Cell-intrinsic and stimulus properties that maximize spike-time reliability and stochastic synchronization

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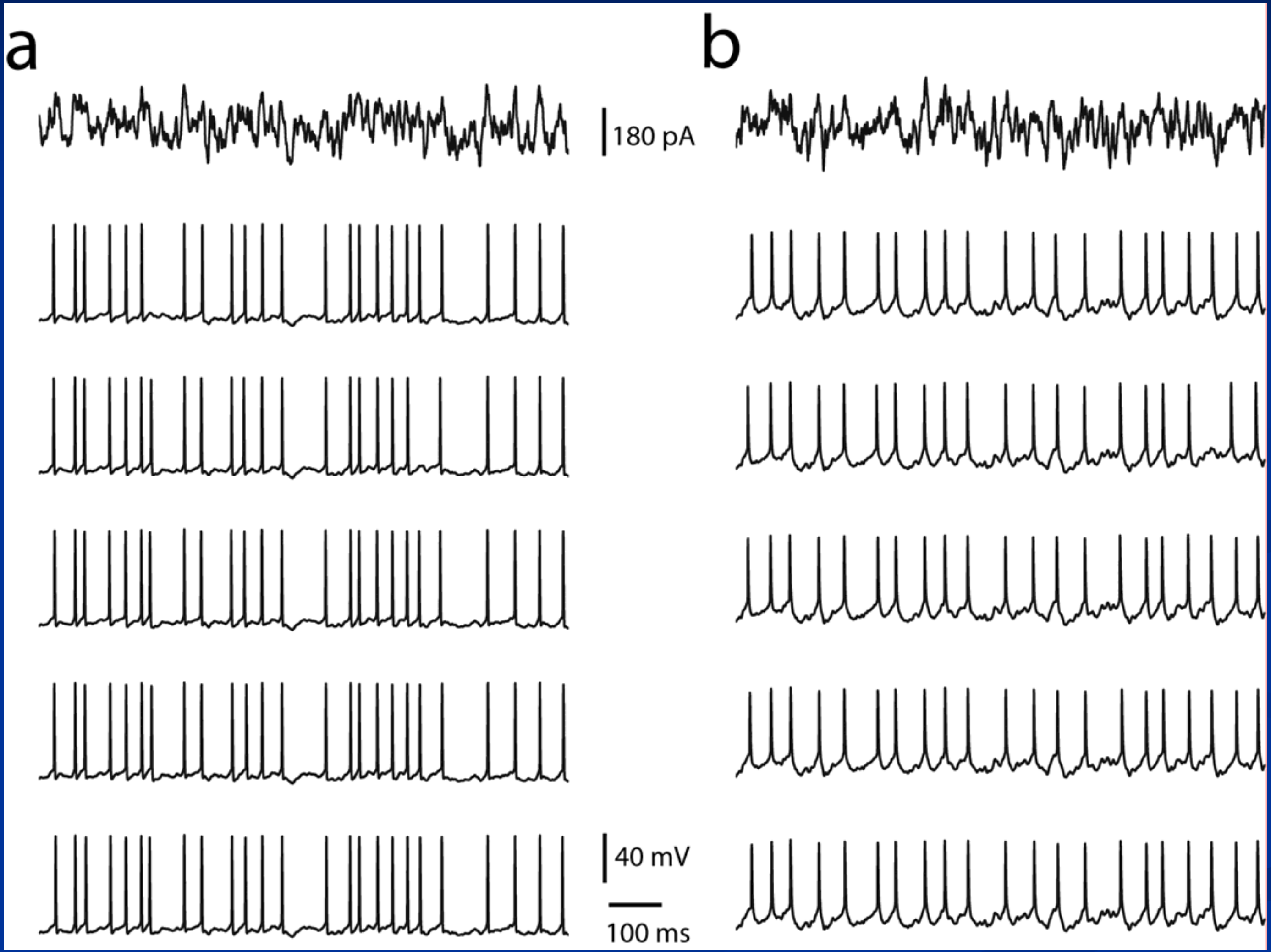
Spike-time reliability in real neurons

Mitral cell in the olfactory bulb



Pyramidal cell in the neocortex

R.F. Galán et al. (2007) *Journal of Neurophysiology*

$x_i(t) = I(t) + \eta_i(t),$

Linear filter approximation of neural dynamics

output

$$\begin{cases} y_1(t) = \int_0^{\infty} K(s)\,x_1(t-s)\,ds \\ y_2(t) = \int_0^{\infty} K(s)\,x_2(t-s)\,ds \end{cases}$$

input

spike-triggered average reversed in time

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Signal + background noise

$$x_i(t) = I(t) + \eta_i(t),$$

fluctuating signal

background noise

$$\langle \eta_1(t)\eta_2(t-s) \rangle = 0, \qquad \langle \eta_i(t)\eta_i(t-s) \rangle = \sigma_\eta^2 \delta(t-s),$$

$$\langle I(t)I(t-s) \rangle = \sigma_I^2 \exp\left(-|s|/\tau\right).$$

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Reliability as a cross-correlation

$$R \equiv \frac{\int_{-\infty}^{\infty} y_1(t) y_2(t) dt}{\sqrt{\int_{-\infty}^{\infty} y_1(t) y_1(t) dt \int_{-\infty}^{\infty} y_2(t) y_2(t) dt}} = \frac{\int_{-\infty}^{\infty} y_1(t) y_2(t) dt}{\int_{-\infty}^{\infty} y_1^2(t) dt}$$

R.F. Galán et al. (2006) *Journal of Neuroscience*
R.F. Galán et al. (2007) *Journal of Neurophysiology*

Analytical expression of reliability

$$R(\tau) = \frac{\sigma_I^2 \int_0^{\infty} \exp(-u/\tau) Q(u) du}{\sigma_I^2 \int_0^{\infty} \exp(-u/\tau) Q(u) du + \sigma_\eta^2 Q(0)}$$

$$Q(u) = \int_0^{\infty} K(s) K(s+u) ds$$

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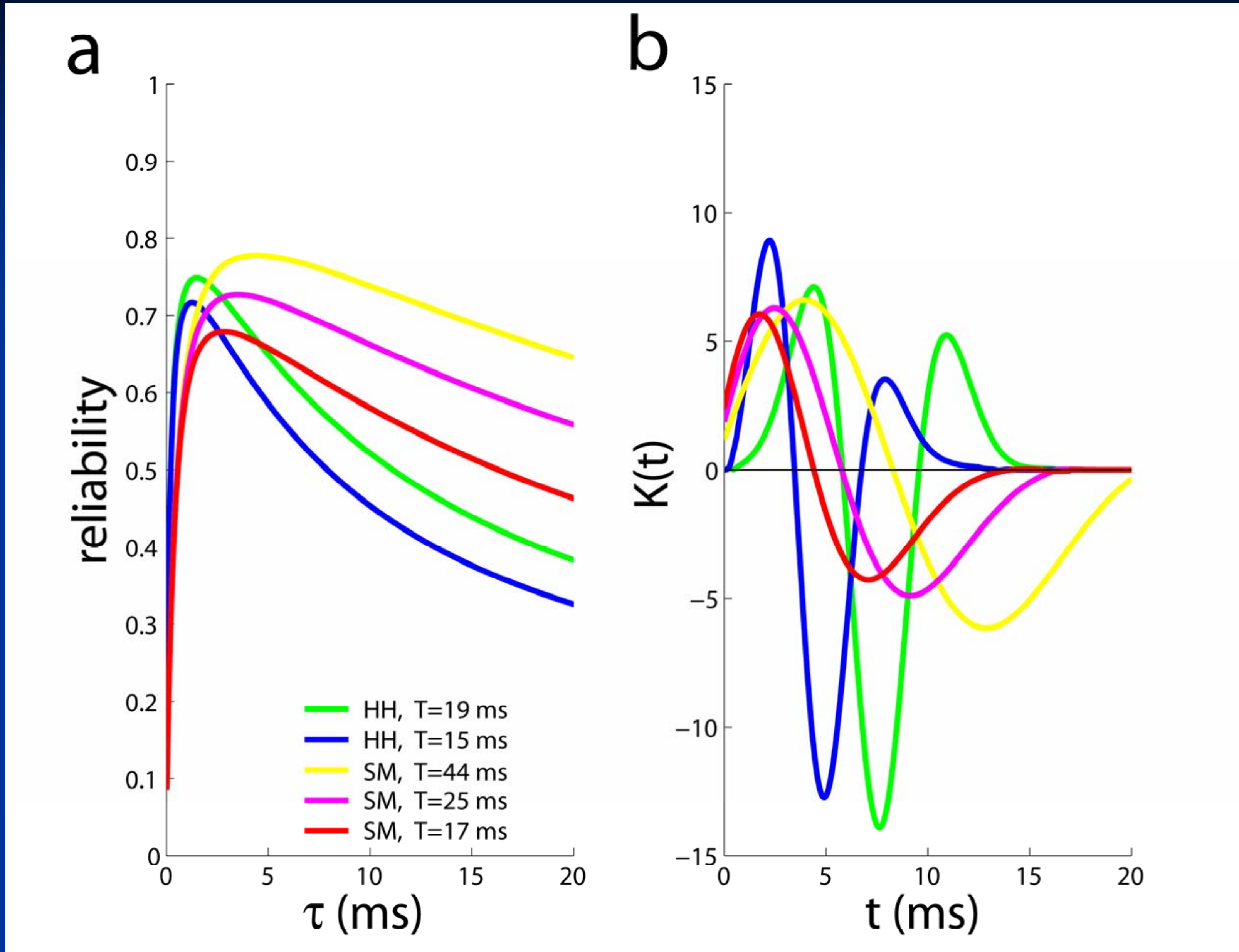
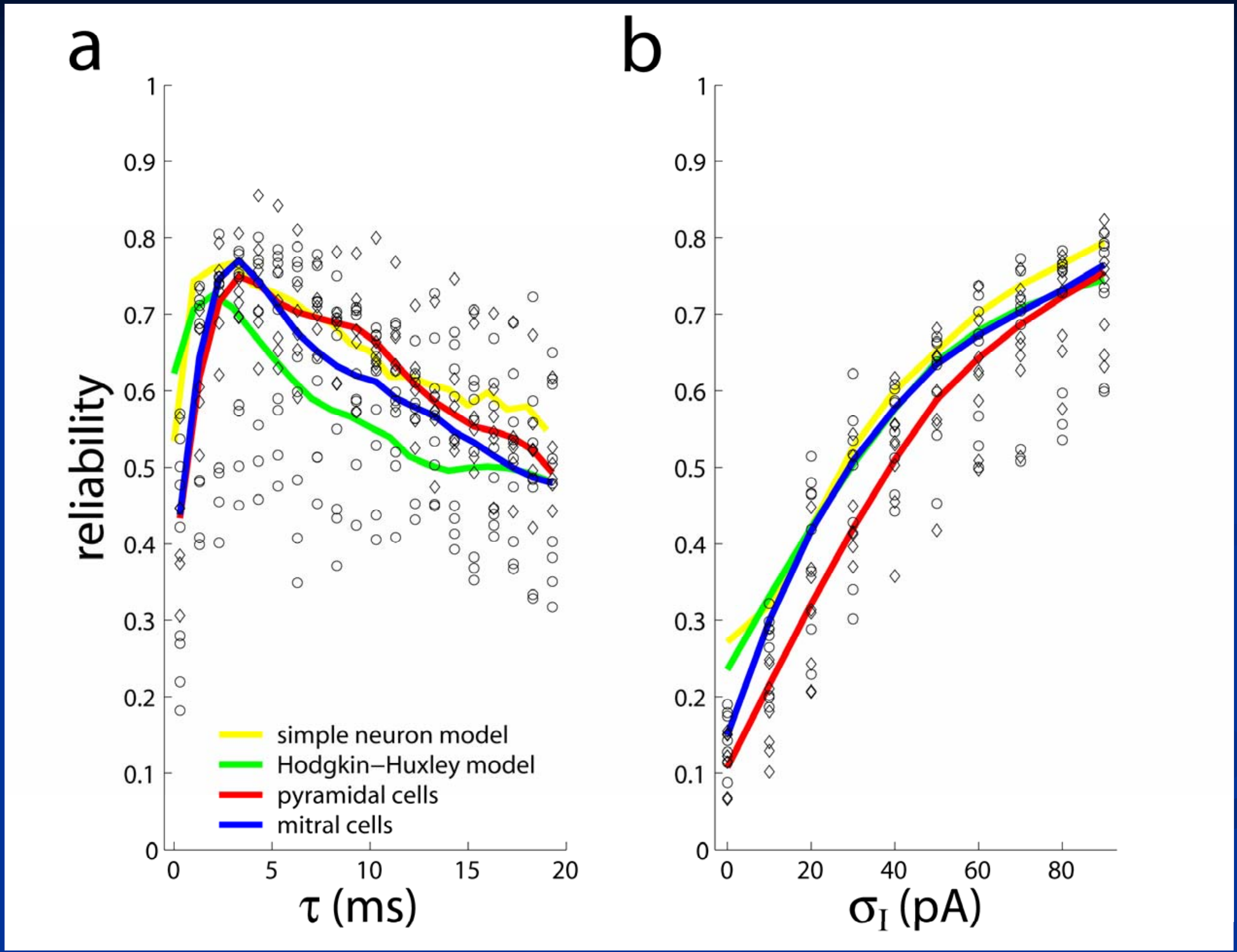

a
b
reliability
τ (ms)
K(t)
t (ms)
HH, T=19 ms
HH, T=15 ms
SM, T=44 ms
SM, T=25 ms
SM, T=17 ms
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
5
10
15
20
−15
−10
−5


a
b
reliability
τ (ms)
σI (pA)
simple neuron model
Hodgkin–Huxley model
pyramidal cells
mitral cells
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
5
10
15
20
0
20
40
60
80

Relationship between the linear kernel and the neuron's phase response

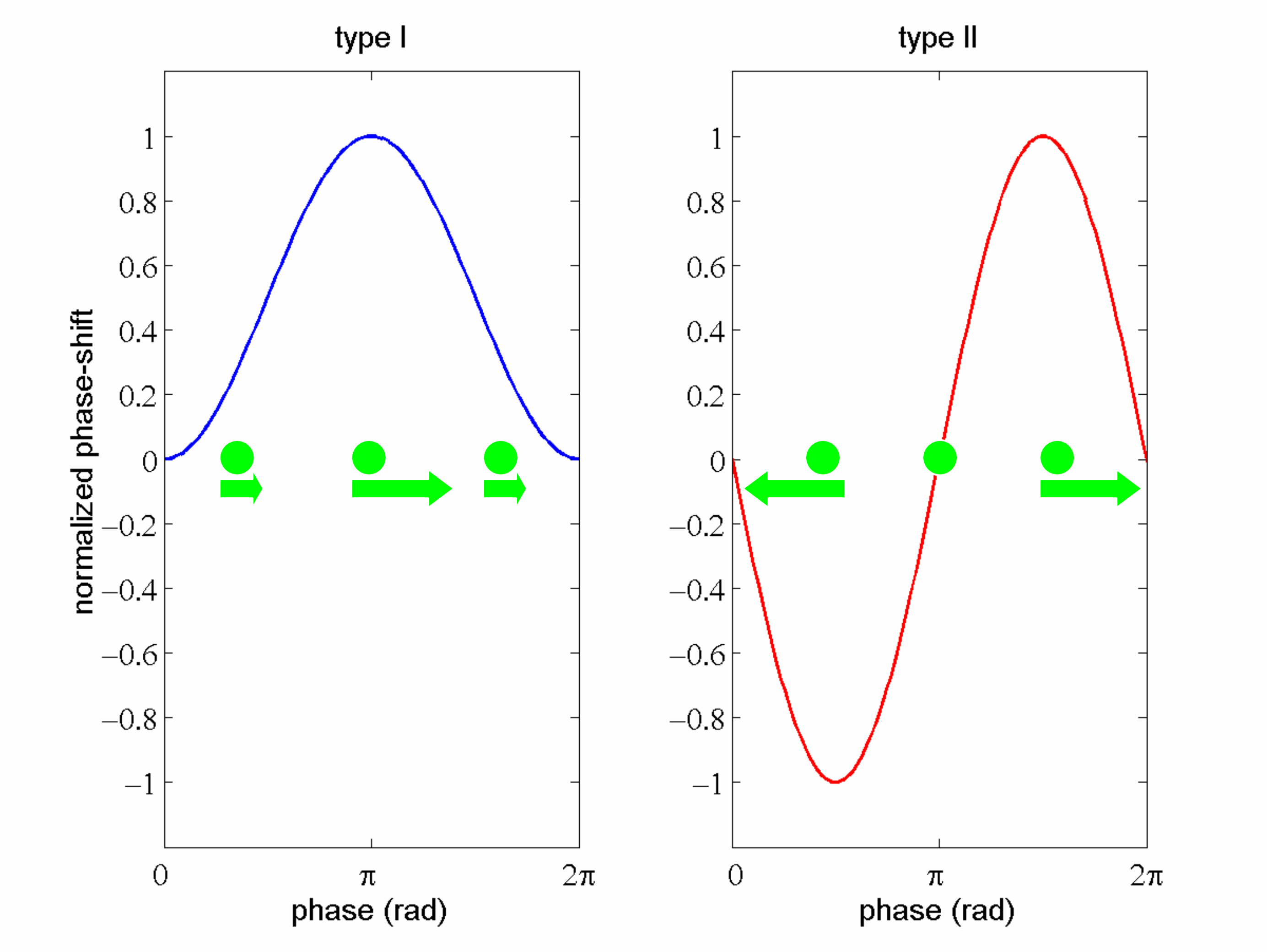
$$Z(\varphi) = -\int_0^{\varphi} K(T-t)\,dt \quad \Longleftrightarrow \quad K(T-t) = -\frac{d}{dt} Z(t)$$

phase-response curve

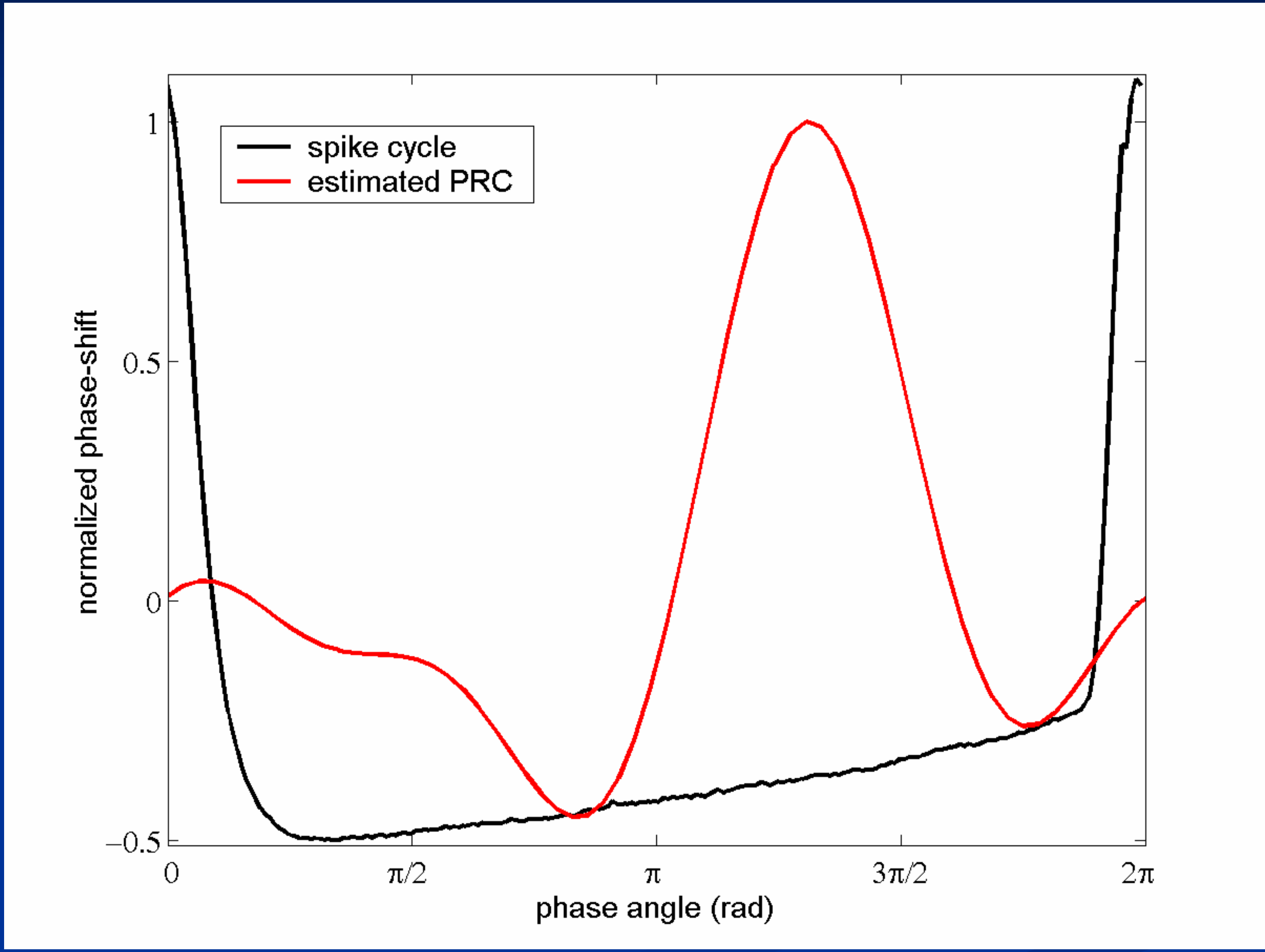
spike-triggered average

Ermentrout, Galán and Urban, *Physical Review Letters* (2007)

Phase-response curves



Phase response in mitral cells



R. F. Galán et al (2005) *Physical Review Letters*

Neuronal oscillators driven by correlated fluctuations

$$\begin{cases} \dfrac{d\varphi_1}{dt} = \omega + \sigma Z(\varphi_1)\eta_1(t) \\ \dfrac{d\varphi_2}{dt} = \omega + \sigma Z(\varphi_2)\eta_2(t) \end{cases}$$

correlated stochastic inputs

phase-response curves

R.F. Galán et al. (2006) *Journal of Neuroscience*

R.F. Galán et al. (2007) *Neurocomputing*

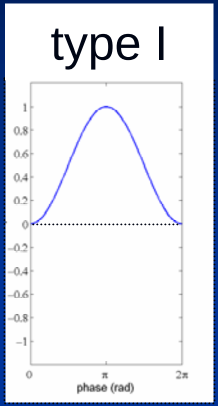
Neuronal oscillators driven by correlated fluctuations

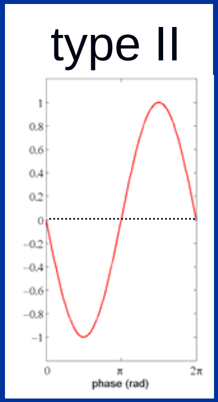
Fokker-Planck equation for *$P=P(\varphi_1,\varphi_2)$*

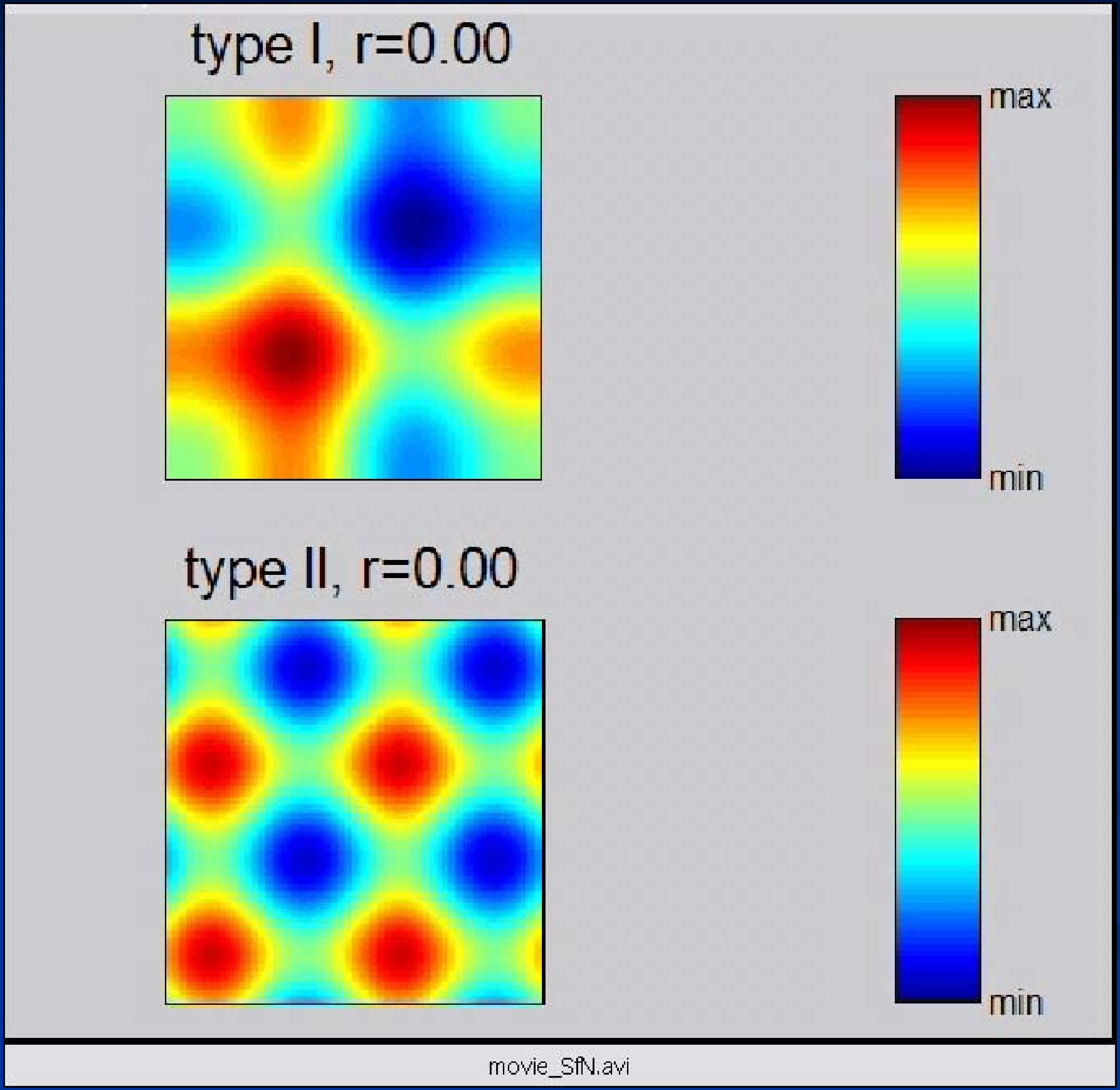
$$\frac{\partial P}{\partial t} = -\omega_1 \frac{\partial P}{\partial \varphi_1} - \omega_2 \frac{\partial P}{\partial \varphi_2} +$$

$$+\frac{\sigma_1^2}{2}\frac{\partial^2}{\partial \varphi_1^2}\left(Z^2(\varphi_1)P\right) + \frac{\sigma_2^2}{2}\frac{\partial^2}{\partial \varphi_2^2}\left(Z^2(\varphi_2)P\right) + c\,\frac{\partial^2}{\partial \varphi_1 \partial \varphi_2}\left(Z(\varphi_1)Z(\varphi_2)P\right)$$

R.F. Galán et al. (2007) *Physical Review E*


type I
phase (rad)


type II
phase (rad)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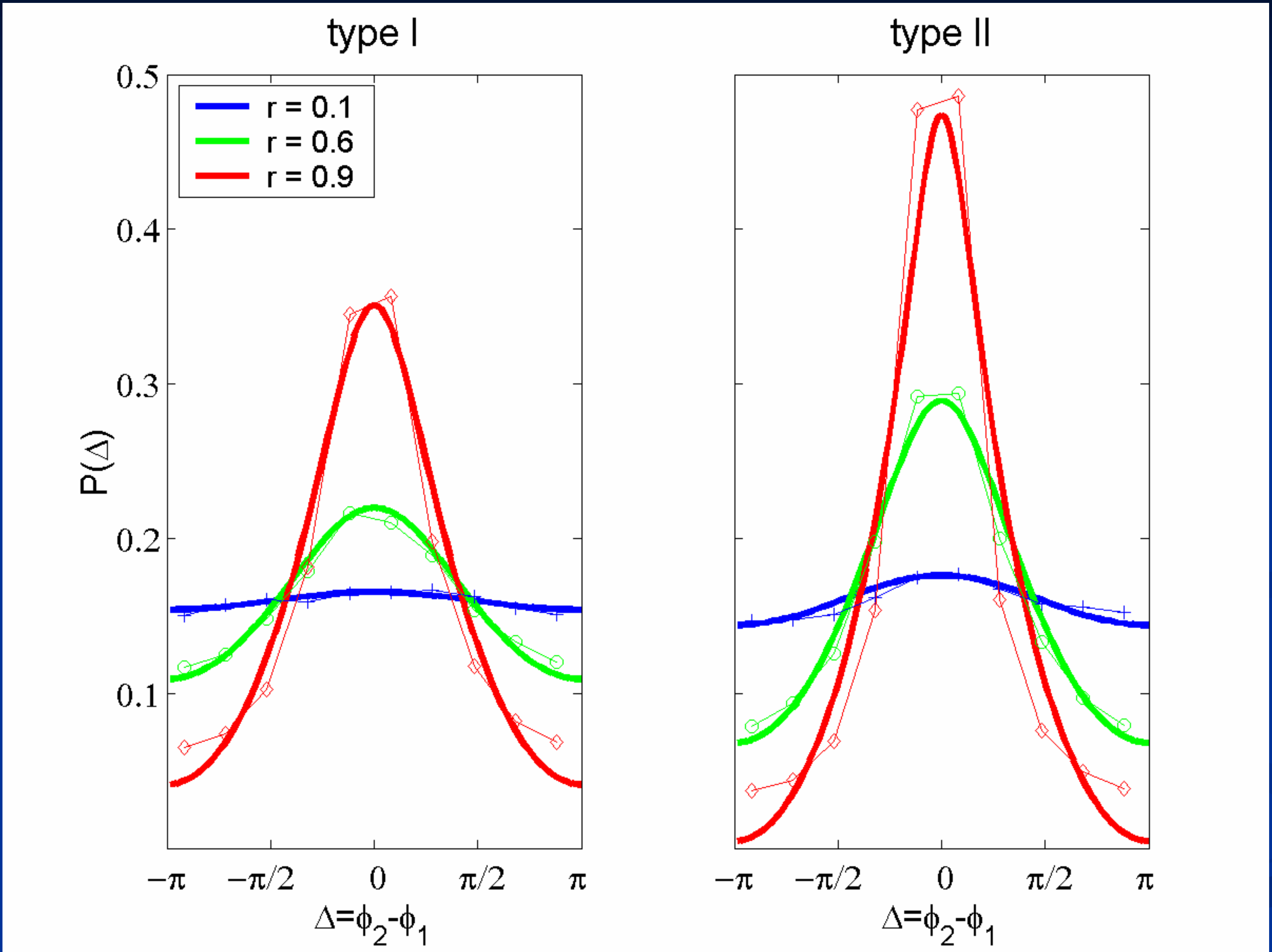
max
min
type II, r=0.00
max
min
movie_SfN.avi



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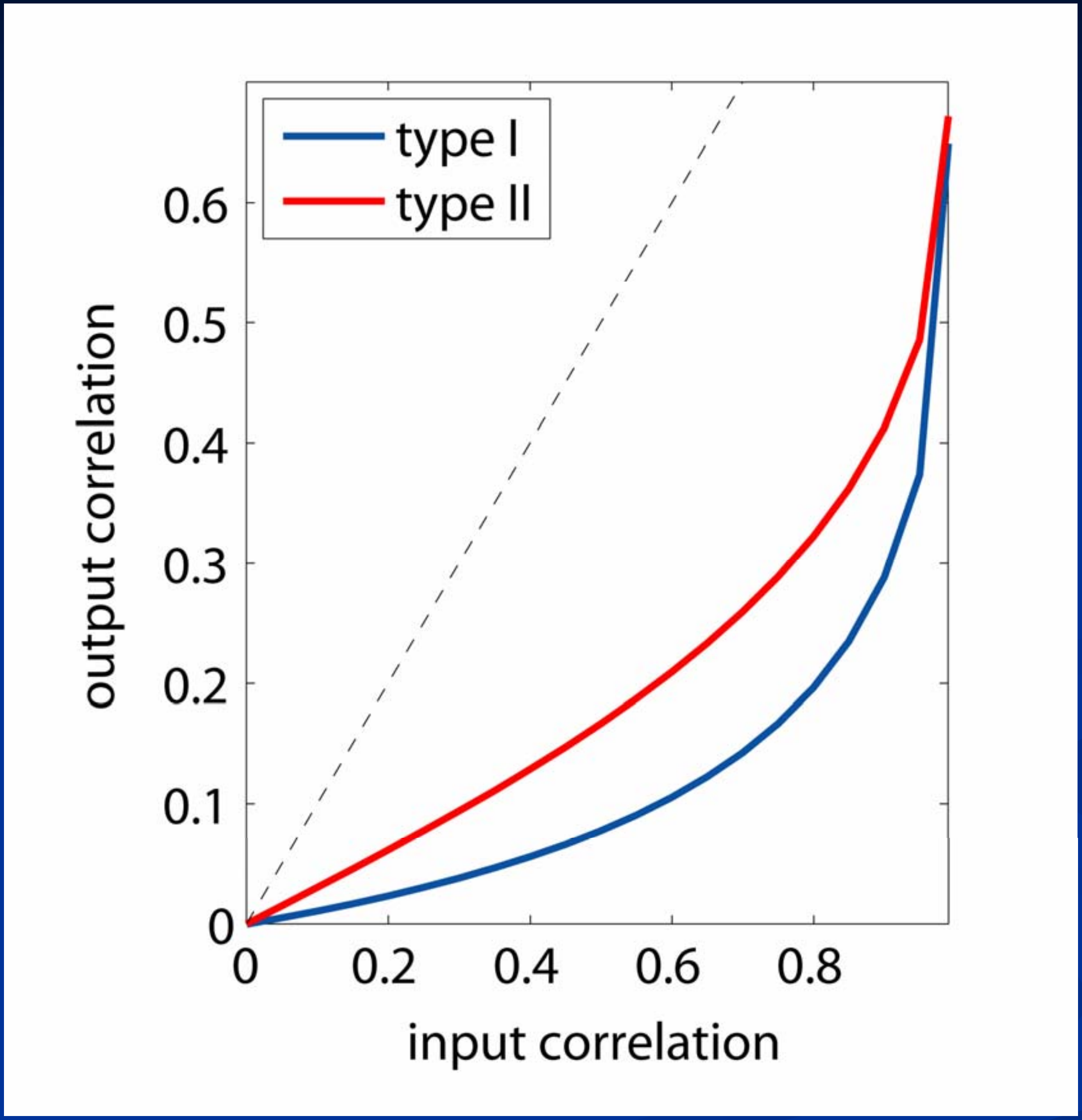

R.F. Galán et al. (2006) *Journal of Neuroscience*
R.F. Galán et al. (2007) *Physical Review E*

Summary

1. Spike-time reliability depends on an intrinsic cell property: the spike-triggered average.

2. In neurons firing periodically, the spike-triggered average can be calculated from the phase response curve, which in turn is determined by the equations describing the neuron's dynamics.

3. For neurons firing in the beta/gamma range, spike-time reliability is optimal for signals fluctuating in a time scale of a few milliseconds.

4. Neurons with resonator properties (type II) are more efficient at synchronizing by correlated fluctuations than neurons with integrator properties (type I).