Predicting Extreme Optical Pulses in Laser Systems

Cristina Masoller

Universitat Politecnica de Catalunya

Cristina.masoller@upc.edu

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Oldenburg, Germany, May 2017

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GOBIERNO DE ESPAÑA MINISTERIO DE CIENCIA E INNOVACIÓN

Calcutta, February 2016

Dresden, October 2016

HAPPY BIRTHDAY !!!

Potsdam, September 2016

Ulrike’s work: a great source of inspiration!

Snowbird, May 2017

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)

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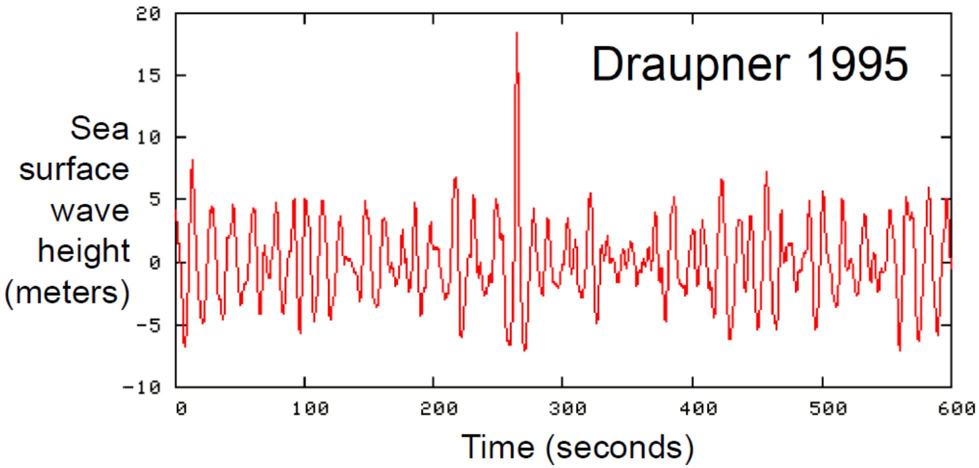
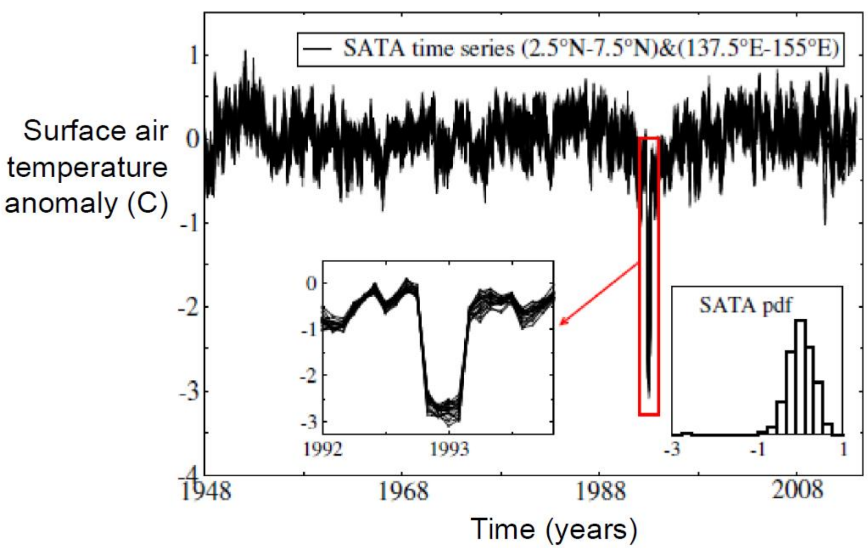
Rogue waves appear suddenly and vanish without a trace

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

Source: National Geographic

Extreme events in nature

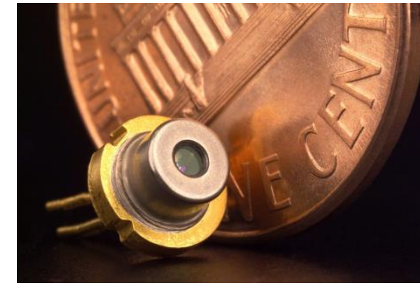


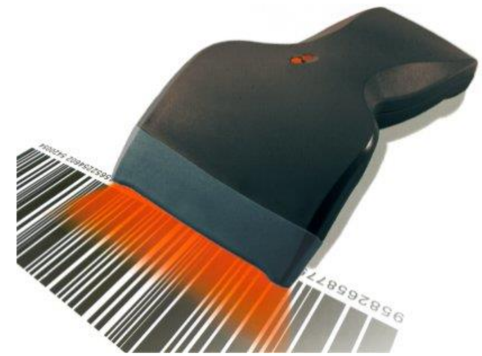


Optical systems generate "big data" and provide an opportunity to understand extreme events & advance their predictability.

Semiconductor lasers (diode lasers)

- Widely used, inexpensive but easily perturbed



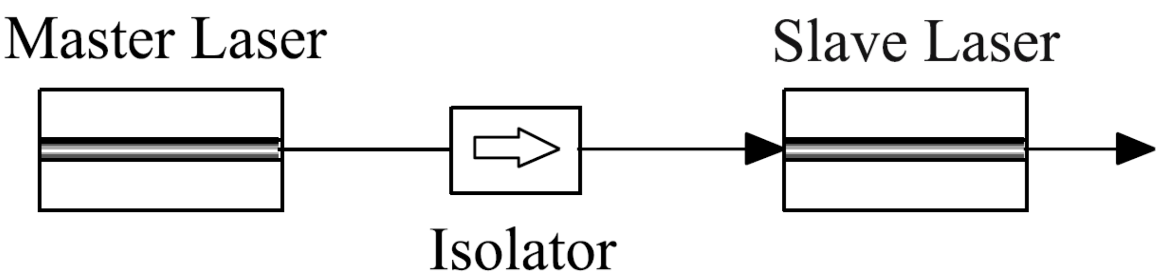


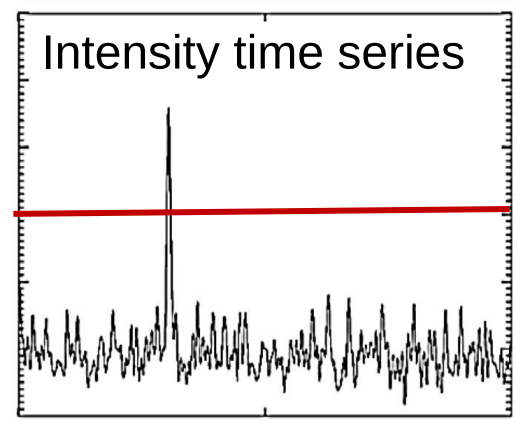
- Optically perturbed semiconductor lasers provide an inexpensive setup to study chaos and nonlinear dynamics.

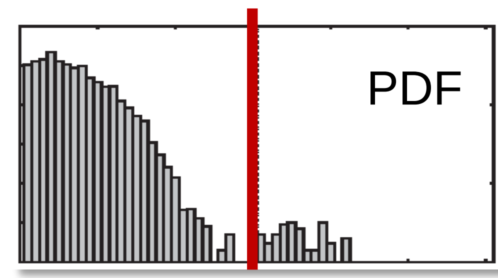
PRL **107,** 053901 (2011) PHYSICAL REVIEW LETTERS week ending 29 JULY 2011

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

What did we learn?

In our system, optical rogue waves can be

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

Governing equations

- Complex field, **E –Laser intensity ~ |E|²**
- Carrier density, **N**

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

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

optical injection
η: injection strength
Δω= ω_s-ω_m: detuning

spontaneous emission noise

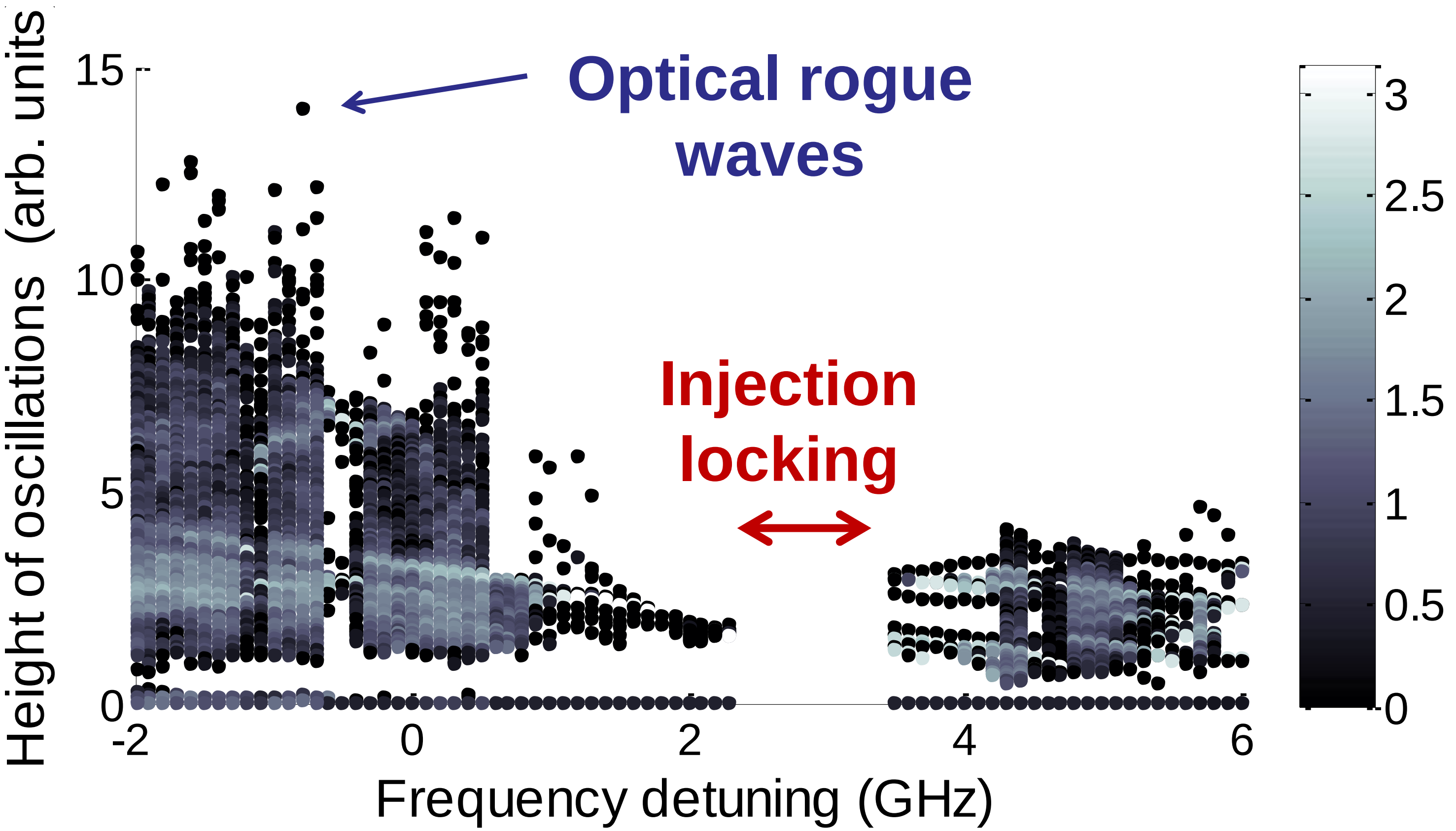
Solitary laser parameters: **α τ_p τ_N μ**

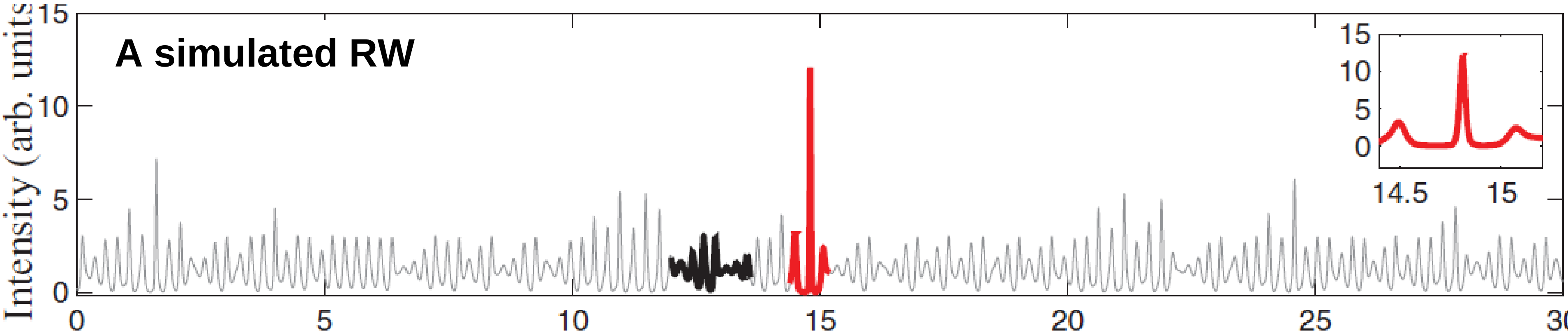
μ: normalized pump current parameter

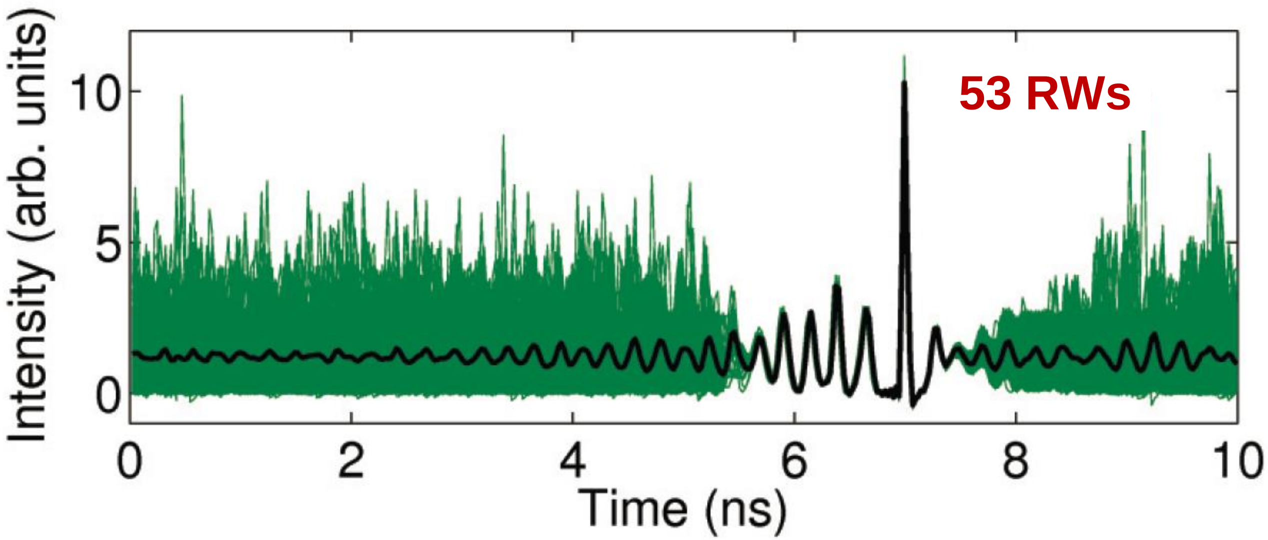
Typical parameter values:
α = 3, τ_p = 1 ps, τ_N = 1 ns

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

Bifurcation diagram in color code: log(number of pulses)







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

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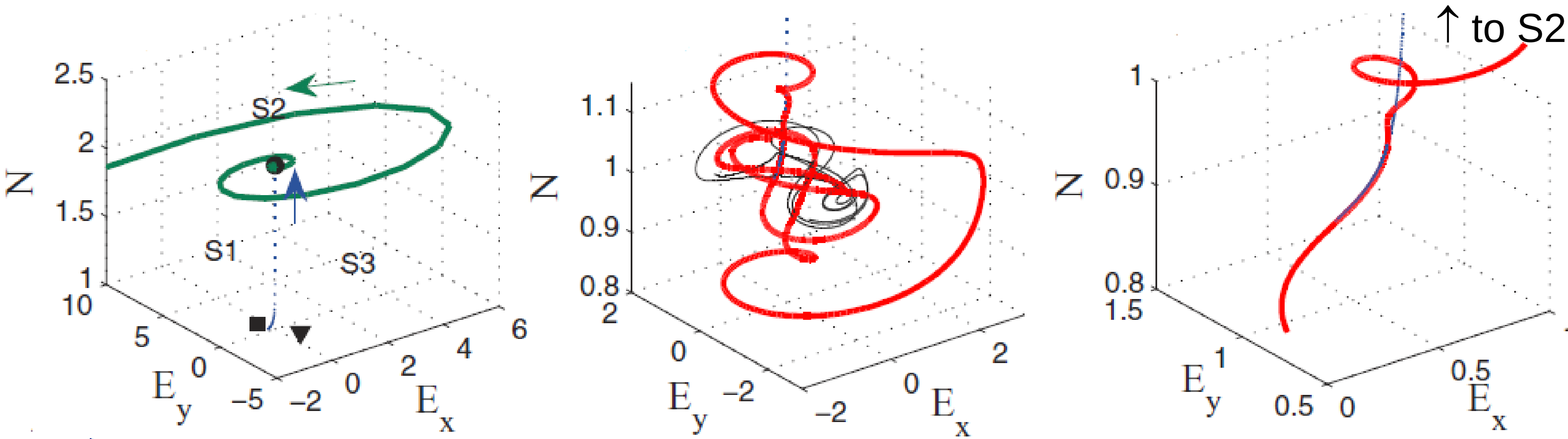
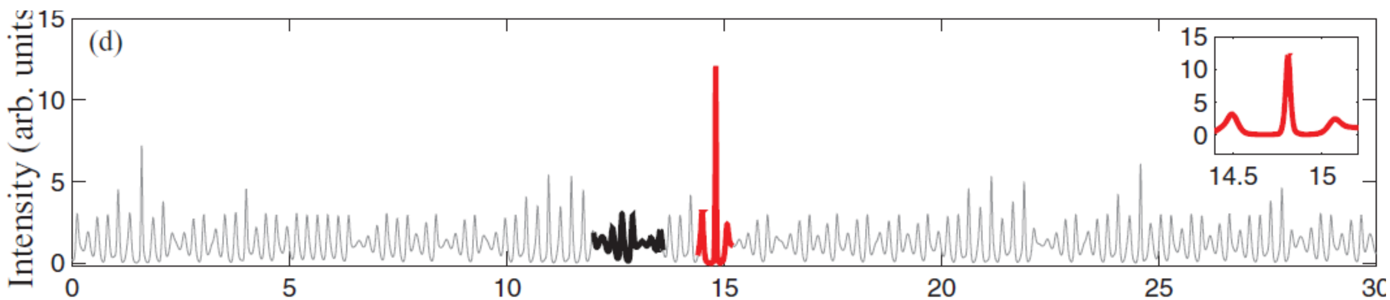
What triggers a RW?





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

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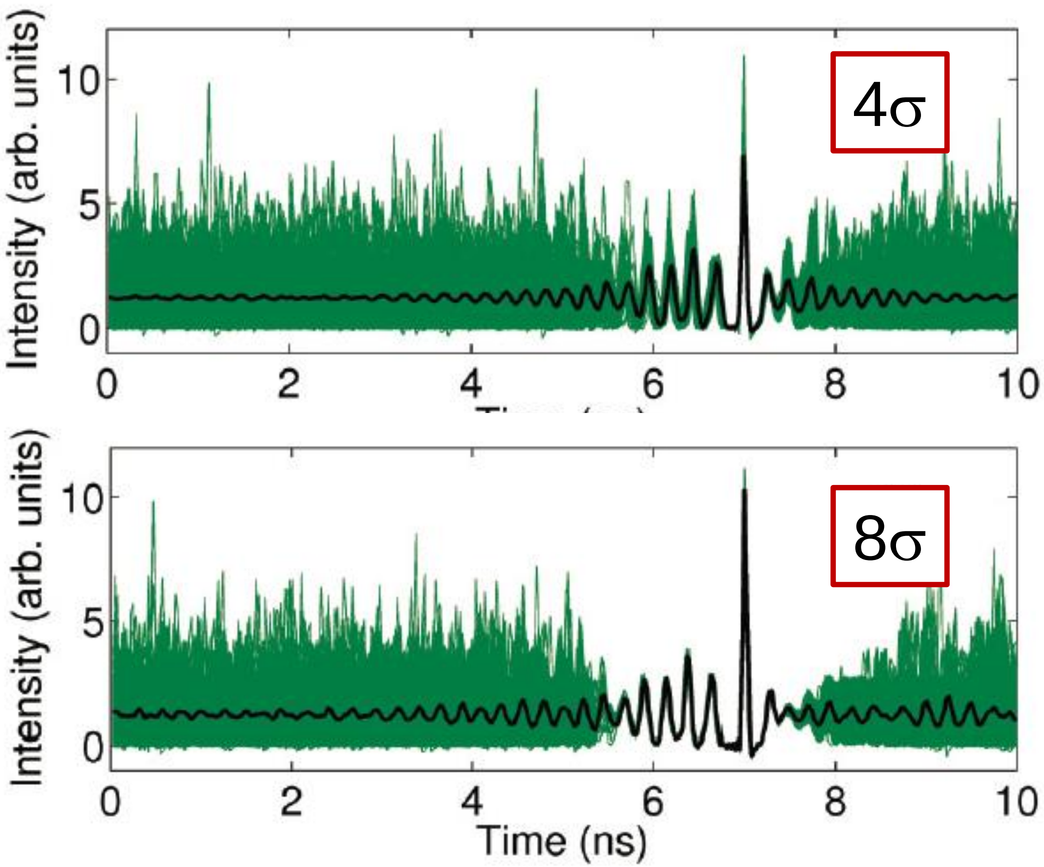
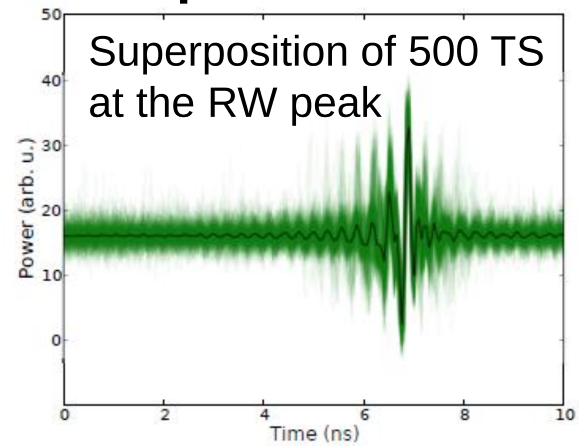
Rogue wave predictability

Deterministic simulations



Superposition of 50 time-series at the RW peak

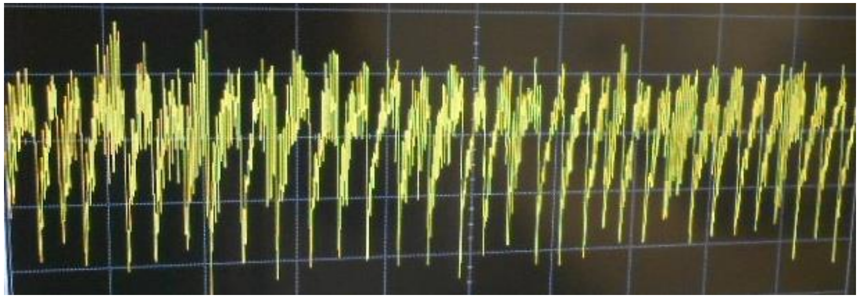
Experiments

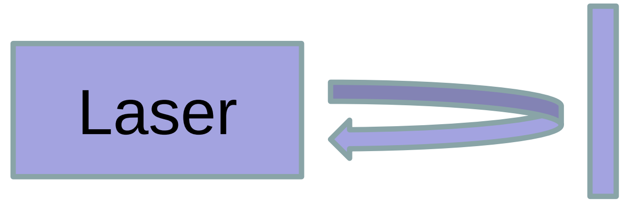


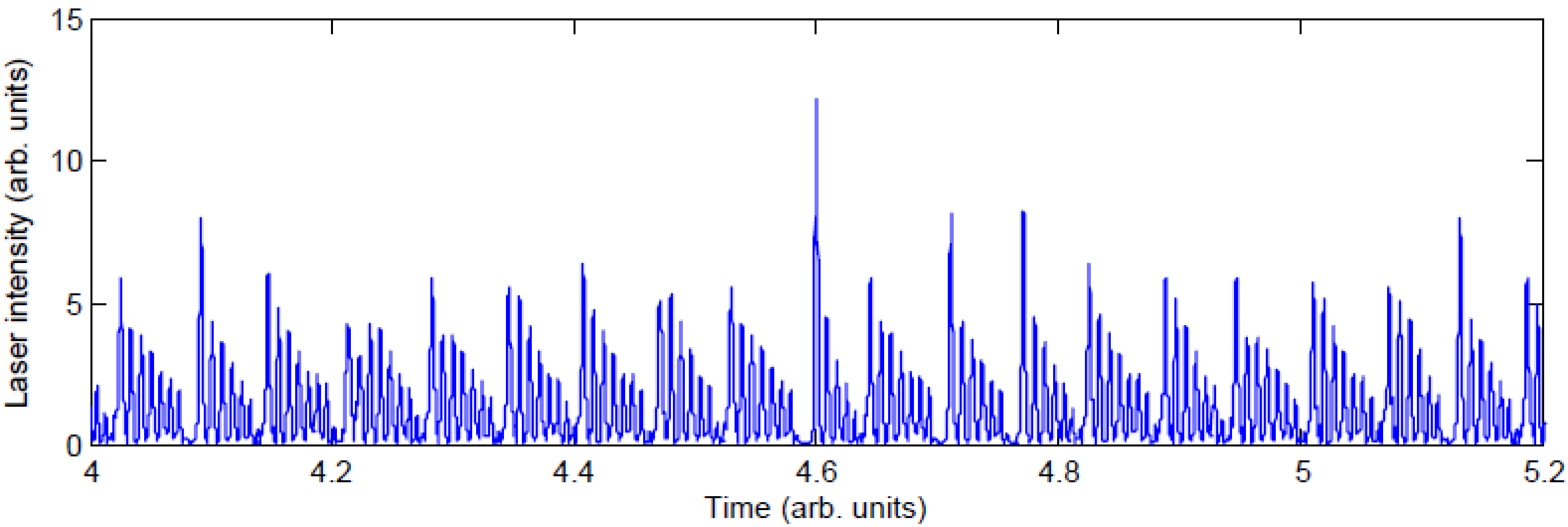
⇒ Well-defined oscillation pattern anticipates extreme pulses.

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

A similar effect in the intensity dynamics induced by optical feedback

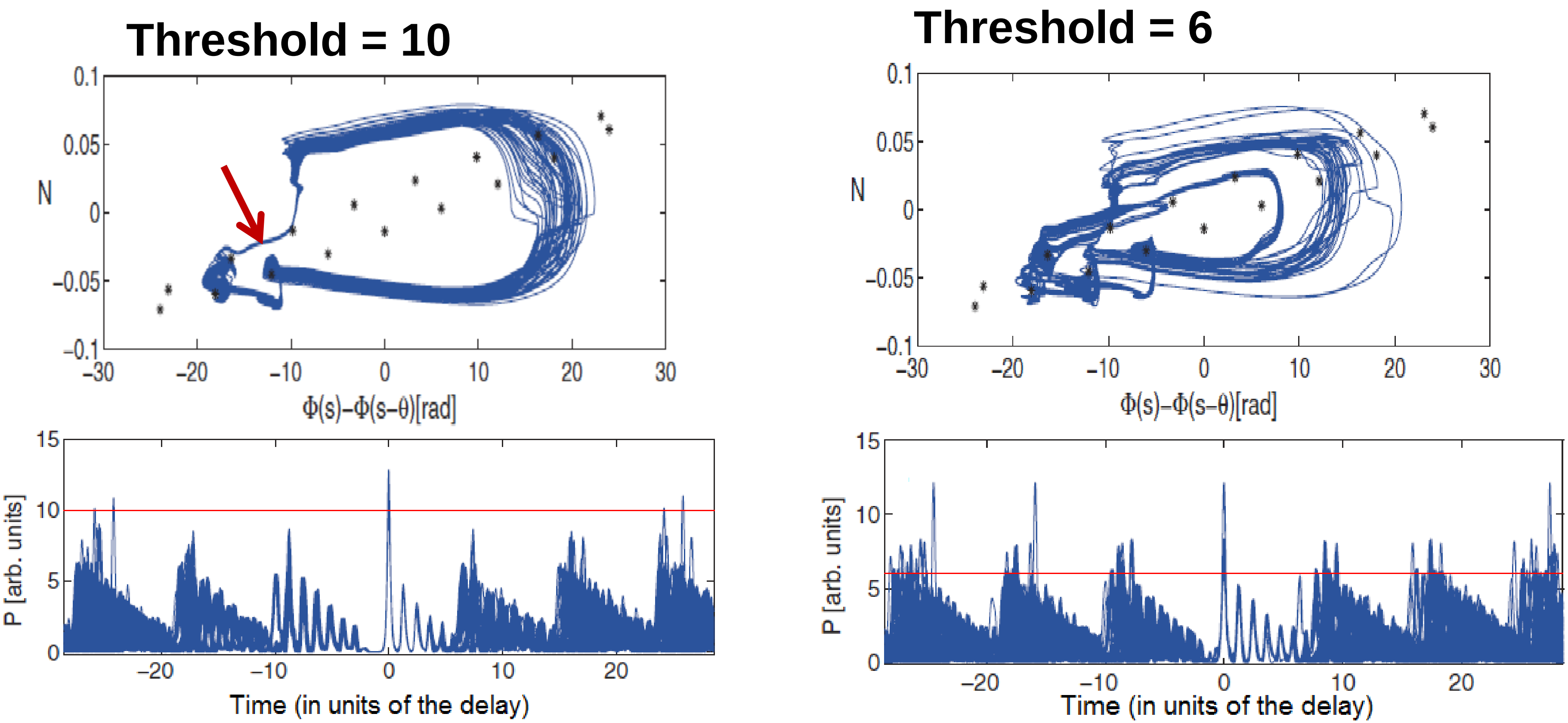






J. A. Reinoso, J. Zamora-Munt and C. Masoller. PRE 87, 062913 (2013)

Superposition of 52 pulses



Narrow channel also seen in other systems

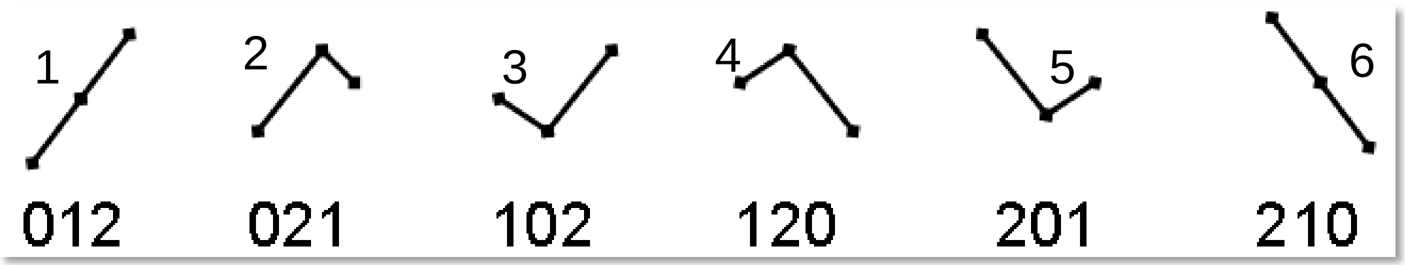
(*G. Ansmann, R. Karnatak, K. Lehnertz, and U. Feudel, PRE 88, 052911 2013*)

How can this effect be quantified?

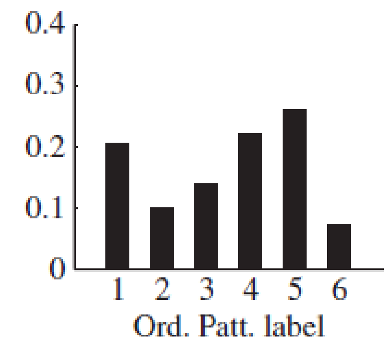
Symbolic method of time-series analysis: Ordinal Patterns

$X = \{\ldots \mathbf{x}_i, \mathbf{x}_{i+1}, \mathbf{x}_{i+2}, \ldots\}$

D=3

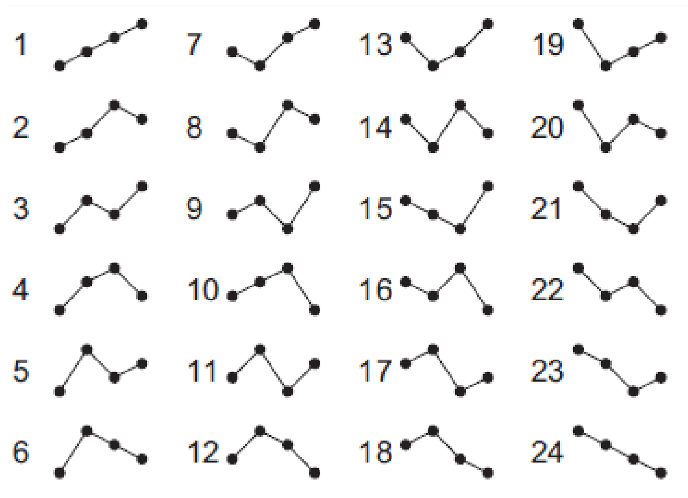


Ordinal probabilities



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

D=4



D=5: 120 patterns

Permutation entropy

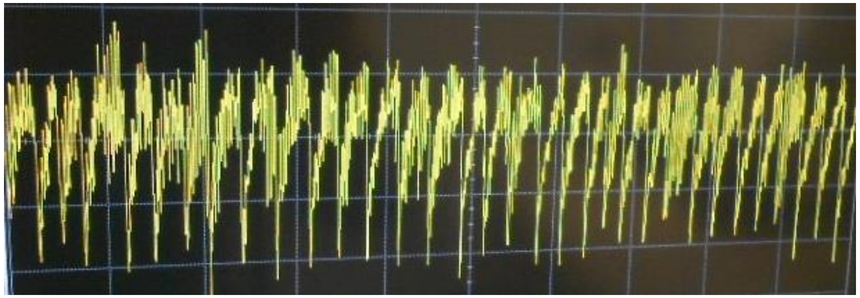
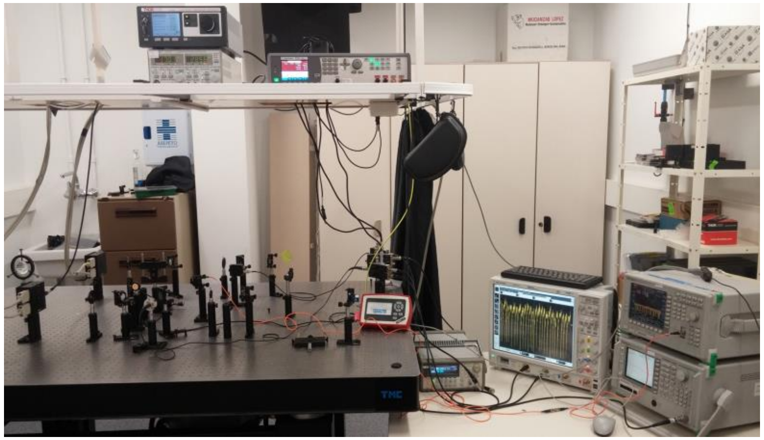
$$s_p = -\sum p_i \log p_i$$

Alternative: use a <u>lag</u>

$\{\ldots \mathbf{x}_i, x_{i+1}, \mathbf{x}_{i+2}, x_{i+3}, \mathbf{x}_{i+4}, x_{i+5} \ldots\}$

Brandt & Pompe, PRL 88, 174102 (2002)

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

Example of application of ordinal analysis

- temporal ISI correlations among optical spikes?
- how do they vary with the control parameters?

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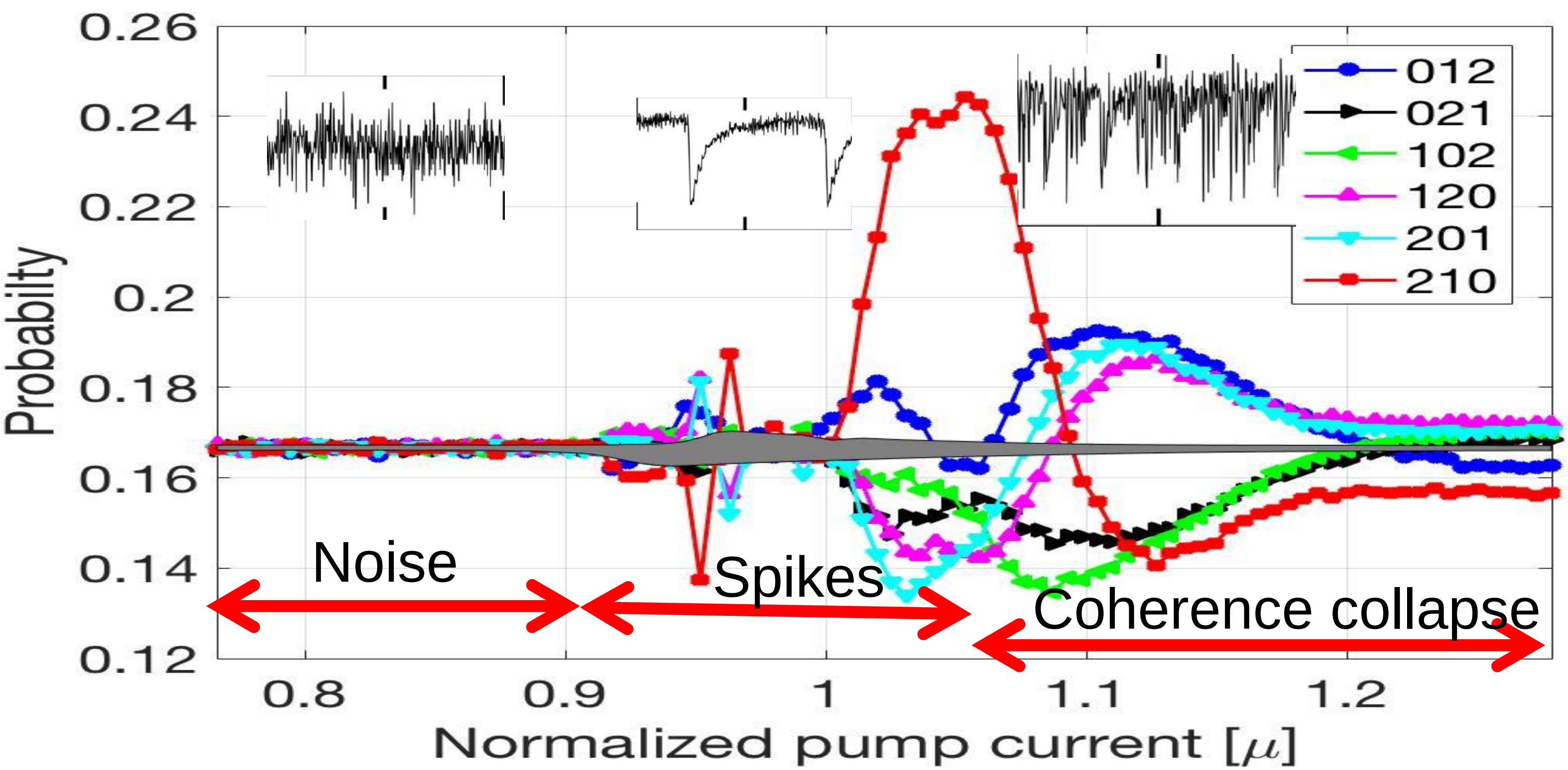
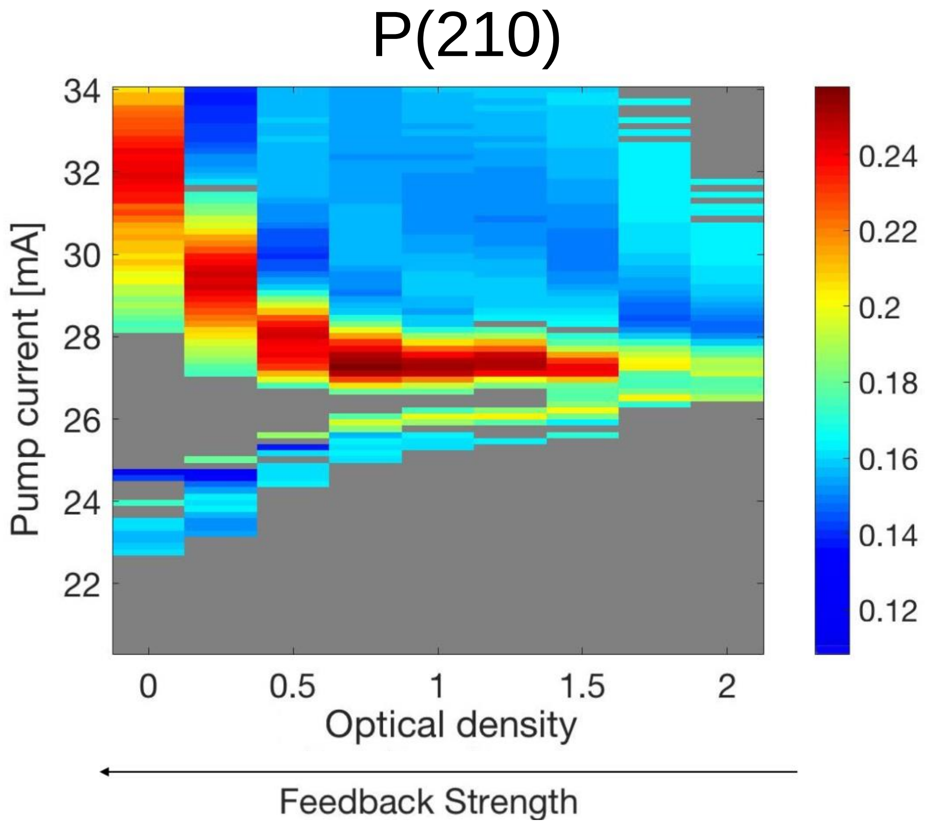
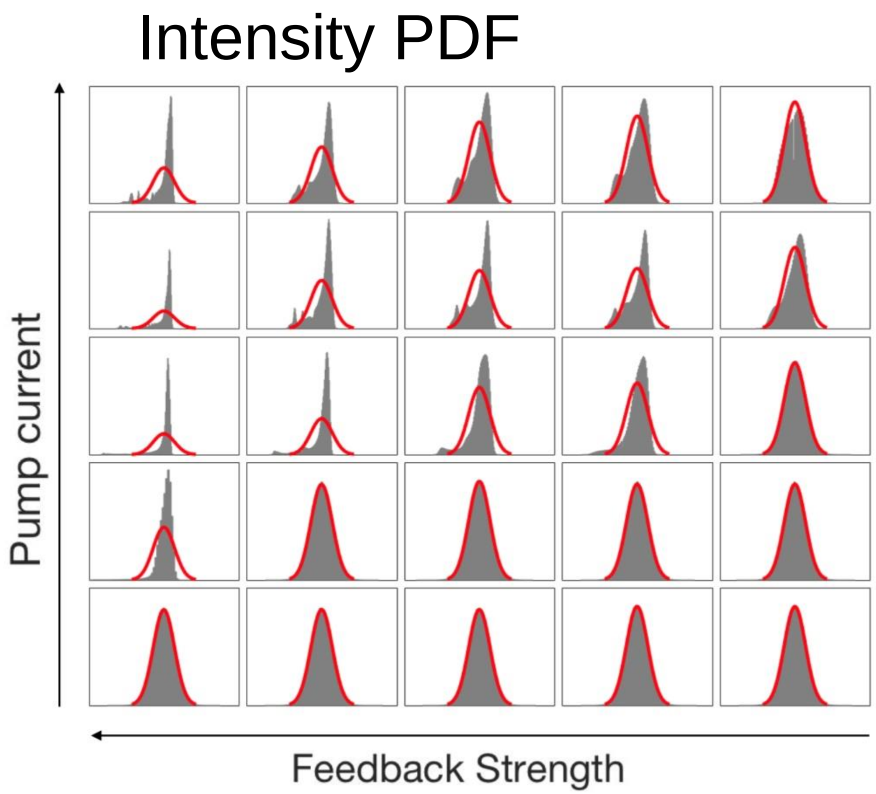
Ordinal analysis allows to quantify the onset of different dynamical regimes



C. Quintero-Quiroz et al, "*Characterizing how complex optical signals emerge from noisy intensity fluctuations*", Sci. Rep. 6 37510 (2016)
M. Panozzo et al, in preparation (2017)

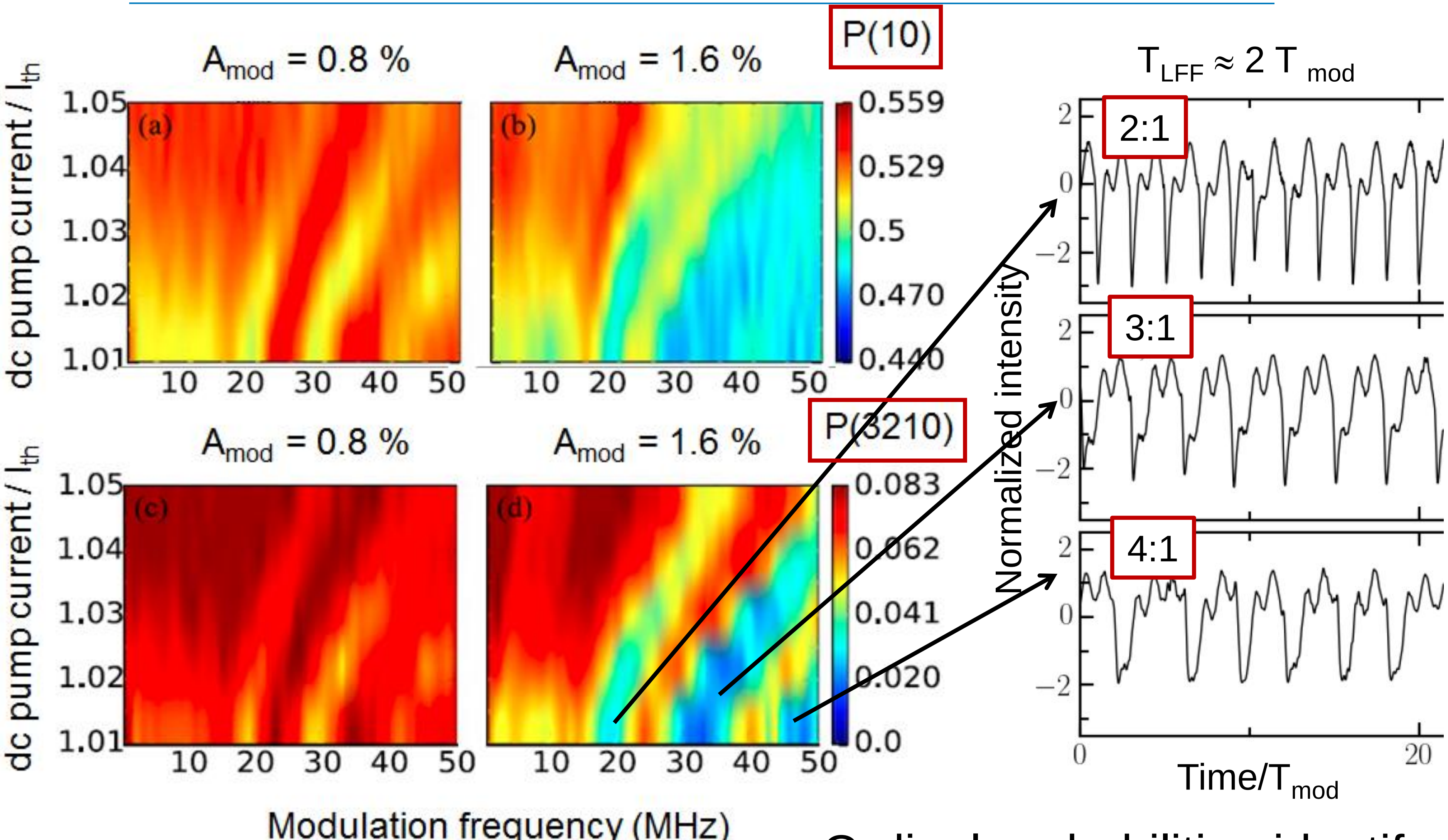
Map of dynamical regimes vs pump current & feedback strength





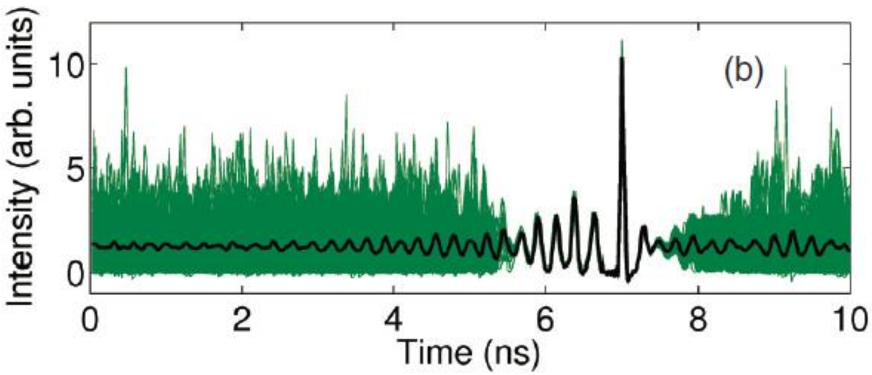
M. Panozzo et al, in preparation (2017)

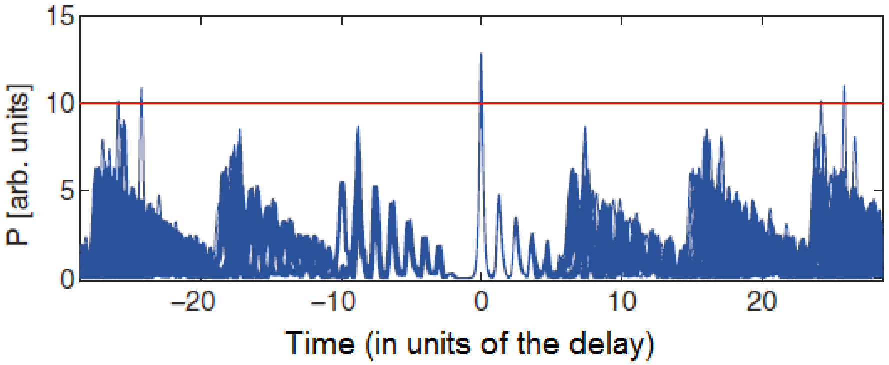
Ordinal analysis allows to identify noisy entrainment to sinusoidal modulation



$\Rightarrow$ Ordinal probabilities identify regions of noisy locking

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





Using ordinal analysis to quantify the predictability of extreme pulses

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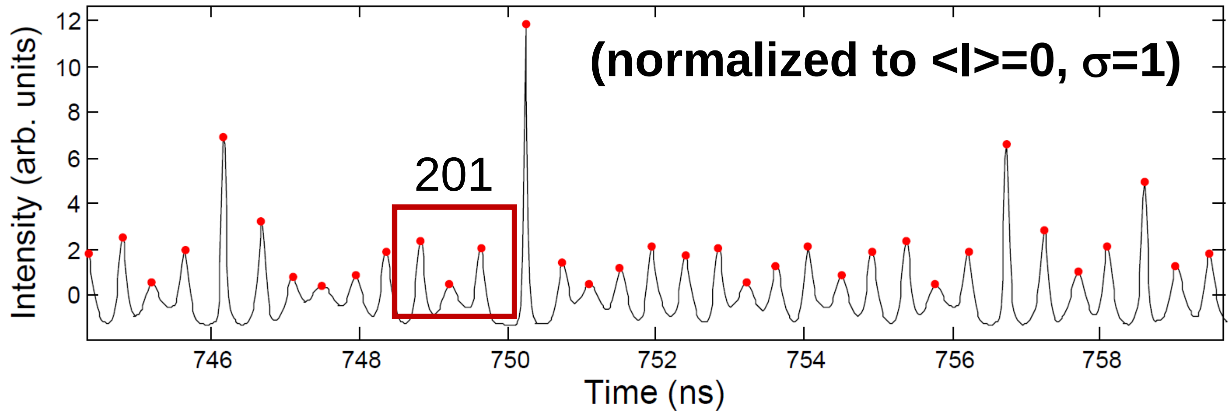
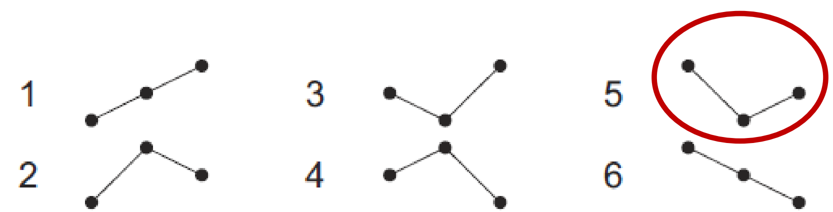
Ordinal analysis for "early warning" of rogue wave



- 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:

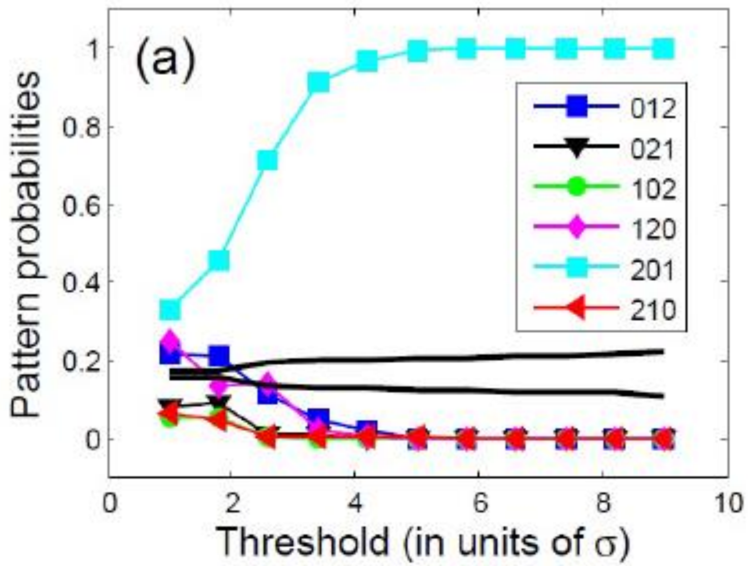


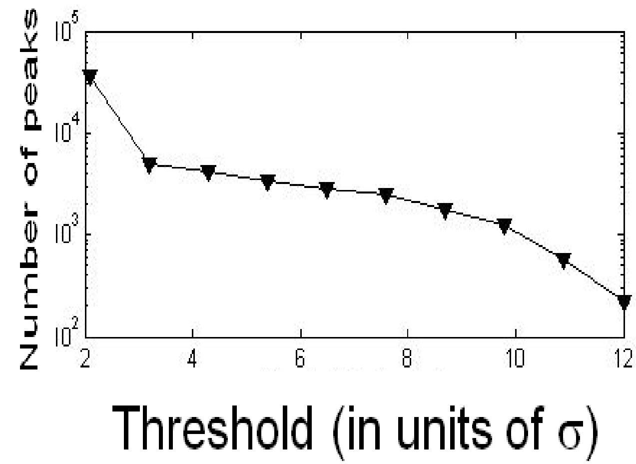
We calculate the probability of the pattern that occurs before each high pulse:

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

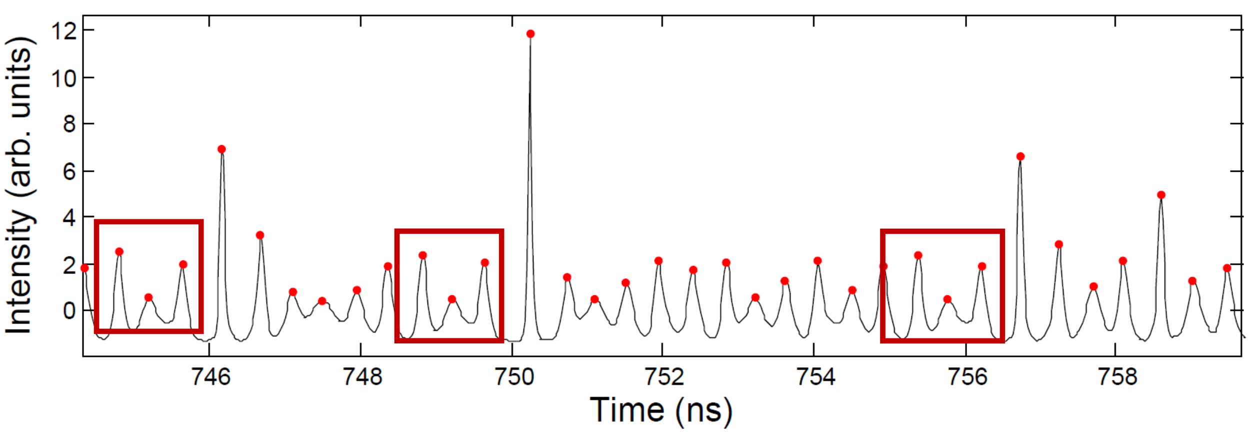
Results: deterministic simulations

Black lines:
99% confidence
$p_i=1/6 \ \forall \ i$





- P(201)=1 if TH >6



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

Model and parameters as in J. Ahuja et al, Optics Express 22, 28377 (2014).

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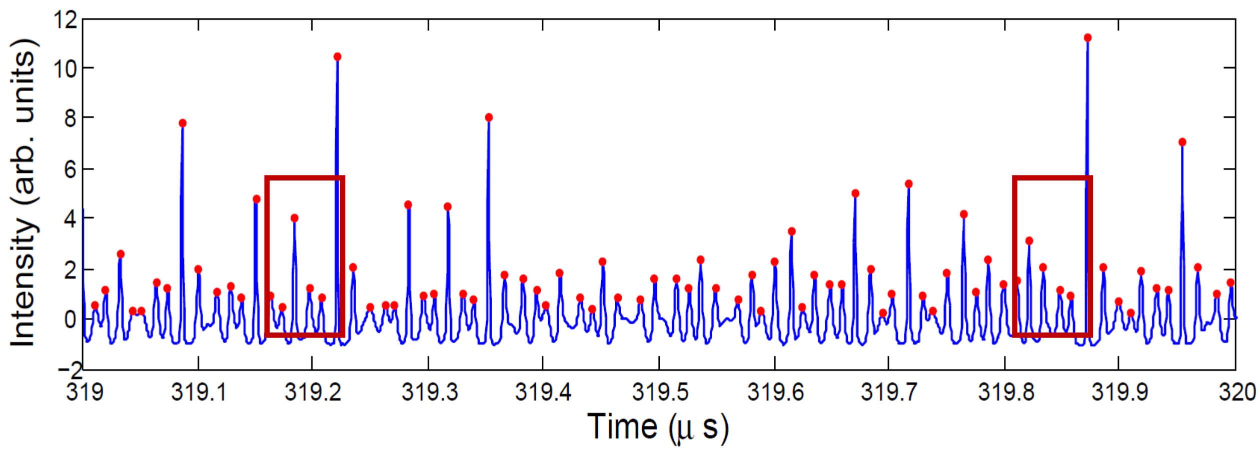
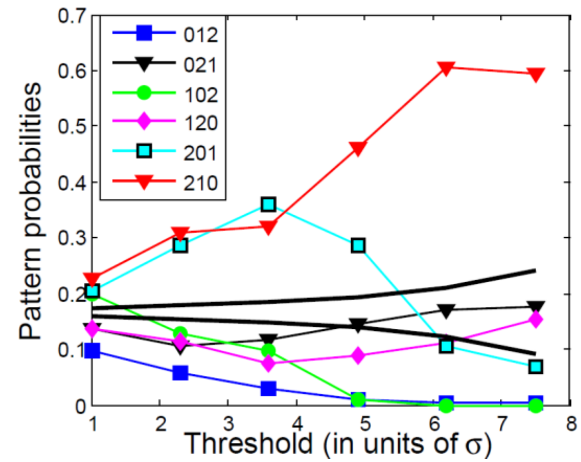
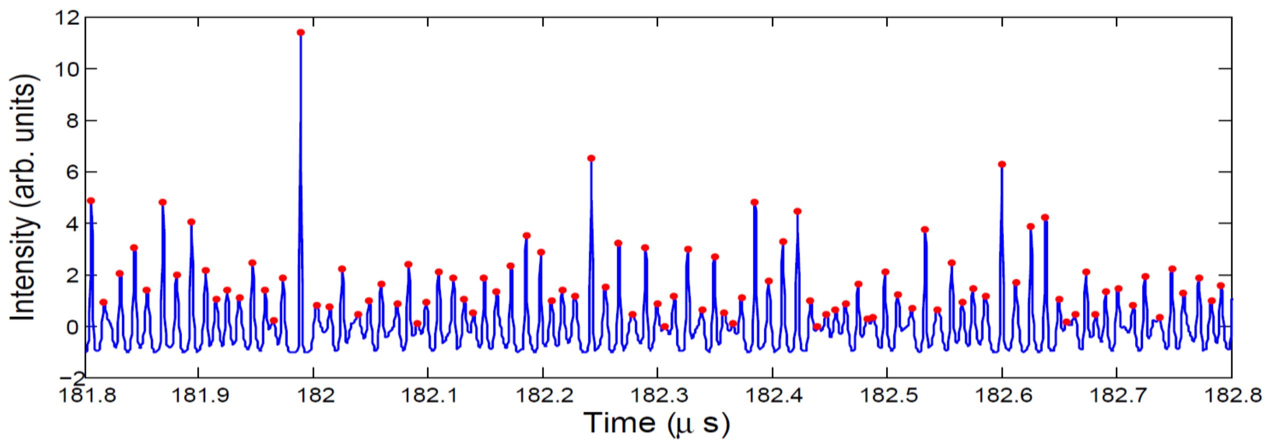
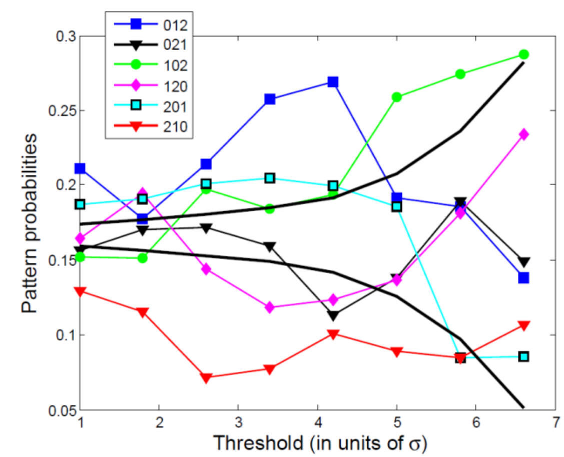
Including spontaneous emission noise and current modulation

- Two different modulation frequencies





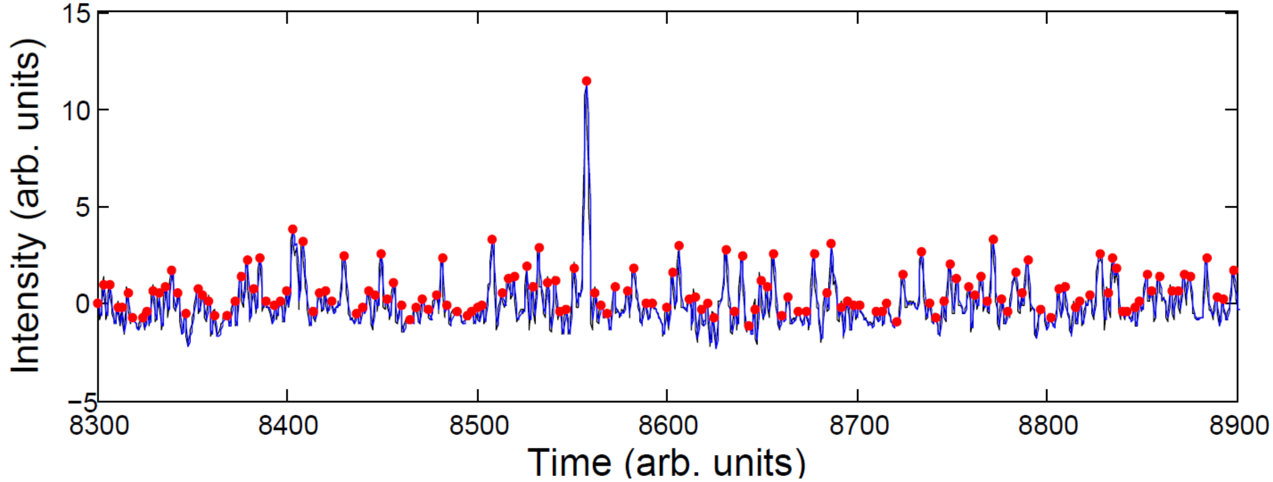


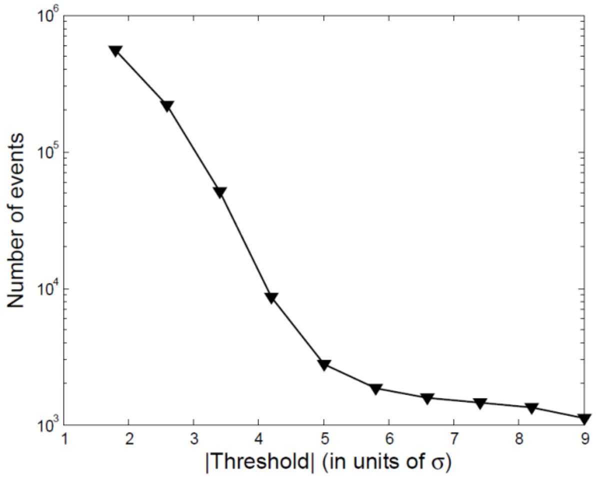


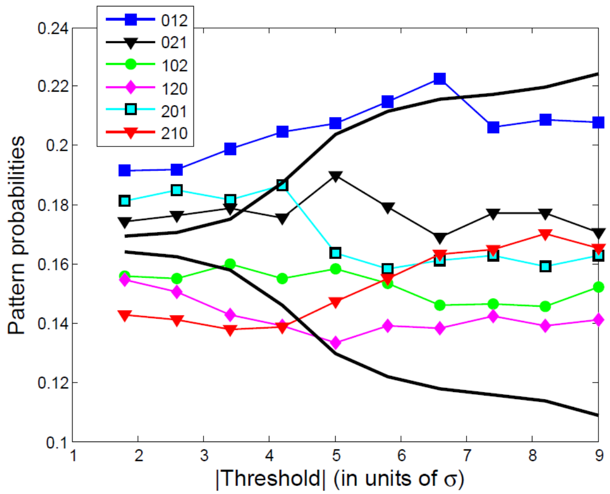
In the first case: 210 is a "good" warning.

⇒"early warning pattern" varies with parameters and might not exist.

Analysis of experimental data (Nice)







Way to improve the "early warning":

- Filter noise
- Use longer patterns or lag

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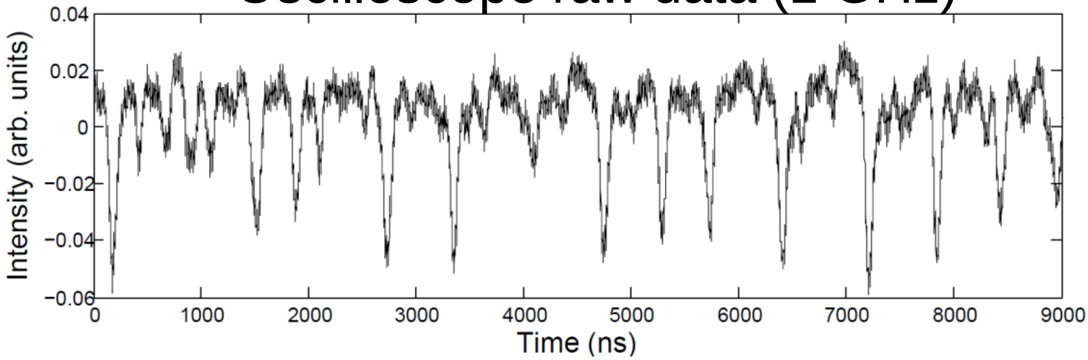
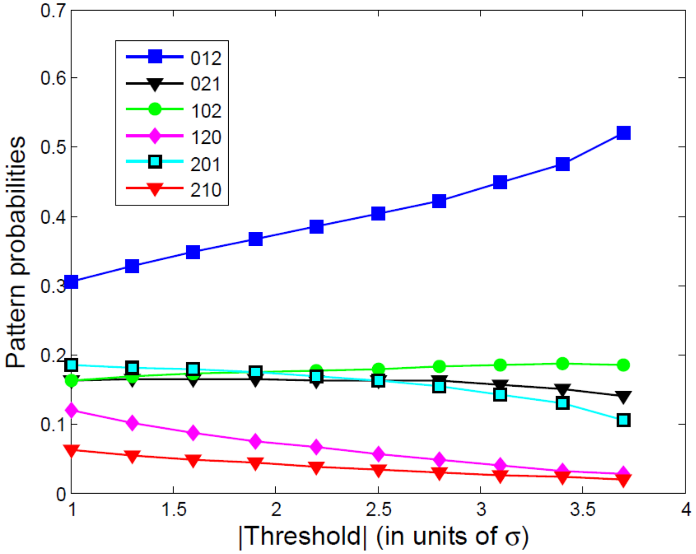
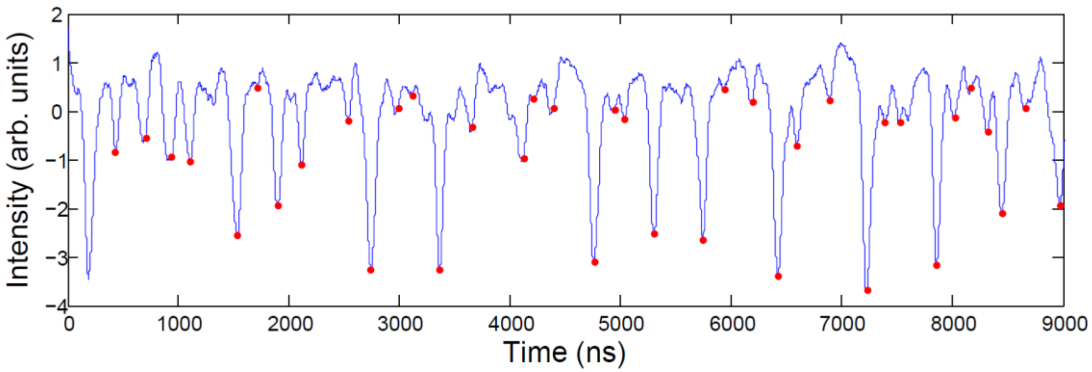
Experimental data (Terrassa): optical feedback-induced dropouts

Oscilloscope raw data (1 GHz)





Filtered time series, zero-mean and σ=1



⇒ **012** is the most probable pattern before a spike; **210** is the less expressed pattern

Summary

- In synthetic data: certain patterns of oscillations can be more (or less) likely to occur before the extreme pulses.

- In experimental data (work in progress): in order to identify patterns that anticipate the extreme pulses, noise needs to be filtered.

- The analysis of the pattern probabilities can provide complementary information to advance rogue wave predictability.

- Open issue: applicability to real-word time-series?

Co-authors

- Nuria Martinez and Saurabh Borkar (IIT Guwahati)
- Mattia Panozzo (Uni. Padova), Carlos Quintero, Jordi Tiana
- Jordi Zamora, Jose M. Aparicio Reinoso
- Carme Torrent

Experimental data: S. Barland (Nice)

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Thank you for your attention!

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

- C. Bonatto et al, PRL 107, 053901 (2011).
- J. Zamora-Munt et al, PRA 87, 035802 (2013).
- J. A. Reinoso, et al, PRE 87, 062913 (2013).
- C. Quintero-Quiroz et al, Sci. Rep. 6, 37510 (2016).

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