A platform for Artificial Intelligence: neuromorphic silicon photonics

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Nanoscience Laboratory

http://nanolab.physics.unitn.it/

Advanced nanomaterials for energy, environment and life

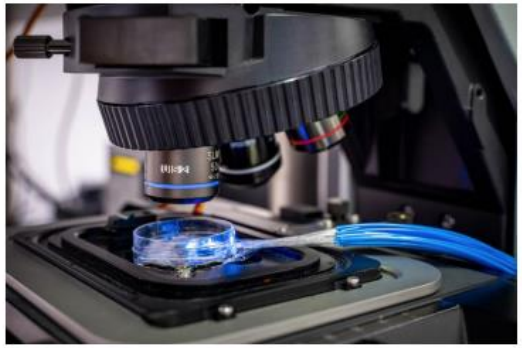
Silicon Photonics: - Quantum Photonics

- Non-Hermitian Photonics
- Neuromorphic Photonics

http://nanolab.physics.unitn.it

UNIVERSITÀ DI TRENTO Dipartimento di Fisica

NANOSCIENCE LABORATORY HIGHLIGHTS 2022



http://nanolab.physics.unitn.it/images/2023/HL_NL-2022.pdf

frontiers in Physics

REVIEW
published: 06 December 2021
doi: 10.3389/fphy.2021.786028

Thirty Years in Silicon Photonics: A Personal View

*Lorenzo Pavesi**

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Silicon Photonics, the technology where optical devices are fabricated by the mainstream microelectronic processing technology, was proposed almost 30 years ago. I joined this research field at its start. Initially, I concentrated on the main issue of the lack of a silicon laser. Room temperature visible emission from porous silicon first, and from silicon nanocrystals then, showed that optical gain is possible in low-dimensional silicon, but it is severely counterbalanced by nonlinear losses due to free carriers. Then, most of my research focus was on systems where photons show novel features such as Zener

https://www.frontiersin.org/articles/10.3389/fphy.2021.786028/full

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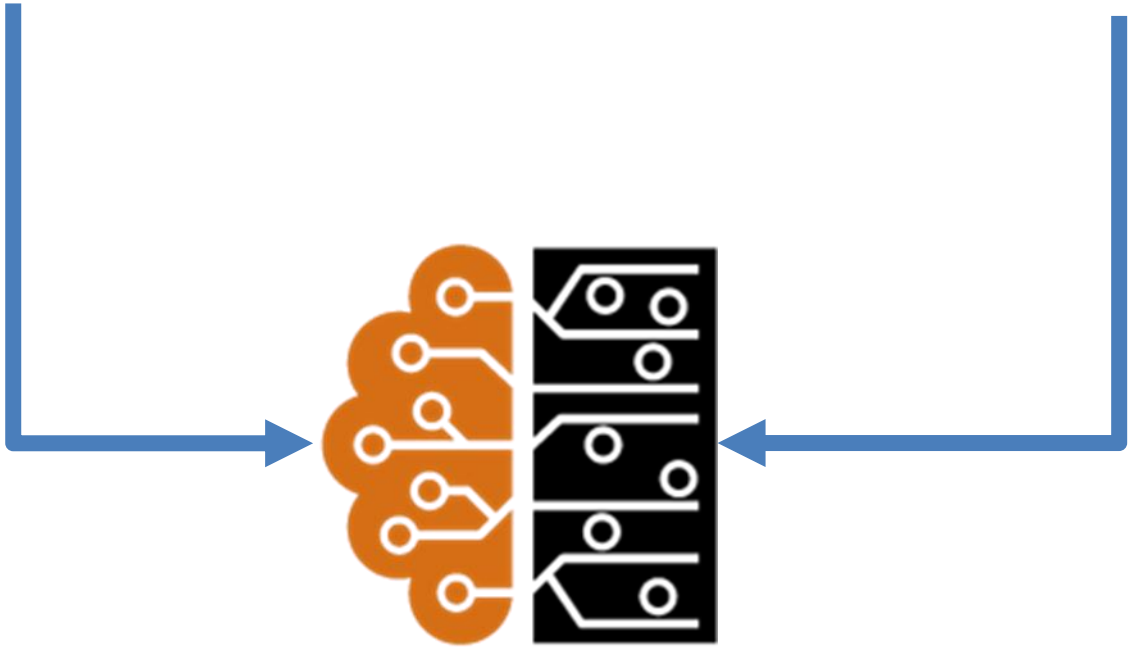
The vision

BIOLOGICAL COLTURE

PHOTONIC INTEGRATED CIRCUIT



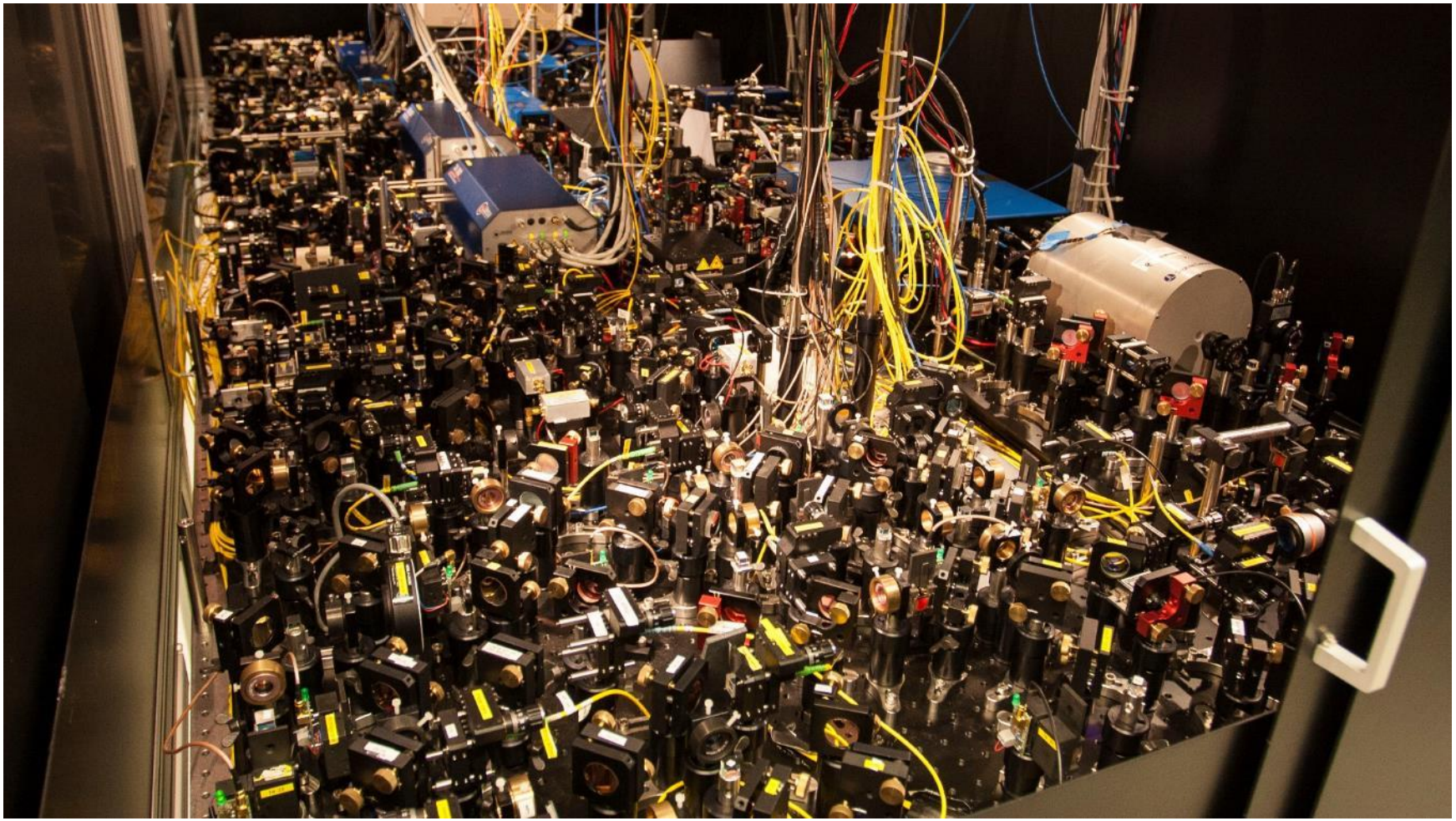
HYBRID ARTIFICIAL-BIOLOGICAL NETWORK

The vision

PHOTONIC INTEGRATED CIRCUIT

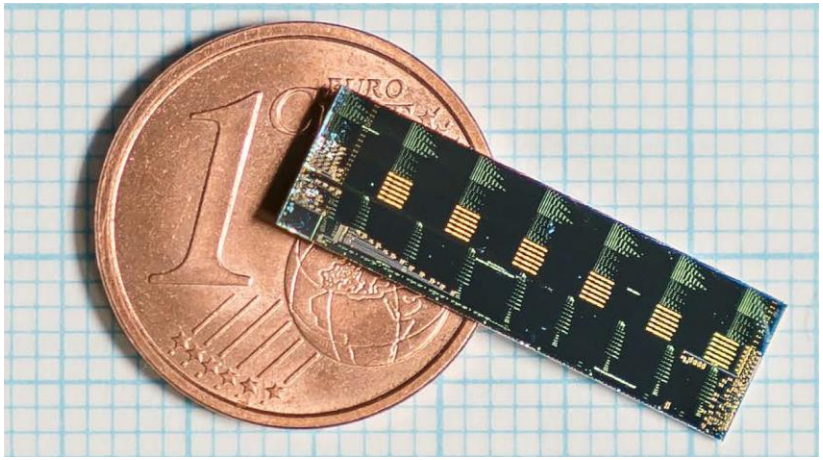
SILICON PHOTONICS

Integrated photonics



Integrated photonics

Photonic Integrated Circuit



Widespread diffusion

- Lower dimensions
- Lower costs
- CMOS compatible

- More stable
- Lower noise
- Lower losses

Efficient devices

THE VISION

PHOTONIC INTEGRATED CIRCUIT

NEUROMORPHIC PHOTONICS

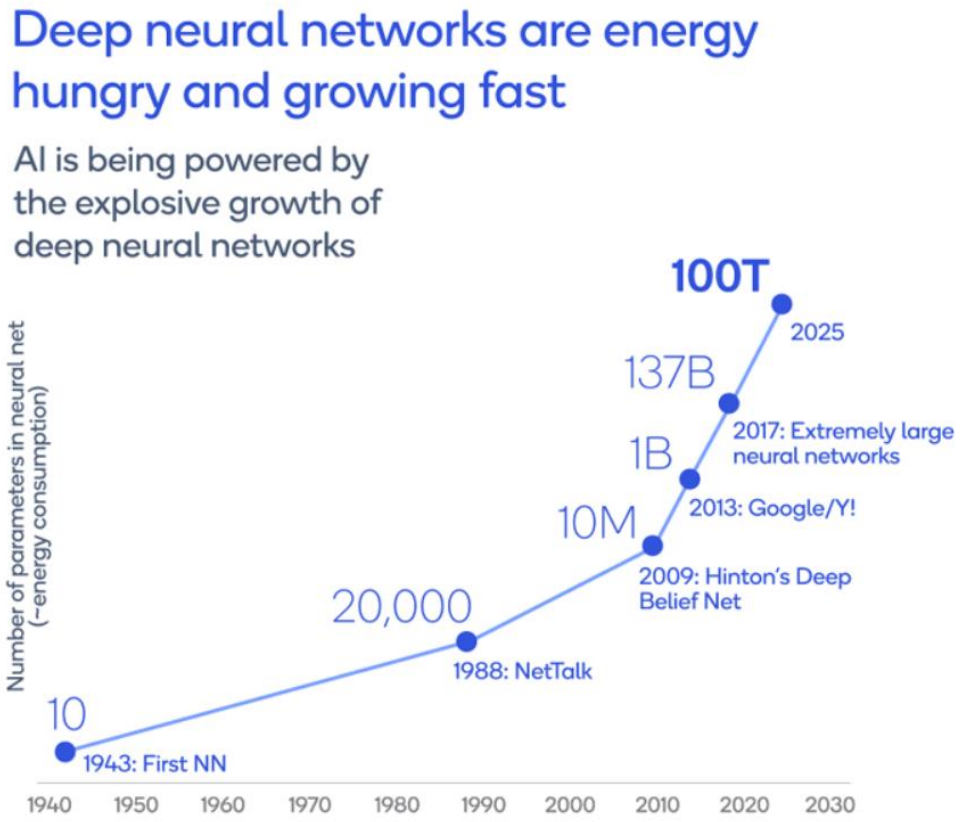
Artificial Neural Networks

Image from https://syncedreview.com/2017/04/08/the-future-of-computing-neuromorphic/

Platform for AI

Amazon AI Google AI Azure AI IBM Watson

https://www.aavista.com/the-ultimate-ai-platform/

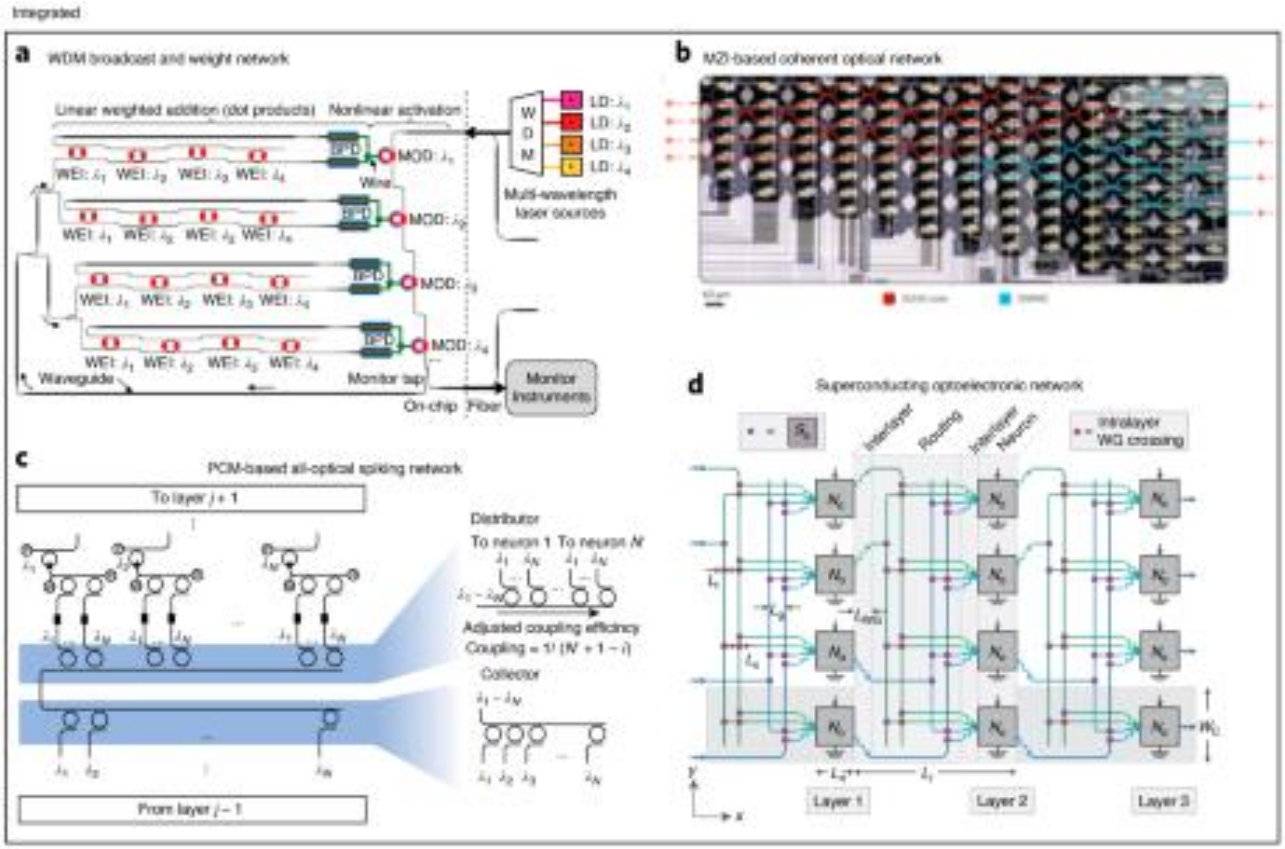


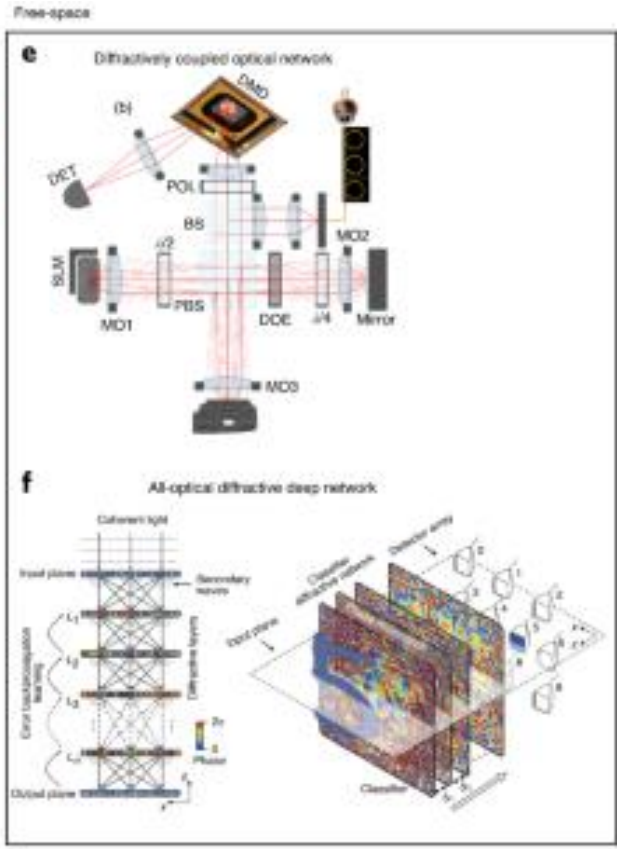
It has been estimated that training chatGPT consumed 1,287 MWh which emitted 552 tons CO_2e (175b parameters).
daily carbon footprint from running ChatGPT to be 23.04 $kgCO_2e$

https://towardsdatascience.com/the-carbon-footprint-of-chatgpt-66932314627d

Human brain
20 W x 20y x 365 d x 24 h =3.5 MWh

Photonics at the rescue





Photonics-based ANN

Light is fast!

Power efficient (no Joule effect)

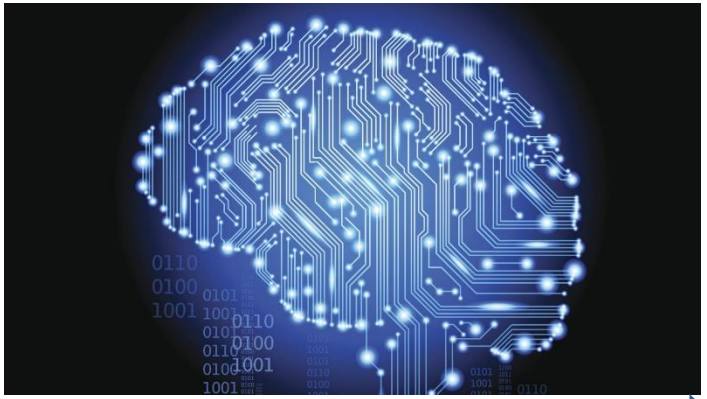
Parallelism (WDM)

Biological neuron timescale ms (10^{-3} s)

Optical neurons timescale ps (10^{-12} s)

Factor of 10^9!!

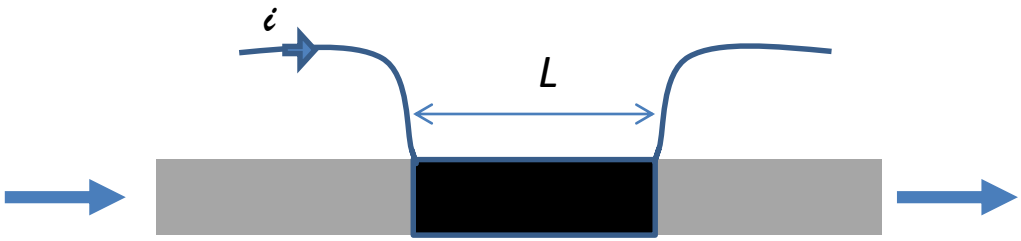
Brain learning process 20 years



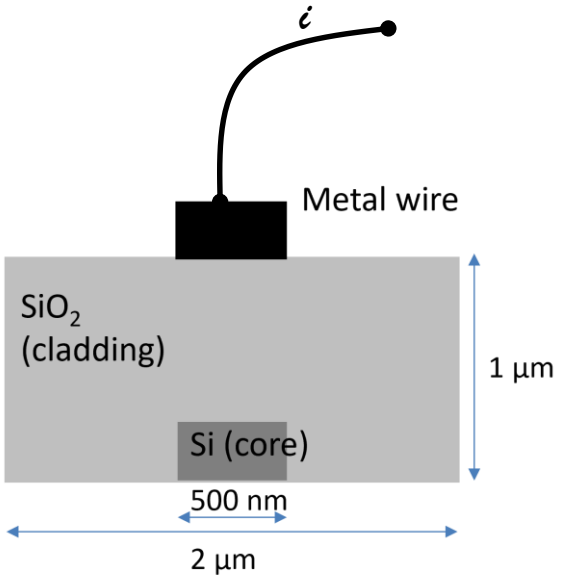
Artificial optical brain 0.5 seconds

The basic building blocks

Thermal phase shifter



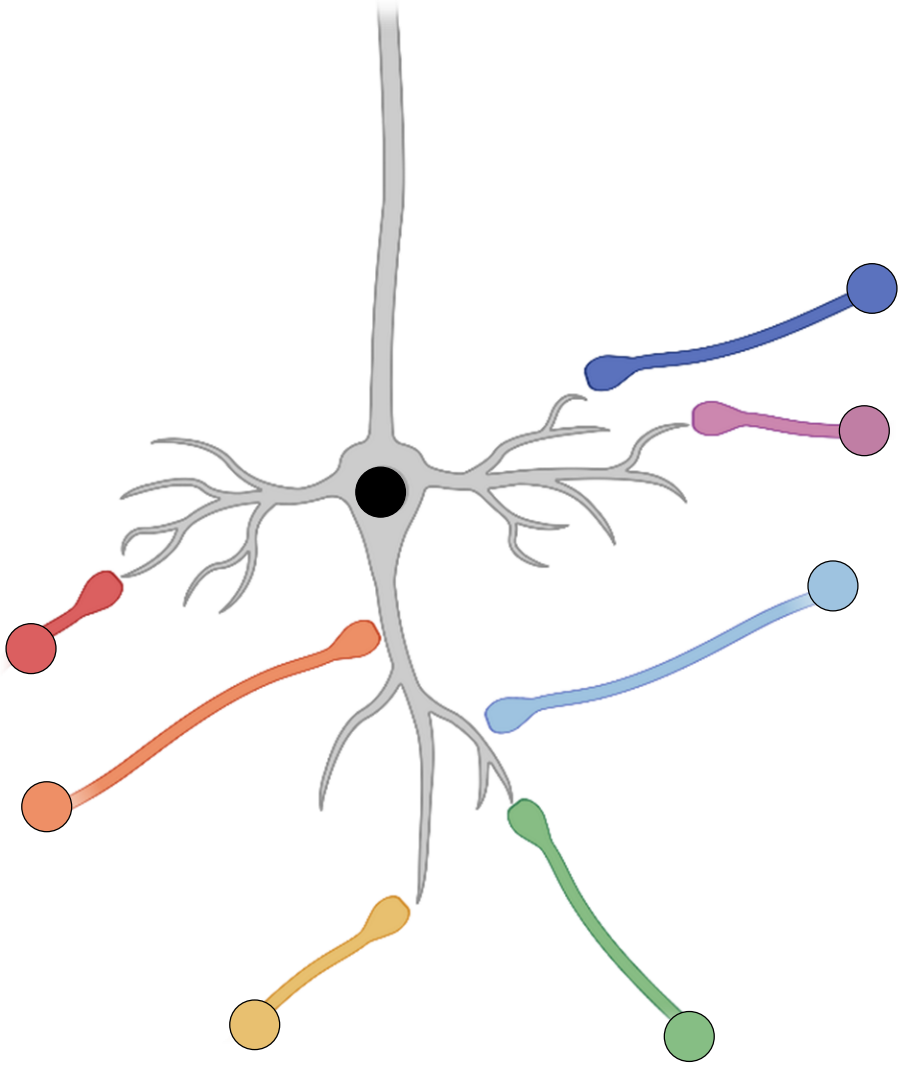
$$\left(e^{i\,\Delta\emptyset}\right)$$

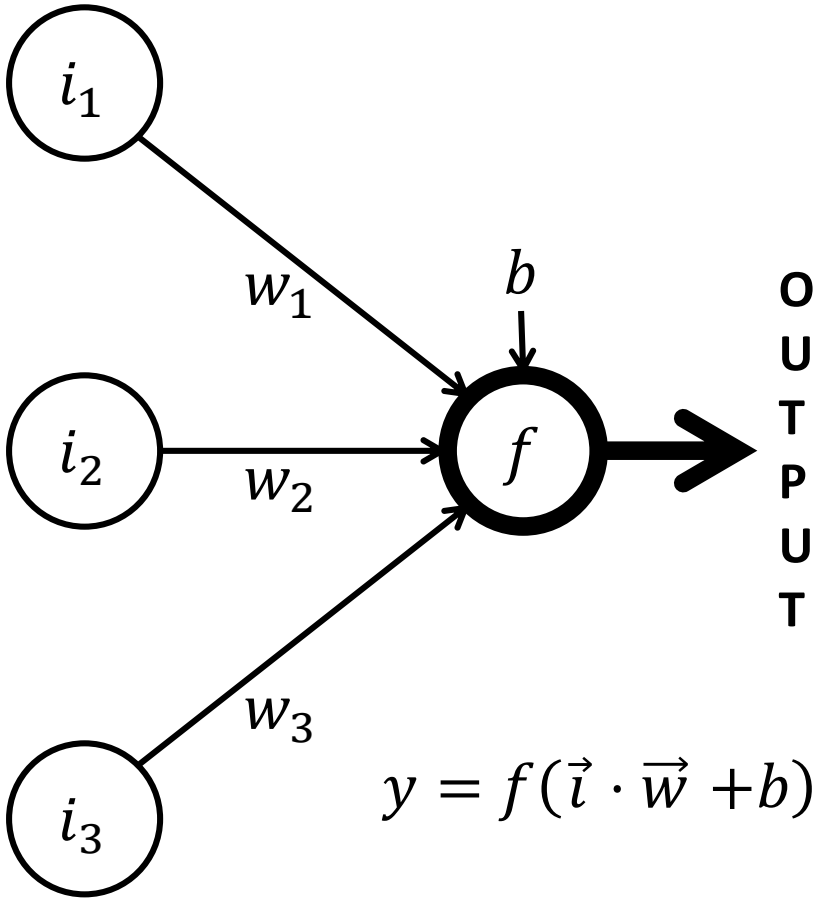


$$\Delta\emptyset = L\frac{2\pi}{\lambda}\frac{dn}{dT}dT$$

$$n = n_0 + \frac{dn}{dT}\Delta T$$

Let's start with one neuron: the perceptron





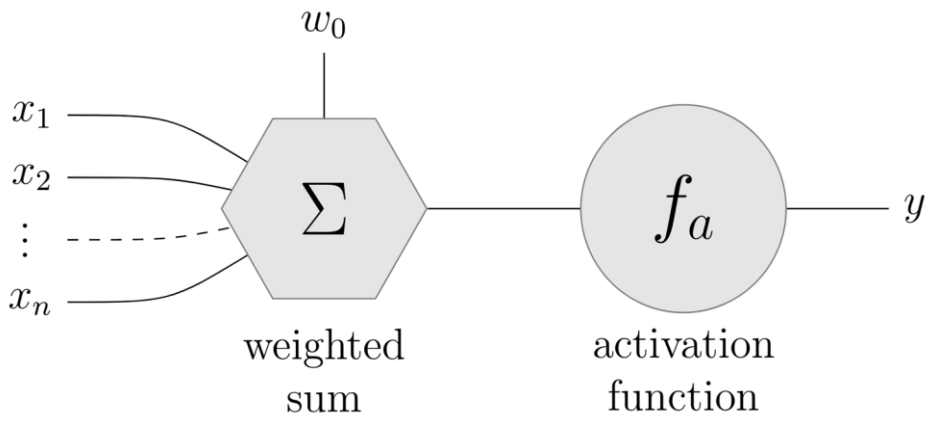
✓ Easily trained (ML)

✓ Can do classification tasks

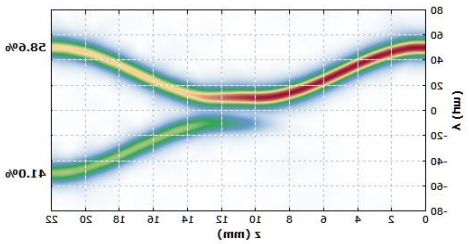
– It has no memory

McCulloch, W., Pitts, W., *Bulletin of Math. Biophys.* **5**:115-133 (1943).

Optical neuron



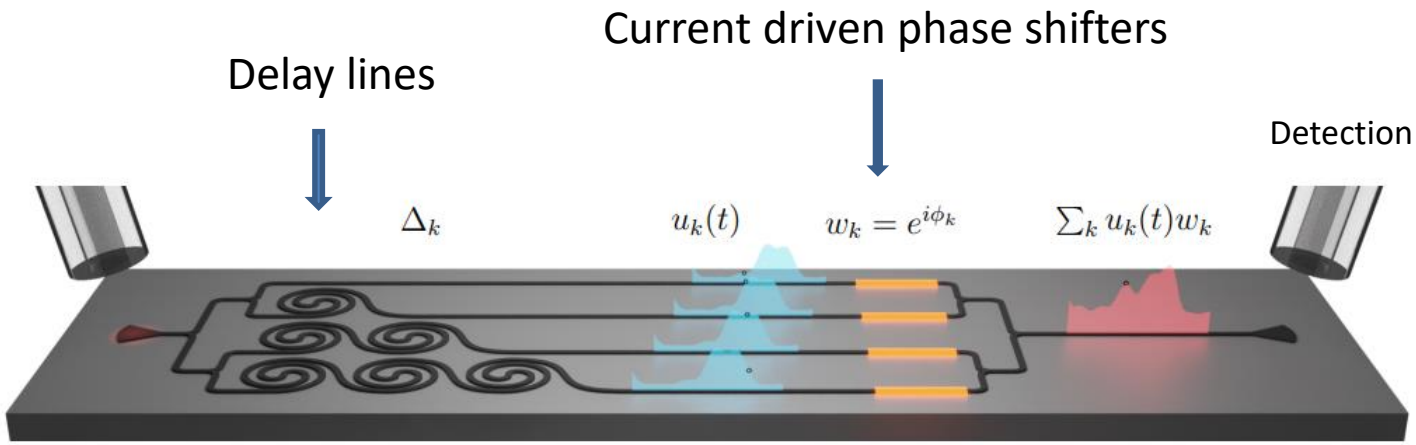
Optical coupler



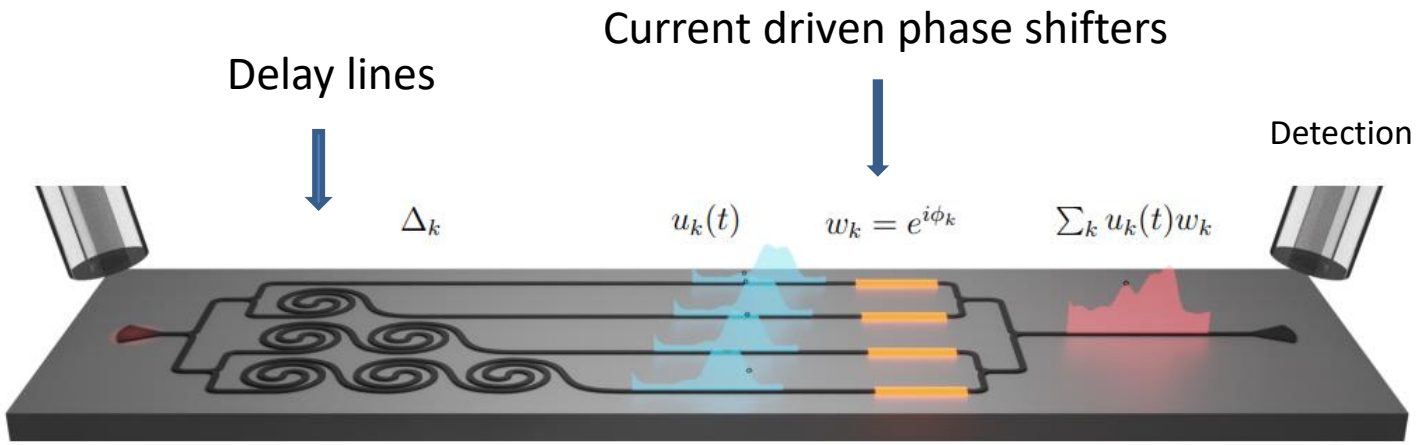
Photodetector

We sum fields, i.e. complex quantities

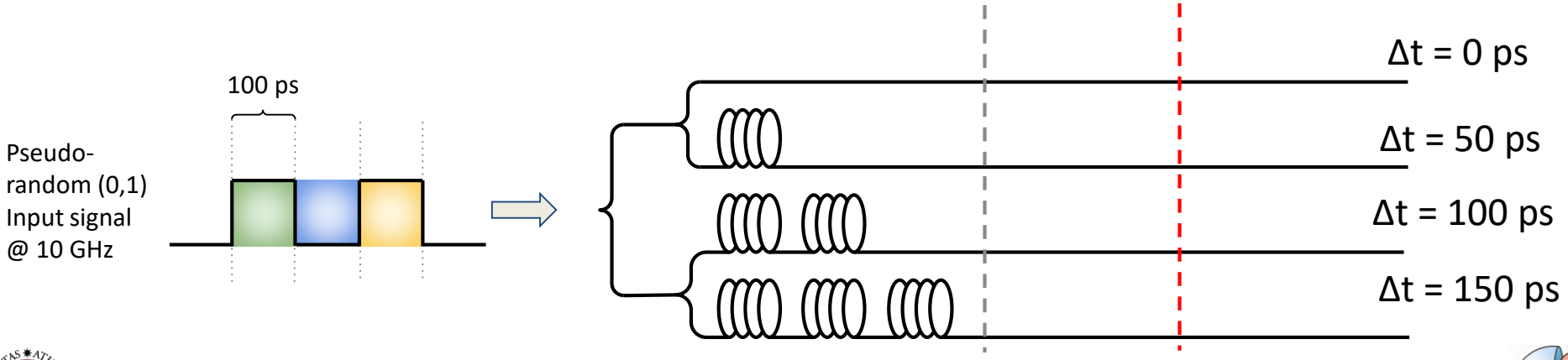
Delayed complex perceptron



Delayed complex perceptron

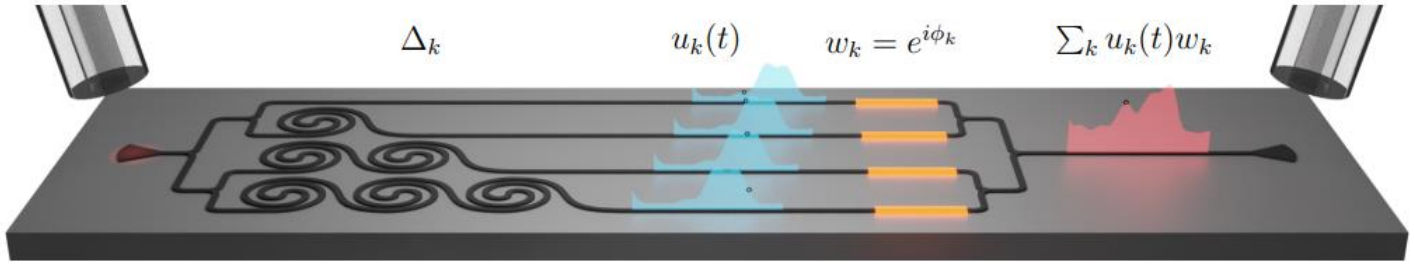


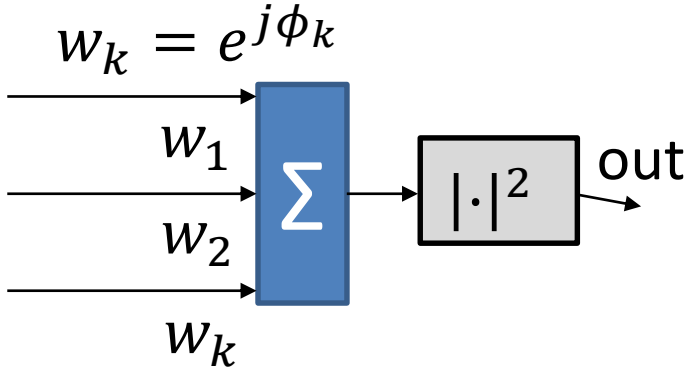
The role of the delay lines



Delayed complex perceptron

Current driven phase shifters

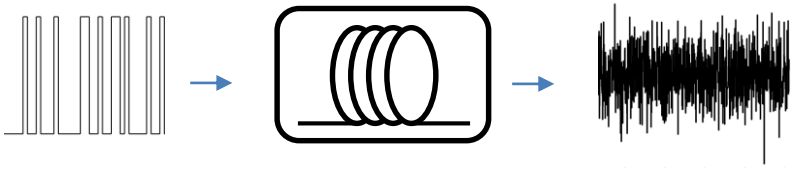




Δ_k=50 ps


2.5 mm
5.2 mm
1.4 mm
0.3 mm

Propagation-related distortions



Optical input | Fiber span | Distorted signal

Chromatic dispersion: frequency dependence of the refractive index $n(\omega)$

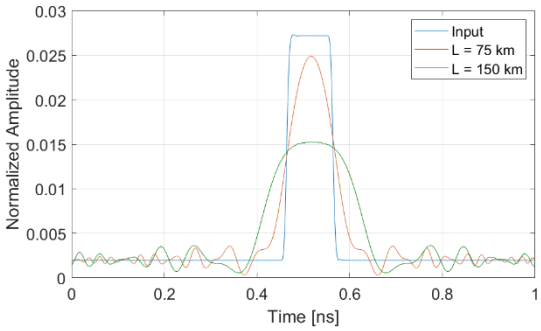
$n(\omega)$ induces $n_g(\omega)$ (group index)

$$n_g(\omega) = \frac{c}{v_g(\omega)}$$

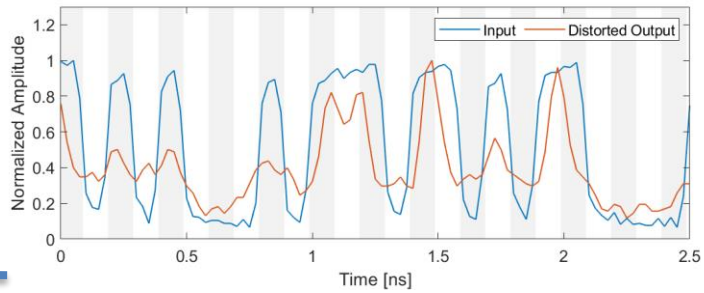
Pulse broadening:

$$\Delta T = \frac{dT}{d\omega}\Delta\omega = \frac{d}{d\omega}\left(\frac{L}{v_g}\right)\Delta\omega = L\beta_2\Delta\omega$$

Effect on single bit



Effect on a sequence of bits



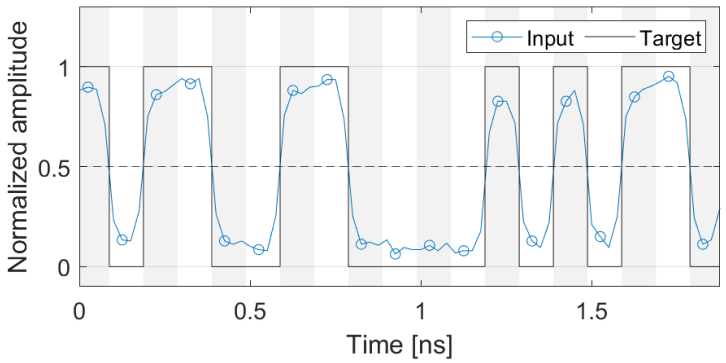
Intersymbol interference

ALPI signal recovery by photonic neural network
erc

Data processing

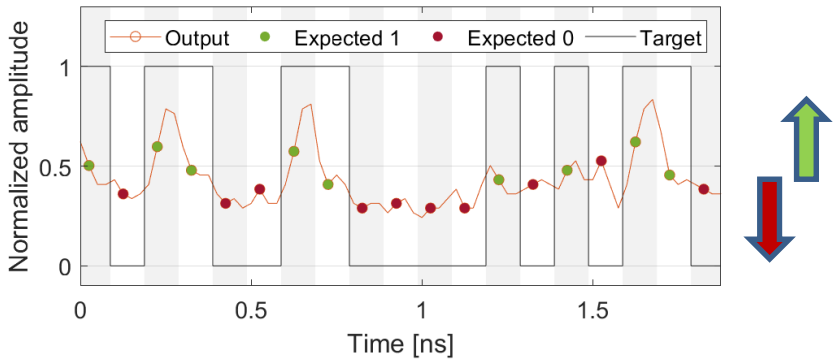
1)

Signal acquisition and target construction



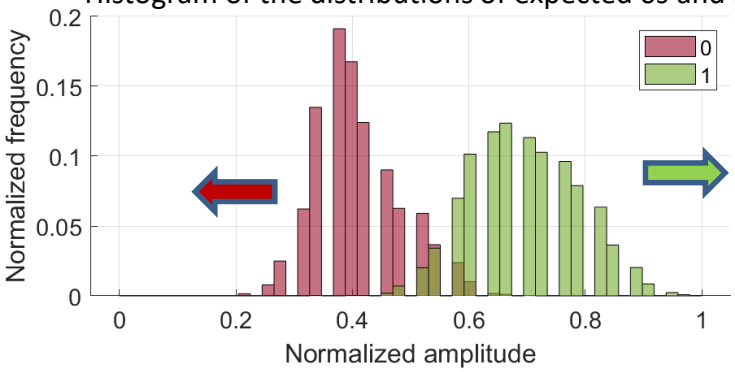
2)

Set expected values for each output bit

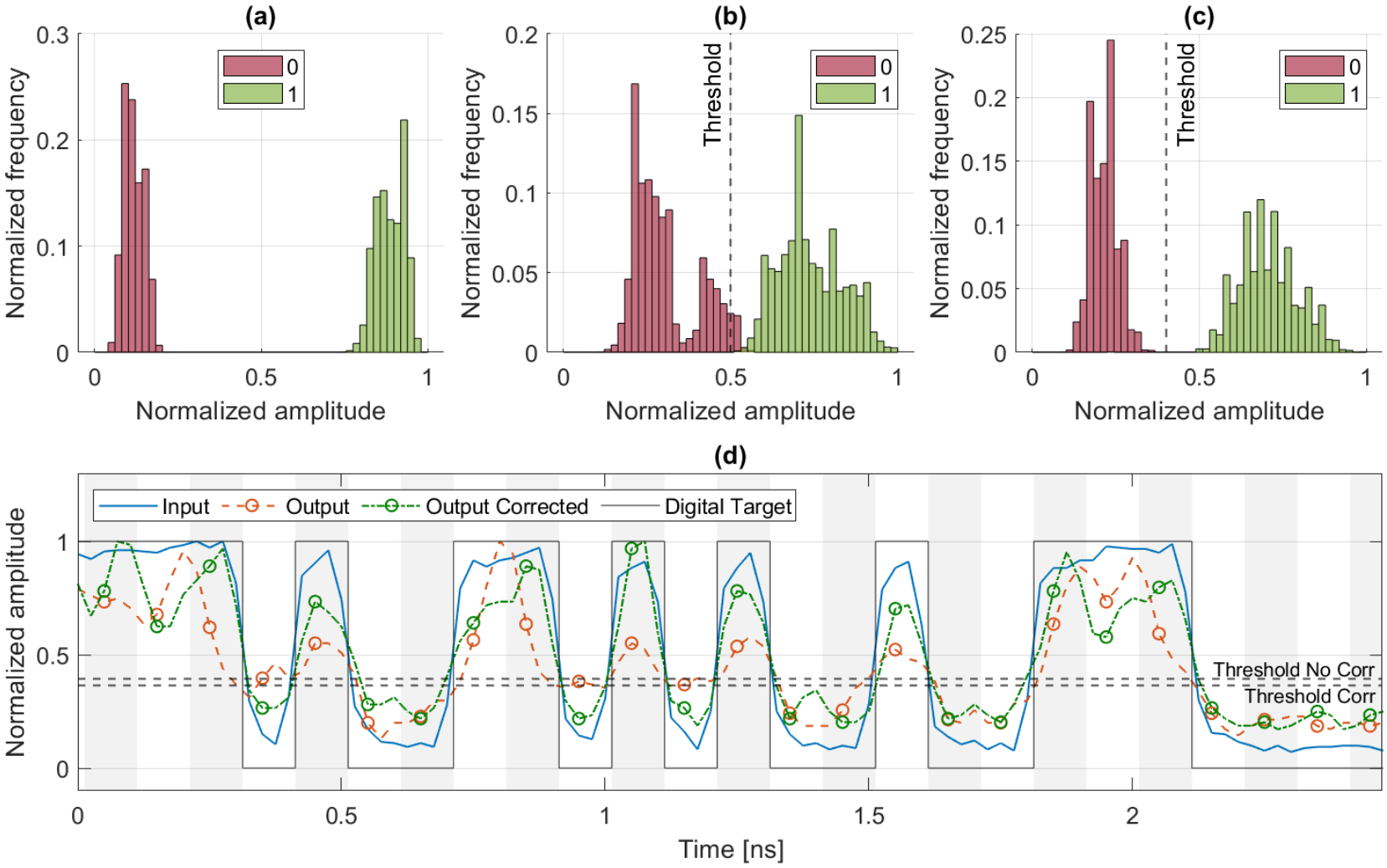


3)

Histogram of the distributions of expected 0s and 1s

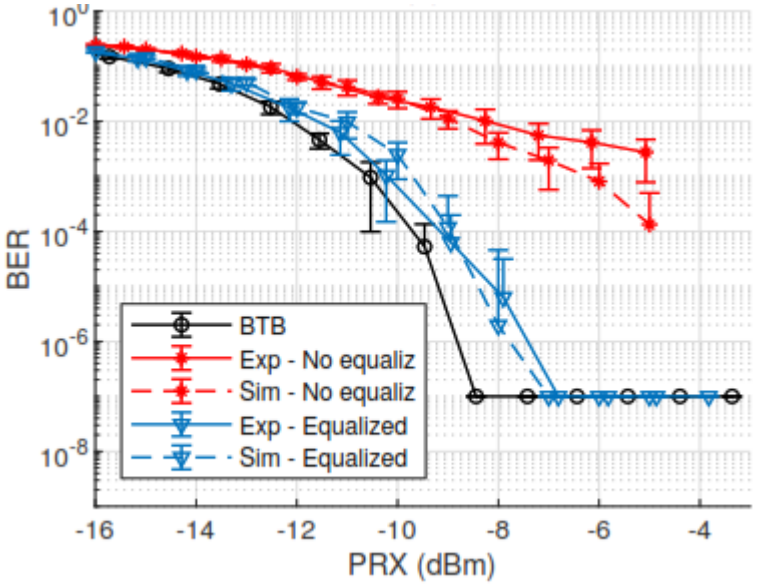


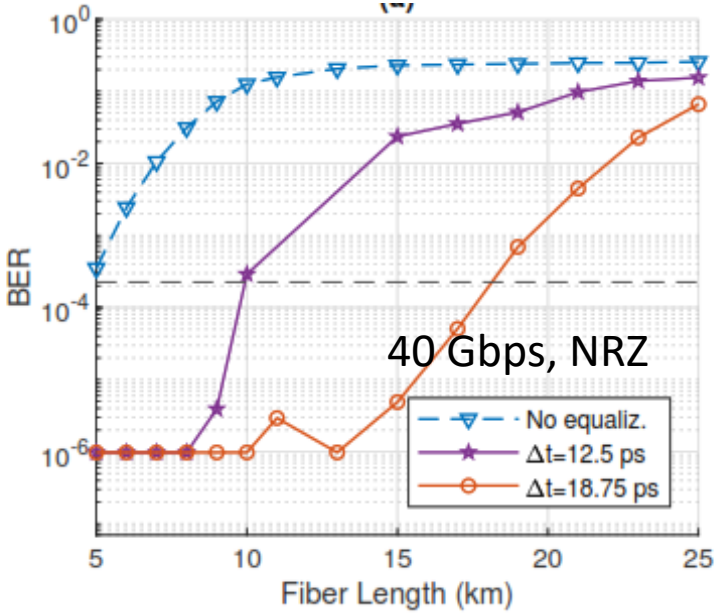
Results


(a)
(b)
(c)
(d)
Normalized frequency
Normalized amplitude
Threshold
0
1
Input
Output
Output Corrected
Digital Target
Threshold No Corr
Threshold Corr
Time [ns]

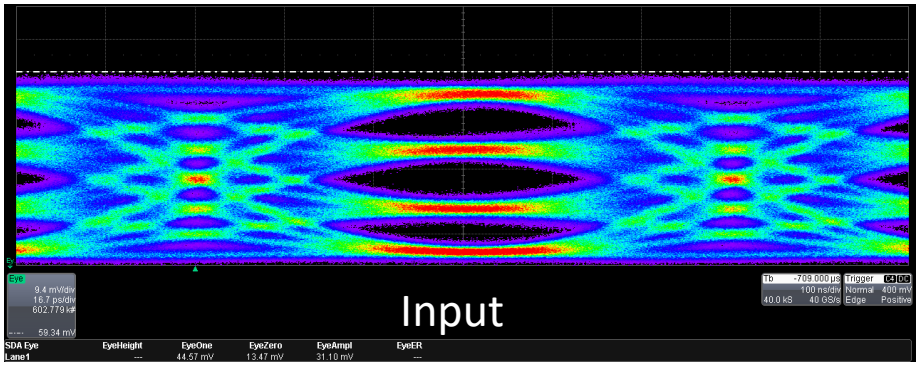
Trained perceptron

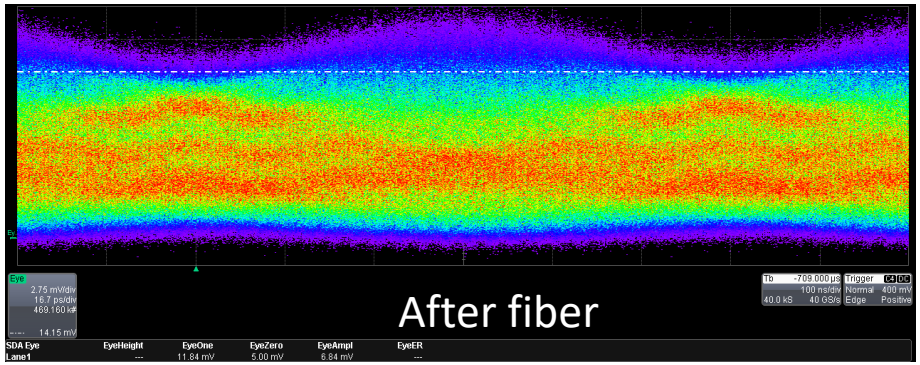
10 Gbps, 100 km NRZ

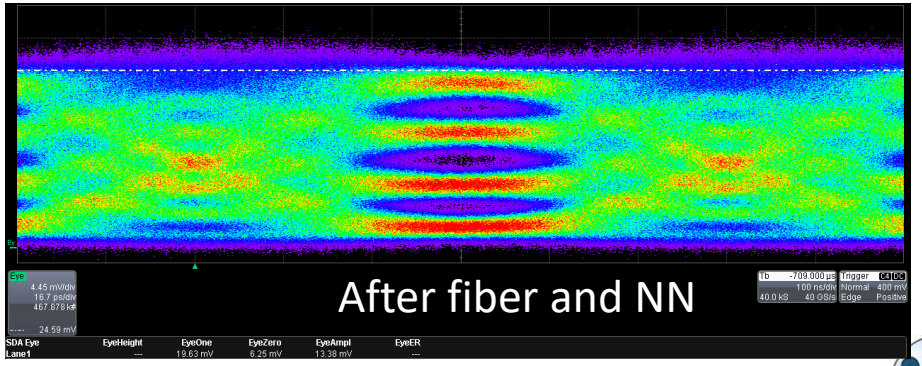




100 km PAM-4 20 Gbs

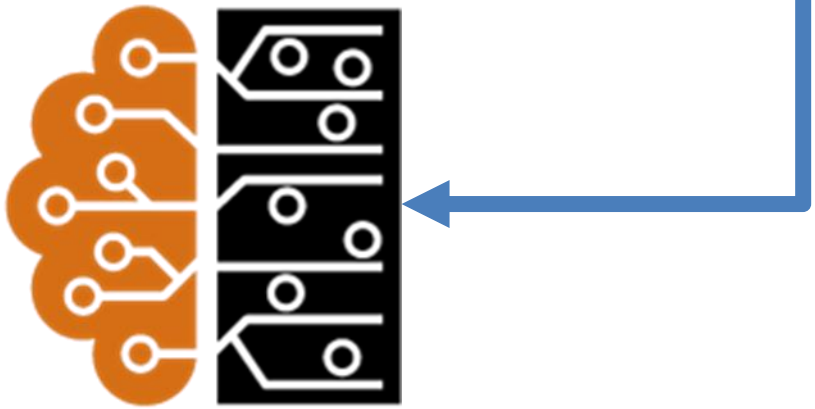






The vision

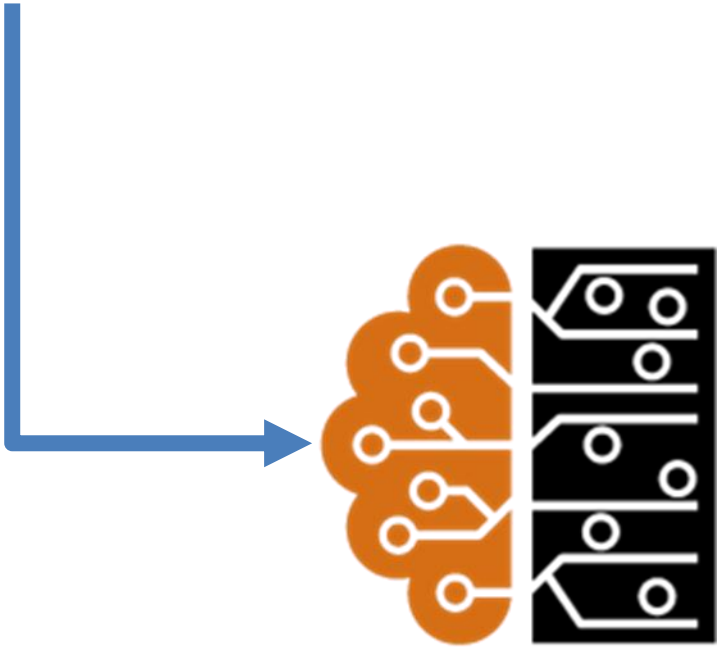
PHOTONIC INTEGRATED CIRCUIT



HYBRID ARTIFICIAL-BIOLOGICAL NETWORK

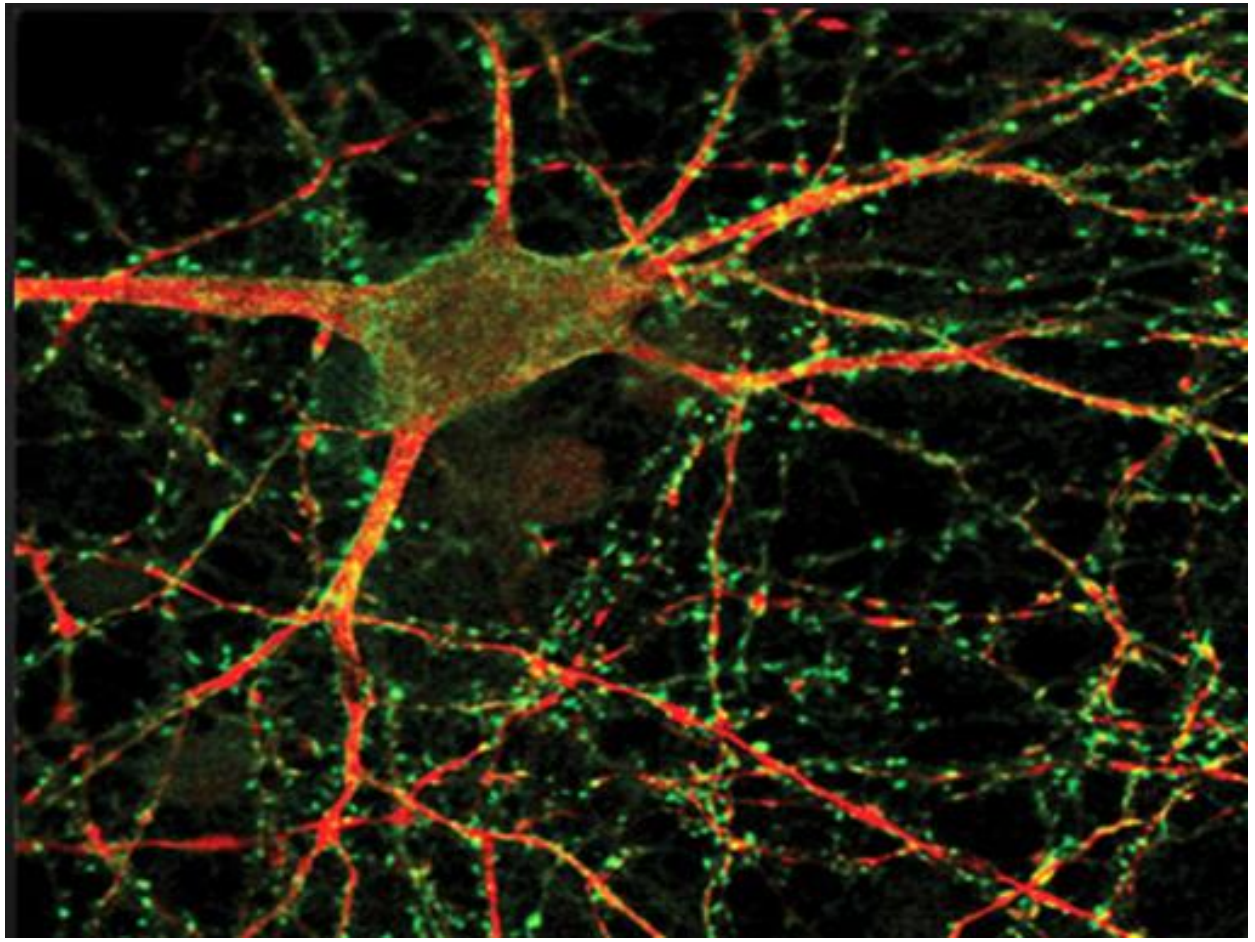
The vision

BIOLOGICAL COLTURE



HYBRID ARTIFICIAL-BIOLOGICAL NETWORK

The experimental platform

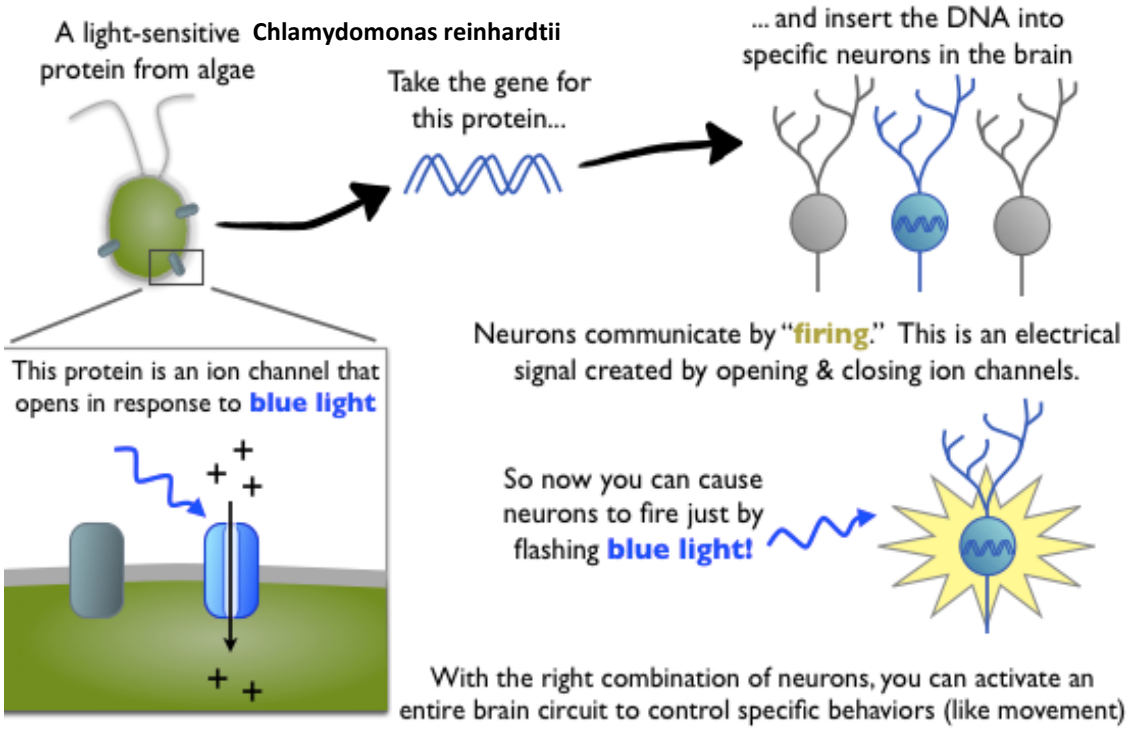


How do we influence neuron activity

Optogenetics

Karl Desseiroth, Stanford University, 2005

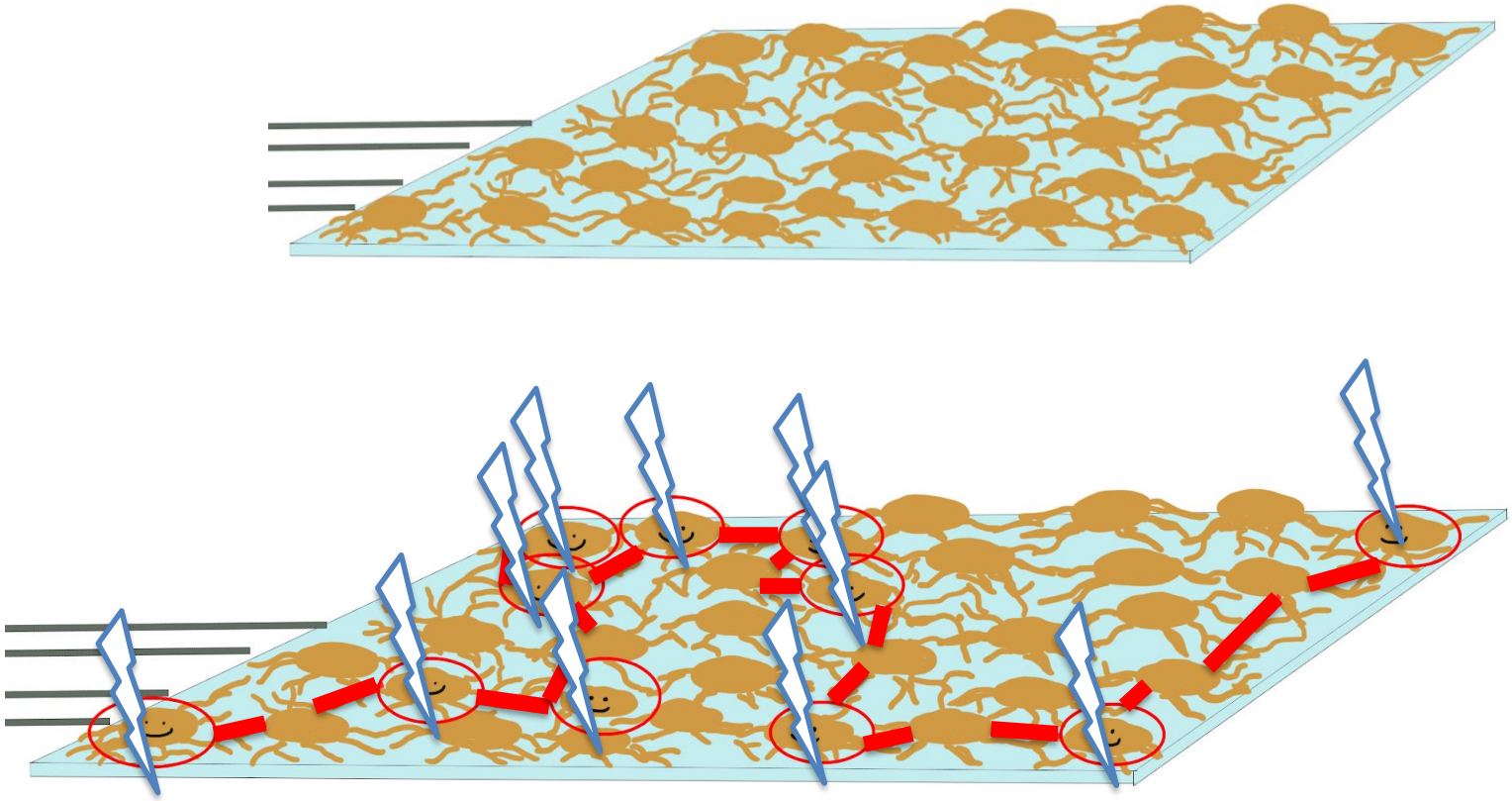
https://www.hhmi.org/scientists/karl-deisseroth



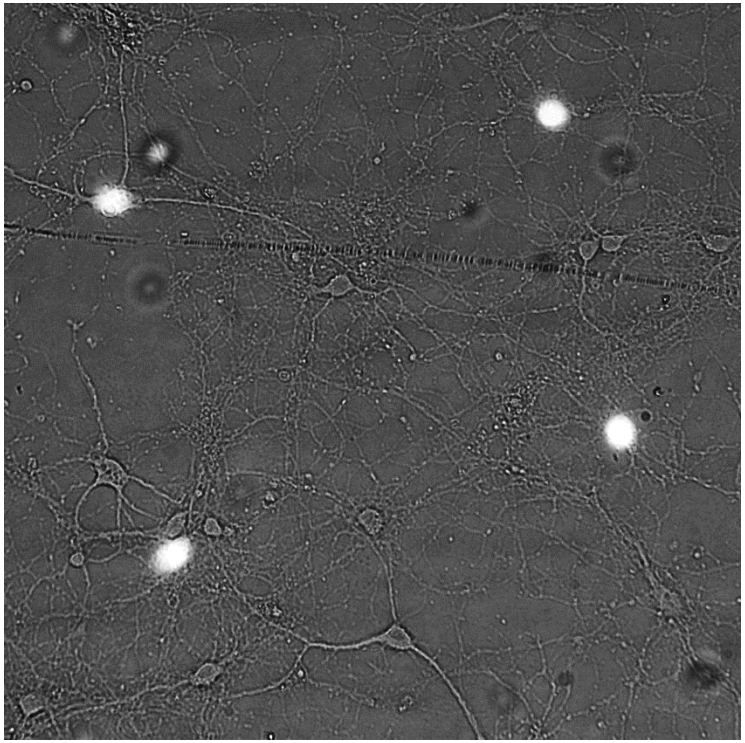
LIGHT CAN ACTIVATE NEURONS

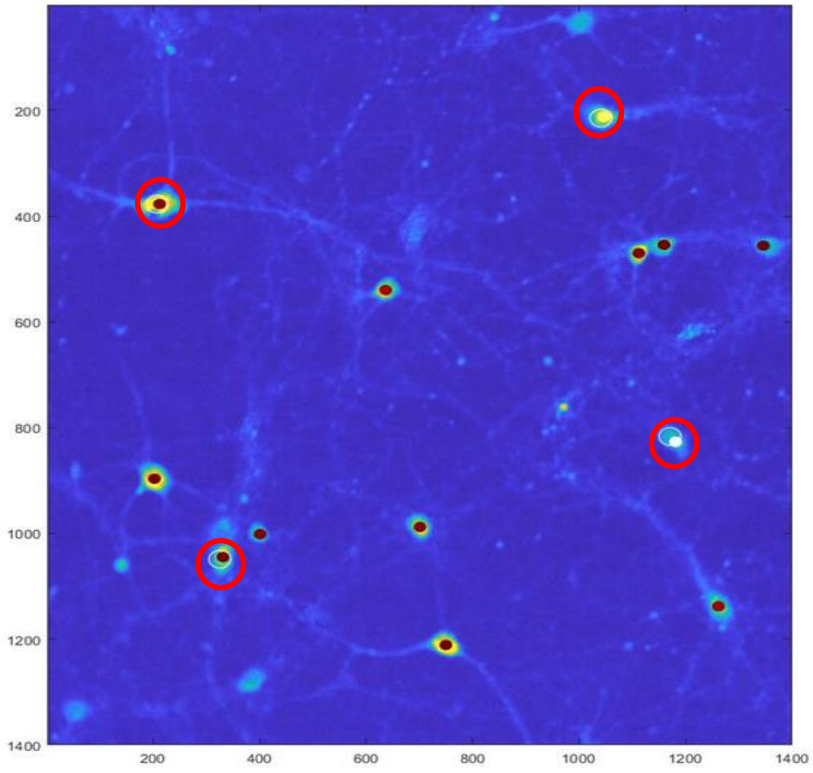
Writing a neuronal circuit

Patterned illumination activates a group of interconnected neurons



Writing a neuronal circuit : patterned illumination

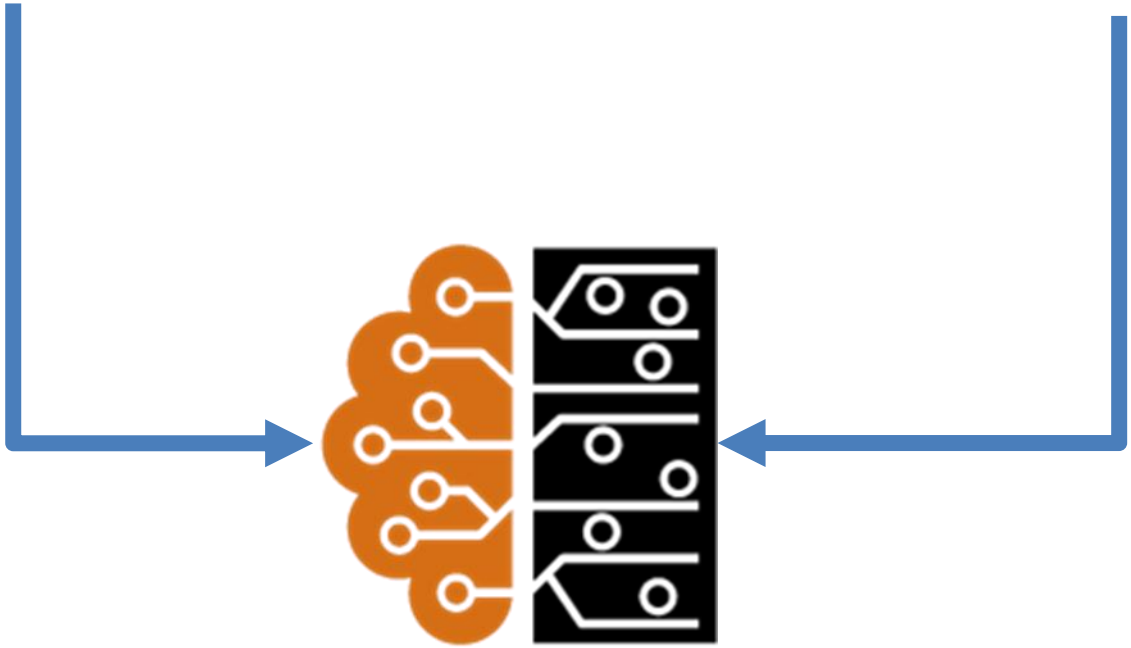




The vision

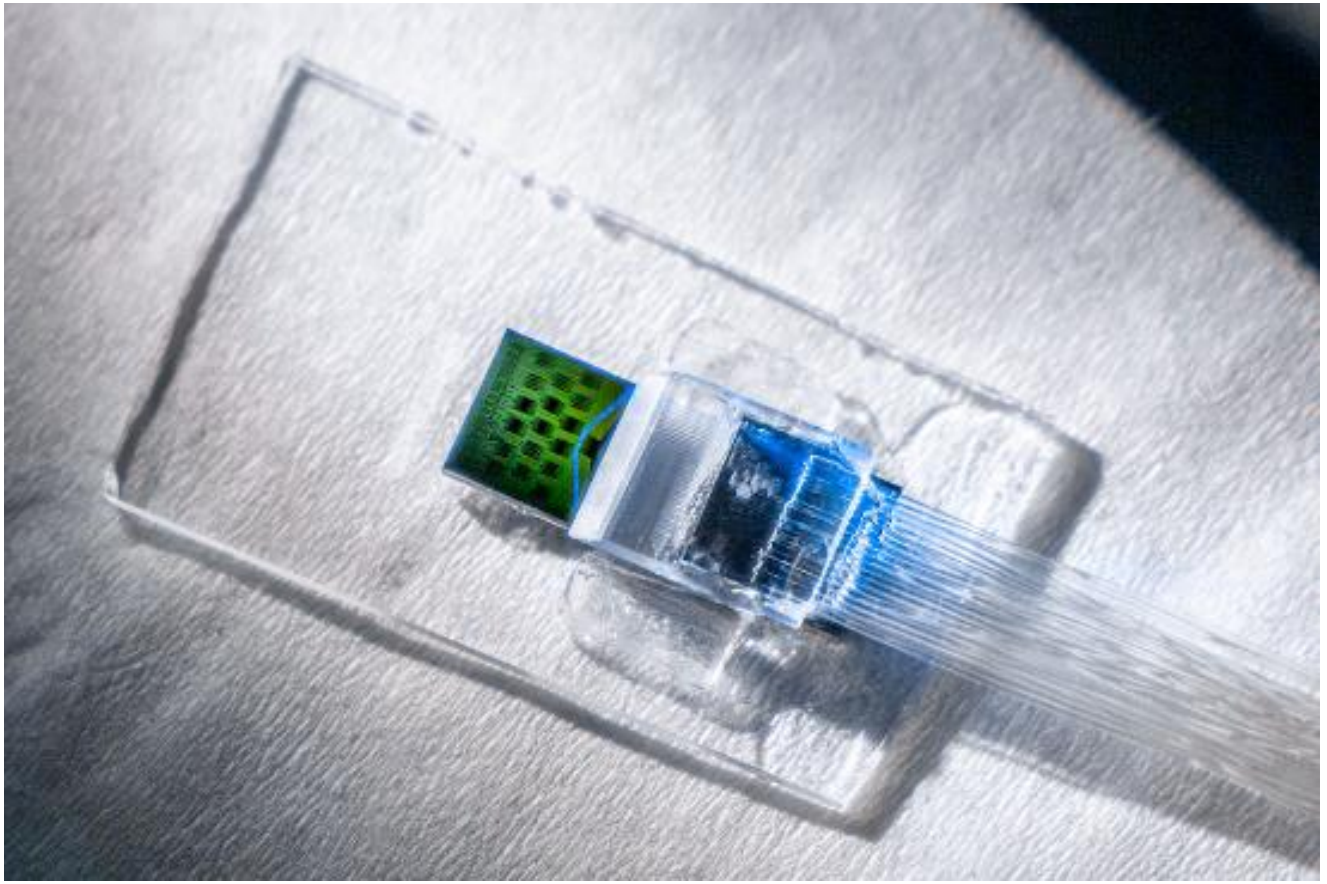
BIOLOGICAL COLTURE

PHOTONIC INTEGRATED CIRCUIT

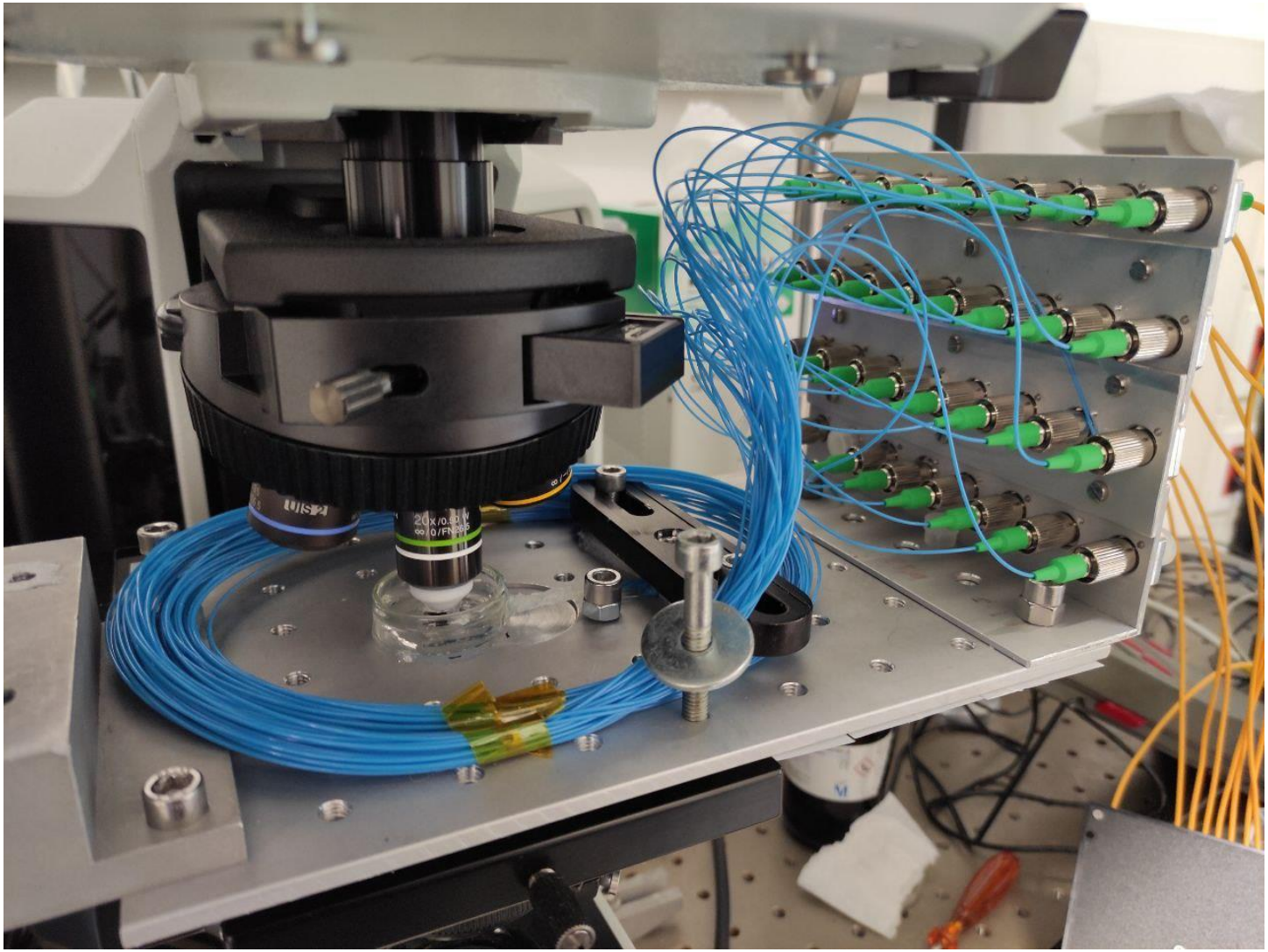


HYBRID ARTIFICIAL-BIOLOGICAL NETWORK

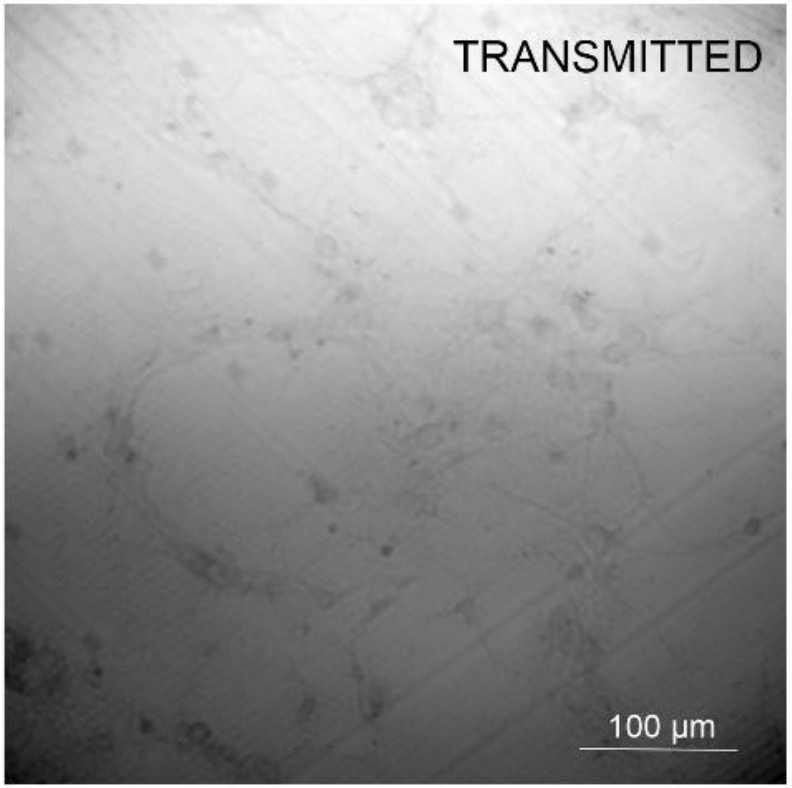
The setup



The setup

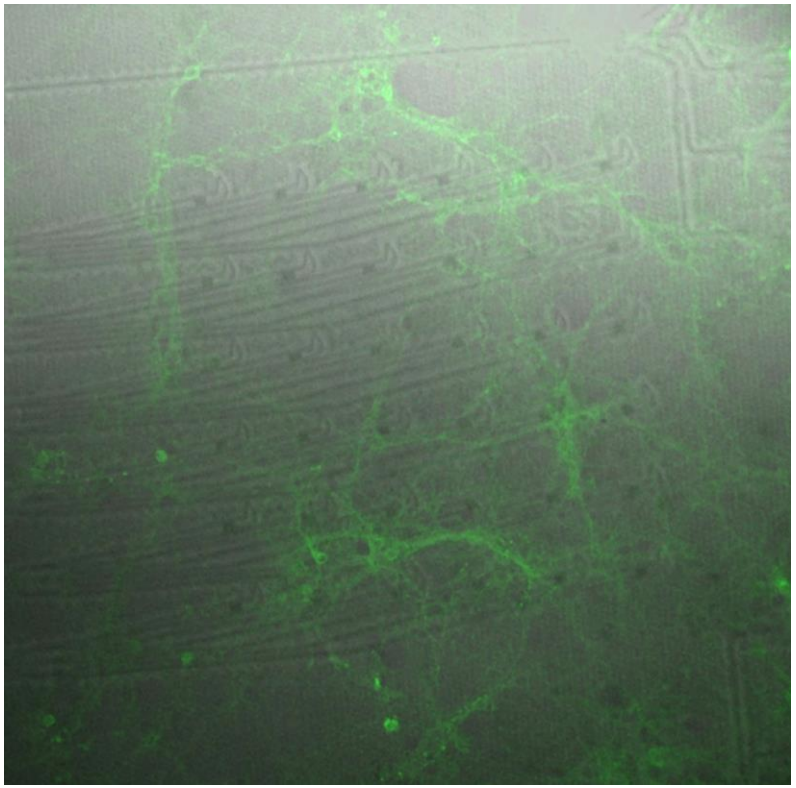


First experiments



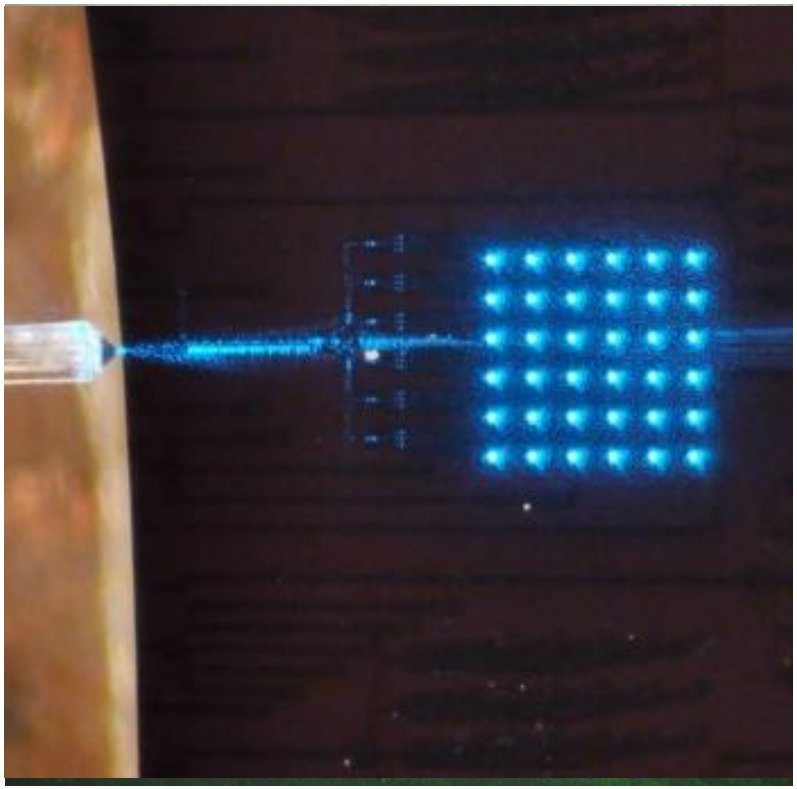
Neurons on the photonic chip

First experiments



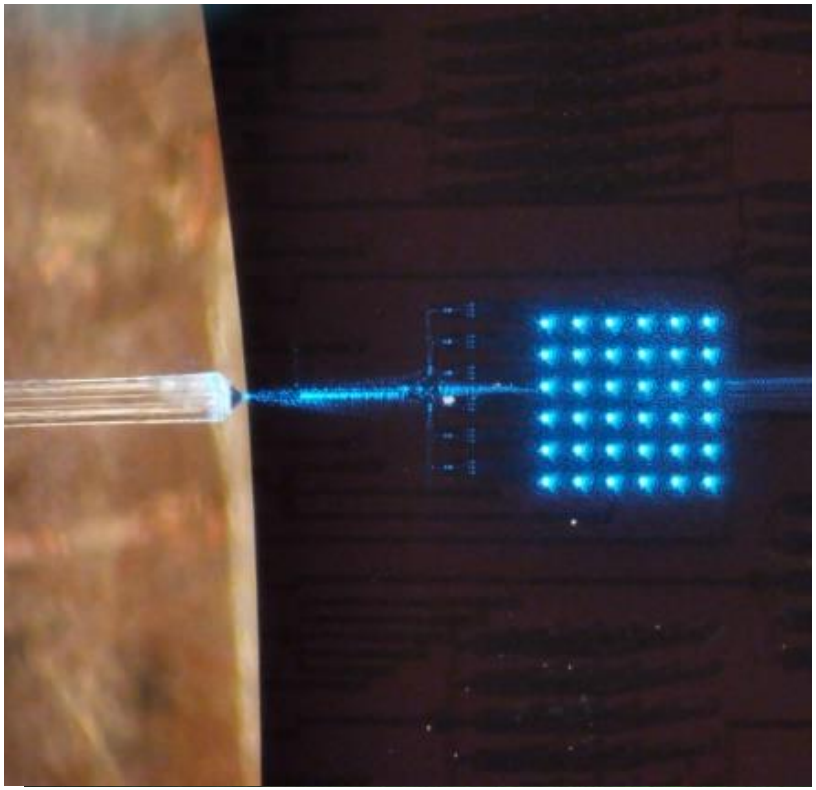
Neurons and chip under the microscope

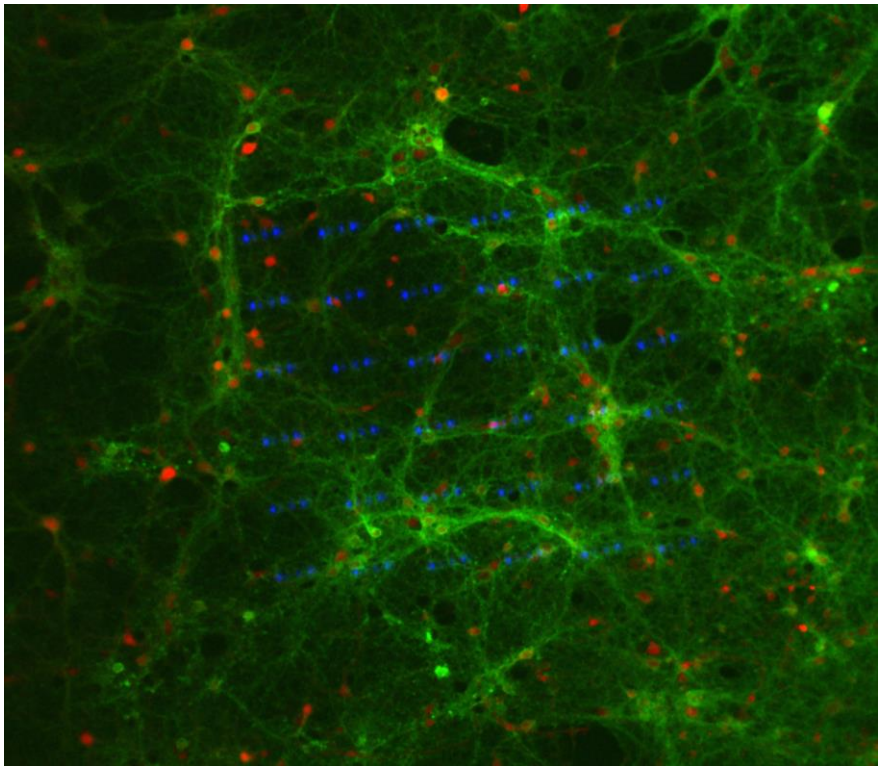
First experiments



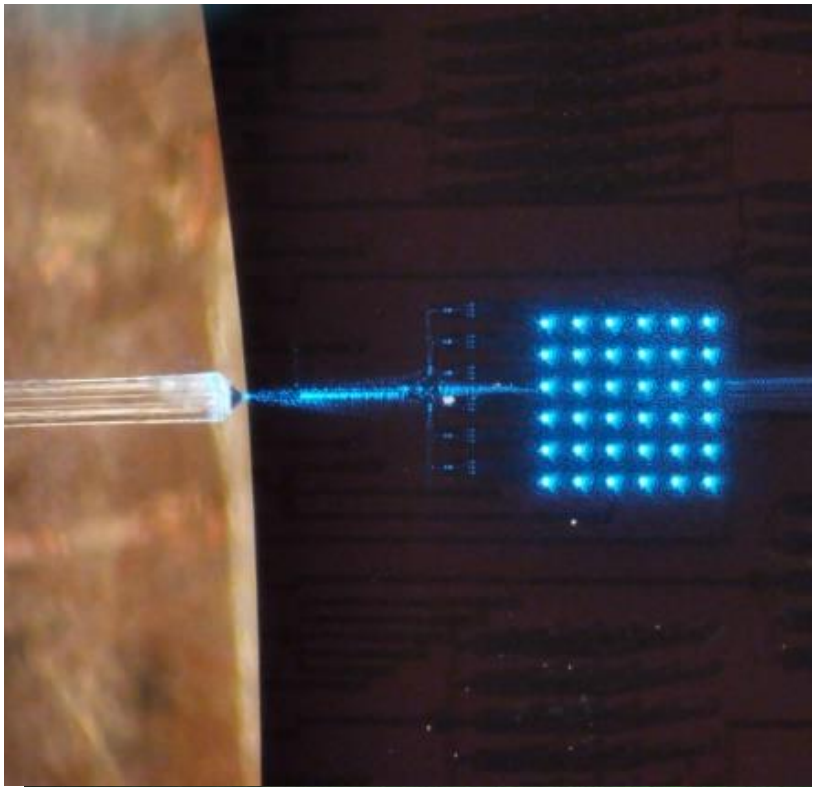
Turn on the light in the photonic chip

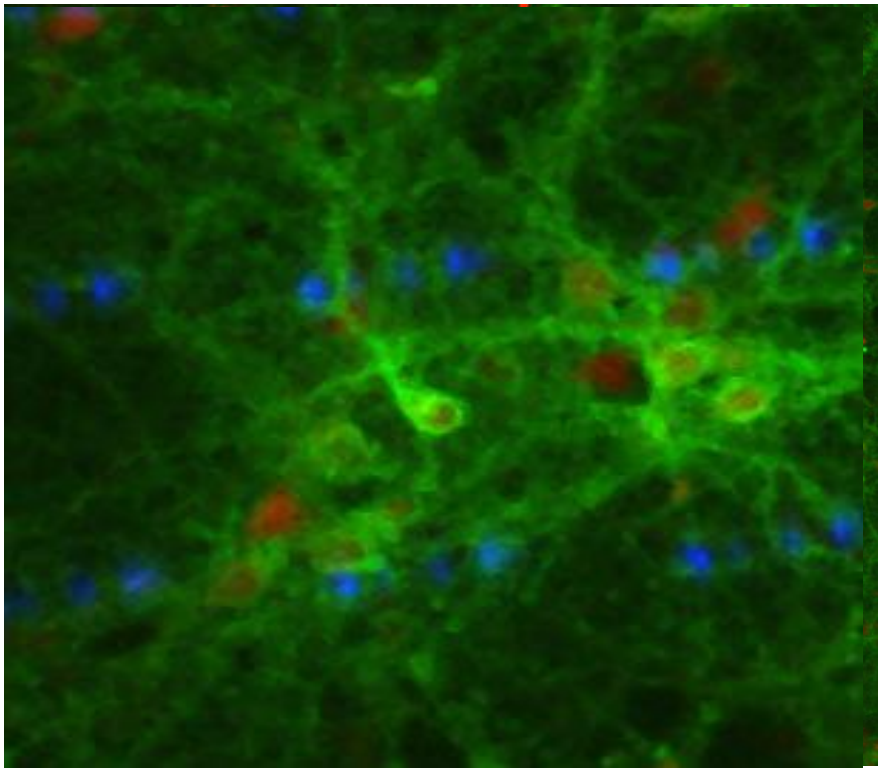
First experiments



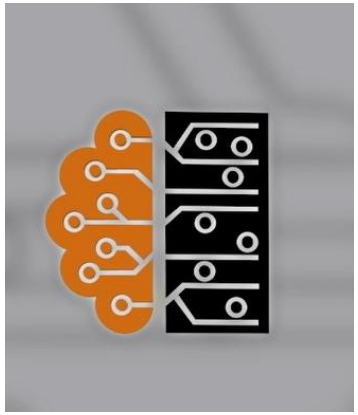


First experiments



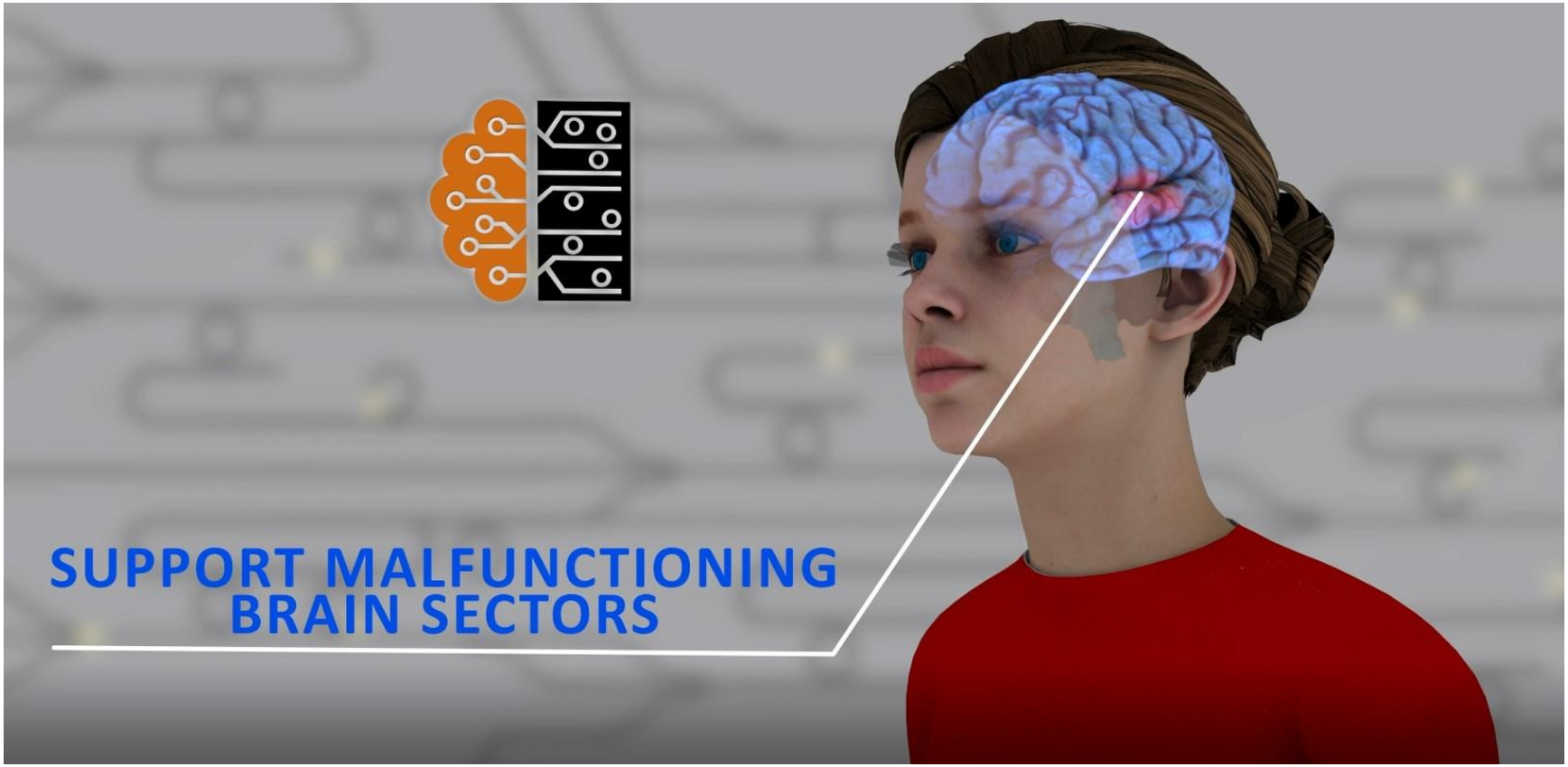


Use of the hybrid artificial network



https://www.youtube.com/watch?v=rCeEm-LF6q0&t=2s

Use of the hybrid artificial network



https://www.youtube.com/watch?v=rCeEm-LF6q0&t=2s

Acknowledgements

- Quantum science and technologies

Quantum Science and Technology in Trento

EPIQUS

SPEQK

POC UNITN

- Neuromorphic photonics

ISLAND
read and write
neurons

BACKUP
neuromorphic
photonics
and the brain

European Research Council