NEUROMORPHIC SILICON PHOTONICS: APPLICATIONS, CLASSICAL TO QUANTUM

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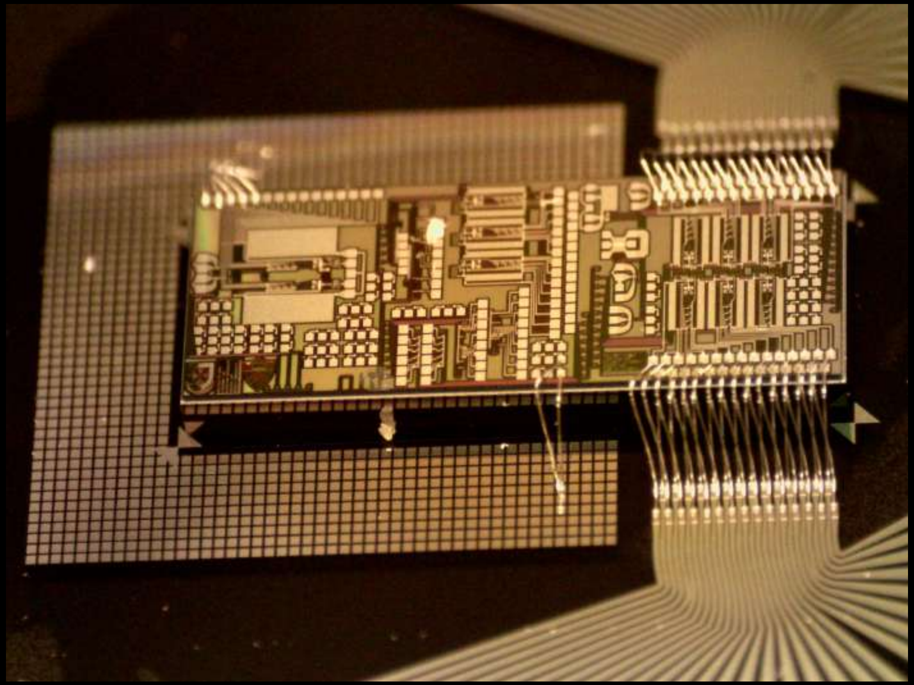
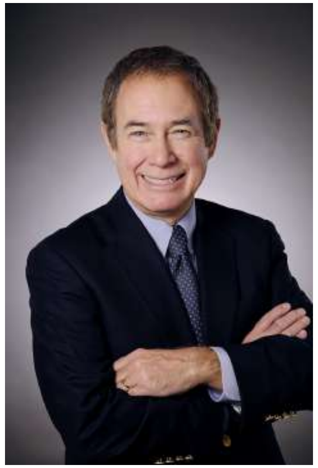
Faculty Affiliate: Vector Institute
Visiting Faculty: Princeton University



Collaborators



P. Prucnal
Princeton

L. Chrostowski
UBC

S. Shekhar
UBC

A. Tait
Queen's

C. Huang
CUHK

Volker Sorger
GWU

N. Rotenberg
Queen's

N. Youngblood
Pittsburgh

+ many others and co-authors

Fabrication Support

CMC MICROSYSTEMS

SiEPIC FAB

ANT APPLIED NANOTOOLS INC.

amf ADVANCED MICRO FOUNDRY

GlobalFoundries™

Students and Postdocs

Credit: Ishana Gopaul

Shastri Lab (Queen's)

Researcher: B. Marquez

Current Graduate Students: Z. Guo; H. Morison; M. Tamura; M. Moridsadat; A. Khaled; J. Ewaniuk; A. Grace; A. McCaw; T. Austin; N. Al-Kayed; L. Rantz

+ former students

Prucnal Lightwave Lab (Princeton)

Researcher: T. Ferreira de Lima; Lei Xu

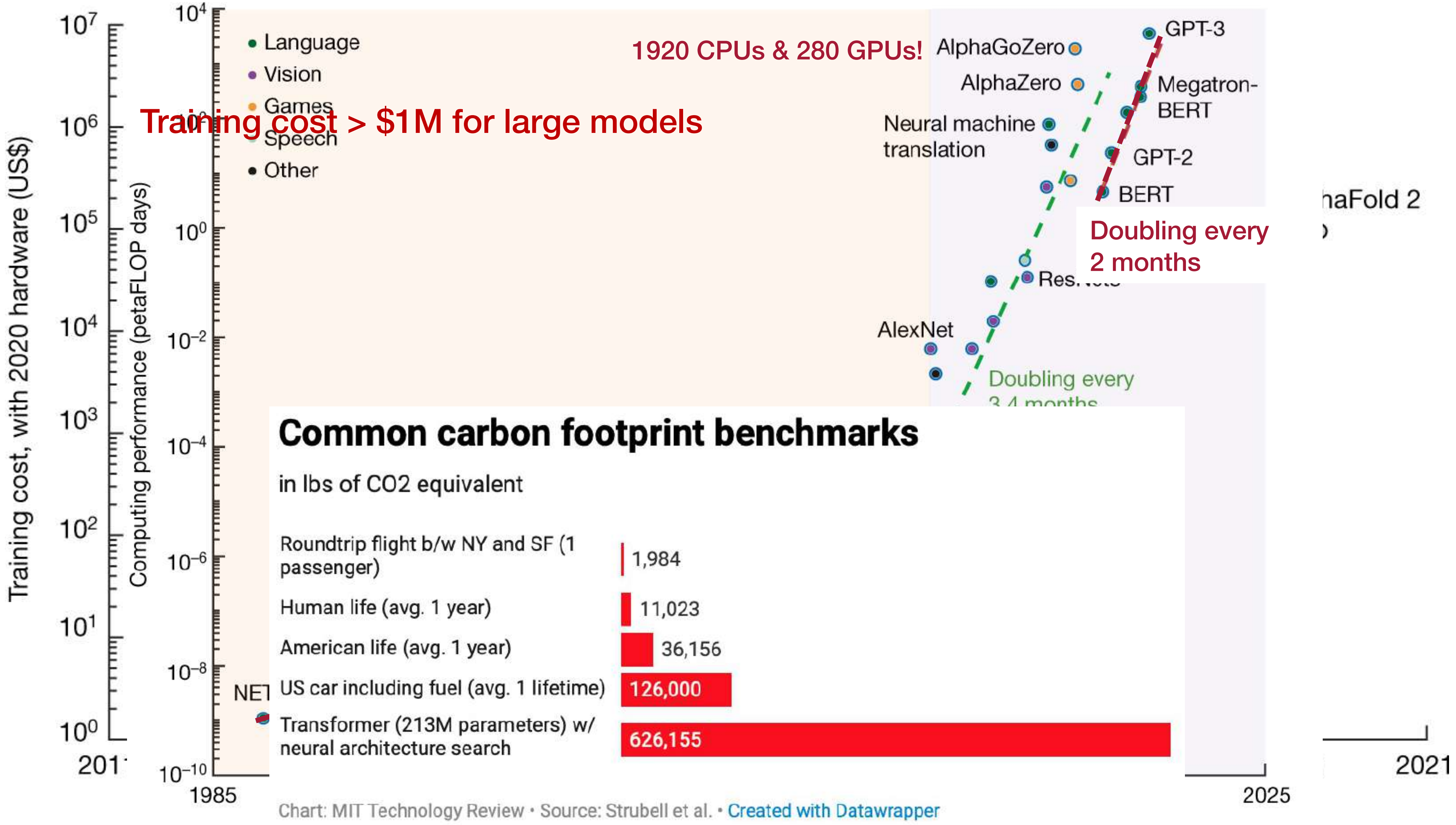
Graduate Students: E. Blow, A. Jha; S. Bilodeau; W. Zhang; J. Lederman; H-T. Peng

+ former students and postdocs

Outline

- Recent work in neuromorphic photonics
- Silicon photonic neural networks
  - weighted interconnects: synapses
  - nonlinearities: electro-optic & reconfigurable
- Neuromorphic photonics demonstrations
  - Highlight applications: wireless, fiber
  - Quantum photonic neural networks
- Roadmap for neuromorphic photonics

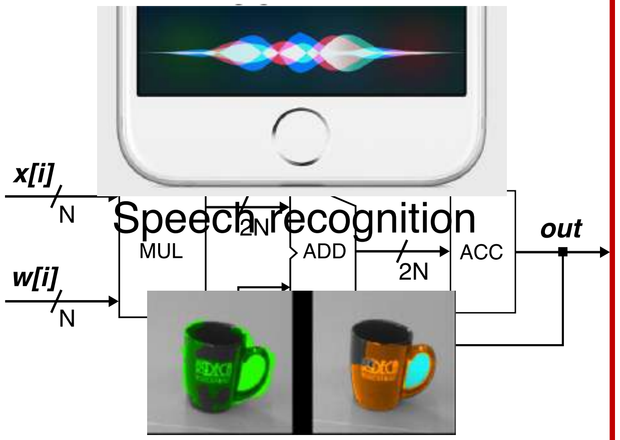
Compute Usage in AI Systems



Mehonic, Kenyon, *Nature* **604** (2022)

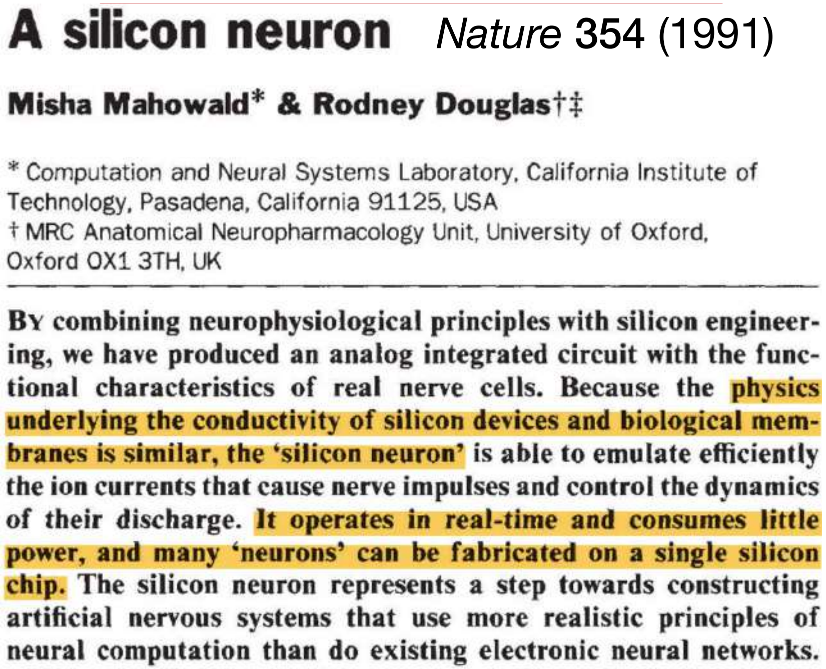
Toward Neuromorphic (*neuron-isomorphic*) Hardware

Software neural networks on **digital hardware**	Hardware neural networks **Neuromorphic Electronics**	Photonic neural networks **Neuromorphic Photonics**



Object recognition

Hz - kHz



A silicon neuron *Nature* **354** (1991)

Misha Mahowald* & Rodney Douglas†‡

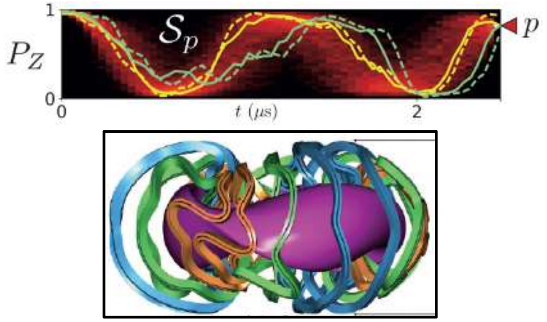
* Computation and Neural Systems Laboratory, California Institute of Technology, Pasadena, California 91125, USA
† MRC Anatomical Neuropharmacology Unit, University of Oxford, Oxford OX1 3TH, UK

By combining neurophysiological principles with silicon engineering, we have produced an analog integrated circuit with the functional characteristics of real nerve cells. Because the physics underlying the conductivity of silicon devices and biological membranes is similar, the 'silicon neuron' is able to emulate efficiently the ion currents that cause nerve impulses and control the dynamics of their discharge. It operates in real-time and consumes little power, and many 'neurons' can be fabricated on a single silicon chip. The silicon neuron represents a step towards constructing artificial nervous systems that use more realistic principles of neural computation than do existing electronic neural networks.

Bandwidth-complexity tradeoff!

Capacitive loading, EMI, electrical constraints

- *Bandwidth-complexity tradeoff!*



Nonlinear optimization
Ultrafast control
RF signal processing
Quantum tomography

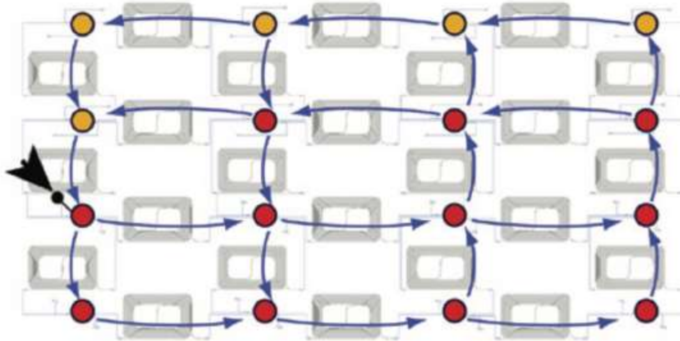
GHz

Could enable new applications that are challenging to be achieved with electronics!

Shastri, Tait, Prucnal et al. **Nature Photonics 15** (2021)

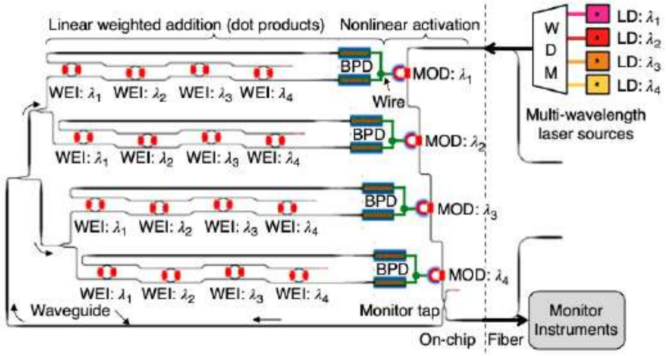
Recent Work on Neuromorphic Photonics

Reservoir computing
(UIB, Ghent, Femto-St)



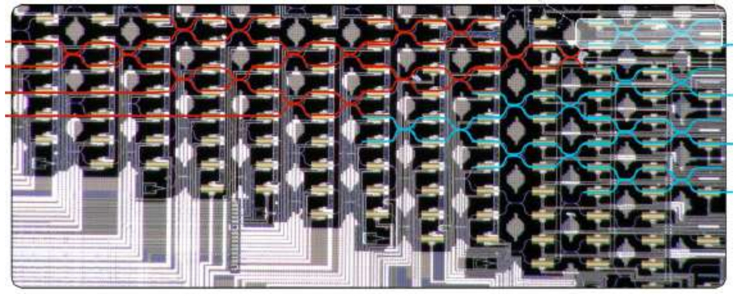
Brunner et al. *Nat. Commun.* 4 (2012)
Vandoorne et al. *Nat. Commun.* 5 (2014)

Multiwavelength Networks
(Princeton, Queen's, GWU)



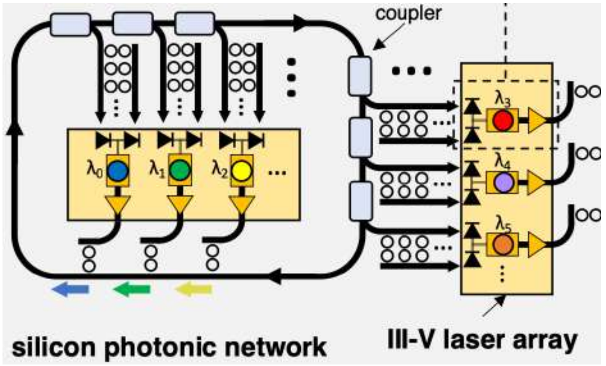
Huang et al. *Nature Electronics* 4 (2021)
Tait et al *Sci. Rep.* 4 (2017)
Feldman et al. *Nature* 589 (2021)

Coherent networks
(MIT, Stanford)



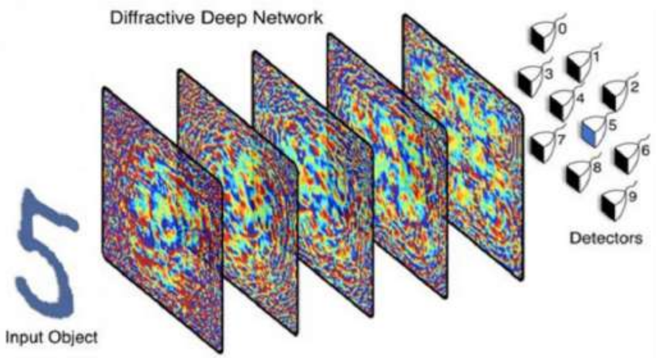
Shen et al. *Nat. Photon.* **11** (2017)
Hughes et al. *Optica* **5** (2018)

Spiking networks
(Princeton, Oxford, Strathclyde)



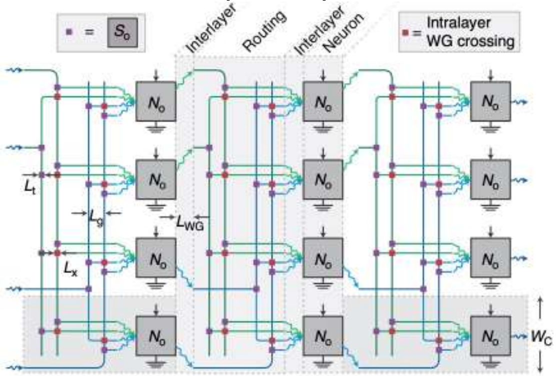
Shastri et al. *Sci. Rep.* **6** (2016)
Feldman et al. *Nature* **569** (2019)

Diffractive Optics
(UCLA, Femto-St)



Bueno et al. *Optica* **5** (2018)
Lin et al. *Science* **361** (2019)

Superconducting
(NIST)



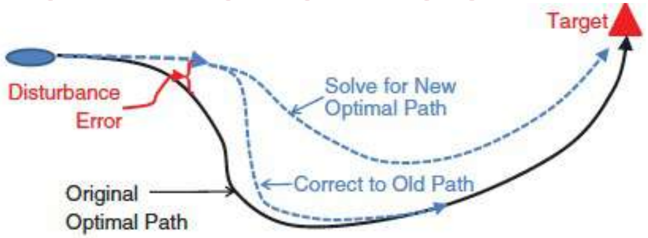
Shainline et al. *Phys. Rev. Appl.* **7** (2017)

Shastri, Tait, Prucnal et al. **Nature Photonics 15** (2021)

Applications for Neuromorphic Photonics

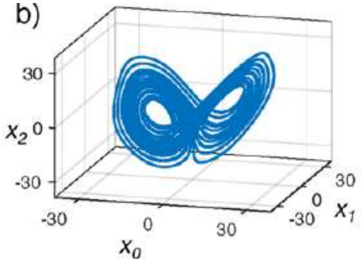
- **Nonlinear programming**
  - Nonlinear optimization problems (robotics, predictive control, autonomous vehicles)
  - Ordinary/partial differential equations
- **High-performance computing and Machine Learning**
  - Vector-matrix multiplications
  - Deep learning inference
  - Ultrafast and online learning
- **Intelligent signal processing**
  - Optical fiber communications
  - mm-wave edge processing
  - Spectral mining
- **Quantum and high-energy physics**
  - Quantum neural networks
  - High-energy particle collision experiments

Shastri, Prucnal et al. **Nature Photonics** 15 (2021)
Huang, Shastri et al. **Adv. Phys-X** 7 (2022)

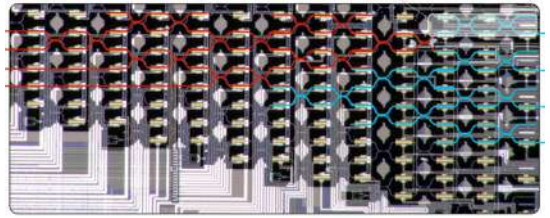


Ferreira de Lima, Prucnal et al. JLT (2019)
Model predictive control

Tait, Shastri, Prucnal et al. Sci. Rep. (2017)
Lorenz attractor



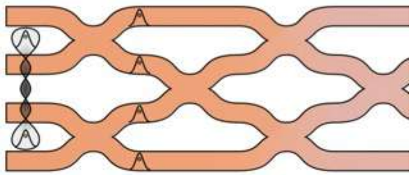
Shen et al. Nat. Photon. (2017)
Vector-matrix multiplier



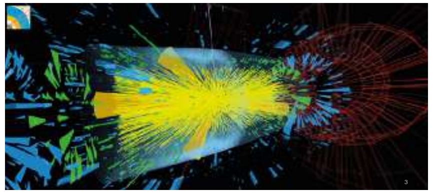
Zhang, Shastri, Prucnal et al.
Natue Communications (2022)
Broadband cognitive radio

Huang, Shastri, Prucnal et al.
Nature Electronics (2021)
Fiber nonlinearity compensation

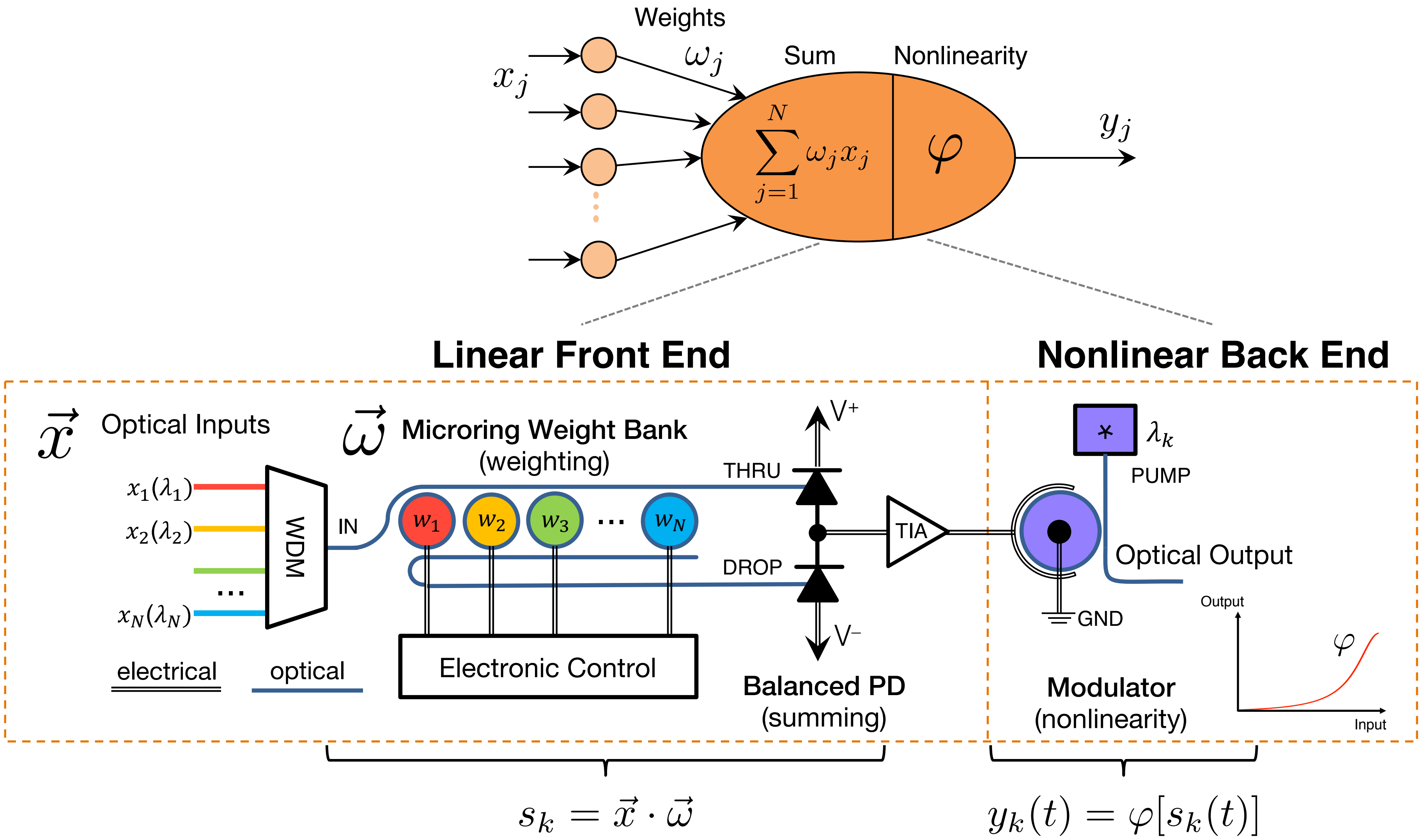
Ewaniuk, Rotenberg, Shastri et al.
Adv. Quantum Technol. (2023)
Quantum neural networks



CMS detector at CERN

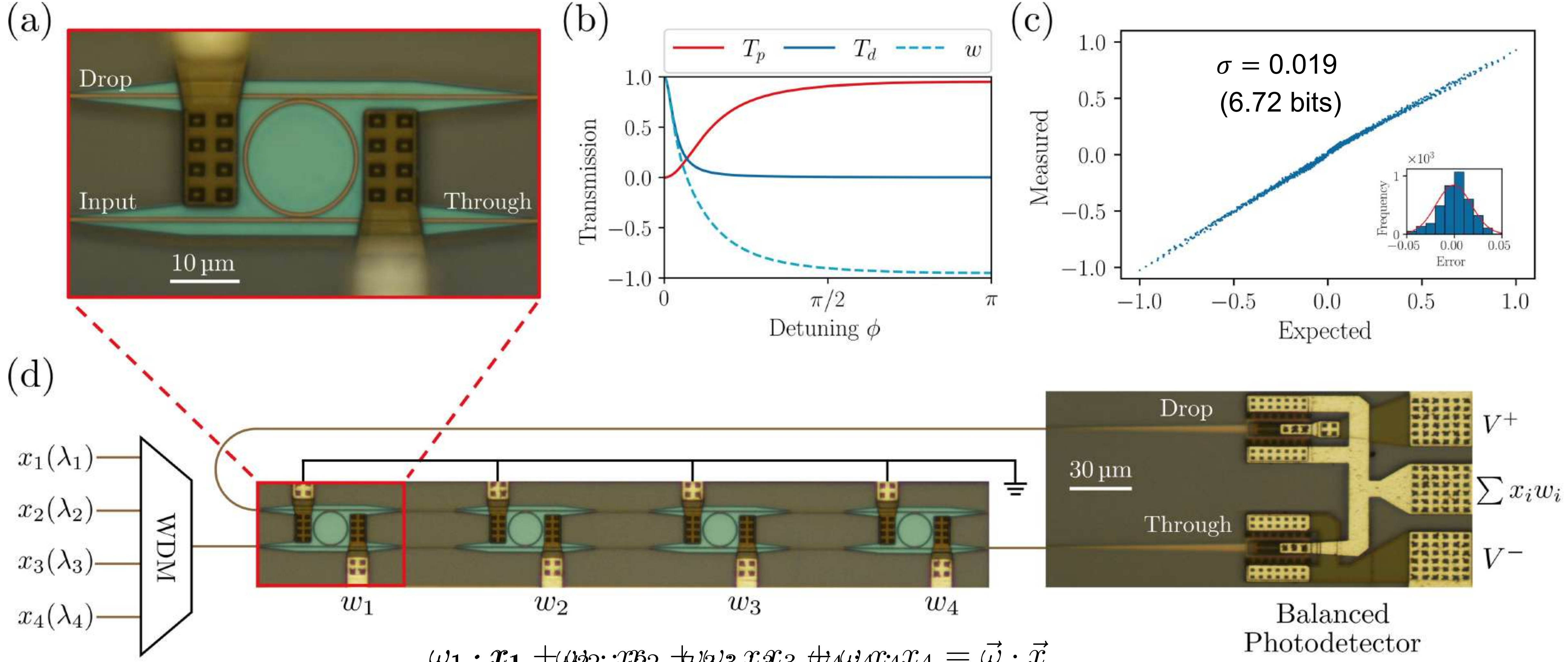


Multiwavelength Photonic Neuron



- ❑ All key functions are physically localized in each neuron, enabling distributed processing
- ❑ OEO enables gain, thresholding and cascadability/recurrent operation

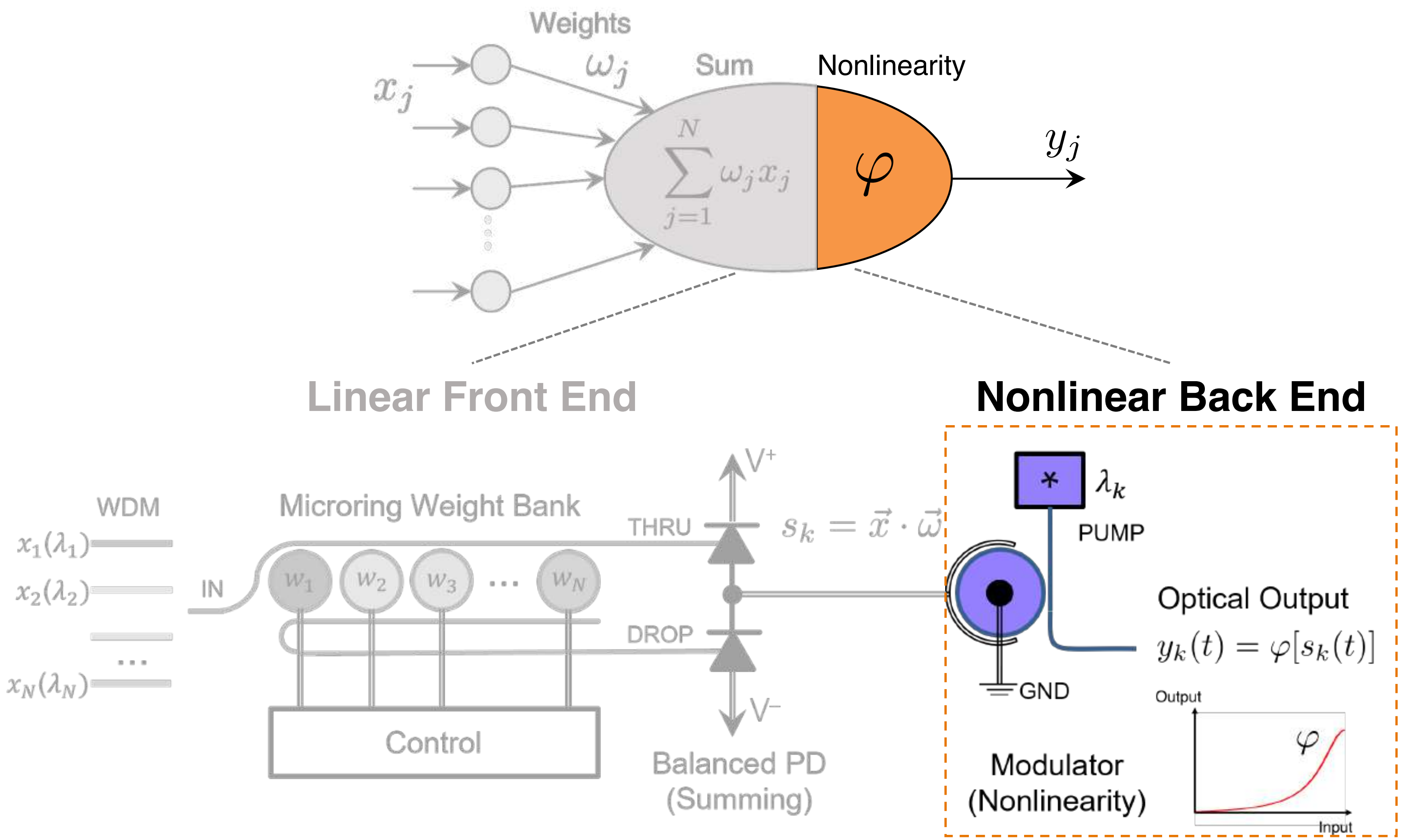
Silicon MRR and BPD = Dot Product



$$\omega_1 \cdot x_1 + \omega_2 \cdot x_2 + \omega_3 x_3 + \omega_4 x_4 = \vec{\omega} \cdot \vec{x}$$

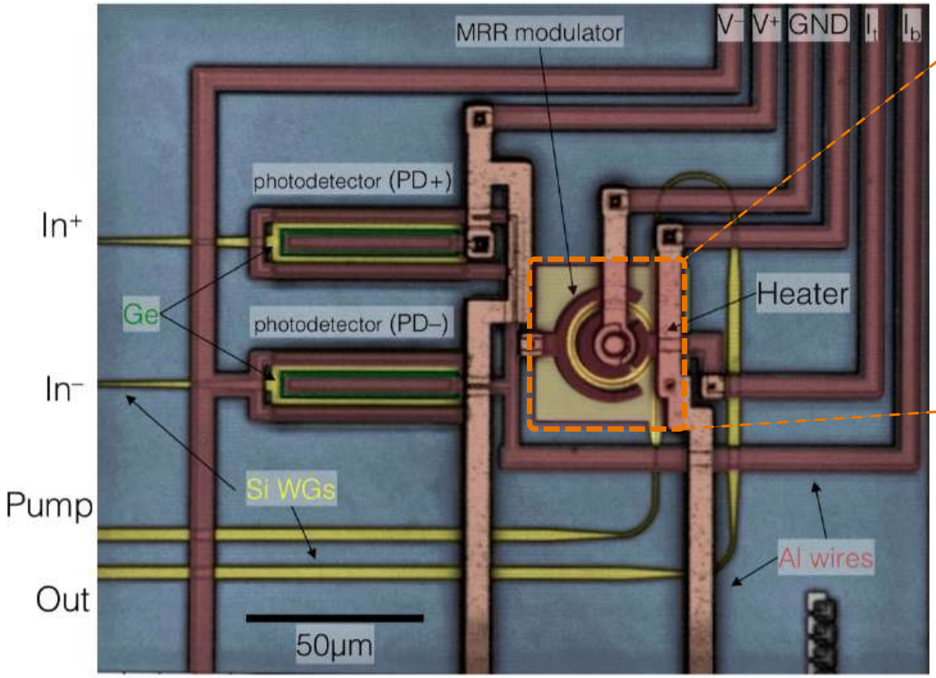
Filipovich, Guo, Shastri et al. **Optica** 9 (2022)

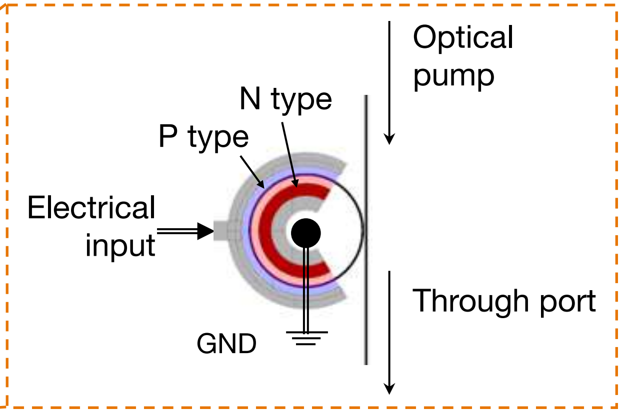
Multiwavelength Photonic Neuron



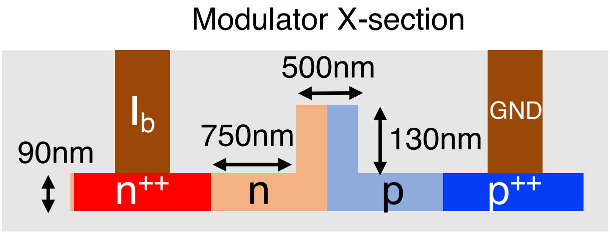
- ❑ All key functions are physically localized in each neuron, enabling distributed processing
- ❑ OEO enables gain, thresholding and cascadability/recurrent operation

EO Nonlinearity: Reconfigurable Activation Functions





- **Bias shifts the operating point on the resonance curve and changes its depth (see below)**
- **Drive signal modulates around the operating point**



The Soref Equations

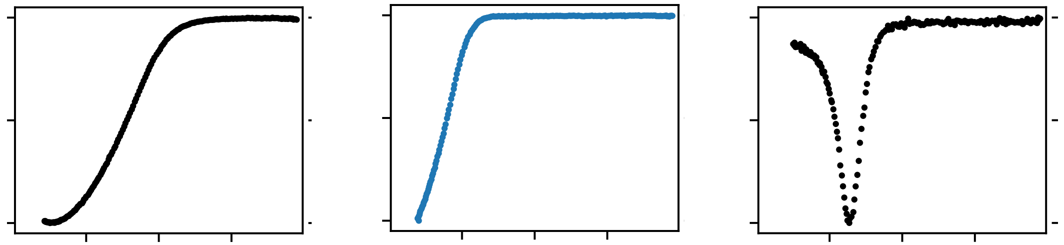
Index modulation

$$\Delta n_{FCD} = -8.8\times10^{-22}\Delta N - 8.5\times10^{-18}(\Delta P)^{0.8}$$

Loss modulation

$$\alpha_{FCA} = 8.5\times10^{-18}\Delta N - 6.0\times10^{-18}\Delta P$$

Experimental Nonlinear Modulation Curves (Power out vs. power in)



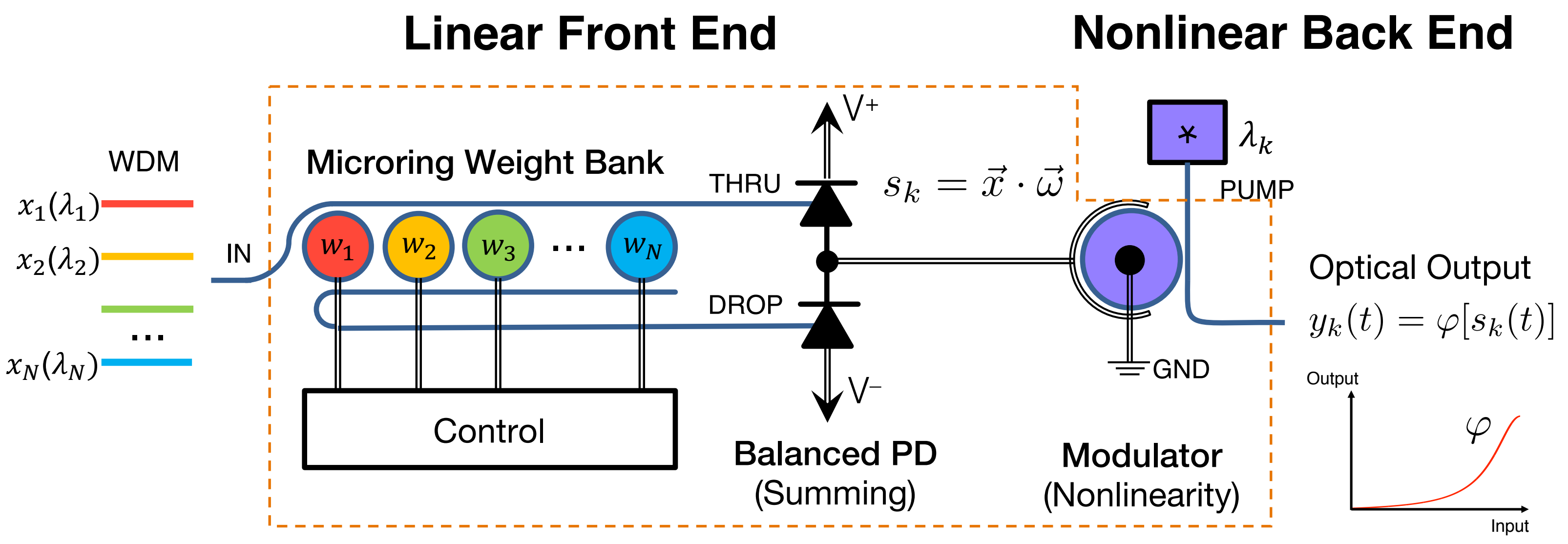
Sigmoid

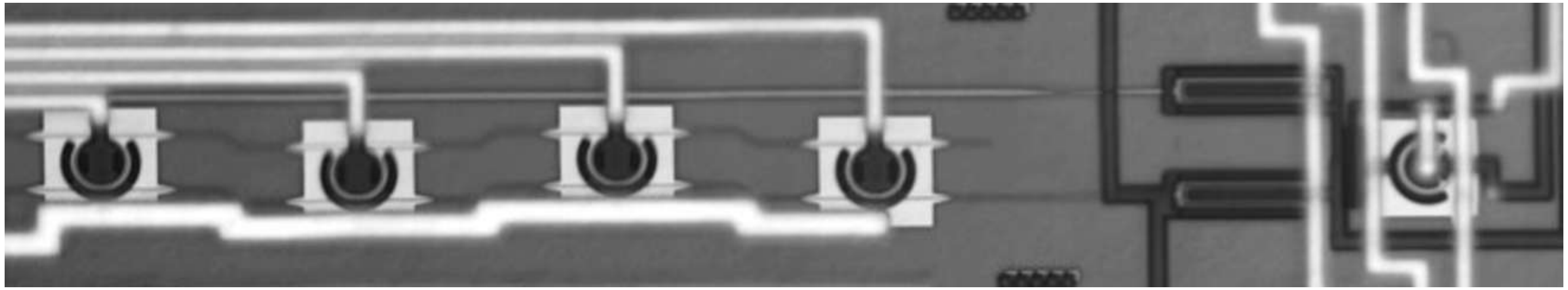
ReLU
Feedforward (CNNs)

Quadratic
Support vector machines

Tait, Shastri, Prucnal et al. *Phys. Rev. Appl.* **11** (2019)

Monolithically-Integrated Photonic Neuron



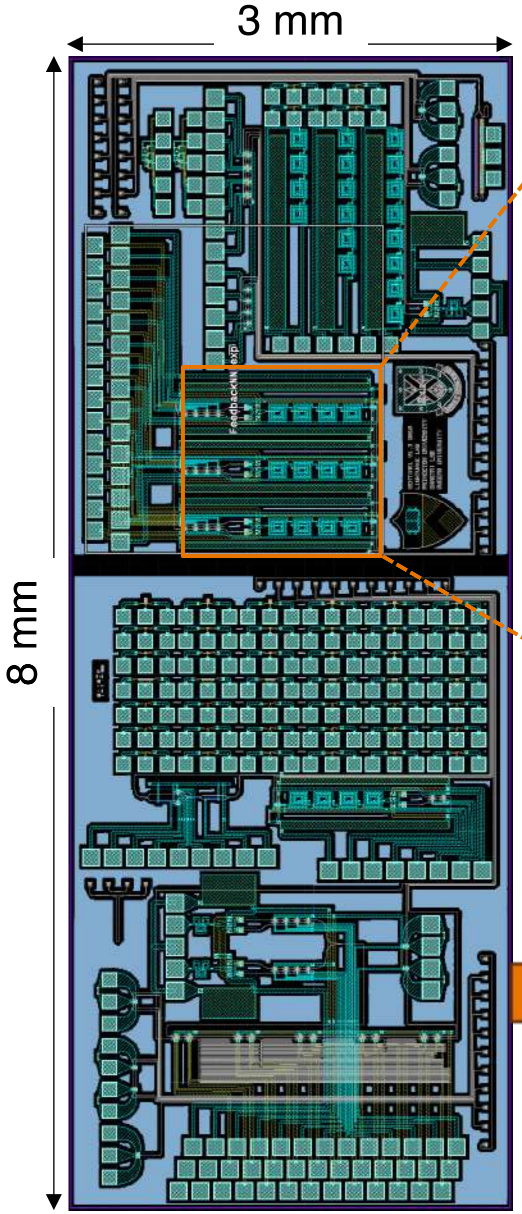


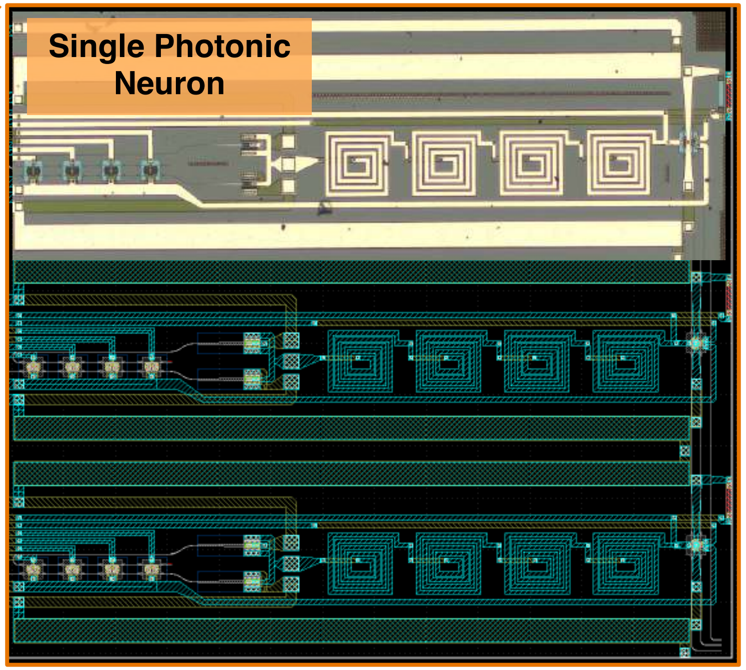
- ❑ **Integrates both linear and nonlinear neuron functionality**
- ❑ **Energy efficiency today: 500fJ/MAC; foreseeable: 1.1 fJ/MAC***
- ❑ **Operational speed: GHz**

*Nozaki, K. *et al.* *Nat. Photonics* **13**, 454–459 (2019)

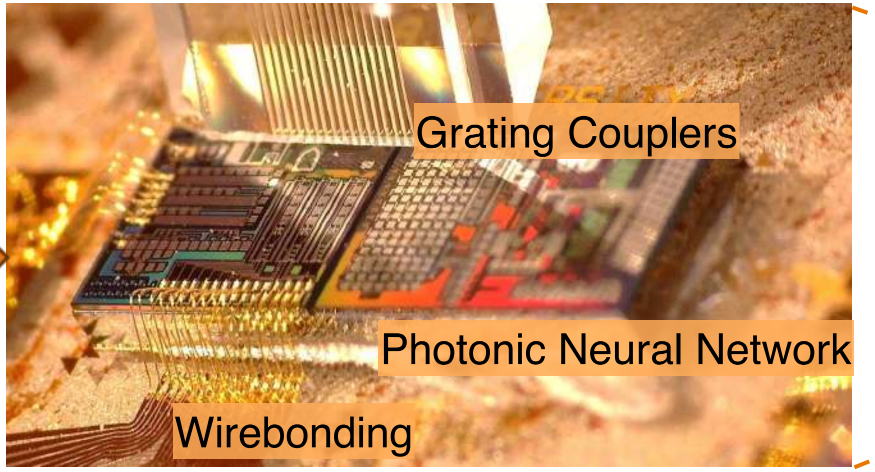
Huang, Shastri, Prucnal et al. **Nature Electronics** 4 (2021)

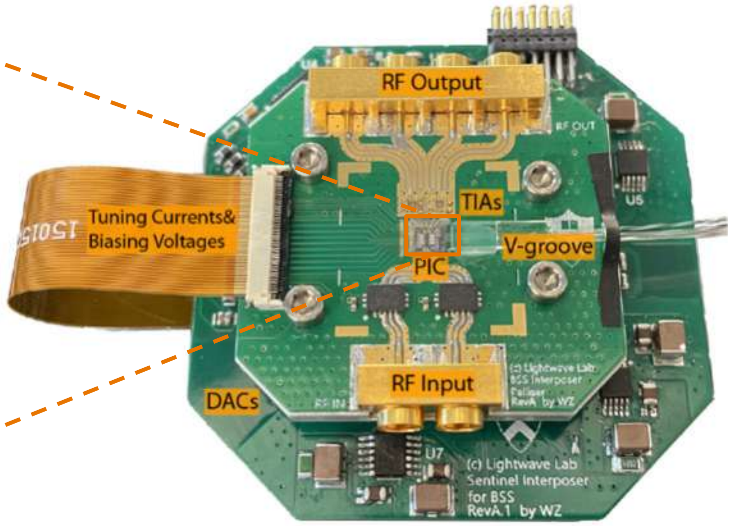
Silicon Photonic Neural Network Chips





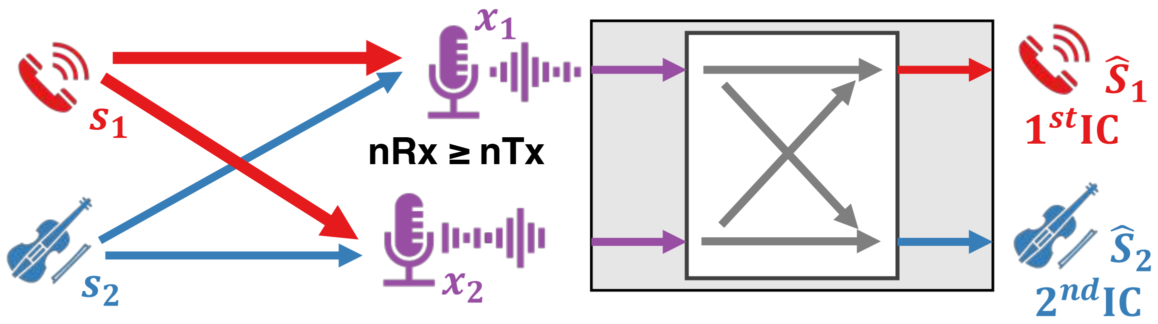
- Operational speed: **10s GHz**
- Energy efficiency today: **500fJ/OP ->** 1.1 fJ/OP
- Demonstrated **complete system integration** and applications
- **Foundry compatible;** in-house optical and electrical packaging
- Utilizes open-source design tools created by our lab (https://github.com/lightwave-lab)
- Neural networks trained via mature software tools such as TensorFlow
- Experimentation is fully automated





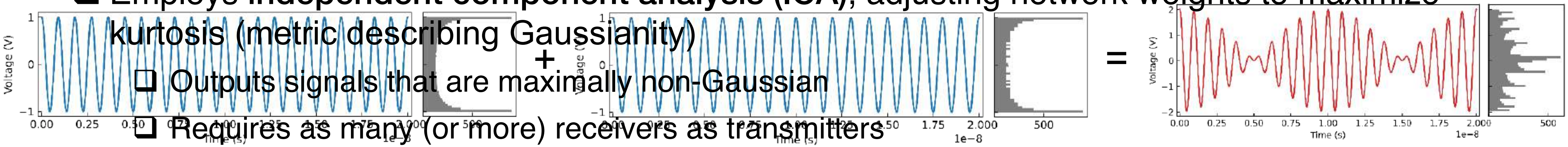
Huang, Shastri, Prucnal et al. **Nature Electronics** 4 (2021)

Application: Cognitive Radio - Blind Source Separation (BSS)



Recovery of unknown signals from arbitrary mixtures using multiple receivers

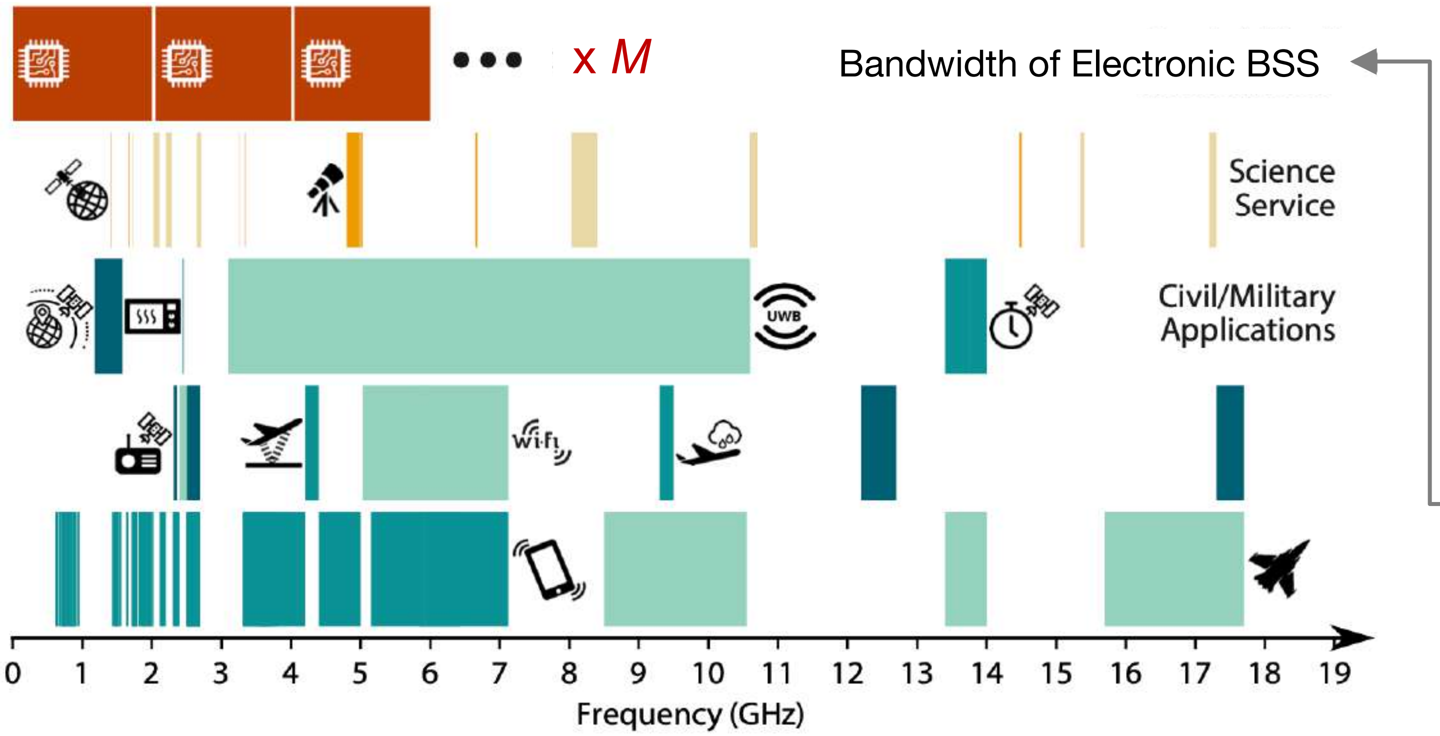
- ❑ Employs **independent component analysis (ICA)**, adjusting network weights to maximize kurtosis (metric describing Gaussianity)
  - ❑ Outputs signals that are maximally non-Gaussian
  - ❑ Requires as many (or more) receivers as transmitters

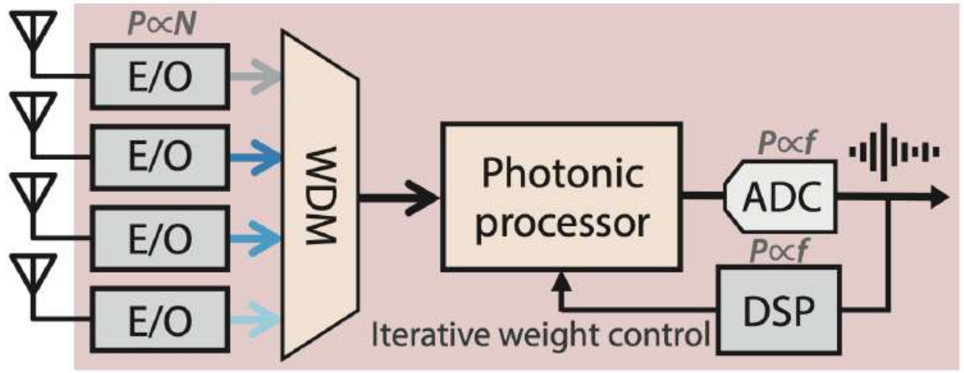


- ❑ Applications:
  - ❑ Image denoising, object detection
  - ❑ RF signal separation, speech isolation

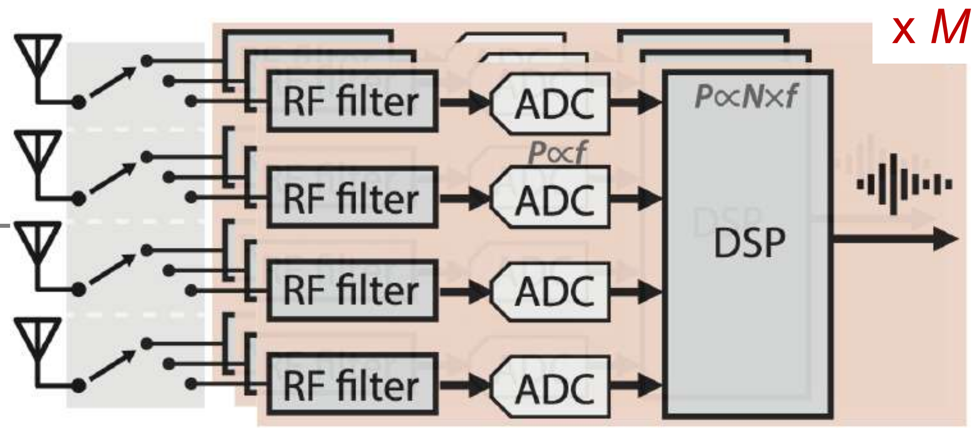
Zhang, Shastri, Prucnal et al. **Nature Communications** 14 (2023)

Application: Cognitive Radio - Blind Source Separation (BSS)





$P \propto N \times P_{E/O} + f \times (E_{ADC} + E_{MAC})$



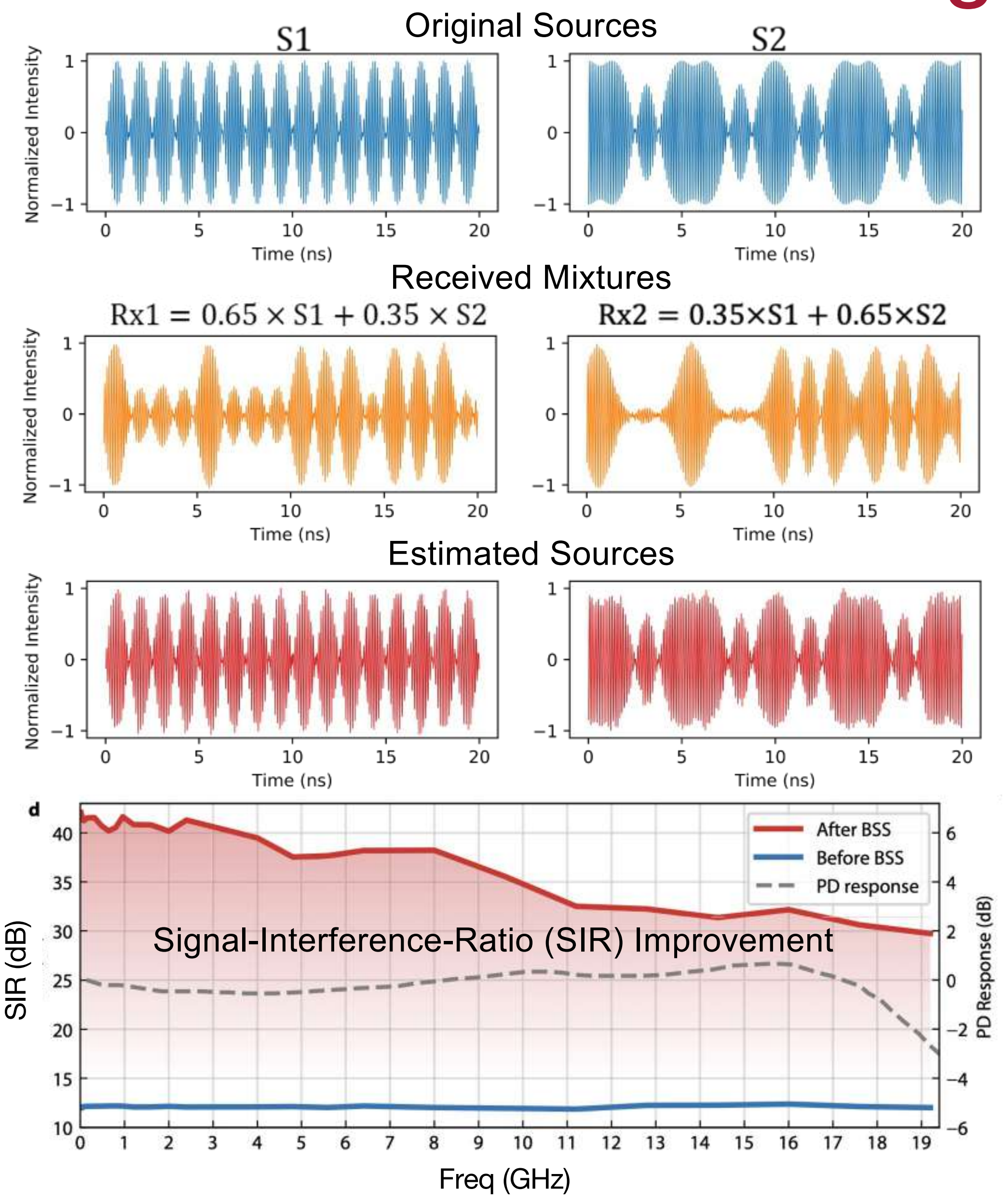
$P \propto N \times M \times f \times (E_{ADC} + E_{MAC})$

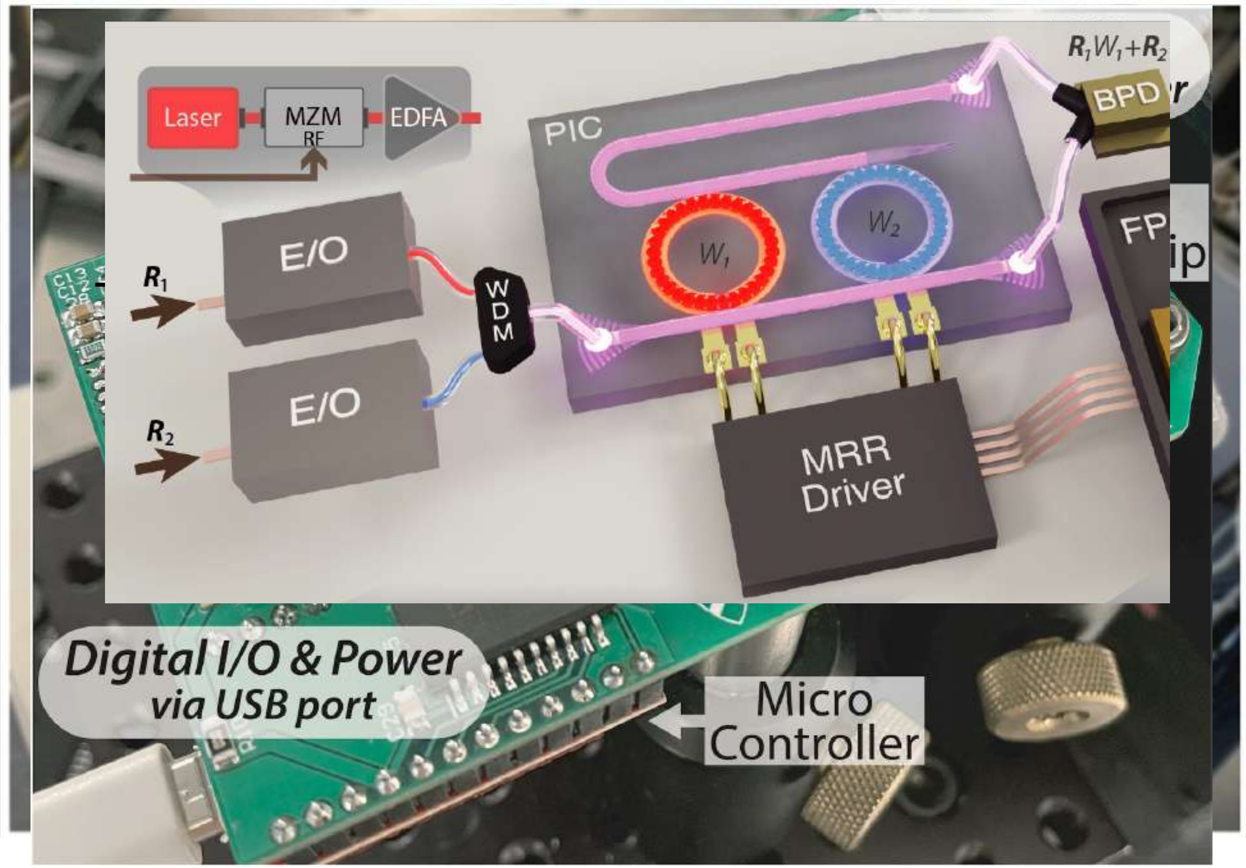
RF components are limited in bandwidth, requiring many different receivers to cover the RF spectrum

Linear photonic front-end allows ICA to be performed on the entire RF spectrum simultaneously (i.e., collective processing)

Zhang, Shastri, et al. **Nature Communications** 14 (2023)

Broadband BSS with Single Photonic Chip

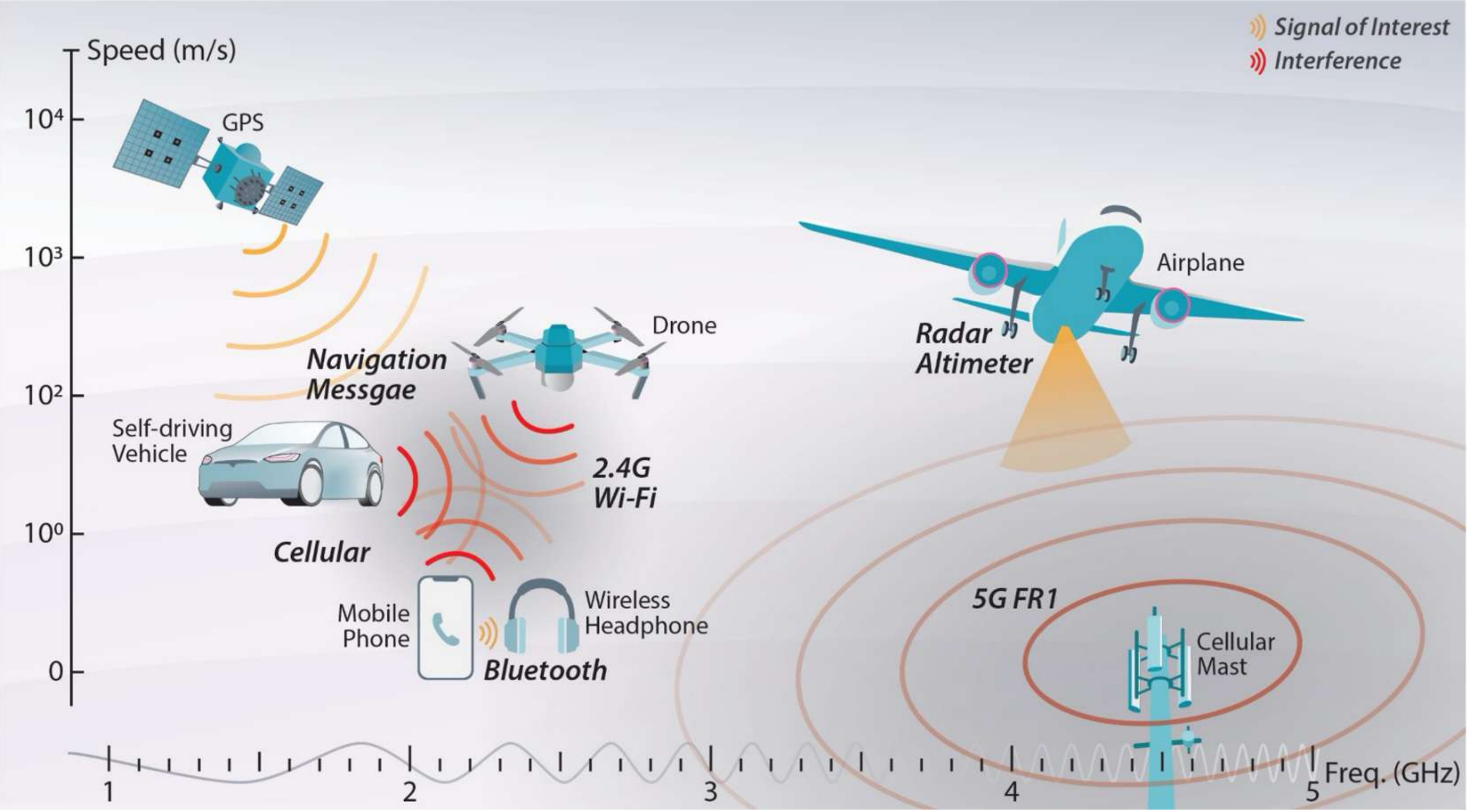




- ❑ Fully-integrated neuron used to demonstrate broadband BSS 20 MHz –19.2 GHz
- ❑ SIR improved >33 dB across entire operating bandwidth

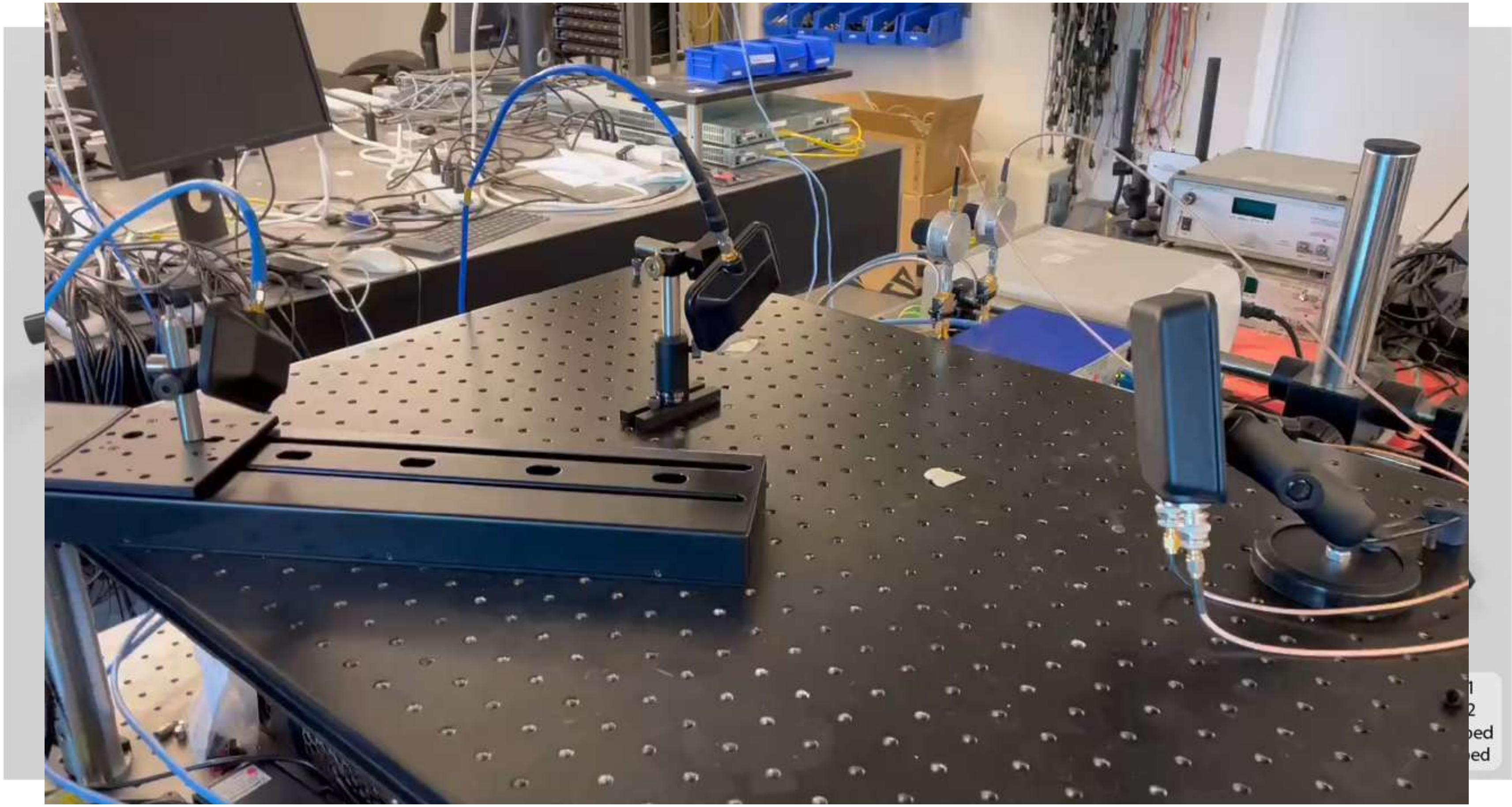
Zhang, Shastri, Prucnal et al. **Nature Communications** 14 (2023)

Dynamical RF Interferences: 5G & Radar Altimeter

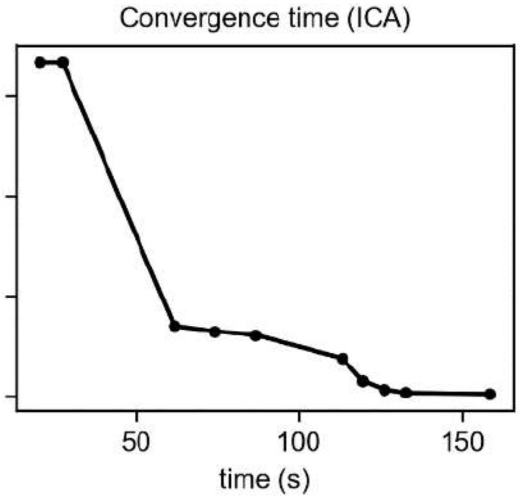


Zhang, Shastri, Prucnal et al. arXiv:2306.14727 (2023); forthcoming in **Light: Science and Applications**

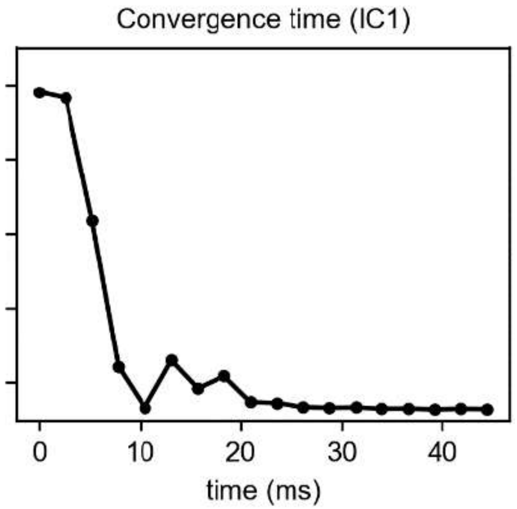
Dynamical and Real-Time BSS



Previous



w/FPGA



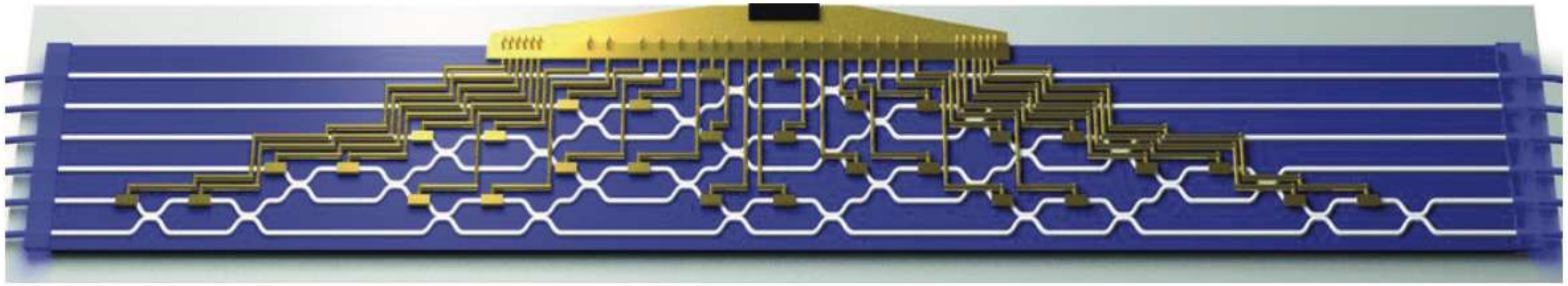
- ❑ Wireless transceivers
  - ❑ TXs: two directional antennas w/ single polarization
  - ❑ Rx: one 2x2 MIMO antenna w/ two orthogonal polarization slots
- ❑ Dynamic mixing ratio
  - ❑ One Tx mounted on a motorized translation stage
  - ❑ 300 mm range, 50mm/s maximal speed

Zhang, Shastri, Prucnal et al. arXiv:2306.14727 (2023); forthcoming in **Light: Science and Applications**
Lederman, Shastri, Prucnal et al. arXiv:2305.05528 (2023); accepted in **Nature Communications**

Universal Linear Optics for Quantum Information Processing

BSA

$\vert\psi_{\text{in}}\rangle$	$\vert\psi_{\text{out}}\rangle$
$\vert\Phi^{+}\rangle$	$\vert 00\rangle$
$\vert\Phi^{-}\rangle$	$\vert 01\rangle$
$\vert\Psi^{+}\rangle$	$\vert 10\rangle$
$\vert\Psi^{-}\rangle$	$\vert 11\rangle$



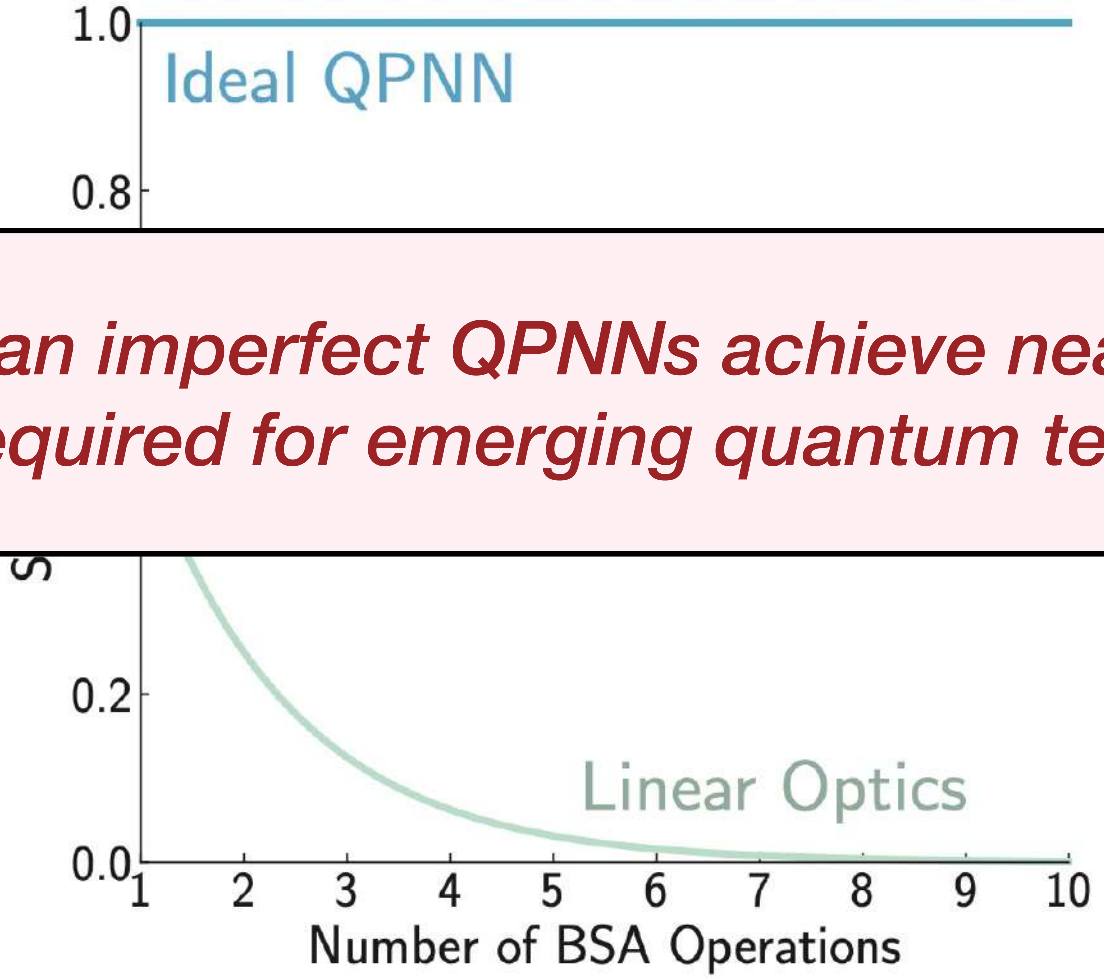
J. Carolan *et al.*, *Science* **349**, 711-716 (2015).

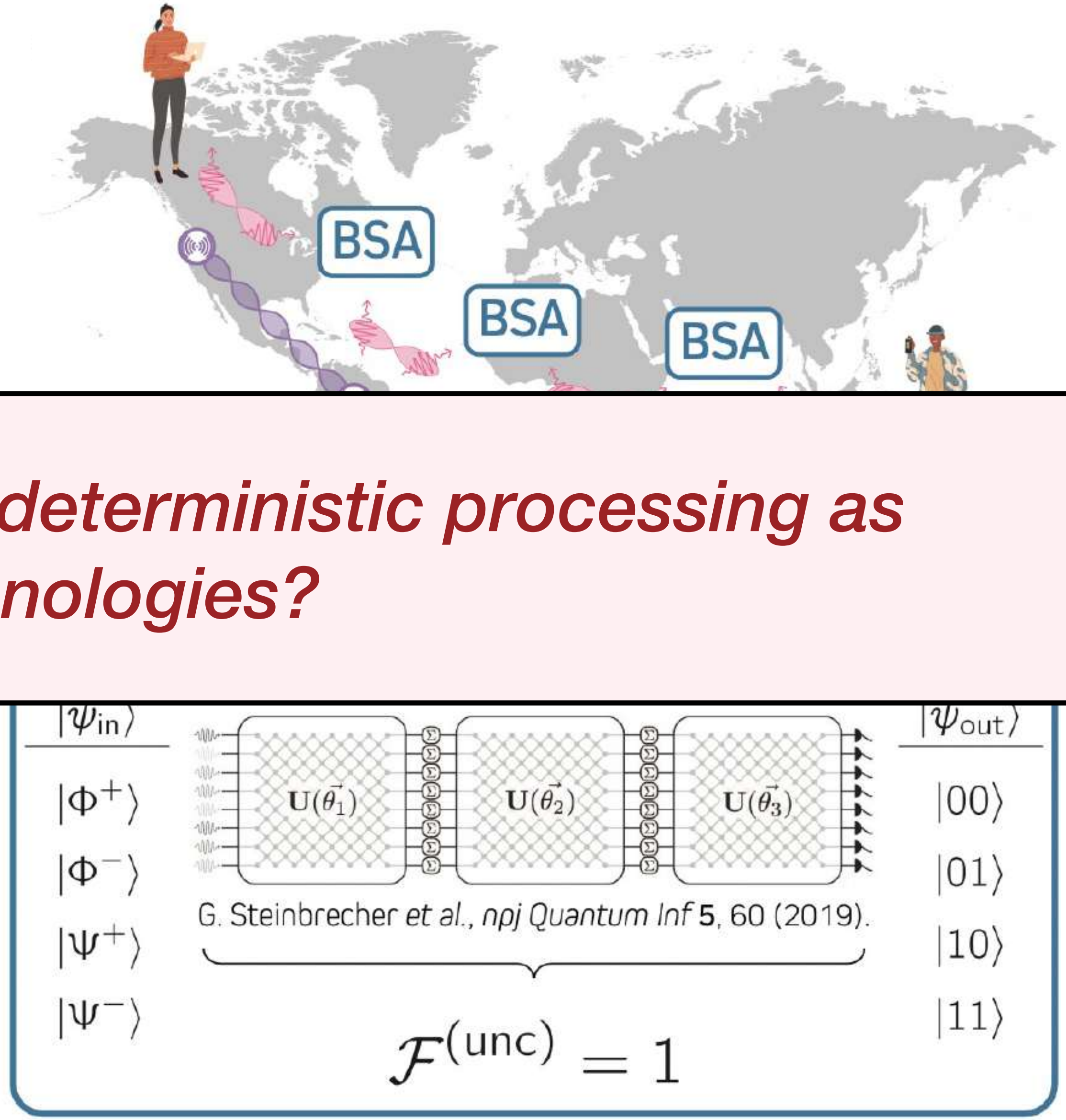
$$\mathcal{F}^{(\text{unc})} = 0.466$$

Even with a perfect circuit, linear optics is limited to $\mathcal{F}^{(\text{unc})} = 0.5$

Carolan et al. *Science* **349** (2015)

Quantum Photonic Neural Network

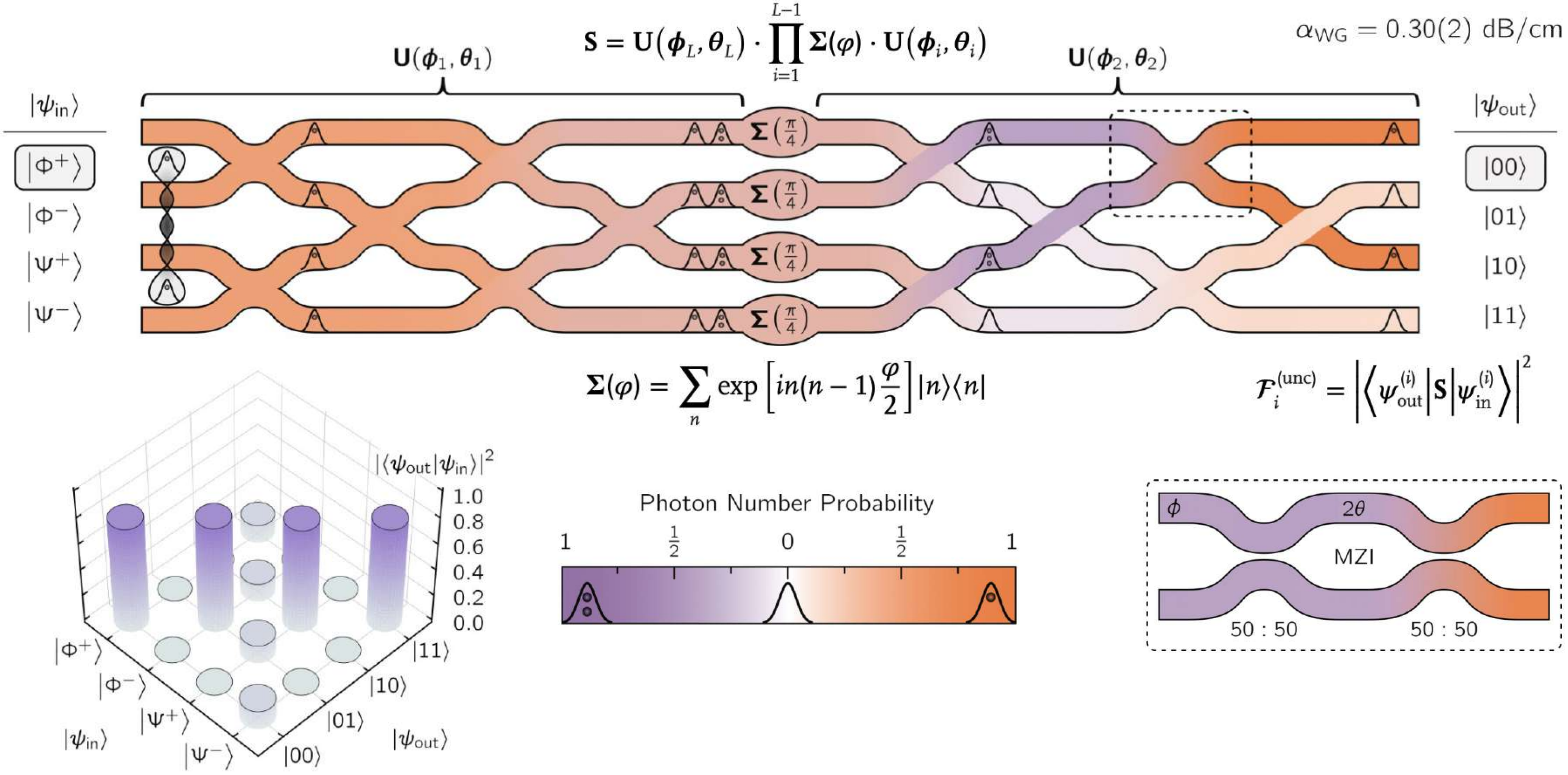




Can imperfect QPNNs achieve near-deterministic processing as required for emerging quantum technologies?

Ewaniuk, Shastri, Rotenberg et al. **Advanced Quantum Technologies** 2200125 (2023)

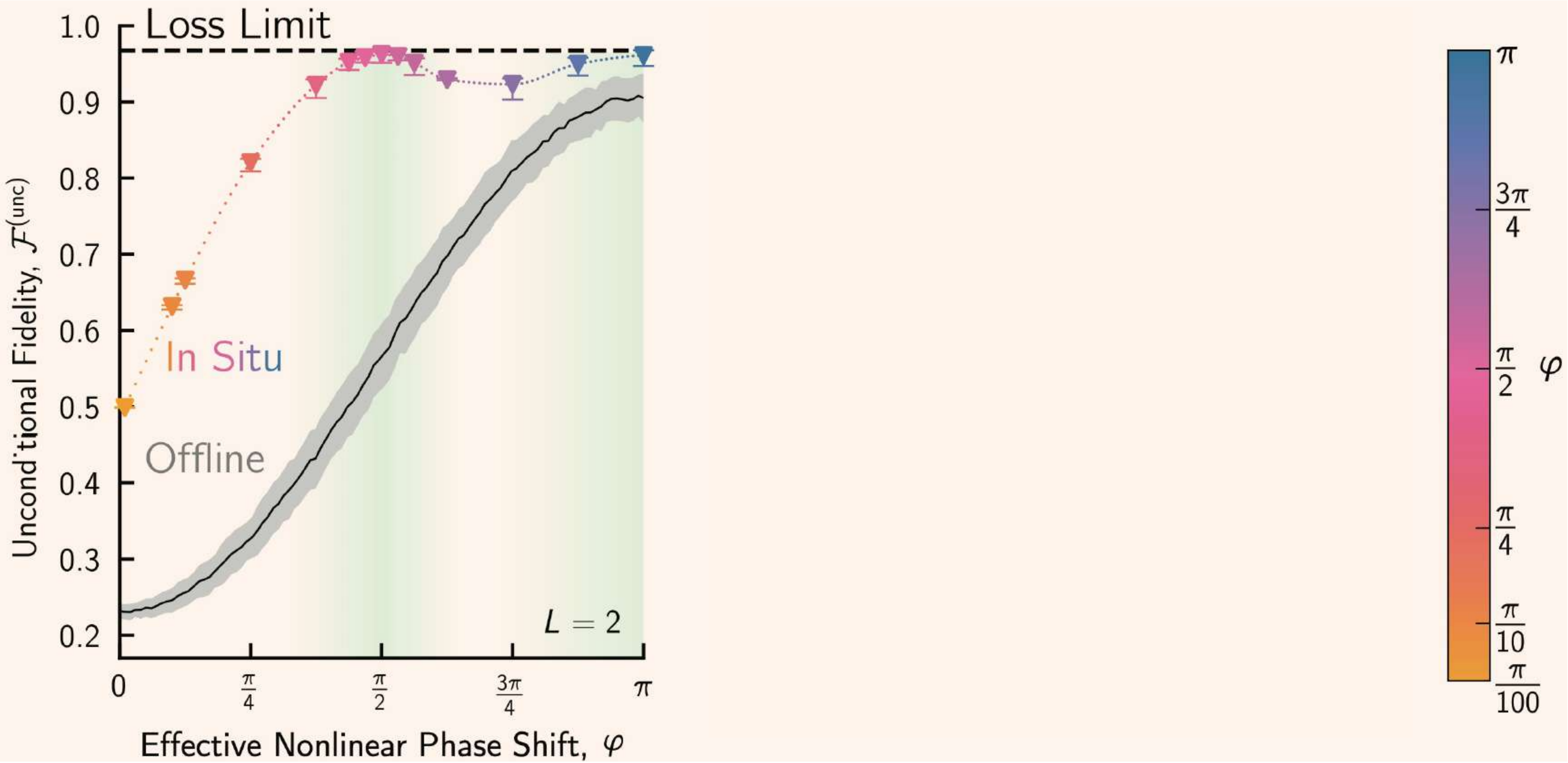
Imperfect Quantum Photonic Neural Network



Ewaniuk, Shastri, Rotenberg et al. **Advanced Quantum Technologies** 2200125 (2023)

Embracing Weak Nonlinearities

$\alpha_{WG} = 0.3\ \mathrm{dB/cm}$

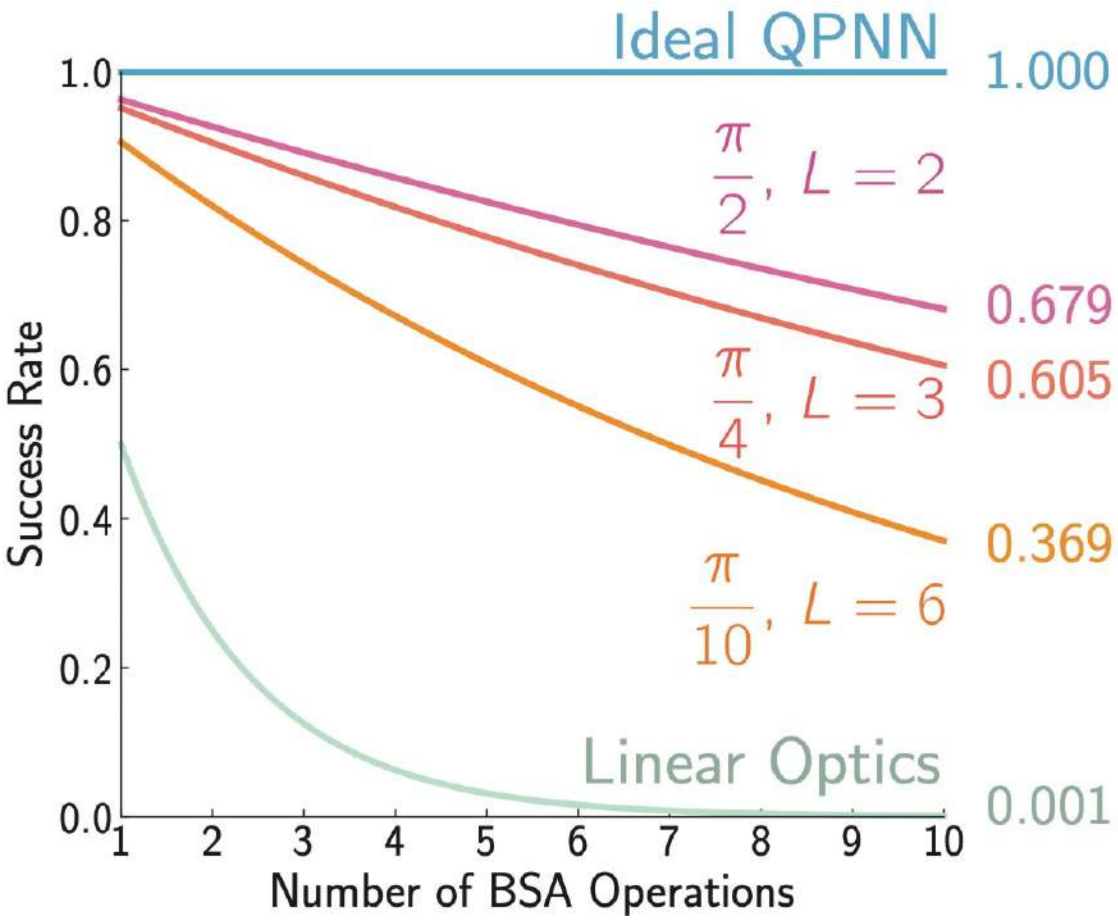


- When trained in situ, QPNNs learn to account for weak optical nonlinearities

Ewaniuk, Shastri, Rotenberg et al. **Advanced Quantum Technologies** 2200125 (2023)

Quantum Photonic Neural Network

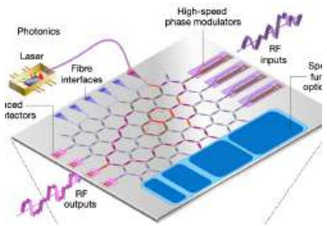
- Perform near-deterministic quantum information processing
- Are reconfigurable and built on a mature photonics platform
- Learn to account for fabrication imperfections
- Optimize in the presence of weak nonlinearities



Ewaniuk, Shastri, Rotenberg et al. **Advanced Quantum Technologies** 2200125 (2023)

Photonics & Computing: A 2023 Perspective

Programmable photonics



Bogaerts et al. *Nature* (2020)

Parallel processing, passive waveguides, matrix multipliers

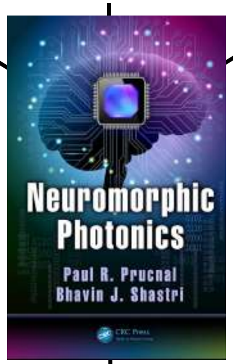
Analog Photonics

Silicon Industry

Silicon photonics, electronics + photonics

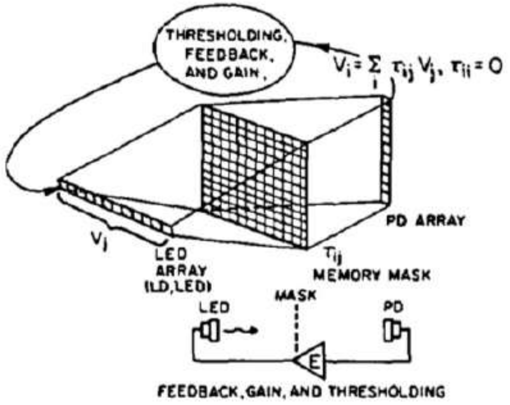
Neuromorphic Photonics

Shastri, *Nat. Photon.* (2021)



Free-space Linear NNs

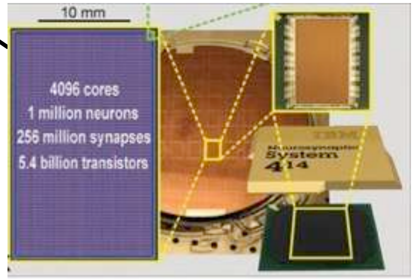
Challenge: integration, nonlinearity



Psaltis & Farhat, *Opt. Lett.* (1985)

Neuromorphic Electronics

Challenge: bandwidth



Merolla et al. *Science* (2014)

Scalable Computing Models

Deep learning, spiking, equilibrium propagation

Prucnal & Shastri, *Neuromorphic Photonics* CRC Press (2017)

Roadmap: Neuromorphic Photonics

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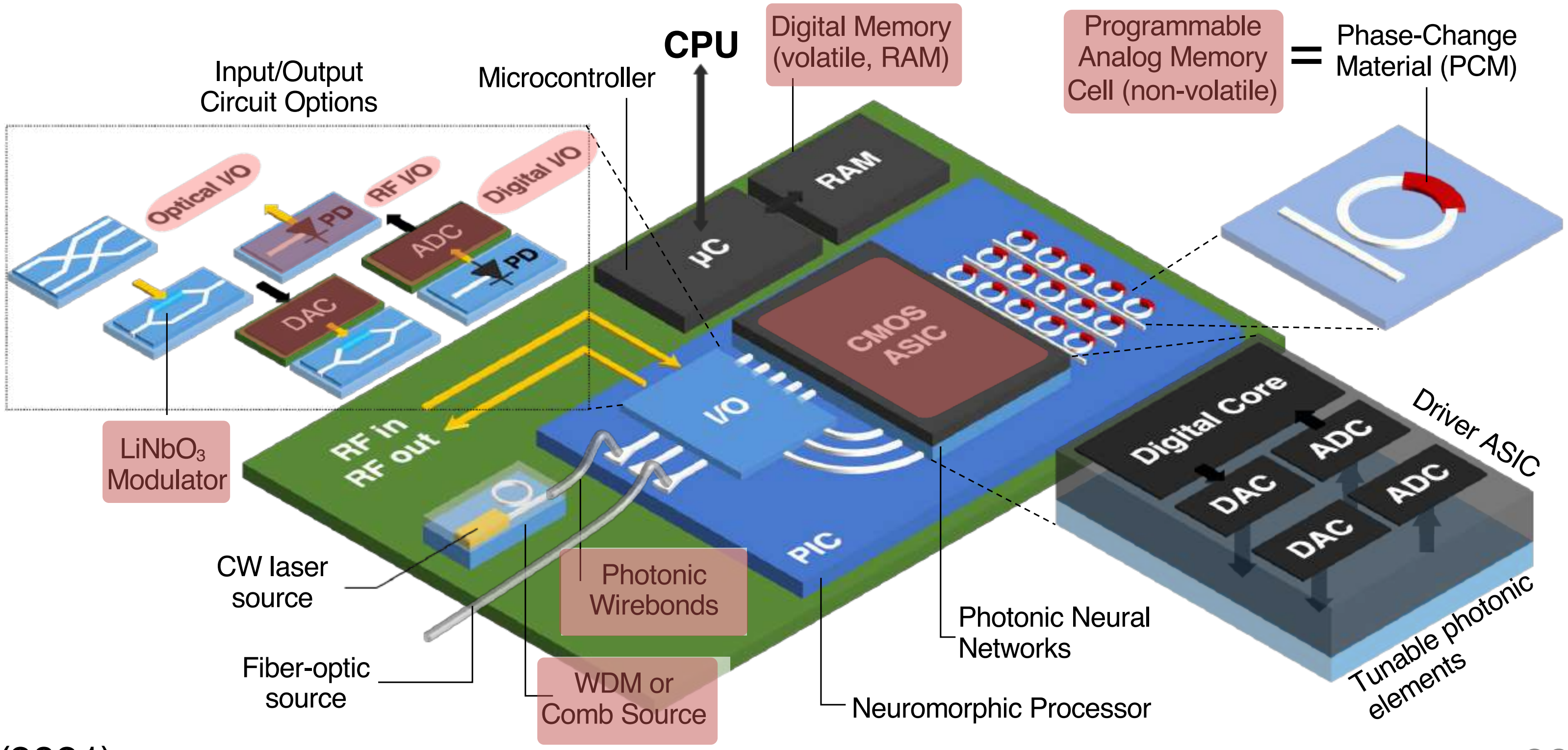
https://doi.org/10.1038/s41566-020-00754-y
nature photonics

Check for updates

Photonics for artificial intelligence and neuromorphic computing

Bhavin J. Shastri[1,2,7] ✉, Alexander N. Tait[2,3,7] ✉, T. Ferreira de Lima[2], Wolfram H. P. Pernice[4], Harish Bhaskaran[5], C. D. Wright[6] and Paul R. Prucnal[2]

- Laser integration
- WDM (frequency comb) sources
- Electronic co-integration
- Memory
- Lithium niobate-on-insulator modulators
- Trimming



Shastri, Tait, Prucnal et al. **Nature Photonics** 15 (2021)

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