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Hybrid Photonics Platform for Quantum Information Processing

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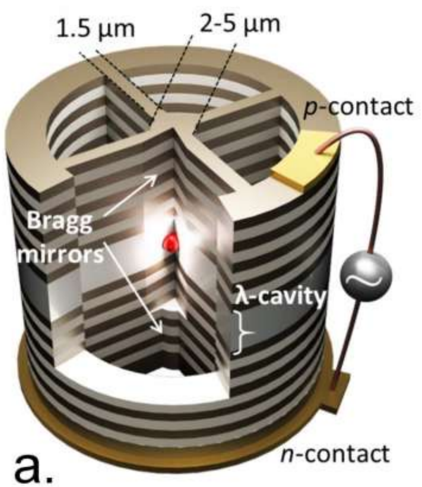
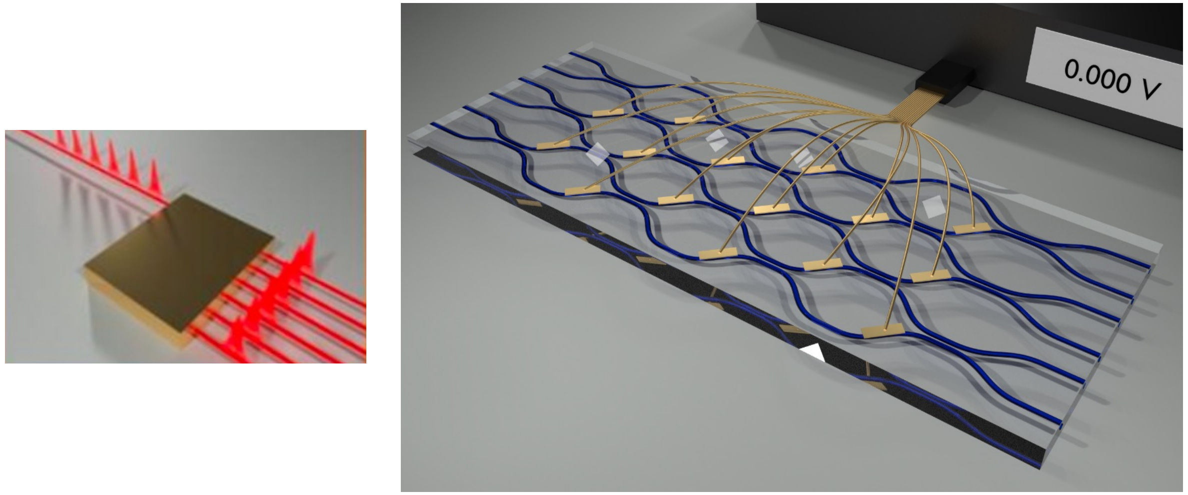
@qlab_sapienza

ICSC
Centro Nazionale di Ricerca in HPC, Big Data and Quantum Computing

Integrated photonic quantum platform: the overall scheme



Source of single photon states



Manipulation via integrated photonics

Single photon detection

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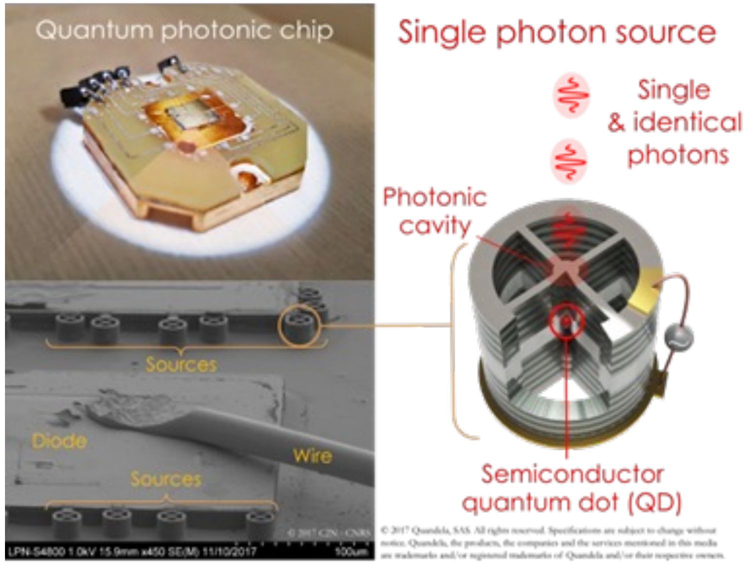
Source: single photon generations via Quantum Dot

Different excitation schemes:



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attocube WITTENSTEIN group

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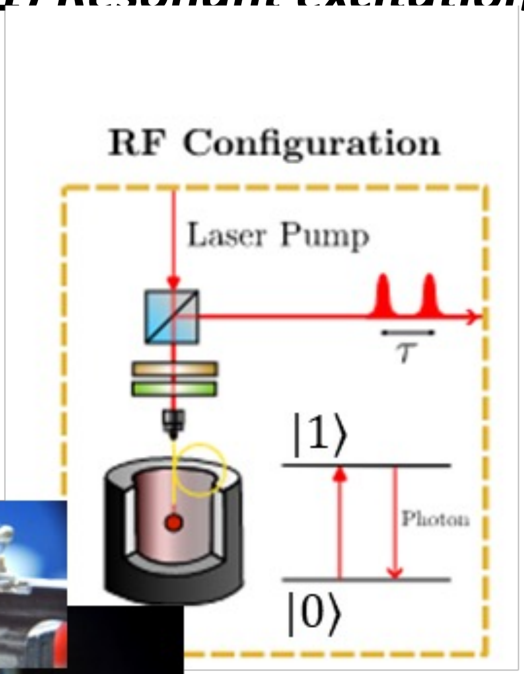
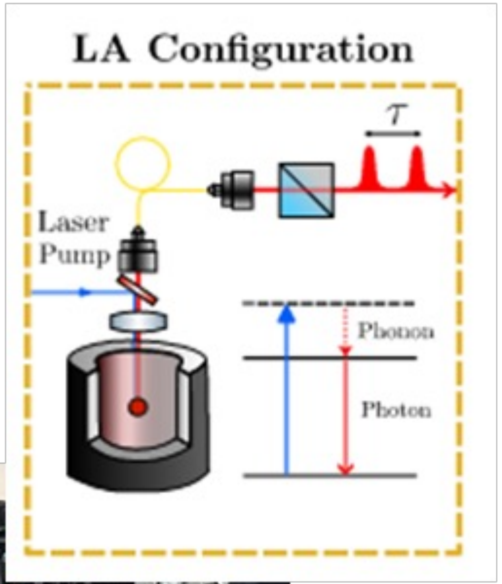
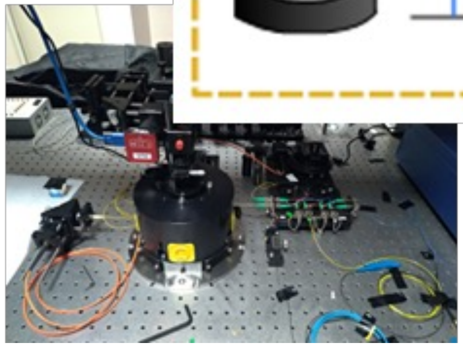
1) Resonant excitation



$\lambda = 928.05\, nm$

2) Phonon-assisted excitation

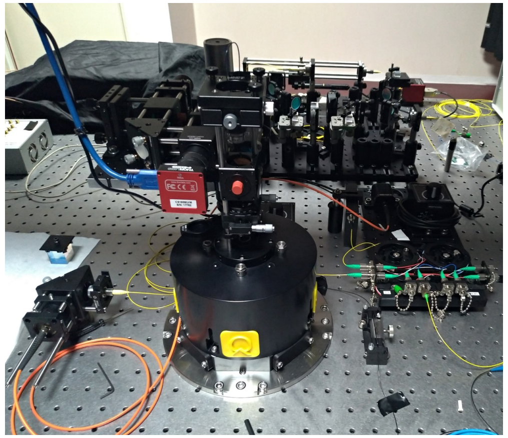


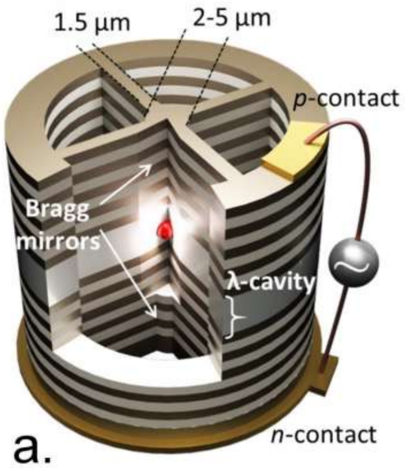


$\lambda = 927.8\, nm$

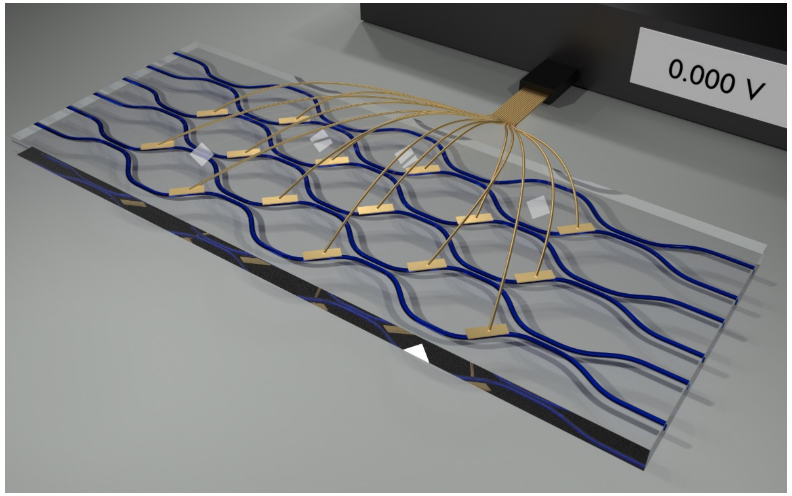
Interfacing deterministic sources and integrated circuits

Single photon sources

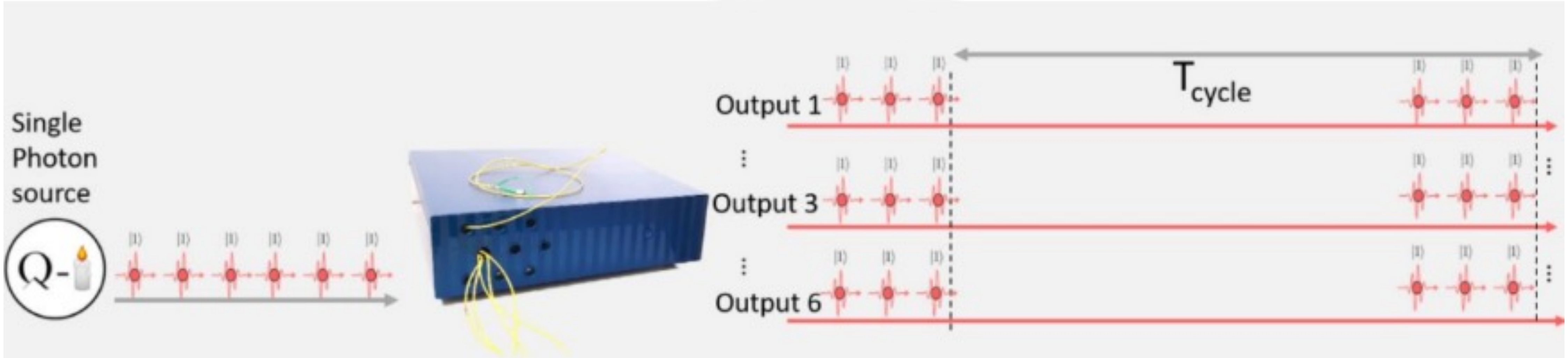




Integrated circuits

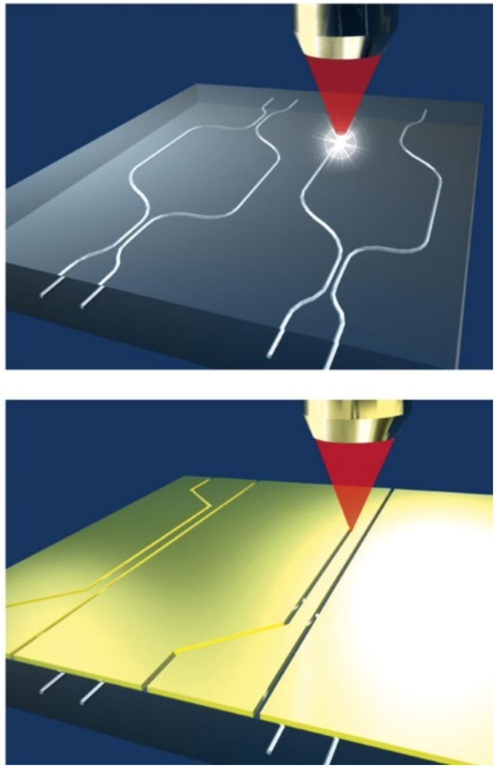


Time demultiplexing



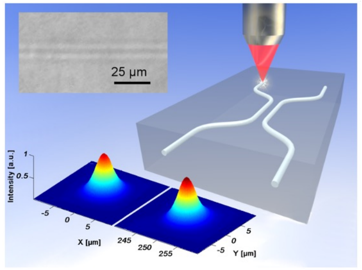
Integrated circuits: femtosecond-laser writing technique

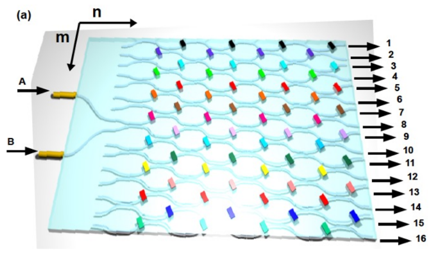
a
b



- Femtosecond pulse tightly focused in a glass
- Permanent and localized refractive index increase in transparent materials
- Waveguides are fabricated in the bulk of the substrate by translation of the sample at constant velocity with respect to the laser beam.

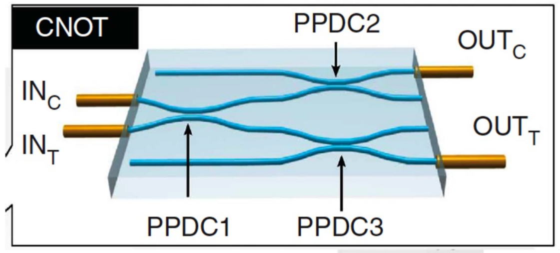
Path-econded circuits

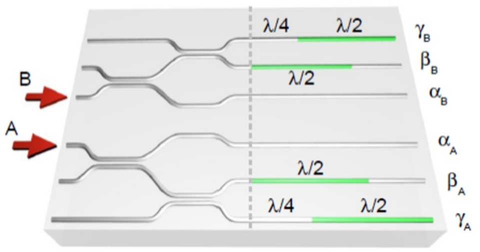




L. Sansoni et al., *Phys. Rev. Lett.* **108**, 010502 (2012)
A. Crespi et al., *Nat. Photon.* **7**, 322-328 (2013)

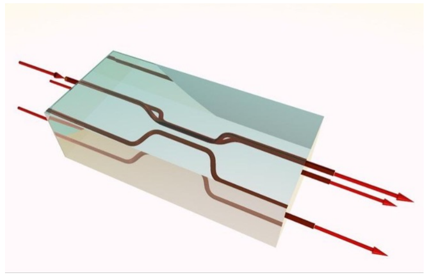
Polarization-econded circuits



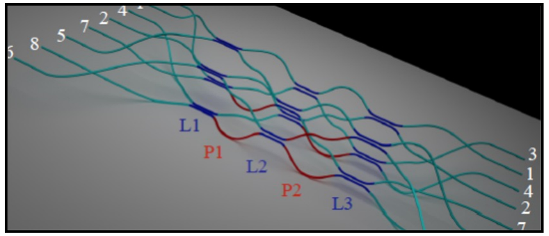


L. Corrielli et al., *Nat. Comm.* **5**, 2549 (2014);
A. Crespi et al., *Nat. Comm.* **2**, 566 (2011)

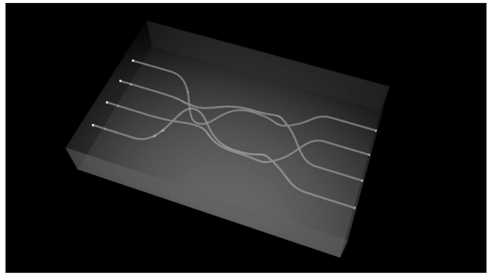
3D geometry



N. Spagnolo, et al., *Nat. Comm.* **4**, 1606 (2013);



A. Crespi, et al., *Nat. Comm.* **7**, 10469 (2016)



N. Viggianiello et al., *New Journal Physics* (2018)

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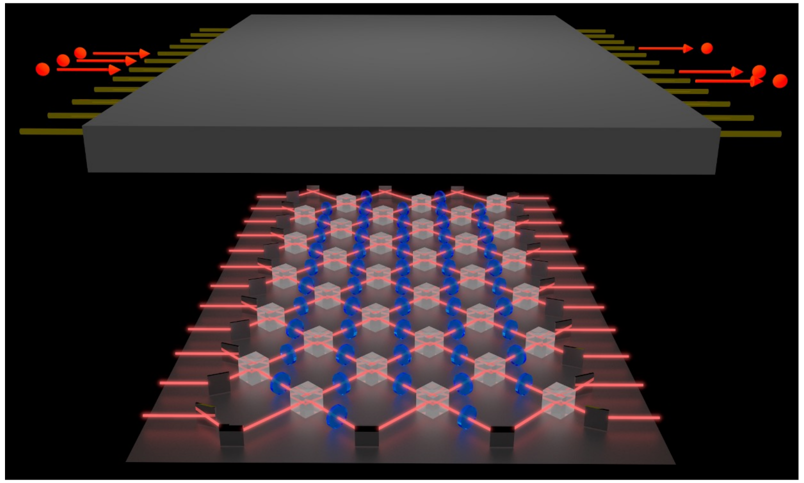
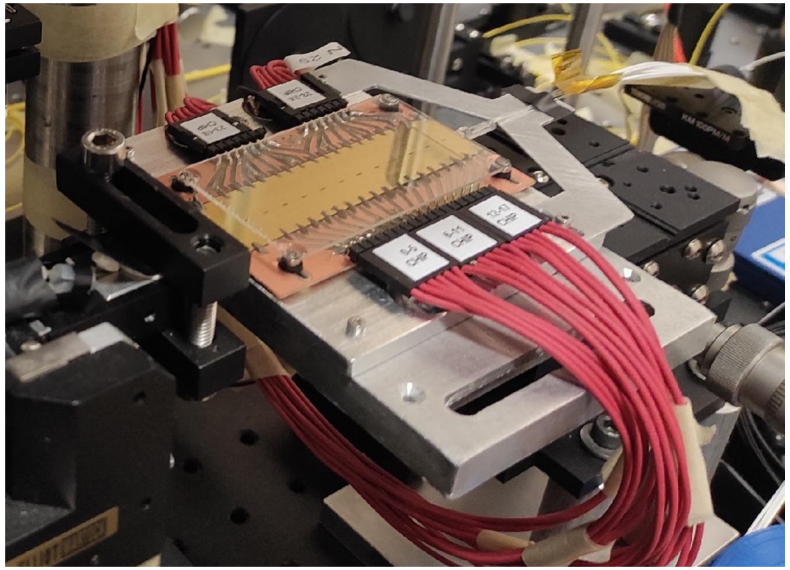
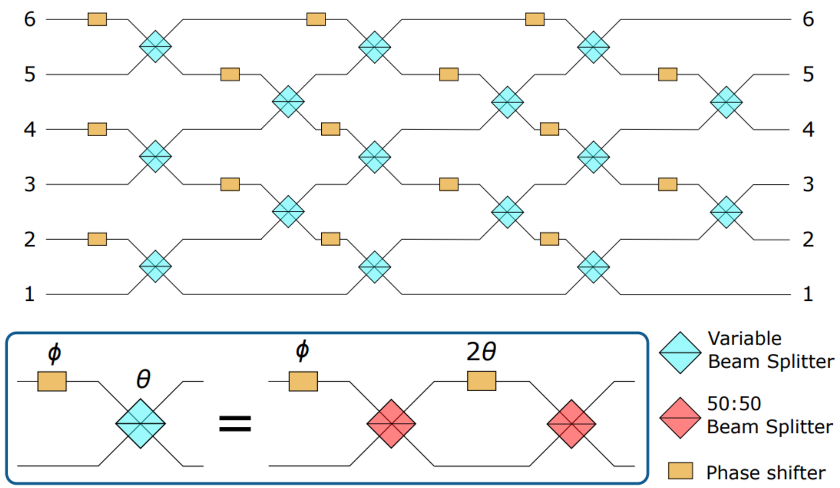
Universal discrete component layouts



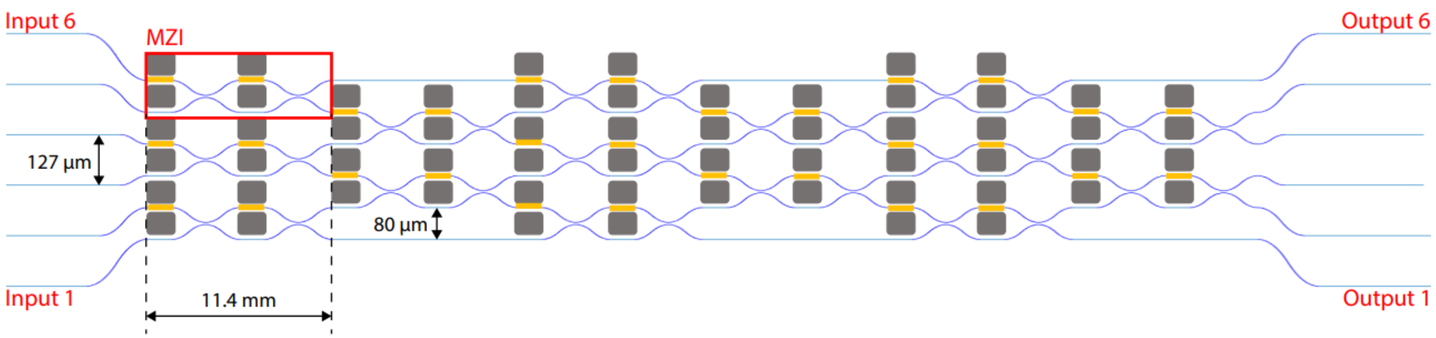




Universal 6-mode integrated photonic chips

- 6 layers of MZ
- 15 programmable phases ϕ_i
- 15 tunable beam splitter θ_i

$$U = \prod_k U_{MZ}^k$$



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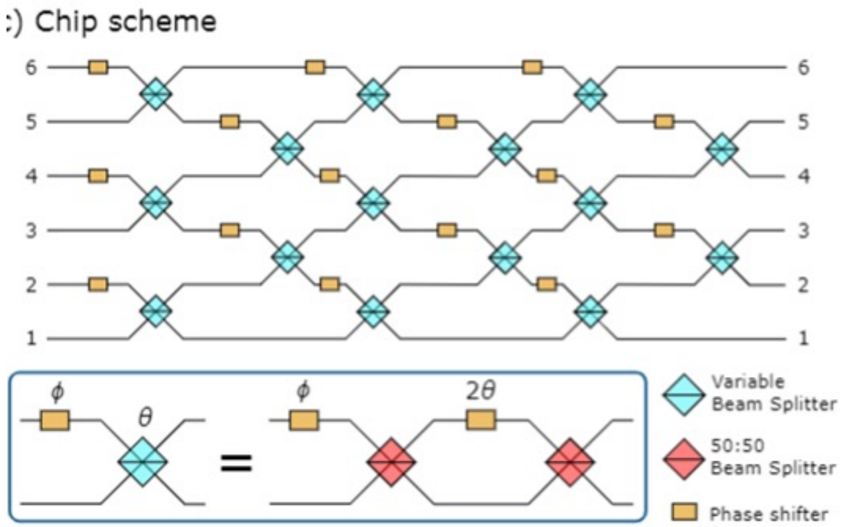
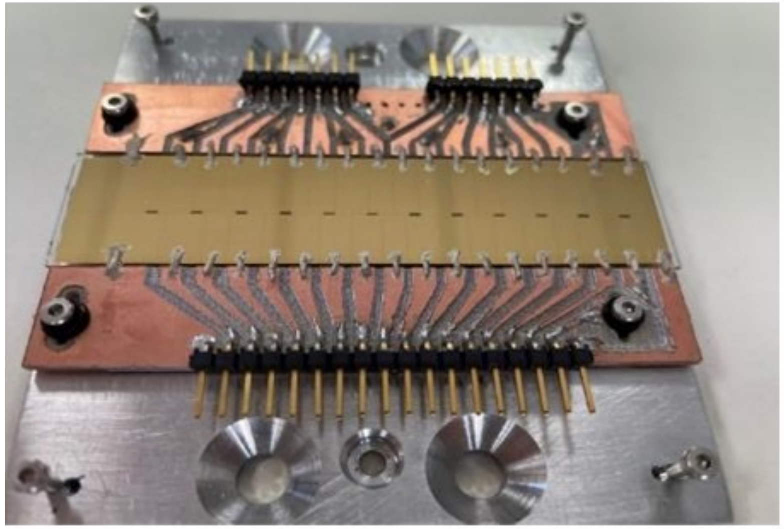
Universal discrete component layouts





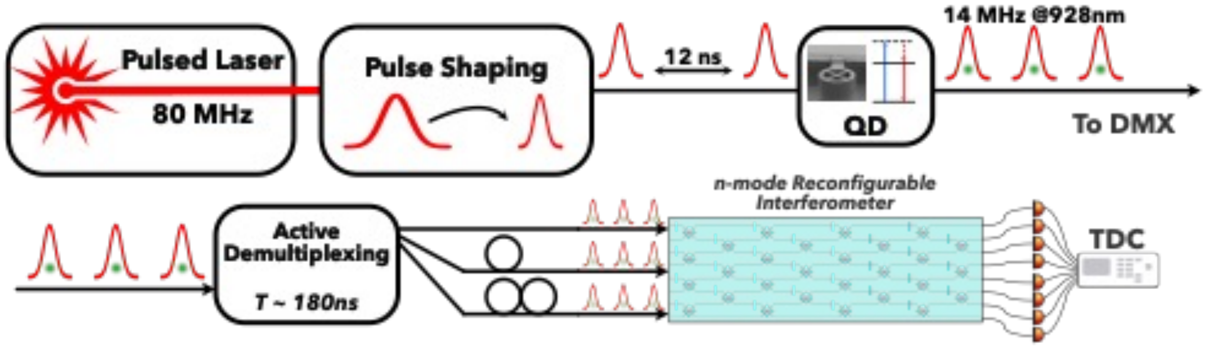
Universal 6-mode integrated photonic chips

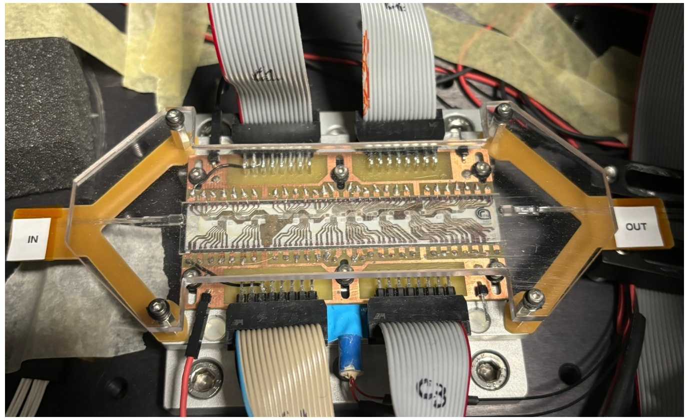
- 6 layers of MZ
- 15 programmable phases ϕ_i
- 15 tunable beam splitter θ_i

$$MZ(\theta,\phi) = i\, e^{i\theta/2} \begin{pmatrix} \sin(\theta/2)e^{i\phi} & \cos(\theta/2)e^{i\phi} \\ \cos(\theta/2) & -\sin(\theta/2) \end{pmatrix}$$

$$U = \prod_k U_{MZ}^k$$

High-dimensional platforms and multi-photon experiment





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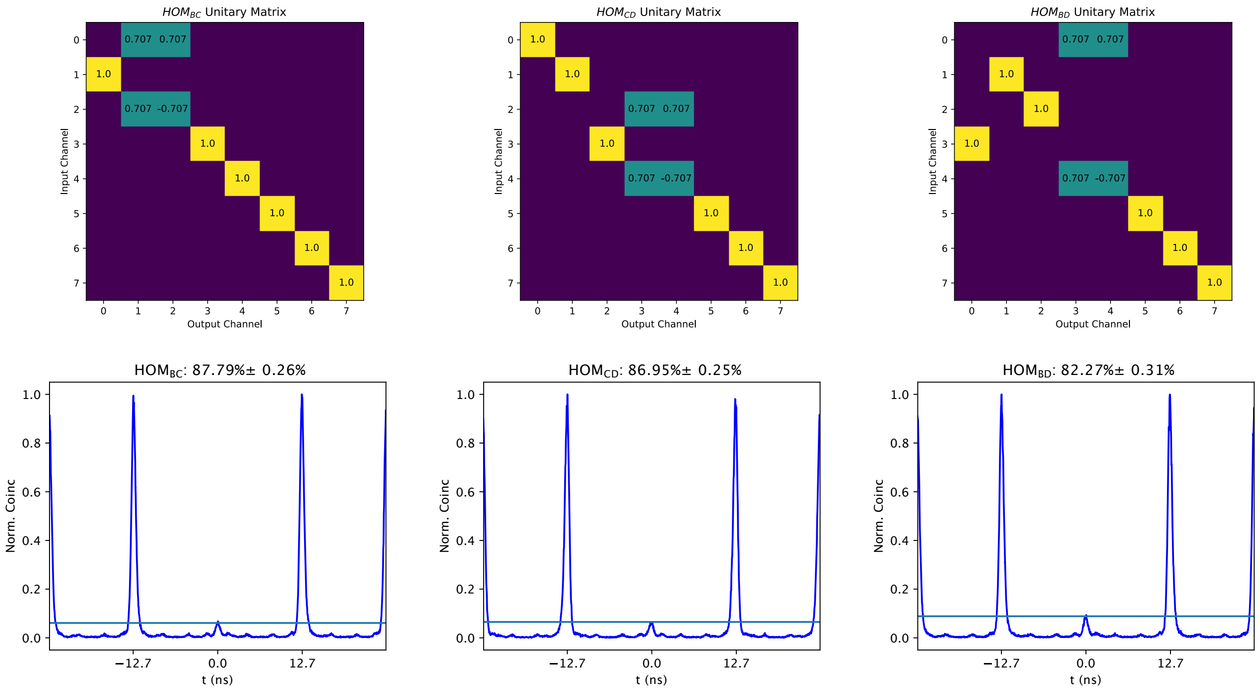
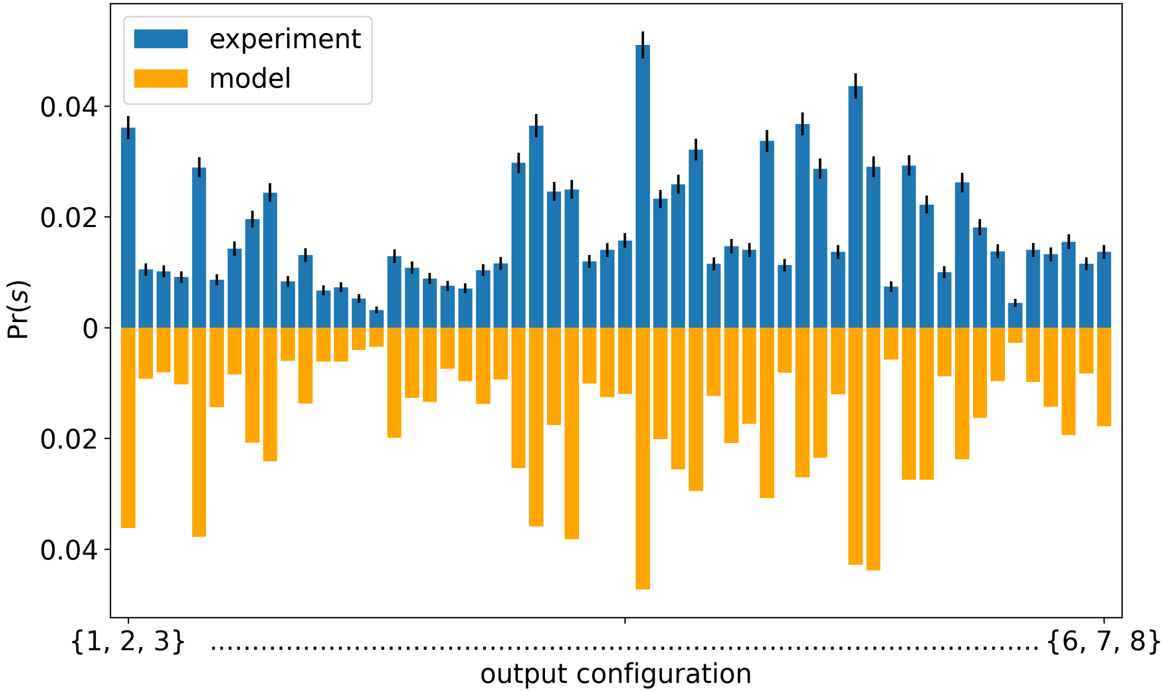
8-mode Universal Interferometer

On chip 2 photon quantum interference

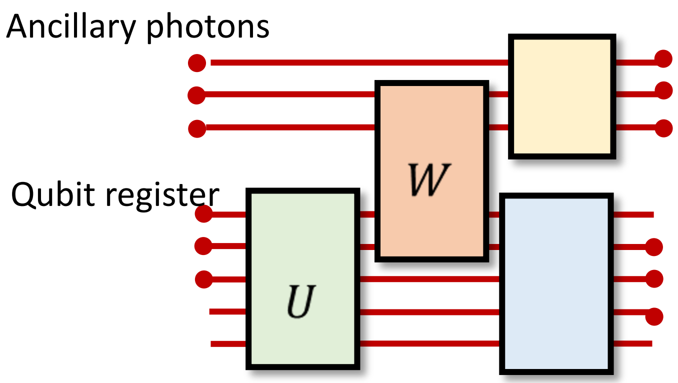


3-photon Boson Sampling



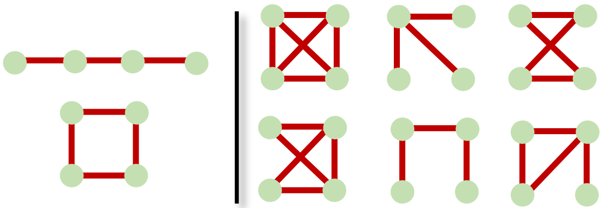
Quantum computing in photonic platforms

Universal schemes for quantum computing with photons



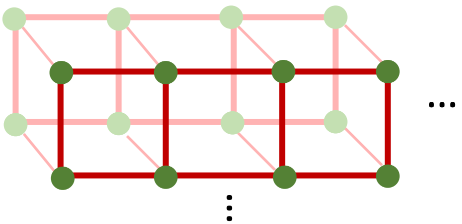
Gate-based model

Knill, E., Laflamme, R. & Milburn, G. A scheme for efficient quantum computation with linear optics. *Nature* **409,** 46–52 (2001)



Measurement-based model

Briegel, H., Browne, D., Dür, W. *et al.* Measurement-based quantum computation. *Nature Phys* **5**, 19–26 (2009).

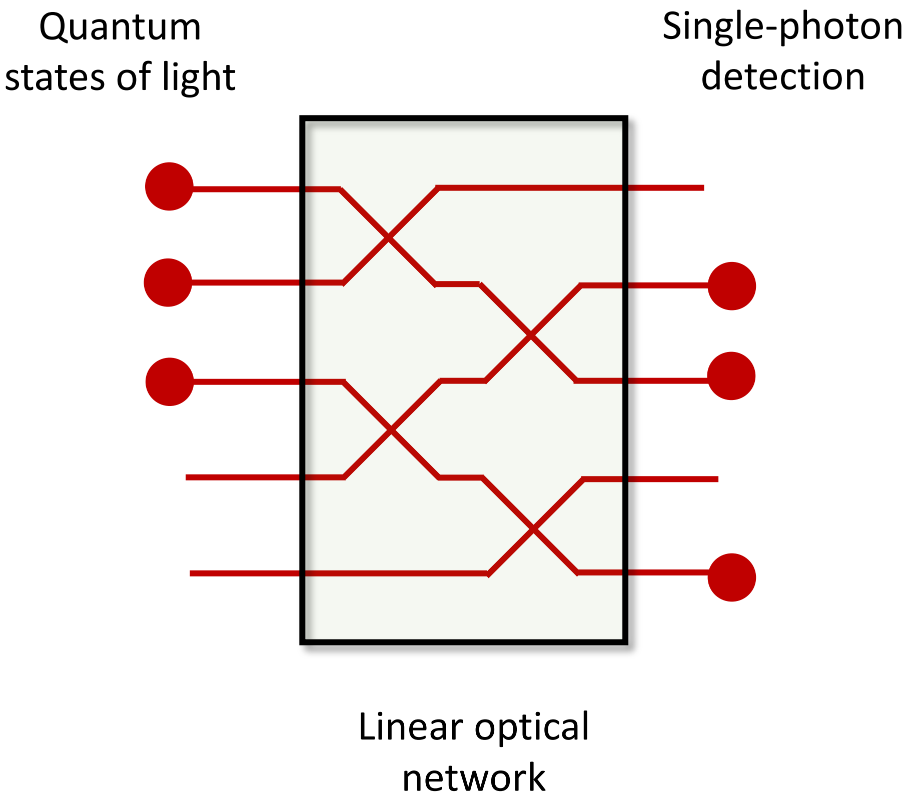


Cluster photonic states

Fusion-based model

Bartolucci, S., Birchall, P., Bombín, H. et al. Fusion-based quantum computation. *Nat Commun* 14, 912 (2023).

Non universal schemes: Photonic sampling machines



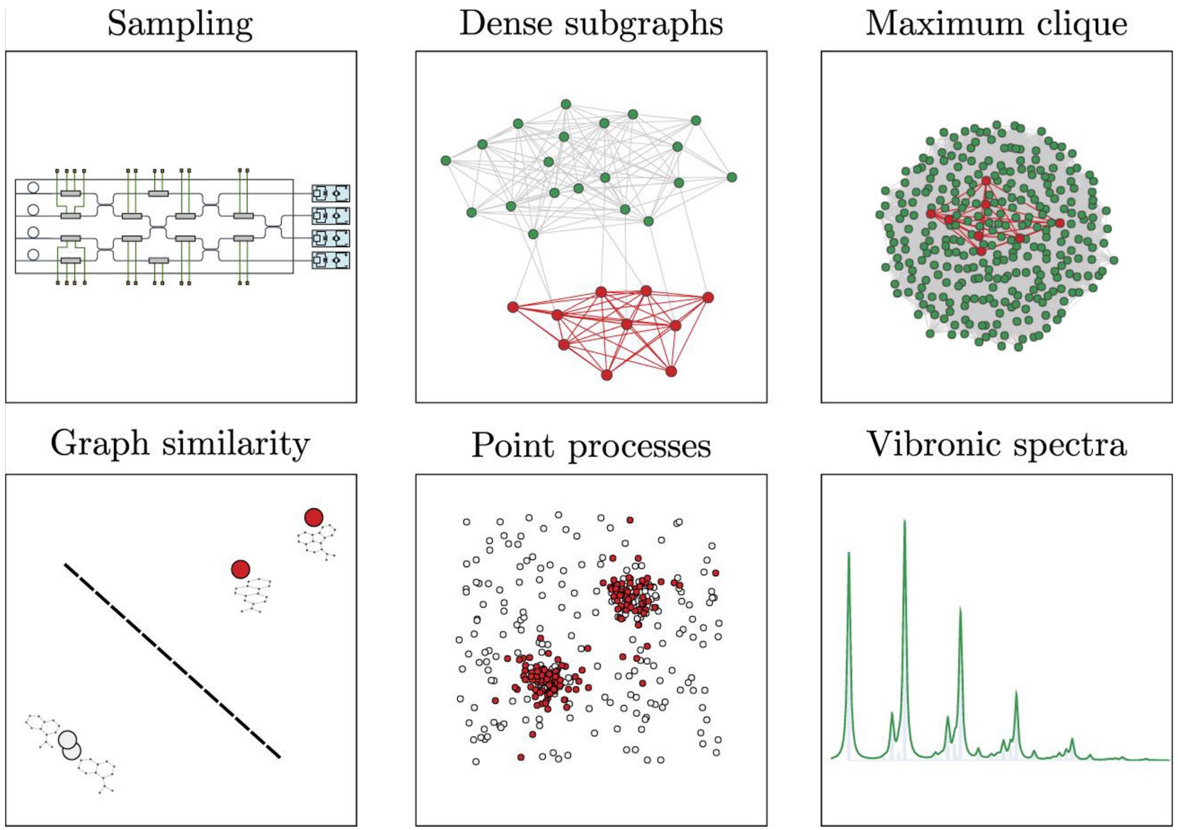
Harrow, A., Montanaro, A. Quantum computational supremacy. *Nature* **549,** 203–209 (2017)

Quantum computing in photonic platforms

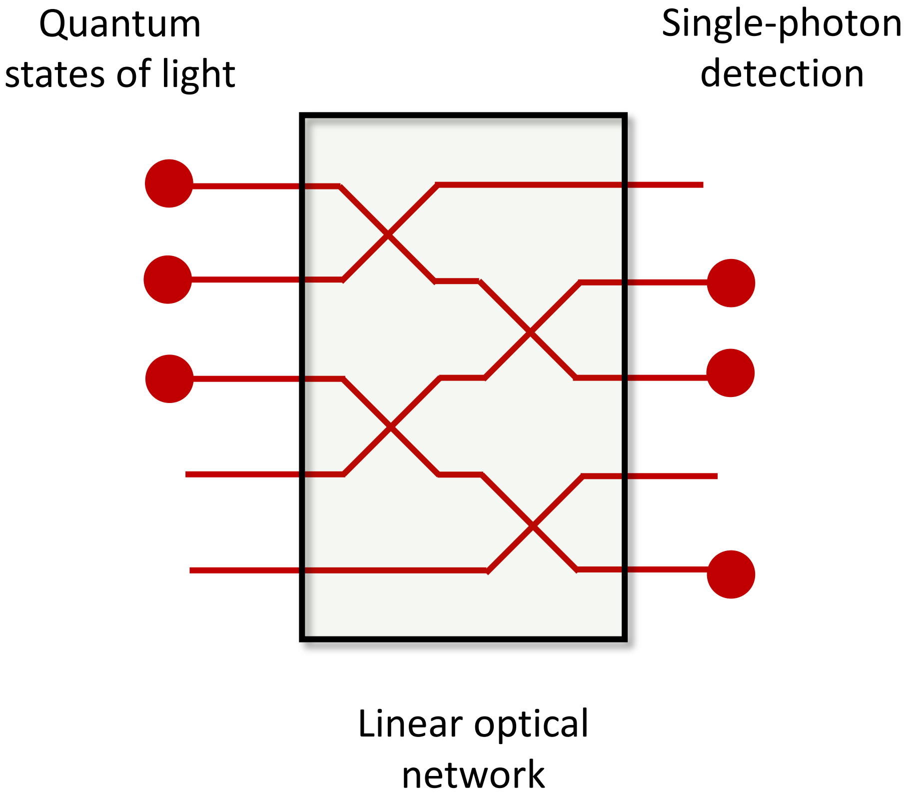
Applications:

- **Demonstration of quantum advantage**
  HS. Zhong et al., Phys. Rev. Lett. 127, 180502 (2021)
  Madsen, L.S, et al., Nature 606, 75–81 (2022).

- **Algorithms for graphs and quantum simulation**
  Thomas R Bromley *et al* 2020 *Quantum Sci. Technol.* 5 034010



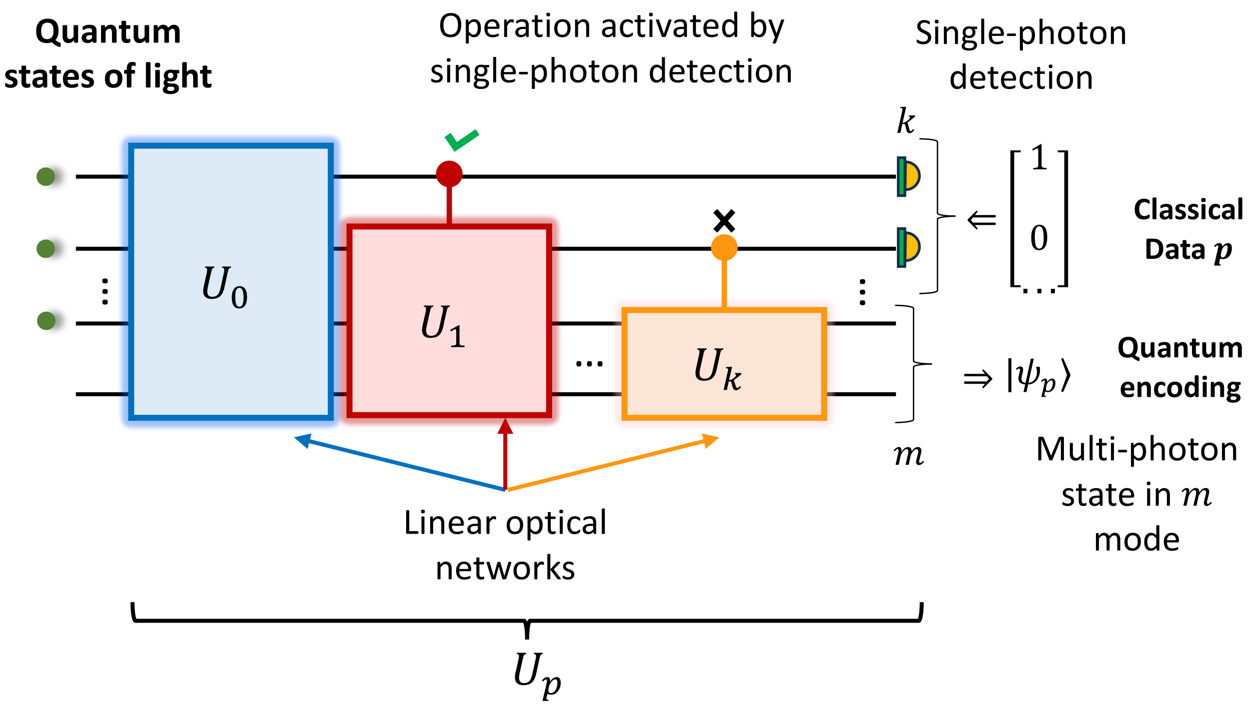
Non universal schemes:
Photonic sampling machines



Harrow, A., Montanaro, A. Quantum computational supremacy. *Nature* **549,** 203–209 (2017)

Quantum computing in photonic platforms

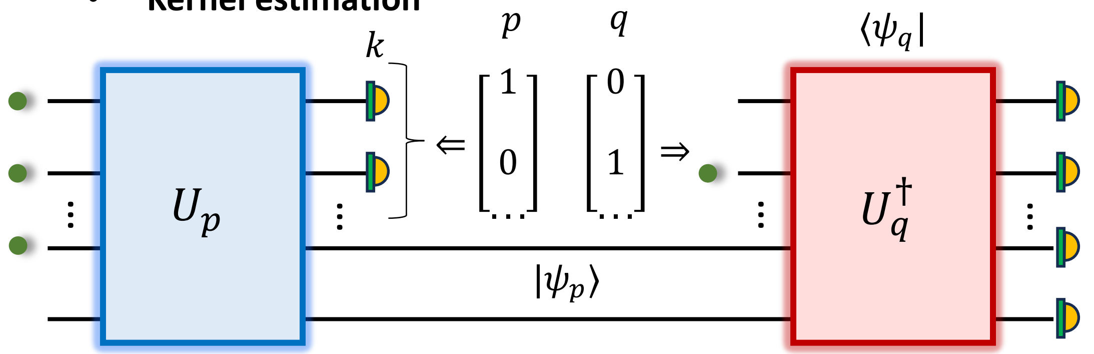
Intermediate schemes: Boson Sampling with adaptive measurements



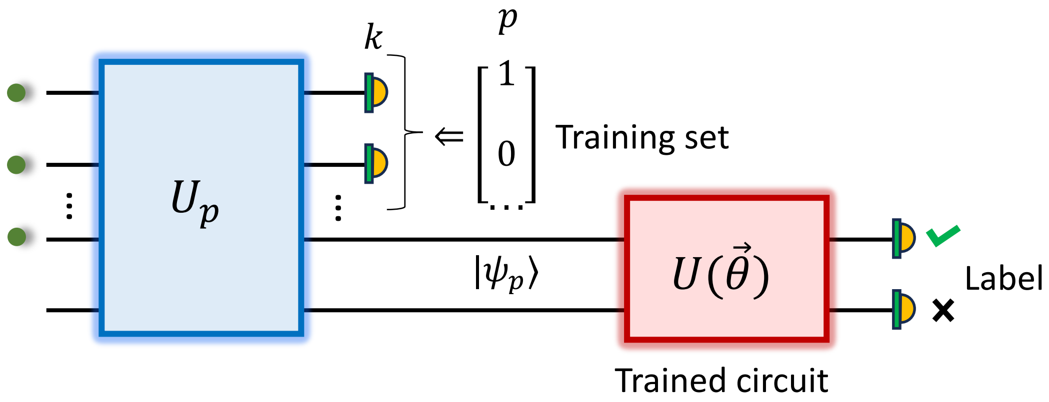
Chabaud, Ulysse, Damian Markham, and Adel Sohbi. "Quantum machine learning with adaptive linear optics." Quantum **5** (2021): 496.

Applications: quantum machine learning

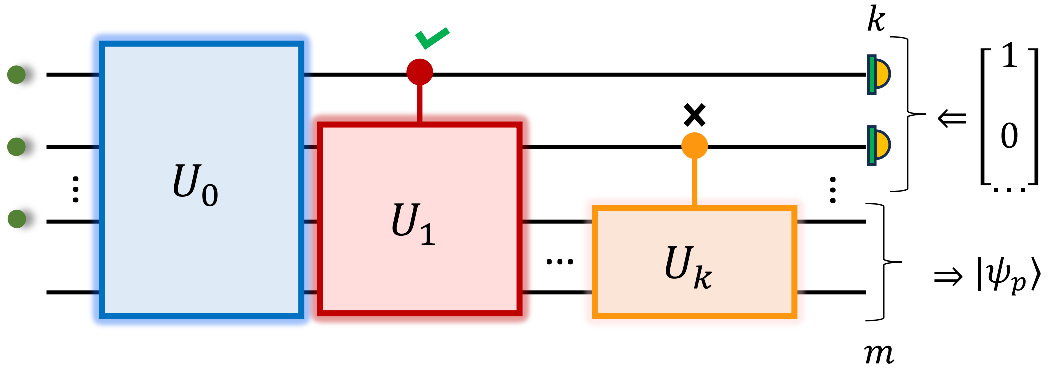
- **Kernel estimation**



- **Classification**



Proof-of-principle experiment on Quantum Machine Learning

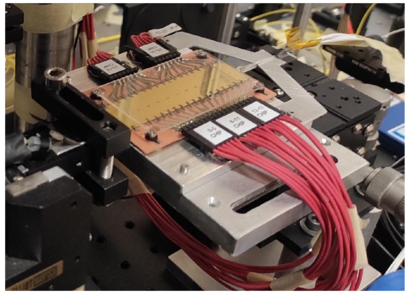


Classical Data p

Quantum encoding

Experiment on the 6-mode universal device

- n=2 photons
- k=4 adaptive measurement
- 3x3 nontrivial Kernel for states with the same number of detected photon (n=1 dual-rail qubit)



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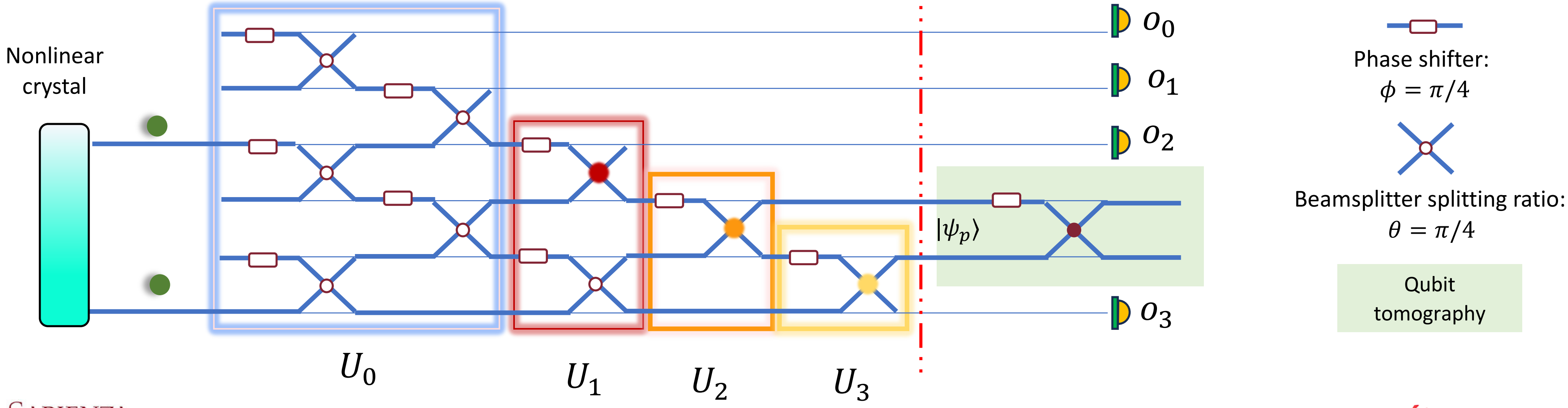

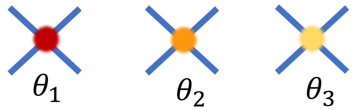

θ_i depends on o_i: $\theta_i = \frac{2\pi \sum_{j=1}^{j=i} o_j}{k}$

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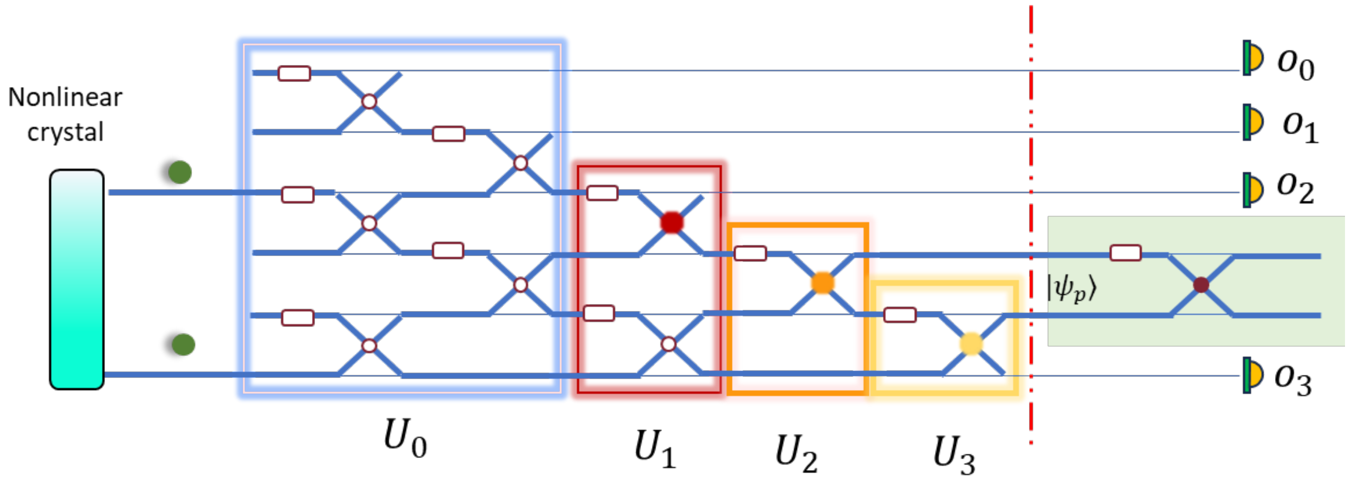
Proof-of-principle experiment: first results



Experiment on the 6-mode universal device

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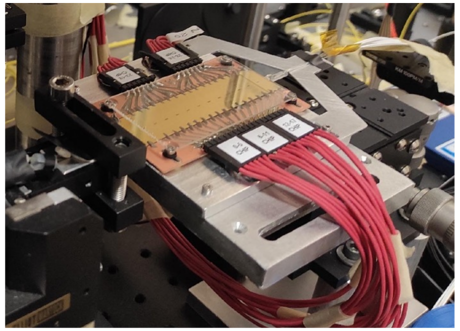

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Theoretical expectations

Bloch vectors of the three qubits

$$\vec{v}_1 = (-0.5954, 0.2302, -0.7698)$$
$$\vec{v}_2 = (-0.1474, -0.9203, 0.3625)$$
$$\vec{v}_3 = (-0.3269, 0.0465, -0.9439)$$

3x3 kernel

$$K = \begin{pmatrix} 1.000 & 0.298 & 0.966 \\ 0.298 & 1.000 & 0.331 \\ 0.966 & 0.331 & 1.000 \end{pmatrix}$$

Experimental data

$$\vec{v}_1 = (-0.523 \pm 0.004, 0.242 \pm 0.006, -0.769 \pm 0.006)$$
$$\vec{v}_2 = (-0.14 \pm 0.04, -0.93 \pm 0.020.34 \pm 0.03)$$
$$\vec{v}_3 = (0.252 \pm 0.005, 0.078 \pm 0.005, -0.964 \pm 0.006)$$

$$K_e = \begin{pmatrix} 1.0 \pm 0 & 0.31 \pm 0.05 & 0.82 \pm 0.04 \\ 0.31 \pm 0.05 & 1.0 \pm 0 & 0.28 \pm 0.02 \\ 0.82 \pm 0.04 & 0.28 \pm 0.02 & 1.0 \pm 0 \end{pmatrix}$$

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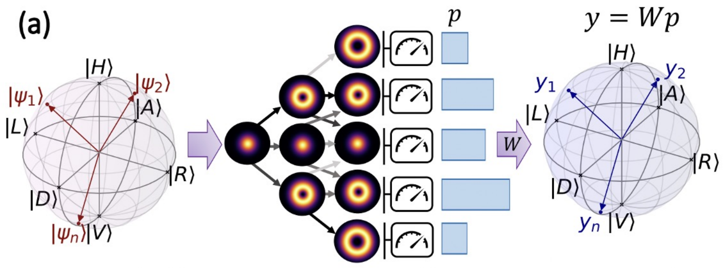
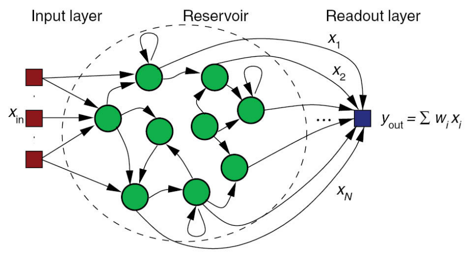
Design and verification of quantum softwares

Software for quantum photonic platforms

Quantum Machine Learning
Randomness manipulation
Alternative scheme for quantum computing

Quantum Reservoir computing





Suprano, Alessia, et al." *arXiv preprint arXiv:2308.04543* (2023).

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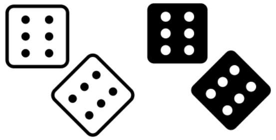
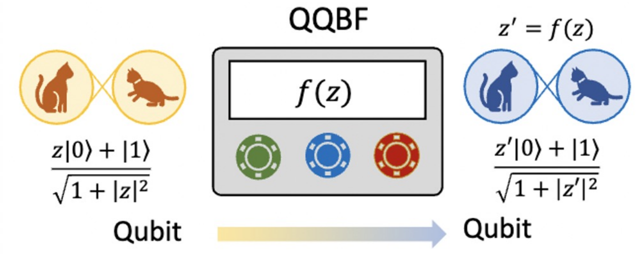
Quantum Bernoulli Factories





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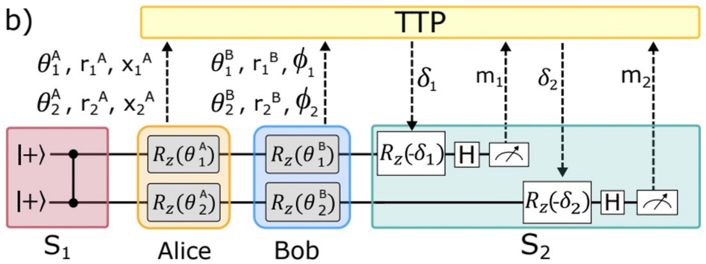
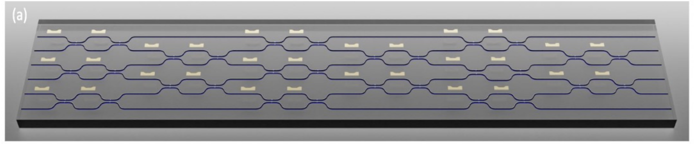
Blind quantum computing

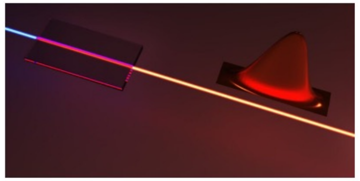
VeriQloud
SORBONNE UNIVERSITÉ



Polacchi, Beatrice, et al. " arXiv preprint arXiv:2306.05195 (2023).

Quantum Metrology





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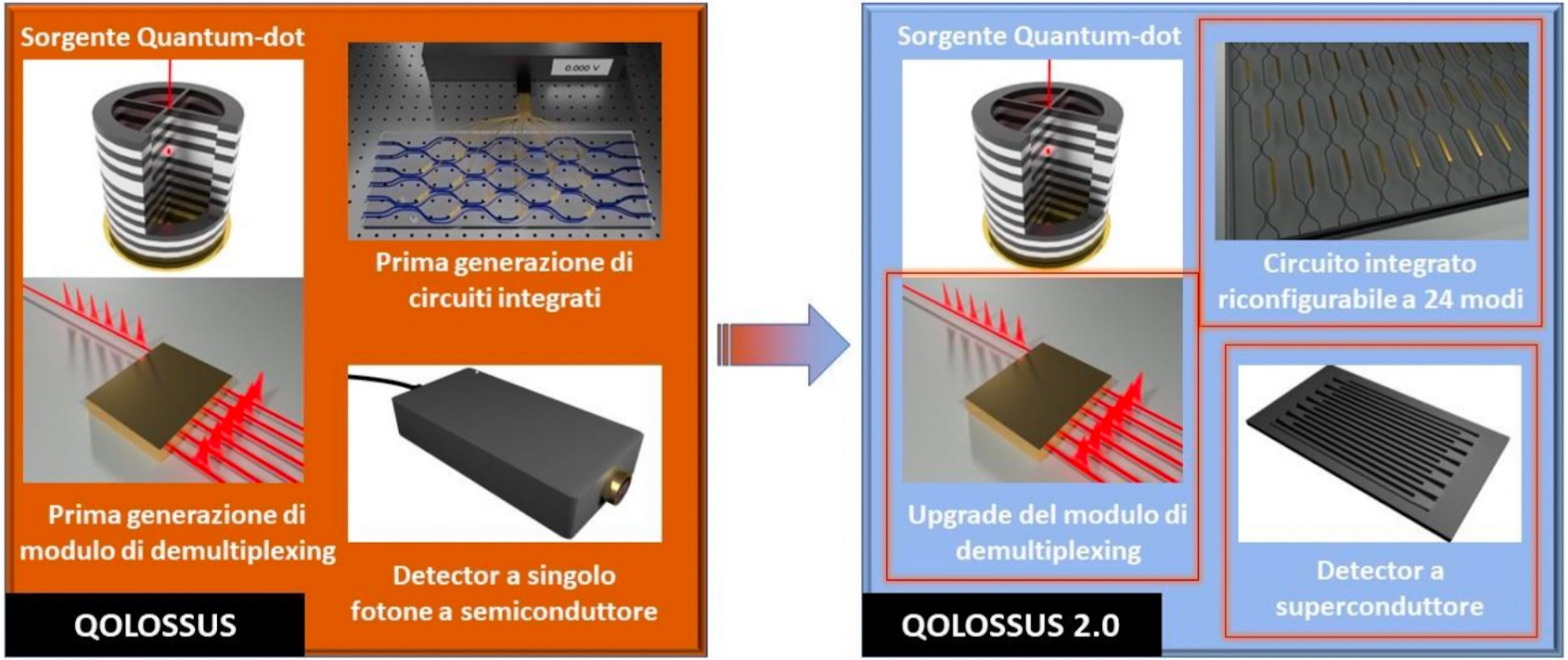
Next steps: upgrade of the hybrid photonics platform



- more photons
- more modes
- detector with higher efficiencies
- higher rates
- full control on platform

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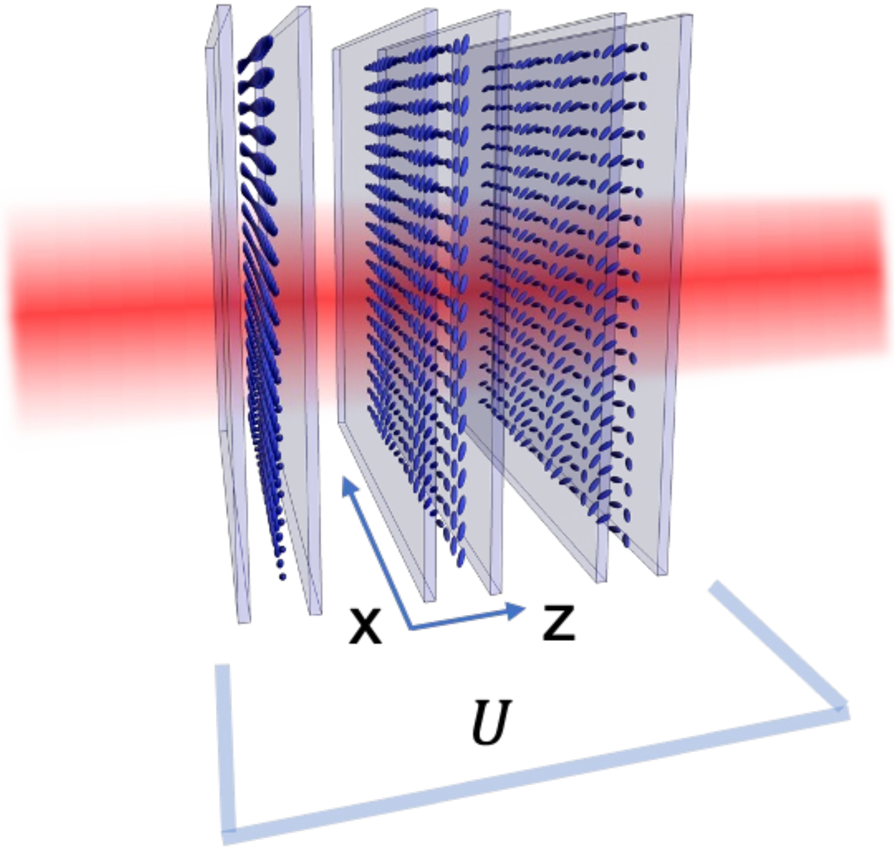
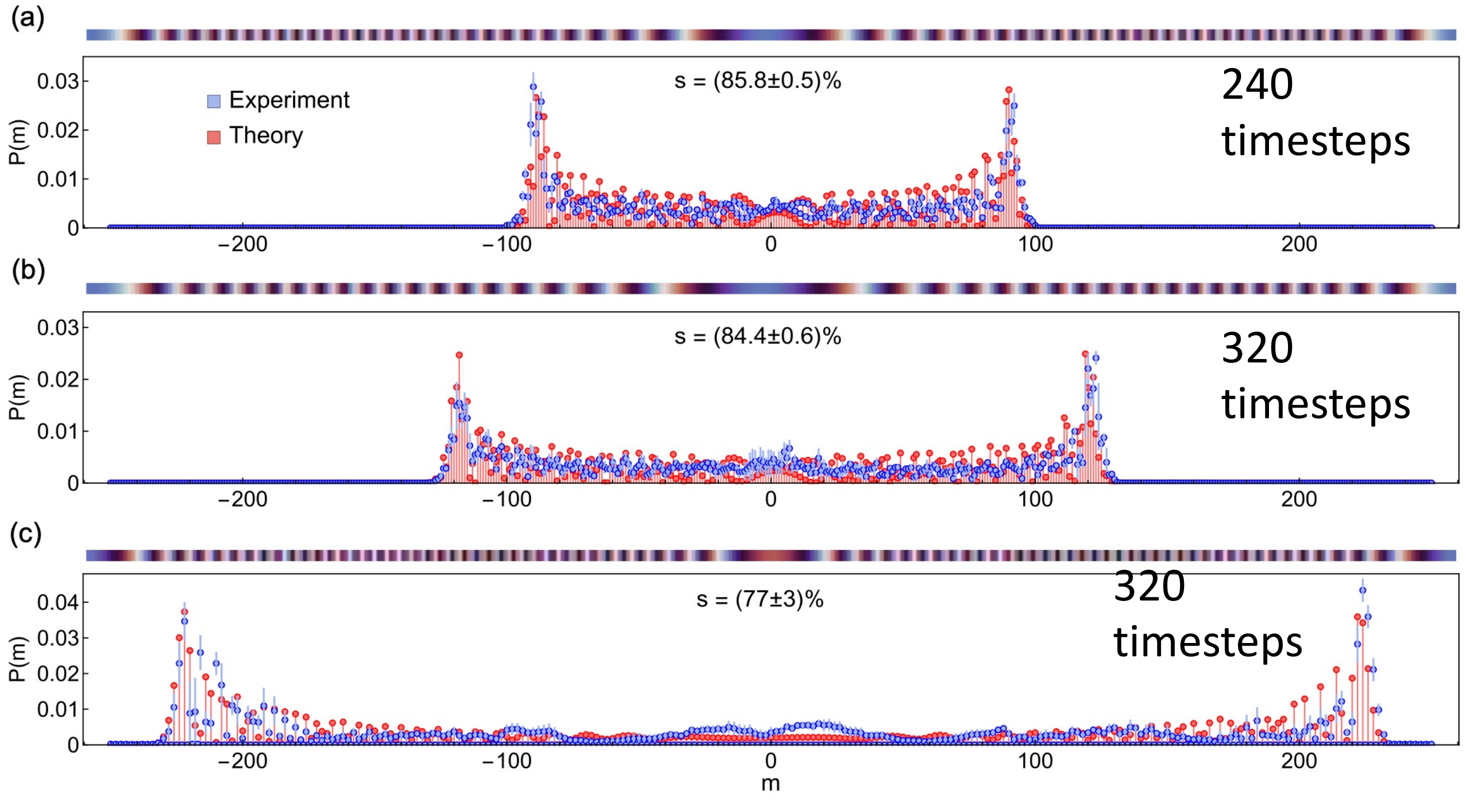
Realizing complex unitaries based on the quantum walk paradigm

Università degli Studi di Napoli Federico II

Novel approach based on few complex metasurfaces





Di Colandrea F. et al., Ultra-long quantum walks via spin–orbit photonics. Optica 10, pp. 324-331 (2023)

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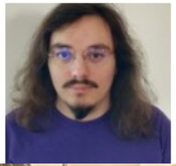
Quantum Computing Lab

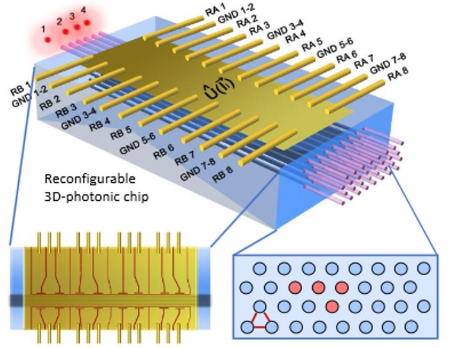
Dipartimento di Fisica, Università di Roma La Sapienza

Sapienza Università di Roma

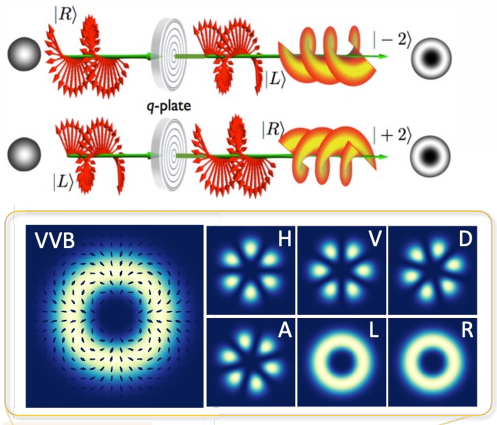




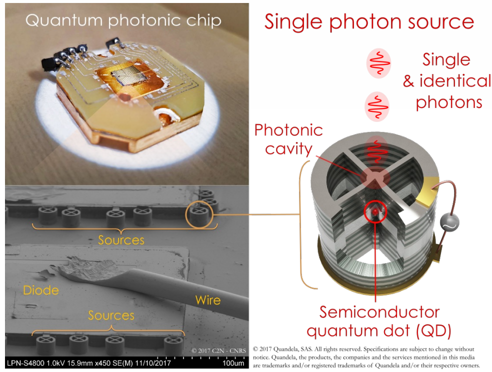
1) Integrated circuits

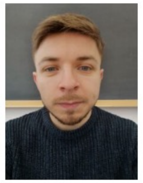


1) Angular momentum states



3) Deterministic sources



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See poster from Sapienza
activities dedicated to quantum algorithms

Parameterized quantum circuits for anomaly detection and generative tasks

Andrea Cacioppo - University of Rome La Sapienza

We investigate the possibility of applying parameterized quantum circuits, in particular, quantum autoencoders, for different machine learning tasks. The first application is for anomaly detection in handwritten digits as well as more complex structures like anomalous patterns in particle detectors. This algorithm has been trained on a classical computer and tested with simulations and on real quantum hardware. Tests on NISQ devices have been performed with IBM quantum computers. The second application is a preliminary study about the possibility of applying parameterized quantum circuits for generative tasks. In this study, the quantum circuit has been used in the denoising steps of a quantum diffusion model.

A General Approach to Dropout in Quantum Neural Networks

Andrea Ceschini - University of Rome La Sapienza

In classical Machine Learning, "overfitting" is the phenomenon occurring when a given model learns the training data excessively well, and it thus performs poorly on unseen data. A commonly employed technique in Machine Learning is the so called "dropout", which prevents computational units from becoming too specialized, hence reducing the risk of overfitting. With the advent of Quantum Neural Networks as learning models, overfitting might soon become an issue, owing to the increasing depth of quantum circuits as well as multiple embedding of classical features, which are employed to give the computational nonlinearity. Here we present a generalized approach to apply the dropout technique in Quantum Neural Network models, defining and analysing different quantum dropout strategies to avoid overfitting and achieve a high level of generalization. Our study allows to envision the power of quantum dropout in enabling generalization, providing useful guidelines on determining the maximal dropout probability for a given model, based on overparametrization theory. It also highlights how quantum dropout does not impact the features of the Quantum Neural Networks model, such as expressibility and entanglement. All these conclusions are supported by extensive numerical simulations, and may pave the way to efficiently employing deep Quantum Machine Learning models based on state-of-the-art Quantum Neural Networks.