Solid State Neuroscience

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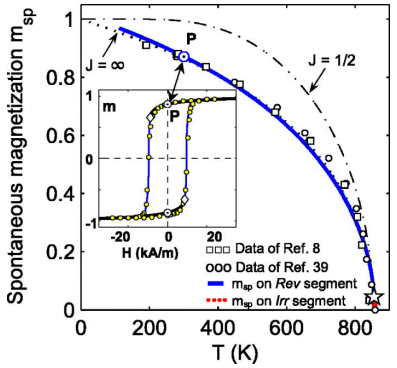
why do Neuroscience in a Solid State Physics Lab??

An analogy

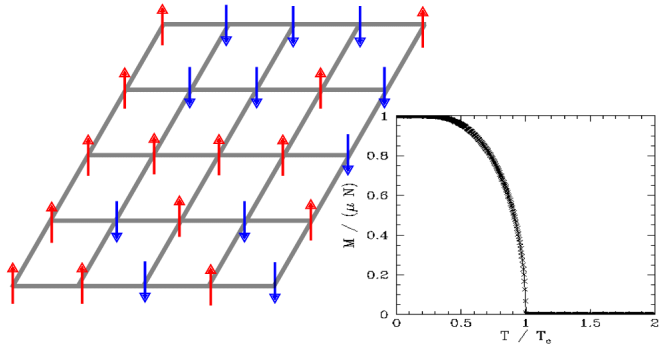
Material

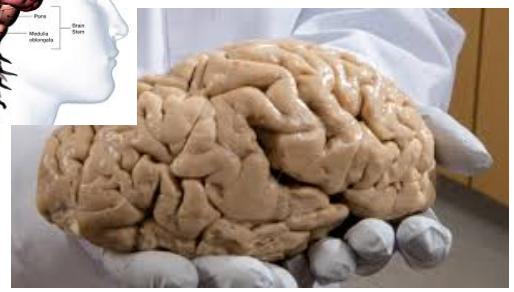
Functionality

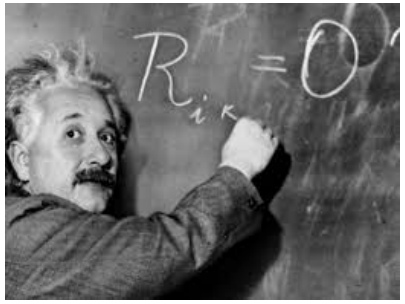
State of matter

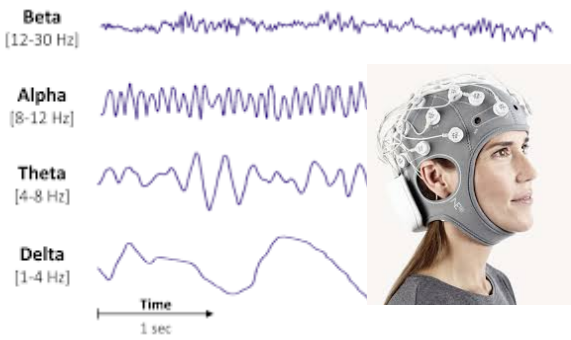


Modeling



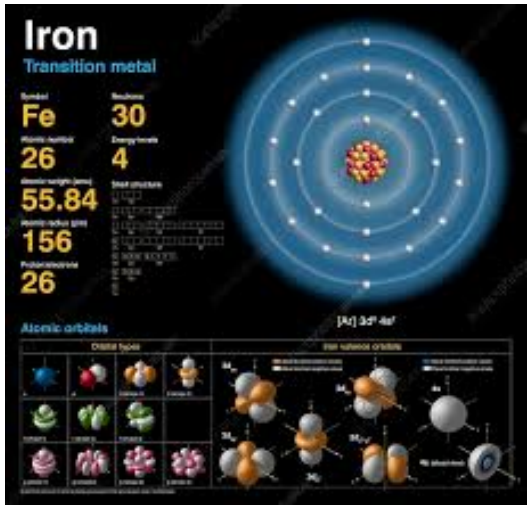


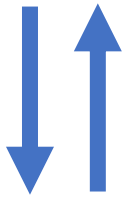




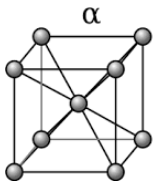
?

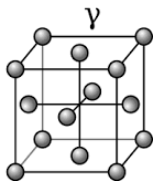
Degrees of freedom?
Interactions?
Networks?



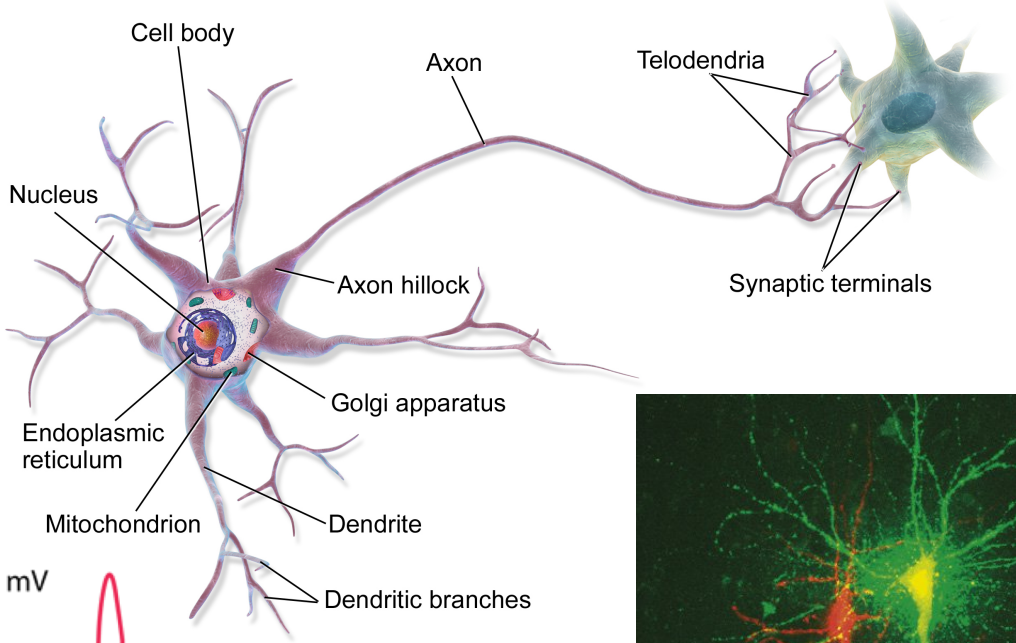


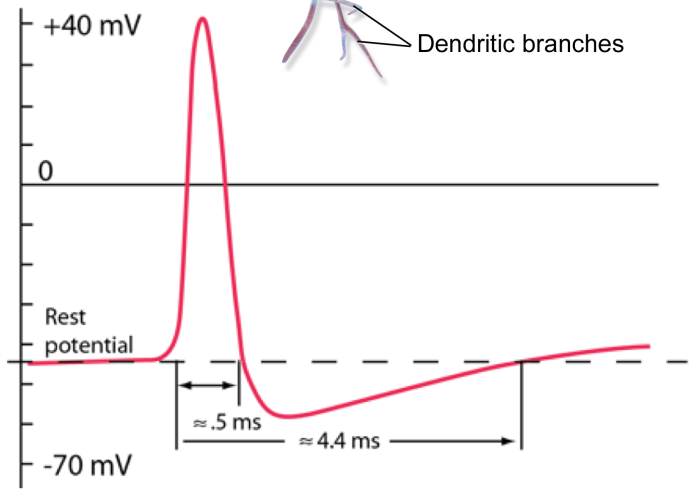
magnetic spin

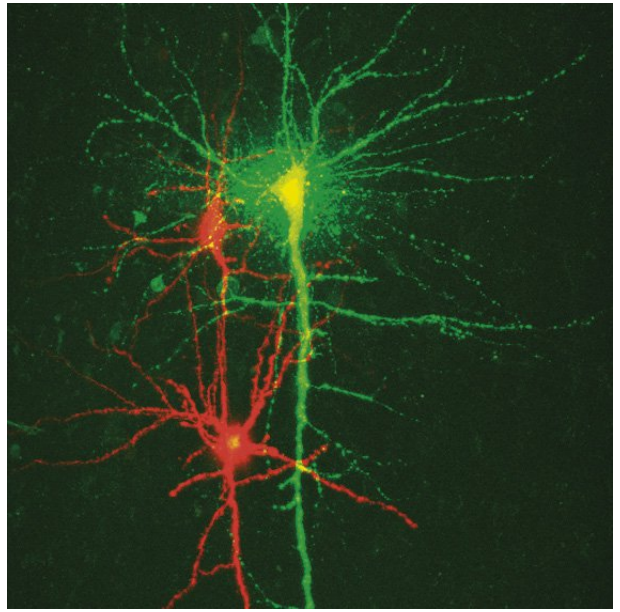




lattices







Neural networks

Mathematical models

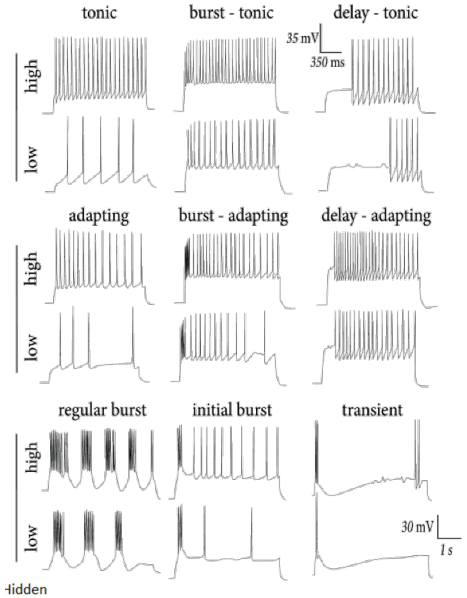
Differential equations that are discretized

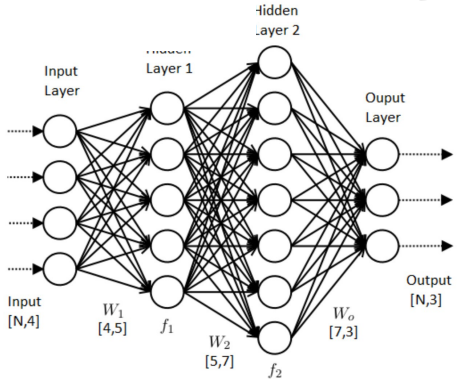
$$C_m \frac{dV}{dt} = -g_L(V - E_L) + g_L \Delta_T e^{\frac{V - V_T}{\Delta_T}} - u + I$$

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

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

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)*

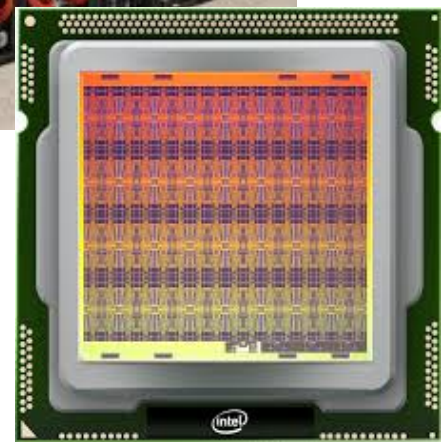




Neuromorphic chips

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

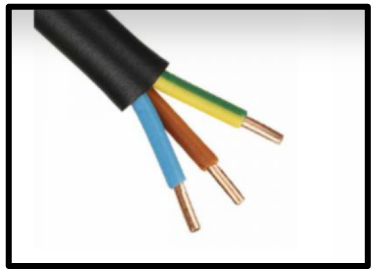
Neuromorphic materials

resistive switching & *memristors*

memory + resistors
sudden change in resistance under applied electric field (voltage)
hysteresis in the *I*-*V*

Electric breakdown in **Mott insulators**:
volatile effect

a new (and unexpected) neuromorphic functionality



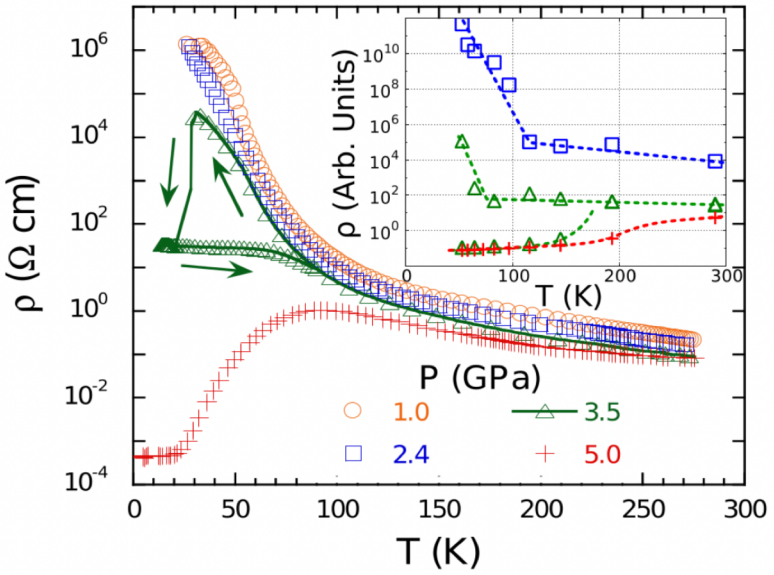
Ordinary matter:
cable made of metal (copper) and insulator (plastic)

Mott Materials (quantum matter)

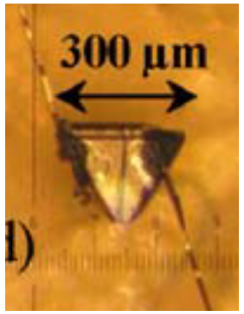
Should be metals…. But are insulators

insulator to metal (1st order) transition

10 orders of magnitude!!

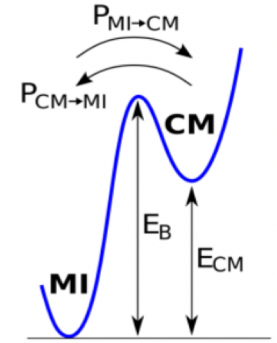


- Strongly Correlated Material
- Famous High Tc Superconductors

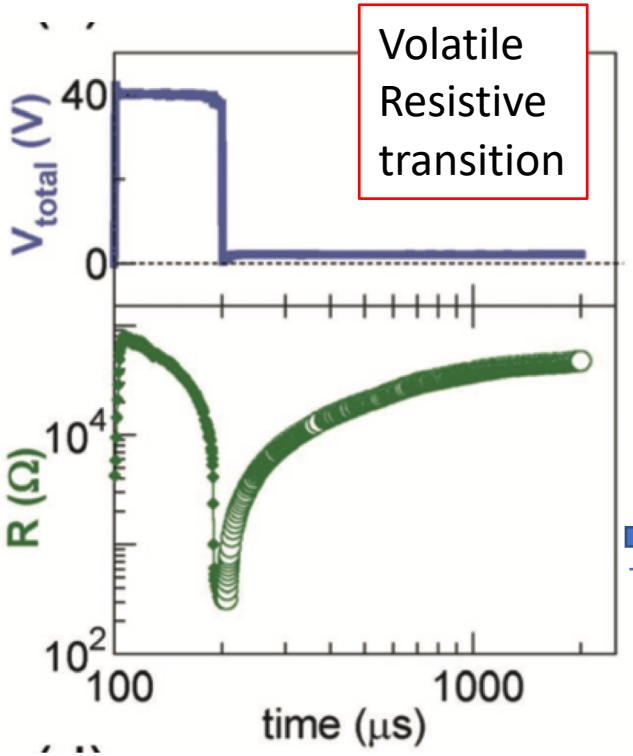


Acha, Camjayi @ UBA
Phys Rev Lett (2014)

Metastability of the
1st order MIT (DMFT)



Surprise: Electrically driven Mott transition

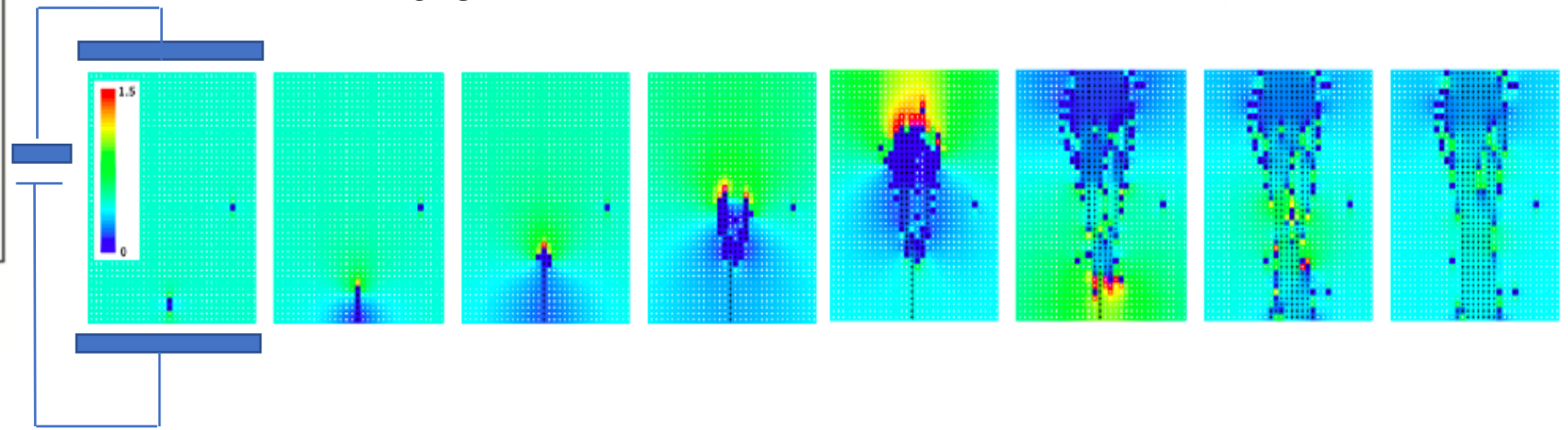


ADVANCED MATERIALS

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

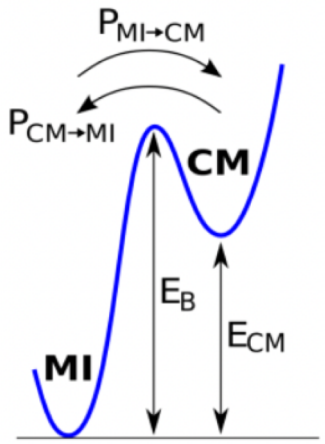
Pablo Stoliar, Laurent Cario, Etiene Janod, Benoit Corraze, Catherine Guillot-Deudon, Sabrina Salmon-Bourmand, Vincent Guiot, Julien Tranchant, Marcelo Rozenberg

2013

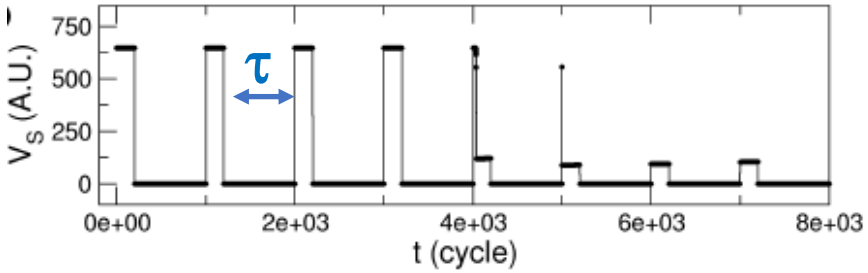


How about a non trivial validation?

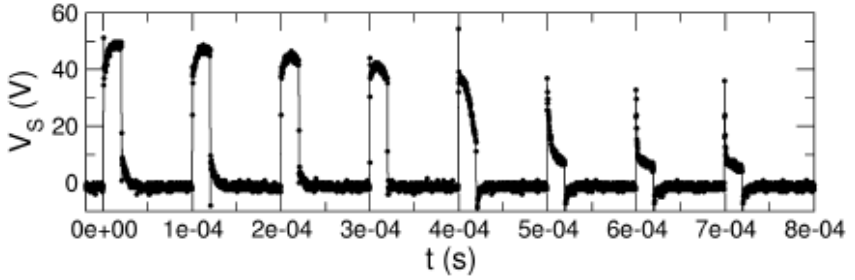
Metastability of the
1st order MIT (DMFT)



Model prediction



Experiment

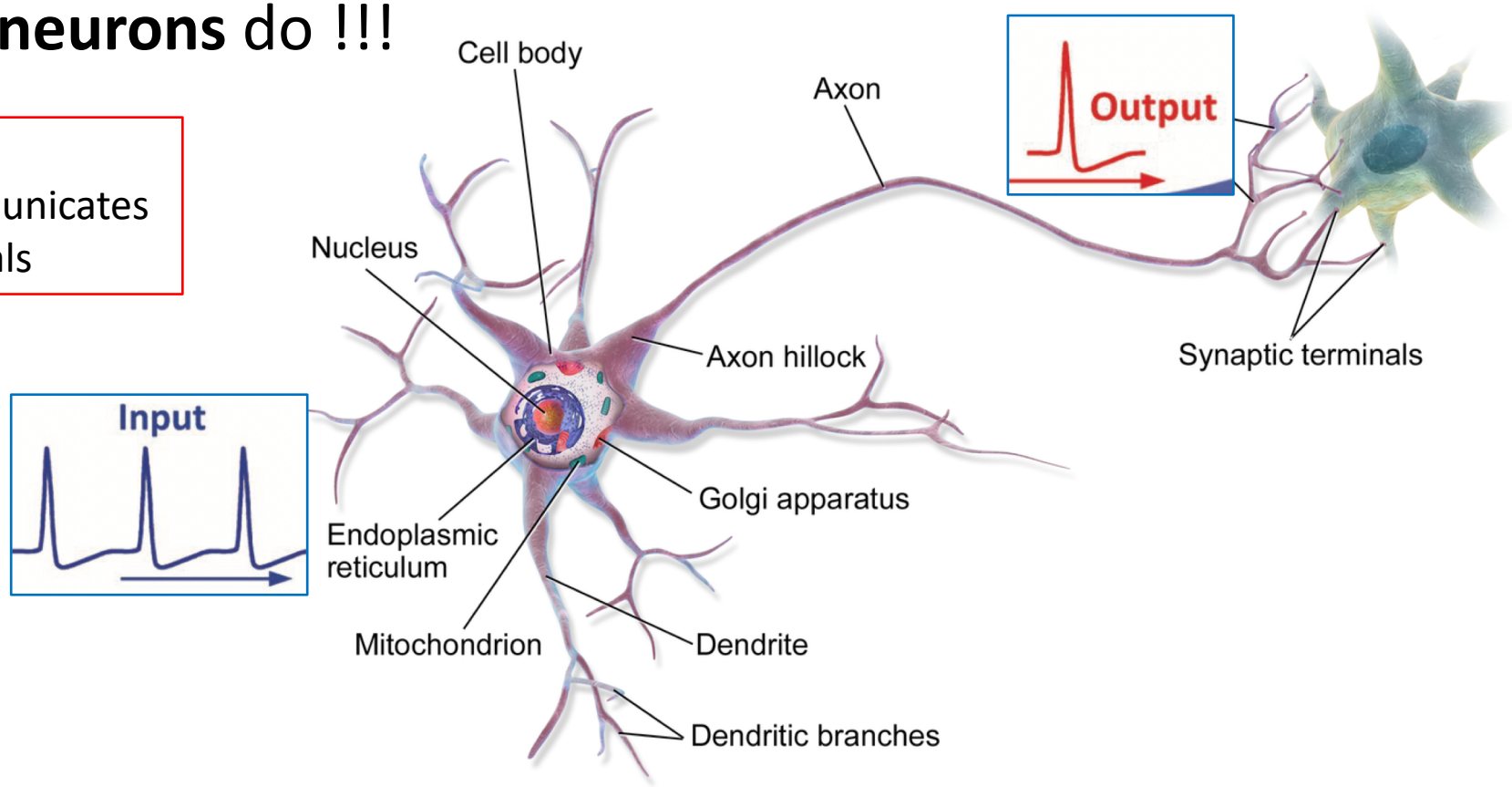


Electric pulses provoke a collapse of resistance, then a surge of current!

1st Aha! Moment !!!!

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

A neuron is a cell
Generates and communicates through electric signals

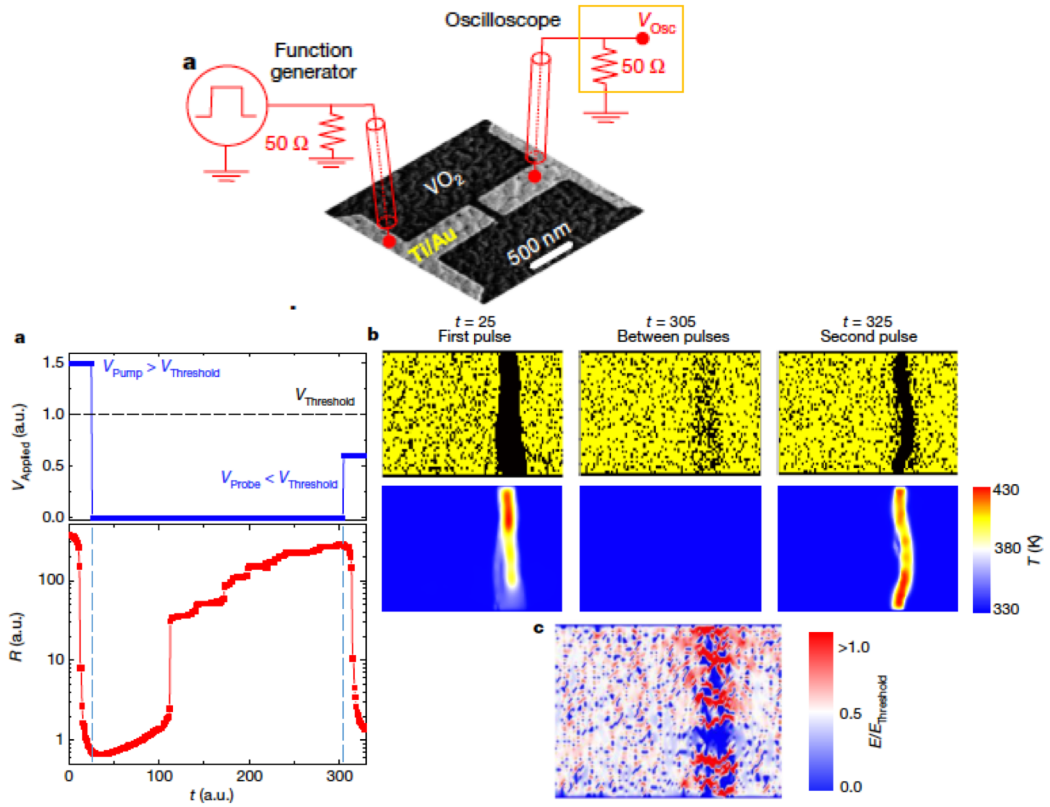


next neuron

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

R.Rocco et al PRApp (2022)
Editor's Suggestion

Silicon neurons are a reality

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

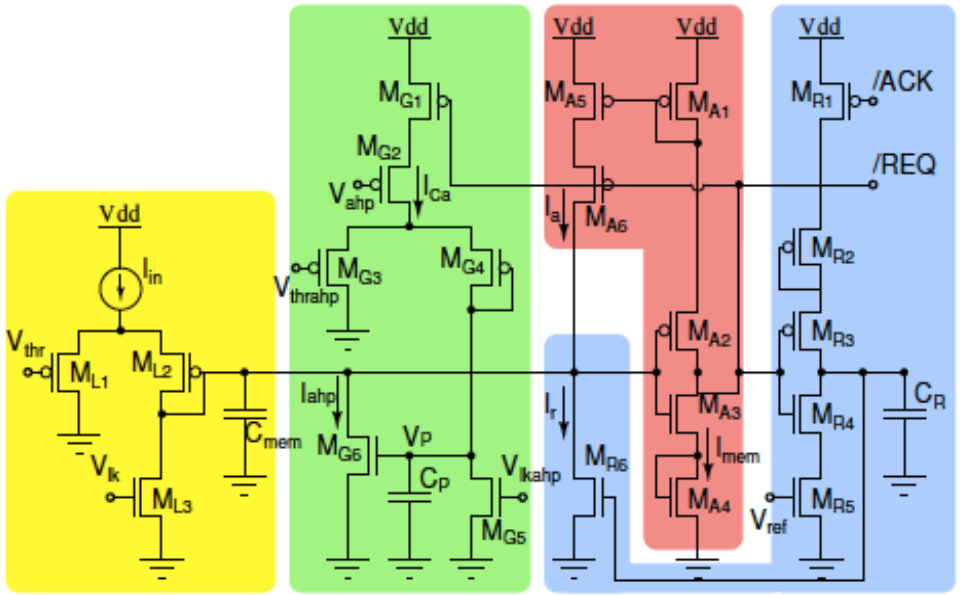


Fig. 2: Adaptive exponential I&F neuron circuit schematic.

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

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

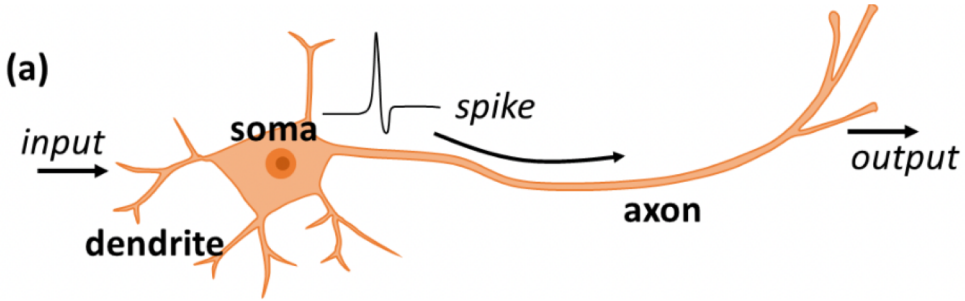
Simplicity of Mott memristors
Reliability of conventional silicon electronics

Best of both worlds:
Memristive Silicon Spiking Neuron
aka Ultra-Compact Neuron

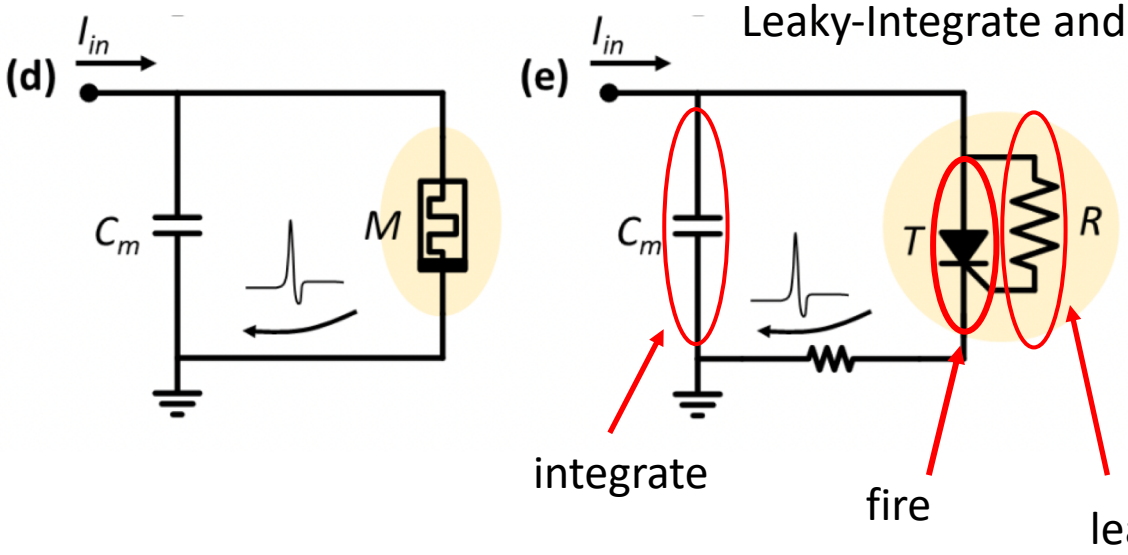
2nd Aha! Moment !!!

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

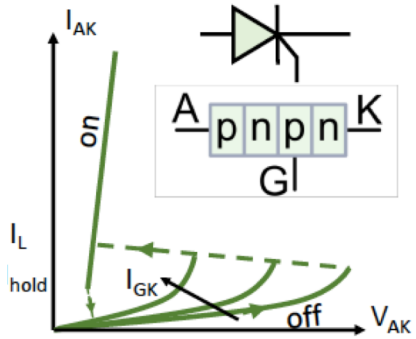
memory-resistive effect ←→ hysteresis

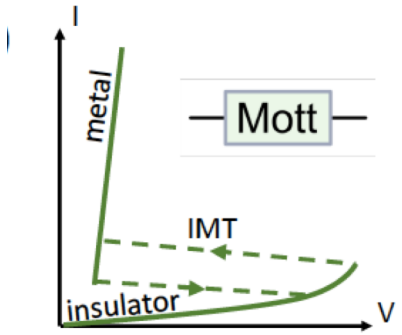


Leaky-Integrate and Fire model



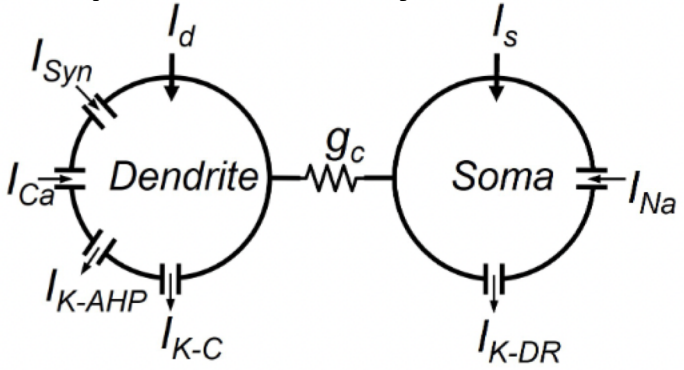
Thyristor
Threshold control diode

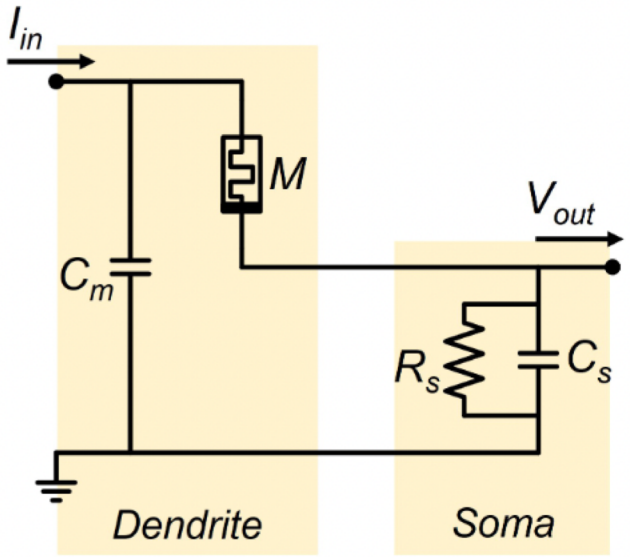


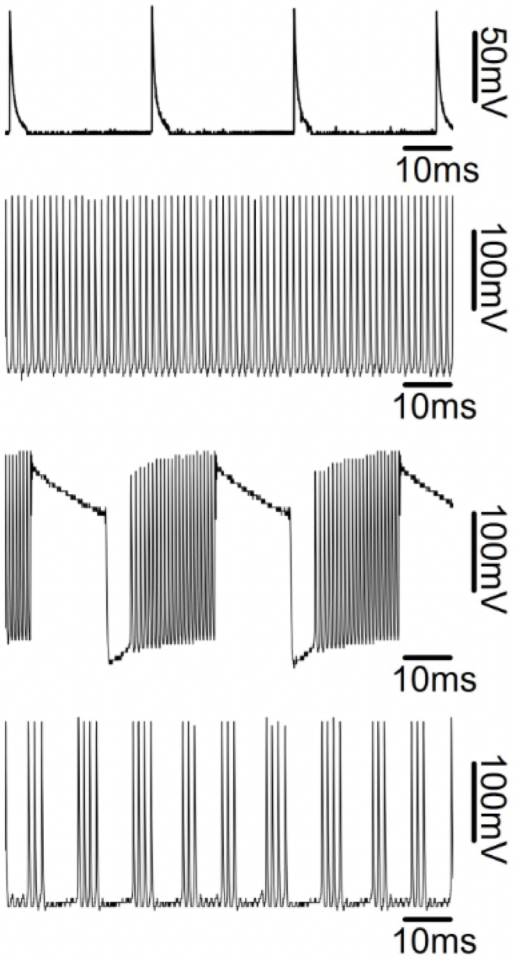


Memristive Bursting neuron

2-compartment Pinsky-Rinzel model







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

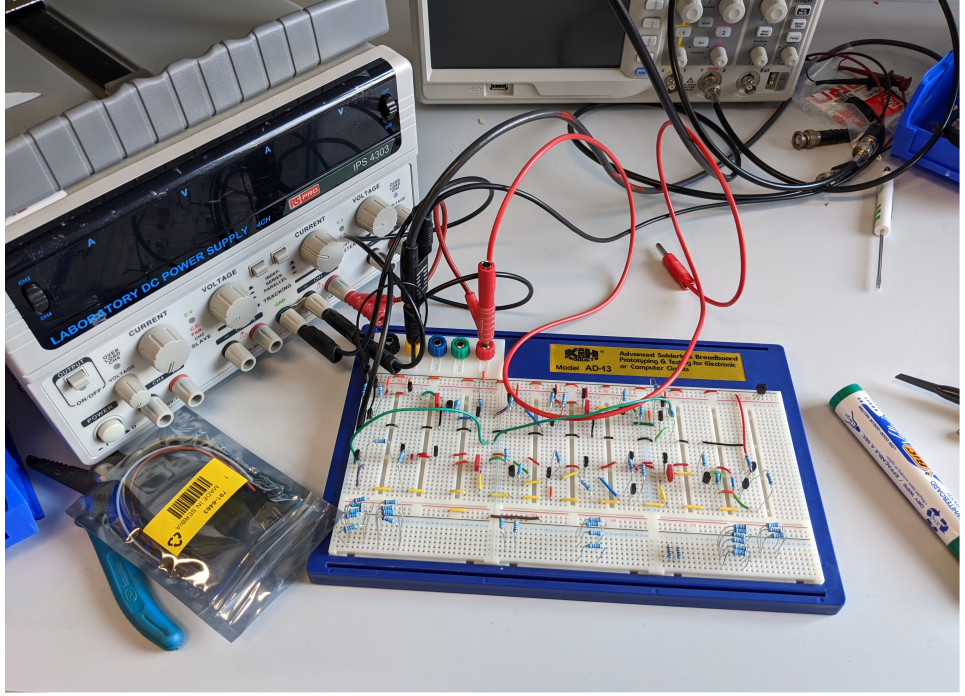
The kinetic equation for each of the gating variables h, n, s, c and q takes the form

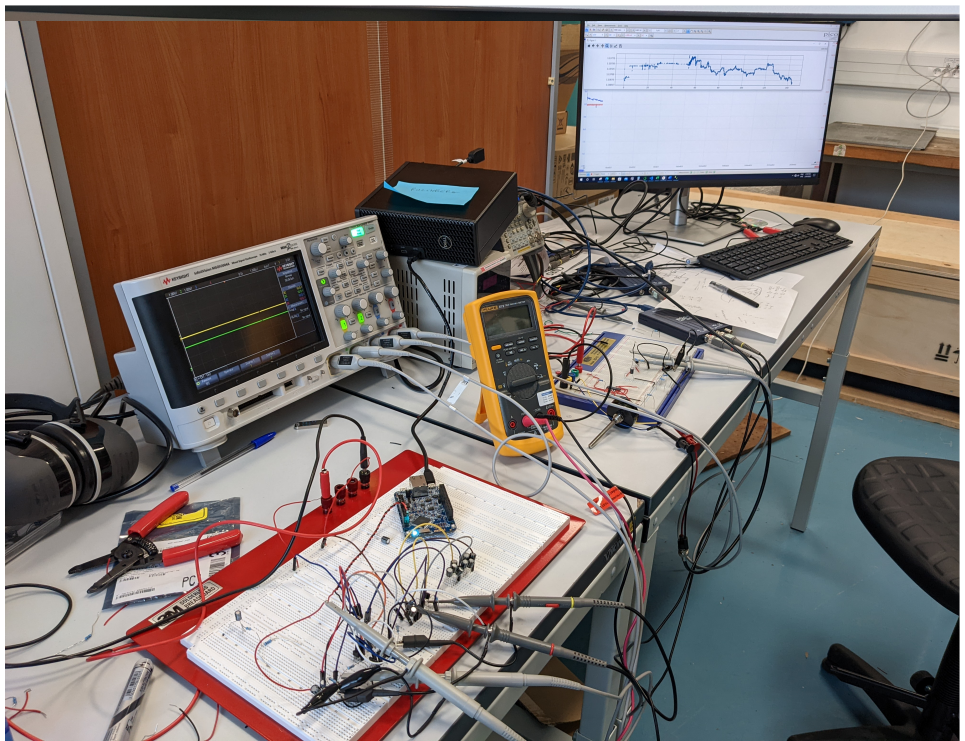
$$y' = (y_\infty(U) - y)/\tau_y(U). \qquad (2)$$

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

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

Wu et al (submitted)





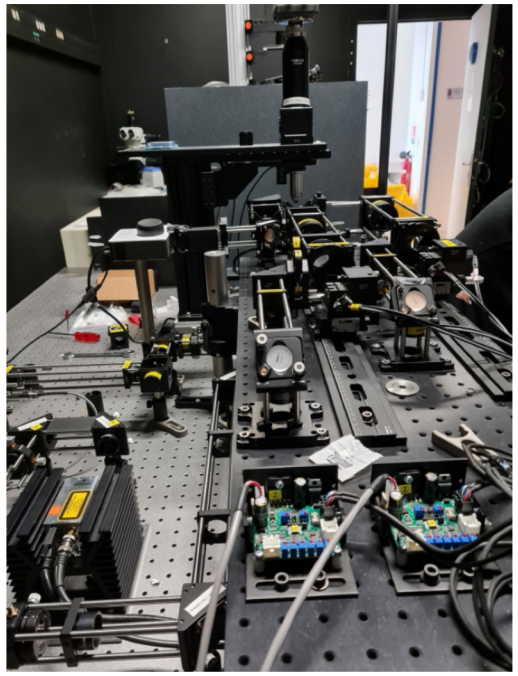
New Experimental Activity at LPS
Solid State Neuroscience Lab
Thanks to LPS for initial support!

New Project:

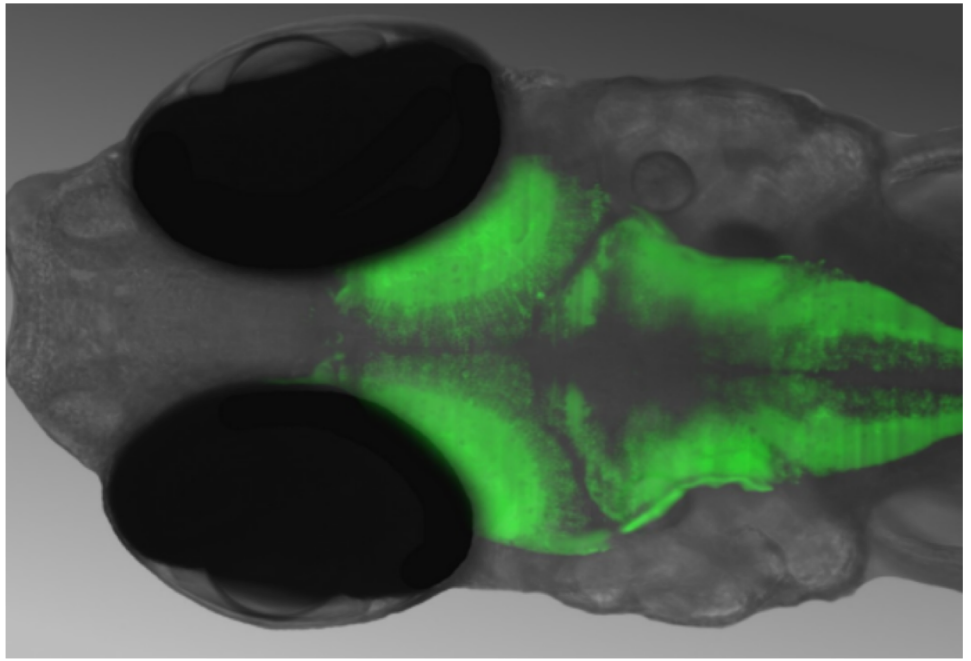
Brain-Machine-Interface:
memristive neural network
zebra fish neural network
w/G. Sumbre @ ENS

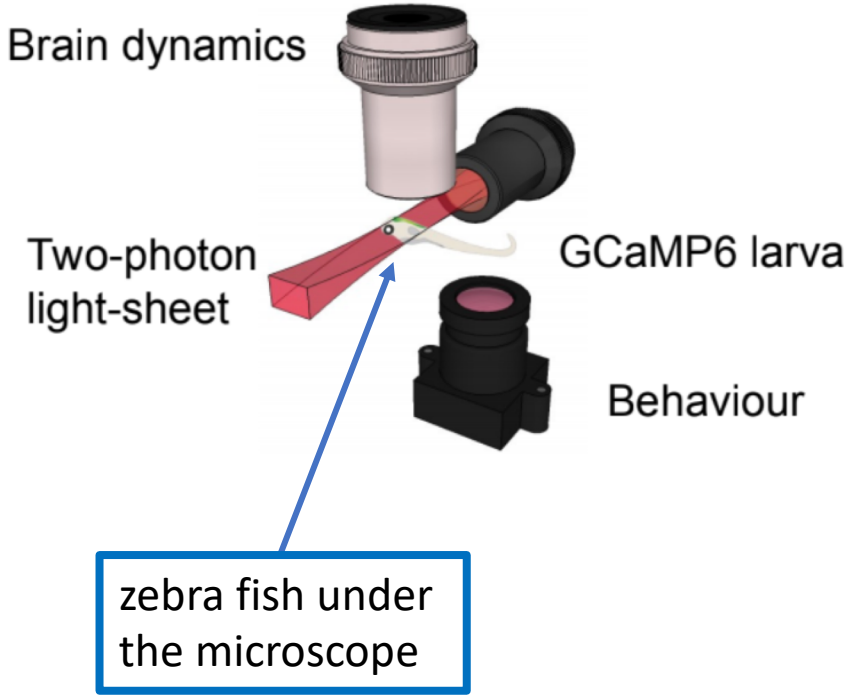
- Zebra fish larva optical recording and stimulation

Study fundamental questions of Neuroscience:
- Neural code? Spike timing versus spike rates
- State of matter? Criticality, chaos, phase diagram
- Dynamics? Waves, bumps, spike avalanches, epilepsy?
- Information How different networks communicate?
- Dynamical patterns, working memory

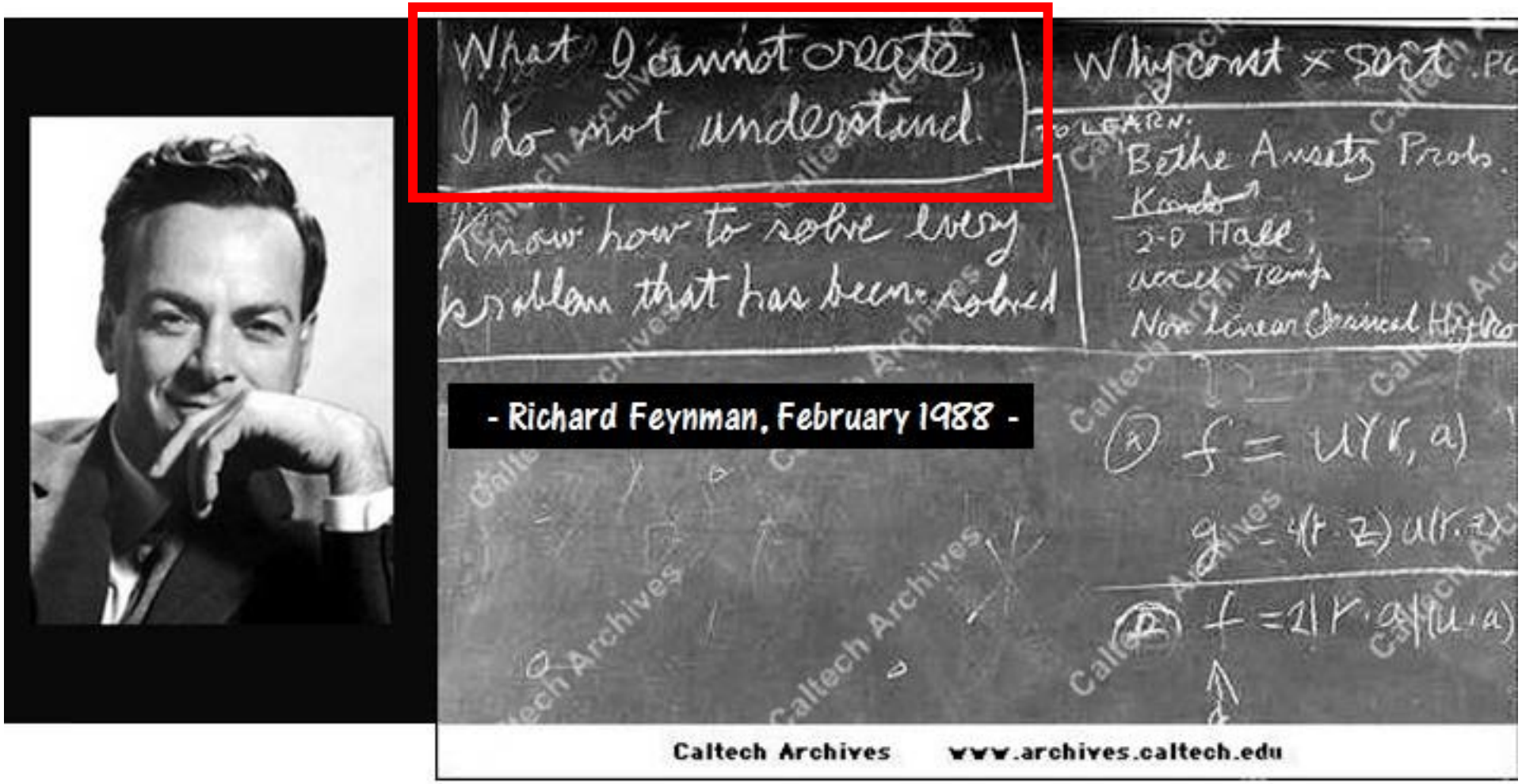


Brain of the zebra fish





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



Thank you