ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Biological Modeling of Neural Networks:

15.1 Review Populations of Neurons
- Transients

15.2 Rate models
-

Week 15 – Fast Transients and Rate models

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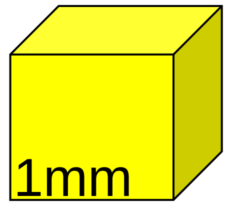
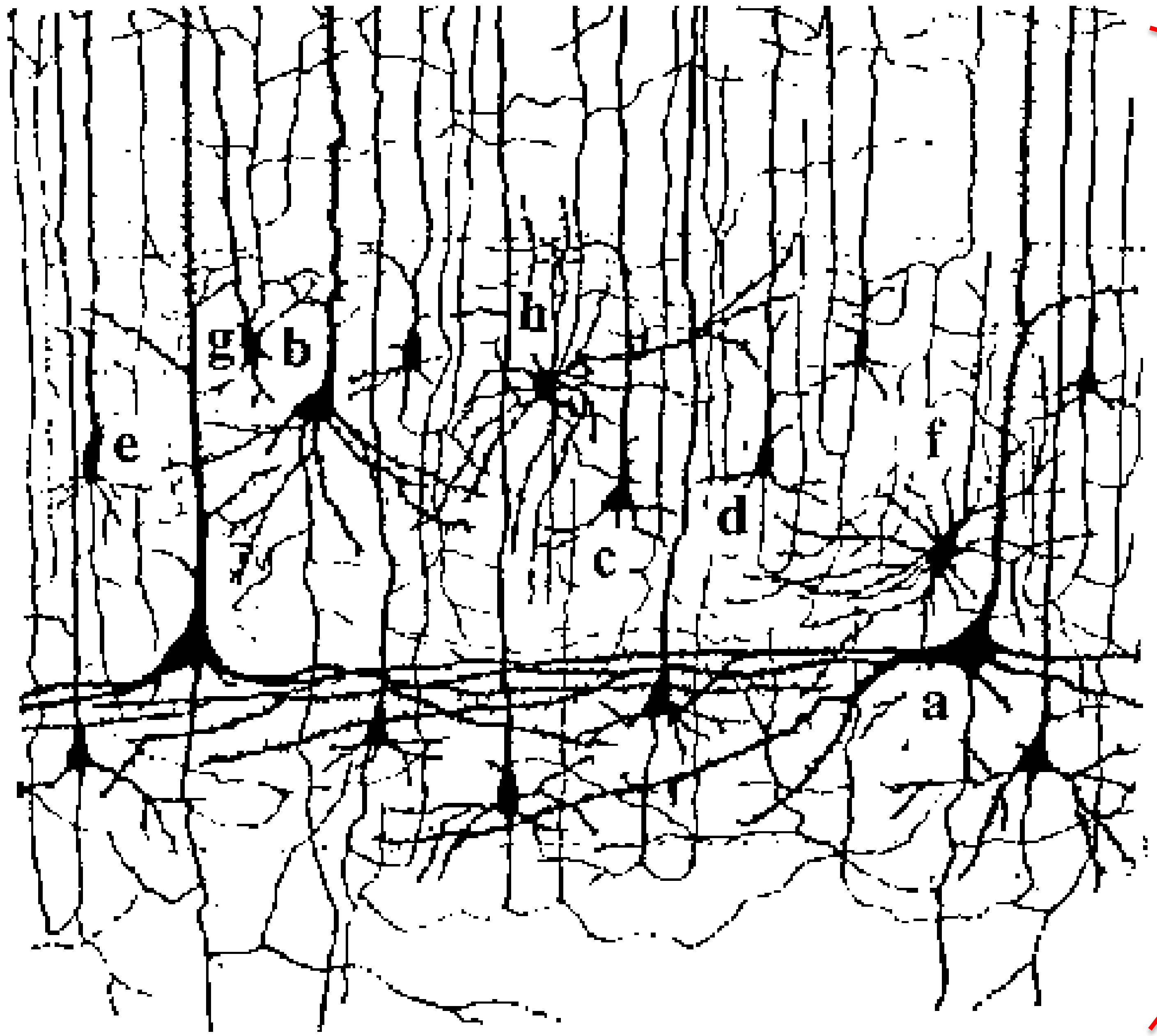
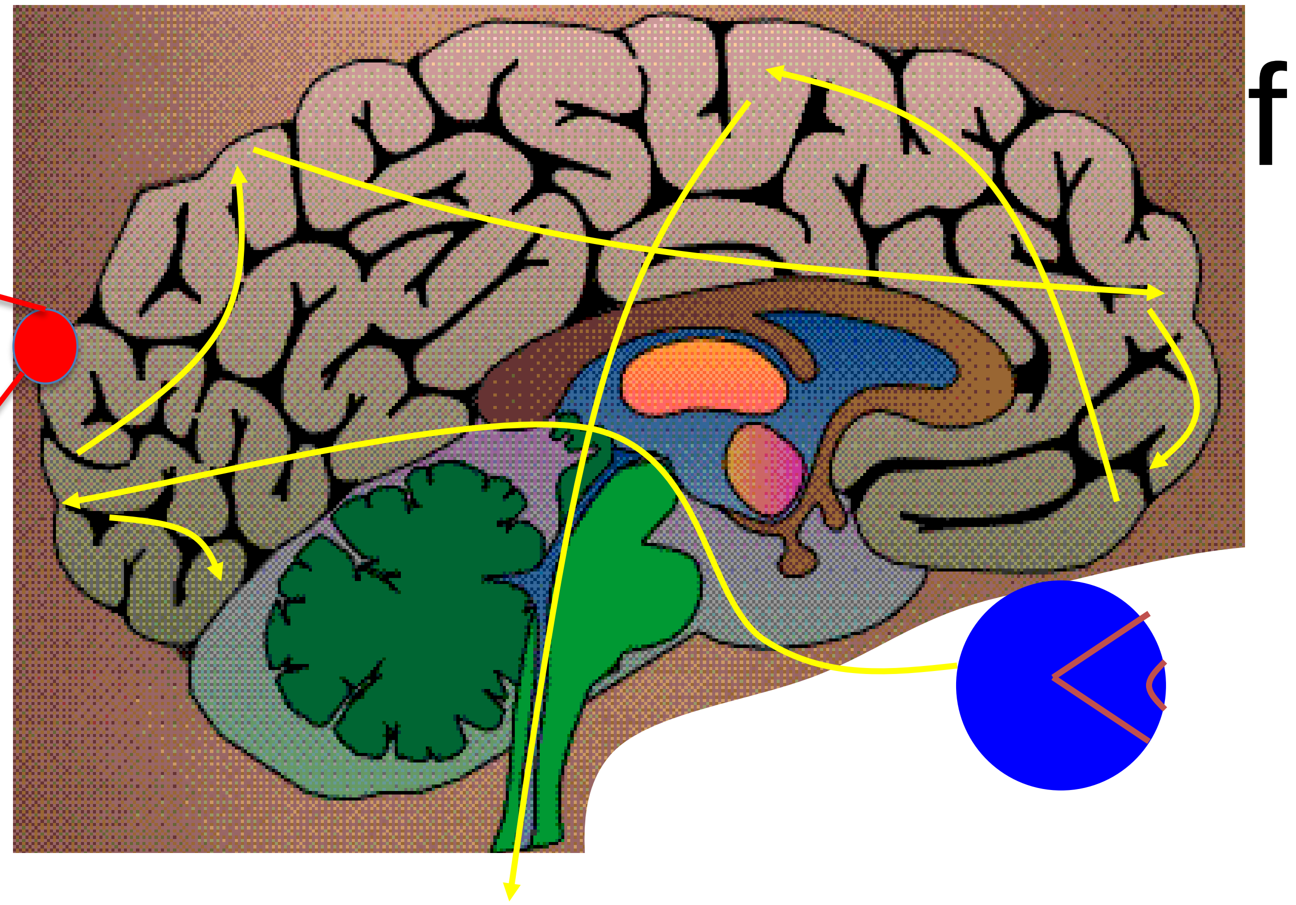
Neuronal Dynamics – Brain dynamics is complex



10 000 neurons
3 km of wire

motor
cortex

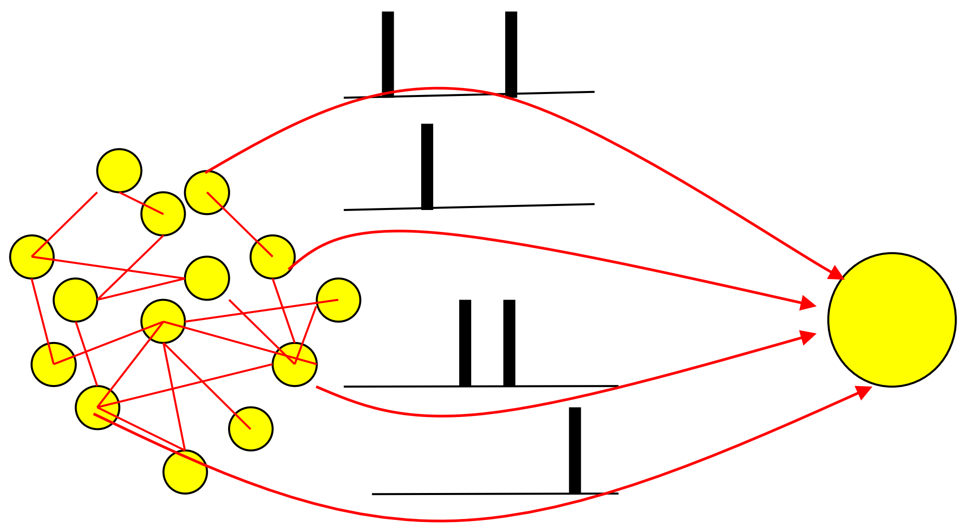




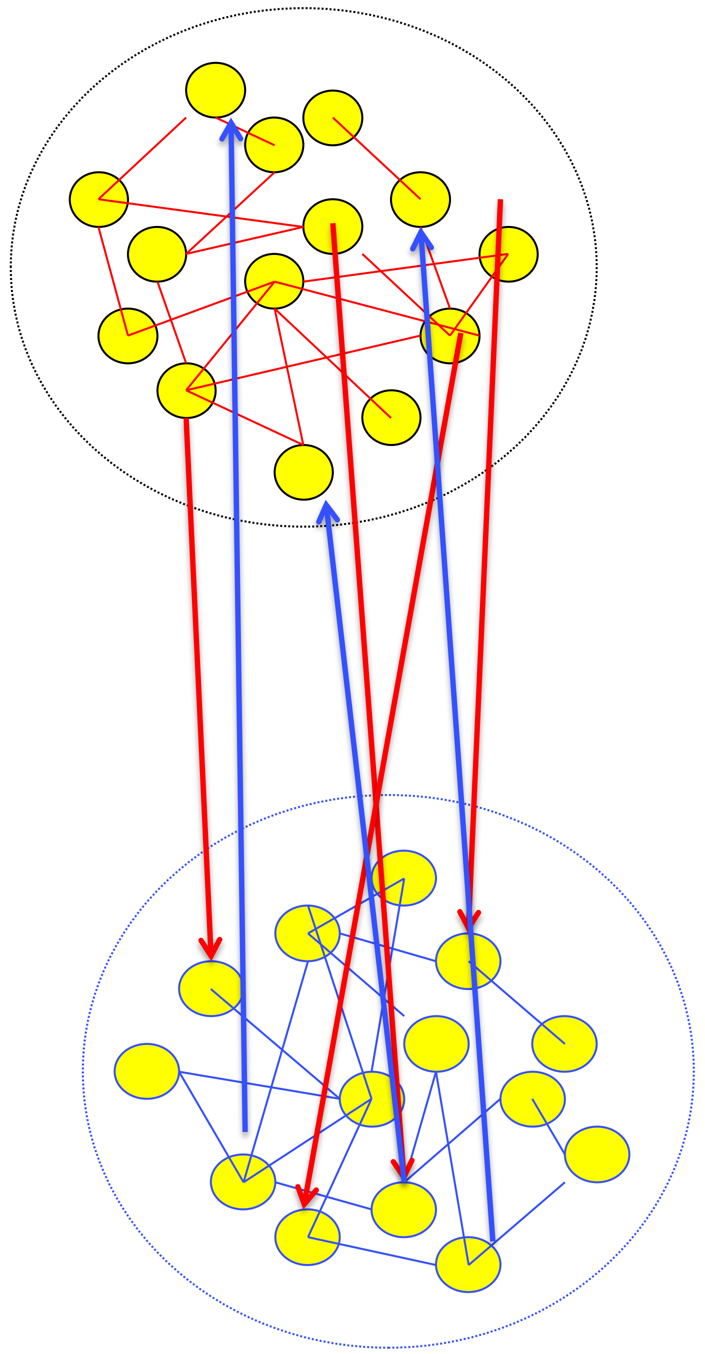
frontal
cortex

to motor
output

Week 15-part 1: Review: Homogeneous Population



Example: 2 populations



excitation

inhibition

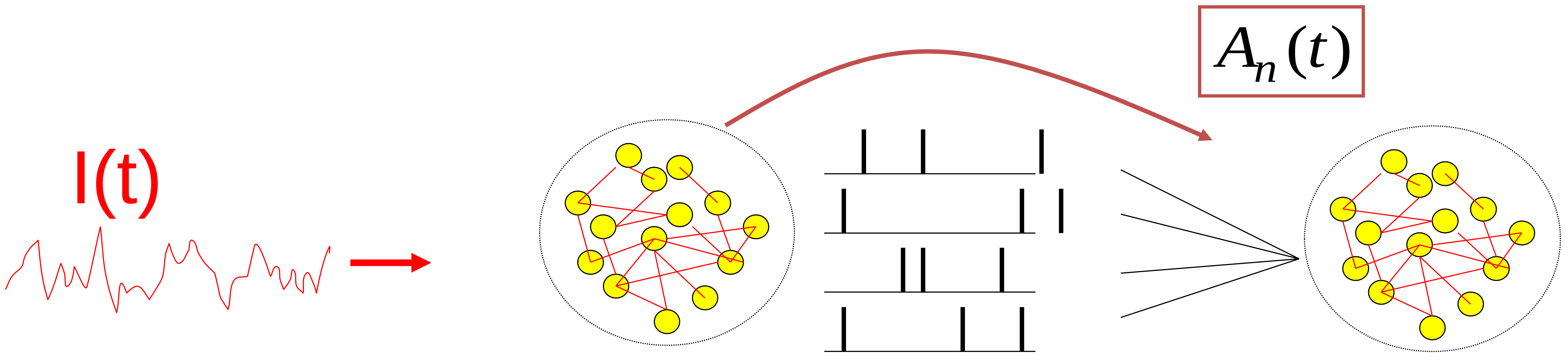
Homogeneous population:

-each neuron receives input from k neurons in the population

-each neuron receives the same (mean) external input (could come from other populations)

-each neuron in the population has roughly the same parameters

Week 15-part 1: Review: microscopic vs. macroscopic



microscopic:

-spikes are generated by individual neurons

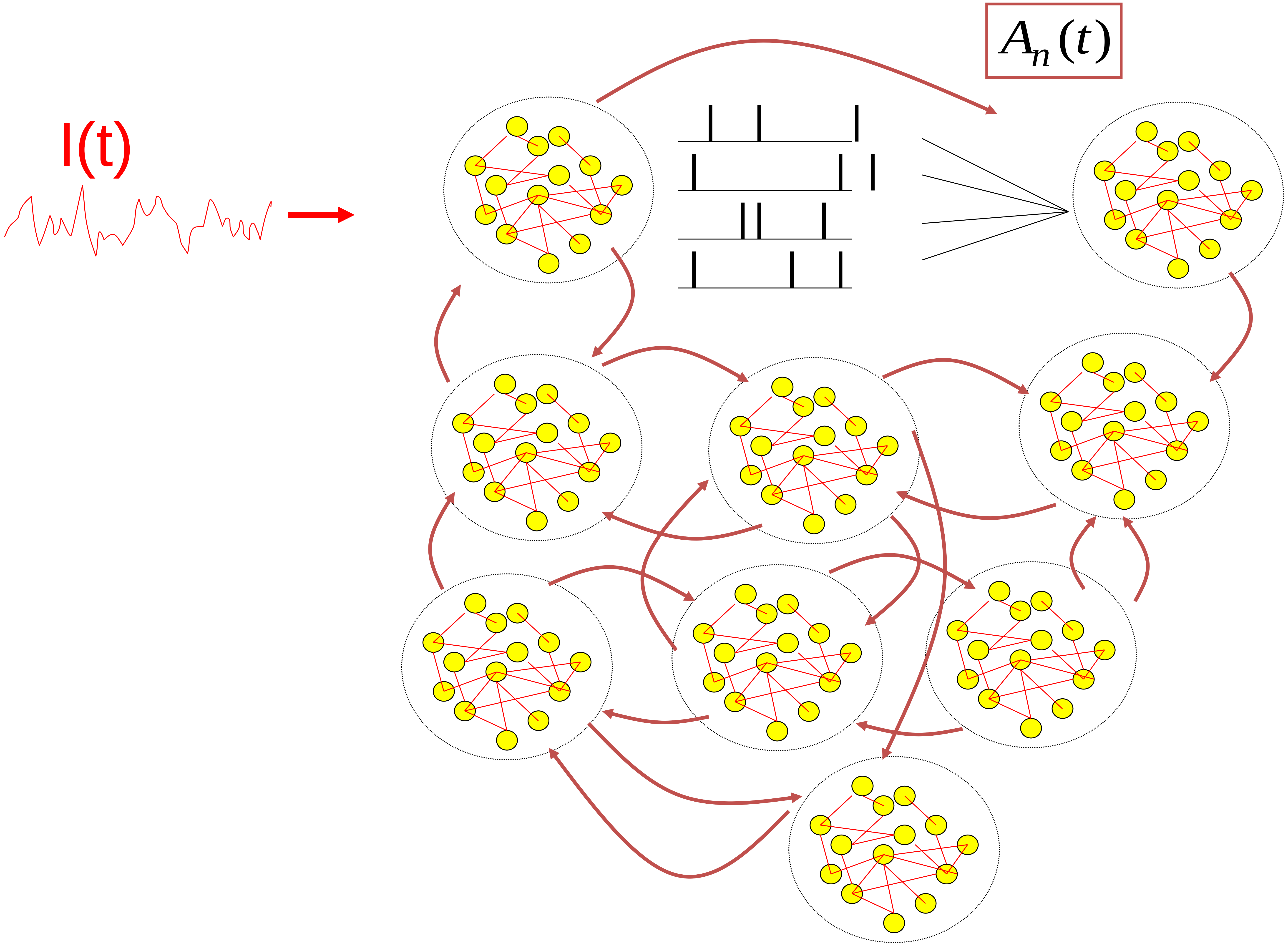
-spikes are transmitted from neuron to neuron

macroscopic:

-Population activity $A_n(t)$

-Populations interact *via* $A_n(t)$

Week 15-part 1: Review: coupled populations



Week 15-part 1: Example: coupled populations in barrel cortex

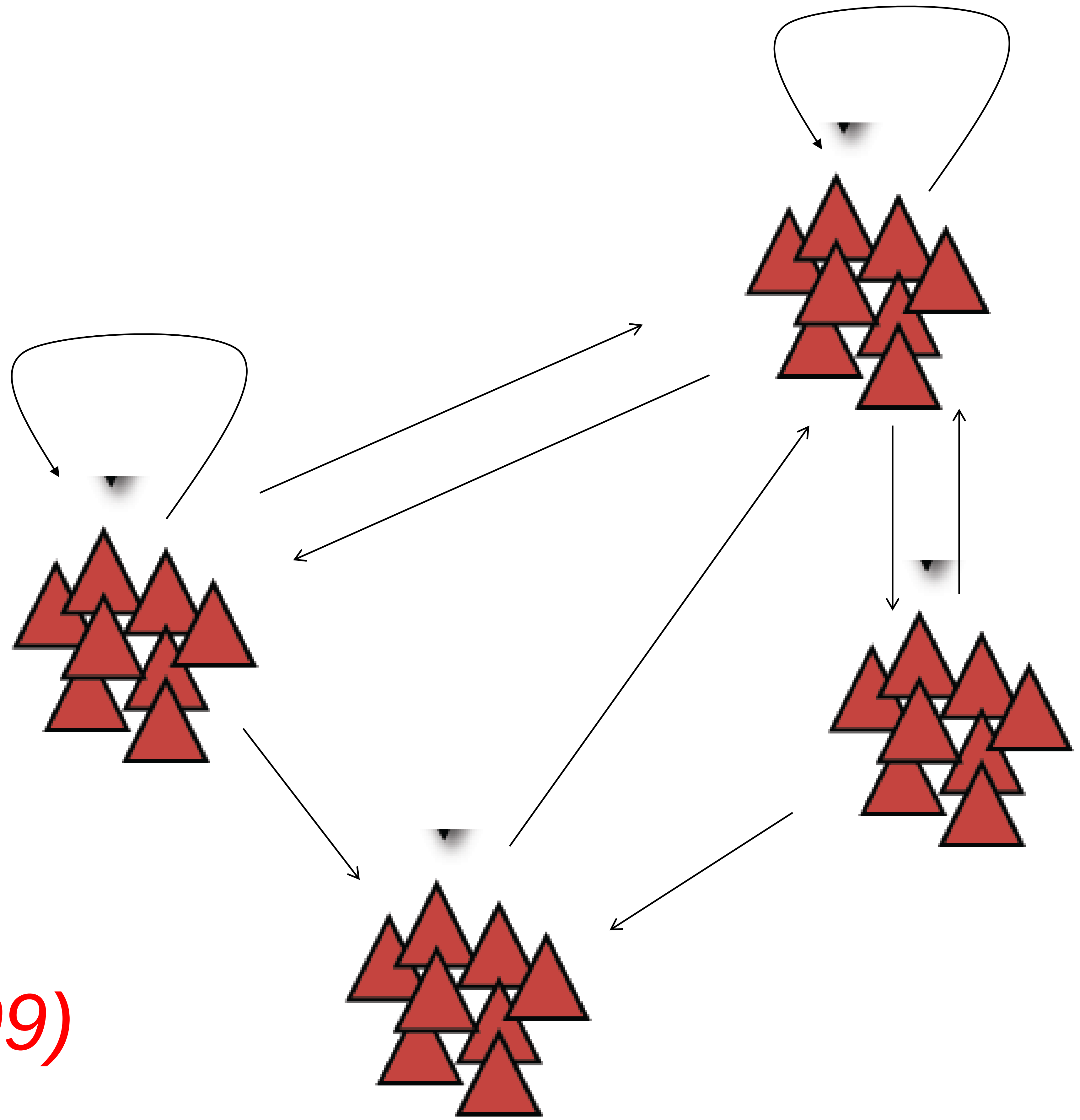
Neuronal Populations

= a homogeneous group of neurons
(more or less)

Populations:

- pyramidal neurons in layer 5 of barrel D1
- pyramidal neurons in layer 2/3 of barrel D1
- inhibitory neurons in layer 2/3 of barrel D1

100-2000 neurons
per group *(Lefort et al., NEURON, 2009)*

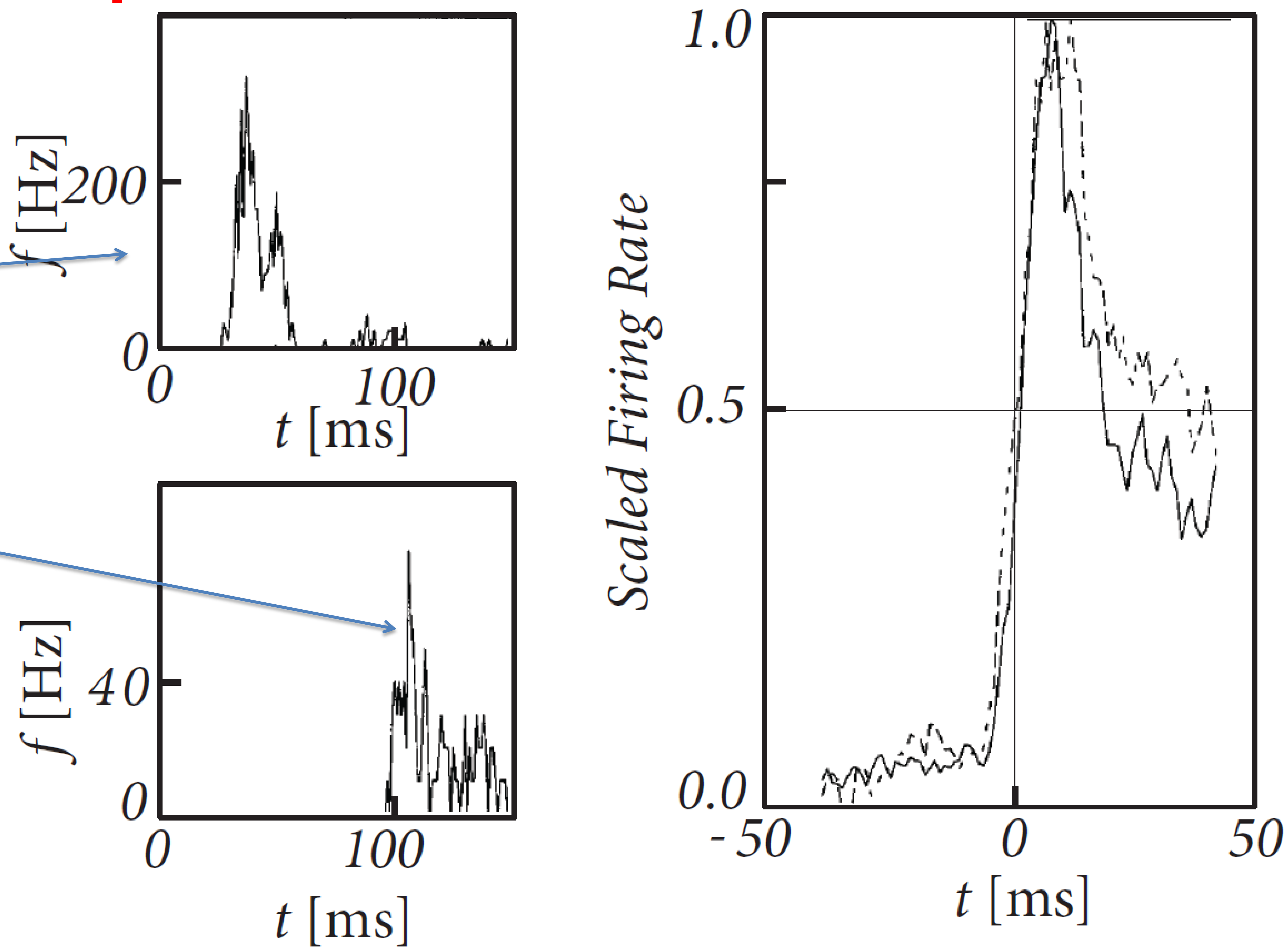


different barrels and layers, different neuron types → different populations

Week 15-part 1: *A(t)* in experiments:light flash, in vivo

Experimental data: *Marsalek et al., 1997*

PSTH, single neurons



aligned PSTH, many neurons in V1 (solid) V4 (dashed)

Fig. 15.3: Transient response of neurons in visual cortex. At $t = 0$ a high-contrast grating is flashed on a gray screen. Top left: A neuron in visual cortex V1 of a behaving monkey responds with a sharp onset after a latency of 27ms, as shown by the PSTH. Bottom left:

Week 15-part 2: *A(t)* in experiments: auditory click stimulus

Experimental data: Sakata and Harris, 2009

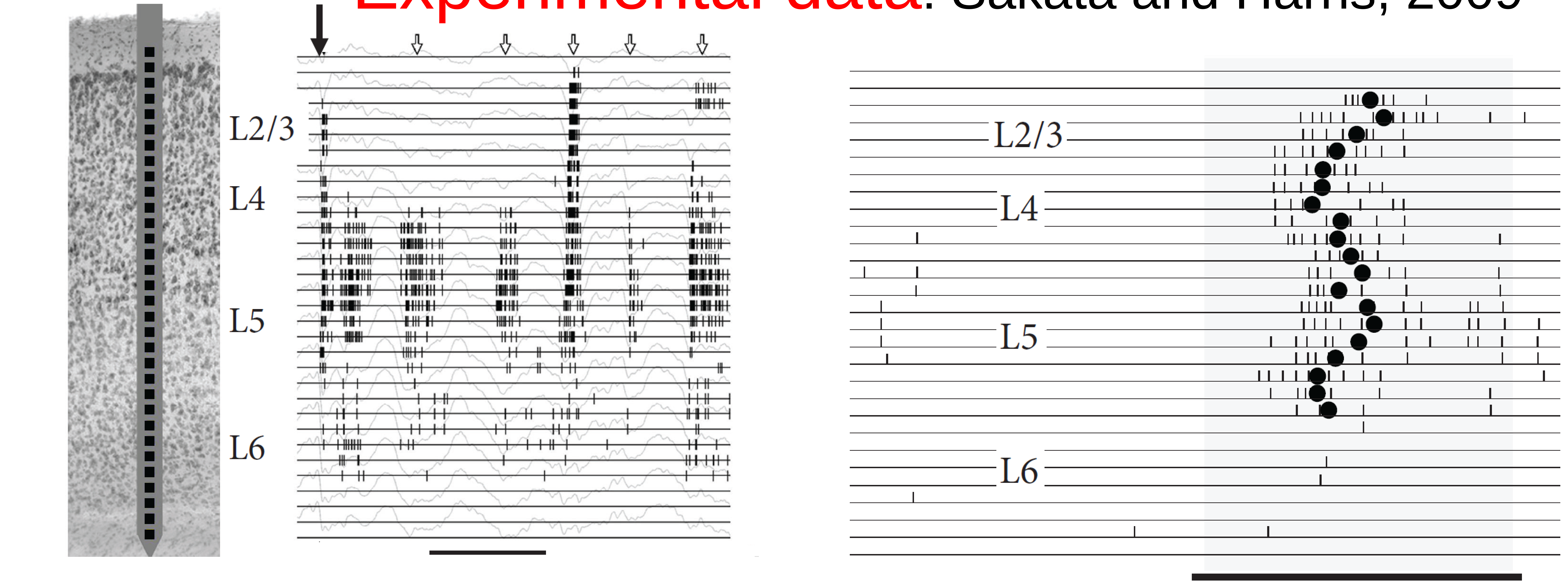
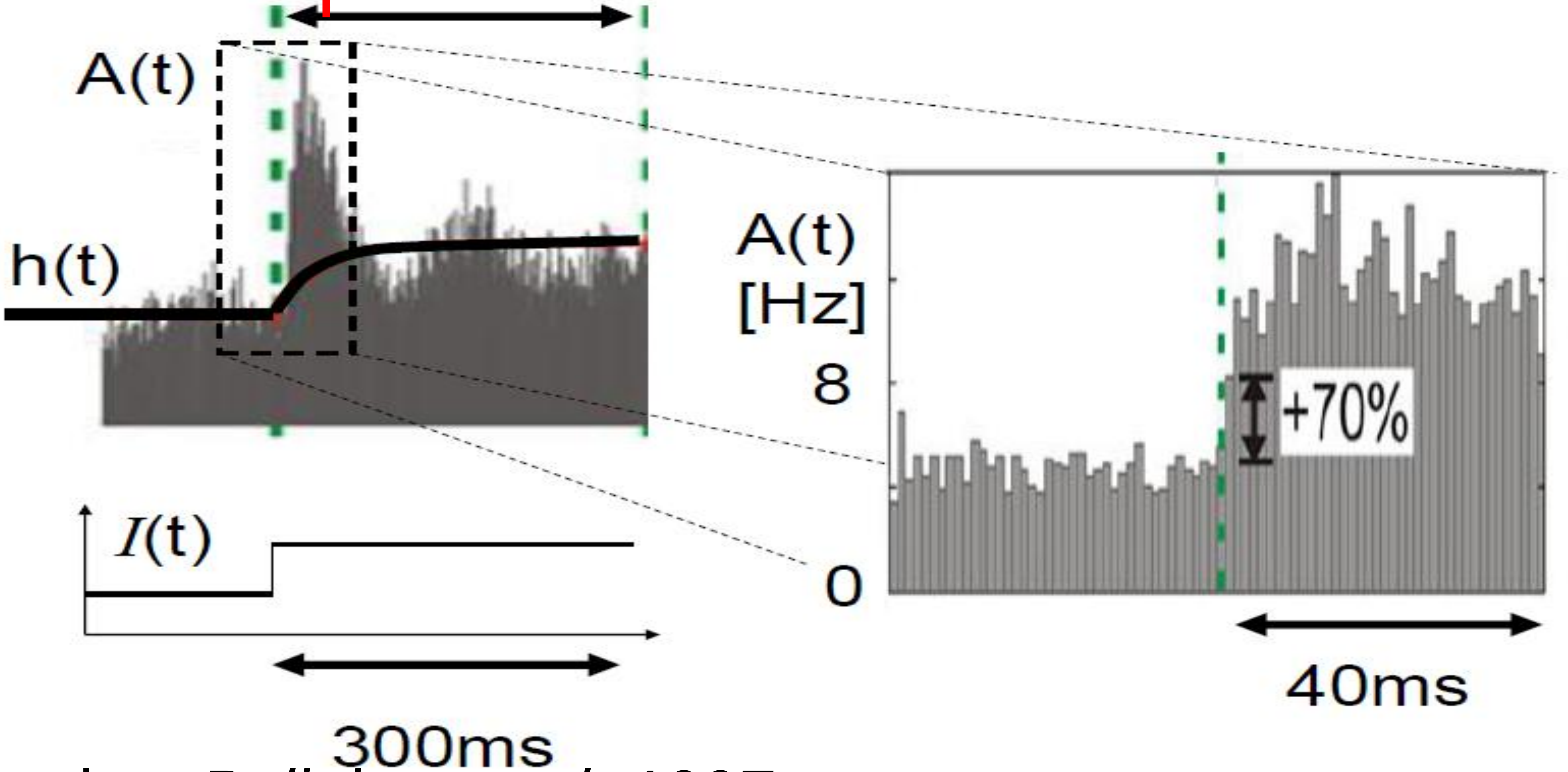


Fig. 15.2: Response of auditory neurons across different layers to short stimuli. **A.** Left Schematic drawing of an electrode with 32 sites overlayed on top of stained cortical tissu in order to show that the electrode crosses all cortical layers. Right: Spike responses o

Week 15-part 1: *A(t)* in experiments: step current, (*in vitro*)

Experimental data: *Tchumatchenko et al. 2011*



See also: *Poliakov et al. 1997*

Week 15-part 1: *A(t)* in simulations of integrate-and-fire neurons

Simulation data: *Brunel et al. 2011*

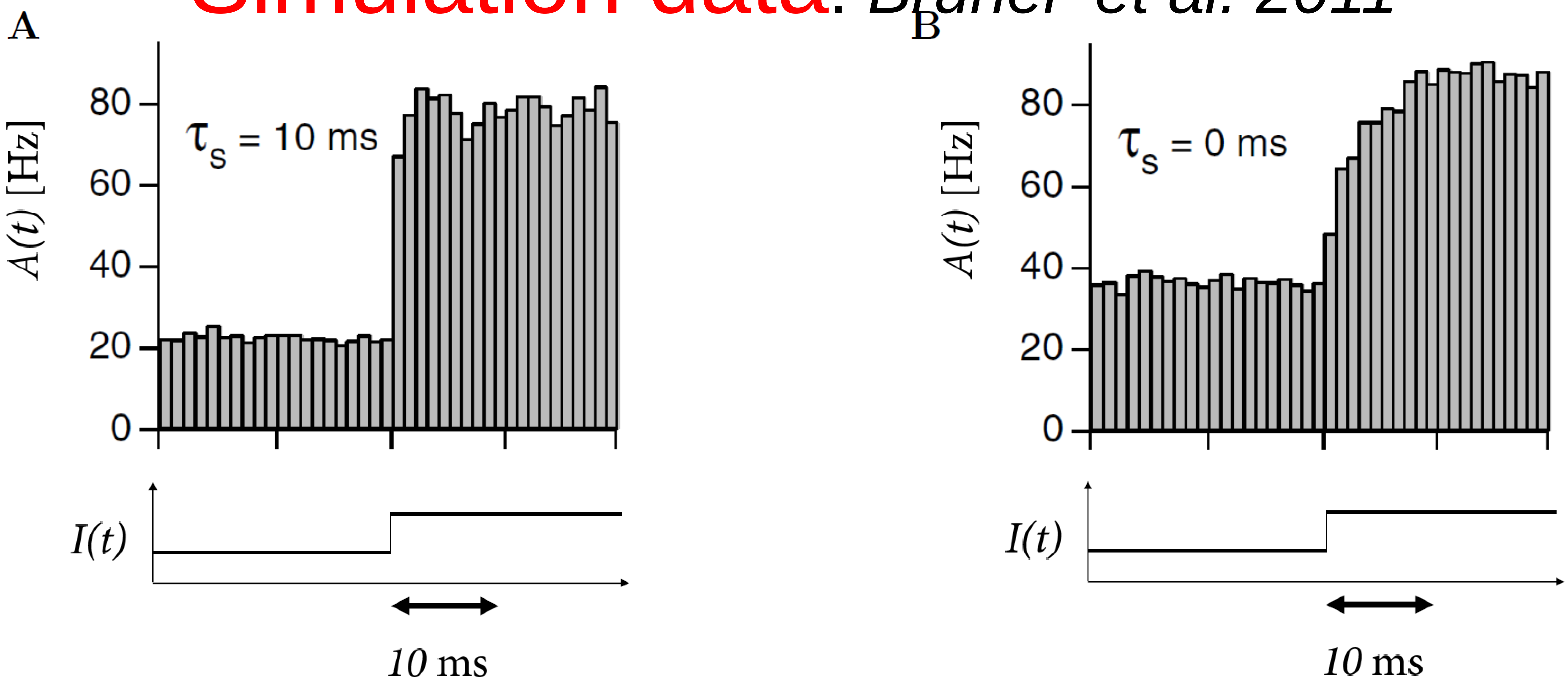


Image: Gerstner et al., Neuronal Dynamics, 2014

Fig. 15.9: Slow (colored) diffusive noise versus white diffusive noise. A population of integrate-and-fire models with a time constant of $\tau_m = 20$ms was simulated and responses to a step stimulus reported in time bins of 1ms. **A**. Colored noise with a filtering time constant τ_s=10ms leads to an abrupt, instantaneous response. **B**. White noise leads to a smoothly increasing fairly slow response. Figures adapted from (Brunel et al., 2001).

Week 15-part 1: *A(t)* in simulations of integrate-and-fire neurons

Simulation data:

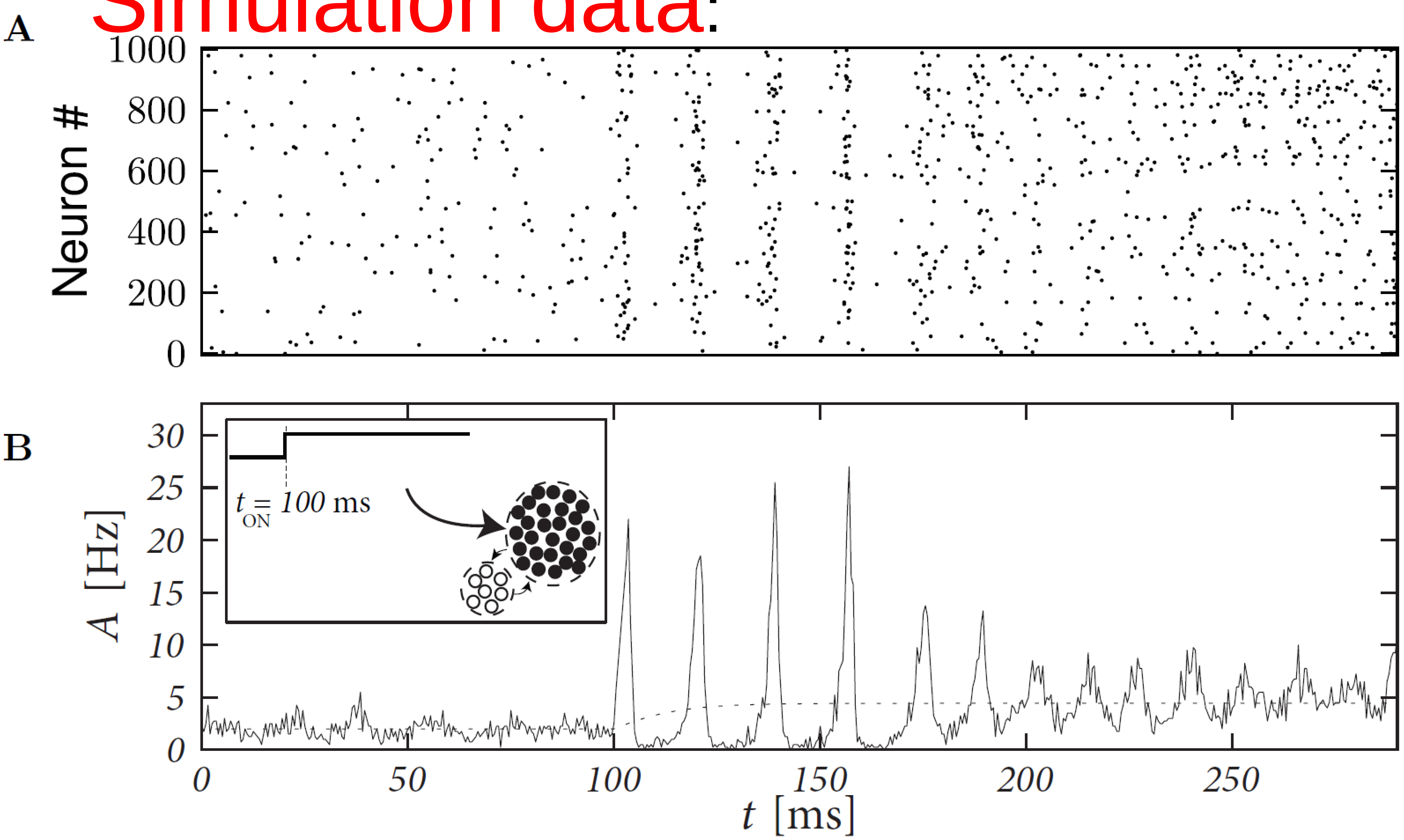


Image: Gerstner et al., Neuronal Dynamics, 2014

Fig. 15.1: Transients and rate models. All neurons receive the same step current stimulus at time $t_{ON} = 100$ms. A randomly connected network of 8000 excitatory and 2000

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Biological Modeling of Neural Networks:

Conclusion of part 1

Week 15 – Fast Transients and Rate models

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Transients are very fast
-In experiments
-In simulations of spiking neurons

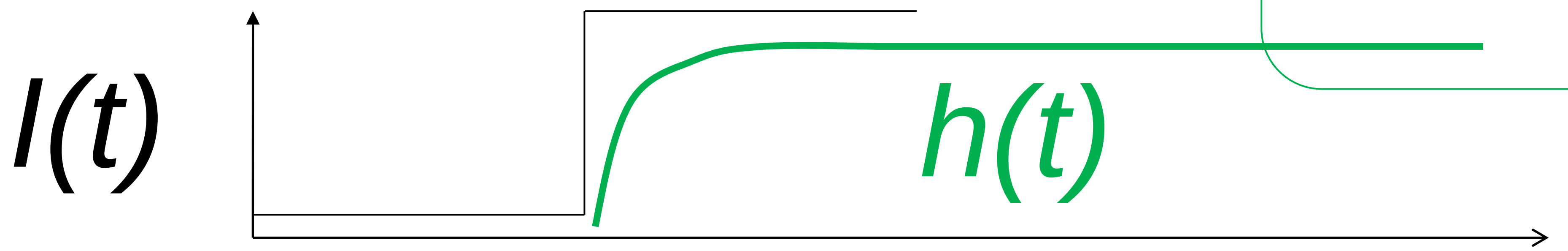
Week 15-part 2: *Rate model* with differential equation

$$A(t) = g(h(t))$$

$$\tau \frac{d}{dt} h(t) = -h(t) + R \cdot I(t)$$

$\rightarrow$ Input potential

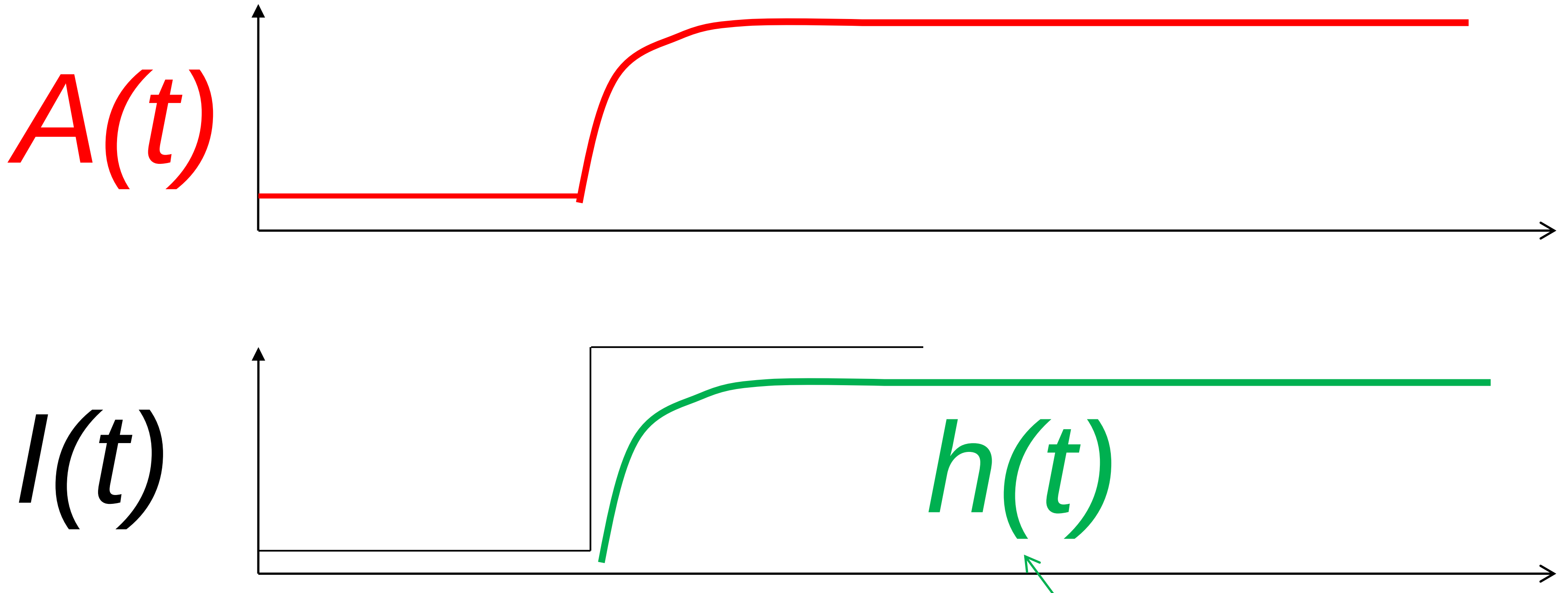
$$h(t) = \int_0^\infty \varepsilon \;\; s \;\; I(t-s)ds$$



Differential equation can be integrated!, exponential kernel

Week 15-part 2: *Rate model*: step current

$$A(t) = g(h(t)) = g(\int \varepsilon(s) I(t-s) ds)$$



Input potential

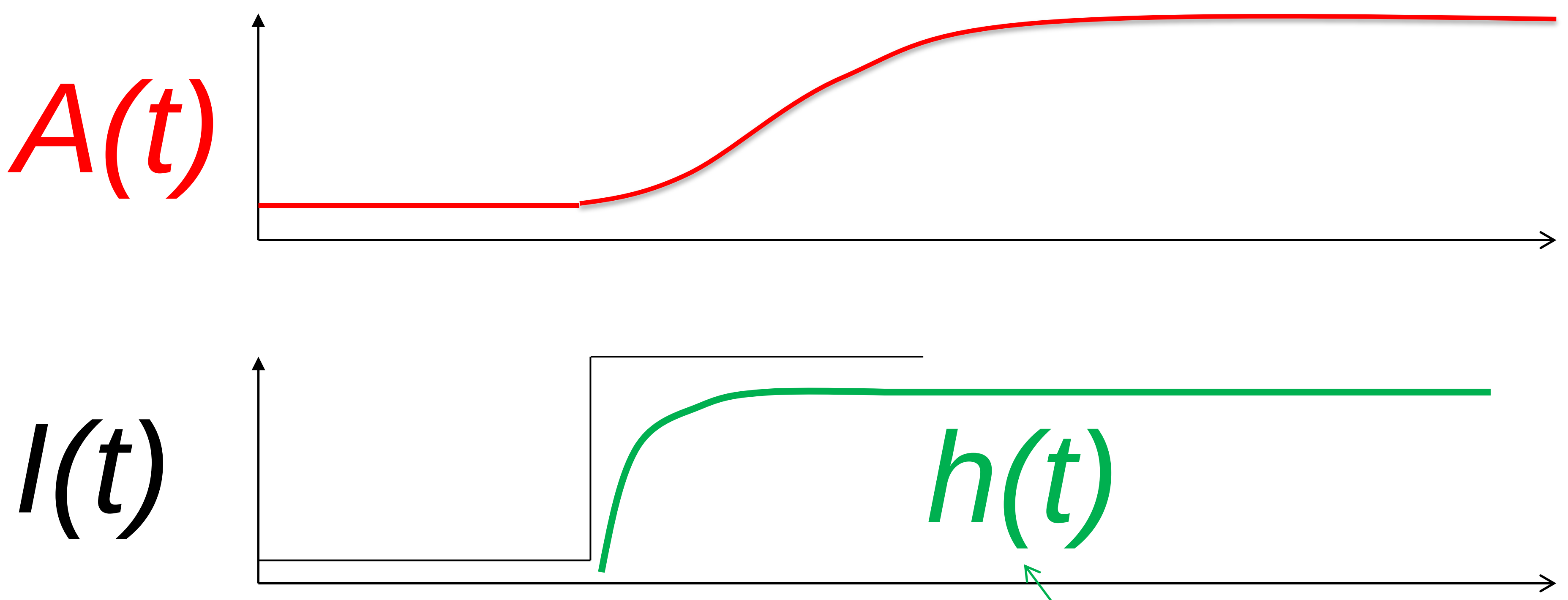
$$h(t) = \boxed{\int_0^\infty \varepsilon \;\; s \;\; I(t-s)ds +} \ldots$$

Example LNP rate model: Linear-Nonlinear-Poisson

Spikes are generated by a Poisson process, from rate model

Week 15-part 2: *Wilson-Cowan model*: step current

$$\frac{d}{dt}A(t) = -A(t) + g(h(t))$$

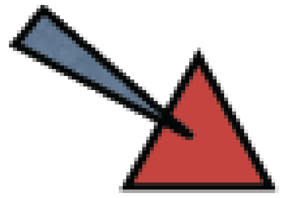


Input potential

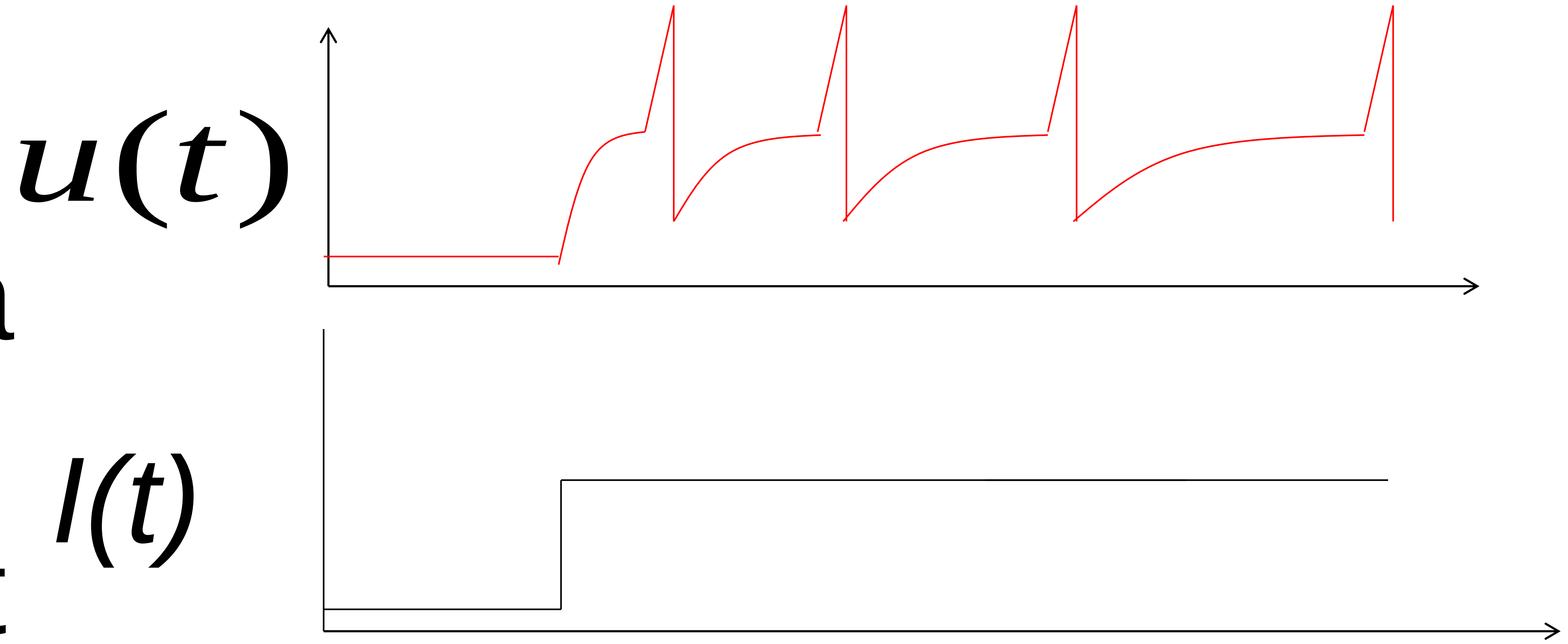
$$h(t) = \boxed{\int_0^\infty \varepsilon(s)\, I(t-s)\, ds} + \ldots$$

Week 15-part 2: Aim: from single neuron to population

Single neurons



- model exists
- parameters extract rom data
- works well for step rent
- works well for tim current



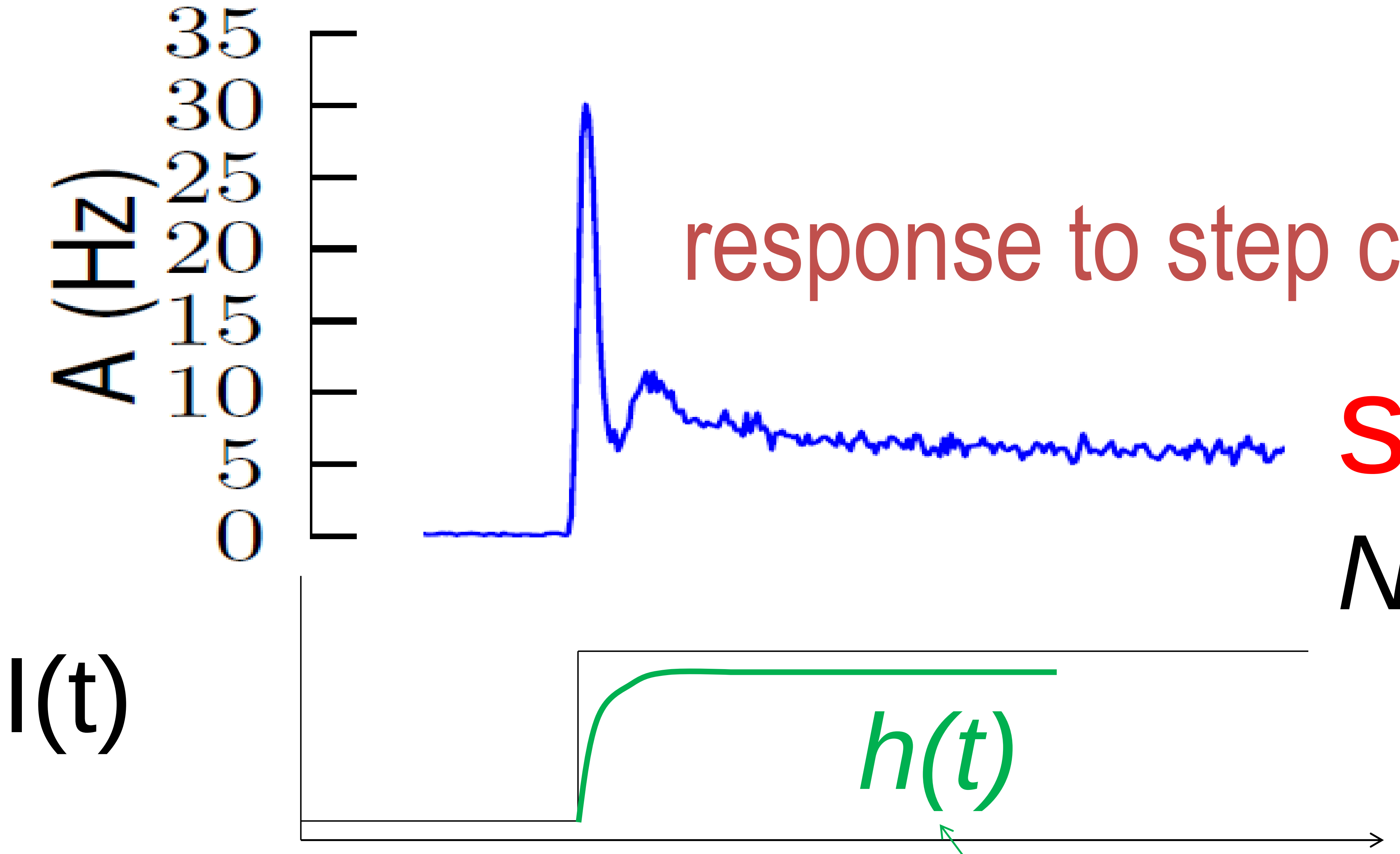
Population of Neurons?

Population equation for *A(t)*

-existing models
- integral equation

Week 15-part 2: *A(t)* in simulations : step current

25000 identical model neurons (GLM/SRM with escape noise)
parameters extracted from experimental data

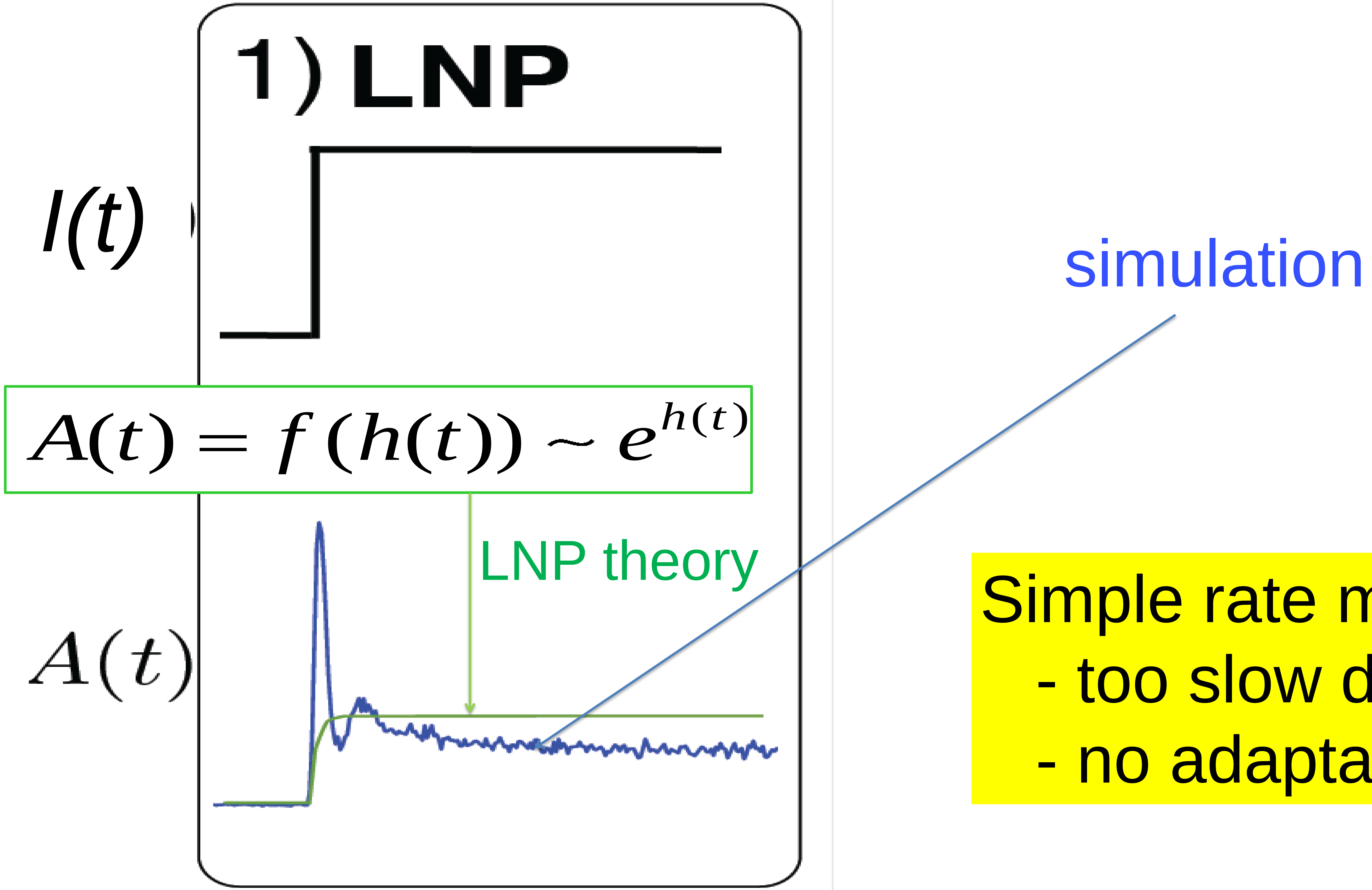


simulation data:
Naud and Gerstner, 2012

Input potential

$$h(t) = \int_0^\infty \varepsilon \;\; s \;\; I(t-s)ds + \ldots$$

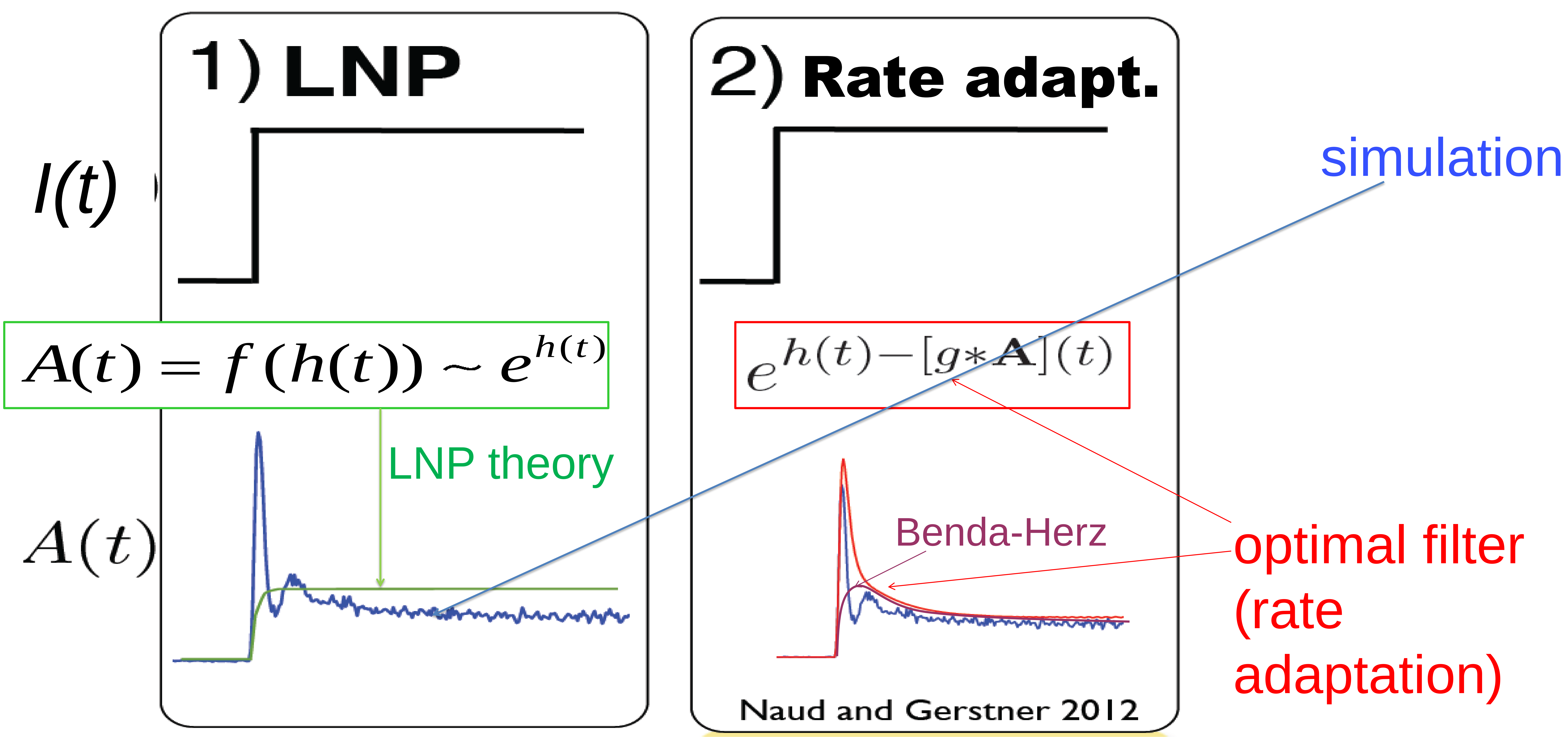
Week 15-part 2: rate model



$$A(t) = f(h(t)) \sim e^{h(t)}$$

Simple rate model:
- too slow during the transient
- no adaptation

Week 15-part : rate model with adaptation



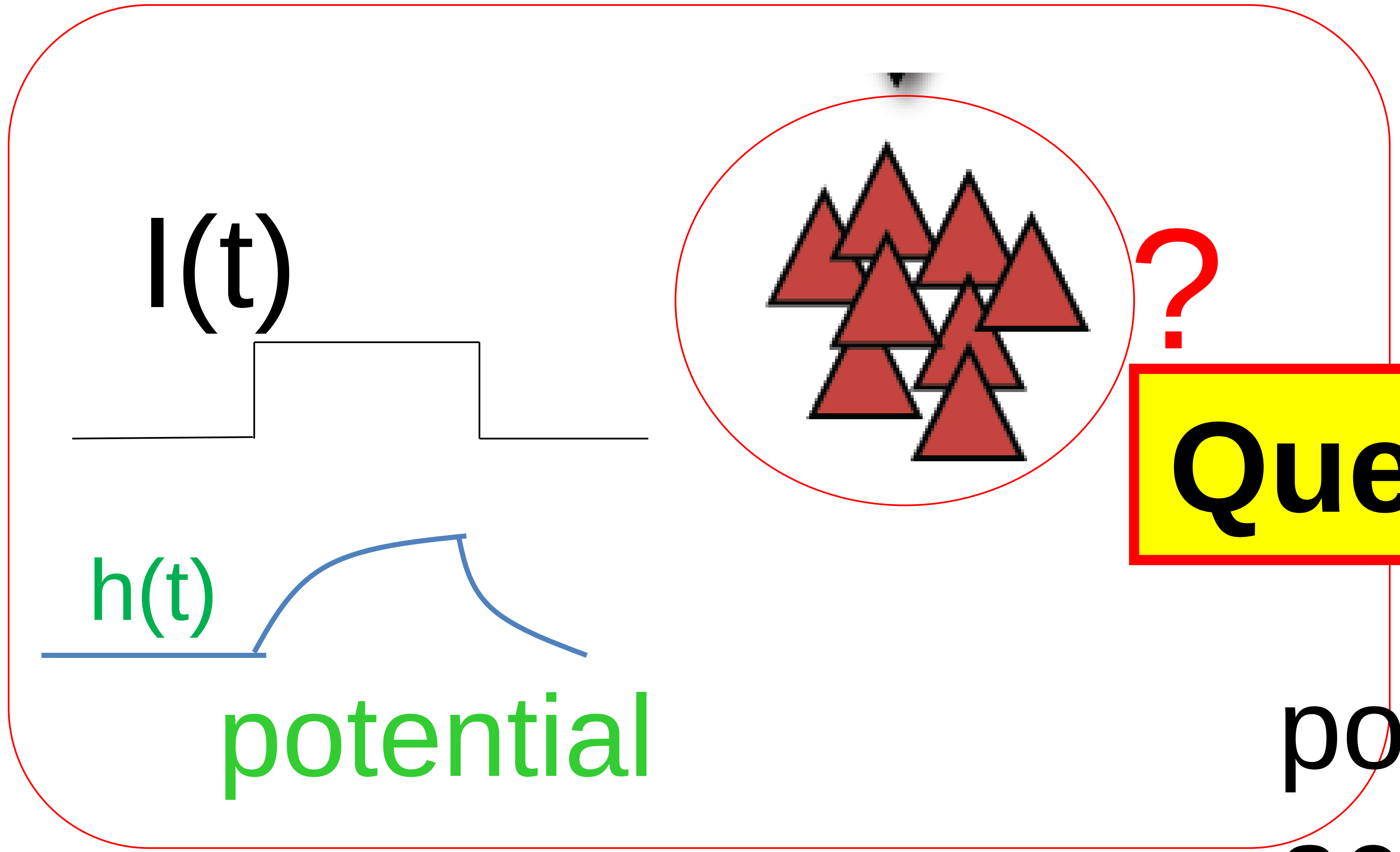
Week 15-part 2: rate model

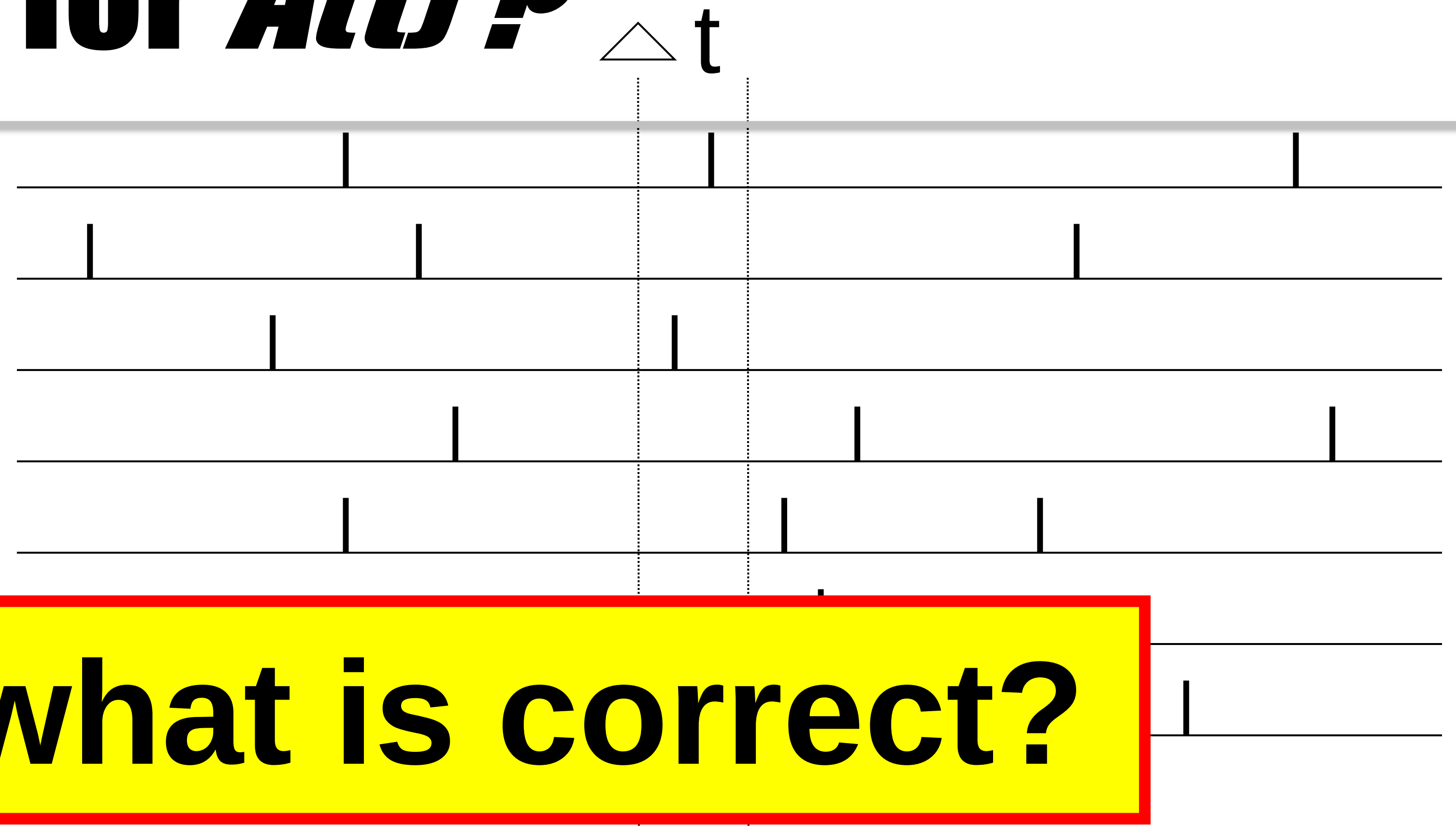
Simple rate model:
- too slow during the transient
- no adaptation

Adaptive rate model:
- too slow during the transient
- final adaptation phase correct

Rate models can get the slow dynamics and stationary state correct, but are wrong during transient

Week 15-part 2: population equation for *A(t)* ?





Question: – what is correct?

population activity

$$A(t) = \frac{n(t;t+\Delta t)}{N\Delta t}$$

A(t)

Wilson-Cowan

$$\tau \frac{d}{dt} A(t) = -A(t) + f(h(t))$$

A(t)

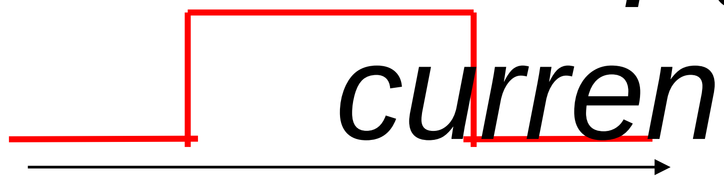
LNP

Ostojic-Brunel

Paninski, Pillow

$$A(t) = f(h(t)) = f(\int \varepsilon(s) I(t-s) ds)$$

A(t)

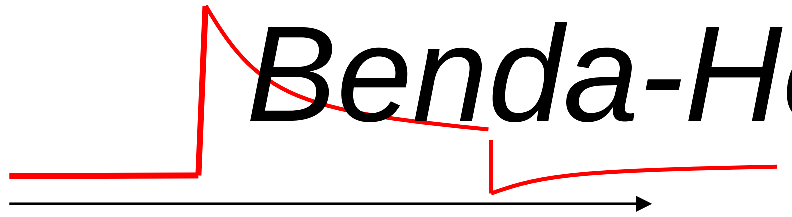


current

$$A(t) = g(I(t))$$

Poll!!!

A(t)



Benda-Herz

$$A(t) = g(I(t) - \int G(s) A(t-s) ds)$$

Week 15-part 2: improved rate models/population models

Improved rate models

a) rate model with effective time constant

→ next slides

b) integral equation approach

→ chapter 14

Week 15-part 2: *Rate model* with effective time constant

$$A(t) = F(h(t))$$

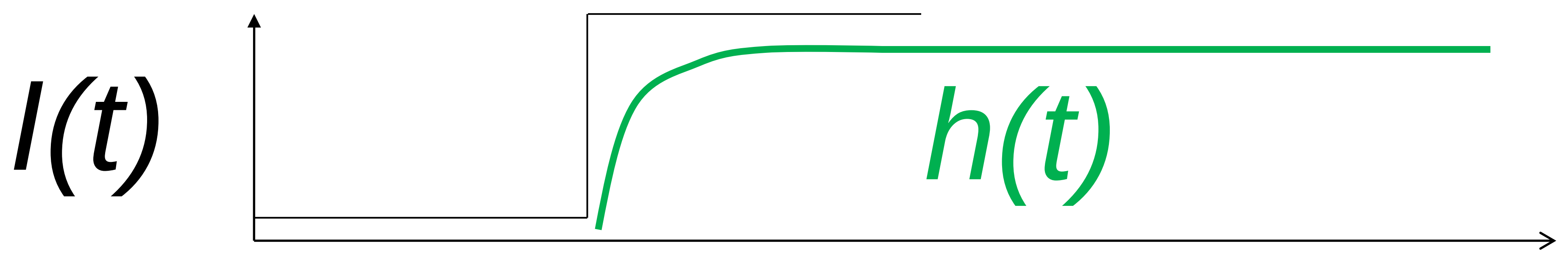
$$\tau_{eff}(t) \sim F' / A_0(t)$$

$$\tau_{eff}(t)\frac{d}{dt}h(t) = -h(t) + R \cdot I(t)$$

Ostojic-Brunel, 2011

→ Input potential

$$h(t) = \int_0^\infty \varepsilon \ \ s \ \ I(t-s)ds$$



→ Shorter effective time constant during high activity

Week 15-part 2: *Rate model* with effective time constant

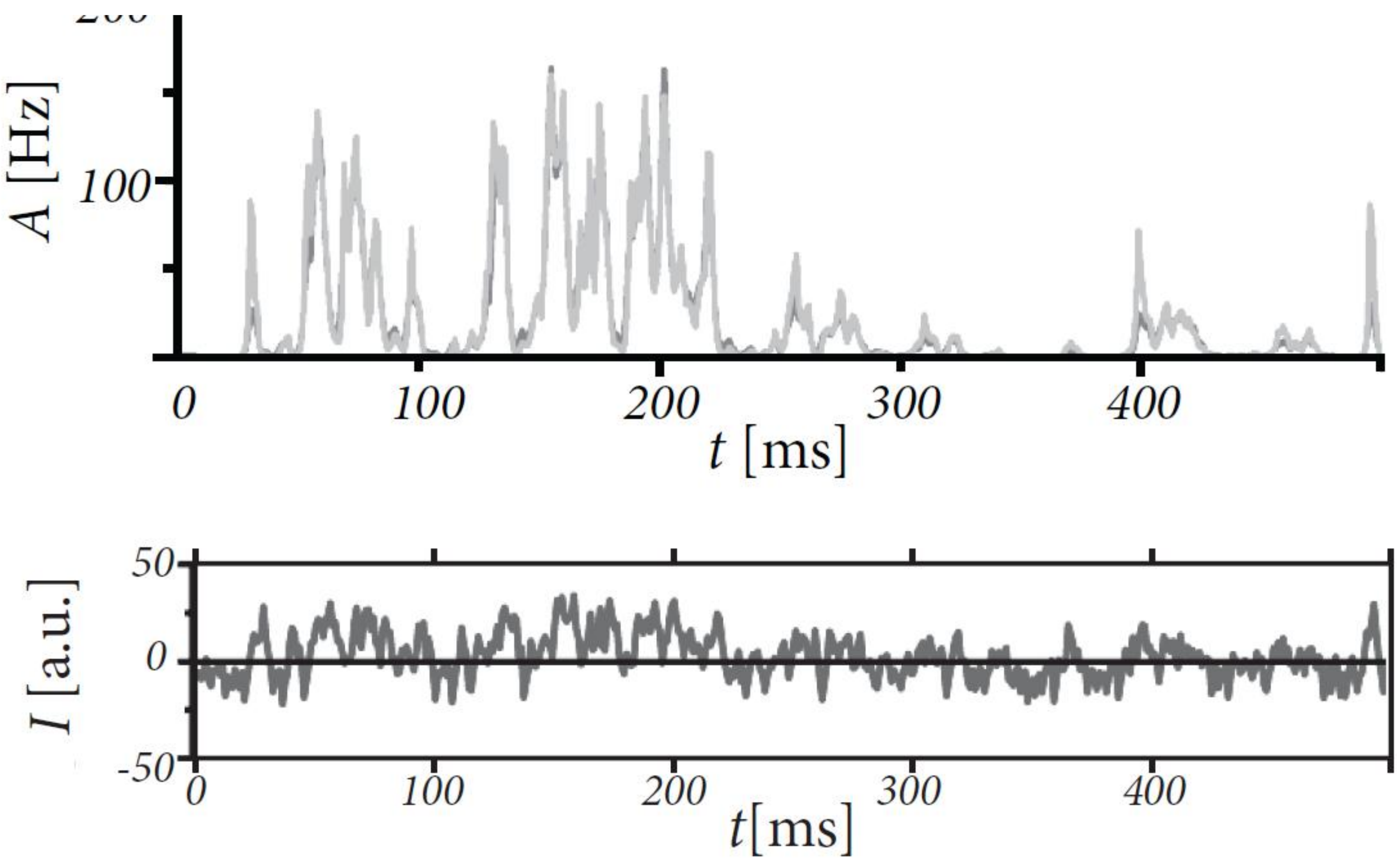
$$A(t) = F(h(t))$$

Image: Gerstner et al.,
Neuronal Dynamics, CUP 2014

$$\tau_{eff}(t)\frac{d}{dt}h(t) = -h(t) + I$$

Ostojic-Brunel, 2011

$$\tau_{eff}(t) \sim F'/A_0(t)$$



→Shorter effective time constant during high activity
→Theory fits simulation very well

Week 15-part 2; Conclusions

Rate models

- are useful, because they are simple
- slow dynamics and stationary state correct
- simple rate models have wrong transients
- improved rate models/population activity models exist

The end

Reading: Chapter 15 of
NEURONAL DYNAMICS,
Gerstner et al., Cambridge Univ. Press (2014)