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Towards Critical SNNs: Astrocytes Detect *Chaos* in Neuronal Dynamics

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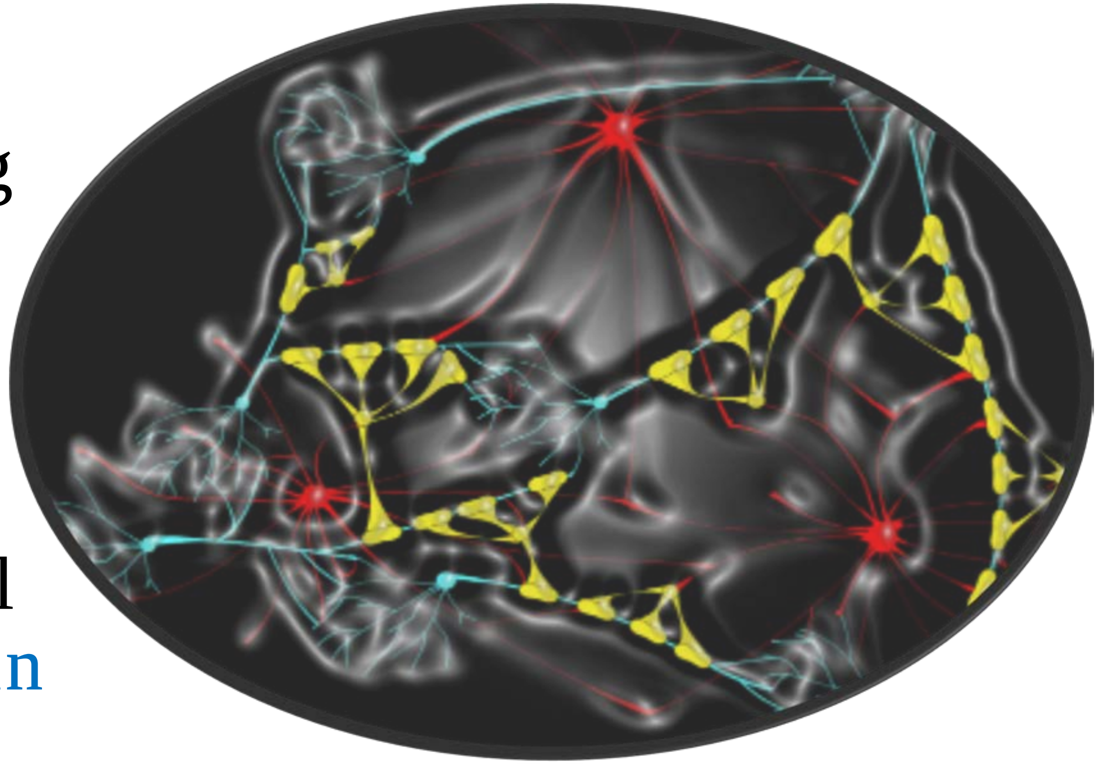
Main Message

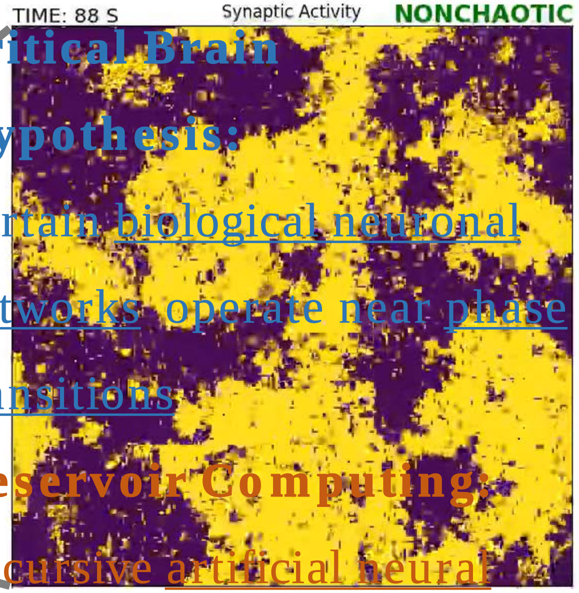
- Brain cells have been computing long before we started recording neurons
- Neuronal processing is mediated by non-neuronal cells – and networks
- Non-neuronal computation: a critical untapped frontier to understand brain function
- Non-neuronal computing: rich opportunities for versatile and robust AI



Astrocytes: *Non*-Neuronal Cells

Detecting Neuronal Chaos

Astrocytes oversee the neuronal activity with *non*-overlapping receptive fields

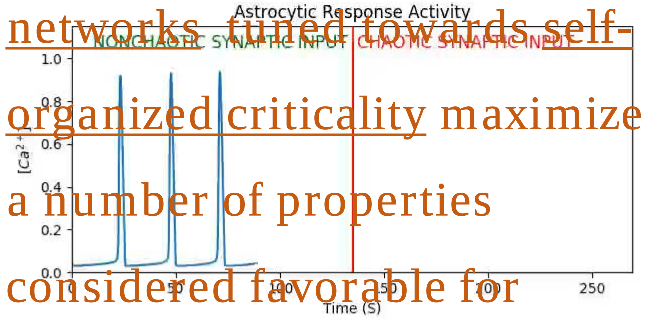


Critical Brain Hypothesis:

Certain biological neuronal networks operate near phase transitions

Reservoir Computing:

Recursive artificial neural networks tuned towards self-organized criticality maximize a number of properties considered favorable for computation




frontiers in SYSTEMS NEUROSCIENCE

ORIGINAL RESEARCH ARTICLE
published: 24 June 2014
doi: 10.3389/fnsys.2014.00108

Spike avalanches *in vivo* suggest a driven, slightly subcritical brain state

Viola Priesemann[1,2,3,4]*, Michael Wibral[5,6], Mario Valderrama[7], Robert Pröpper[8,9], Michel Le Van Quyen[10], Theo Geisel[1,2], Jochen Triesch[3], Danko Nikolić[3,4,6,11] and Matthias H. J. Munk[12]

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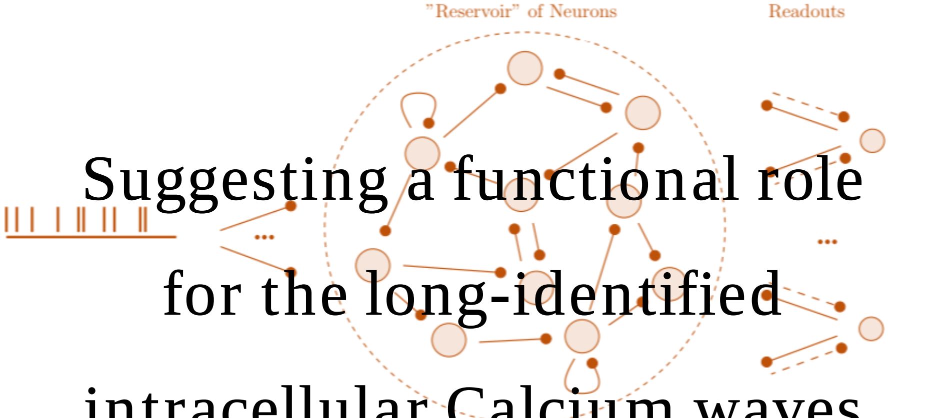


Suggesting a functional role for the long-identified intracellular Calcium waves

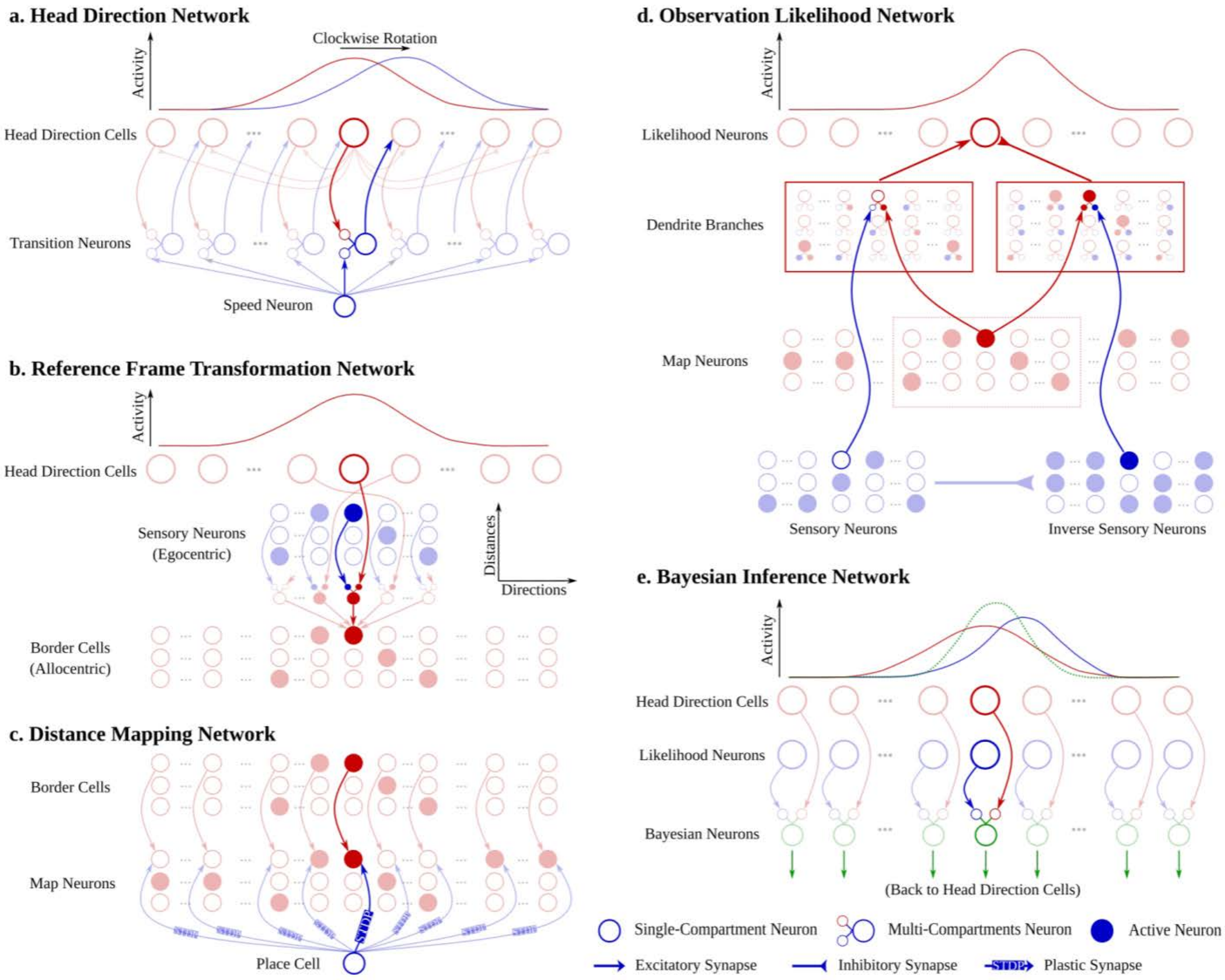
Brodeur & Rouat *ICANN* 2012

Maass, Natschlager, Markram *Neural Computation* 2002

Real-time SNN-control of Robots

Real-world Environment

Experiment 1: 0s to 60s   Speed x10



[*NICE '17 & '18, CCN '17, ICONS '18*]

[*Tang, Shah, Michmizos arXiv:1903.02504*]

Wheel Counter (Odometry Sensing)

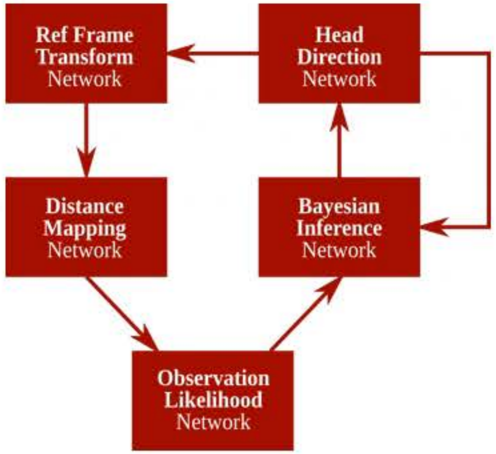
RGB-Depth Camera (Distance Sensing)

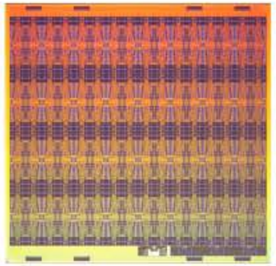
Real-world Environment

Experiment 1: 0s to 60s

Speed x10

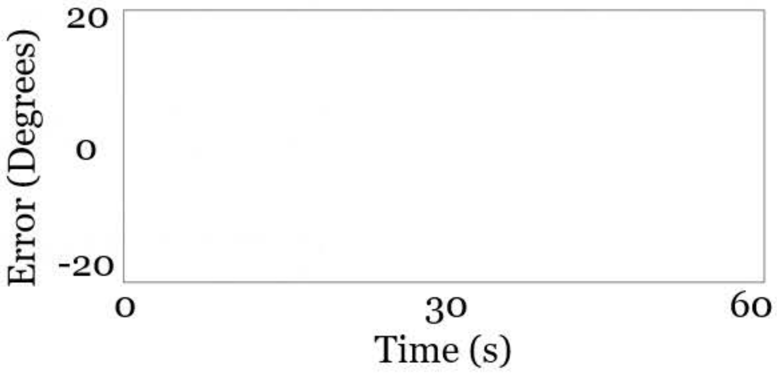
Spiking Neural Network (SNN)



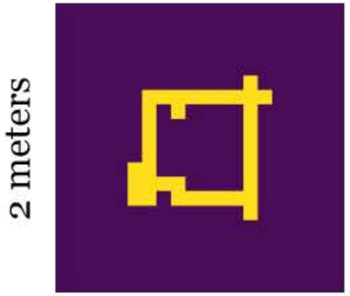


Intel's Loihi [1]

Head Direction Localization



Mapping

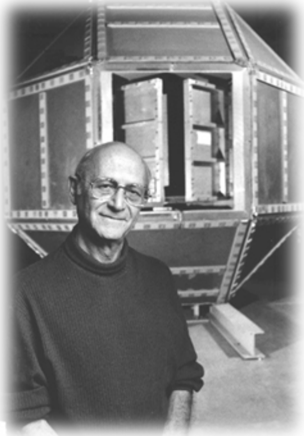


[1] Davies et al. *IEEE Micro*, 2018

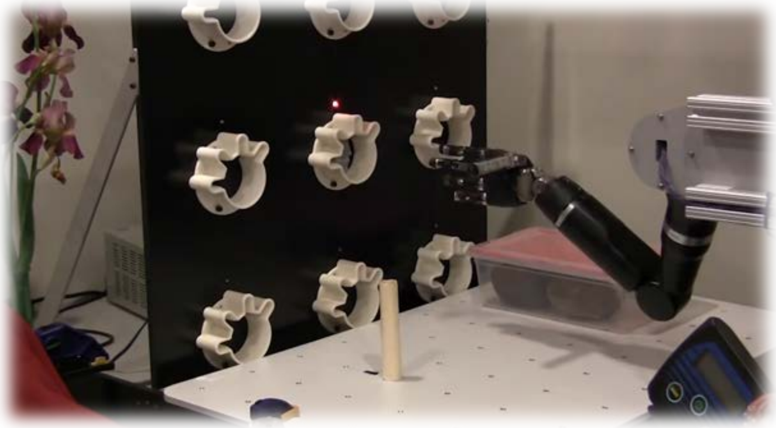
Tong, Shah, Michmizos arXiv:1903.02504

Record

1932. Edgar Adrian, Nobel Prize
Single-Neuron Recordings



1971. David Cohen, MIT
Magnetoencephalography

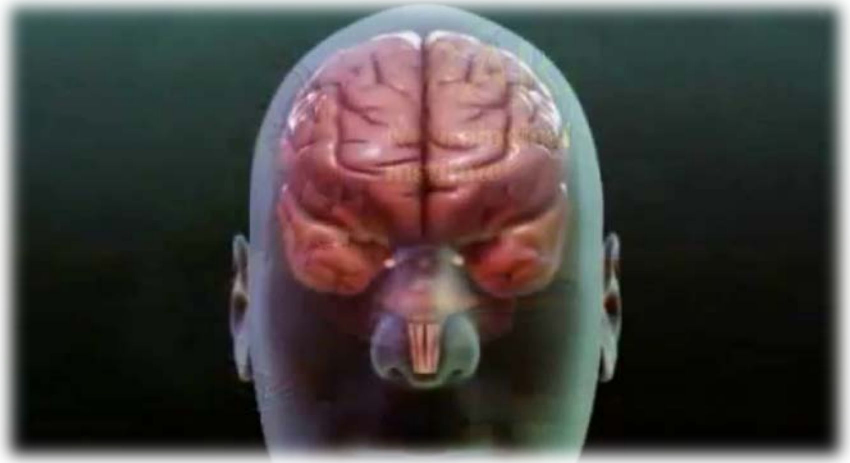


2013. Motor neurons control a robotic arm for paraplegic patients (BrainGate)

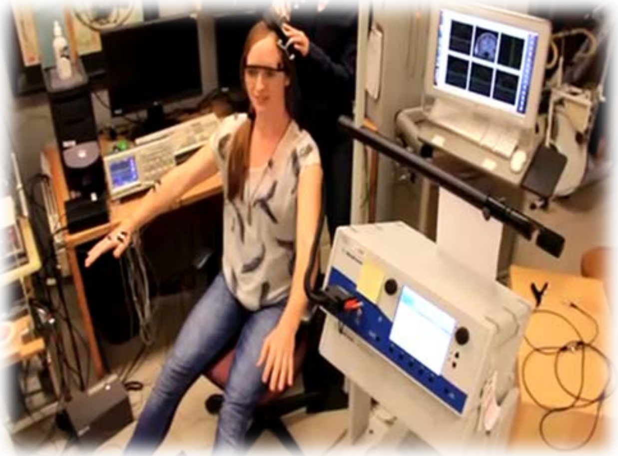
neurons

Information =
f (electrical activity)

Manipulate

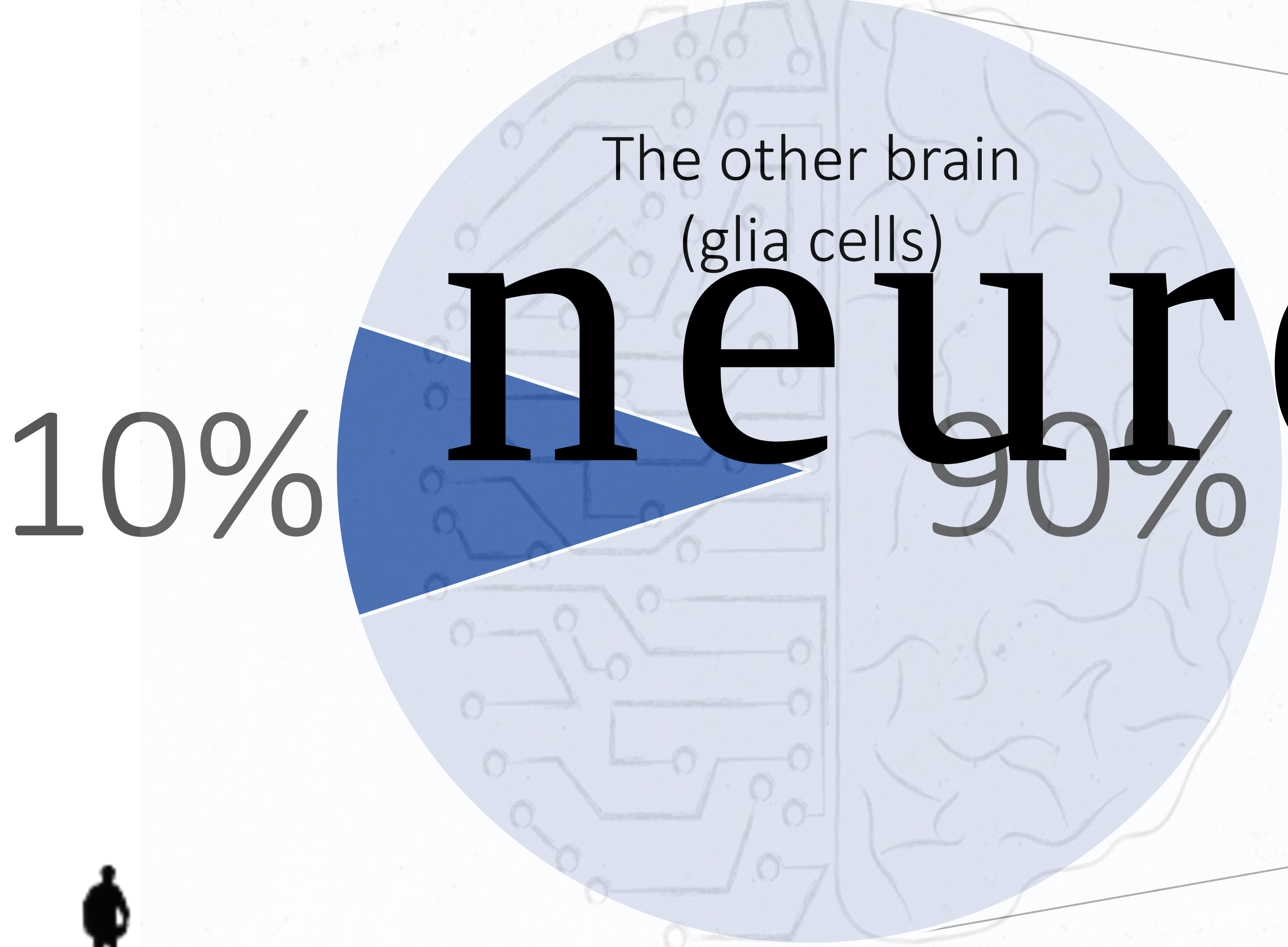


1997. Deep Brain Stimulation for alleviating Parkinson's disease

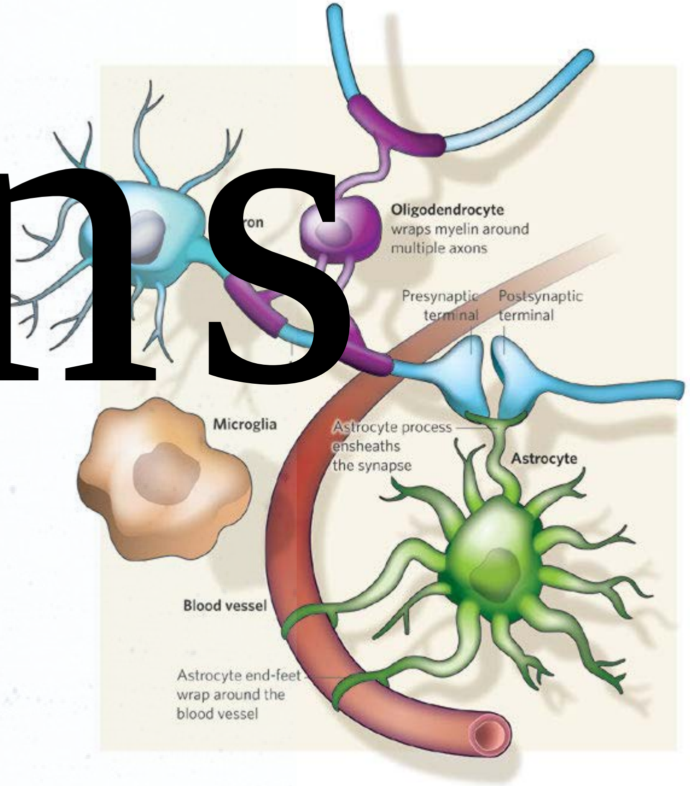


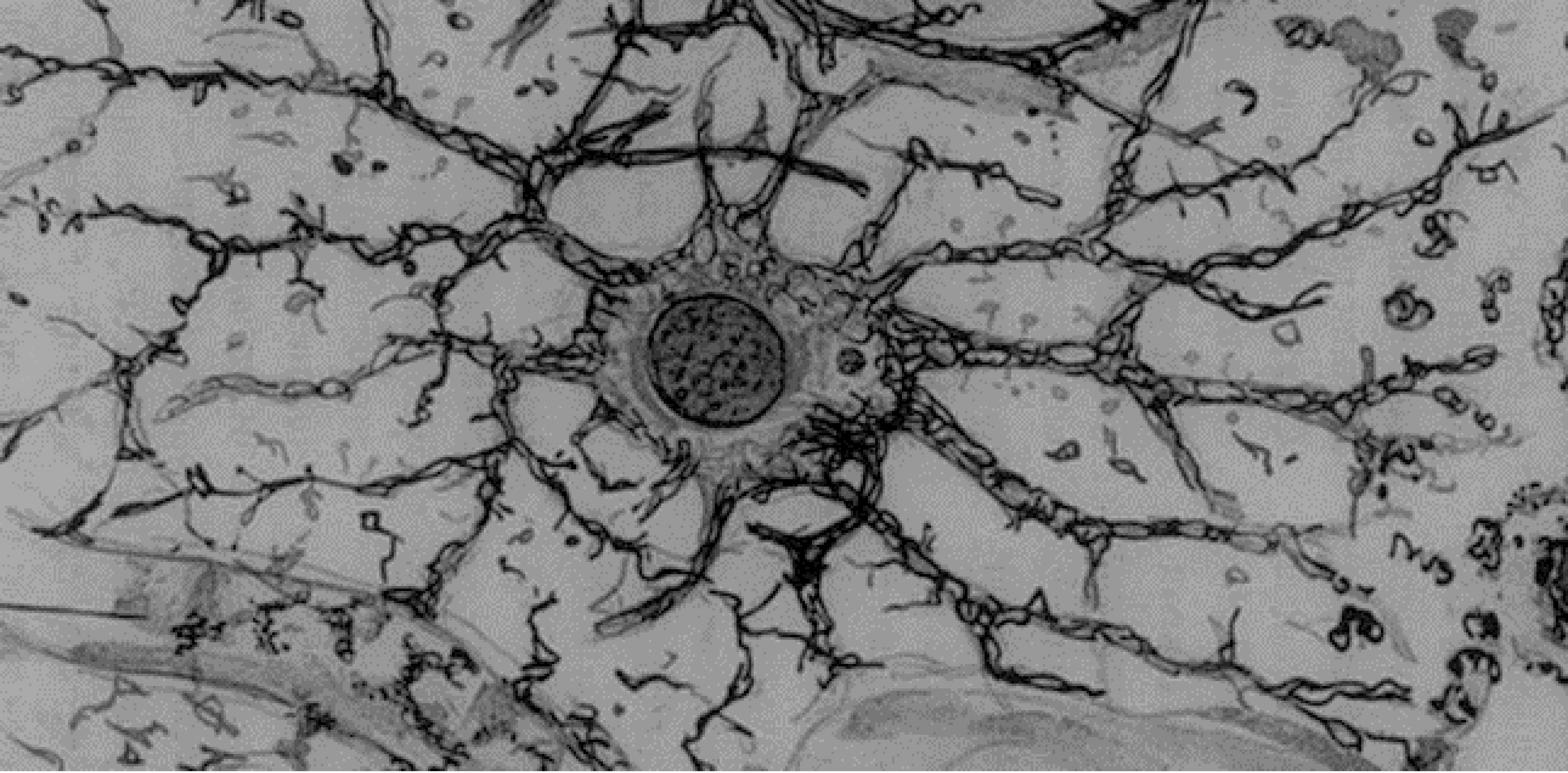
2013. TMS applied to the motor cortex induces hand movement

Non-neuronal brain cells are electrically silent



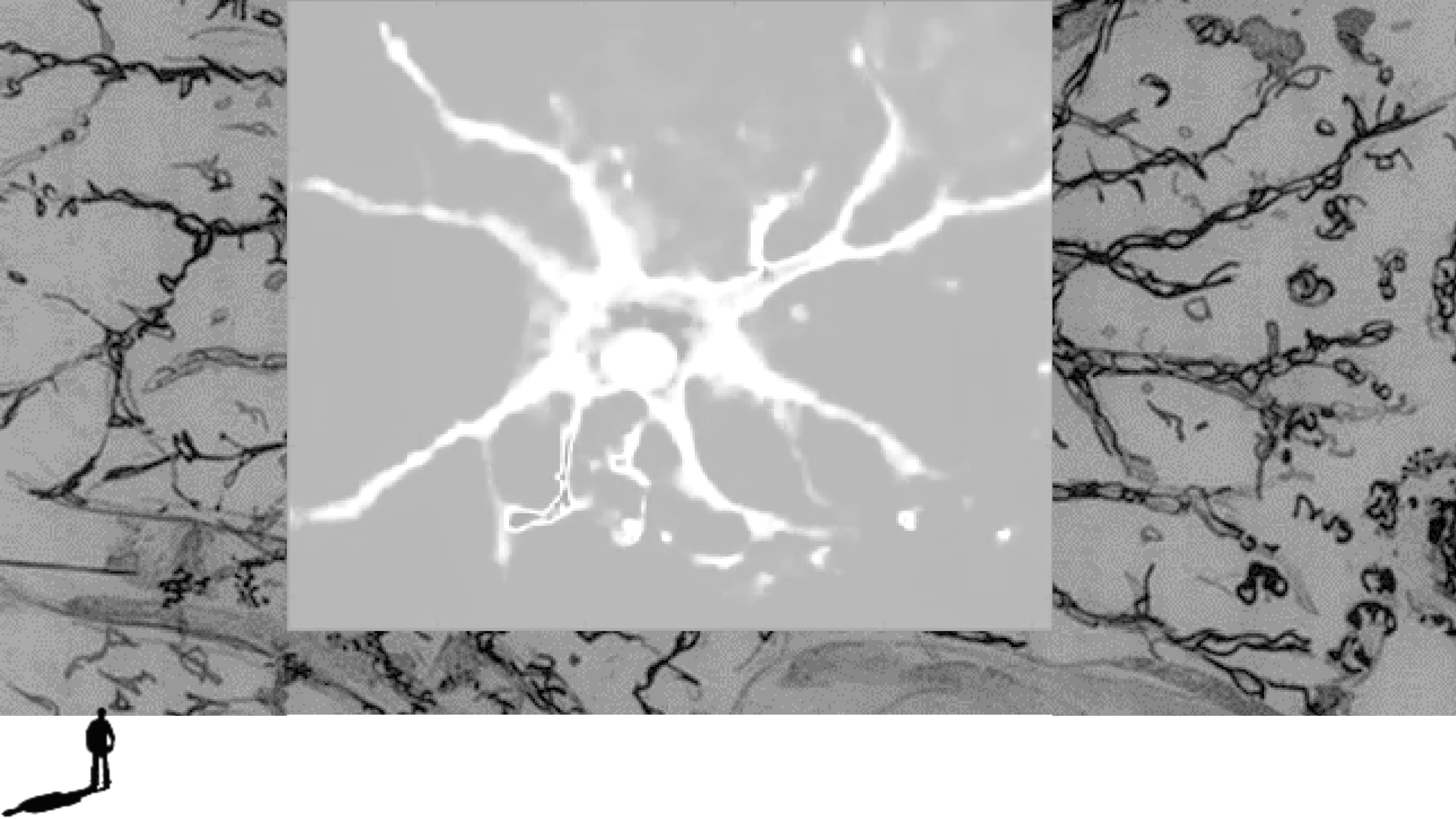
neurons

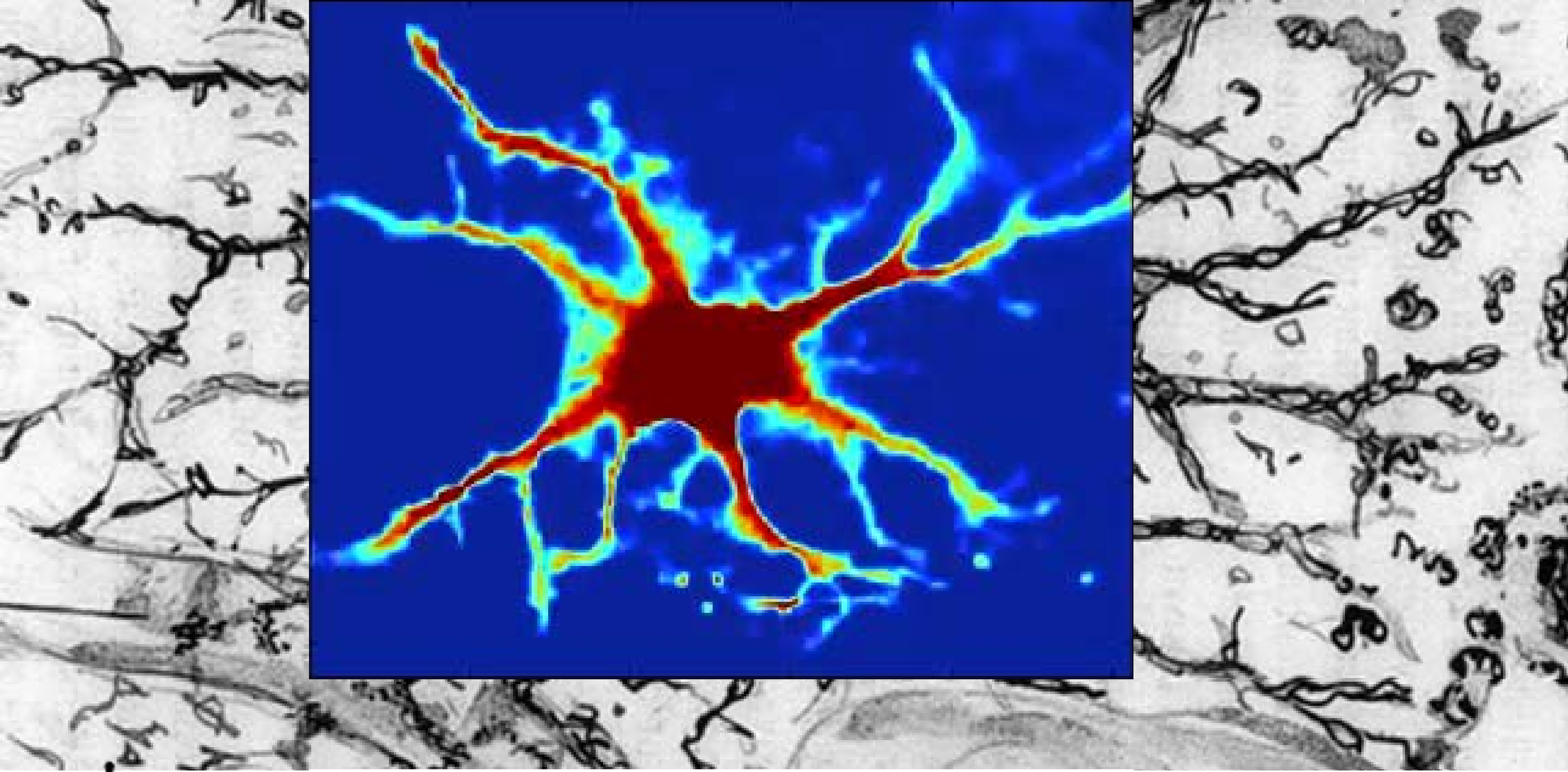




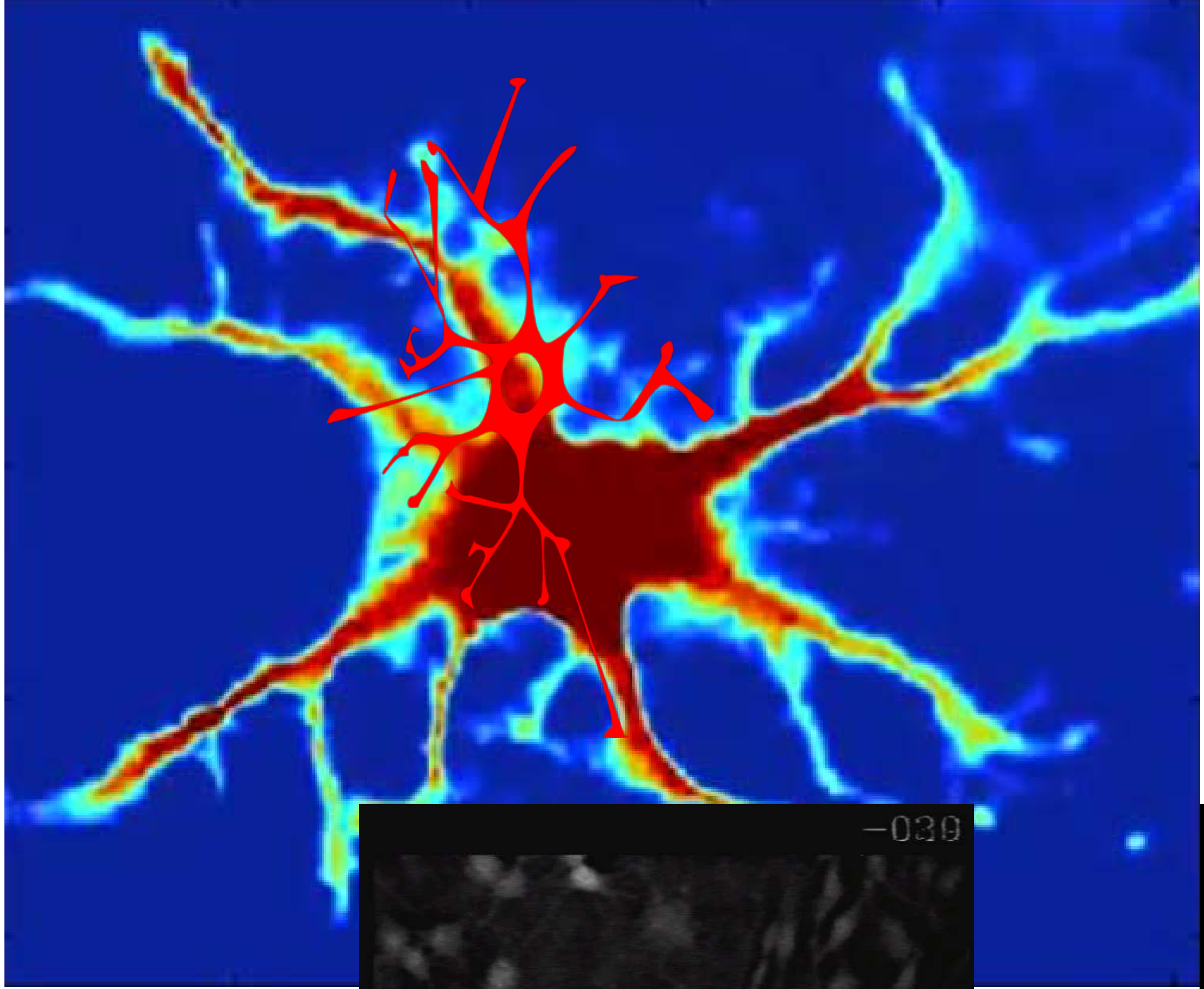
Santiago Ramón y Cajal's drawing of an astrocyte

Ramón y Cajal S. Something about the physiological significance of neuroglia. *Revista Trimestral Micrografía* 1, 3–47, 1897





2015

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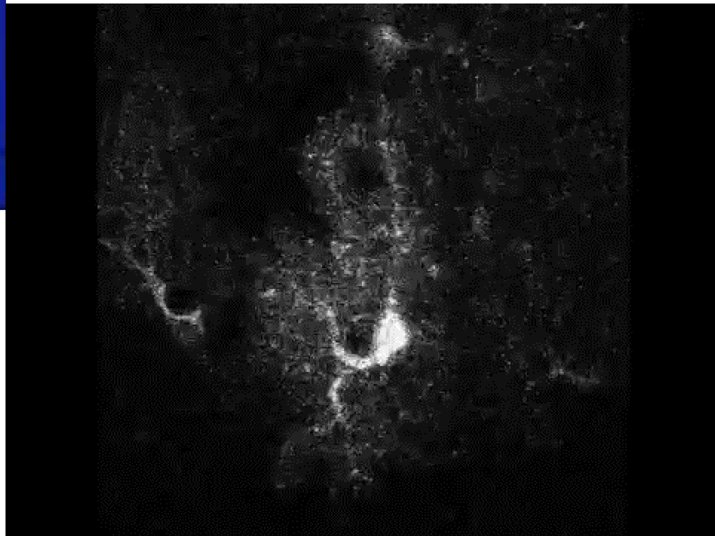

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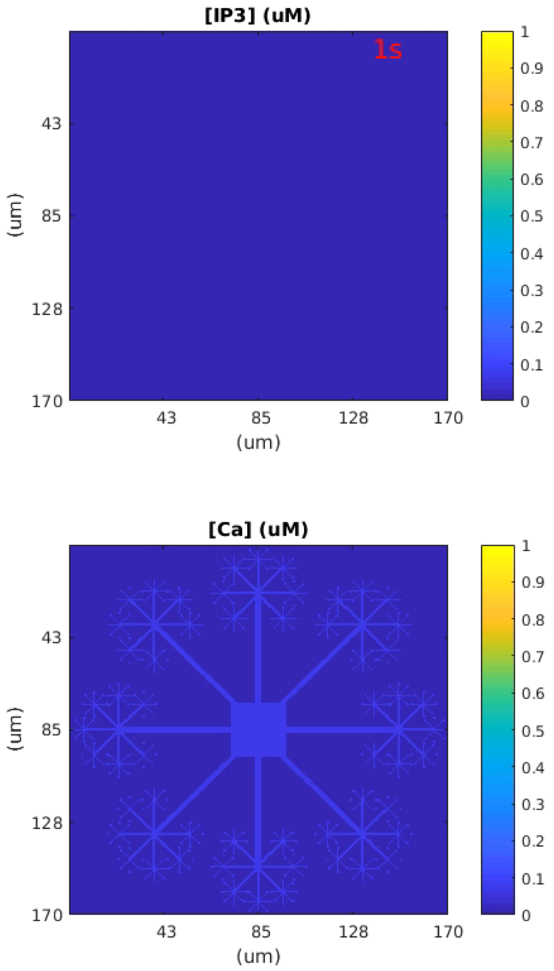
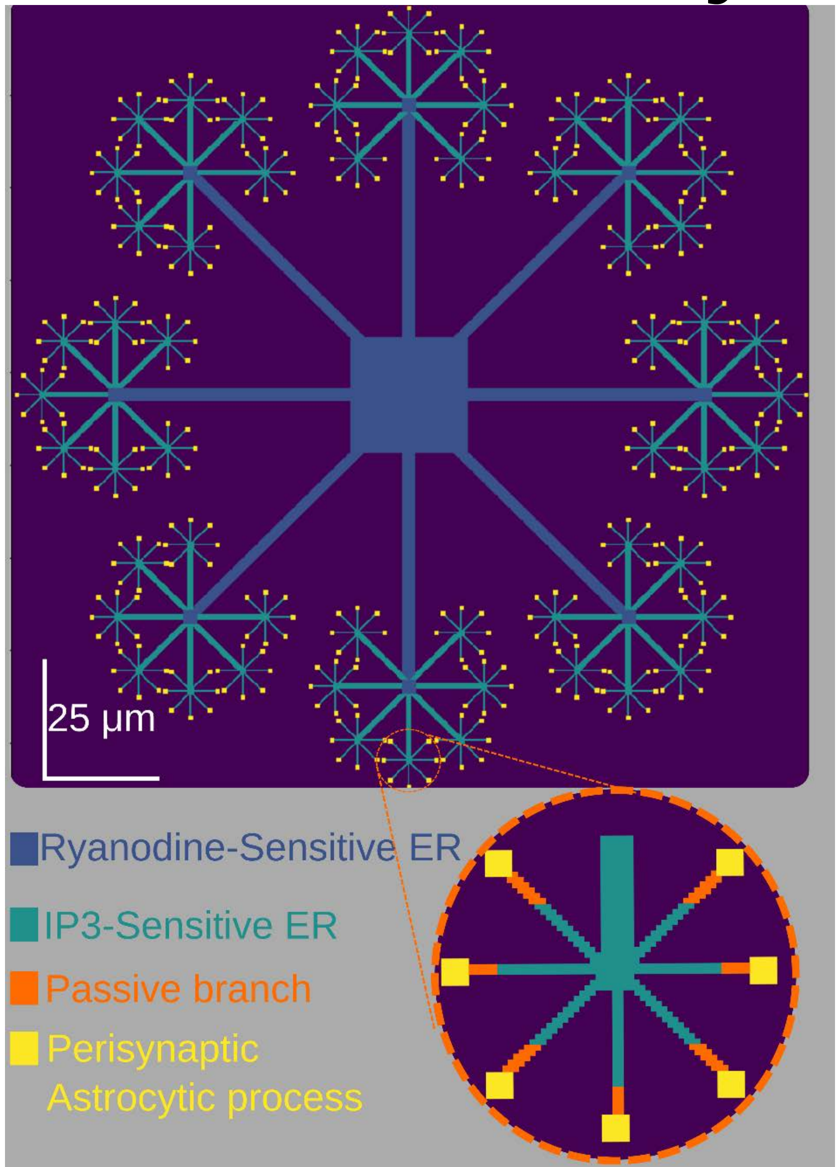
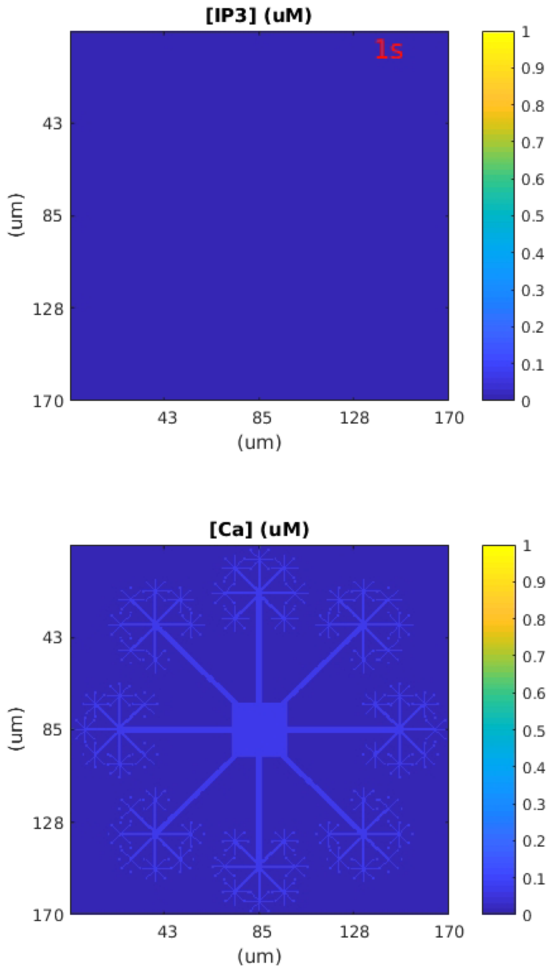
Computational Astrocyence

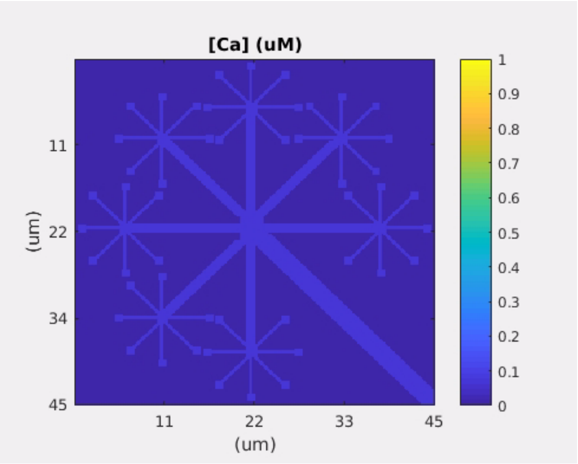
[ACM ICONS ‘18]
[ACM BI ‘18]
[IEEE BHI ‘19]

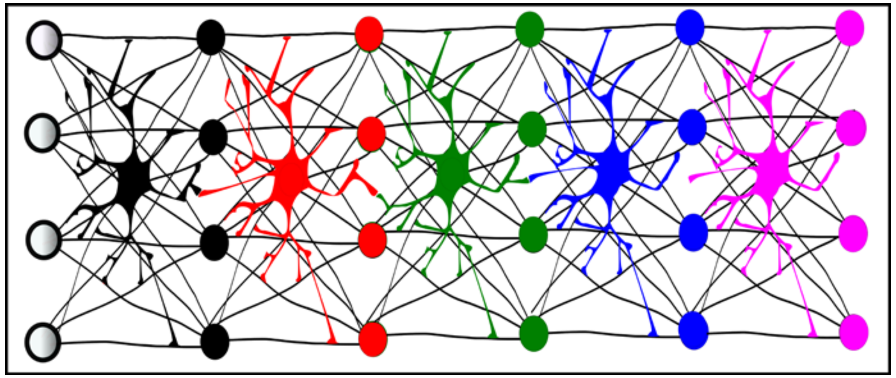






Computational Astrocyence





Oscillations

NeuroModulation

Synchronization

Local Plasticity

Chaos

Astrocytic Cell

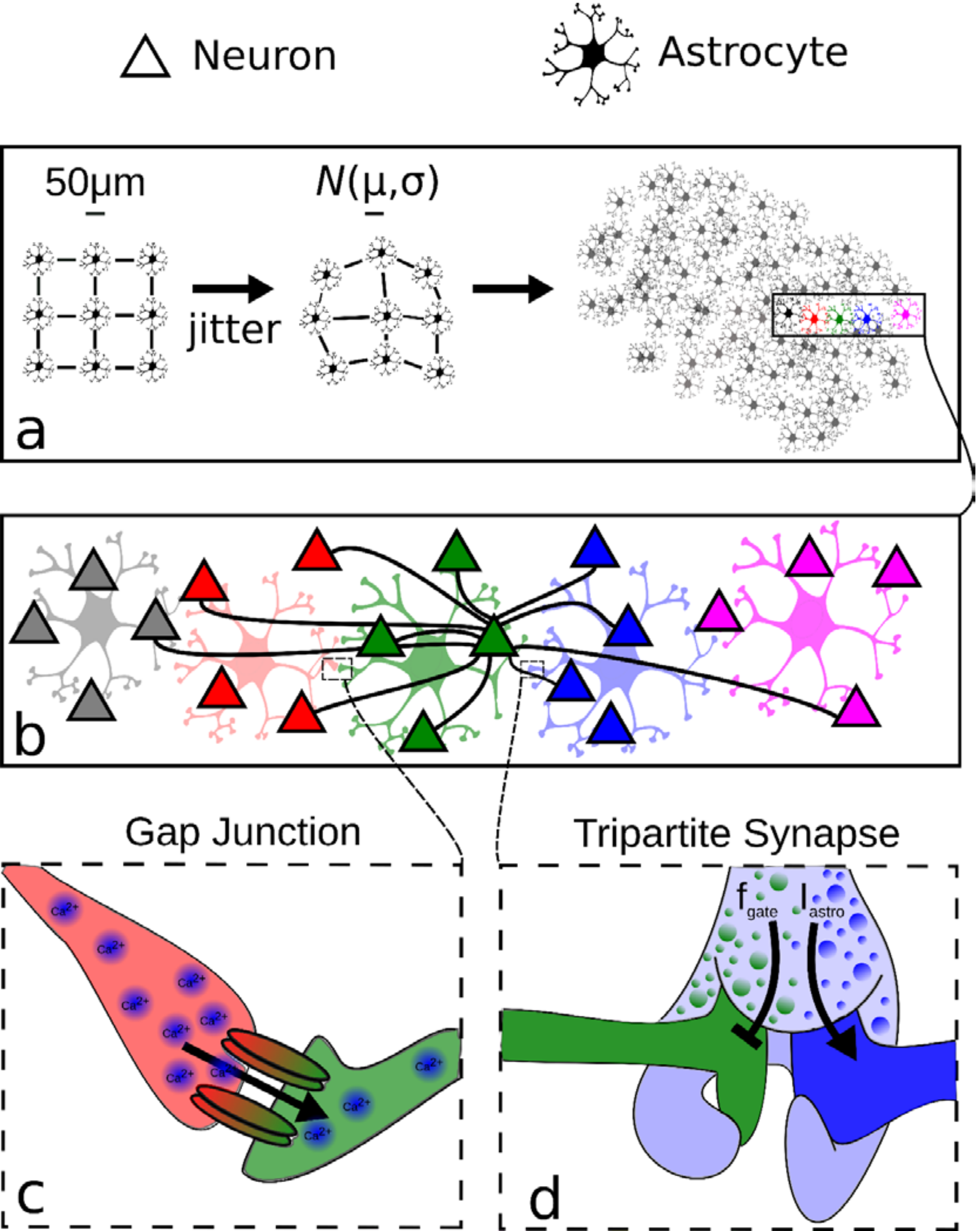
Neuronal-Astrocytic Network

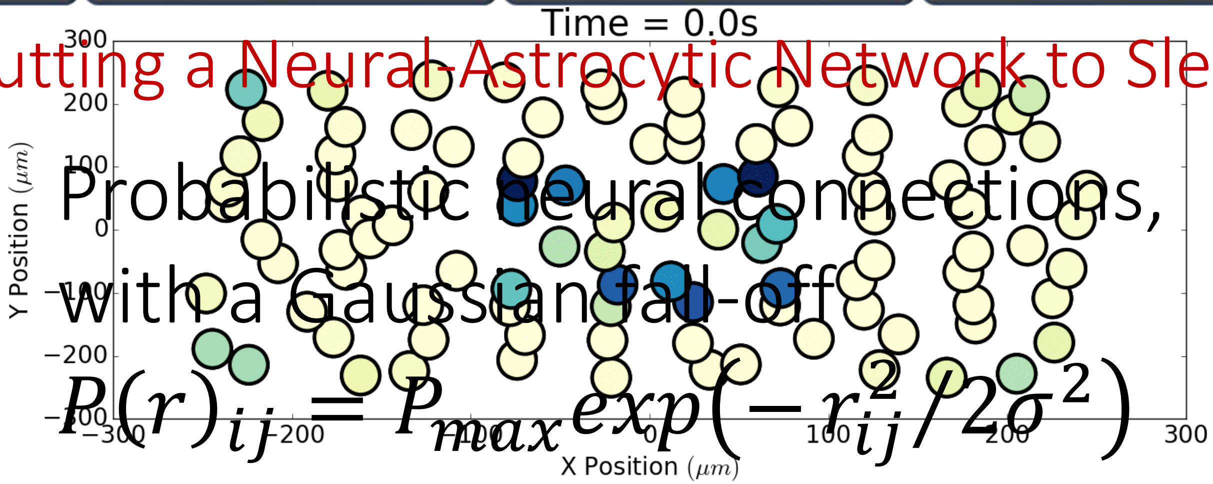
Network Behavior

Microscopic Phenomena

Macroscopic Phenomena

Putting a Neural-Astrocytic Network to Sleep

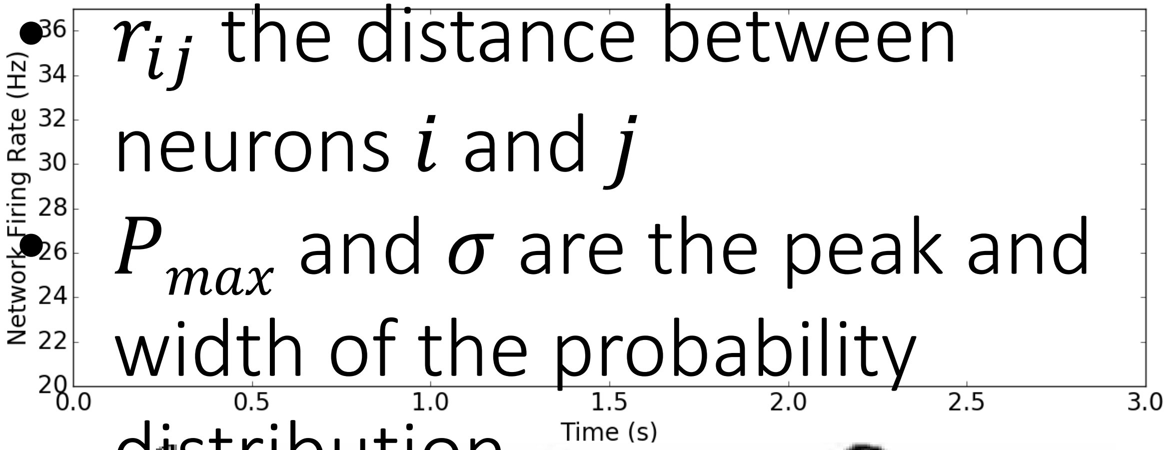


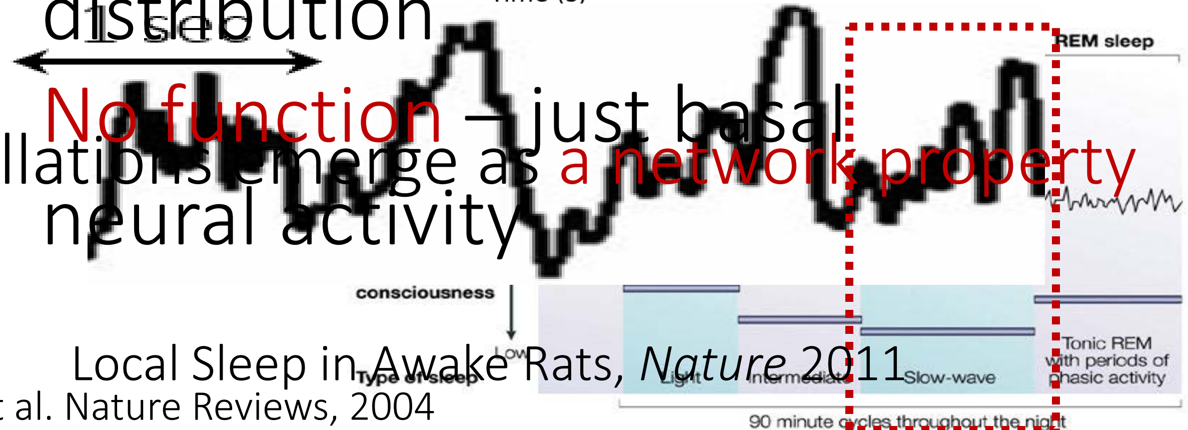


Probabilistic neural connections, with a Gaussian fall-off

$$P(r)_{ij} = P_{max}\, exp(-r_{ij}^2/2\sigma^2)$$

- r_{ij} the distance between neurons i and j
- P_{max} and σ are the peak and width of the probability distribution
- No function – just basal neural activity





Oscillations emerge as a network property

Local Sleep in Awake Rats, *Nature* 2011

Bryant et al. Nature Reviews, 2004

SCIENTIFIC REPORTS

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Extensive astrocyte synchronization advances neuronal coupling in slow wave activity *in vivo*

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Zsolt Szabó[1], László Héja[1], Gergely Szalay[2], Orsolya Kékesi[1], András Füredi[3,6], Kornélia Szebényi[3,6], Árpád Dobolyi[4], Tamás I. Orbán[3], Orsolya Kolacsek[3], Tamás Tompa[2], Zsombor Miskolczy[5], László Biczók[5], Balázs Rózsa[2], Balázs Sarkadi[3] & Julianna Kardos[1]

Slow wave activity (SWA) is a characteristic brain oscillation in sleep and quiet wakefulness. Although the cell types contributing to SWA genesis are not yet identified, the principal role of neurons in the emergence of this essential cognitive mechanism has not been questioned. To address the possibility of astrocytic involvement in SWA, we used a transgenic rat line expressing a calcium sensitive fluorescent protein in both astrocytes and interneurons and simultaneously imaged astrocytic and neuronal activity *in vivo*. Here we demonstrate, for the first time, that the astrocyte network display synchronized recurrent activity *in vivo* coupled to UP states measured by field recording and neuronal calcium imaging. Furthermore, we present evidence that extensive synchronization of the astrocytic network precedes the spatial build-up of neuronal synchronization. The earlier extensive recruitment of astrocytes in the synchronized activity is reinforced by the observation that neurons surrounded by active astrocytes are more likely to join SWA, suggesting causality. Further supporting this notion, we demonstrate that blockade of astrocytic gap junctional communication or inhibition of astrocytic Ca^{2+} transients reduces the ratio of both astrocytes and neurons involved in SWA. These *in vivo* findings conclusively suggest a causal role of the astrocytic syncytium in SWA generation.

Increasing body of evidence substantiating the impact of astrocytes on neuronal activity prompted a paradigm shift from the neurocentric philosophy of nervous system function. Accordingly, astrocytes are increasingly recognized as major players in the modulation of neuronal function under both physiological[1–3] and pathophysiological conditions[4–7]. Beyond the local astroglial control over synaptic activity[8–12], however, little is known about the role of astrocytic networks in modulating large-scale neuronal ensembles. Exploration of the role of large-scale astrocytic networks in information processing and cognition still lags behind its neuronal counterpart[13,14]. We conceived that fundamental properties of networking astrocytes may underlie physiological network-network interaction between astrocytes and neurons. Astrocytes are capable of 1) detecting neuronal activity, 2) responding to this activity by raising local Ca^{2+} transients, 3) propagating the local changes over extended spatial scales by Ca^{2+} waves traveling through the directly and densely interconnected astrocytic syncytium and 4) modulating neuronal activity at multiple locations by releasing gliotransmitters and other neuromodulatory substances or regulating ionic homeostasis[15]. Thus, astrocytes are ideally positioned to induce or contribute to synchronization of large-scale neuronal networks. Along this line, we have previously demonstrated that the astrocytic and

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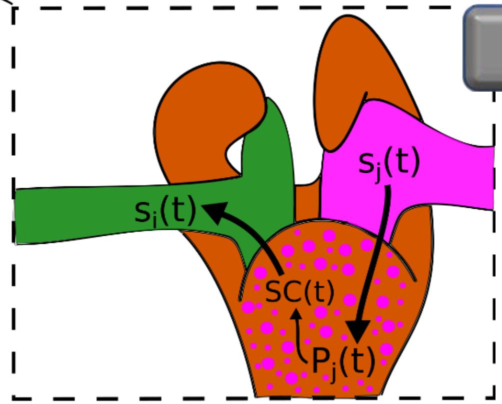
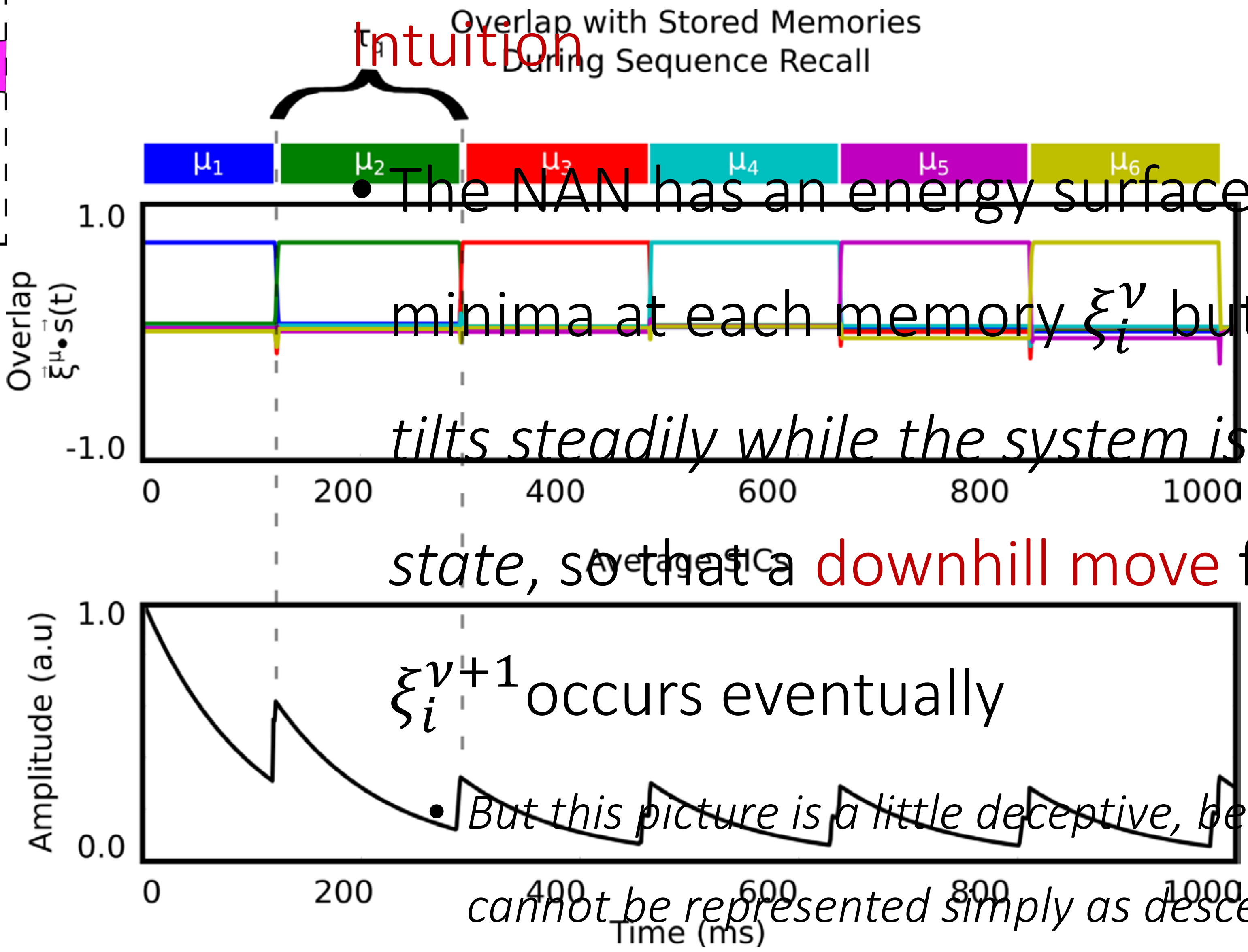
"This hypothesis was reinforced by a recent modelling study showing that intercellular Ca2+ signaling potentially can introduce slow oscillation in neurons [our Ref]. Our experimental data strongly supports this hypothesis by demonstrating that increasing astrocytic influence on neurons indeed drives them to join the oscillatory activity (Fig. 5C). In this context it is also important to note, that the ratio of astrocytes involved in the SWA was found to start decreasing right after virtually all neurons joined the simultaneous activity (Figs 4 and 5). This observation further supports the view that astrocytic activity corresponds to the generation or maintenance, rather than termination of SWA."



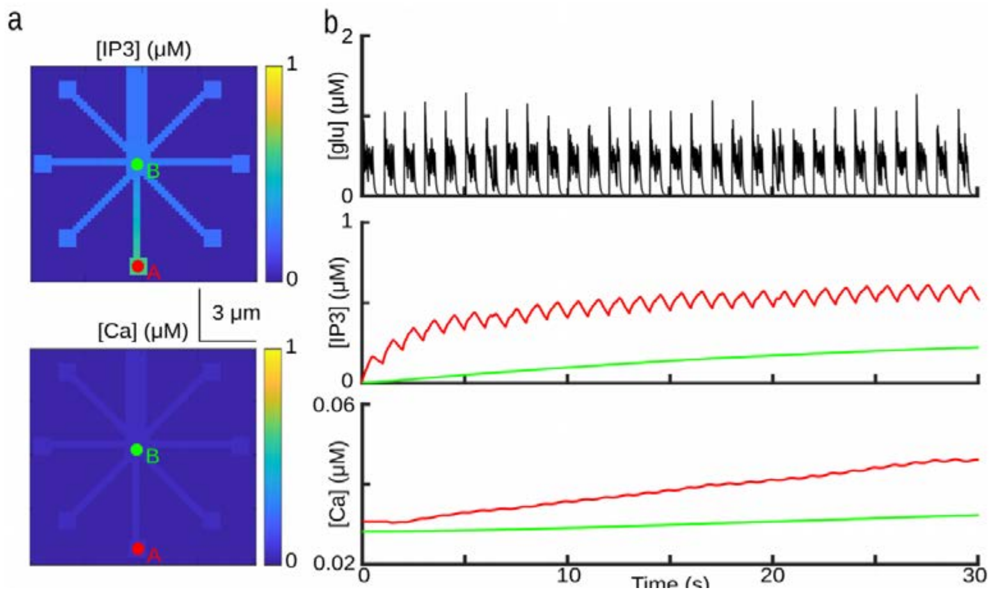
Intuition

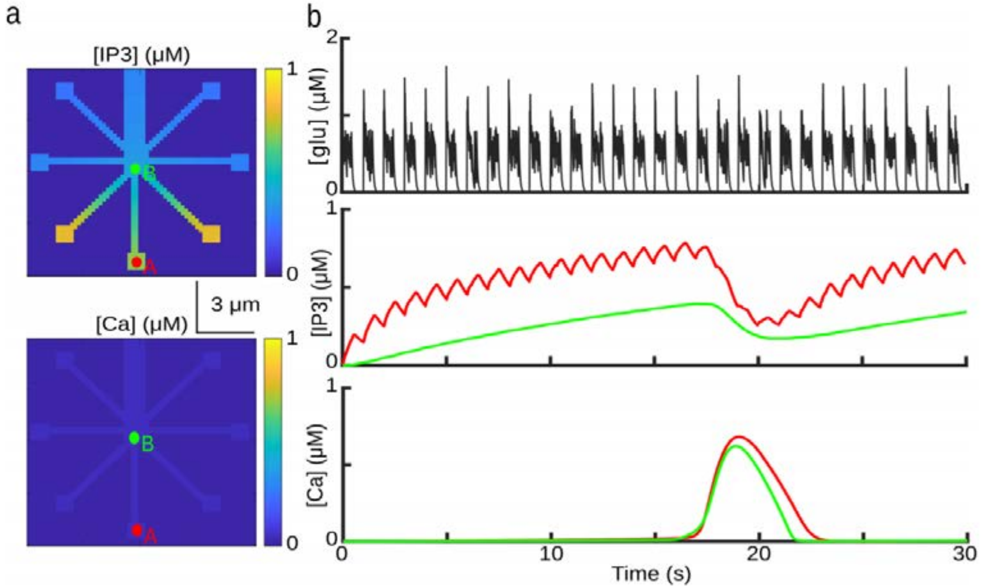


- The NAN has an energy surface that has minima at each memory ξ_i^{ν} but which also *tilts steadily while the system is in a particular state*, so that a downhill move from ξ_i^{ν} to $\xi_i^{\nu+1}$ occurs eventually
  - *But this picture is a little deceptive, because the dynamics cannot be represented simply as descent on an energy landscape, unless the connections are symmetric*

The overlap of the neural network state with the stored memories. N = 500, p=7, q=6

Astrocytes **sense** and **impose** synchronized neuronal activity



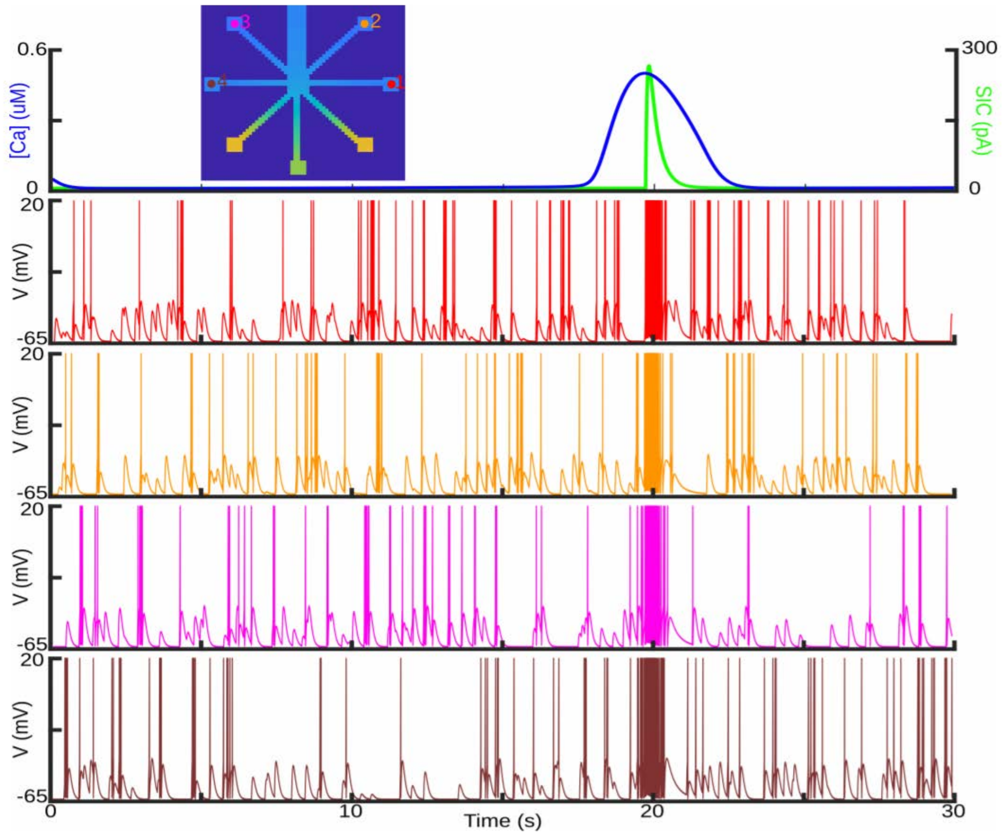


KEY POINT #1

- Astrocytes encode synchronous synaptic activity into the extent of their Ca2+ waves

KEY POINT #2

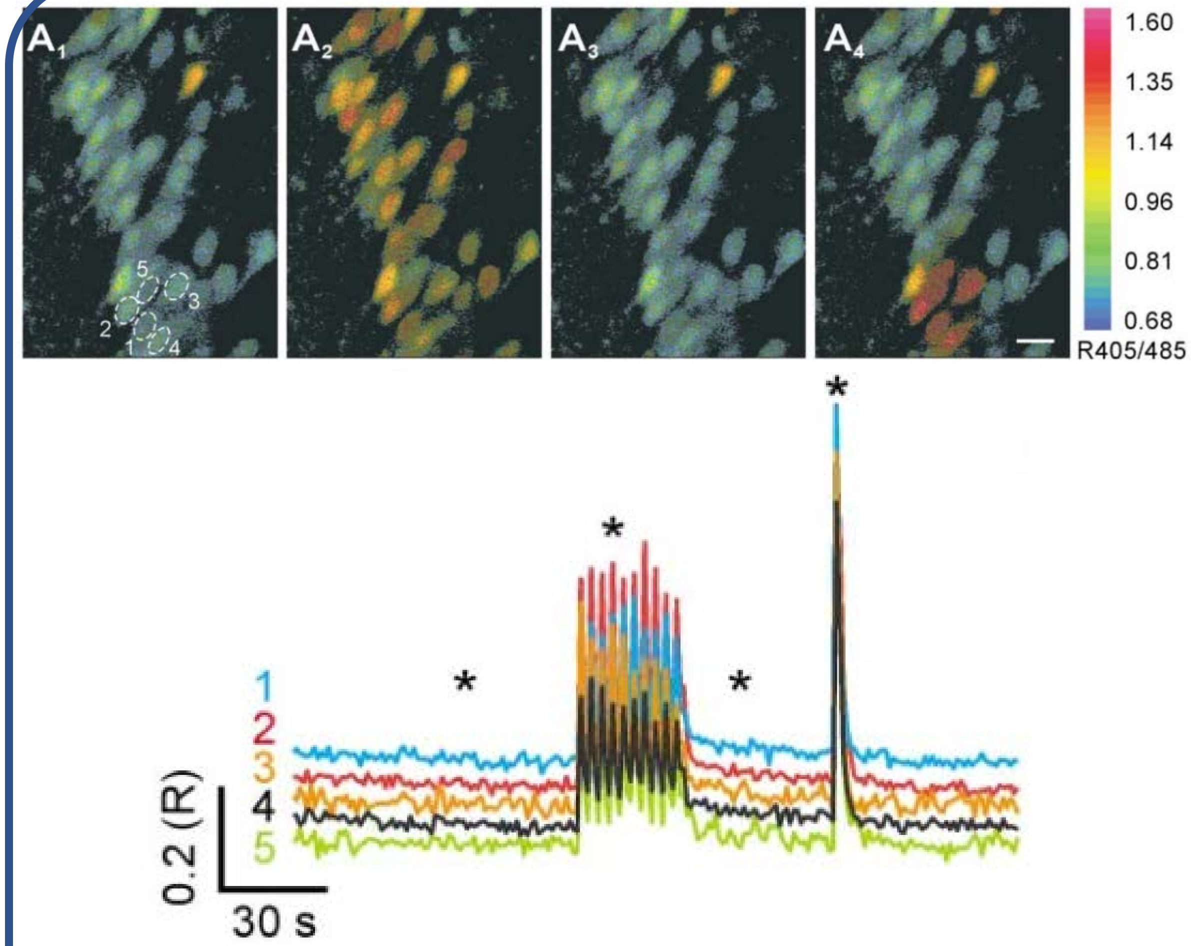
- They can impose synchronization to a group of postsynaptic neurons



[ACM ICONS '18]
[ACM BI '18]
[IEEE BHI '19]

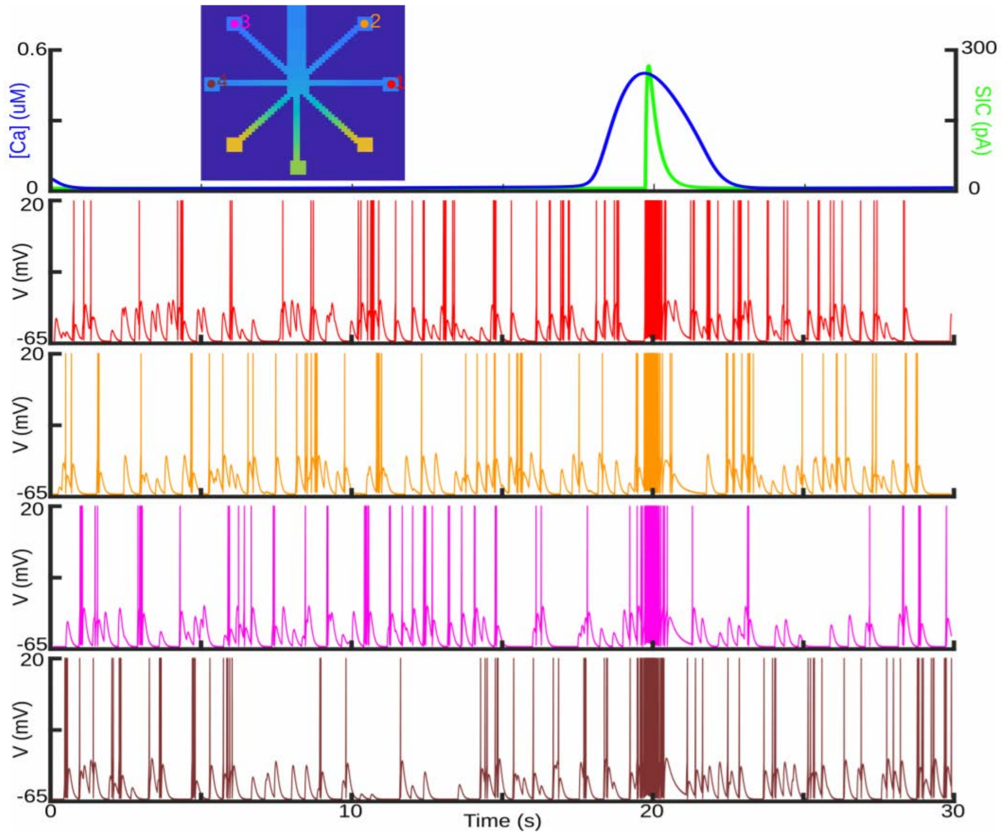
Experimentally-verified Computational Results

Synchronous astrocytic-induced activity in pyramidal neurons



Fellin *et al*, Neuron, 2004

Data

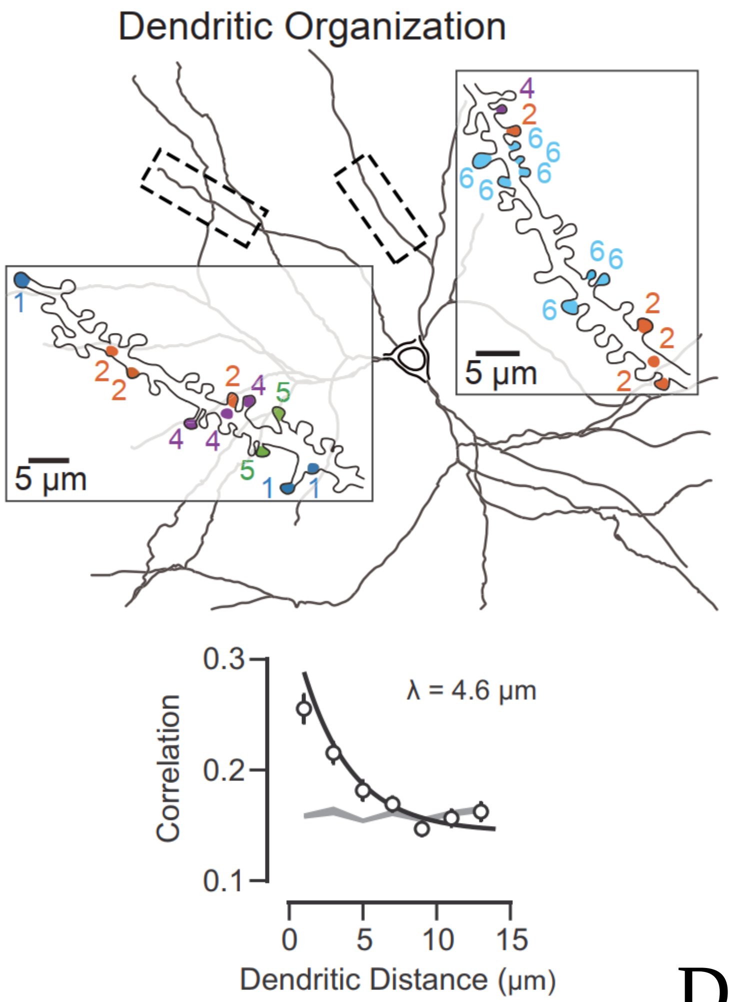


Model

[ACM ICONS ‘18]
[ACM BI ‘18]
[IEEE BHI ‘19]

Computationally-explained Experimental Results

Astrocytic-induced local plasticity

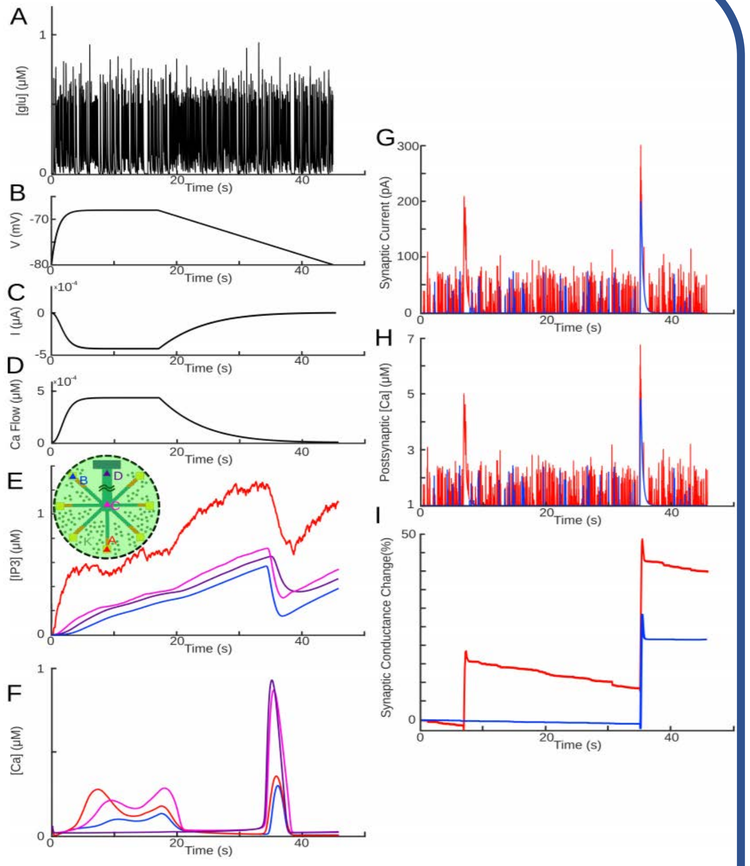


Scholl *et al.* Neuron 2017

Data

KEY POINT #3

- Two Ca^{2+} waves in the micro-domain: a) VGCCs and b)Glu-IP_3
- Process-specific VGCC Ca^{2+} waves restricted to processes with active presynaptic sites
- Microdomain-wide Ca^{2+} waves induced heteroshynaptic plasticity in inactive synapses
- Possible astrocytic mechanism for local clustering of dendritic spines *within 15 µm*



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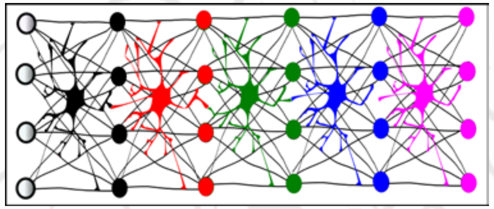
[ACM BI '18]
[IEEE BHI '19]

Model

Brain ~~Neuro~~Science

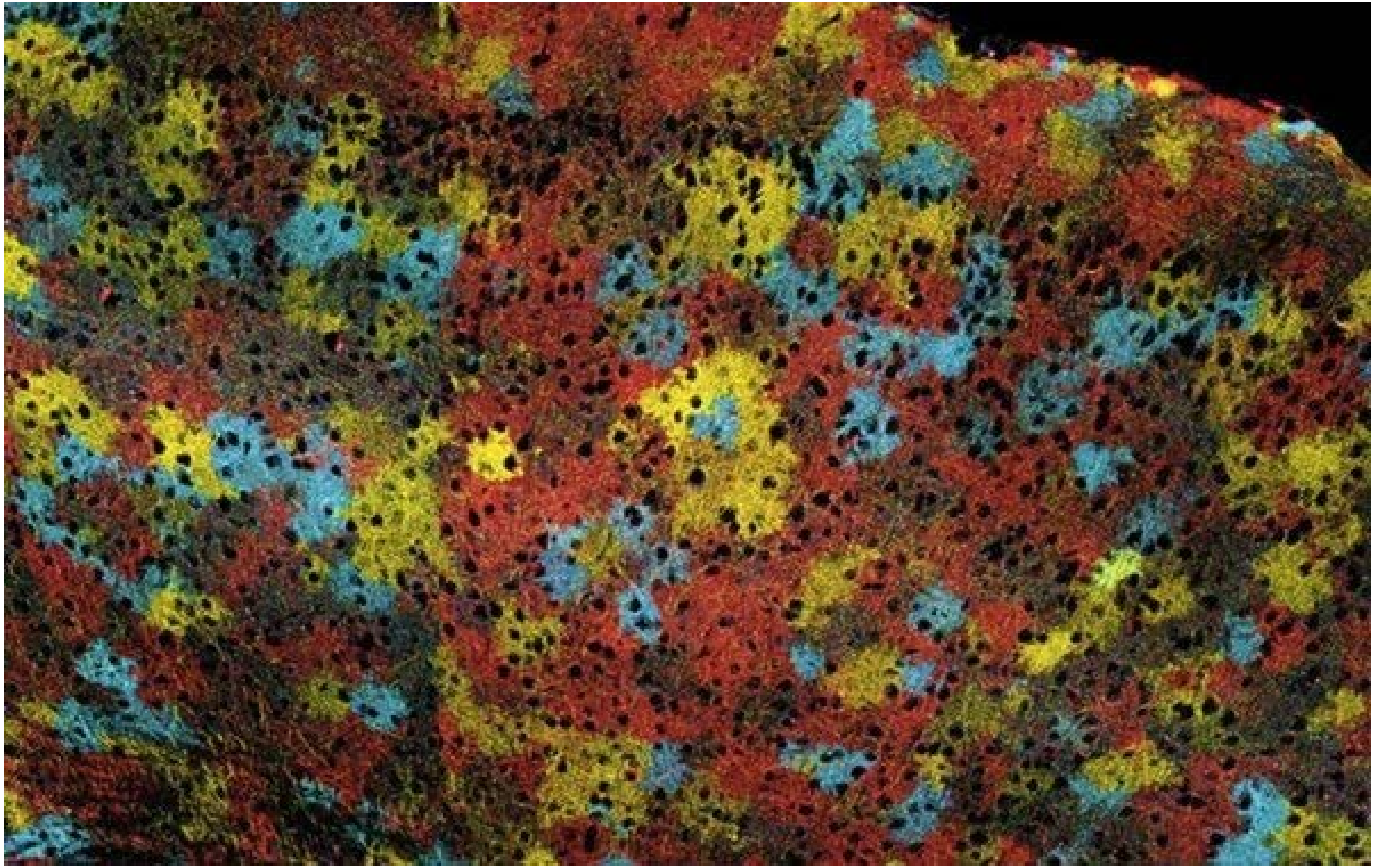


Brain ~~Neuro~~Computing

Mechanistic Origin	Mesochronous Communication
Memory Transitions	Behavioral Time Scales
Hebbian Learning	Contrast
Mechanistic Origin	Optimize Computation

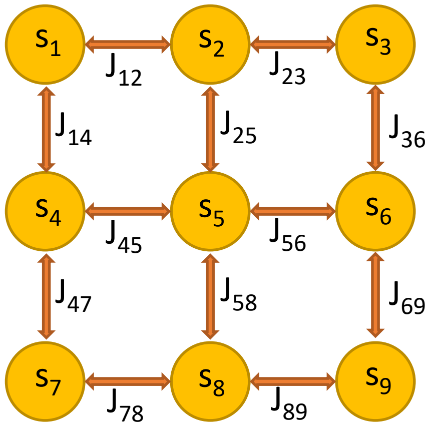
Understand *Use*

Astrocyte: A single cell Detects Neuronal *Chaos*

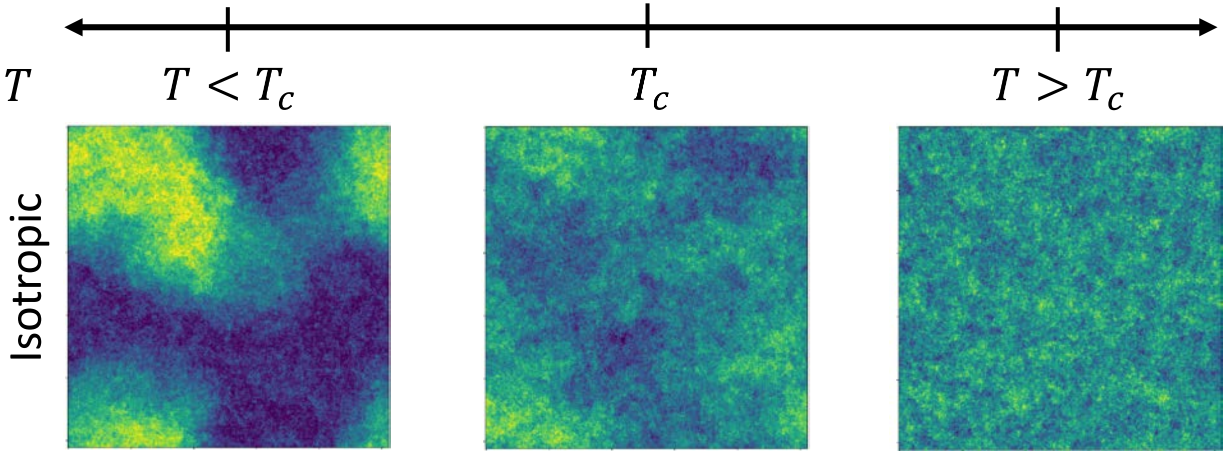


Synaptic Activity as an Ising Model

- Spins $s_i, s_j \in \{1, -1\}$
- Uniform Couplings $\forall i, j \; J_{ij} = 1$



- **Why**?
  - Brain-like near-critical dynamics *Fraiman et al. 2009*
    - Second-order phase transition between order and chaos
  - Online control of dynamics using a single parameter T



- Isotropic Ising model:
  - Minimize Energy function: $H = \sum_{i,j} -J_{ij} s_i s_j$
  - MC algorithm:
    1. Make Random Spin flip
    2. **If** $H_{current} - H_{previous} \leq 0$

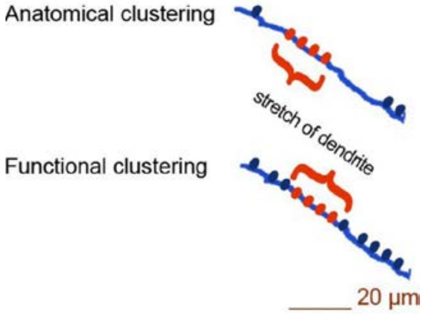
       Accept flip

       Else

       Accept flip with probability: $p = e^{-(H_{current} - H_{previous})/kT}$

Synaptic Activity as an *modified* Ising Model

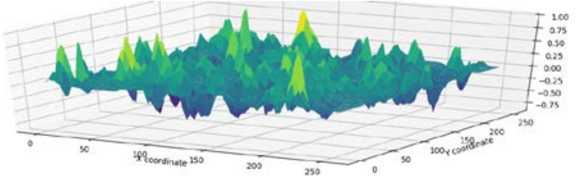
Takahashi et al. 2012

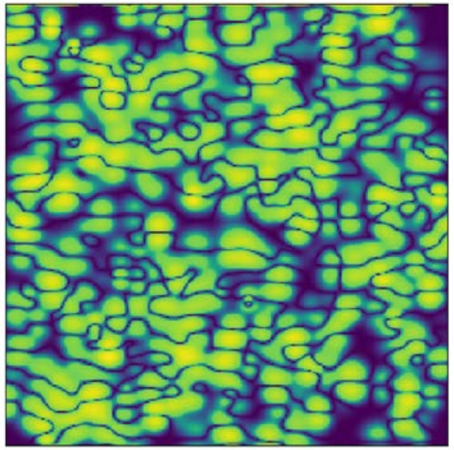


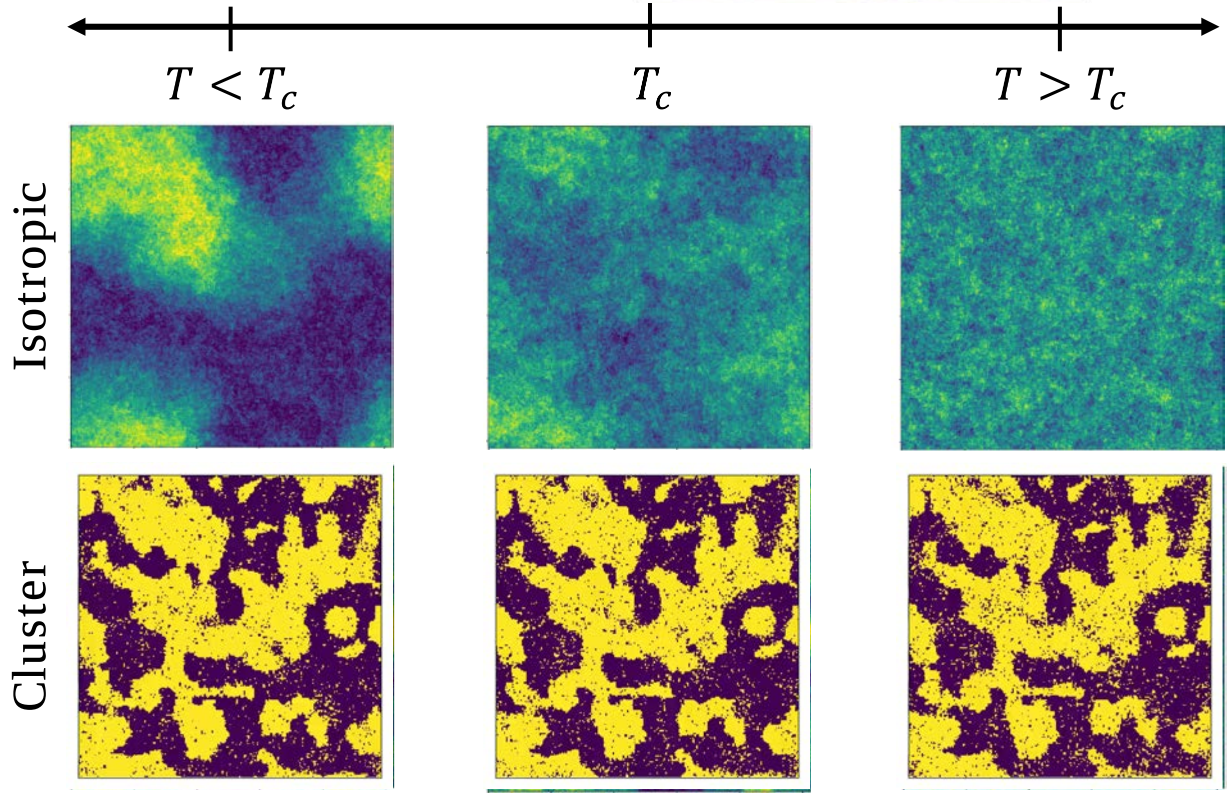
Kastelakis et al. 2016

- Spins $s_i, s_j \in \{1, -1\}$
- Uniform Couplings $\forall i,j\ J_{ij} = 1$

Clustered Couplings







Experimental Data:
- Spatially correlated synaptic activity
- Functional and synchronous clusters of neurons

Biological Implausibility:
Spin clusters lack local spatial correlation

Finding 2nd order Phase Transition in the *modified* Ising Model

- Confirmed phase transition with measures of variability in macroscopic Ising variables
- Magnetic susceptibility:

$$\chi = \frac{1}{T} < M^2 > - < M >^2$$

M Ising magnetization for N spins, $\frac{\sum_i^N s_i}{N}$

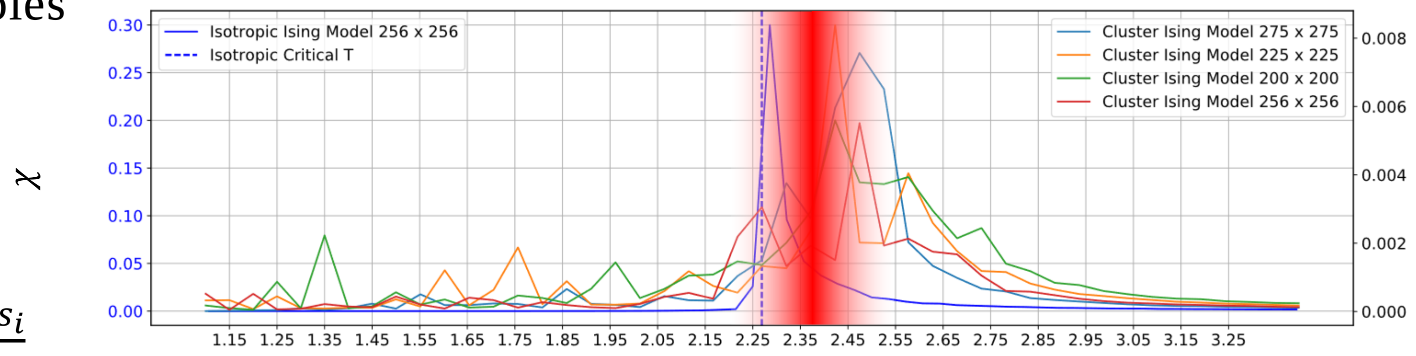
<> temporal average

- Heat capacity:

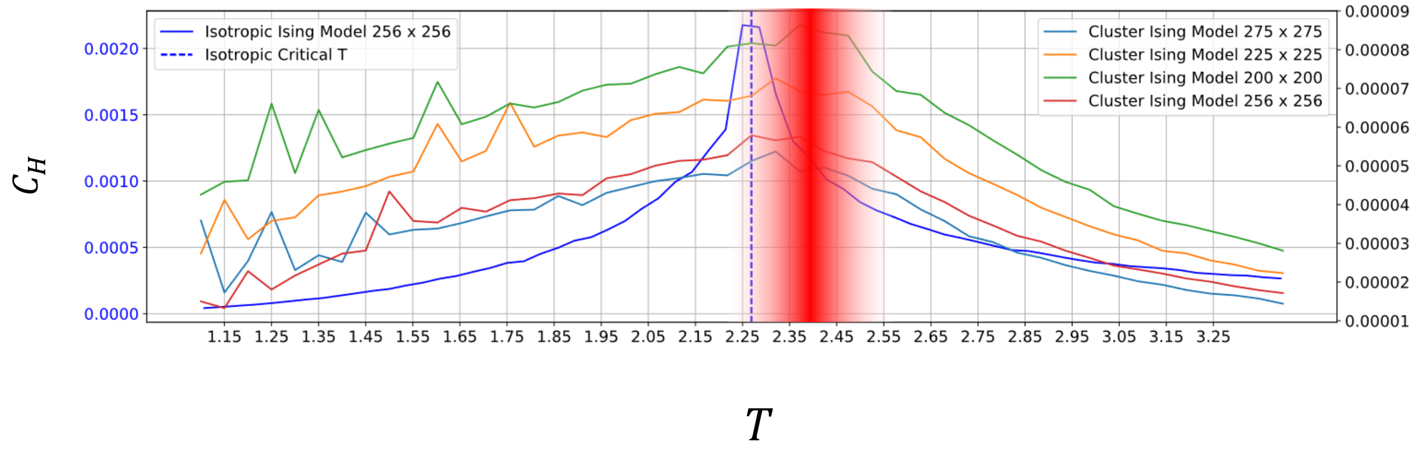
$$C_H = \frac{1}{T^2} < H^2 > - < H >^2$$

H is system energy

Magnetic Susceptibility



Heat Capacity



Brain-Like Critical Transition in the modified Ising Model

- Correlation Network
  - Constructed pair-wise spin correlation matrix C

$$C_{ij} = \frac{< s_i(t) s_j(t) > - < s_i(t) >< s_j(t) >}{(< s_i^2(t) > - < s_i(t) >^2)(< s_j^2(t) > - < s_j(t) >^2)}$$

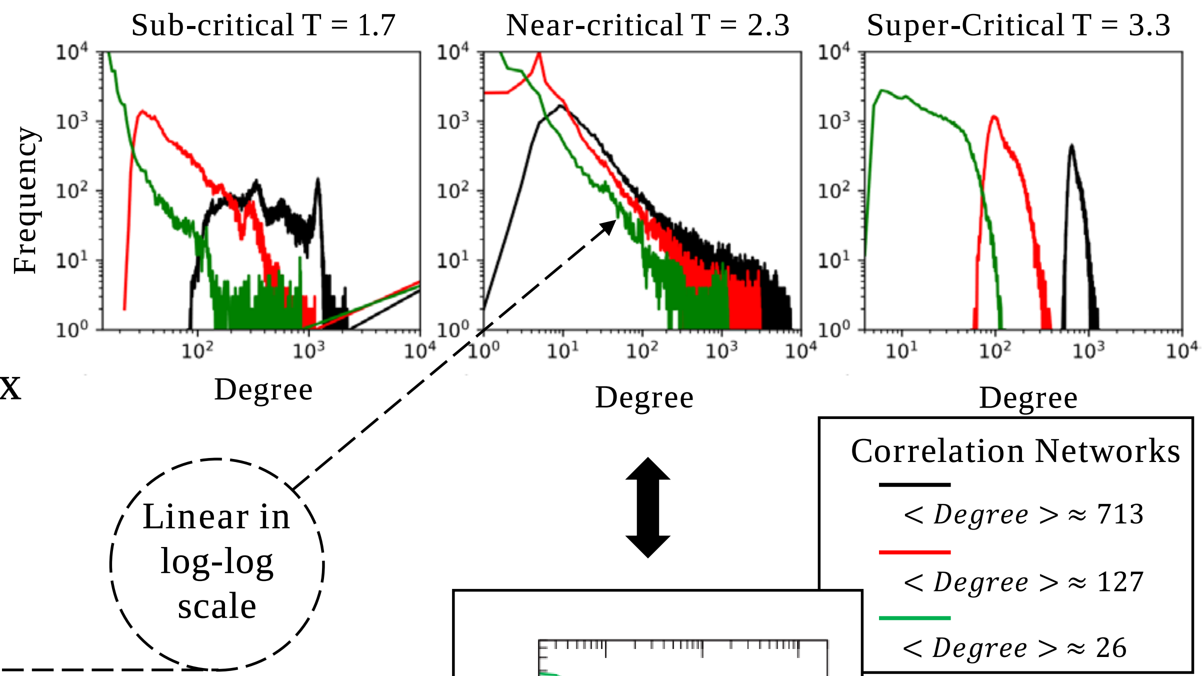
  - Selected various correlation thresholds ρ
  - Binarize correlation network connectivity matrix

W:

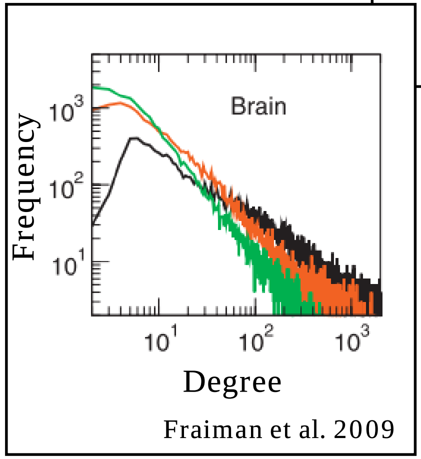
$$W_{ij} = \begin{cases} 1, & C_{ij} > \rho \\ 0, & C_{ij} \leq \rho \end{cases}$$

- Power law scaling at T_{nc}
  - Agrees with second order phase transition
  - Near-critical dynamics similar to fMRI data

Correlation Network Degree Distributions



Linear in log-log scale



Touboul & Destexhe 2017

Disclaimer

Power-law statistics alone are not sufficient indications of criticality

From Synaptic Activity to Astrocytic Ca^{2+} waves

- Comprehensive 3D model of astrocytic biochemical pathway:

$IP3$: • Cytosolic $IP3$ (I)

$$\frac{dI}{dt} = v_\beta \left(\frac{\gamma^{0.7}}{\gamma^{0.7} + K_R\left(1 + \left(\frac{K_p}{K_R}\right)\left(\frac{C}{C+K_\pi}\right)\right)} \right) + \left(\frac{v_\delta}{1+\frac{I}{\kappa_\delta}}\right)\left(\frac{C^2}{C^2+K_{PLC\delta}}\right) - v_{3K}\left(\frac{C^4}{C^4+K_D}\right)\left(\frac{I}{I+K_3}\right) - r_{5P} I$$

Ca^{2+}: • Cytosolic Ca^{2+} (C)

$$\frac{dC}{dt} = \left(r_C m_\infty^3 n_\infty^3 h^3 + r_L\right)\left(C_0 - (1+c_1)C\right) - v_{ER}\left(\frac{C^2}{C^2+K_{ER}^2}\right)$$

h: • Dimensionless hidden variable h

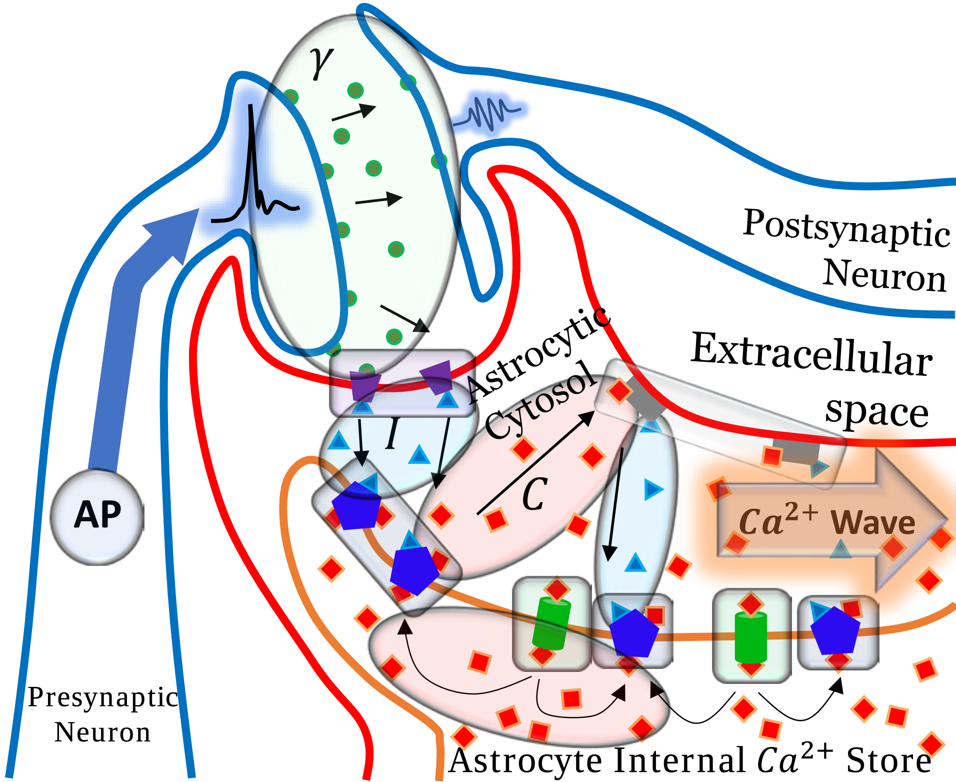
$$\frac{dh}{dt} = \frac{h_\infty(C,I) - h}{\tau_h(C,I)}$$

- Removed from cytosol by $SERCA$

Enzyme

Pumps

De Pitta *et al.* 2009



From Synaptic Activity to Astrocytic Ca^{2+} waves

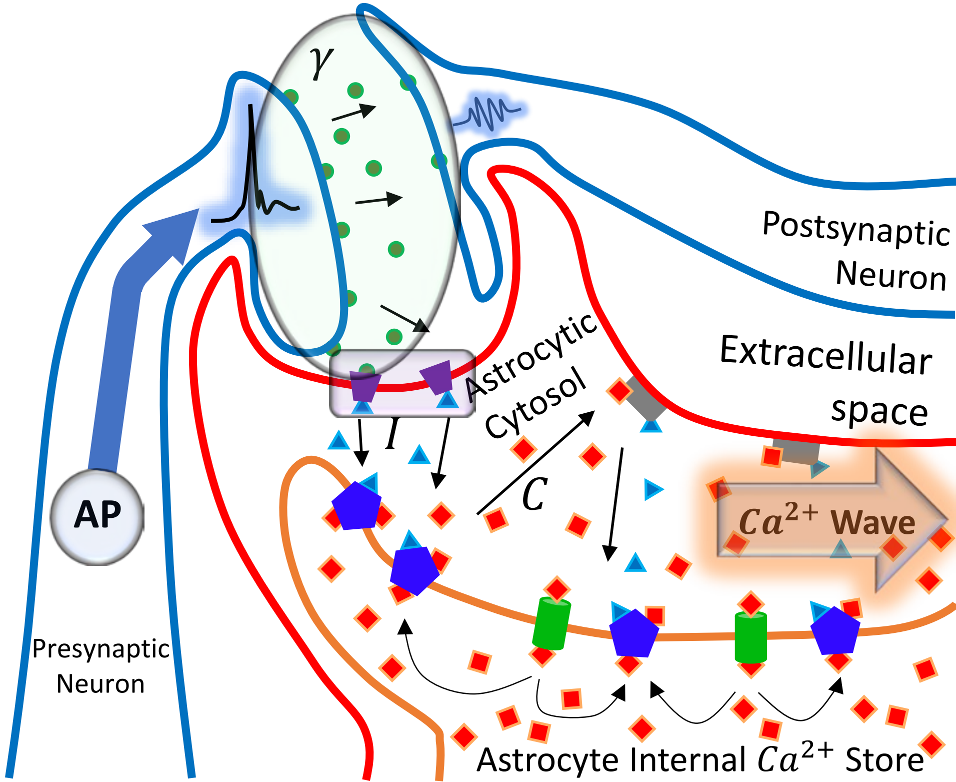
$$IP3: \quad \frac{dI}{dt} = \frac{1}{N}\sum_{i=1}^{N}\left[v_{\beta_i}\left(\frac{\gamma_i^{0.7}}{\gamma_i^{0.7} + K_R^{0.7}\left(1+\frac{K_p}{K_R}\left(\frac{C}{C+K_\pi}\right)\right)}\right)\right] + \left(\frac{v_\delta}{1+\frac{I}{\kappa_\delta}}\right)\left(\frac{C^2}{C^2+K_{PLC\delta}}\right) - v_{3K}\left(\frac{C^4}{C^4+K_D}\right)\left(\frac{I}{I+K_3}\right) - r_{5P}I$$

$$Ca^{2+}: \quad \frac{dC}{dt} = (r_C m_\infty^3 n_\infty^3 h^3 + r_L)(C_0 - (1+c_1)C) - v_{ER}\left(\frac{C^2}{C^2+K_{ER}^2}\right)$$

$$h: \quad \frac{dh}{dt} = \frac{h_\infty(C,I) - h}{\tau_h(C,I)}$$

Our Modifications:

- Expanded the neurotransmitter input (γ_i) and release probability (v_{β_i}) per synapse i



modified

De Pitta *et al.* 2009

From Synaptic Activity to Astrocytic Ca^{2+} waves

$$IP3: \quad \frac{dI}{dt} = \frac{1}{N}\sum_{i=1}^{N}\left[v_{\beta_i}\left(\frac{\gamma_i^{0.7}}{\gamma_i^{0.7} + K_R\left(1+\left(\frac{K_p}{K_R}\right)\left(\frac{C}{C+K_\pi}\right)\right)}\right)\right] + \left(\frac{v_\delta}{1+\frac{I}{\kappa_\delta}}\right)\left(\frac{C^2}{C^2+K\right.}$$

$$Ca^{2+}: \quad \frac{dC}{dt} = (r_C m_\infty^3 n_\infty^3 h^3 + r_L)(C_0 - (1+c_1)C) - v_{ER}\left(\frac{C^2}{C^2+K_{ER}^2}\right)$$

$$h: \quad \frac{dh}{dt} = \frac{h_\infty(C,I) - h}{\tau_h(C,I)}$$

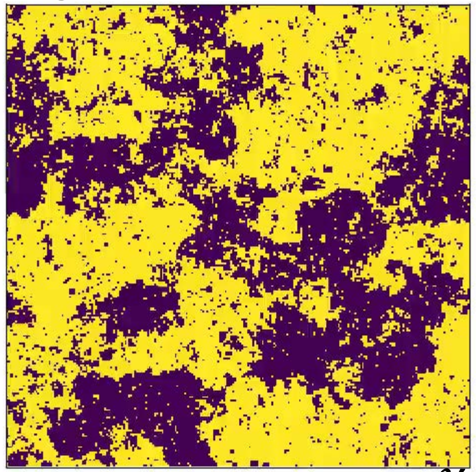
Old Model formulations / Our Modification:

- Ca^{2+} wave independent of synaptic inputs / Dependent on previous synaptic rate $\hat{r}$
- Inversely scaled to Glutamate Receptor density (v_{β_i}) / Learning added to *Glutamate Receptor* density (v_{β_i})

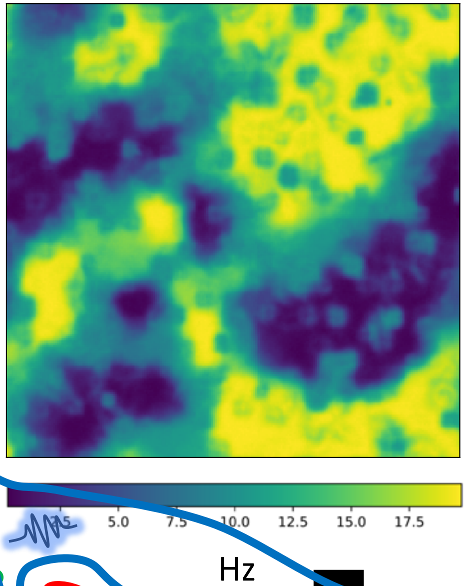
modified

De Pitta *et al.* 2009

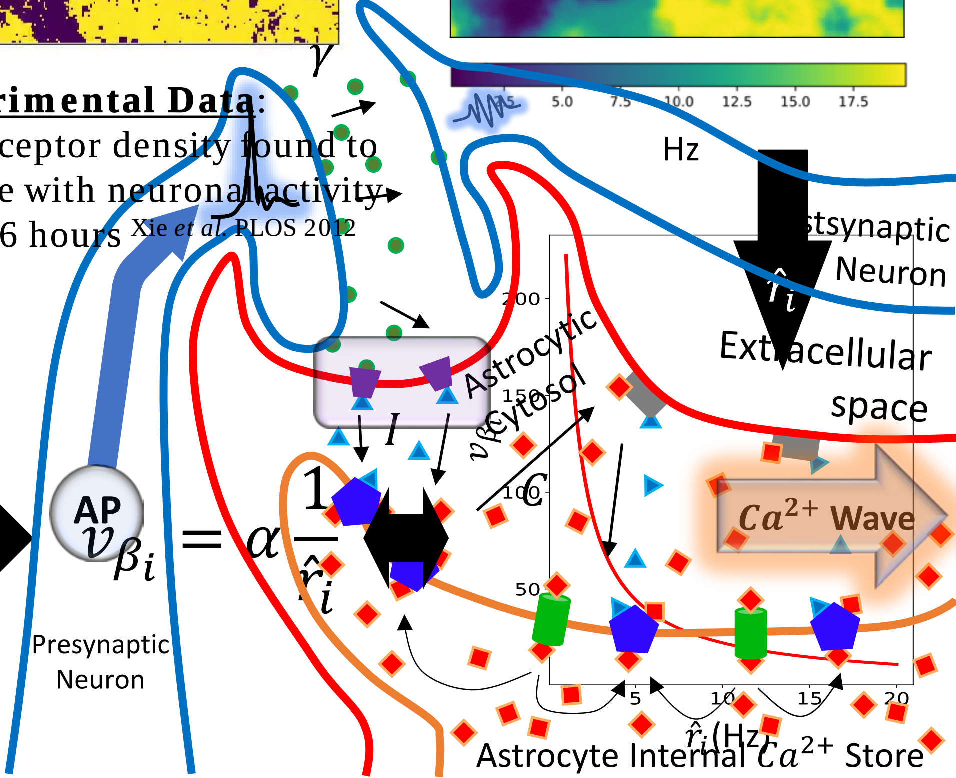
Brain-like Ising Dynamics



Training Rates $\hat{r}$

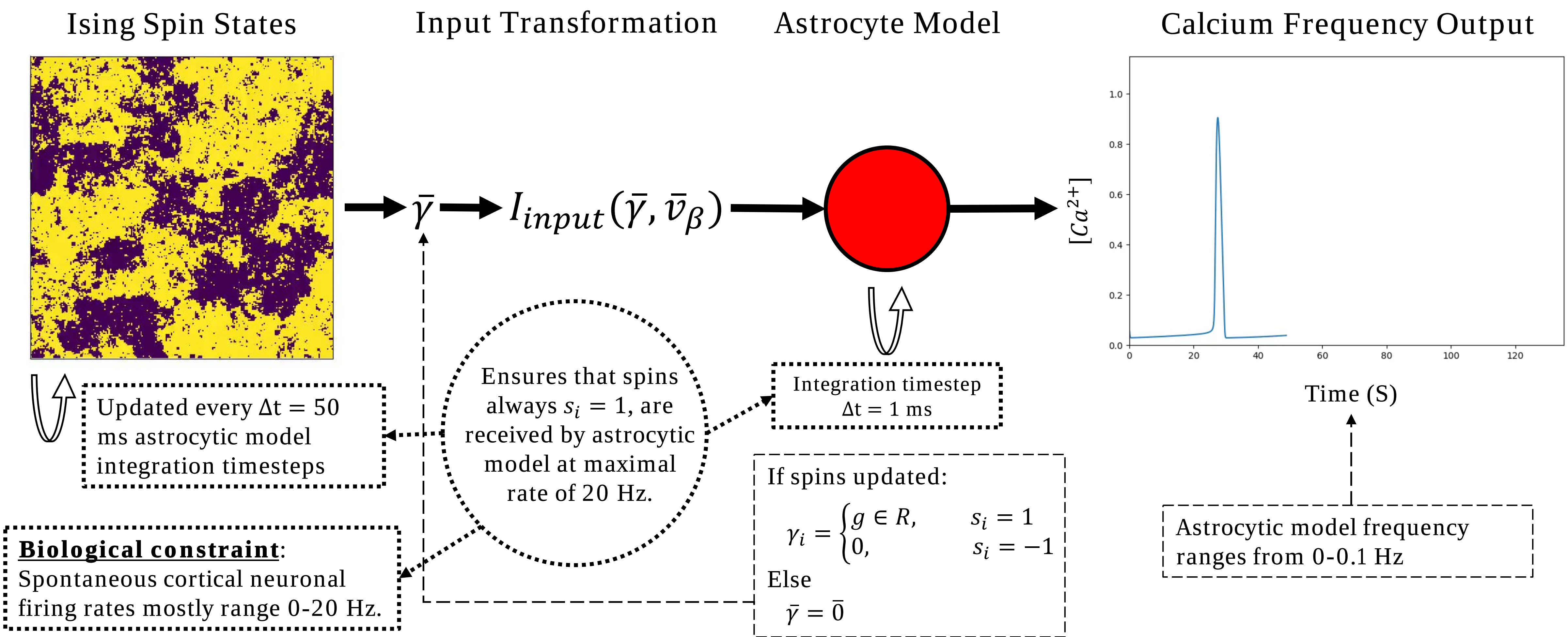


Experimental Data:
Glutamate receptor density found to inversely scale with neuronal activity over past 4-6 hours Xie *et al.* PLOS 2012

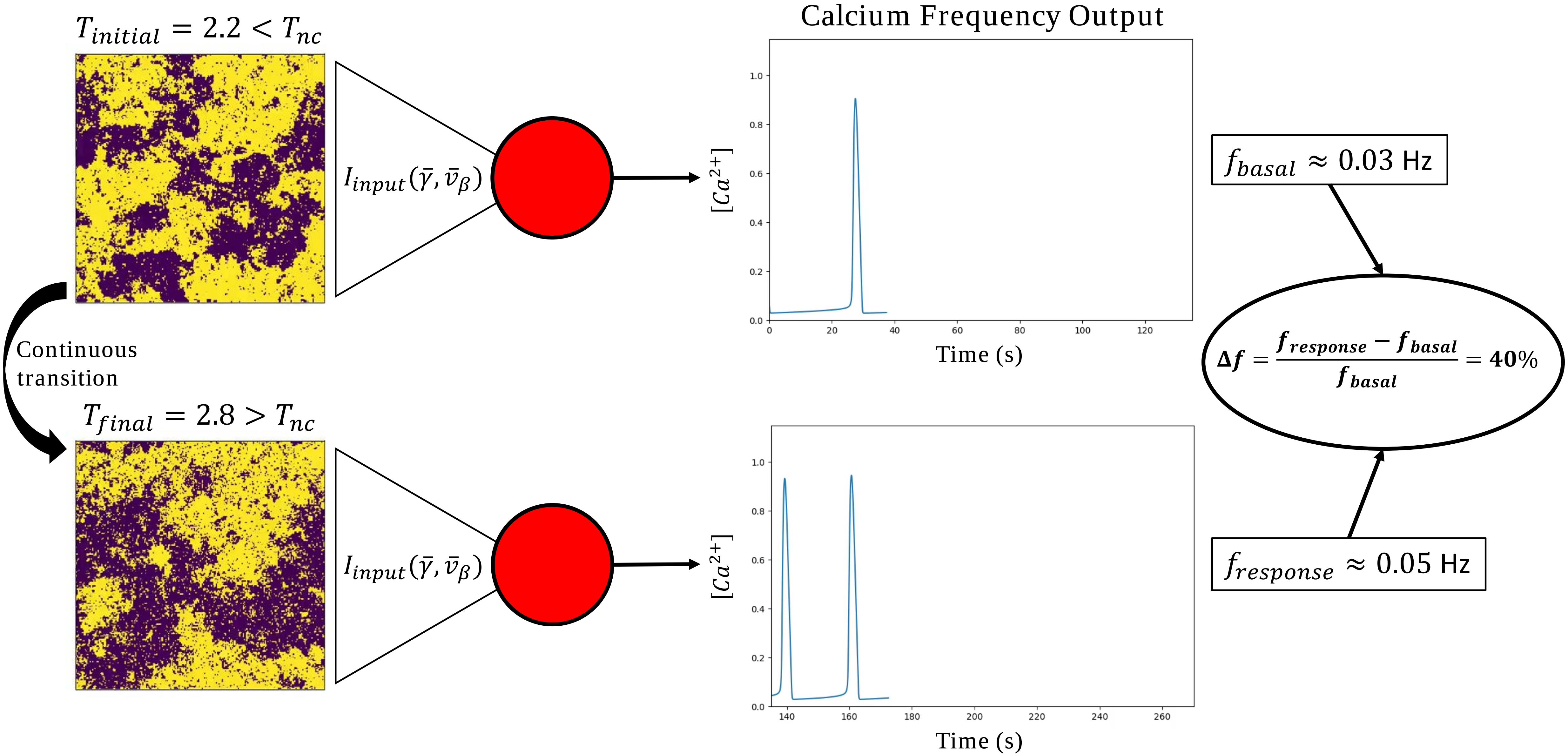


Simulation

- Ising model spin states were transformed into biological scales of time and quantity



Astrocytic Response to Neuronal Dynamics

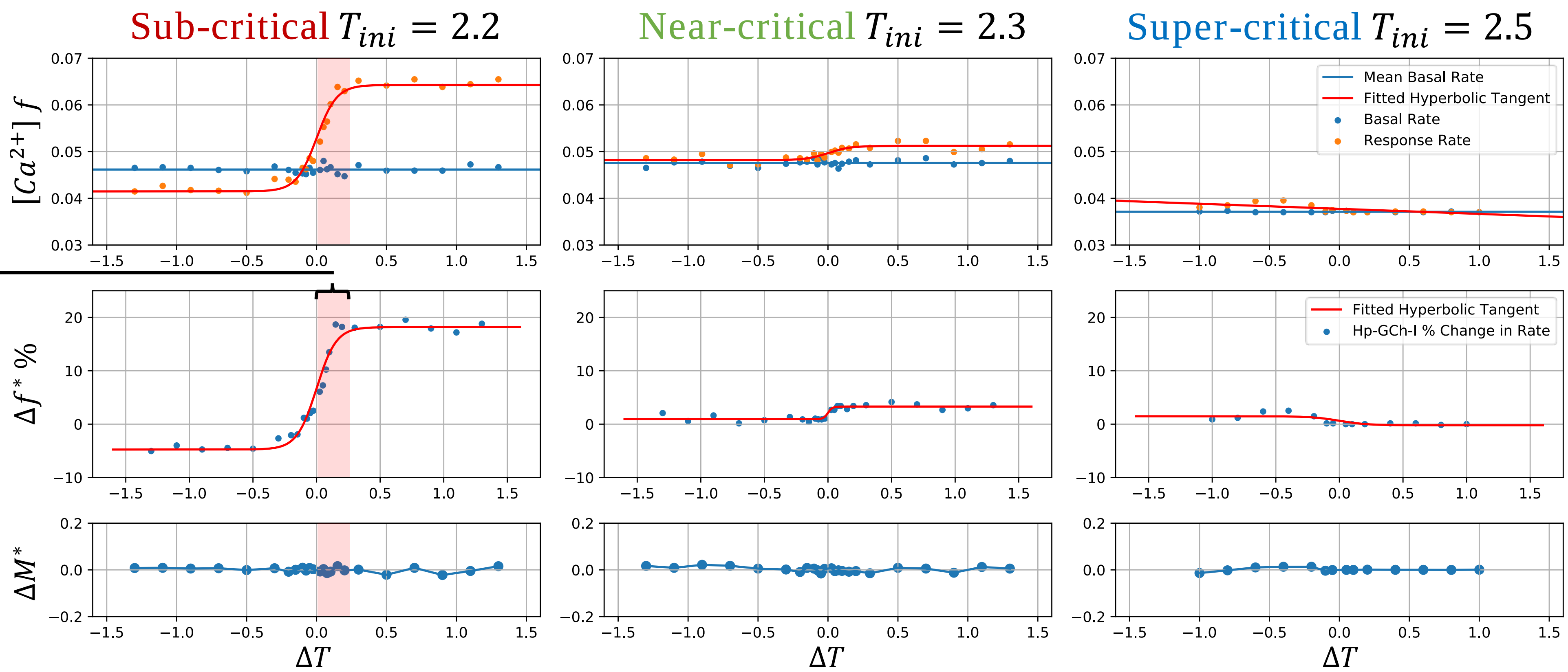


Astrocyte detects transitions from order to disorder

- Astrocytic response existed only for transition $T_{ini} < T_{near\_critical} \rightarrow T_{final} > T_{nc}$
- Response averaged over 5 cluster Ising models
  - Each transition $T_{ini} \rightarrow T_{final}$ was averaged over 10 simulations

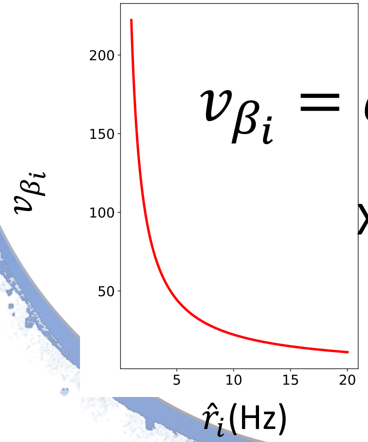
Both near-critical and chaotic T_{ini} did not alter astrocytic response

Astrocytic frequency changes at the transition across the near-critical range, $T_{nc} = [2.25, 2.45]$, where a 2nd order phase transition exists between order and chaos.



Changes in magnetization did not drive astrocytic response

$\Delta M^* = < M_{T_{final}} > - < M_{T_{initial}} >$

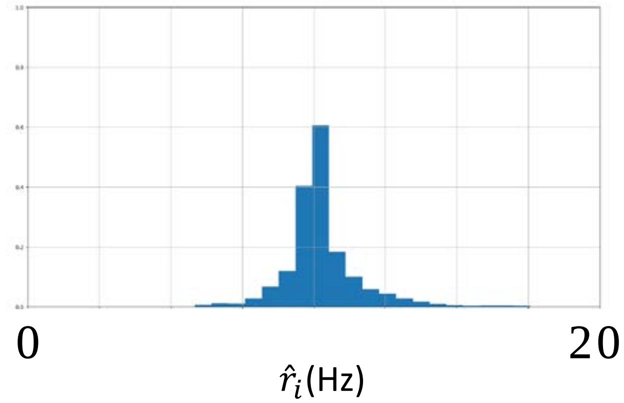


$$v_{\beta_i} = \alpha \frac{1}{\hat{r}_i}$$

Xie et al. PLOS 2012

Super-critical (Chaos)

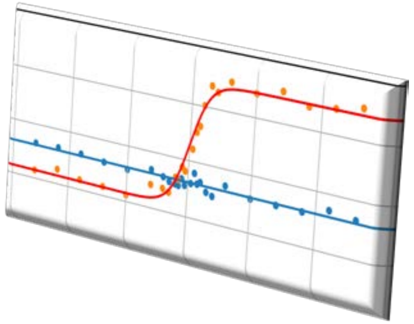
T=2.4



Order — Critical Region — Chaos — *Network State*

Binomial — Uniform — Gaussian — *Spiking Rate Distribution*

Is this magic?

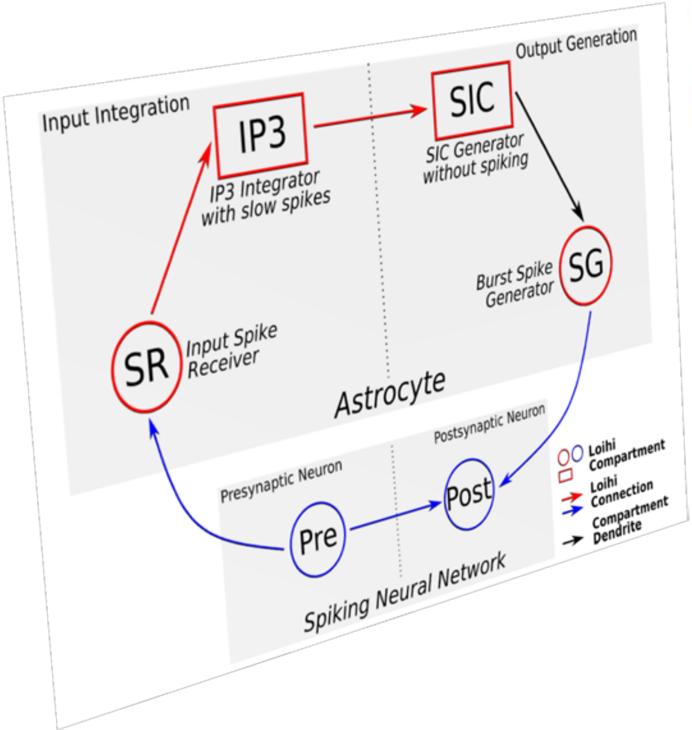


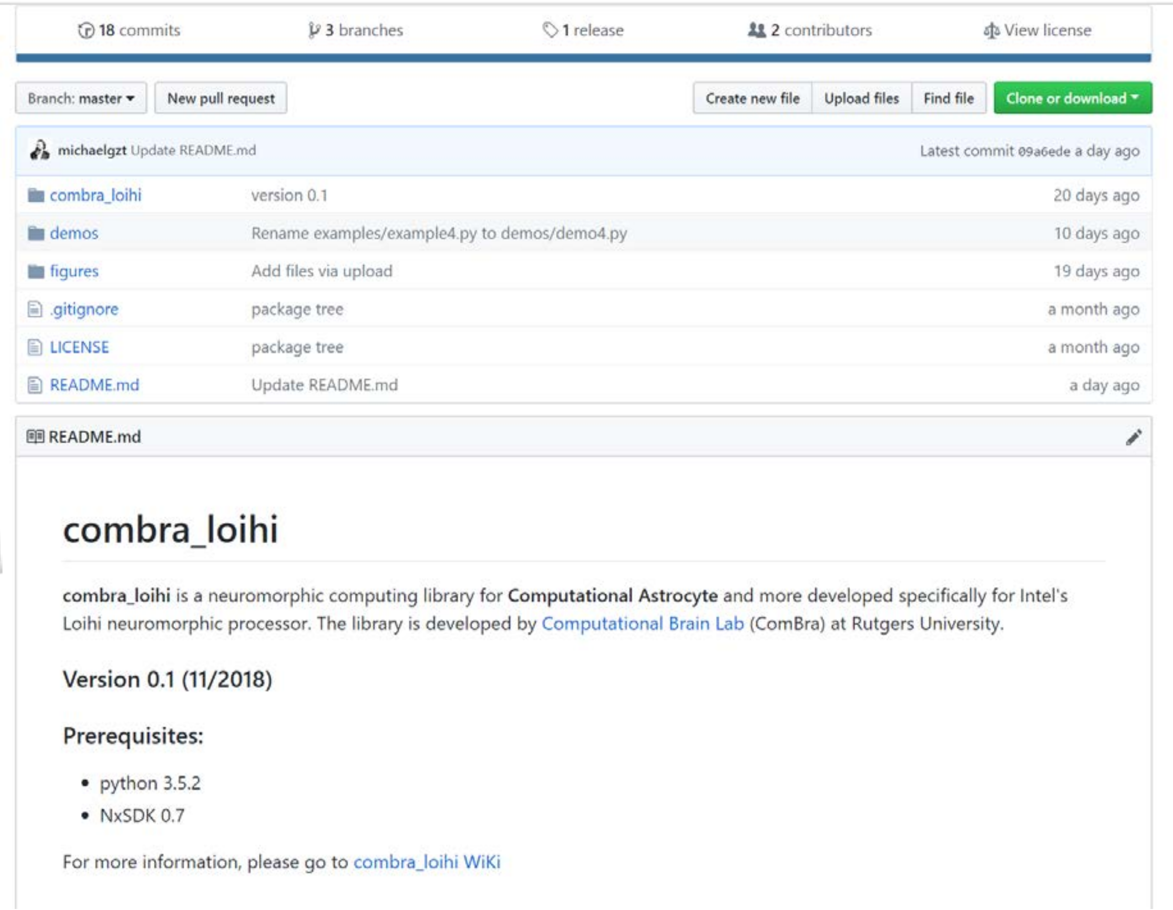
Insight

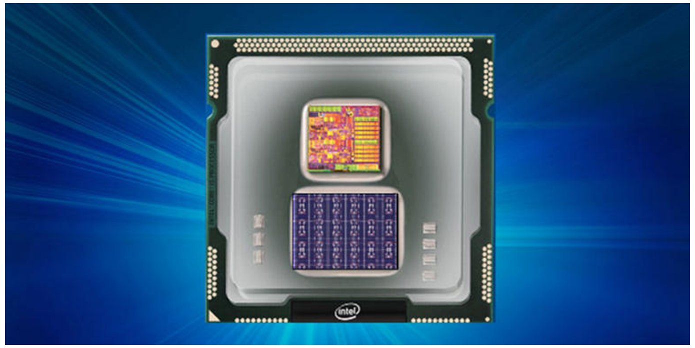
- Inverse scaling in learning the Glu receptor density
- Disproportional learning of Glu weights between lower synaptic rates and higher synaptic rates
  - Sensitivity to Glu in lower-rate synapses is much higher than the insensitivity of the higher rate synapses
- In chaos, the distribution of spiking rates changes to Gaussian μ=10Hz: Synapses that had low rates (<10Hz) increase to ~10Hz and synapses with high rates (>10Hz) decrease to ~10Hz
- The sudden increase in rates in the learned as low-rate synapses provides disproportionally larger Glu stimulation to the astrocyte, which results in an overall increase in Ca^{2+} frequency

Astrocytic module @ Loihi chip

released December 2018







https://github.com/combra-lab/combra_loihi

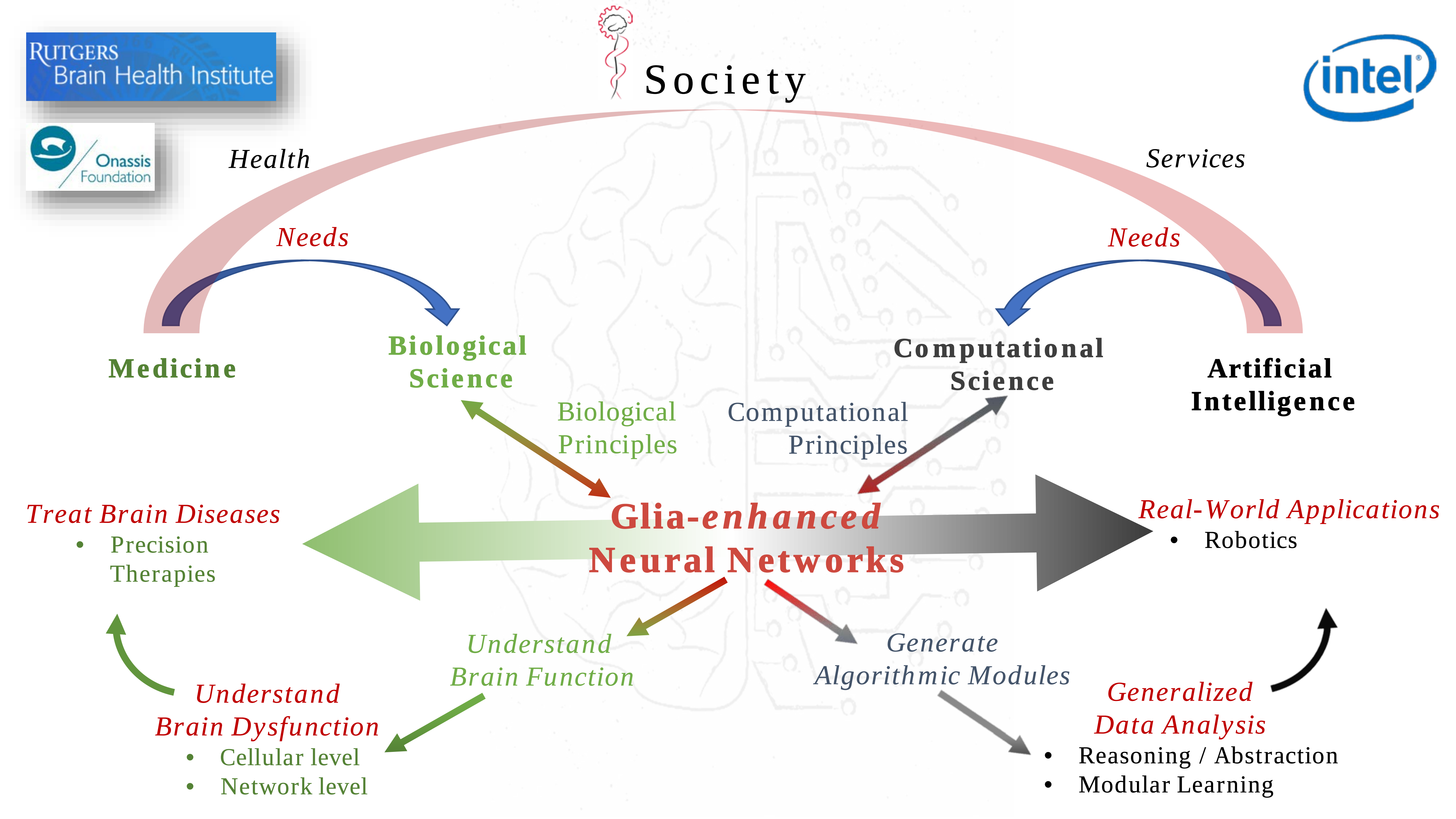
Computations at the edge of *Chaos*

- Carrying out computations at the edge of chaos is based on the hypothesis that complex systems can show an extended computational power when performing in between ordered and chaotic dynamics

- A Liquid State Machine whose reservoir shows critical dynamics could perform efficient computations in real-time

- Not much is yet known about the computational power of neural networks that are constructed consistently with neurobiology

- Our results pave the way for an ~~SOC~~ AOC, ~~self~~ astrocytic-organized criticality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Biological Science
Computational Science
Artificial Intelligence
Biological Principles
Computational Principles
Treat Brain Diseases
• Precision Therapies
Glia-enhanced Neural Networks
Real-World Applications
• Robotics
Understand Brain Function
Generate Algorithmic Modules
Understand Brain Dysfunction
• Cellular level
• Network level
Generalized Data Analysis
• Reasoning / Abstraction
• Modular Learning

combra.cs.rutgers.edu

Biological Intelligence

Glia-*enhanced* Neural Networks

Artificial Intelligence

Giannis Polykretis

Astrocytic Mechanisms for

- Neural Synchronization
- Synaptic Changes

Vladimir Ivanov

Astrocytic Computation for

- Network Oscillations
- Order/Chaotic network

Guangzhi Tang

Neuromorphic Hardware for

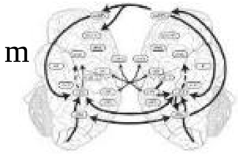
- Astrocytic Processing
- Astrocytic Learning

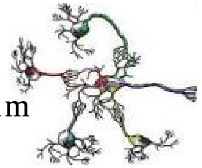
Neelesh Kumar

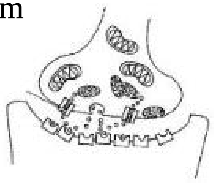
Less Machine Learning

- Reservoir Networks
- Learning Methods

CNS	1 m
Systems	10 cm
Maps	1 cm
Networks	1 mm
Neurons	100 μm
Synapses	1 μm
Molecules	1 Å







Computational Astrocyence @ ComBra Lab

- *G Tang, A Shah,* ***KP Michmizos*** , "Spiking Neural Network on Neuromorphic Hardware for Energy-Efficient Unidimensional SLAM", *arXiv preprint arXiv:1903.02504,* ***2019***
- *I Polykretis, V Ivanov,* **KP Michmizos**, "Computational Astrocyence: Astrocytes encode inhibitory activity into the frequency and spatial extent of their calcium elevations," *IEEE Brain Health Informatics*, Chicago, May 2019
- *V Ivanov, I Polykretis,* **KP Michmizos**, "Axonal Conduction Velocity Impacts Neuronal Network Oscillations," *IEEE Brain Health Informatics*, Chicago, May 2019
- *I Polykretis, V Ivanov,* **KP Michmizos**, "The Astrocytic Microdomain as a Generative Mechanism for Local Plasticity," International Conference on Brain Informatics, **2018** (pp.10)
- *I Polykretis, V Ivanov,* **K.P. Michmizos**, " A Neural-Astrocytic Network Architecture: Astrocytic calcium waves modulate synchronous neuronal activity," International Conference on Neuromorphic Systems (ICONS), Knoxville, Tennessee, July 23-26, 2018 (pp. 8)
- *G Tang*, **KP Michmizos**, " Gridbot: An autonomous robot controlling by a spiking neural network mimicking the brain's navigational system," International Conference on Neuromorphic Systems (ICONS), Knoxville, Tennessee, July 23-26, 2018 (pp. 8)
- *G. Tang*, **KP Michmizos**, " Gridbot: A Spiking Neural Network Model of the Brain's Navigation System for Autonomous Robots," 6th Neuro Inspired Computational Elements Workshop (NICE 2017), Intel Hillsboro, OR, February 27th- March 1st, 2018
- *L. Kozachkov*, **KP. Michmizos**, " Brain-morphism: Astrocytes as Memory Units," 6th Neuro Inspired Computational Elements Workshop (NICE 2017), Intel Hillsboro, OR, February 27th- March 1st, 2018
- *L. Kozachkov*, **KP Michmizos**, " A Computational Role for Astrocytes in Memory," arXiv:1707.05649, **2017**
- *L. Kozachkov*, **KP Michmizos**, " The Causal Role of Astrocytes in Slow-Wave Rhythmogenesis: A Computational Modelling Study," arXiv:1702.03993, 2017

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Towards Critical SNNs: Astrocytes Detect *Chaos* in Neuronal Dynamics

Back-Up Slides

Konstantinos Michmizos

Computational Brain Lab
Computer Science | Rutgers University

NICE 2019 | March 27th 2019

NANs=Neural-Astrocytic Networks

NANS

Research on capsules is now at a similar stage to research on recurrent neural networks for speech recognition at the beginning of this century. There are fundamental representational reasons for believing that it is a better approach but it probably requires a lot more small insights before it can out-perform a highly developed technology. The fact that a simple capsules system already gives ~~unparalleled performance at segmenting overlapping digits~~ is an early indication that capsules are a direction worth exploring.

NAN

new time and learning dimensions

NANs

Hinton *NIPS* 2017