Signal encoding and transmission by noisy coupled neurons

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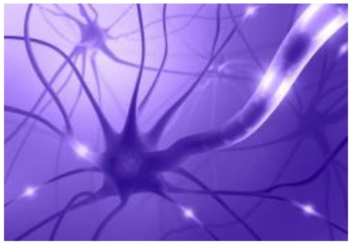
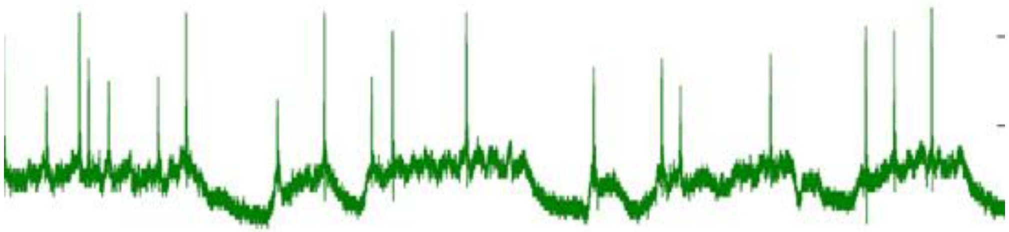
How neurons encode information?





- In the spike **rate**?
- In the relative **timing** of the spikes?
- **Single** neuron encoding or **ensemble** encoding?
- How can temporal correlations be detected and quantified?

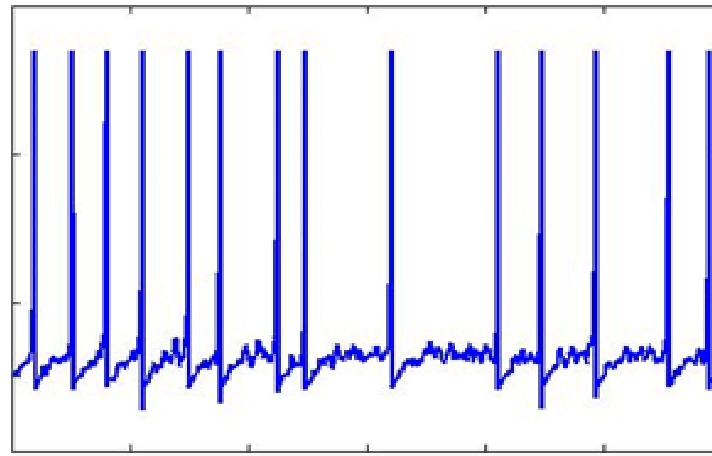
- Our goal: try to understand how neurons **encode**, in the sequence of spikes, an external *weak (**subthreshold**) signal*, in the presence of **noise**.

Cracking the neural code is an important problem in neuroscience, with huge potential applications in information processing systems.

Laser spikes

Time (μs)

Neuronal spikes

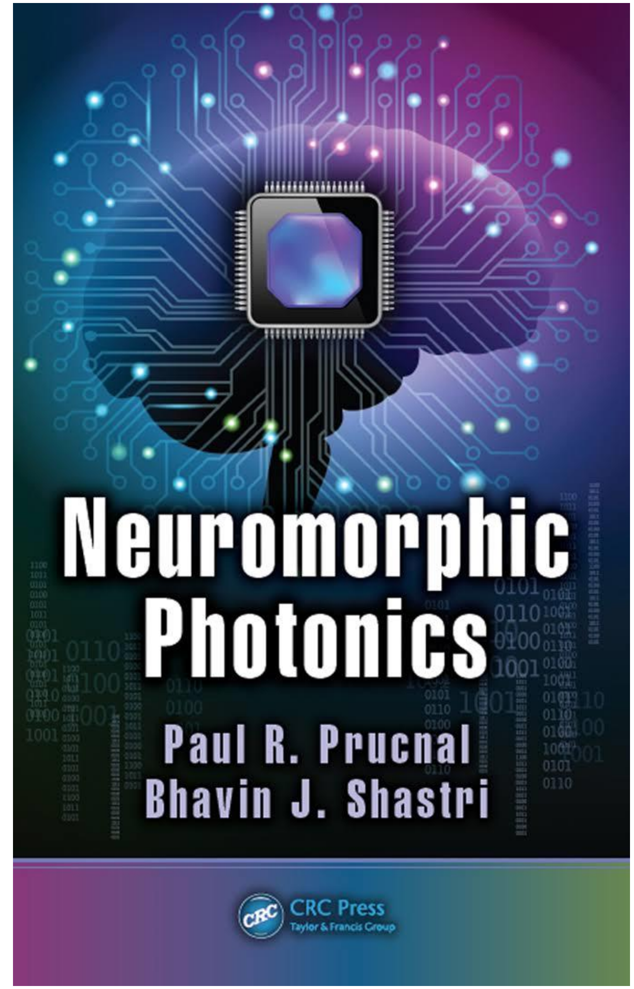


Time (ms)

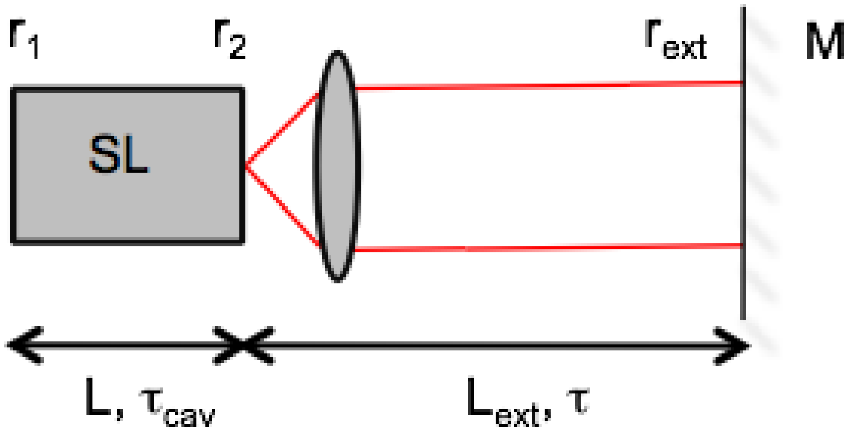
Can lasers mimic real neurons?

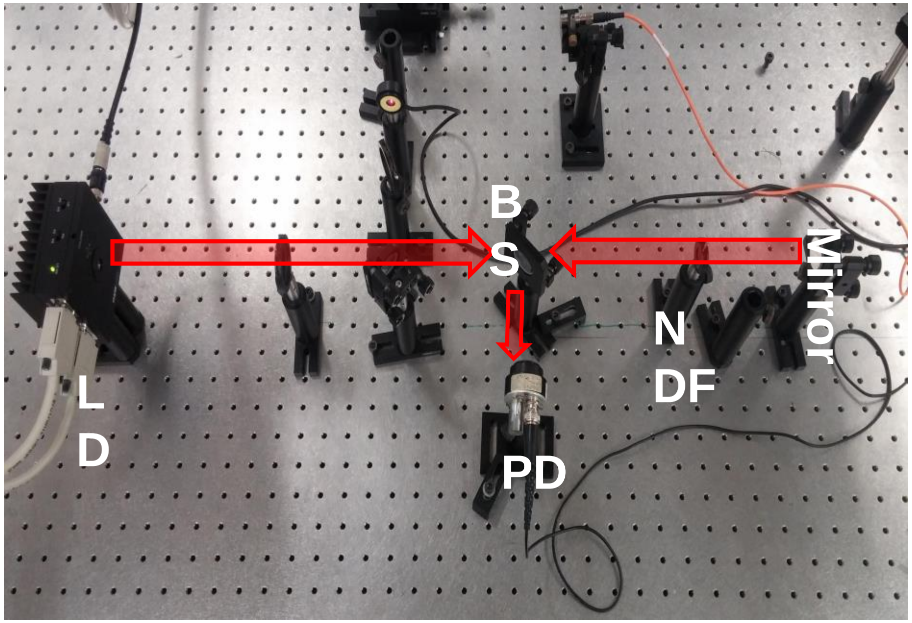
How the laser encodes a weak external signal?

Photonic neurons

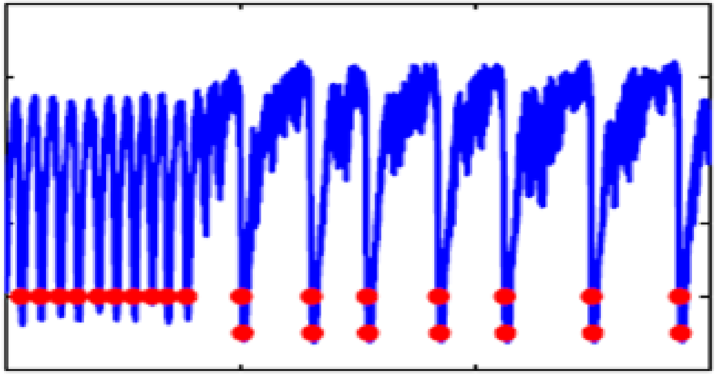


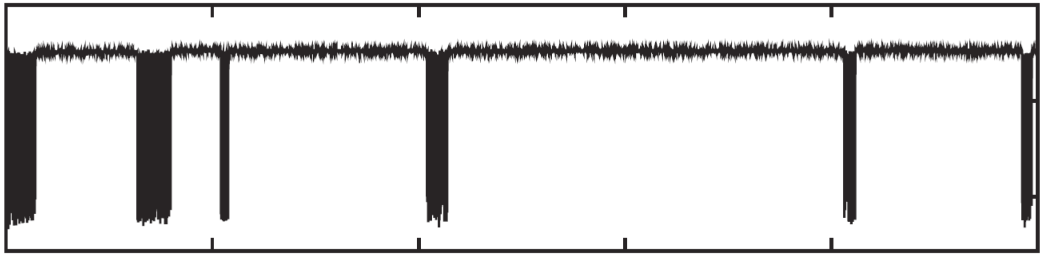
- Excitable lasers could be the building blocks of ultra-fast, energy-efficient information processing systems.
- Inexpensive laser diodes (perturbed by optical feedback).

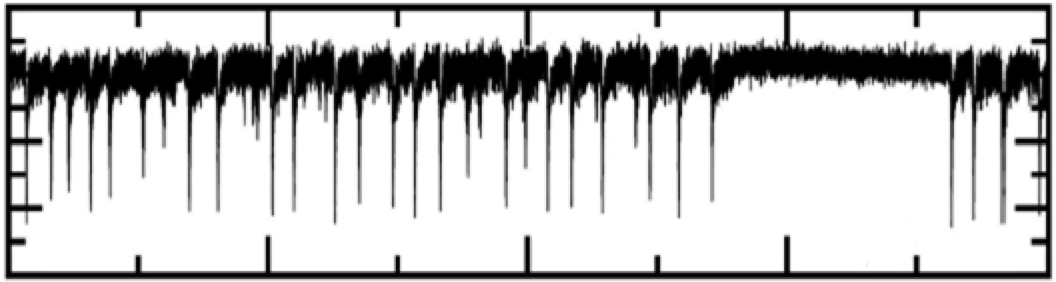

r1
r2
rext
M
SL
L, τcav
Lext, τ


L
D
B
S
PD
N
DF
Mirror

The laser dynamics: excitability, tonic spikes and bursting. Similar to real neurons?







A. Aragoneses, S. Perrone, T. Sorrentino, M. C. Torrent and C. Masoller, "*Unveiling the complex organization of recurrent patterns in spiking dynamical systems*", Sci. Rep. **4**, 4696 (2014).

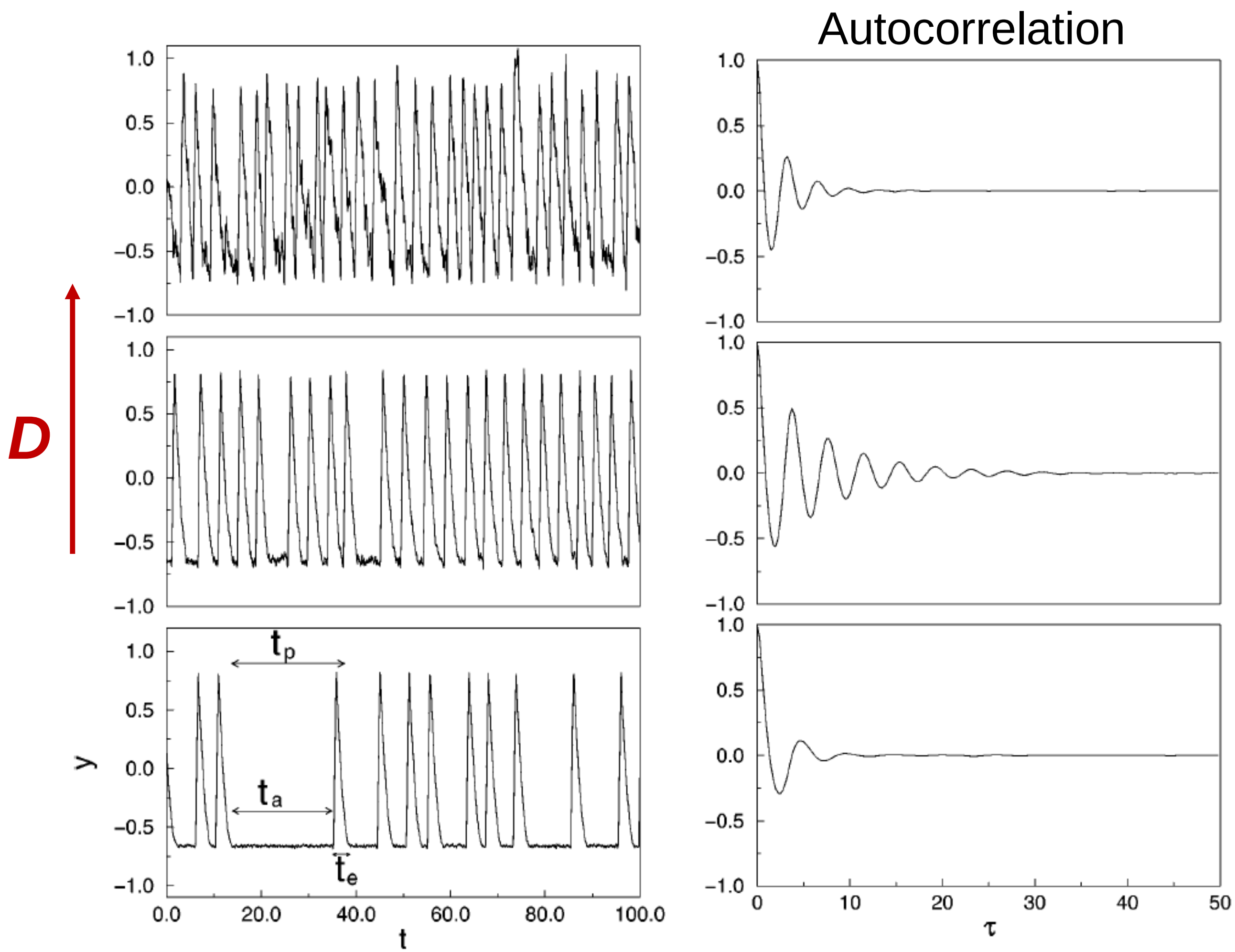
C. Quintero-Quiroz, J. Tiana-Alsina, J. Roma, M. C. Torrent, and C. Masoller, "*Characterizing how complex optical signals emerge from noisy intensity fluctuations*", Sci. Rep. **6** 37510 (2016).

Coherence resonance

- Fitz Hugh–Nagumo model (ε=0.01, *a* =1.05)

$$\varepsilon \frac{dx}{dt} = x - \frac{x^3}{3} - y,$$

$$\frac{dy}{dt} = x + a + D\xi(t)$$



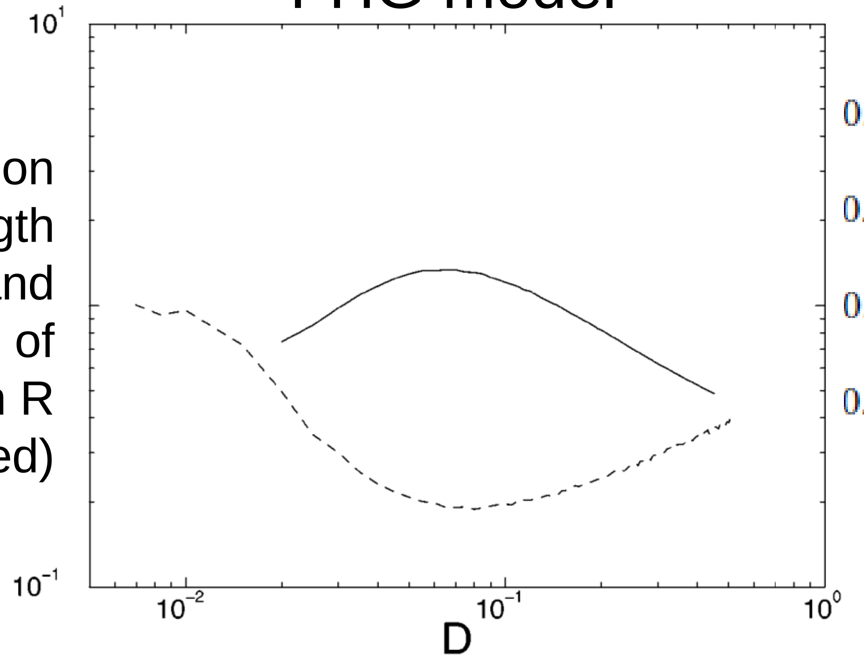
Pikovsky and Kurths, Phys. Rev. Lett. 78, 775 (1997)

Quantification of coherence resonance

$$R = \frac{\sqrt{\langle I^2 \rangle - \langle I \rangle^2}}{\langle I \rangle}$$

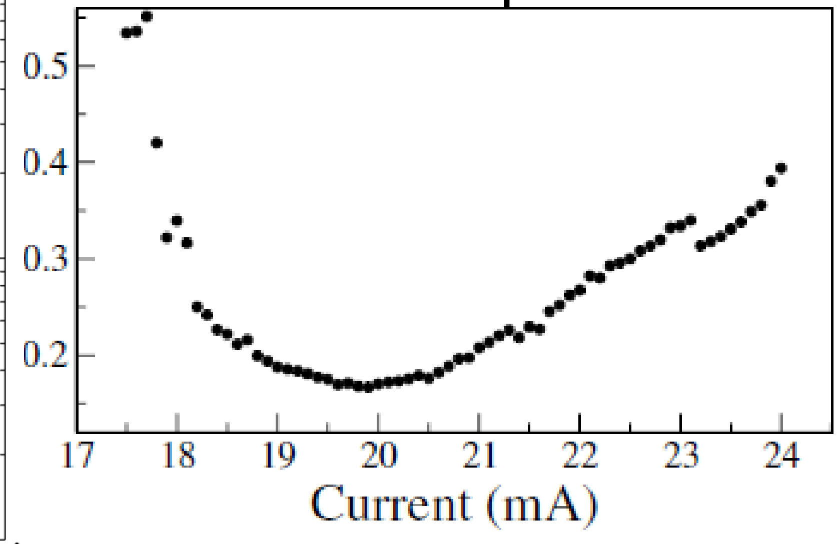
FHG model

Correlation length (solid) and Coef. of variation R (dashed)



Pikovsky and Kurths, PRL (1997)

Laser spikes



J. F. Martinez Avila, H. L. D. de S. Cavalcante, and J. R. Rios Leite, PRL (2004)

With an external signal, are there statistical similarities between neuronal and laser spikes?

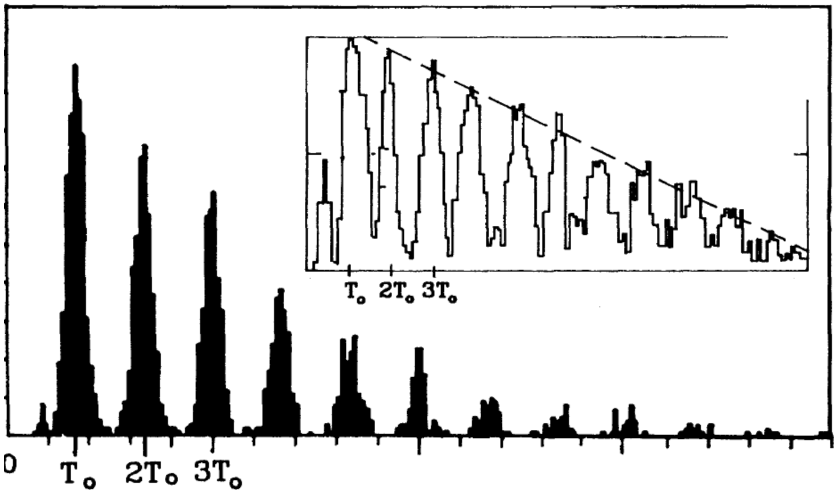
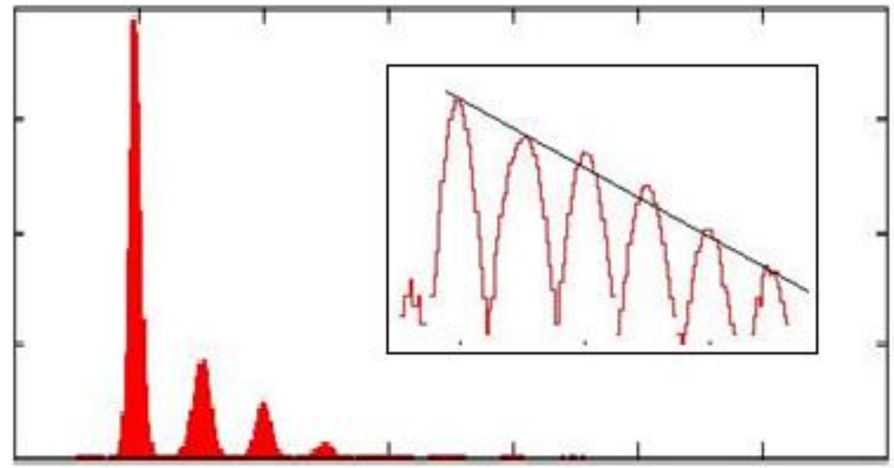


FIG. 1. (a) An experimental ISIH obtained from a single auditory nerve fiber of a squirrel monkey with a sinusoidal 80-dB sound-pressure-level stimulus of period $T_0 = 1.66$ ms applied at the ear. Note the modes at integer multiples of T_0. Inset:

A. Longtin et al. PRL (1991)



$2T_0$ $4T_0$

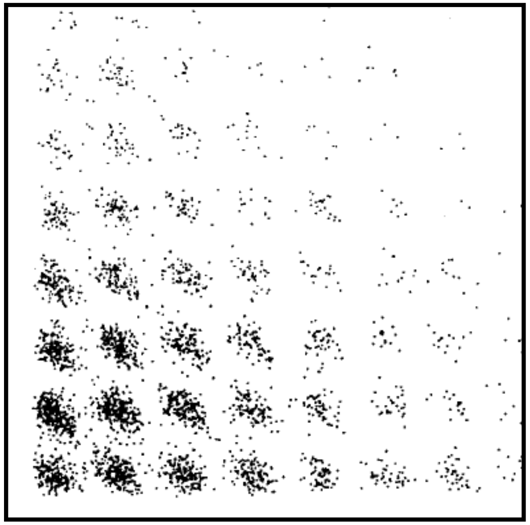
Experimental data when the laser current is modulated with a sinusoidal signal of period T_0.

A. Aragoneses et al. Optics Express (2014)

Return maps of inter-spike-intervals

Neuronal ISIs

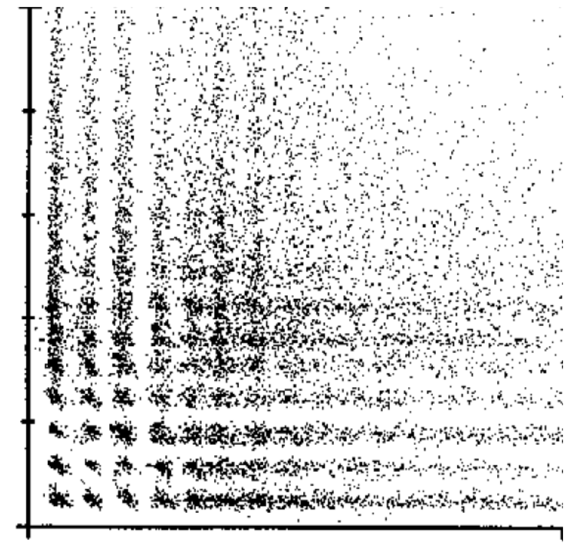
ΔT_{i+1}



ΔT_i

A. Longtin
Int. J. Bif. Chaos (1993)

Laser ISIs



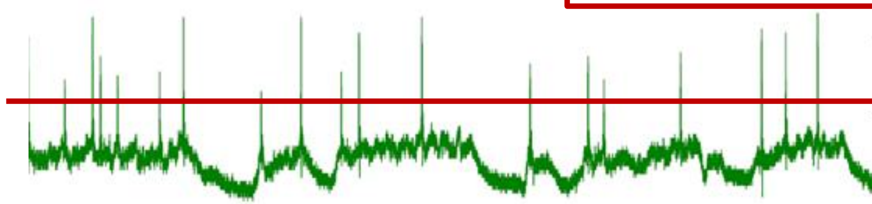
M. Giudici et al PRE (1997)
A. Aragoneses et al
Optics Express (2014)

HOW TO INDENTIFY TEMPORAL ORDER?
SIMILAR MORE/LESS EXPRESSED PATTERNS?

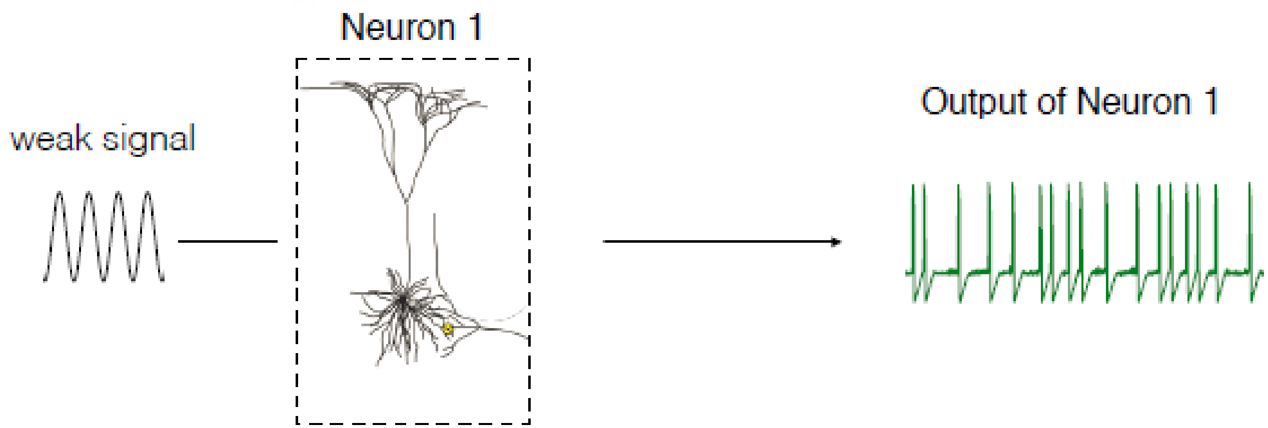
Outline

$$\{\ldots I_{i-1}, I_i, I_{i+1} \ldots\}$$

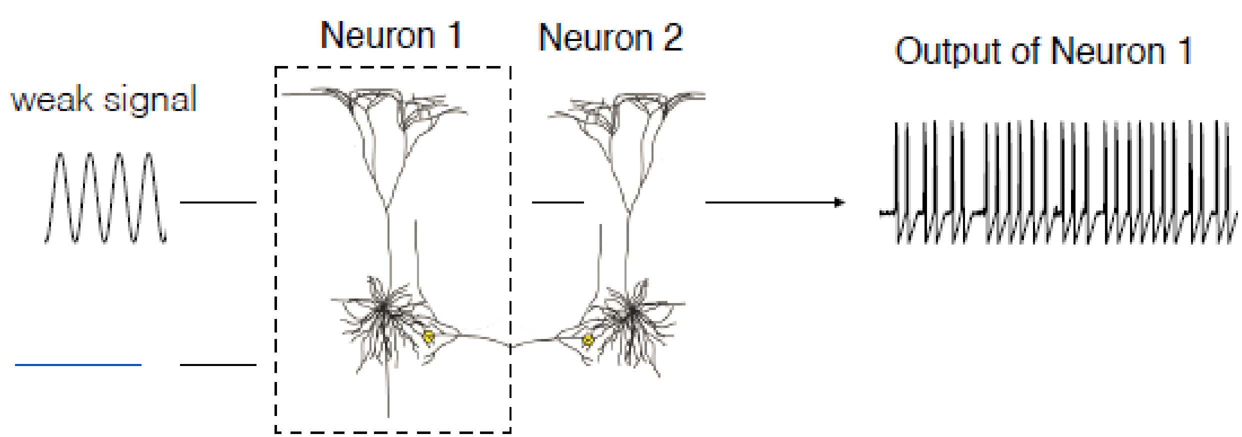
inter-spike-intervals $I_i = t_{i+1} - t_i$



- Symbolic method of analysis of ISI sequences



- Single neuron



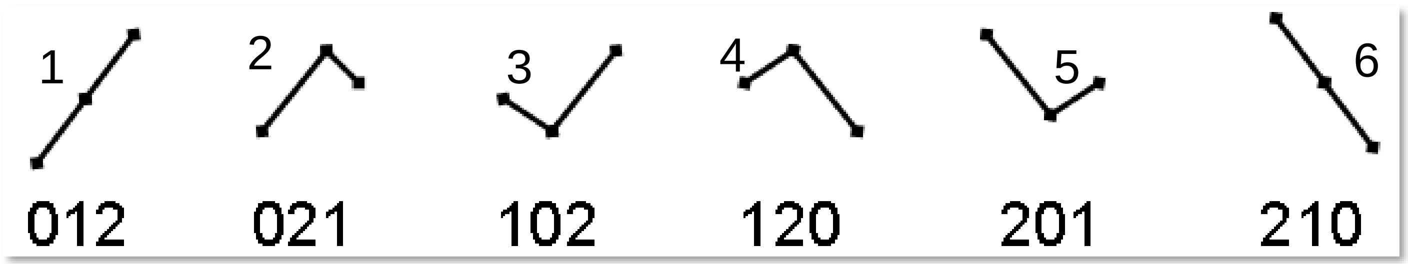
- Two coupled neurons
- Neuronal ensemble

Symbolic method of time-series analysis

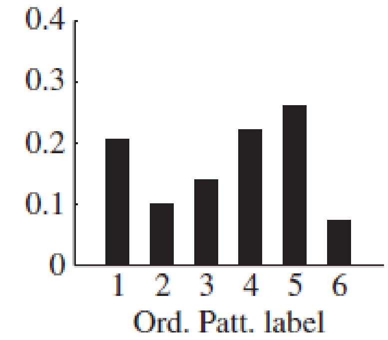
Relative order of three consecutive intervals

$I_i = t_{i+1} - t_i$

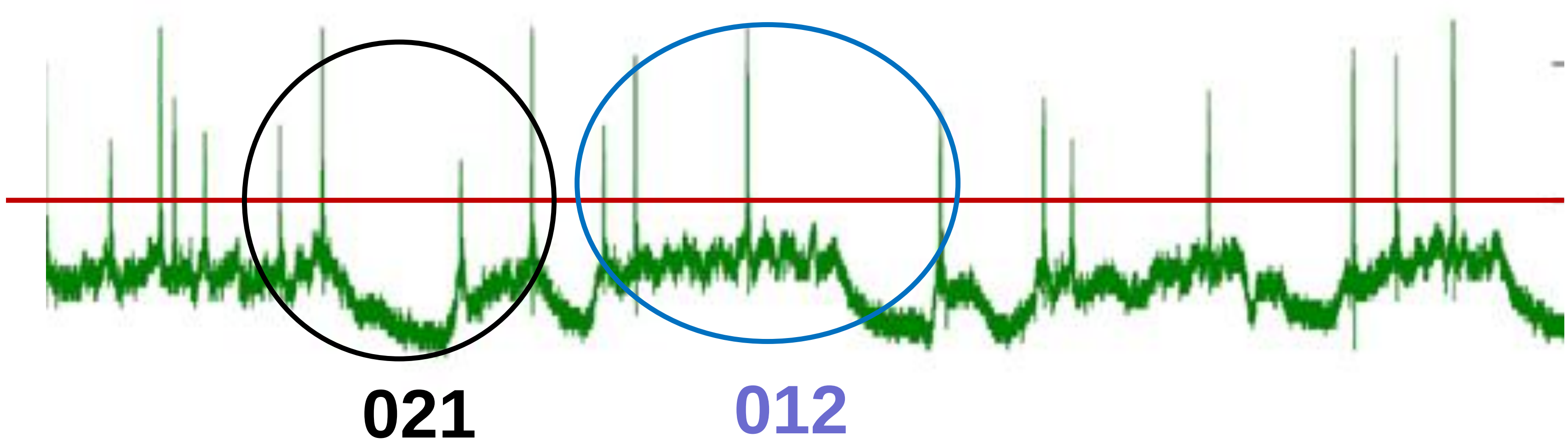
$\{\ldots I_i, I_{i+1}, I_{i+2}, \ldots\}$



Ordinal probabilities

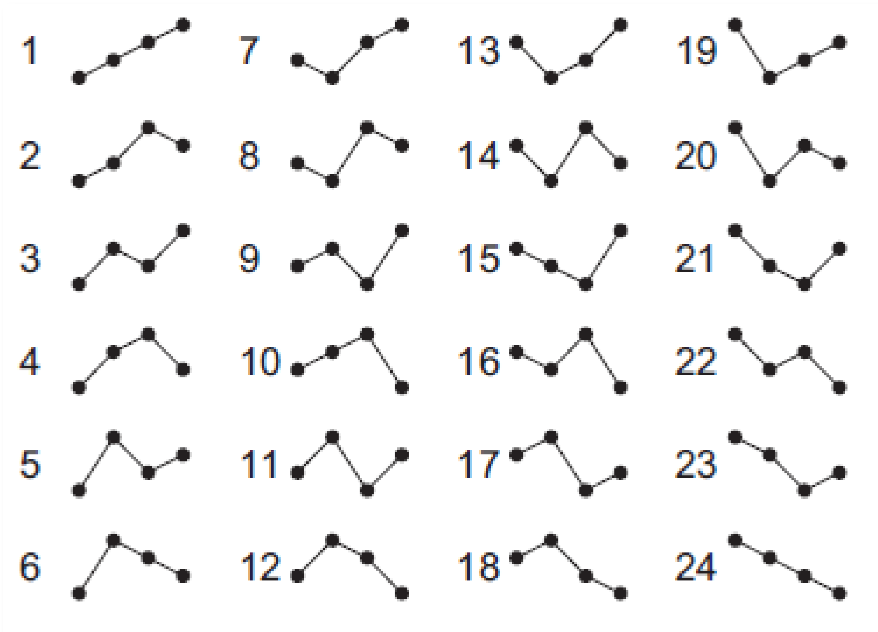


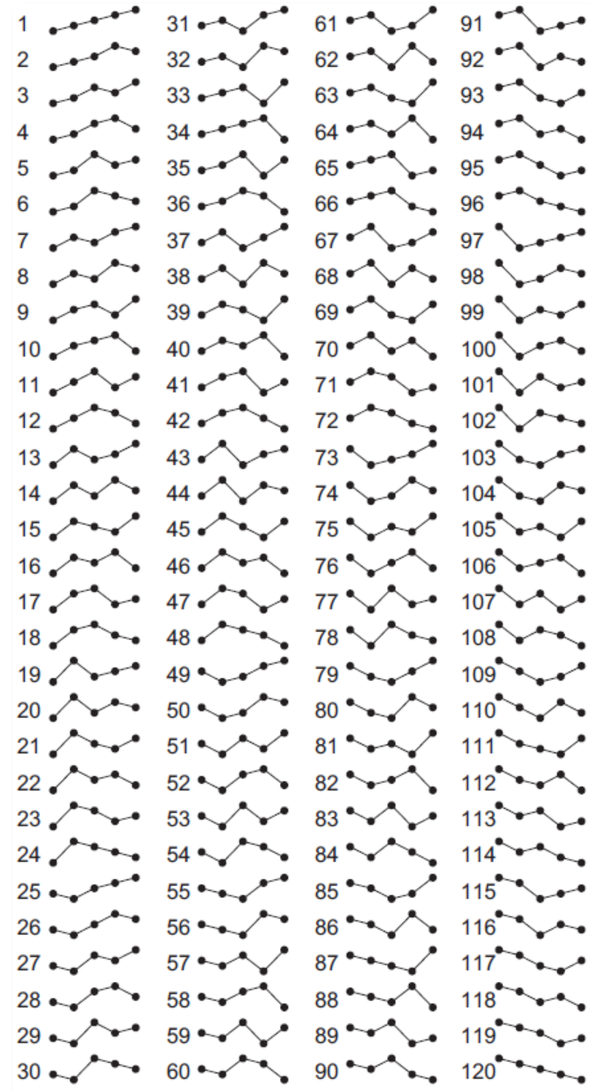
Example: (5, 1, 7) gives “102” because 1 < 5 < 7



Brandt & Pompe, PRL 88, 174102 (2002)

The number of ordinal patterns increases as D!



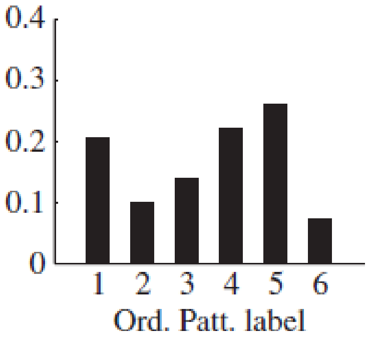


- How to select the optimal *D*?

  it depends on:
  - The length of the data
  - The length of the correlations

U. Parlitz et al. / Computers in Biology and Medicine 42 (2012) 319–327

Are the *D*! ordinal patterns equally probable?



- **Null hypothesis**:

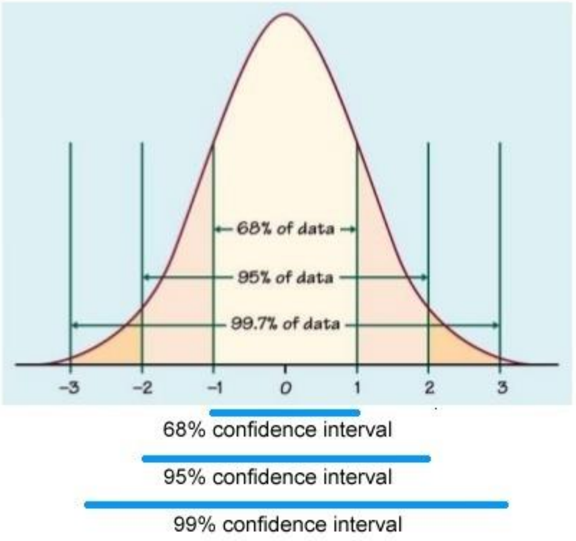
  $p_i = p = 1/D!$ for all $i = 1 \ldots D!$

- If at least one probability **is not** in the interval $p \pm 3\sigma$ with $\sigma = \sqrt{p(1-p)/N}$ and N the number of ordinal patterns:

  We **reject** the NH with 99.74% confidence level.

- Else

  We **fail to reject** the NH.

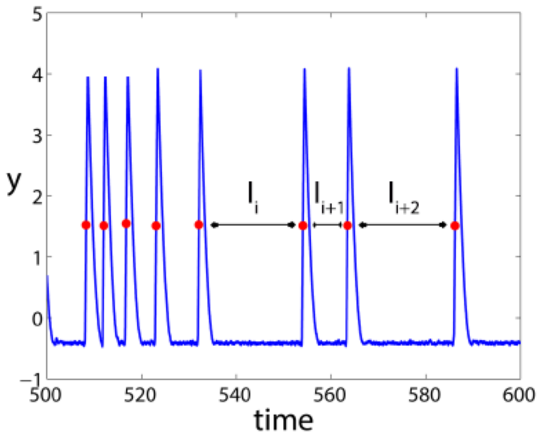


Individual neuron

- more / less expressed patterns in spike sequences encode information about subthreshold signal?

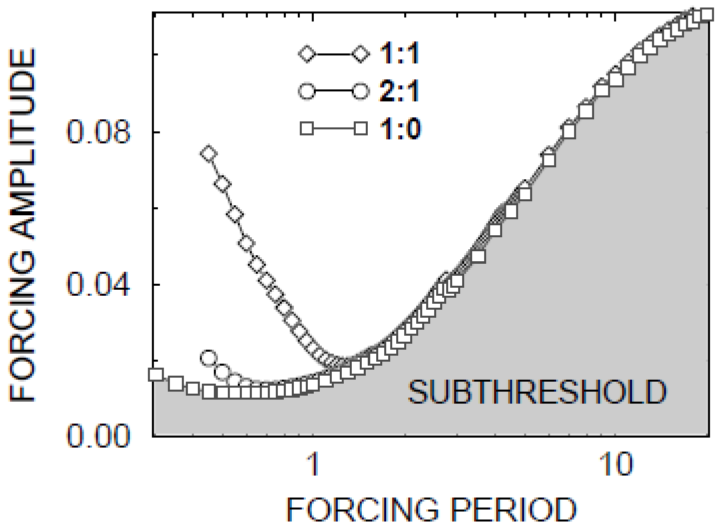
FitzHugh-Nagumo model

$$\epsilon \frac{dx}{dt} = x - \frac{x^3}{3} - y,$$
$$\frac{dy}{dt} = x + a + a_o \cos(2\pi t/T) + D\xi(t),$$



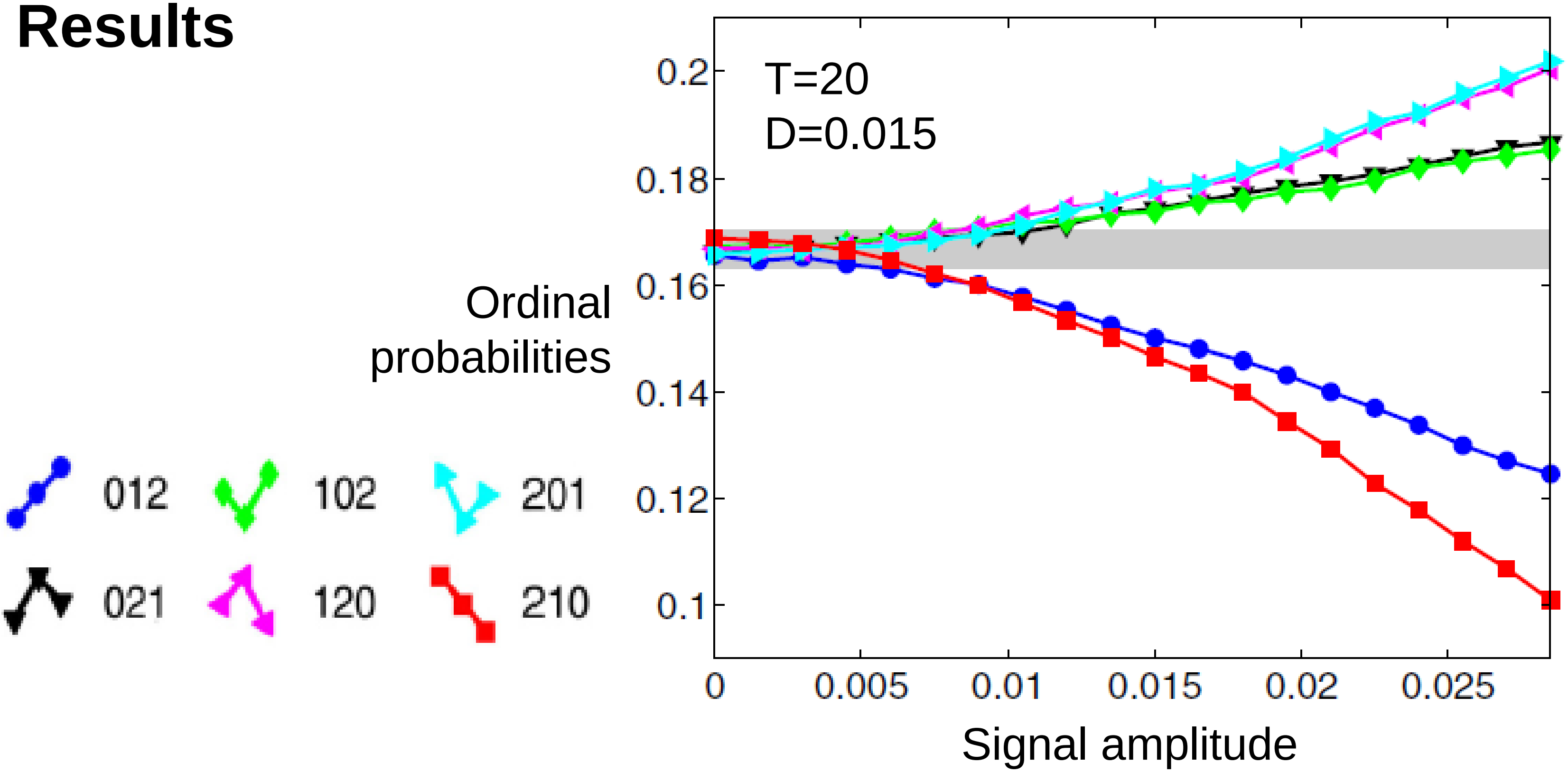
- Gaussian white noise and <u>subthreshold</u> signal: **a_0** and **T** such that spikes are **noise-induced**.

- Time series with M=100,000 spikes simulated (a=1.05, ε=0.01).



Longtin and Chialvo, PRL 1998

Results

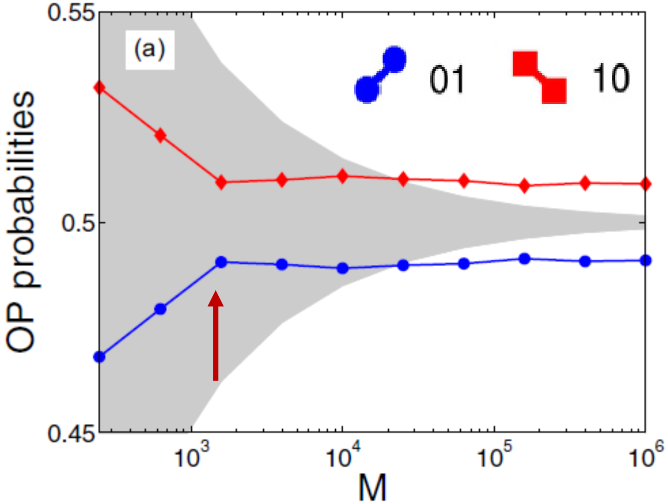


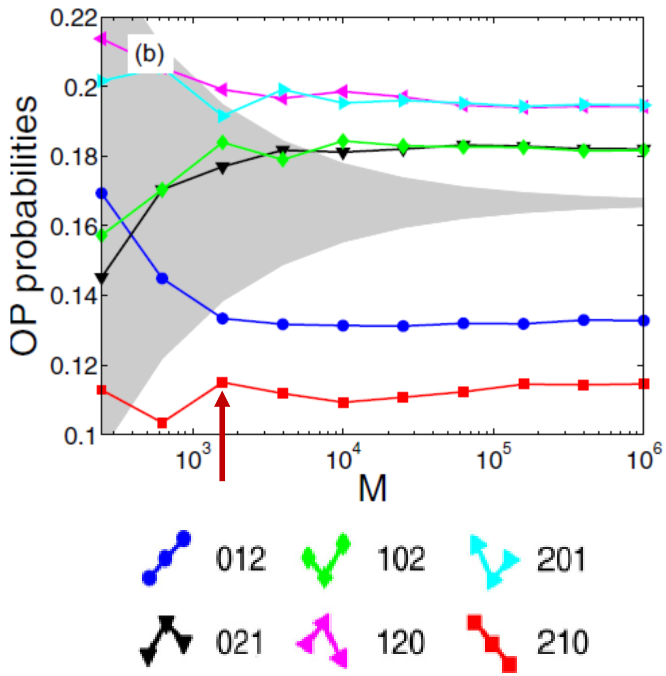
- Gray region: 3σ confidence level.

J. M. Aparicio-Reinoso, M. C. Torrent and C. Masoller, PRE 94, 032218 (2016)

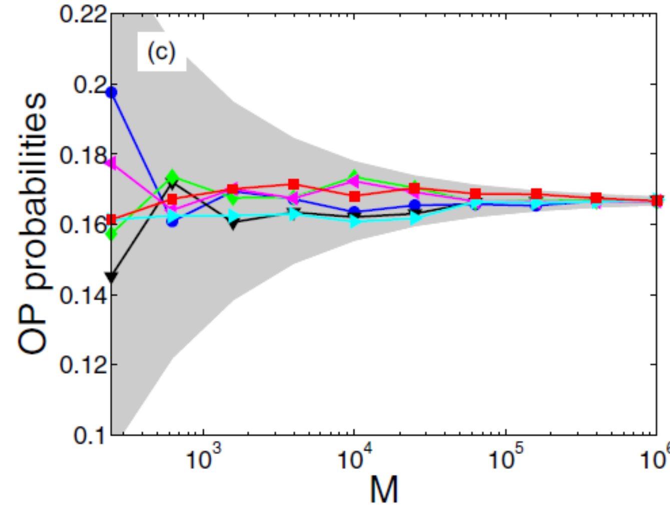
Data requirements

With signal



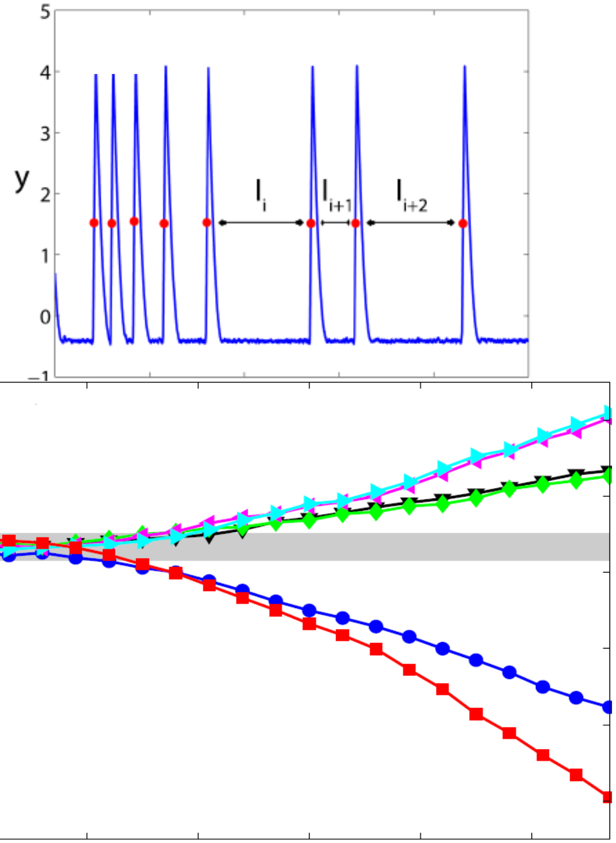


Without signal

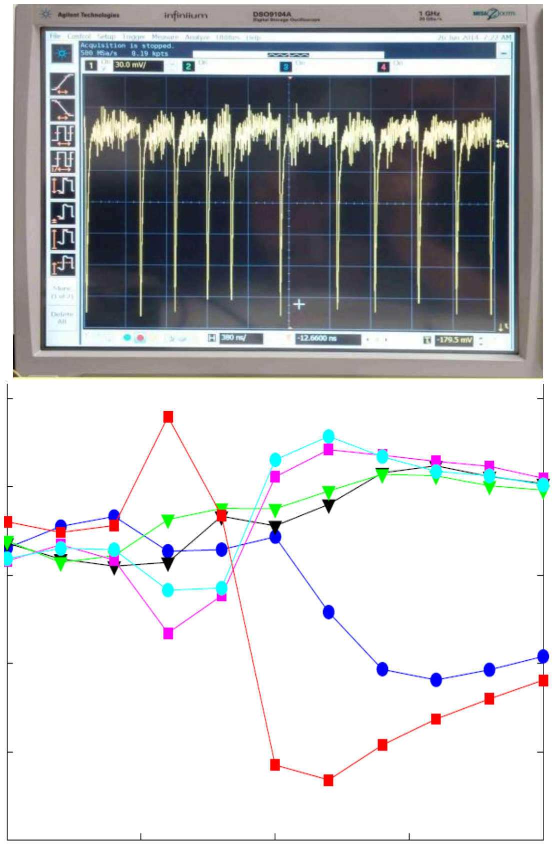


J. M. Aparicio-Reinoso et al PRE 94, 032218 (2016)

Comparison with the laser spikes, when a small sinusoidal modulation is applied to the laser pump current



Signal amplitude



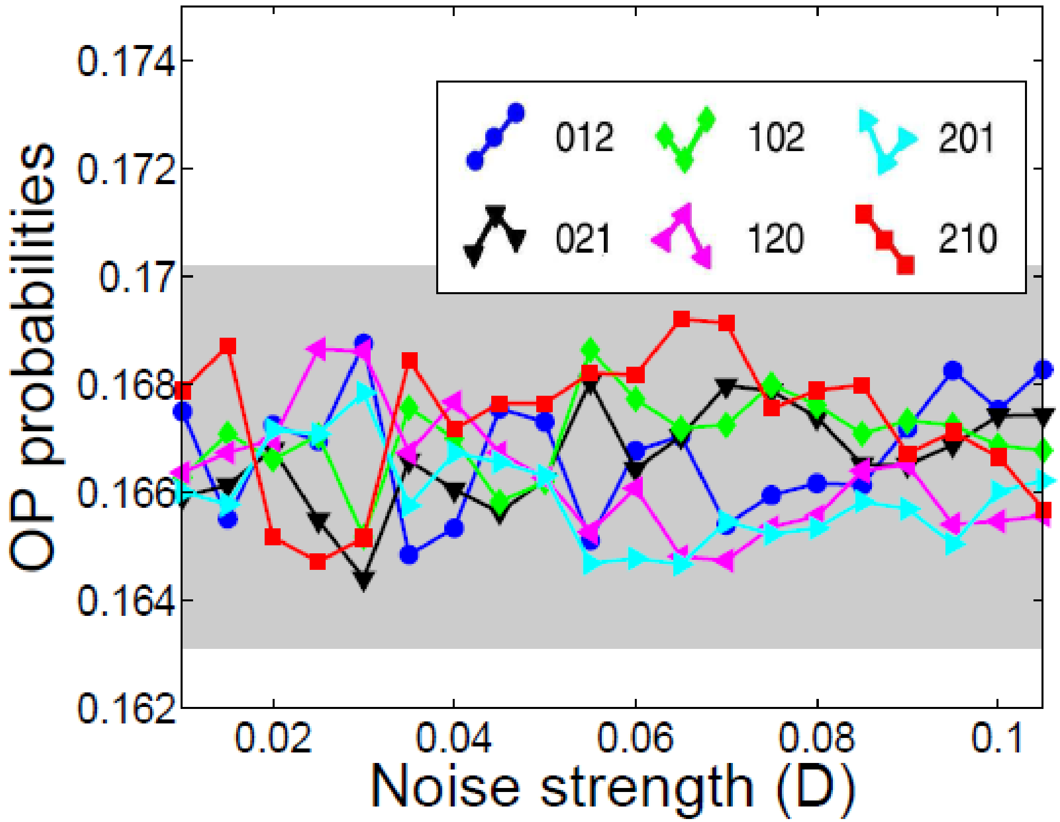
Signal amplitude

J. M. Aparicio-Reinoso et al PRE 94, 032218 (2016)

A. Aragoneses et al, Sci. Rep. **4**, 4696 (2014)

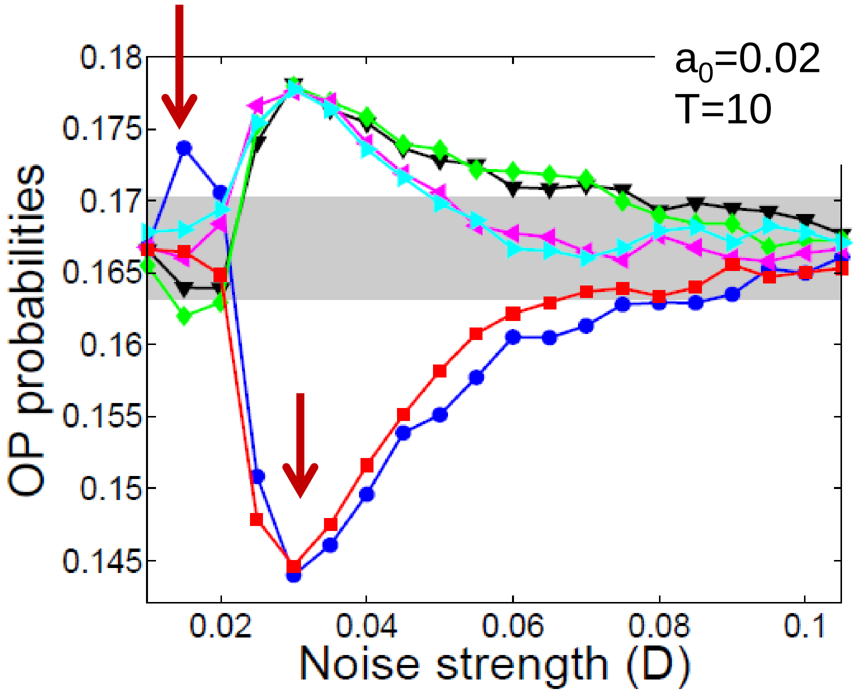
Role of the level of noise

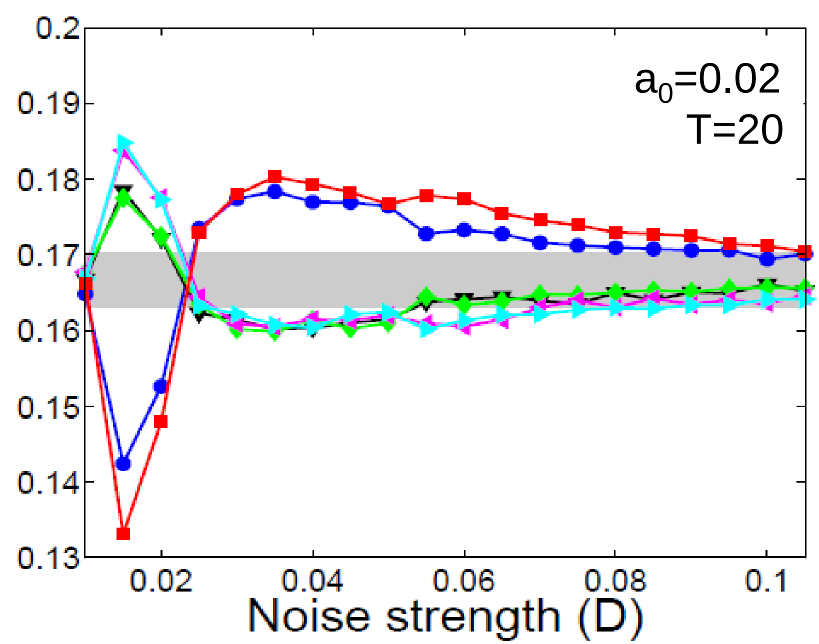
$a_0=0$



No signal $\Rightarrow$ no temporal ordering

With external signal

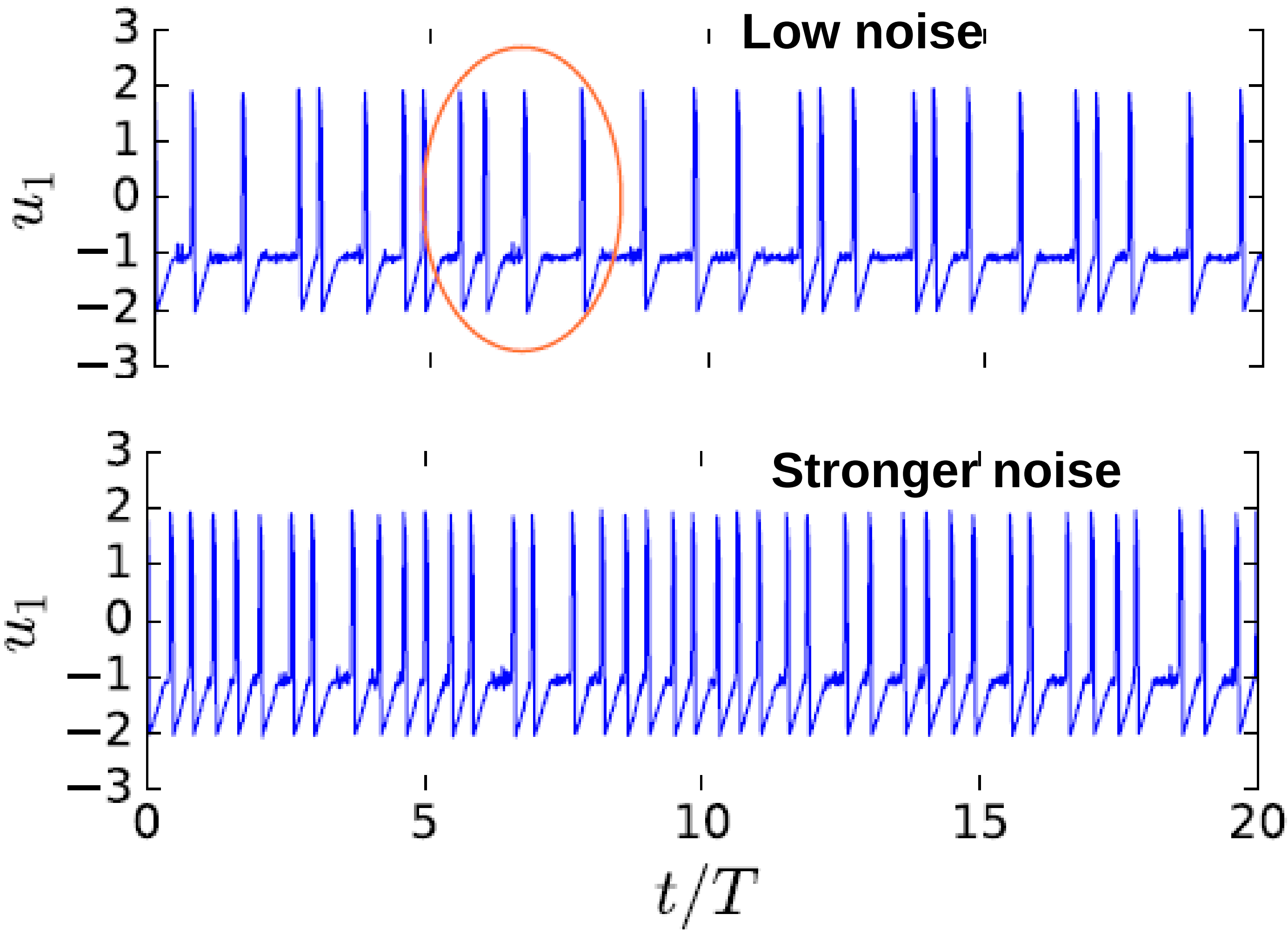




- The signal induces preferred and infrequent patterns.
- They depend on the period and on the noise strength.
- Resonant-like behavior.

J. M. Aparicio-Reinoso M. C. Torrent and C. Masoller, PRE 94, 032218 (2016).

Time series with different P(012)

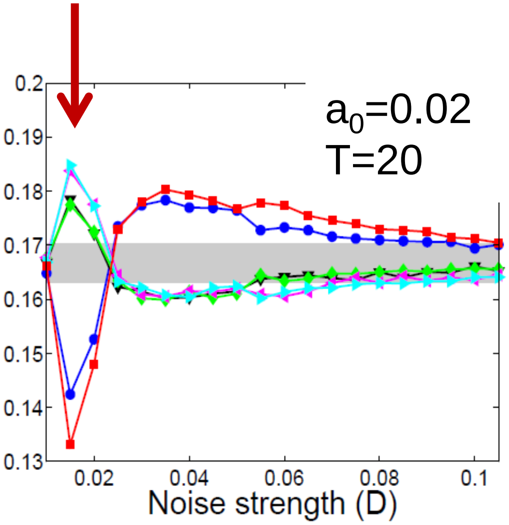


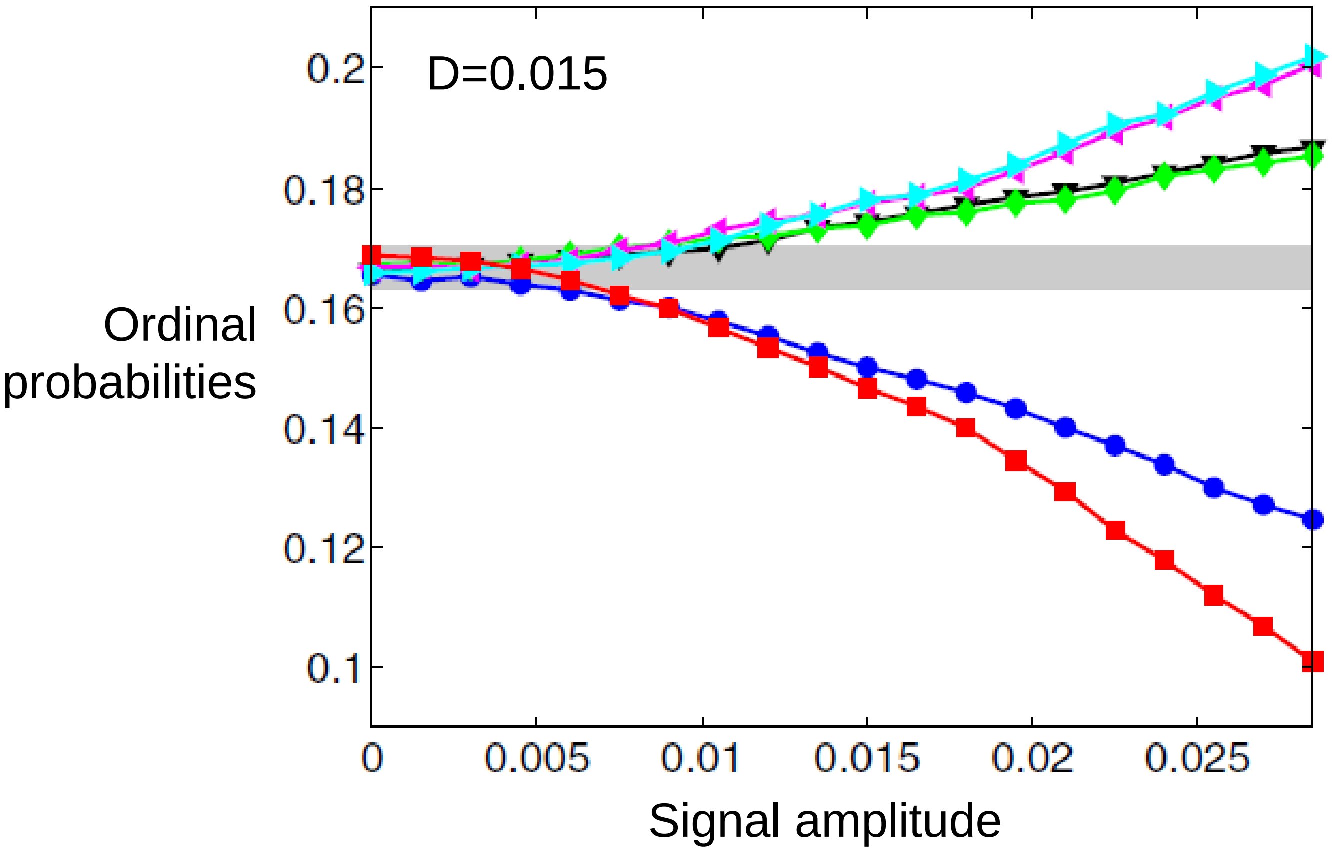
P(012)>1/6

P(012)<1/6

~ 40 spikes in 20 T

Role of the signal amplitude





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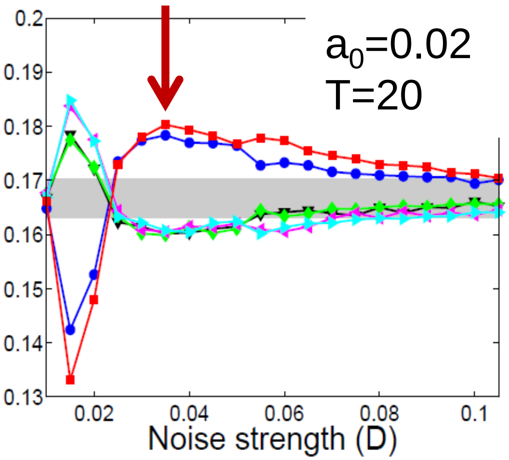
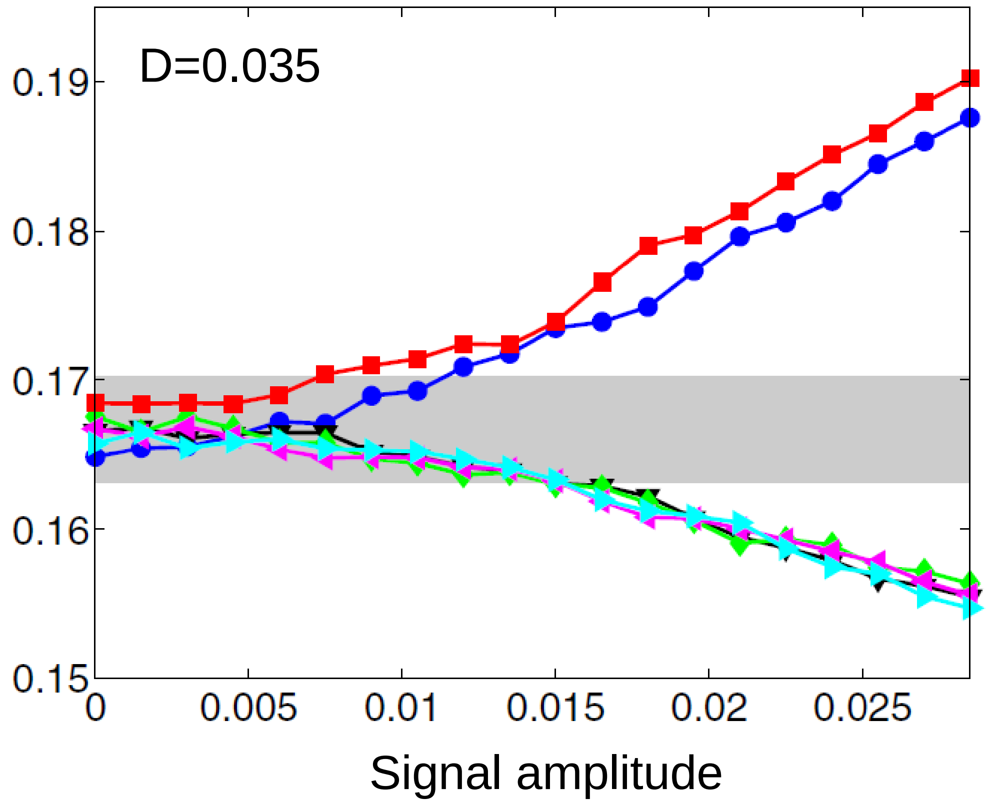
Role of the signal amplitude



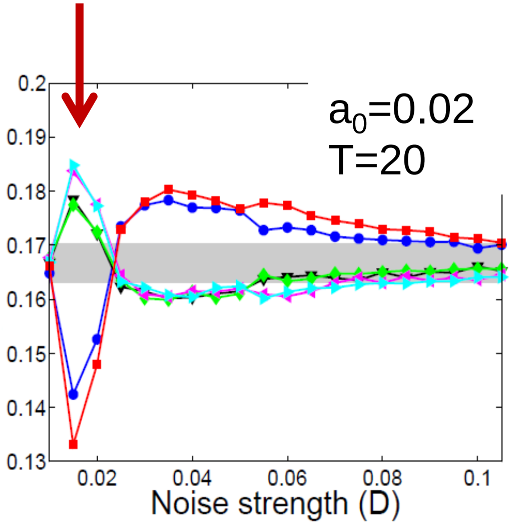
Ordinal probabilities

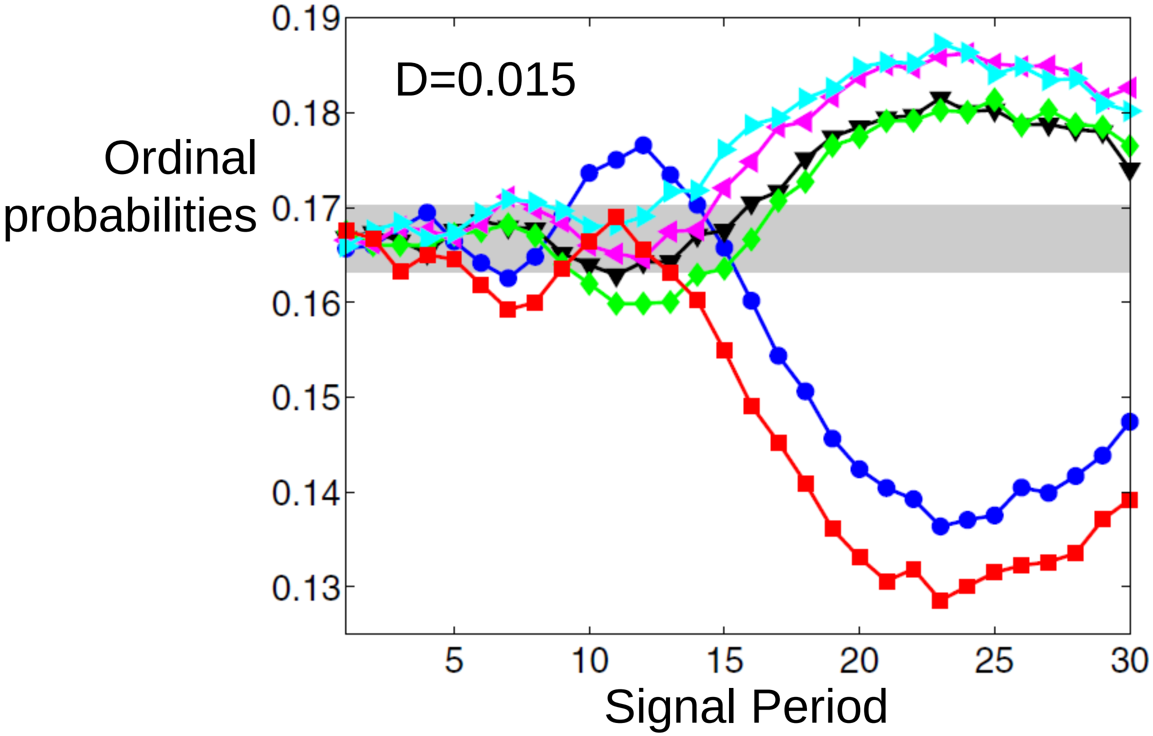


- The amplitude of the (subthreshold) signal does not modify the preferred or the infrequent patterns.
- The values of the probabilities encode information about the amplitude of the signal.

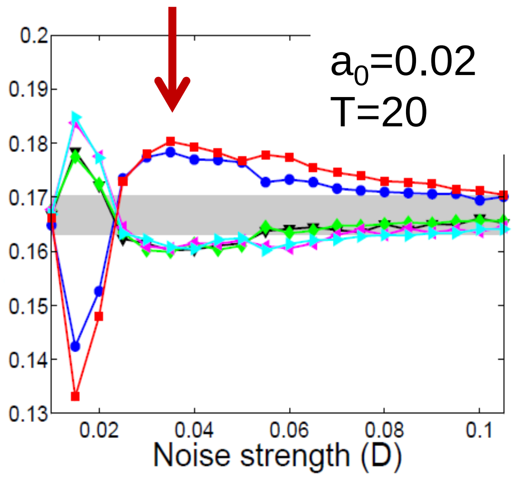
J. M. Aparicio-Reinoso, M. C. Torrent and C. Masoller, PRE 94, 032218 (2016)

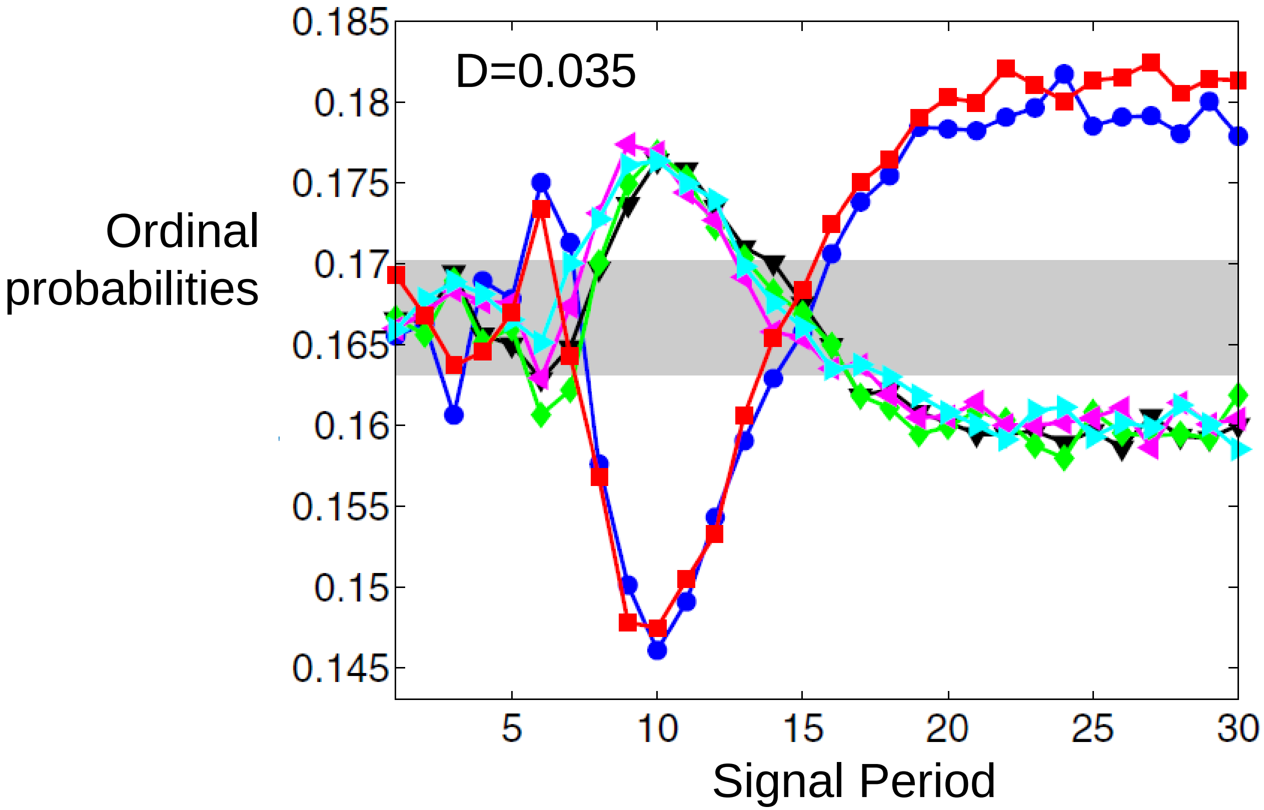
Role of the signal period





Role of the signal period

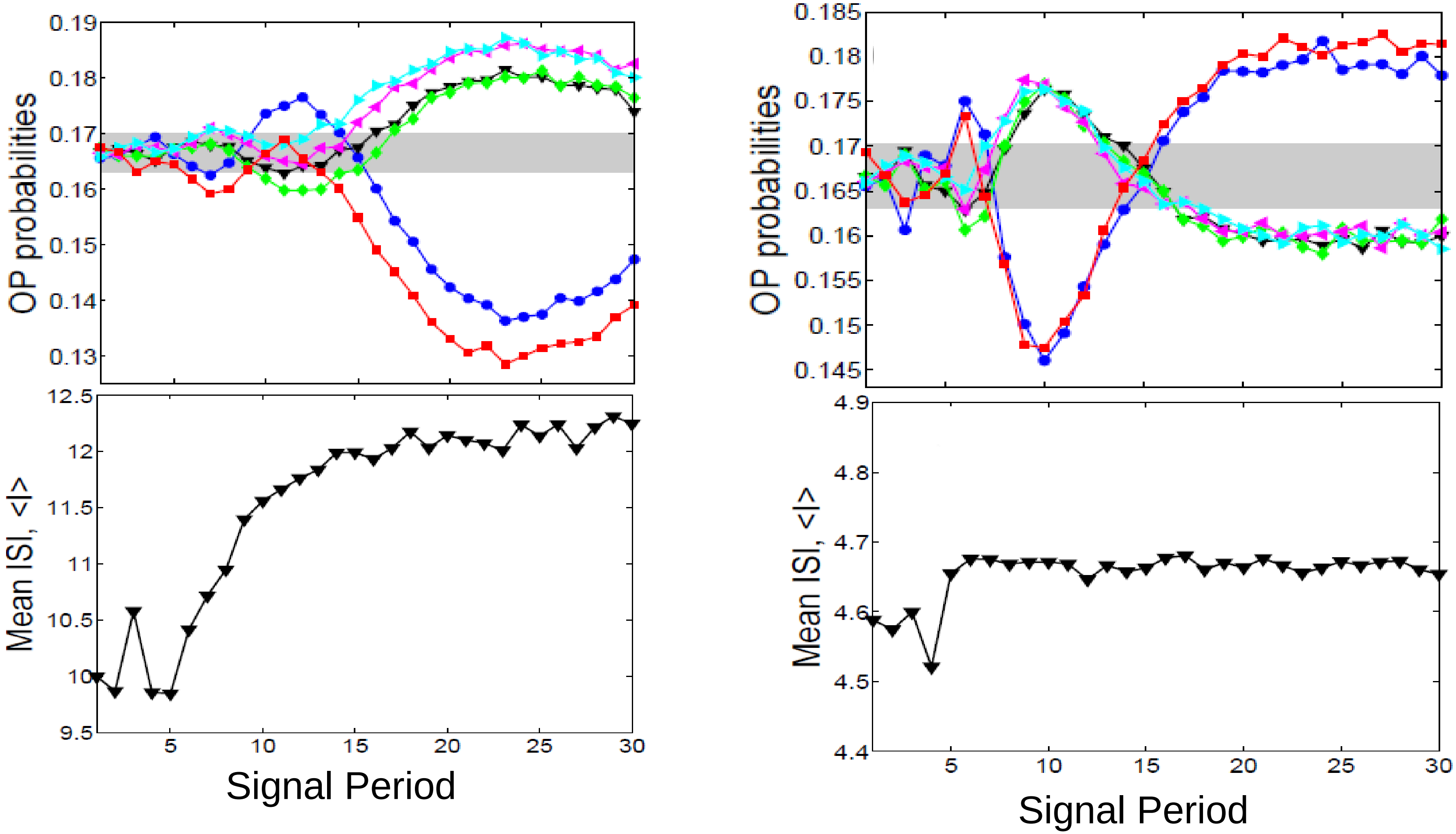




- More probable patterns depend on period and noise strength.

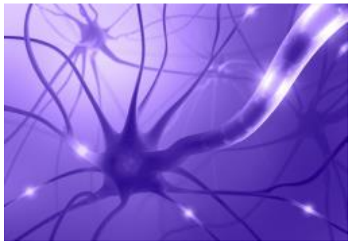
J. M. Aparicio-Reinoso, M. C. Torrent and C. Masoller, PRE 94, 032218 (2016)

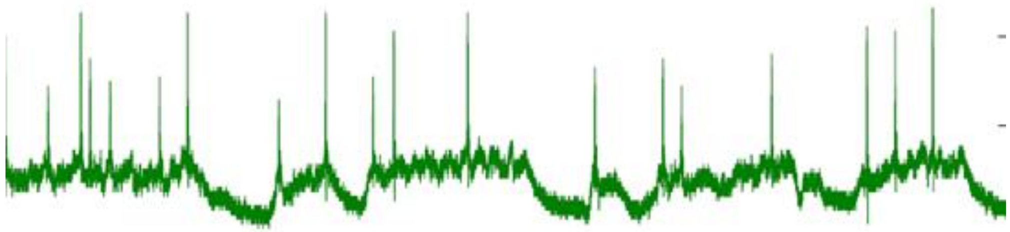
Which is the underlying mechanism?
A change of the mean inter-spike-interval?

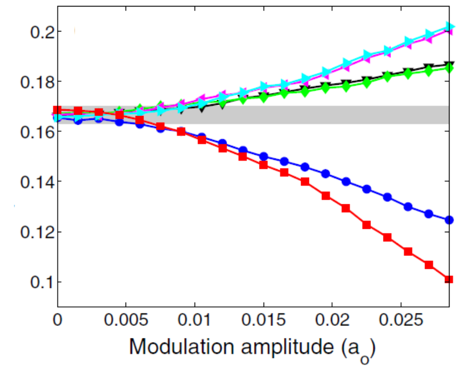


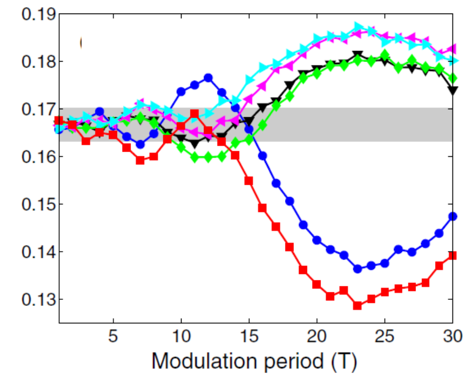
$\Rightarrow$ No direct relation.

So… how neurons might encode a weak periodic external signal?

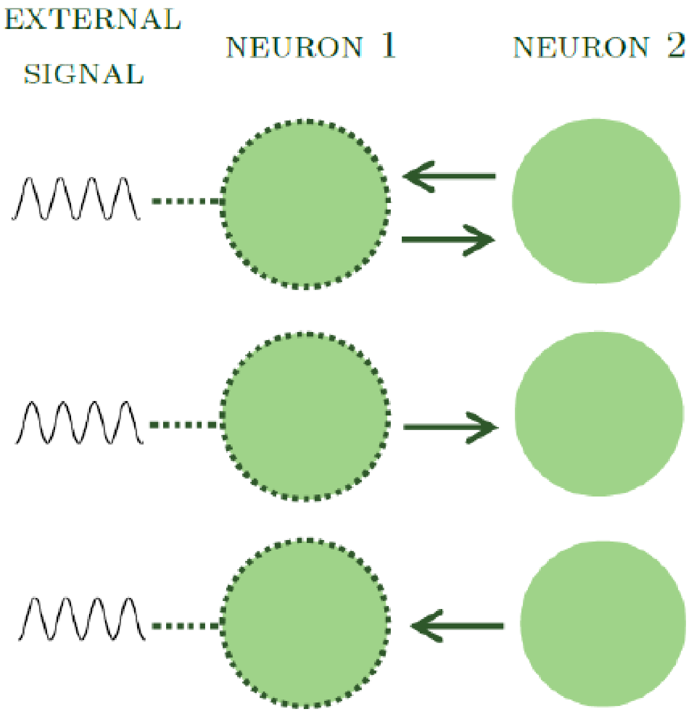








- The amplitude and the period of the signal might be encoded in more and less expressed patterns.
- <u>Single-neuron encoding</u>: very **slow** because long spike sequences are needed to estimate the probabilities.
- <u>Ensemble encoding</u>: can be **fast** because few spikes per neuron are enough to estimate the probabilities.



Coupling to a second neuron

- how does it affect signal encoding?

Model

$$\epsilon \dot{u}_1 = u_1 - \frac{u_1^3}{3} - v_1 + a_0 \cos(2\pi t/T) + \sigma_1 u_2 + \sqrt{2D}\xi_1(t)$$

$$\dot{v}_1 = u_1 + a,$$

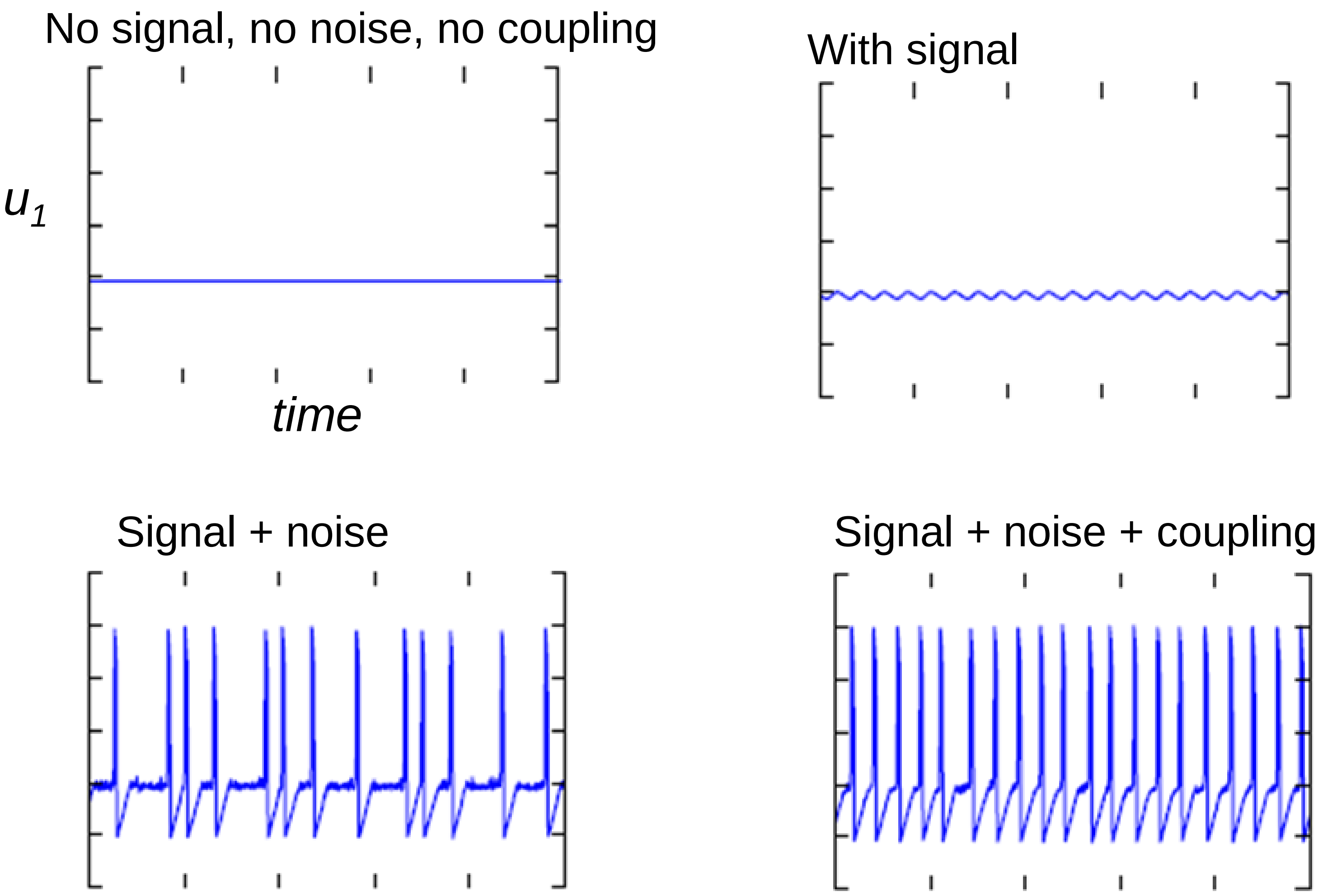
$$\epsilon \dot{u}_2 = u_2 - \frac{u_2^3}{3} - v_2 + \sigma_2 u_1 + \sqrt{2D}\xi_2(t)$$

$$\dot{v}_2 = u_2 + a$$

- Identical neurons.
- Linear & instantaneous & asymmetric coupling
- Signal, coupling and noise in the fast variable.
- a=1.05 and ε=0.01; parameters: a_0, T, D, σ_1, σ_2

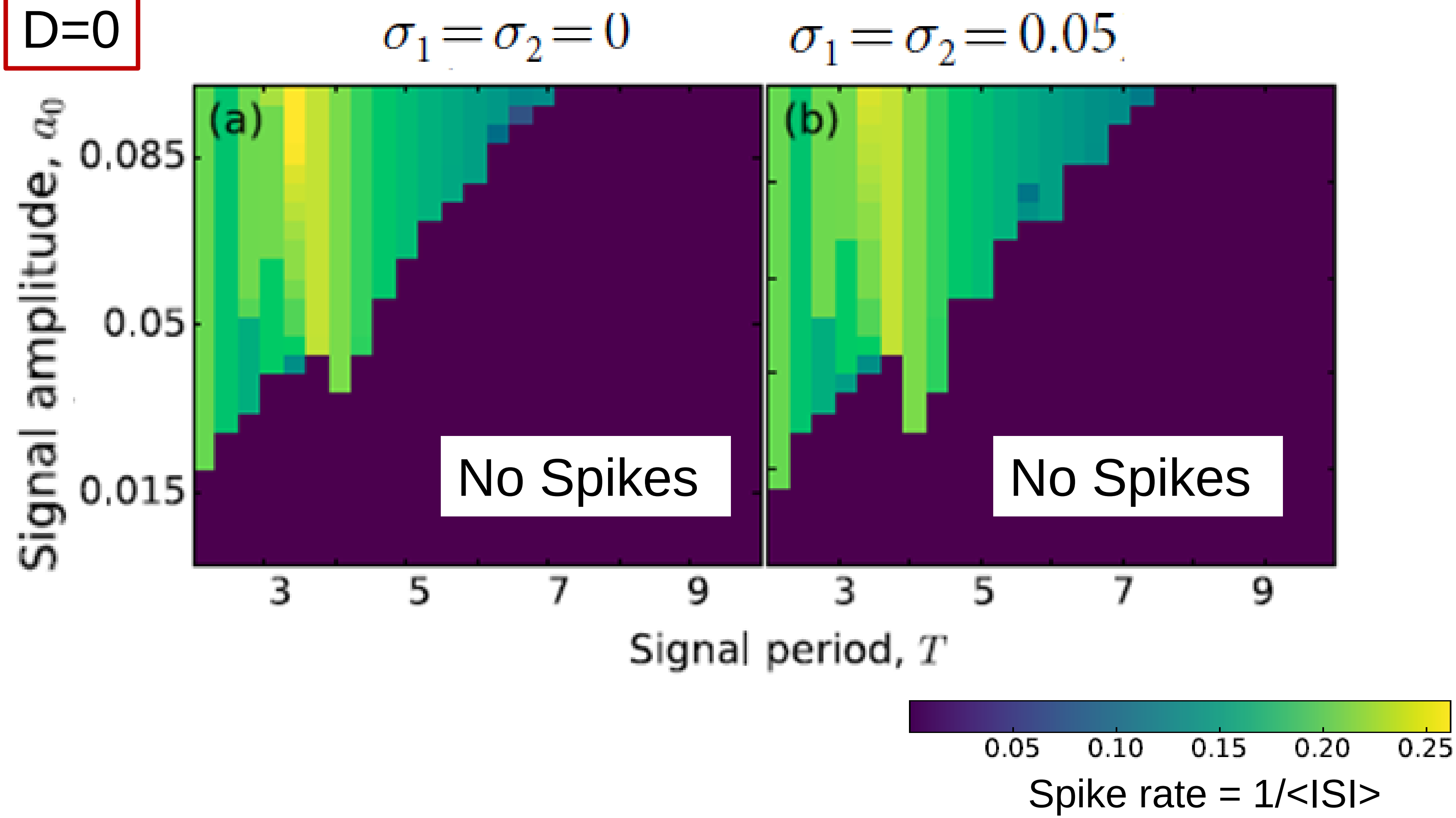
M. Masoliver and C. Masoller, Scientific Reports 8, 8276 (2018)

Output of neuron 1 (that perceives the signal)



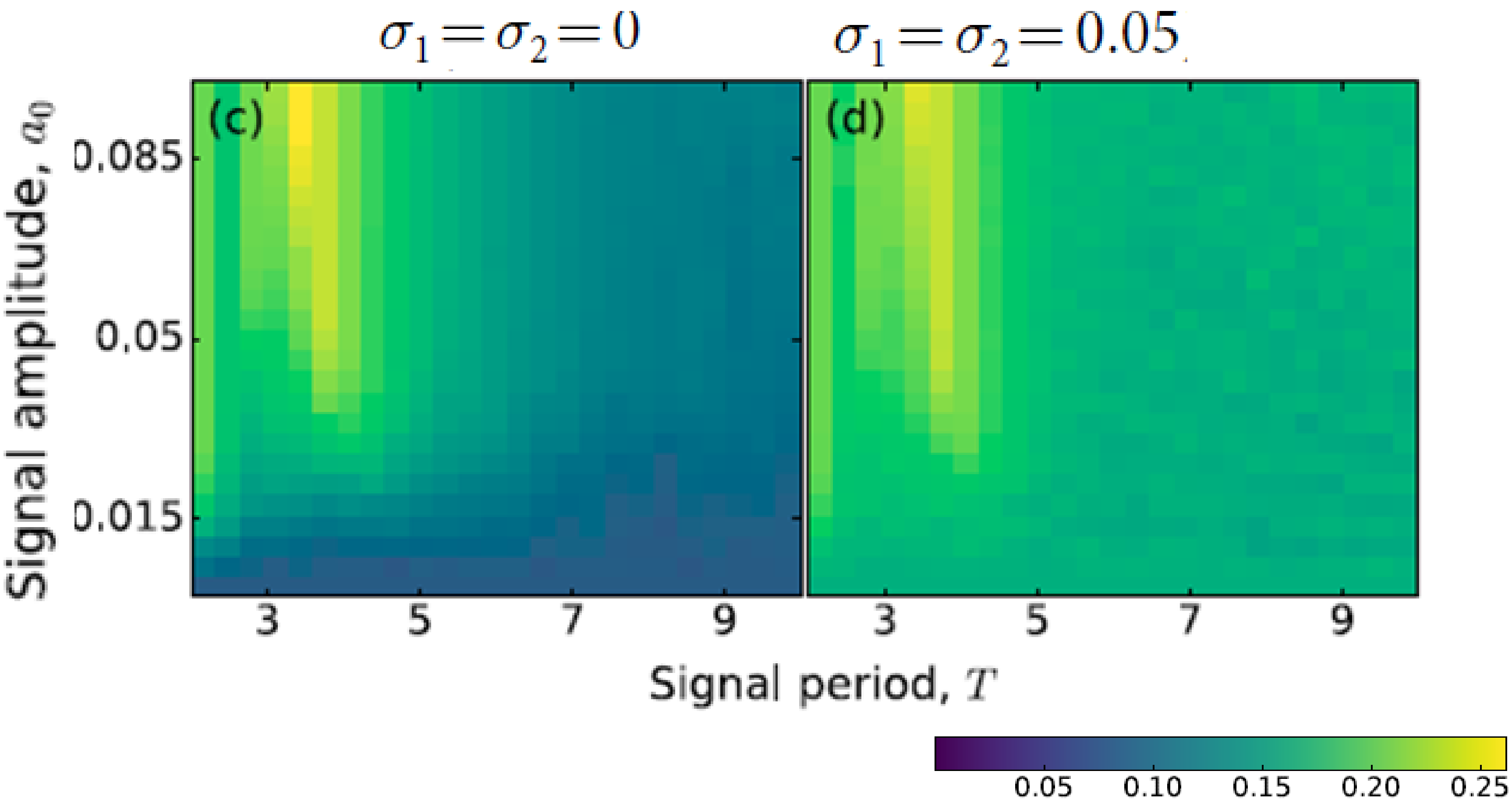
Identification of the subthreshold region

D=0



The signal is subthreshold if the amplitude is small and/or the period is long

With noise

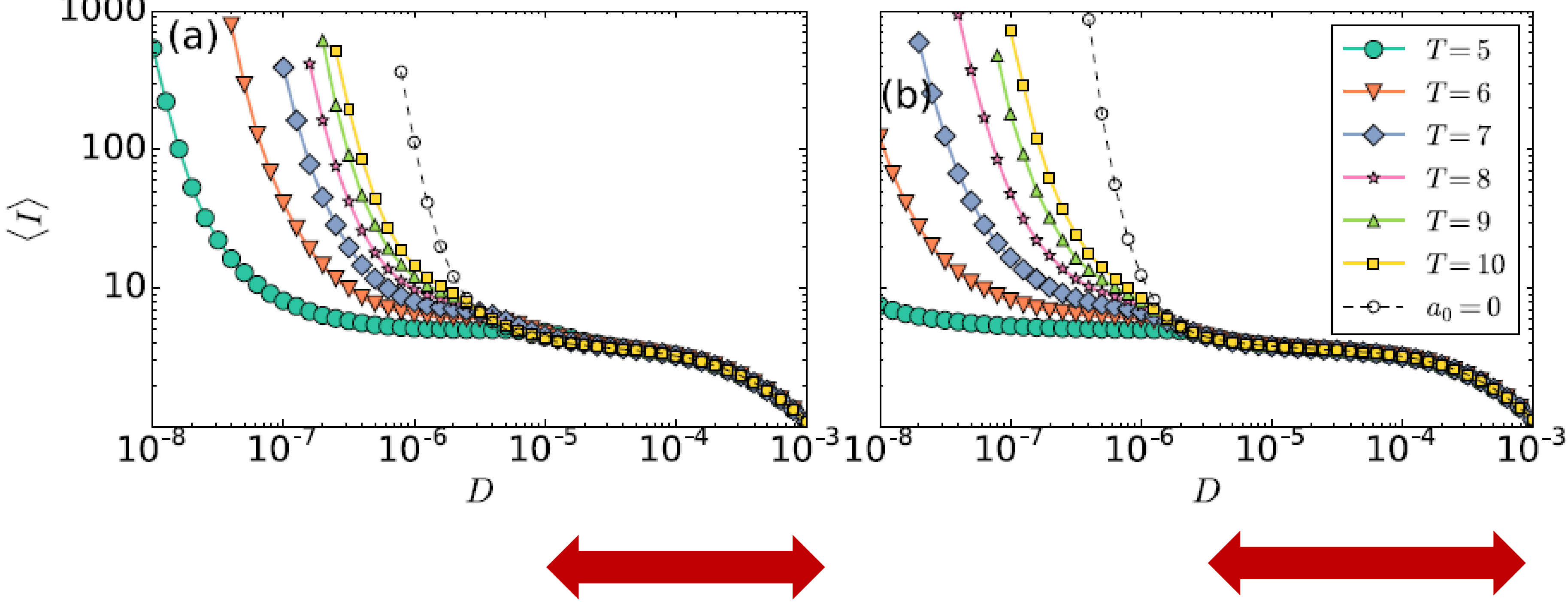


Spike rate = 1/<ISI>

Coupling increases the spike rate

Effect of noise

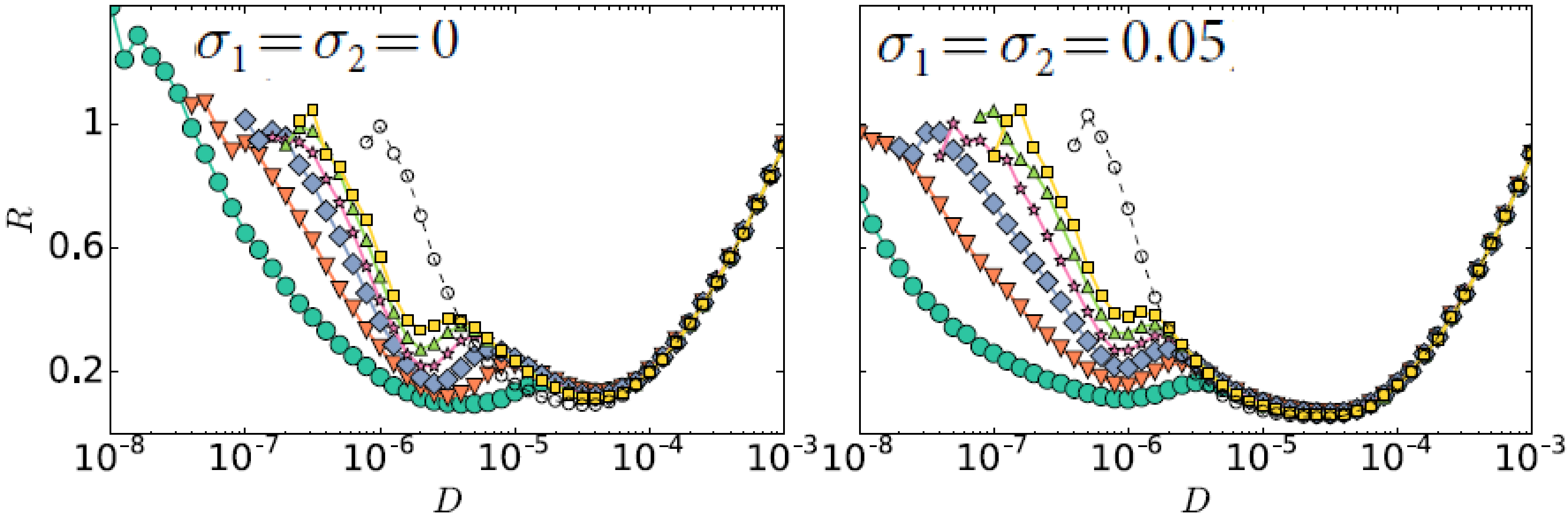
$\sigma_1 = \sigma_2 = 0$ | $\sigma_1 = \sigma_2 = 0.05$



The spike rate (=1/<I>) does not encode the period of the signal.

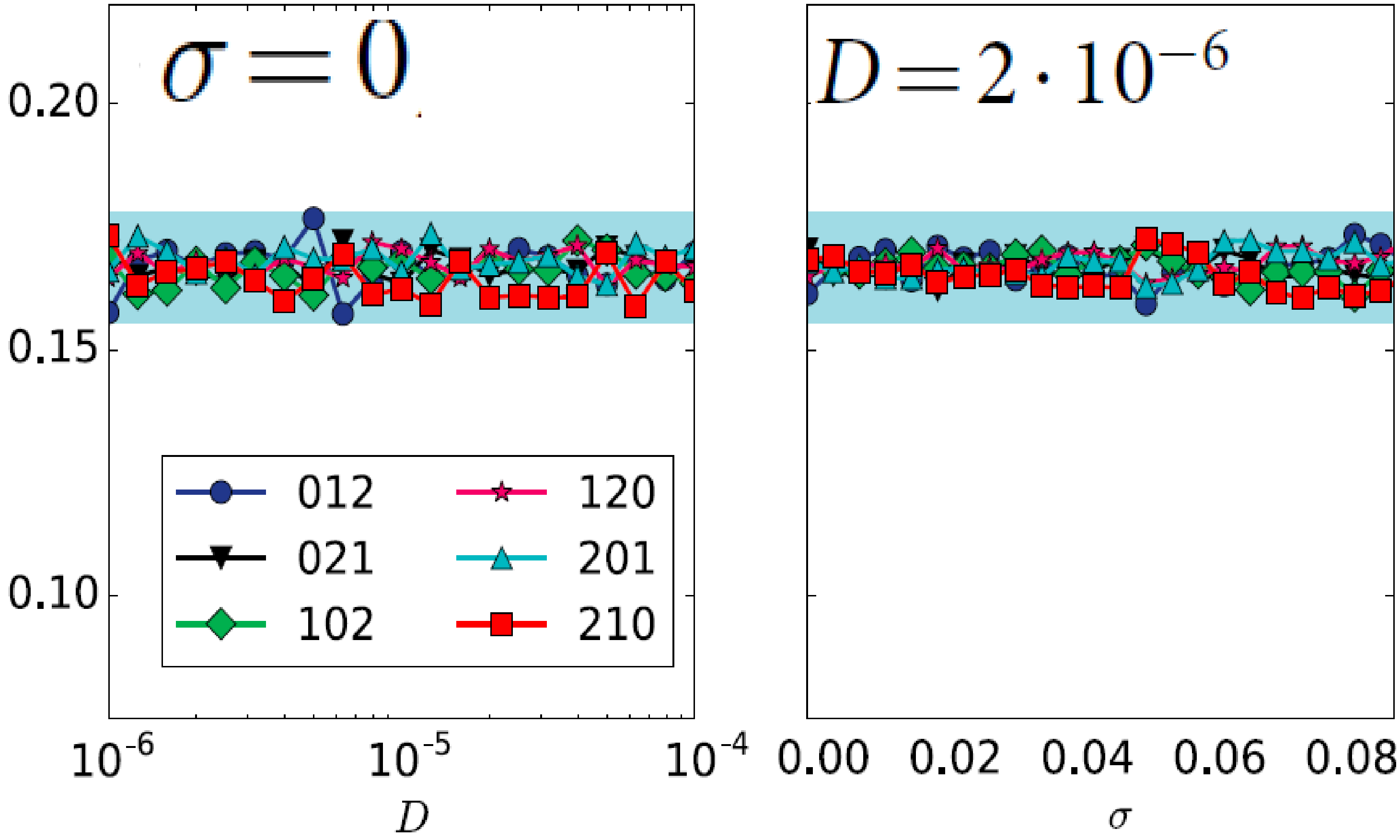
Coherence and stochastic resonances

$$R = \frac{\sqrt{\langle I^2 \rangle - \langle I \rangle^2}}{\langle I \rangle}$$



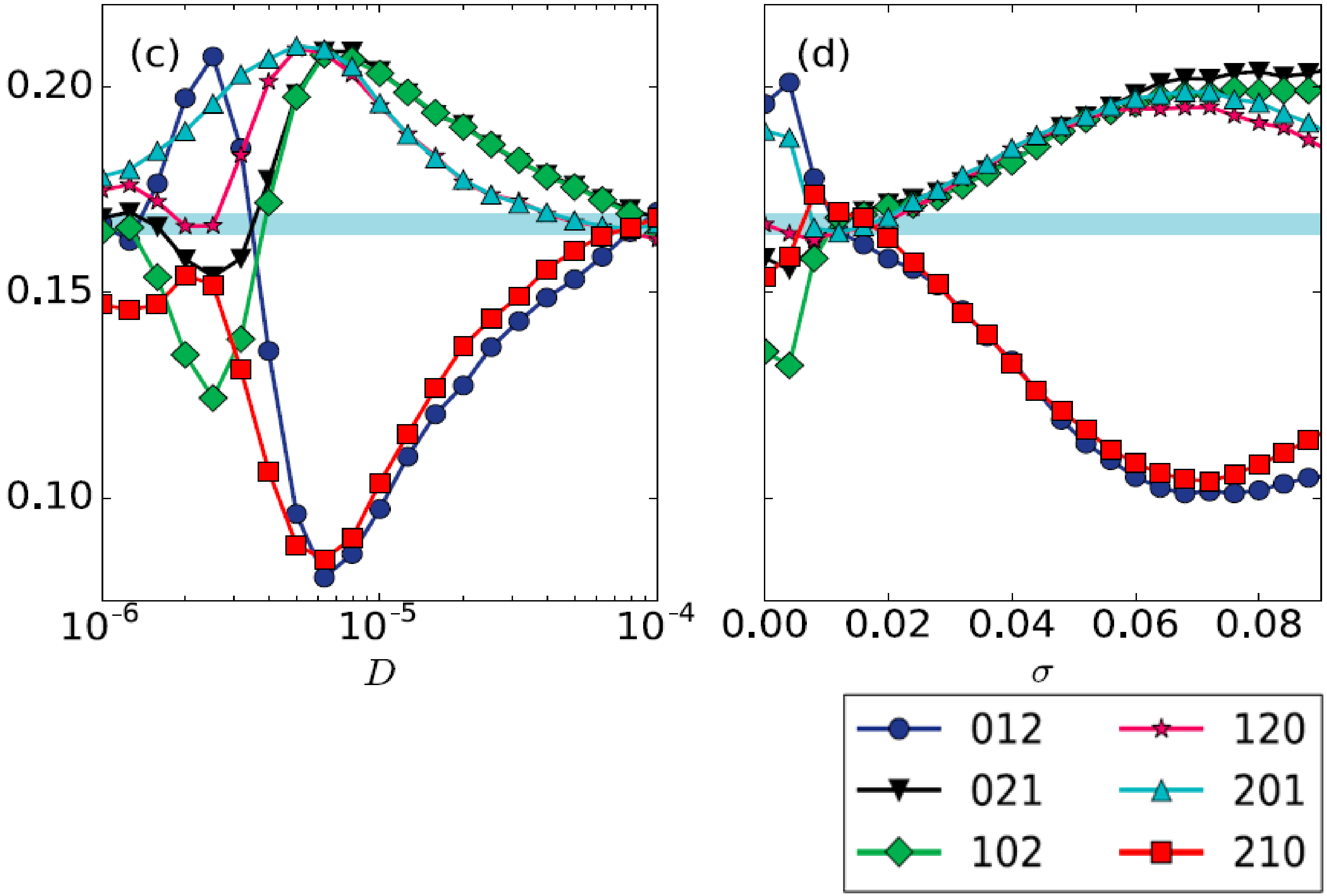
No signal ⇒ no spike correlations

a_0=0



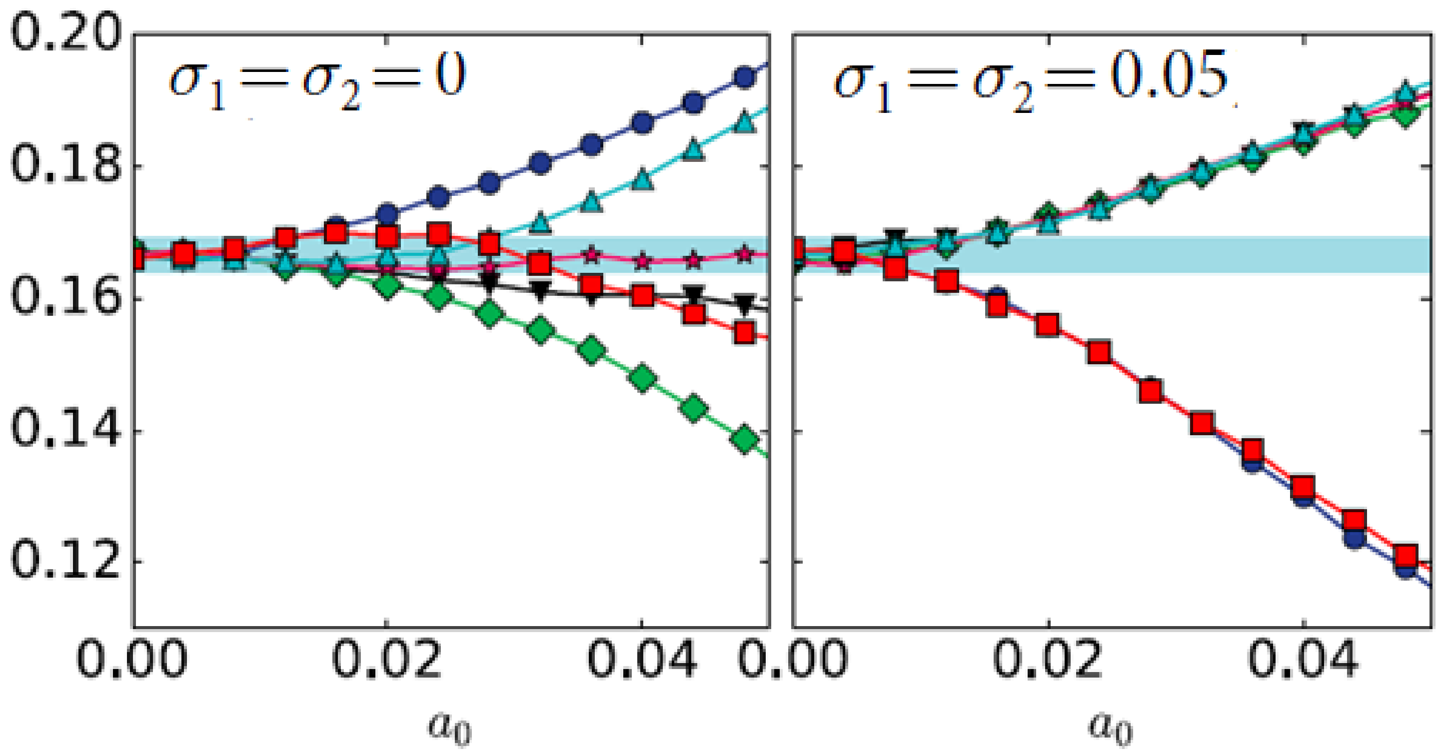
The signal induces spike correlations

a_0=0.05
T=10



M. Masoliver and C. Masoller, Scientific Reports 8, 8276 (2018)

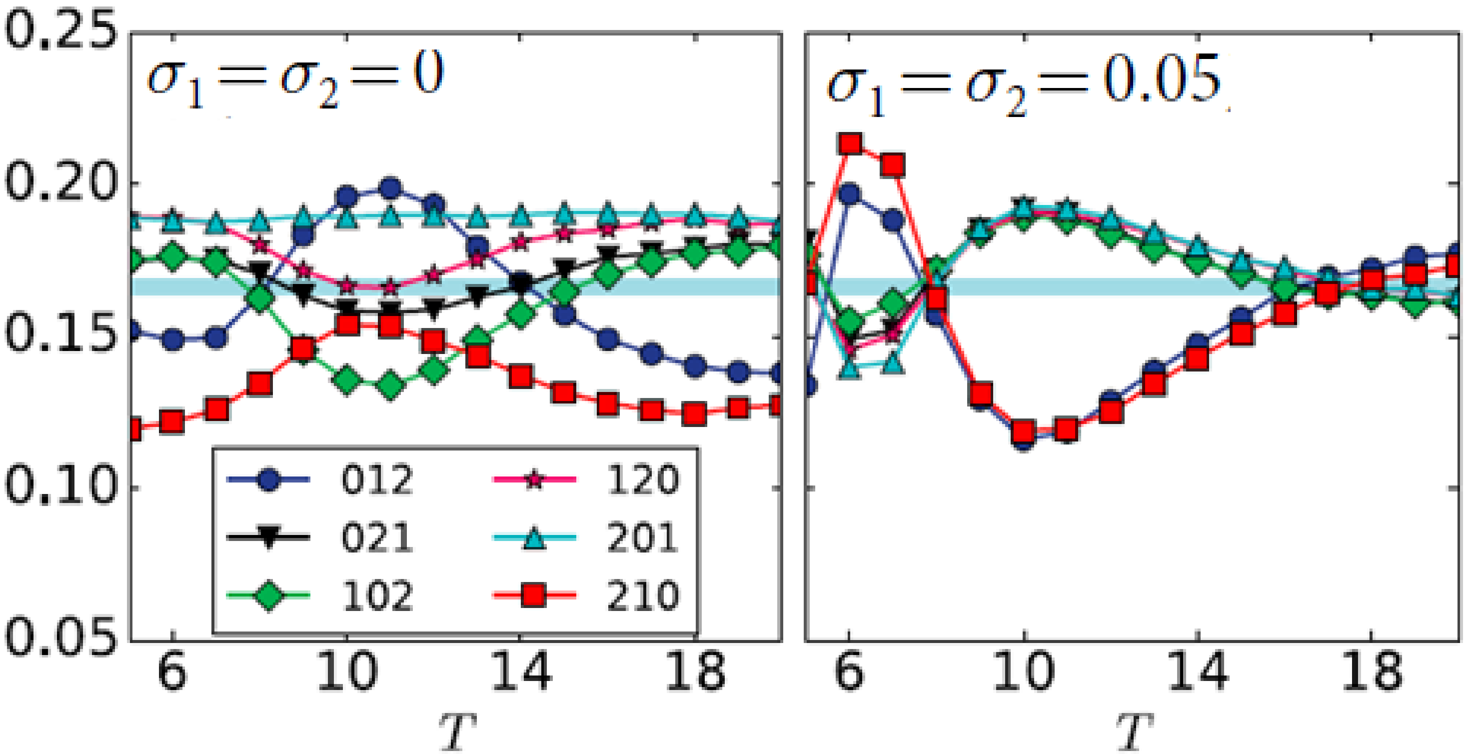
Spike correlations depend on the amplitude of the signal



⇒ With coupling the signal is still encoded in the ordinal probabilities.

⇒ Coupling changes the more and less expressed patterns.

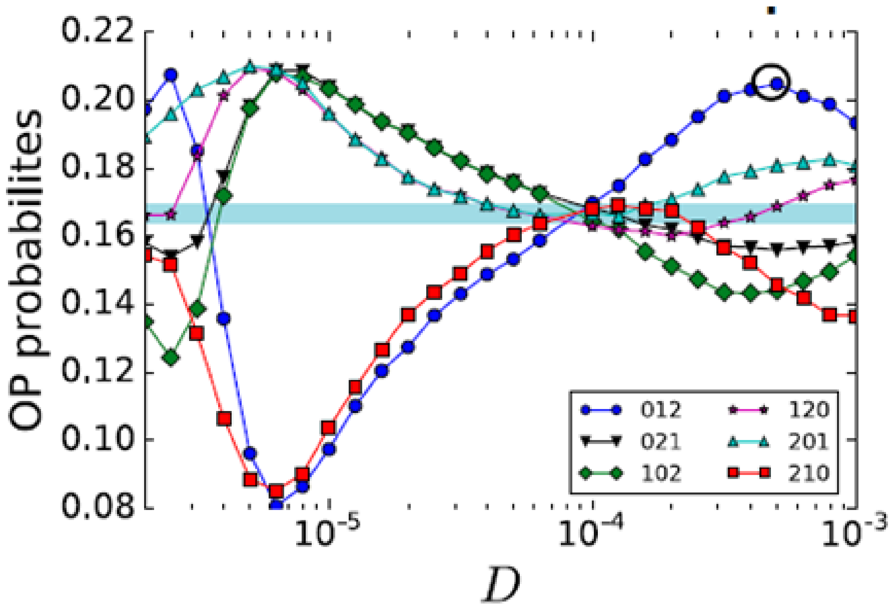
The probabilities also depend on the period of the signal



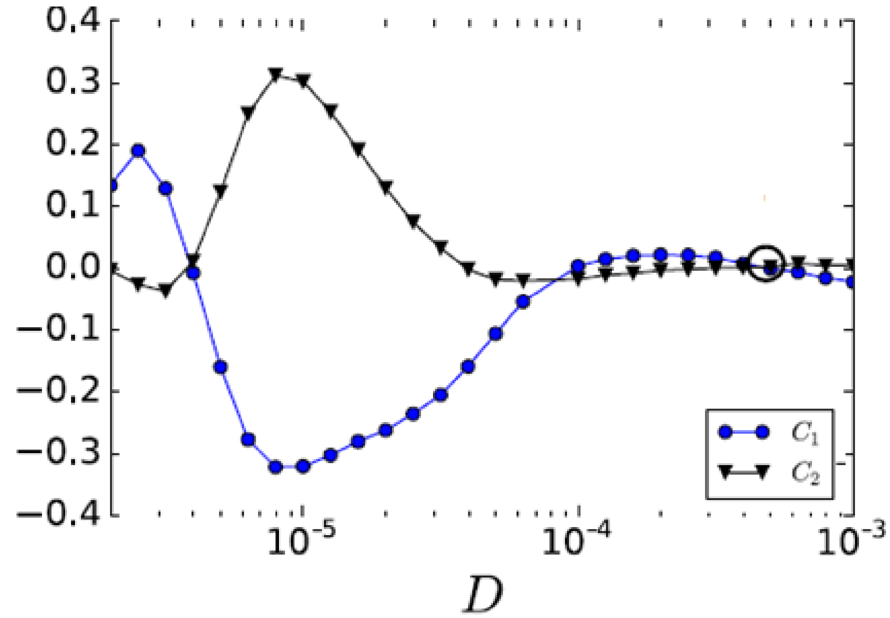
⇒ Coupling changes the preferred patterns.

Are the spike correlations captured by linear analysis?

$a_0 = \sigma = 0.05$, T=8



$$C_j = \frac{\langle (I_i - \langle I \rangle)(I_{i-j} - \langle I \rangle) \rangle}{\sigma^2}$$



$\Rightarrow$ For strong noise, correlation coefficients at lag 1 and 2 vanish but ordinal analysis detects more / less expressed patterns.

Neuronal ensemble?

Model

$$\epsilon \dot{u}_i = u_i - \frac{u_i^3}{3} - v_i + a_0 \cos(2\pi t/T) + \frac{\sigma_i}{\langle k \rangle} \sum_{j=0}^{N} A_{ij}(u_j - u_i) + \sqrt{2D}\xi_i \qquad j \neq i$$

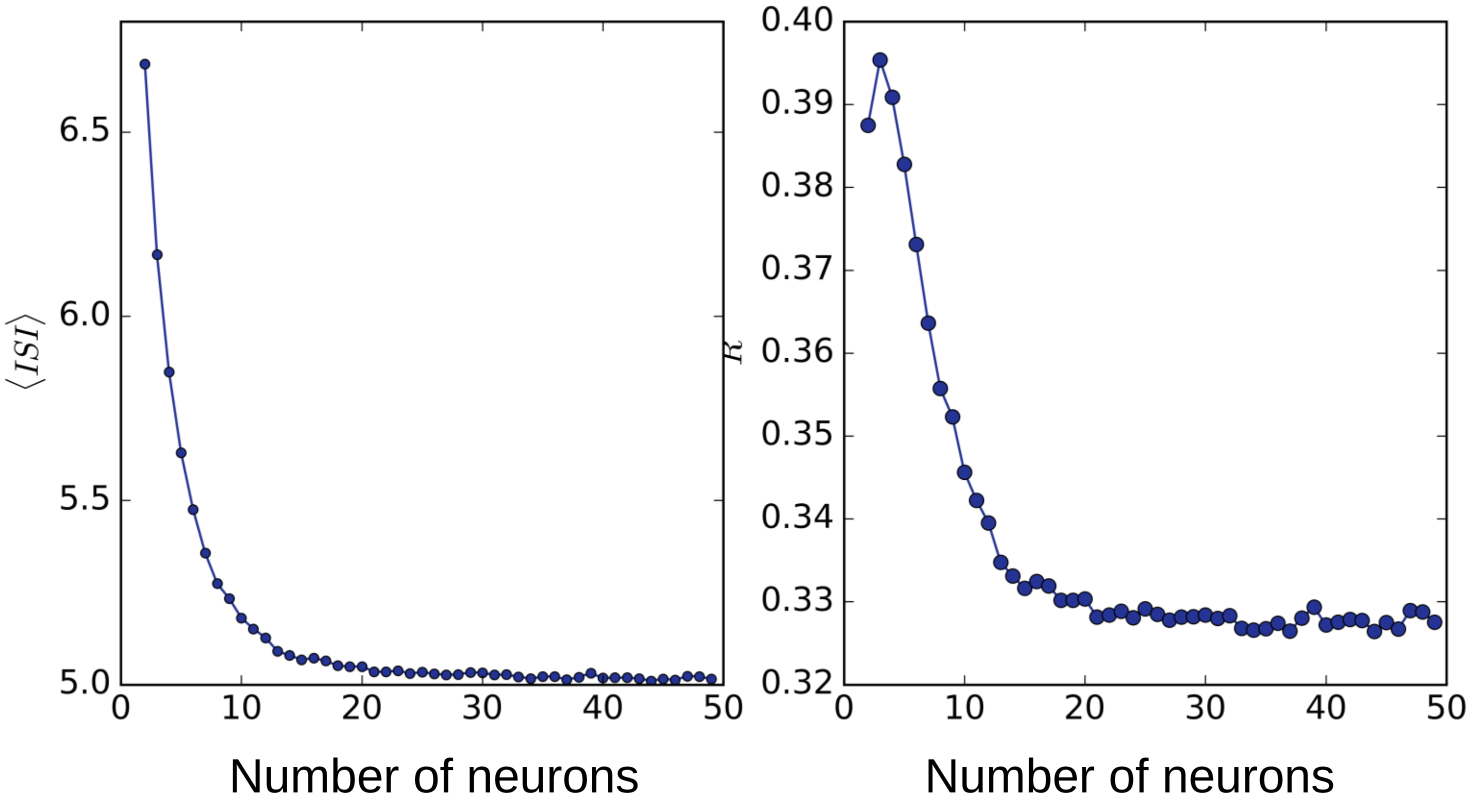
$$\dot{v}_i = u_i + a$$

The signal is applied to each neuron.

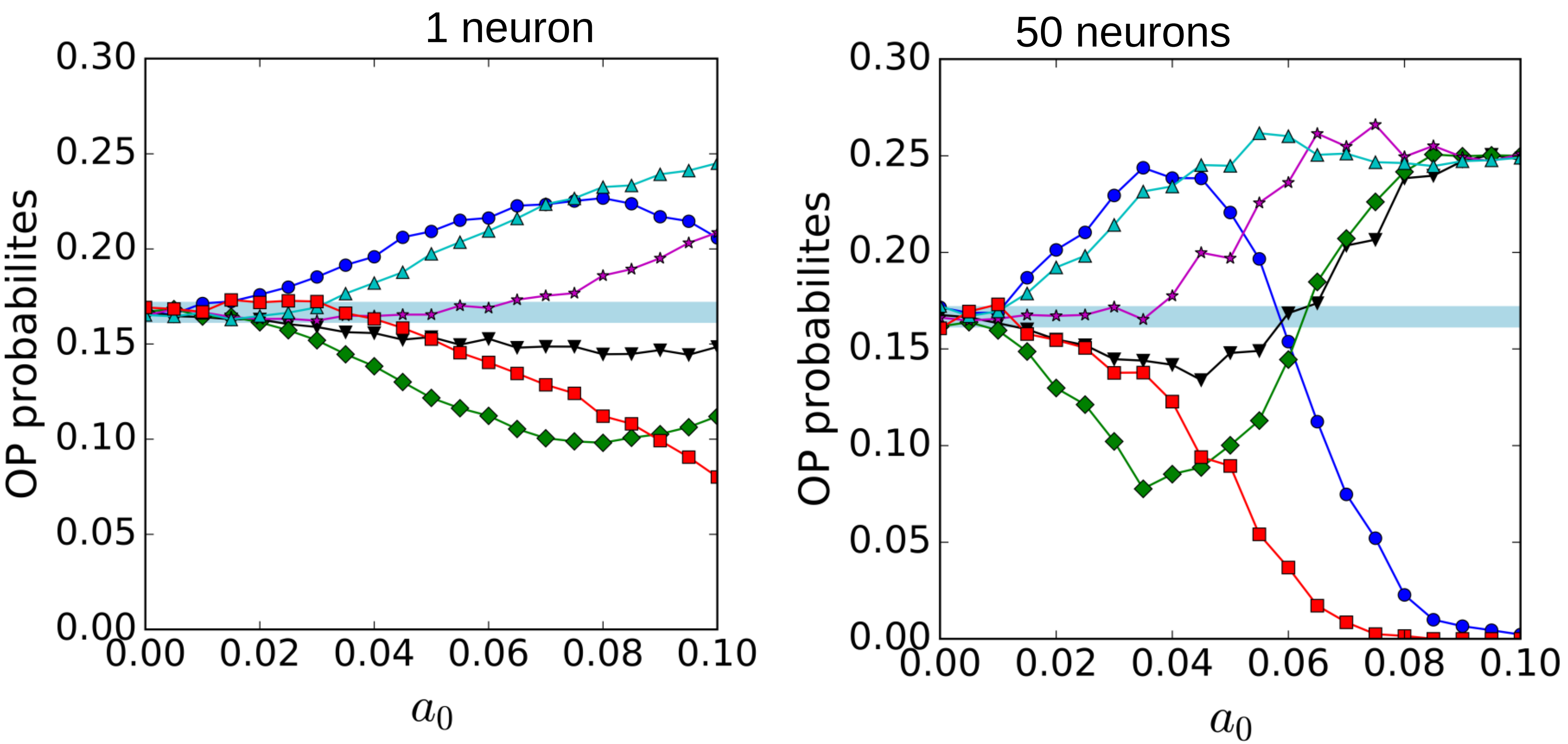
The signal is subthreshold for each individual neuron: with D = 0 and σ_i=0, no spikes.

Spike rate and spike sequence regularity

$A_{ij} = 1 \ \forall \ i \neq j$

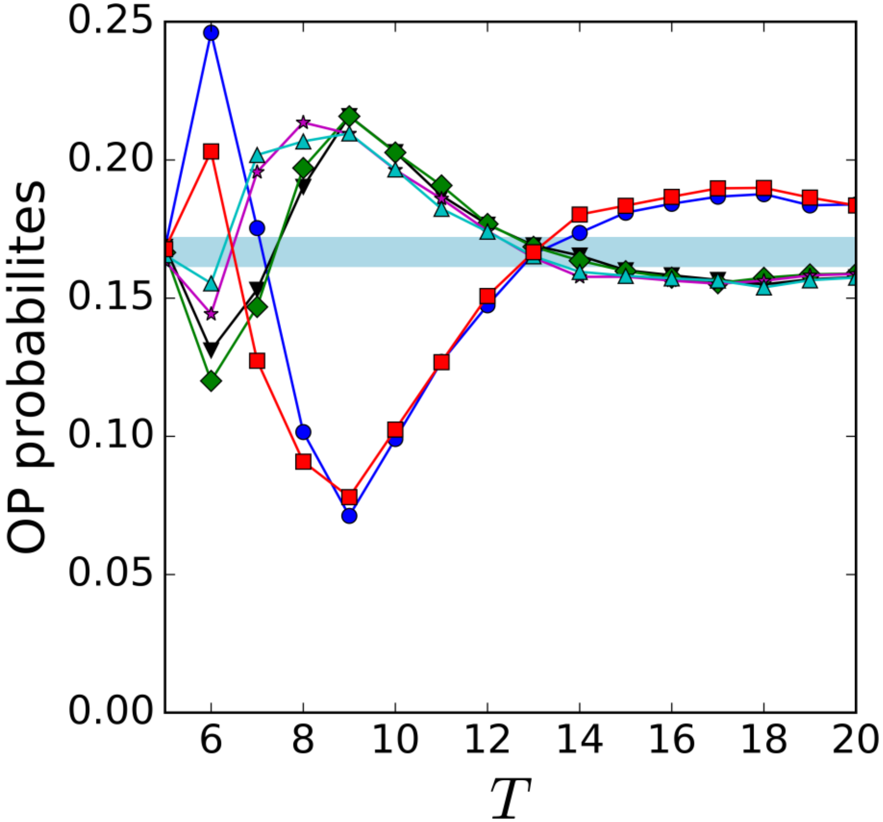


Influence of the signal amplitude

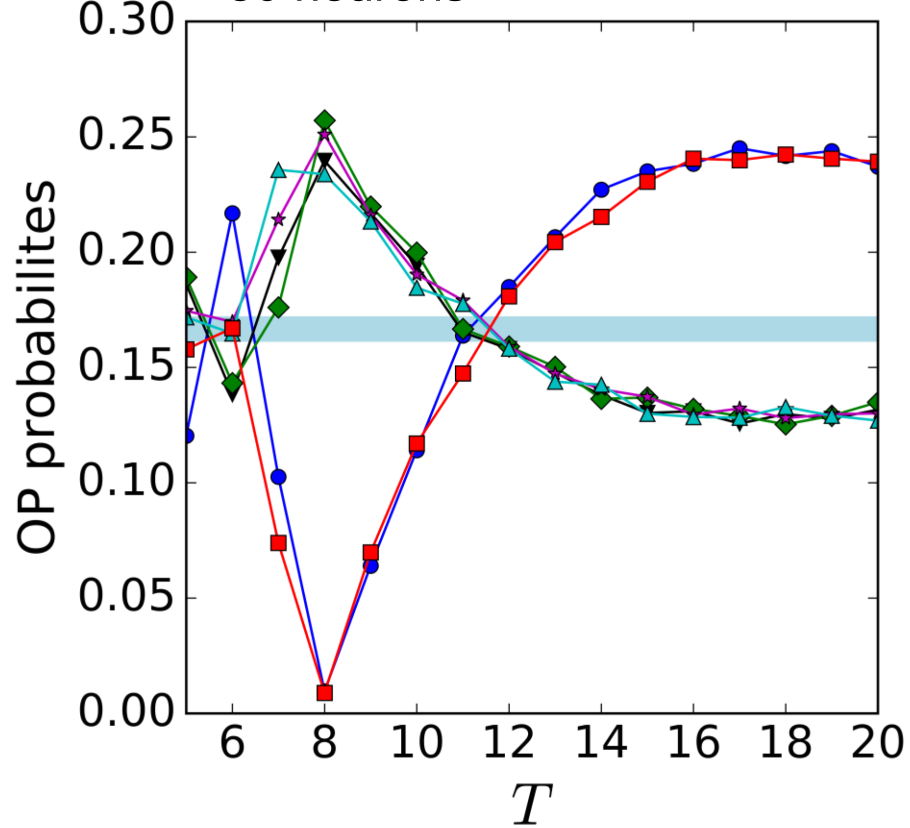


Influence of the signal period

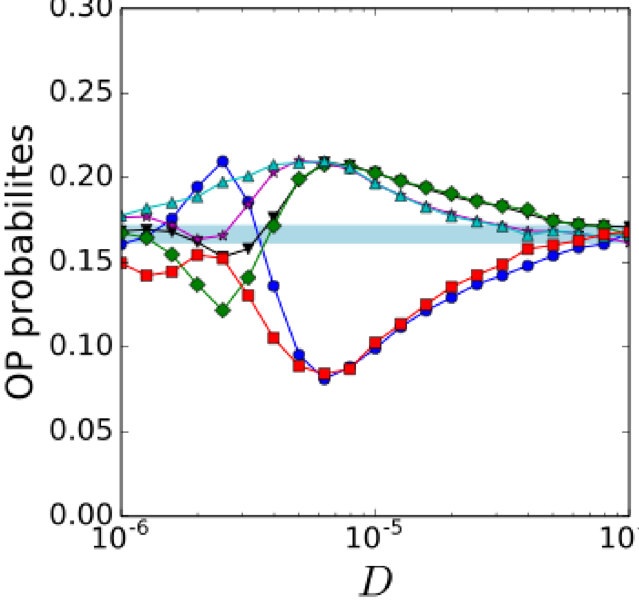
1 neuron

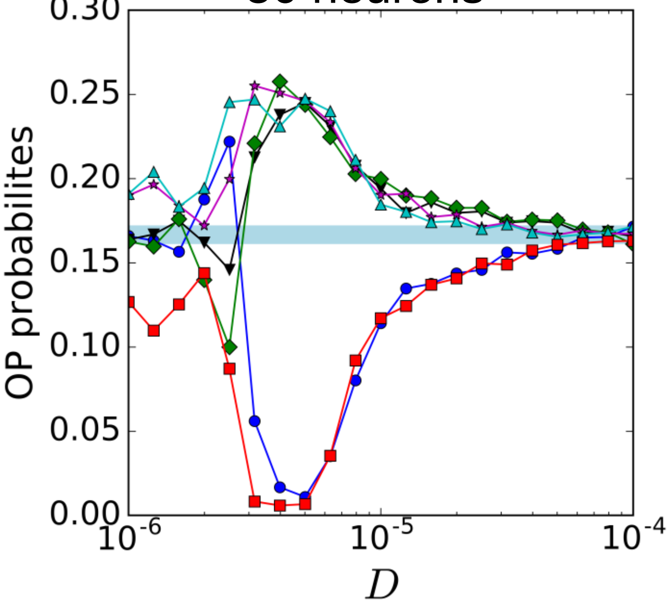


50 neurons

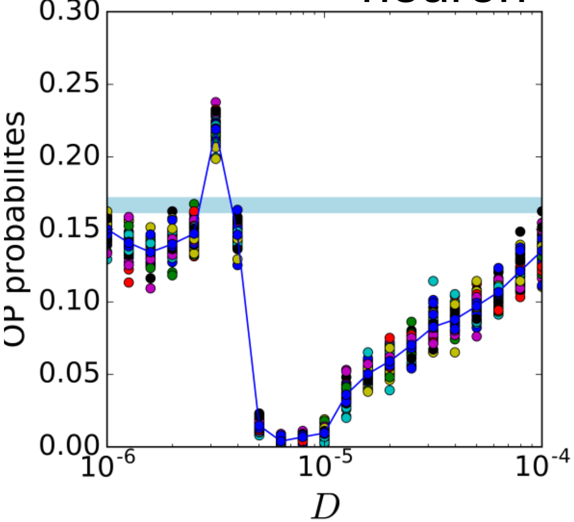


Influence of noise

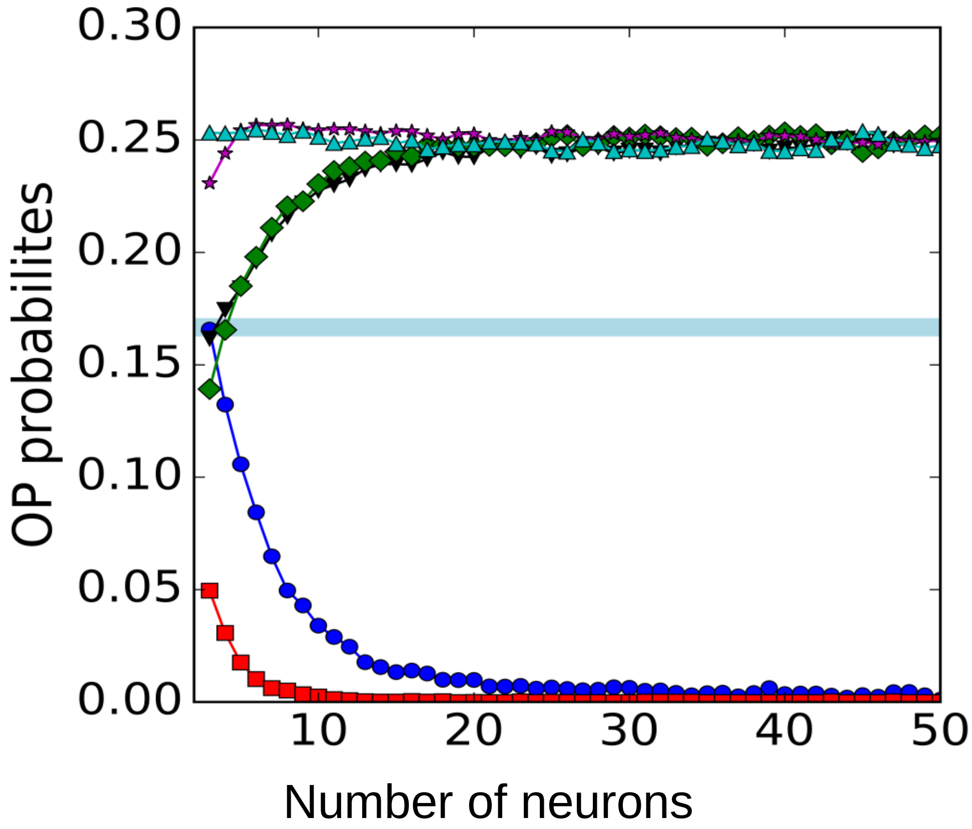




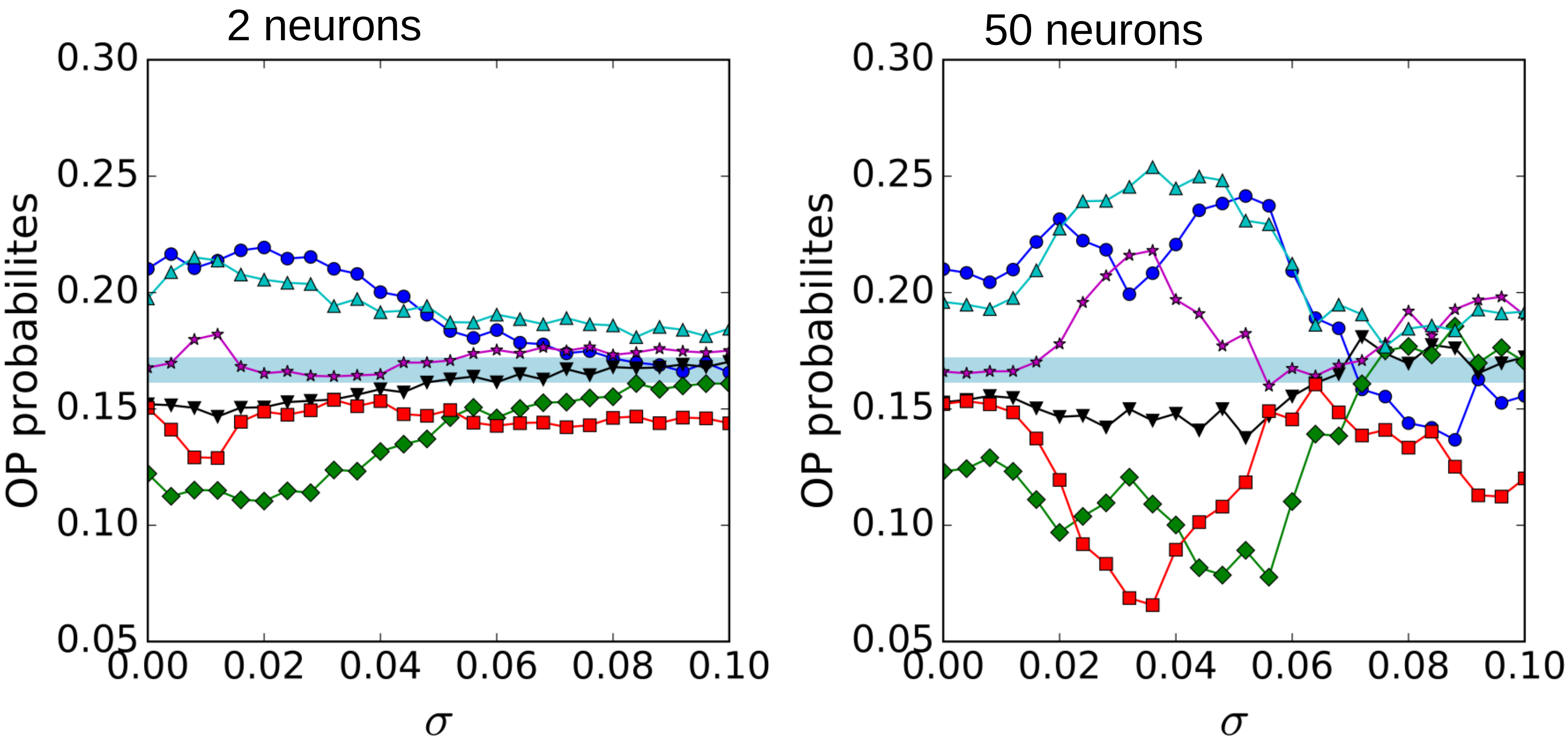
P(012) of each neuron



Influence of the number of neurons



Influence of the coupling strength



- In the model the coupling is normalized to the number of links: it does not increase with the network size.
- Sincronization?

Conclusions

What did we learn?

- Take home message:
  - Ordinal time-series analysis uncovers patterns in data.
  - It detects correlations that might not be captured by linear analysis.
- Main conclusions:
  - Neuron fires at lower noise level when coupled.
  - The ordinal probabilities carry information about the signal (amplitude and period) with or without coupling.
  - Coupling changes the preferred/infrequent patterns.
  - In neuronal ensembles the encoding of the signal can be more pronounced.
- Ongoing work:
  - Similar results with other models and types of coupling.
  - Sincronization, network structure?

THANK YOU FOR YOUR ATTENTION !

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

Emergence of spike correlations in periodically forced excitable systems

J. A. Reinoso, M. C. Torrent and C. Masoller, PRE 94, 032218 (2016).

Subthreshold signal encoding in coupled FitzHugh-Nagumo neurons

M. Masoliver and C. Masoller, Scientific Reports 8, 8276 (2018).