Stochastic facilitation in the brain?

Lawrence M. Ward
Priscilla E. Greenwood
University of British Columbia
Vancouver, Canada

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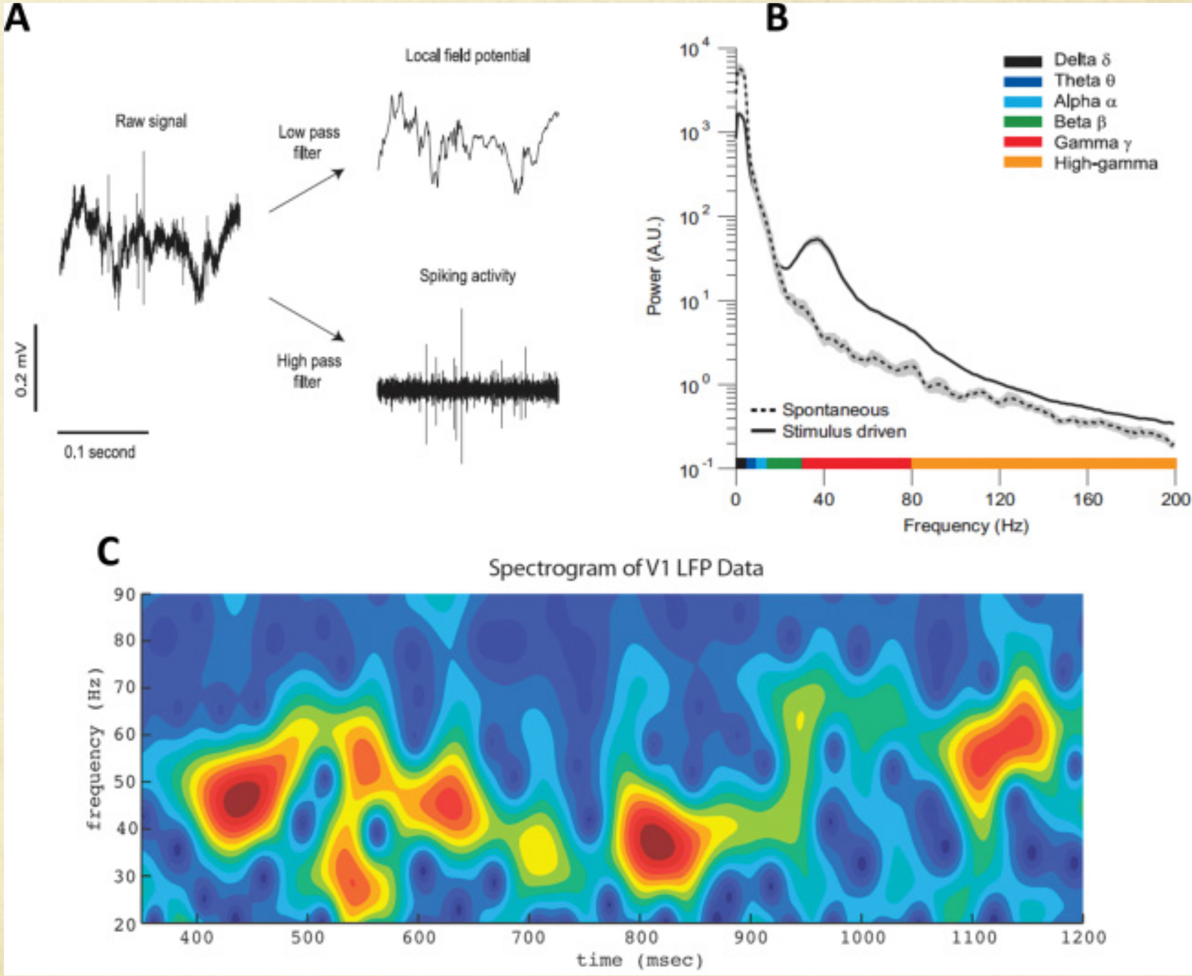
Unsolved Problems of Neural Noise

- To what extent may the oscillatory behavior of individual neurons, or linked populations of neurons, best be characterized as noise-driven quasi-cycles or as noisy limit cycles (or both)?
- What role(s) does neural noise play in the synchronization of, and information transmission between, neural populations located far from one another in the brain?
- To what extent do noise-driven quasi-patterns arise in the brain and affect its overall functioning?

Neural oscillations

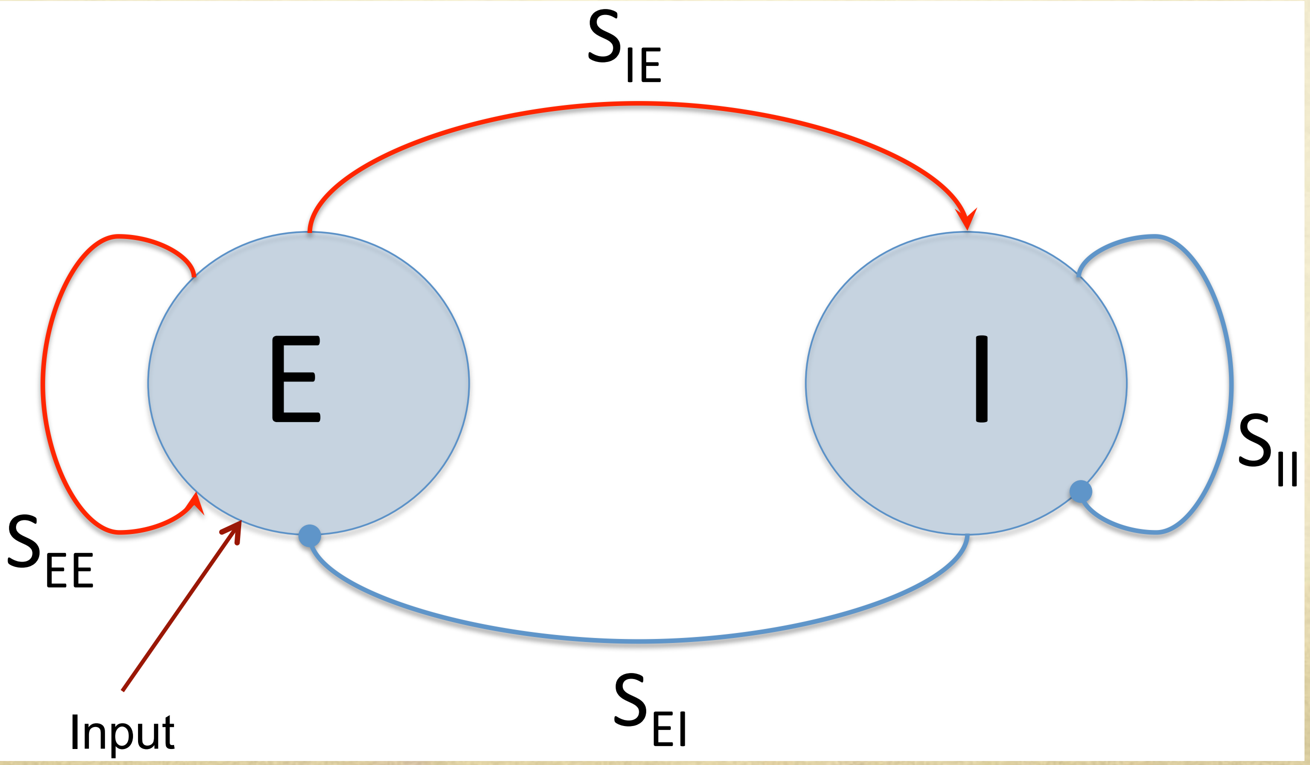
Measure electrical activity of brain in any of several ways to get fluctuating brioadband signal with roughly 1/f poser spectrum with bumps at some particular frequencies

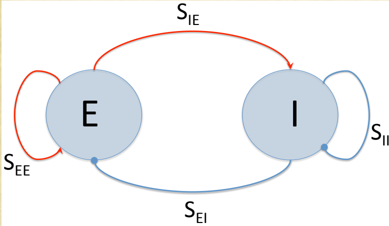


Greenwood, McDonnell, Ward, 2015, *Neural Computation*

Noisy limit cycles or quasi-cycles?

- A common model of interaction of Excitatory and Inhibitory neurons in cortex of brain
- S_{EE}, S_{II}, S_{EI}, S_{IE}: Synaptic efficacies between neurons





Noisy limit cycles or quasi-cycles?

- A general rate/local field potential (LFP) model of E-I neural interaction (orig. Wilson & Cowan, *Biophysical Journal*, 1972):

$$\tau_E dV_E(t) = \left[-V_E(t) + g\left[a_E(S_{EE}V_E(t) - S_{EI}V_I(t) - \theta_E + P_E(t)) \right] \right] dt + \sigma_E dW_E(t)$$

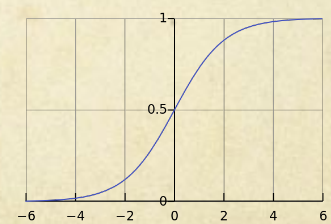
$$\tau_I dV_I(t) = \left[-V_I(t) + g\left[a_I(S_{II}V_I(t) - S_{IE}V_E(t) - \theta_I) \right] \right] dt + \sigma_I dW_I(t)$$

V_E: firing rate/LFP of excitatory neurons; $P_E(t)$: input current

V_I: firing rate/LFP of inhibitory neurons; τ_E, τ_I: time constants

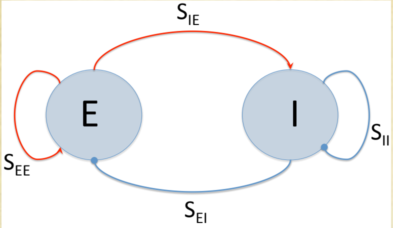
S_{EE}, S_{II}, S_{EI}, S_{IE}: synaptic efficacies between neurons

g: threshold function, usually $g(x) = 1/(1+e^{-x})$, i.e. logistic



$W_E(t)$, $W_I(t)$: standard Brownian motions (NOISE!)

Θ_E, Θ_I, σ_E, σ_I, a_E, a_I: constants

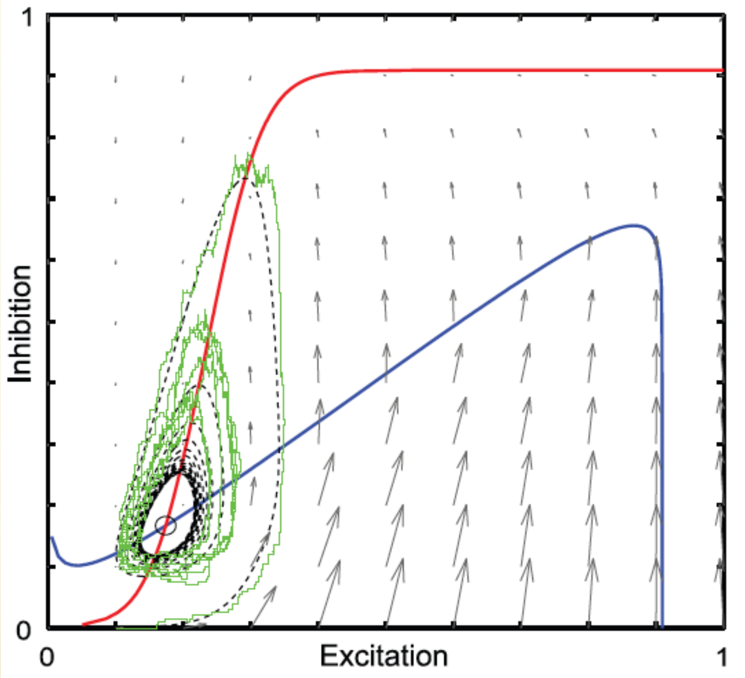


Noisy limit cycles

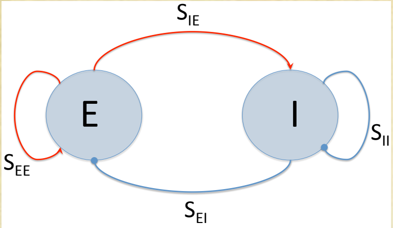
$$\tau_E dV_E(t) = \left[-V_E(t) + g\left[a_E(S_{EE}V_E(t) - S_{EI}V_I(t) - \theta_E + P_E(t))\right]\right]dt + \sigma_E dW_E(t)$$

$$\tau_I dV_I(t) = \left[-V_I(t) + g\left[a_I(S_{II}V_I(t) - S_{IE}V_E(t) - \theta_I)\right]\right]dt + \sigma_I dW_I(t)$$

- $g(x) = 1/(1+e^{-x})$
- $\sigma_E = \sigma_I = 0$: deterministic limit cycles around unstable fixed point
- $\sigma_E = \sigma_I > 0$: noisy limit cycles



Wallace et al., 2011

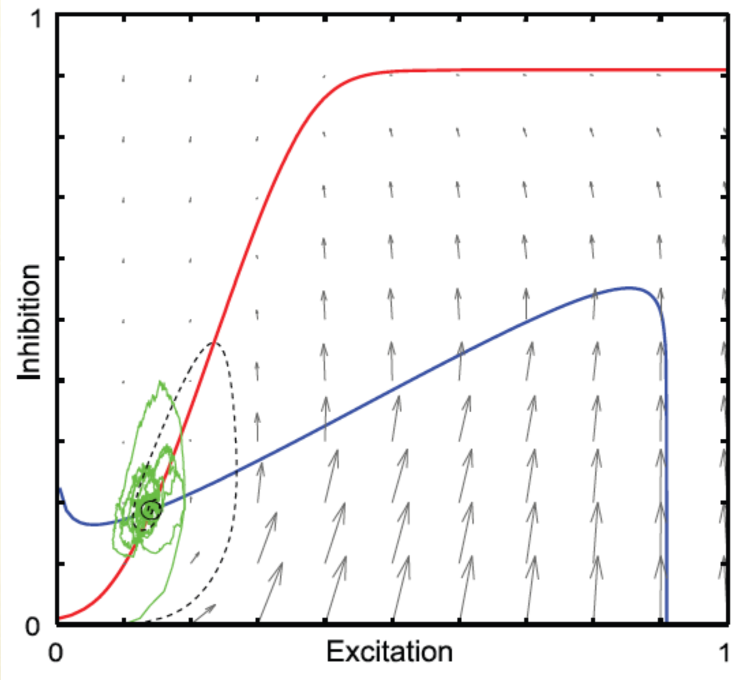


Quasi-cycles

$$\tau_E dV_E(t) = \left[-V_E(t) + g\left[a_E(S_{EE}V_E(t) - S_{EI}V_I(t) - \theta_E + P_E(t))\right]\right]dt + \sigma_E dW_E(t)$$

$$\tau_I dV_I(t) = \left[-V_I(t) + g\left[a_I(S_{II}V_I(t) - S_{IE}V_E(t) - \theta_I)\right]\right]dt + \sigma_I dW_I(t)$$

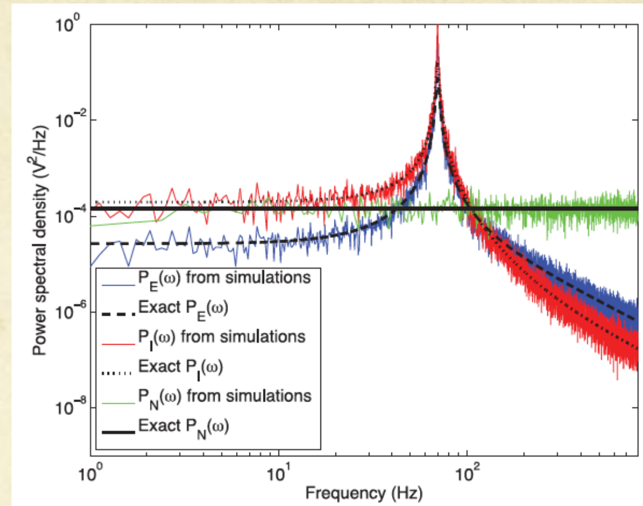
- $g(x) = x$; $a_E = a_I = 1$;
- $P_E(t) = 0$; $\Theta_E = \Theta_I = 0$
- $\sigma_E = \sigma_I = 0$: damps to stable fixed point
- σ_E, $\sigma_I > 0$: quasi-cycles – i.e. noise-driven oscillations at frequency determined by S_{EE}, S_{II}, S_{EI}, S_{IE} and τ_E, τ_I
- Inputs to neurons are typically Poisson-like, i.e. noise-driven

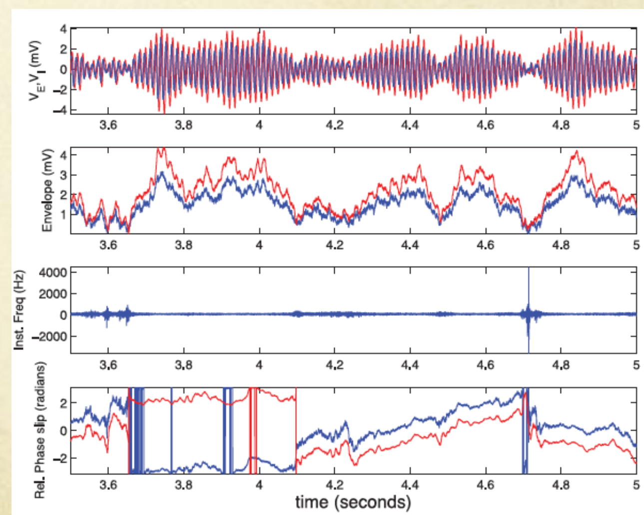


Wallace et al., 2011

Noisy limit cycles or quasi-cycles?

- Both models can generate narrow band oscillations
- Both models generate bursting, but with different mechanisms
- Both models generate a physiological range of local field potential oscillation frequencies
- We need new methods to distinguish the mechanism in data from brain recordings

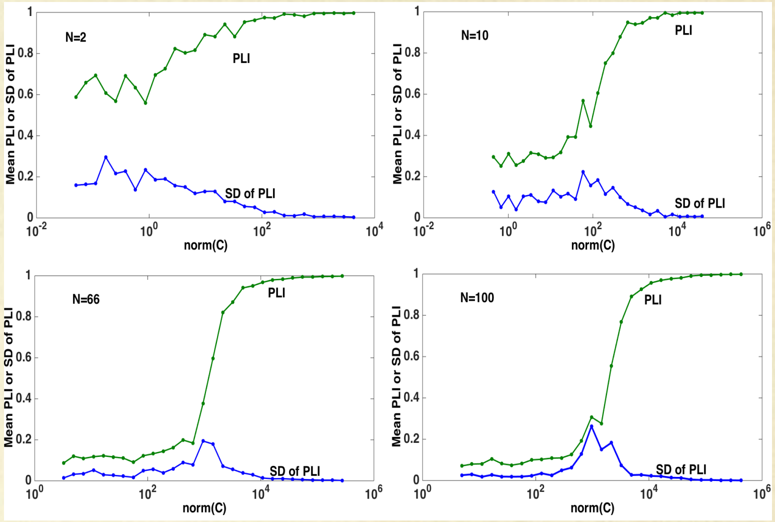




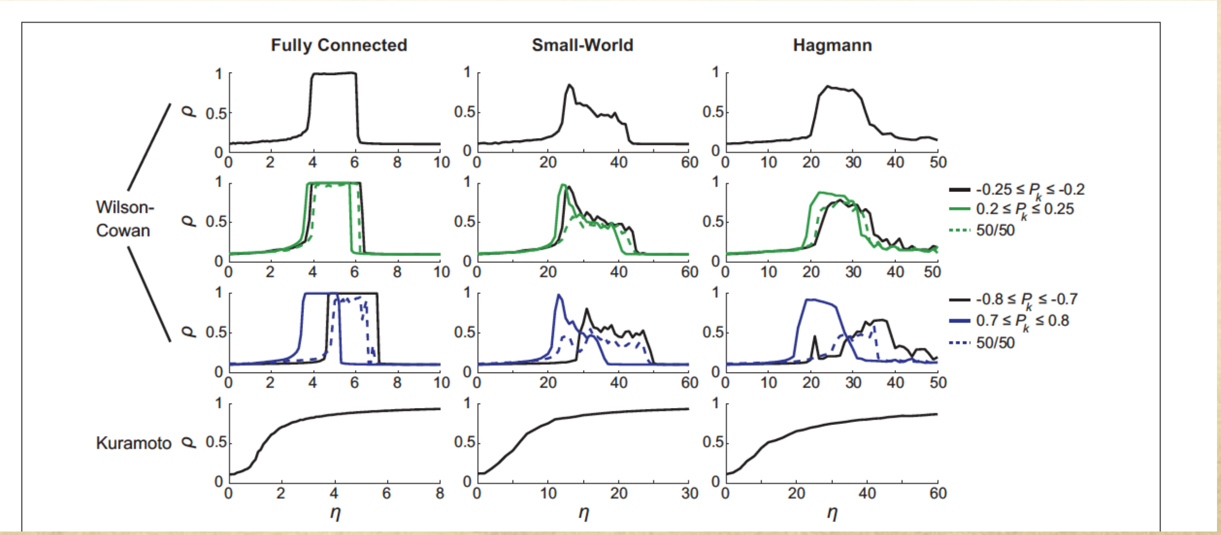
Greenwood, McDonnell, Ward, 2015, *Neural Computation*

Noisy synchronization?

- Noise can enhance synchronization between oscillators
- Both noisy limit cycles and quasi-cycles display synchronization between distant populations
- Synchronization is supposed to benefit neural information transfer
- Does noise benefit information transfer via synchronization?



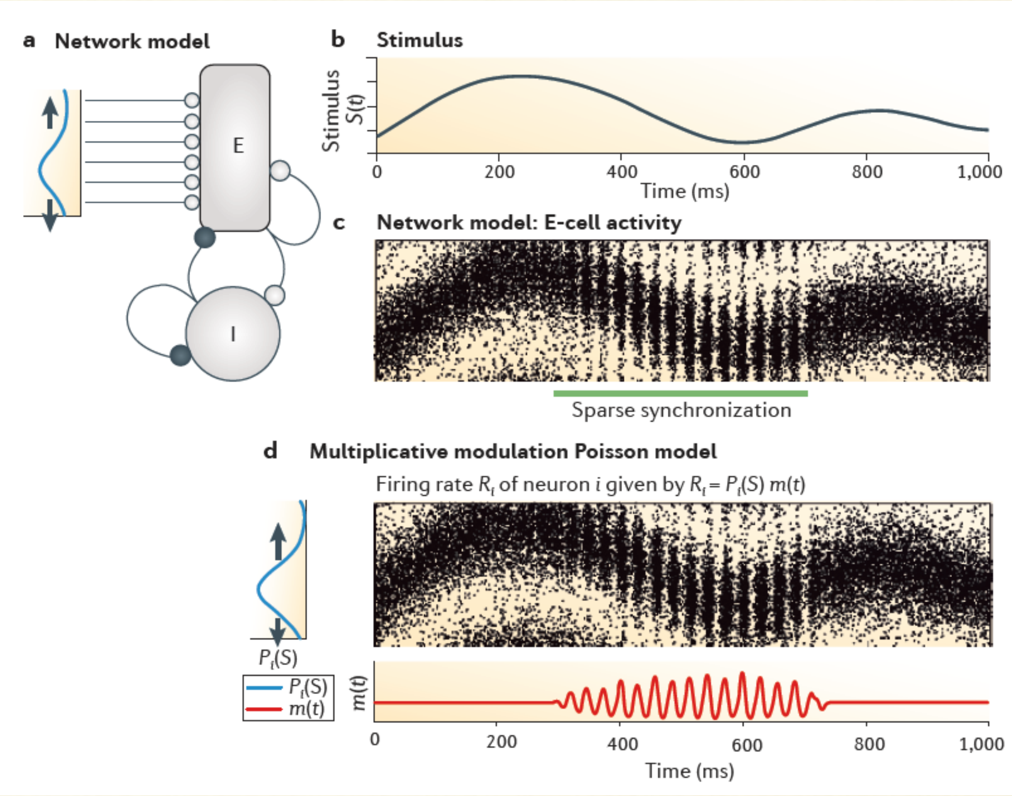
Greenwood, McDonnell, Ward, 2015, unpublished



Daffertshoffer & vanWijk, 2011, *Frontiers*

Noisy multiplexing?

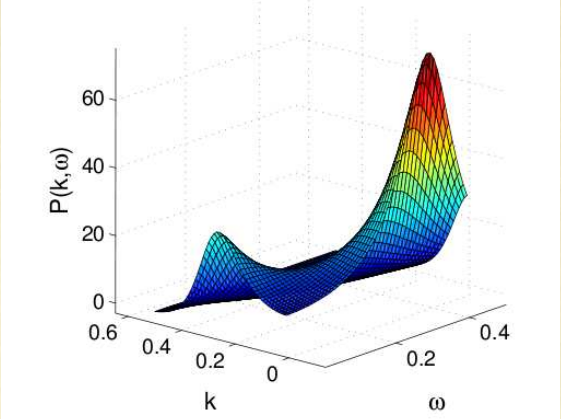
- Population neural codes are noisy – sparse neural firing
- Noisy oscillations can be modulated by a signal and decoded at another area to recover the signal
- Does the noise play a computational role? Via quasi-cycles?



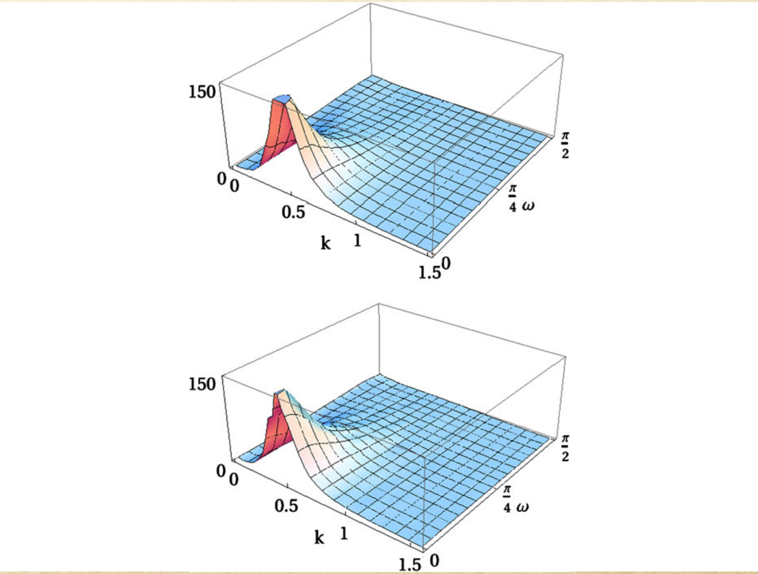
Akam & Kullman, 2014, *Nat Rev Neurosci*

Spatial quasi-patterns?

- Noise-driven systems can exhibit both quasi-cycles and quasi-patterns
- Quasi-patterns are analogous to quasi-cycles but are spatial and characterized by a wave number instead of a frequency
- Demonstrated in predator-prey and epidemiological models.
- Quasi-patterns of quasi-cycles in brains? Do they affect information processing and information transmission?



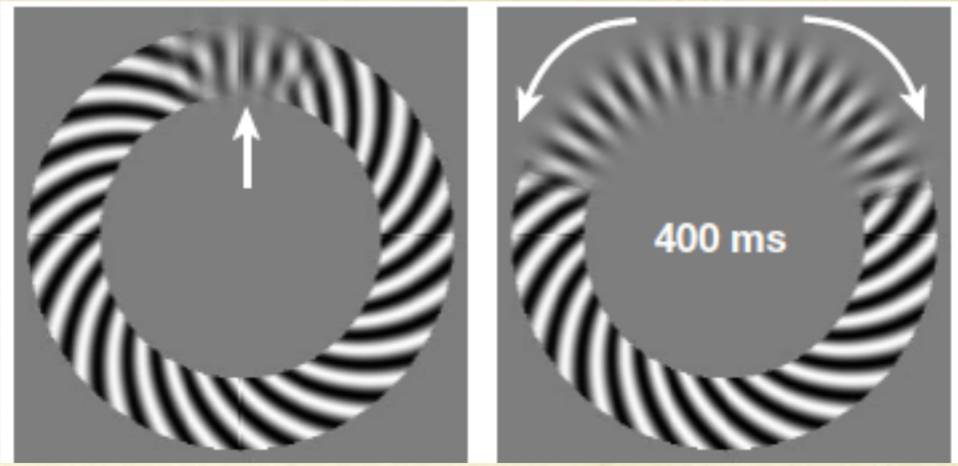
Butler & Goldenfeld, 2011, *PRE*



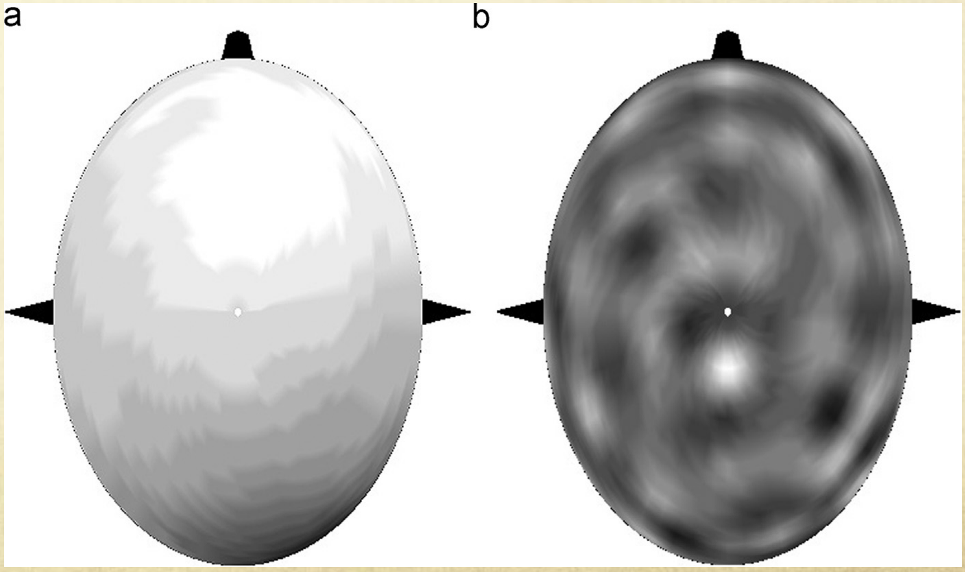
McKane et al, 2014, *Bull Math Biol*

Cortical waves

- Binocular-rivalry-induced cortical traveling waves: waves of dominance move across the visual cortex as perception of dominant stimulus changes
- EEG standing alpha (8-12 Hz) waves: areas with similar colour are roughly in phase; dark and light are 180 deg out of phase.



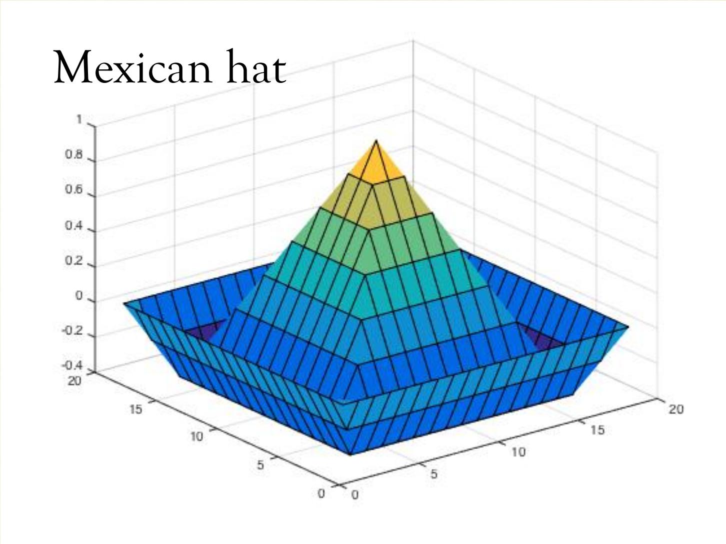
Wilson, Blake, Lee, *Nature*, 2001

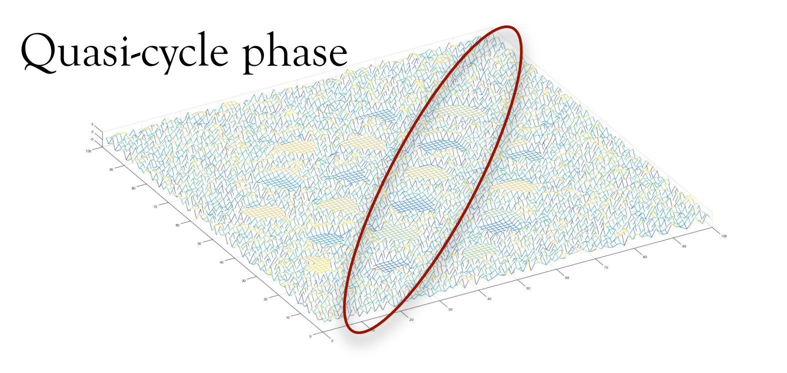


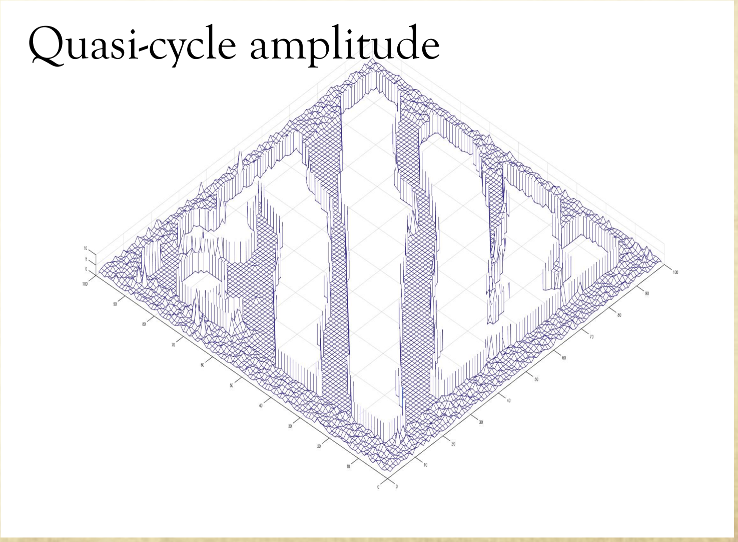
Nunez & Srinivassan, *Brain Research*, 2014

Mexican Hat coupling on a 100 x 100 lattice of stochastic E-I processes

- Quasi-cycles at ~70 Hz at each lattice location
- Local Mexican hat coupling only; run for 10,000 iterations
- Quasi-Turing patterns at ≈ 5-6 cycles in amplitudes (100/19=5.26)
- Little mathematical understanding







Greenwood & Ward, 2015, unpublished

Summary

- Noisy limit cycles or quasi-cycles?
- Noise-driven synchronization and information transfer?
- Spatial quasi-patterns mixed with noisy or noise-driven oscillations?