Twenty projects with Galves-Loecherbach stochastic elements

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Background: Scientific Reports paper

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Phase transitions and self-organized criticality in networks of stochastic spiking neurons

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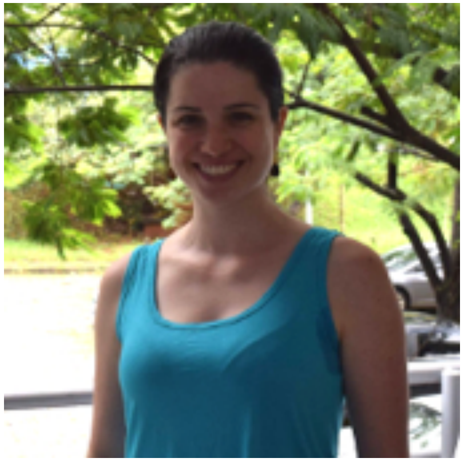
Phase transitions and critical behavior are crucial issues both in theoretical and experimental neuroscience. We report analytic and computational results about phase transitions and self-organized criticality (SOC) in networks with general stochastic neurons. The stochastic neuron has a firing probability given by a smooth monotonic function $\Phi(V)$ of the membrane potential V, rather than a sharp firing threshold. We find that such networks can operate in several dynamic regimes (phases) depending on the average synaptic weight and the shape of the firing function Φ. In particular, we encounter both continuous and discontinuous phase transitions to absorbing states. At the continuous transition critical boundary, neuronal avalanches occur whose distributions of size and duration are given by power laws, as observed in biological neural networks. We also propose and test a new mechanism to produce SOC: the use of dynamic neuronal gains – a form of short-term plasticity probably located at the axon initial segment (AIS) – instead of depressing synapses at the dendrites (as previously studied in the literature). The new self-organization mechanism produces a slightly supercritical state, that we called SOSC, in accord to some intuitions of Alan Turing.

Collaborators at NEUROMAT



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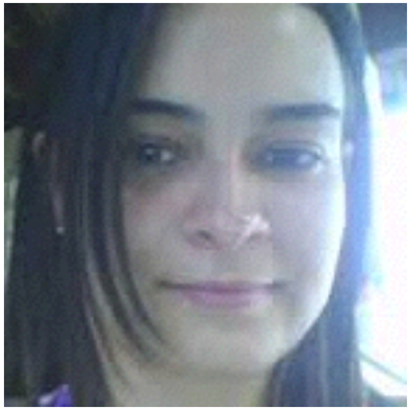


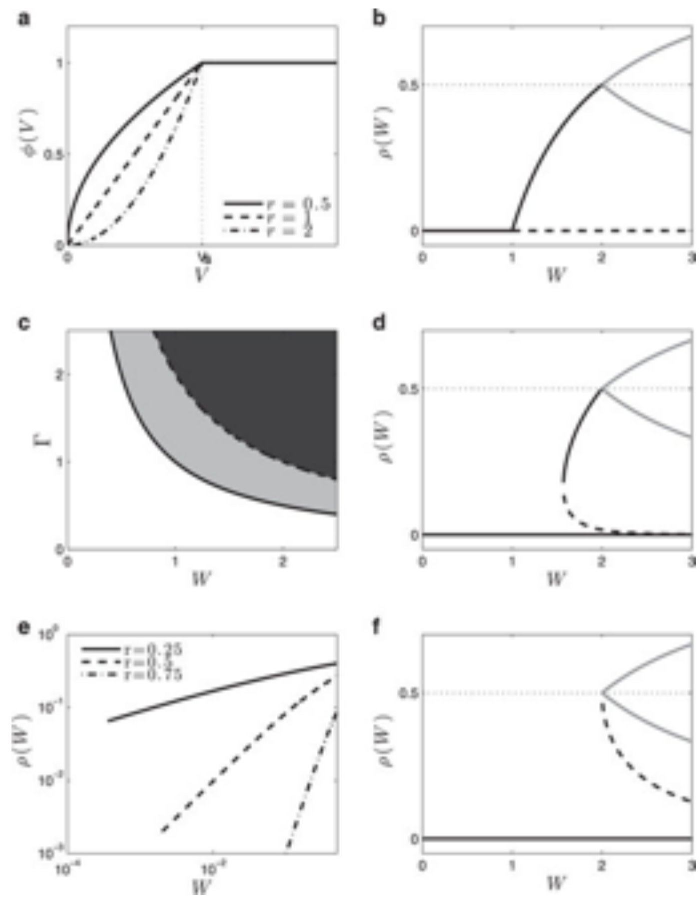
Ariadne A. Costa

http://neuromat.numec.prp.usp.br/team

Antônio C. Roque

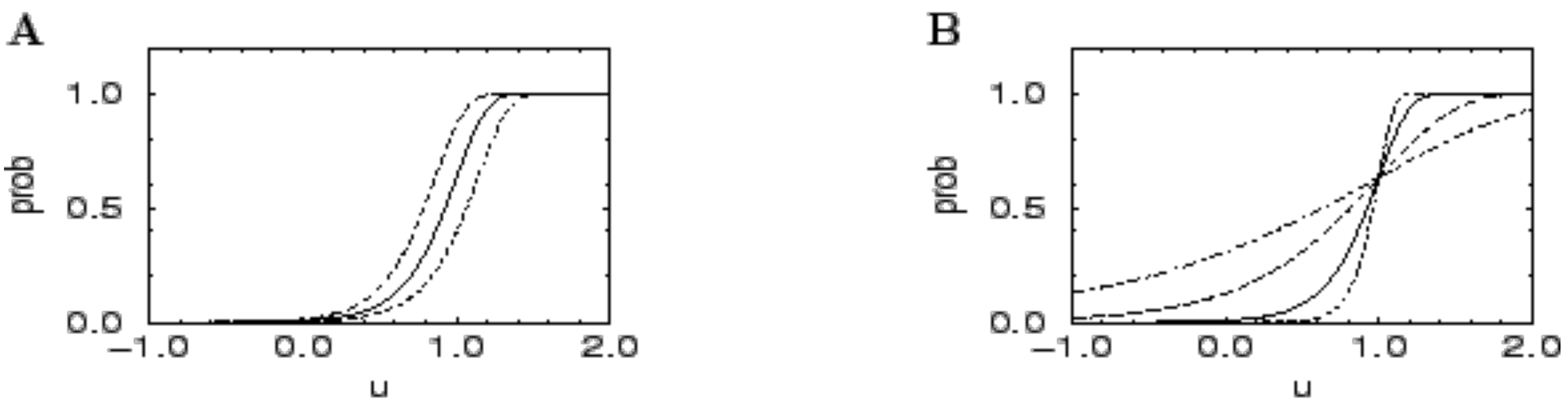
The GL stochastic element in voltage representation

- X_i = post-synaptic neuron, X_j = pre-synaptic neuron
- $X_j[t] = 0$ (not firing), $X_j[t] = 1$ (firing)
- $V_i[t+1] = \mu V_i[t] + I_{ext} + \sum W_{ij} X_j[t]$ if $X_j[t] = 0$
- $V_i[t+1] = 0$ if $X_j[t] = 1$
- $P(X=1| V) = \Phi(V)$



1. NEUROSCIENCE: COMPARISON OF GL NEURONS WITH GESTNER'S ESCAPE-NOISE (EN) NEURON

Novelty: To relate and compare GL neurons with EN neurons (Gerstner, 2002) [12].



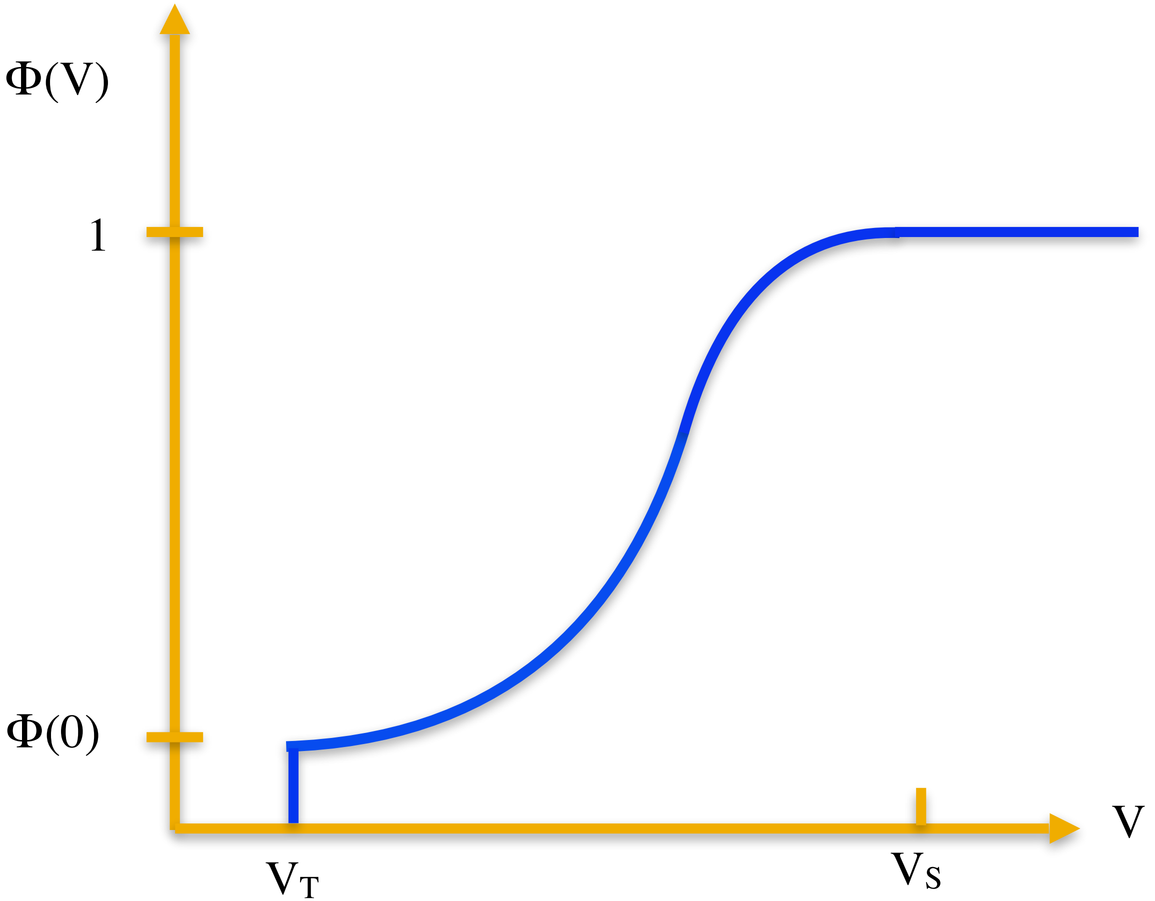
Escape rate model, discrete time version:

$$V[t+1] = \mu V[t] + I_{syn}[t] + I_{ext}[t]$$

$$P(X = 1 \mid V) = \text{sigmoid function}$$

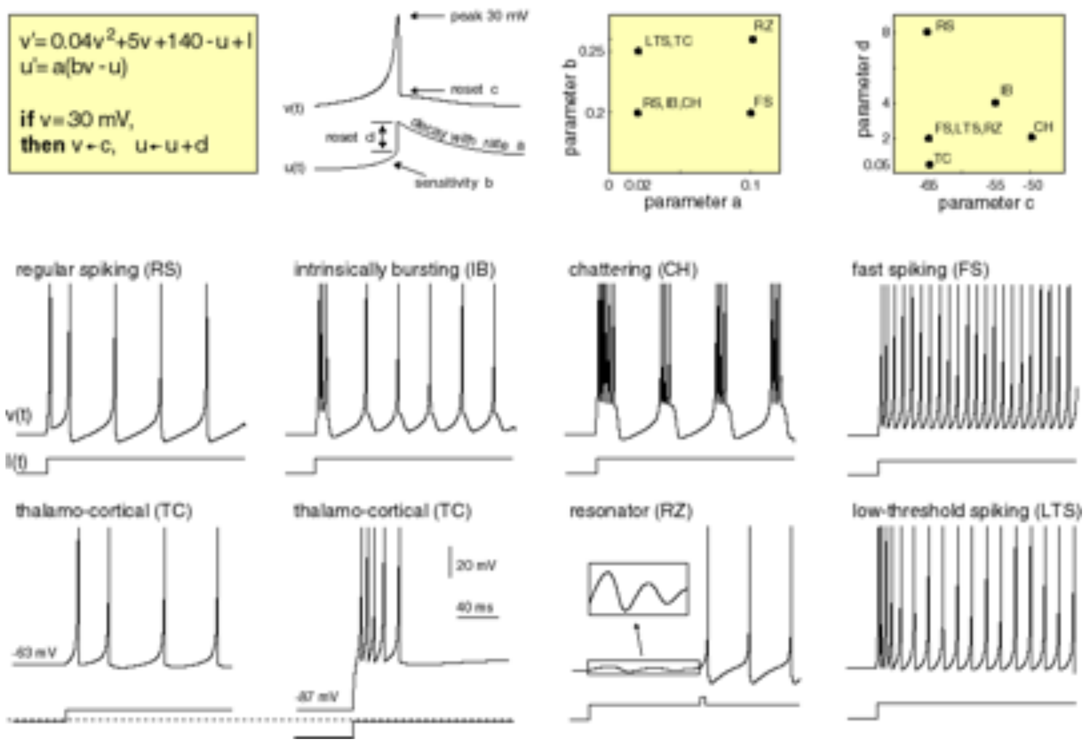
2. NEUROSCIENCE: DIFFERENT $\Phi(V)$ FUNCTIONS

Novelty: To explore different and more general $\Phi(V)$ functions.



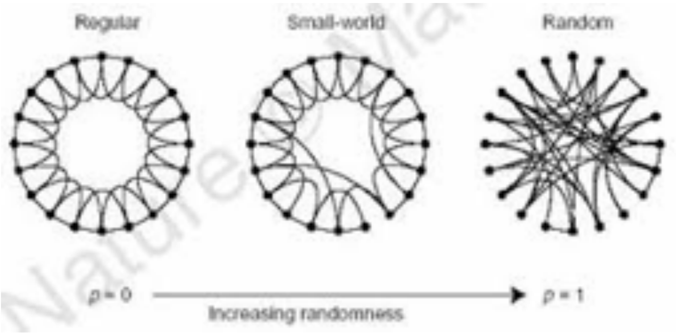
3. NEUROSCIENCE: SINGLE NEURONS

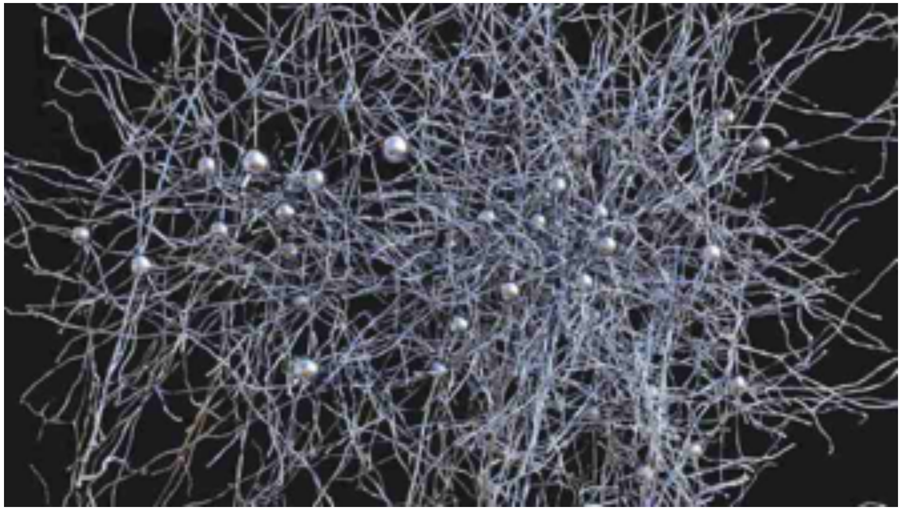
Novelity: model different types of neurons by using the GL formalism



4. NEUROSCIENCE: DIFFERENT NETWORK TOPOLOGIES

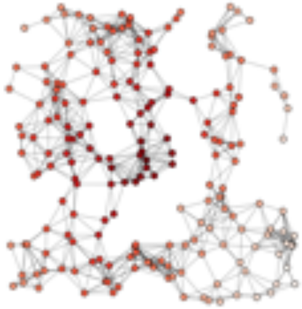
Novelty: To obtain results for GL networks with different topologies that are motivated by biological data and compare them with mean-field solutions obtained by [5].





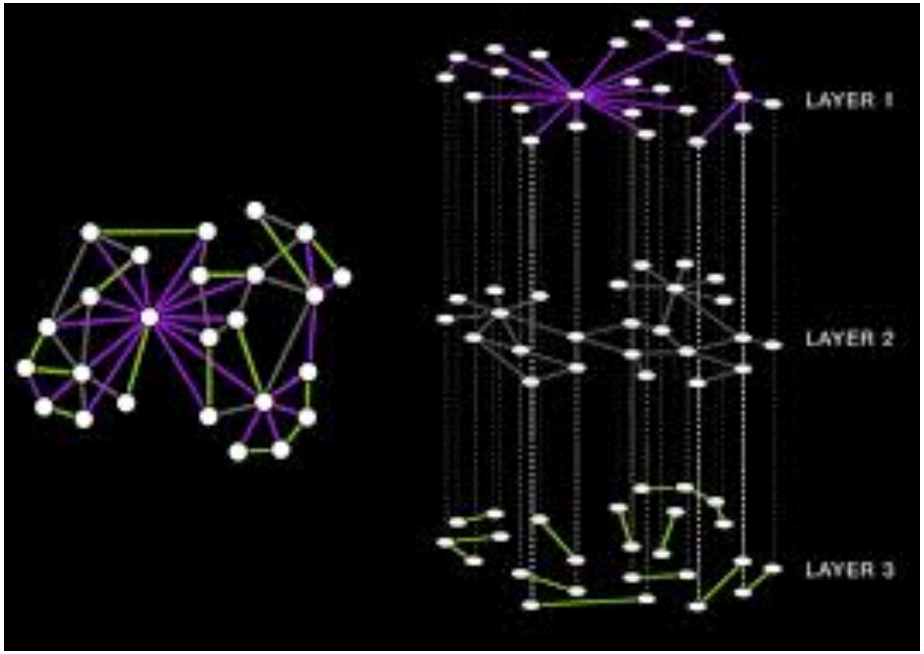
This is a network of neurons reconstructed with large-scale electron microscopy. Credit: Clay Reid, Allen Institute; Wei-Chung Lee, Harvard Medical School; Sam Ingersoll, graphic artist.

Scale-free network



5. NEUROSCIENCE: LAYERED NETWORKS

Novelty: Architectures with layered networks and possible Psychophysics interpretation.



For a single layer (Kinouchi and Copelli, *Nat. Phys.* **2**, 2006):

Out criticality: $\rho = c\, I$
At criticality: $\rho = c\, I^m$, $m = 1/2 < 1$
Enlarged dynamic range
m = Stevens Psychophysical Exponent

What occurs if we couple *n* layers?
Out of criticality, nothing:
At criticality, $\rho = c\, I^{m'}$?
$m' = m^n$
New psychophysical exponents?
Larger dynamic range?

6. NEUROSCIENCE: DIFFERENT GAINS AND SYNAPTIC DYNAMICS

Novelty: Simpler self-organization rules for the synapses and neuronal gains with mean-field analytic results.

$$\Gamma_i[t+1] = \Gamma_i[t] + \frac{1}{\tau}(A - \Gamma_i[t]) - u\Gamma_i[t]X_i[t]$$

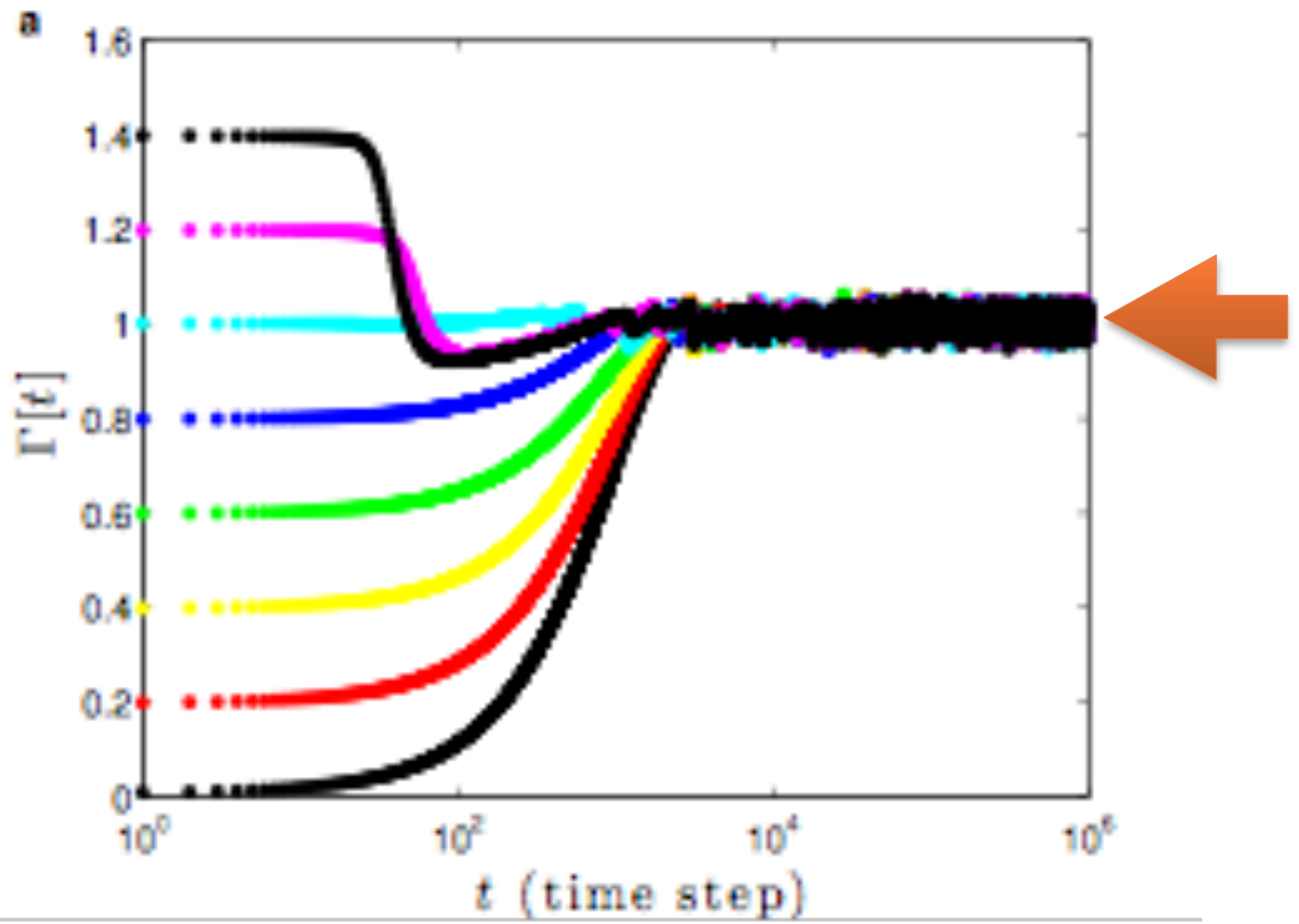
Brochini *et al.*, 2016

New proposal:

$$\Gamma_i[t+1] = \Gamma_i[t] + \frac{1}{\tau}\Gamma_i[t] - \Gamma_i[t]X_i[t] = \left(1 + \frac{1}{\tau} - X_i[t]\right)\Gamma_i[t]$$

$$\Gamma^* = (1 + 1/\tau)\,\Gamma_c$$

Self-organization of the average gain toward the critical region

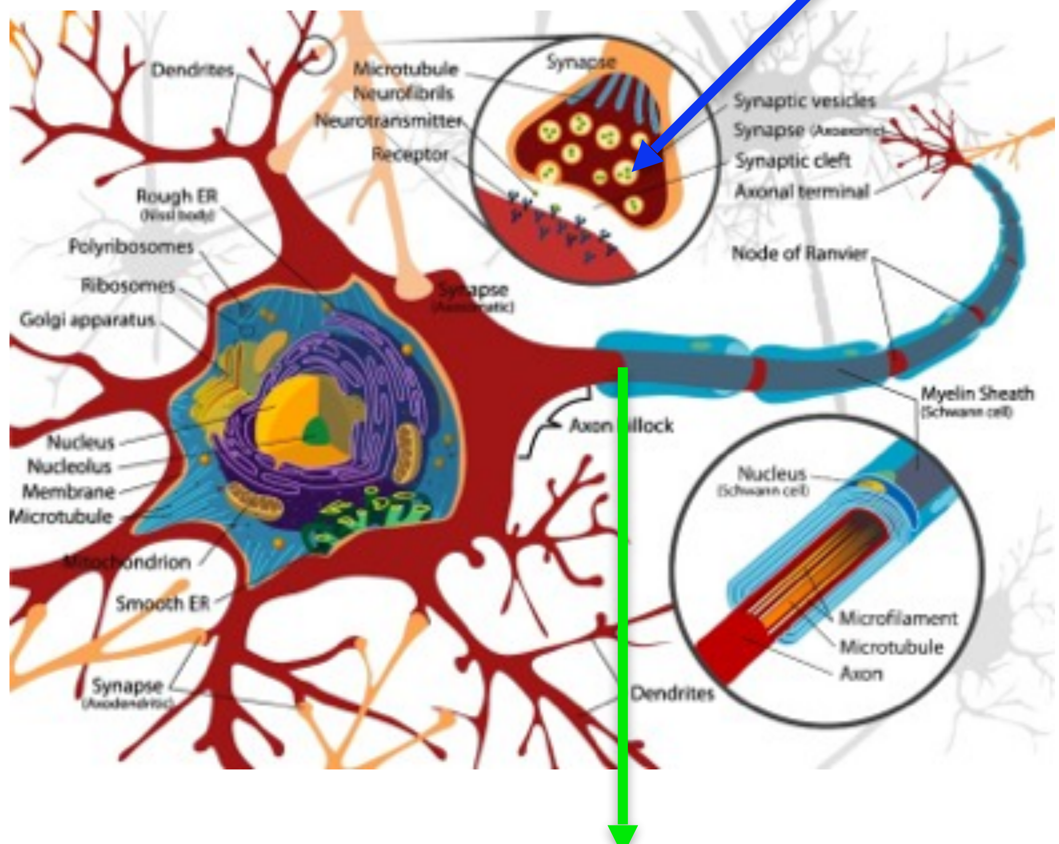


$\Gamma^* \rightarrow \Gamma_c$

Why to separate the average gain Γ from the average synaptic weight W?

- In a biological network, each neuron i has a neuronal gain $\Gamma_i[t]$ located at the *Axonal Initial Segment* (AIS). Its dynamics is linked to sodium channels.
- The synapses $W_{ij}[t]$ are located at the dendrites, very far from the axon. Its dynamics is due to neurotransmitter vesicle depletion.
- So, although in our model they appear always together as ΓW, this is due to the use of point like neurons. A neuron with at least two compartments (dendrite + soma) would segregate these variables.

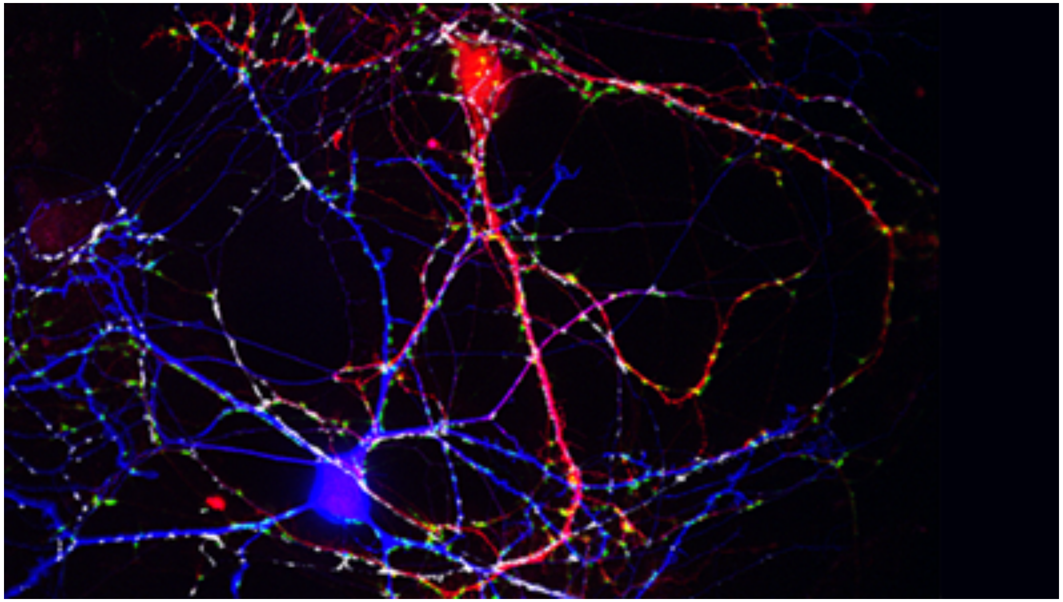
$W_{ij}[t]$



AIS, $\Gamma_i[t]$

7. NEUROSCIENCE: INHIBITORY NEURONS

Novelty: Explore the effect of inhibitory neurons in GL networks.

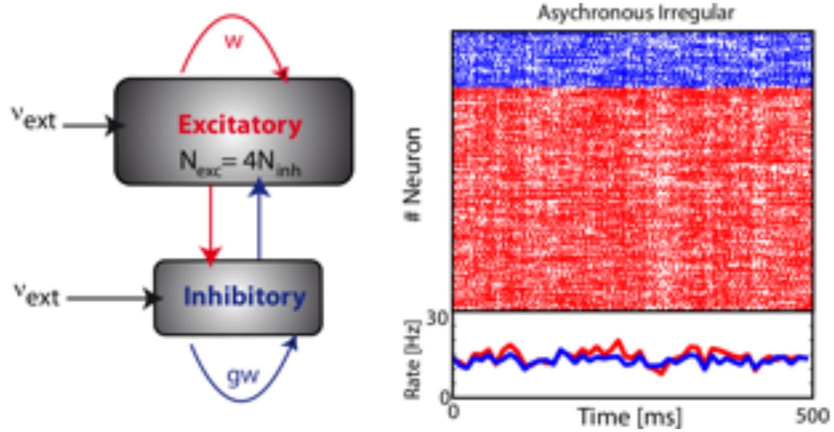


Brain activity is a balancing act — some brain cells are tasked with keeping others in check. This image of brain neurons cultured from a mouse shows this interaction: the "inhibitory" neuron (blue) sends signals that can prevent the "excitatory" neuron (red) from firing. Studying these inhibitory neurons in a dish could reveal important clues about how they regulate the activity of more complex brain circuits. Source: Society for Neuroscience

8. NEUROSCIENCE: SELF-ORGANIZED BALANCED NETWORKS

Novelty: A mechanism to self-organized GL networks toward the balanced state based in local balance dynamics of the g ratio.

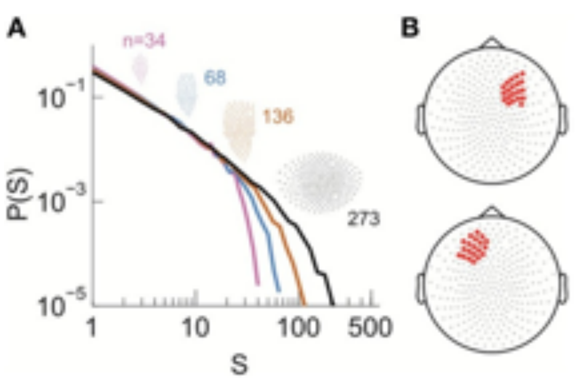
$$g = W_I / W_E$$

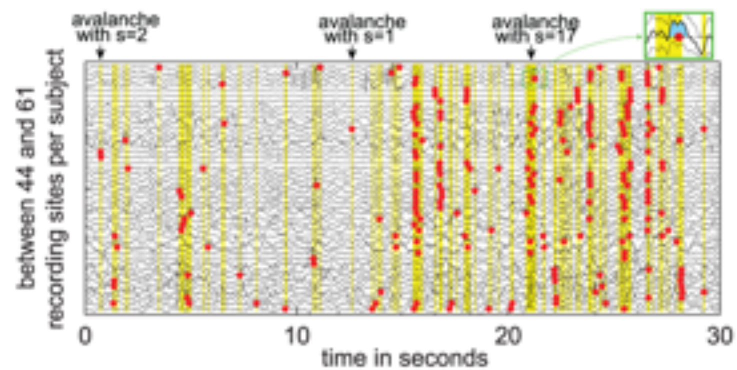


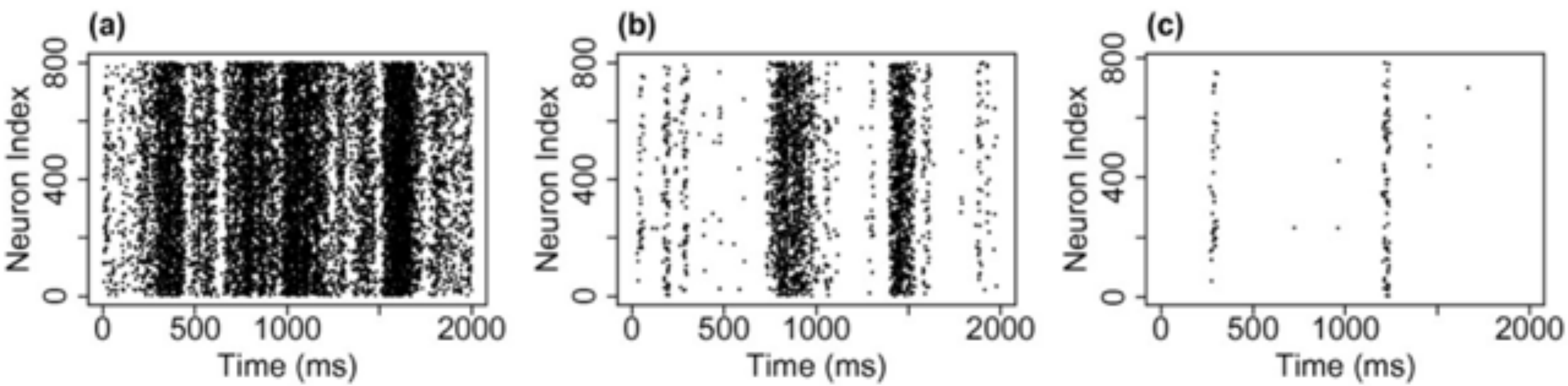
$$g_i[t+1] = g_i[t] + 1/\tau g_i[t] - X_i[t]$$

9. NEUROSCIENCE: SUBSAMPLING IN CRITICAL AND SUPERCRITICAL NETWORKS

Novelty: To examine the effect of subsampling in GL networks.



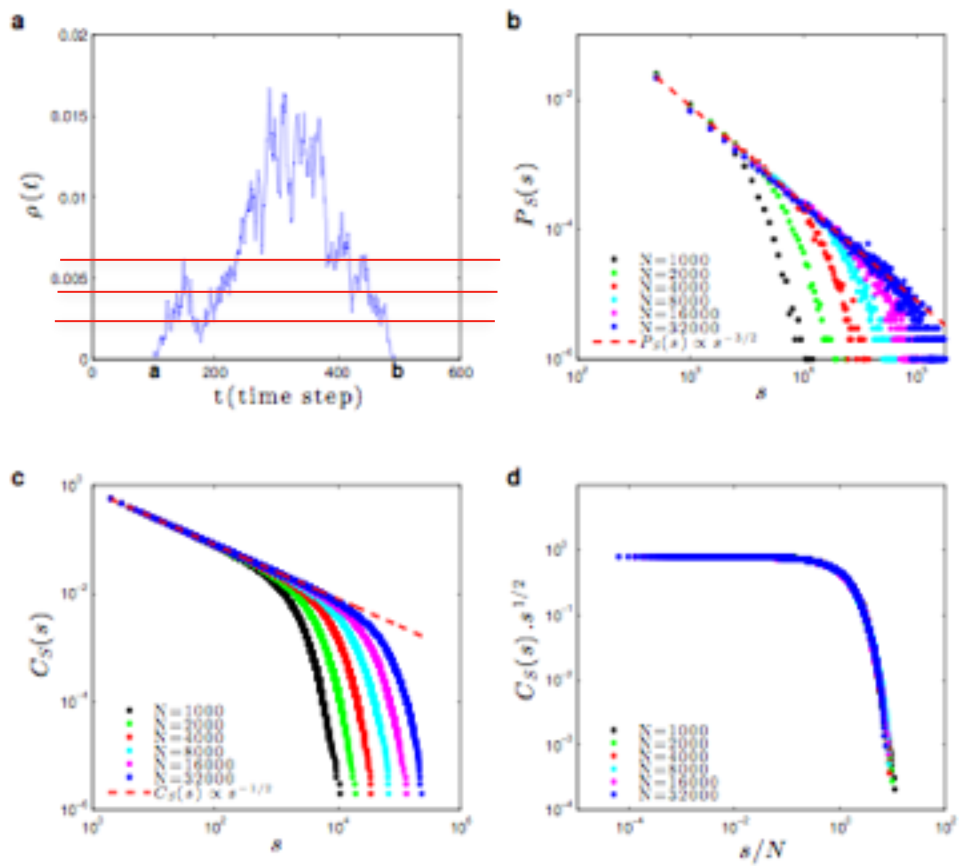




Effect of input level

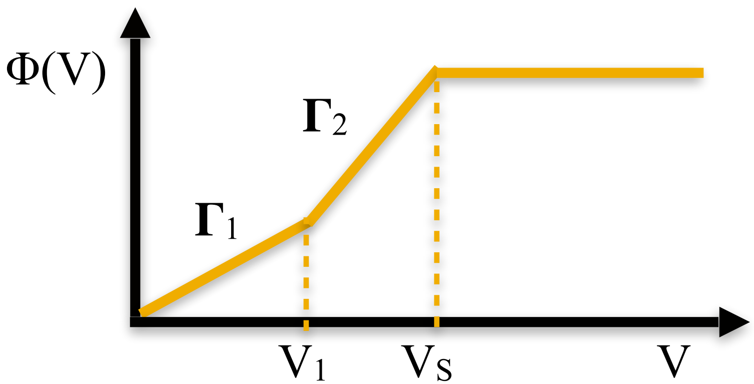
10. NEUROSCIENCE: EFFECT OF AVALANCHE THRESHOLD DEFINITION IN CRITICAL AND SUPERCRITICAL NETWORKS

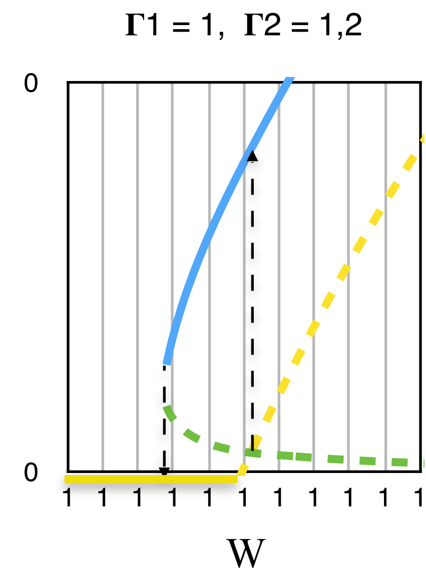
Novelty: To examine the effect of a threshold for defining the avalanches sizes and avalanches intervals.

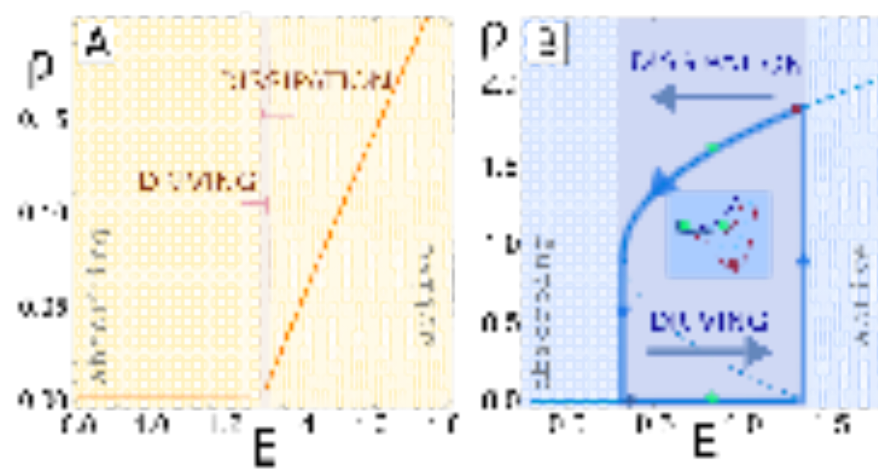


11. NEUROSCIENCE: SELF-ORGANIZED BI-STABILITY (SOB)

Novelty: Self-organization toward bi-stability region in discontinuous phase transitions.





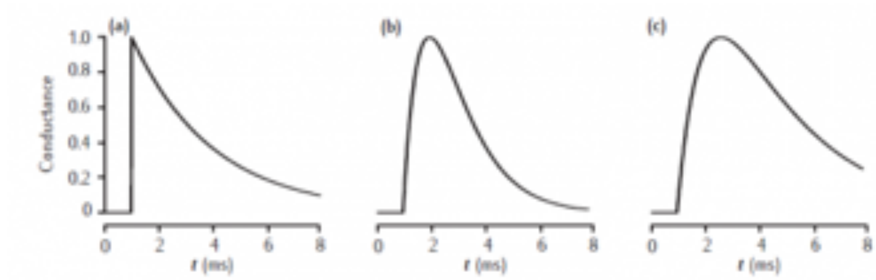


di Santo, S., Burioni, R., Vezzani, A., & Muñoz, M. A. (2016). Self-Organized Bistability Associated with First-Order Phase Transitions. *Physical Review Letters*, *116*(24), 240601.

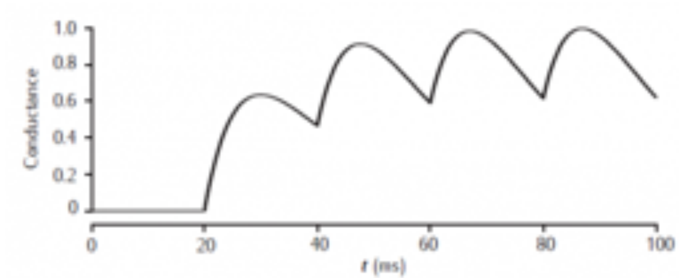
12. NEUROSCIENCE: DIFFERENT SYNAPTIC MODELS

Novelty: More realistic chemical synaptic coupling between the GL neurons.

$$I_i[t] = \sum_{j=1}^{N} g_{ij}[t]\,(V_j[t] - V_i[t])$$

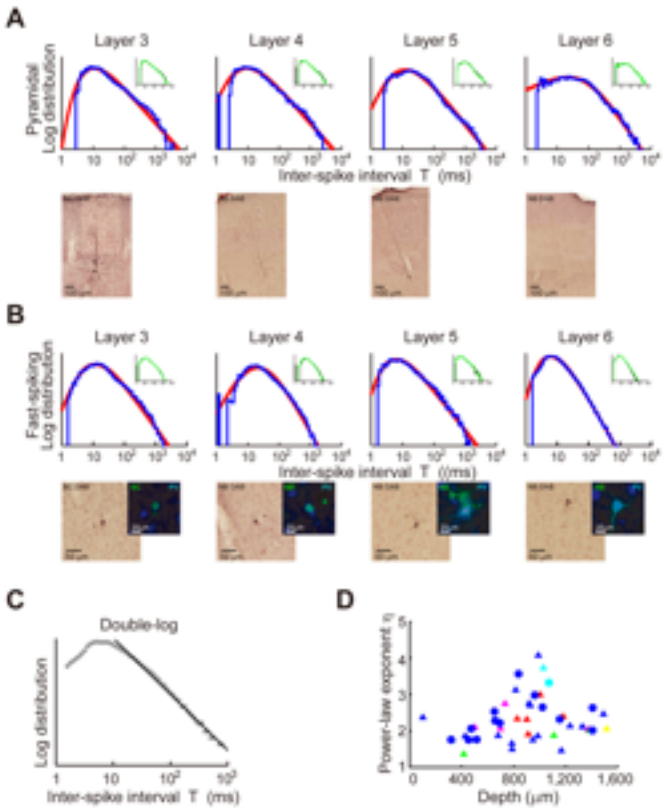


$$g_{ij}[t+1] = \left(1 + \frac{1}{\tau_1}\right) g_{ij}[t] + h_{ij}[t]\,,$$
$$h_{ij}[t+1] = \left(1 + \frac{1}{\tau_2}\right) h_{ij}[t] + J_{ij} X_j[t]\,.$$



13. NEUROSCIENCE: INTERSPIKE INTERVALS (ISI) HISTOGRAM FOR GL NEURONS

Novelty: Search for ISI histograms with long tails in GL neurons.



PLoS Computational Biology April 12 (2012).
Power-Law Inter-Spike Interval Distributions Infer a Conditional Maximization of Entropy in Cortical Neurons

- **Yasuhiro Tsubo ,**
- **Yoshikazu Isomura,**
- **Tomoki Fukai**

arXiv.org q-bio
The emergence of power-law distributions of inter-spike intervals characterizes status epilepticus induced by pilocarpine administration in rats
Massimo Rizzi
(Submitted on 7 Jan 2015)

14. PLANT NEUROBIOLOGY: ONE-DIMENSIONAL (OR CAYLEY TREE) NETWORK WITH NEAREST NEIGHBOR INTERACTION

Novelty: electric coupling, one dimensional lattice with stochastic excitable waves, possible analytic solutions.

$$V_i[t+1] = \mu V_i[t](1 - X_i[t]) + g_{i-1,i}(V_{i+1}[t] - V_i[t]) + \\ + g_{i,i+1}(V_{i+1}[t] - V_i[t])$$

15. SOCIOPHYSICS: THE ”FENCE BUILDING” ONE DIMENSIONAL MODEL

Novelty: New imitation-based sociological problem with possible empirical data, one dimensional lattice with external fields.

$$V_i[t+1] = \mu V_i[t] + h_i + H + \sum_j W_{ij} X_j[t] \, .$$

16. GEOPHYSICS: SOC MODELS FOR LIGHTNINGS AND EARTHQUAKES IN A SQUARE LATTICE

Novelty: Square lattice and SOC.

$V_i[t+1] = \mu V_i[t] + \sum_{j \in 2d} W_{ij} X_j[t]$ if $X_j[t] = 0$

$V_i[t+1] = 0$ if $X_j[t] = 1$

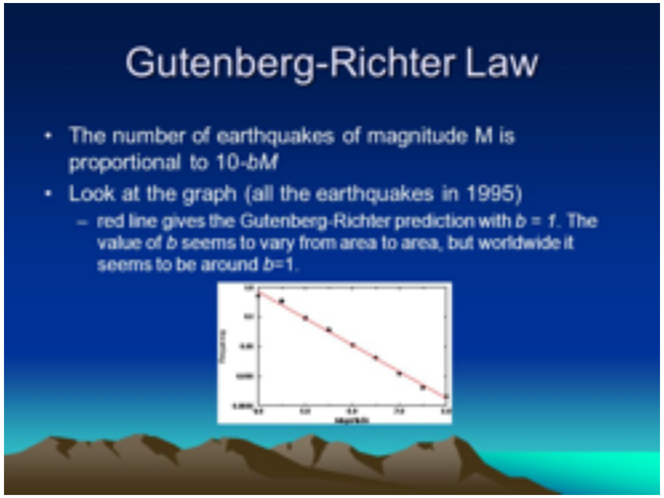
$P(X=1 \mid V) = \Phi(V)$

Spiking sorting algorithms applied to radio pulses

time series from lightnings?

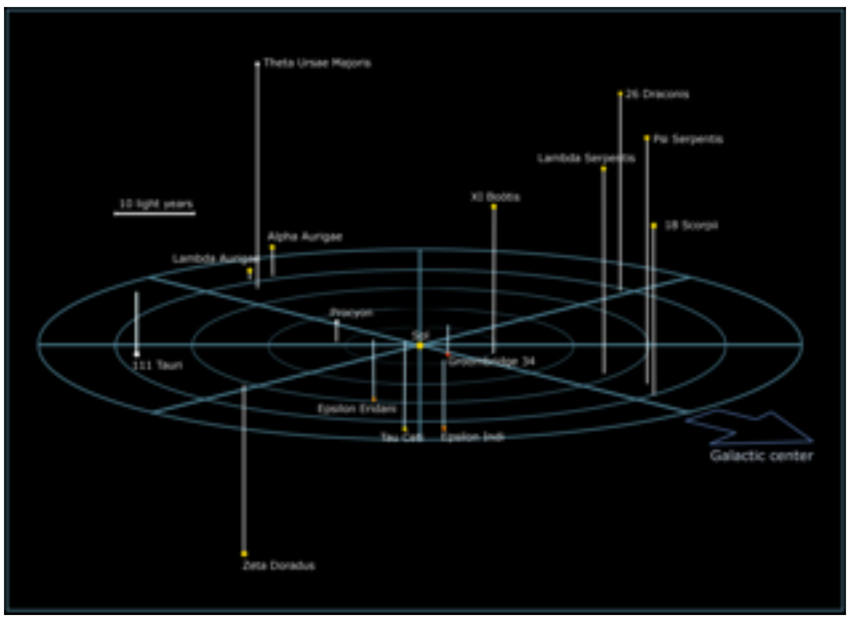
Could we measure the ISI histogram of lightnings?

This histogram has a heavy tail?



17. COLONIZATION PROCESSES: DIFFUSION MODEL IN A CUBIC LATTICE

Novelty: Cubic lattice, different functions $\Phi_i(V)$ for each site, Invasion Percolation dynamics based in variable thresholds V_{Ti}.



Persistence solves Fermi Paradox but challenges SETI projects

Osame Kinouchi

Persistence phenomena in colonization processes could explain the negative results of SETI search preserving the possibility of a galactic civilization. However, persistence phenomena also indicates that search of technological civilizations in stars in the neighbourhood of Sun is a misdirected SETI strategy. This last conclusion is also suggested by a weaker form of the Fermi paradox. A simple model for galactic colonization based in a generalized Invasion Percolation dynamics
illustrates the Percolation solution for the Fermi Paradox.

$$V_i[t+1] = \mu V_i[t] + \sum_{j \in S_d} W_{ij}\delta(X_j[t] - 1)$$

$$\Phi_i(V) = \Gamma(V - V_{Ti})\,\Theta(V - V_{Ti})\Theta(V_{Si} - V) + \Theta(V_{Si} - V)$$

18. EPIDEMIOLOGY: STOCHASTIC SIRS MODELS

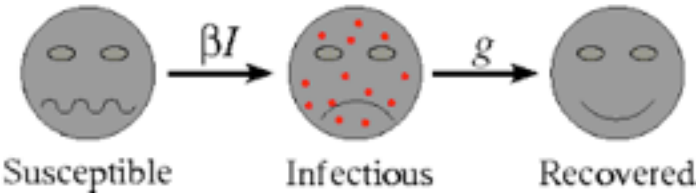
Novelty: large firing state interval, very large refractory period.

Three state neurons:

X = 0 (resting = susceptible)

X = 1 (firing = infected)

X = 2 (refractory = recovered)



P(0 → 1) = Φ(V) , P(1 → 2) < 1, P(2 → 0) << 1

$$V_i[t+1] = \mu V_i[t] + \sum_j W_{ij}\delta(X_j[t] - 1)$$

19. ECONOPHYSICS: WEALTH DISTRIBUTION MODELS

Novelity: negative electrical coupling, complex networks.

$$V_i[t+1] = \mu_i V_i[t] + \sum_i G_{ji}\left(V_i[t] - V_j[t]\right) X_i[t]$$

$$+ \sum_j G_{ij}\left(V_i[t] - V_j[t]\right) X_j[t] \, .$$

For economy, no reset mechanism $V[t+1] = 0 \ \ (1 - X_i[t])$
The ohmic coupling is negative: capital flows from the poor to the rich.
Random factors μ_i are individual and can be greater than one, since they represent decay or growth of capital V.

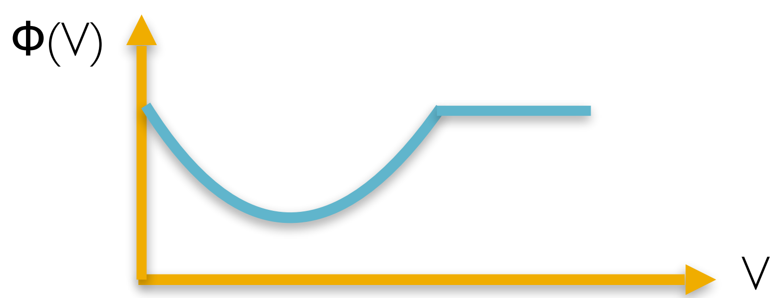
20. SOCIOPHYSICS: MODELS OF EMERGENCE OF ALTRUISM

Novelity: Non-monotonous functions, diode-like coupling.

$$V_i[t+1] = \mu V_i[t] + \sum_j W_{ij}\,(V_j[t] - V_i[t])\,X_j[t]\,\Theta(V_j[t] - V_i[t])$$
$$- \sum_j W_{ji}\,(V_i[t] - V_j[t])\,X_i[t]\,\Theta(V_i[t] - V_j[t])\,.$$

This context of sociological altruism with a U curve justifies the study of non-monotonous functions for $\Phi(V)$. The simplest could be a saturating parabola:

$$\Phi(V) = \left(aV^2 + bV + c\right)\,\Theta(V_S - V)\Theta(V) + \Theta(V - V_S)\,, \qquad (38)$$



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