Superconducting Bio-inspired Neurons for Spiking Networks

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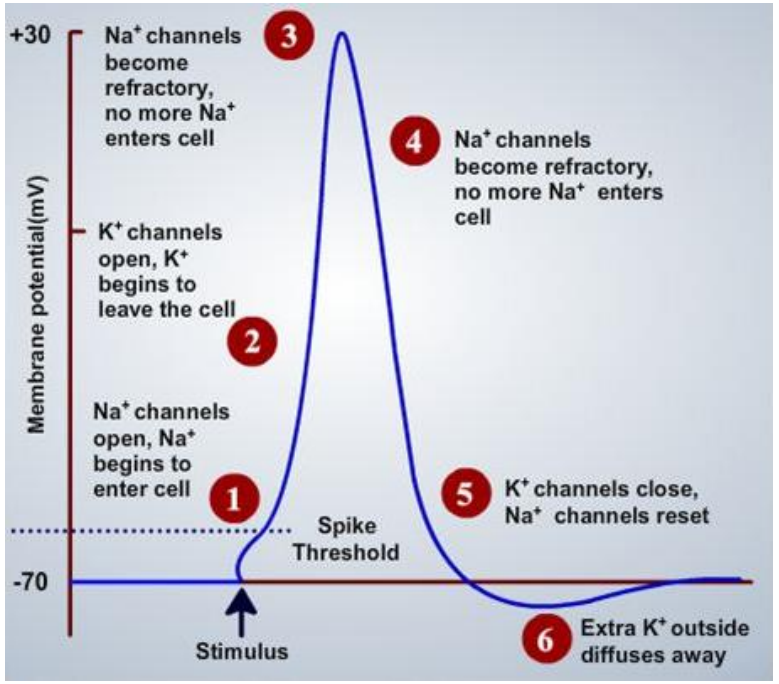
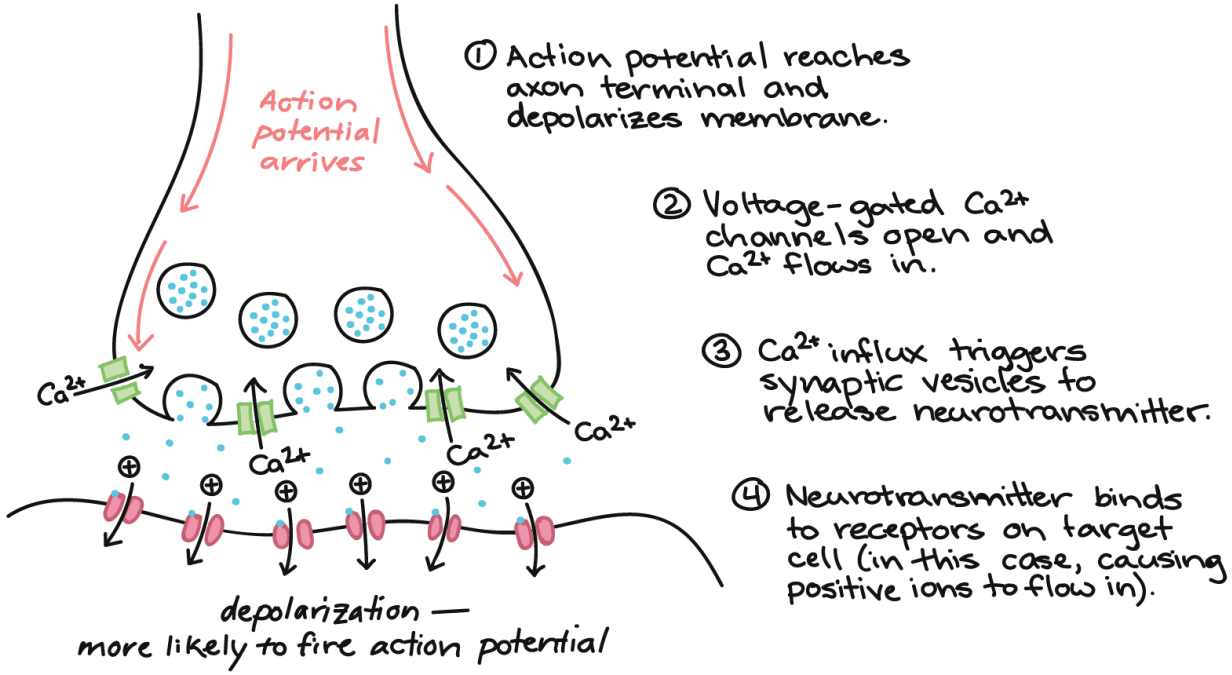
What are Spiking Neural Networks?

SNN are artificial neural networks that
more closely mimic natural neural networks

SNNs can model the central nervous system of
biological organisms,
such as an insect seeking food without prior knowledge of the environment

Biological and bio-inspired models of neurons





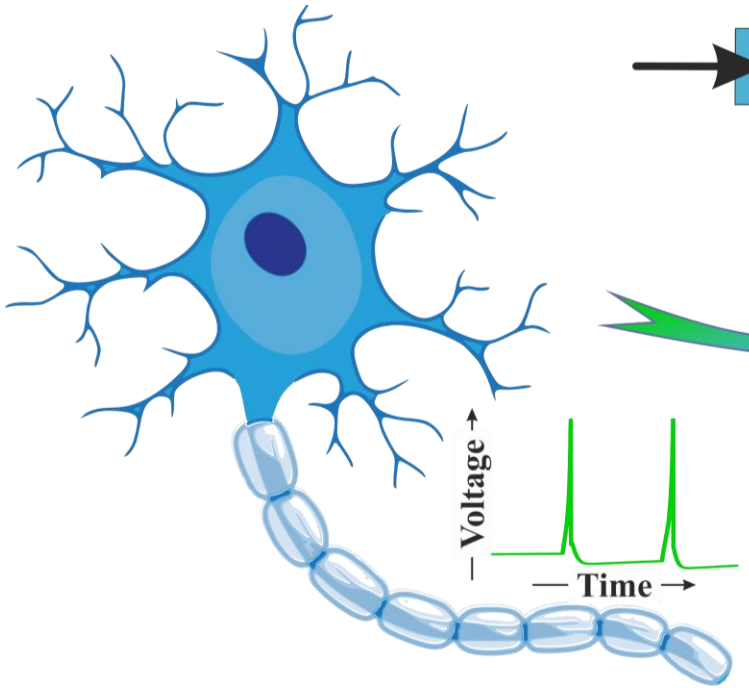
Bio-inspired models	Authors / *Year*
Hodgkin–Huxley model (*conductance-based model, CBM*)	**Hodgkin A. L., Huxley A. F. *1952***
FitzHugh–Nagumo model (*FHN*)	**FitzHugh R. *1955***
Morris–Lecar model (*CBM + FHN*)	**Morris C., Lecar H. *1981***
Izhikevich model (*model based on fractional derivative*)	**Izhikevich E.M. *2003***

Main idea

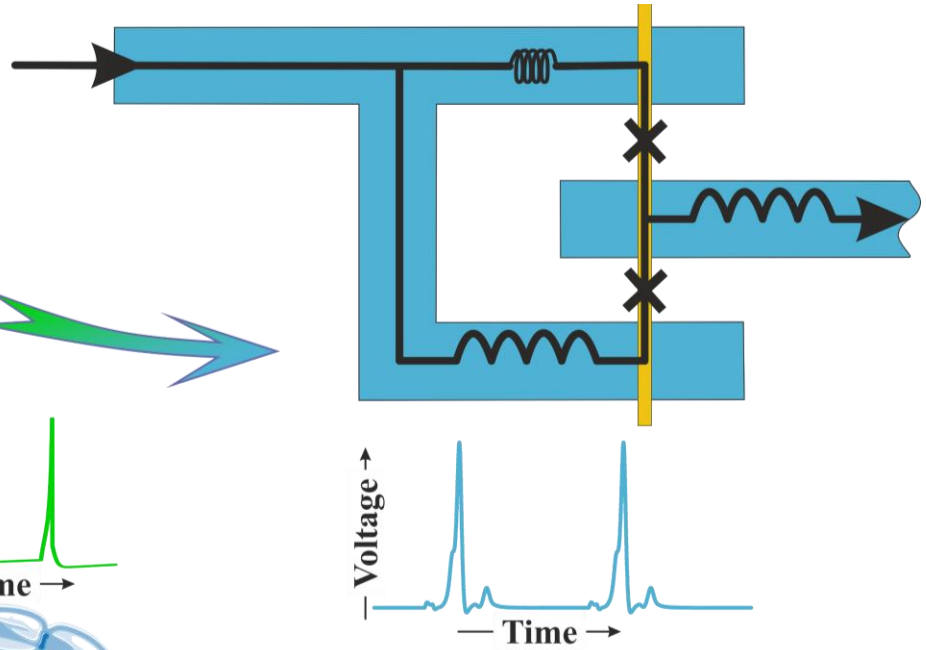
The application of superconducting materials also allows for competing CMOS in the implementation of artificial neurons

Josephson junction switching provides the generation of picosecond-width quantized voltage spike of mV amplitude accompanied by sub-aJ energy dissipation.
The shape of this spike can be quite close to the one produced in neurophysiological processes

Biological neuron



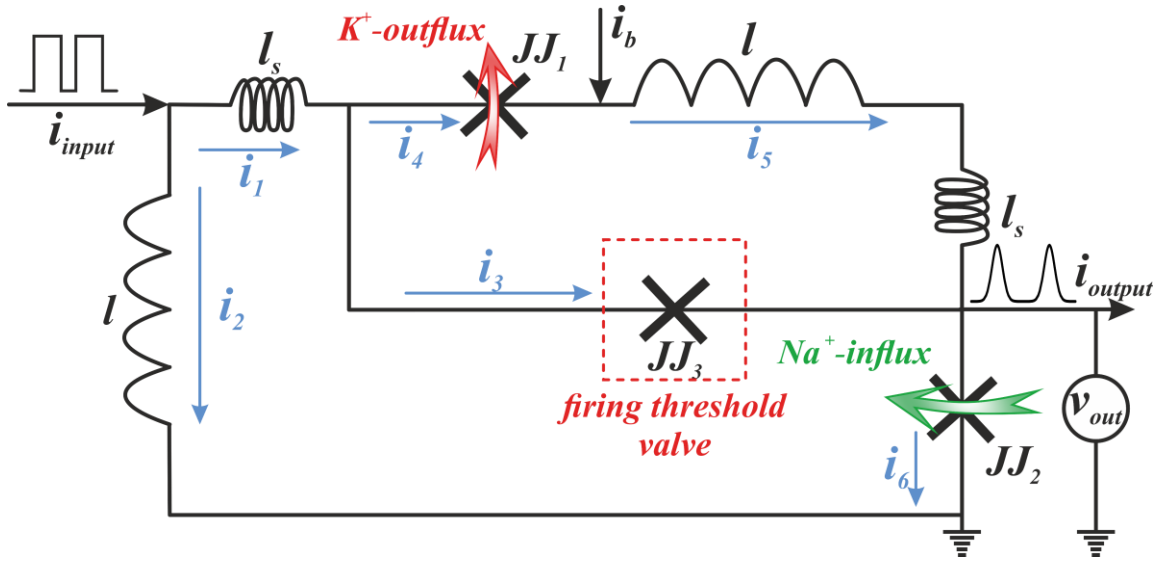
Superconducting neuron



Benefits of superconducting technology:

1) **picosecond spikes;**
2) **low energy dissipation;**
3) **serious scientific background;**
4) **ballistic signal transfer;**
5) **high transmission speed (near the speed of light) over long distances with low crosstalk;**
6) **opportunity of 3D fabrication.**

Bio-inspired Neuron



Kirchhoff's equations augmented by the phase-based circuit equations

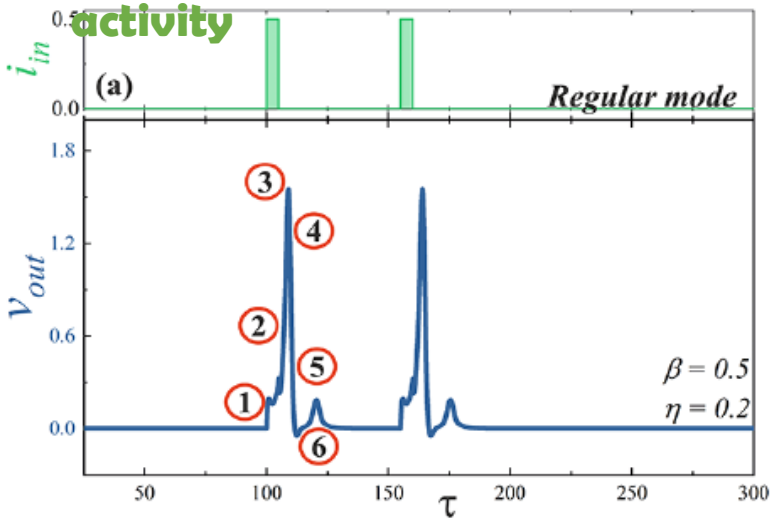
$$\begin{cases} \ddot{\phi}_1 = -\frac{1}{\beta}\{i_b + \lambda(\phi_1 - \phi_3) + \dot{\phi}_1 + \sin\phi_1\}, \\ \ddot{\phi}_2 = \frac{1}{\beta}\{i_b + i_{in}\Lambda - \lambda(\phi_2 + \phi_3) - \dot{\phi}_2 - \sin\phi_2\}, \\ \ddot{\phi}_3 = \frac{1}{\beta}\left\{\frac{1}{\eta}(i_b + i_{in}\Lambda + \lambda(\phi_1 - \phi_2 - 2\phi_3)) - \dot{\phi}_3 - \sin\phi_3\right\} \end{cases}$$

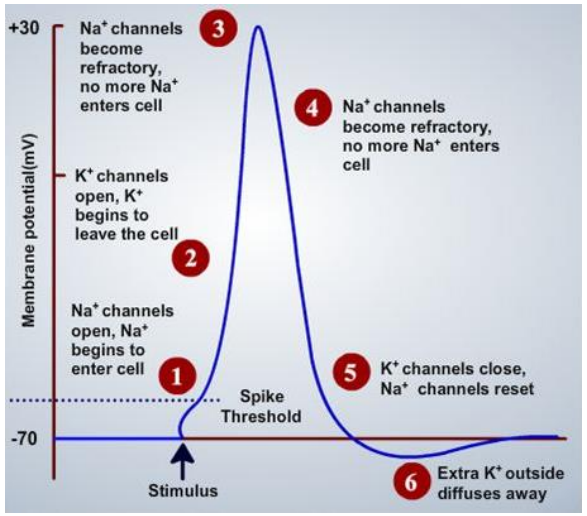
Here $\Lambda = \lambda l$, $\lambda = (l + l_s)^{-1}$, $\beta = \omega_c RC$

The first and second Josephson junctions play the role of sodium (Na+) and potassium (K+) ion channels in the neuron membrane respectively.

The voltage across the cell, v_{out}, reflects the following processes during the neuron firing, see the circled numbers on a spike, similar to the biological one.

The proposed neuron is capable of mimic the biological activity





nanomaterials

Skryabina, O. V., Schegolev, A. E., Klenov, N. V., et al. (2022). Superconducting Bio-Inspired Au-Nanowire-Based Neurons. *Nanomaterials, 12*(10), 1671. DOI:

Operating Modes of Bio-inspired Neuron

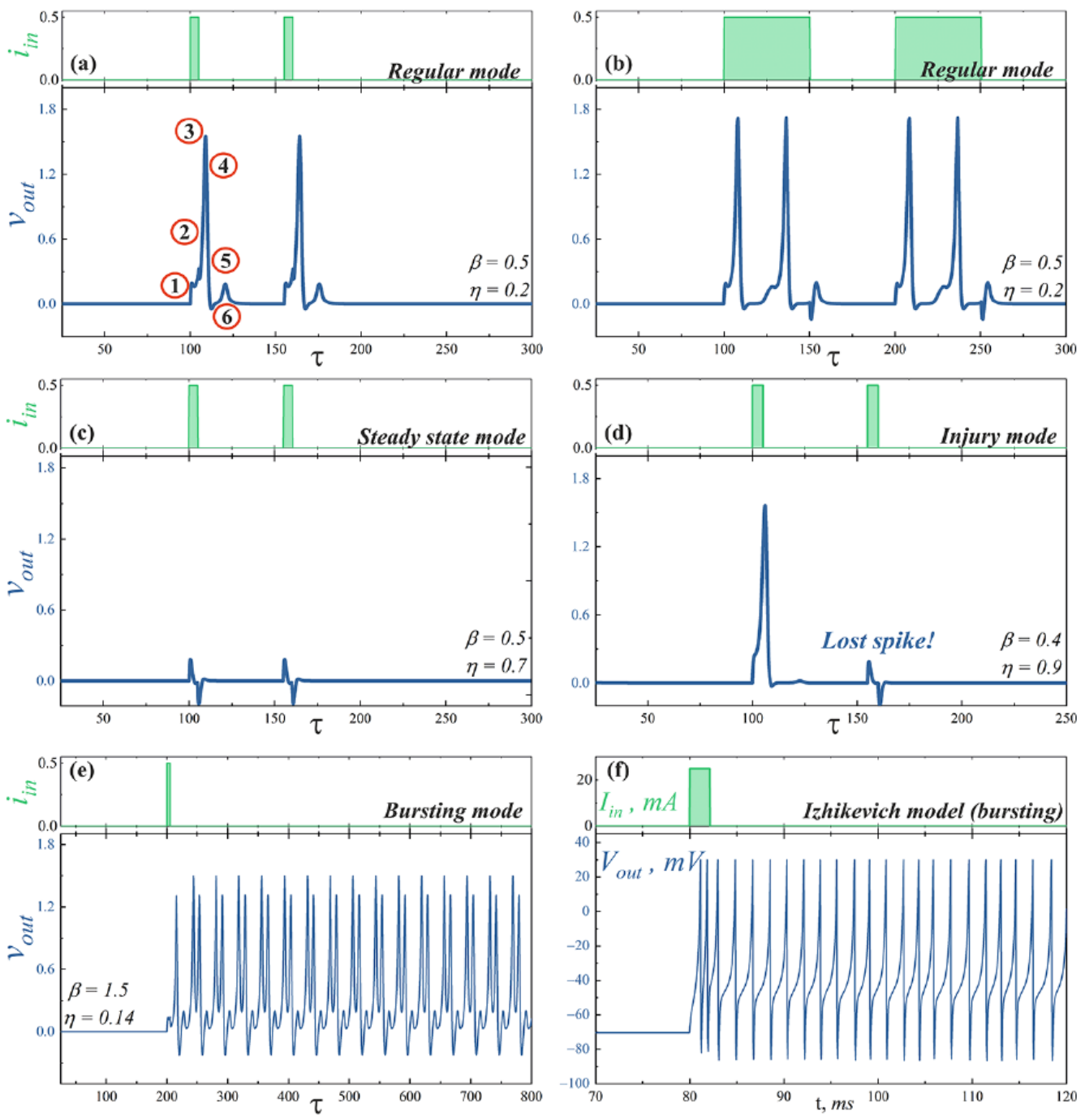
a-b) regular mode - typical response of a neuron to external stimulation.

c) steady state mode - characterized by the weak damped output pulses.

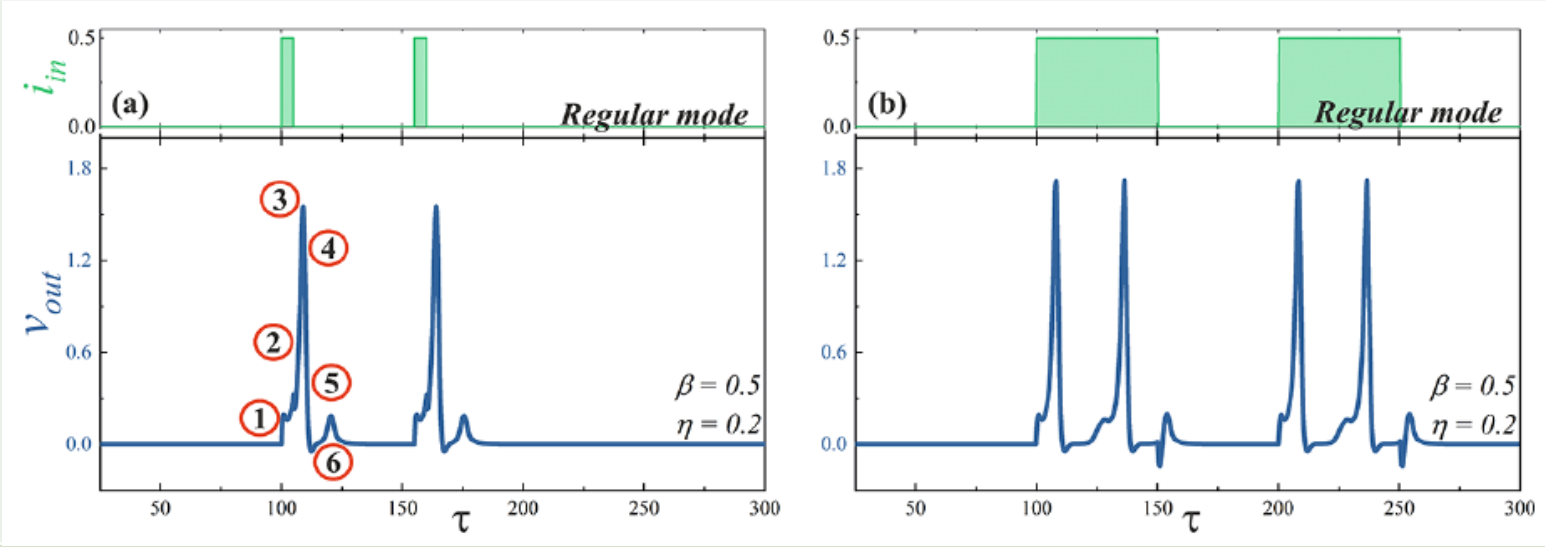
d) injury mode - characterized by the losses of spikes, or vice versa, the generation of "extra" spikes.

e) bursting mode - demonstrates the generation of a series of spikes in response to single stimulating current pulse.

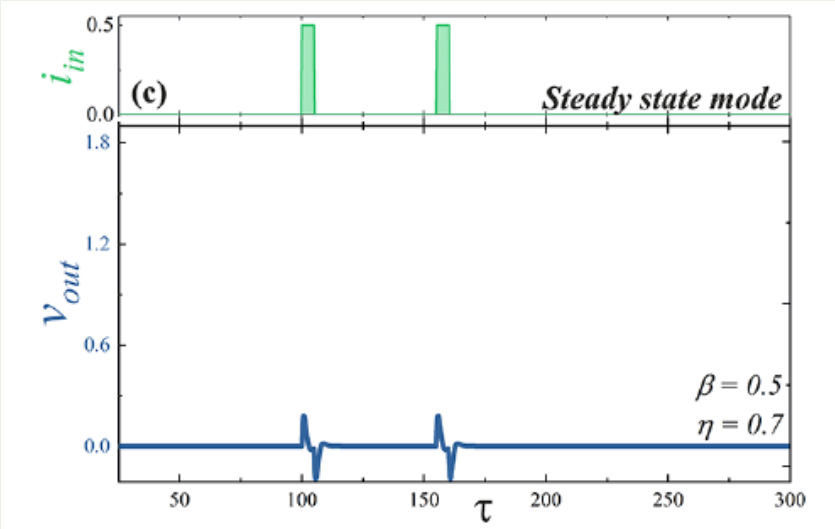
f) Izhikevich model demonstrate comparison of bursting in mathematical model of neuron and superconducting one.



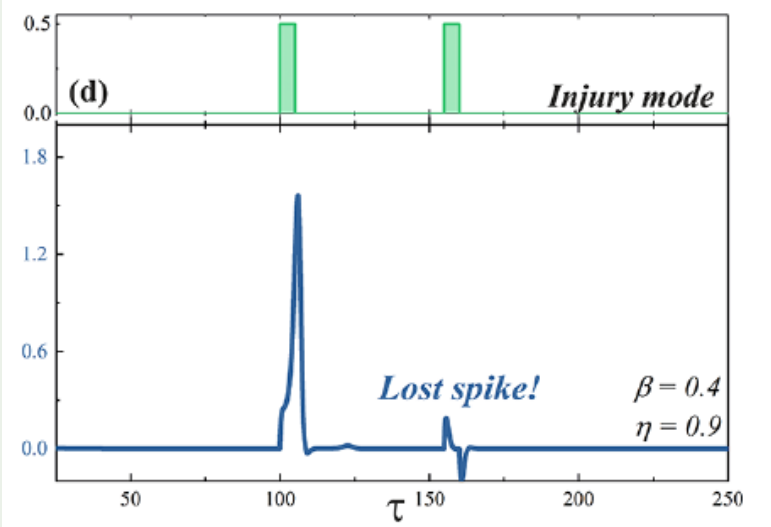
Operating mode	Biological interpretation
Regular	**The interspike interval is determined by a neuron refractory period, which, in consequence, is related to the recovery of Na^+ channels**



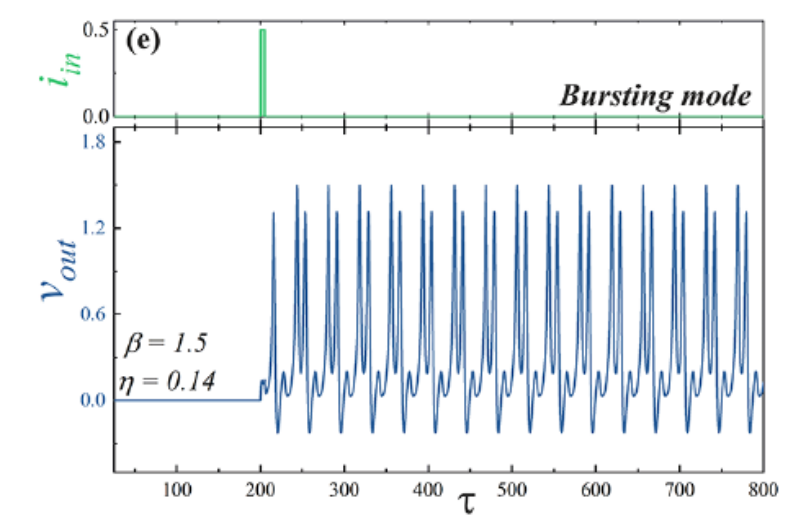
Steady state	**Analog of the maintenance of constant internal concentrations of ions in the cell in response to an under threshold stimulation.**



Injury	**Mimics the biophysical abnormality caused by different nervous diseases and neuron injuries.**



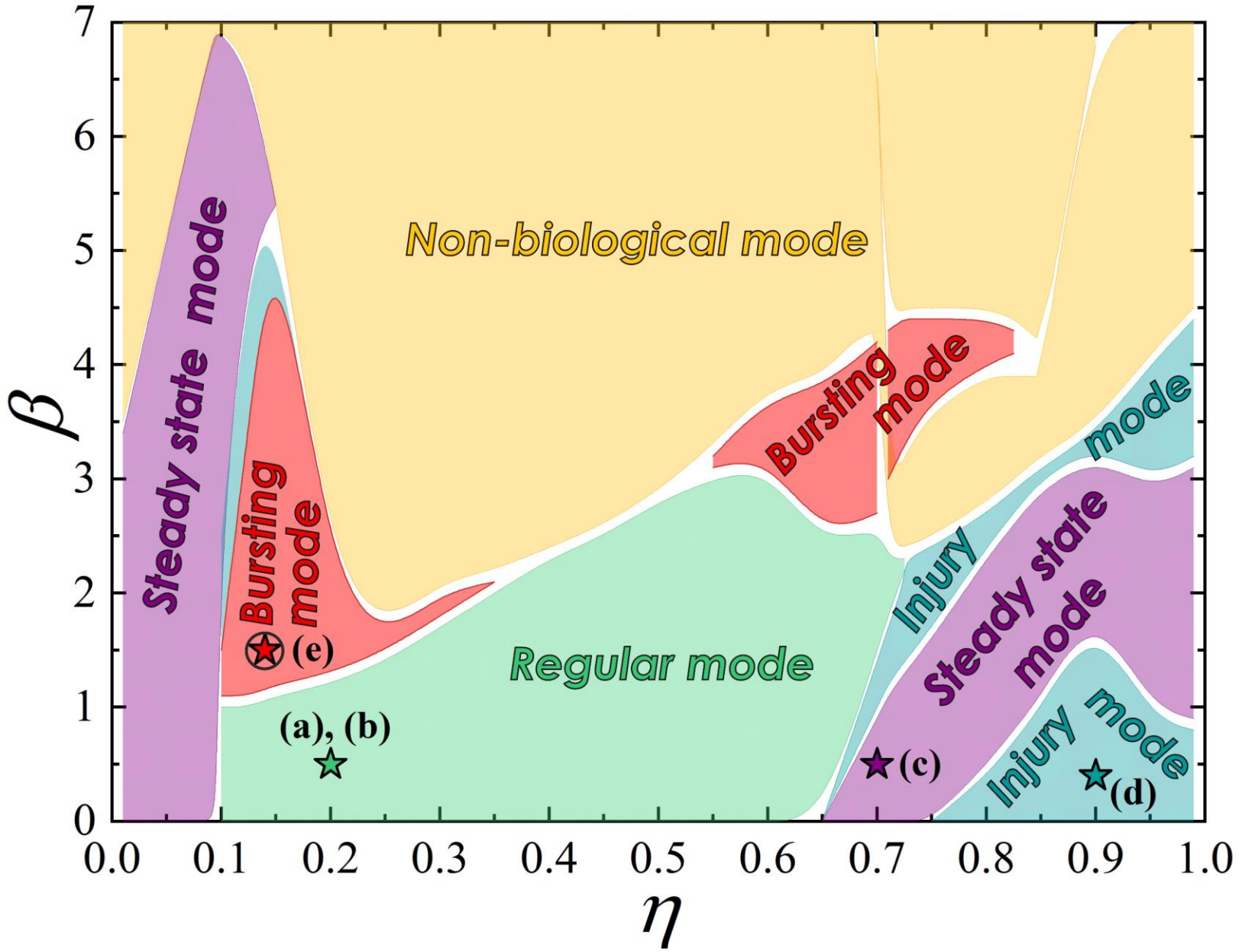
Bursting	**Such behavior may be the result of the complex neuron interaction in the network. However, this can also be a consequence of internal processes in a neuron.** **In the last case, the reason is the after-depolarization (ADP), a membrane depolarisation at the last stages of repolarisation (circled "4" on spike of regular mode).**



Mapping of Operating Modes

Main advance is the foundation of *injury* and *burting modes*!

***Stars mark parameters taken for simulations presented in figures earlier**



Discussing

Superconducting bio-inspired neuron has been introduced capable to mimic different operating behavior of biological neuron

Processing possibility up to 10^{10} spikes per second by an artificial neuron versus maximum ~453 spikes per second in the human brain

Numerical simulations show that the proposed three-junction cell is capable of mimic specific biological neuron activity missed in previously presented superconducting artificial neurons (injury and bursting modes).

Thank You for Your Attention!