

Synchronization transitions in Hodgkin–Huxley neural networks

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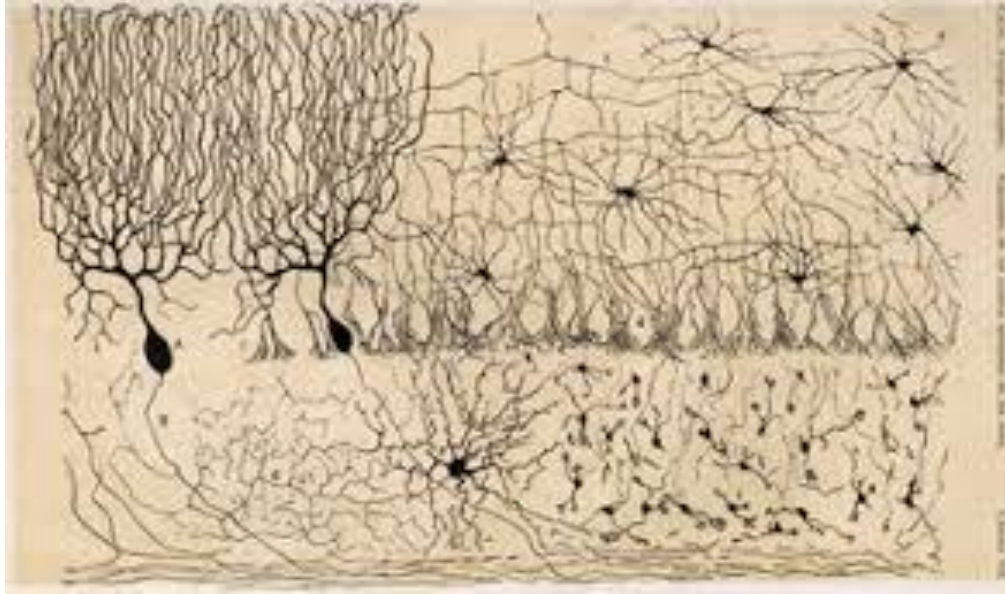
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Motivation and research question



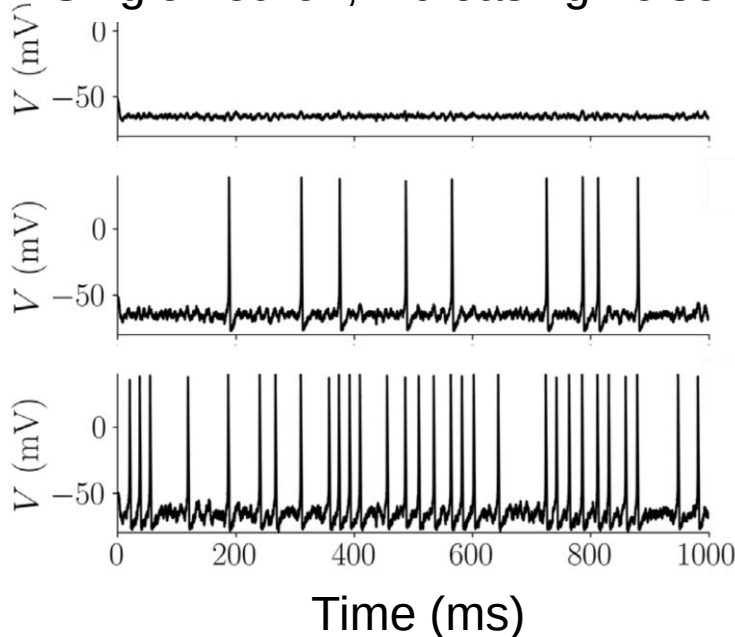
- Neural systems display a rich variety of complex regimes
incoherent spiking, “avalanches”, highly synchronized spiking
- Diversity of neural activity allows
 - Information processing,
 - Flexible adaptation to environmental changes.

*Which mechanisms can induce different regimes
and trigger transitions?*

Dynamics of globally-coupled identical Hodgkin–Huxley neurons

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

Single neuron, increasing noise



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

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

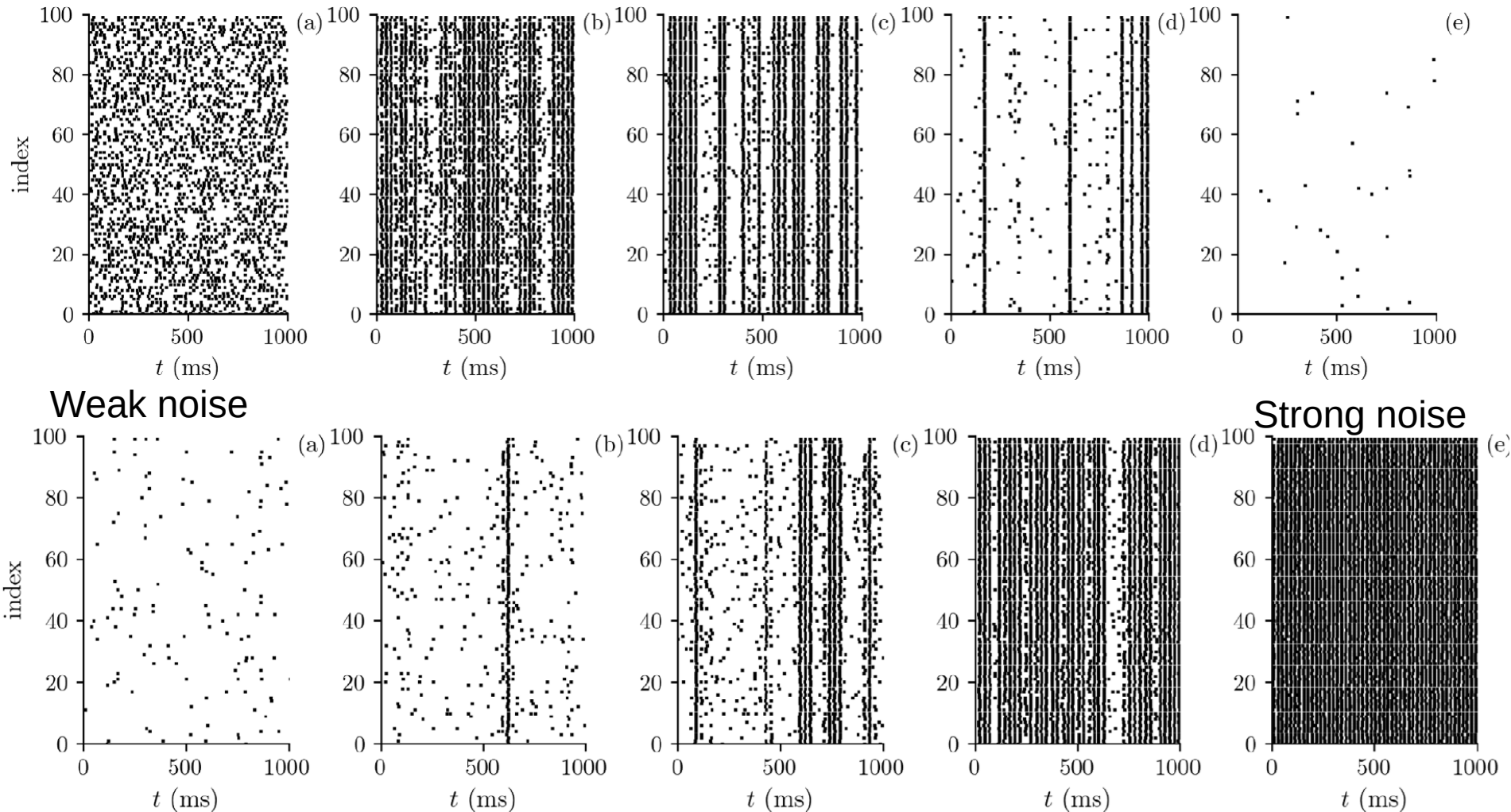
Mean field: $\bar{V} = \frac{1}{N} \sum_{i=1}^N V_i$

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

Dynamics of N=100 identical neurons

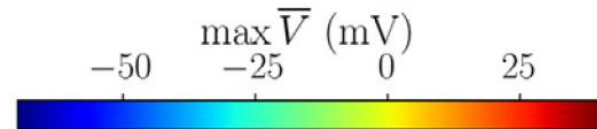
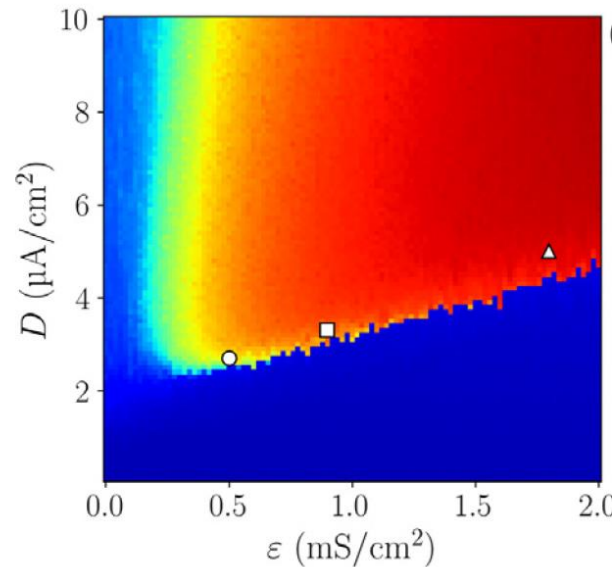
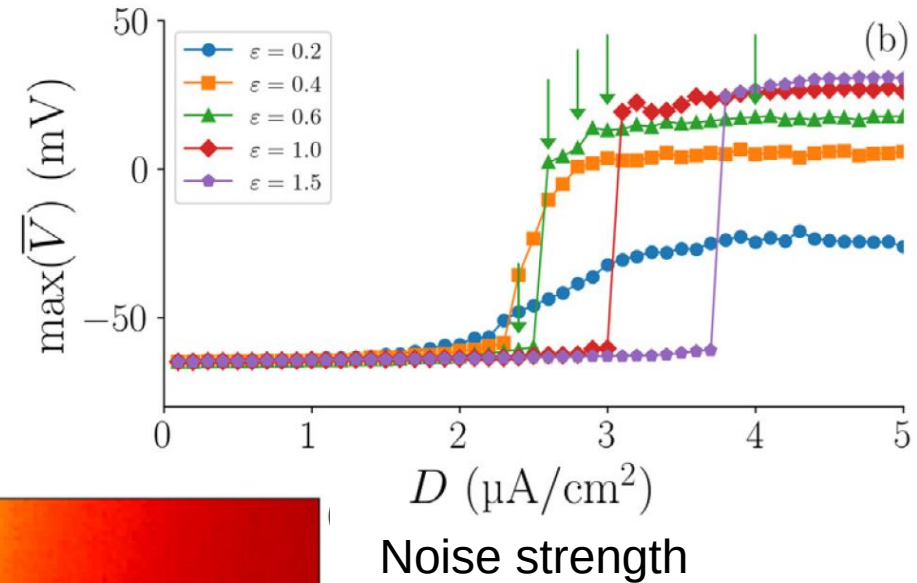
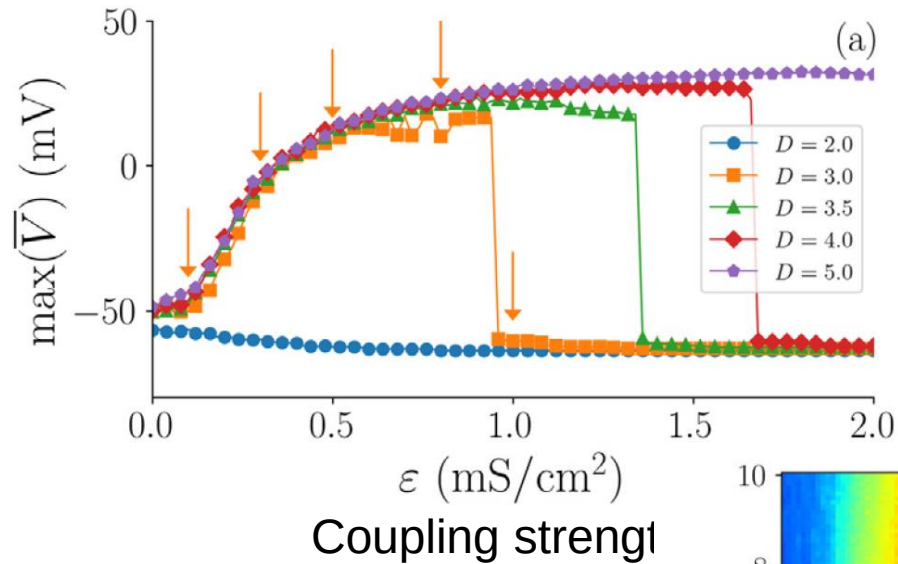
Weak coupling:
incoherent
spiking activity

Strong coupling:
spiking activity
suppressed

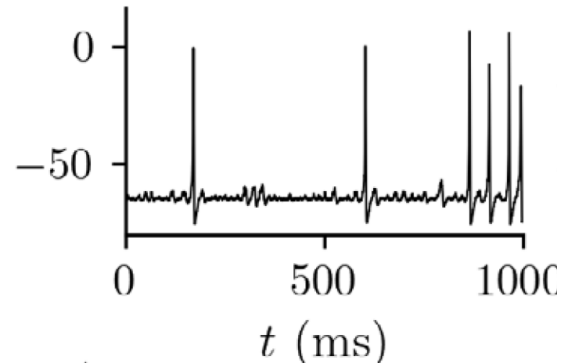
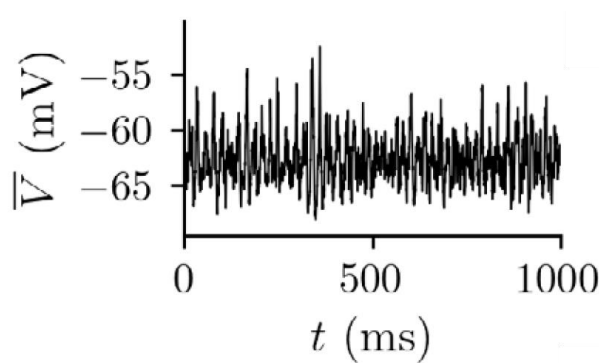


Order parameter: $\max(\bar{V})$

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

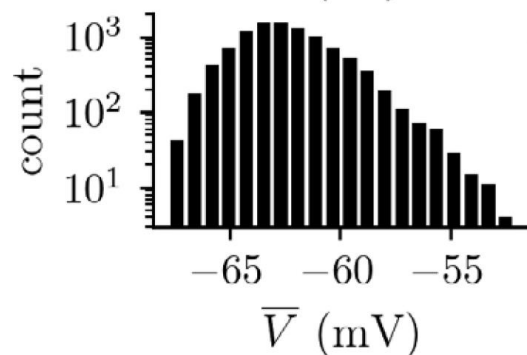


Identifying the extreme event region by analyzing the entropy of the distribution of the values of the mean field

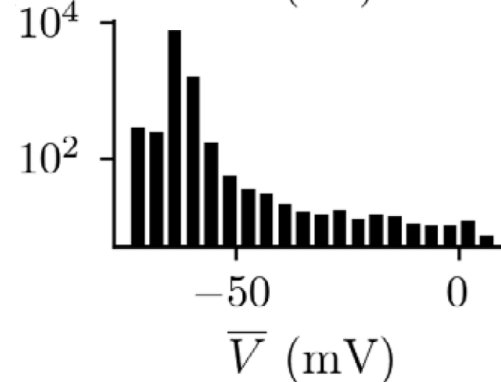


$$\overline{V} = \frac{1}{N} \sum_{i=1}^N V_i$$

High entropy



Low entropy

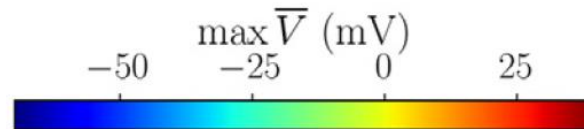
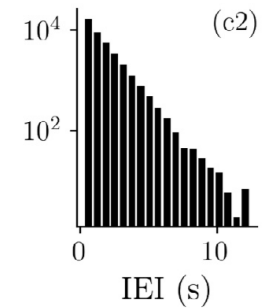
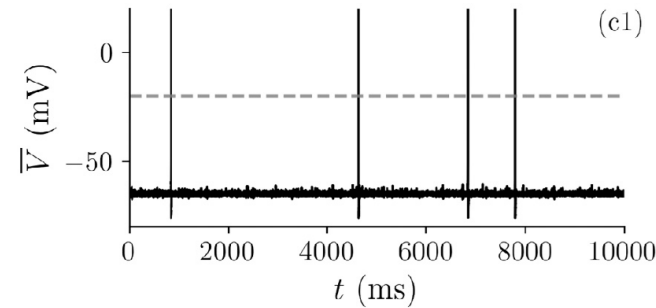
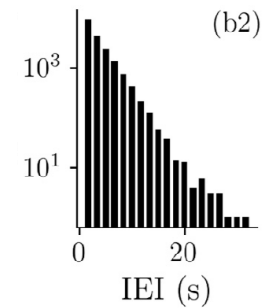
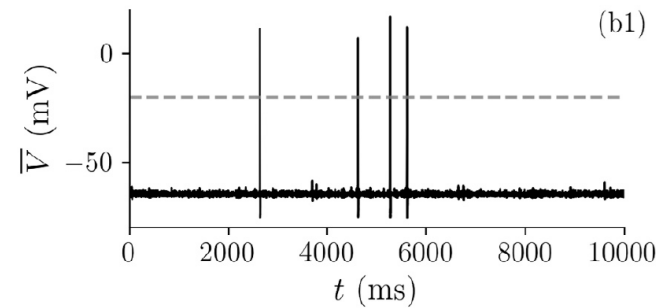
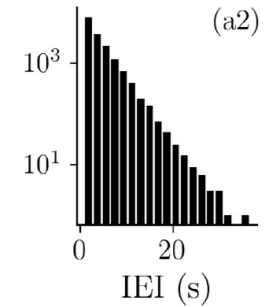
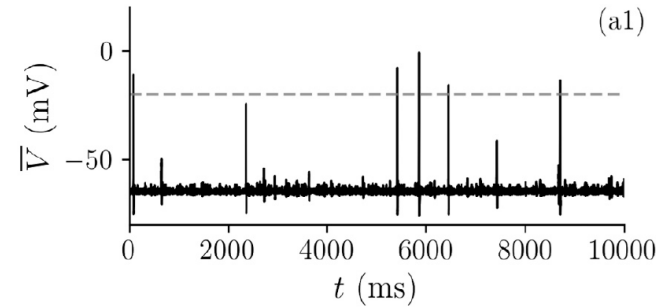
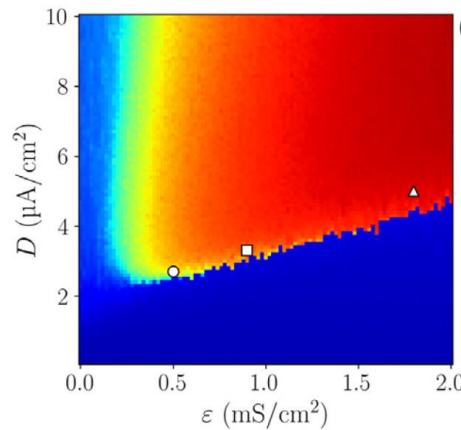
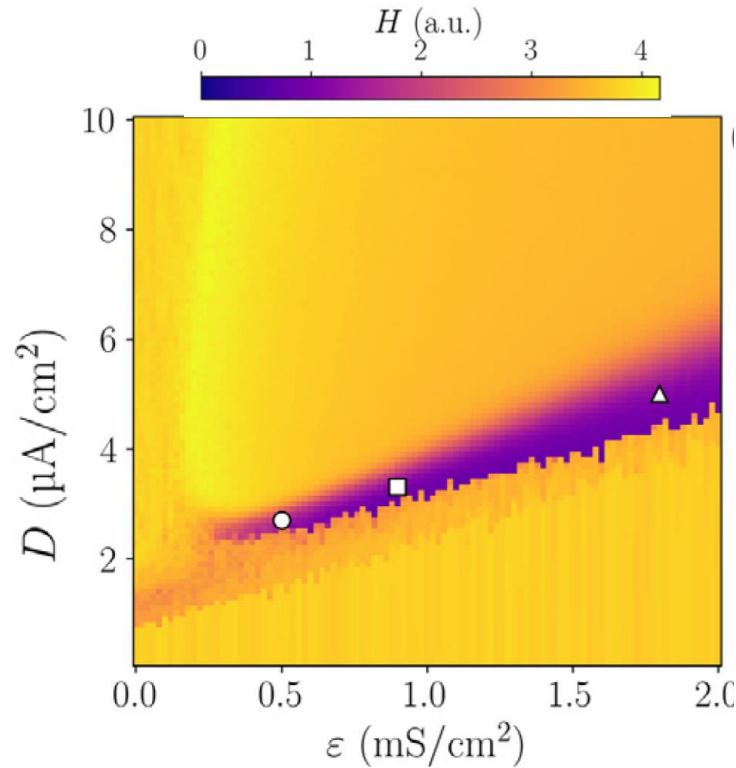


$$H = - \sum_{i=1}^N p_i \log p_i$$

p_i (probability that $\overline{V}(t)$ is in the i th 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.

Extreme event region: low entropy

Distribution of Inter-Event-Intervals

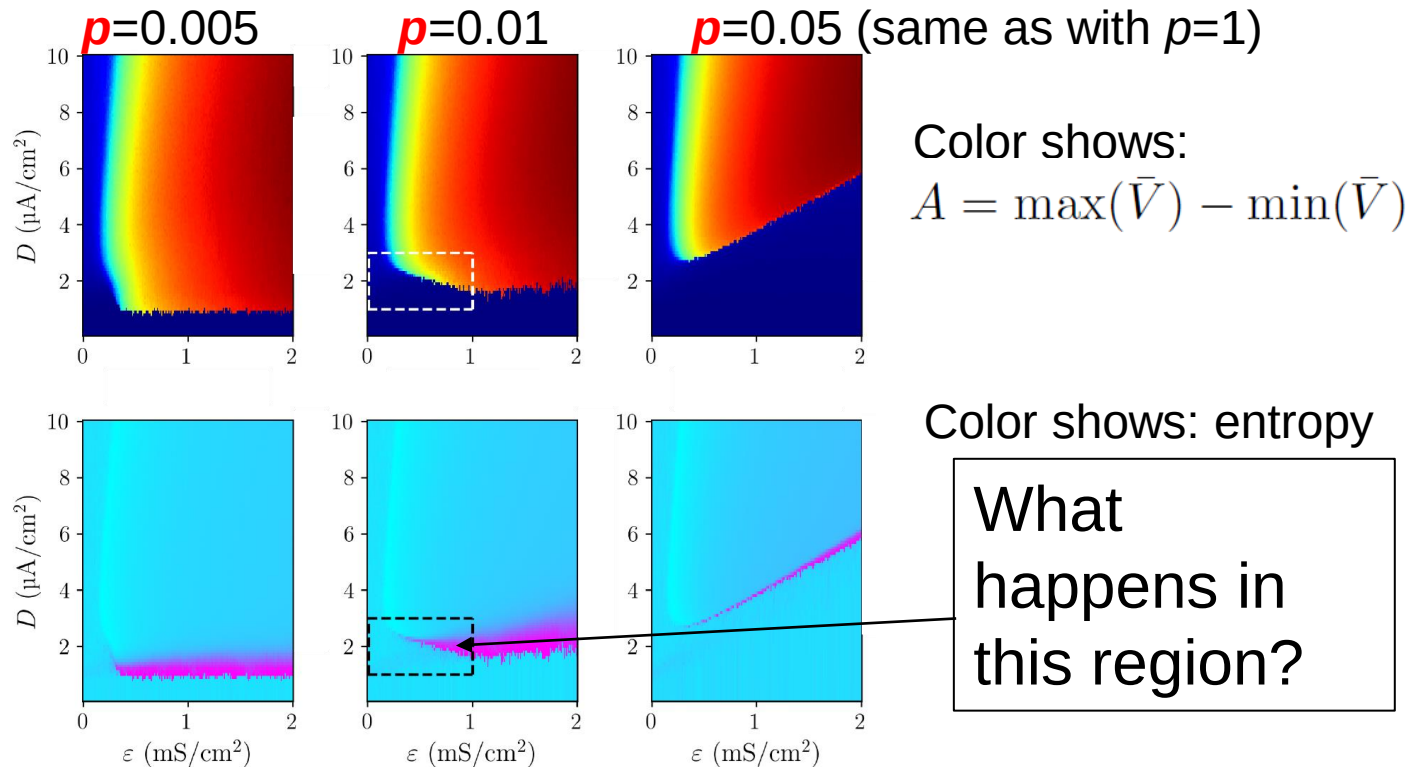


Role of the connectivity of the network

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

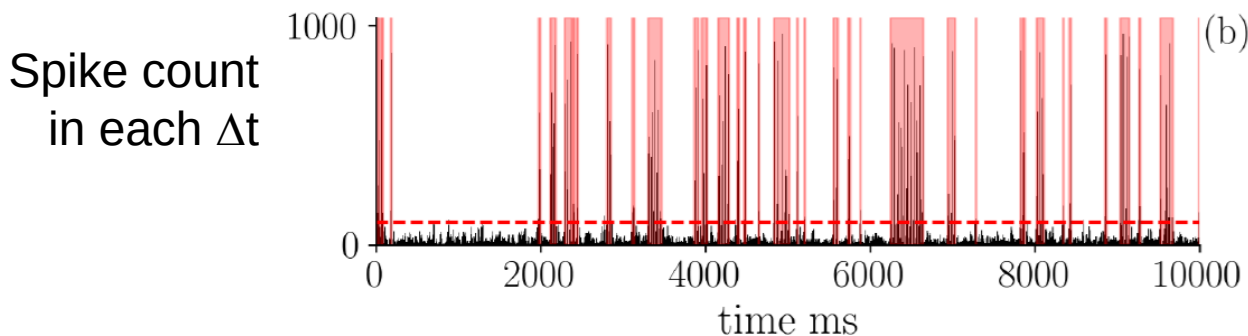
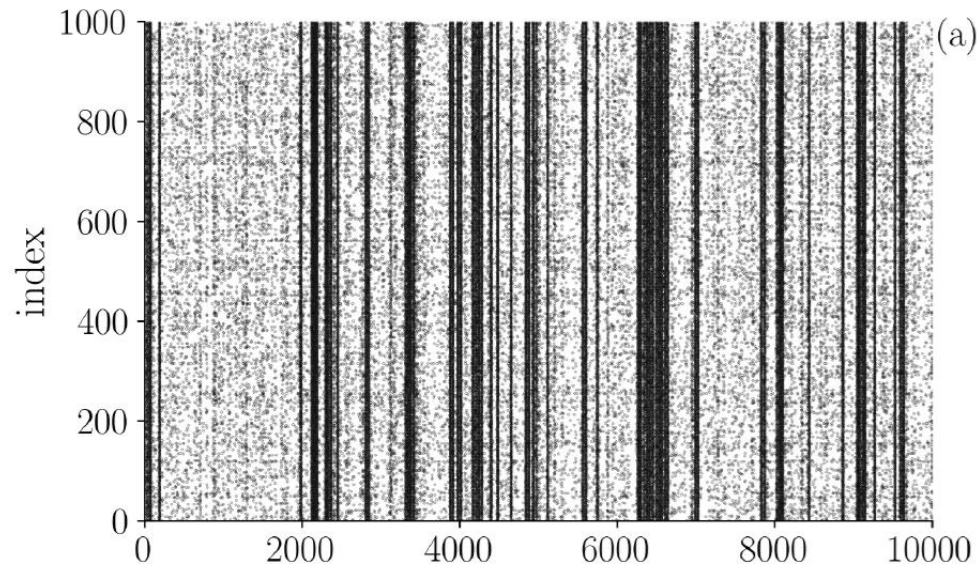
Average number of links
per neuron

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



Boaretto, Macao and Masoller, submitted (2026)

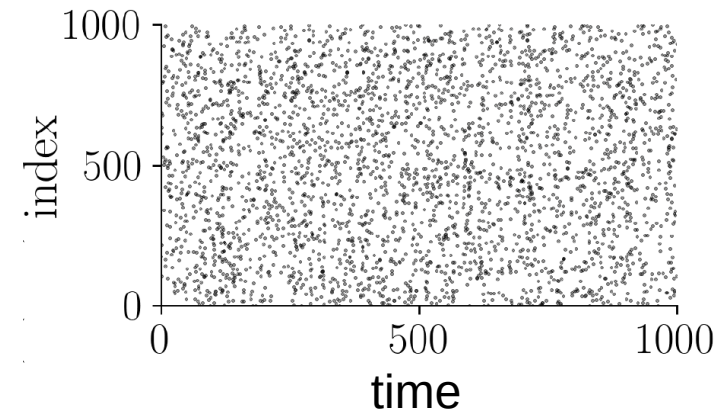
Identifying and characterizing neuronal avalanches



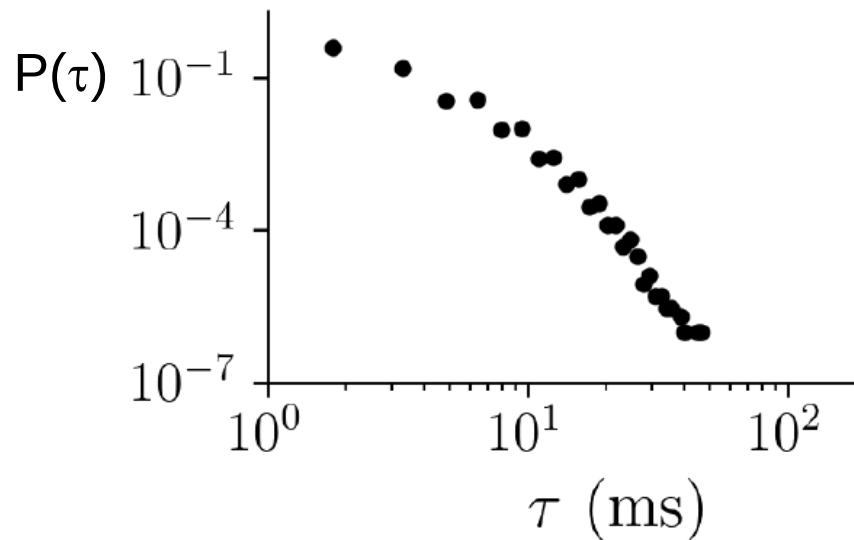
red dashed line: threshold
used to define active bins

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

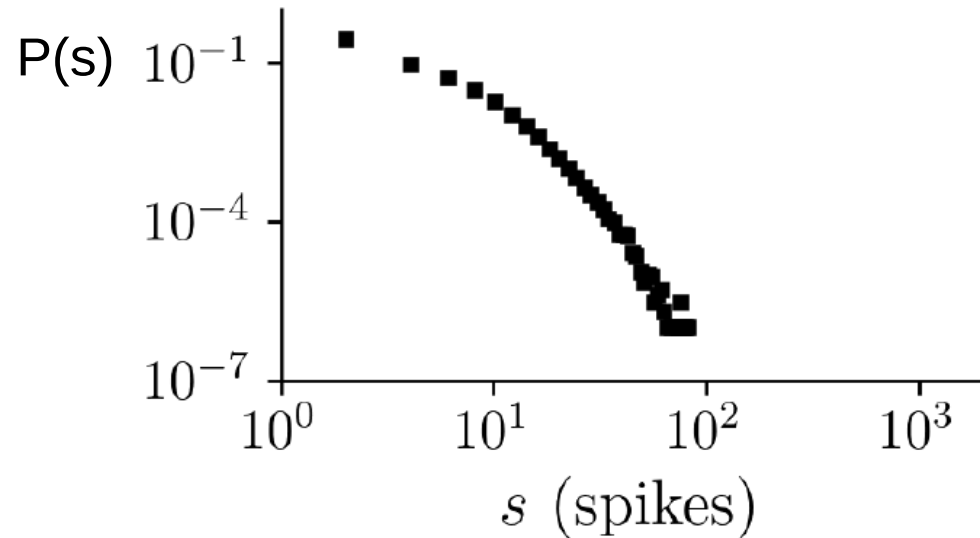
In the asynchronous region (weak coupling)



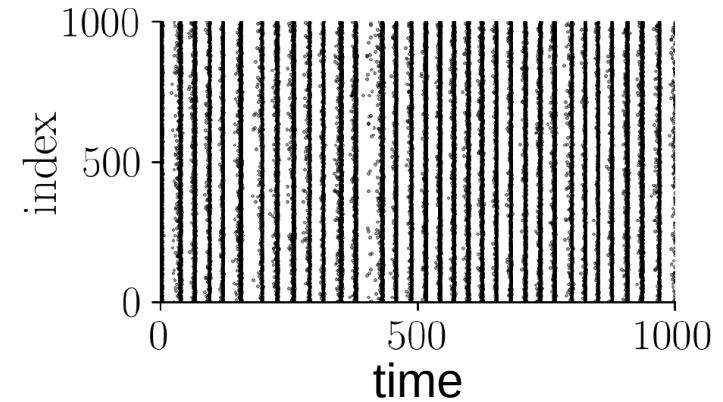
Distribution of avalanche durations



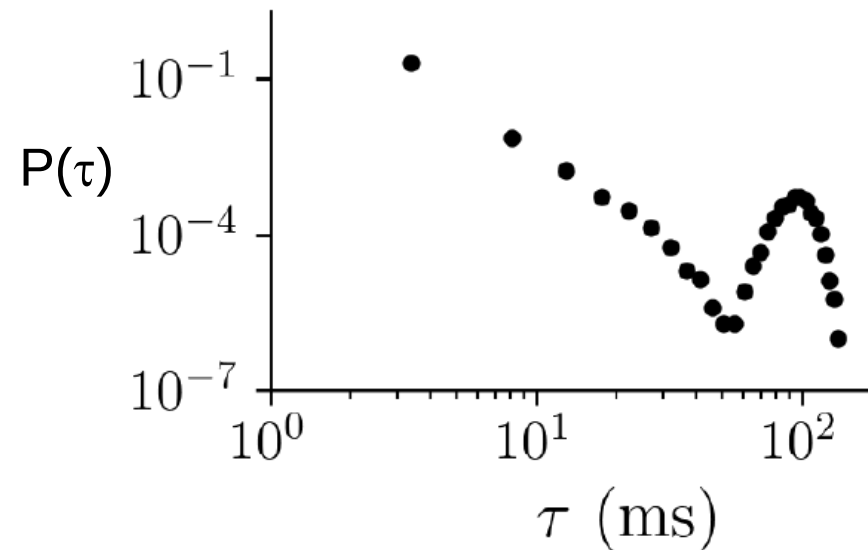
Distribution of avalanche sizes



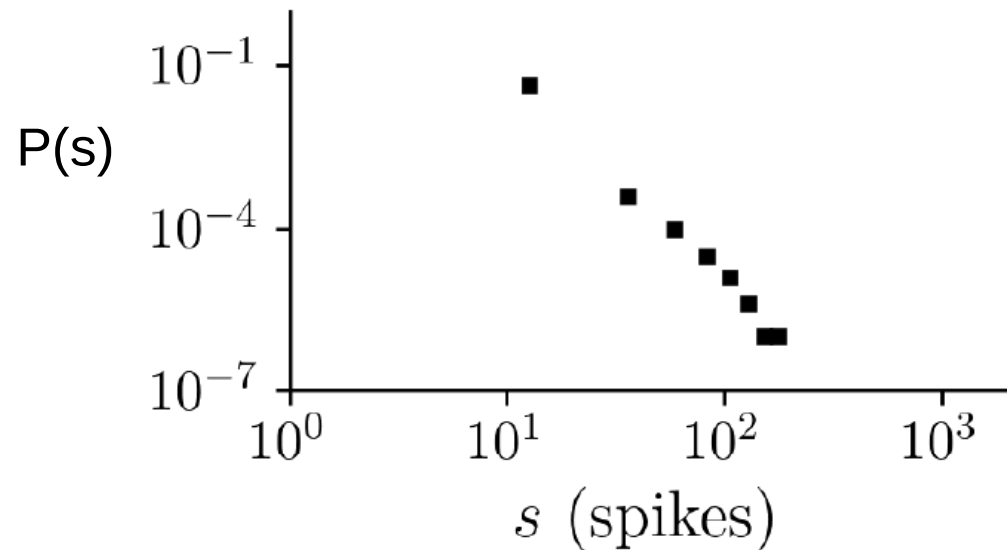
In the “extreme events” region: synchronized spiking due to strong coupling



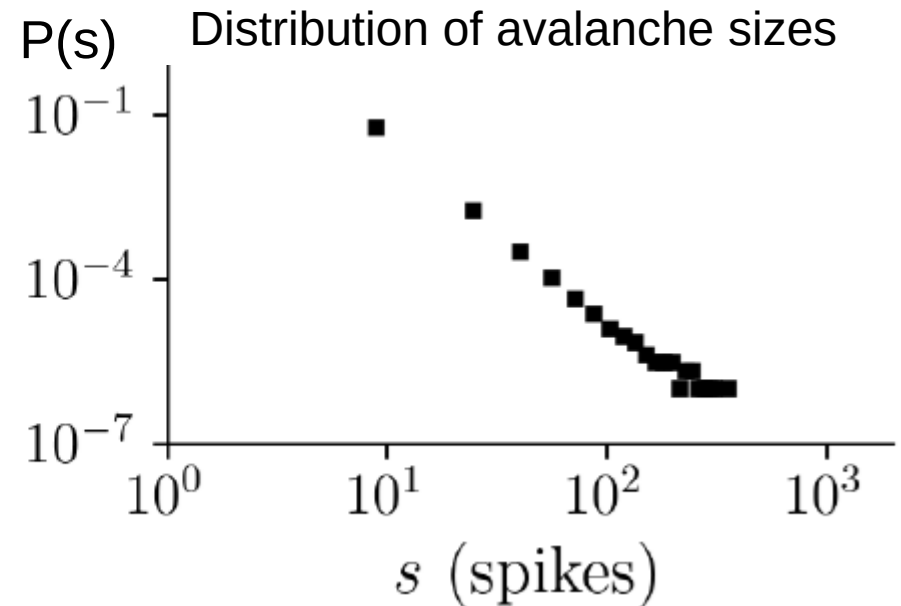
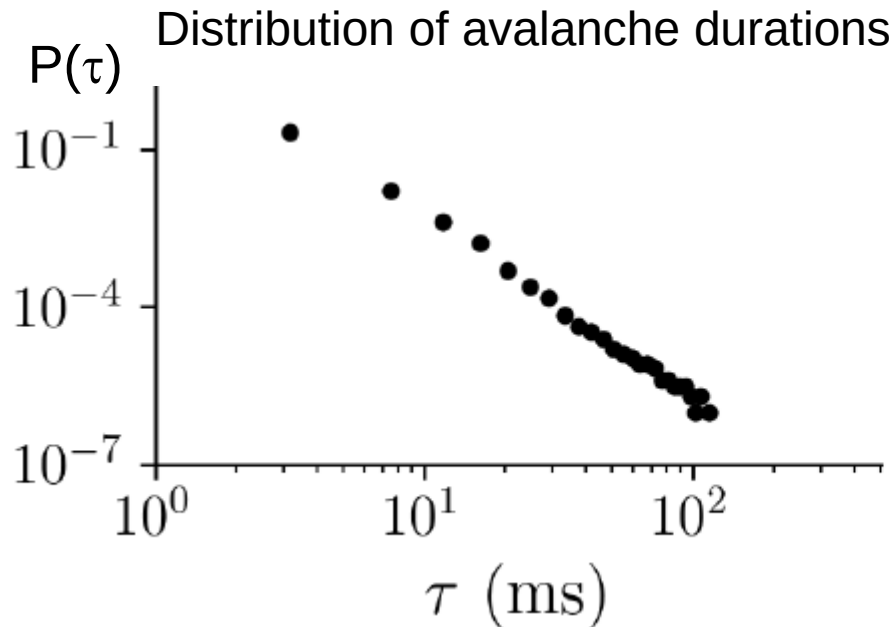
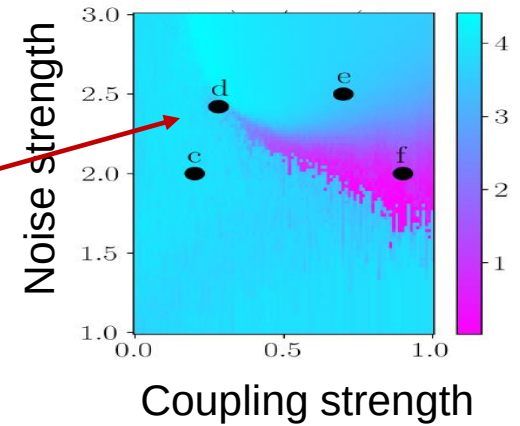
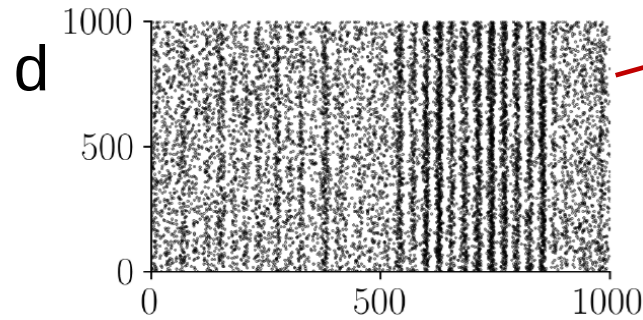
Distribution of avalanche durations



Distribution of avalanche sizes



Critical regime: power laws distributions

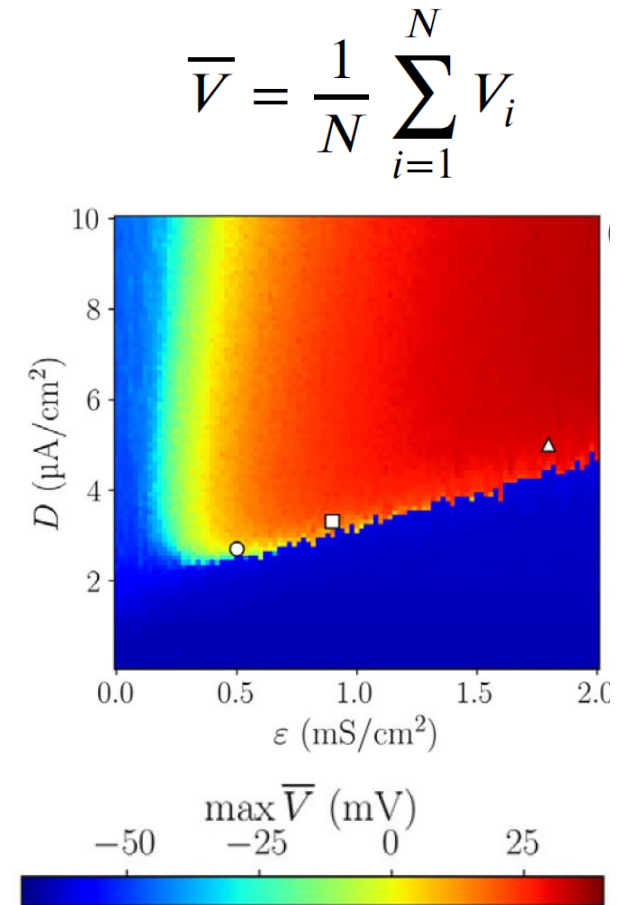


Take home messages (I/II)

Which mechanisms can induce different regimes and trigger transitions?

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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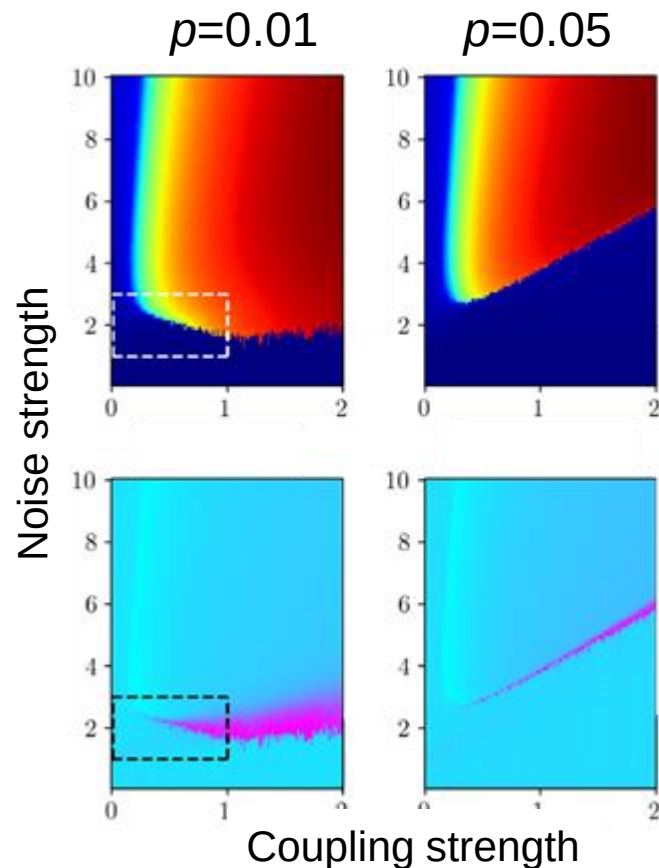
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Take home messages (II/II)

- The entropy of the distribution of the mean field unveils a critical point at the intersection of coupling-driven and noise-driven transitions.
- Sparse connectivity enlarges the critical region.
- 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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