Anticipated synchronization in neuronal populations: Reconciling information directionality with negative time lag

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Motivation

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

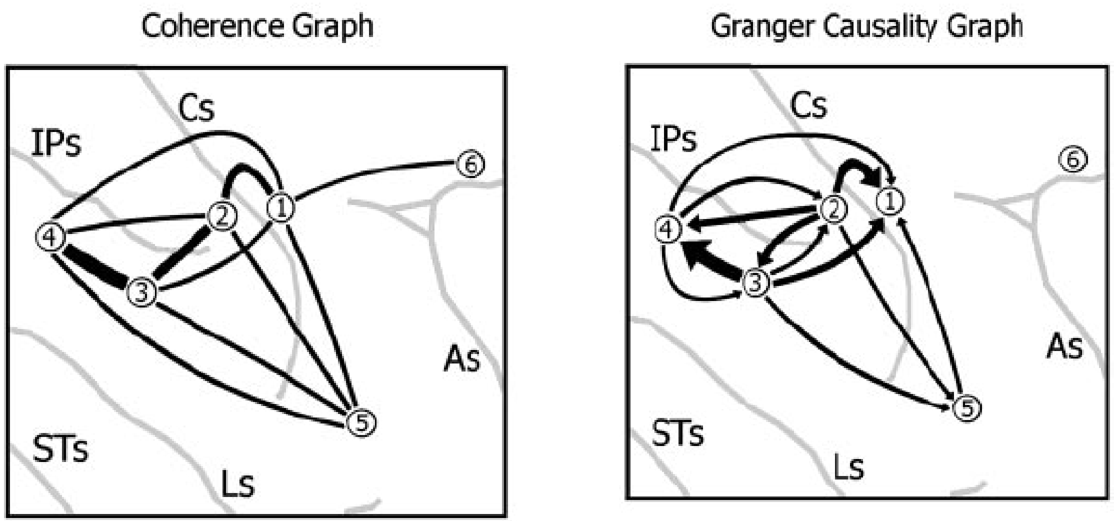
Content-Specific Fronto-Parietal Synchronization During Visual Working Memory

R. F. Salazar,[1] N. M. Dotson,[1] S. L. Bressler,[2] C. M. Gray[1]*

SCIENCE VOL 338 23 NOVEMBER 2012 1097

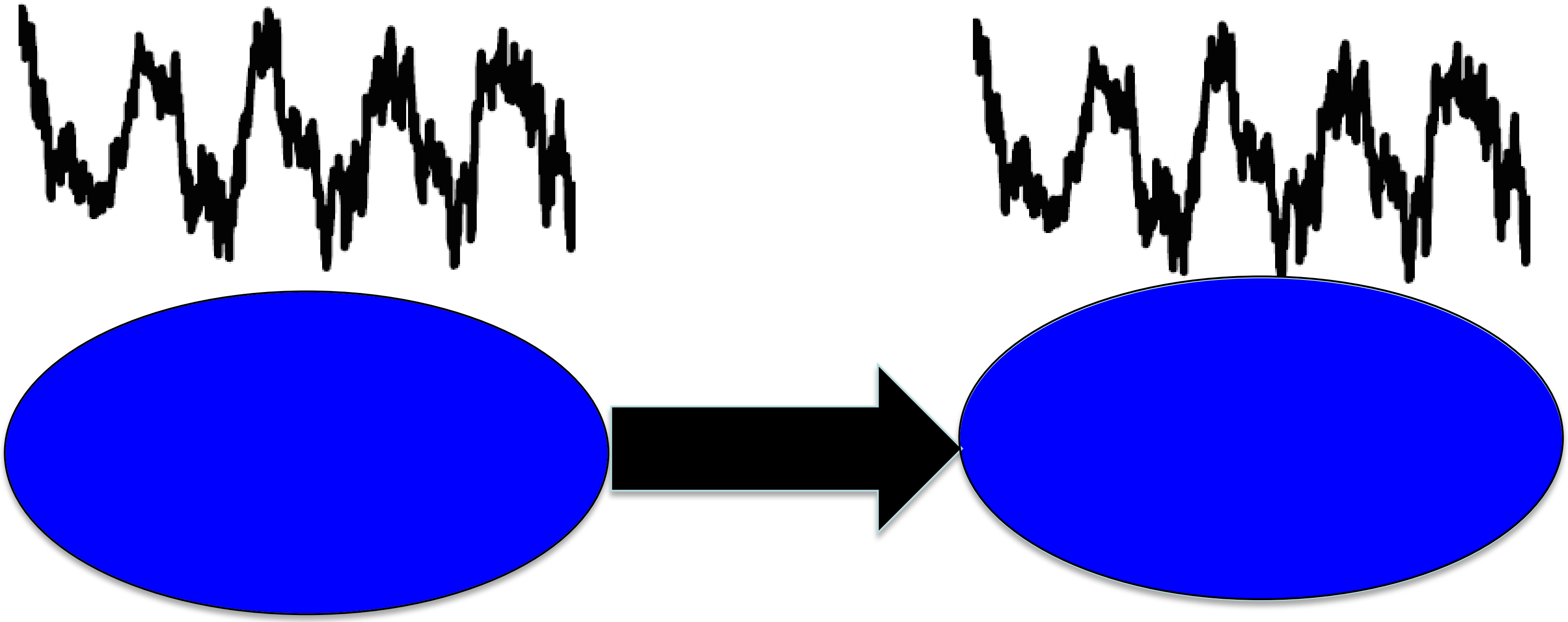
PNAS: Functional relations of the synchronization, in the beta band, of neuronal assemblies in pre- and post-central areas of monkeys.

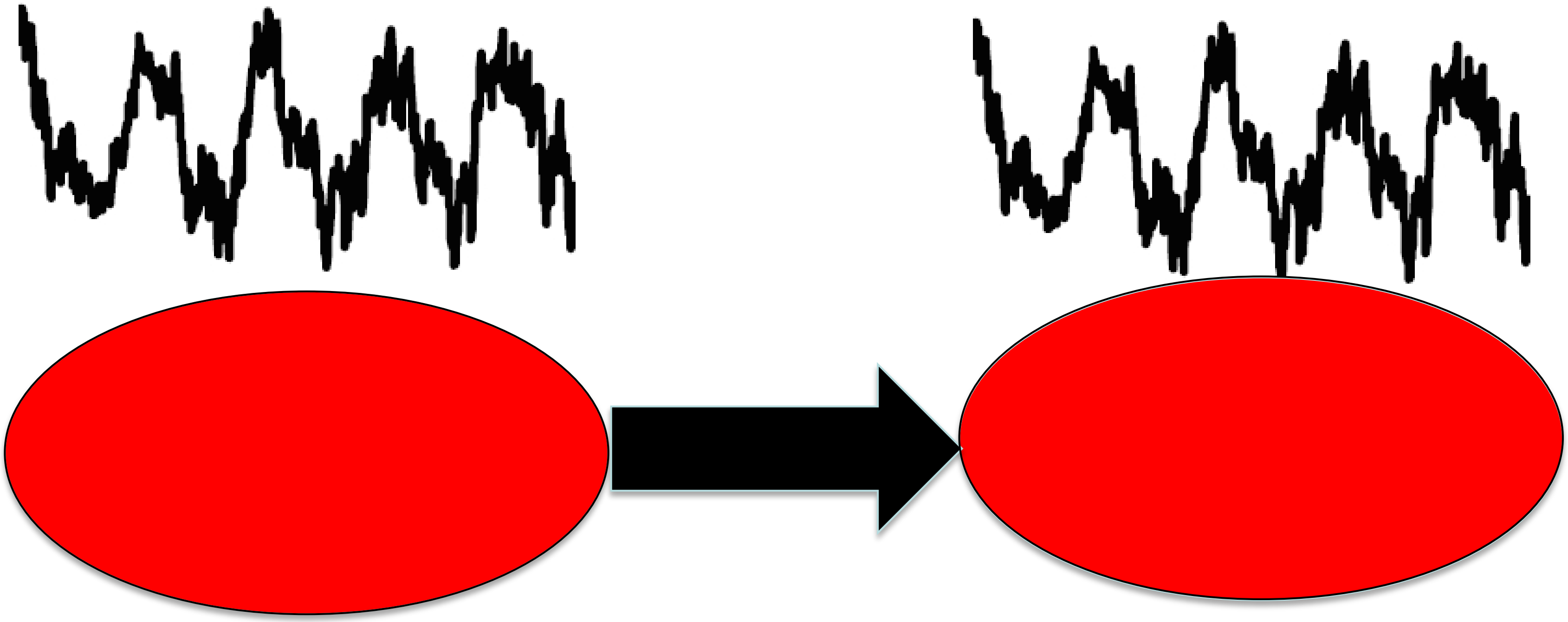
Power and coherence spectral analyses of cortical LFPs as well as Granger causality were measured.



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

Granger causality relations were generally inconsistent with time delay values: the sign of the time delay did not predict the direction of GC: **"relative phase is not a reliable index of neural influence"**





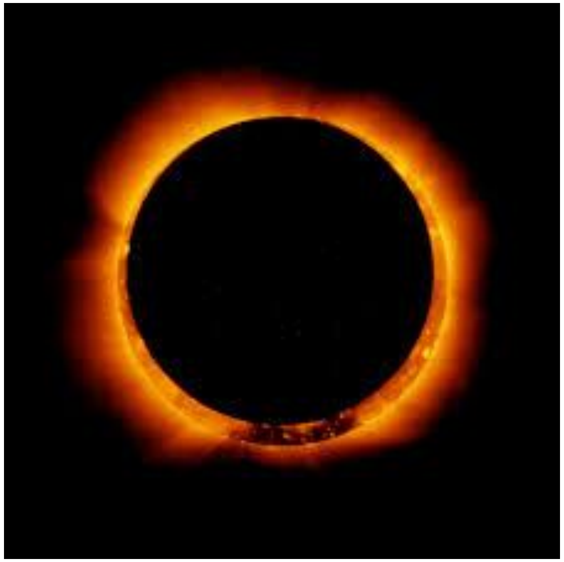
The receiving population is predicting what the emitting population is going to do in the future

Can we predict or anticipate the future?

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

$$\frac{dx}{dt} = F(x, t),$$

of course ***YES!***



Next Total Eclipse: March 20th, 2015

Will be visible in Iceland, Europe, North Africa and Northern Asia

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

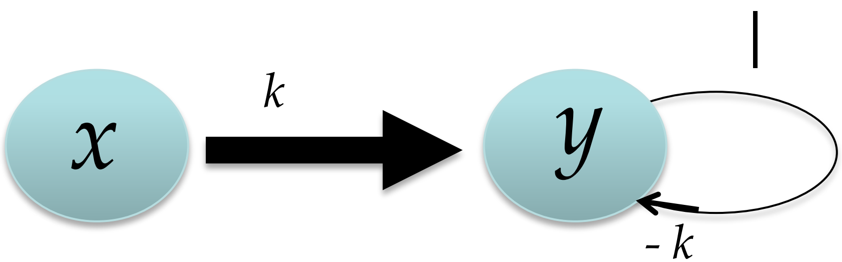
Proposed a novel method to predict the response of a dynamical system based on the use of an auxiliary system.

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

Anticipated Synchronization

Voss discovered a new synchronization scheme, the ***"Anticipated Synchronization" where the*** *slave system predicts the dynamics of the master system.* H. U. Voss, P.RE **61**, 5115 (2000)

One of the proposed schemes:



Delayed Coupling

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

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

- ✓ *y(t) = x(t+ □) is a solution*
- ✓ *Stable for certain values of □ and □*
- ✓ *AS observed in electronic circuits, lasers, oscillators, and other systems*

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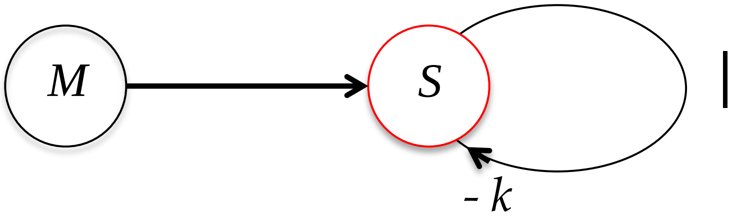
Can we translate the idea to neuronal circuits?



Hodgkin-Huxley Neuron Model

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

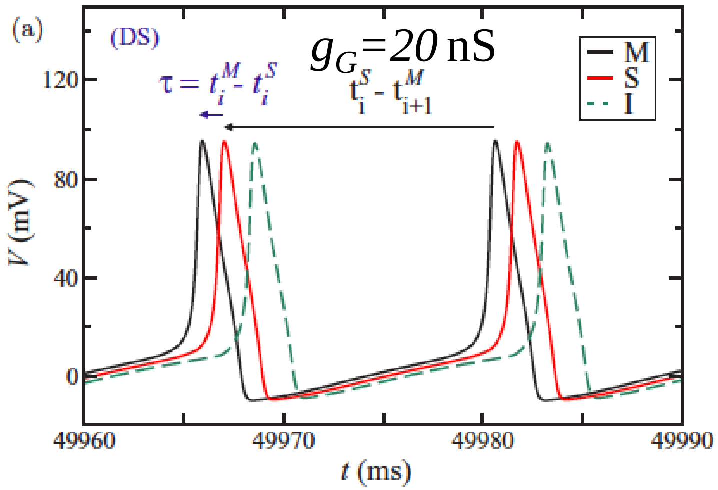
$$\frac{dr^{(i)}}{dt} = \alpha_i [T](1 - r^{(i)}) - \beta_i r^{(i)}$$

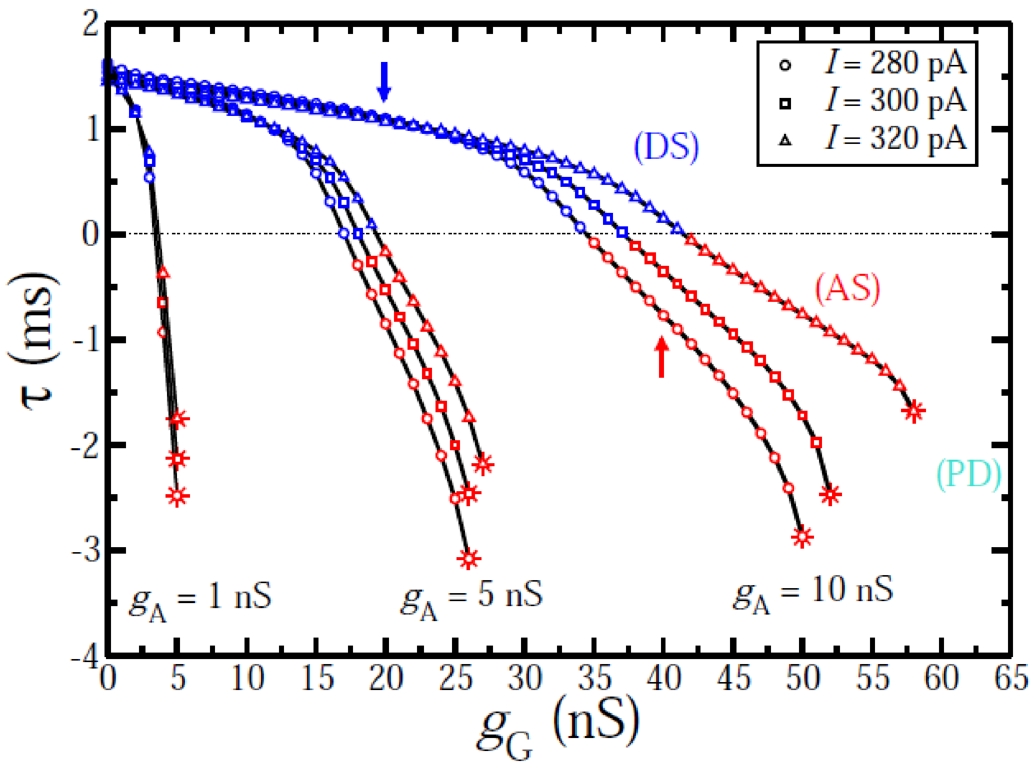
r: fraction of bound synaptic receptors

T: neurotransmitter concentration in the synaptic cleft

3 coupled neurons

g_A=*10* nS, *I*=*280* pA



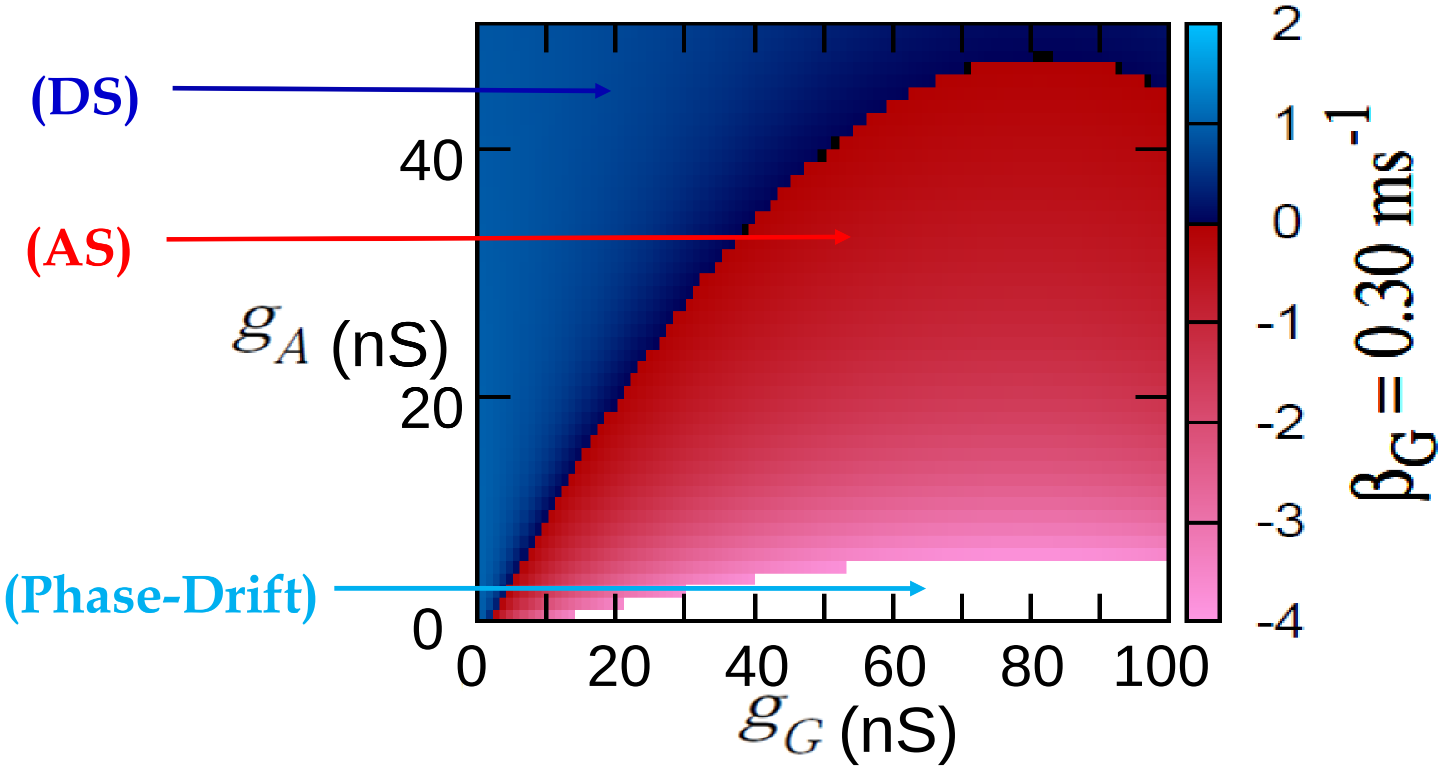


F. S. Matias, et al., Phys. Rev. E **84**, 021922 (2011)

Time Delay 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:

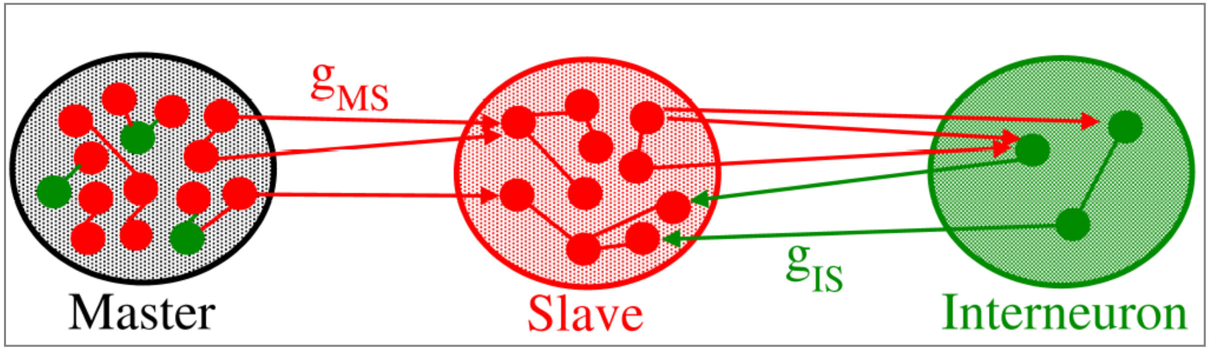
-External current

-Decay constants of the synapse

-Driver neuron

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

AS in neuronal populations



Izhikevich Neuron Model

$$\frac{dv}{dt} = 0.04v^2 + 5v + 140 - u + \sum I_x$$

$$\frac{du}{dt} = a(bv - u) \qquad v \geq 30\text{mV} \quad \begin{matrix} v \longrightarrow c \\ u \longrightarrow u+d \end{matrix}$$

Synapses mediated by AMPA and $GABA_A$

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

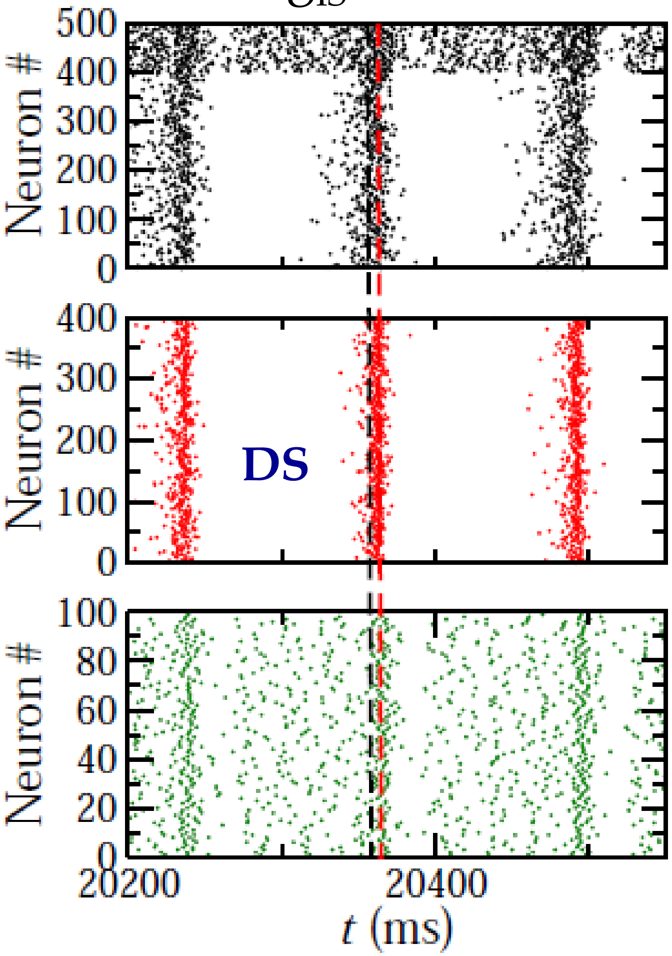
Include neuronal diversity

Each neuron receives an independent Poisson input

Raster plots

g_{MS}=0.5 nS

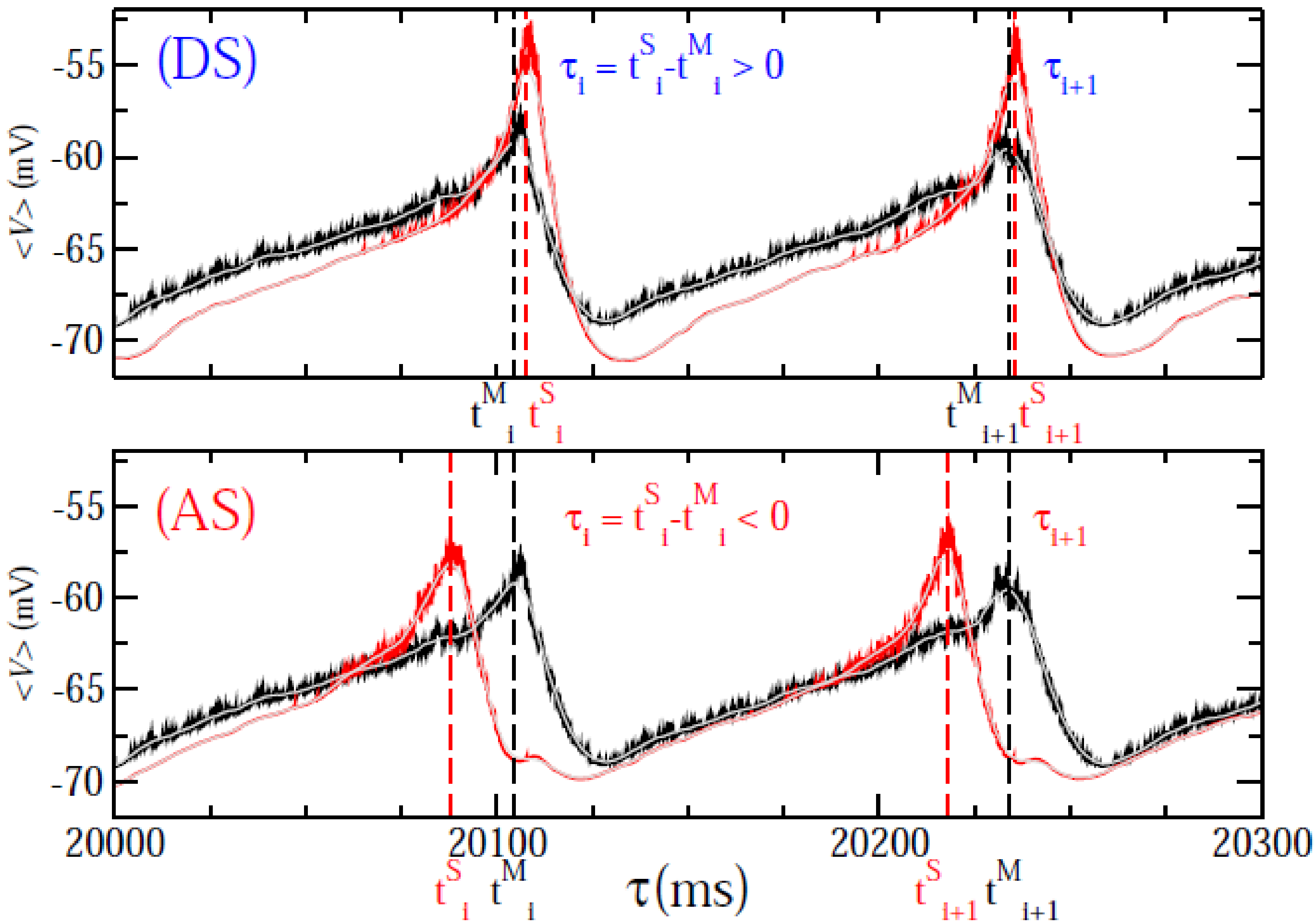
g_{IS}=8 nS



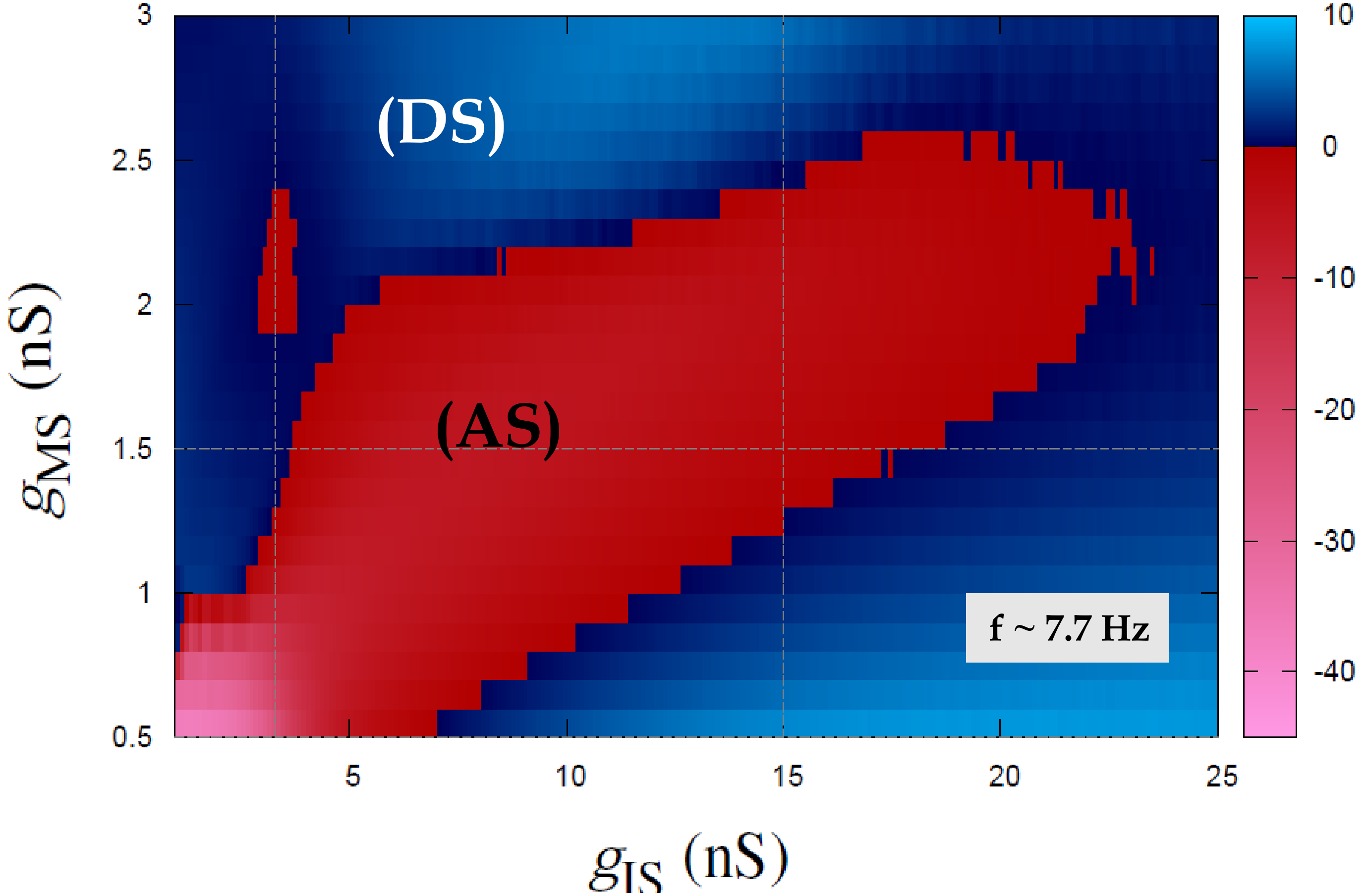
Mean Membrane Potential (LFP)

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

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



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


(DS)
(AS)
f ~ 7.7 Hz
g_{MS} (nS)
g_{IS} (nS)
3
2.5
2
1.5
1
0.5
5
10
15
20
25
10
0
-10
-20
-30
-40

Experimental Evidence?

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

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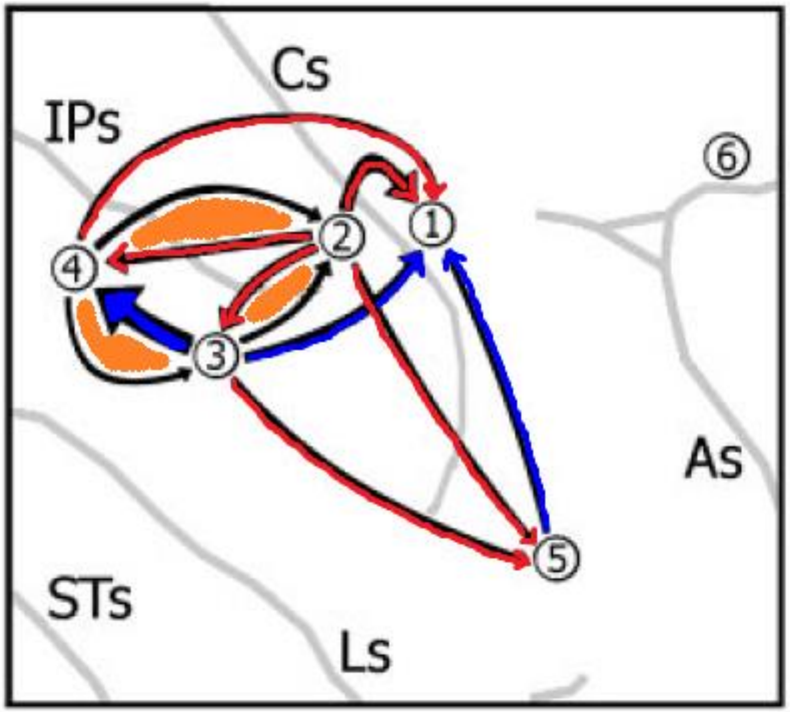
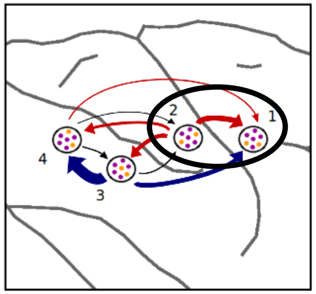
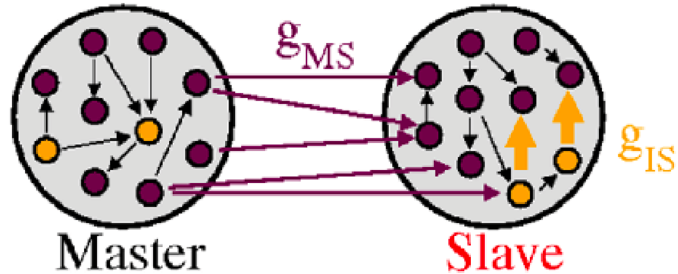
Experimental Results:
Coherence (and Time Delay) vs Granger Causality

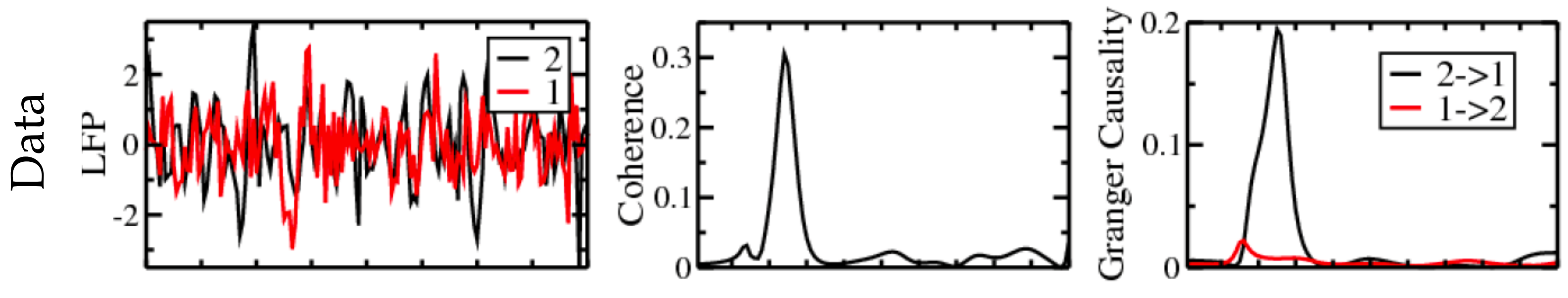
Granger Causality Graph







Site 2 Granger causes site 1

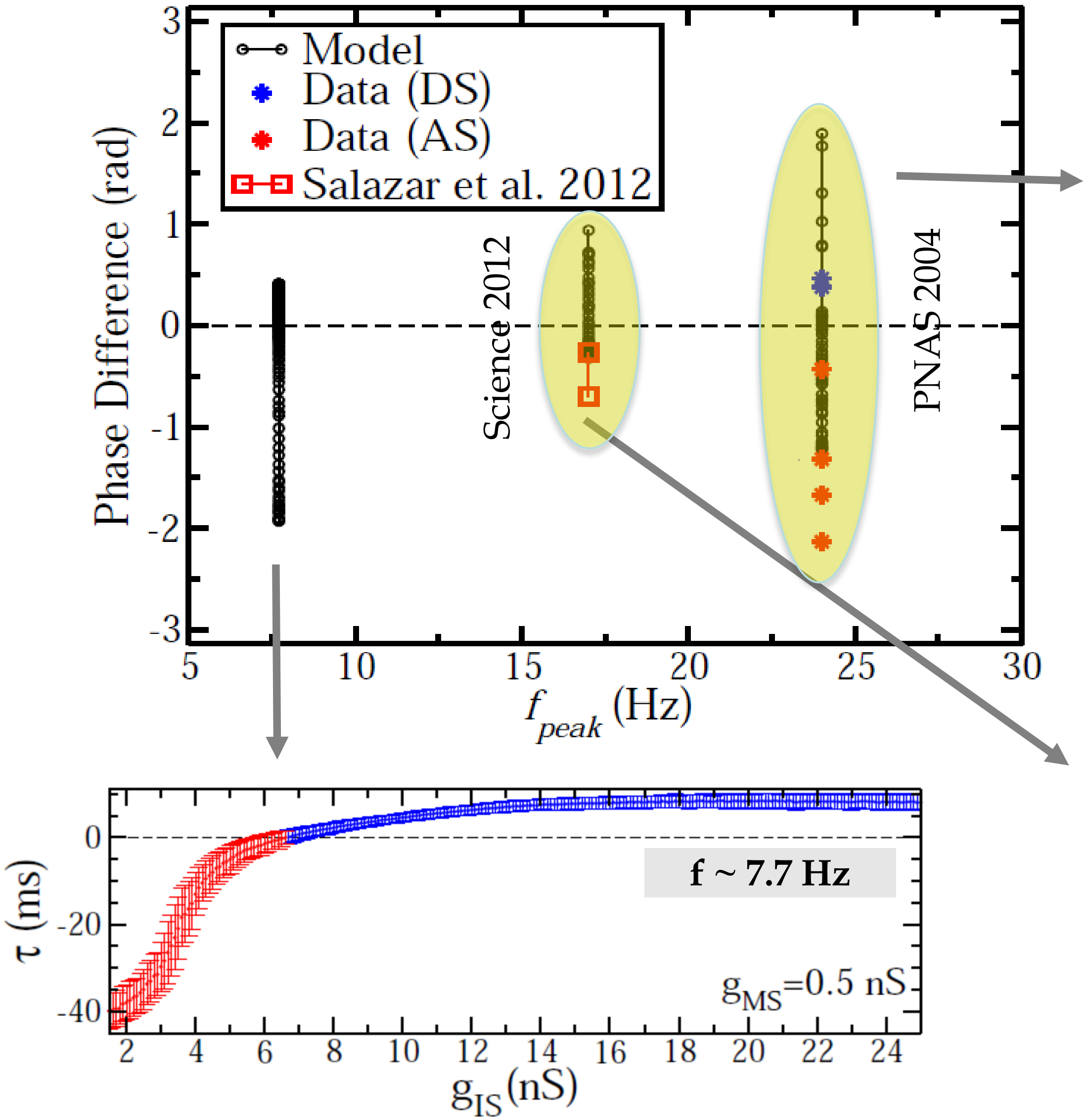


| = -8,7 ms

Matias et al., Neuroimage 2014

DOI information: 10.1016/j.neuroimage.2014.05.063

Matias et al. (Neuroimage)

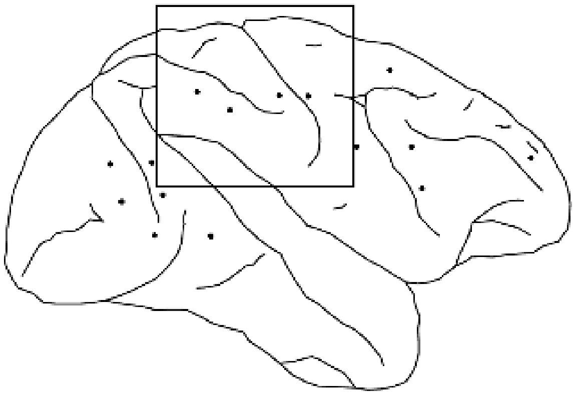


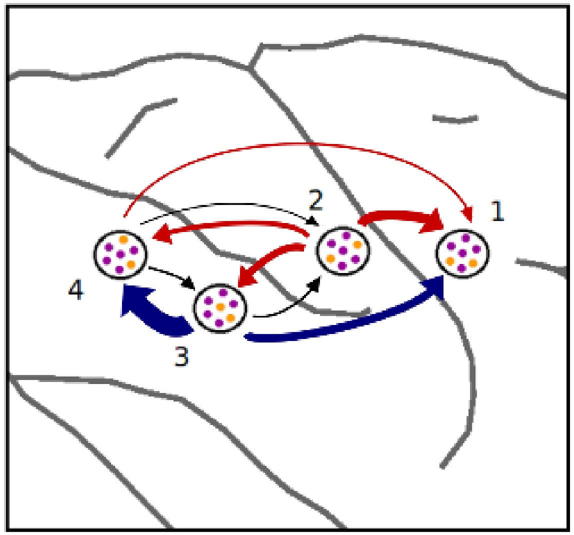
Summary & Conclusions

- ✓ A neuronal circuits of excitatory and inhibitory neurons gives rise to anticipated synchronization, even in the absence of an explicit delay loop.
- ✓ the strength of the 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.
- ✓ Besides the reduction of information transmission time, any other functional role of AS is not clear yet.

Thanks for your attention

DATA





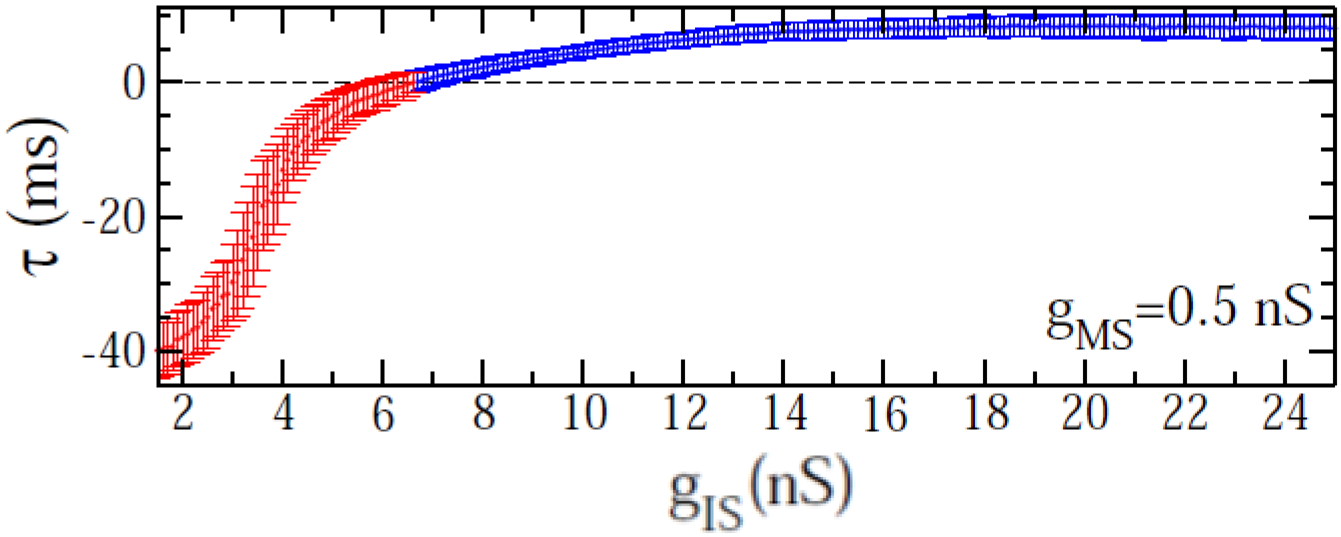
sample rate 200 Hz (5 ms)

1) Motor
2) Somatosensory
3) Posterior parietal
4) Parietal

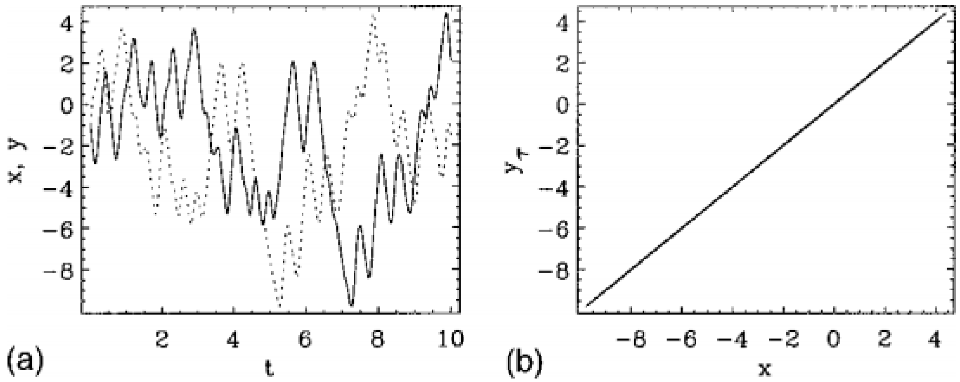
Time Delay vs Inhibitory Synaptic Conductance

(DS)

(AS)



g_{IS} (nS)

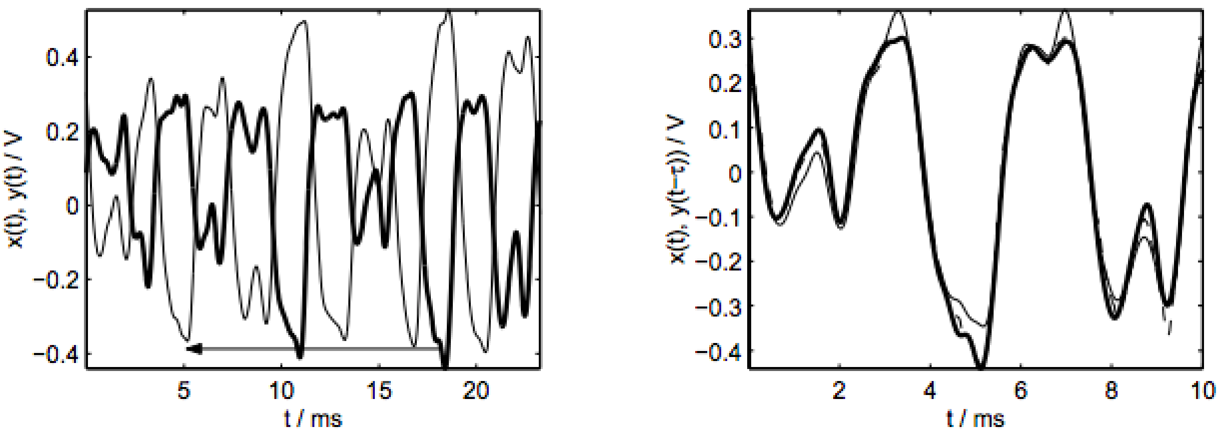


Ikeda Equations

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

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

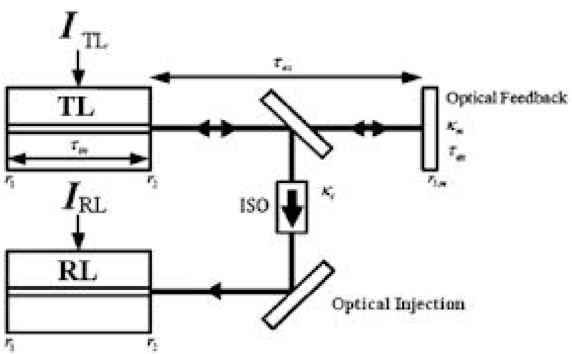
H.Voss, Phys. Rev. E 61, 5115 (2000)

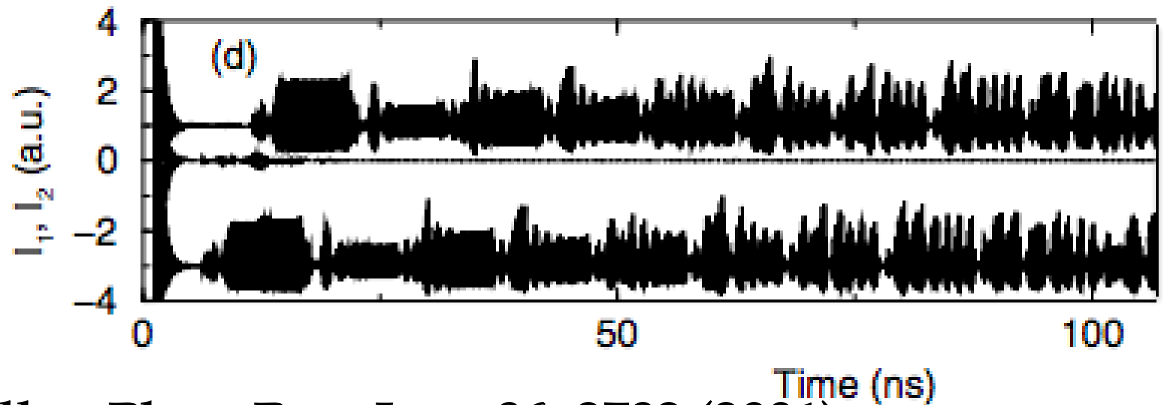


Electronic circuit with a strong non-linearity

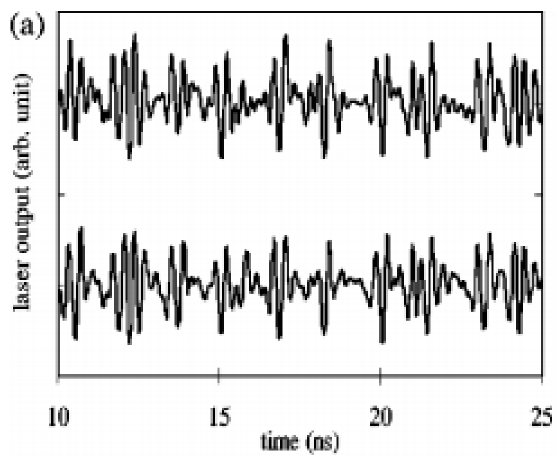
H.Voss, Int. J. Bifurc. Chaos 12, 1619 (2002)

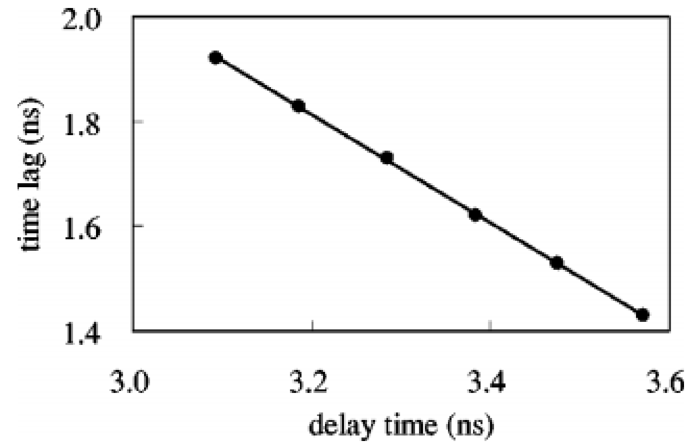
Complete replacement scheme in laser systems





C. Masoller, Phys. Rev. Lett. 86, 2782 (2001)



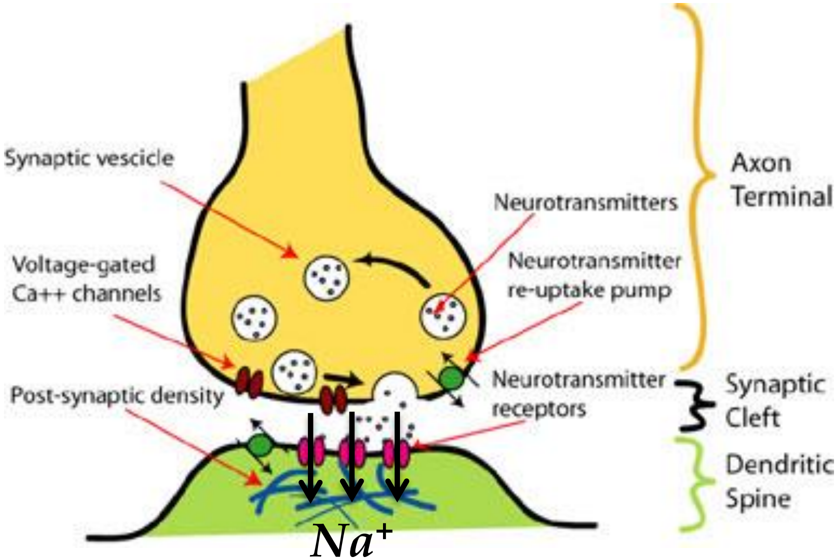


Y. Liu et al., Appl. Phys Lett. 80, 4306 (2002)

Synchronization of three coupled neurons

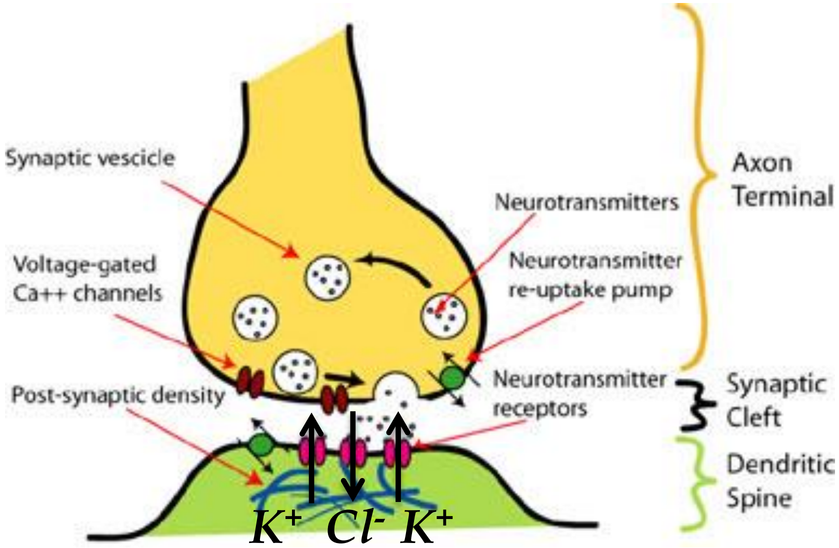
We propose a circuit composed by excitatory and inhibitory neurons

Excitatory Neurons



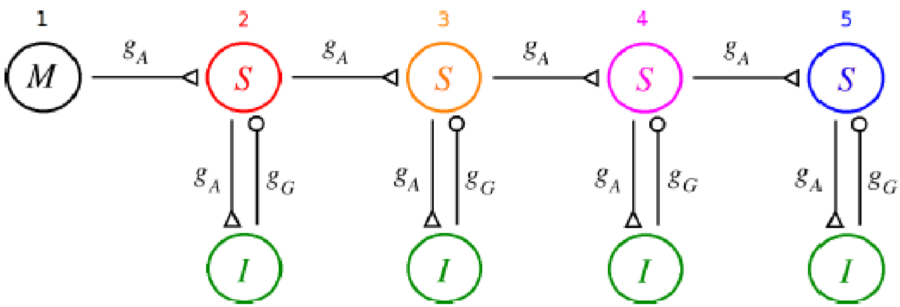
Glutamate
Dopamine, etc.
Reduce firing threshold

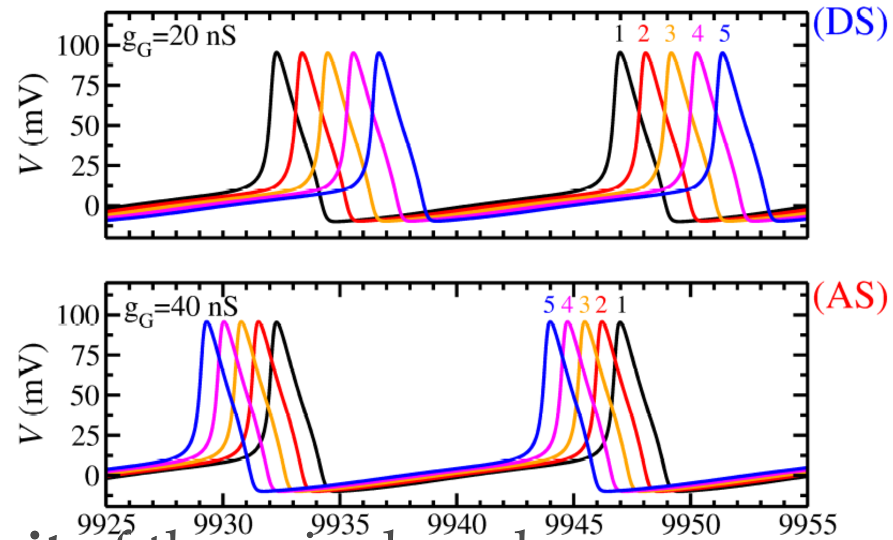
Inhibitory Neurons



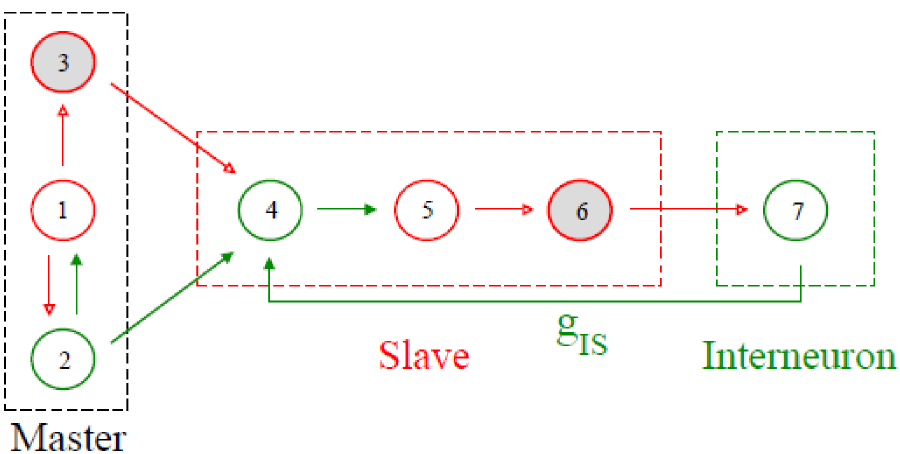
GABA
Glycine, etc.
Increase firing threshold

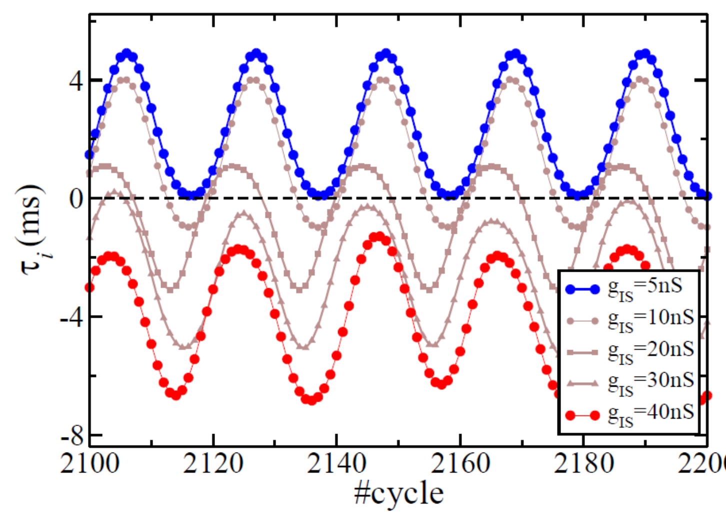
Cascade of slave-inteneuron



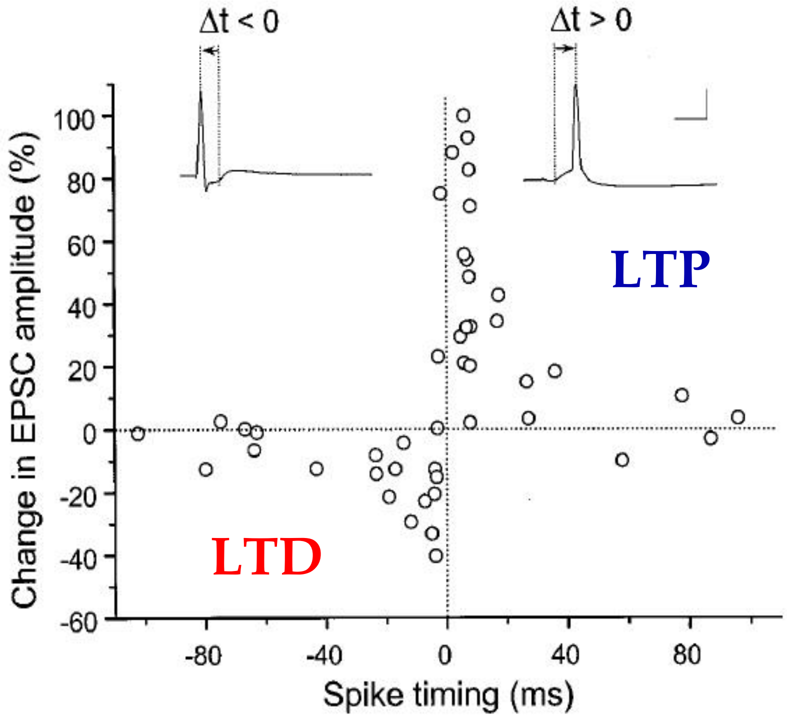


AS in a **motor circuit** of the spinal cord:





Interplay between STDP and AS in the organization of neuronal networks



Additive STDP rule:

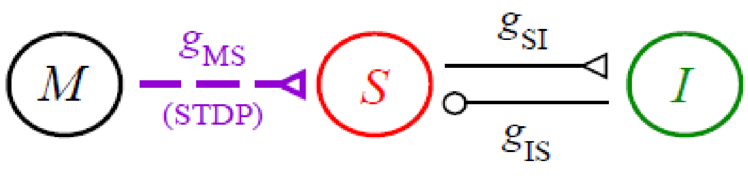
$$g = \begin{cases} g + A_+ \exp(-t/\tau_+), & \text{if } t > 0 \quad \text{(LTP)} \\ g - A_- \exp(t/\tau_-), & \text{if } t < 0 \quad \text{(LTD)} \end{cases}$$

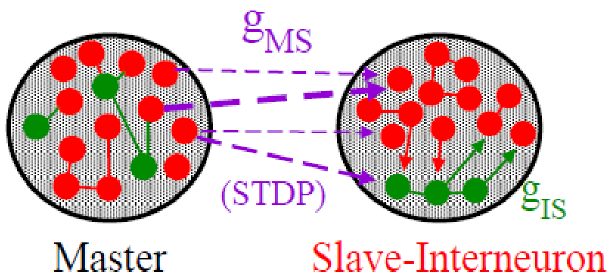
Multiplicative STDP rule:

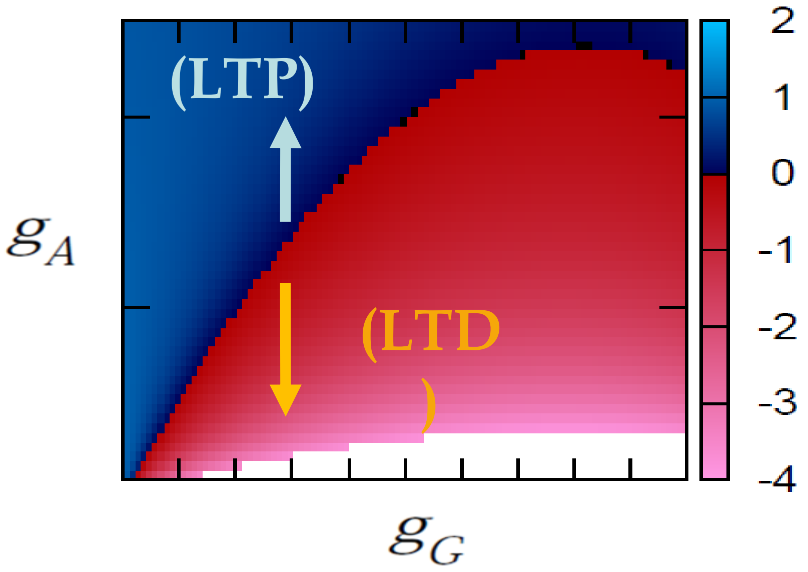
$$g = \begin{cases} g + A_+ \, g \exp(-t/\tau_+), & \text{if } t > 0 \\ g - A_- \, g \exp(t/\tau_-), & \text{if } t < 0 \end{cases}$$

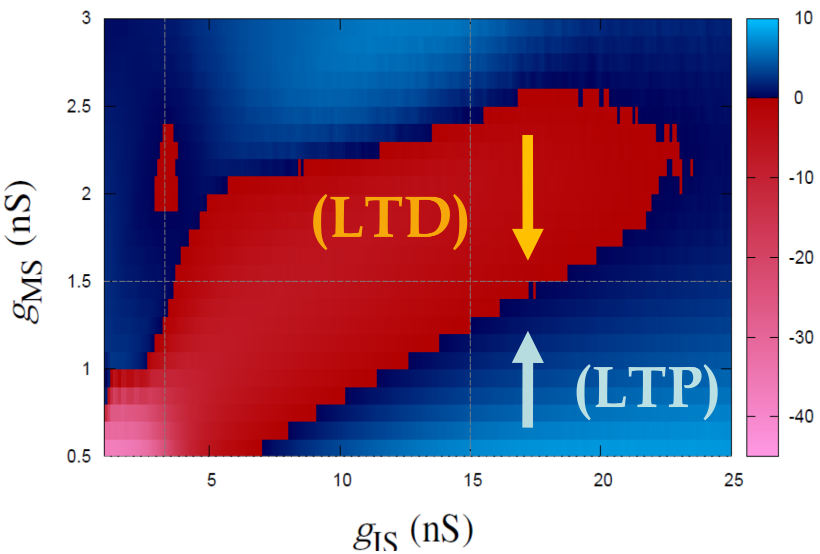
Hybrid STDP rule: g_{MS}

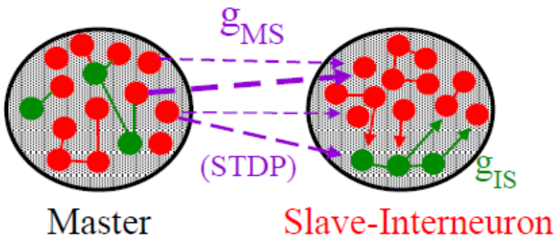
$$g = \begin{cases} g + A_+ \exp(-t/\tau_+), & \text{if } t > 0 \quad \text{(additive LTP)} \\ g - A_- g \exp(t/\tau_-), & \text{if } t < 0 \quad \text{(multiplicative LTD)} \end{cases}$$



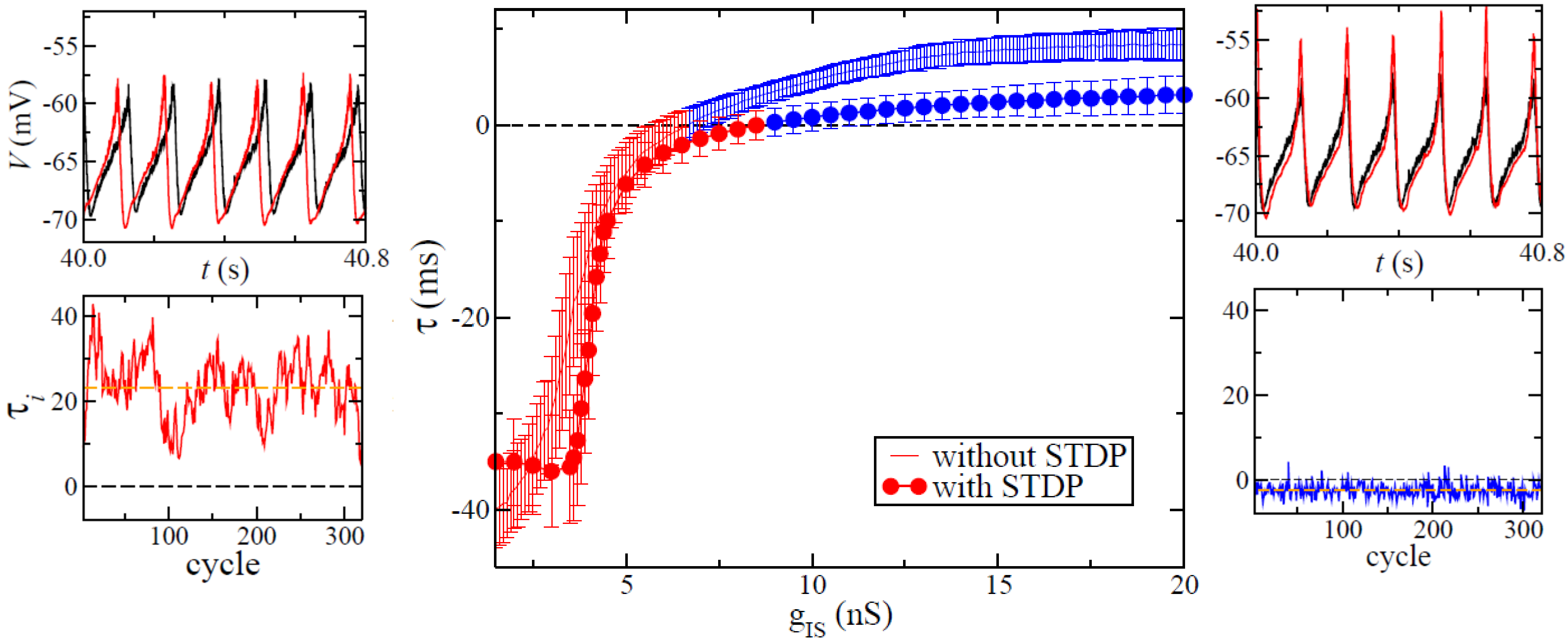








g_{MS}
(STDP)
g_{IS}
Master
Slave-Interneuron



V (mV)
t (s)
τ_i
cycle
τ (ms)
g_{IS} (nS)
without STDP
with STDP

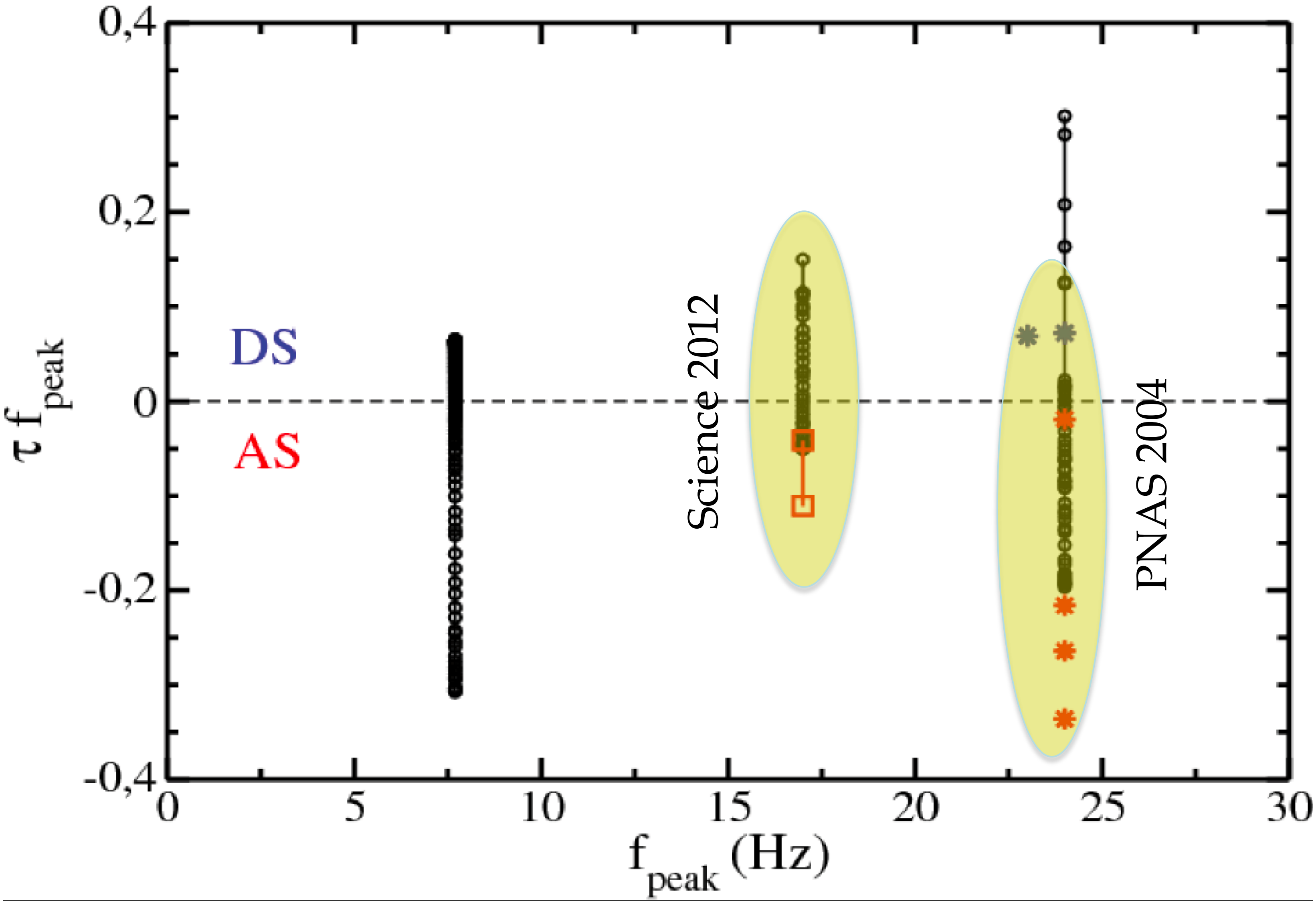
- ✓ *f (x) is a function which defines the autonomous dynamical system under consideration.*

- ✓ *The manifold y(t) = x(t+□) is a solution of the equations and Voss showed that can be structurally stable.*

- ✓ *This is more remarkable when the dynamics of the emitter system x is "intrinsically unpredictable" as in the case of chaotic systems.*

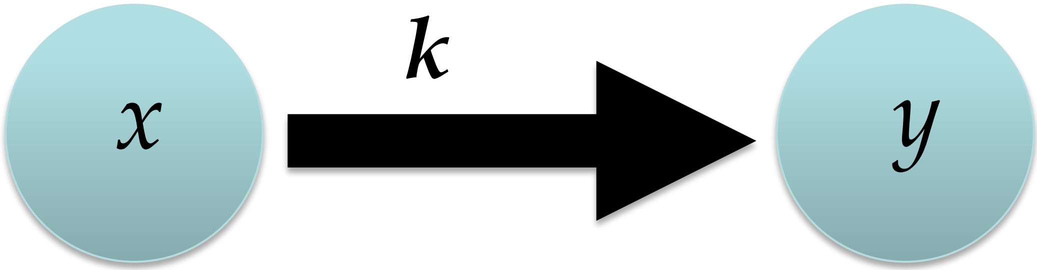
- ✓ *In the delay coupling scheme there are some constrains on the values of □ and □*

- ✓ *AS synchronization has been found in electronic circuits, laser systems, nonlinear oscillators, and other systems.*



0,4
0,2
0
-0,2
-0,4
DS
AS
Science 2012
PNAS 2004
0
5
10
15
20
25
30
f_{peak} (Hz)
τf_{peak}

Synchronization of coupled systems



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

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

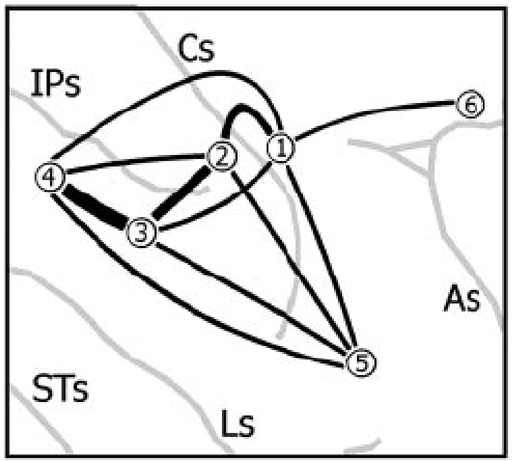
$\dot{\otimes}(t) = [f\,'(t) - k]\,\otimes(t)$ might be stable for large enough ***k***

This is true even for chaotic systems

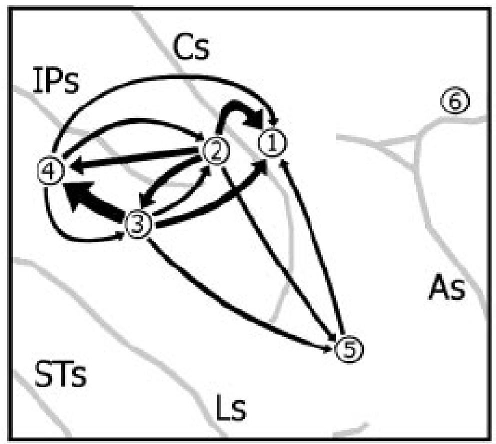
Functional relations of the synchronization, in the beta band, of neuronal assemblies in pre- and postcentral areas of monkeys.

Power and coherence spectral analyses of cortical LFPs as well as Granger causality were measured.

Coherence Graph



Granger Causality Graph



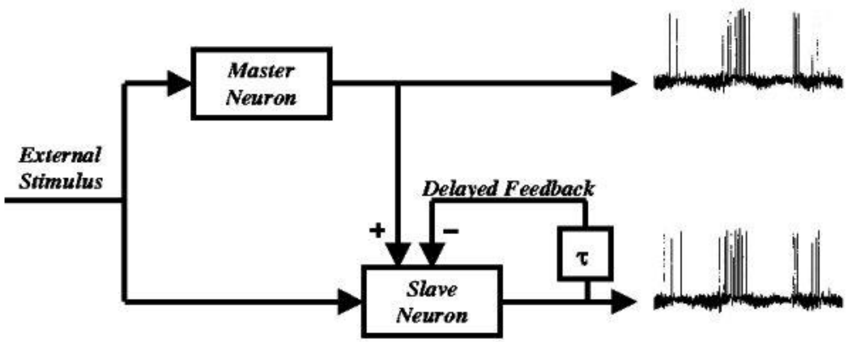
“**positive**” Granger causality was found with **negative** delay times

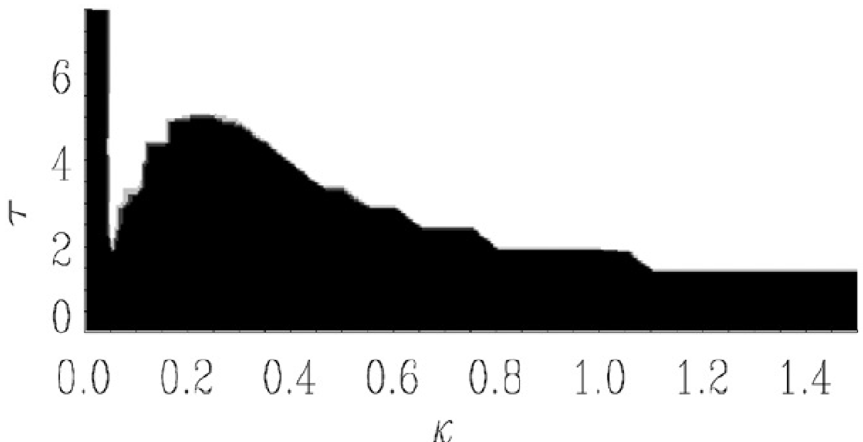
Granger causality relations were generally inconsistent with time delay values: the sign of the time delay did not predict the direction of GC: “**relative phase is not a reliable index of neural influence**

Coupled Fitzhugh-Nagumo Systems

$$\dot{x}_1 = -x_1(x_1 - a)(x_1 - 1) - x_2 + I(t)$$
$$\dot{x}_2 = \epsilon(x_1 - bx_2)$$

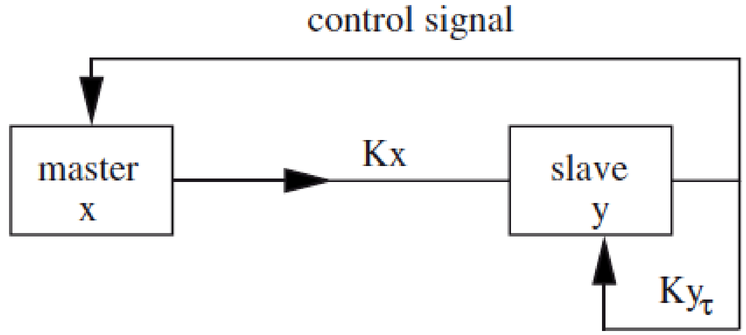
$$\dot{y}_1 = -y_1(y_1 - a)(y_1 - 1) - y_2 + I(t) + K[x_1(t) - y_1(t - \tau)]$$
$$\dot{y}_2 = \epsilon(y_1 - by_2)$$

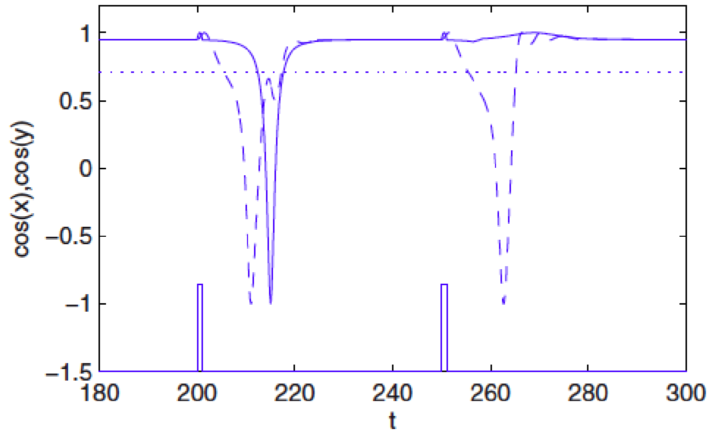


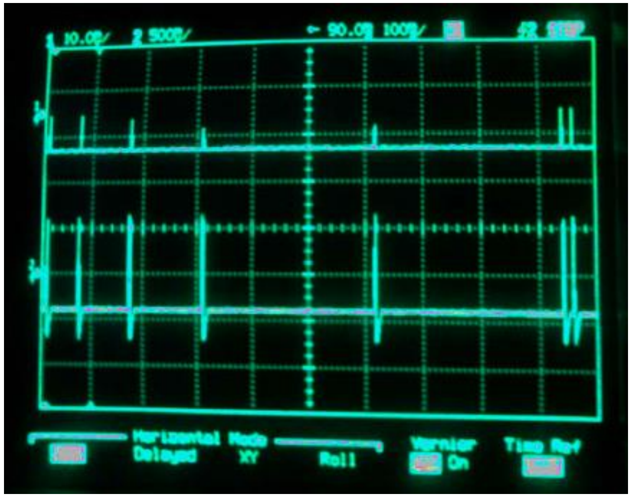


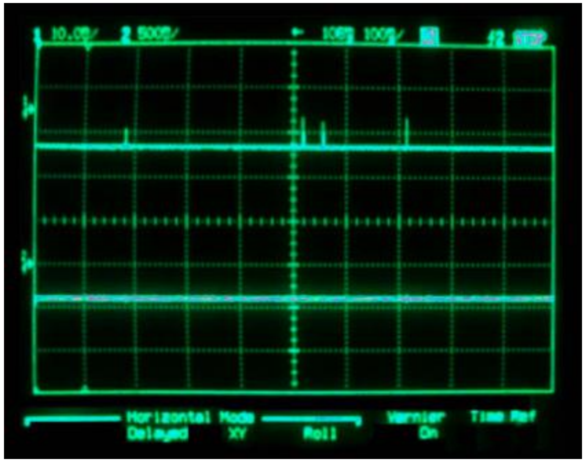
R. Toral et al., Physica A **325**, 192 (2003), M. Ciszak et al., Phys. Rev. Lett. **90**, 204102 (2003)

Controlling System's Dynamics



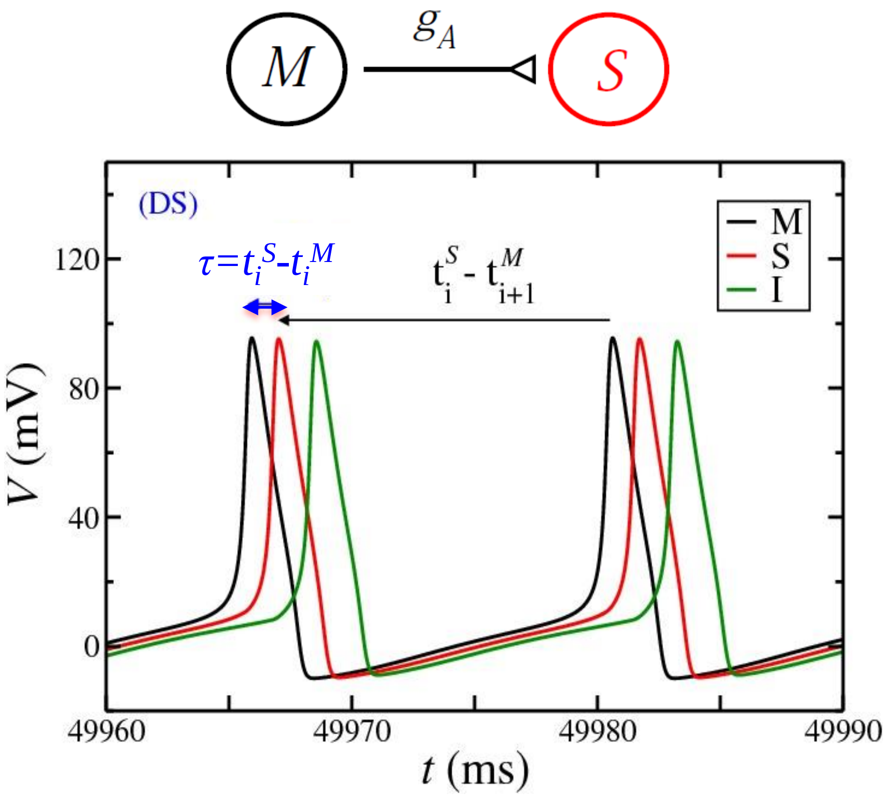


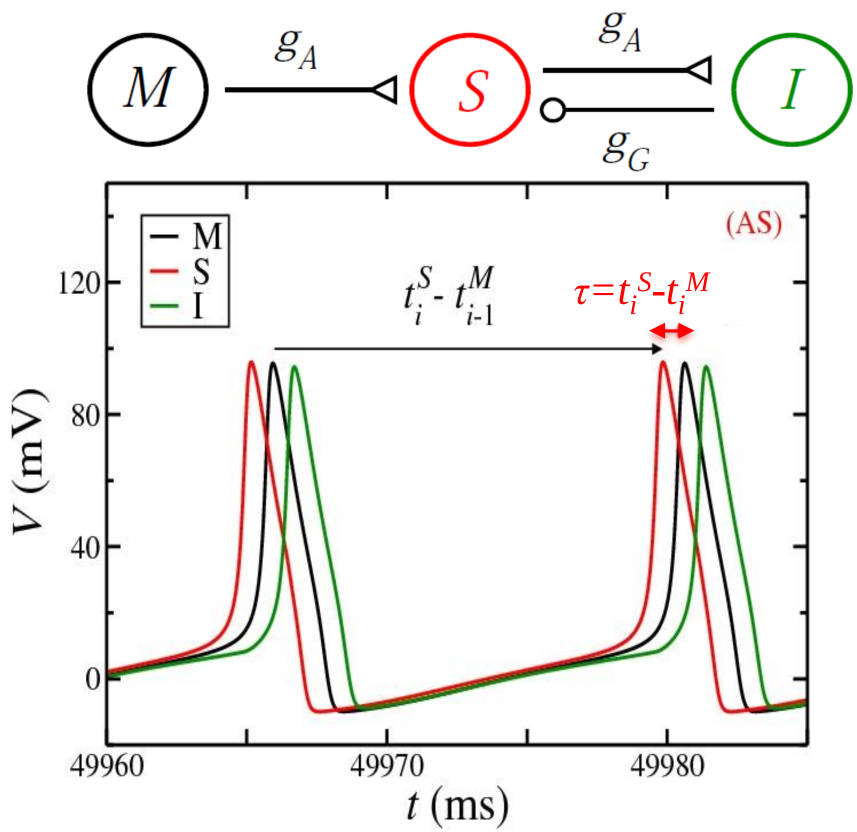




M. Ciszak et al., Phys. Rev. E **79**, 046203 2009

How to characterize AS?





Delayed Synchronization (DS)
Master spikes before the slave (τ>0)

Anticipated Synchronization (AS)
Slave spikes before the master (τ<0)

We define the Time Delay (τ):

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

Functional Significance

Functional Significance

Functional significance

DS

According to Hebbian rules
for STDP

AS