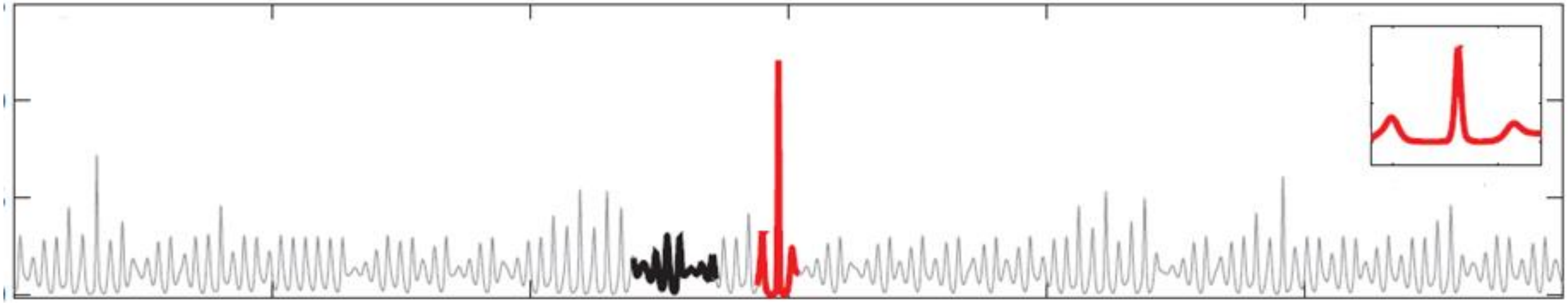

Influence of Periodic Modulation in Rare and Extreme Optical Pulses

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2015 SIAM Conference on Dynamical Systems
MS33: Rare Events in Stochastic Systems

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What is a rogue wave?

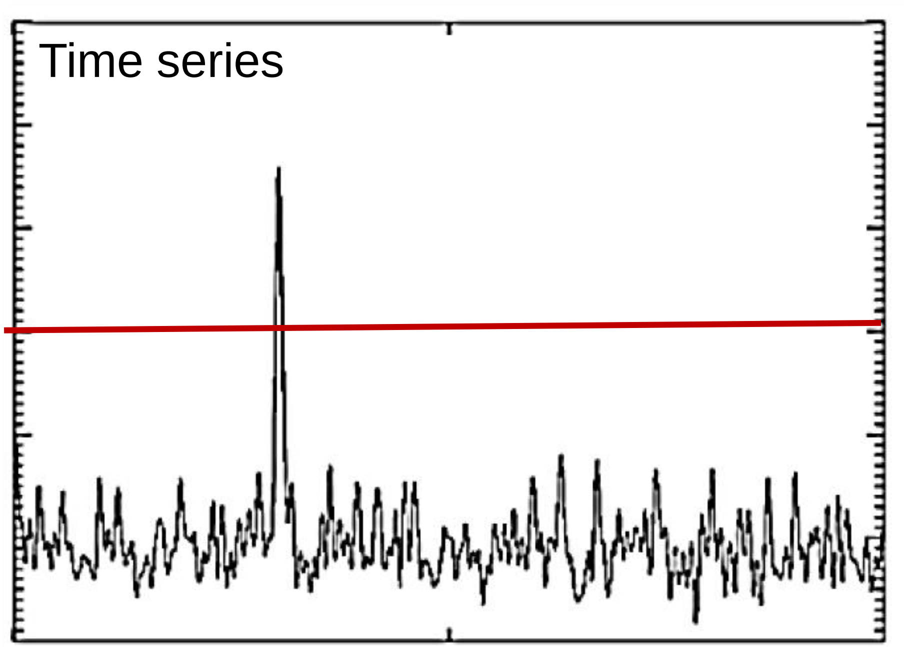
RWs are rare, ultra-high waves that fall outside (and far from) the main part of long-tailed probability distributions.

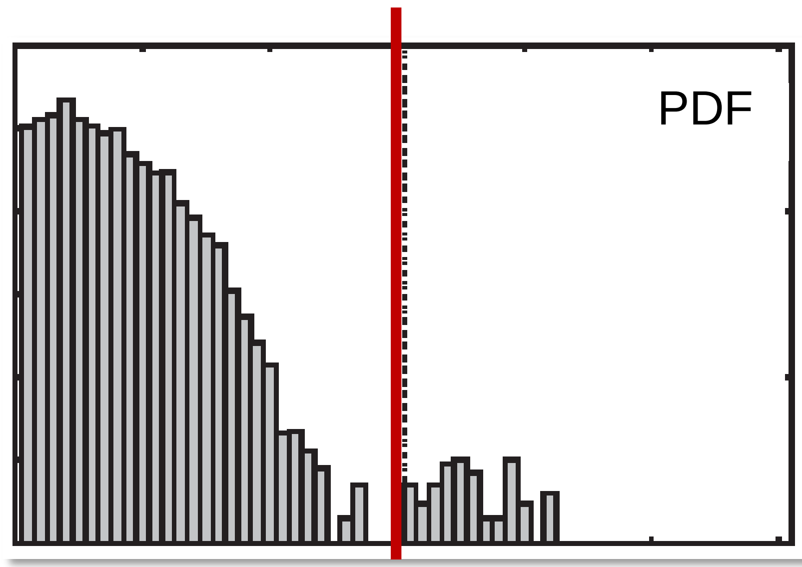
The Great Wave of Kanagawa, Katsushika Hokusai. Source: Wikipedia

Two more precise rogue wave definitions

- A RW: above **twice** the significant wave height (SWH).
  SWH = <highest 1/3 waves> that occur over a certain period of time.

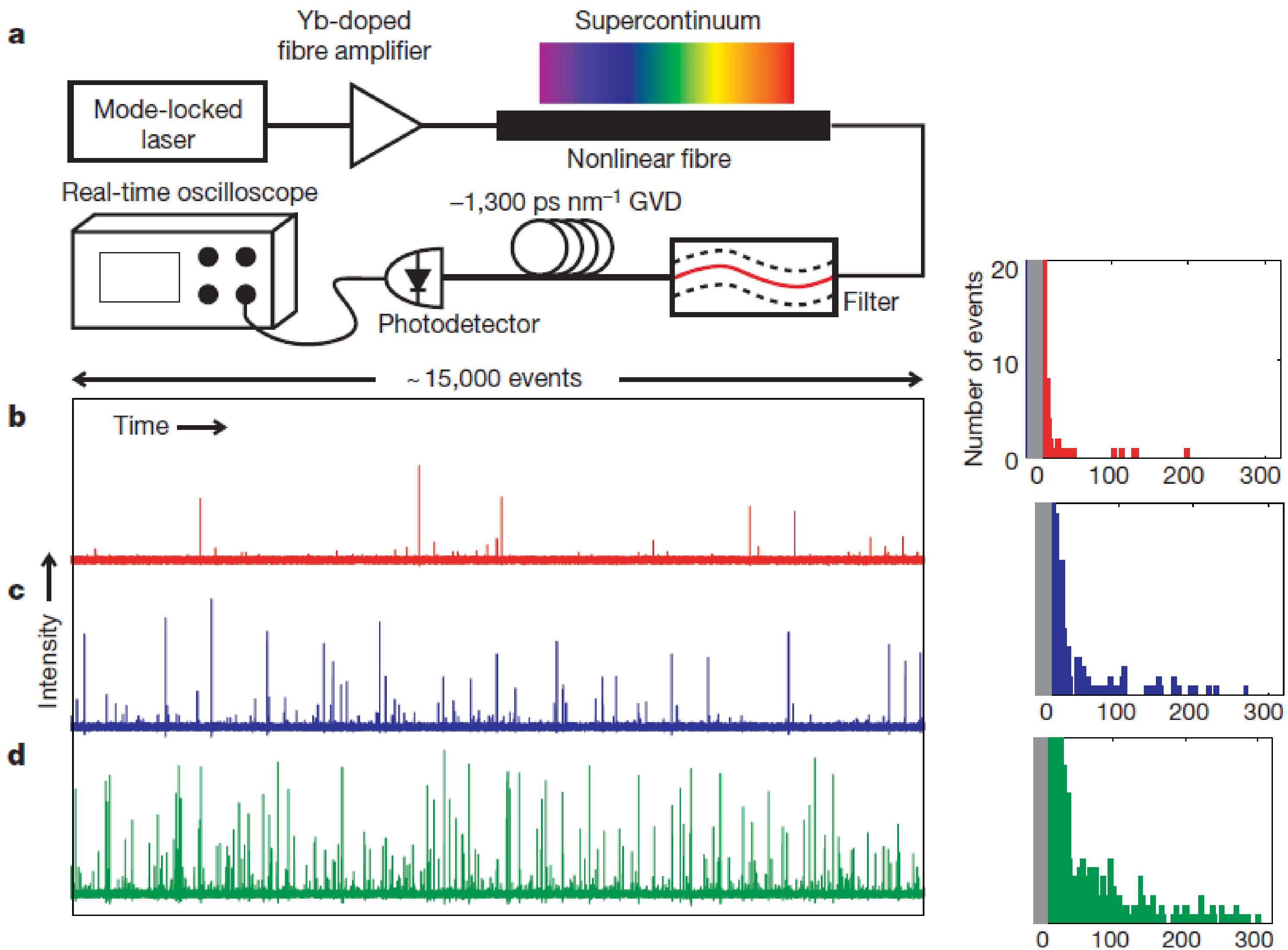
- A RW: above a certain threshold (<A> + **4-8** σ)





Optical rogue waves

Rare and extreme intensity pulses



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

Since then, optical rogue waves are attracting increasing attention

You searched for: **TOPIC:** (optical rogue waves) **...More**

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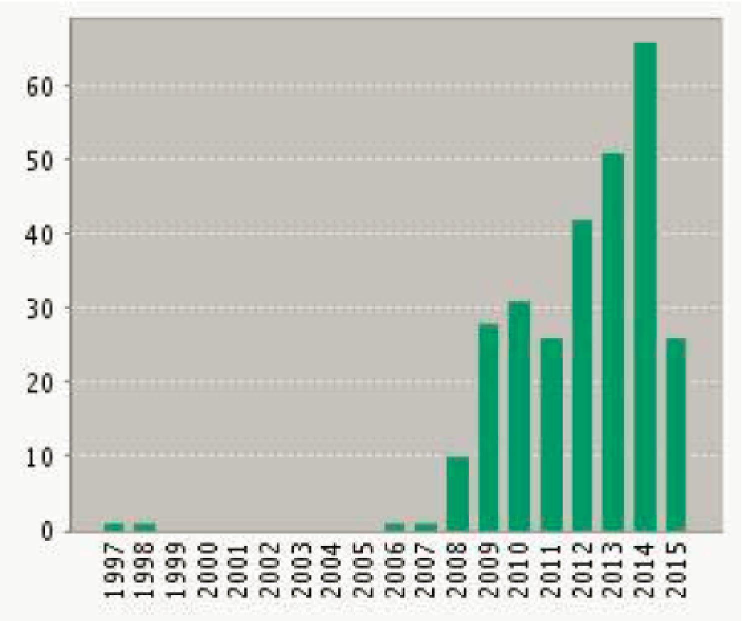
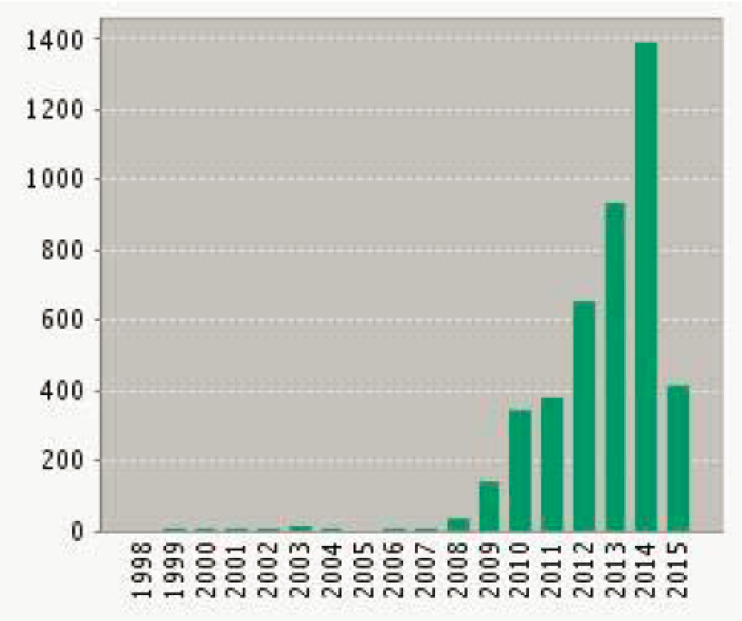
Published Items in Each Year



The latest 20 years are displayed.

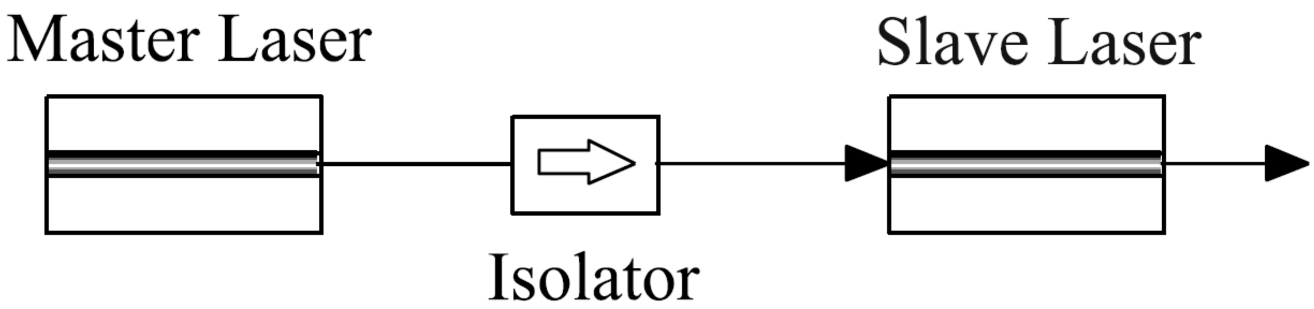
Citations in Each Year



The latest 20 years are displayed.

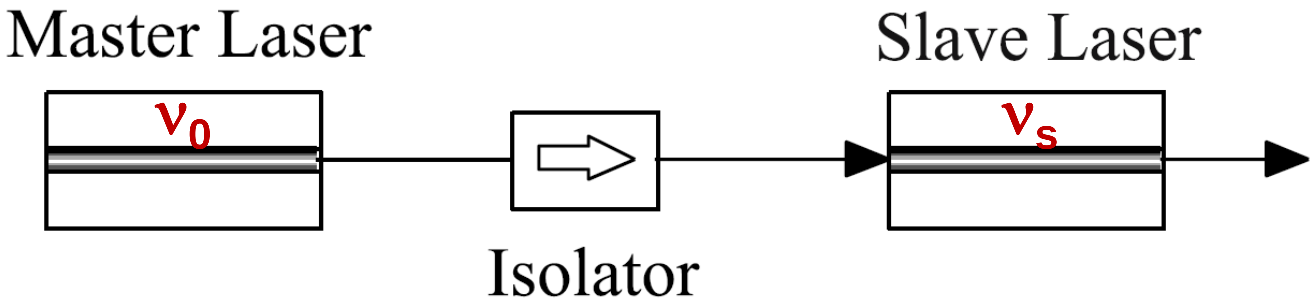
RWs in semiconductor lasers

Optically injected semiconductor lasers provide an inexpensive and controllable setup to study RWs

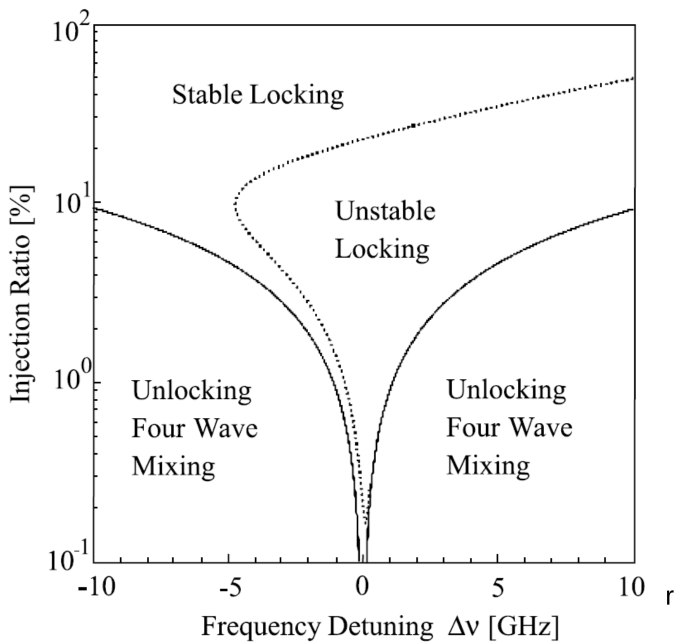


Detection system (photo detector, oscilloscope, spectrum analyzer)

Key parameters and main dynamical regimes



- Injection ratio
- Frequency detuning $\Delta\nu = \nu_s - \nu_0$



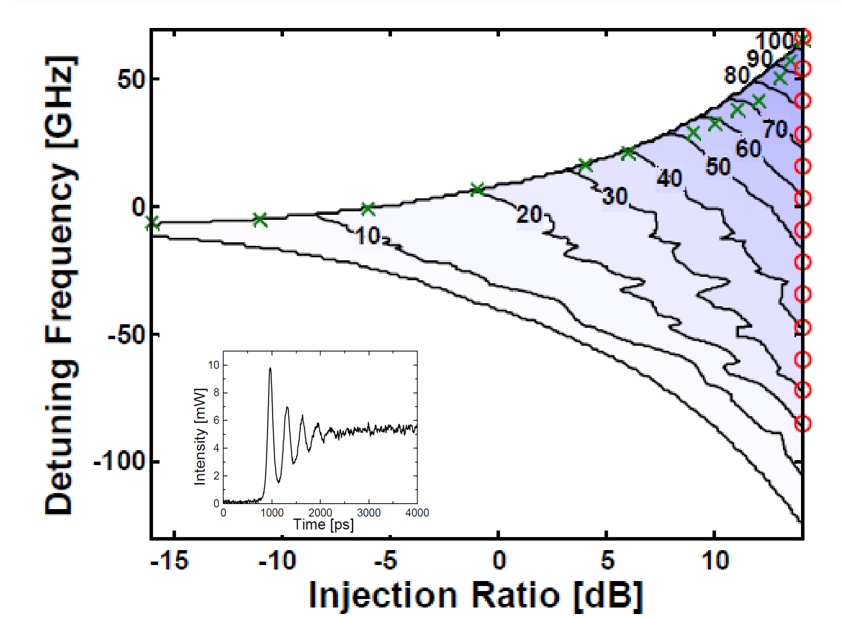
- Regimes:
  - Stable locking: stable output at the frequency of the master laser
  - Regular oscillations
  - Excitability and Chaos

Adapted from J. Ohtsubo, *Semiconductor Lasers: Stability, Instability and Chaos*. Springer, 2006.

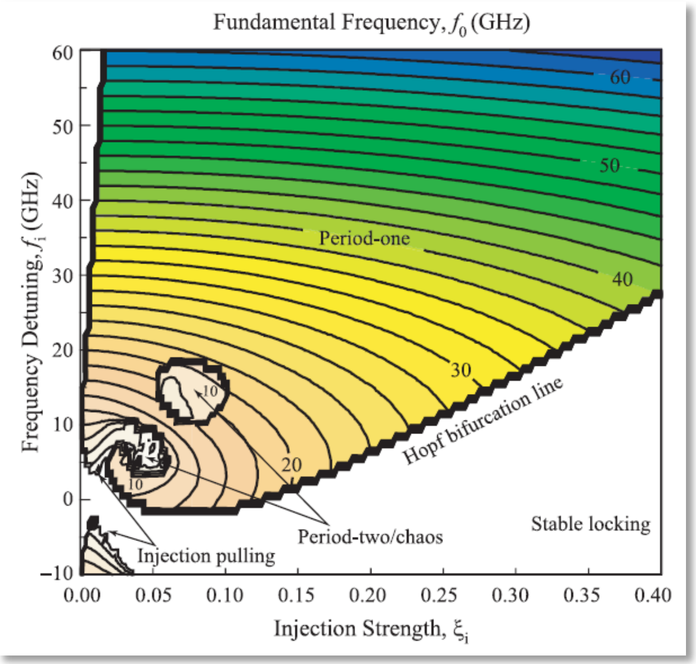
Practical use of optical injection

- Inside the locking region: increased resonance frequency and modulation bandwidth.

- Outside the locking region: regular oscillations, with tunable frequency (controlled by the injection parameters).



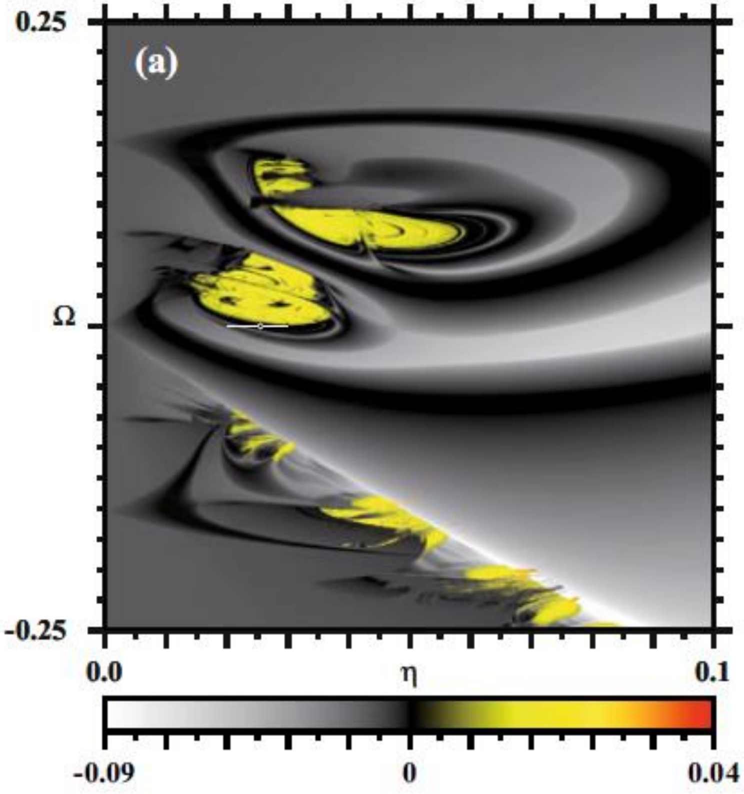
E. K. Lau et al, Opt. Express 16, 6609 (2008)



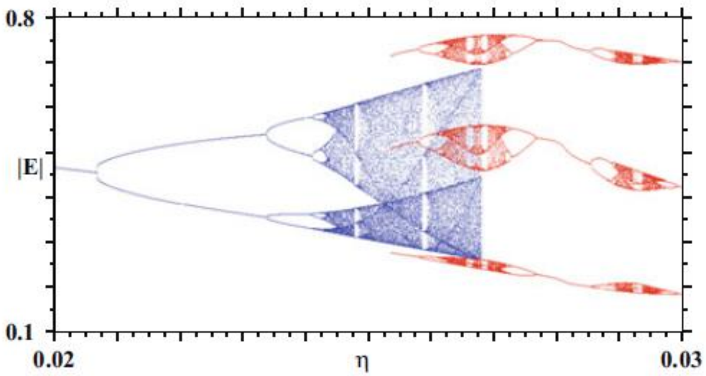
S-C Chan et al, Optics Express 15, 14921 (2007)

Chaotic oscillations, bistability, etc.

Lyapunov diagram



Bifurcation diagram



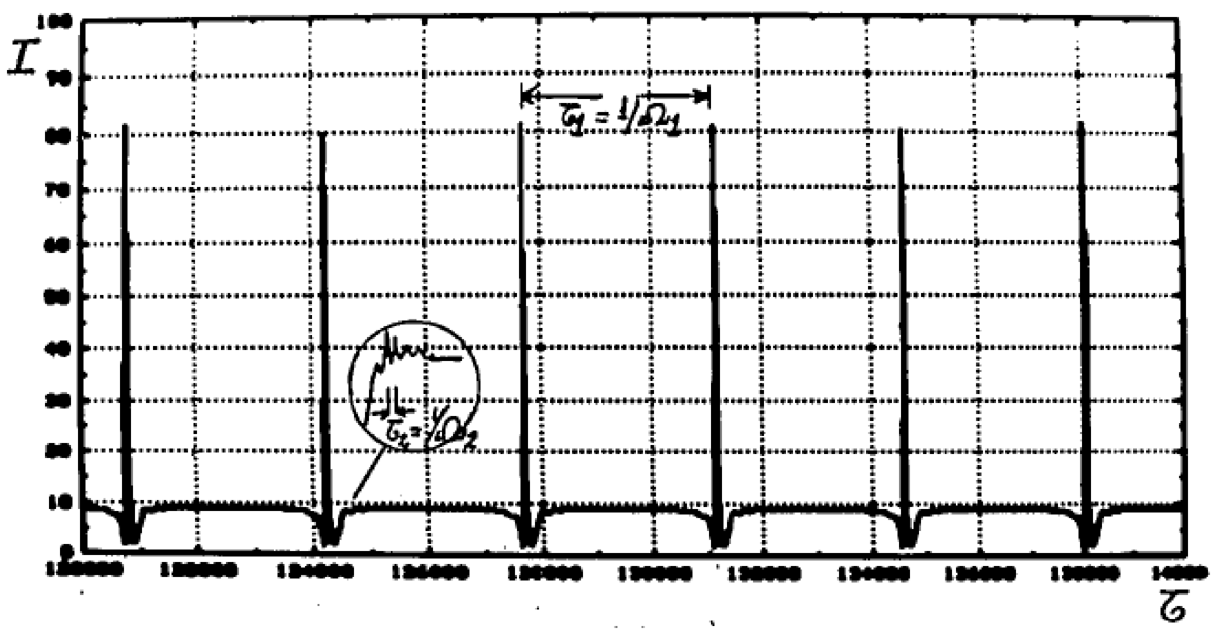
V. Kovanis et al, EPJD 58, 181 (2010)

Also RWs?

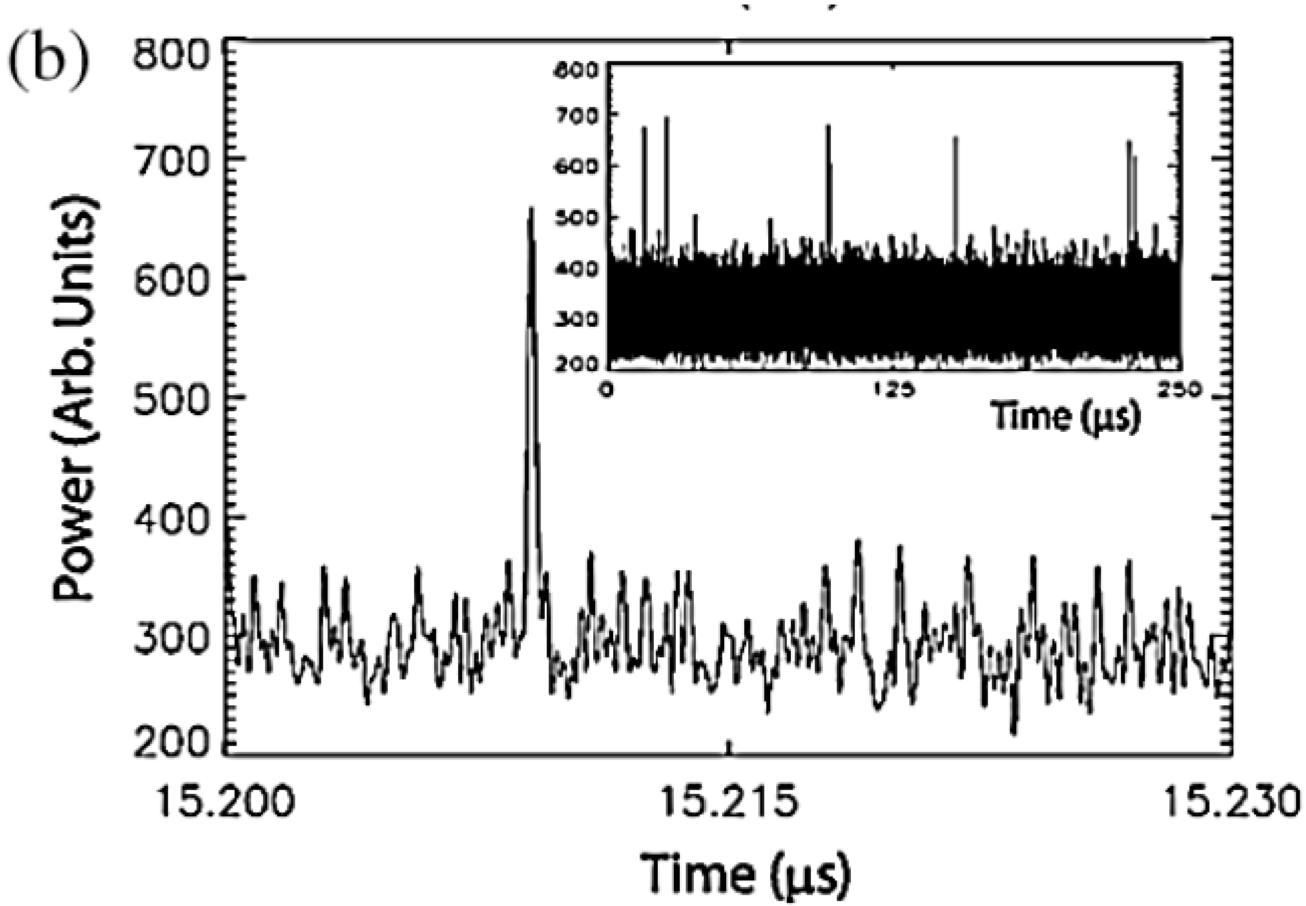
Instabilities in lasers with an injected signal

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 observation



C. Bonatto, M. Feyereisen, S. Barland, M. Giudici, C. Masoller, J. R. Rios Leite, and J. R. Tredicce, "*Deterministic optical rogue waves*", PRL 107, 053901 (2011)

Governing equations

- Complex field, **E** (photon number $\propto$ **$|E|^2$**)
- Carrier density, **N**

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

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

optical injection

P_{inj}: injection strength

spontaneous emission

$\Delta\omega$: frequency detuning

Solitary laser

β_{sp}: noise strength

μ: pump current parameter

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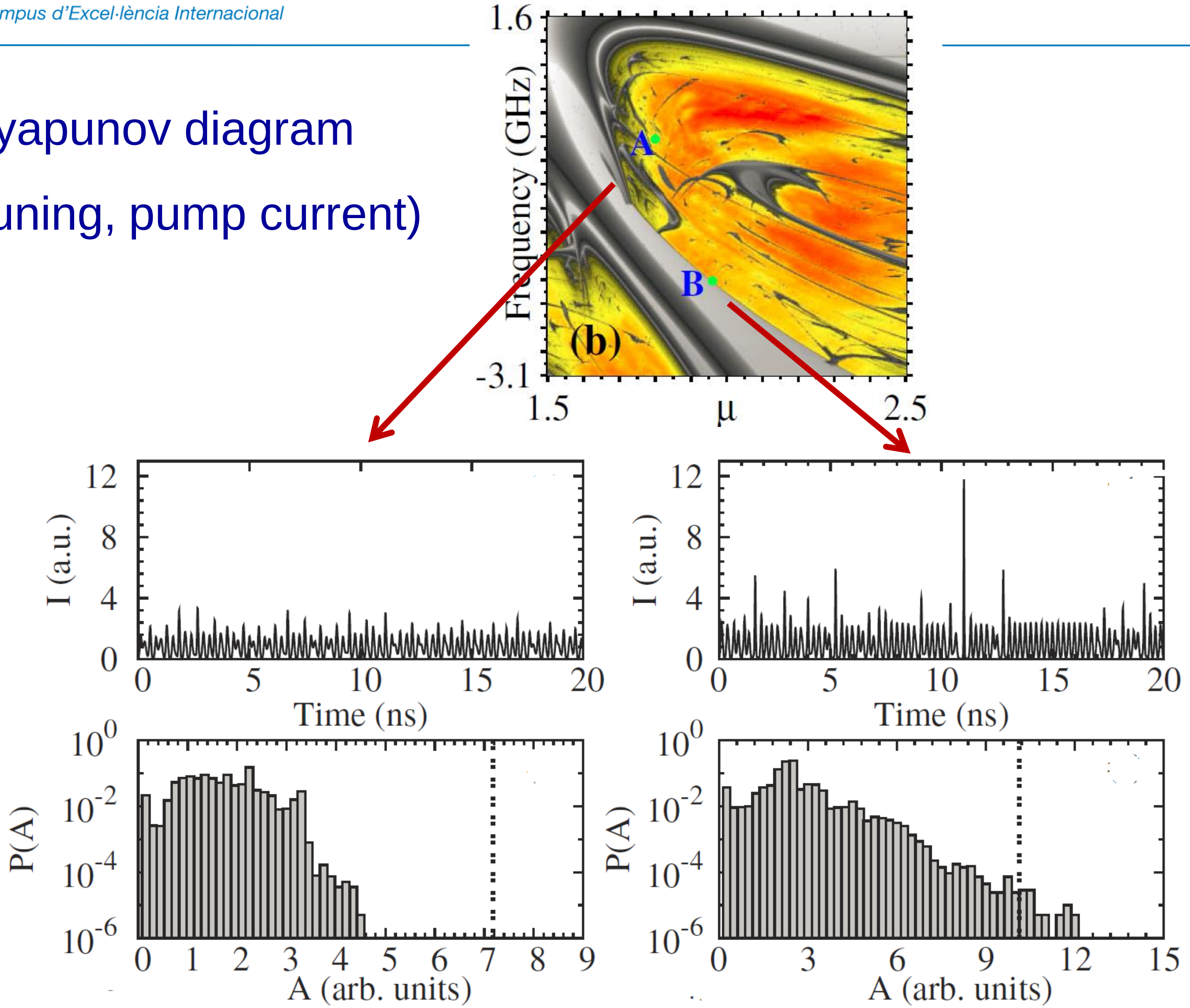
Deterministic simulations (β_{sp}=0)

Lyapunov diagram

(detuning, pump current)



Chaos without RWs

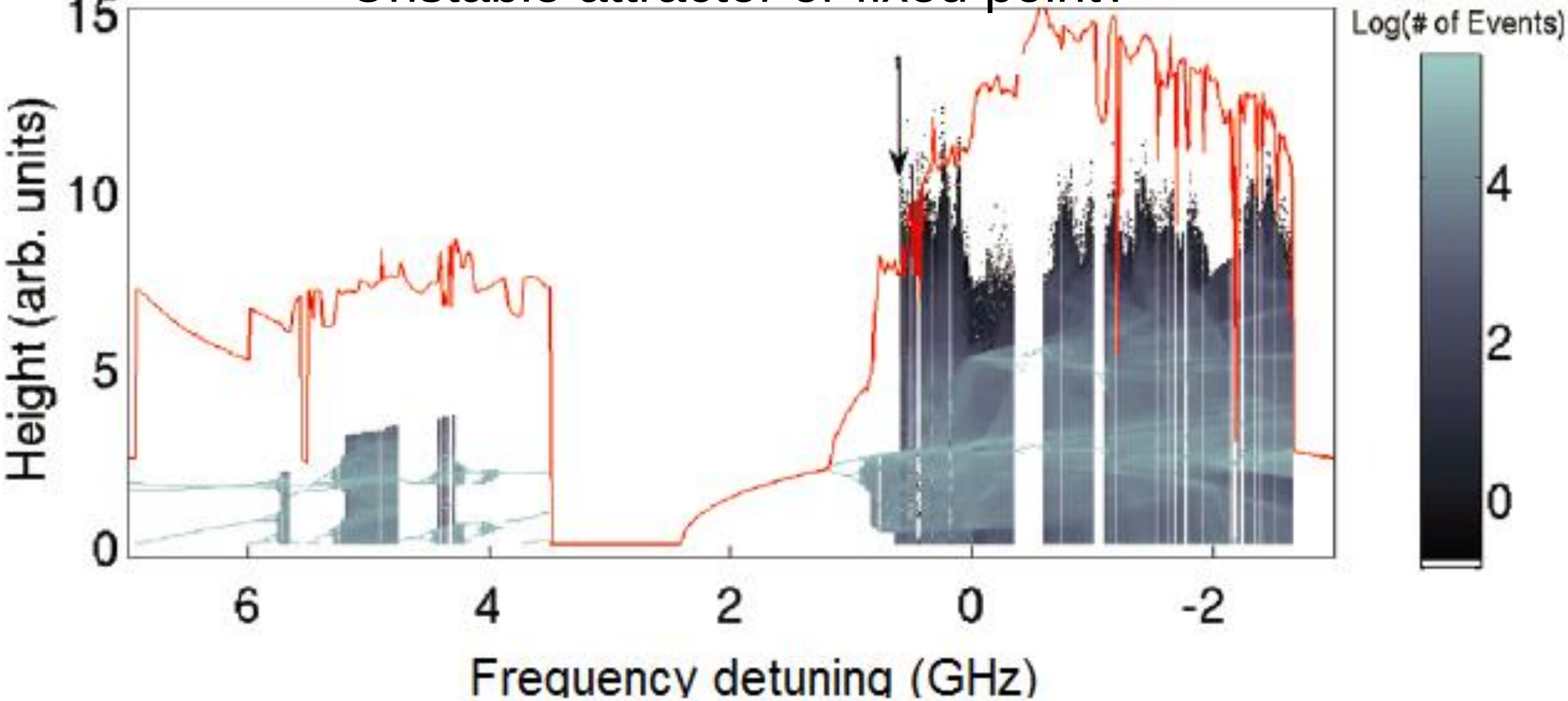
Chaos with RWs

Questions

- What triggers a rogue wave?
- Can rogue waves be predicted?
- Can rogue waves be controlled?

What triggers a RW?

Unstable attractor or fixed point?

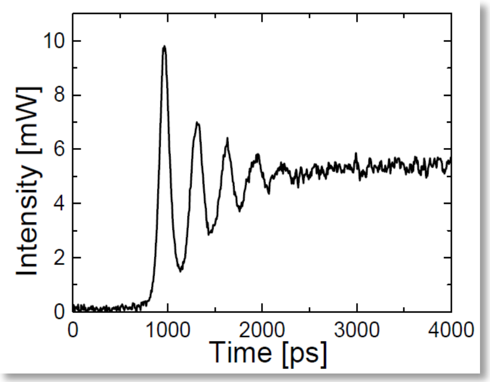


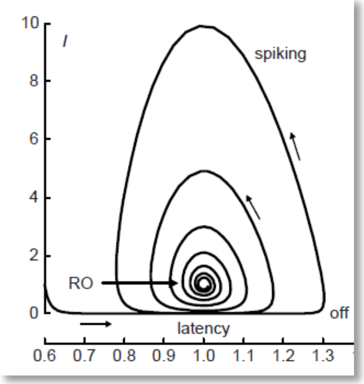
Threshold: <H> + 8σ

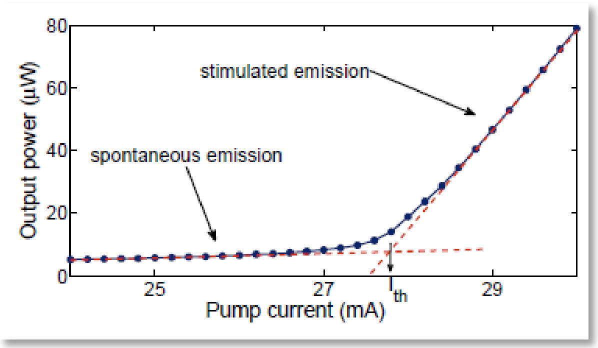
Fixed point solutions

<u>Solitary laser</u>: two fixed points.

- transient spikes

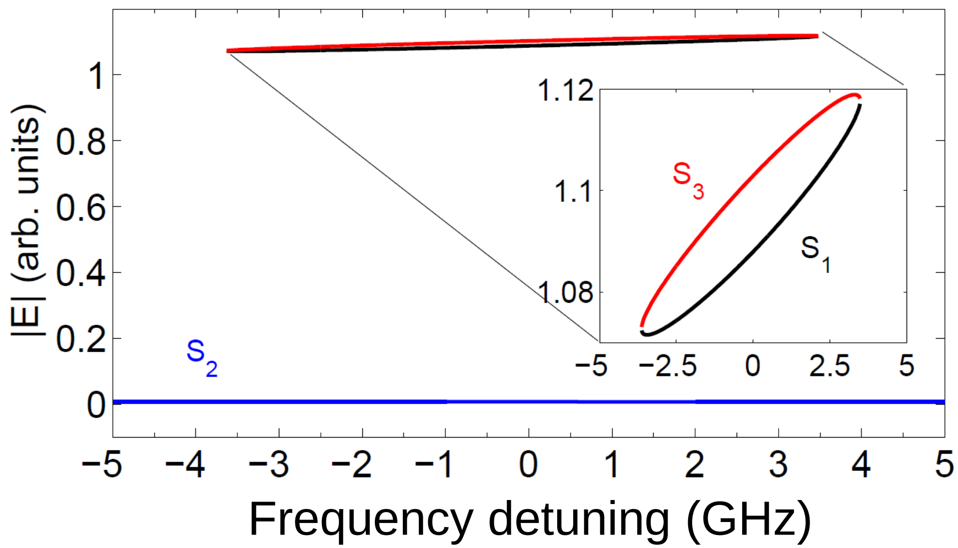


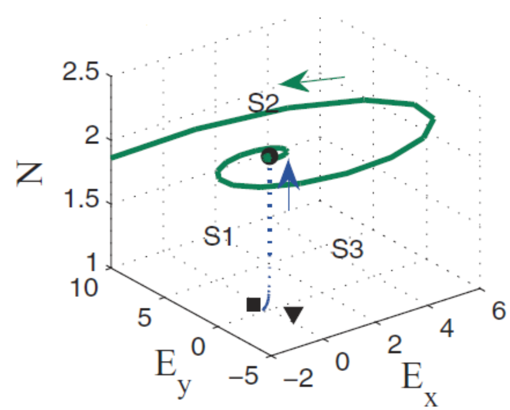




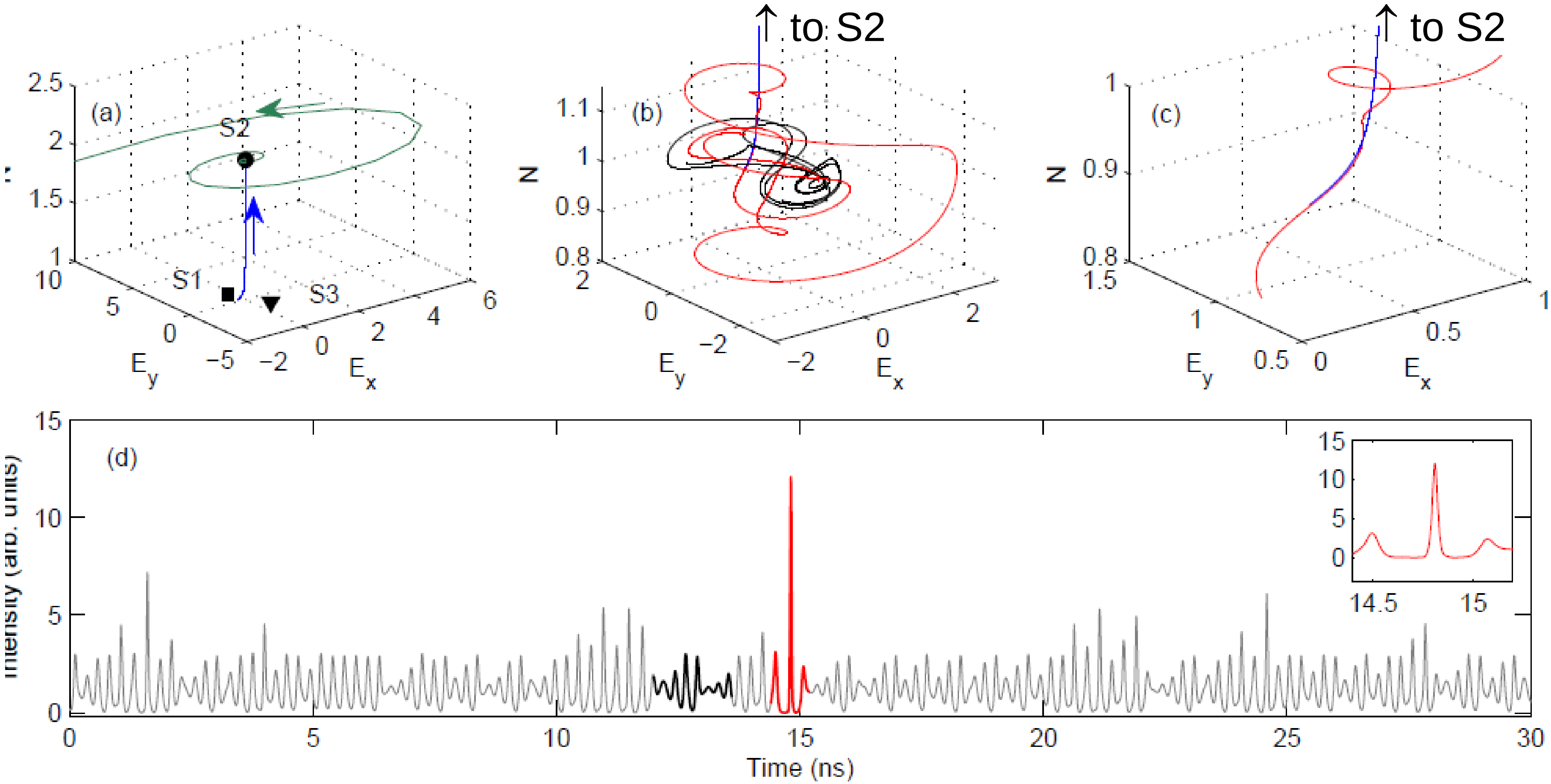
<u>Injected laser</u>: three fixed points.

- chaotic attractor develops from S3





Stable manifold of S2: "RW door"



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

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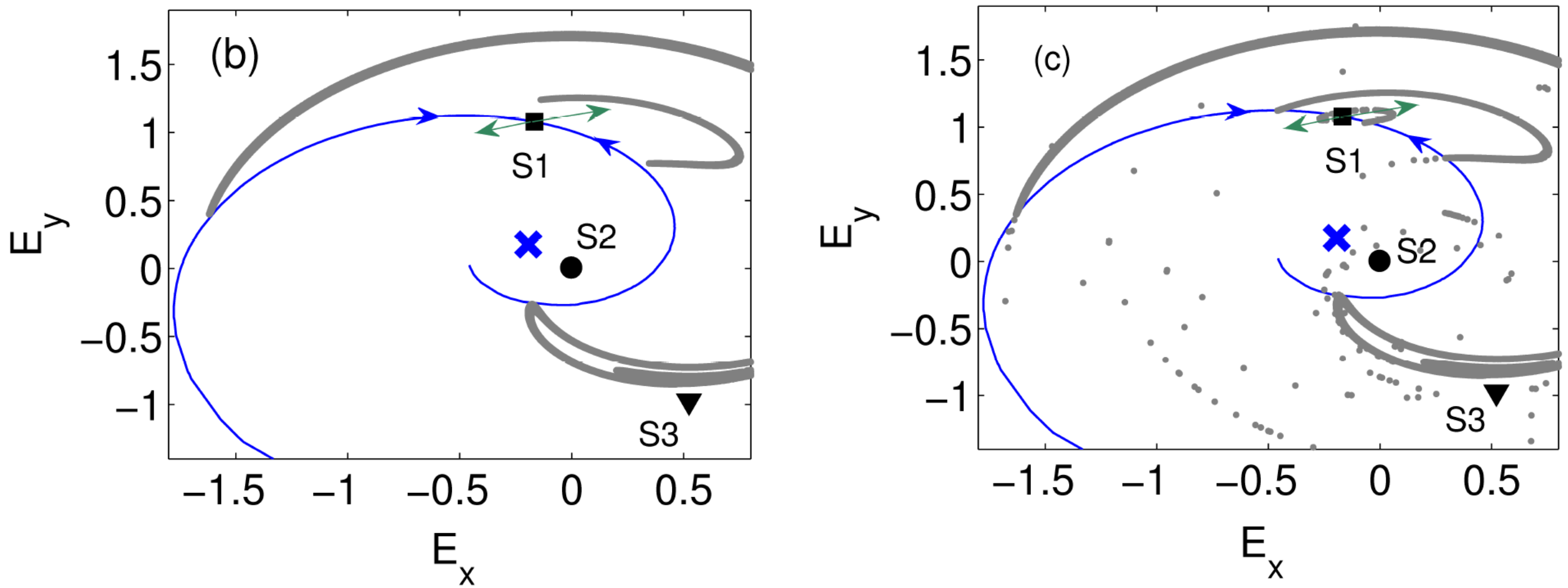
Why chaos with RWs and chaos without them?

Before attractor explosion

Just after attractor explosion



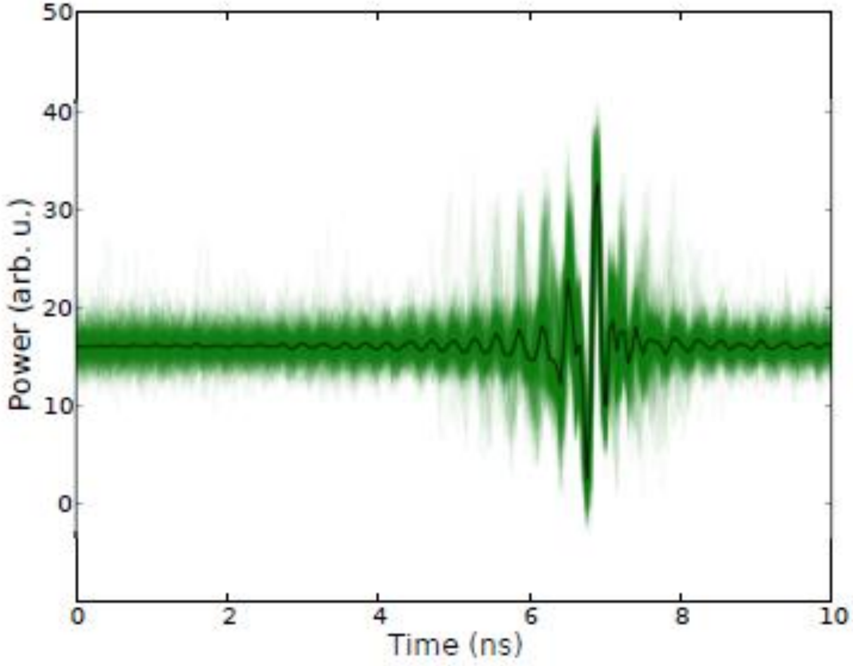
- In between the attractor originated from S3 and the "RW door" there is a "barrier": the stable manifold of S1
- A crises-like process enables access to the region where the "RW door" is.

Questions

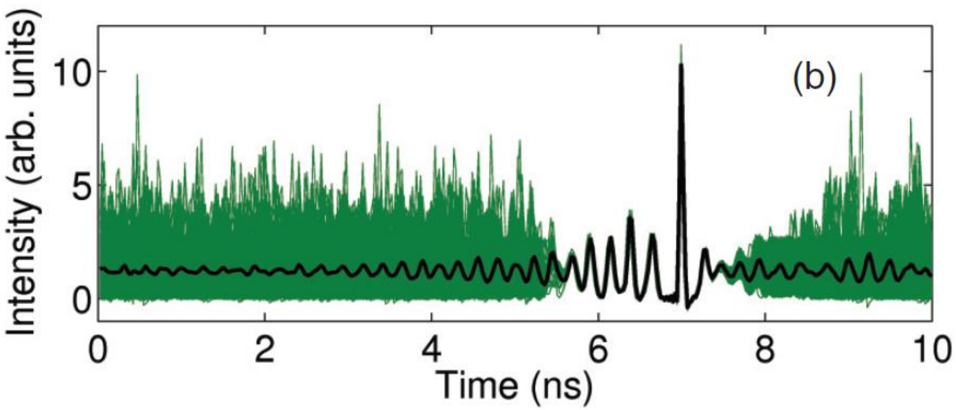
- What triggers a rogue wave?
- Can rogue waves be predicted?
- Can rogue waves be controlled?

RW predictability

Experiments



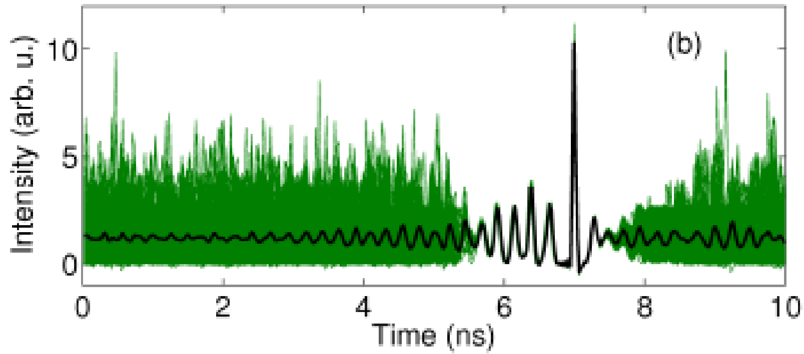
Simulations



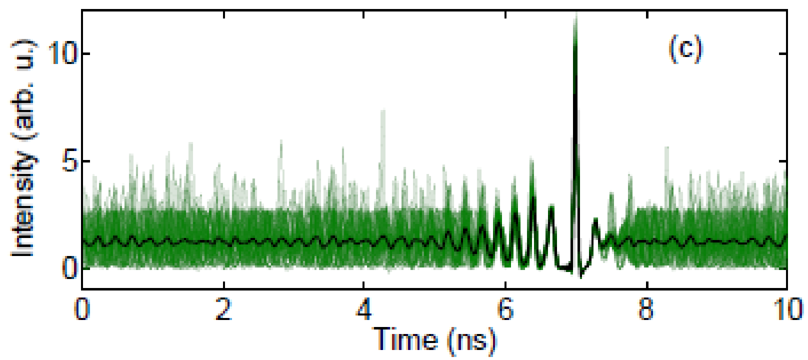
Superposition of 500 time series at the RW peak

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

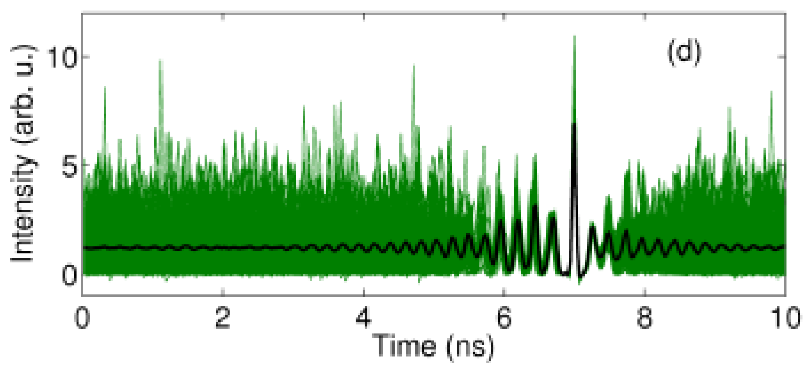
Influence of noise & RW threshold



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



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



$\langle A \rangle + 4\sigma$

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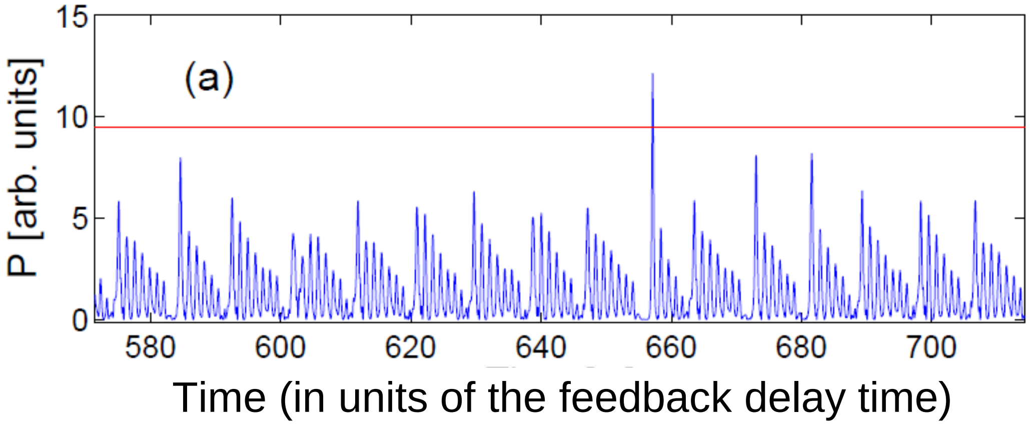
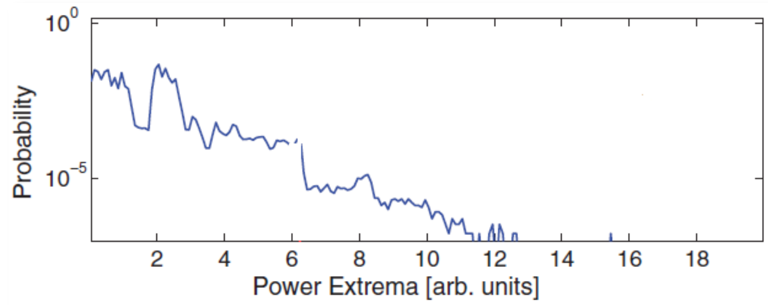
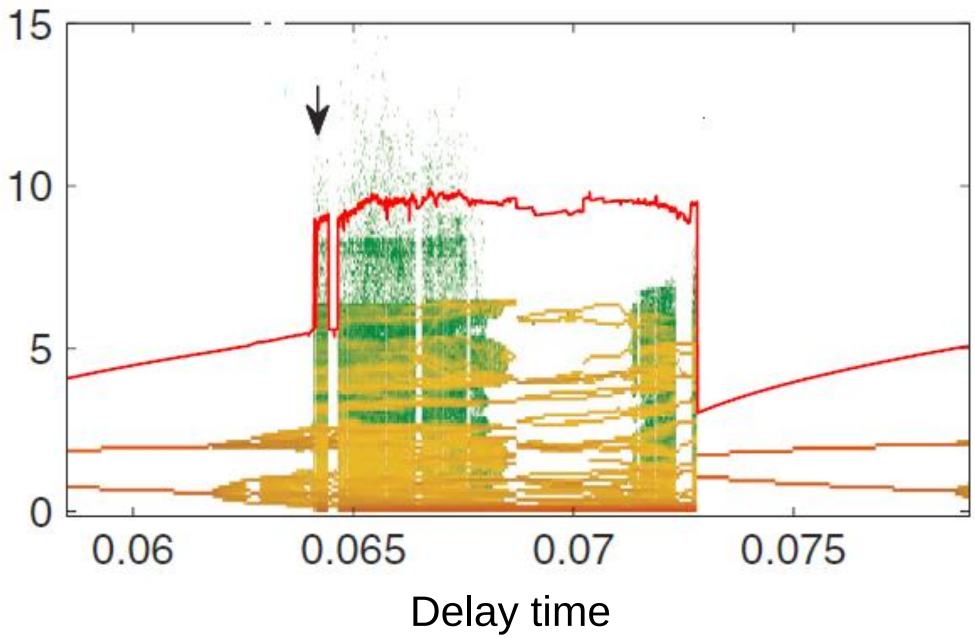
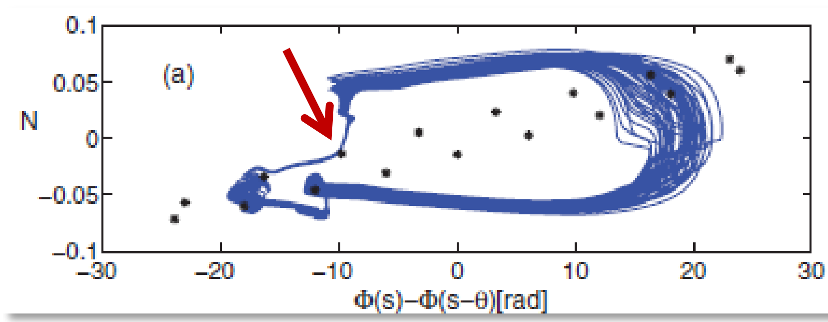
Similar behavior also in a laser with optical feedback



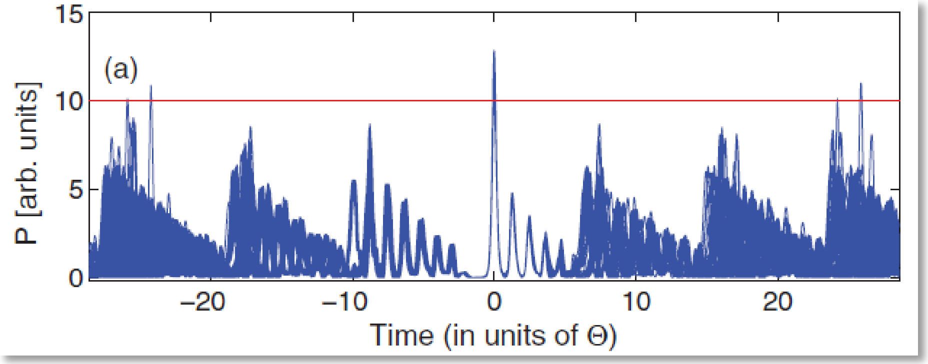




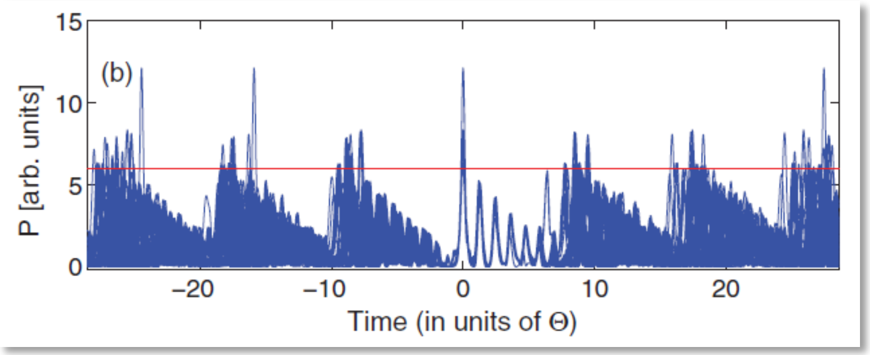


J. A. Reinoso, J. Zamora-Munt and C. Masoller. PRE 87, 062913 (2013)

Using a high threshold



Using a lower threshold



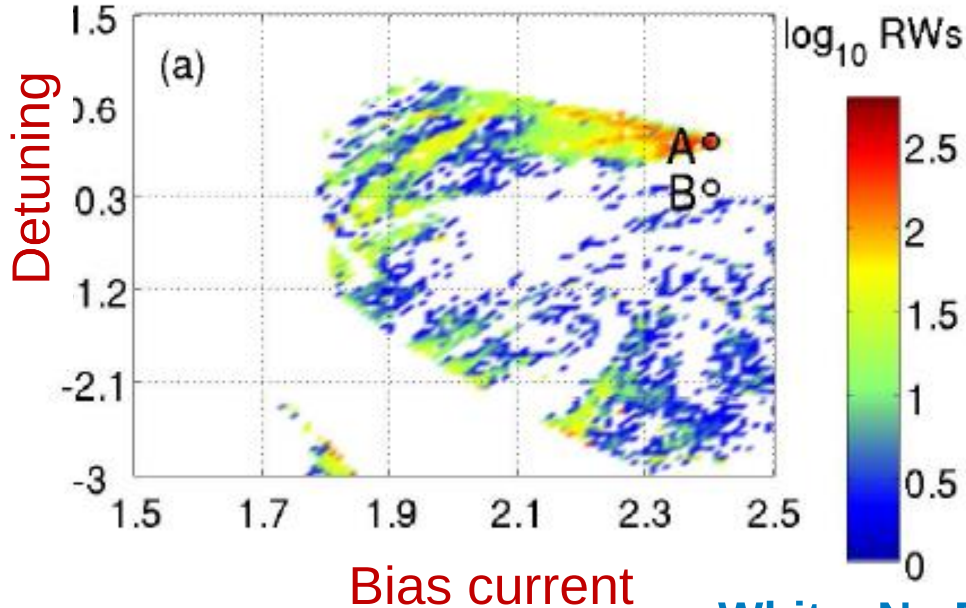
J. A. Reinoso, J. Zamora-Munt and C. Masoller. PRE 87, 062913 (2013)

Questions

- What triggers a rogue wave?
- Can rogue waves be predicted?
- Can rogue waves be controlled?

Influence of noise

Number of RWs in noiseless simulations

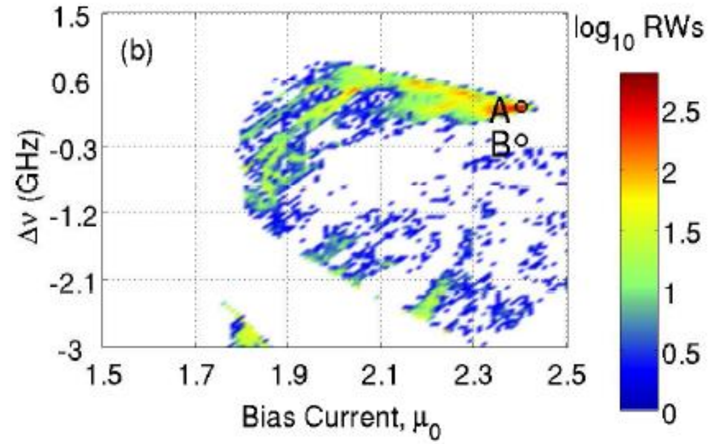


White=No RWs

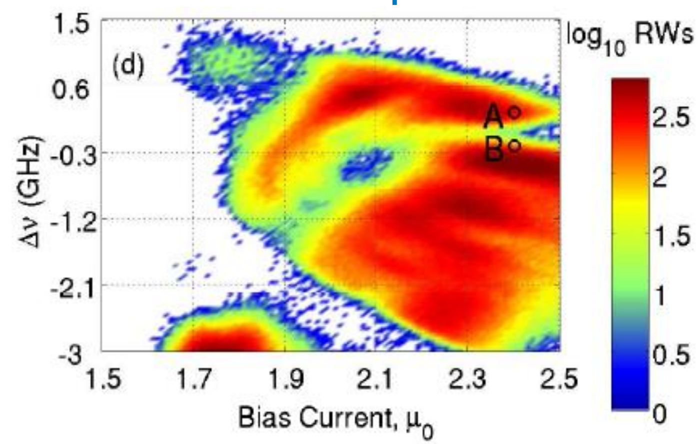
In point A: Deterministic RWs

In point B: no RWs

Weak noise (β_{sp}=0.0001)



Stronger noise (β_{sp}=0.01)

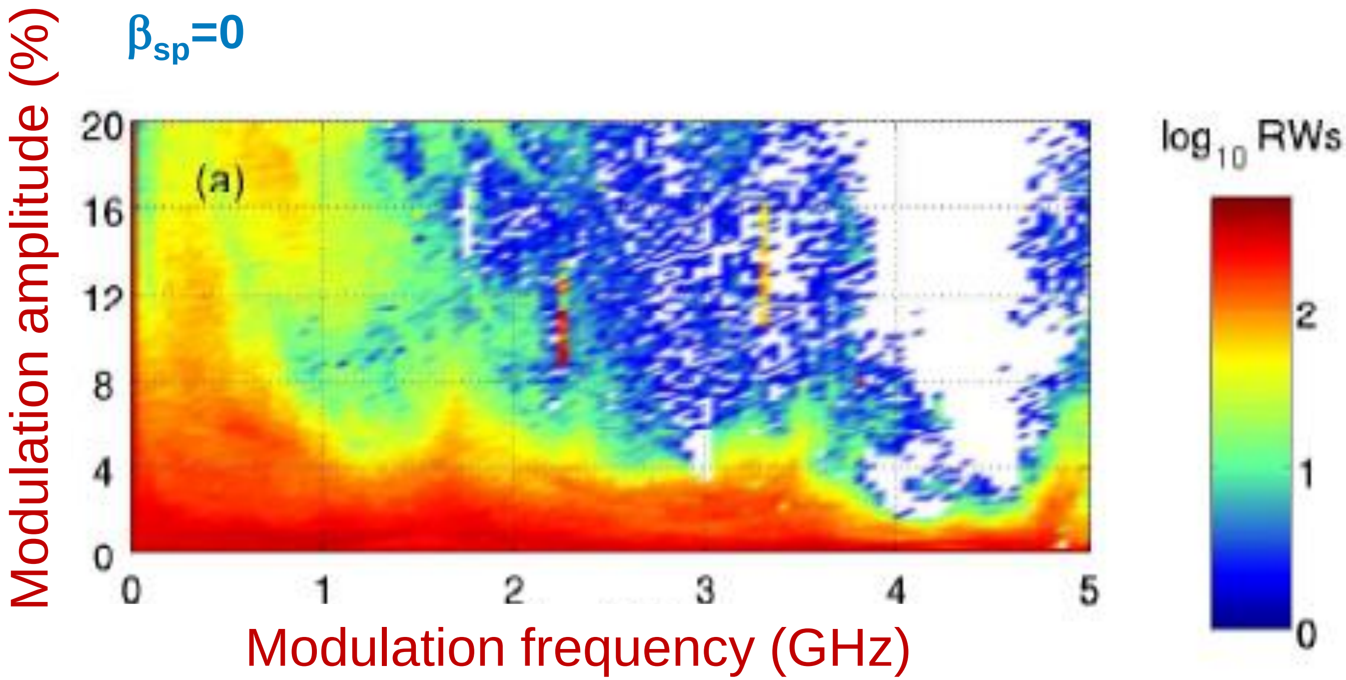


Weak noise reduces the number of RWs, strong noise increases it

Influence of current modulation when RWs are deterministic (point A)

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

β_{sp}=0



White = No RWs

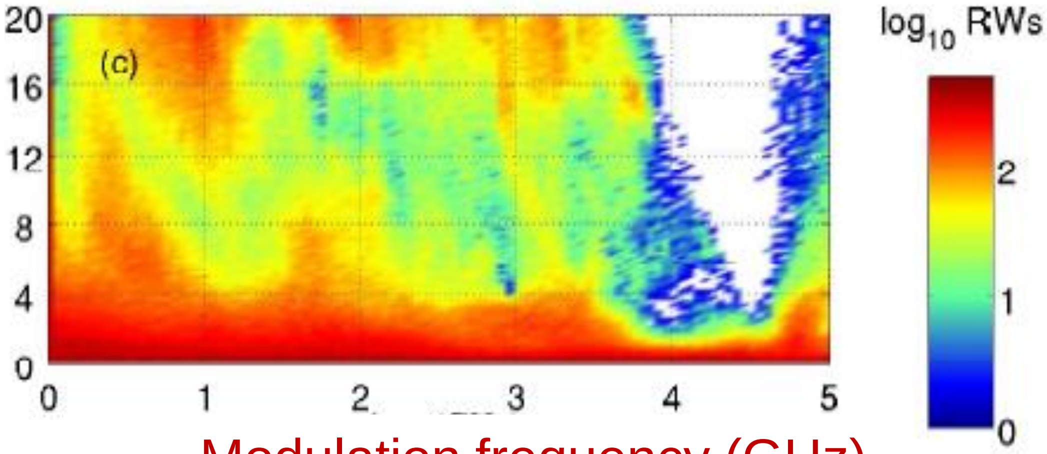
Current modulation with frequency close to the natural resonance frequency fully suppresses RWs: there is a "safe parameter region" where no RWs occur.

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

Role of noise

β_{sp}=0.01

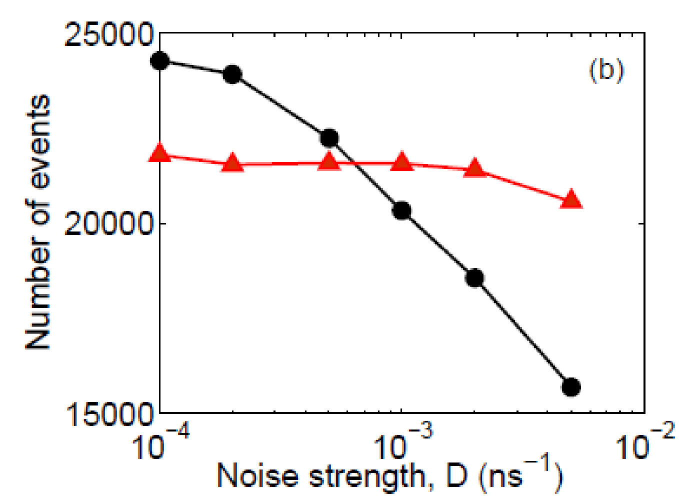
Modulation amplitude (%)



Modulation frequency (GHz)

White = No RWs

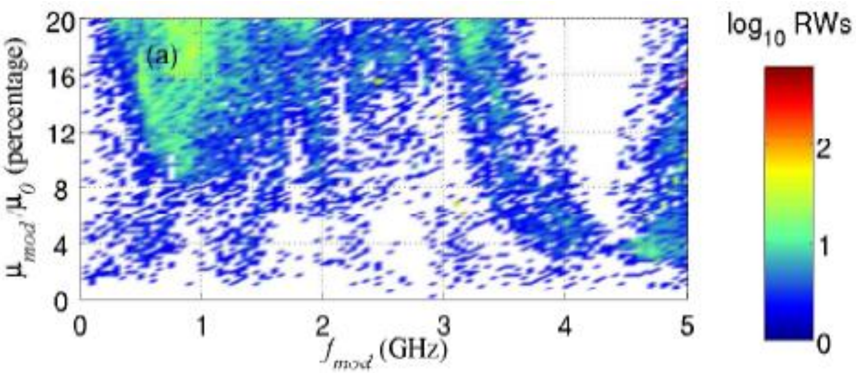
The "safe region" is robust to noise.



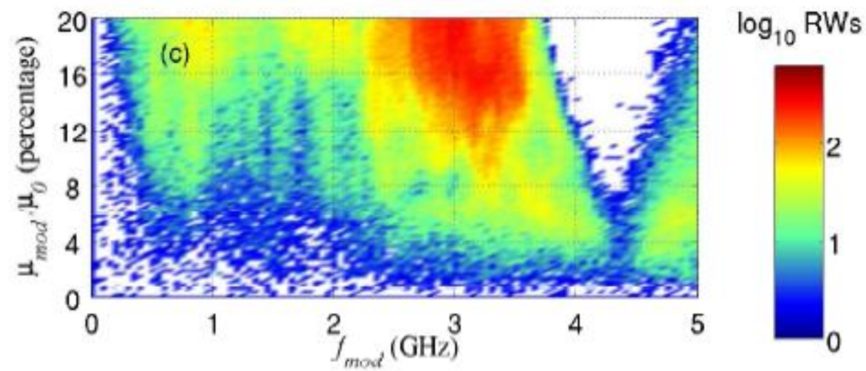
- Without modulation: noise reduces the number of RWs
- With modulation: noise does not affect the RW number

Influence of current modulation when there are no deterministic RWs (Point B)

β_{sp}=0



β_{sp}=0.01



White = No RWs

Current modulation can induce RWs but the "safe region" remains and is robust to noise.

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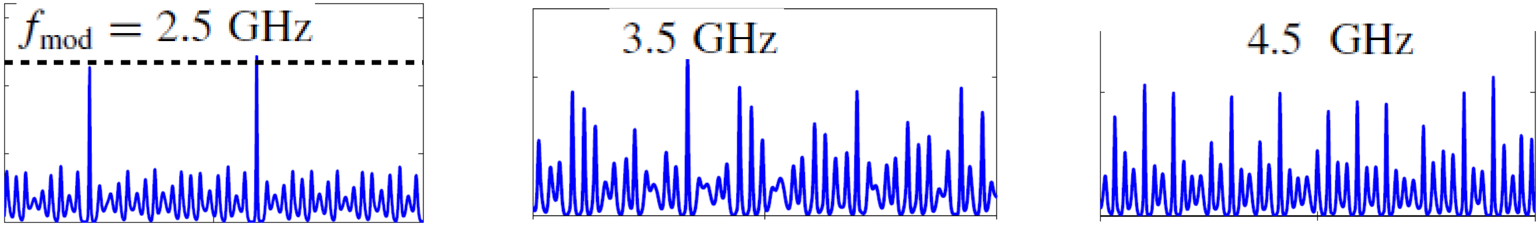
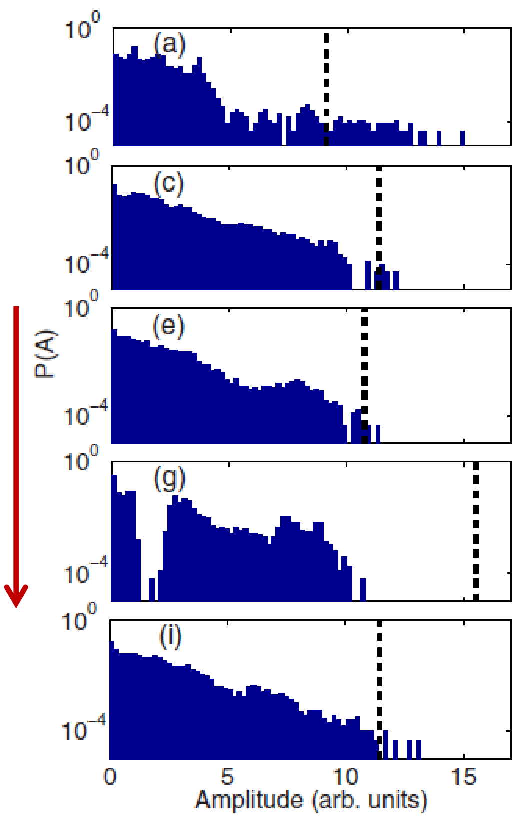
Why RWs are suppressed?



High pulses become regular, therefore, they are not RWs.

Distribution of pulse amplitudes

Increasing f_{mod}



Threshold = <A> + **6** σ

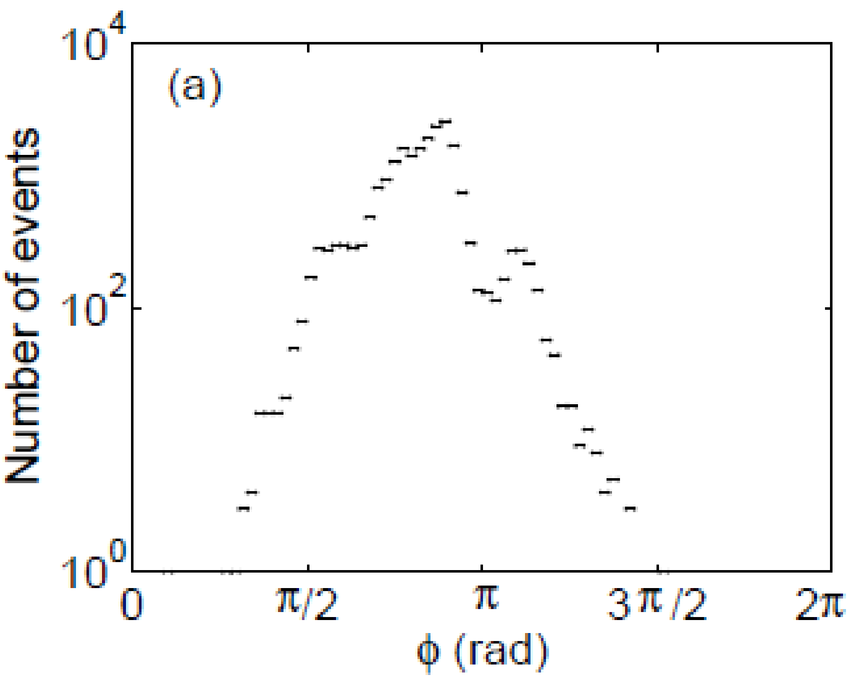
← RW threshold increases.

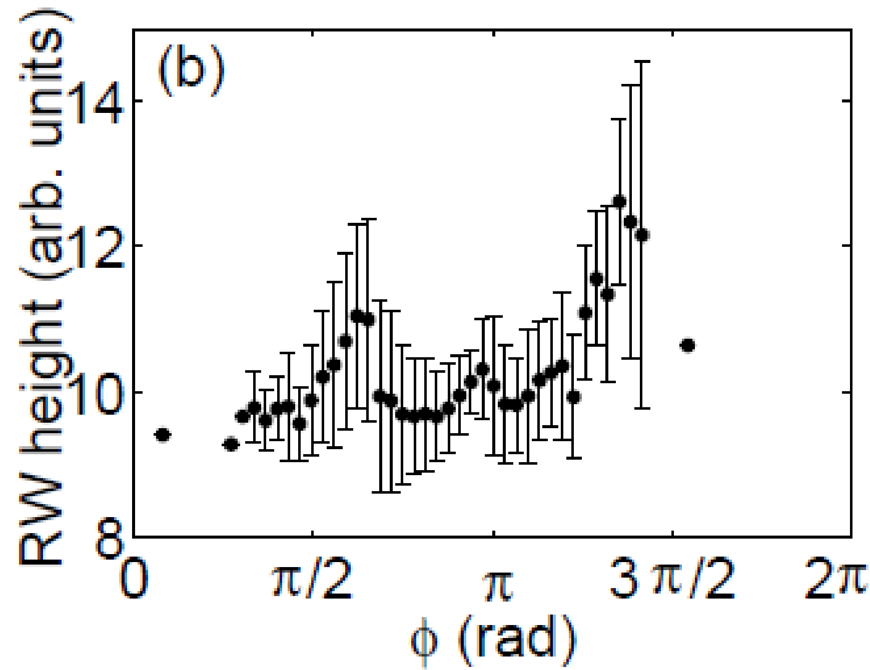
Analogy: avalanche risk

- Modulation suppressed extreme pulses:

  We can think of controlled avalanches in a snow-covered mountain that reduce the accumulated snow that could feed a large and dangerous avalanche.

Outside the "safe parameter region": role of the modulation phase





"**safe phase window**" where no RWs occur.

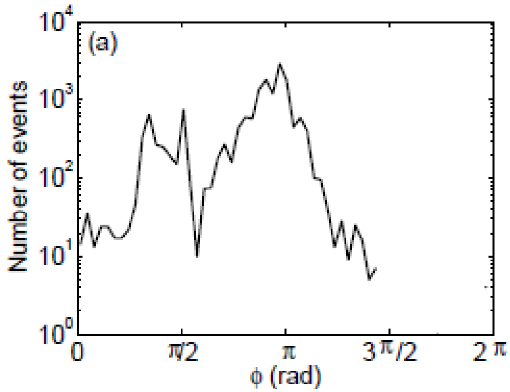
highest (most extreme) RWs occur before "safe phase window".

J. Ahuja et al, Optics Express 22, 28377 (2014).

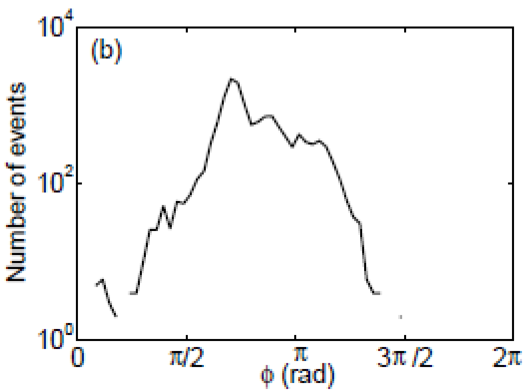
Influence of the modulation frequency

Slow modulation

2 GHz



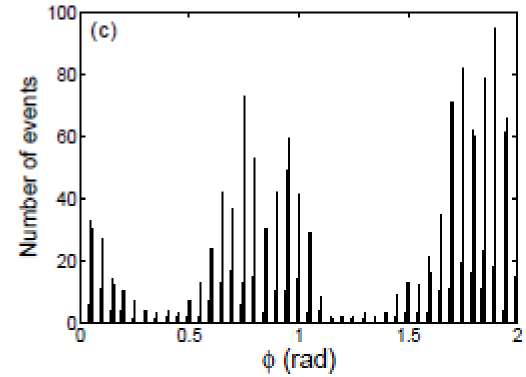
3 GHz

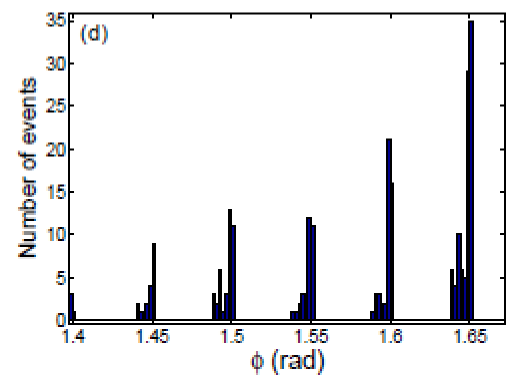


"safe" phase window remains

Faster modulation

5 GHz





No "safe" phase window but RWs likely occur at specific values of the modulation phase

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What we have learned

- In our system RWs can be **deterministic**, generated by a crisis-like process.
- RWs can be **predicted** with a certain anticipation time.
- RWs can be **controlled** by noise and/or modulation.
    - Within a "safe parameter region": modulation fully suppresses RWs.
    - Outside this safe region: RWs occur in an specific window (or for specific values) of the modulation phase.

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Summary

THANK YOU FOR YOUR ATTENTION !

<cristina.masoller@upc.edu>

papers available at:

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

- 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).

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