Predictability of optical rogue waves in optically injected semiconductor lasers

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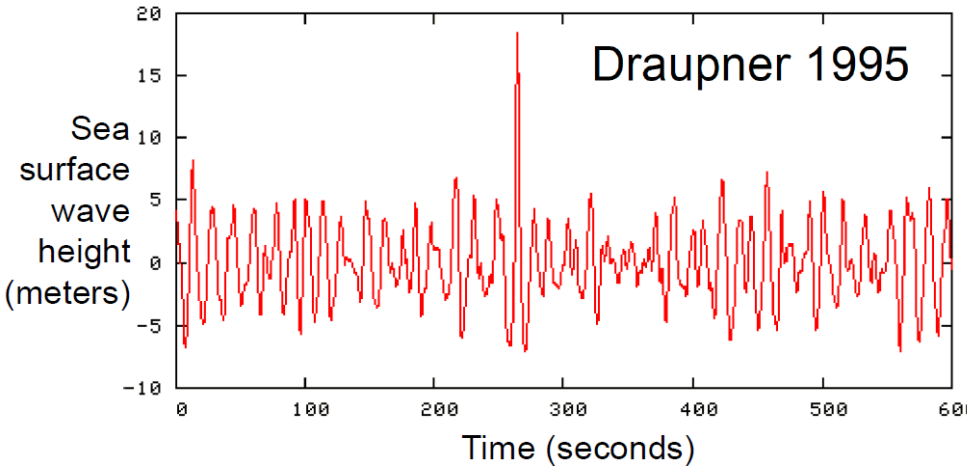
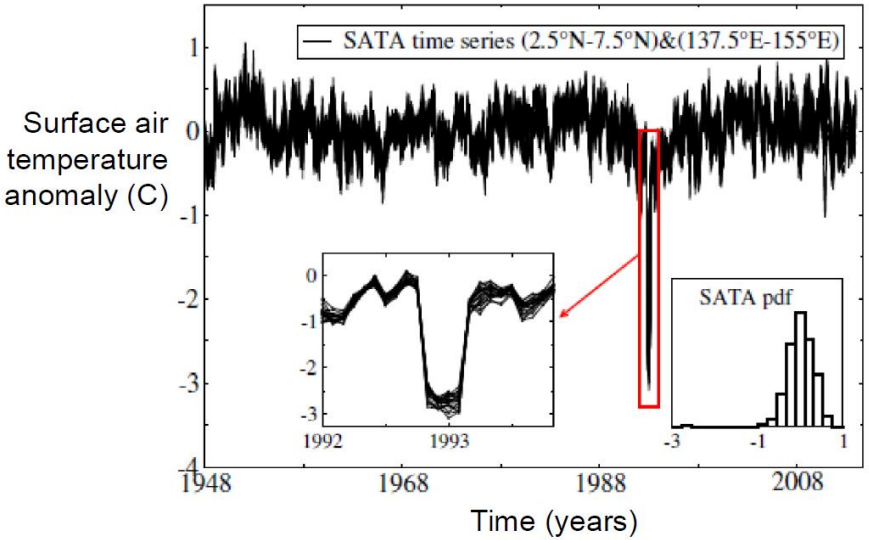
Motivation: extreme events in nature



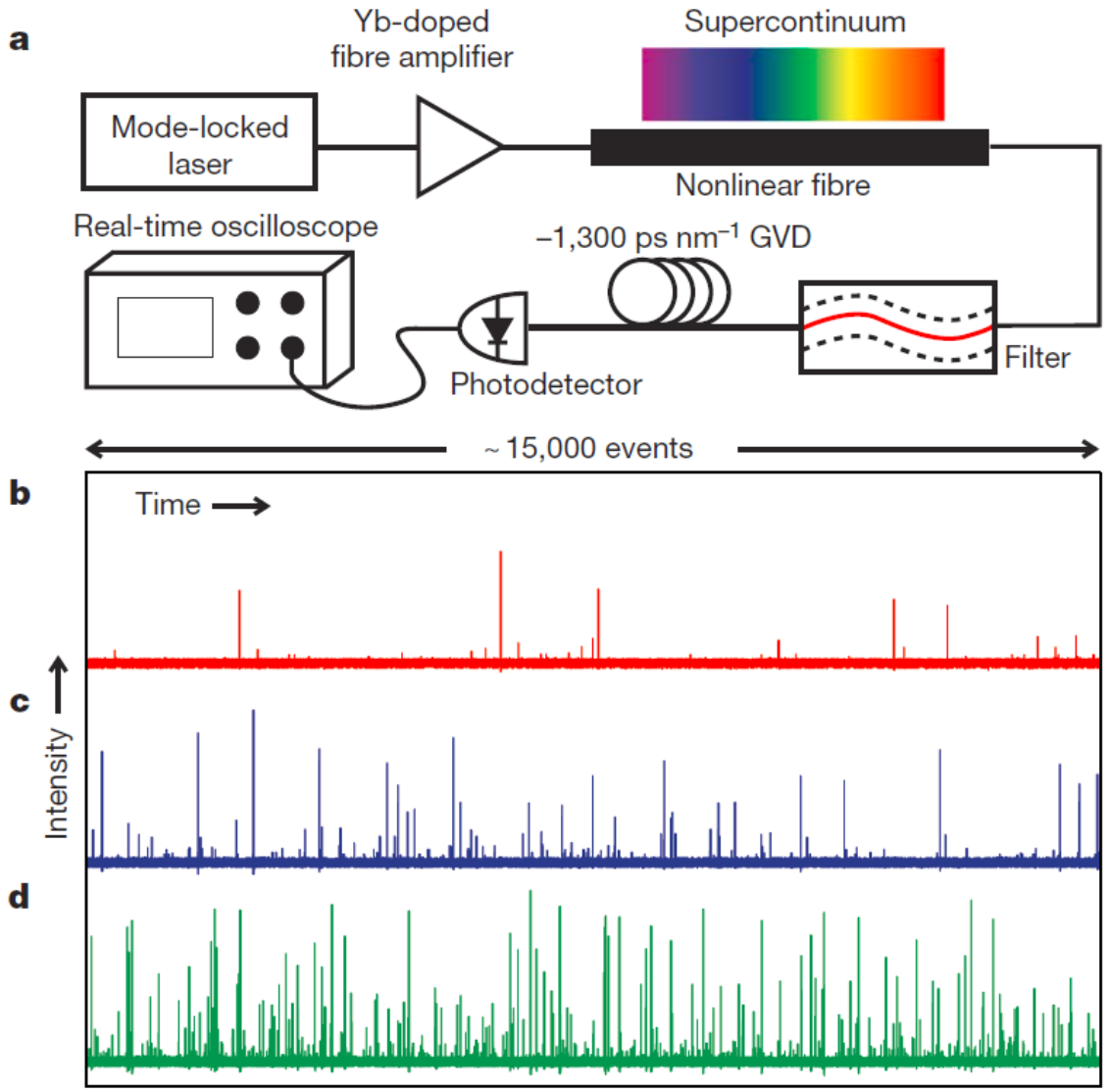


Optical chaos: an opportunity to better understand and to advance predictability

Optical rogue waves

Solli et al, Nature 2007

- Optical systems contribute to better understand the physical mechanisms capable of triggering (or suppressing) extreme events.
- Optical systems generate "big data", valuable for testing diagnostic tools for "early warnings" of extreme events.
- The analysis of extreme pulses yields new light into nonlinear & stochastic phenomena.



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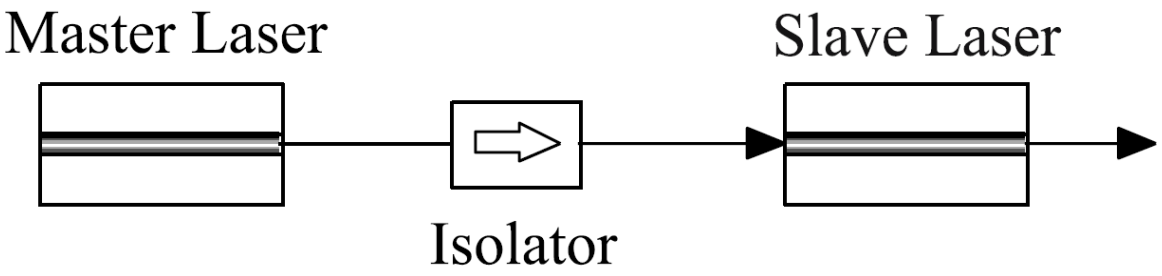
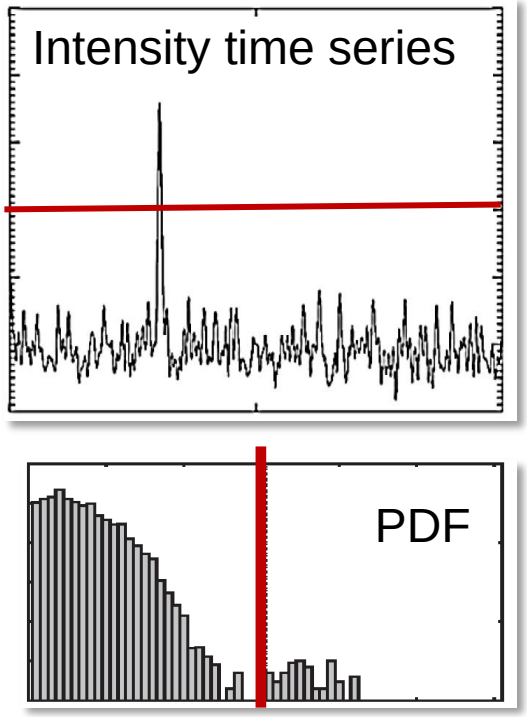
Deterministic Optical Rogue Waves

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

Governing equations

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

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

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

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

spontaneous emission noise

Solitary laser parameters: α τ_p τ_N μ

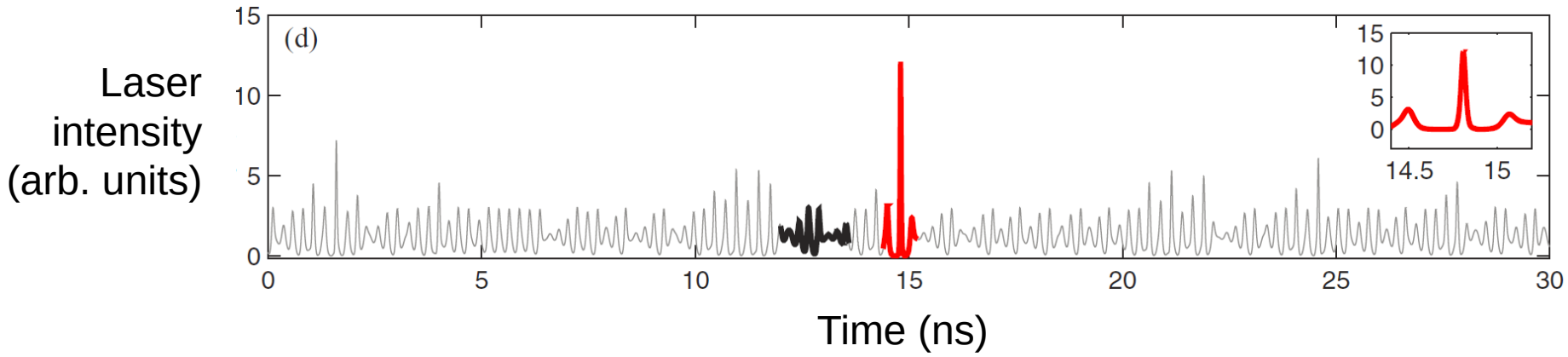
μ: normalized pump current parameter

Typical parameter values:

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

This simple rate-equation model provides good qualitative agreement with experimentally observed dynamical behaviors.

Getting started: a simulated rogue wave



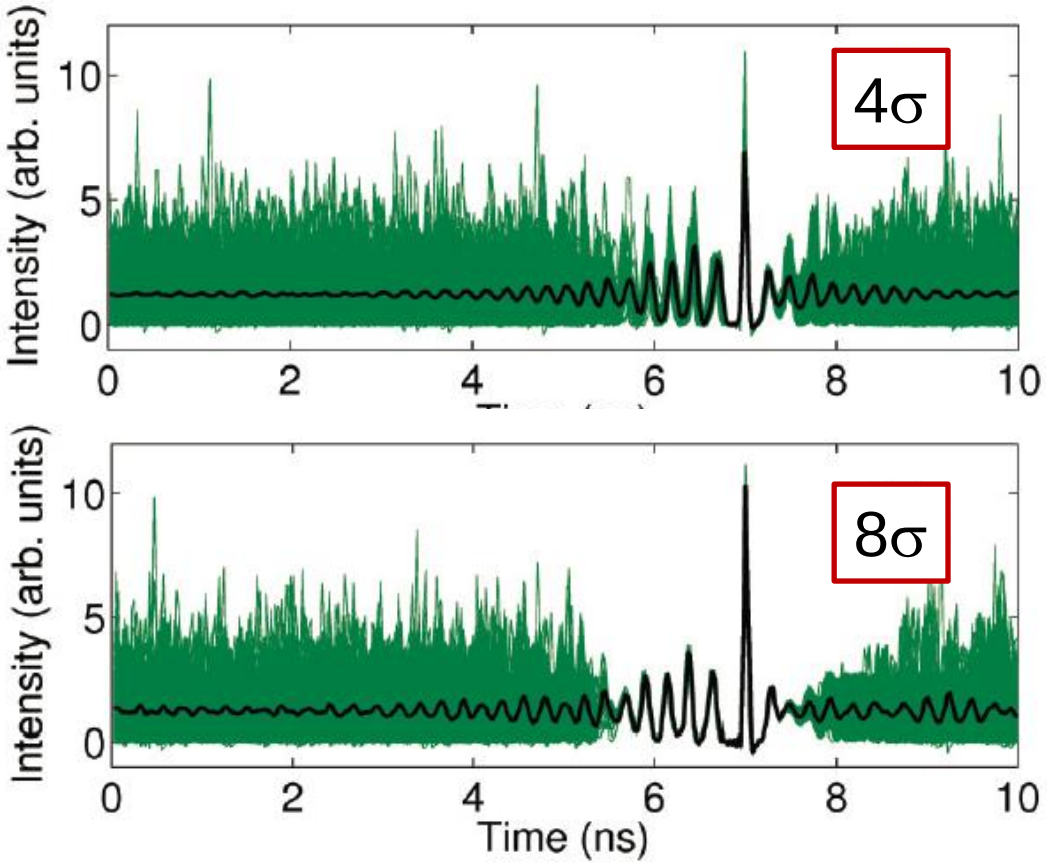
What did we learn from simulations?

In our system, ORWs can be

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

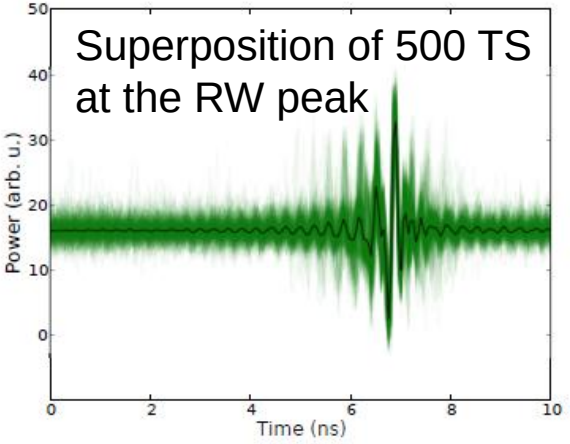
RW predictability

Deterministic simulations



Superposition of 50 time-series at the RW peak

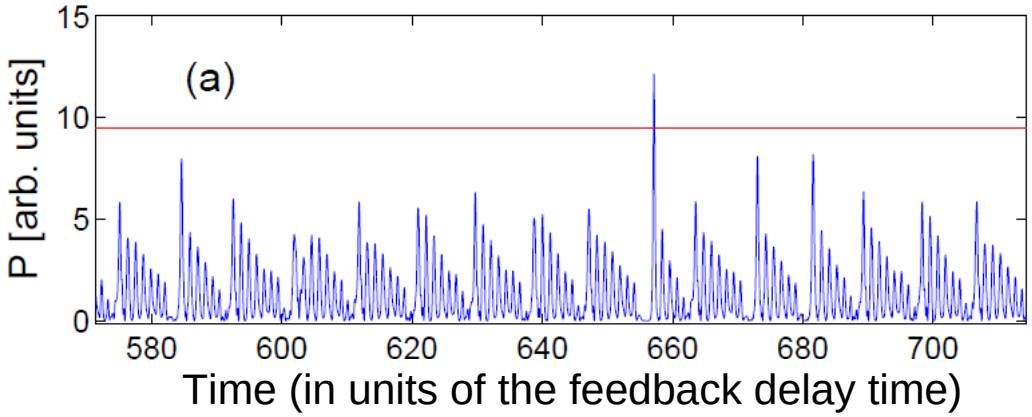
Experiments



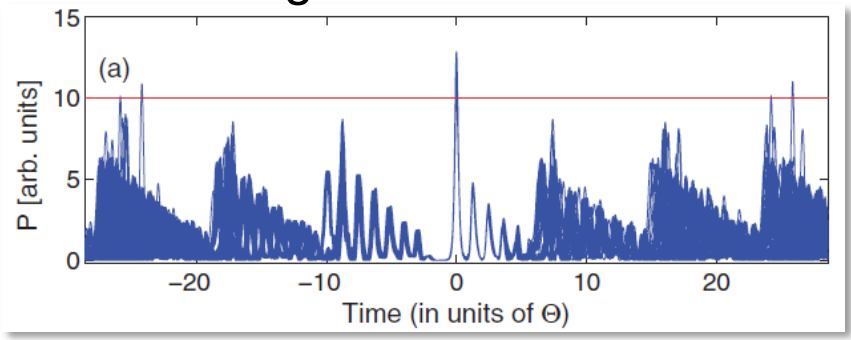
⇒ Well-defined oscillation pattern anticipates extreme pulses.

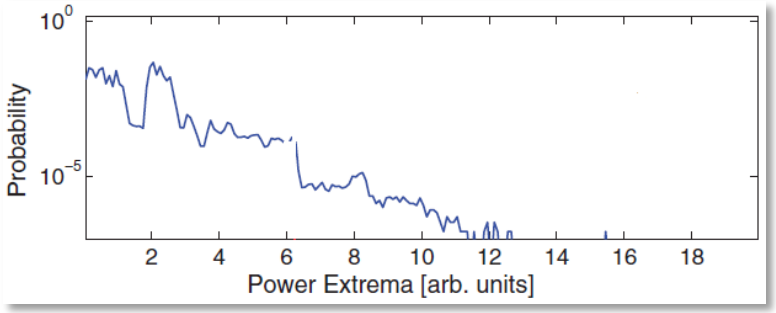
J. Zamora-Munt et al, PRA 87, 035802 (2013)

We found a similar effect with optical feedback

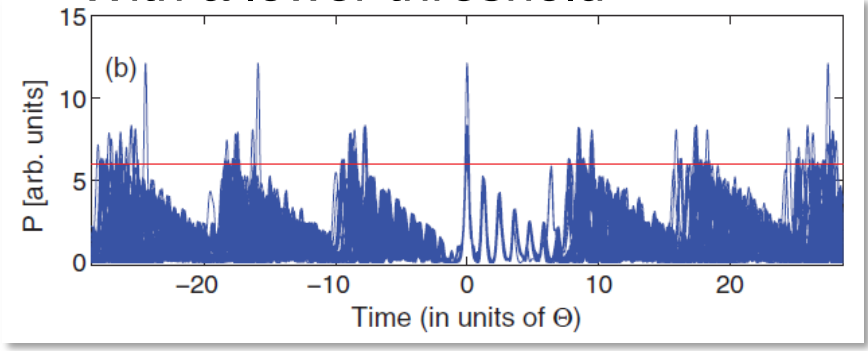


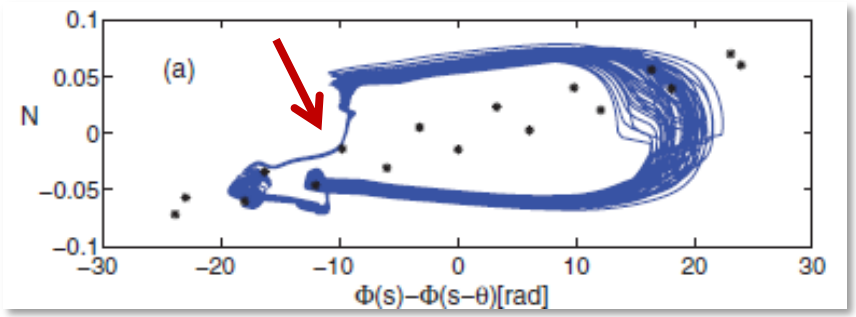
With a high threshold





With a lower threshold



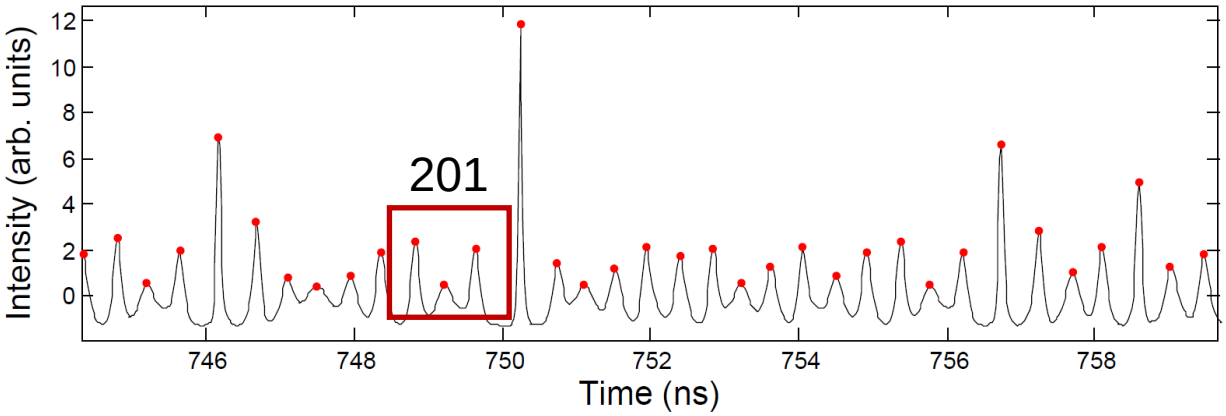


How can this effect be quantified?

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

Method of symbolic time-series analysis

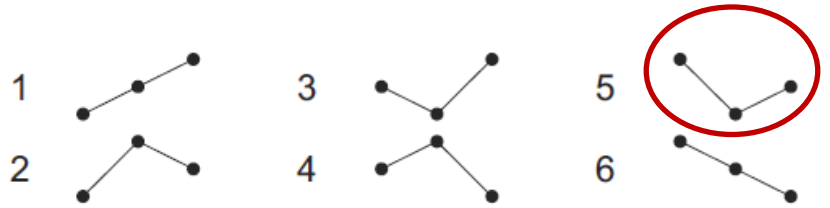
Brandt & Pompe, PRL 88, 174102 (2002)



- 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 $(I_{i-3}, I_{i-2}, I_{i-1})$

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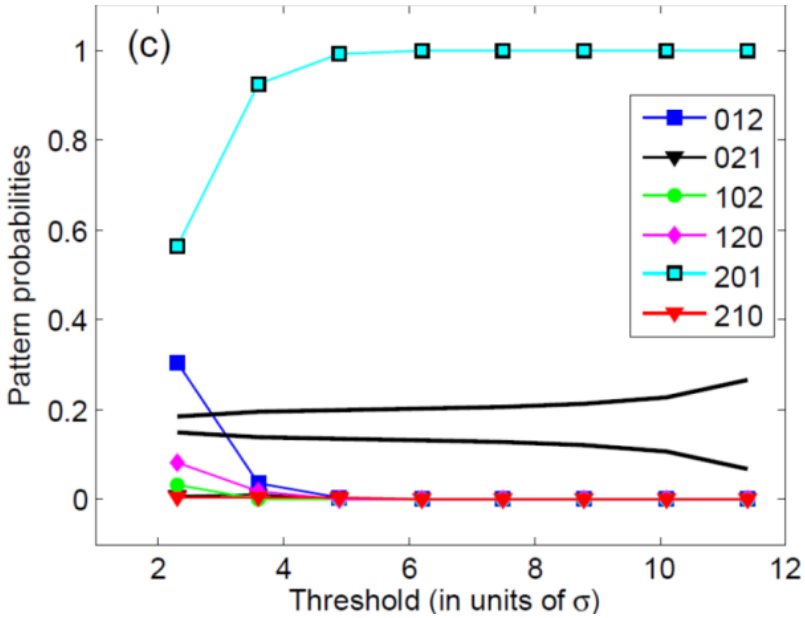
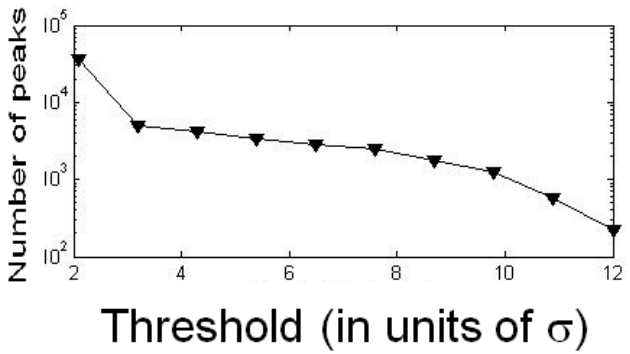
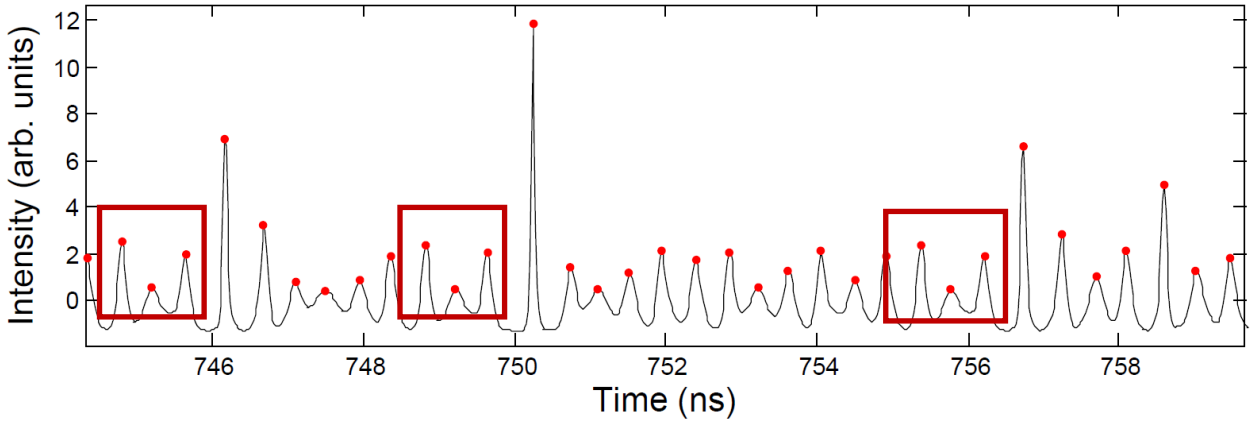
Results: deterministic simulations

Black lines: 95% confidence $p_i=1/6\ \forall\ i$





- P(201)=1 if TH >6

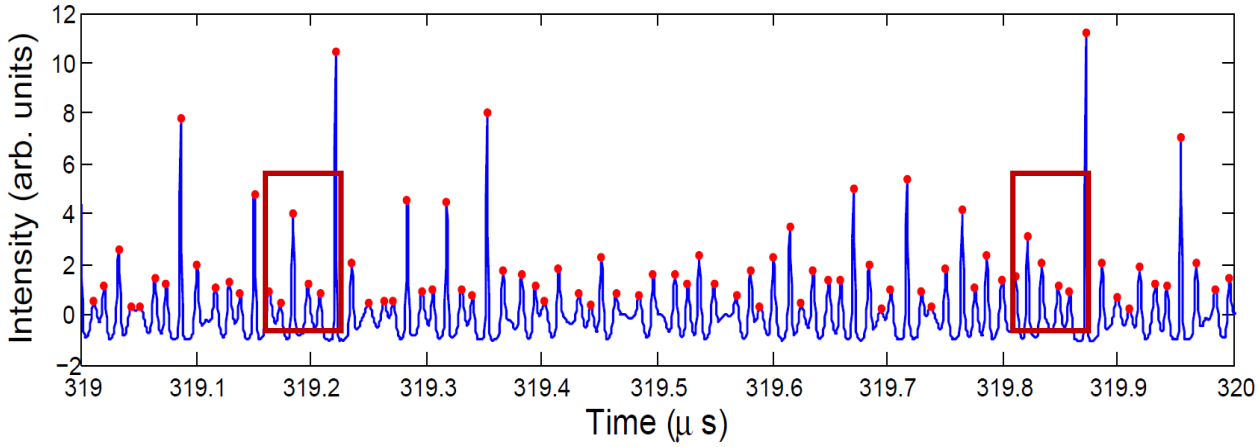


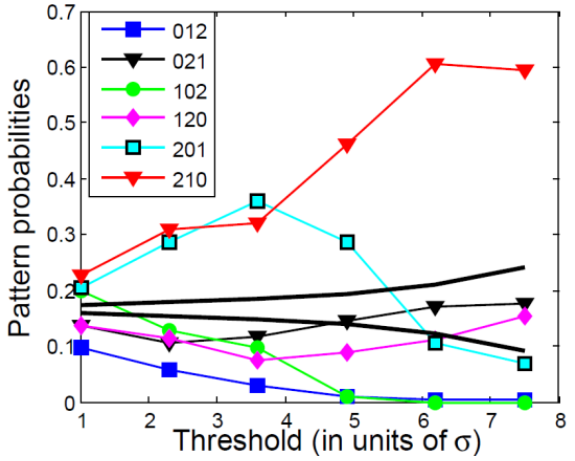
- Problem: P(201)≠0 if TH <6 (pattern 201 also anticipates some small pulses) ⇒ false alarms (false positives)

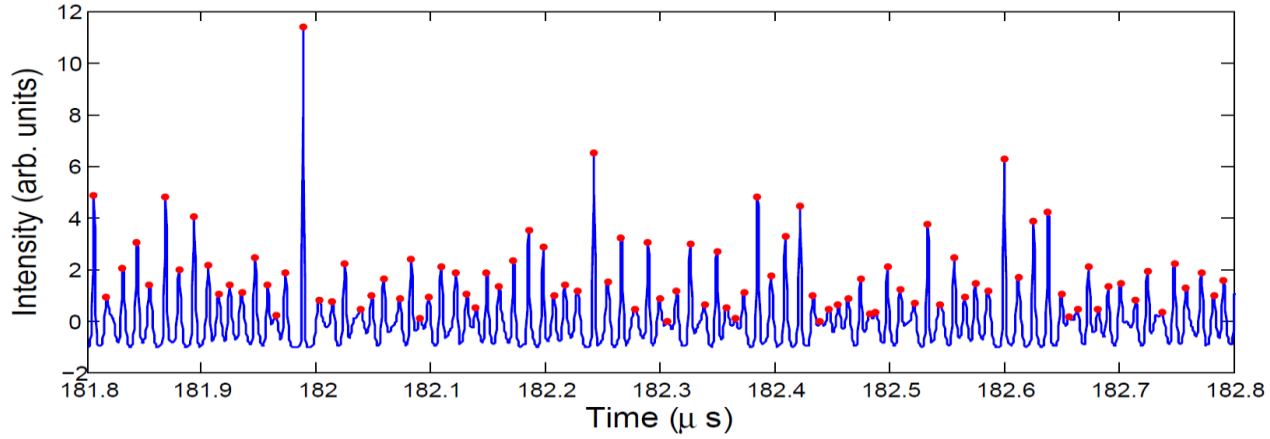
Model and parameters as in J. Ahuja et al, Optics Express 22, 28377 (2014).

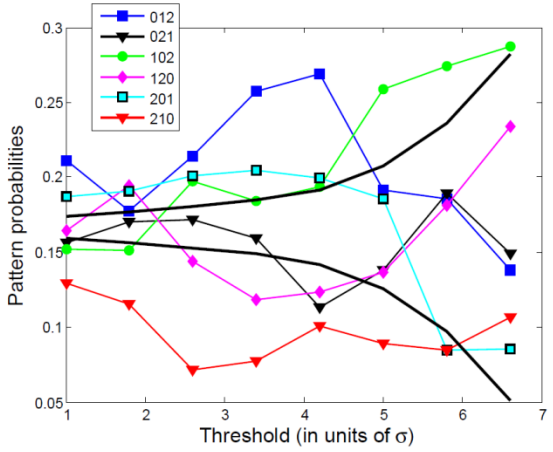
Including spontaneous emission noise and current modulation

- Two different modulation frequencies









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

⇒"early warning pattern" varies with parameters and not always well-defined.

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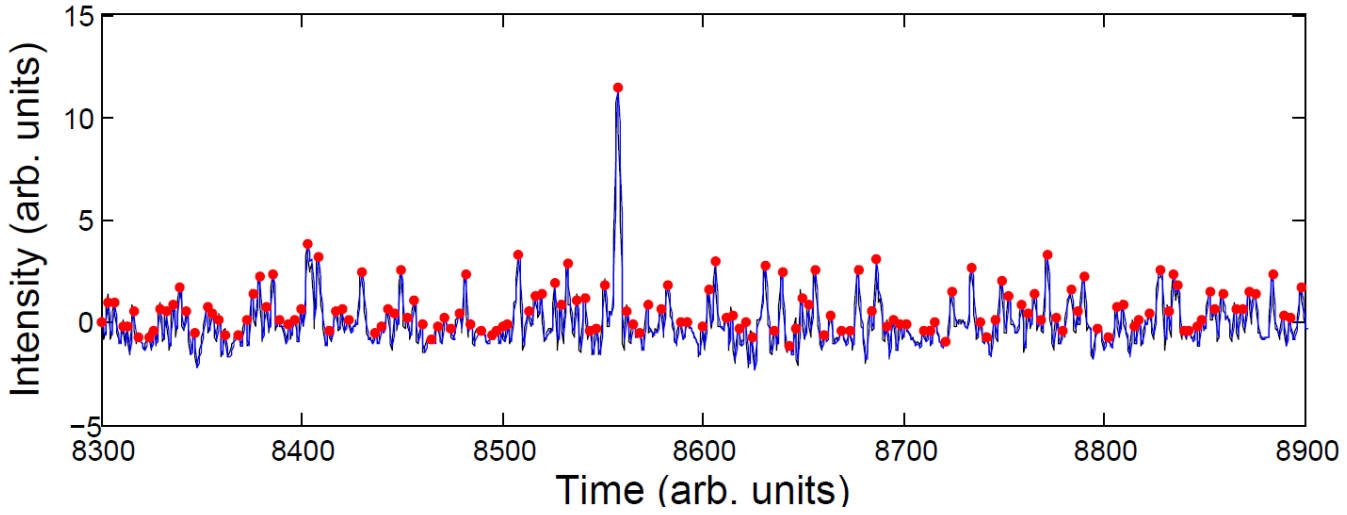
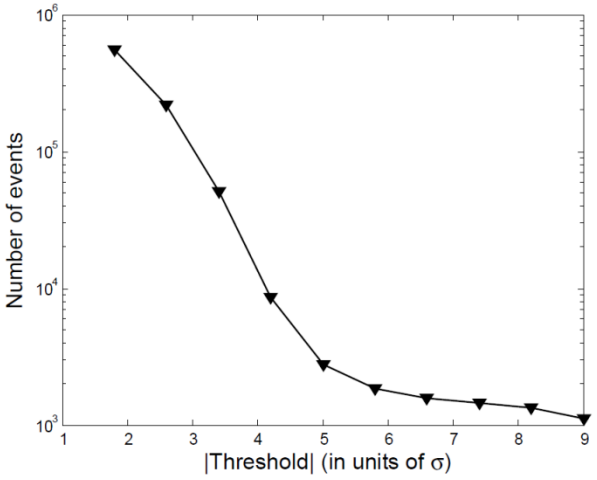
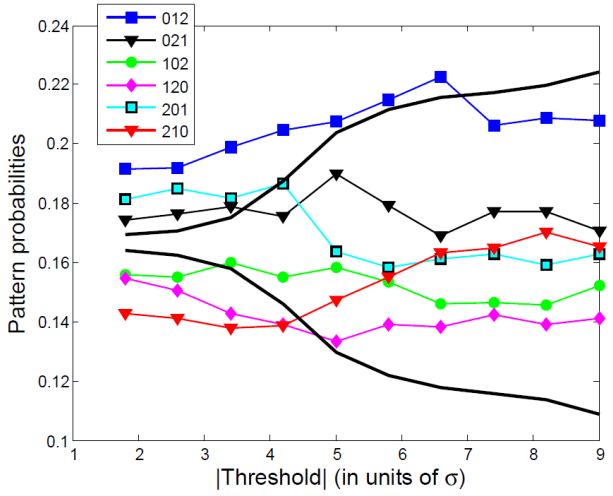
Analysis of experimental data: intensity of an optically injected semiconductor laser





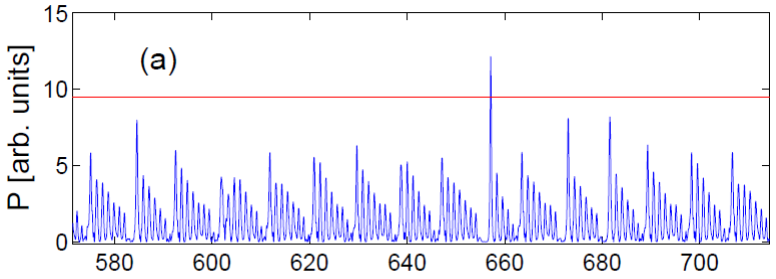


Way to improve the "early warning":

- Filter noise
- Longer patterns

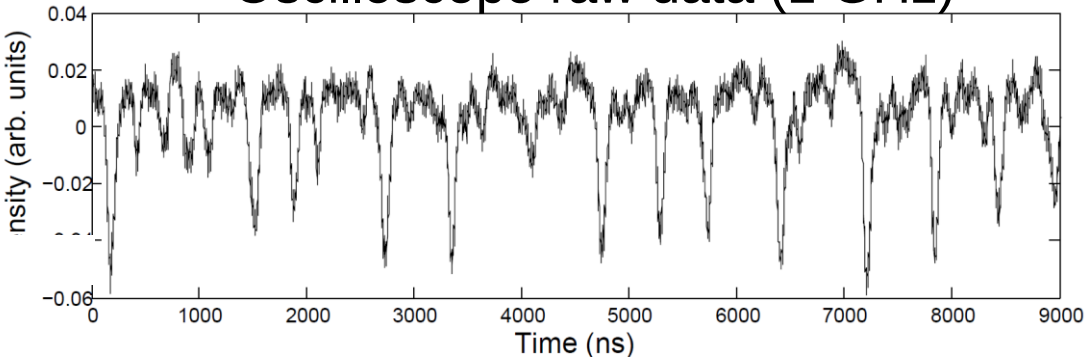
$\{\ldots I_i, I_{i+1}, I_{i+2}, I_{i+3}, \ldots\}$

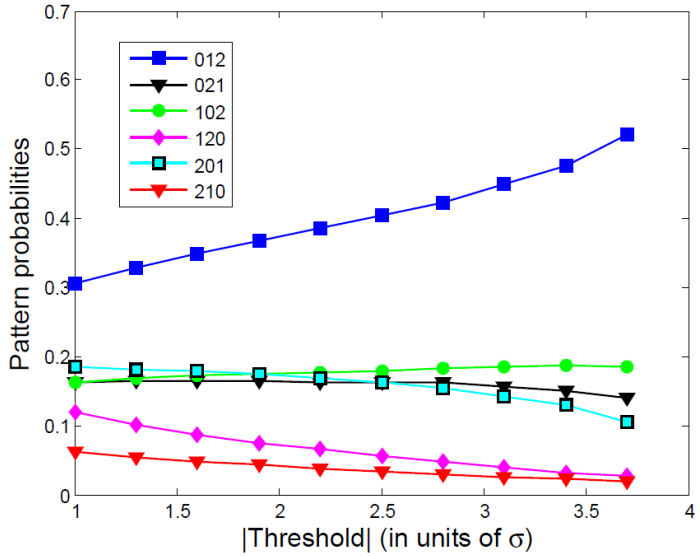
Experimental data: feedback-induced intensity dropouts



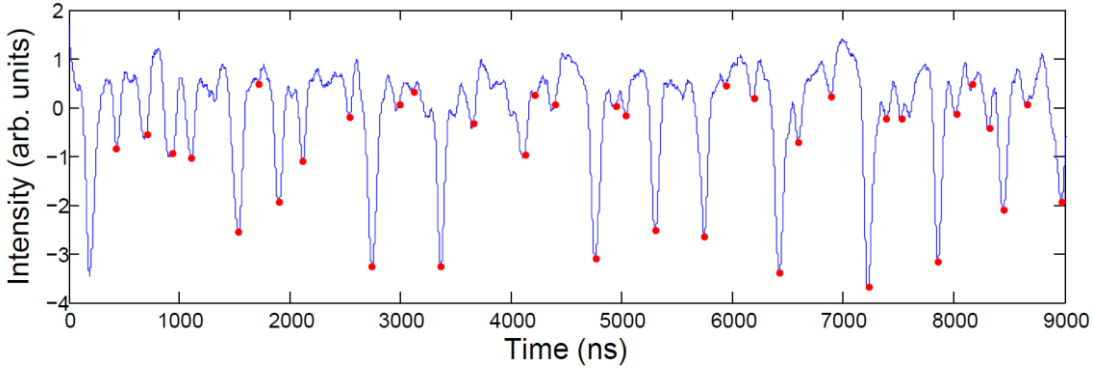
Time (in units of the feedback delay time)

Oscilloscope raw data (1 GHz)





Filtered time series, zero-mean and σ=1



⇒ Here 210 is a "good sign" that no dropout is likely to occur after this pattern

Summary

- Take home message: symbolic time-series analysis can yield more information from optical data.
- Extreme pulses: certain "symbols" are more (or less) likely to occur before the pulses.
- Open issue: applicability to real-word time-series?

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

Thank you for your attention!

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