SpikeAnts: A Spiking Neuron Network Modelling the Emergence of Organization in a Complex System

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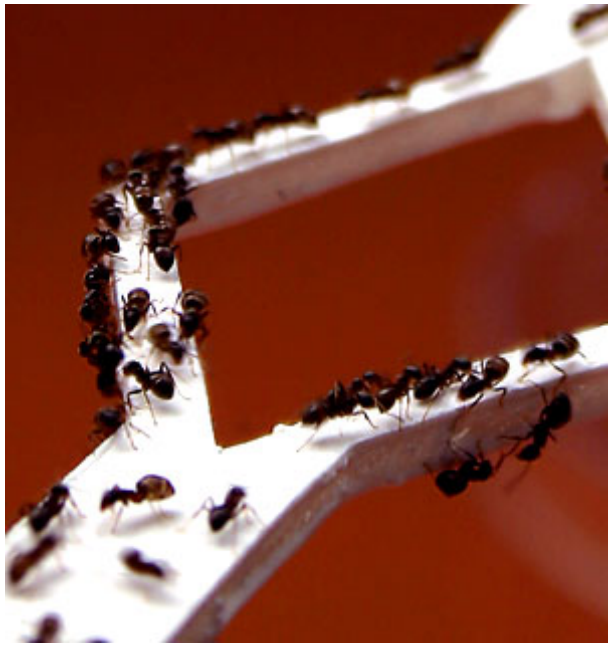
Emergent Synchrony

Emergence of synchronization is at the core of many biological systems, e.g:

- Fireflies
- Cricket chirping
- Pacemaker heart cells
- Neural cells
- ...



How social insects proceed to temporally synchronize their activities ?

Foraging synchronization in ant colonies

- Division of labor
- How do ants synchronize?

A Spiking Neuron Approach of Ant Colonies

- Synchronization of activity is a consequence of temporal coupling between individuals [Cole, 91]
- The basis of spiking neuron network (SNN) processing is temporal dynamics

SpikeAnts: A single ant is modelled by two spiking neurons
$\Rightarrow$ Local decision based on interactions (microscale)
$\Rightarrow$ Global synchronization in the colony (macroscale)

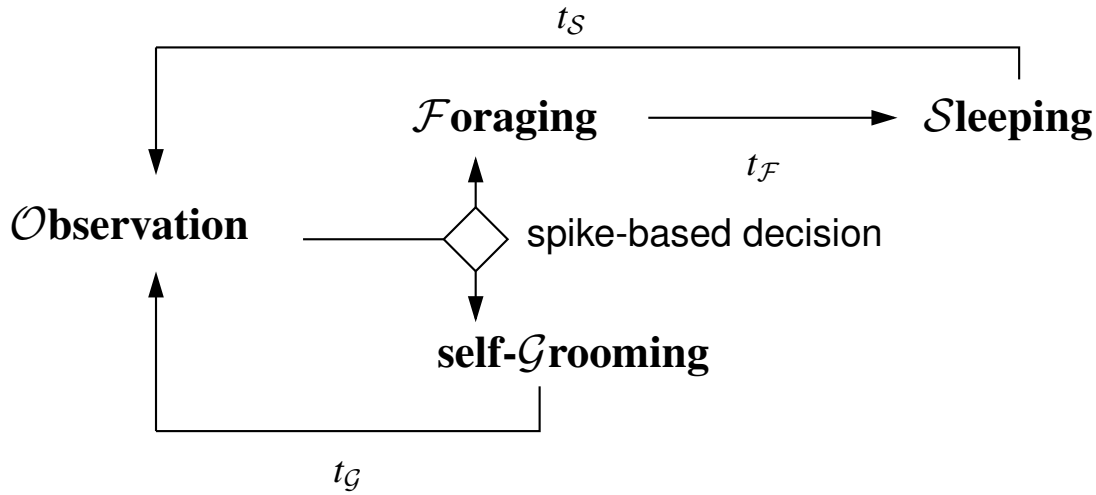
Spiking neurons

- Synchrony in cell assemblies [Hebb, 49]
- Complete synchrony [Mirollo, 90]
- Transient synchrony [Hopfield, 01]
- Order-chaos phase transition [Schrauwen, 08]
- Polychronization [Izhikevich, 06]
- Rhythmic oscillations [Brunel, 03]

SpikeAnts Model

Agent's state

- $\mathcal{F}$orage
- $\mathcal{O}$bserve
- $\mathcal{S}$leep
- self-$\mathcal{G}$rooming



Agents follow these rules:

1. If "sufficiently many" foragers are seen, start grooming activities
2. If none or few foragers are seen, go forage
3. Once grooming or foraging (and sleep) is done, come back to observation

SpikeAnts Model

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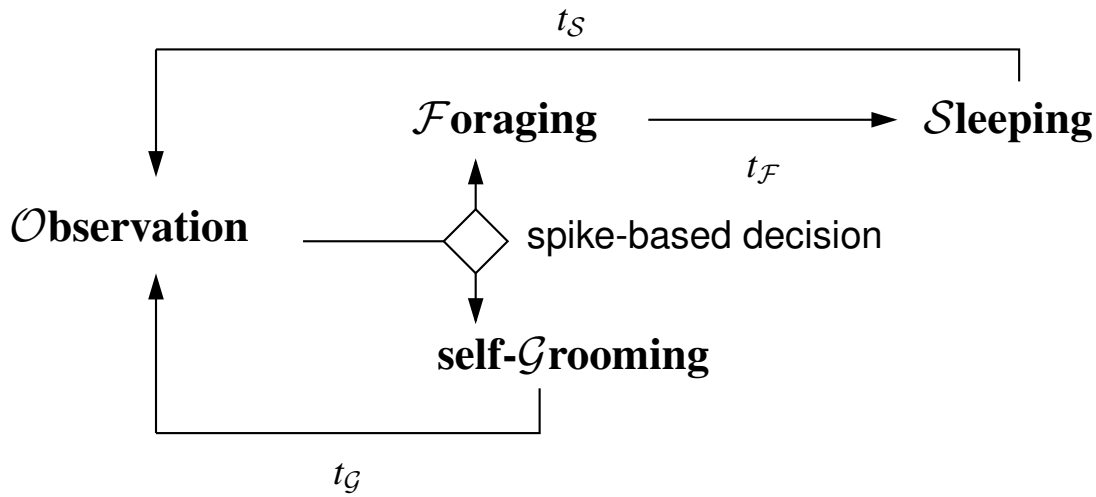

A competition between two spiking neurons implements local decision

Passive neuron **P**:

Leaky Integrate-and-Fire (LIF)

$$\begin{cases} \frac{dV_p}{dt} = -\lambda(V_p(t) - V_{\text{rest}}) + I_{\text{exc}}(t), & \text{if } V_p < \vartheta \\ \text{else fires a spike and } V_p \text{ is set to } V^p_{\text{reset}} \end{cases}$$

Active neuron **A**:

Quadratic

Integrate-and-Fire (QIF)

$$\begin{cases} \frac{dV_a}{dt} = -\lambda(V_a(t) - V_{\text{rest}})(V_a(t) - V_{\text{thres}}) + I_{\text{inh}}(t) + I_{\text{clock}}(t), & \text{if } V_a < \vartheta \\ \text{else fires a spike and } V_a \text{ is set to } V^a_{\text{reset}} \end{cases}$$

with $I_{\text{inh}}(t) = -I_{\text{exc}}(t)$.

SpikeAnts Model

Agent's state

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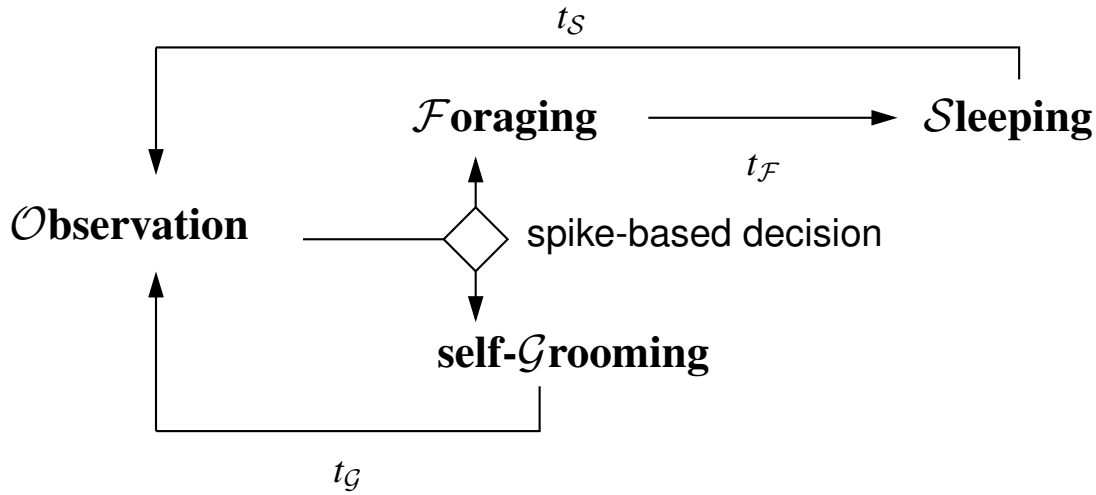
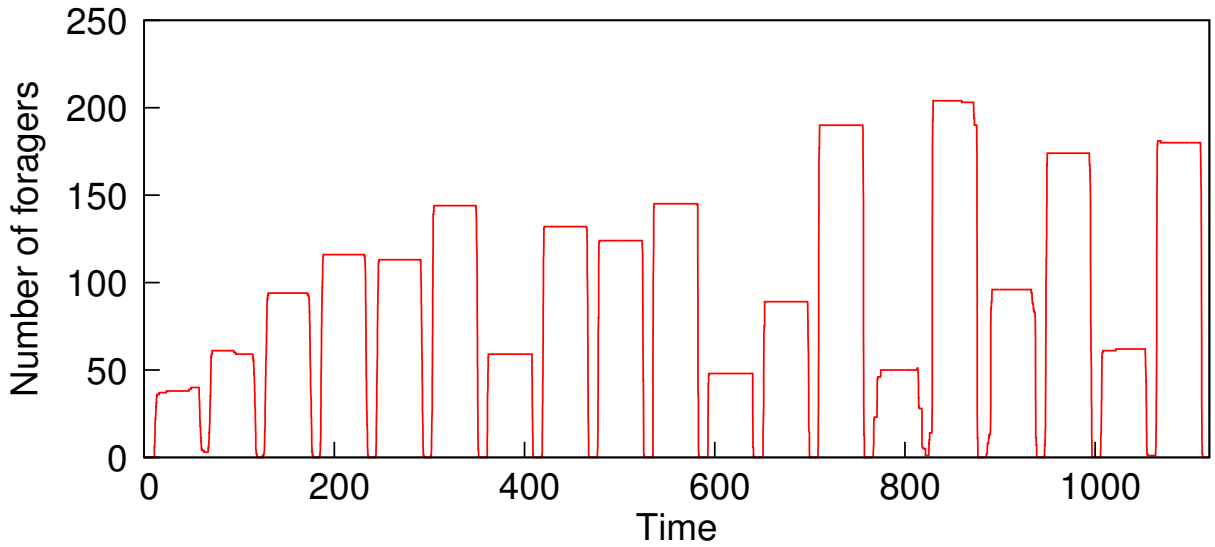
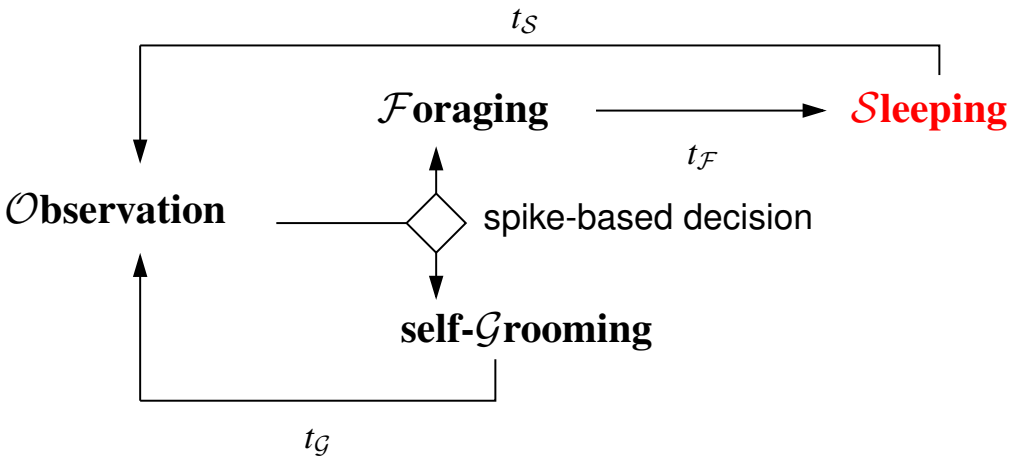


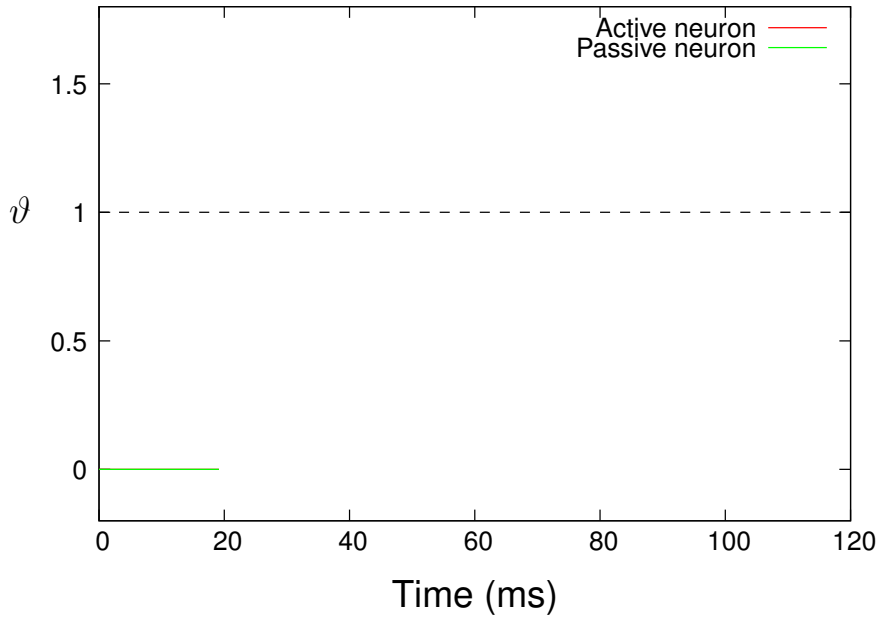
Global synchronization: emergent subpopulations of foragers



Microscopic Scale: A Neuronal Competition

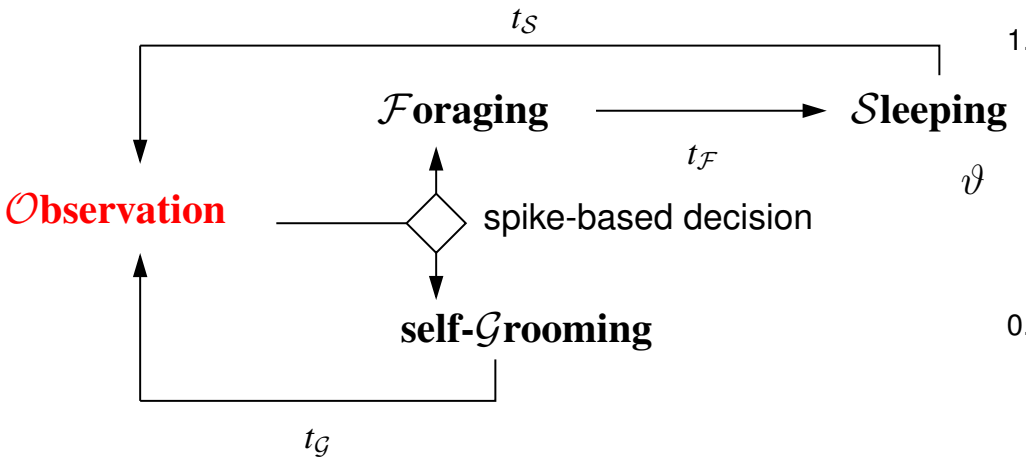
Sleep state

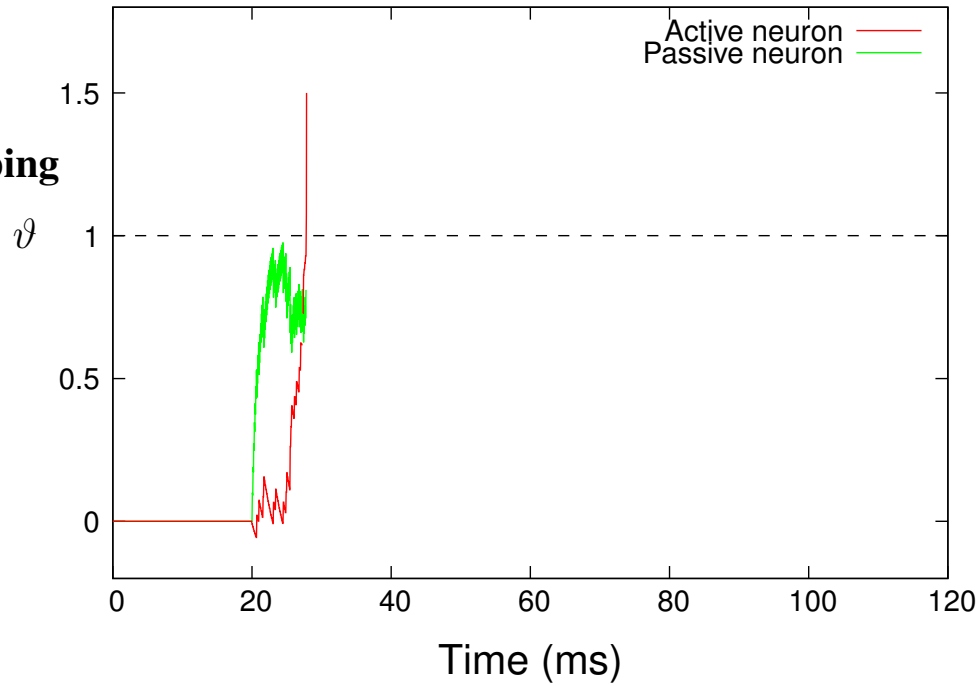




Microscopic Scale: A Neuronal Competition

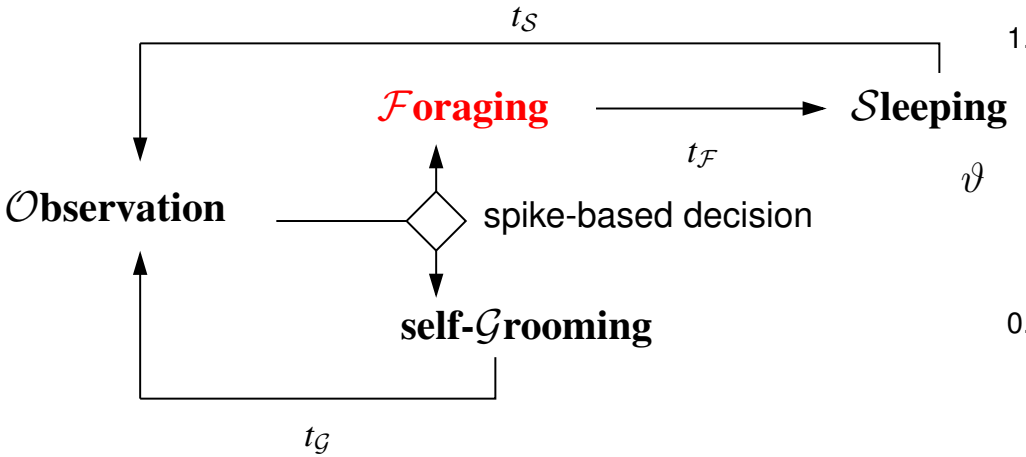
Observation state

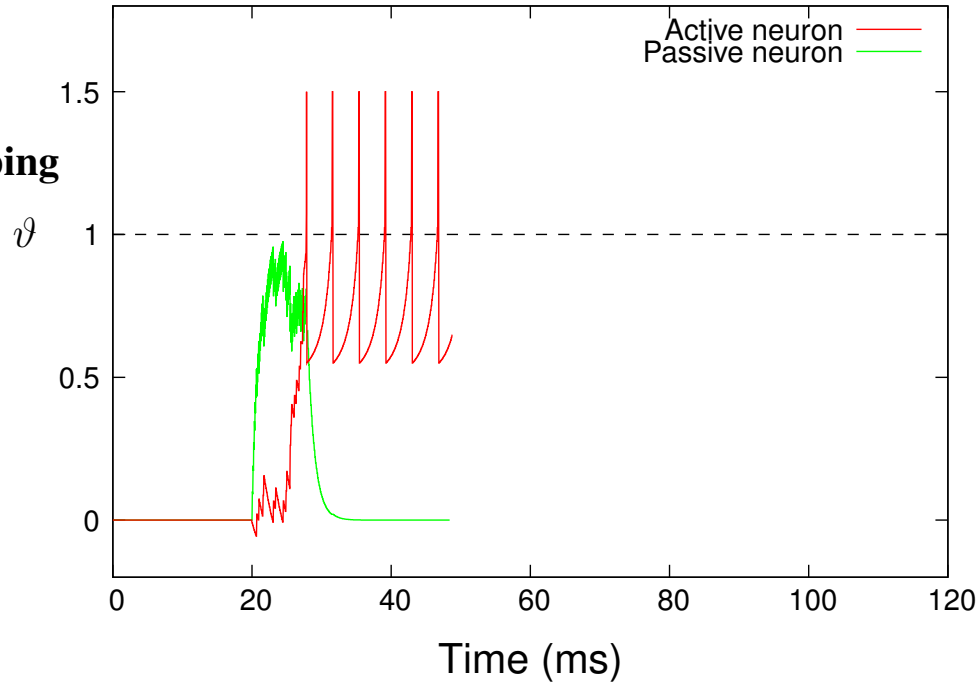




Microscopic Scale: A Neuronal Competition

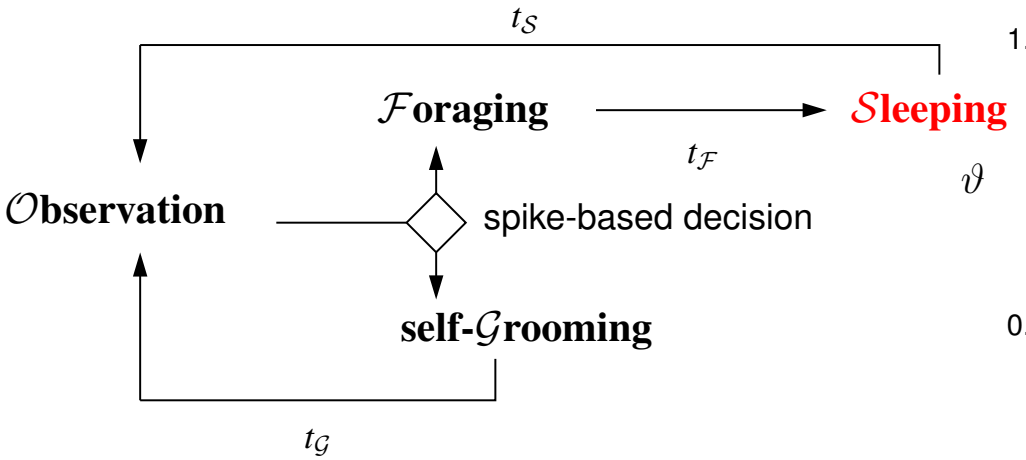
Foraging state

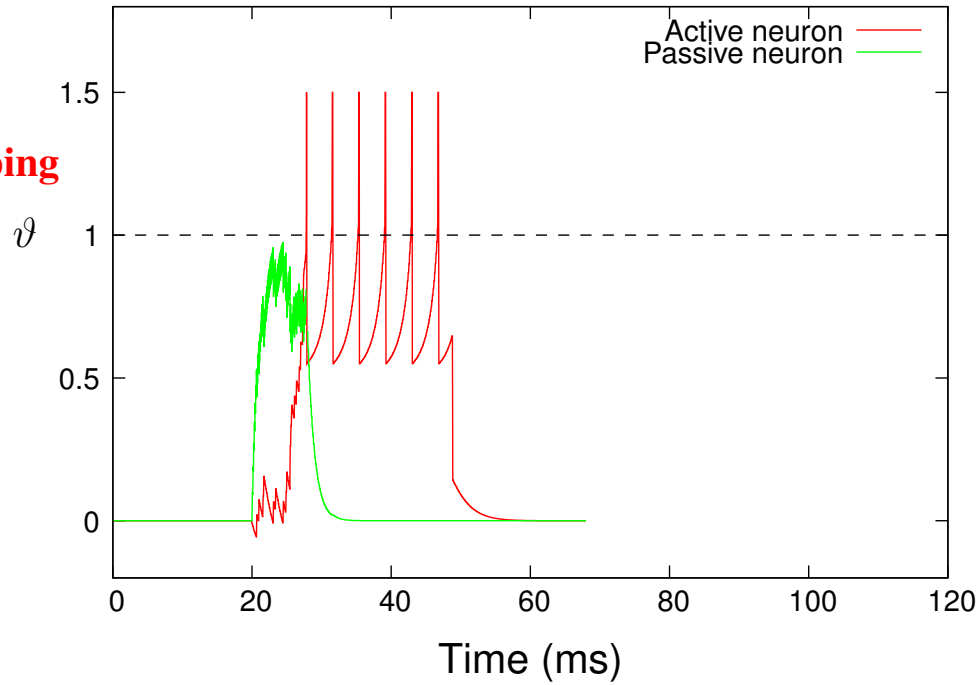




Microscopic Scale: A Neuronal Competition

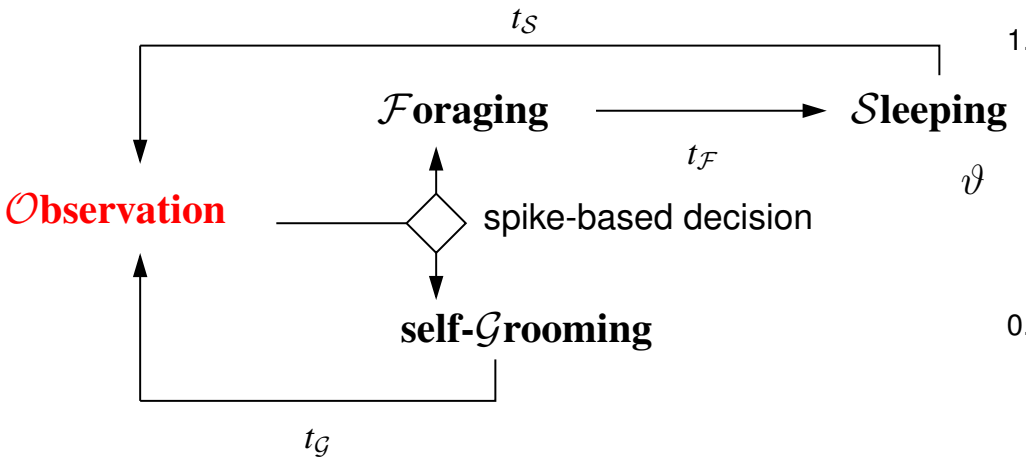
Sleep state

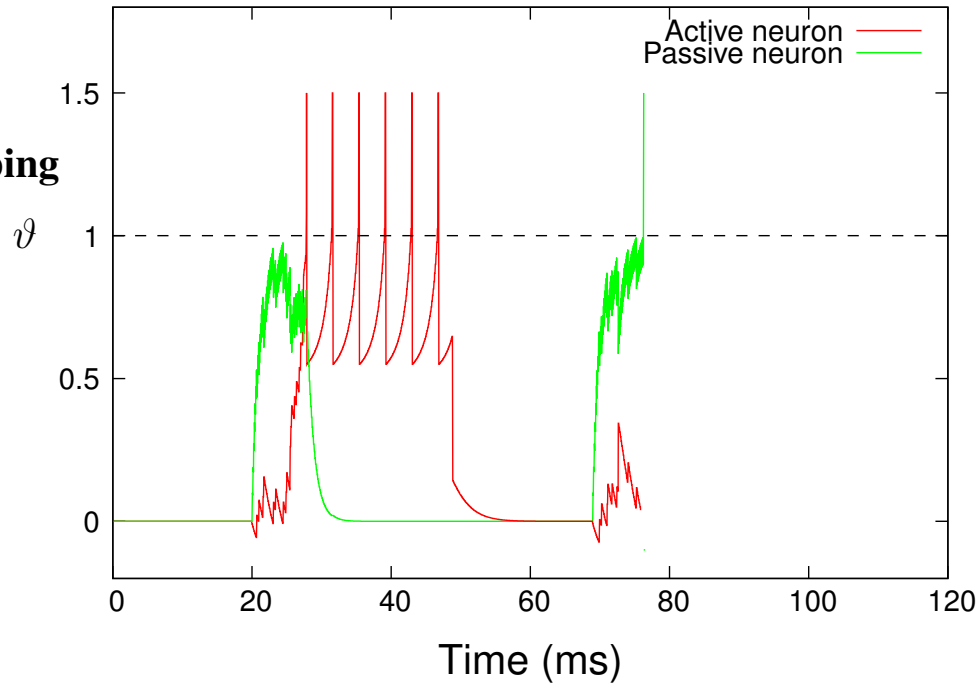




Microscopic Scale: A Neuronal Competition

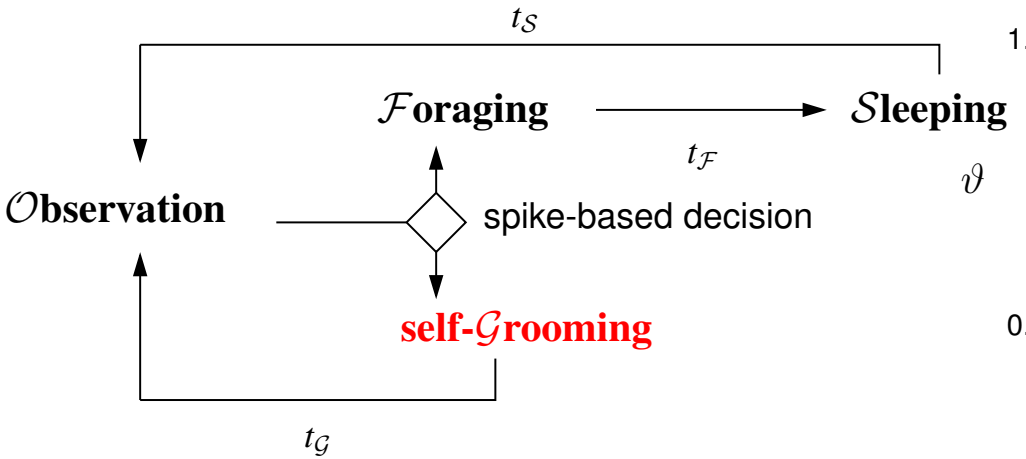
Observation state

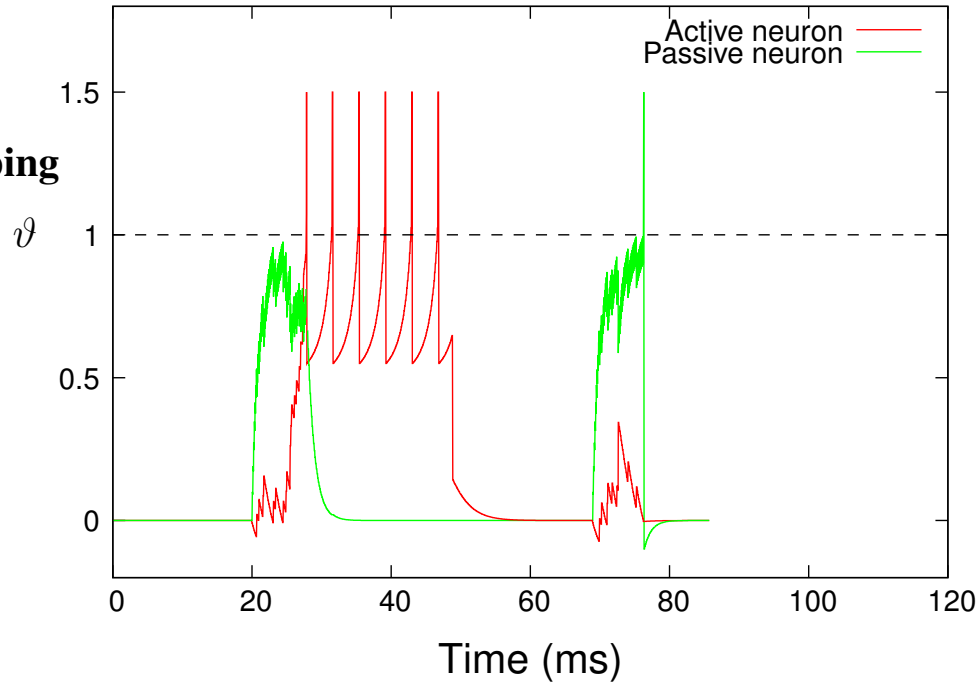




Microscopic Scale: A Neuronal Competition

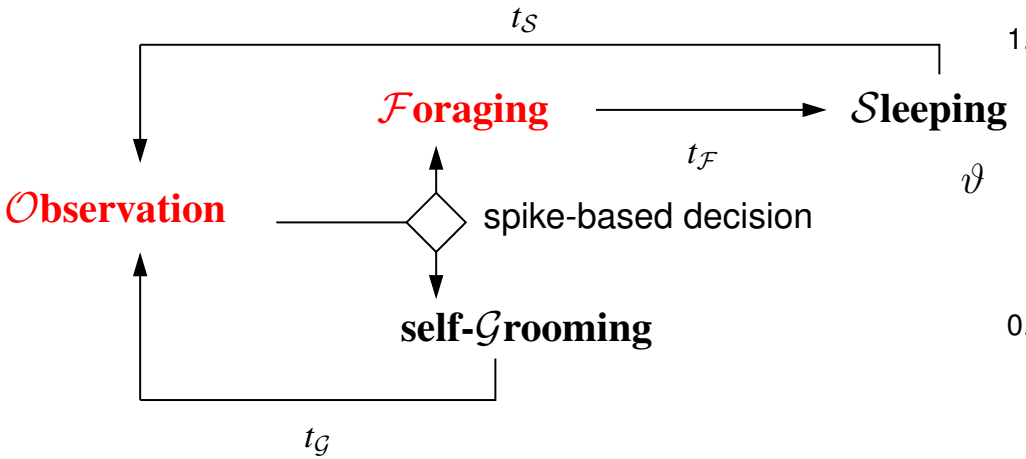
Grooming state

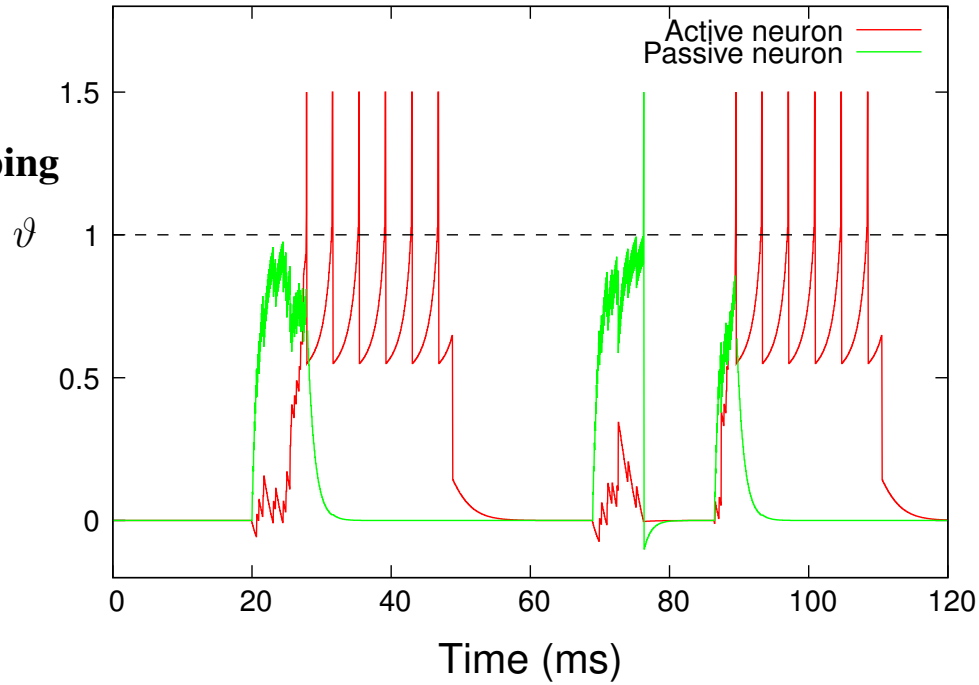




Microscopic Scale: A Neuronal Competition

Another foraging decision

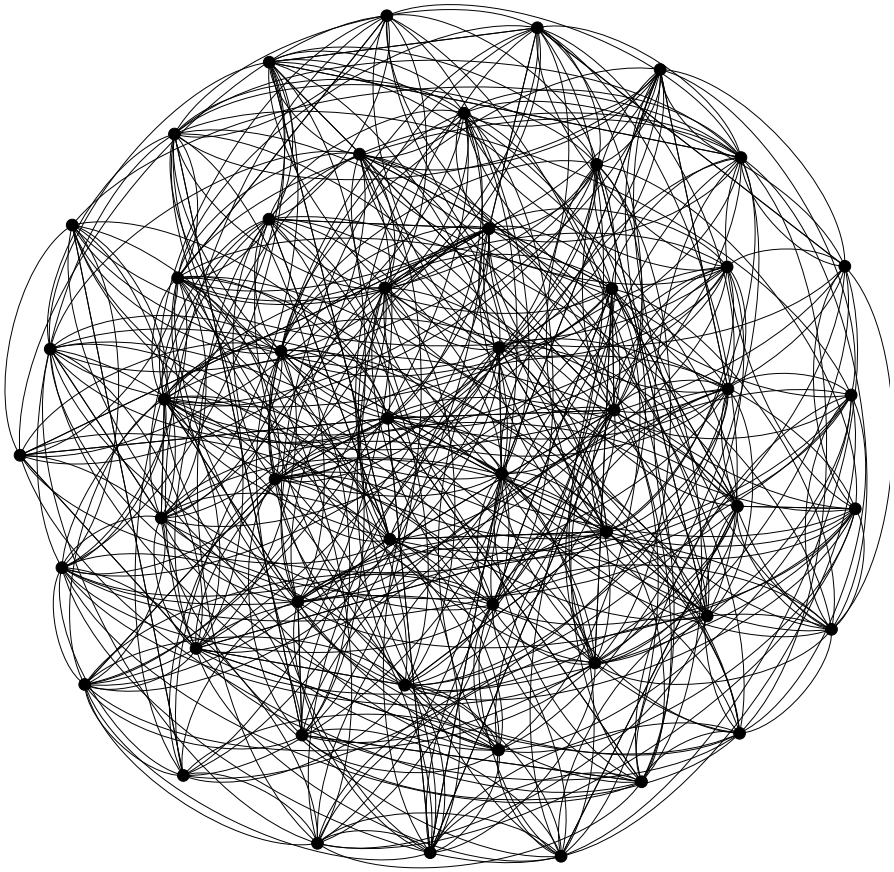




Macroscopic Scale

Population

- M agents
- Connectivity ρ
- Sparsely connected spiking neuron network



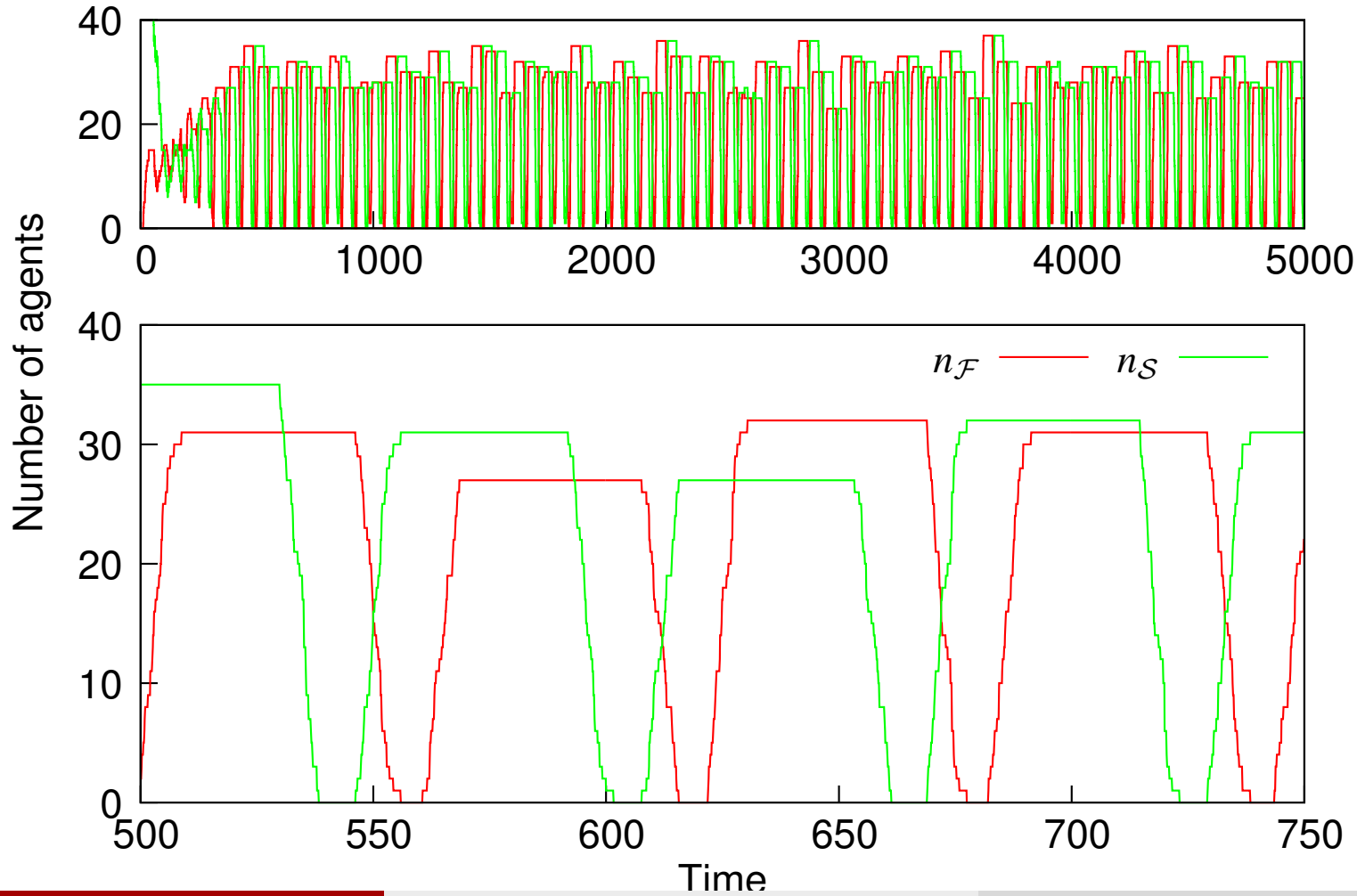
Model Parameters

Parameter type	Symbol	Description	Value	(units)
Neural	λ	Membrane relaxation constant	0.1	mV^{-1}
	V_{rest}	Resting potential	0.0	mV
	ϑ	Spike firing threshold	1.0	mV
	V^{p}_{reset}	Passive neuron reset potential	-0.1	mV
	V_{thres}	Active neuron bifurcation threshold	0.5	mV
	V^{a}_{reset}	Active neuron reset potential	0.55	mV
	I_{clock}	Active neuron constant input current	0.1	mV
	w	Synaptic weight	0.01	mV^{-1}
Agent	$t_{\mathcal{F}}$	Foraging duration	47.1	ms
	$t_{\mathcal{O}}$	Maximum observation duration	10.5	ms
	$t_{\mathcal{S}}$	Sleeping duration	45.7	ms
	$t_{\mathcal{N}}$	Nap duration	16.7	ms
Population	ρ	Connection probability	0.3	%
	M	Population size	150	agents

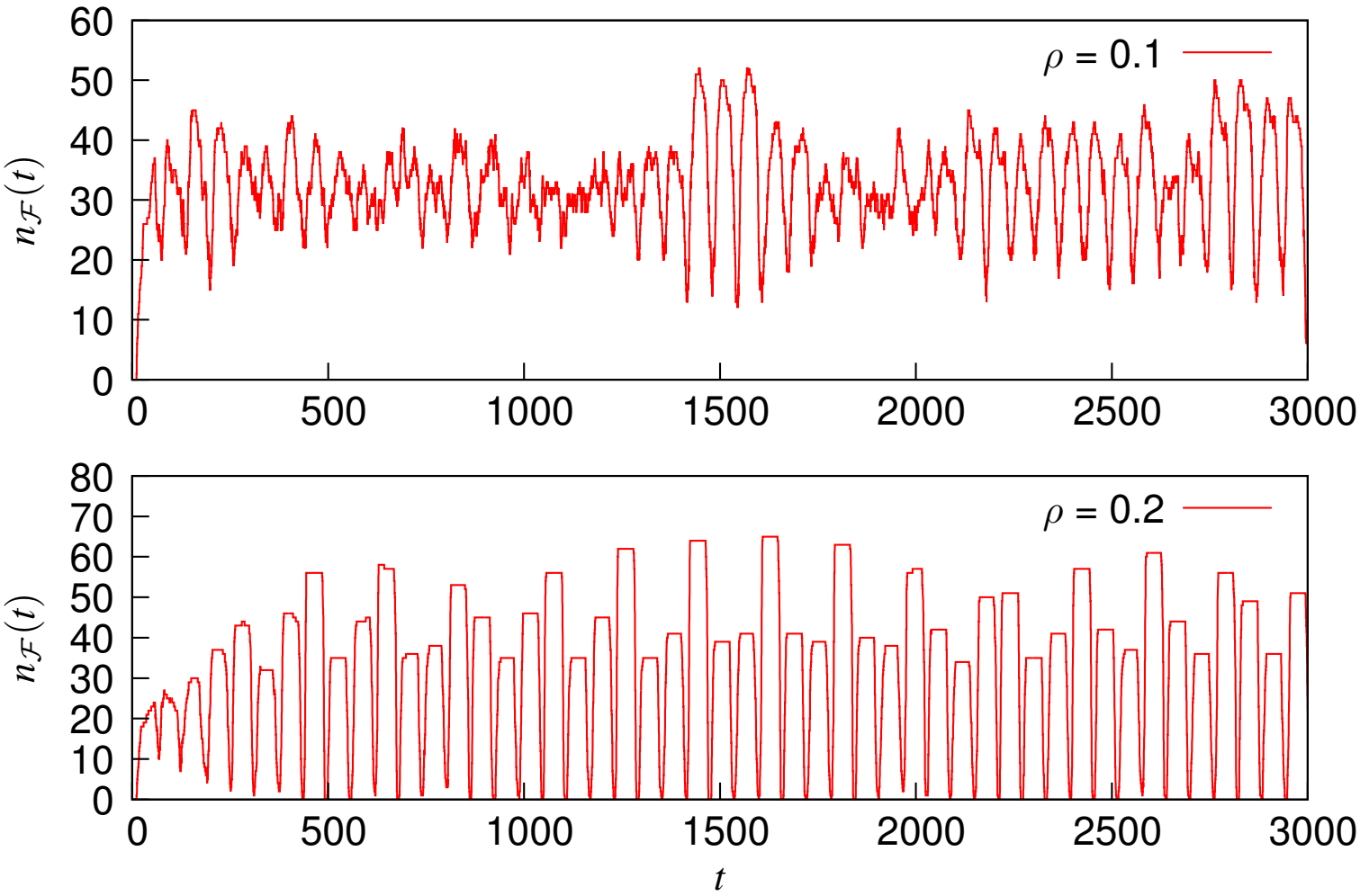
Example of Synchronization

Experimental setting:

- Initial state: $\mathcal{S}$ for $]0, 2t_{\mathcal{S}}]$
- 100,000 time steps

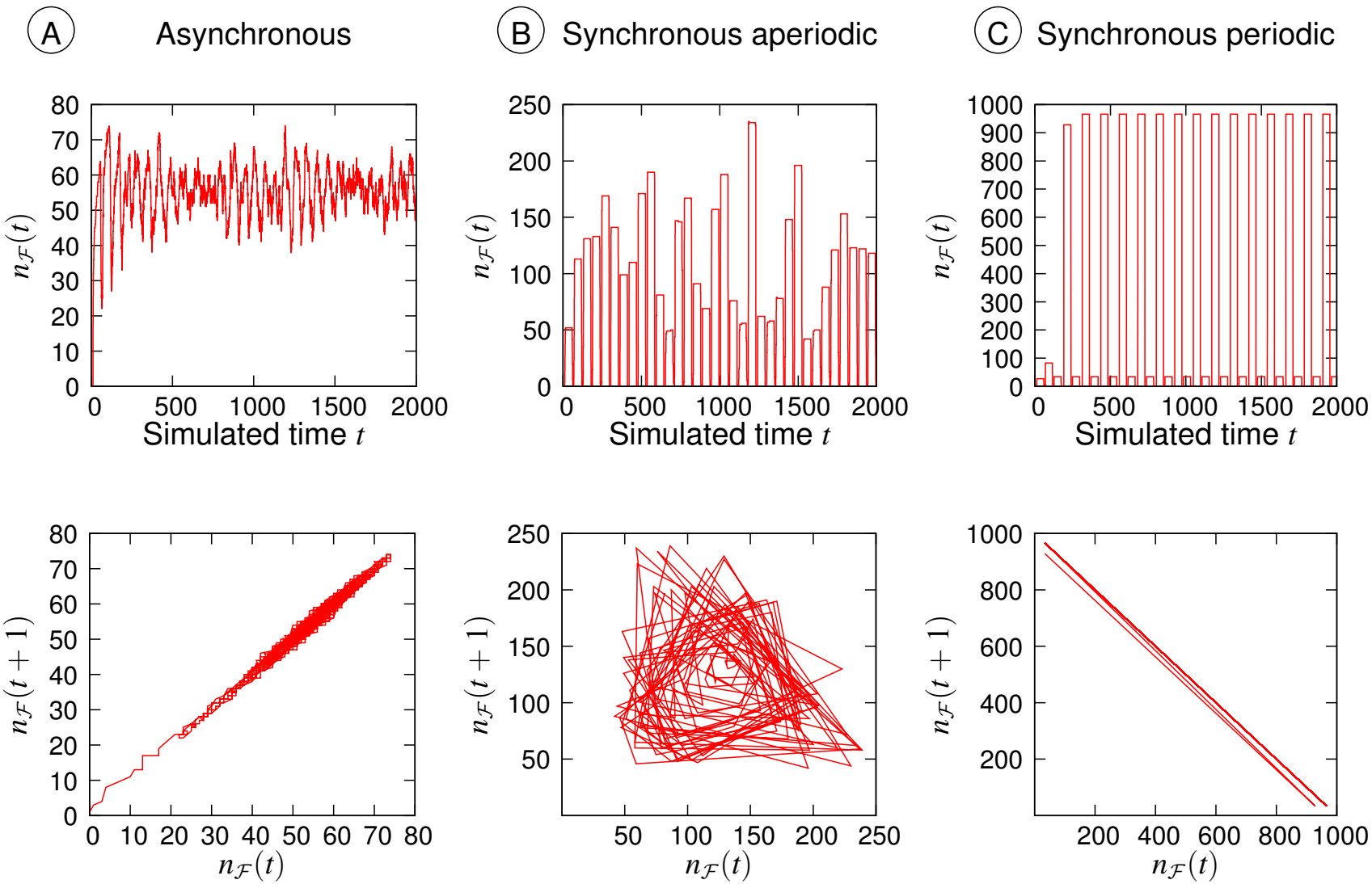


Connectivity influence

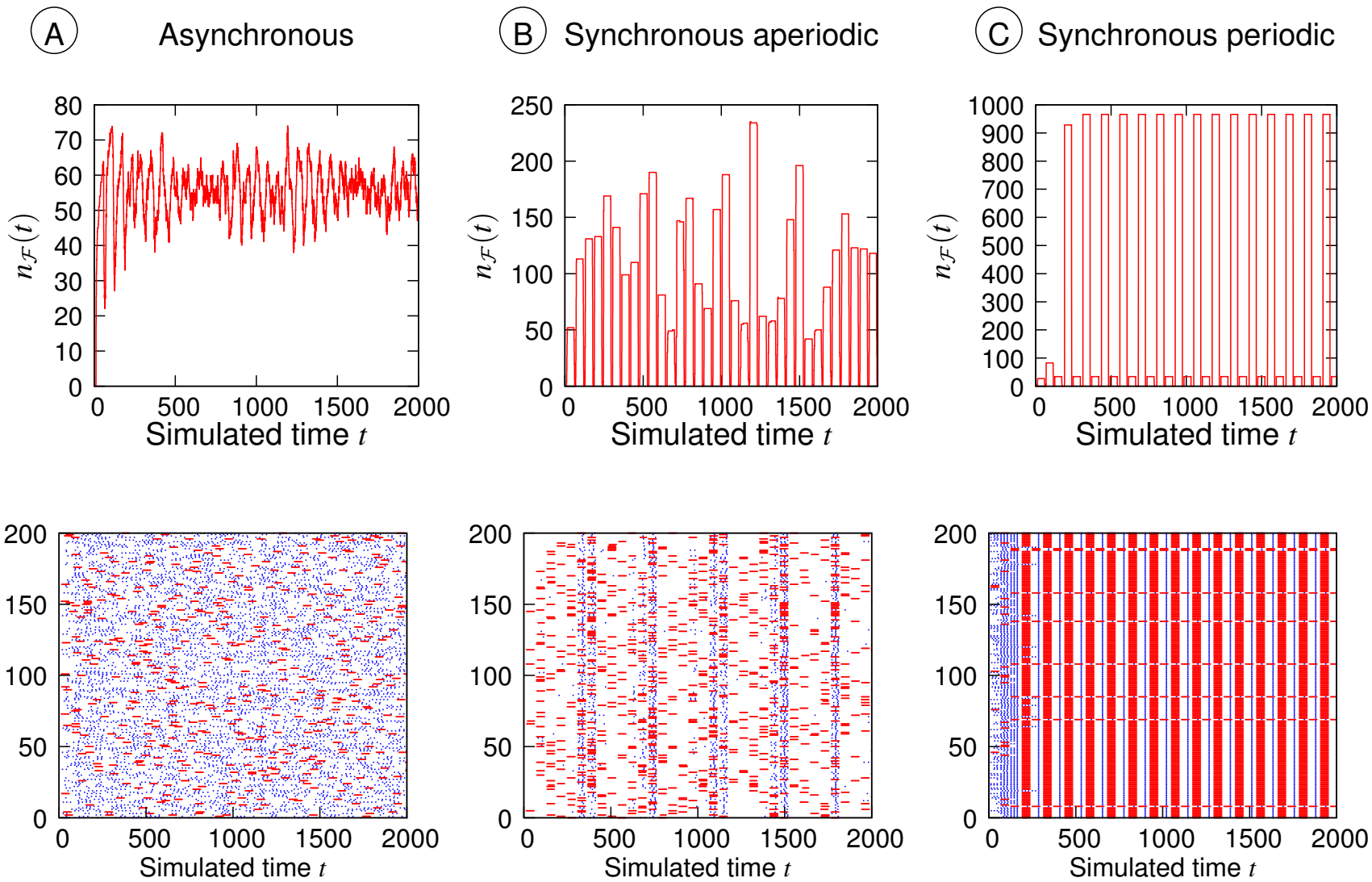


Two different activity shapes around $\rho = 0.1$

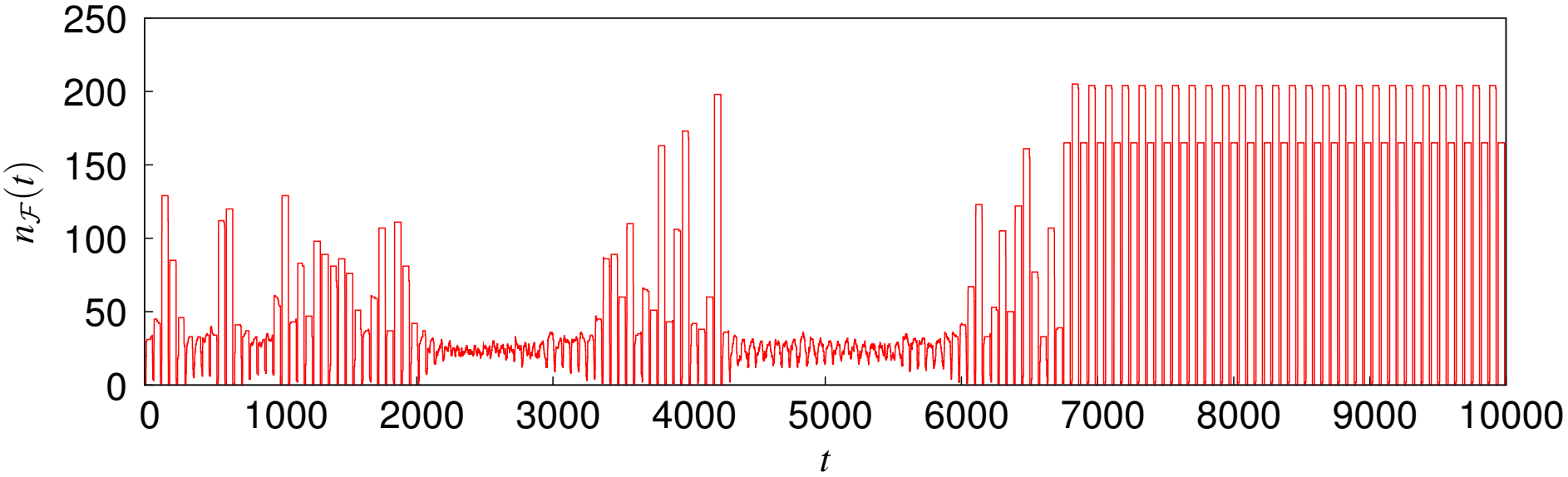
Emergent Synchronization: Shapes of Activity



Emergent Synchronization: Shapes of Activity



Transitions between Shapes of Activity



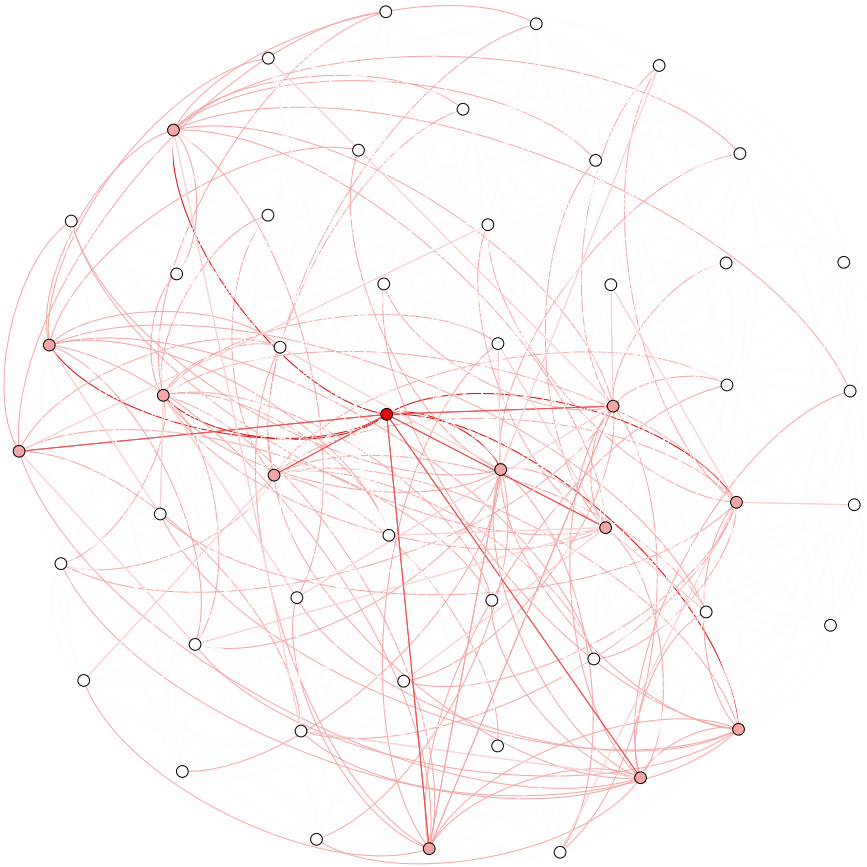
Control Parameters

15 model parameters

Which parameters govern the emergence of activity shapes?

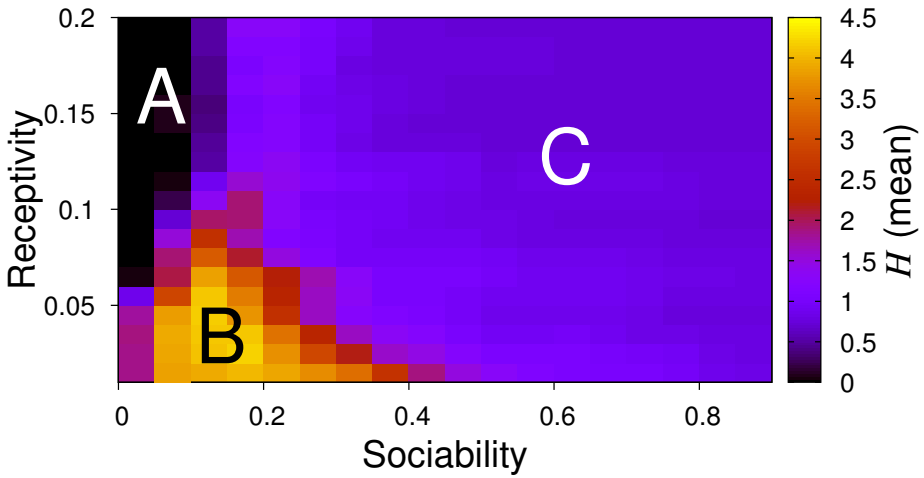
Control parameters

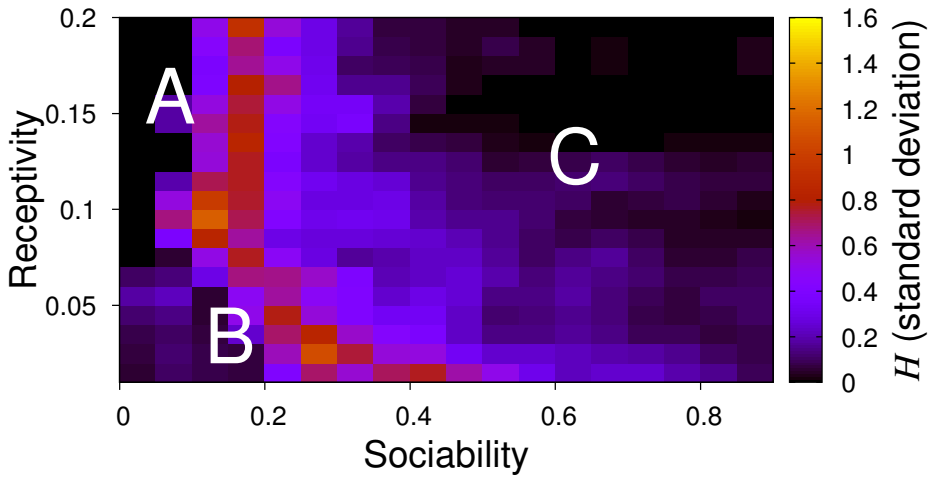
- Sociability $\rho\sqrt{M}$
- Receptivity $\frac{w}{|\vartheta - V_{\text{rest}}|}$



Phase Diagram of Emergent Synchronization

Entropy-based indicator: $H = -\sum_{k=1}^{K} \frac{n_k}{\sum_m n_m} \log\left(\frac{n_k}{\sum_m n_m}\right)$





Order parameters govern emergence of shape of activity:

- A Asynchronous, $H = 0$
- B Synchronous aperiodic, $H > \log 2$
- C Periodic synchronous, $H \sim \log 2$

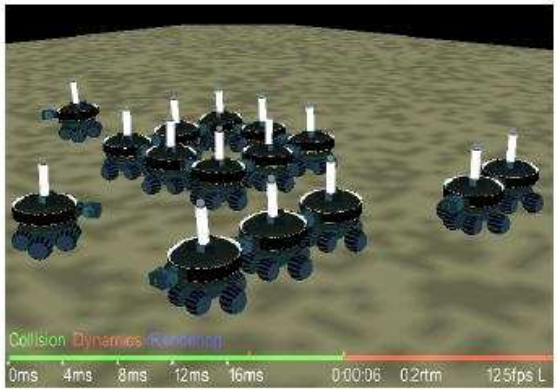
Conclusion and Perspectives

SpikeAnts: a local and parsimonious system modelling emergent collective behavior

- Deterministic model
- No asumption on agent's computational ability

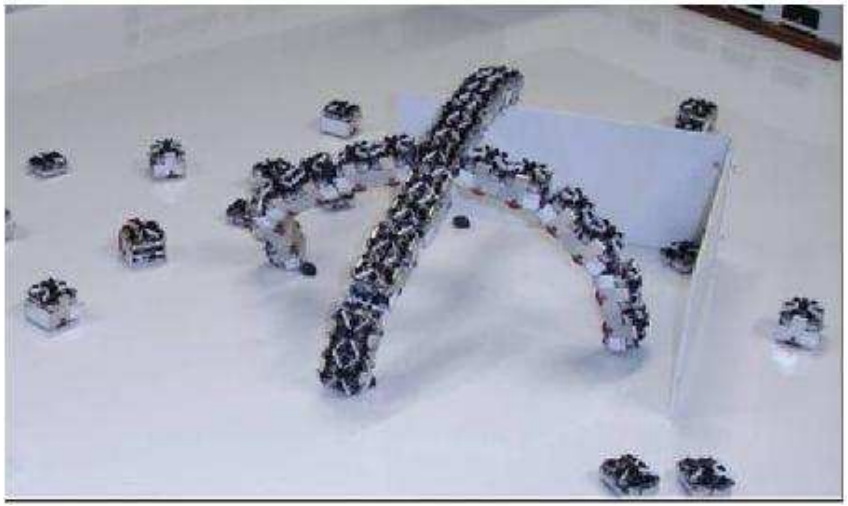
Perspectives

- Influence of synchrony detection at neuronal level
- Role of excitation/inhibition balance
- Learning ability of agents (e.g. STDP, IP)
- Reaction to external perturbations
- Application to swarm robotics



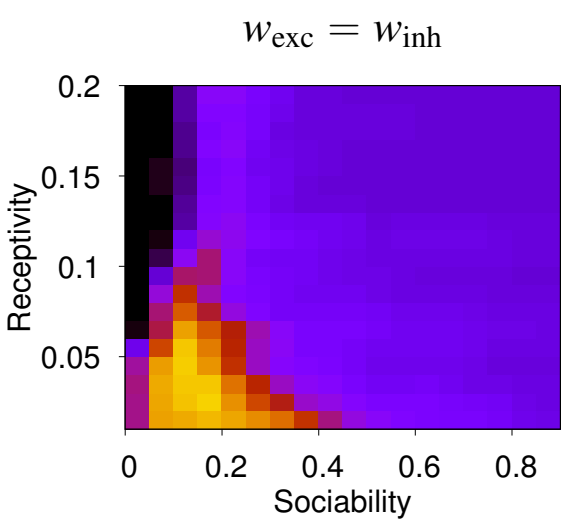
Thank you for your attention

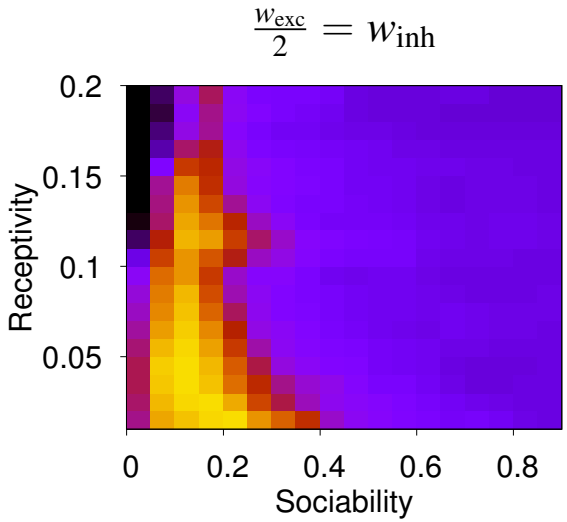
Do you have any questions ?

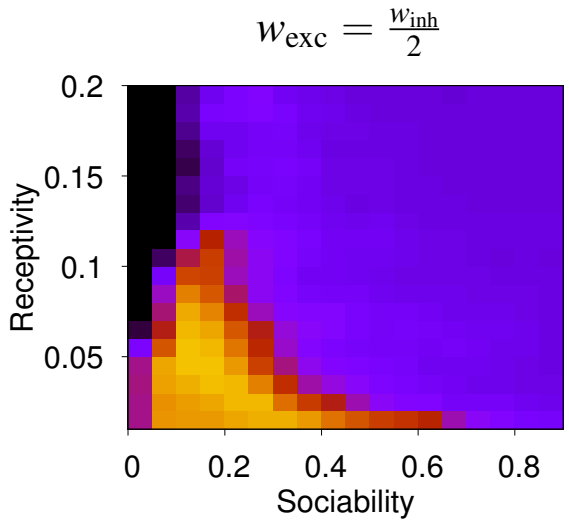


Addendum

Influence of Weight Balance

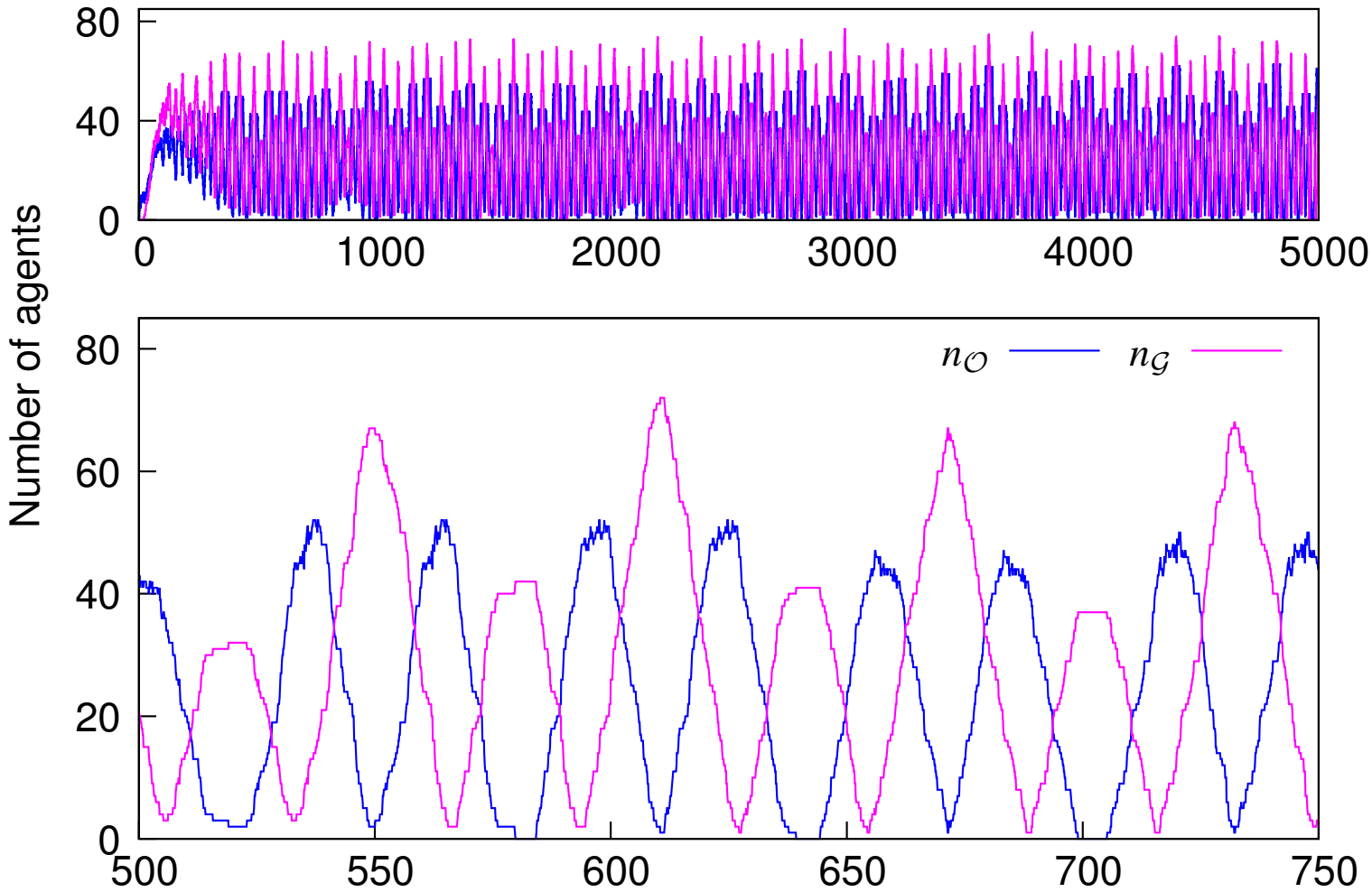




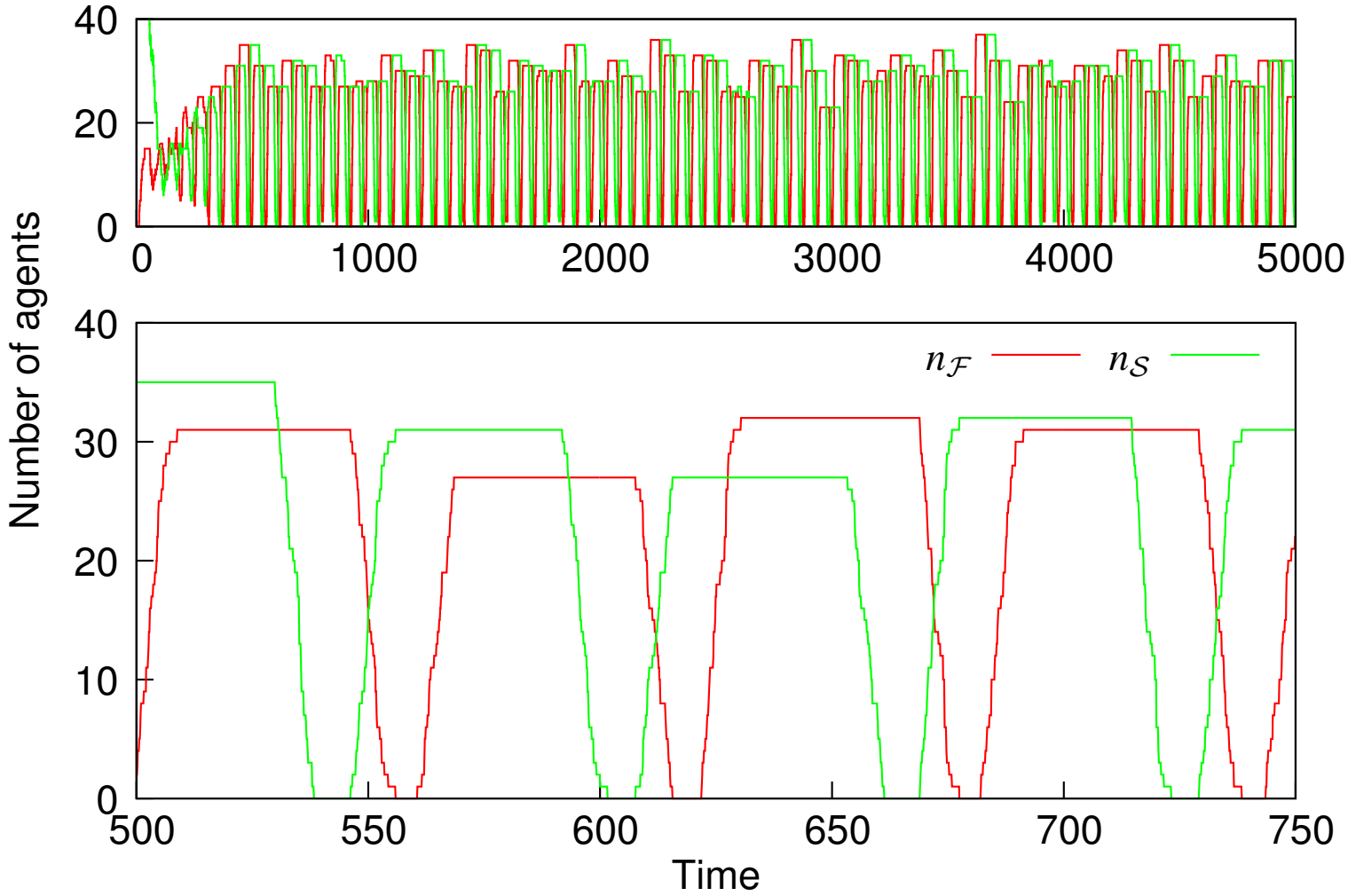


The weight balance influences the asynchronous/synchronous boundary

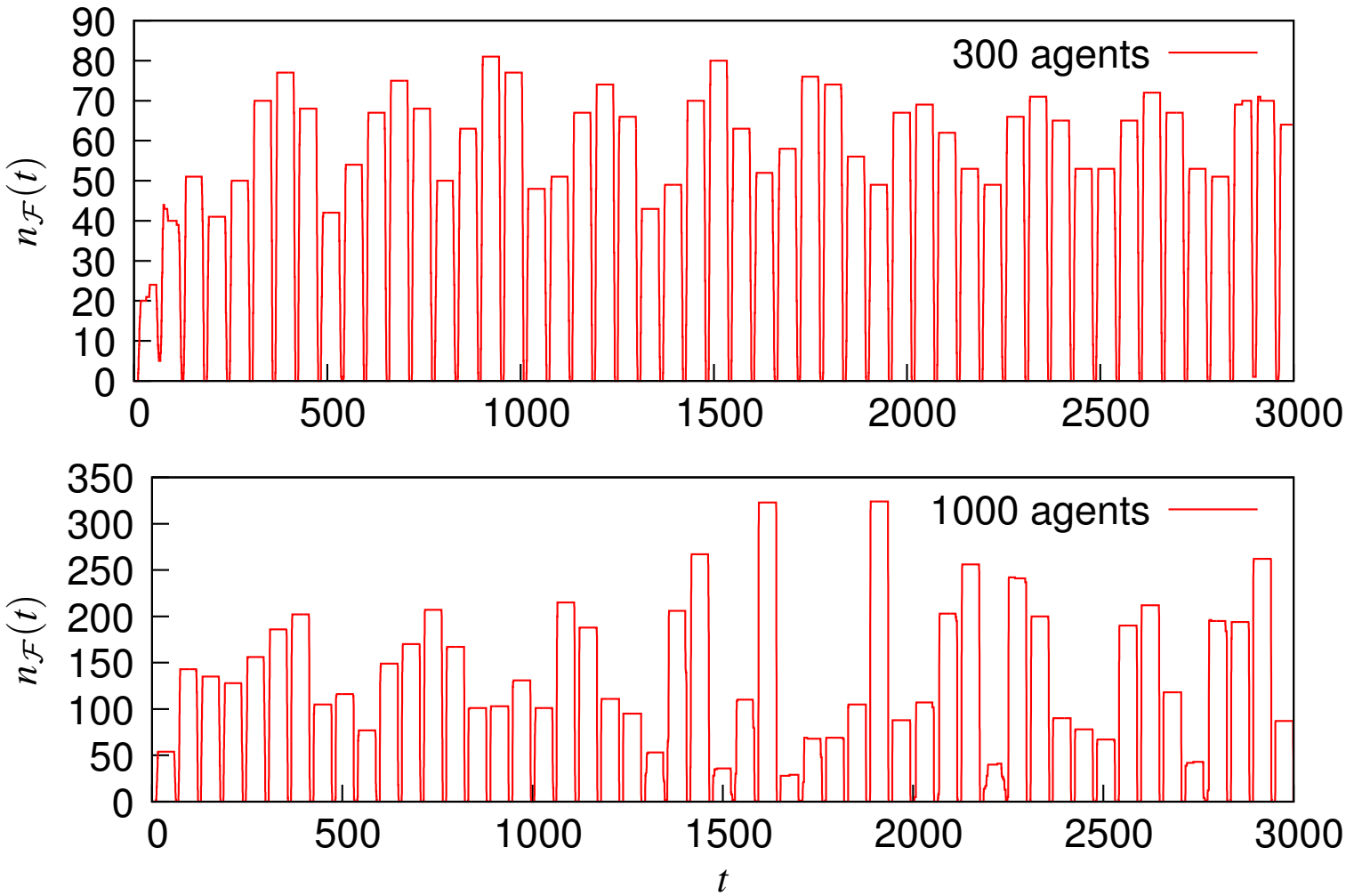
A Sample Run


Number of agents
80
40
0
0
1000
2000
3000
4000
5000
80
60
40
20
0
500
550
600
650
700
750
$n_{\mathcal{O}}$
$n_{\mathcal{G}}$

A Sample Run

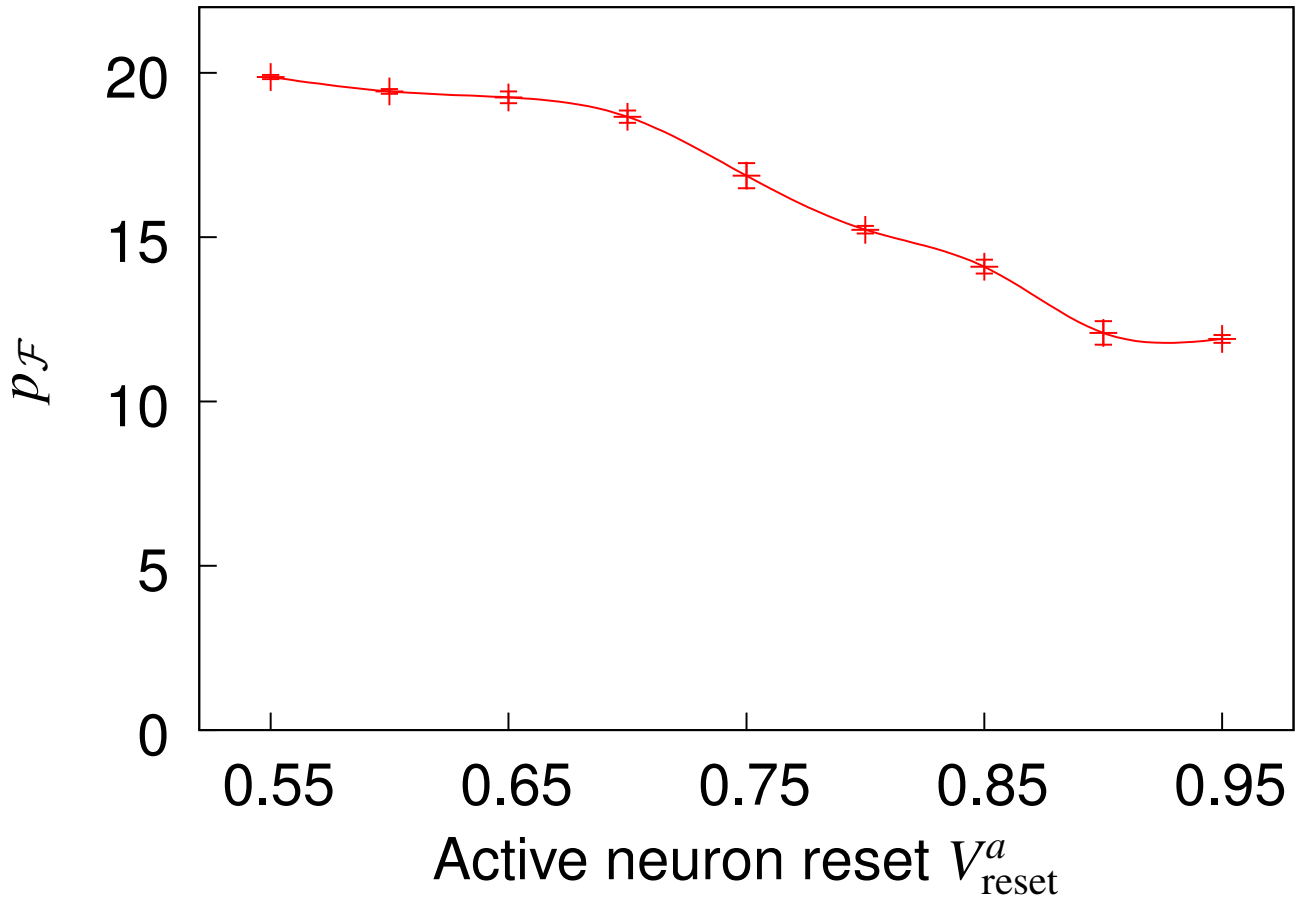

40
20
0
0
1000
2000
3000
4000
5000
40
30
20
10
0
500
550
600
650
700
750
Number of agents
Time
$n_{\mathcal{F}}$
$n_{\mathcal{S}}$

Population Size



For $M > 600$, subpopulation size variability increases

Active neuron reset potential



V^a_{reset} governs the firing rate during bursting