Extreme Optical Pulses: Prediction and Generation On-Demand

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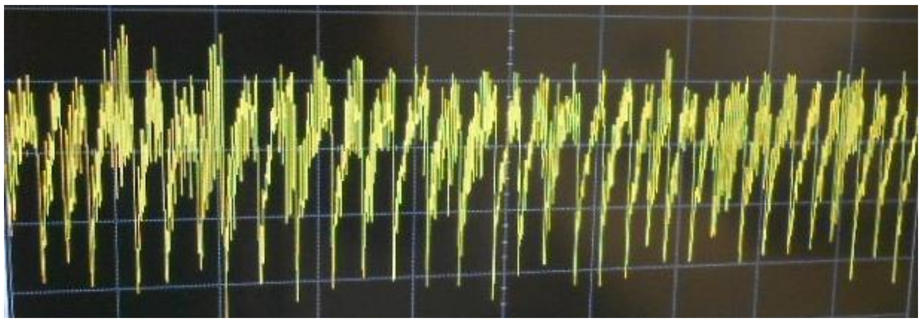
ICREA

GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA E INNOVACIÓN

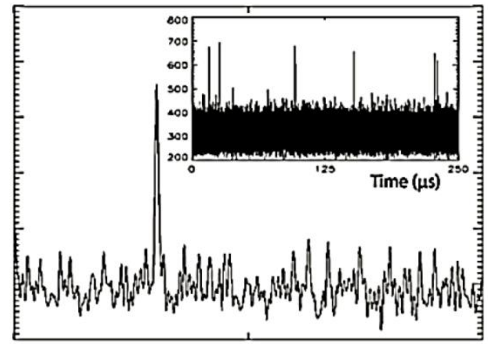
Lasers provide “big data” for testing analysis tools

- Diode laser with time-delayed optical feedback



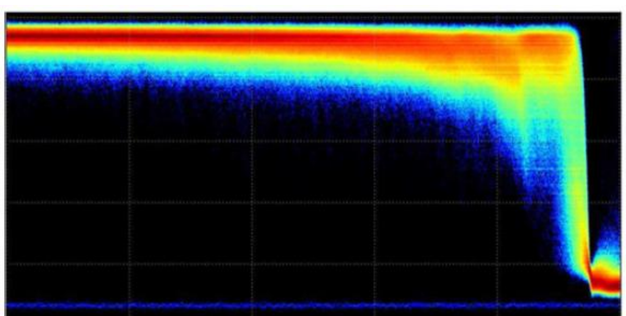
Time

- Extreme pulses
  diode laser with injection



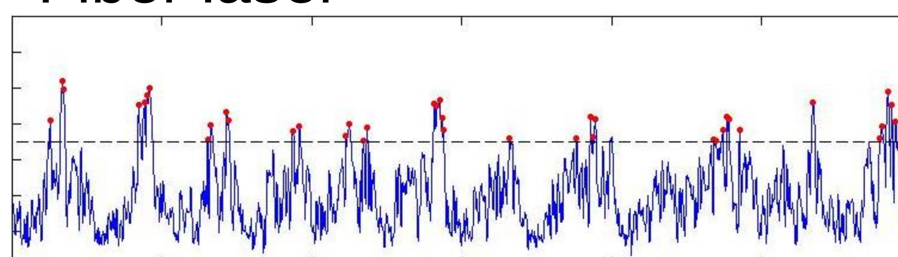
Time

- Polarization switching
  VCSEL



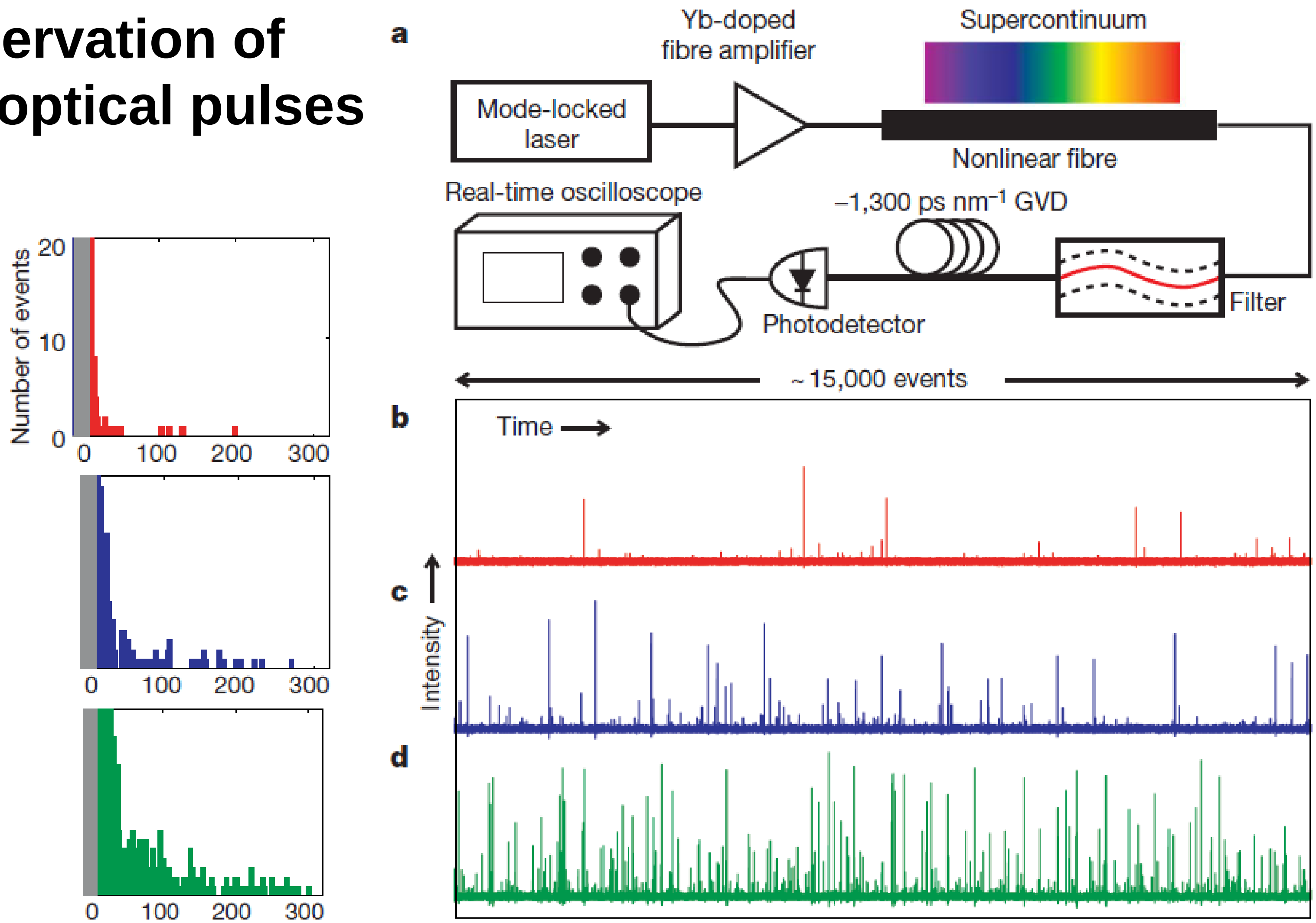
Time

- Transition to optical turbulence
  Fiber laser



Time

First observation of extreme optical pulses



Solli et al, Nature 2007

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

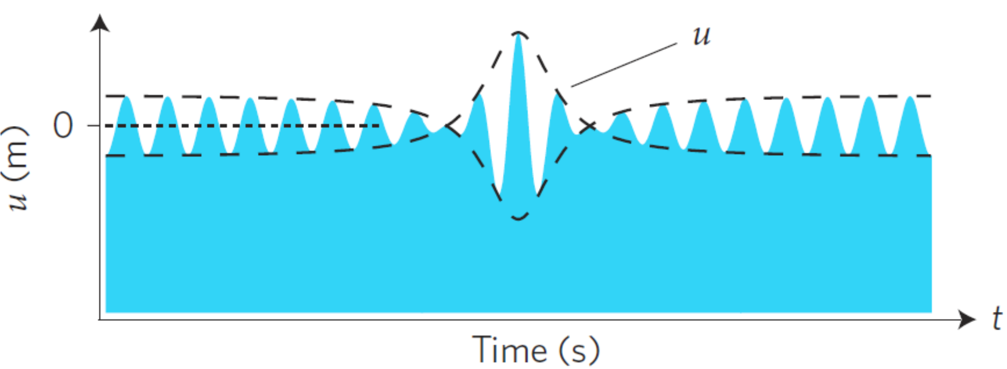
Deep water wave group envelope

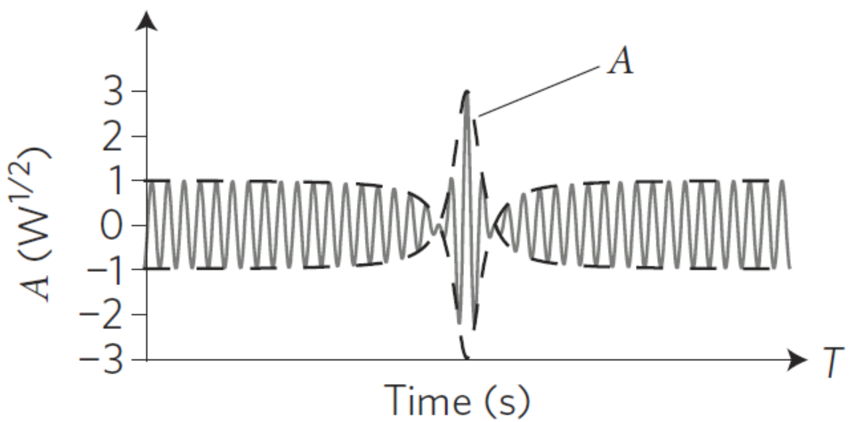
$$i\frac{\partial u}{\partial z} - \frac{k_0}{\omega_0^2}\frac{\partial^2 u}{\partial t^2} - k_0^3|u|^2 u = 0$$

Light pulse envelope in fibre

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

Soliton on finite background





NATURE PHOTONICS | VOL 8 | OCTOBER 2014 |

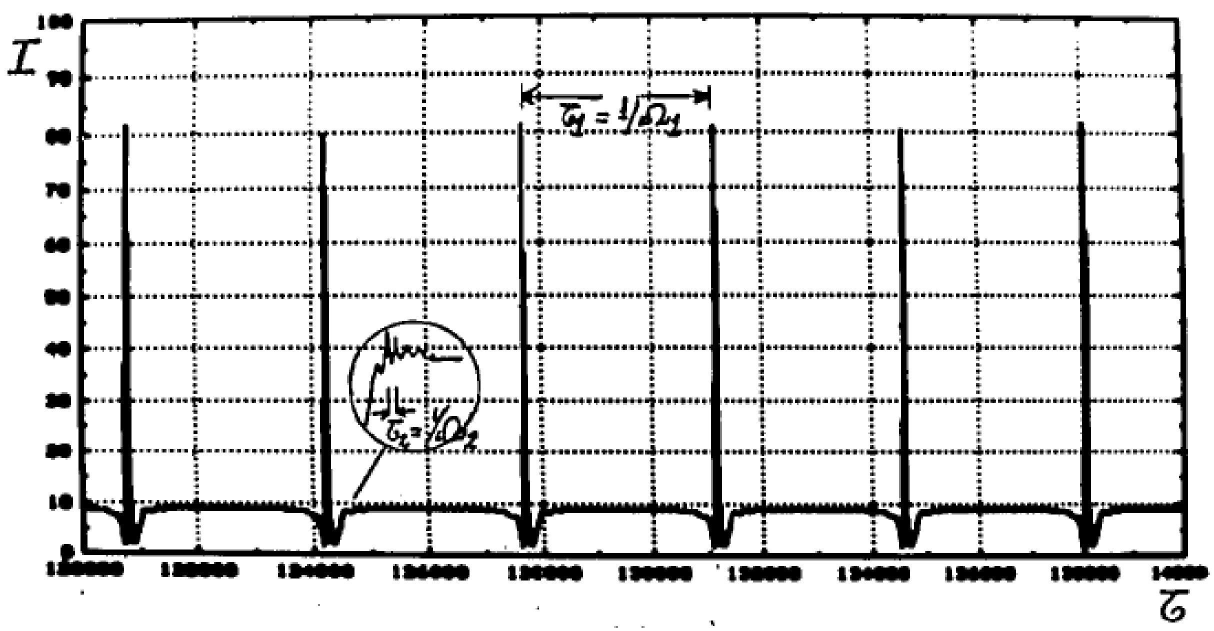
Initial idea: “rogues waves that appear from nowhere and disappear without a trace”

Instabilities in lasers with an injected signal

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

Istituto Nazionale di Ottica, Largo E. Fermi 6, I50125 Firenze, Italy

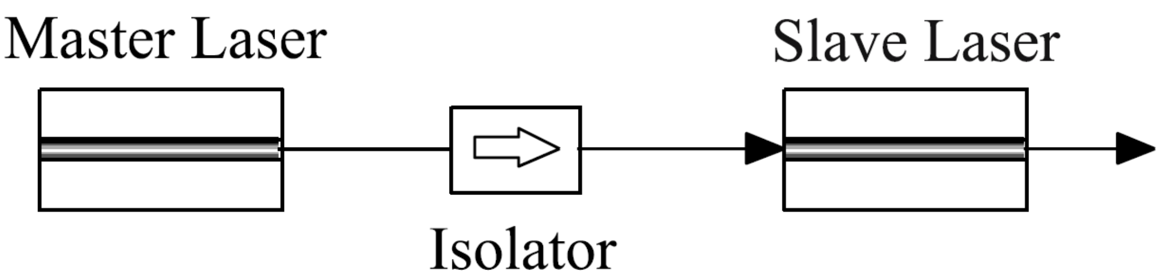
178 J. Opt. Soc. Am. B/Vol. 2, No. 1/January 1985

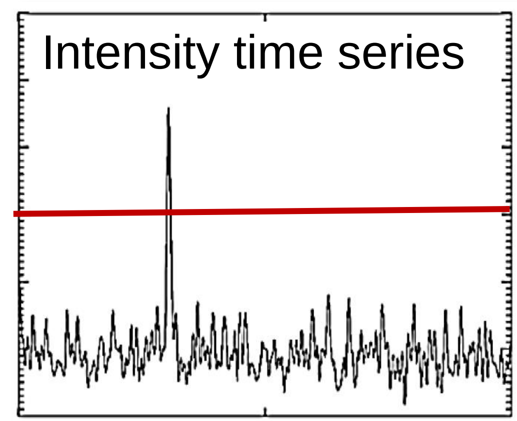


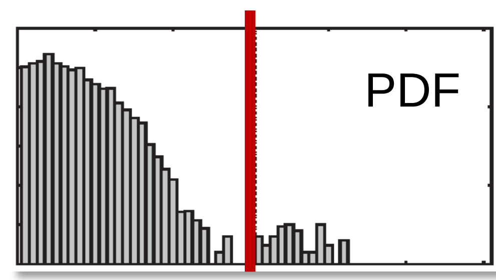
PRL **107,** 053901 (2011) PHYSICAL REVIEW LETTERS week ending 29 JULY 2011

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)

RW: pulse above

<A> + **6-8** σ

Questions

In our system:

- Which mechanism induces ultra-high pulses?
- Role of noise?
- Is it possible to suppress them?
- Can they be predicted ?
- Can they be generated “on demand”?

Rogue Wave predictability?

… "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."

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

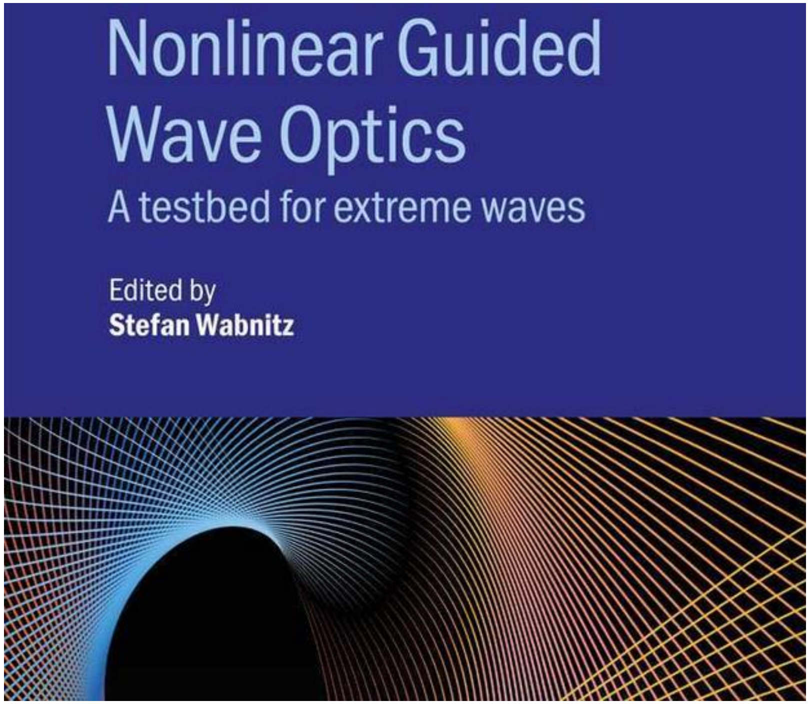
December 2017

Chapter 1

⇐ **Open access**

Extreme events in forced oscillatory media in zero, one and two dimensions

S Barland, M Brambilla, L Columbo, B Garbin, C J Gibson, M Giudici, F Gustave, C Masoller, G L Oppo, F Prati, C Rimoldi, J R Rios, J R Tredicce, G Tissoni, P Walczak, A M Yao and J Zamora-Munt



-0D
-1D
-2D

J. Opt. **18** (2016) 063001 (37pp)

Roadmap on optical rogue waves and extreme events

Nail Akhmediev[1,22], Bertrand Kibler[2], Fabio Baronio[3], Milivoj Belić[4], Wei-Ping Zhong[5], Yiqi Zhang[6], Wonkeun Chang[1], Jose M Soto-Crespo[7], Peter Vouzas[1], Philippe Grelu[2], Caroline Lecaplain[8], K Hammani[2], S Rica[9], A Picozzi[2], Mustapha Tlidi[10], Krassimir Panajotov[11], Arnaud Mussot[12], Abdelkrim Bendahmane[12], Pascal Szriftgiser[12], Goery Genty[13], John Dudley[14], Alexandre Kudlinski[12], Ayhan Demircan[15], Uwe Morgner[15], Shalva Amiraranashvili[16], Carsten Bree[16], Günter Steinmeyer[17], C Masoller[18], Neil G R Broderick[19], Antoine F J Runge[19], Miro Erkintalo[19], S Residori[20], U Bortolozzo[20], F T Arecchi[21], Stefan Wabnitz[3], C G Tiofack[12], S Coulibaly[12] and M Taki[12]

Governing equations

Complex field, **E –Laser intensity ~ |E|²**

Carrier density, **N**

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

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

optical injection

η: injection strength

$\Delta\omega = \omega_s - \omega_m$: detuning

spontaneous emission noise

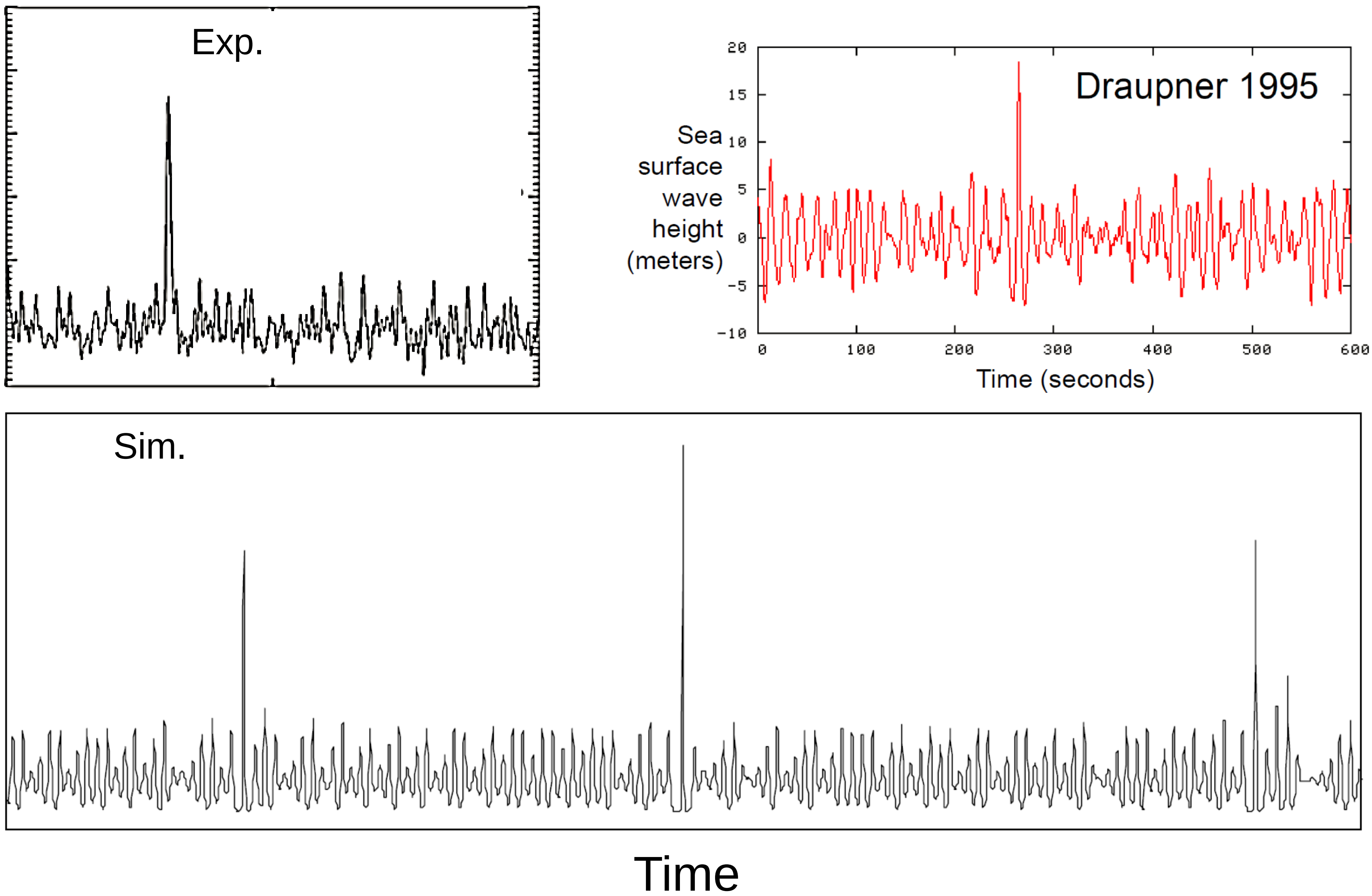
Solitary laser parameters: **α τ_p τ_N μ**

μ: normalized pump current parameter

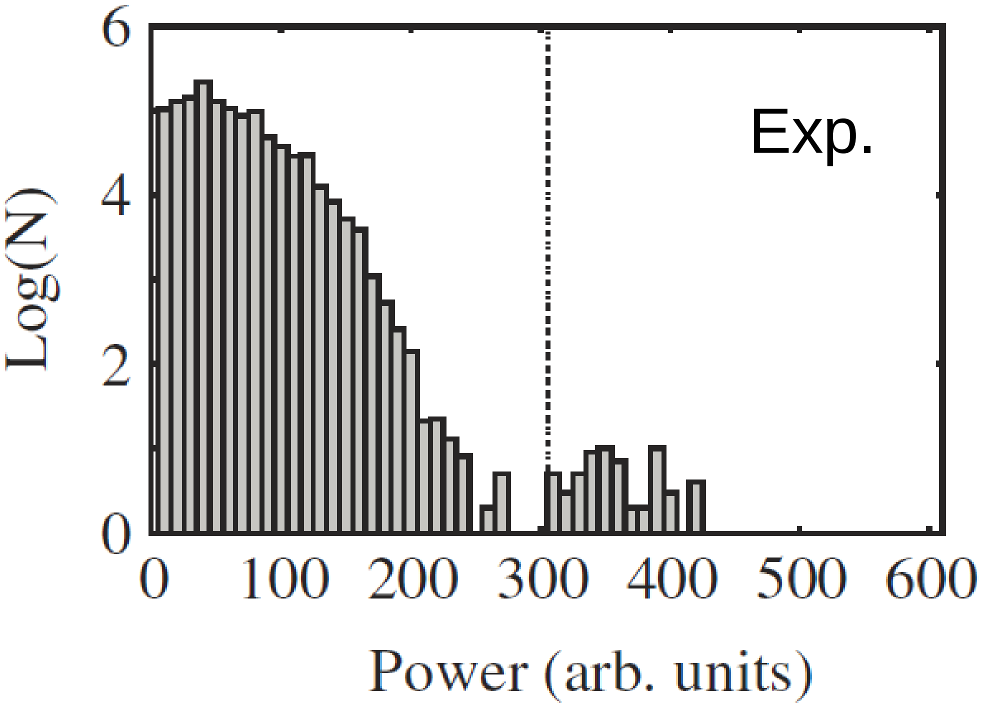
Typical parameter values:

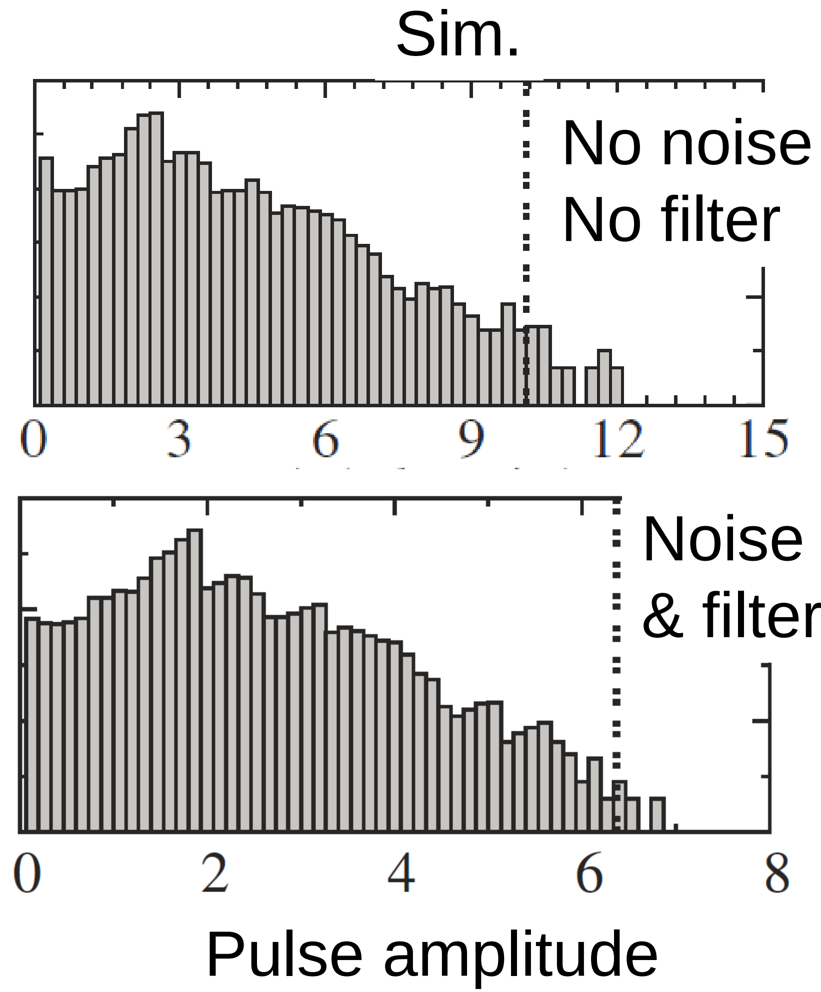
$\alpha = 3$, $\tau_p = 1$ ps, $\tau_N = 1$ ns

These 0D rate-equations provide good qualitative agreement with the experimentally observed intensity dynamics.

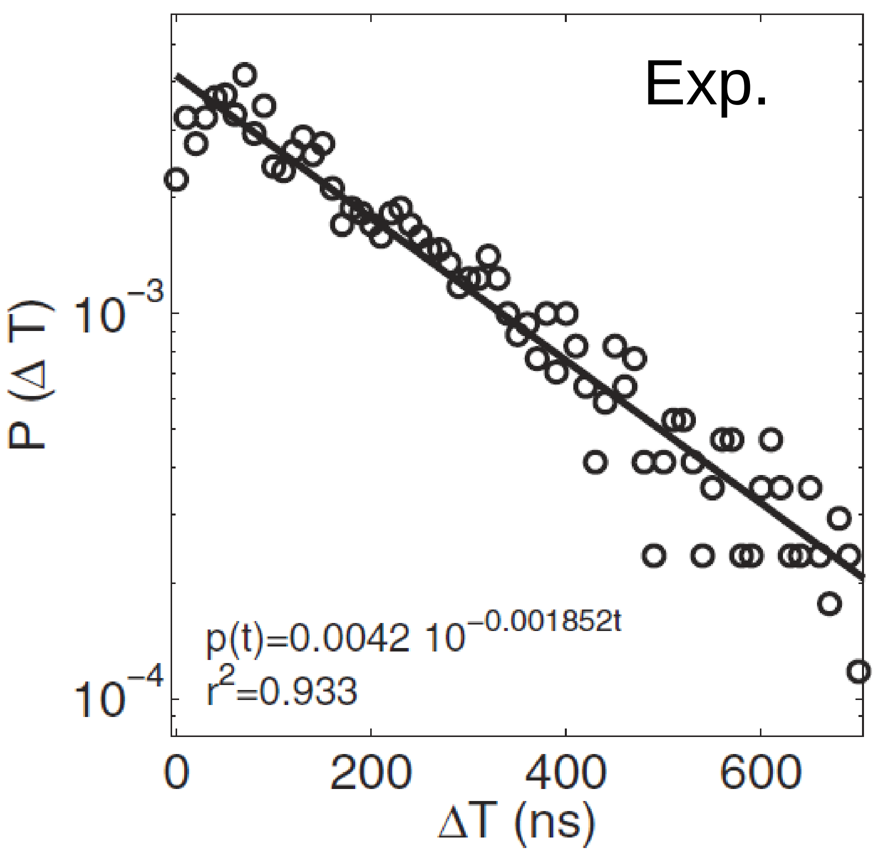

Exp.
Draupner 1995
Sea surface wave height (meters)
20
15
10
5
0
-5
-10
0
100
200
300
400
500
600
Time (seconds)
Sim.
Time

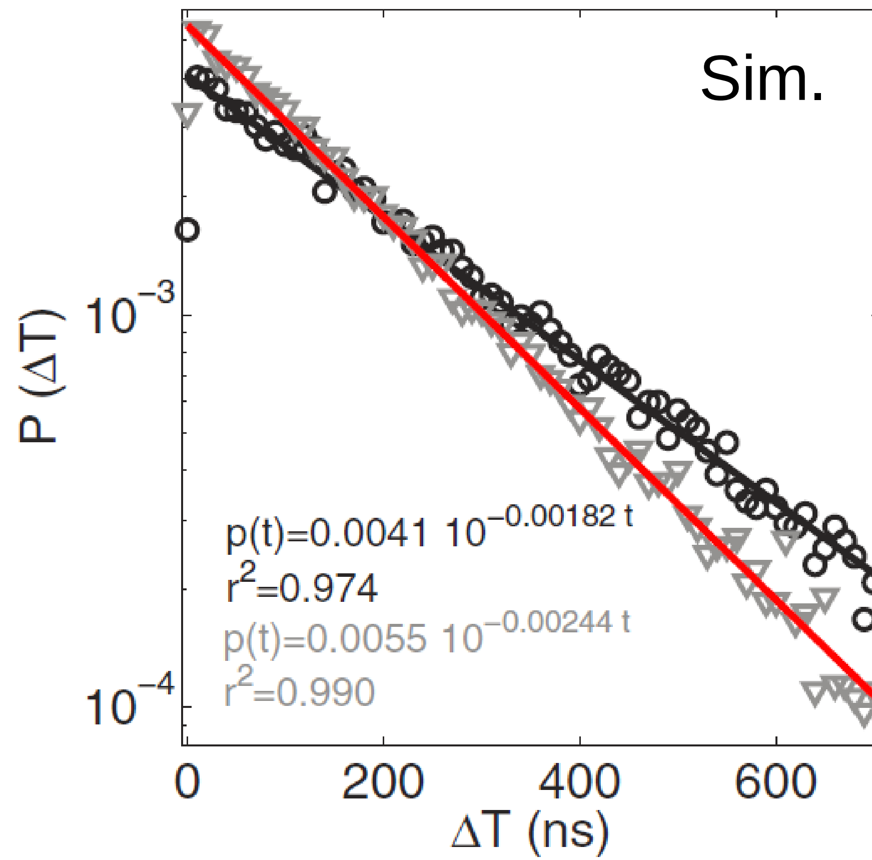
Distribution of pulse amplitudes



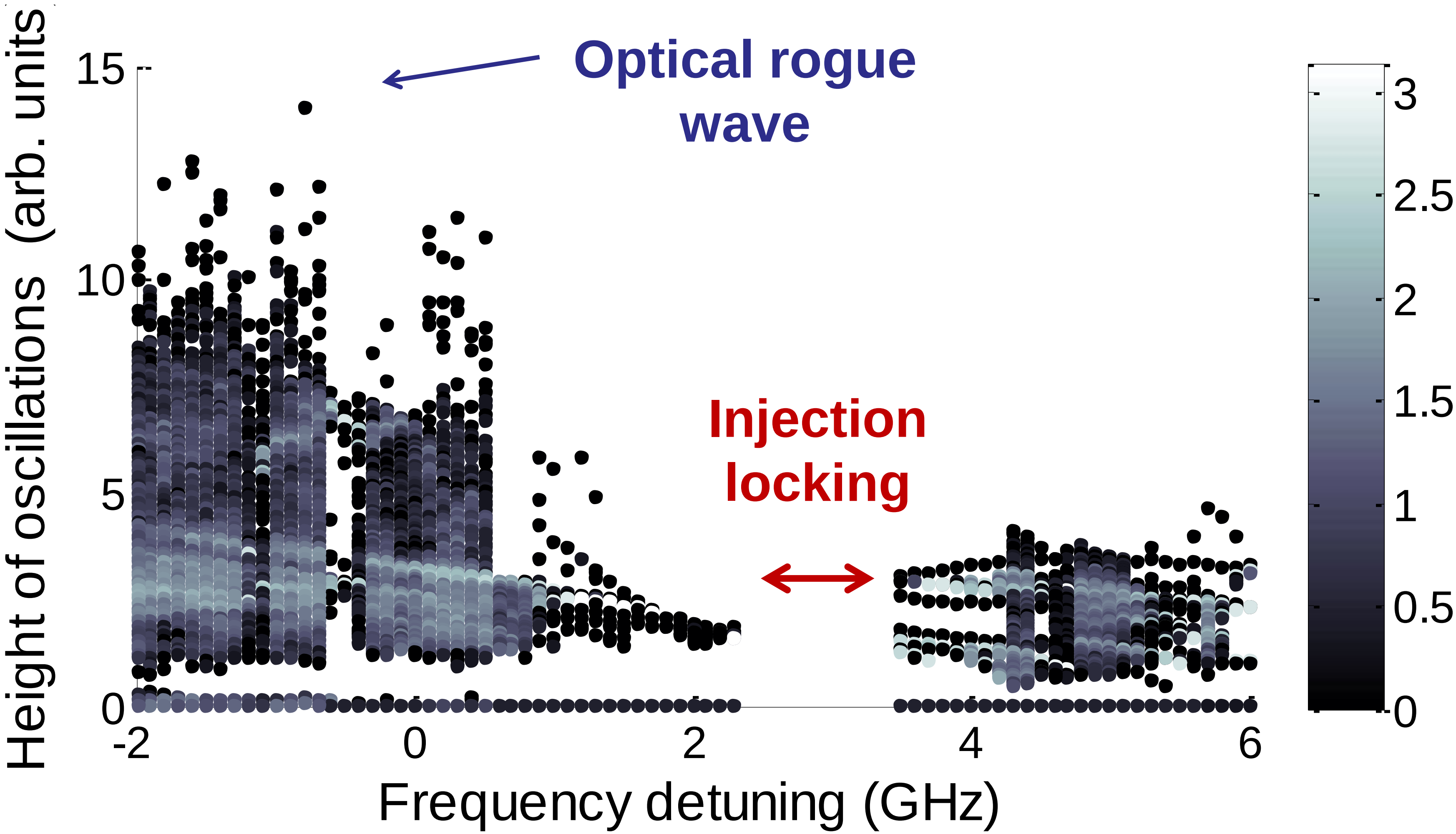


Distribution of waiting times: quantitative agreement in stochastic simulations

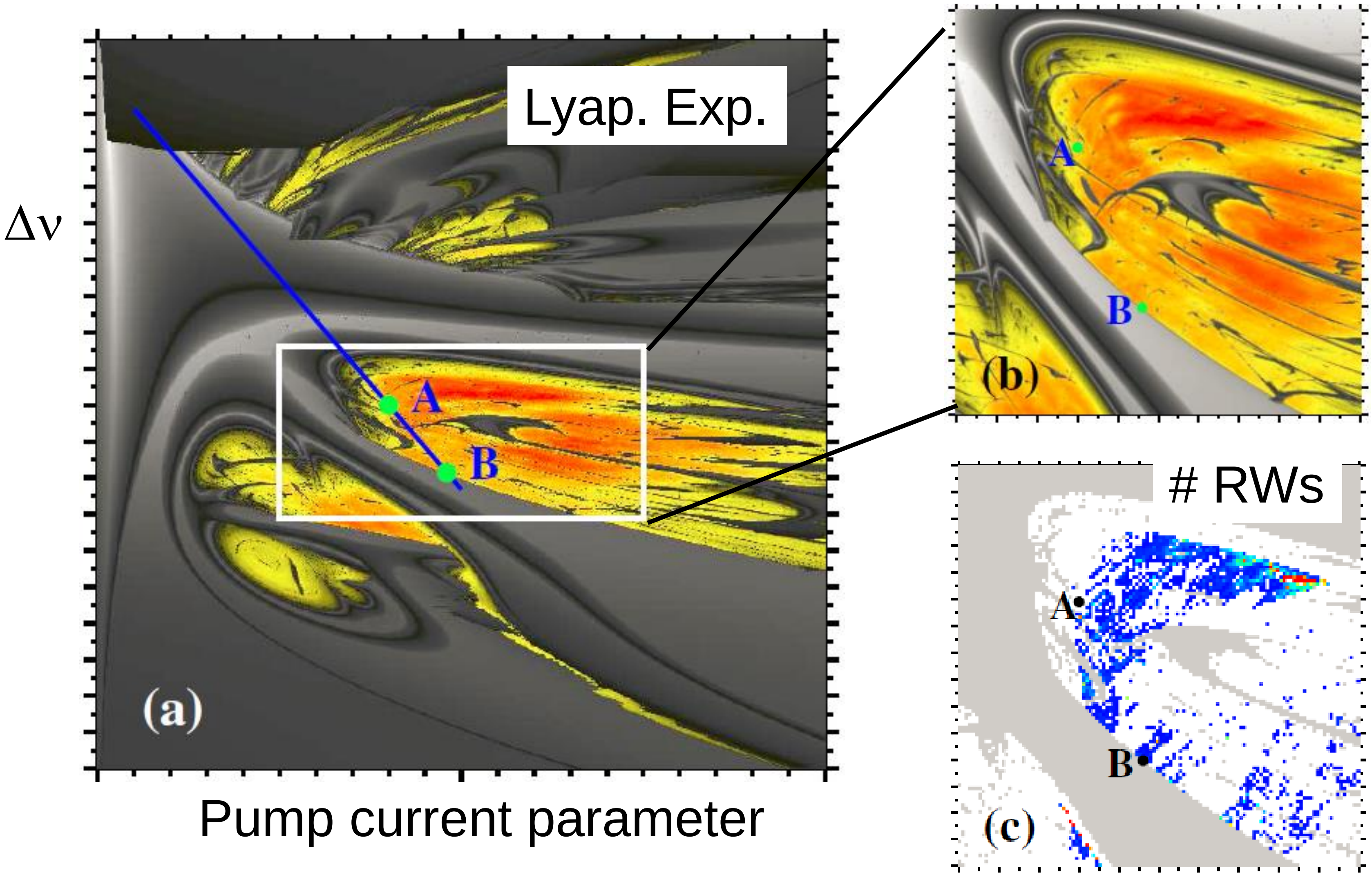




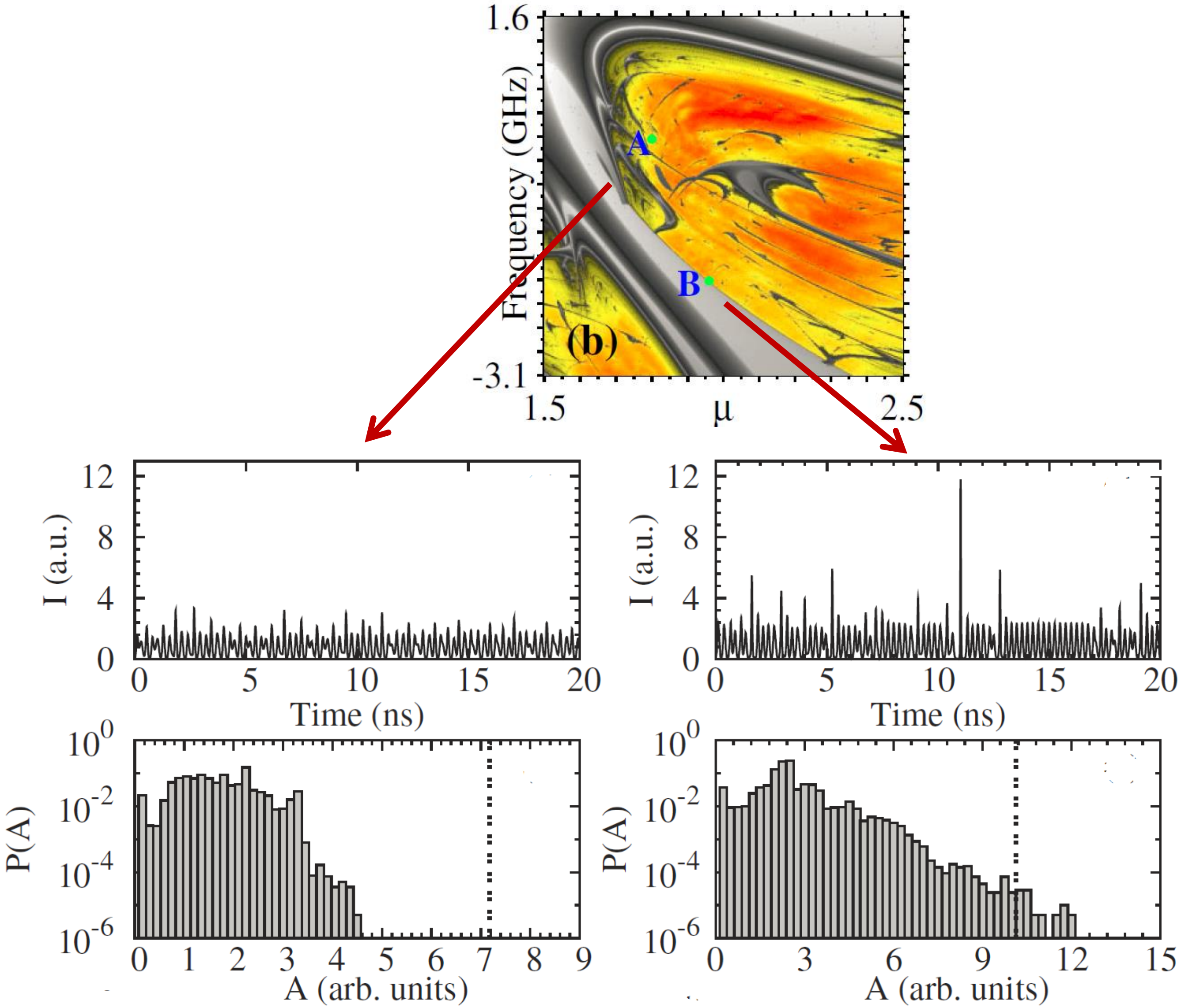
Bifurcation diagram: in color code: log(# of pulses)



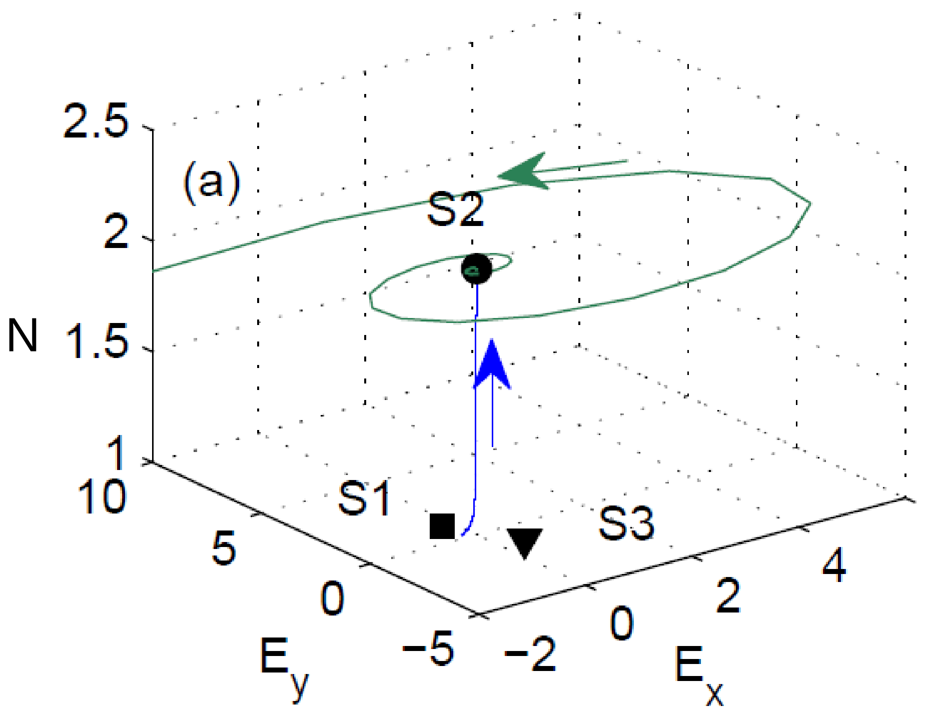
In the parameter space, there are chaotic regions with RWs and chaotic regions without them

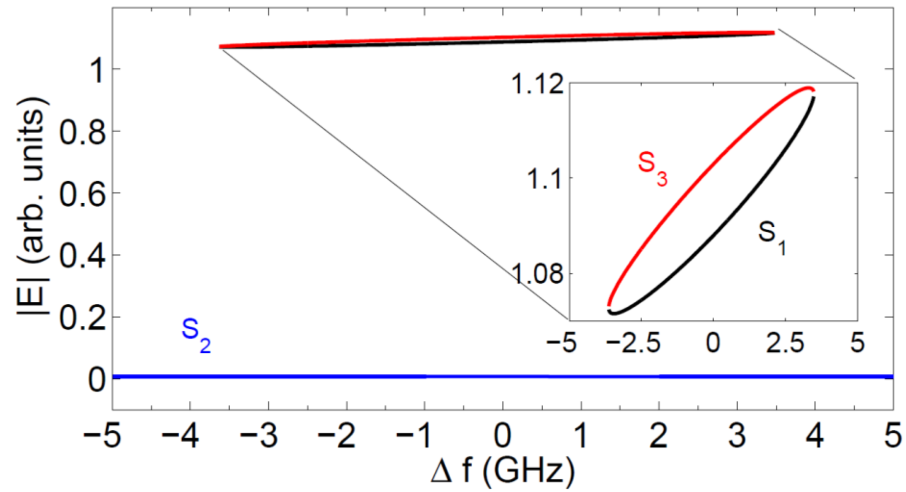


Deterministic simulations



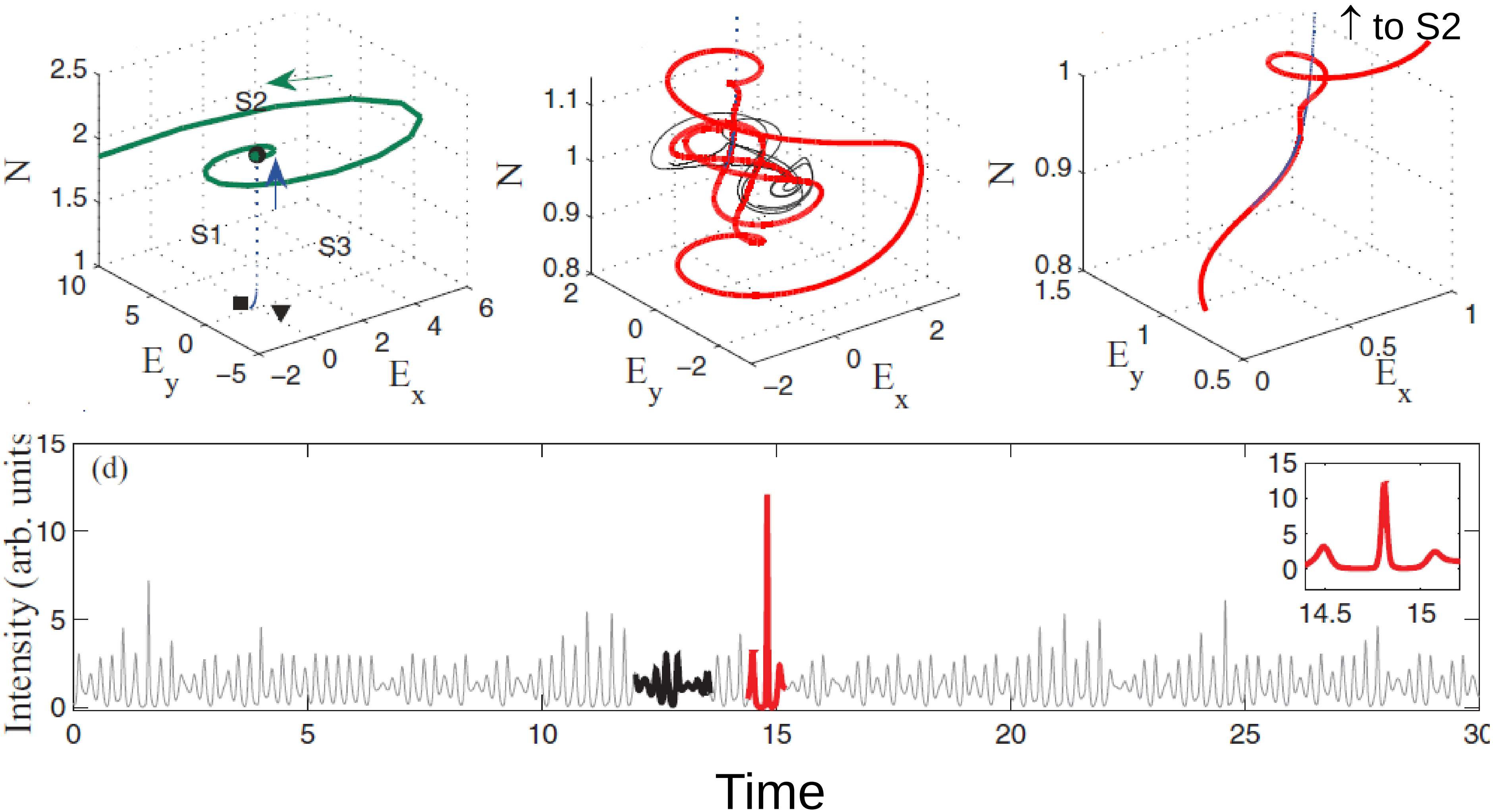
To understand the RW dynamics we need to look at the location the three fixed points in the phase space.



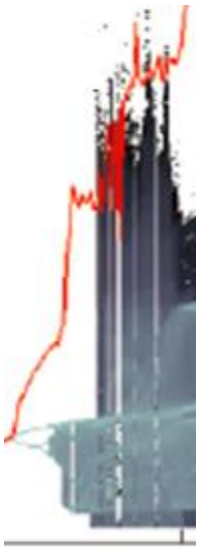


During an extreme pulse the trajectory moves towards S1/S3?

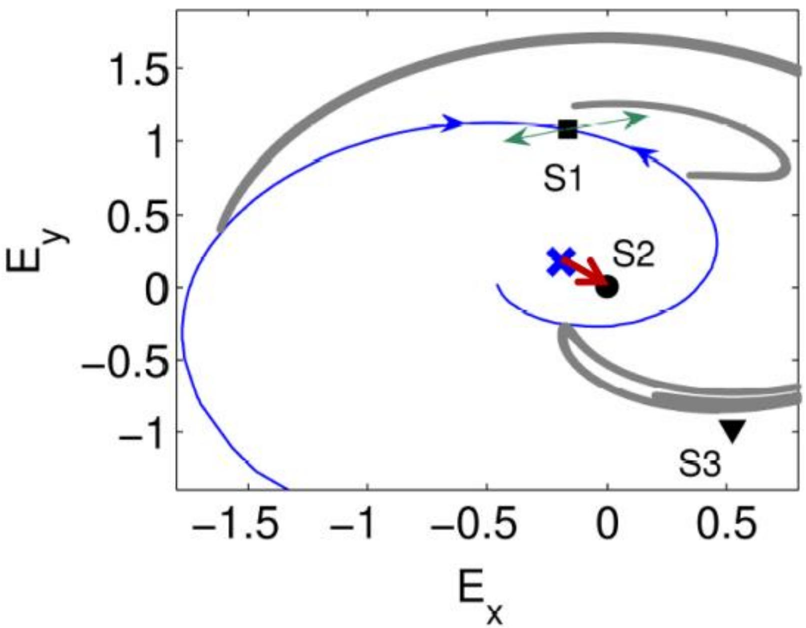
A RW is triggered whenever the trajectory closely approaches the stable manifold of S2 (the “RW door”)



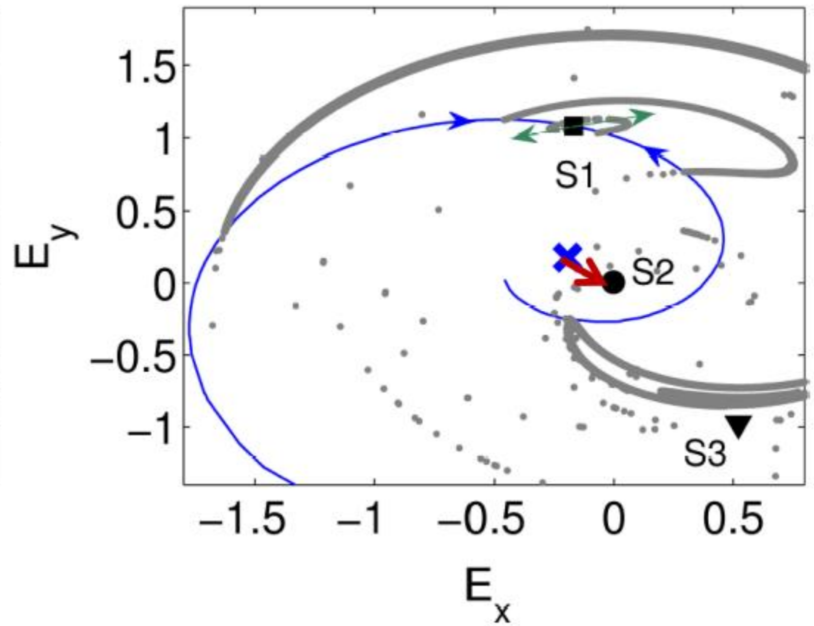
With the Poincare map (N=1) we see the expansion of the attractor, when the RWs appear, due to the collision of the attractor with the stable manifold of saddle point S1.



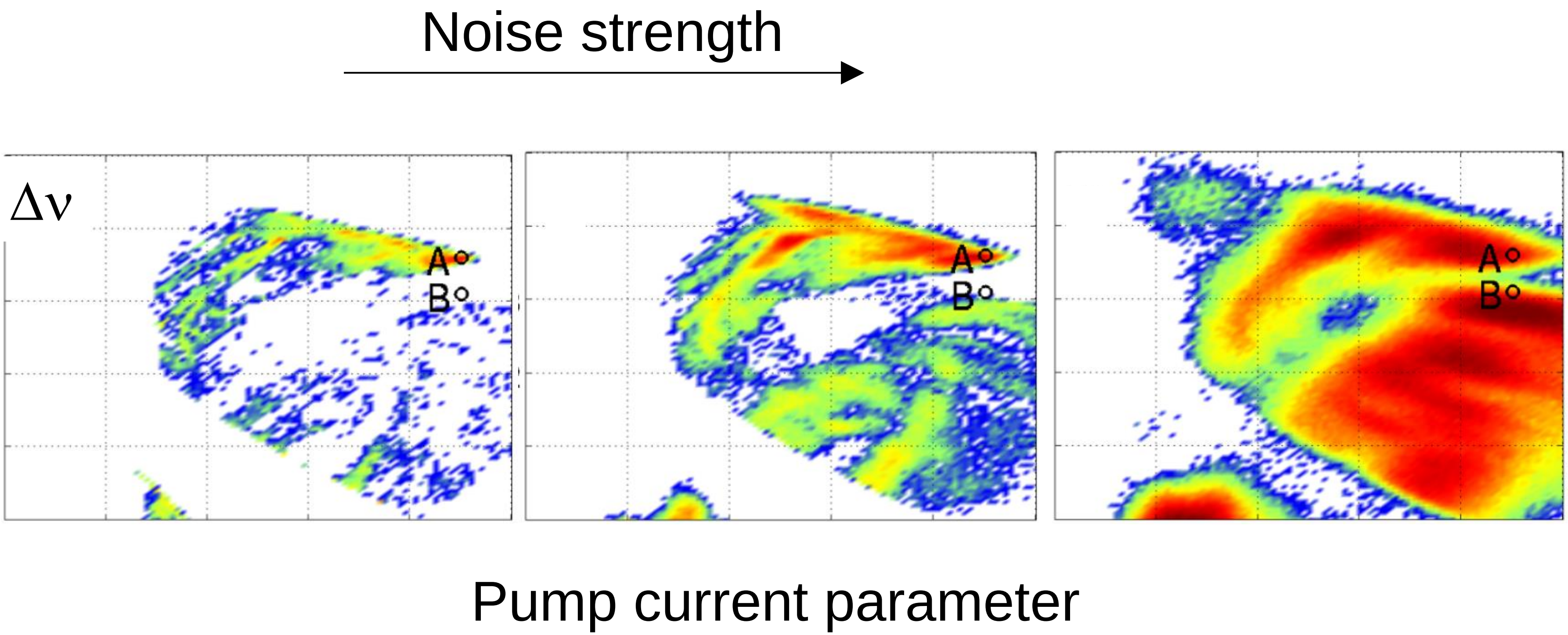
Before



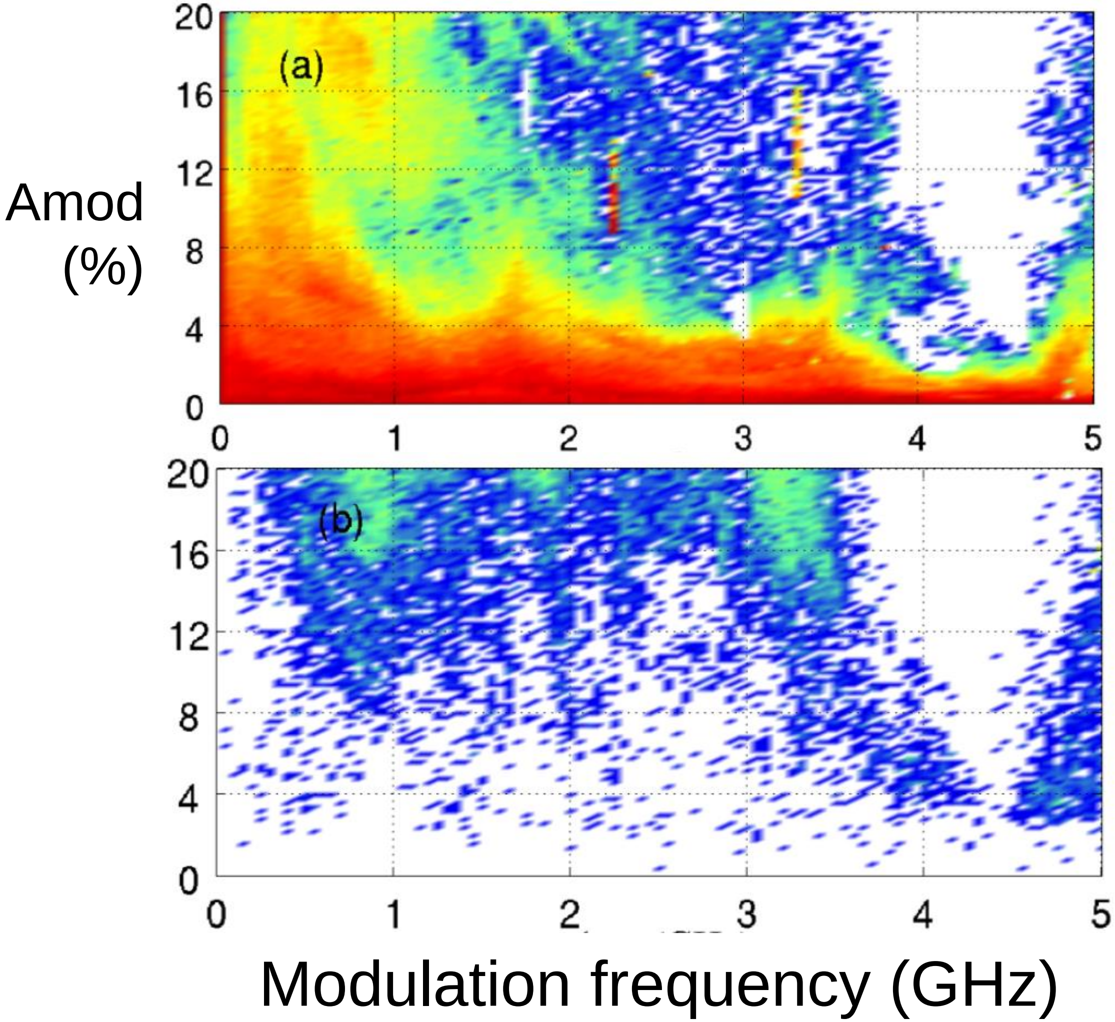
After



Noise can induce RWs



Role of current modulation: at the natural laser frequency, modulation (even small amplitude) suppresses the RWs



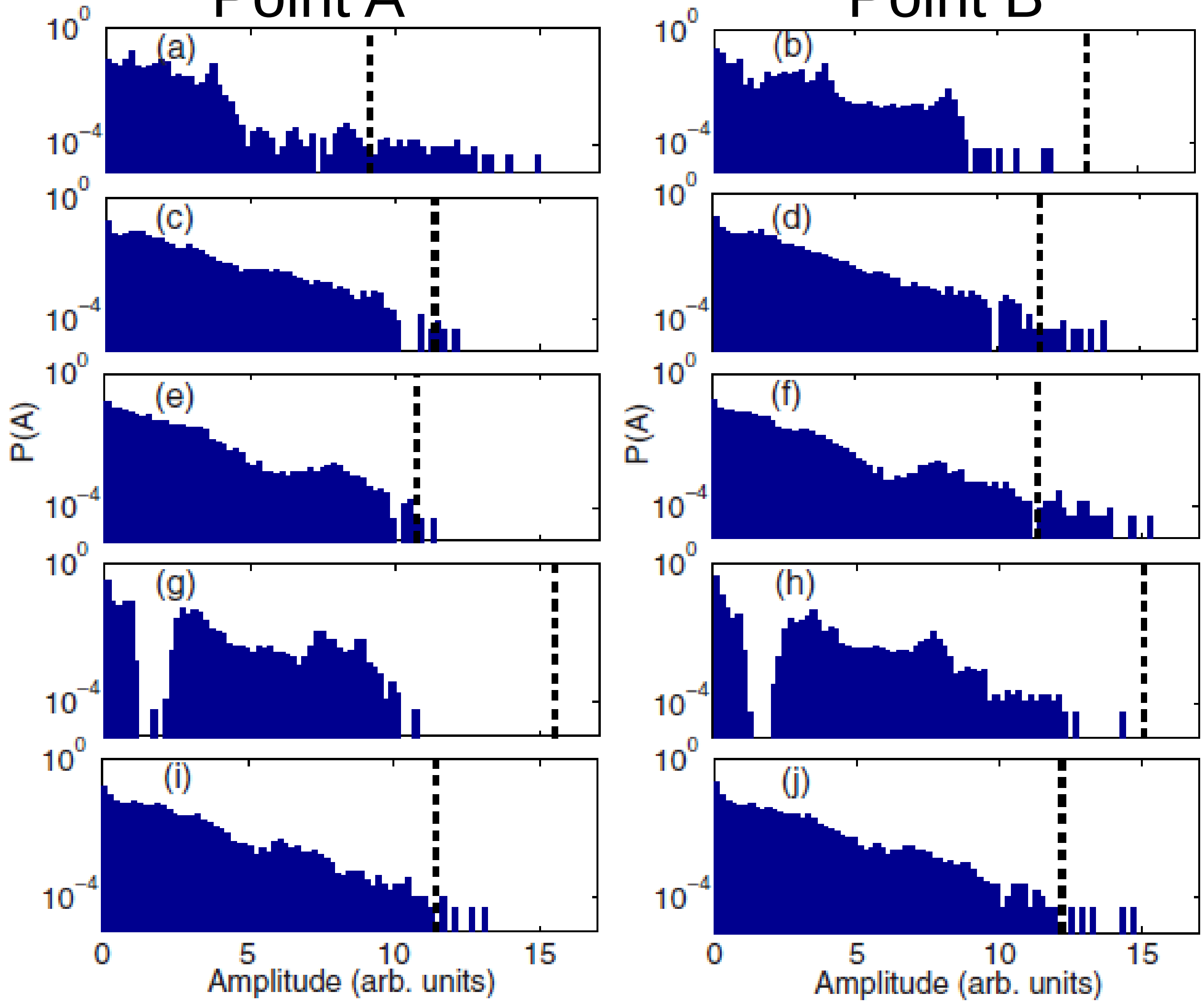
S. Perrone et al, PRA (2014)

Why extreme pulses are suppressed?

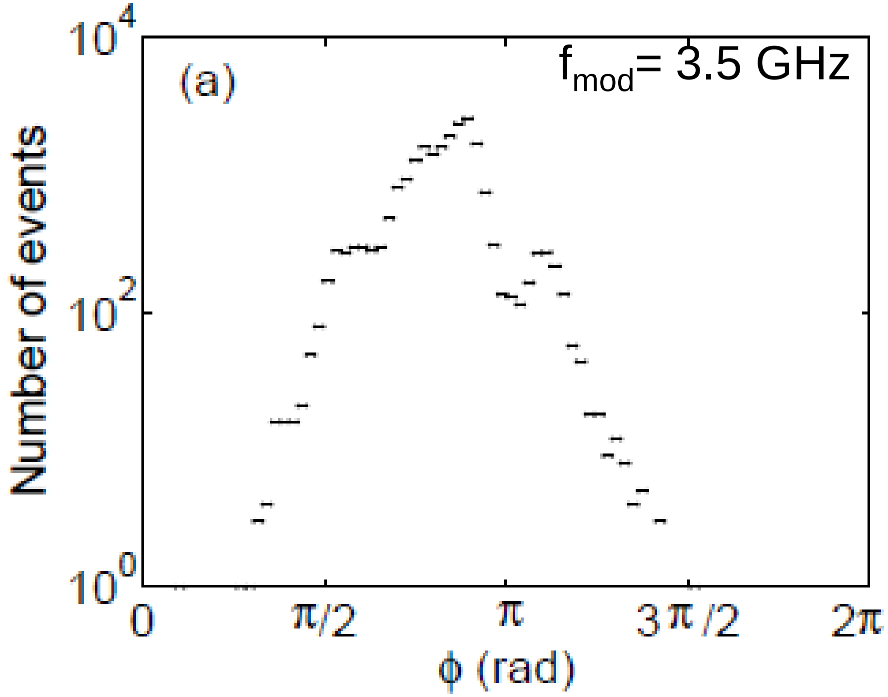
Threshold = <A> + **6** σ

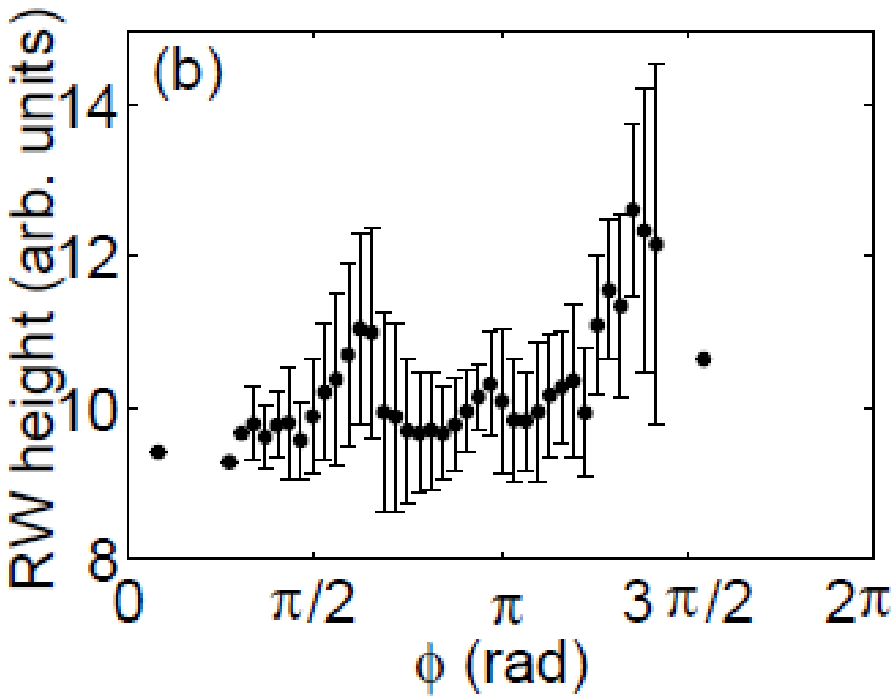
Point A Point B

Modulation frequency



When RWs are not suppressed: they occur during a well defined window of the modulation cycle



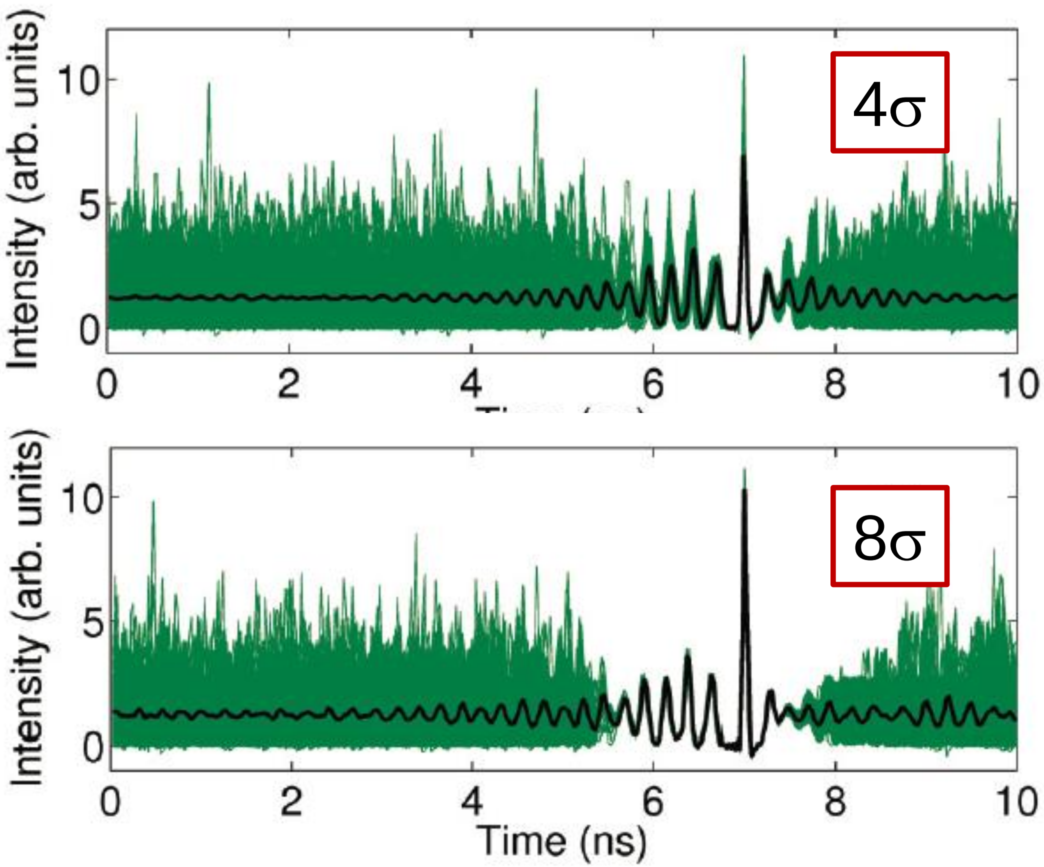


The highest RWs occur just before the “safe” window.

J. Ahuja et al Optics Express (2014)

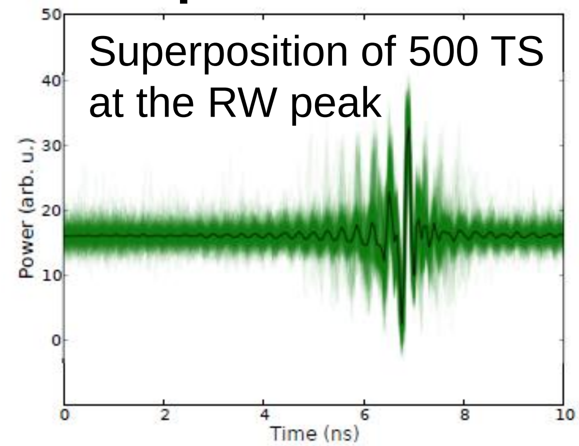
Predictability?

Deterministic simulations



Superposition of 50 time-series at the RW peak

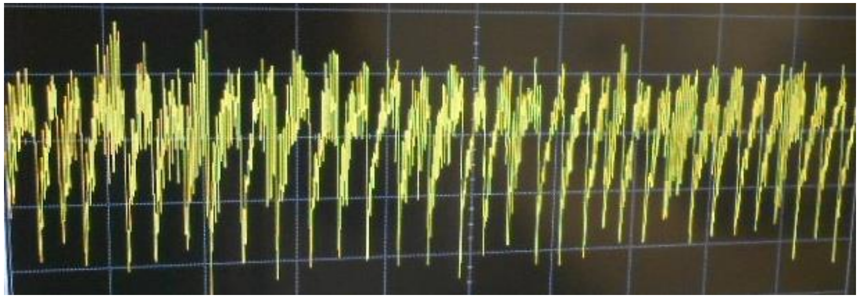
Experiments

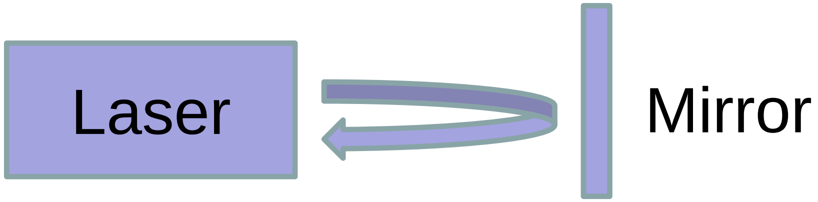


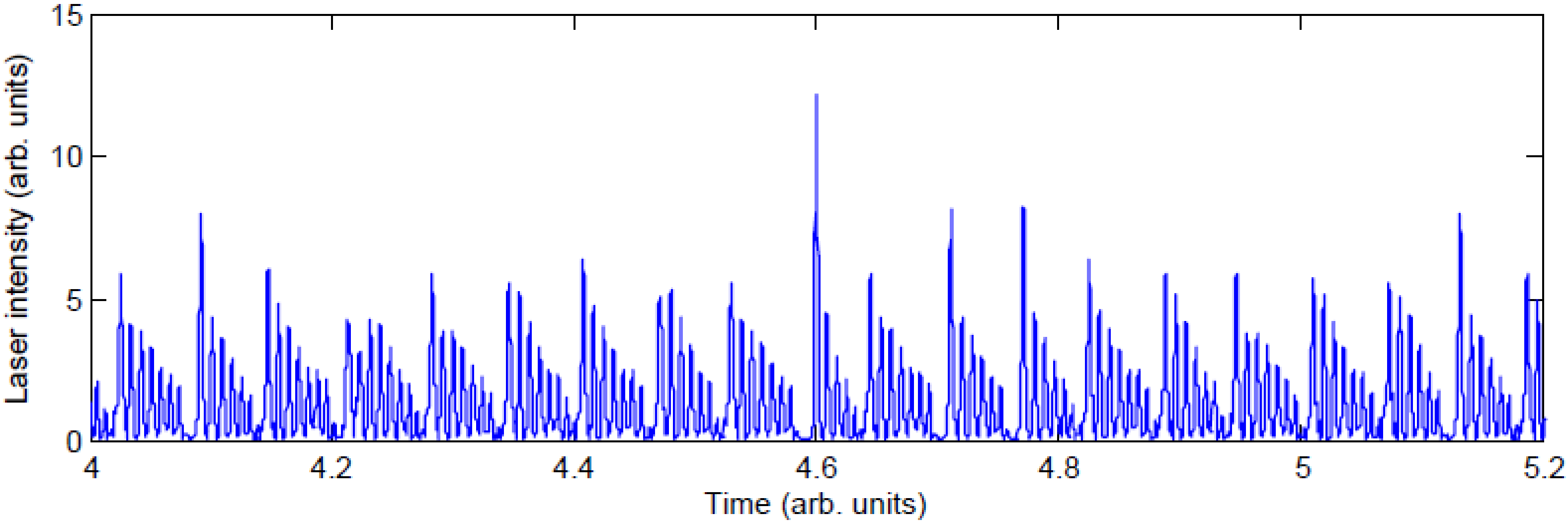
⇒ Well-defined oscillation pattern anticipates extreme pulses.

J. Zamora-Munt et al (2013)

A similar effect is seen in the intensity dynamics induced by optical feedback



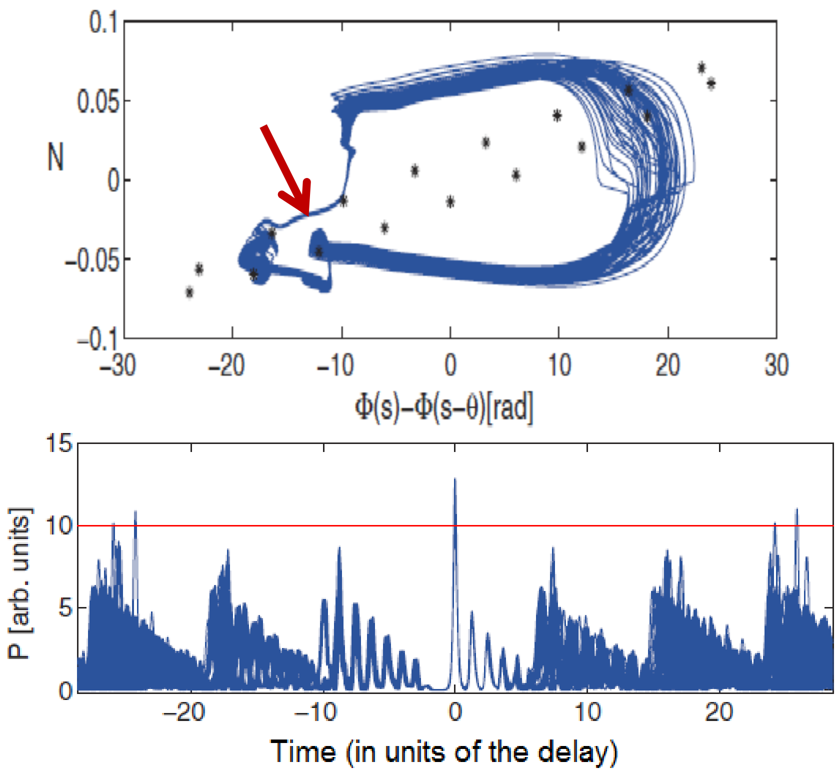




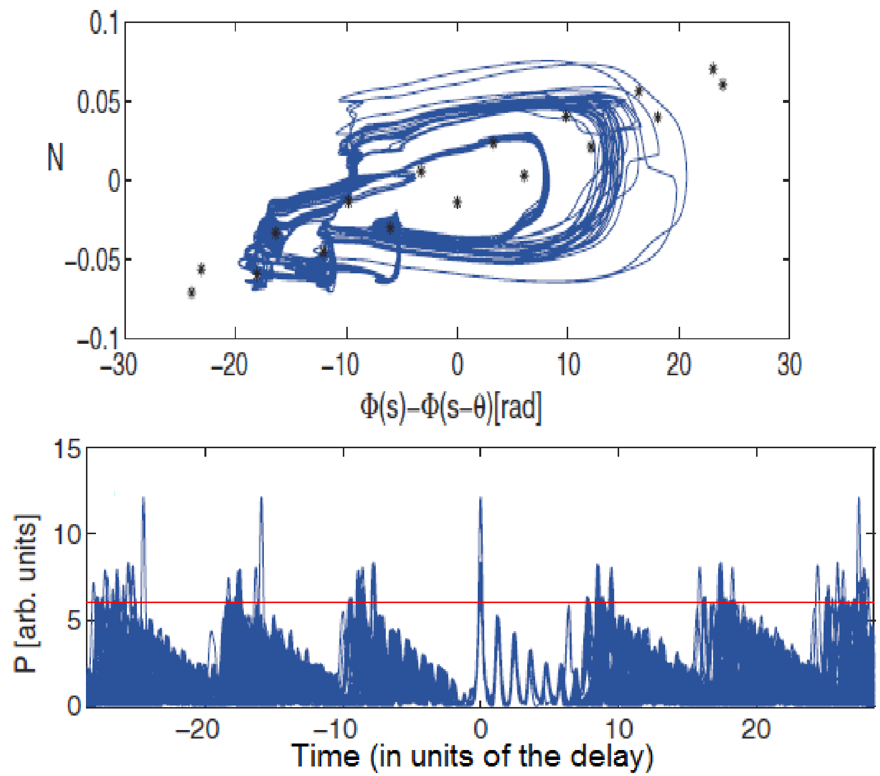
J. A. Reinoso et al, PRE (2013)

Superposition of 52 pulses

Threshold = 10



Threshold = 6

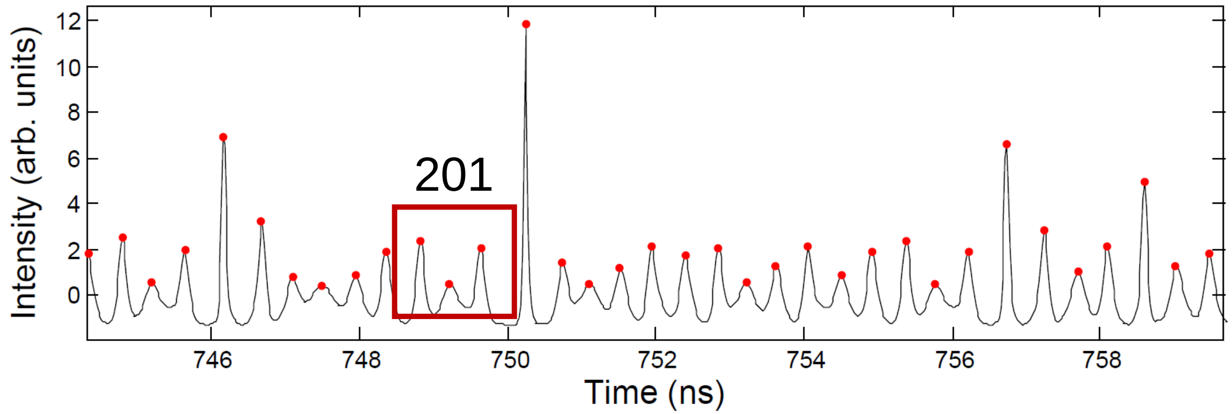


Narrow channel also seen in other systems

(*G. Ansmann, R. Karnatak, K. Lehnertz, and U. Feudel, PRE 88, 052911 2013*)

How can this effect be quantified?

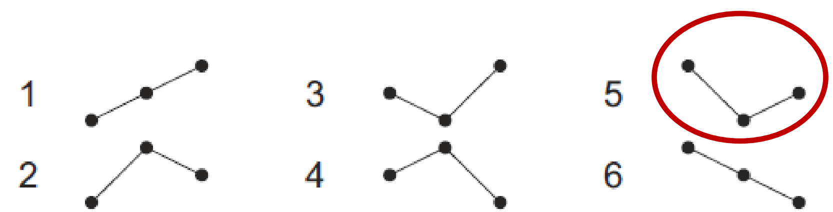
Identifying the pattern that tends to occur before the pulse



- 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:

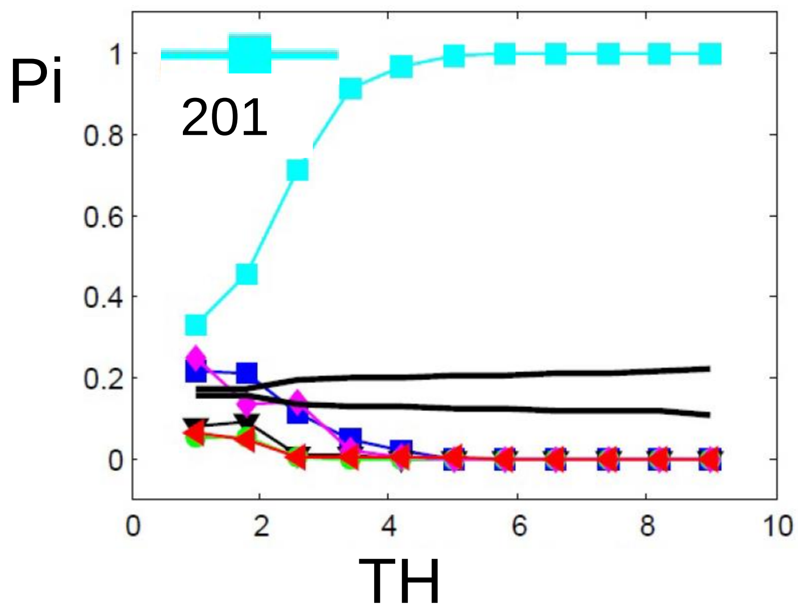


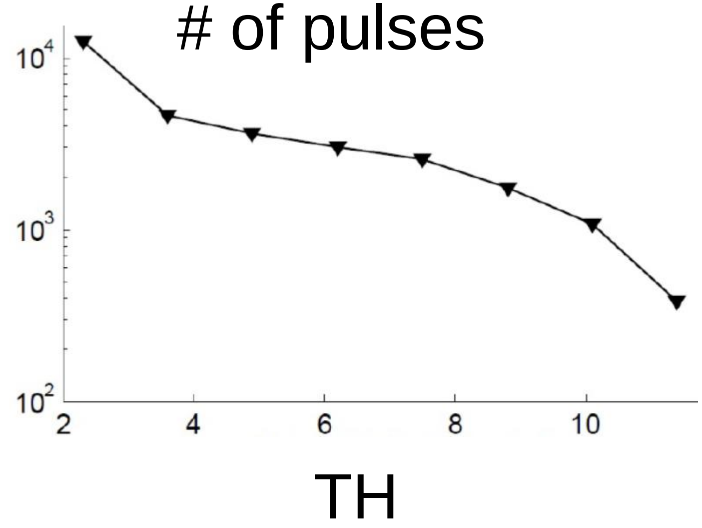
We calculate the probability of the pattern that occurs before each high pulse:

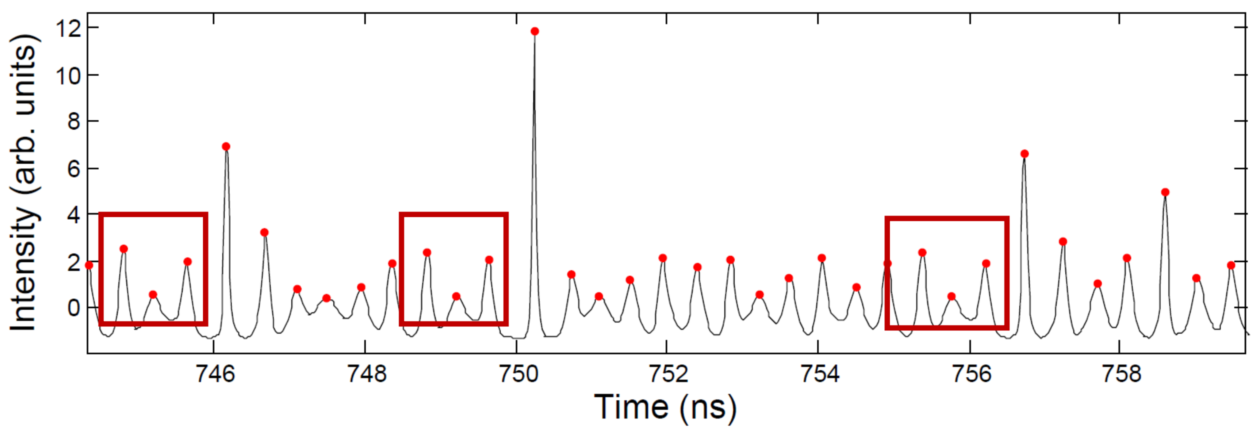
If $I_i >$ **TH**, we analyze the pattern defined by $(I_{i-3}, I_{i-2}, I_{i-1})$

"Good" results in deterministic simulations: P(201)=1 if TH >6

Black lines: 3σ confidence probabilities consistent with p_i=1/6 $\forall$ i





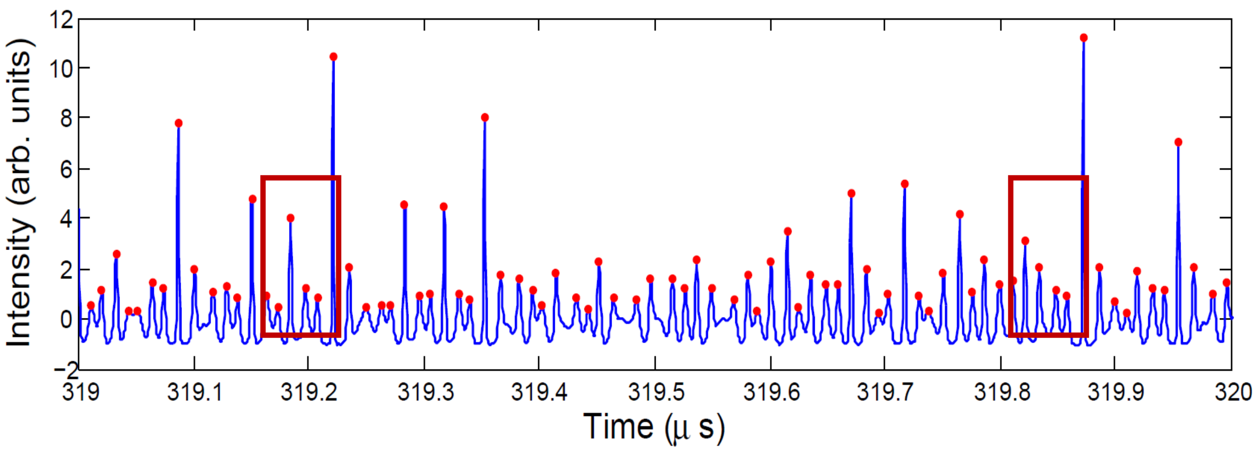


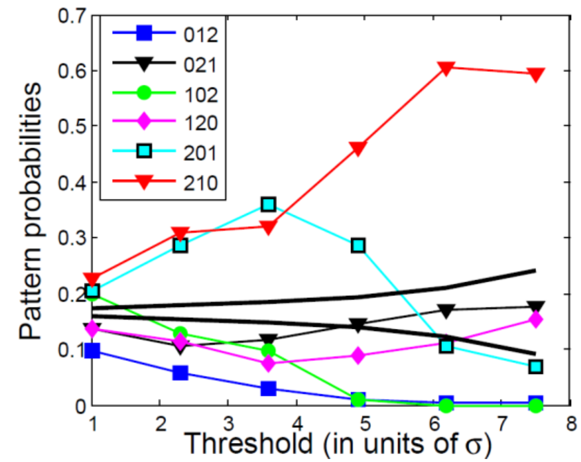
Problem: P(201)$\neq$0 if TH <6 (pattern 201 also anticipates some small pulses) $\Rightarrow$ false alarms (false positives)

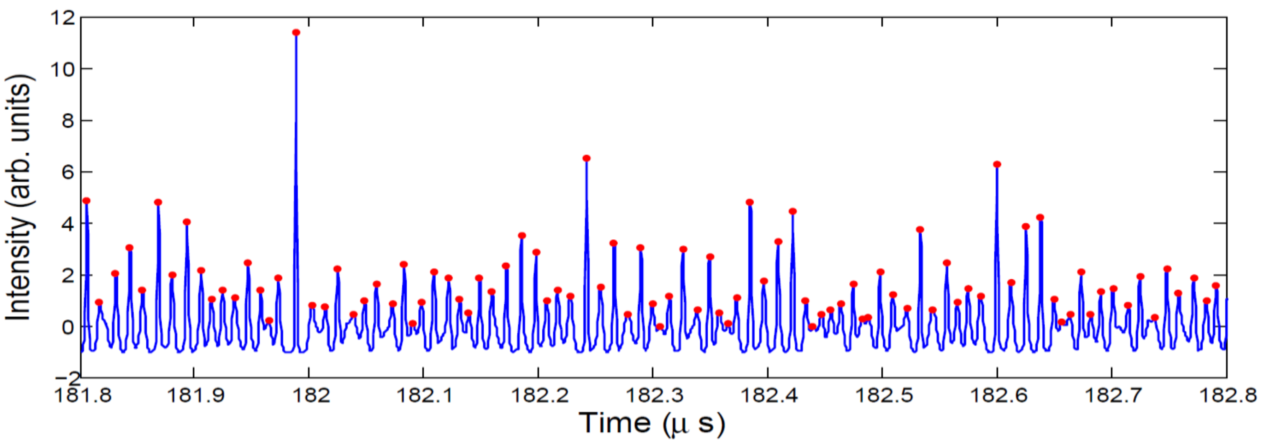
N. Martinez Alvarez et al, EPJST (2017)

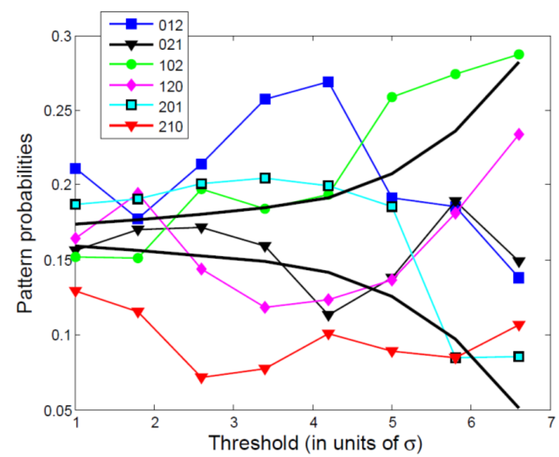
The “early warning pattern” varies with the parameters and might not exist.

Including noise, two modulation frequencies

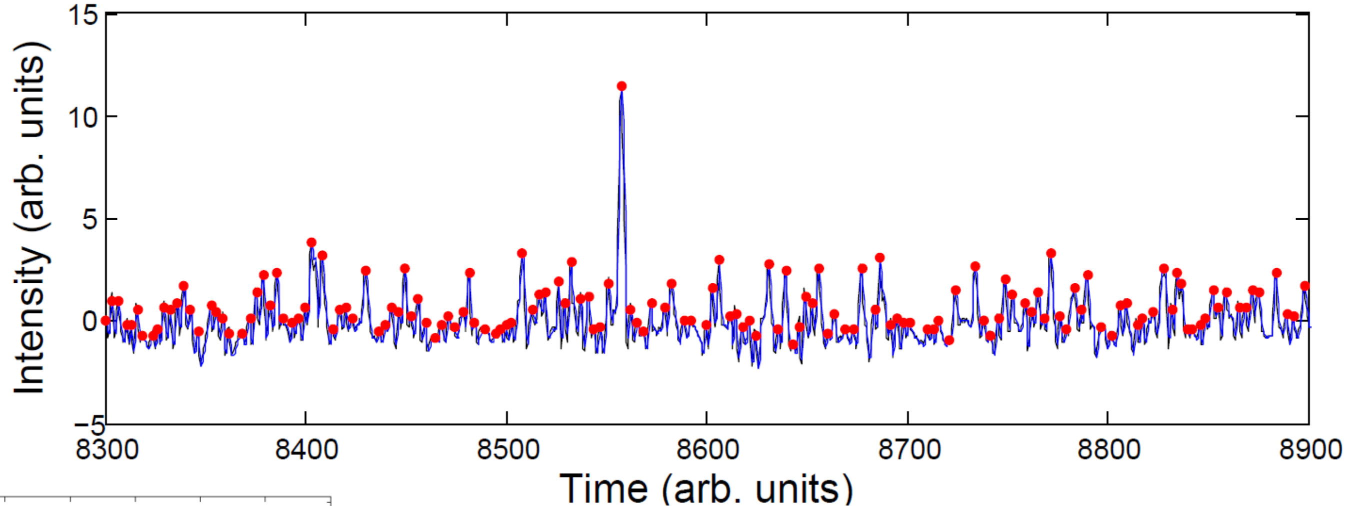


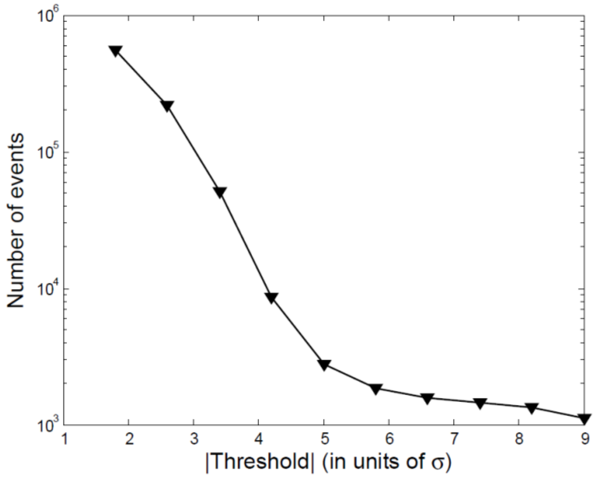


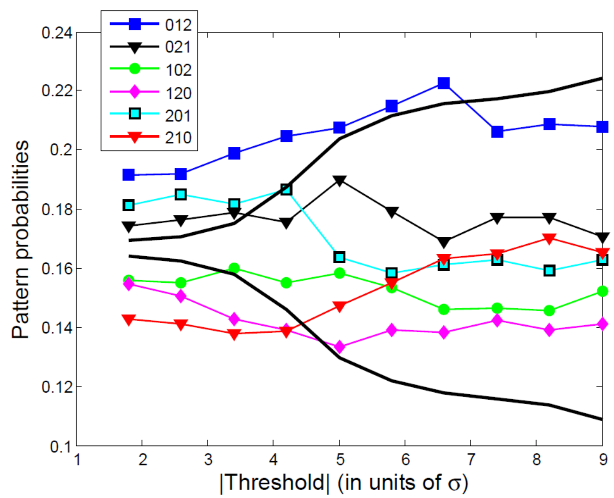




Analysis of experimental data





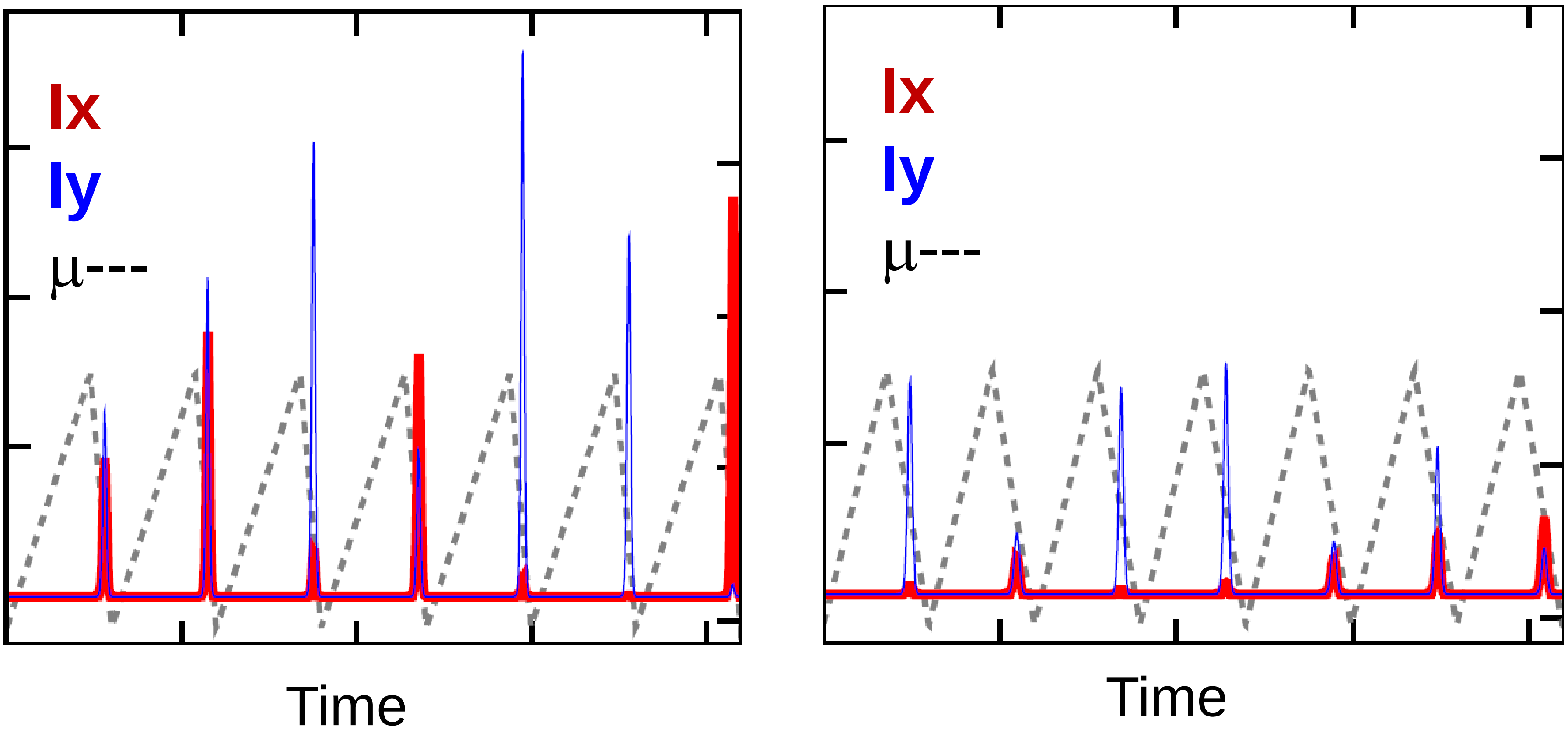


Way to improve the "early warning":

- Filter noise
- Longer patterns

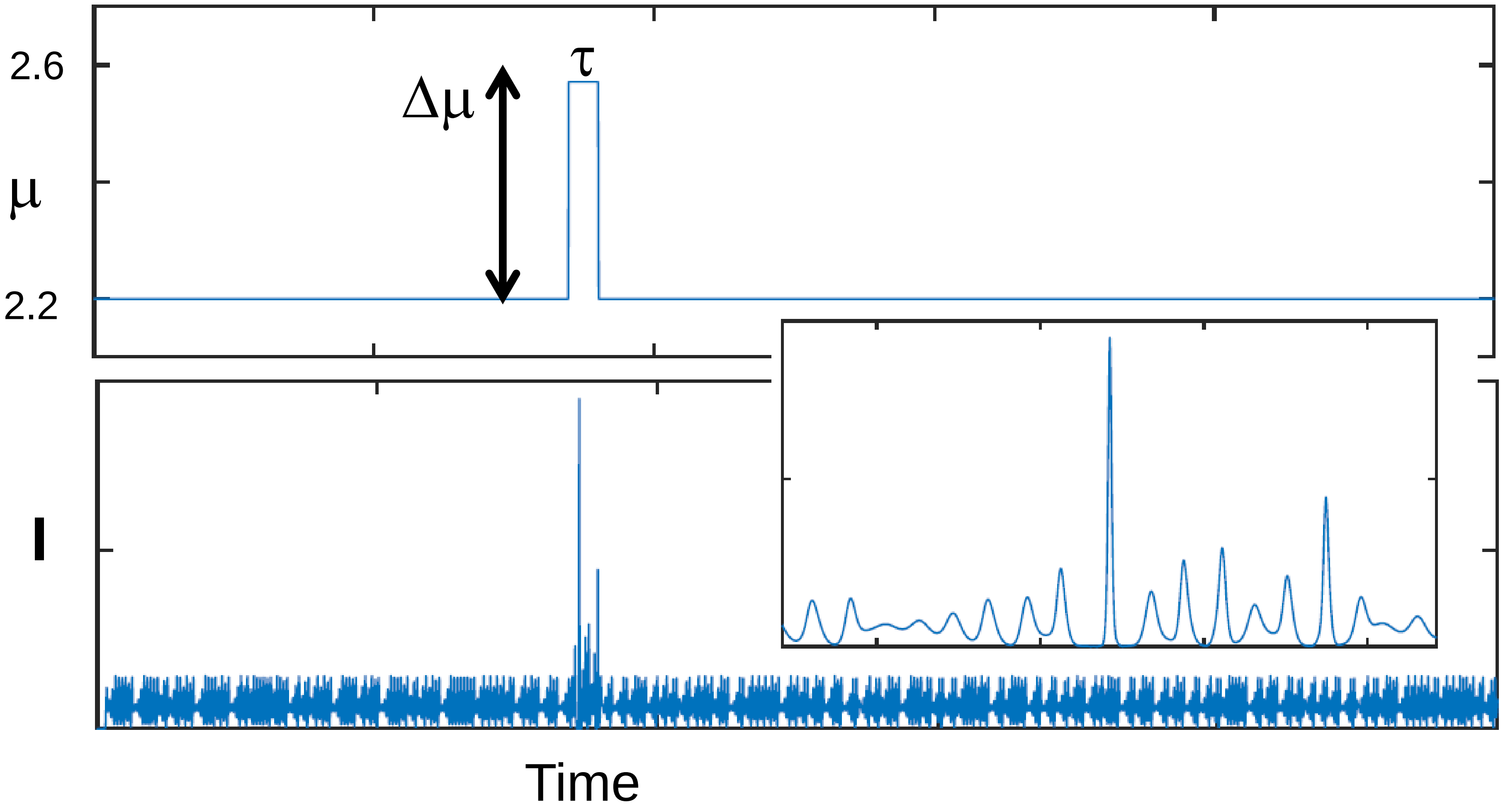
$\{\ldots I_i, I_{i+1}, I_{i+2}, I_{i+3}, \ldots\}$

On demand generation?
Motivation and early work



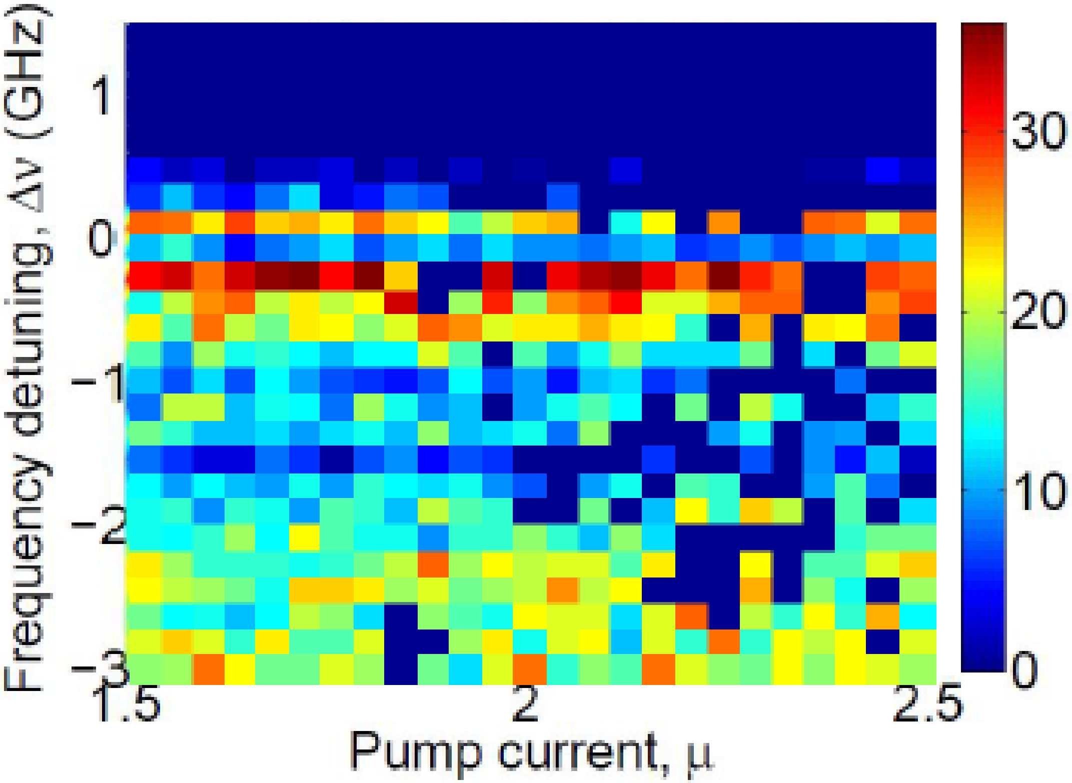
Zamora and Masoller, Opt. Exp. 2008

On demand generation via small step-up current perturbation (a step down perturbation does not work)



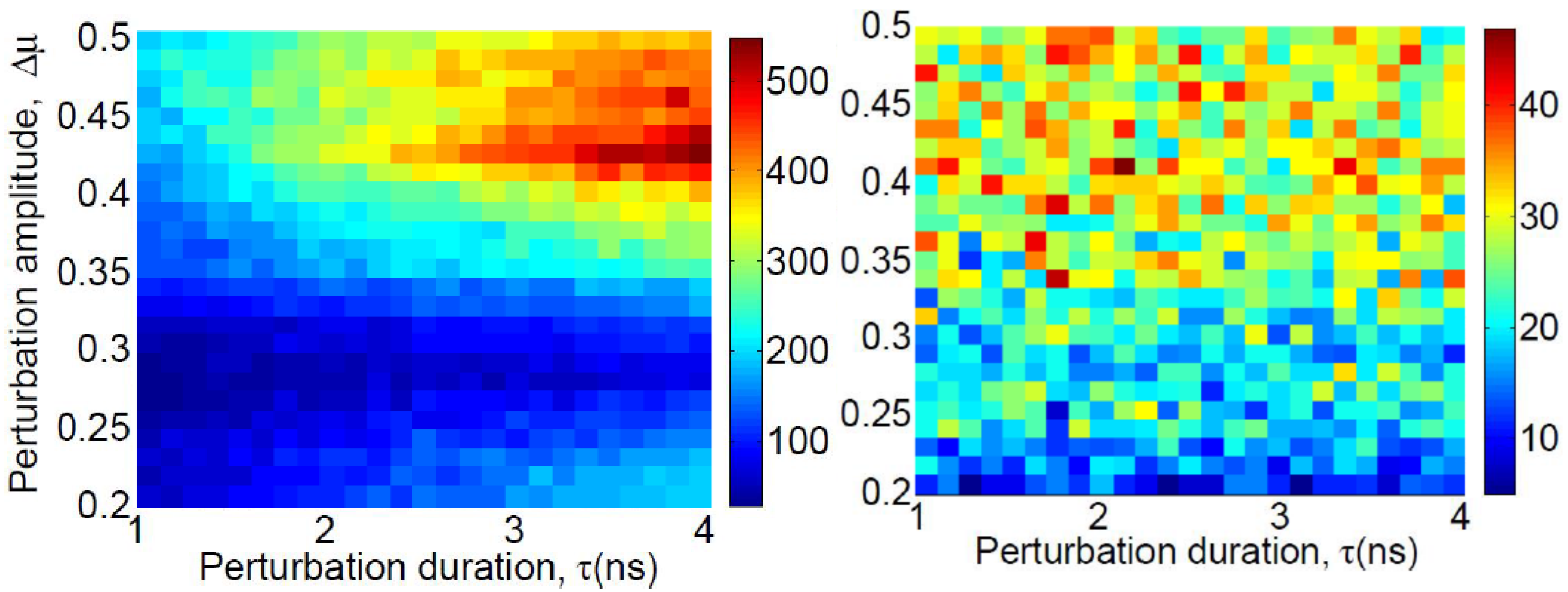
T. Jin et al, Opt. Express (2017)

Where in the parameter space is easier to generate pulses?



100 perturbations. In regions where there are spontaneous extreme pulses, no perturbation is applied.

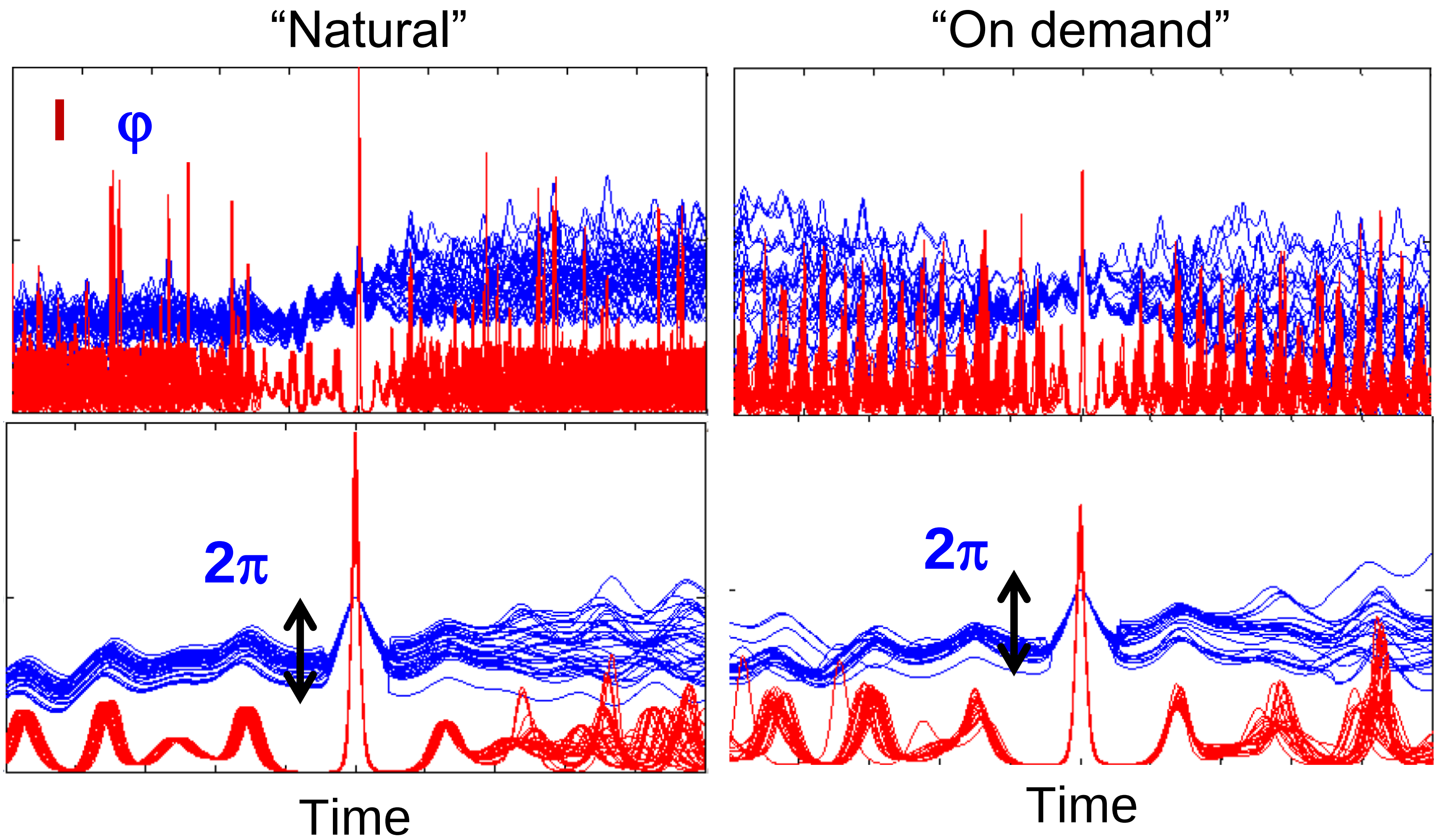
The number of RWs generated after 1000 perturbations as a function of the perturbation parameters: can be as large as 50% or as small as 5%



The “success rate” depends on the laser parameters and on the perturbation parameters.

Excitability?

Are the generated pulses similar to the “natural” ones?



Summary

- Extreme optical pulses can be deterministic or triggered by noise, and can be suppressed by appropriated modulation.
- Certain patterns of oscillations can be more (or less) likely to occur before the extreme intensity pulses.
- They can be generated “on demand” by appropriated perturbation of the control parameter.
- Open issue: model-specific results?

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- **Dynamic Days LAC**

  Punta del Este, Uruguay

  26--30 November 2018

  (MS Time Series Analysis)

  https://ddayslac2018.org/

- **Statphys 27**

  Buenos Aires,

  Argentina

  8--12 July 2019

  http://statphys27.df.uba.ar/ (under construction)

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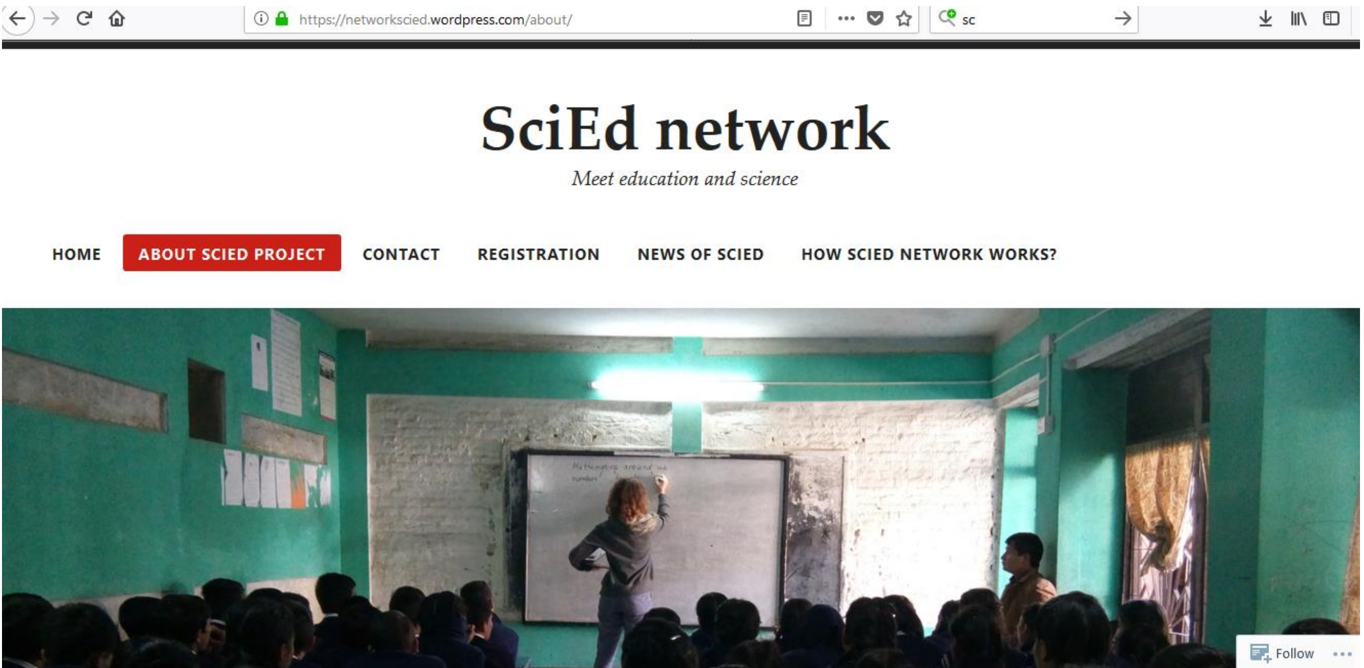

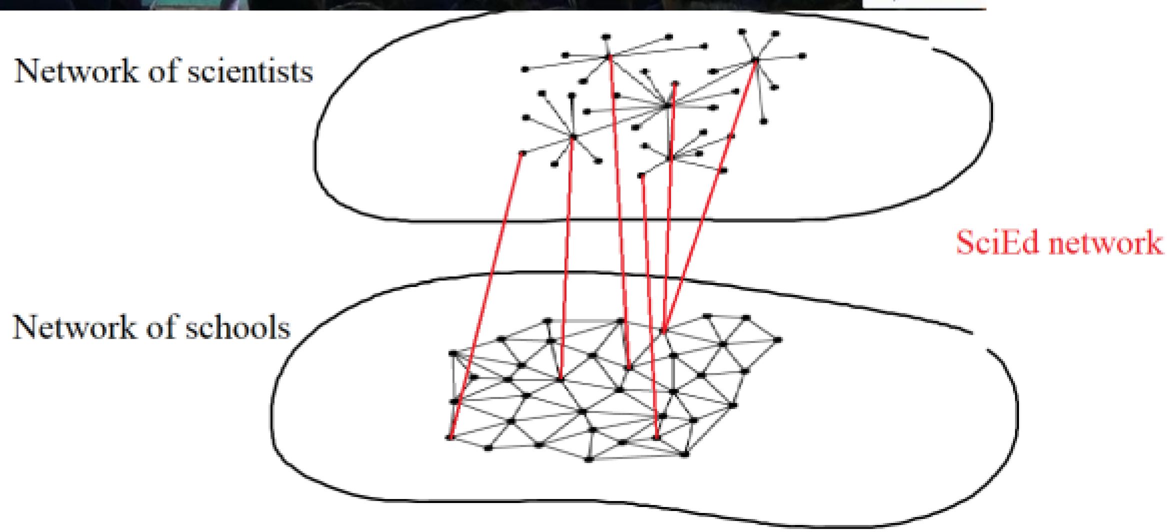

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Tian Jin, Chen Siyu, and C. Masoller, "*Generation of extreme pulses on demand in semiconductor lasers with optical injection*", Opt. Express **25**, 031326 (2017).

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