Effects of the topology and delay in a neuronal network

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Outline

- Introduction
  - Importance of delay in neuronal system
  - Network topology
  - Synchronization measure
- Homogeneous delay
  - Rewiring and neighbors dependence
  - Frequency locking
  - Natural frequency dispersion
- Heterogeneous delay
  - Preliminary results
- Anatomical network
- Conclusions & future work

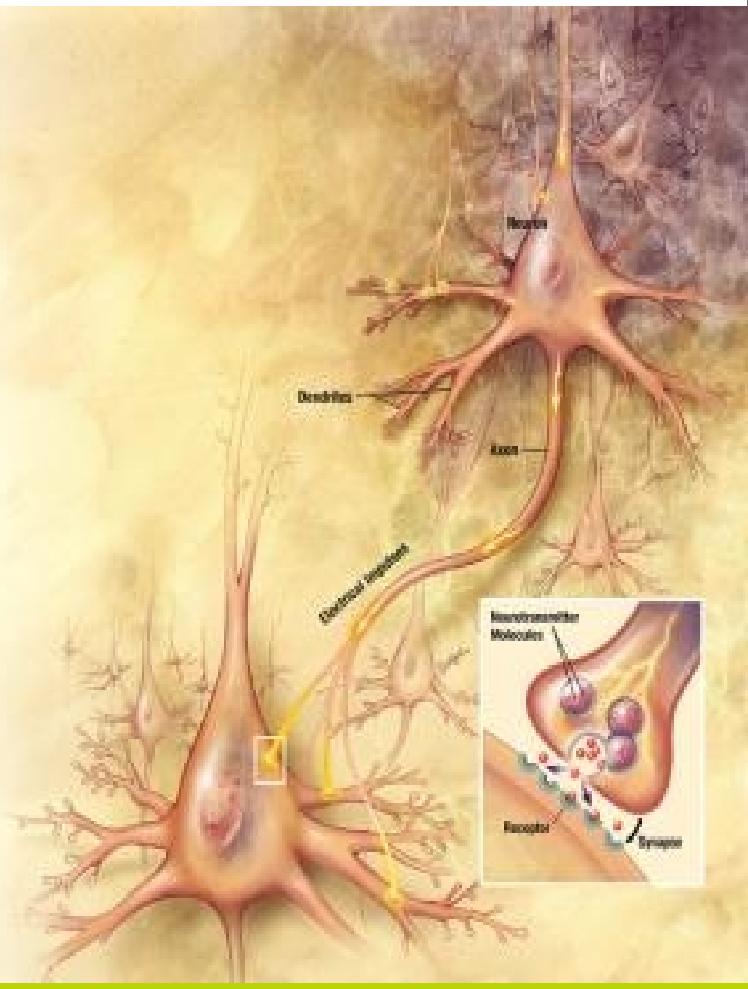
Introduction

> Why consider delay in Neuronal Systems?

- Finite propagation speed
- Chemical reactions
- Latency times of neural excitation
- Integration of information from multiple sources

> Interested in:

- Understand the role of the delay in synchronization



Introduction

> Our system

- 10^3 neurons (Hodking-Huxley model)

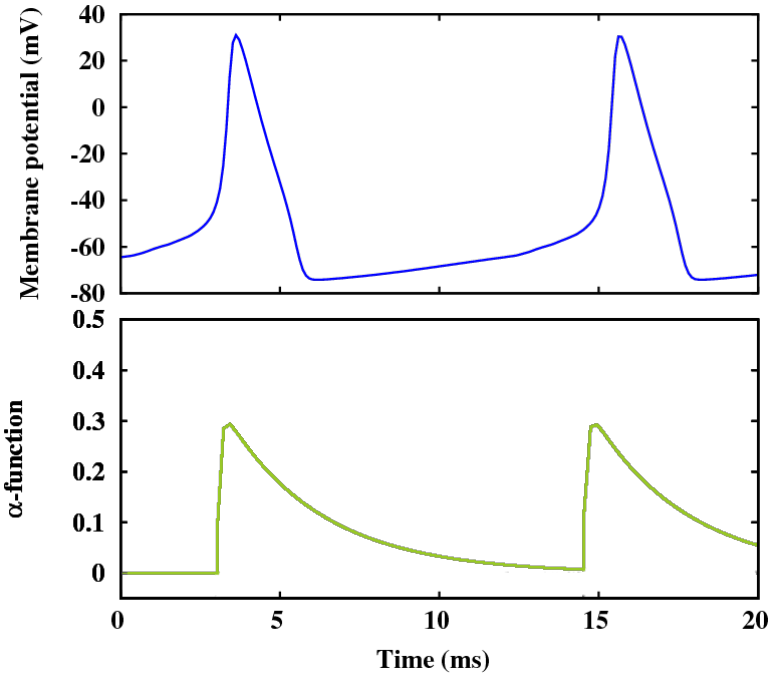
$$C_m \dot{V}_i = I_i - I_i^{ion} - I_i^{syn}$$

- Synaptically connected (α-functions)
- Delay in the connections (τ)

$$I_i^{syn} = -\frac{g_{max}}{n_i} \sum_{spikes(j)} \alpha(t - t_{spikes(j)} - \tau)(V_i(t) - E_{syn})$$

$$\alpha(t) = \frac{1}{\tau_d - \tau_r}(\exp(-t/\tau_d) - \exp(-t/\tau_r))$$

with $\tau_d = 3 \ ms$; $\tau_r = 0.1 \ ms$; $E_{syn} = 0 \ mV$



[Destexhe, Neural. Comp. 6, 1418 (1994)]

> Model details

[Hodgkin-Huxley, J. Physiol. 117, 500 (1952)]

$$C_m \dot{V}_i = I^{app} - I_i^{ion} - I_i^{syn}$$

$$I_i^{ion} = -g_{Na} m^3 h (V_i - E_{Na}) - g_K n^4 (V_i - E_K) - g_L (V_i - E_L)$$

with gatering variable dynamics

$$\dot{m} = \alpha_m(V)(1-m) - \beta_m(V) m$$
$$\dot{n} = \alpha_n(V)(1-n) - \beta_n(V) n$$
$$\dot{h} = \alpha_h(V)(1-h) - \beta_h(V) h$$

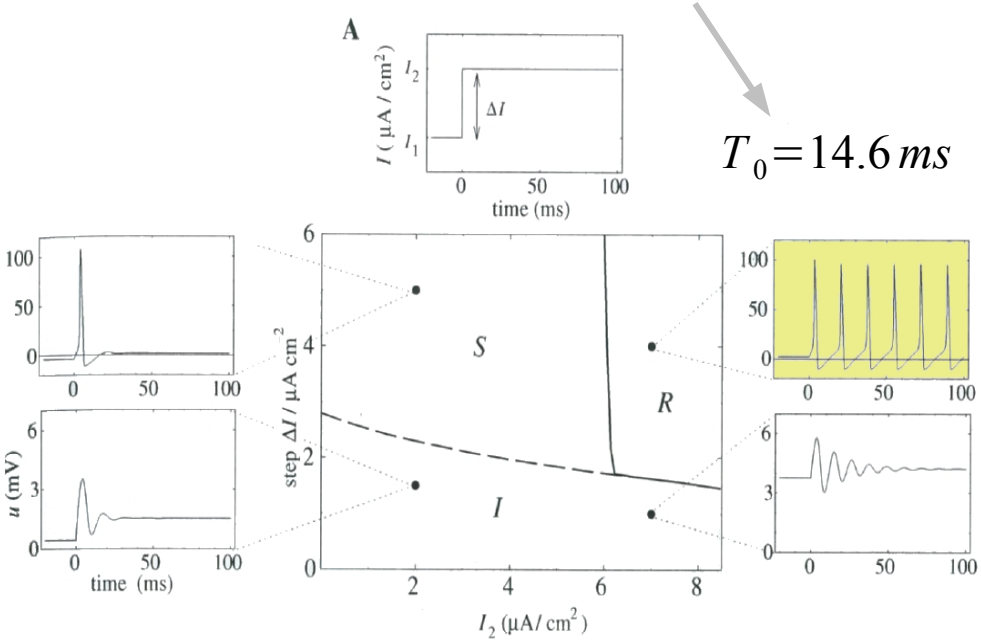
> Parameters

x	E_x	g_x
Na	115 mV	120 mS/cm^2
K	-12 mV	36 mS/cm^2
L	10.6mV	0.3mS/cm^2

x	$\alpha_x(u/\mathrm{mV})$	$\beta_x(u/\mathrm{mV})$
n	$(0.1-0.01\,u)/[\exp(1-0.1\,u)-1]$	$0.125\exp(-u/80)$
m	$(2.5-0.1\,u)/[\exp(2.5-0.1\,u)-1]$	$4\exp(-u/18)$
h	$0.07\exp(-u/20)$	$1/[\exp(3-0.1\,u)+1]$

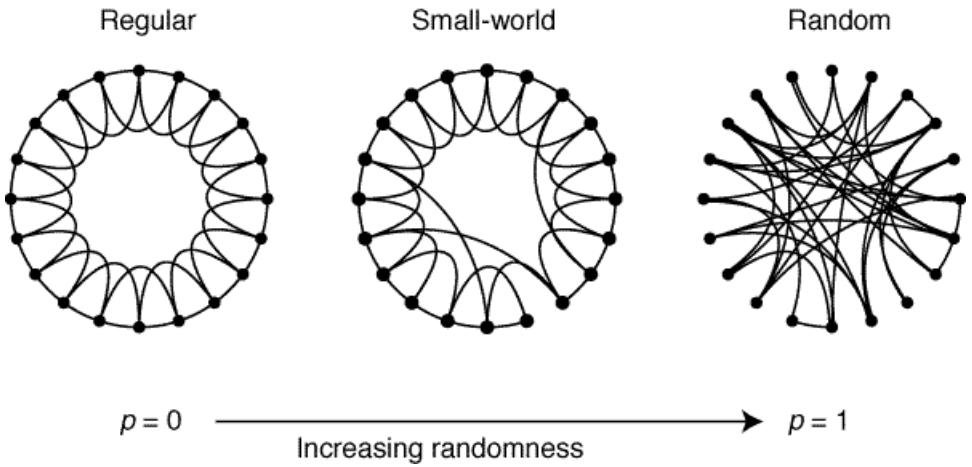
> Operation regime $I^{app} = 10\,\mu A/cm^2$

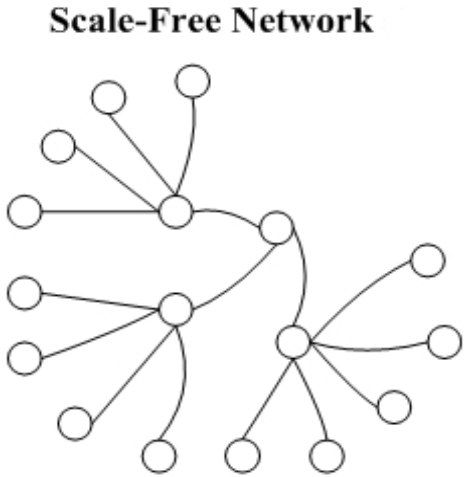
$T_0 = 14.6\,ms$

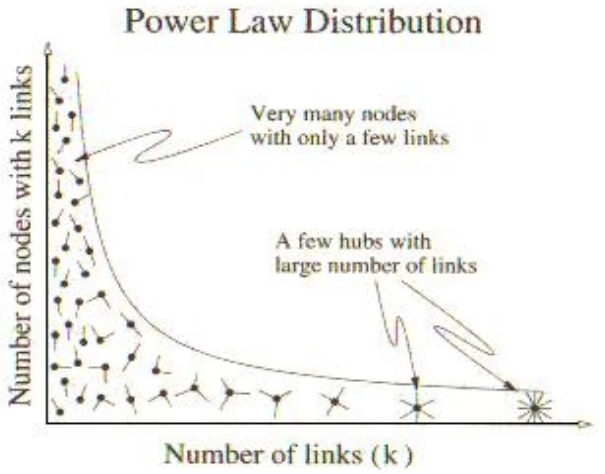


Introduction

- Network topology
  - Regular
  - Small-world
  - Random
  - Scale-free
  - Mean-field (all2all)



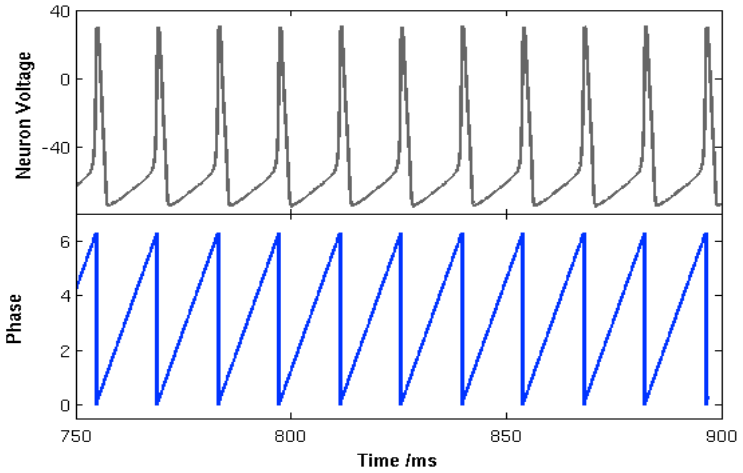




Introduction

- Synchronization measure
  - Phase of each neuron

$$\phi_i(t) = 2\pi \frac{t-\tau_k}{\tau_{k+1}-\tau_k}$$



  - Local order parameter

$$s_i(t) = \frac{1}{n_i} \sum_{j \in neigh(i)} \sin^2\left(\frac{\phi_i(t)-\phi_j(t)}{2}\right)$$

$$S^{loc} = \lim_{T\to\infty} \frac{1}{T}\int_0^T \left(\frac{1}{N}\sum_{i=1}^{N} s_i\right) dt$$

  - Global order parameter

$$s_i'(t) = \frac{1}{N}\sum_{j=1}^{N} \sin^2\left(\frac{\phi_i(t)-\phi_j(t)}{2}\right)$$

$$S^{glob} = \lim_{T\to\infty} \frac{1}{T}\int_0^T \left(\frac{1}{N}\sum_{i=1}^{N} s_i'\right) dt$$

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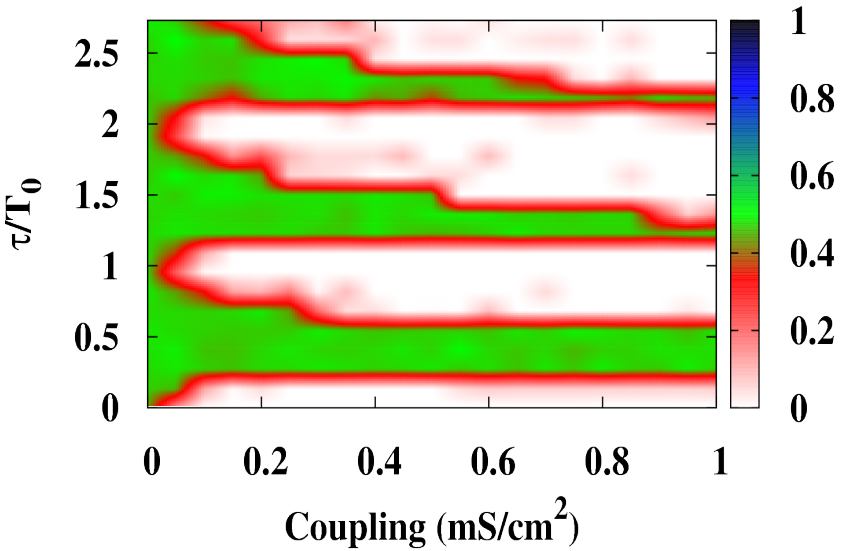
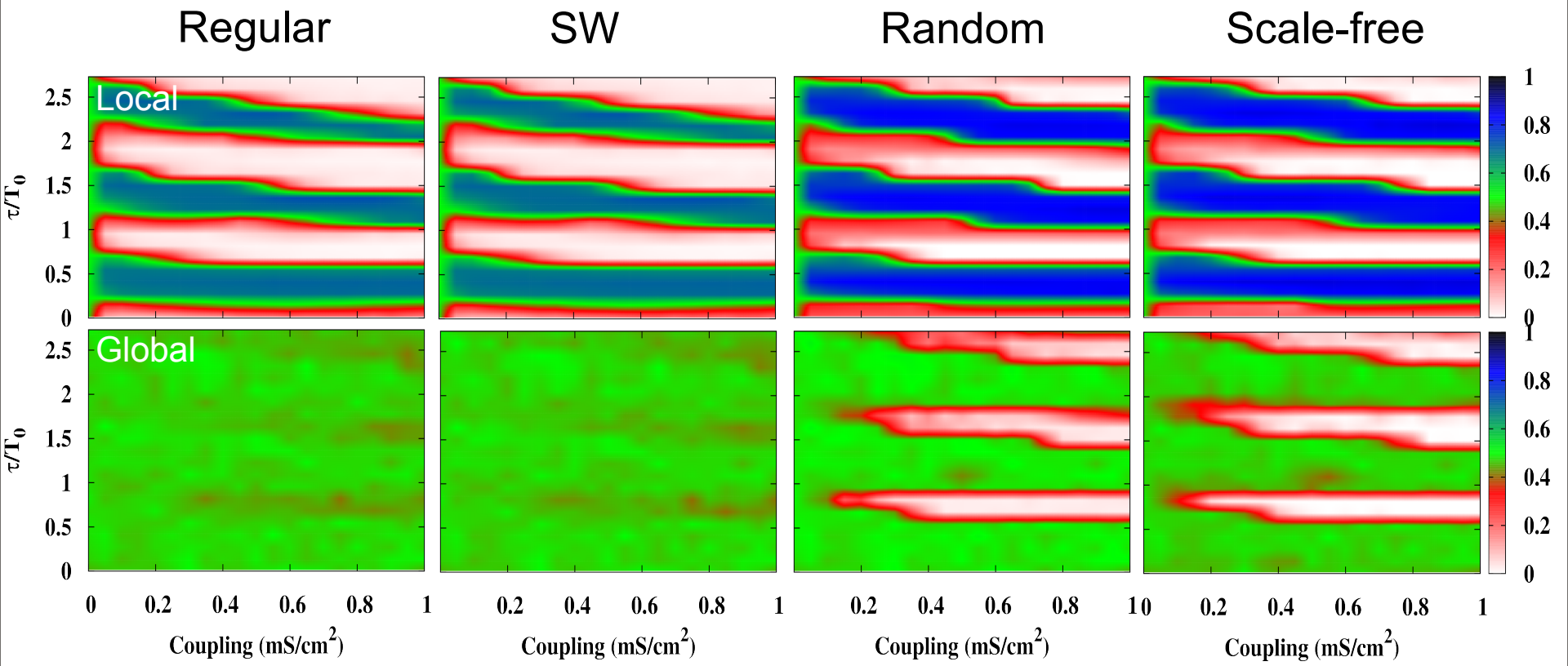
Synchronization regions

Mean-field (all-to-all)



Local and global synchronization regions



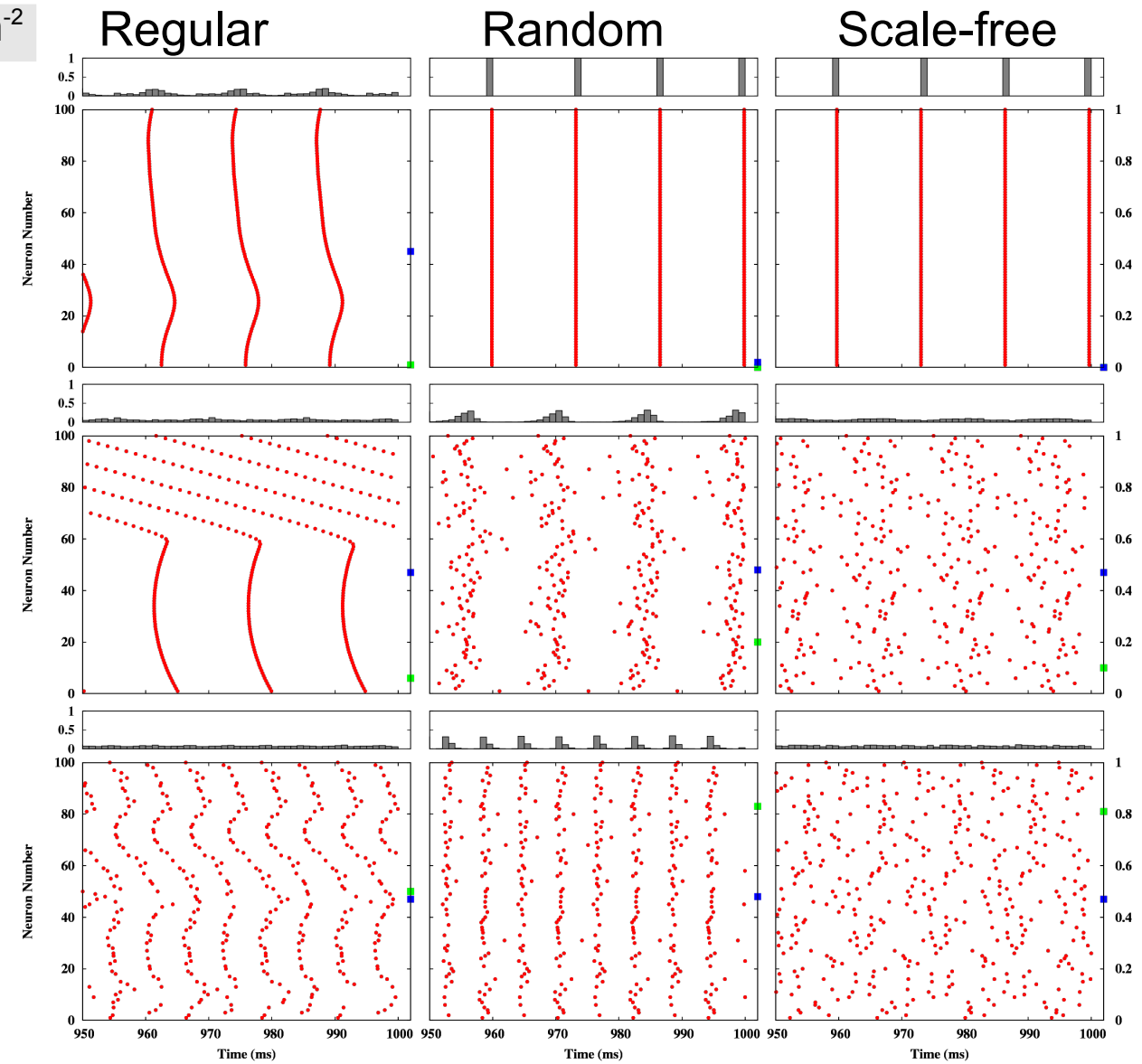
Raster plots and firing histograms

coupling: 0.8 mS cm^{-2}

τ: 12 ms

τ: 14 ms

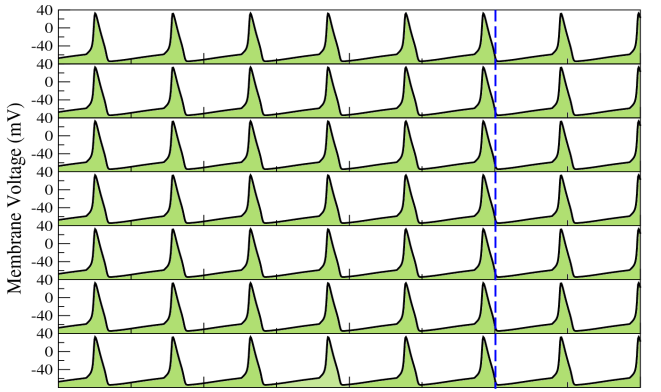
τ: 16 ms



Membrane voltage traces (Random Network)

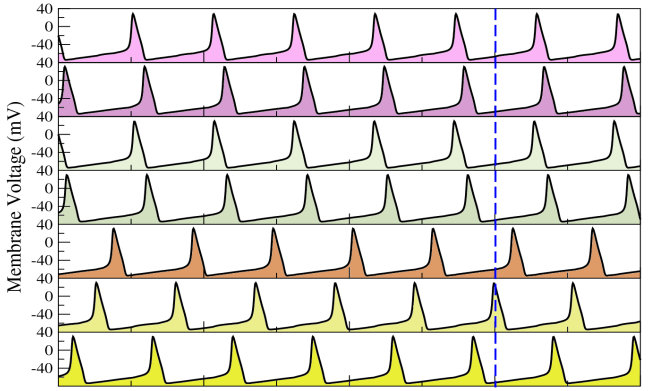
coupling: 0.8 mS cm^{-2}

τ: 12 ms



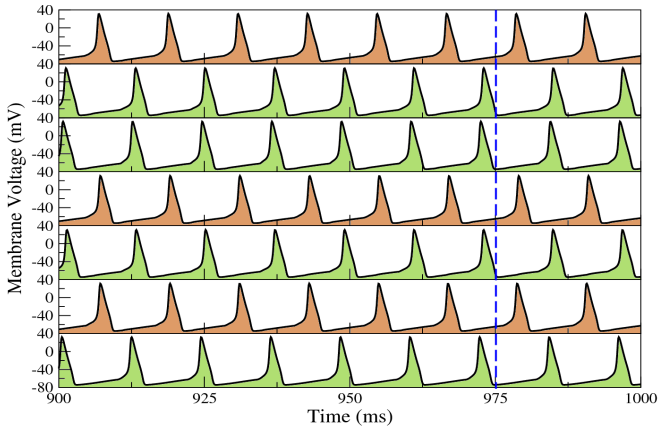
in-phase state

τ: 14 ms



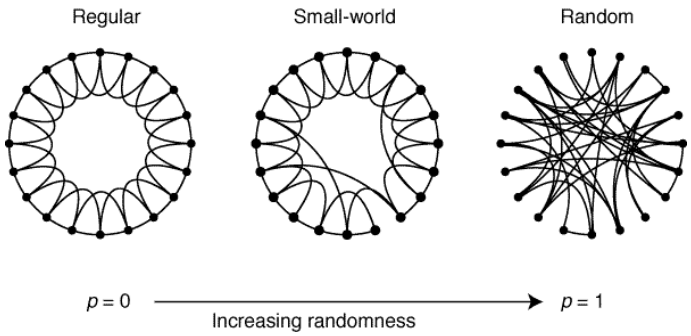
out-of-phase state

τ: 16 ms



anti-phase state

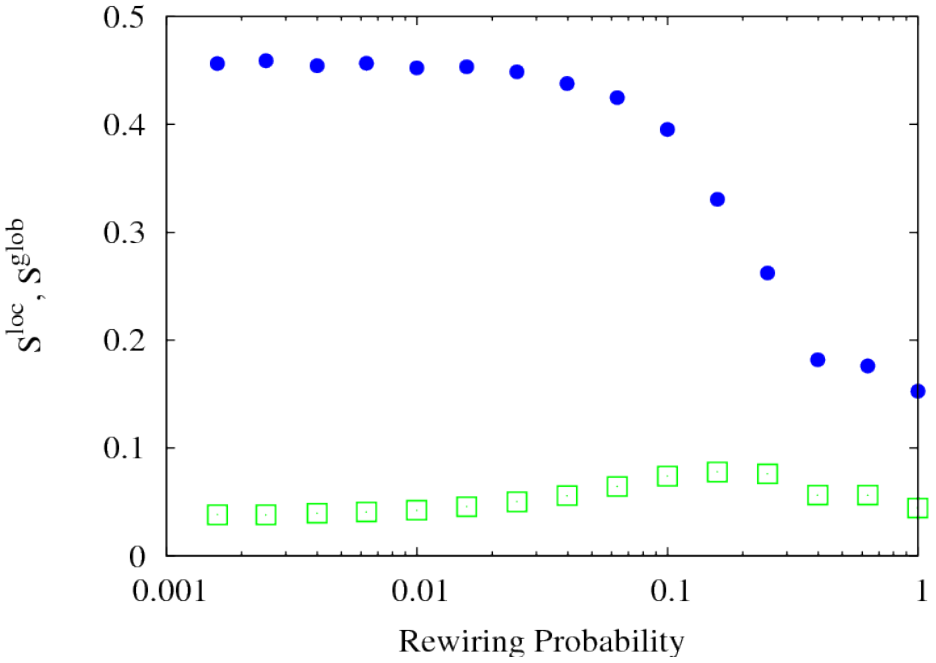
Rewiring dependence



coupling: 0.2 mS cm^{-2}

delay: 12 ms

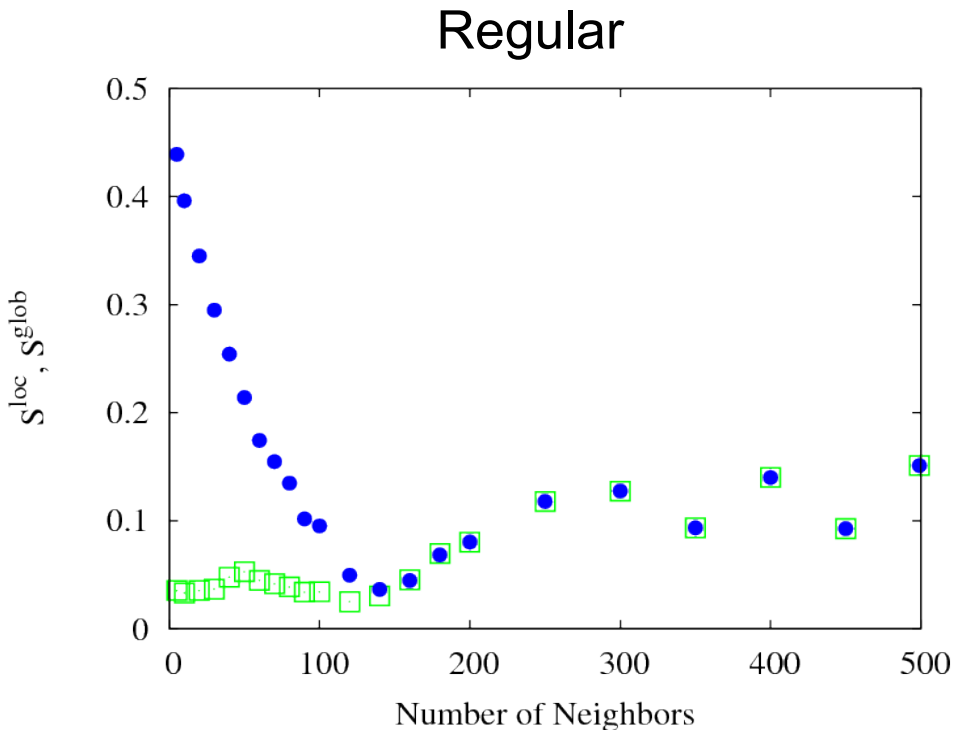
SW Random



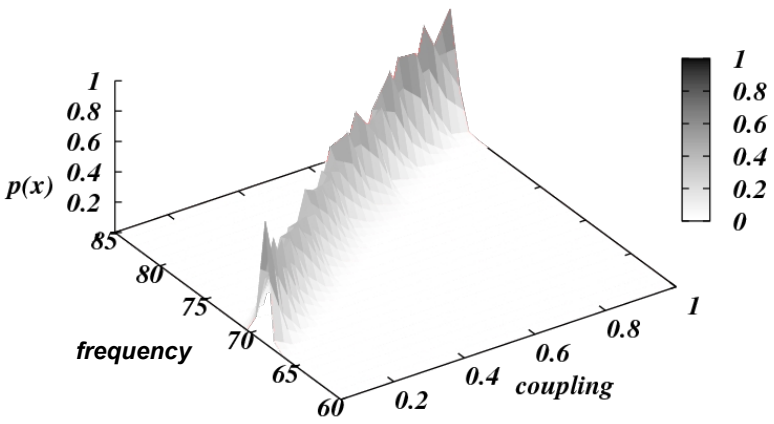
Effect of the neighbors

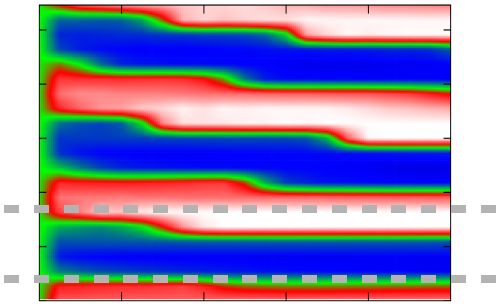
coupling: 0.2 mS cm^{-2}

delay: 12 ms



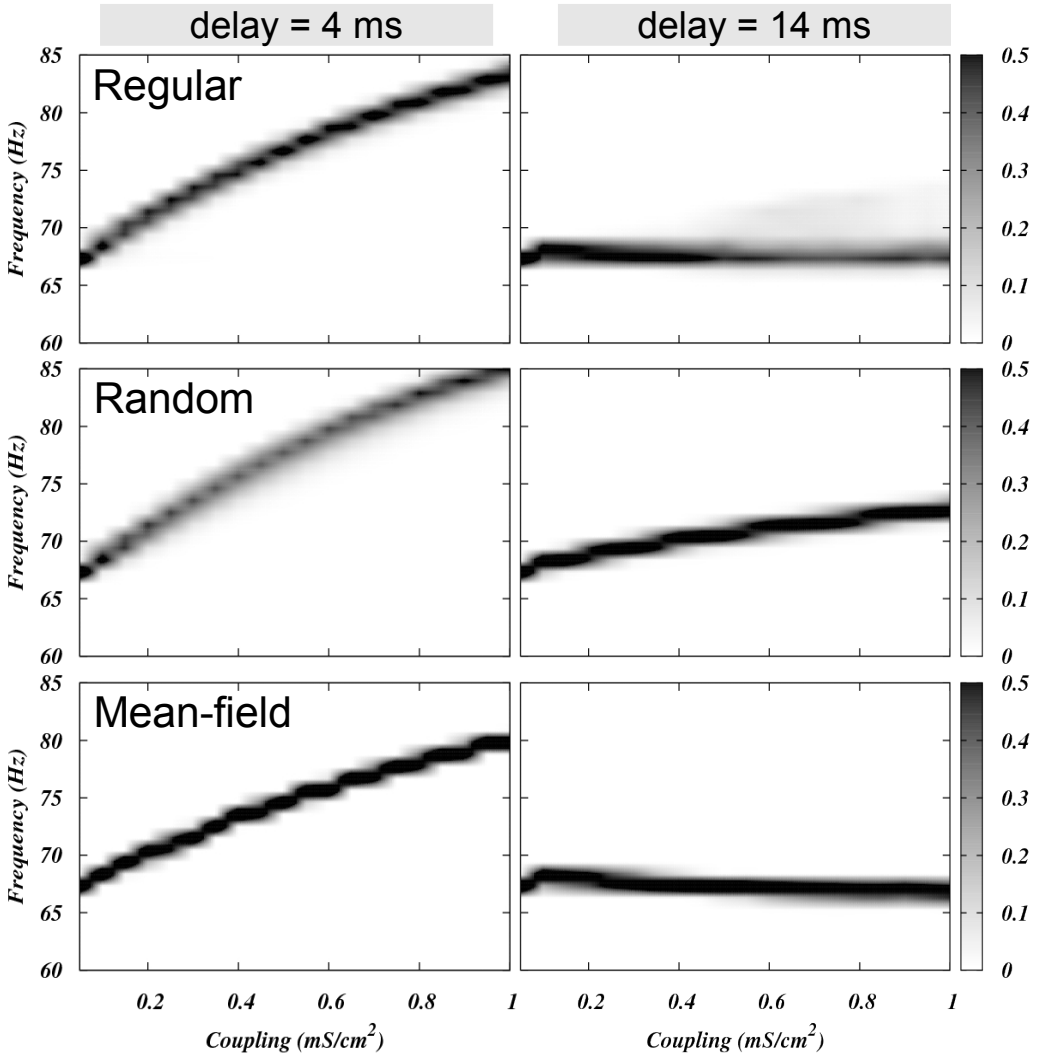
Frequency locking



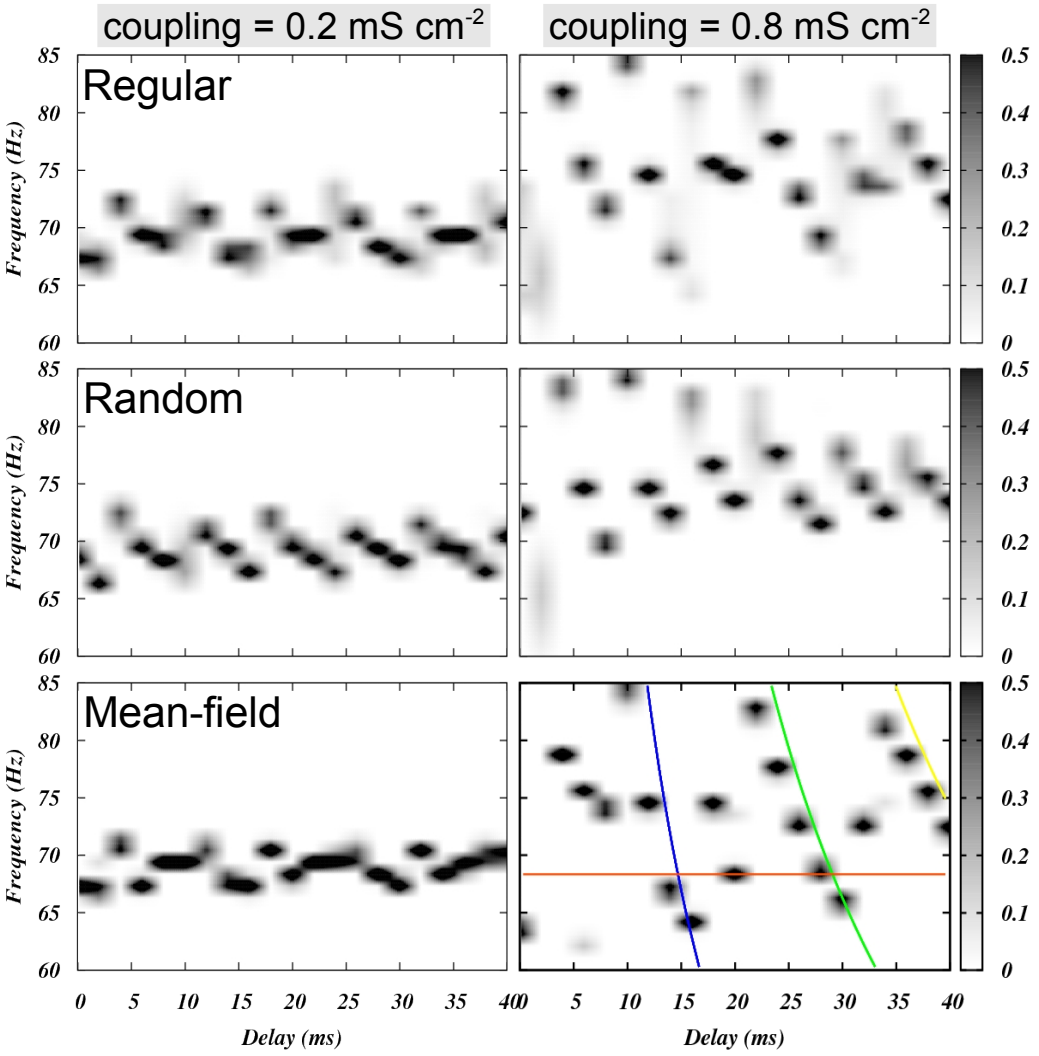


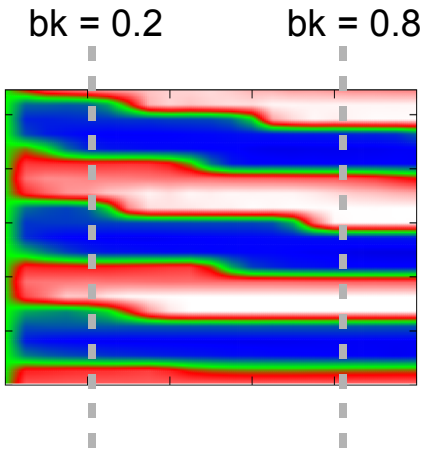
τ = 14 ms

τ = 4 ms



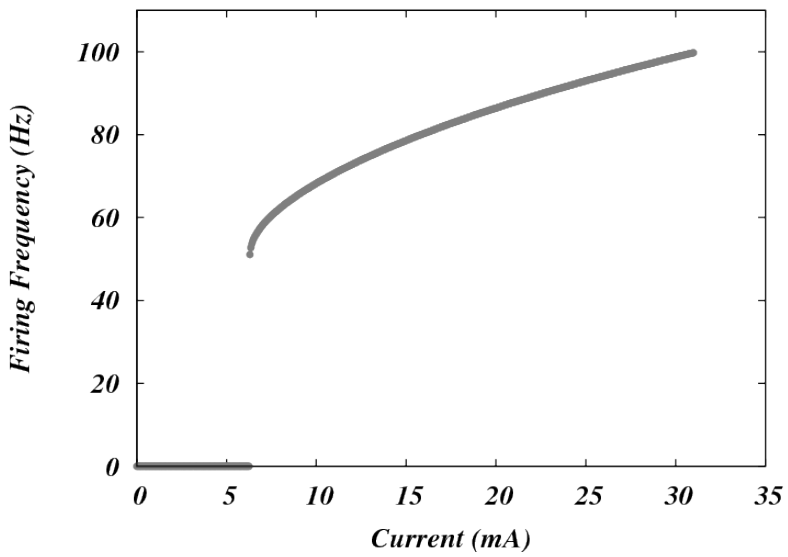
Frequency locking

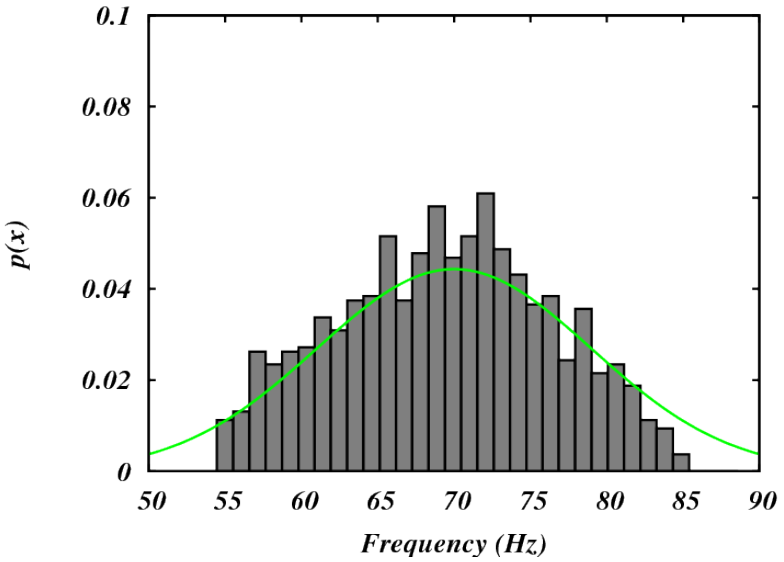




> Gaussian distribution of natural frequencies (f_m=70 Hz ; σ^2=9 Hz^2)

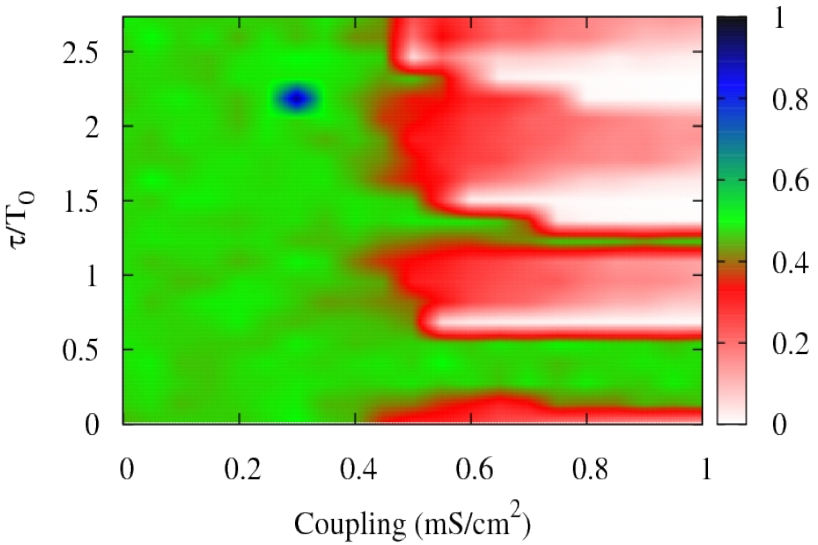
Excitable type II



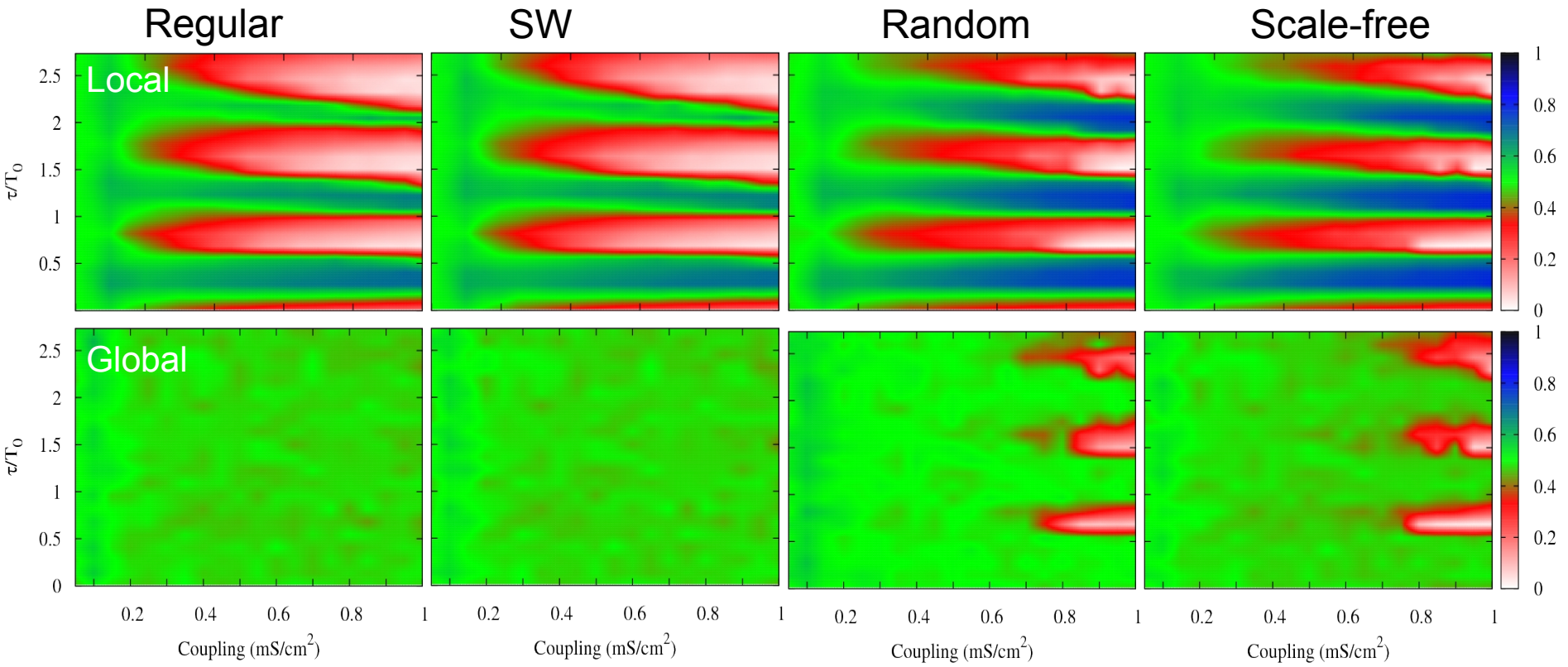


> Gaussian distribution of natural frequencies (f_m=70 Hz ; σ^2=9 Hz^2)

Mean-field (all-to-all)



> Gaussian distribution of natural frequencies (f_m=70 Hz ; σ^2=9 Hz^2)



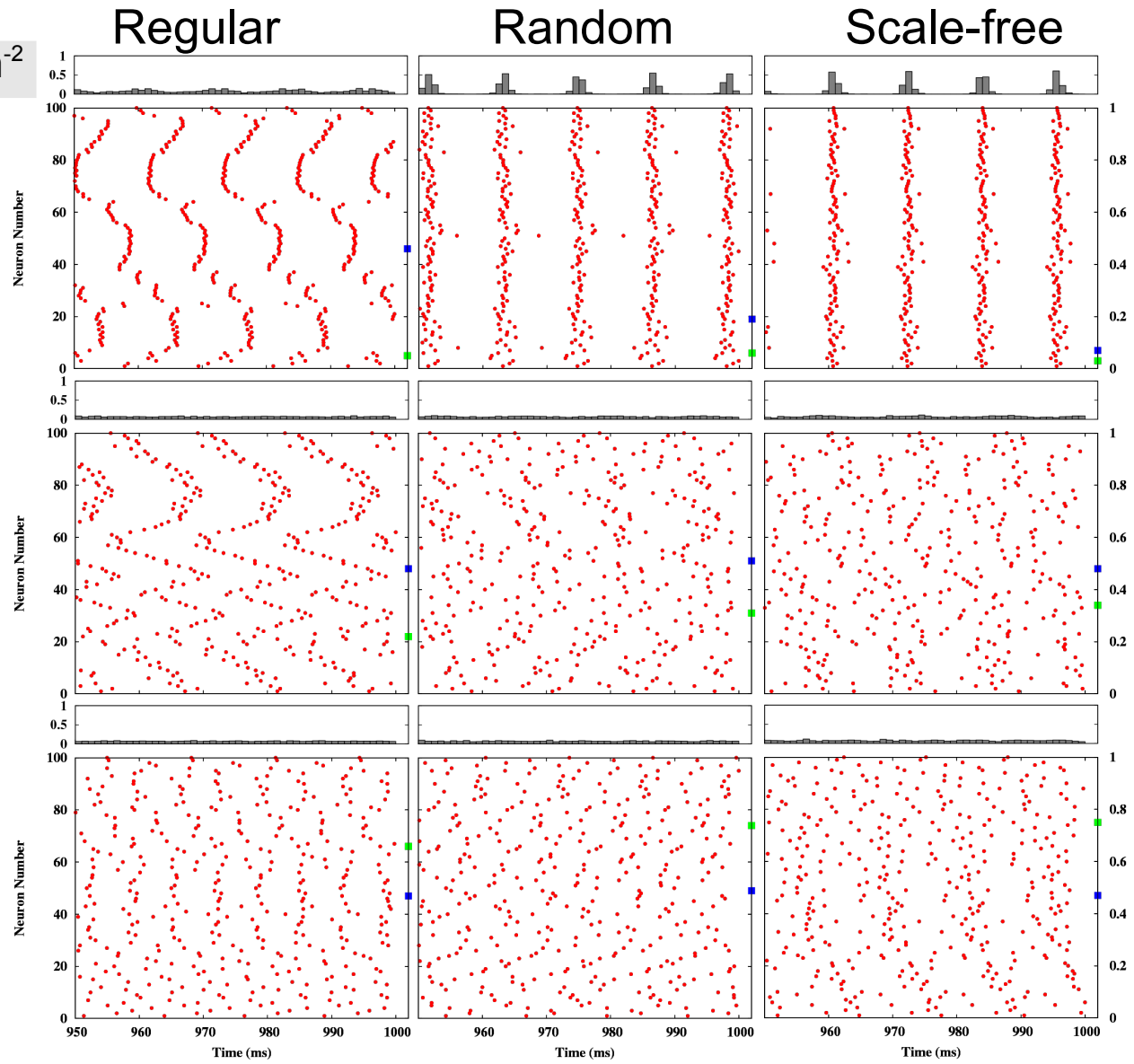
Raster plots and firing histograms

coupling: 0.8 mS cm^{-2}

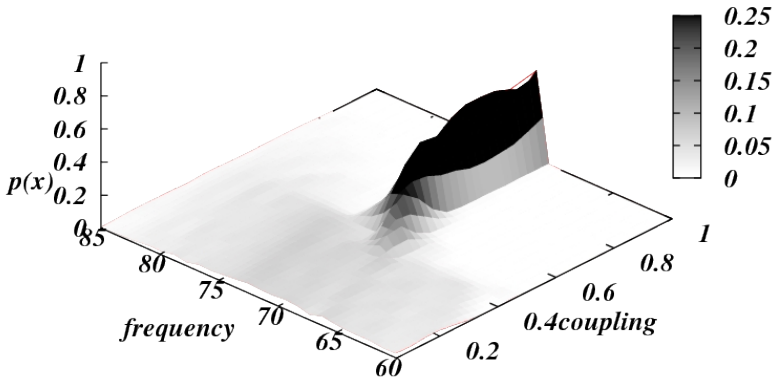
τ: 10 ms

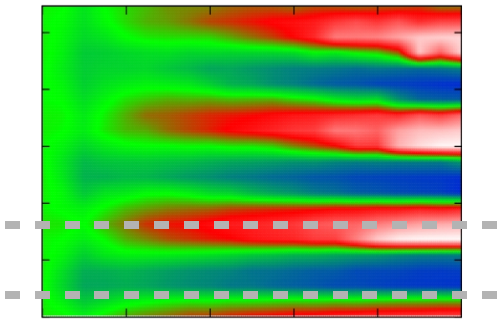
τ: 14 ms

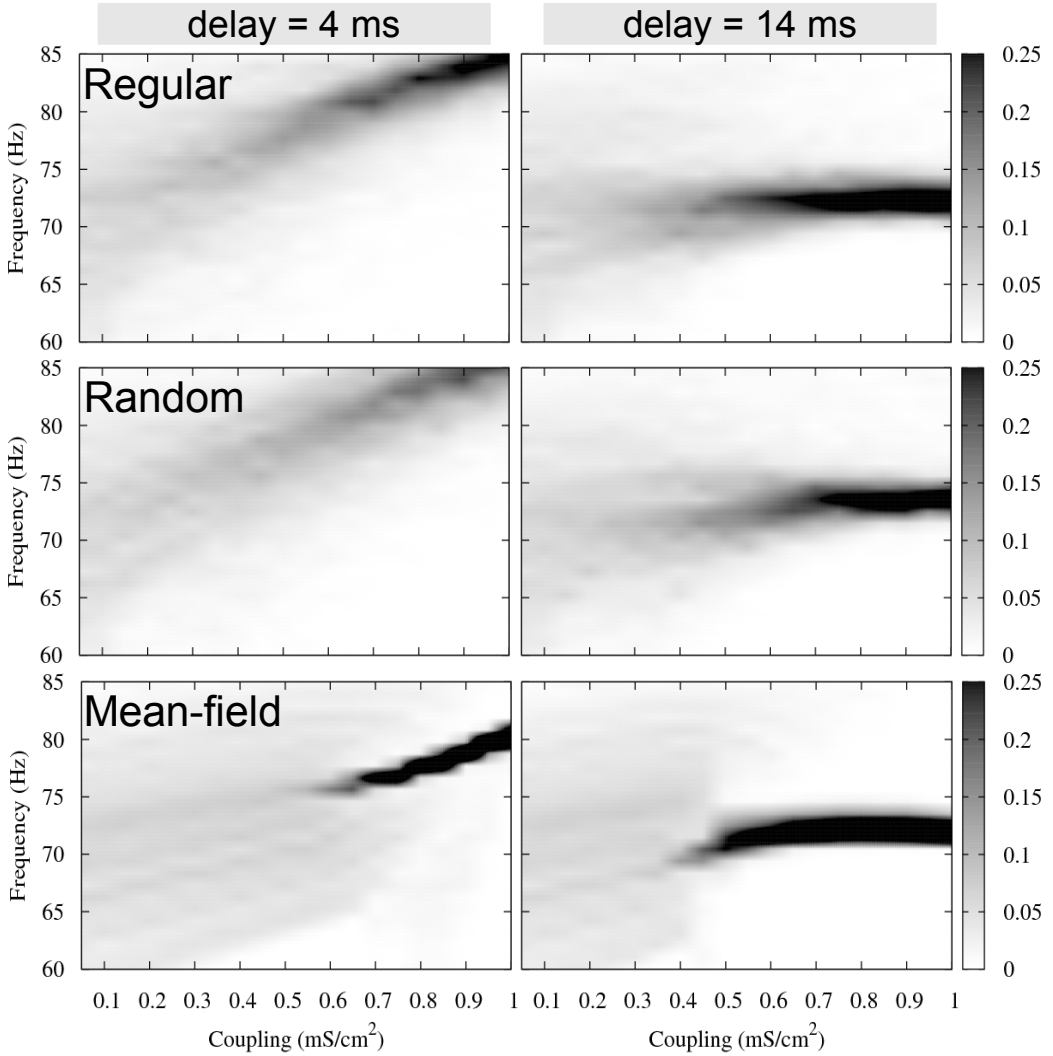
τ: 18 ms



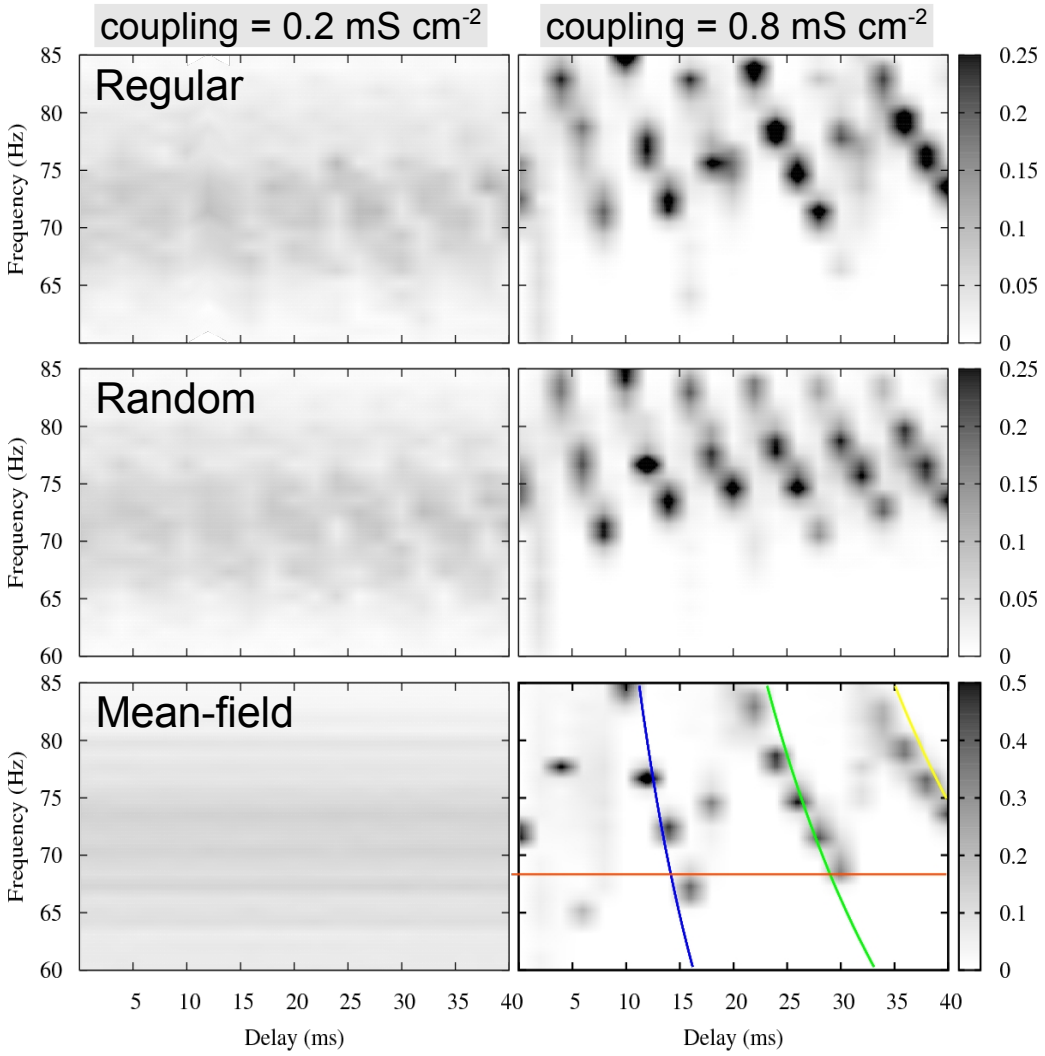
Frequency locking (Gaussian distribution of natural frequencies)

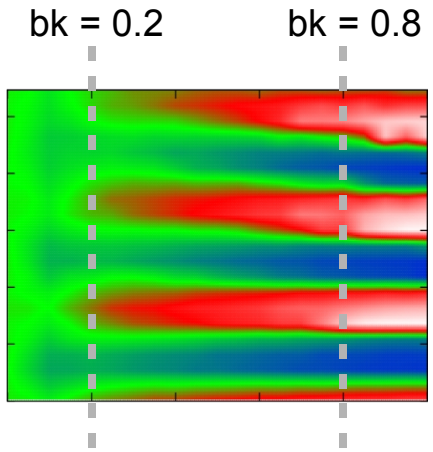






Frequency locking (Gaussian distribution of natural frequencies)



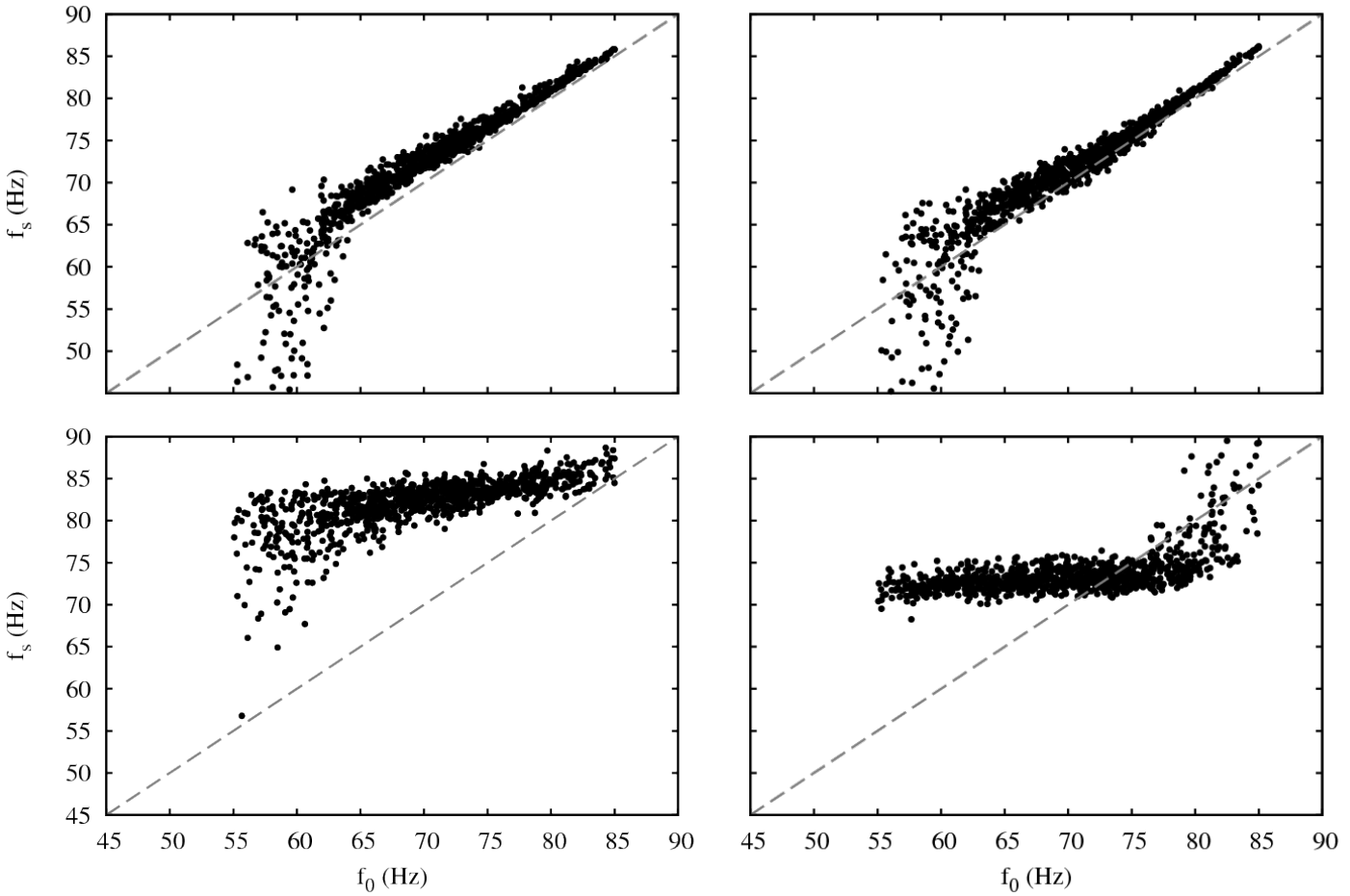


Frequency distribution

Random

delay: 4 ms

delay:14 ms



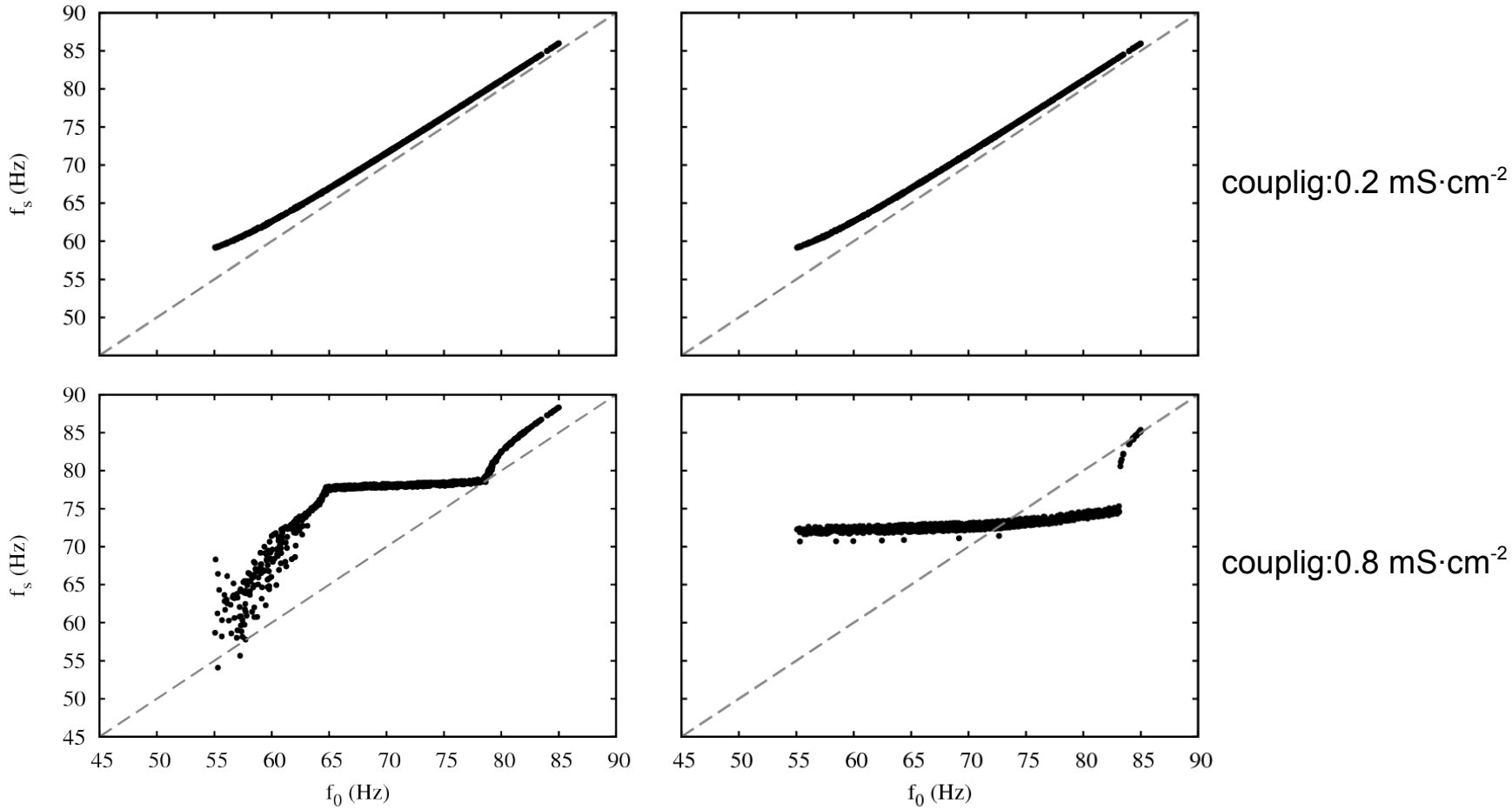
couplig:0.2 mS·cm^{-2}

couplig:0.8 mS·cm^{-2}

Frequency distribution Mean-field (all-to-all)

delay: 4 ms

delay:14 ms



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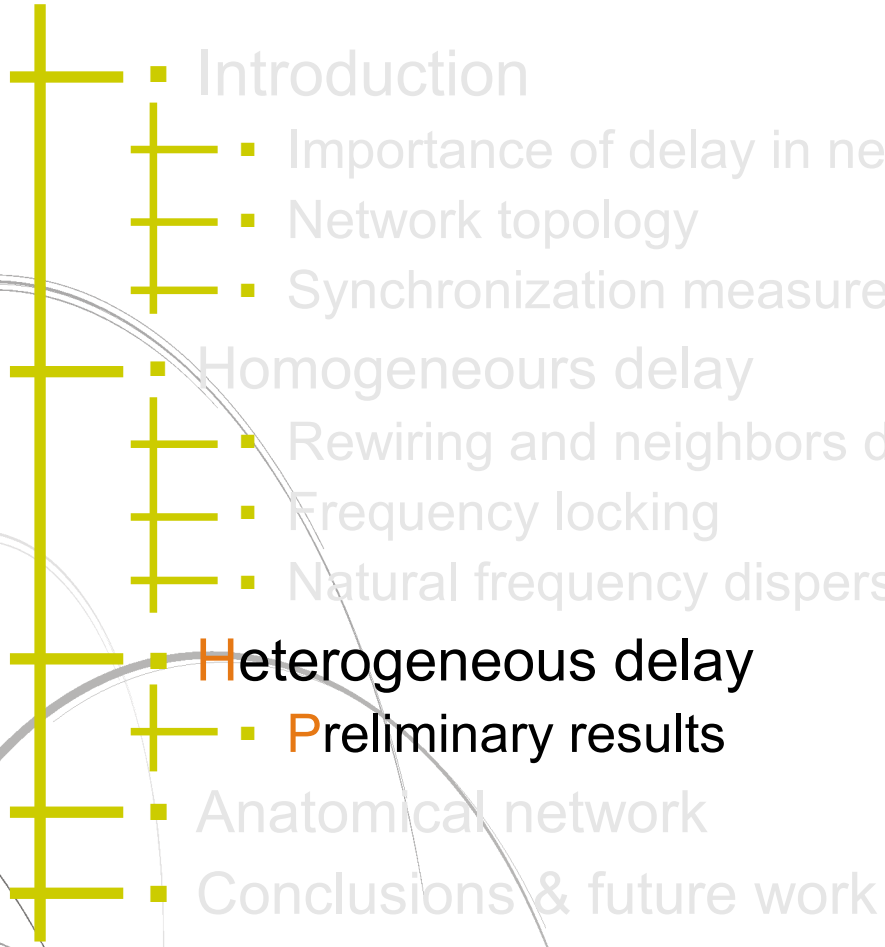
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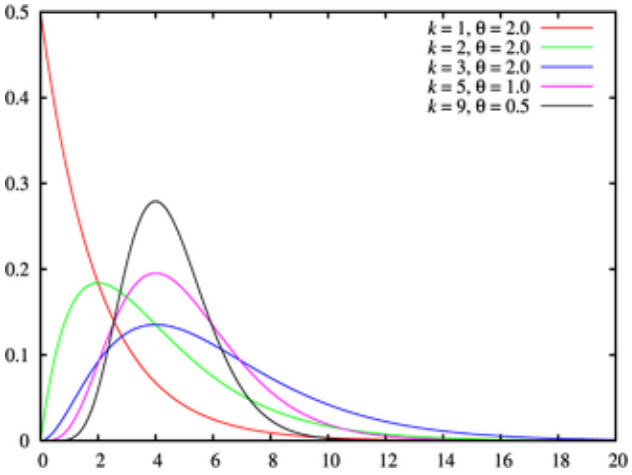
Heterogeneous delays

- Gamma distribution

$$f(x;k;\theta)=x^{k-1}\frac{e^{-x/\theta}}{\theta^{k}\,\Gamma(k)} \qquad for\ x>0 \quad ; \quad k,\theta>0$$



- Mean:

$$\langle\tau\rangle = k\,\theta$$

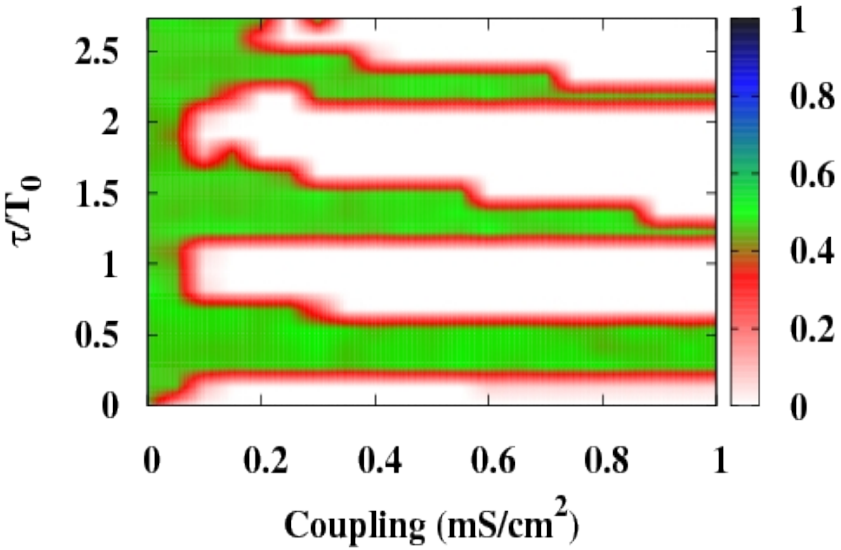
- Variance:

$$\sigma^{2} = k\,\theta^{2}$$

Synchronization regions

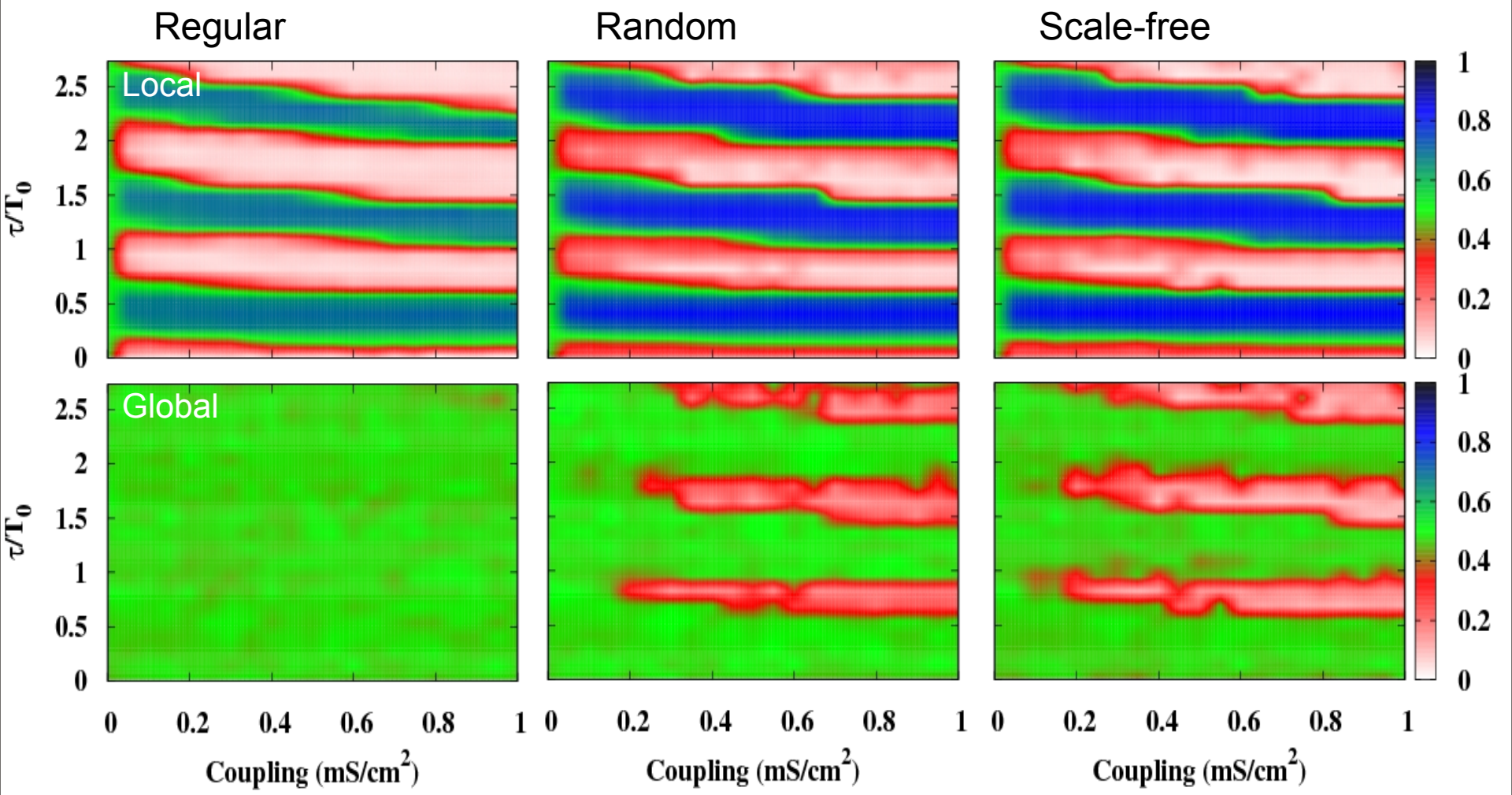
$\sigma^2 = 0.5\ ms^2$

Mean-field (all-to-all)



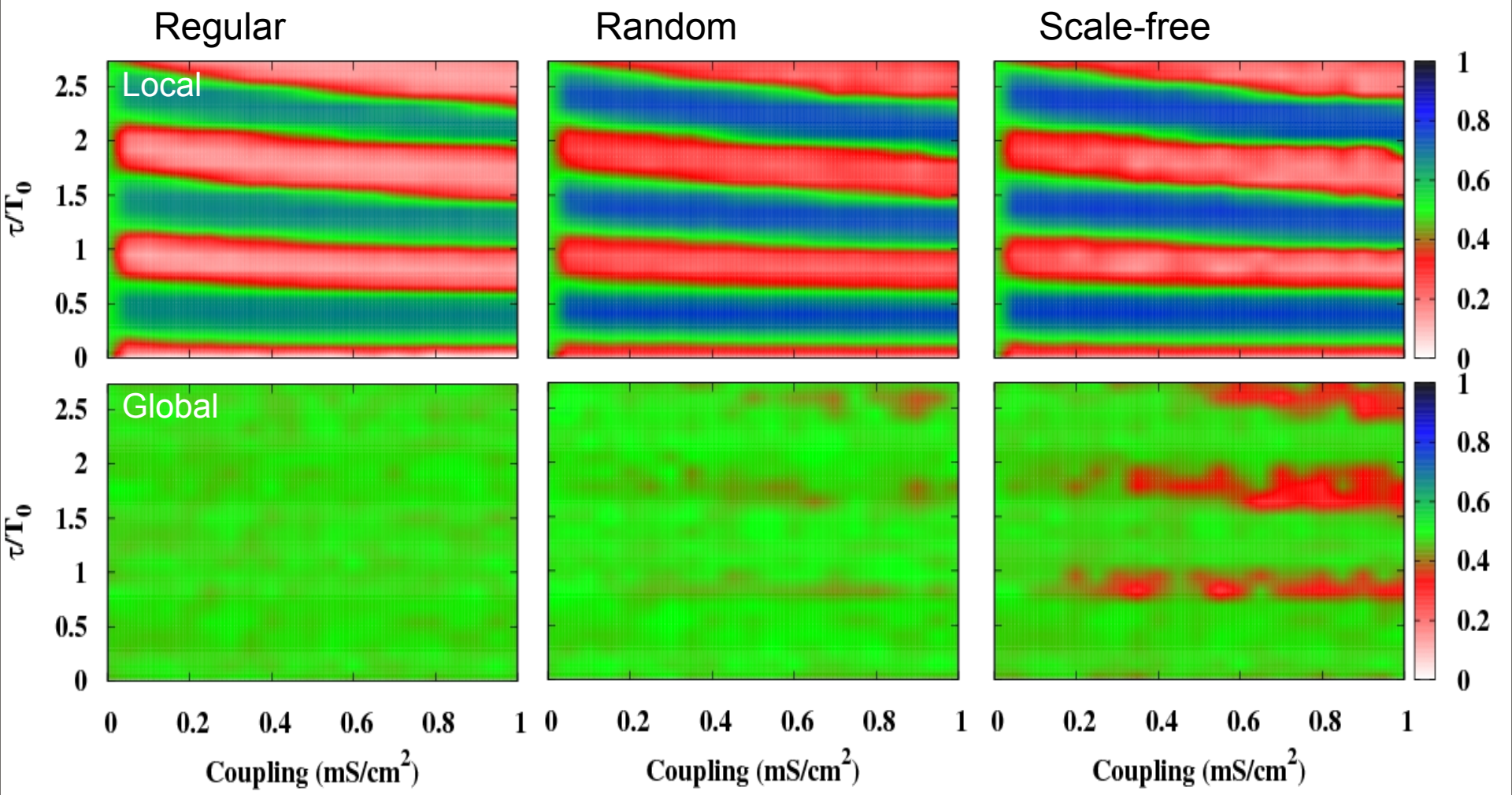
Local versus global synchronization

$\sigma^2 = 0.5\ ms^2$

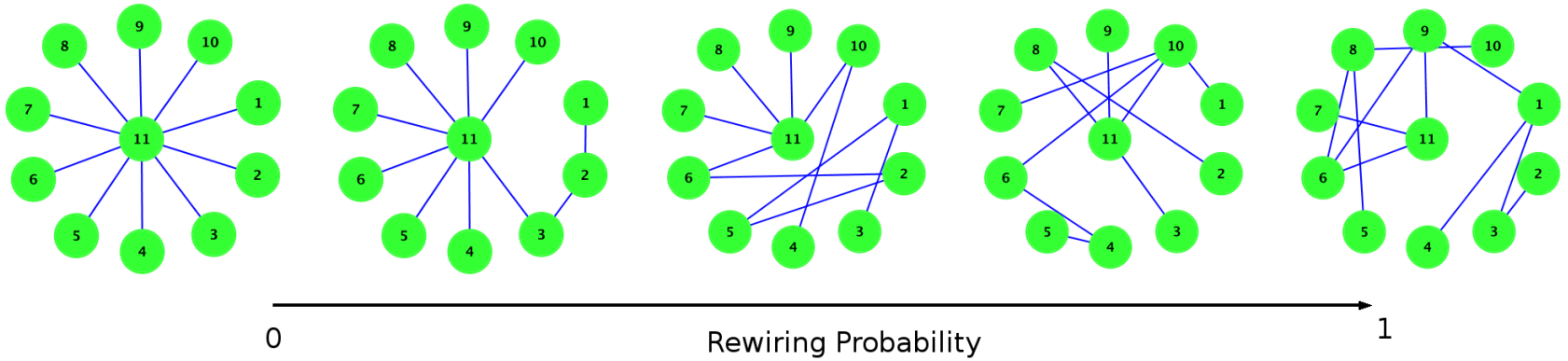


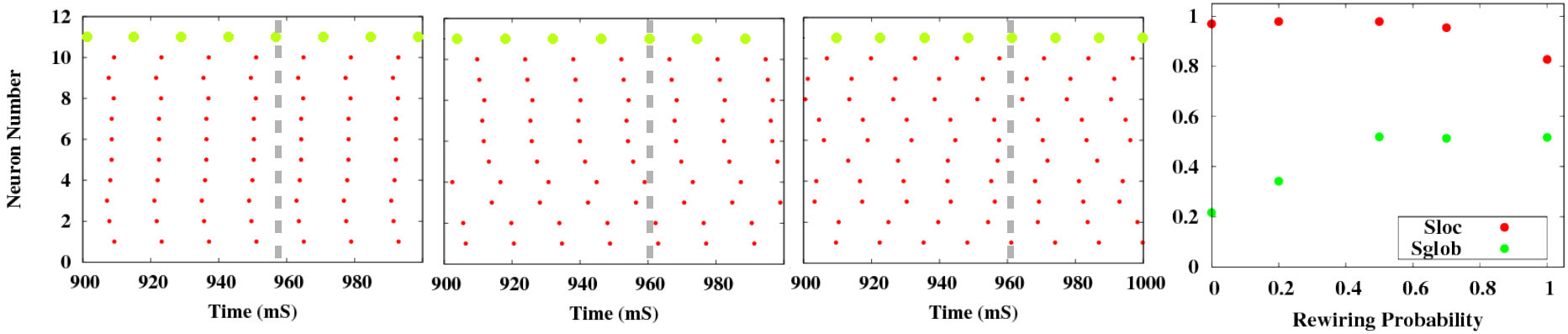
Local versus global synchronization

$\sigma^2 = 2\ ms^2$



Simple example





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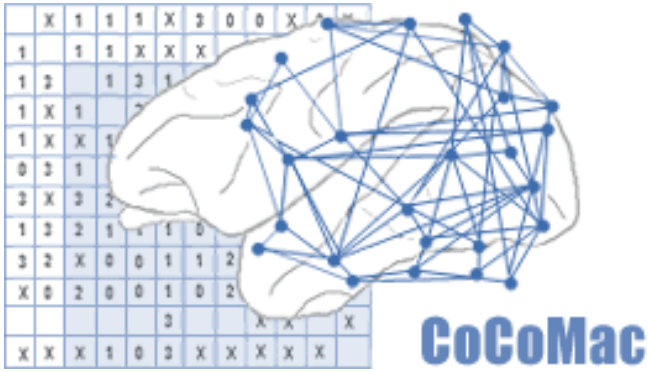
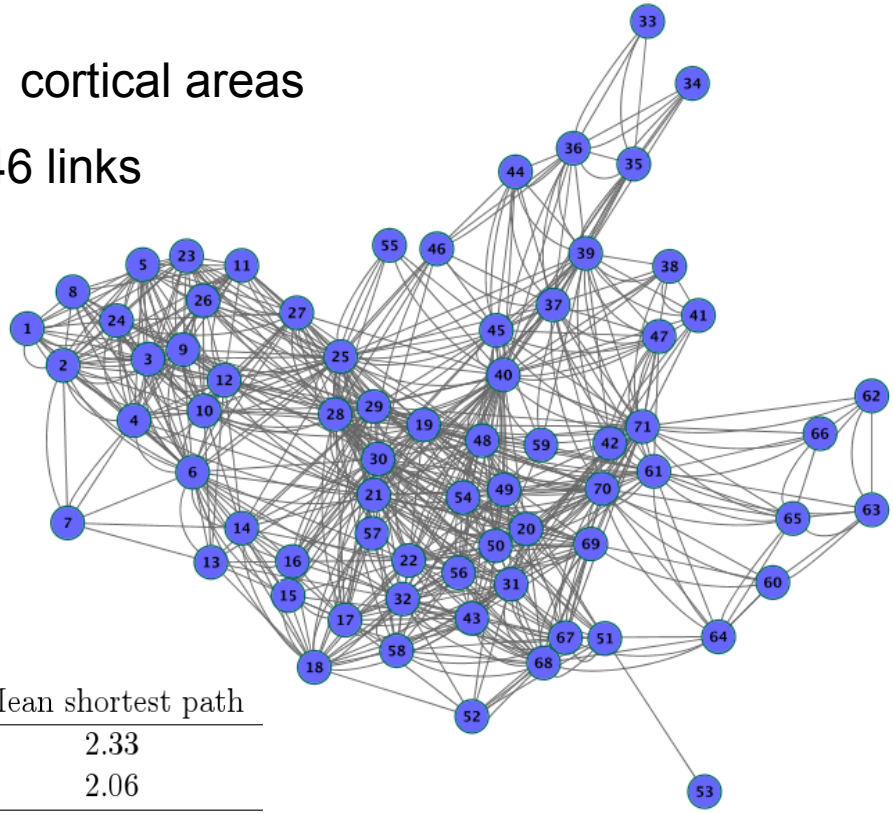
Anatomical Network

> Macaque cortico-cortical network



www.cocomac.org

- 71 cortical areas
- 746 links

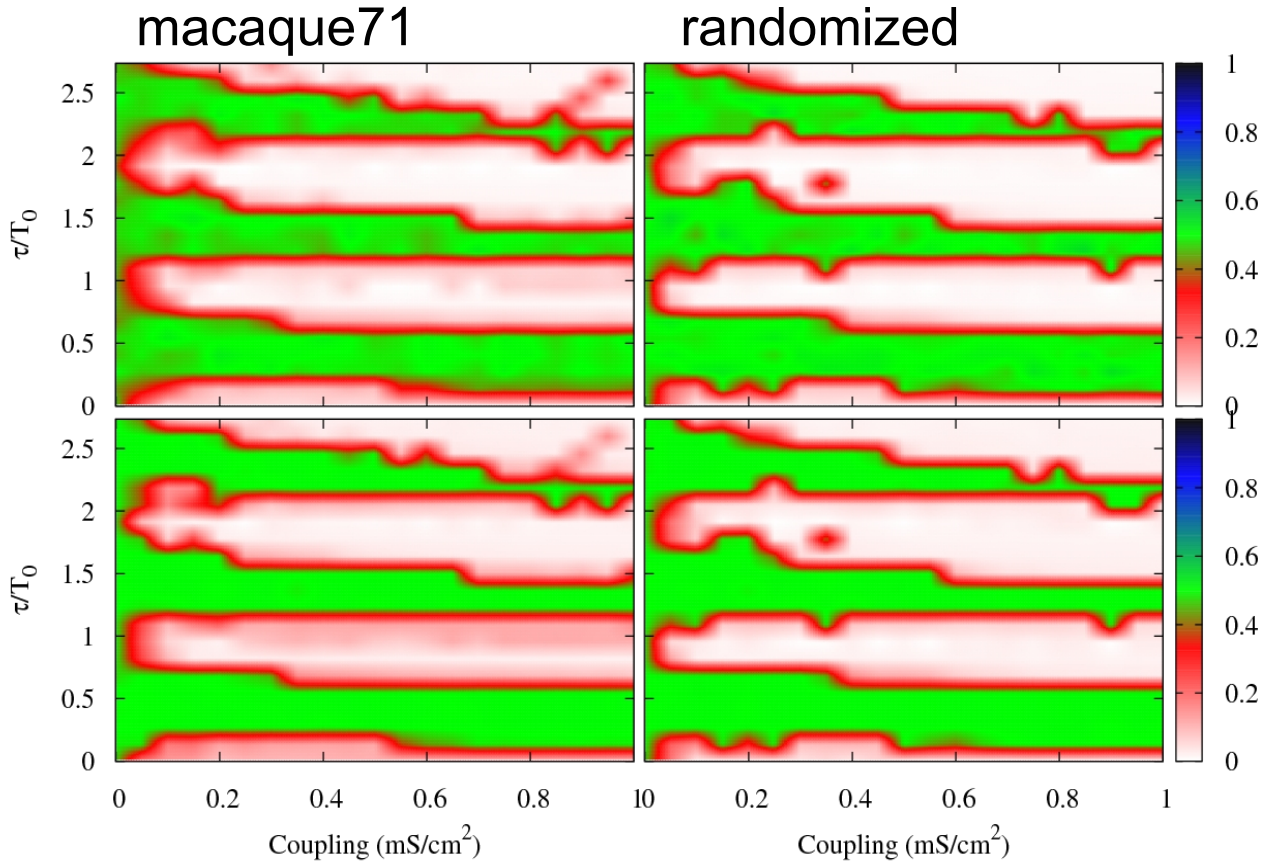


Metric	Clustering coefficient	Average degree	Mean shortest path
Macaque Network	0.46	10.5	2.33
Randomized version	0.24	10.5	2.06

> Local and global synchrony

Local

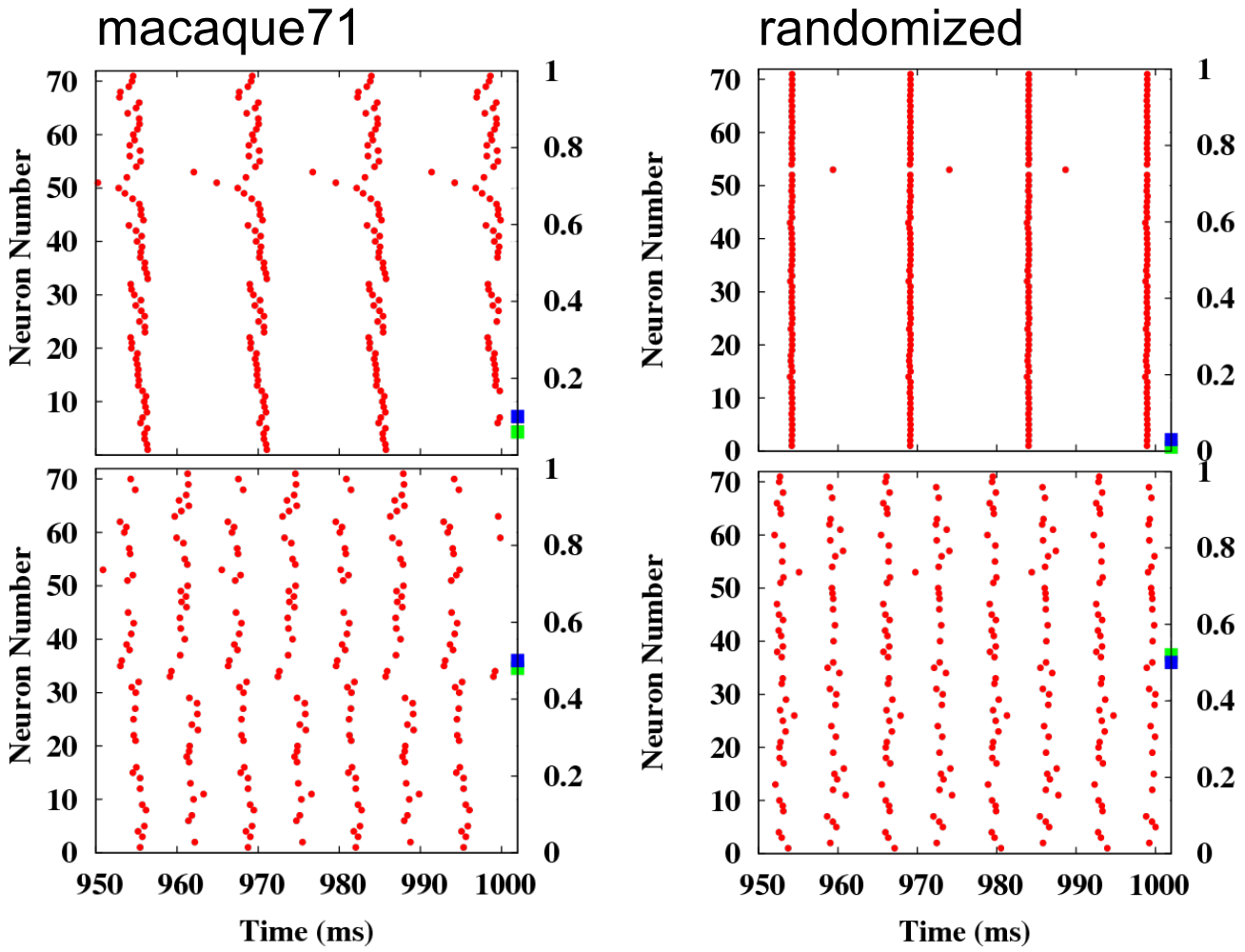
Global



> Raster plots

τ: 14 ms

τ: 18 ms



Conclusions & future work

- NN with different topologies and delayed connections
  - Single delay
    - Distribution of natural frequencies
  - Heterogeneous delay
    - Preliminary results
  - Anatomical network
- Next
  - Extend heterogeneous delay
  - Study the effect of inhibition
  - Include plasticity rule

Thank you for your attention!