Predicting Extreme Optical Pulses in Laser Systems

Cristina Masoller

Universitat Politecnica de Catalunya

Cristina.masoller@upc.edu

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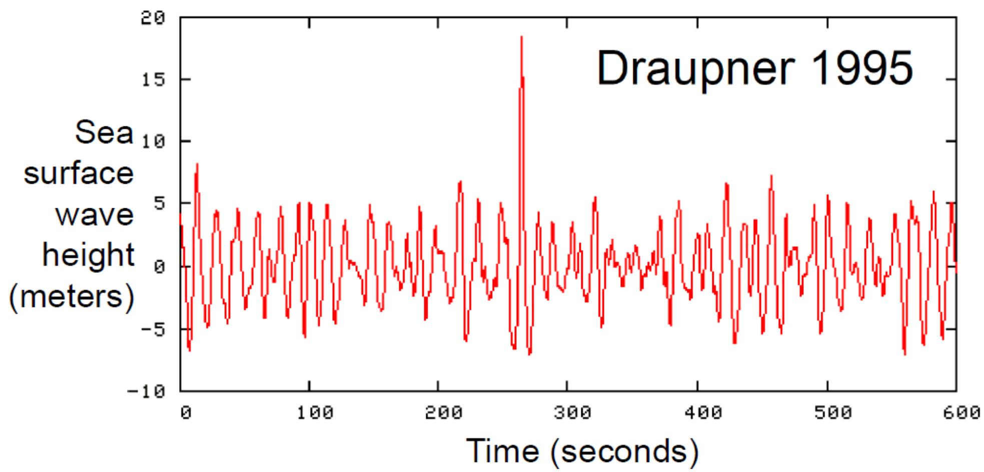
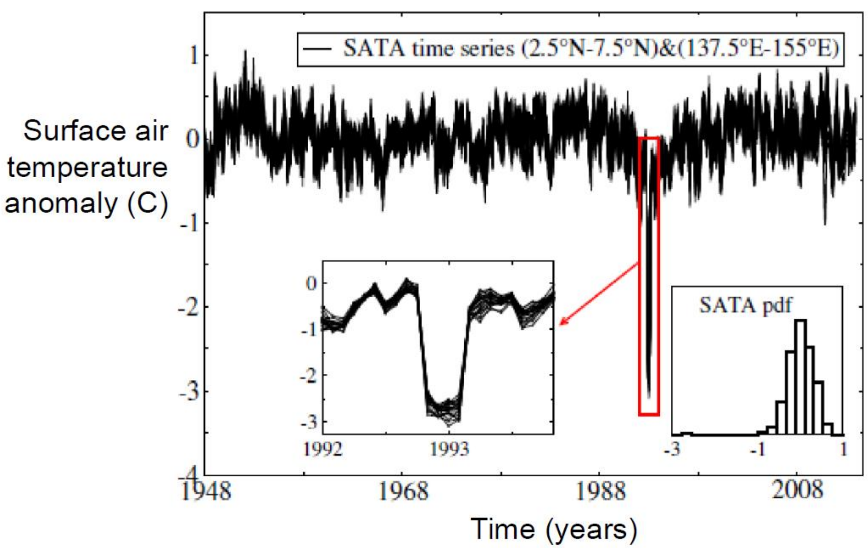
Extreme events in nature



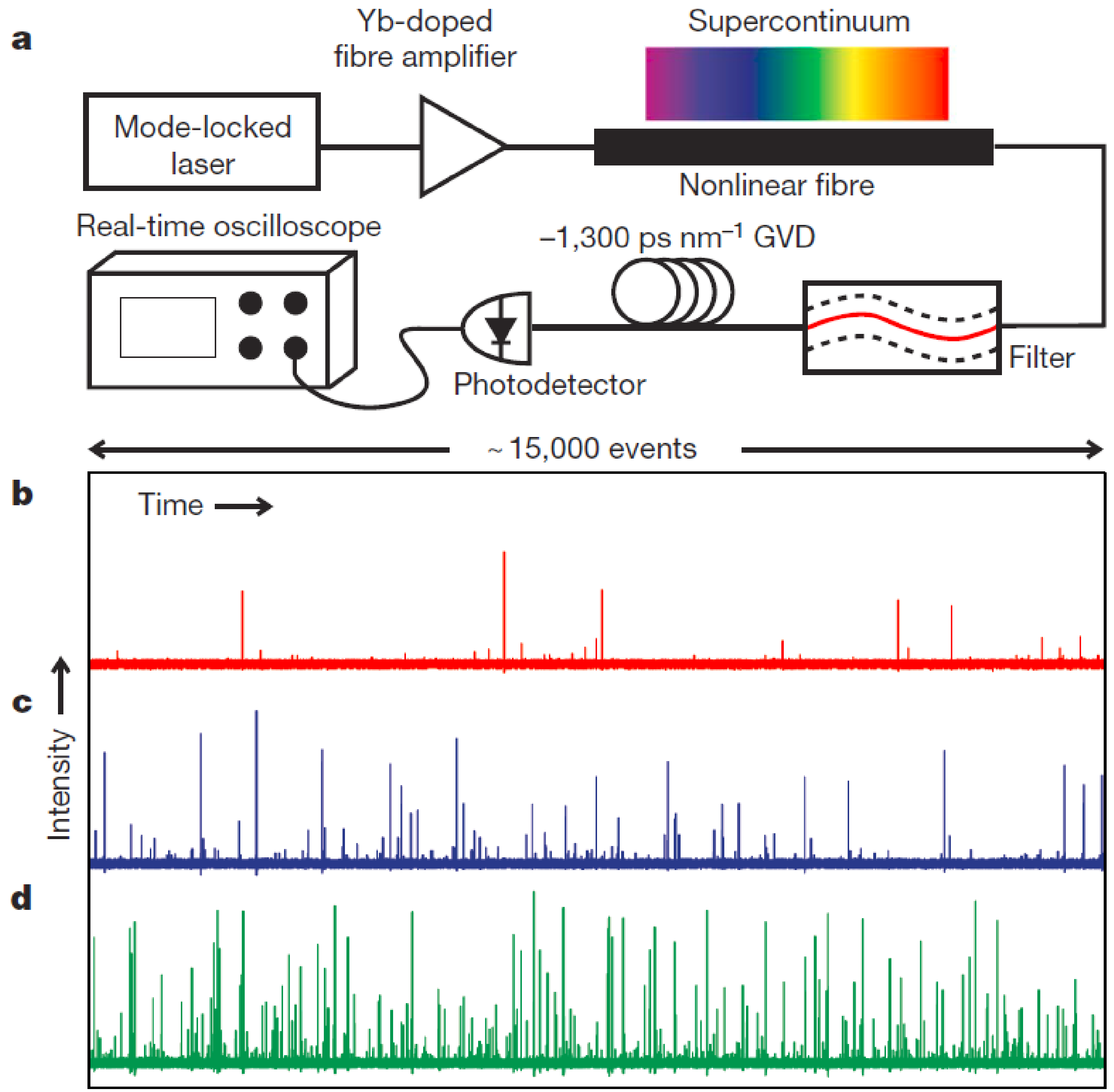


Optical chaos: provides an opportunity to advance predictability.

Optical rogue waves

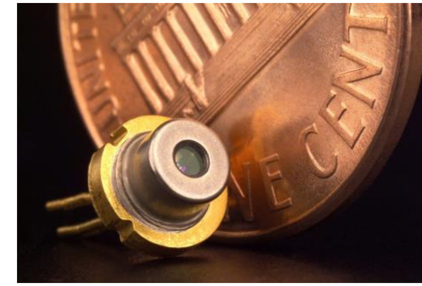
Solli et al, Nature 2007

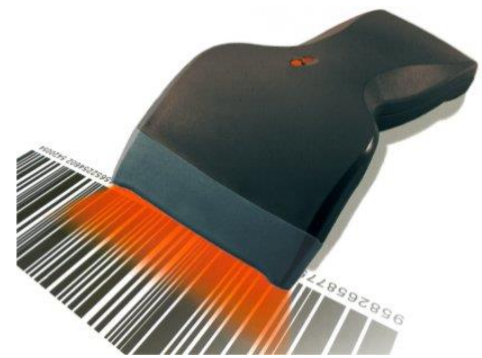
- Optical systems can contribute to understand the mechanisms capable of triggering / suppressing extreme events.
- Optical systems generate “big data”, valuable for testing diagnostic tools for “early warnings” of extreme events.
- The study of extreme pulses can yield new light into nonlinear & stochastic phenomena in optical systems.



Semiconductor lasers (diode lasers)

- Widely used, inexpensive but easily perturbed



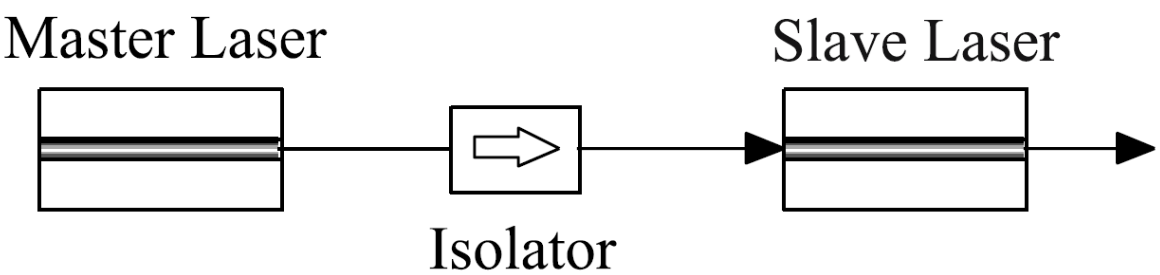


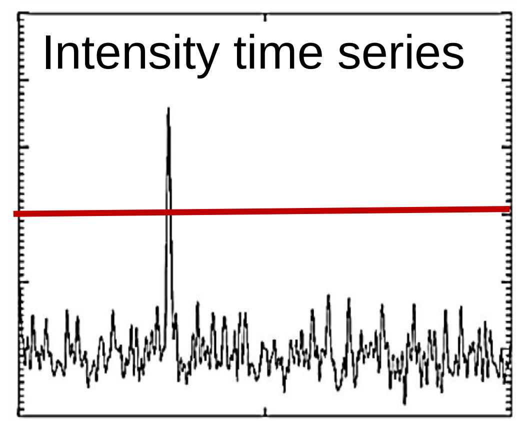
- Optically perturbed semiconductor lasers provide an inexpensive setup to study chaos and nonlinear dynamics.

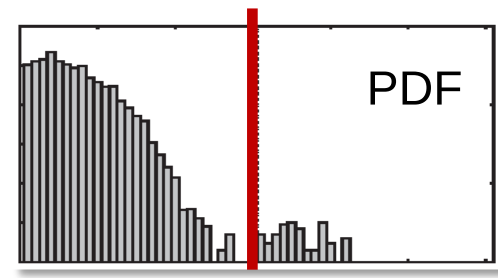
PRL 107, 053901 (2011) PHYSICAL REVIEW LETTERS week ending 29 JULY 2011

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**

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

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

optical injection
η: injection strength
Δω= ω$_s$-ω$_m$: detuning

spontaneous emission noise

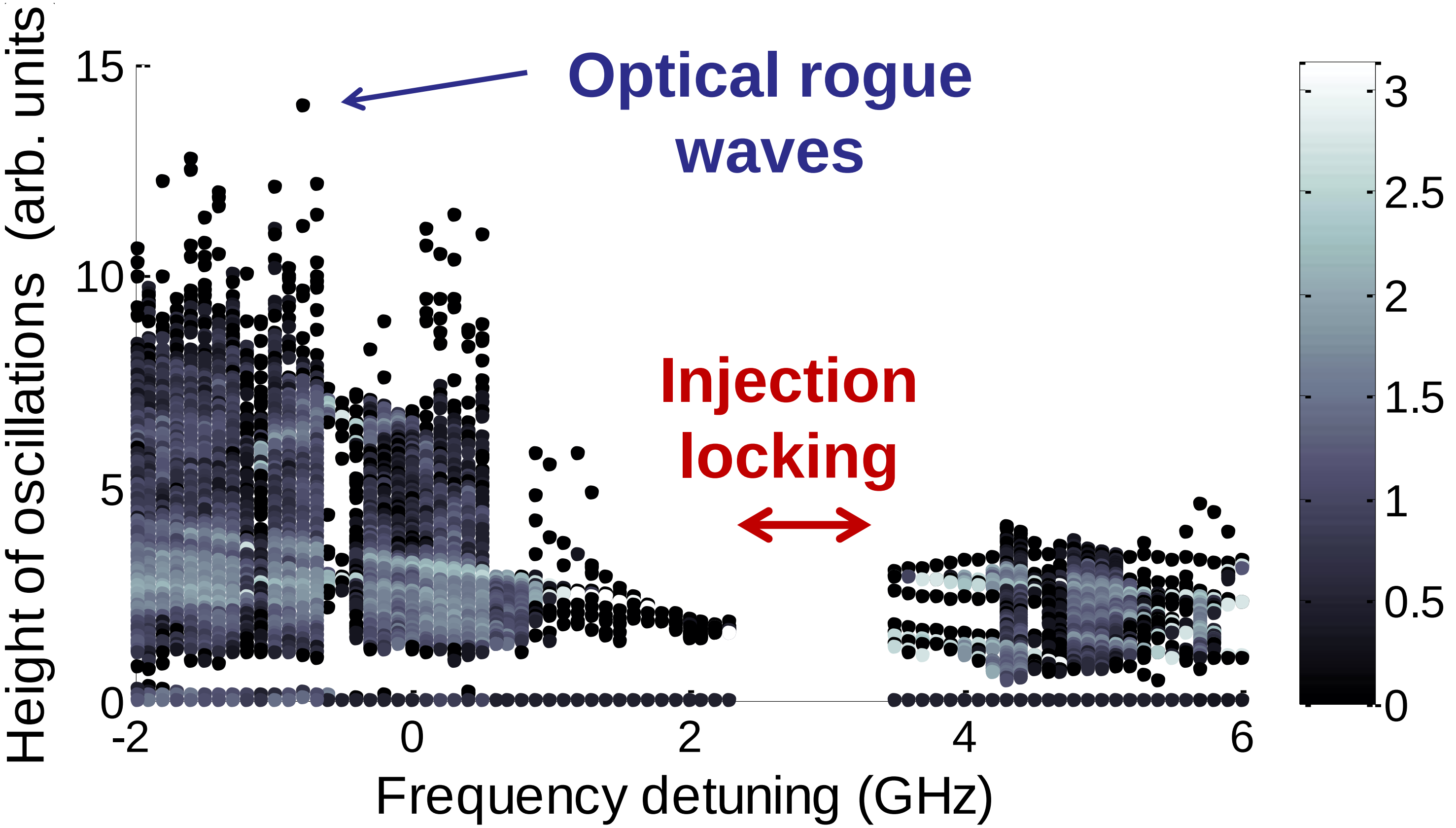
Solitary laser parameters: **α τ$_p$ τ$_N$ μ**

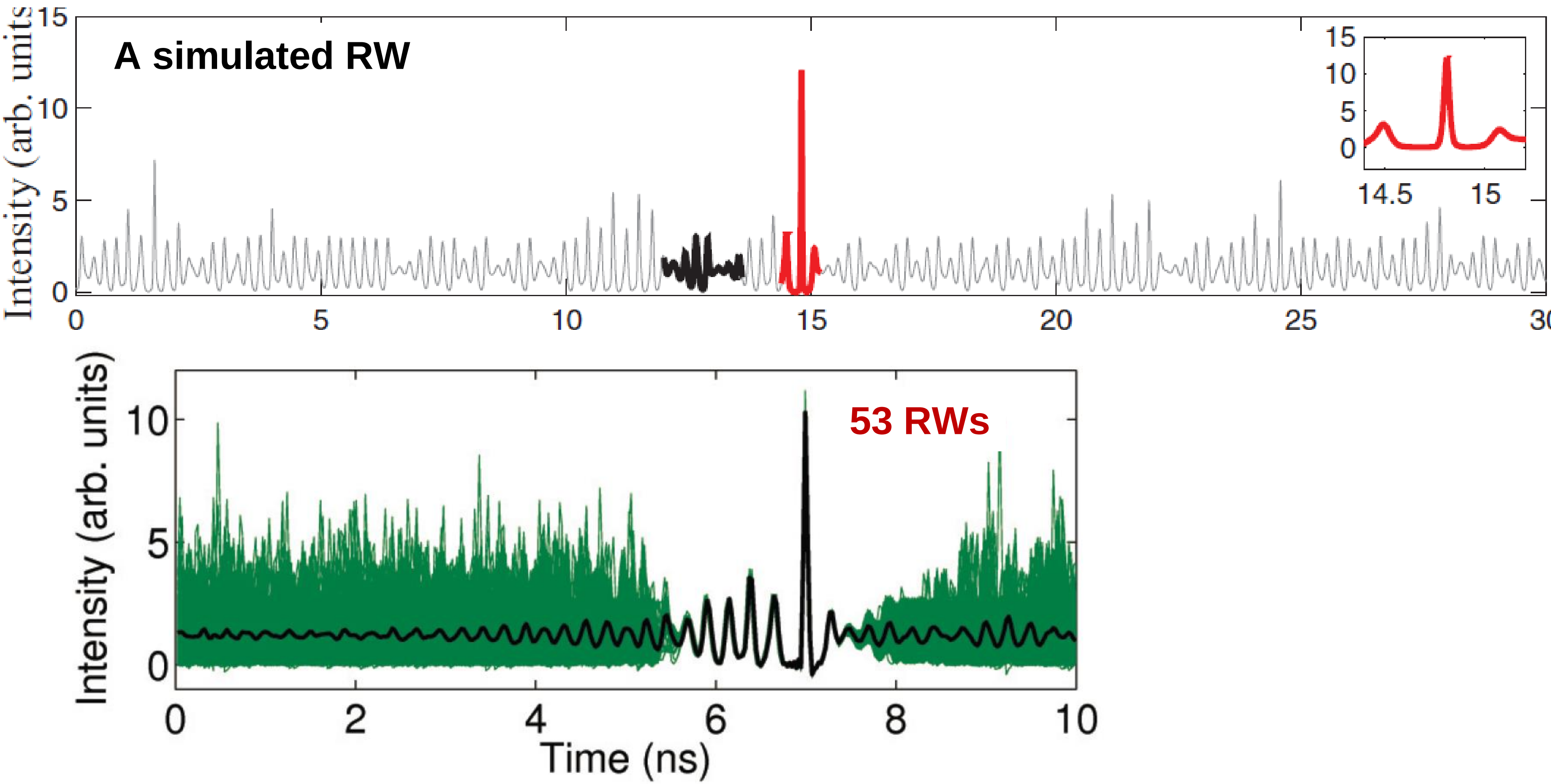
μ: normalized pump current parameter

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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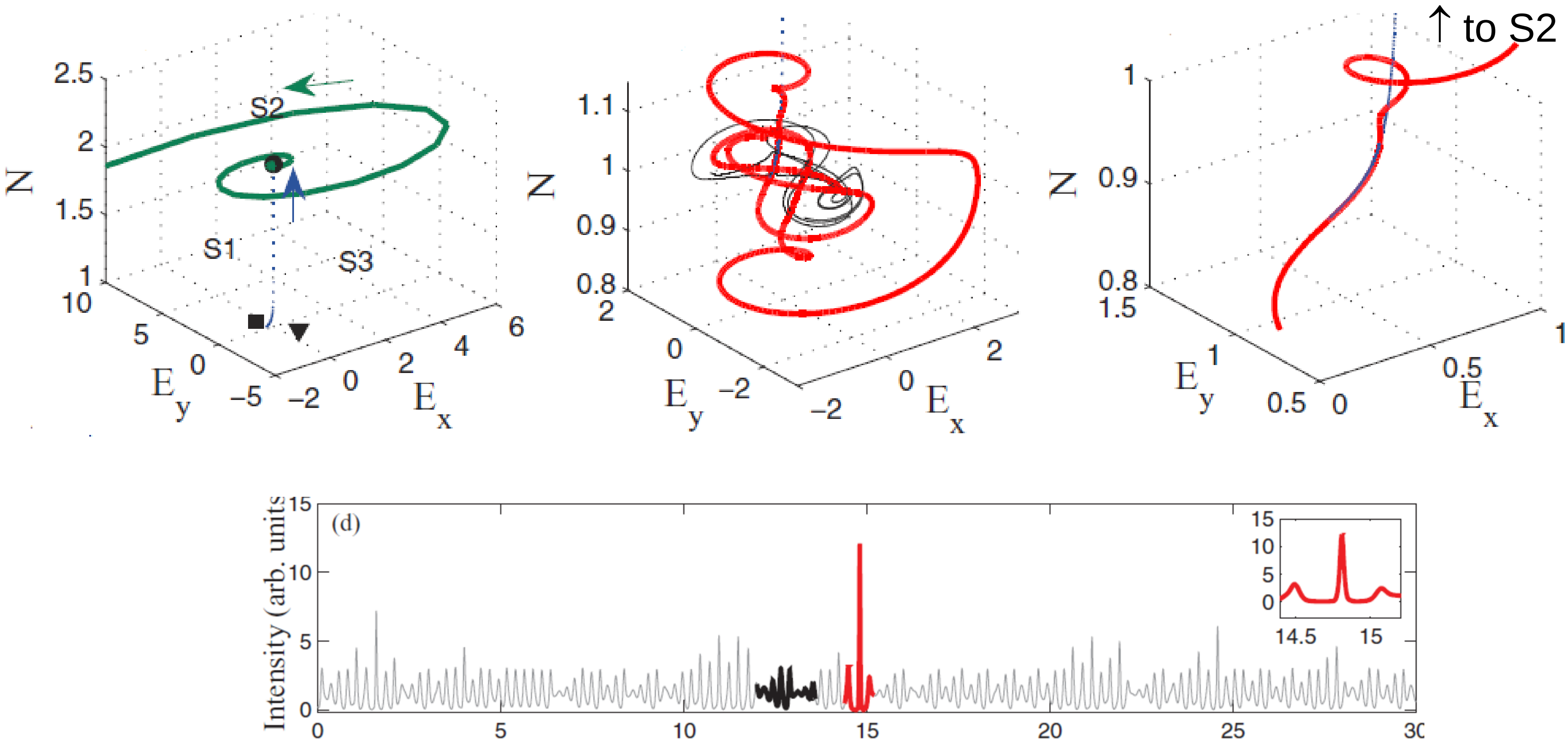
What triggers a RW?



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

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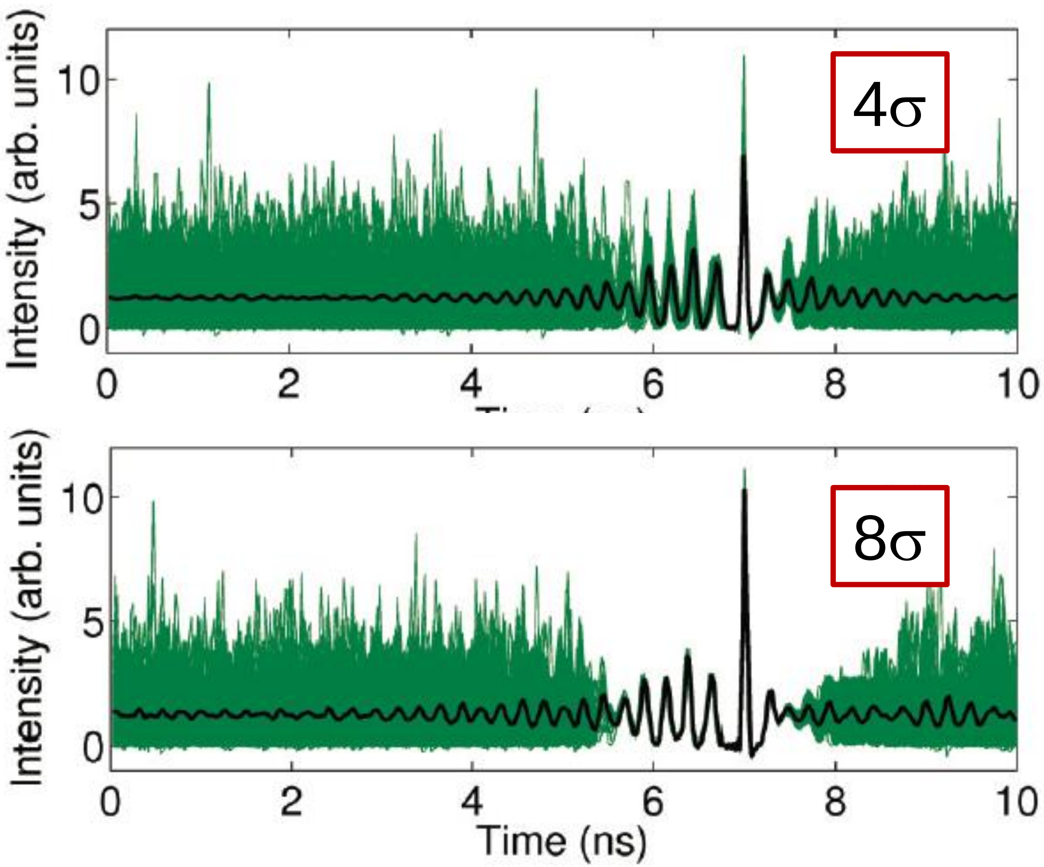
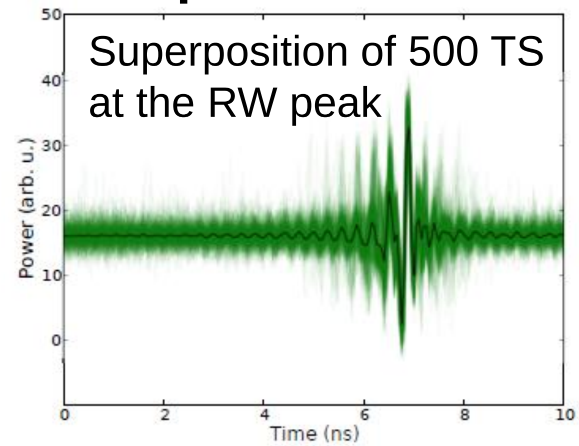
Rogue wave predictability

Deterministic simulations



Superposition of 50 time-series at the RW peak

Experiments



$\Rightarrow$ Well-defined oscillation pattern anticipates extreme pulses.

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

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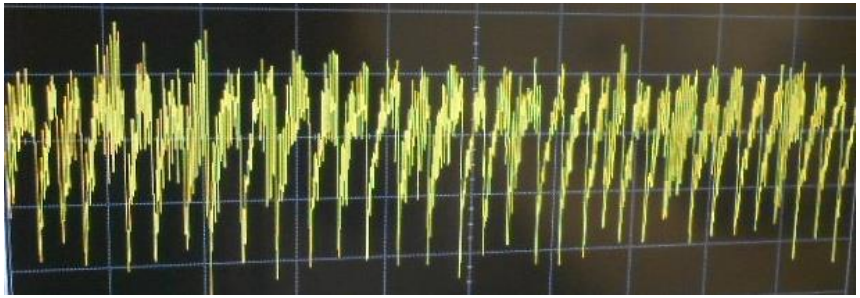
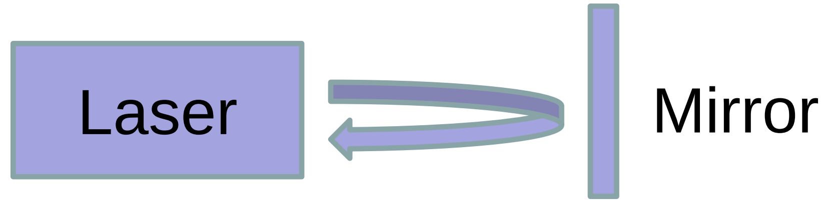
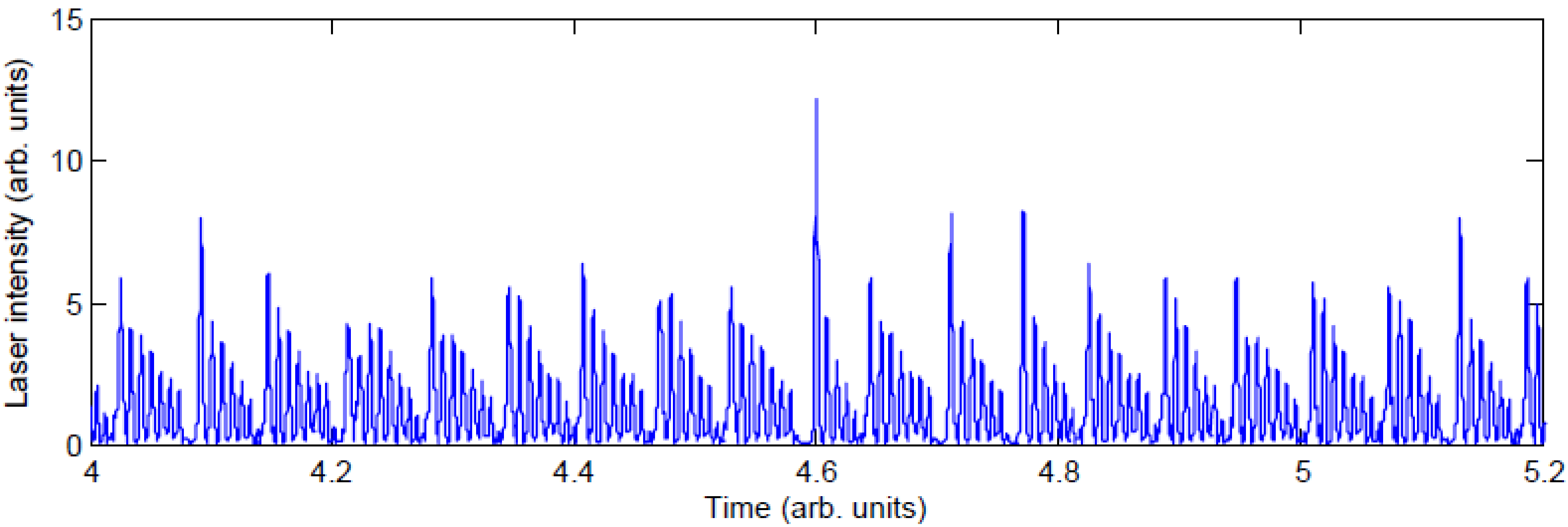
A similar effect in the intensity dynamics induced by optical feedback



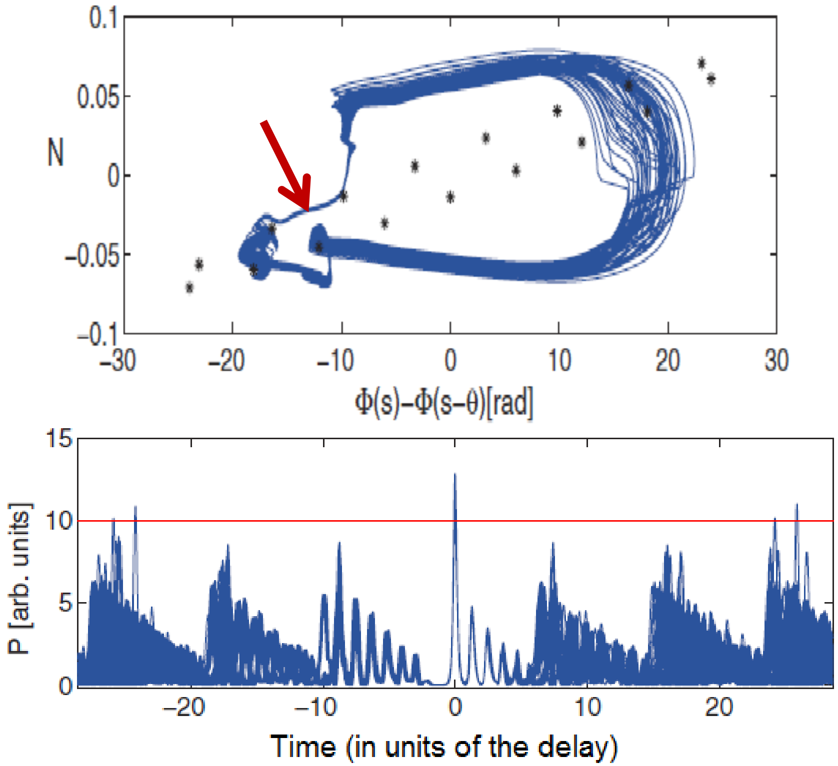




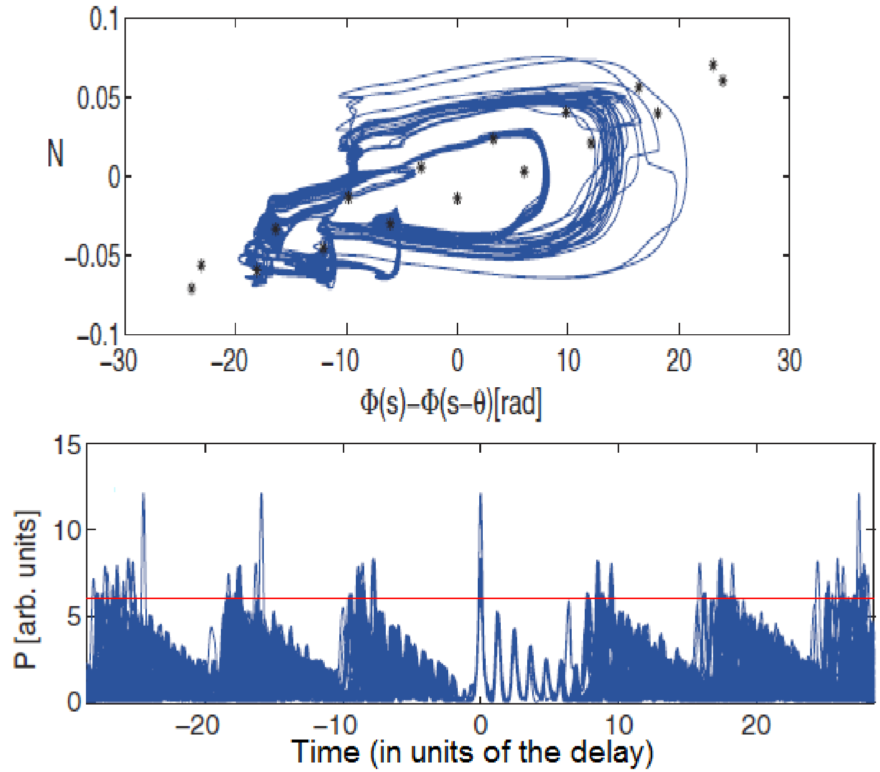
J. A. Reinoso, J. Zamora-Munt and C. Masoller. PRE 87, 062913 (2013)

Superposition of 52 pulses

Threshold = 10



Threshold = 6



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?

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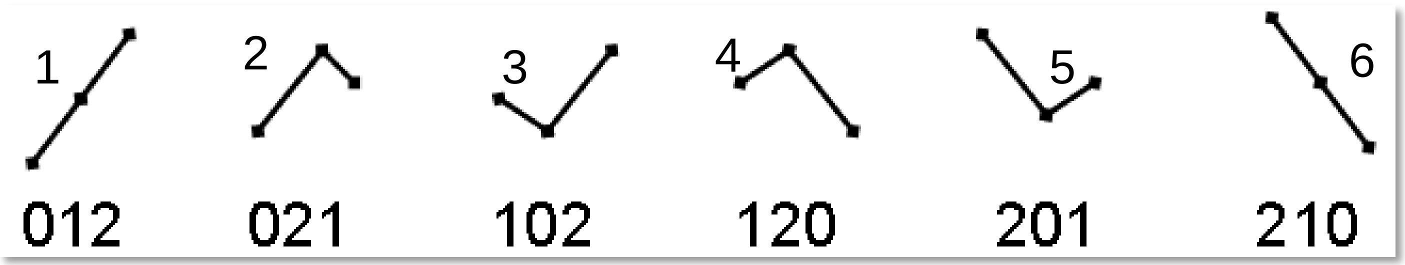
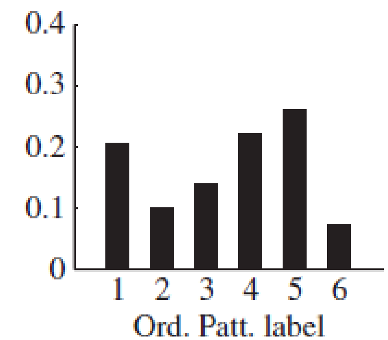
Symbolic method of time-series analysis: Ordinal Patterns

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

D=3

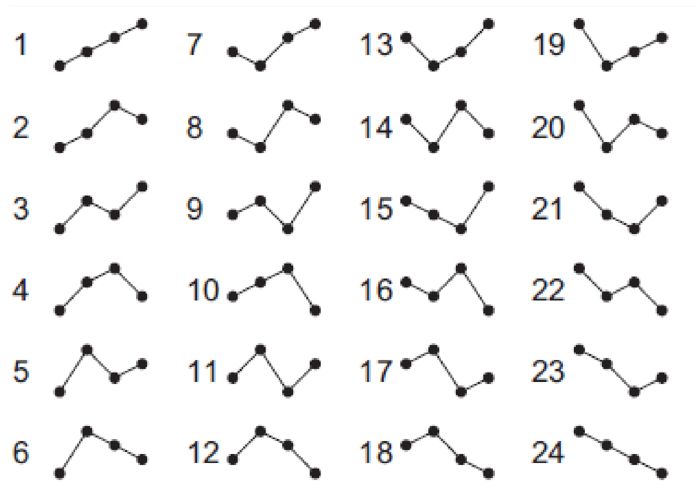


Ordinal probabilities



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>

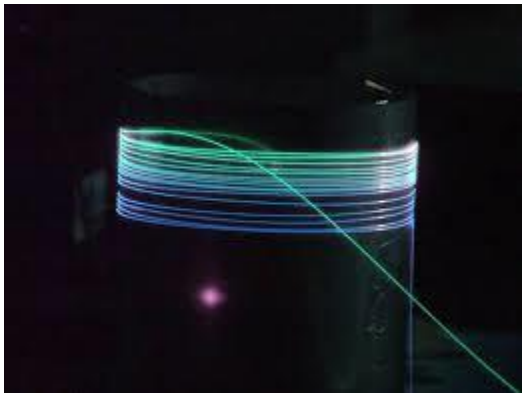
$\{\ldots \mathbf{x}_i, x_{i+1}, \mathbf{x}_{i+2}, x_{i+3}, \mathbf{x}_{i+4}, x_{i+5} \ldots\}$

Brandt & Pompe, PRL 88, 174102 (2002)

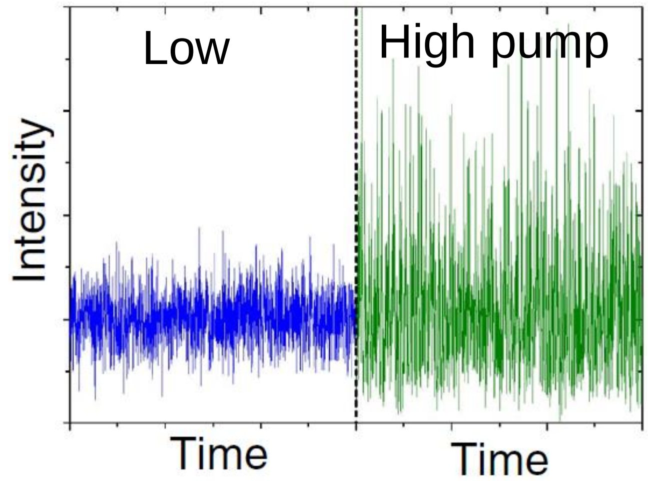
U. Parlitz et al. / Computers in Biology and Medicine 42 (2012) 319–327

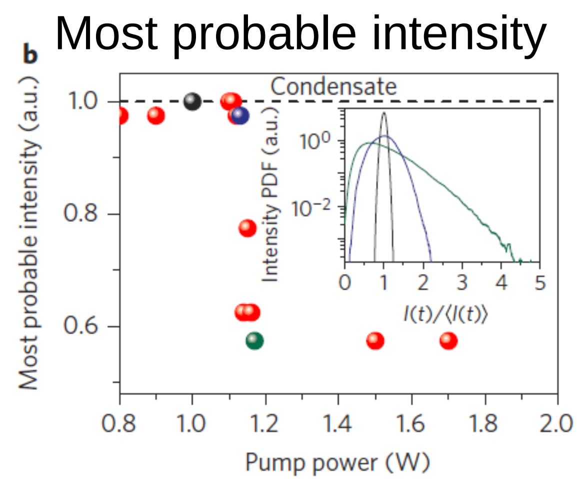
Example of application

Characterizing the laminar-turbulence transition in a fiber laser

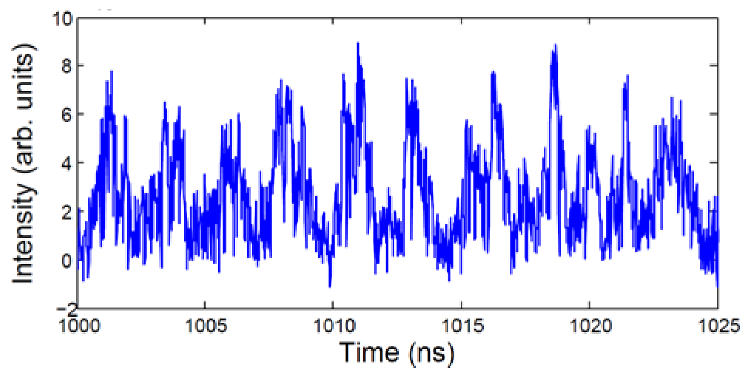


L=1 km,
millions of modes





At the transition:

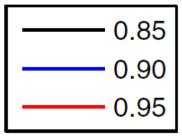


Experimental data from Prof. Turitsyn' group (Aston University, UK)

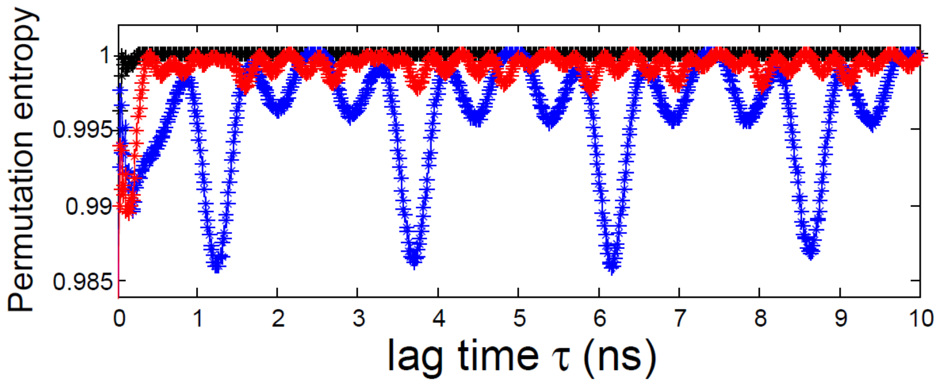
E. G. Turitsyna et al. Nat. Phot. 7, 783 (2013)

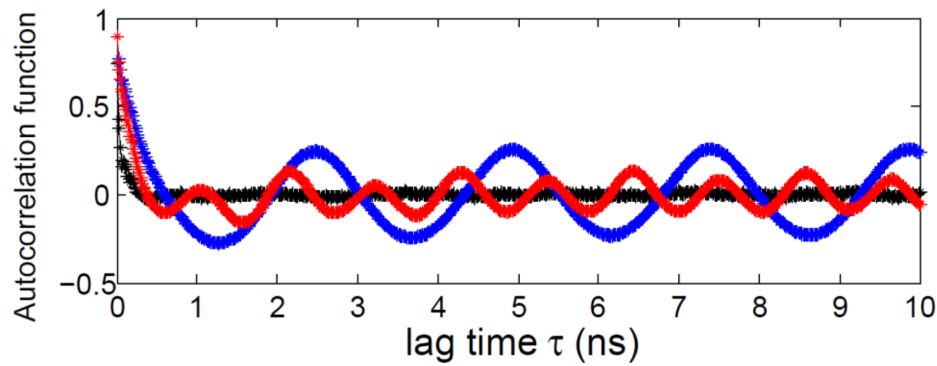
Ordinal analysis of lagged intensity data

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



Pump power below, at, and above the transition.



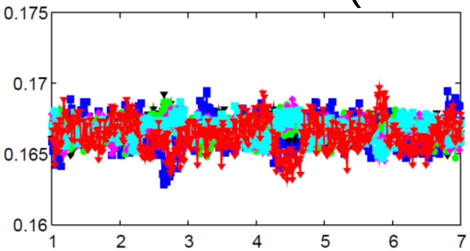


$\Rightarrow$ Sharp variations not captured by correlation analysis.

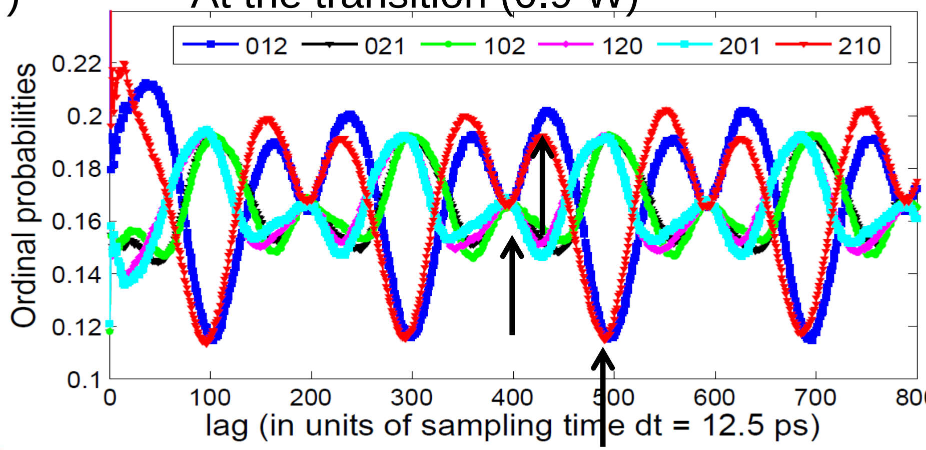
Aragoneses et al, PRL 116, 033902 (2016)

Ordinal probabilities vs. lag

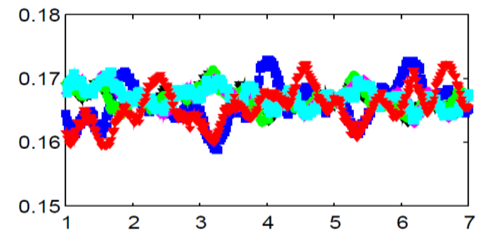
Before transition (0.85 W)

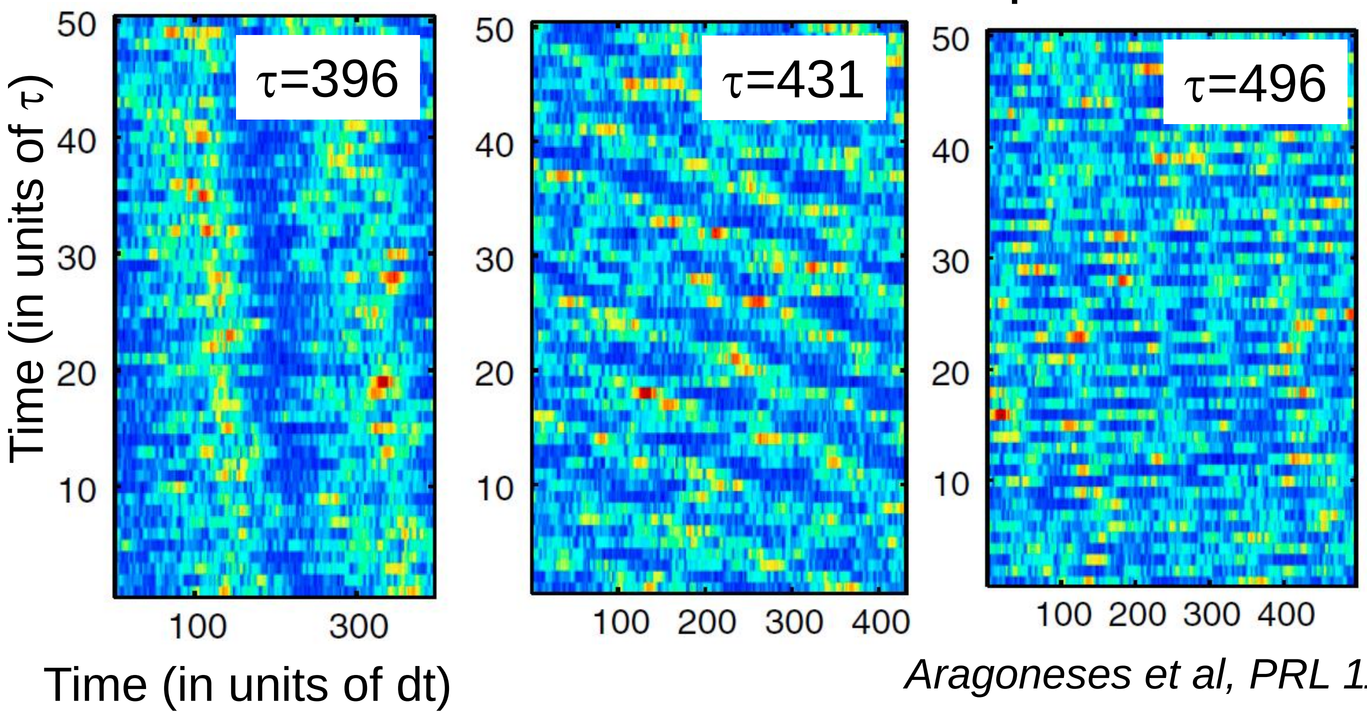


At the transition (0.9 W)



After transition (1.0 W)





⇒ Different coherent structures uncovered with different lags (sampling times).

Aragoneses et al, PRL 116, 033902 (2016)

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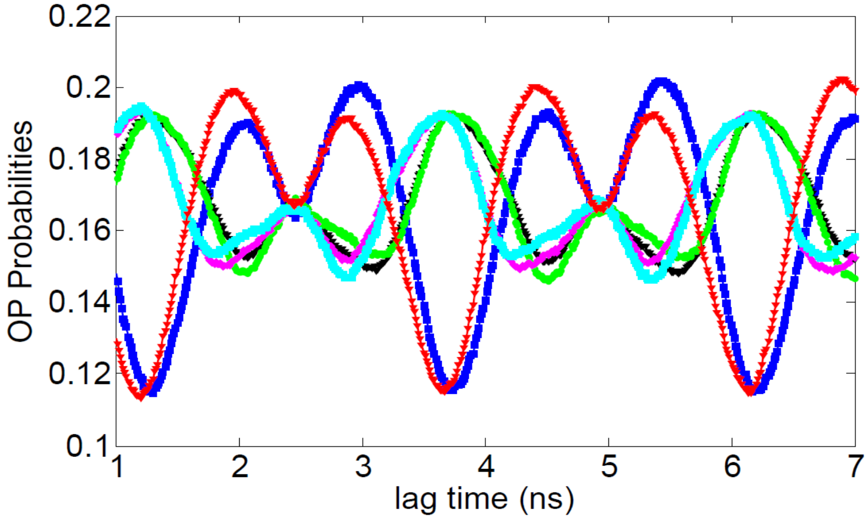
Circle map: minimal model of ordinal probabilities at the transition

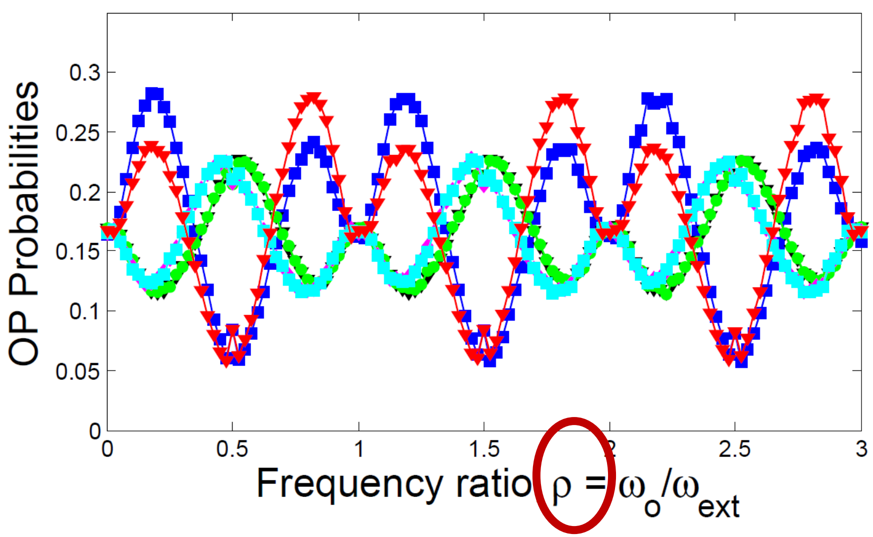
$$\varphi_{i+1} = \varphi_i + \rho + \frac{K}{2\pi}\sin(2\pi\varphi_i) + D\xi$$

Fiber laser data $\{I_i, I_{i+\tau}, I_{i+2\tau}, \ldots\}$
(at the transition, pump power 0.9 W)



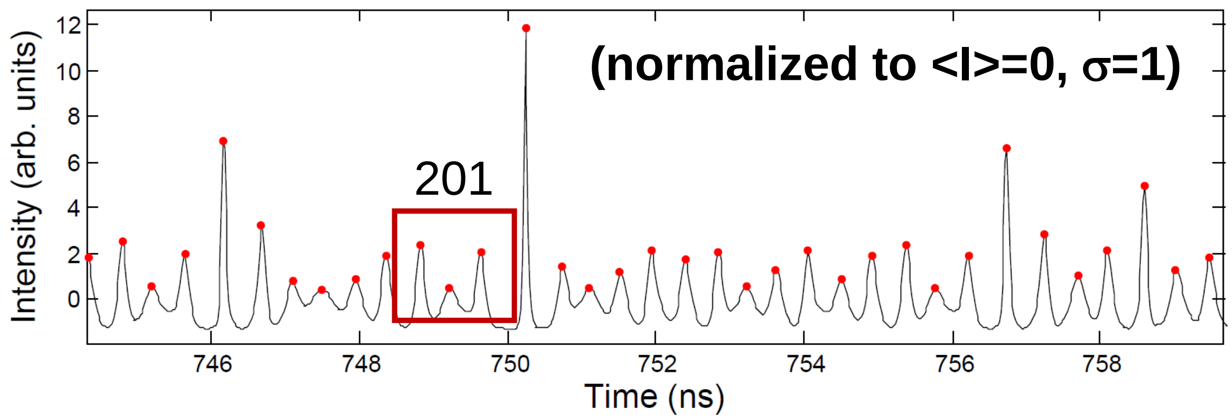
Synthetic data
(K=0.23 & D=0.02)

$$\{X_i, X_{i+1}, X_{i+2}, \ldots\}$$
$$X_i = \varphi_{i+1} - \varphi_i$$



Due to some type of locking ?
Present work is aimed at understanding this similarity.

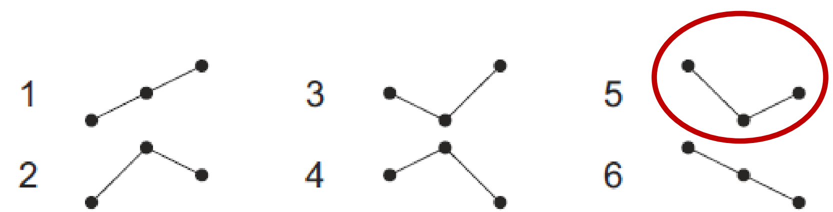
Ordinal analysis for "early warning" of rogue wave



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

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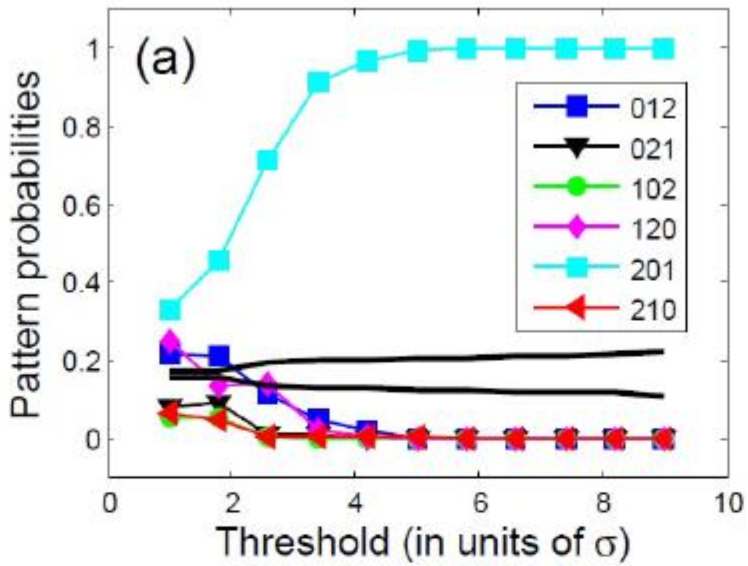
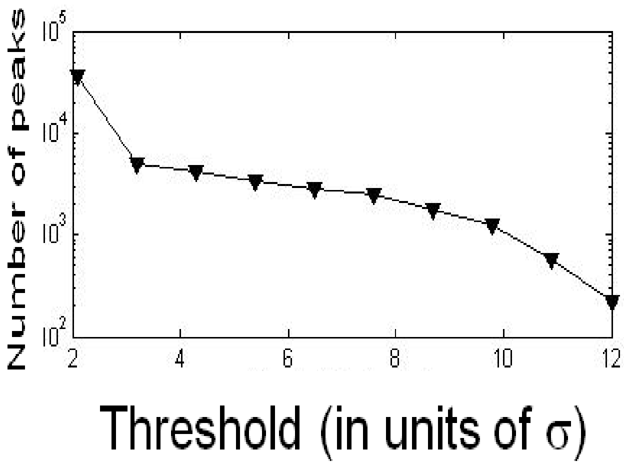
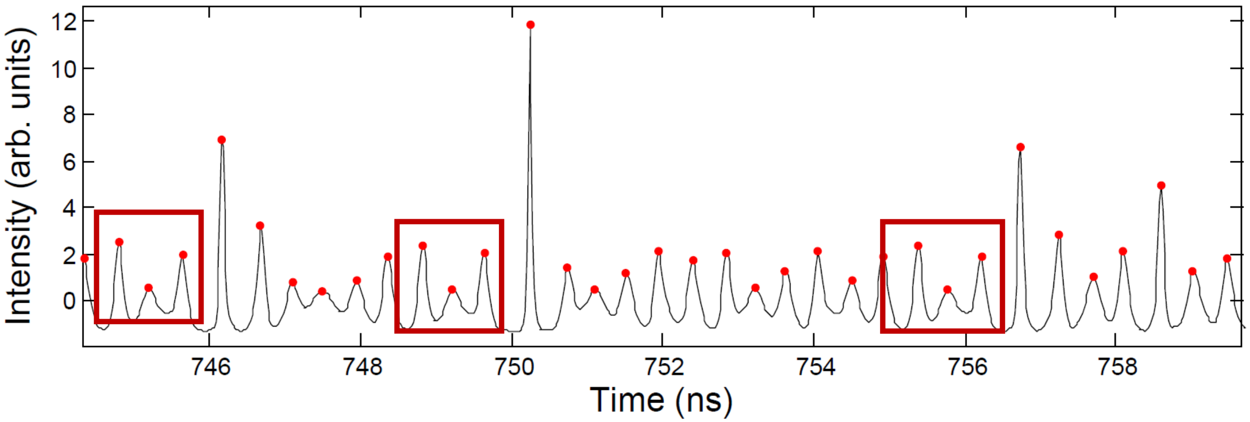
Results: deterministic simulations

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





- P(201)=1 if TH >6

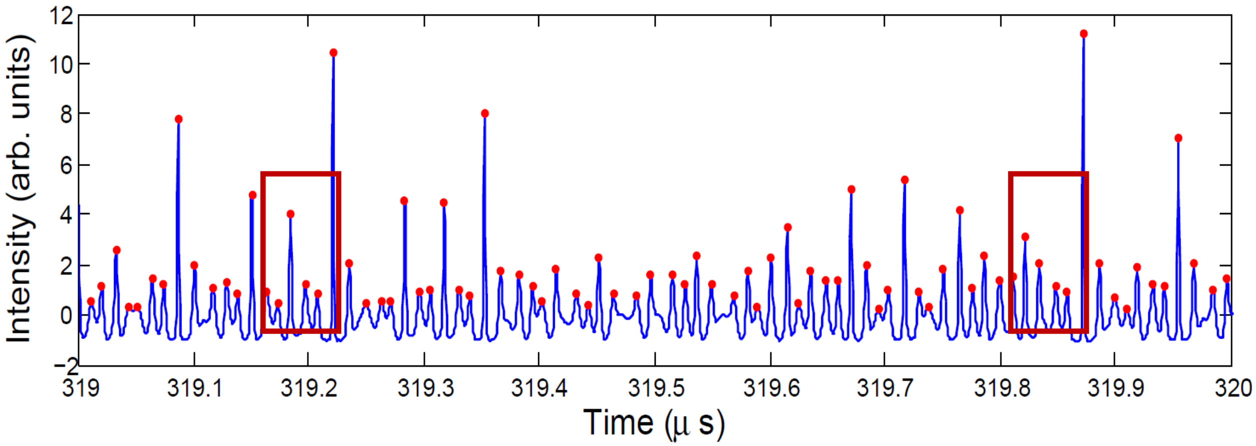


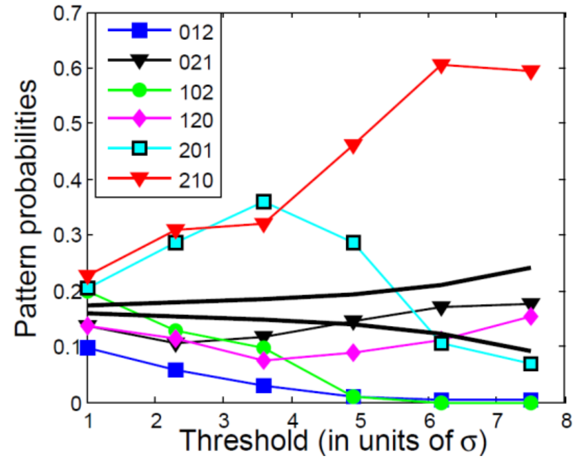
- Problem: P(201)≠0 if TH <6 (pattern 201 also anticipates some small pulses) ⇒ false alarms (**false positives**)

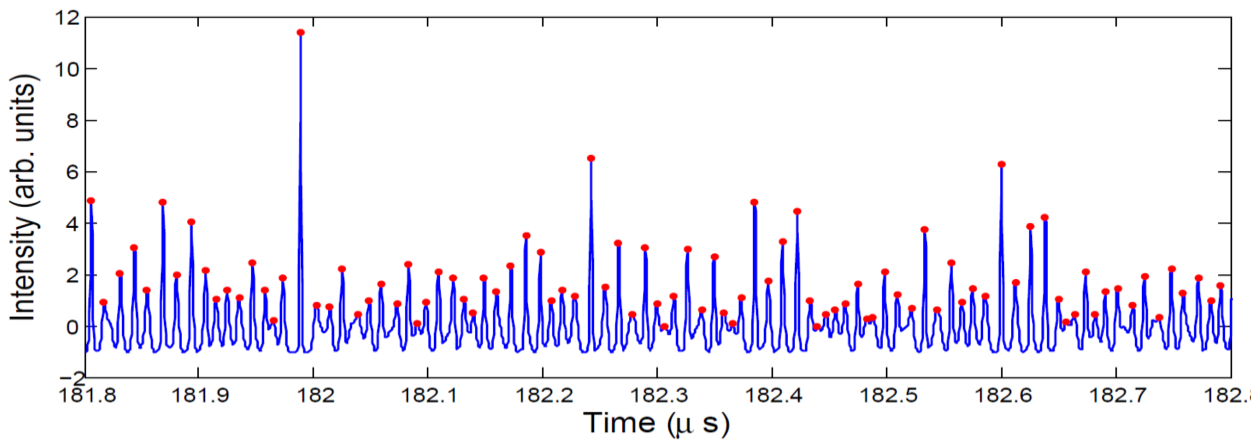
Model and parameters as in J. Ahuja et al, Optics Express 22, 28377 (2014).
N. Martinez Alvarez, S. Borkar, C. Masoller, EPJST in press (2017)

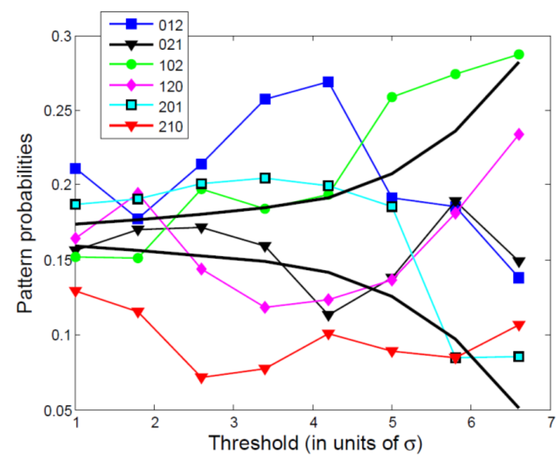
Including spontaneous emission noise and current modulation

- Two different modulation frequencies





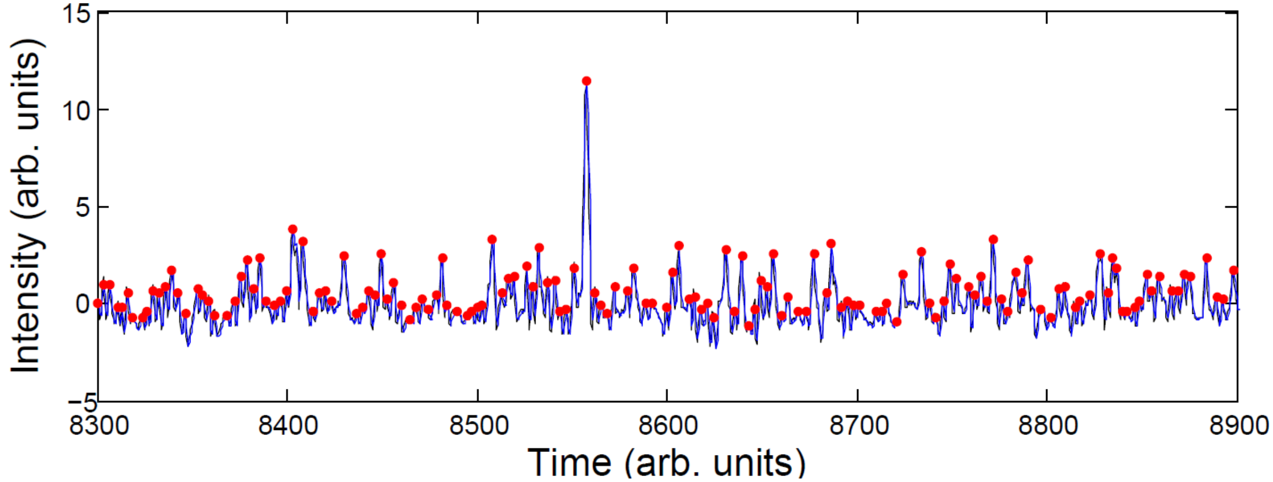


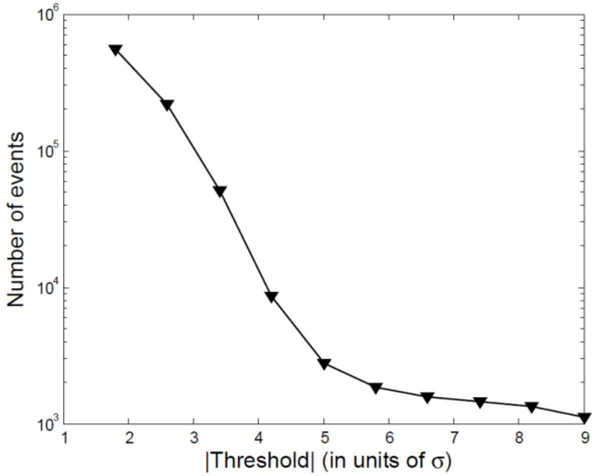


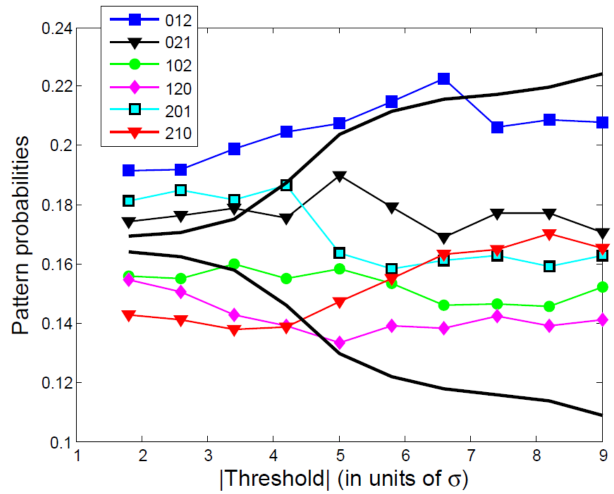
In the first case: 210 is a "good" warning.

$\Rightarrow$"early warning pattern" varies with parameters and might not exist.

Analysis of experimental data (Nice)





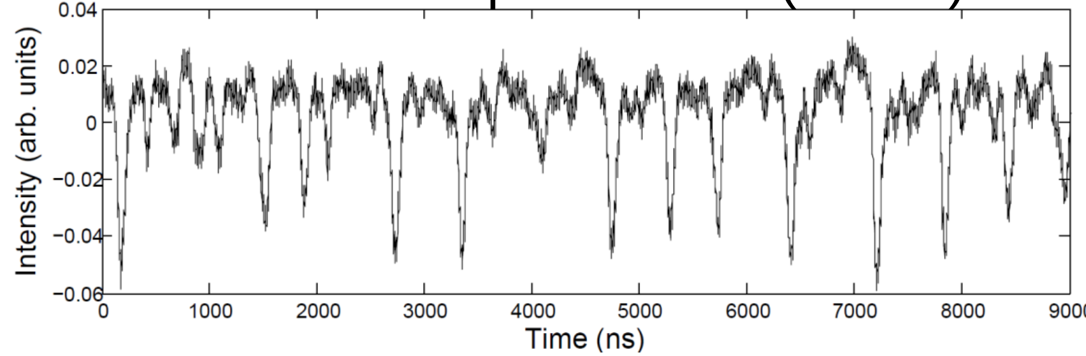


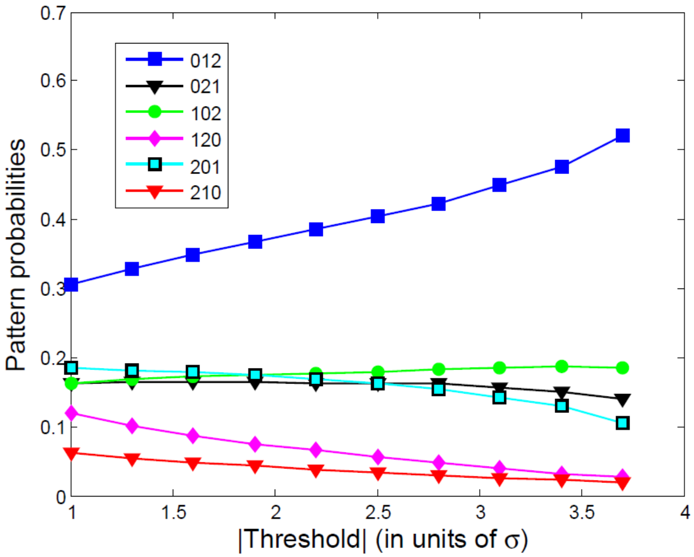
Way to improve the "early warning":

- Filter noise
- Use longer patterns or lag

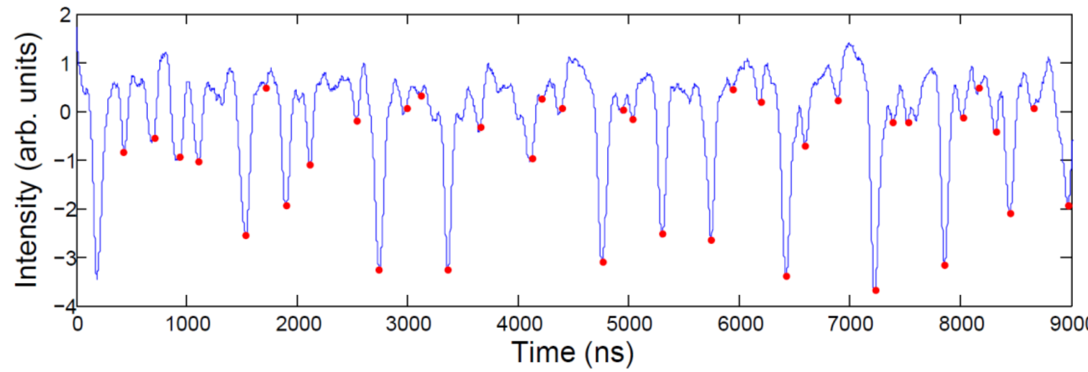
Experimental data (Terrassa): optical feedback-induced dropouts

Oscilloscope raw data (1 GHz)





Filtered time series, zero-mean and σ=1



⇒ 210 is a "good sign" that a dropout is NOT likely to occur after this 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?

Collaborators

At UPC

- Nuria Martinez and Saurabh Borkar (IIT Guwahati)
- Andres Aragoneses, Jordi Zamora, Jose M. Aparicio Reinoso
- M. C. Torrent

Experimental data: S. Barland (Nice) and S. Turitsyn (Aston University)

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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. Zamora-Munt et al, PRA 87, 035802 (2013).
- J. A. Reinoso, et al, PRE 87, 062913 (2013)
- Aragoneses et al, PRL 116, 033902 (2016).
- N. Martinez, S. Borkar, C. Masoller, EPJST in press (2017).

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