Neuromorphic Photonics

Lorenzo Pavesi

Nanoscience Laboratory

Department of Physics - UNITN

BACKUP
neuromorphic photonics and the brain

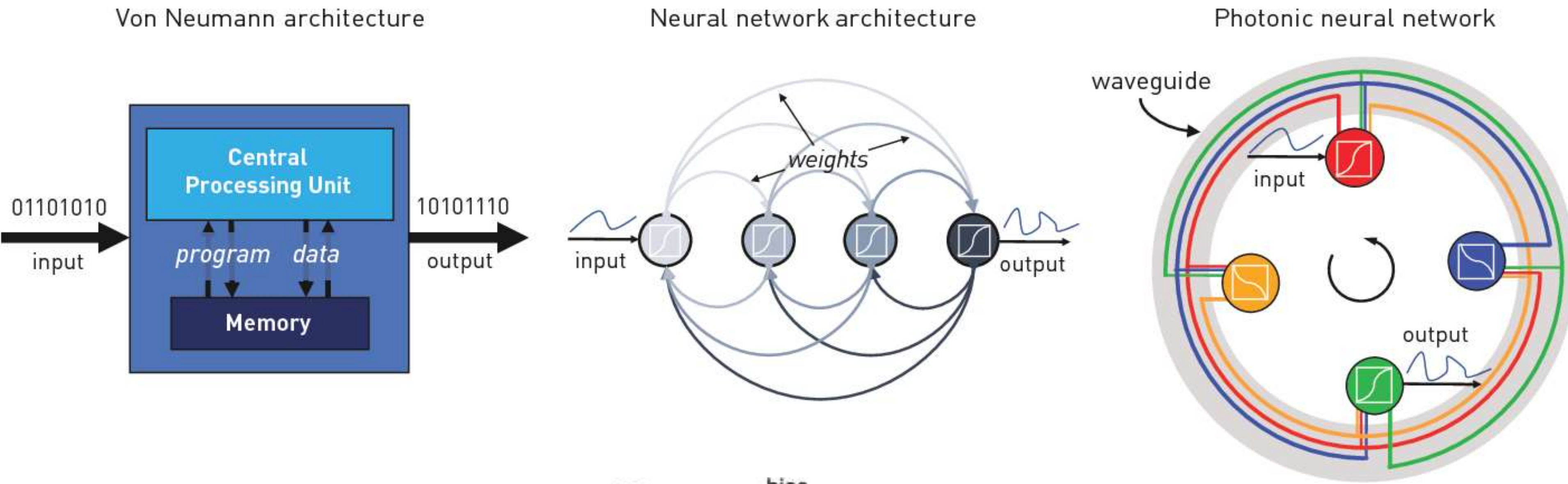
erc
European Research Council
Established by the European Commission

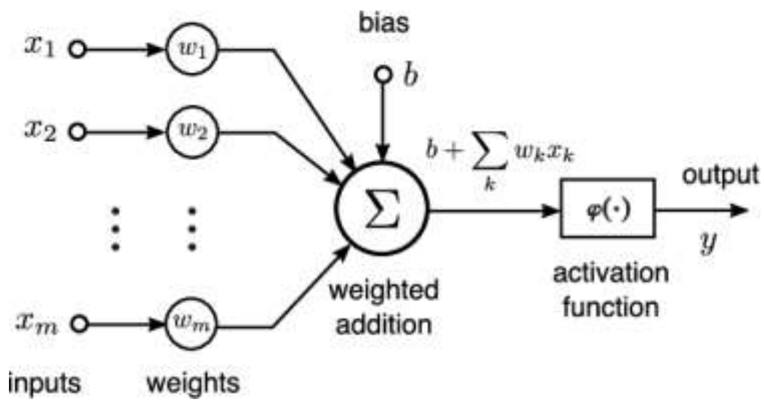
Most of the Slides are from

Outline

- Neuromorphics photonics
- The single neuron: the microresonator
- Interconnected Neurons: the SCISSOR
- The BACKUP project
- Conclusions

Neuromorphic Photonics



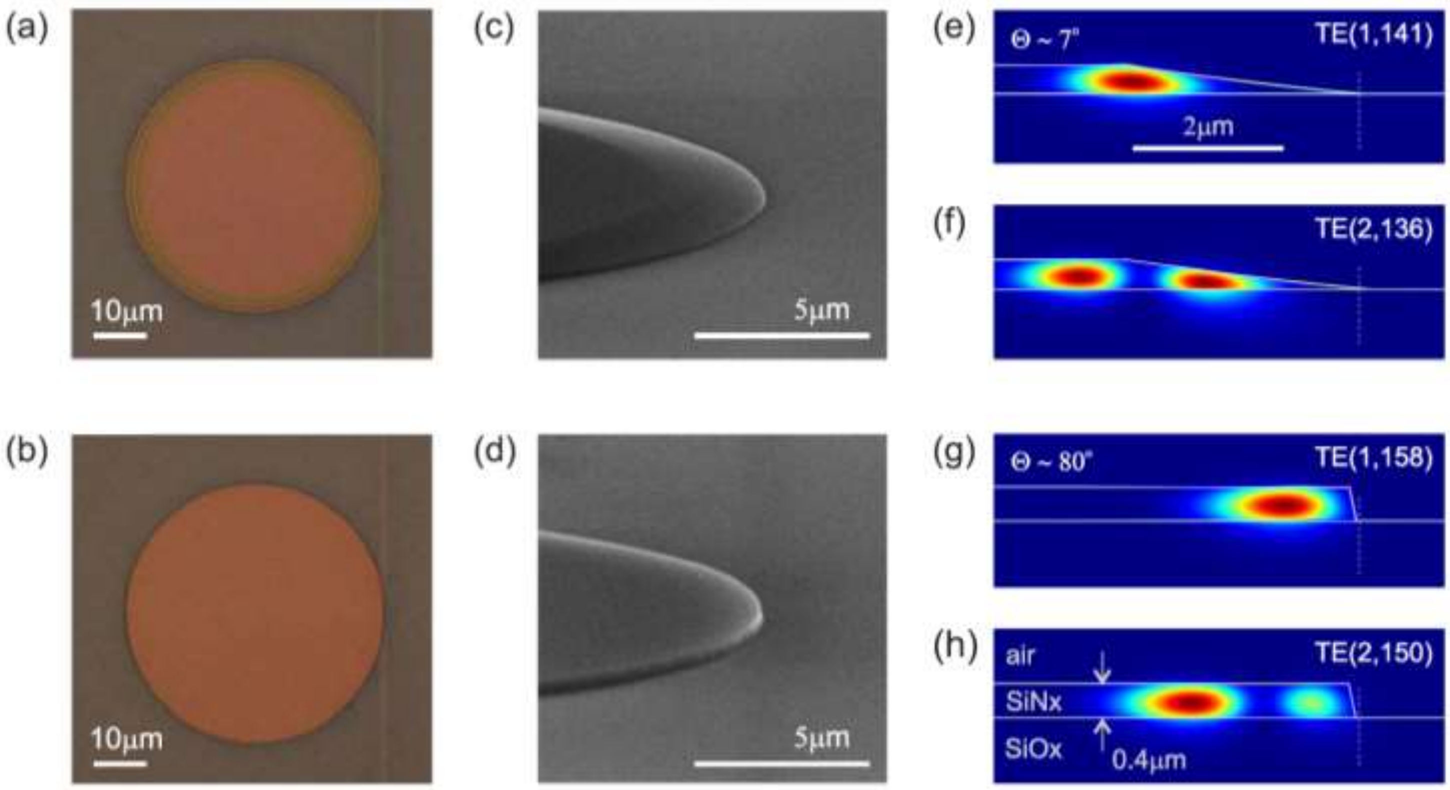


Principles of Neuromorphic Photonics

Bhavin J. Shastri, Alexander N. Tait, Thomas Ferreira de Lima, Mitchell A. Nahmias, Hsuan-Tung Peng, Paul R. Prucnal

https://doi.org/10.1007/978-3-642-27737-5_702-1

Integrated Silicon Photonics

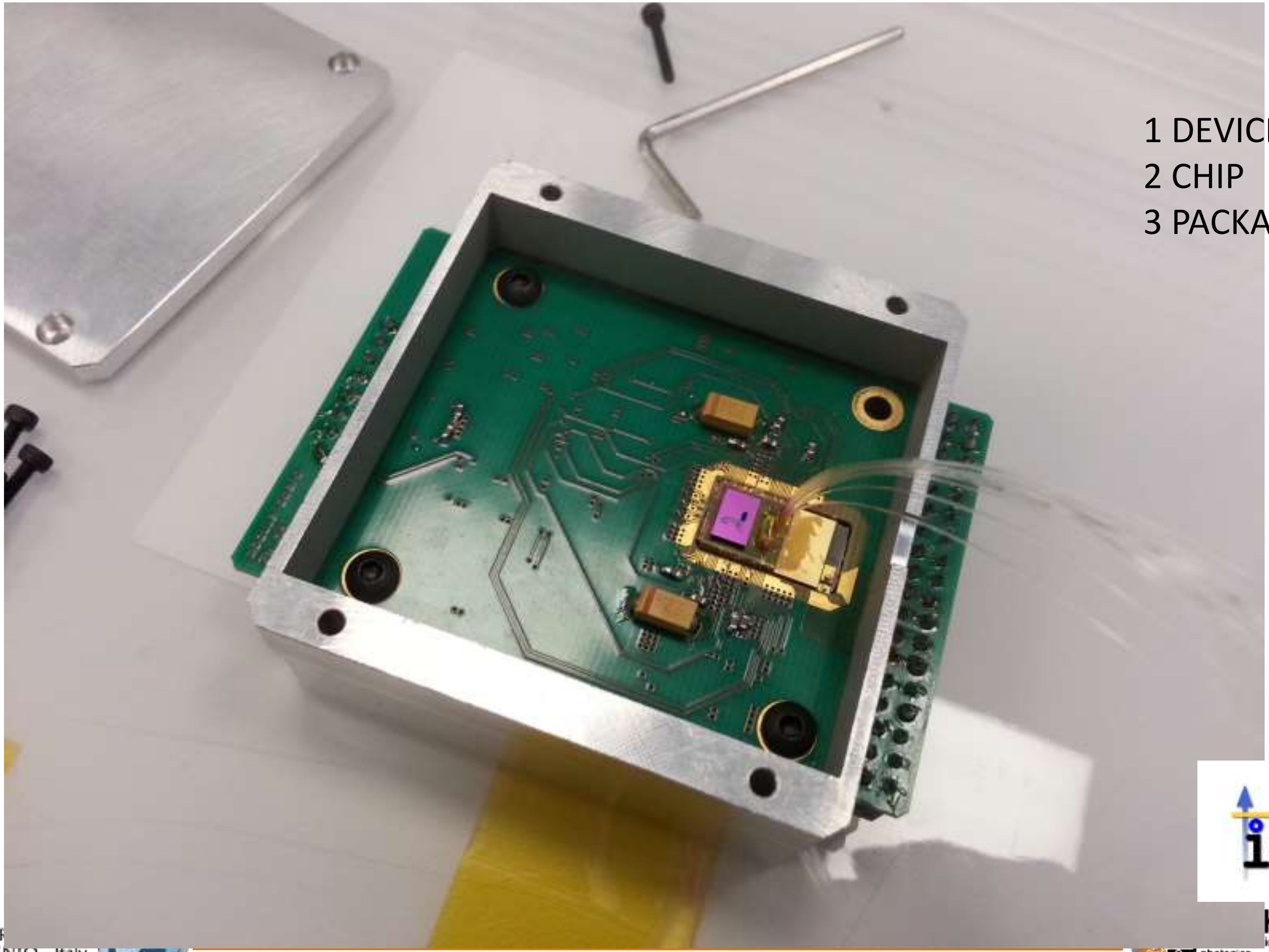


1 DEVICE

Integrated Silicon Photonics

1 DEVICE
2 CHIP

Integrated Silicon Photonics

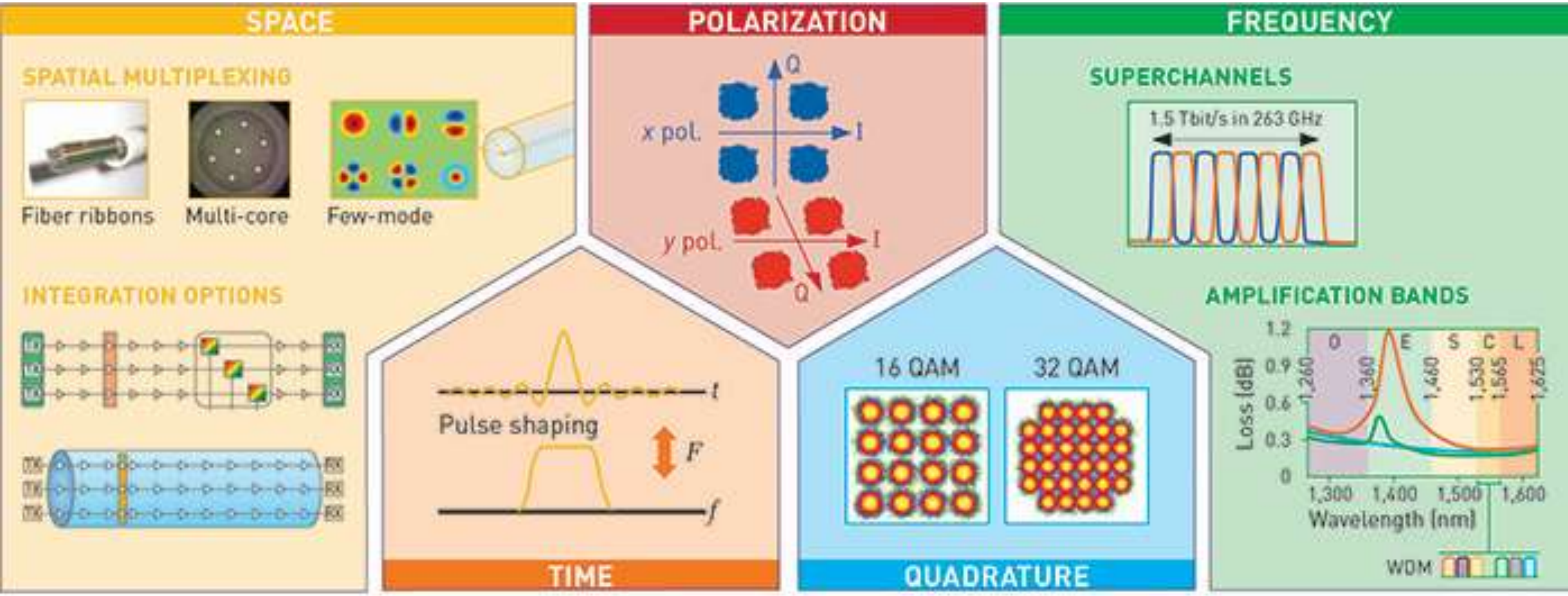


1 DEVICE
2 CHIP
3 PACKAGE

Neuromorphic Photonics

- Waveguides can boost interconnectivity by carrying many signals at the same time through multiplexing
- Low-energy, photonic operations can reduce the computational burden of performing linear functions such as weighted sum
- Neuromorphic photonics combines the efficiency of neural networks and the speed of photonics to build computing systems

Different multiplexing possibilities

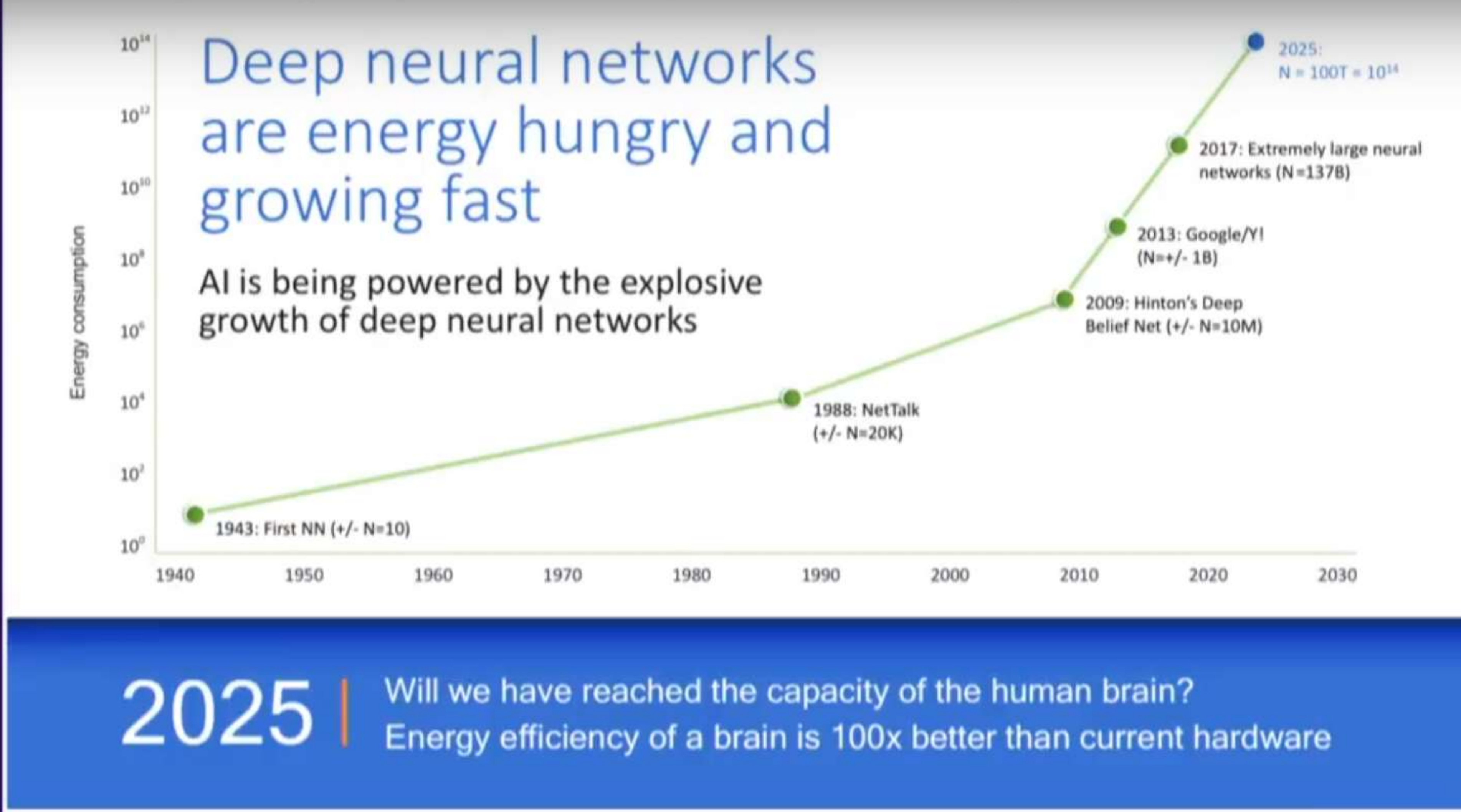


The five physical dimensions and their use in optical modulation and multiplexing

Neuromorphic Photonics

- Waveguides can boost interconnectivity by carrying many signals at the same time through optical multiplexing,
- Low-energy, photonic operations can reduce the computational burden of performing linear functions such as weighted sum
- Neuromorphic photonics combines the efficiency of neural networks and the speed of photonics to build computing systems

Max Welling: Intelligence per Kilowatthour (ICML 2018 invited talk)



30:50 / 1:01:29

Scorri per i dettagli

Power advantage of optics

Even for small ONNs, this power efficiency is **already at least five orders of magnitude** better than conventional GPUs, where P/R ≈ 100 pJ per FLOP (shown in fig. 1.1.8 of ref. 47), or **at least three orders of magnitude** better than an 'ideal' (see Method for a detailed definition of 'ideal') electronic computer, where P/R ≈ 1 pJ per FLOP assuming low-energy operations (by doing a 16 bit FLOP instead of the conventional 64 bit FLOP) and locality (no energy is used on data movement).

Deep learning with coherent nanophotonic circuits, Nature Photonics (2017) DOI: 10.1038/NPHOTON.2017.93

Neuromorphic Photonics

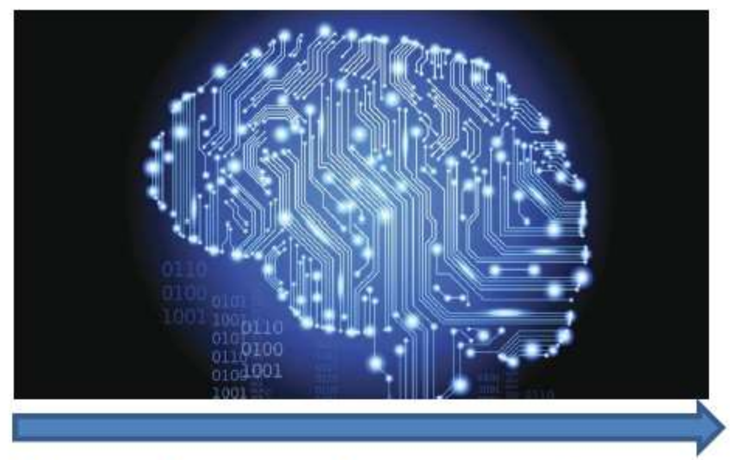
- Waveguides can boost interconnectivity by carrying many signals at the same time through optical multiplexing,
- Low-energy, photonic operations can reduce the computational burden of performing linear functions such as weighted sum
- Neuromorphic photonics combines the efficiency of neural networks and the speed of photonics

Why photonics?

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

Factor of 10^9!!

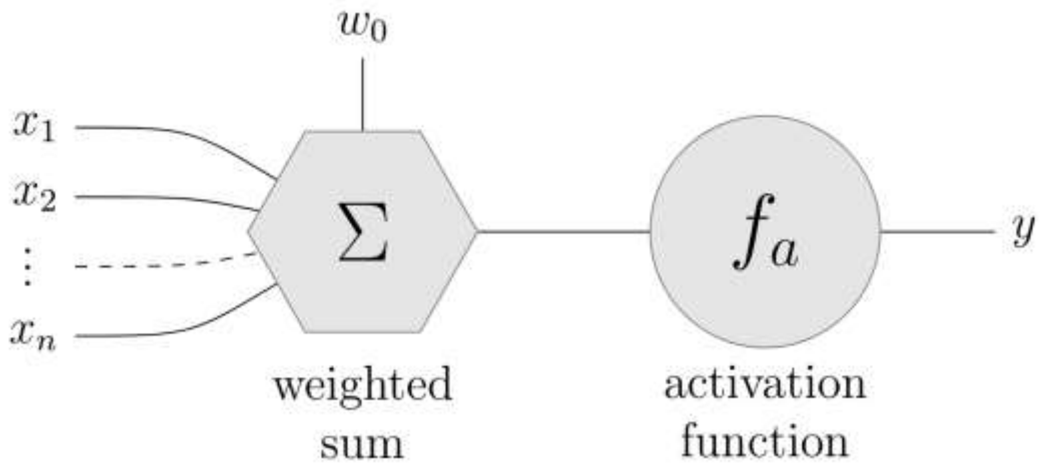
Brain learning process 15 years



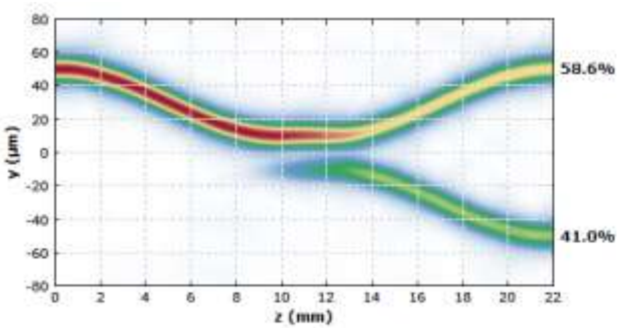
Artificial optical brain 0.5 seconds

By Mattia Mancinelli

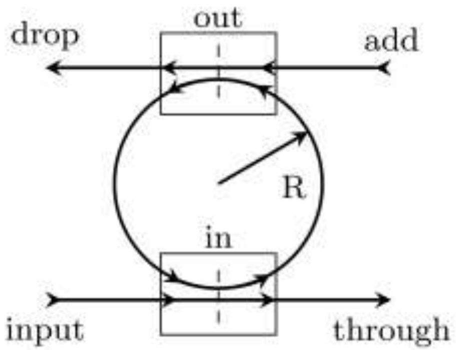
Optical neuron



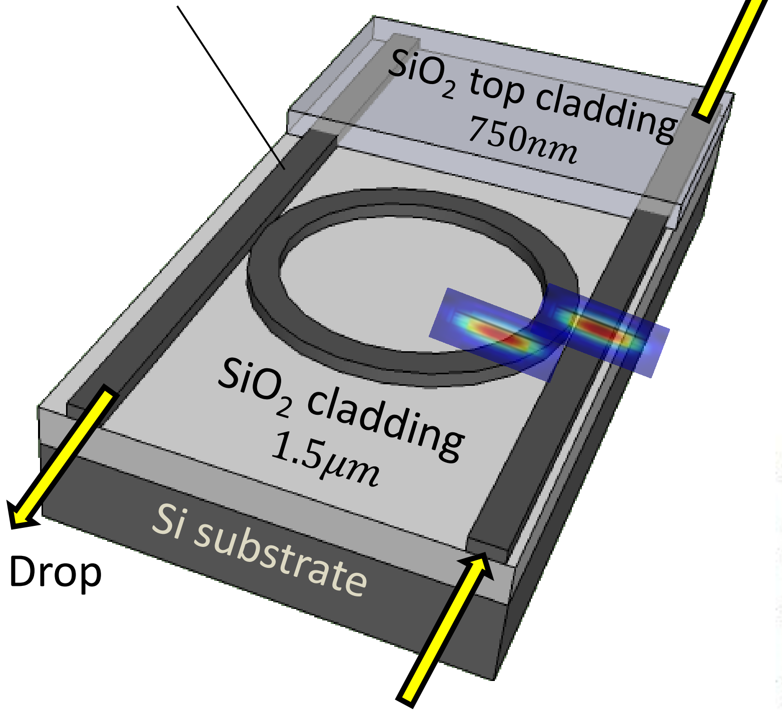
Optical coupler



Microring resonator

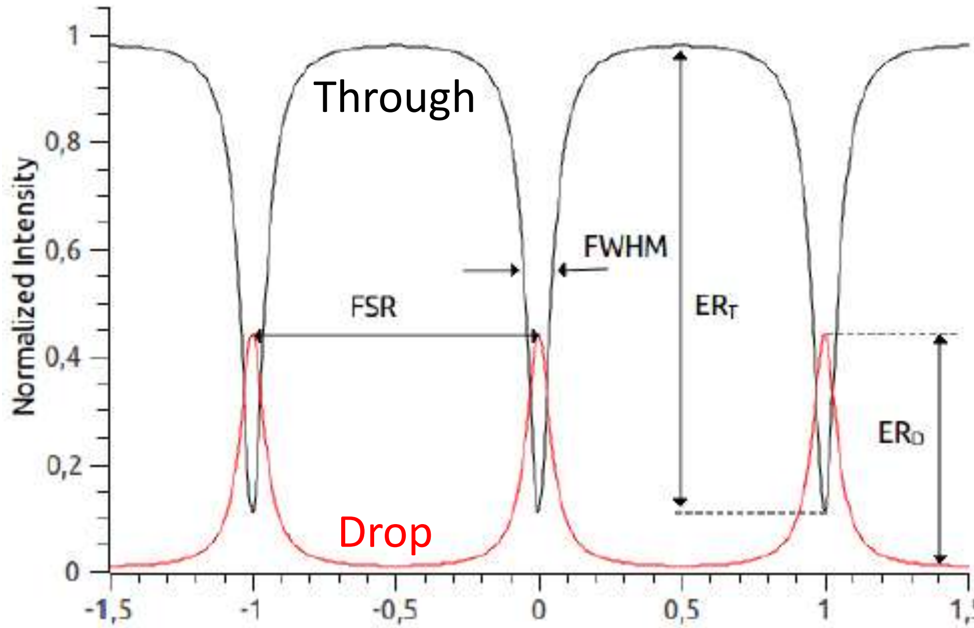


Silicon Microresonators



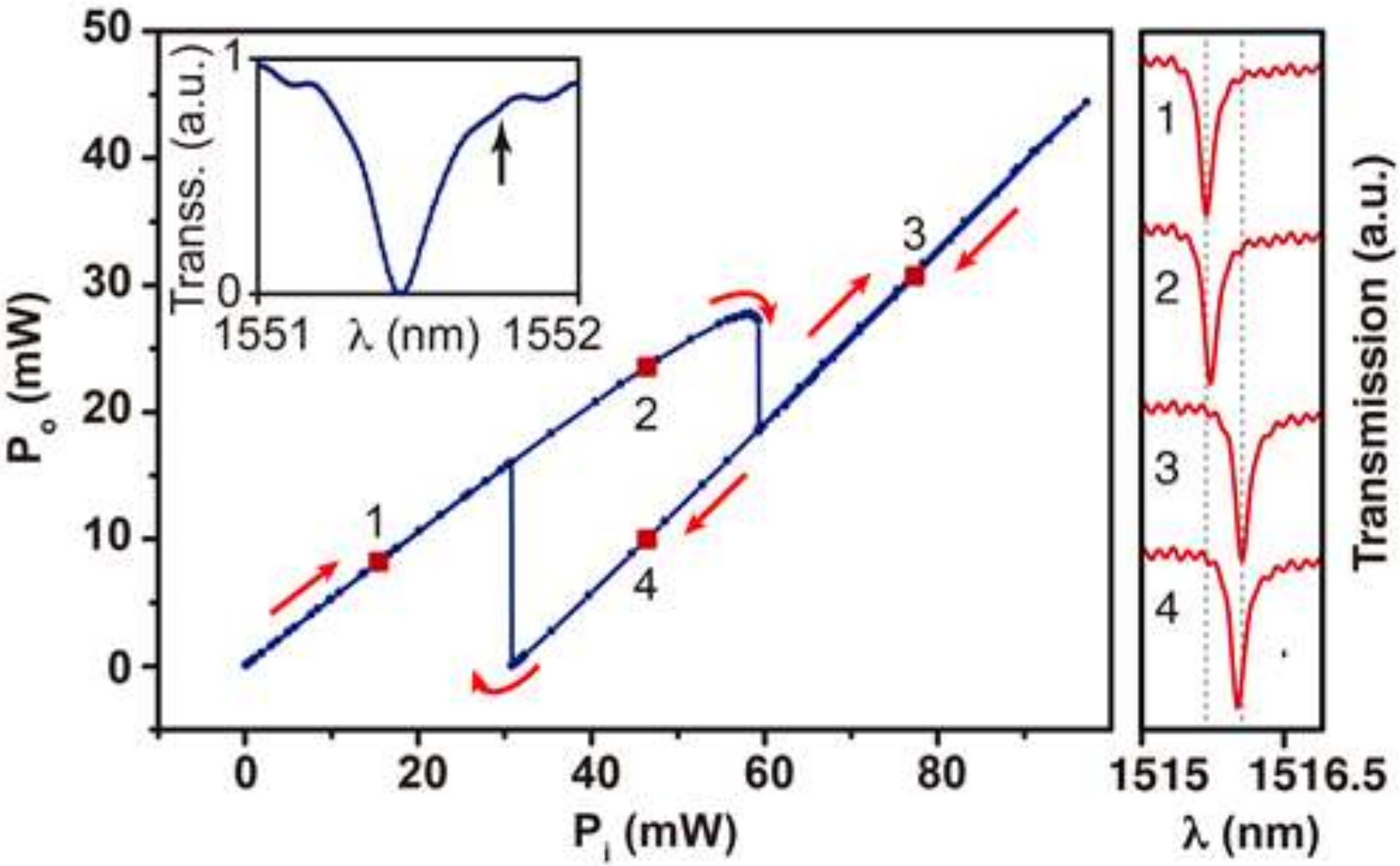
Resonance condition

$$n_{eff} \times 2\pi R = m\lambda_m$$



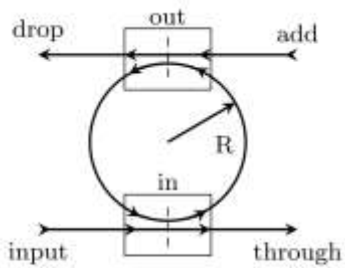
Through response (optical bistability)

$$\Delta\lambda_{TOE} \approx \lambda_{cold} \cdot \Gamma \frac{dn_{Si}}{dT} \Delta T$$



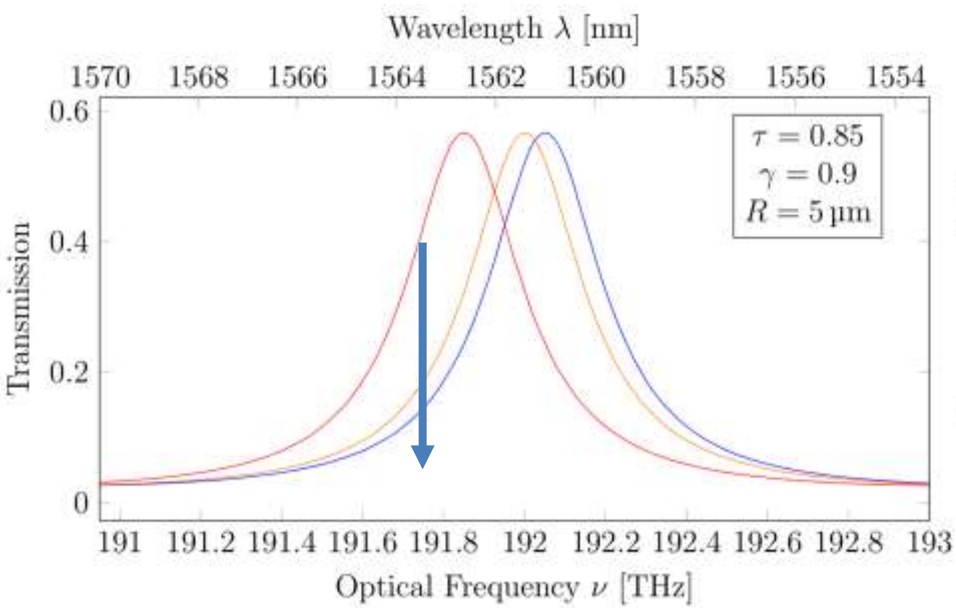
OPTICS LETTERS / Vol. 38, No. 18 / September 15, 2013

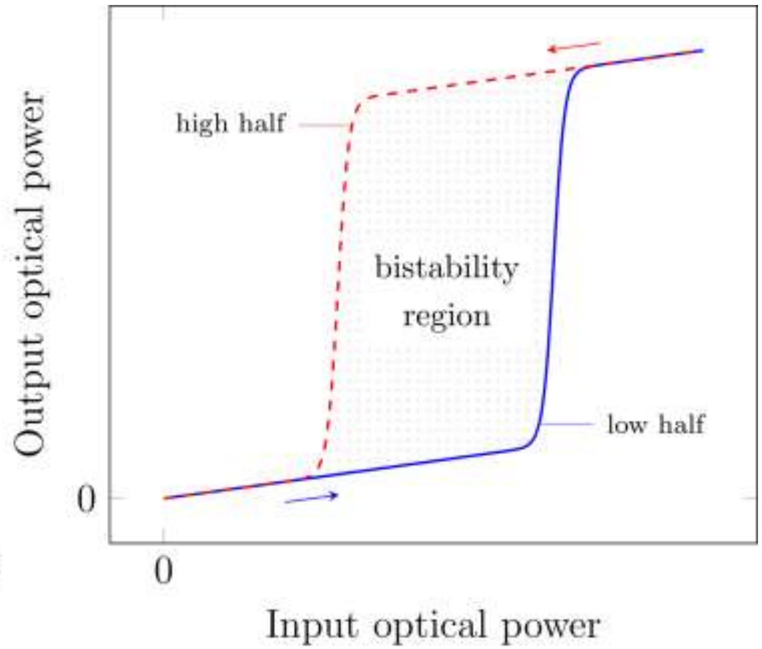
Optical nonlinear activation function



The thermo optic effect shifts the resonances to the left

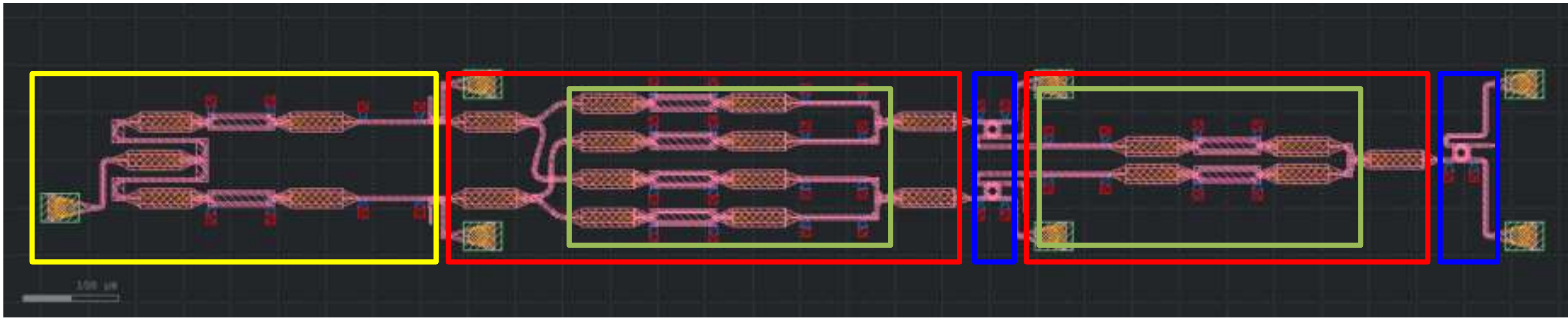
Optical bistability is a nonlinear optical effect exploited for our activation function

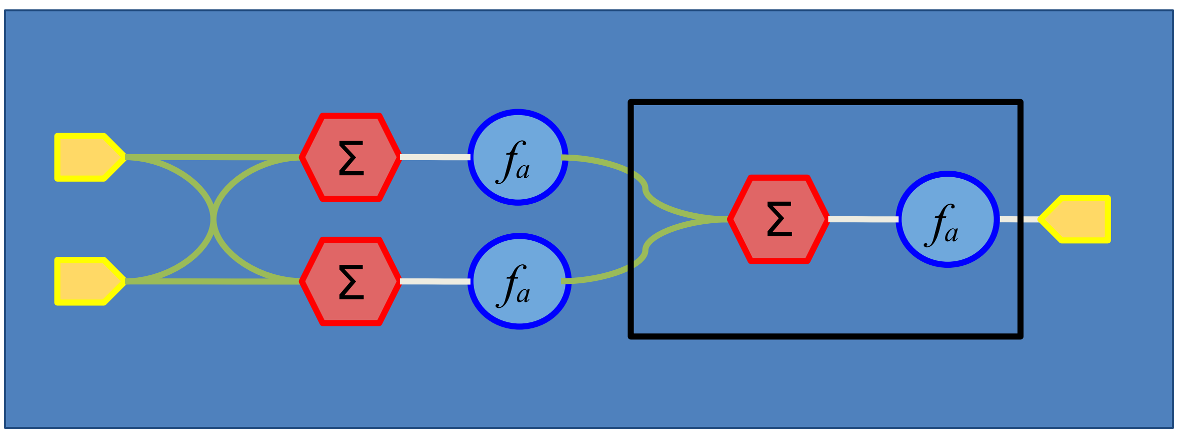


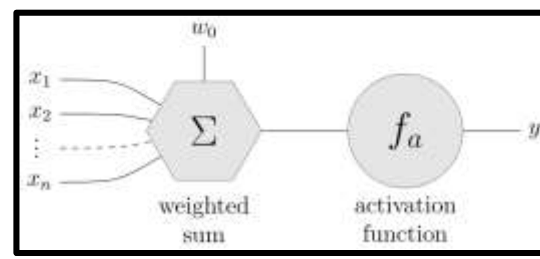


DROP RESPONSE

Optical Feed Forward Neural Network







Are
feed forward
networks
the best
for optics?

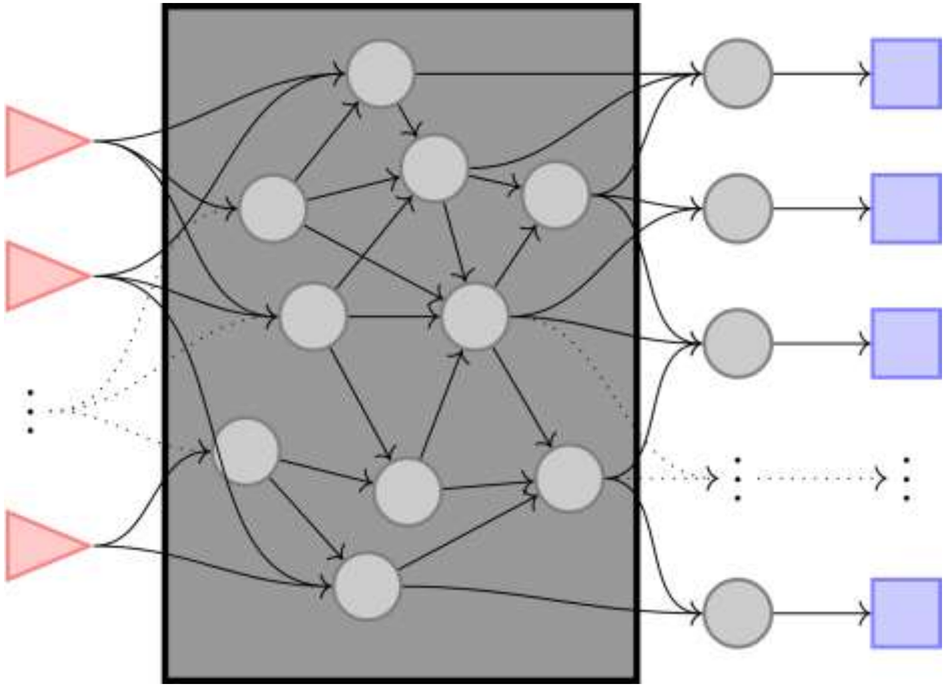
Needs accurate control over
all parameters
of each and every node

Reservoir computing

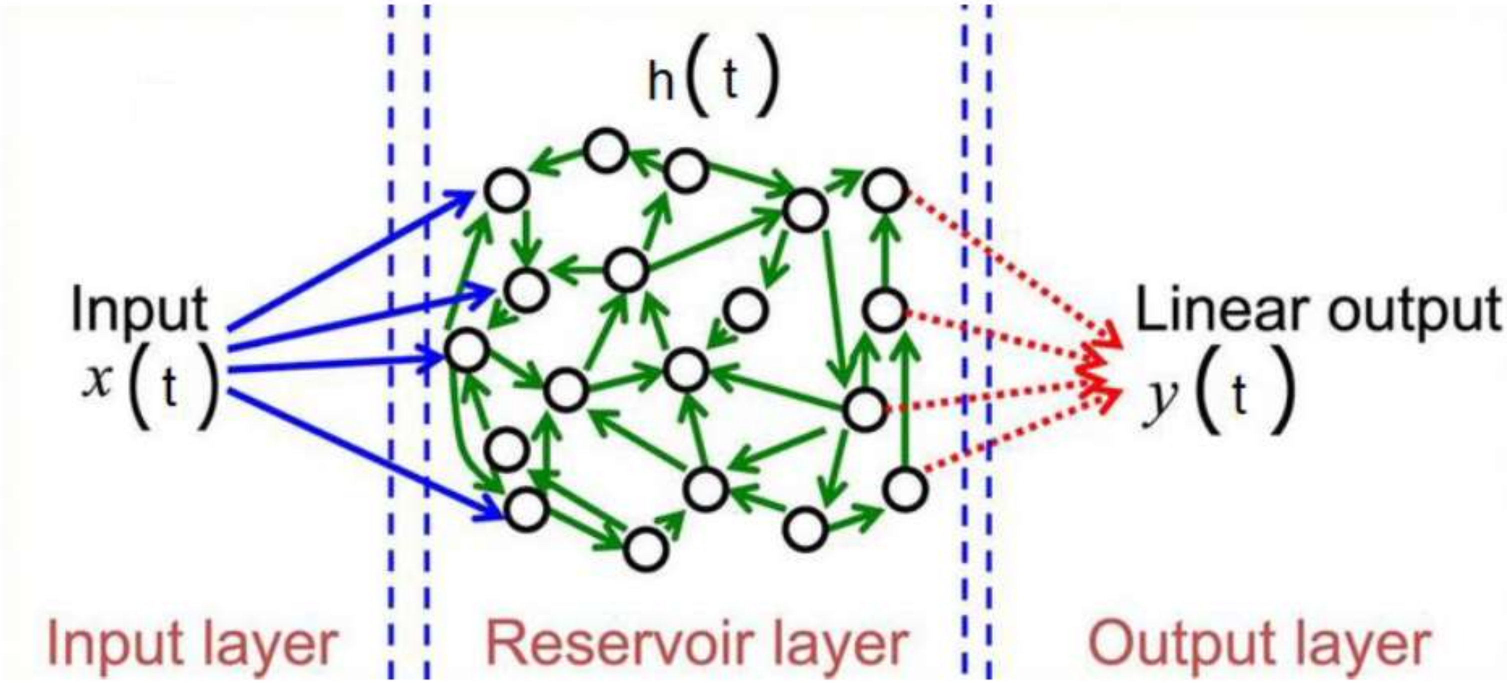
Only the parameters of the output nodes are learned

The “reservoir” increases the dimensionality of the input

The output layer can distinguish more easily the inputs



Reservoir Computing (RC): Introduction

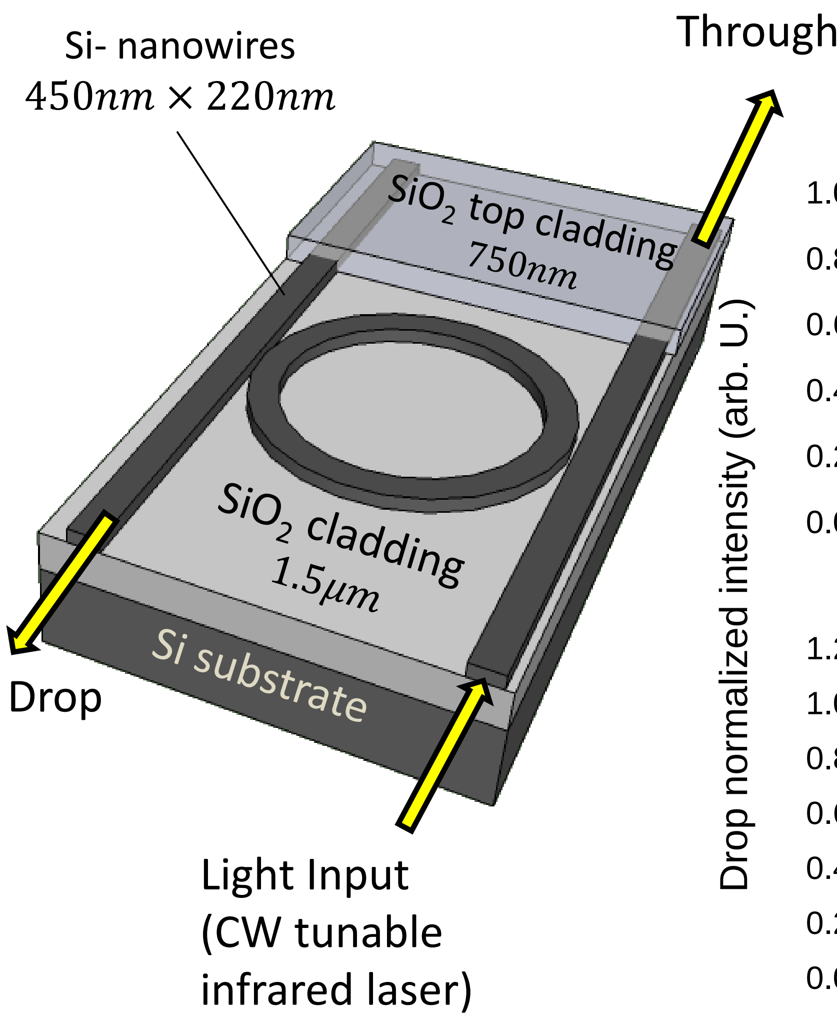


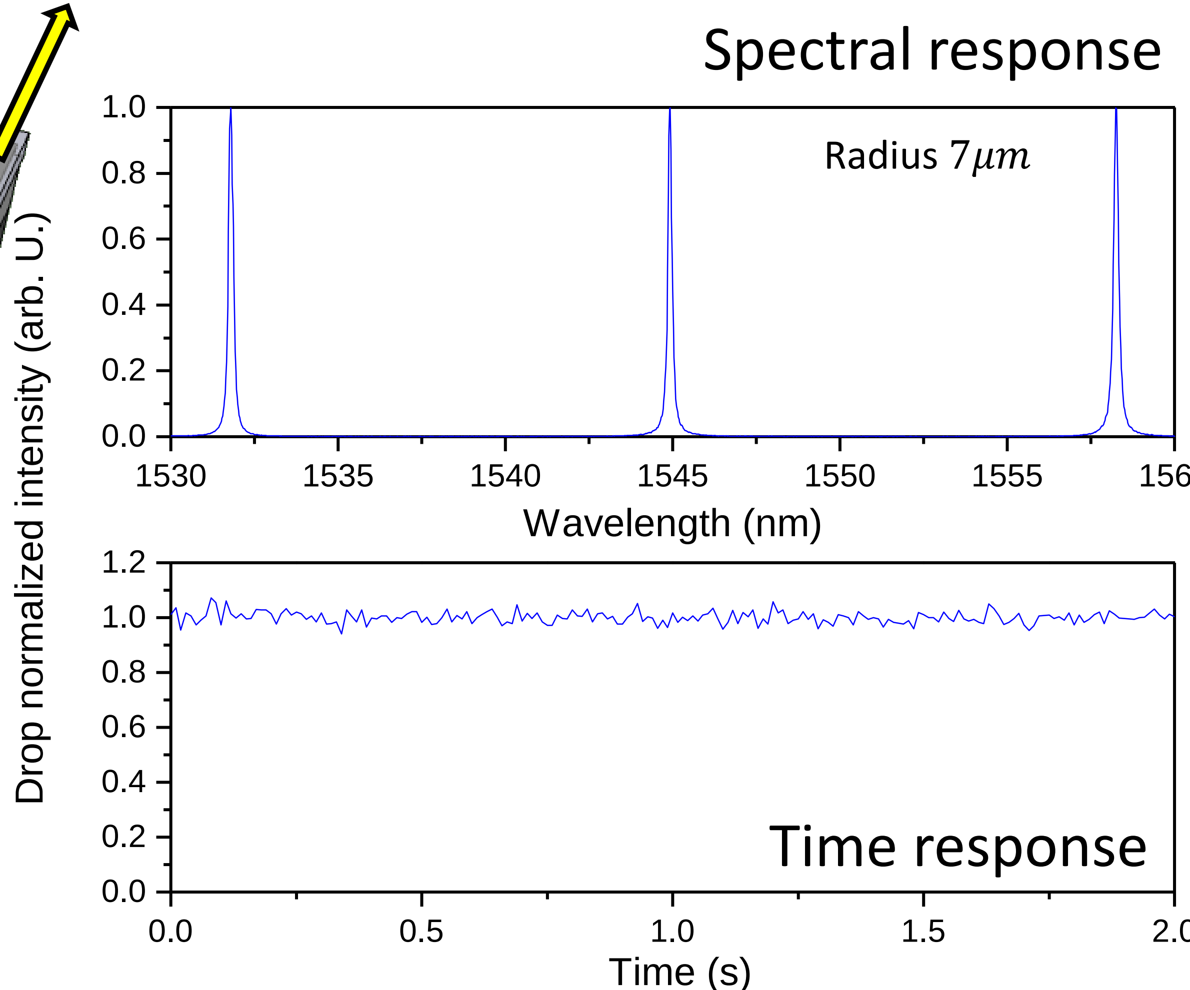
Reservoir Computing (RC): Introduction

- It is an RNN with:
  - input-to-hidden layer weights randomly fixed
  - hidden-to-hidden layer weights randomly fixed
  - hidden-to-output layer weights (*readout*) learned
- Main advantage: it is easy to train
- Can be implemented using photonic circuits

Chaos

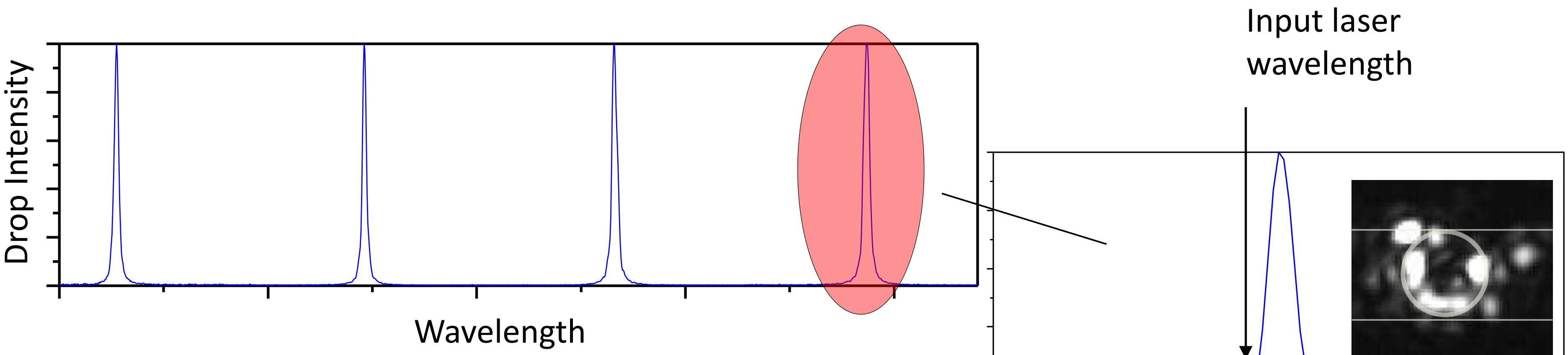
Resonator in the temporal domain

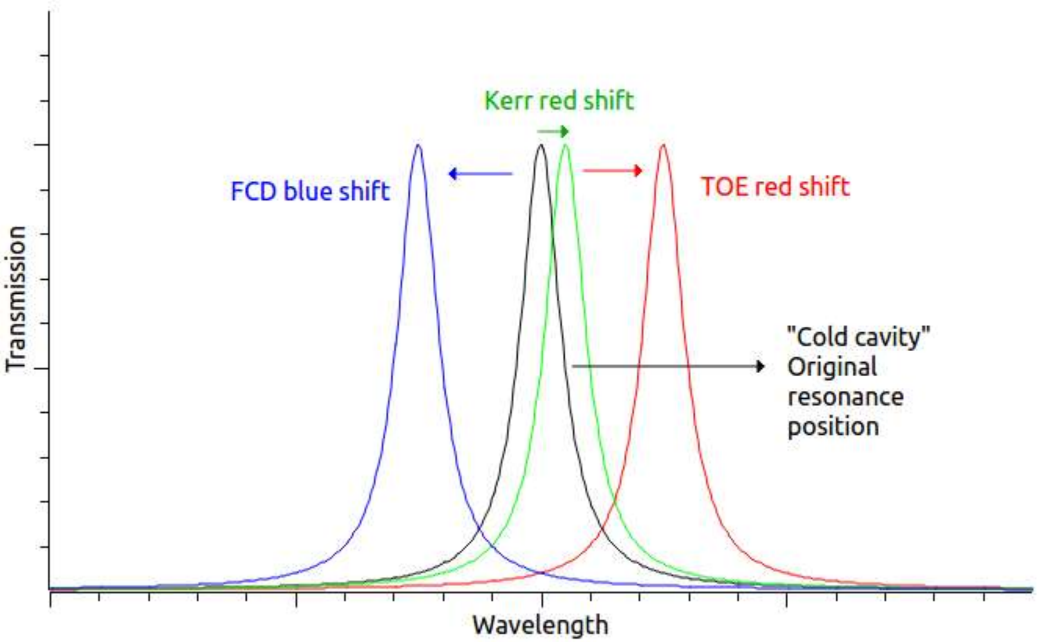




UNIVERSITY OF TRENTO - Italy
Department of Physics

Main nonlinearities at CW power





$$\Delta\lambda_{TOE} \approx \lambda_{cold} \cdot \Gamma \frac{dn_{Si}}{dT} \Delta T$$

$$\Delta\lambda_{FCD} \approx \lambda_{cold} \cdot \Gamma \frac{dn_{Si}}{dN_{e,h}} \Delta \mathrm{N}_{\mathrm{e,h}}$$

FCD : Free Carrier Dispersion

TOE : Thermo Optic Effect

Simplified view

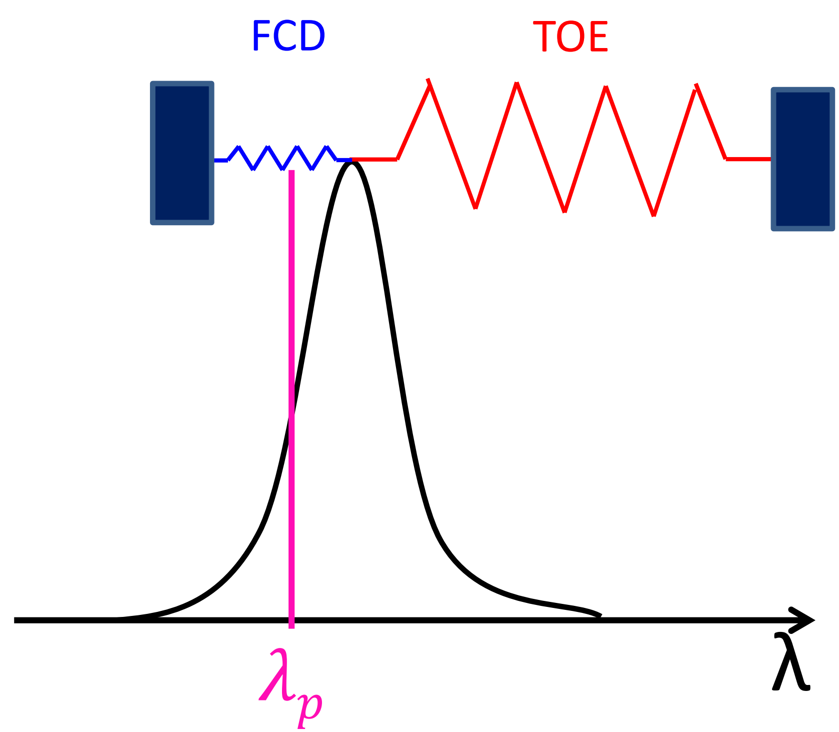
TOE $\frac{dn}{dT} > 0$ Red shift $\tau_{TOE} \approx$ ns

FCD $\frac{dn}{dN} < 0$ Blu shift $\tau_{FCA} \approx$ ps

$\frac{dn}{dT} > \frac{dn}{dN}$ *Thermal* is predominant

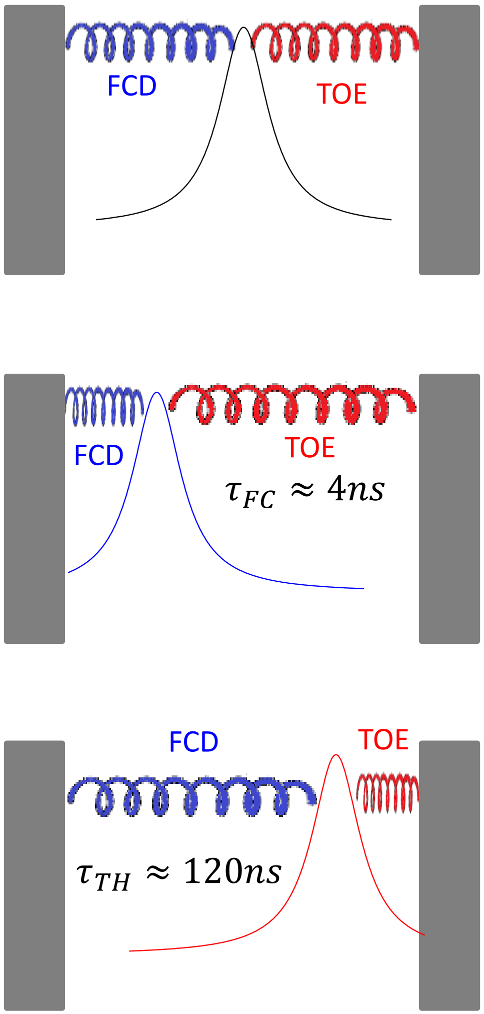
$$n_{tot} = n_0 + \Delta n_{TOE}(P) - \Delta n_{FCD}(P)$$

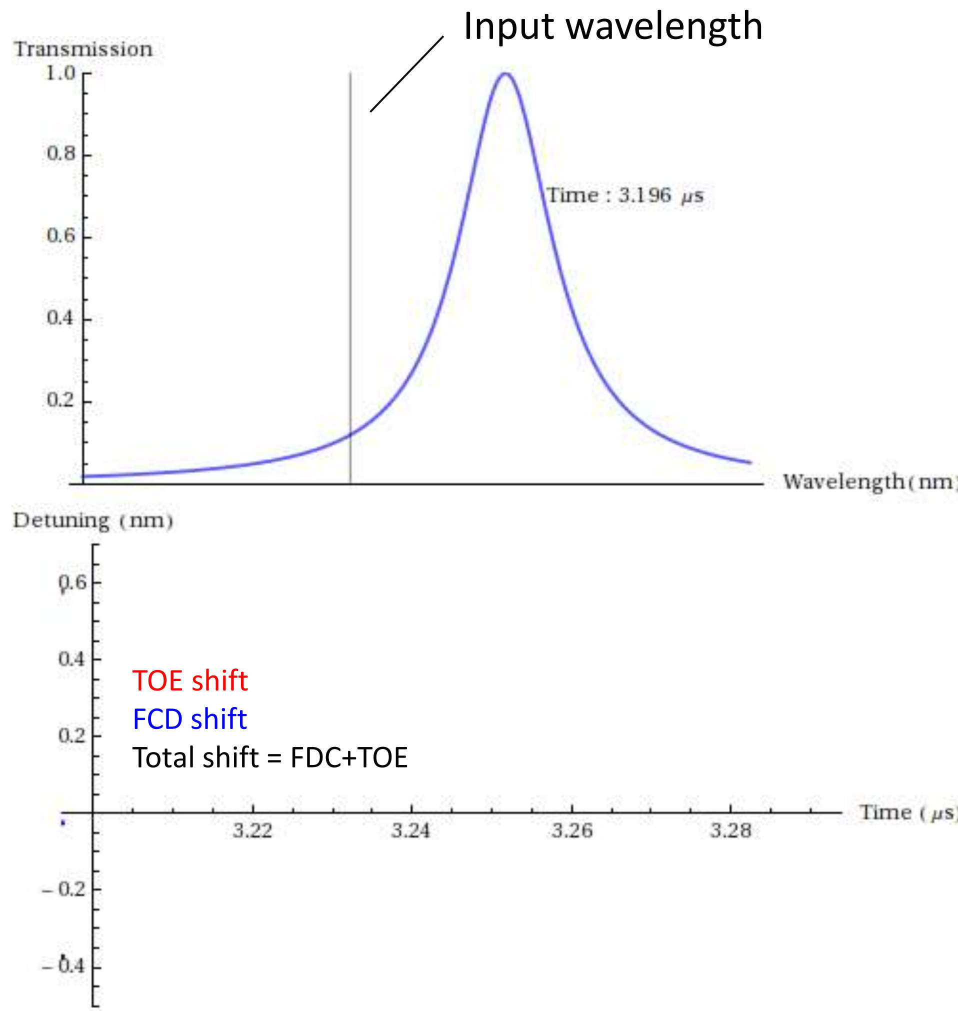
Function of power



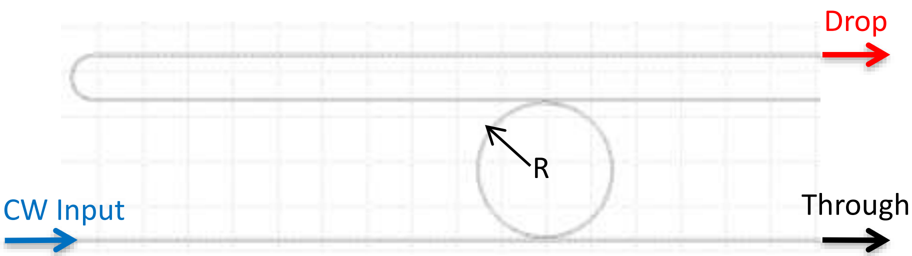
Nonlinear refractive index: n=n0+Δn(I)

Competing resonance shifts act as springs that pull the resonance in the opposite directions



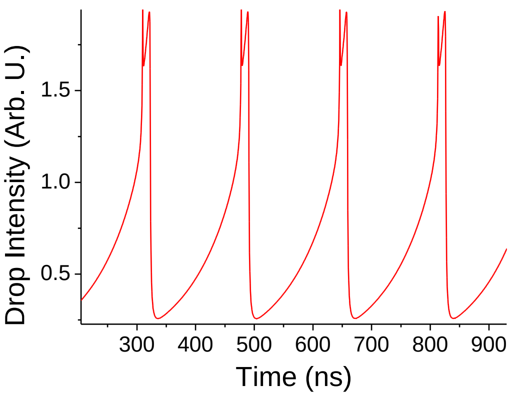


Temporal measurements

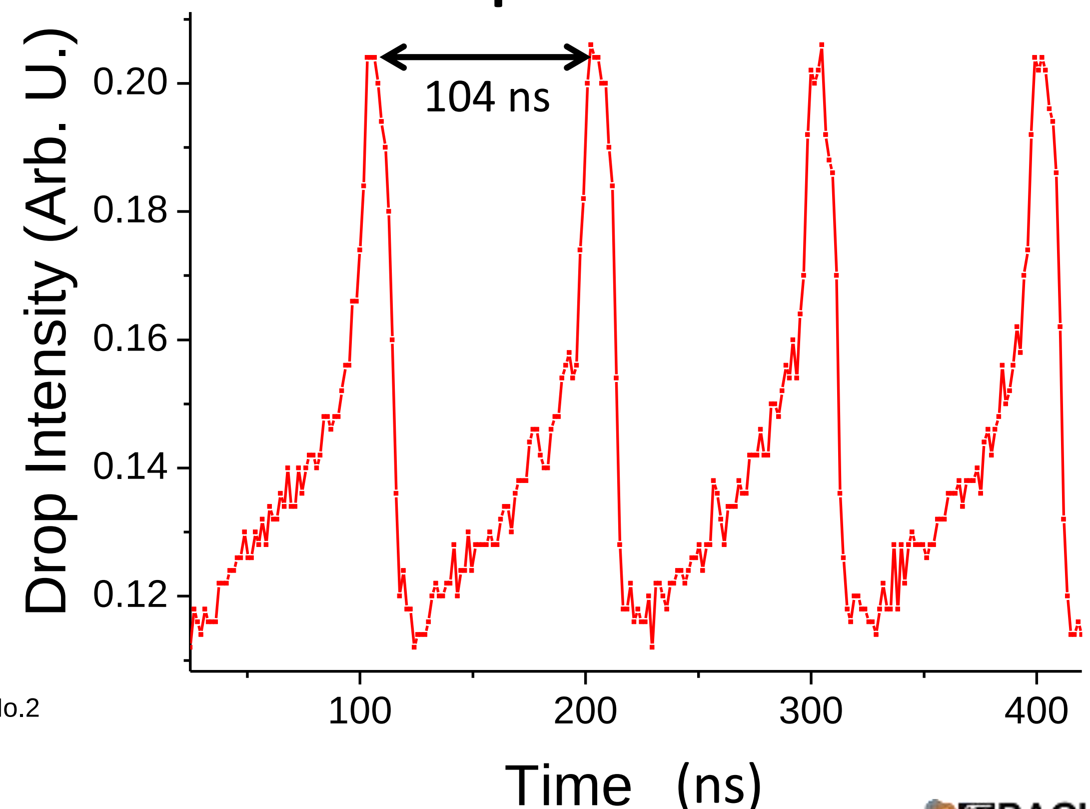


- R = 7 µm
- Gap = 180 nm

Simulation



Experiment

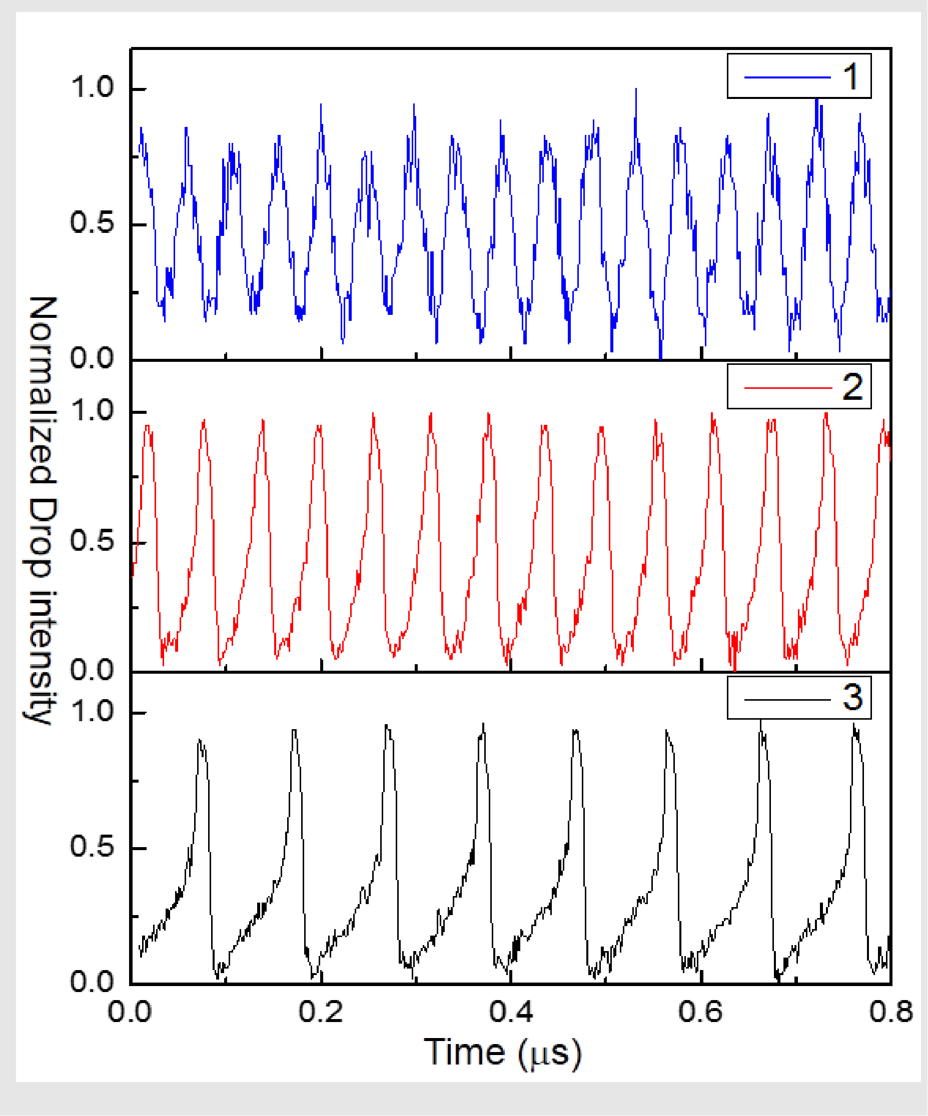


Thomas J. Johnson, Matthew Borselli and Oskar Painter, Optics Express, Vol. 14, No.2 (2006)

UNIVERSITY OF TRENTO - Italy
Department of Physics

BACKUP neuromorphic photonics and the brain
erc

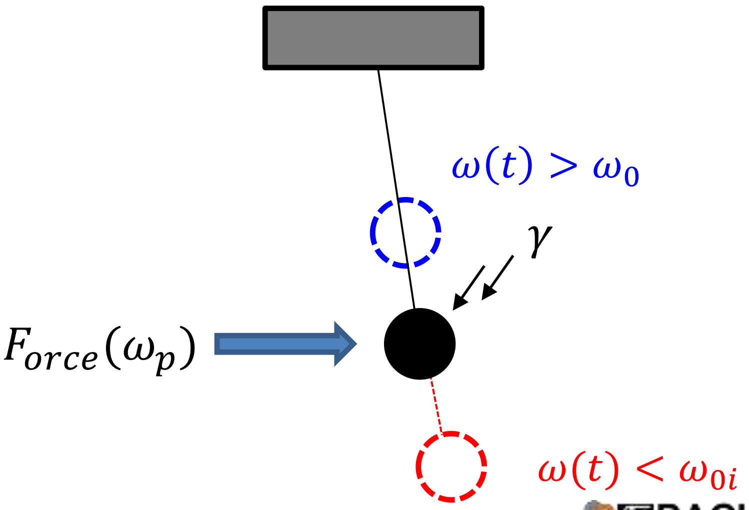
Self induced intensity modulation



Pump scheme	Input wavelength	Input power (in wg)
1	1550 nm	2.3 mW
2	1550 nm	4.9 mW
3	1550 nm	6.0 mW

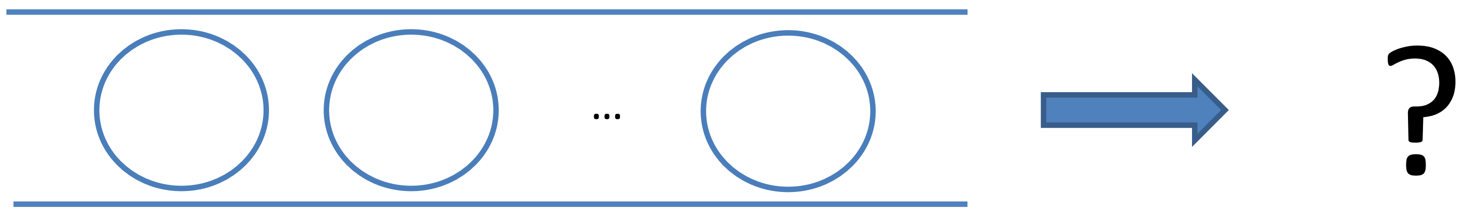
Low power resonance peak (λ_0) : $1549.66nm$
Q factor $\approx 10^5$

Mechanical equivalent



Single vs sequence

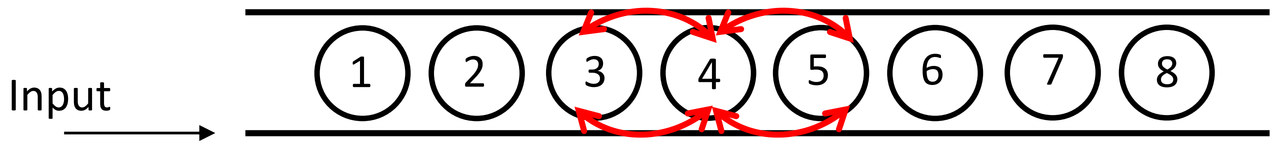
SCISSOR



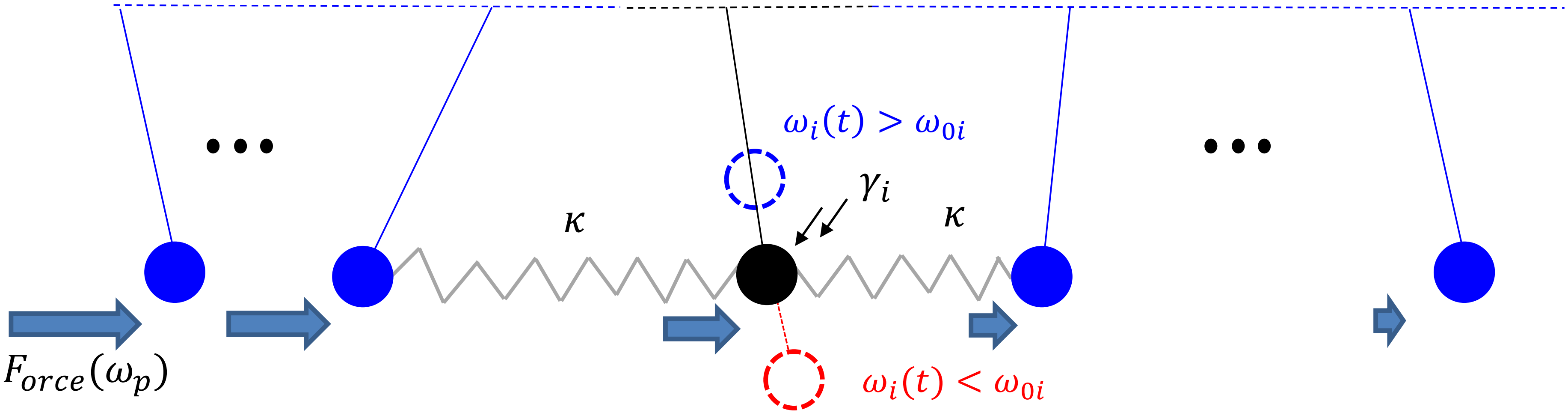
Side-coupled integrated spaced sequence of resonators

SCISSOR

- Periodicity breaking by cavity coupling (optical feedback)

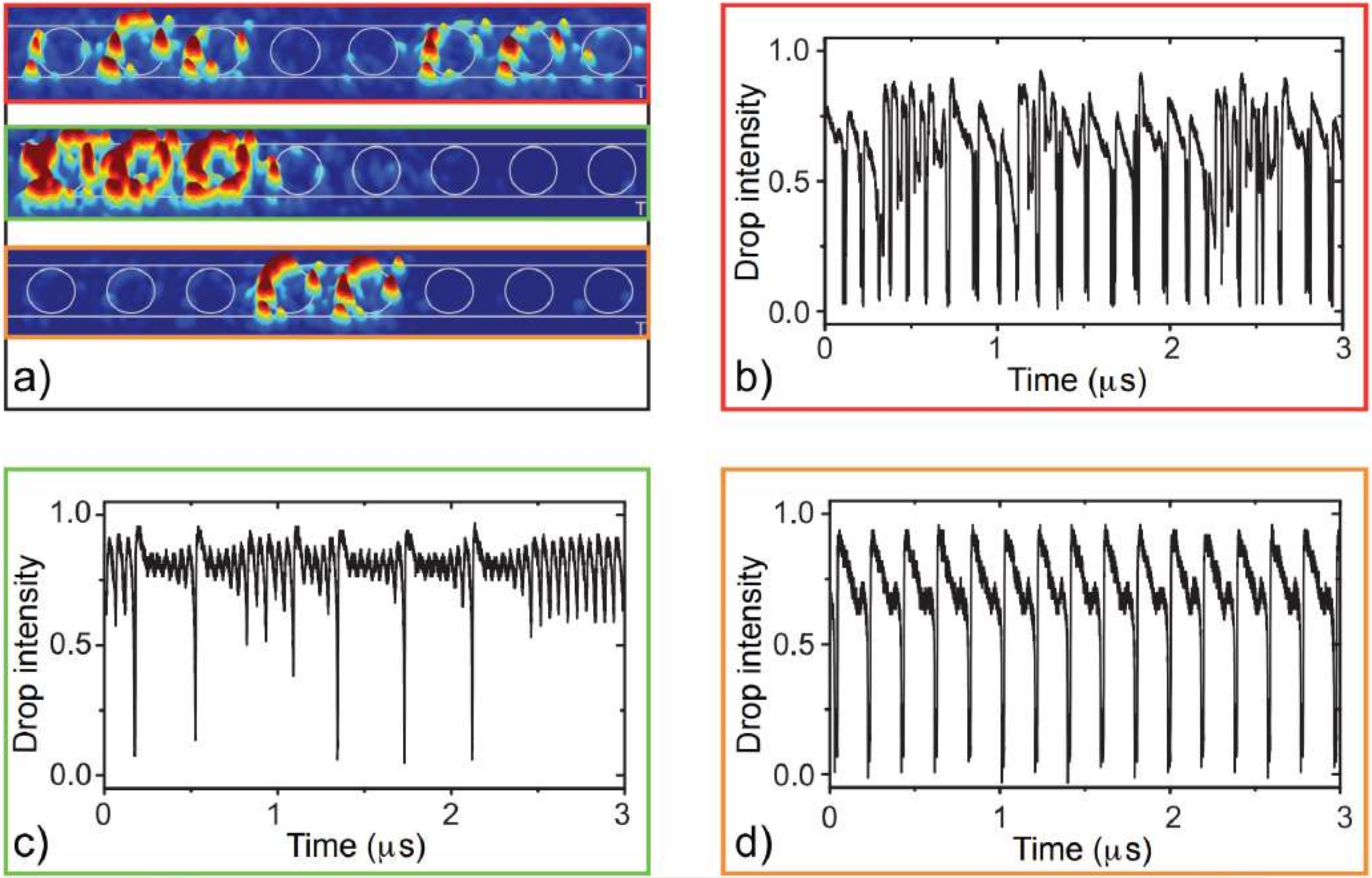


Mechanical equivalent



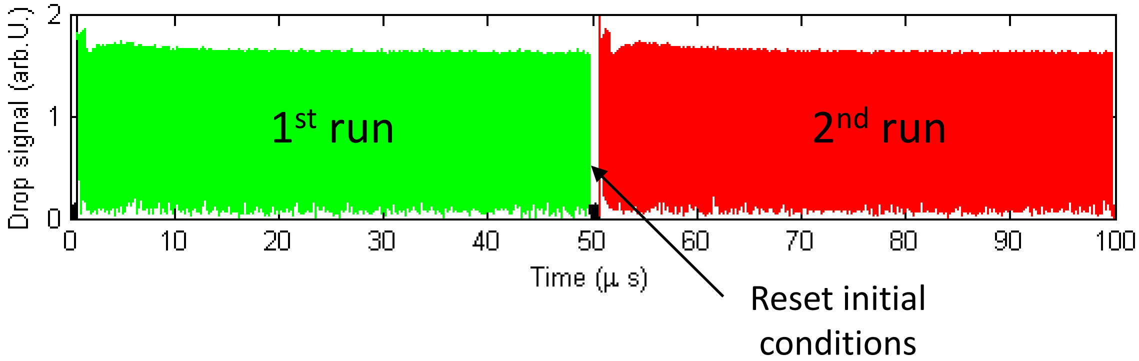
From CW to chaos

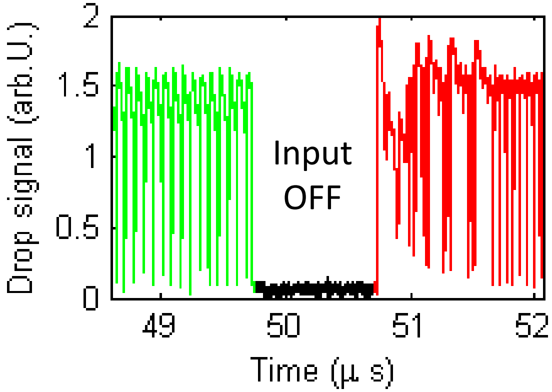
The waveform complexity is linked to the number of cavities involved

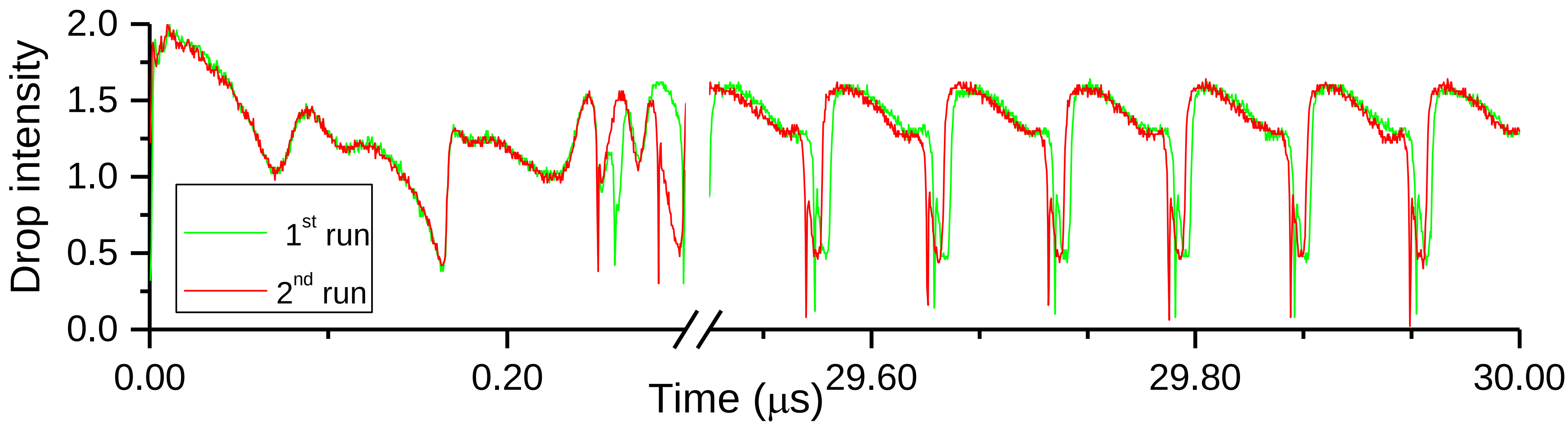


Sensitivity to initial conditions

Sensitivity to initial conditions: periodic case



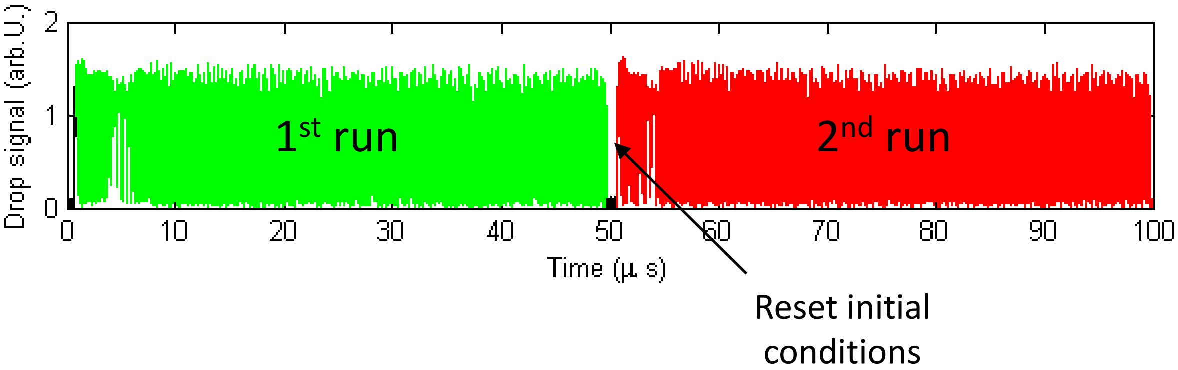


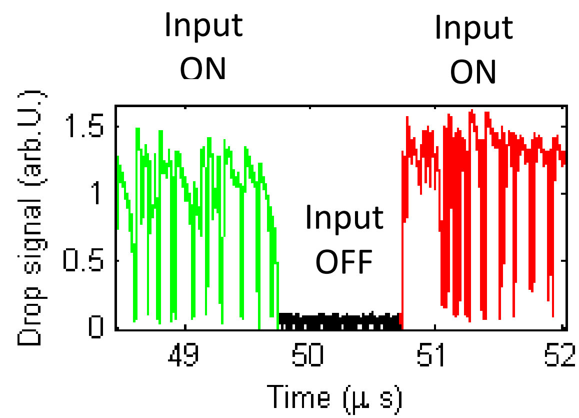


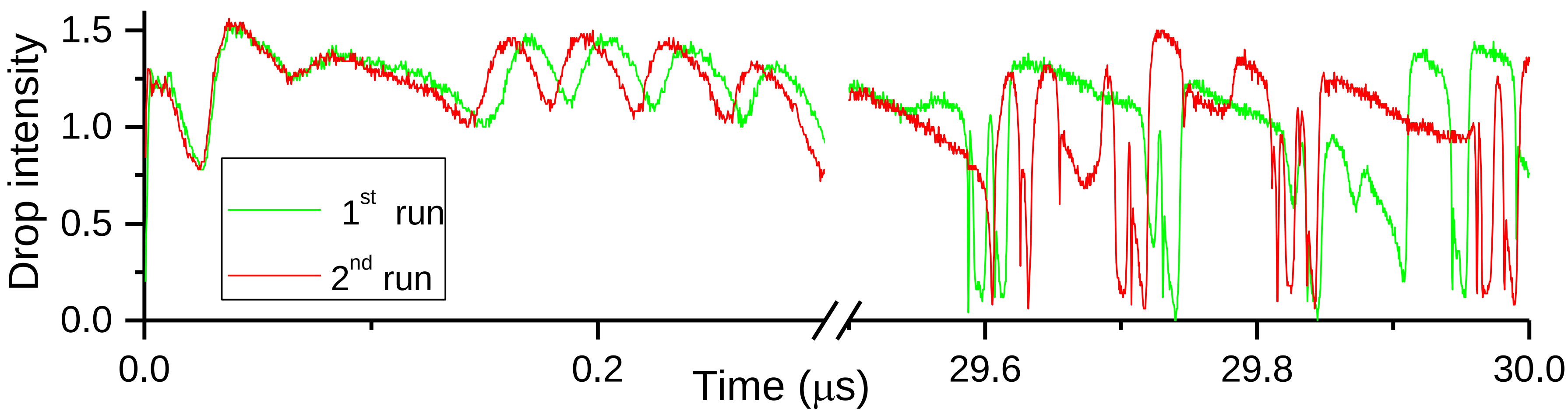
Input conditions: λ = 1543.420 nm P = 21 mW

Sensitivity to initial conditions

Sensitivity to initial conditions: chaotic case







Input conditions: λ = 1543.225 nm P = 21 mW

Coupled cavities dynamics: chaos

- Reconstructed phase space

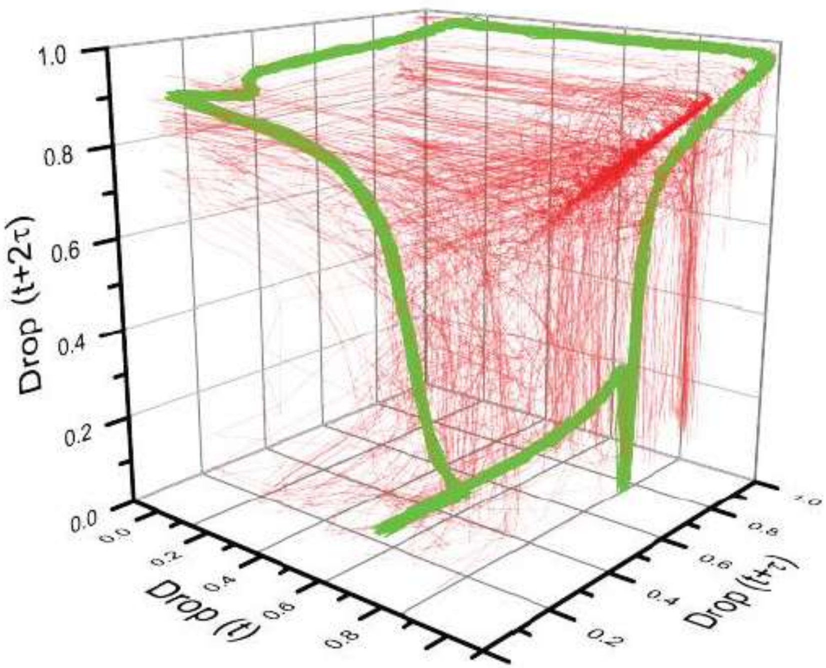
Chaotic dynamics in coupled resonator sequences

M. Mancinelli,[1,*] M. Borghi,[1] F. Ramiro-Manzano,[1] J. M. Fedeli[2] and L. Pavesi[1]

[1]*Nanoscience Laboratory, Department of Physics, University of Trento, Povo 38123, Trento, Italy*

[2]*CEA, LETI, MINATEC, 17 rue des Martyrs, 38054 Grenoble Cedex 9, France*

*mancinelli@science.unitn.it



- 8 cavities for a total of 32 degree of freedom
  - Complex field of 8 cavities: 16 degrees
  - Resonator temperature: 8
  - Resonator free-carrier-density: 8

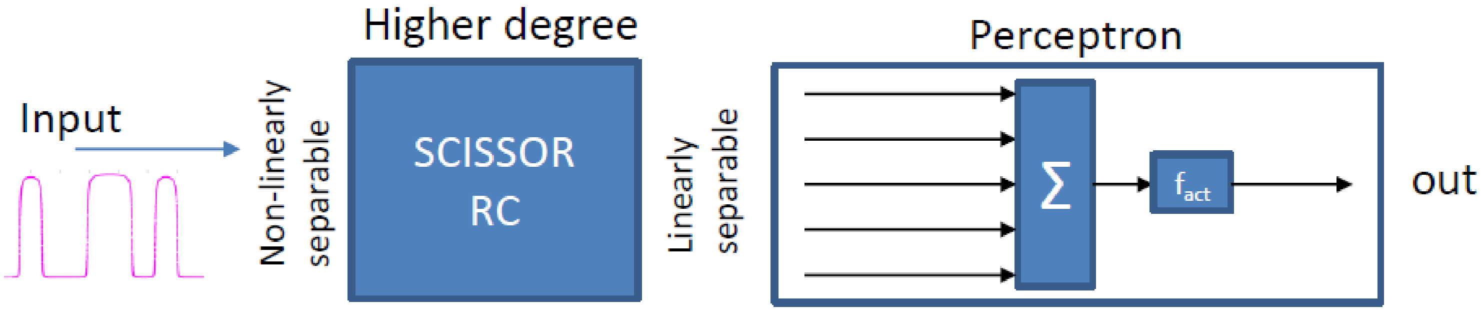
Optics Express 22, 14505 (2014)

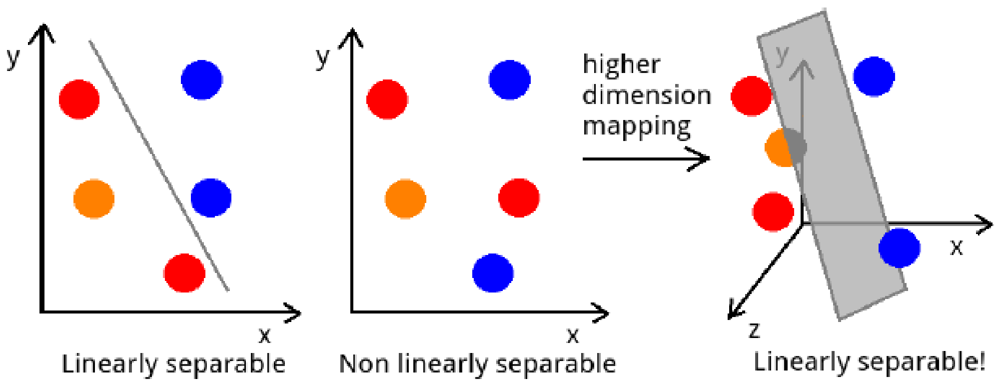
Coupled cavities dynamics summary

- *Rich spectrum*, *sensitivity* to initial conditions and *dense phase space* are sign of chaotic regime
- Dense phase space means high number of degree of freedom involved in the dynamics
- Optical memory (µs) that originates from the phenomena timescale and the coupling
- 1 cavity gives 4 degree of freedom

Couple cavities for reservoir computing

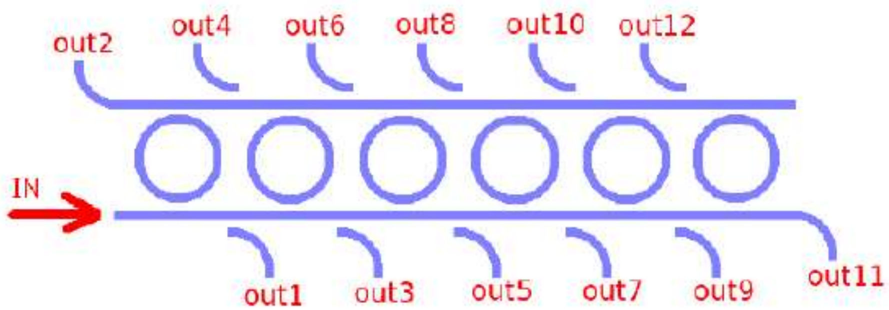
- Optical input is projected to an higher dimensional space
- Complex non-linear task are simplified before being classified by a Perceptron





Reservoir Computing

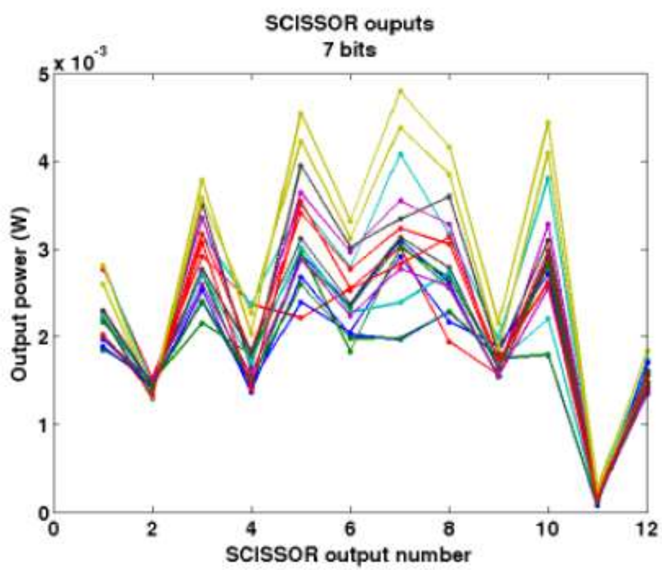
SCISSOR classification performance

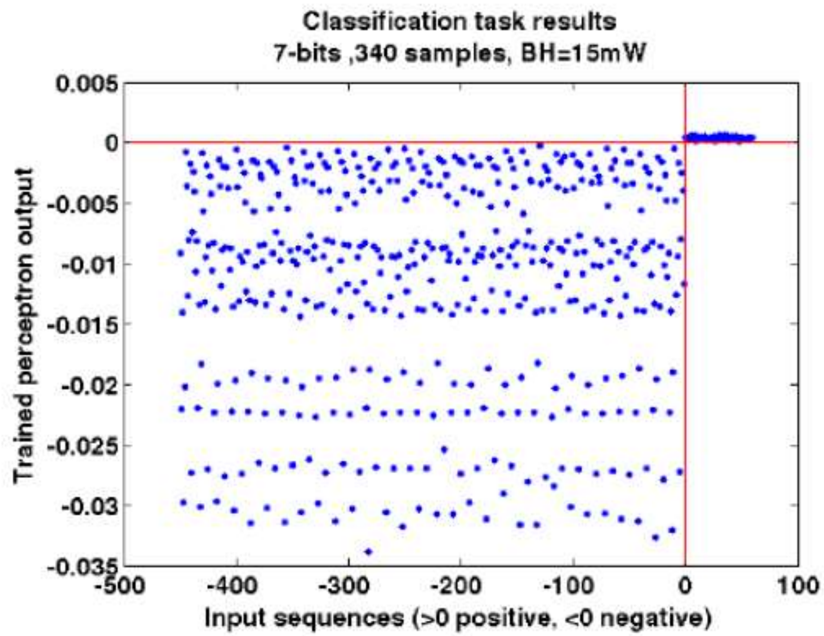


Bitrate 13 Gbit/s

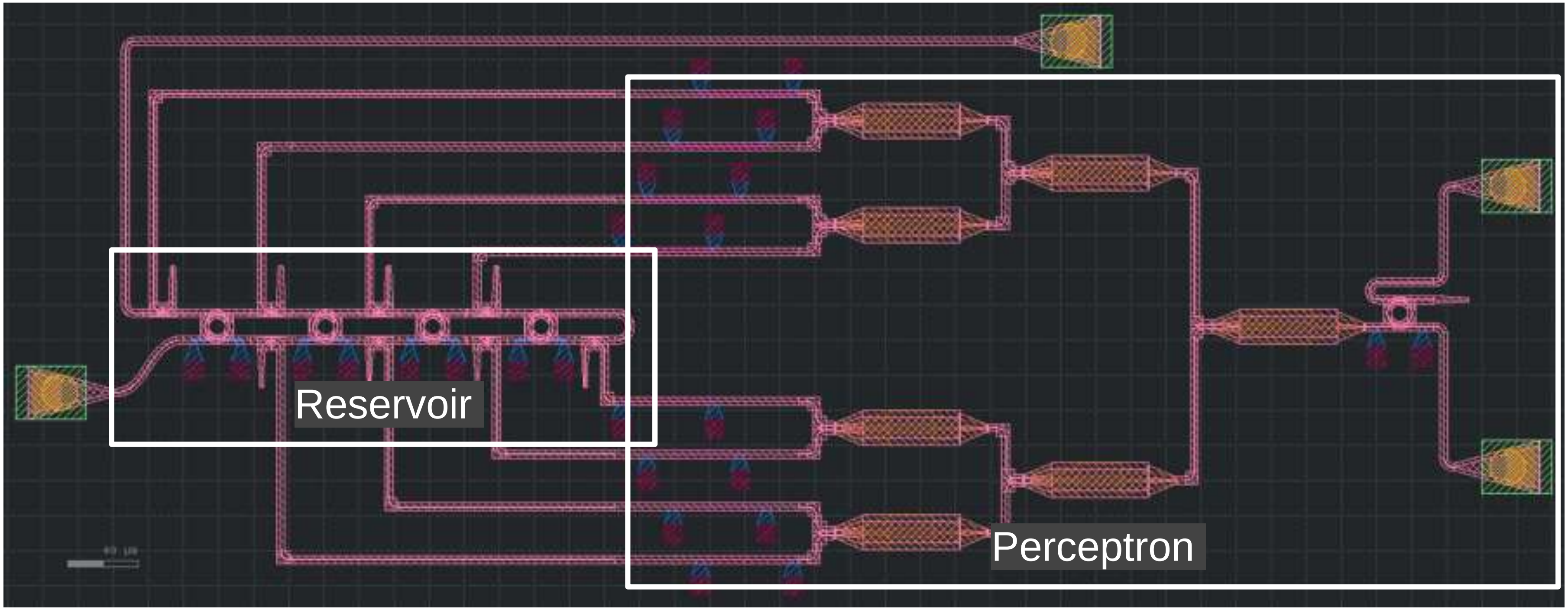
```
%7 bit signal

p=[1 0 0 1 1 0 1];
n=[1 0 0 0 1 1 1
   1 0 0 1 0 1 1
   1 0 1 0 1 0 1
   1 0 1 0 0 1 1
   1 0 1 1 0 0 1
   1 1 0 0 0 1 1
   1 1 0 0 1 0 1
   1 1 0 1 0 0 1
   1 1 1 0 0 0 1
   0 1 1 0 1 0 1
   1 0 1 0 1 1 0
   0 1 1 0 1 1 0
   0 1 1 1 1 0 0
   0 1 1 1 0 1 0
   0 1 0 1 1 1 0];
```





Scissor



The Reservoir is a series of coupled ring resonators the “***scissor***”

The field inside the cavity is probed by a number of waveguides and sent to the perceptron.

Neuromorphic photonics

- Reservoir computing approach
- All optical?
- … and then?

The BACKUP Project

This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement No 788793-BACKUP)

BACKUP's main research fields

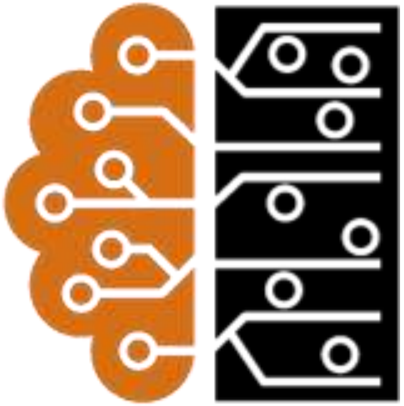
Biological

Understand the mechanisms at the base of our brain

Computational

Learn to perform computation by imitating the brain's mechanisms

BACKUP's end goal



Hybrid Neural Network

The end goal of the BACKUP project is to develop a hybrid biological-photonic neural network

THE TEAM







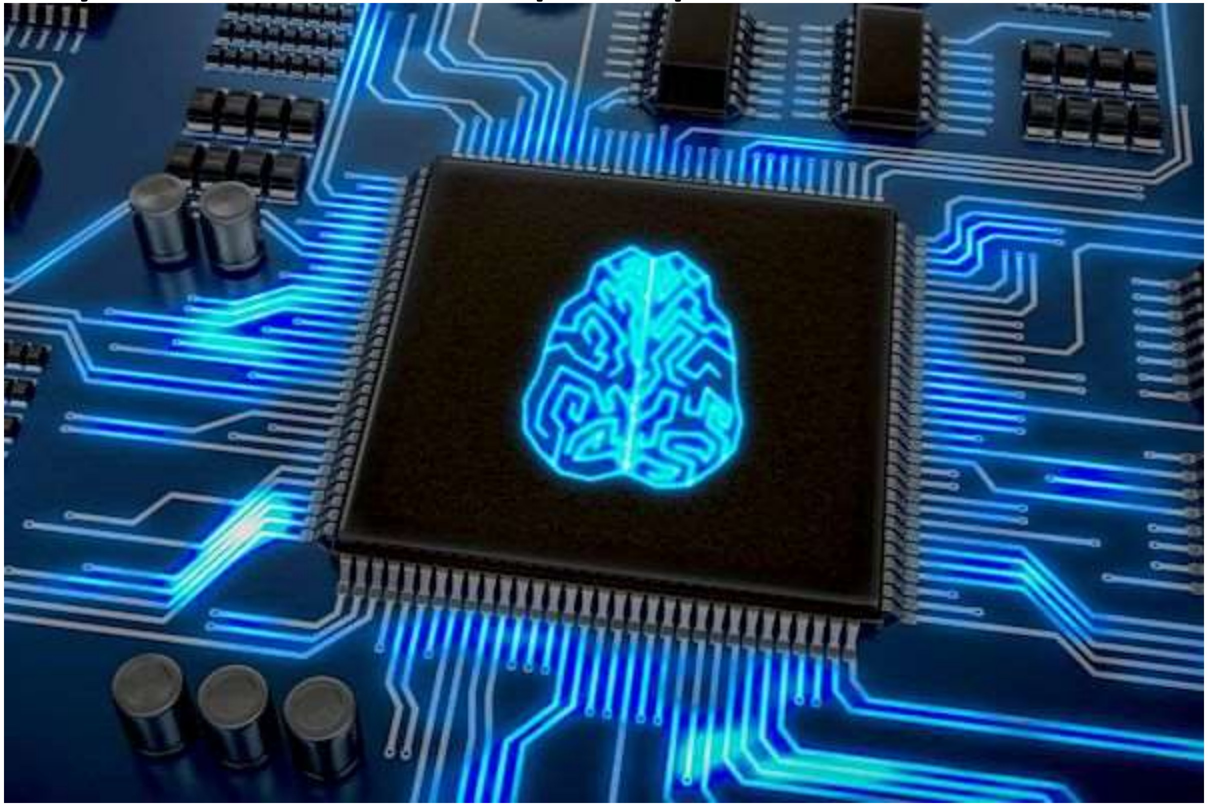






Long-term vision

hybrid neuromorphic photonic networks



clarify the way brain thinks

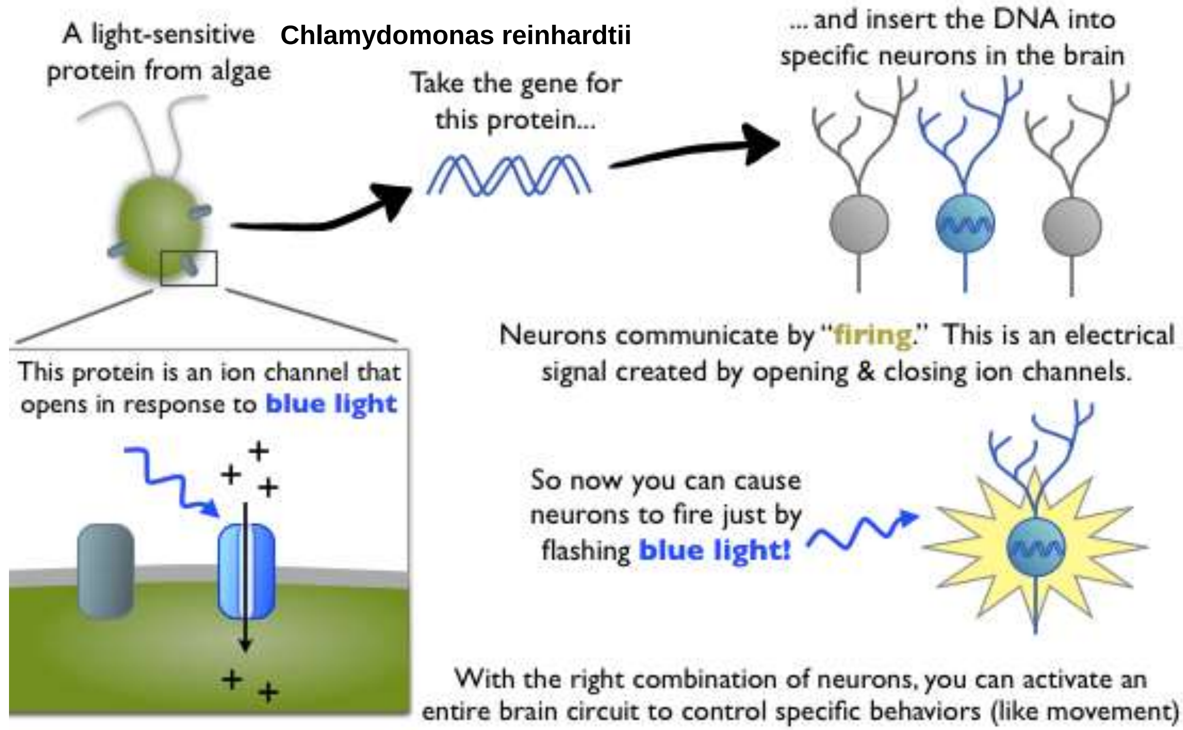
compute beyond von Neumann,

control and supplement specific neuronal functions

Optogenetics:

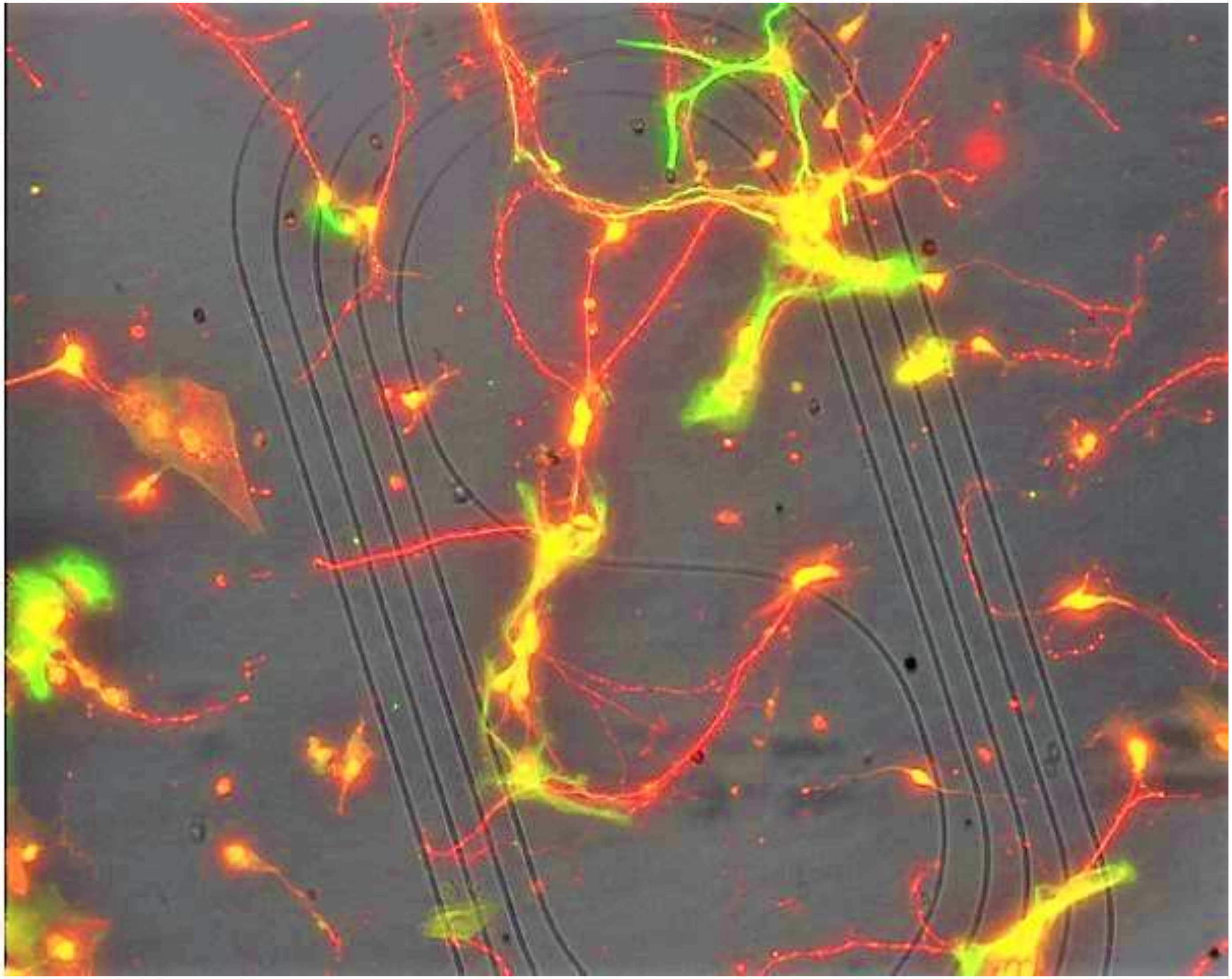
Karl Desseiroth, Stanford University, 2005

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

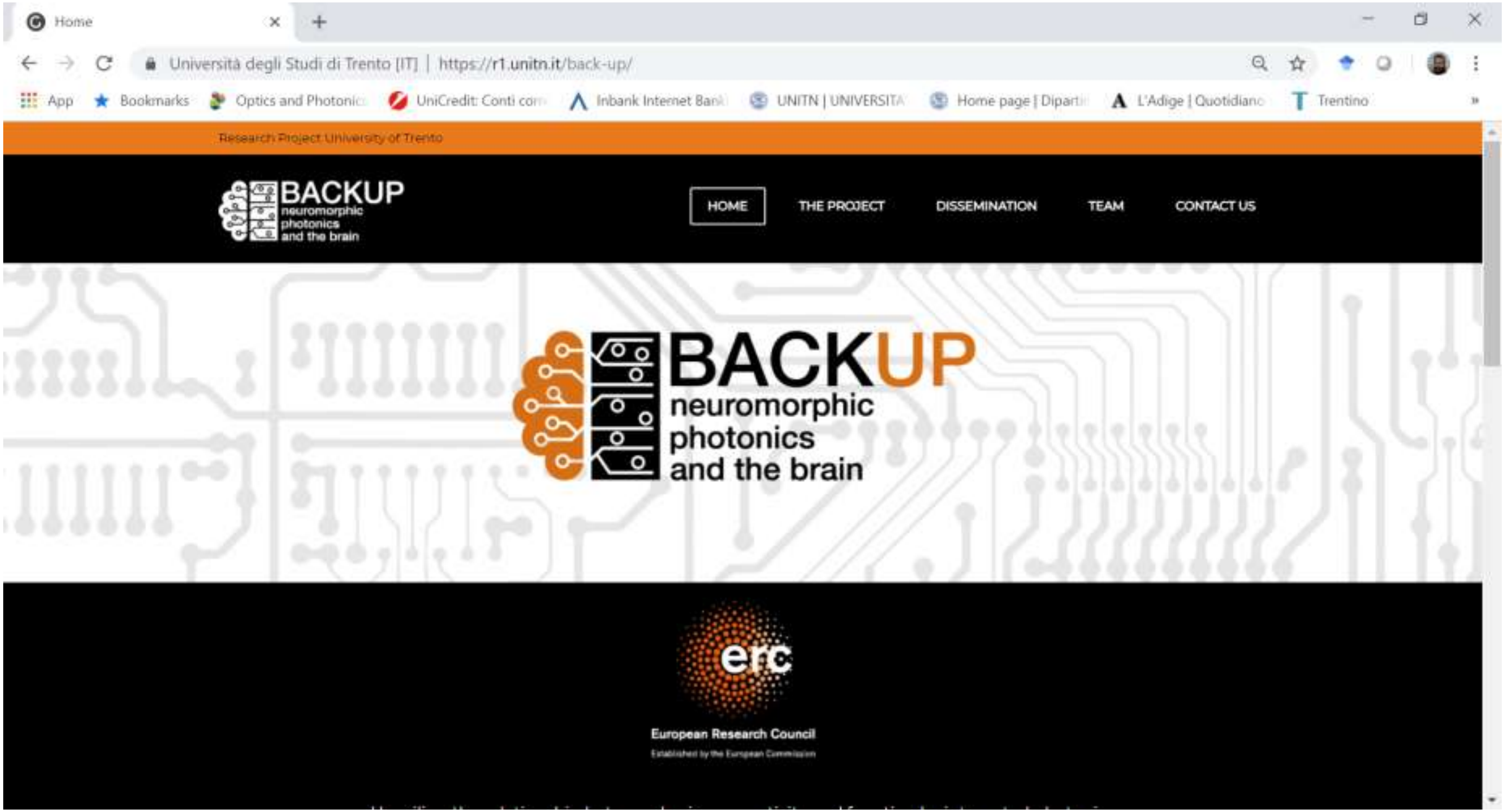


LIGHT CAN ACTIVATE NEURONS

Hybrid photonic-biological networks

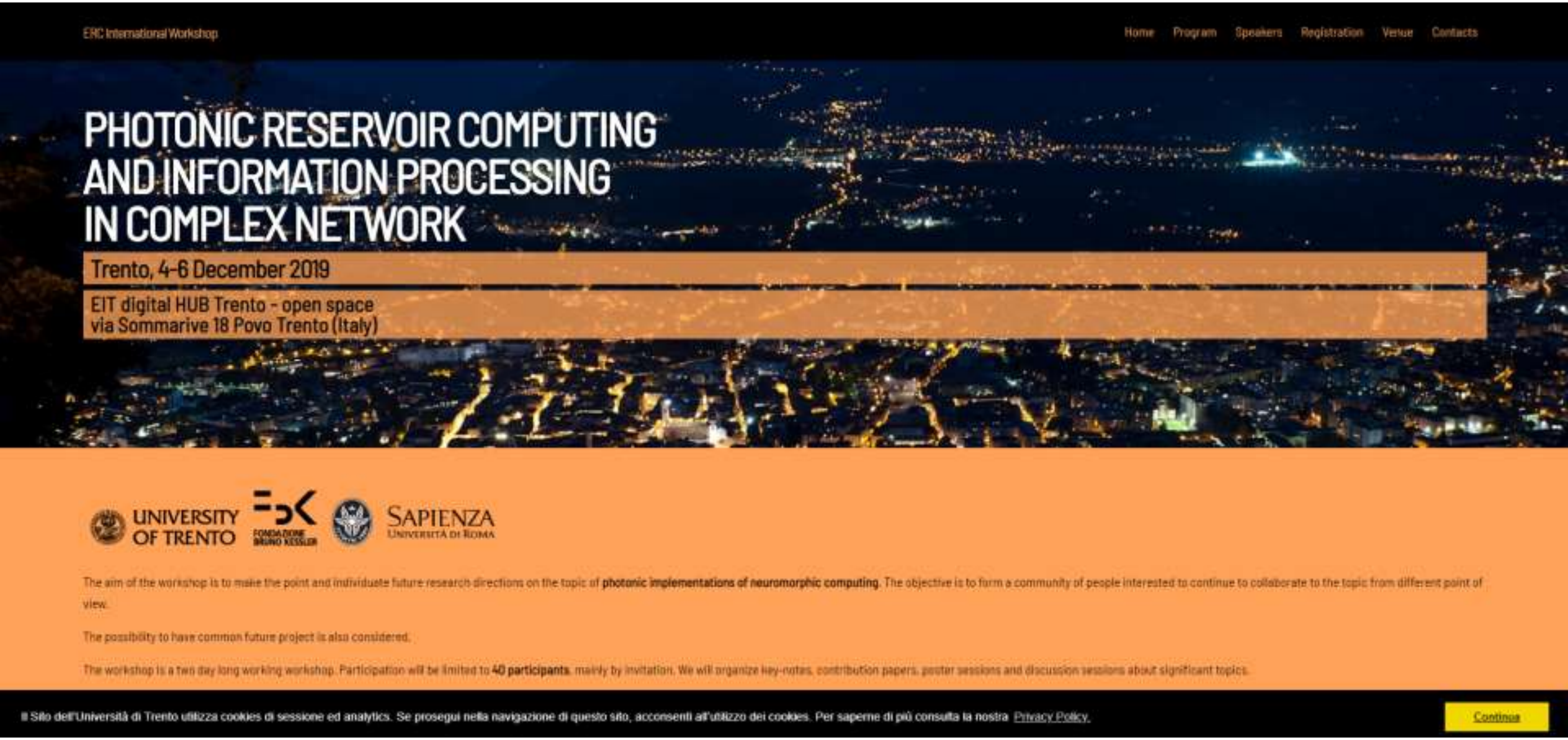


To know how the project evolves

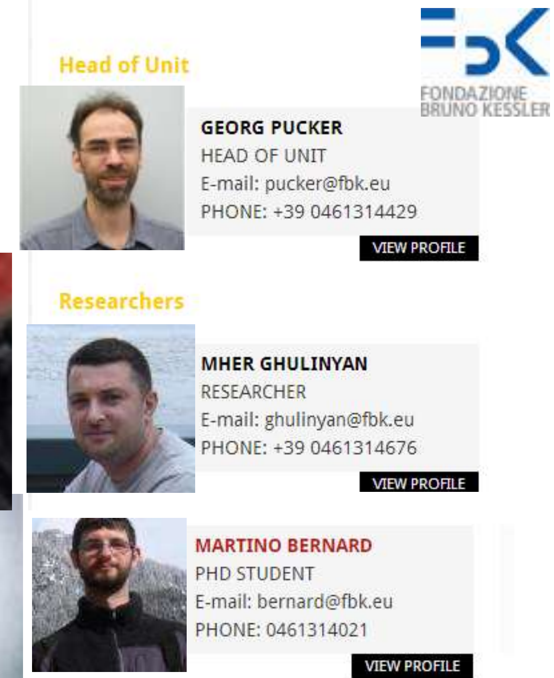


https://r1.unitn.it/back-up/

https://event.unitn.it/erc/



acknowledgments



We are hiring 5 PhD positions (july deadline, november start)
see http://nanolab.physics.unitn.it/index.php/open-positions

acknowledgments

Q@TN

www.quantumtrento.eu

PROVINCIA AUTONOMA DI TRENTO

erc
European Research Council

BACKUP
neuromorphic photonics and the brain

SIQURO

SEVENTH FRAMEWORK PROGRAMME

iris

Nemo

PELM

SYMPHONY

ORANGE

ITPAR

UNIVERSITY OF TRENTO - Italy
Department of Physics

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

BACKUP
neuromorphic photonics and the brain
erc