

# Neuromorphic photonic platform for hybrid artificial intelligence?

Lorenzo Pavesi  
University of Trento



# Trento - Italy

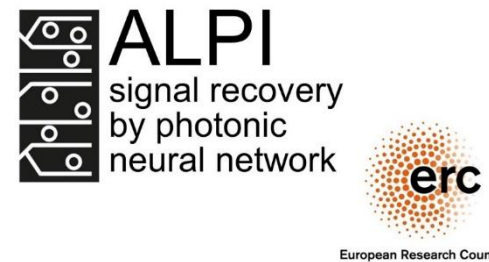
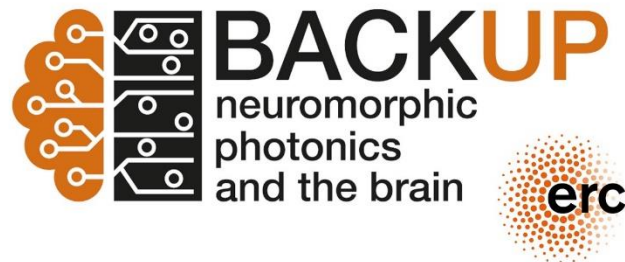
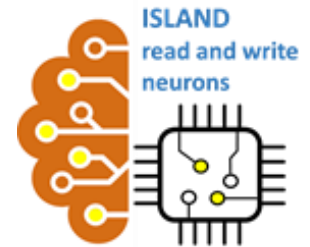
This Sunday



# Neuromorphic photonic platform for hybrid artificial intelligence?



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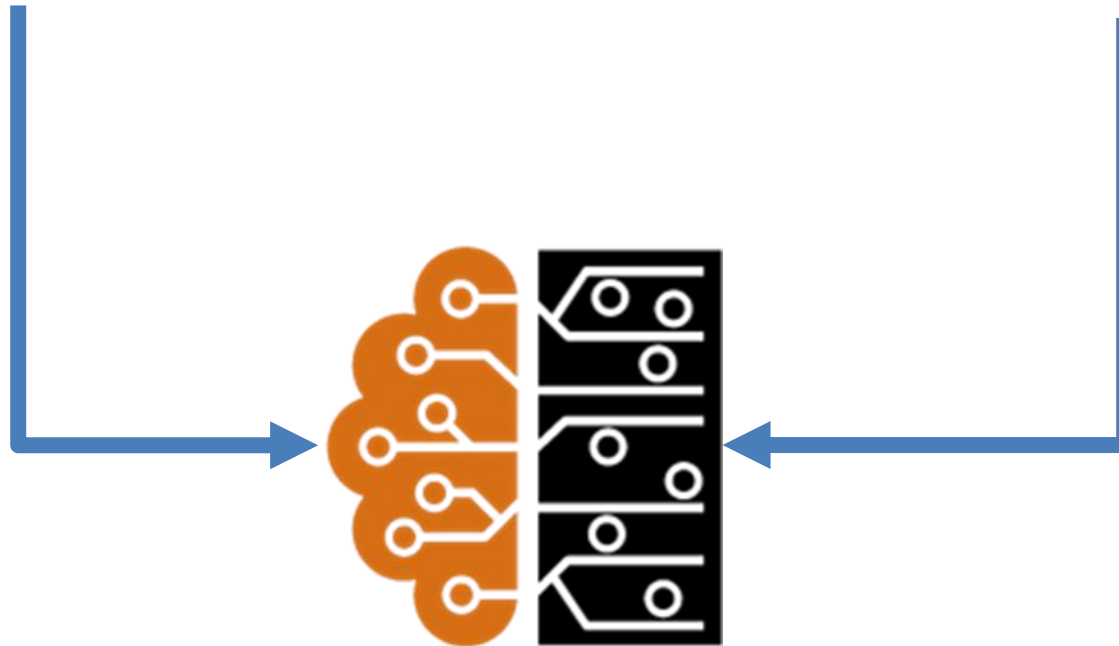
# The vision



BIOLOGICAL CULTURE



PHOTONIC INTEGRATED CIRCUIT



HYBRID ARTIFICIAL-BIOLOGICAL NETWORK

# Why photonics?

- Light is fast!
  - Biological neuron timescale *ms*
  - Optical neurons timescale *ps*
  - Information processing at TBit/s
- Power efficient

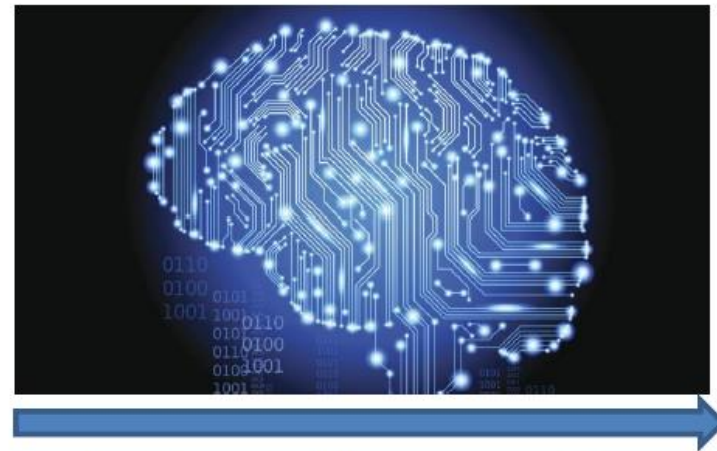
Factor of  $10^9$ !!



Brain learning process

15 years

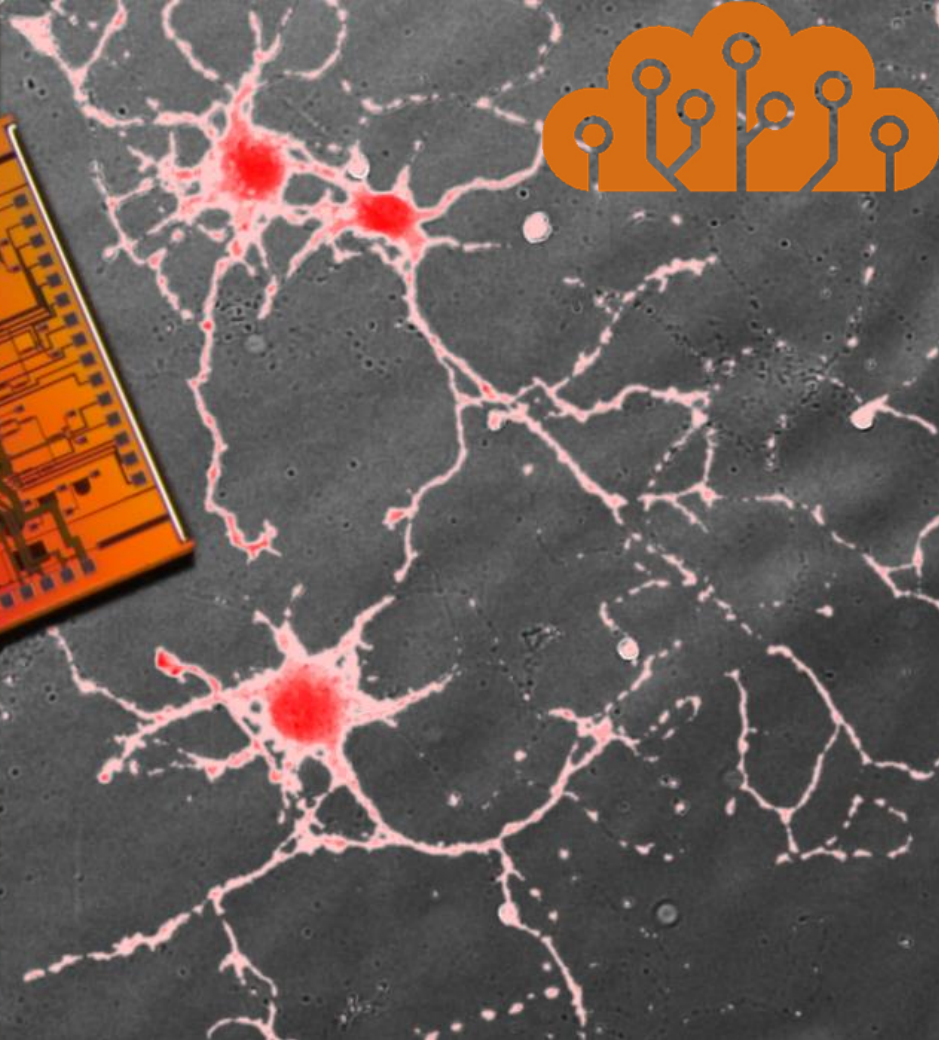
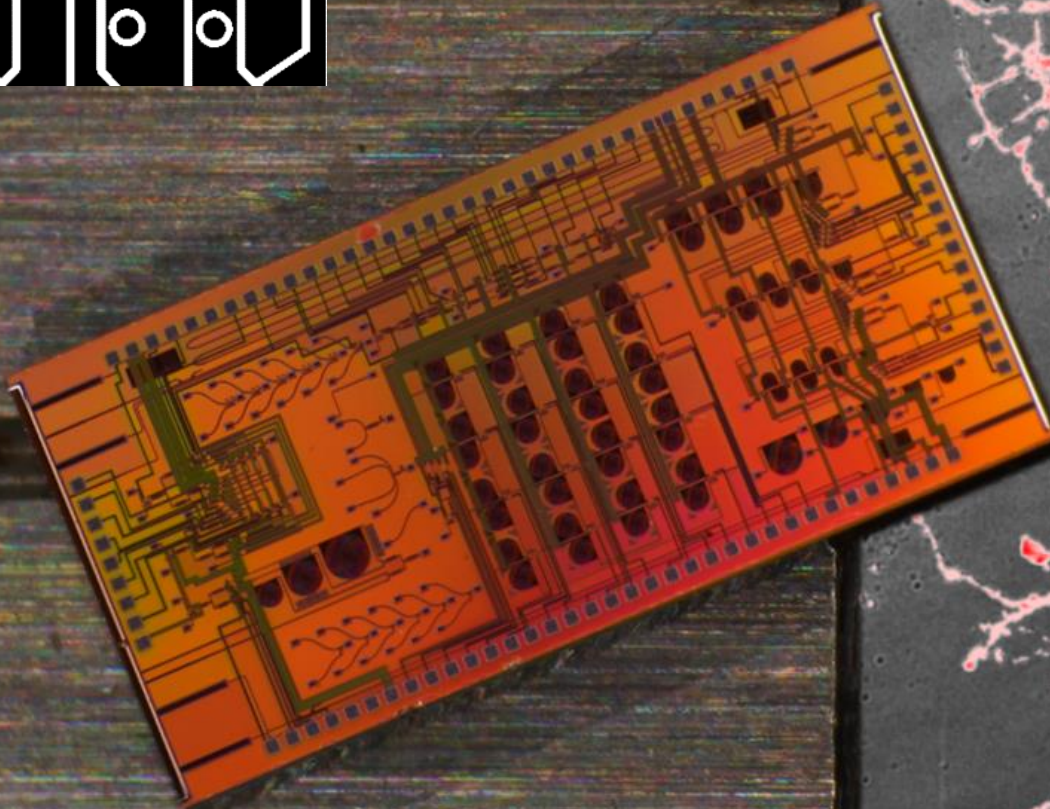
$473 \times 10^6$  seconds



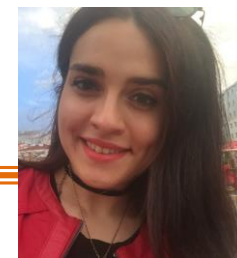
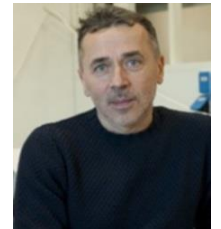
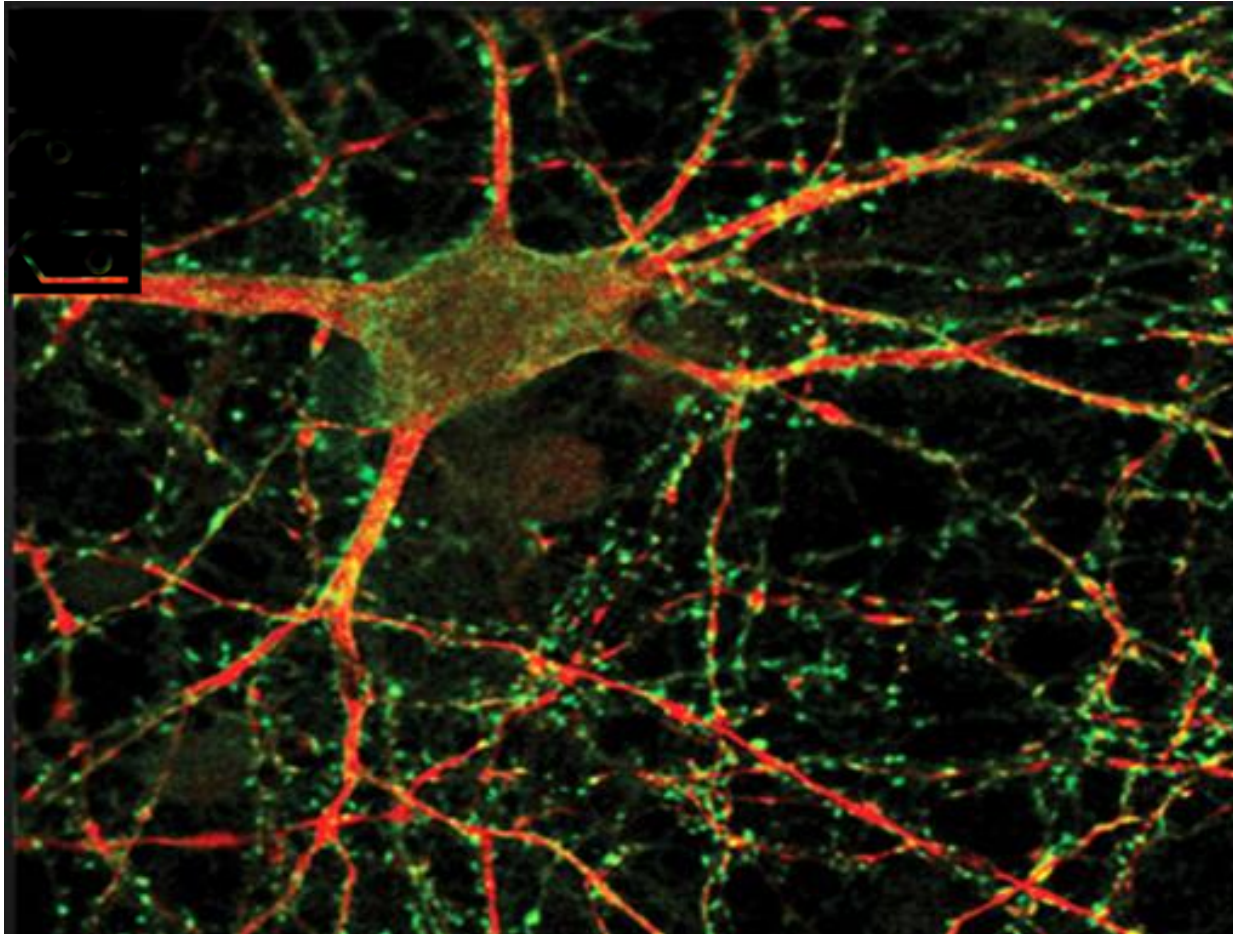
Artificial optical brain

0.5 seconds

# The experimental platform

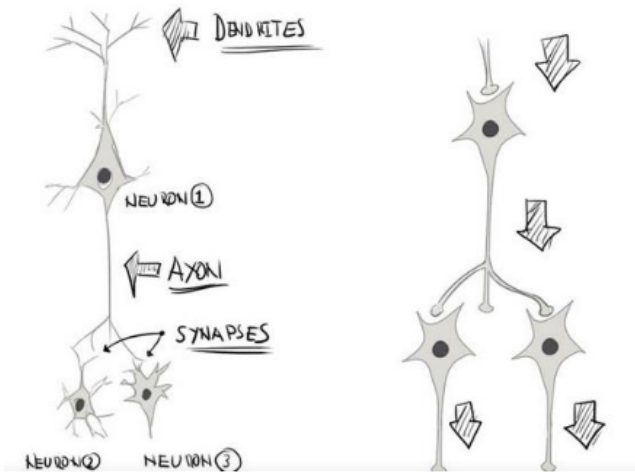


# The experimental platform

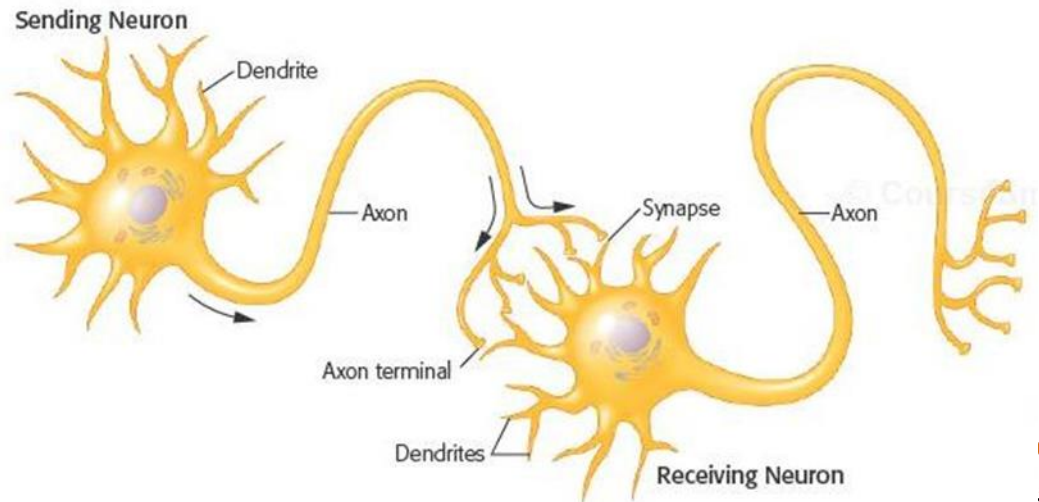


# Neurons

The **Neuron** is the basic unit of computation in the brain, it receives and integrates chemical signals from other neurons and depending on a number of factors it either does nothing or generates an electrical signal or *Action Potential* which in turn signals other **connected** neurons via synapses.



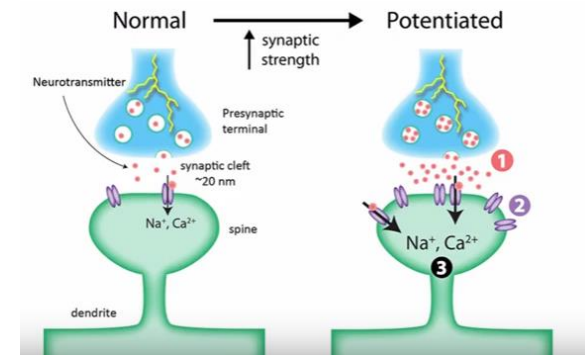
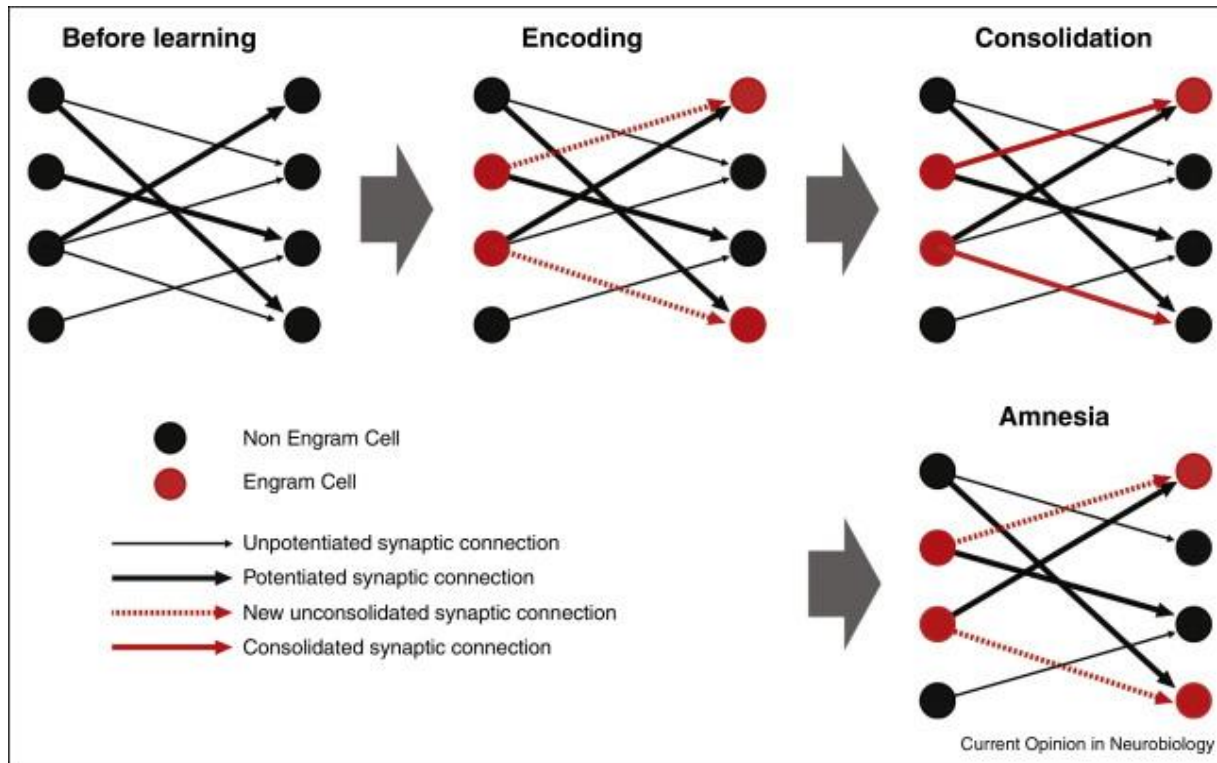
Neurons are morphologically “polarized” having an input end (dendrites, which collect information from other neurons) and an output end (axon that propagate information towards other cells; synapses)





# Memory and Engrams

Memory resides in specific “cell assemblies” (engrams) formed by the **strengthening of neuronal connections**



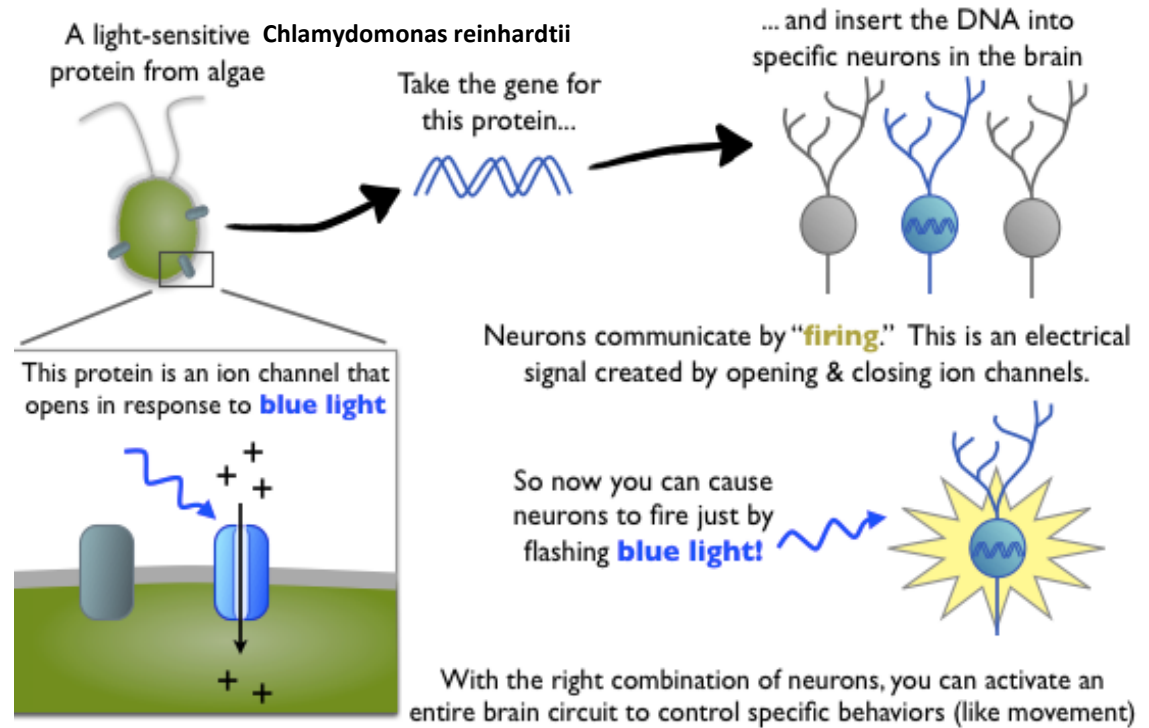
# How do we influence neuron activity

## Optogenetics:

Karl Deisseroth, Stanford University, 2005



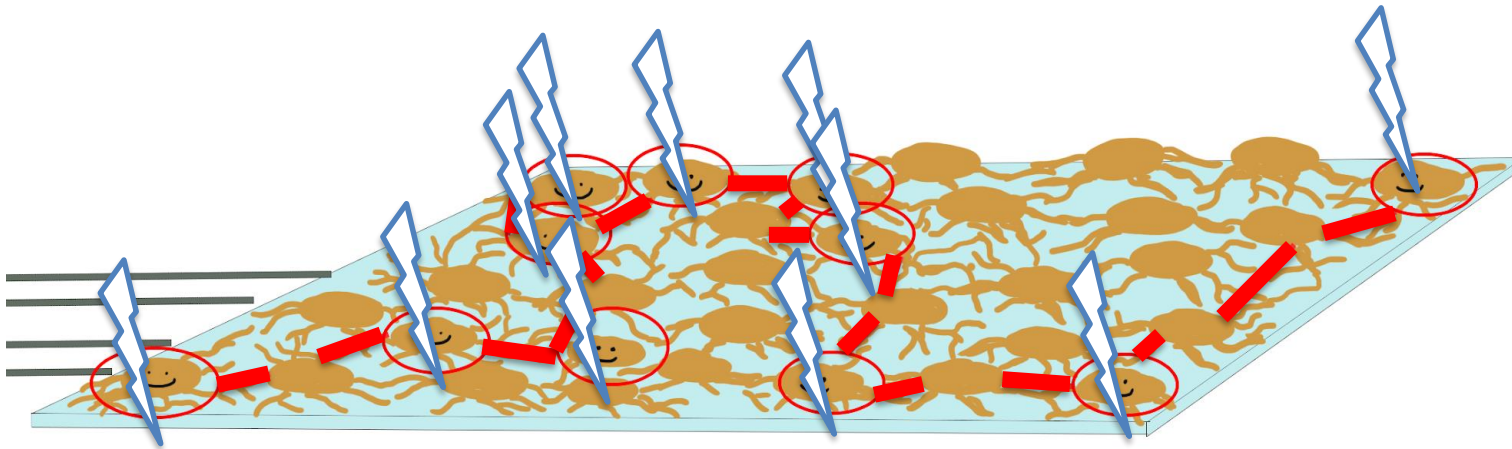
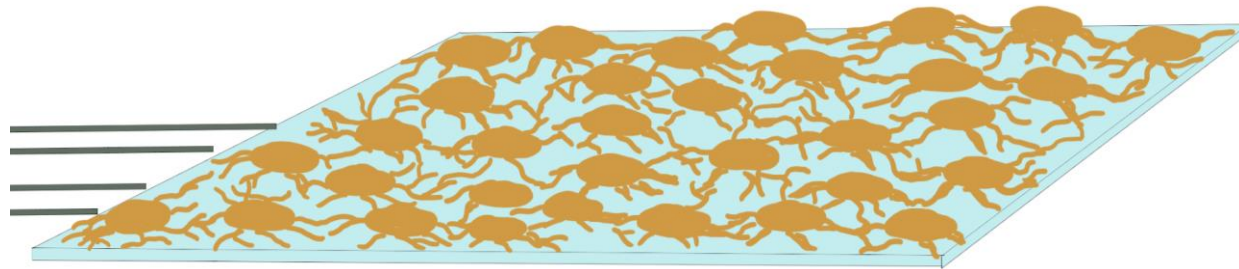
<https://www.hhmi.org/scientists/karl-deisseroth>



**LIGHT CAN ACTIVATE NEURONS**

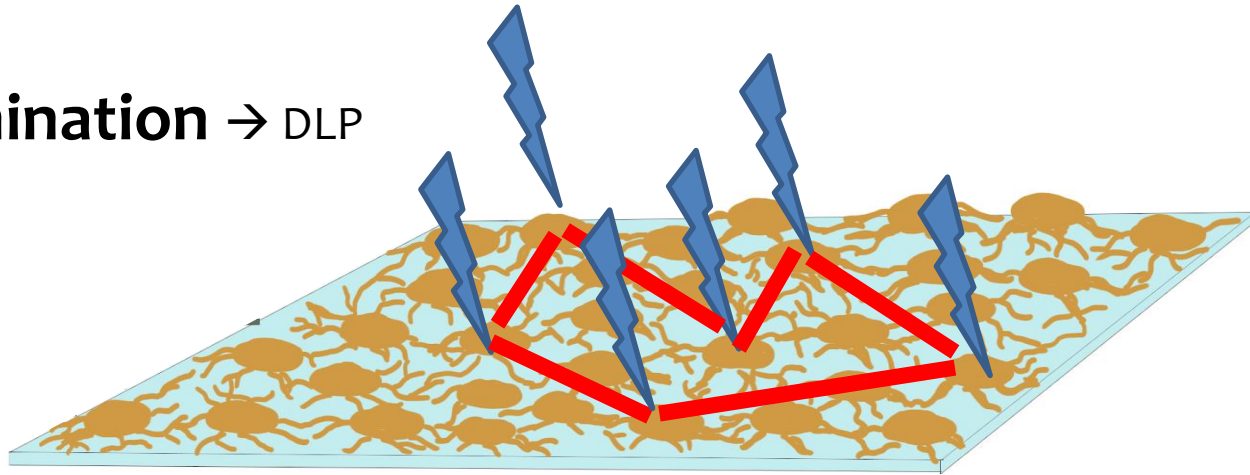
# Writing an engram

Patterned illumination activates a group of interconnected neurons



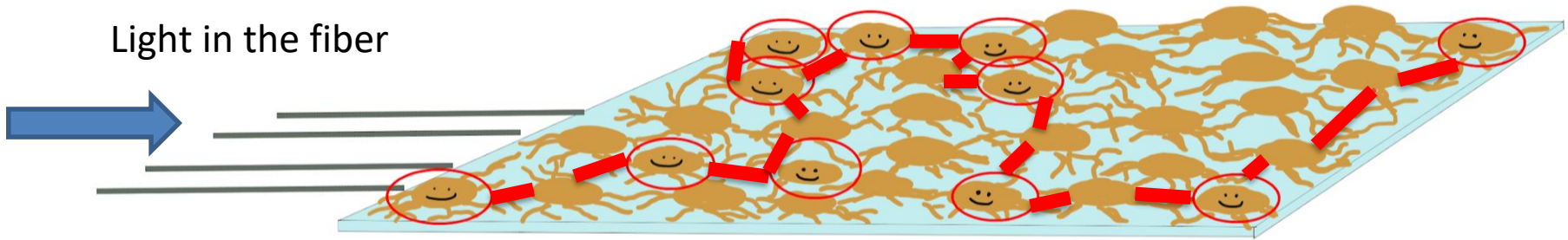
# Writing an engram

**Top illumination** → DLP



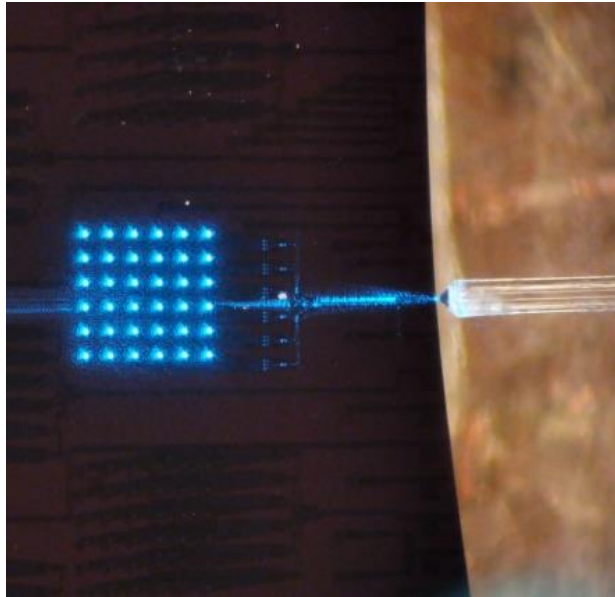
**Bottom illumination** → photonic chip

Light in the fiber

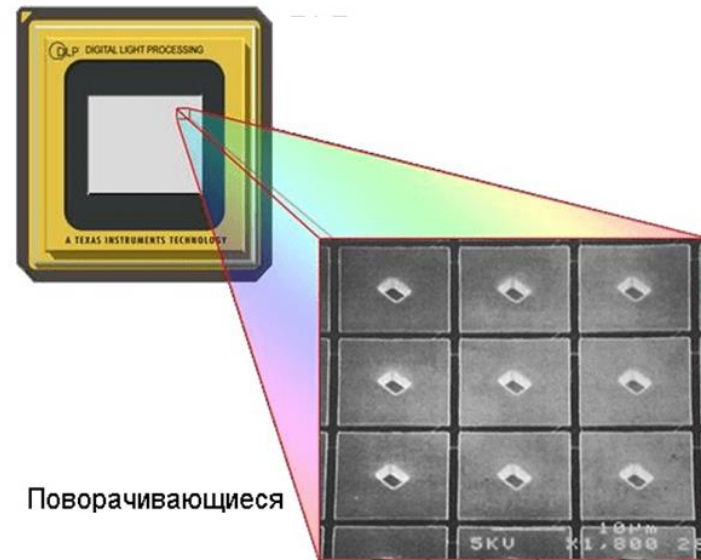


# Writing an engram: patterned illumination

## Photonic Chip

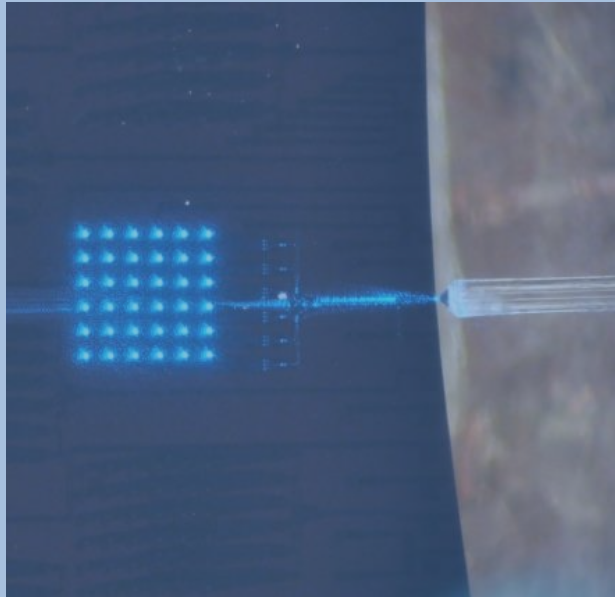


## Digital Light Processing (DLP)

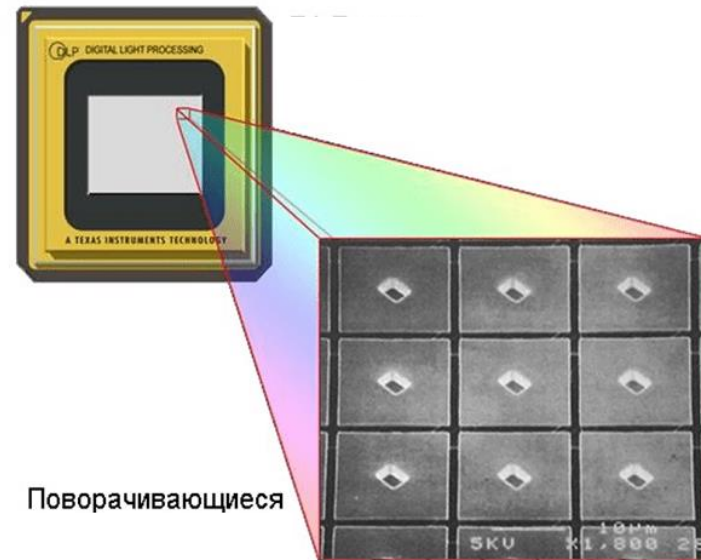


# Writing an engram: patterned illumination

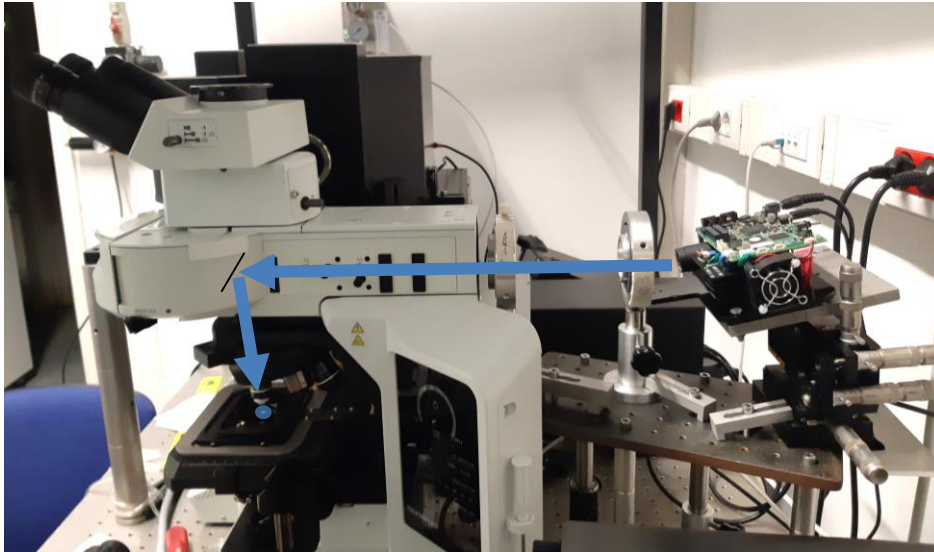
Photonic Chip



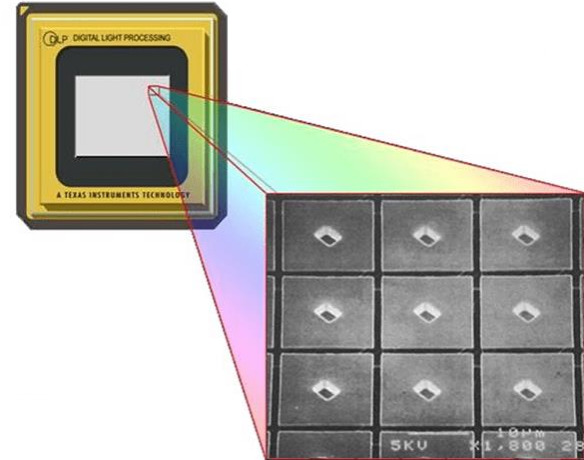
Digital Light Processing (DLP)



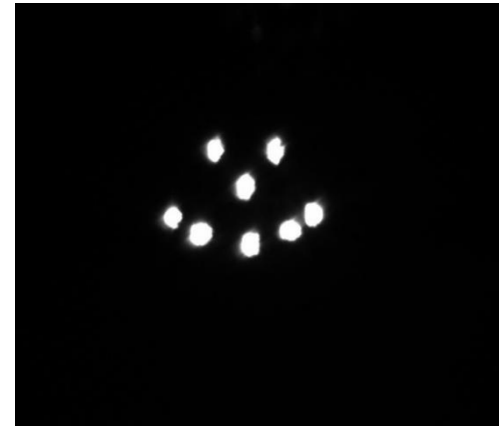
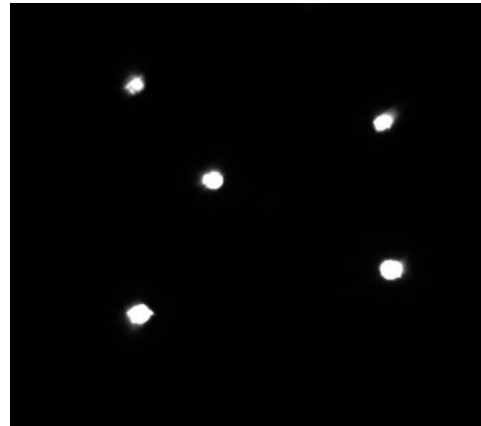
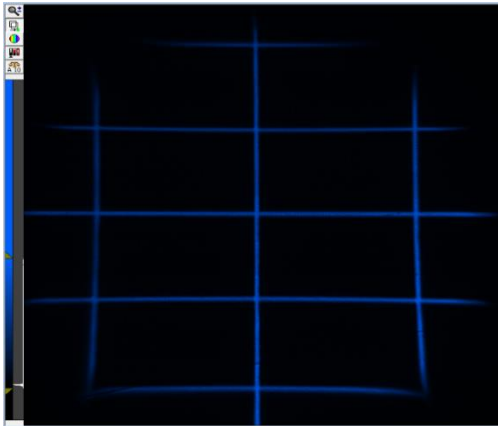
# Writing an engram: patterned illumination



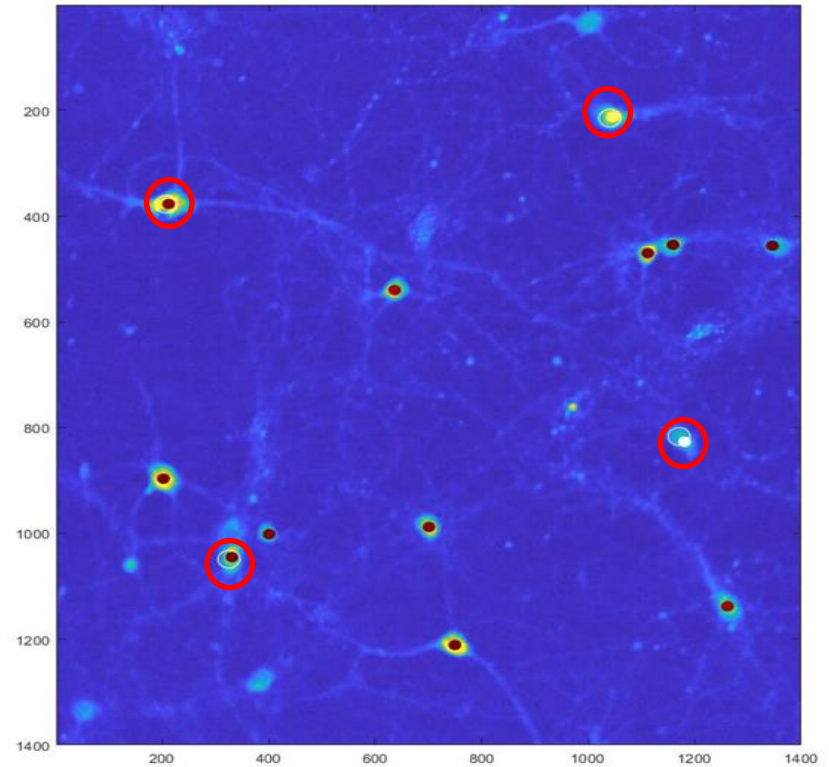
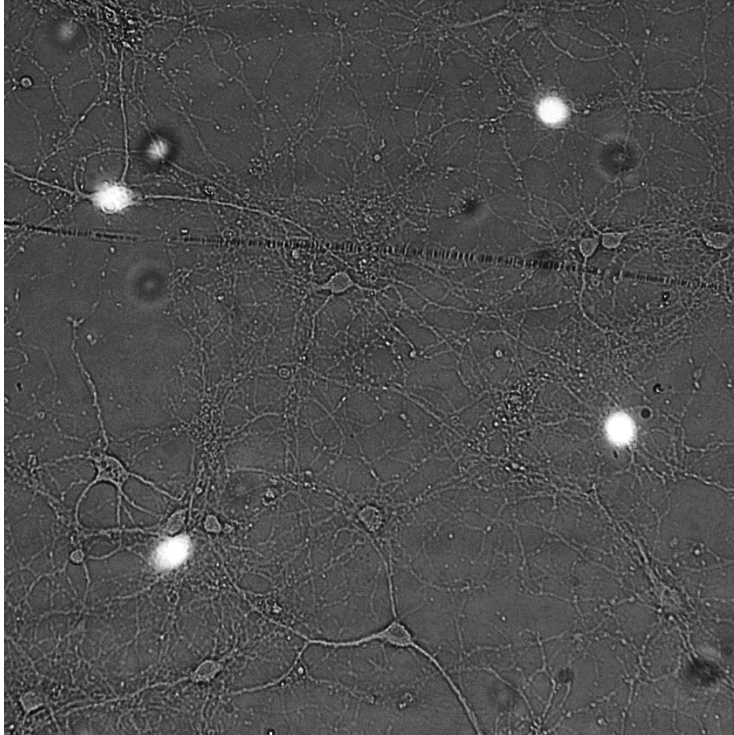
16 mW/mm<sup>2</sup>



Digital Light Processing (DLP)

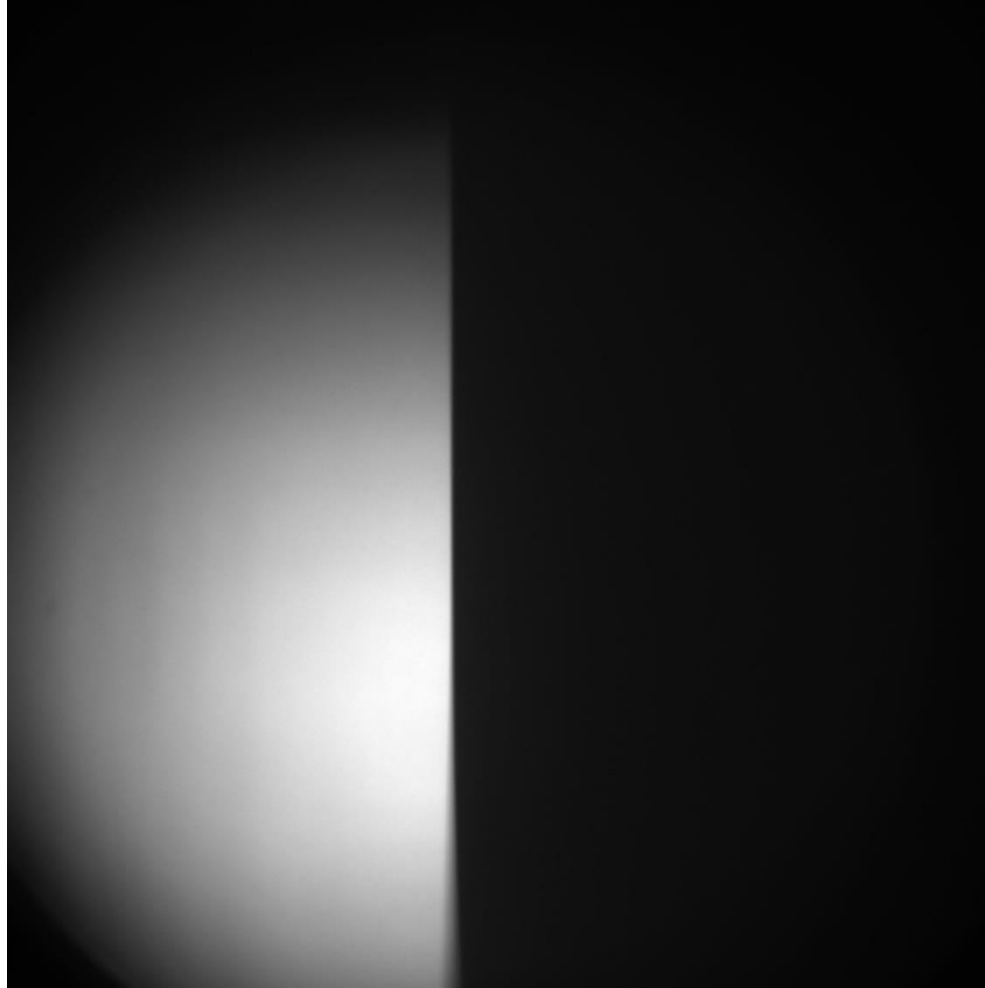


# Writing an engram: patterned illumination

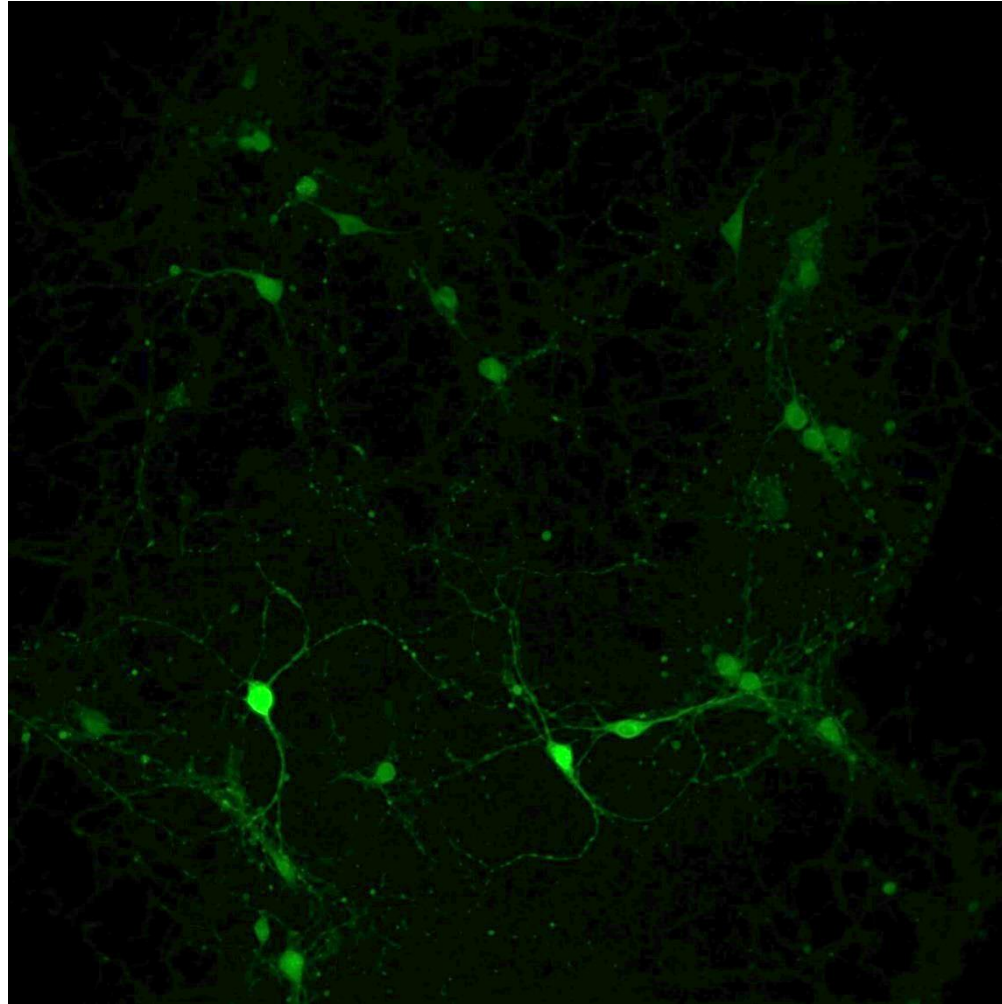




# Writing an engram: patterned illumination



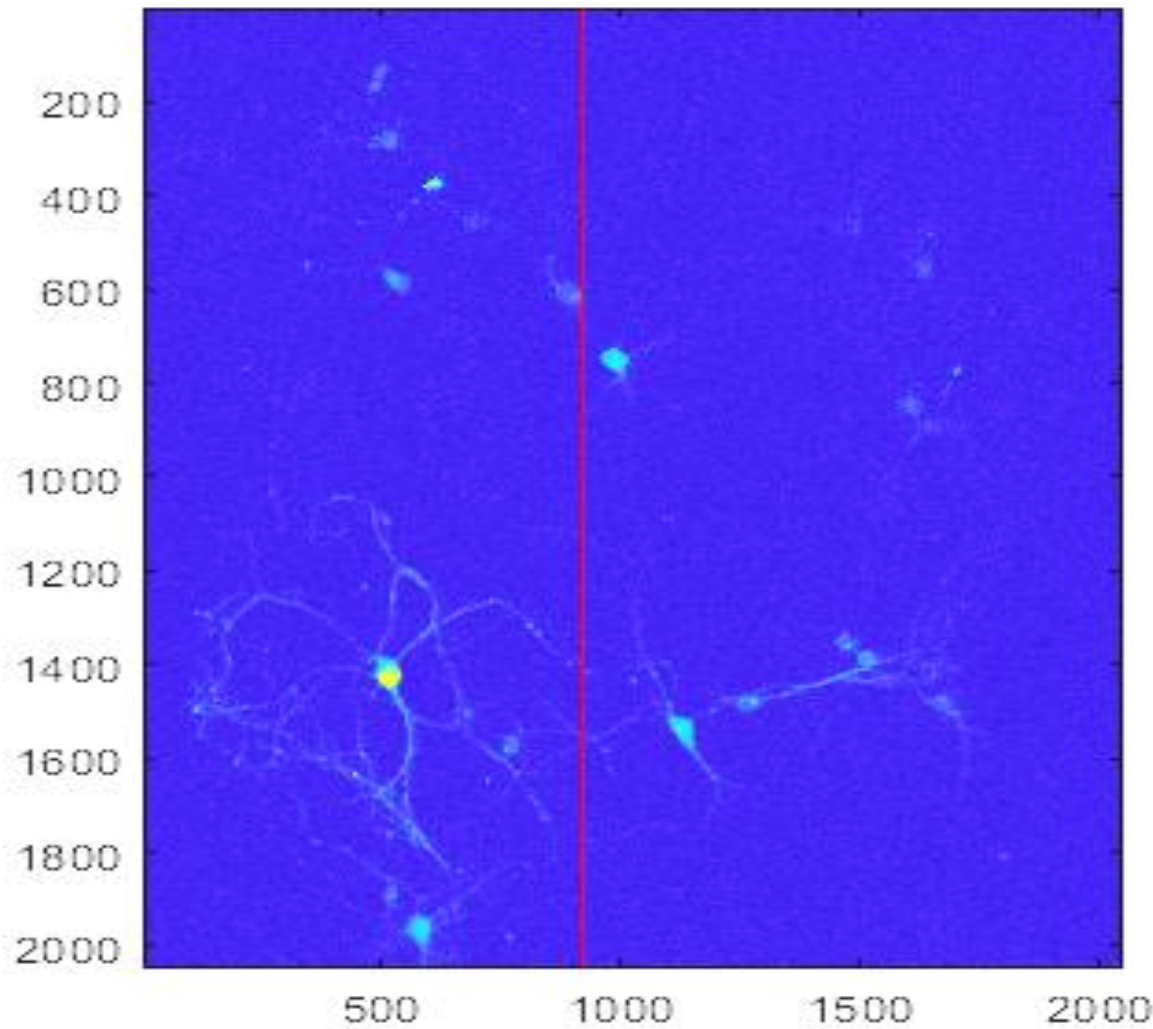
# Writing an engram: patterned illumination



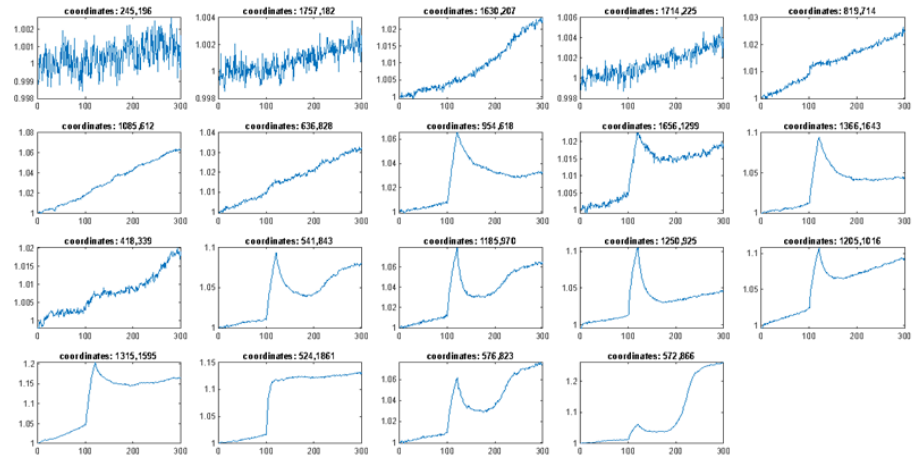
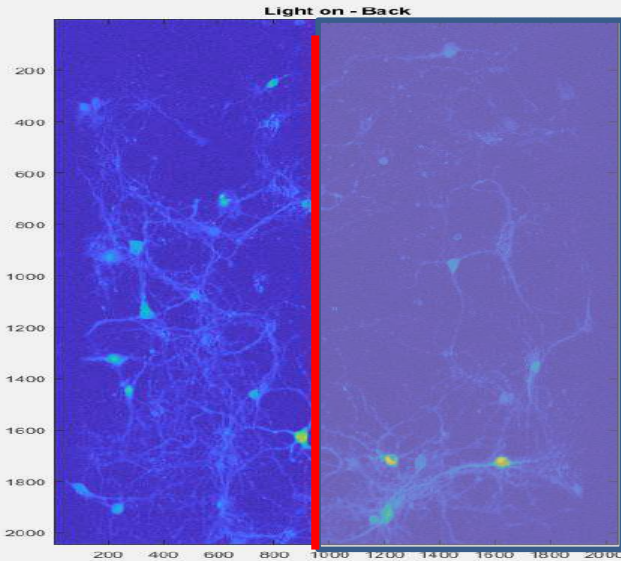
# Writing an engram: patterned illumination



# Writing an engram: patterned illumination

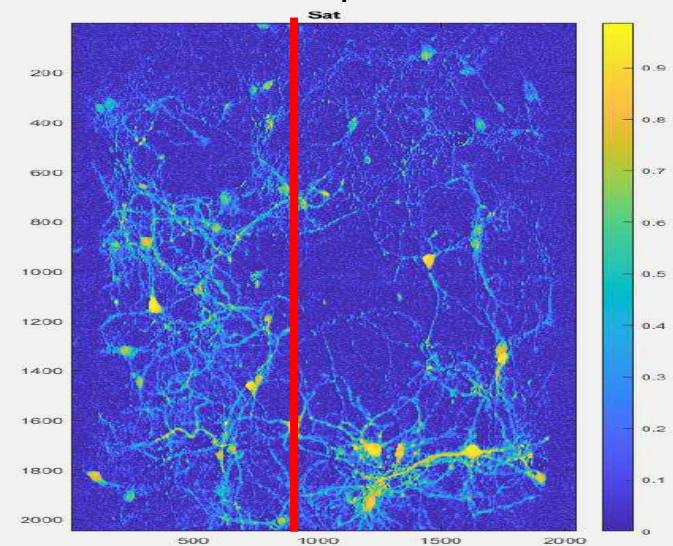
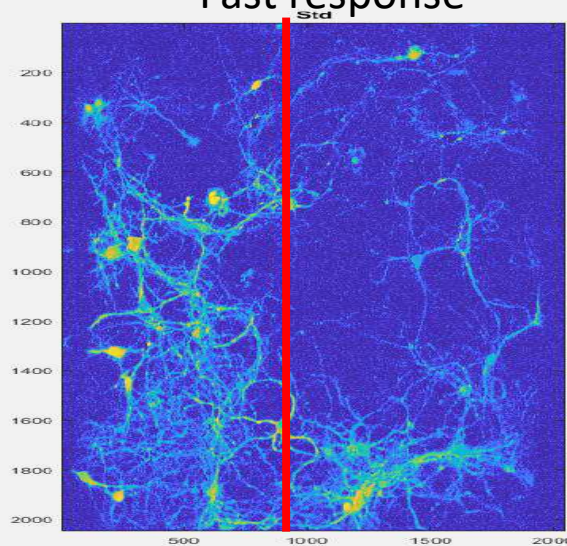


# Writing an engram: patterned illumination



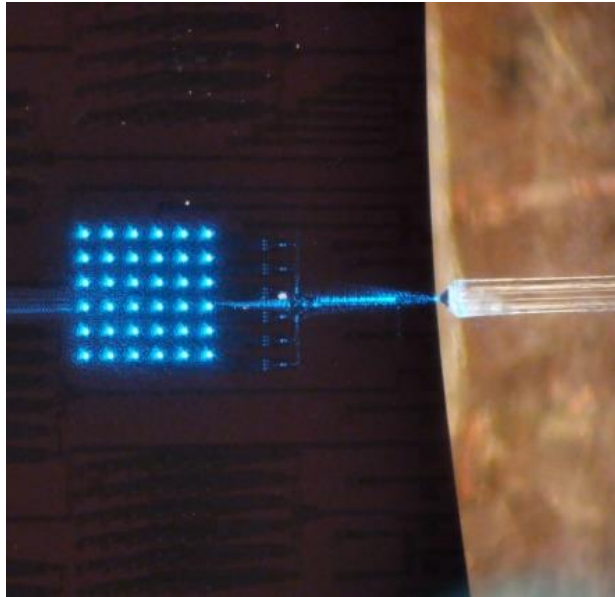
Fast response

late response

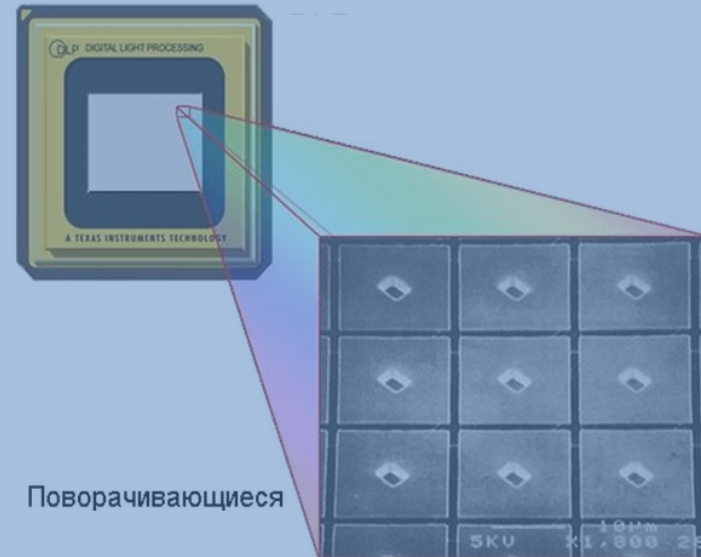


# Writing an engram: patterned illumination

## Photonic Chip

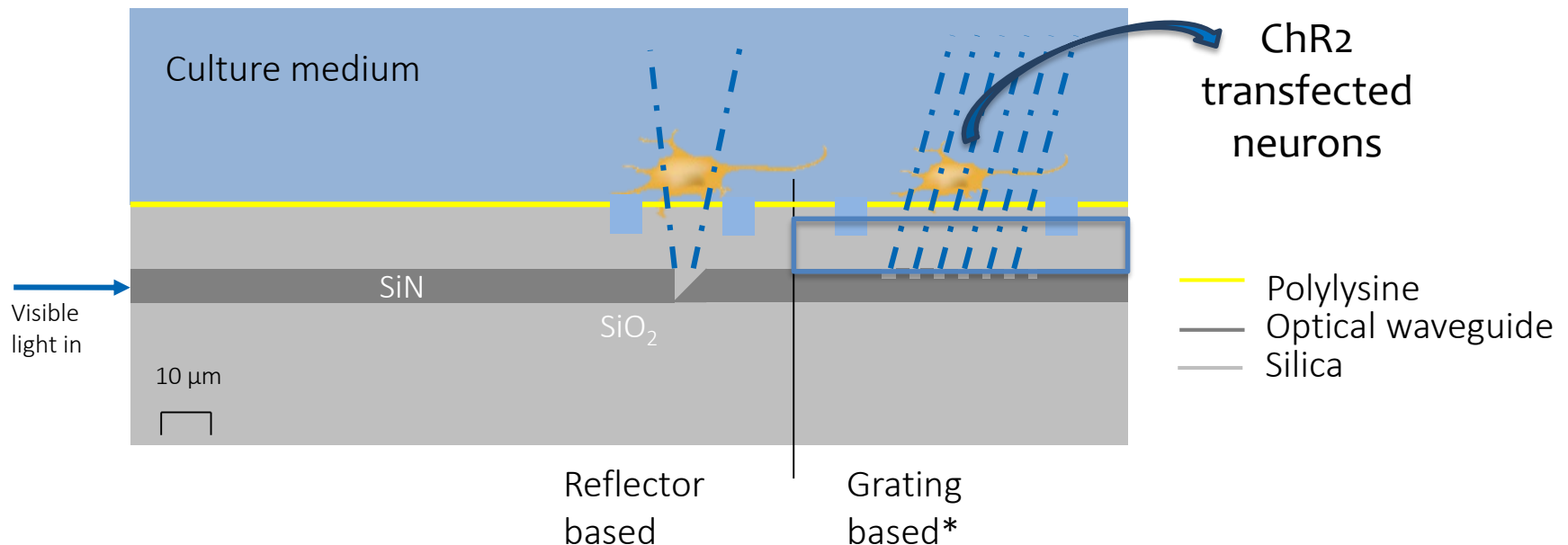


## Digital Light Processing (DLP)

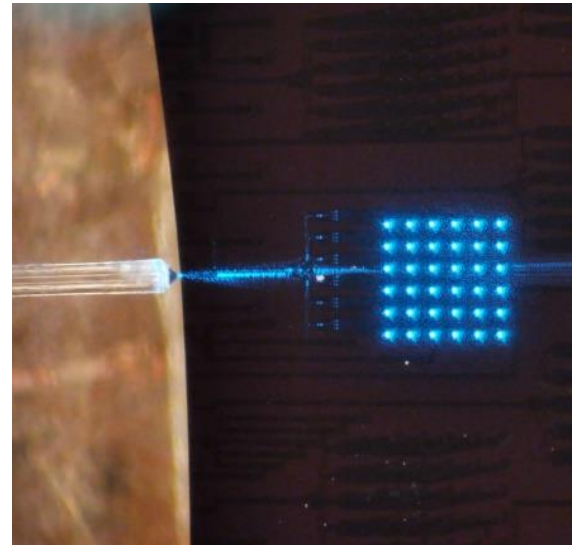
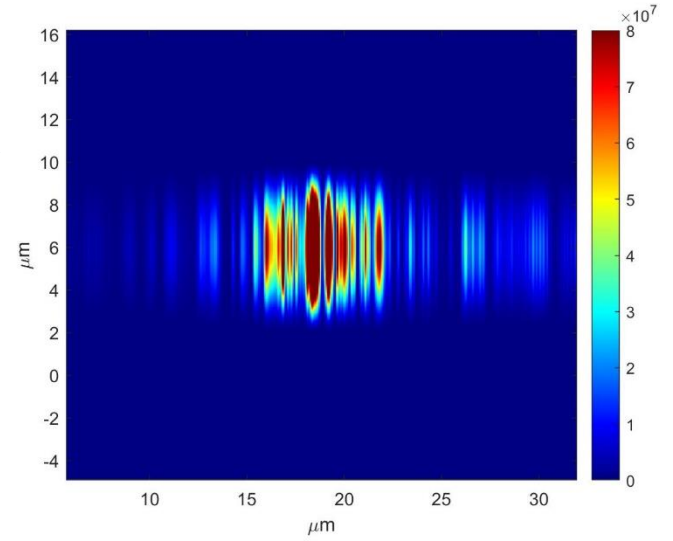
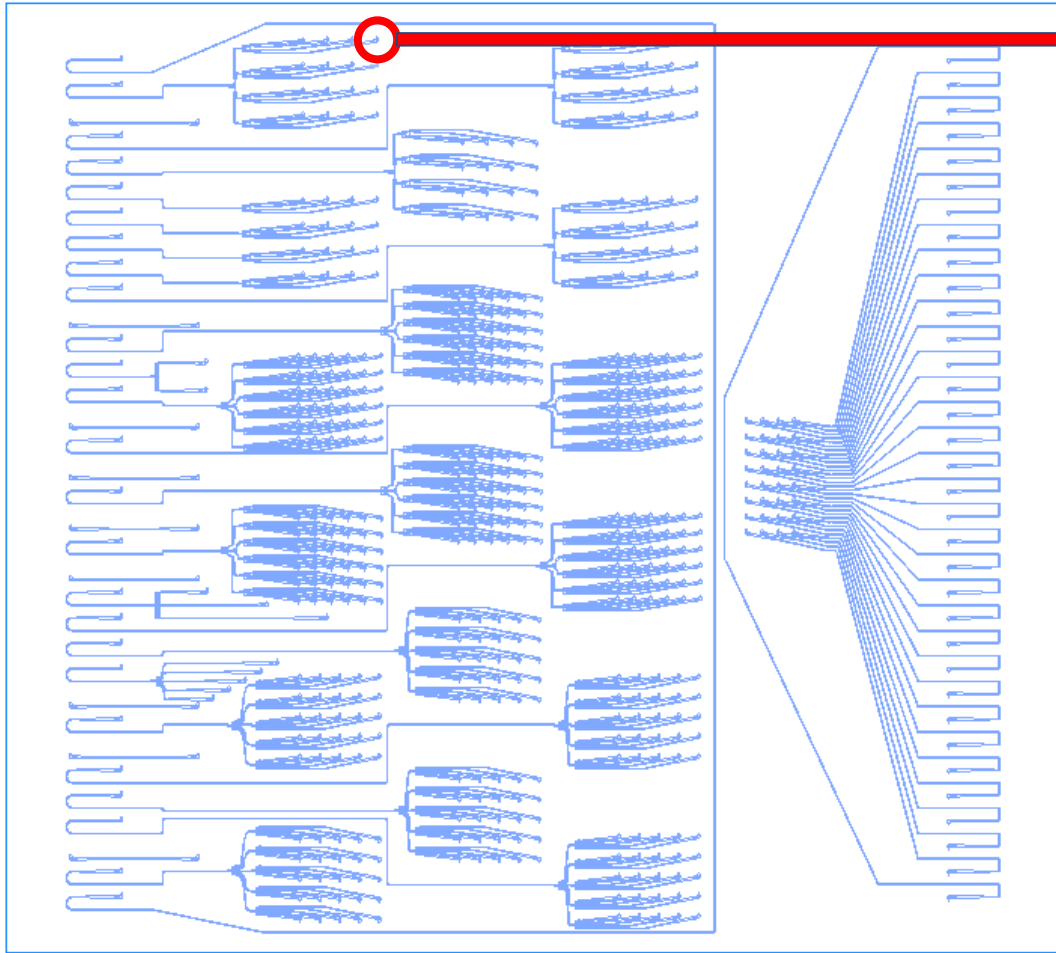


# Photonic chip

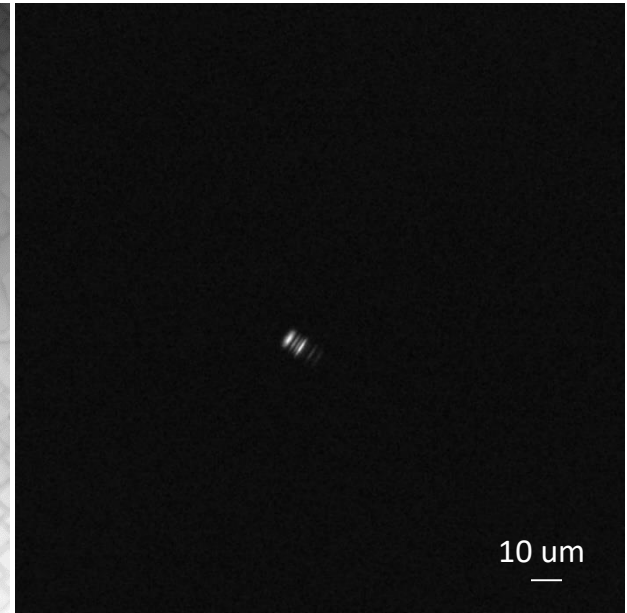
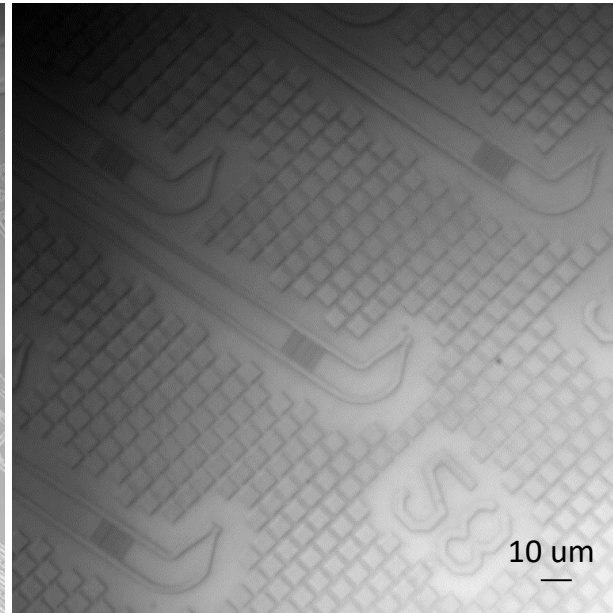
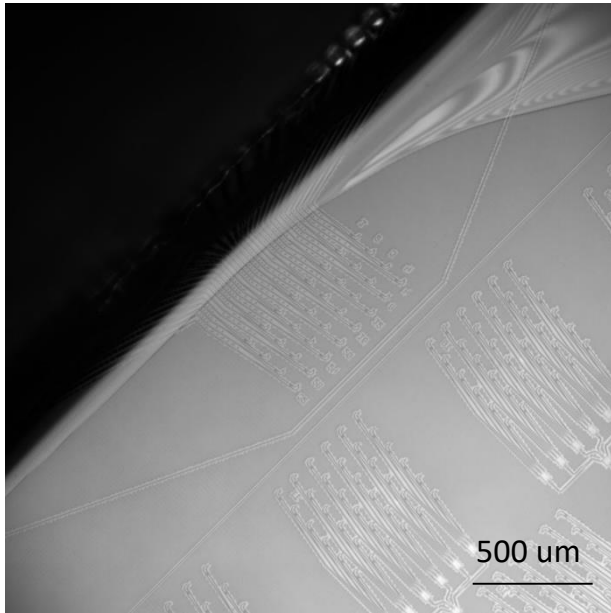
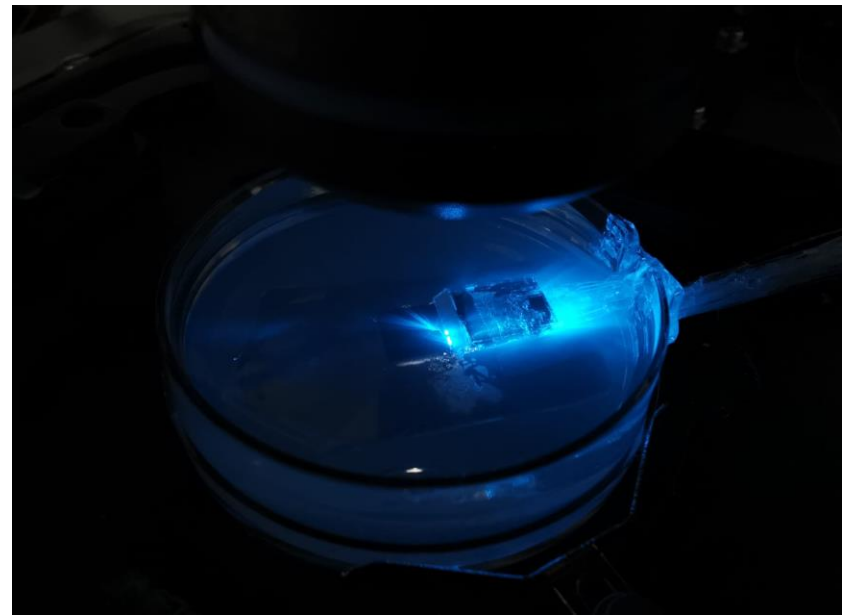
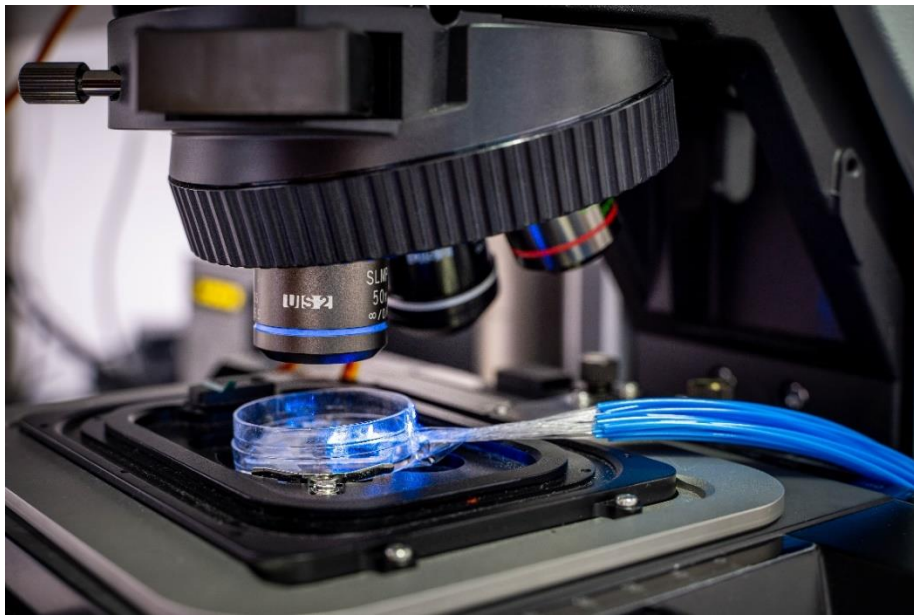
- Design of the structures in the visible range of the spectrum
- Design of scattering structures
- Respect biological constrains:  $10 \frac{\text{mW}}{\text{mm}^2}$  on 10  $\mu\text{m}$  diameter body



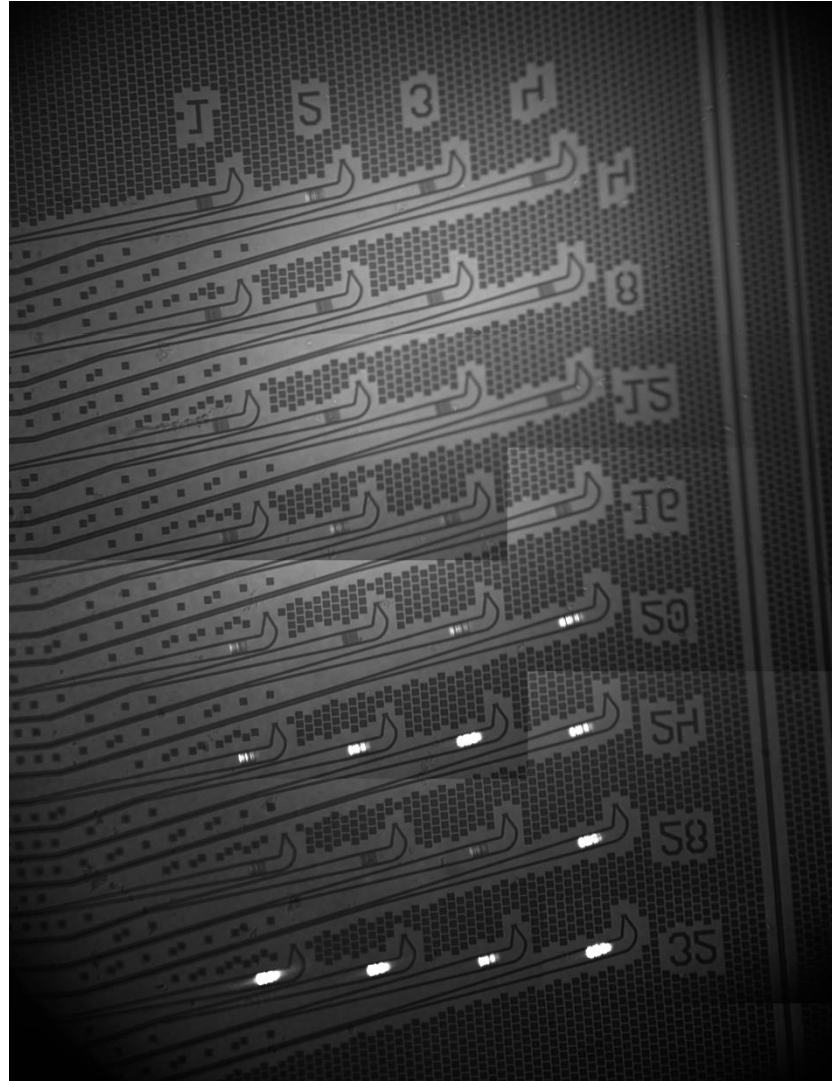
# Scattering grating



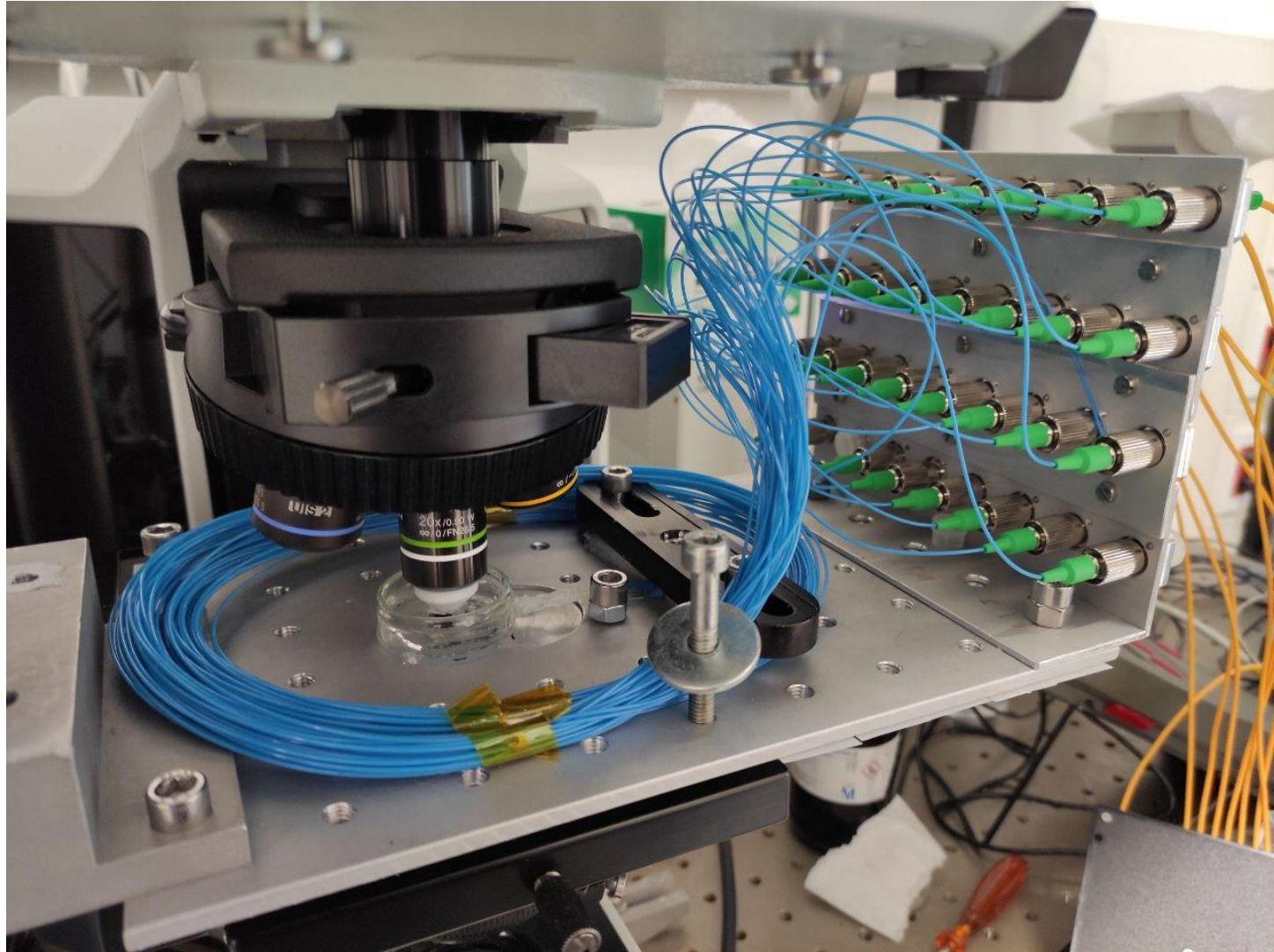




# Selective turn on of specific gratings



# The final system



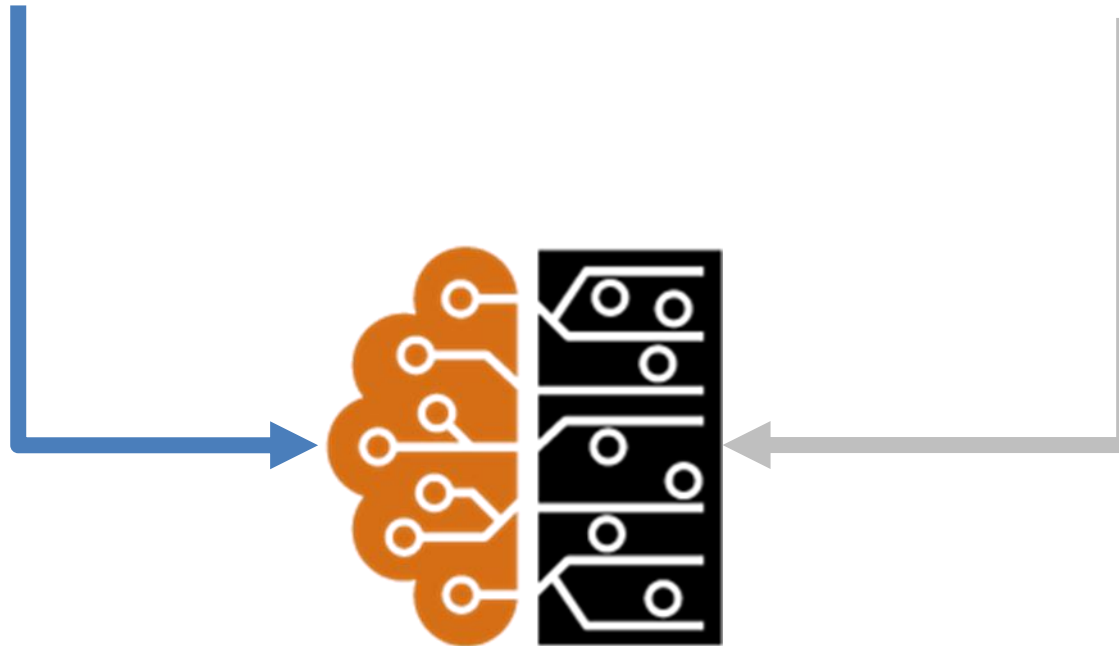
# The vision



BIOLOGICAL CULTURE



PHOTONIC INTEGRATED CIRCUIT



HYBRID ARTIFICIAL-BIOLOGICAL NETWORK

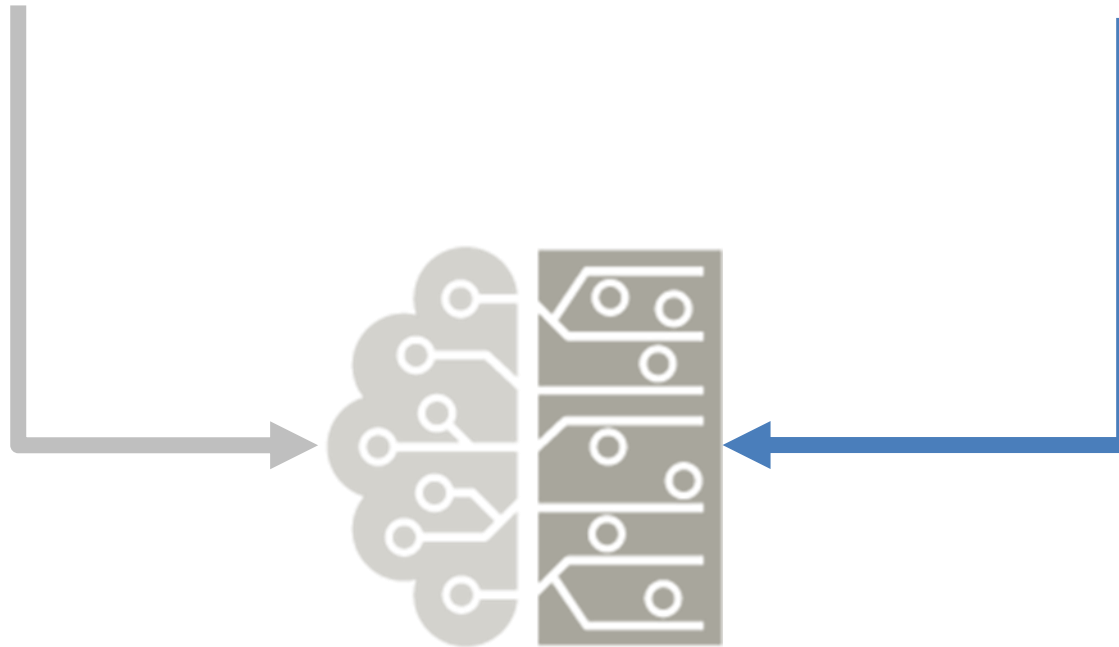
# The vision



BIOLOGICAL CULTURE

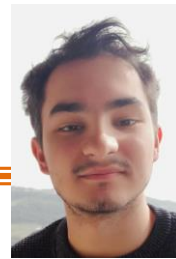
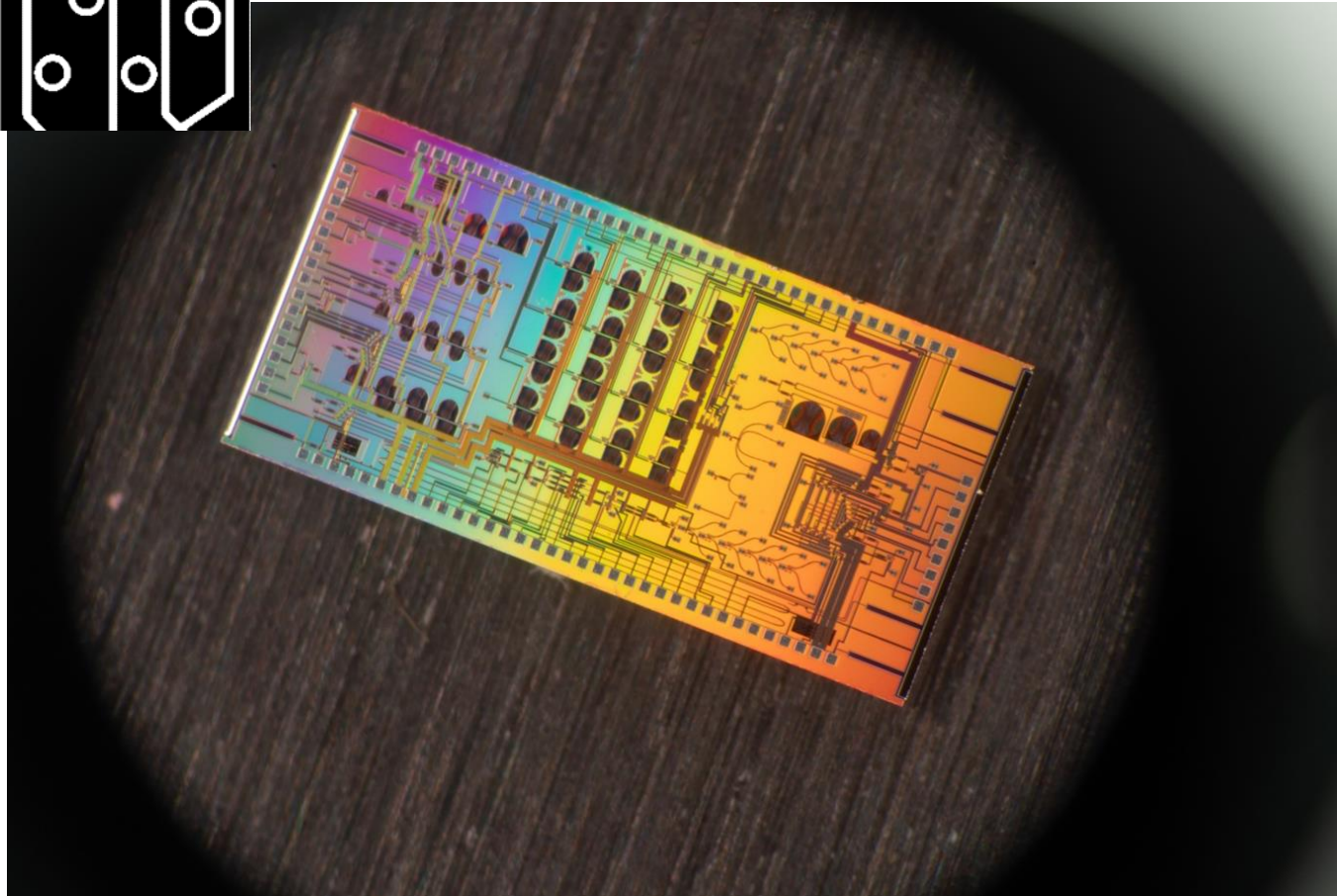


PHOTONIC INTEGRATED CIRCUIT

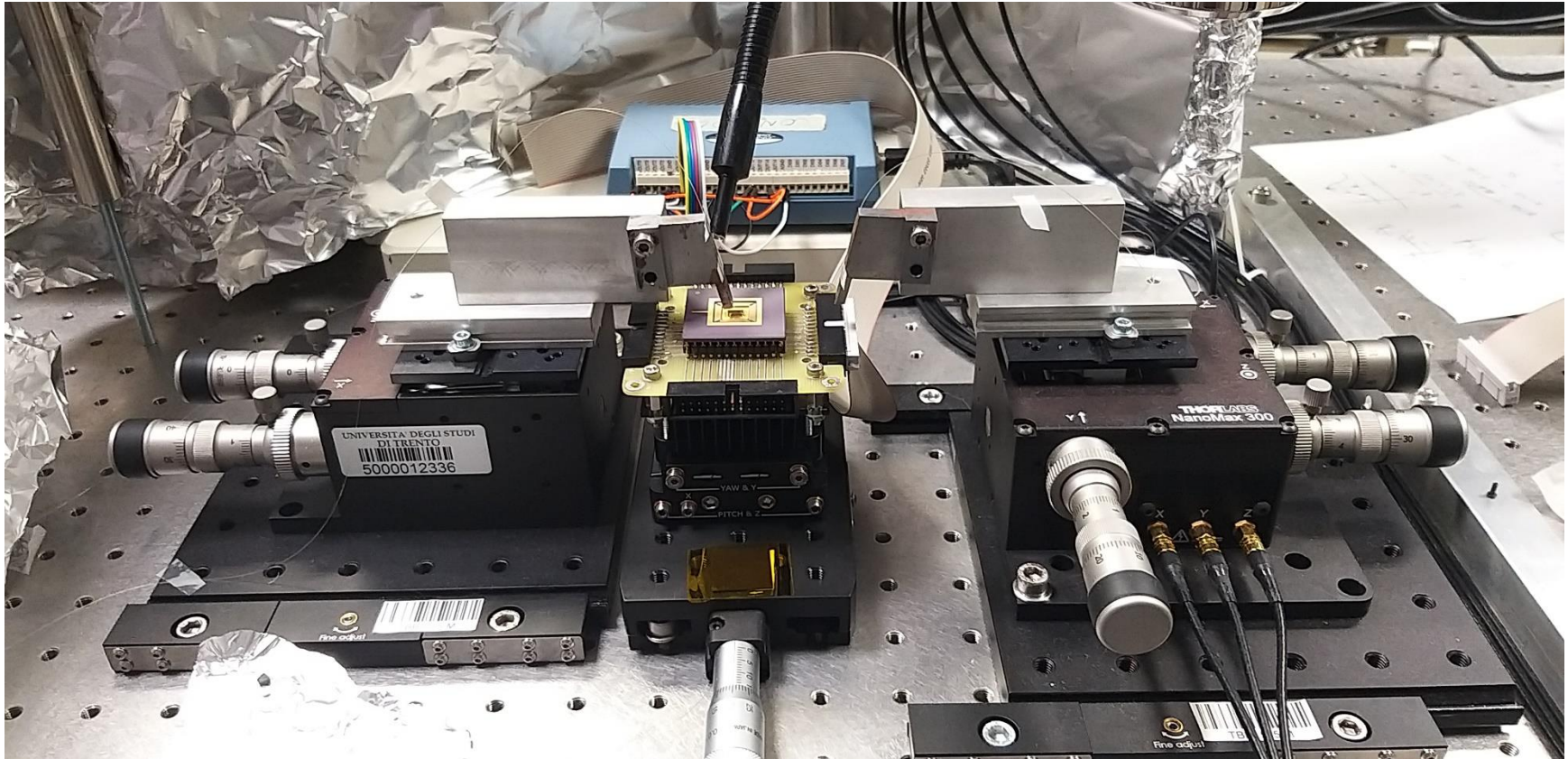


HYBRID ARTIFICIAL-BIOLOGICAL NETWORK

# Neuromorphic Photonics



# Photonic circuits



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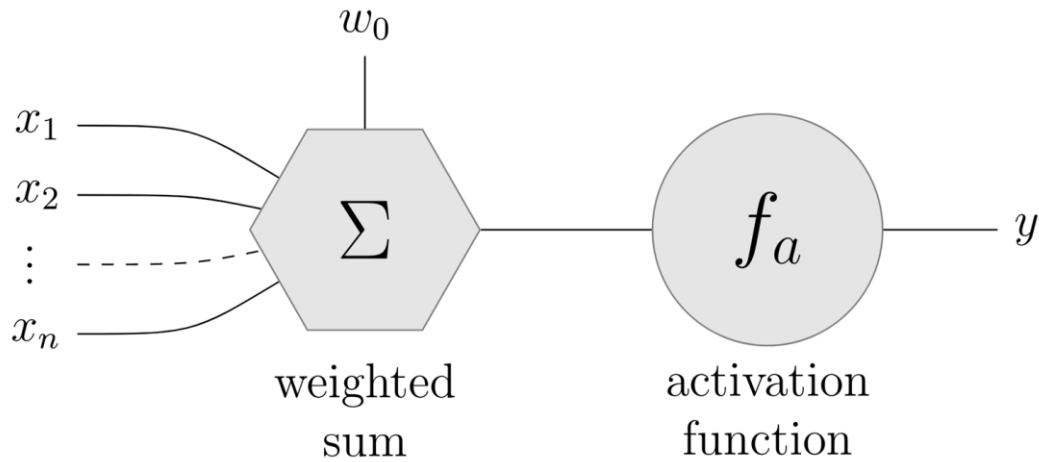
A first example

# THE FEED-FORWARD NEURAL NETWORK

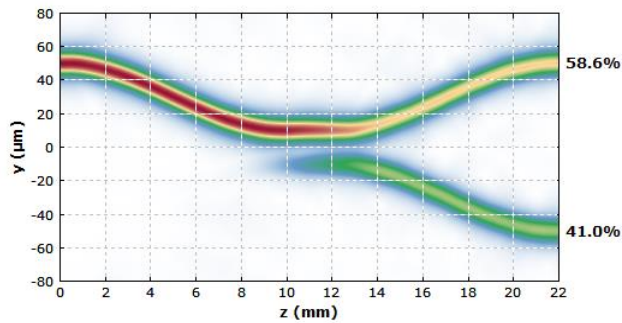




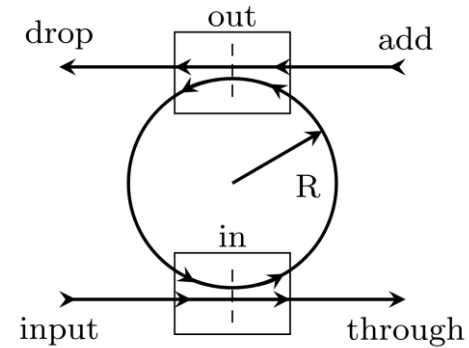
# Optical neuron



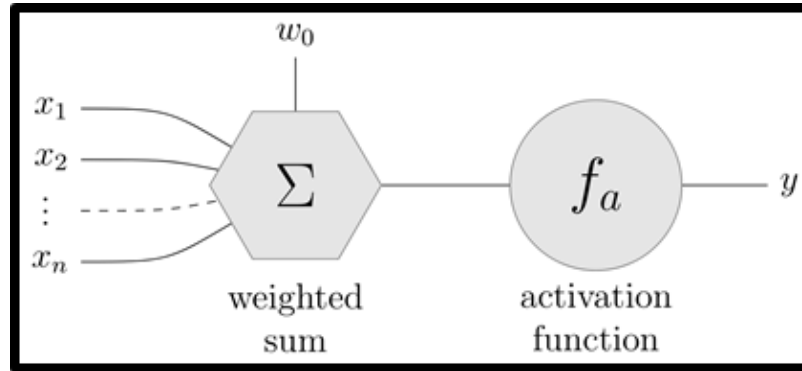
## Optical coupler



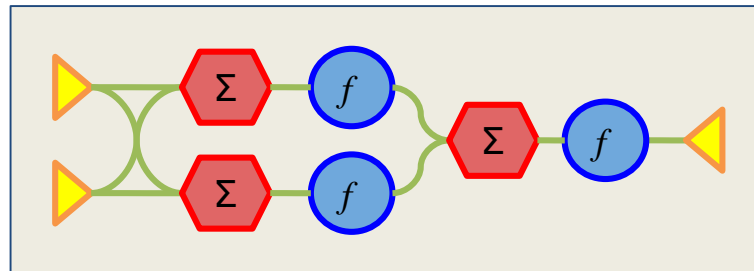
## Microring resonator



# Feed Forward Neural Network



Simple deep learning network

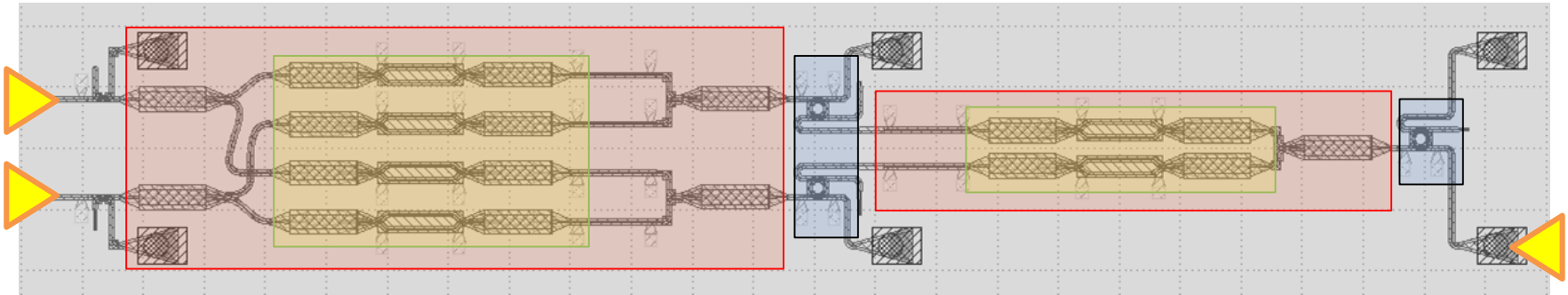


2 input neurons

2 neurons in the  
hidden layer

1 output neuron

# Feed Forward Neural Network



- 2 input neurons, 2 neurons in the hidden layer, 1 output neuron
- 2+1 microresonators
- 15 heaters in total:
  - 6 weights, 2 for each Mach-Zehnder Interferometer (12)
  - 3 tunable rings (3), nonlinear node
- Serial execution of layers
- Network training via a gradient-free method (particle swarm technique)

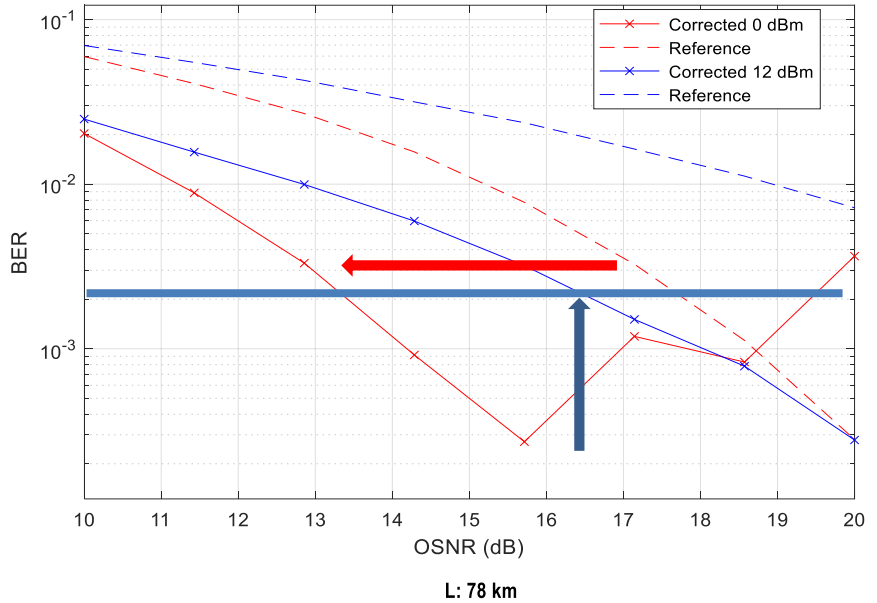
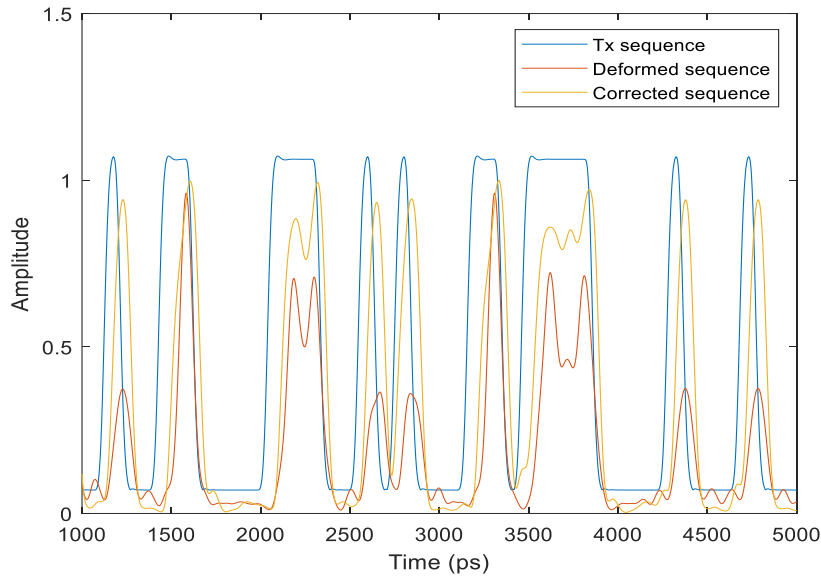
# Feed Forward (FF) Neural Network

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- Applications to a TLC problem
  - Nonlinear distortion of optical signal along an optical fiber
  - Signal recovery

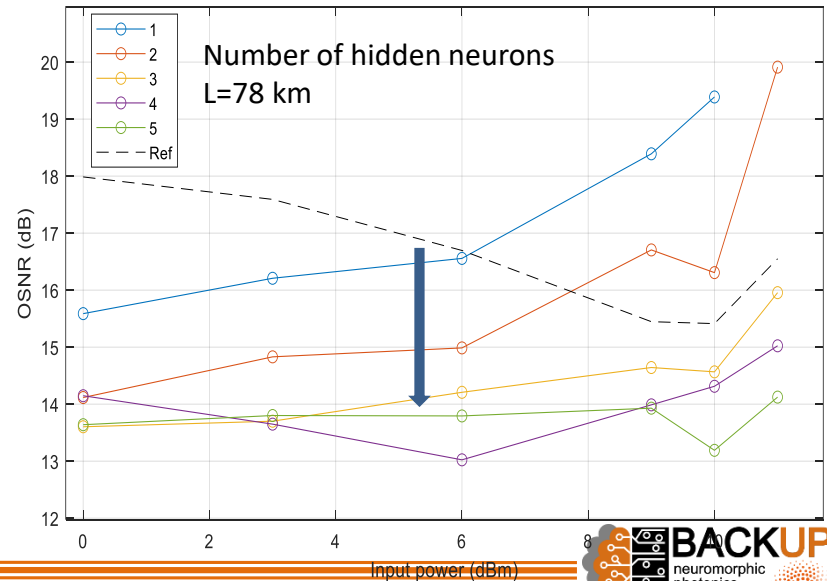


# Feed Forward FF Neural Network



238 km fibre, 10 Gbps  
 10 input neurons, 5 hidden neurons,  
 1 output neuron  
 One-bit inter-symbol interference

pre-FEC BER threshold of  $2 \times 10^{-3}$   
 typical of 100G systems



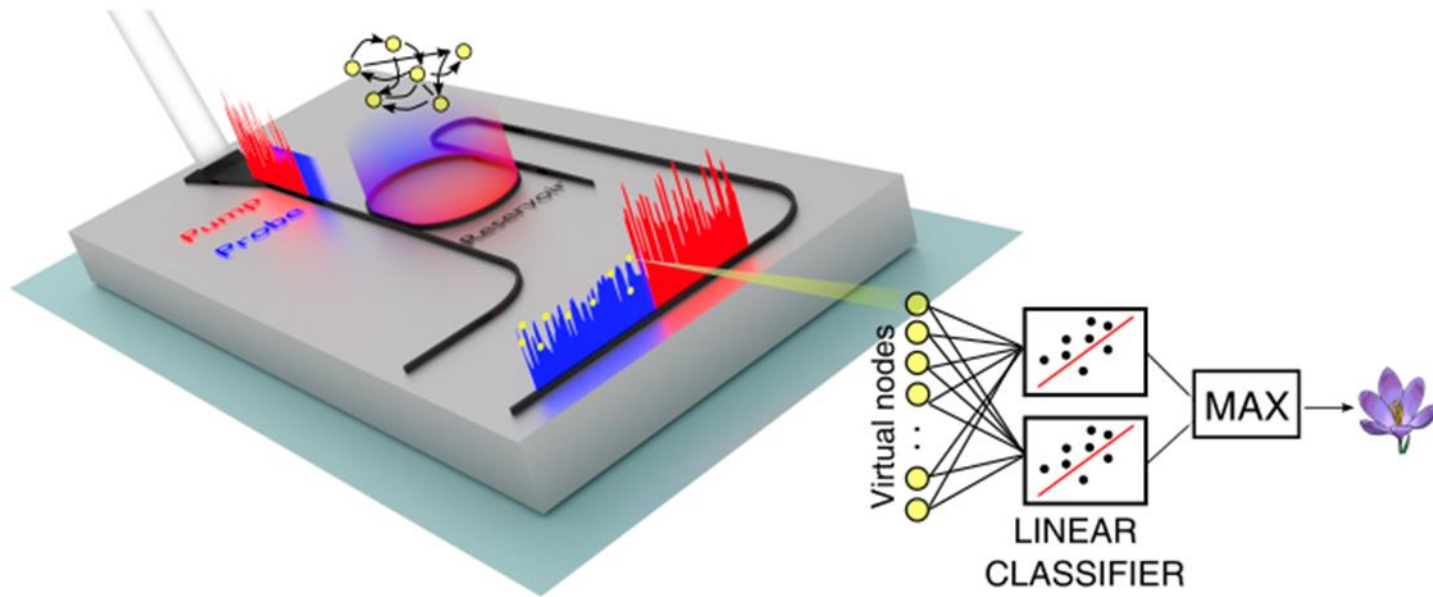
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A second example

# THE RESERVOIR COMPUTING NETWORK



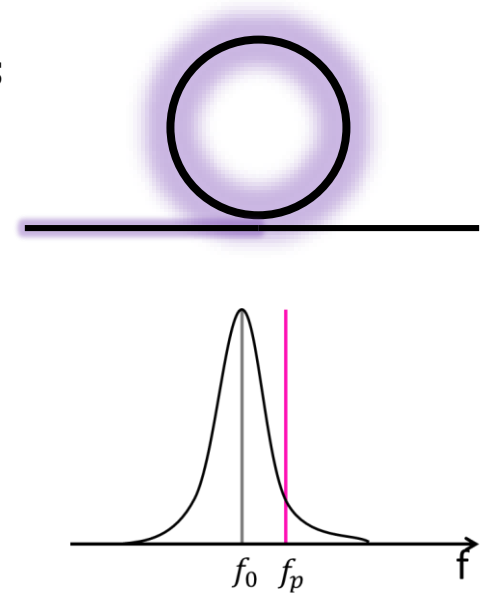
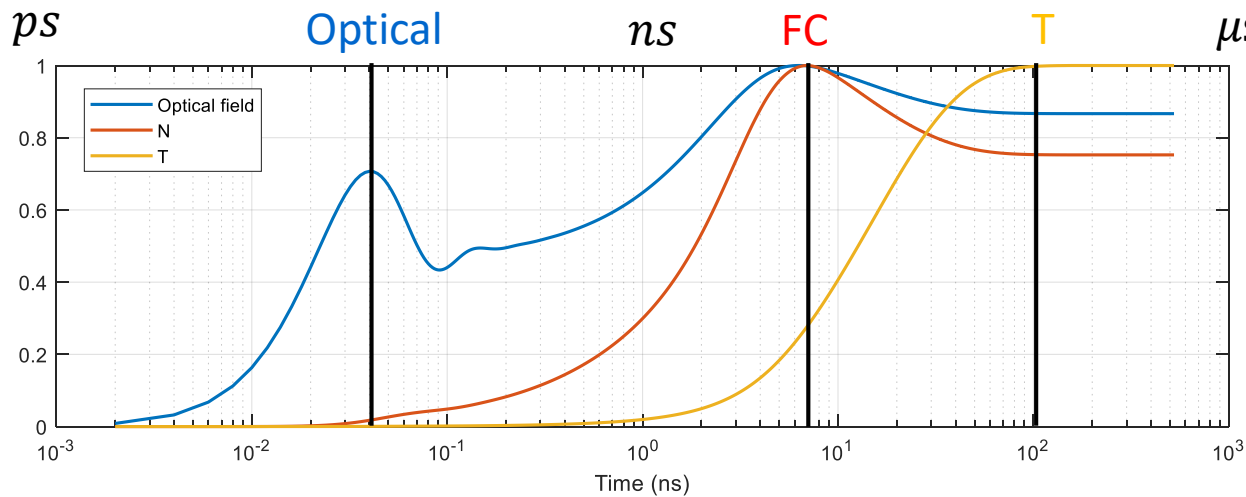
# Reservoir computing based on a silicon microring and time multiplexing for binary and analog operations



arXiv.org > physics > arXiv:2101.01664

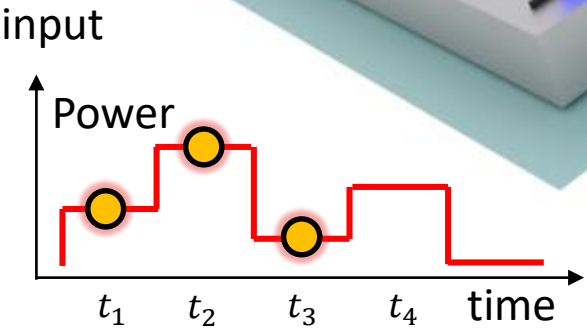
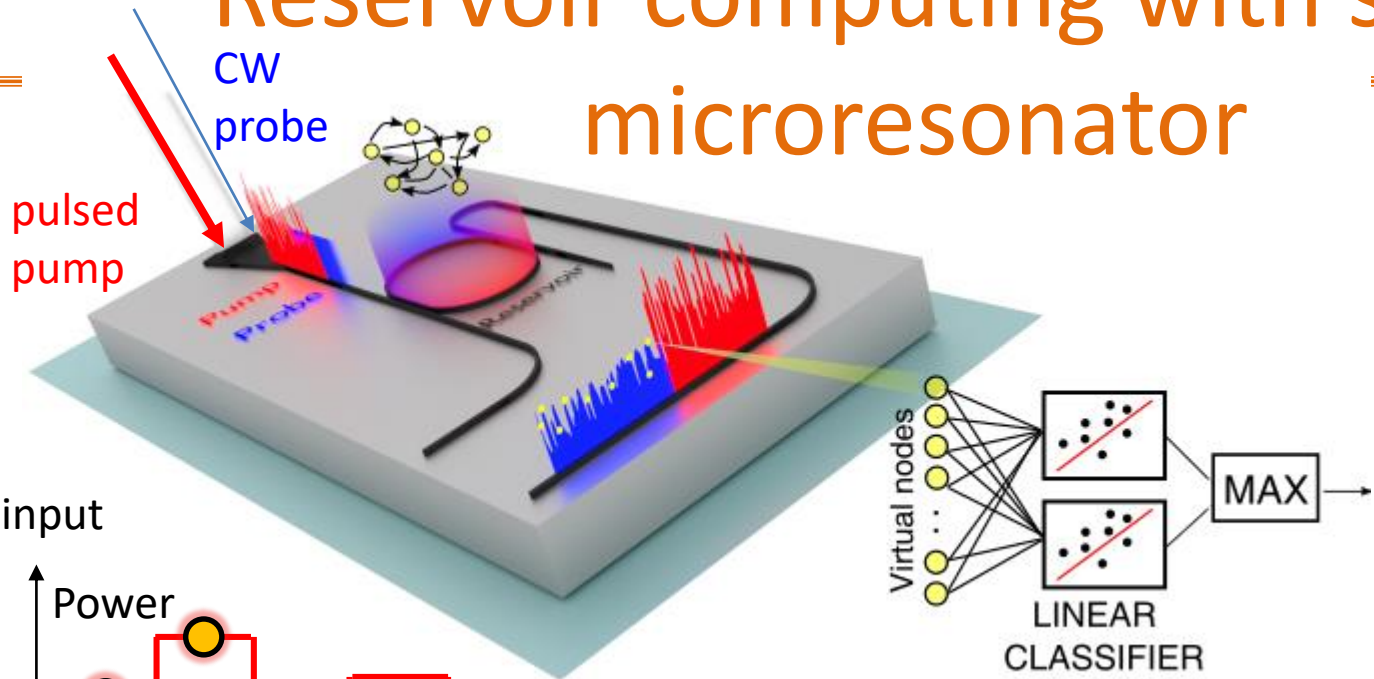
# Reservoir time scale

- **Optical field dynamics, free carrier dynamics**, temperature dynamics
- Possibility to have short and long term memory (time scale varying by 5 order of magnitude)

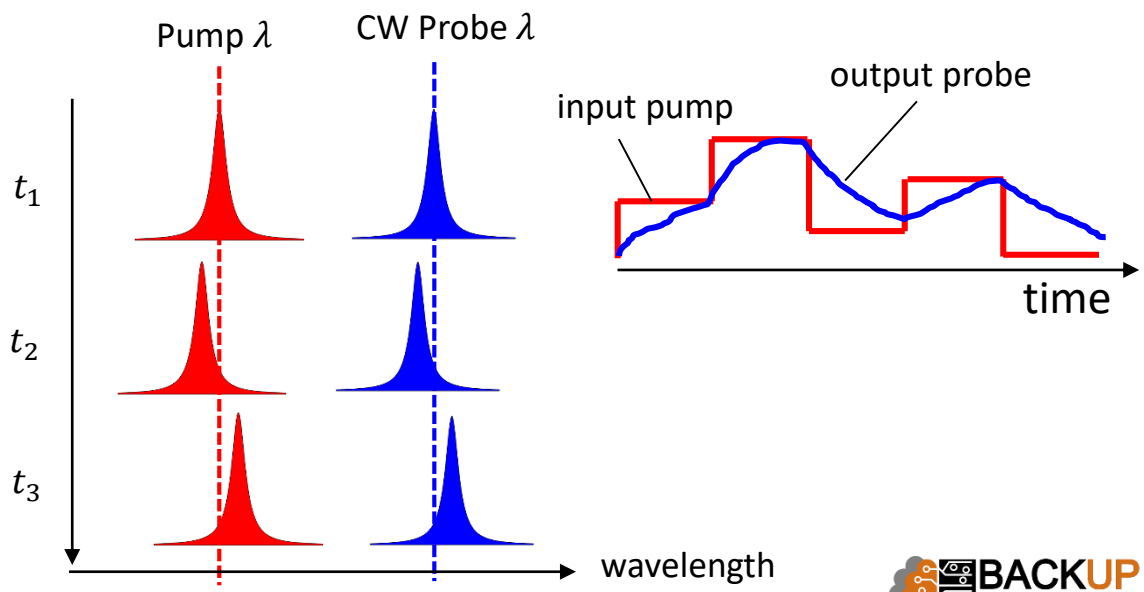




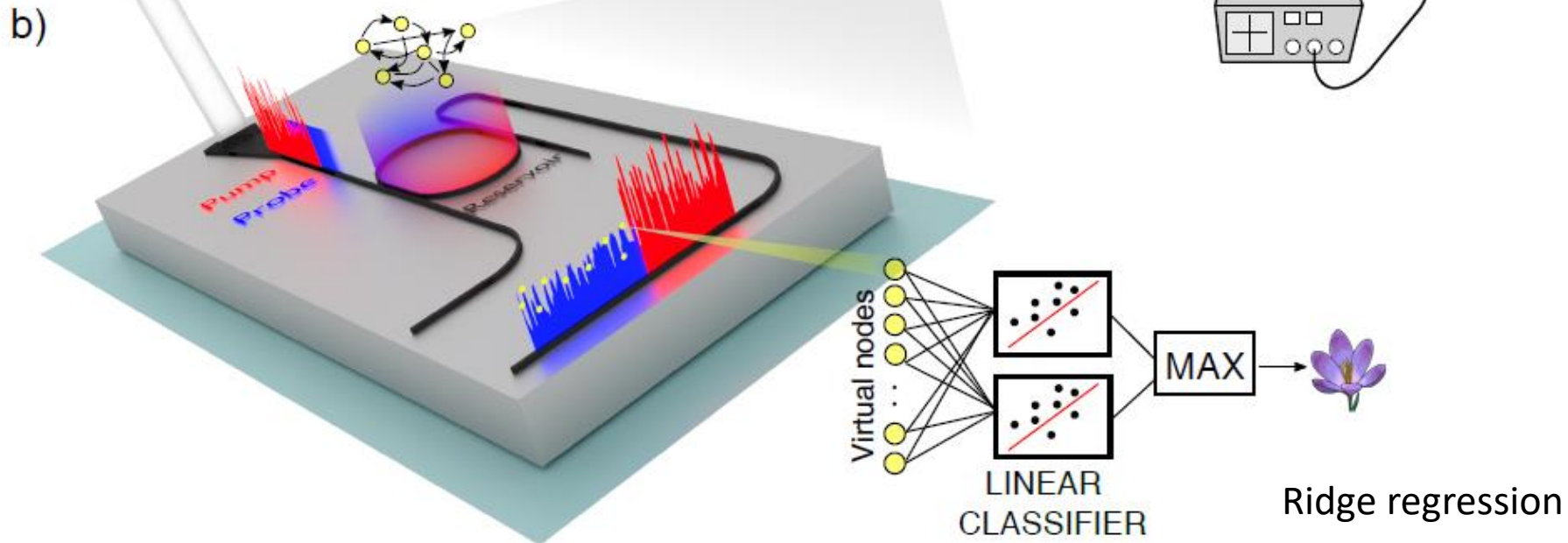
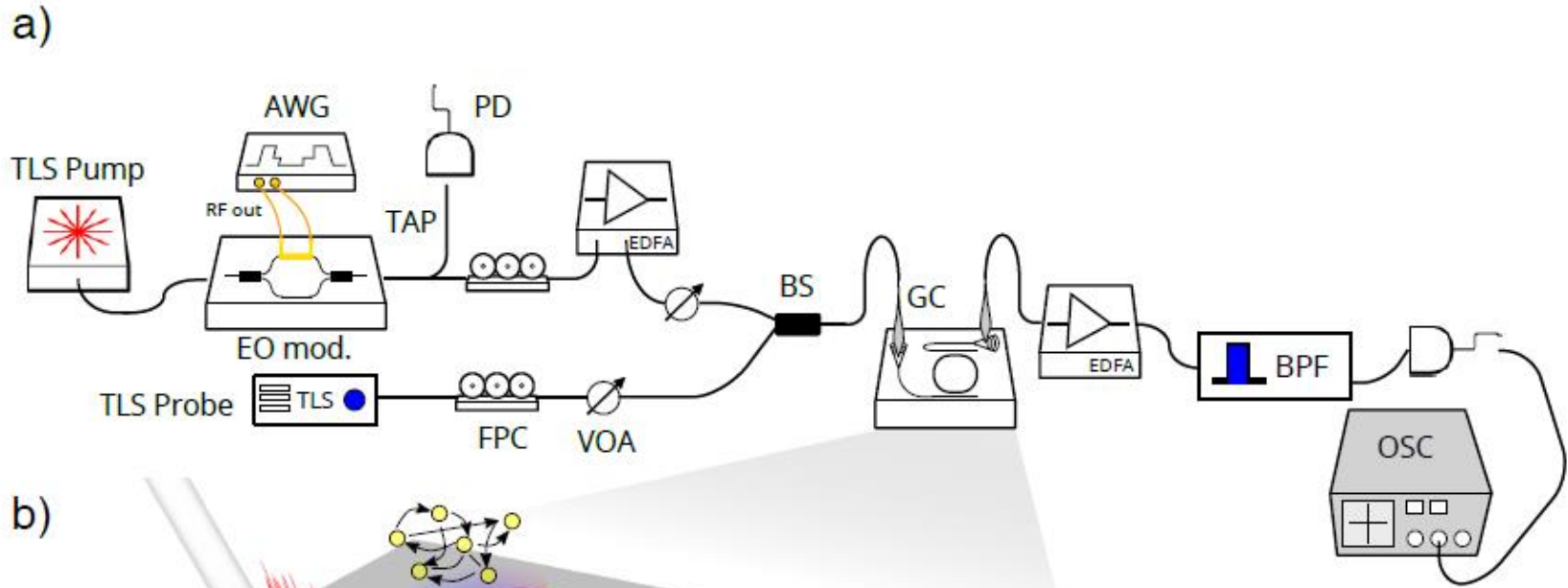
# Reservoir computing with silicon microresonator



Pump induces TPA  
 TPA generates FC  
 FC by FCA and FCD affect Probe  
 →  
 The input information is nonlinearly transferred to the probe



# The experimental setup



# Analog input: Iris species recognition

**iris setosa**



petal    sepal

**iris versicolor**

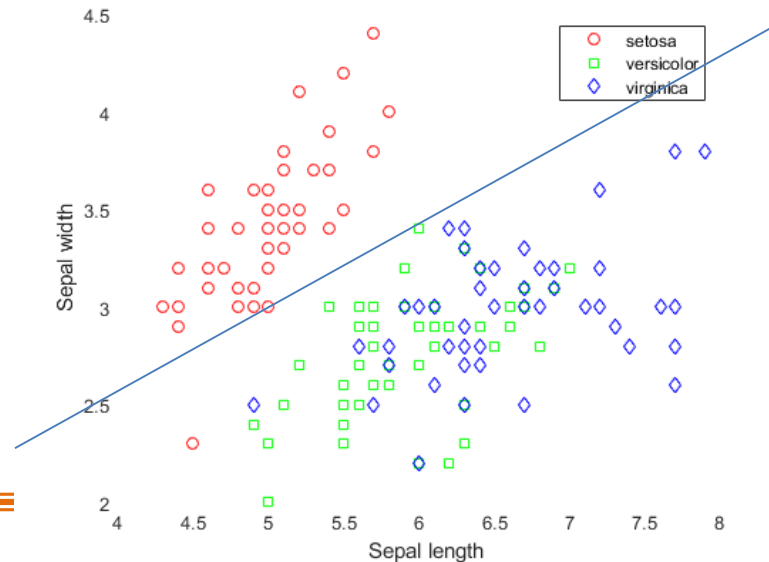
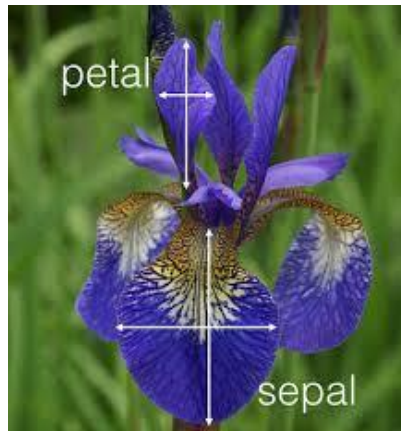


petal    sepal

**iris virginica**

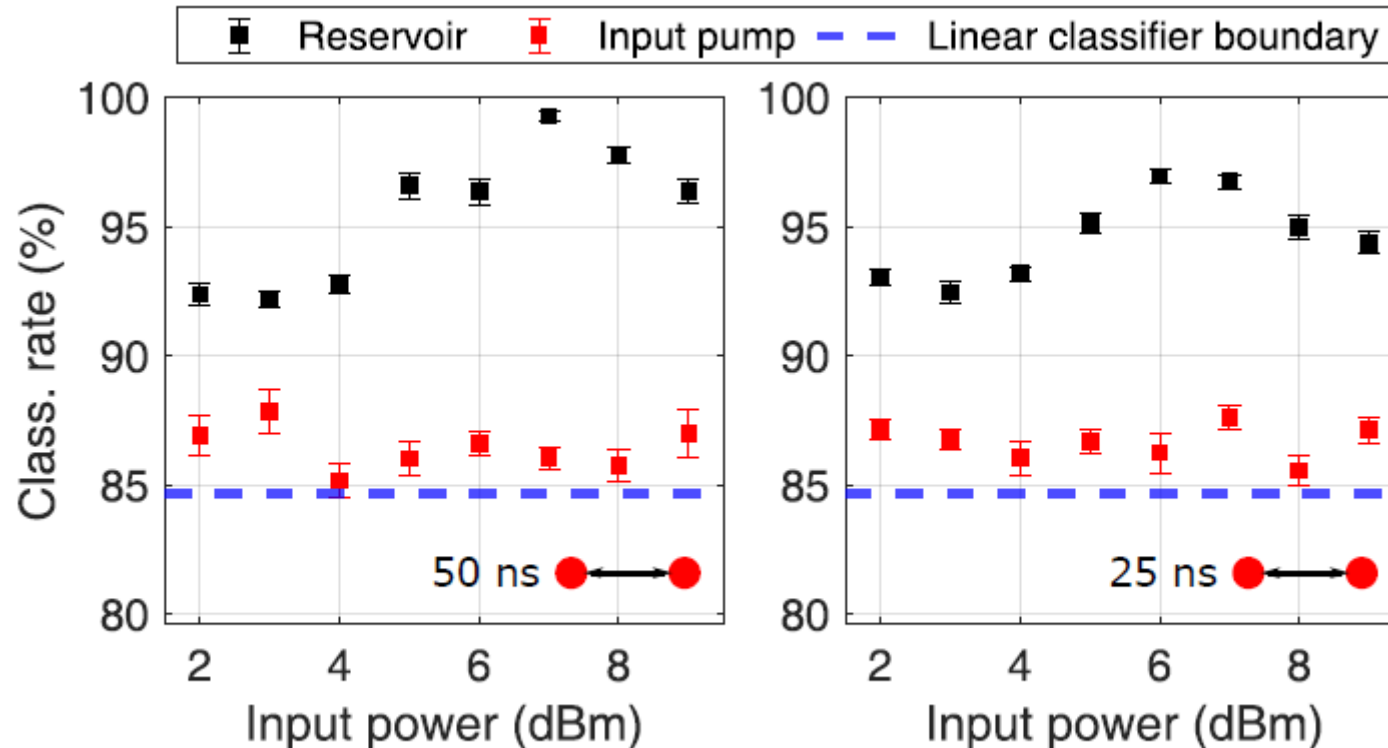


petal    sepal



Not  
linearly  
separable

# Classification results



20 Mbps

40 Mbps

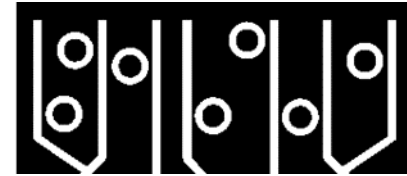
~ 380000 flowers classified each second  
with  $(99.3 \pm 2)\%$  accuracy

Categories are assigned by training multiple linear classifiers, one for each subspecies, and decisions are made on the basis of a winner takes all scheme

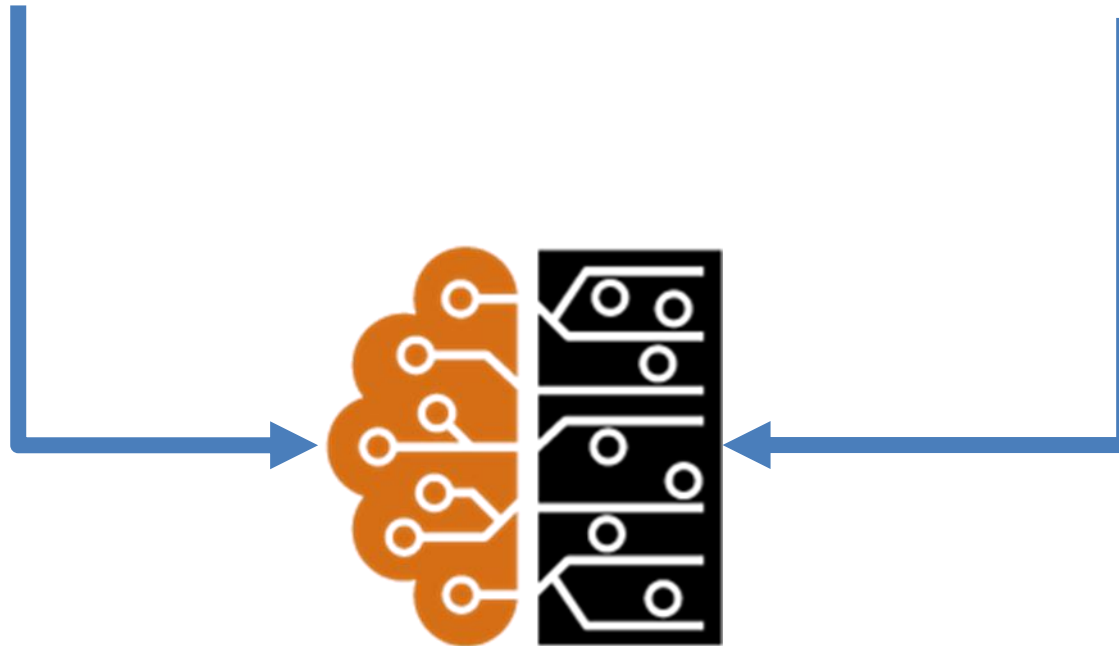
# Conclusion



BIOLOGICAL CULTURE



PHOTONIC INTEGRATED CIRCUIT



HYBRID ARTIFICIAL-BIOLOGICAL NETWORK

# Acknowledgments



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



UNIVERSITY  
OF TRENTO - Italy  
Department of Physics



# Acknowledgements

- Quantum science and technologies



- Neuromorphic photonics

