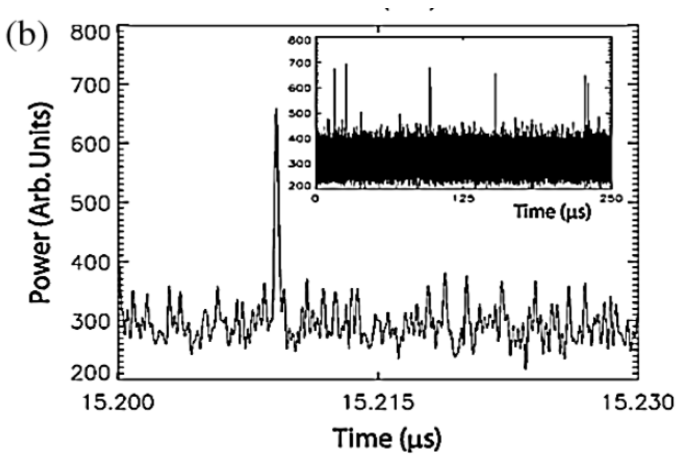

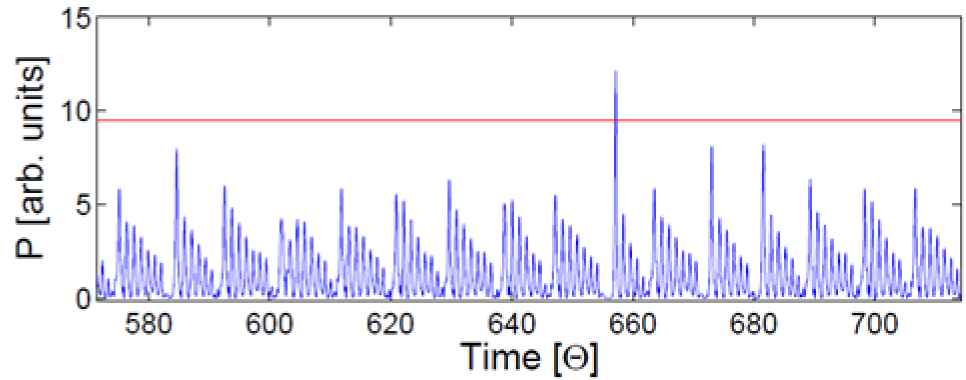

Extreme optical pulses: origin, predictability and suppression

Cristina Masoller

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14th Workshop on Instabilities and Non-equilibrium Structures
Viña del Mar, Chile, December 2013

Collaborators

- José A. Reinoso (Universidad Nacional de Educación a Distancia, UNED, Spain)

- Jordi Zamora Munt (IFISC, Mallorca, Spain)
- B. Garbin, M. Feyereisen, S. Barland, M. Giudici (INLN, Nice, France)
- Jorge Tredicce (INLN, now at Universite de la Nouvelle Caledonie)
- Jose Rios Leite (Universidade Federal de Pernambuco, Recife, Brasil)

Outline

- Introduction to extreme events & optical rogue waves.
- Semiconductor laser with **optical injection**: experimental observations & numerical results.
- Semiconductor laser with **optical feedback**: numerical results.
- Summary and conclusions.

Rogue waves

RWs are rare, ultra-high waves that fall outside (and far from) the main part of long-tailed probability distributions.

The Great Wave of Kanagawa, Katsushika Hokusai. Source: Wikipedia

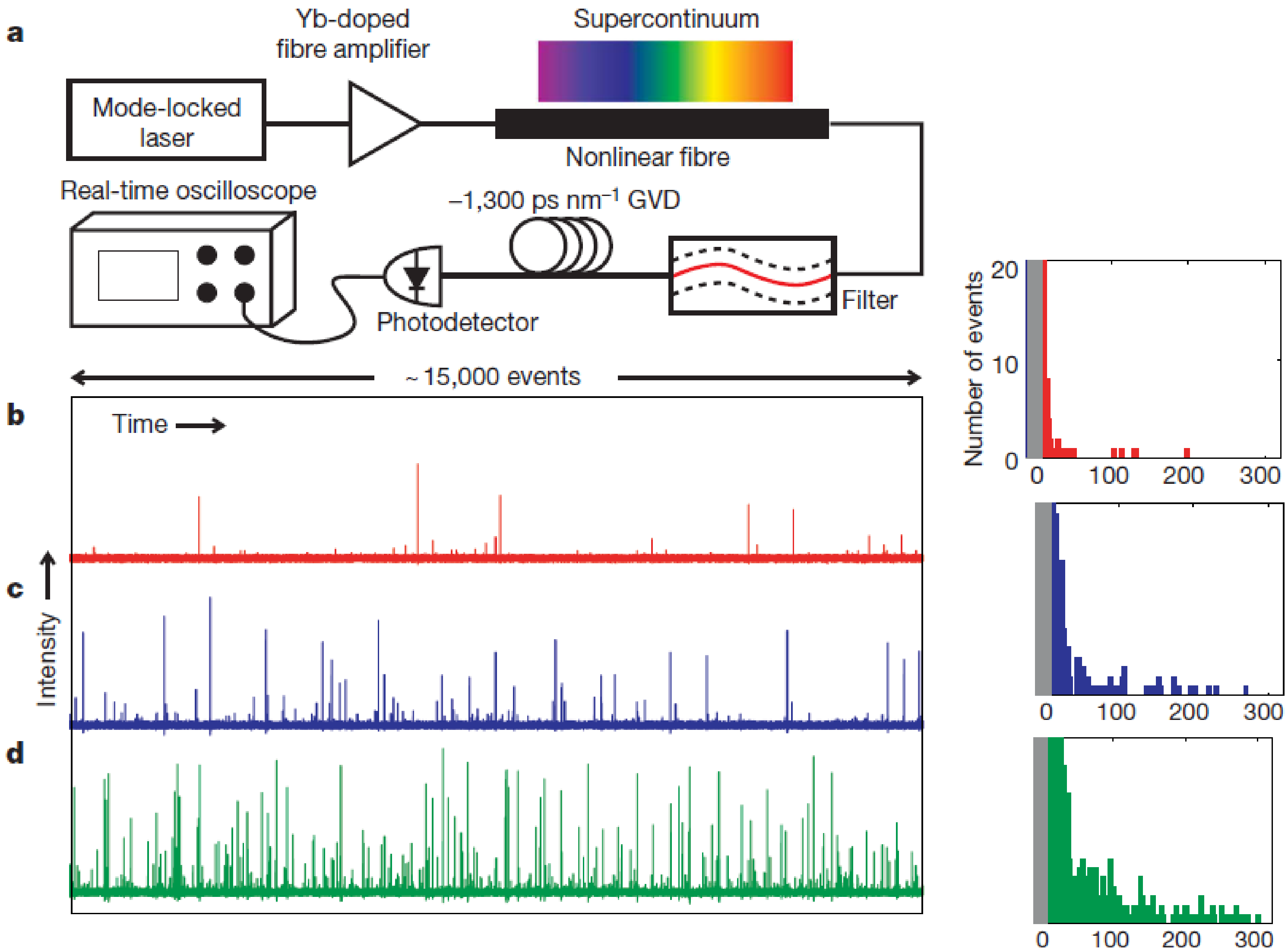
More precisely

- A RW is usually defined as a wave that is two times the significant wave height of the area. The significant wave height is the average of the highest one-third of waves that occur over a given period.

- Serious problem for the design of off-shore platforms.

Source: National Geographic

Optical RWs: first observation



D. R. Solli et al, Nature 450, 1054, 2007 (O. Vincent's talk yesterday afternoon)

Since 2007: a lot of work

Citation Report Topic=(optical rogue wave)

Timespan=All years. Databases=SCI-EXPANDED, SSCI, A&HCI, CPCI-S, CPCI-SSH.

This report reflects citations to source items indexed within Web of Science. Perform a Cited Reference Search to include cita
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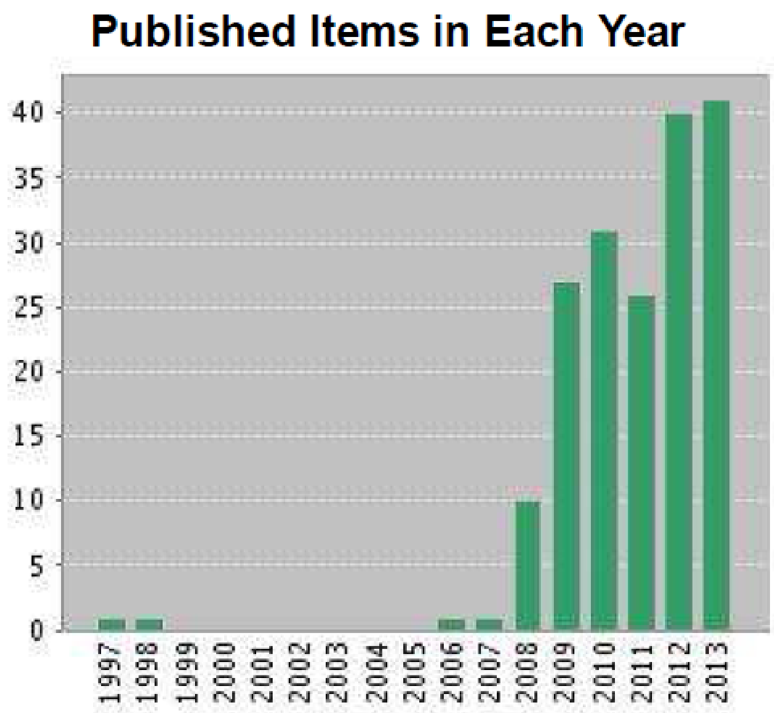
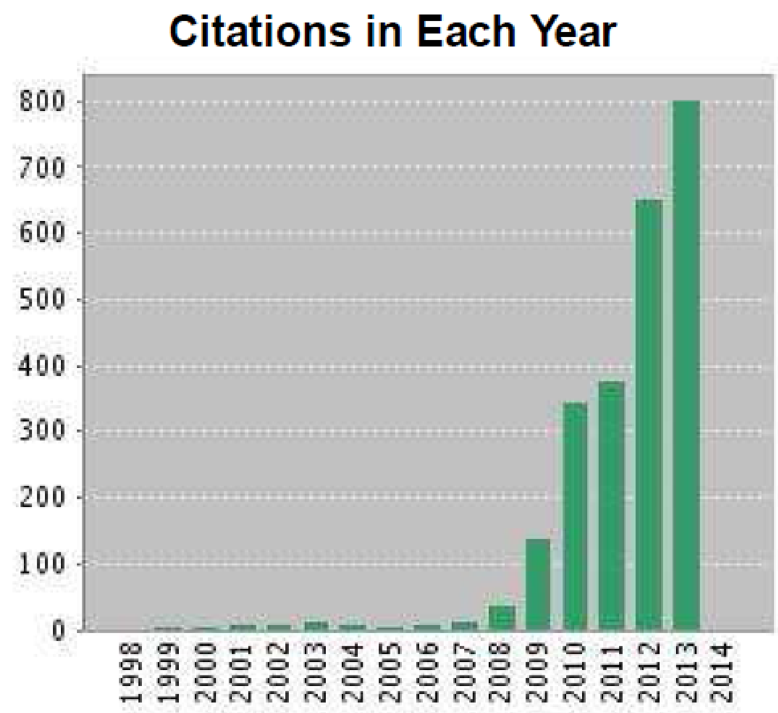


The latest 20 years are displayed.



The latest 20 years are displayed.

Our work in optically injected semiconductor lasers

- Experimental and numerical identification of deterministic rogue waves.

C. Bonatto et al, *Deterministic optical rogue waves*, PRL 107, 053901 (2011).

- RWs can be predicted with a certain anticipation time.
- They are generated by an external crisis-like process.
- Noise can either enhance or diminish their probability of occurrence.

J. Zamora-Munt et al, *Rogue waves in optically injected lasers: origin, predictability and suppression,* PRA 87, 035802 (2013).

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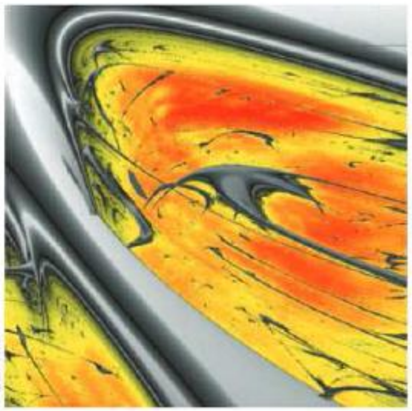
Highlighted in OPN and Nature Photonics

ROGUE WAVES

Surely deterministic

Phys. Rev. Lett. **107,** 053901 (2001)



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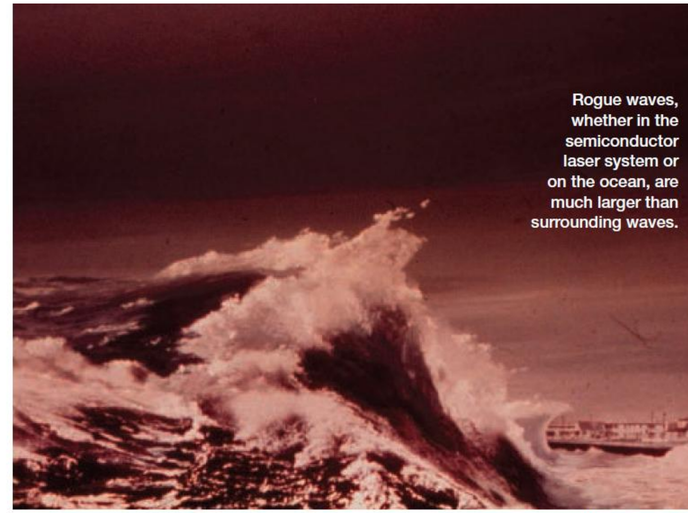
The physical mechanism behind the formation of rogue waves — waves with seemingly spontaneous large amplitudes — has long been an interesting research topic for oceanologists and physicists, including those working in photonics. An important question is whether rogue waves can be described by a fully deterministic process with noise as a driving force. Cristian Bonatto and co-workers from Spain, France and Brazil recently carried out an investigation into the generation of rogue waves using a semiconductor laser that received optical injection from a continuous-wave master laser. The researchers not only showed that sporadic high-amplitude pulses can be observed with such a simple and inexpensive laser set-up, but also concluded that the rogue waves they observed are generated from deterministic nonlinearities. Their conclusion was based on good qualitative agreement between experimental results and simulated results from a simple, deterministic noise-free rate equation model. *RW*

SCATTERINGS | NEWS

Deciphering Rogue Waves



Rogue waves, whether in the semiconductor laser system or on the ocean, are much larger than surrounding waves.

Wikimedia Commons

Rare pulses with giant intensities—the optical equivalent of rogue ocean waves—have been shown to occur in common laser systems. A team of researchers from Spain, France and Brazil found a way to generate rogue waves and developed a model for understanding them as a result of a deterministic nonlinear process (Phys. Rev. Lett. **107**, 053901). Extremely high waves have been a subject of interest over the past decade in oceanography as well as in other fields (including optics), but we still don't fully understand what triggers them and how they develop.

Rogue waves on the ocean are typically twice the height of surrounding waves and have steep sides, like "a wall of water." They have high amplitude, with a fast rise and fast fall. In the laser system demonstrated by the researchers, a rogue wave has an intensity so high that—according to Gaussian statistics—it should be vanishingly improbable. Such waves are unusual, but occur more often than Gaussian statistics can explain. Rogue waves also can be destructive: paper coauthor Jorge Tredicce at the Université de Nice Sophia Antipolis (France) says, "in mode-locked lasers, those extreme pulses may damage the optics and the crystal … it is the death of the laser!"

Light from a continuous wave master laser is injected into a stabilized vertical cavity surface-emitting laser (VCSEL) with stabilized pump current and temperature. The VCSEL emitted at 980 nm in a single transverse mode.

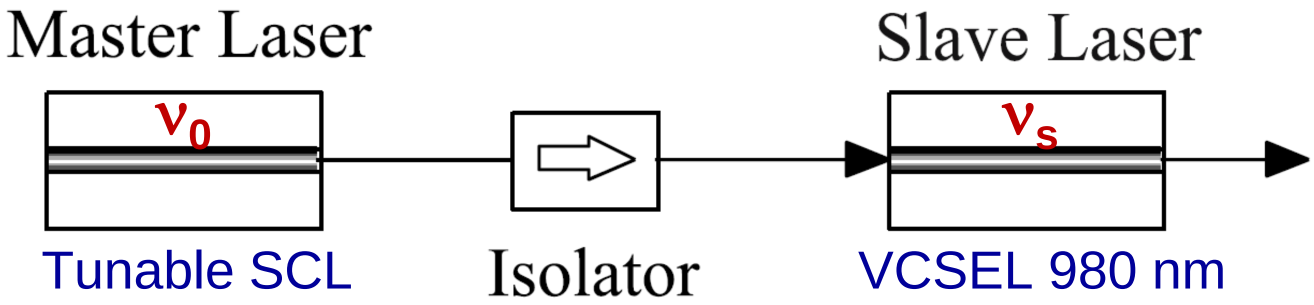
Researchers detuned the injection laser from the VCSEL and found that the slave laser output falls into four regions—one of which is stable-locked behavior. As the VCSEL current is increased, the output becomes more and more chaotic. Near the border of the mode-locked region, the researchers found a series of small pulses interrupted by occasional extremely large pulses. Coauthor Cristina Masoller at the Universitat Politècnica de Catalunya (Spain) explains, "we identify two types of optical chaos: one in which rogue waves are rare but they certainly appear and one in which practically they do not exist." There appear to be areas where rogue waves don't occur even if the behavior is chaotic.

The experiments were inspired by Tredicce's theoretical paper that suggested the existence of huge intensity pulses in this laser system. The researchers found that a simple noise-free rate equation model produced results that agree with the experiments. This allowed them to interpret the sporadic high amplitude pulses as the result of a deterministic nonlinear process.

The group now has a simple system that allows them to experiment with optical rogue waves, as well as a model for describing them. Because rogue waves occur in other systems, ranging from ocean surface to acoustic waves to economics, their work could have implications far beyond the realm of optics. Next, they want to find a mechanism that creates rogue waves in their system, as well as whether they can increase or decrease their likelihood.

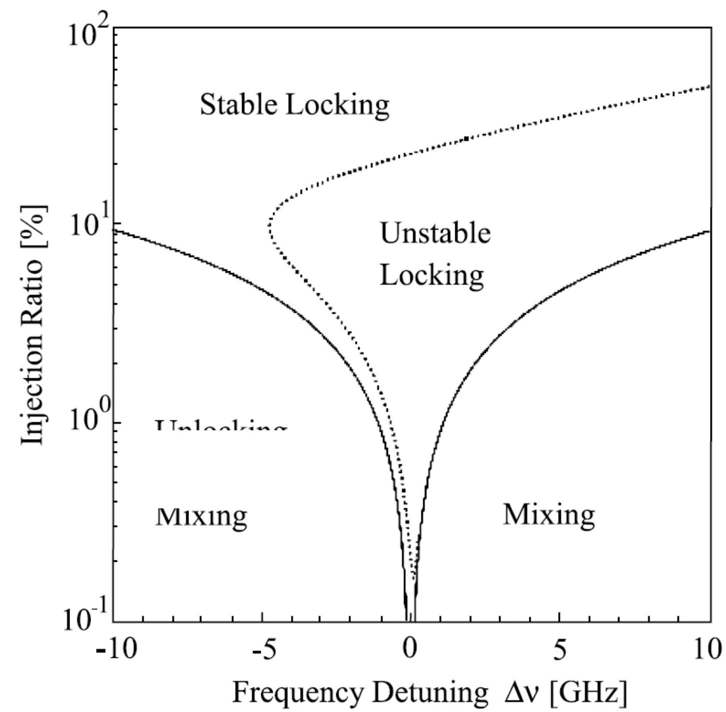
—Yvonne Carts-Powell

Continuous-wave optically injected semiconductor lasers



Detection system (photo detector, oscilloscope, spectrum analyzer)

- Parameters:
  - Injection ratio
  - Frequency detuning $\Delta\nu = \nu_s - \nu_0$
- Dynamical regimes:
  - Injection locking (cw output)
  - Period-one oscillation
  - Period-two oscillation
  - Chaos



Adapted from J. Ohtsubo

Eur. Phys. J. D **58**, 181–186 (2010)
DOI: 10.1140/epjd/e2010-00061-4

THE EUROPEAN PHYSICAL JOURNAL D

Regular Article

Labyrinth bifurcations in optically injected diode lasers

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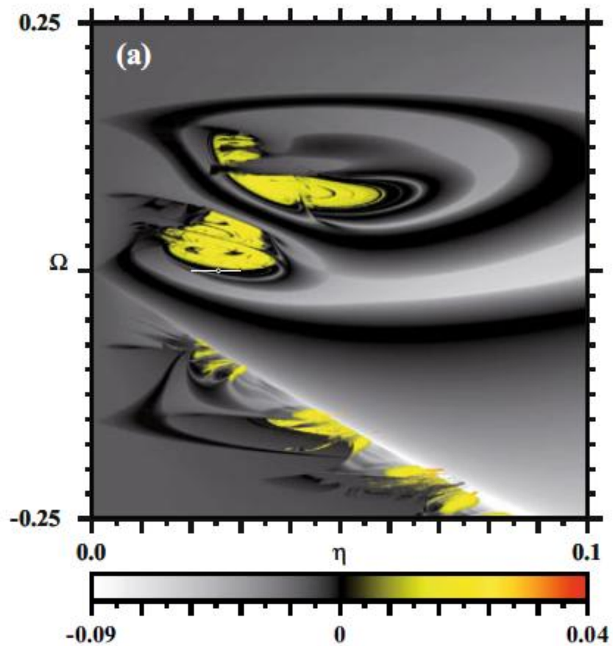
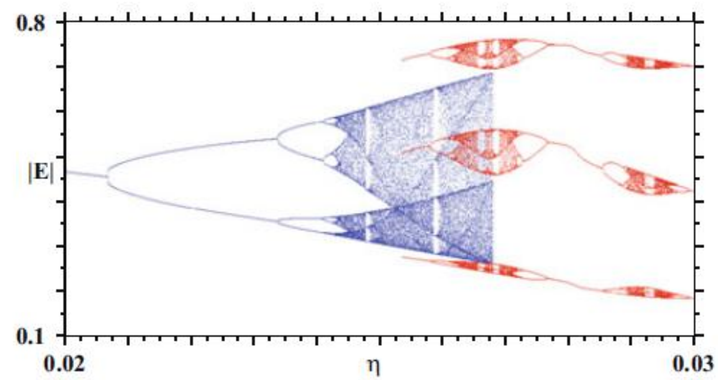
Lyapunov diagram



Bifurcation diagram

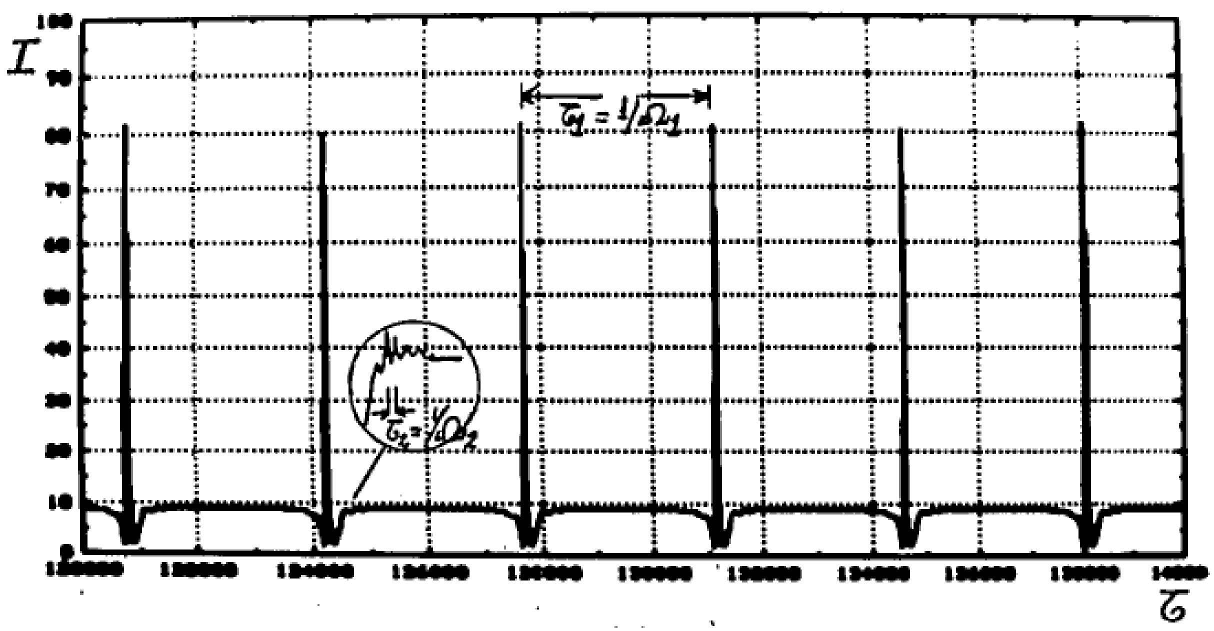


Also RWs?

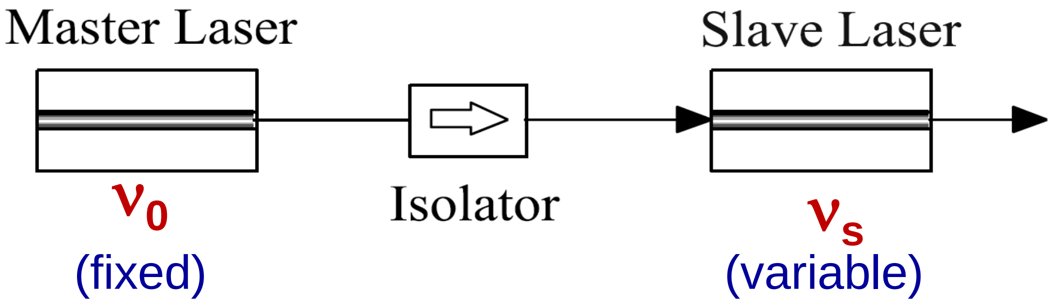
Instabilities in lasers with an injected signal

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



Experimental setup and control parameters



- Photo detector: 9.5GHz
- Oscilloscope: 6 GHz, 20GS/s
- Spectrum analyzer: 72GHz

The **frequency detuning** between the lasers, $\Delta\nu = \nu_s - \nu_0$, is controlled by the slave laser pump current, **I**

When **I** increases:

→ **Joule heating**

→ **the temperature modifies the cavity refractive index**

→ **decreases the cavity resonance frequency**

$$\nu_s = g(Temp) = f\,(I)$$

(f approximately linear)

We varied the slave laser pump current and detected the output of the laser:

- **Intensity time - series (with a 6 GHz oscilloscope)**
- **Intensity Fourier spectrum (spectrum analyzer)**

Experimental observations

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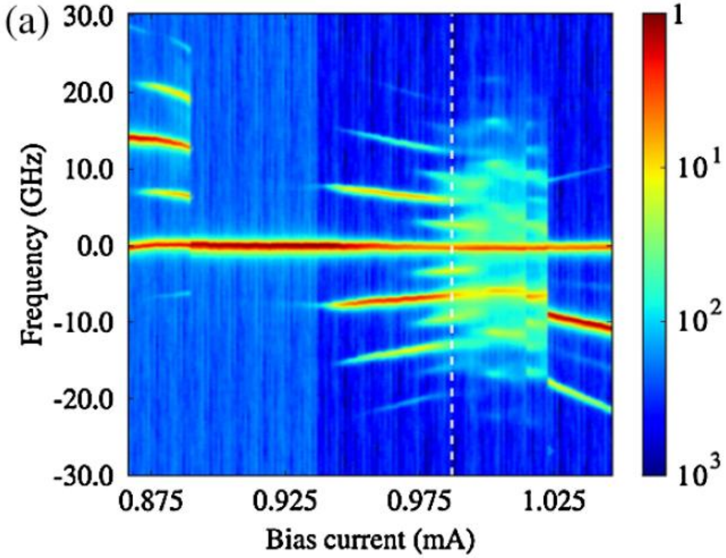
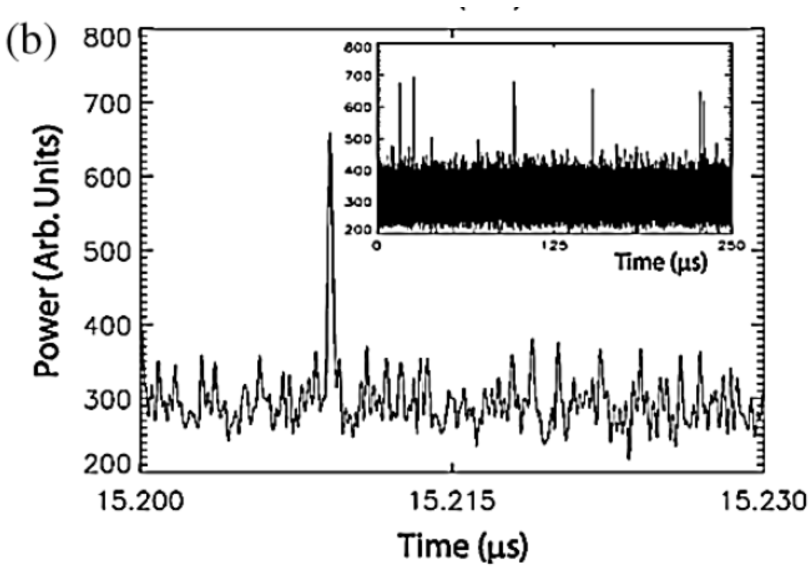
Fourier spectrum of the laser intensity



Time series of the laser intensity



Five regions:

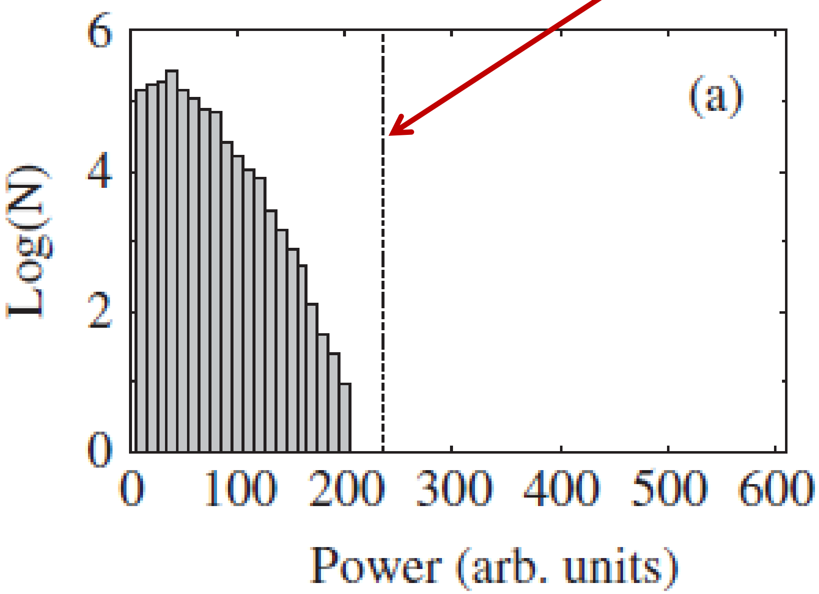
- Beating (independent lasers)
- Period 2 of the beat note
- Stable locking
- Periodic & chaotic oscillations
- Beating (independent lasers again)

(In the chaotic region,
I = 0.976 mA, $\Delta\nu$ = -1.34 GHz)

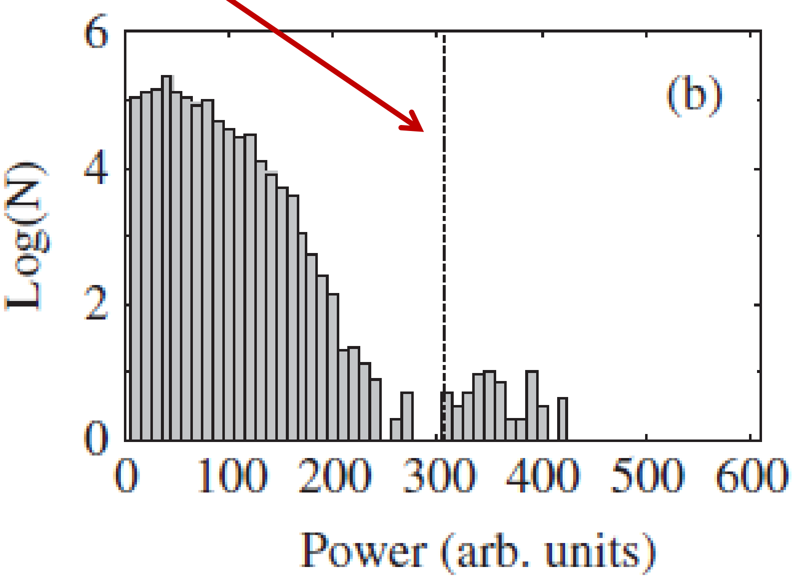
C. Bonatto et al, PRL 107, 053901 (2011)

Histograms of pulse amplitude

Border = mean value + 8 σ



I = 0.972 mA



I = 0.976 mA

Governing equations

- The *complex* optical field, **E** (photon number $\propto$ **|E|²**)
- The 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
Δω: frequency detuning

spontaneous emission noise

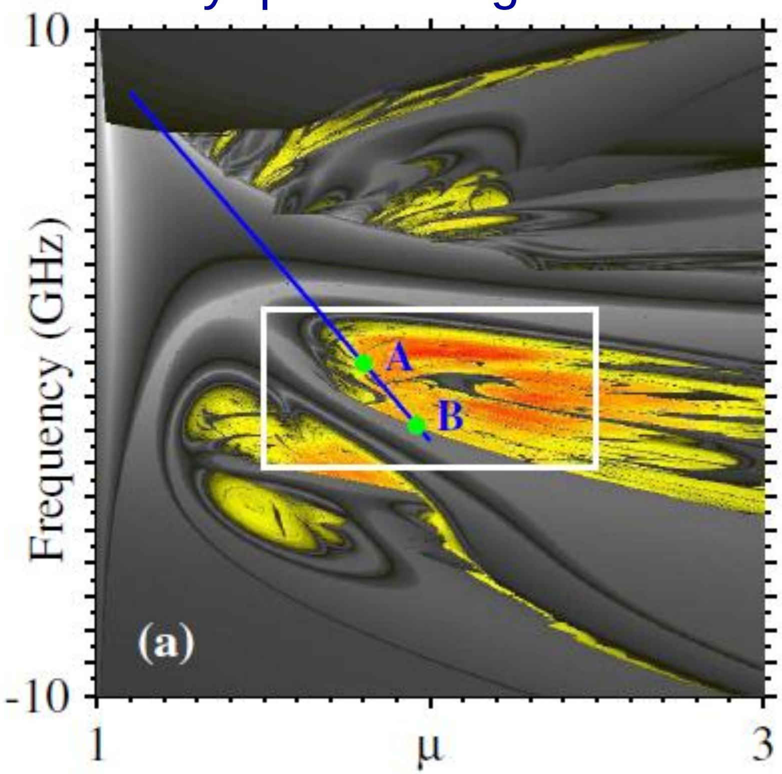
Solitary laser parameters: **α τ_p τ_N μ**

Typical parameter values:
α = 3, τ_p = 1 ps, τ_N = 1 ns

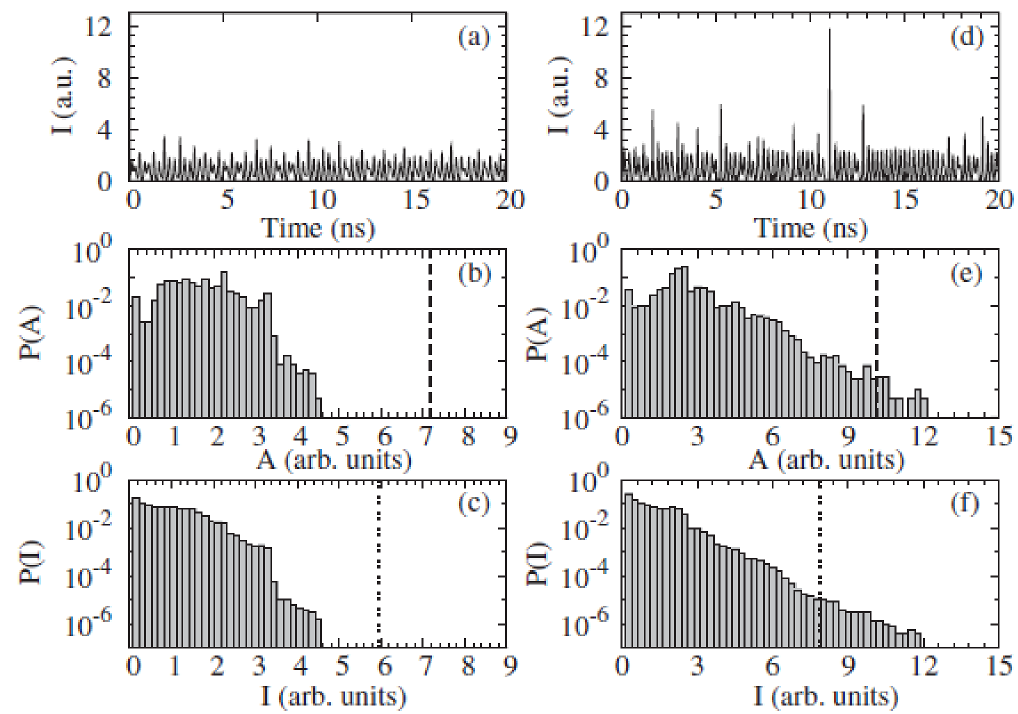
μ: normalized pump current parameter

Deterministic simulations (β_{sp}=0)

Lyapunov diagram



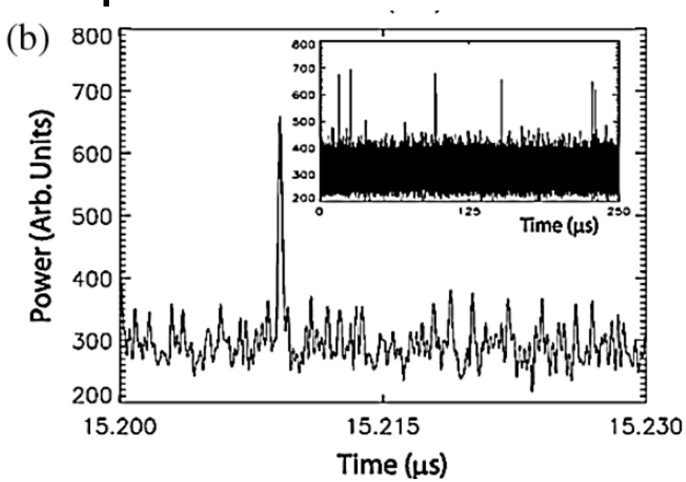
Slave laser pump current

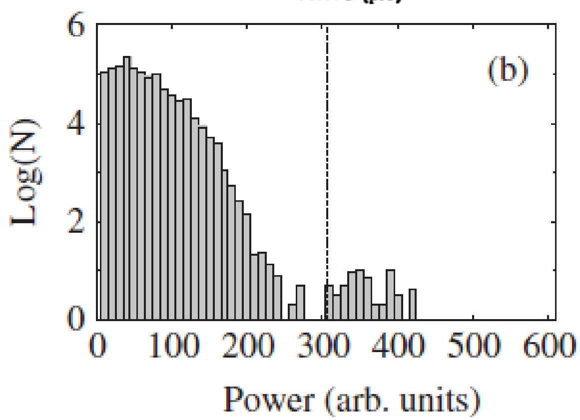


Point A: No RWs   Point B: RWs

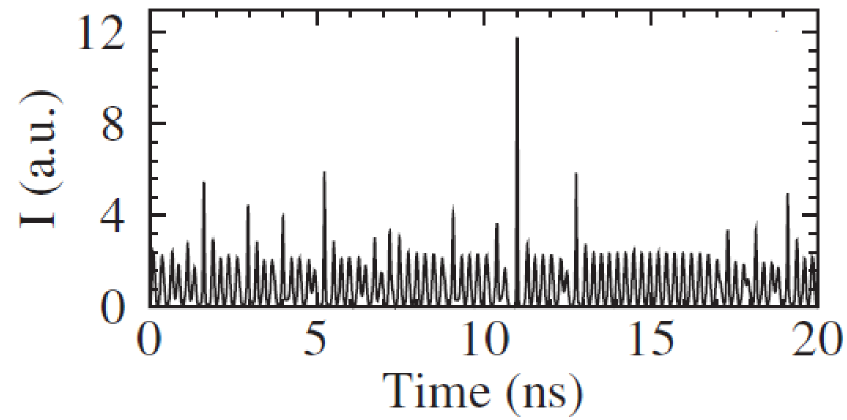
Comparison

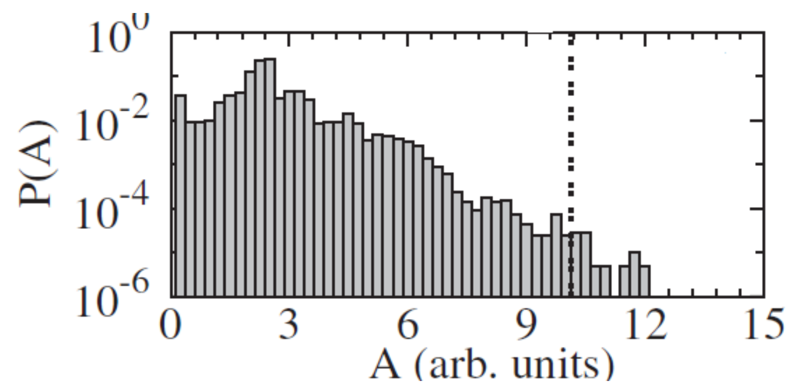
Experiments





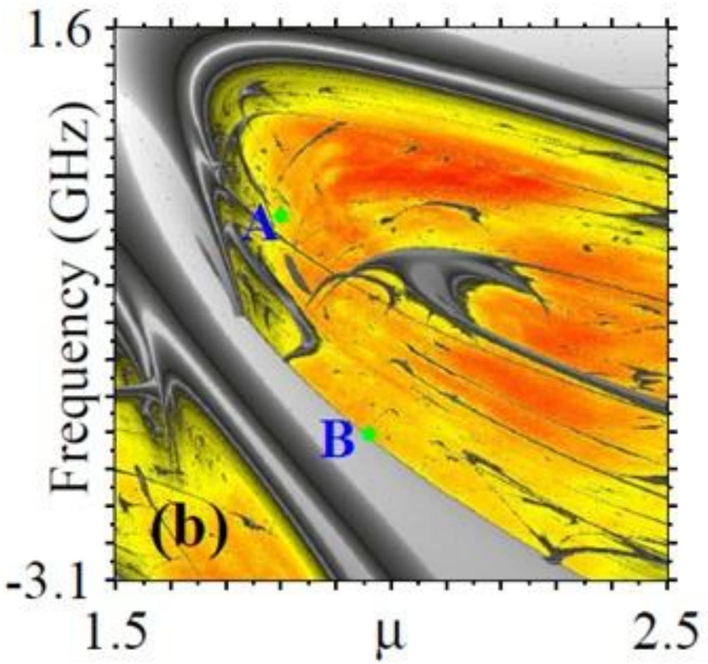
Simulations



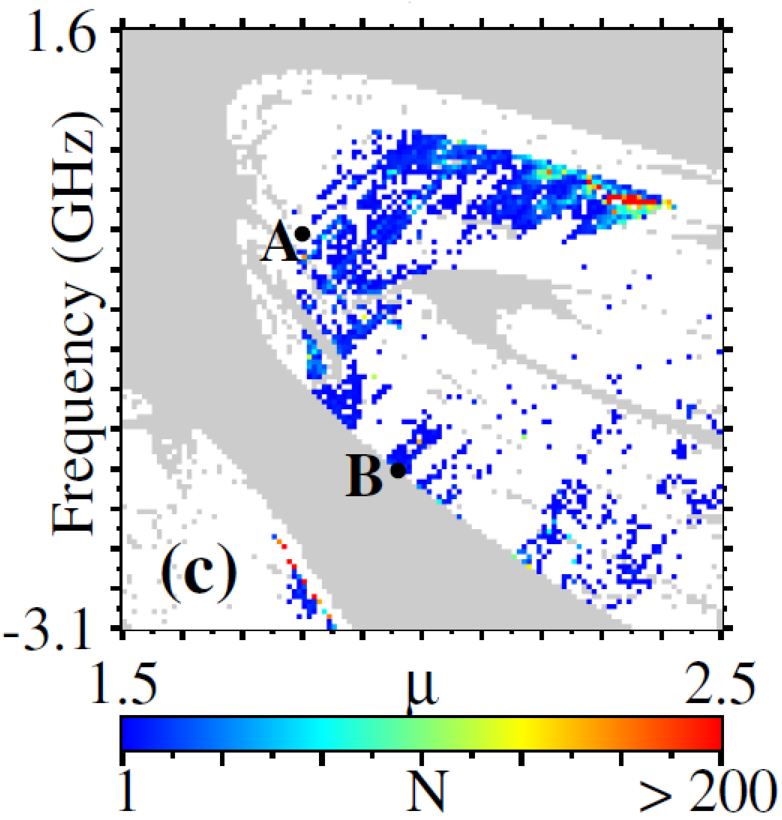


Rogue waves in the parameter space (pump current, frequency detuning)

Lyapunov diagram



Number of RWs



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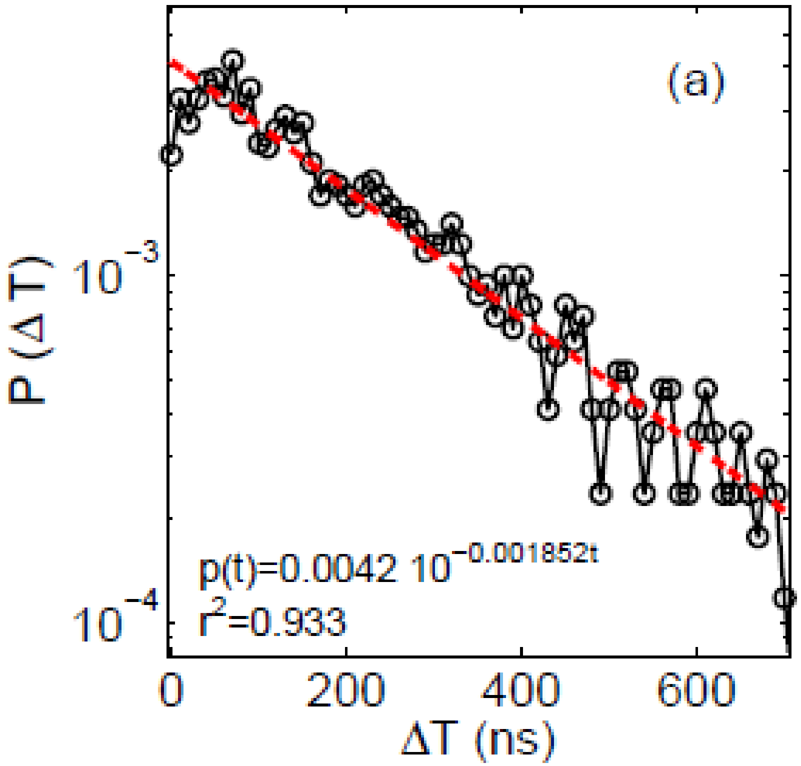
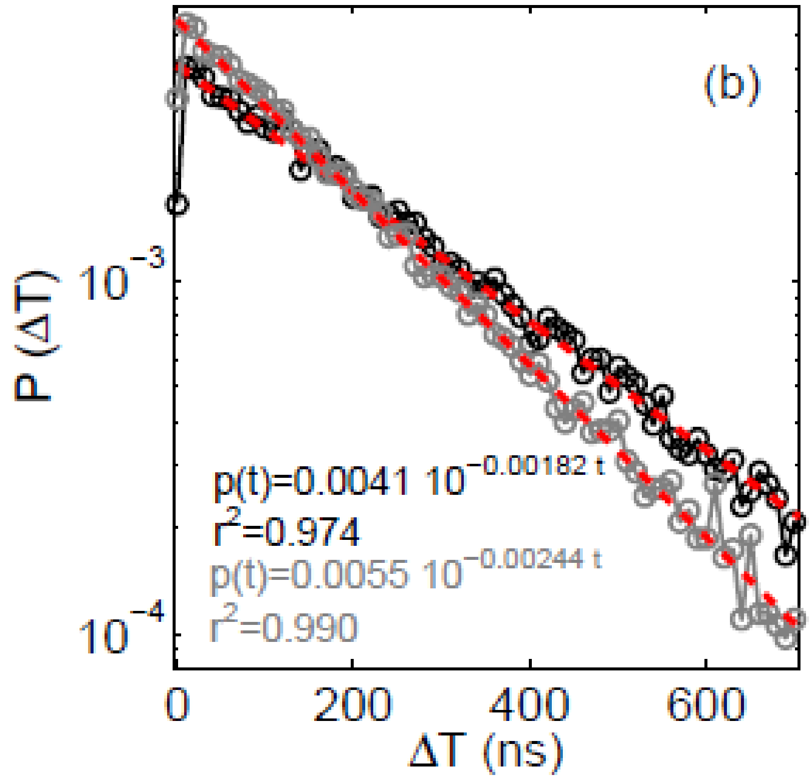
Statistics of the RW waiting time

Experimental data

Deterministic (gray) & stochastic (black) simulations

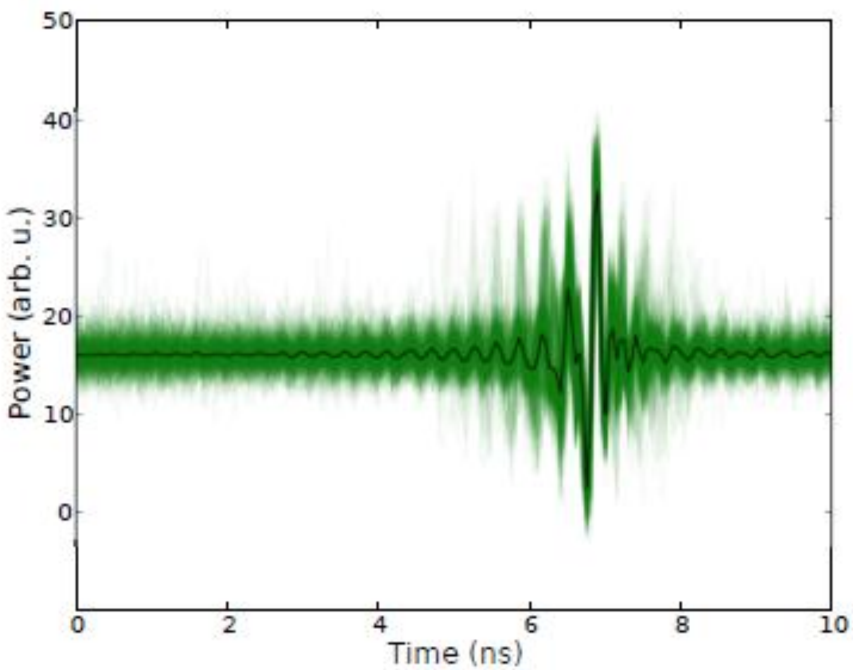




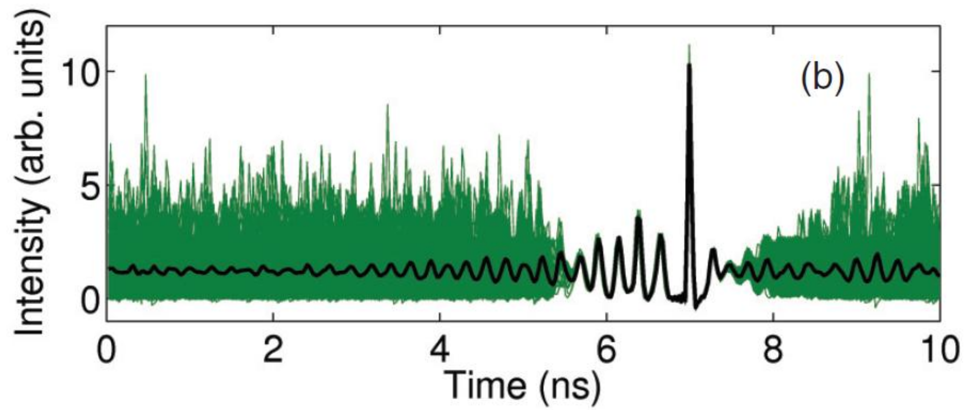
Good agreement when a realistic noise strength is included in the simulations

RW predictability

Experimental data



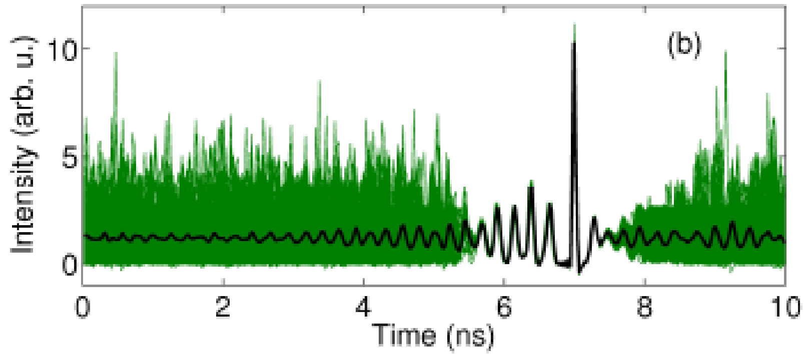
Numerical data



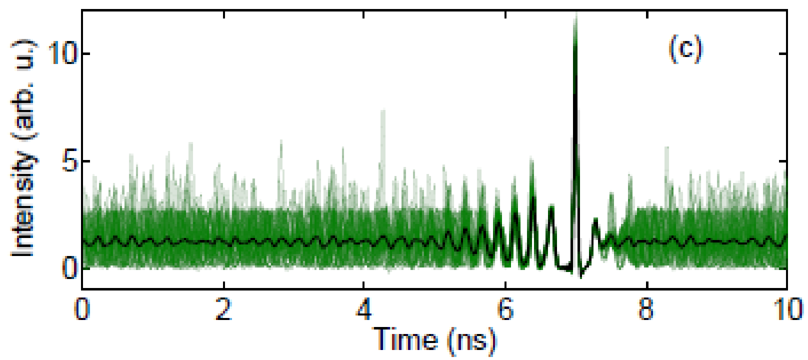
Superposition of 500 time series at the RW peak

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

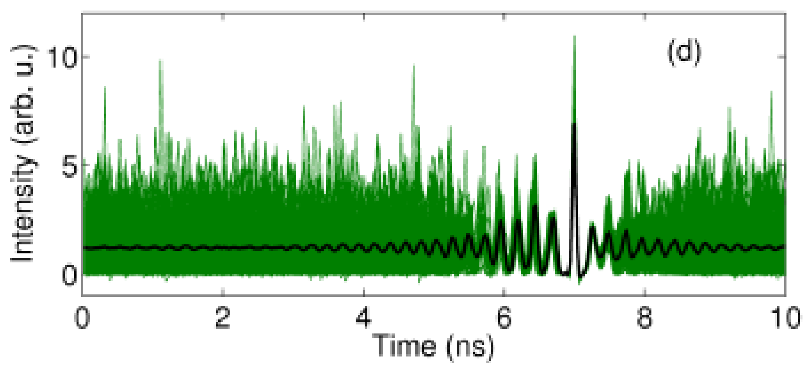
Influence of threshold & noise in RW predictability



$\langle H \rangle + 8\sigma$
$\beta_{sp} = 0$
459 RWs

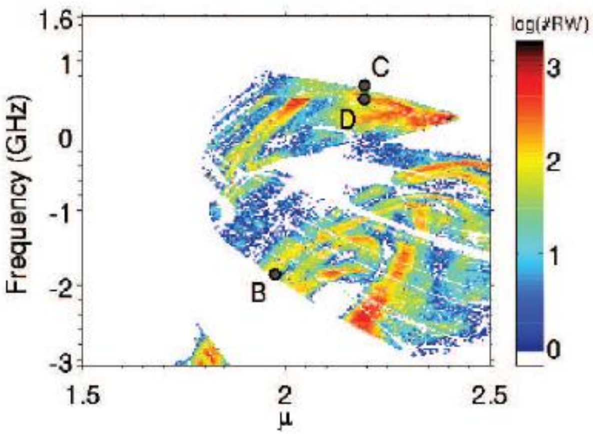


$\langle H \rangle + 8\sigma$
$\beta_{sp} = 10^{-2}$
53 RWs

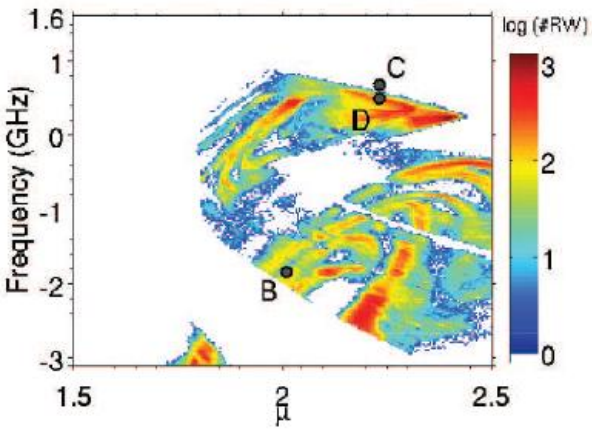


$\langle H \rangle + 4\sigma$

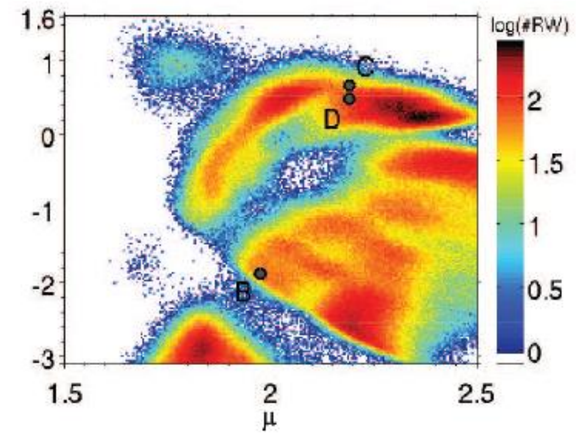
Influence of spontaneous emission noise



$\beta_{sp} = 0$



$\beta_{sp} = 10^{-4}$

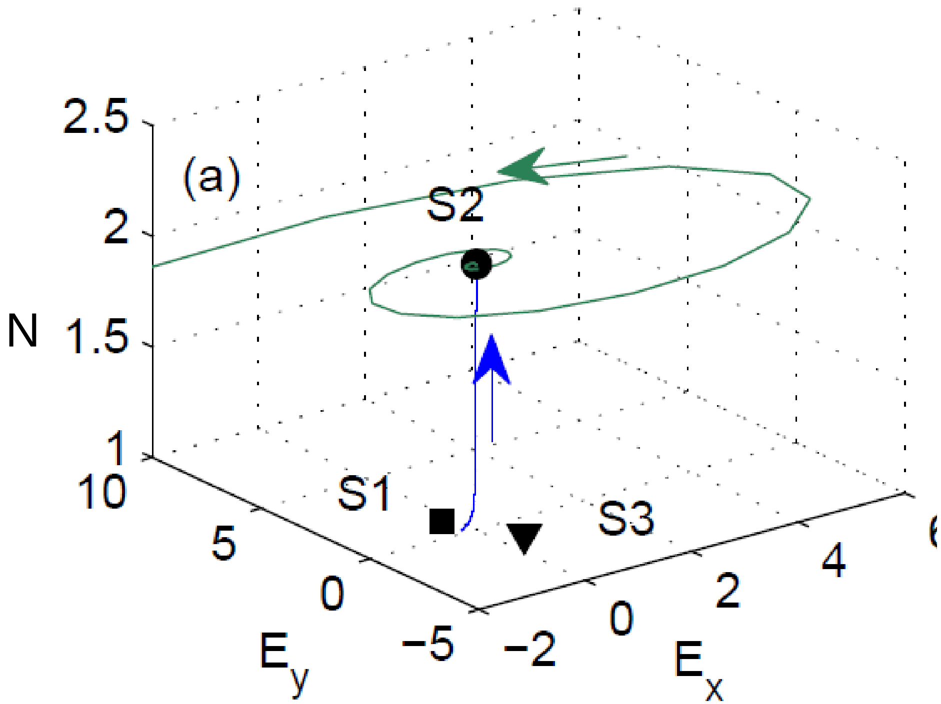


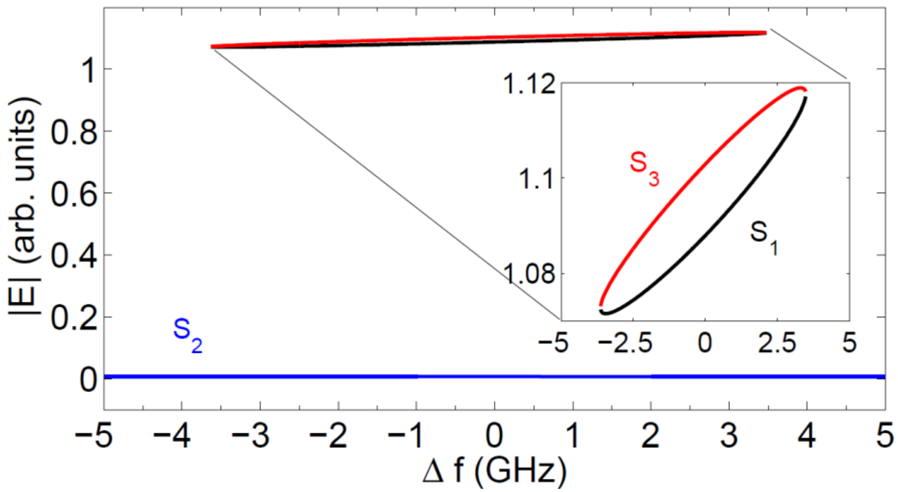
$\beta_{sp} = 10^{-2}$

Depending on the parameters, noise decreases the number of RWs, or it induces RWs.

What triggers a RW?

Fixed points in the phase space





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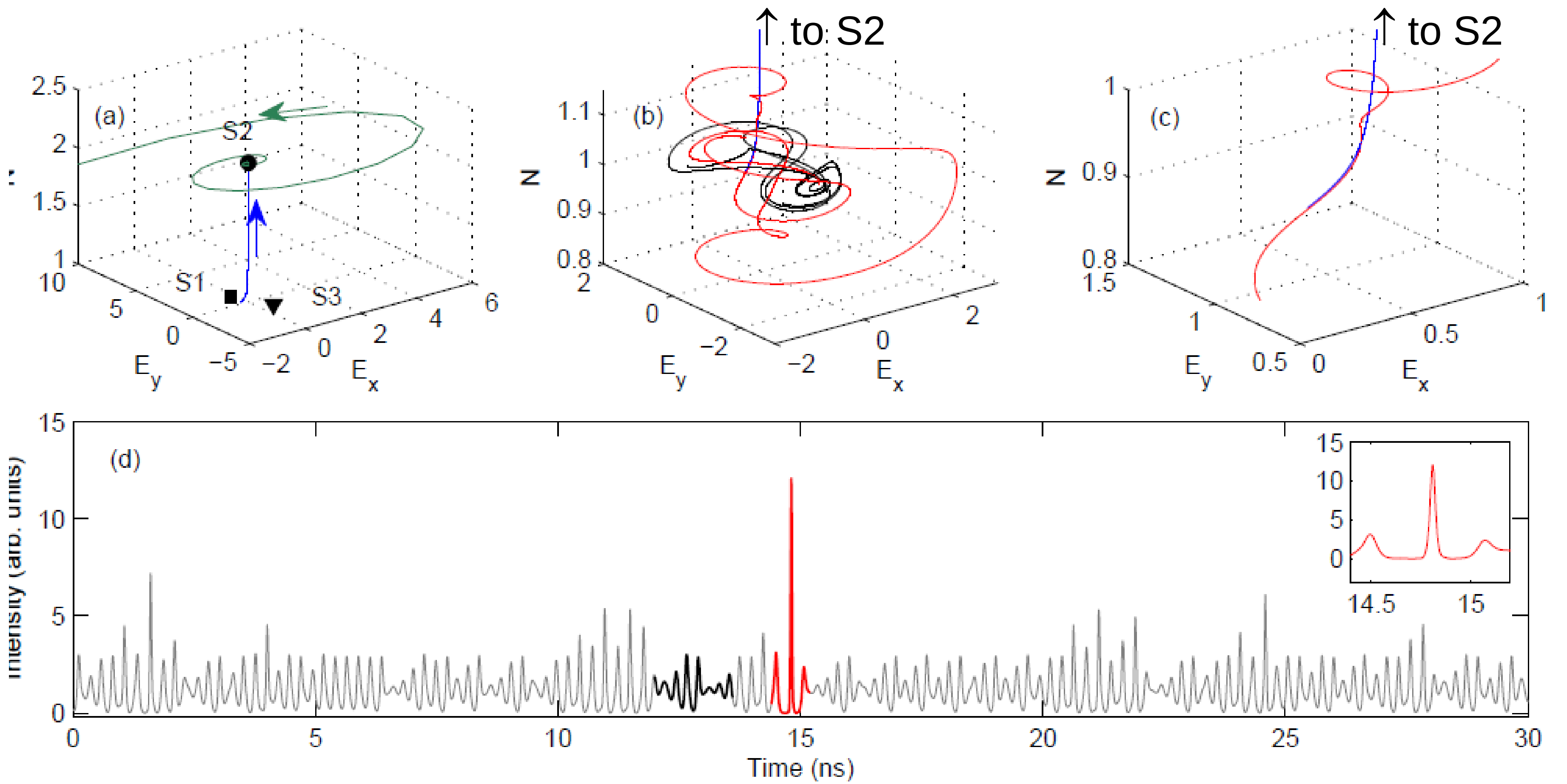
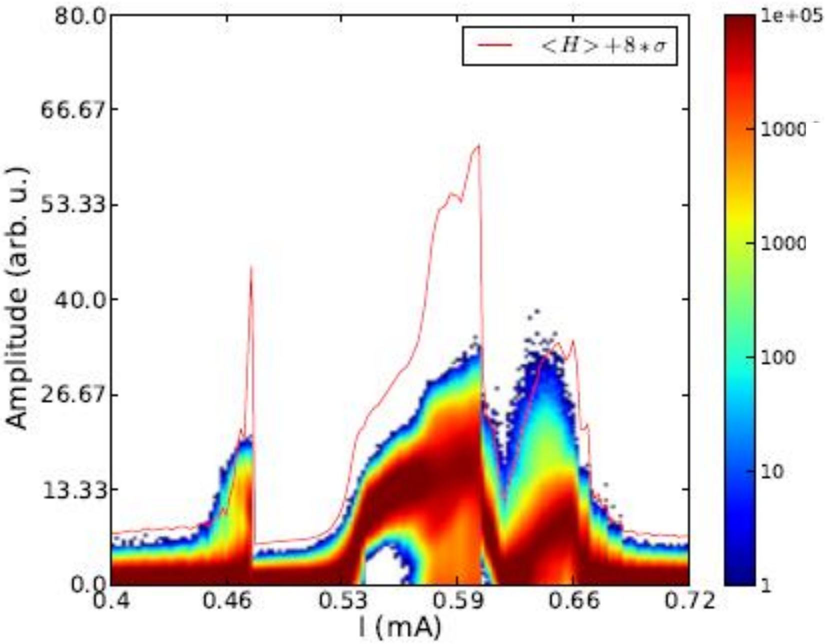
A narrow channel: the RW "door"



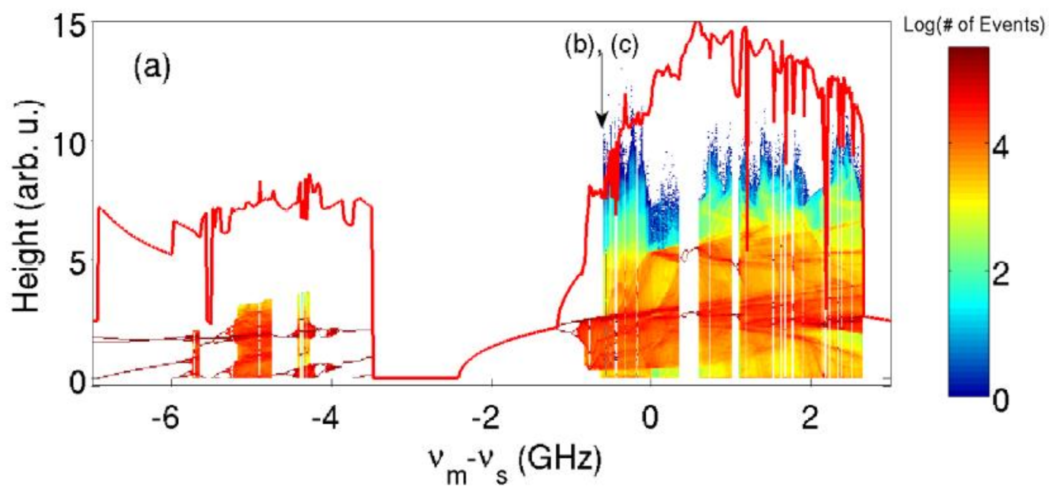
A RW is triggered whenever the trajectory closely approaches the stable manifold of S2

Bifurcation diagram: amplitude of the intensity pulses

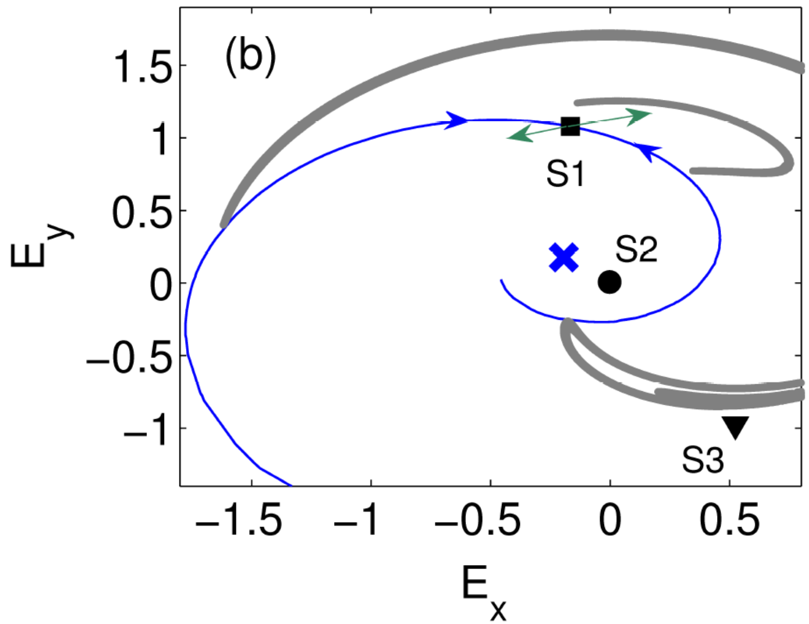
Experimental data

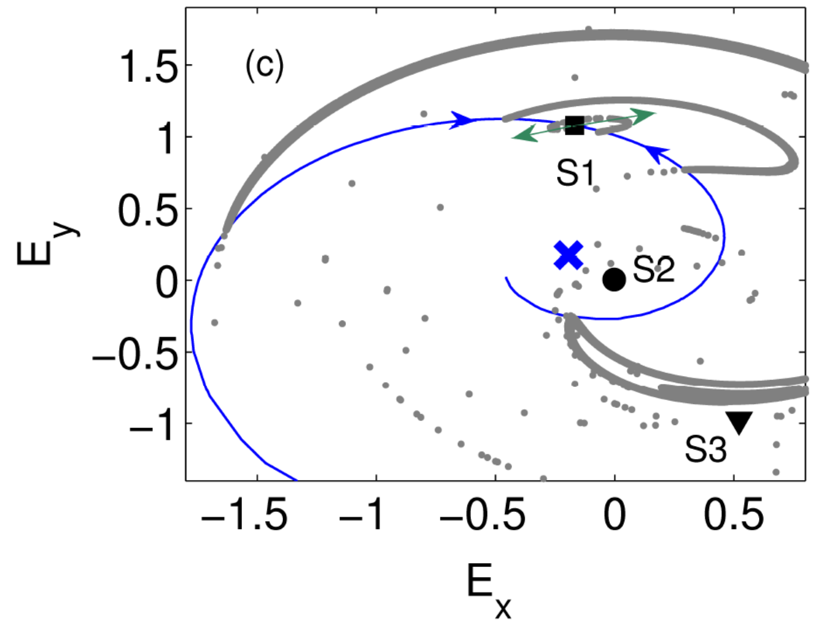


Numerical data



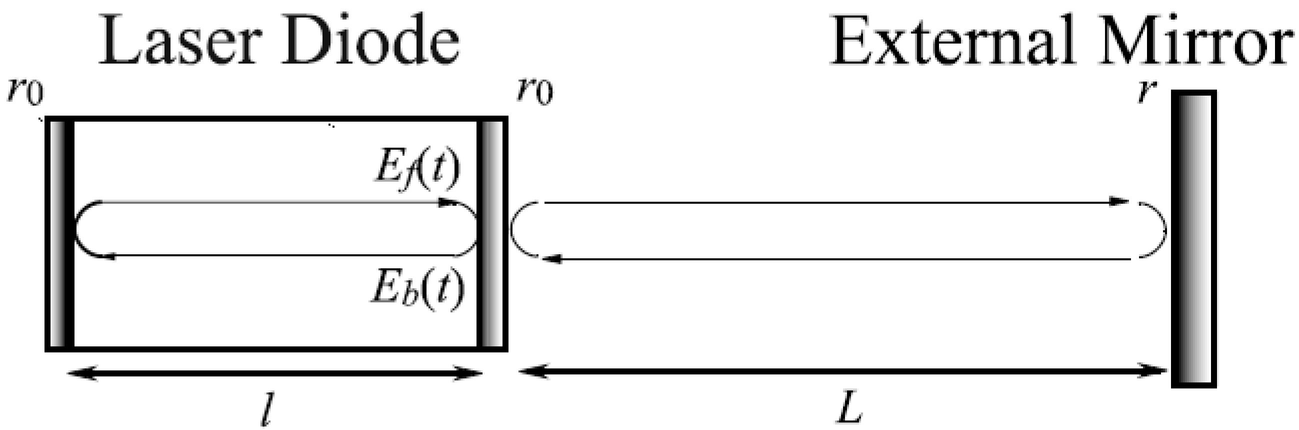
Why chaos with RWs and chaos without them?





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

Dynamics with optical feedback from a short external cavity



τ=2L/c

Short EC:
$f_{ext}=1/\tau > f_{ro}$

$$dE/ds = (1 + i\alpha)NE(s) + \underline{\eta e^{-iw\theta} E(s-\theta)} + \beta\xi,$$

$$T\,dN/ds = J - N - (1+2N)|E(s)|^2.$$

Typical parameter values:

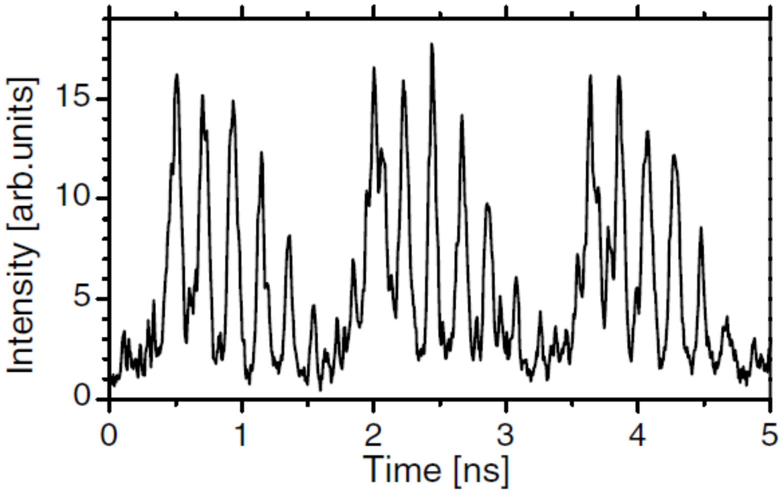
α =5, T = 1710, θ =70, J = 1.155

$s = t/\tau_p \qquad \theta = \tau/\tau_p$

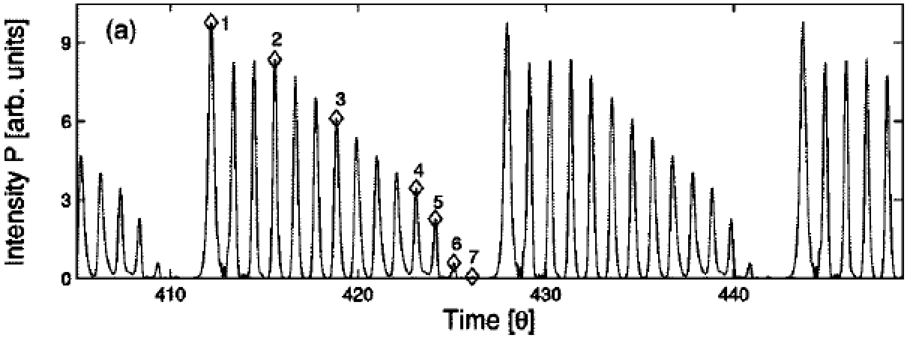
$T_{RO} = \pi\sqrt{2T/J} = 171$

Regular Pulse Packages (RPPs)

- Experiments



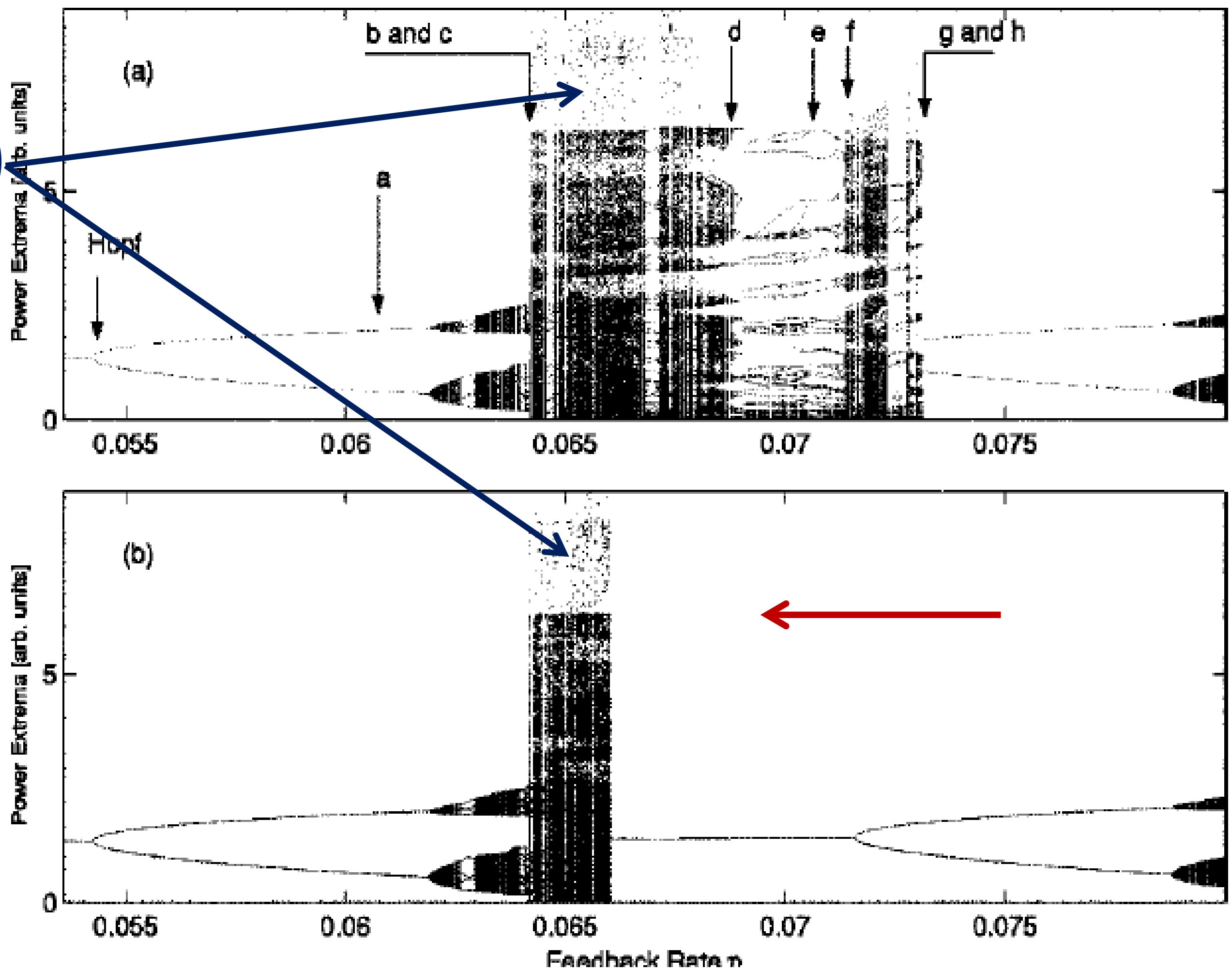
- Simulations

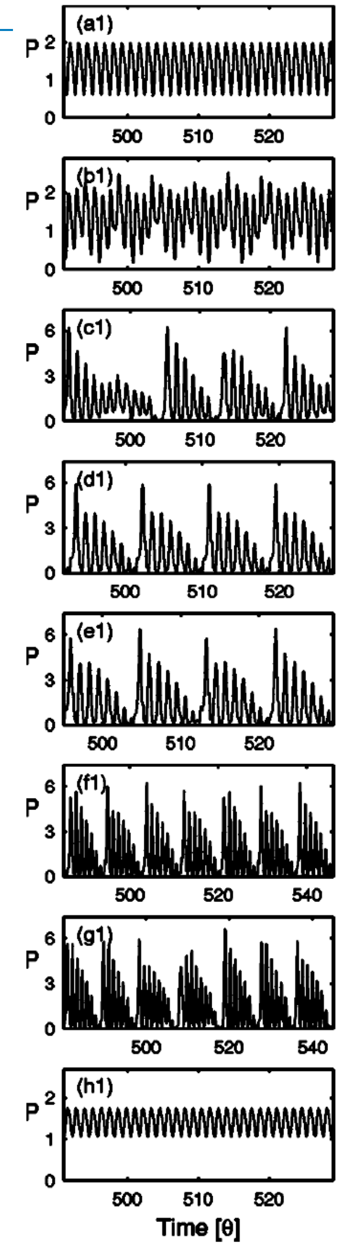


T. Heil et al, PRL 87, 243901 (2001)
A. Tabaka,et al. PRE 70, 036211 (2004)

Numerical bifurcation diagram

Extreme
pulses?

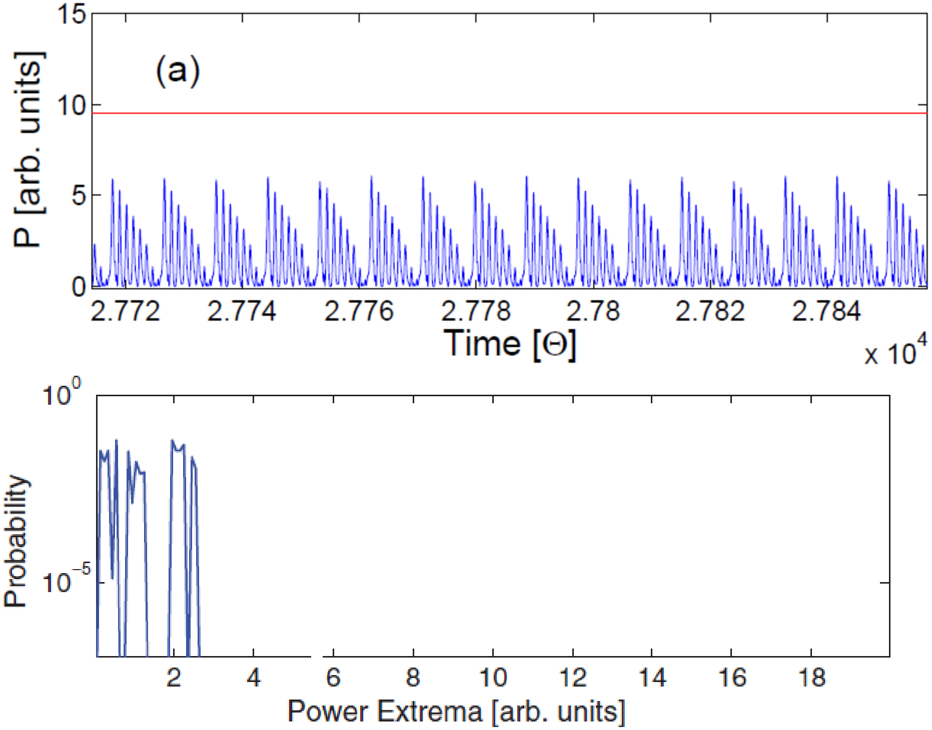




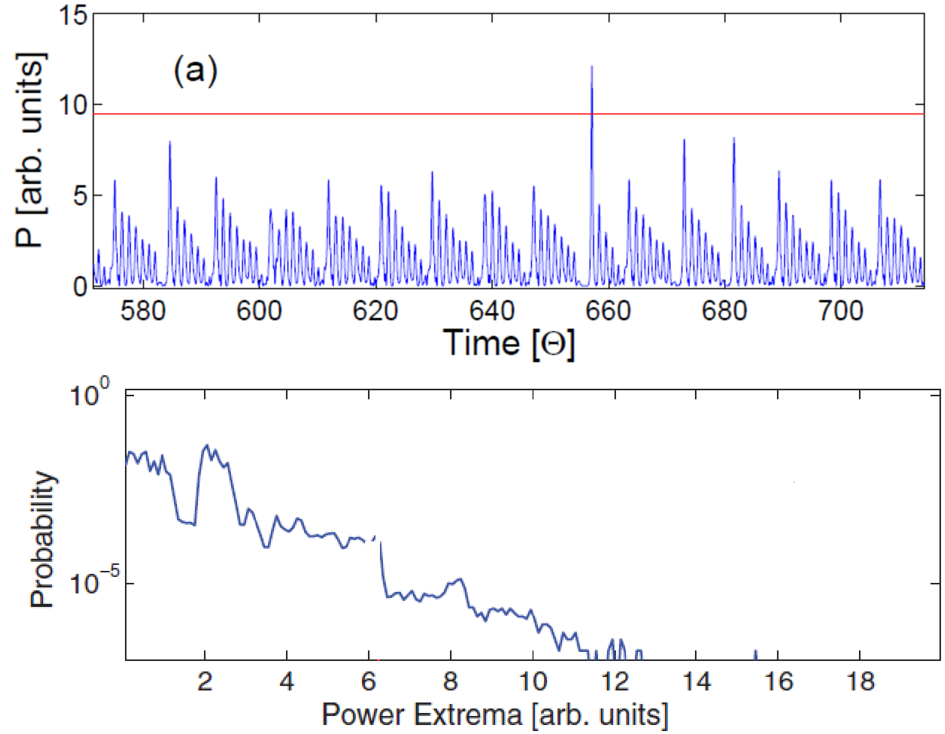
A. Tabaka,et al. PRE 70, 036211 (2004)

Comparison

Regular pulse packages



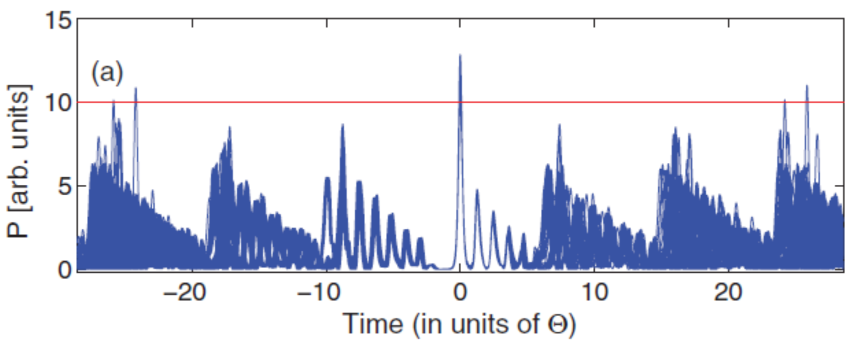
Extreme pulses

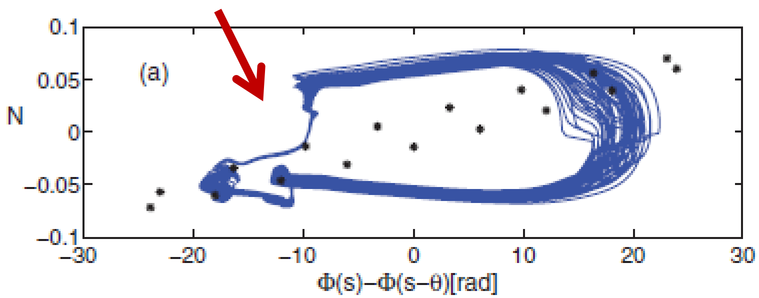


J. A. Reinoso, J. Zamora-Munt and C. Masoller. PRE 87, 062913 (2013)

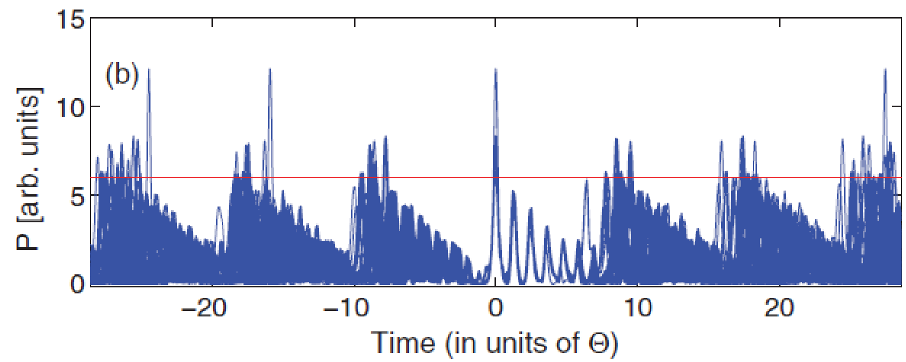
Predictability

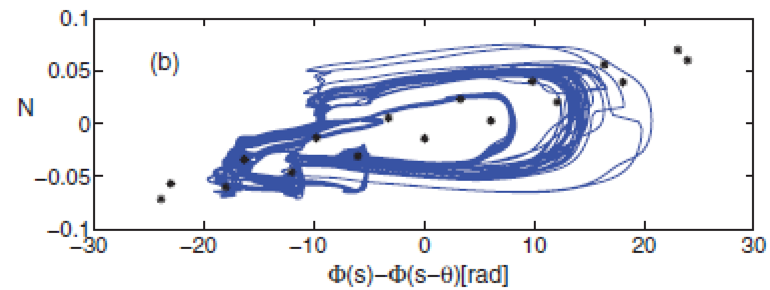
Using a high threshold



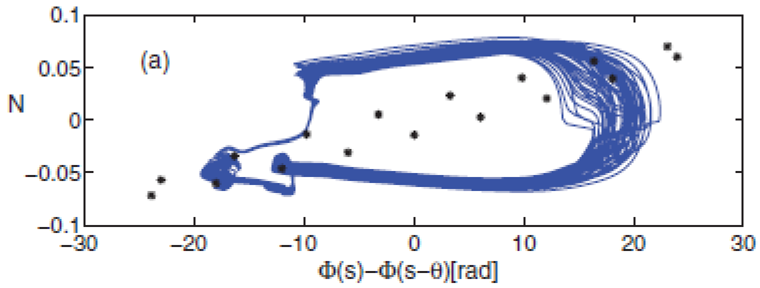


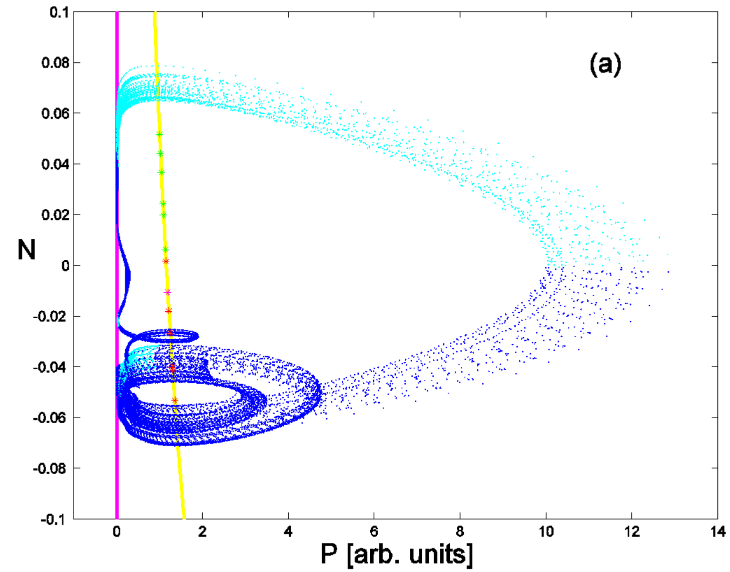
Using a lower threshold

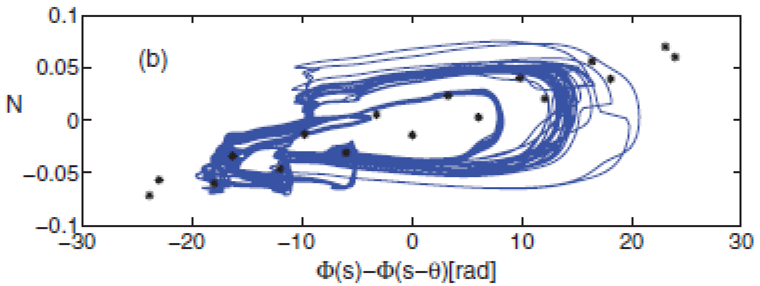


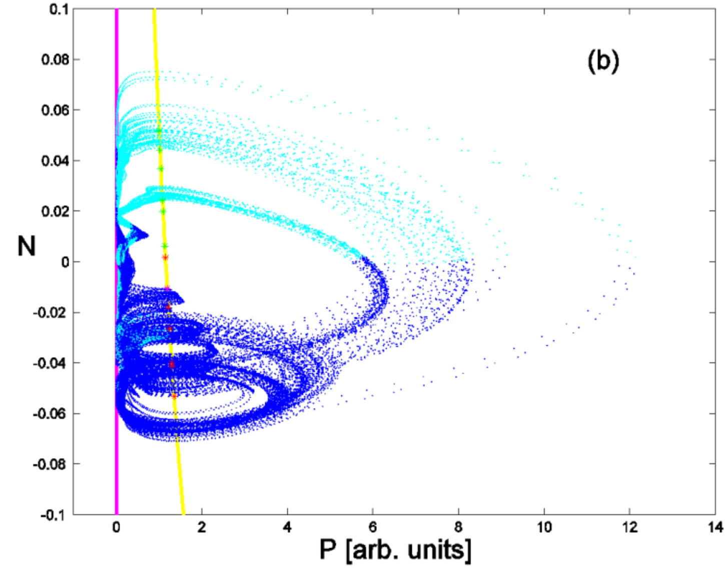


A narrow "door" (similar to that for a RW in an optically injected laser)

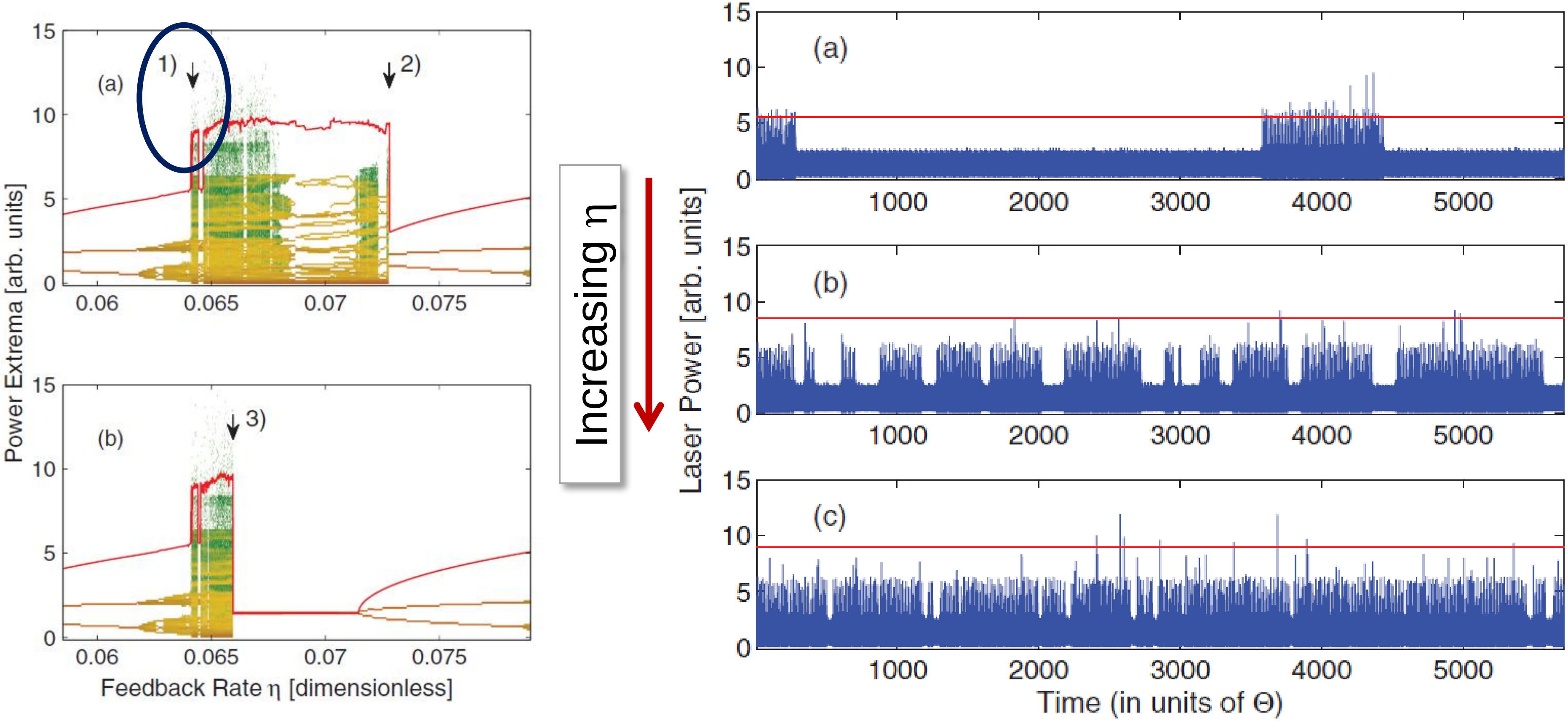






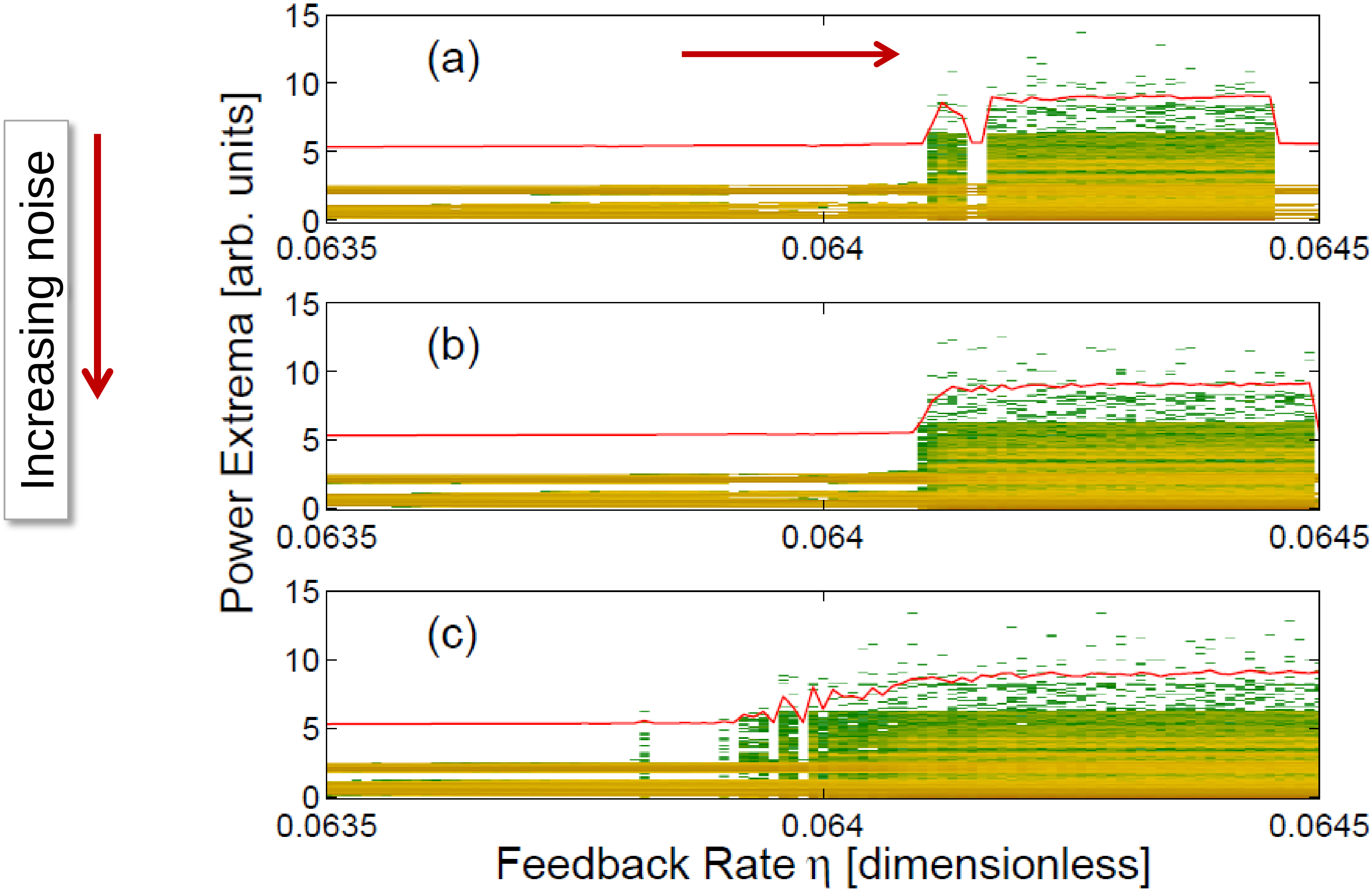


Deterministic intermittency



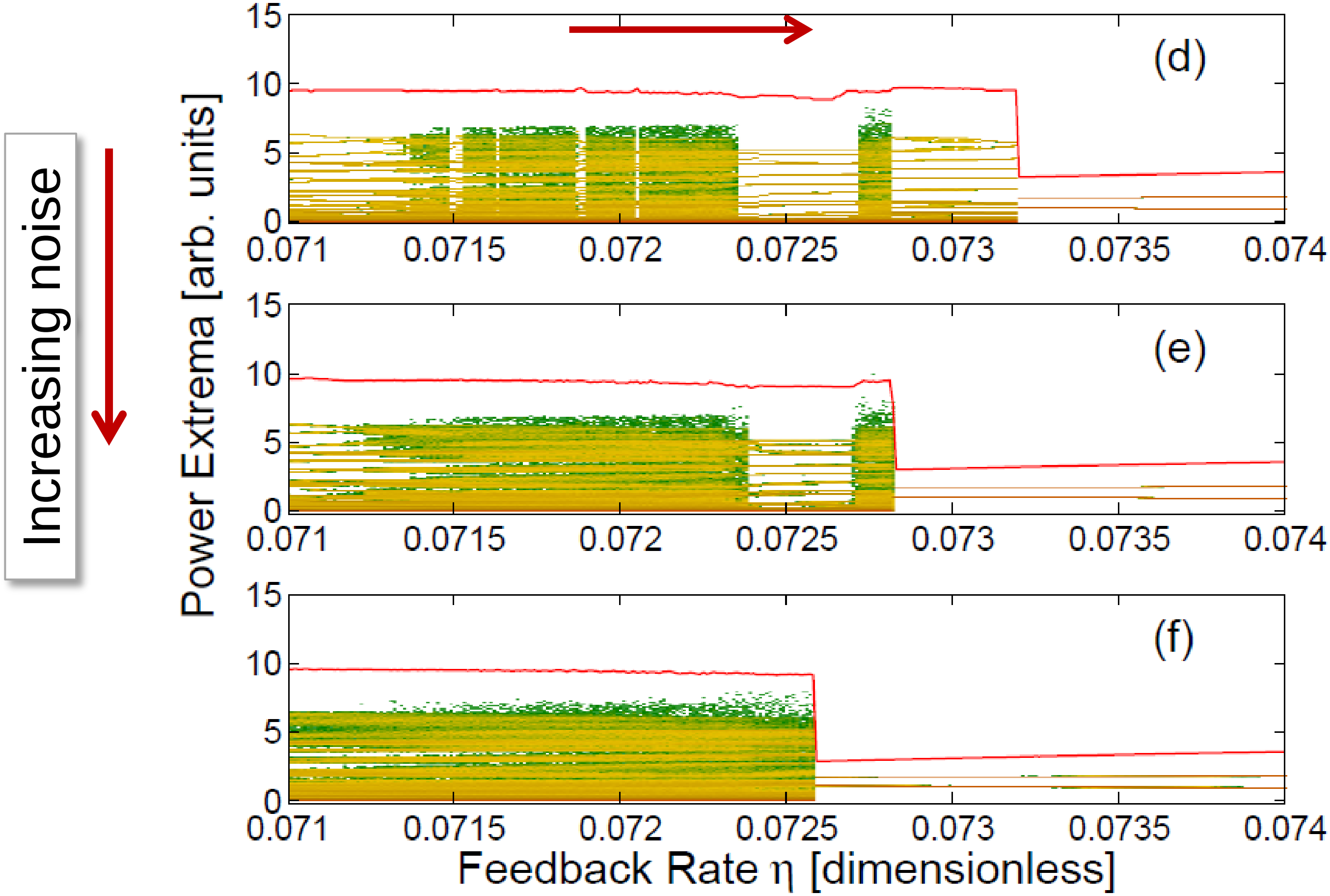
Influence of noise

- Transition 1: noise induced extreme pulses



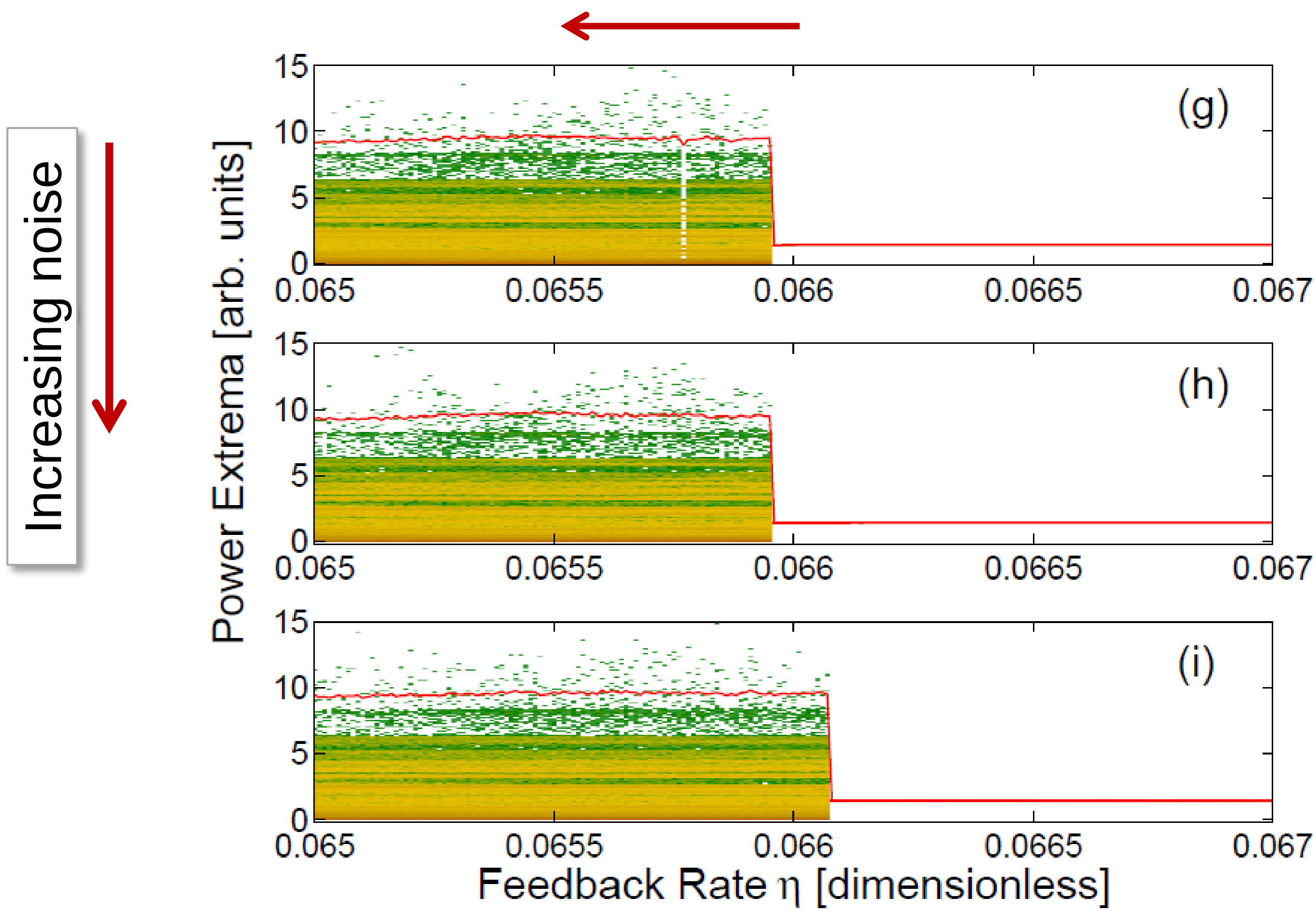
Influence of noise

- **Transition 2: noise advances the switching**



Influence of noise

- **Transition 3: noise advances the switching**



Summary

Optically injected semiconductor lasers:

- Intensity pulses characterized by long-tailed histograms; giant rare pulses interpreted as Rogue Waves.
- Different types of chaos identified: without and with rogue waves.
- **Origin** of RWs: deterministic. An external crises-like process enables access to the region in phase space where RWs can be triggered.
- **Predictability**: in our system RWs can be predicted with some anticipation.
- **Control**: noise strongly affects their probability of occurrence.

External-cavity lasers:

- Similar results, intermittency is the route to extreme pulses.

THANK YOU FOR YOUR ATTENTION !

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

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