

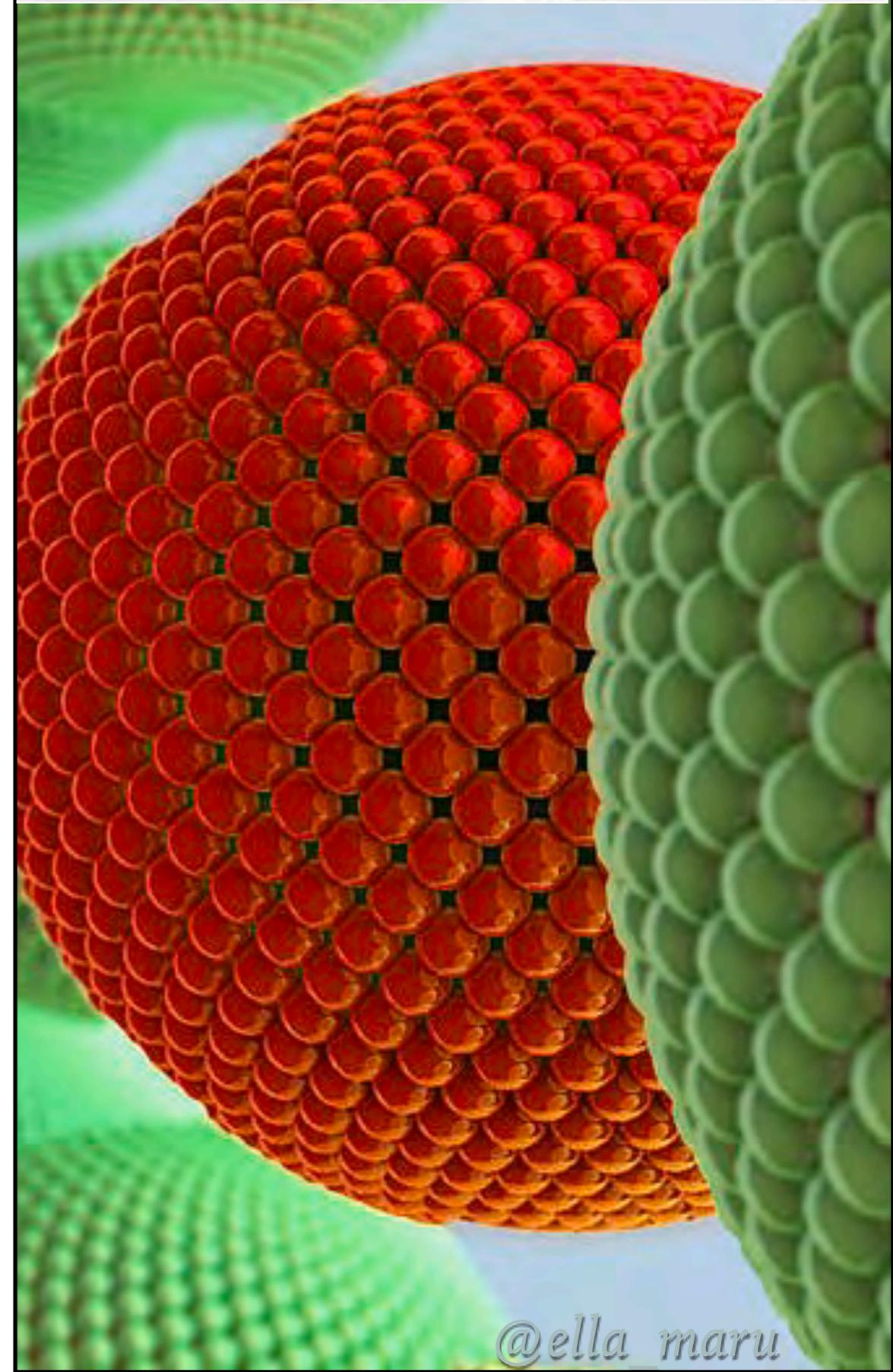
# ROOM TEMPERATURE SPIN FILTERING IN A METALLOPEPTIDE

## TOWARDS MOLECULAR MEMRISTIVITY?

.....  
*Salvador Cardona-Serra, ICMol*  
*SPICE WORKSHOP 2019, Mainz, 18/10/2019*

 *@salvajcardona*

*@ella maru*



*Salvador Cardona  
Alejandro Gaita  
Luis Escalera  
Silvia Giménez  
Jose Jaime Baldoví  
Lorena Rosaleny*



*Salvador Cardona  
Alejandro Gaita  
Luis Escalera  
Silvia Giménez  
Jose Jaime Baldoví  
Lorena Rosaleny*



.....

## **Vibronic Coupling**

2006

*BACHELOR*

**ICMOL**  
Institut de Ciència Molecular

*Salvador Cardona  
Alejandro Gaita  
Luis Escalera  
Silvia Giménez  
Jose Jaime Baldoví  
Lorena Rosaleny*



**Vibronic  
Coupling**

2006

BACHELOR

**DFT &  
Magnetism**

2007-2008

MASTER



*Salvador Cardona  
Alejandro Gaita  
Luis Escalera  
Silvia Giménez  
Jose Jaime Baldoví  
Lorena Rosaleny*



**Vibronic  
Coupling**

2006

*BACHELOR*



**DFT &  
Magnetism**

2007-2008

*MASTER*

**SIMs &  
Mixed-Valence**

2009-2013

*PREDOC*



*Salvador Cardona  
Alejandro Gaita  
Luis Escalera  
Silvia Giménez  
Jose Jaime Baldoví  
Lorena Rosaleny*



**Vibronic  
Coupling**

2006

*BACHELOR*



**DFT &  
Magnetism  
SIMs &  
Mixed-Valence**

2007-2008

*MASTER*



**SIMs &  
Mixed-Valence**

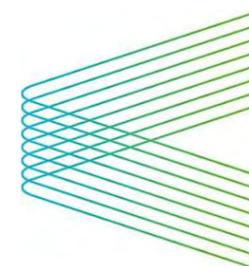
2009-2013

*PREDOC*

**Spintronics**

2014-2018

*POSTDOC*



CRANN

*Salvador Cardona  
Alejandro Gaita  
Luis Escalera  
Silvia Giménez  
Jose Jaime Baldoví  
Lorena Rosaleny*



**Vibronic  
Coupling**

2006

BACHELOR



**DFT &  
Magnetism  
SIMs &  
Mixed-Valence**

2007-2008

MASTER



**SIMs &  
Mixed-Valence**

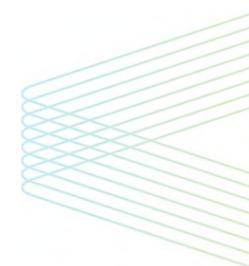
2009-2013

PREDOC

**Spintronics**

2014-2018

POSTDOC



**Memristor**

2019

NANOMEM



# TECHNOLOGICAL REVOLUTION TIMELINE

## Four Industrial Revolutions

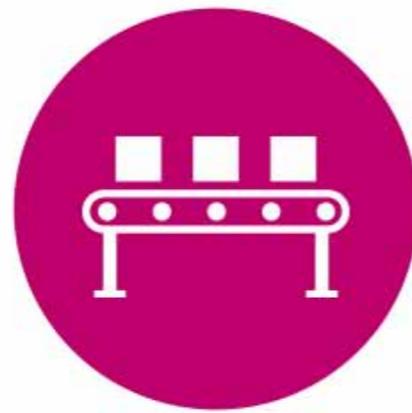


**1765**

1<sup>st</sup> revolution

**MECHANIZATION**

led by the steam engine



**1870**

2<sup>nd</sup> revolution

**MASS  
PRODUCTION**

driven by electricity  
and oil-based power



**1969**

3<sup>rd</sup> revolution

**AUTOMATED  
PRODUCTION**

supported by electronics  
and information  
technologies



**Today**

4<sup>th</sup> revolution

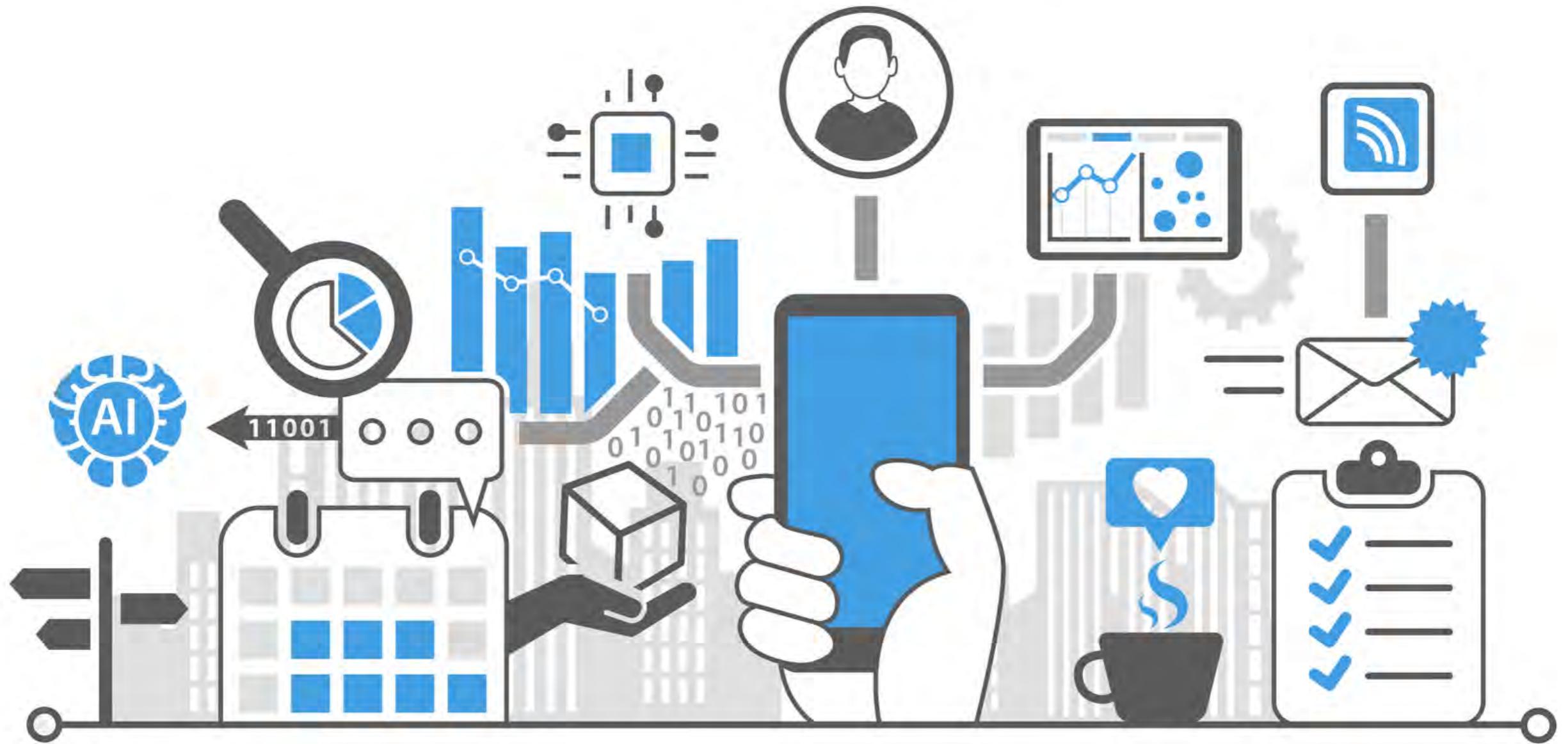
**NEW  
TECHNOLOGIES**

Internet of Things (IoT),  
Artificial Intelligence (AI);  
Big Data, Cloud,  
Cyber-Physical Systems...

# BIG DATA AND PATTERN RECOGNITION



# BIG DATA AND PATTERN RECOGNITION



# INTERNET OF THINGS

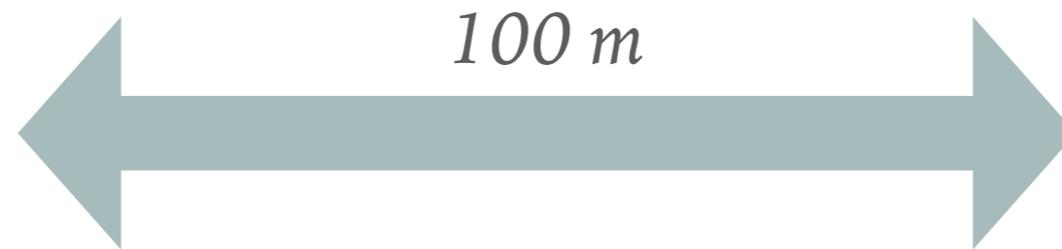


# VON NEUMANN BOTTLENECK



**MOST ENERGY/TIME CONSUMING PROCESS**

# VON NEUMANN BOTTLENECK



*Für Elise*  
in A minor  
for piano solo  
L. van Beethoven (1770-1827)

edited by  
Fabrizio Ferrari

Poco moto  
pp

12 a tempo  
p dim

18

www.virtualsheetmusic.com

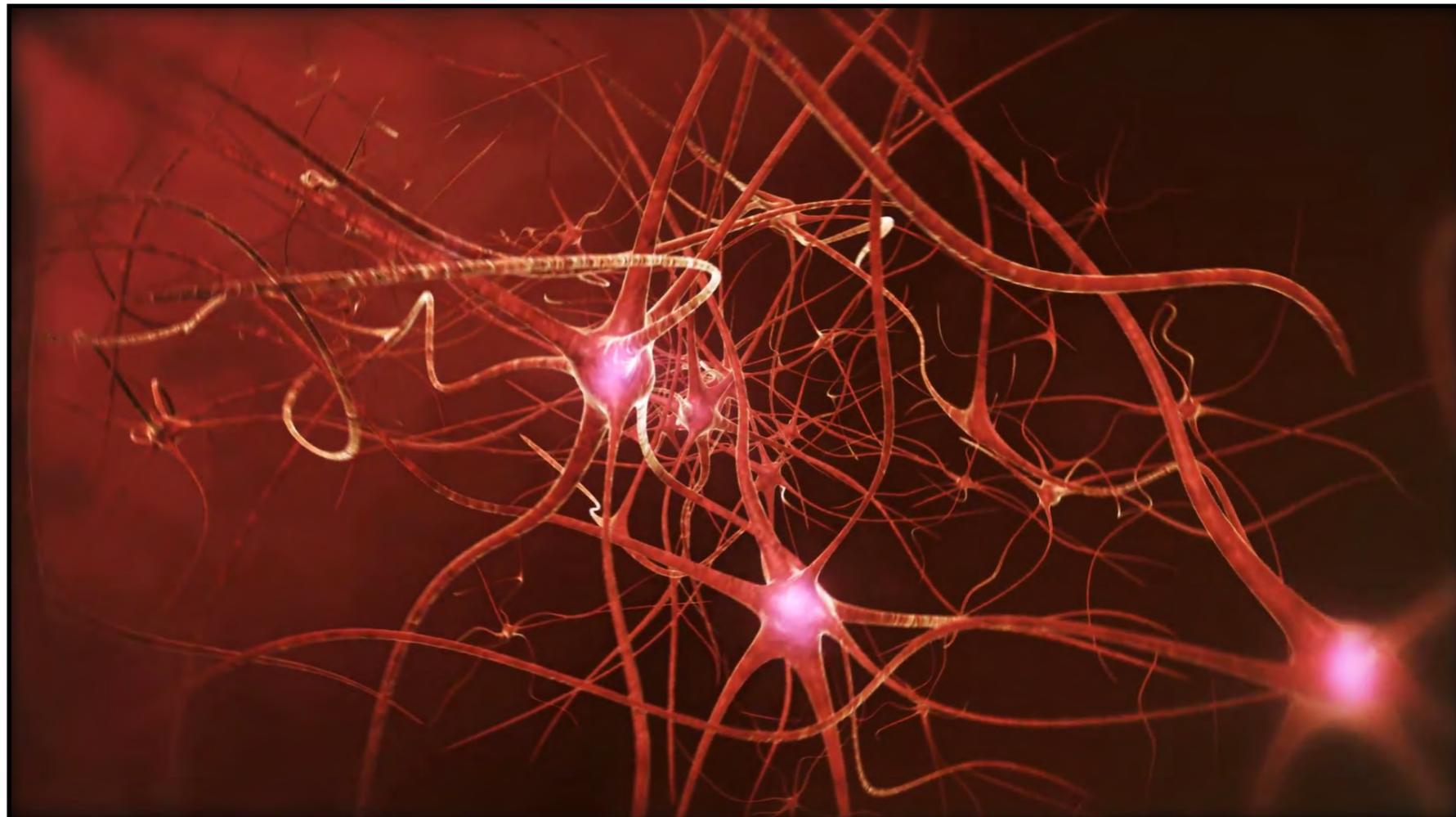
1

# MOST ENERGY/TIME CONSUMING PROCESS

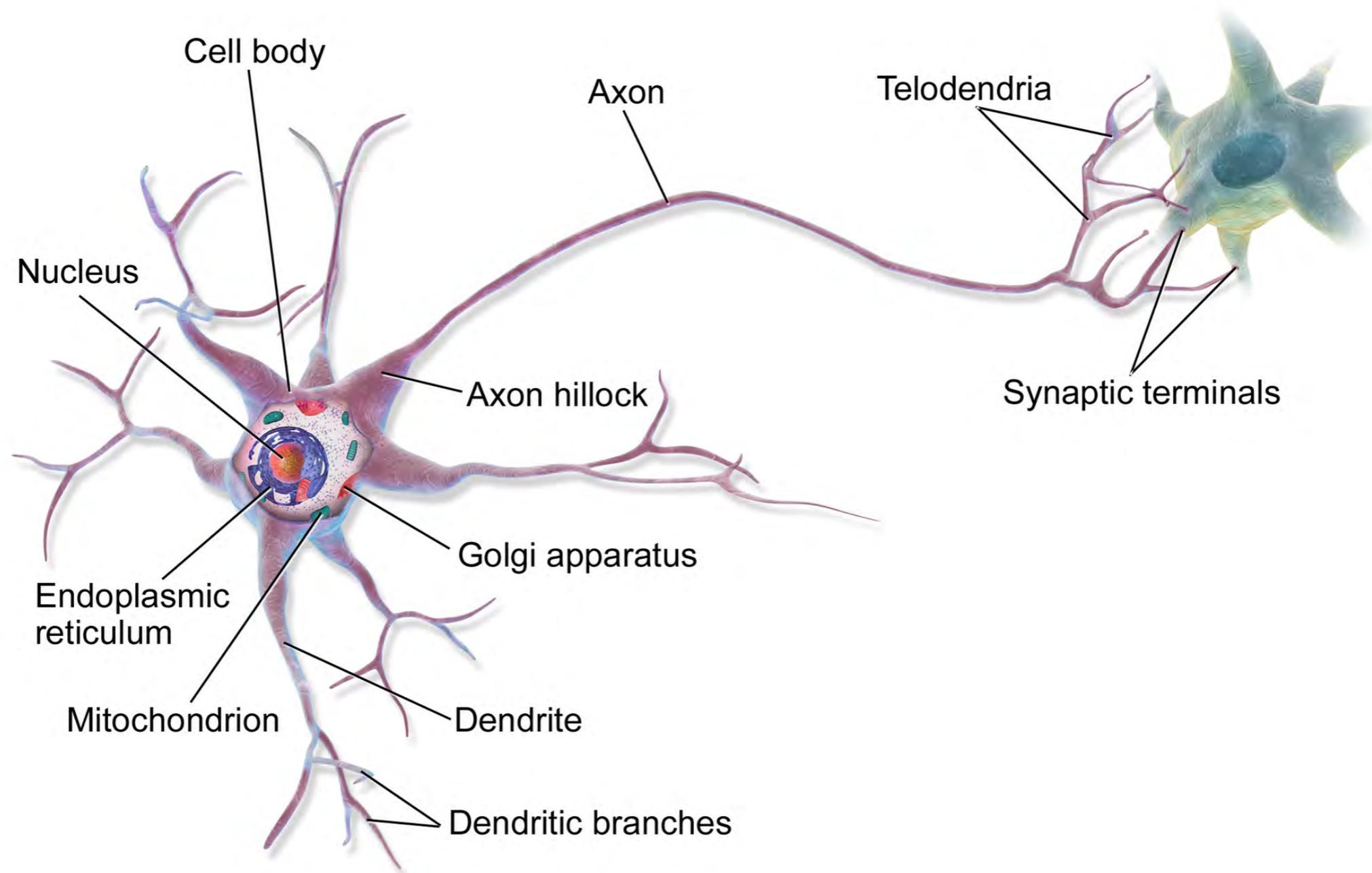


# NEUROMORPHIC COMPUTING

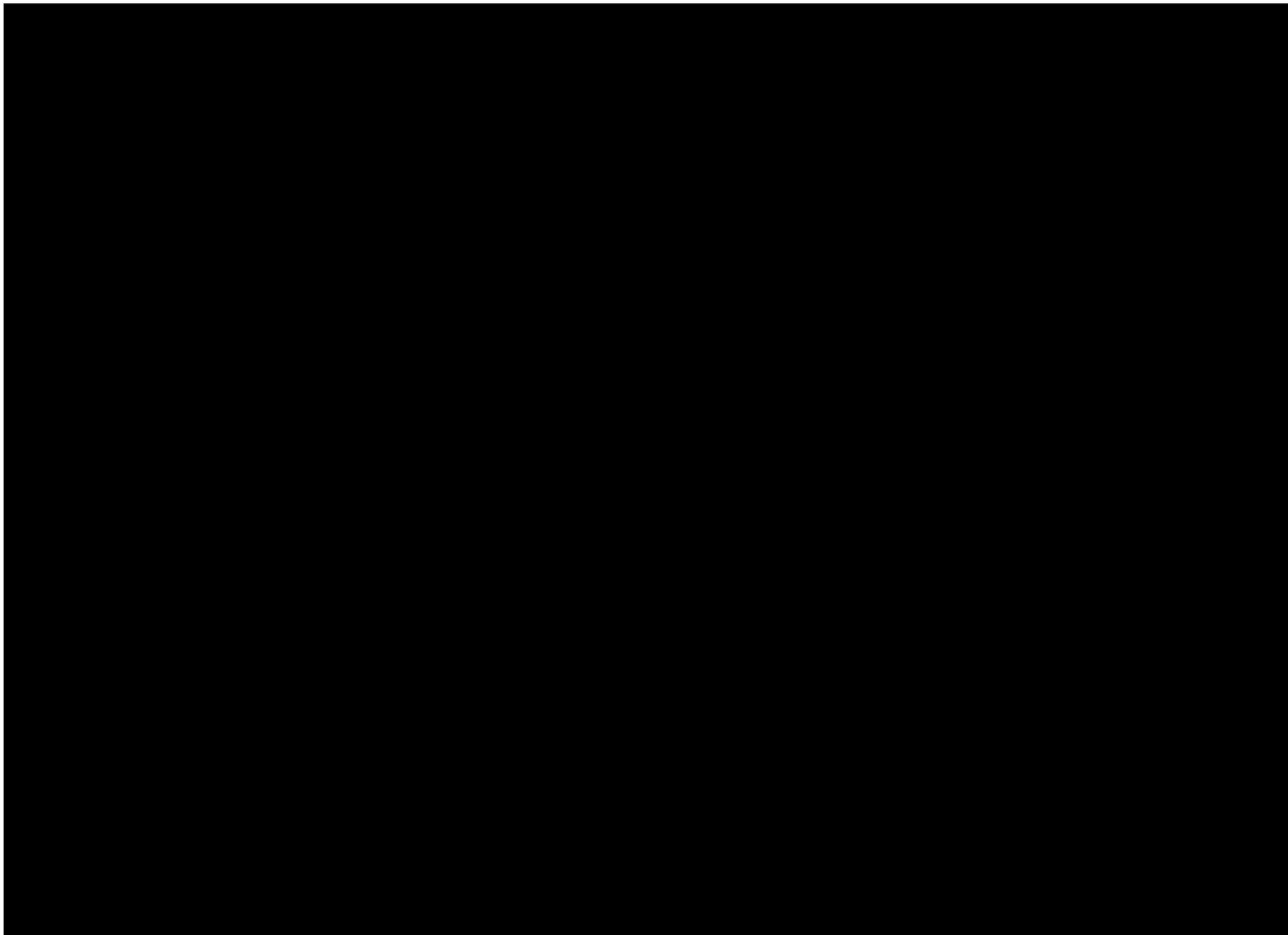
# BEYOND VON NEUMANN



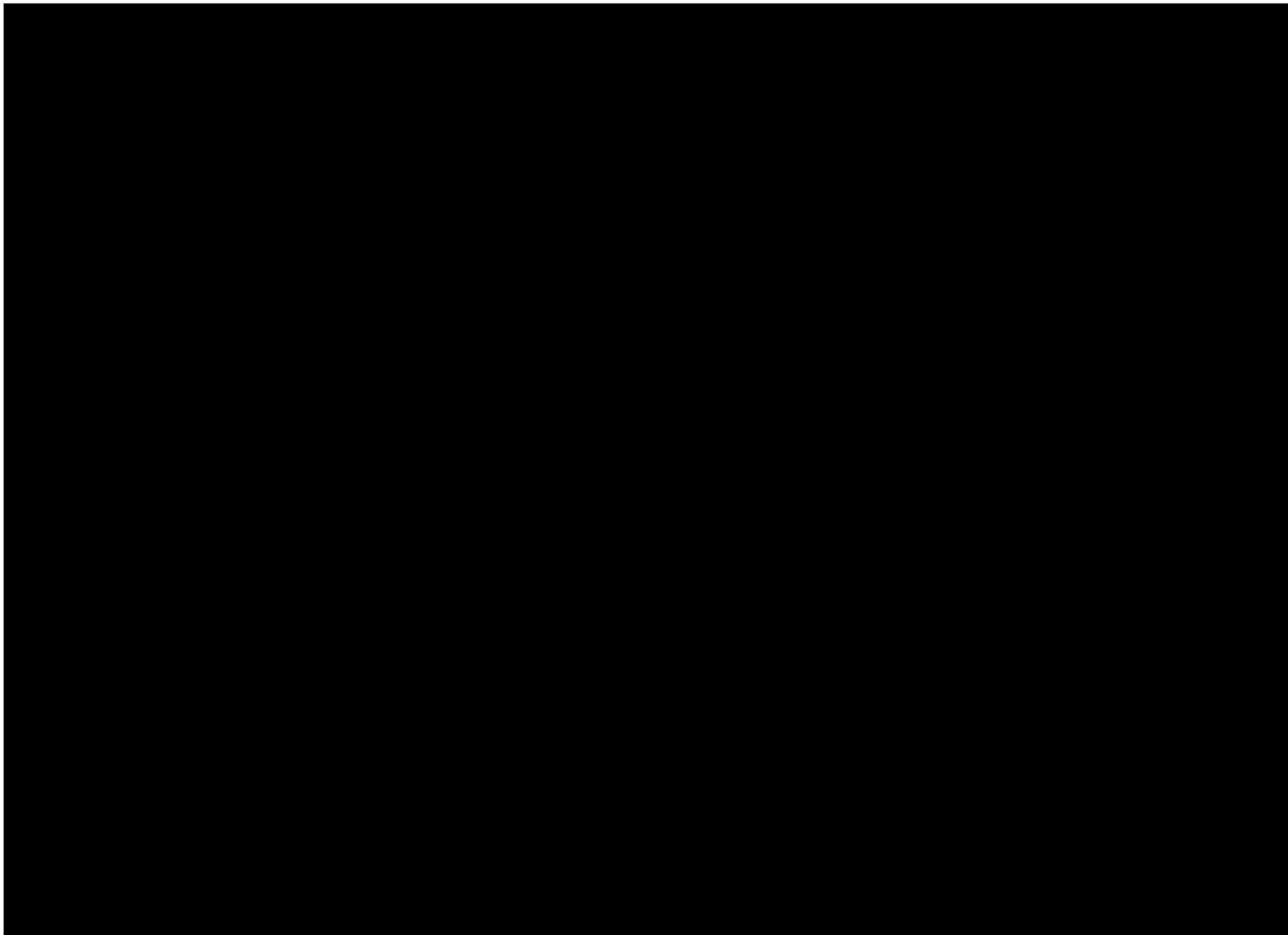
# HOW DOES A NEURON WORKS?



# HOW DOES A NEURON WORKS?

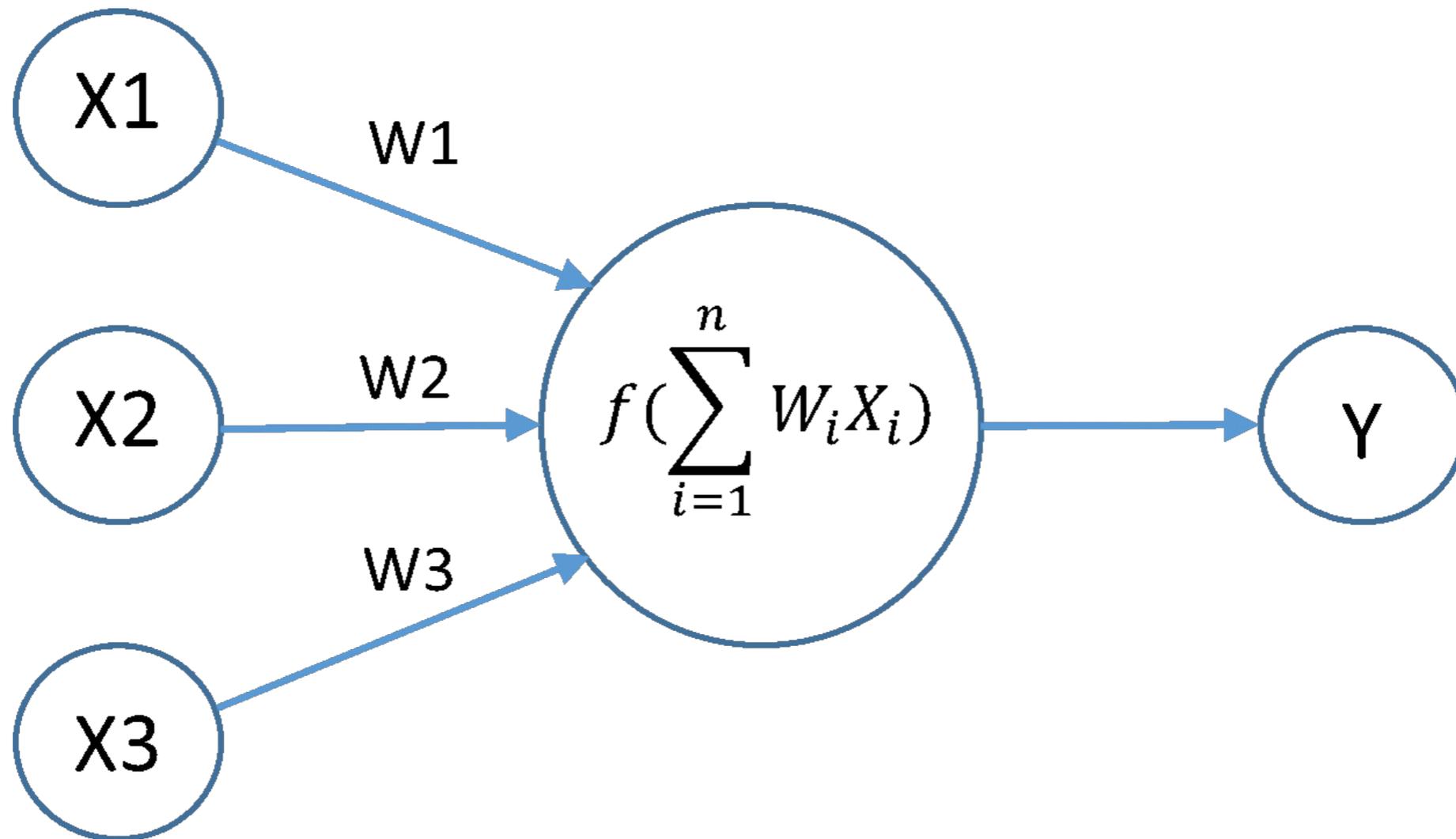


# HOW DOES A NEURON WORKS?

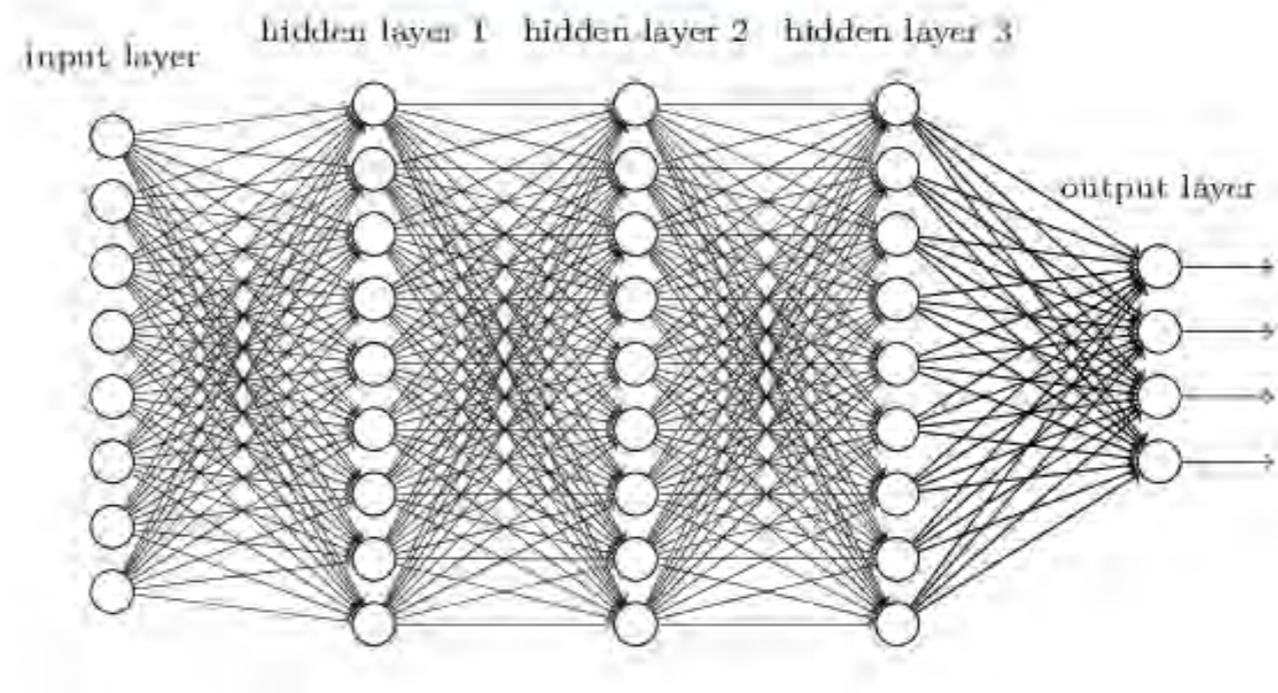
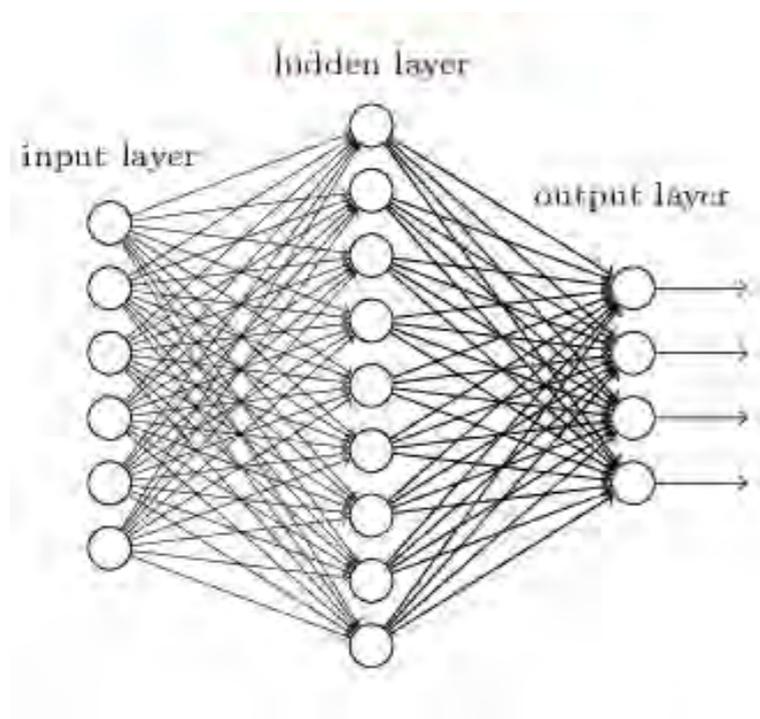


# HOW DOES AN ARTIFICIAL NEURON WORKS?

# HOW DOES AN ARTIFICIAL NEURON WORKS?



# HOW DOES AN ARTIFICIAL NEURON WORKS?



# EU FLAGSHIP + ERC PROJECTS

**Human Brain Project** Science ▾ Platforms ▾ Collaborate ▾ Follow HBP ▾ About ▾ Education & Training ▾

## Welcome to the Human Brain Project

The Human Brain Project aims to put in place a cutting-edge research infrastructure that will allow scientific and industrial researchers to advance our knowledge in the fields of neuroscience, computing, and brain-related medicine

[Learn more about the project](#)

3D-Polarized Light Imaging of the human hippocampus.  
Image: Axer, Amunts and team, Jülich.

- Explore the Brain
- Brain Simulation
- Silicon Brains
- Understanding Cognition
- Medicine
- Robots
- Massive Computing
- Social, Ethical, Reflective

---

# EU FLAGSHIP + ERC PROJECTS

The screenshot shows the homepage of the Human Brain Project. At the top left is the HBP logo. To its right is the text "Human Brain Project" followed by a navigation menu with items: "Science", "Platforms", "Collaborate", "Follow HBP", "About", and "Education & Training". Below the navigation is a large banner image of a brain cross-section with a colorful overlay. The text "Welcome to the Human Brain Project" is centered on the banner. Below this is a paragraph: "The Human Brain Project aims to put in place a cutting-edge research infrastructure that will allow scientific and industrial researchers to advance our knowledge in the fields of neuroscience, computing, and brain-related medicine". A link "Learn more about the project" is positioned to the right of the paragraph. In the bottom right corner of the banner, there is a small caption: "3D-Polarized Light Imaging of the human hippocampus. Image: Axer, Amunts and team, Jülich." Below the banner is a horizontal bar with eight colored boxes, each containing an icon and a label: "Explore the Brain" (red), "Brain Simulation" (orange), "Silicon Brains" (yellow), "Understanding Cognition" (light yellow), "Medicine" (teal), "Robots" (blue), "Massive Computing" (dark blue), and "Social, Ethical, Reflective" (darkest blue).

The screenshot shows a webpage for an ERC Project titled "Projector" Projected Memristor. The IBM logo is in the top left corner. The text "ERC Project" is in the top left of the main content area. The title "Projector" is in a large font, with "Projected Memristor" below it. Underneath the title is the subtitle "A nanoscale device for cognitive computing". On the right side of the page is a 3D visualization of a memristor array, showing a grid of vertical pillars on a base, with green lines representing connections or data flow.

# EU FLAGSHIP + ERC PROJECTS

Human Brain Project Science Platforms Collaborate Follow HBP About Education & Training

Welcome to the Human Brain Project

The Human Brain Project aims to put in place a cutting-edge research infrastructure that will allow scientific and industrial researchers to advance our knowledge in the fields of neuroscience, computing, and brain-related medicine

[Learn more about the project](#)

3D-Polarized Light Imaging of the human hippocampus.  
Image: Axer, Amunts and team, Jülich.

Explore the Brain Brain Simulation Silicon Brains Understanding Cognition Medicine Robots Massive Computing Social, Ethical, Reflective

☰ Damien Querlioz Research

## NANOINFER ERC project

### The Project

NANOINFER is my newest project! It started in 2017 and is funded by a [European Research Council Starting Grant](#) for a duration of 5 years.

[I am hiring for this exciting project](#)

Cognitive tasks are increasingly necessary in modern electronics. The energy efficiency of associated algorithms, which rely on abundant stored parameters, is severely limited by the separation of computation and memory elements in conventional computers. In NANOINFER, I will directly address this challenge by developing intelligent memory chips that **natively perform both memory and computing functions**, using CMOS and emerging nanodevices.

# EU FLAGSHIP + ERC PROJECTS

Human Brain Project Science Platforms Collaborate Follow HBP About Education & Training

## Welcome to the Human Brain Project

The Human Brain Project aims to put in place a cutting-edge research infrastructure that will allow scientific and industrial researchers to advance our knowledge in the fields of neuroscience, computing, and brain-related medicine

[Learn more about the project](#)

3D-Polarized Light Imaging of the human hippocampus. Image: Axer, Amunts and team, Jülich.

- Explore the Brain
- Brain Simulation
- Silicon Brains
- Understanding Cognition
- Medicine
- Robots
- Massive Computing
- Social, Ethical, Reflective

home why memristors spin torque publications collaborations

## why nanodevices for bio-inspired computing ?

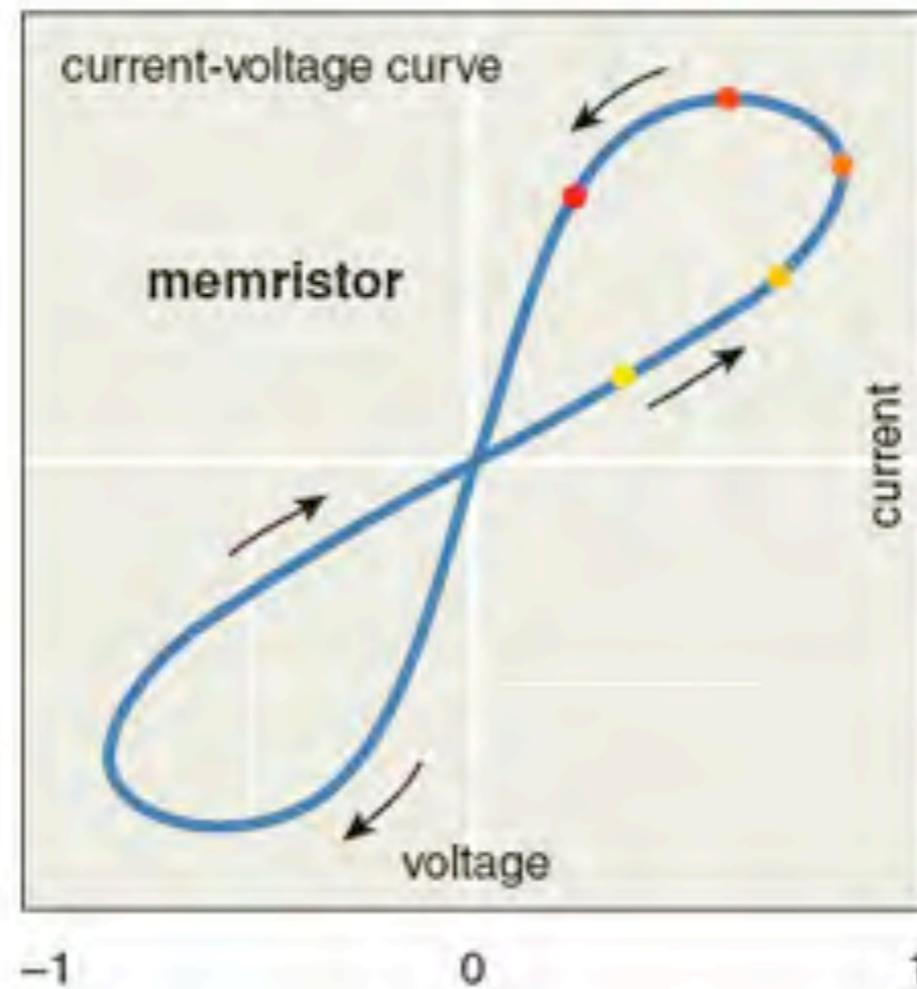
- nanodevices can implement complex functions at the nano-scale
- bio-inspired architectures are very relevant today
- bio-inspired hardware need complex nanodevices to be performant
- memristor nanodevices for artificial neural networks is a recent example
- bio-inspiration can take different forms
- interdisciplinary approaches are necessary

The Pro  
NANOINFER  
I am hiring fo

ars.  
stored parameters, is severely allenge by developing intelligent

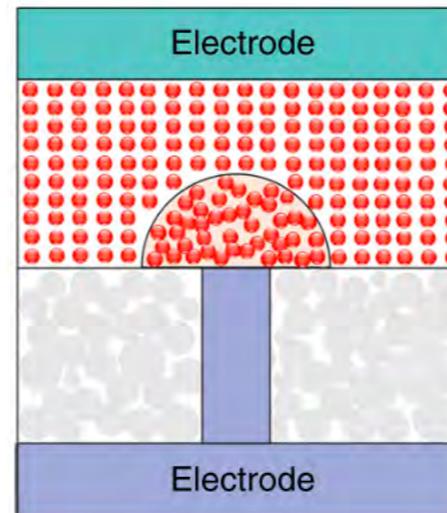
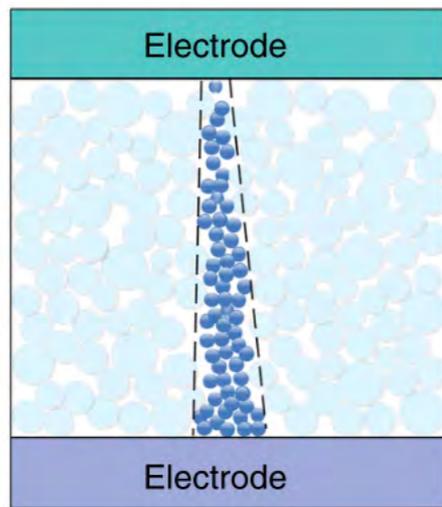
# HOW?

# (MOLECULAR) MEMRISTORS

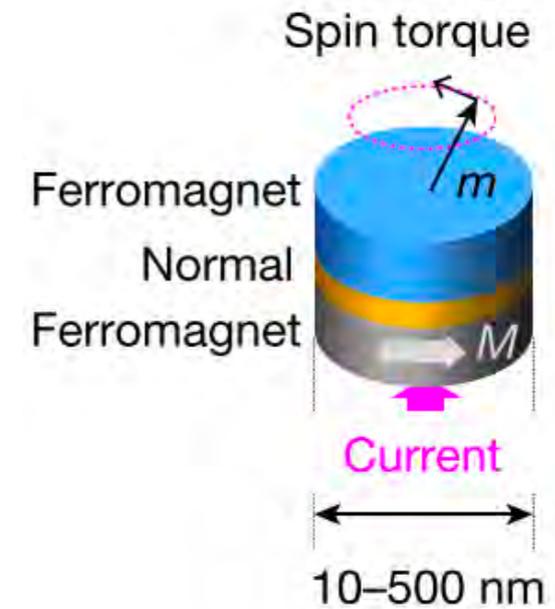


# MEMRISTIVITY MECHANISMS

## Solid-State



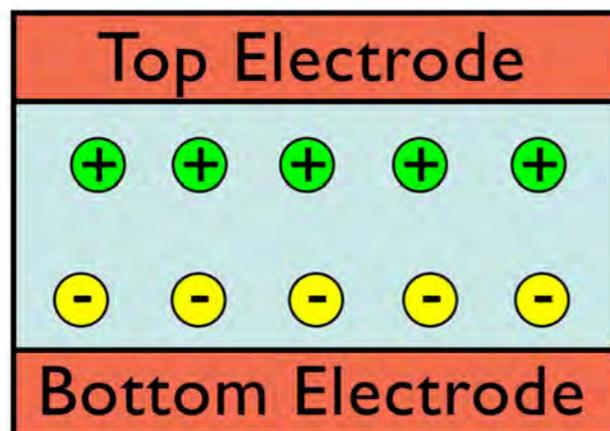
*Yang et al. Nat. Comm. 2019*



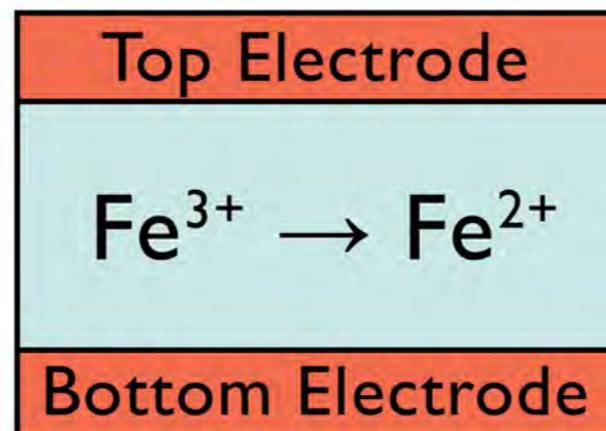
*Grollier et al. Nature. 2017*

## Molecular

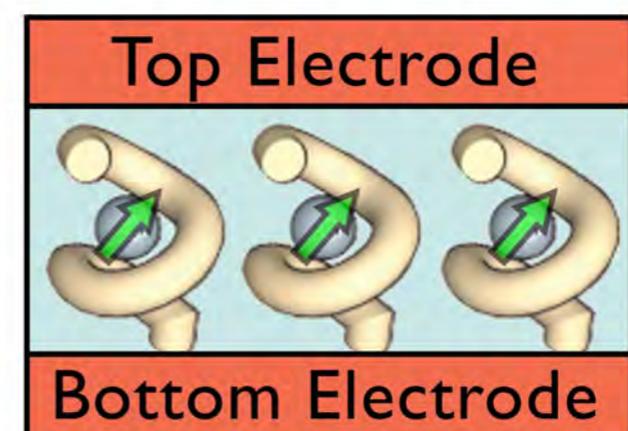
### Ion Migration



### Redox-active



### Magnetism



# CISS EFFECT

## CISS EFFECT + PARAMAGNETIC ION = MAGNETORESISTANCE?



Article | OPEN | Published: 06 August 2013

### A chiral-based magnetic memory device without a permanent magnet

Oren Ben Dor, Shira Yochelis, Shinto P. Mathew, Ron Naaman & Yossi Paltiel



Article | OPEN | Published: 23 February 2017

### Magnetization switching in ferromagnets by adsorbed chiral molecules without current or external magnetic field

Oren Ben Dor, Shira Yochelis, Anna Radko, Kiran Vankayala, Eyal Capua, Amir Capua, See-Hun Yang, Lech Tomasz Baczewski, Stuart Stephen Papworth Parkin, Ron Naaman & Yossi Paltiel

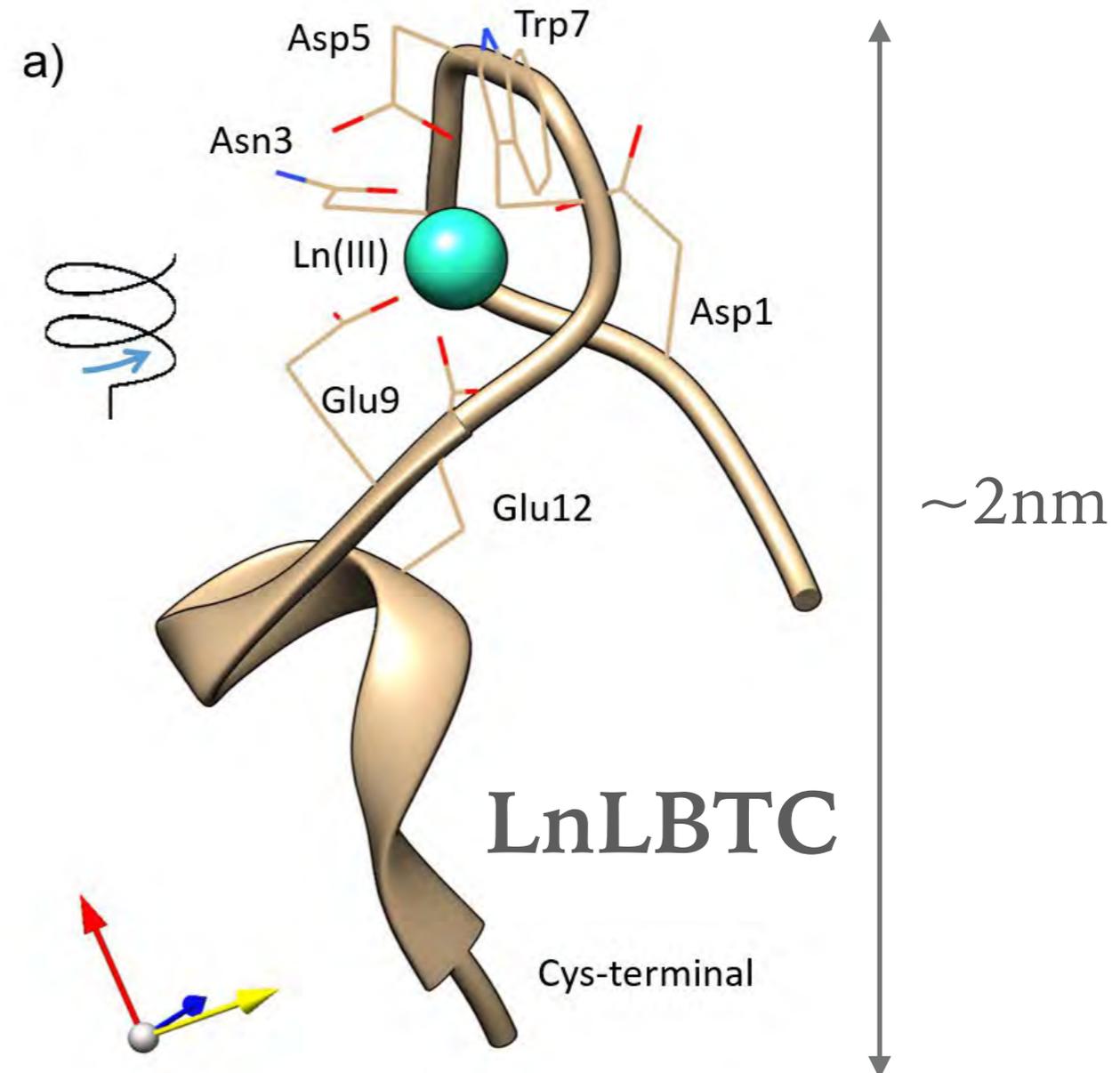
#### COMMUNICATION

Molecular Spintronics



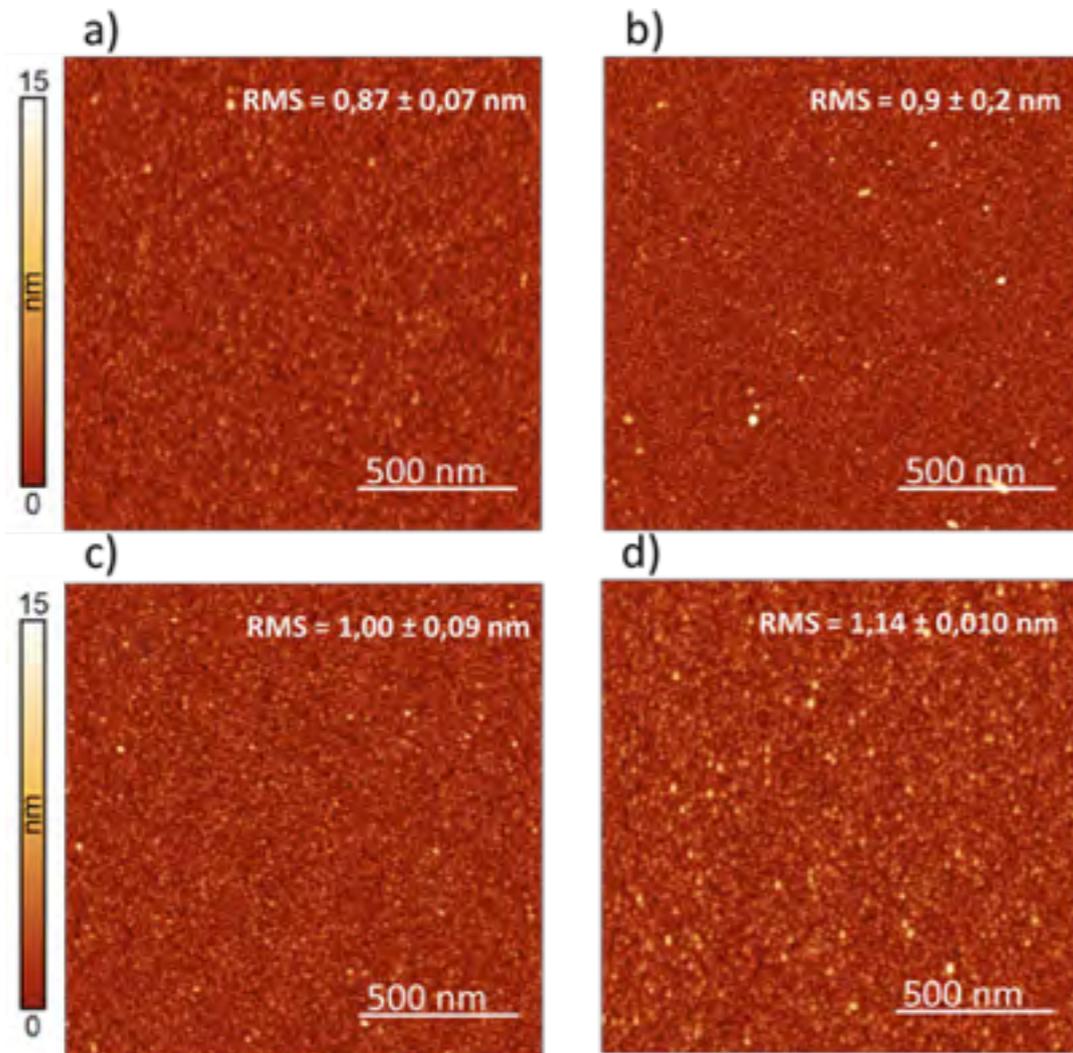
### Single Nanoparticle Magnetic Spin Memristor

Hammam Al-Bustami, Guy Koplovitz, Darinka Primc, Shira Yochelis, Eyal Capua, Danny Porath, Ron Naaman, and Yossi Paltiel\*

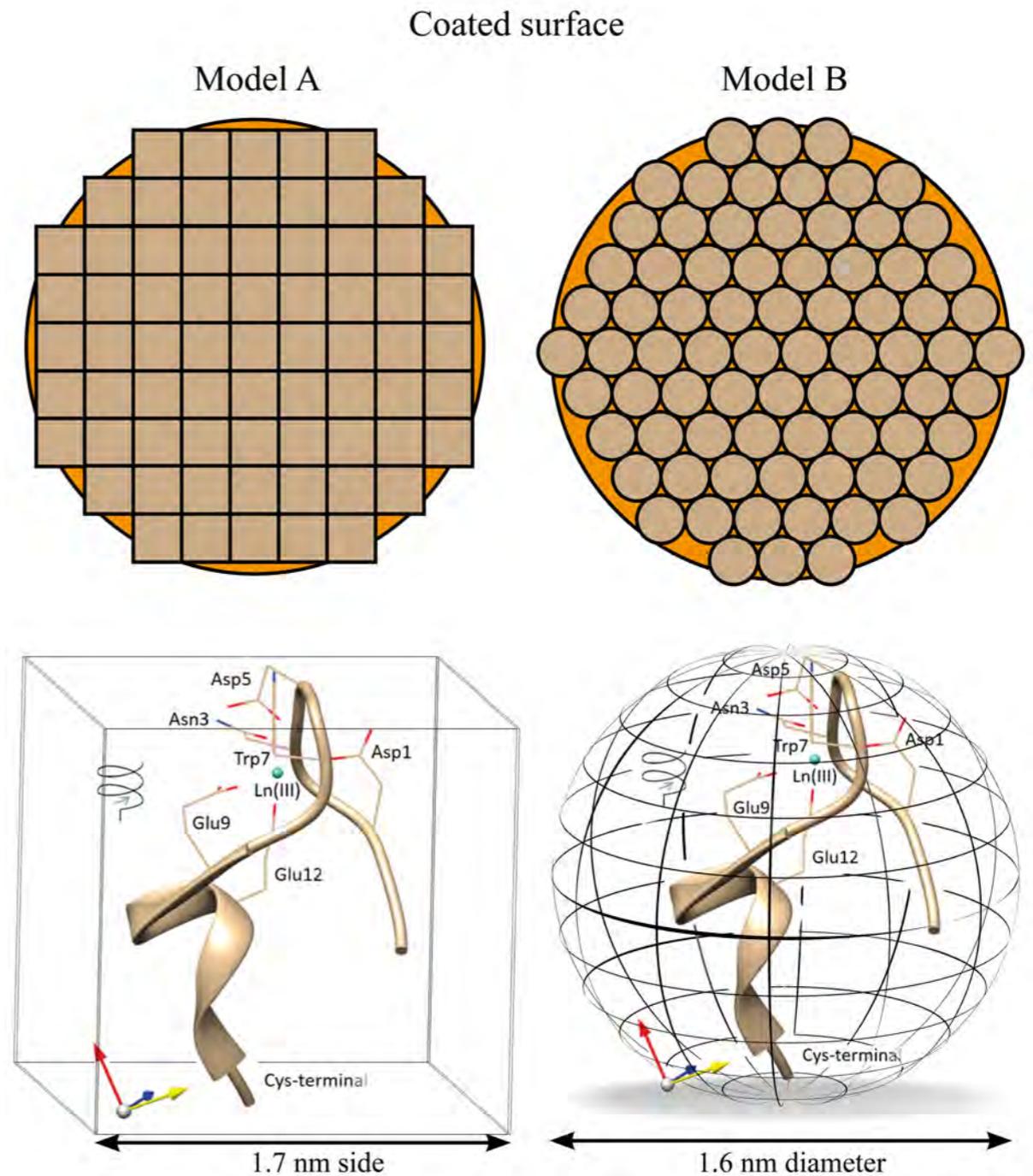


# SAMs ASSEMBLY

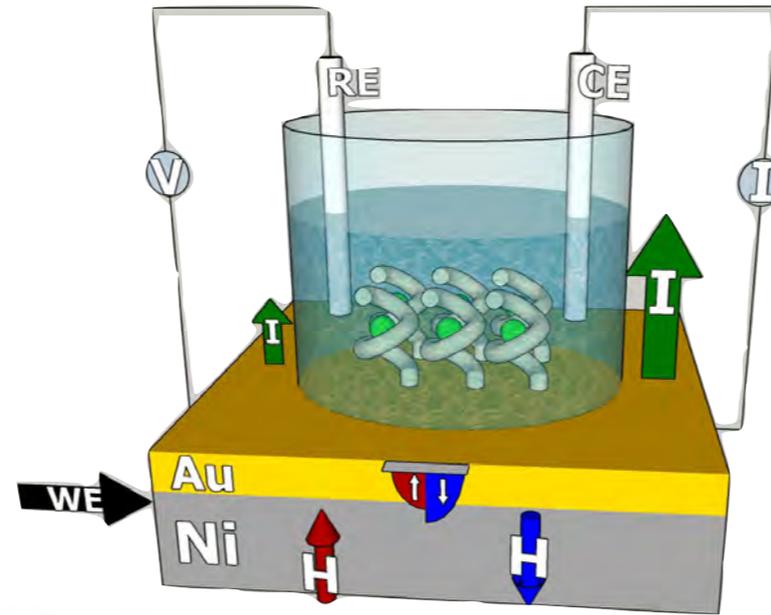
Coverage > 90%



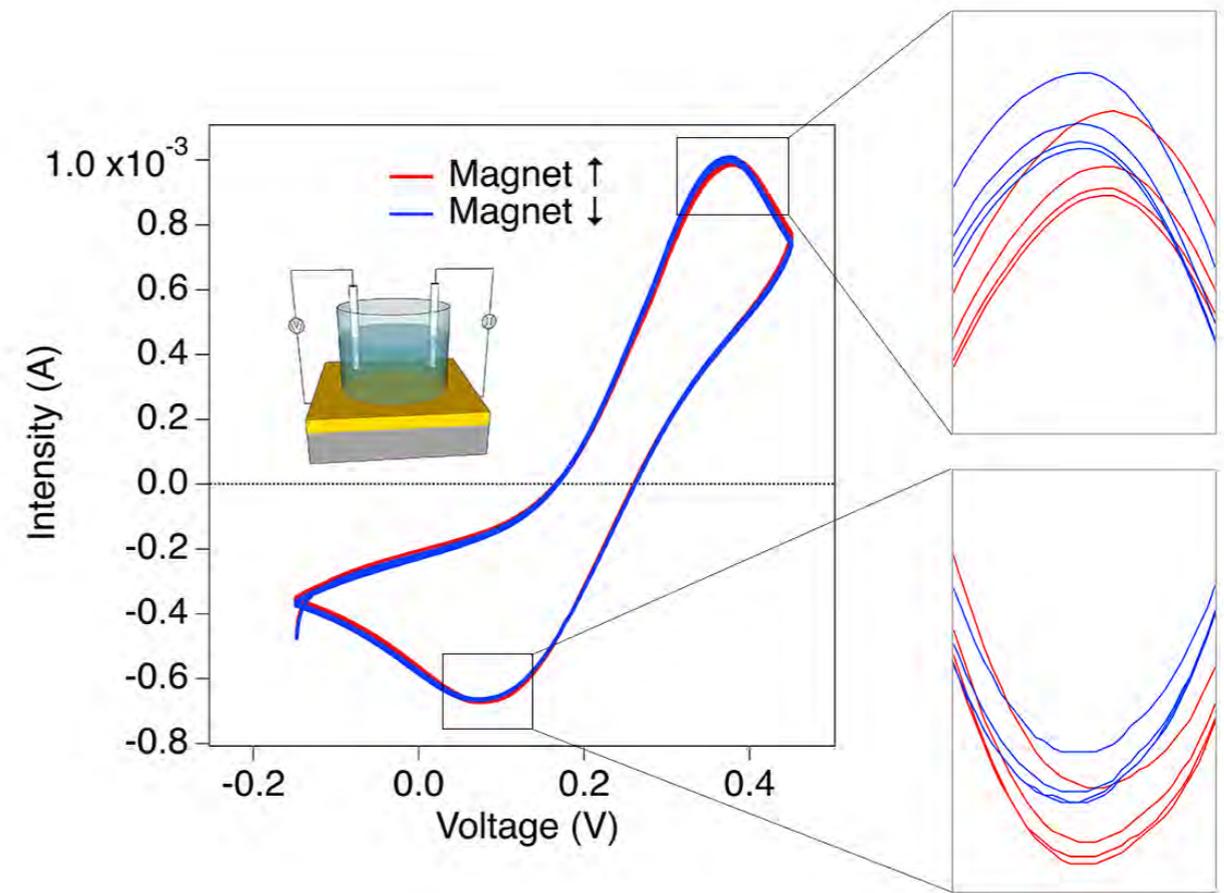
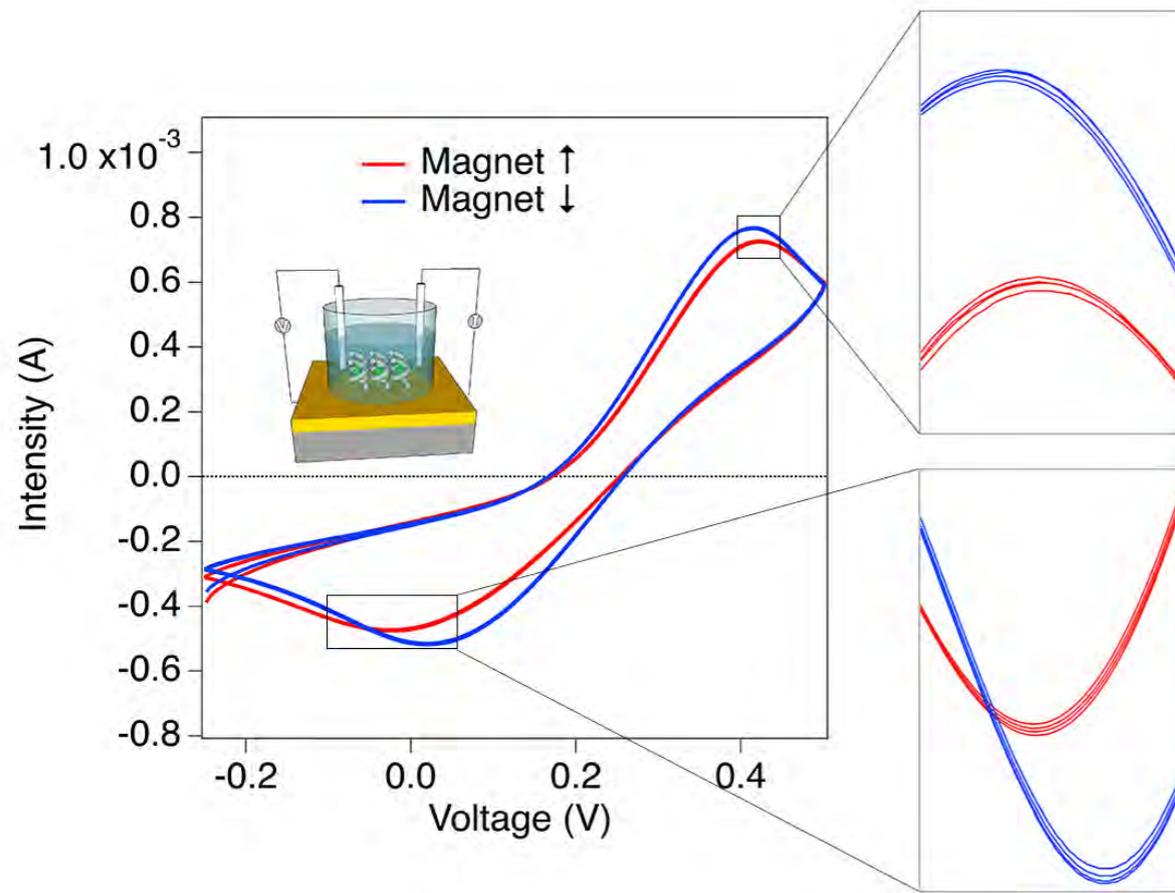
(a-d) Atomic force microscopy images of a Ni@Au surfaces incubated overnight in buffer solution



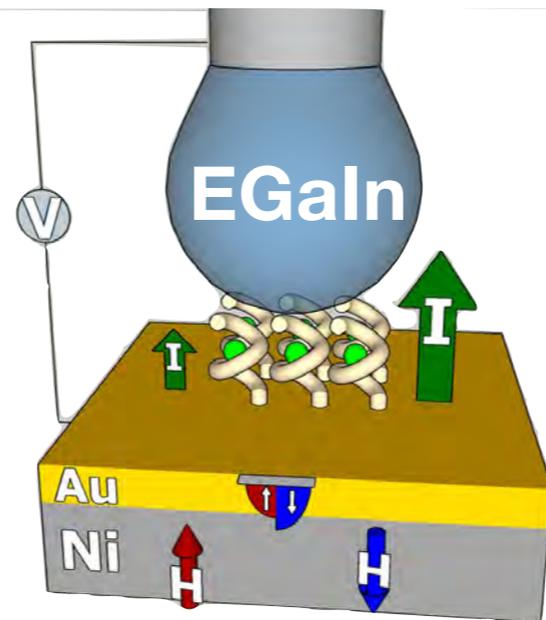
# ELECTROCHEMISTRY



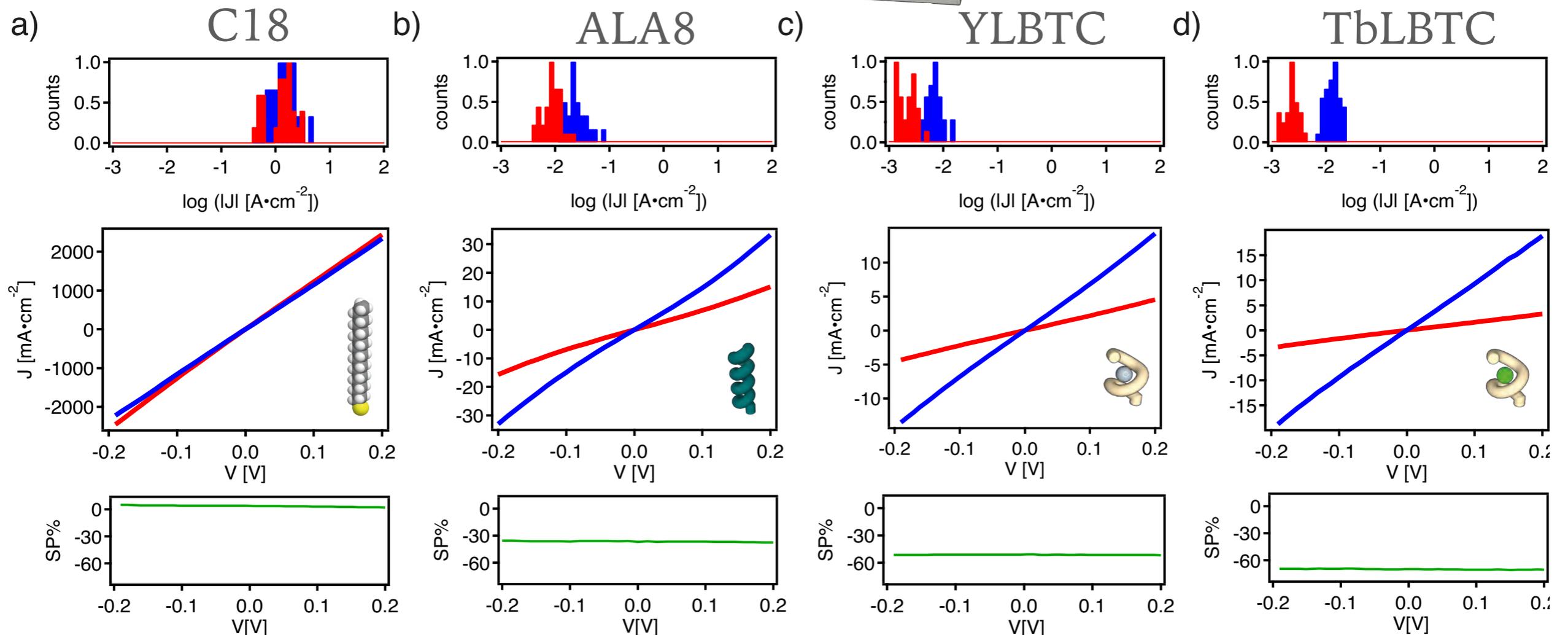
Obtained Spin Polarization  
(TbLBTC)SP  $\sim 5\%$



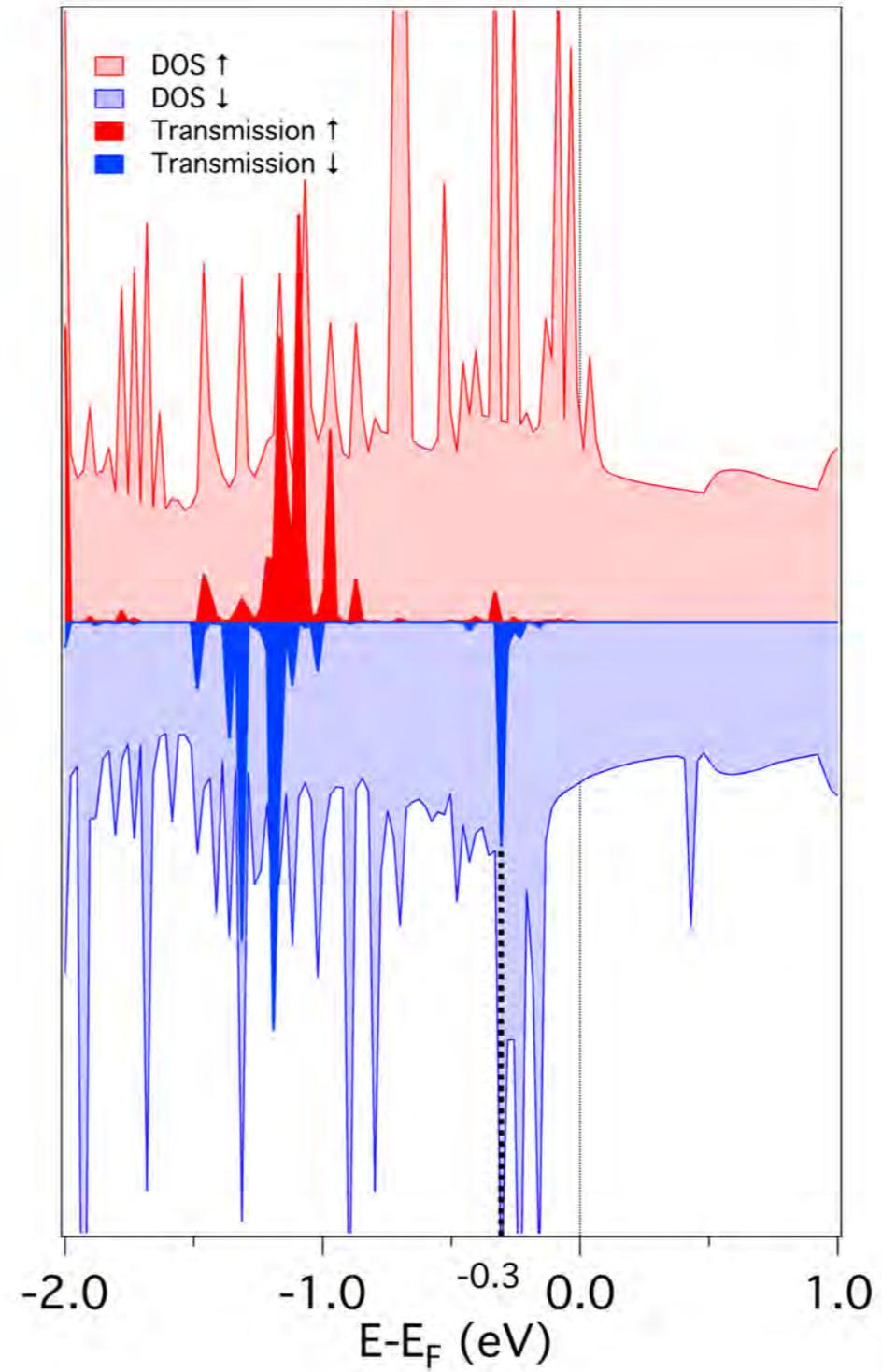
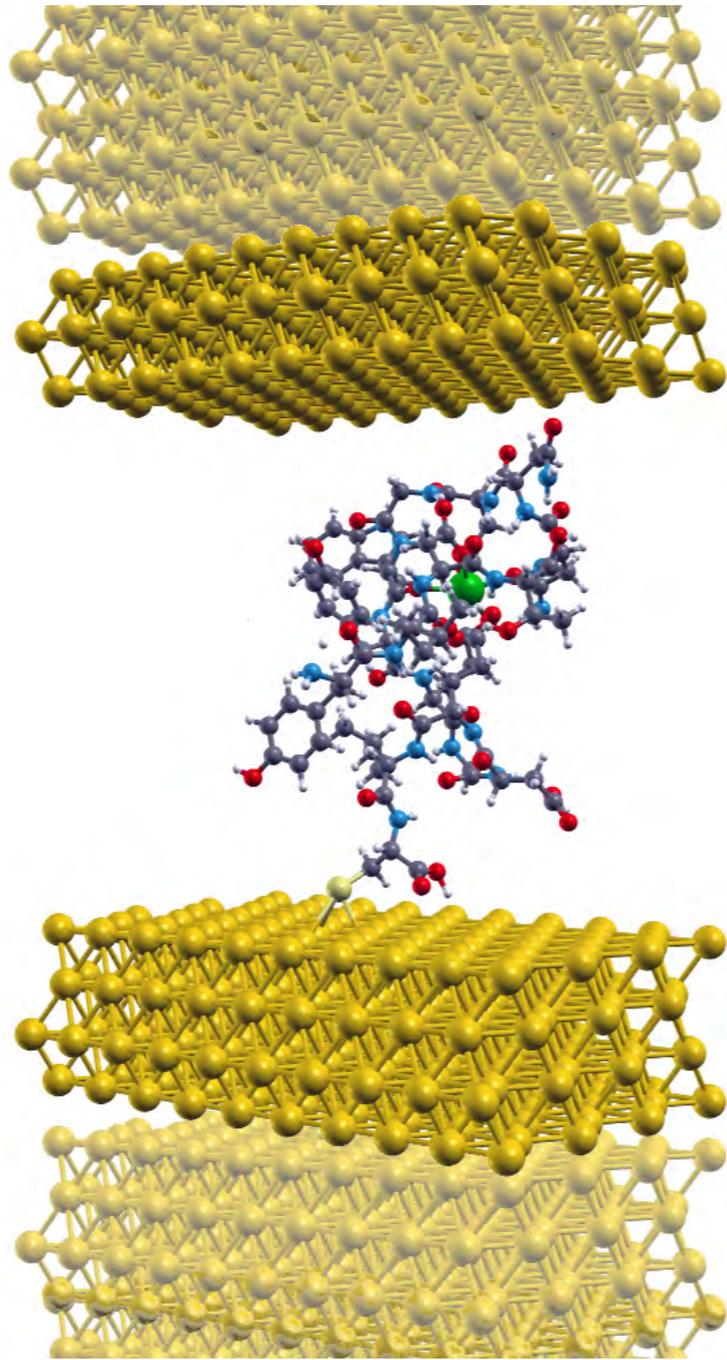
# EGaIN SPIN POLARIZATION



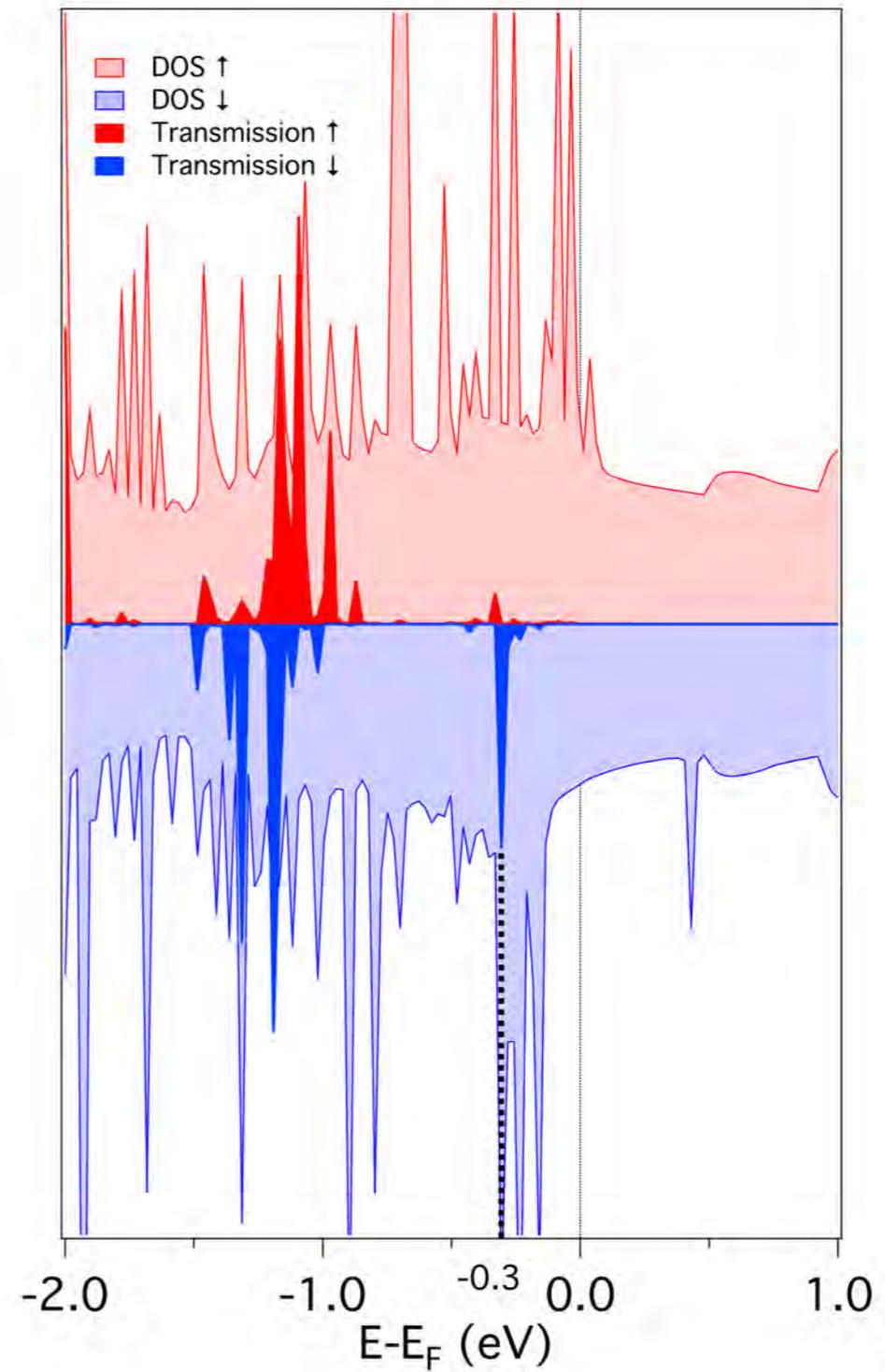
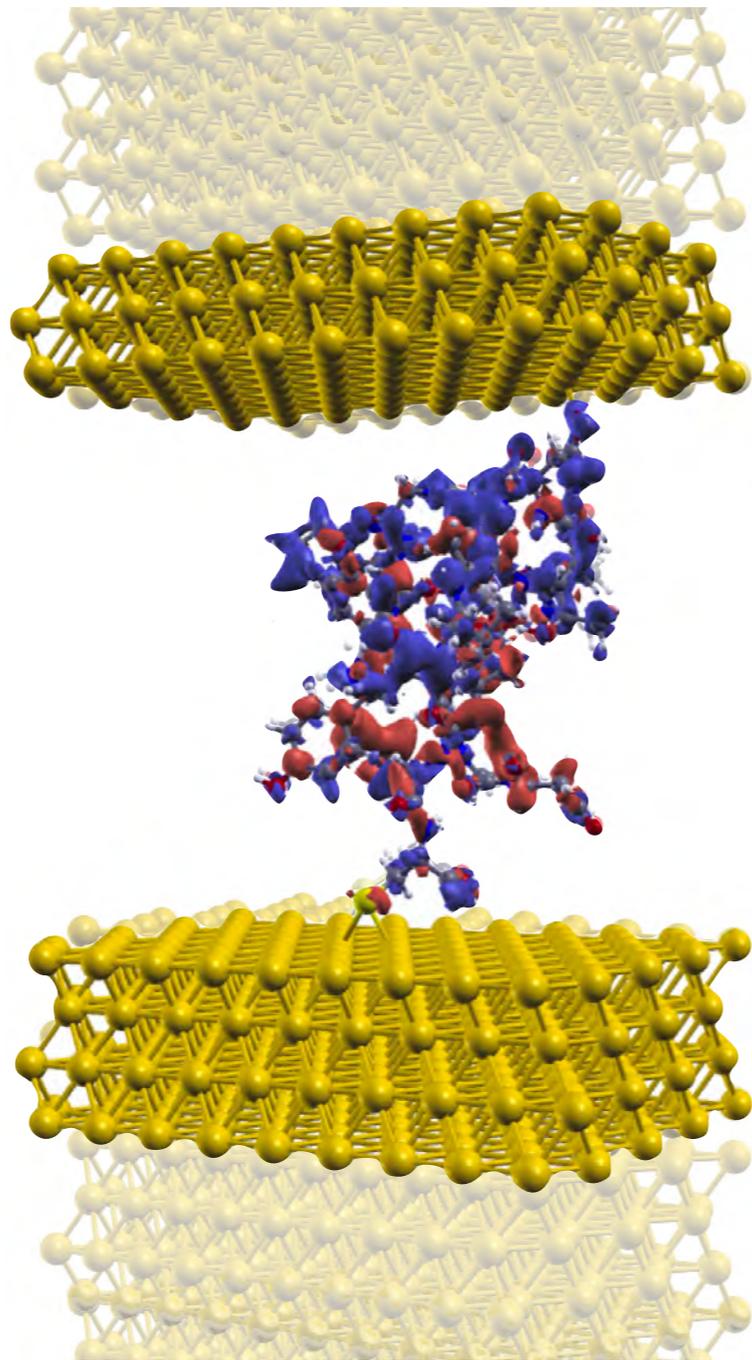
Obtained Spin Polarization  
(TbLBTC)SP  $\sim 70\%$



# TRANSPORT PROPERTIES

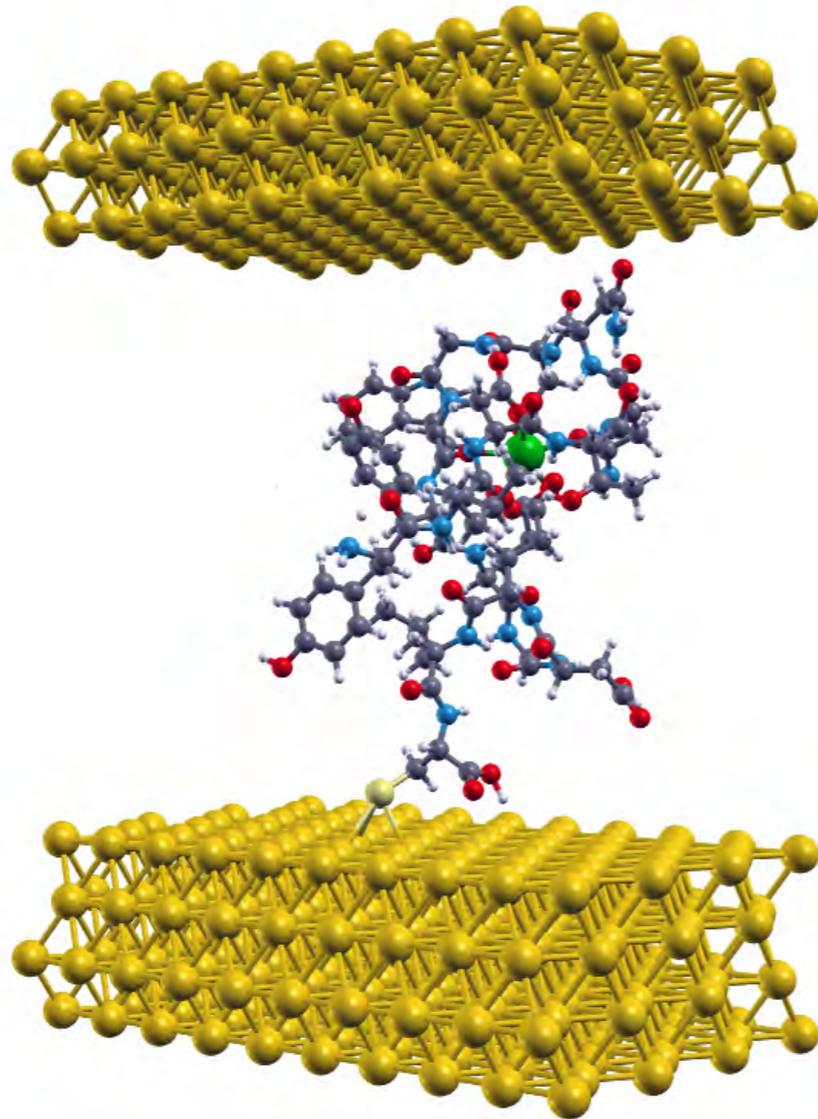


# TRANSPORT PROPERTIES

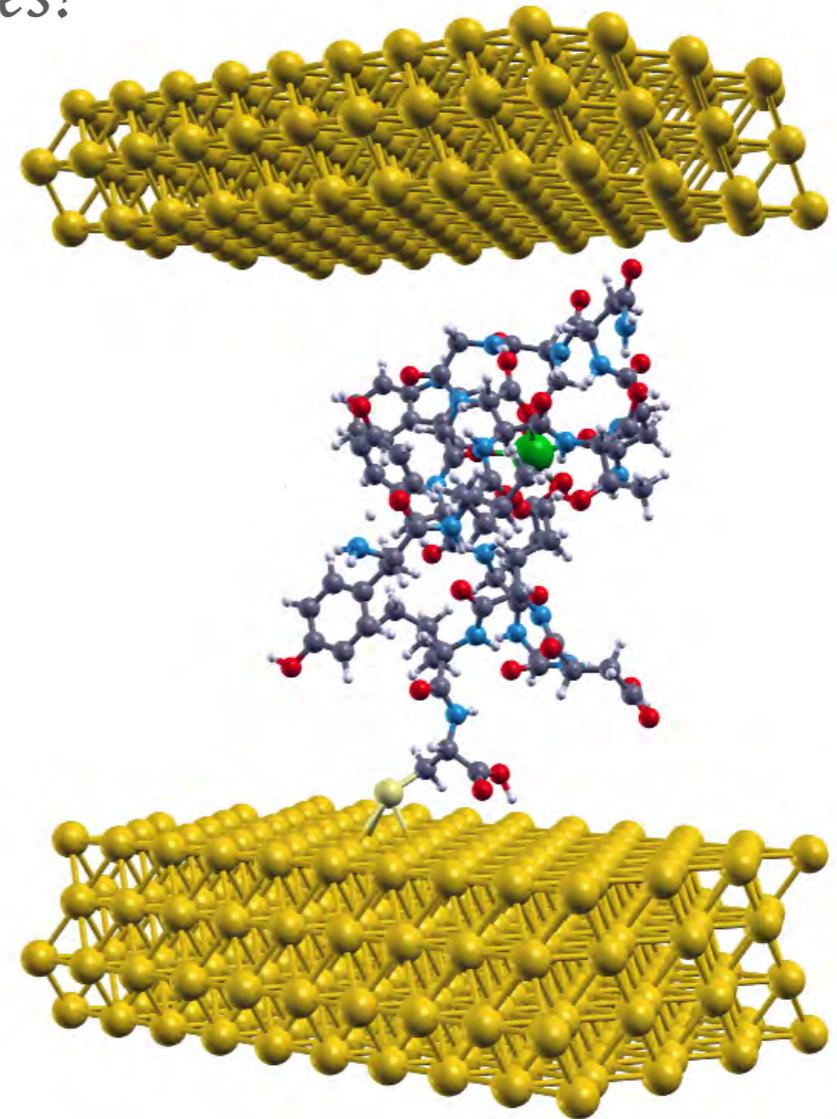


# CAN THIS BE RELATED WITH MEMRISTIVE BEHAVIOR?

*Think about time scales!*



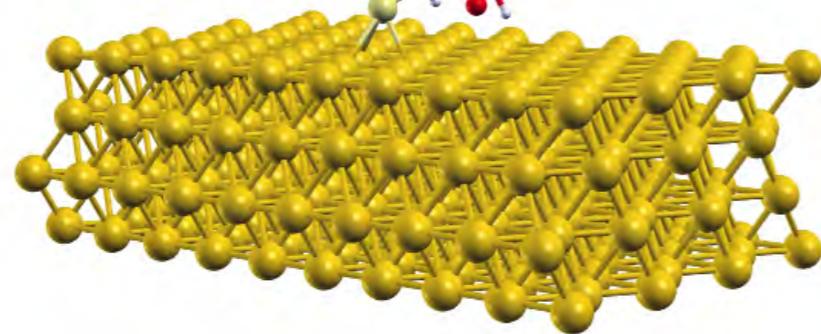
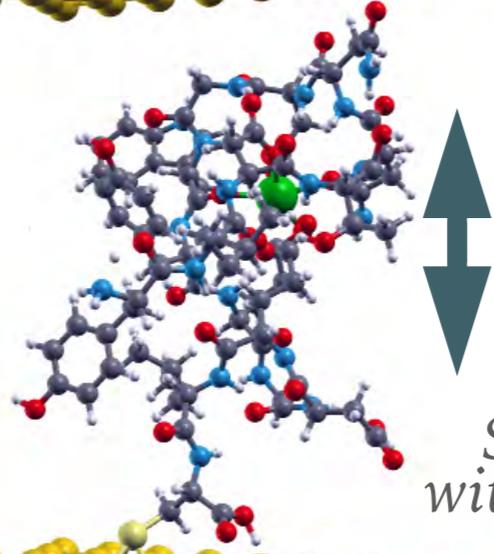
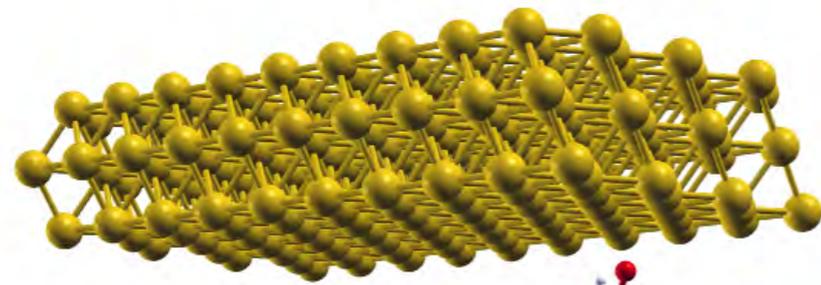
Slow pulsed  
measurements



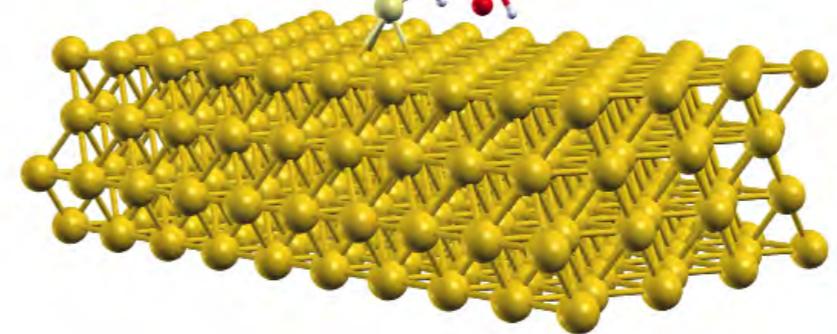
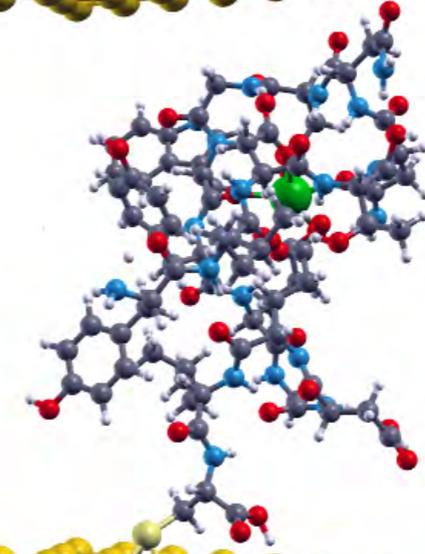
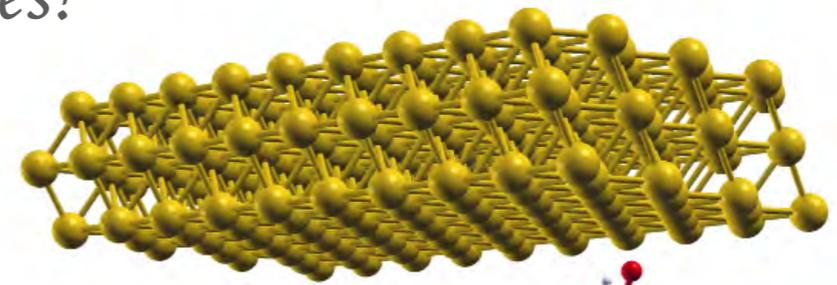
Fast pulsed  
measurements

# CAN THIS BE RELATED WITH MEMRISTIVE BEHAVIOR?

*Think about time scales!*



Slow pulsed  
measurements

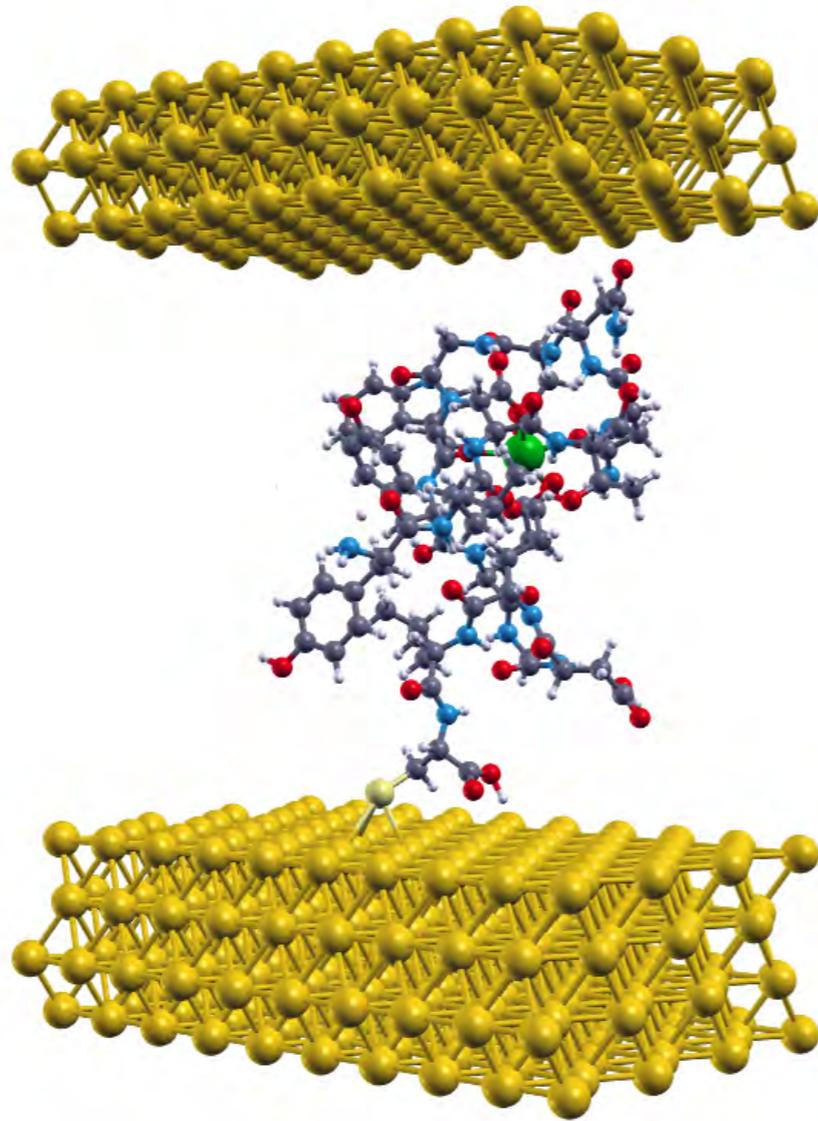


Fast pulsed  
measurements

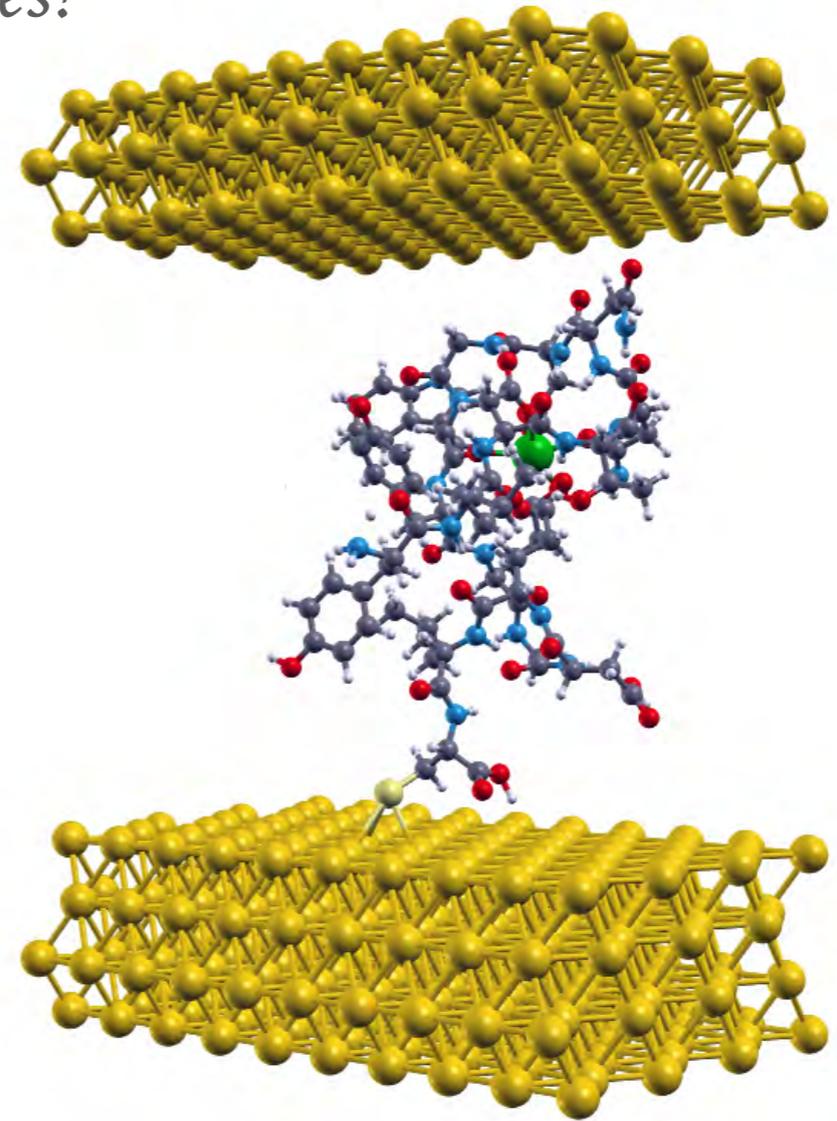
*Spin is oriented by current  
with time enough to follow AC*

# CAN THIS BE RELATED WITH MEMRISTIVE BEHAVIOR?

*Think about time scales!*



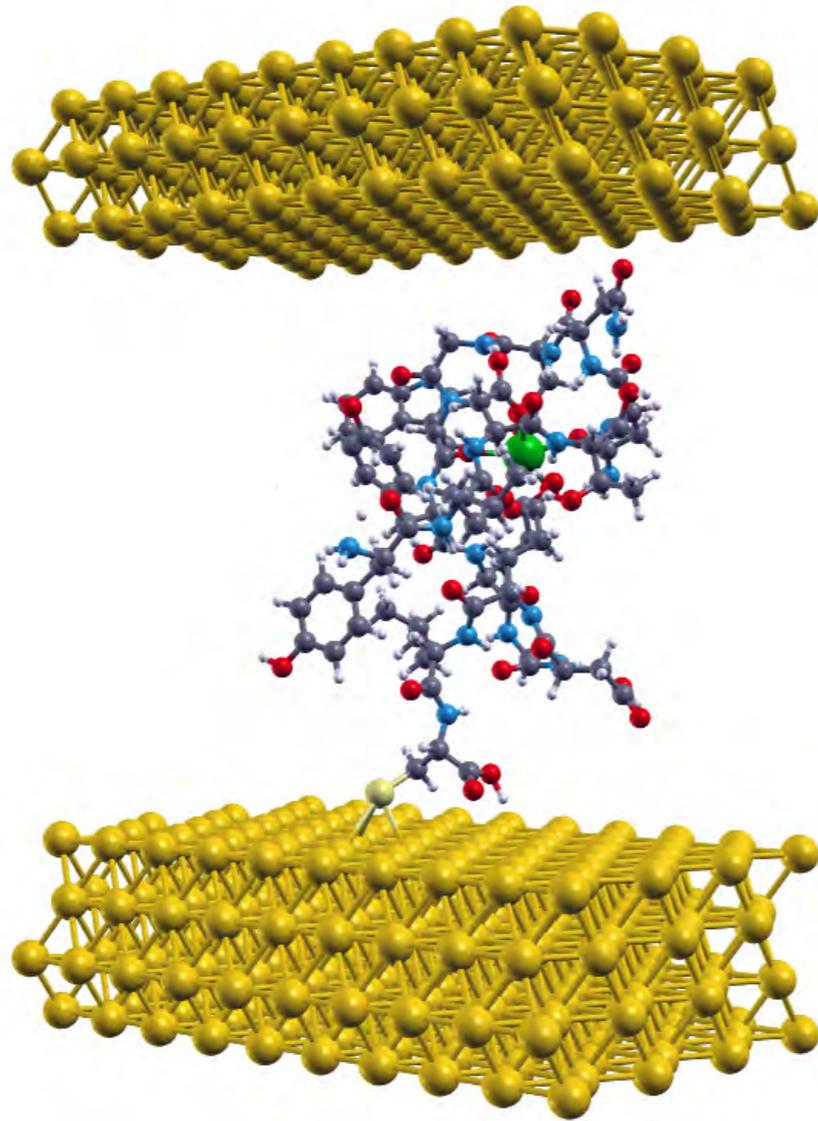
Slow pulsed  
measurements



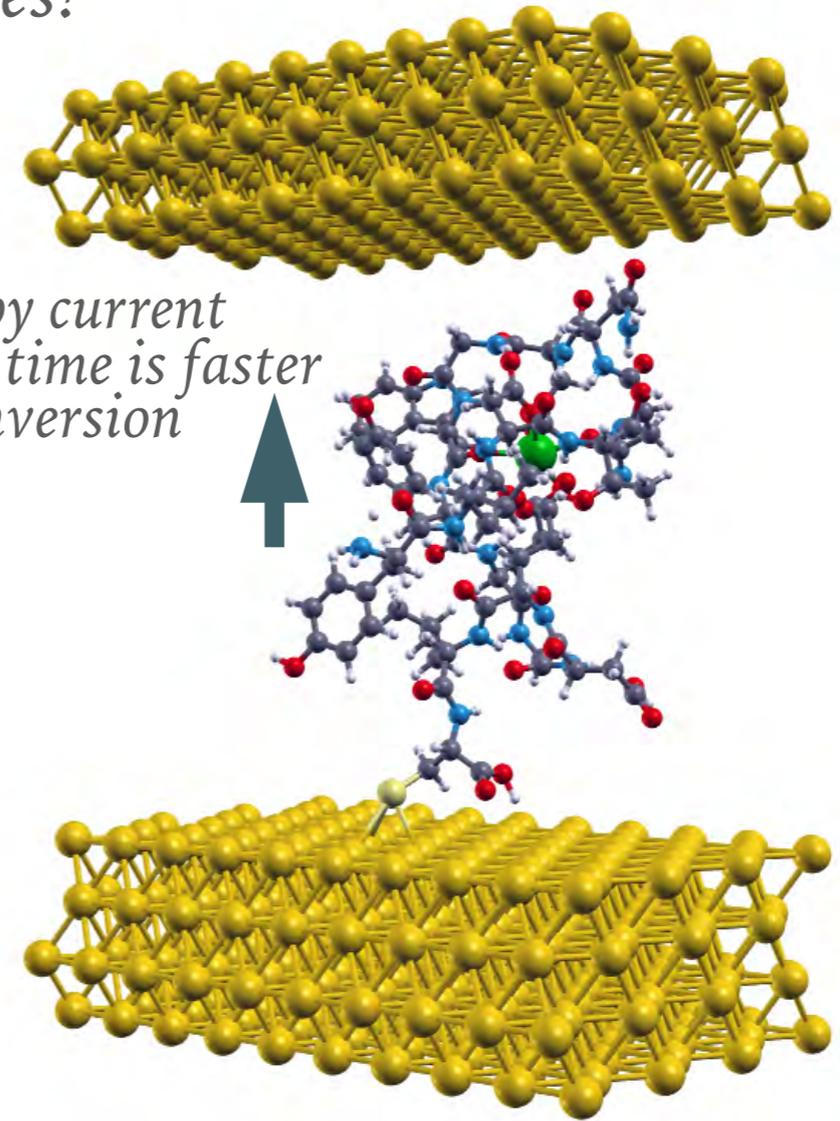
Fast pulsed  
measurements

# CAN THIS BE RELATED WITH MEMRISTIVE BEHAVIOR?

*Think about time scales!*



Slow pulsed  
measurements

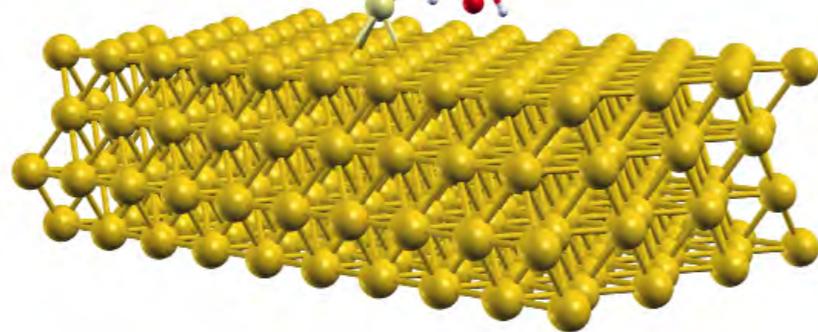
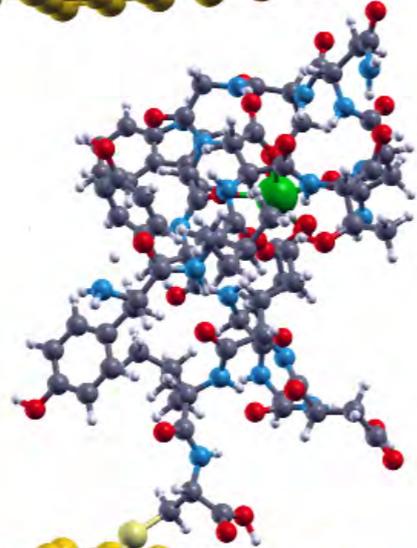
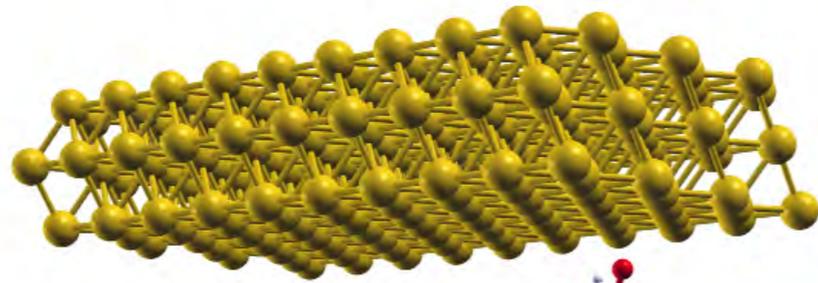


Fast pulsed  
measurements

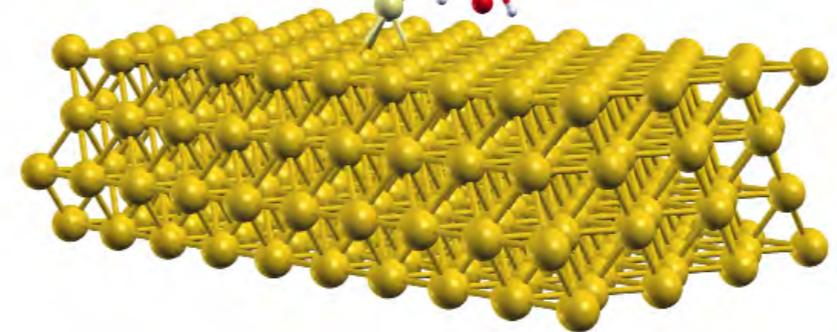
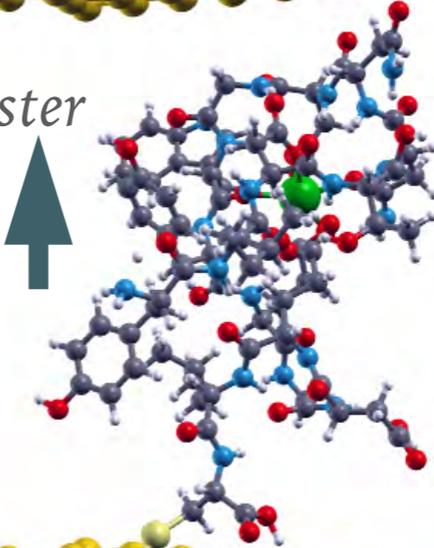
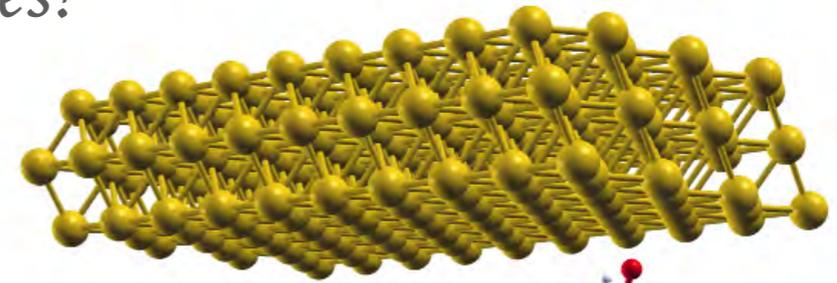
*Spin is oriented by current  
but the measurement time is faster  
than the spin inversion*

# CAN THIS BE RELATED WITH MEMRISTIVE BEHAVIOR?

*Think about time scales!*



Slow pulsed  
measurements



Fast pulsed  
measurements

*Spin is oriented by current  
but the measurement time is faster  
than the spin inversion*

*Intensity would depend  
on previous voltage history*



# TAKE HOME MESSAGE

Spin-dependent transport calculations confirmed an **interaction** between the magnetic polarizations of the **current** and the **lanthanide** ion.

Since the sign of the magnetic polarization affects the total resistance, the **conductance** of the device effectively **depends on the applied voltage history**.

Next step: Performing elaborate measurements to **confirm memristive behavior** in our Ln-biomolecule.

# ACKNOWLEDGEMENTS

*Eugenio Coronado*

*Alejandro Gaita-Ariño*

*Alicia Forment-Aliaga*

*Silvia Giménez-Santamarina*

*Lorena E. Rosaleny*

