Extreme pulses in optically injected semiconductor lasers: characterization, prediction, and control

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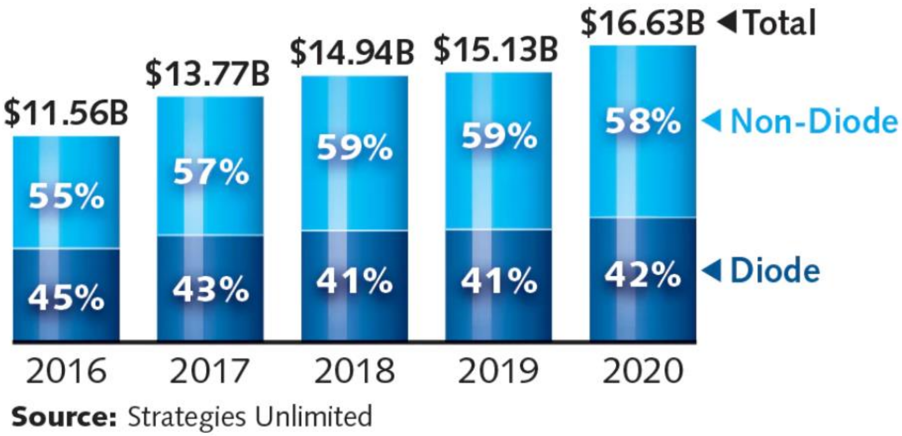
Semiconductor lasers play a crucial role in photonic technologies

- Inexpensive, compact, efficient
- Emit a wide range of wavelengths (optical communications, biomedical applications),
- Emit a wide range of powers (μWs-KWs).



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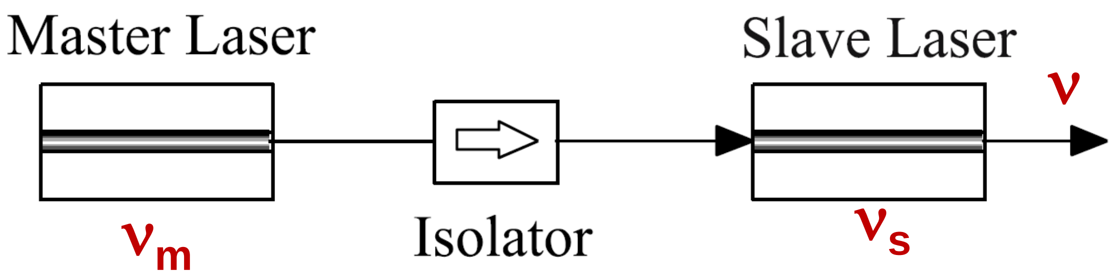
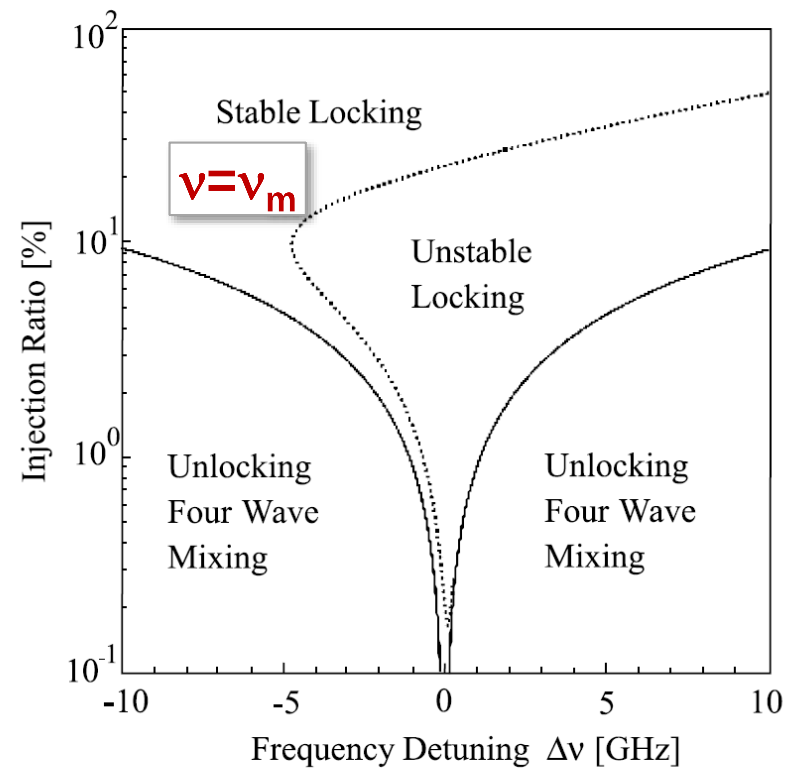
Optically injected lasers are nonlinear dynamical systems



Detection system (photo detector, oscilloscope, spectrum analyzer)

- Two Parameters:
  - Injection ratio
  - Frequency detuning $\Delta\nu = \nu_s - \nu_m$
- Dynamical regimes:
  - Stable locking (cw output)
  - Periodic oscillations
  - Chaos
  - Beating (no interaction)



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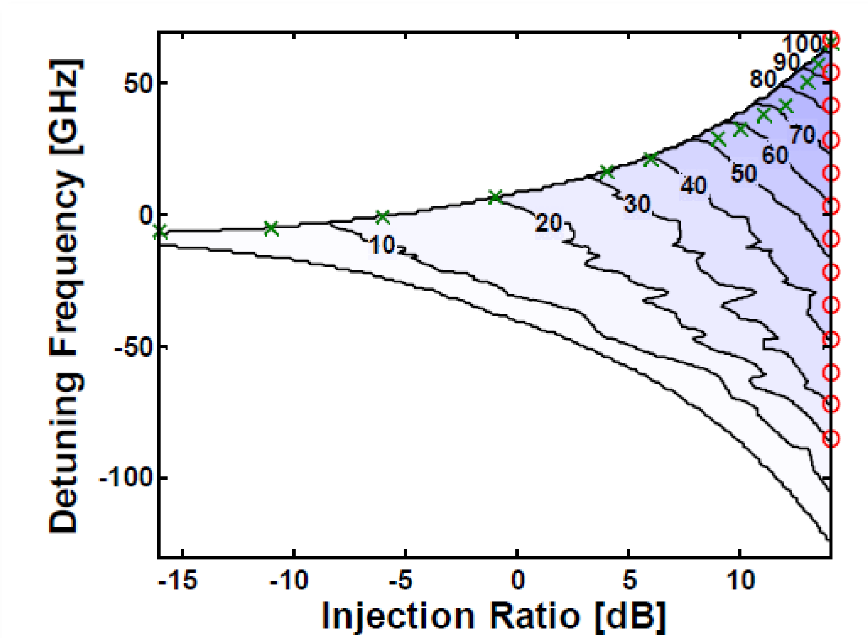
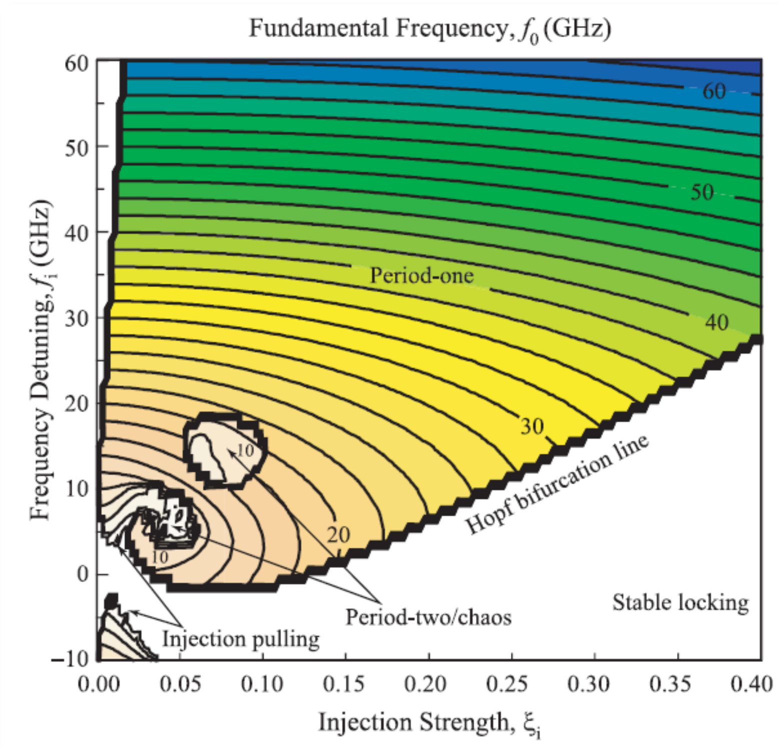
Injection locking increases the modulation bandwidth; outside the locking region: intensity oscillations



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



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

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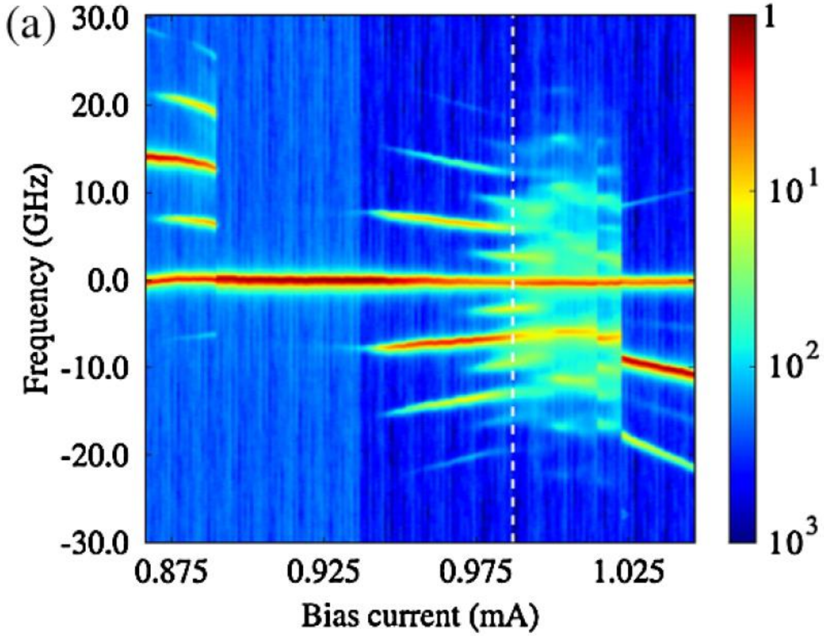
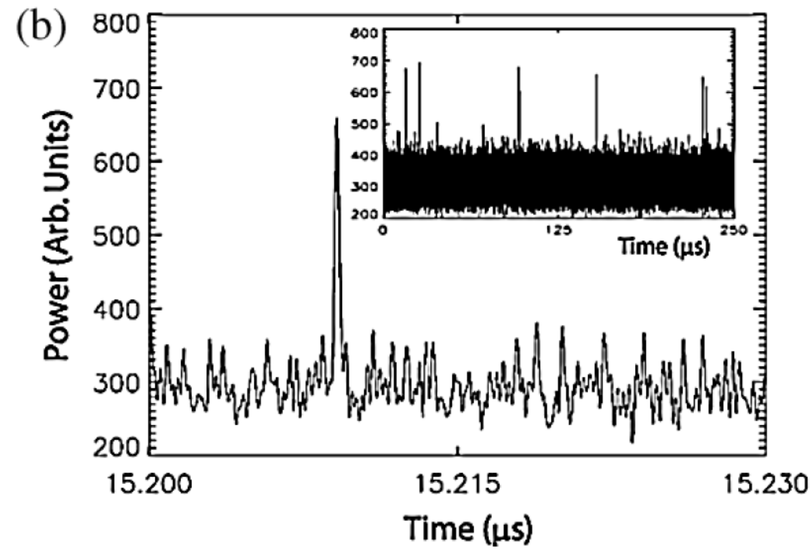
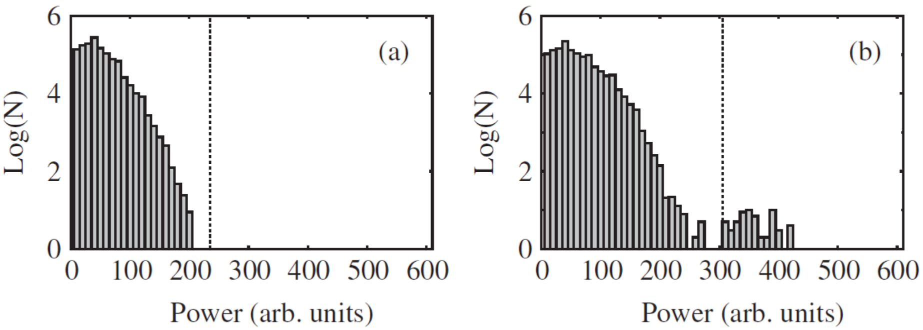
In a narrow parameter region (outside the locking region): extreme pulses







Extreme pulse:

amplitude above <I> + **8** σ

C. Bonatto et al, PRL 107, 053901 (2011), Optics & Photonics News February 2012, Research Highlight in Nature Photonics DOI:10.1038/nphoton.2011.240

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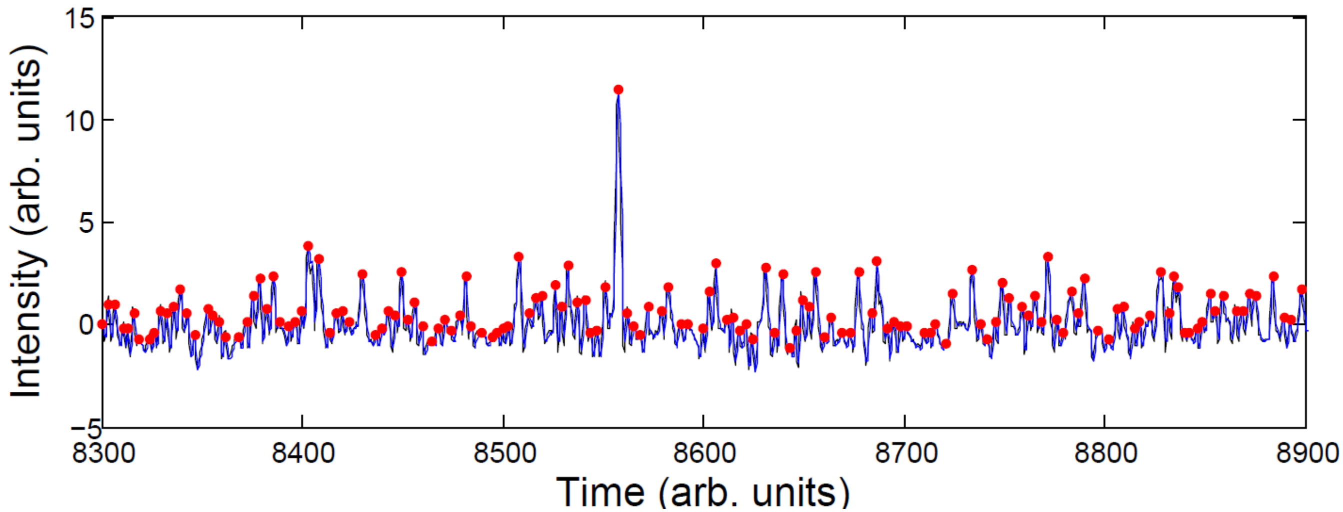
Questions



In our system:

- Which mechanisms induce extreme pulses?
- Role of noise?
- Can they be suppress?
- Can they be generated “on demand”?
- Can they be predicted?

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Governing equations

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

Carrier density, **N**

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

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

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 observed intensity dynamics.

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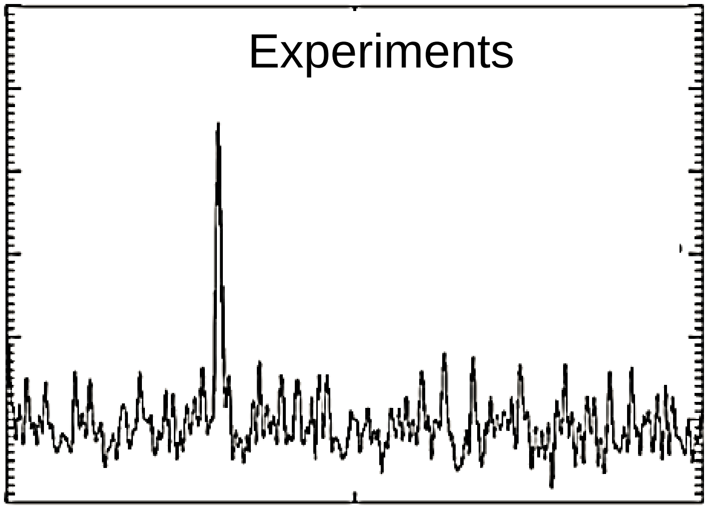

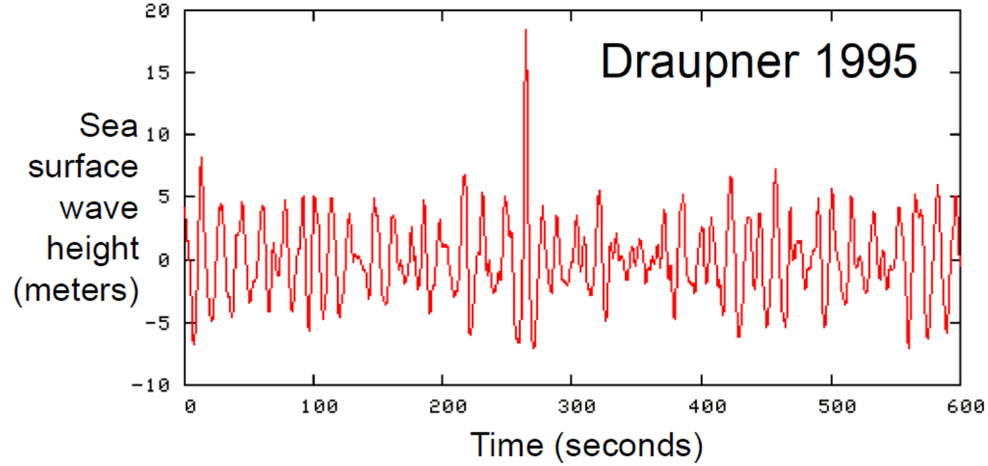

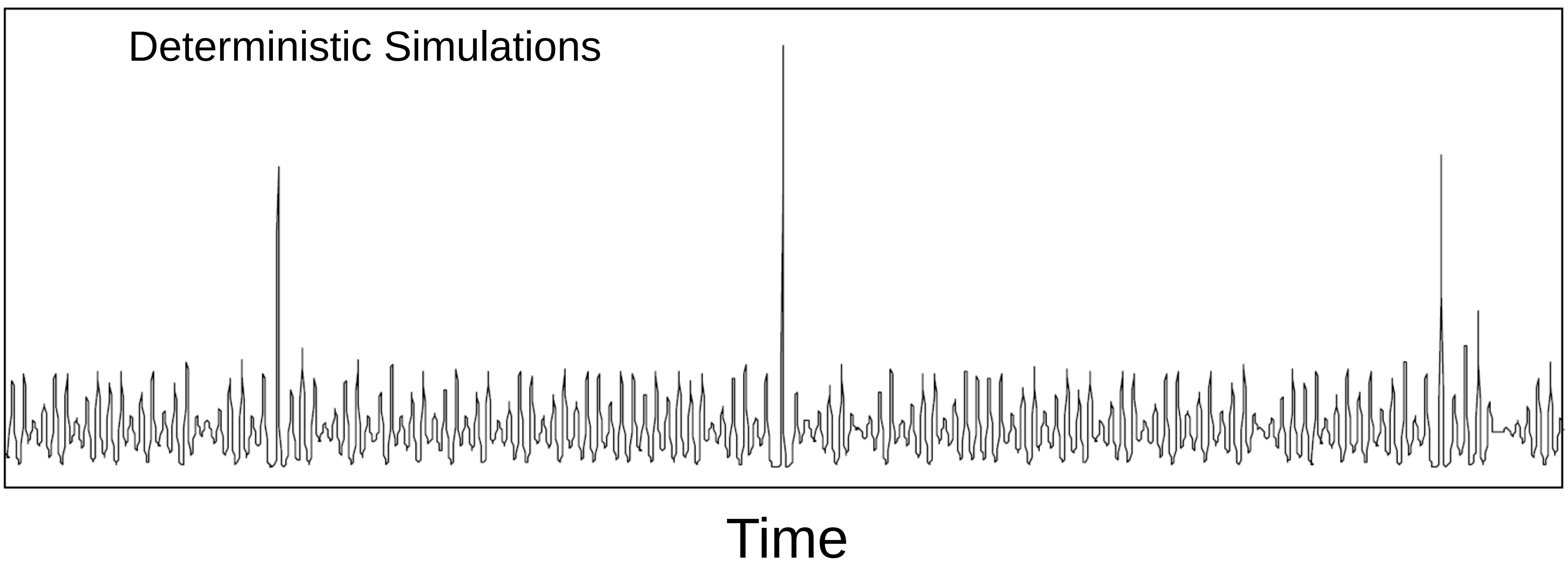

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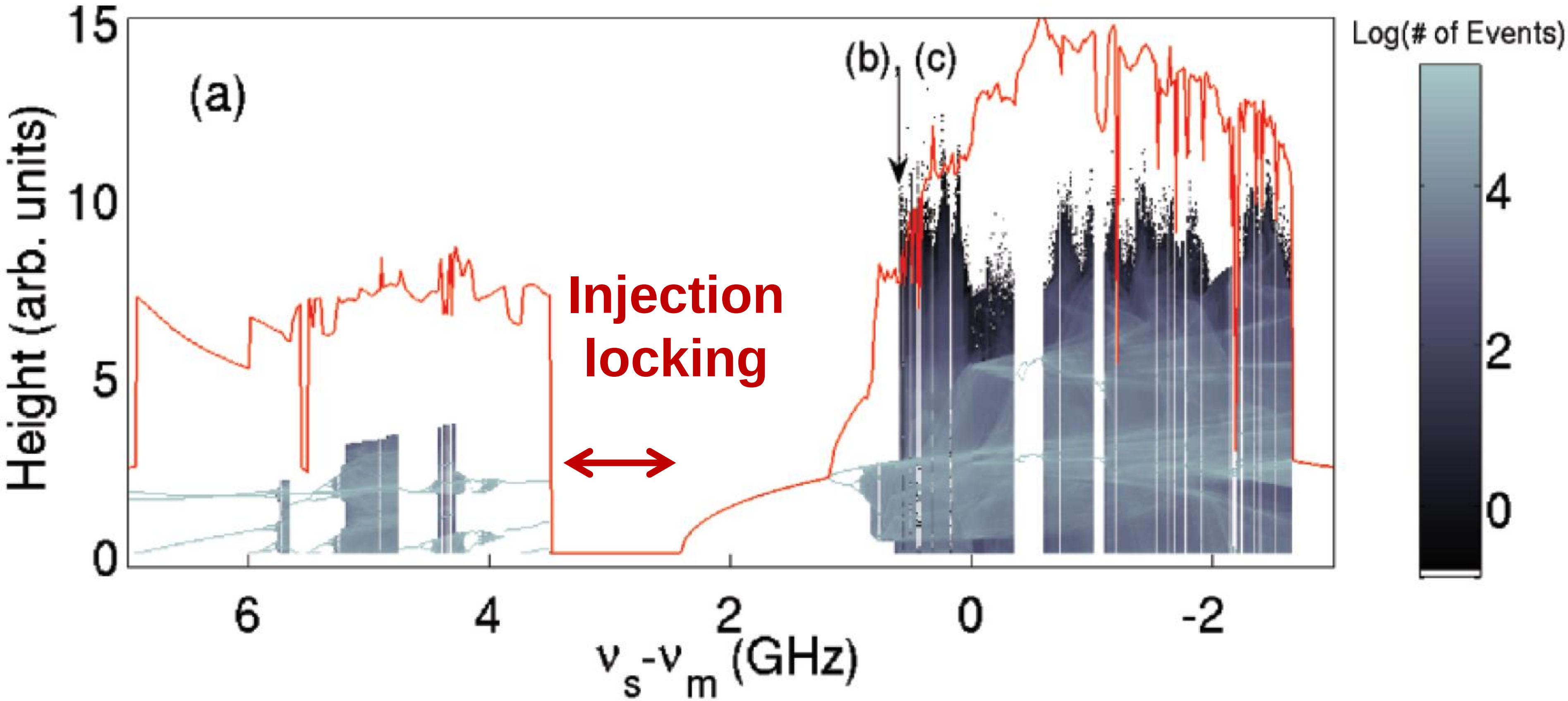
Bifurcation diagram: in color code: log(# of pulses)



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

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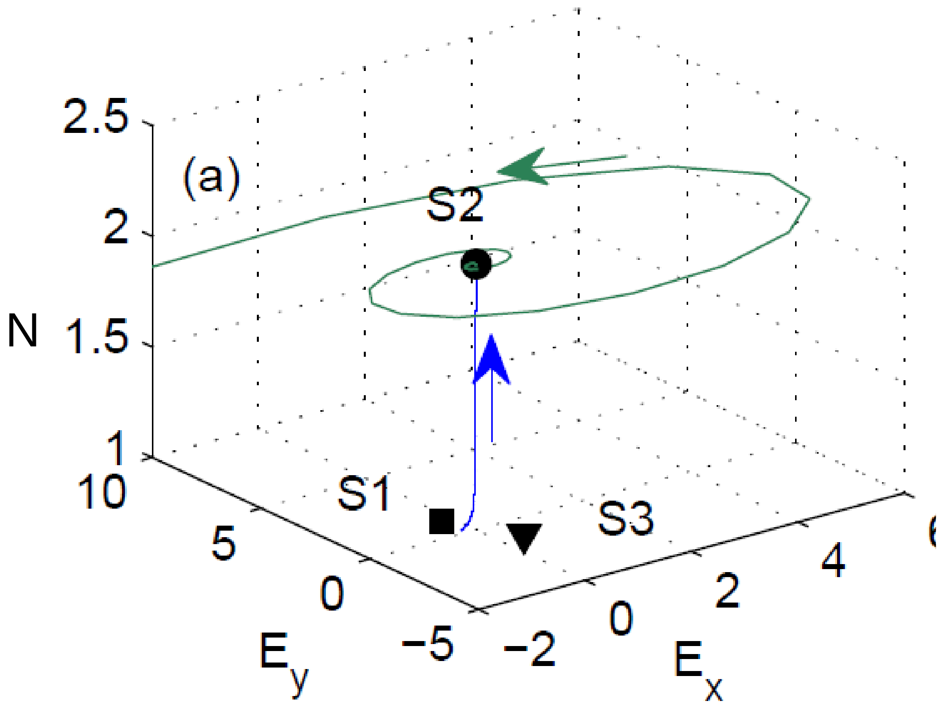
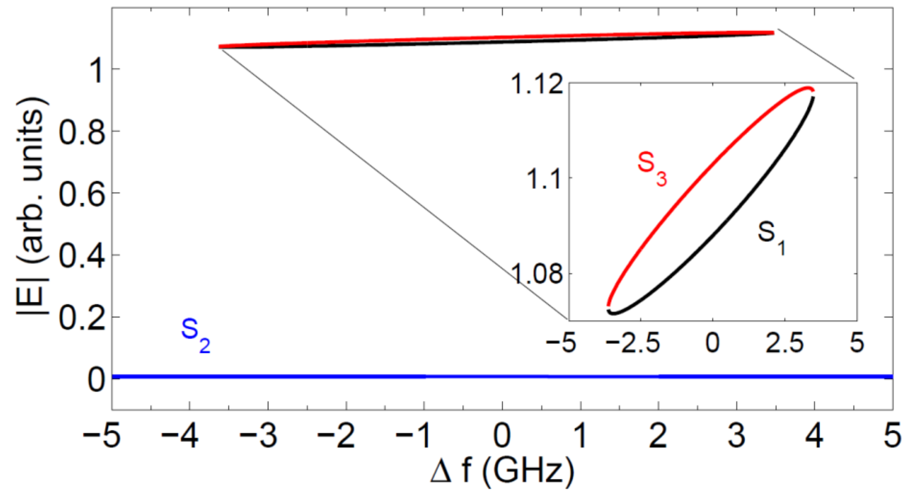
To understand the mechanism underlying the extreme pulses we need to examine the location the three fixed points.





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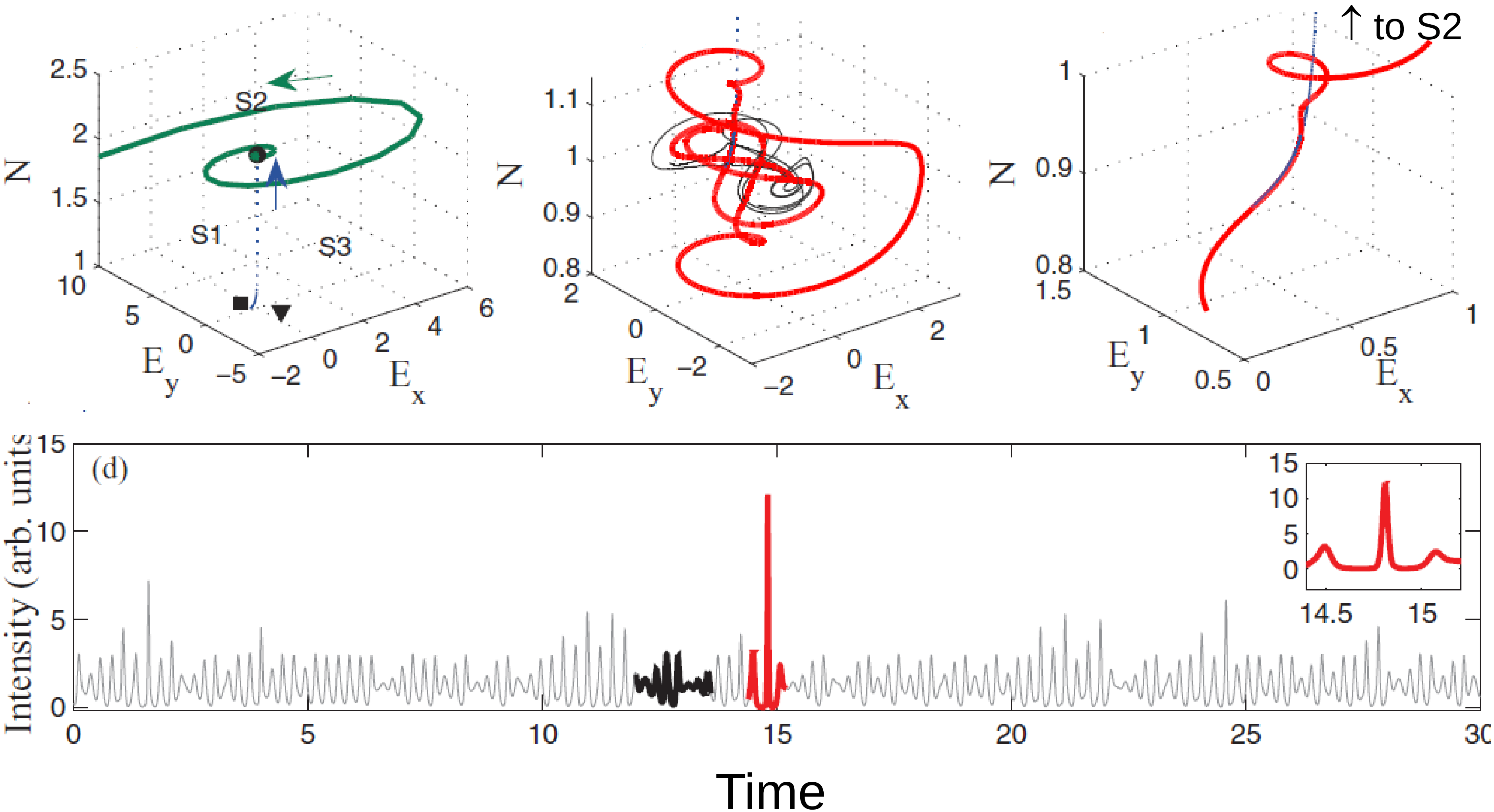
An extreme pulse may be triggered when the trajectory closely approaches the stable manifold of S2 (“the door”)



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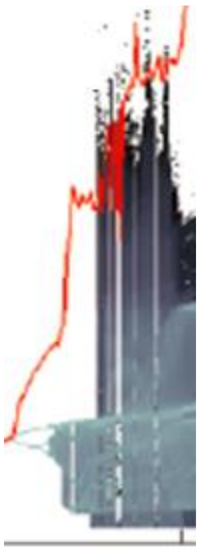
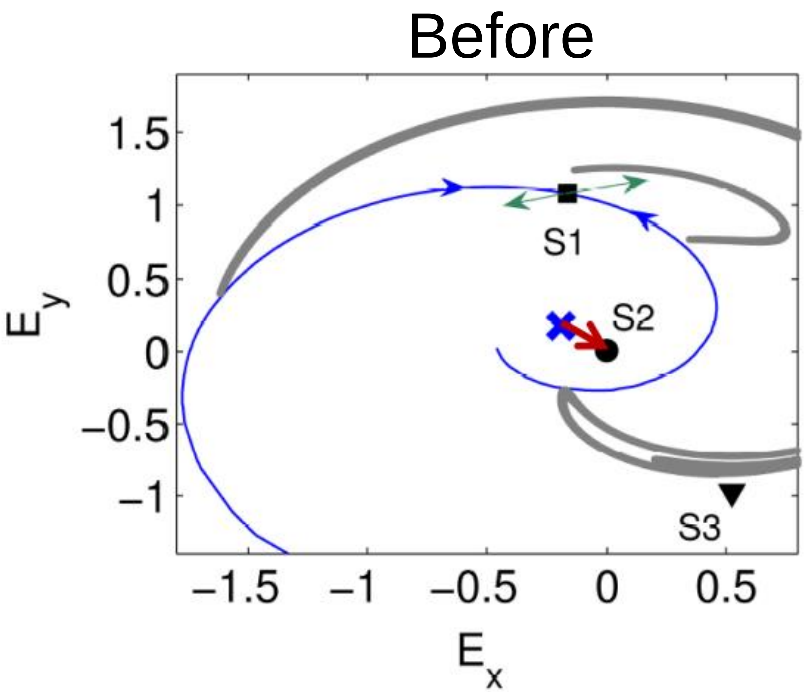
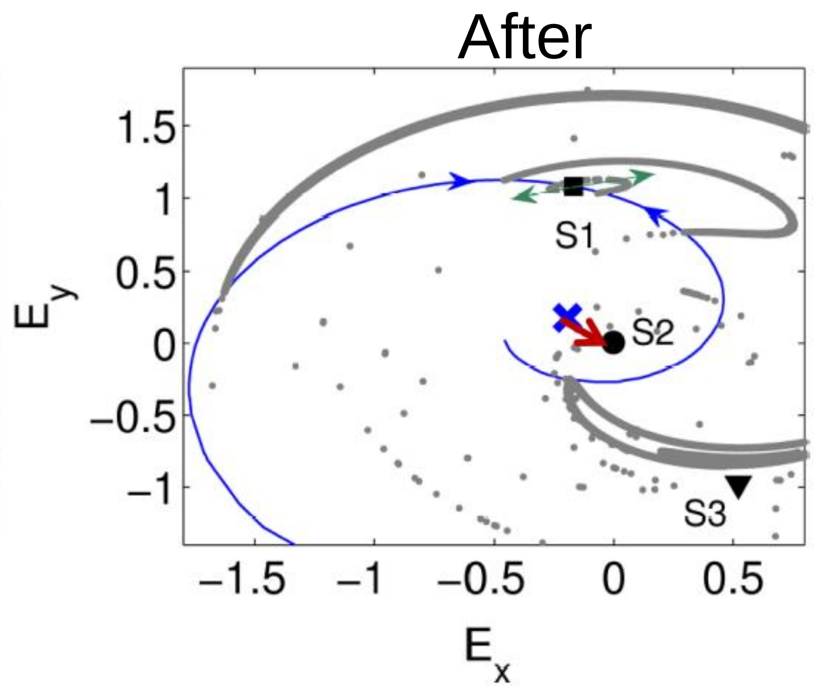
With a Poincare map (N=1) we see the expansion of the attractor when extreme pulses appear







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

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Spontaneous emission noise can induce extreme pulses

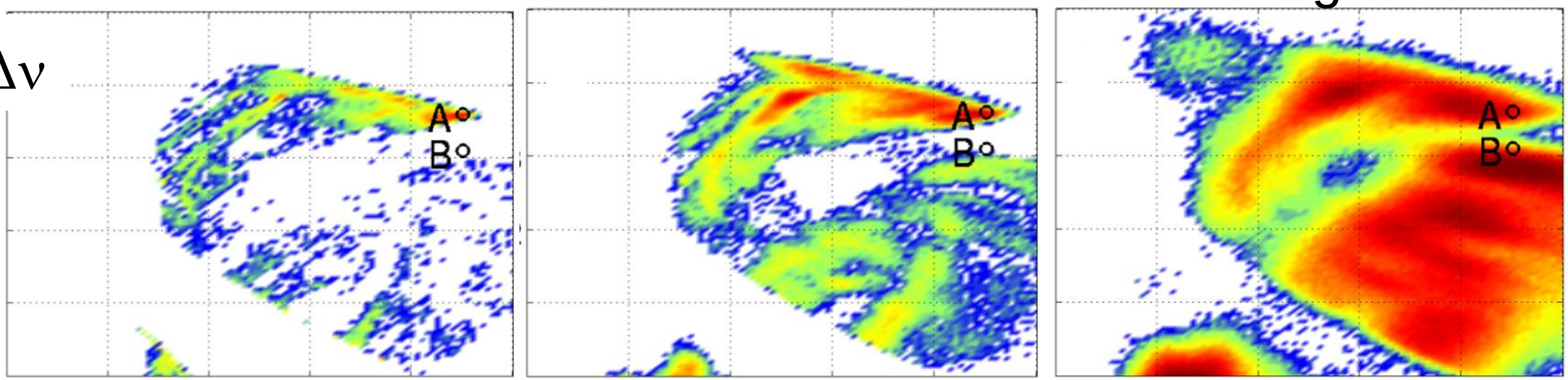
$$\frac{dE}{dt} = \kappa(1+i\alpha)(N-1)E + i\Delta\omega E + \sqrt{P_{\text{inj}}} + \sqrt{D}\xi(t),$$

In color code the number of pulses

No noise

Strong noise

$\Delta\nu$



Pump current

Th = <I>+6σ

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

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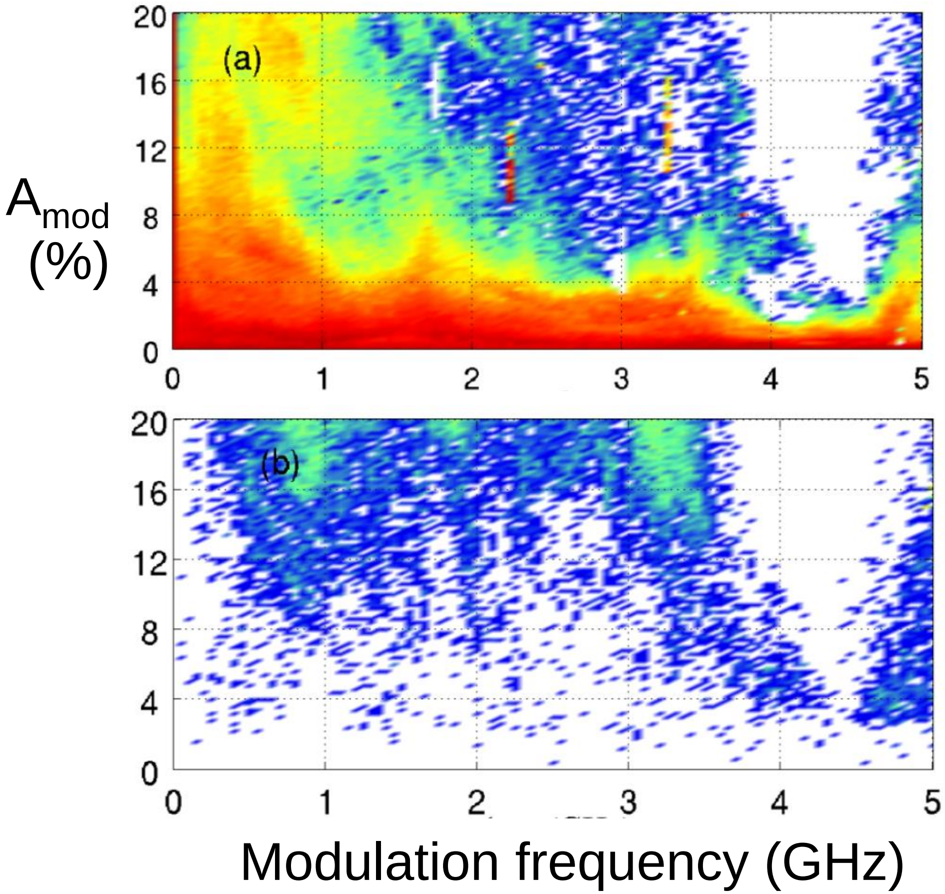
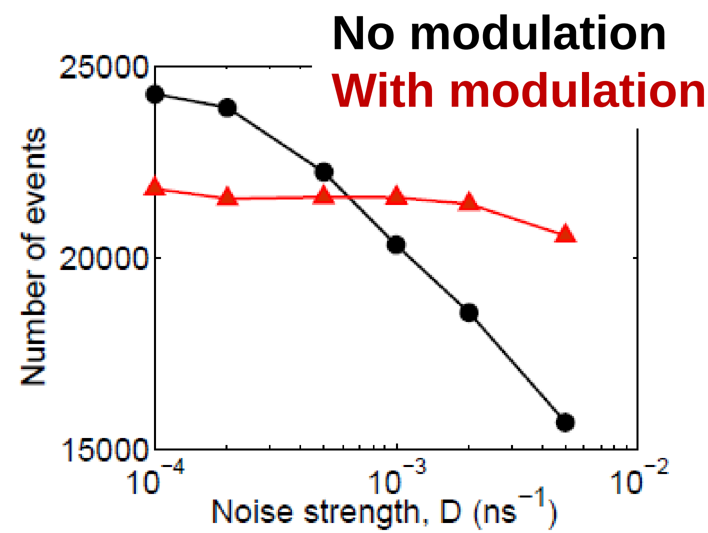
Current modulation suppresses or induces pulses

$$\frac{dN}{dt} = \gamma_N [\mu(t) - N - |E|^2] \qquad \mu(t) = \mu_0 + \mu_{\text{mod}} \sin(\omega_{\text{mod}} t)$$



Color code:
log (# of pulses)



Th = <I>+6σ

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

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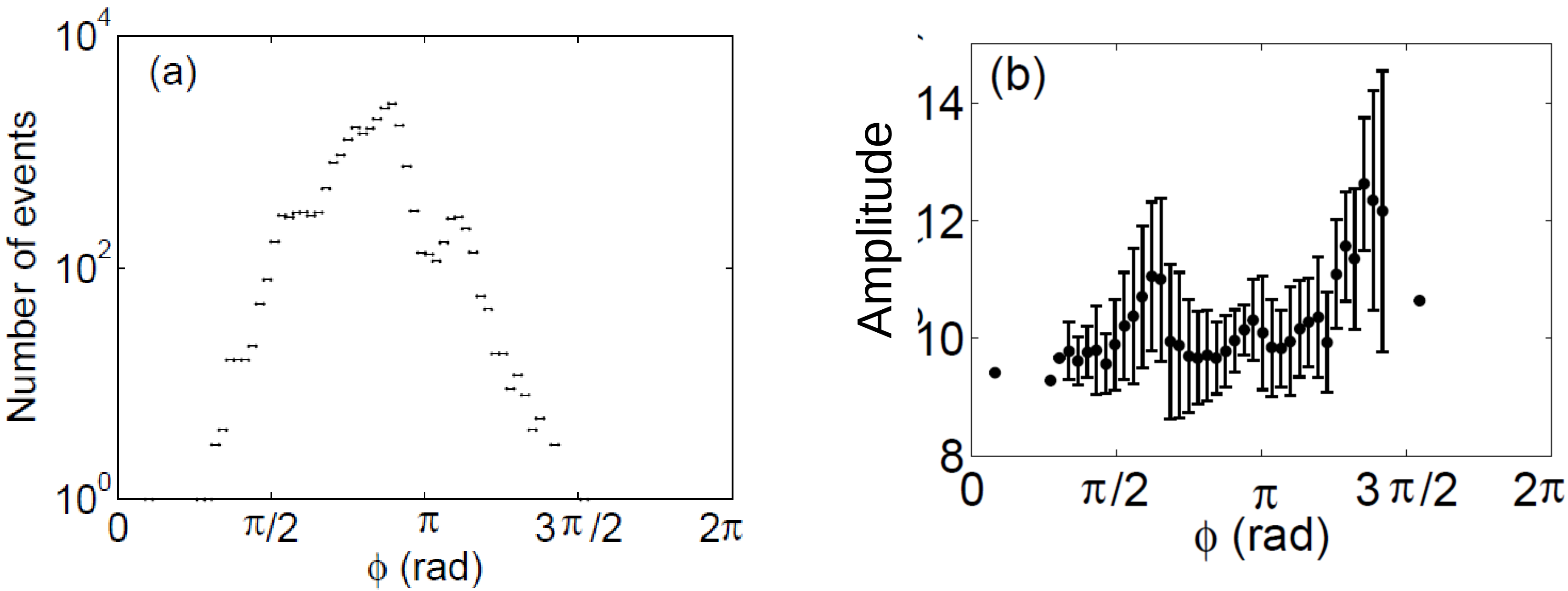
When extreme pulses are not suppressed by current modulation, their probability and amplitude depend on the phase of the modulation



J. Ahuja et al., Opt. Express 2014

Acknowledgments

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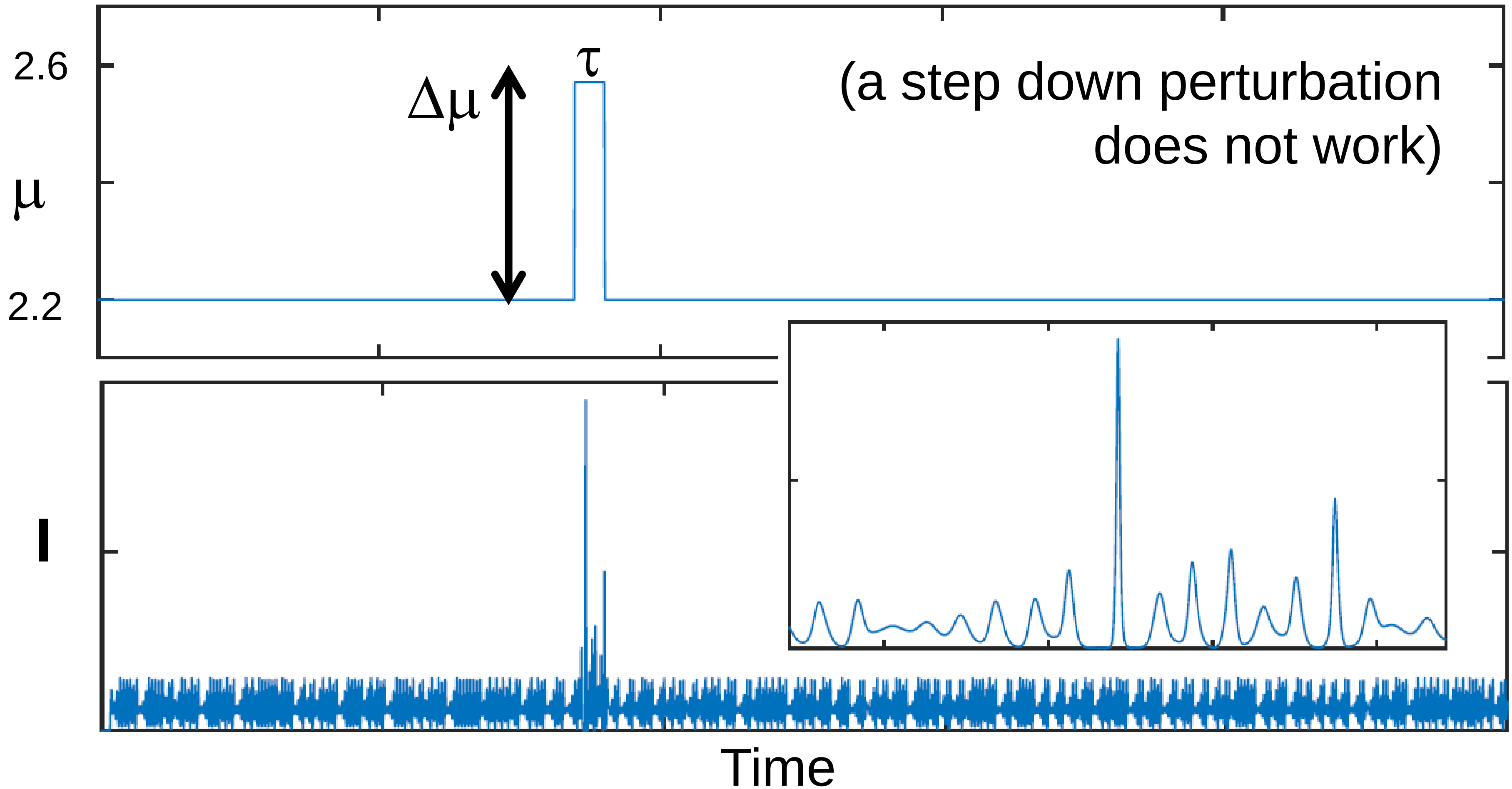
Can extreme pulses be generated ``on demand''?



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

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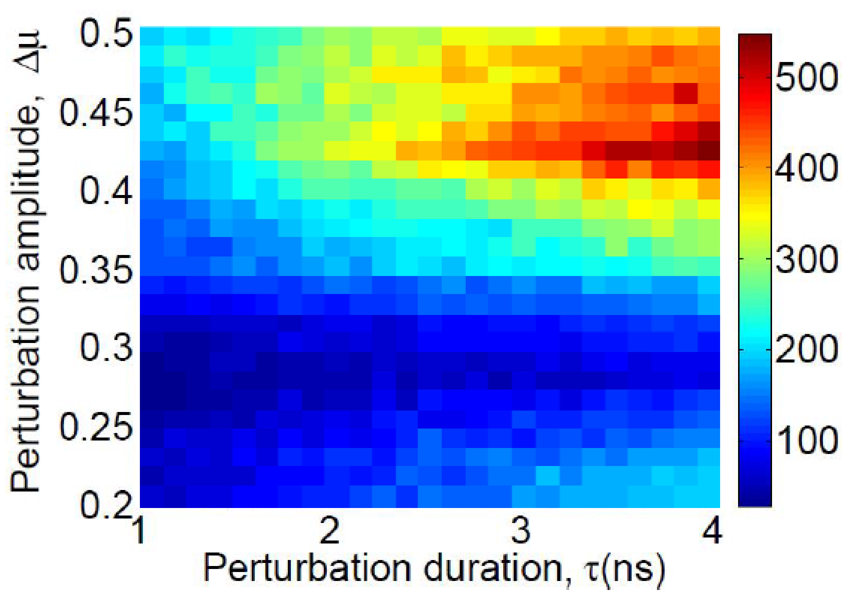
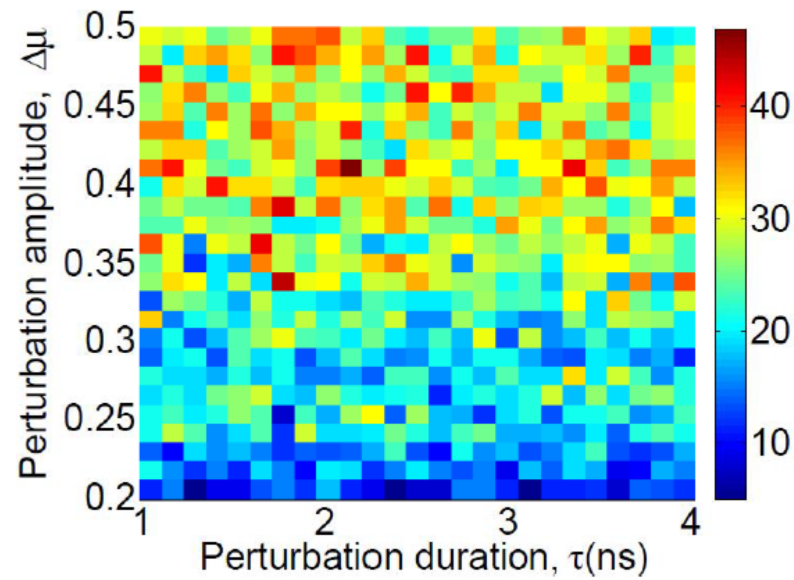
Number of extreme pulses generated by 1000 perturbations as a function of the perturbation parameters: as large as 50% or as small as 5%

C (μ = 1.8 and $\Delta\nu$ = 0.22 GHz)



B (μ = 2.2 and $\Delta\nu$ = 0.6 GHz)



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

Th = <I>+8σ

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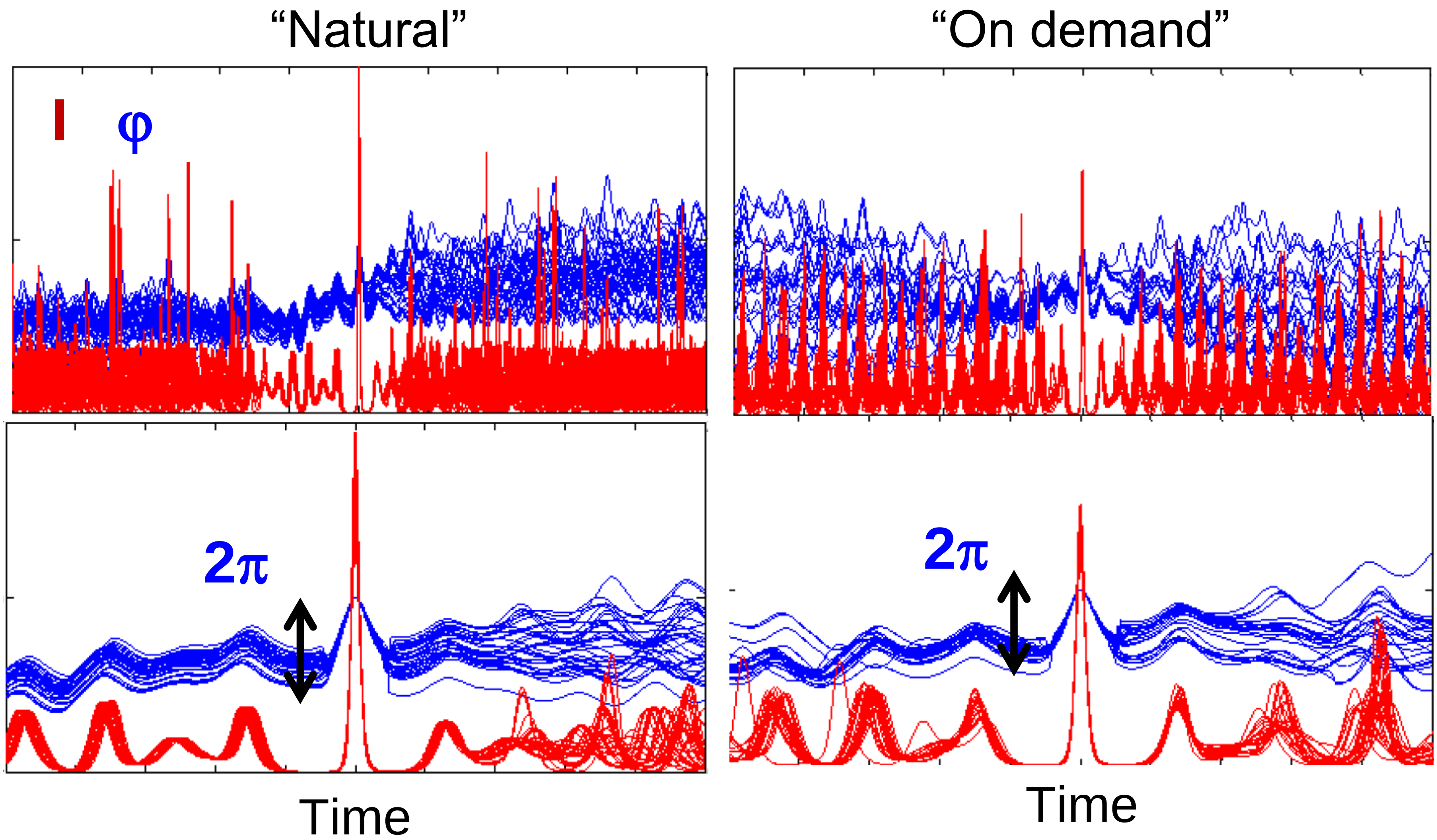
Are the generated pulses similar to “natural” ones?



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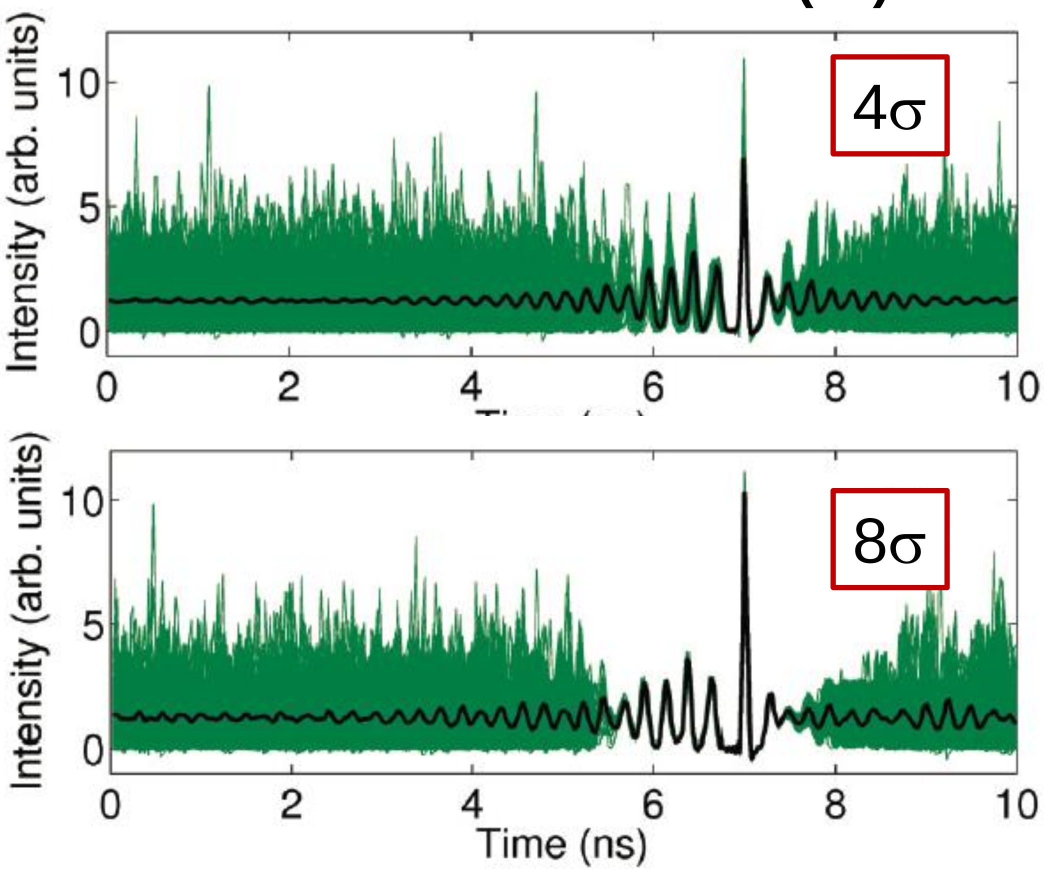
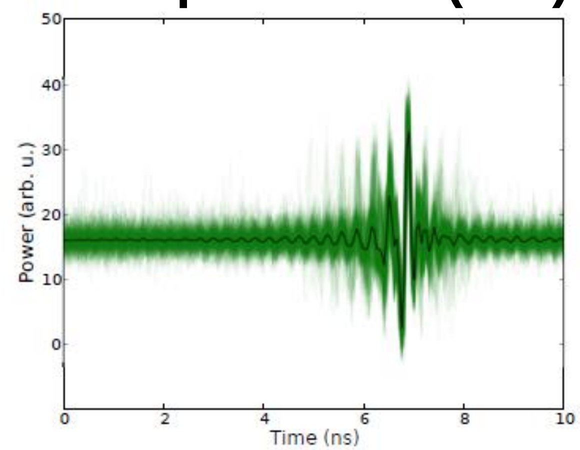
Predictability?

Superposition of 50/500 time series at the peak of the pulse

Deterministic simulations (50)



Experiments (500)



⇒ Well-defined oscillation pattern anticipates extreme pulses.

How can this effect be quantified?

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

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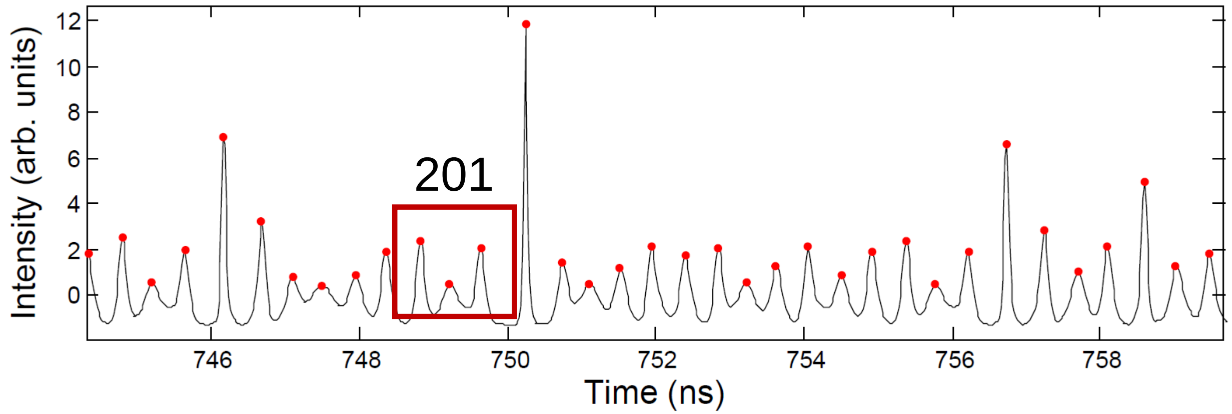
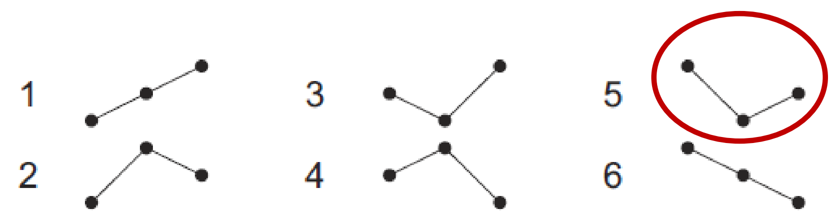
We try to identify a "pattern" that occurs before the pulse



- 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 these pattern before each extreme pulse:

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

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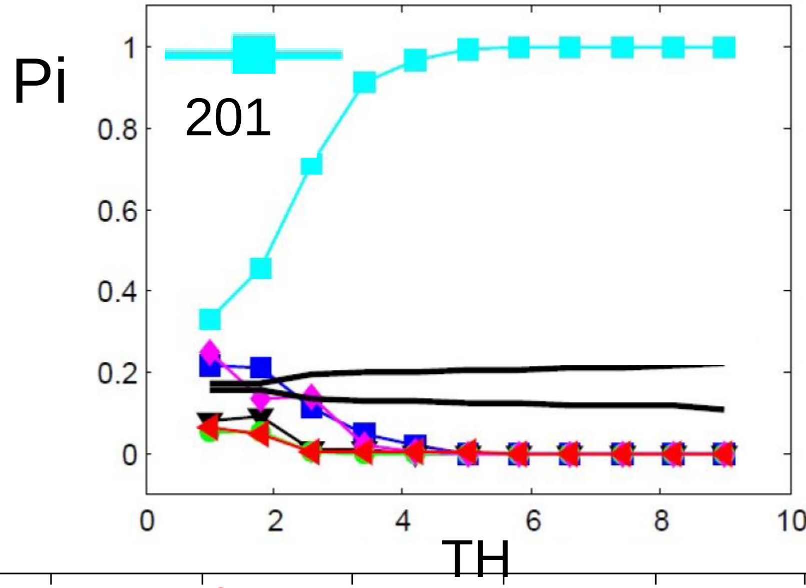
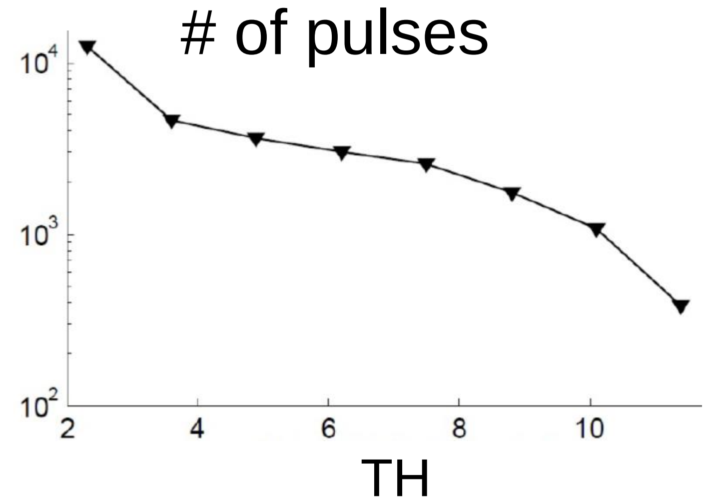
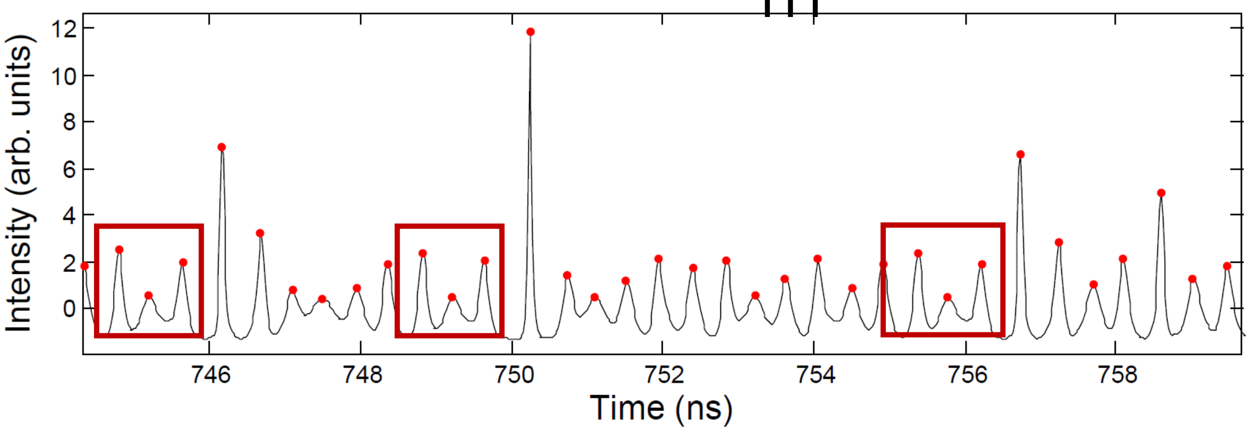
"Good" results in deterministic simulations: P(201)=1 if TH >6

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).

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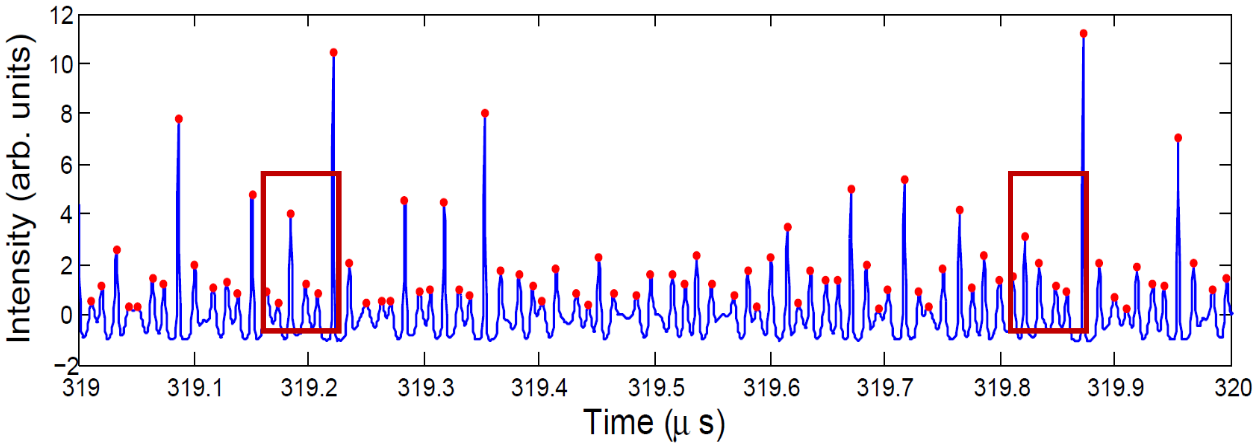
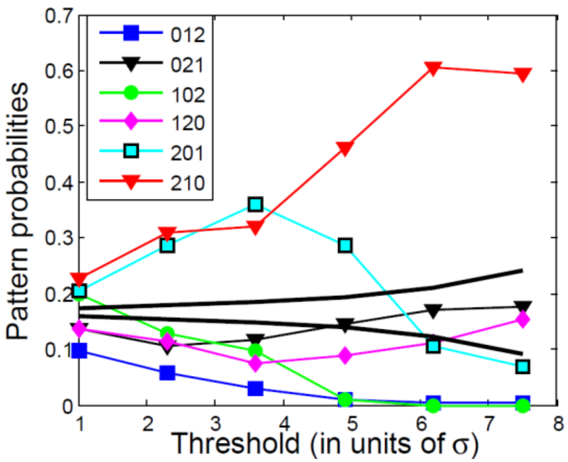
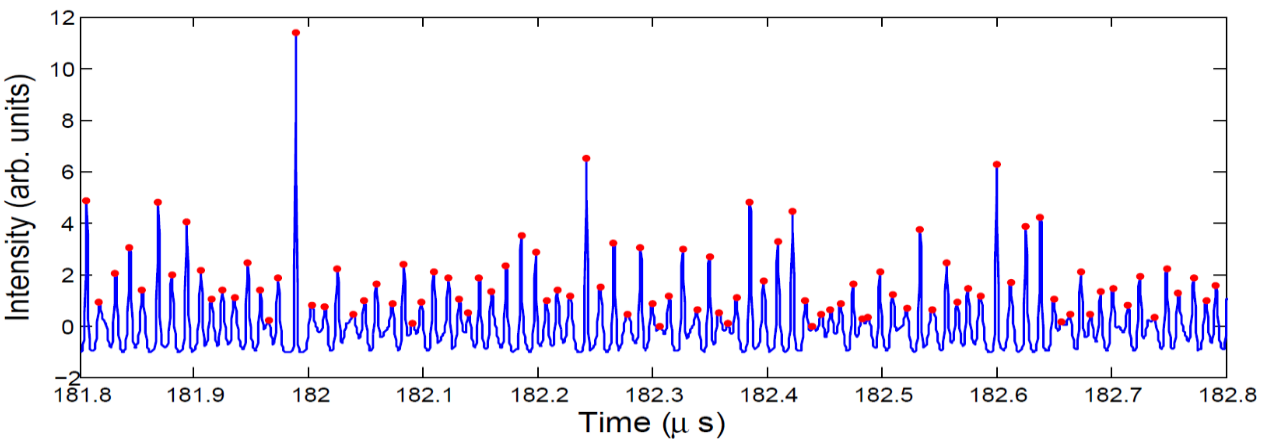
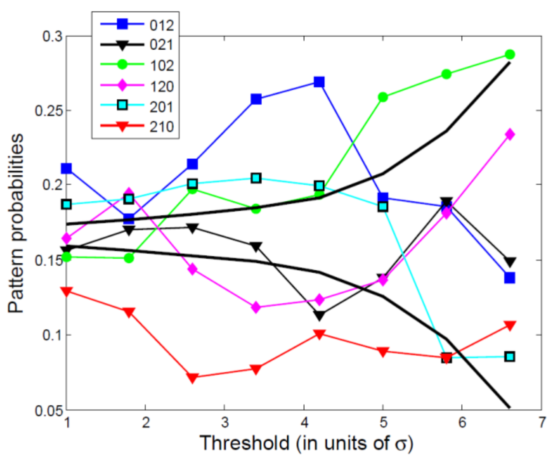
The "early warning pattern" varies with the parameters and might not exist

Including noise, two modulation frequencies









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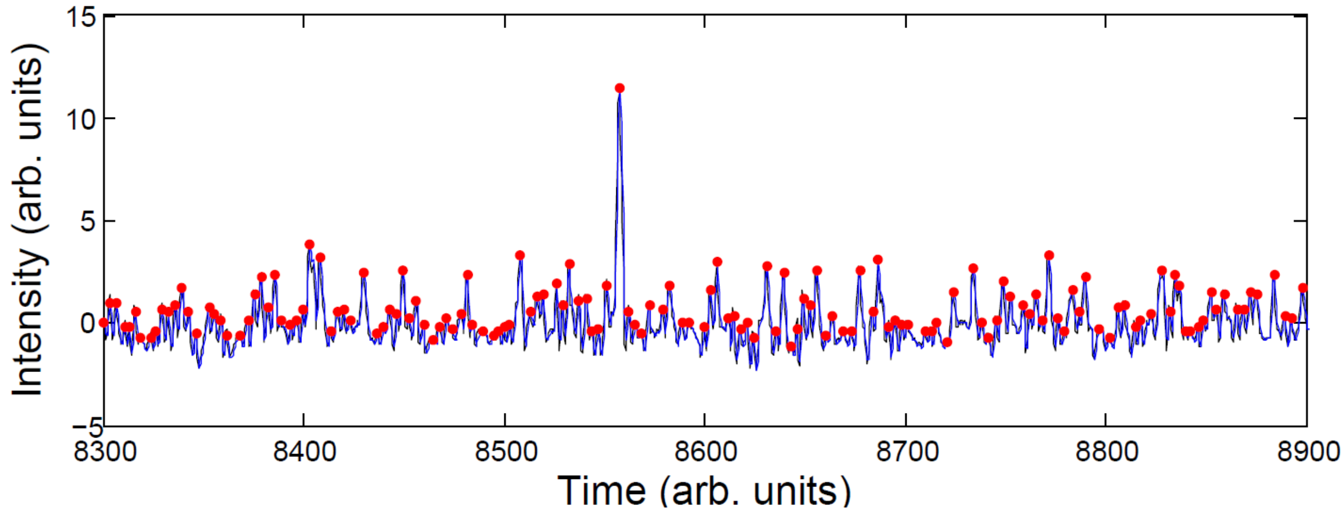
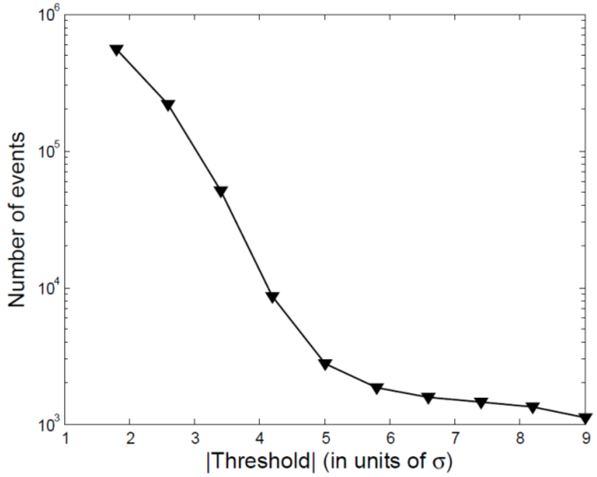
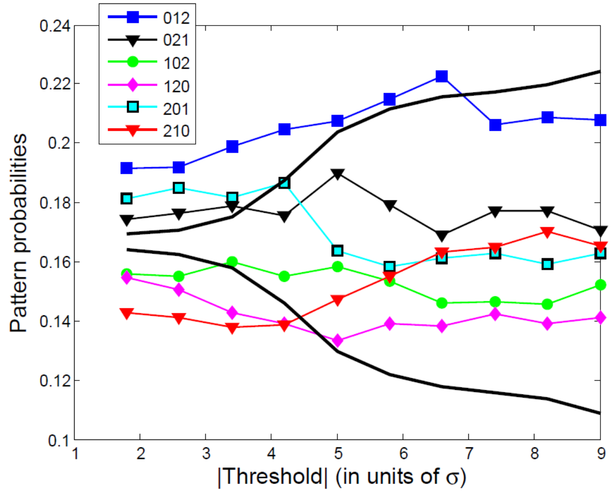
Analysis of experimental data







Way to improve the "early warning":

- Filter noise
- Longer pattern $\{I_{i-4}, I_{i-3}, I_{i-2}, I_{i-1}\}$

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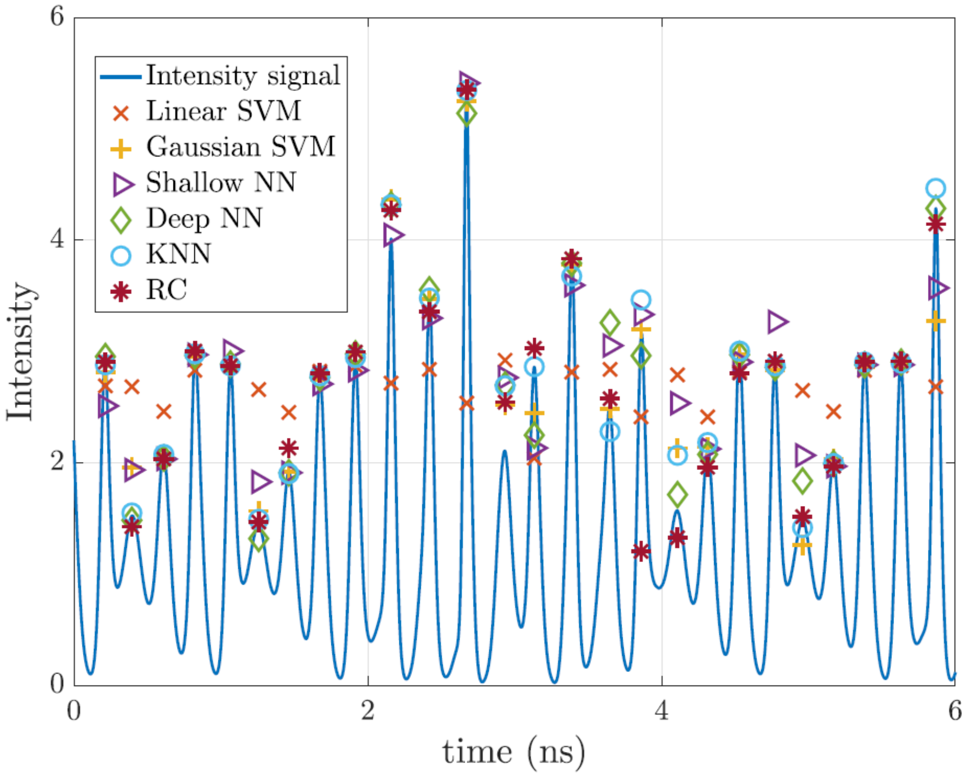
Can the amplitude of the next pulse be predicted?

$$I_i = f(I_{i-n} \ldots I_{i-3}, I_{i-2}, I_{i-1})$$

- Support Vector Machine (SVM), Linear and Gaussian
- Neural Networks (NN), Shallow and Deep
- k-Nearest Neighbors (KNN)
- Reservoir Computing (RC)



n = 3 yields minimum prediction error (increasing n does not increase the accuracy).

P. Amil et al., Chaos (2019)

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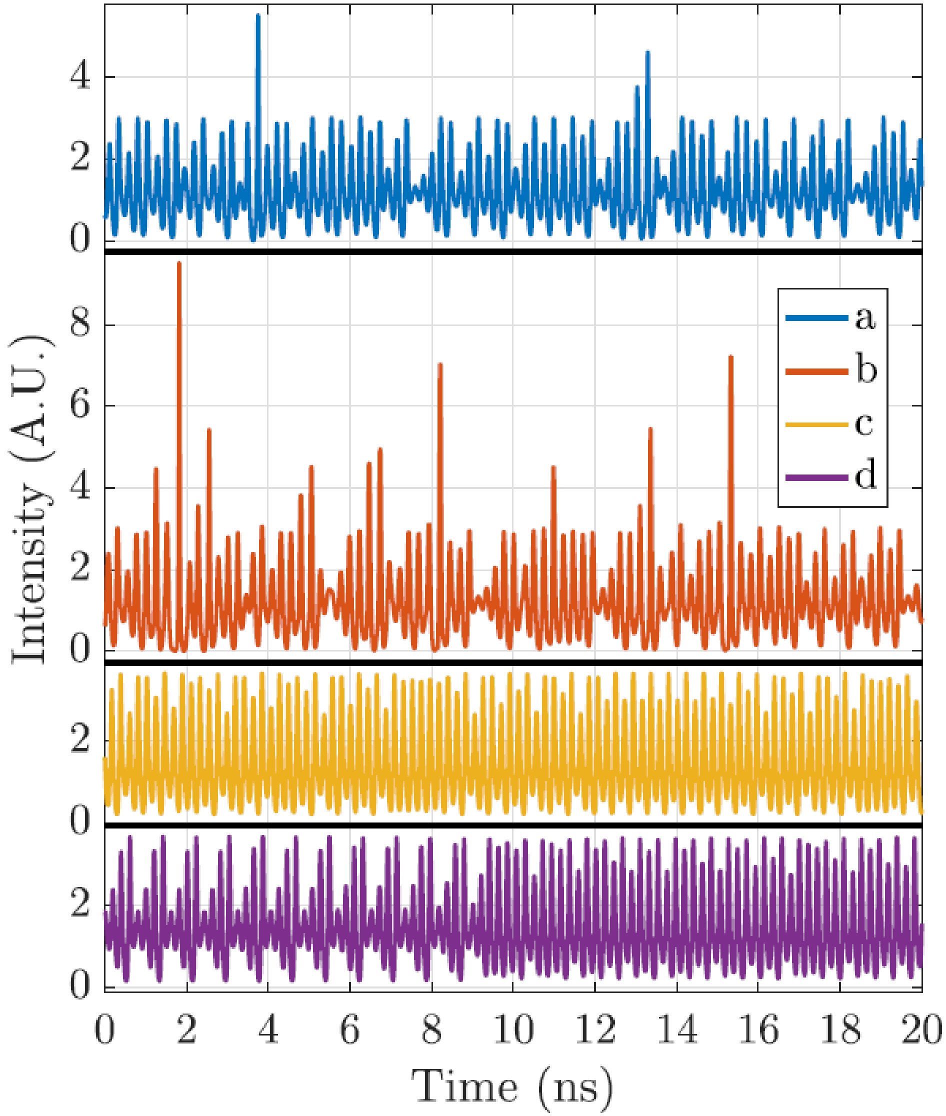
Influence of the pump current and noise?

$\mu = 2.2$

$D = 0$

$D = 10^{-4}\ \mathrm{ns}^{-1}$



$\mu = 2.45$

$D = 0$

$D = 10^{-4}\ \mathrm{ns}^{-1}$

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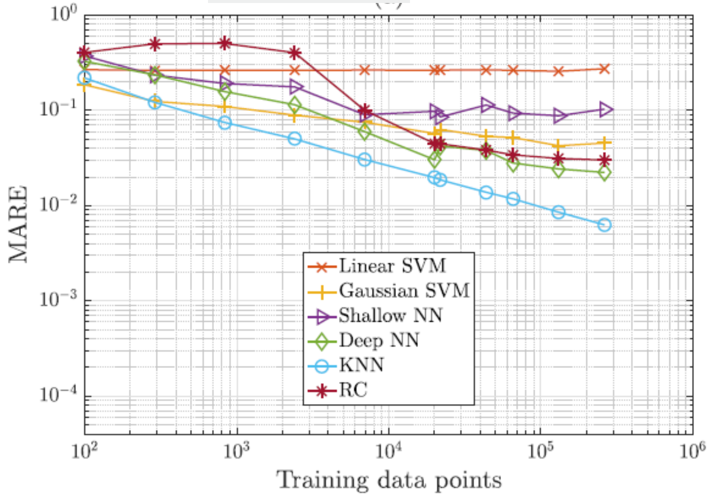
Performance quantification: the mean absolute relative error

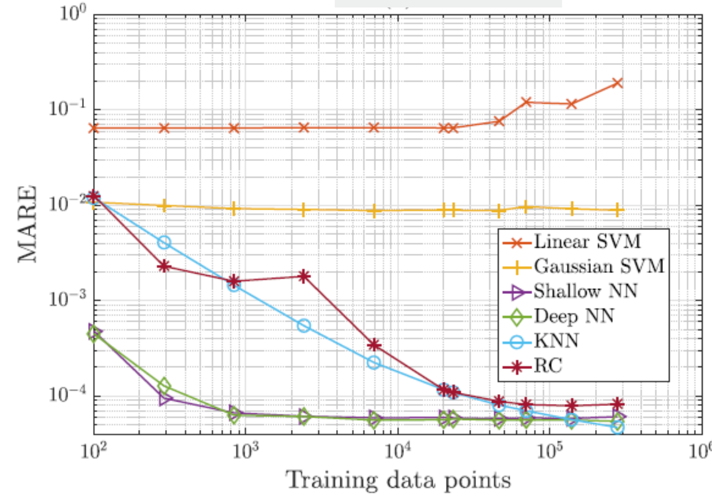
$$\mathrm{MARE} = \frac{1}{N}\sum_{i=1}^{i=N}\frac{\left|\tilde{y}_i - y_i\right|}{y_i}$$

$\mu = 2.2$

$\mu = 2.45$

$D = 0$

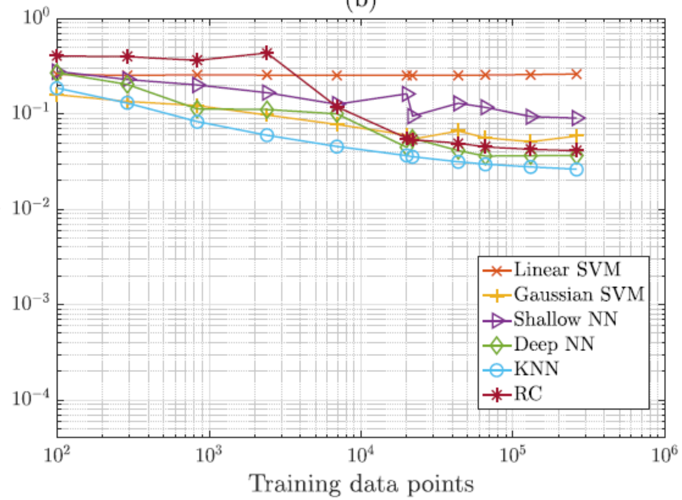


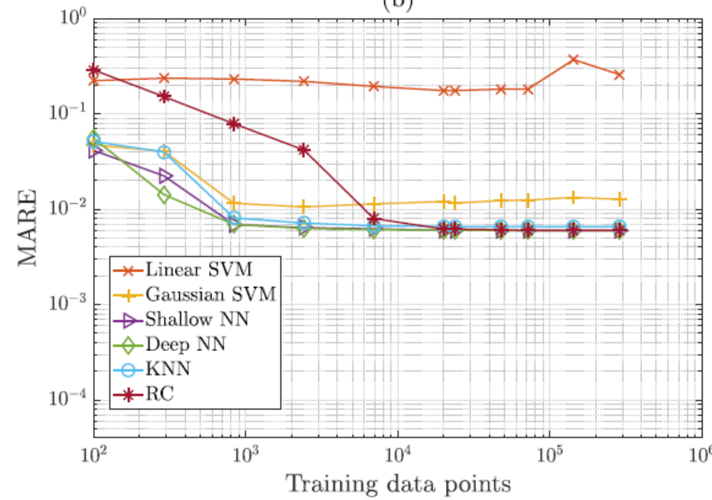


(b)

(b)

$D = 10^{-4}\ \mathrm{ns}^{-1}$





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Summary

- In optically injected semiconductor lasers, extreme pulses can be deterministic, or triggered by noise, and can be suppressed or induced by current modulation.
- Extreme pulses can be generated “on demand” by a small perturbation of the pump current.
- The pulse amplitude can be predicted with good accuracy, even for extreme pulses that have very low probability.
- Future work: potential for sensing applications?
- Future work: the symbolic approach to predict extreme events needs to be further explored.

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Thank you for your attention!

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