Neural activity sequence in prefrontal cortex for sensory-guided decision making

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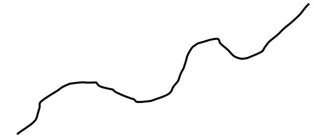
I got a PhD in theoretical particle physics.

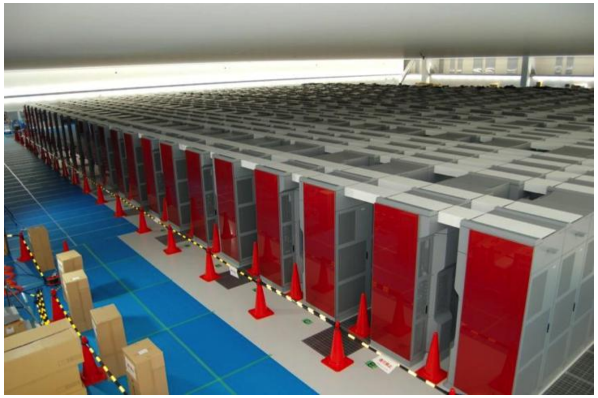


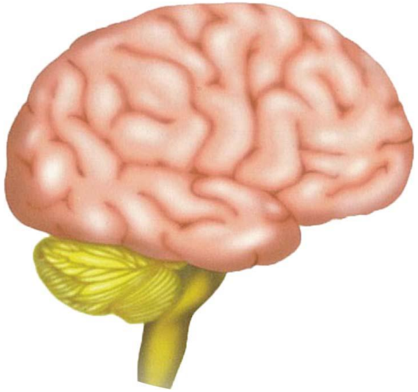
Then, I shifted to statistical physics of Hopfield network model.

Then, I further shifted to more biological network models, and started to collaborate with experimentalists.

Brain computation is probabilistic

Computer versus Brain





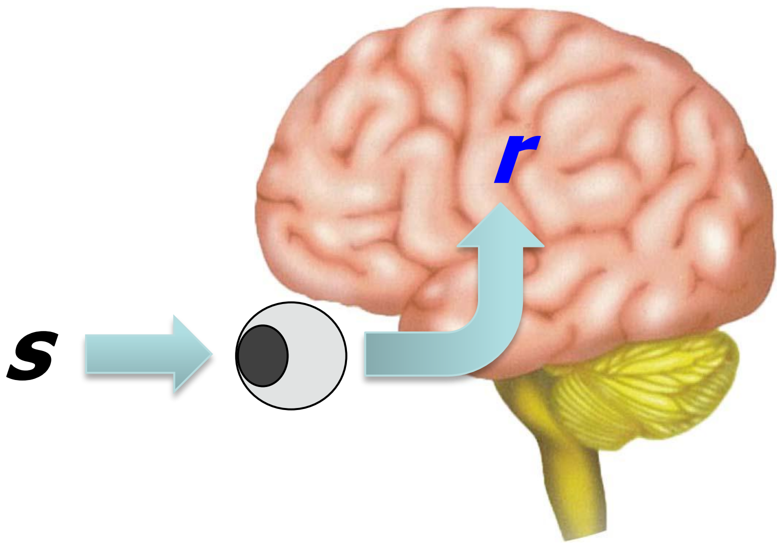
Computer	Brain
Binary representation	Spike sequences
Serial sequential	Parallel Distributed
Deterministic	**Probabilistic inference**
Execute prescribed programs	**Reward-based learning**
High energy consumption	**Ecological**

Noise improves visual perception

(Stochastic resonance)

E. Simonotto et al., Phys Rev Lett (1997)

Stochastic sampling by the brain = Bayesian inference



Physical events in the brain：
stimulus *s* → response *r*

Brain computes :
response *r* → stimulus *s*

$$P(s\,|\,r) = \frac{P(r\,|\,s)P(s)}{P(r)}$$

$P(s)$ Prior = Knowledge on possible sensory events

$P(s\,|\,r)$ Posterior = Knowledge on sensory events when the response *r* is known

$$P(r) = P(r\,|\,s_1)P(s_1) + P(r\,|\,s_2)P(s_2) + \cdots = \sum_s P(r\,|\,s)P(s)$$

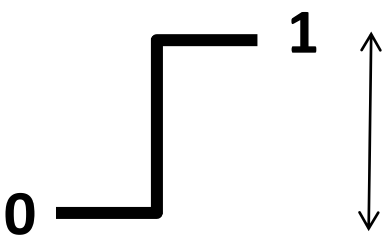
Prior is the internal model of the external world

Spontaneous cortical activity gives a prior (Berkes et al., 2011)

Why is noise interesting?

How does the brain keep energy consumption so low?

Energy consumption vs noise tolerance in electric computers

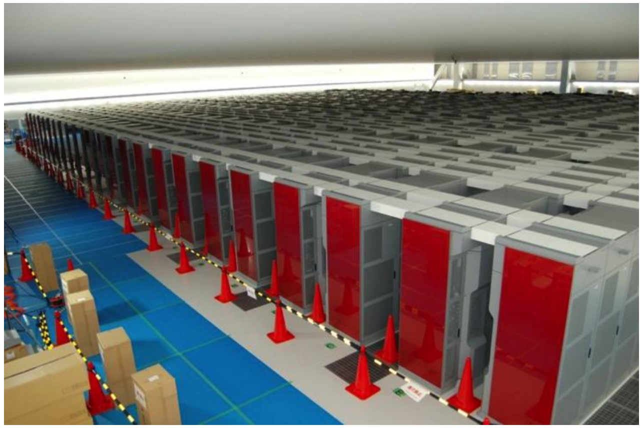


E [V] ~ 1.5 V

Energy µ E^2

12.7 MW = 30, 000 families!

K computer



1. Neural population dynamics in probabilistic decision-making

2. Mechanism of innate sequence generation in the neocortex and hippocampus

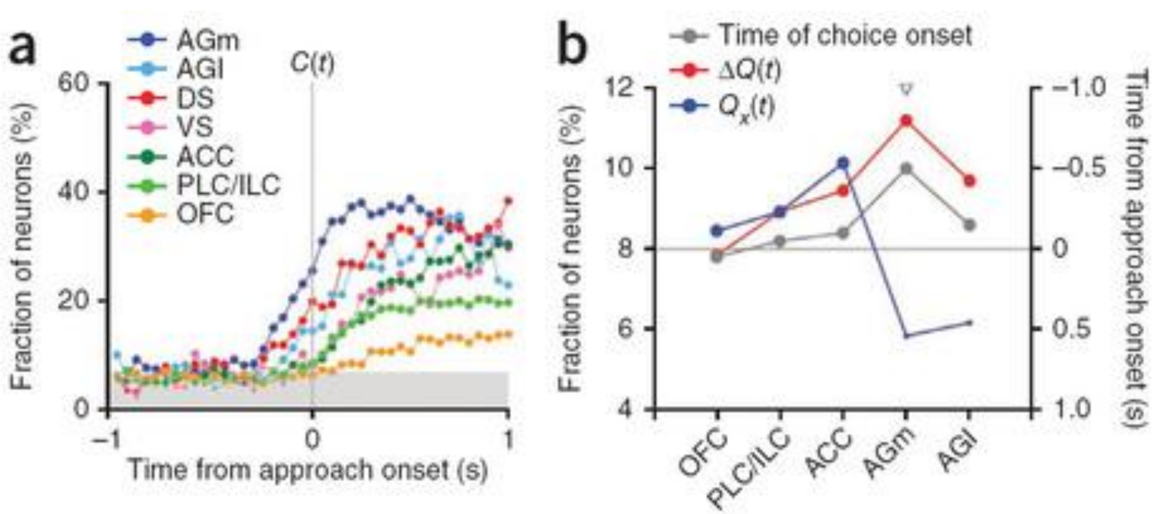
Sensory-guided choices by medial agranular cortex (AGm)

AGm receives afferents from sensory (visual, auditory, somatosensory) cortices and sends efferents to motor areas (M1, spinal cord, and brainstem).

AGm is reciprocally connected with mediodorsal (MD) motor thalamic nucleus (Reep *et al.*, 1984,1987,1990; Conde *et al.*, 1995)**.**

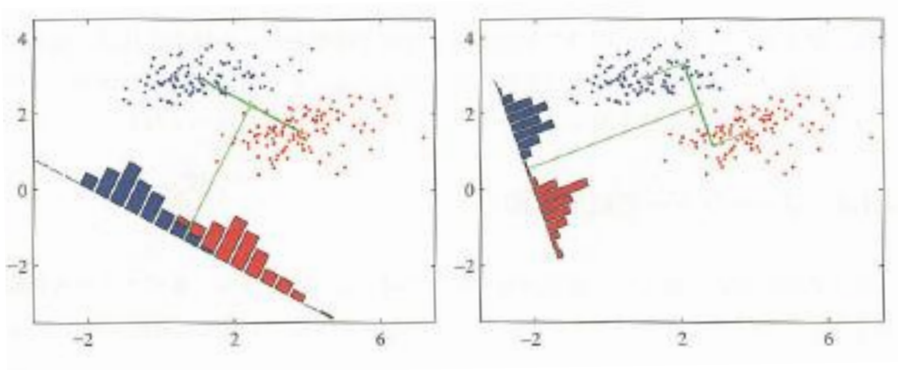
Unilateral inactivation impairs sensory-based movement selection towards contralateral orientation (Crowne and Pathria, 1982; Erlich *et al.*, 2011)**.**

AGm is activated eariler tham any other regions of the rat brain (Sul et al., 2011)**.**

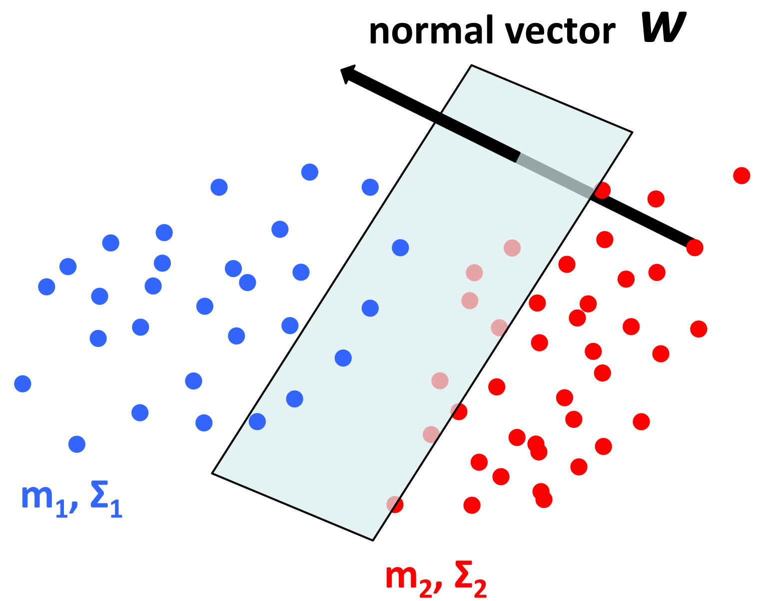


Fisher's linear discriminant

"Bad" **"Good"**



(Bishop, *"Pattern Recognition and Machine Learning"*)



Degree of discrimination

$$S = \frac{(\mathbf{w}^T\mathbf{m}_1 - \mathbf{w}^T\mathbf{m}_2)^2}{\mathbf{w}^T S_t \mathbf{w}} = \frac{\text{between-class variance}}{\text{within-class variance}} = d'^2$$

discriminating vector $$\mathbf{w} \propto S_{tot}^{-1}(\mathbf{m}_2 - \mathbf{m}_1)$$

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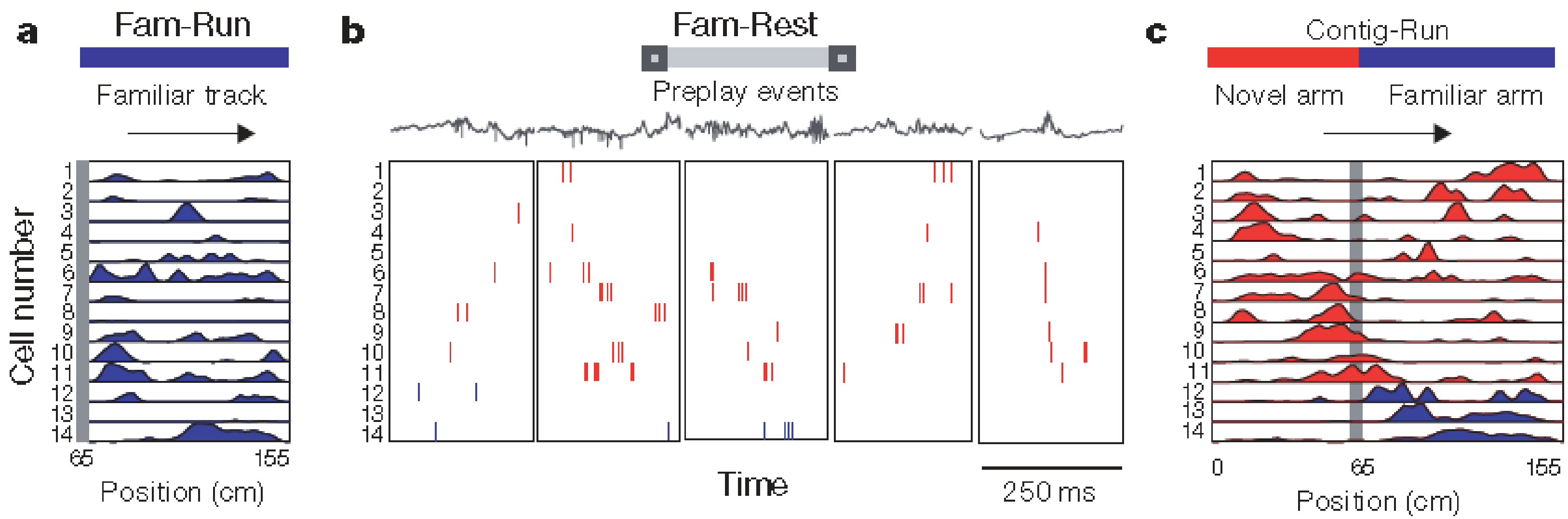
Preplay of future place cell sequences



Hippocampal CA1 (Dragoi and Tonegawa, Nature 2011)

Probably the preplay reflects sequences in CA3

Spontaneous neuronal activity preceding a novel spatial experience may prime and contribute to the formation of new spatial representations via a neuronal ensemble selection process

(Dragoi and Tonegawa, PNAS 2013)

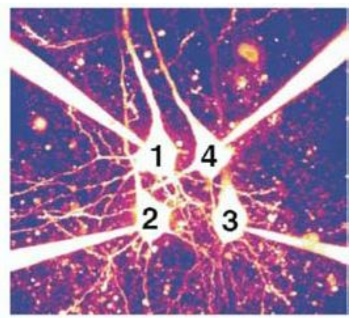
Heavy-tailed EPSP distributions of cortical synapses

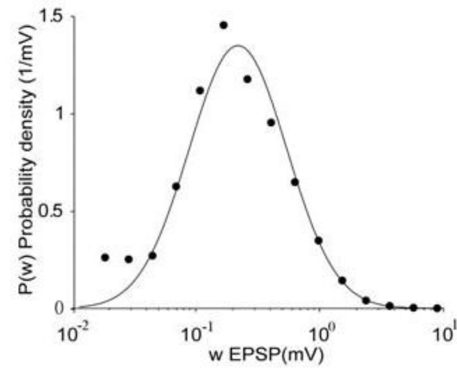
Strong-sparse synapses vs. weak-dense synapses

Brain’s machinery to generate noise?

rat visual cortex

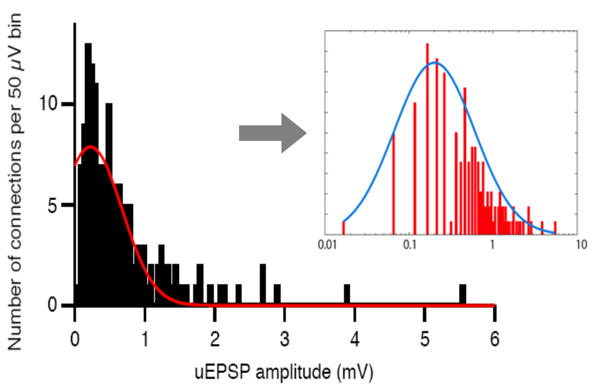
Song et al., PLoS Biol (2005)





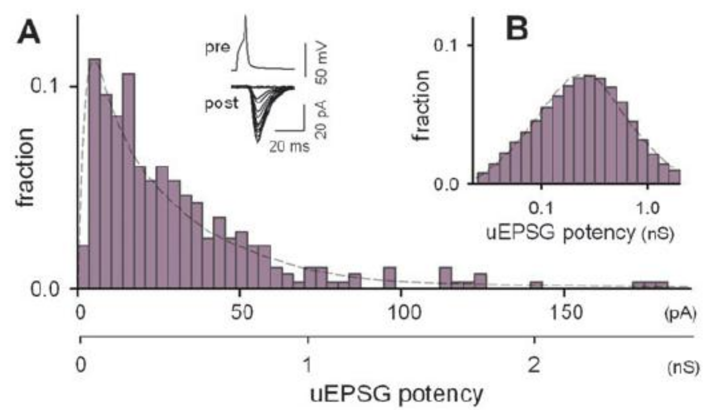
mouse somatosensory cortex

Lefort et al. Neuron (2009)



rat hippocampus

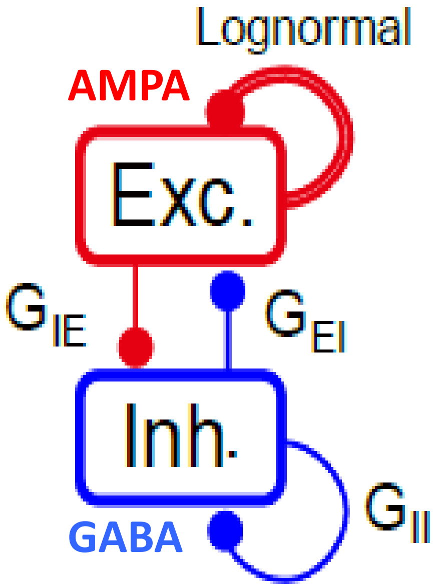
Ikegaya et al., Cereb Cortex (2013)

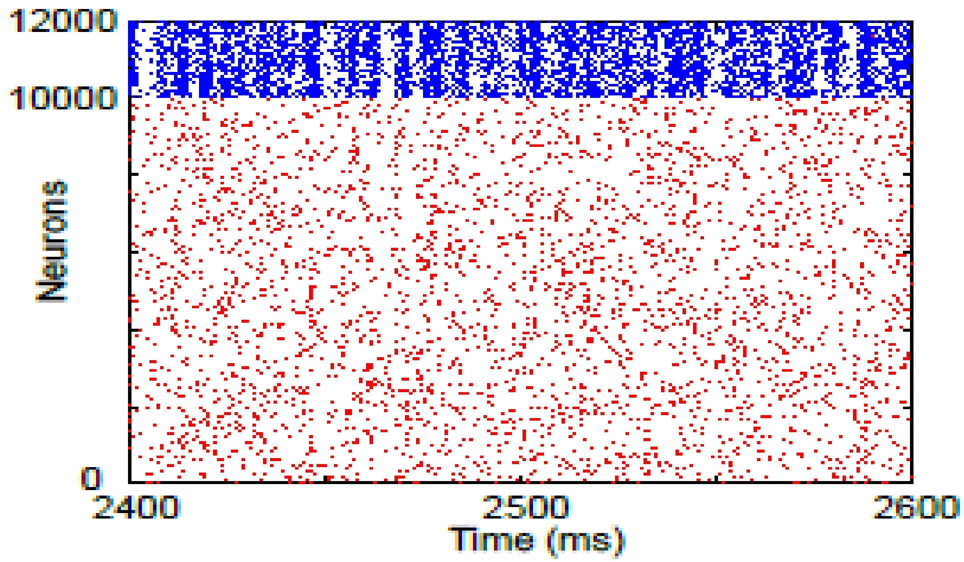


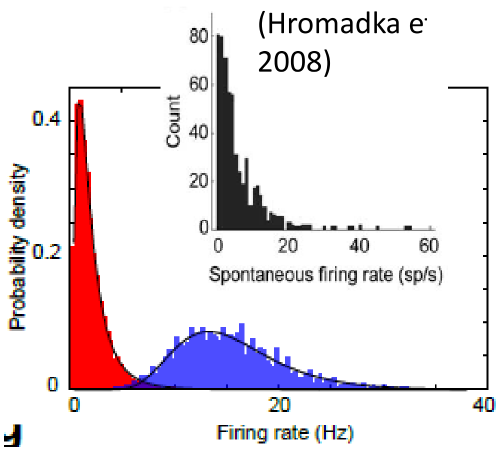
LgN wgt distribution generates spontaneous activity in recurrent networks

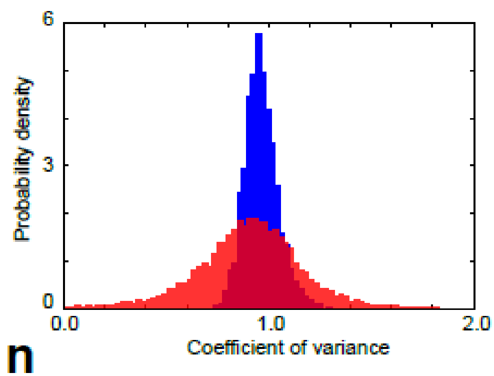
Jun-nosuke Teramae
→ Osaka University

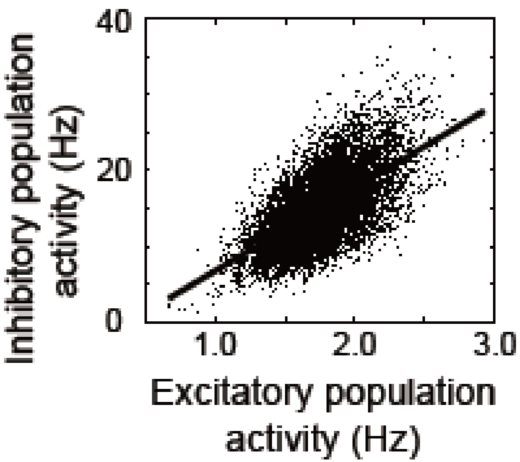
Teramae, Tsubo and Fukai (Sci Rep, 2012)



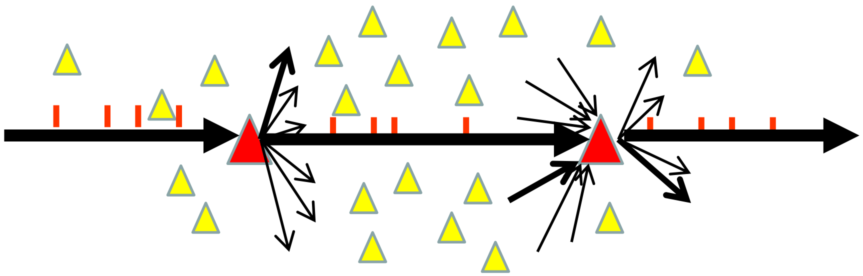


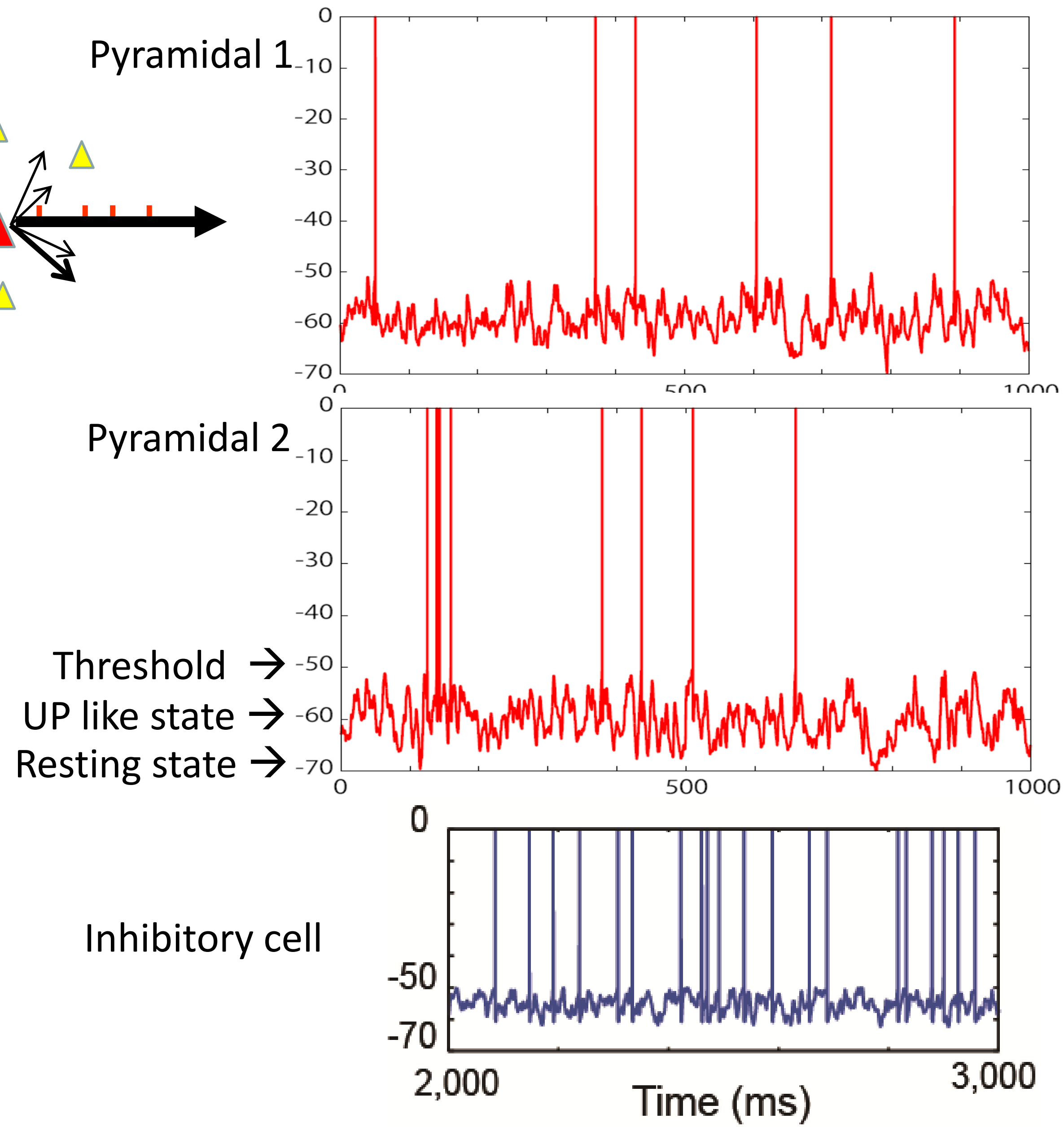




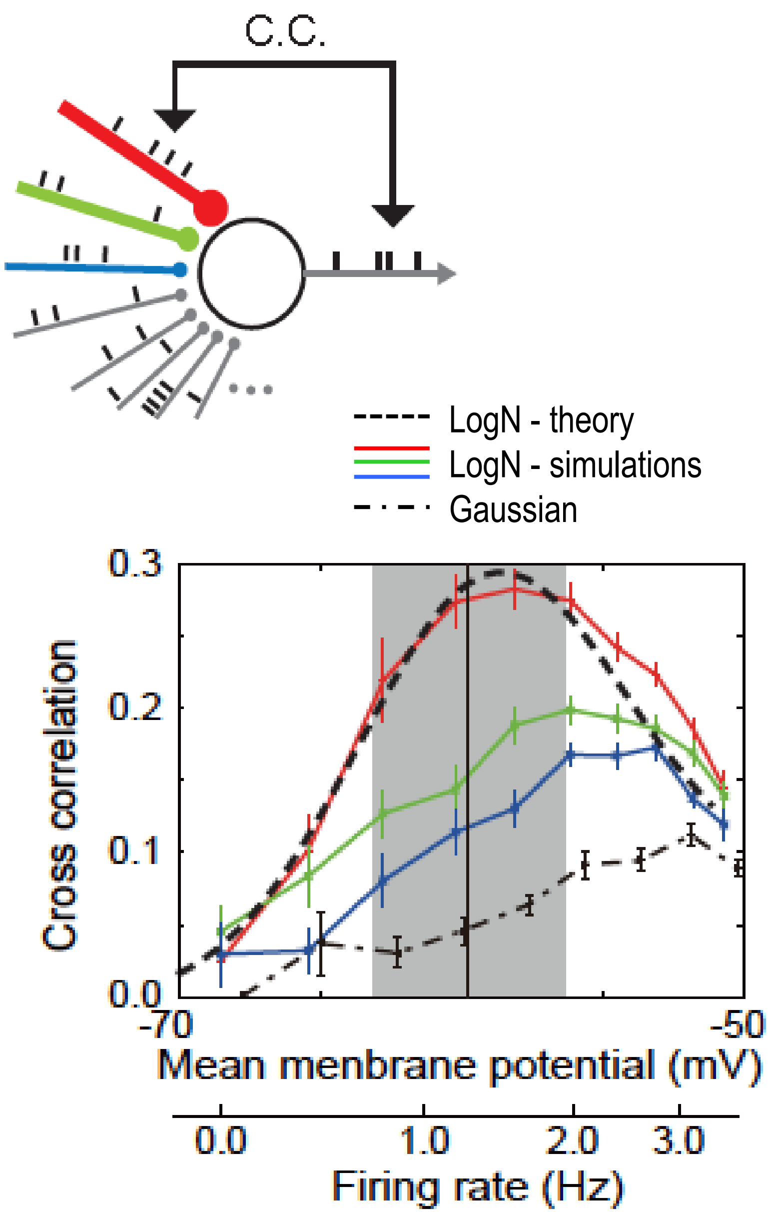


Membrane potential fluctuates in the optimal range



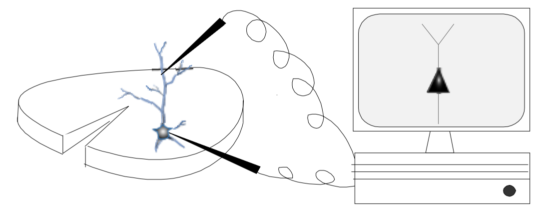


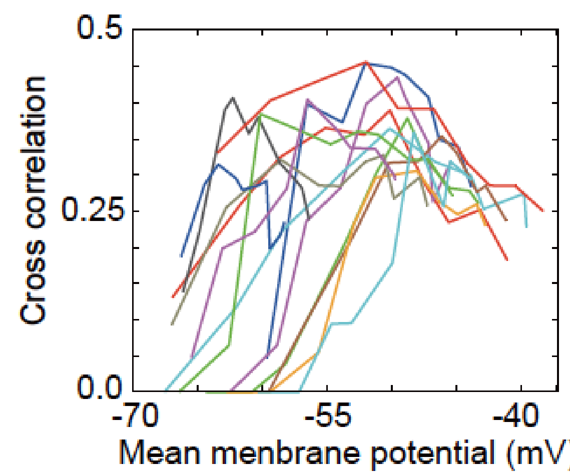
Lognormal (long-tailed) EPSP distributions generate optimal noise



Dynamic clamp

$$I_{\mathrm{syn}}(t) = -\sum_j g_{\mathrm{E},j}(t)(V - E_{\mathrm{E}}) - \sum_j g_{\mathrm{I},j}(t)(V - E_{\mathrm{I}})$$

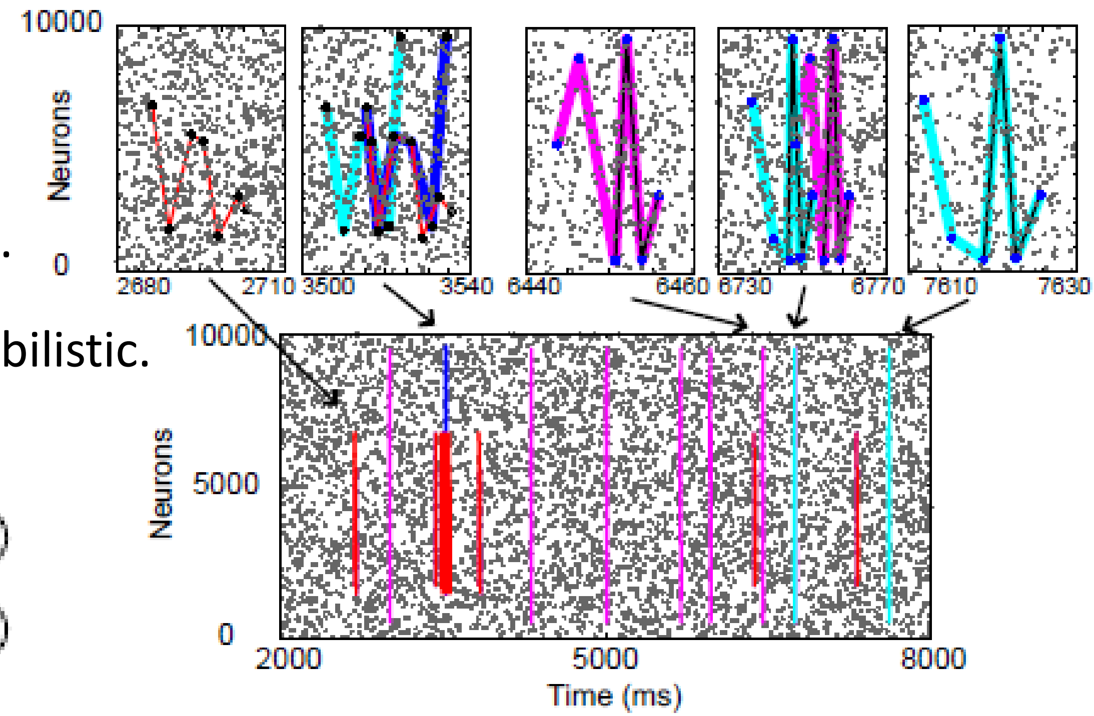


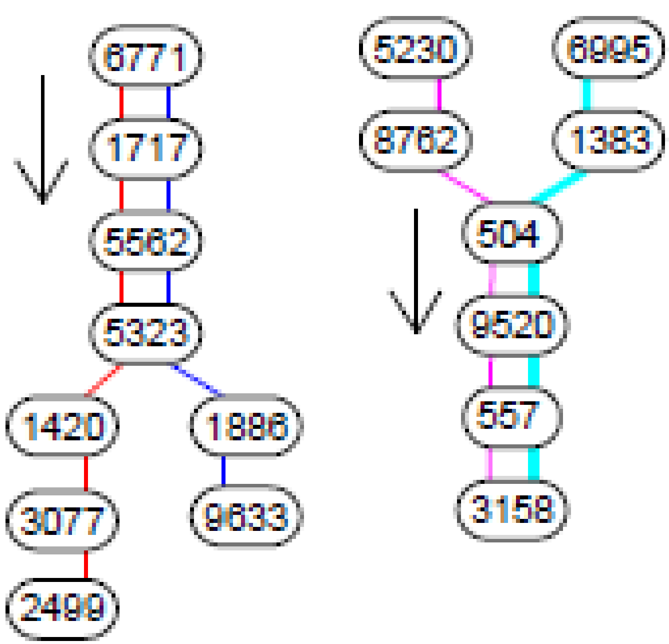


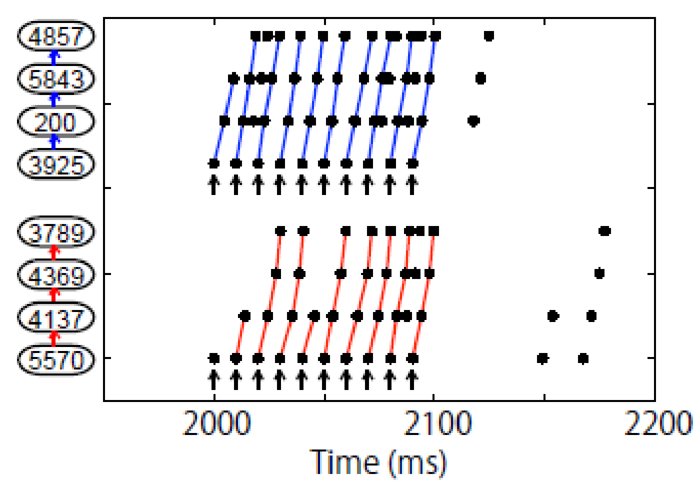
Teramae, Tsubo and Fukai (Sci Rep, 2012)

The noisy state consists of many spike sequences

- Sequences can be stretched or compressed.
- Sequences can branch or merge.
- Sequences propagation is probabilistic.







Summary

- Lognormal (long-tailed) EPSP distributions found in the neocortex and hippocampus embed sequences into asynchronous irregular states of cortical circuits.
- Such a distribution generates internal noise for enabling stochastic resonance.