Avalanches and dynamical transitions in networks of Hodgkin–Huxley neurons

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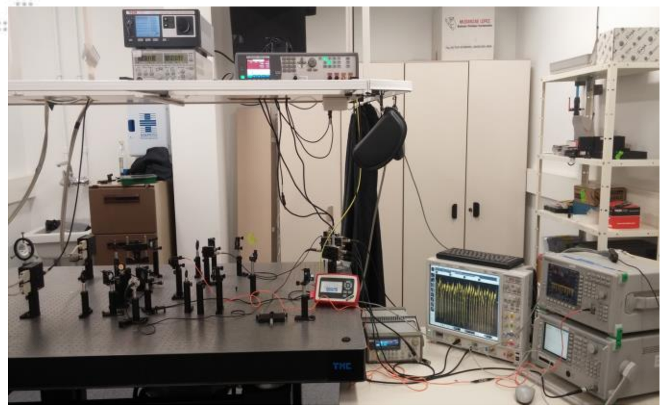
Where are we? Universitat Politècnica de Catalunya Campus Terrassa

Viernes, 25 de septiembre de 2009 Diari de Terrassa

El edificio Gaia centraliza grupos científicos consolidados y emergentes.



Semiconductor laser lab

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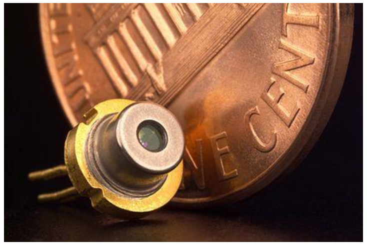
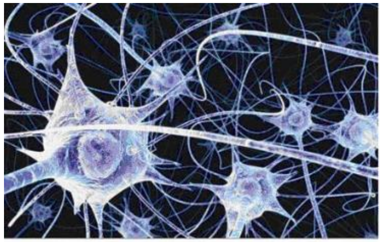
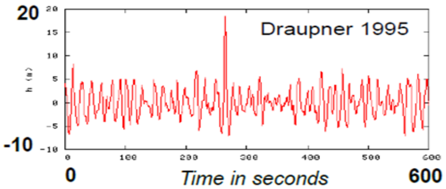
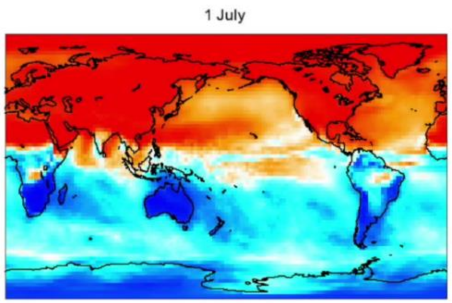
Research topics

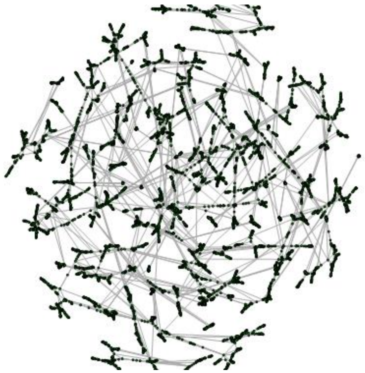
- Nonlinear laser dynamics
- Neuronal dynamics
- Synchronization
- Complex networks
- Extreme events
- Climate data analysis
- Biomedical data analysis

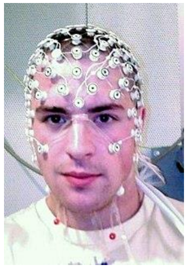


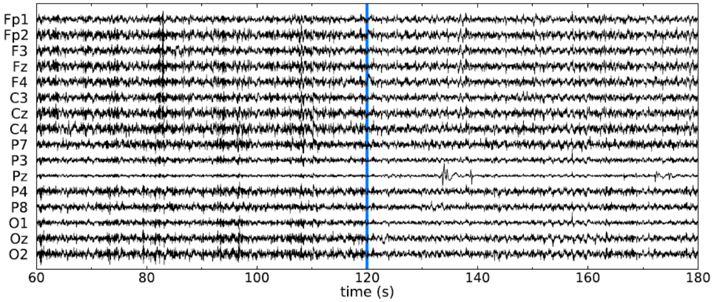












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Word cloud

https://shiny.rcg.sfu.ca/u/rdmorin/scholar_googler/

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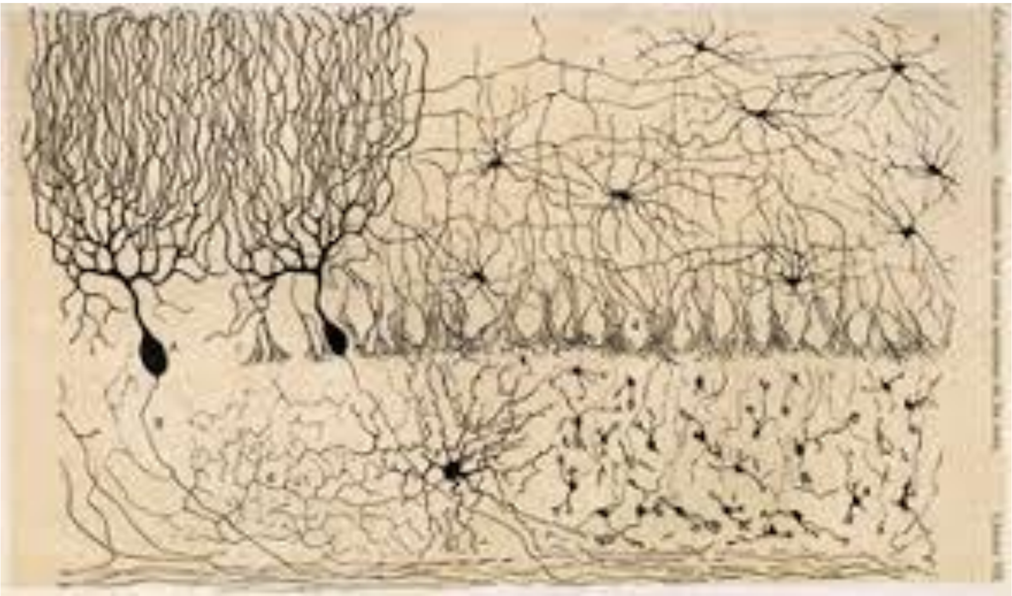
Motivation and research question



- Neural systems display a rich variety of complex regimes

  incoherent spiking, "avalanches", highly synchronized spiking

- Diversity of neural activity allows
  - Information processing,
  - Flexible adaptation to environmental changes.

Which mechanisms can induce different dynamical regimes and induce regime transitions?

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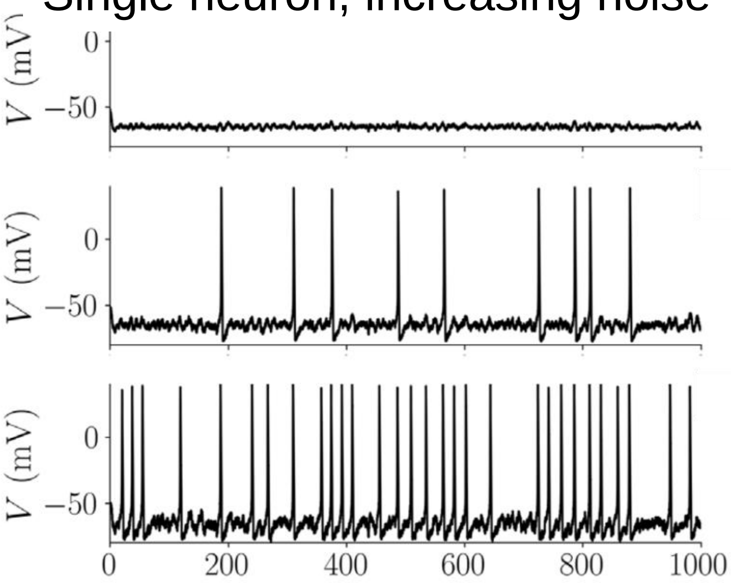
Dynamics of globally-coupled identical Hodgkin–Huxley neurons

$$C_M \frac{dV_i}{dt} = -g_K n_i^4 (V_i - E_K) - g_{Na} m_i^3 h_i (V_i - E_{Na})$$
$$- g_\ell (V_i - E_\ell) + D\xi_i(t) + I_{i,\text{coup}}.$$

Single neuron, increasing noise



Time (ms)

$\xi_i(t)$: uncorrelated Gaussian white noise, $\mu=0$ $\sigma=1$

$$I_{i,\text{coup}} = \frac{\varepsilon}{N} \sum_{j=1}^{N} (V_j - V_i) = \varepsilon(\overline{V} - V_i)$$

Mean field: $\overline{V} = \frac{1}{N} \sum_{i=1}^{N} V_i$

Boaretto, Macao and Masoller, Chaos, Solitons and Fractals 194 (2025) 116133

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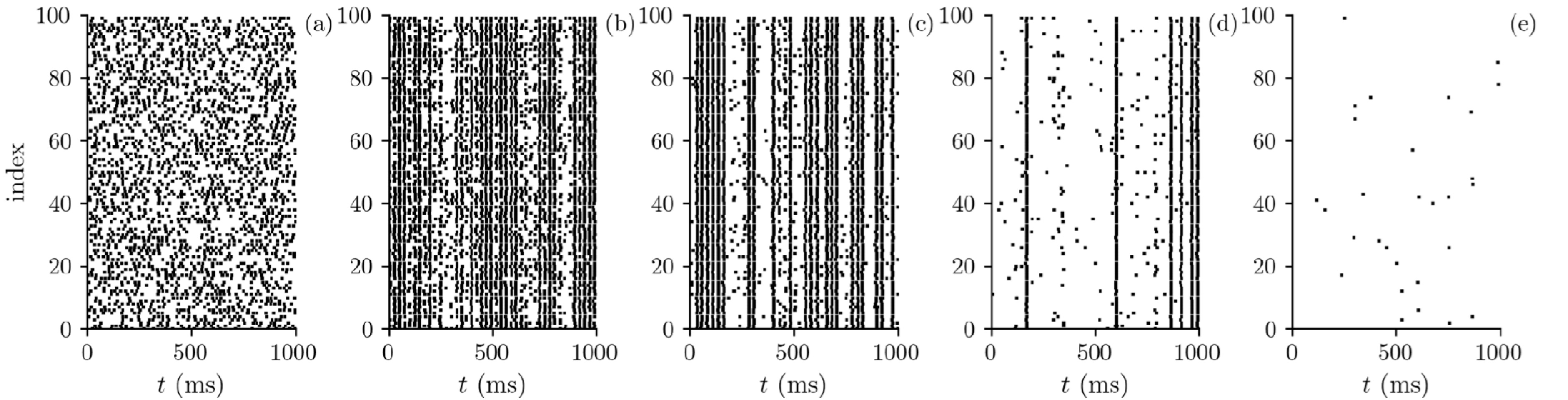
Dynamics of N=100 identical neurons

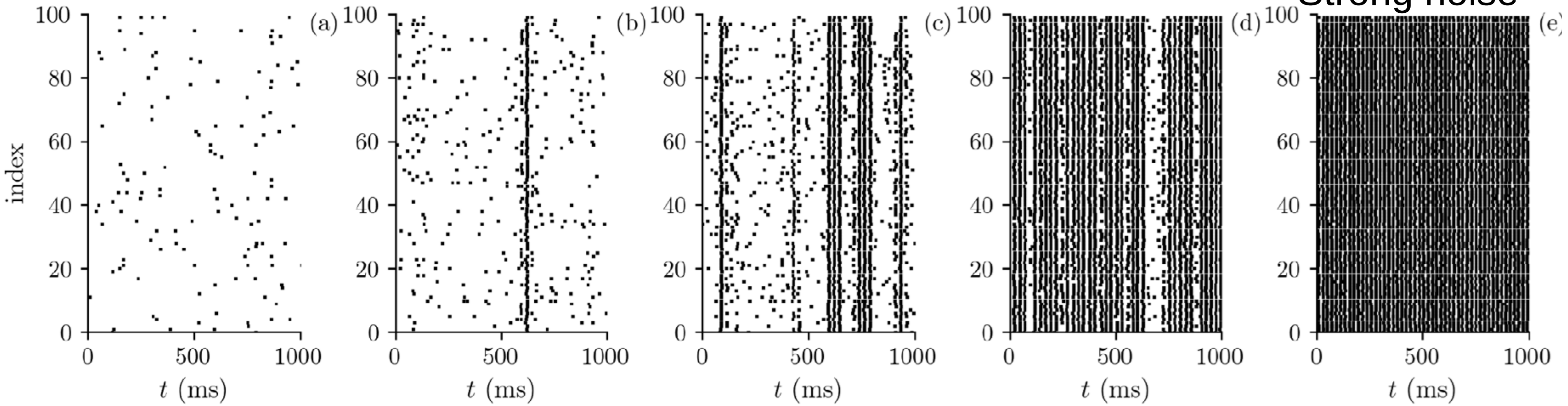
Weak coupling:
incoherent
spiking activity

Strong coupling:
spiking activity
suppressed



Weak noise

Strong noise



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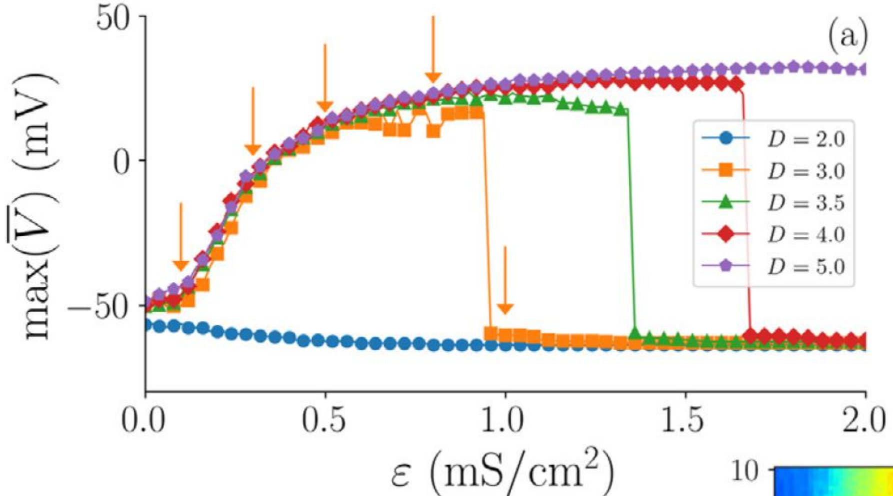
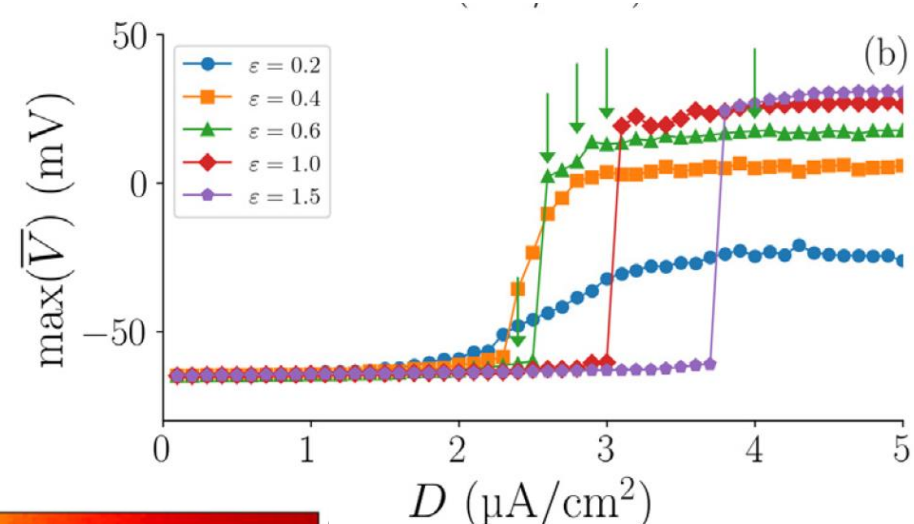
Order parameter: max($\overline{V}$)

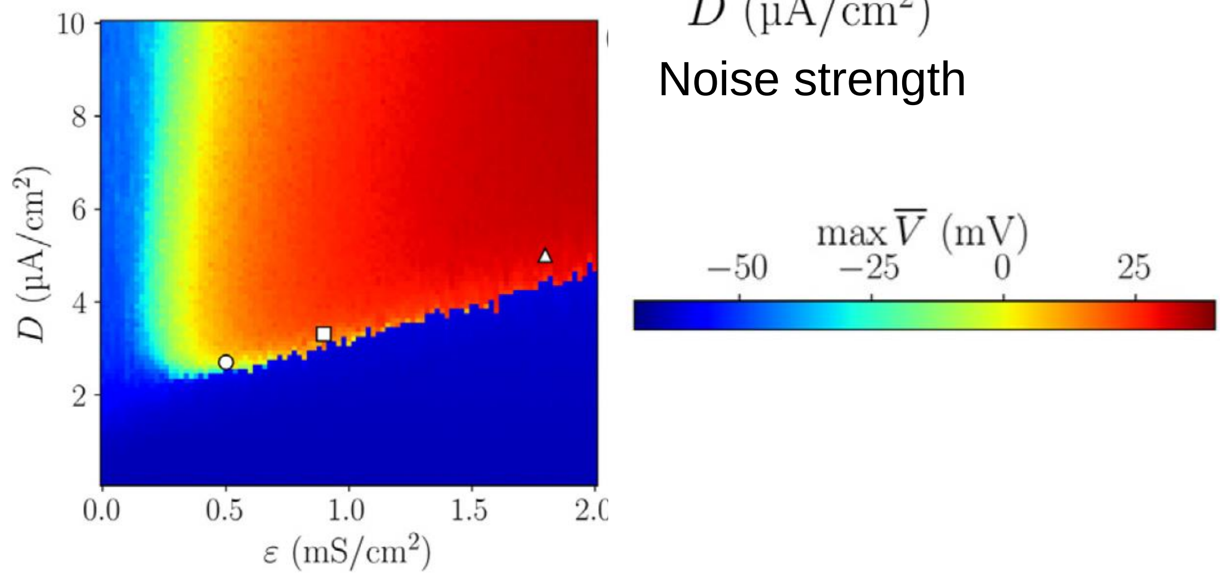
$$\overline{V} = \frac{1}{N}\sum_{i=1}^{N} V_i$$





Coupling strengt

Noise strength



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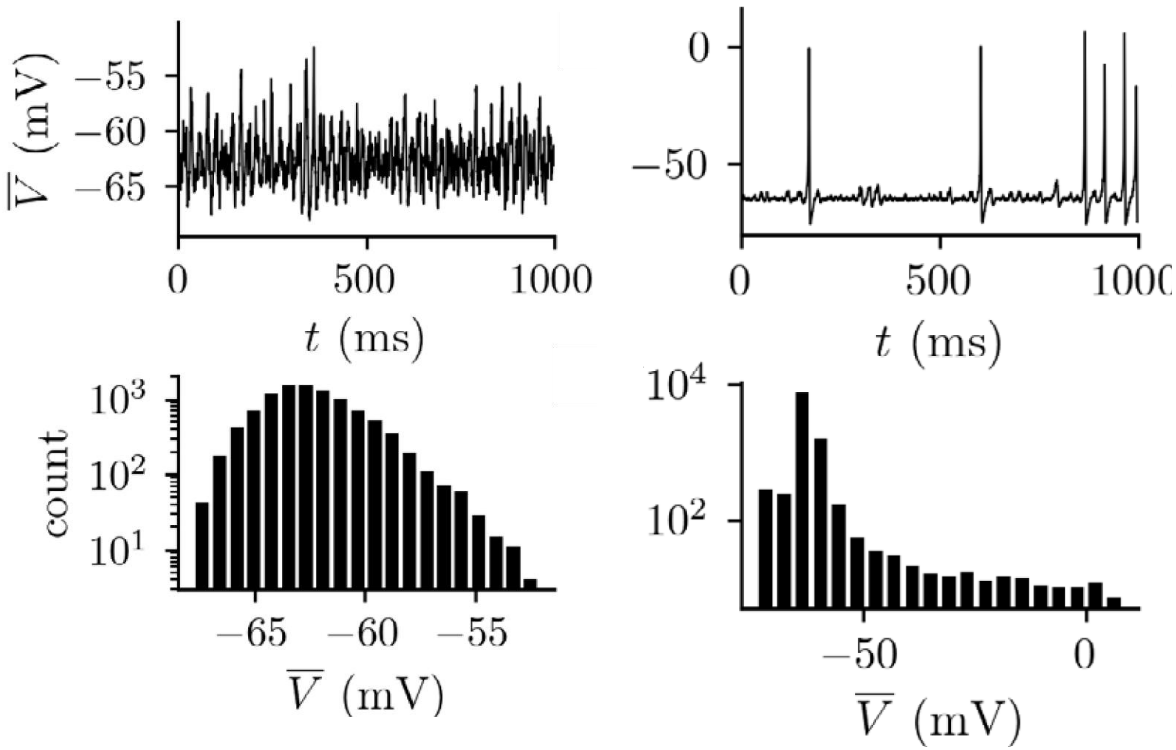
Identifying the extreme event region by analyzing the entropy of the distribution of the values of the mean field

High entropy



Low entropy

$$\overline{V} = \frac{1}{N}\sum_{i=1}^{N} V_i$$

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

p_i (probability that $\overline{V}(t)$ is in the ith bin) is estimated from the histogram of values, using N=100 bins and adjusting their range to the min and max values in each time series.

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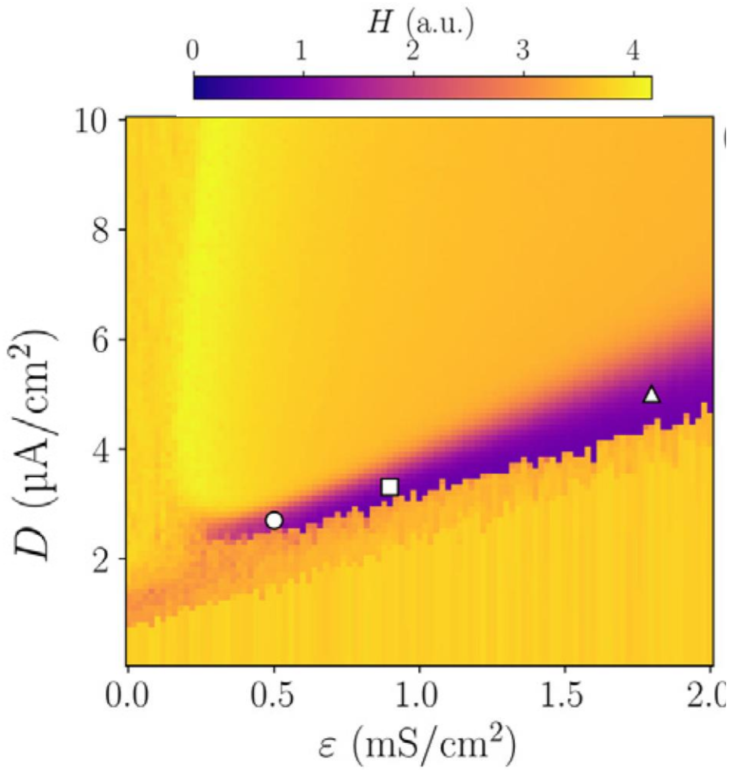
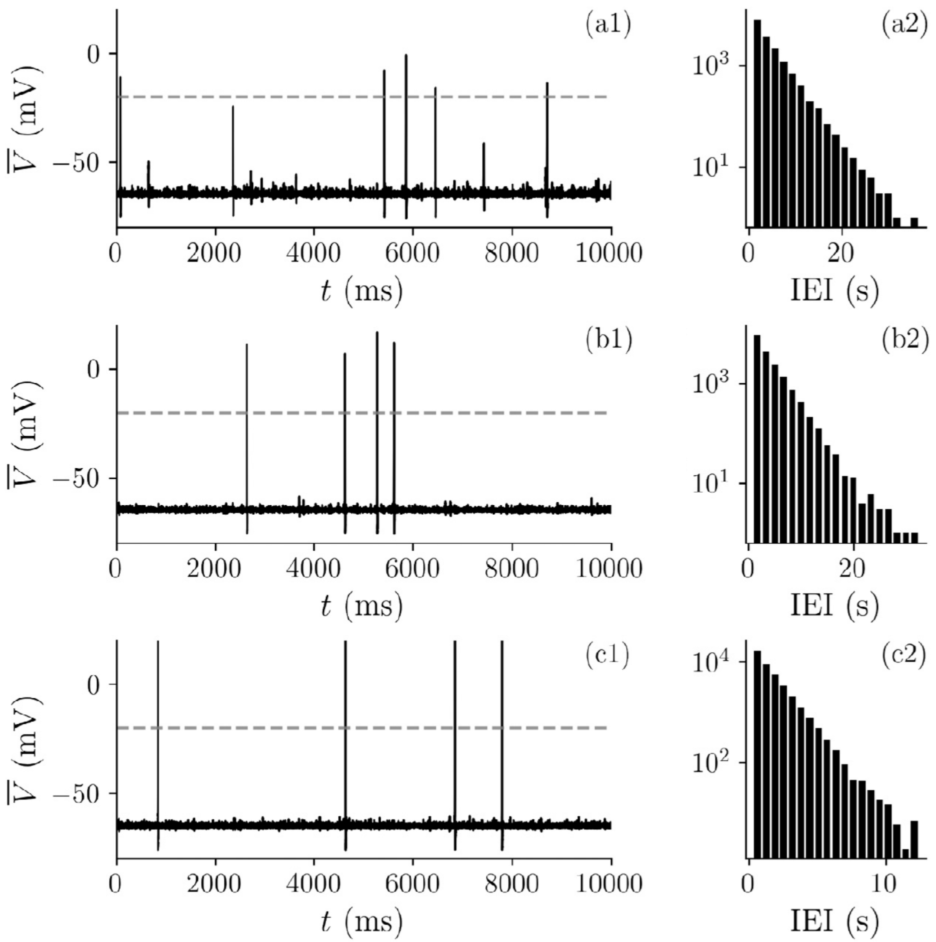
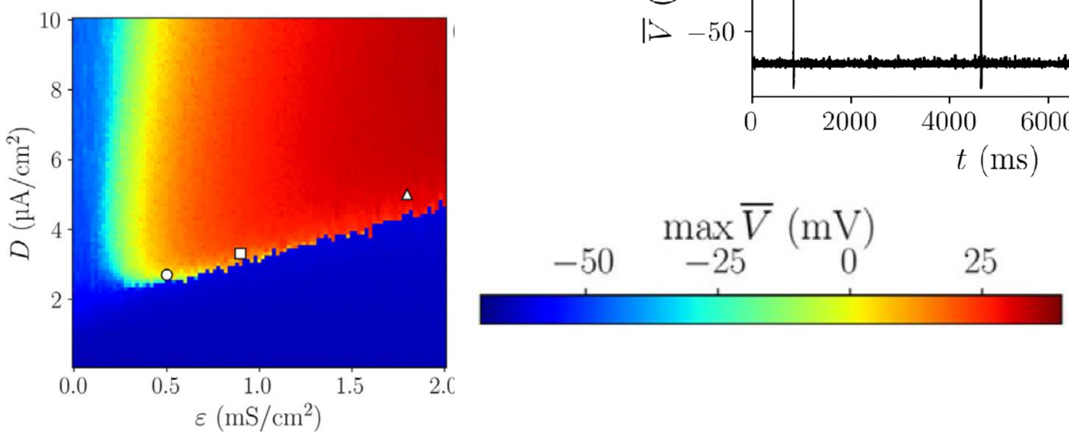
Extreme event region: low entropy

Distribution of Inter-Event-Intervals







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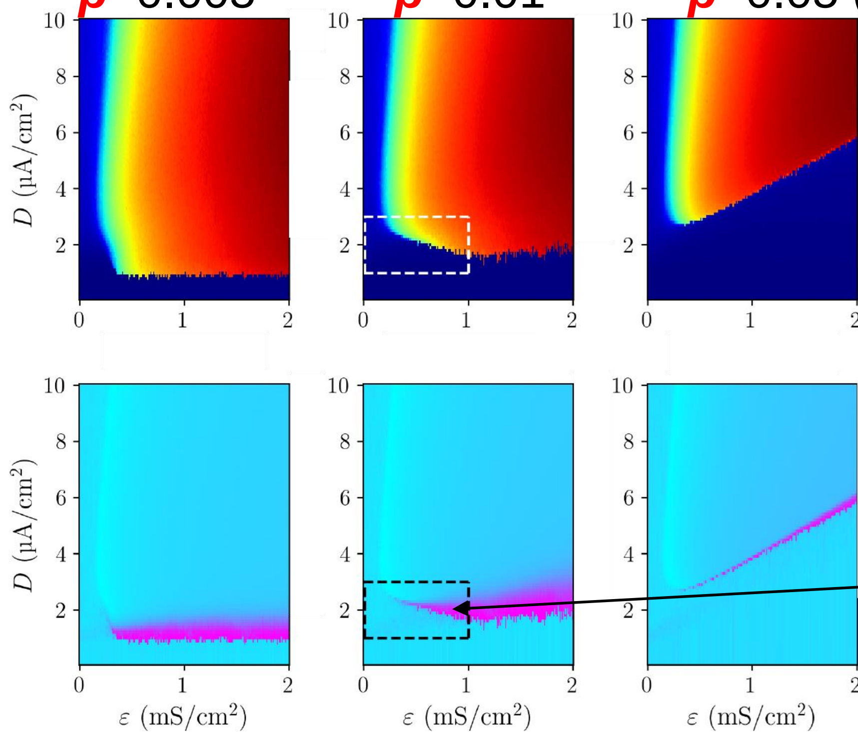
Role of the connectivity of the network

$$I_{i,\mathrm{coup}} = \frac{\varepsilon}{\bar{n}} \sum_{j=1}^{N} e_{ij}(V_j - V_i)$$

Average number of links per neuron

$e_{ij} = e_{ji} = 1$ with probability ***p***
0 with probability ***1-p***

p=0.005 ***p***=0.01 ***p***=0.05 (same as with *p*=1)



N=1000 neurons

Color shows:
$A = \max(\bar{V}) - \min(\bar{V})$

Color shows: entropy

What happens in this region?

Boaretto, Macao and Masoller, submitted (2026)

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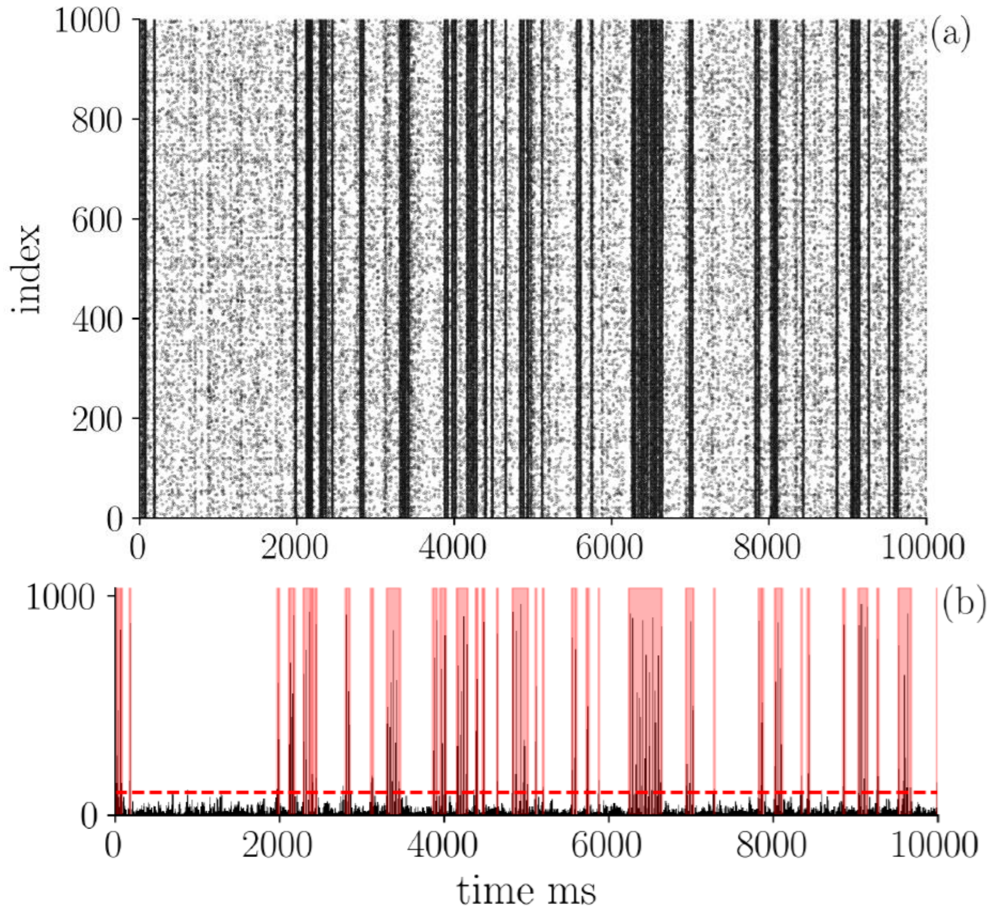
Identifying and characterizing neuronal avalanches

Spike count in each Δt



red dashed line: threshold used to define active bins

- Avalanche duration τ: number of consecutive active bins.
- Avalanche size s: total number of spikes during the avalanche.

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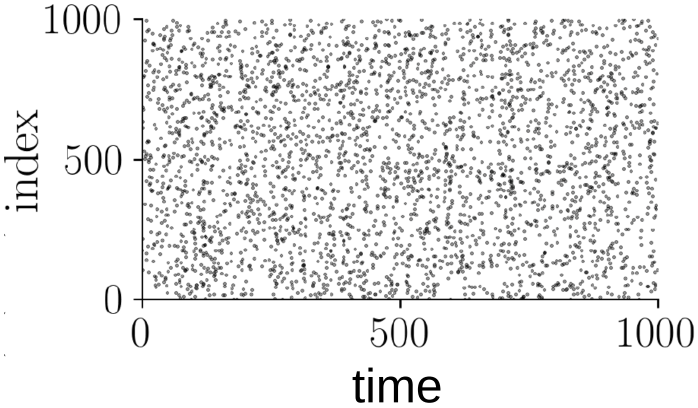
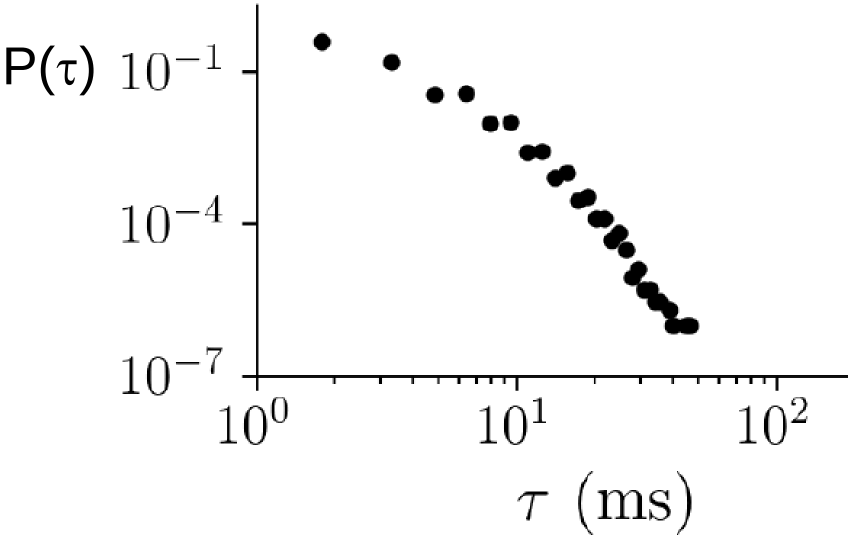
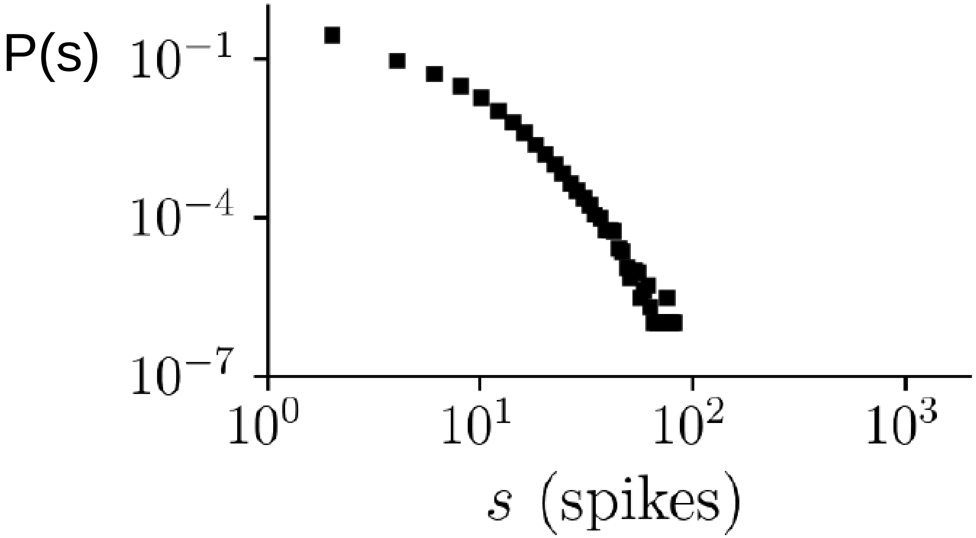
In the asynchronous region (weak coupling)



Distribution of avalanche durations



Distribution of avalanche sizes



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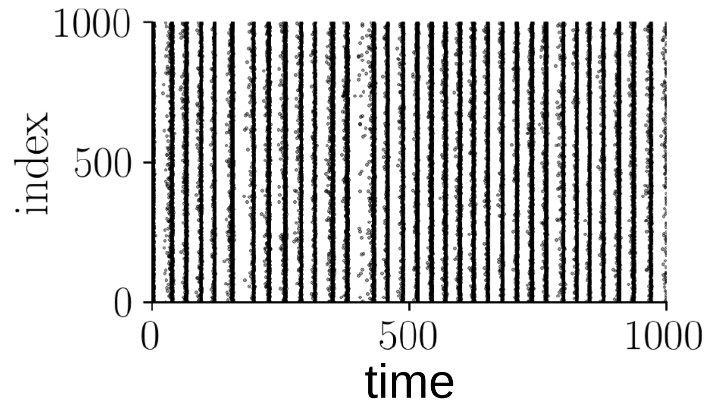
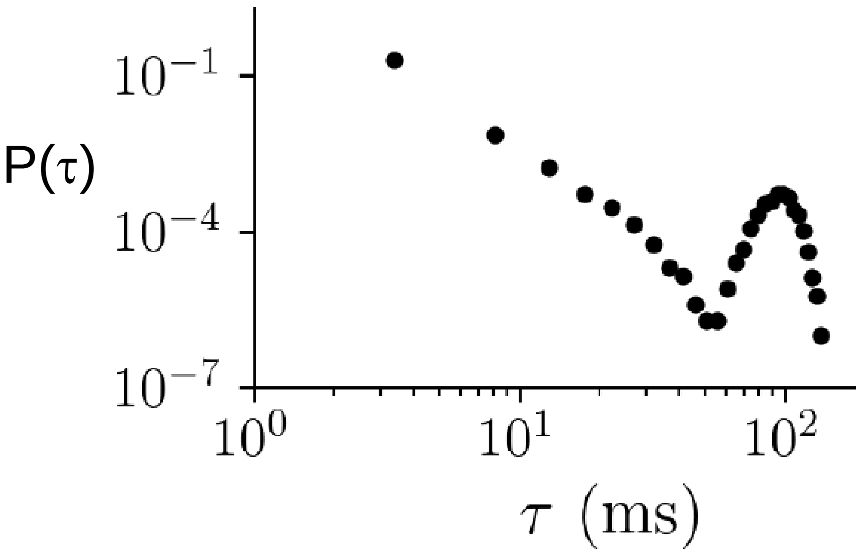
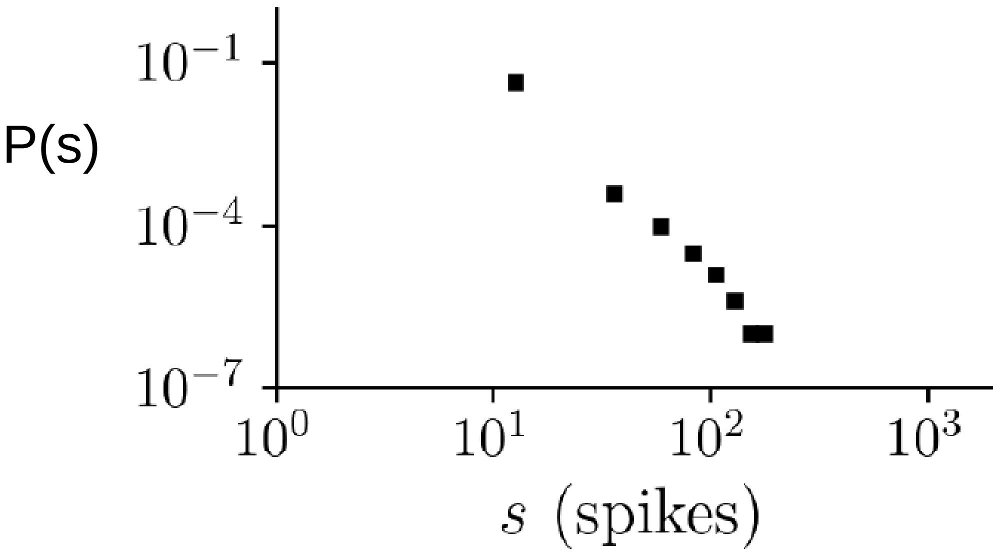
In the “extreme events” region: synchronized spiking due to strong coupling



Distribution of avalanche durations



Distribution of avalanche sizes



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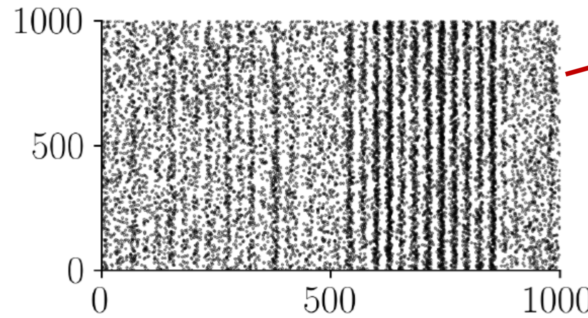
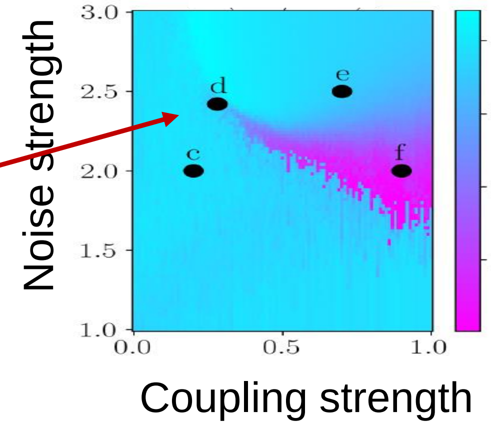
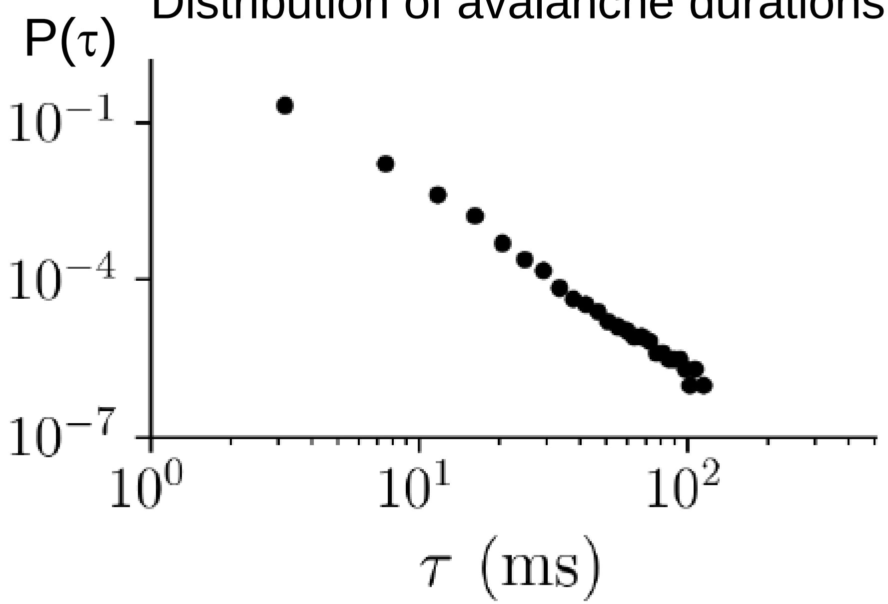
Critical-like regime: power laws distributions

d

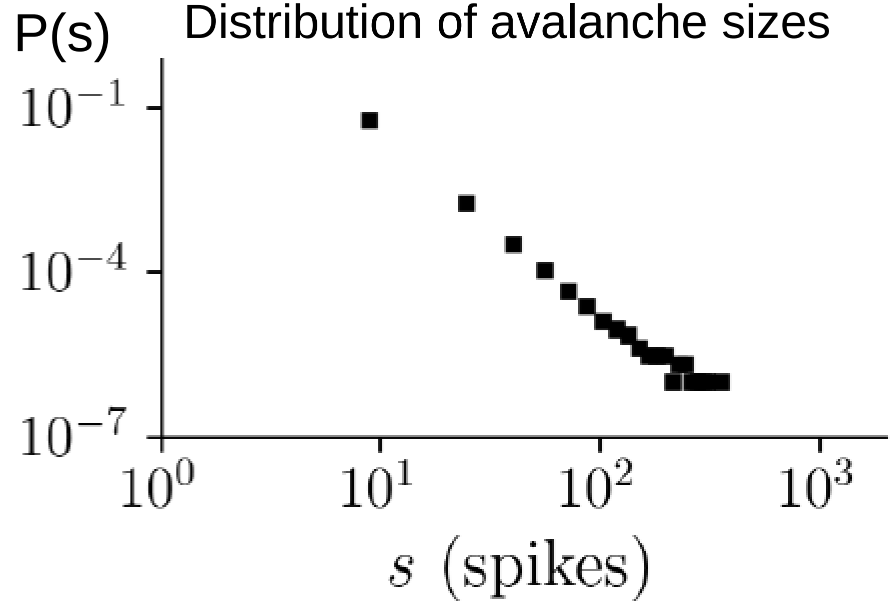




Distribution of avalanche durations



Distribution of avalanche sizes



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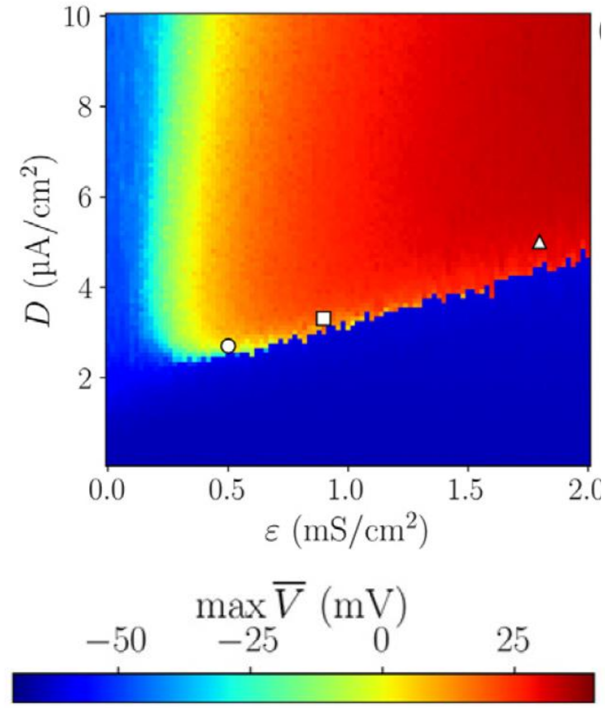
Take home messages (I/II)

Which mechanisms can induce different regimes and trigger transitions?

$$\overline{V} = \frac{1}{N}\sum_{i=1}^{N} V_i$$



Three regime transitions identified:

- Gradual increase of neural activity when increasing the coupling.
- An abrupt suppression of neural activity for too strong coupling.
- A gradual or an abrupt transition when the noise level increases.

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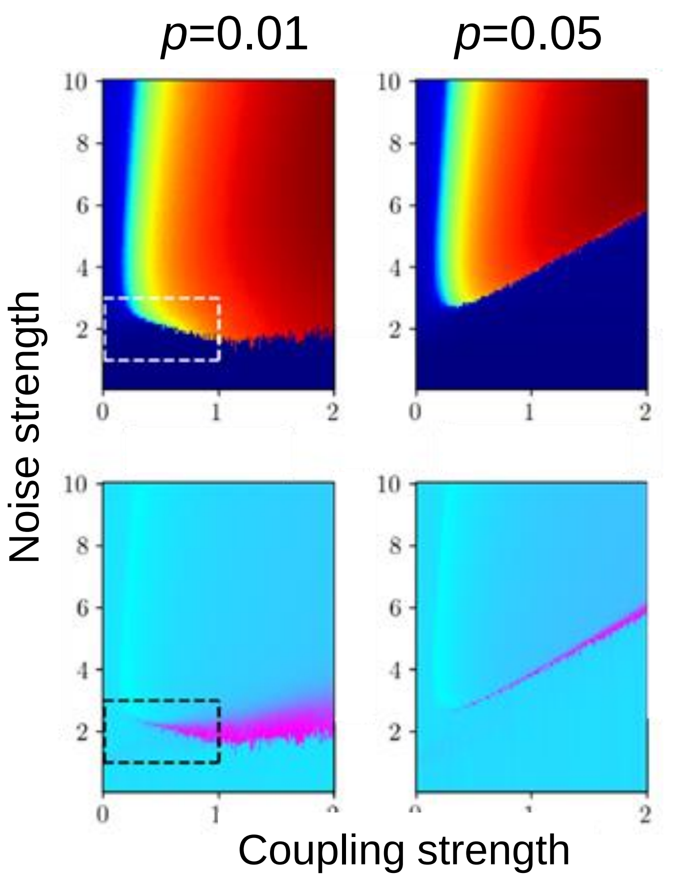
Take home messages (II/II)

- The entropy of the distribution of the mean field unveils a critical point at the intersection of coupling-driven and noise-driven transitions.
- Sparce connectivity enlarges the region of critical-like dynamics.
- A simple model (identical neurons, symmetric coupling, no-delays, no inhibitory neurons) can explain critical behavior in neural systems.
- To do: fit exponents, goodness-of-fit tests. inhibitory neurons? chemical synapses? transmission delays?



Boaretto, Macau, Masoller, Chaos, Solitons & Fractals 194, 116133 (2025).

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