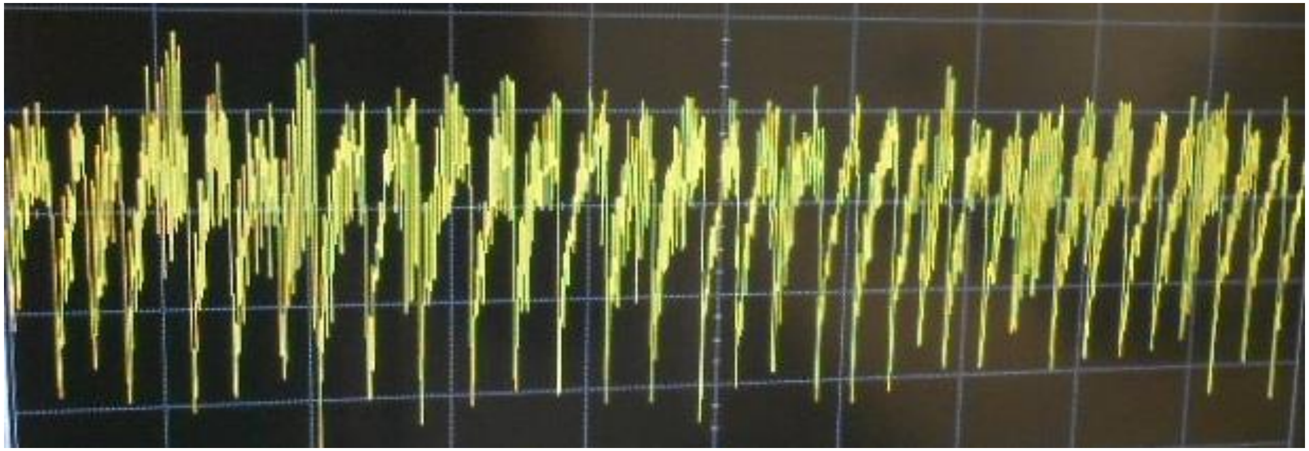

Characterizing optical complexity with tools of nonlinear time-series analysis

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XXXI Trobades científiques de la Mediterrània
Josep Miquel Vidal

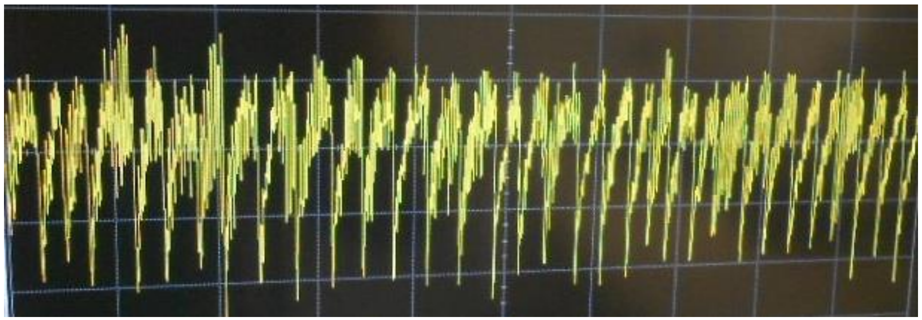
Maó, Menorca, October 2015

GOBIERNO DE ESPAÑA MINISTERIO DE CIENCIA E INNOVACIÓN

Dynamical optical complexity

- ## Optical spikes

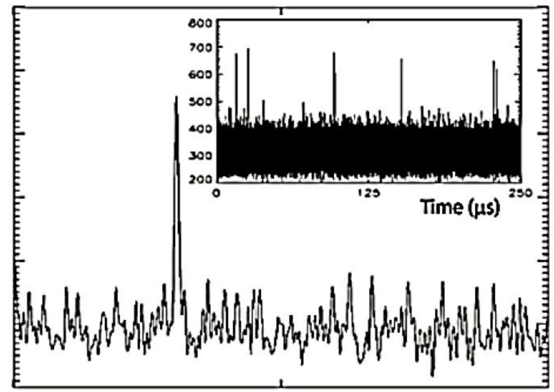
Semiconductor laser with optical feedback



Time

- ## Extreme pulses

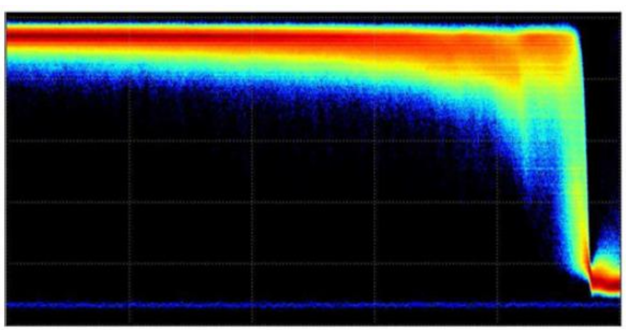
Semiconductor laser with injection



Time

- ## Polarization switching

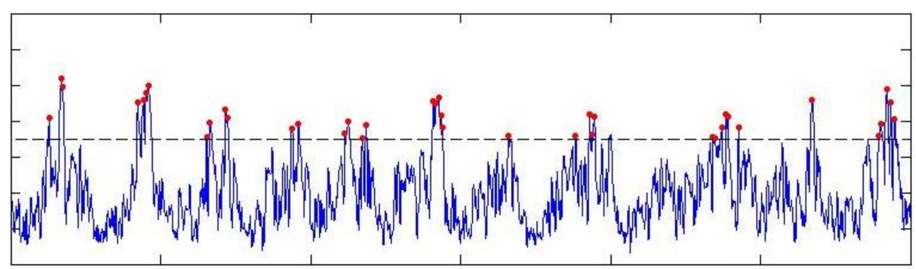
VCSELs



Time

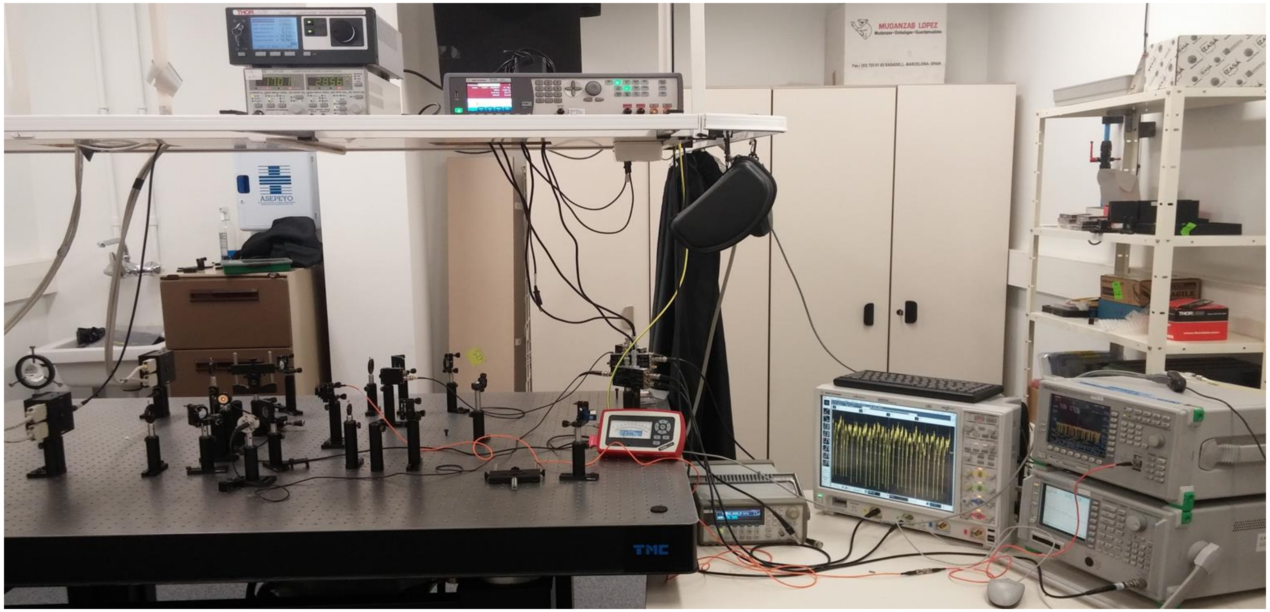
- ## Optical turbulence

Fibre laser



Time

Big data approach



- Optical systems allow recording long time-series under controlled conditions.
- With this "optical big data" we can
  - test novel analysis tools (prediction, control).
  - capture relevant features in the data (classification, model verification, parameter estimation).

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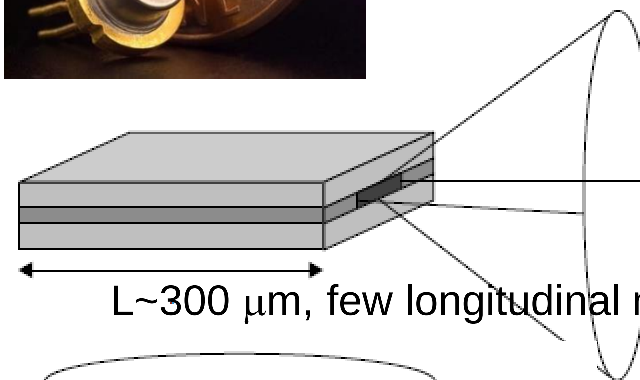
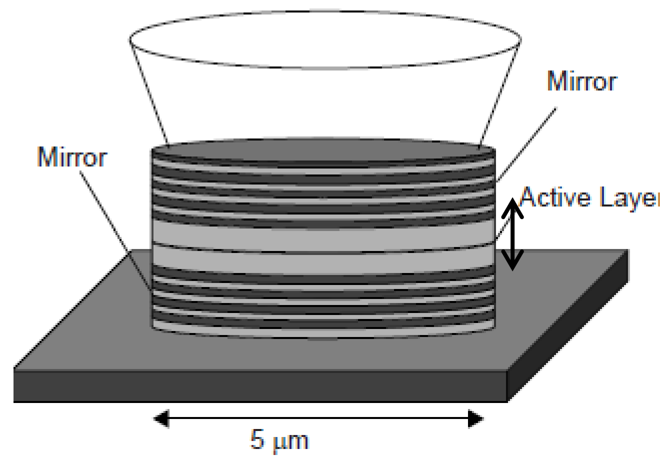
Optical systems: three types of lasers

- Semiconductor lasers
  - Edge-emitting lasers (EELs)
  - Vertical-cavity (VCSELs)

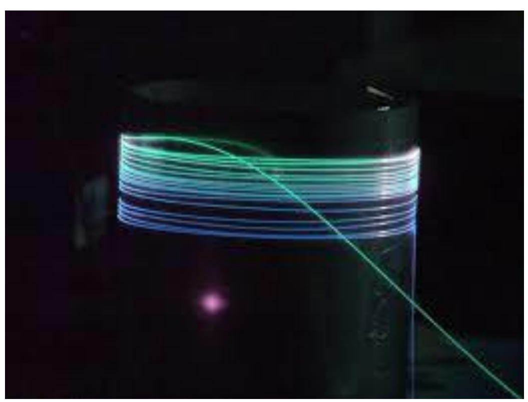


L~300 μm, few longitudinal modes



L=1-10μm, single longitudinal mode

- Fibre laser

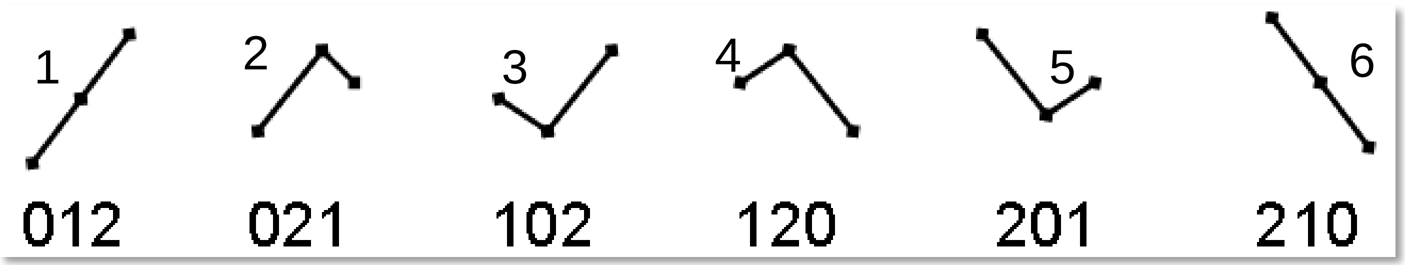


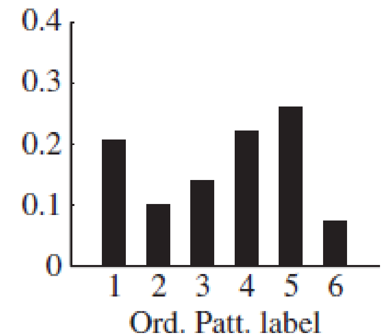
L=1 km, millions of longitudinal modes

Method of 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

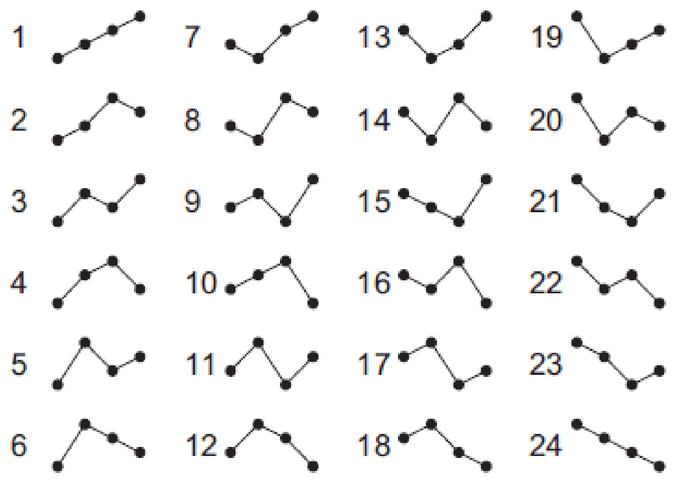
Random data $\Rightarrow$ OPs are equally probable

– Advantage: the probabilities uncover temporal correlations.

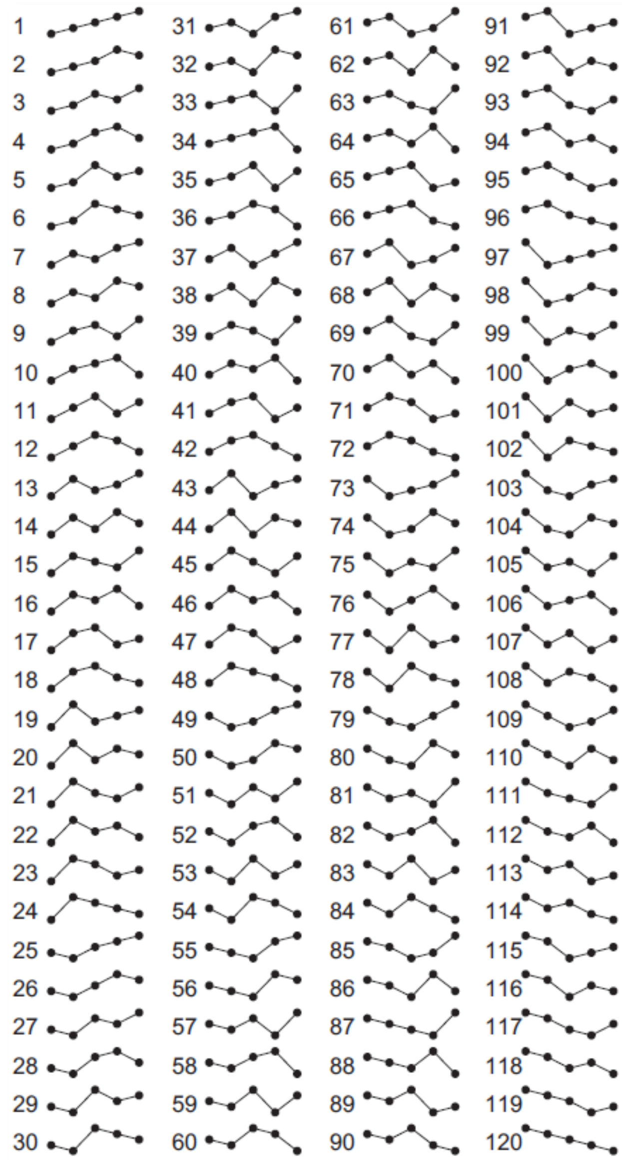
– Drawback: we lose information about the actual values.

Number of possible ordinal patterns: D!

D=4



D=5

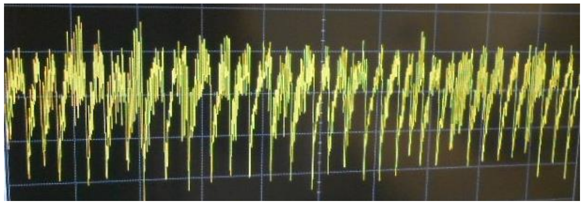


- How to select D?

  depends on:
  - The length of the data.
  - The length of correlations in the data.

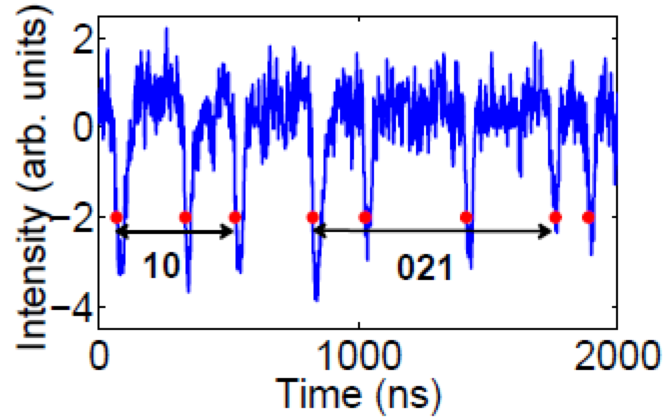
U. Parlitz et al. / Computers in Biology and Medicine 42 (2012) 319–327

First example: optical spikes in EELs with optical feedback

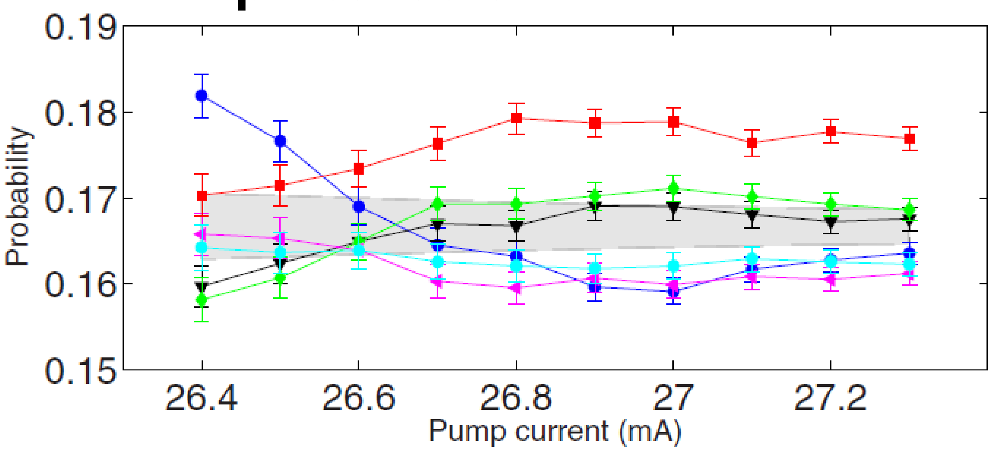


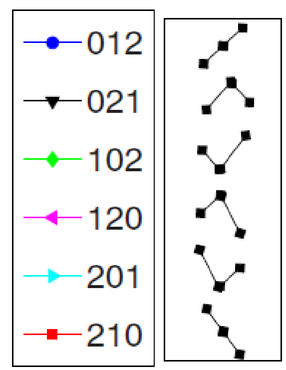
$X = \{\ldots \Delta T_i, \Delta T_{i+1}, \Delta T_{i+2}, \ldots\}$

Time intervals between spikes

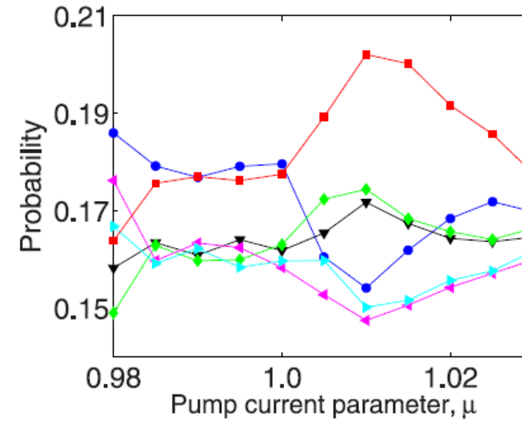


Empirical data





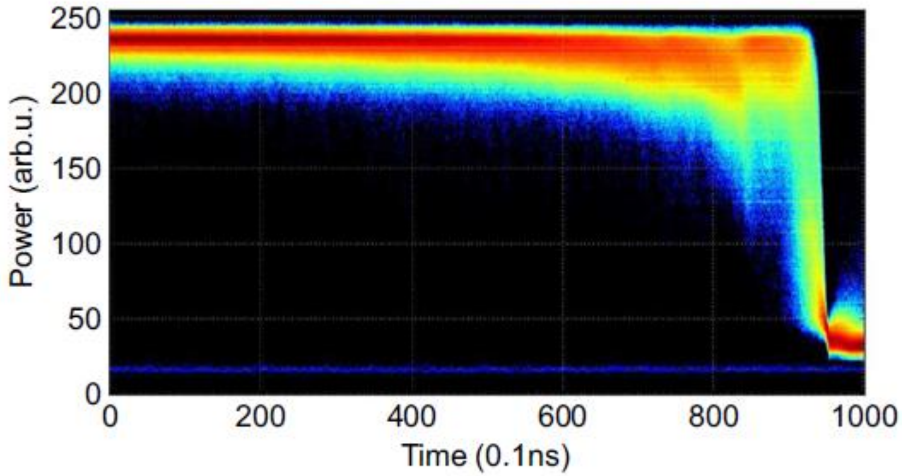
LK Model



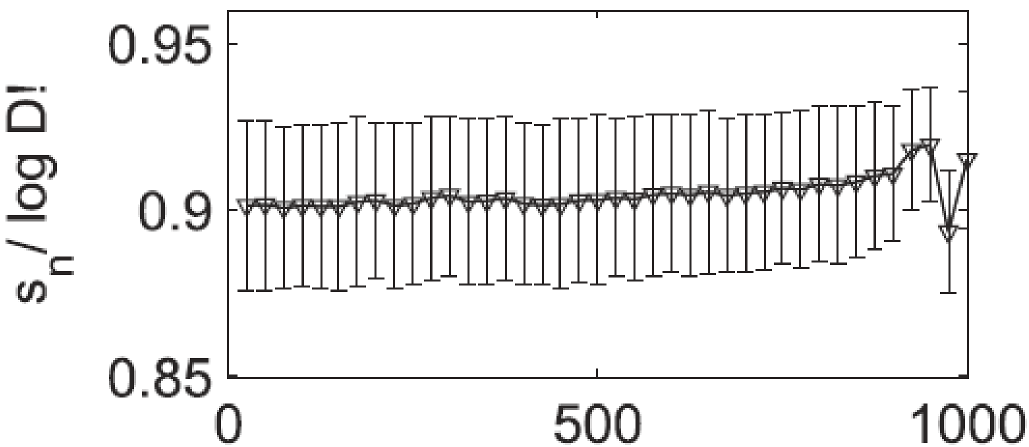
Error bars computed with a binomial test, gray region is consistent with $p_i = 1/6 \ \forall\ i$.

A. Aragoneses et al, Sci. Rep. 4, 4696 (2014)

Example 2: early warning of an abrupt transition



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



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

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

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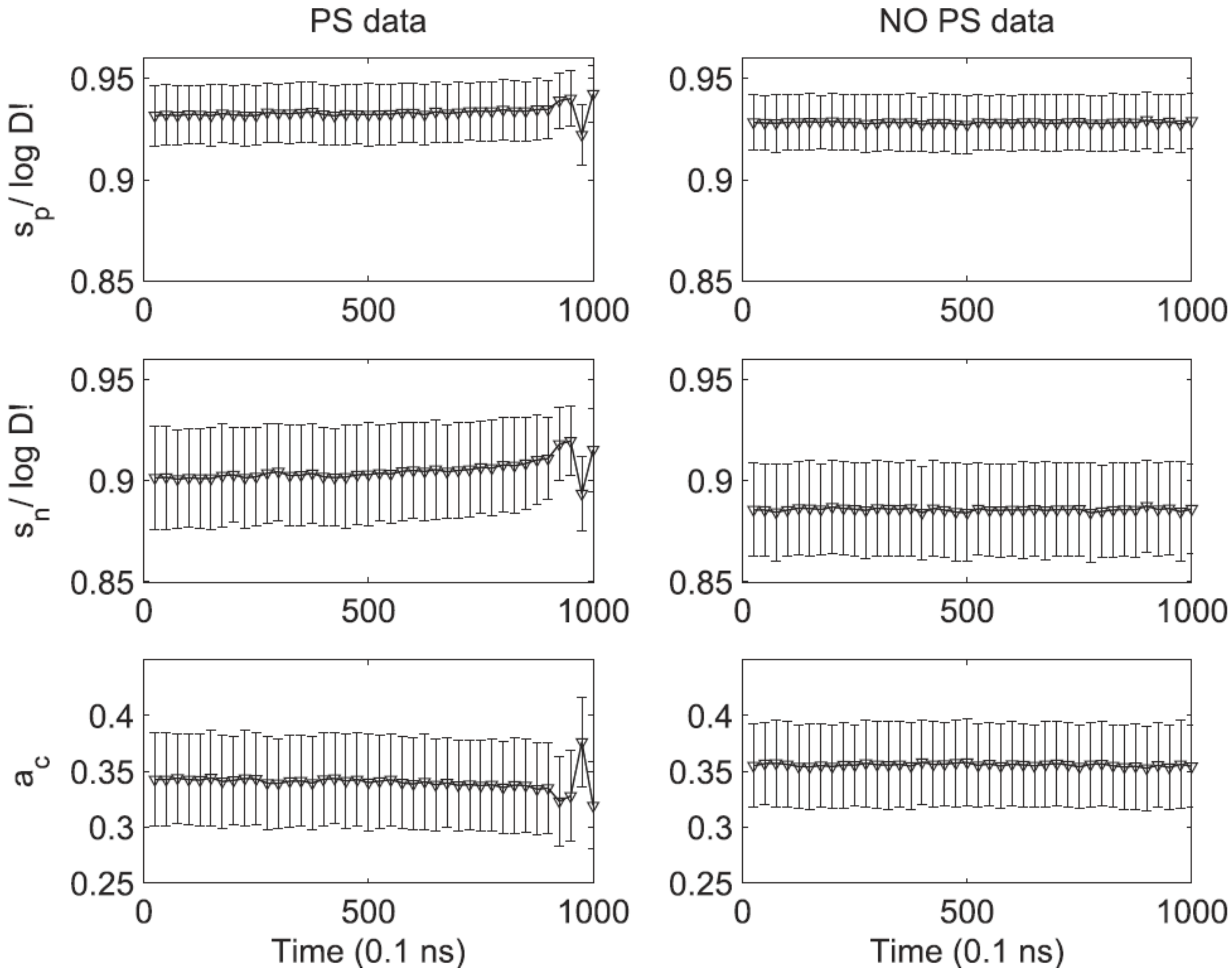
Three early-warning indicators



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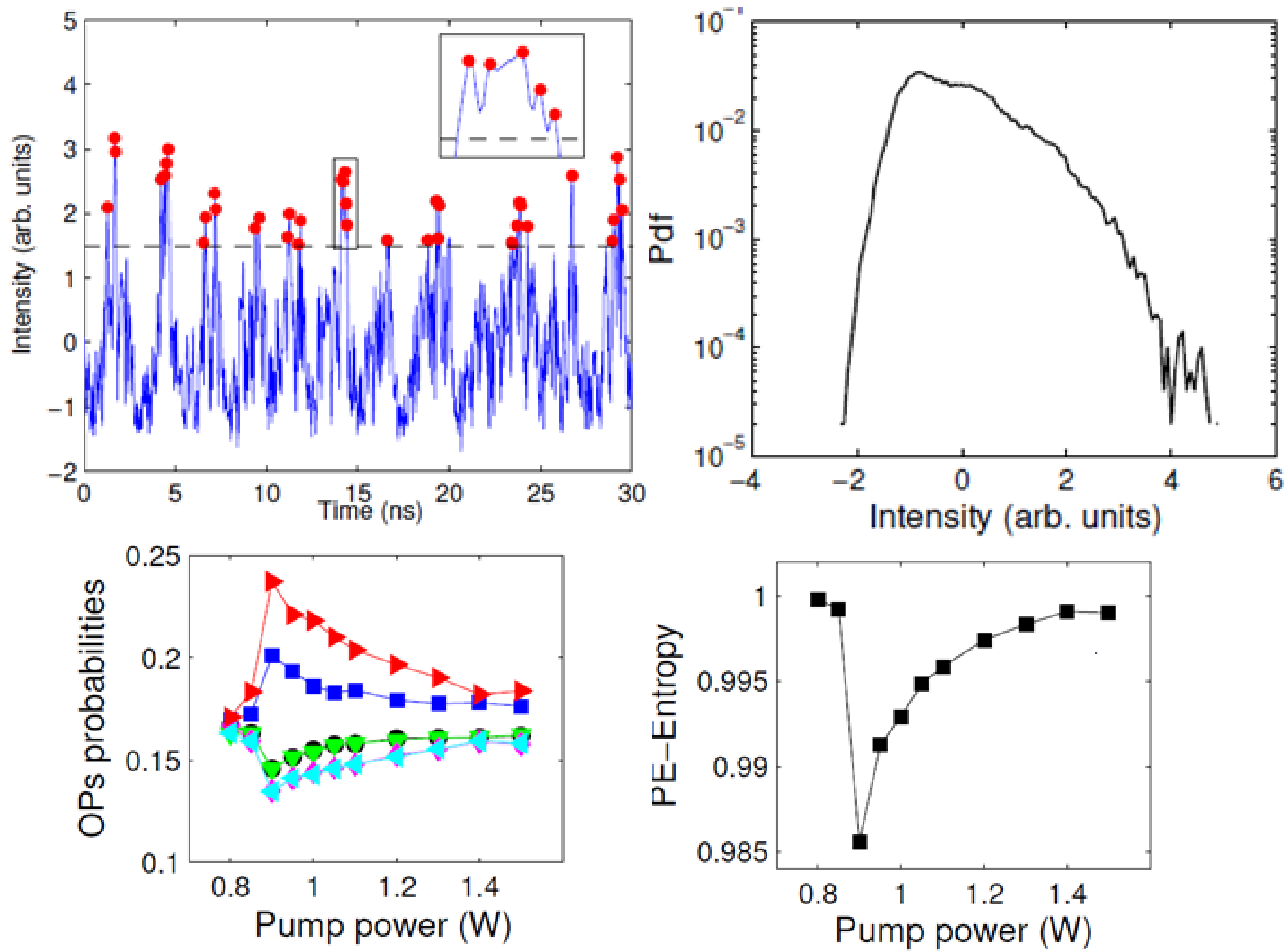
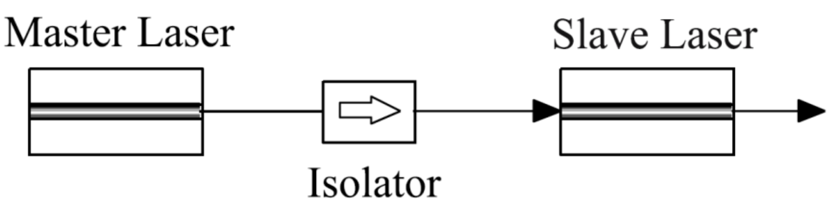
Example 3: laminar– turbulence regime transition in a fiber laser

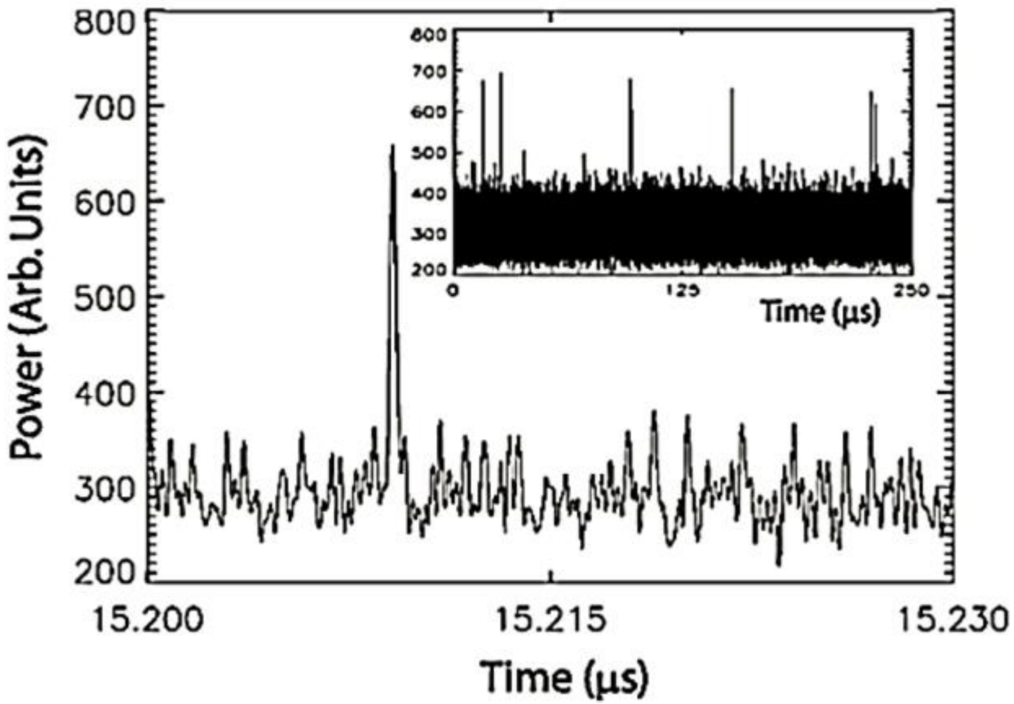


A. Aragoneses et al, arxiv.org/abs/1505.07365

Example 4: extreme pulses in an injected semiconductor laser

- Optical rogue waves





C. Bonatto et al, PRL 107, 053901 (2011)

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)

RWs 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

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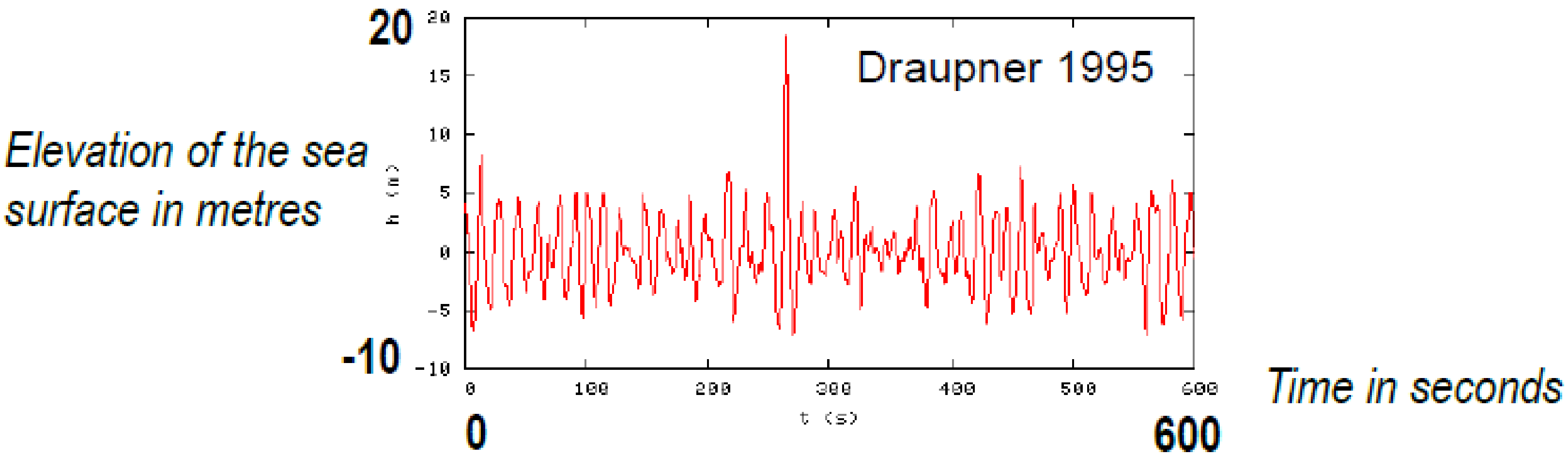
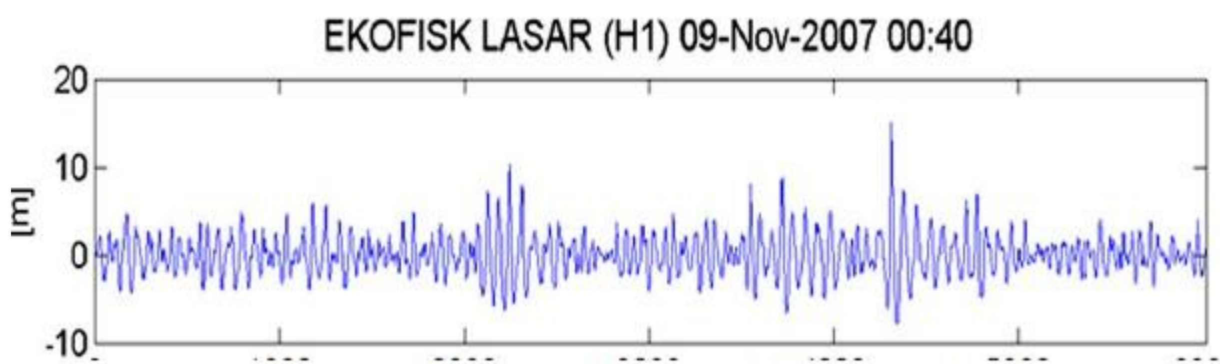
Examples



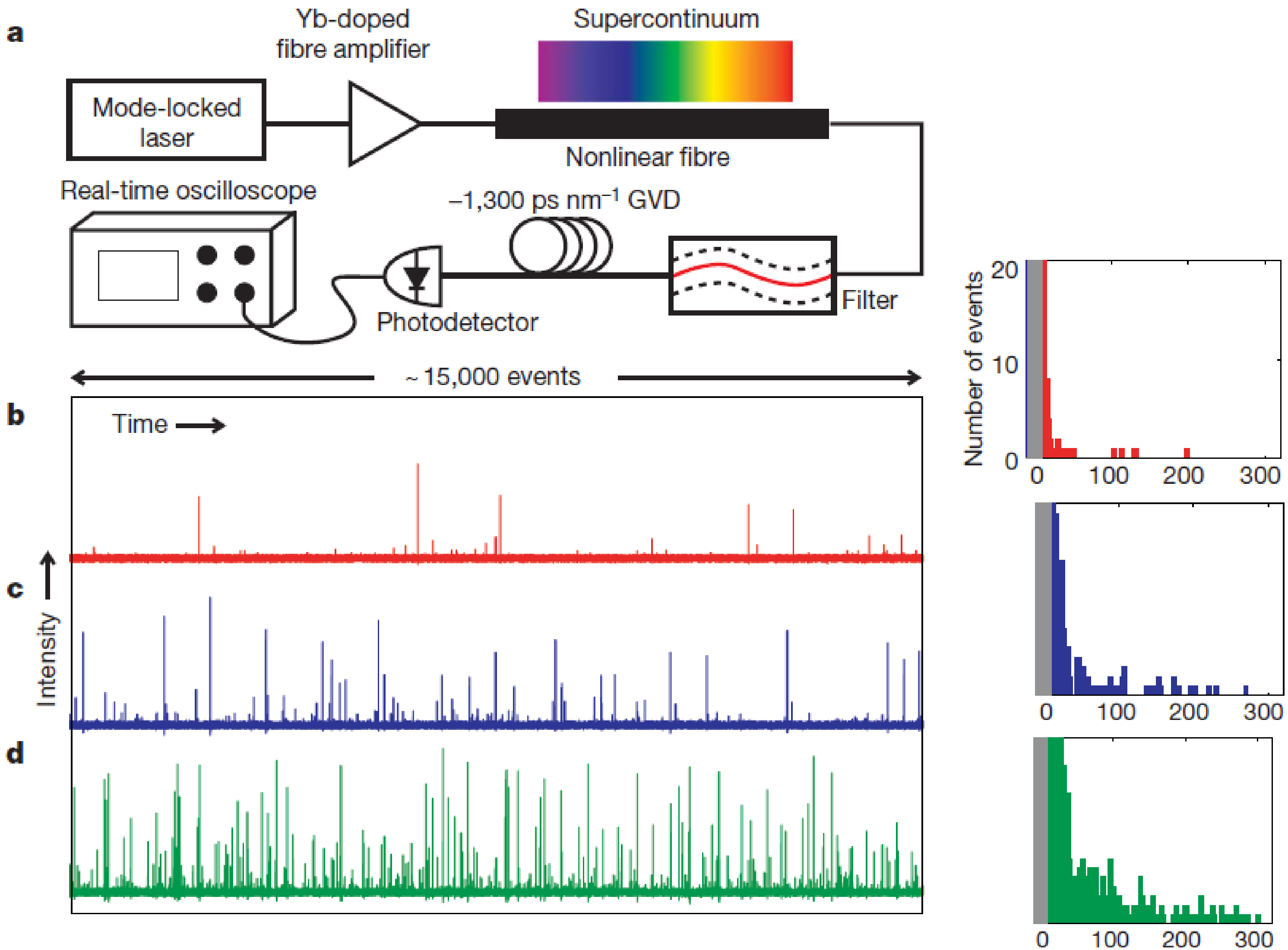
- Since 2003 wave profiles were measured with 4 lasers mounted on a bridge at the oil production site Ekofisk in the North Sea.
- A RW was detected 9/11/2007 during a storm.



Wave profile time series during **20 min** with 5 Hz sampling frequency

Adapted from F. Dias (Dublin)

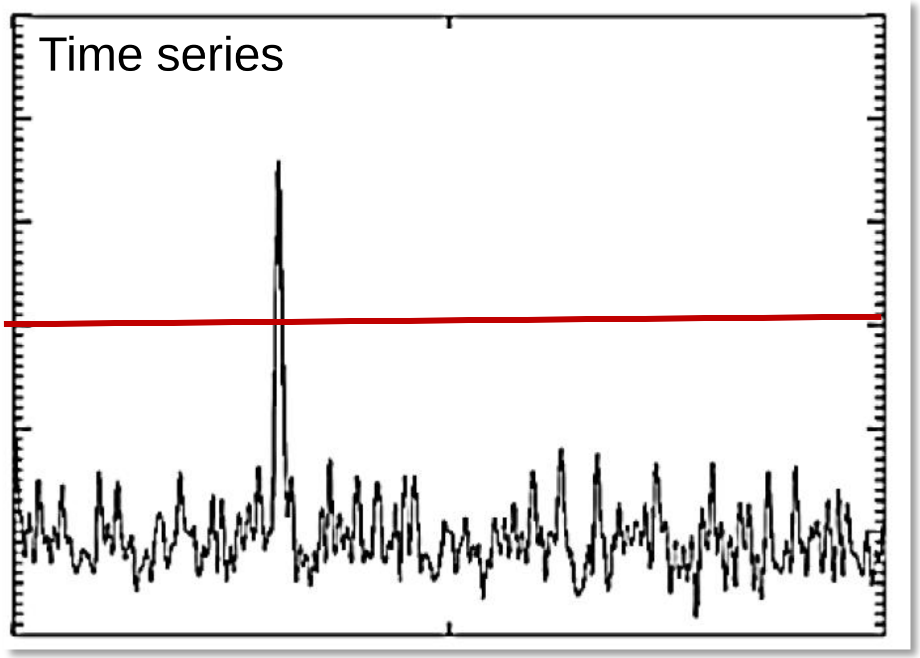
Optical RWs: first observation

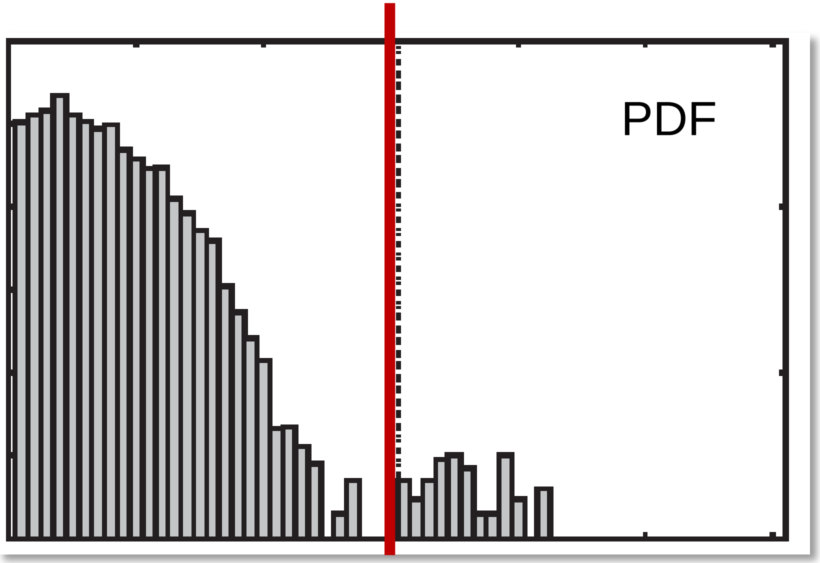


D. R. Solli et al, Nature 450, 1054, 2007

Injected semiconductor lasers provide a controllable setup for the study of RWs

- RW definition: pulse above a <u>threshold</u> (<H> + **4-8** σ)





What we have learned

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

- 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**

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

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

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

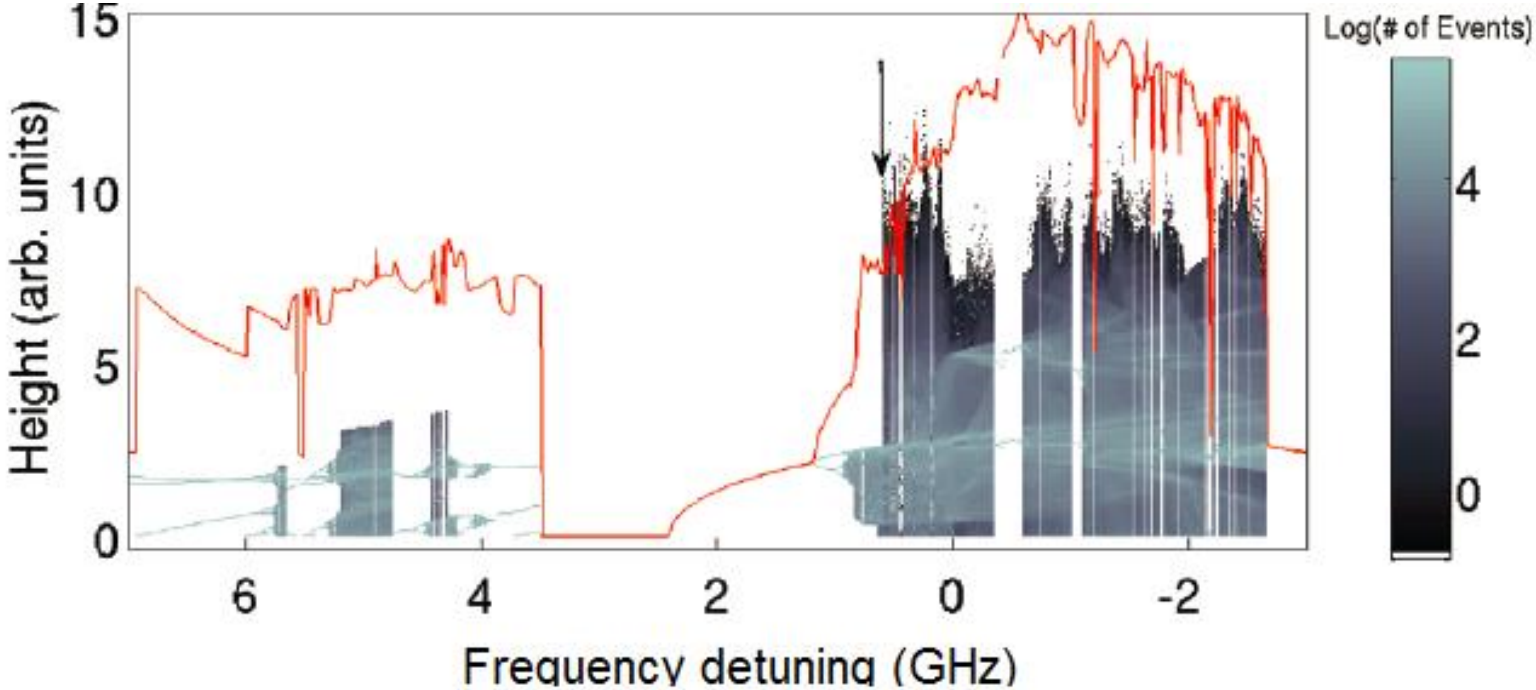
spontaneous emission noise

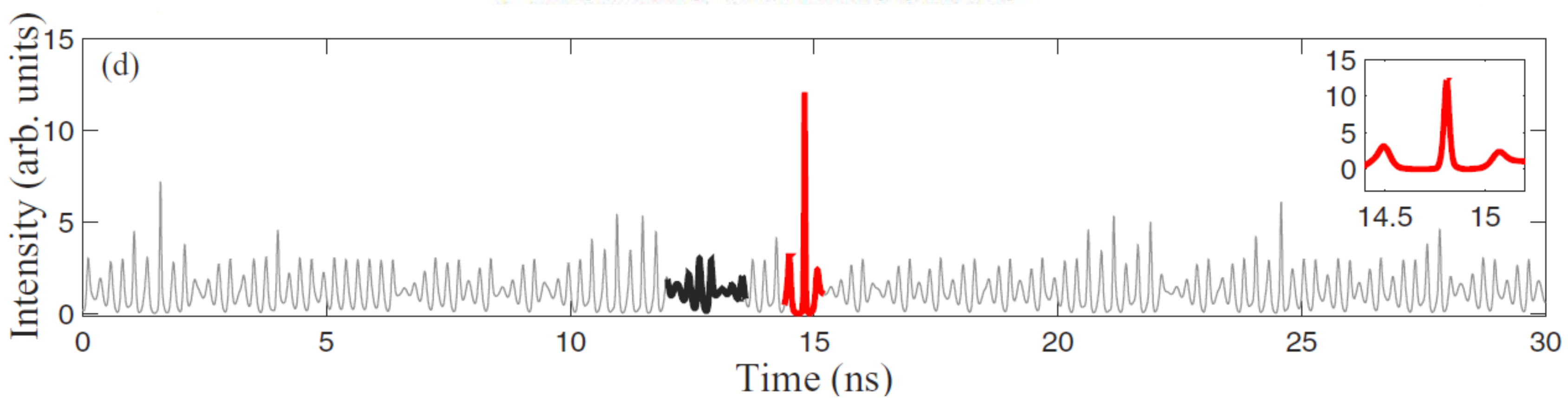
Solitary laser parameters: α τ_p τ_N μ

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

μ: normalized pump current parameter

Threshold: <H> + 8σ





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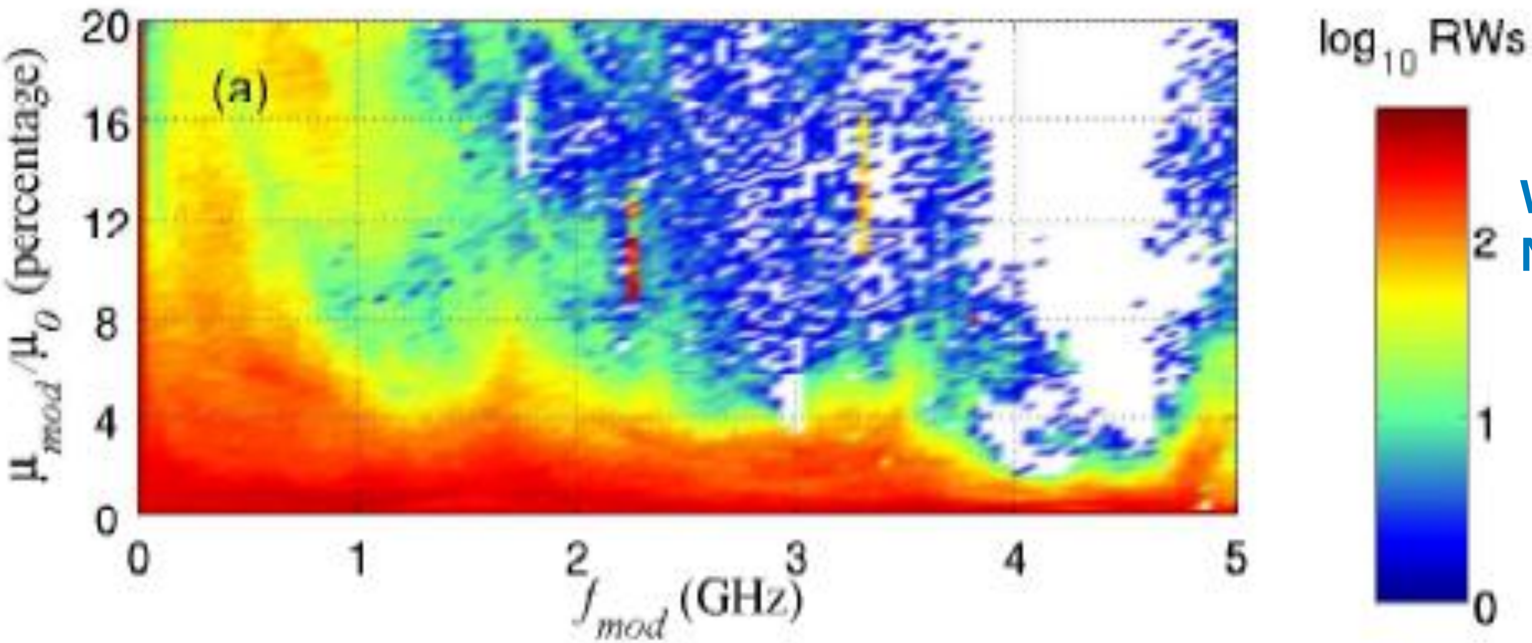
RWs can be suppressed by periodic modulation

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



White = No RWs

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

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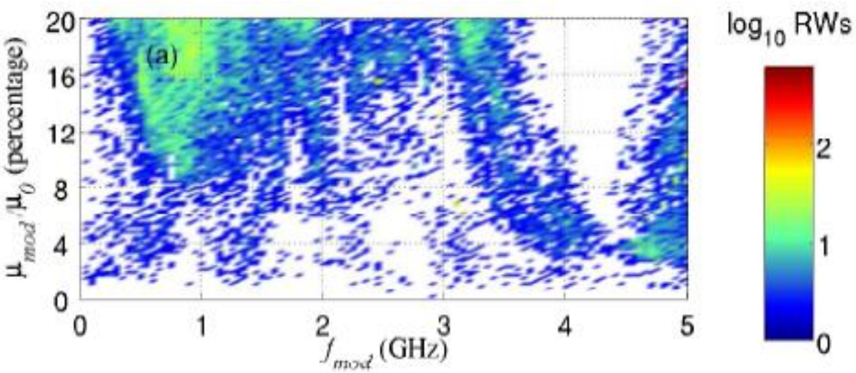
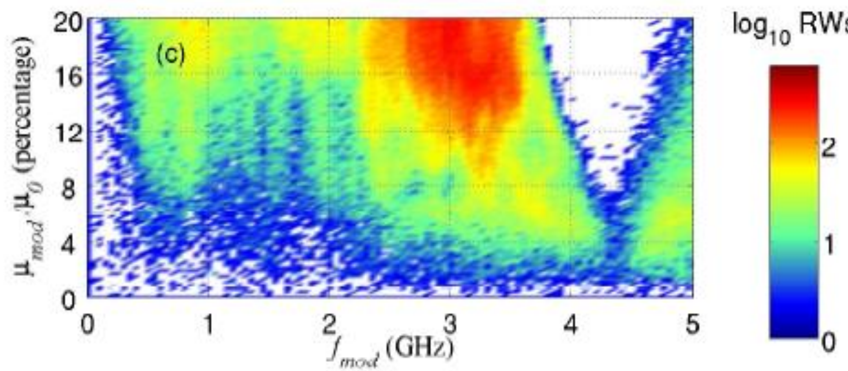
RWs can be induced by the combined influence of noise and modulation

β_{sp}=0

β_{sp}=0.01





White = No RWs

"safe" parameter region is robust to noise

Take home message and present work

- Take home message:

  When observing complex output signals, nonlinear analysis tools might capture hidden features in the data.

- Present work:
  - characterizing the performance of these analysis tools for anticipating i) extreme pulses (identifying precursors) and ii) abrupt transitions (false positives and false negatives).
  - applying nonlinear tools to 2D optical biomedical images (H2020 BE-OPTICAL).

Extreme Events in Complex Optical Systems
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Carme Torrent

VCSEL polarization-switching data:

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- S. Barland (INLN, Nice, France)

Fibre laser data:

- Prof. Turitsyn'group (Aston University, UK)

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THANK YOU FOR YOUR ATTENTION !

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http://www.fisica.edu.uy/~cris/

- A. Aragoneses, et al, *Unveiling the complex organization of recurrent patterns in spiking dynamical systems*, Sci. Rep. 4, 4696 (2014).
- C. Bonatto et al, *Deterministic optical rogue waves*, PRL 107, 053901 (2011).
- S. Perrone et al, *Controlling the likelihood of RWs in an optically injected semiconductor laser via direct current modulation*, PRA 89, 033804 (2014).
- C. Masoller et al, *Quantifying sudden changes in dynamical systems using symbolic networks*, New J. Phys. 17, 023068 (2015).
- A. Aragoneses et al, *Unveiling temporal correlations characteristic to phase transition in the intensity of a fibre laser radiation*, arxiv.org/abs/1505.07365

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