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Grup de Recerca en Dinàmica No Lineal, Òptica No Lineal i Làsers
UNIVERSITAT POLITÈCNICA DE CATALUNYA

Rogue waves in optically injected lasers: Origin, predictability and suppression

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Workshop 'Nonlinear dynamics in semiconductor lasers', Berlin, September 12-14 2012

Outline

- Introduction: extreme events, ocean rogue waves, & optical rogue waves.
- Semiconductor laser with cw optical injection: experimental observations & numerical results.
- Summary and conclusions.

Rogue waves are rare and extreme events

- Ocean rogue waves, also referred to as “freak waves”, are several times the average height of surrounding waves and have steep, fast rising and fast falling sides, like “a wall of water”.

- They can develop suddenly even in calm and apparently safe seas.

- They have been responsible of several boat accidents.

Optical rogue waves: young & active research field

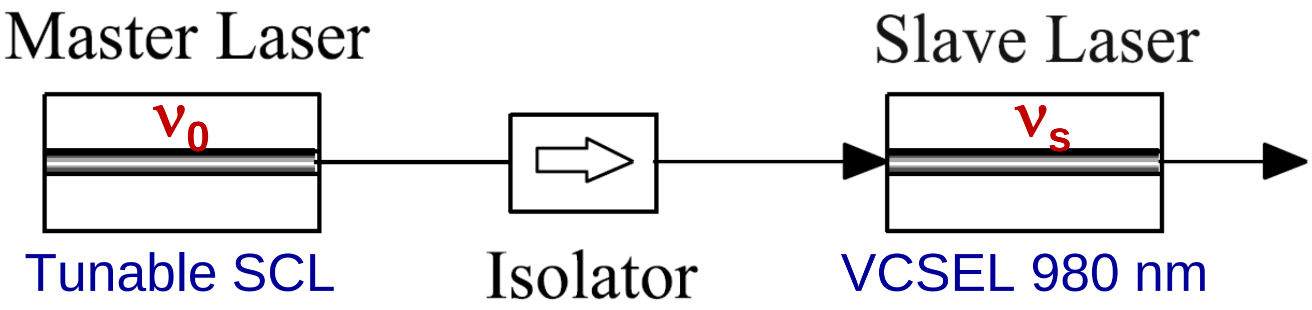
- RWs represent a major challenge for the design of robust off-shore platforms for the oil and gas industry, and off-shore wind farms.
- They have been identified not only in oceanography but also in many fields (optics, acoustics, financial markets…)
- In optics:
  - D. R. Solli et al, *Optical rogue waves*, Nature 450, 1054 (2007)
  - J. M. Dudley et al, *Harnessing and control of optical rogue waves in supercontinuum generation*, Opt. Express 16, 3644 (2008).
  - A. Mussot et al, *Observation of extreme temporal events in CW-pumped supercontinuum*, Opt.Express 17, 17010 (2009).
  - F. T. Arecchi et al, *Granularity and in homogeneity are the joint generators of optical rogue waves*, Phys. Rev. Lett. 106, 153901 (2011).
  - M. Kovalsky et al, *Extreme events in the **Ti:sapphire laser***, Opt. Lett 36, 4449 (2011).
  - S. Randoux and P. Suret, *Experimental evidence of extreme value statistics in **Raman fiber lasers***, Opt. Lett 37, 500 (2012).
  - A. Zaviyalov et al, *Rogue waves in **mode-locked fiber lasers***, PRA 85, 013828 (2012).
  - F. Baronio et al, *Solutions of the vector nonlinear Schrodinger equations: evidence for deterministic rogue waves*, Phys. Rev. Lett. 109, 044102 (2012).

Rogue waves in semiconductor lasers

- We have recently shown experimentally and numerically that continuous-wave optically injected semiconductor lasers can display huge intensity pulses that we identified as deterministic rogue waves.
- These pulses can be predicted with a certain anticipation time.
- They are generated by an external crisis-like process.
- Noise can be employed either to enhance or to diminish their probability of occurrence.

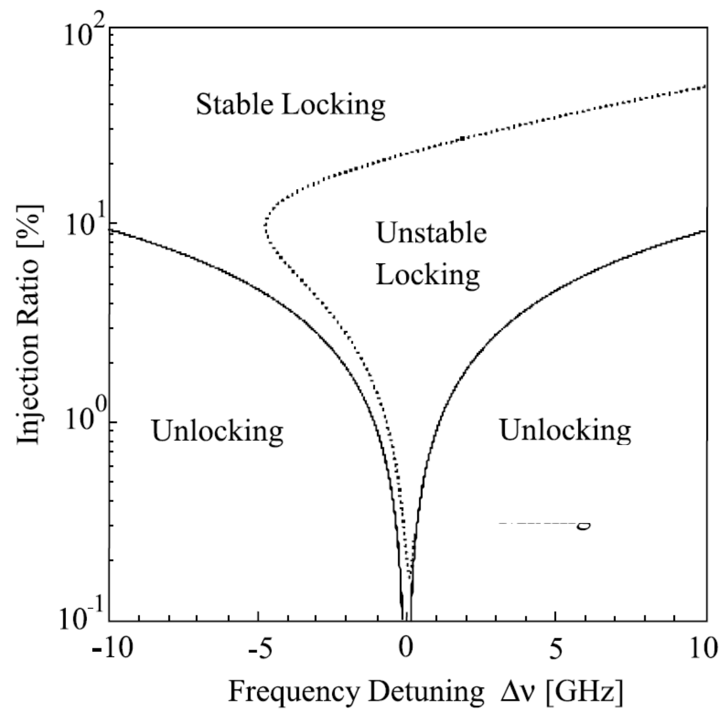
C. Bonatto, et al, *Deterministic optical rogue waves*, Phys. Rev. Lett. 107, 053901 (2011).

SCLs with cw optical injection



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



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

THE EUROPEAN
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Regular Article

Labyrinth bifurcations in optically injected diode lasers

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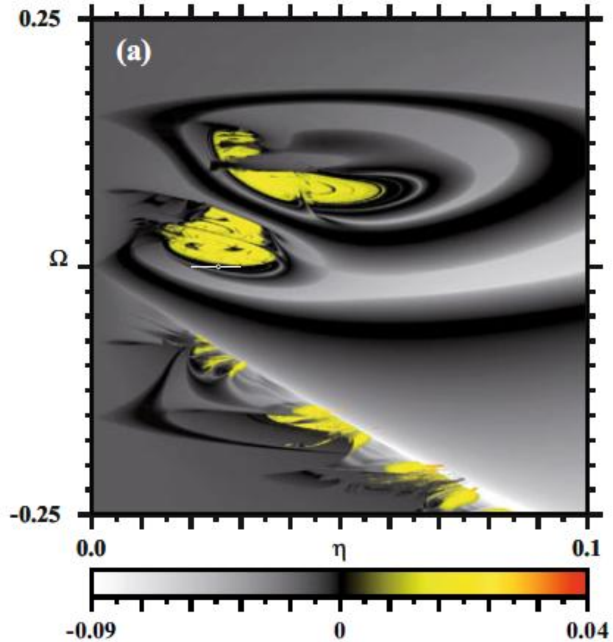
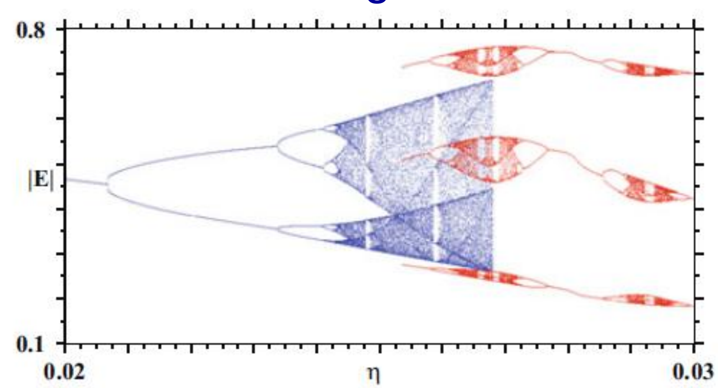
Lyapunov diagram



Bifurcation diagram

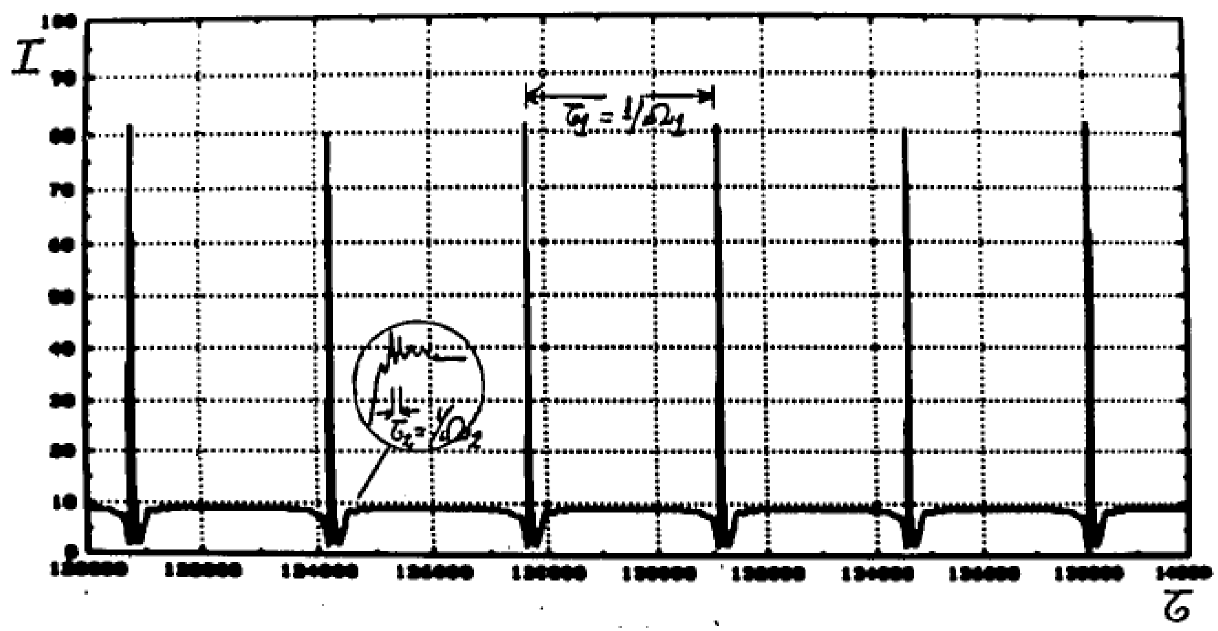


Also Rogue Waves?

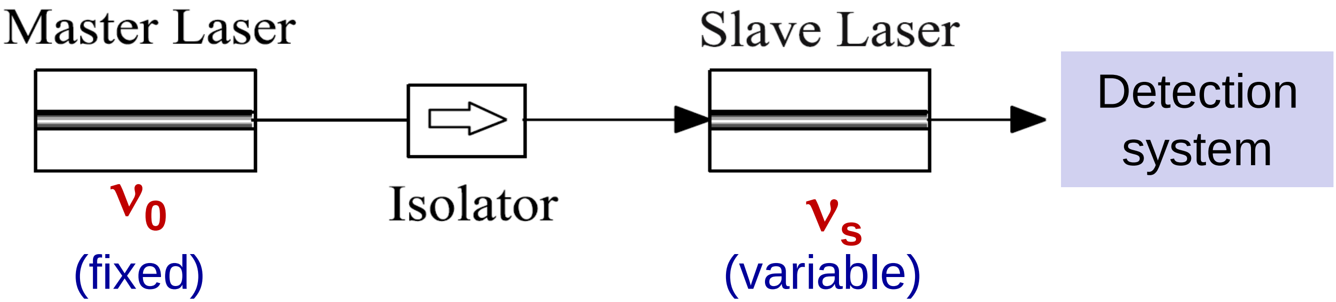
Instabilities in lasers with an injected signal

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 control parameters



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**

ν_s **= g(Temp) = f (I)**

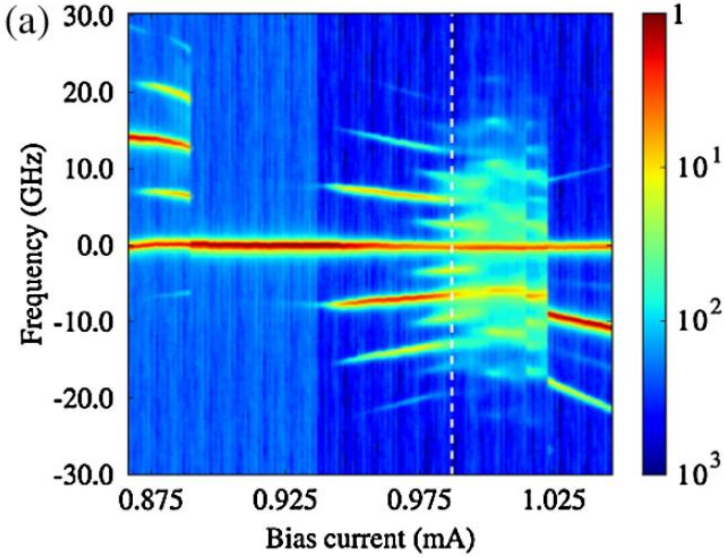
(f approximately linear)

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

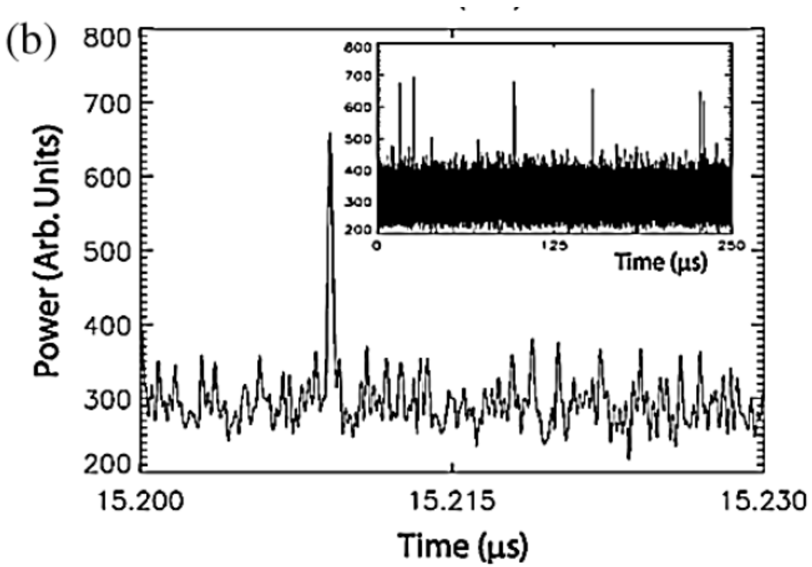
- **Intensity time - series (with a 6 GHz oscilloscope)**
- **Intensity Fourier spectrum (spectrum analyzer)**

Experimental observations

Fourier spectrum of the laser intensity



Time series of the laser intensity



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

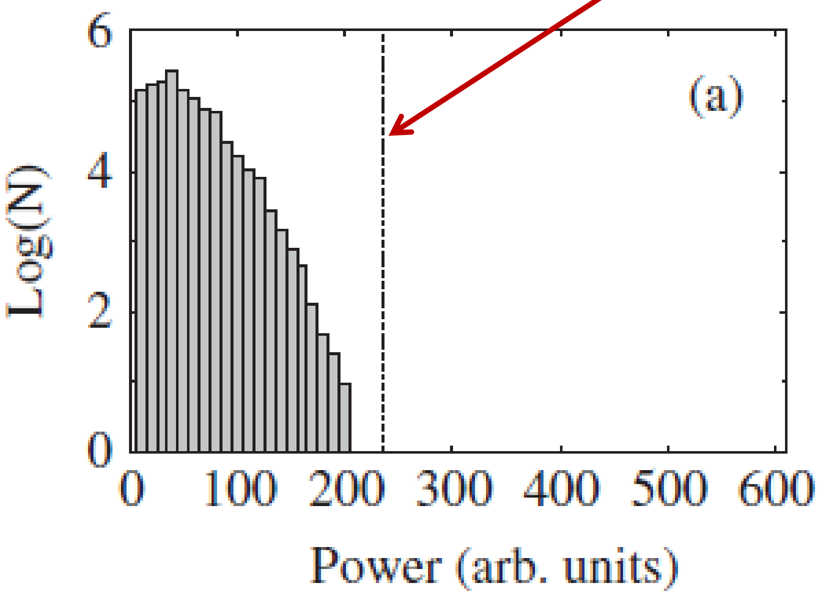
Five regions as I increases:

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

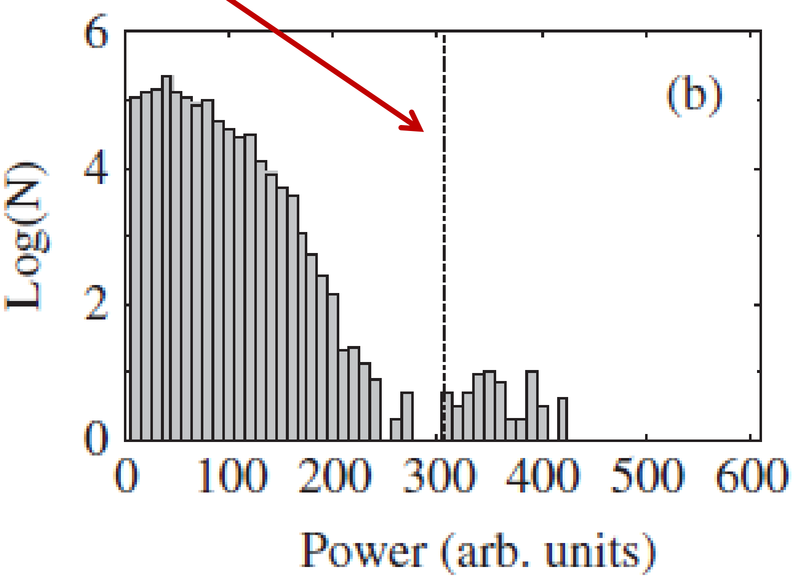
C. Bonatto et al, PRL 107, 053901 (2011)

Histograms of pulse amplitude (log scale)

Border = mean value + 8 σ



I = 0.972 mA



I = 0.976 mA

Single-mode rate-equation model

- The *complex* optical field, **E** (photon number $\propto$ **$|E|^2$**)
- The carrier density, **N**

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

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

optical injection

η: injection strength

$\Delta\omega$: frequency detuning

spontaneous emission noise

Solitary laser

4 parameters: α τ_p τ_N μ

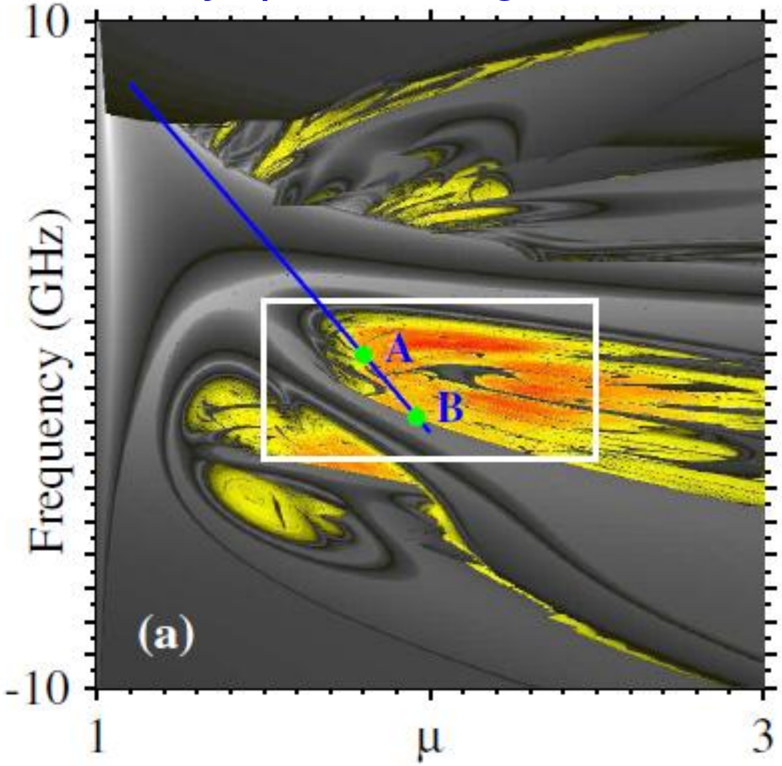
Typical parameter values:

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

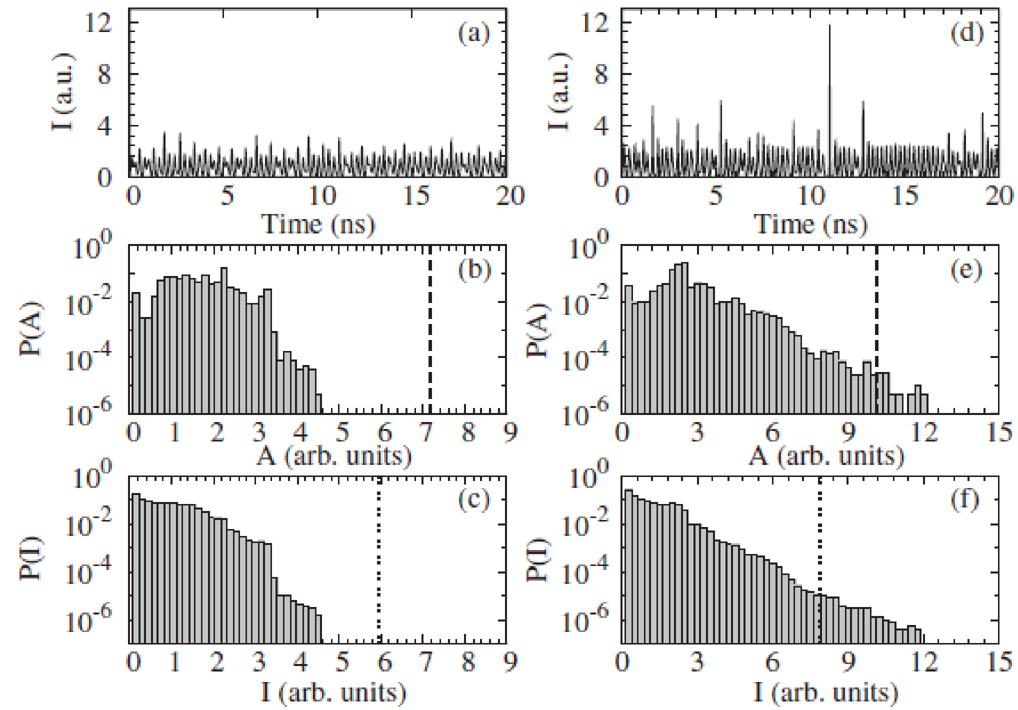
μ: normalized pump current parameter

Deterministic simulations

Lyapunov diagram



Slave laser pump current

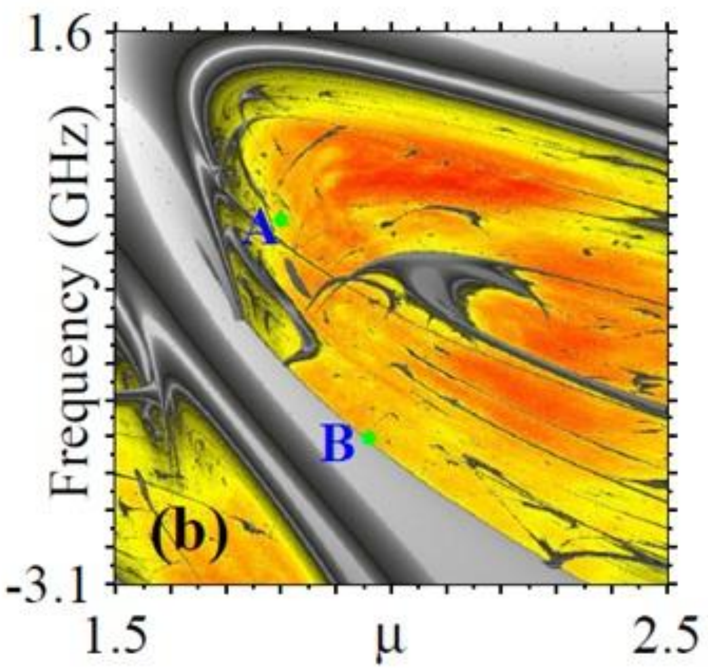


Point A: No RWs

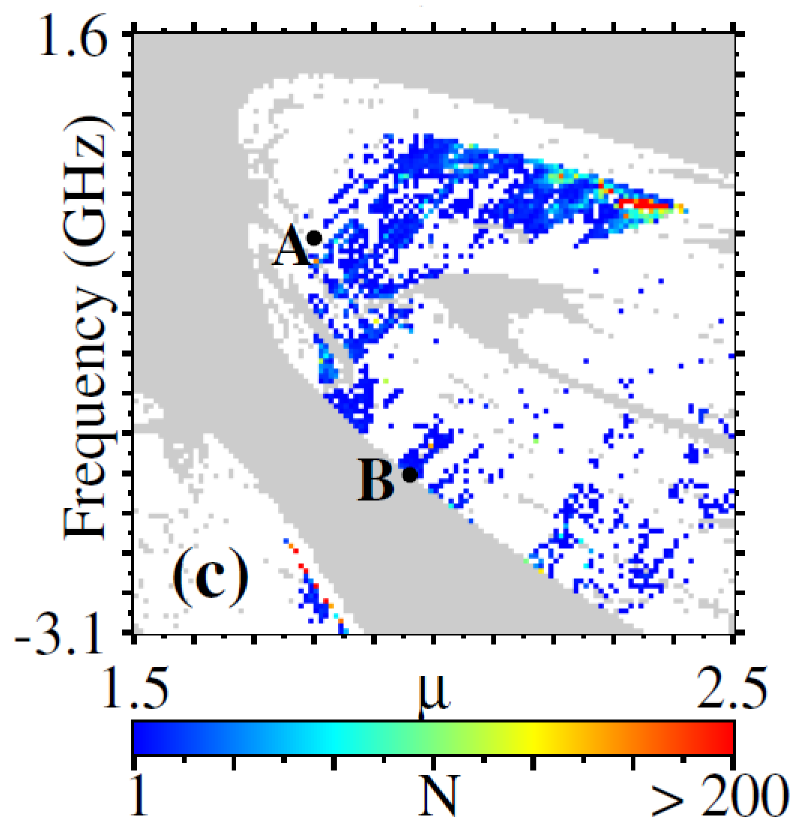
Point B: RWs

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

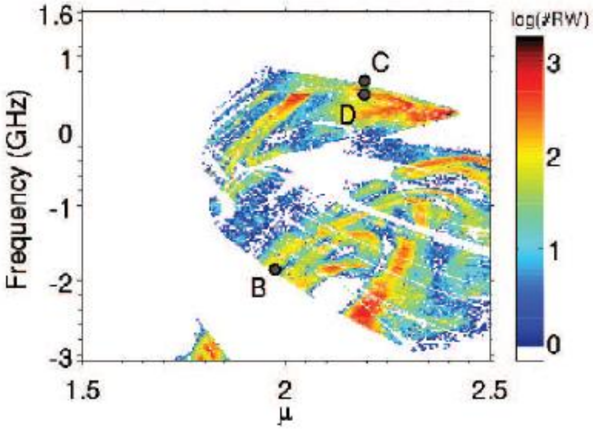
Lyapunov diagram



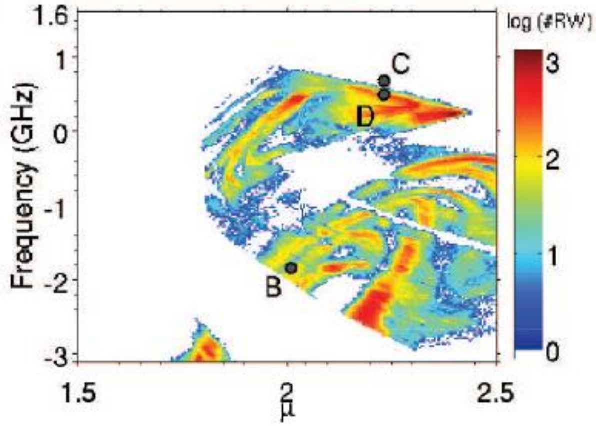
Number of RWs



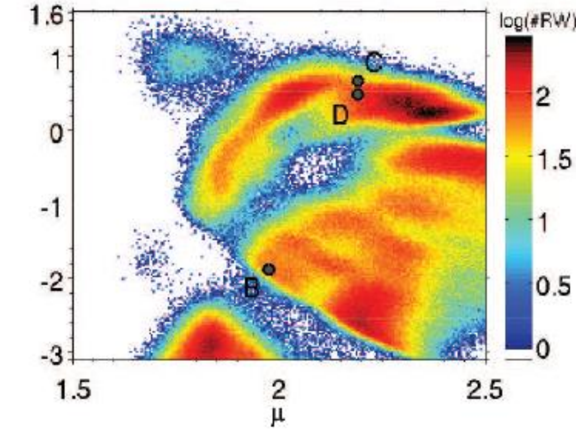
Influence of spontaneous emission noise



$\beta_{sp} = 0$

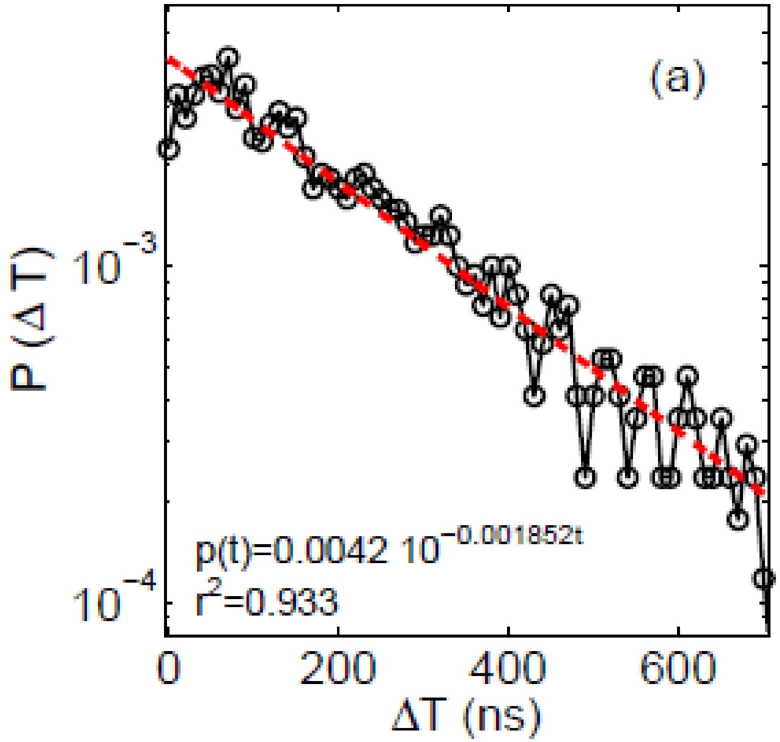


$\beta_{sp} = 10^{-4}$

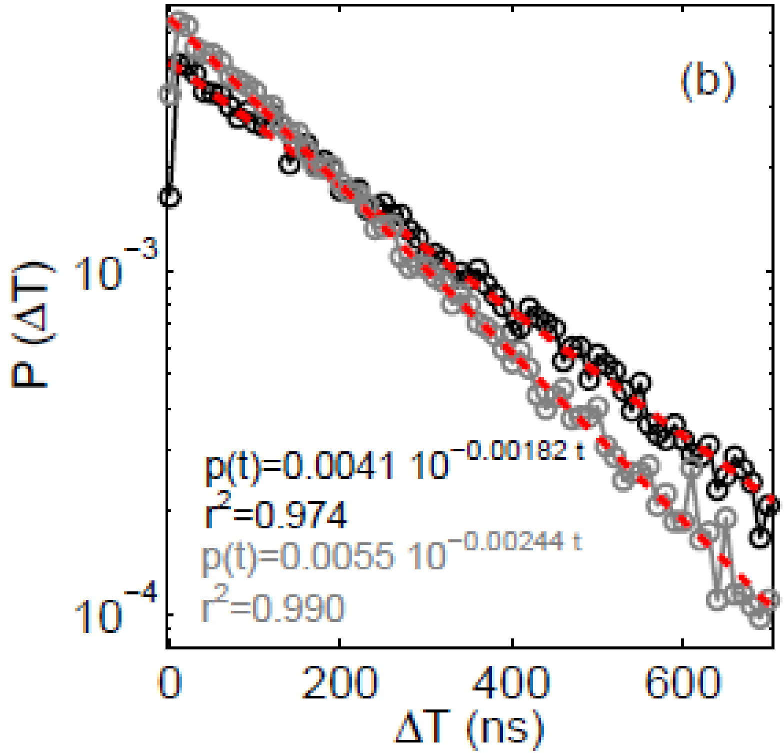


$\beta_{sp} = 10^{-2}$

Statistics of the RW waiting time



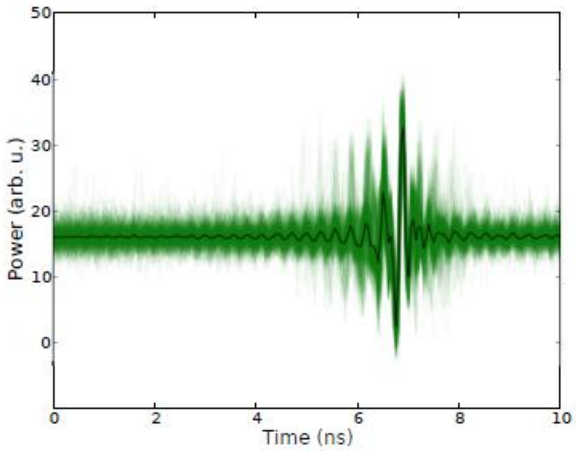
Experimental data



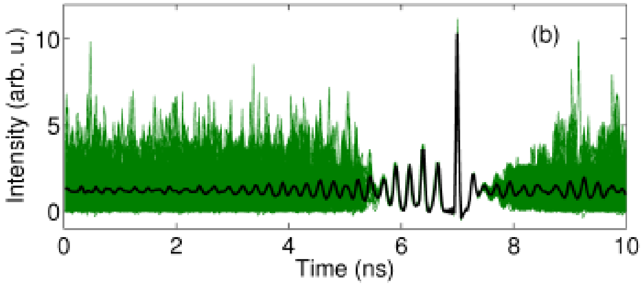
Deterministic & stochastic simulations (β_{sp} = 10^{-4})

RW predictability

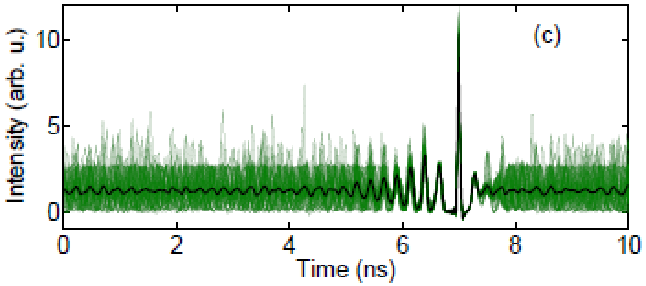
Measured intensity time traces (500 RWs)



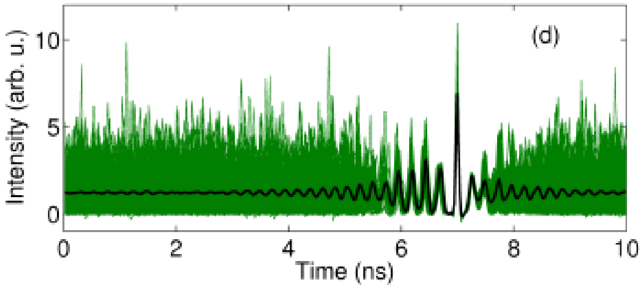
Simulated time traces



<H>+8σ
$\beta_{sp} = 0$
459 RWs



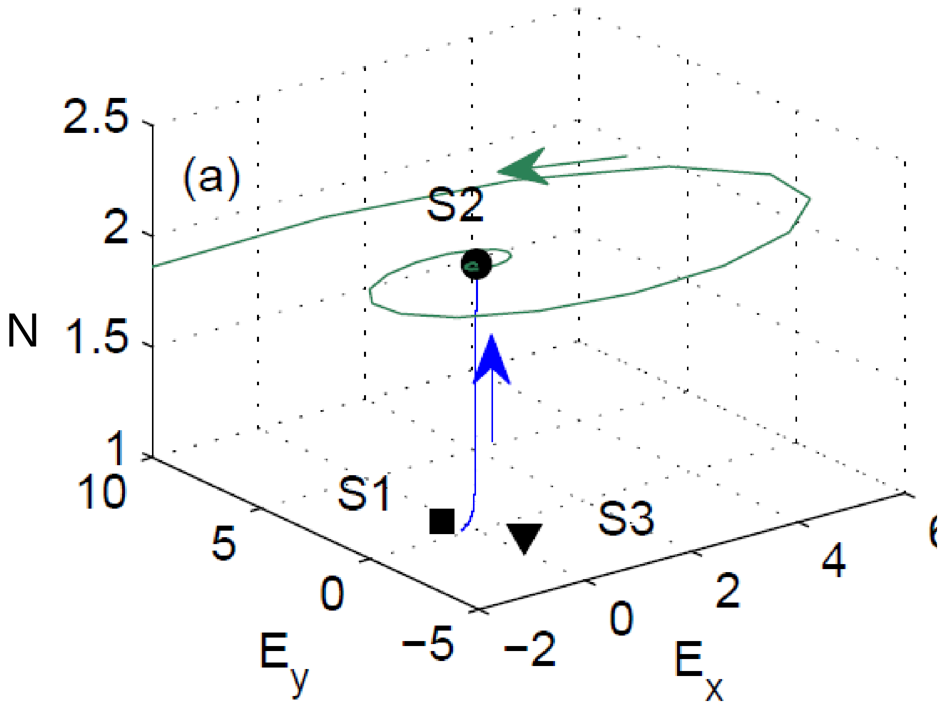
<H>+8σ
$\beta_{sp} = 10^{-2}$
53 RWs

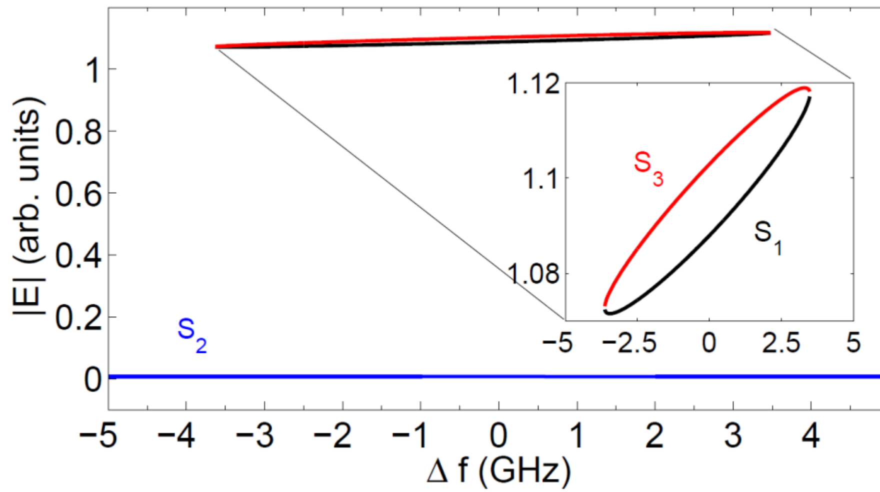


<H>+4σ

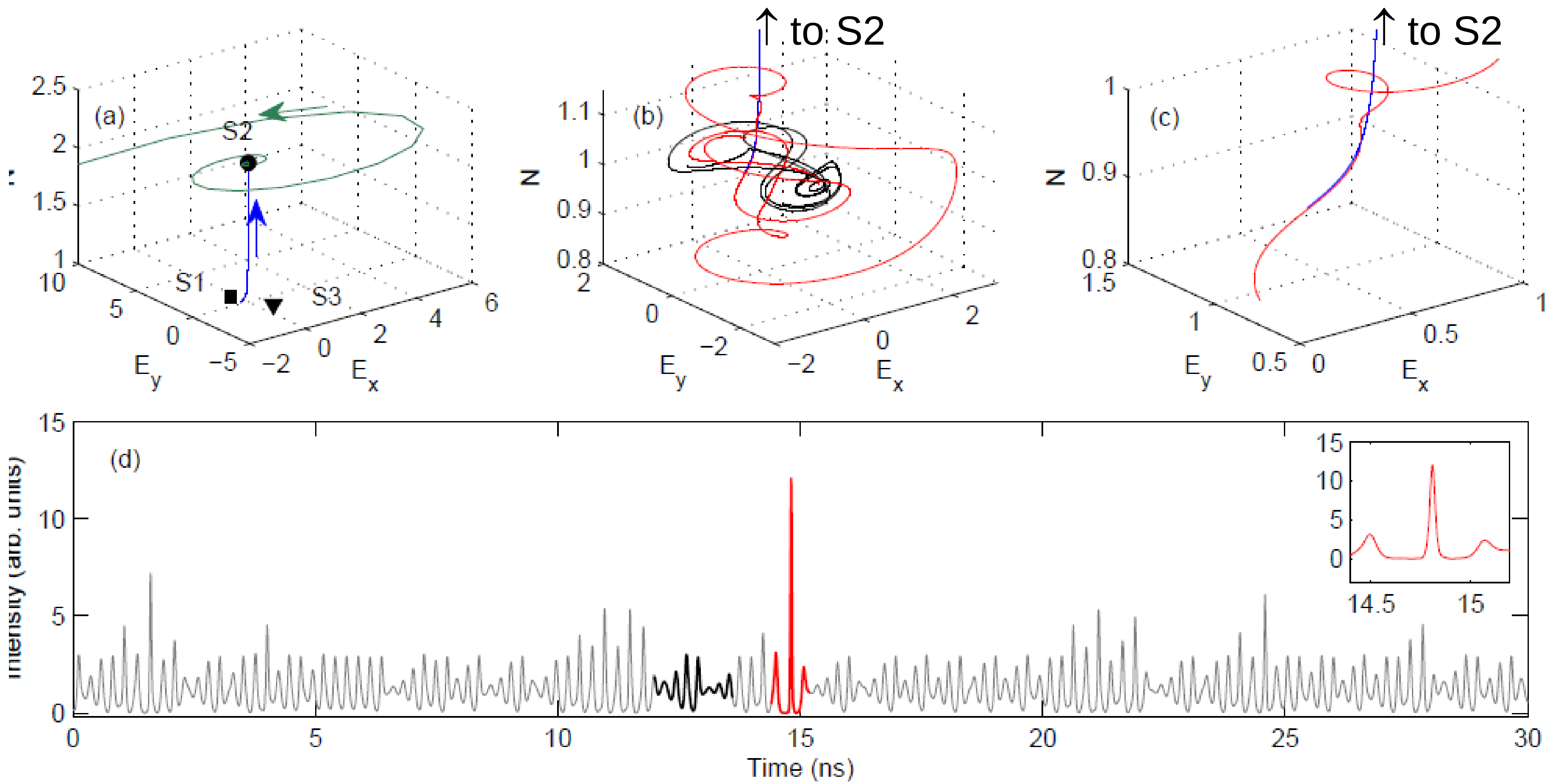
What triggers a RW pulse?

Model fixed points in the phase space



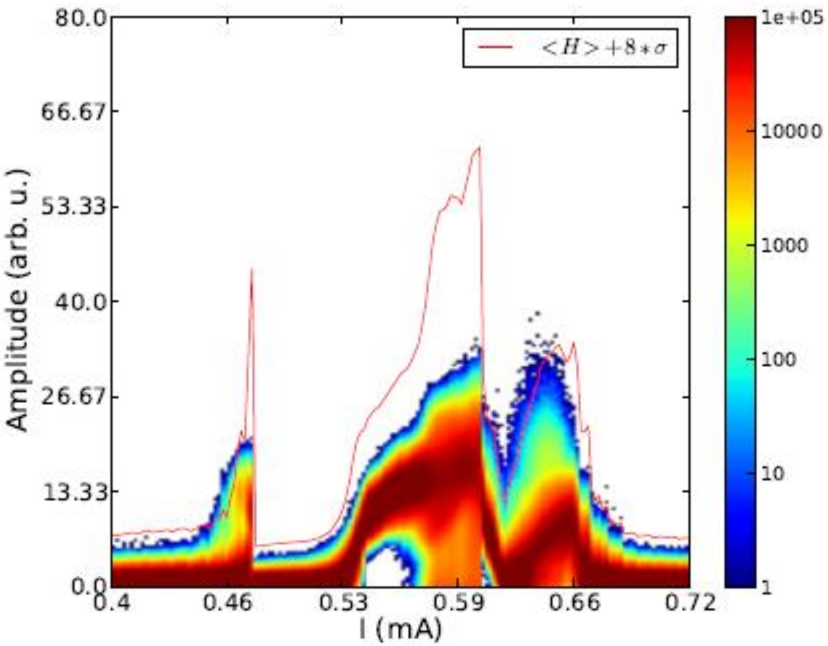


What triggers a RW pulse?

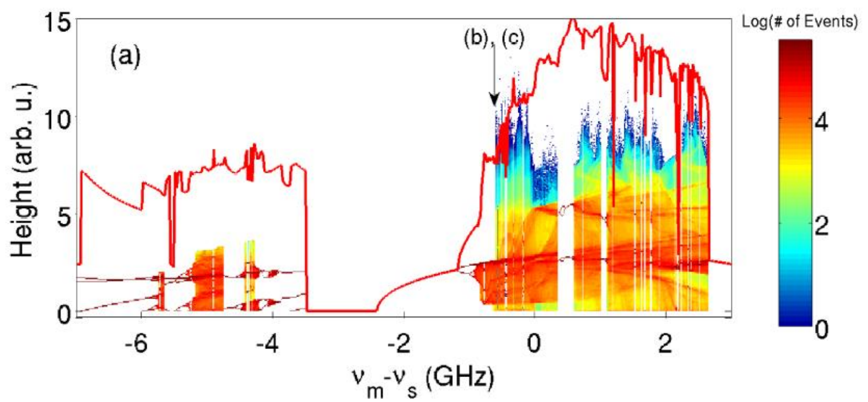


A Rogue Wave is triggered whenever the trajectory closely approaches the unstable manifold of S2.

Bifurcation diagram: chaos with RWs and chaos without them

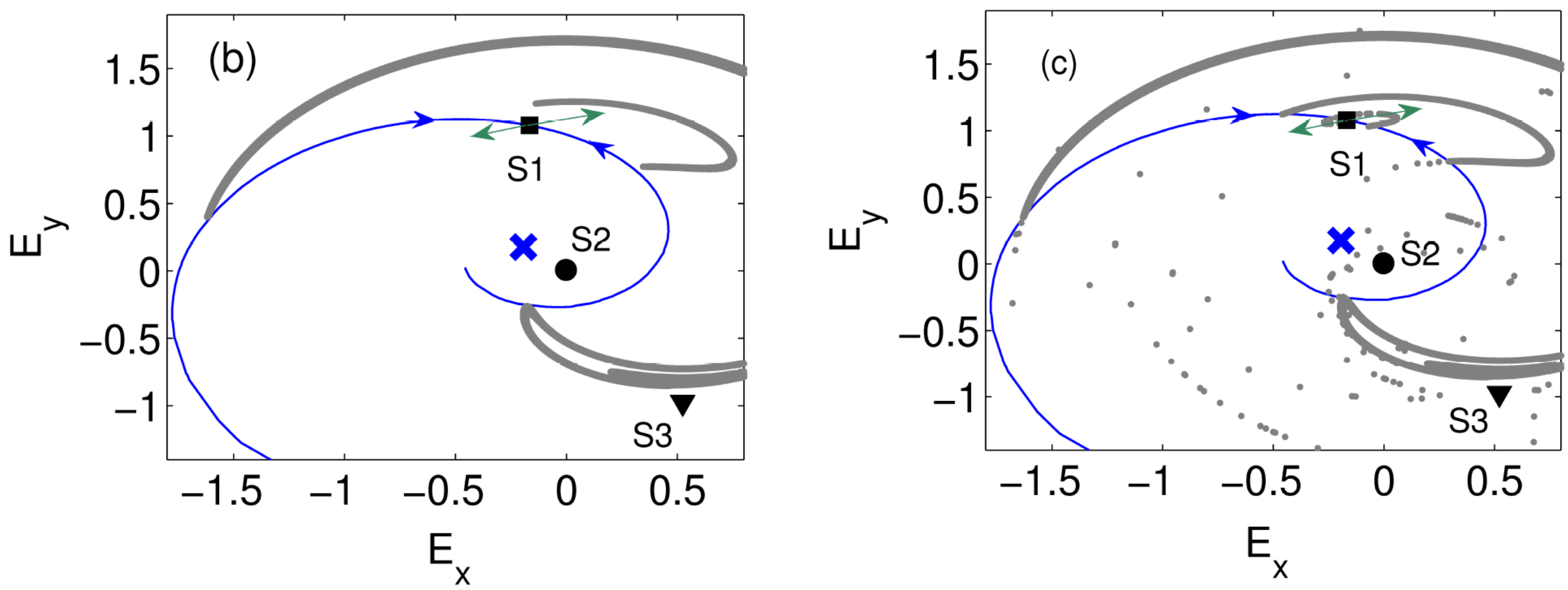


Experimental data: amplitude of the intensity pulses



Numerical simulations

Why chaos with RWs and chaos without them?



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

Summary and conclusions

- Giant intensity pulses were interpreted as Rogue Waves.
- Different types of chaos: without and with rogue waves.
- RWs characterized by non-gaussian histograms with long tails.
- Deterministic nature of these rare and extreme events.
- They can be predicted with some anticipation.
- Noise strongly affects their probability of occurrence.
- An external crises-like process enables access to the region in phase space where RWs can be triggered.