Neural coding of weak signals in noisy environments using ordinal spike patterns

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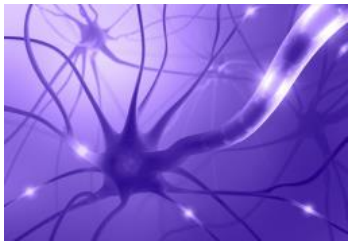
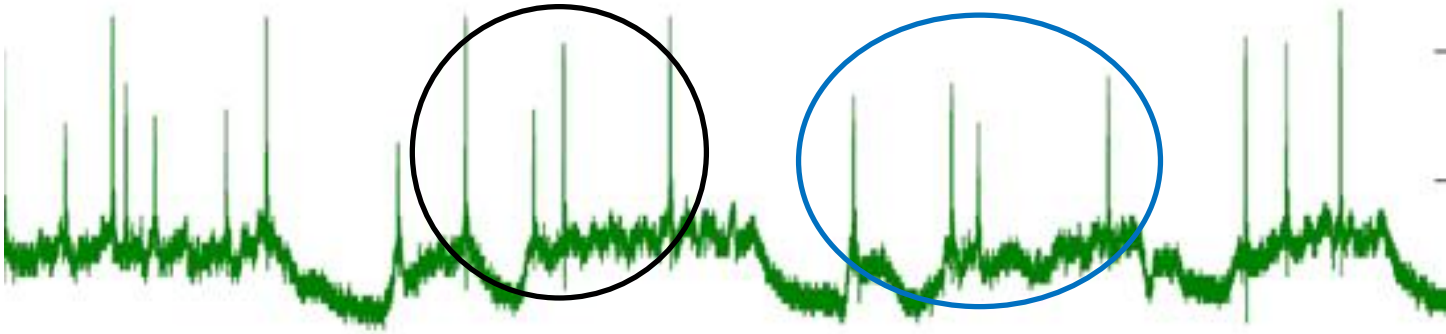
Ordinal methods: Concepts, applications, new developments and challenges
Dresden, March 2, 2022

How neurons encode information?





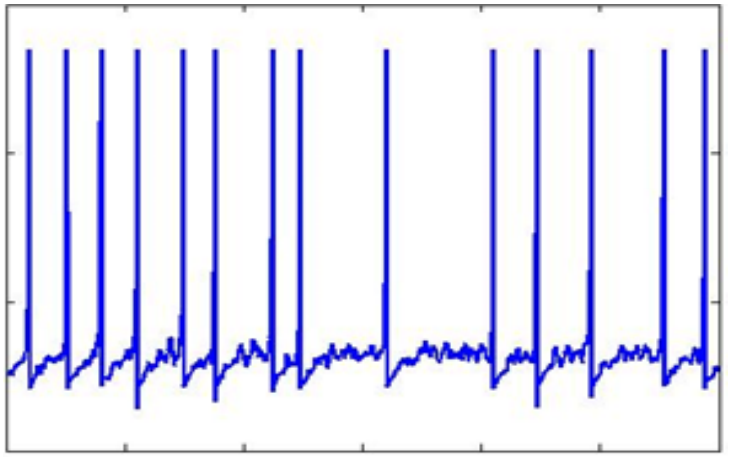
- In the spike rate?
- In the timing of the spikes?
- In ordinal spike patterns?
- Our goal: try to understand how neurons encode and transmit information of a **weak** *input signal*.
- Exploit **noise**? / Robust to **noise?**

Can lasers mimic real neurons?

Laser spikes

Time (μs)

Simulated neuronal spikes



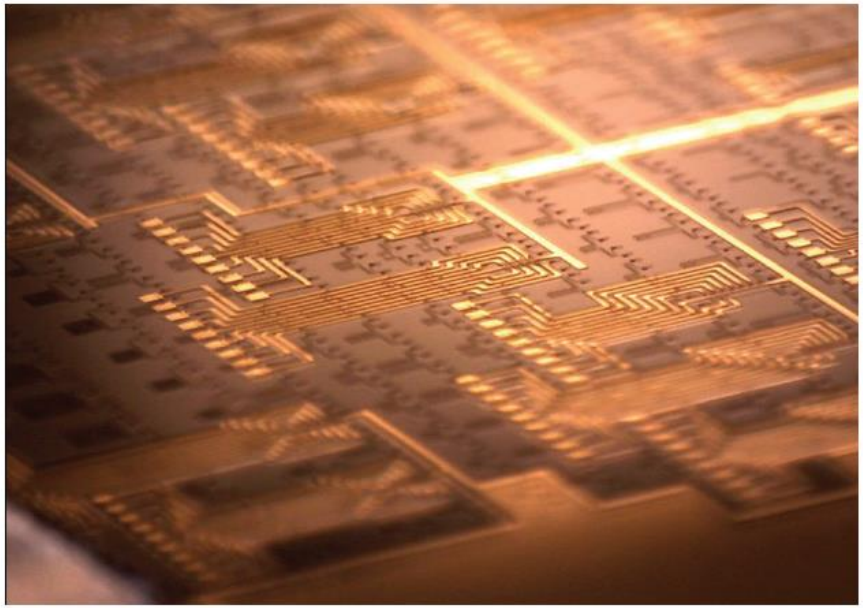
Time (ms)

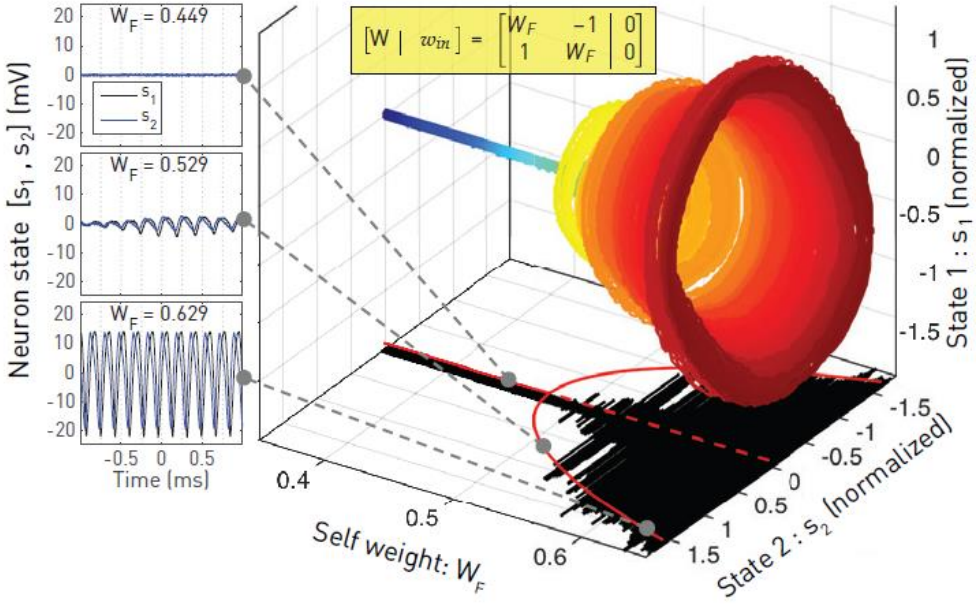
Motivation: Using **neural code** may lead to the development of fast and energy-efficient photonic neural networks.

Photonic neurons

Semiconductor lasers (optically perturbed) can operate in excitable, spiking regimes.

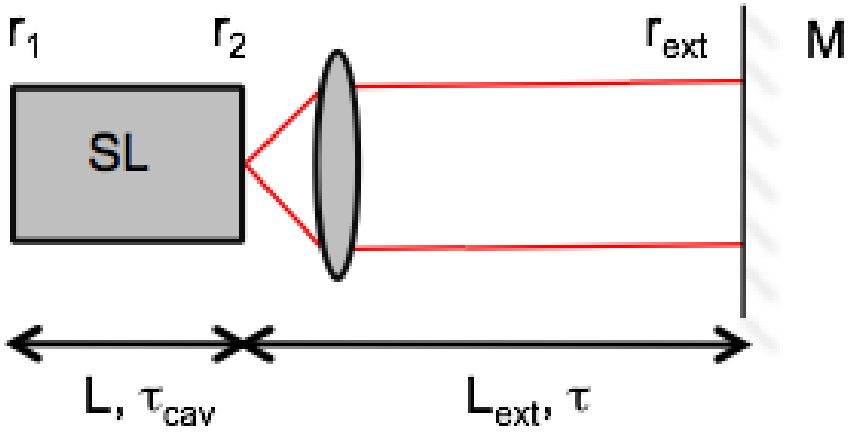
Main advantages: inexpensive, fast, electrically pumped, energy efficient and can be integrated into chips.

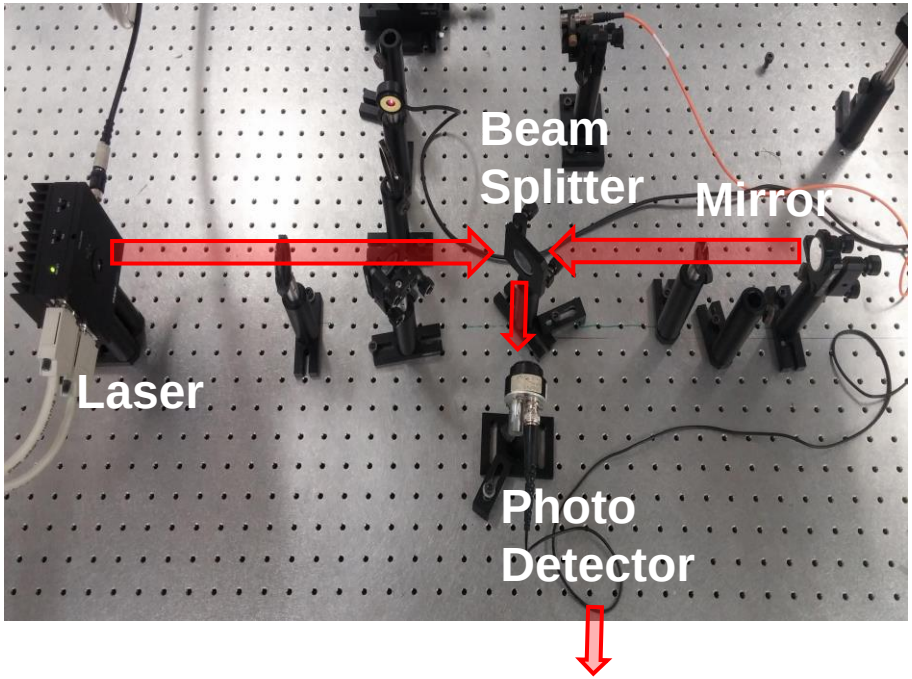




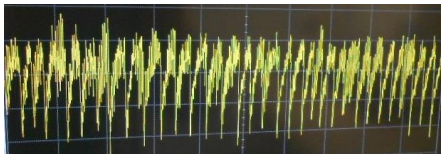
Left: A photonic neural network that can be implemented in silicon photonics. Right: The on-chip system with modulator neurons displays a characteristic oscillation called a Hopf bifurcation, which confirms the presence of an integrated neural network. Princeton University Lightwave Lab, 2017/ A. Tait et al., Sci. Rep. **7**, 7430 (2017).

Experimental setup in our lab

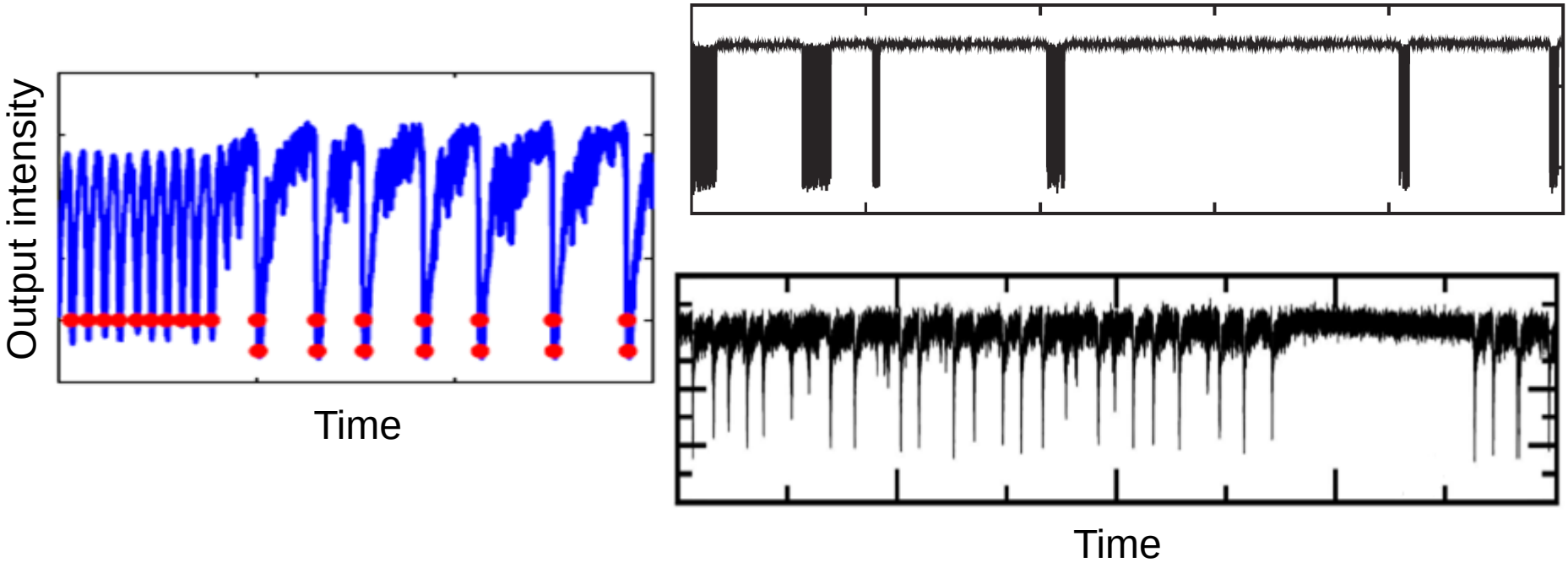




Oscilloscope



Observed behavior: excitability, tonic spikes, 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).

With a weak periodic input, are there statistical similarities between neuronal and laser spikes?

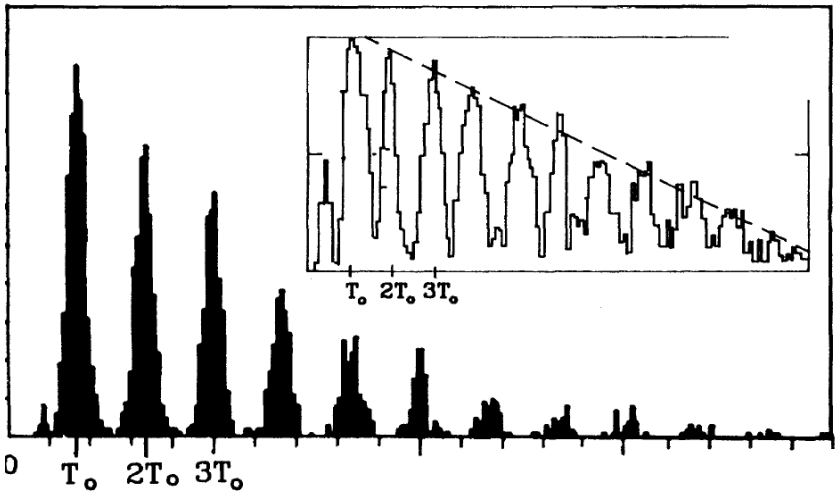
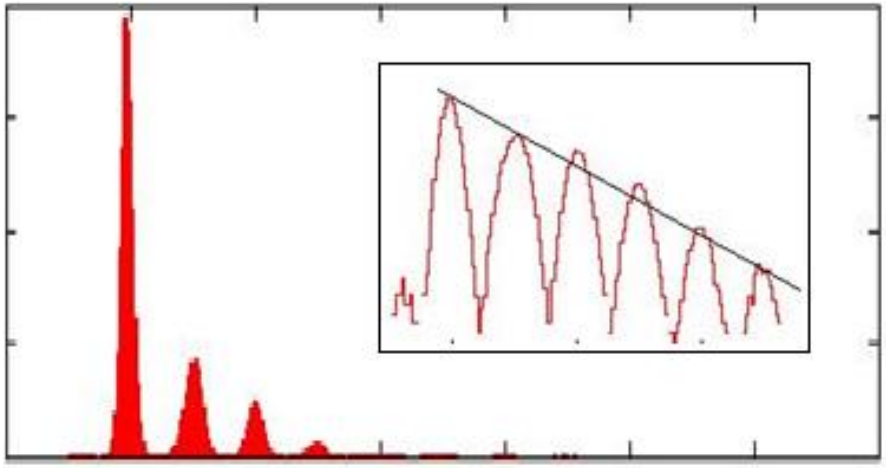


FIG. 1. (a) An experimental ISIH obtained from a single auditory nerve fiber of a squirrel monkey with a sinusoidal 80-dB sound-pressure-level stimulus of period $T_0 = 1.66$ ms applied at the ear. Note the modes at integer multiples of T_0. Inset:

A. Longtin et al. PRL (1991)



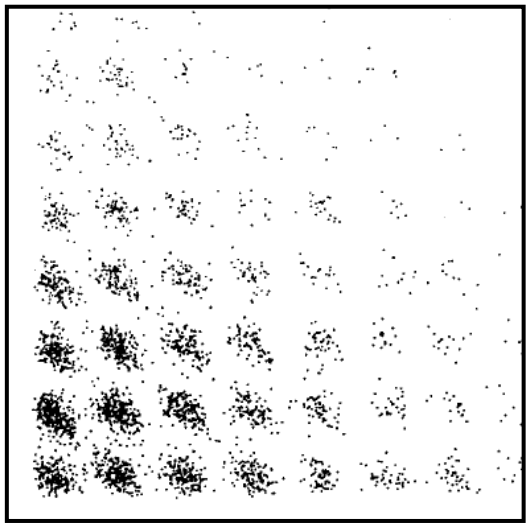
$2T_0$ $4T_0$

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

A. Aragoneses et al. Optics Express (2014)

Return maps of the inter-spike-intervals (ISIs)

Neuronal ISIs

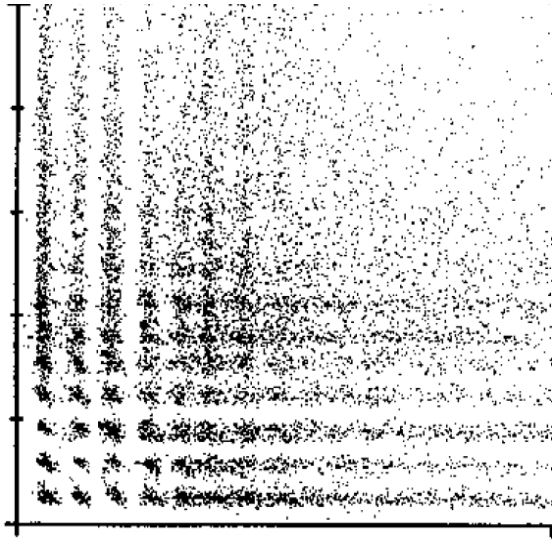


ΔT_{i+1}

ΔT_i

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

Laser ISIs



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

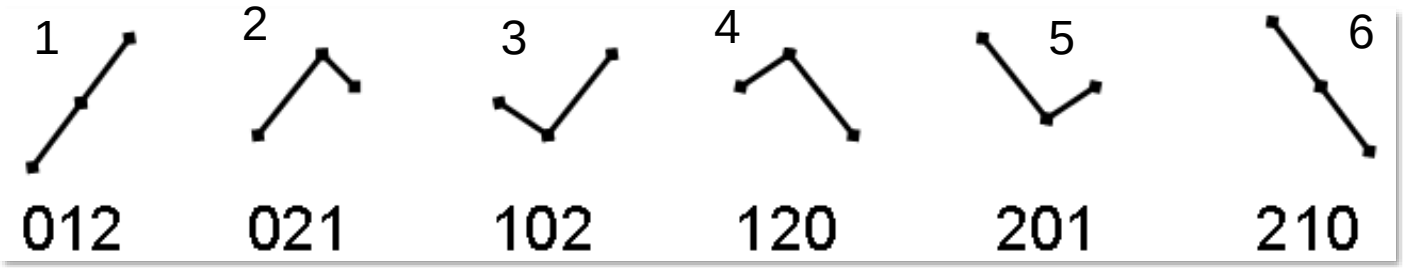
SIMILAR SPIKE PATTERNS?

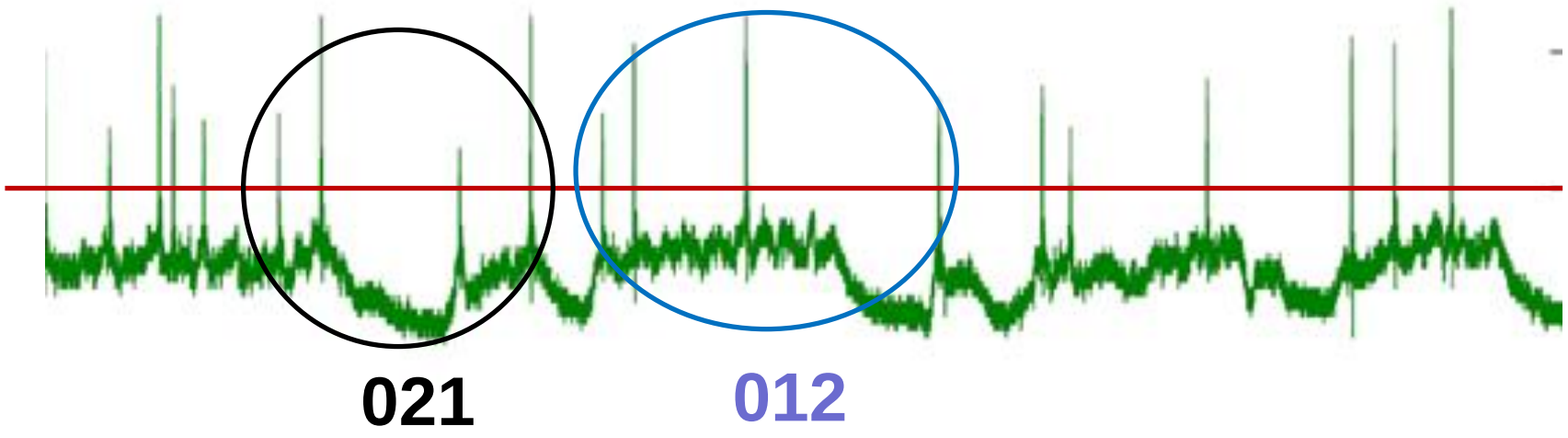
Ordinal method of analysis of sequences of inter-spike-intervals

Relative order of three consecutive intervals

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

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





Brandt & Pompe, PRL 88, 174102 (2002)

Are differences in ordinal probabilities significant?

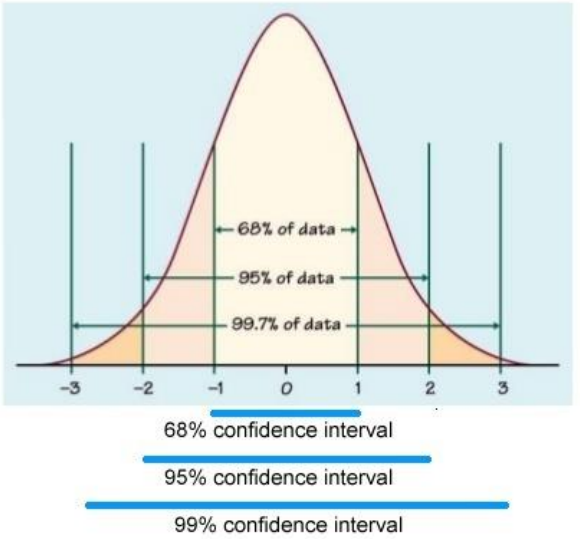
- **Null hypothesis**:

  $p_i = p = 1/D!$ 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).



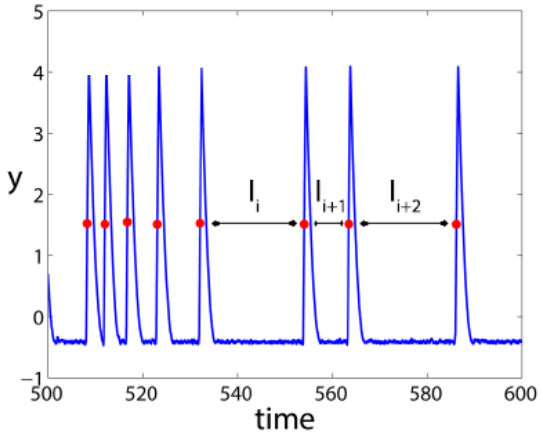
Single neuron

More / less frequent ordinal spike patterns encode information about a weak input?

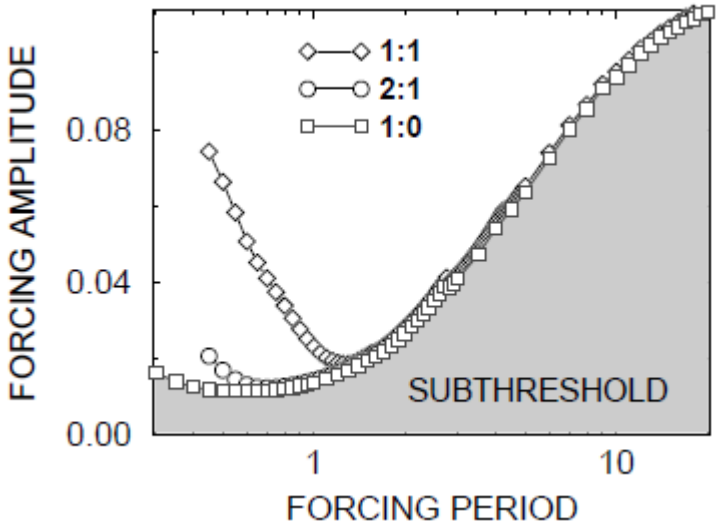
FitzHugh-Nagumo model

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

$$\frac{dy}{dt} = x + a + a_o \cos(2\pi t/T) + D\xi(t),$$

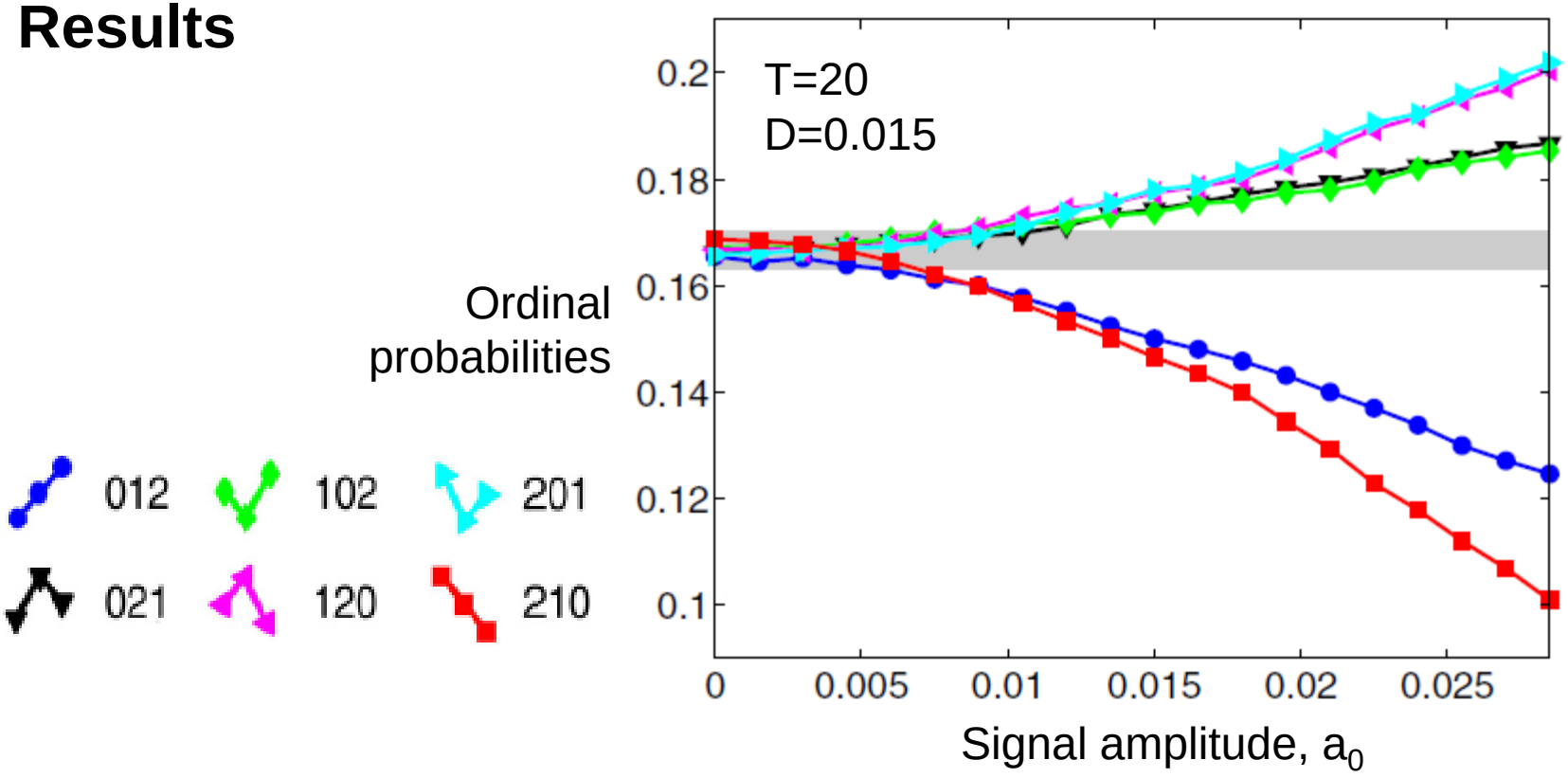


- a=1.05, ε=0.01
- Gaussian white noise
- Subthreshold signal: a_0 and **T** such that **spikes are noise-induced**.
- Time series with M=100,000 spikes.



Longtin and Chialvo, PRL 1998

Results

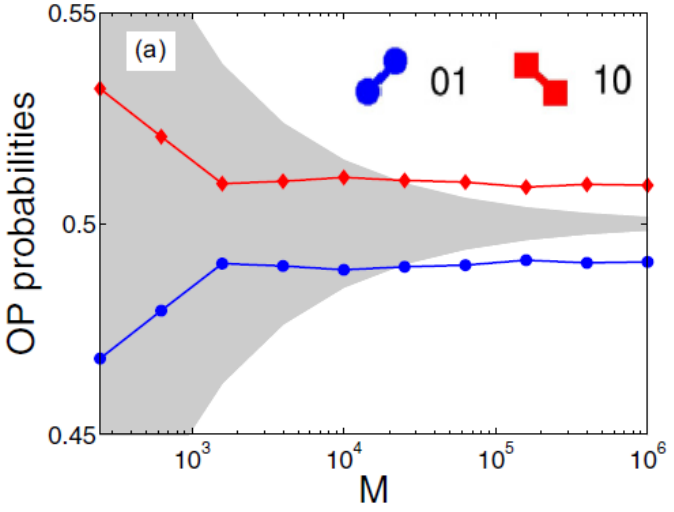


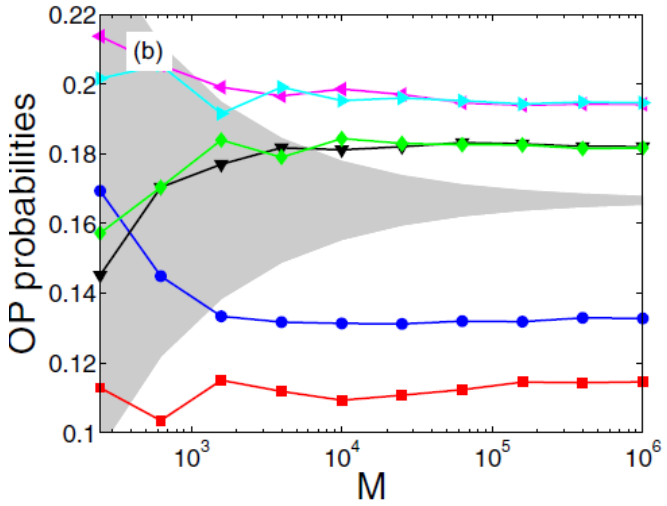
- Gray region: 3σ confidence level.

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

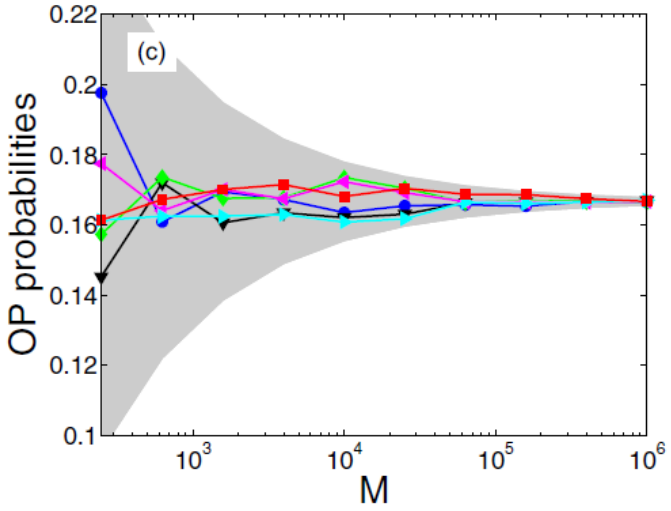
Data requirements

With signal



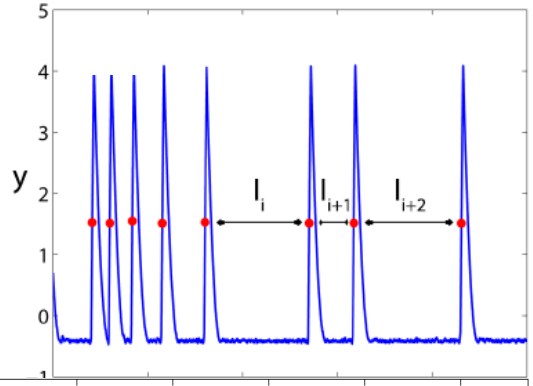


Without signal

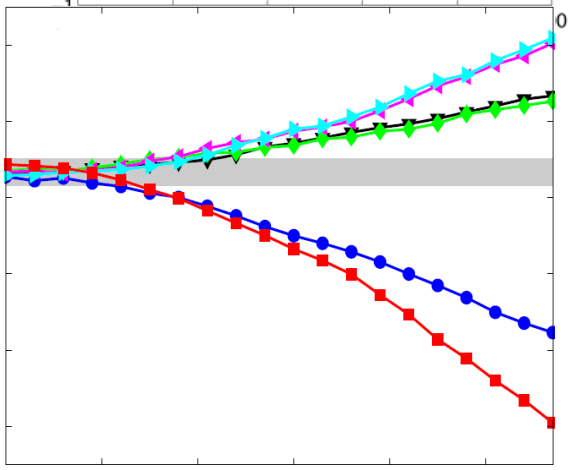


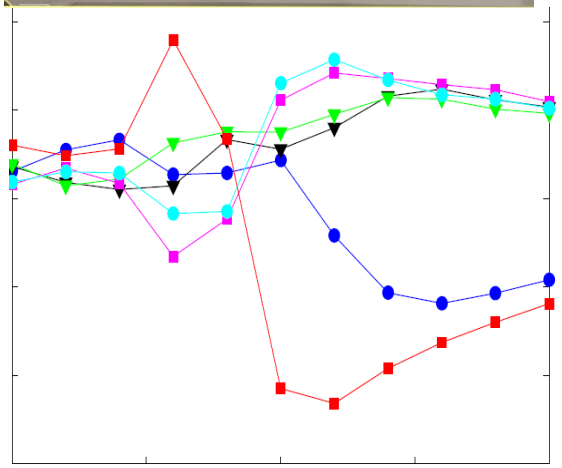
J. M. Aparicio-Reinoso et al PRE 94, 032218 (2016)

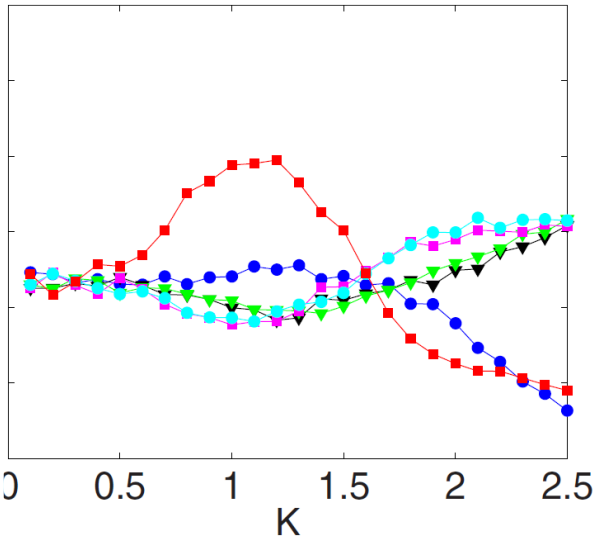
Comparison with the laser spikes, when a small sinusoidal signal is added to the laser current

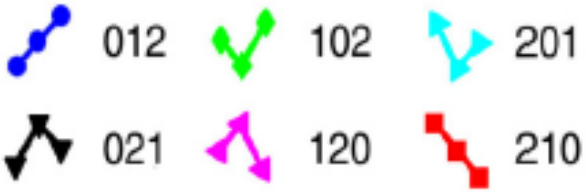


$$\phi(i+1) = \phi(i) + \rho + \frac{K}{2\pi}[\sin(2\pi\phi(i)) + \alpha_c \sin(4\pi\phi(i))] + \beta_c \xi(i)$$







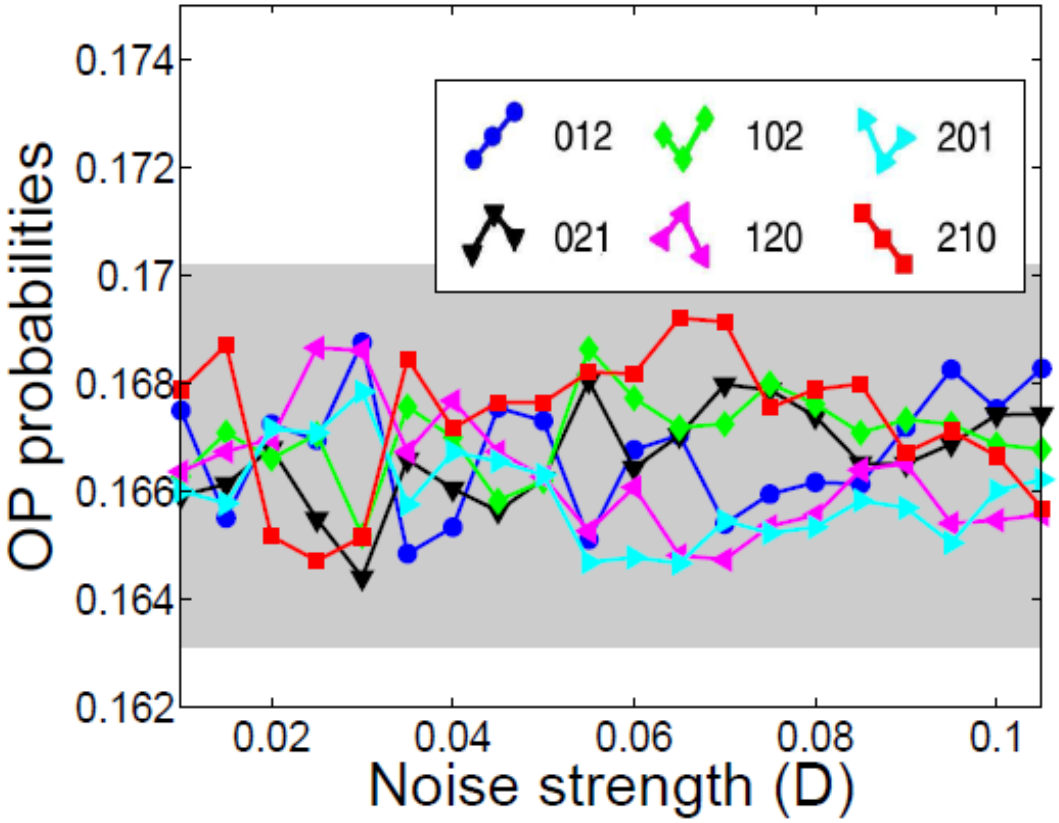


J. M. Aparicio-Reinoso et al PRE 94, 032218 (2016)

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

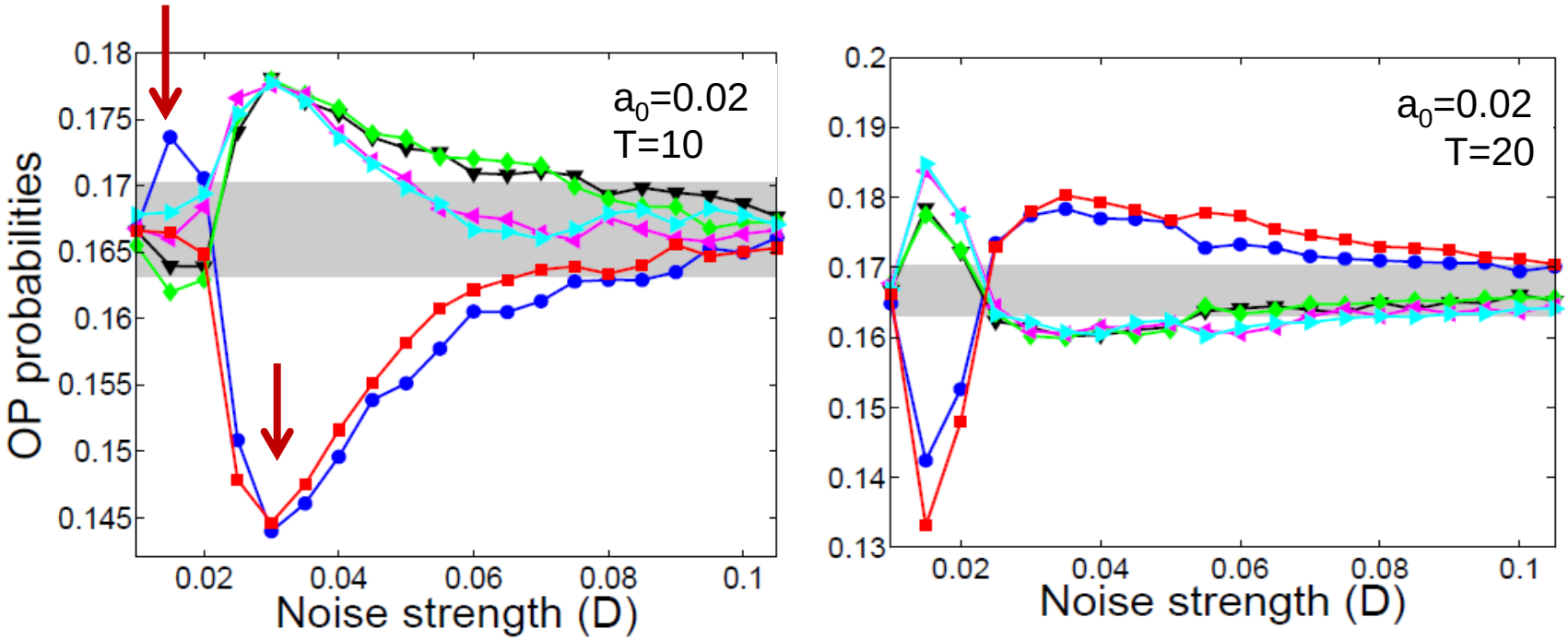
Role of the level of noise

$a_0=0$



No signal $\Rightarrow$ no preferred spike patterns

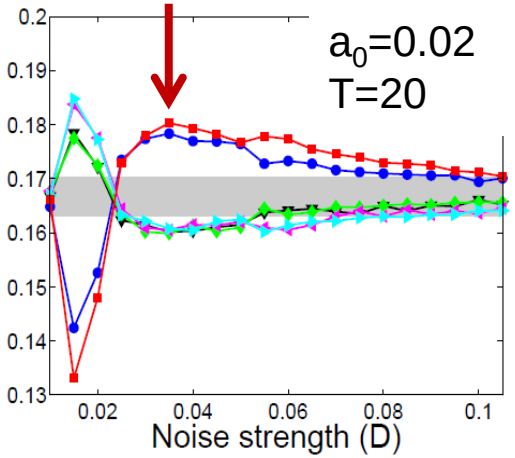
With a sinusoidal input



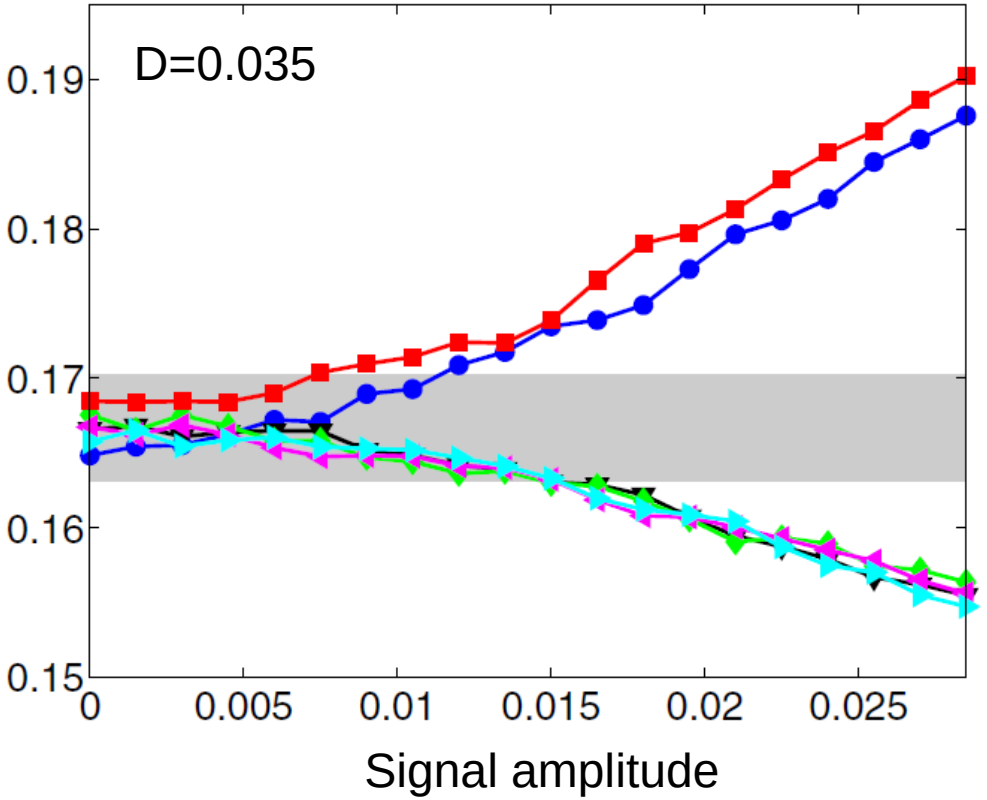
- The signal induces more / less expressed patterns.
- They depend on the amplitude, period and noise strength.
- Resonant-like behavior.

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

Role of the signal amplitude



Ordinal probabilities



The values of the probabilities may encode the amplitude of the signal?

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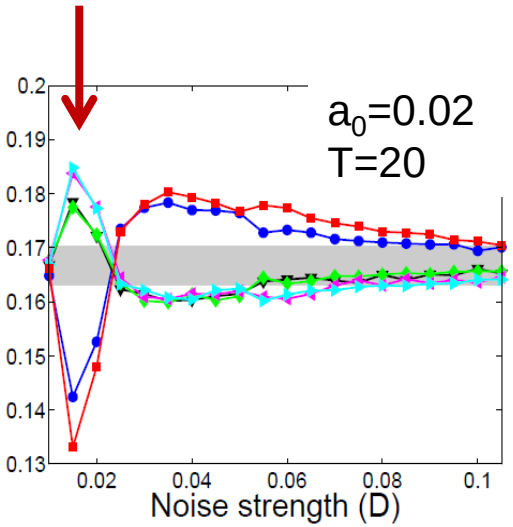
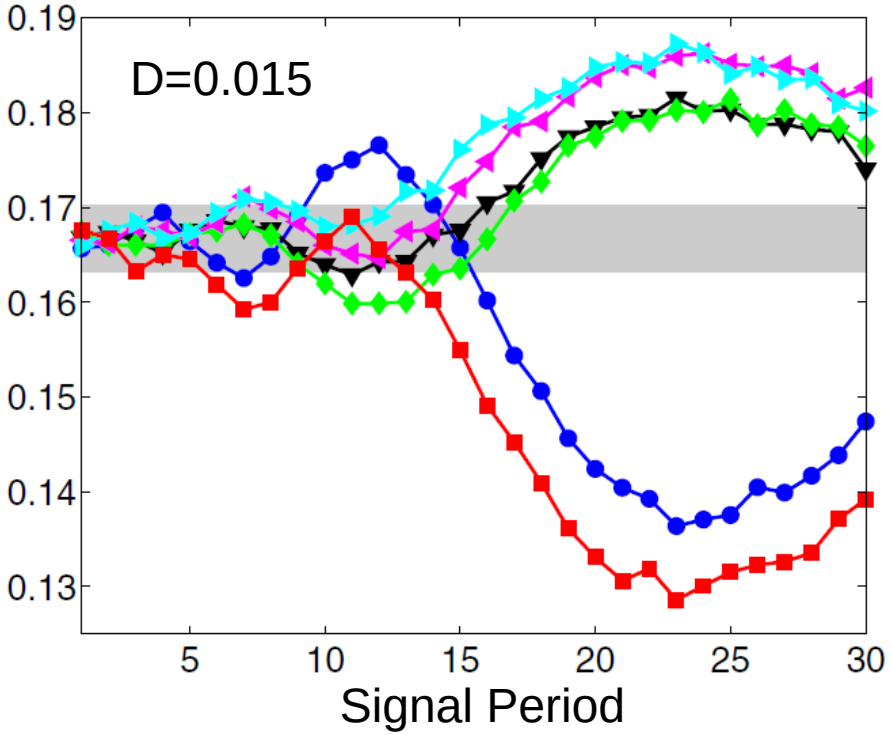
Role of the signal period



Ordinal probabilities



More / less expressed patterns depend on the signal's period.

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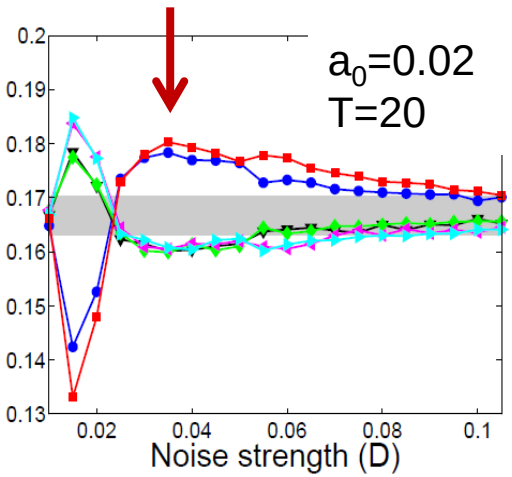
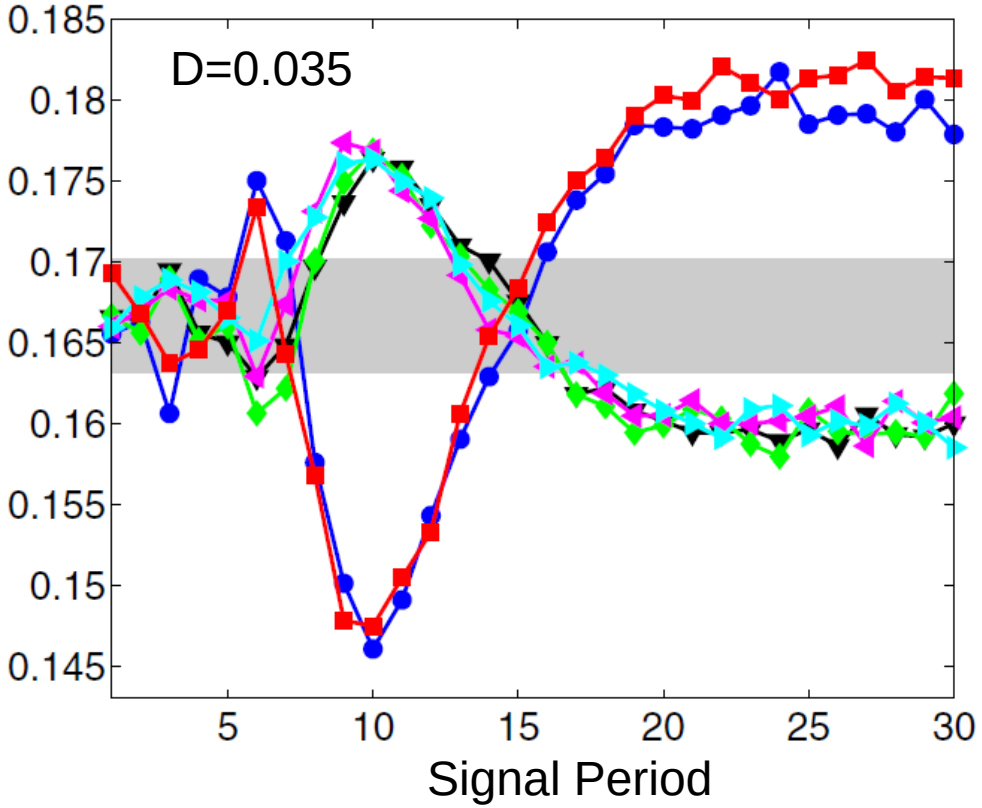
Role of the signal period



Ordinal probabilities



More / less expressed patterns also depend on the noise strength.

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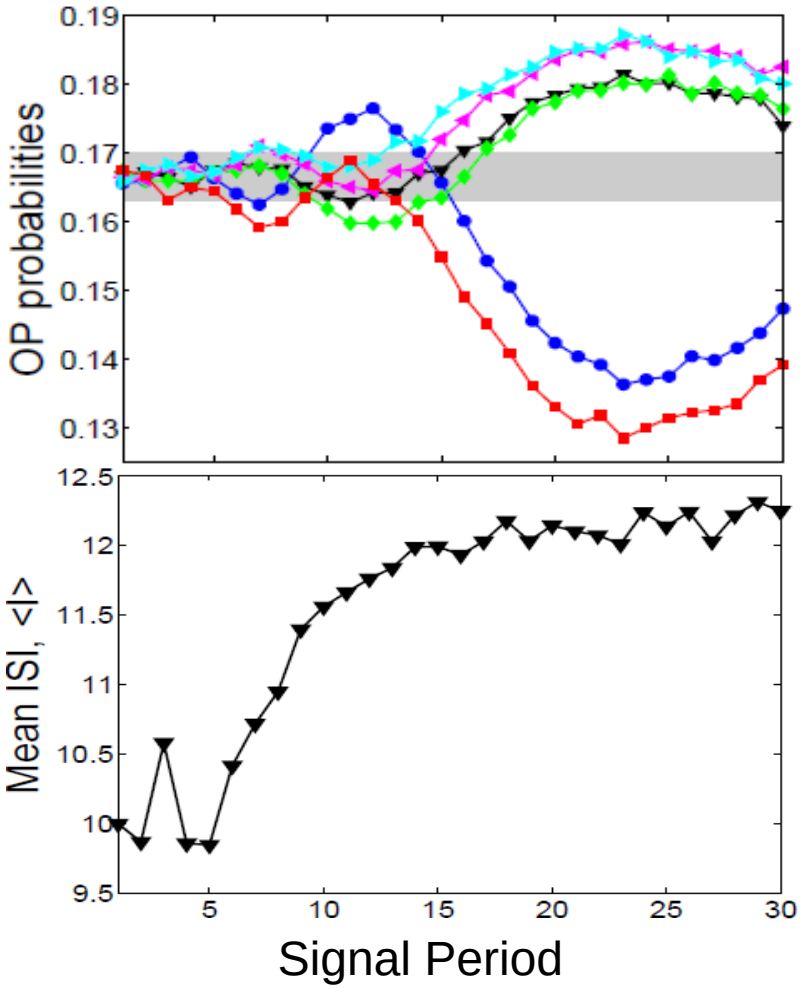
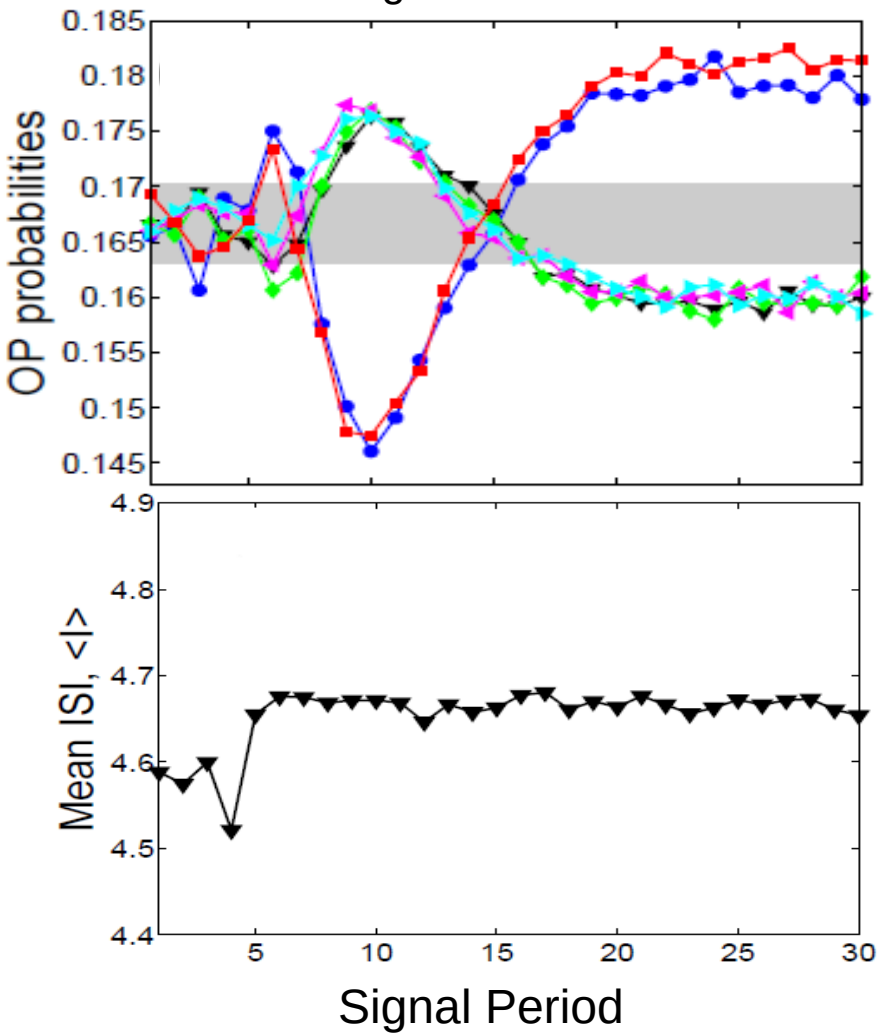
How about “rate coding”? Does the mean inter-spike-interval carry information of the period of the signal?

weak noise

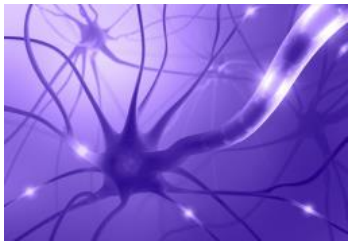


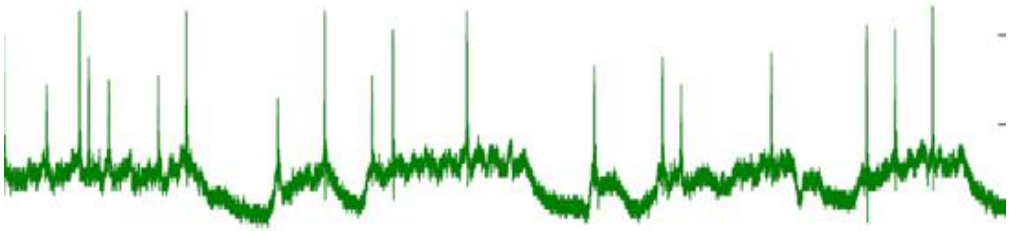
stronger noise



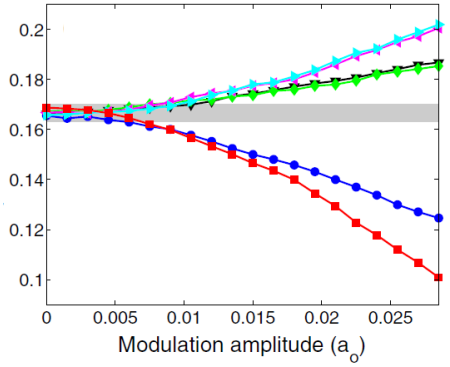
$\Rightarrow$ Not always.

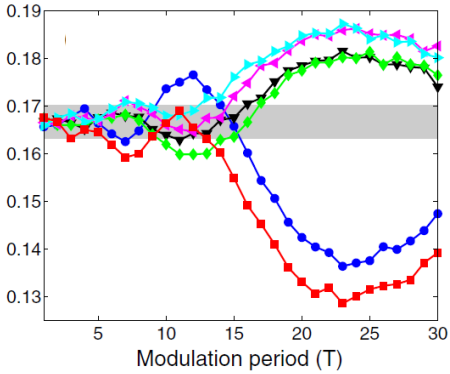
So… how neurons might encode a weak periodic signal?





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





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Research paper

Neuronal coupling benefits the encoding of weak periodic signals in symbolic spike patterns

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$$\epsilon \dot{u}_i = u_i - \frac{u_i^3}{3} - v_i + a_0 \cos(2\pi t/T) + \frac{\sigma}{k_i} \sum_j^N a_{ij}(u_j - u_i) + \sqrt{2D}\xi_i(t), \qquad i \neq j$$

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

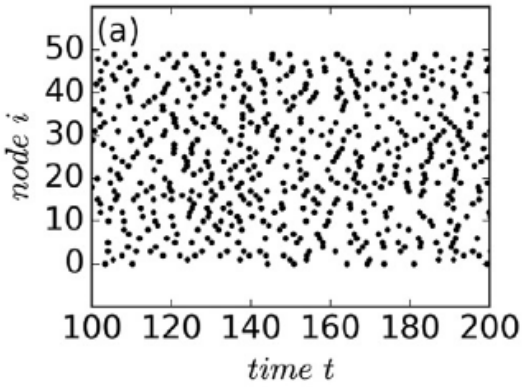
$$k_i = \sum_j a_{ij}$$

$$a_{ij} = a_{ji} = 1$$
$$a_{ij} = a_{ji} = 0$$

The ordinal probabilities are calculated from the ISI sequences of all the neurons.

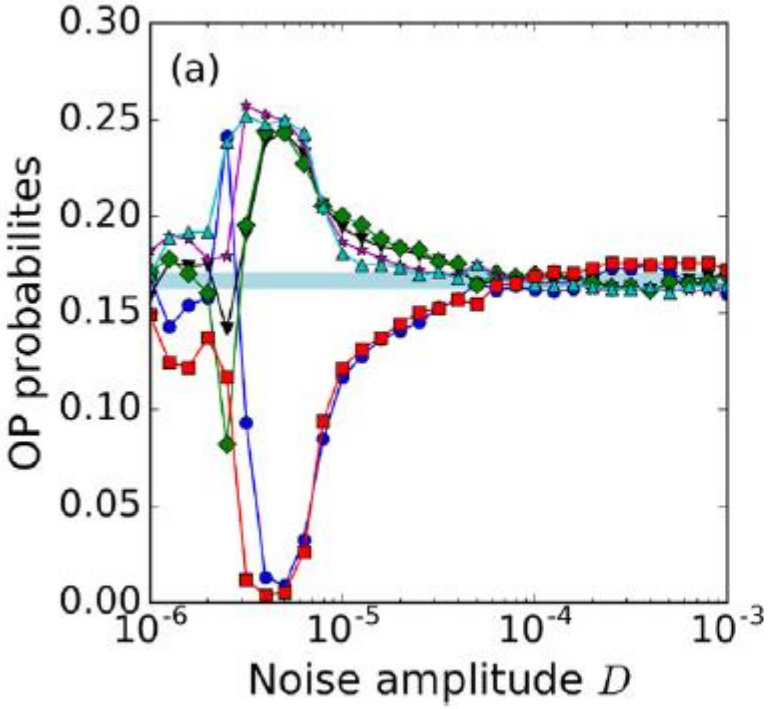
Dynamics of an ensemble of 50 neurons, all-to-all coupled, for input signals that have different periods

No coupling,
no signal

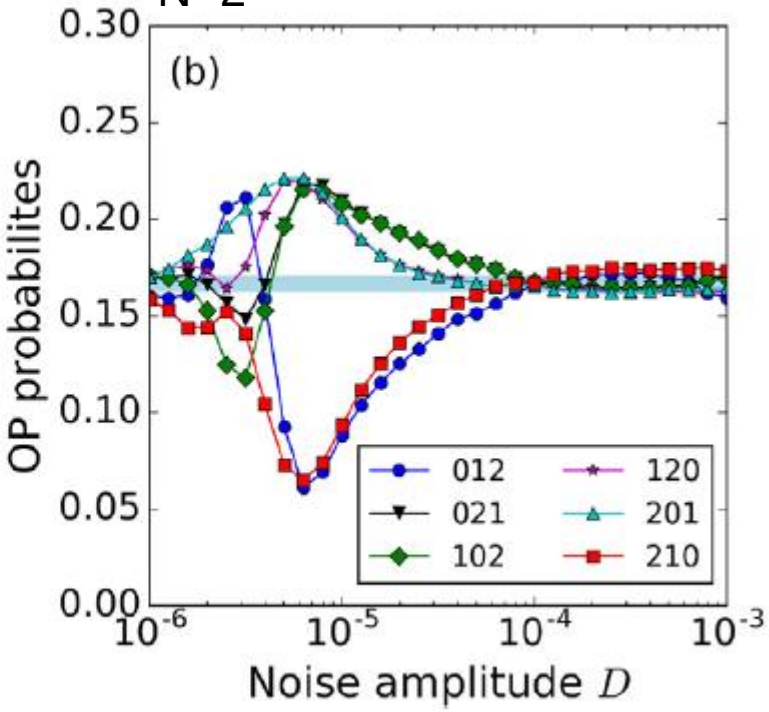


Role of noise?

N=50 (all-to-all coupled)

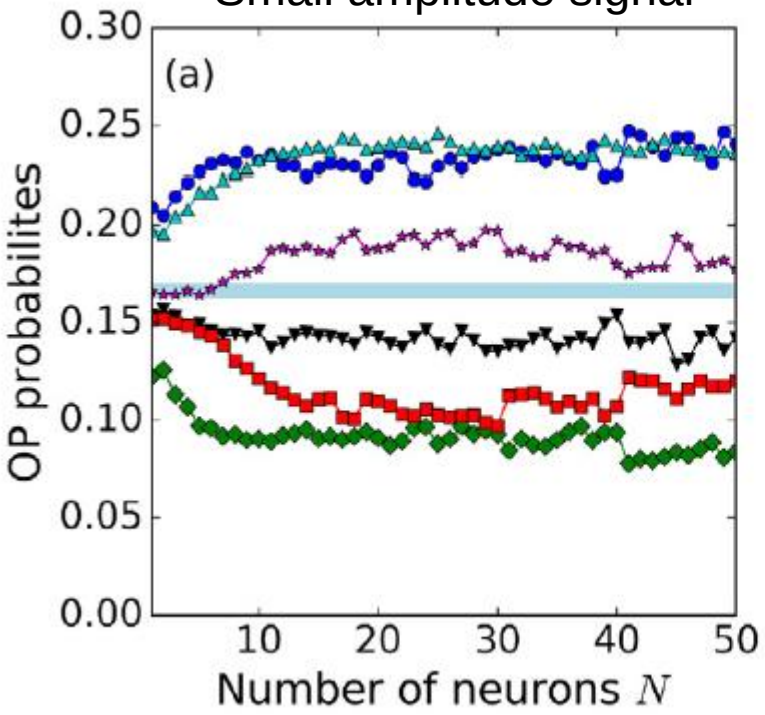


N=2

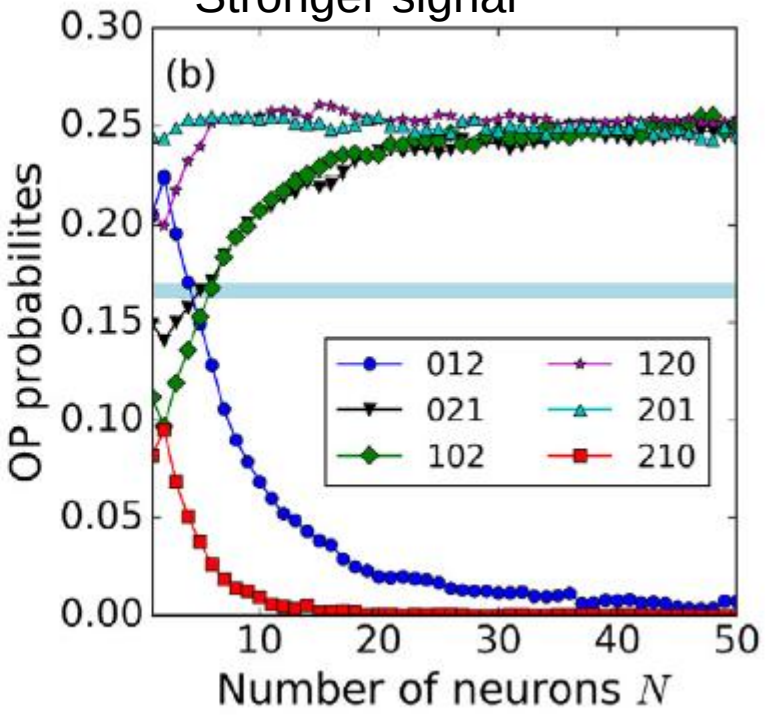


Role of the networks size? (all-to-all coupling)

Small amplitude signal

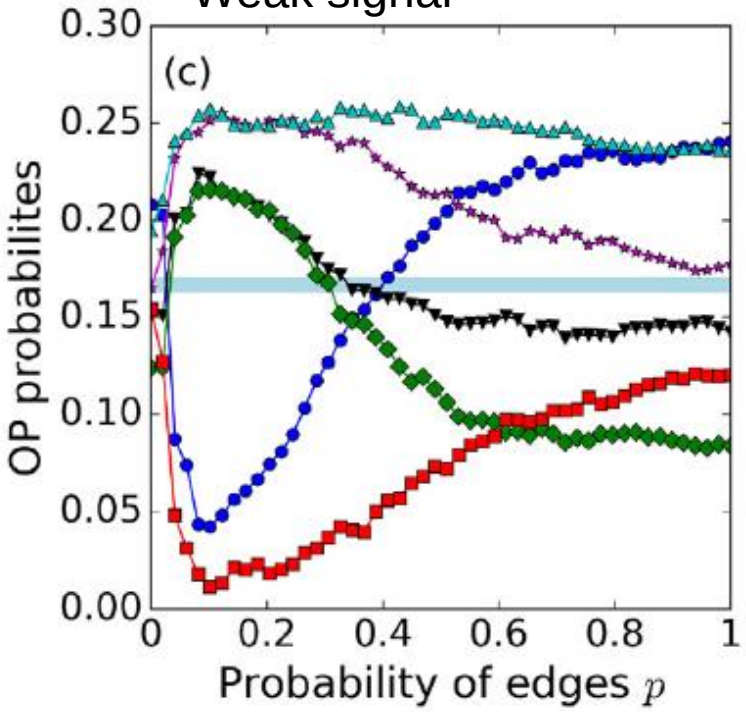


Stronger signal

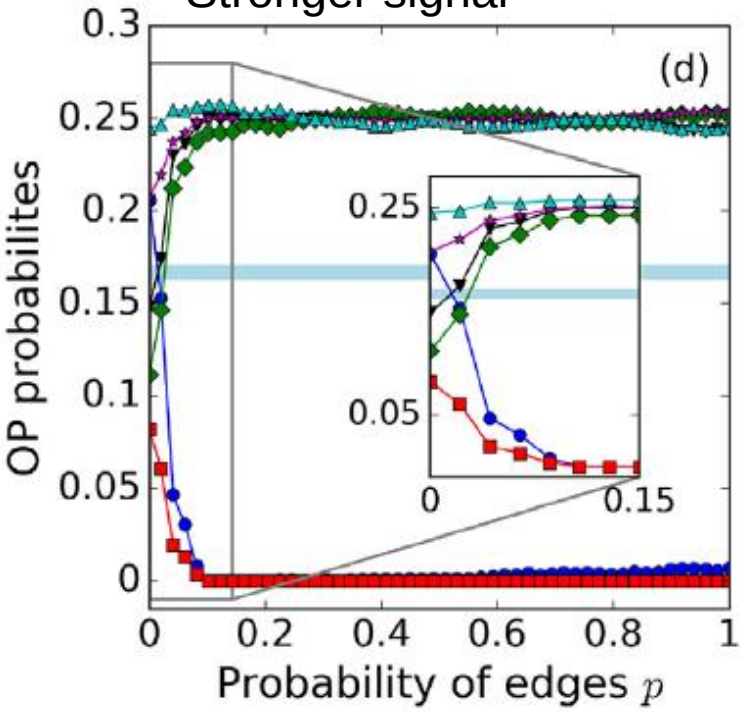


Role of the number of connections? (random network)

Weak signal



Stronger signal



Conclusions

Summary

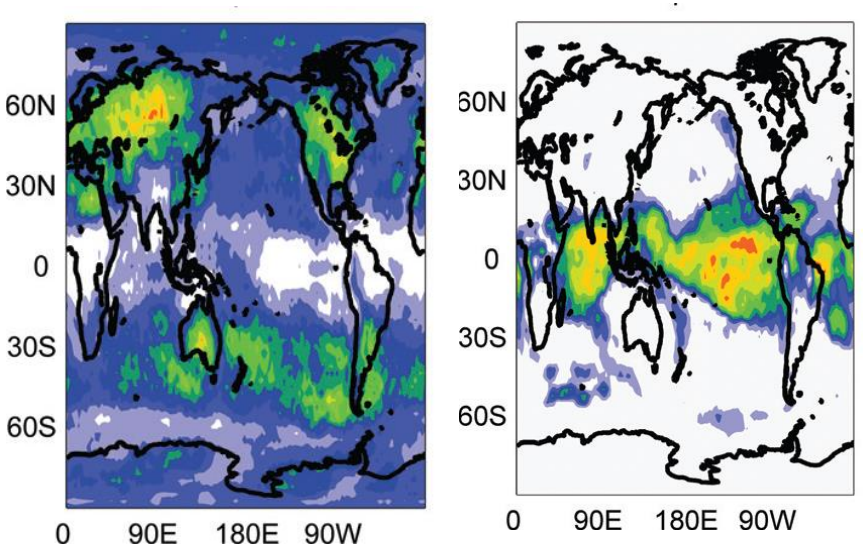
- Conclusions:
  - The ordinal probabilities may carry information of a weak sinusoidal input (amplitude and period).
  - Resonance with the noise strength.
  - In a neuronal ensemble the encoding of the signal is more pronounced.

- Ongoing work: can we recover quantitative information of the signal from the analysis of the ISI sequences?

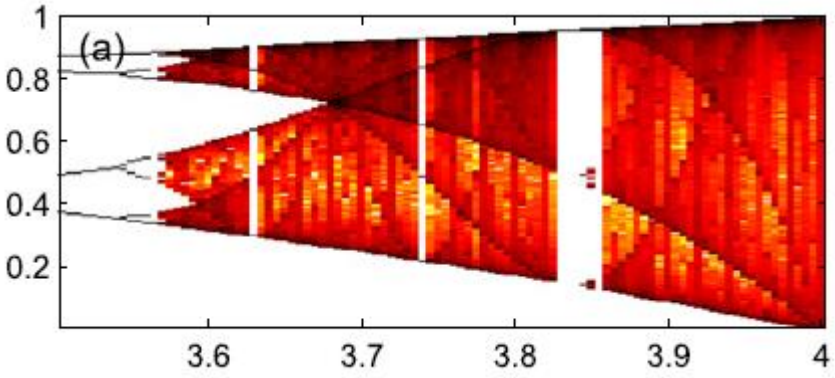
- Future work: Aperiodic signals? Comparison with laser arrays?

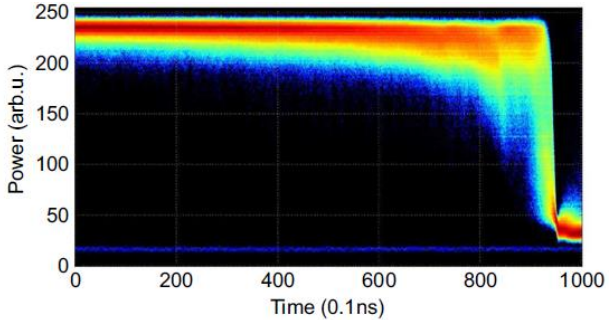
Other problems in which I have used ordinal analysis

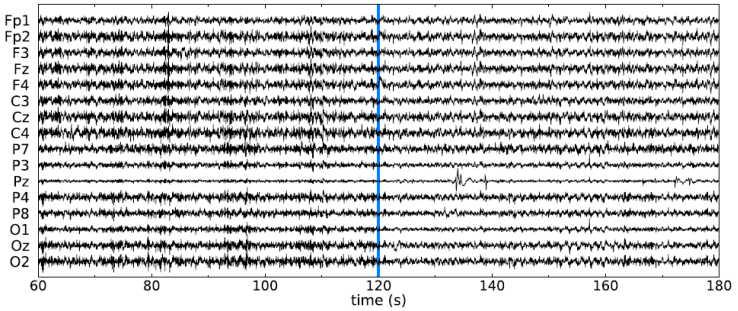
- Climate data analysis: identification of interactions acting in different time-scales (Chaos 2011).



- Ordinal networks: identify transitions between different regimes (New J. Phys 2015, Chaos 2018).







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).

Neuronal coupling benefits the encoding of weak periodic signals in symbolic spike patterns

M. Masoliver, C. Masoller,

Commun. Nonlinear Sci. Numer. Simulat. 88, 105023 (2020).

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