

**Predicting  
synchronized neural assemblies  
from experimentally estimated  
phase-response curves**

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Bard Ermentrout & Nathaniel Urban

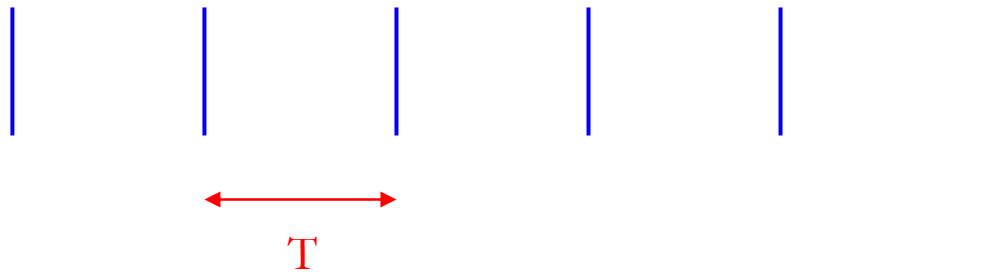


# Assemblies of synchronized neurons

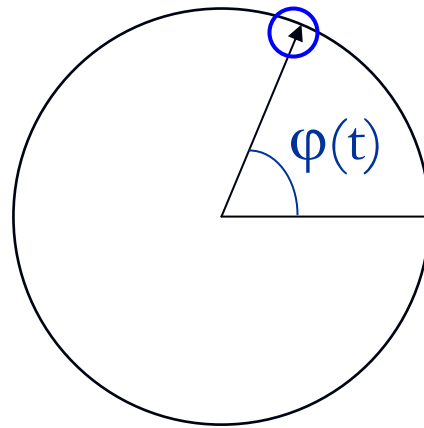
- Assemblies of synchronized neurons have been observed in a variety of neural systems (e.g. Harris, 2003; Plenz & Aertsen, 1996; Wehr & Laurent, 1996).
- These neural assemblies are thought to encode sensory information or store short-term memories.
- This phenomenon is reminiscent of the formation of clusters in models of coupled phase oscillators (e.g. Kuramoto, 1986; Golomb et al., 1992; Crawford, 1995)

# Phase model of a spiking neuron

spikes



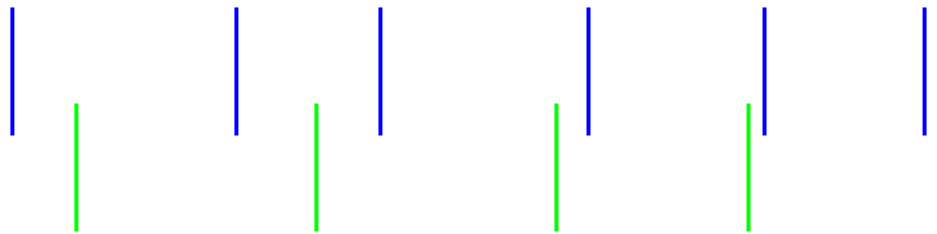
phase  
description



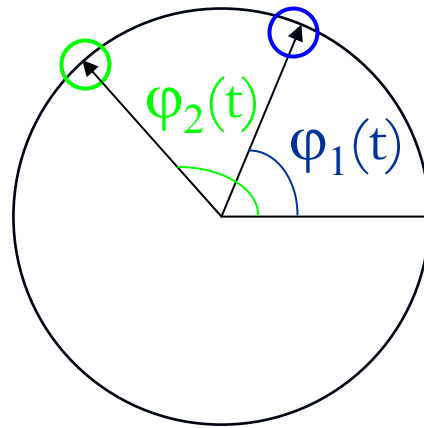
$$\frac{d\varphi}{dt} = \frac{2\pi}{T} = \omega$$

# Phase model of coupled neurons

spikes



phase  
description



$$\frac{d\varphi_1}{dt} = \omega_1 + J_{12} \cdot H_1(\varphi_1 - \varphi_2)$$

$$\frac{d\varphi_2}{dt} = \omega_2 + J_{21} \cdot H_2(\varphi_2 - \varphi_1)$$

# Network dynamics of coupled phase oscillators

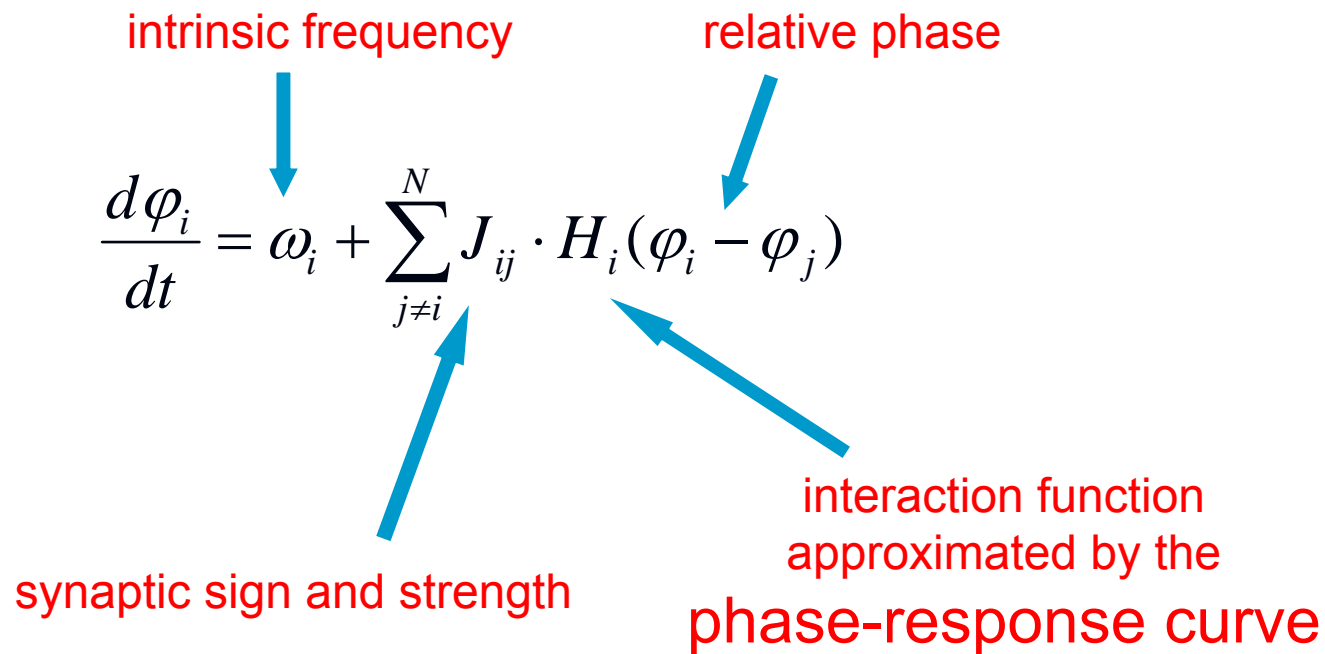
$$\frac{d\varphi_i}{dt} = \omega_i + \sum_{j \neq i}^N J_{ij} \cdot H_i(\varphi_i - \varphi_j)$$

intrinsic frequency

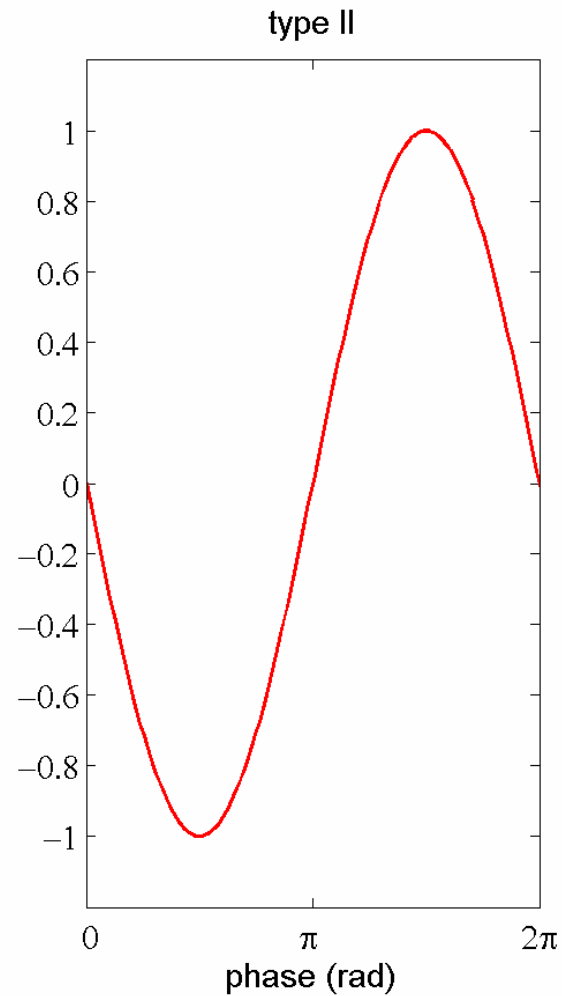
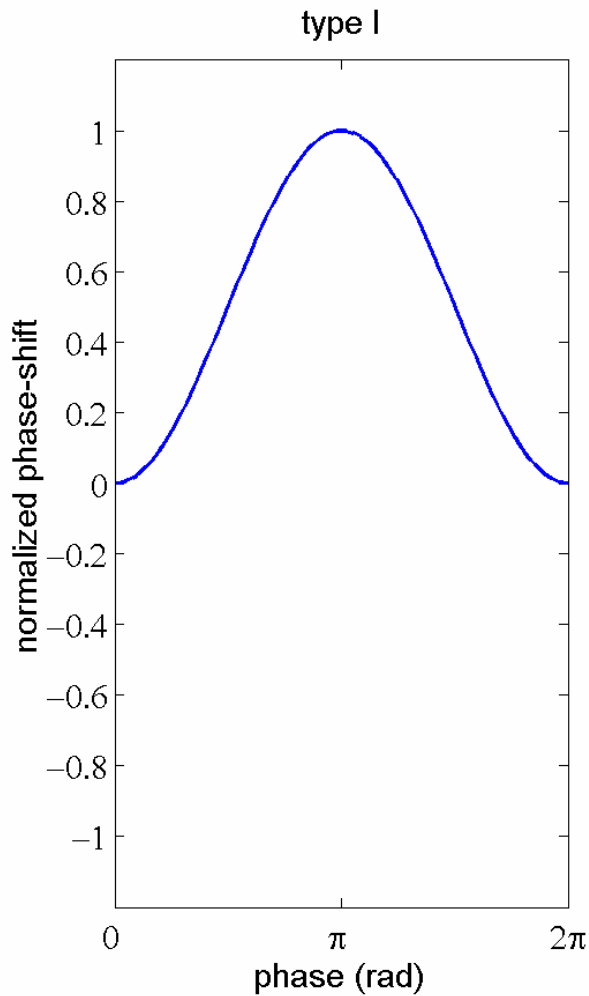
relative phase

synaptic sign and strength

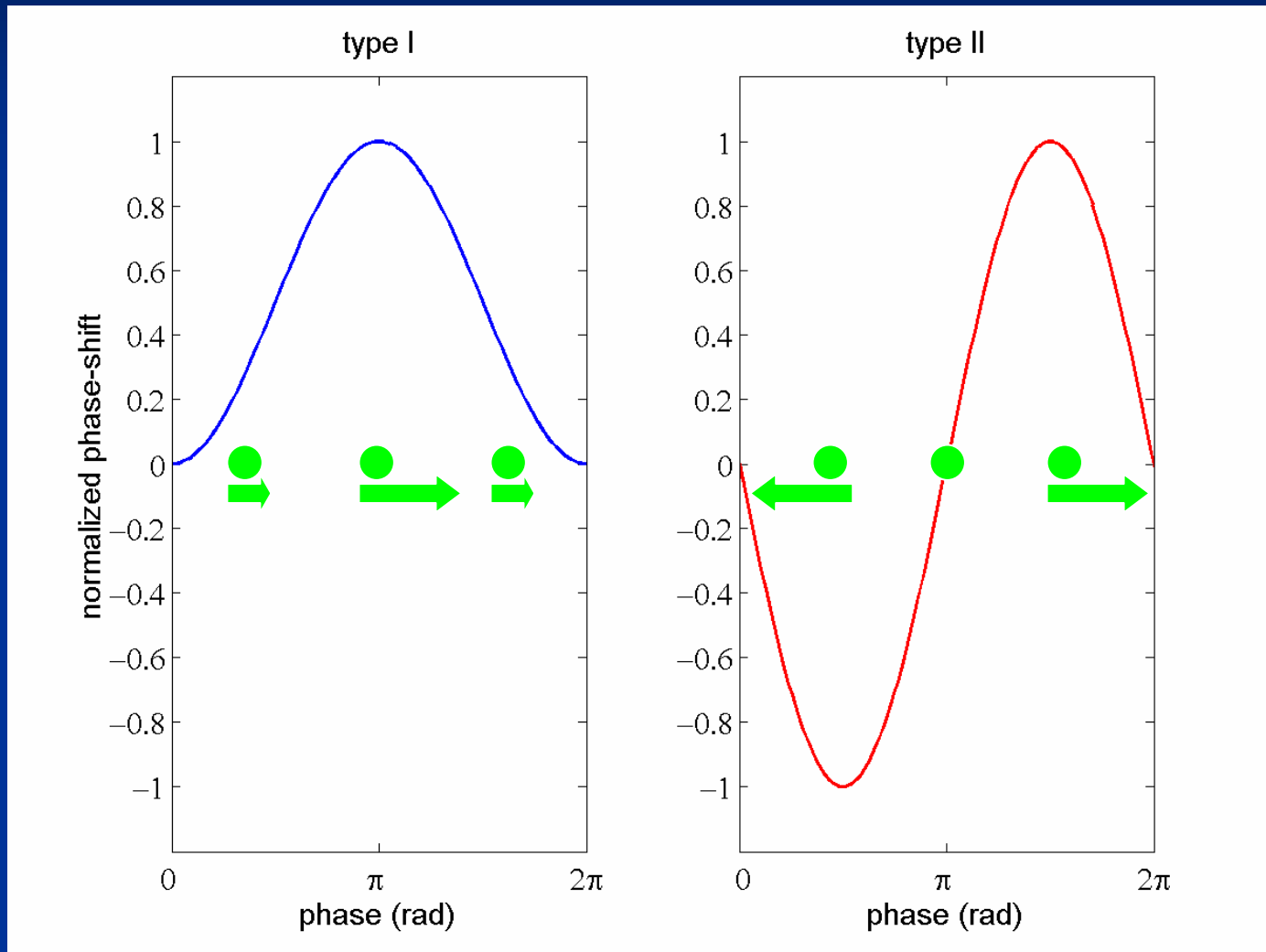
interaction function approximated by the phase-response curve



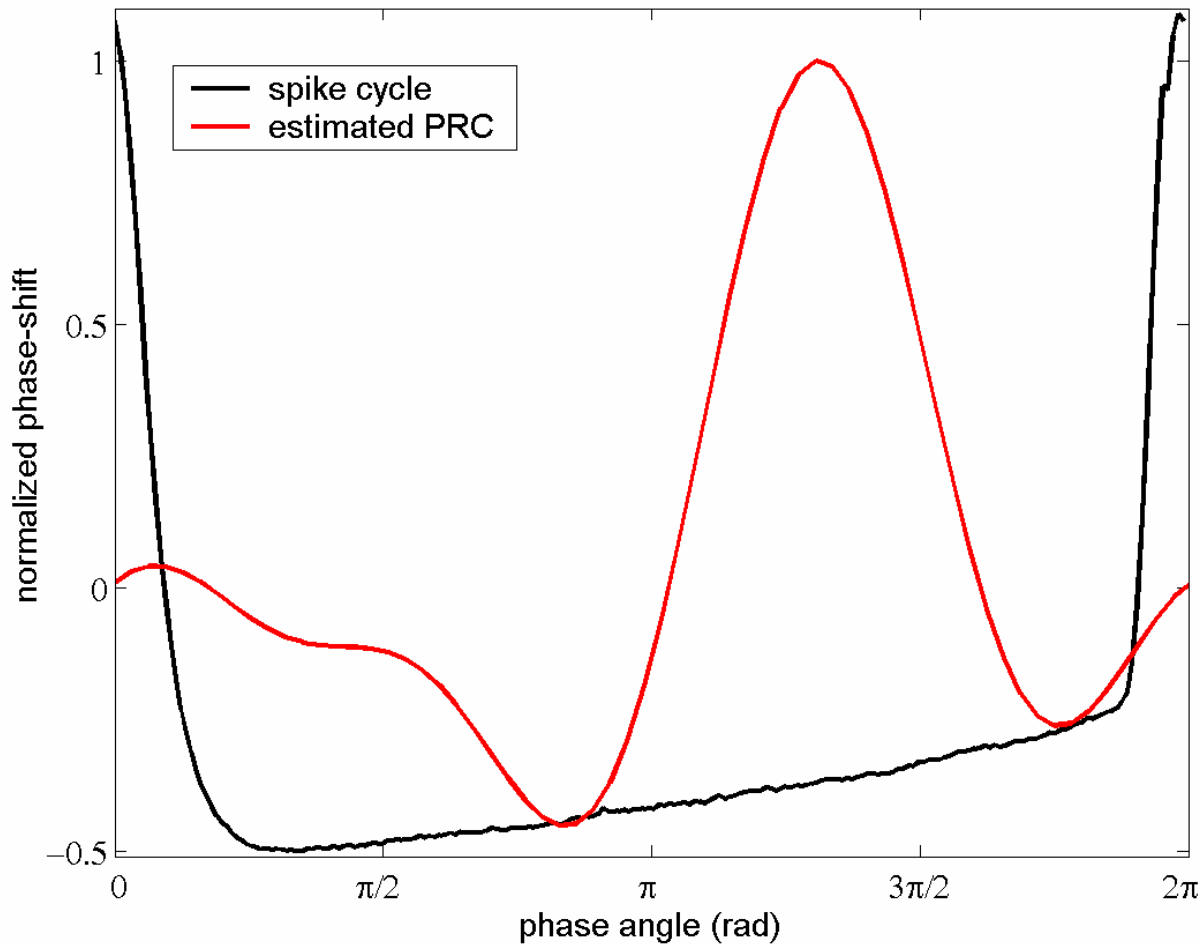
# Phase-response curves



# Phase-response curves

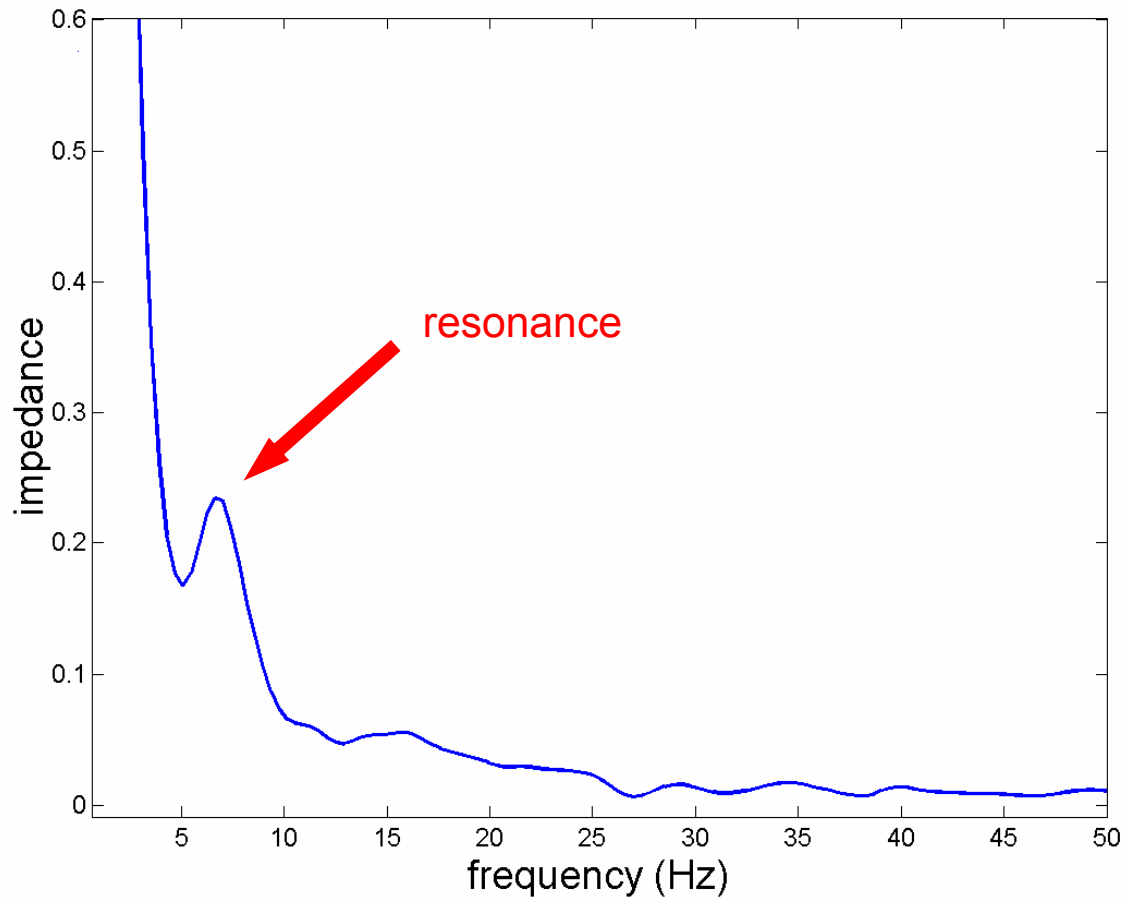


# Phase response in mitral cells



R. F. Galán et al (2005) Phys. Rev. Lett.

# Resonance in mitral cells

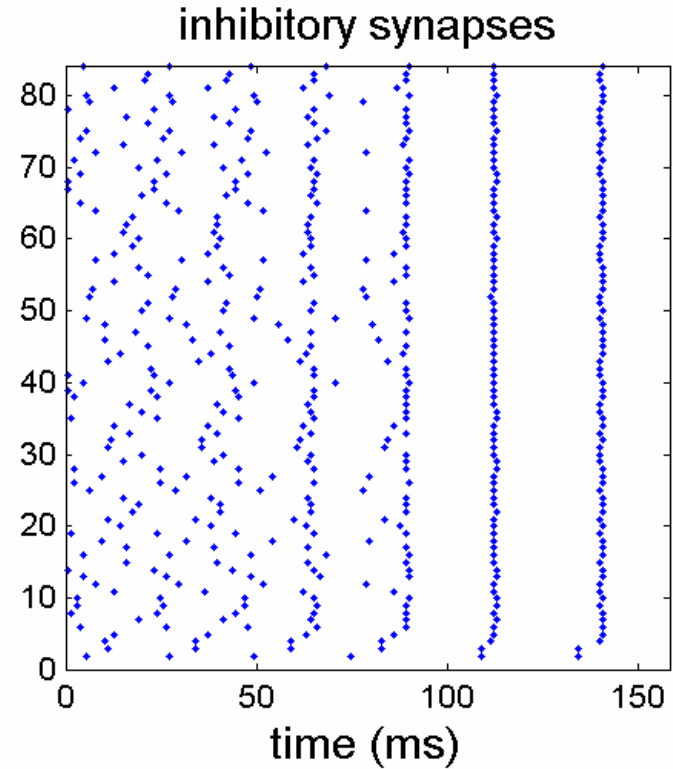
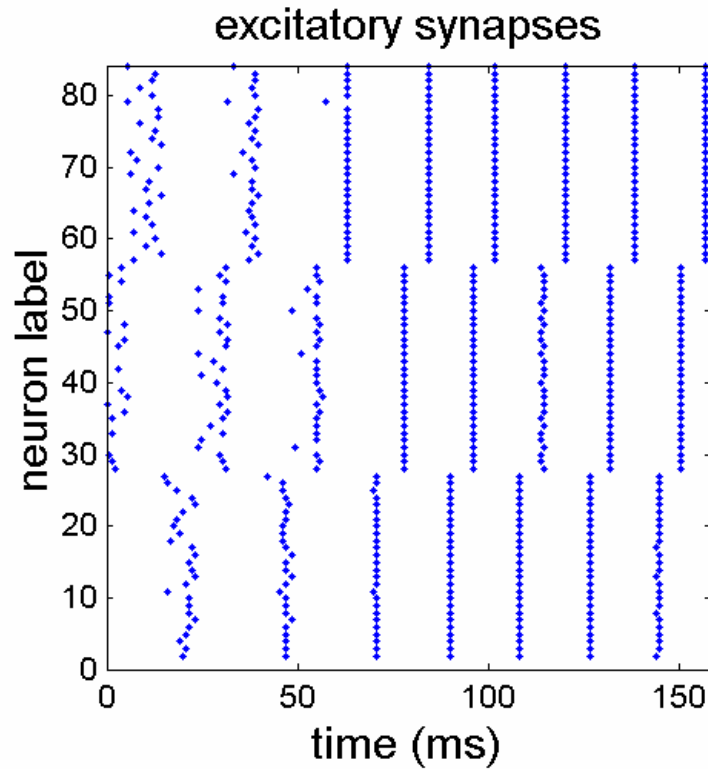


R. F. Galán et al., in preparation

# Network dynamics of coupled phase oscillators

- Excitatory connections
- Inhibitory connections

# Clustering of neural oscillators



# Network dynamics of coupled phase oscillators

Continuum approximation in homogenous networks of phase oscillators ( $N \rightarrow \infty$ ,  $\omega_{ij} = \omega$ ,  $J_{ij} = J$ ,  $H_i = H$ )

$$\frac{d\varphi}{dt} = \omega + J \int_0^{2\pi} H(\varphi - \theta) \rho(\theta) d\theta$$

Continuity equation for the **oscillator density,  $\rho$**

$$\frac{d\rho}{dt} = -\frac{\partial}{\partial\varphi} \left[ \rho \left( \omega + J \int_0^{2\pi} H(\varphi - \theta) \rho(\theta) d\theta \right) \right]$$

# Symmetry breaking and emergence of synchronized assemblies

The linearization of the continuity equation around an initial uniform state reads:

$$\frac{dy}{dt} = -\omega \frac{\partial y}{\partial \varphi} - J \frac{\partial y}{\partial \varphi} \int_0^{2\pi} H(\varphi - \theta) y(\theta) d\theta$$

whose solutions are associated with the eigenvalues:

$$\lambda_n = J \pi n (S_n - i\omega C_n)$$

Sine coefficients

Cosine coefficients

# Symmetry breaking and emergence of synchronized assemblies

$$PRC(\theta) \approx H(\theta) = \sum_n (C_n \cos n\theta + S_n \sin n\theta)$$

	$n = 0$	$n = 1$	$n = 2$	$n = 3$
$C_n$	0.1135	0.1775	-0.2560	-0.1734
$S_n$	0	-0.3158	-0.1878	0.1300

Unstable mode for **excitatory** synapses

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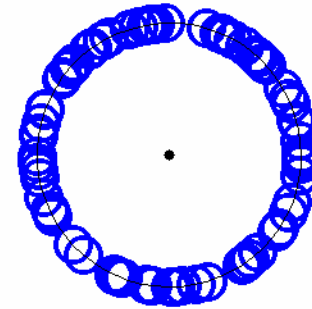
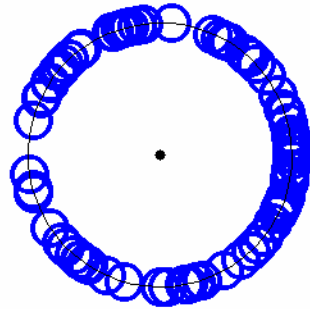
Unstable modes for **inhibitory** synapses

# Clustering of neural oscillators

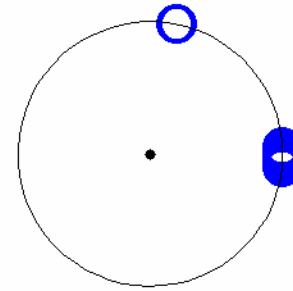
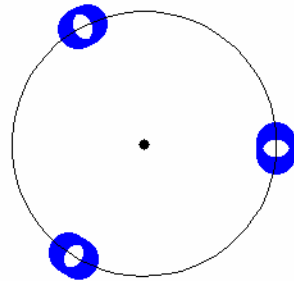
excitatory synapses

inhibitory synapses

initial state



steady state



# Summary

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- Higher order harmonics of the phase-response curve are necessary for the formation of more than one **synchronized neural assemblies**
- Positive sine coefficients break the symmetry of the homogeneous state leading to **cluster formation**
- **Inhibitory interactions** between mitral cells lead to the formation of a dominant synchronized neural assembly in the **gamma frequency band**

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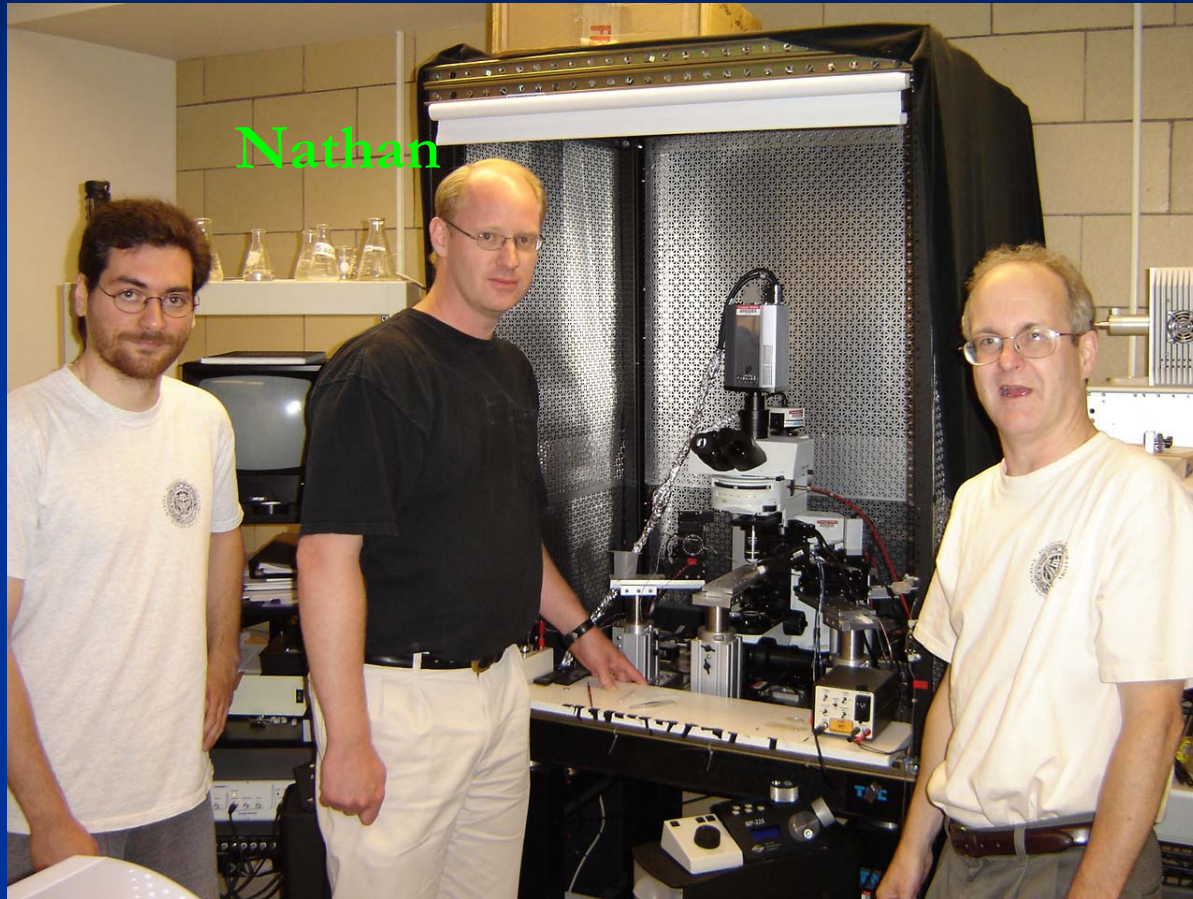
# Final words

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- Equidistant oscillator clusters may account for different **frequency bands** (gamma band  $\approx 2 \cdot$  beta band)

# Final words

- The formation of synchronized neural assemblies does not require short-term **plasticity**
- Alternatively, synchronized assemblies may emerge from a **symmetry breaking** transition determined by the neural phase response
- Equidistant oscillator clusters may account for different **frequency bands** (gamma band  $\approx 2 \cdot$  beta band)
- Do cell assemblies represent a **neural code**, or are they a by-product of the network connectivity?

# Thanks for your attention



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Me

Bard

[www.andrew.cmu.edu/user/rfgalan/home.htm](http://www.andrew.cmu.edu/user/rfgalan/home.htm)