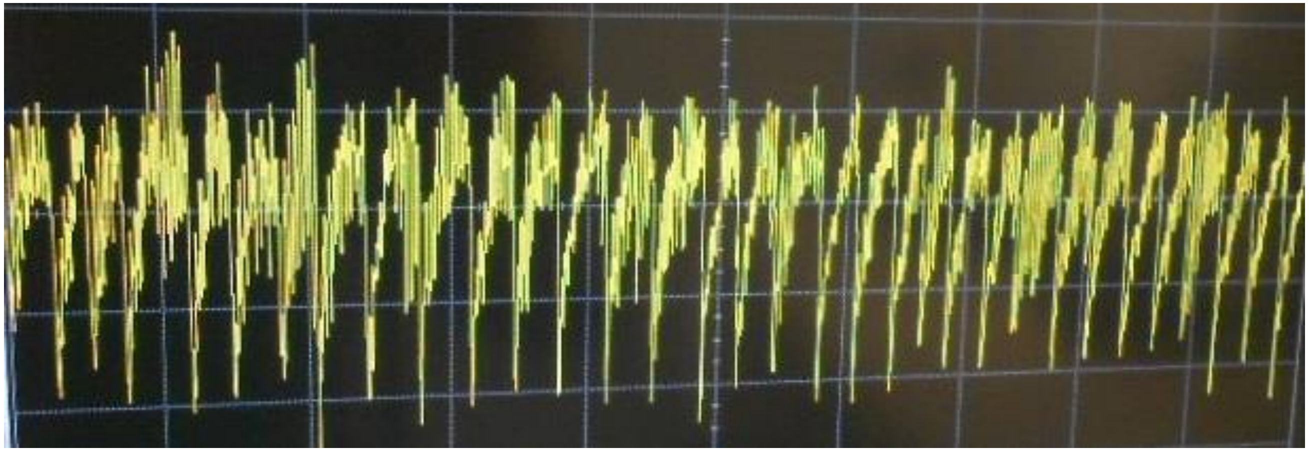

Big data approach to optical complexity:
investigating optical output signals with nonlinear data analysis tools

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Extreme events in complex optical systems (EECOS)

Buenos Aires, Argentina, December 2015

GOBIERNO DE ESPAÑA MINISTERIO DE CIENCIA E INNOVACIÓN

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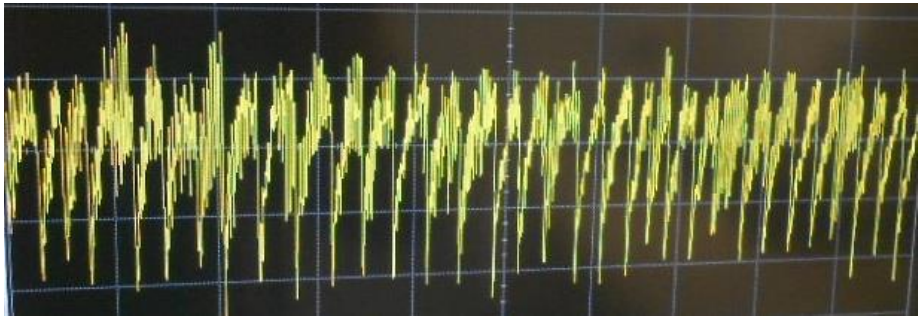
Dynamical optical complexity

- ## Optical spikes

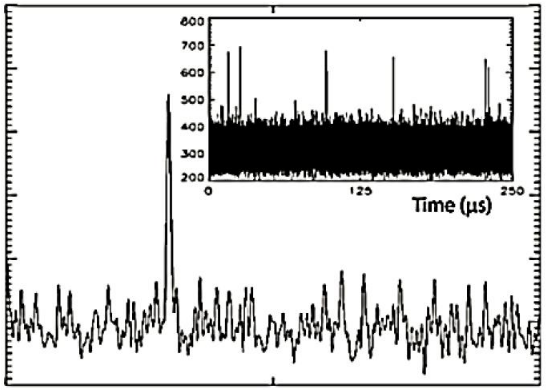
Semiconductor laser with optical feedback



Time

- ## Extreme pulses

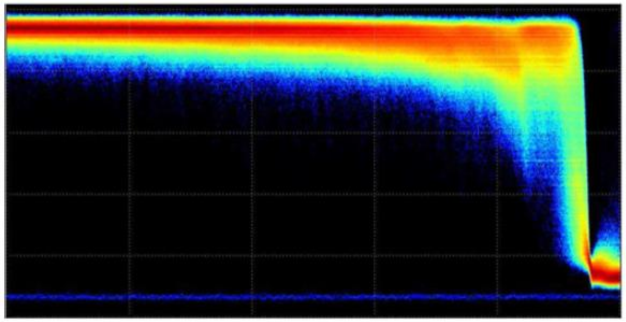
Semiconductor laser with injection



Time

- ## Polarization switching

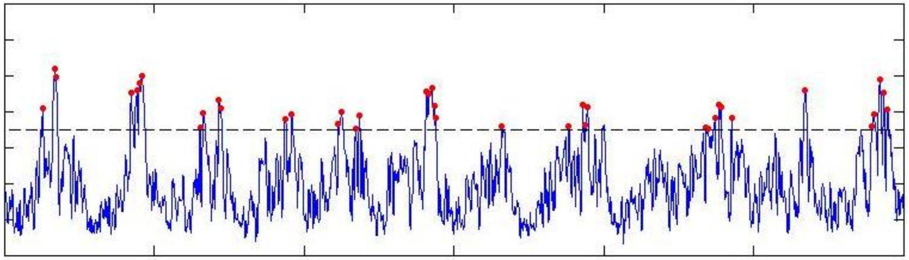
VCSELs



Time

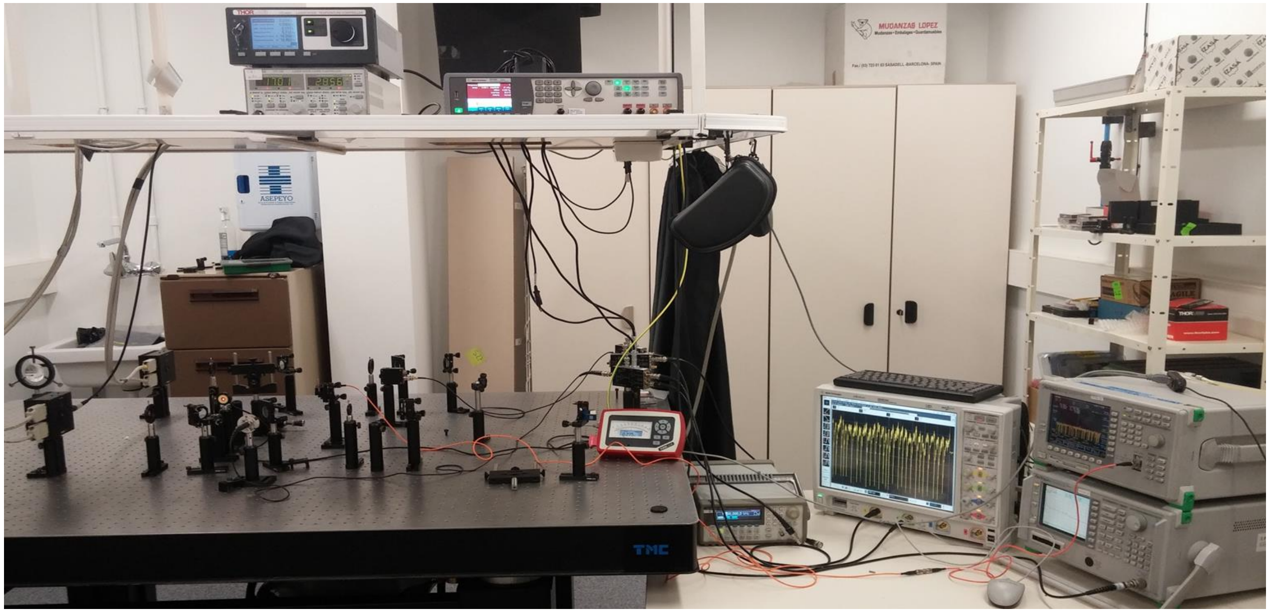
- ## Optical turbulence

Fibre laser



Time

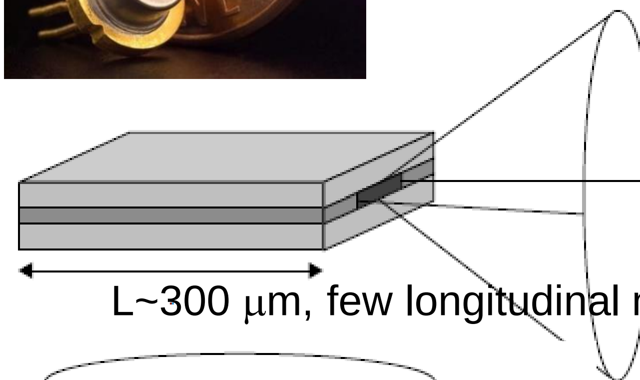
Big data approach



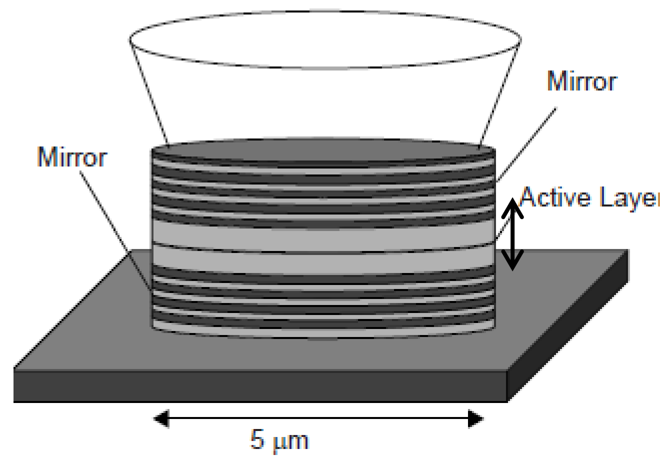
- Optical systems allow recording long time-series under controlled conditions.
- With this "optical big data" we can
  - test novel analysis tools (prediction, control).
  - capture relevant features in the data (classification, model verification, parameter estimation).

Optical systems: three types of lasers

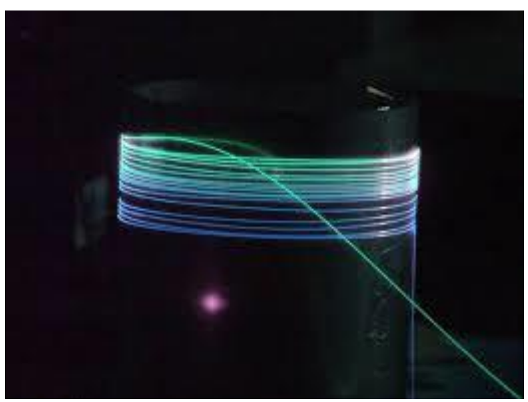
- Semiconductor lasers
  - Edge-emitting lasers (EELs)
  - Vertical-cavity (VCSELs)
- Fibre laser



L~300 μm, few longitudinal modes



L=1-10μm, single longitudinal mode



L=1 km, millions of longitudinal modes

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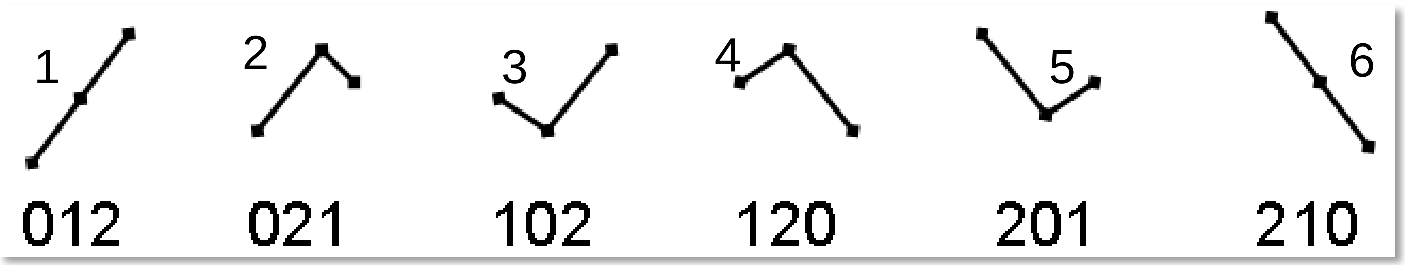
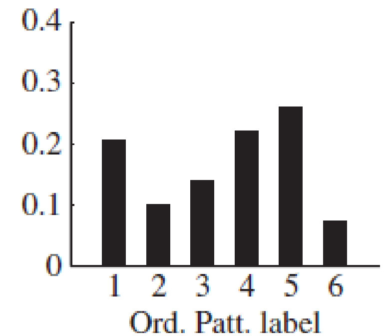
Method of time-series analysis: ordinal patterns

- $X = \{\ldots x_i, x_{i+1}, x_{i+2}, \ldots\}$

Brandt & Pompe, PRL 88, 174102 (2002)





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

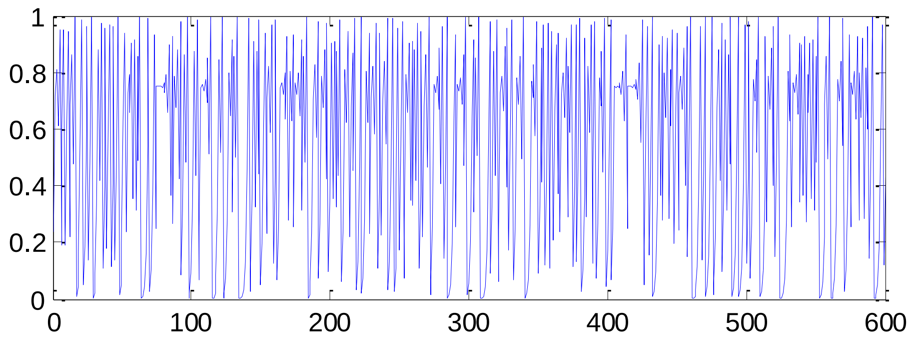
Random data $\Rightarrow$ OPs are equally probable

– Advantage: the probabilities uncover temporal correlations.

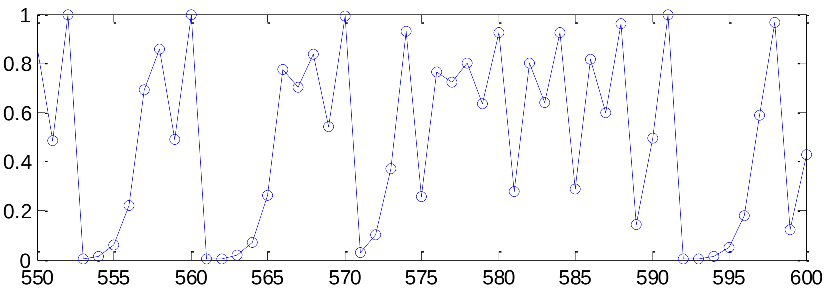
– Drawback: we lose information about the actual values.

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

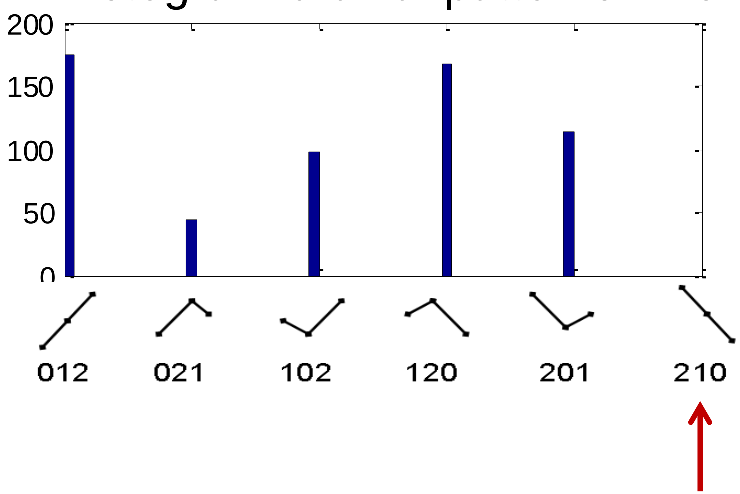
Time series



Detail

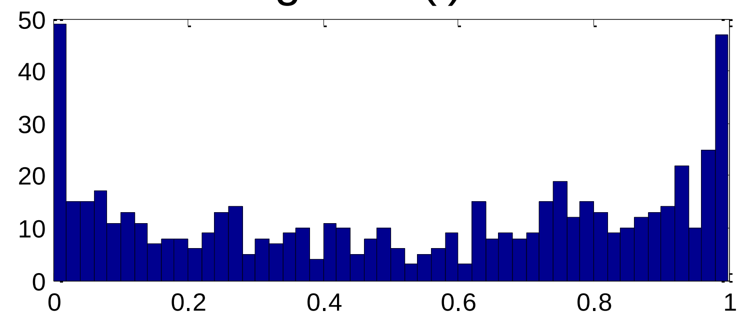


Histogram ordinal patterns D=3



Forbidden pattern

Histogram x(i)



Ordinal analysis provides complementary information.

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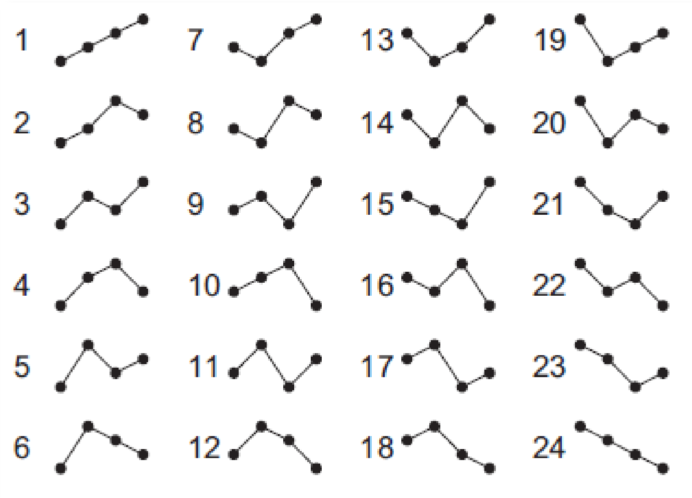
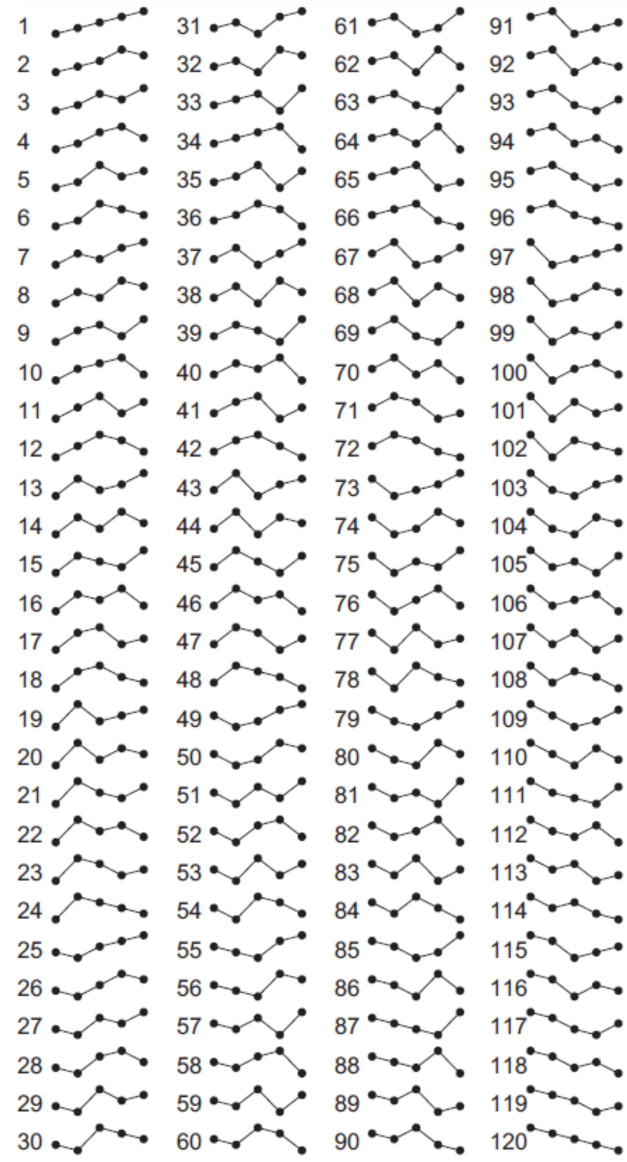
Number of possible ordinal patterns: D!

D=4



D=5



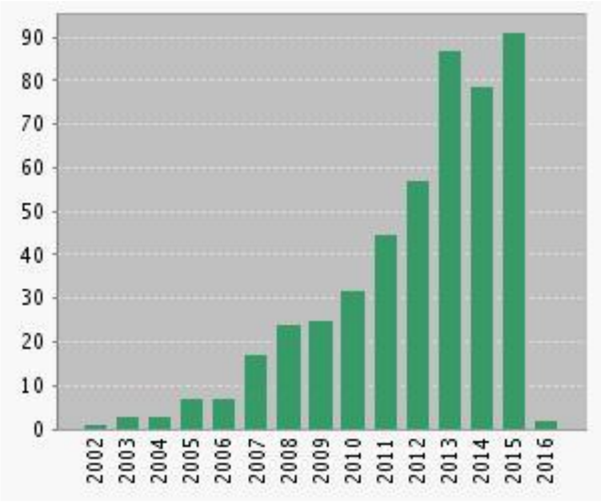
- How to select D?

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

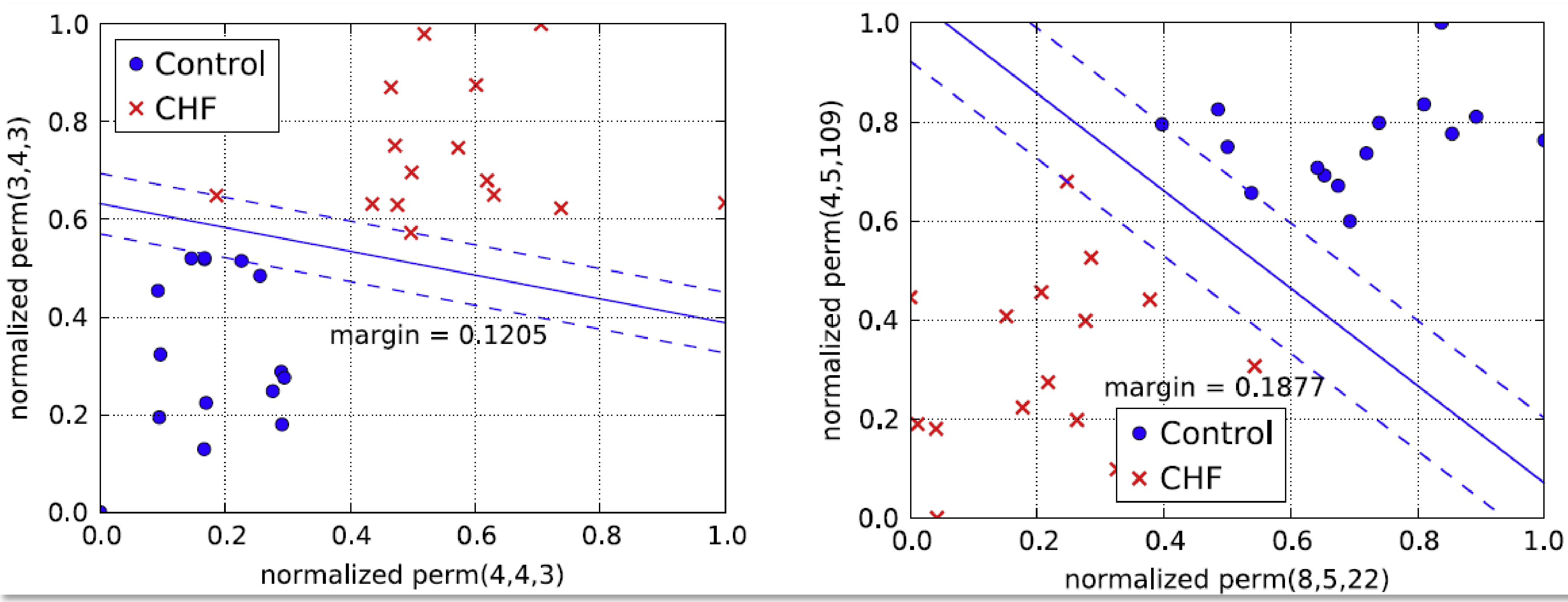
U. Parlitz et al. / Computers in Biology and Medicine 42 (2012) 319–327

- Ordinal analysis has been widely used to study the output signals of complex systems
  - Financial, economical
  - Biological, life sciences
  - Geosciences, climate
  - Physics, chemistry, etc
- It has been shown to be able to:
  - Distinguish stochasticity and determinism
  - Classify different types of behaviors
  - Quantify complexity
  - Identify coupling and directionality.

Number of papers citing PRL 2002



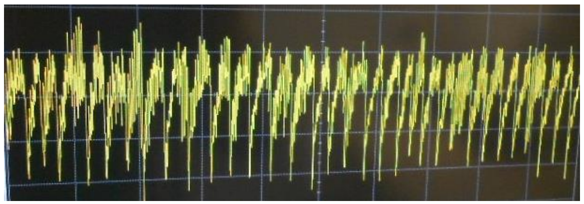
Example: classifying electrocardiography signals

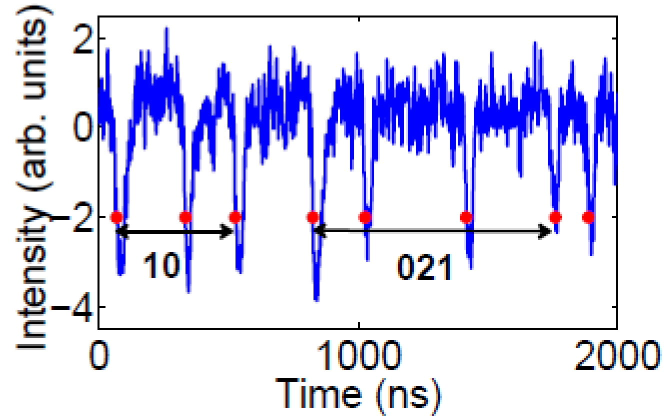


U. Parlitz et al. / Computers in Biology and Medicine 42 (2012) 319–327

(the probabilities are normalized with respect to the smallest and the largest value occurring in the data set)

First example: optical spikes in EELs with optical feedback

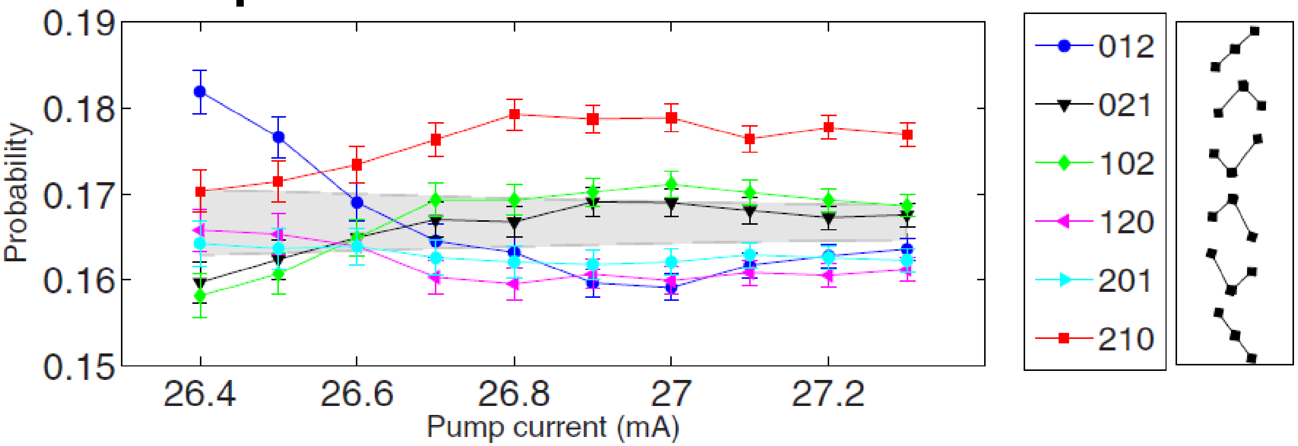




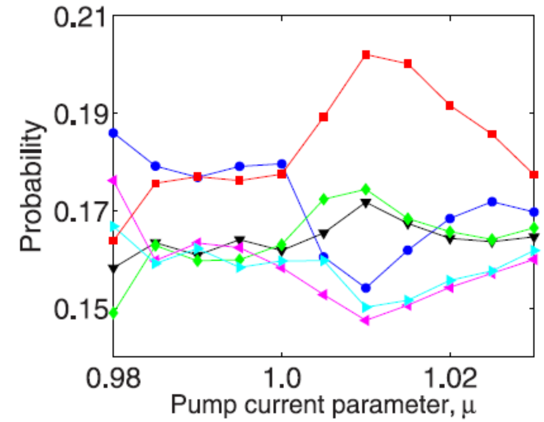
$X = \{\ldots \Delta T_i, \Delta T_{i+1}, \Delta T_{i+2}, \ldots\}$

Time intervals between spikes

Empirical data



LK Model



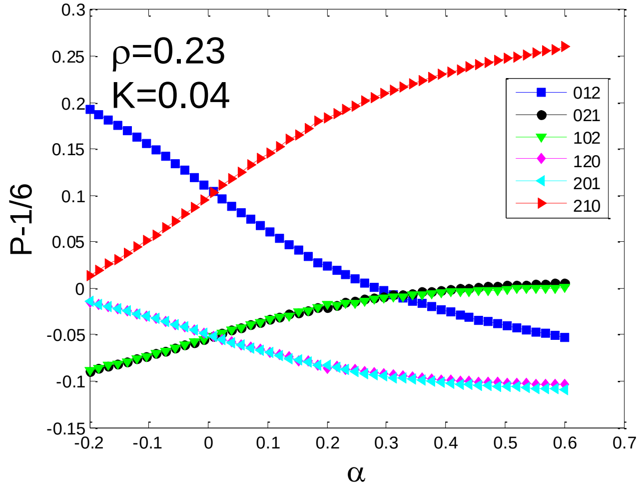
Error bars computed with a binomial test, gray region is consistent with $p_i = 1/6\ \forall\ i$.

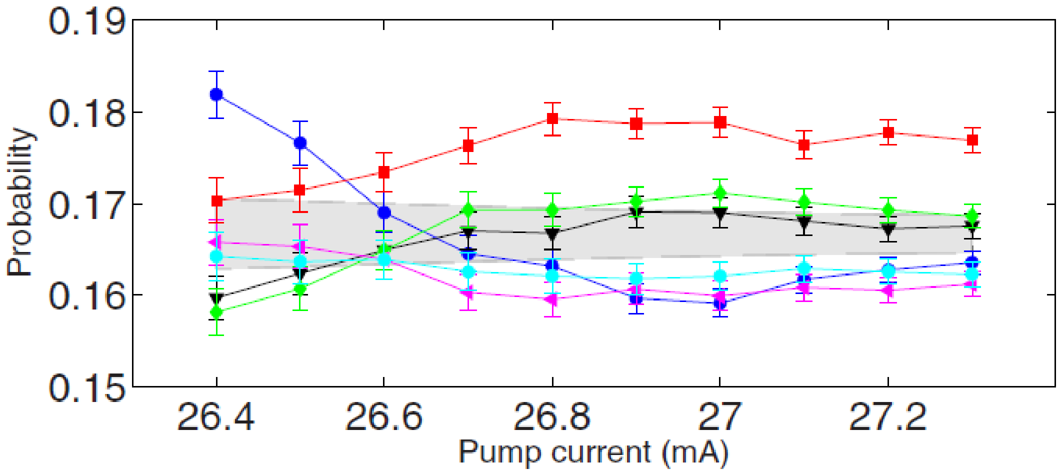
A. Aragoneses et al, Sci. Rep. 4, 4696 (2014)

Minimal model for spike temporal correlations: modified circle map

$$\varphi_{i+1} = \varphi_i + \rho + \frac{K}{2\pi}\left[\sin(2\pi\varphi_i) + \alpha \sin(4\pi\varphi_i)\right]$$

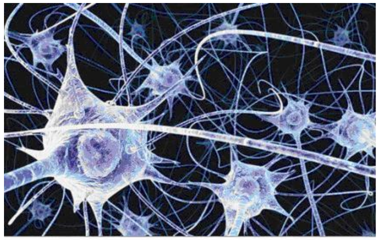
$$X_i = \varphi_{i+1} - \varphi_i$$





- The circle map describes many excitable systems
- The modified circle map has been used to describe correlations in the spikes of biological neurons.

Neiman and Russell, *Models of stochastic biperiodic oscillations and extended serial correlations in electroreceptors of paddlefish*, PRE 71, 061915 (2005)



How similar optical spikes and neuronal spikes are?

Neuron Interspike interval (ISI) histogram

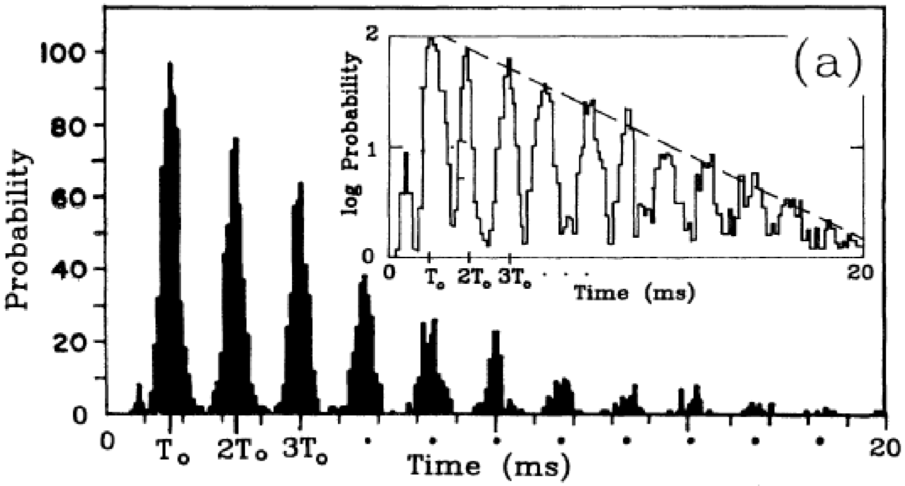
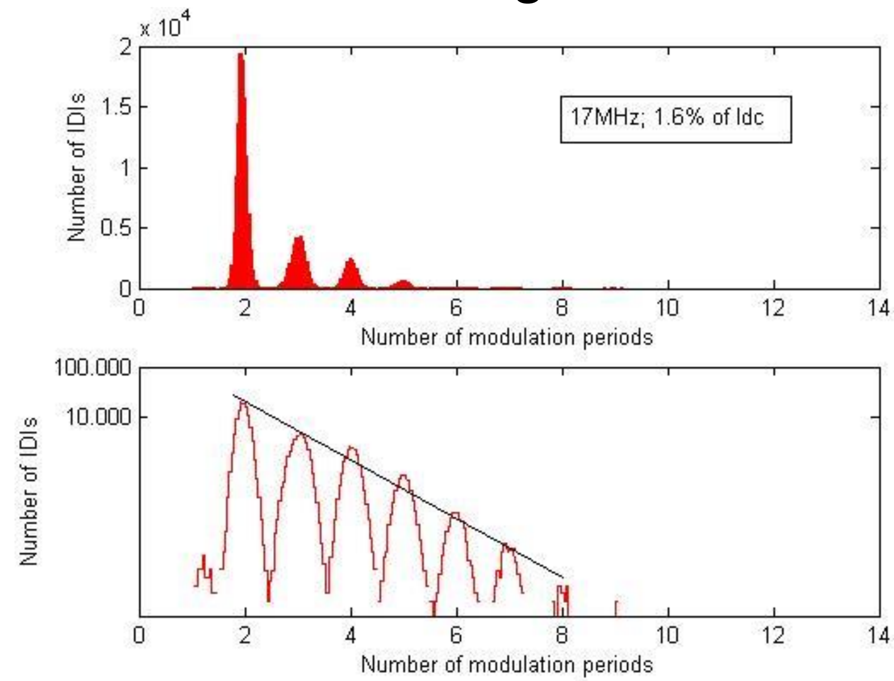


FIG. 1. (a) An experimental ISIH obtained from a single auditory nerve fiber of a squirrel monkey with a sinusoidal 80-dB sound-pressure-level stimulus of period $T_0 = 1.66$ ms applied at the ear. Note the modes at integer multiples of T_0. Inset:

Laser ISI histogram



With direct current modulation, data recorded in our lab

A. Longtin et al, PRL 67 (1991) 656.

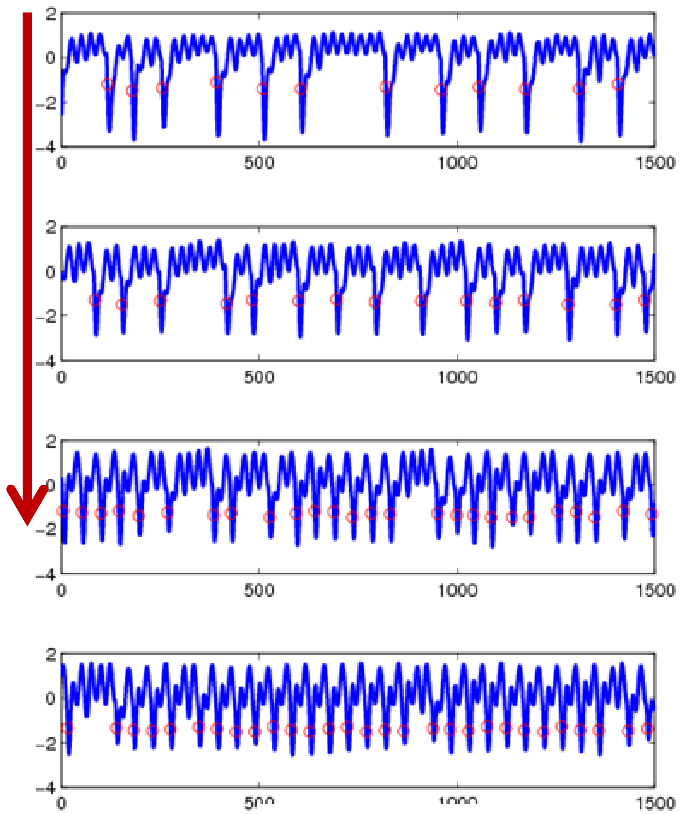
Response to periodic modulation

Relevant for understanding neuronal encoding of external stimuli

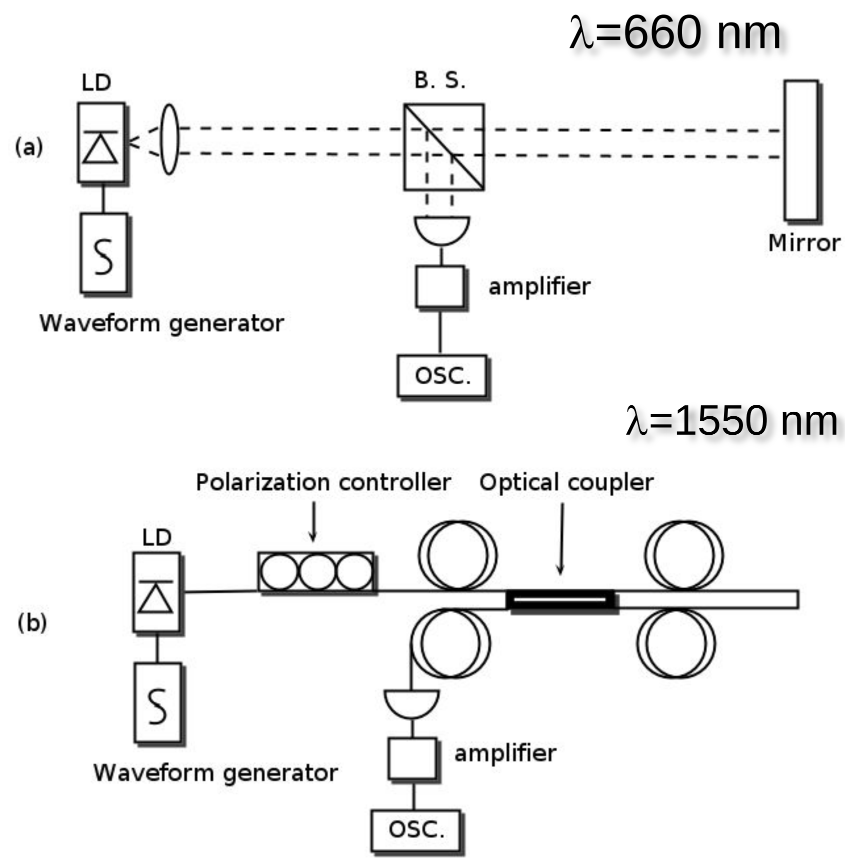
Laser intensity:

Increasing modulation amplitude

Tendency to lock



Two experiments:



Experiments - minimal model comparison

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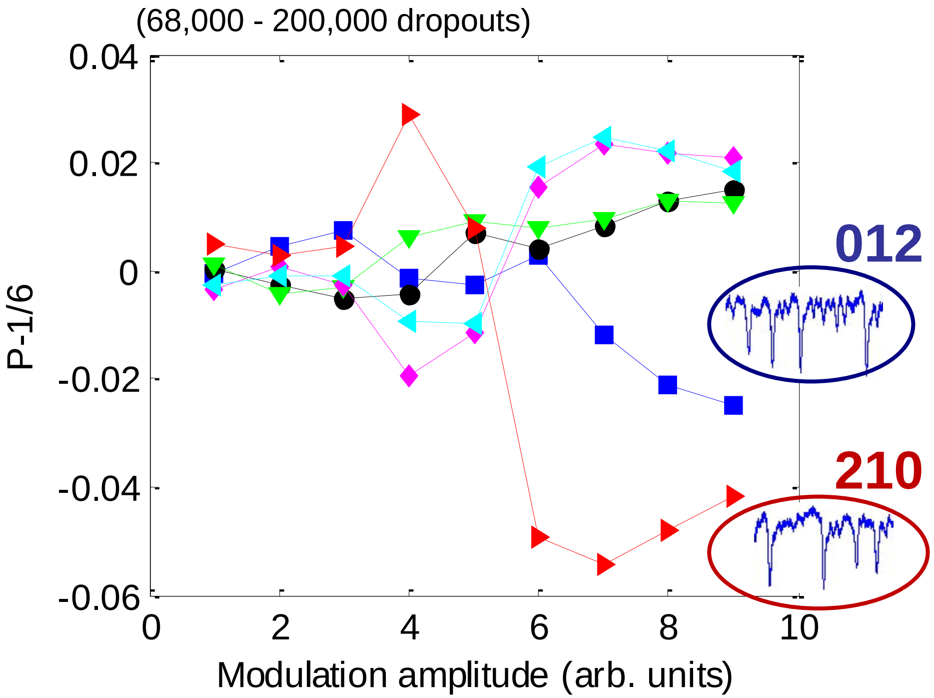
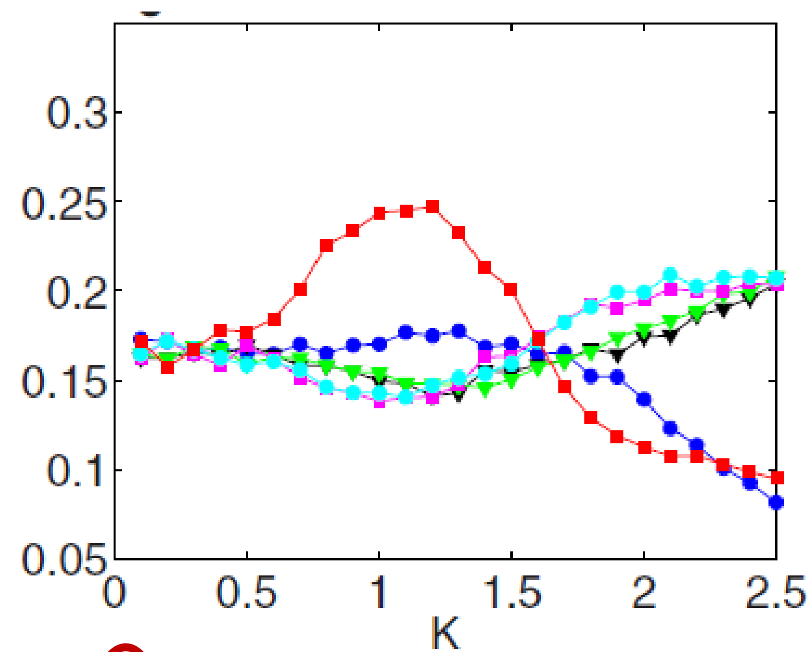
Experiments @ 660 nm



Modified circle map



$$\varphi_{i+1} = \varphi_i + \rho + \frac{K}{2\pi}\left[\sin(2\pi\varphi_i) + \alpha\sin(4\pi\varphi_i)\right] + D\zeta$$

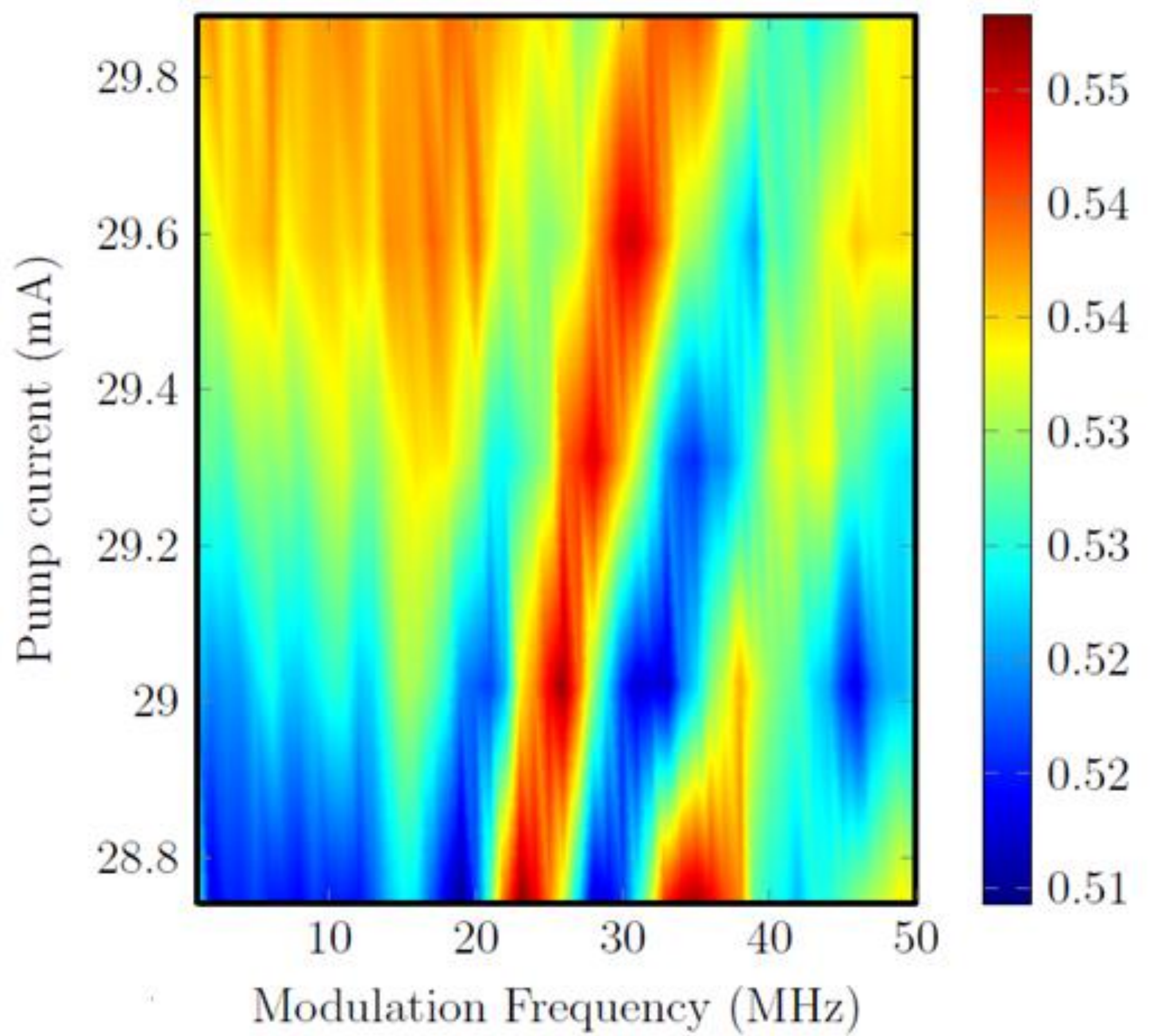
Similar observations @ 1550 nm

Interpretation: locking to external forcing

Ordinal analysis: a valuable tool for identifying noisy locking

Probability of “10” computed from empirical data.

Pump current: modifies the natural (unmodulated) spike rate



T. Sorrentino et al,
Optics Express **23**, 5571 (2015).

IEEE J. Sel. Top. Quantum Electron. **21**, 1801107 (2015).

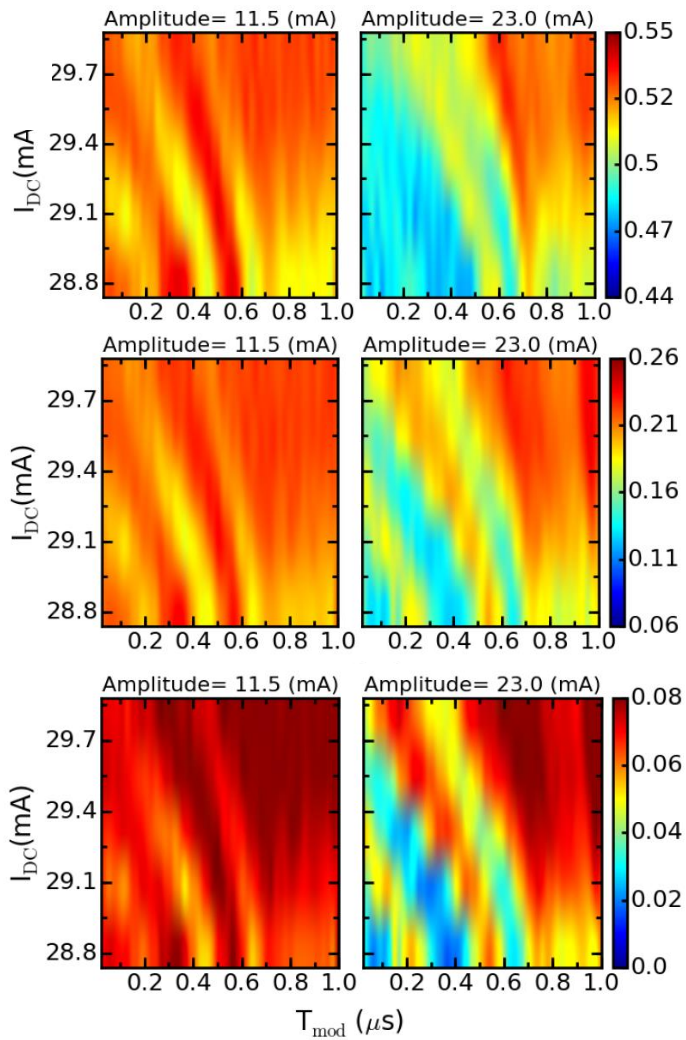
Ordinal analysis allows to uncover long correlations

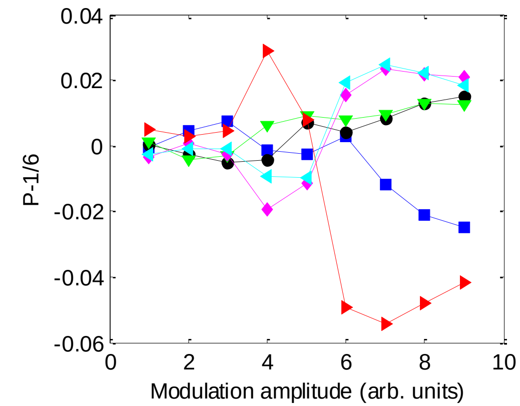
Weak modulation Stronger modulation

Probability of "10"

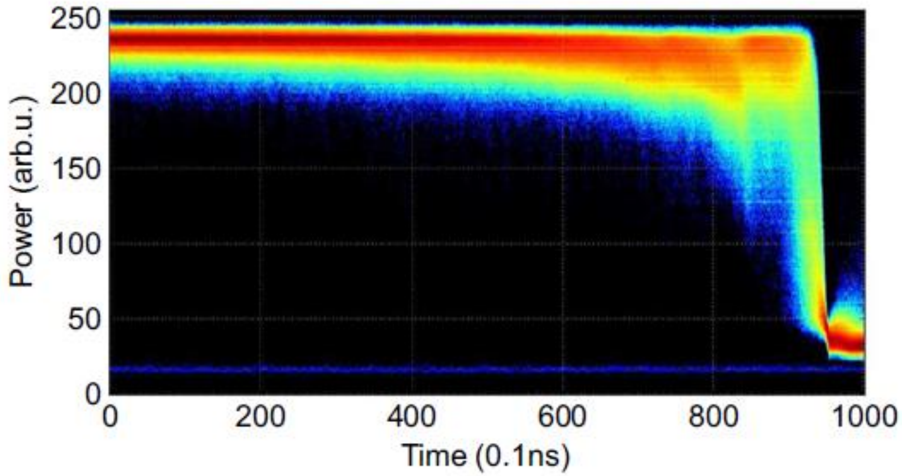
Probability of "210"

Probability of "3210"

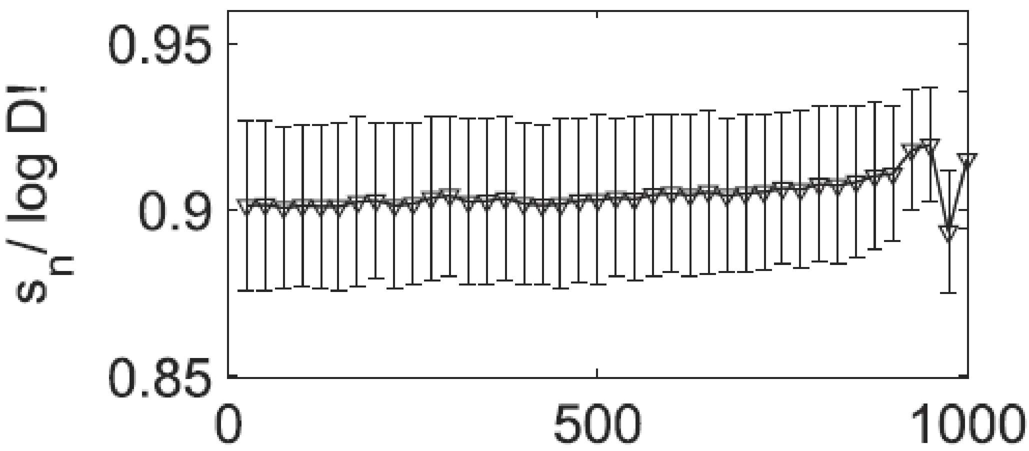




Example 2: early warning of an abrupt transition



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.

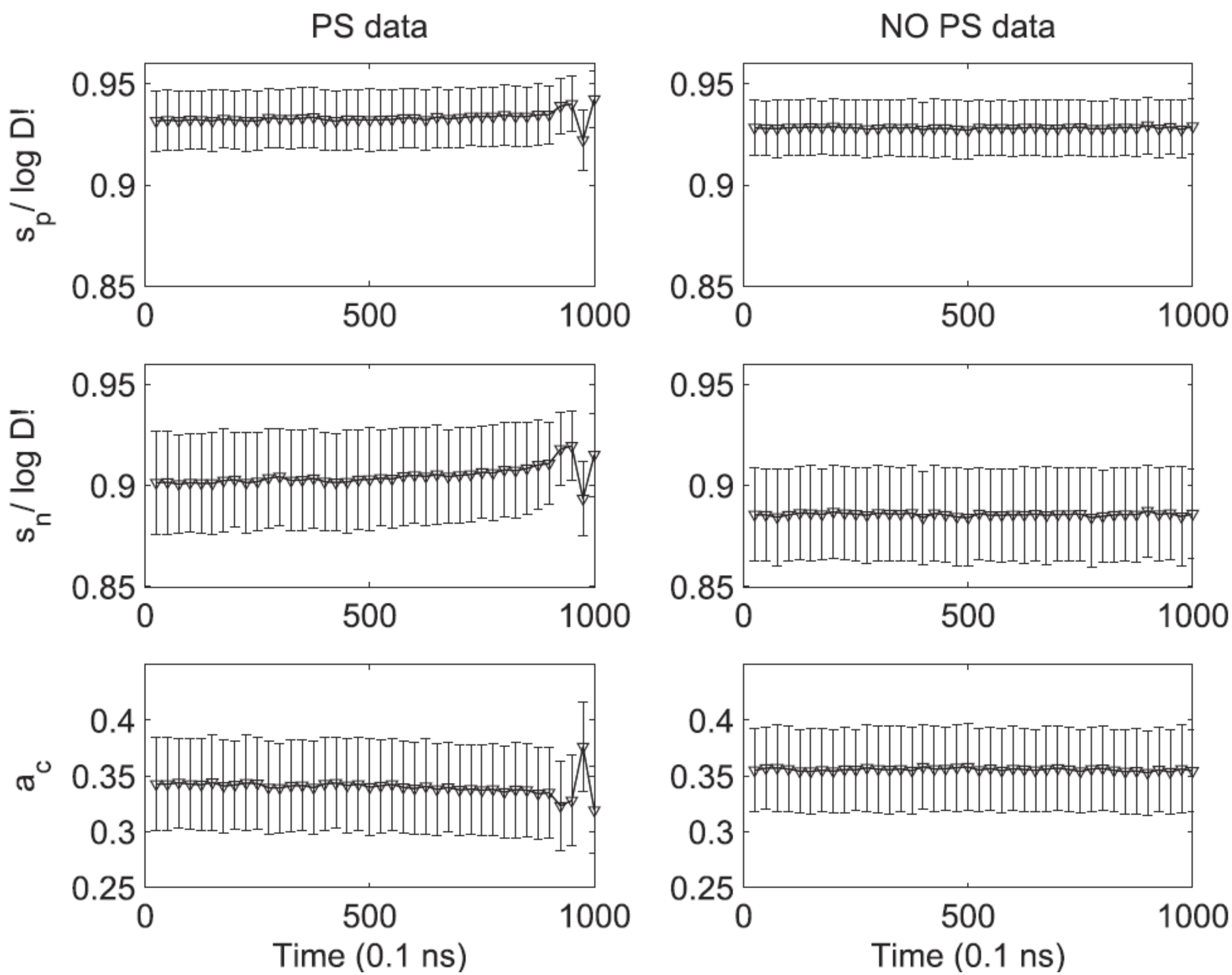
C. Masoller et al, New J. Phys. 17 (2015) 023068

Three early-warning indicators

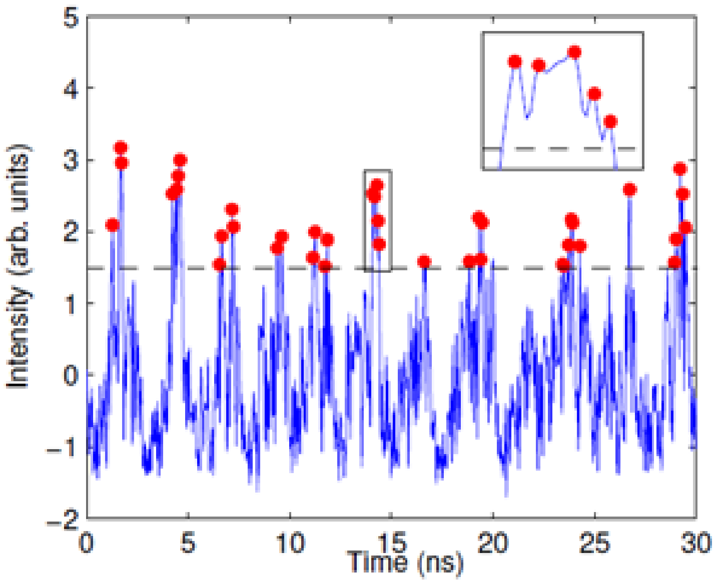
Entropy computed from the probabilities of the ordinal patterns

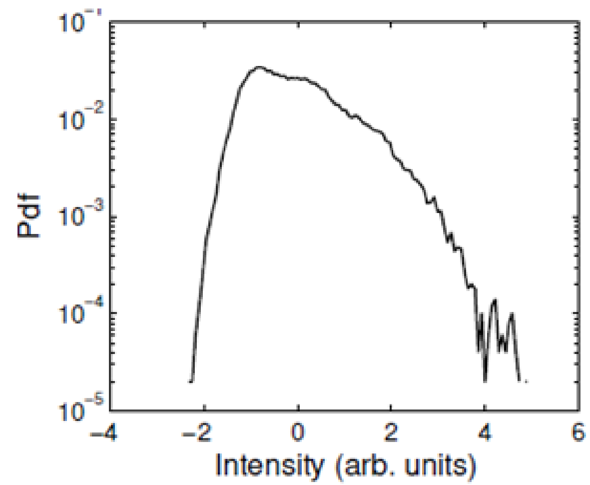
Entropy computed from the transition probabilities (TPs)

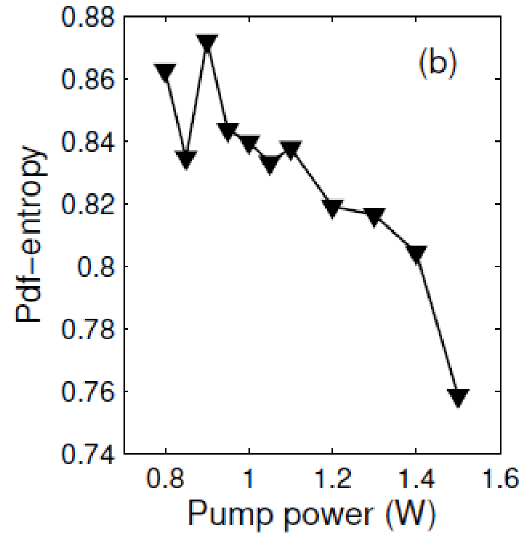
Asymmetry coefficient computed from TPs

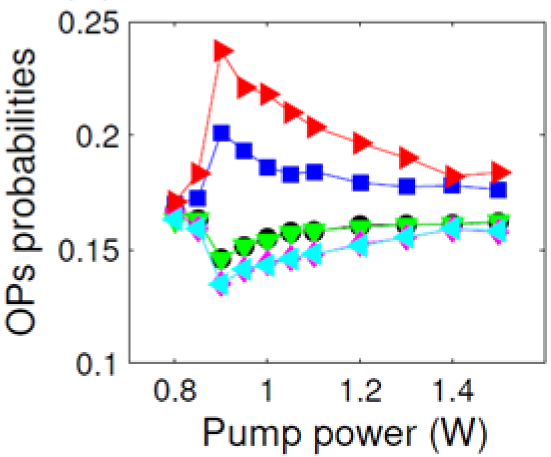


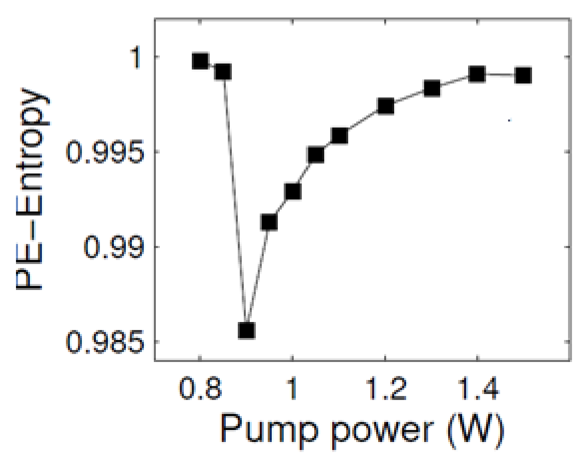
Example 3: laminar– turbulence regime transition in a fiber laser









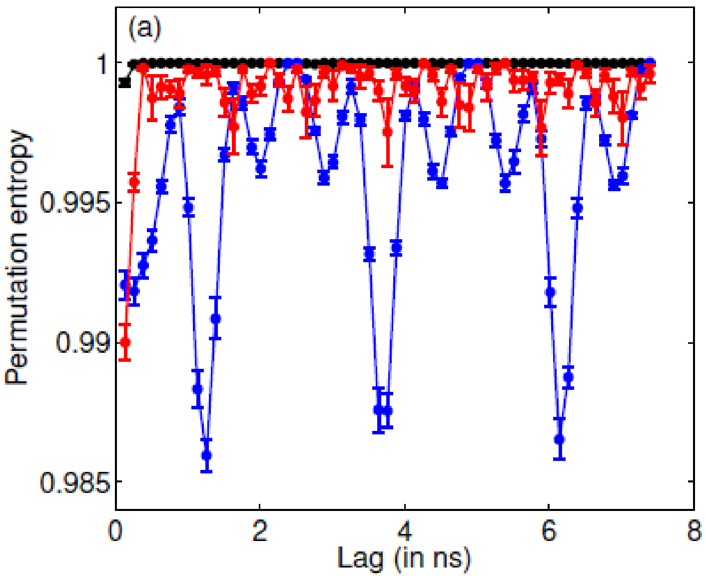


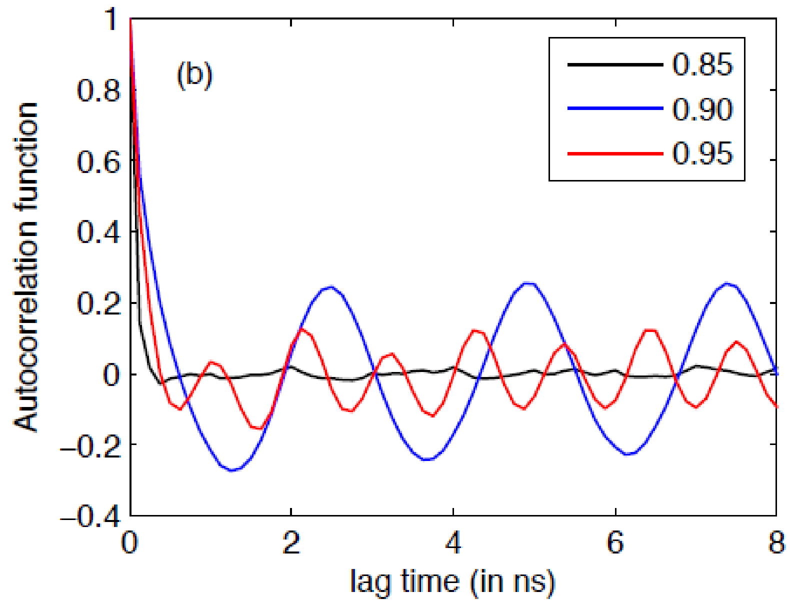
A. Aragoneses et al, arxiv.org/abs/1505.07365

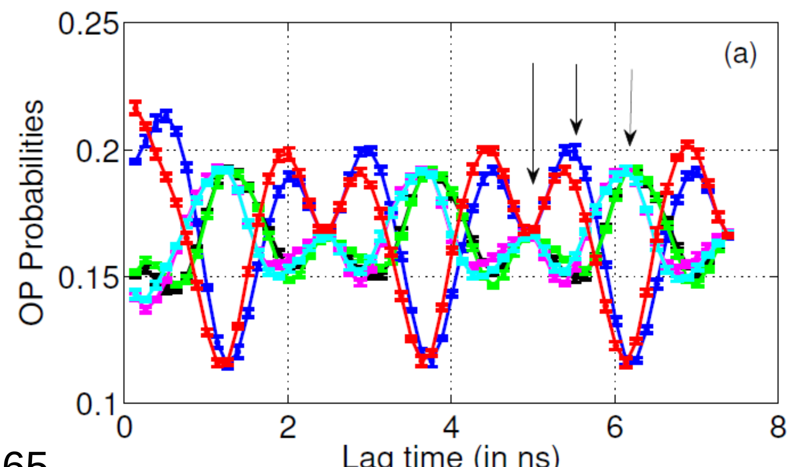
Unveiling specific time-scales

Ordinal patterns constructed
with lagged data points

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

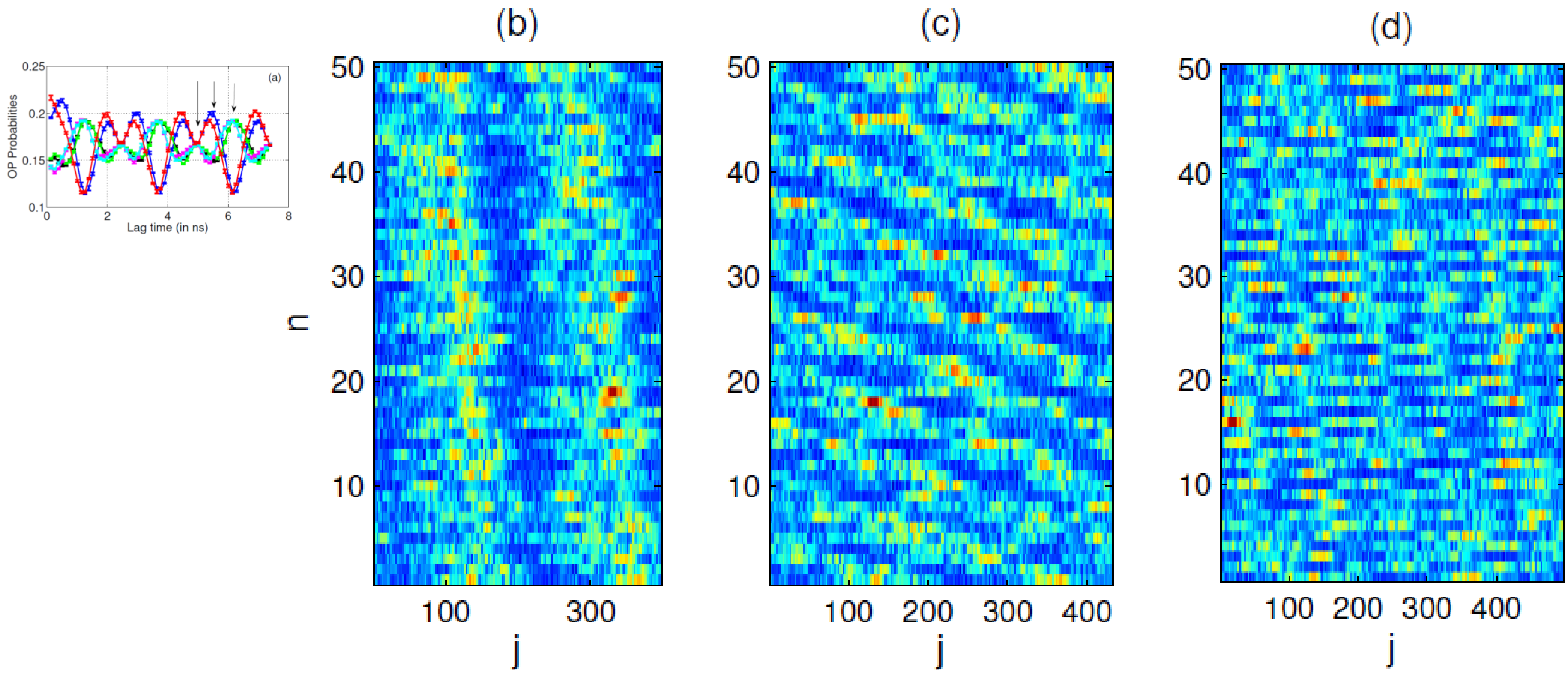






A. Aragoneses et al, arxiv.org/abs/1505.07365

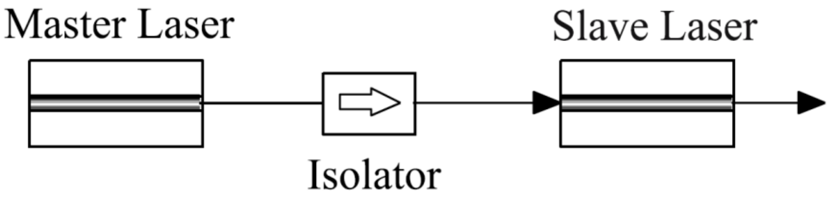
Uncovering spatio-temporal coherent structures

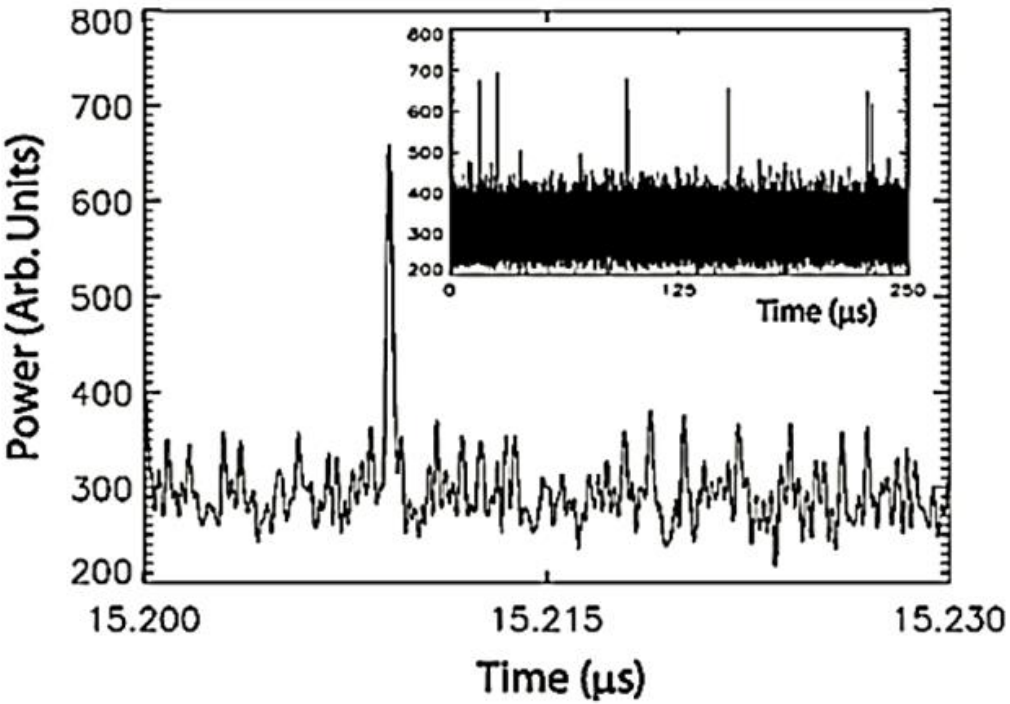


A. Aragoneses et al, arxiv.org/abs/1505.07365

Example 4: extreme pulses in an injected semiconductor laser

- Optical rogue waves

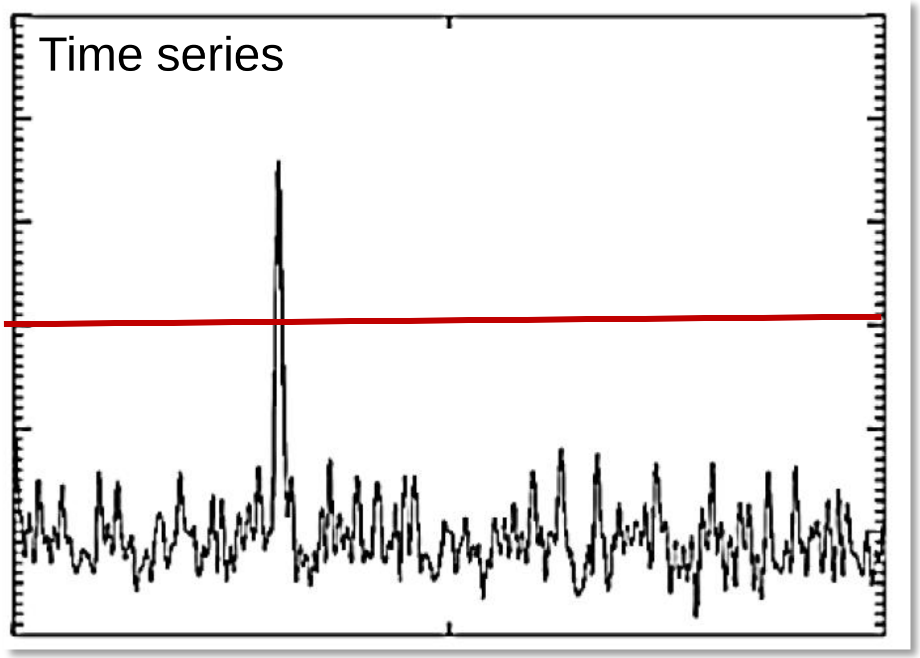


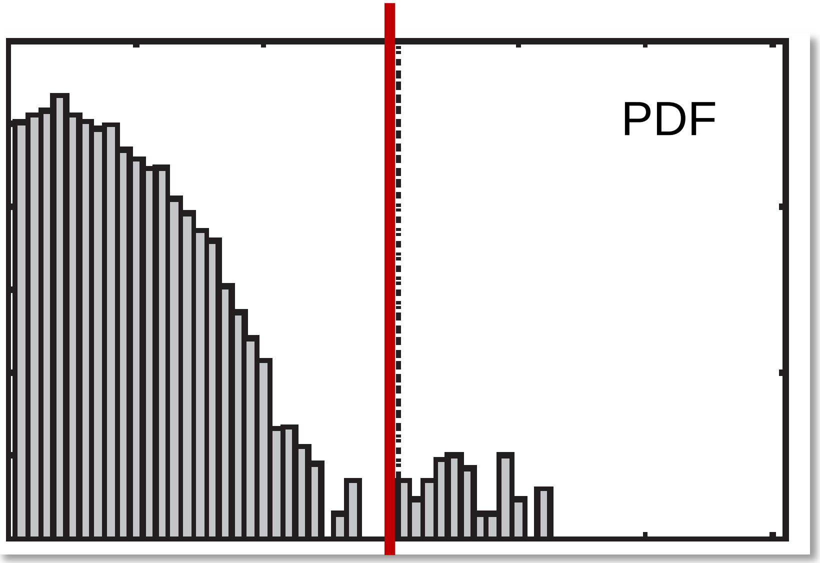


C. Bonatto et al, PRL 107, 053901 (2011)

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**

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

η: injection strength

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

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

Typical parameter values:

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

μ: normalized pump current parameter

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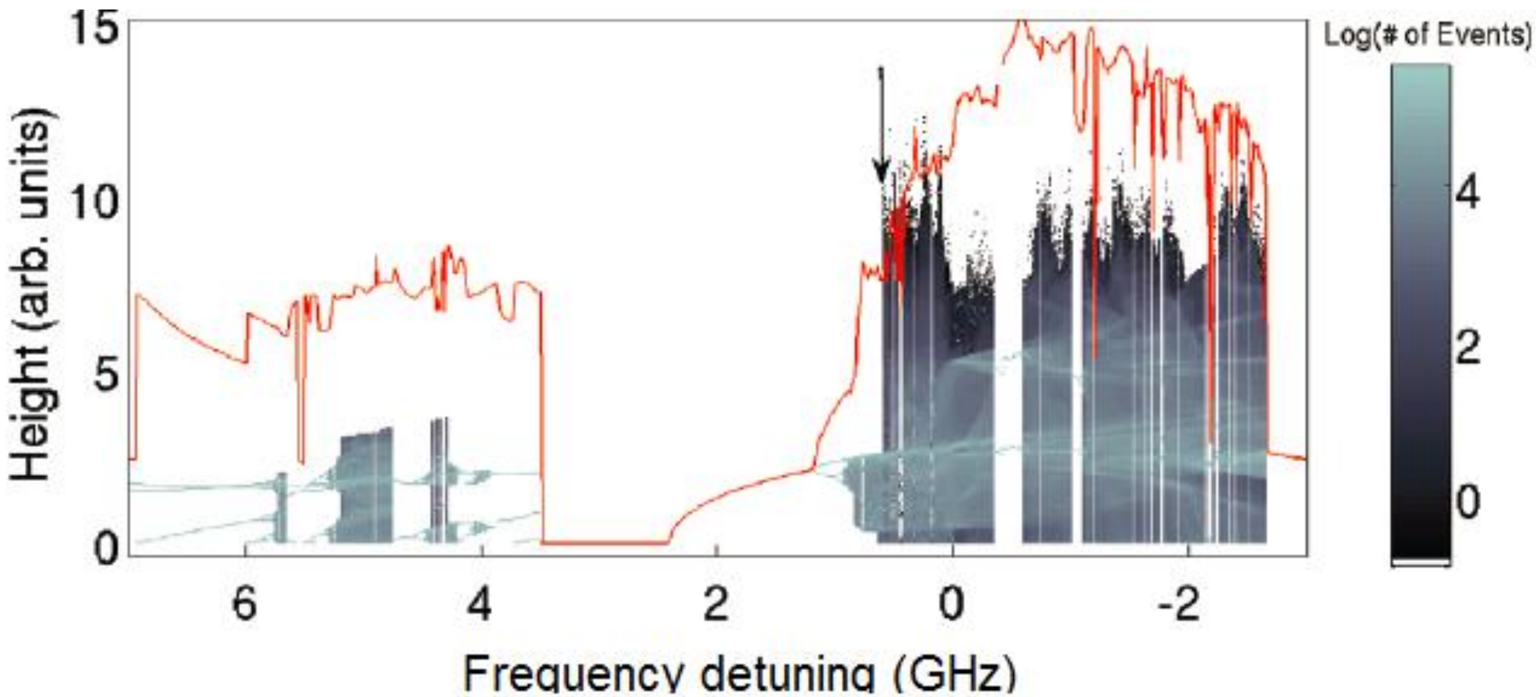
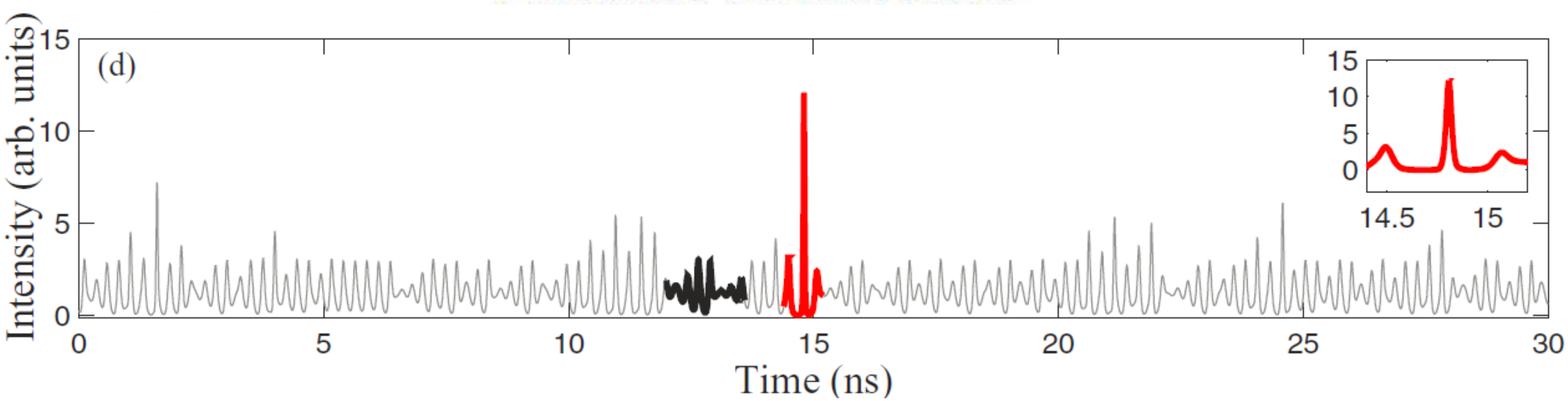
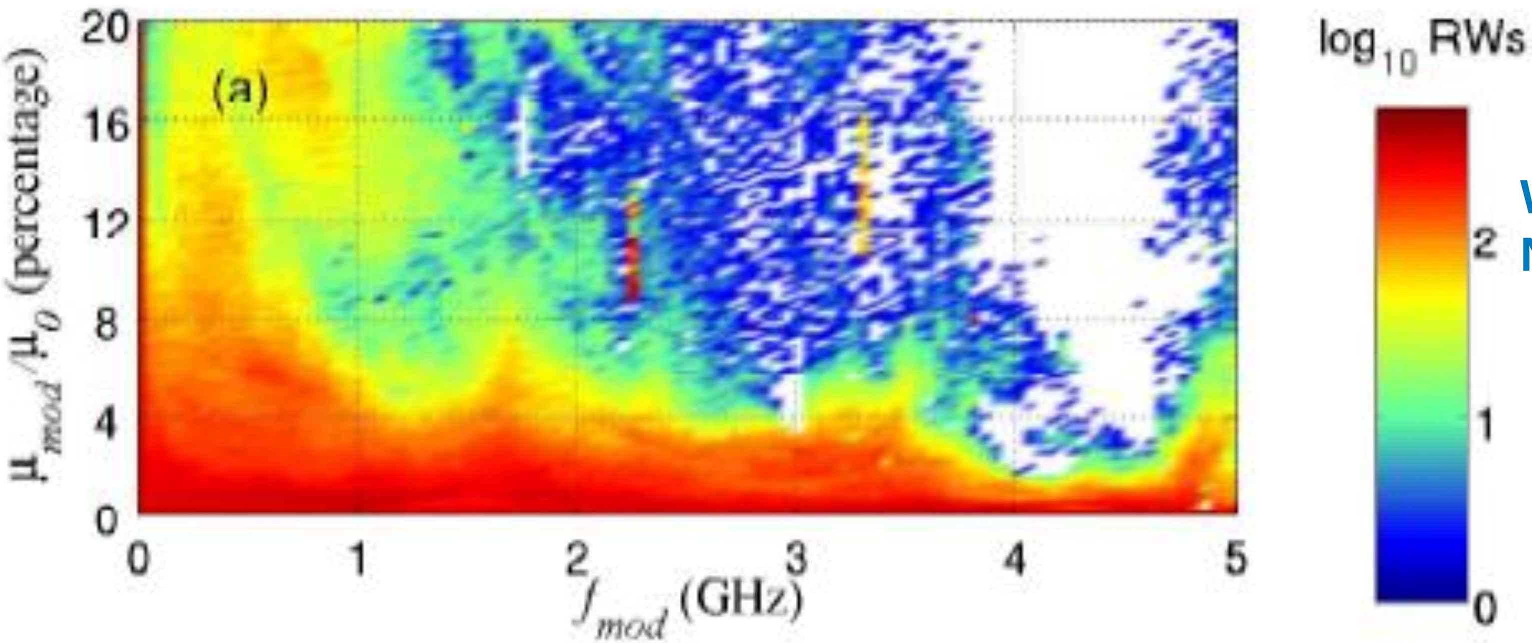
Threshold: <H> + 8σ





RWs can be suppressed by periodic modulation

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



White =
No RWs

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

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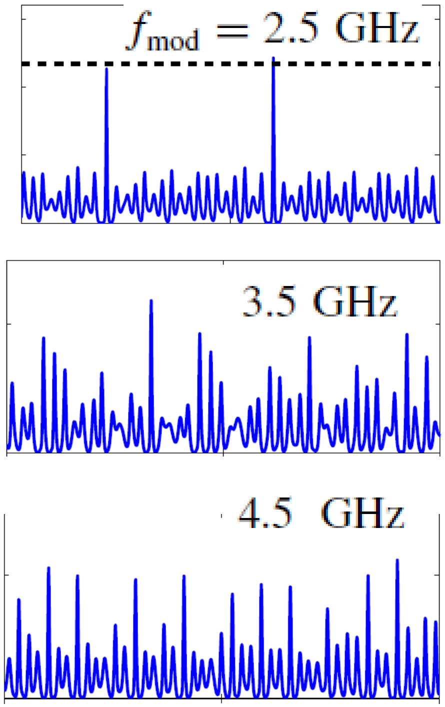
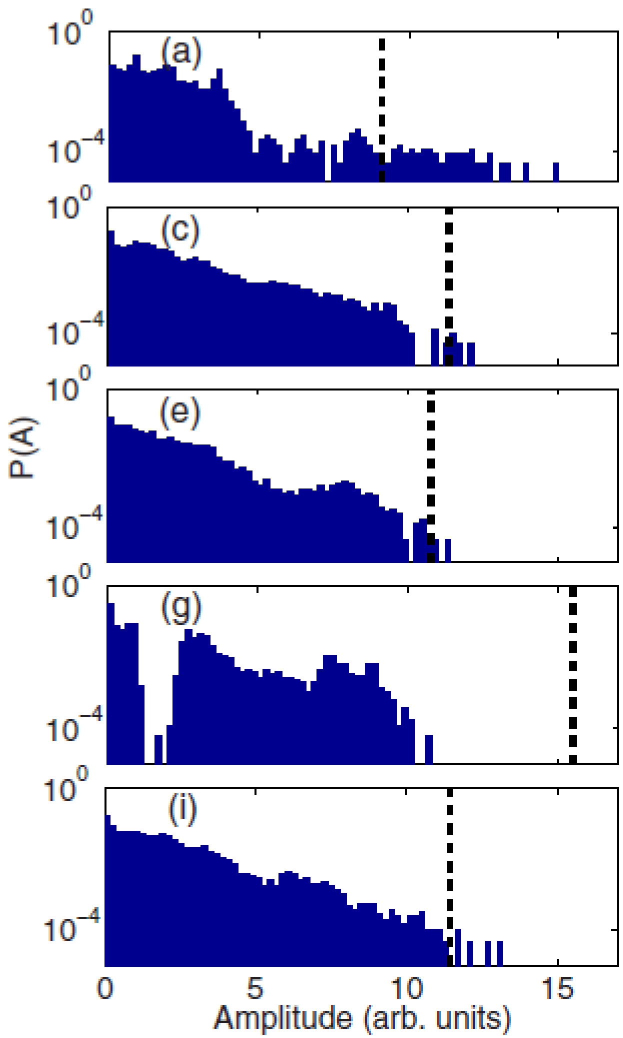
Why RWs are suppressed?



Histograms of pulse amplitudes



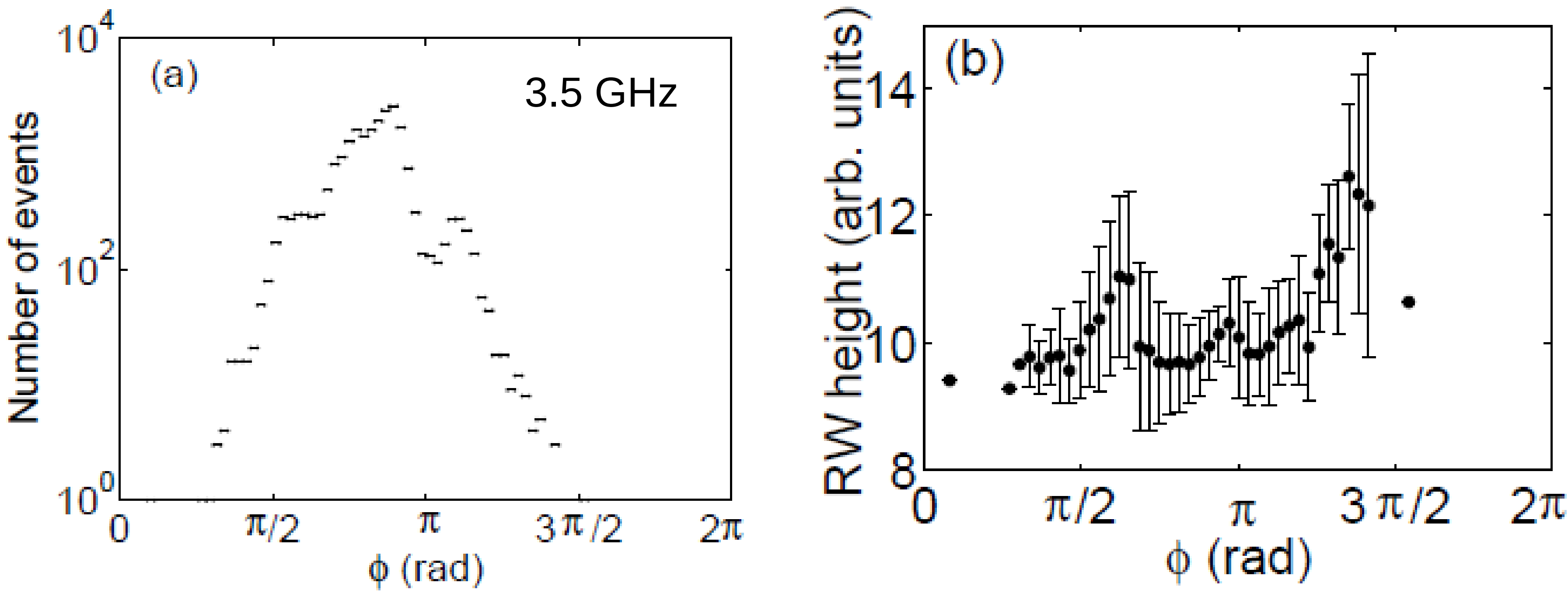
Threshold = <A> + **6** σ

RWs are suppressed because the pulses are high but NOT ultra high.

Analogy: avalanche risk

Controlled small avalanches in a snow-covered mountain reduce the amount of accumulated snow that could feed a large and dangerous avalanche.

When RWs are not suppressed: role of the modulation phase

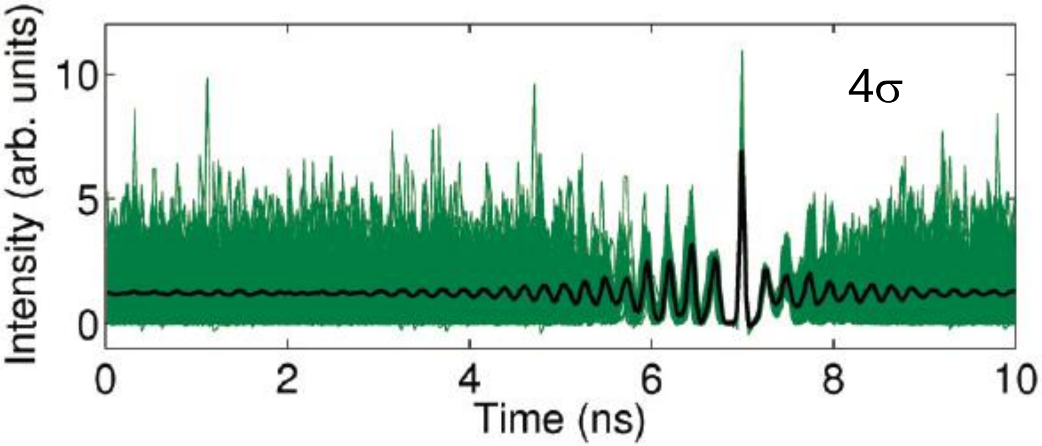


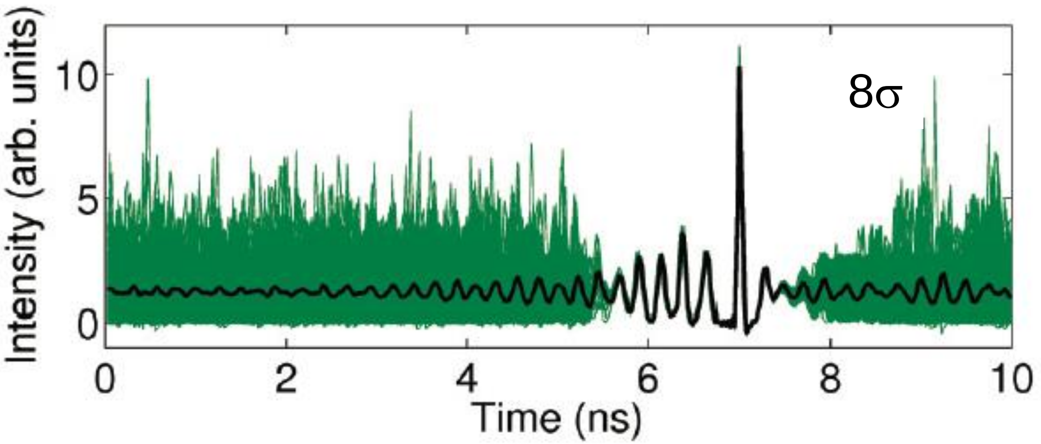
RWs occur during the first ¾ of the modulation cycle.

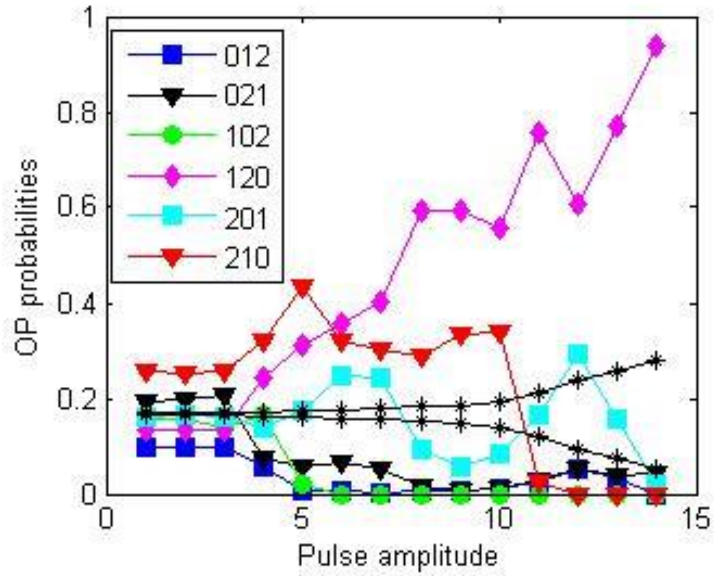
The highest RWs occur just before the "safe" phase window.

J. Ahuja et al, Opt. Exp. 22, 28377 (2014)

RW predictability?







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

Take home message and present work

- Take home message:
  - When observing complex optical output signals, nonlinear tools might capture hidden relevant features in the data.
  - Optics provides "big data" for testing novel analysis tools.
- A few specific conclusions
  - In VCSELs ,"early warnings" of PS were inferred from data.
  - In fiber lasers, long-range temporal correlations during the laminar-turbulence transition.
  - With optical feedback, noisy locking detected; minimal model identified
  - With optical injection, RWs were controlled via direct current modulation.
- Present work:

  Characterizing the performance of the analysis tools for anticipating
  - extreme pulses and
  - abrupt transitions.

Collaborators

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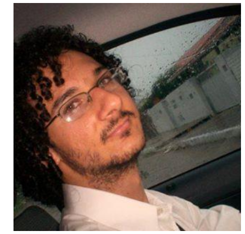

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Experimental data from:

- VCSEL polarization-switching
  - Y. Hong (Bangor University, UK)
  - 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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Publications:

- A. Aragoneses et al, Sci. Rep. 4, 4696 (2014).
- T. Sorrentino et al, Optics Express **23**, 5571 (2015).
- T. Sorrentino et al, IEEE J. Sel. Top. Quantum Electron. **21**, 1801107 (2015).
- C. Bonatto et al, PRL 107, 053901 (2011).
- S. Perrone et al, PRA 89, 033804 (2014).
- J. Ahuja et al, Opt. Exp. 22, 28377 (2014).
- C. Masoller et al, New J. Phys. 17, 023068 (2015).
- A. Aragoneses et al, arxiv.org/abs/1505.07365.
- Symbolic, ordinal bif. Diag.

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