Synchronization in cortical neural networks – results, techniques and tools

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Overview

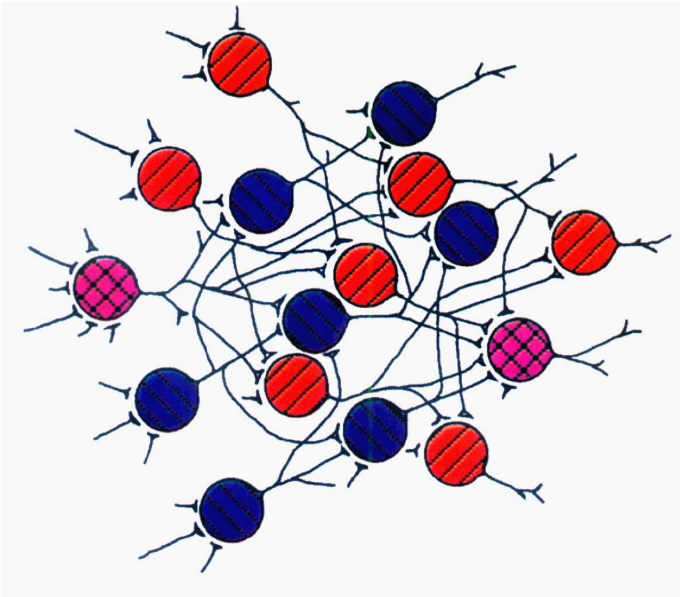
- Wednesday
  1. Feed-forward subnetworks in the cortex
  2. Parameters and variability of the synchronization dynamics
- Thursday
  3. Stability in recurrent cortical networks
  4. Integration of pulse-coupled neural networks
- Friday
  5. Simulation of realistic network structures by distributed computing

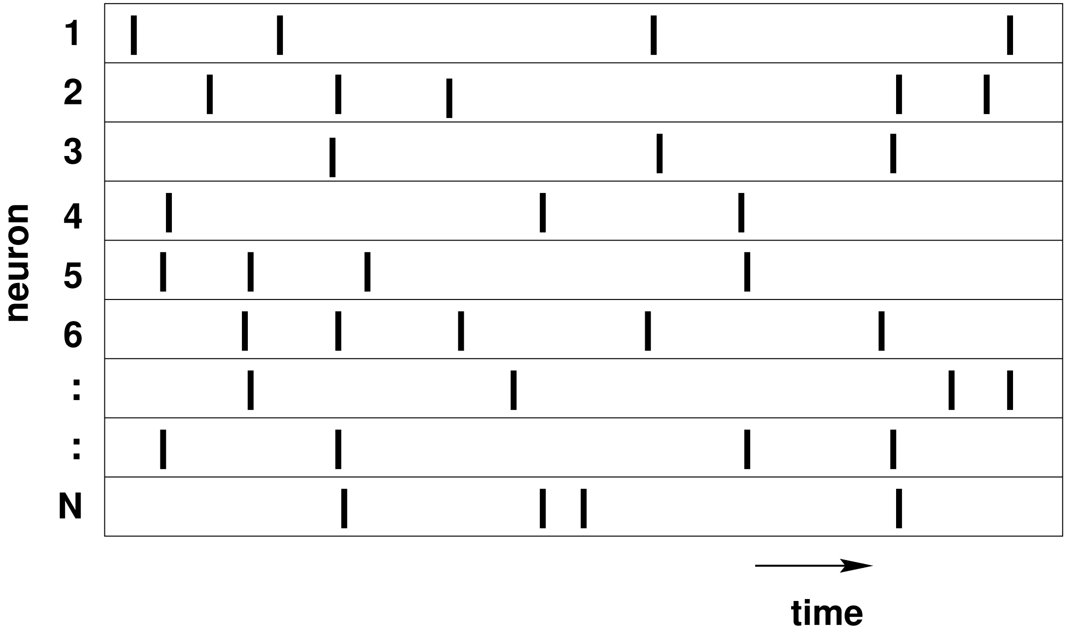
Feed-forward subnetworks in the cortex

- Concept: Time as coding space
- Experimental data
- Single neuron properties
- Network model "synfire chain"
- Dynamics of spike synchronization

Brain mechanisms supporting simultaneous action potentials?

Time as coding space





M. Abeles, S. Grün

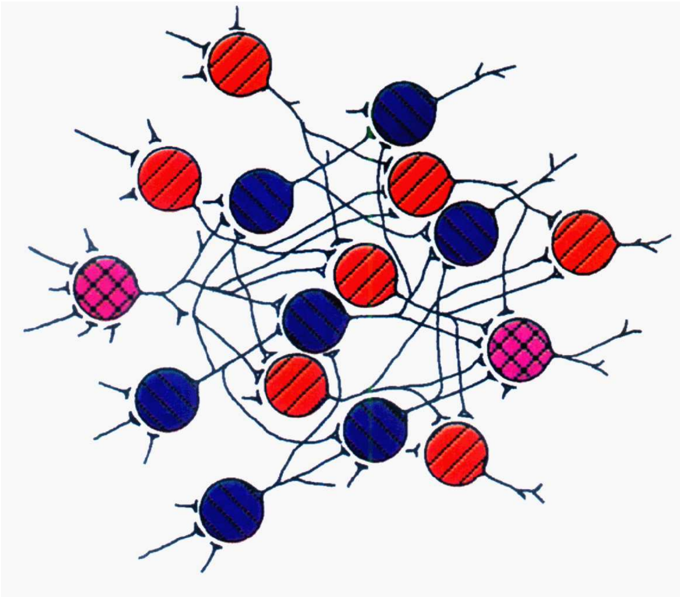
Idea (Hebb, 1949):

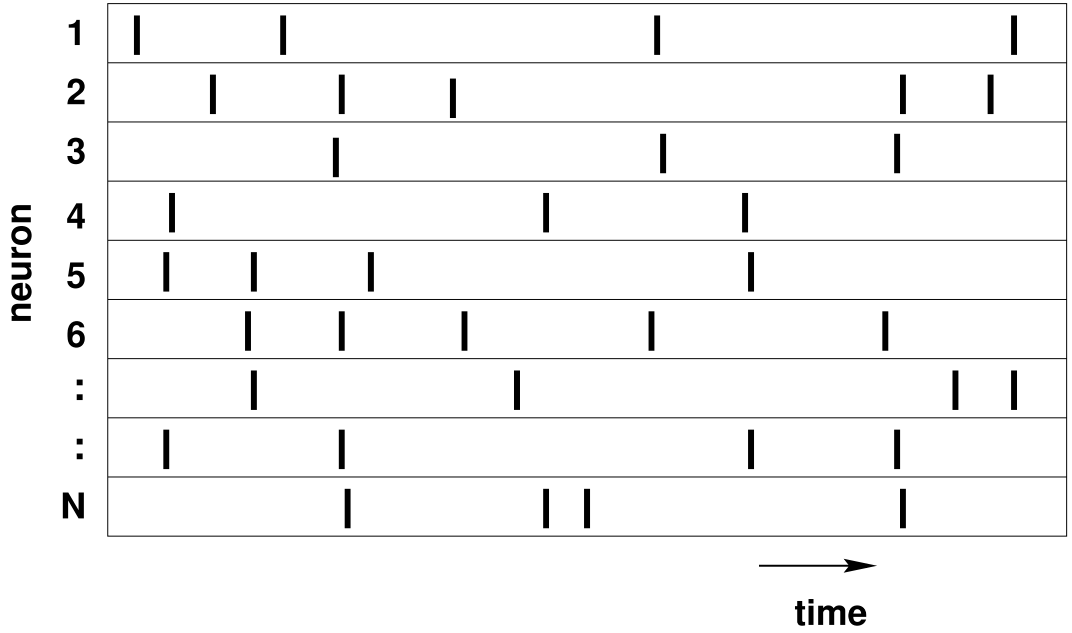
- Functional groups (cell assemblies) are the building blocks of information processing
- Membership expressed by simultaneous activation

Problem:

- Simultaneous activation of two assemblies causes ambiguity

Time as coding space





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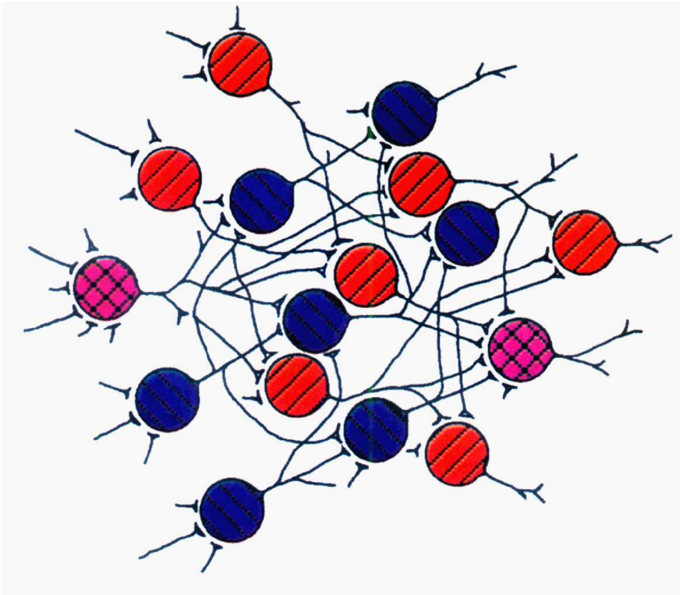
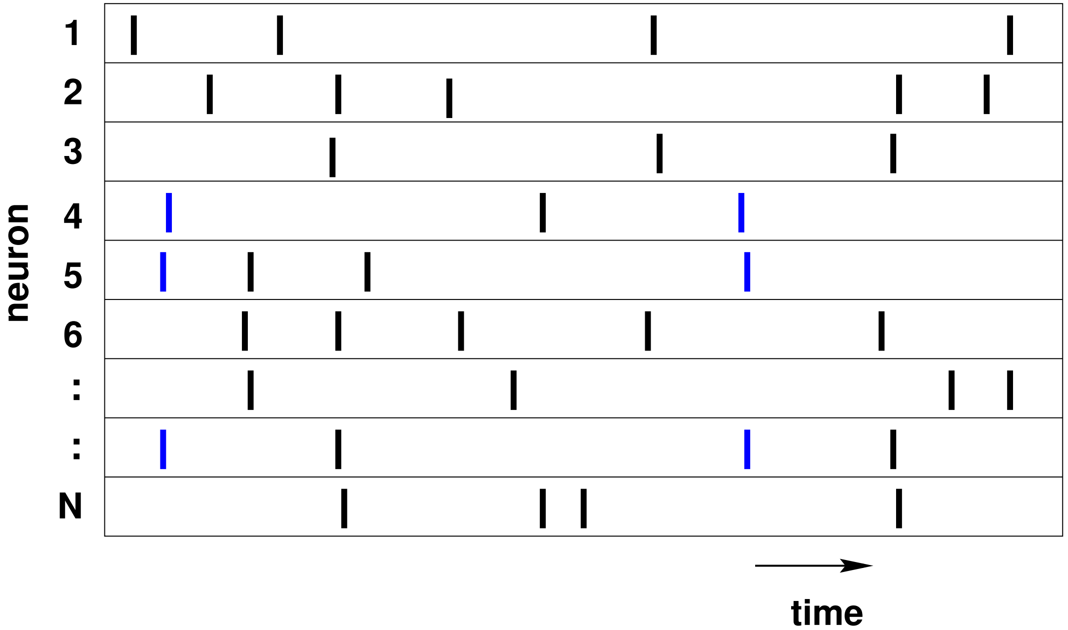
- precise coordination of spike timing

Time as coding space





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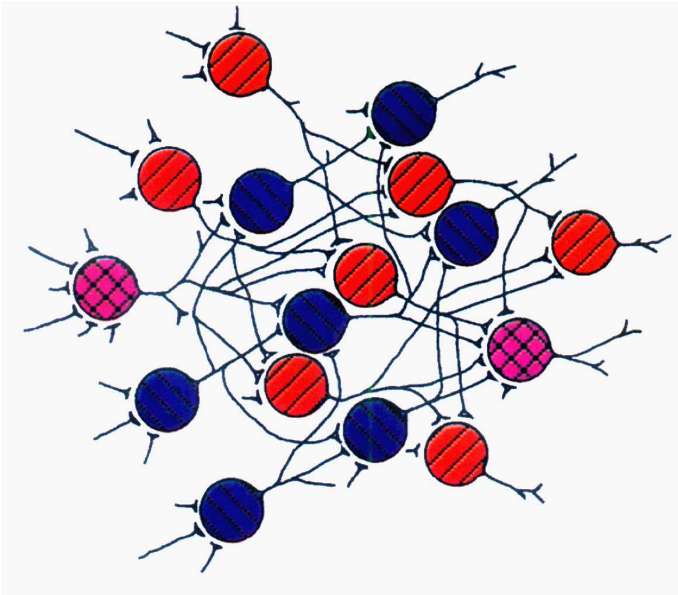
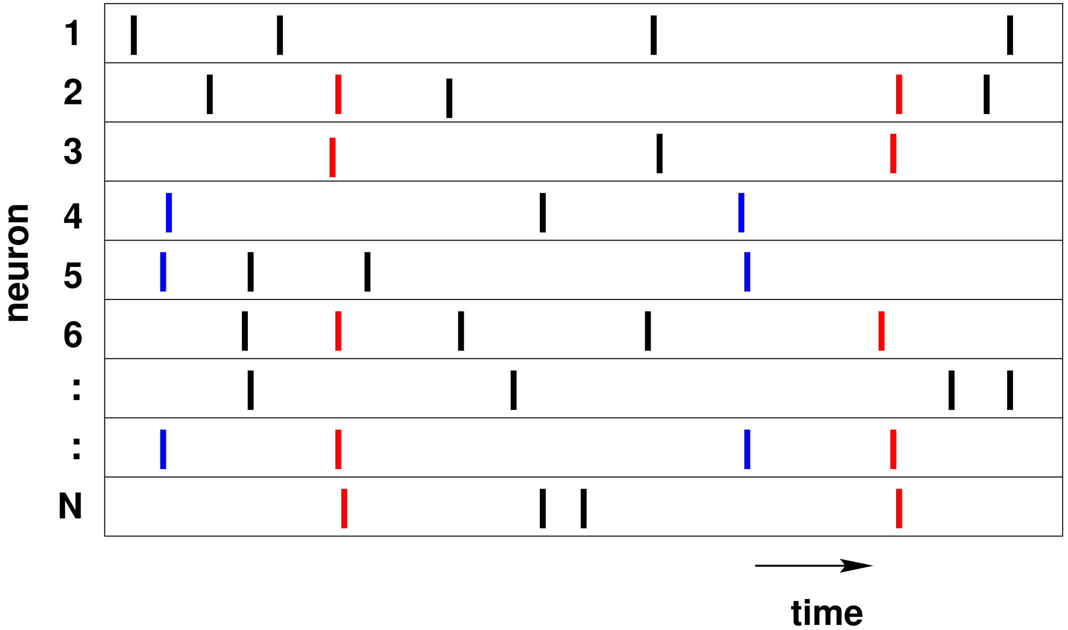
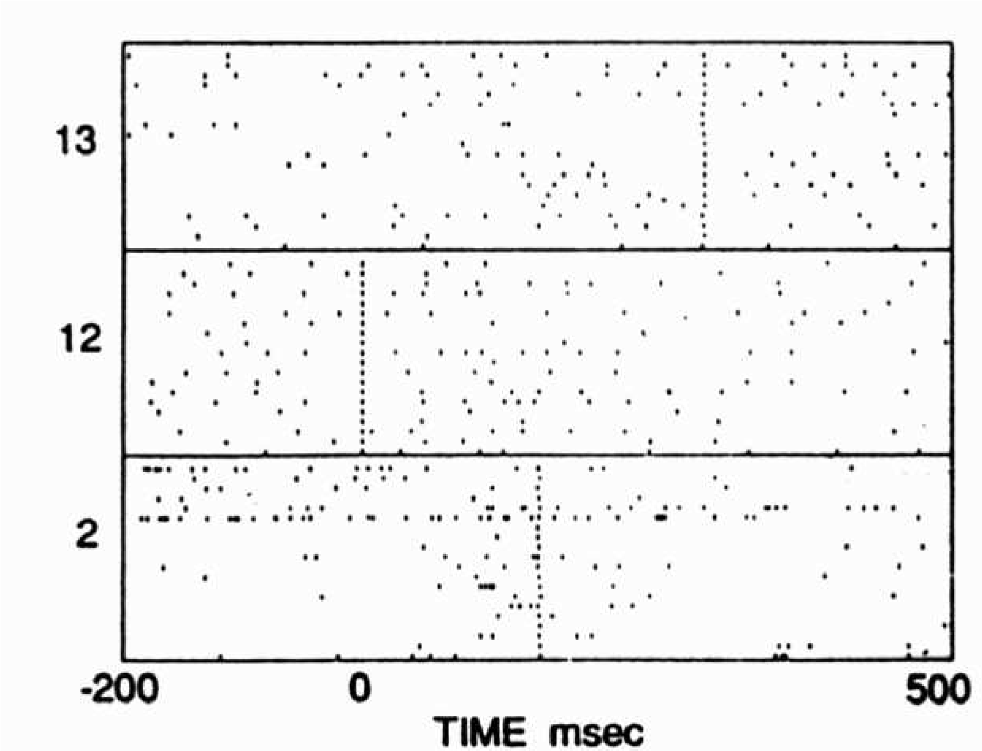


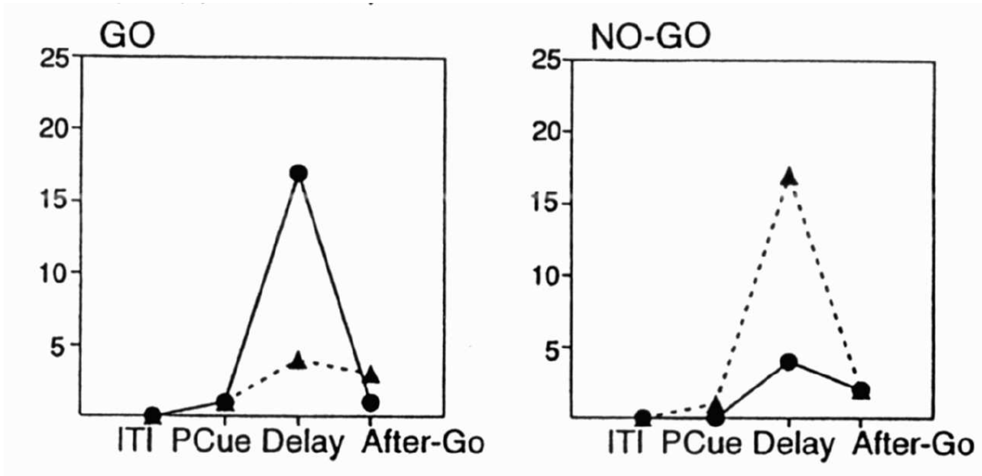


M. Abeles, S. Grün

- Simultaneous representation ("multiplexing")
- Membership of neurons in several assemblies

Experimental data

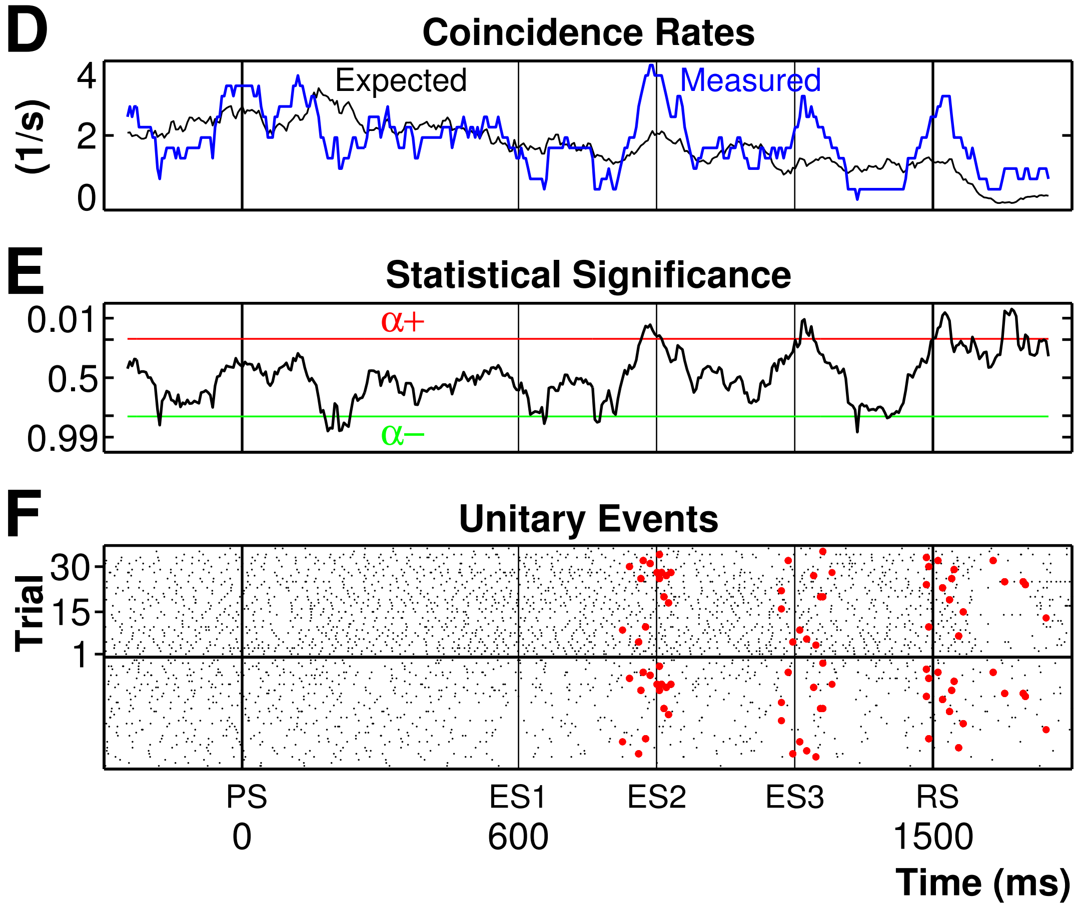




- Occurrence of spatio-temporal spike patterns
- Relationship to behavior

M. Abeles et al. (1993) In A. Aertsen (ed.) *Brain Theory. Spatio-Temporal Aspects of Brain Function* pp 149–181. Elsevier, Amsterdam

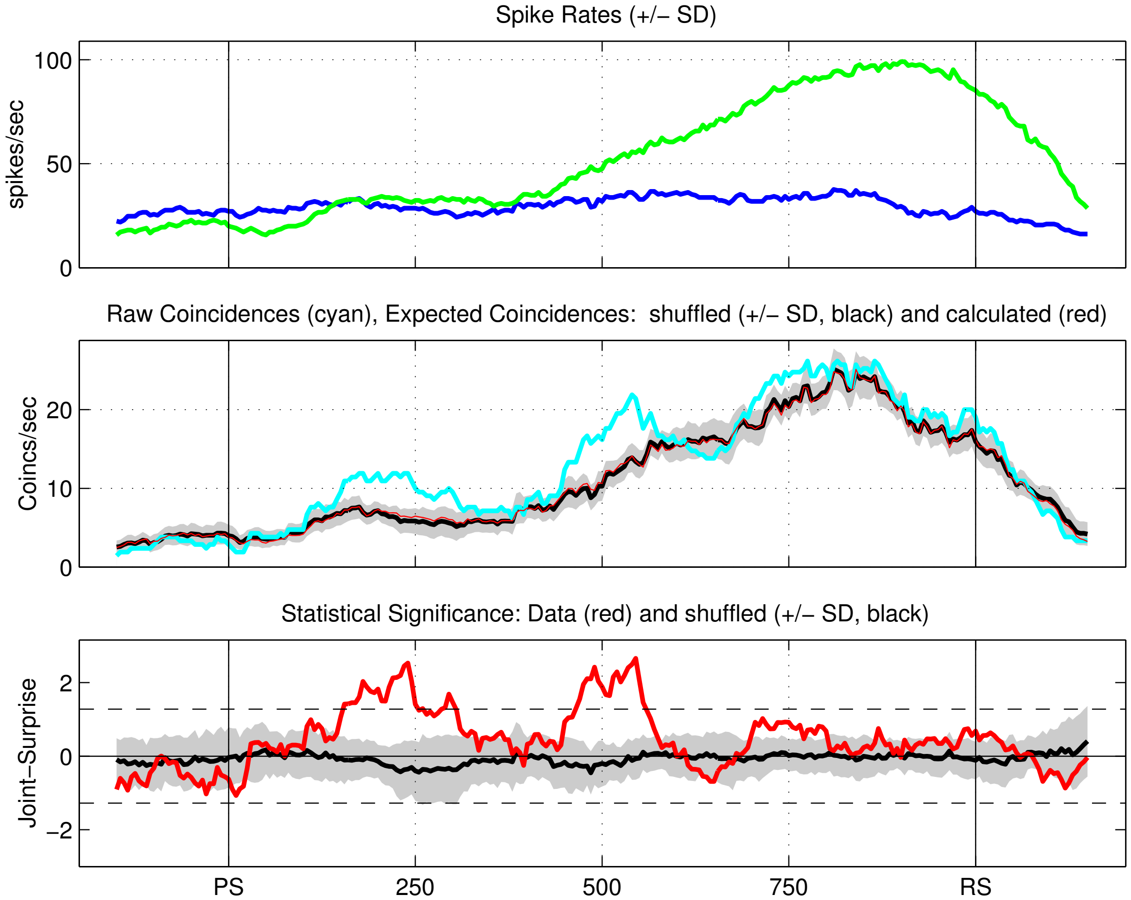
Experimental data



- Occurrence at behaviorally relevant points in time

A. Riehle, S. Grün, M. Diesmann, & A. Aertsen (1997) Science **278**:1950–1953
S. Grün, M. Diesmann, & A. Aertsen (2002) Neural Comput. **14**(1):43–80,81–119

Origin of precise spike events



precise spike events accompanied by co-variation of spike counts:

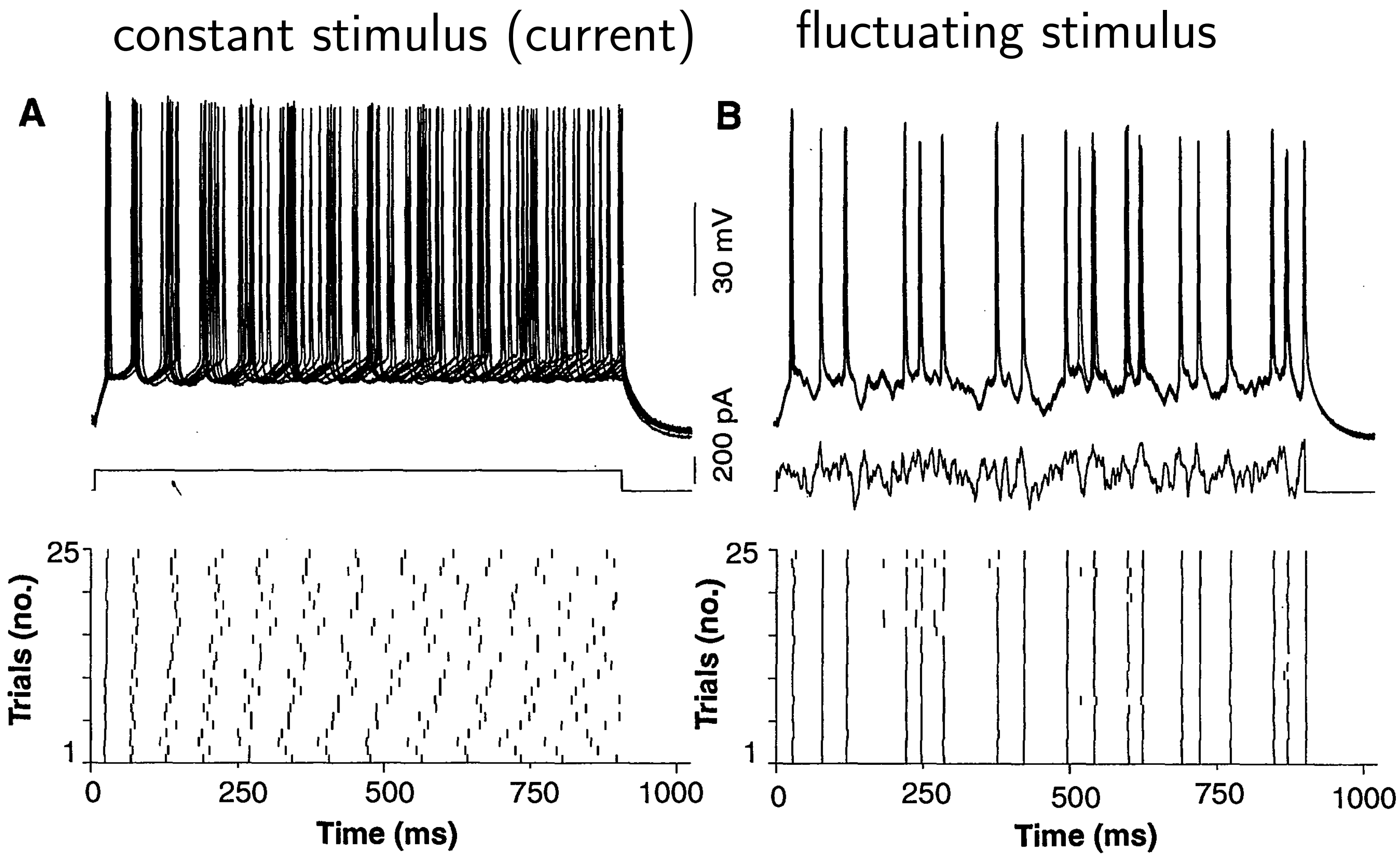
- first indication of relationship to other statistical measure

candidate mechanisms:

- alignment of random spikes
- activation of subnetworks injecting spikes

S. Grün, A. Riehle, & M. Diesmann (2003) Biol Cybern **88**(5):335–351

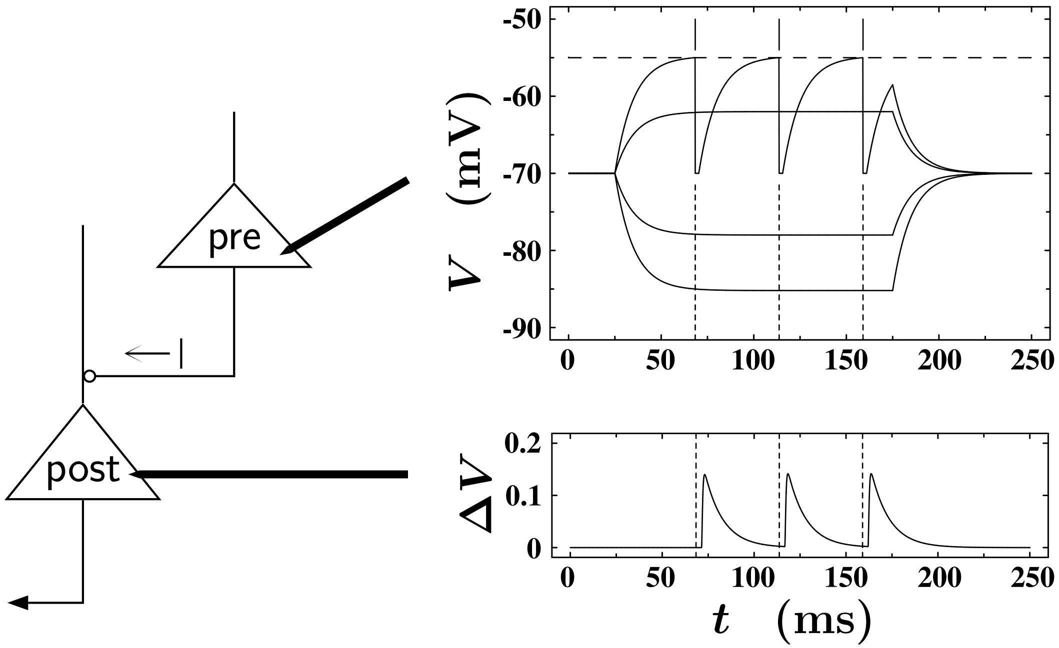
Reliability of a neuron



unreliable **reliable**

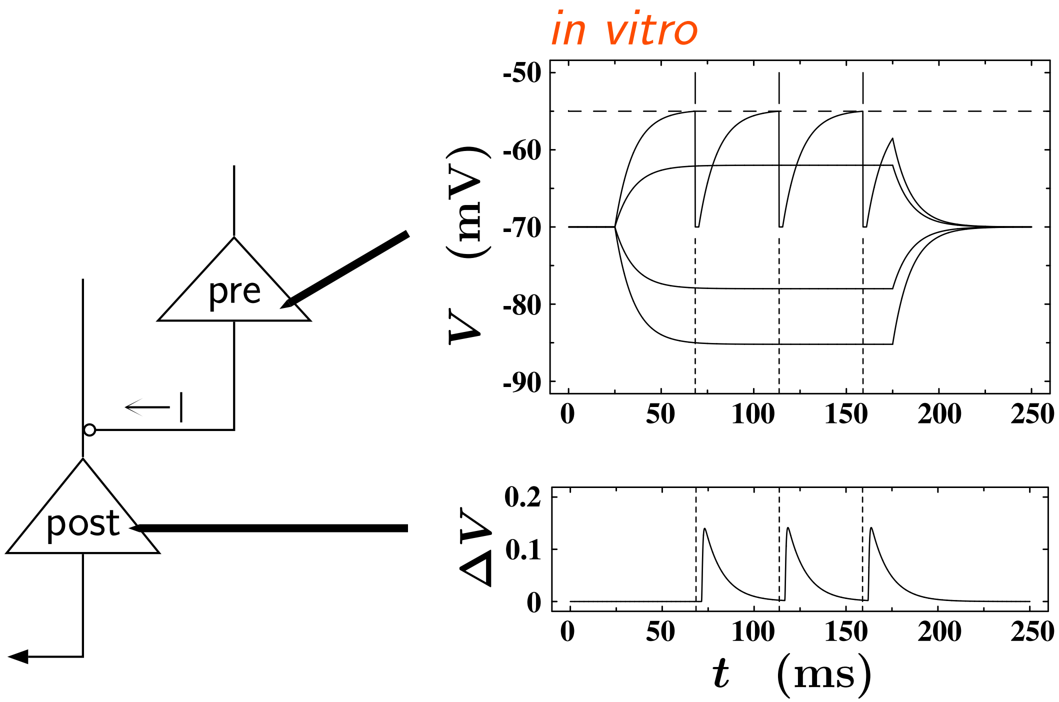
Z. Mainen & T. Sejnowski (1995) Science **268**:1503–1506
earlier work: H. Bryant & J. Segundo (1976) J. Physiol. **260**:279–314

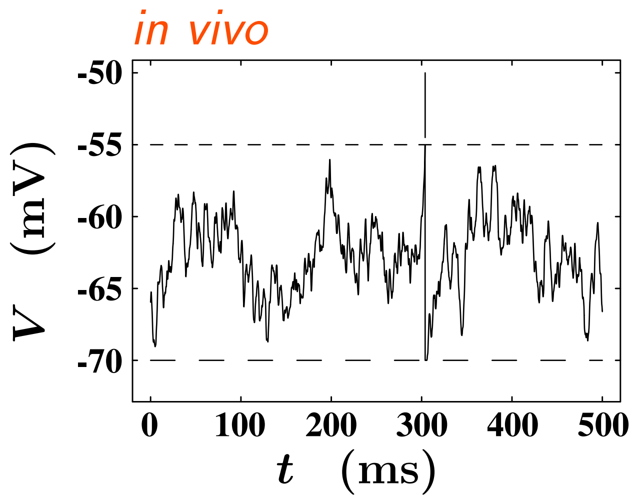
Properties of a neuron



- Membrane time constant $10\,\mathrm{ms}$
- Delay of synaptic events $1\,\mathrm{ms}$
- small post-synaptic potentials
- 80% excitatory, 20% inhibitory

Properties of a neuron



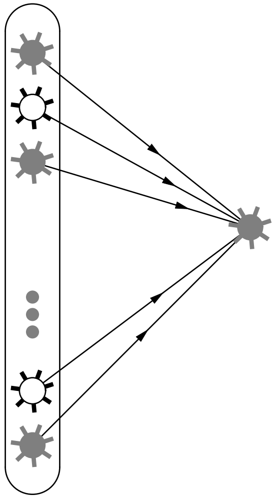


- Membrane time constant $10\,\mathrm{ms}$
- Delay of synaptic events $1\,\mathrm{ms}$
- small post-synaptic potentials
- 80% excitatory, 20% inhibitory

- spontaneous Spiking $1\text{-}10\,\mathrm{Hz}$
- 10^5 neurons per mm^3
- 10^4 synapses per neuron

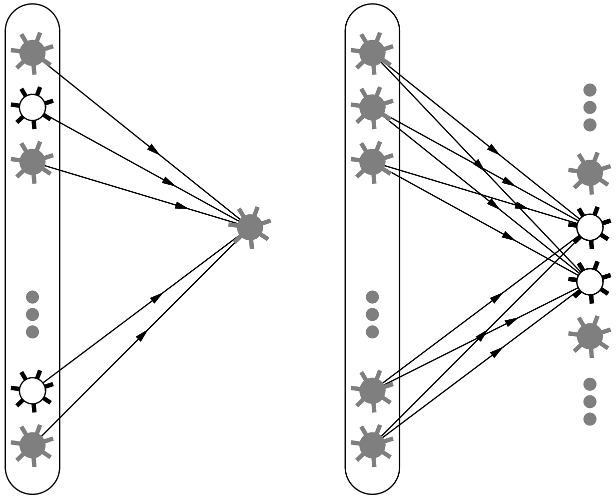
} 10^9

Feed-forward subnetworks –Synfire Chains



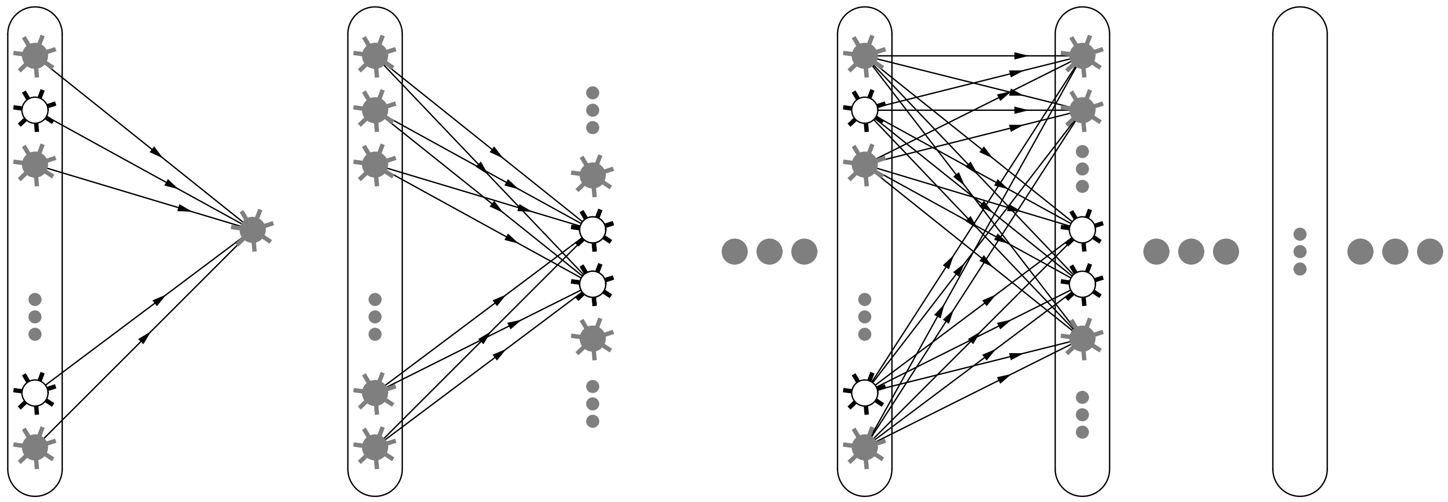
M. Abeles (1982) *Local Cortical Circuits* Springer, Berlin

Feed-forward subnetworks –Synfire Chains



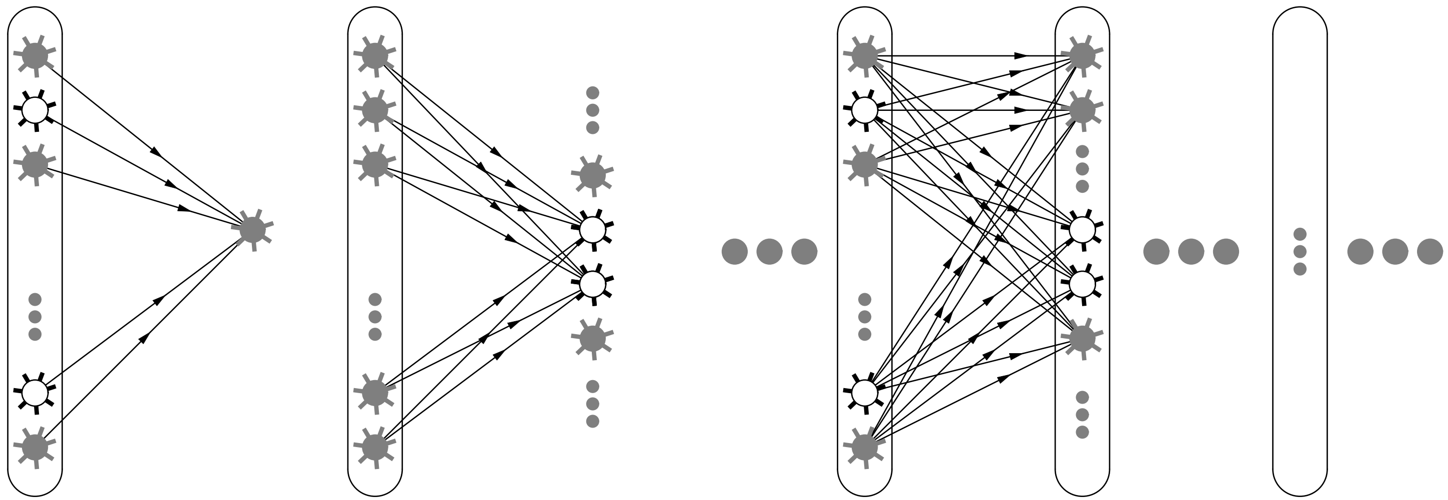
M. Abeles (1982) *Local Cortical Circuits* Springer, Berlin

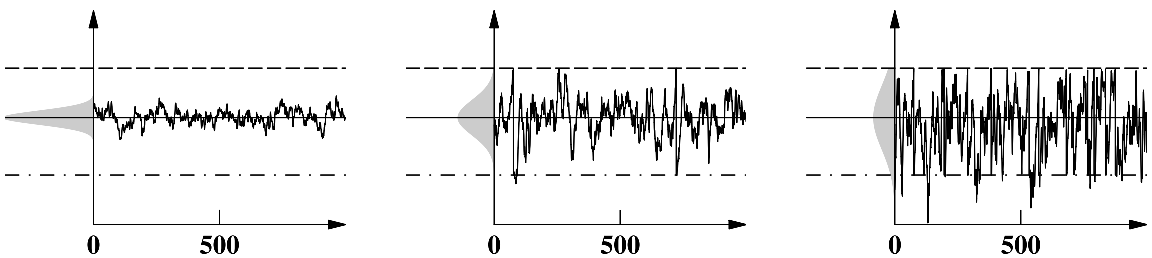
Feed-forward subnetworks
–Synfire Chains



M. Abeles (1982) *Local Cortical Circuits* Springer, Berlin

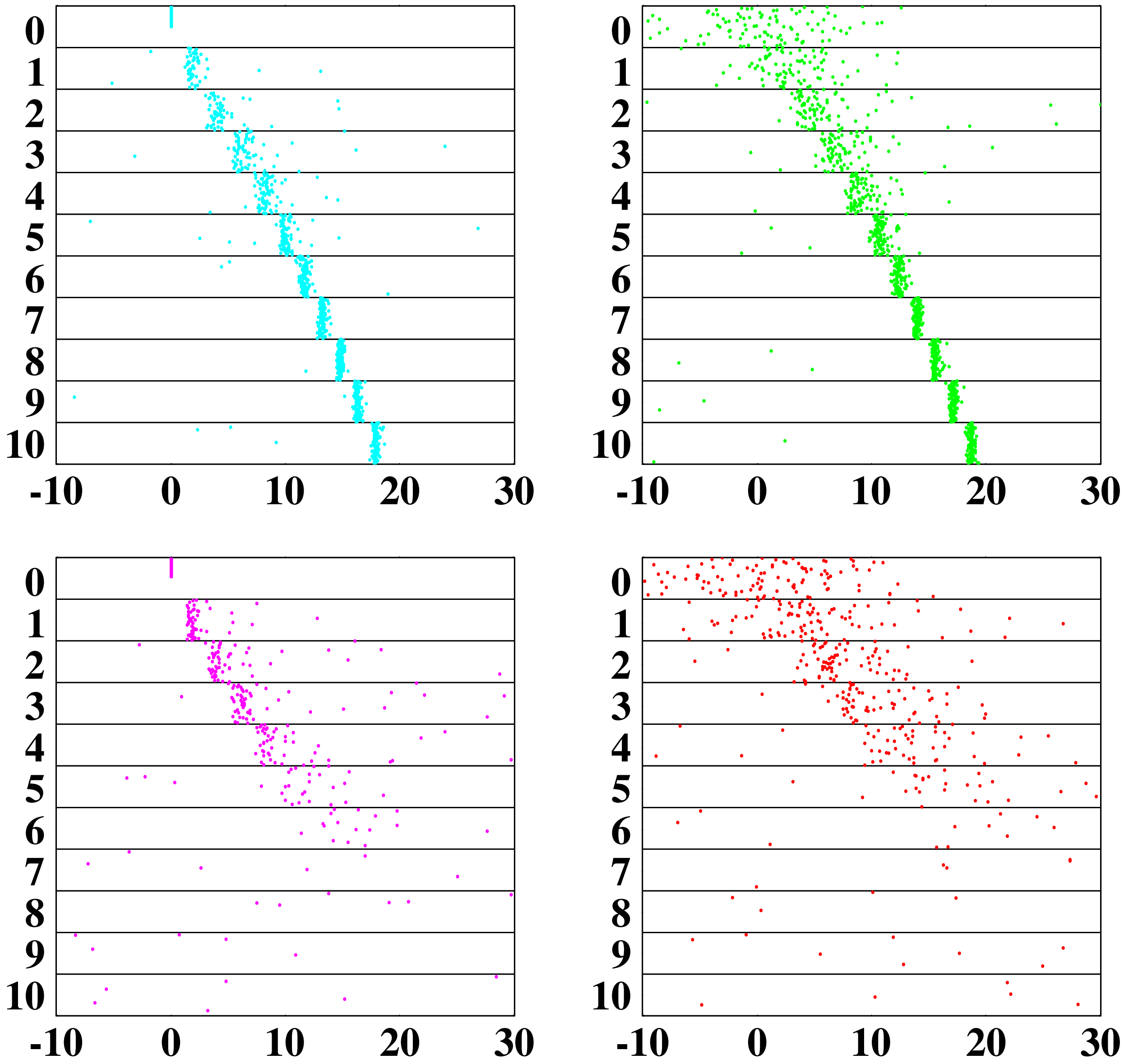
Feed-forward subnetworks –Synfire Chains



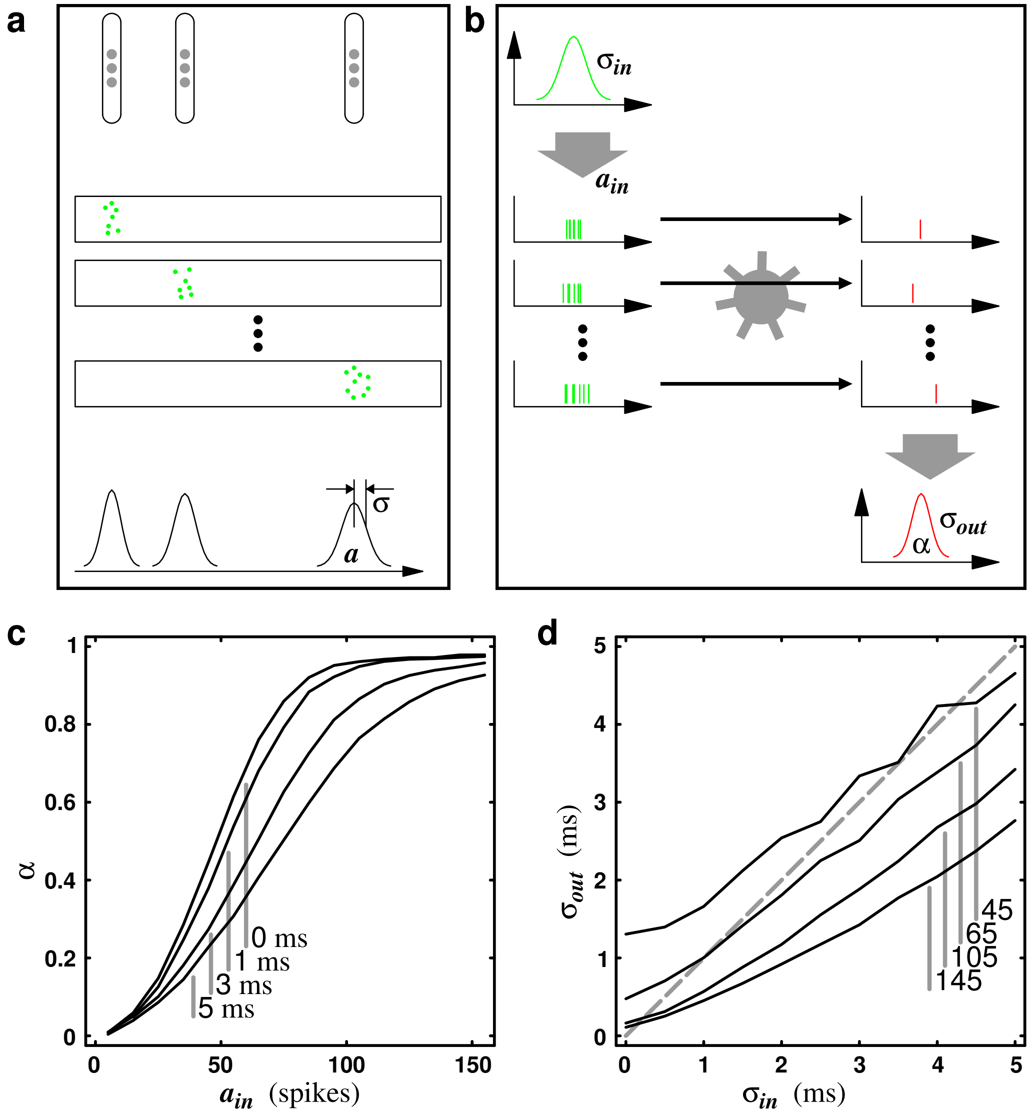


M. Abeles (1982) *Local Cortical Circuits* Springer, Berlin

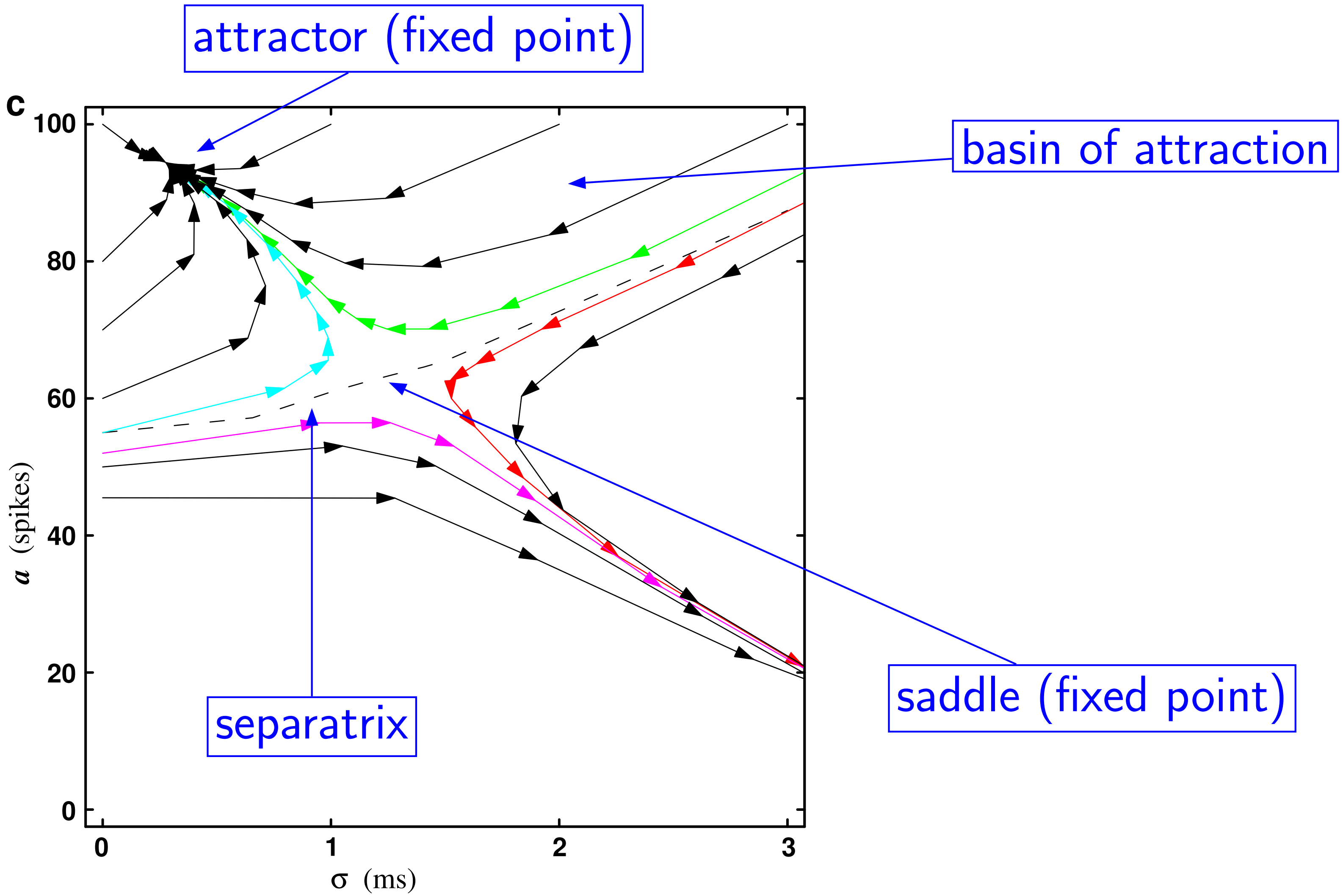
Propagation of synchronous activity



Pulse packets

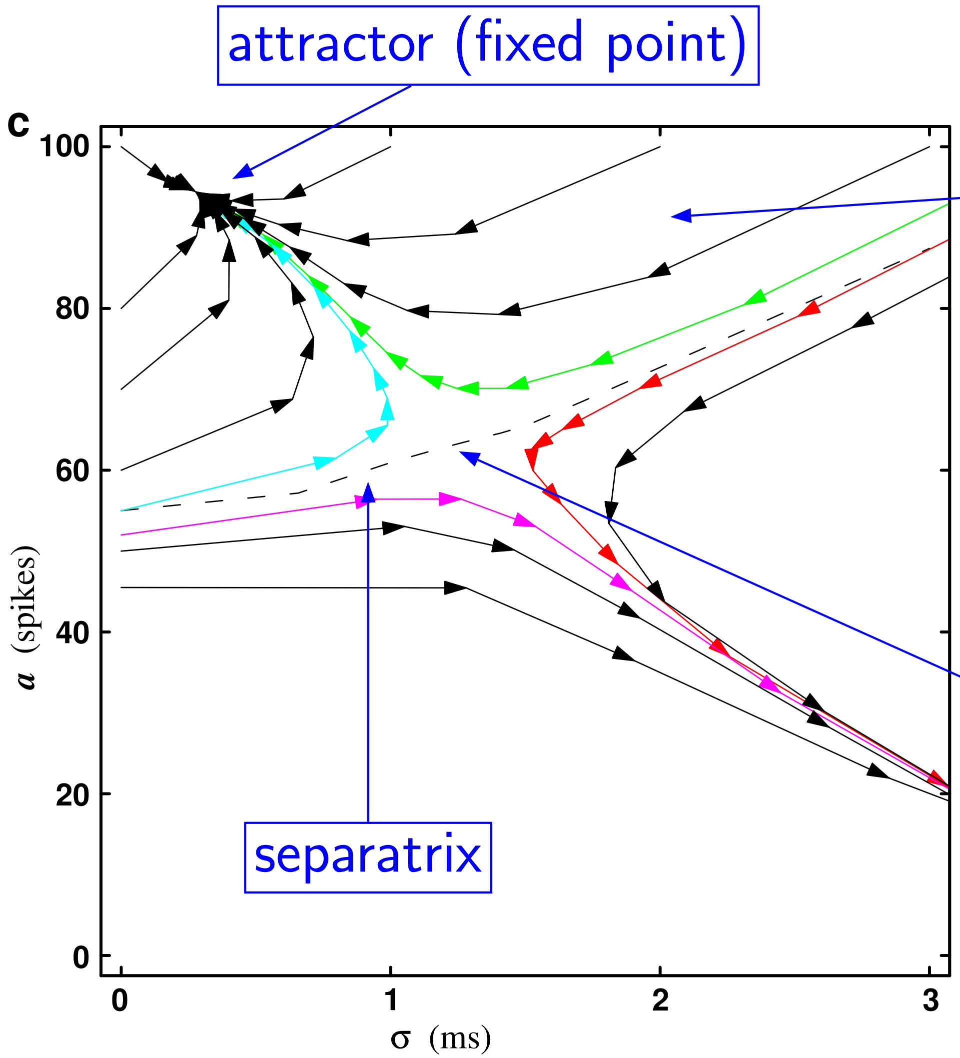


(a, σ) state space



M. Diesmann, M.-O. Gewaltig, & A. Aertsen (1999) Nature **402**:529–533

(a, σ) state space



$$(a_i, \sigma_i) \xrightarrow{T} (\alpha_{i+1}, \sigma_{i+1})$$

$$\downarrow \; a_{i+1} = w\alpha_{i+1}$$

$$(a_i, \sigma_i) \xrightarrow{T_w} (a_{i+1}, \sigma_{i+1})$$

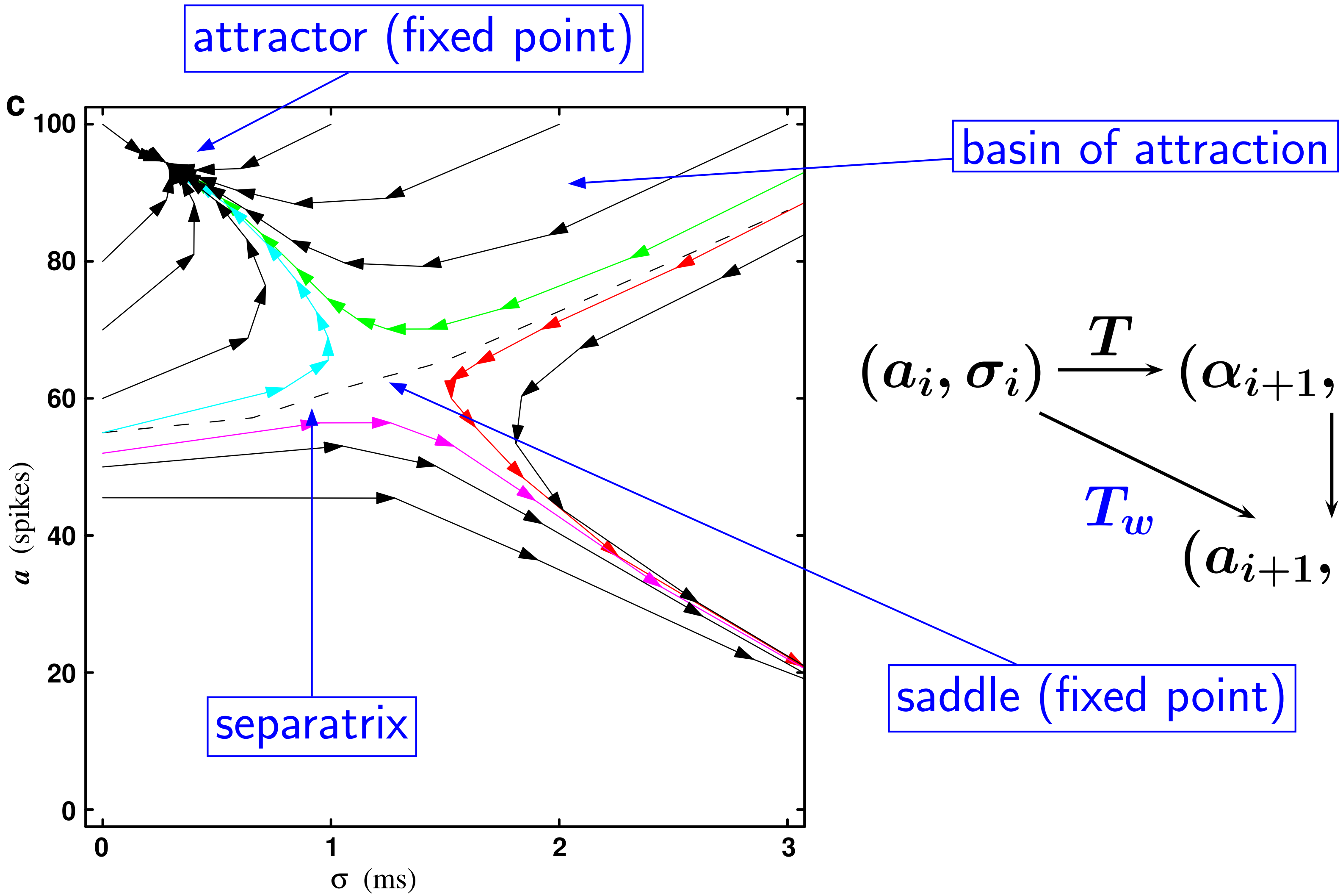
- 2-dimensional iterative map describes synchronization dynamics

M. Diesmann, M.-O. Gewaltig, & A. Aertsen (1999) Nature **402**:529–533

Parameters and variability of the synchronization dynamics

- Bifurcation analysis of biologically relevant parameters
- Variability in a stochastic model
- Summary

Reminder



$$(a_i, \sigma_i) \xrightarrow{T} (\alpha_{i+1}, \sigma_{i+1})$$

$$a_{i+1} = w\alpha_{i+1}$$

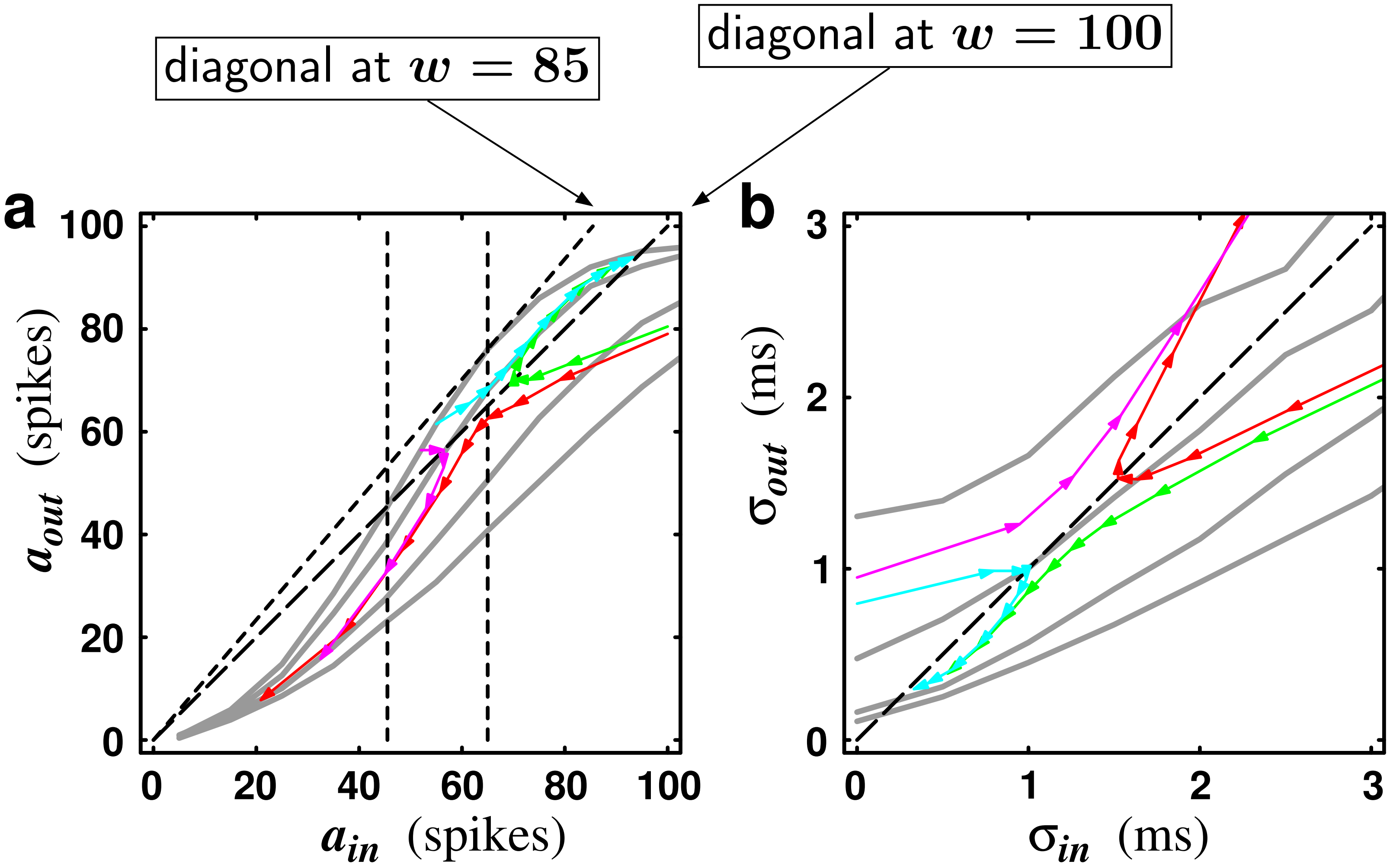
$$(a_i, \sigma_i) \xrightarrow{T_w} (a_{i+1}, \sigma_{i+1})$$

. . . but, state space portrait is valid only for a specific set of model parameters

$\mathbf{3}$ physiologically relevant parameters:

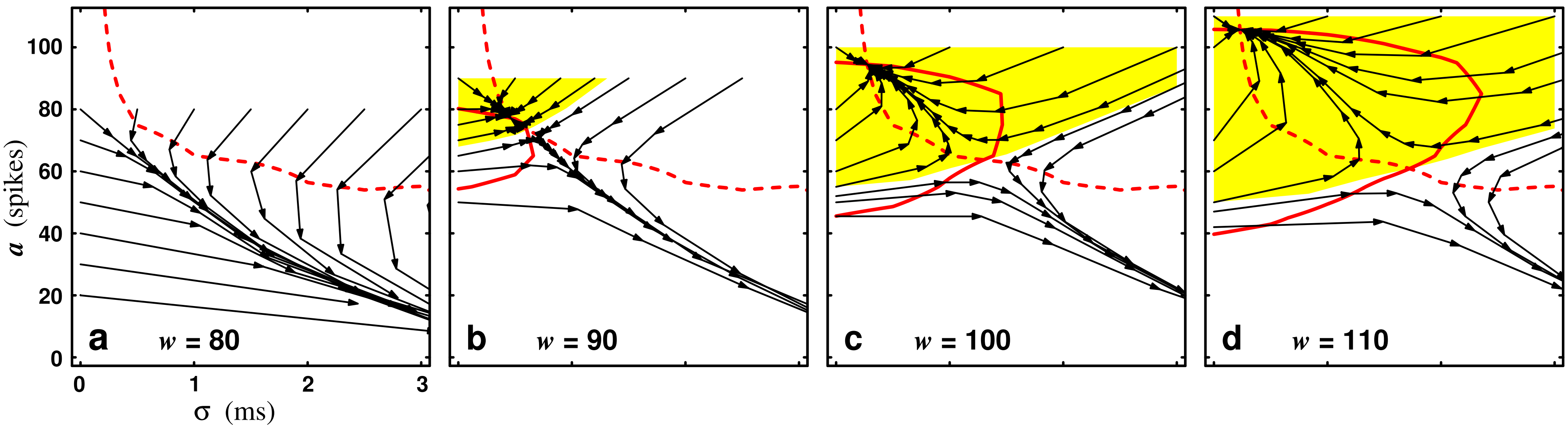
- Number of neurons per group $\boldsymbol{w}$
- Amplitude of membrane potential fluctuations $\boldsymbol{\sigma_U}$
- Rise time of the post-synaptic potential $\boldsymbol{\tau_0}$

Critical number of neurons w



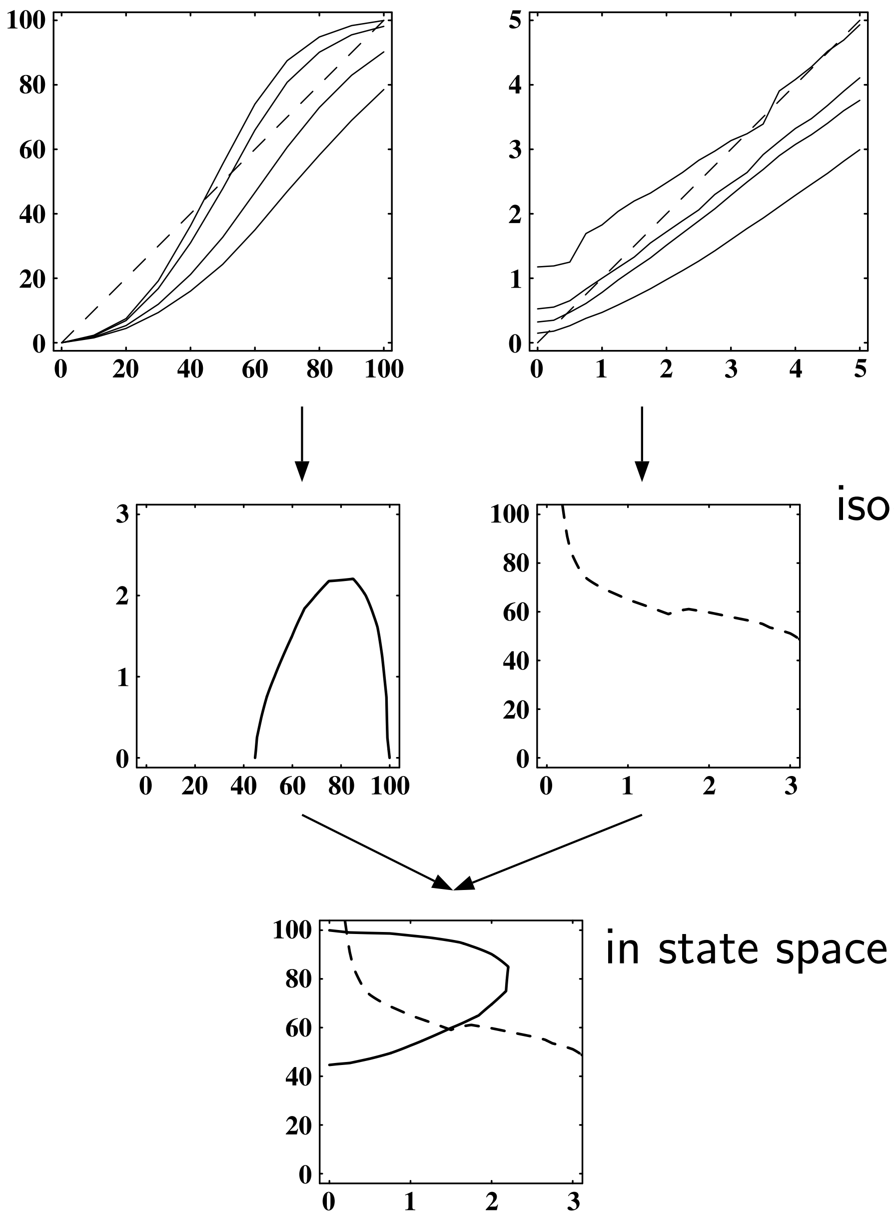
- Below a critical w a structural change of state space is expected

Number of neurons per group w



- Stable propagation of synchronous activity requires a minimal number of neurons per group

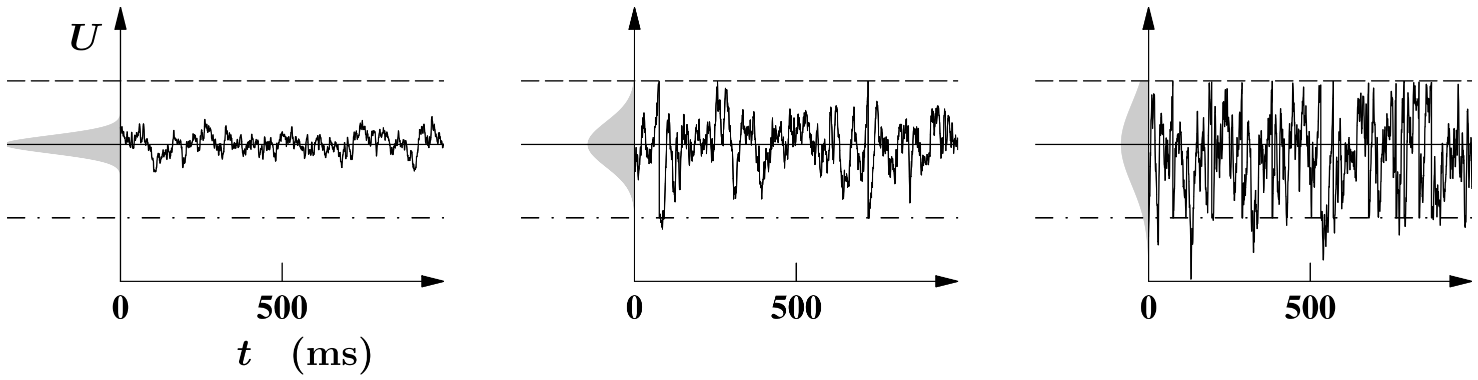
Finding Fixed Points



Traveling along the diagonal for a we can write down for which value of σ, a remains unchanged: a-isocline.

- the a-isocline describes the loci of horizontal flow
- the σ-isocline describes the loci of vertical flow
- fixed points are located at the intersections of the isoclines

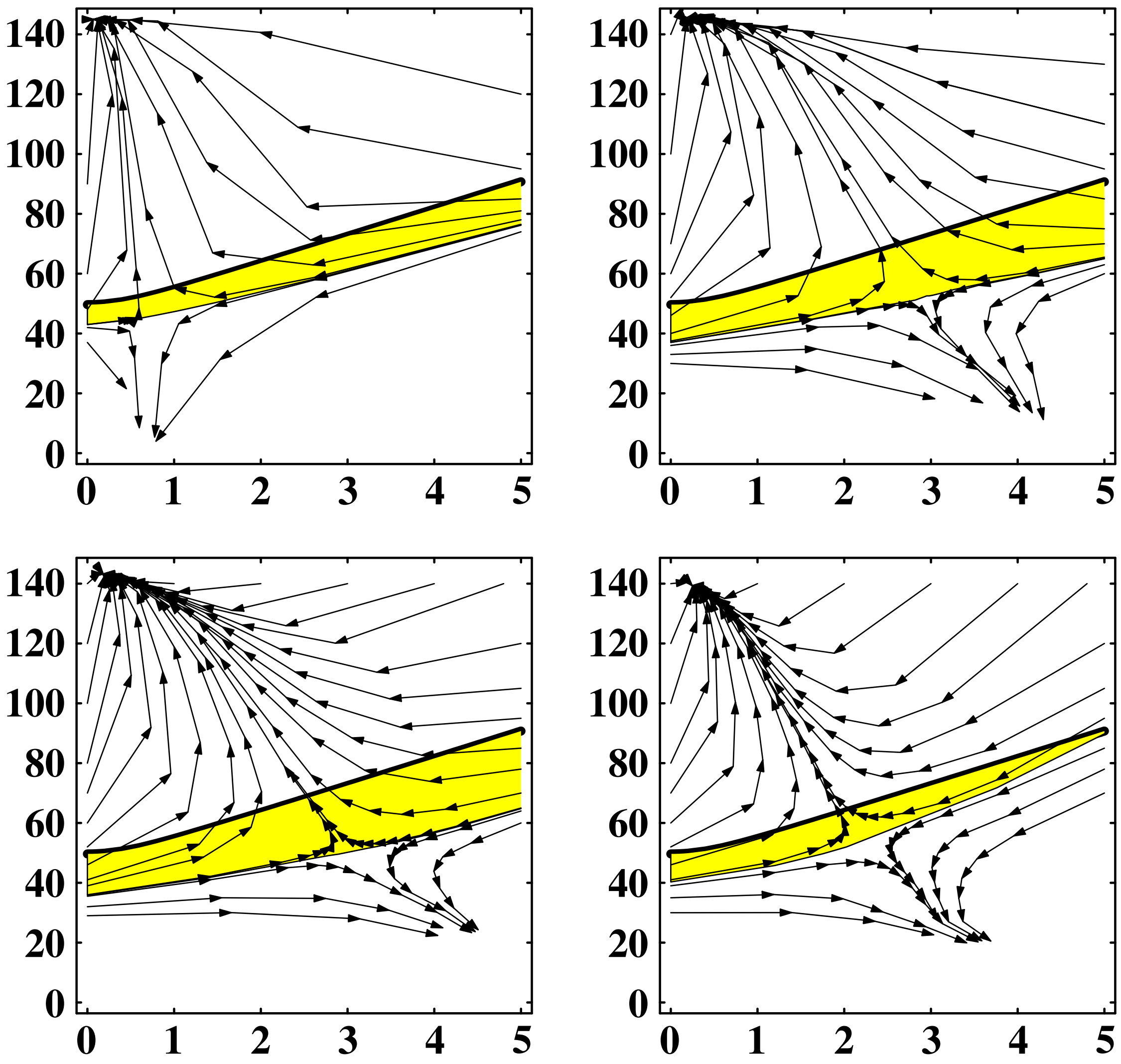
Background activity



$$\eta_U = \eta_{U+} + \eta_{U-}$$
$$\sigma^2_U = \sigma^2_{U+} + \sigma^2_{U-}$$

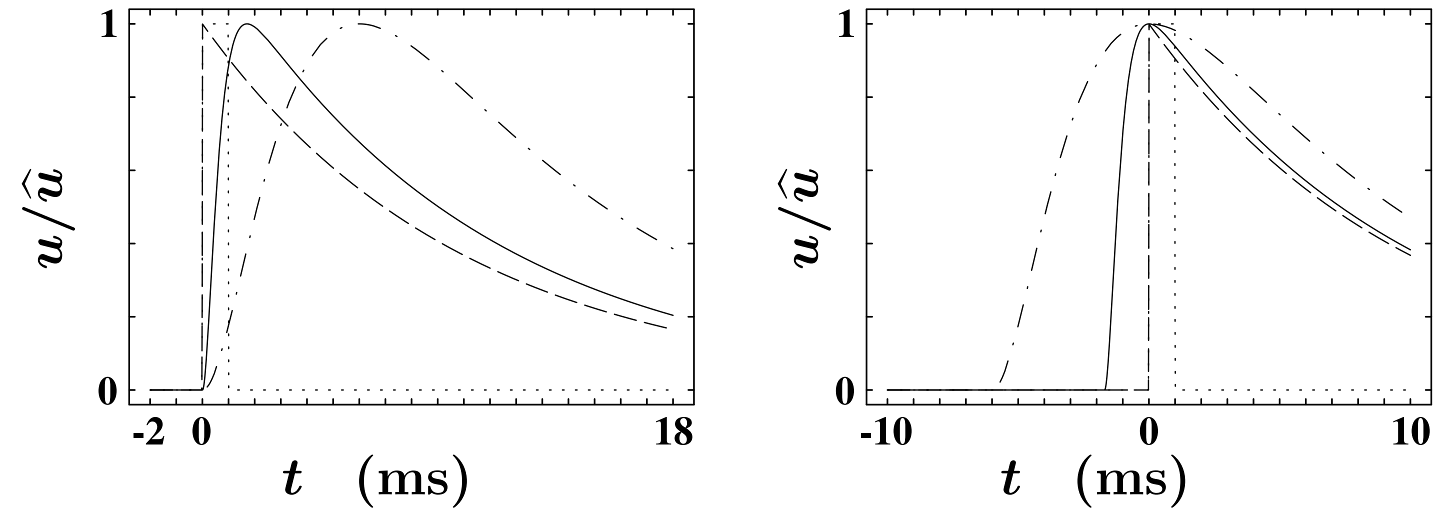
- A balance of excitatory and inihibitory inputs creates large fluctuations of membrane potential

Constructive effect of background activity



- The basin of attraction reaches its largest extend in the presence of realistic fluctuations of the membrane potential

Rise time of the post-synaptic potential

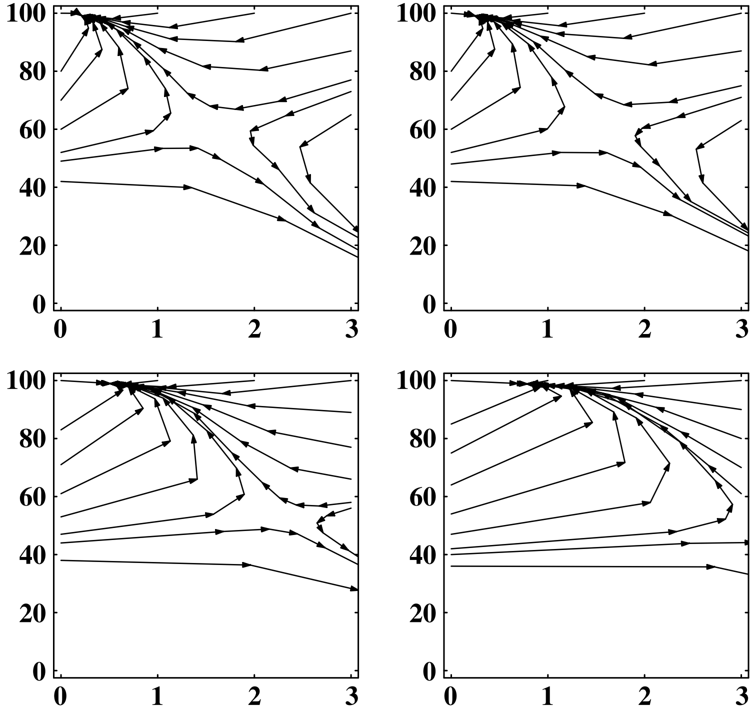


Post-synaptic potentials of different rise time
$\tau_0 = 0\,\mathrm{ms}, 1.7\,\mathrm{ms},$ und $6\,\mathrm{ms}$.

Rise time limits precision

increasing from top left to bottom right

constant amplitude

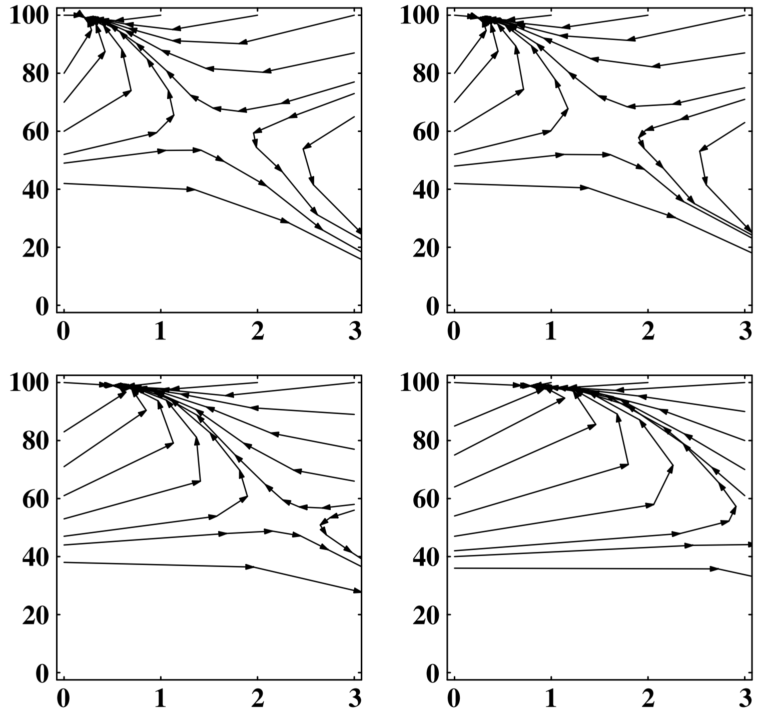


- Rise time limits precision of synchronous spiking
- however, synchronous activity remains a stable mode

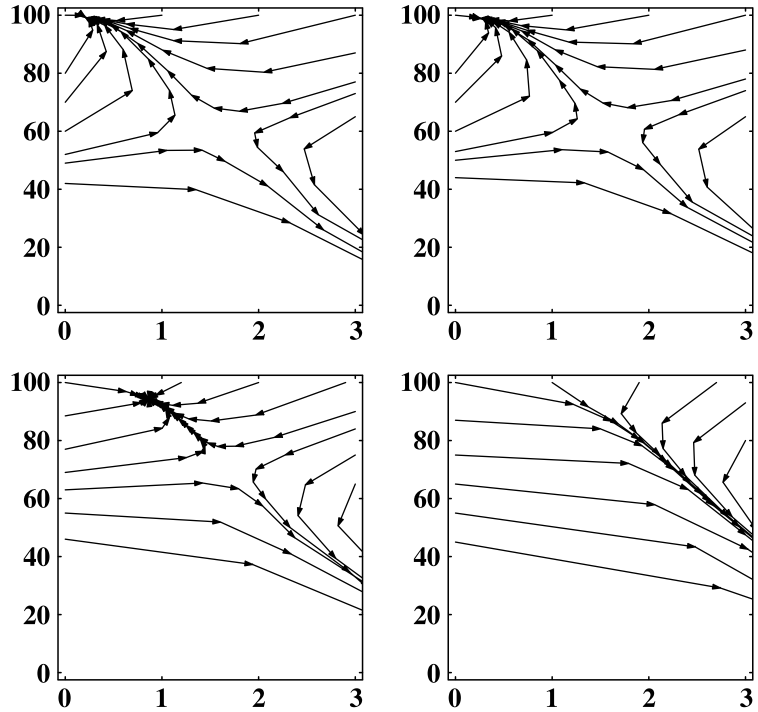
Rise time

increasing from to left to bottom right

constant amplitude



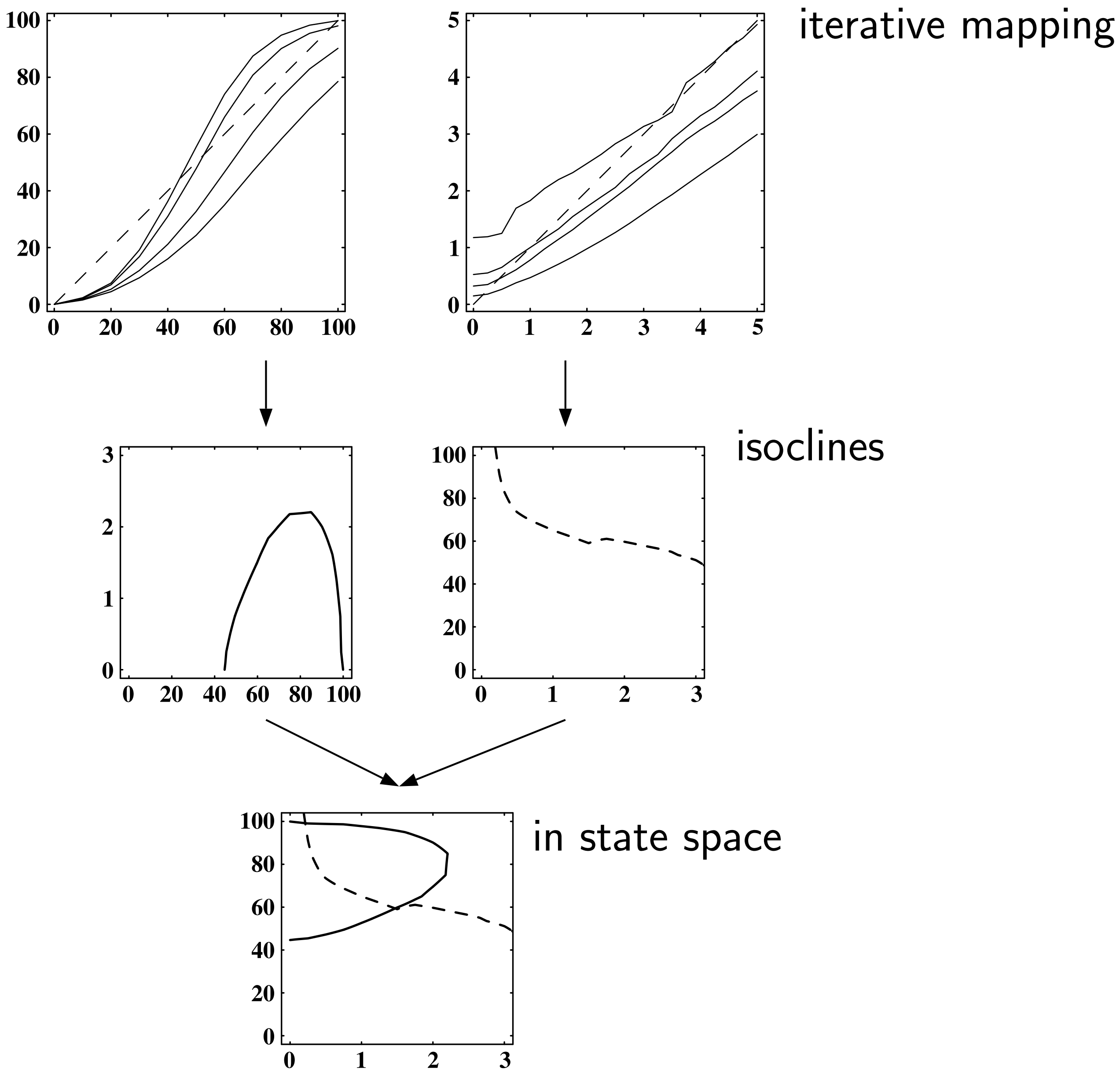
constant area



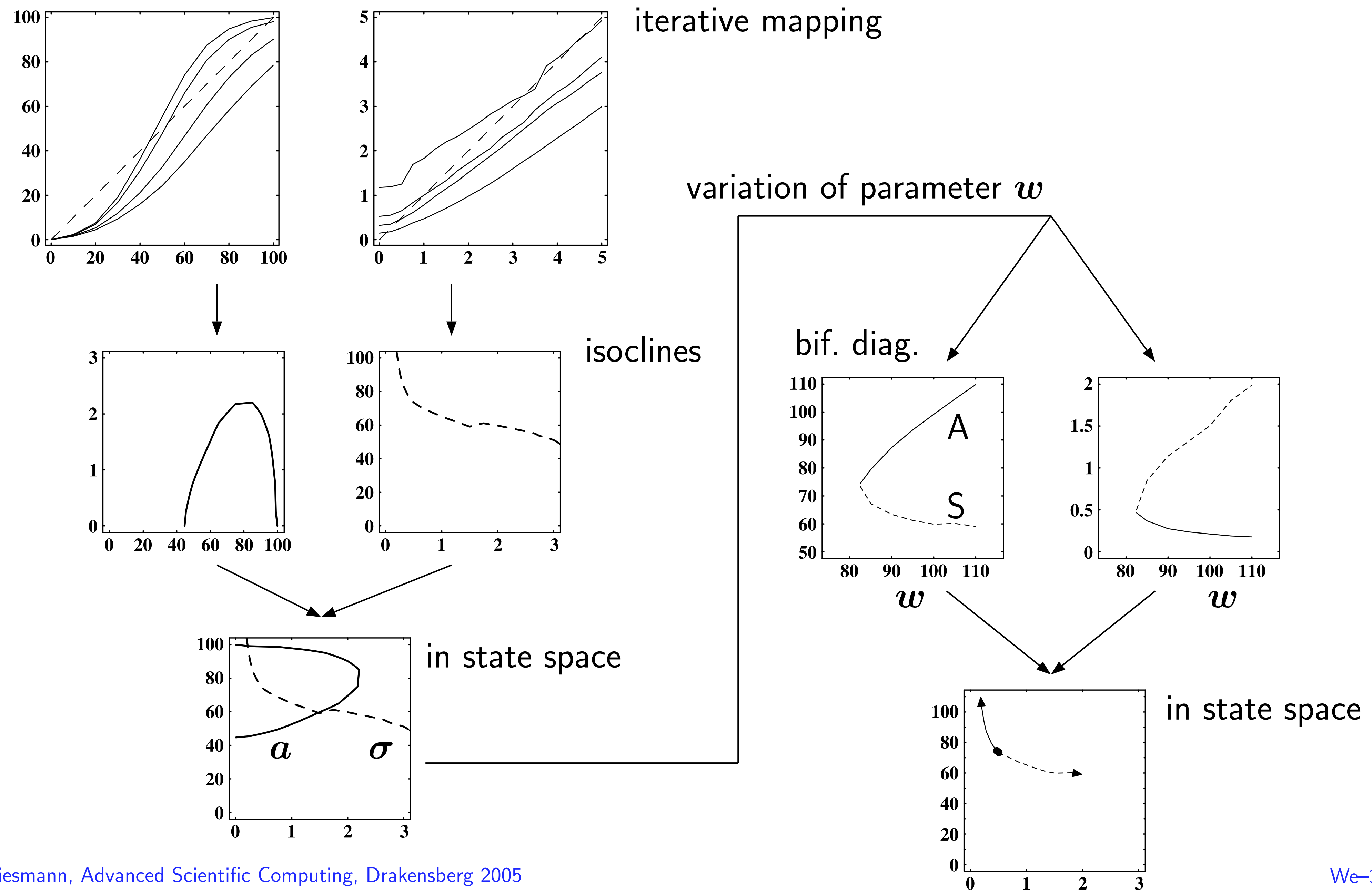
- Rise time limits precision of synchronous spiking
- however, synchronous activity remains a stable mode

- attractor is destroyed

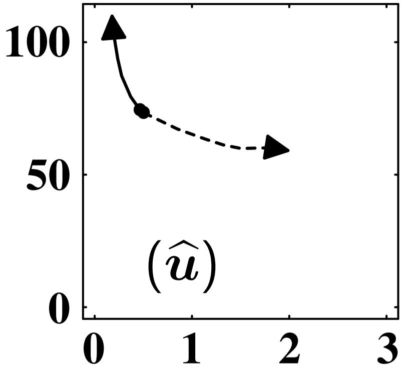
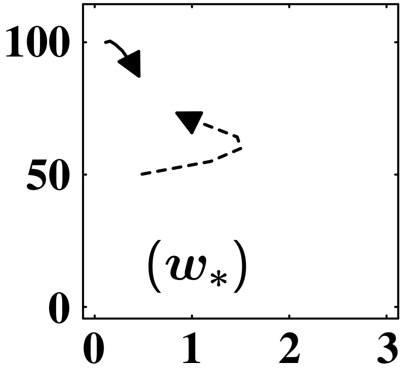
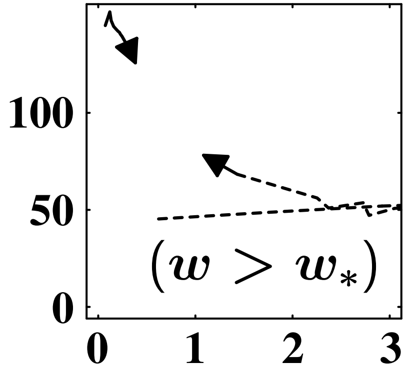
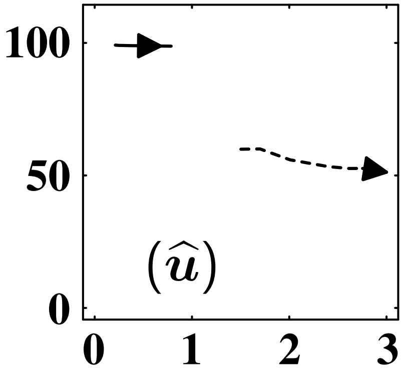
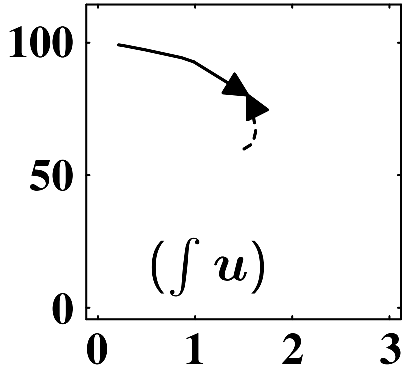
Summarizing



Summarizing: Bifurcation Diagrams



Parameters of Synchronization Dynamics

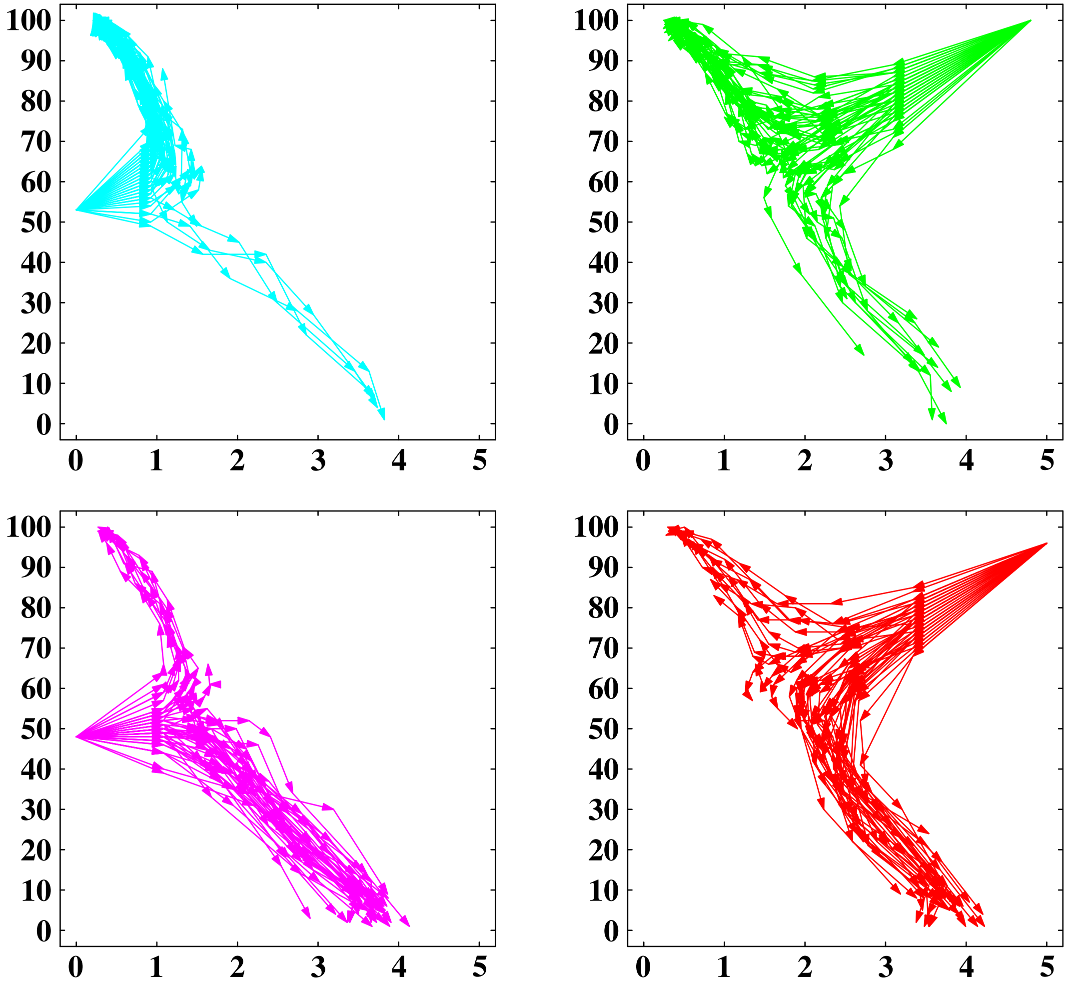
Parameter	Bifurcation Diagram		Interpretation
w		(const)	• Existence of minimal group size
σ_U			• Existence of optimal level • Dynamic control of pulse packet propagation
τ_0			• Time scale of synchrony • Spike synchronization not limited to short rise times

. . . but, our analysis only describes the dynamics of the mean

- Can we account for the variability of neuronal spiking?
- Is the analysis provided meaningful, given the variability?

Variability of spike count

- Spike probability α makes spike count a a random variable with mean αw

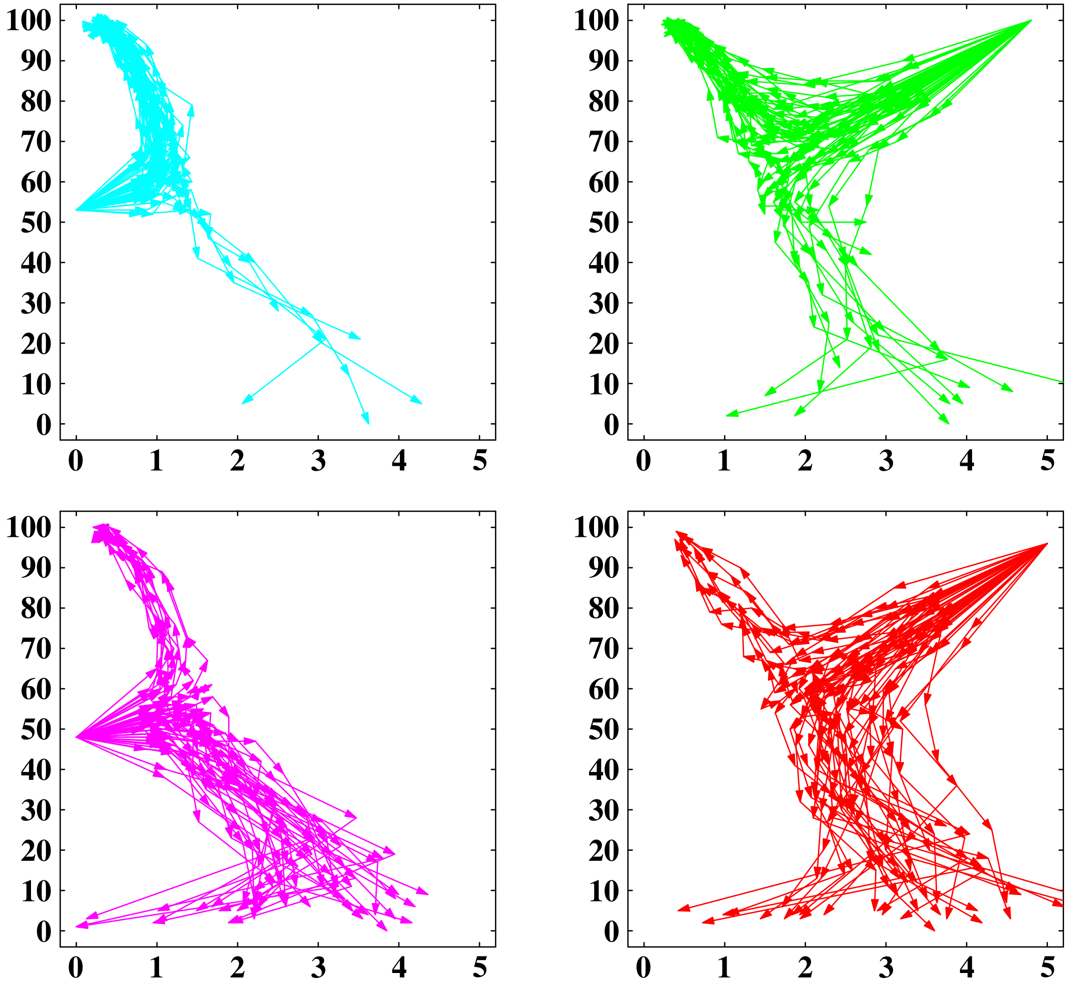


$$A_w(\alpha, \sigma) = (B[\alpha], \sigma)$$

$$(a_i, \sigma_i) \xrightarrow{T} (\alpha, \sigma_{i+1}) \xrightarrow{A_w} (a_{i+1}, \sigma_{i+1})$$

Variability of spike jitter

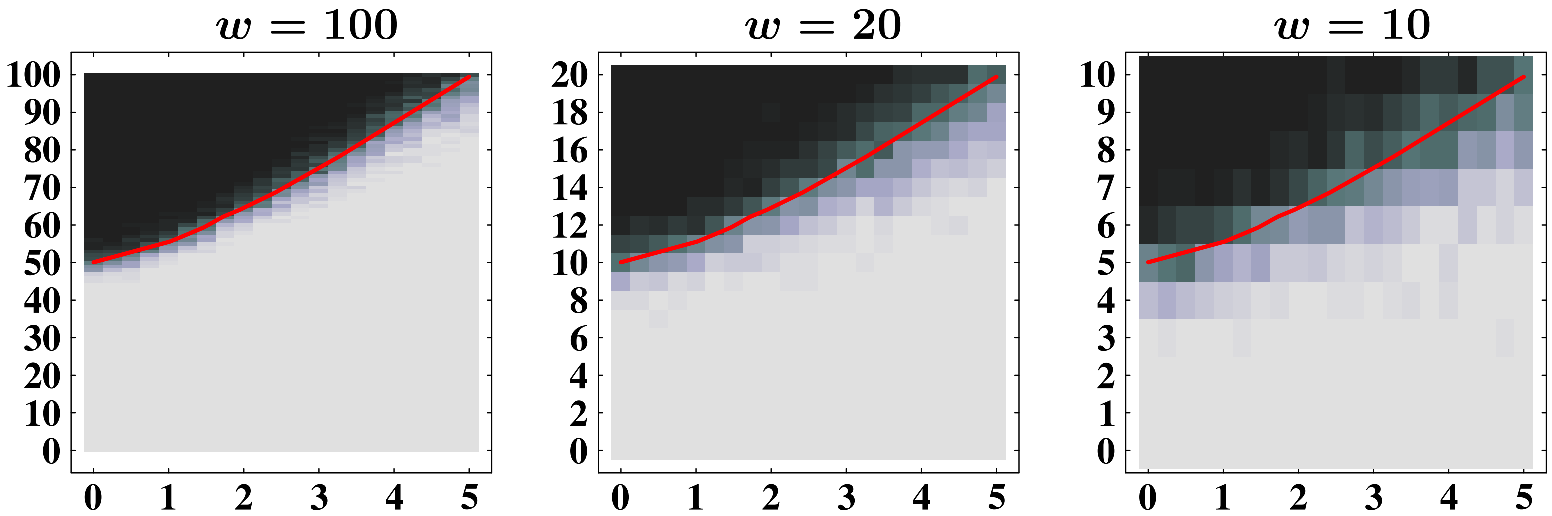
- σ is also a random variable. A neuron responds to the temporal jitter in the actual input spike times.



M. Diesmann (2002)
`www.ub.ruhr-uni-bochum.de`

$$(a_i, \sigma_i) \xrightarrow{T} (\alpha, \sigma) \xrightarrow{A_w} (a_{i+1}, \sigma) \xrightarrow{S} (a_{i+1}, \sigma_{i+1})$$

Survival probability



with $w \times$ synaptic strength $=$ const

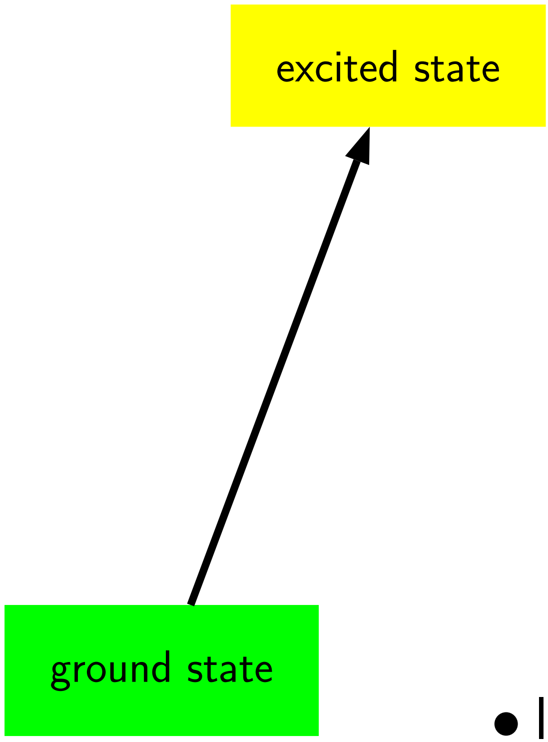
- The separatrix of the deterministic case is replaced by an (abrupt) change in survival probability

M.-O. Gewaltig, M. Diesmann, & A. Aertsen (2001) Neural Networks **14**:657–673

Summary

- For a wide regime of parameters,
  stable propagation of synchronous spiking is possible
- The question whether the cortical neuron supports precise spike timing can only be answered in the light of a specific network structure
- Subnetworks are distinguished by connectivity –not synaptic strength
- Rise-time of the post-synaptic potential –not membrane time constant– determines the ability to synchronize and the residual temporal spread
- Background activity can control synchronous spiking
- It seems that, in principle, the prerequisites to use time as coding space are fulfilled

Outlook



- stable propagation of pulse packets
- provides synfire functionality

- low spike rate
- asynchronous spiking

requires stable ground state