QUANTUM LAB

Quantum Computing Lab

Dipartimento di Fisica, Università di Roma La Sapienza

SAPIENZA UNIVERSITÀ DI ROMA

Photonics Quantum Technologies @NQSTI for Quantum Computing

Fabio Sciarrino

Sapienza Università di Roma

www.quantumlab.it

@qlab_sapienza

ICSC

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

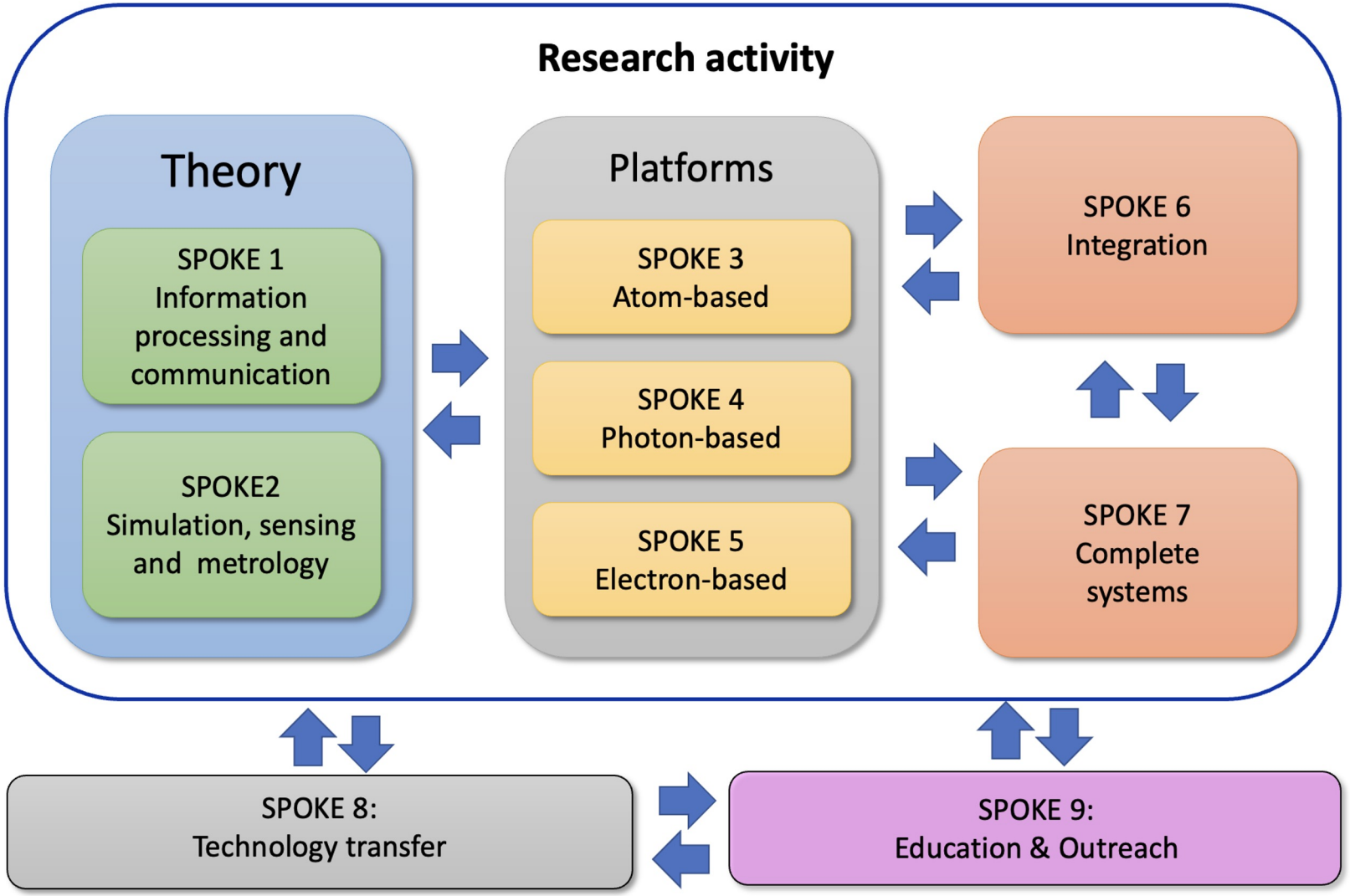
NQSTI

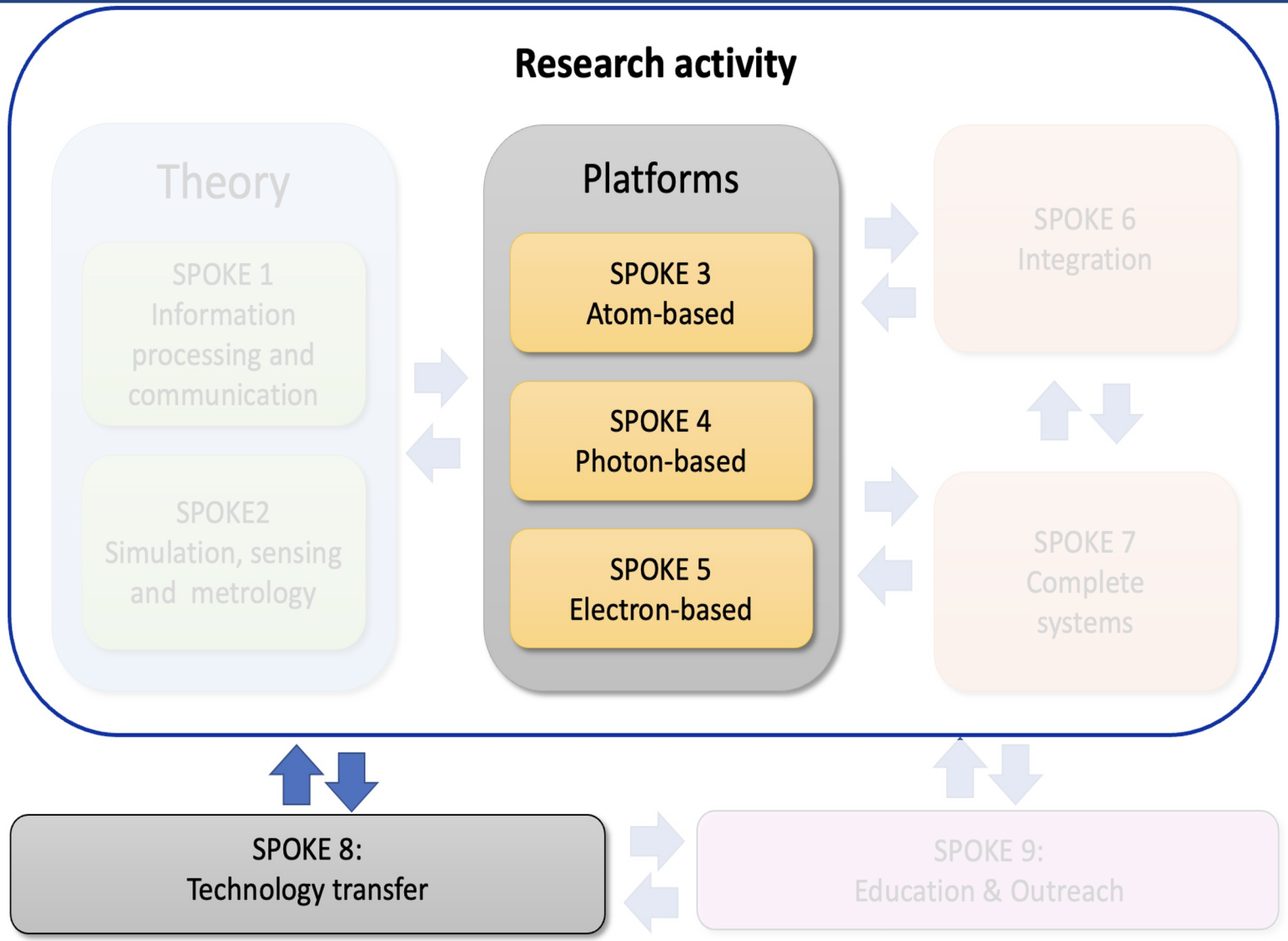
National Quantum Science and Technology Institute


International programs
New companies
Outreach and education
SME
Small Medium Enterprises
NQSTI
National Quantum Science and Technology Institute
Quantum research
Industries

Spoke

1. Università di Pavia
2. Università di Camerino
3. Consiglio Nazionale delle Ricerche
4. Università di Roma Sapienza
5. Scuola Normale Superiore
6. Università di Milano Bicocca
7. Fondazione Bruno Kessler
8. Consiglio Nazionale delle Ricerche
9. Università di Catania




Research activity
Theory
SPOKE 1
Information processing and communication
SPOKE2
Simulation, sensing and metrology
Platforms
SPOKE 3
Atom-based
SPOKE 4
Photon-based
SPOKE 5
Electron-based
SPOKE 6
Integration
SPOKE 7
Complete systems
SPOKE 8:
Technology transfer
SPOKE 9:
Education & Outreach

Objectives

Spoke 4 "Photonic Platform for Quantum Technologies» aims to develop all **technologies** needed **to generate** in either single photon or multi-photon configurations, **manipulate**, and **detect quantum states of light** across a broad range of frequencies (from the visible to the far-infrared).

The Spoke targets **bulk and integrated platforms**, employing different material platforms (e.g. molecules, semiconductor quantum dots, 2D materials, diamonds), different technologies relying on dissimilar architectures (e.g. 1d, 2d or heterostructured geometries) and with interdisciplinary scientific approaches lying at the interface between **quantum optics, (nano) fabrication and photoni**c.

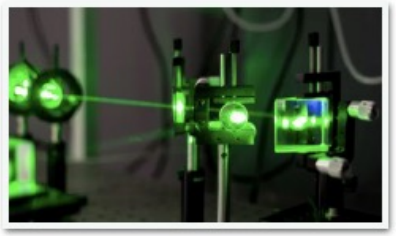
Single photon devices (for both generation, detection and manipulation) require strong optical nonlinearity at the single photon level while for continuous variable approaches high-bandwidth squeezing will be targeted.

Passive and active integrated optical components for manipulating/modulating/switching the generated quantum states of light or for probing/imaging quantum properties at the micro- and nanoscale will be also devised to complement this groundbreaking program of technological development.

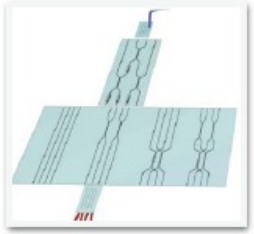
Objectives

Spoke 4 aims to develop all **technologies** needed **to generate** in either single photon or multi-photon configurations, **manipulate**, and **detect quantum states of light** across a broad range of frequencies (from the visible to the far-infrared).

Targered Platforms



Bulk optics



Integrated photonics

Aiming to…

- Multiphoton
- Single-photon
- Broad wavelenght
- Nanofabrication

Single photon devices

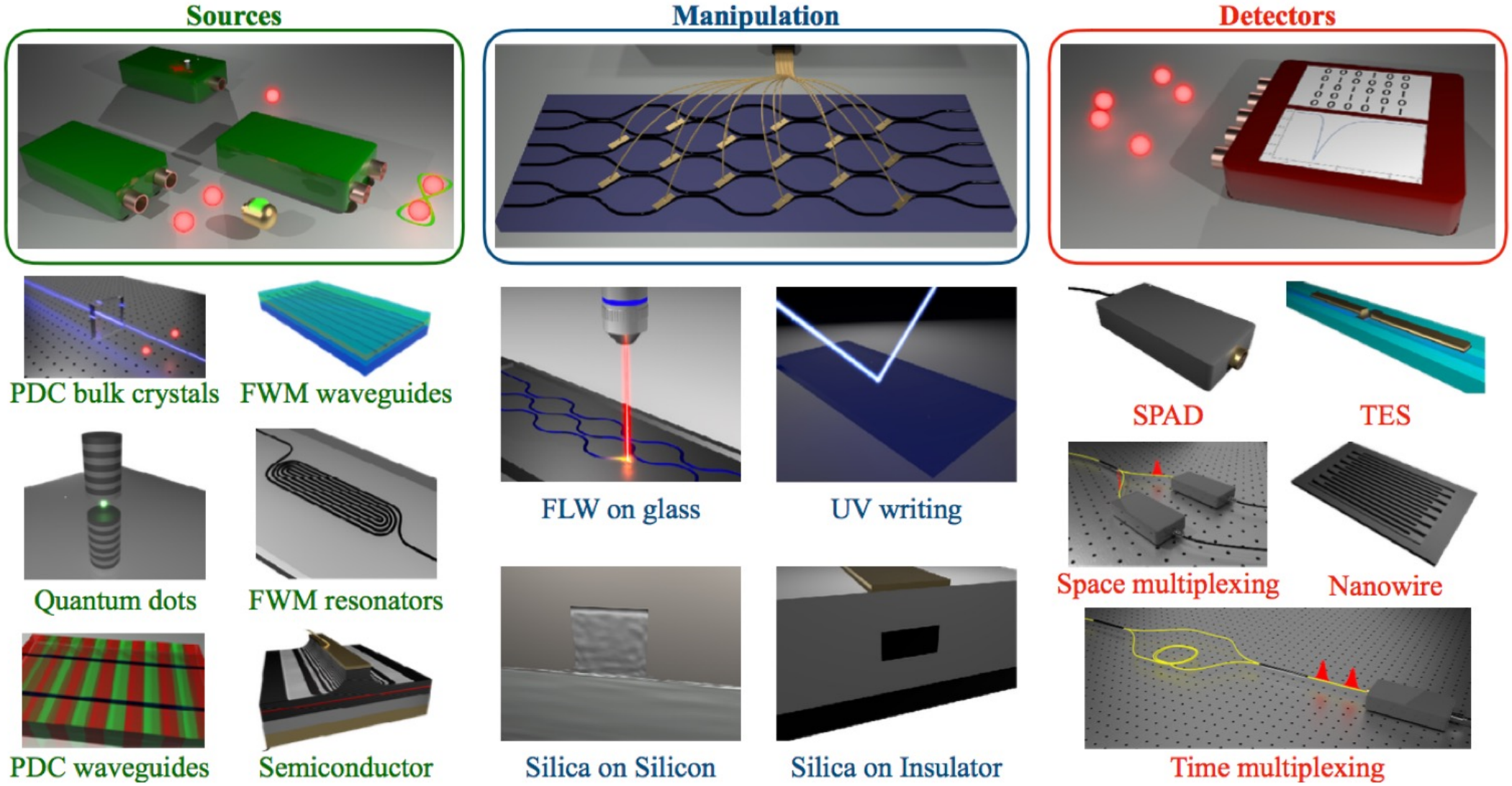
Passive and active Integrated optical components

Passive and active integrated optical components for manipulating/modulating/switching the generated quantum states of light or for probing/imaging quantum properties at the micro- and nanoscale will be also devised to complement this groundbreaking program of technological development.

Activities

SOURCES	A4.1	Semiconductor based sources of single/two photon quantum states
	A4.2	Development of scalable single photon sources based on molecular systems or 2D materials
	A4.3	Development of integrated non-classical light sources with non-linear material
	A4.4	Heterostructured quantum source
MANIPULATION	A4.5	Manipulation of photonics quantum states via integrated photonics
	A4.6	Innovative free-space methodologies for quantum photonics manipulation
	A4.7	Manipulation of photonics quantum states via nonlinear optical systems
DETECTORS	A4.8	Semiconductor based sources of single/two photon quantum states
INTERFACE	A4.9	Development of interfaces between photons and other quantum systems

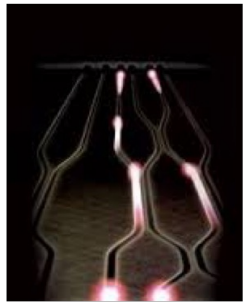
Photonics platform



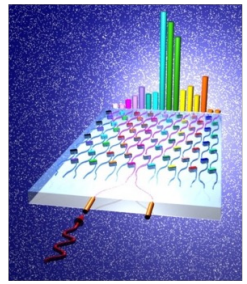
Impact

NQSTI
National Quantum Science and Technology Institute

Quantum computation

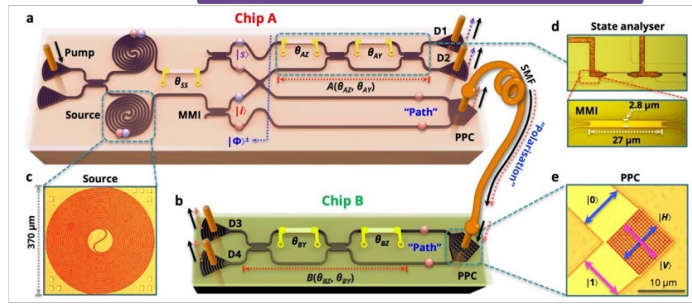


Quantum simulation

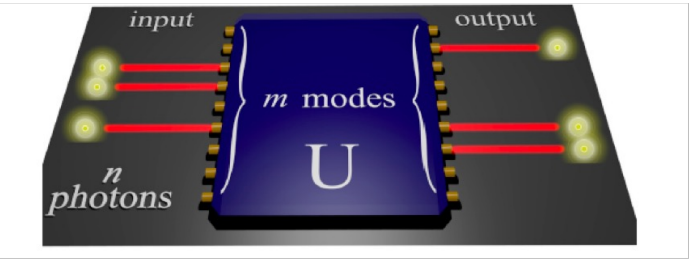


Quantum communication

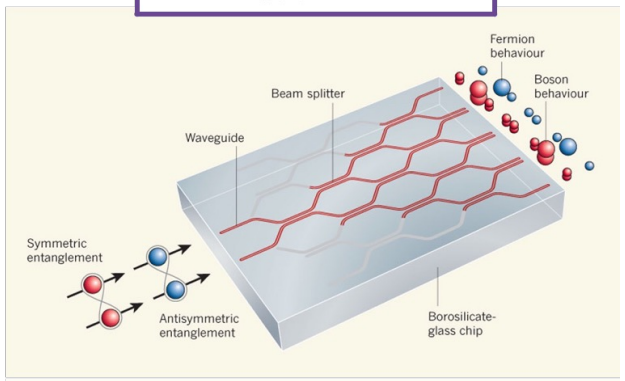
Fundamental science

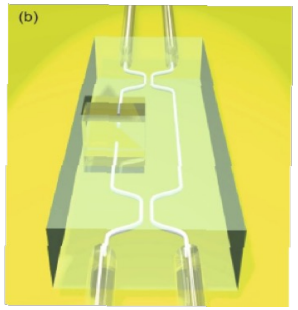


Boson Sampling

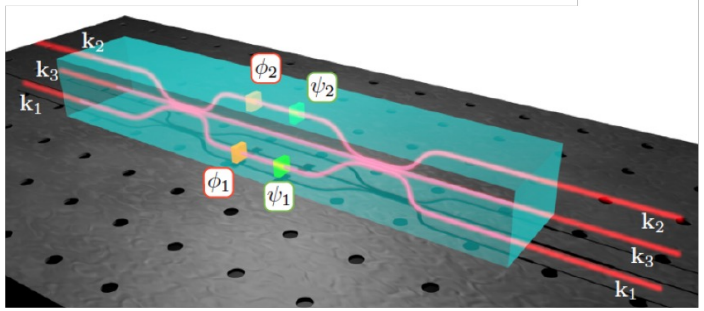


Quantum walk

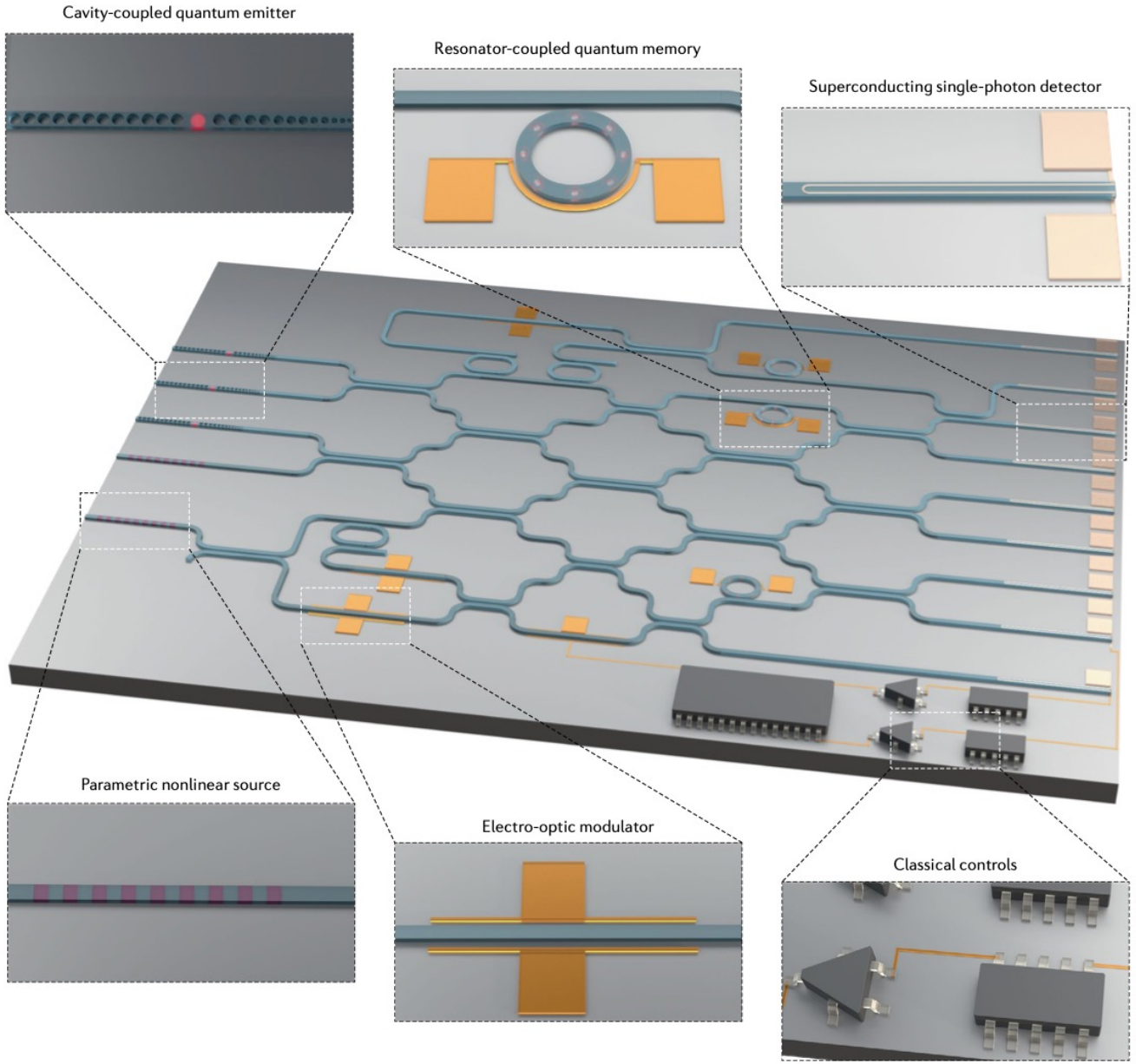




Quantum metrology and sensing



Quantum photonic integrated circuit architecture



The potential and global outlook of integrated photonics for quantum technologies, Nature Reviews Physics, 4, 194-208 (2022)

Integrated photonic quantum platform: the overall scheme

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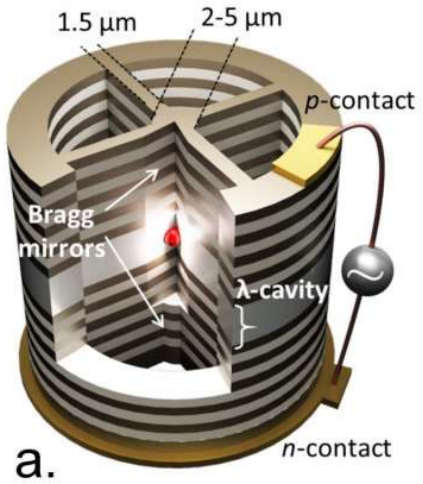
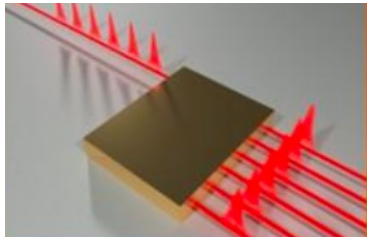
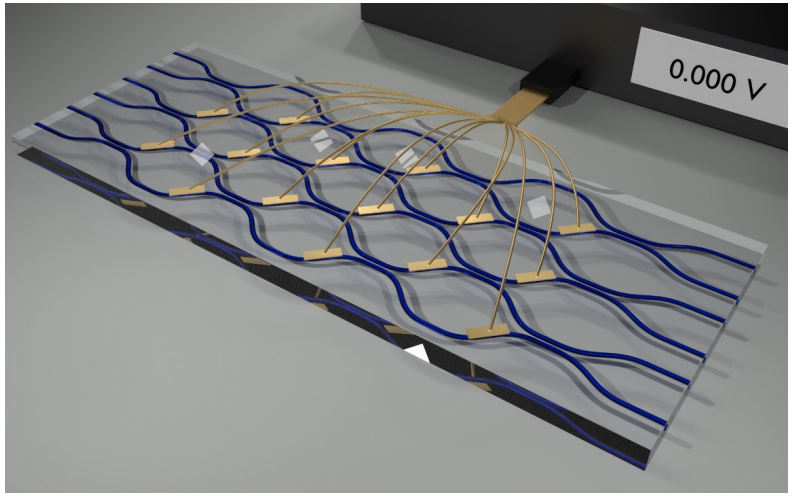
Quantum Computing – Spoke 10
Workpackage : photonics platform







Source of single photon states

Manipulation via integrated photonics

Single photon detection

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UNIVERSITÀ DEGLI STUDI DI NAPOLI FEDERICO II

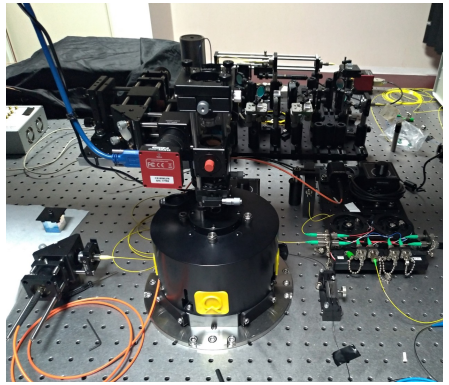
Consiglio Nazionale delle Ricerche

UNIVERSITÀ DI PAVIA

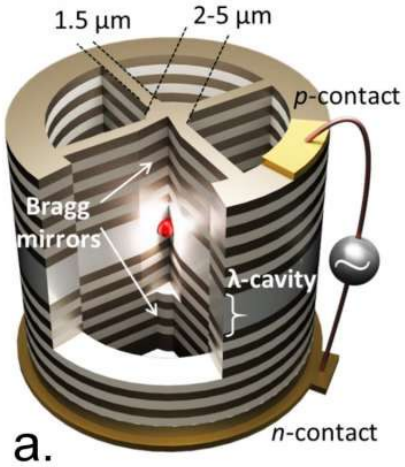
UNIVERSITÀ DEGLI STUDI DI MILANO BICOCCA

Merging deterministic sources and integrated circuits

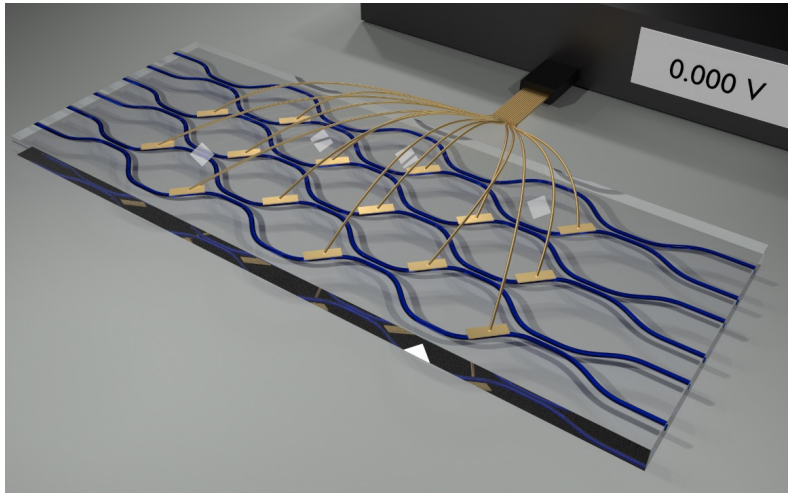
Single photon sources



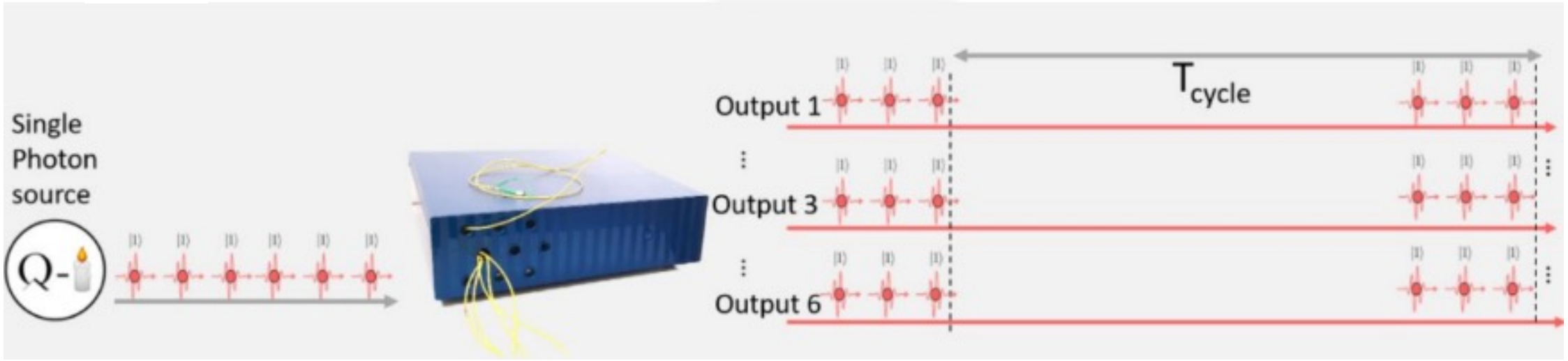
QUANDELA



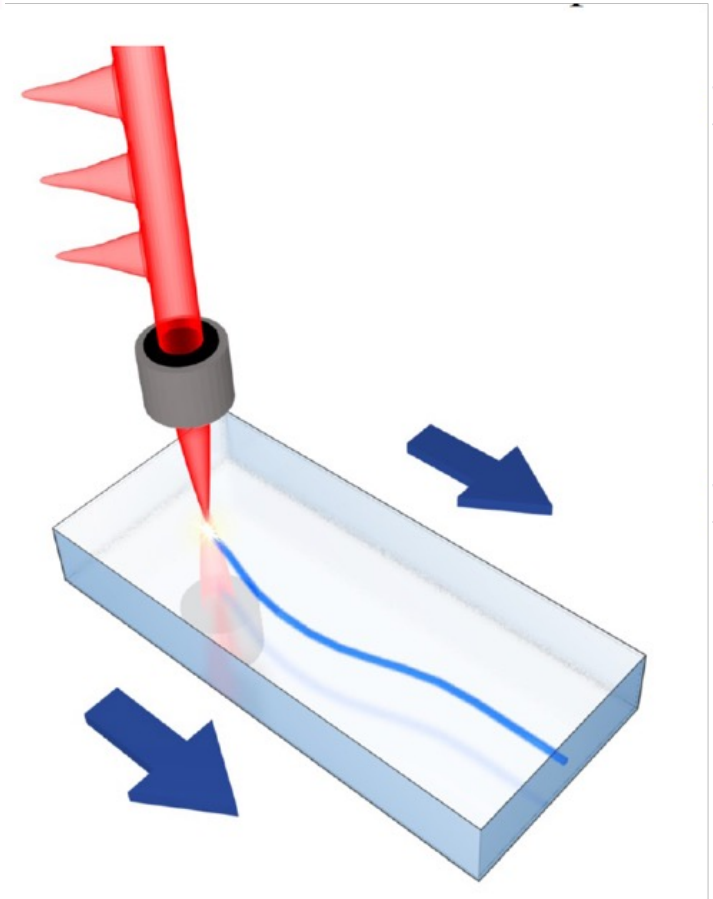
Integrated circuits



Time demultiplexing



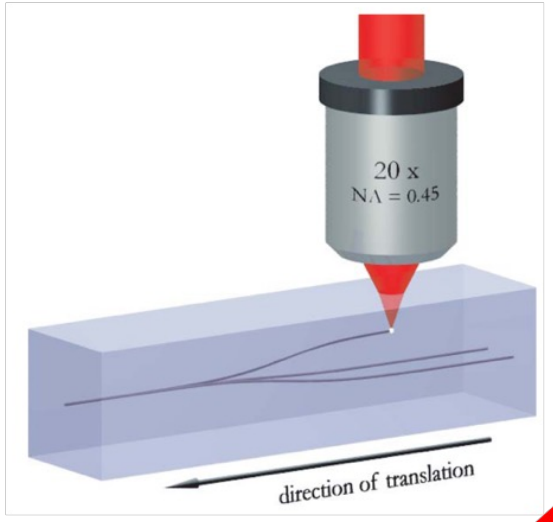
Integrated circuits via femtosecond laser writing



- Femtosecond pulse tightly focused in a glass
- Combination of multiphoton absorption and avalanche ionization induces *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, along the desired path.

Integrated circuits via femtosecond laser writing

3-dimensional capabilities

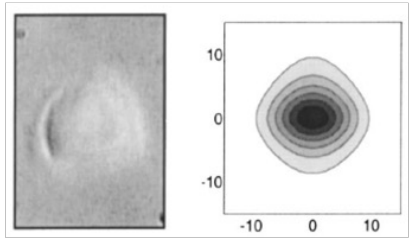


Rapid device prototyping: writing speed =4 cm/s

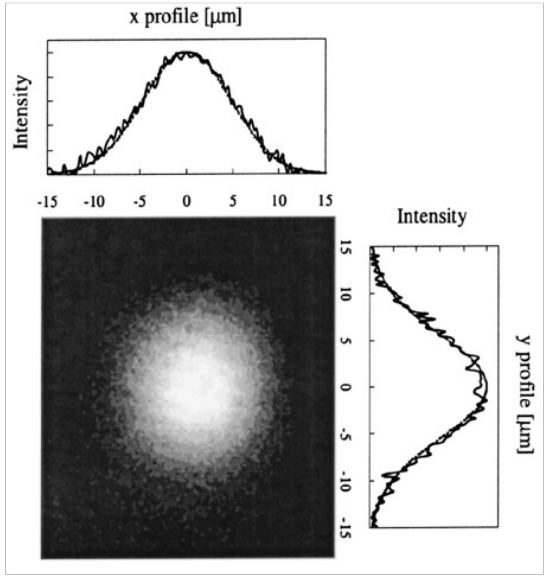
Propagation of circular gaussian modes

Characteristics:

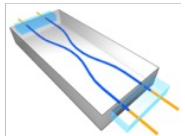
Circular waveguide transverse profile



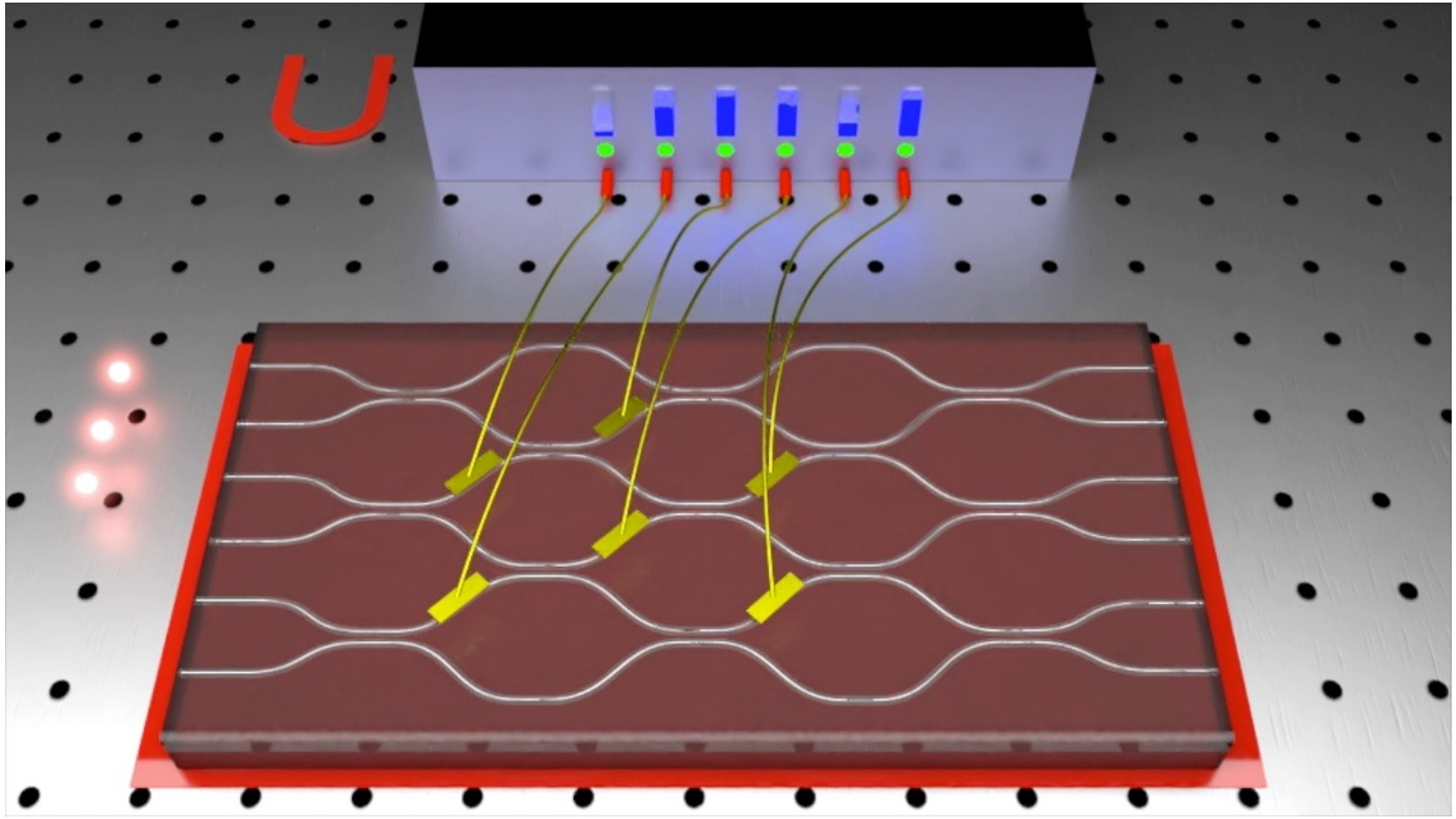
Low birefringence



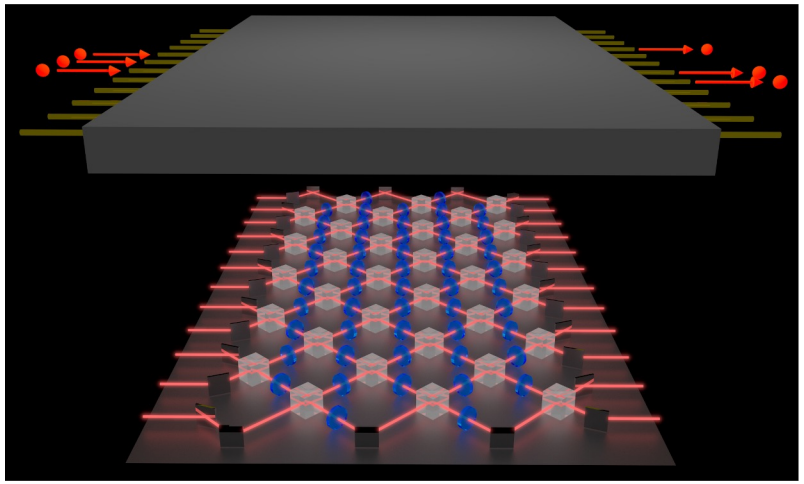
SUITABLE TO SUPPORT ANY POLARIZATION STATE

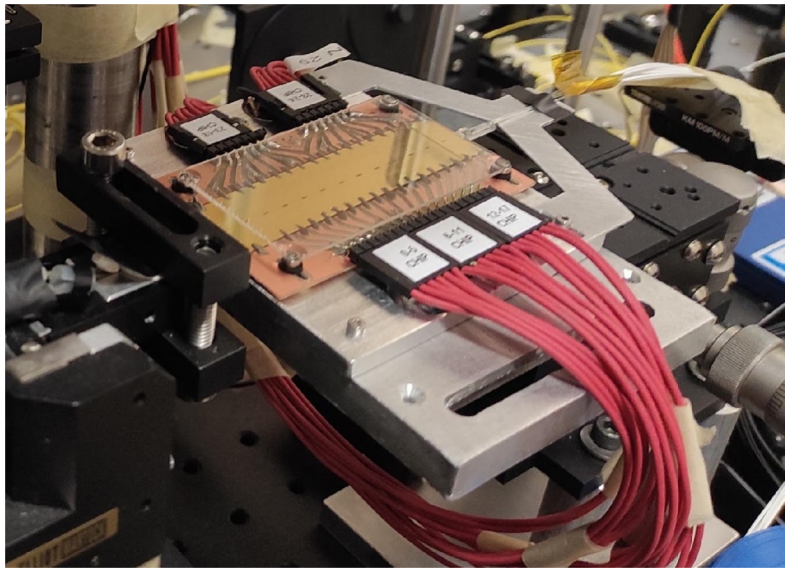


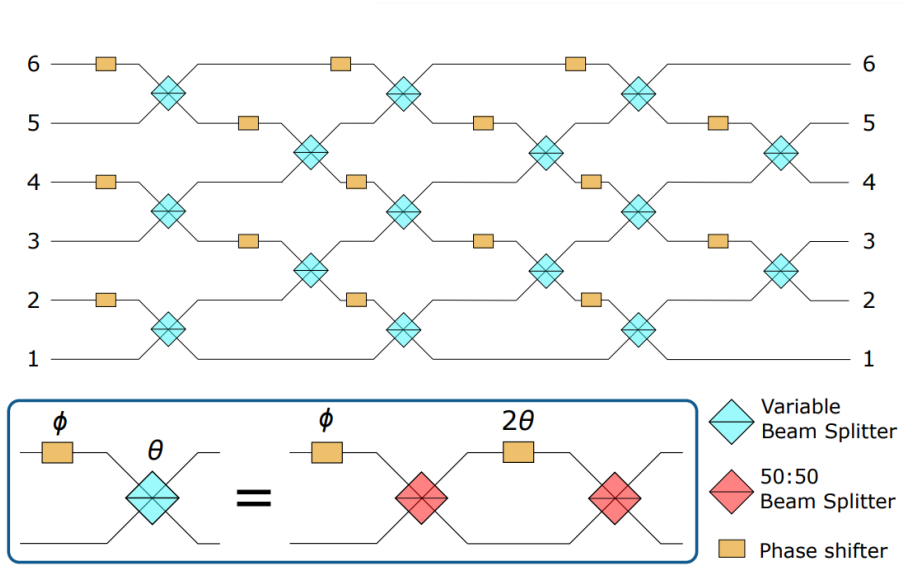
Integrated circuits via femtosecond laser writing: reconfigurability



Universal discrete component layouts



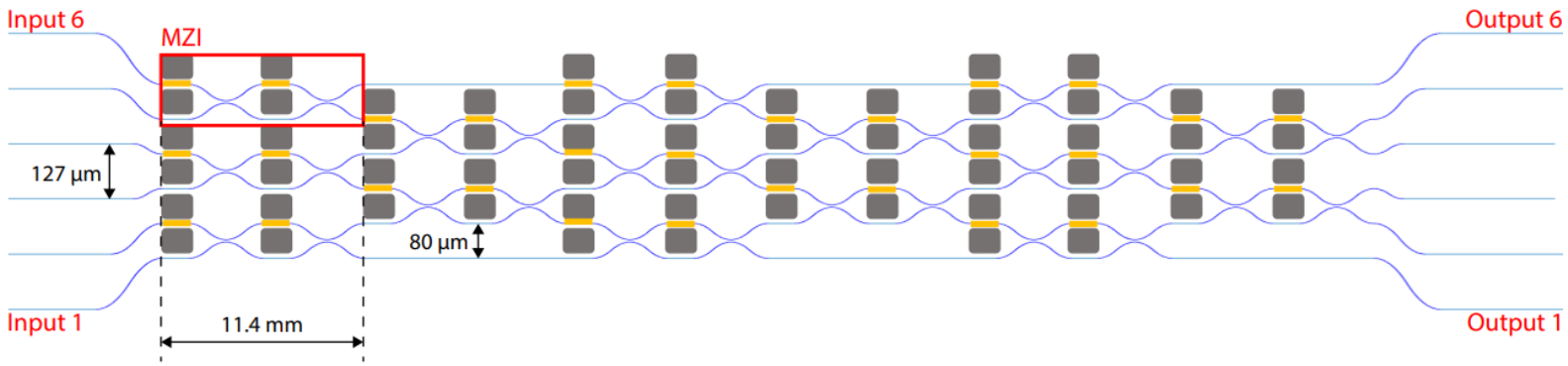




Universal 6-mode integrated photonic chips

- 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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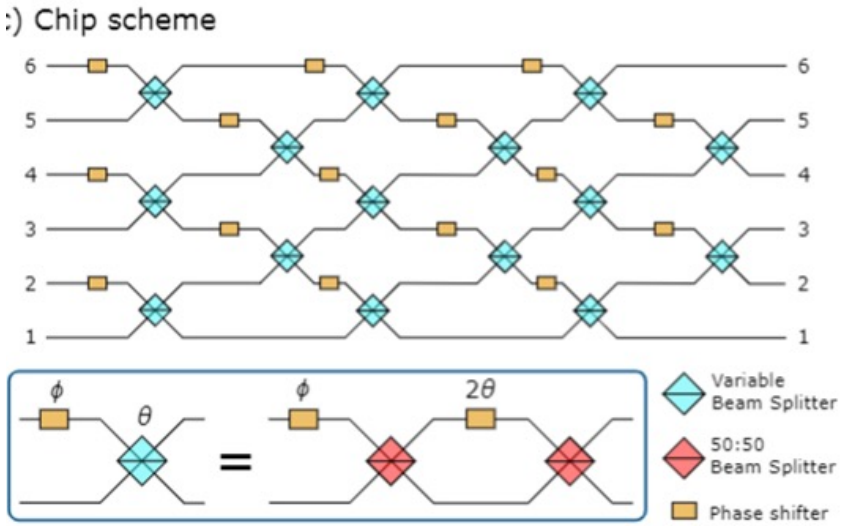
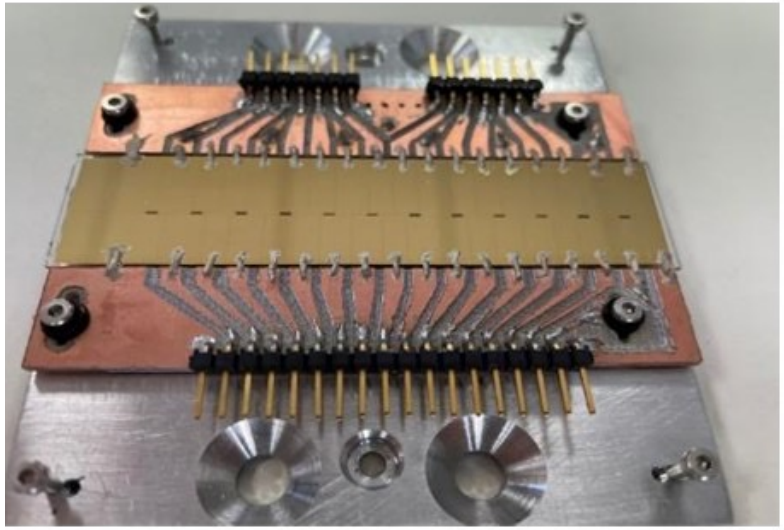
Sapienza Università di Roma

Universal discrete component layouts

SAPIENZA UNIVERSITÀ DI ROMA





Universal 6-mode integrated photonic chips

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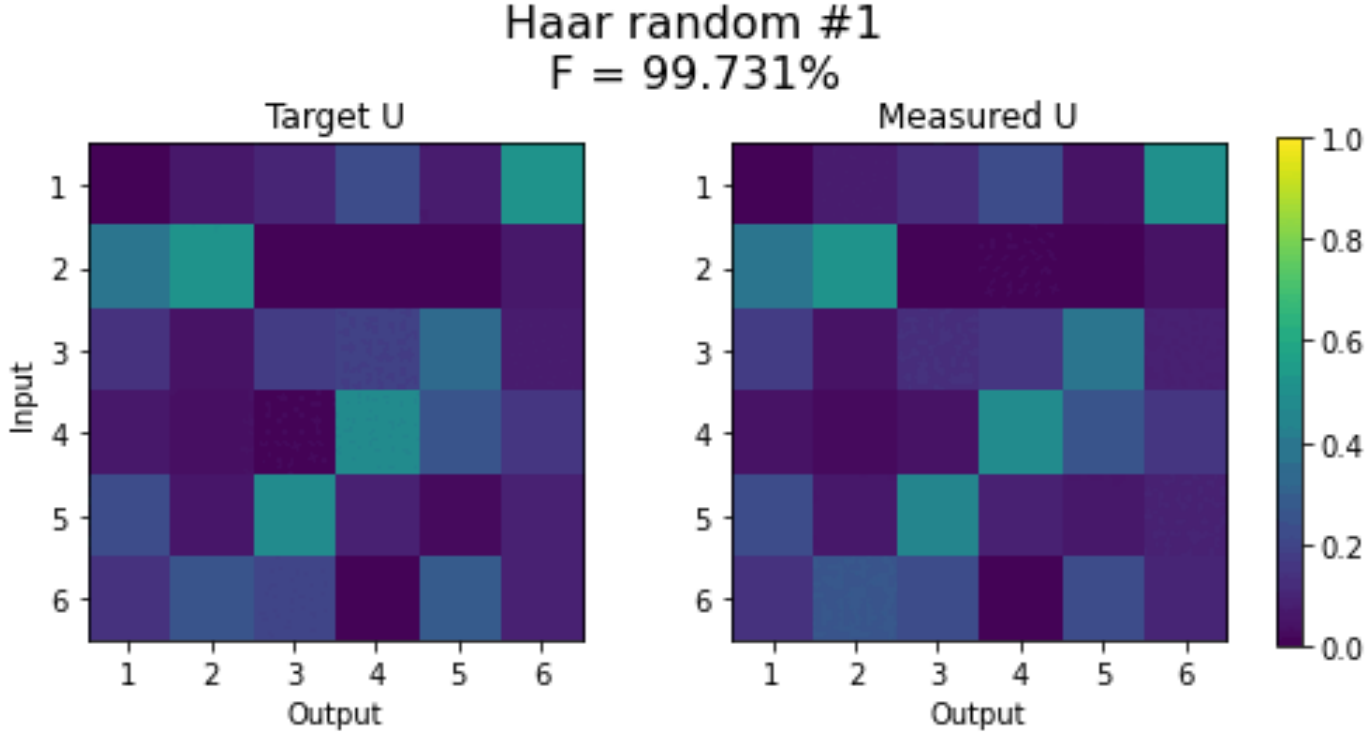
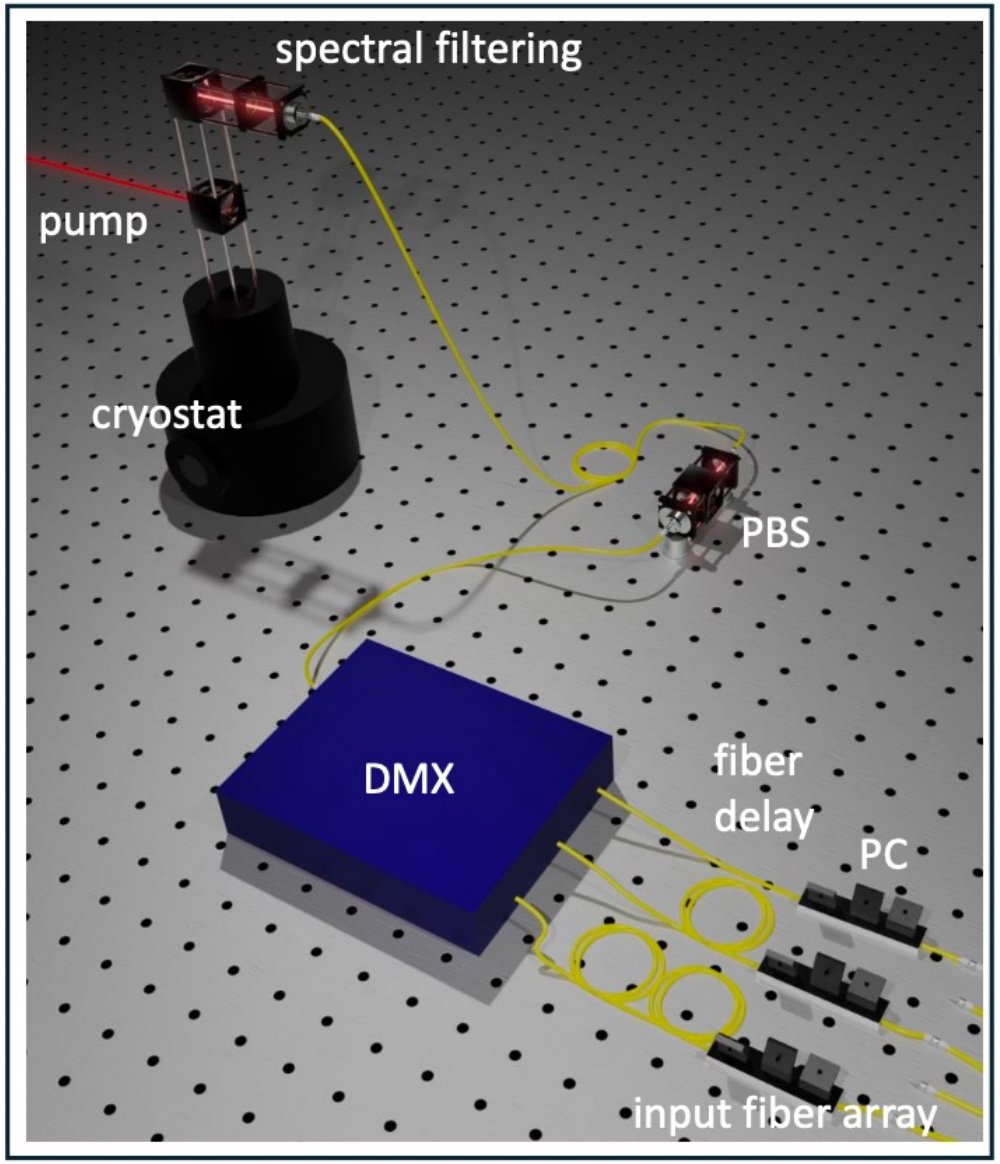
POLITECNICO MILANO 1863

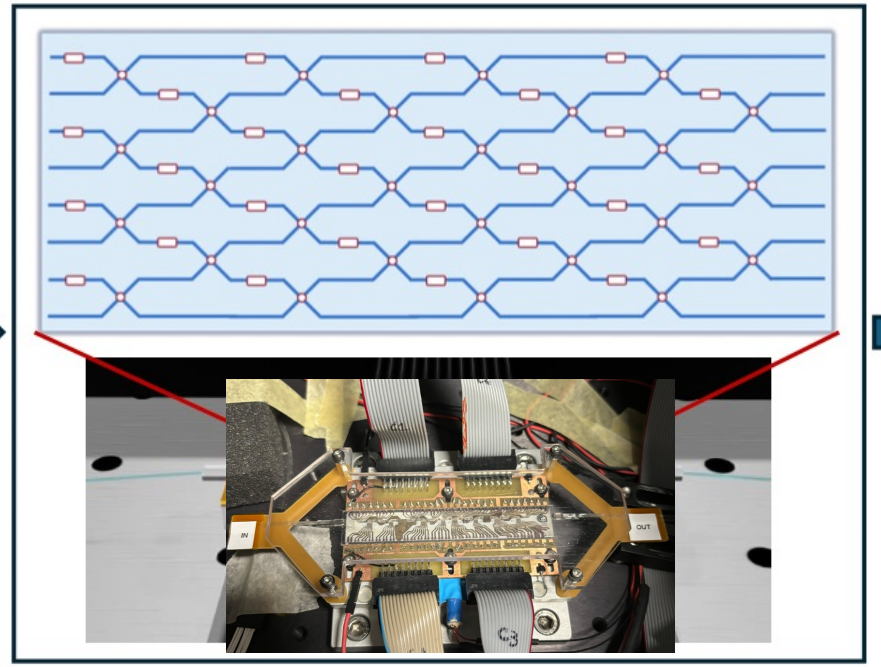
$$MZ(\theta,\phi) = i\, e^{i\theta/2} \begin{pmatrix} \sin(\theta/2)e^{i\phi} & \cos(\theta/2)e^{i\phi} \\ \cos(\theta/2) & -\sin(\theta/2) \end{pmatrix} \qquad U = \prod_k U_{MZ}^k$$



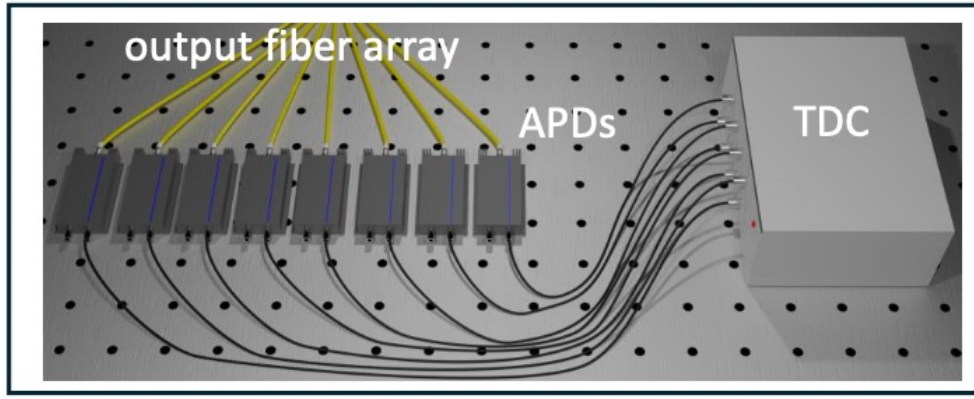
Hybrid Photonic Sampling Machine - QOLOSSUS 2.0

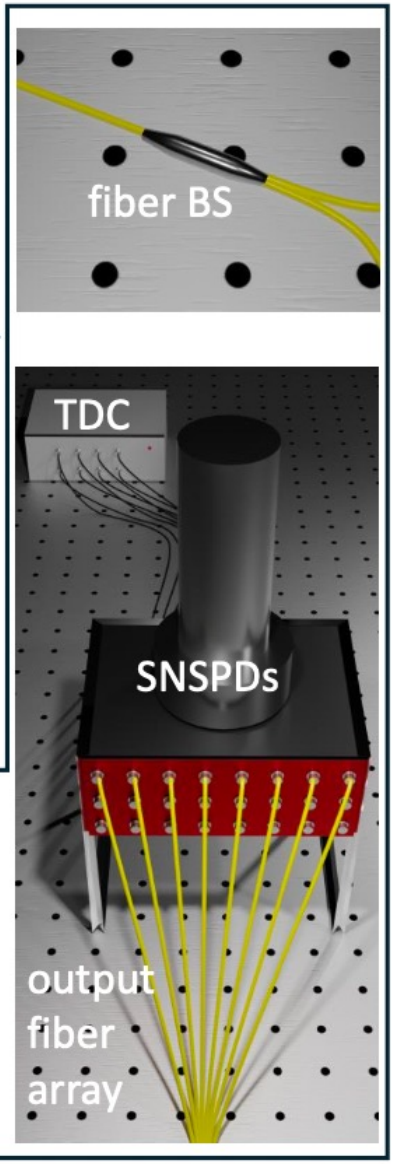


quantum-dot source



8-mode universal processor

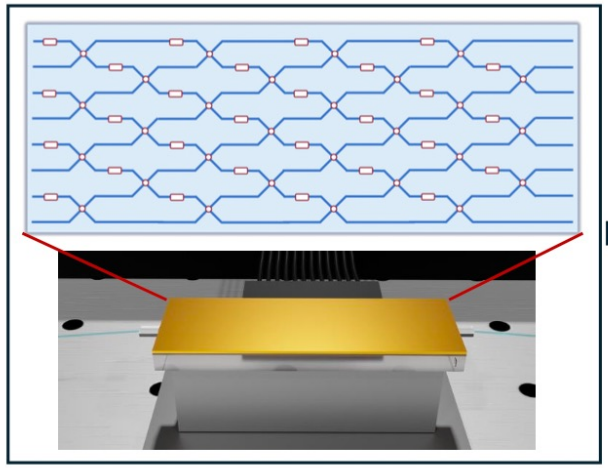




detection

Next hardware developments

Larger Universal Chips

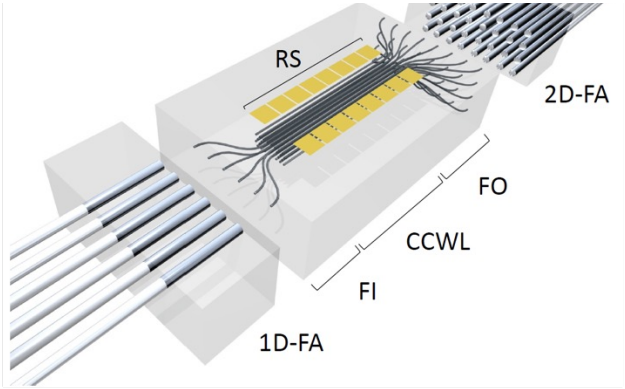


8-mode universal processor

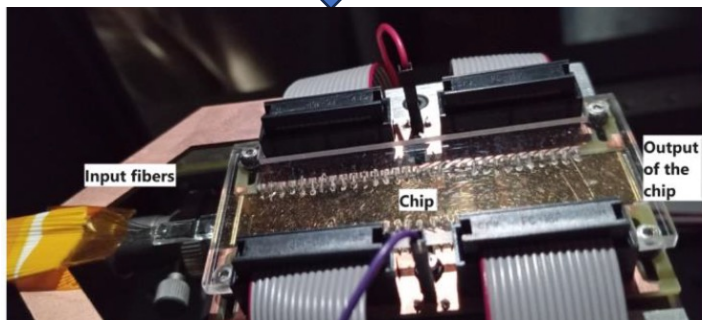
12 mode processor

20 mode processor

3D-devices



Hoch, et al., *npj Quantum Information* **8**, 55 (2022)



128 mode processor

Module for scalable photonics quantum computing

Generation of heralded 3 photon GHZ state

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QLASS

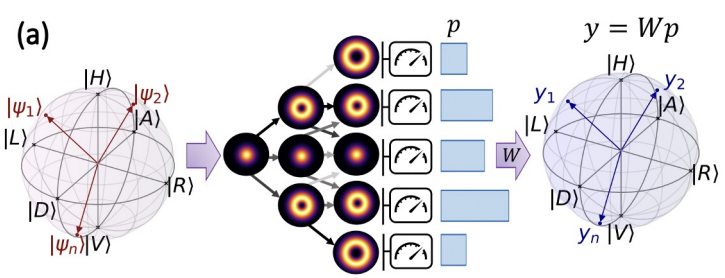
EPIQUE

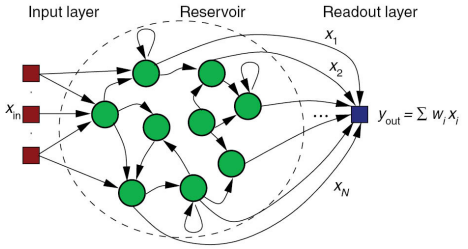
Design, implementation and verification of quantum softwares

Software for quantum photonic platforms

Quantum machine learning
Randomness manipulation
Blind quantum computing
Alternative scheme for quantum computing

Quantum Reservoir computing





A. Suprano, et al., *Phys. Rev. Lett,* **132**, 160802 (2024)

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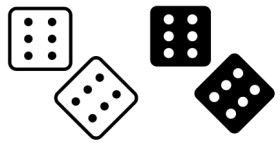
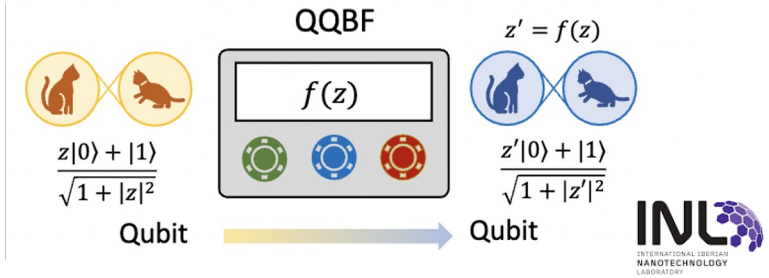
QUEEN'S UNIVERSITY BELFAST

Quantum Bernoulli Factories





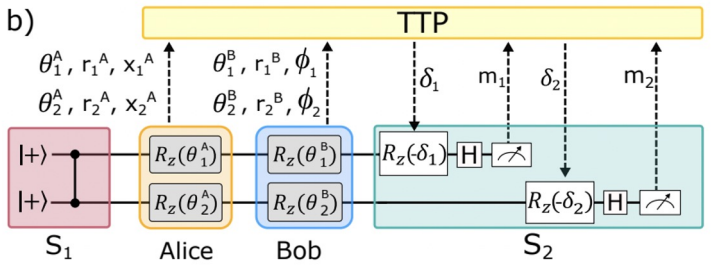
INL INTERNATIONAL IBERIAN NANOTECHNOLOGY LABORATORY

G. Rodari, et al., *Science Advances* **10**, 30 (2024)
F. Hoch, et al., *Nature Photonics* (2024)

Blind quantum computing

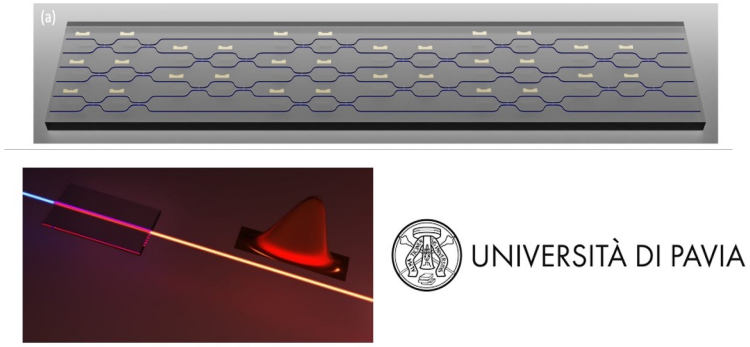
VeriQloud

SORBONNE UNIVERSITÉ



B. Polacchi, et al. *Nature Communications* **14**, 7743 (2023)

Quantum Metrology



UNIVERSITÀ DI PAVIA

Quantum Bernoulli Factory: the concept

Manipulating randomness via photonic Bernoulli factories

State-of-the-art: Quantum Bernoulli factories

- A **Bernoulli Factory (BF)** is a randomness processing protocol that inputs coins with unknown bias *p,* and outputs coins with a different bias *f(p)*
  - Useful as a sub-routine in Monte Carlo applications
- A **Quantum Bernoulli Factory (QBF)** manipulates distributions encoded in quantum states:

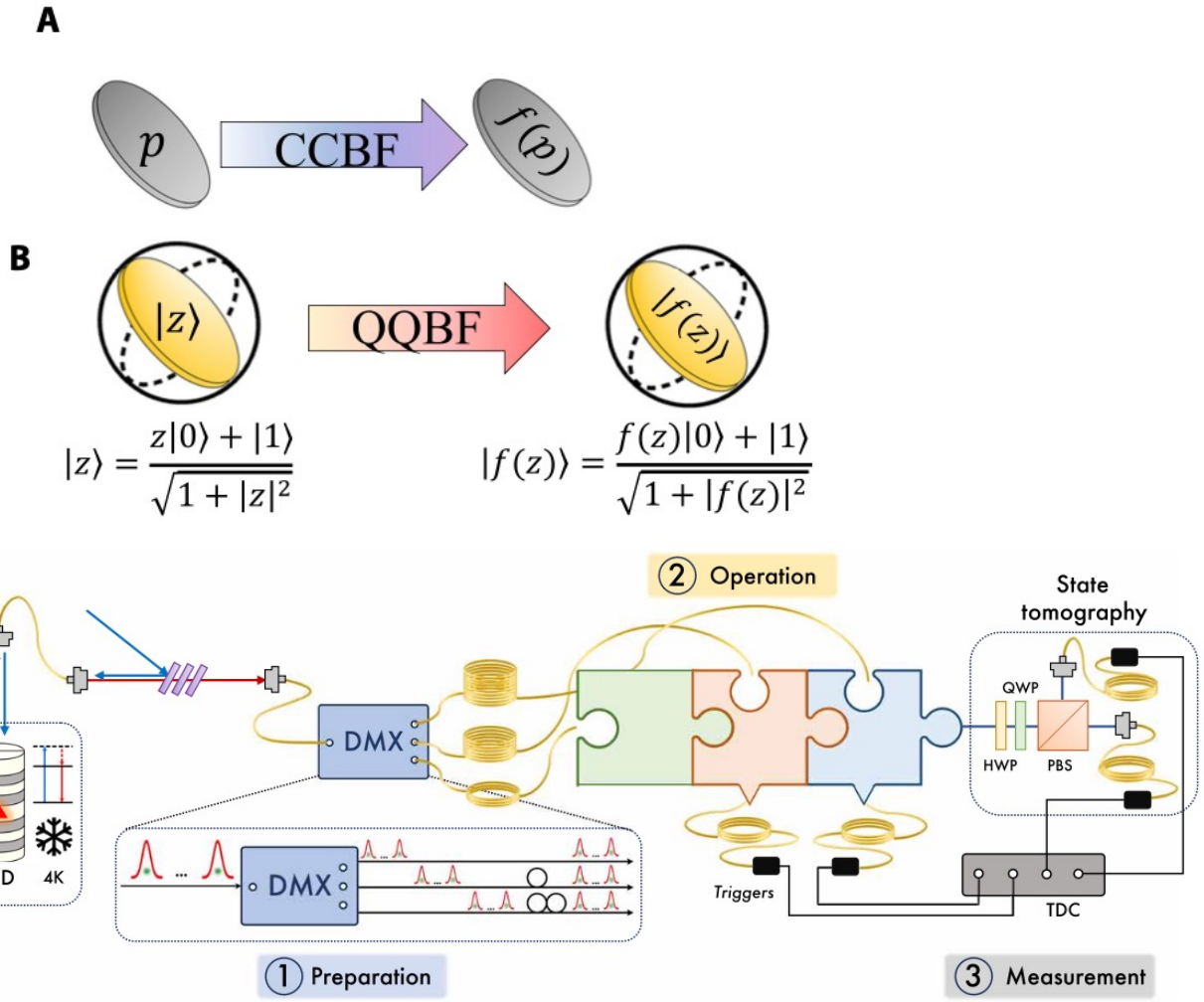
From: Patel *et al.*, *Sci. Adv.* **5** (1), eaau6668 (2019)

$$|\psi_p\rangle = \sqrt{p}|0\rangle + \sqrt{1-p}|1\rangle \xrightarrow{\text{Quantum BF}} |\psi_{f(p)}\rangle = c[\sqrt{f(p)}|0\rangle + \sqrt{1-f(p)}|1\rangle]$$

Dale *et al.*, Nat. Comm. 6, 8203 (2015)

- QBFs have just started to be investigated, and show advantage over classical randomness processing

Polarization encoding - Quantum Bernoulli Factories



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SCIENCE ADVANCES | RESEARCH ARTICLE

PHYSICS

Polarization-encoded photonic quantum-to-quantum Bernoulli factory based on a quantum dot source

Giovanni Rodari[1], Francesco Hoch[1], Alessia Suprano[1], Taira Giordani[1], Elena Negro[1], Gonzalo Carvacho[1]*, Nicolò Spagnolo[1], Ernesto F. Galvão[2,3], Fabio Sciarrino[1]

Rodari *et al.*, *Sci. Adv.* **10**, eado6244 (2024) 26 July 2024

nature photonics

Article

https://doi.org/10.1038/s41566-024-01526-8

Modular quantum-to-quantum Bernoulli factory in an integrated photonic processor

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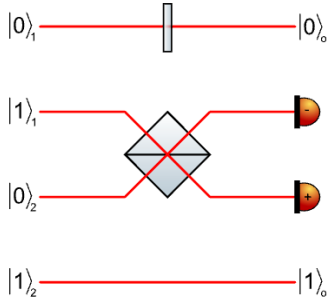
Francesco Hoch[1], Taira Giordani[1], Luca Castello[1], Gonzalo Carvacho[1], Nicolò Spagnolo[1], Francesco Ceccarelli[2], Ciro Pentangelo[2,3], Simone Piacentini[2], Andrea Crespi[2,3], Roberto Osellame[2], Ernesto F. Galvão[4,5] & Fabio Sciarrino[1]

Path encoding - Quantum Bernoulli Factories

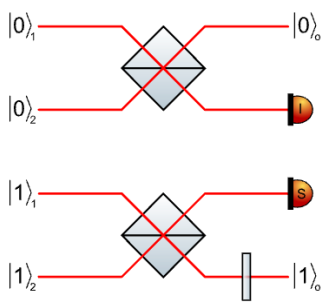
Photonic building blocks

Our proposal: dual-rail encoding in integrated interferometers



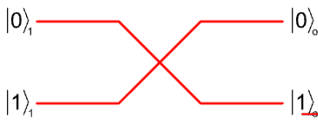
Product $|z_1\rangle|z_2\rangle \rightarrow |z_1 z_2\rangle$

$$P = \frac{1 + |Z_1|^2|Z_2|^2}{2(1 + |Z_1|^2)(1 + |Z_2|^2)}$$



Sum $|z_1\rangle|z_2\rangle \rightarrow |z_1 + z_2\rangle$

$$P = \frac{1 + |Z_1 + Z_2|^2}{5(1 + |Z_1|^2)(1 + |Z_2|^2)}$$

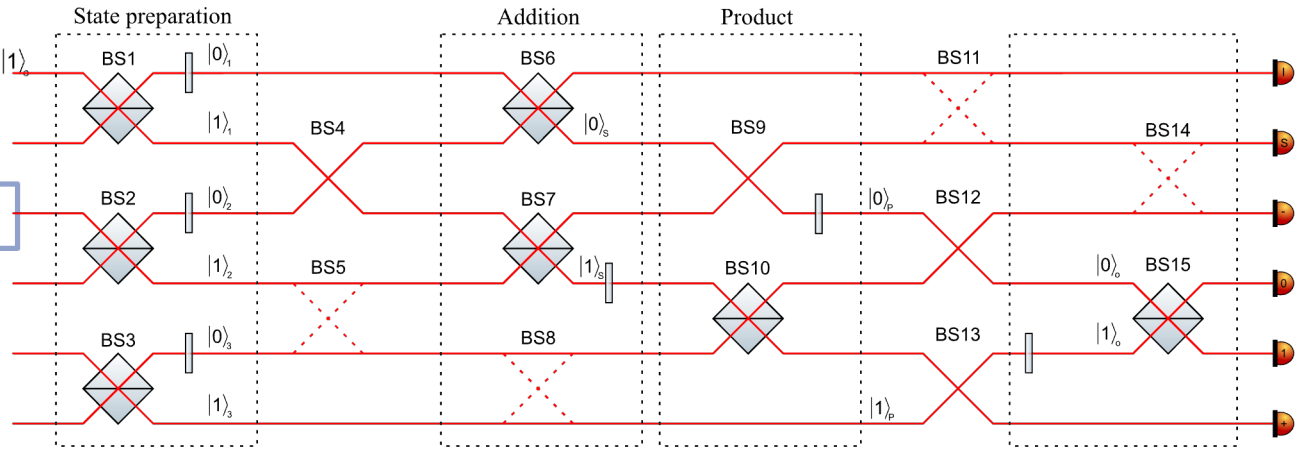


Inverse $|z\rangle \rightarrow |\frac{1}{z}\rangle$

$P = 1$

Concatenation of operations

Implementation via universal 6-mode interferometer



Next step: more sophisticated operations

Open to collaborations on applications

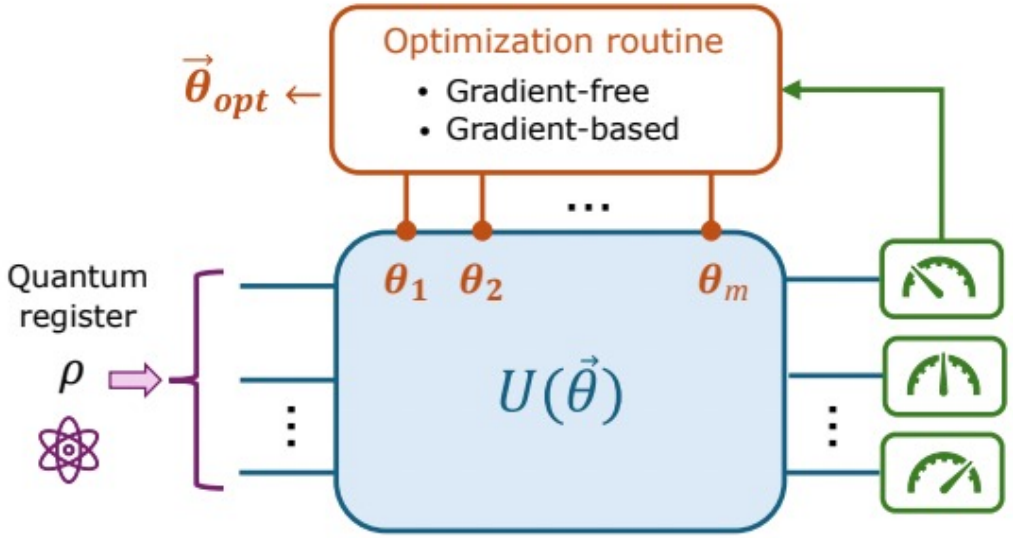
nature photonics

Article

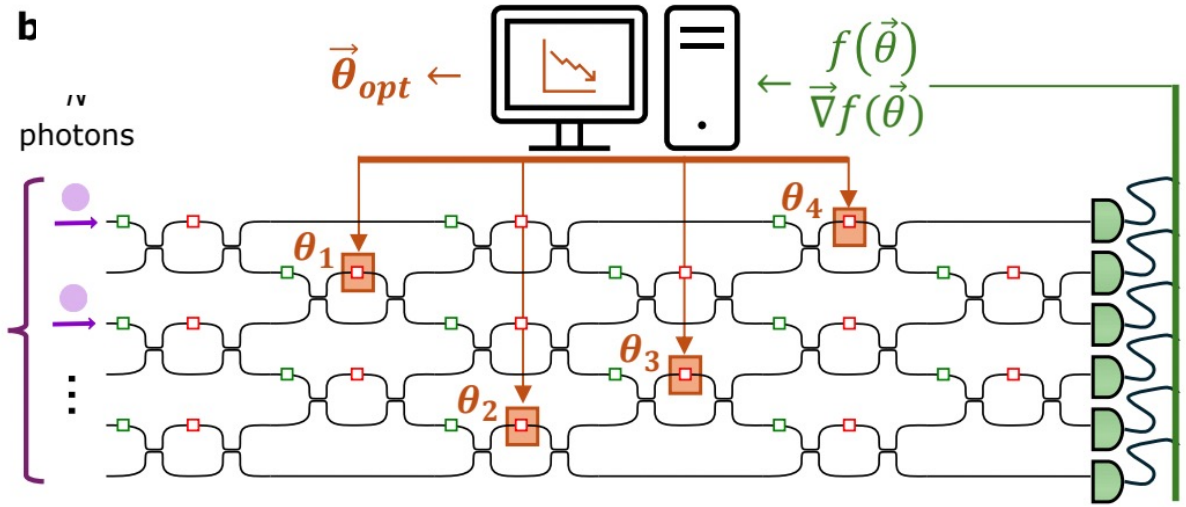
https://doi.org/10.1038/s41566-024-01526-8

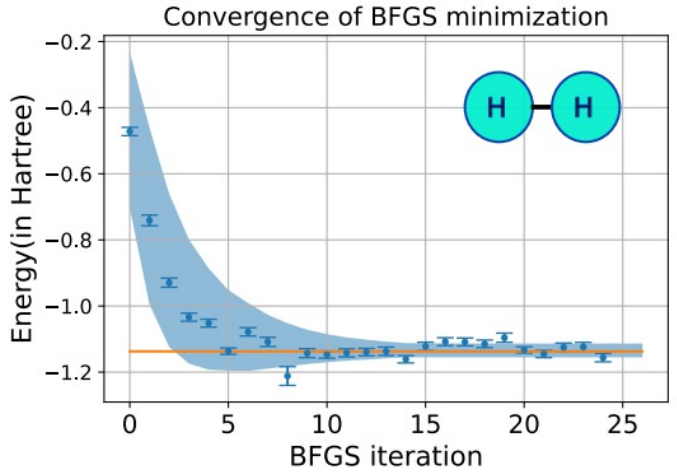
Modular quantum-to-quantum Bernoulli factory in an integrated photonic processor

Variational approach to photonic quantum circuits via the parameter shift rule



- We derive a formulation of the parameter shift rule for reconfigurable optical linear circuits based on the Boson Sampling paradigm.
- Natural embedding the common types of experimental noise, such as partial distinguishability, and mixedness of the states. Similar rules for the computations of integrals over the variational parameters.
- experimentally test variational algorithms with single-photon states processed in a reconfigurable universal integrated interferometer.





F. Hoch, et al. [arXiv:2410.06966]

QLASS

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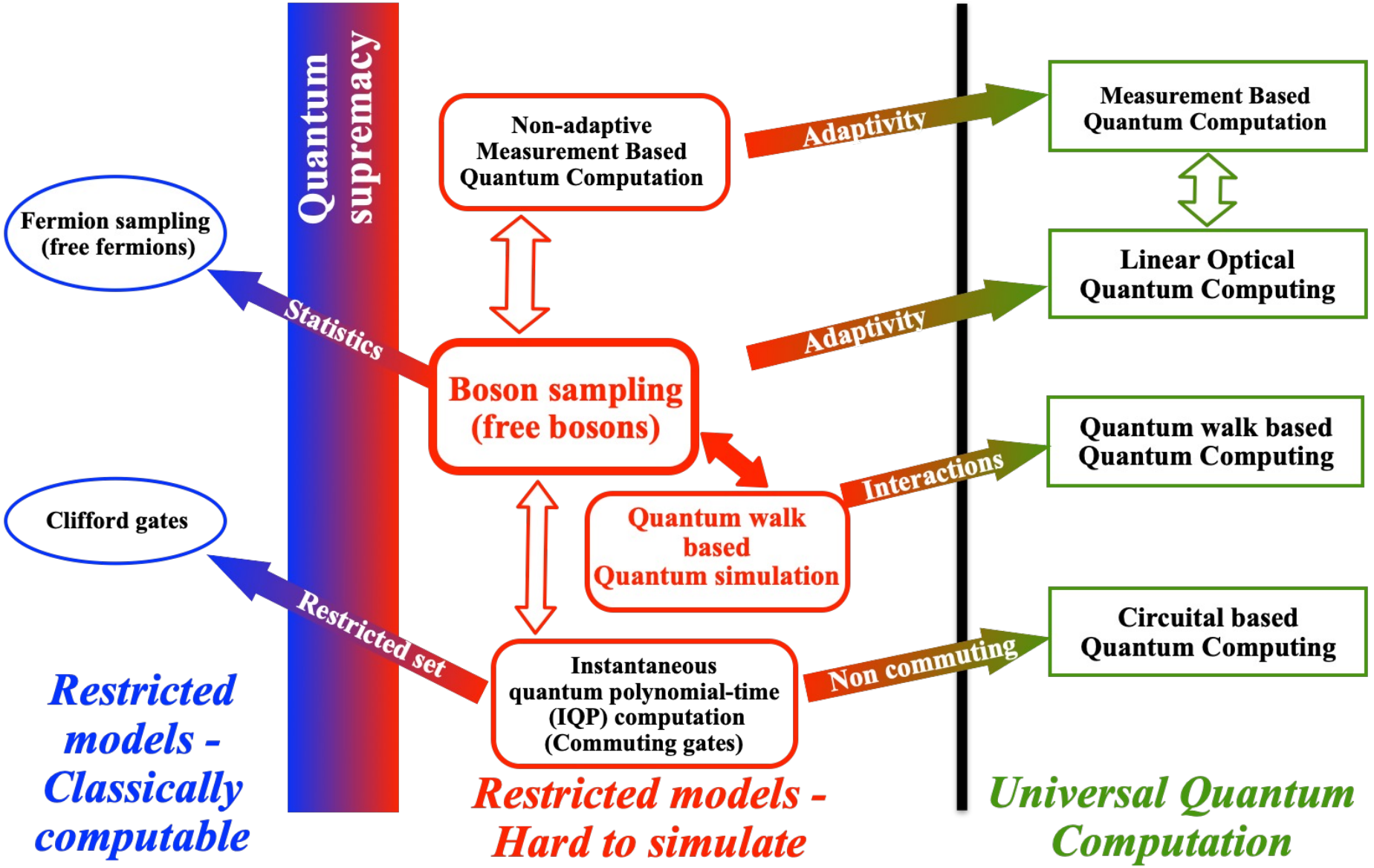
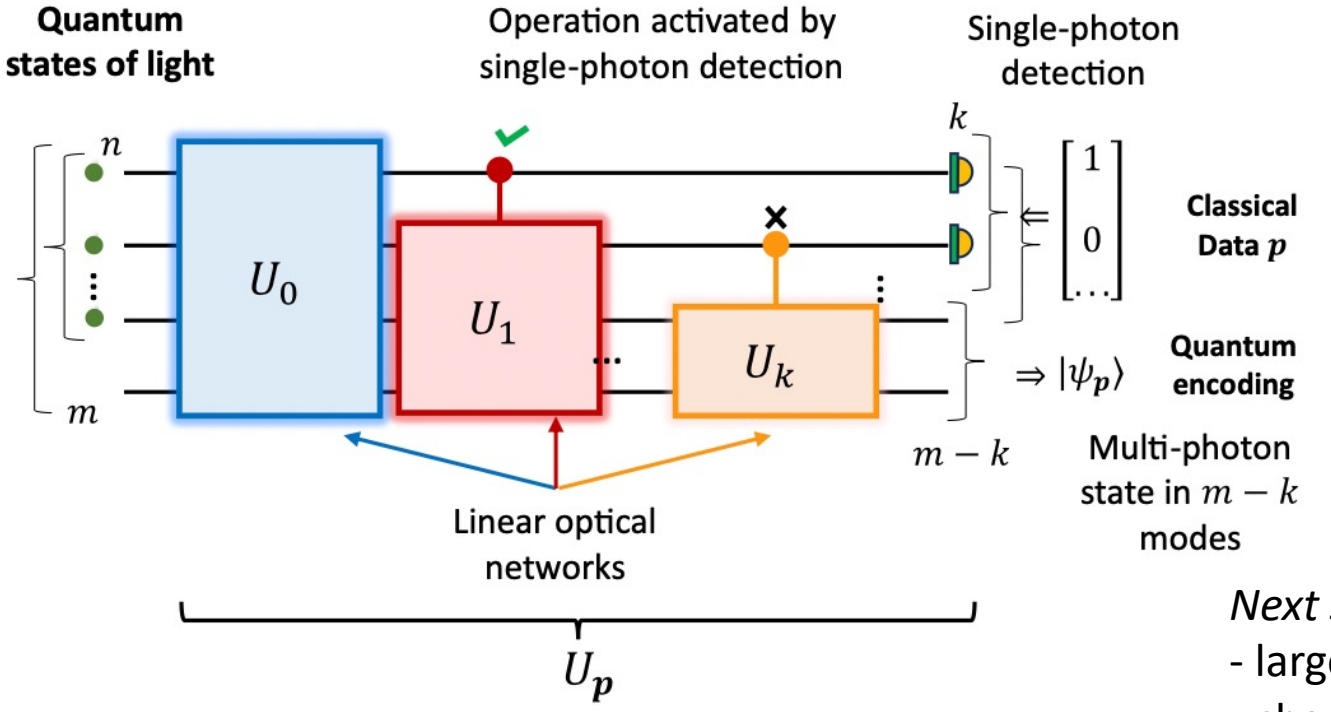
Quantum computing in photonic platforms

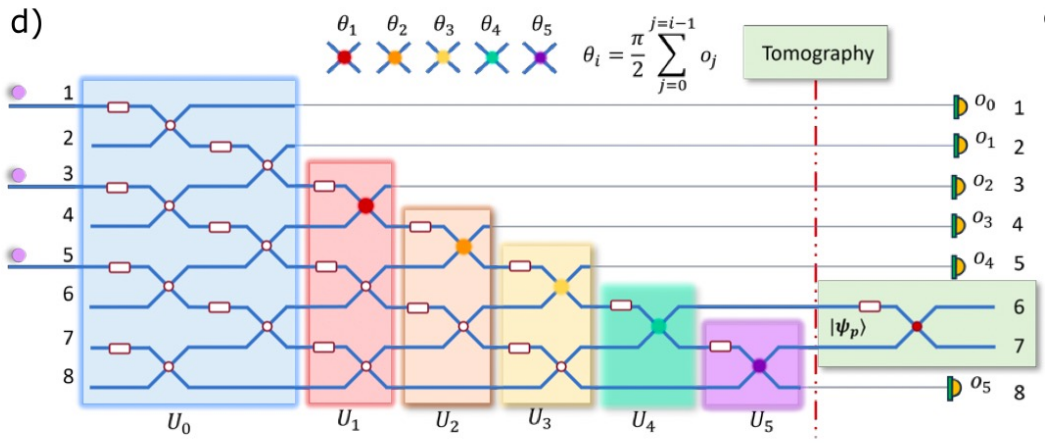


Adaptive Boson Sampling: the concept

Intermediate regime between non-universal, linear-optics-based schemes and universal computation:

Enlarging the spectrum of applications by employing intermediate measurements and adaptivity in a standard linear optical quantum experiment





Next steps:

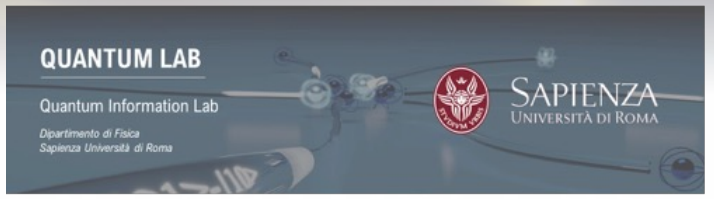
- larger number of photons/modes
- characterization of the generated output states
- realization of kernel with different features
- adoption of different learning schemes
- introduce adaptivity by fiber delay lines and multiple chips

QUANTUM LAB

Quantum Computing Lab

Dipartimento di Fisica, Università di Roma La Sapienza

SAPIENZA UNIVERSITÀ DI ROMA



QUANTUM CAUSALITY

QUANTUM FOUNDATIONS

QUANTUM ALGORITHMS

BOSON SAMPLING WITH INTEGRATED PHOTONICS

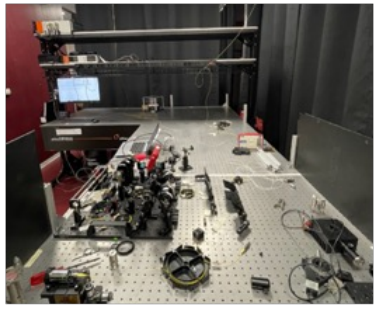
QUANTUM INTEGRATED OPTICAL SIMULATION

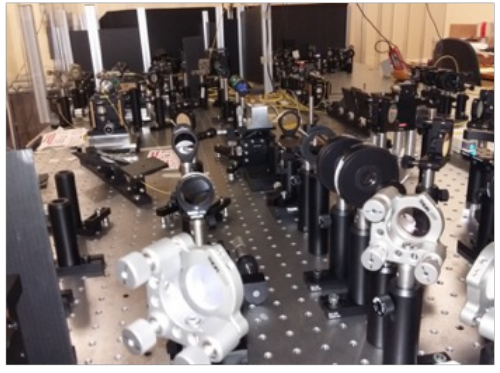
QUANTUM DOT SOURCES

PHOTONICS OF SPIN–ORBIT OPTICAL PHENOMENA

QUANTUM COMMUNICATIONS

MULTIPHASE INTEGRATED INTERFEROMETRY





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