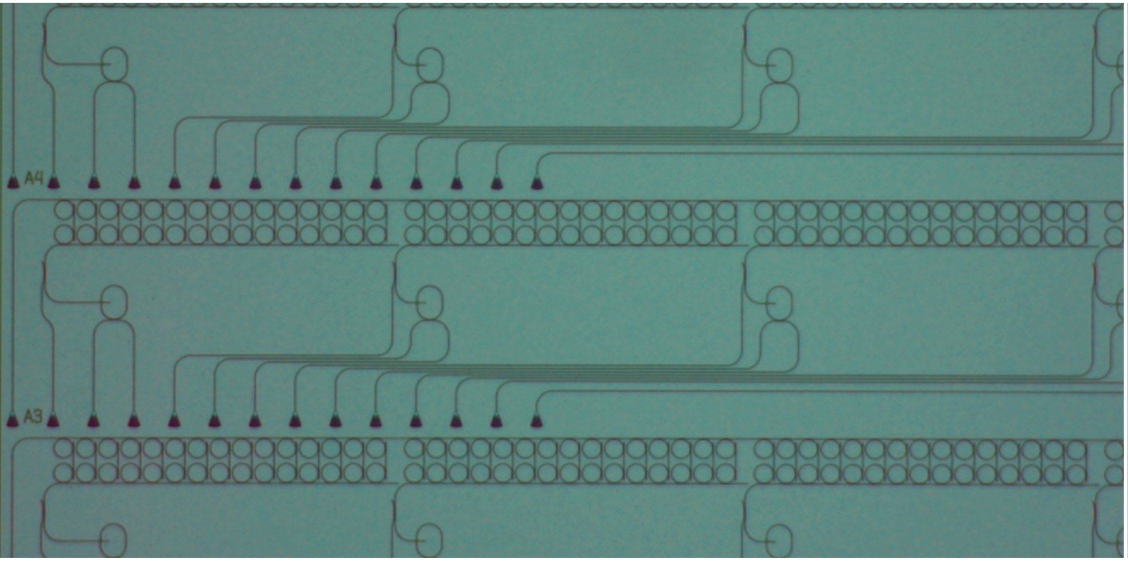
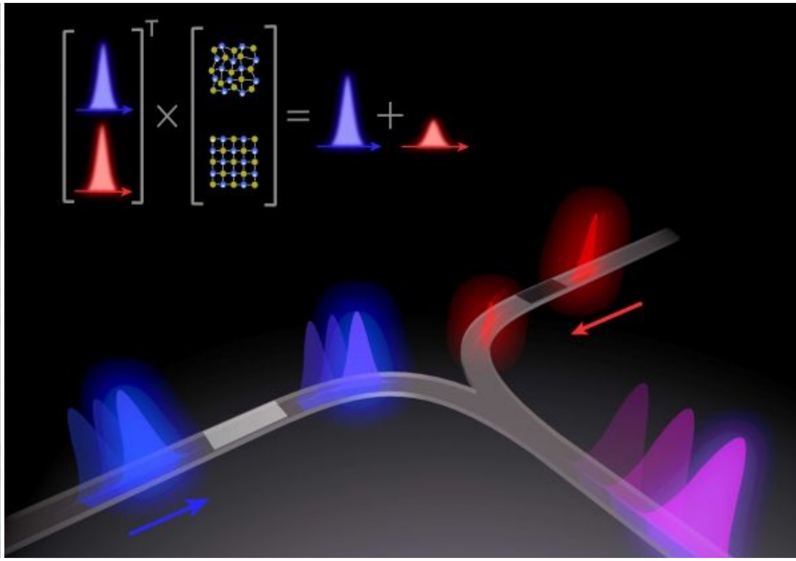
Photonic neuromorphic processing

Wolfram Pernice
https://www.kip.uni-heidelberg.de/photon/

Heidelberg University, Kirchhoff-Institute for Physics



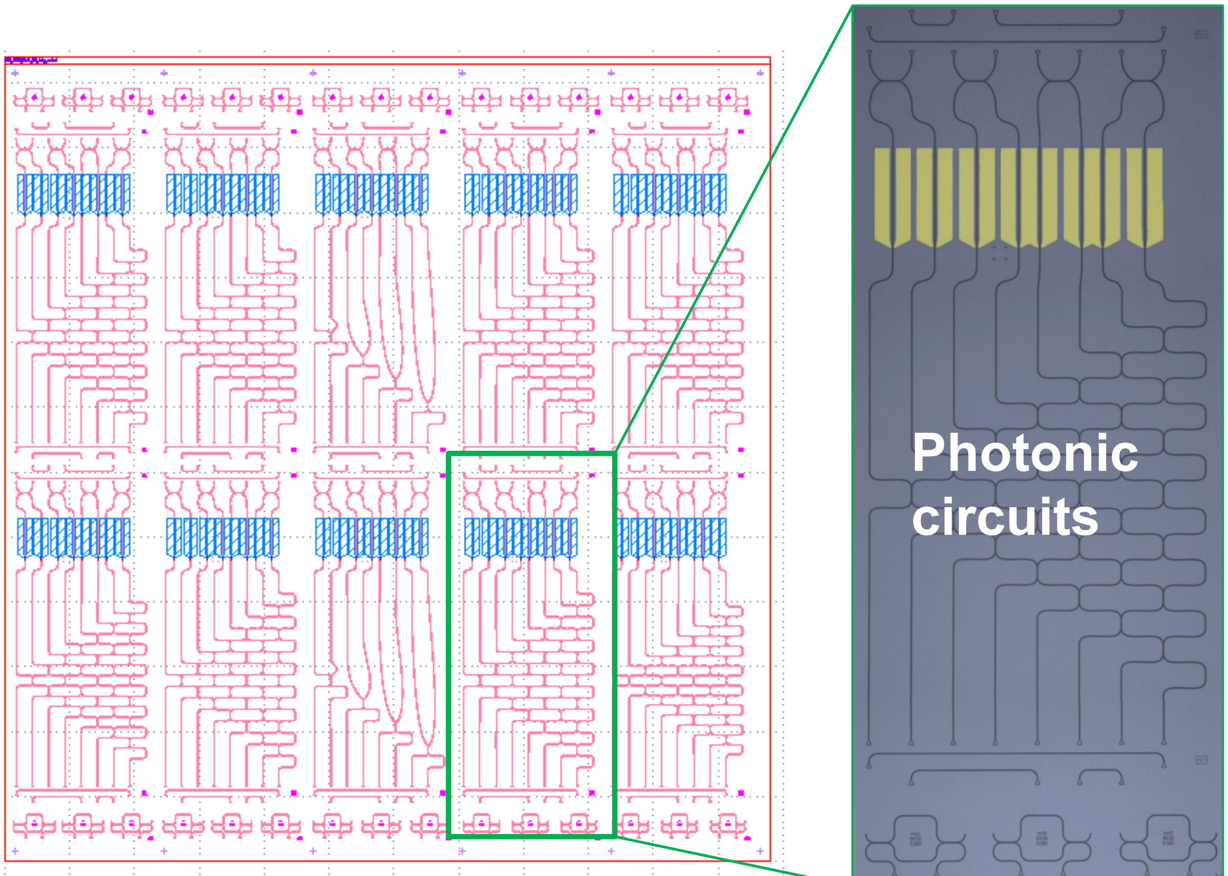


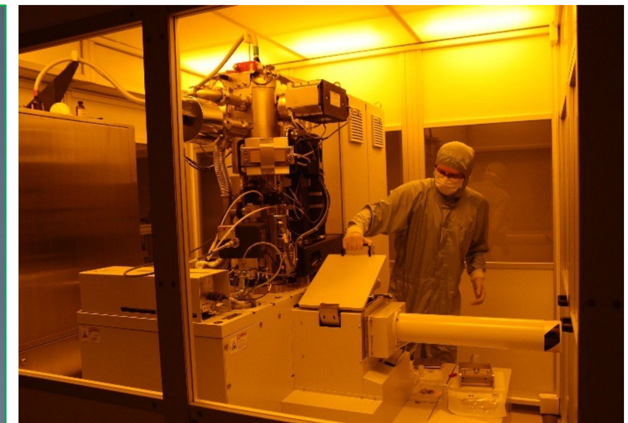
Photonic circuits for computing

- Waveguide based devices
- Nanofabricated in Uni cleanrooms
- Photonic CAD with Python framework

MÜNSTER NANOFABRICATION FACILITY

Funded by
DFG Deutsche Forschungsgemeinschaft
German Research Foundation

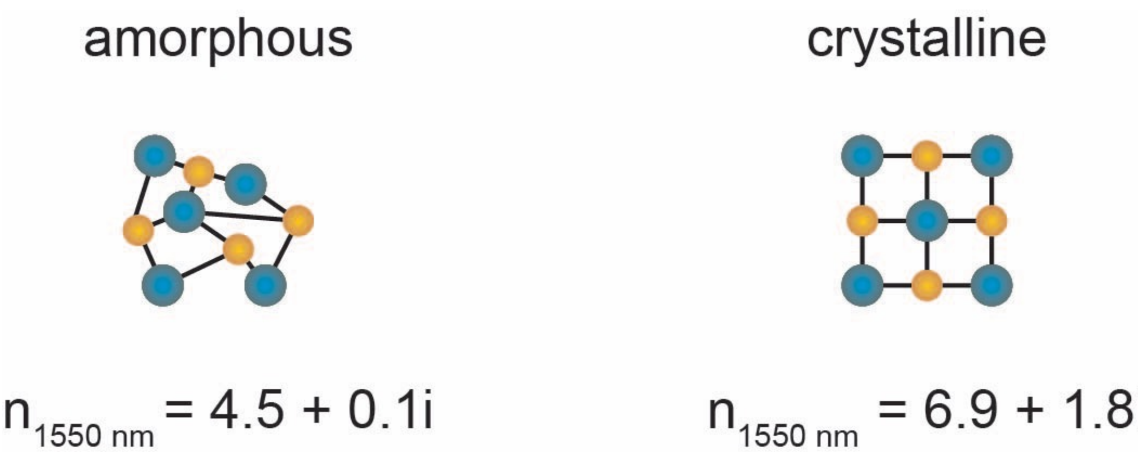




Gehring, et al., OSA Contin. 2, 3091 (2019)

Re-programmable photonics

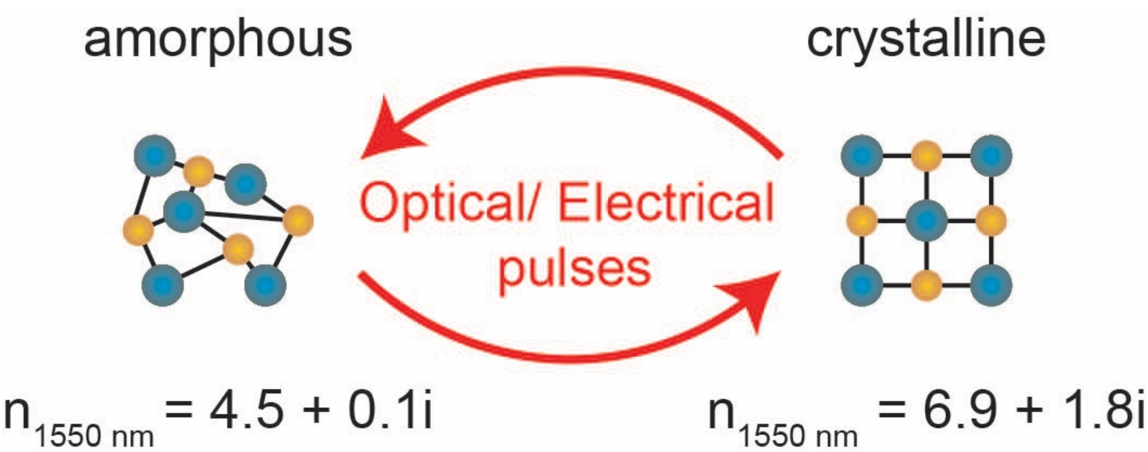
- Add active elements to passive waveguides
- Implement synapses and neuron soma with phase change materials (PCMs)



$Ge_2Sb_2Te_5$ (GST)

Re-programmable photonics

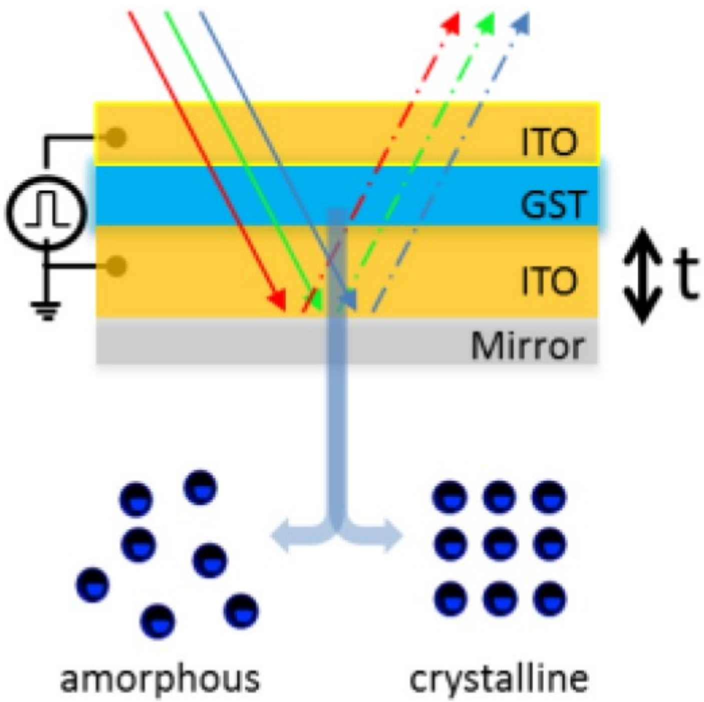
- Add active elements to passive waveguides
- Implement synapses and neuron soma with phase change materials (PCMs)
- All-optical reconfiguration within sub-nanoseconds

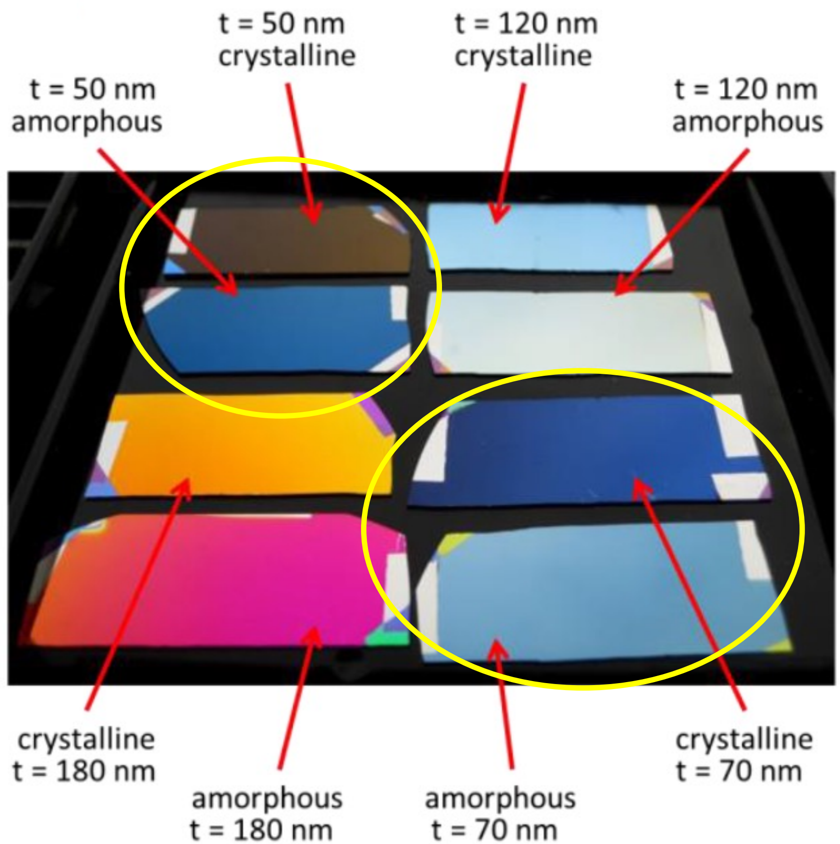


$Ge_2Sb_2Te_5$ (GST)

Re-programmable photonics

- Change of optical properties is directly visible
  => use reflectivity, transmission, absorption

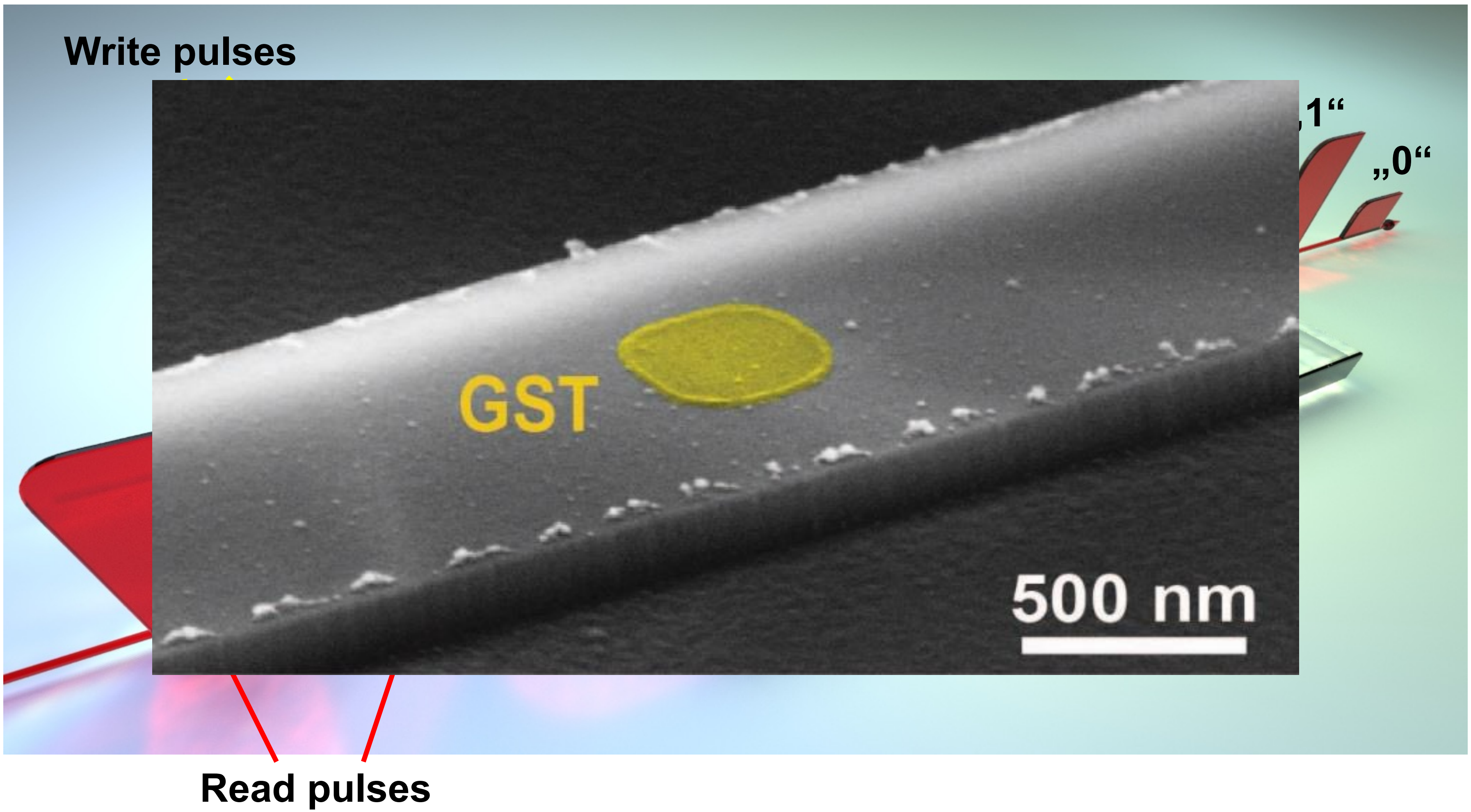




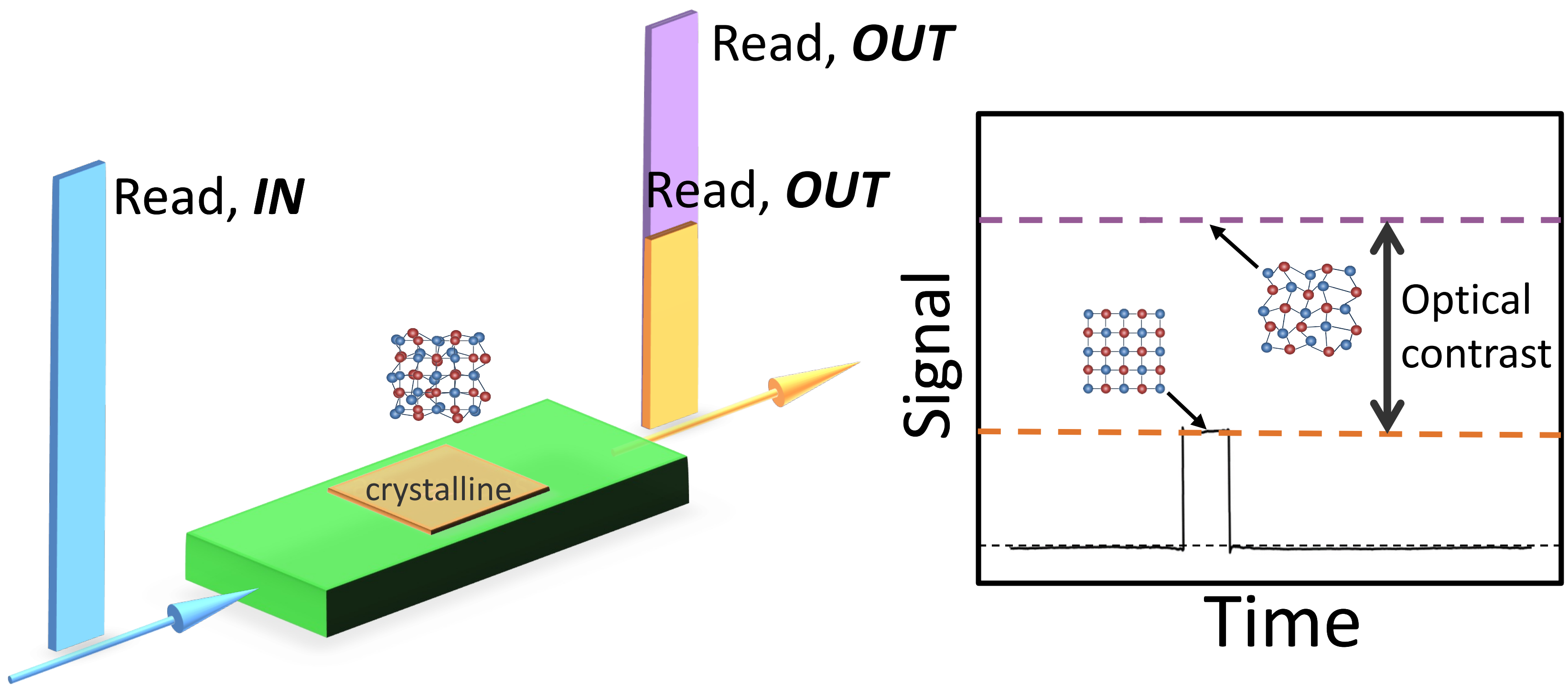
P. Hosseini, C D Wright & H Bhaskaran, Nature 511, 206 (2014)

PCM nanophotonic devices

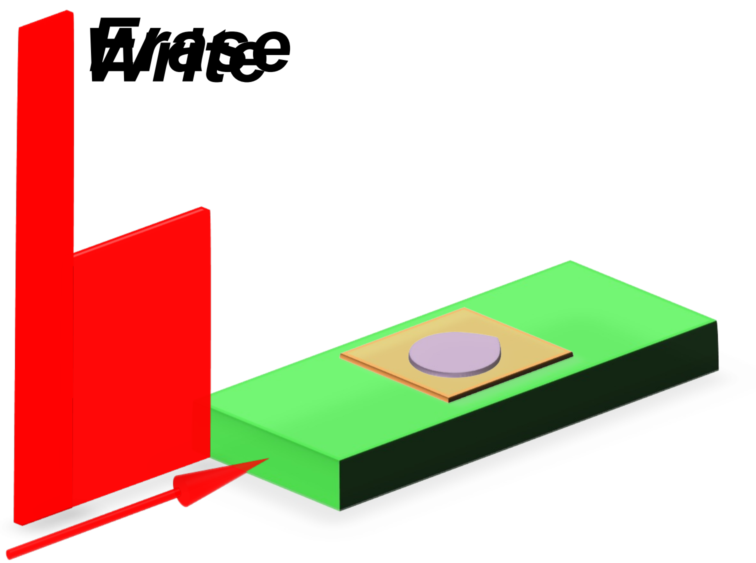
- Place PCM in near-field of optical waveguide
- Data is encoded in the amount of transmitted power

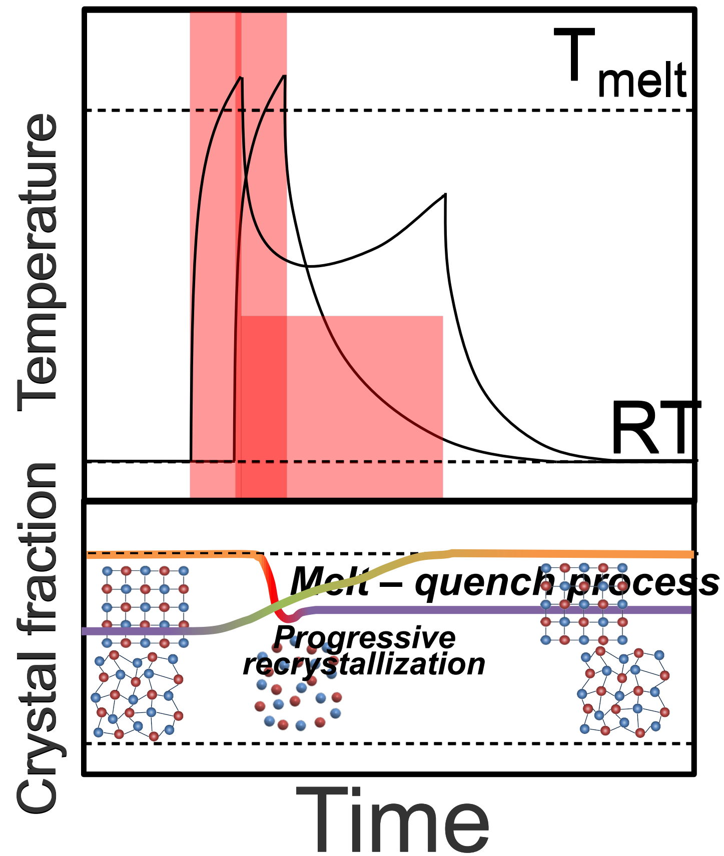


Operating principle: readout process



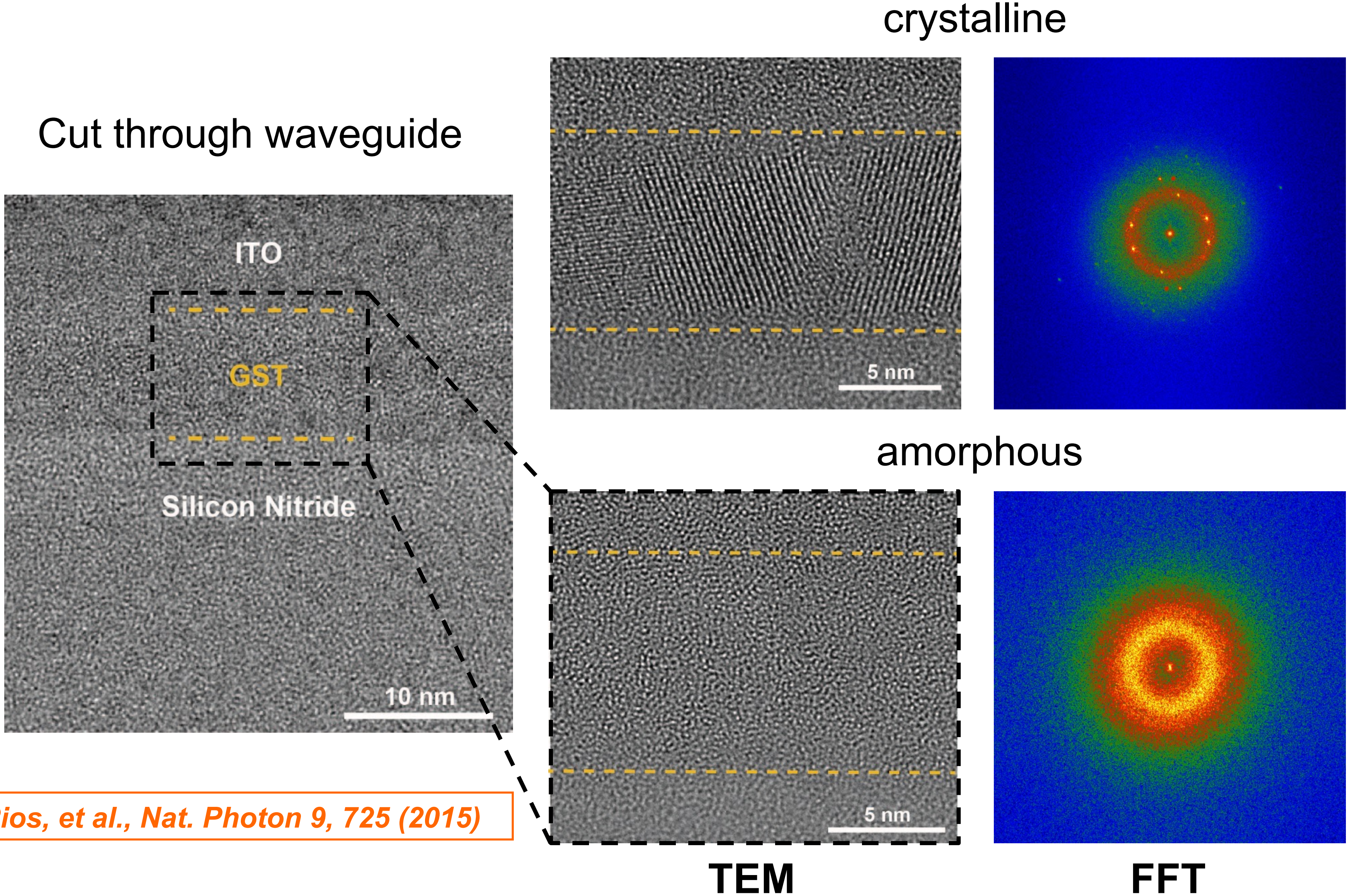
Operating principle: write/erase process





Change of atomic ordering

Cut through waveguide

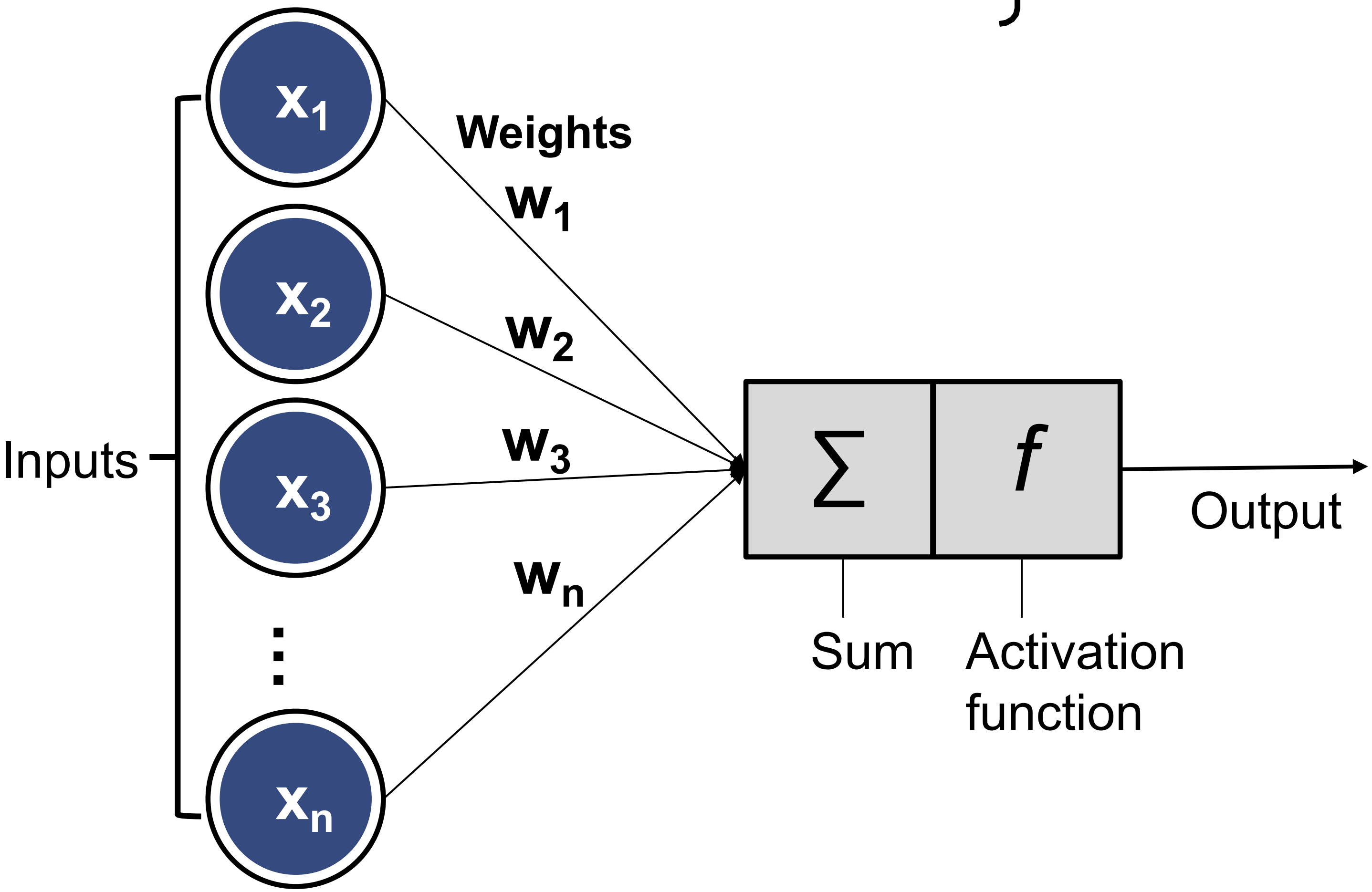


Rios, et al., Nat. Photon 9, 725 (2015)

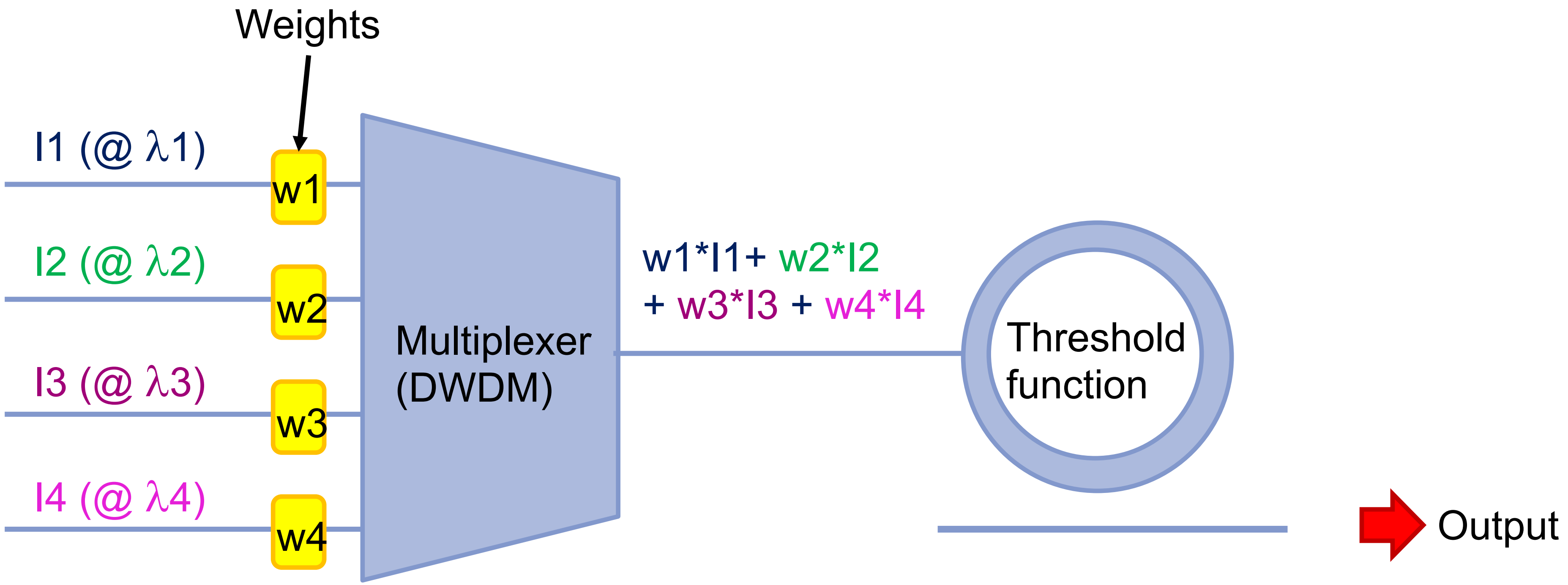
Artifical neuron - concept

- Operations required for matrix multiplication:
  - Multiplication
  - Addition

  } Multiply-accumulate (MAC)



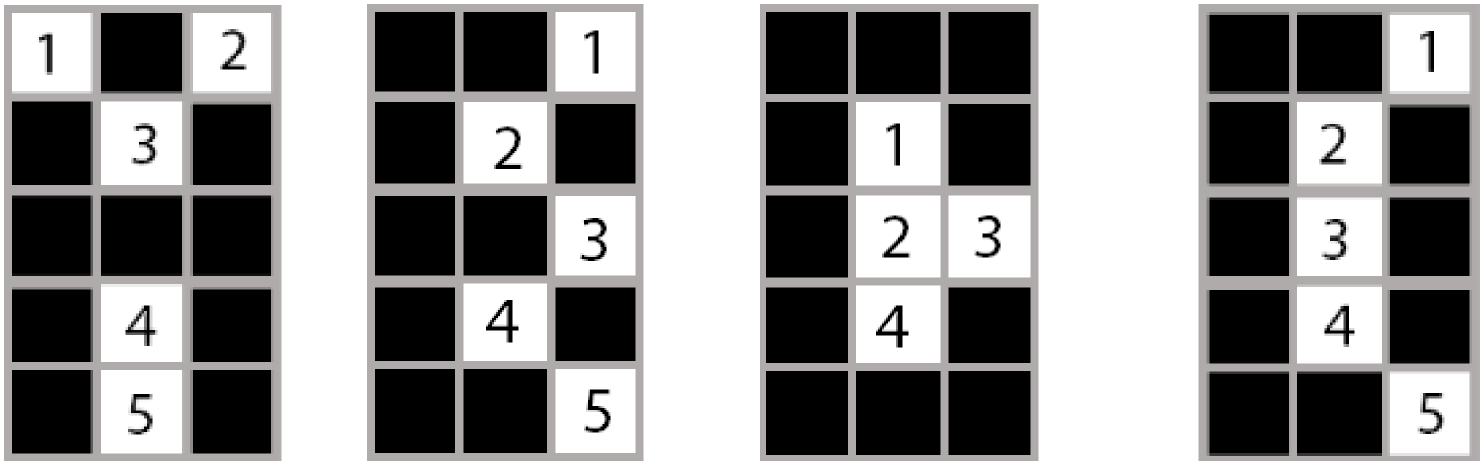
Photonic neurons

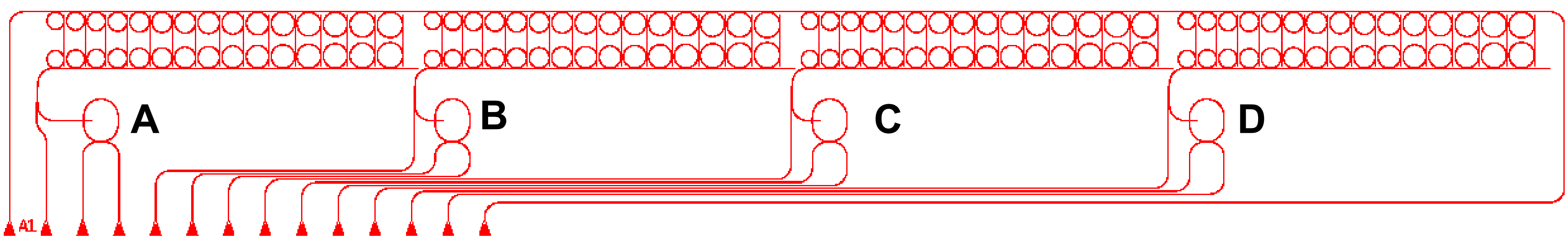


- Tunable weights using phase-change materials
- WDM multiplexer to perform signal addition without interference
- Tunable ring resonator as threshold generator

Feldmann, et al., Nature 569, 208 (2019)

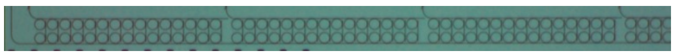
A small-scale ANN

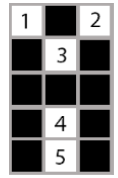


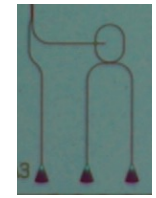


- 15 input neurons and 4 output neurons
- Each letter is pixelized into 15 digital elements
- Complementary basis to reduce number of input wavelengths

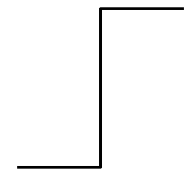
A closer look at the phontonic ANN







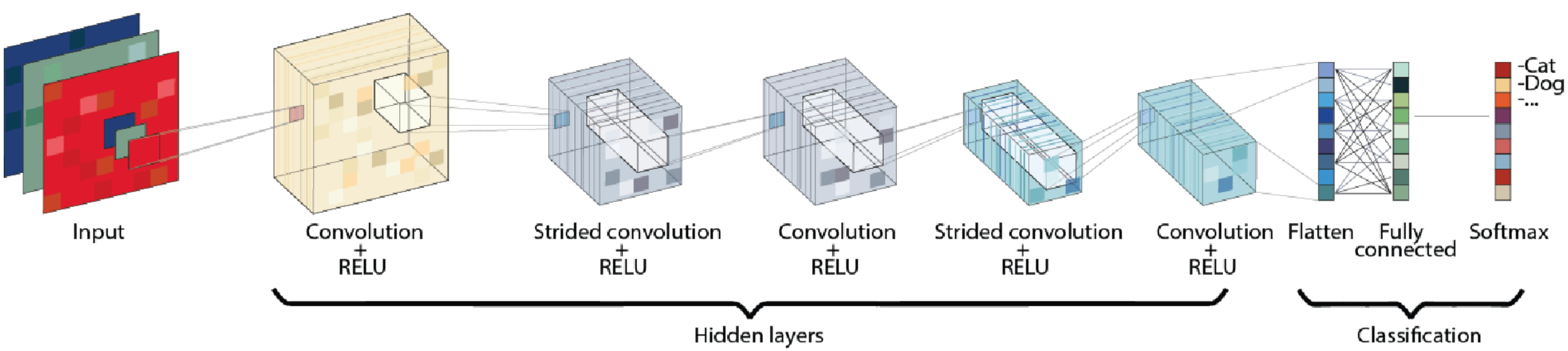
$$\begin{bmatrix} a_{11} & \cdots & a_{1N} \\ \vdots & \ddots & \vdots \\ a_{M1} & \cdots & a_{MN} \end{bmatrix} \times \begin{pmatrix} X_1 \\ X_2 \\ \vdots \\ X_N \end{pmatrix} = \begin{pmatrix} Y_1 \\ Y_2 \\ \vdots \\ Y_M \end{pmatrix} \times$$



Synaptic weights

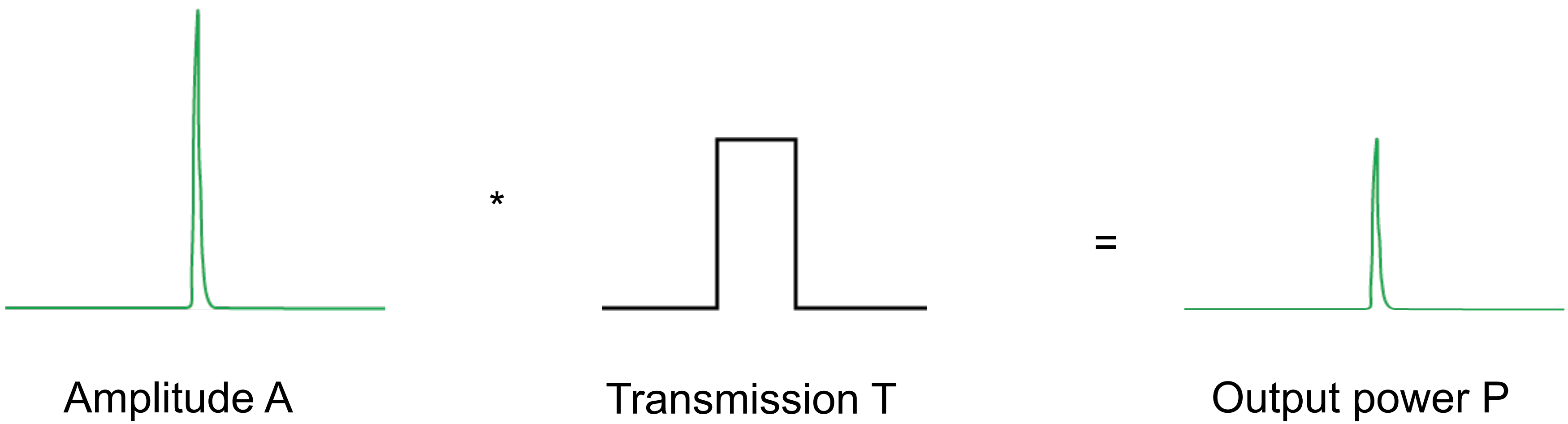
Input-Vector

Rectification



Convolutional neural networks

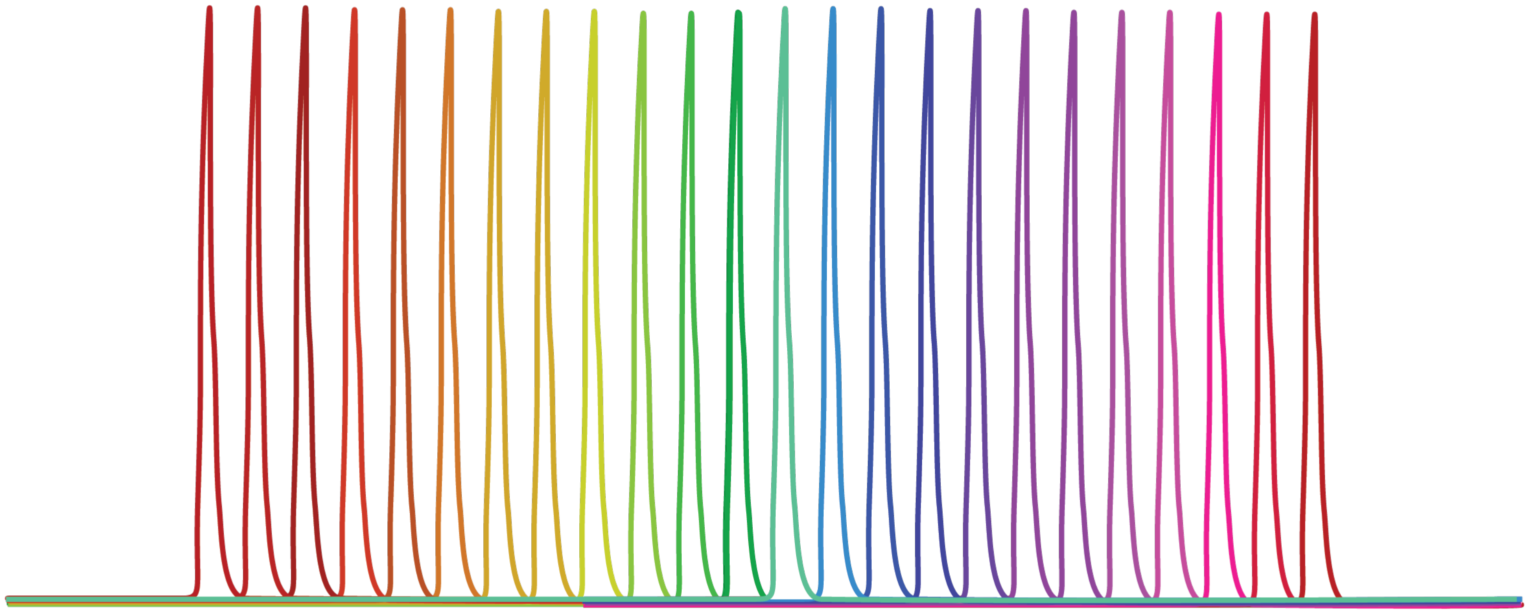
Matrix multiplication on amplitude



$$A*T = P$$

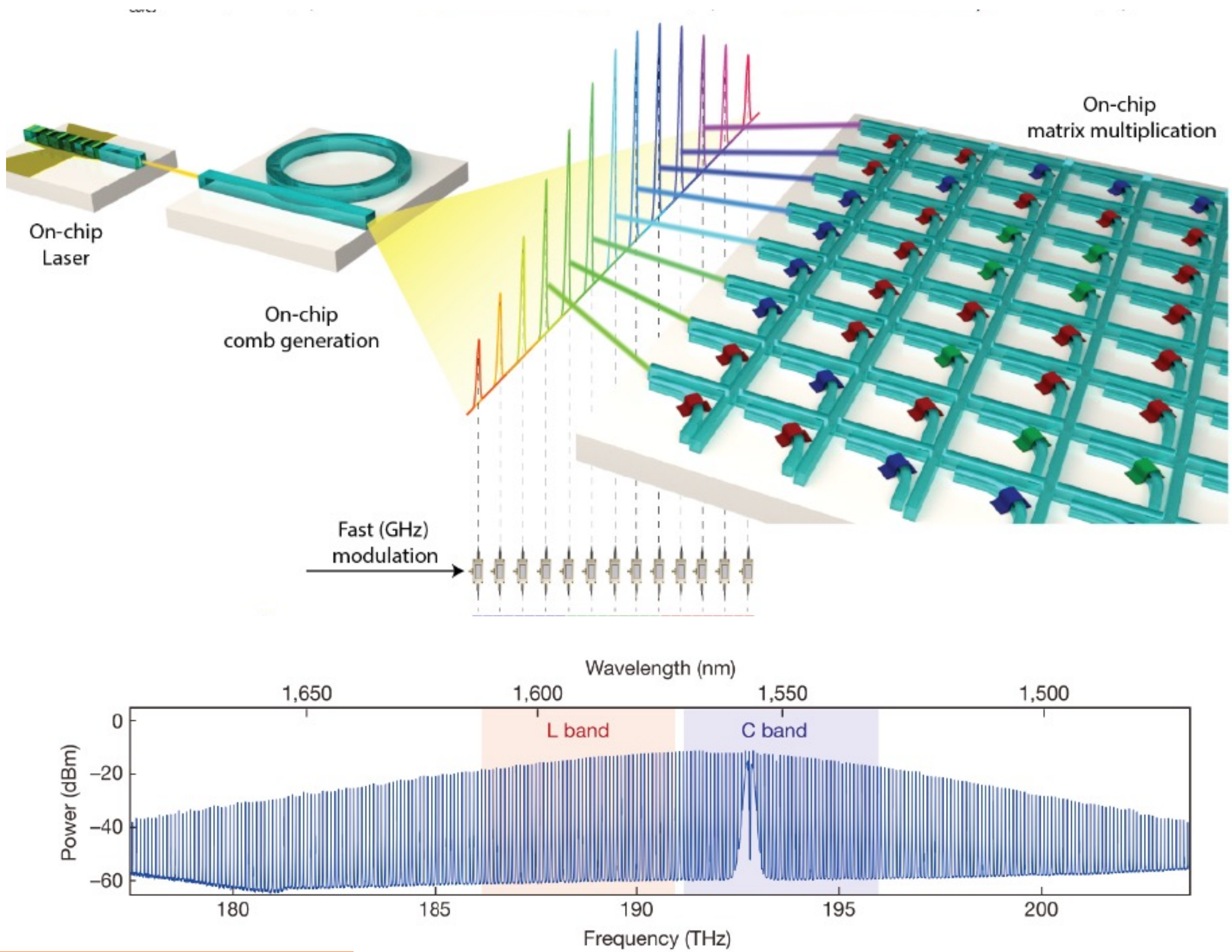
- Performing multiplication corresponds to:
  - Set amplitude A
  - Set transmission T
  - measure P

More multiplications in parallel



- What works with one color …
- … also works with more

Ultrafast convolution processing

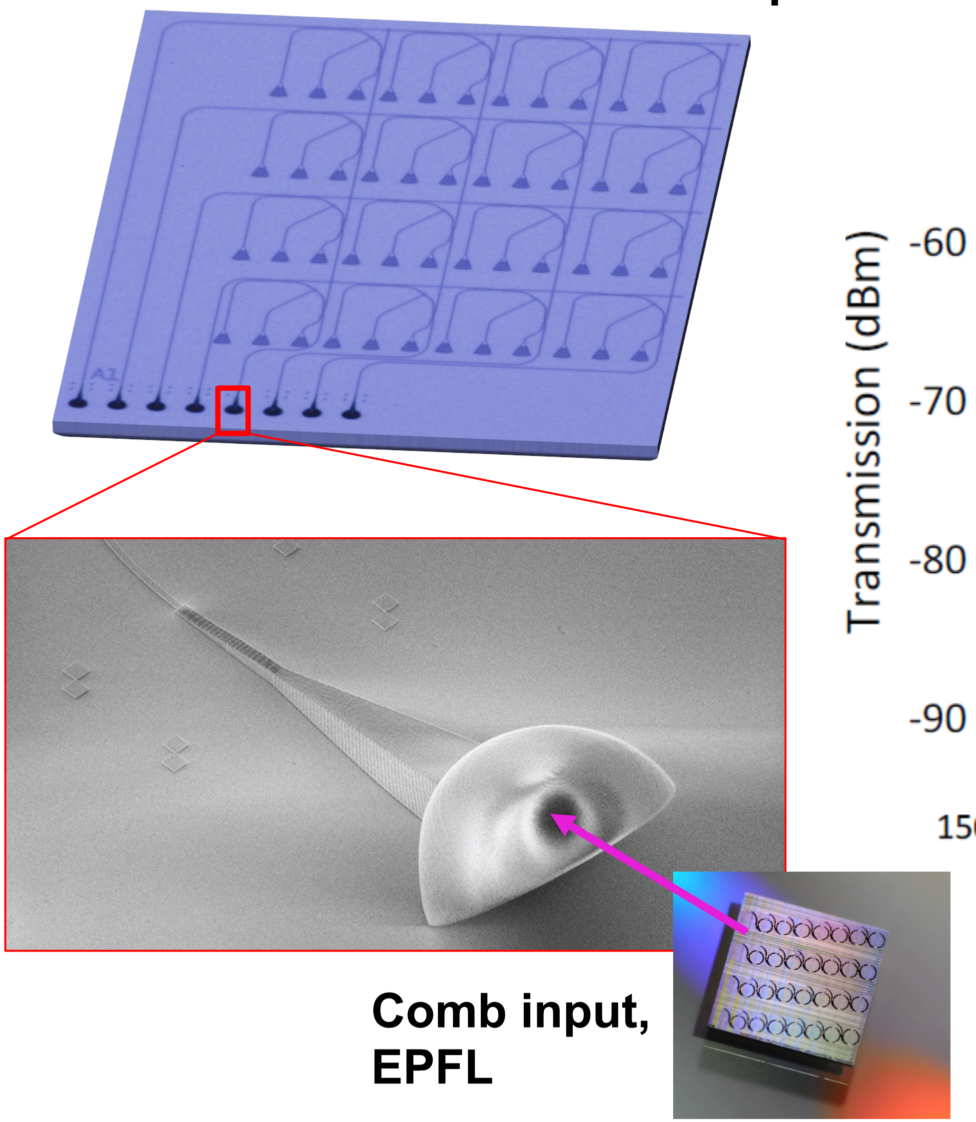


Feldmann, et al., Nature 589, 52 (2021)

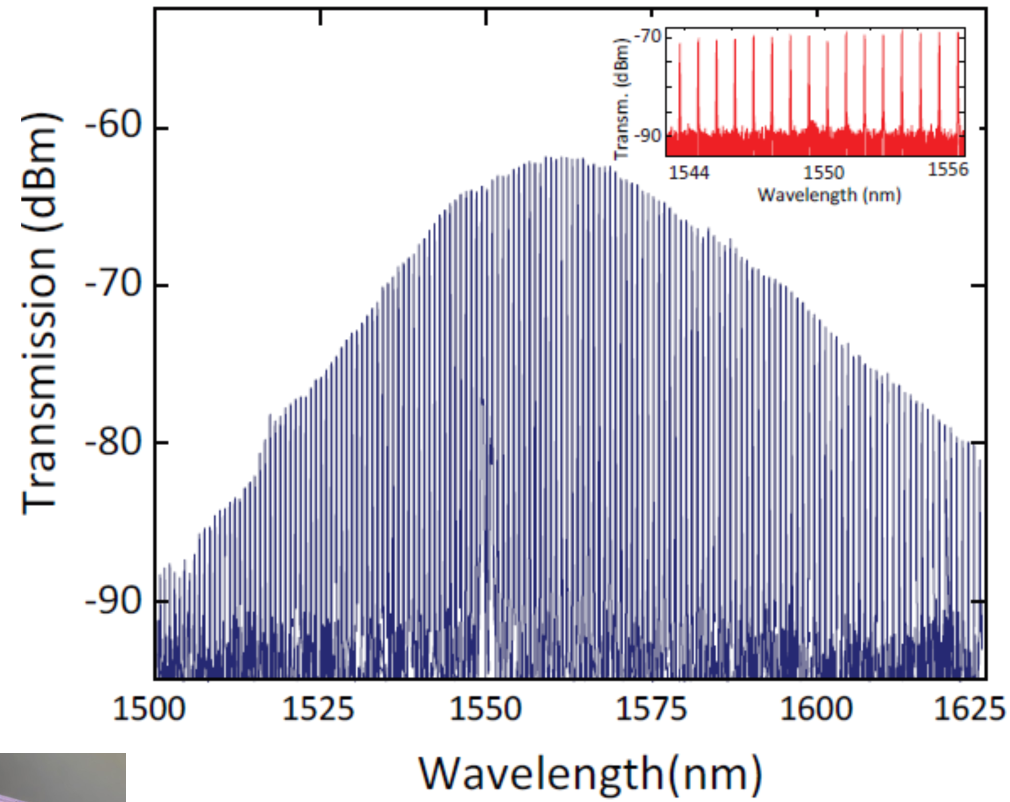
Frequency comb, Kippenberg group (EPFL)

Ultrafast convolution processing

PCM Matrix chip

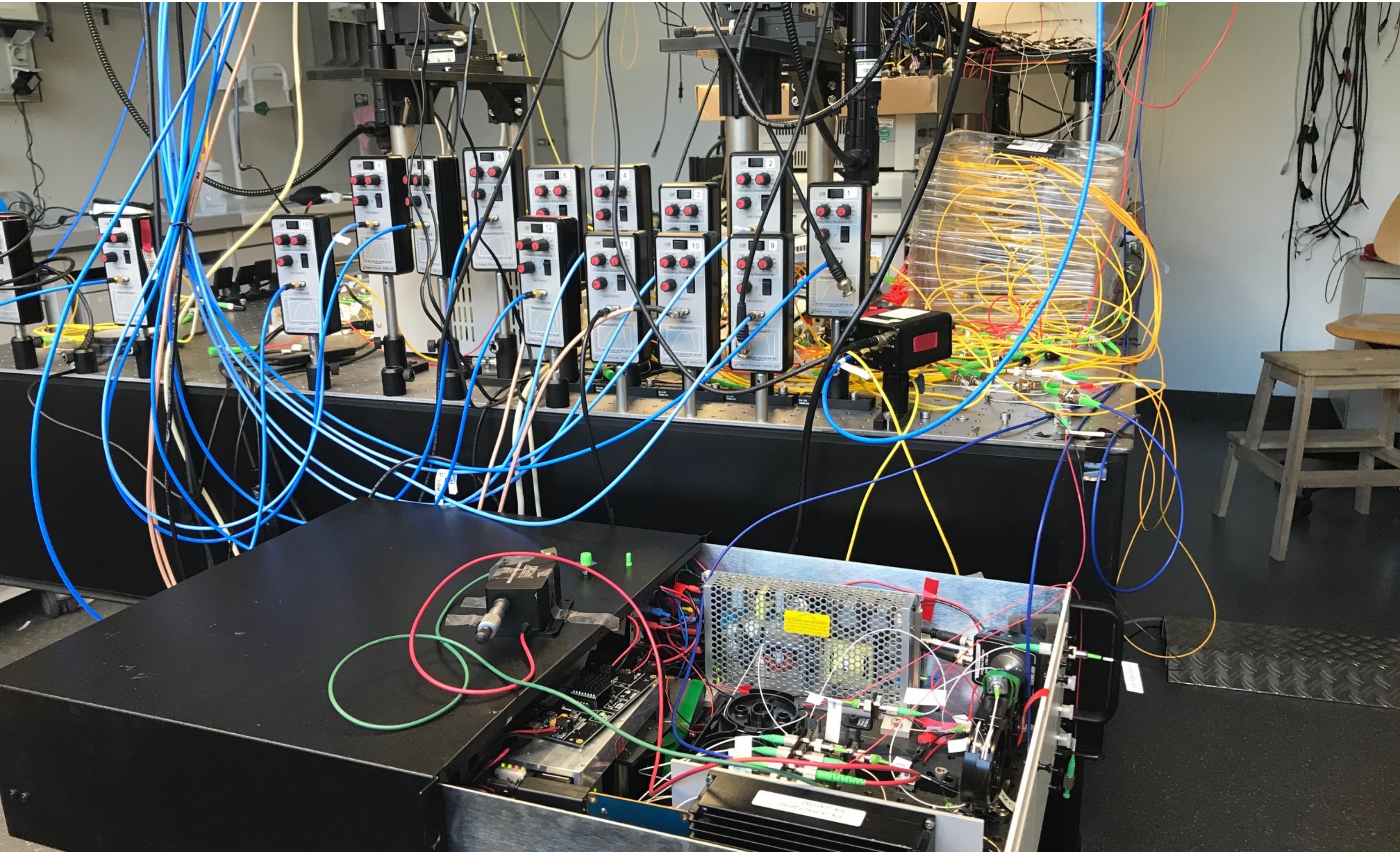


Comb input, EPFL

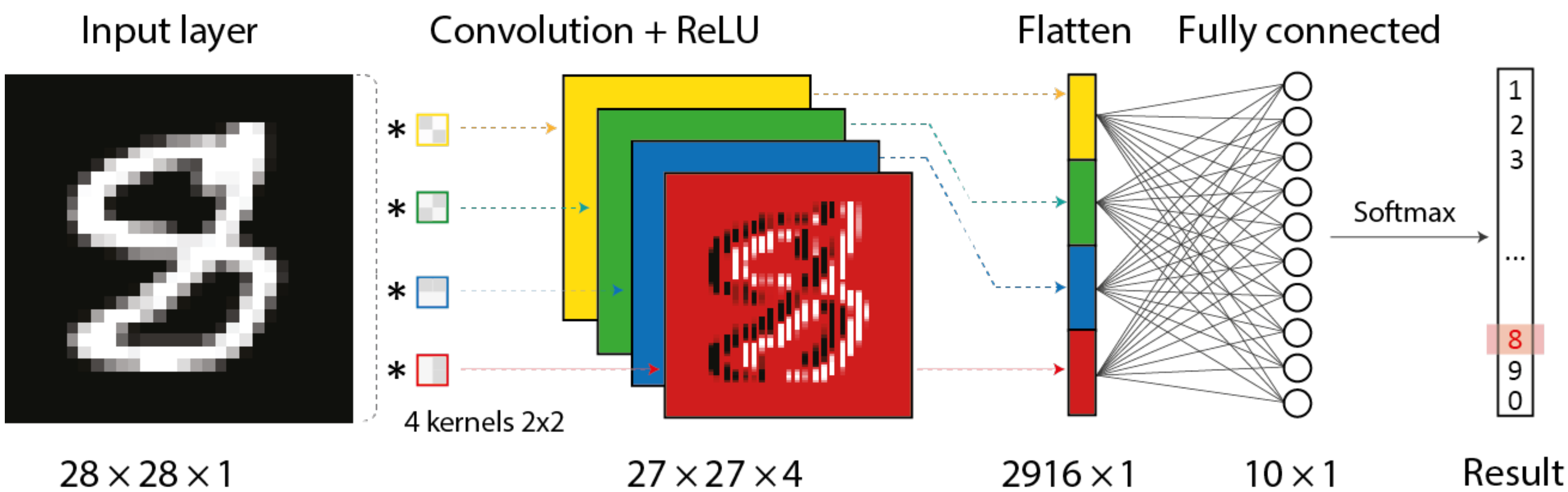


Feldmann, et al., Nature 589, 52 (2021)

Ultrafast convolution processing

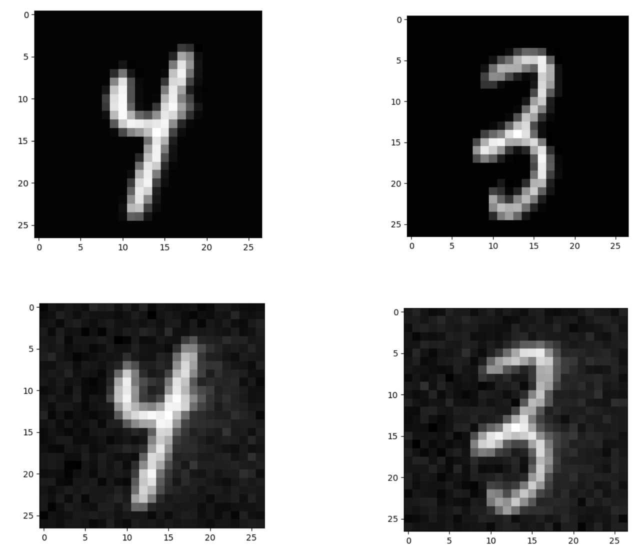


Digit recognition with photonic NNs



~95% accurate

Prediction \ Label	0	1	2	3	4	5	6	7	8	9
0	97.6		0.6		0.6		2.3			
1		99.4	0.6					0.7		
2			93.0	0.6				4.0	1.4	
3		0.6	0.6	98.7		2.2		1.3	0.7	
4					95.8			0.7	1.4	2.1
5						93.4	0.8		1.4	1.4
6	1.6		1.7		1.2	0.7	95.4			
7			0.6					89.3	0.7	3.5
8	0.8		2.3	0.6	2.4	3.6	1.5	1.3	94.3	4.2
9			0.6					2.7		88.9



The people who really do the work:

At WWU:
C. Schuck and team

F. BP, A. Ovvyan, S. Ferrari, N. Walter, F. Beutel, M. Stappers, H. Gehring, C. Kaspar, F. Lenzini, T. Grottke, J. Lin, J, Schütte, E. Lomonte, R. Terhaar, I. Bente, D. Wendland, A. Varri, L. Deriks, R. Jaha, D. Raskhodchikov

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M. Karpov

At IBM:
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