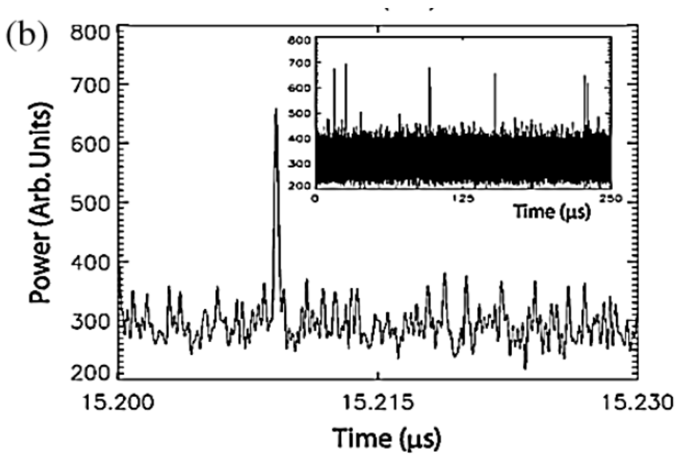

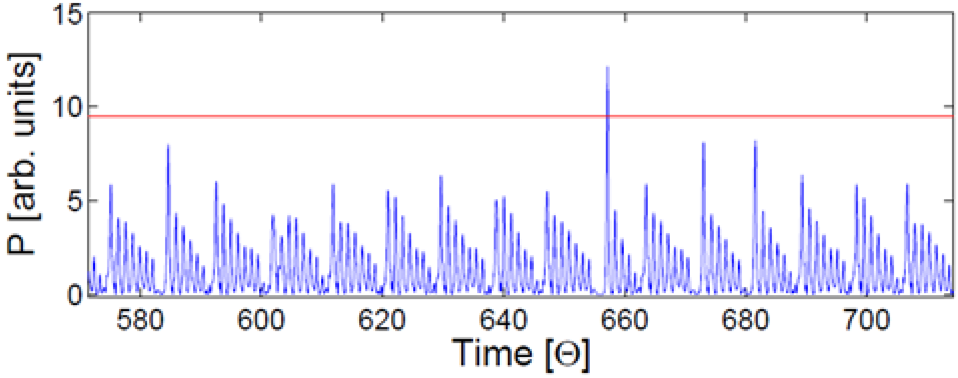

Extreme optical pulses: origin, predictability and control

Cristina Masoller

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Campus d'Excel·lència Internacional

Dynamic Days Europe, Bayreuth, Germany, September 2014

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Collaborators




- José A. Reinoso   Sandro Perrone
  Jordi Zamora Munt   Ramon Vilaseca
- B. Garbin, M. Feyereisen, S. Barland, M. Giudici (INLN, Nice, France)
- Jorge Tredicce (Universite de la Nouvelle Caledonie)
- Jose Rios Leite (Universidade Federal de Pernambuco, Recife, Brasil)

What is a rogue wave?

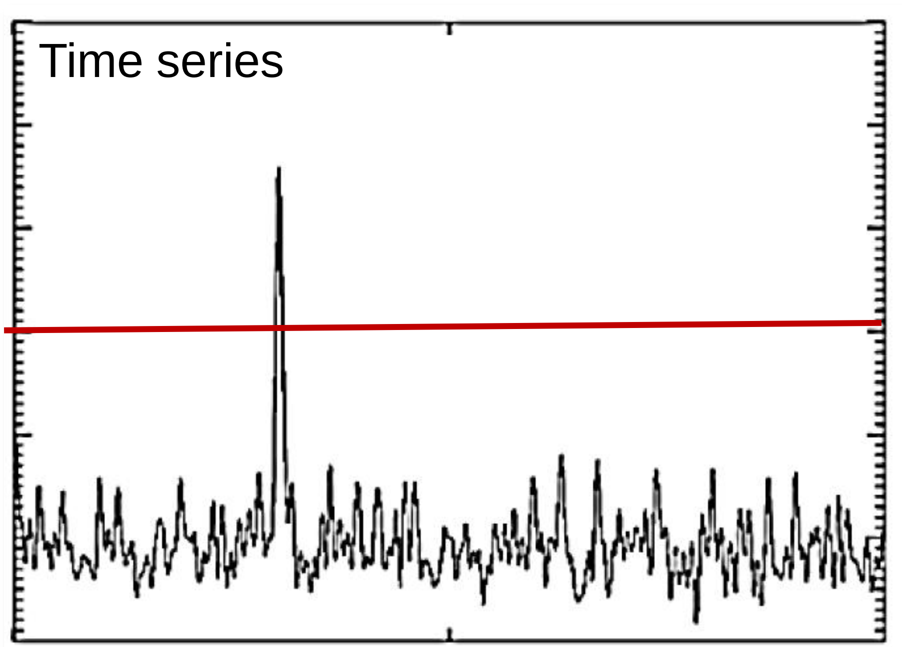
A "monster wave", ultra-high wave that falls outside (and far from) the main part of a long-tailed probability distribution.

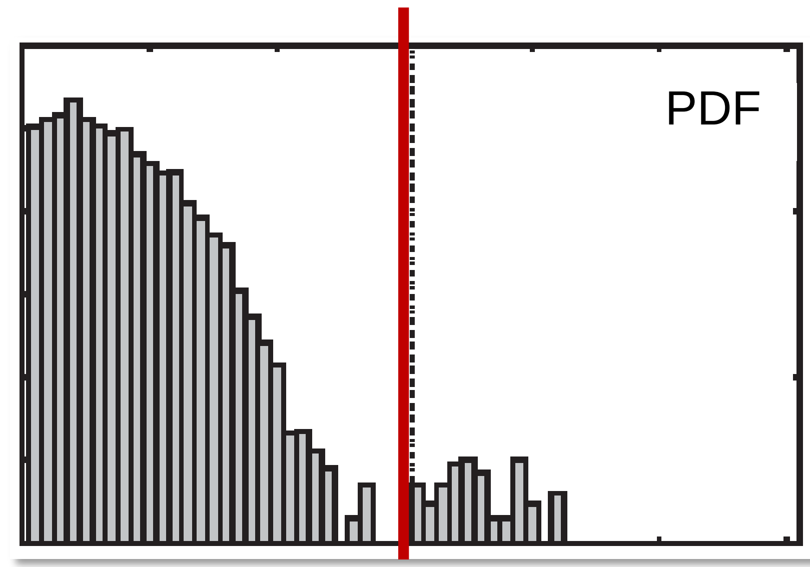
The Great Wave of Kanagawa, Katsushika Hokusai. Source: Wikipedia

Two more precise 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 (<H> + **4-8** σ)



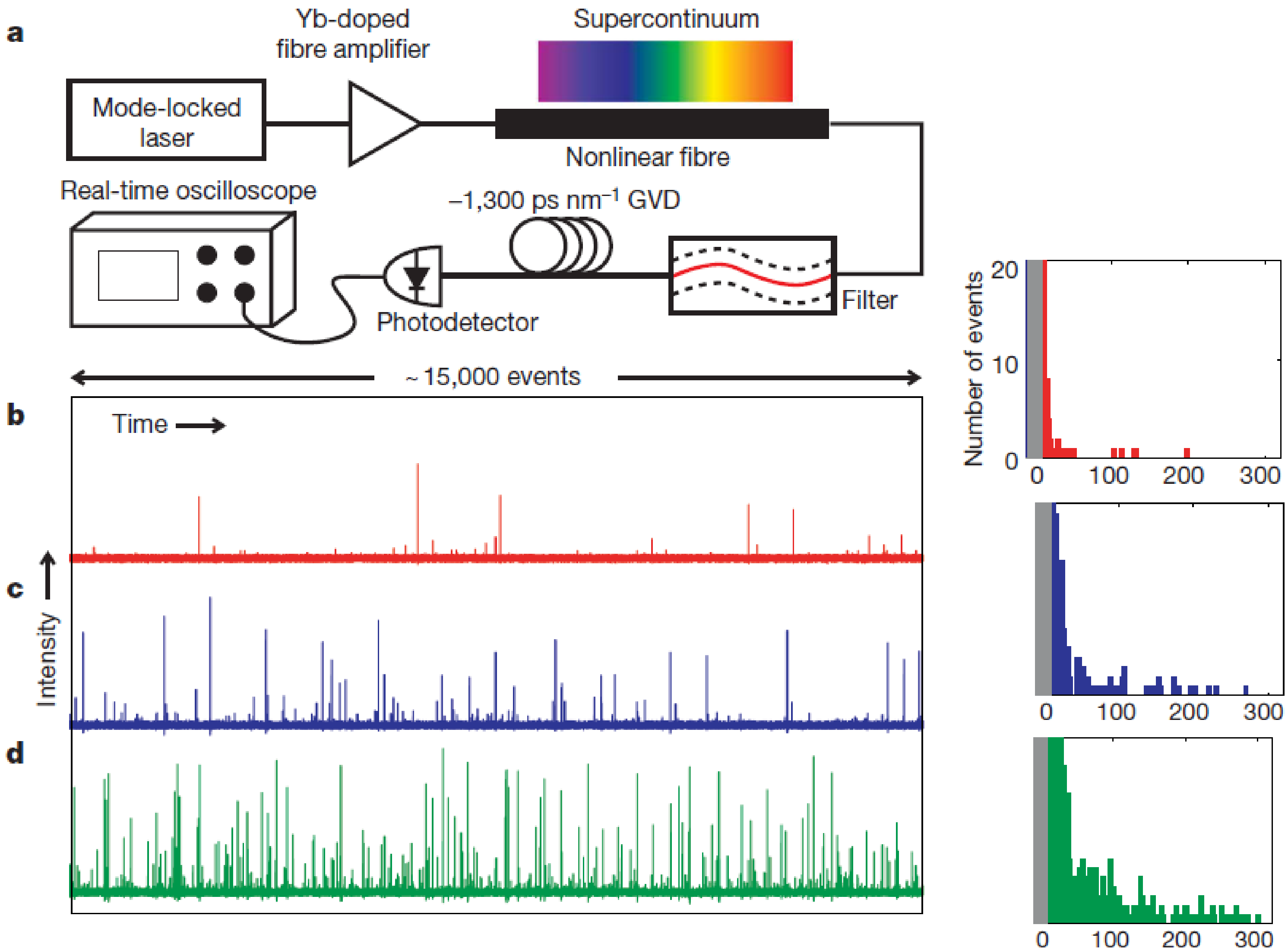


RWs appear suddenly

A challenge for the oil and gas industry, for the design of safe off-shore platforms.

Source: National Geographic

Optical RWs: first observation



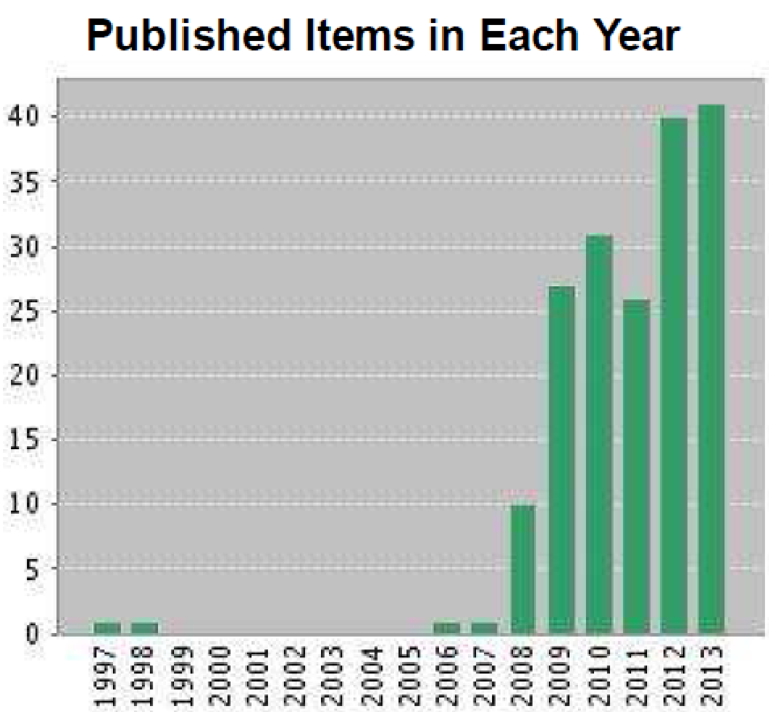
D. R. Solli et al, Nature 450, 1054, 2007

Since 2007: a lot of work

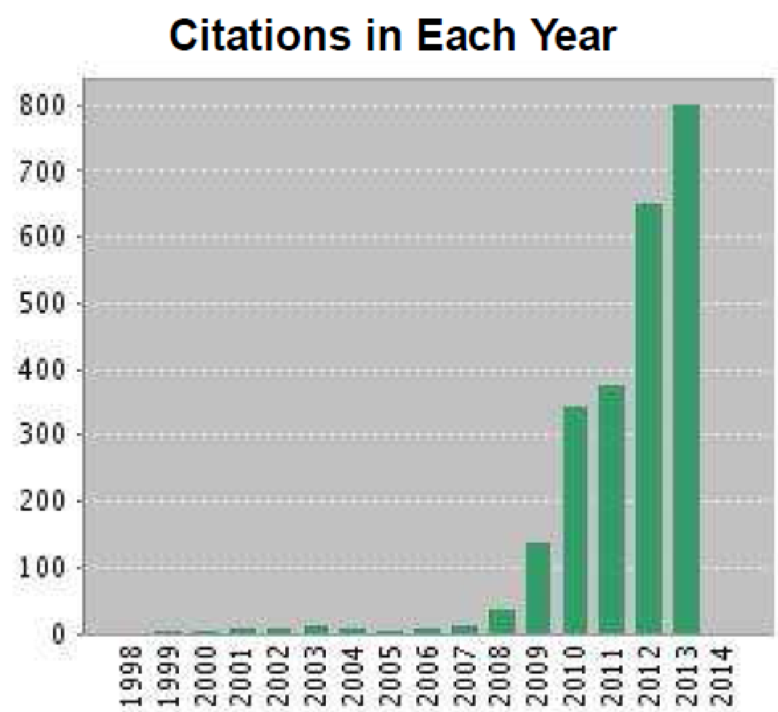
Citation Report Topic=(optical rogue wave)

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
indexed within Web of Science.



The latest 20 years are displayed.

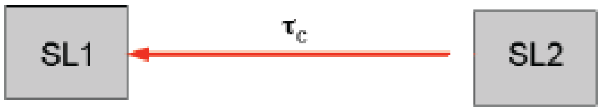


The latest 20 years are displayed.

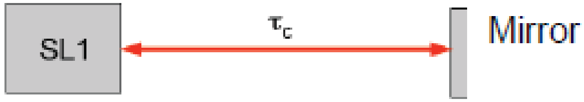
Optical RWs in semiconductor lasers

Two setups:

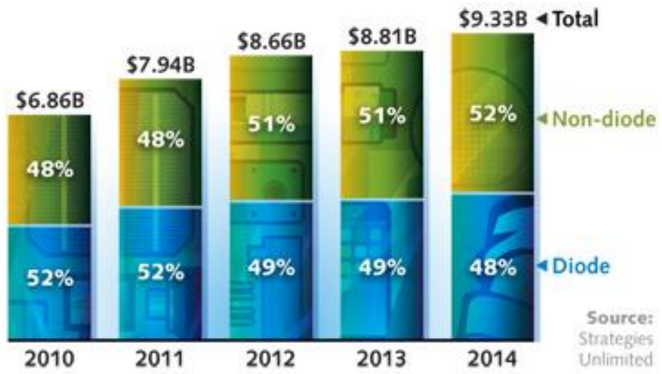
- With **optical injection**:
  observations & numerical results.



- With **optical feedback**:
  numerical results.



Why semiconductor lasers? (diode lasers)



- Used in:
  - Telecommunications
  - Optical data storage (CDs, DVDs, Blu rays)
  - Barcode scanners, printers, mouse
  - Biomedical applications (imaging, sensing, etc)

Semiconductor lasers provide an inexpensive and controllable setup for the study of optical rogue waves

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).
- J. M. Reinoso et al, PRE 87, 062913 (2013).
- S. Perrone et al, PRA 89, 033804 (2014).

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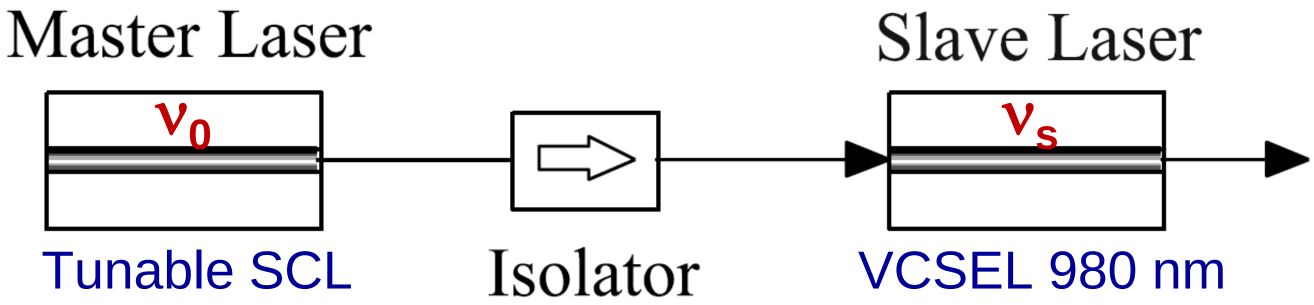
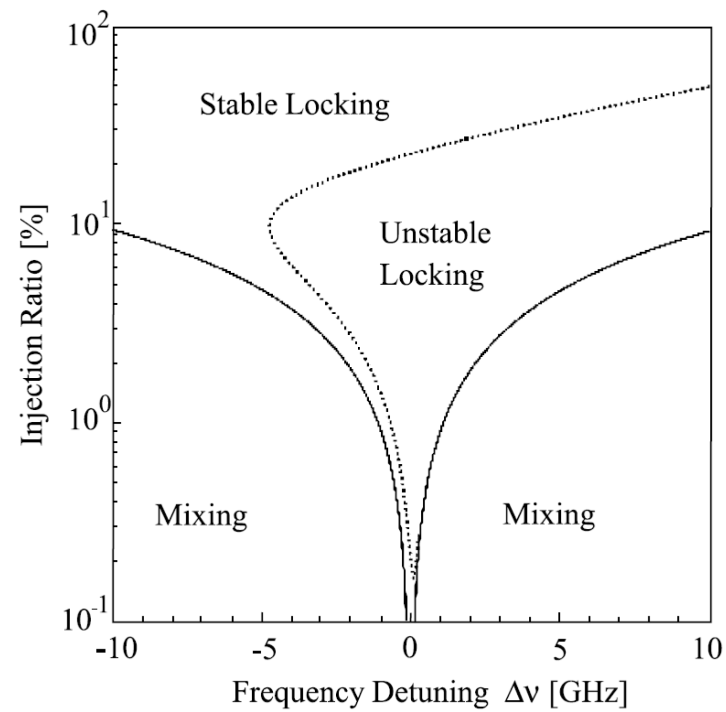
First setup: an optically injected laser



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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[2] USAF, Research Laboratory, High Power Solid State Lasers Branch, Kirtland AFB, NM 87117, USA
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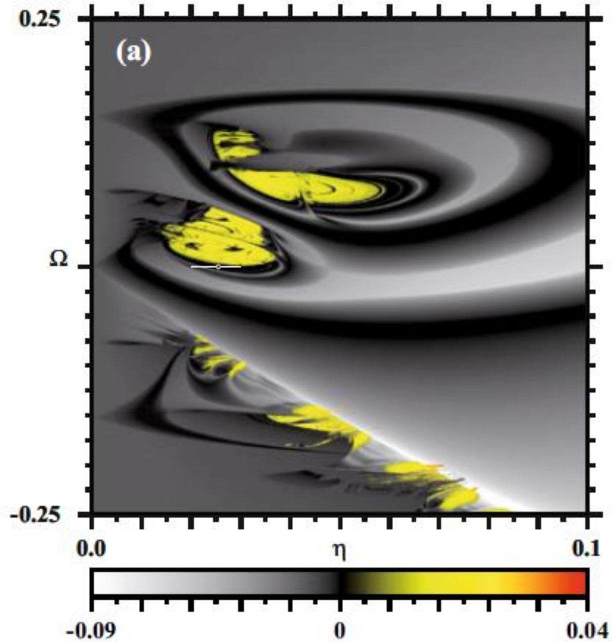
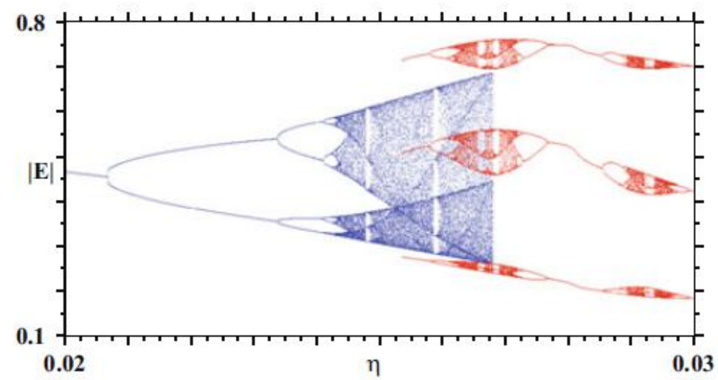
[4] Departamento de Física, Universidade Federal da Paraíba, 58051-970 João Pessoa, Brazil
[5] Instituto de Física, Universidade Federal do Rio Grande do Sul, 91501-970 Porto Alegre, Brazil

Lyapunov diagram



Bifurcation diagram

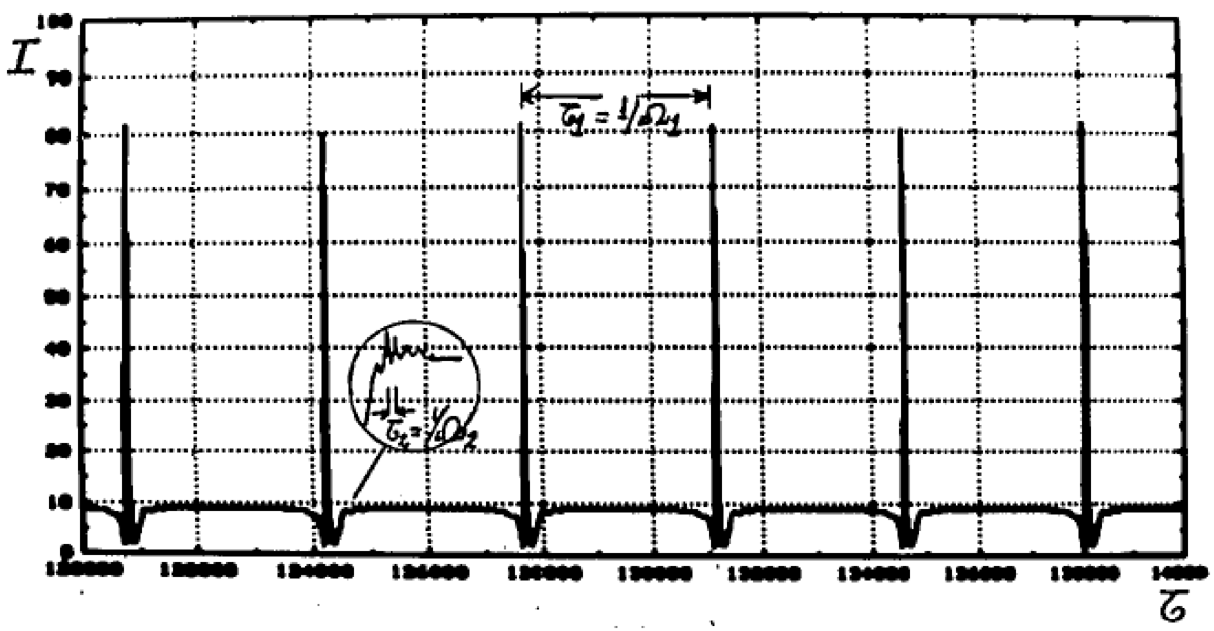


Also RWs?

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



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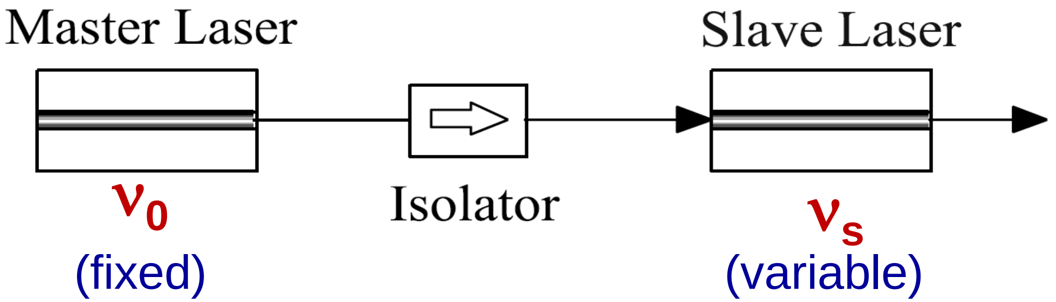
Experimental control parameters



- 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**

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

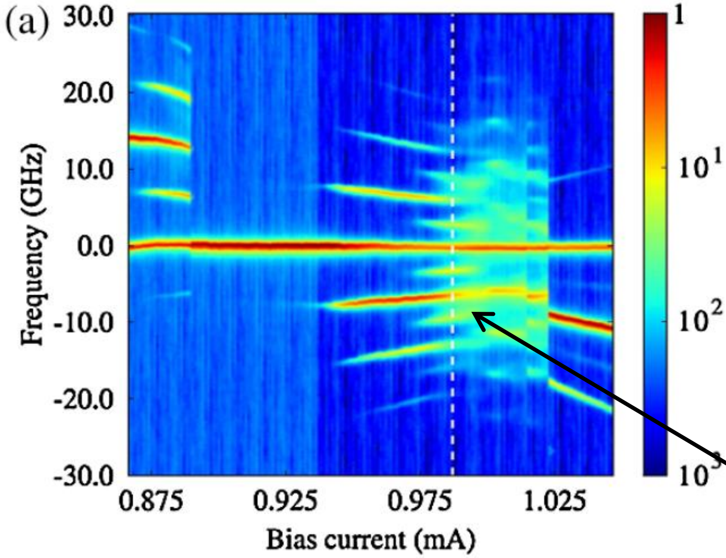
(f approximately linear)

Observed laser output:

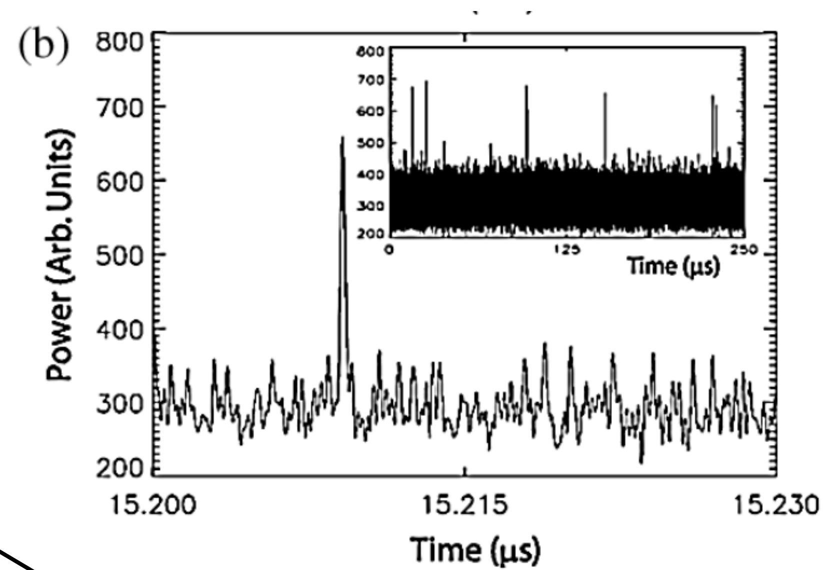
- **Intensity time - series (oscilloscope)**
- **Intensity Fourier spectrum (spectrum analyzer)**

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)

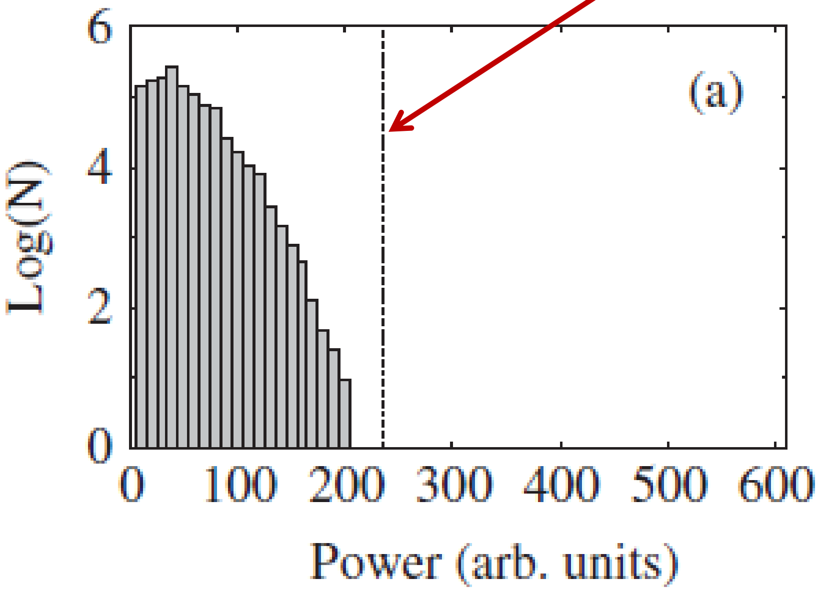
Five regions:

- Beating (independent lasers)
- Locking
- Period 2 of the beat note
- Chaos
- Beating (independent lasers again)

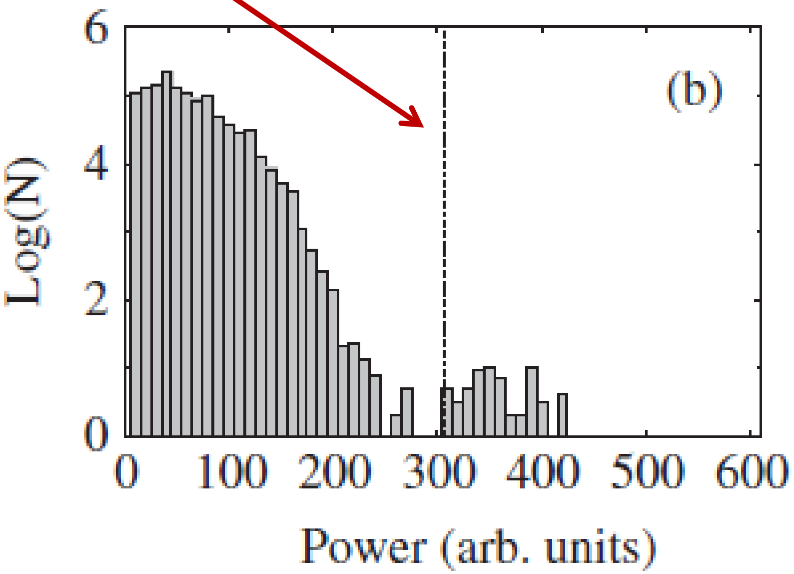
C. Bonatto et al, PRL 107, 053901 (2011)

Histograms of pulse amplitude

RW threshold = mean value + **8** σ



I = 0.972 mA



I = 0.976 mA

Governing equations

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

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

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

optical injection
η: injection strength
Δω: frequency detuning

spontaneous emission noise

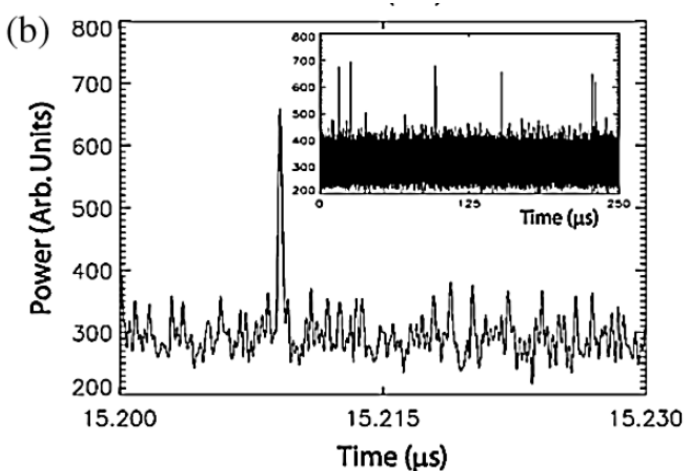
Solitary laser parameters: α τ_p τ_N μ

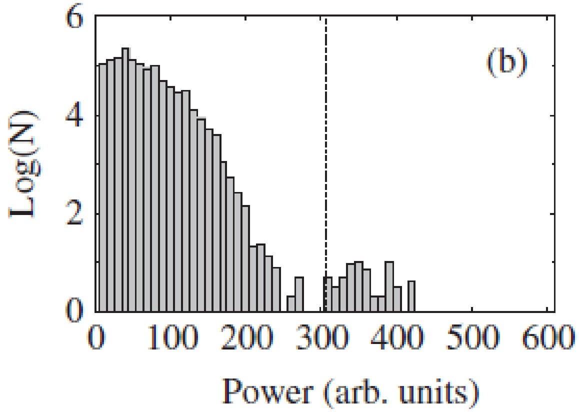
Typical parameter values:
$\alpha = 3$, $\tau_p = 1$ ps, $\tau_N = 1$ ns

μ: normalized pump current parameter

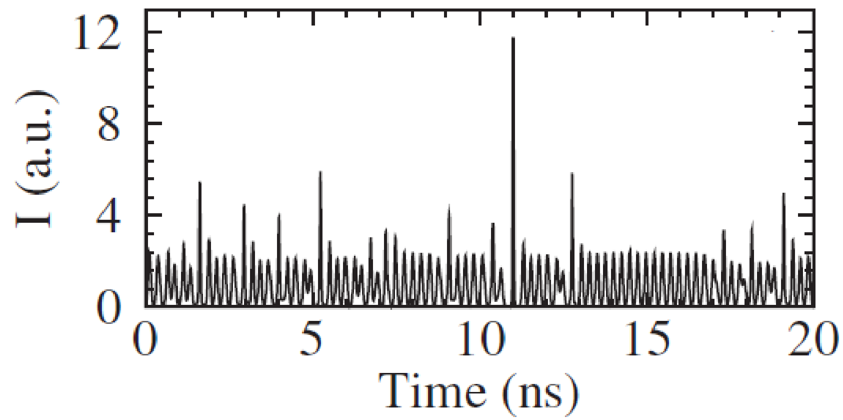
Comparison

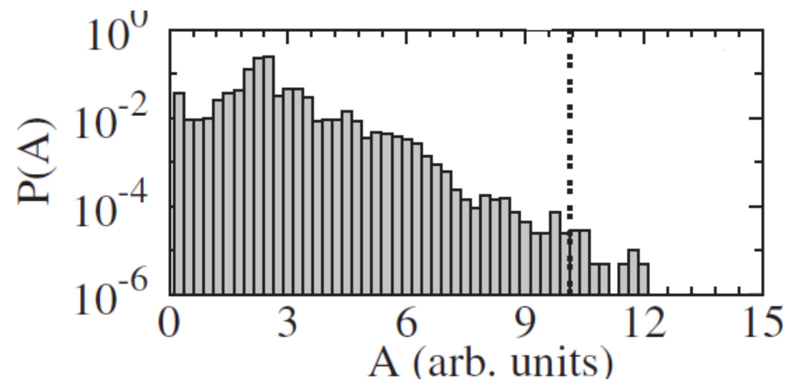
Experiments





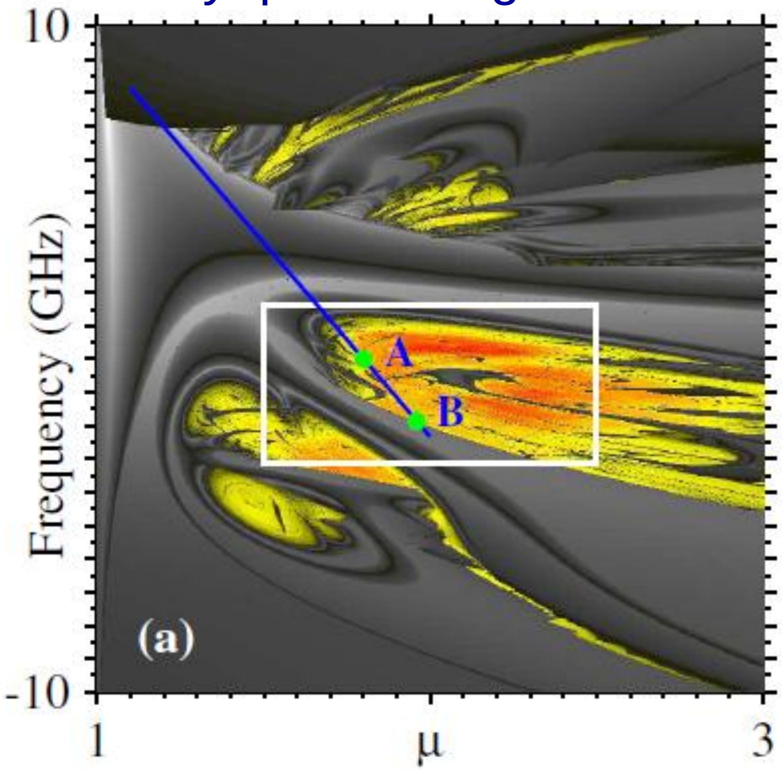
Simulations



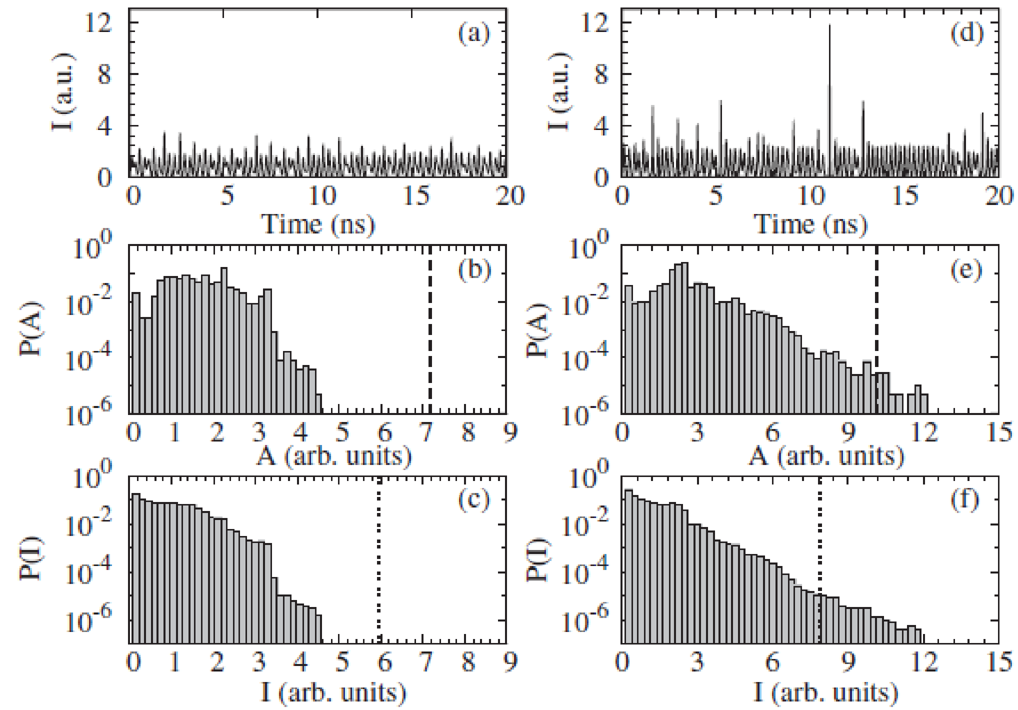


Deterministic simulations (β_{sp}=0)

Lyapunov diagram



Pump current parameter

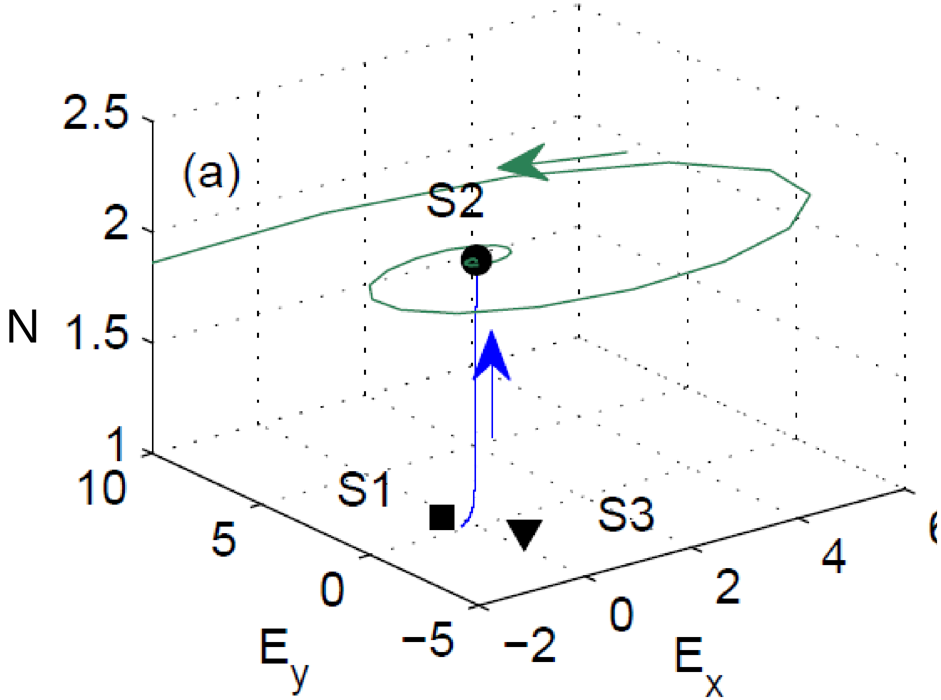


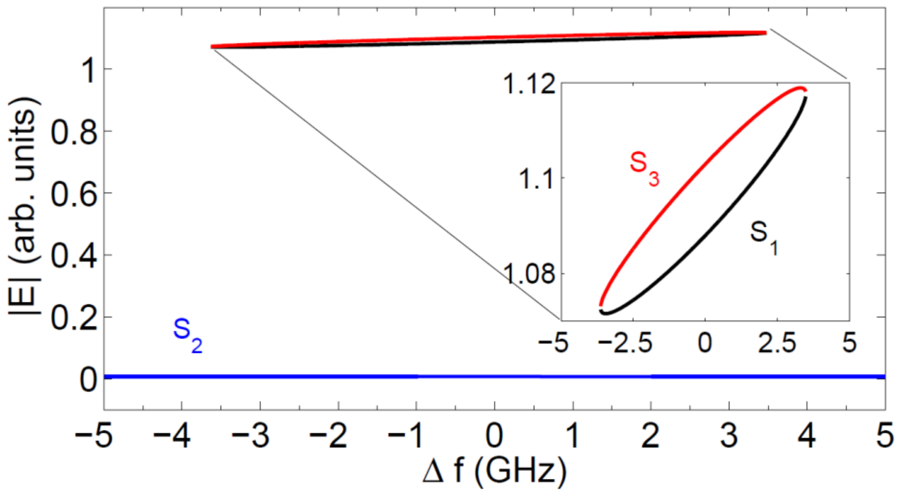
Point A: No RWs

Point B: RWs

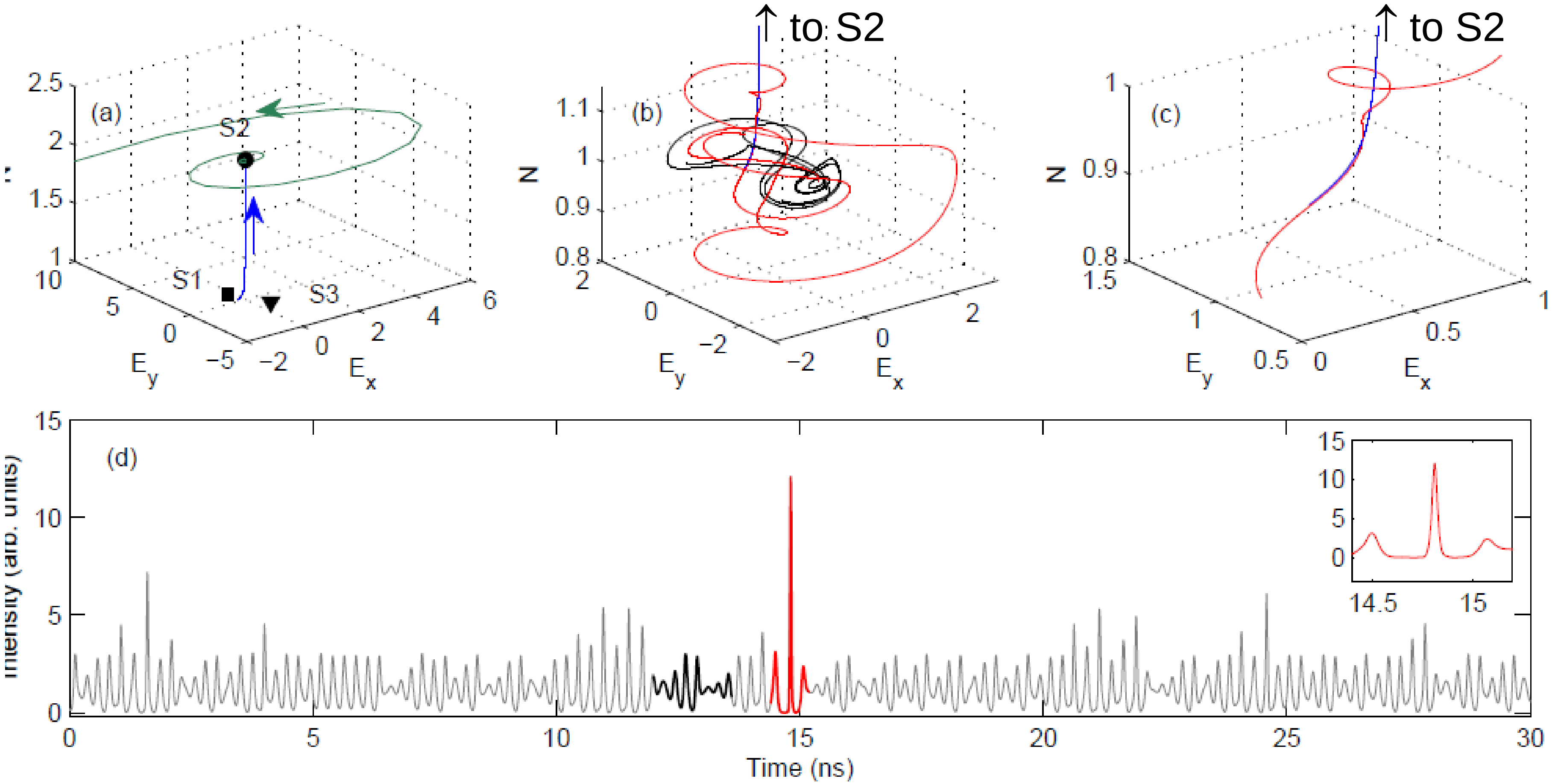
What triggers a RW?

Three fixed points in the phase space



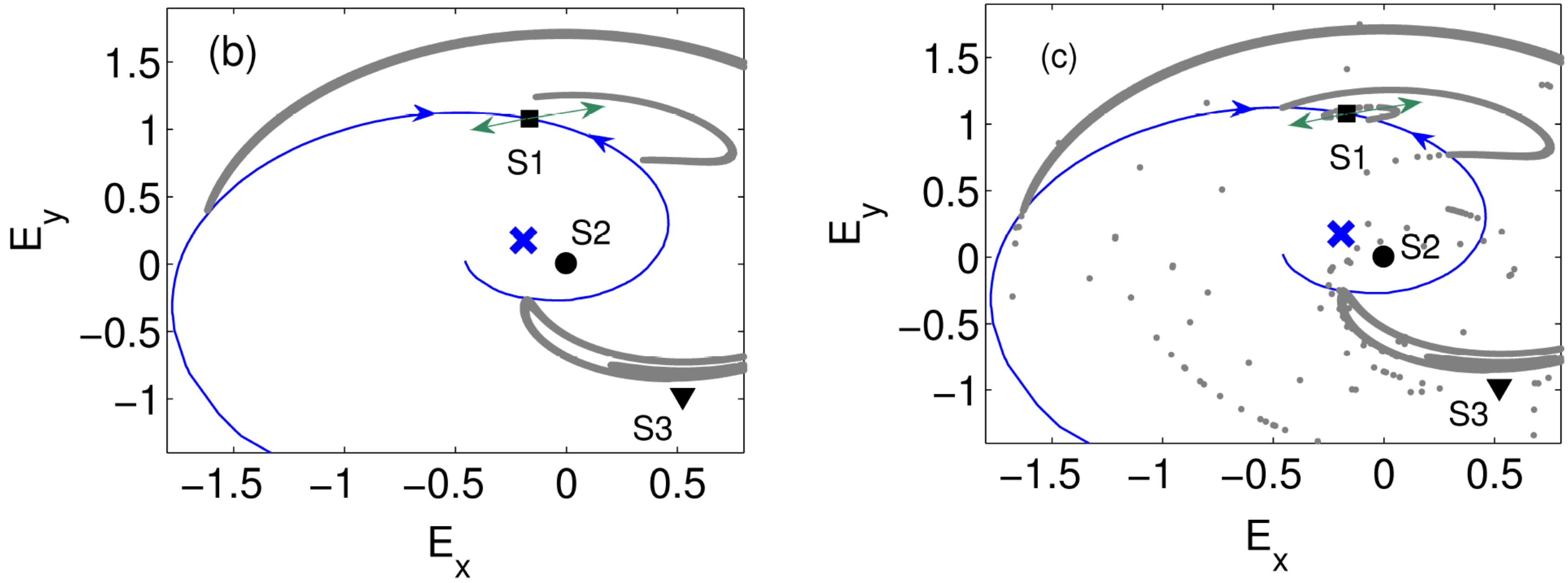


A narrow channel: the RW "door"



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

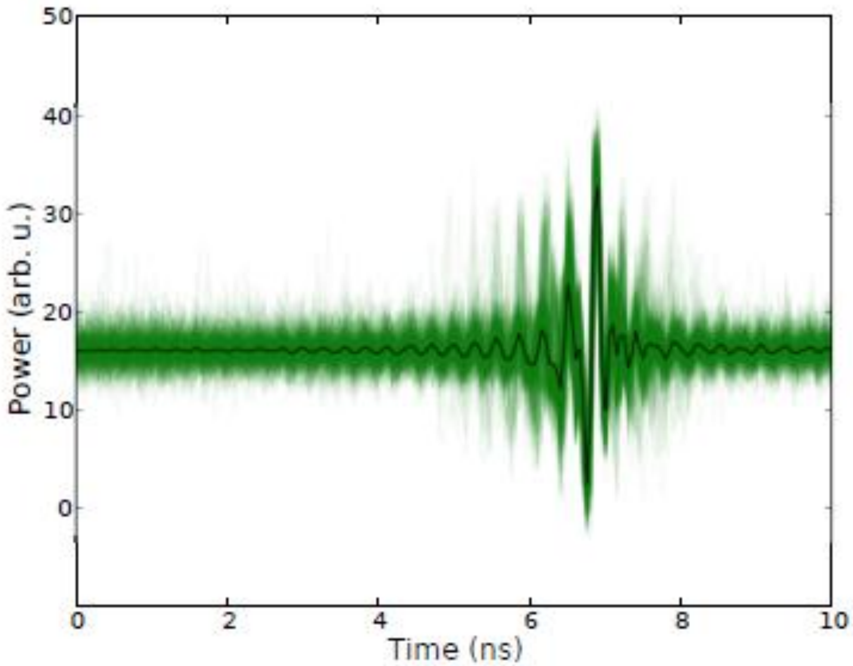
Why chaos with RWs and chaos without them?



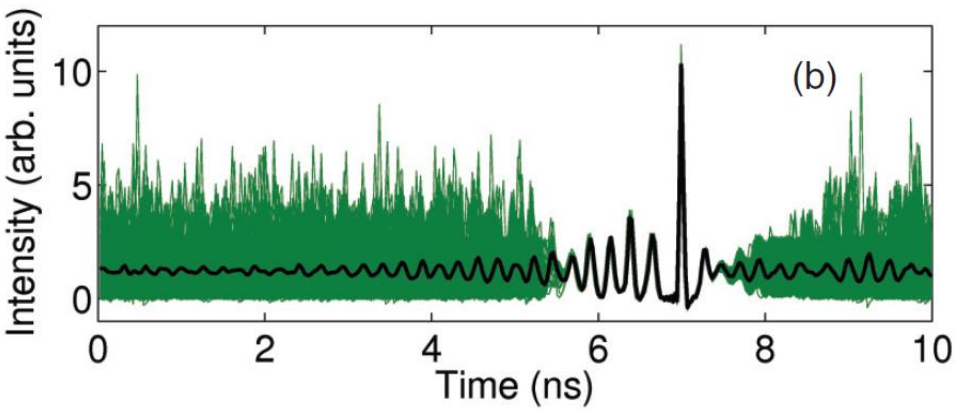
An external crises-like process enables access to the region of phase space where the stable manifold of S2 (x) is.

RW predictability

Experiments



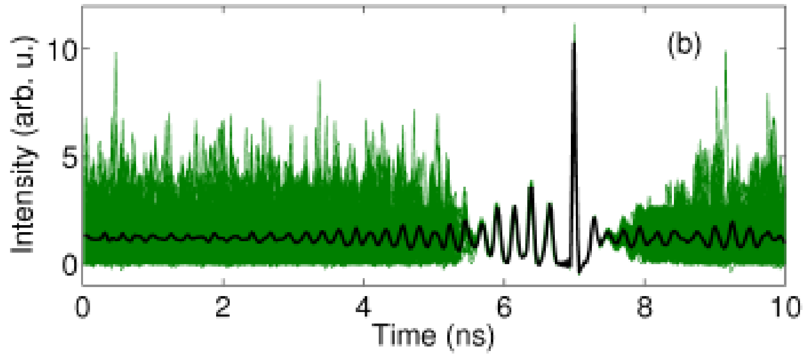
Simulations



Superposition of 500 time series at the RW peak

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

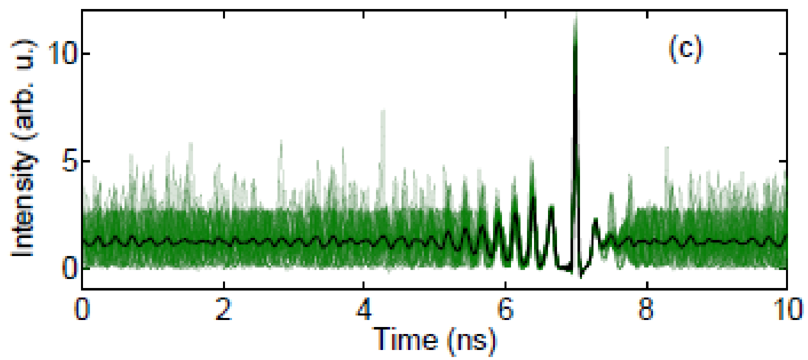
Influence of noise & RW threshold



$\langle H \rangle + 8\sigma$

$\beta_{sp} = 0$

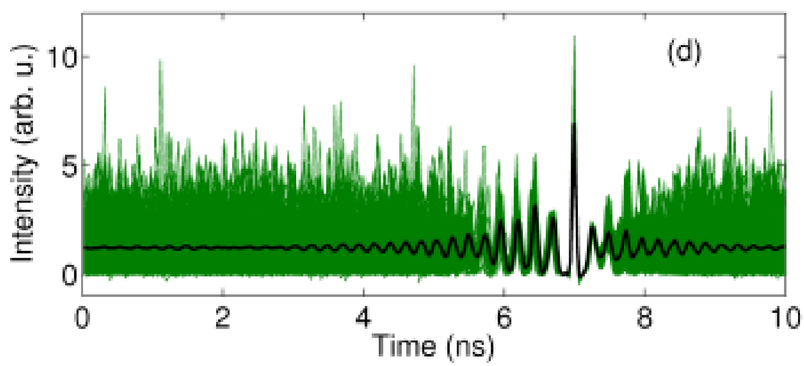
459 RWs



$\langle H \rangle + 8\sigma$

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

53 RWs



$\langle H \rangle + 4\sigma$

Number of RW in the parameter space (pump current, detuning)

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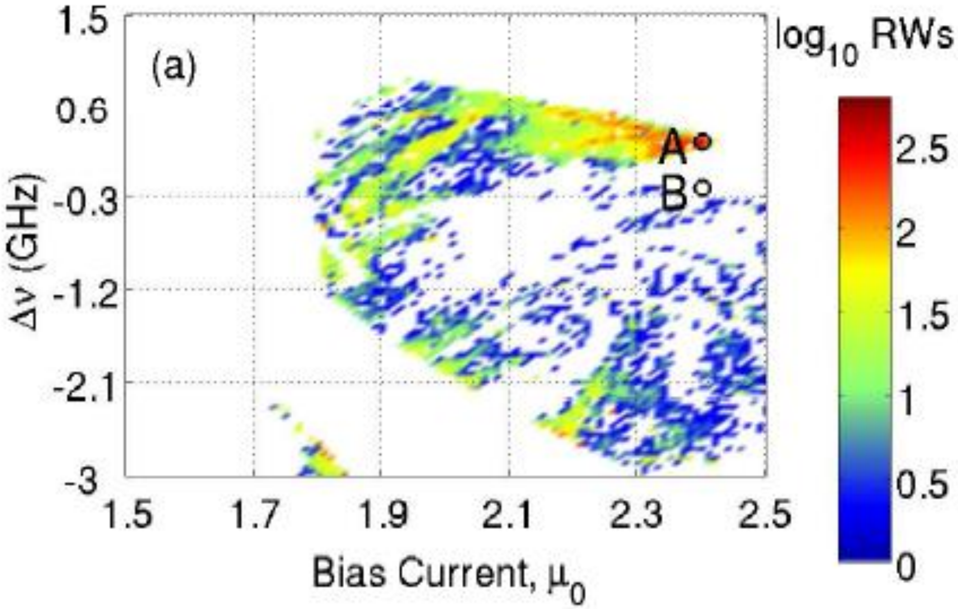
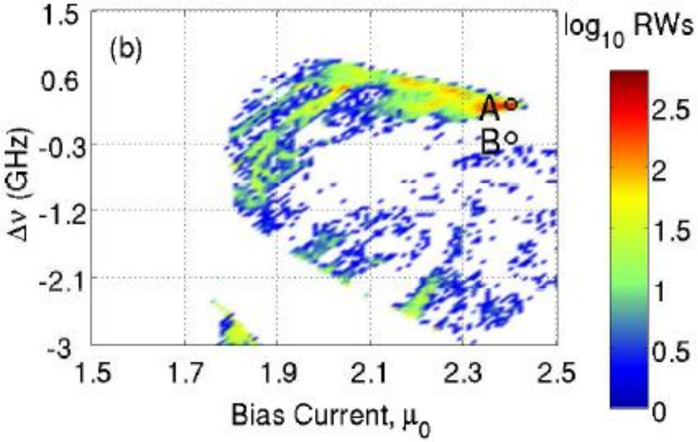
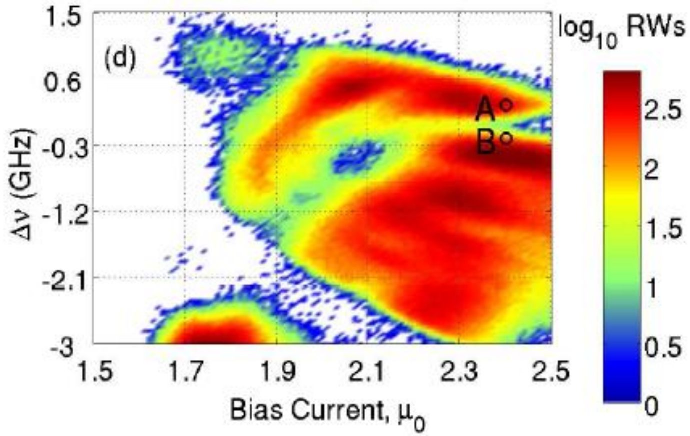
Deterministic RWs (β_{sp}=0)



Weak noise (β_{sp}=0.0001)



Stronger noise (β_{sp}=0.01)



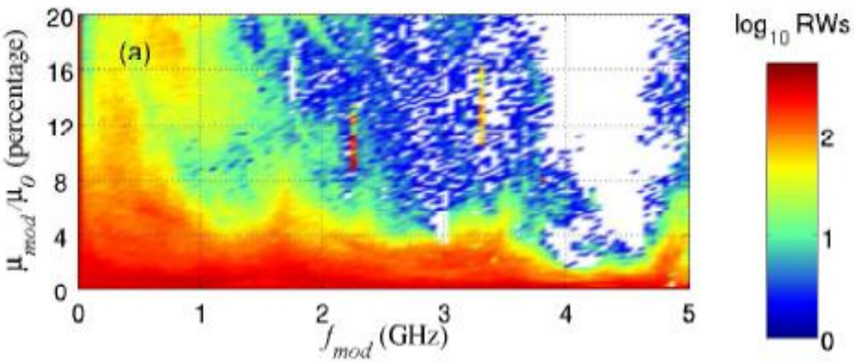
White = No RWs

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

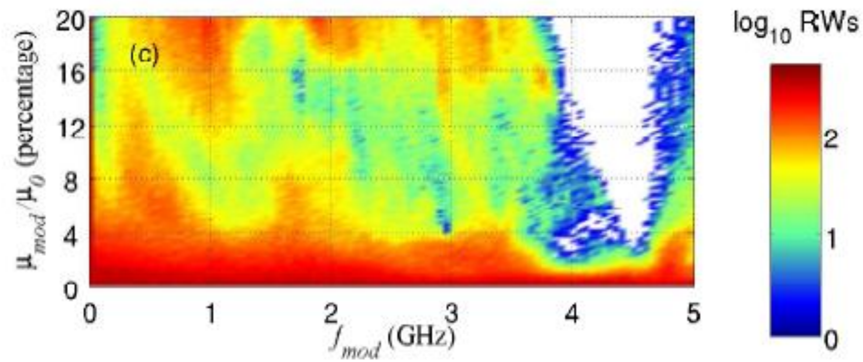
RW control in Point A (deterministic RWs)

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

β_{sp}=0



β_{sp}=0.01



White = No RWs

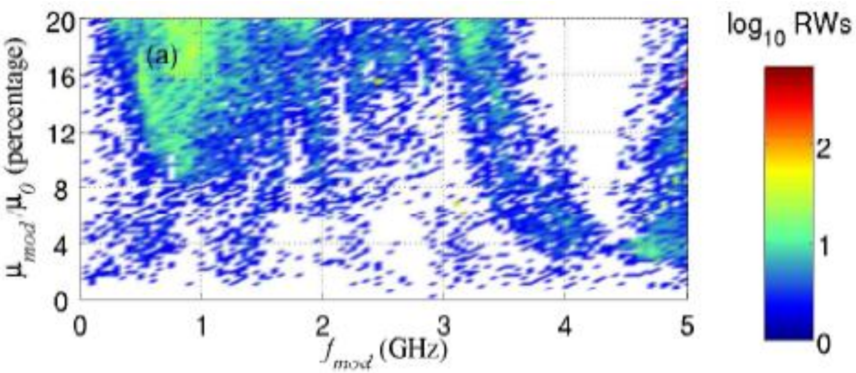
Current modulation with appropriated amplitude and frequency can completely suppress the RWs.

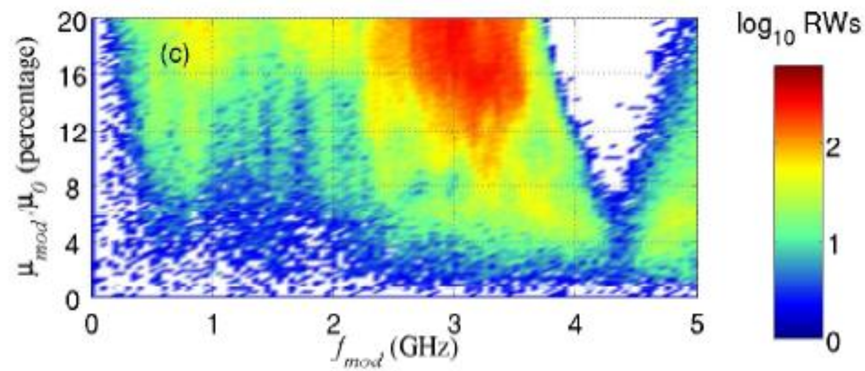
S. Perrone et al, PRA 89, 033804 (2014)

Controlling noise-induced RWs in point B (no deterministic RWs)

β_{sp}=0

β_{sp}=0.01



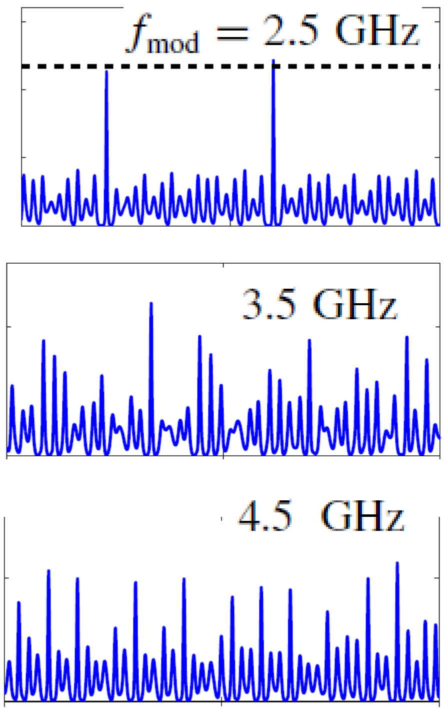


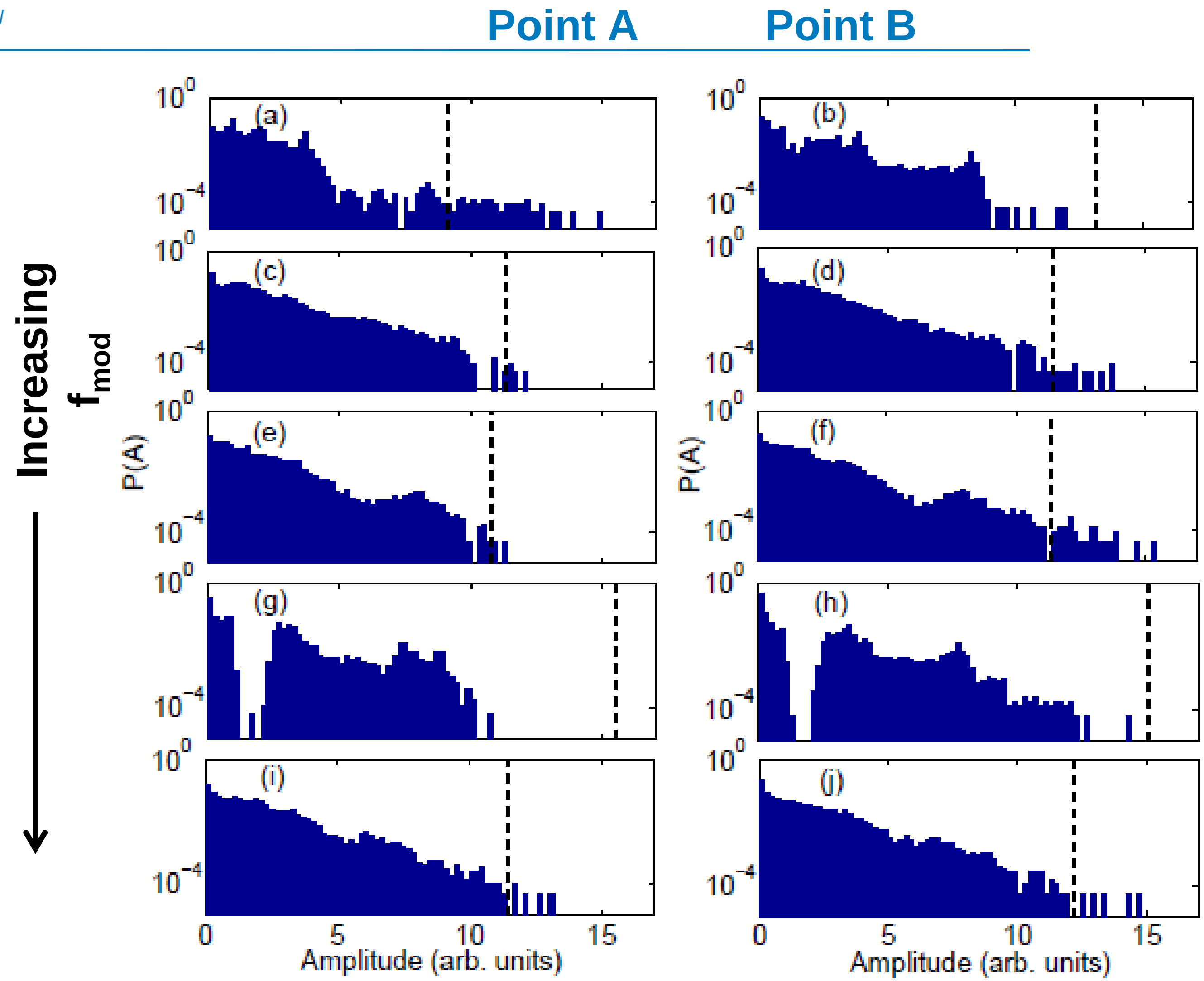
White = No RWs

Current modulation provides a "safe" parameter region (amplitude, frequency) where no RWs occur.

Histograms of pulse amplitudes

$\mu_{mod}/\mu_0 = 0.16$





RWs are suppressed because high (but not ultra high) pulses are frequent

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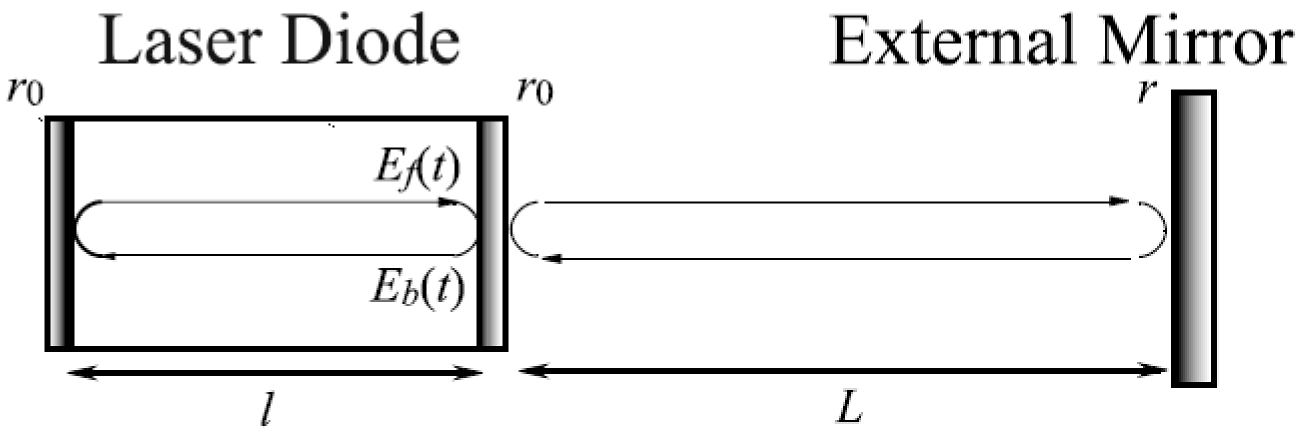
Second setup: a laser diode with optical feedback



τ=2L/c

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

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

$$TdN/ds = J - N - (1+2N)|E(s)|^2.$$

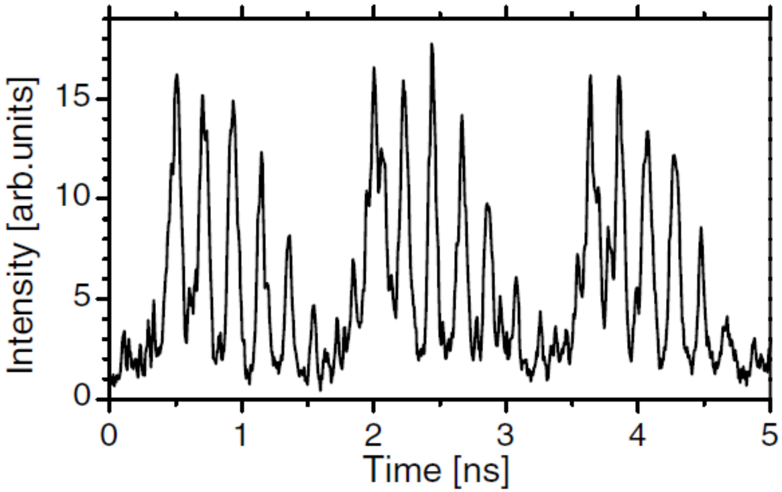
Typical parameter values:
α =5, T = 1710, θ =70, J = 1.155

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

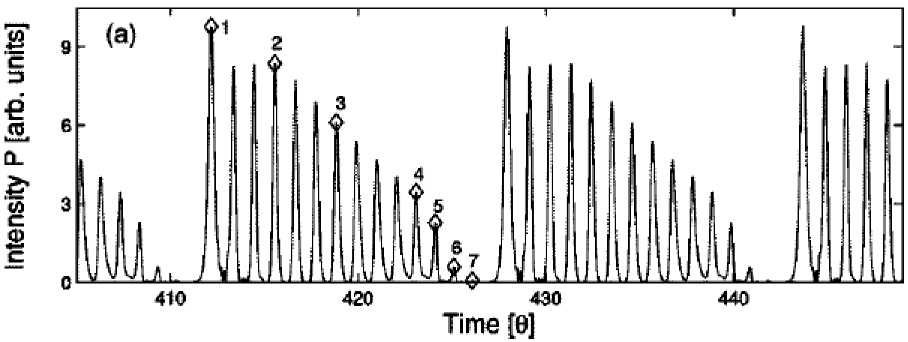
$T_{RO} = \pi\sqrt{2T/J} = 171$

Dynamics: Regular Pulse Packages (RPPs)

- Experiments

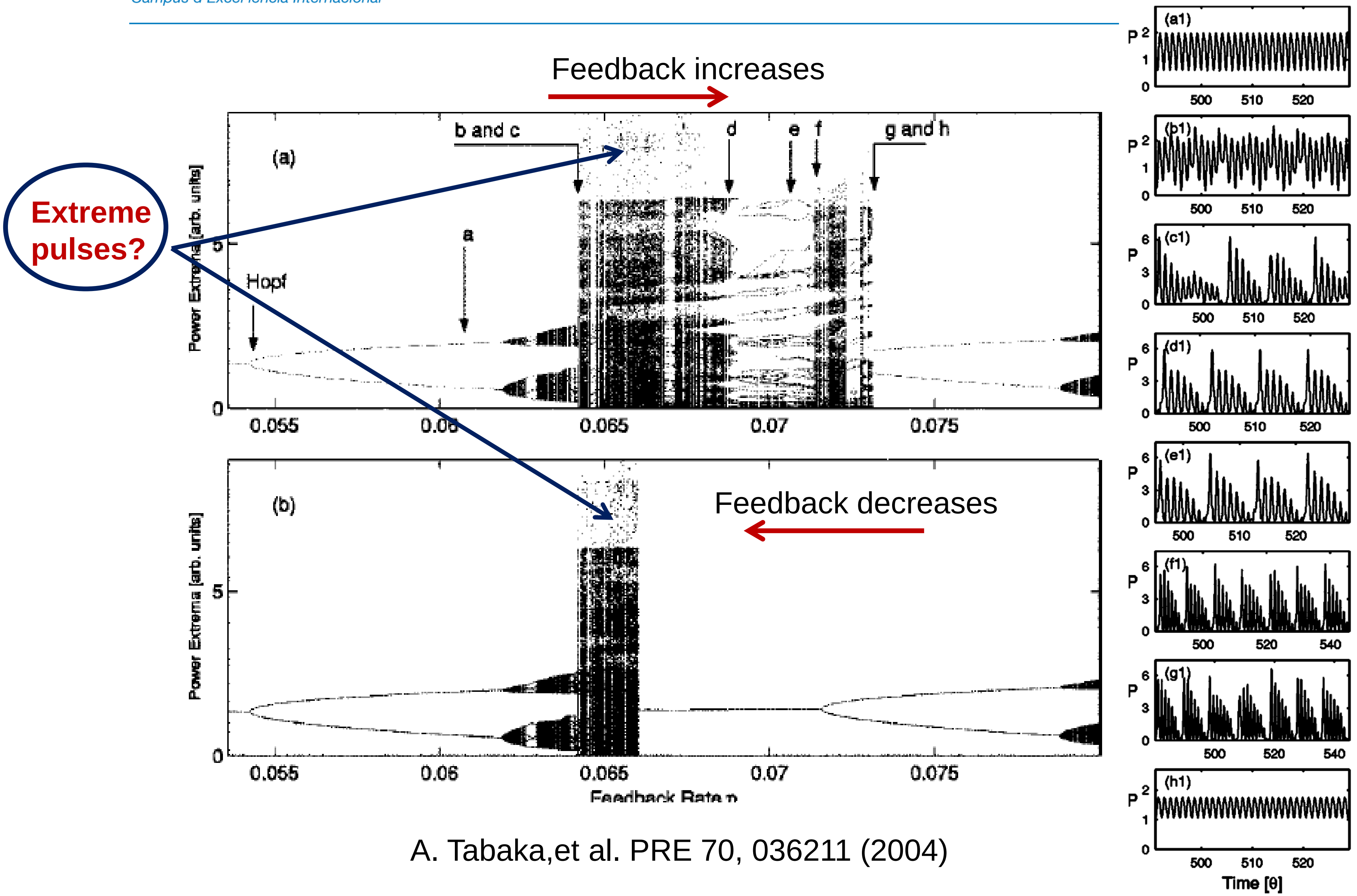


- Simulations



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

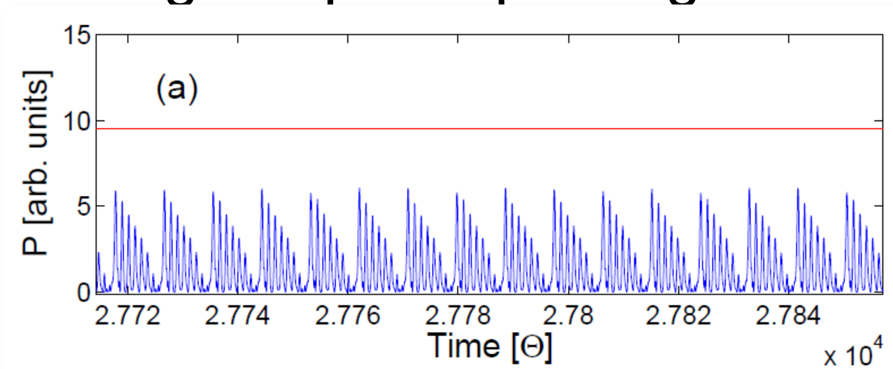
Numerical bifurcation diagram



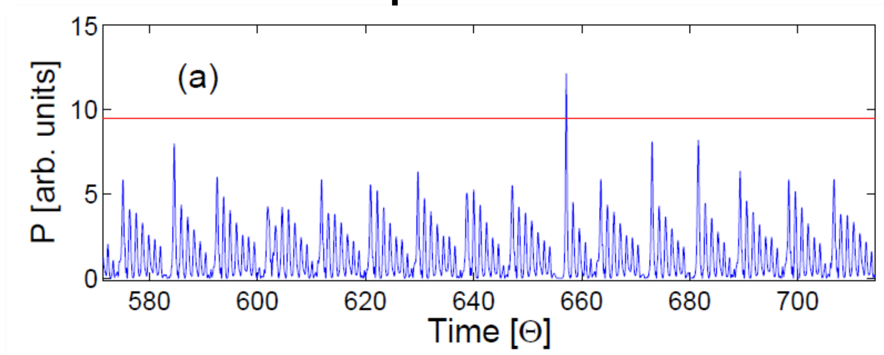
A. Tabaka,et al. PRE 70, 036211 (2004)

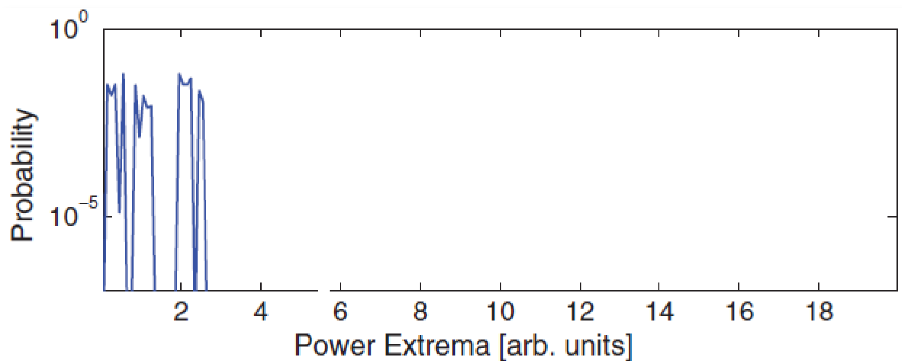
Comparison

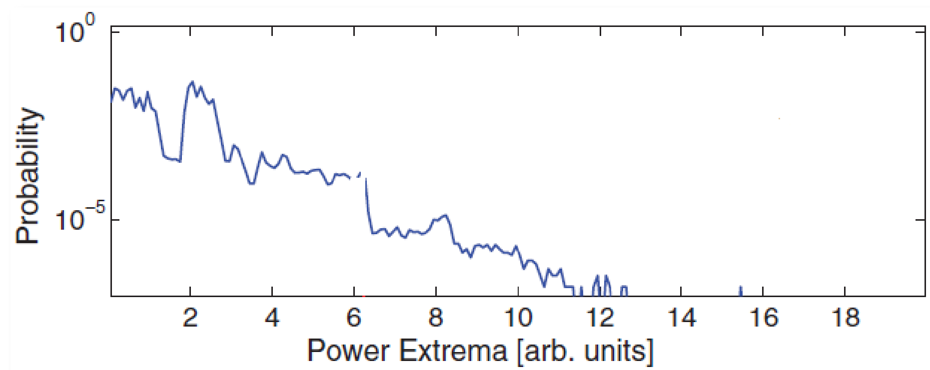
Regular pulse packages



Extreme pulses







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

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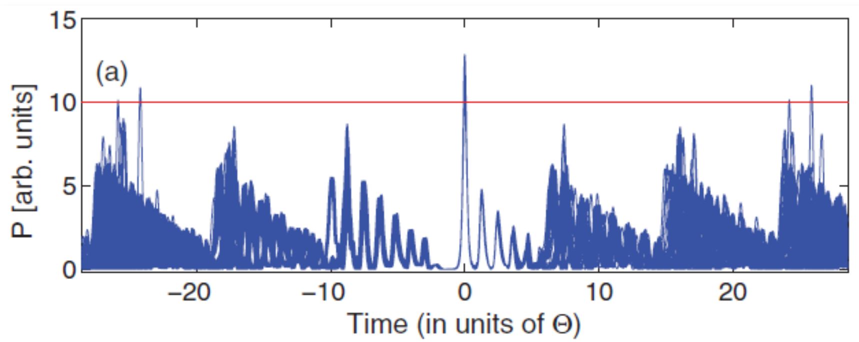
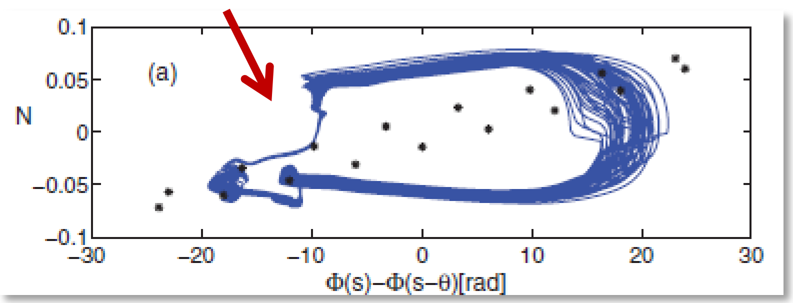
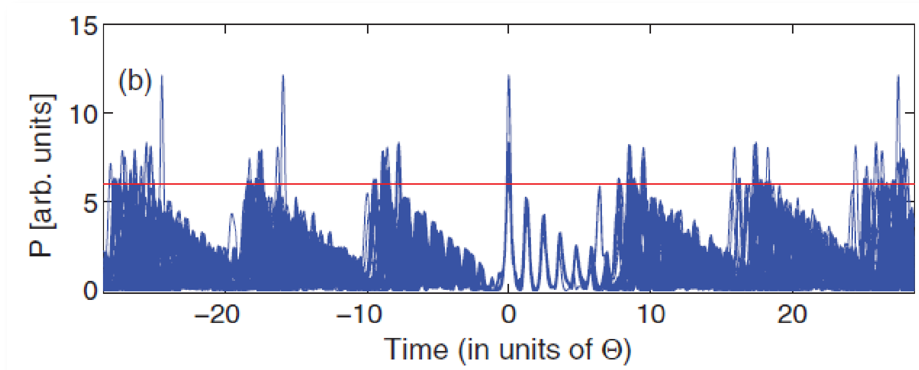
Predictability

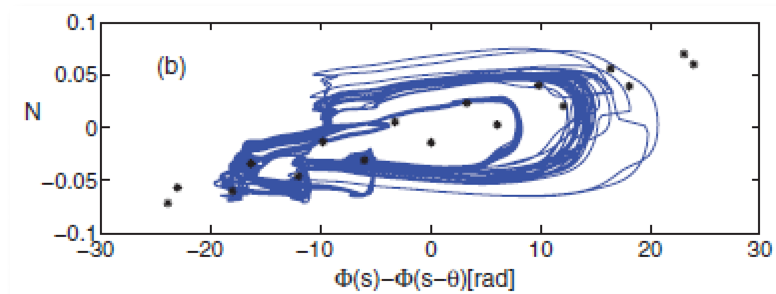
Using a high threshold



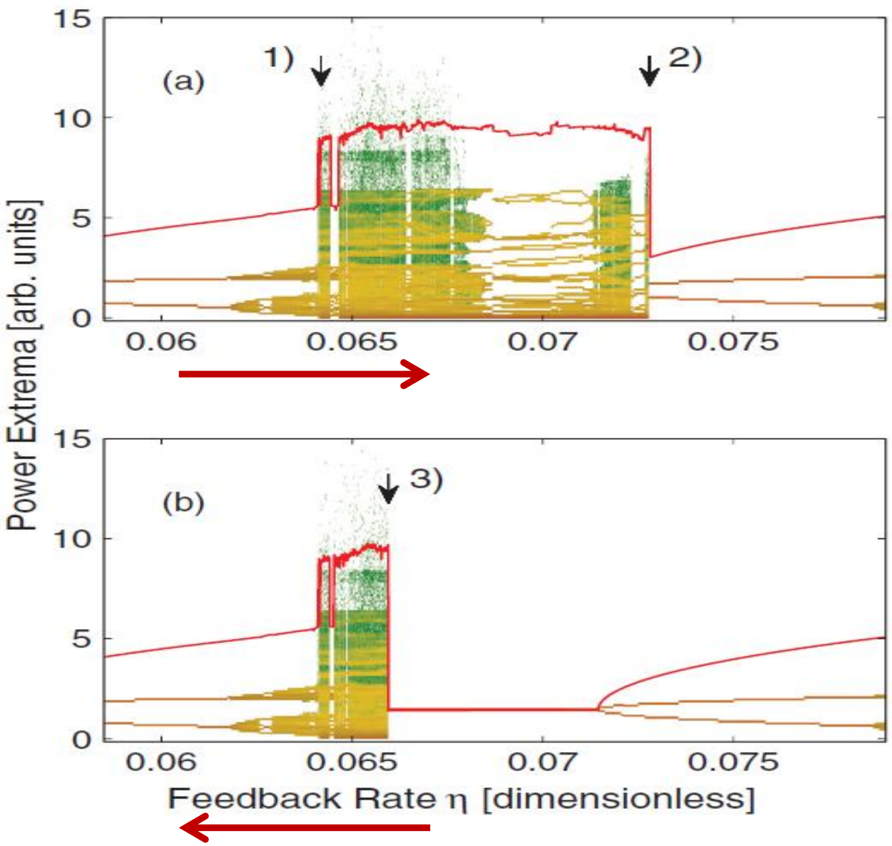


Using a lower threshold



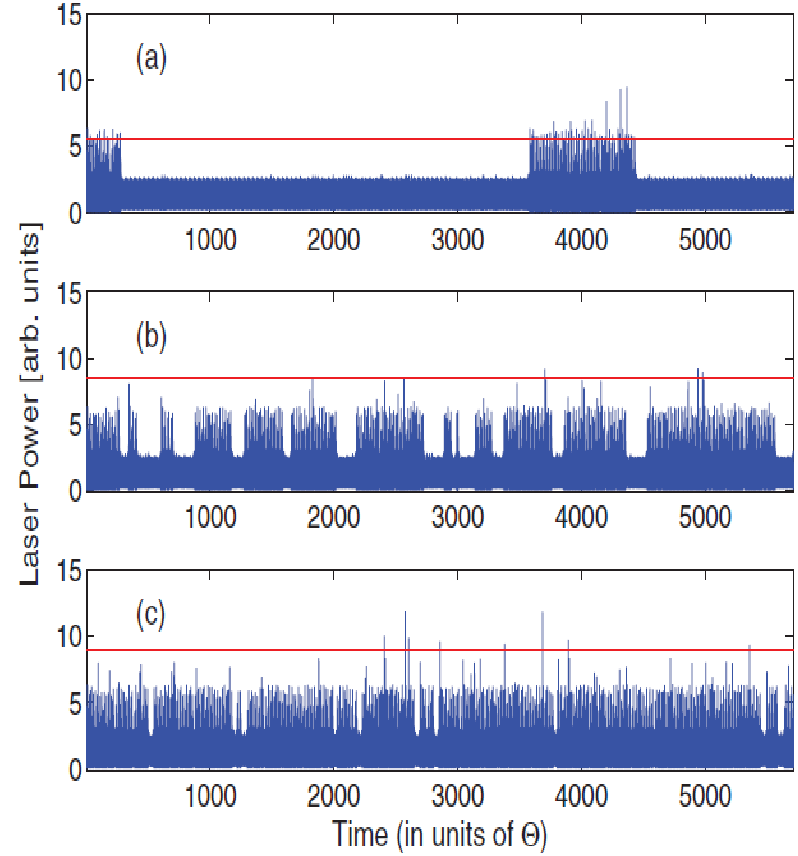


Deterministic intermittency



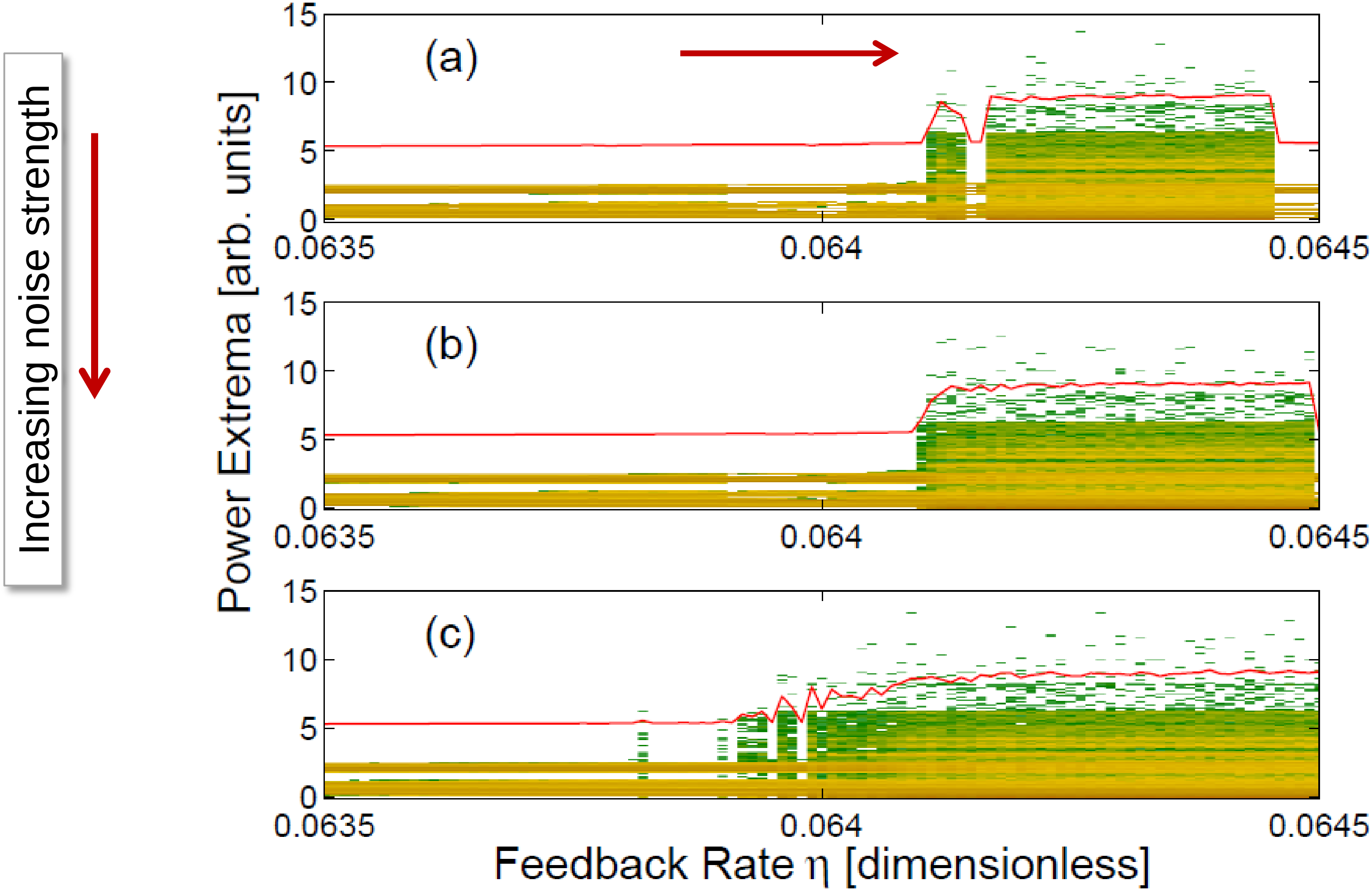
Feedback increases

At transition 1:



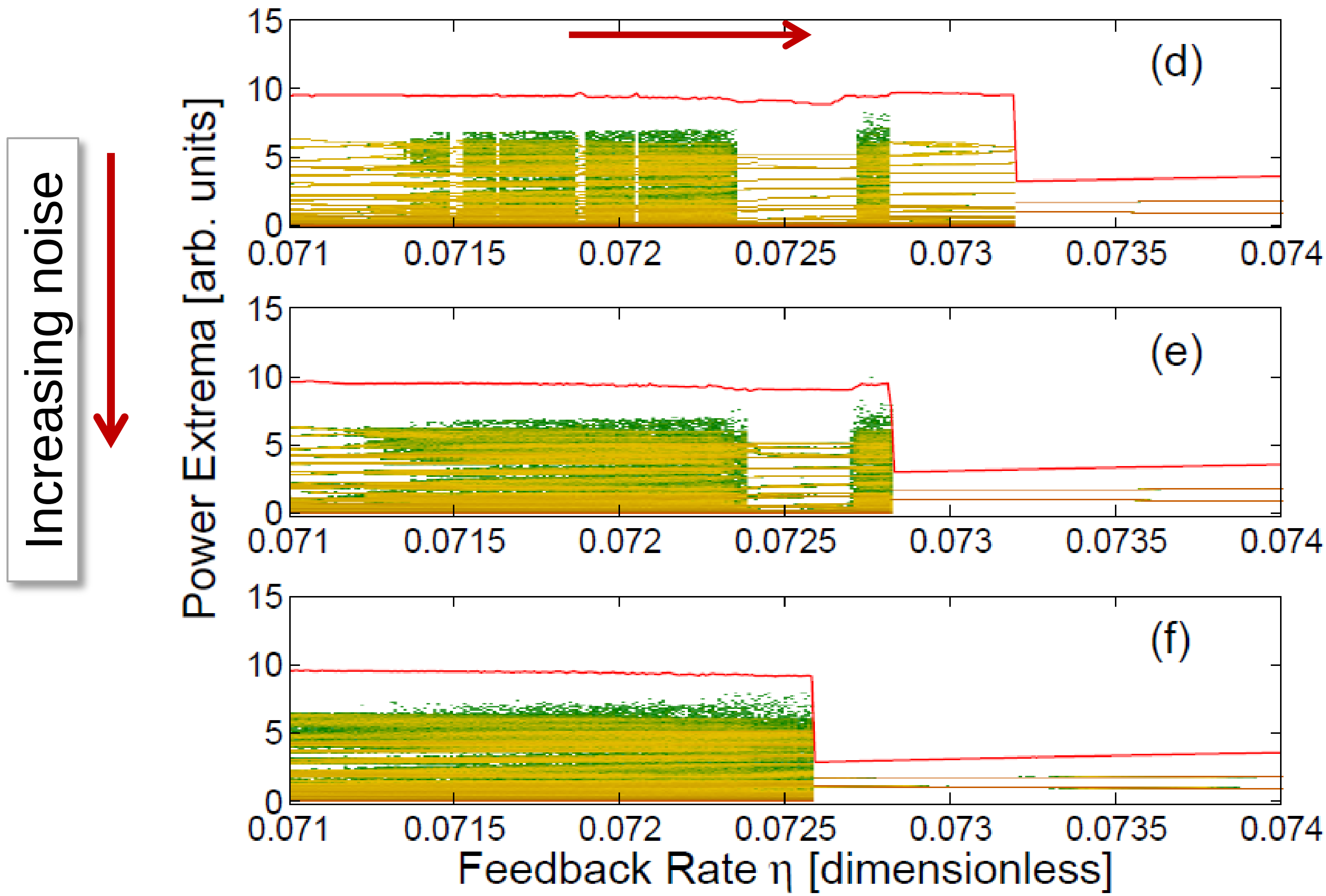
Influence of noise

- Transition 1: noise induced extreme pulses



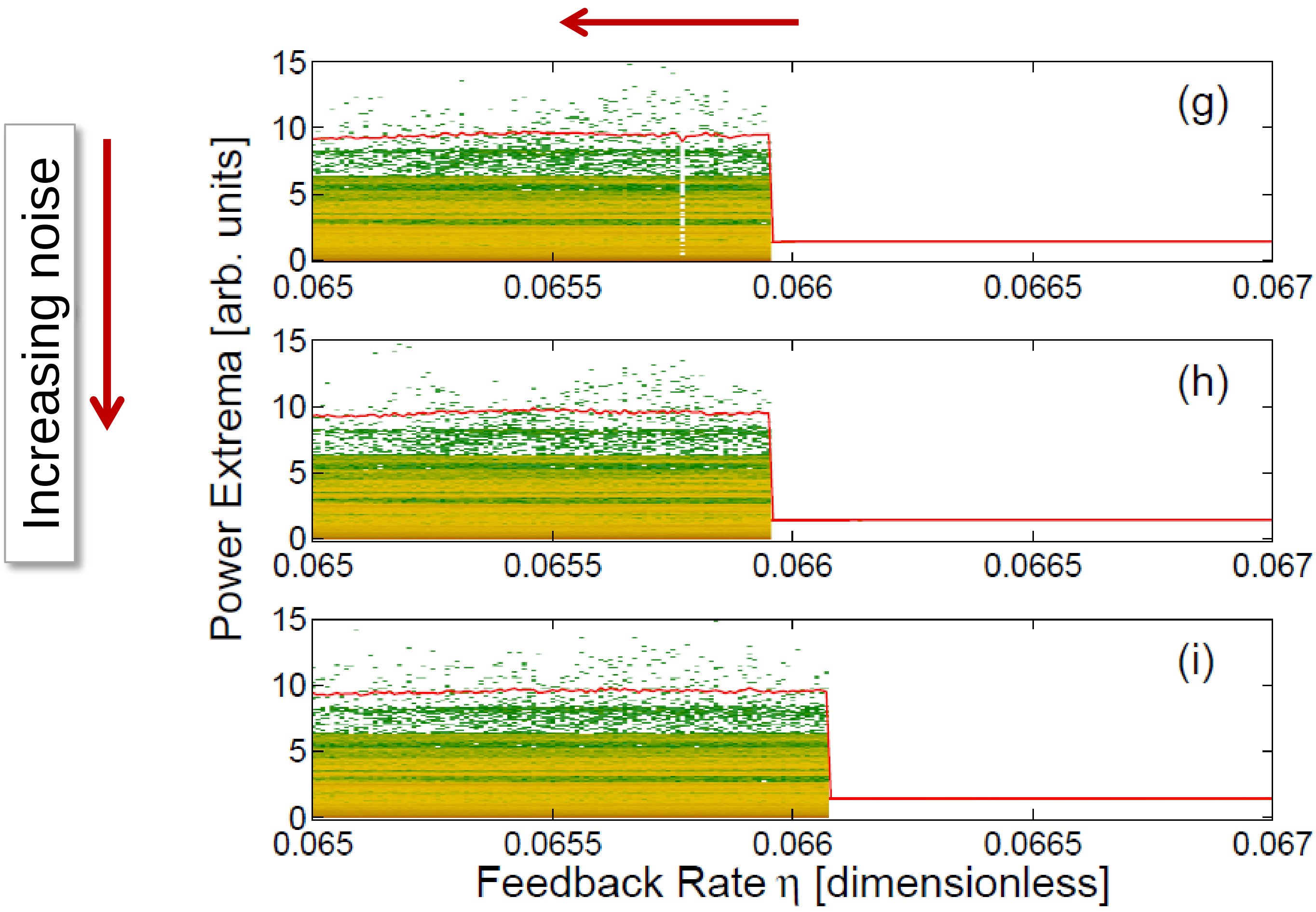
Influence of noise

- Transition 2: noise advances the switching



Influence of noise

- Transition 3: noise advances the switching



Summary

Laser with optical injection:

- **Origin** of RWs: an external crises-like process enables access to the region in phase space where RWs can be triggered.
- **Predictability**: RWs can be predicted with some anticipation.
- **Control**: noise and modulation strongly affects their probability of occurrence.

Lasers with optical feedback:

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

Ongoing work: modulation-induced periodicity in the RW waiting times?

THANK YOU FOR YOUR ATTENTION !

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

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