

Synchronization of neuronal circuits: modeling and dynamics

Claudio R. Mirasso

Institute for Cross-Disciplinary Physics and Complex Systems,
IFISC

University of the Balearic Islands
Palma de Mallorca, Spain



1st Summer School of “Interdisciplinary Research
on Brain Network Dynamics”,
Terzolas, June 24-28 2019.

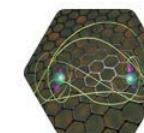
Institute for Cross-Disciplinary Physics & Complex Systems



- ~ 72 Scientists
- 18 Permanent
- 15 different countries
- Master degree in Physics of Complex Systems + PhD degree in Complex Systems



COMPLEX SYSTEMS:
STATISTICAL AND NONLINEAR PHYSICS



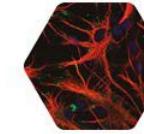
TRANSPORT AND INFORMATION
IN QUANTUM SYSTEMS



NONLINEAR PHOTONICS



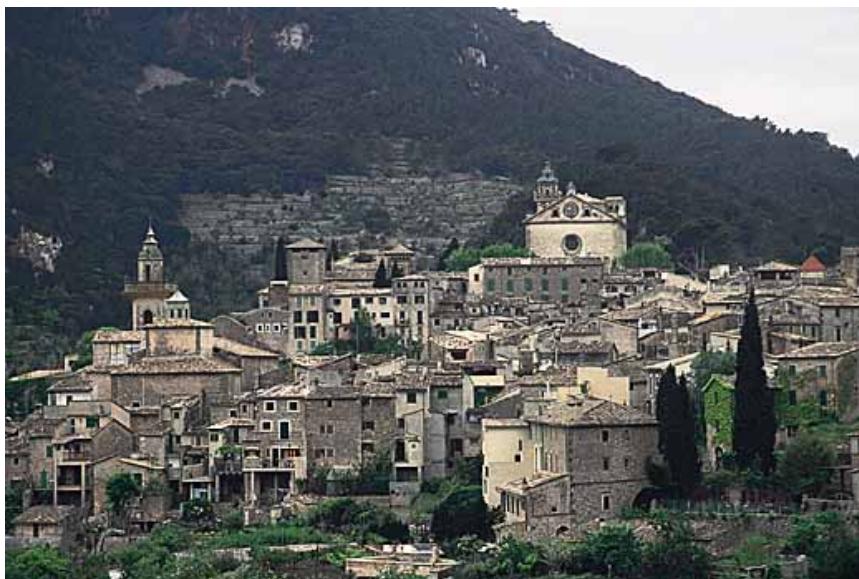
NONLINEAR DYNAMICS
IN FLUIDS



BIOCOMPLEXITY



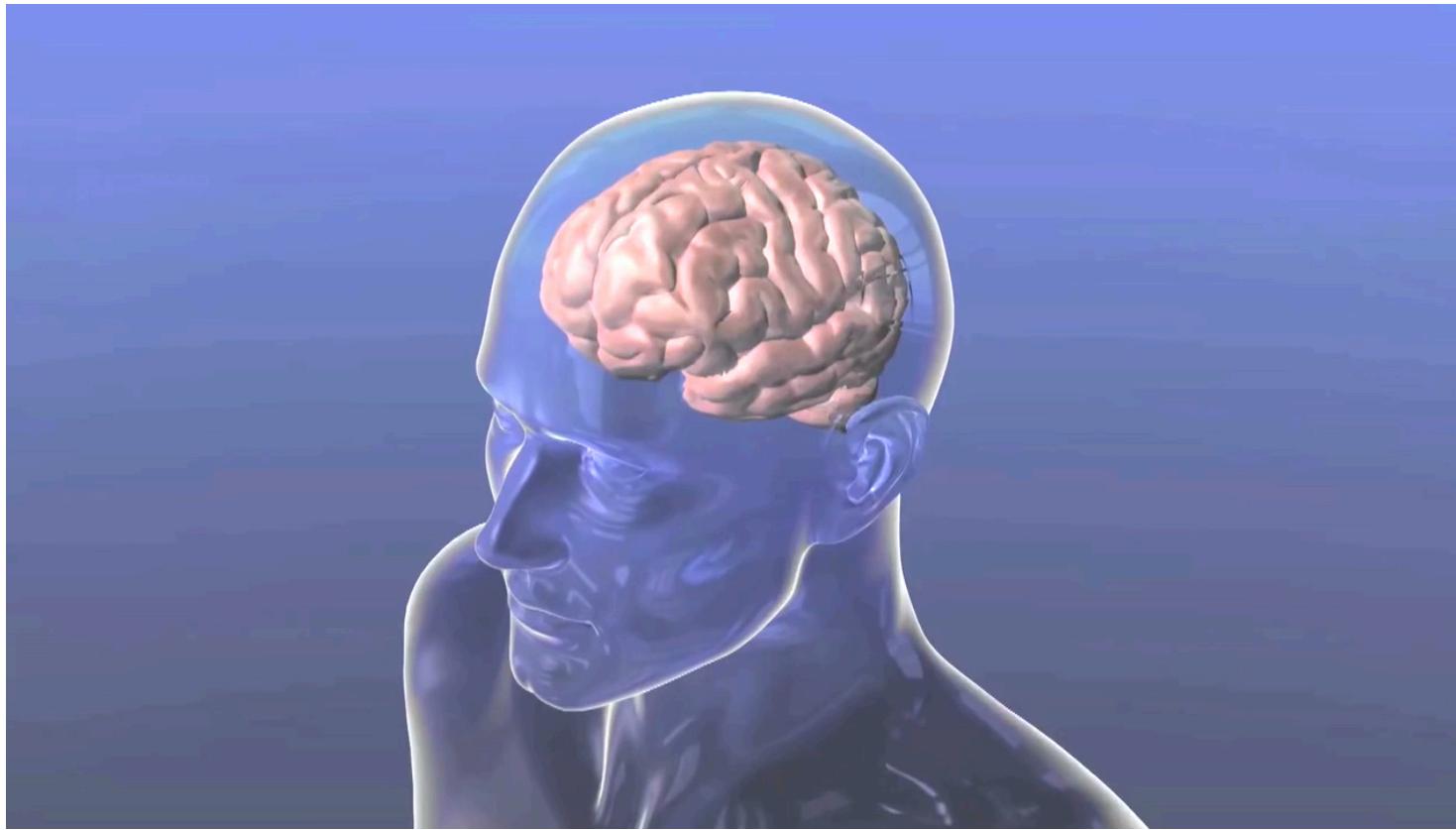
COLLECTIVE PHENOMENA IN
SOCIAL AND SOCIO-TECHNICAL
SYSTEMS



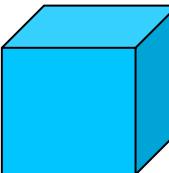
Outline

- General introduction
- Neuronal models and interactions
- Dynamical aspects: case studies
 - ✧ Zero-lag synchronization
 - ✧ Anticipated synchronization
- Summary

Basic Concepts



Complex network with $\sim 10^{11}$ neurons each connected to about 10^4 neighbors.

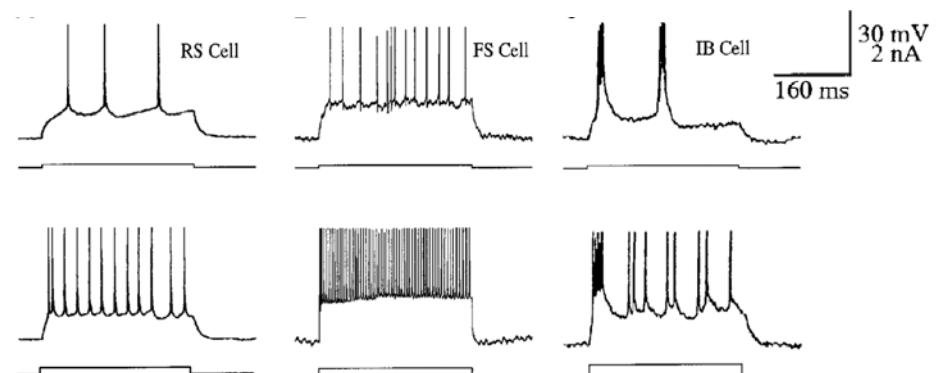
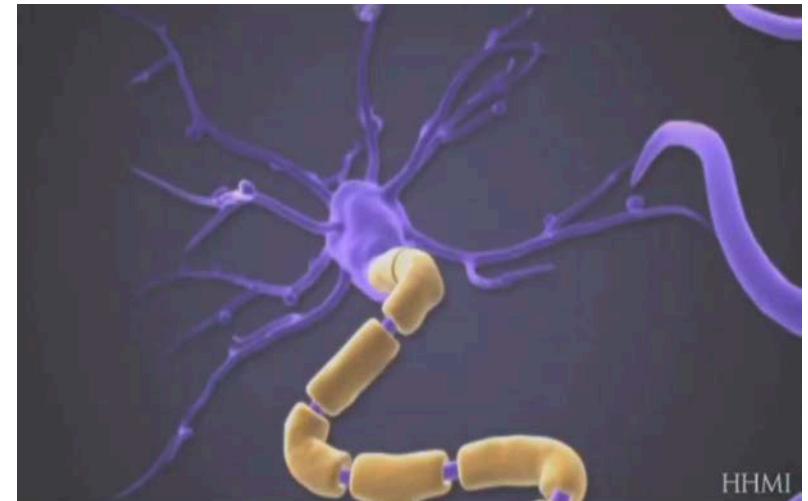
1 mm  ~ 10.000 neurons
 ~ 3 km of cables

Neurons' Properties

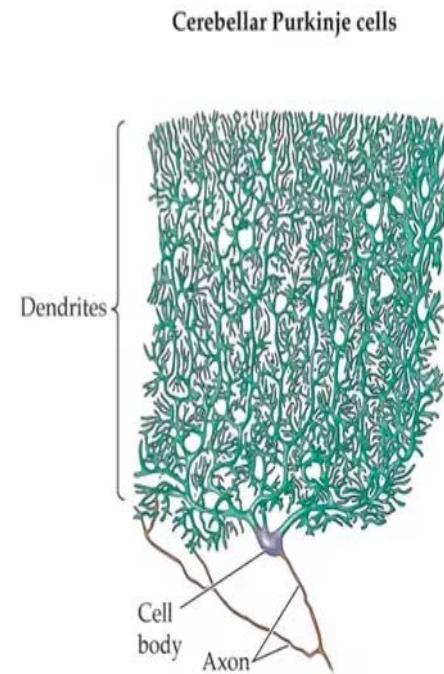
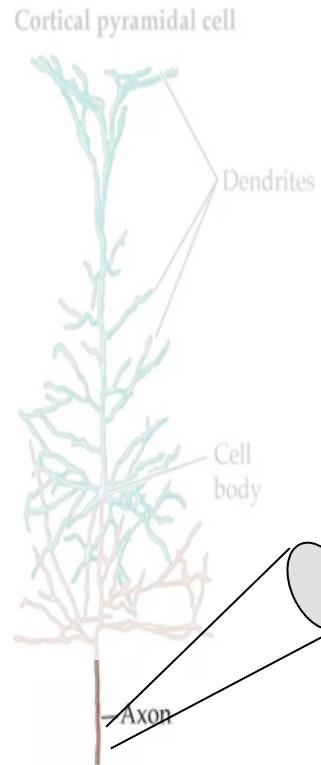
Neurons propagate signals fast and over long distances.

They do this by generating electrical pulses called action potentials: spikes of ~ 1 ms duration that travel through the axons.

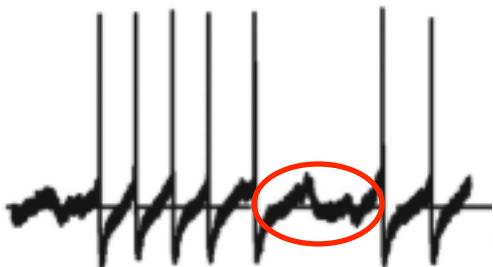
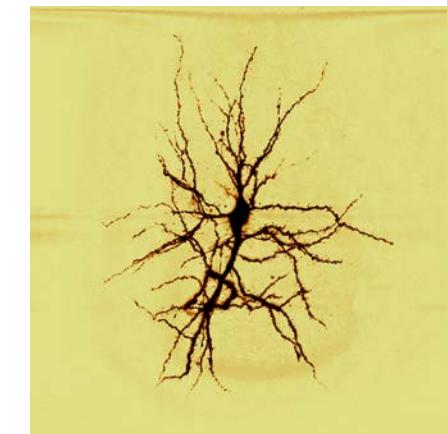
Neurons trigger sequences of action potentials in various time patterns, where information is encoded in the presence of stimuli such as light, sound, taste, smell and touch.



How can we mathematically describe such a complex system?

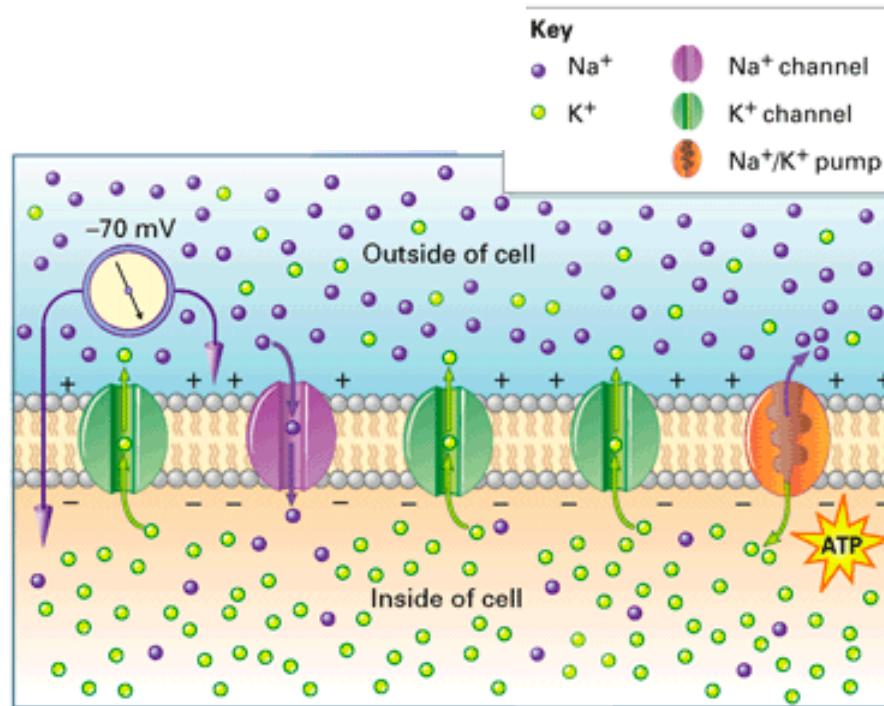
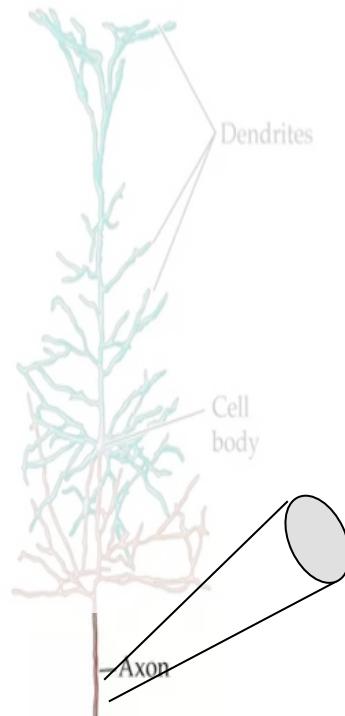


Stellate neuron

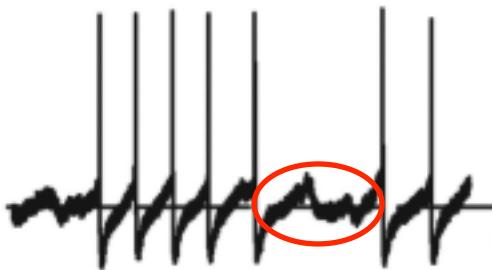


How can we mathematically describe such a complex system?

Cortical pyramidal cell



Membrane resting potential ~ -70 mV



Neurons fire pulses due to the exchange of ions between the inside and outside of the membrane: Na^+ , K^+ and Cl^- ; this is also valid at the synapse.

Mesoscopic Level of description

- In between very detailed models (The Human Brain Project) and whole brain description models (K. Friston's one on **perceptual inference and learning**).
 - Mesoscopic models range from simple neurons to population or neural masses (cortical columns), circuits, networks, etc.
- ✧ These models are computationally less expensive. 
- ✧ Contain less free parameters. 
- ✧ Allow us to understand the emergence of collective behaviors (coherence perception, information encoding/decoding, routing....). 
- ✧ In general, only give qualitative results. 
- ✧ Do not account simultaneously for the many interactions (protein interactions, neurotransmitter/receptors specific dynamics, etc.). 

Large variety of ingredients: Which are important?

The brain contains $\sim 10^{11}$ neurons with $\sim 10^4$ connections each (+ astrocytes).

Single or multiple compartments (dendrites, soma, axon) can be used.

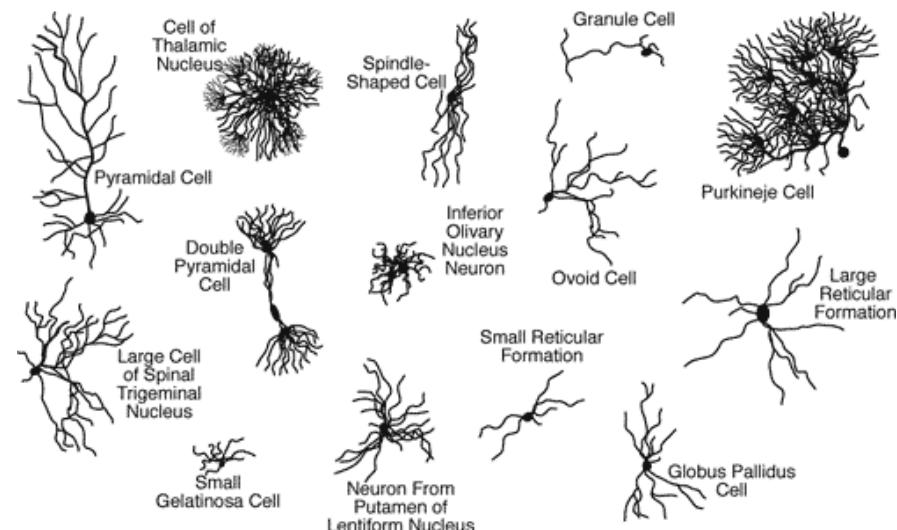
Ionic currents that participate include Na^+ , K^+ , Cl^- , Ca^{+2} , Mg^{+2} , etc.

Synapses: Chemical/electrical, Fast/slow, direct/indirect transmitters and receptors. Network structure, etc.

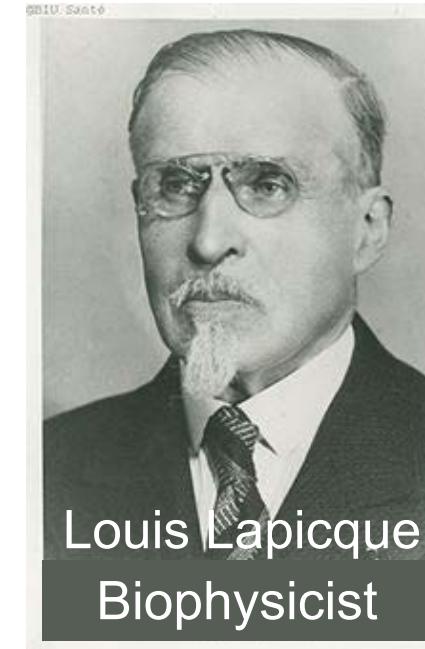
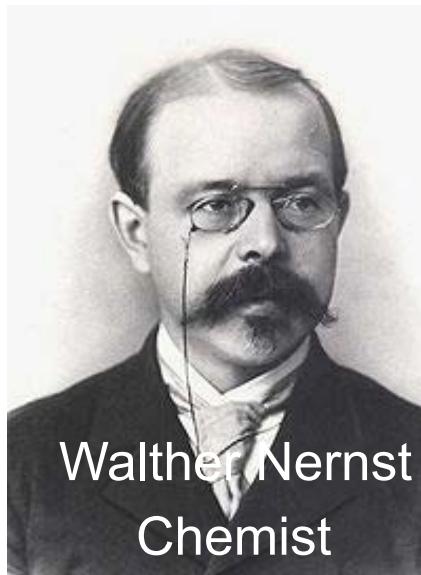
Plasticity effects: STP/STD, LTP/LTD, STDP and others.

Our aim is to keep a level of description sufficiently simple but which at the same time allows us to obtain robust dynamical properties of our system

Simple oscillator models?

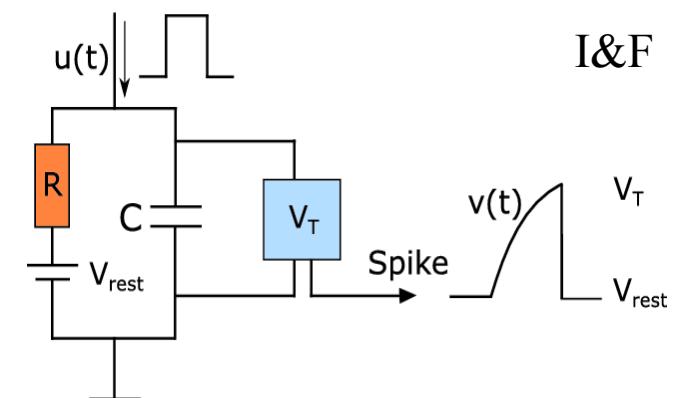


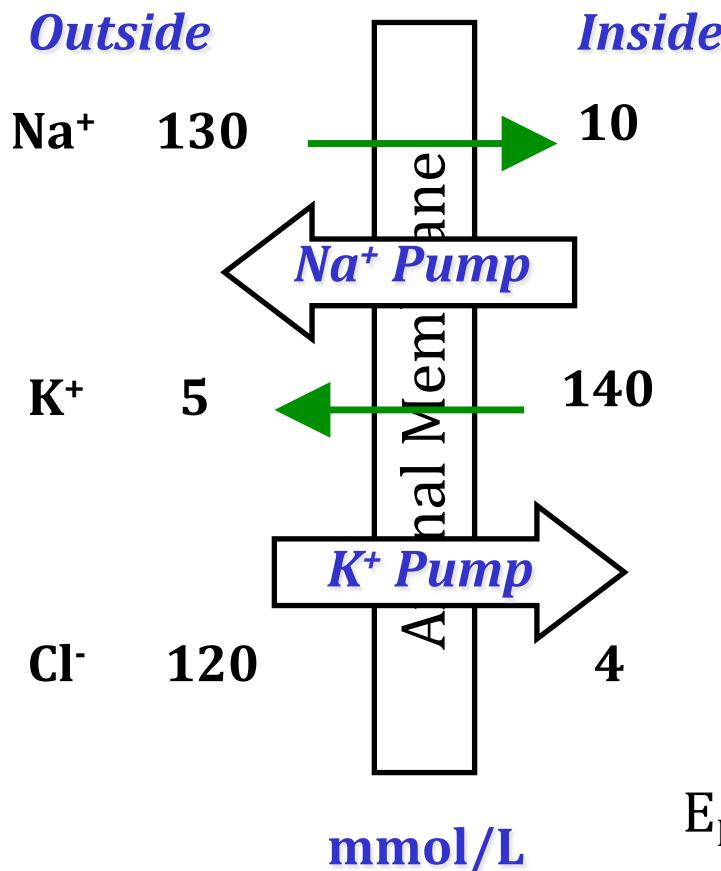
The beginnings



Ecuación de Nernst

$$E_x = \frac{RT}{zF} \ln \frac{[X]_2}{[X]_1}$$





Chemical diffusion tends to reduce the concentration gradient

Ion pumps reestablish the gradient

The membrane potential at which there is no net flow of a particular ion from one side of the membrane to the other, is given by the Nernst Eq.

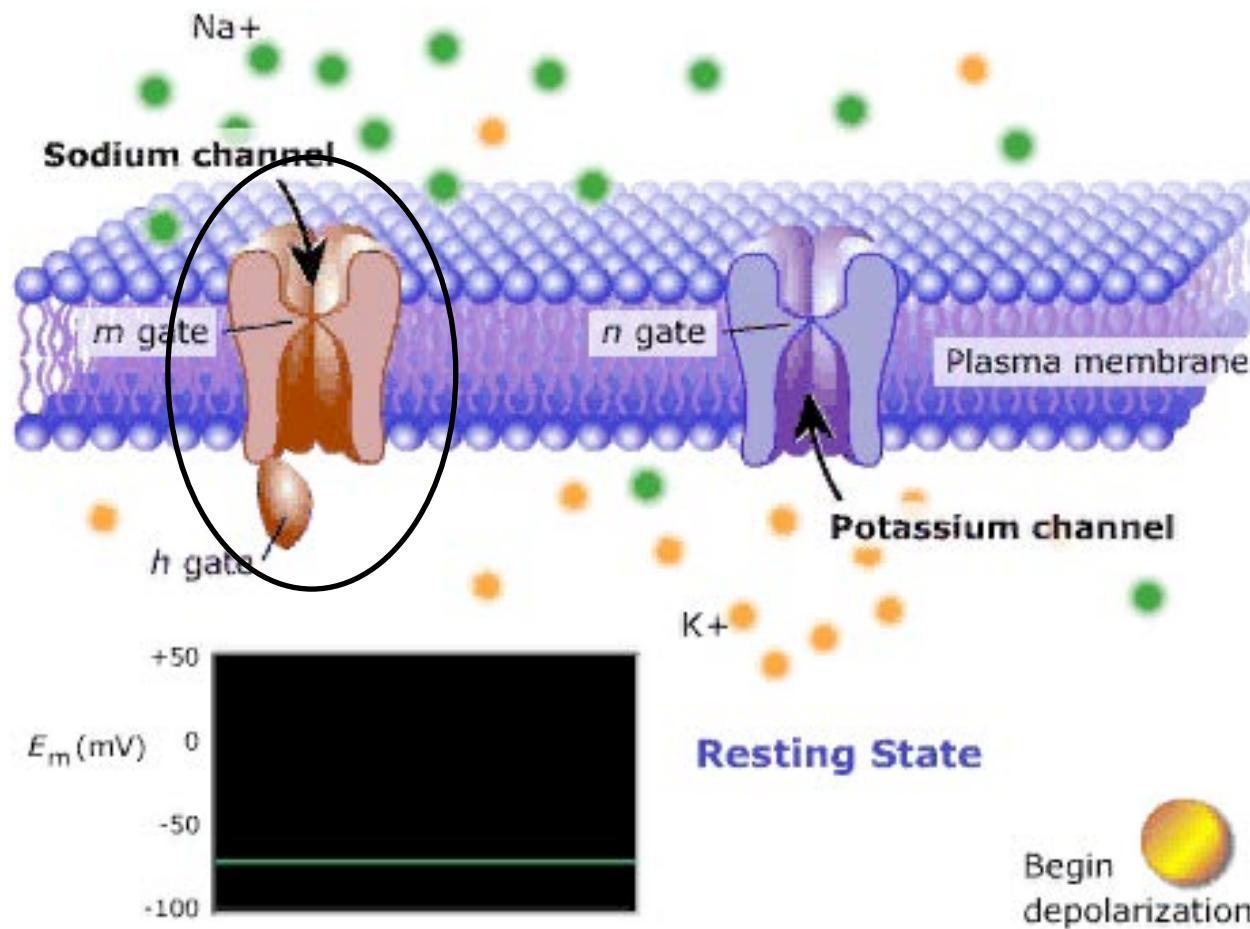
$$E = (RT/zF) \ln(X_o/X_i)$$

$$E_{\text{K}^+} = -88 \text{ mV}; E_{\text{Na}^+} = 68 \text{ mV}; V_{\text{rest}} = -85 \text{ mV} \text{ for a mammal}$$

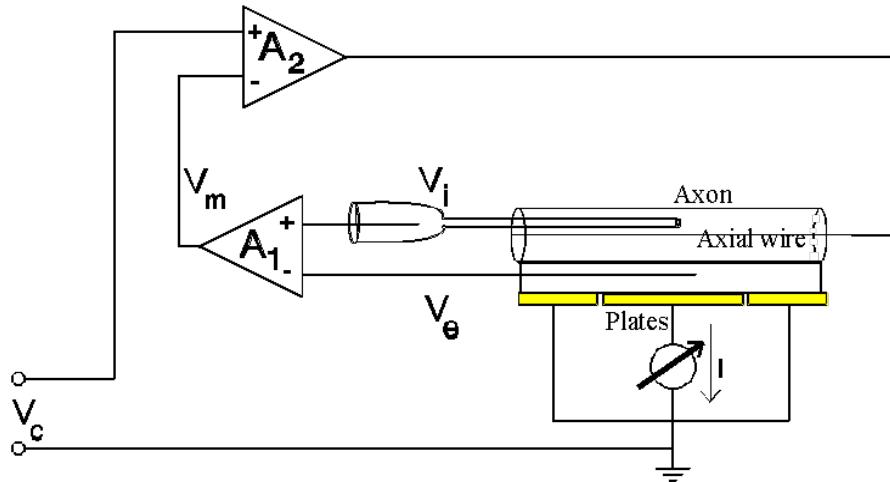
When all ions are combined the membrane potential is given by the Goldman-Hodgkin-Katz eq.

$$V_M = (RT/zF) \ln \frac{[\text{Na}^+]_o P_{\text{Na}^+} + [\text{K}^+]_o P_{\text{K}^+} + [\text{Cl}^-]_i P_{\text{Cl}^-}}{[\text{Na}^+]_i P_{\text{Na}^+} + [\text{K}^+]_i P_{\text{K}^+} + [\text{Cl}^-]_o P_{\text{Cl}^-}}$$

Ion channels are voltage dependent

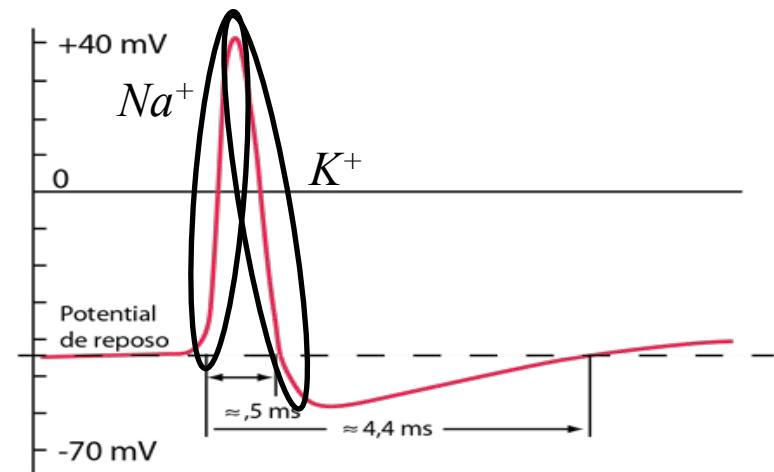


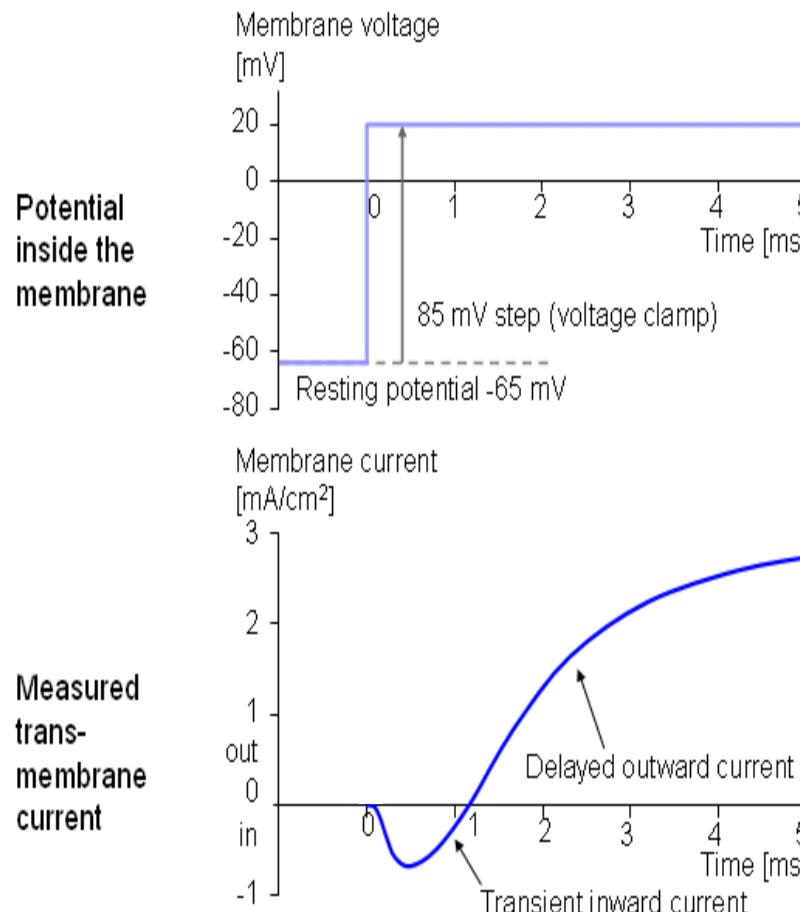
The Hodgkin-Huxley experiment



- They studied the giant nerve fibers in the squid.
- Using small electrodes they recorded the potential difference between the inside and outside of the axon.
- Precise measurements and sophisticated mathematical models allowed them to formulate a theory of how neurons fire.

Changes in membrane permeability allow charged ions to flow inside and outside of the nerve fiber, resulting in action an potential.





The membrane potential is fixed externally at a value above the threshold.

The current is measured and the Ohm law $V=I/R$ is applied to determine the conductance ($g=1/R$)

The measurement is repeated for different values of V

To separate the Na^+ and K^+ components, Hodgkin & Huxley used salt water to equilibrate the concentration of Na^+ ions

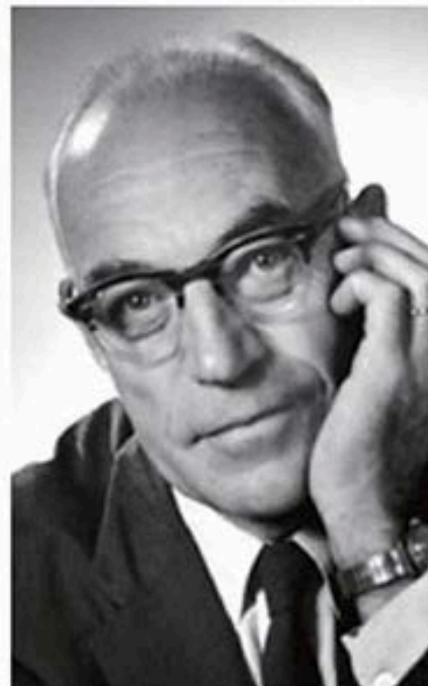
$$g_{ion} = \frac{I_{ion}}{V_M - E_{ion}}$$

$$g_{K^+} = \frac{I_{K^+}}{V_M - E_{K^+}}$$

$$g_{\text{Na}^+} = \frac{I_{\text{Na}^+}}{V_M - E_{\text{Na}^+}}$$

"for their discoveries concerning the ionic mechanisms involved in excitation and inhibition in the peripheral and central portions of the nerve cell membrane"

Nobel Prize of Medicine or Physiology in 1963



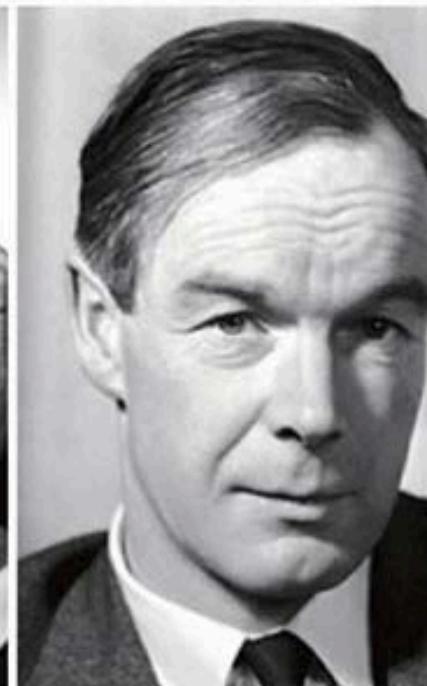
Sir John Carew Eccles

⌚ 1/3 of the prize

Australia

Australian National University
Canberra, Australia

b. 1903
d. 1997



Alan Lloyd Hodgkin

⌚ 1/3 of the prize

United Kingdom

University of Cambridge
Cambridge, United Kingdom

b. 1914
d. 1998



Andrew Fielding Huxley

⌚ 1/3 of the prize

United Kingdom

University College
London, United Kingdom

b. 1917

The Hodgkin-Huxley model

- It considers 3 currents: K⁺ (with four activation gates), Na⁺ (with three activation and one inactivation gates) and a leakage current (mainly Cl⁻ ions)
- The equation for the membrane potential is:

$$C \dot{V} = I - \overbrace{\bar{g}_K n^4 (V - E_K)}^{I_K} - \overbrace{\bar{g}_{Na} m^3 h (V - E_{Na})}^{I_{Na}} - \overbrace{g_L (V - E_L)}^{I_L}$$

$$\dot{n} = \alpha_n(V)(1-n) - \beta_n(V)n$$

$$\dot{m} = \alpha_m(V)(1-m) - \beta_m(V)m$$

$$\dot{h} = \alpha_h(V)(1-h) - \beta_h(V)h,$$

$$\alpha_n(V) = 0.01 \frac{10 - V}{\exp(\frac{10-V}{10}) - 1}$$

$$\beta_n(V) = 0.125 \exp\left(\frac{-V}{80}\right)$$

$$\alpha_m(V) = 0.1 \frac{25 - V}{\exp(\frac{25-V}{10}) - 1}$$

$$\beta_m(V) = 4 \exp\left(\frac{-V}{18}\right)$$

$$\alpha_h(V) = 0.07 \exp\left(\frac{-V}{20}\right)$$

$$\beta_h(V) = \frac{1}{\exp(\frac{30-V}{10}) + 1}.$$

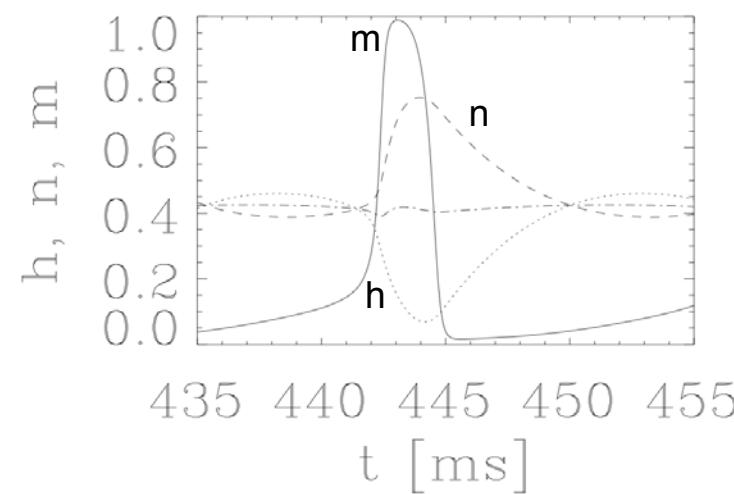
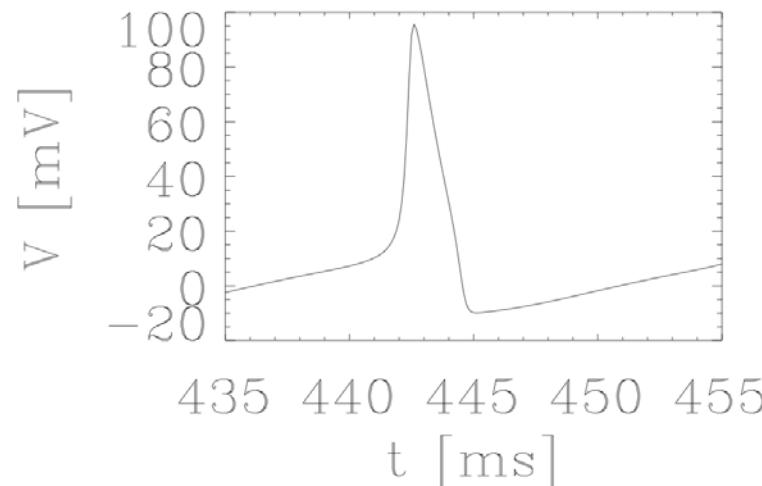
V has been shifted by 65 mV so that the resting potential is 0

The Nerst shifted potentials, maximal conductances and membrane capacitance are

$$E_K = -12 \text{ mV} \quad E_{Na} = 120 \text{ mV}, \quad E_L = 10.6 \text{ mV};$$

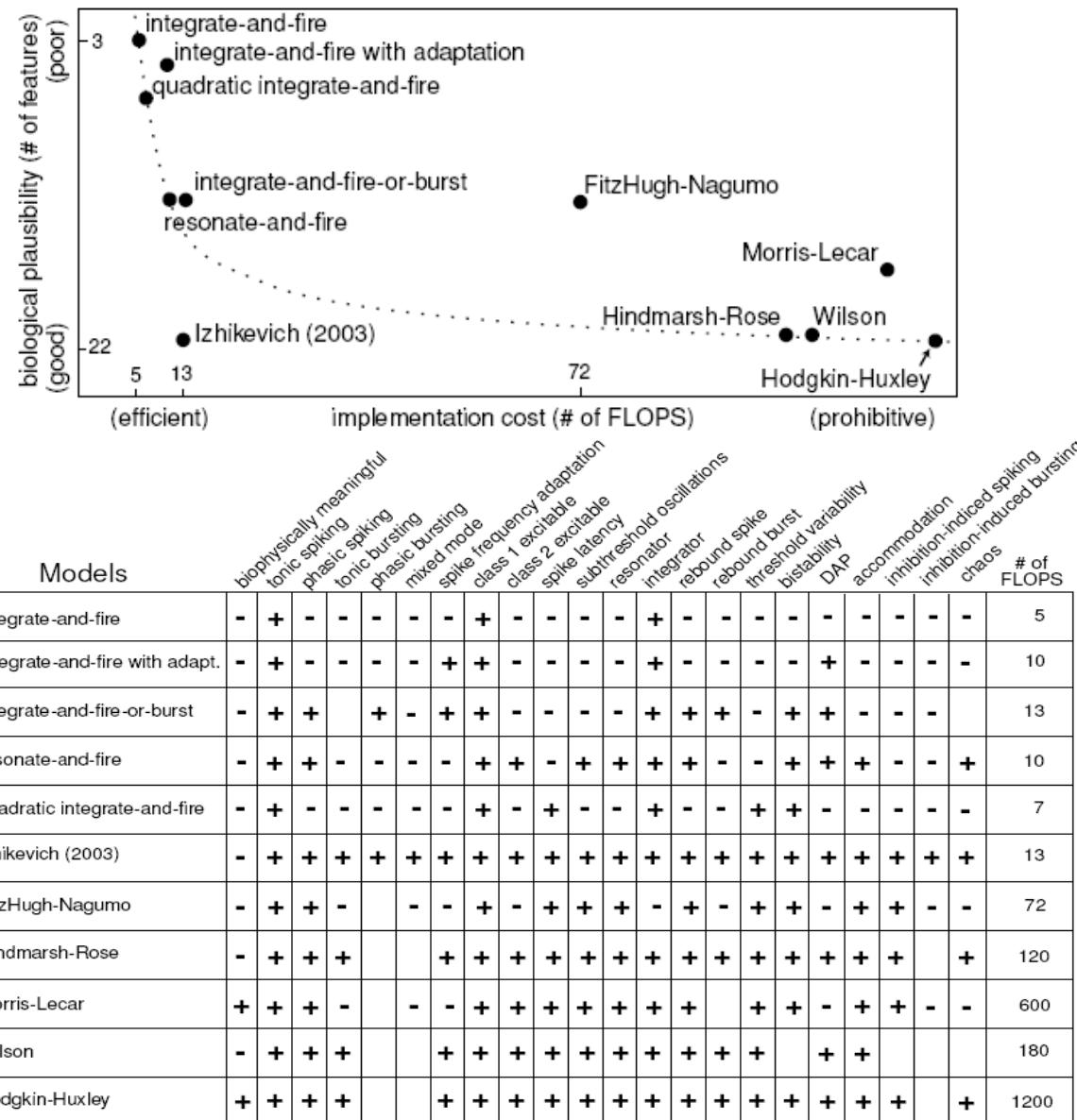
$$\bar{g}_K = 36 \text{ mS/cm}^2 \quad \bar{g}_{Na} = 120 \text{ mS/cm}^2, \quad g_L = 0.3 \text{ mS/cm}^2.$$

$C = 1 \mu\text{F}/\text{cm}^2$ is the membrane capacitance



Reduced models

- The different time scales of the HH model allow for dimensionality reduction.
- Na^+ channels opens much faster than K^+ channels (m variable).
- The inactivation of the Na^+ (h variable) channels and the opening of K^+ channels (n variable) follow a certain relationship.
- Several models are obtained (including FitzHugh-Nagumo, Integrated and Fire, Morris- Lecar, Hindmarsh-Rose, Izhikevich, etc.)



E. Izhikevich, IEEE TRANSACTIONS ON NEURAL NETWORKS, VOL. 15, NO. 5, SEPTEMBER 2004

Synapses

- Neurons are connected through synapses.
- Synapses can be chemical (more abundant in the brain) or electrical
- Chemical synapses:
 - Occur in few ms time scales.
 - Have asymmetric morphology: are unidirectional.
 - Most of pre-synaptic terminals are axons and postsynaptic ones are dendrites.
 - Use neurotransmitters (Glutamate, GABA, etc) and receptors (AMPA, NMDA, GABA_A, GABA_B, etc.).
- Electrical synapses
 - Are almost instantaneous.
 - Have a symmetric morphology.
 - Might be more robust.

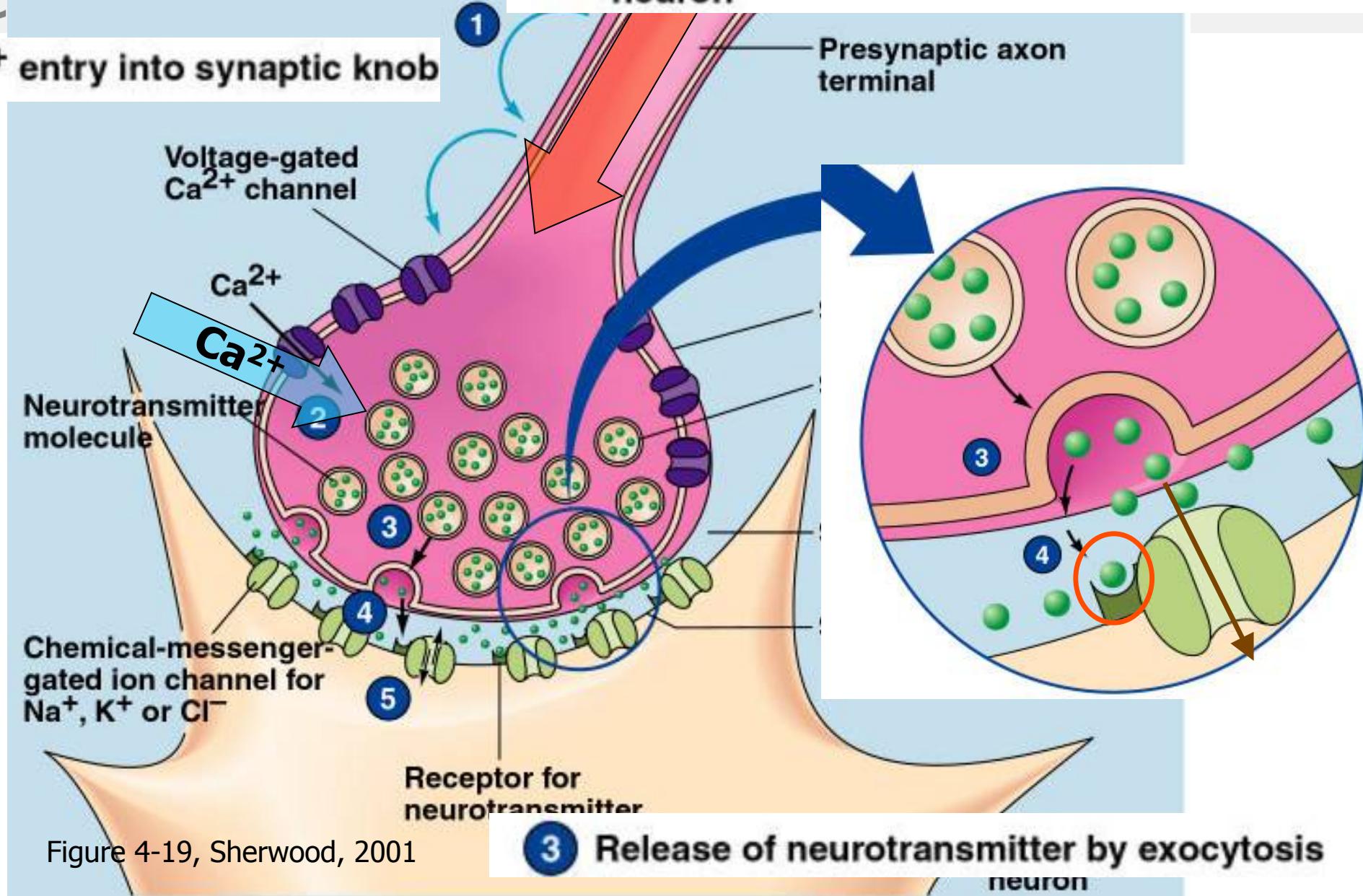
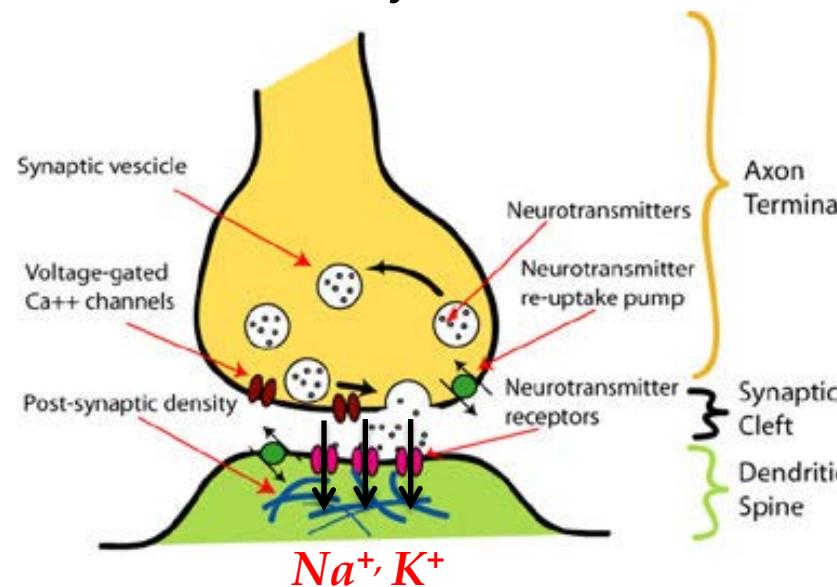
1 Action potential propagation in presynaptic neuron**2 Ca^{2+} entry into synaptic knob**

Figure 4-19, Sherwood, 2001

3 Release of neurotransmitter by exocytosis**4 Binding of neurotransmitter to postsynaptic receptor****5 Opening of specific ion channels in subsynaptic membrane**

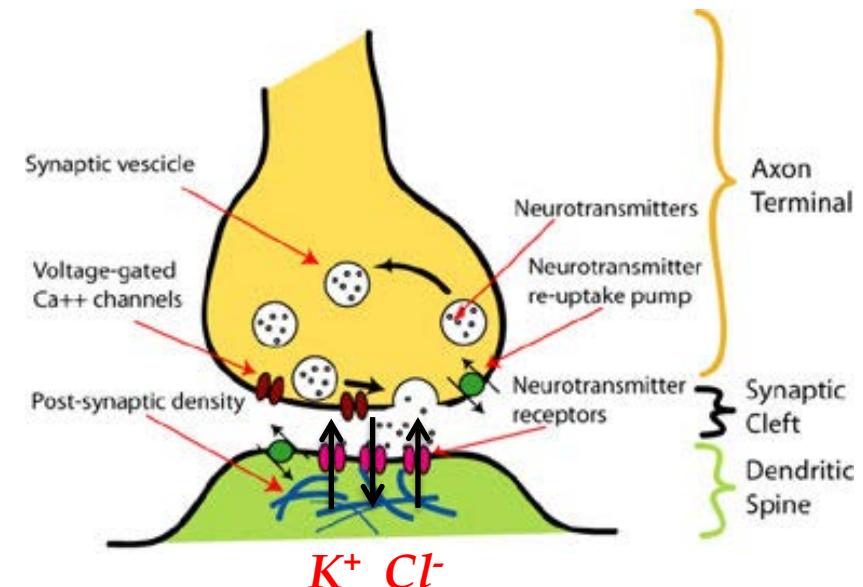
Excitatory Neurons



Neurotransmisor: Glutamate.
Receptores: AMPA, NMDA

Excitatory Neurons: favor the firing of the target neuron; the membrane potential ↑

Inhibitory Neurons



Neurotransmisor: GABA
Receptores: GABA_A, GABA_B

Inhibitory Neurons: inhibit the firing of the target neuron; the membrane potential ↓

- A synaptic conductance can be written as the product of a maximal conductance and a probability to open the channel.
- This probability can be expressed as a product of two terms: P_s (the probability that a postsynaptic channel opens) and P_{rel} (probability that transmitter is released by pre-synaptic terminal under an action potential).
- In a simple model of a directly activated receptor channel the transmitter interacts with the channel and opens it.

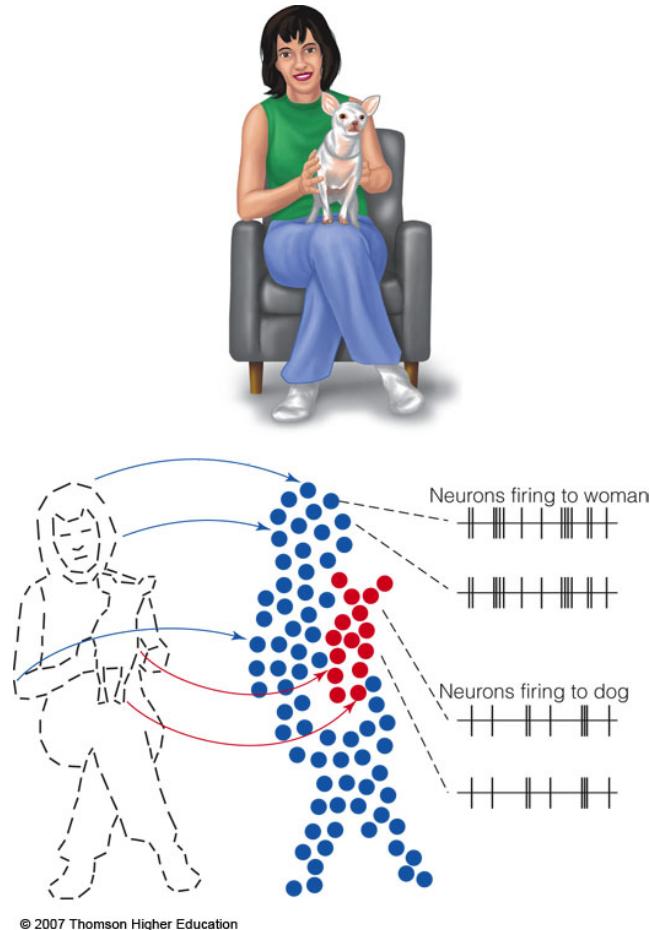
$$\frac{dP_s}{dt} = \alpha_s(1 - P_s) - \beta_s P_s$$

α_s determines the opening rate of the channel and depends on the concentration of neurotransmitters

β_s determines the closing rate of the channel and is assumed to be constant.

Zero-lag synchronization in Brain Motifs

The Feature Binding Problem



Separate neurons respond to color (green, blue, white), contours (orientations), textures, so on.

Synchrony hypothesis:

When the features come from the same object (i.e., the woman), these neurons fire at the same time in the same manner.

When the neurons fire at the same time and in the same manner, we perceive “binding” of features.

Singer, W. 2007. Binding by synchrony. Scholarpedia 2:1657.

Zero-Lag Long-Range Synchronization in the Brain

Neurophysiological experiments: even in the presence of substantial coupling delays different cortical areas exhibit isochronous synchronization at zero lag

Visuomotor integration is associated with zero time-lag synchronization among cortical areas

Pieter R. Roelfsema*,†, Andreas K. Engel*,
Peter König‡ & Wolf Singer*

NATURE · VOL 385 · 9 JANUARY 1997

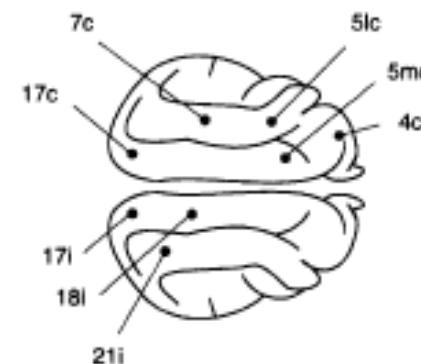
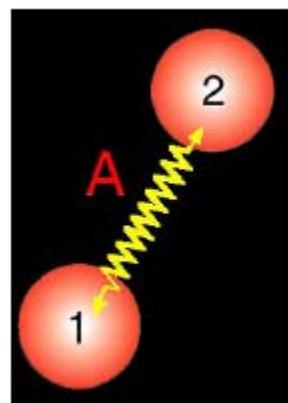


TABLE 1 Strength of zero-time-lag synchronization between cortical areas

Areas	Correlation coefficient (%)	Range	N	Areas	Correlation coefficient (%)	Range	N
17c-7c	9 ± 4	4-14	4	5lc-4c	2 ± 3	0-5	2
17c-5lc	0		2	5lc-17i	0		2
17c-5mc	0		3	5lc-18i	4 ± 5	0-8	2
17c-4c	0		2	5lc-21i	4 ± 4	0-8	3
17c-17i	22 ± 7	12-28	4	5mc-4c	10 ± 1	9-11	2
17c-18i	12 ± 3	7-14	4	5mc-17i	0		3
17c-21i	8 ± 2	7-10	3	5mc-18i	0		3

How can two distant neural assemblies synchronize their firings at zero-lag even in the presence of non-negligible delays in the transfer of information between them?

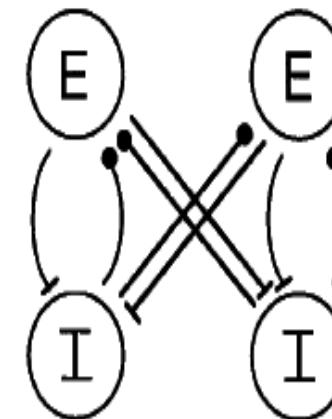


Which is the physical and anatomical substrate for this dynamical and precise synchrony?

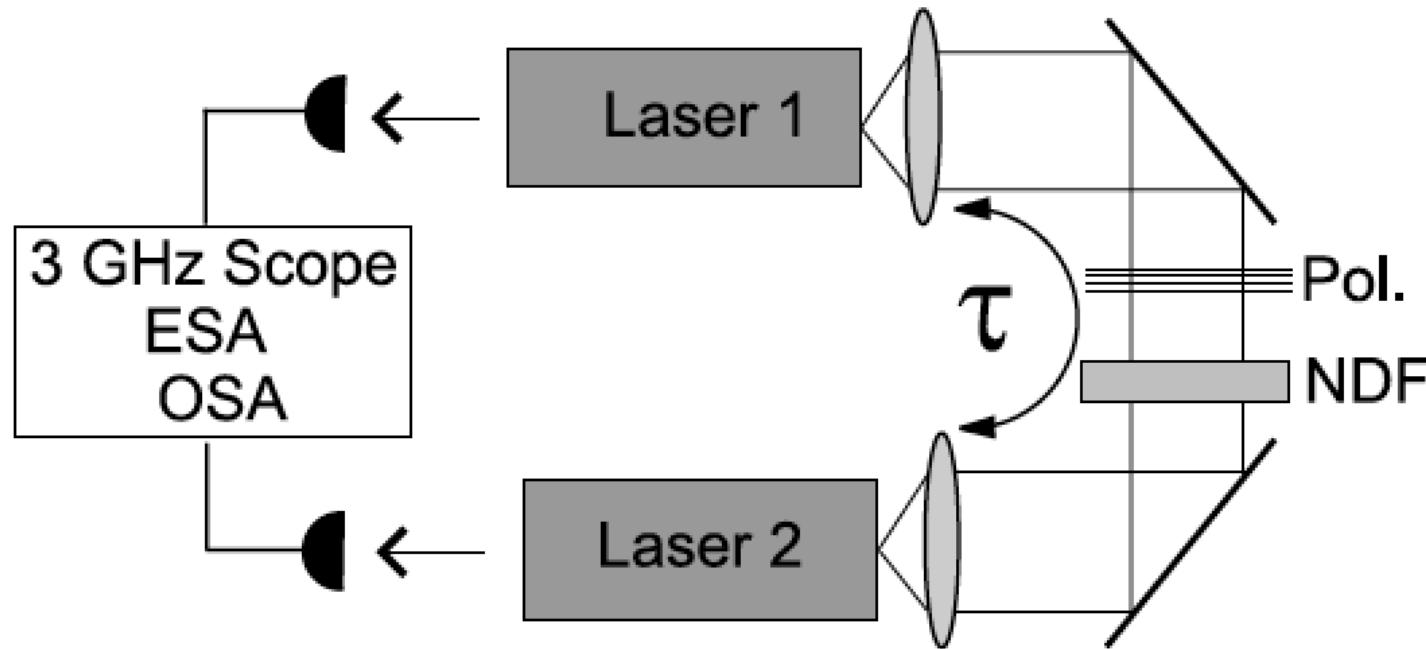
- Direct cortico-cortical connections
 - Inhibitory connections
 - Gap junctions
 - Complex Networks
- } Enhance synchronization

R. Traub et al., *Nature* **383**, p. 621, 1996;
G. B. Ermentrout & N. Kopell, *Proc. Natl. Acad. Sci.
USA* **95**, p. 1259, 1998;

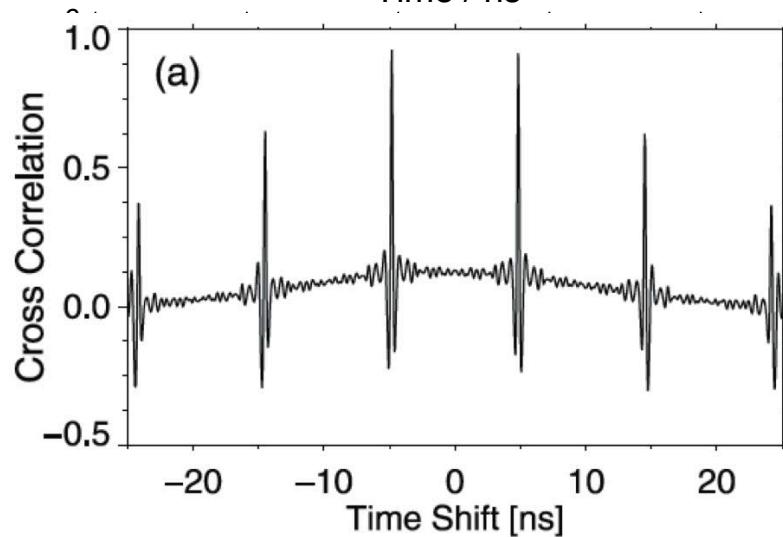
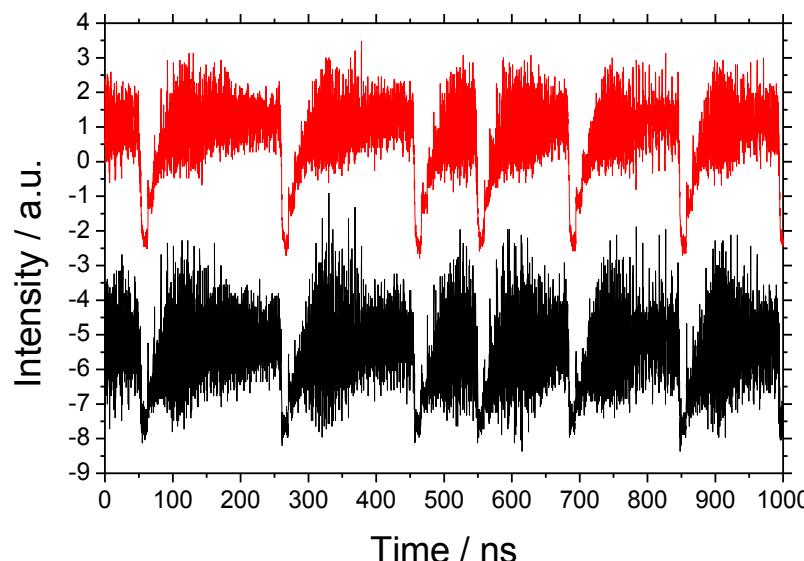
- Excitatory-Inhibitory networks favor γ -frequency rhythms
- Inhibitory cells produce spike doublets
- Connections between such networks favor zero-lag synchronization.



Mutually Coupled Semiconductor Lasers



Mutually Coupled Semiconductor Lasers

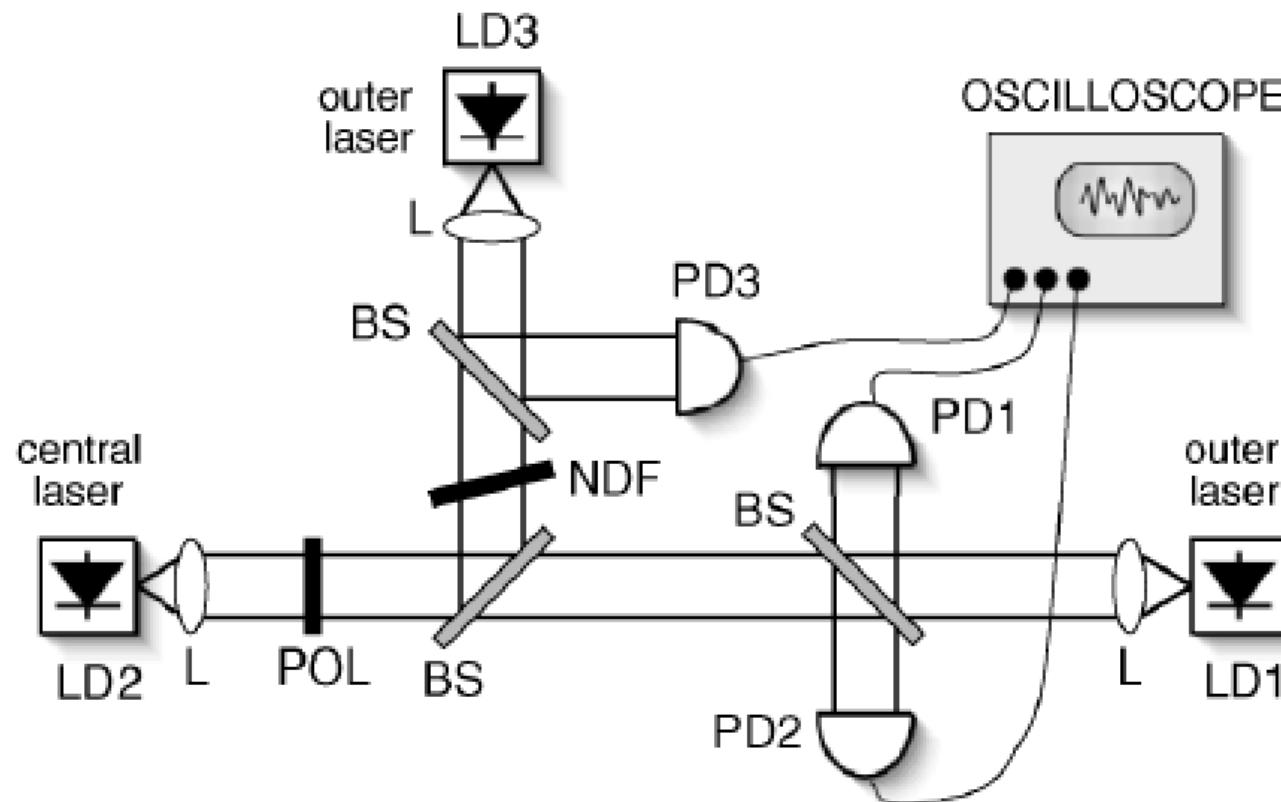


- onset of coupling-induced intensity pulsations
- synchronization among the two lasers
- synchronization of ns and sub-ns pulsations
- however:
- one time series temporally shifted by τ_{cp}
- leader & laggard (achronal synchronized solution)

$$CC_{\max} \text{ at } +/ - n^* \tau$$

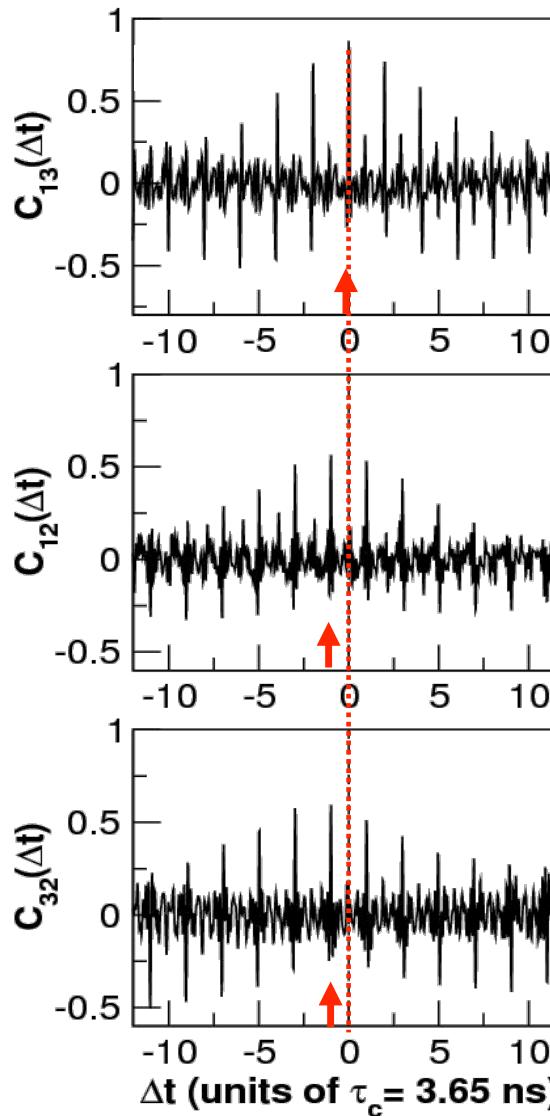
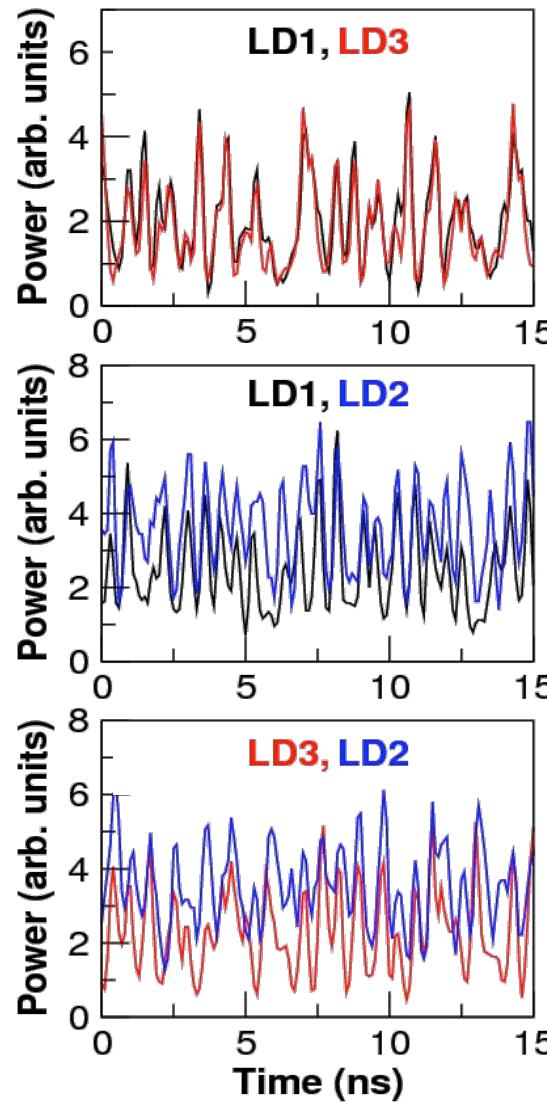
T.Heil, I.Fischer, W.Elsäßer, J.Mulet, .R.Mirasso,
Phys.Rev.Lett. 86, 795 (2001)

Chain of Three Mutually Coupled Semiconductor Lasers

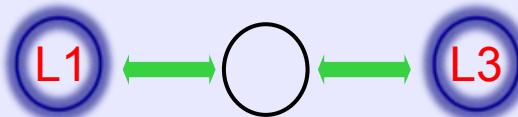


I.Fischer et al., Phys.Rev.Lett. 97, 123902 (2006)

Chain of Three Mutually Coupled Semiconductor Lasers



- L1 and L3 identically synchronise with zero lag



- center laser (L2) lags behind the outer laser (L1)



- center laser (L2) lags behind the outer laser (L3)



- excellent agreement with modelling

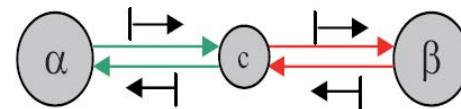
I.Fischer et al., Phys.Rev.Lett. 97, 123902 (2006)



Center laser (L2) lags behind the outer lasers (L1,L3), **no master!**

Can the zero-lag sync mechanism observed in lasers be generalized to models of neuronal systems?

Neuron are excitable systems



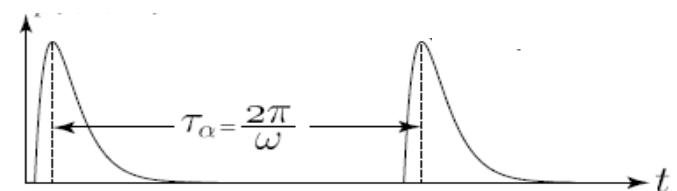
They couple via chemical synapses (pulse coupling)

Model at the level of Hodgkin-Huxley:

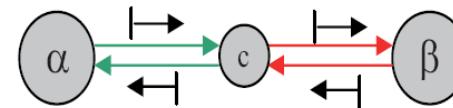
$$C \frac{dV}{dt} = -g_{Na}m^3h(V - E_{Na}) - g_Kn^4(V - E_k) - g_L(V - E_L) + I_{ext} + I_{syn}$$

$$I_{syn}(t) = -g_{max} \sum_{\tau_l} \sum_{spikes} \alpha(t - t_{spike} - \tau_l)(V(t) - E_{syn})$$

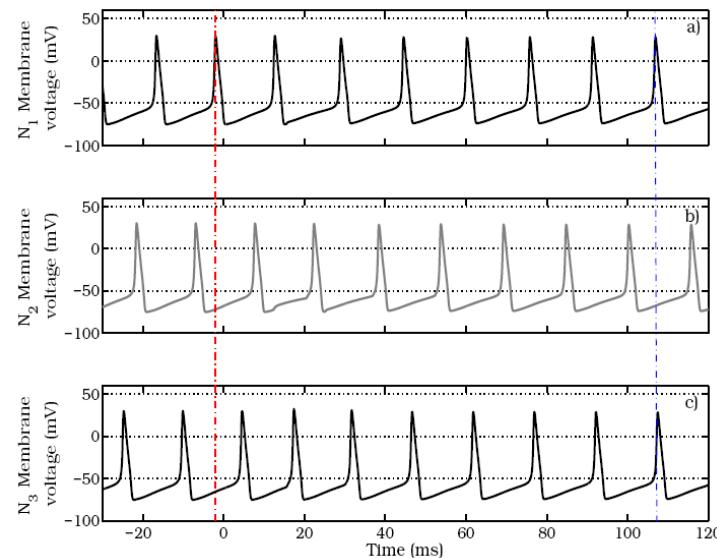
$$\alpha(t) = \frac{1}{\tau_d - \tau_r} (\exp(-t/\tau_d) - \exp(-t/\tau_r))$$



Simulating conditions:



- Periodic firing regime ($T = 14.7$ ms, $f = 68.02$ Hz)
- Each neuron with a random initial phase
- Different synaptic rise and decay times
- Excitatory and inhibitory synapses



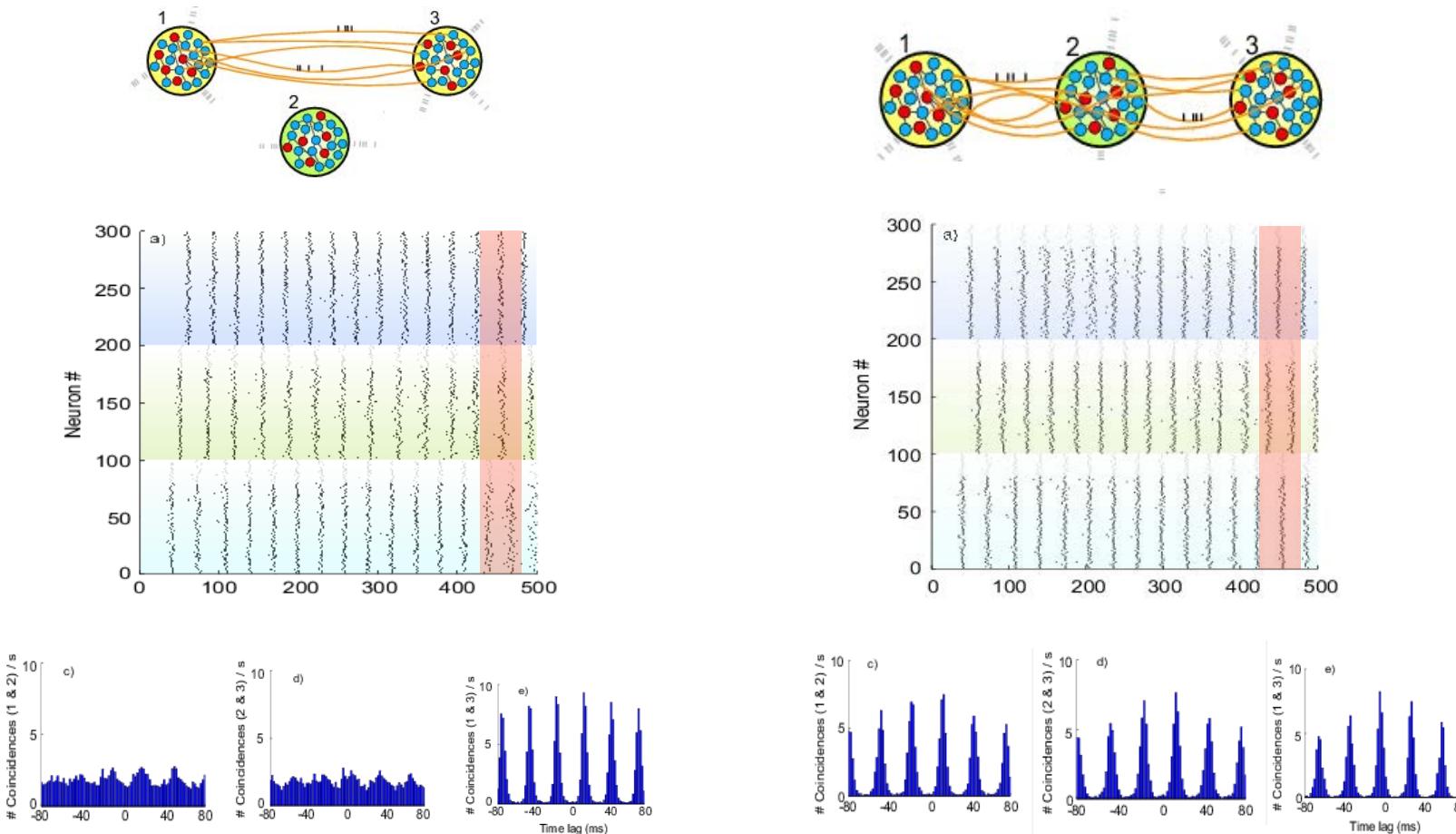
$g_{max} = 0.5$ $E_{syn} = 0$ mV $\tau_l = 8$ ms $\tau_r = 0.1$ ms $\tau_d = 3$ ms
--

- self-organization toward the synchronization of outer neuron spikes
- zero-phase sync due to relay and redistribution of EPSP / IPSP

True for E-E or I-I couplings and different α -functions

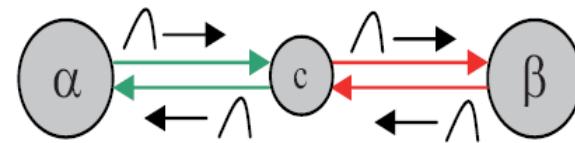
What would happen in Populations?

Each neuron connects excitatory and randomly to 0.25% of the neurons of the other population with 15 ms delay

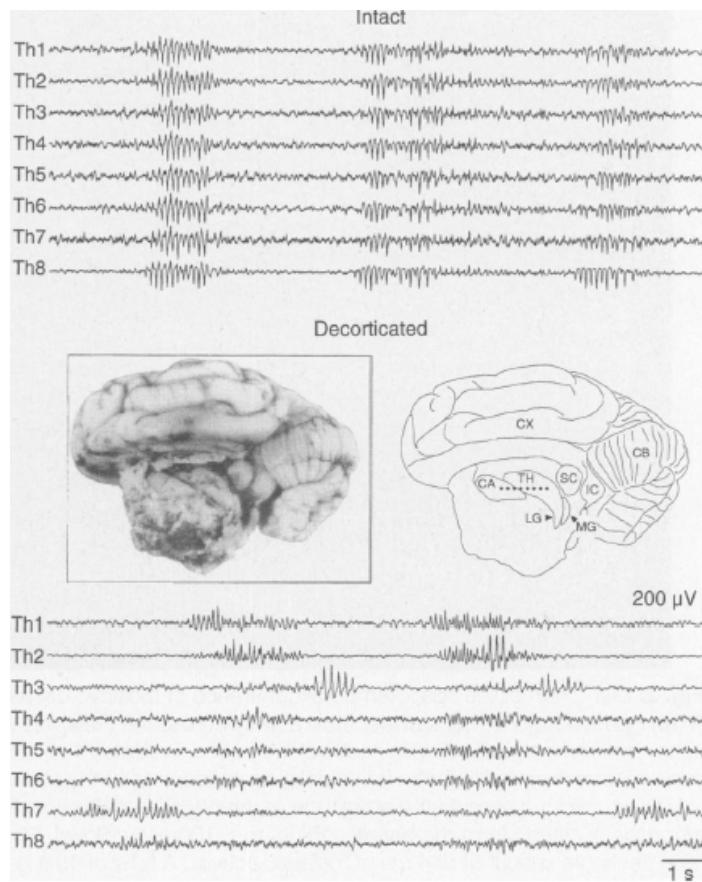


R. Vicente, et al., PNAS 105, 17157 (2008).

Is there a physiological evidence?

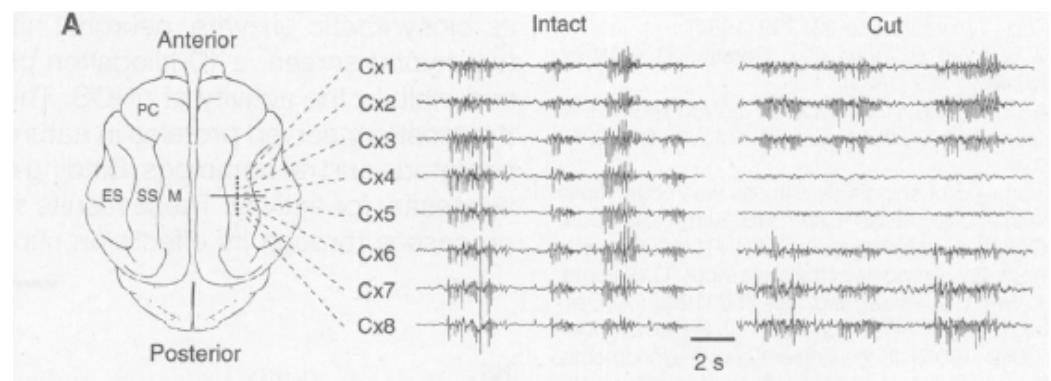
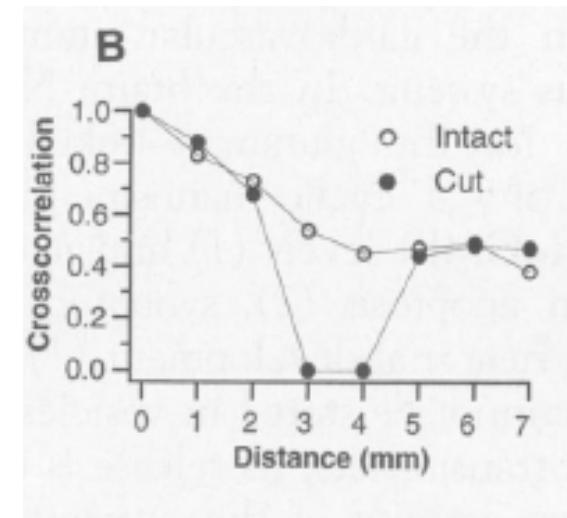


Thalamus is the main relay unit of sensory information to the cortex with bidirectional connections



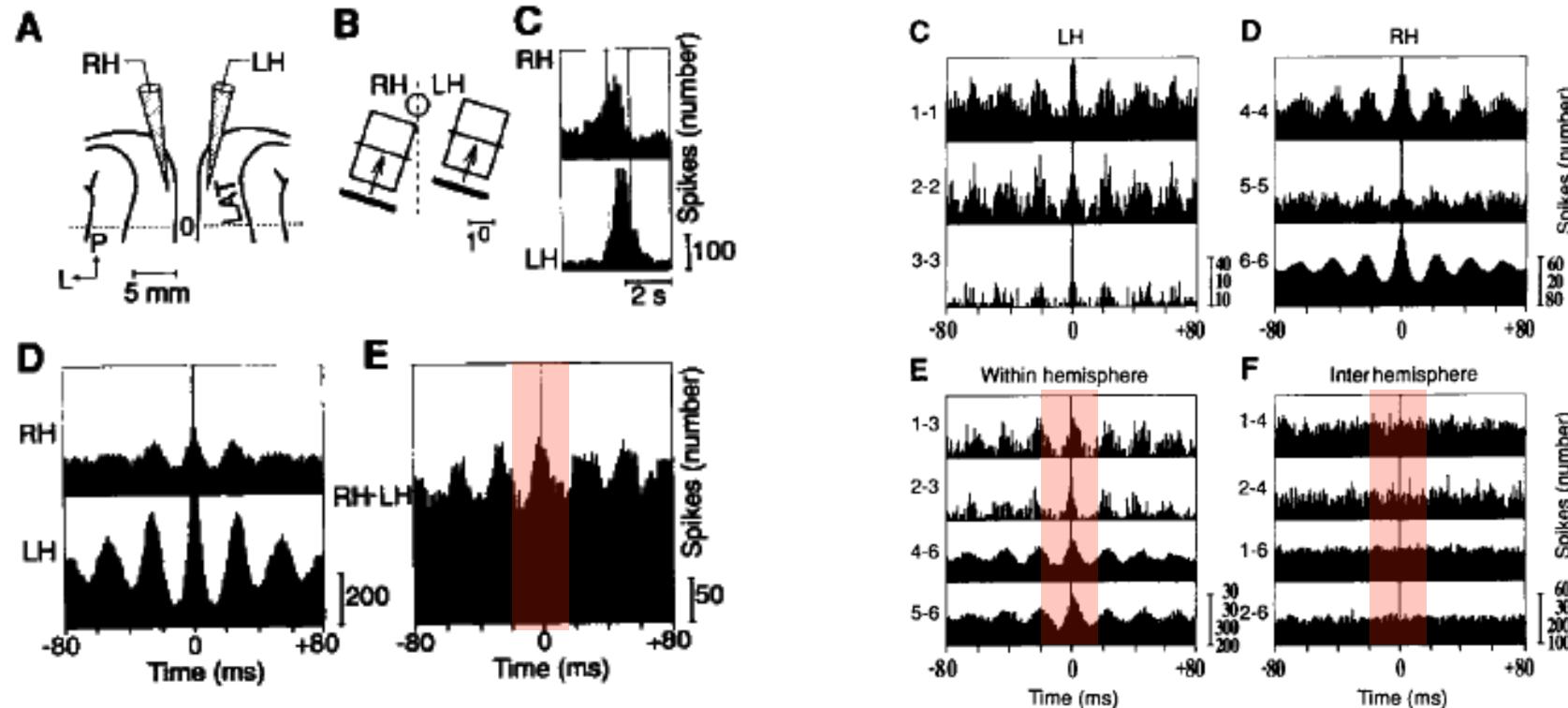
*9-10 Hz oscillation in the thalamus.
Intact and with a cortex lesion.*

Control of Spatiotemporal Coherence of a Thalamic Oscillation by Corticothalamic Feedback,
D. Contreras, A. Destexhe, T. J. Sejnowski, M. Steriade, Science 274, 771 (1996).



Synchrony of oscillations is not determined by intra-cortical connectivity

Interhemispheric Synchronization



Interhemispheric Synchronization of Oscillatory Neuronal Responses in Cat Visual Cortex. A. Engel, et al. *Science* 252, 5009 (1991).

Interhemispheric synchronization is absent when the corpus callosum is sectioned

CPC circuits mimic direct CC pathways but with more overlap → facilitation of transarea sync.

S. Shipp, Philos Trans R Soc Lond B Biol Sci, 358, 1605, (2003).

"The driving projections to thalamus would thus provide a significant alternative path for inter-areal communication".

Douglas and Martin, Annu. Rev. Neurosci. 27, 419, 2004

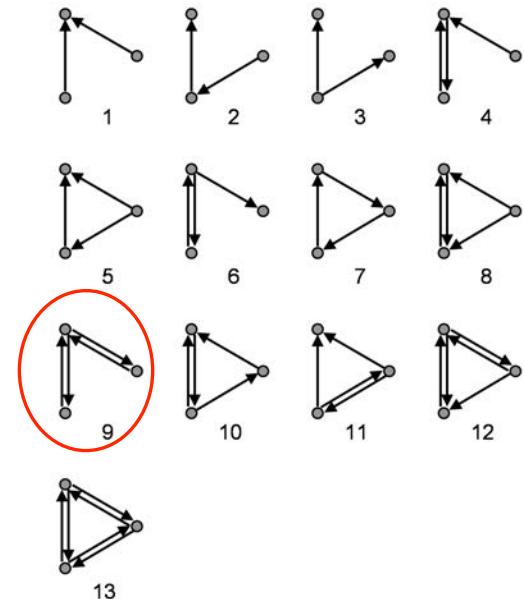
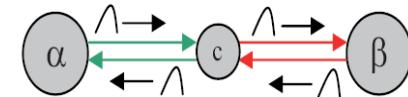
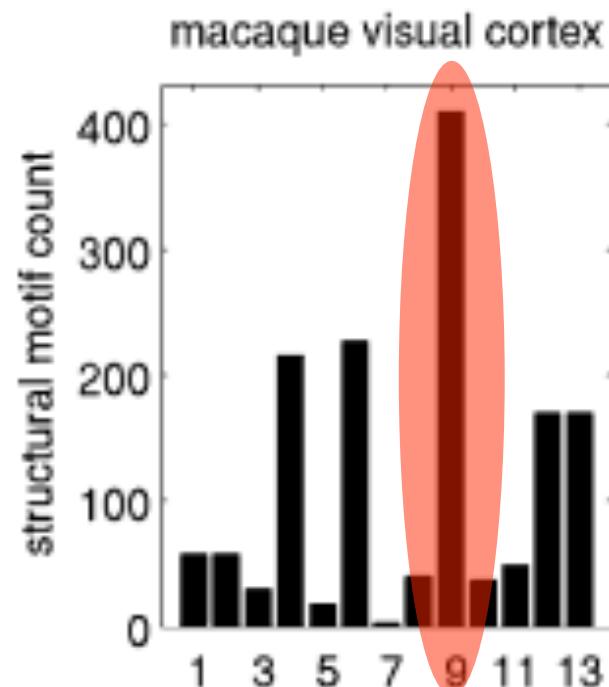
Some studies have shown the constant latency between the thalamus and almost any area in the rat cortex.

Salami et al., PNAS, 100, 6174, (2003).

Stronger TC connections than expected.

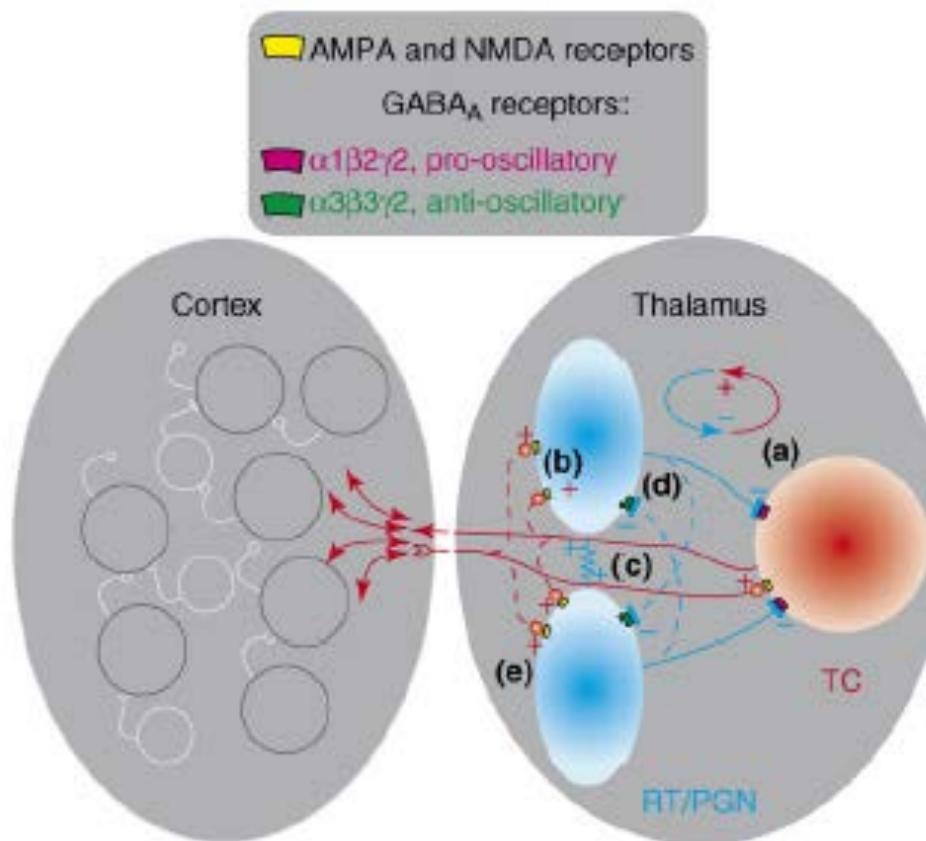
"Cortex Is Driven by Weak but Synchronously Active Thalamocortical Synapses" Bruno and Sakmann, Science, 312, 1622, (2006).

Also.....the proposed motif is a building block of the mammalian cortex. But has the proposed motif a specific role in the brain network?



Sporns & Kötter
PLoS Biology, 2, 1910,
(2004).

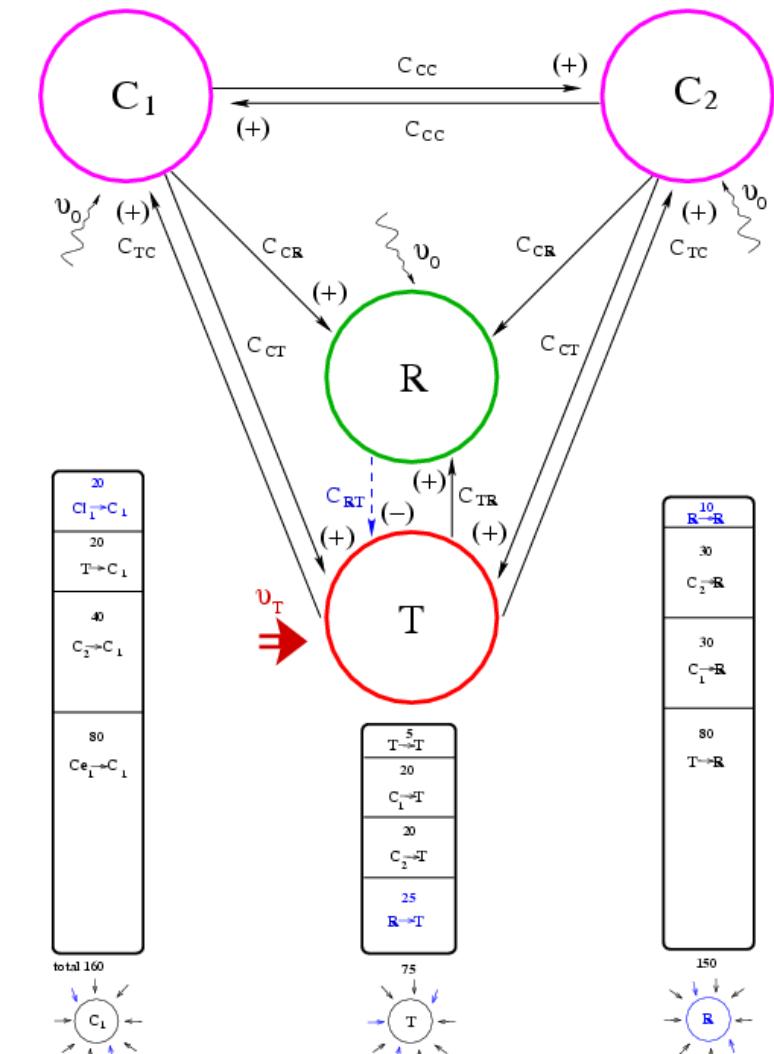
Thalamo-Cortical Interactions



TC: Thalamo-Cortical Network

RT: Reticular Nuclei

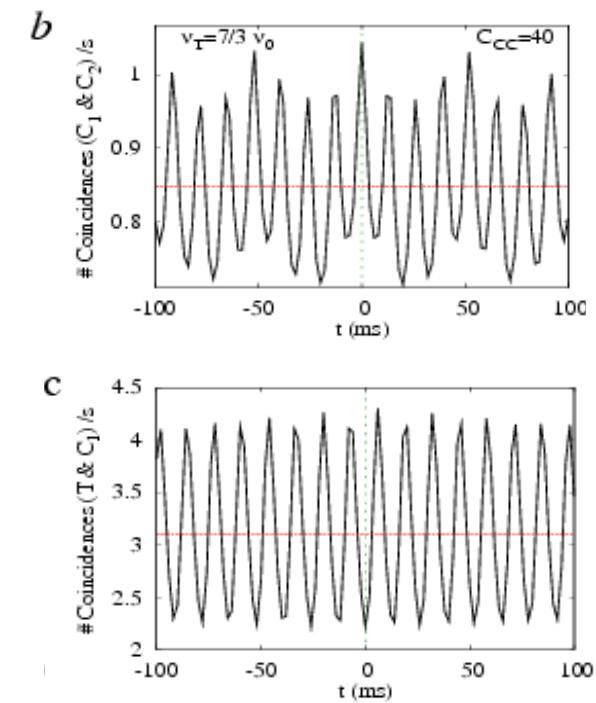
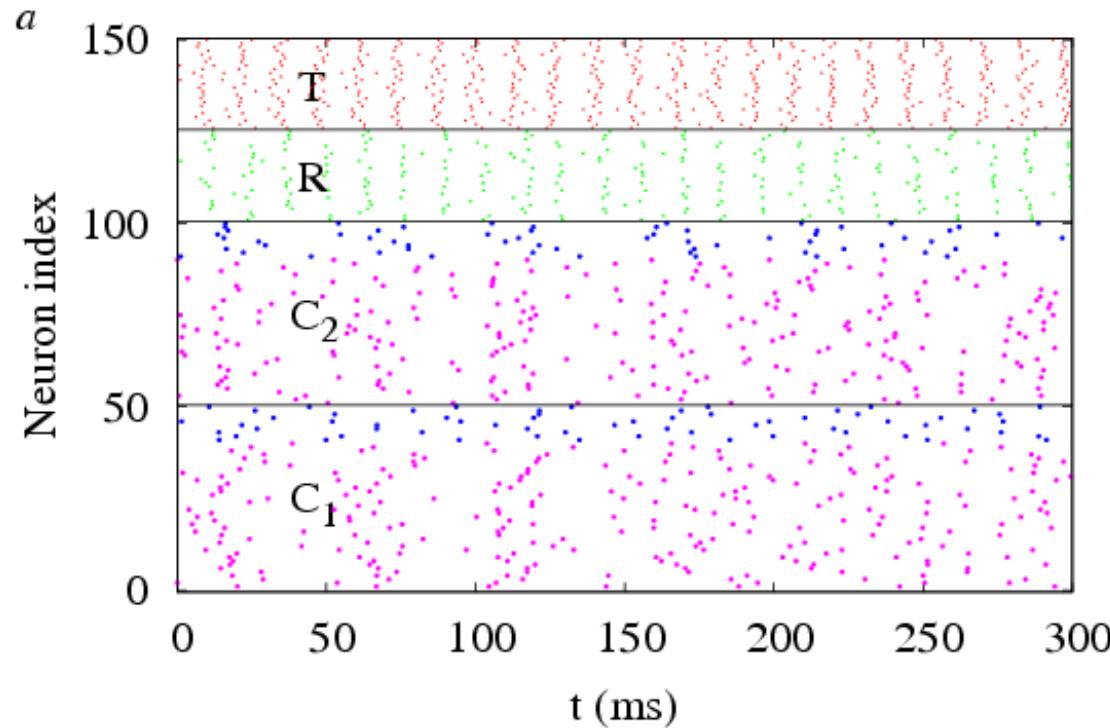
PGN: Perigeniculate Nuclei



L. Gollo et al., Neuroimage 52 (2010) 947–955

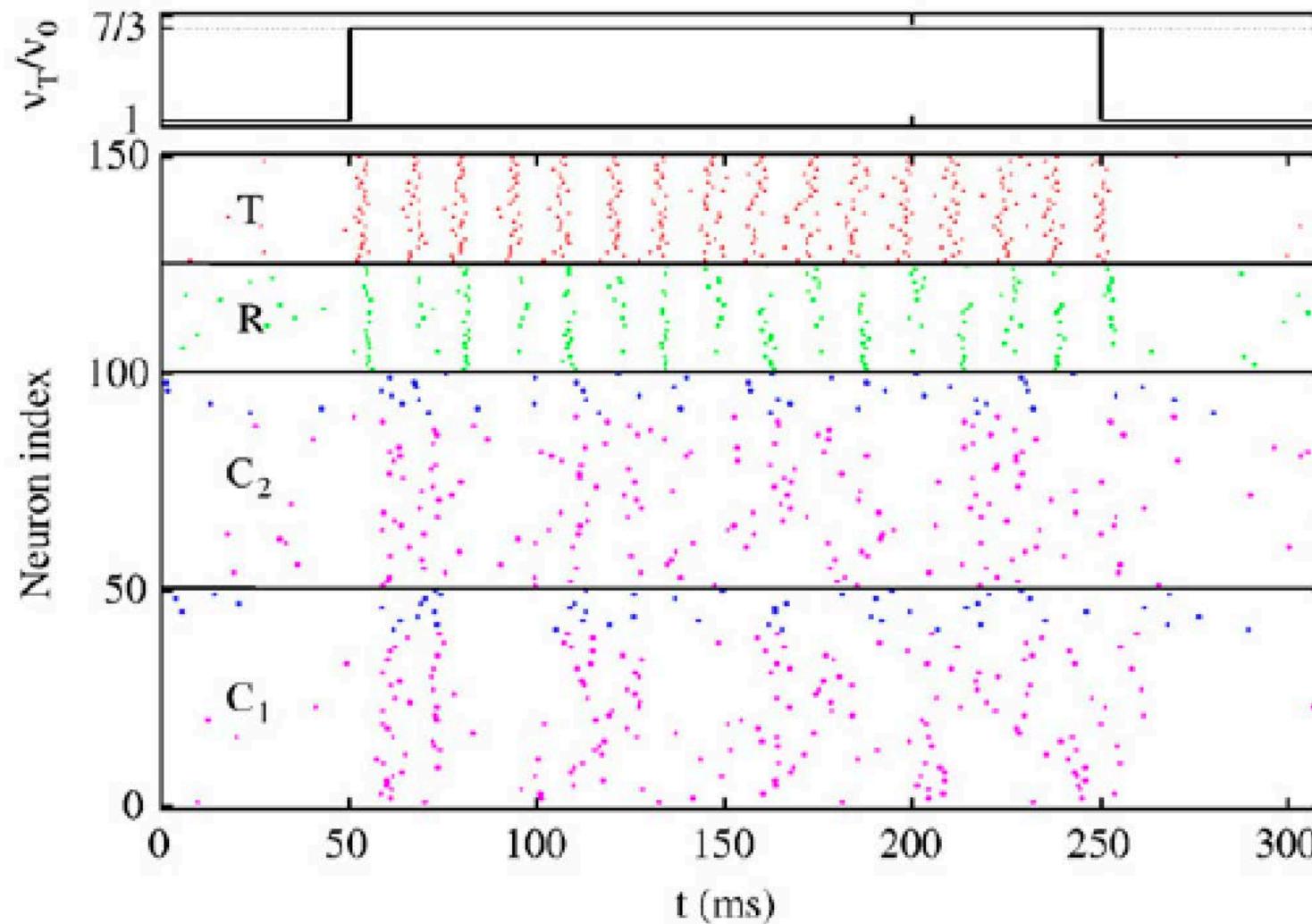
Each neuron is subject to an independent Poisson noise $P(t)=\kappa e^{v_0 t}$

Thalamic neurons are subject to a Poisson noise $P(t)=\kappa e^{v_T t}$



L. Gollo et al., Neuroimage 52 (2010) 947–955

ON-OFF synchronization



- We found an **alternative mechanism** that gives rise to zero (or almost zero)-lag (or phase) long-range synchronization in neuronal models in the presence of delayed interactions.
- Zero-lag synchronization is an behavior that **emerges** from the interaction between the three neurons or neuron populations.
- A **relay element** must mediate the dynamics between two neurons or neuron populations.
- It might be possible that **the thalamus acts as a relay element**, although cortico-cortical interaction without thalamus mediation are also possible.
- In active and passive mice, the synchronize activity observed between frontal and visual cortex might be mediated by the hippocampus (not shown)

Anticipated synchronization

Can we predict or anticipate the future?

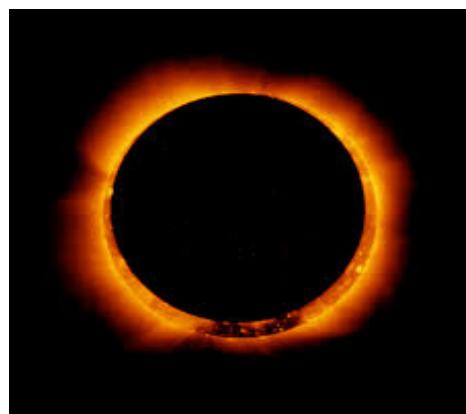


If you give me the equation of motion
and the initial conditions

$$\frac{d\mathbf{x}}{dt} = \mathbf{F}(\mathbf{x}, t), \quad \mathbf{x}(0) = \mathbf{x}_0$$

of course

YES!



Total Eclipse: April 8th, 2024

Will be visible in North America

But many times we have to deal with fast varying (even chaotic) dynamical systems for which initial conditions are not known with enough precision.....



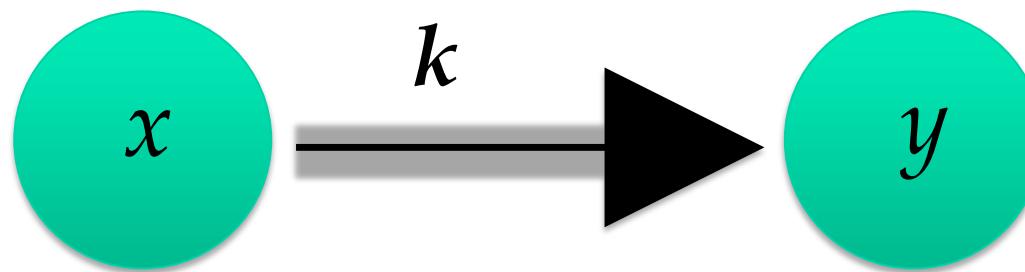
Henning Voss



Proposed a novel method to predict the response of a dynamical system based on the use of an auxiliary system.

The prediction is done in real time by anticipating the evolution of the system of interest.

Synchronization in Coupled Systems



$$\begin{aligned}\dot{x} &= f(x(t)) \\ \dot{y} &= f(y(t)) + k [x(t) - y(t)]\end{aligned}\left.\right\} \rightarrow x(t) = y(t)$$

$\Delta(t) = x(t) - y(t) = 0$ is a fixed point of the dynamics

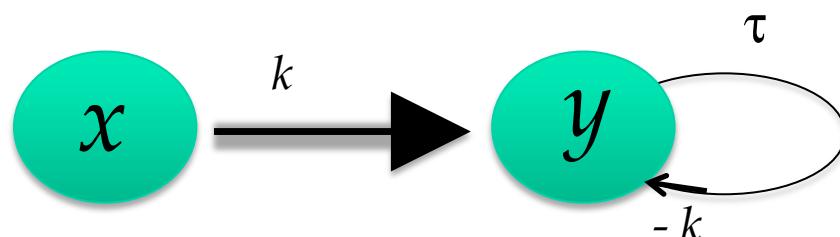
$\dot{\Delta}(t) = [f'(t) - k] \Delta(t)$ might be stable for large enough k

This is true even for chaotic systems

Anticipated Synchronization

Voss discovered a new synchronization scheme, the “Anticipated Synchronization” where the *receiver system predicts the dynamics of the sender system*. H. U. Voss, P.RE 61, 5115 (2000)

Proposed the coupling scheme:



Delayed Coupling

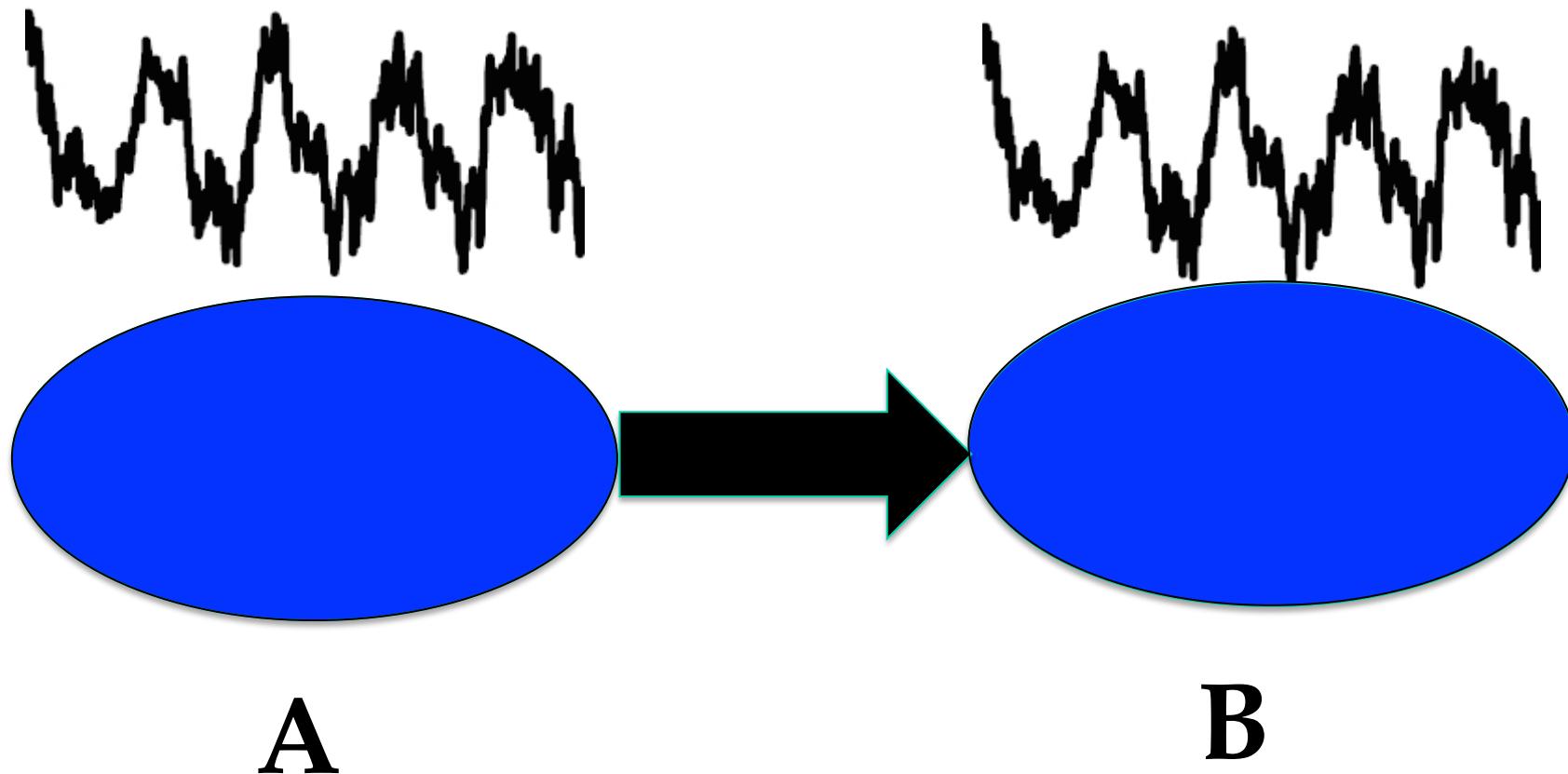
$$\dot{x}(t) = f(x(t))$$

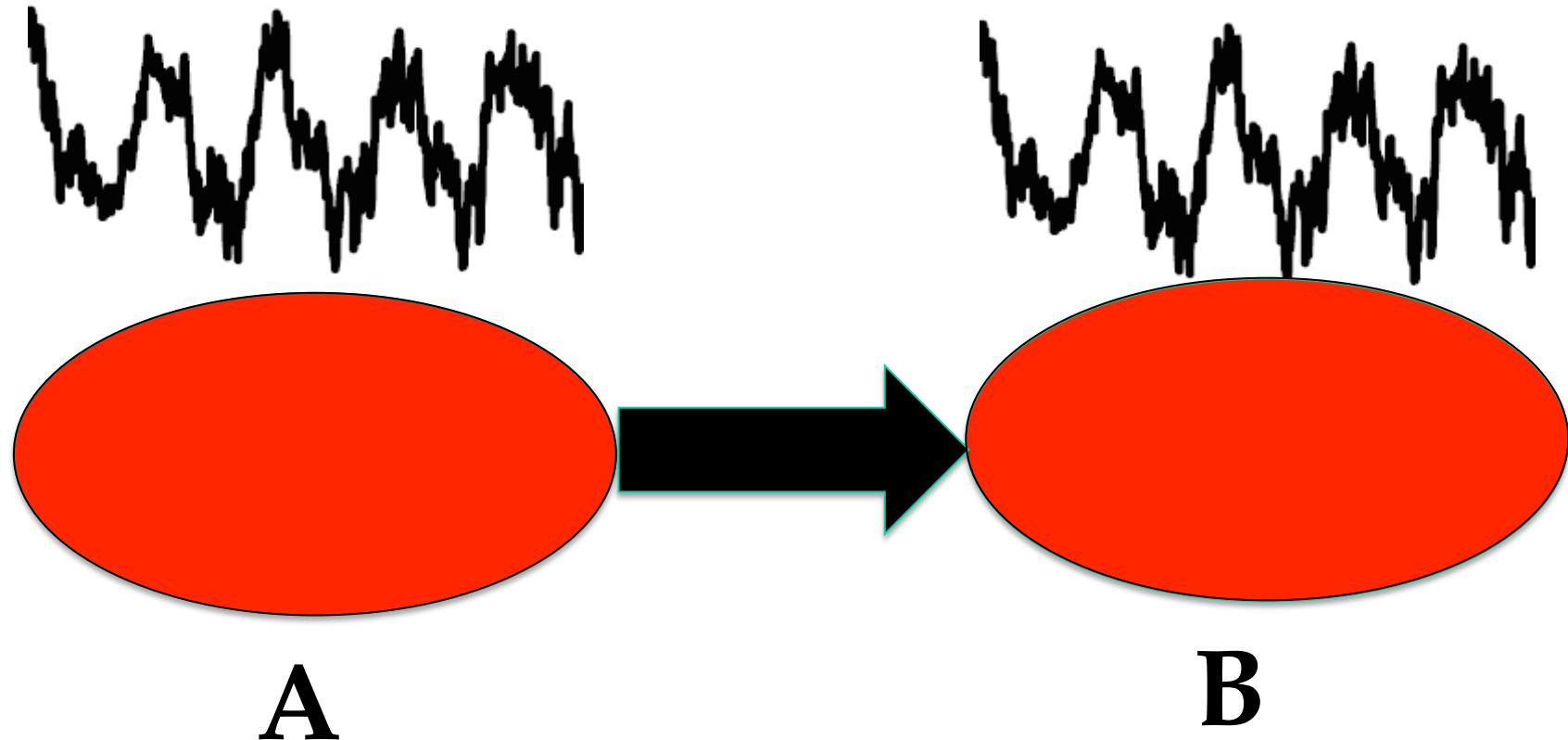
$$\dot{y}(t) = f(y(t)) + k [x(t) - y(t-\tau)]$$

✓ $f(x)$ is an autonomous function.

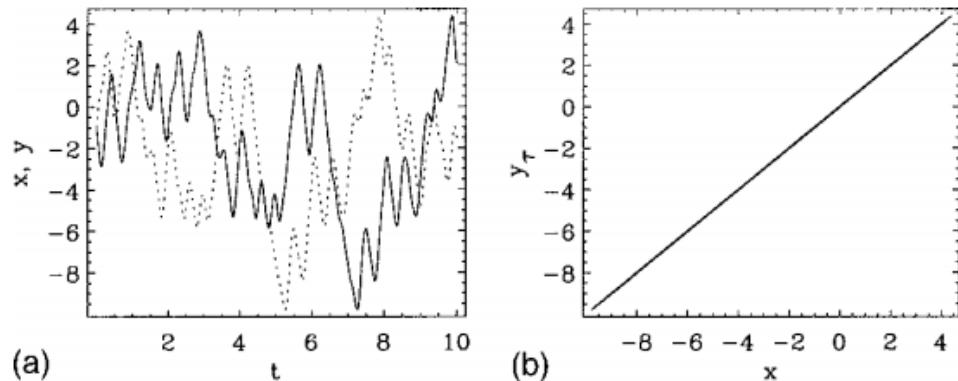
✓ $y(t) = x(t+\tau)$ is a solution of the equations that can be stable.

✓ Constraints on τ and k



**A****B**

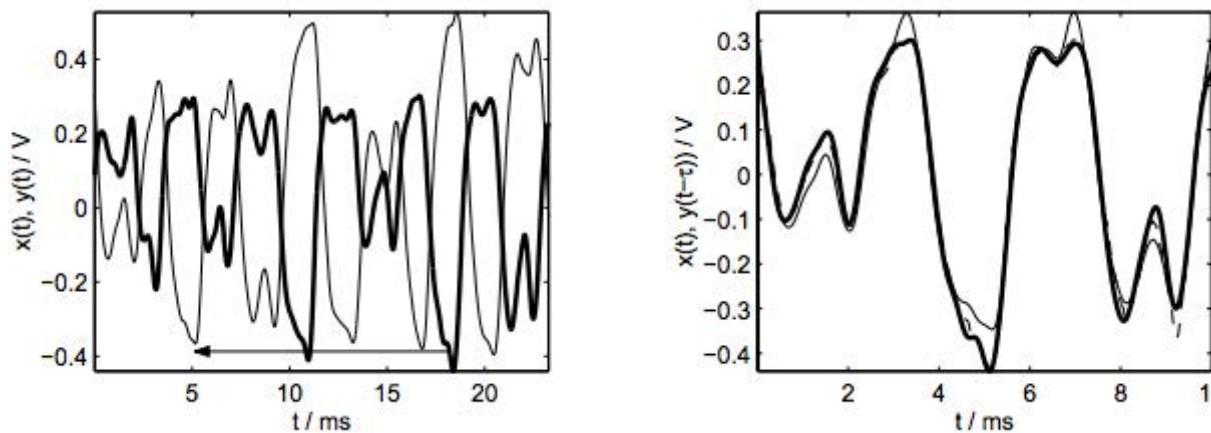
The receiving population is predicting what the emitting population is going to do in the future

**Ikeda Equations**

$$\dot{x} = -a x - b \sin(x(t-\tau))$$

$$\dot{y} = -a y - b \sin(y)$$

H.Voss, Phys. Rev. E 61, 5115 (2000)



**Electronic circuit with
a strong non-linearity**

H.Voss, Int. J. Bifurc. Chaos 12, 1619 (2002)

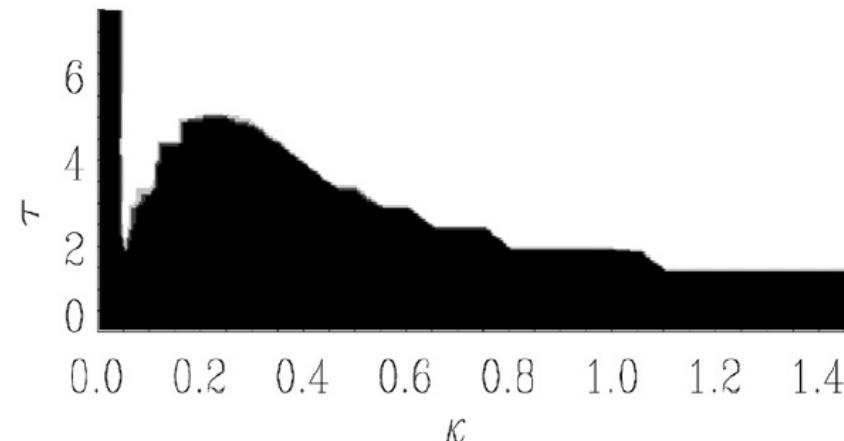
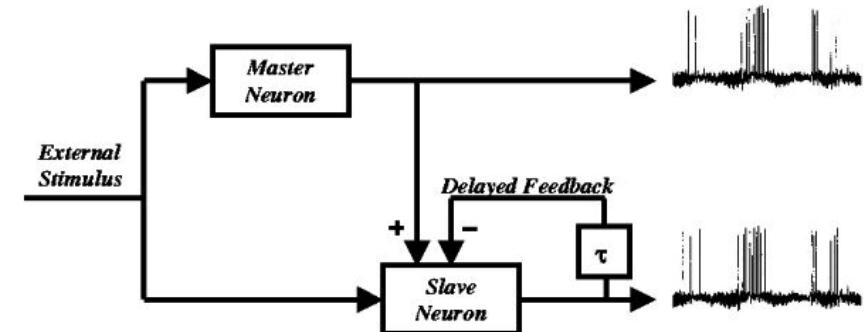
Non-autonomous Coupled Fitzhugh-Nagumo Systems

$$\dot{x}_1 = -x_1(x_1 - a)(x_1 - 1) - x_2 + I(t)$$

$$\dot{x}_2 = \epsilon(x_1 - bx_2)$$

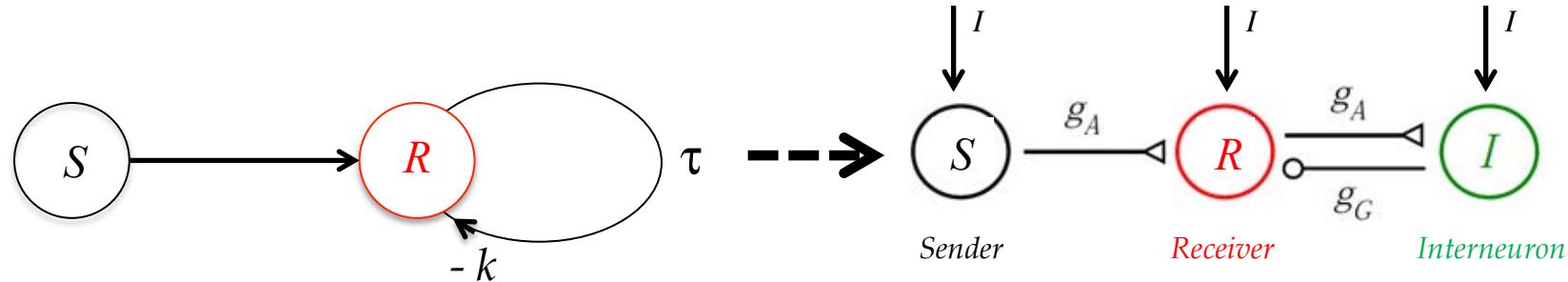
$$\begin{aligned}\dot{y}_1 &= -y_1(y_1 - a)(y_1 - 1) - y_2 + I(t) \\ &\quad + K[x_1(t) - y_1(t - \tau)]\end{aligned}$$

$$\dot{y}_2 = \epsilon(y_1 - by_2)$$



R. Toral et al., Physica A **325**, 192 (2003), M. Ciszak et al., Phys. Rev. Lett. **90**, 204102 (2003)

How do we extend Voss ideas to neuronal circuits?



Membrane potential

$$C_m \frac{dV}{dt} = \overline{G}_{Na} m^3 h (E_{Na} - V) + \overline{G}_K n^4 (E_K - V) \\ + G_m (V_{rest} - V) + I + \sum I_{syn}$$

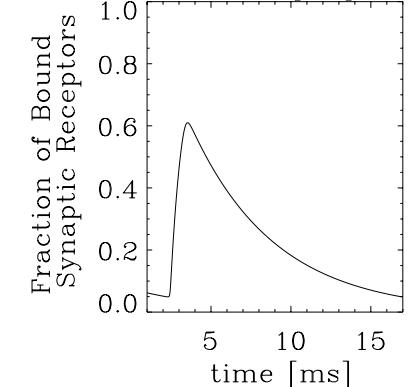
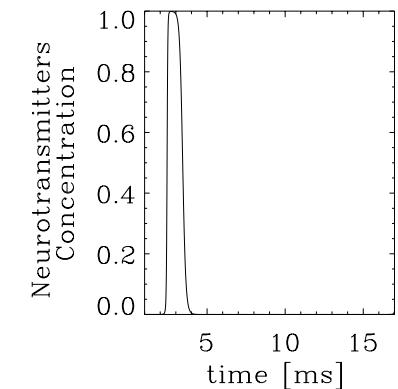
Synapsis dynamics

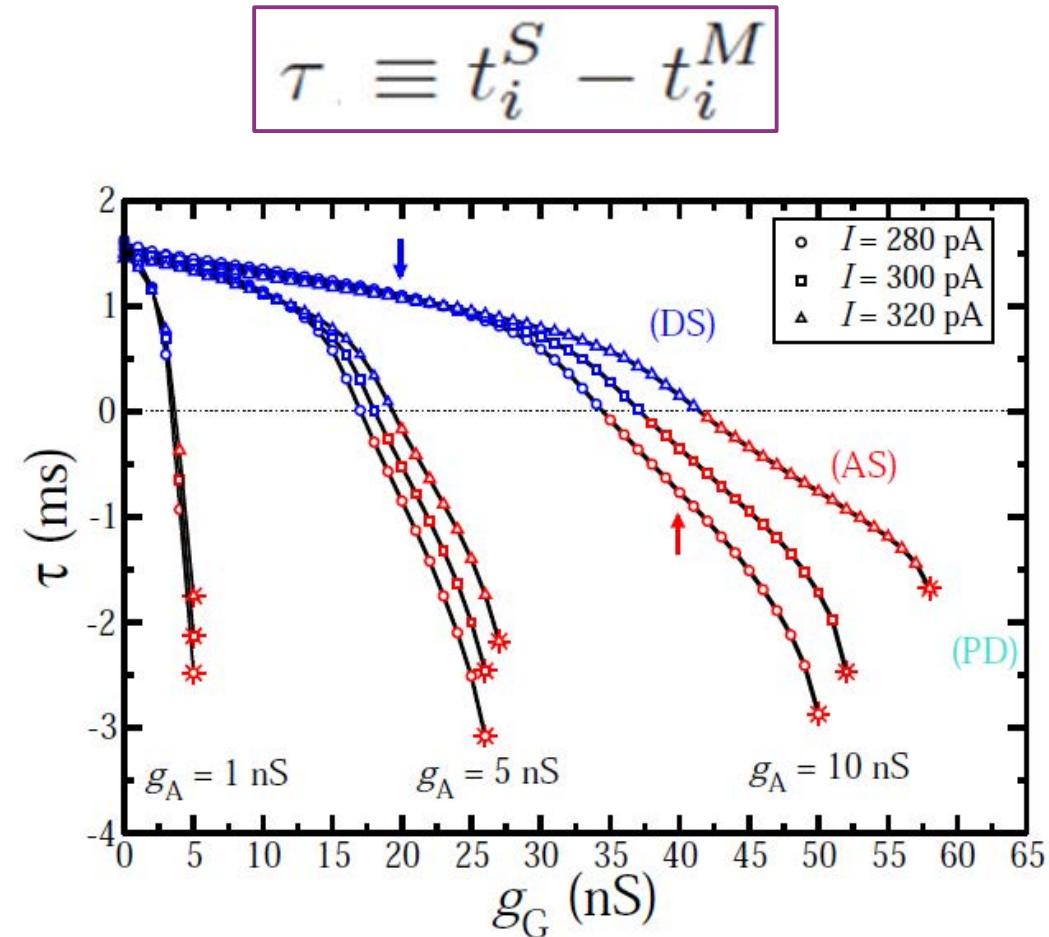
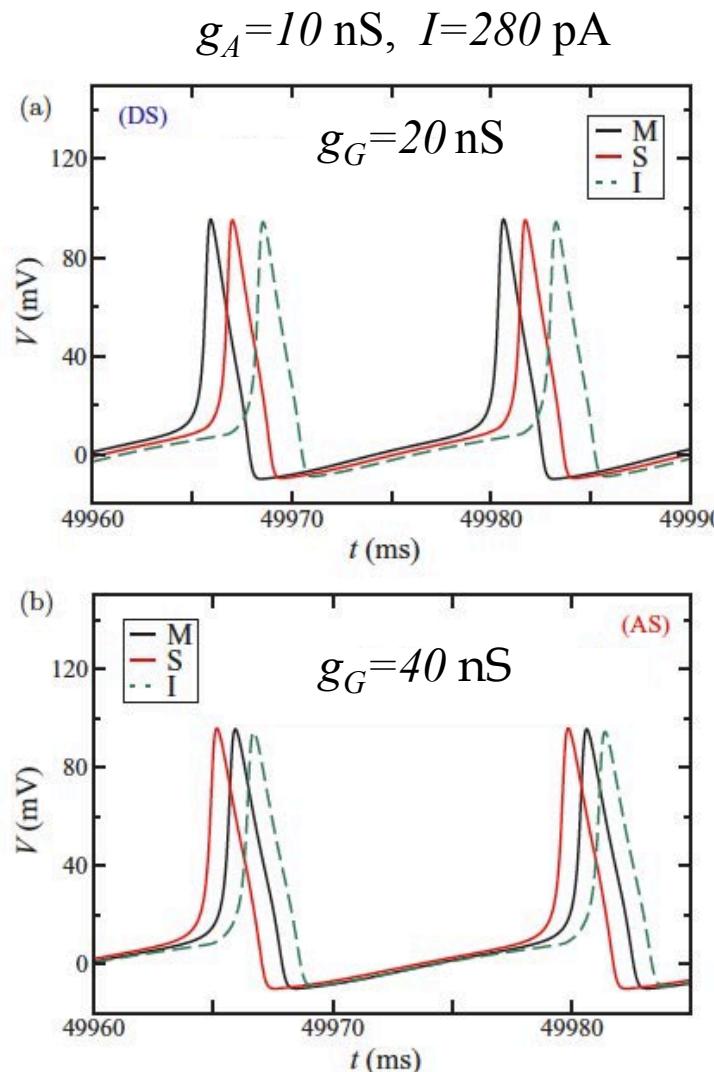
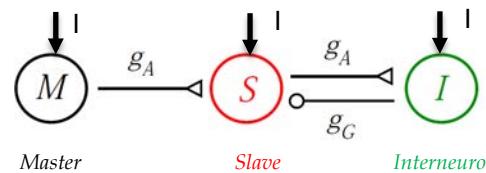
$$I^{(i)} = -g_i r^{(i)} (V - E_i)$$

$$\frac{dr^{(i)}}{dt} = \alpha_i [T] (1 - r^{(i)}) - \beta_i r^{(i)},$$

r : fraction of bound synaptic receptors

T : neurotransmitter concentration in the synaptic cleft



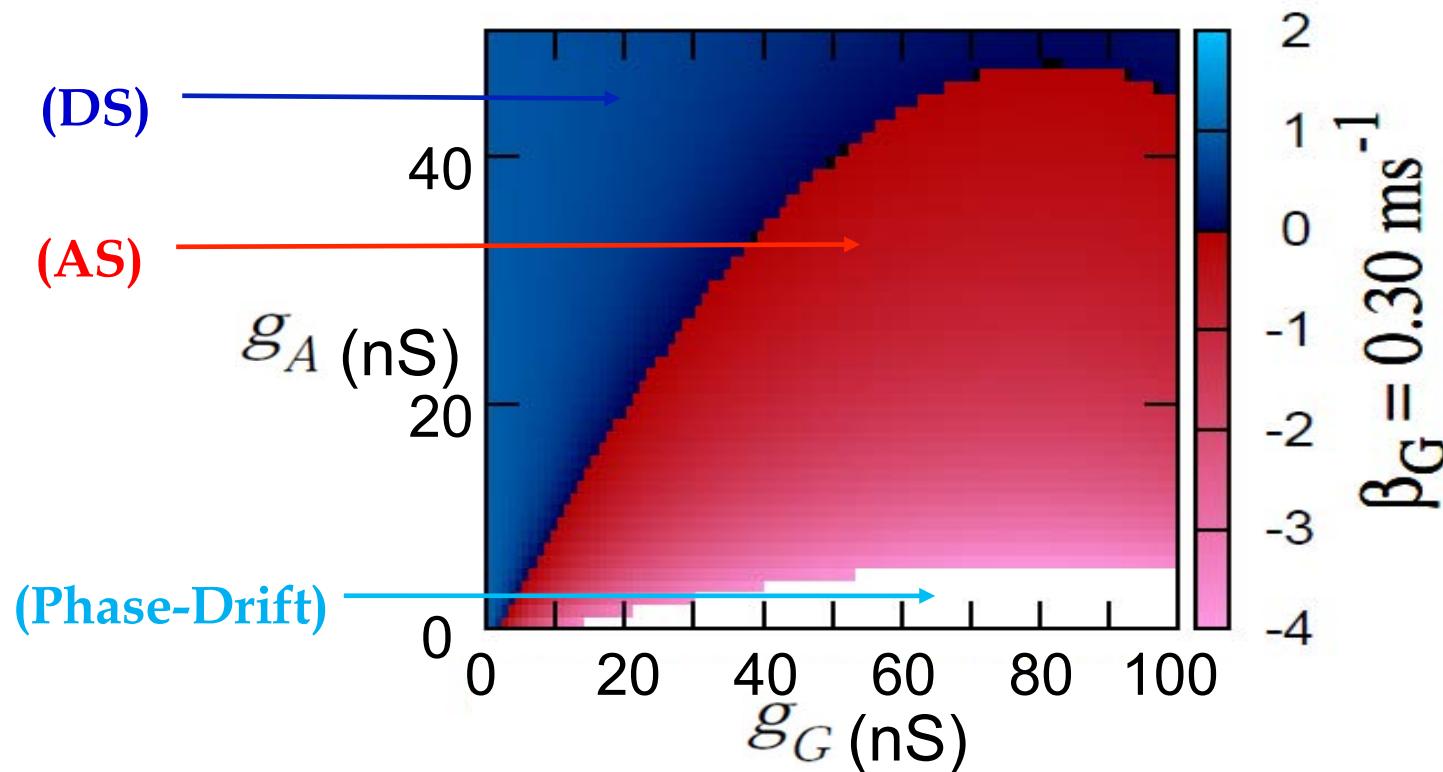


F. S. Matias, et al., Phys. Rev. E **84**, 021922 (2011)

Synchronization in the g_A vs. g_G plane

Large regions of AS and DS in the parameter space

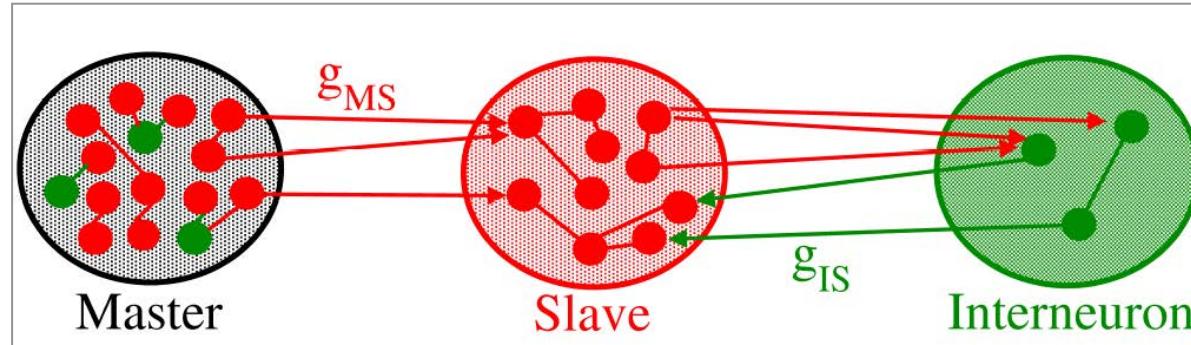
Independent of initial conditions and stable to perturbations



Robust against:
-External current
-Decay constants
of the synapse
-Driver neuron

F. S. Matias, et al., Phys. Rev. E **84**, 021922 (2011)

Neuron populations



Izhikevich
Neuron Model

$$\begin{aligned} \frac{dv}{dt} &= 0.04v^2 + 5v + 140 - u + \sum I_x \\ \frac{du}{dt} &= a(bv - u). \quad v \geq 30\text{mV} \end{aligned} \quad \begin{array}{c} v \longrightarrow c \\ u \longrightarrow u+d \end{array}$$

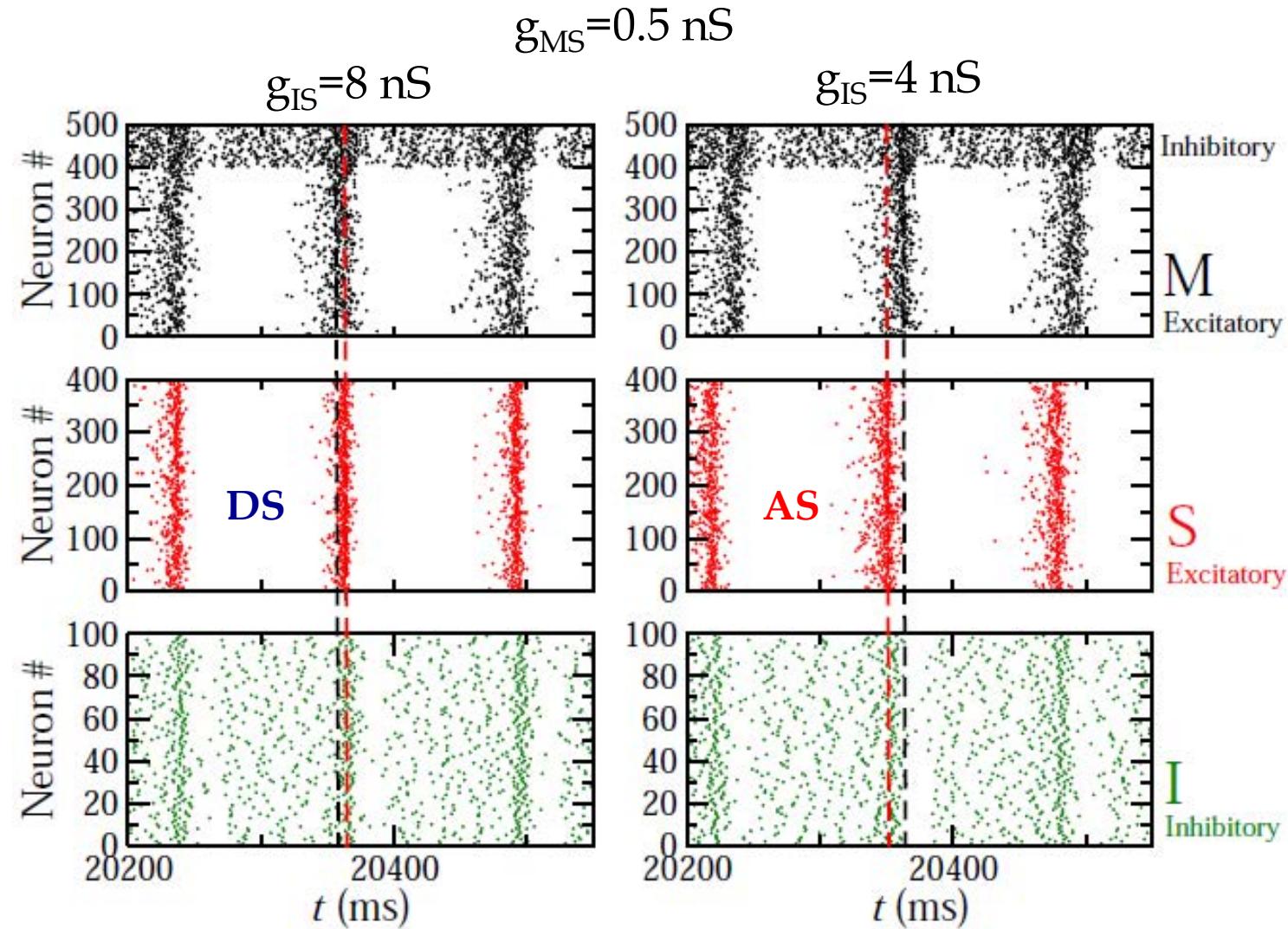
Synapses mediated by
AMPA and GABA_A

Short-range interactions:
excitatory and inhibitory
Long-range interactions: excitatory

Include neuronal diversity

Each neuron receives an
independent Poisson input

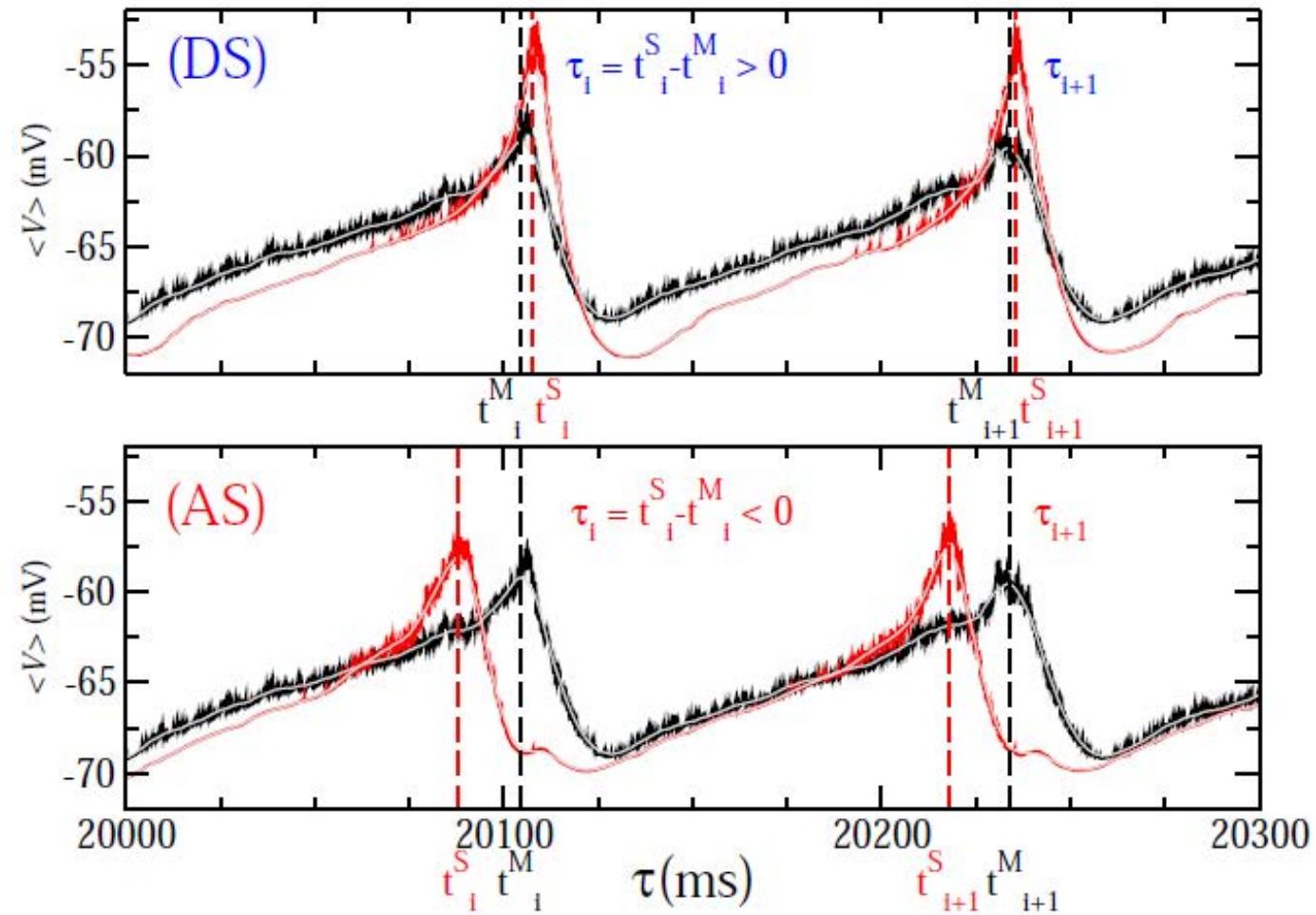
Raster plots



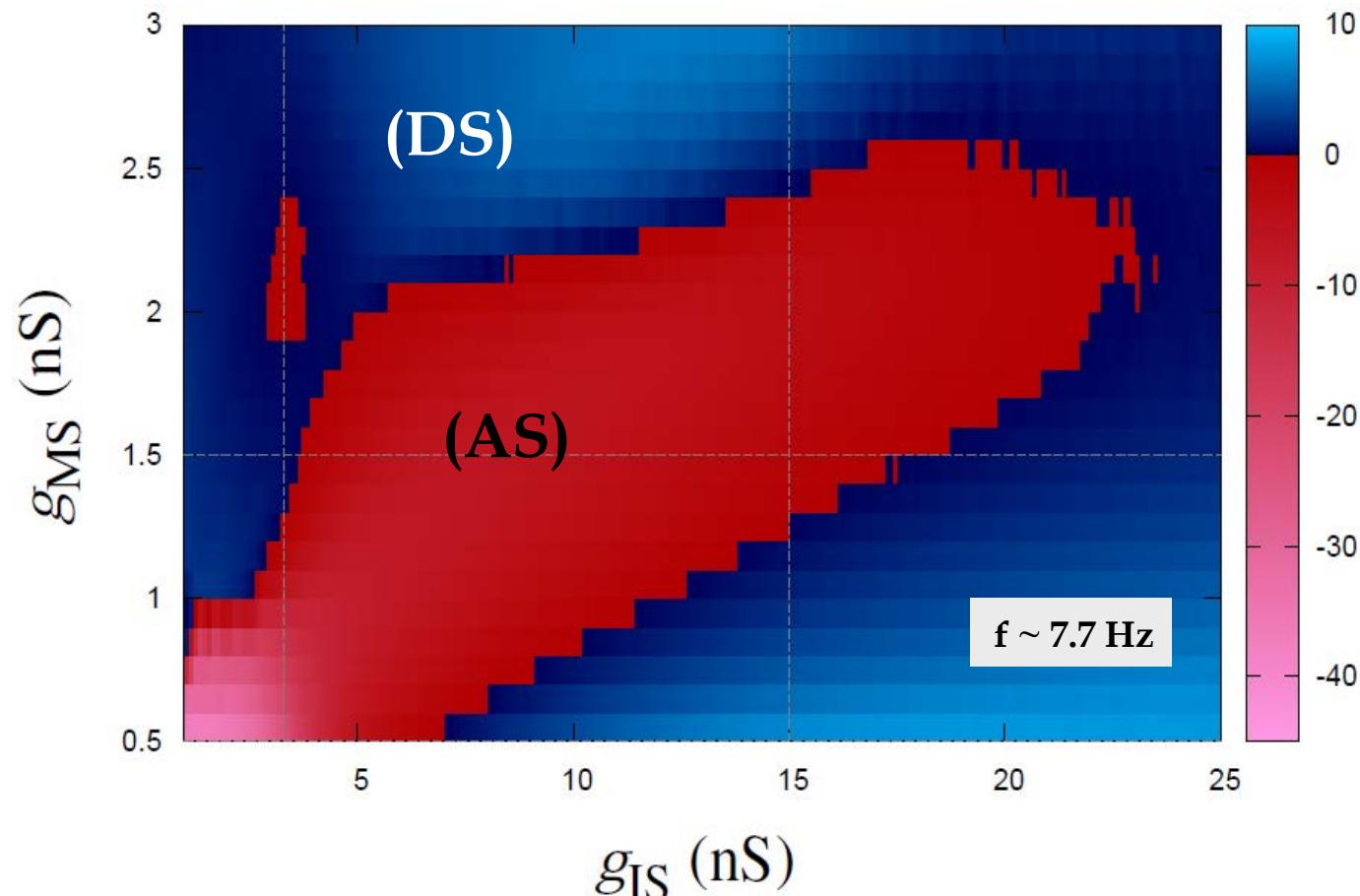
Mean Membrane Potential (LFP)

$$T_i^x \equiv t_{i+1}^x - t_i^x$$

$$\tau_i \equiv t_i^S - t_i^M$$



Mean Period $T = 130$ ms ($f = 7.7$ Hz)



Is there Experimental Evidence of AS?

Beta oscillations in a large-scale sensorimotor cortical network: Directional influences revealed by Granger causality

Andrea Brovelli*, Mingzhou Ding*, Anders Ledberg*, Yonghong Chen*, Richard Nakamura†, and Steven L. Bressler*‡

PNAS | June 29, 2004 | vol. 101 | no. 26 | 9849–9854

**Content-Specific Fronto-Parietal
Synchronization During Visual
Working Memory**

R. F. Salazar,¹ N. M. Dotson,¹ S. L. Bressler,² C. M. Gray^{1*}

SCIENCE VOL 338 23 NOVEMBER 2012 1097

Coherence (and Activation time) & Granger Causality

Coherence: The coherence function gives the linear correlation between two signals as a function of the frequency.

Activation time: it is estimated from the coherence spectrum as:

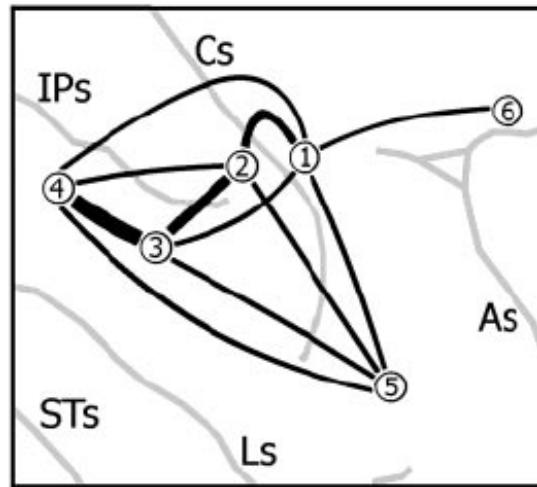
$$\tau_{lk} = \phi_{lk}(f_{peak})/(2\pi f_{peak})$$
$$\phi_{lk}(f) = \tan^{-1}[\text{Im}(S_{lk})/\text{Re}(S_{lk})]$$

Granger Causality: if a signal X is influencing Y, then adding past values of the first variable to the regression of the second one will improve its prediction performance.

Experimental Results: Coherence (and Time Delay) vs Granger Causality

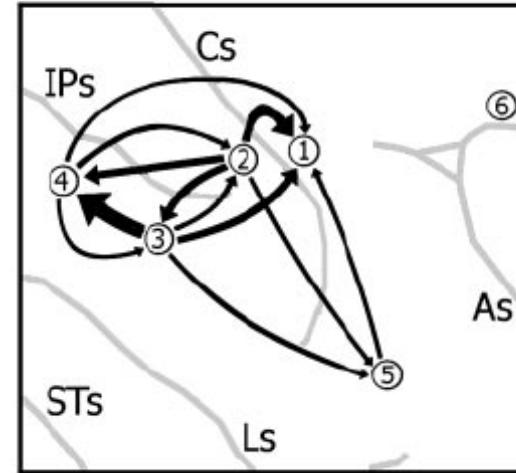
1- Primary motor site

Coherence Graph



2, 3 and 4 postcentral sites

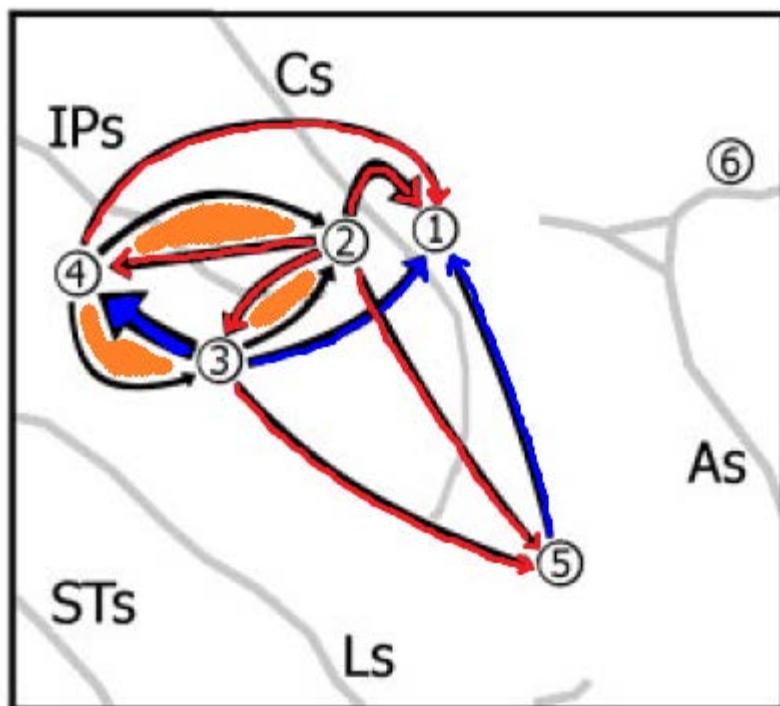
Granger Causality Graph



"positive" Granger causality was found with **negative** delay times

Granger causality relations were generally inconsistent with time delay values derived from phase spectra because the sign of the time delay did not predict the direction of Granger causality:
relative phase is not a reliable index of neural influence

Granger Causality Graph



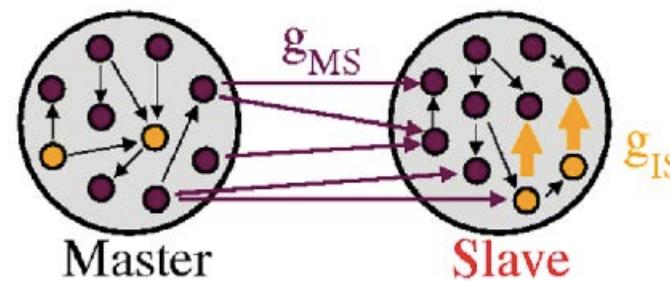
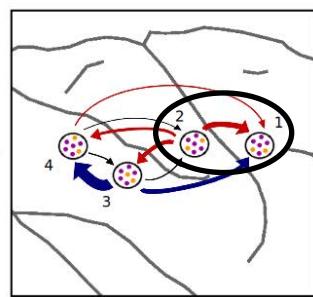
Granger causality and phase difference have different directions

(AS)

Granger causality and phase difference have the same direction

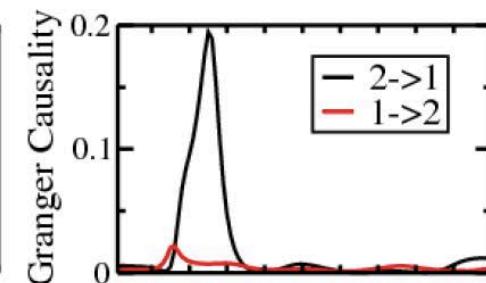
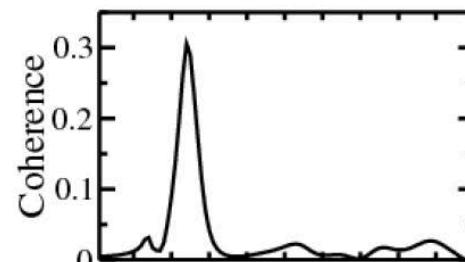
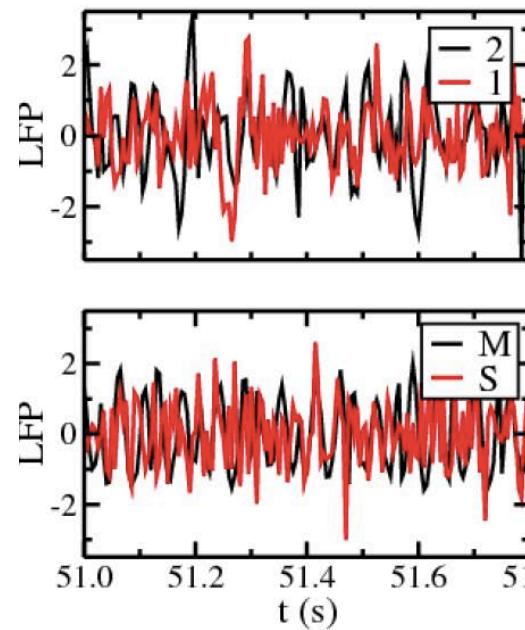
(DS)

Granger causality is bidirectional but stronger in one direction



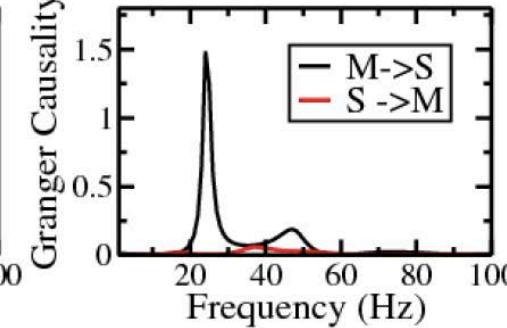
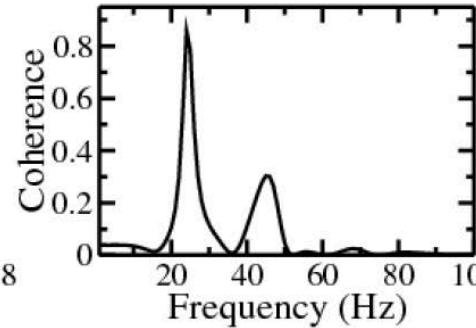
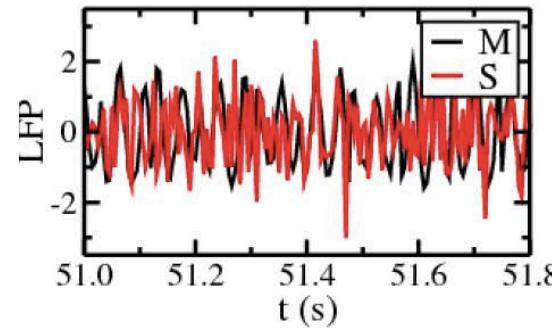
Site 2 Granger causes site 1

Data



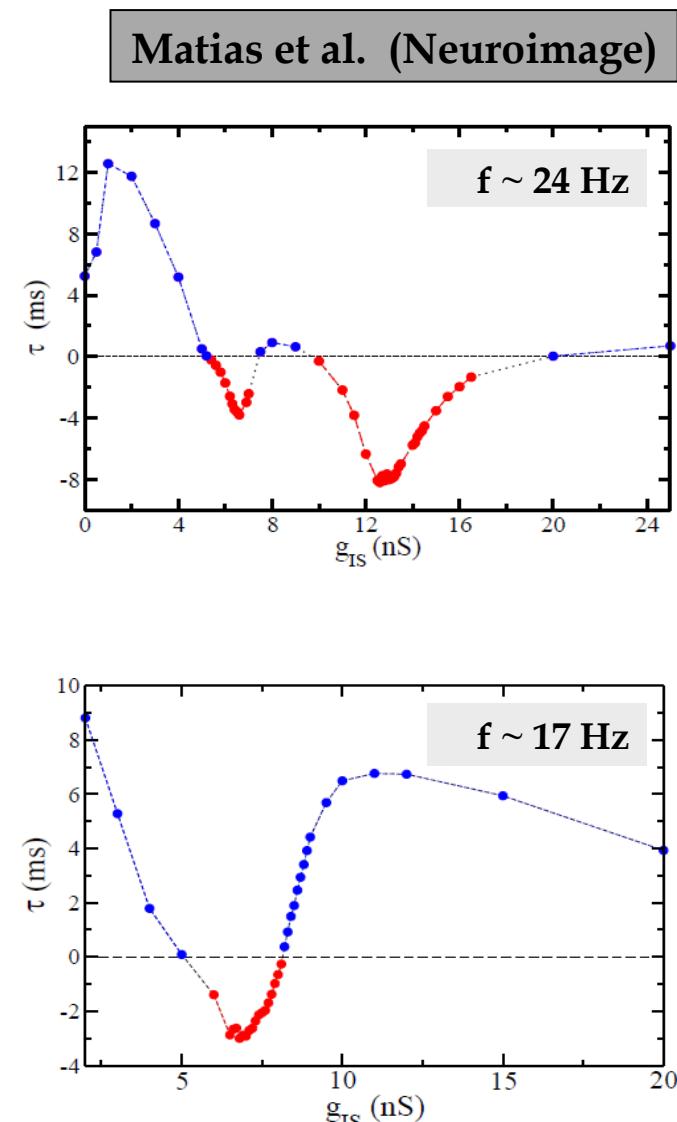
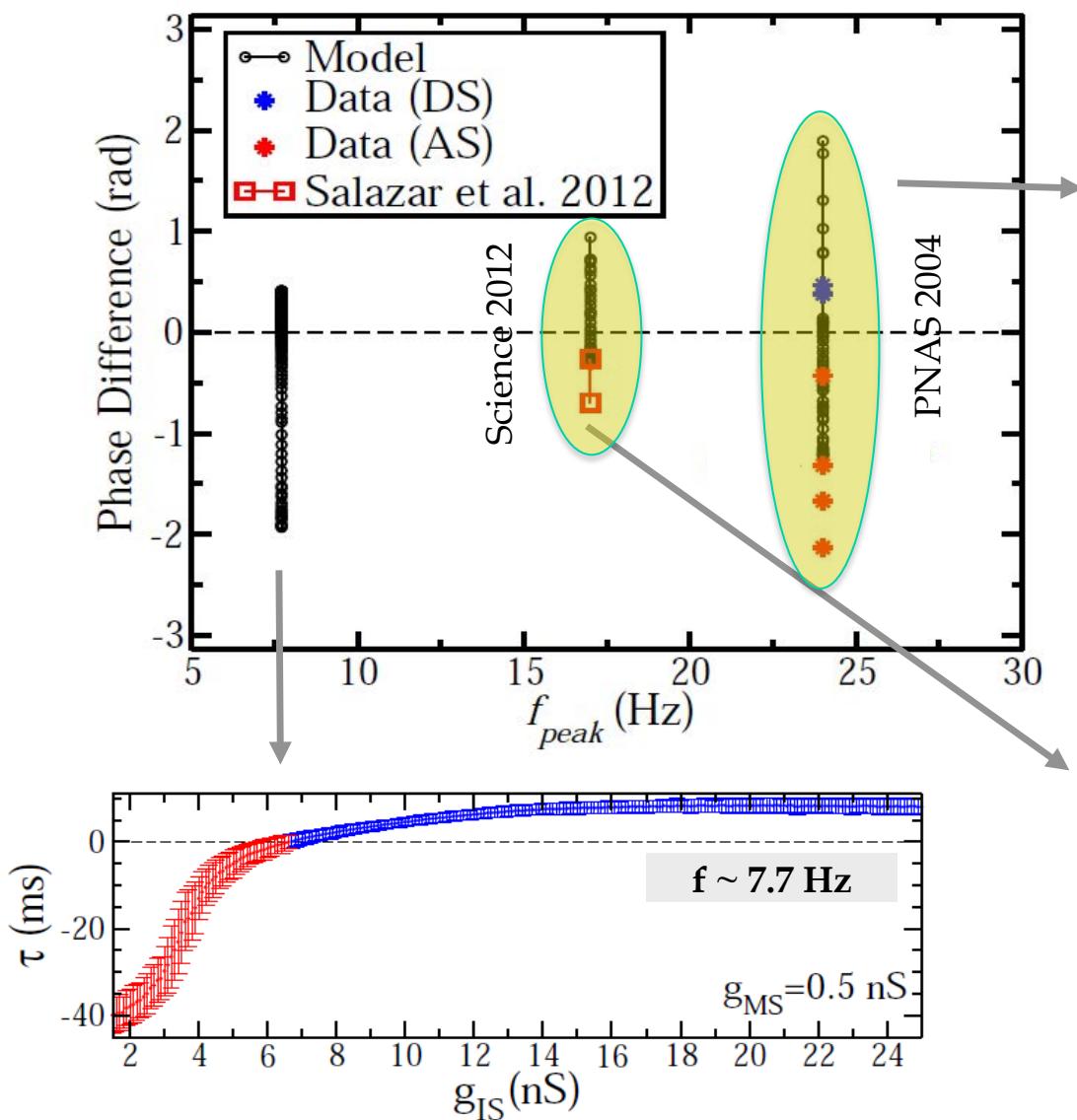
$$\tau = -8.7 \text{ ms}$$

Simulations



$$\tau = -8.2 \text{ ms}$$

Matias et al., NeuroImage **99**, 411 (2014)



Conclusions

- ✓ A neuronal circuits of excitatory and inhibitory neurons gives rise to anticipated synchronization, even in the absence of an explicit delay loop.
- ✓ the interplay between excitation and inhibition regulates the transition between DS and AS.
- ✓ Experimental observations of negative delay with “positive” Granger causality has been experimentally observed in monkeys and reproduced with the model. A similar effect has been observed in the cat primary visual cortex (not shown)
- ✓ Besides the reduction of information transmission time, any other functional role of AS is not clear yet.

Summary

- ✓ Mesoscopic models allow us to tackle dynamical aspects of neuronal circuits.
- ✓ A large variety of neuronal models and synapsis types can be incorporated quite straightforwardly.
- ✓ They have the advantage of being (quite) simple with not many parameters to fit, although results can only be compared (in general) qualitatively with experiments.
- ✓ They are easy to implement and run fast in nowadays computers.
- ✓ Can be considered quite simple or more complicated depending on the level of description we want to incorporate.

Pre- & Post-doc Positions available

IFISC is opening a call for Ph.D. positions (3 years) and junior postdoc positions (2 years) in

Information processing in and by complex systems.

Main research topics include

- Information processing in biological systems
- Brain-inspired computing (photonic & electronic)
- Quantum information
- Information processing in socio-technical systems

Selection process: August/September 2019

More information at:

<https://ifisc.uib-CSIC.es/en/about-ifisc/join-us/>



THANK YOU

for your attention