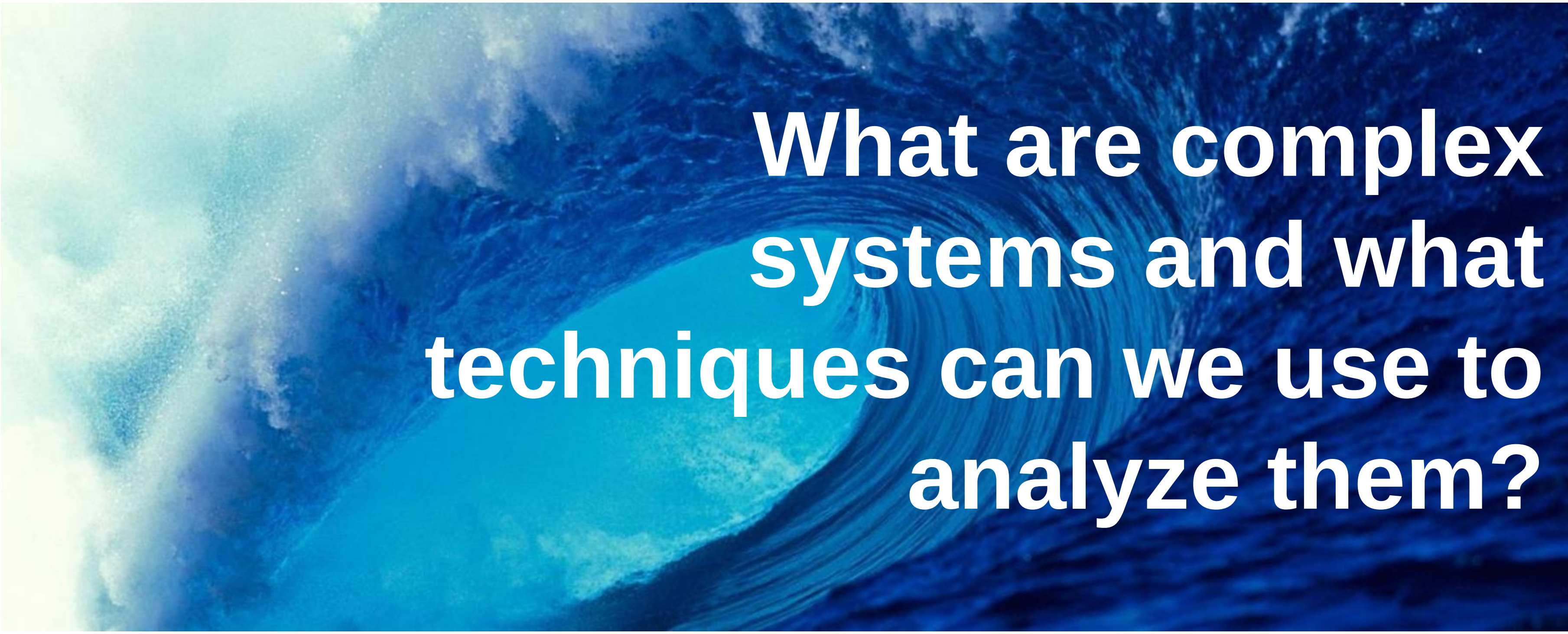

What are complex systems and what techniques can we use to analyze them?

Cristina Masoller,
Departament de Física, UPC

Col·loquis FMC, Universitat de Barcelona
March 27, 2023

UNIVERSITAT POLITÈCNICA DE CATALUNYA
BARCELONATECH

Campus d'Excel·lència Internacional

ICREA
AGAUR
GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA E INNOVACIÓN

Presentation

- Bachelor & Master in Physics (1986-1991)

UNIVERSIDAD DE LA REPÚBLICA URUGUAY

- PhD in Physics (1999, Bryn Mawr College, PA, USA)

BRYN MAWR COLLEGE

- At Physics Department UPC since 2004 (Ramon I Cajal, Prof. Agregat, Prof. Catedratica).

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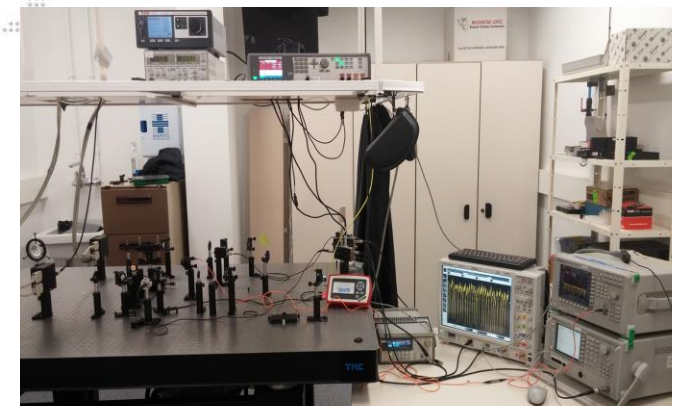
Where are we? UPC Campus Terrassa

Viernes, 25 de septiembre de 2009 Diari de Terrassa

El edificio Gaia centraliza grupos científicos consolidados y emergentes.



Laser lab in Gaia Building, UPC Campus Terrassa

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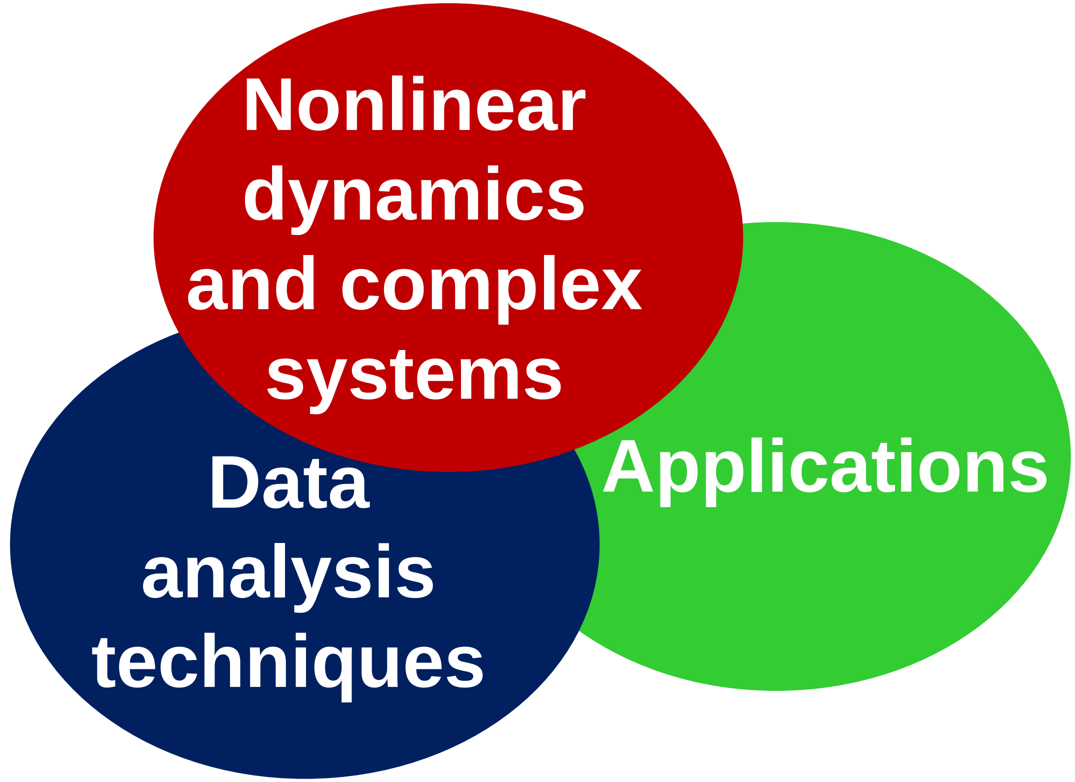
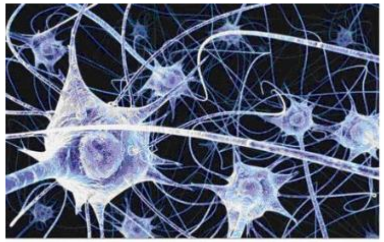
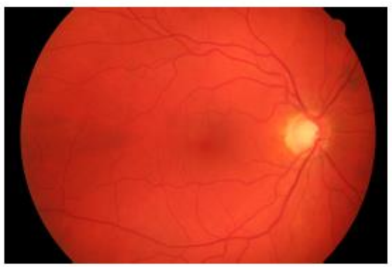
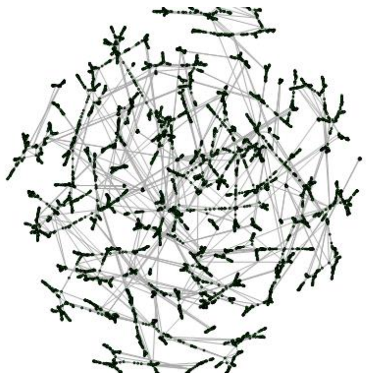
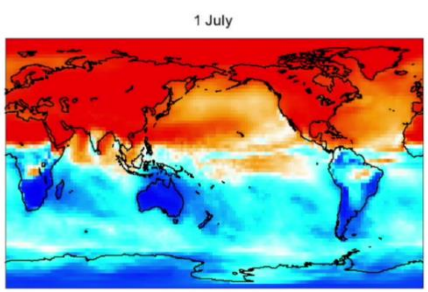
Research lines

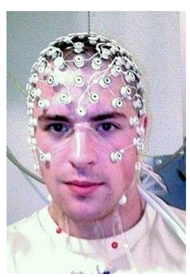


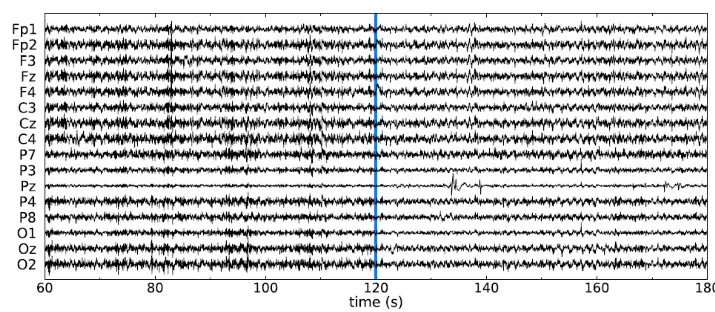


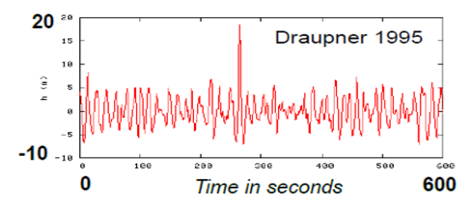












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Outline

- Complex systems and data analysis
- Ordinal analysis: Lasers and neurons
- Hilbert analysis: Climate data
- Network analysis: Retina fundus images

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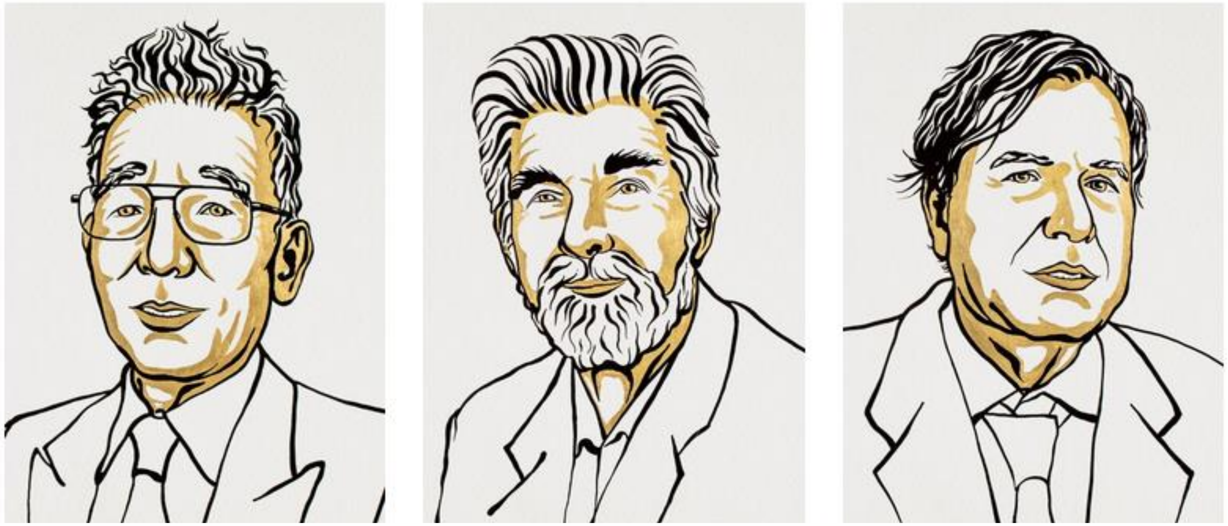
The Nobel Prize in Physics 2021



for groundbreaking contributions to our understanding of **complex systems**

½ Syukuro Manabe and Klaus Hasselmann ½ Giorgio Parisi

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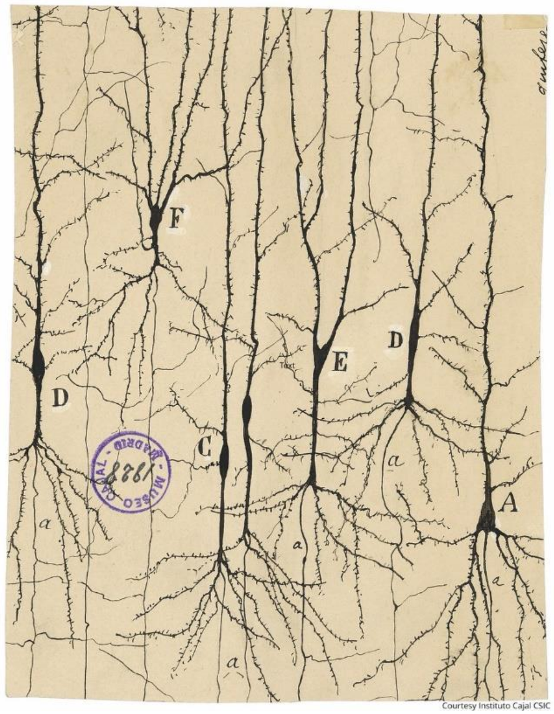
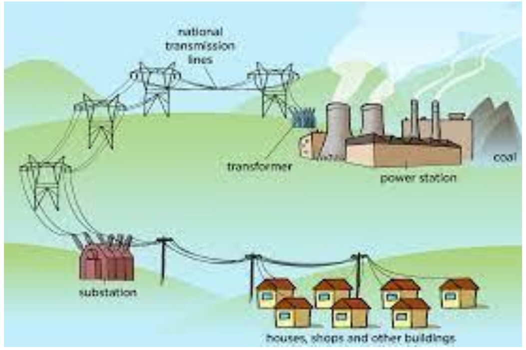
What is a complex system?

- High-dimensional, large number of interacting elements, heterogeneous structure, multiscale, memory, adaptation.
- The elements and/or the interactions are **nonlinear**.
- Often display abrupt transitions and extreme events.





G. Bianconi et al, *Complex systems in the spotlight: next steps after the 2021 Nobel Prize in Physics*, J. of Phys: Complexity 4, 010201 (2023).

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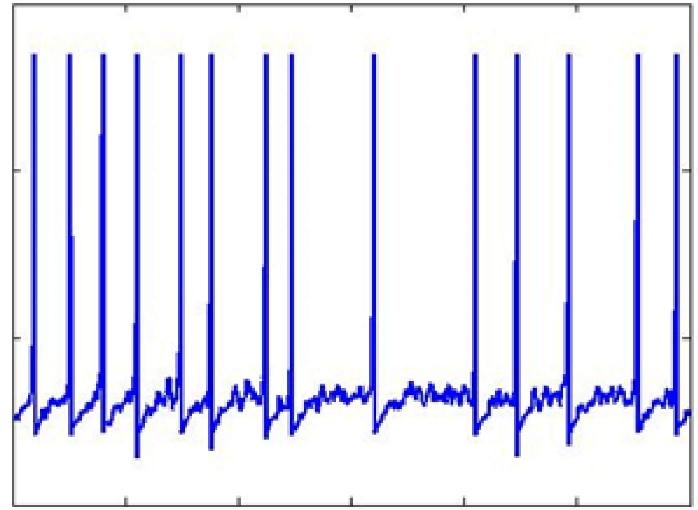
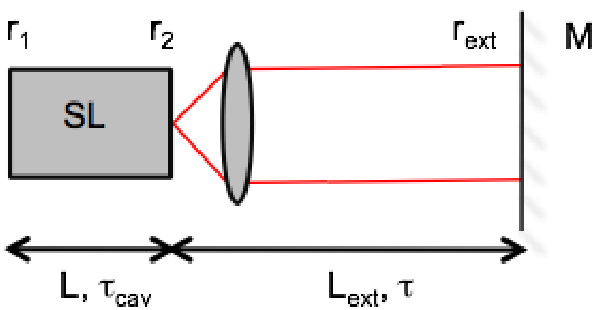
Data analysis methods allow to discover statistical similarities in very different systems



Time 10^{-9} s

Time 10^{-3} s



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

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

(High-dimensional, Memory)

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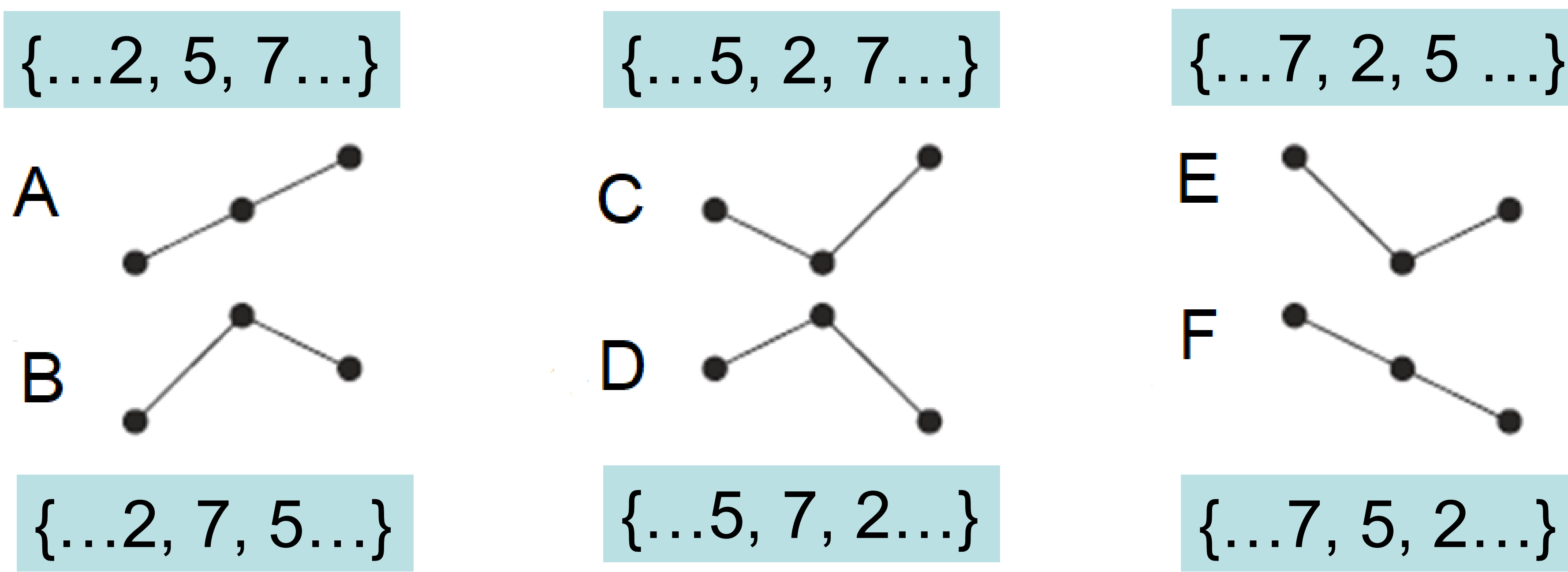
First data analysis method: ordinal analysis

$\{\ldots x_i, x_{i+1}, x_{i+2}, \ldots\}$

Possible order relations among three numbers (e.g., 2, 5, 7)



Bandt and Pompe: Phys. Rev. Lett. 2002

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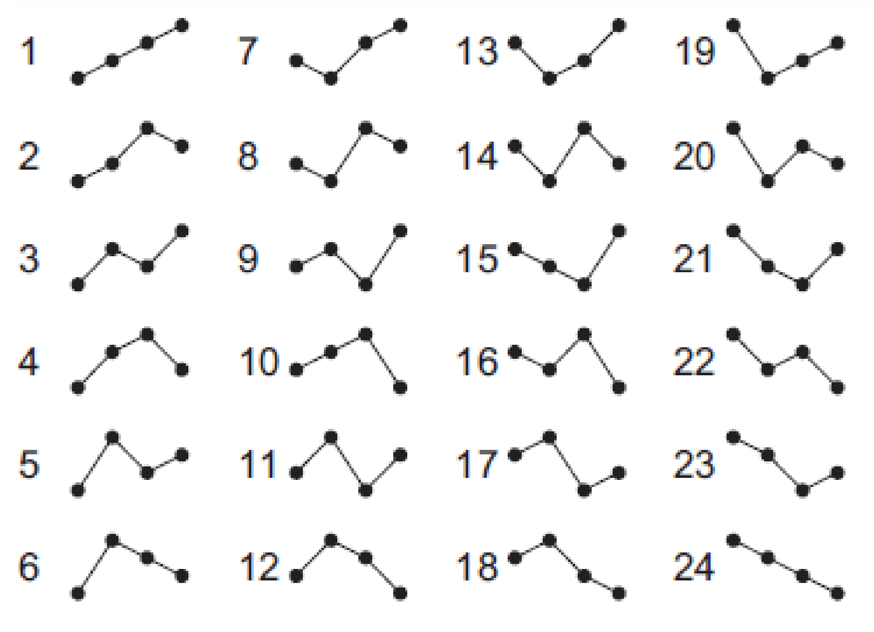
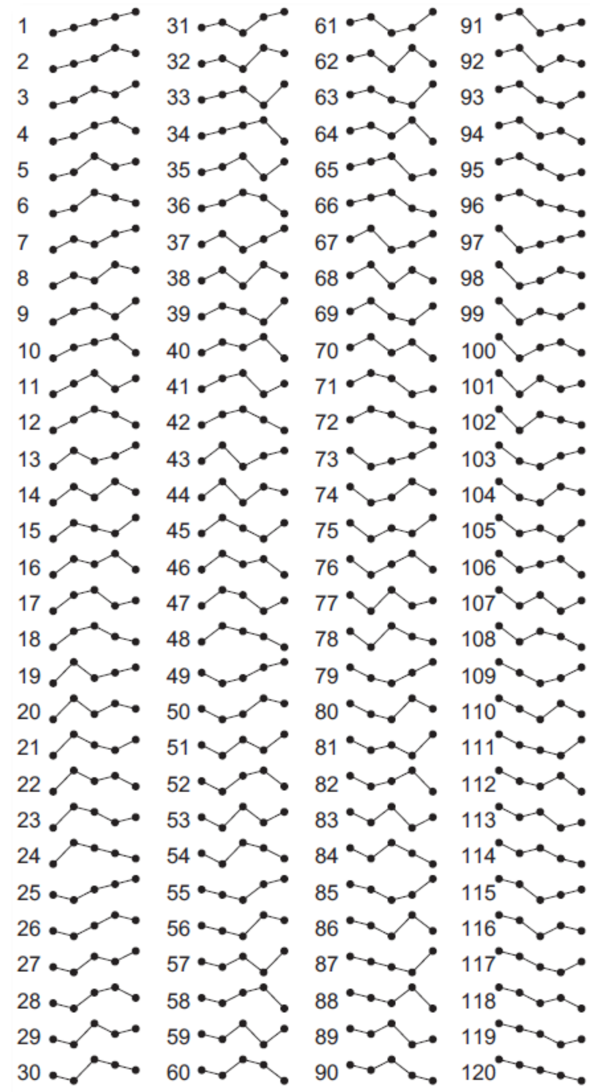
The number of ordinal patterns increases as D!





A problem for short datasets.

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

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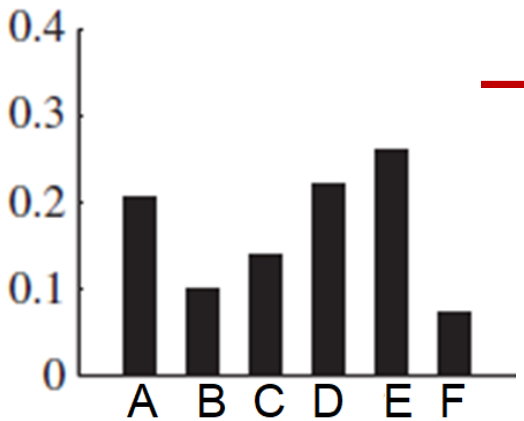
From a time series, by counting the different patterns, we can calculate the set of "ordinal probabilities"

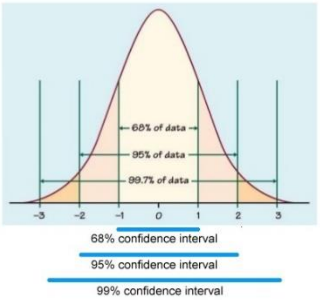


→ ?

A. Analyze the probabilities (are differences statistically significant?)

B. Compute information theory measures (entropy, complexity)

Probability from surrogates



$$H = -\sum_{i=1}^{N} p_i \ln p_i$$

Ordinal analysis has been extensively used:

- to test if a model is good for the data,
- to fit the model's parameters,
- to classify different types of data based on similarities of probabilities of ordinal patterns.

I. Leyva, J. M. Martinez, C. Masoller, O. A. Rosso, M. Zanin, "*20 Years of Ordinal Patterns: Perspectives and Challenges*", EPL 138, 31001 (2022).

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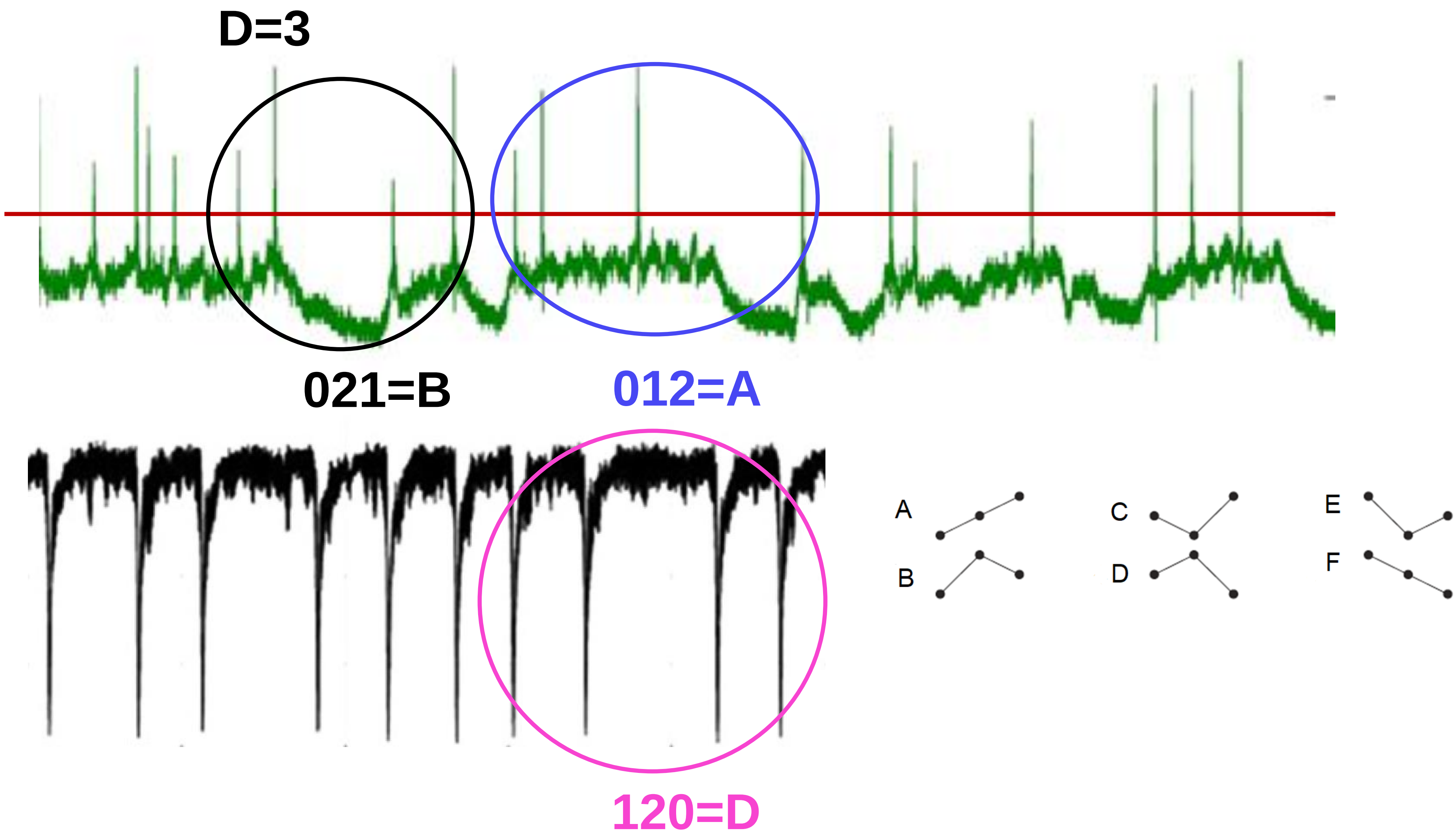
Sequence of inter-spike-intervals (ISIs) ⇒ sequence of ordinal patterns



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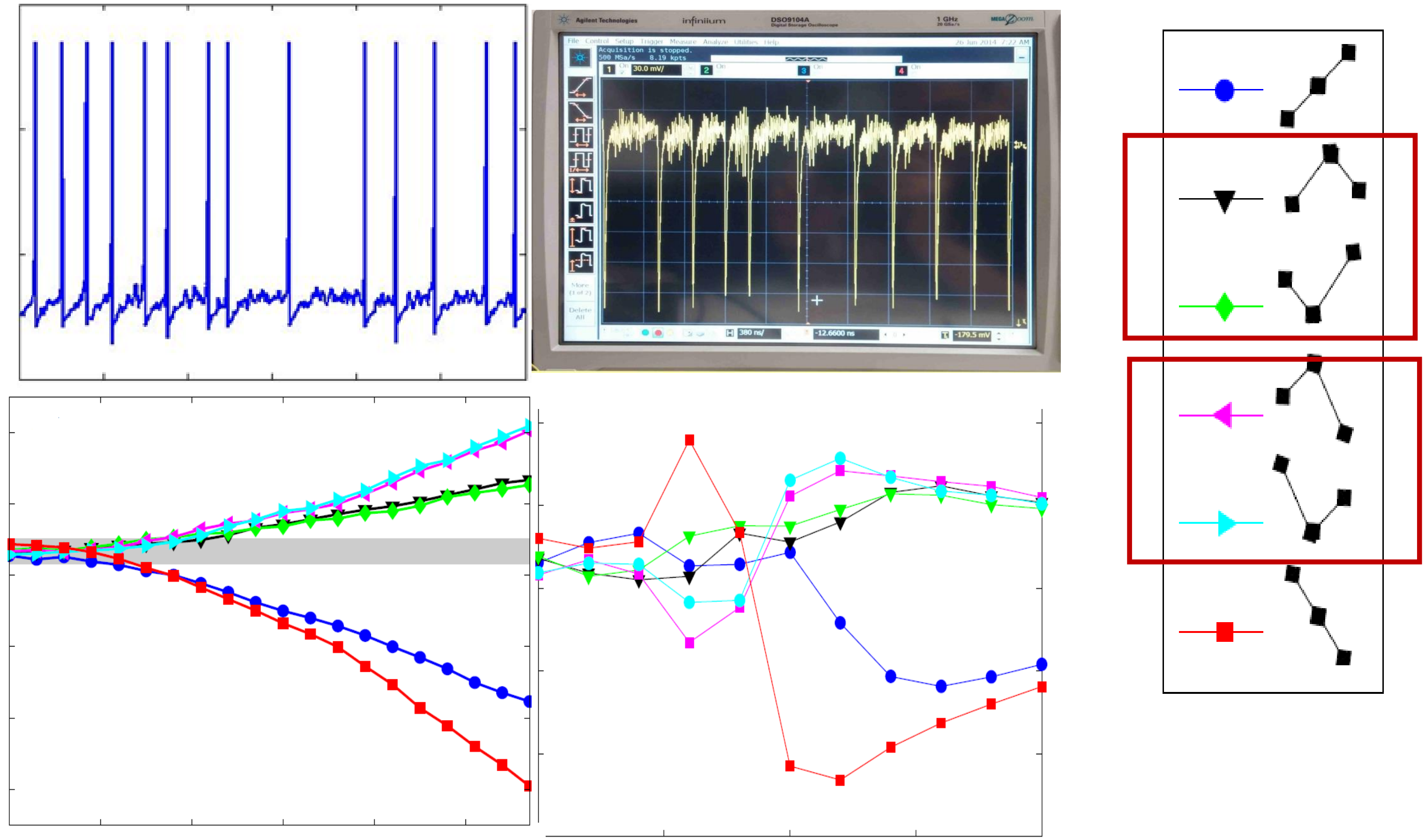
The analysis of the ordinal probabilities uncovers similarities in ISI sequences

Neuron model **Diode laser**



J. M. Aparicio-Reinoso et al PRE 94, 032218 (2016) A. Aragoneses et al, Sci. Rep. **4**, 4696 (2014)

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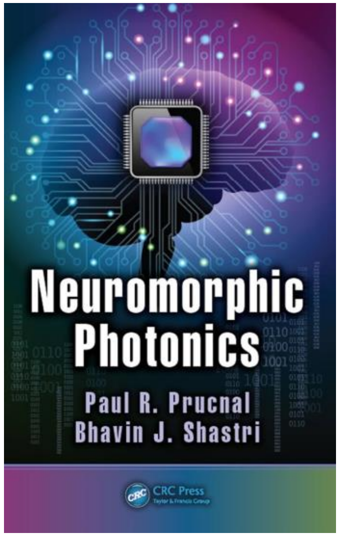
Uncovering similarities between neurons and lasers… Interesting but relevant?

- Data centers, AI systems, HPC consume huge amounts of energy.
- Big concern in the context of climate change.
- The human brain processes huge amounts of information using only 19 Watts.
- Uncovering genuine similarities between neurons and lasers will allow to develop **photonic neurons**, able to process information as real neurons do, but
  - much faster,
  - with much less energy consumption.

European Centre for Medium-Range Weather Forecasts, Reading, UK



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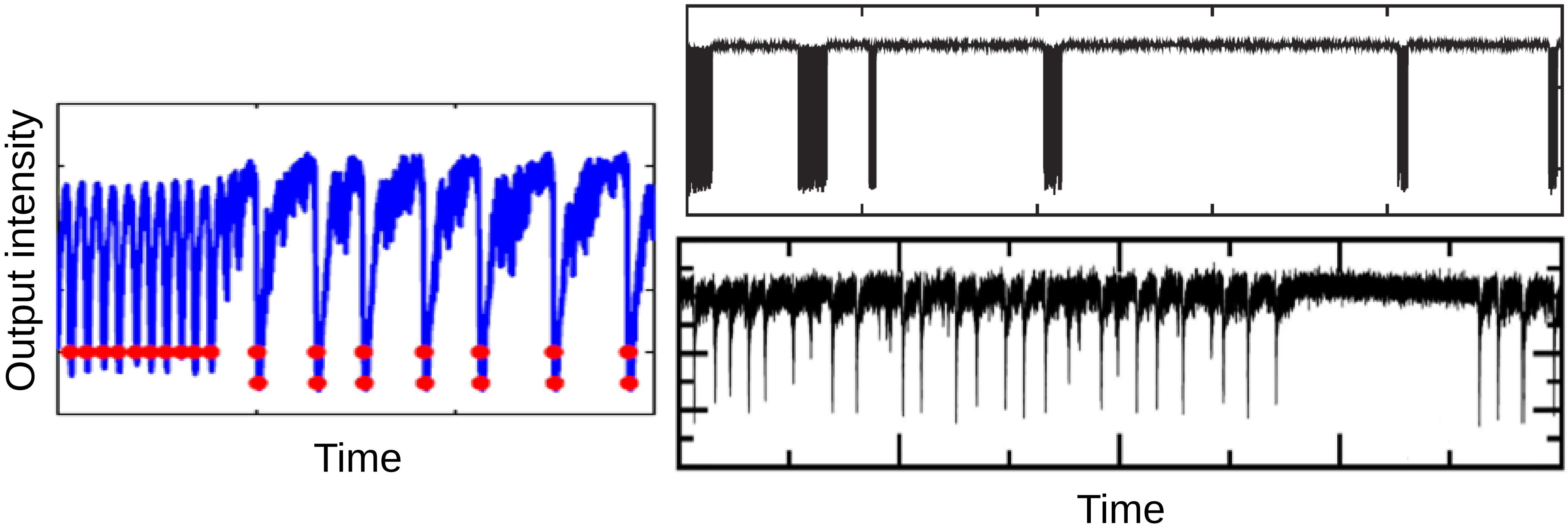
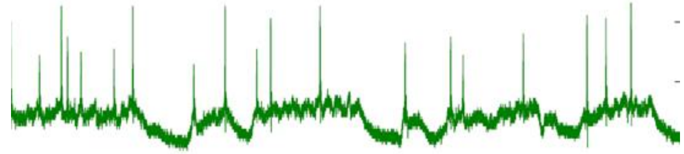
Time series recorded in our lab show excitability, tonic spikes, and bursting. Similar to real neurons?



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).

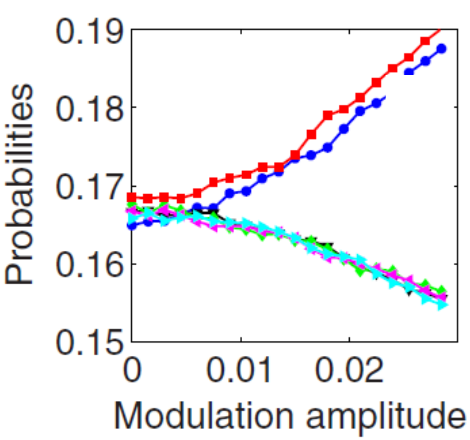
Main challenge

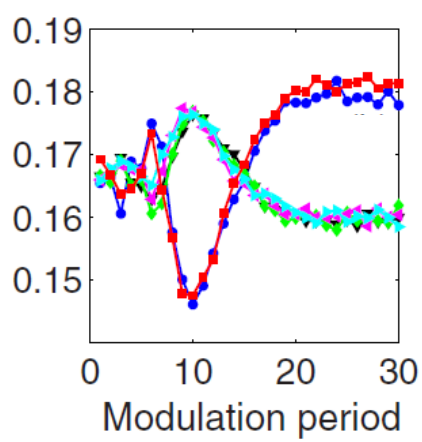


Understand how to mimic with lasers the way neurons encode and process information.

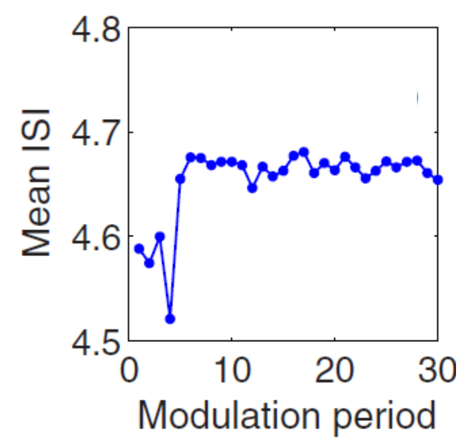
$$\epsilon \frac{dx}{dt} = x - \frac{x^3}{3} - y,$$
$$\frac{dy}{dt} = x + a + a_o \cos(2\pi t/T) + D\xi(t),$$

Weak, subthreshold signal





Rate coding?



J. A. Reinoso, M. C. Torrent, and C. Masoller, “*Emergence of spike correlations in periodically forced excitable systems*”, Phys. Rev. E. 94, 032218 (2016).

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Single-neuron vs ensemble encoding

- Single-neuron encoding: **slow** because long spike sequences are needed to estimate the ordinal probabilities.
- Ensemble encoding: can be **fast** because, from the ISI sequences of all the neurons, few spikes per neuron can be enough to accurately estimate the probabilities.

Weak, subthreshold signal

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

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

$k_i = \sum_j a_{ij}$

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

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

M. Masoliver and C. Masoller, "*Neuronal coupling benefits the encoding of weak periodic signals in symbolic spike patterns*", Commun. Nonlinear Sci. Numer. Simulat. 88, 105023 (2020).

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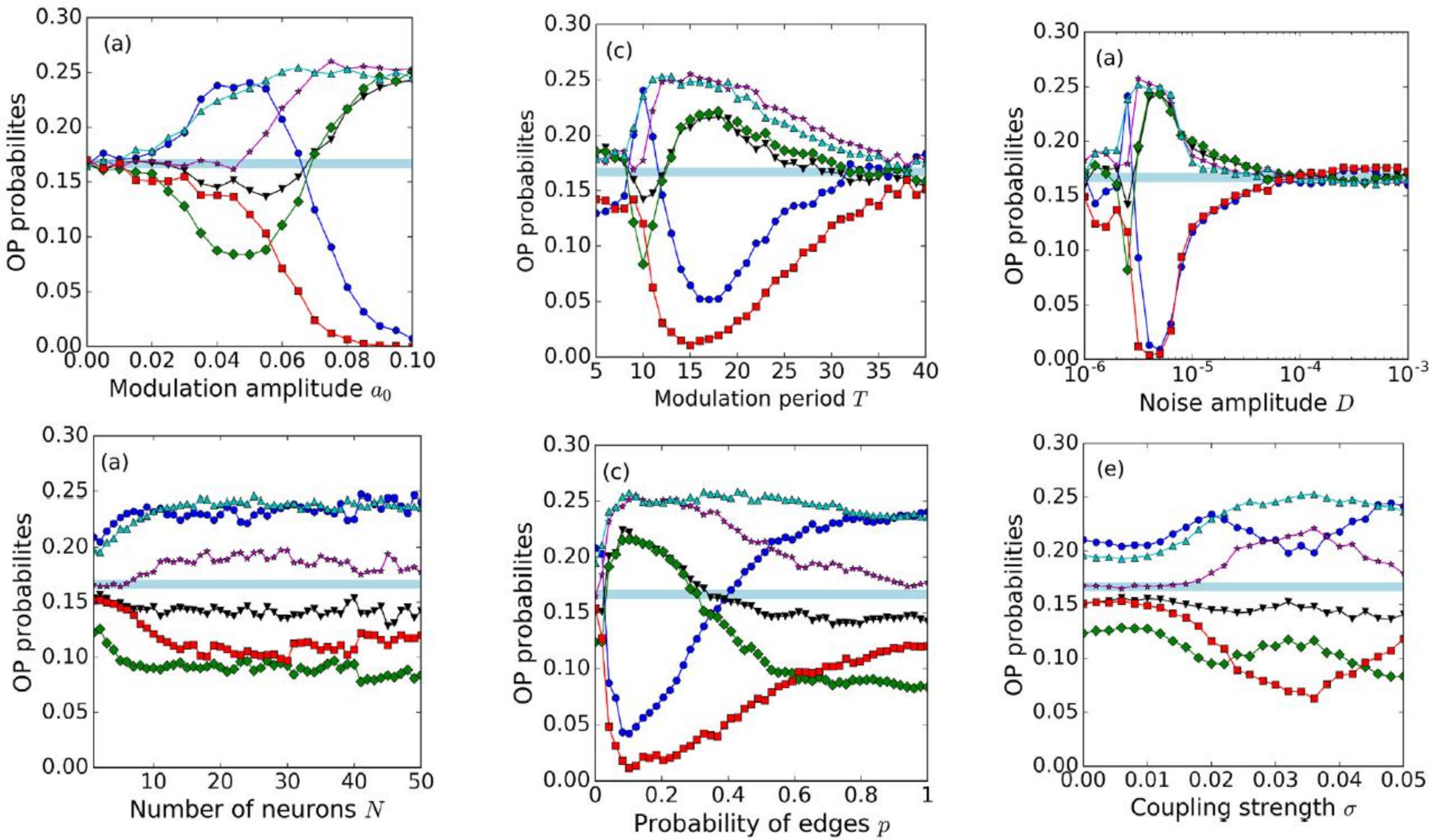
Ensemble encoding of a weak sinusoidal signal in the frequencies of occurrence of ordinal patterns



M. Masoliver and C. Masoller, Commun. Nonlinear Sci. Numer. Simulat. 88, 105023 (2020).

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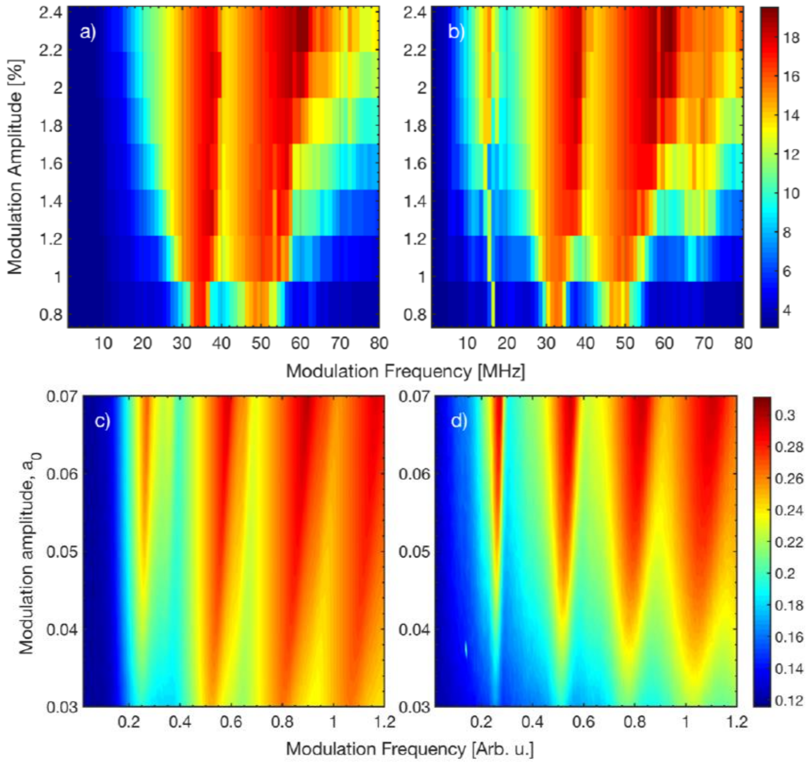
Laser-neuron comparison: encoding a weak periodic signal using spike rate code

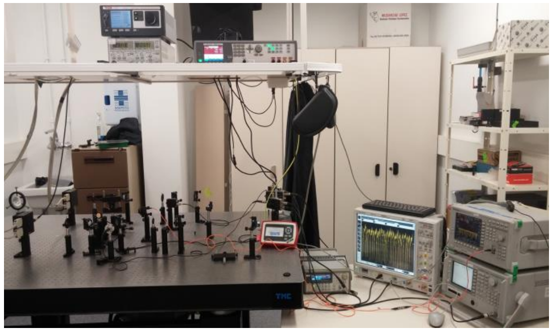
Spike rate in color code

Sinusoidal | Pulsed signal

Experiments modulating the laser current

Neuron model with the same input signal





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

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

J. Tiana-Alsina, C. Quintero-Quiroz and C. Masoller, "*Comparing the dynamics of periodically forced lasers and neurons*", New J. of Phys. 21, 103039 (2019) (2019).
J. Tiana-Alsina, C. Masoller, "*Time crystal dynamics in a weakly modulated stochastic time delayed system*", Sci. Rep. 12, 4914 (2022).

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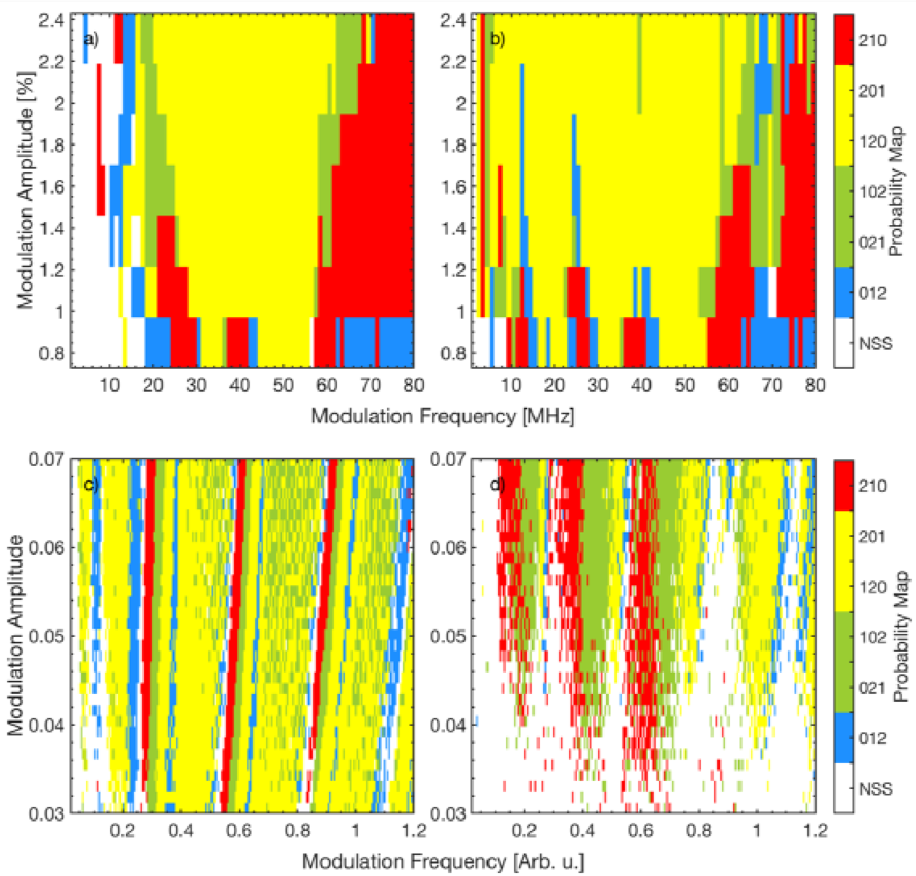
How about the temporal code?

Ordinal analysis unveils differences in spike timing.

Sinusoidal Pulsed signal

Diode laser with optical feedback

FitzHugh-Nagumo model



Most probable pattern in color code

J. Tiana-Alsina, C. Quintero-Quiroz and C. Masoller, New J. of Phys. 21, 103039 (2019).

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Outline

- Complex systems and time series analysis
- Ordinal analysis: Lasers and neurons
- Hilbert analysis: Climate data
- Network analysis: Retina fundus images

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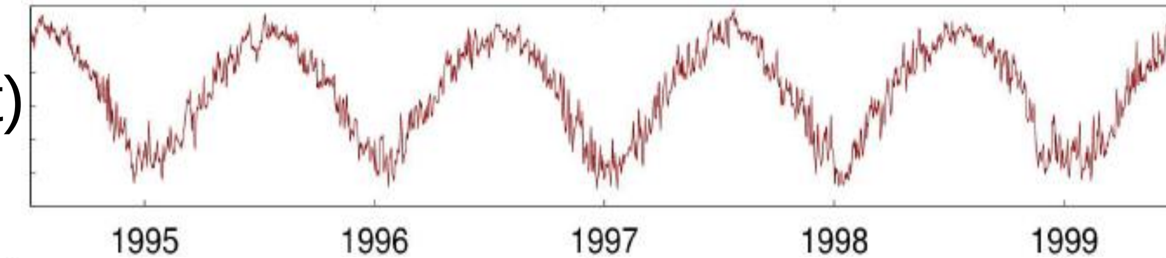
Hilbert Transform applied to Surface Air Temperature (SAT)

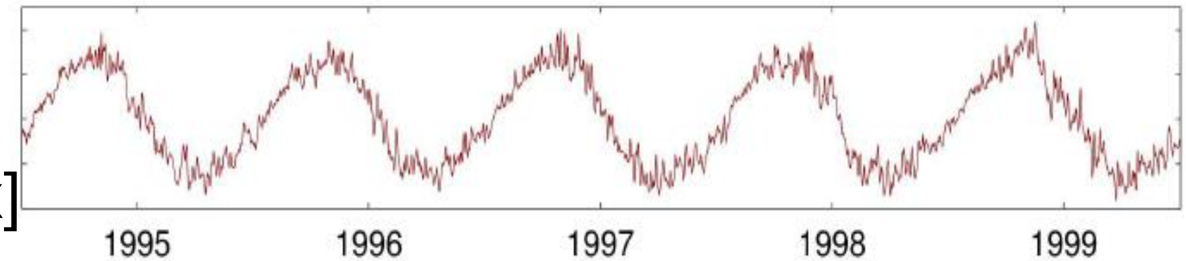
SAT in a geographical region

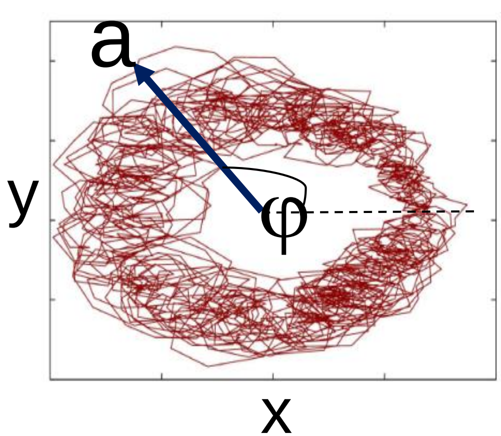
x(t)



HT[sin(x)]=cos(x)

y(t)= HT[x]





Instantaneous amplitude and phase

$$a(t) = \sqrt{[x(t)]^2 + [y(t)]^2}$$

$$\varphi(t) = \arctan[y(t)/x(t)]$$

Clear physical meaning only if *x(t)* is a narrow-band signal. Then, *a(t)* coincides with the envelope of *x(t)* and $\omega(t)=d\varphi/dt$, coincides with the main frequency in the spectrum.

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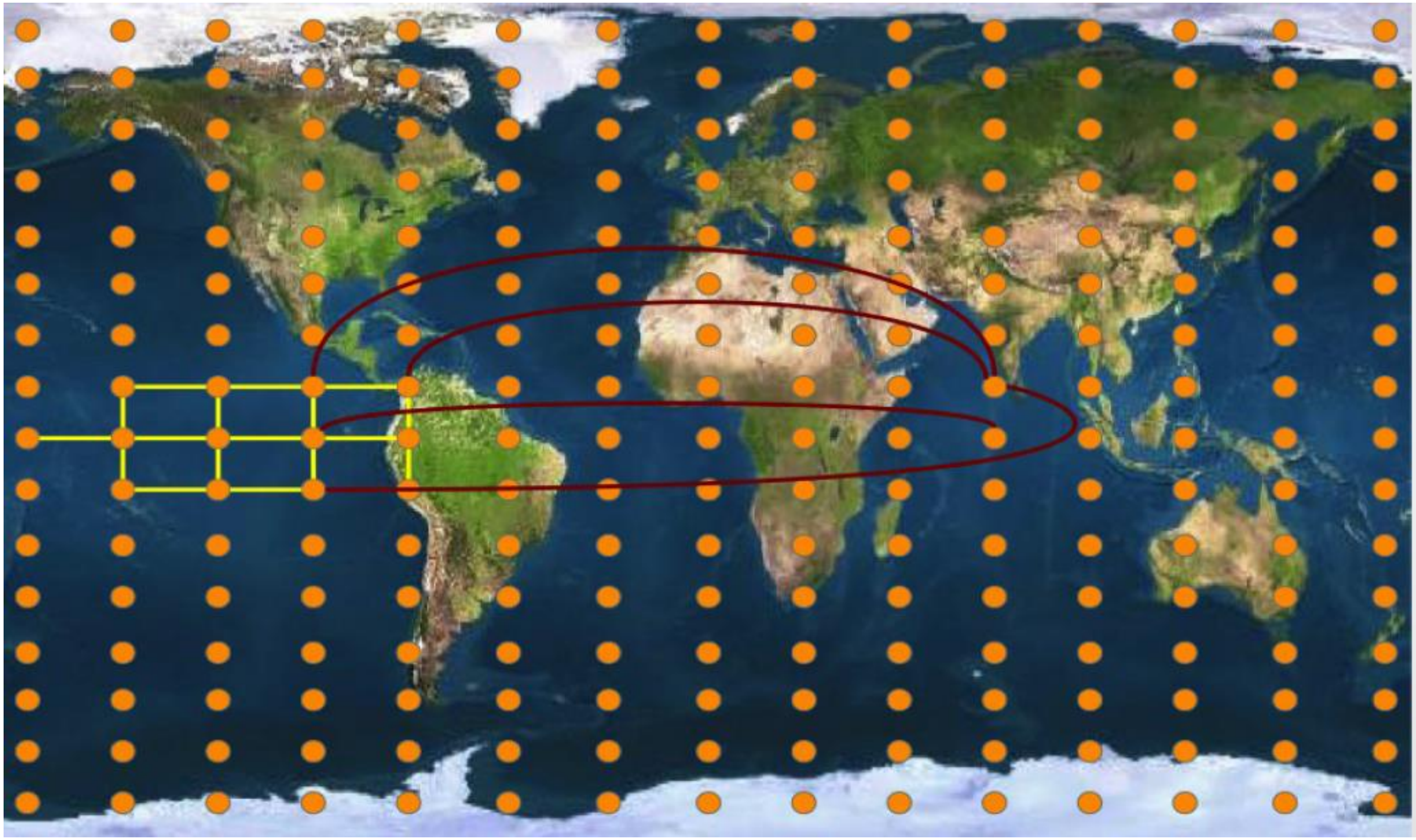
Using the HT we analyzed "re-analysis data" from the *European Centre for Medium-Range Weather Forecasts*, with high spatial and temporal resolution in the period 1979-2016



73 x 144 = 10 512 geographical sites, in each site the SAT time series has 13696 days

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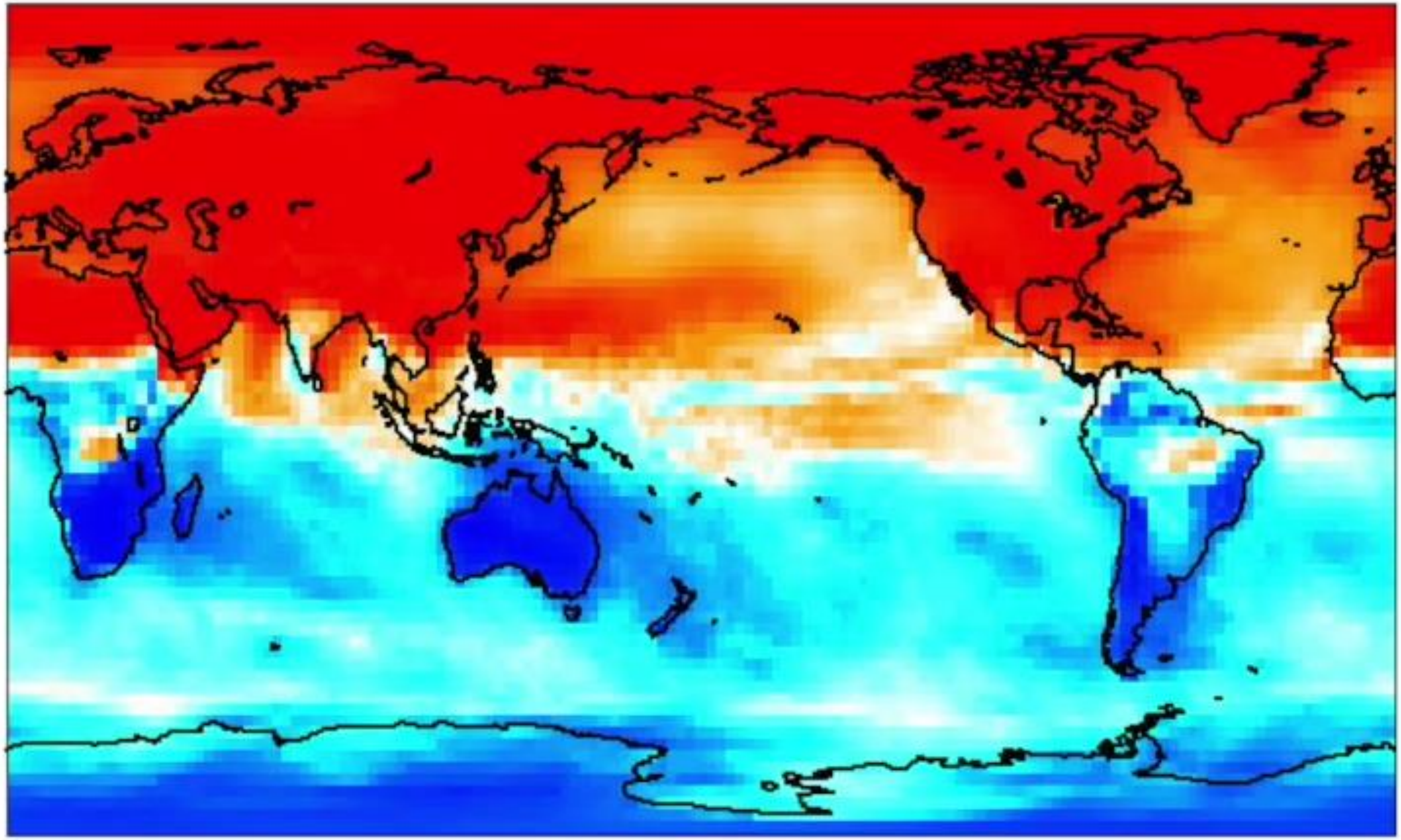
Average of the cosine of the Hilbert phase

1 July



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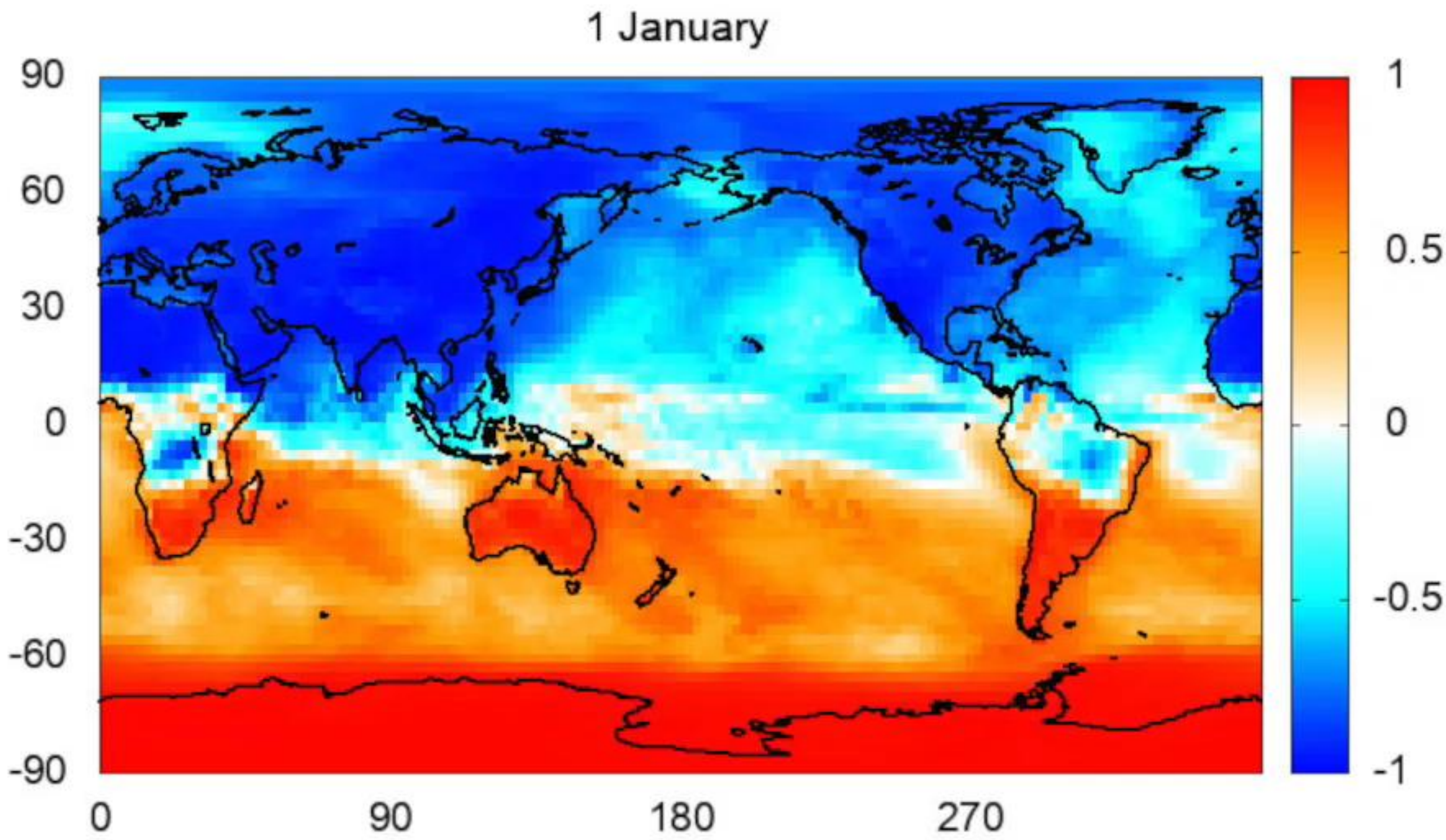
How can we visualize the passing of the seasons? Average annual evolution of cos(φ).



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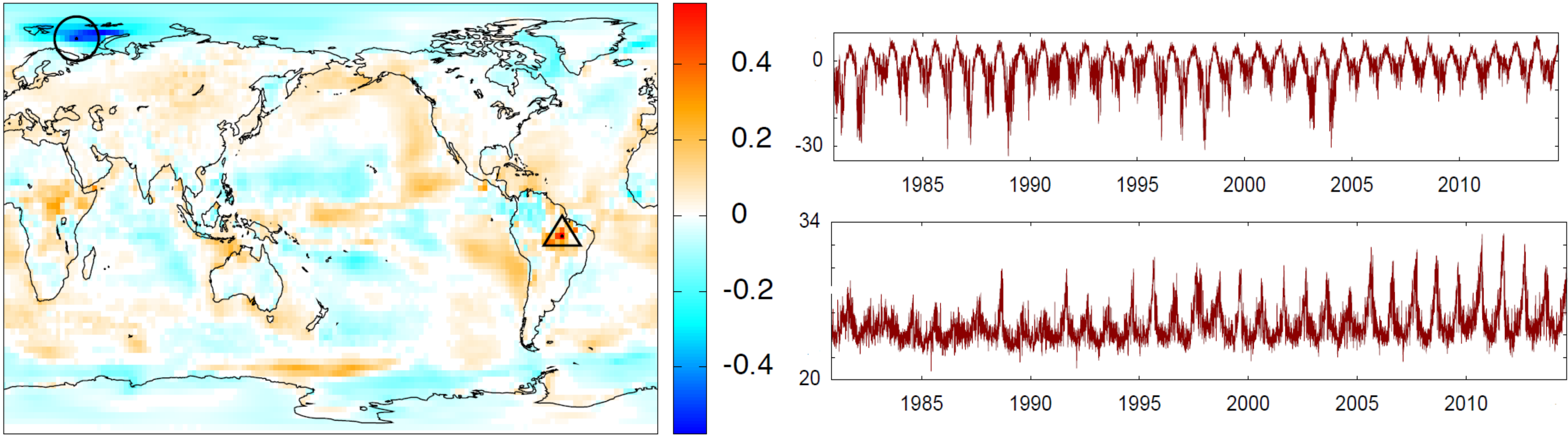
How to detect significant changes in the last 30 years?

$$\Delta a = \langle a \rangle_{2016-2007} - \langle a \rangle_{1988-1979}$$

$$\frac{\Delta a}{\langle a \rangle_{2016-1979}}$$

Significant if: $\frac{\Delta a}{\langle a \rangle} \geq \langle . \rangle_s + 2\sigma_s$ or $\frac{\Delta a}{\langle a \rangle} \leq \langle . \rangle_s - 2\sigma_s$

with σ_s computed from 100 "surrogates"



D. A. Zappala, M. Barreiro, C. Masoller, "Quantifying changes in spatial patterns of surface air temperature dynamics over several decades", Earth Syst. Dynam. 9, 383–391 (2018).

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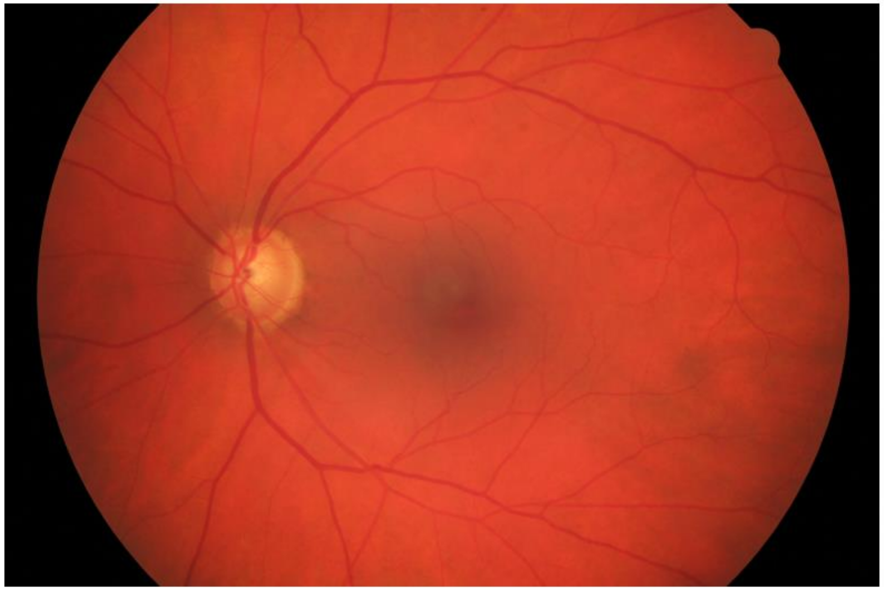
Analysis of retina fundus images

- For the diagnosis of eye diseases & follow up of treatments.
- Biometric identity identification.
- Opportunity to detect other diseases (alterations in retina network may reflect alterations in other arterial systems).



BE-OPTICAL

Advanced Biomedical Optical Imaging and Data Analysis

H2020-675512

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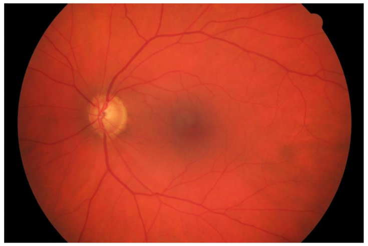
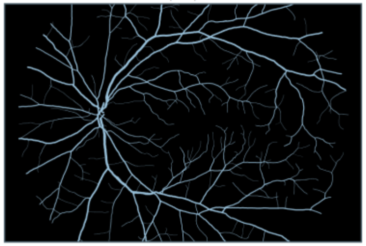
Data and image analysis steps

- 45 high resolution images (3504 × 2336 pixels)
  15 healthy subjects
  15 glaucoma
  15 diabetic retinopathy
- For every subject we had:
  - fundus photography
  - manual segmentation done by an expert ophthalmologist.


Steps:

1. Pre-process and un-supervisely, segment the images.
2. Extract network.
3. Compare networks obtained from different images.
4. Classify the images.

https://www5.cs.fau.de/research/data/fundus-images/

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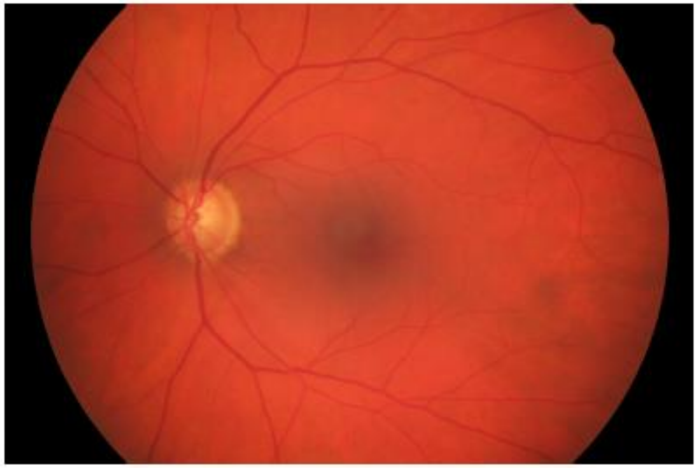
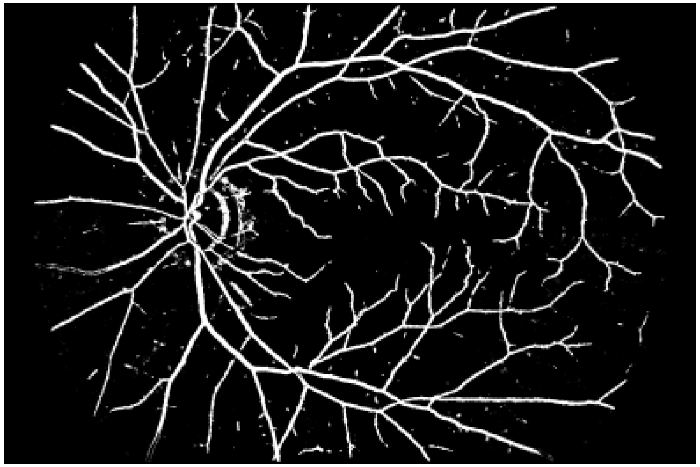
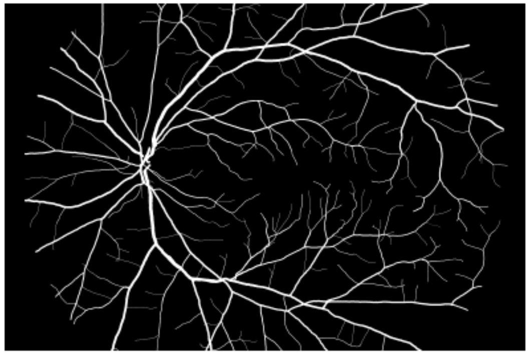
Step 1: Pre-process and segmentation





We adapted an *unsupervised* algorithm, originally developed for segmenting images of cultured neuronal networks.

Manual segmentation



D. Santos-Sierra, I. Sendiña-Nadal, I. Leyva et al. Cytometry Part A. 87, 513 (2015).

P. Amil, F. Reyes-Manzano, L. Guzmán-Vargas, I. Sendiña-Nadal, C. Masoller, "*Network-based features for retinal fundus vessel structure analysis*", PLoS ONE 14, e0220132 (2019).

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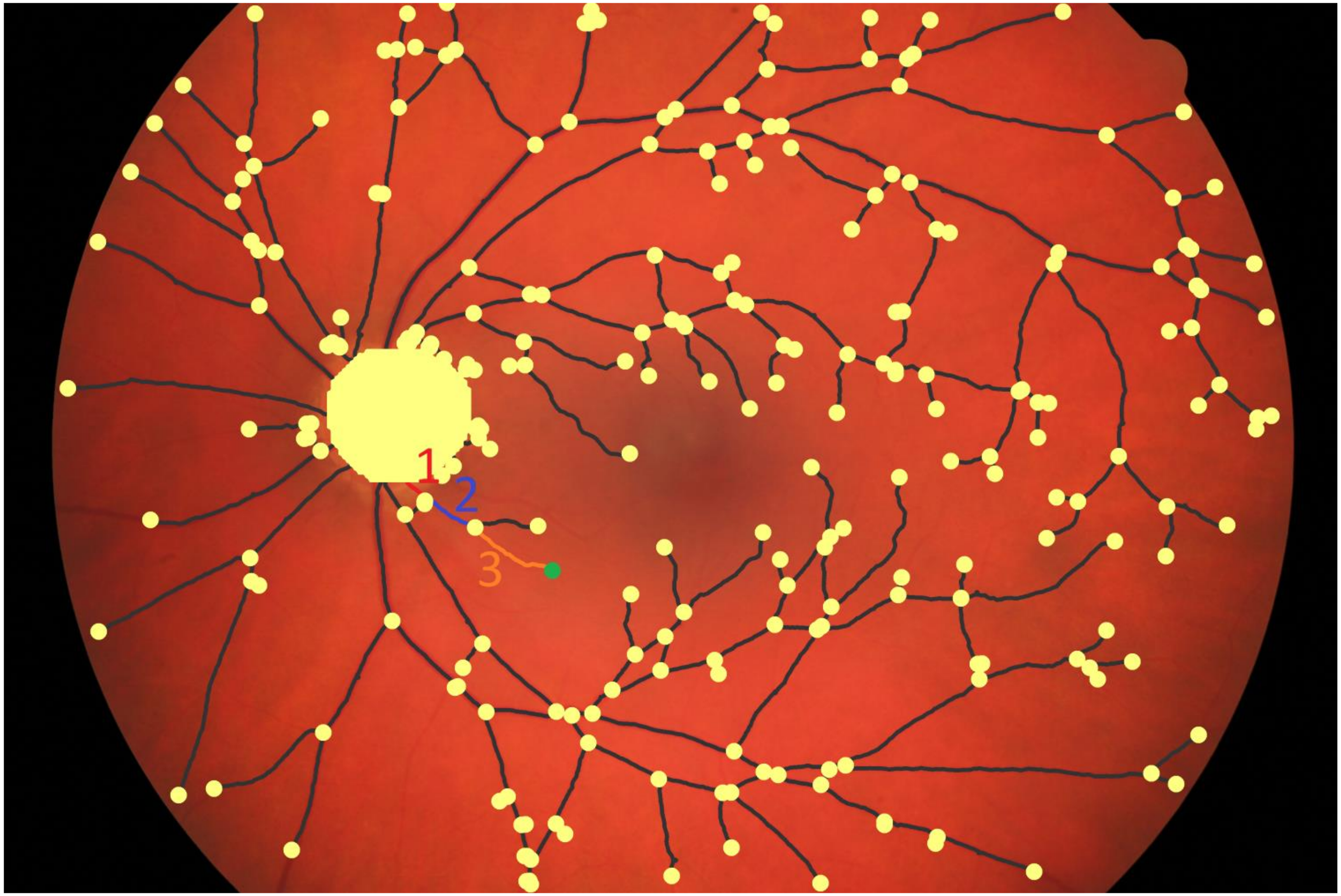
Step 2: extract the network (identification of the optical nerve, nodes and links and assign weights to the links).



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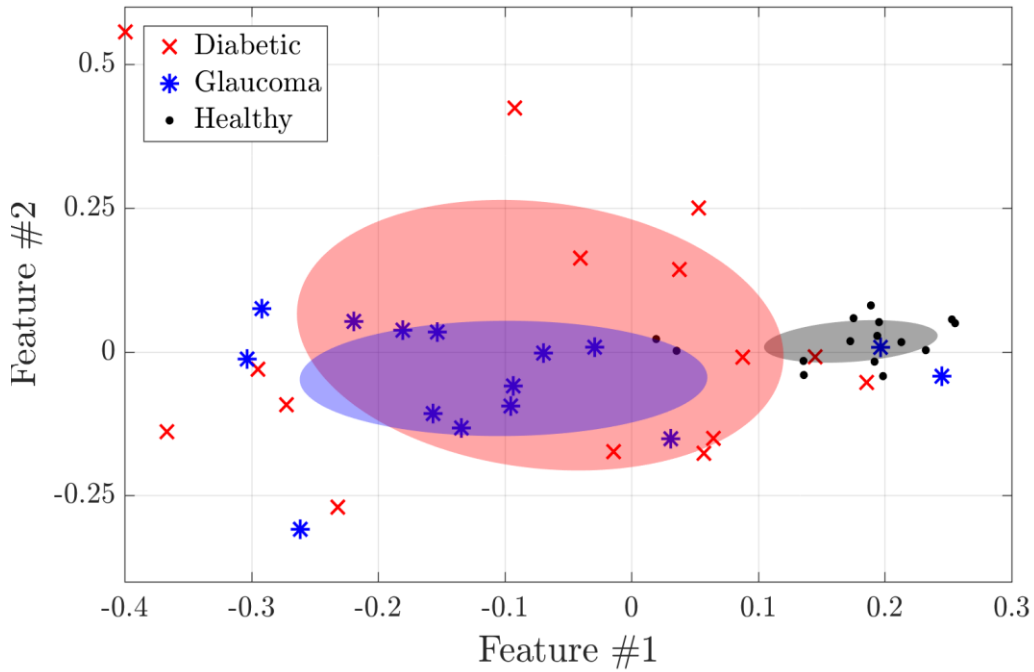
Steps 3 and 4: Compare the networks extracted from different images and classify the images.

- $\{p_{i,j}\}$: distances between probability distributions that characterize the networks obtained from images i and j.
- We used nonlinear dimensionality reduction (*Isomap*) to reduce the set of 45x45 $\{p_{i,j}\}$ values to only two features.

Distance distribution to the central node in the *manual* segmentation



P. Amil et al, Network-based features for retinal fundus vessel structure analysis, PLoS ONE 14 e0220132 (2019).

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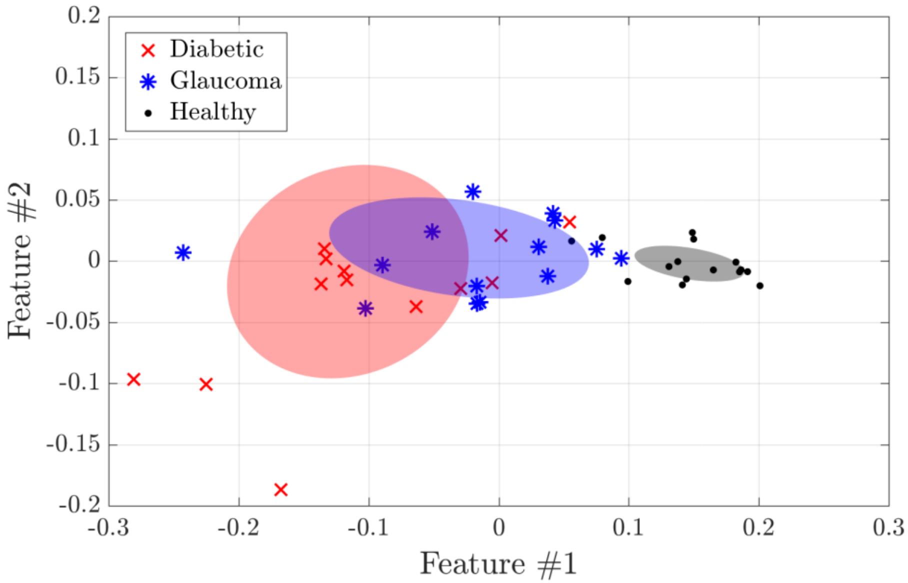
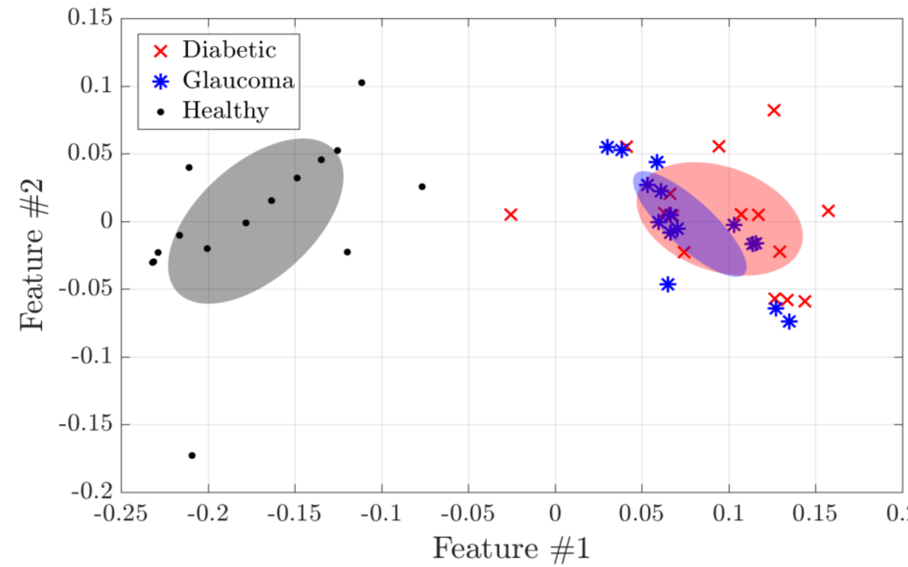
Performance of network features in the *manual* segmentation

Distribution of weights along the shortest path to central node



Distribution of weighted degrees



P. Amil et al, Network-based features for retinal fundus vessel structure analysis, PLoS ONE 14 e0220132 (2019).

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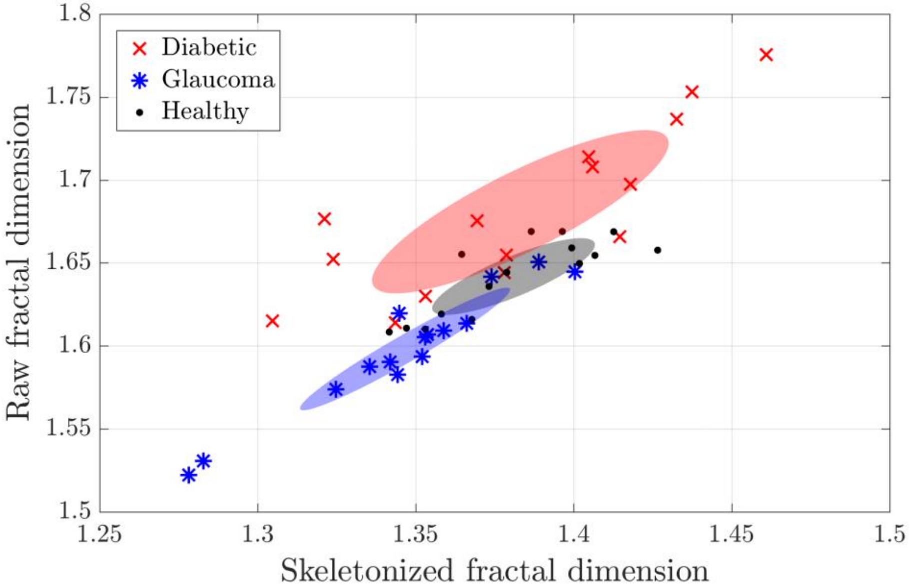
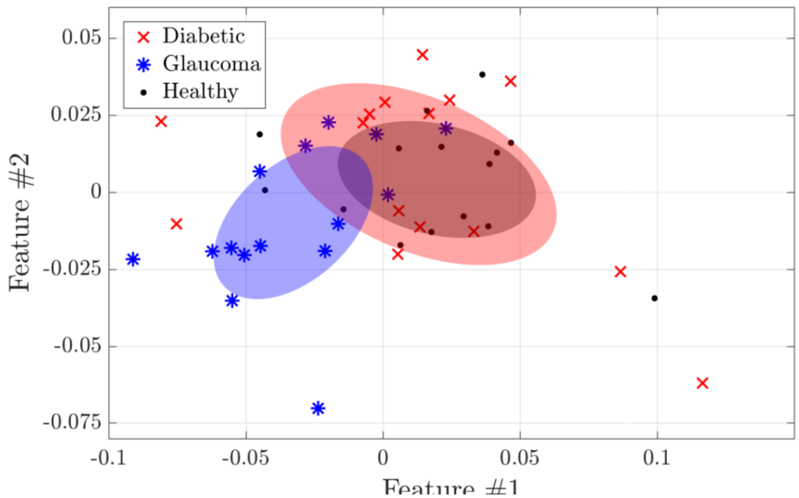
In the automated segmentation

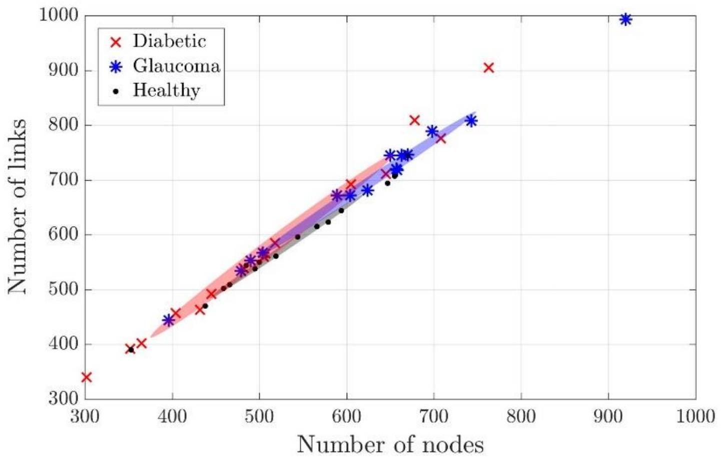
Fractal dimension $D = \lim_{\varepsilon \to 0} \frac{\log(N(\varepsilon))}{\log(1/\varepsilon)}$



Mean weight distribution along the shortest path to central node



Simple network features do not differentiate



P. Amil et al, Network-based features for retinal fundus vessel structure analysis, PLoS ONE 14 e0220132 (2019).

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Take home messages

- Data analysis techniques allow us to uncover patterns and relationships in data, which characterize (and sometimes predict) the behavior of complex systems.
- Even when the data does not meet the mathematical or algorithmic requirements, the results can give useful info.
- Different methods provide *complementary* information.
- "Surrogate" tests are needed to determine if the numerical values are statistically significant.
- Data analysis is a fast growing field with many applications.

Holger Kantz: "*Every data set bears its own difficulties: data analysis is never routine*"

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Thanks!

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Thank you for your attention!

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