Extreme Pulses in Optically Injected Semiconductor Lasers: Precursors and on-demand Generation

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Deterministic Optical Rogue Waves

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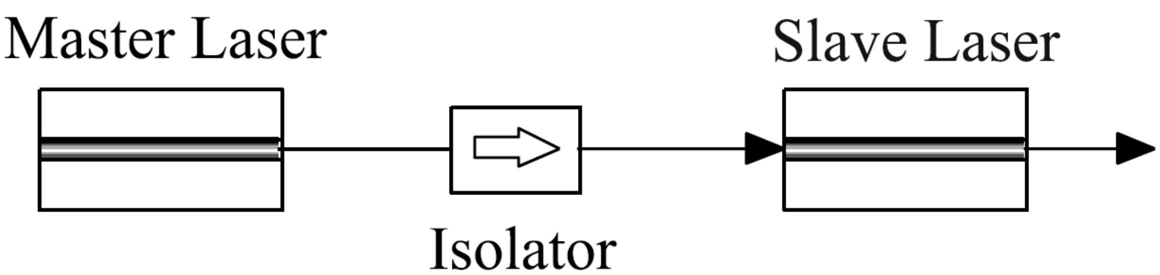
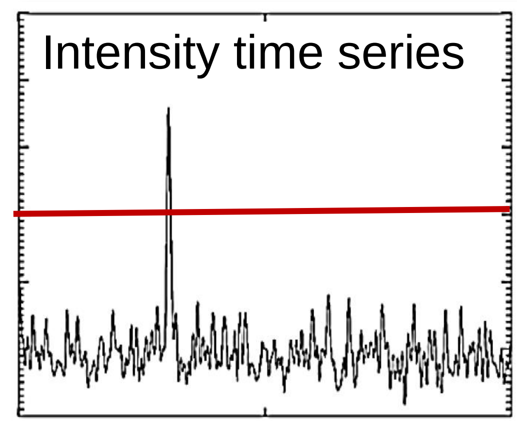
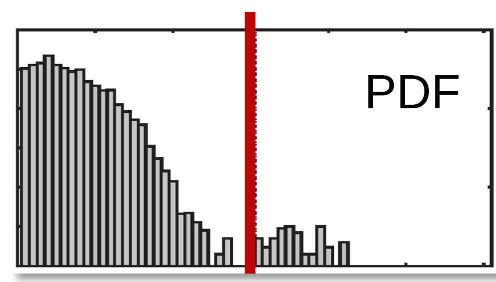
José R. Rios Leite,[2,3] and Jorge R. Tredicce[2,3]







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 (rogue waves) ?
- Role of noise ?
- Can the RWs be suppress ?
- Can they be predicted ?
- Can they be generated “on demand” ?

Governing equations

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

Carrier density, **N**

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

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

optical injection
η: injection strength
$\Delta\omega = \omega_s - \omega_m$: detuning

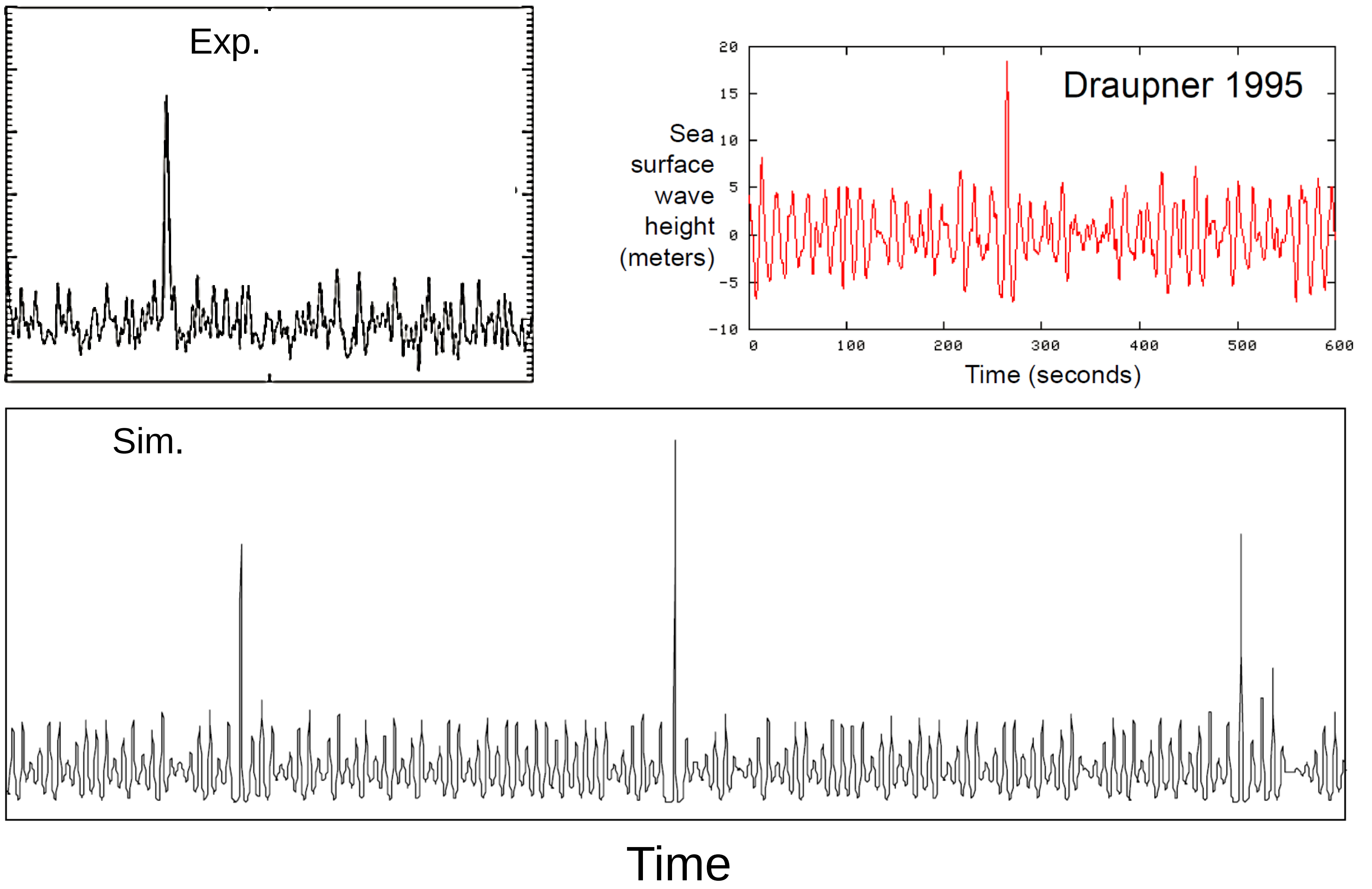
spontaneous emission noise

Solitary laser parameters: α τ_p τ_N μ

μ: normalized pump current parameter

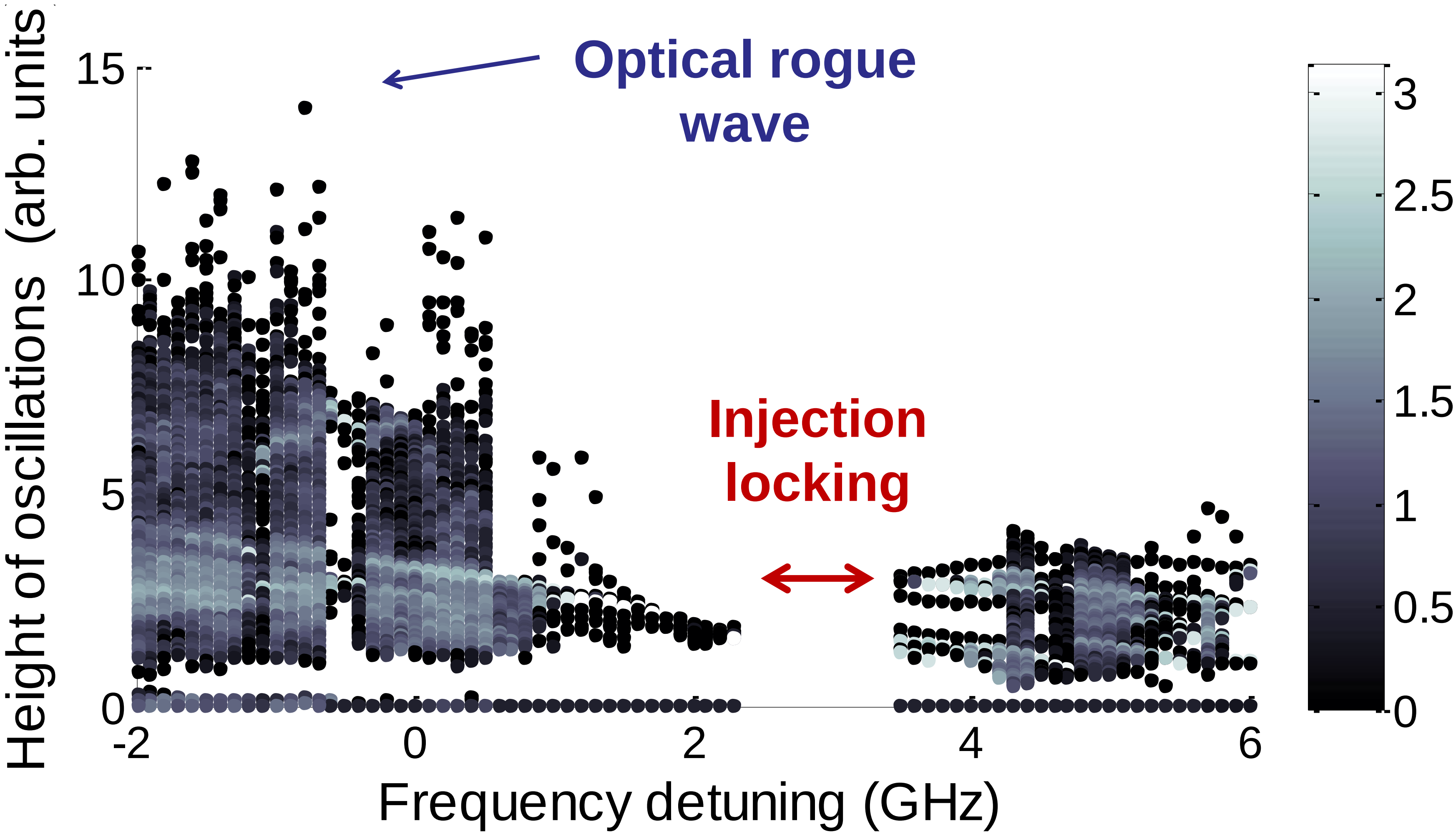
Typical parameter values:
$\alpha = 3$, $\tau_p = 1$ ps, $\tau_N = 1$ ns

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

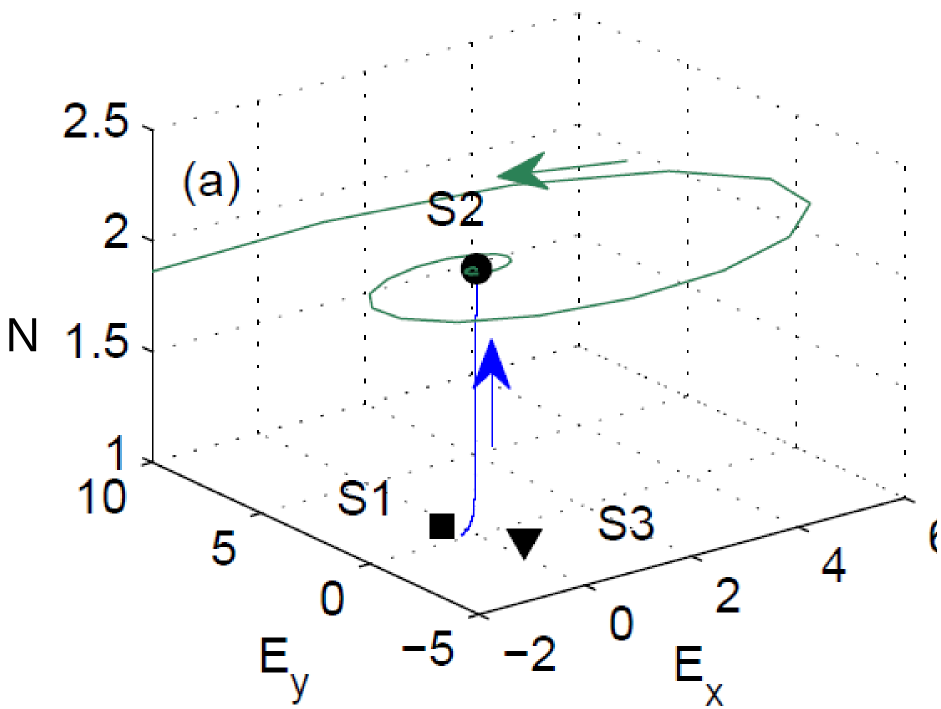


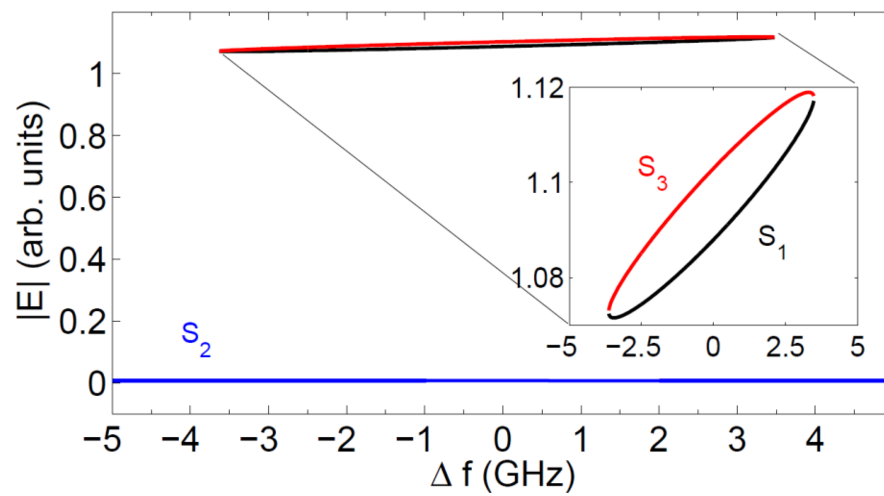
Exp.
Draupner 1995
Sea surface wave height (meters)
20
15
10
5
0
-5
-10
0
100
200
300
400
500
600
Time (seconds)
Sim.
Time

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



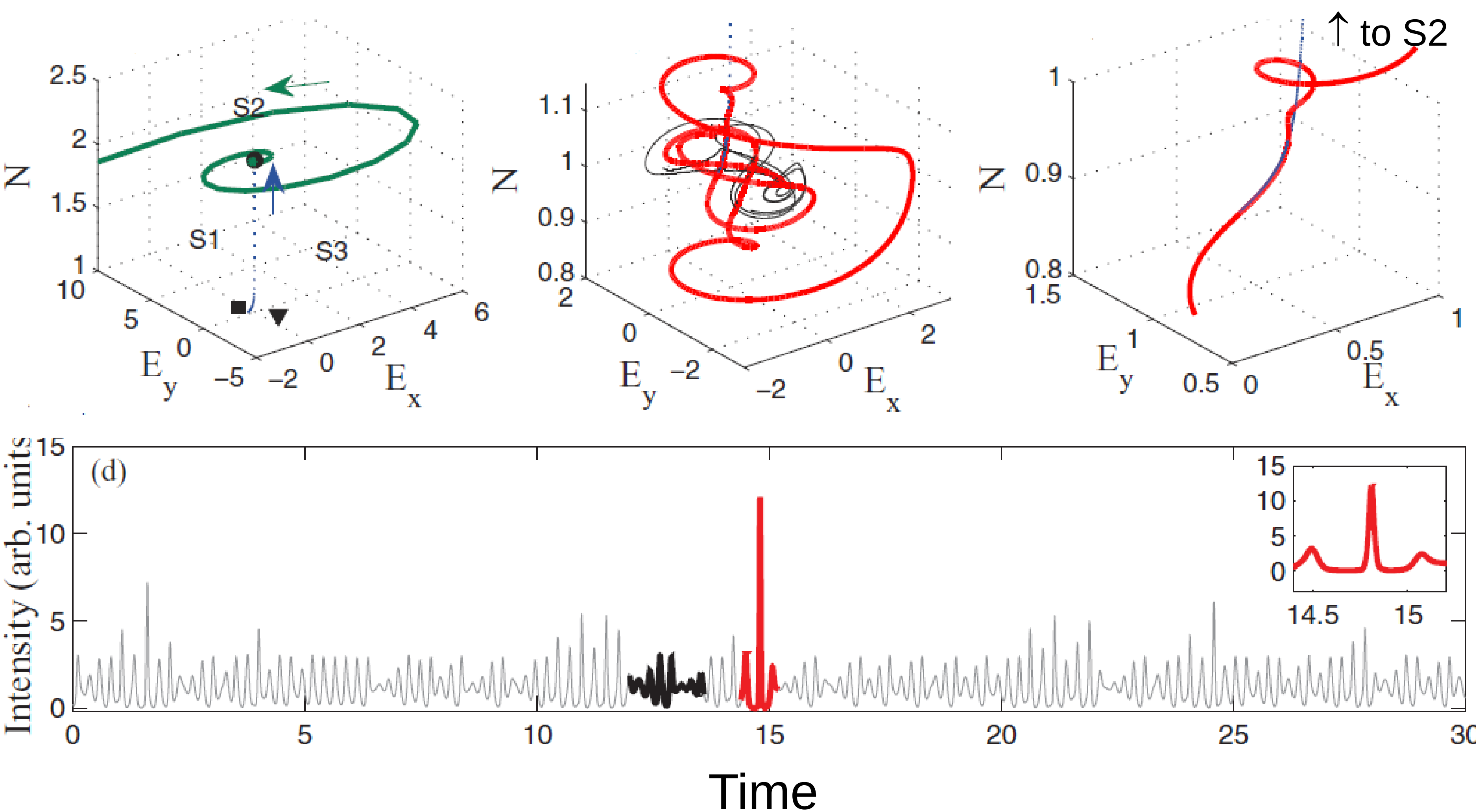
To understand the mechanism underlying the extreme pulses we need to examine the location the three fixed points.



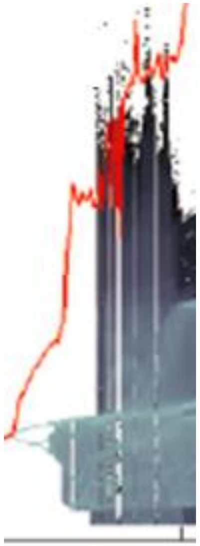


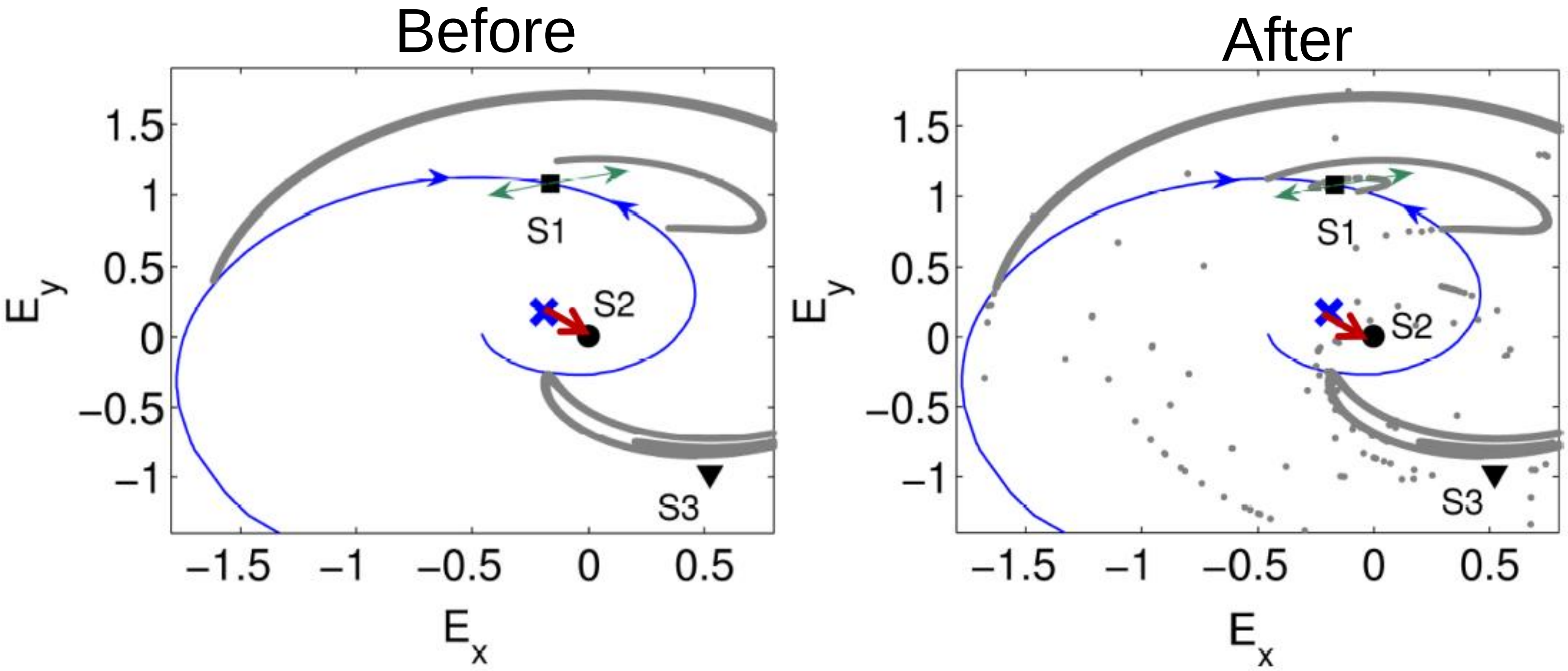
During an extreme pulse the trajectory moves towards S1/S3?

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 RWs appear.



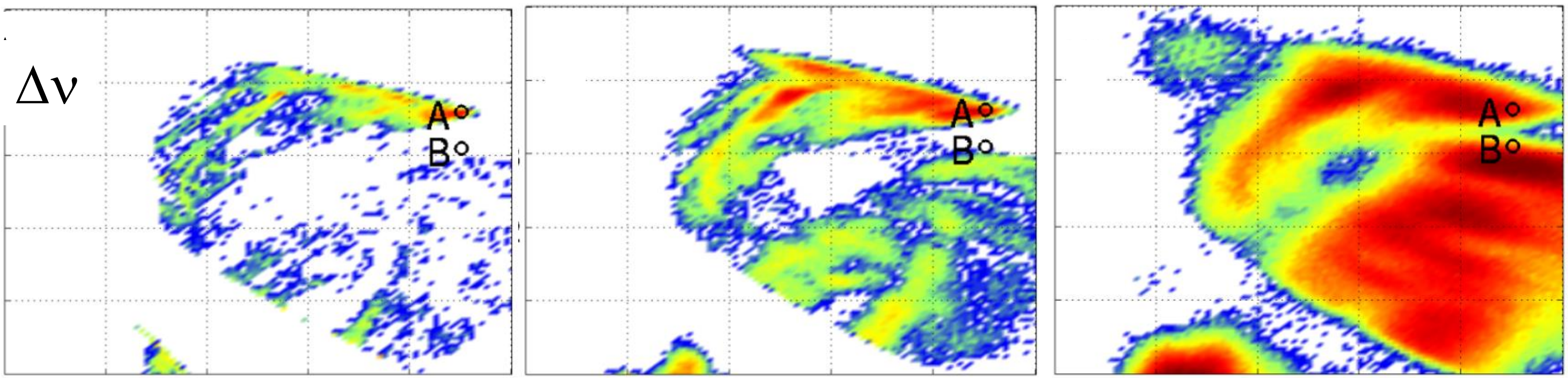


J. Zamora-Munt et al. PRA (2013).

Noise can induce RWs

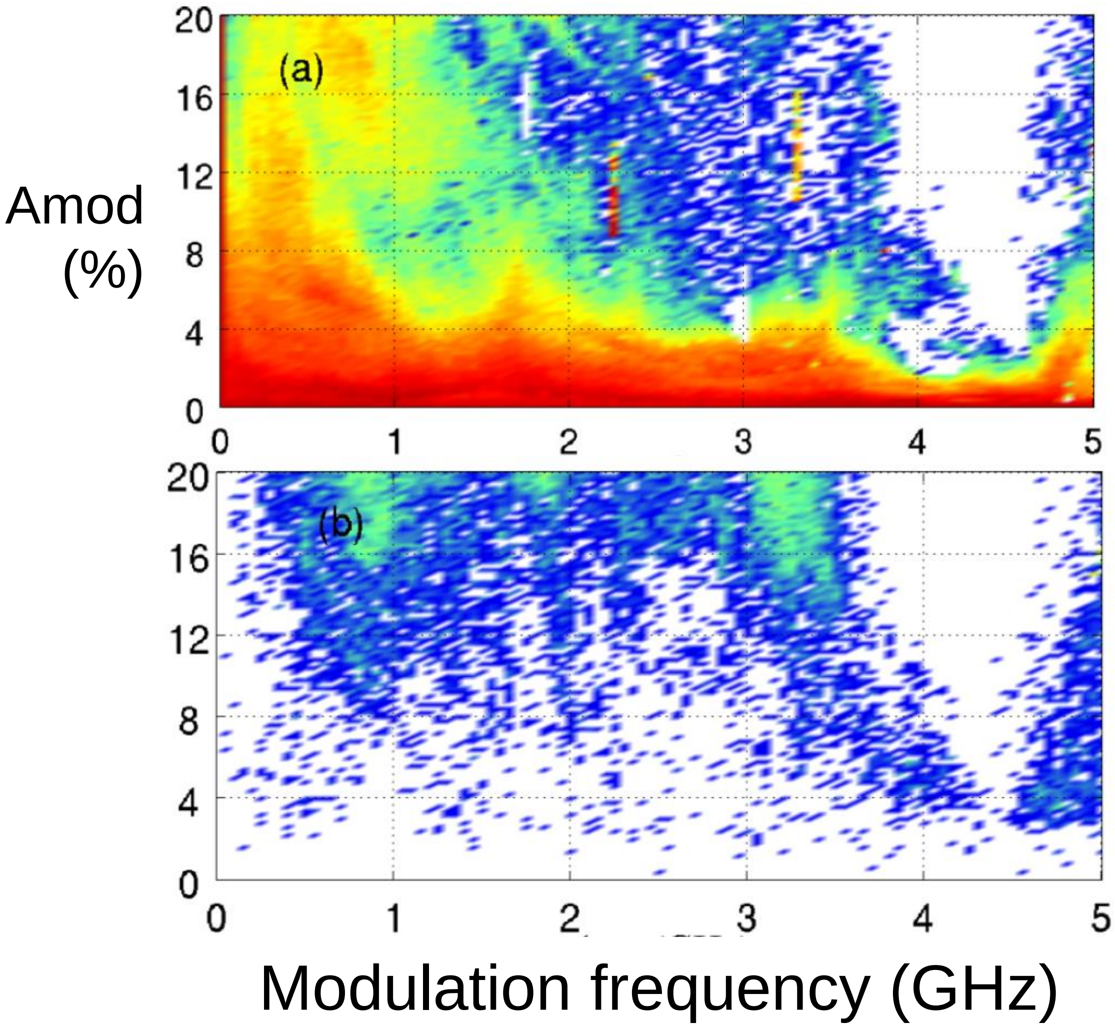
Noise strength →

In color code the
number of RWs



Pump current parameter

Current modulation can suppress RWs, but can also induce RWs

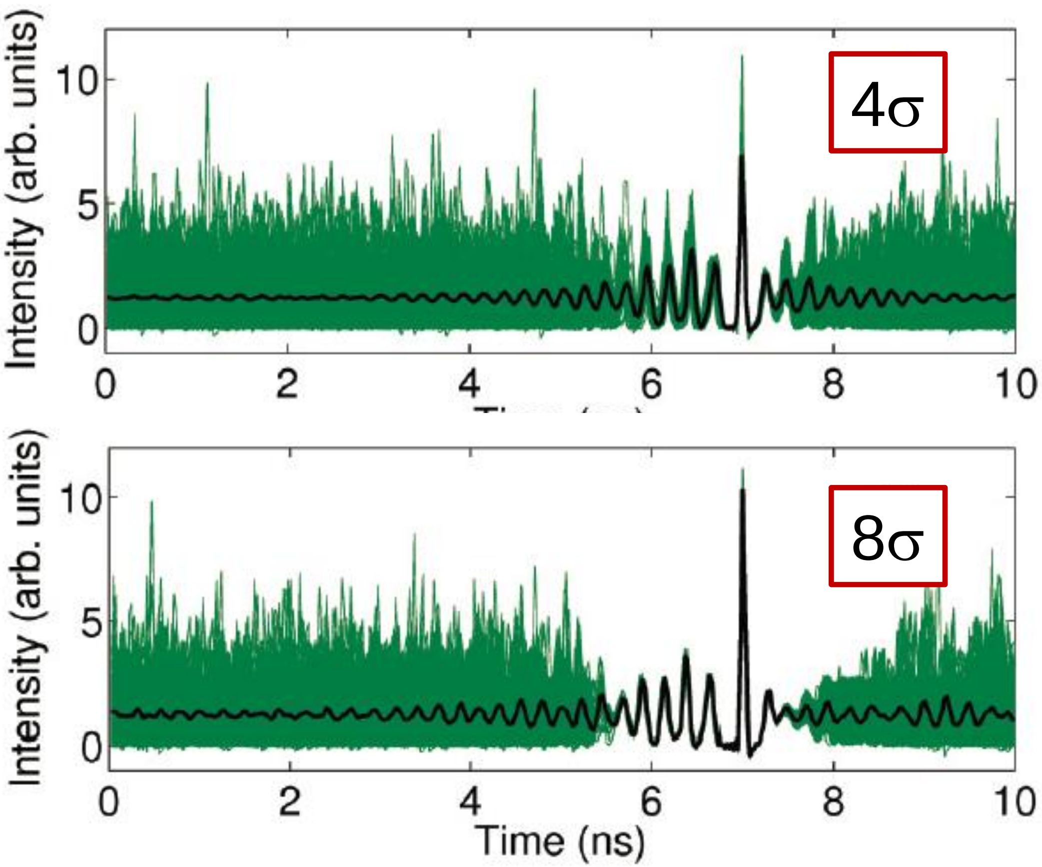


In color code the number of RWs

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

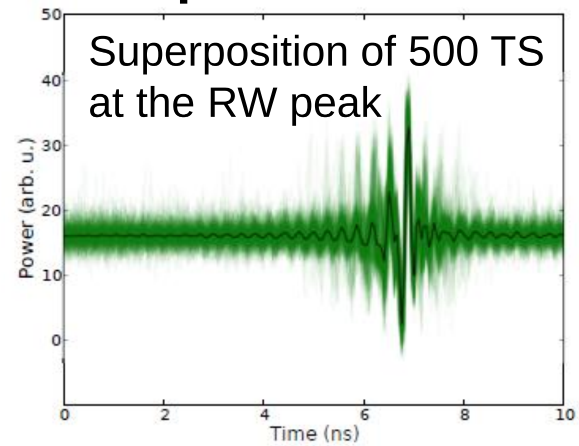
Predictability?

Deterministic simulations



Superposition of 50 time-series at the RW peak

Experiments

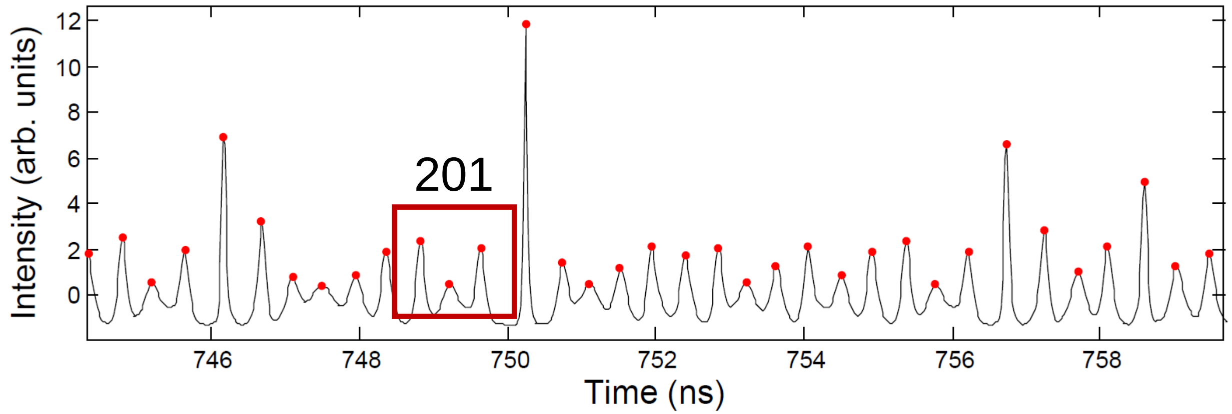


⇒ Well-defined oscillation pattern anticipates extreme pulses.

How can this effect be quantified?

J. Zamora-Munt et al. PRA (2013).

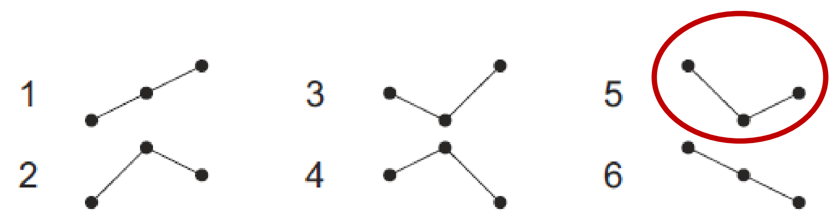
Identifying the pattern that tends to occur before the pulse



- 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:

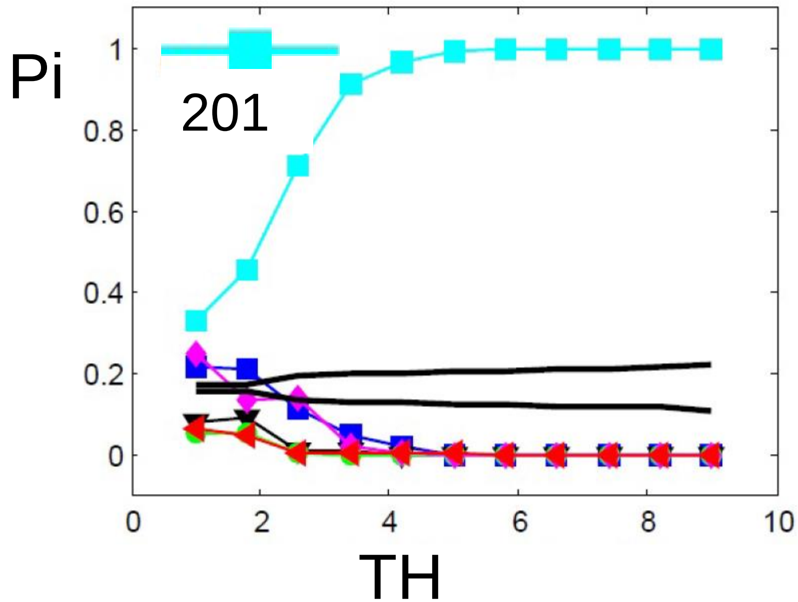


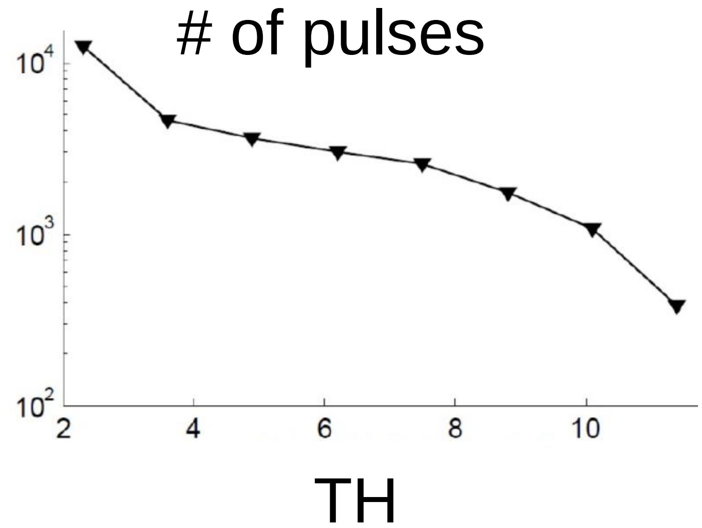
We calculate the probability of the pattern that occurs before each high pulse:

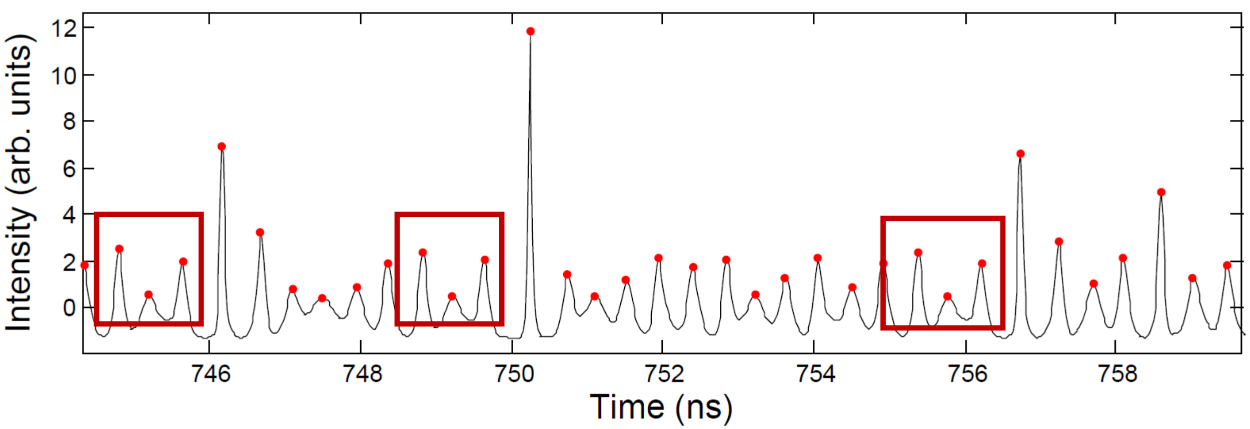
If I_i > **TH**, we analyze the pattern defined by $(I_{i-3}, I_{i-2}, I_{i-1})$

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

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





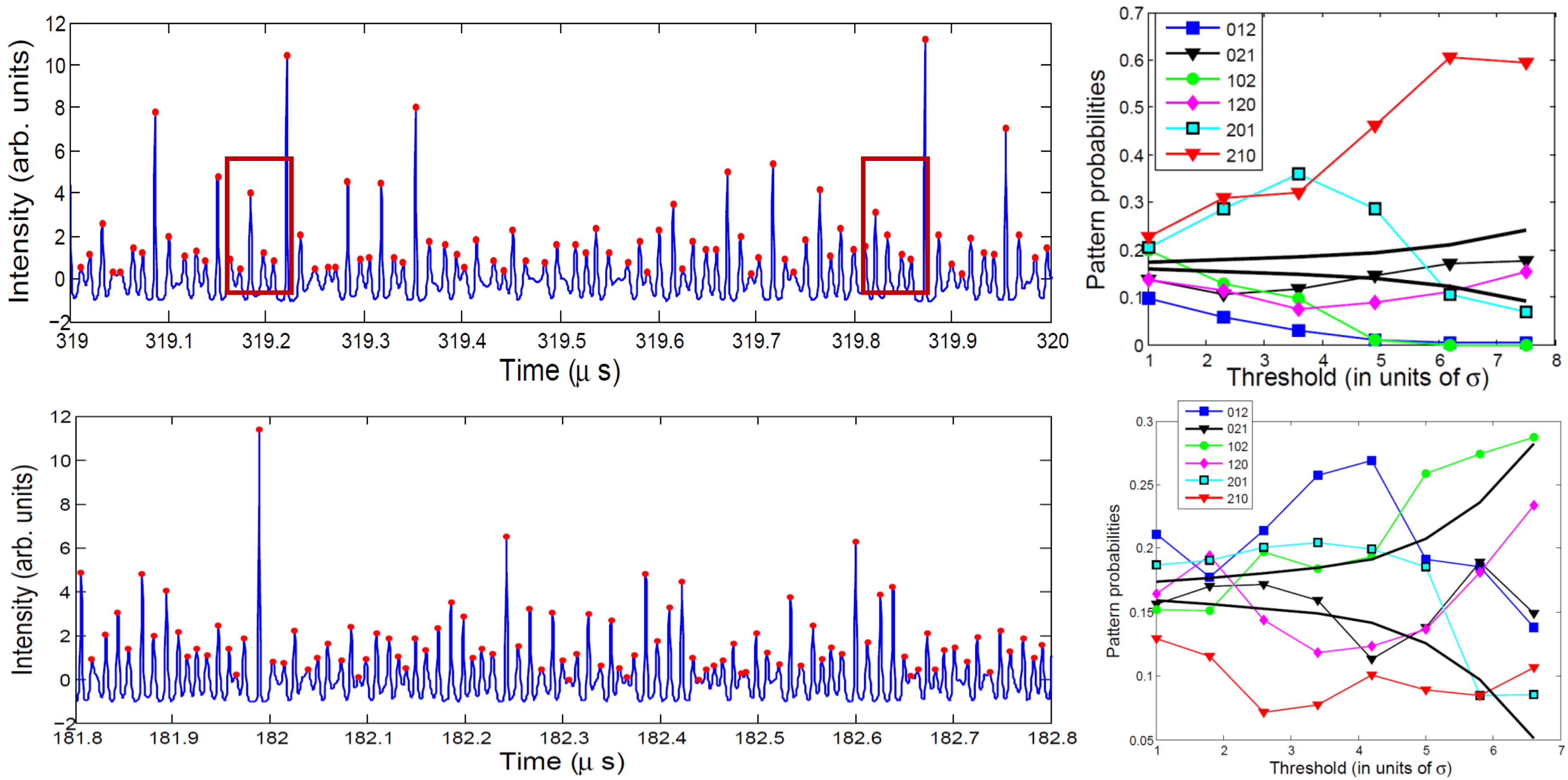


Problem: P(201)≠0 if TH <6 (pattern 201 also anticipates some small pulses) $\Rightarrow$ false alarms (false positives)

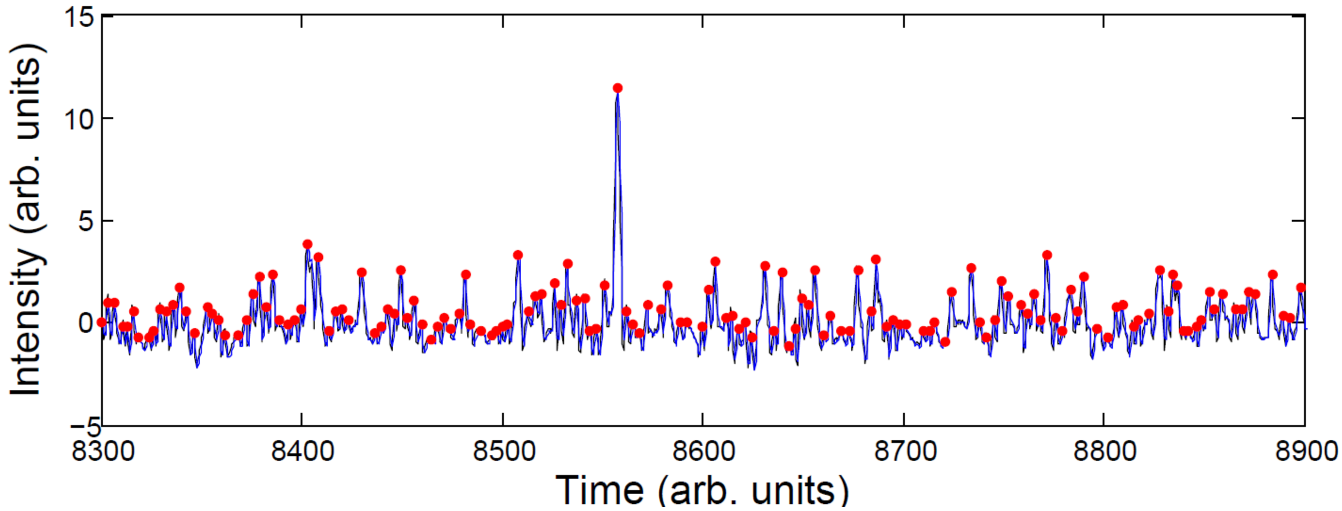
N. Martinez Alvarez et al., EPJST (2017).

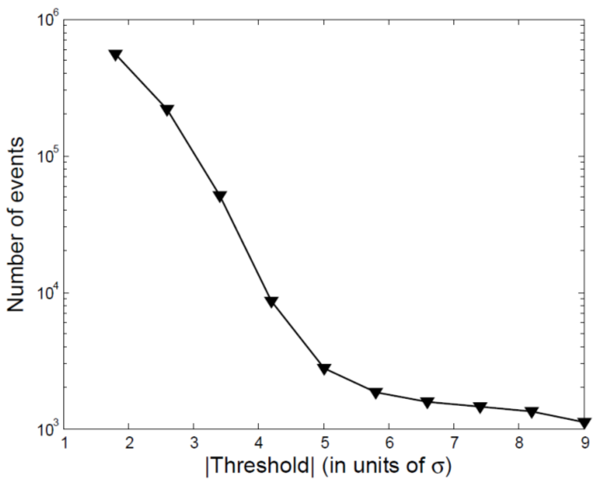
The “early warning pattern” varies with the parameters and might not exist.

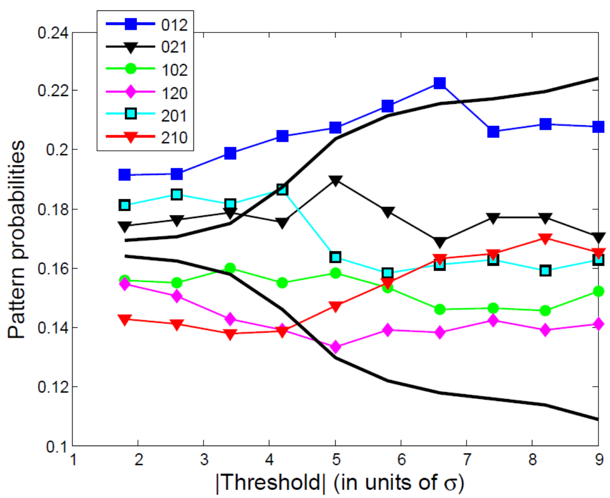
Including noise, two modulation frequencies



Analysis of experimental data







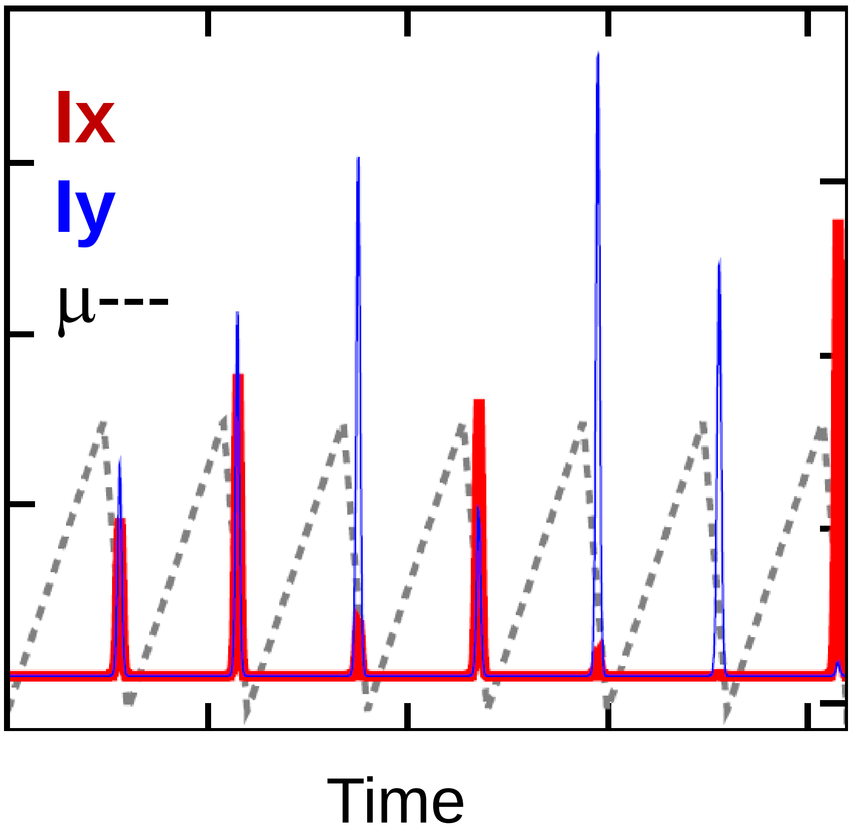
Way to improve the "early warning":

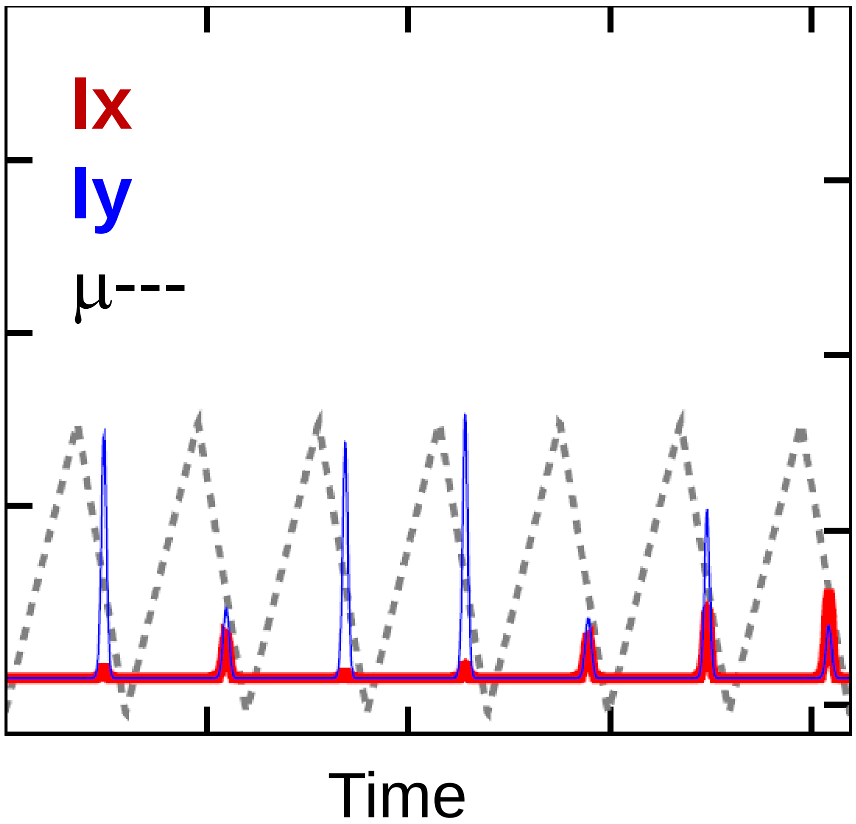
- Filter noise
- Longer patterns

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

Data from S. Barland, M. Giudici (Nice)

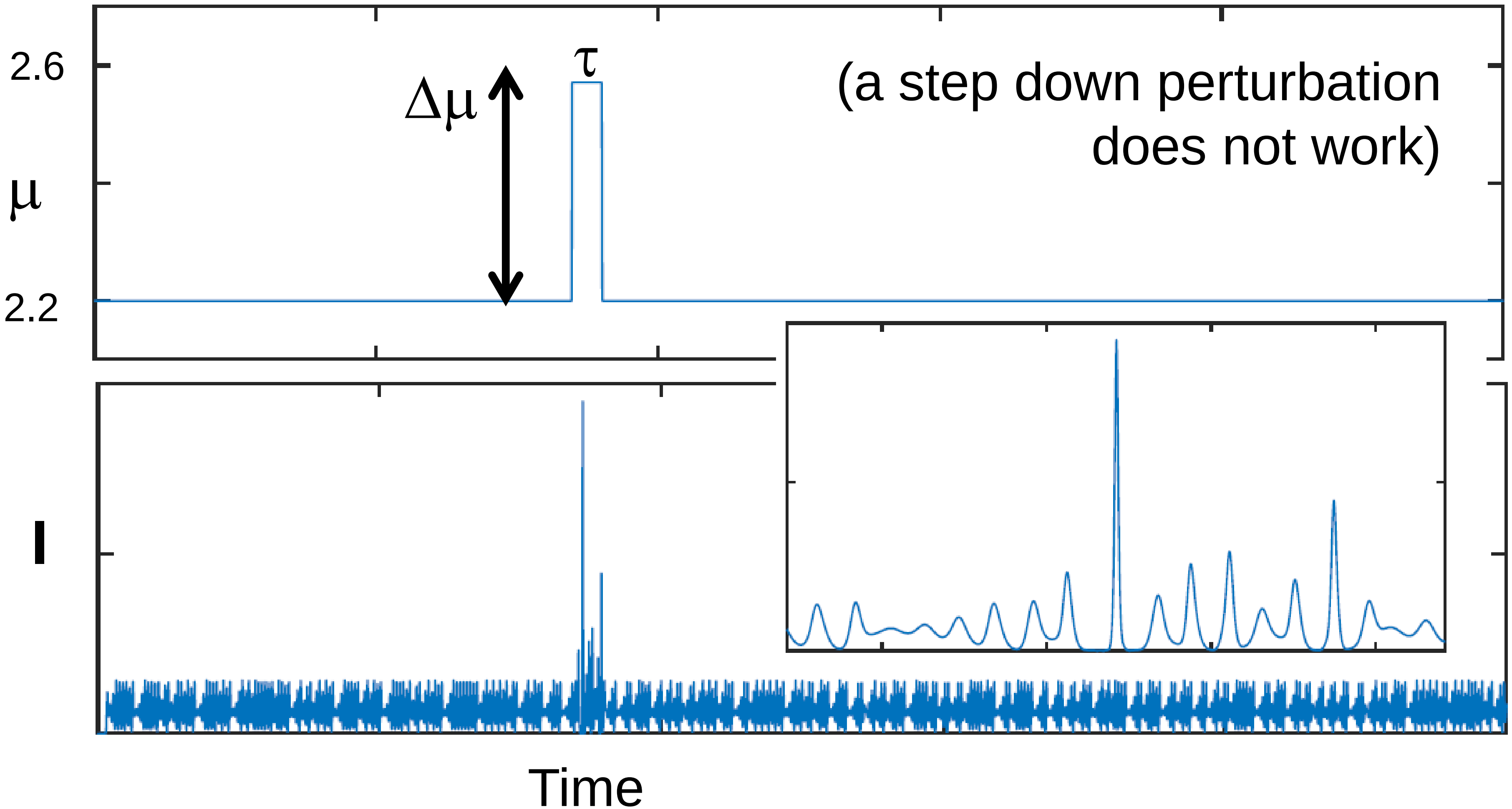
On demand generation? Simulations of VCSEL model





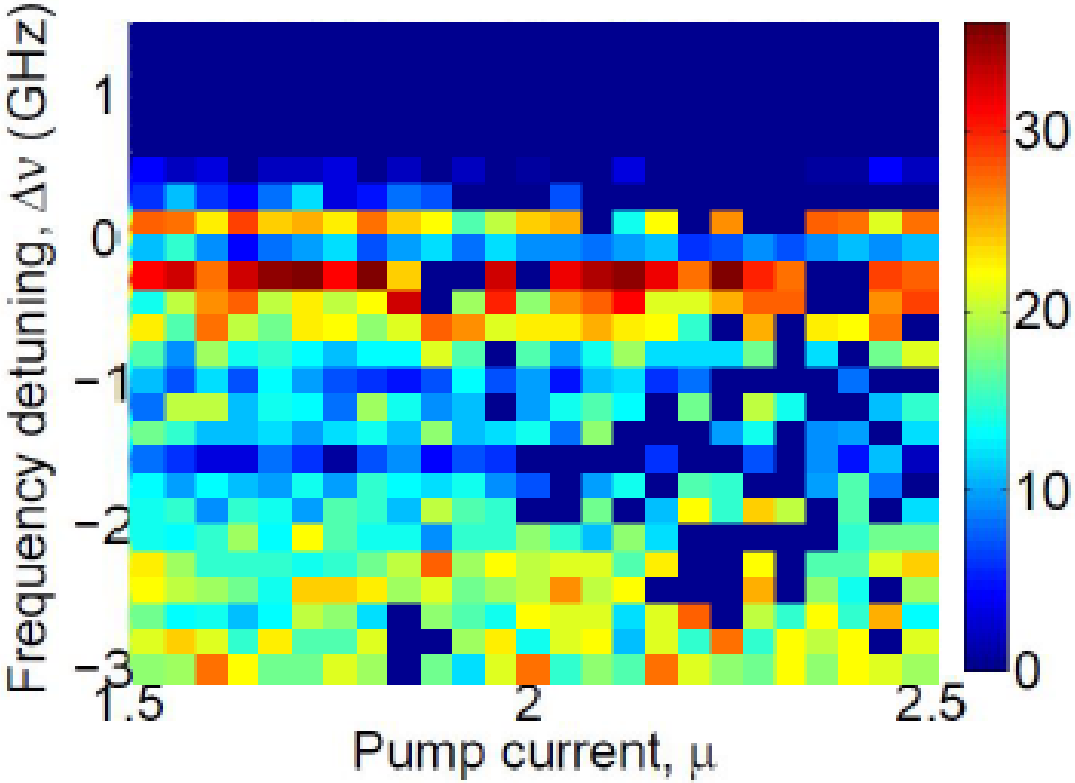
Zamora and Masoller, Opt. Express (2008).

On demand generation?



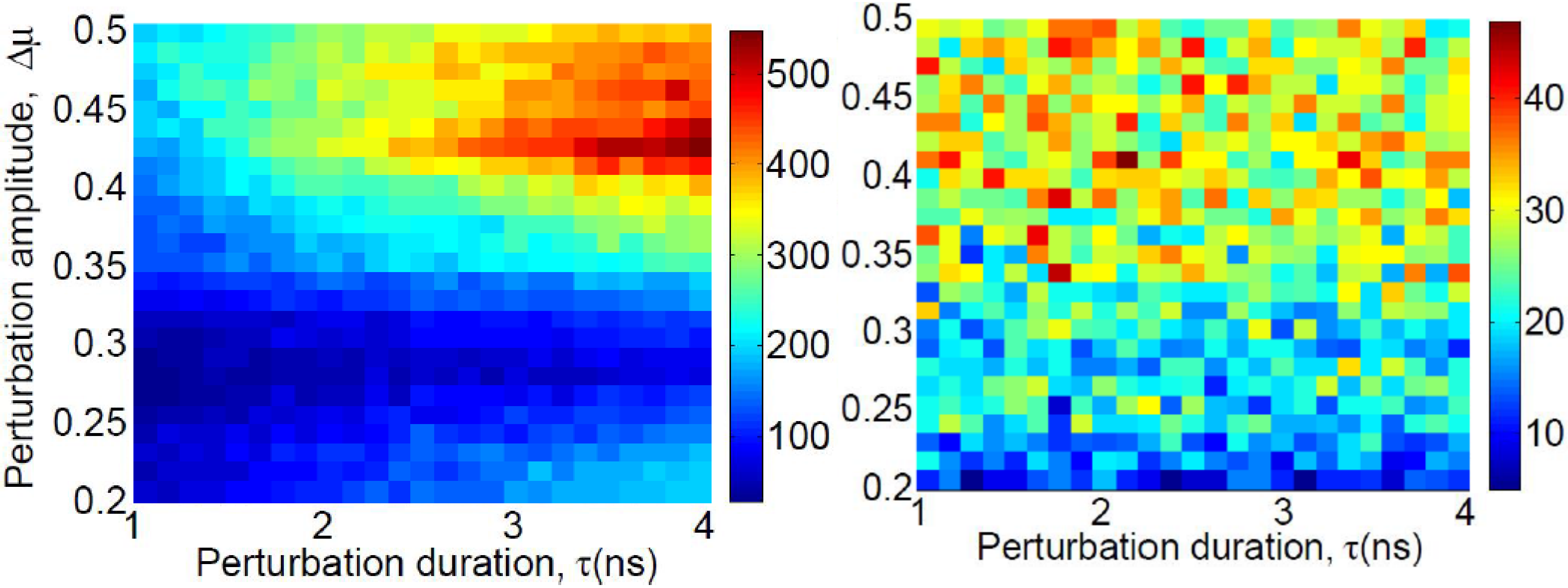
T. Jin et al, Opt. Express (2017).

Where in the parameter space is easier to generate pulses?



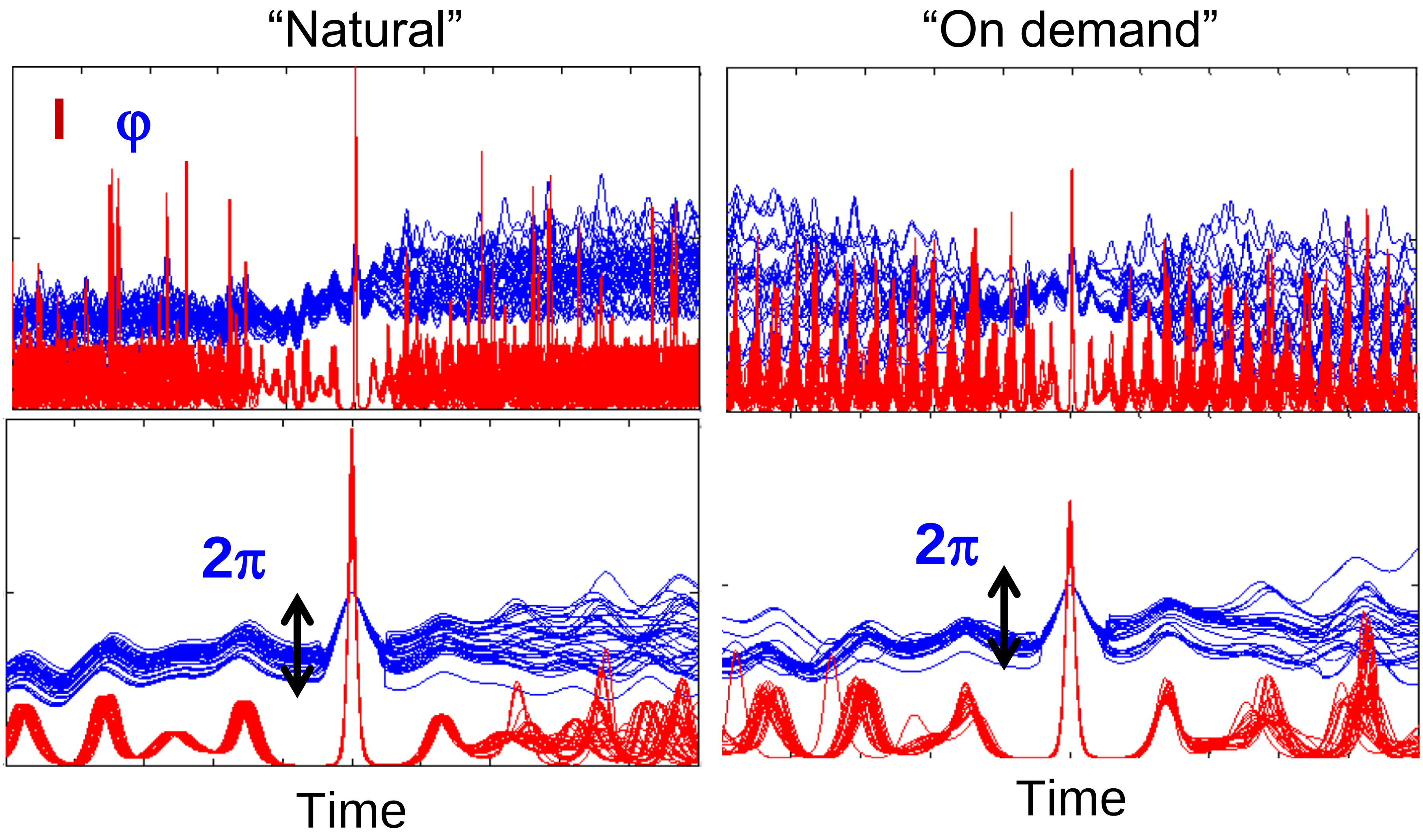
100 perturbations. In regions where there are “natural” extreme pulses, no perturbation is applied.

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.

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 current modulation.
- Certain patterns of oscillations can be more (or less) likely to occur before the extreme intensity pulses.
- Extreme pulses can be generated “on demand” by appropriated perturbation of the pump current parameter.
- Ongoing work: potential for sensing applications?
- To do in the future: the symbolic approach to predict extreme events in empirical data needs to be explored.

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

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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