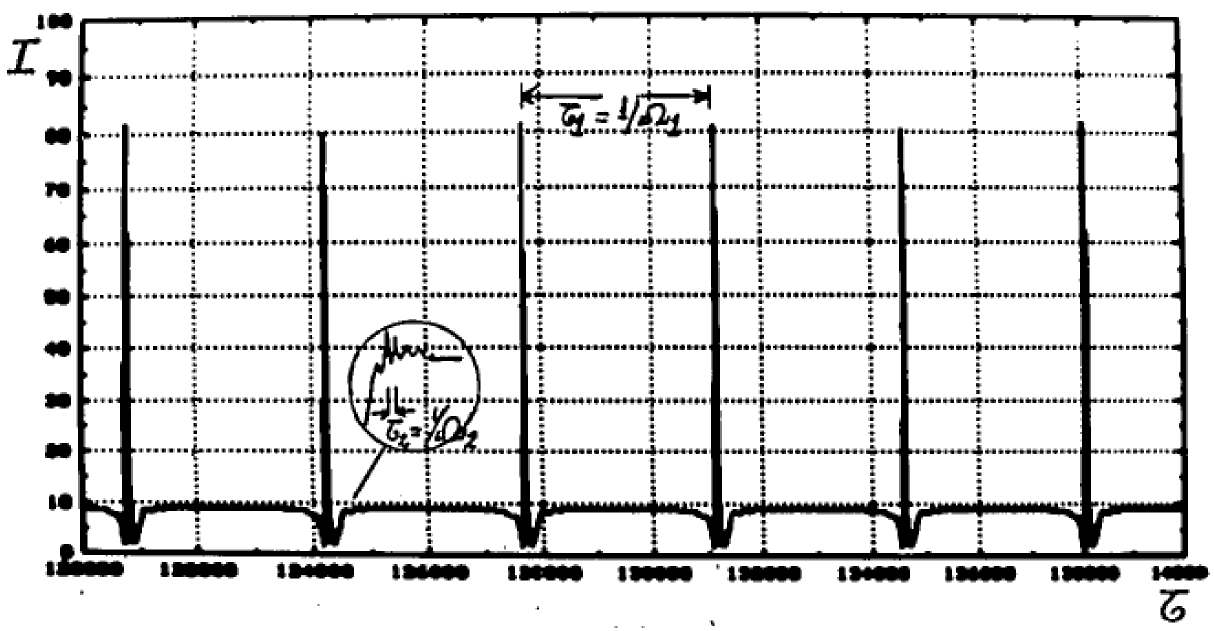
Also optical rogue waves?

Also RWs?

Instabilities in lasers with an injected signal

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

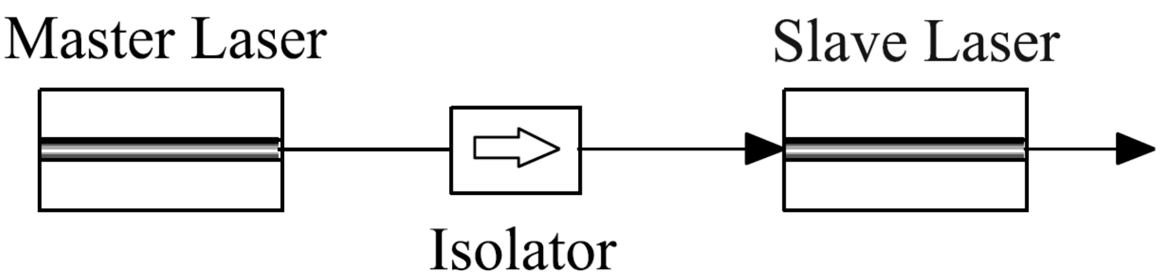
178 J. Opt. Soc. Am. B/Vol. 2, No. 1/January 1985

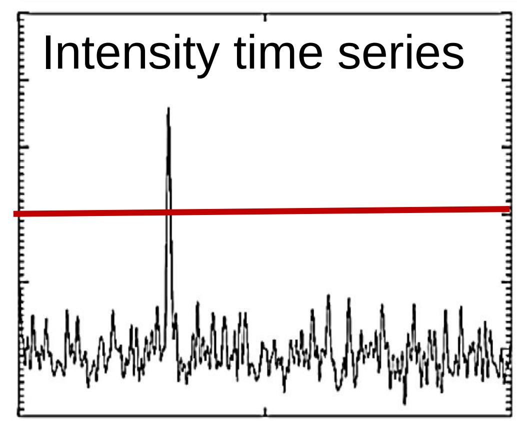


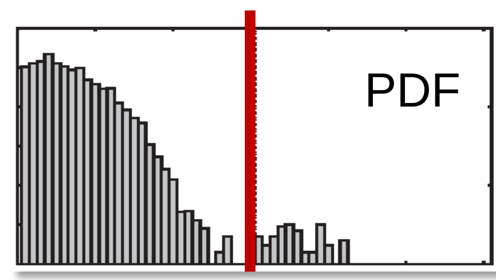
PRL 107, 053901 (2011) PHYSICAL REVIEW LETTERS week ending 29 JULY 2011

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]







- Parameters:
  - Injection ratio
  - Frequency detuning (controlled via the pump current)

ORW: pulse above

<A> + **6-8** σ

Outline

What we have learned: in our system, ORWs can be

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

The challenge

- Data-driven approach to advance **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).

Governing equations

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

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

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

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

spontaneous emission noise

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

μ: normalized pump current parameter

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

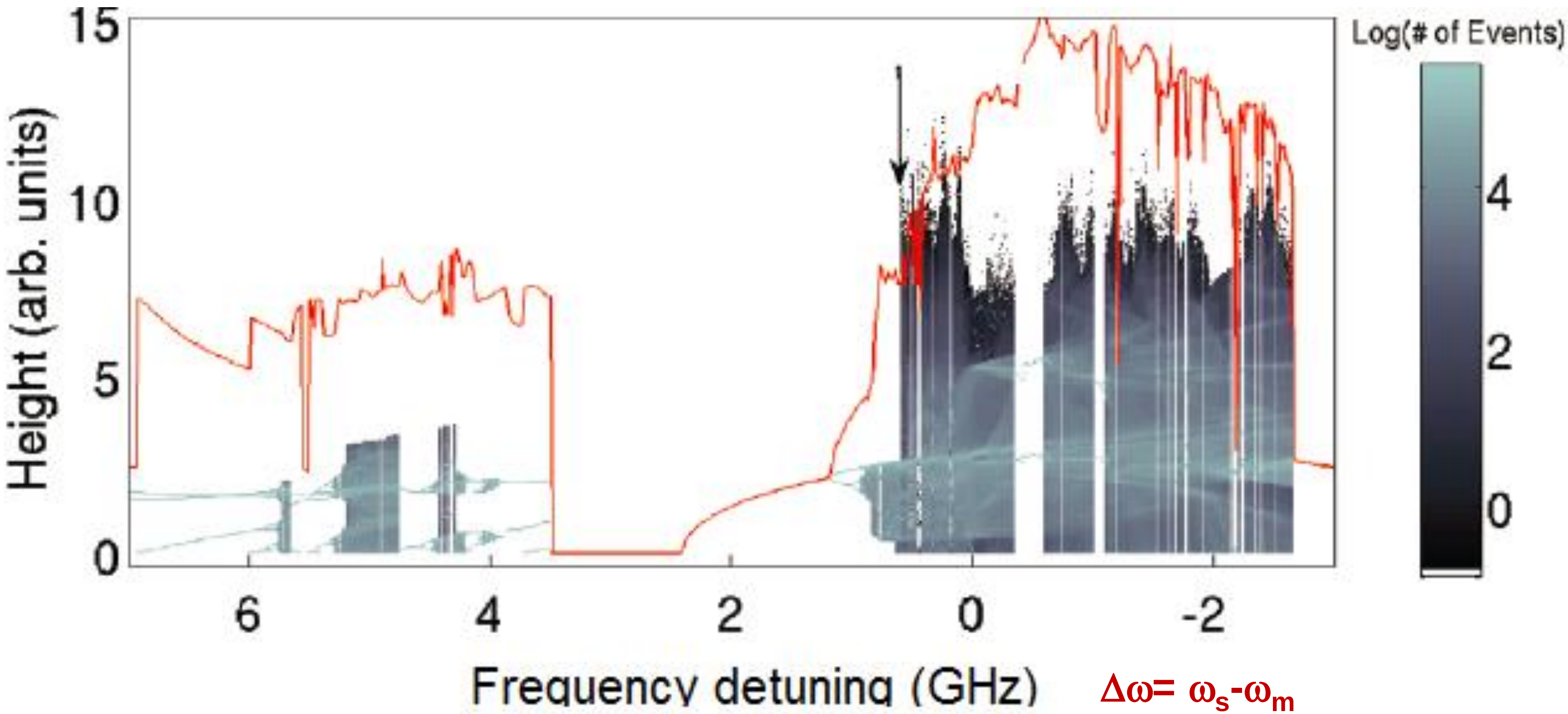
Spatial effects are not taken into account.

This is because this simple model provides good qualitative agreement with experimentally observed dynamical behaviors.

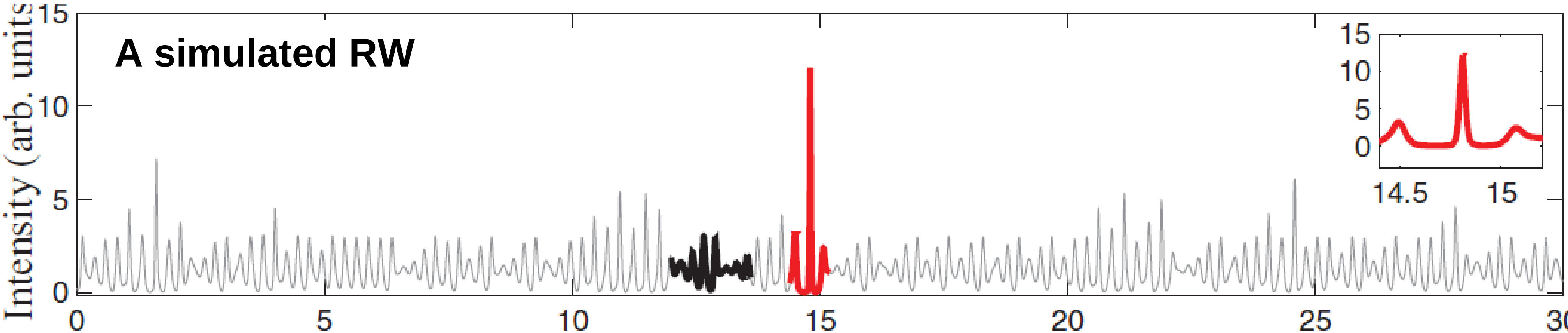
Dynamical regimes

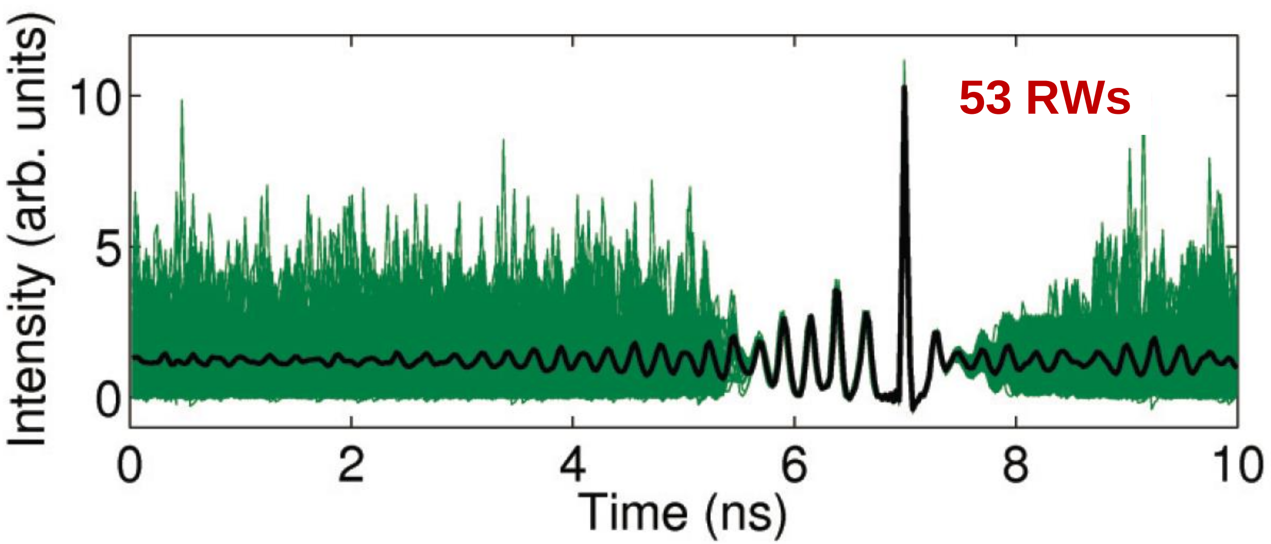
- Injection locking (cw output)
- Periodic oscillations
- Chaos

Threshold: <H> + 8σ



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

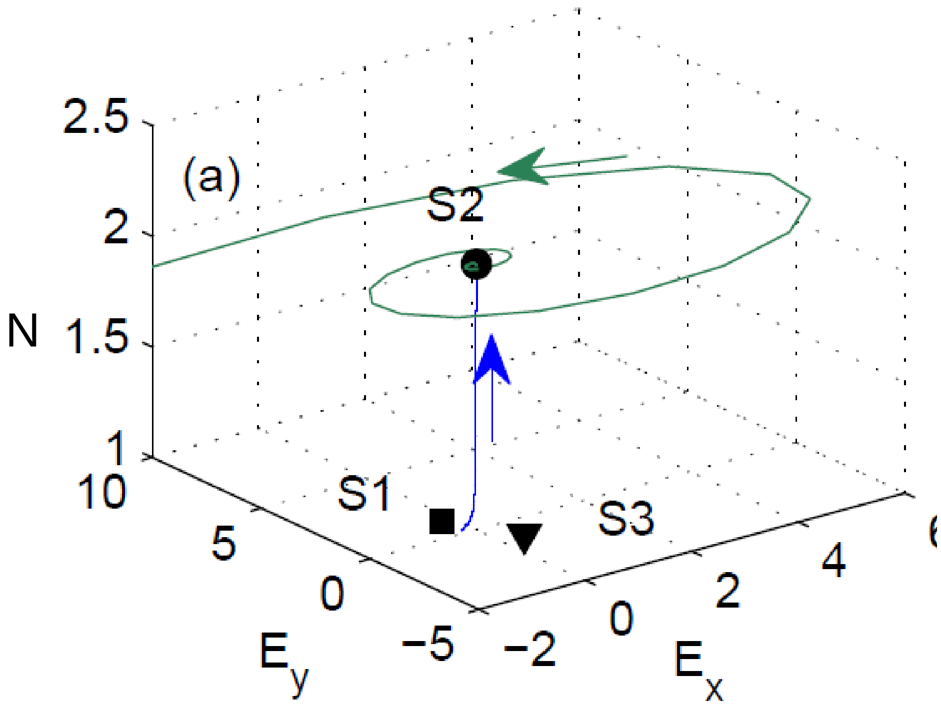


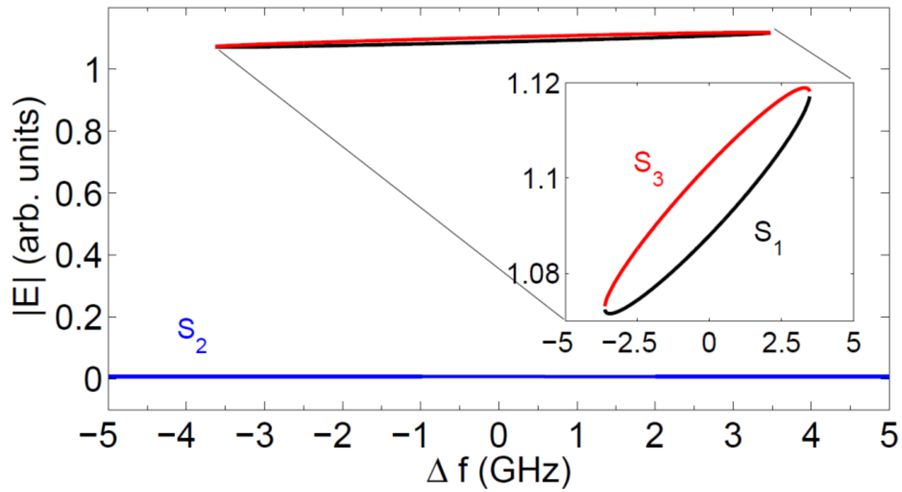


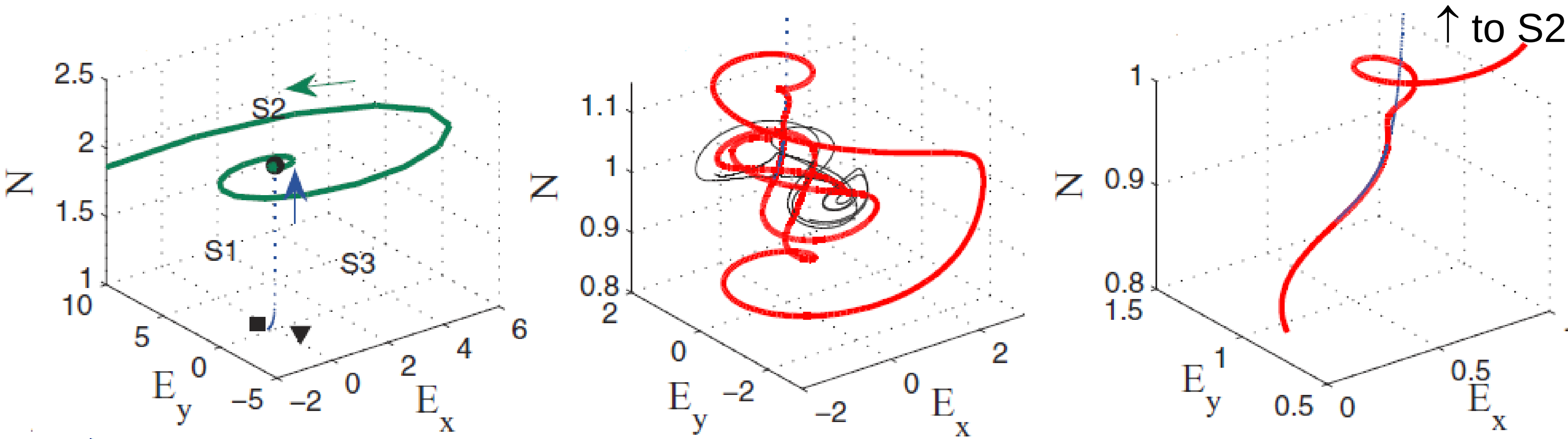
J. Zamora-Munt et al, PRA 87, 035802 (2013)

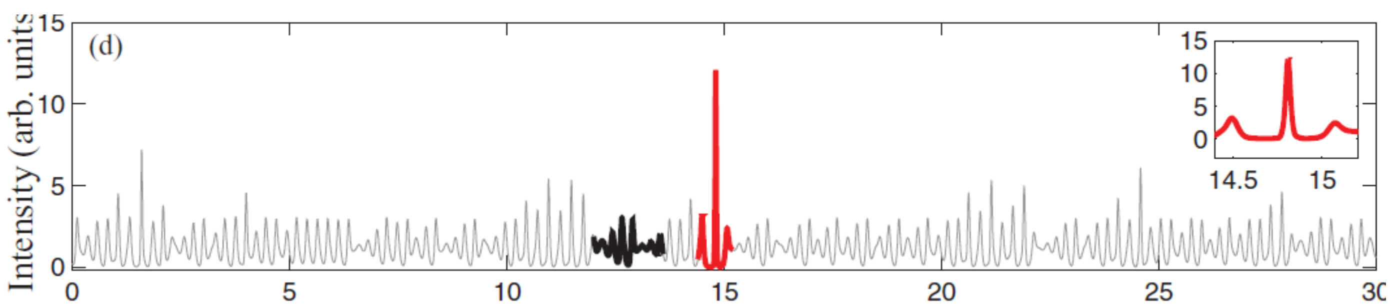
What triggers a RW?

Fixed points in the phase space







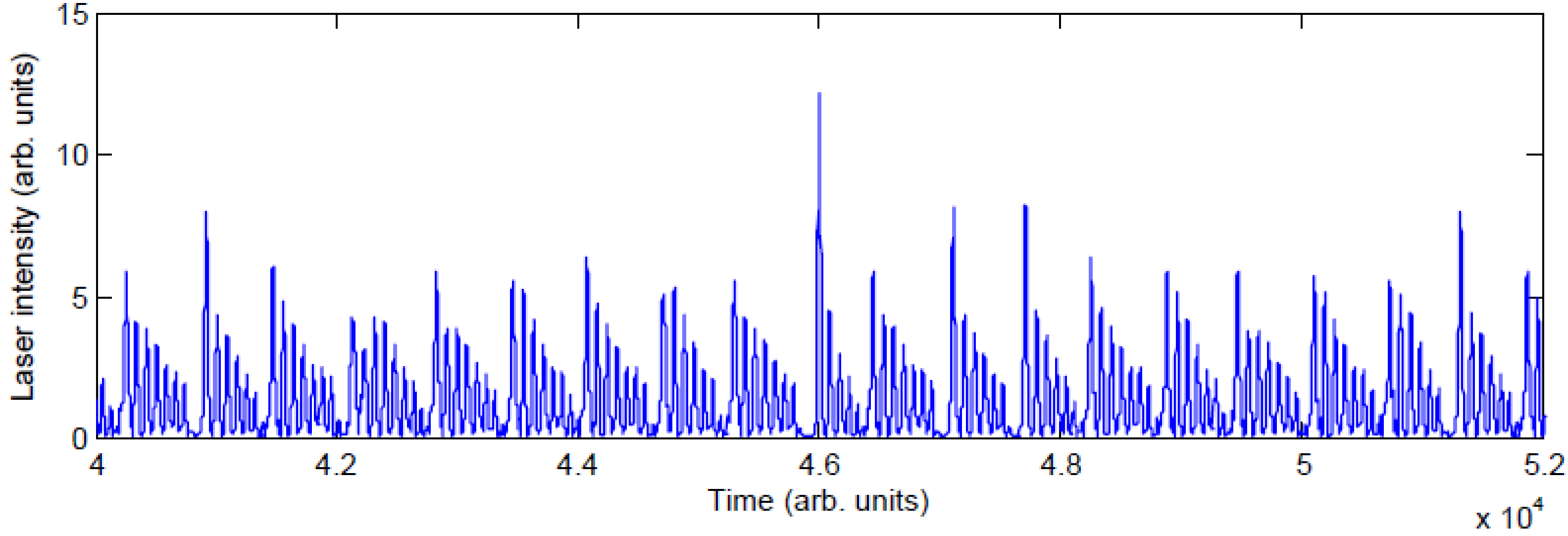


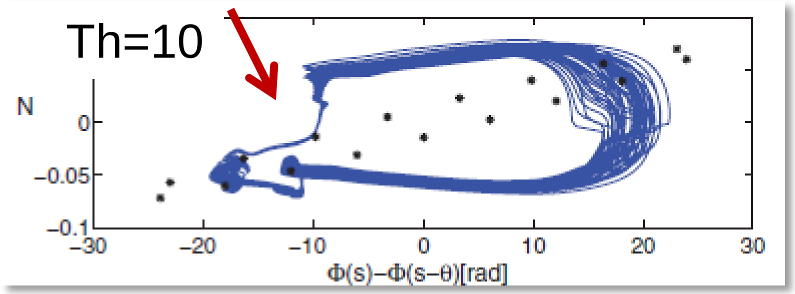
A RW is triggered whenever the trajectory closely approaches the stable manifold of S2 (the "RW door")

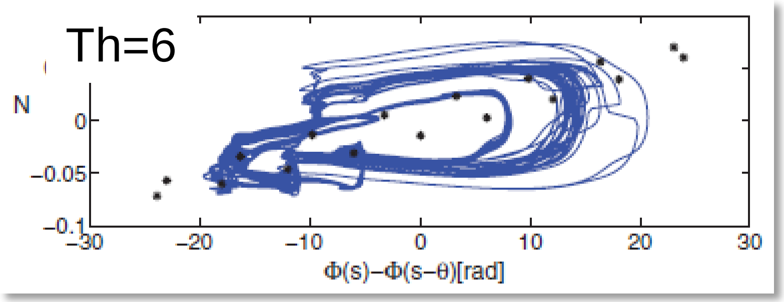
UNIVERSITAT POLITÈCNICA
DE CATALUNYA
BARCELONATECH

Campus d'Excel·lència Internacional

A similar mechanism generates extreme pulses in a model of a semiconductor laser with optical feedback







Superposition of 50 pulses

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

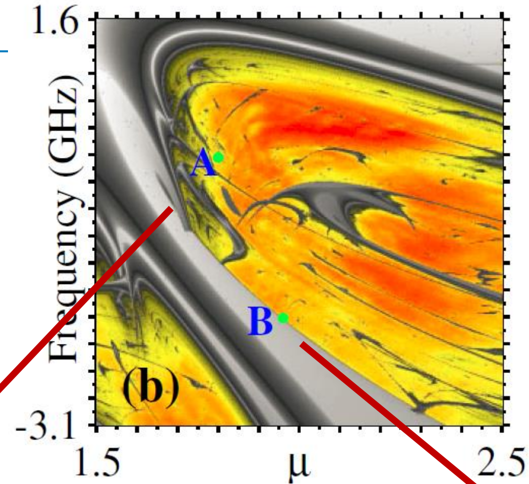
Deterministic simulations (β_{sp}=0)

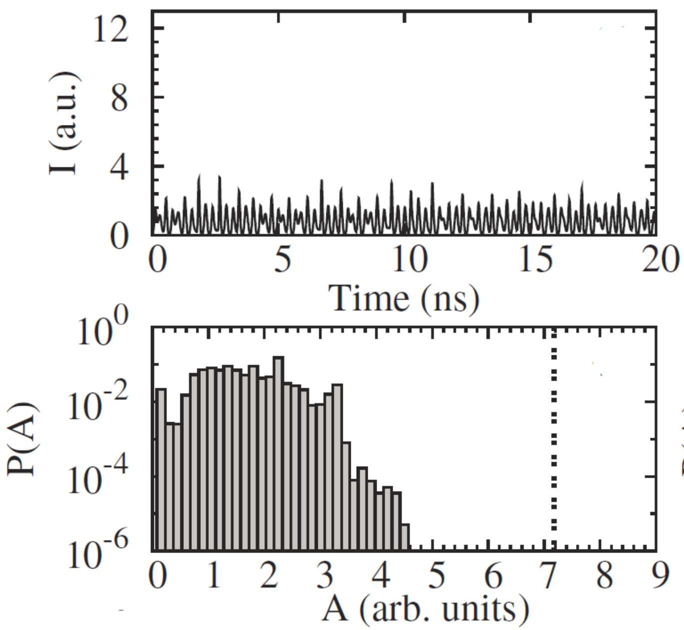
UNIVERSITAT POLITÈCNICA DE CATALUNYA
BARCELONATECH

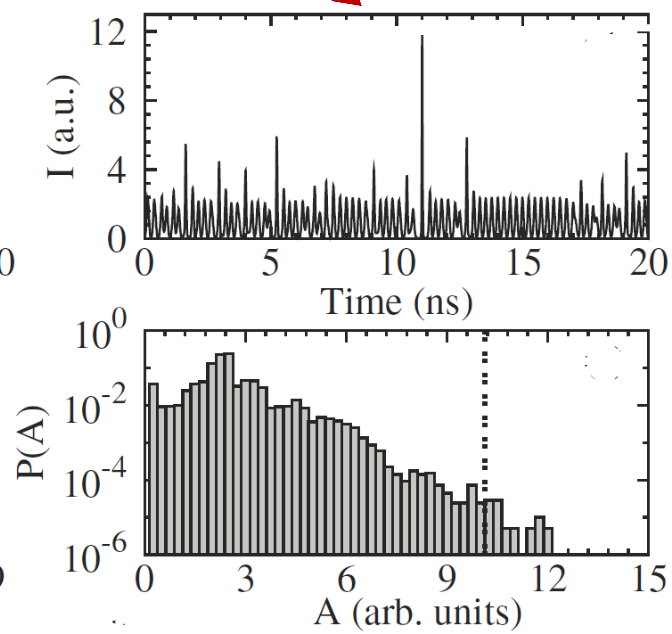
Campus d'Excel·lència Internacional

Lyapunov diagram

(detuning, pump current)



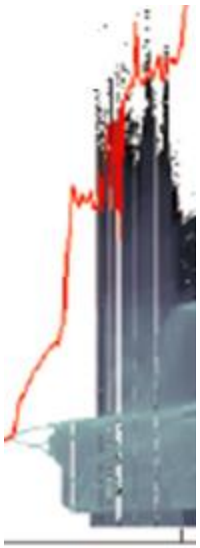


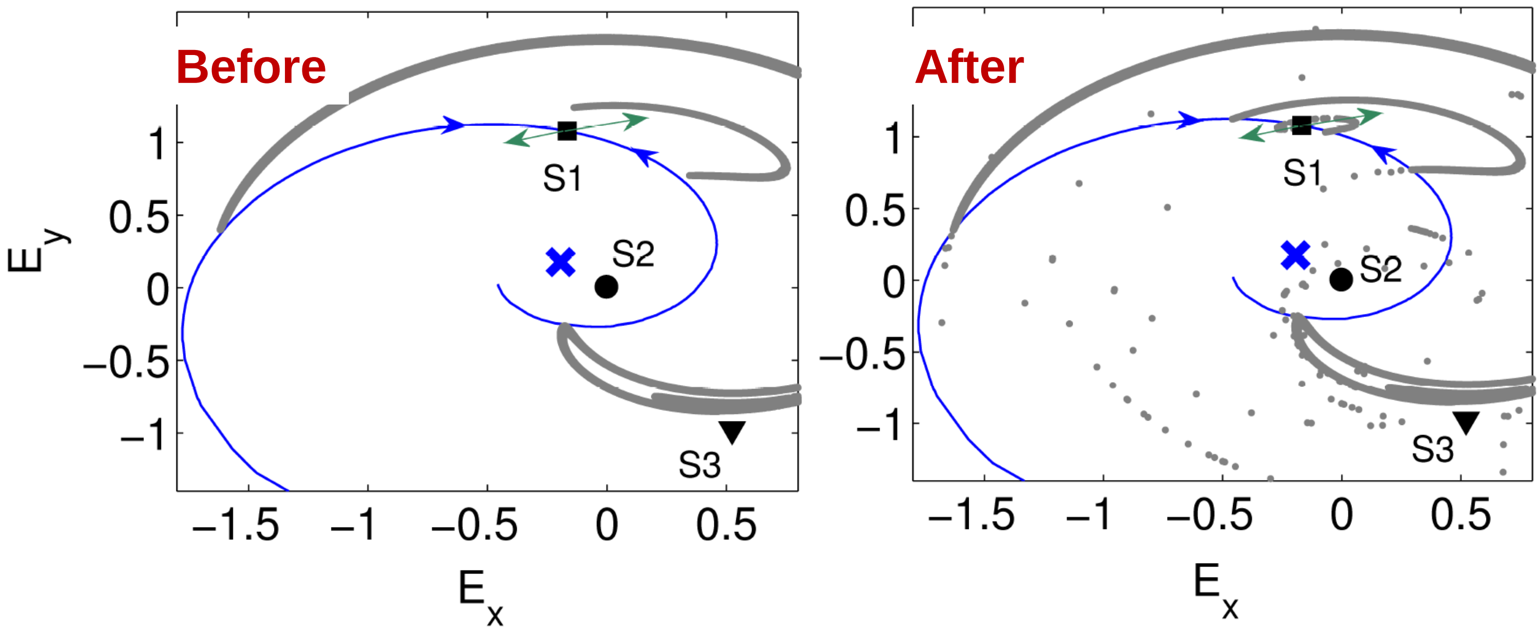


Chaos without RWs

Chaos with RWs

Why chaos with RWs and chaos without them?

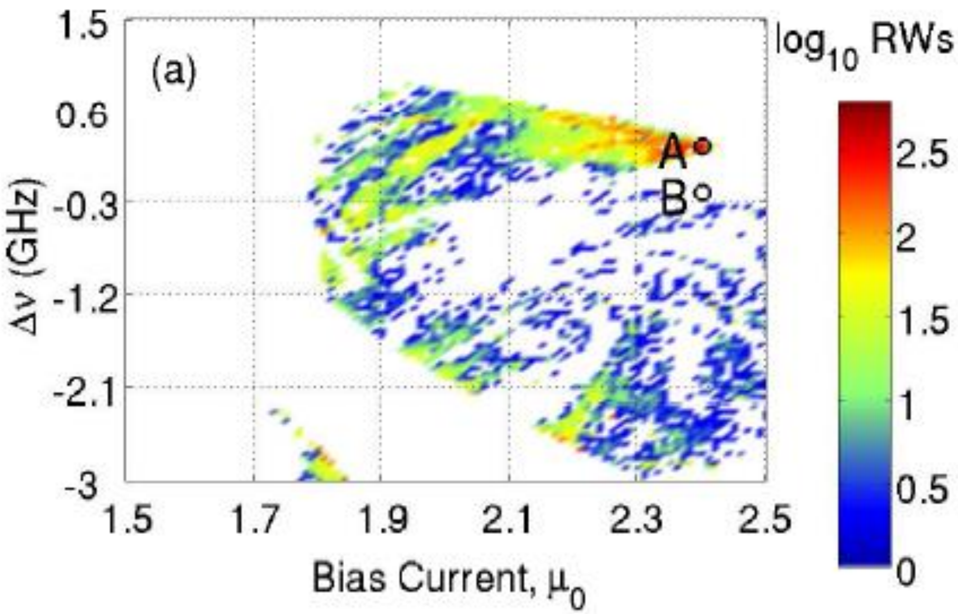




An **external crises-like** process enables access to the region of phase space where the **stable manifold of S2 (x)** is.

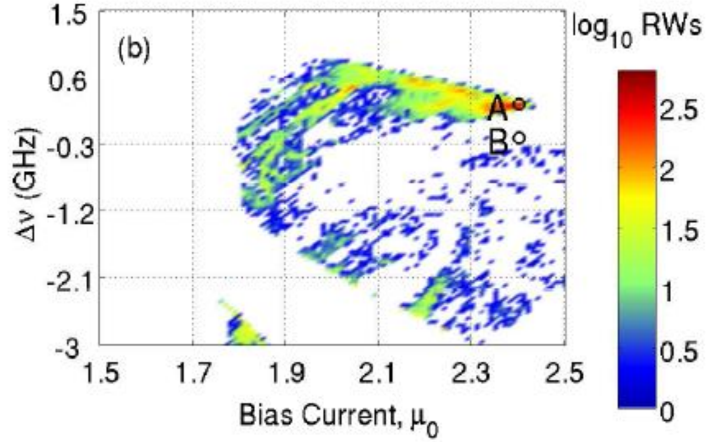
Number of RWs vs (pump current & detuning)

Deterministic RWs (β_{sp}=0)

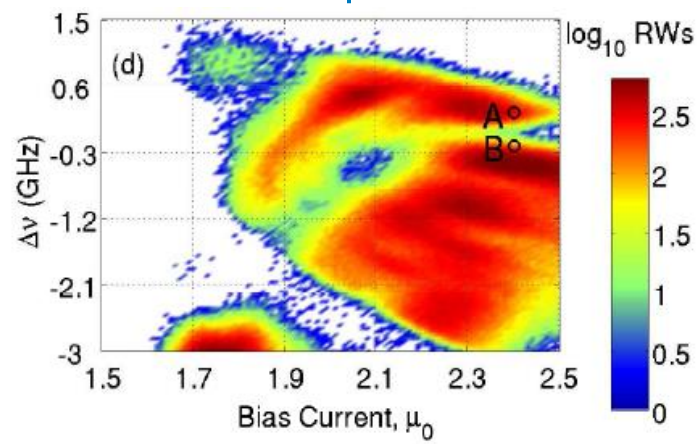


White = No RWs

Weak noise (β_{sp}=0.0001)



Strong noise (β_{sp}=0.01)



Strong enough noise can induce RWs

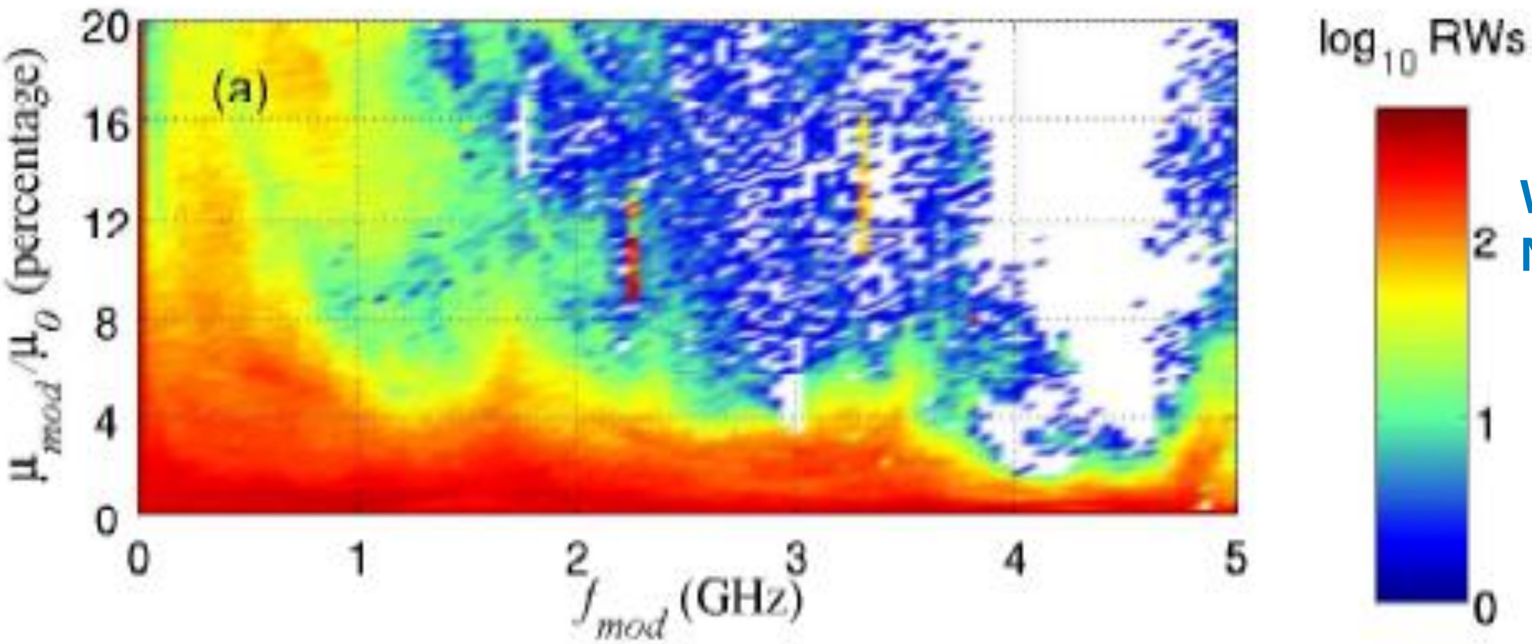
UNIVERSITAT POLITÈCNICA DE CATALUNYA BARCELONATECH

Campus d'Excel·lència Internacional

Pump current modulation:

RW control in Point A (deterministic RWs)

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



White = No RWs

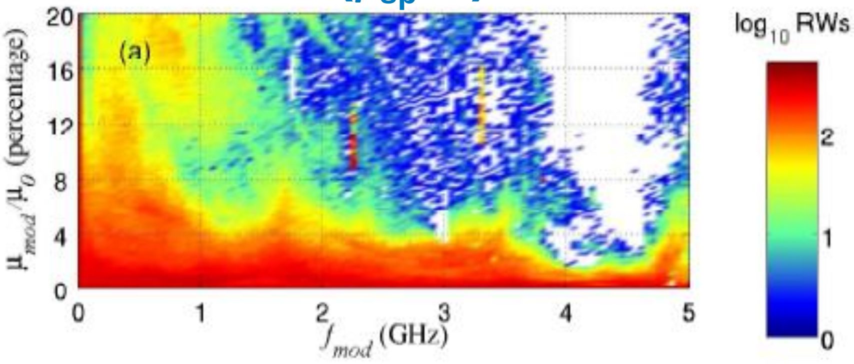
Current modulation with appropriated amplitude and frequency can completely suppress the RWs.

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

RW control in Point A: influence of noise

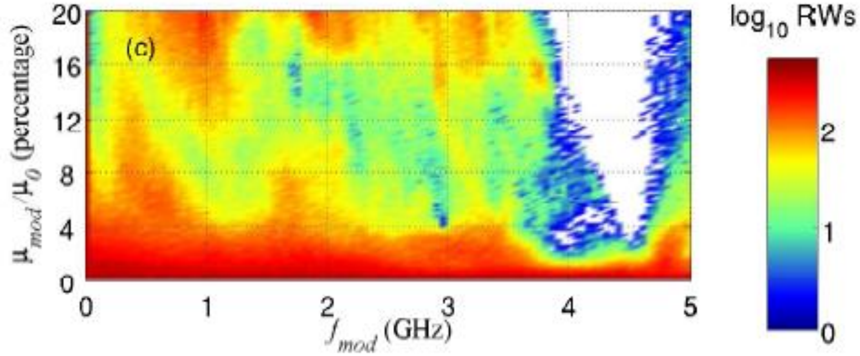
$$\mu = \mu_0 + \mu_{mod} \sin(2\pi\ f_{mod}\ t)$$

No noise (β_{sp}=0)



White = No RWs

Stochastic simulations (β_{sp}=0.01)



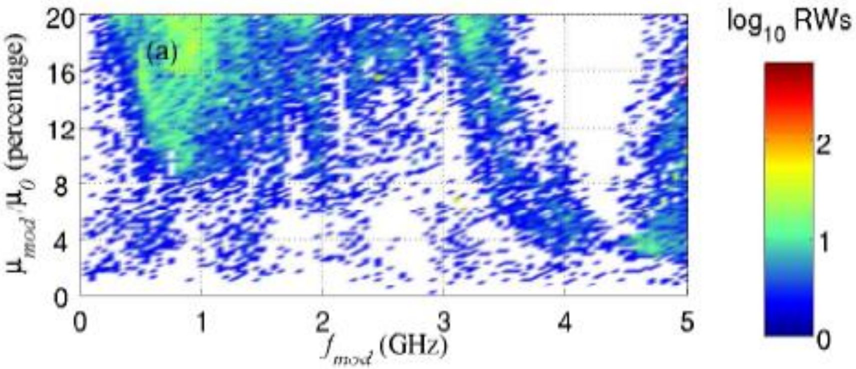
White = No RWs

“safe parameter region” is robust to the presence of noise.

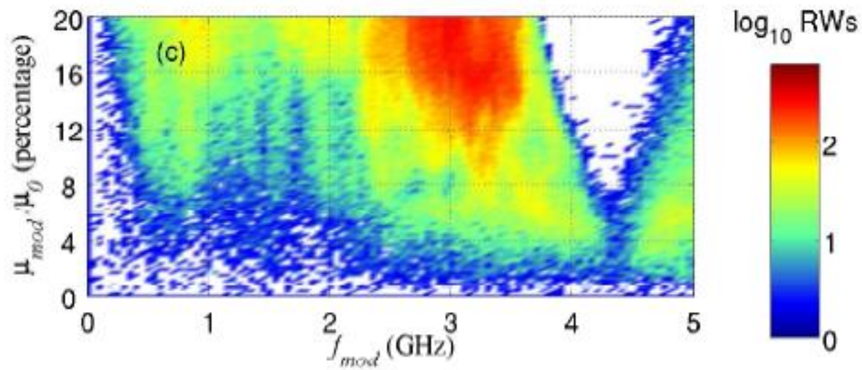
S. Perrone, J. Zamora Munt, R. Vilaseca and C. Masoller, PRA 89, 033804 (2014)

in Point B (no deterministic RWs)

β_{sp}=0



β_{sp}=0.01

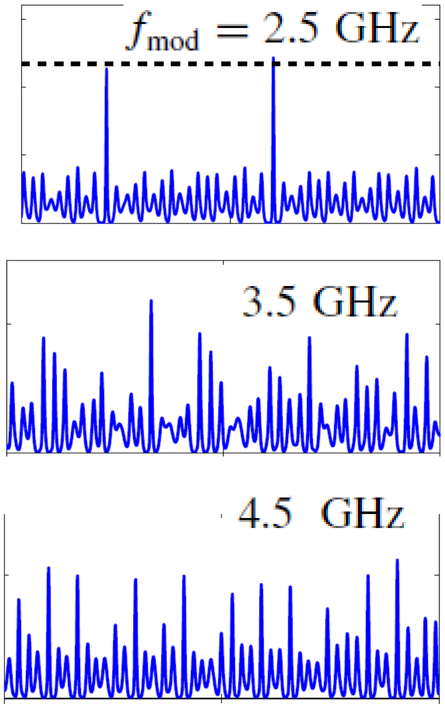


White = No RWs

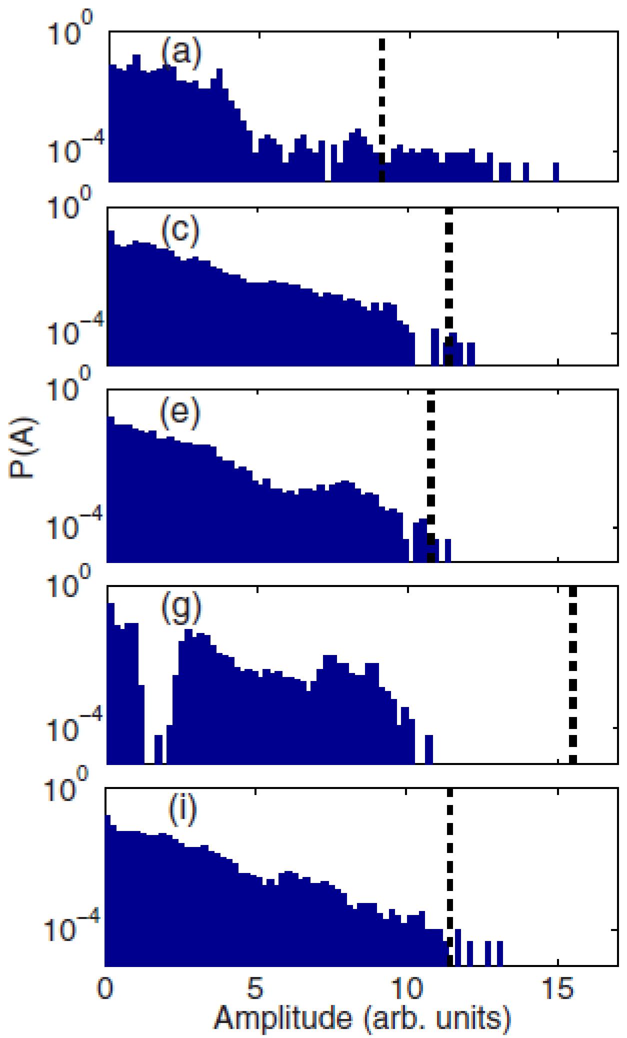
Modulation can induce RWs

"safe" parameter region is also robust to noise

Why RWs are suppressed?



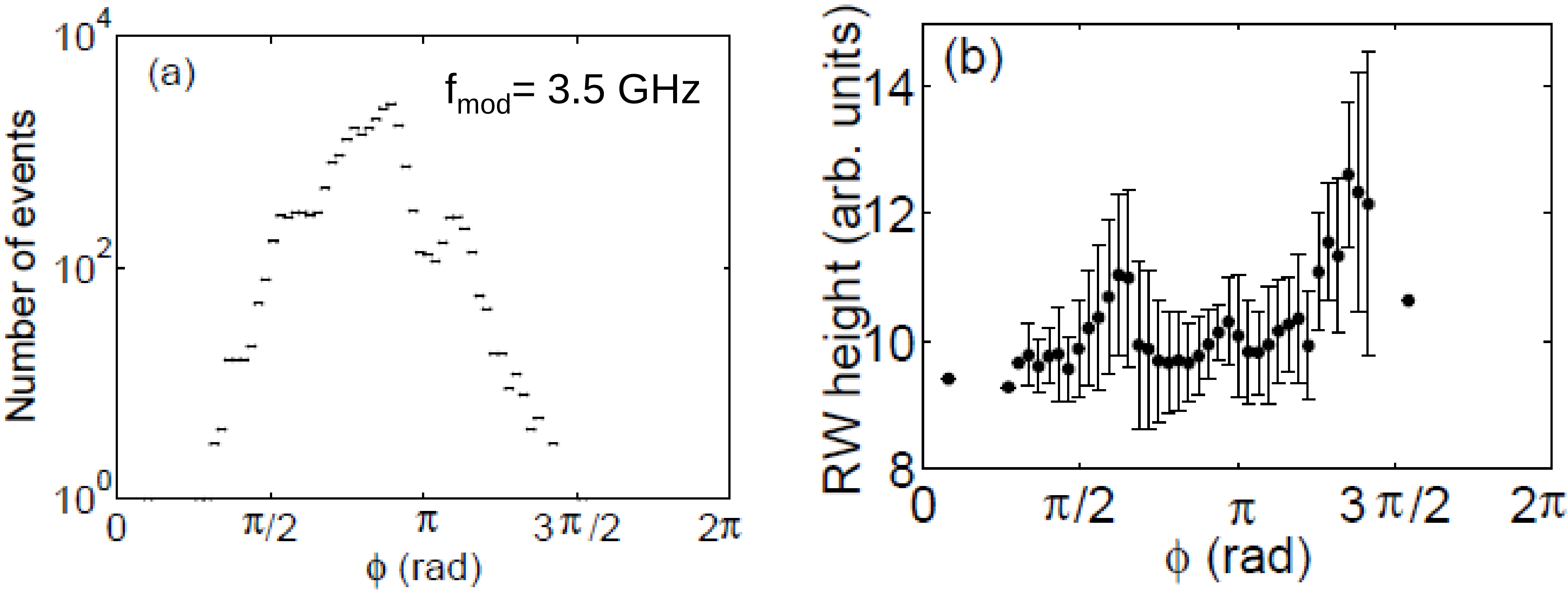
Histograms of pulse amplitudes



Threshold = <A> + **6** σ

RWs are suppressed because high pulses are not rare.

When RWs are not suppressed: role of the modulation phase



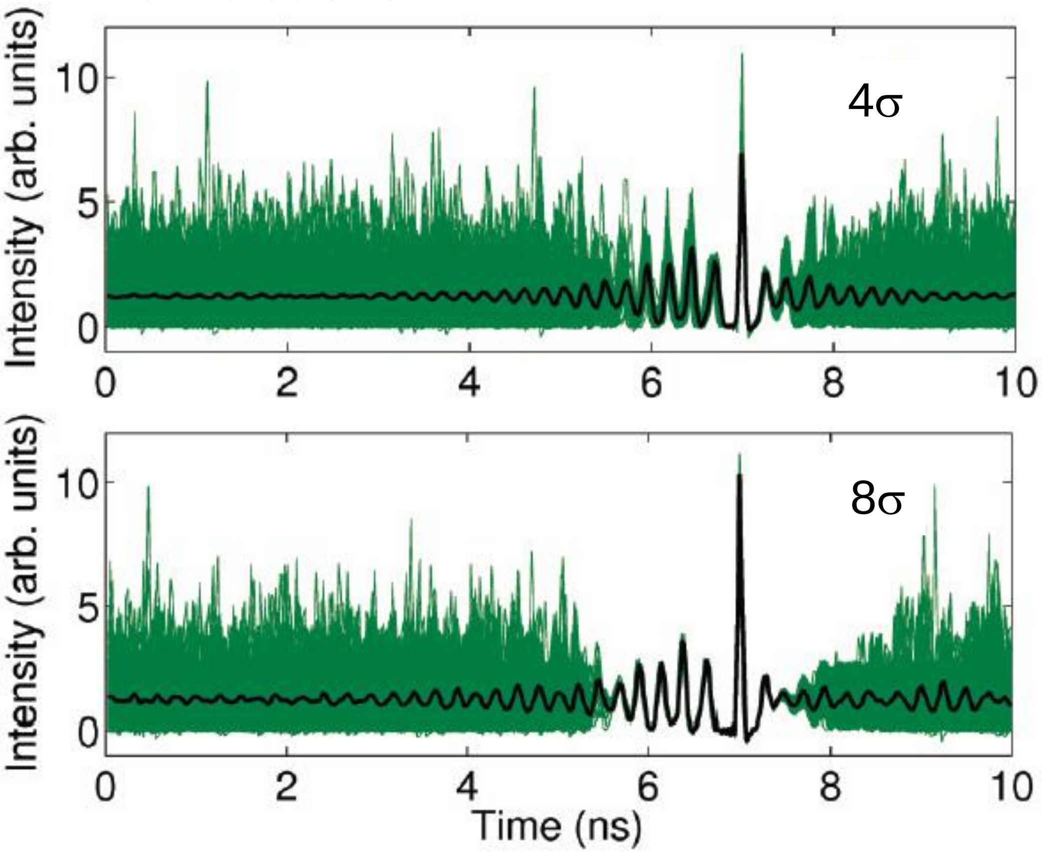
RWs occur during the first ¾ of the modulation cycle.

The highest RWs occur just before the "safe" phase window.

J. Ahuja, D. Bhiku Nalawade, J. Zamora-Munt, R. Vilaseca and C. Masoller, Optics Express 22, 28377 (2014)

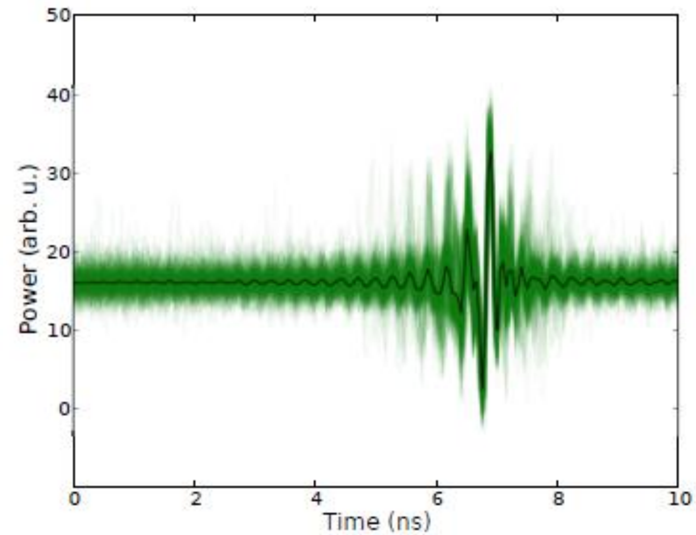
RW predictability?

Simulations



Superposition of 50 time
series at the RW peak

Experiments



Superposition of 500 time
series at the RW peak

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

Data-driven approach for improving rogue wave predictability

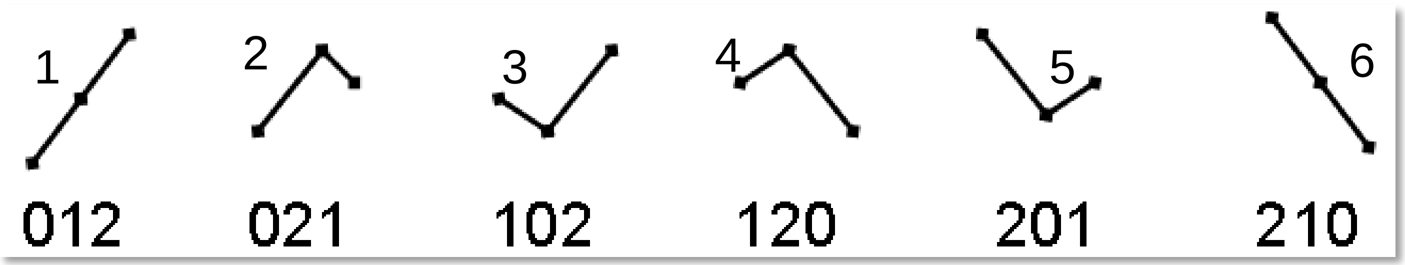
UNIVERSITAT POLITÈCNICA DE CATALUNYA
BARCELONATECH

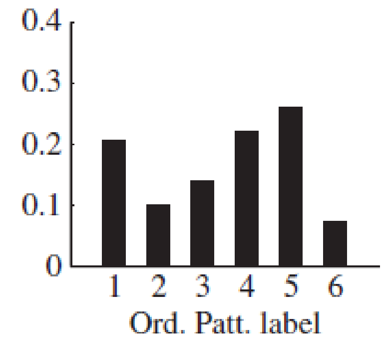
Campus d'Excel·lència Internacional

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)





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

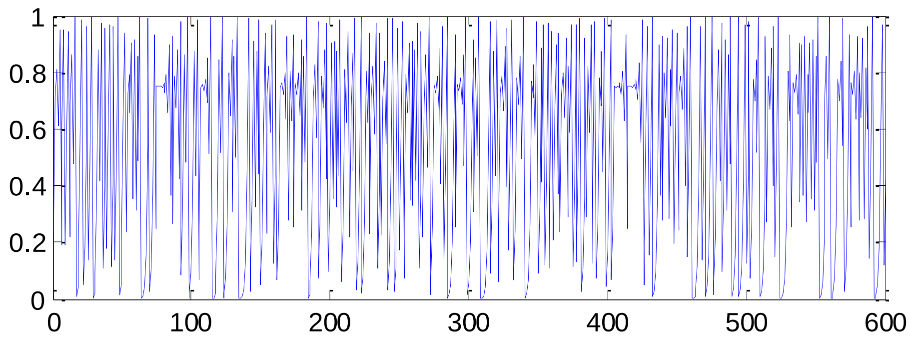
Random data $\Rightarrow$ OPs are equally probable

– Advantage: the probabilities uncover temporal correlations.

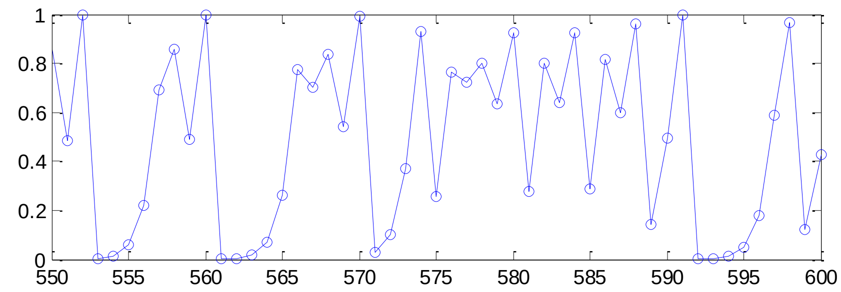
– Drawback: we lose information about the actual values.

Example1: the logistic map $x(i+1)=4x(i)[1-x(i)]$

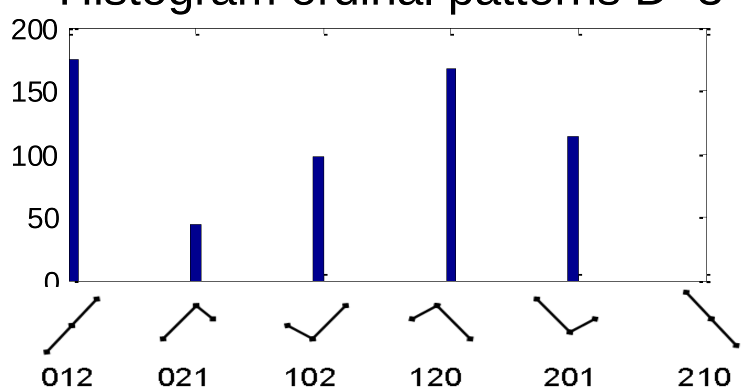
Time series



Detail

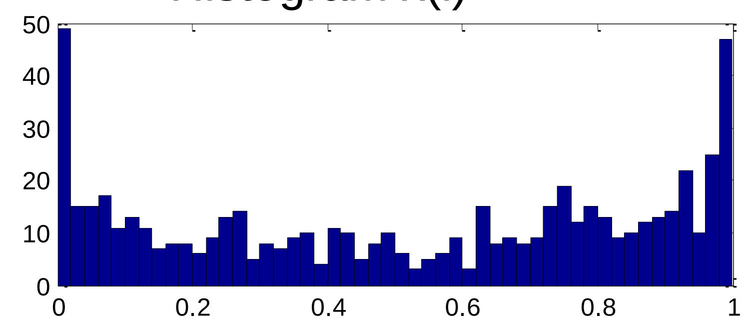


Histogram ordinal patterns D=3



Forbidden pattern

Histogram x(i)

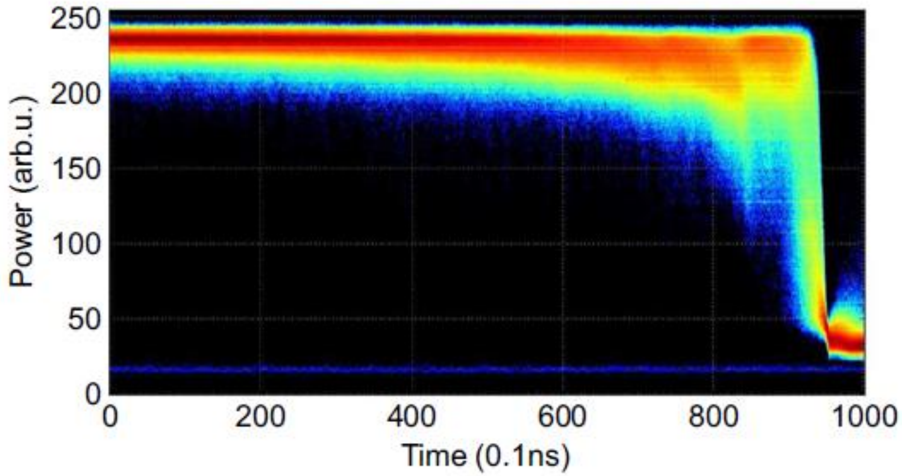


Ordinal analysis provides complementary information.

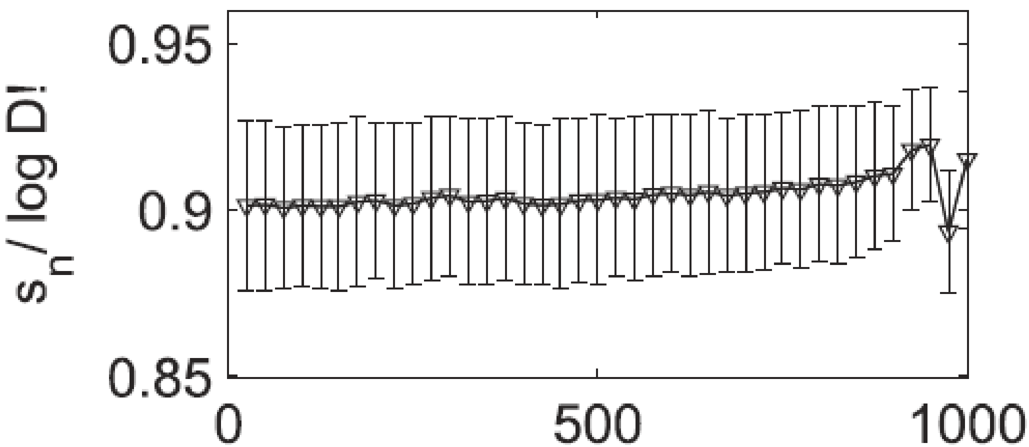
UNIVERSITAT POLITÈCNICA DE CATALUNYA BARCELONATECH

Campus d'Excel·lència Internacional

Example 2: early warning of an abrupt transition



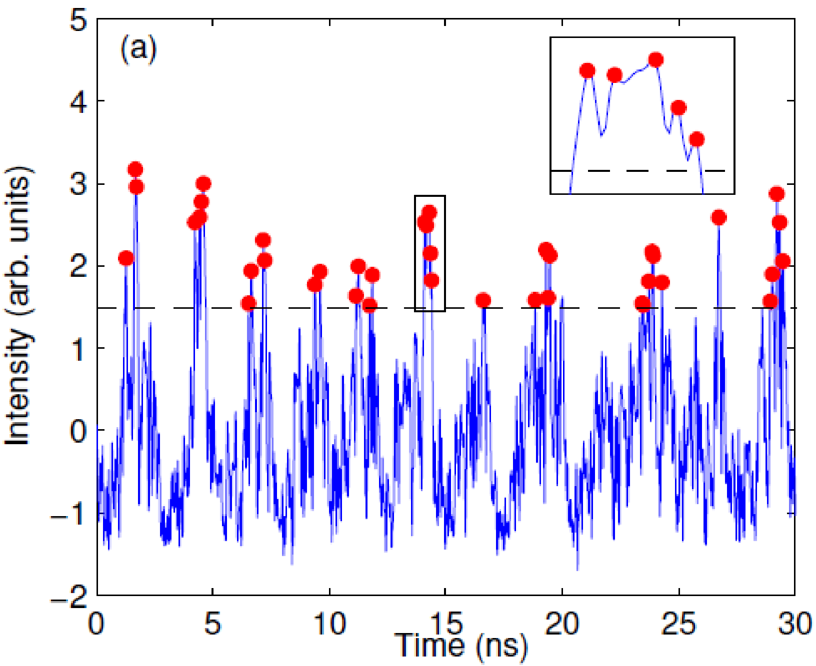
VCSEL polarization-resolved intensity when a control parameter varies (pump current)

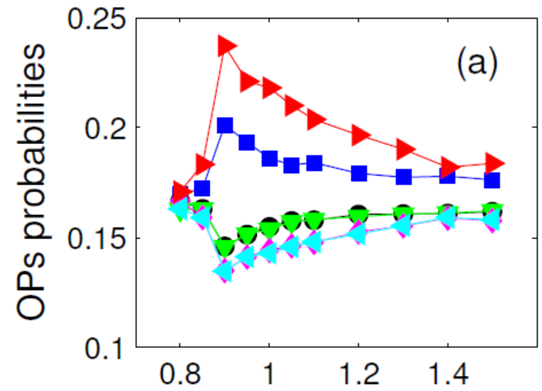


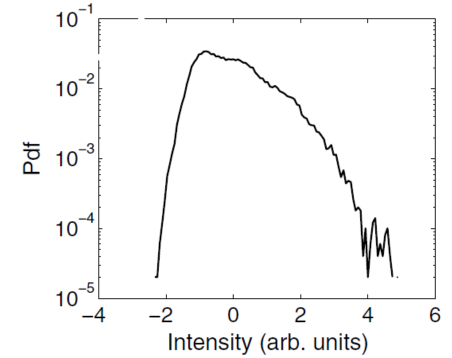
Entropy computed from ordinal transition probabilities ('012'→ '012', etc.) in a sliding window of 500 data points.

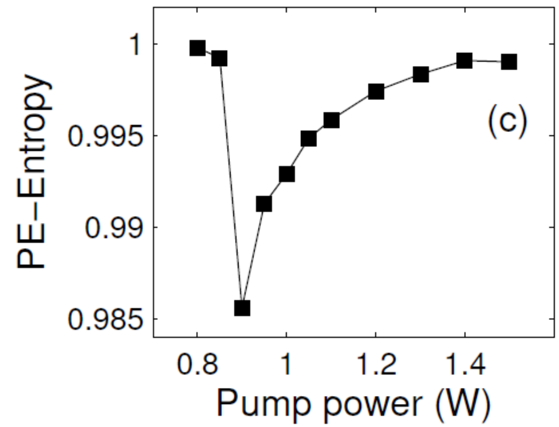
C. Masoller et al, New J. Phys. 17 (2015) 023068

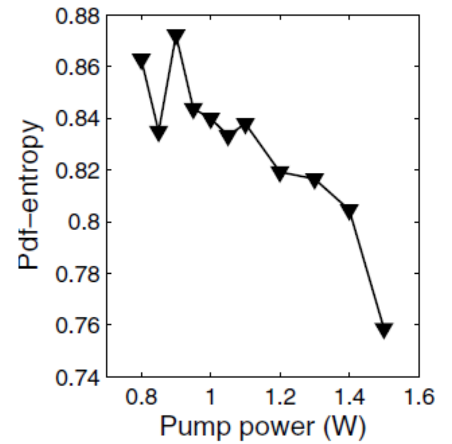
Example 3: Laminar – turbulent transition in a fiber laser











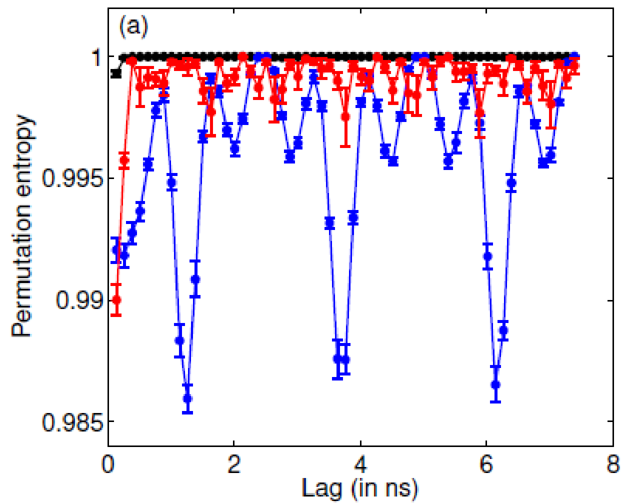
Aragoneses et al, PRL 116, 033902 (2016)

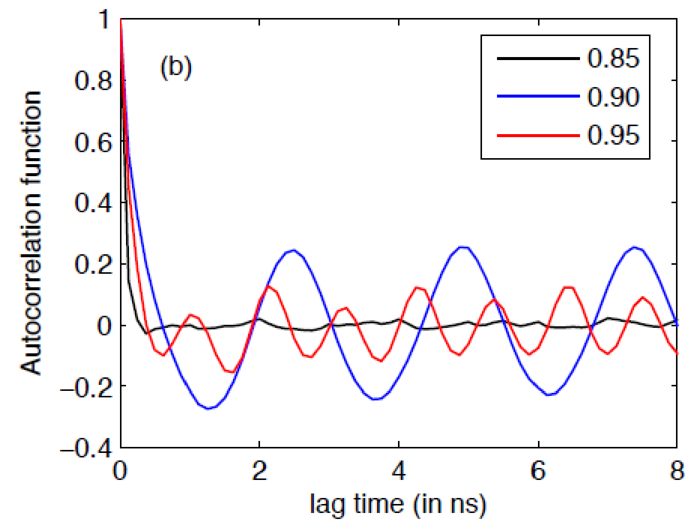
E. G. Turitsyna et al, "*The laminar–turbulent transition in a fibre laser*", Nat. Phot. 7, 783 (2013)

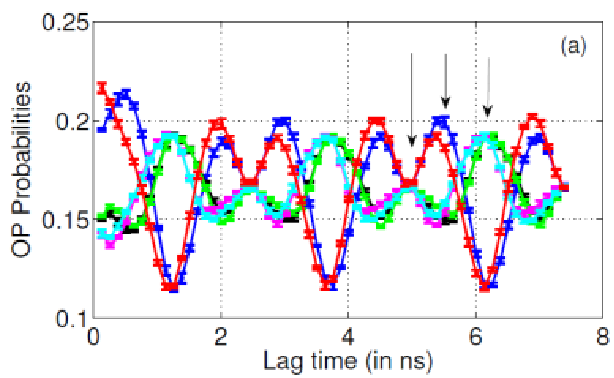
Ordinal analysis allows to unveil "hidden" intrinsic time-scales

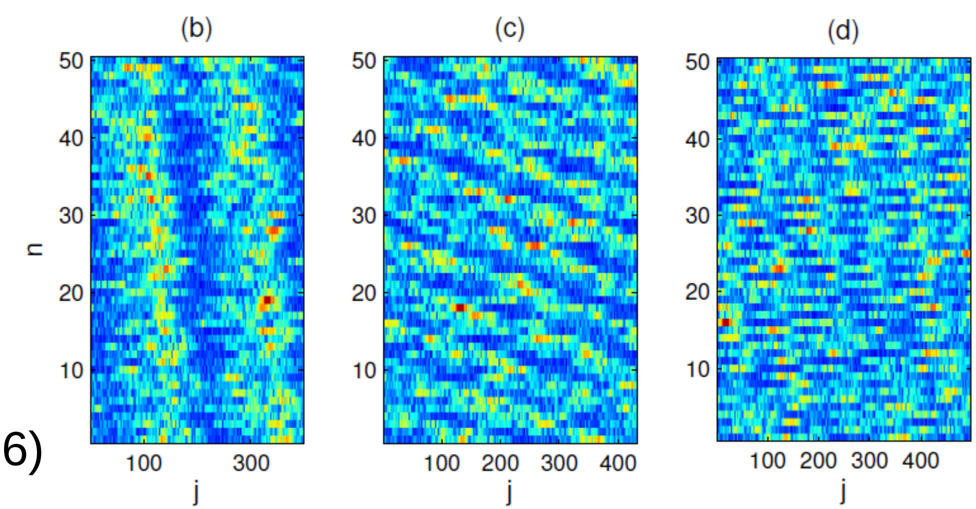
$$\{I_i, I_{i+\tau}, I_{i+2\tau}, \dots\};$$

all data points, no threshold used







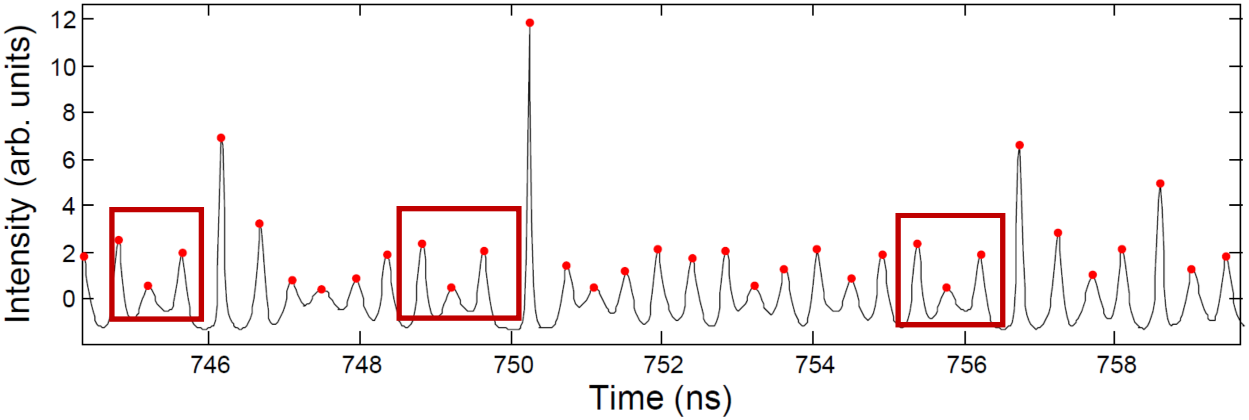


Aragoneses et al, PRL 116, 033902 (2016)

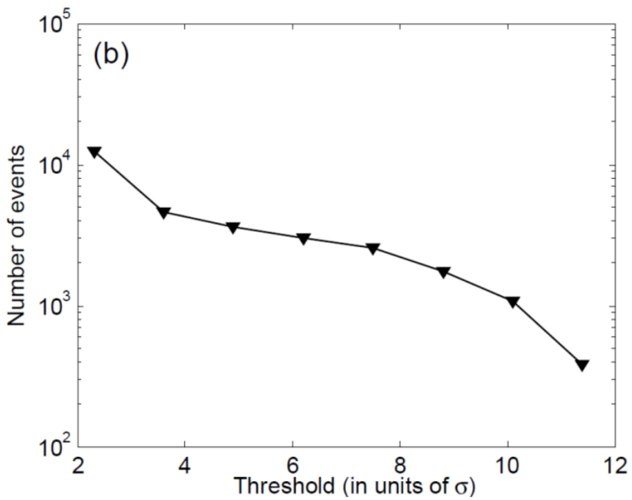
Ordinal analysis applied to three pulse heights before a RW

UNIVERSITAT POLITÈCNICA DE CATALUNYA
BARCELONATECH
Campus d'Excel·lència Internacional

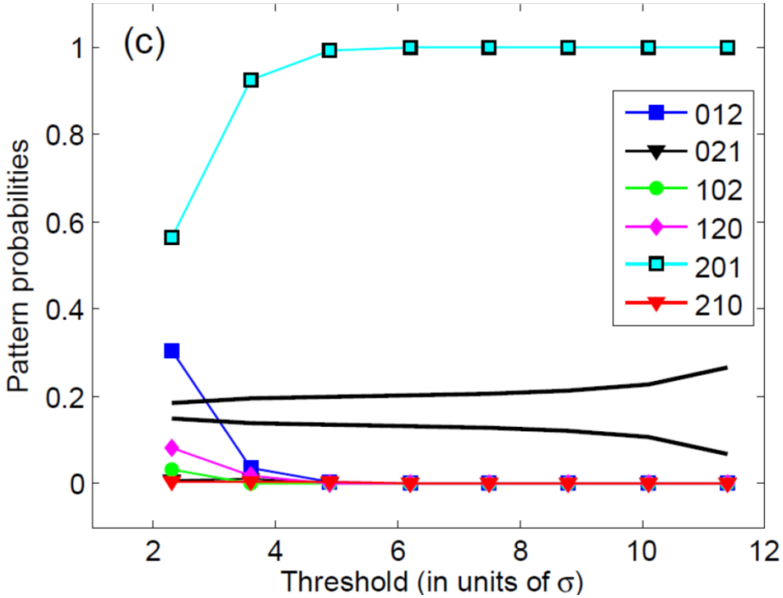
Time series (deterministic simulations), normalized to zero-mean and σ=1



If I_i > TH, we analyze the ordering of (I_{i-3}, I_{i-2}, I_{i-1})

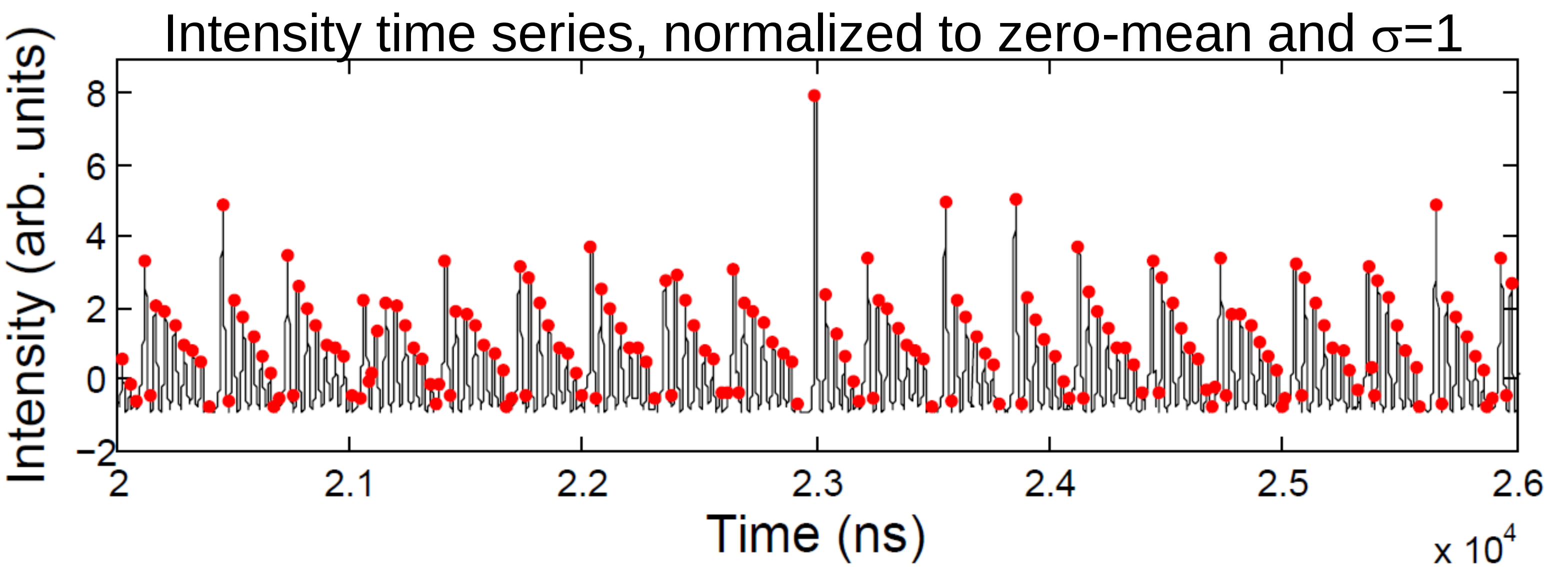


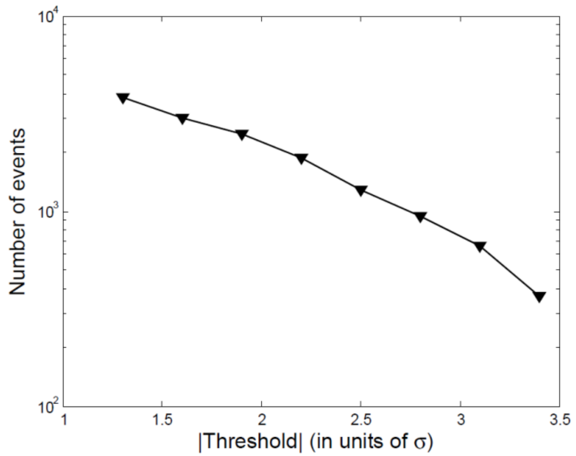
Ordinal probabilities computed from 3 peak heights before a pulse.

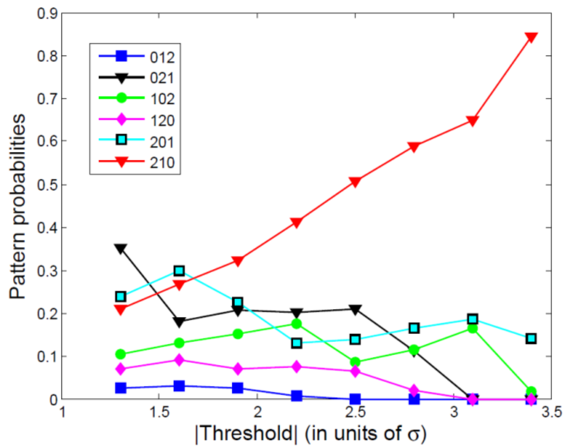


N. Martinez et al., in preparation (2016)

Extreme pulses in a model of a semiconductor laser with optical feedback







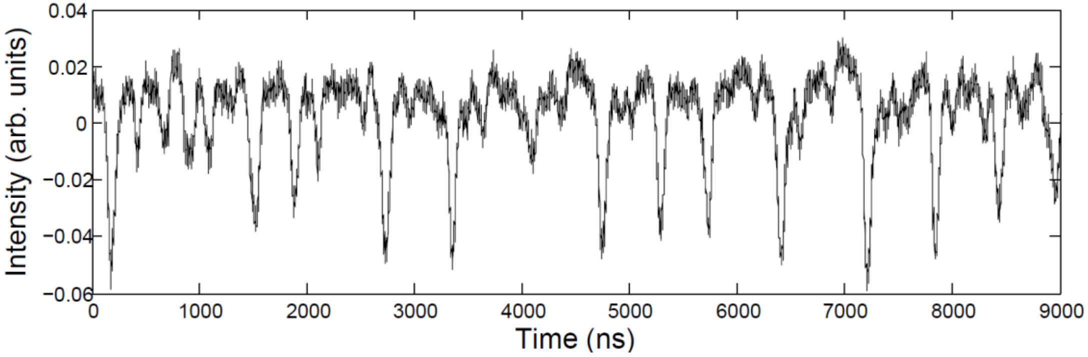
N. Martinez Alvarez et al., in preparation (2016)

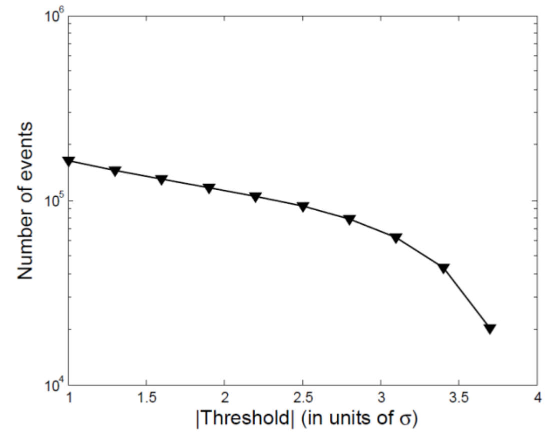
UNIVERSITAT POLITÈCNICA
DE CATALUNYA
BARCELONATECH

Campus d'Excel·lència Internacional

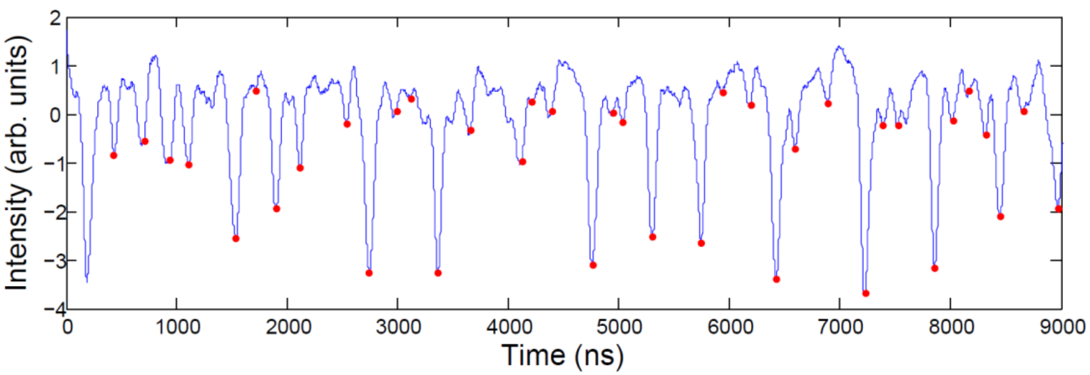
Empirical data: low frequency fluctuations induced by optical feedback

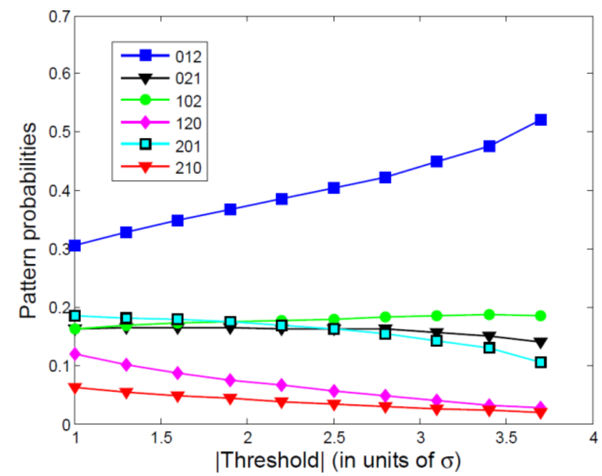
Oscilloscope raw data



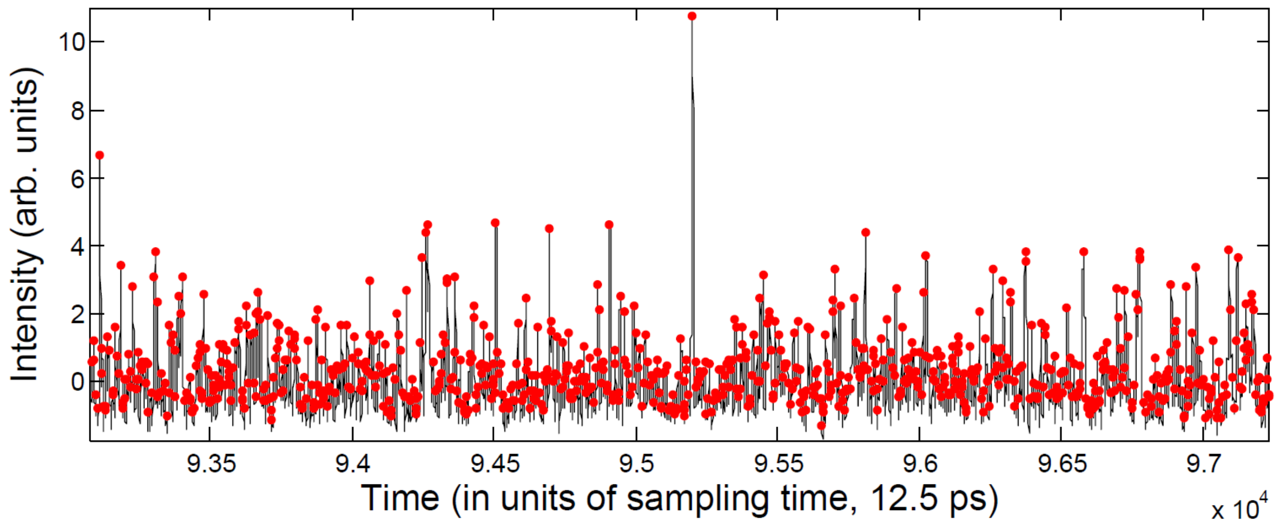


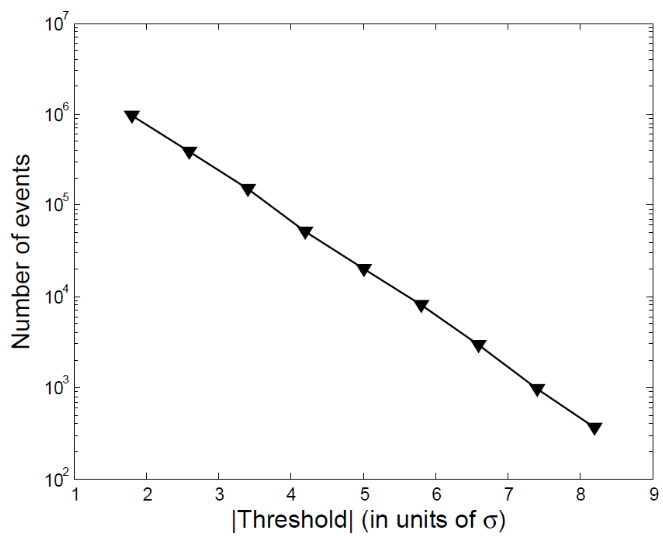
Filtered time series, zero-mean and σ=1

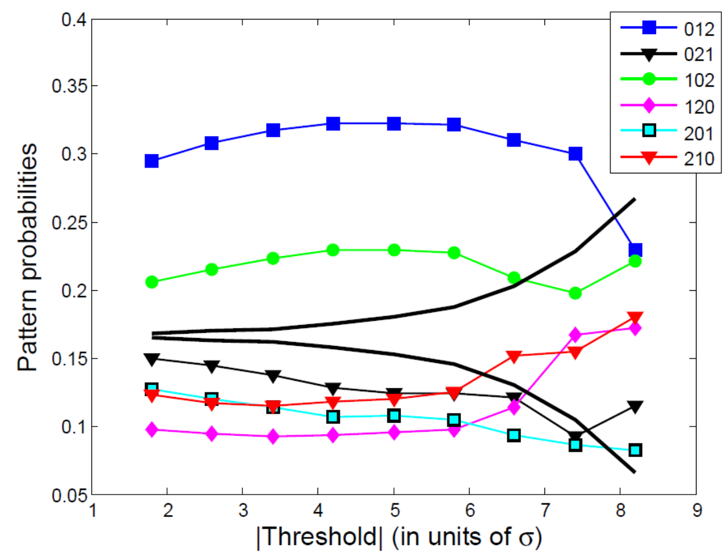




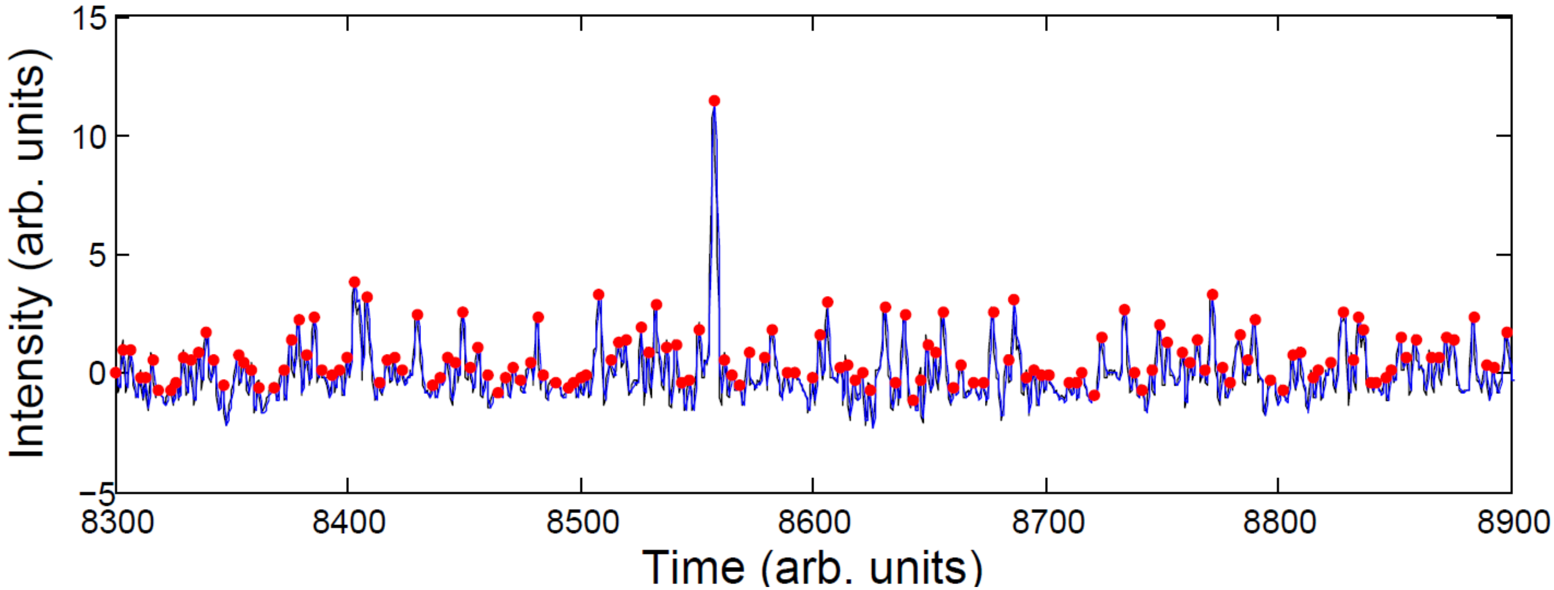
Empirical data: fiber laser intensity in the turbulent regime

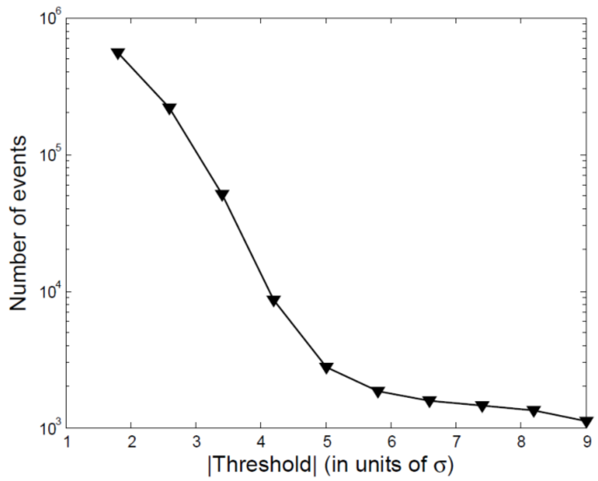


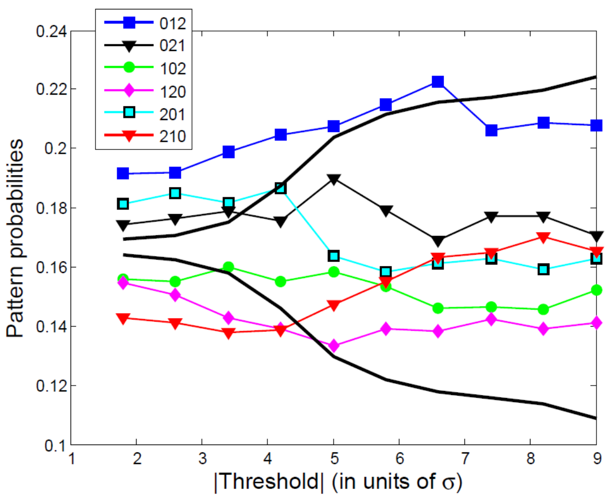




Empirical data: optically injected semiconductor laser







Conclusions

- Take home message:
  - Optical rogue waves provide "big data" for testing novel analysis tools.
  - Nonlinear tools might capture relevant features in the data.
- A few specific conclusions: in our system
  - 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.
  - RW Control: noise and modulation affect the likelihood of RWs.
  - RW Predictability:
    - When modulation does not suppress RWs, they occur only in certain windows of the modulation cycle.
    - Preliminary results: more frequent (precursors) and less frequent ordinal patterns occurring before high pulses identified.
    - Could be useful for distinguishing different types of pulses?
- Ongoing work: characterizing the performance of these tools.

Collaborators


Sandro Perrone


Jordi Zamora


Ramon Vilaseca


Andres Aragoneses


Laura Carpi


Jatin Ahuja


D. Bhiku


Nuria Martinez


José A. Reinoso


Carme Torrent

Experimental data from:

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

UNIVERSITAT POLITÈCNICA
DE CATALUNYA
BARCELONATECH

Campus d'Excel·lència Internacional

THANK YOU FOR YOUR ATTENTION !

<cristina.masoller@upc.edu>

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

- C. Bonatto et al, PRL 107, 053901 (2011).
- 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).
- C. Masoller et al, New J. Phys. 17, 023068 (2015).
- Aragoneses et al, PRL 116, 033902 (2016).

ICREA

GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA E INNOVACIÓN