Solid State Neuroscience

M. Rozenberg

Laboratoire de Physique des Solides (Orsay)

CNRS & Université Paris-Saclay

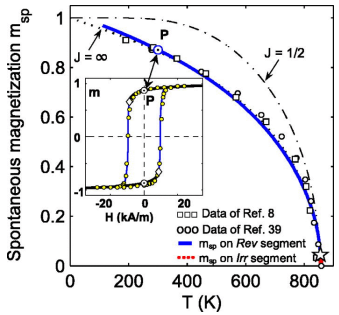
why do Neuroscience in a Solid State Physics Lab??

An analogy

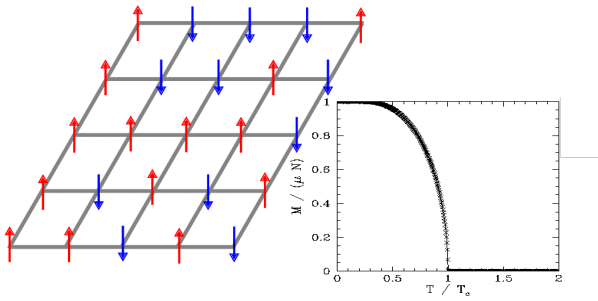
Material

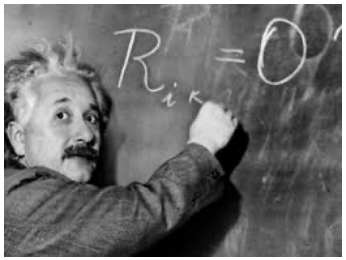
Functionality

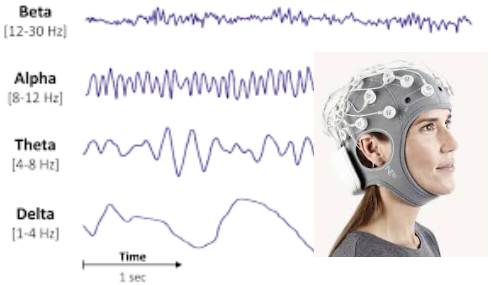
State of matter



Modeling



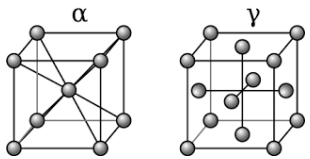




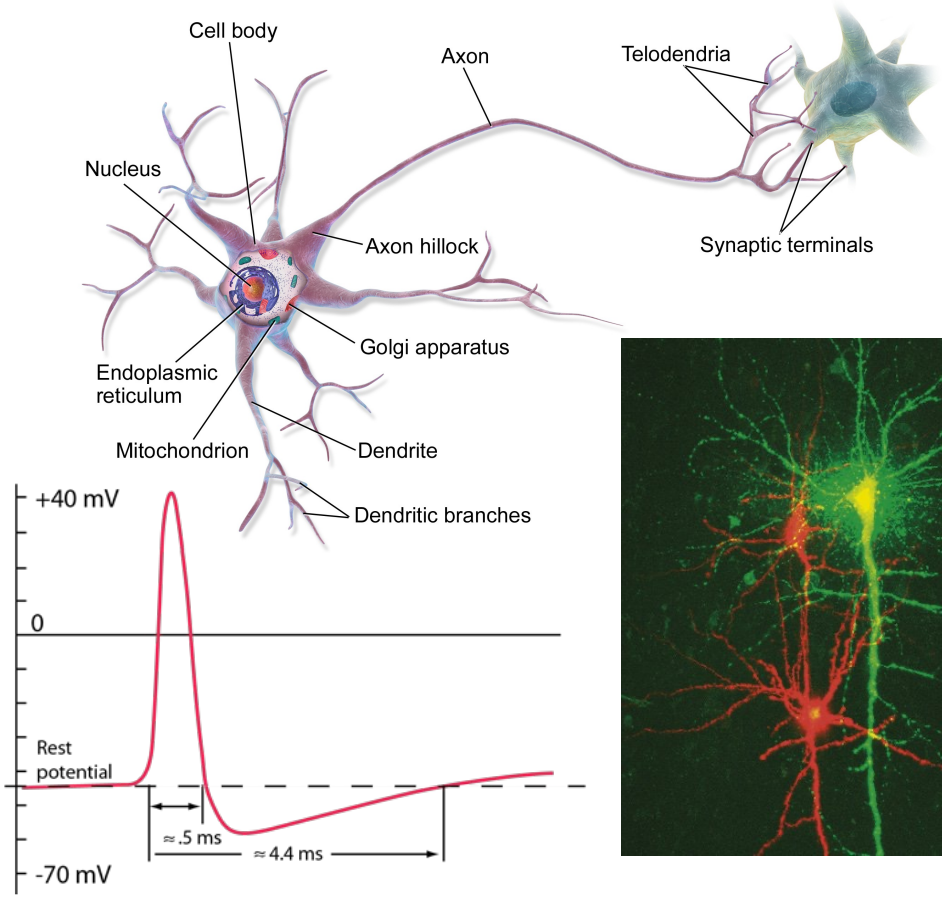
?

Degrees of freedom?
Interactions?
Networks?

magnetic spin



lattices



Neural networks

Mathematical models

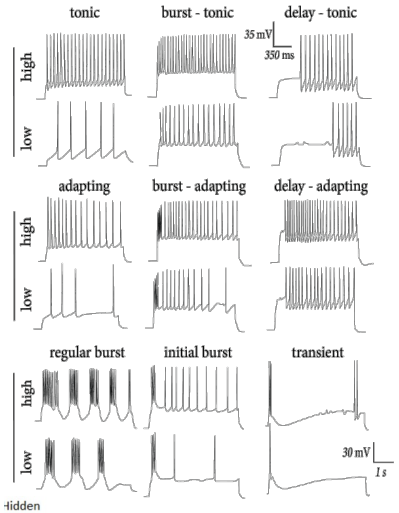
Differential equations that are discretized

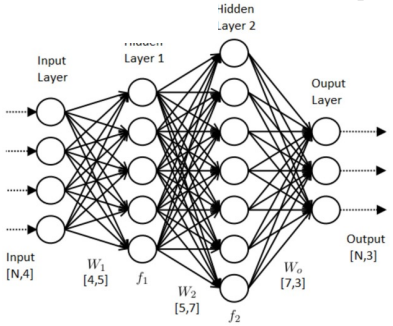
$$C_m \frac{dV}{dt} = -g_L(V - E_L) + g_L \Delta_T e^{\frac{V - V_T}{\Delta_T}} - u + I$$

$$\tau_w \frac{du}{dt} = a(V - E_L) - u$$

$$if\ V > V_{peak} = \begin{cases} V \rightarrow V_r \\ u \rightarrow u + b \end{cases}$$

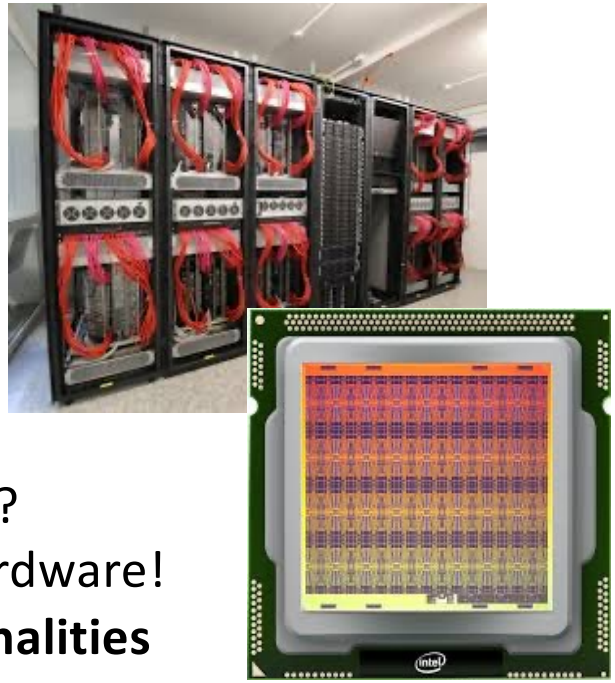
C_m = *membrane capacitance (pF)*
E_L = *leak reversal potential (mV)*
g_L = *leak conductance (nS)*
V_T = *spike threshold (mV)*
V_r = *resting potential (mV)*
τ_w = *adaptation time constant (ms)*
Δ_T = *spike slope factor (mV)*
a = *subthreshold adaptation (nS)*
b = *spike triggered adaptation (pA)*
I = *total current (pA)*





Neuromorphic chips

IBM *TrueNorth*, Intel *Loihi*, FPGAs
Conventional computers optimized to run the mathematical models



AI driven

Long-time simulations
Mathematical artifacts?

Is there an alternative route?
Make neurons directly in hardware!
New neuromorphic functionalities

Neuromorphic materials

resistive switching & *memristors*

Electric breakdown in **Mott insulators**:
a new (and unexpected) neuromorphic functionality

nature COMMUNICATIONS

Received 4 Sep 2012 | Accepted 14 Mar 2013 | Published 16 Apr 2013

DOI: 10.1038/ncomms2735

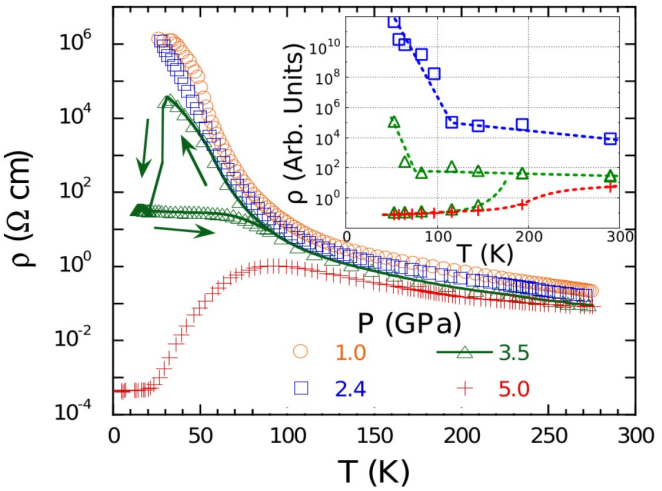
Avalanche breakdown in $GaTa_4Se_{8-x}Te_x$ narrow-gap Mott insulators

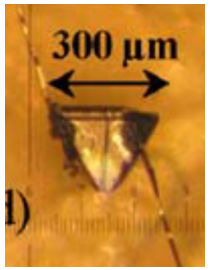
V. Guiot[1], L. Cario[1], E. Janod[1], B. Corraze[1], V. Ta Phuoc[2], M. Rozenberg[3], P. Stoliar[3], T. Cren[4] & D. Roditchev[4]

(IMN Nates)

- Strongly Correlated Material
- Mott Insulator (3D)
- Metal-insulator transition with 10 orders of magnitude!
- Fully consistent with DMFT

Acha, Camjayi @ UBA
Phys Rev Lett (2014)





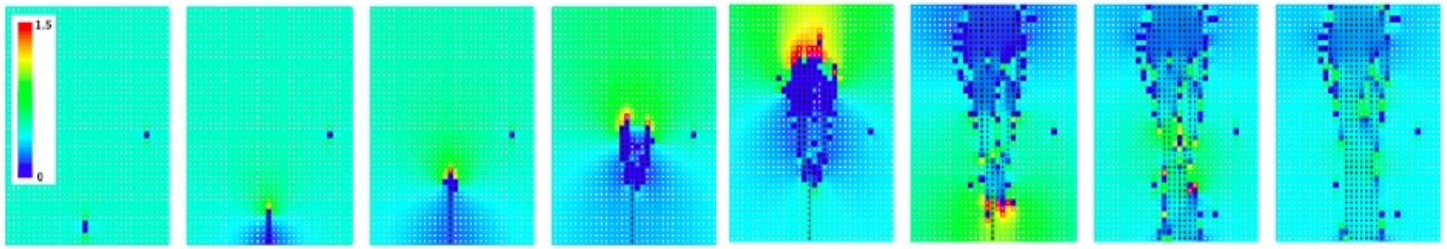
Out-of-equilibrium Mott transition?

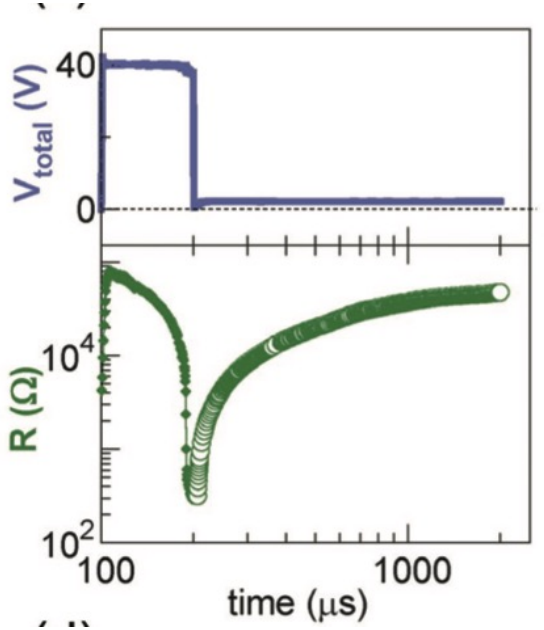
Pablo Stoliar

ADVANCED MATERIALS

Universal Electric-Field-Driven Resistive Transition in Narrow-Gap Mott Insulators

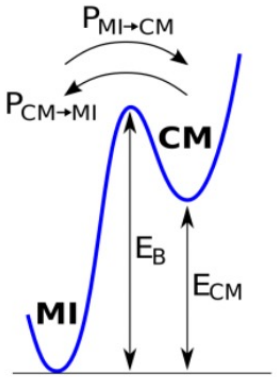
Pablo Stoliar, Laurent Cario, Etiene Janod, Benoit Corraze, Catherine Guillot-Deudon, Sabrina Salmon-Bourmand, Vincent Guiot, Julien Tranchant, Marcelo Rozenberg 2013



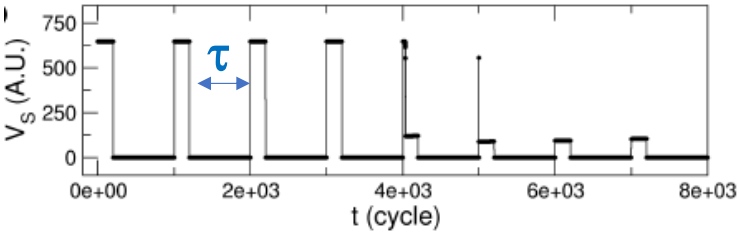


How about a non trivial validation?

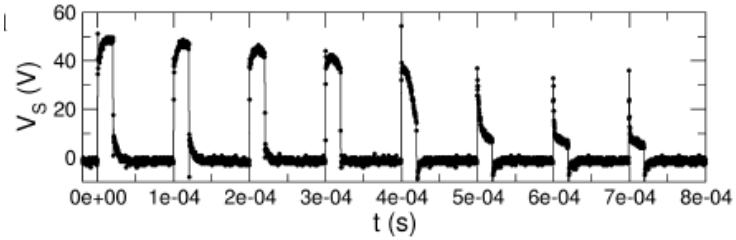
Metastability of the
1st order MIT (DMFT)



Model prediction



Experiment

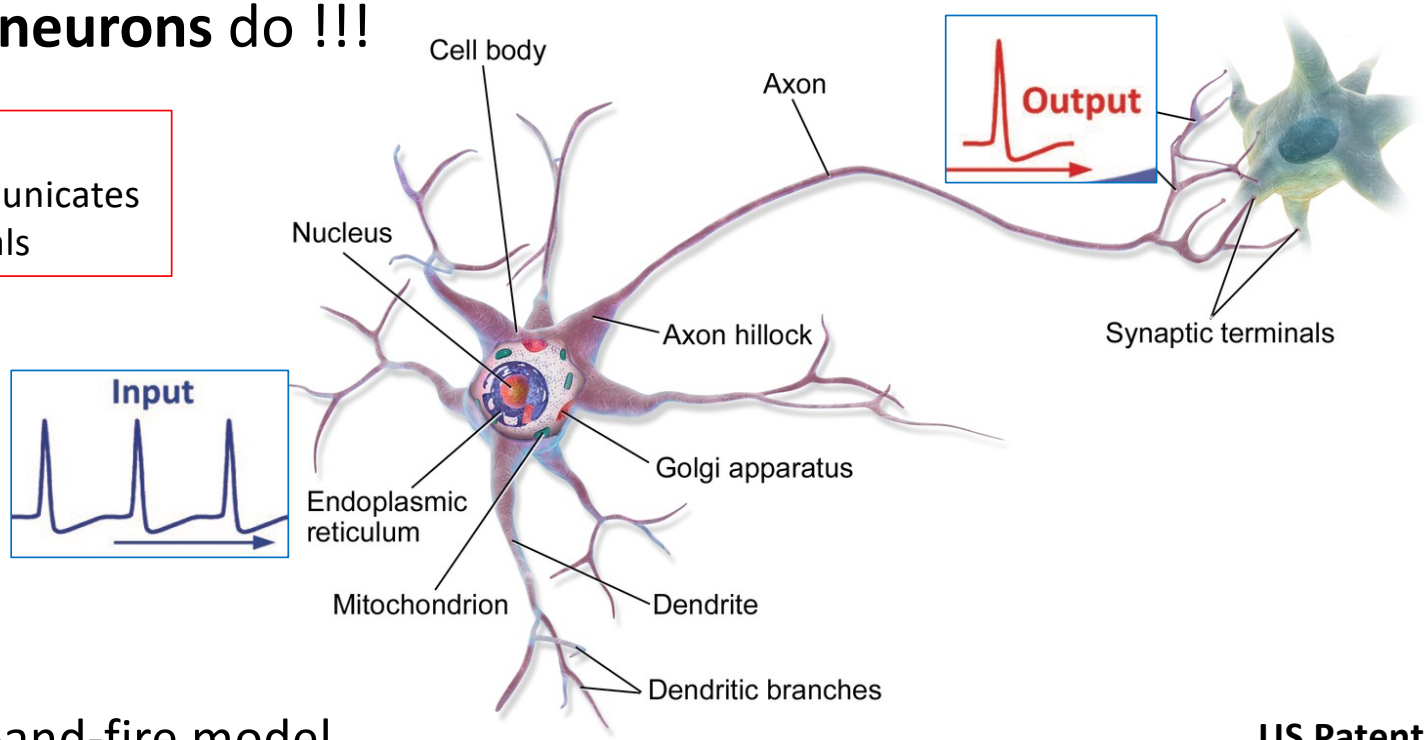


Electric pulses provoke a collapse of resistance, then a surge of current!

1st Aha! Moment !!!!

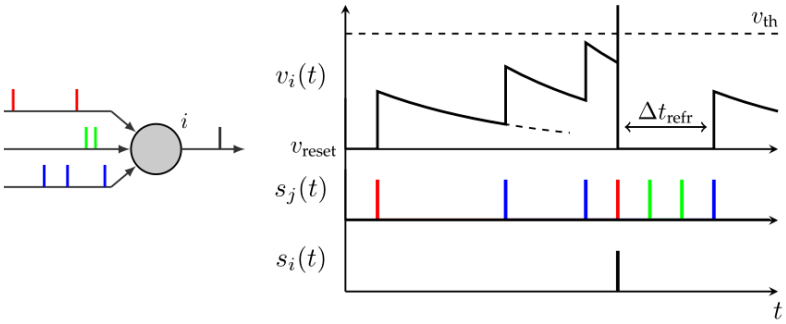
it is like what **neurons** do !!!

A neuron is a cell
Generates and communicates through electric signals



Leaky-integrate-and-fire model

Louis and Marcelle Lapicque **1907 !!**



US Patent 10867237 (2020)

ADVANCED FUNCTIONAL MATERIALS
www.afm-journal.de

2017

ADVANCED SCIENCE NEWS
www.advancedsciencenews.com

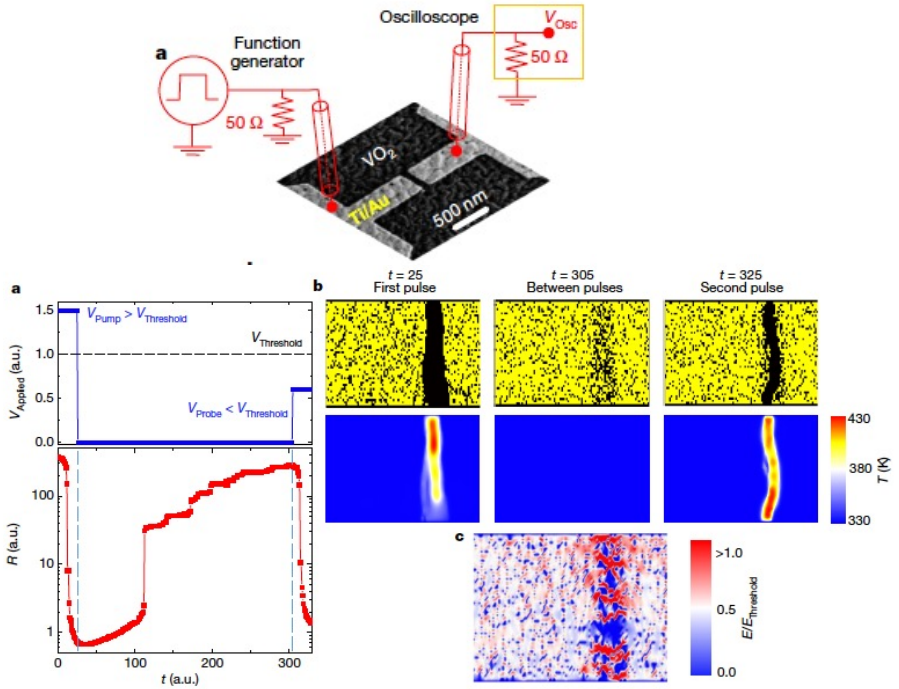
A Leaky-Integrate-and-Fire Neuron Analog Realized with a Mott Insulator

*Pablo Stoliar, Julien Tranchant, Benoit Corraze, Etienne Janod, Marie-Paule Besland, Federico Tesler, Marcelo Rozenberg, and Laurent Cario**

Towards physical artificial neurons

Mott materials (VO_2) are promising

But also difficult to make and control, and we are beginning to understand (filamentary conduction)



Del Valle et al, Nature 2019

Del Valle, Ramirez, MR, Schuller JAP 2018 (review)
Kalcheim et al Nat Comm 2020
Del Valle et al, Science 2021

UC San Diego cnrs U.S. DEPARTMENT OF ENERGY Office of Science

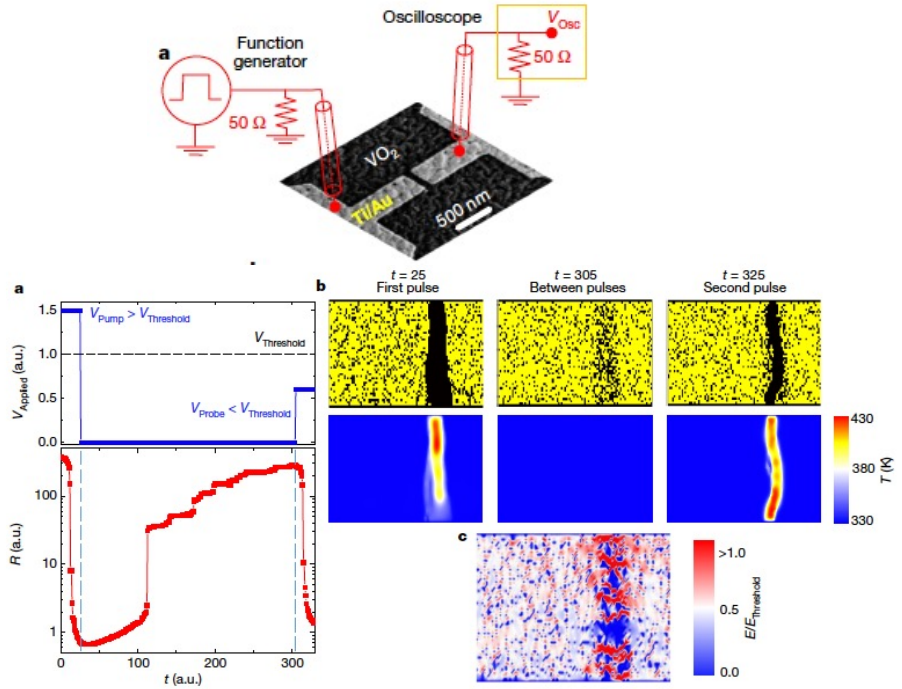
2018-2022

Ivan Schuller

Towards physical artificial neurons

Mott materials (VO_2) are promising

But also difficult to make and control, and we are beginning to understand (filamentary conduction)



Del Valle et al, Nature 2019

Del Valle, Ramirez, MR, Schuller JAP 2018 (review)
Kalcheim et al Nat Comm 2020
Del Valle et al, Science 2021

Silicon neurons are a reality

Everything can be done with conventional electronics
But ***silicon neurons*** are not that simple

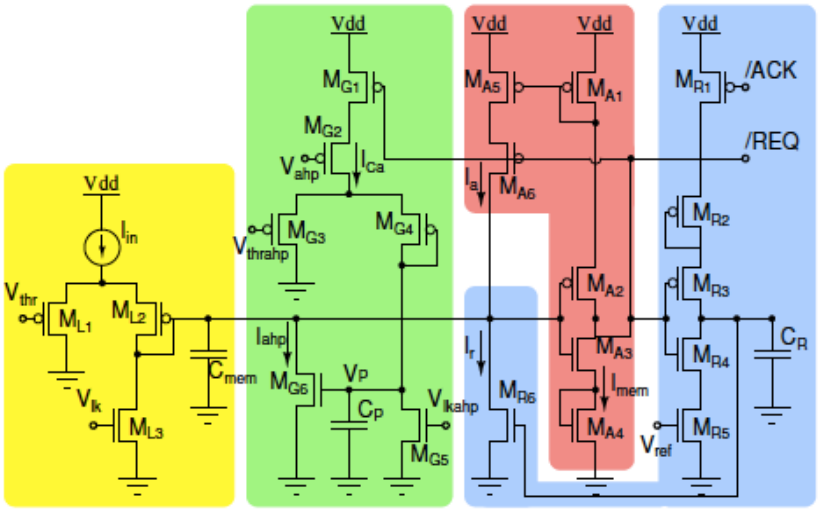


Fig. 2: Adaptive exponential I&F neuron circuit schematic.

Indiveri, Stefanini, Chicca IEEE (2010)
Indiveri et al Front Neurosci 2011 (review)

Can’t we have the “best of both worlds”?

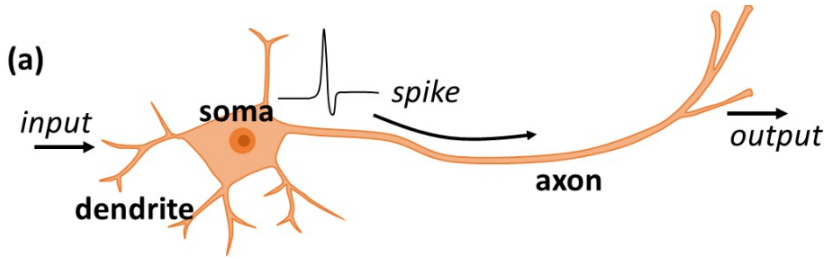
Simplicity of Mott memristors
Reliability of conventional silicon electronics

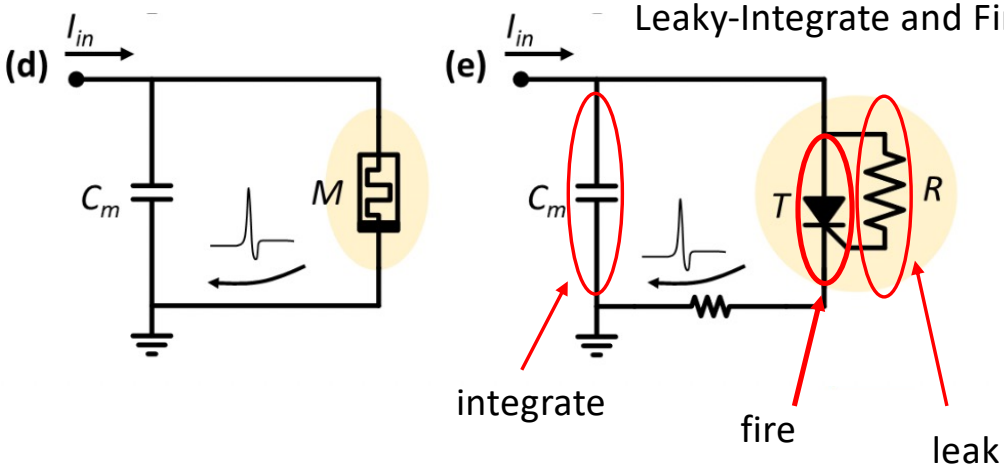
Best of both worlds:
Memristive Silicon Spiking Neuron
aka Ultra compact Neuron

2nd Aha! Moment !!!

MR, O. Schneegans and P. Stoliar, Sci Rep (2019)

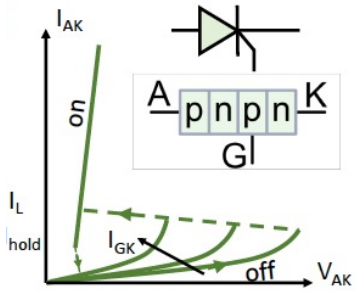
memory-resistive effect ←→ hysteresis

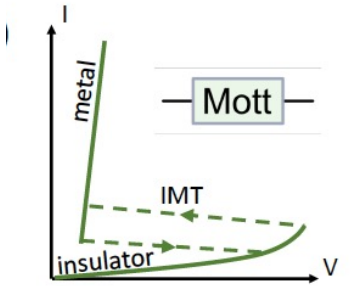




Leaky-Integrate and Fire model

Thyristor
Threshold control diode



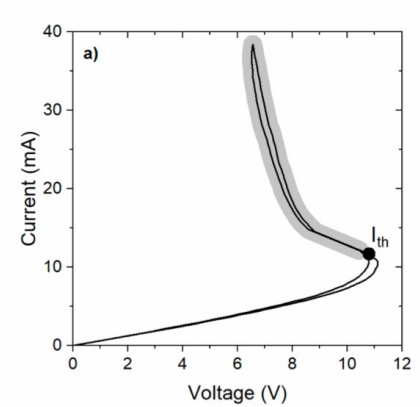


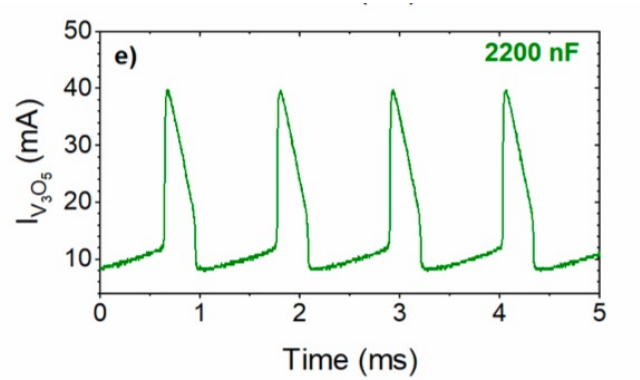
A thyristor fires like a Mott material

I-V characteristics

spiking

Mott

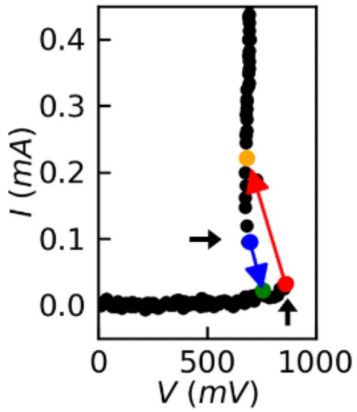


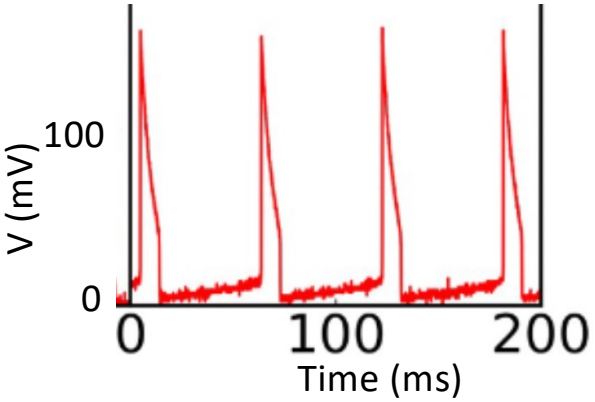


PRX 2021

Mott materials
V_3O_5, vanadates nickelates
thin film deposition
10+ of know how
Hard to fabricate consistently
Lithography equipment
Sputtering, PLD, etc

Memristor





Sci Rep 2019
To be submitted

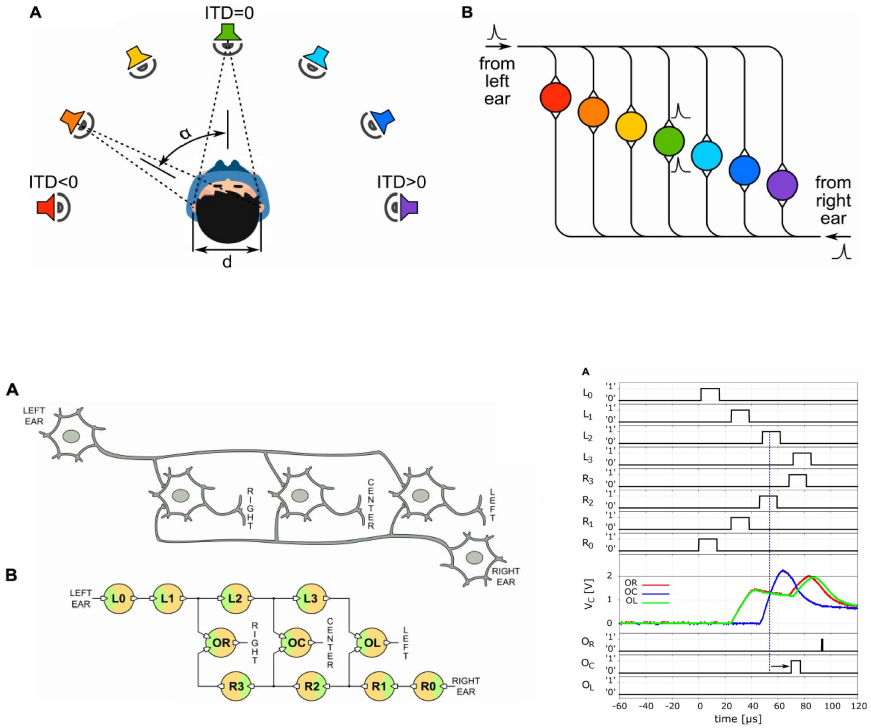
Thyristors available on-line for next day delivery, for pennies.
And they always work

Towards *Networks and Neuroscience*

all non-conventional memristive neurons are still at the single neuron level

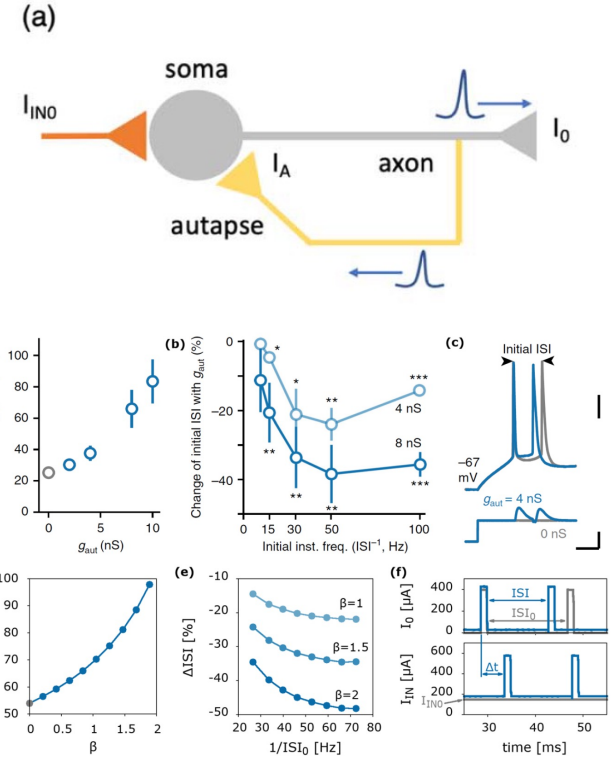
A Functional Spiking Neural Network of Ultra Compact Neurons

Pablo Stoliar[1†], Olivier Schneegans[2†] and Marcelo J. Rozenberg[3†]*



Front Neurosci 2021

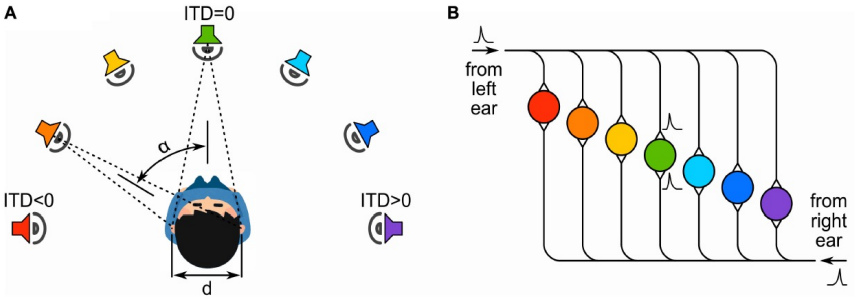
A minimal recurrent spiking neural network, the autapse, implemented in Solid State

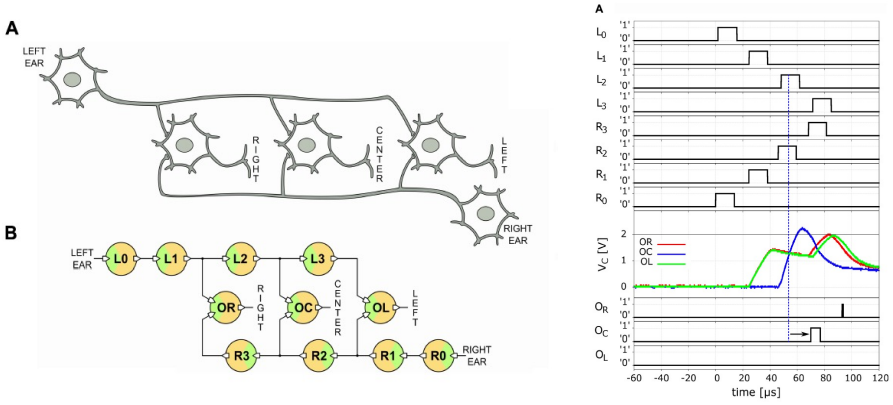


Phys Rev App 2021

A Functional Spiking Neural Network of Ultra Compact Neurons

Pablo Stoliar[1†], Olivier Schneegans[2†] and Marcelo J. Rozenberg[3†]*



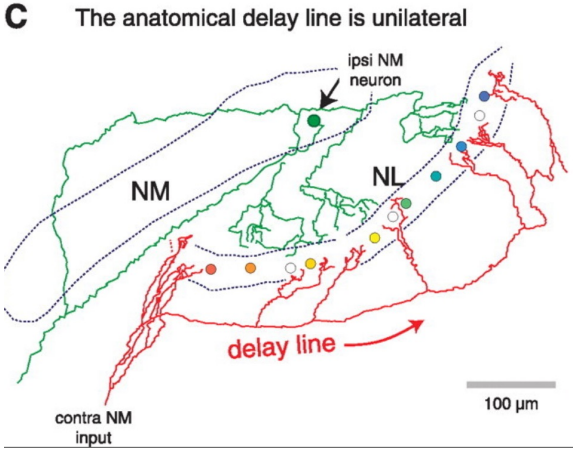


frontiers in Neuroscience (2021)

Binaural sound localization

Jeffress model 40's

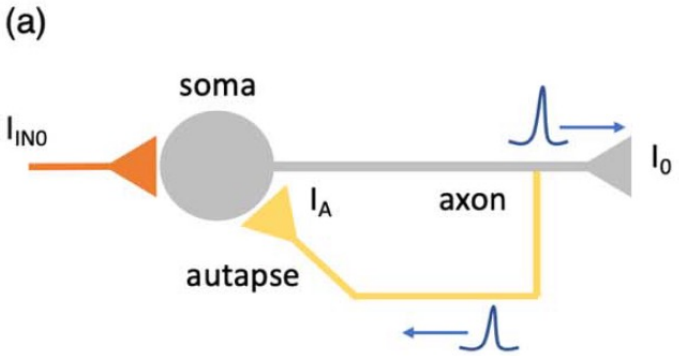
Delay lines in the auditory system of birds



M. Burger et al (2011) Review

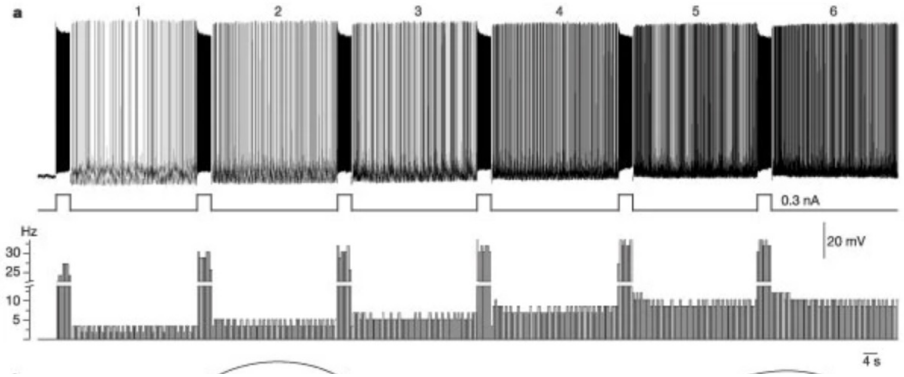
A minimal ***Recurrent Spiking Neural Network***,
the autapse,
implemented in Solid State

Phys Rev App 2021

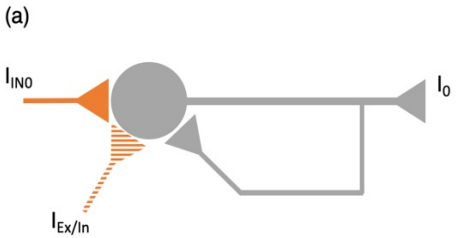


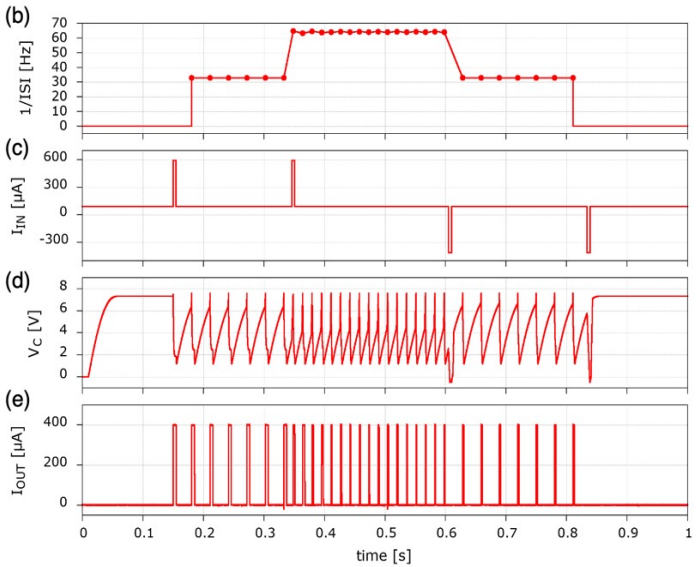
Dynamical working memory
Graded Persistent Activity
S. Seung et al (2000)

Figure 2: Graded persistent activity.



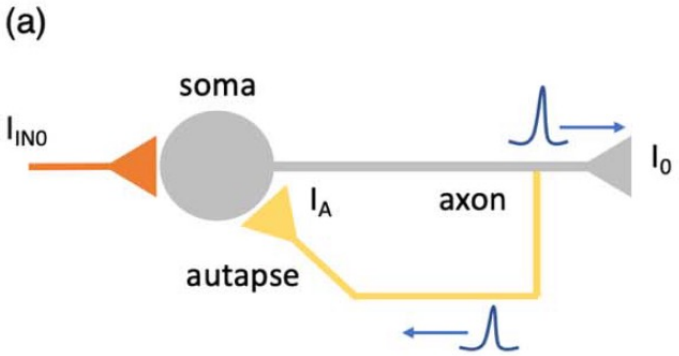
Egorov et al Nature (2002)





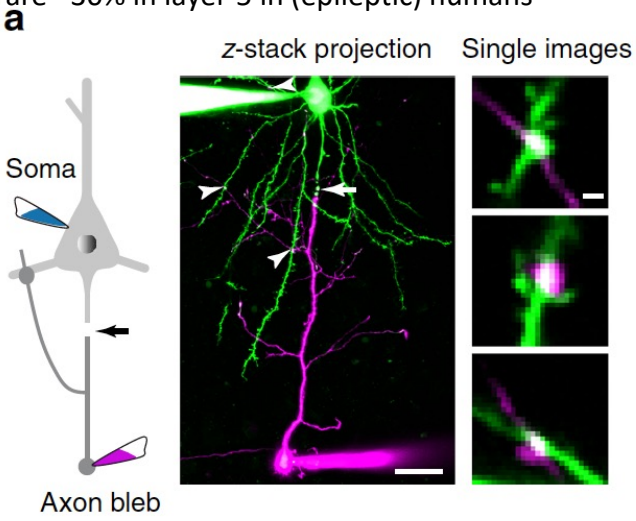
A minimal ***Recurrent Spiking Neural Network***,
the autapse,
implemented in Solid State

Phys Rev App 2021

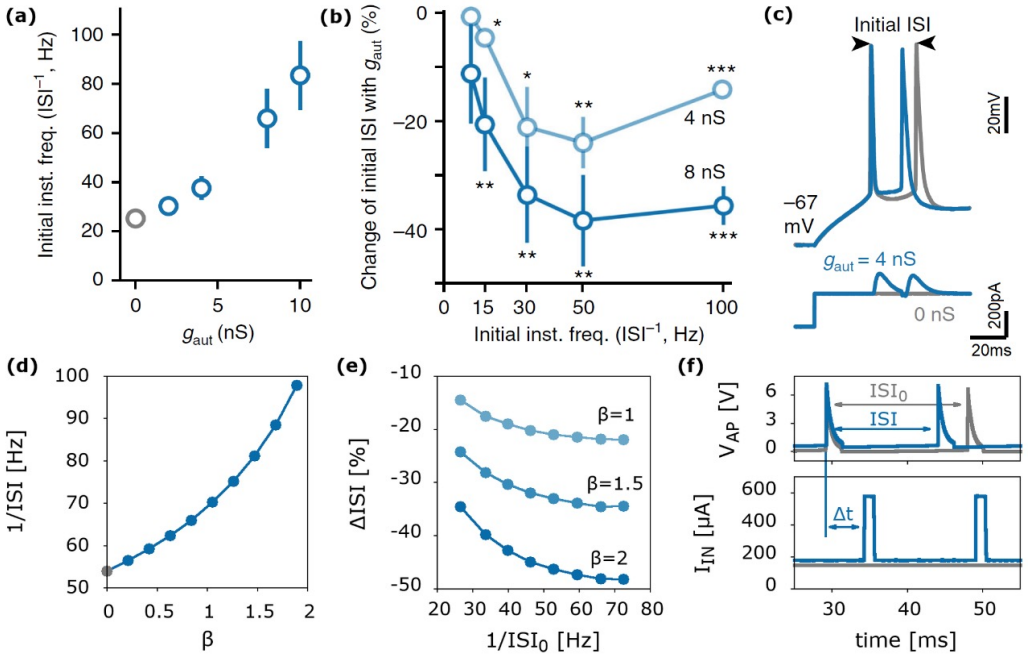


Autapses in neocortical pyramidal cells

Not rare ~30% in layer-5 in (epileptic) humans



Yin et al Nat Comm (2018)



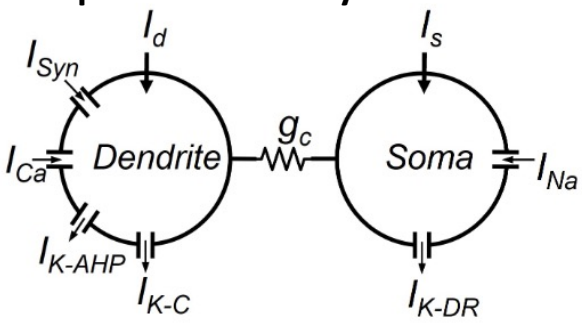
Biological Experiment

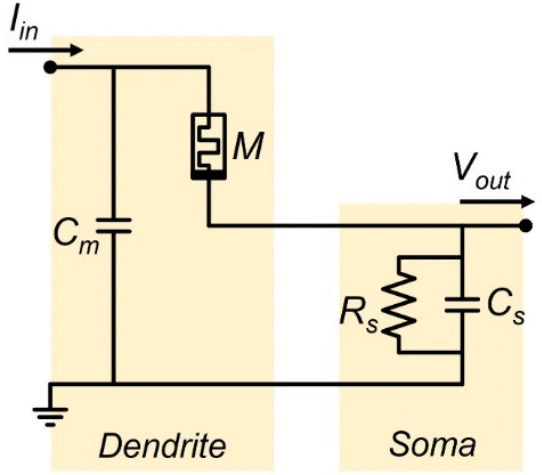
Yin et al (2018)

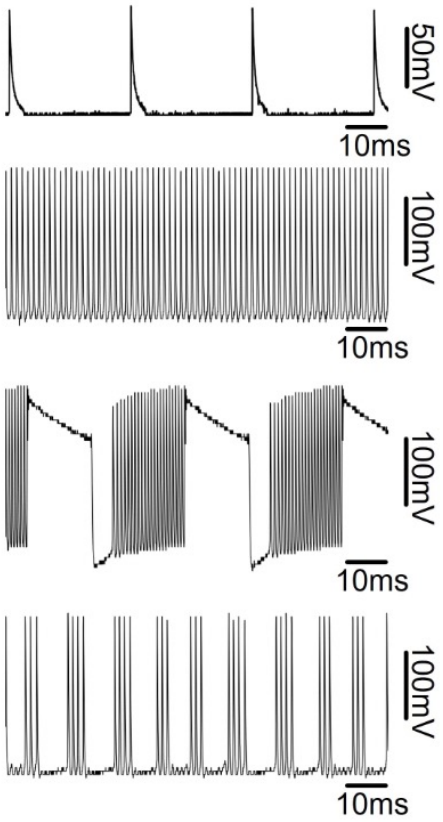
Solid State Experiment

Memristive Bursting neuron

2-compartment Pinsky-Rinzel model







$$
\begin{aligned}
C_m V_s' &= -I_{\text{Leak}}(V_s) - I_{\text{Na}}(V_s, h) - I_{\text{K-DR}}(V_s, n) \\
&\quad +(g_c/p)(V_d - V_s) + I_s/p \\
C_m V_d' &= -I_{\text{Leak}}(V_d) - I_{\text{Ca}}(V_d, s) - I_{\text{K-AHP}}(V_d, q) \\
&\quad -I_{\text{K-C}}(V_d, Ca, c) - I_{\text{Syn}}/(1-p) \\
&\quad +(g_c/(1-p))(V_s - V_d) \\
&\quad +I_d/(1-p) \qquad (1)
\end{aligned}
$$

The kinetic equation for each of the gating variables h, n, s, c and q takes the form

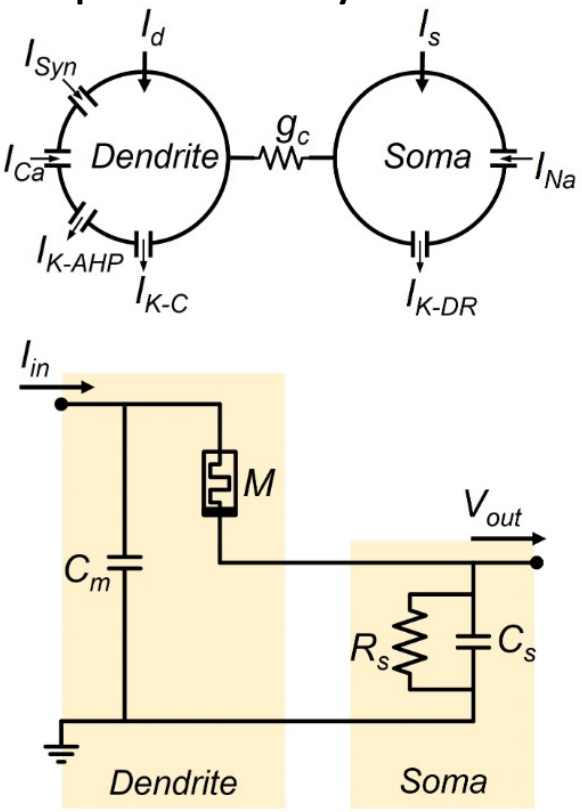
$$y' = (y_\infty(U) - y)/\tau_y(U). \qquad (2)$$

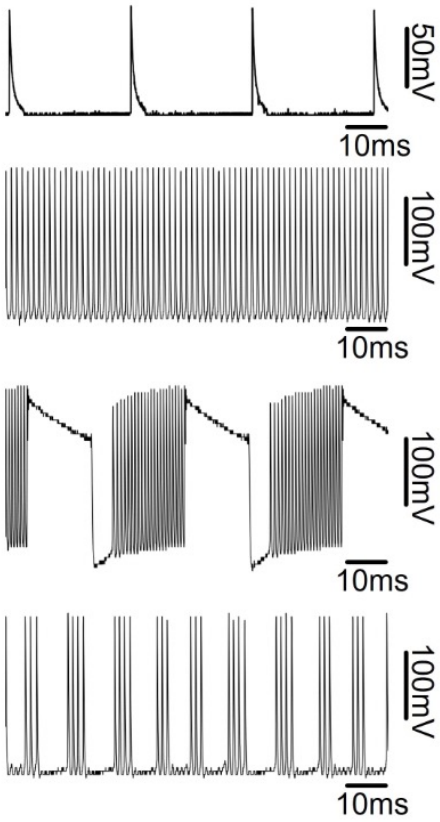
$$Ca' = -0.13 I_{\text{Ca}} - 0.075 Ca$$

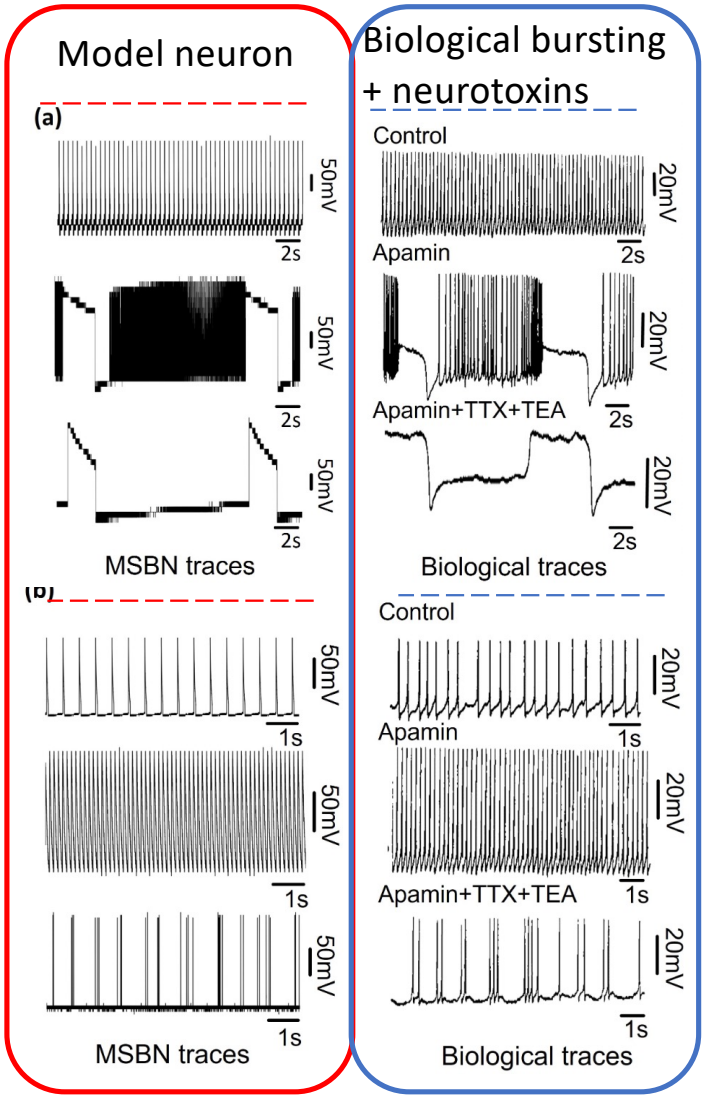
$$
\begin{aligned}
I_{\text{Leak}}(V_s) &= \bar{g}_L(V_s - V_L) \\
I_{\text{Leak}}(V_d) &= \bar{g}_L(V_d - V_L) \\
I_{\text{Na}} &= \bar{g}_{\text{Na}} m_\infty^2(V_s) h (V_s - V_{\text{Na}}) \\
I_{\text{K-DR}} &= \bar{g}_{\text{K-DR}} n (V_s - V_{\text{K}}) \\
I_{\text{Ca}} &= \bar{g}_{\text{Ca}} s^2 (V_d - V_{\text{Ca}}) \\
I_{\text{K-C}} &= \bar{g}_{\text{K-C}} c \chi(\text{Ca})(V_d - V_{\text{K}}) \\
I_{\text{K-AHP}} &= \bar{g}_{\text{K-AHP}}\ q\ (V_d - V_{\text{K}})
\end{aligned}
$$

Memristive Bursting neuron

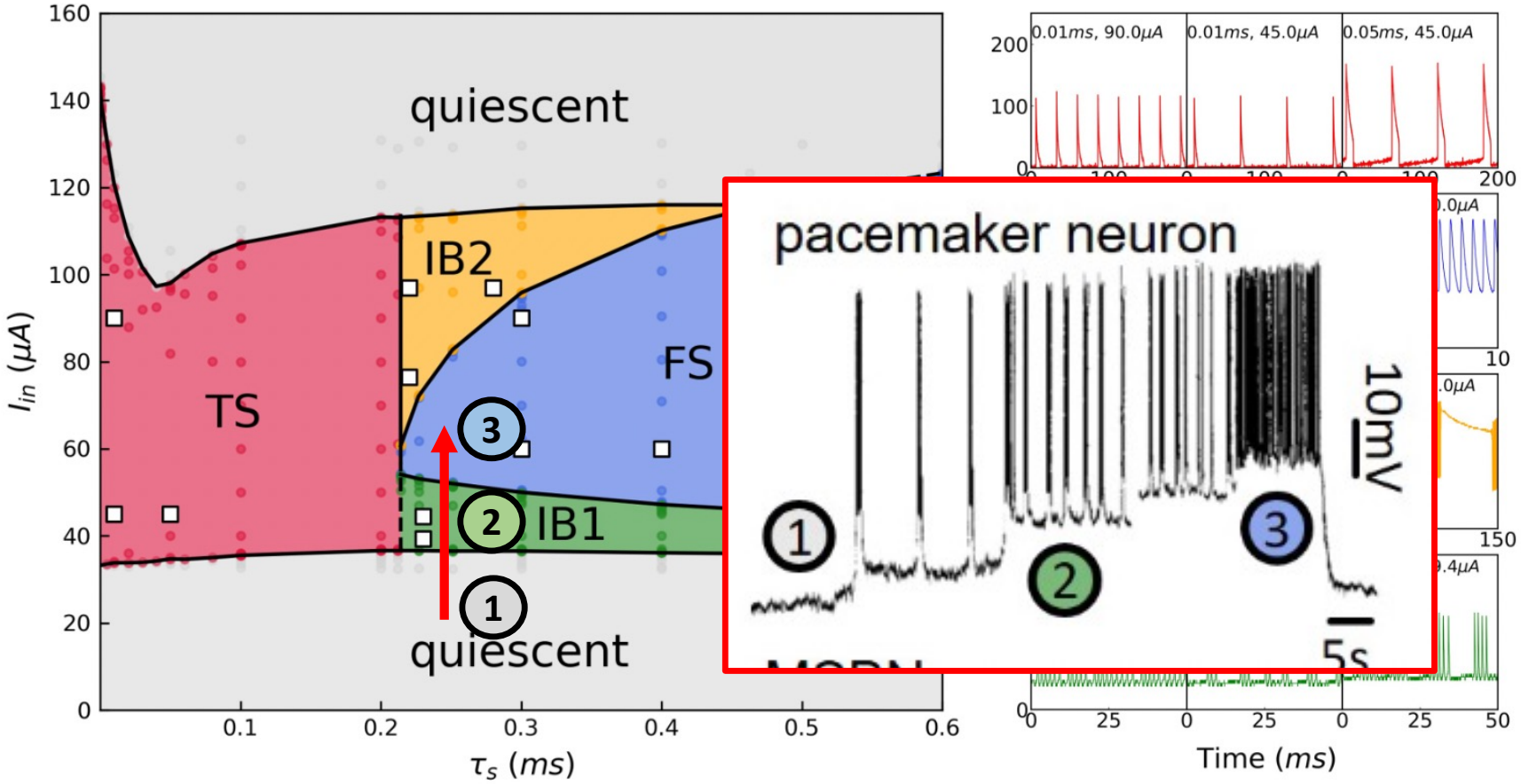
2-compartment Pinsky-Rinzel model







Das Sarma et al Molecular Autism 11, 52 (2020).
Ping et al Neuroreport 7, 809 (1996).

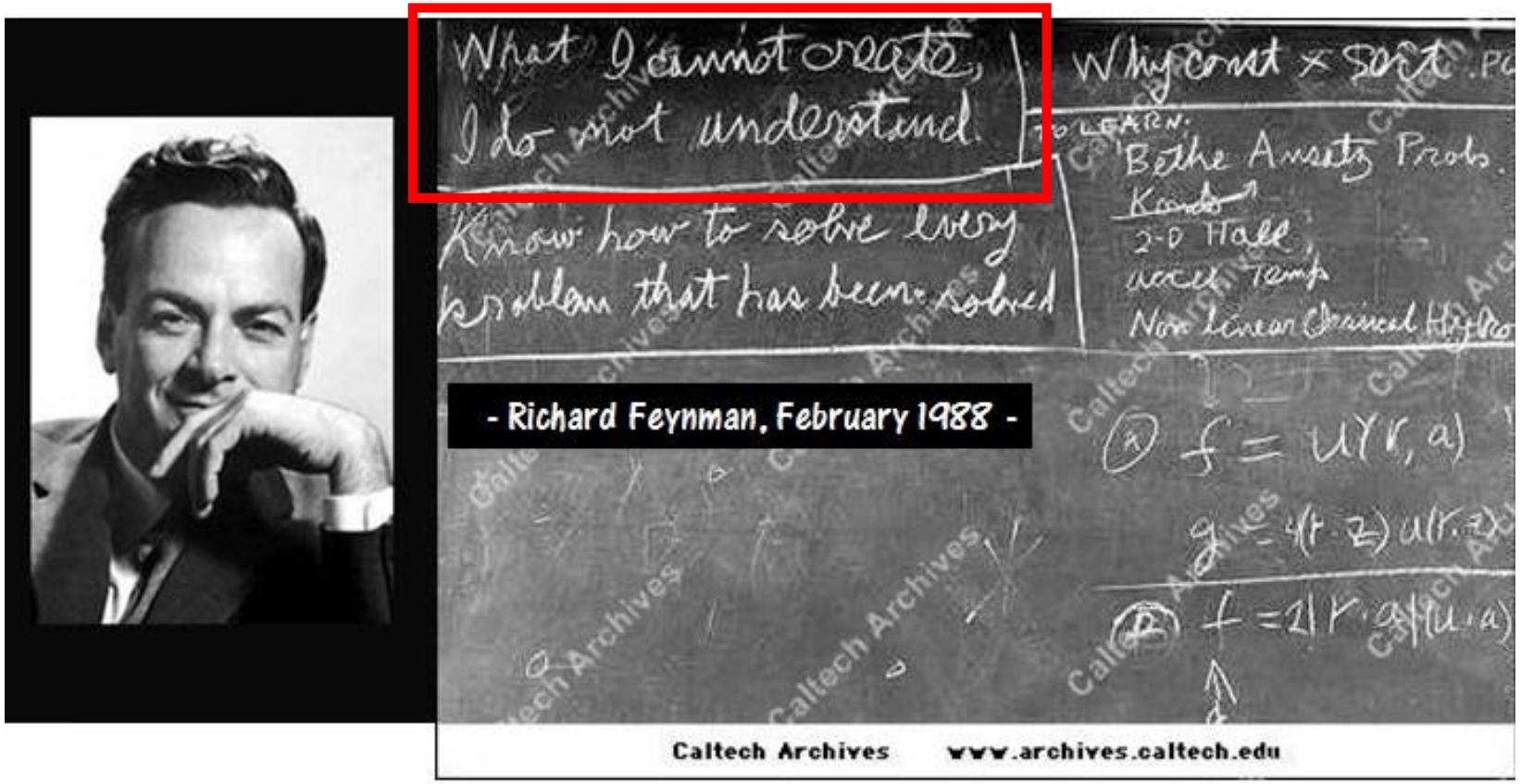

quiescent
IB2
FS
TS
3
2
IB1
1
quiescent
I_{in} (μA)
τ_s (ms)
0.01ms, 90.0μA
0.01ms, 45.0μA
0.05ms, 45.0μA
pacemaker neuron
10mV
5s
Time (ms)

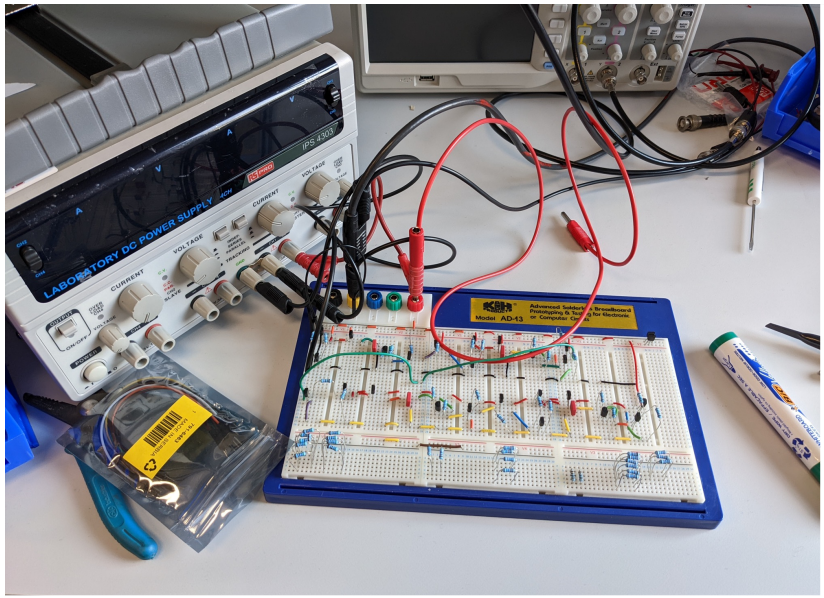
…and one year ago, I fell victim of the
Theoretical Phycisist's "Midlife" crisis…

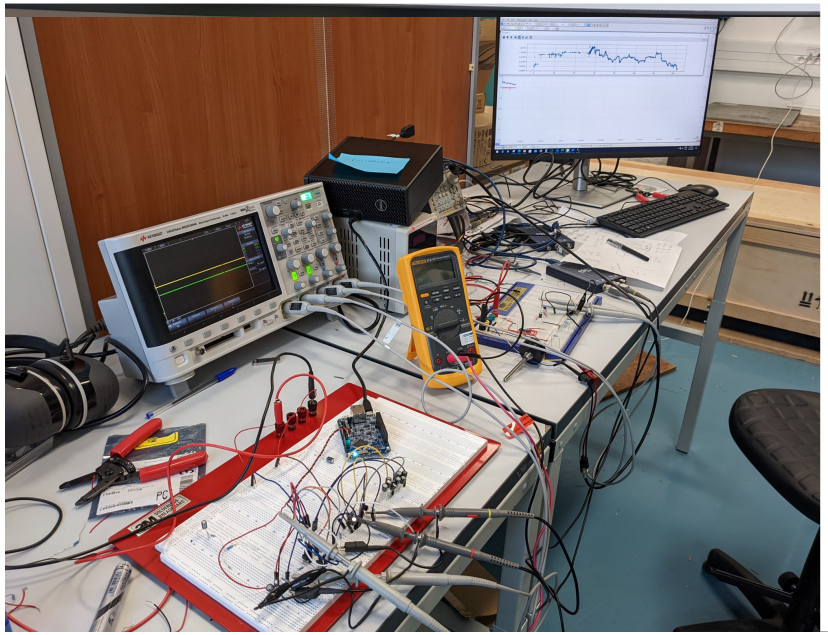
I "bought" myself a lab, and started a new life as an Experimentalist !!

Thank you to Pascal Foury and the LPS for support !!!

“What I cannot create, I do not understand” (R. Feynman)







New Experimental Activity at LPS
Solid State Neuroscience Lab
Thanks to LPS for initial support!

Thank you