Predictability of optical rogue waves in optically injected semiconductor lasers

Cristina Masoller

Universitat Politecnica de Catalunya

Cristina.masoller@upc.edu

UNIVERSITAT POLITÈCNICA DE CATALUNYA
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Nonlinear Waves and Turbulences in Optics and Hydrodynamics
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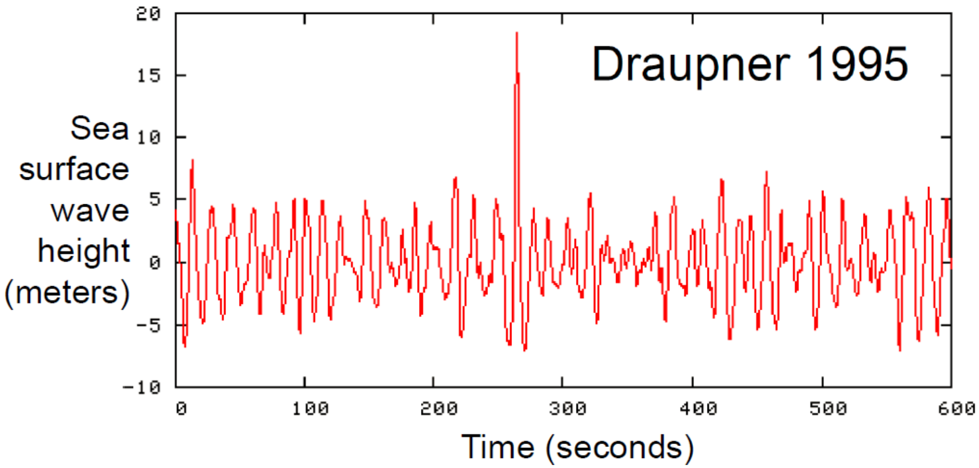
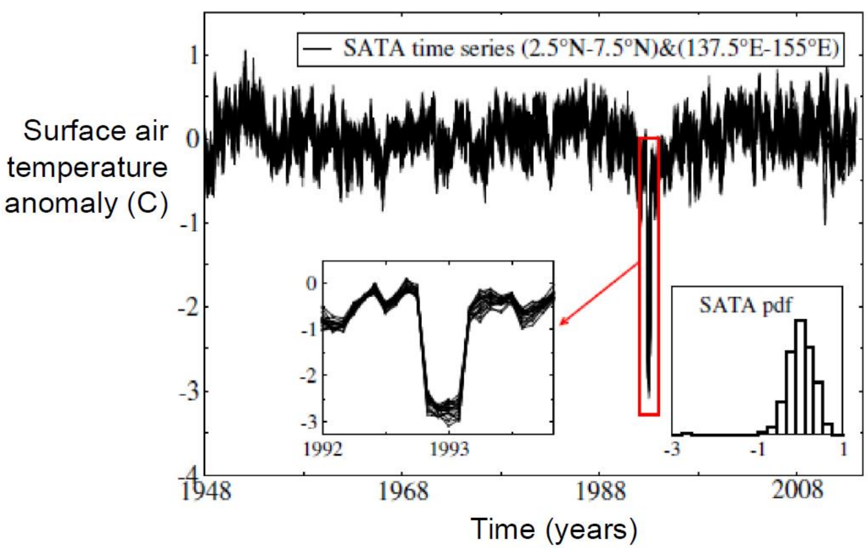
Extreme events in nature



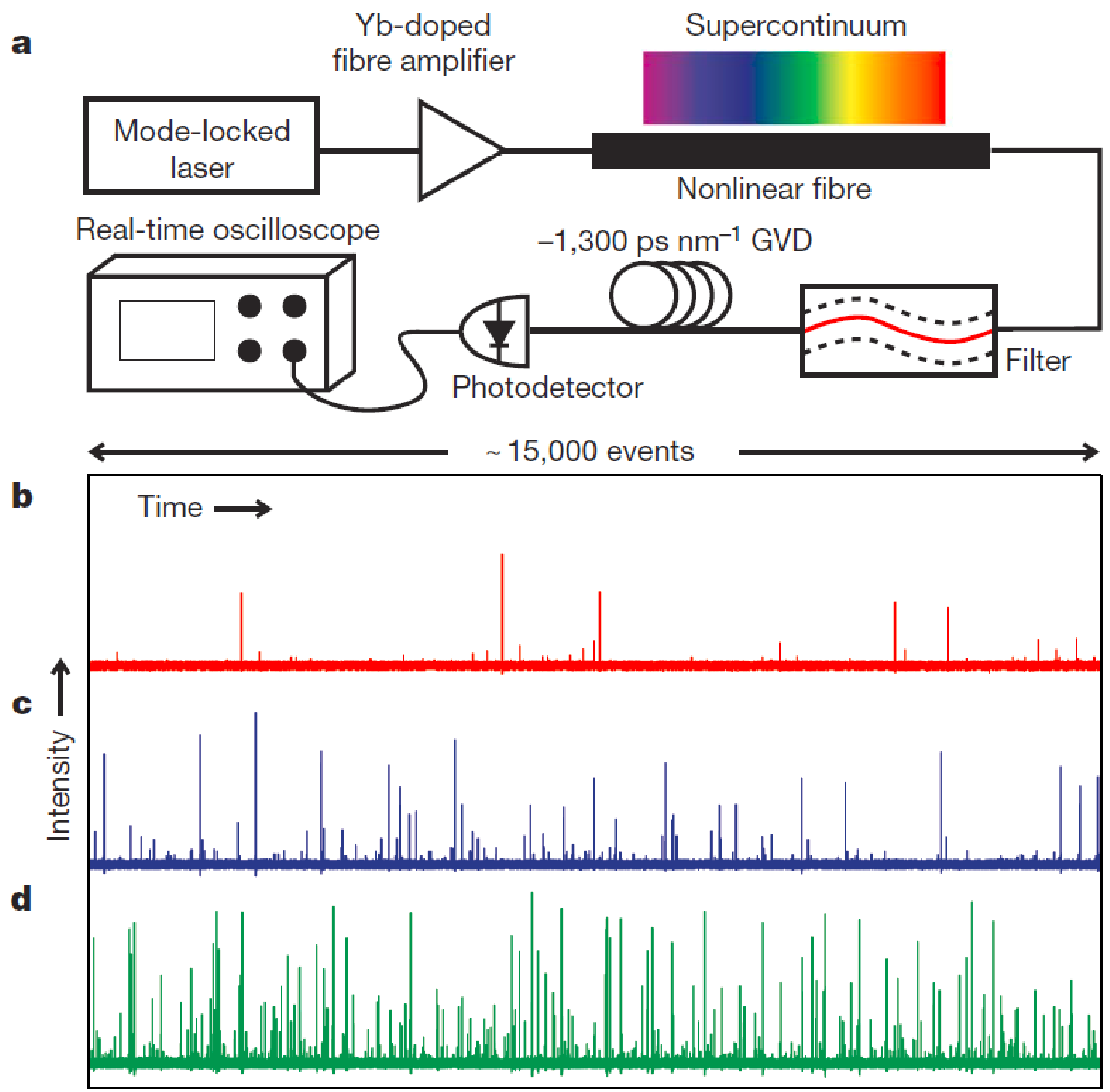


Optical chaos: provides an opportunity to advance predictability.

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.



nature photonics

REVIEW ARTICLE

PUBLISHED ONLINE: 28 SEPTEMBER 2014 | DOI: 10.1038/NPHOTON.2014.220

Instabilities, breathers and rogue waves in optics

John M. Dudley[1], Frédéric Dias[2], Miro Erkintalo[3] and Goëry Genty[4*]

“The analogy between the dynamics of ocean waves and pulse propagation in optical fibres arises from the central role of the NLSE in both systems.”

a

Deep water wave group envelope

$$i\frac{\partial u}{\partial z}-\frac{k_0}{\omega_0^2}\frac{\partial^2 u}{\partial t^2}-k_0^3|u|^2u=0$$

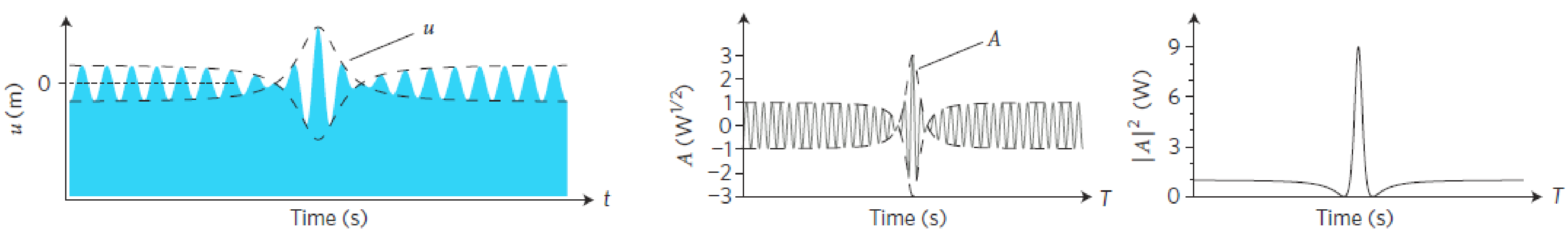
b

Light pulse envelope in fibre

$$i\frac{\partial A}{\partial z}+\frac{1}{2}|\beta_2|\frac{\partial^2 A}{\partial T^2}+\gamma|A|^2A=0$$

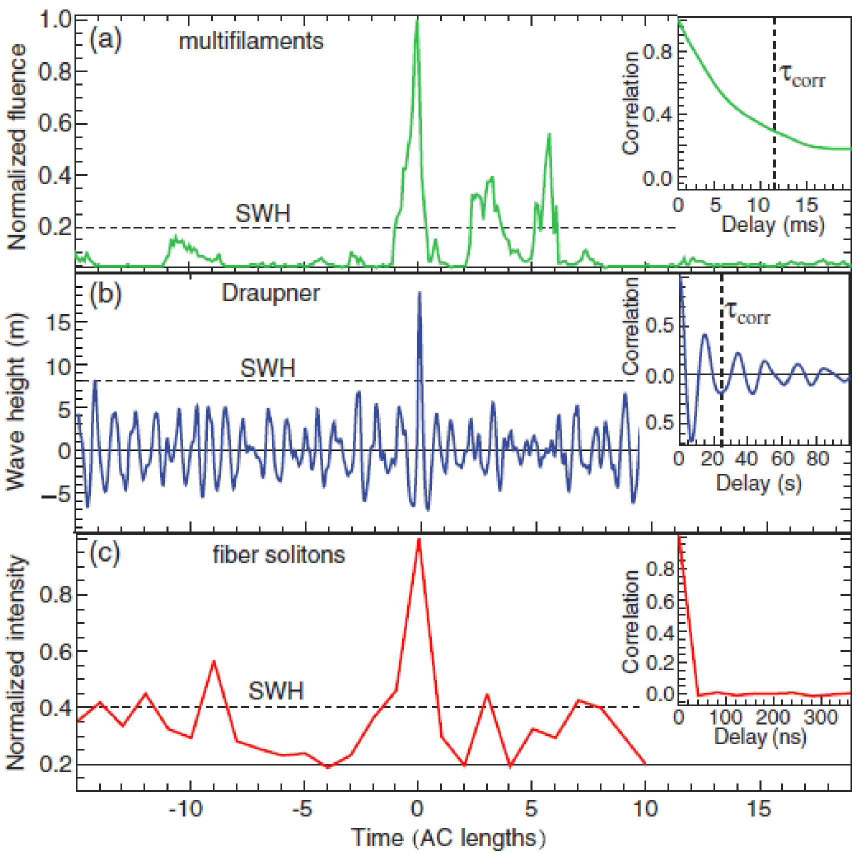
Soliton on finite background

Soliton on finite background



Predictability?

Birkholz et al, *Predictability of Rogue Events*, PRL 114, 213901 (2015)

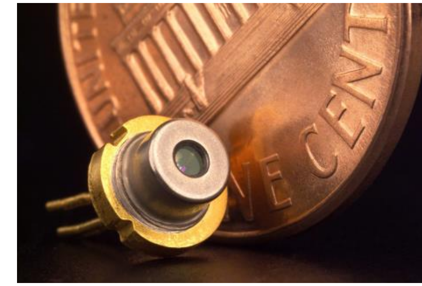


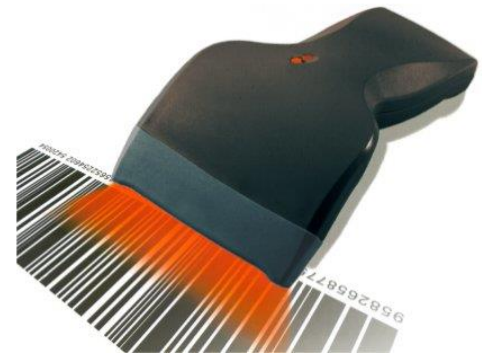
"Transferring these findings to ocean rogue waves, one may at best expect to predict an ocean rogue wave ***a few tens of seconds*** *before impact, and it would require many future sightings* ***to isolate characteristic patterns*** *preceding an ocean rogue wave.*

Therefore any practical rogue wave prediction appears not overly realistic, despite the determinism in the system."

Semiconductor lasers (diode lasers)

- Widely used, inexpensive but easily perturbed





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

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The dynamical complexity of optically injected semiconductor lasers

S. Wieczorek[a,*], B. Krauskopf[b,d], T.B. Simpson[c], D. Lenstra[d,e]

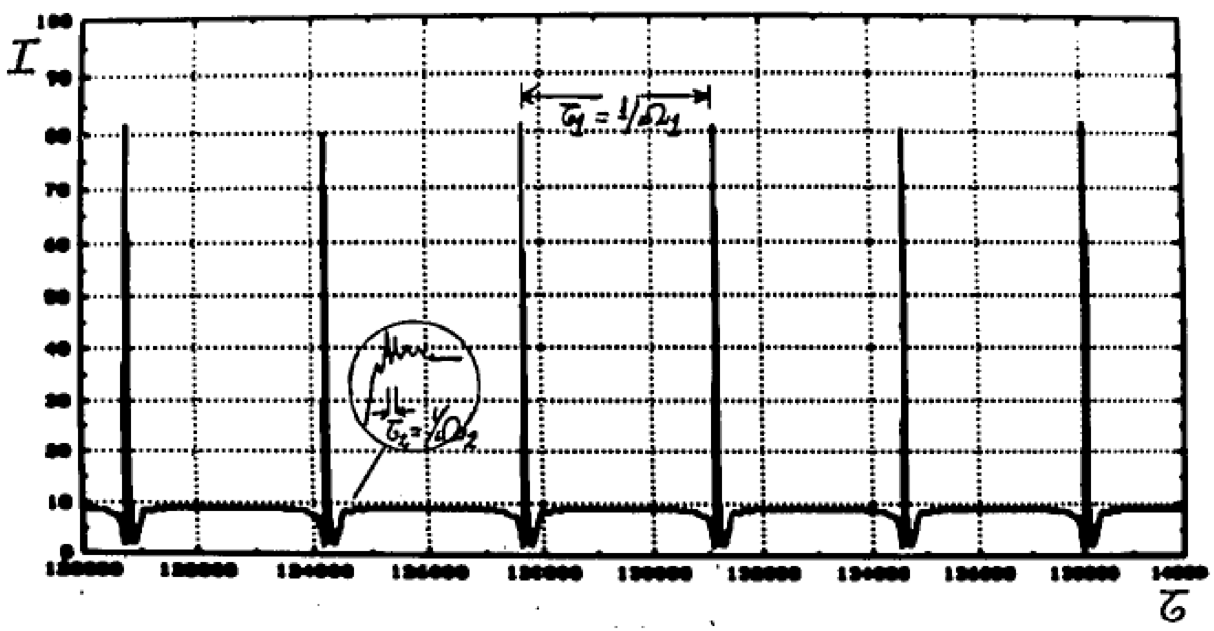
Also optical rogue waves?

Also RWs?

Instabilities in lasers with an injected signal

J. R. Tredicce, F. T. Arecchi, G. L. Lippi, and G. P. Puccioni

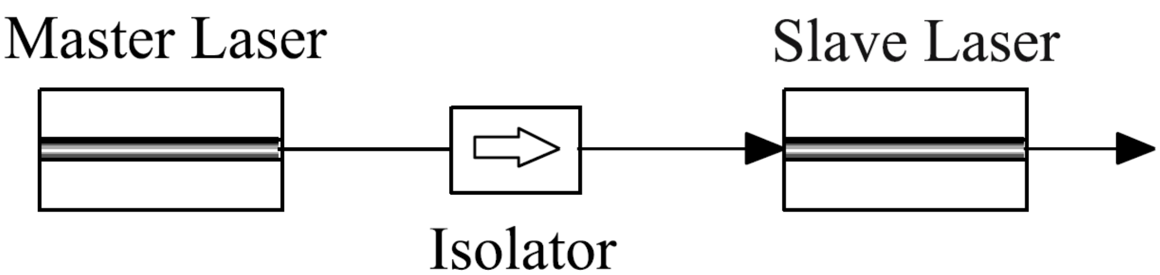
178 J. Opt. Soc. Am. B/Vol. 2, No. 1/January 1985

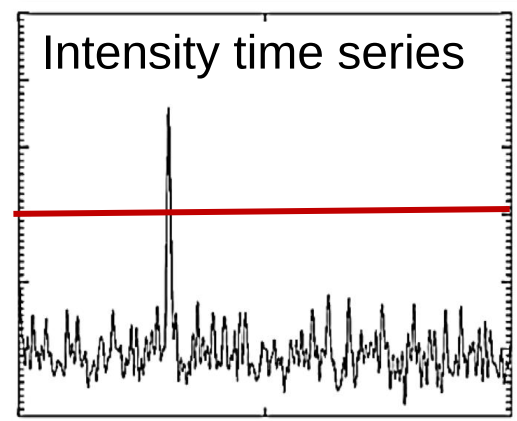


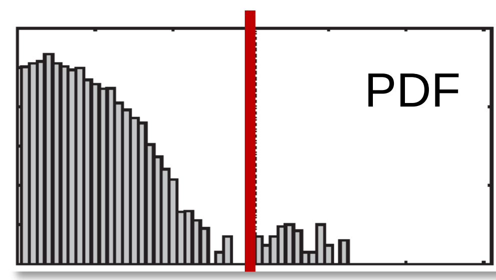
PRL 107, 053901 (2011) PHYSICAL REVIEW LETTERS week ending 29 JULY 2011

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

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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

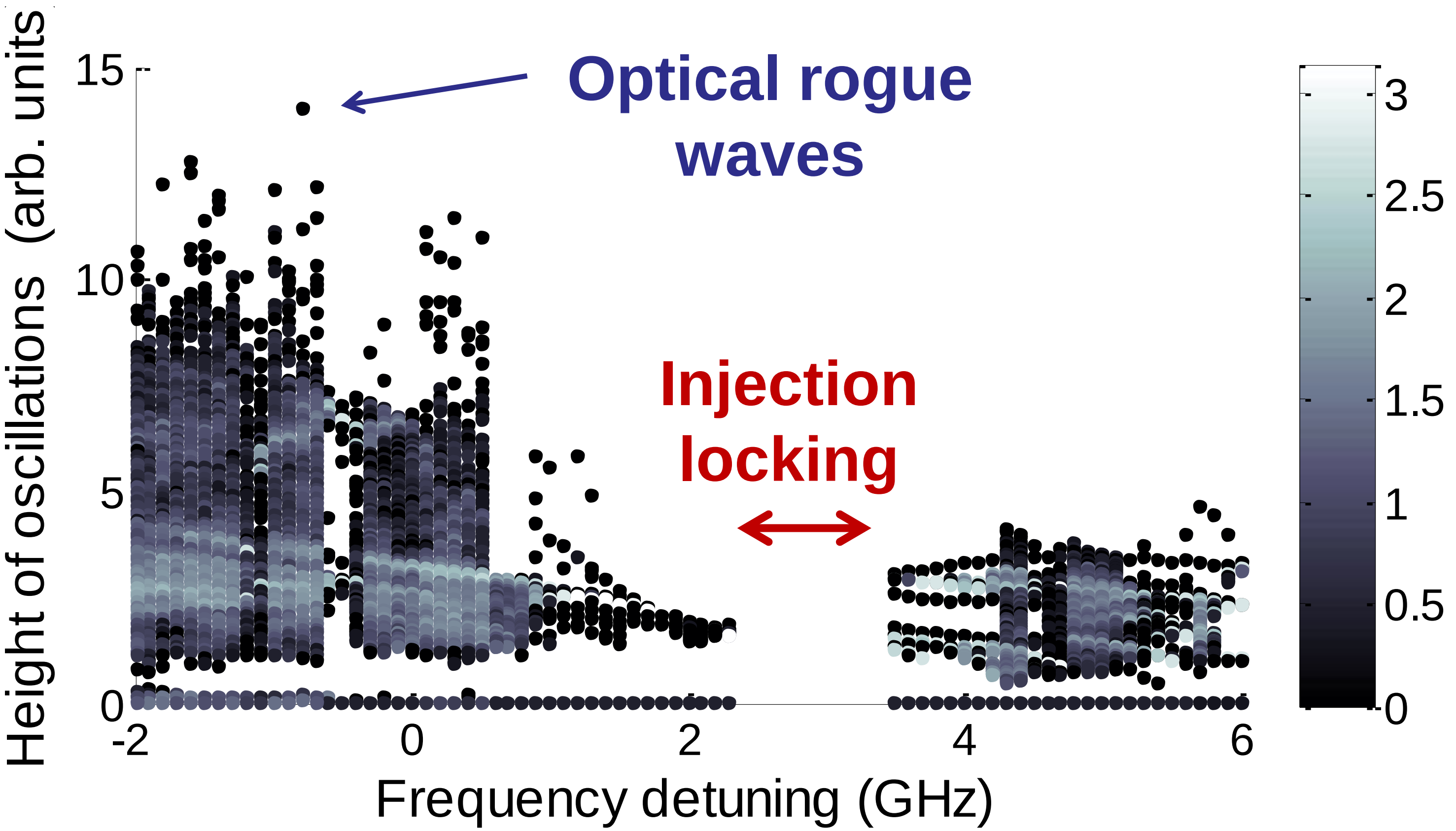
Solitary laser parameters: **α τ$_p$ τ$_N$ μ**

μ: normalized pump current parameter

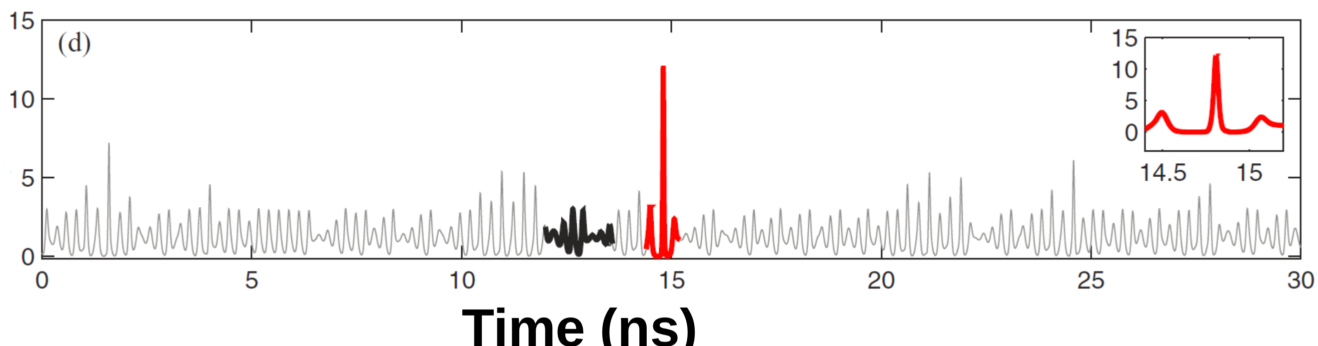
Typical parameter values:
α = 3, τ$_p$ = 1 ps, τ$_N$ = 1 ns

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

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



Laser intensity (normalized to <I>=0, σ=1)



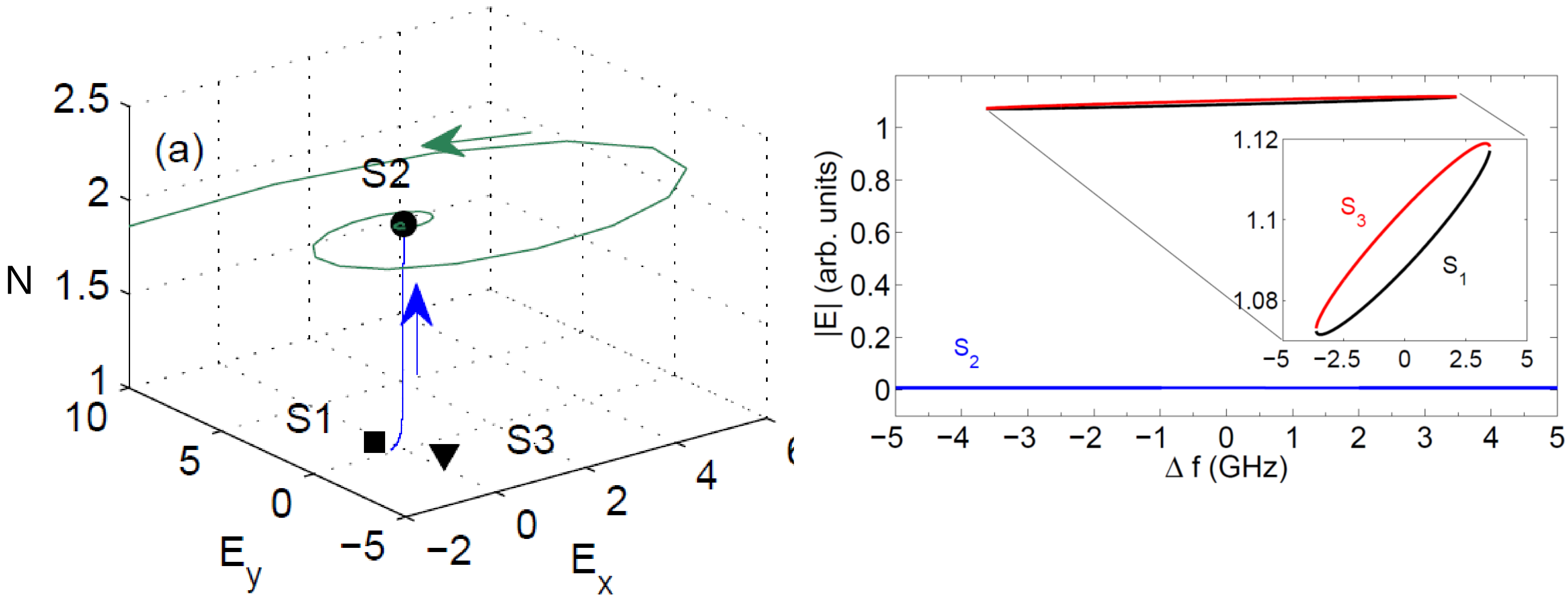
What did we learn from simulations?

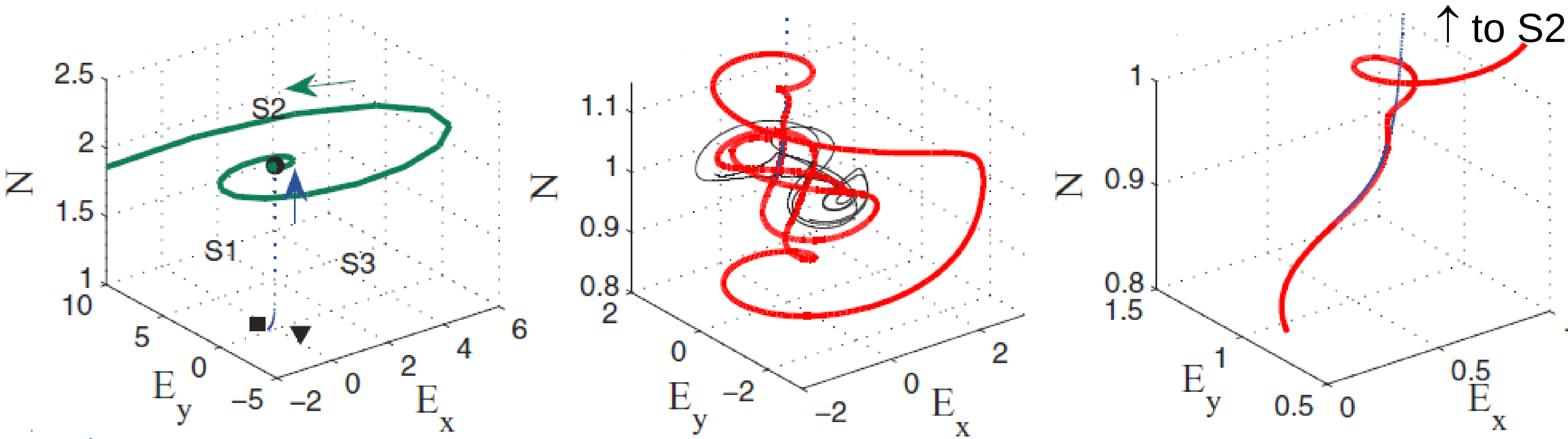
In our system, ORWs can be

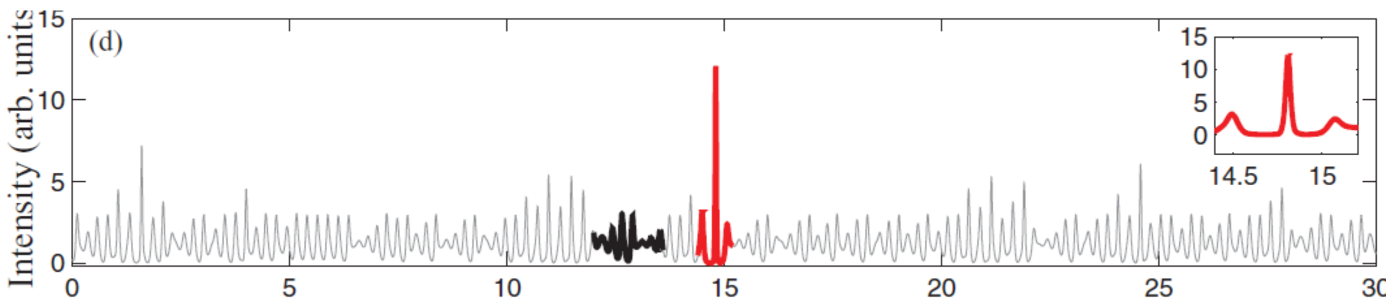
- **deterministic**, generated by a crisis-like process.
- **controlled** by noise and/or by current modulation.
- **predicted** with a certain anticipation time.

What triggers a RW?

Fixed points in the phase space





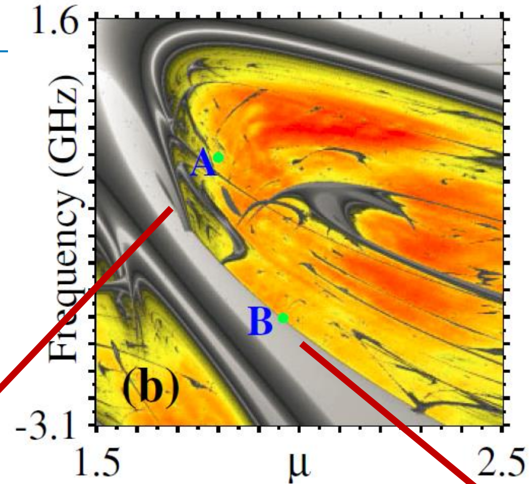


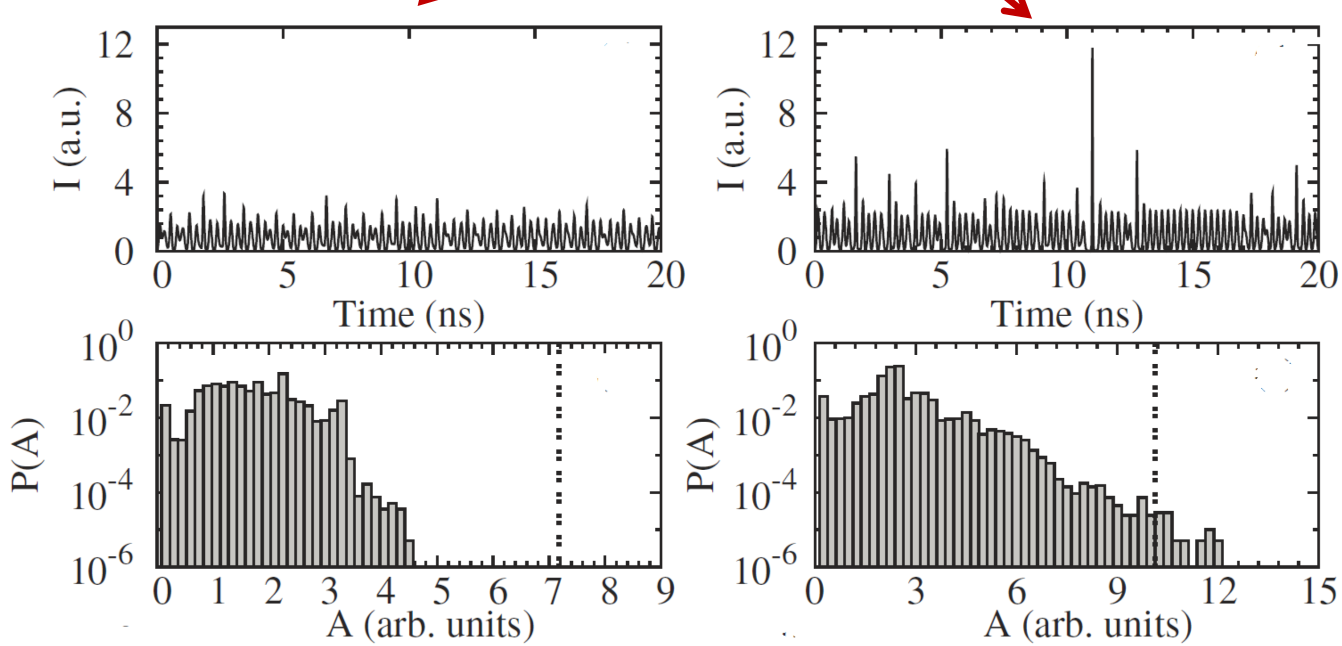
A RW is triggered whenever the trajectory closely approaches the stable manifold of S2 (the "RW door")

Deterministic simulations (β_{sp}=0)

Lyapunov diagram

(detuning, pump current)

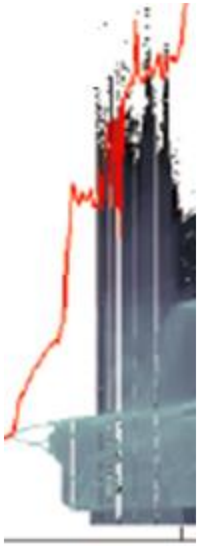


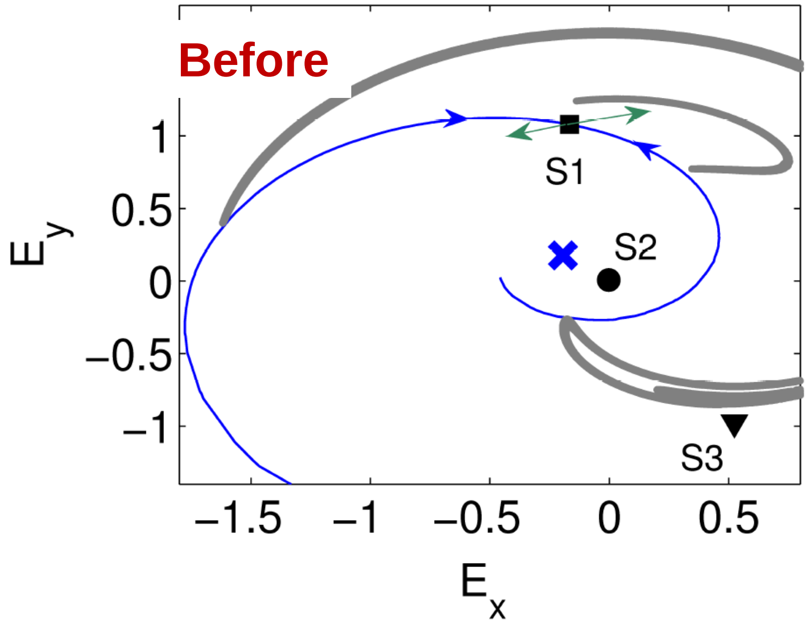


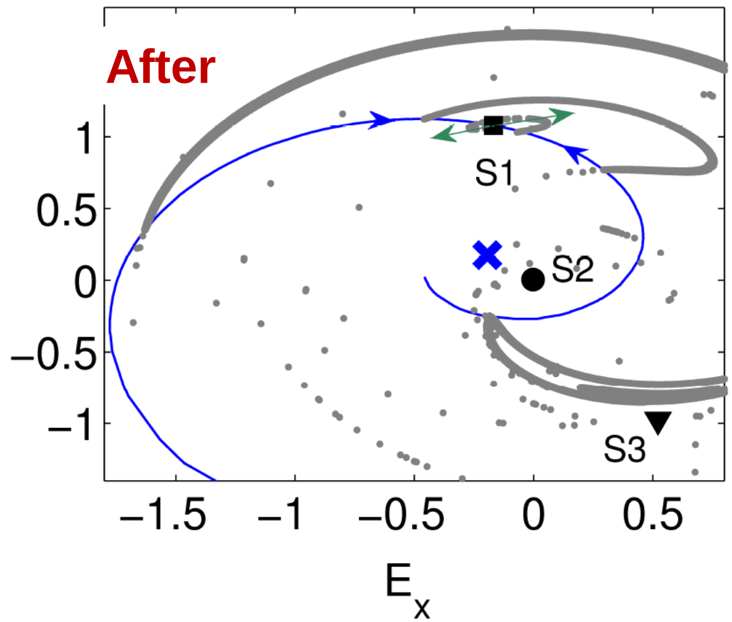
Chaos without RWs

Chaos with RWs

Why chaos with RWs and chaos without them?







An **external crises-like** process enables access to the region of phase space where the **stable manifold of S2 (x)** is.

Number of RWs vs (pump current & detuning)

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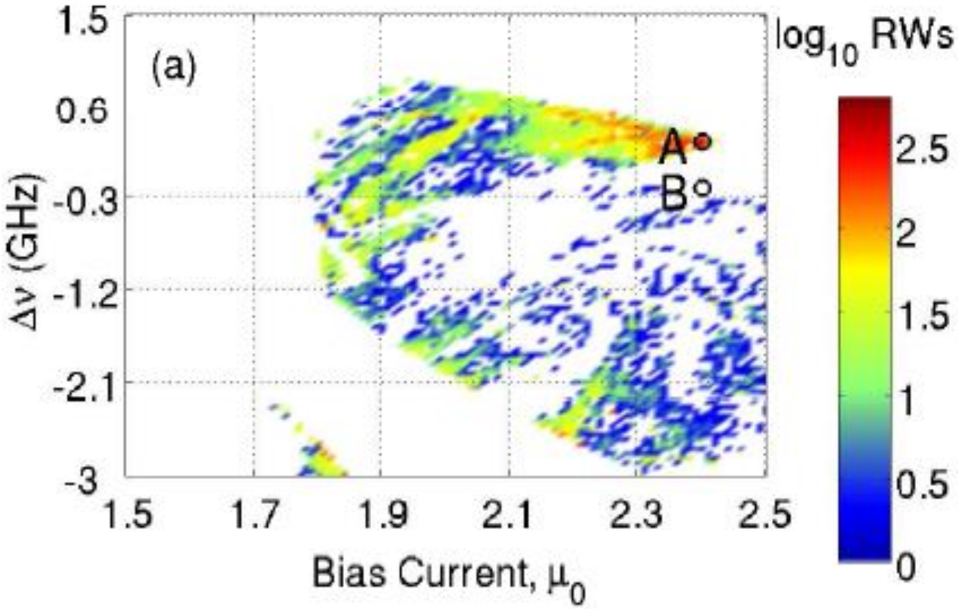
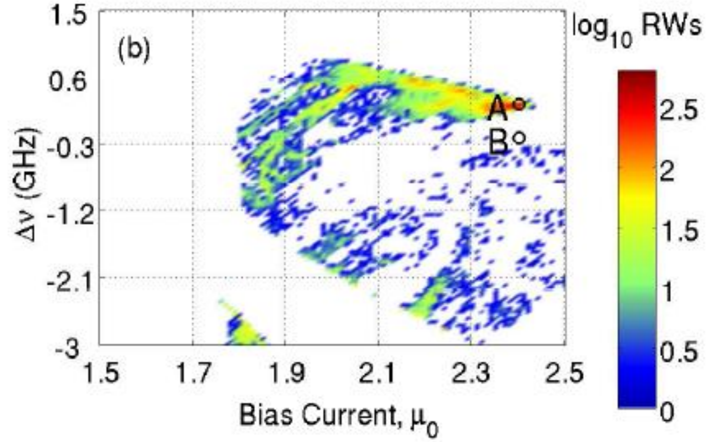
Deterministic RWs (β_{sp}=0)

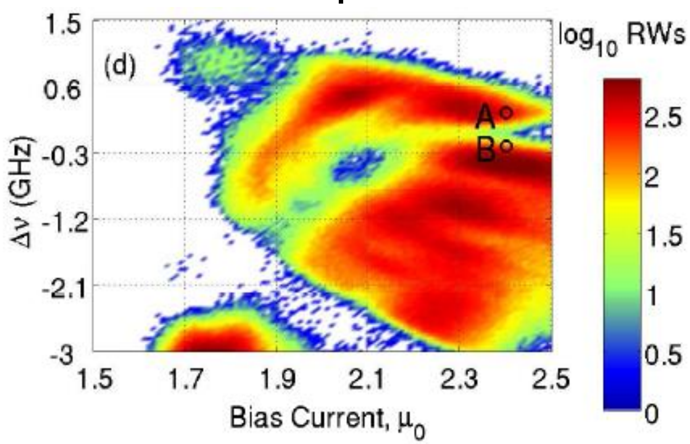


Weak noise (β_{sp}=0.0001)



White = No RWs

Strong noise (β_{sp}=0.01)

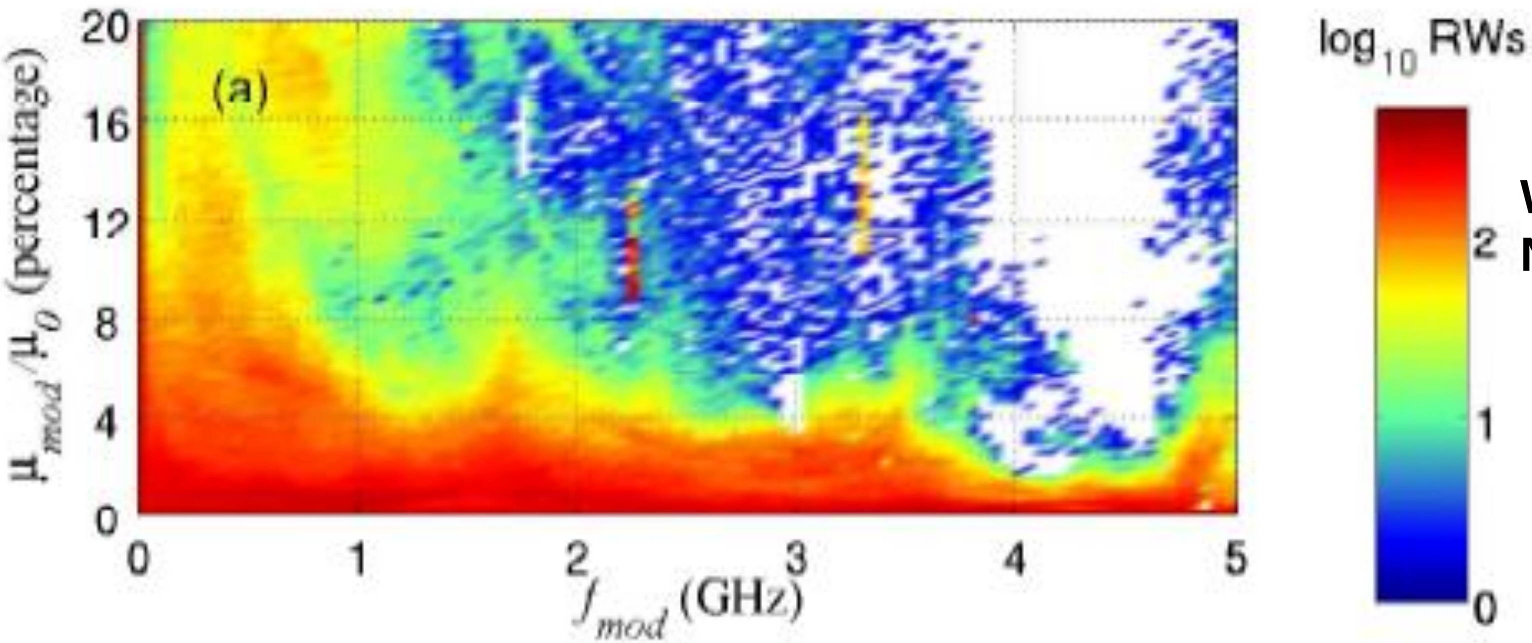


Strong enough noise can induce RWs

Pump current modulation:

RW control in Point A (deterministic RWs)

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



White = No RWs

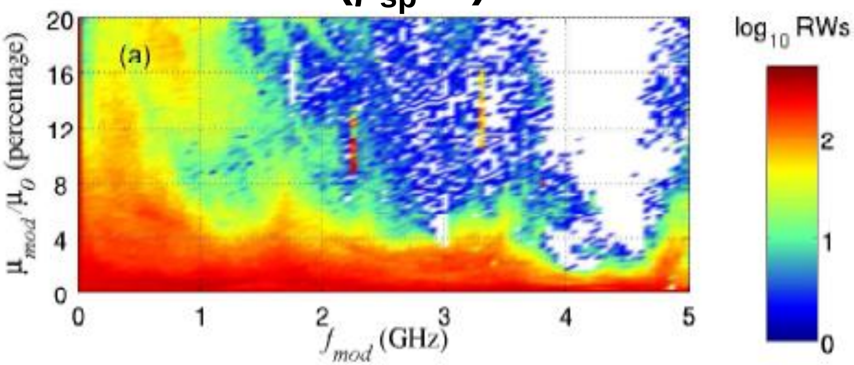
Current modulation with appropriated amplitude and frequency can completely suppress the RWs.

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

RW control in Point A: influence of noise

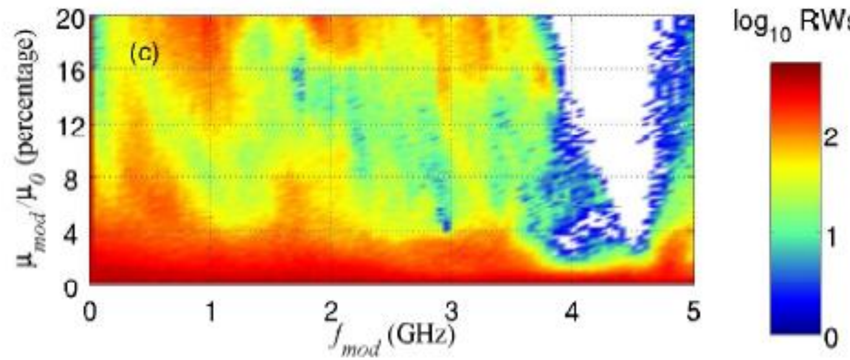
$$\mu = \mu_0 + \mu_{\text{mod}} \sin(2\pi \ f_{\text{mod}} \ t)$$

No noise (β_{sp}=0)



White = No RWs

Stochastic simulations (β_{sp}=0.01)



White = No RWs

"safe parameter region" is robust to the presence of noise.

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

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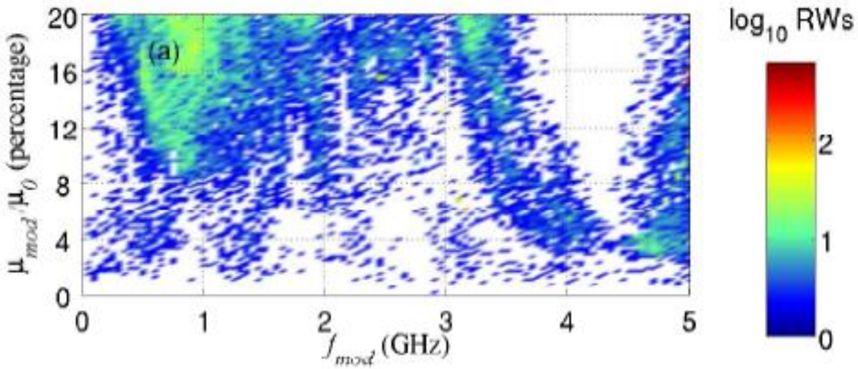
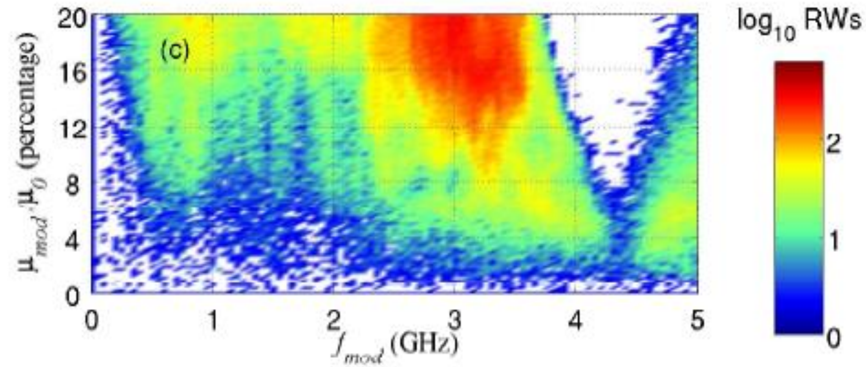
in Point B (no deterministic RWs)

β_{sp}=0



β_{sp}=0.01

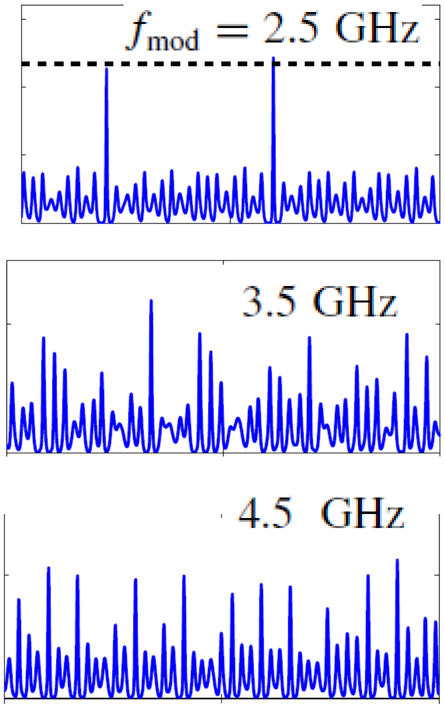


White = No RWs

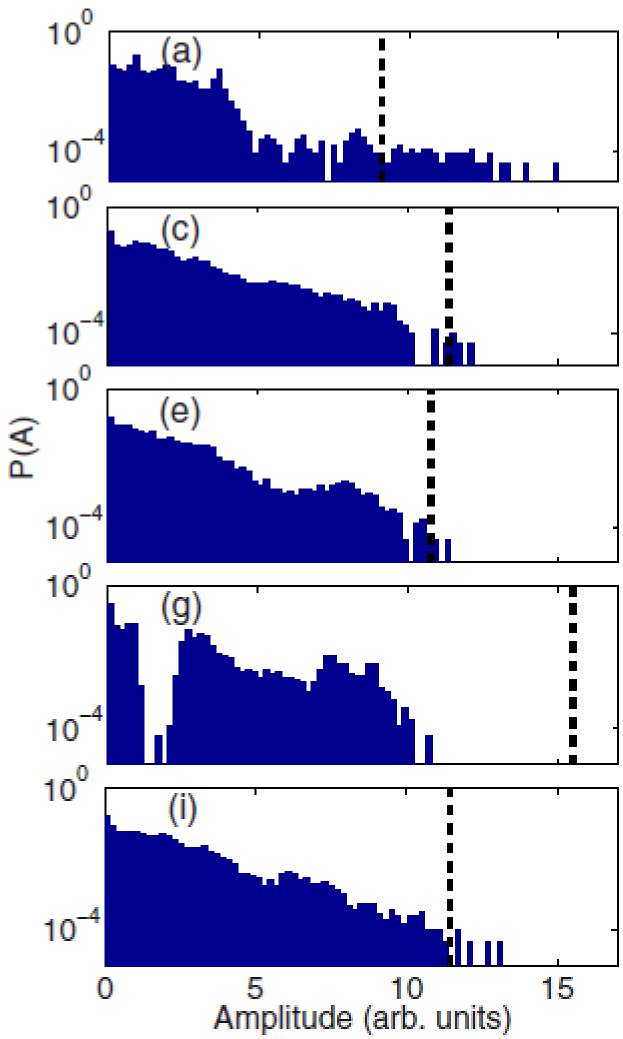
Modulation can induce RWs

"safe" parameter region is also robust to noise

Why RWs are suppressed?



Histograms of pulse amplitudes



Threshold = <A> + **6** σ

RWs are suppressed because high pulses are not rare.

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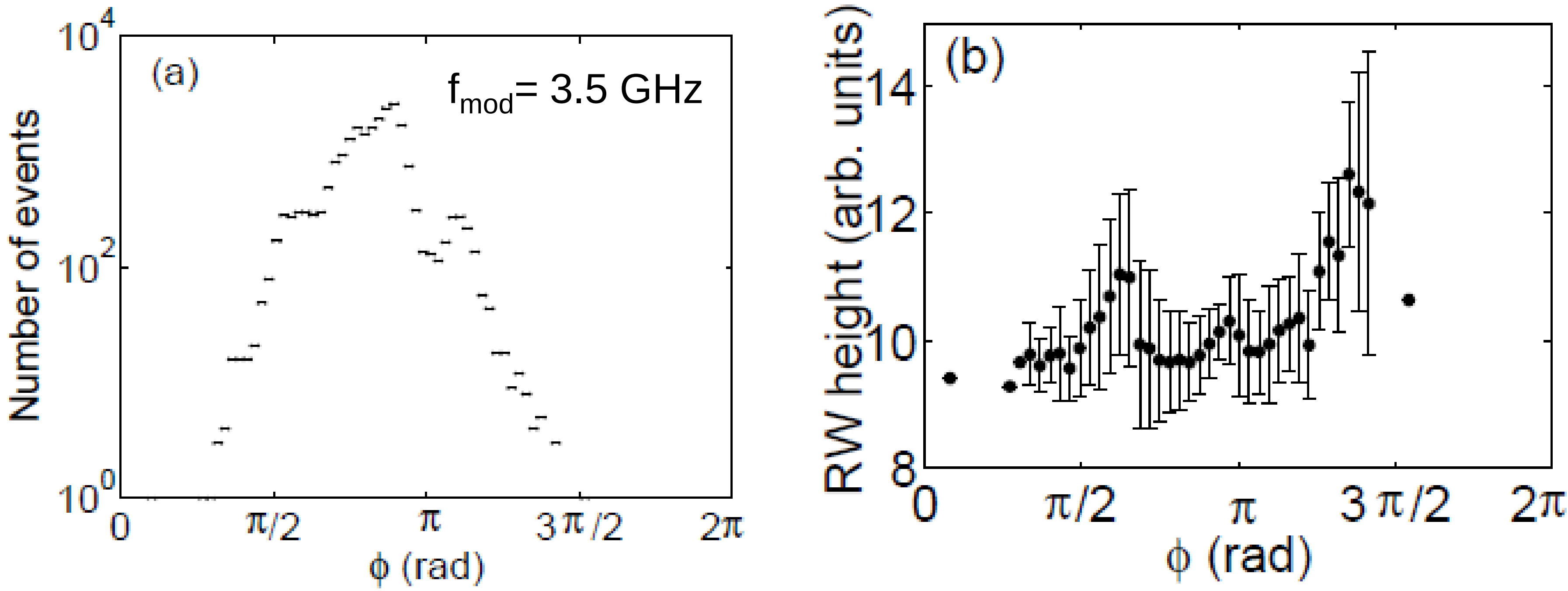
When RWs are not suppressed: role of the phase of the modulation



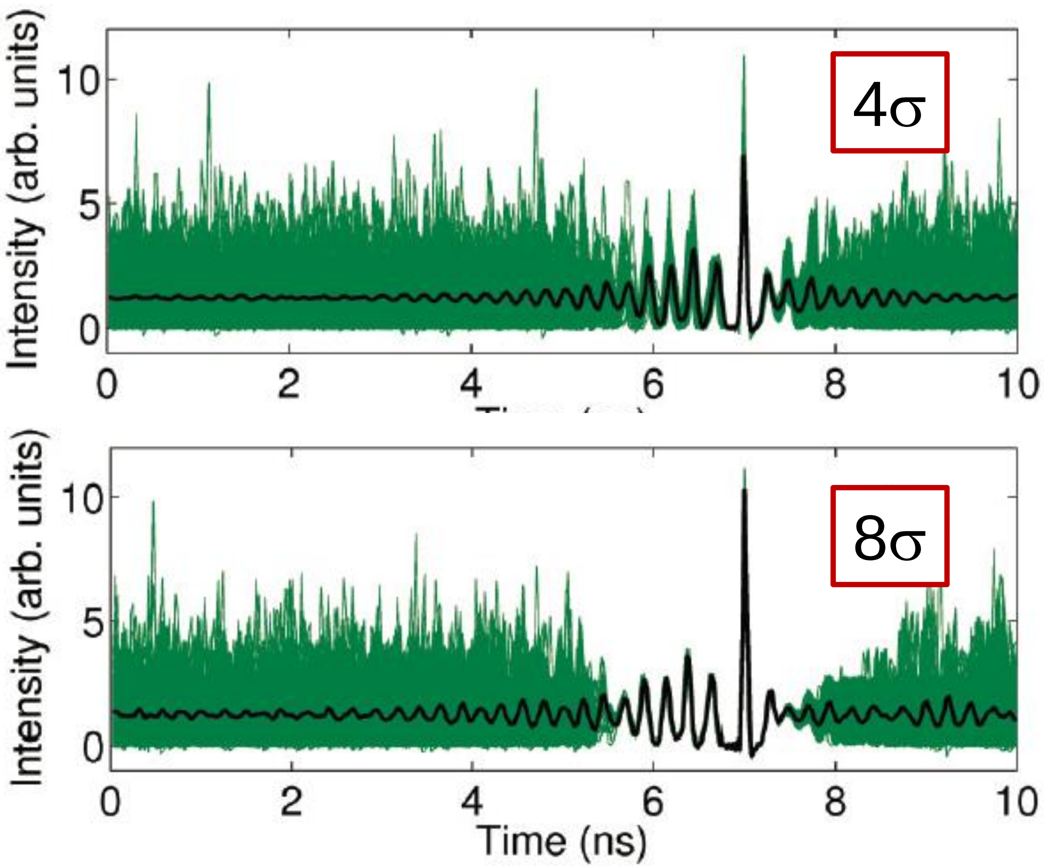
RWs occur during the first ¾ of the modulation cycle.

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

J. Ahuja, D. Bhiku Nalawade, J. Zamora-Munt, R. Vilaseca and C. Masoller, Optics Express 22, 28377 (2014)

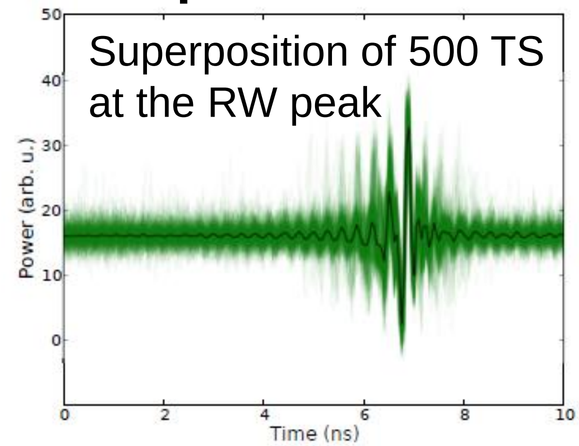
RW predictability

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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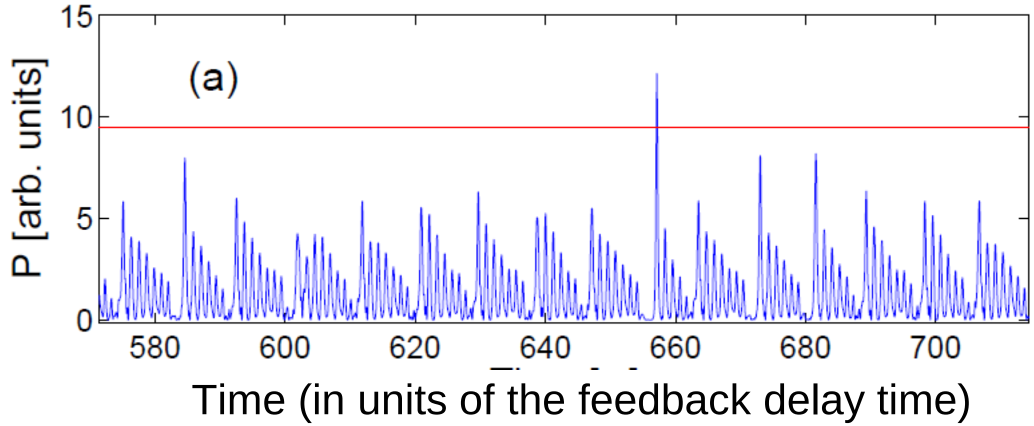
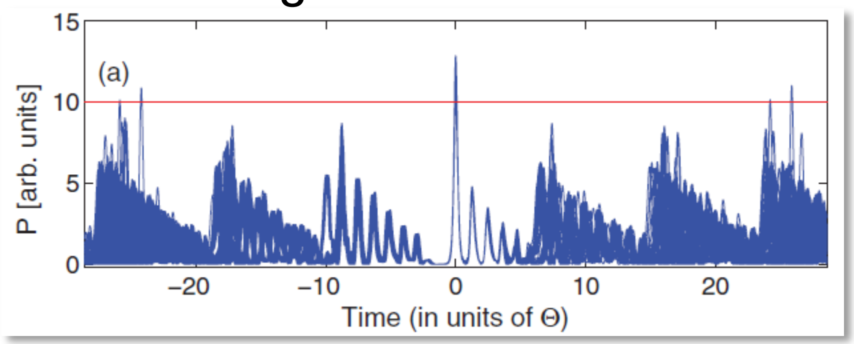
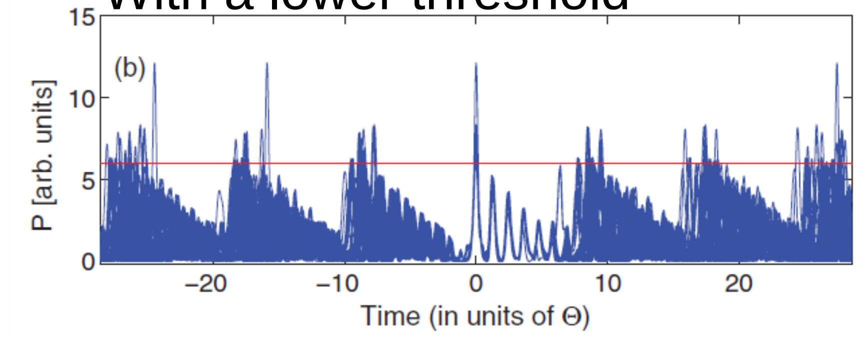
A similar effect in the intensity dynamics induced by optical feedback



With a high threshold



With a lower threshold

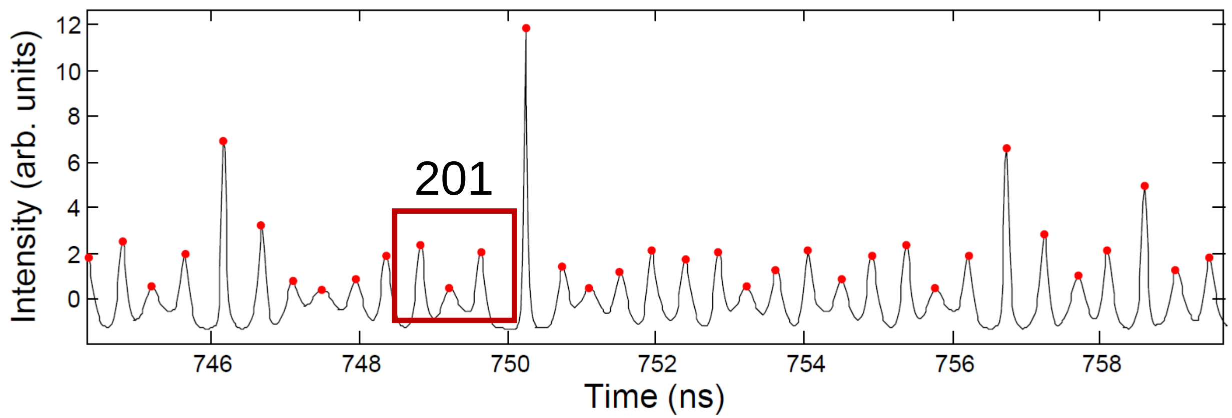


How can this effect be quantified?

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

Method of symbolic time-series analysis

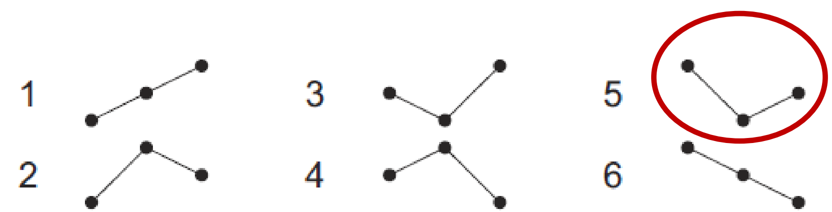
Brandt & Pompe, PRL 88, 174102 (2002)



- 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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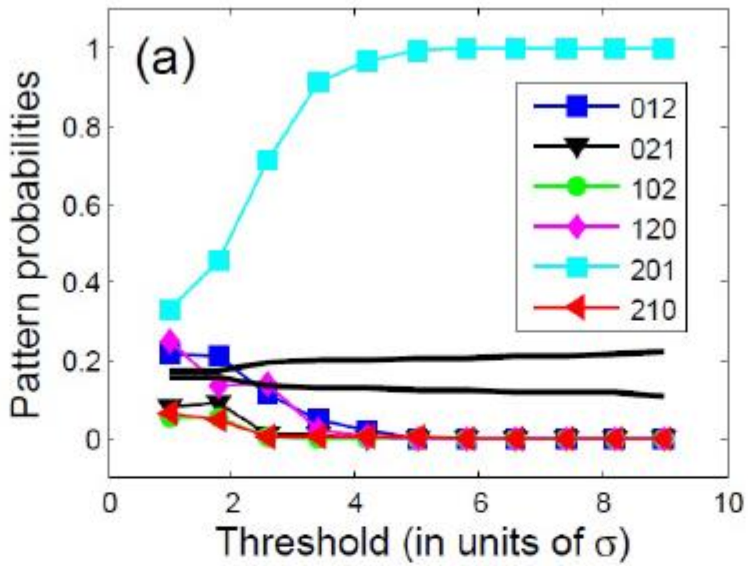
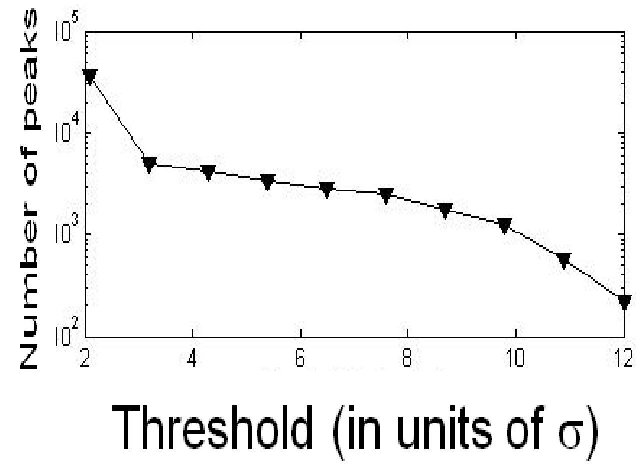
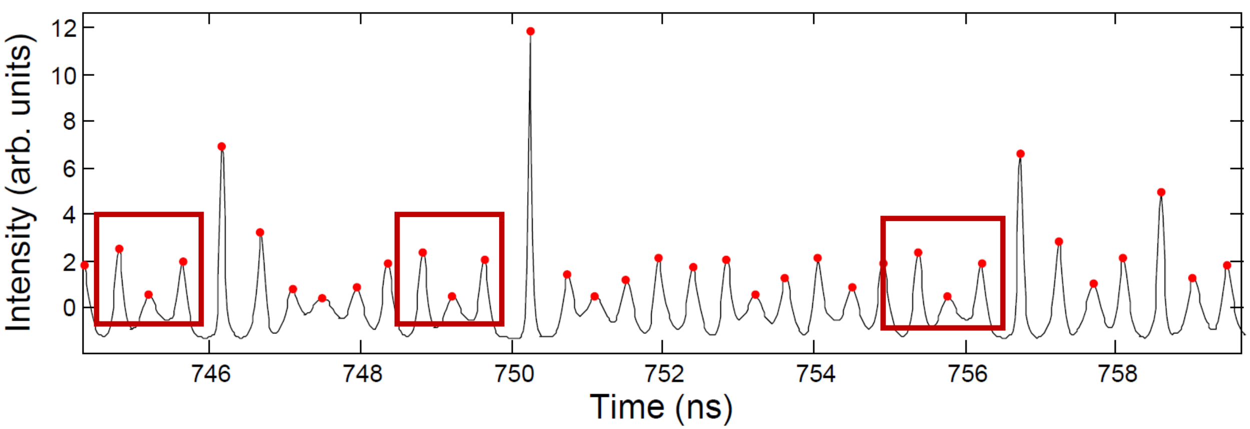
Results: deterministic simulations

Black lines: 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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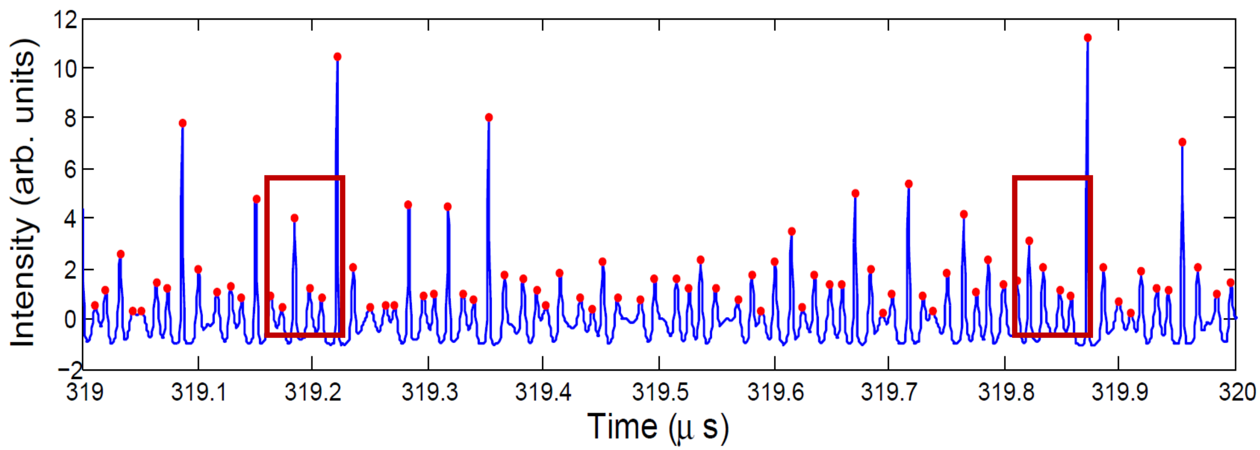
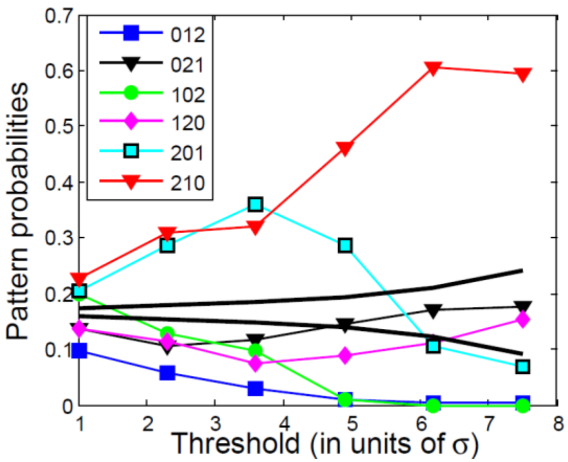
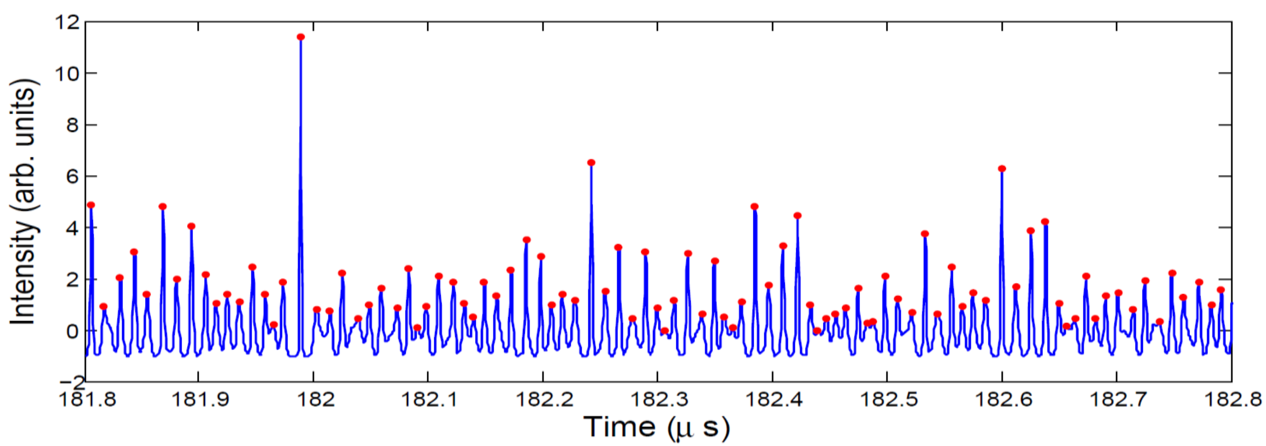
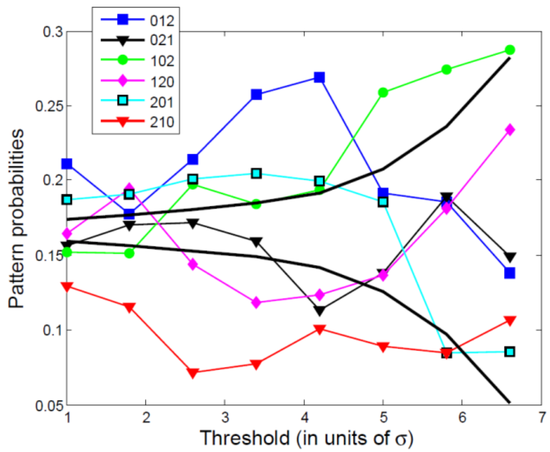
Including spontaneous emission noise and current modulation

- 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)

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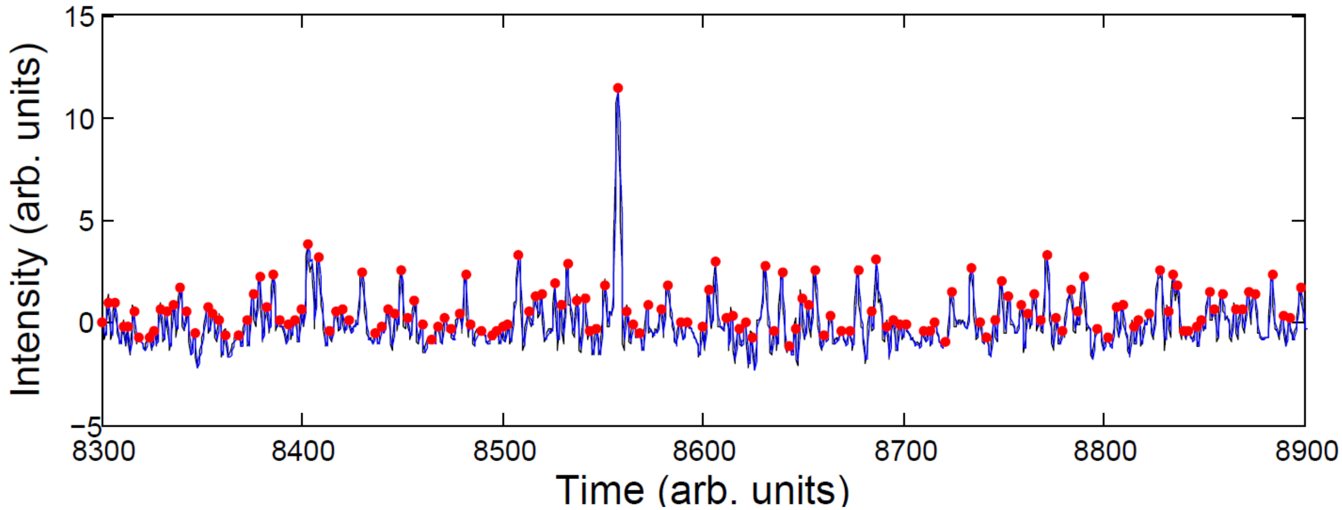
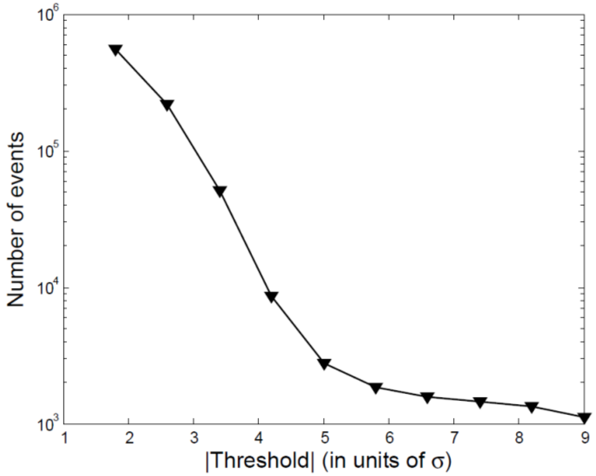
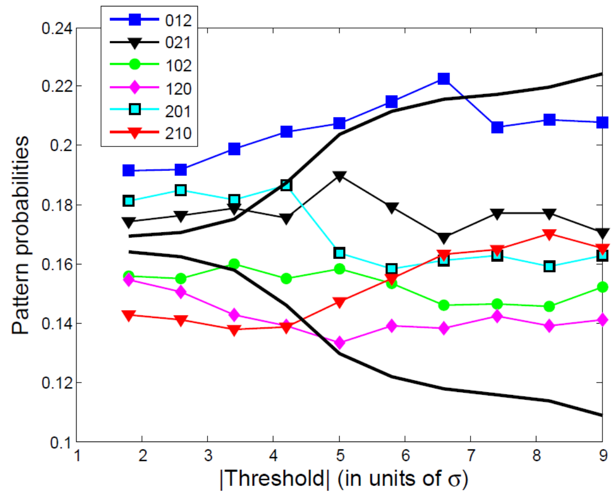




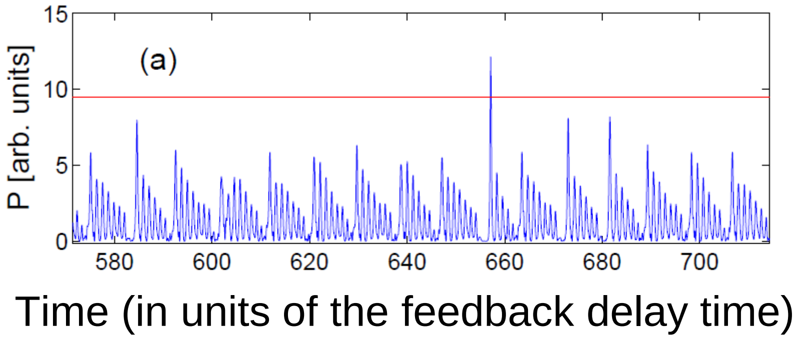


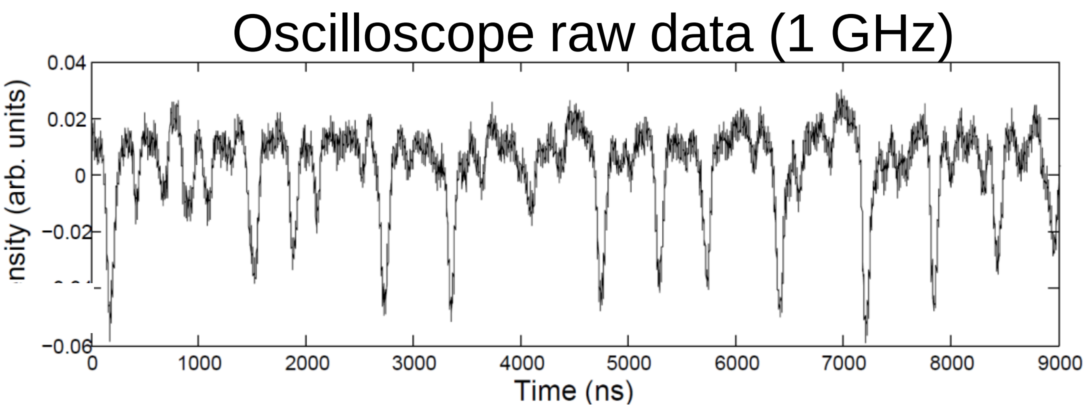
Way to improve the "early warning":

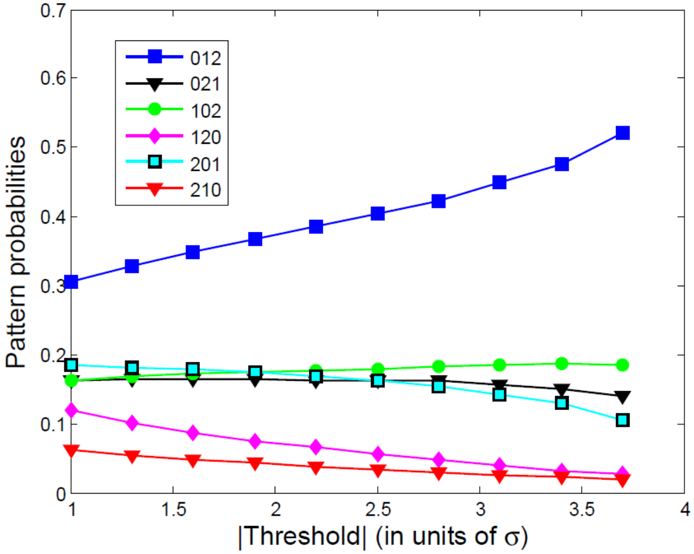
- Filter noise
- Longer patterns

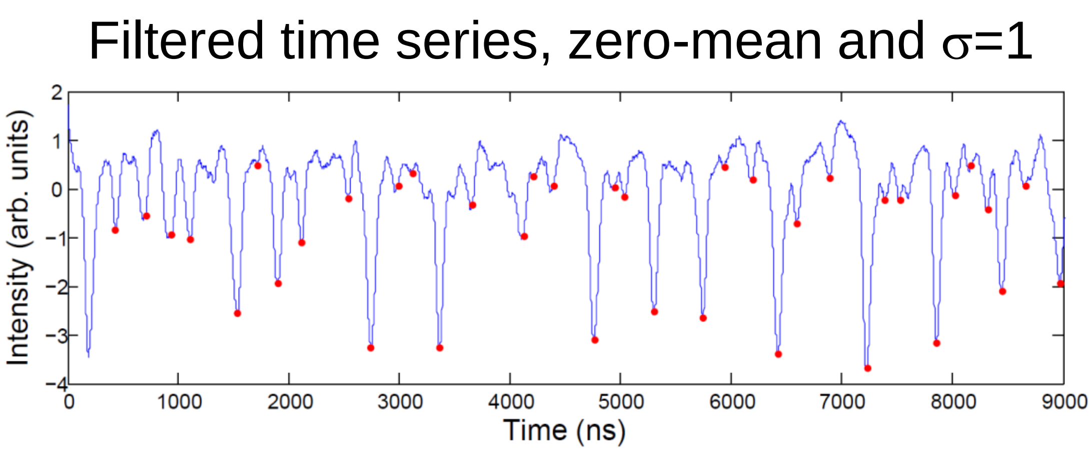
$\{\ldots I_i, I_{i+1}, I_{i+2}, I_{i+3}, \ldots\}$

Experimental data (Terrassa): optical feedback-induced dropouts









$\Rightarrow$ 210 is a “good sign” that a dropout is NOT likely to occur after this pattern

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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): 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 RW predictability.
- Open issue: applicability to real-word time-series?

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

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Thank you for your attention!

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