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QUANDELA

Benasque Spring School on Near-Term Quantum Computing

Photonic circuits

Alexia Salavrakos

24-25 April 2024

@Quandela_SAS
@AlexiaSalavra

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Structure of the lectures

- Experimental components in photonics
- Linear optical quantum computing
- Designing algorithms with linear optics
- Measurement-based quantum computing and photonics

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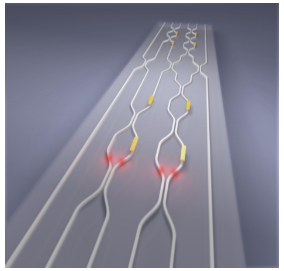
Photonic quantum computing companies

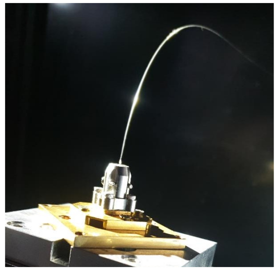
Not an exhaustive list!

Psi-Quantum
USA - 2016



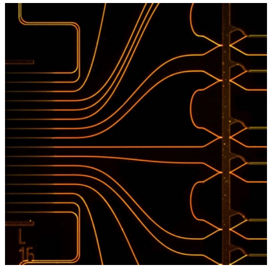
DV QC

Quandela
France - 2017



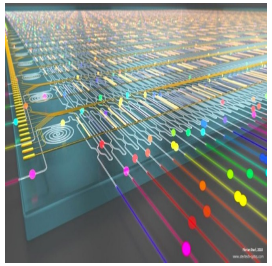
DV QC

Xanadu
Canada - 2018



Continuous variable QC

QuiX
Netherlands - 2019



SiN4 based DV QC

ORCA
UK - 2020

Memory-based QC

DV QC: discrete variable quantum computing
Information is encoded in single photons that can be in different modes (e.g. spatial or polarization)

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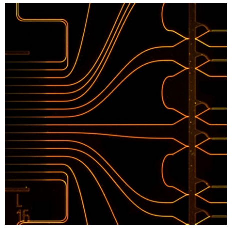
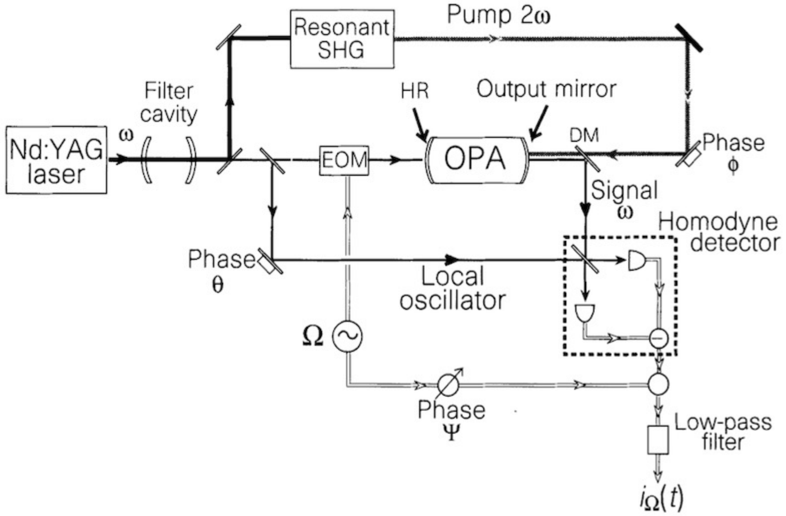
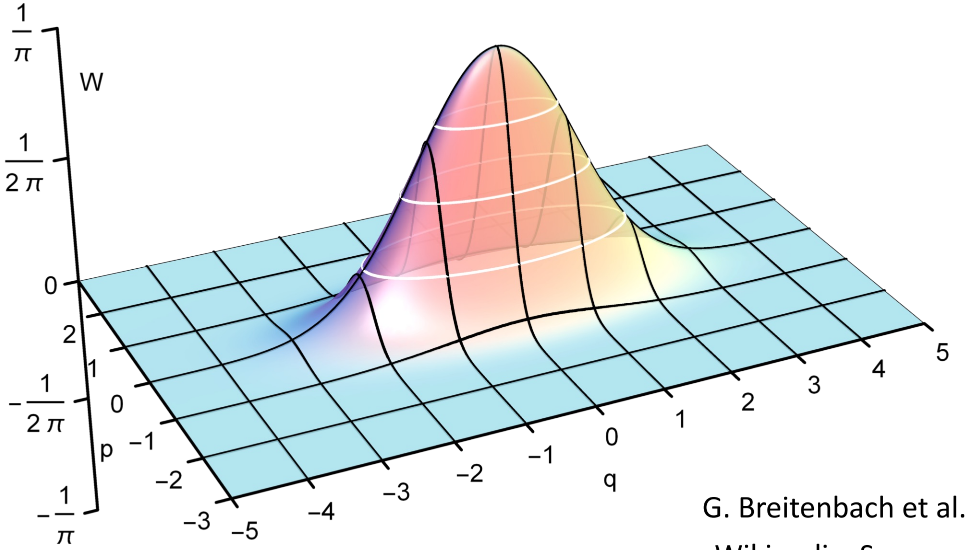
Not covered: continuous variable photonics



Qubit $$|\phi\rangle = \phi_0 |0\rangle + \phi_1 |1\rangle$$

Qumode $$|\psi\rangle = \int dx\, \psi(x) |x\rangle$$





G. Breitenbach et al. Nature 387 (1997)

Wikipedia. Squeezed coherent states.

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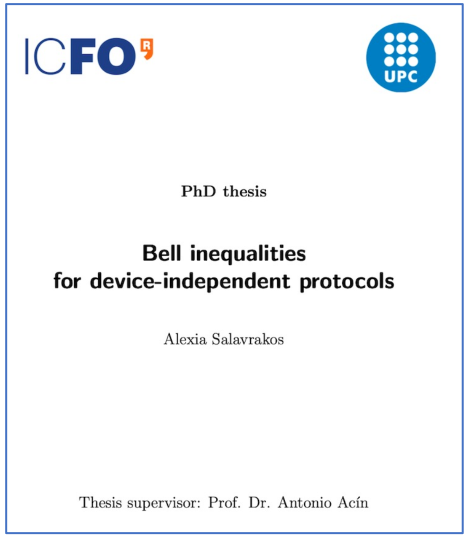
My academic and professional experience

- Studied physics at Universite Libre de Bruxelles
- PhD at ICFO in quantum correlations
- Worked for a couple of years in data science and machine learning
- Now working at Quandela
- Topics:
  - photonic quantum computing
  - quantum machine learning
  - machine learning for quantum



ICFO UPC

PhD thesis

Bell inequalities
for device-independent protocols

Alexia Salavrakos

Thesis supervisor: Prof. Dr. Antonio Acín

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Experimental components in photonics

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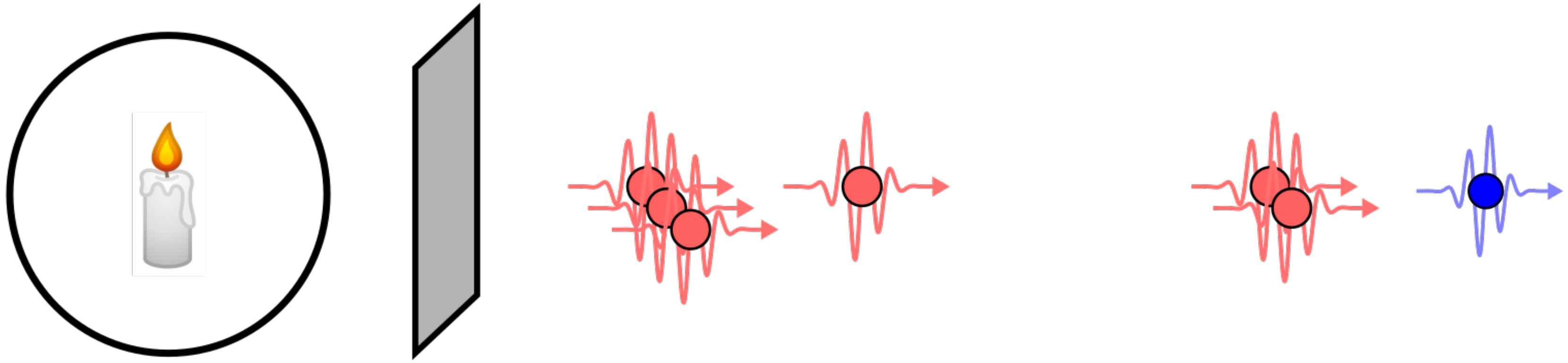
Desired properties of a single-photon source



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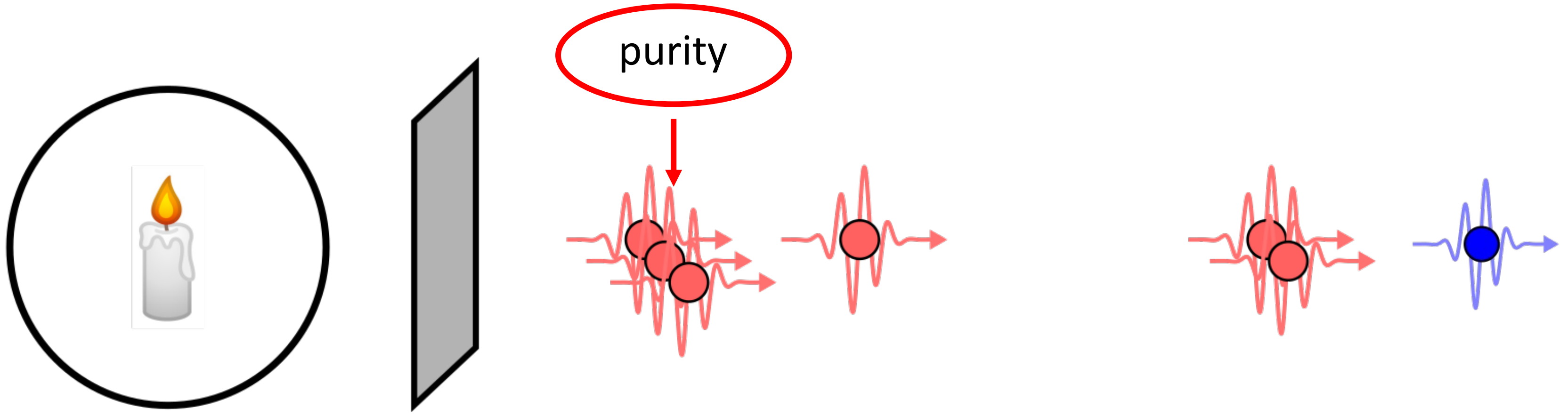

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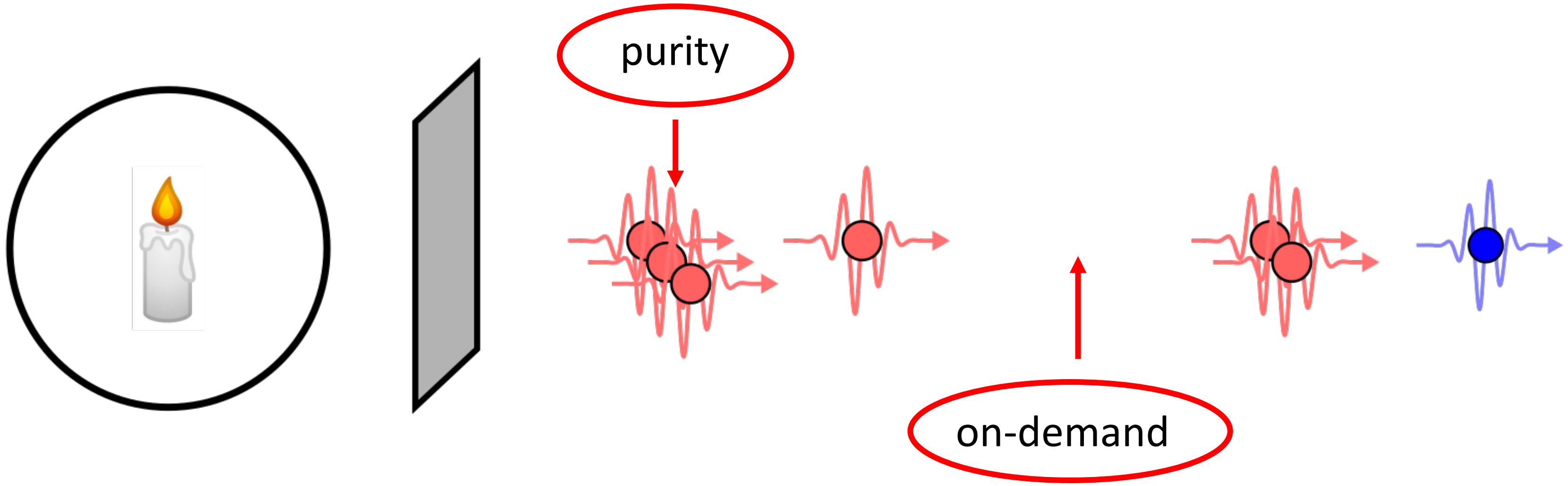

purity

on-demand

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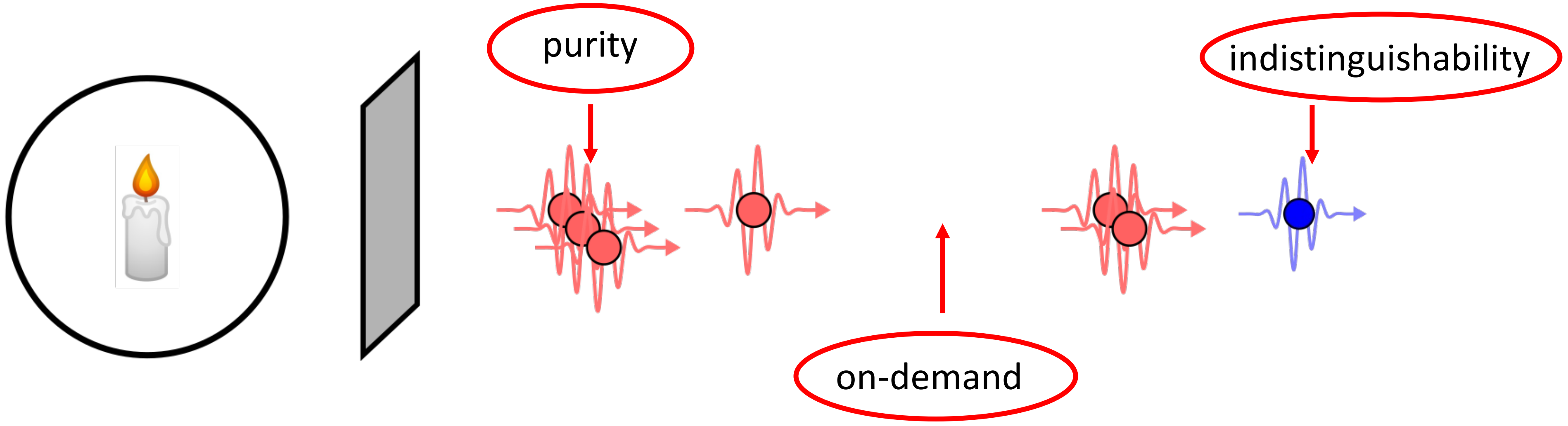
Desired properties of a single-photon source



purity

on-demand

indistinguishability

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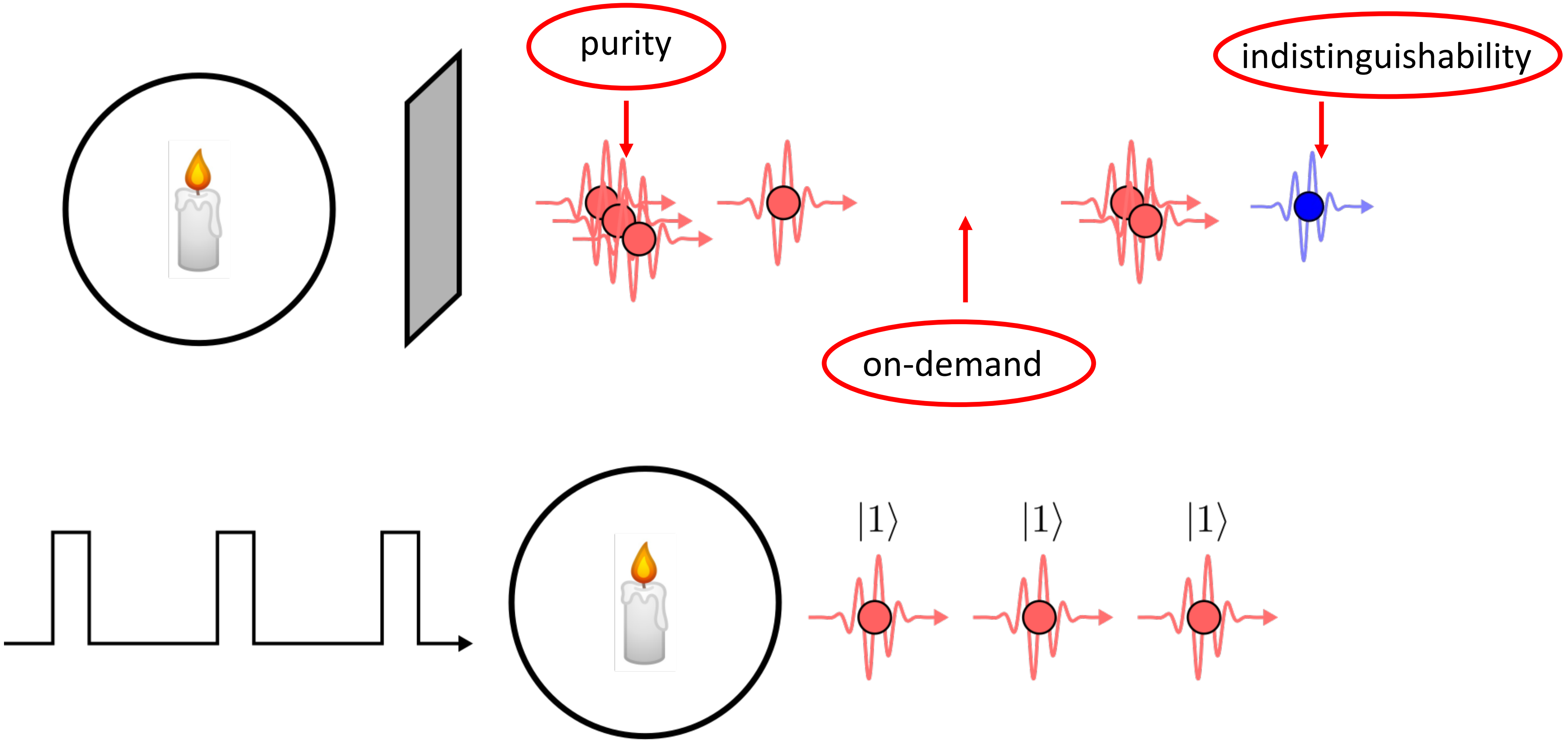
Desired properties of a single-photon source



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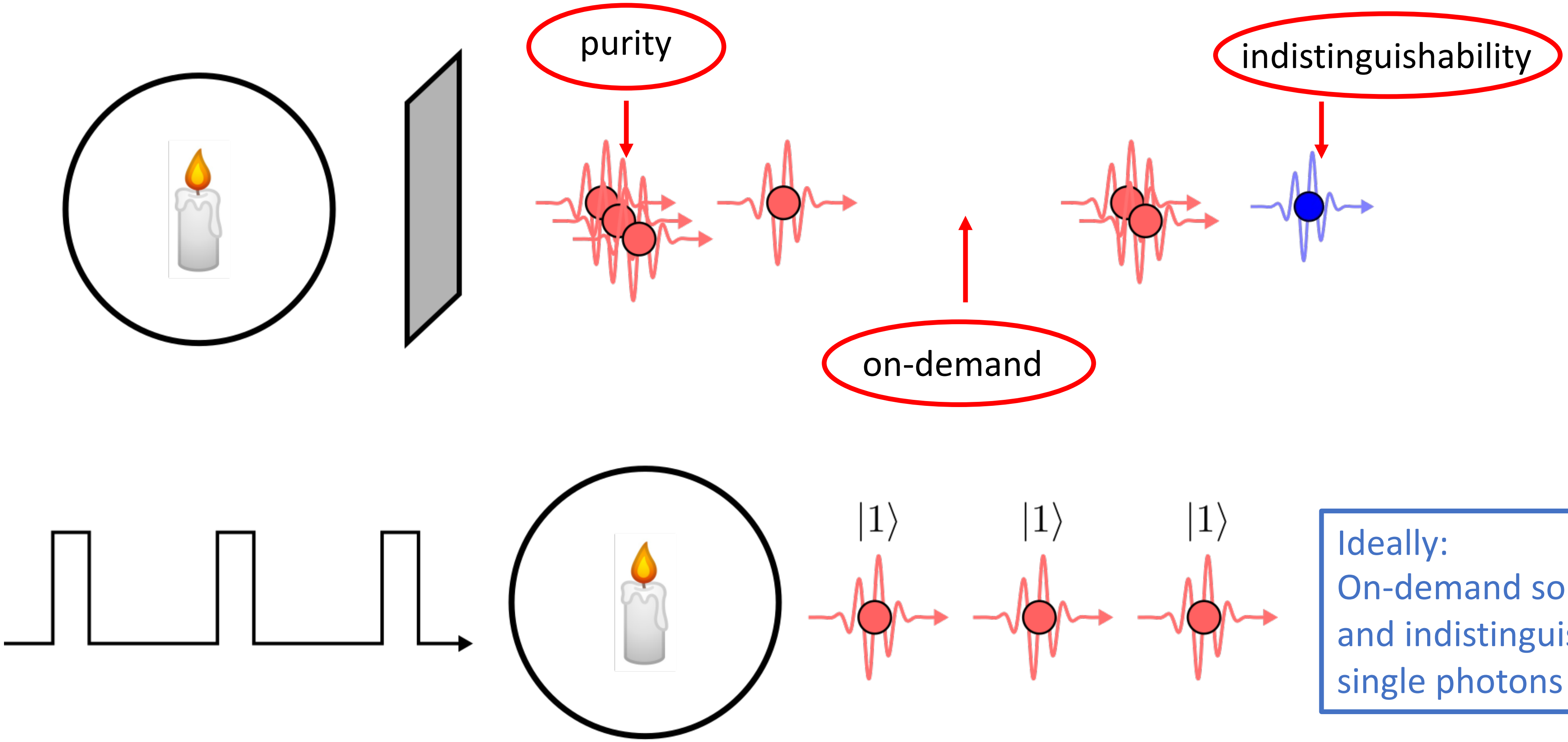
Desired properties of a single-photon source



Ideally:
On-demand source of pure and indistinguishable single photons

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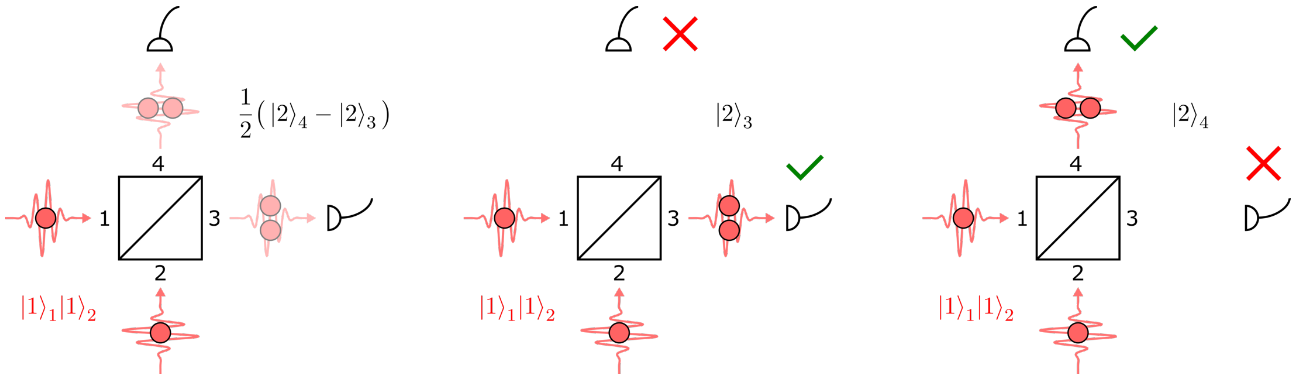
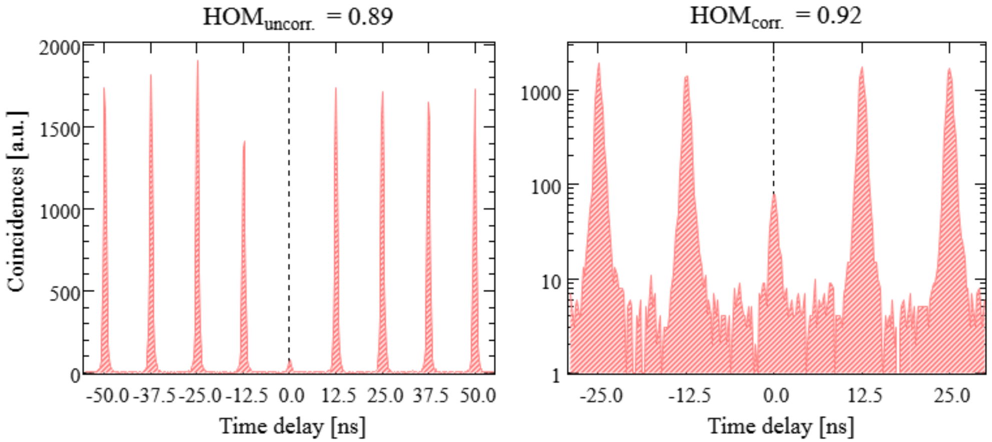
Metrics

Hong–Ou–Mandel (HOM) interference for measuring **indistinguishability**





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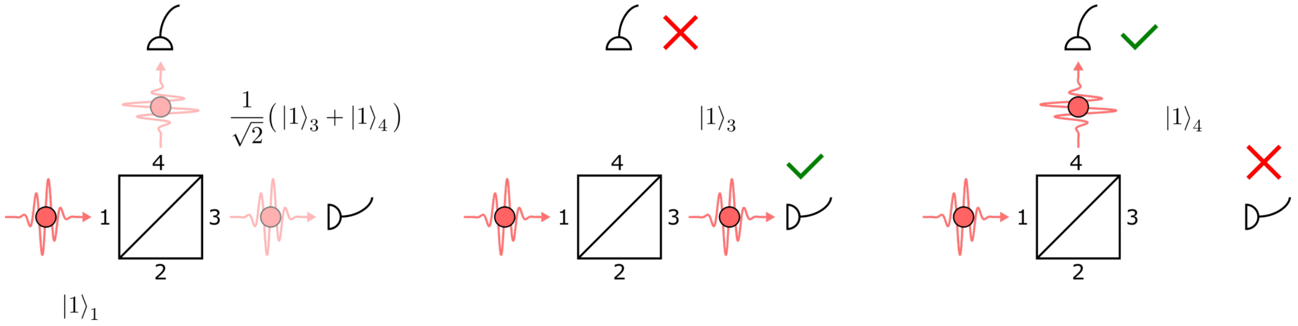
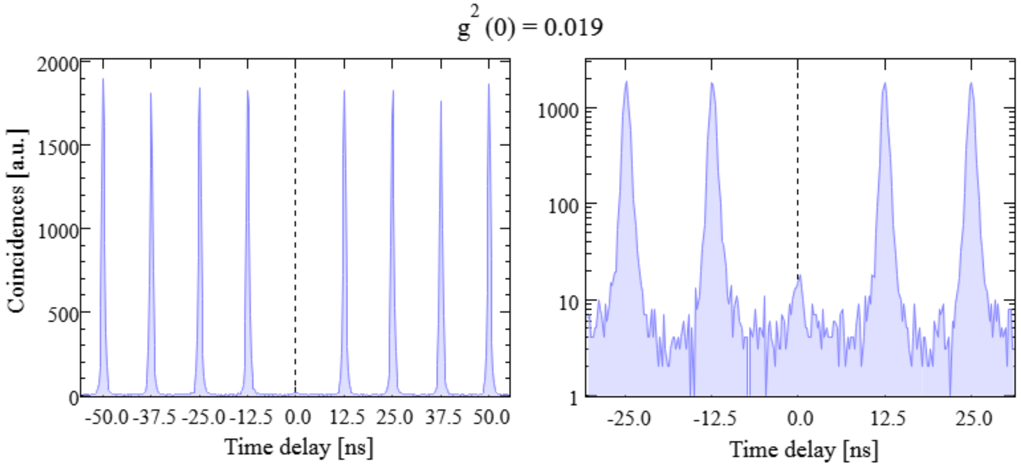
Metrics

Hanbury Brown and Twiss (HBT) effect for measuring **single photon purity**



Second order correlation function $g^2(0)$



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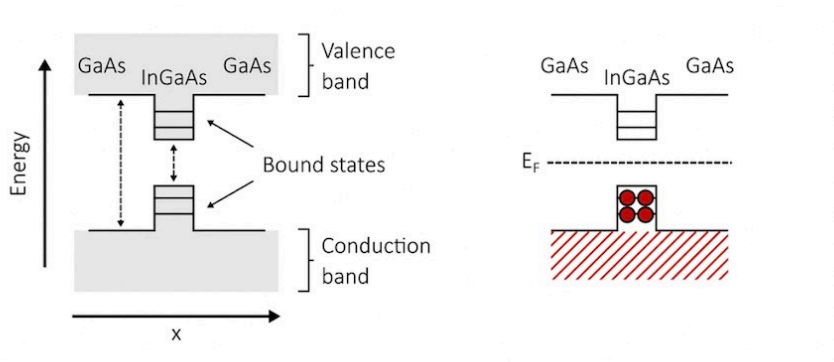
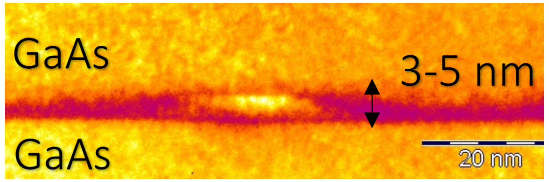
Quantum dots as single photon sources

Quantum dot



InGaAs



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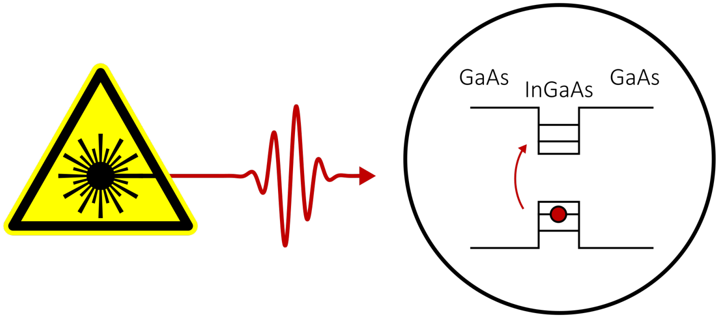
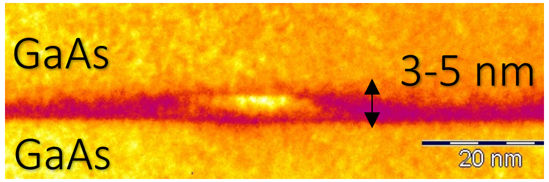
Quantum dots as single photon sources

Quantum dot



InGaAs



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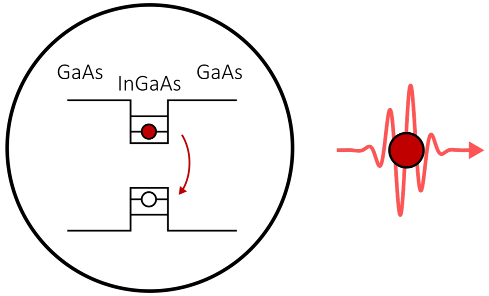
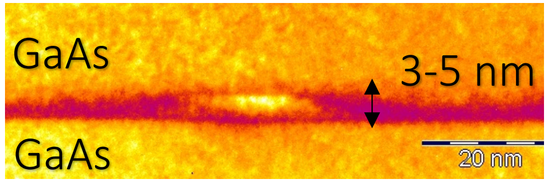
Quantum dots as single photon sources

Quantum dot



InGaAs



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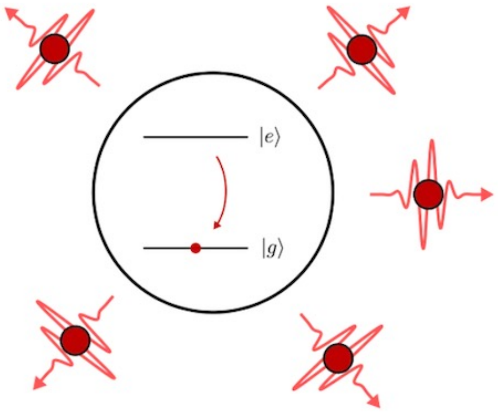
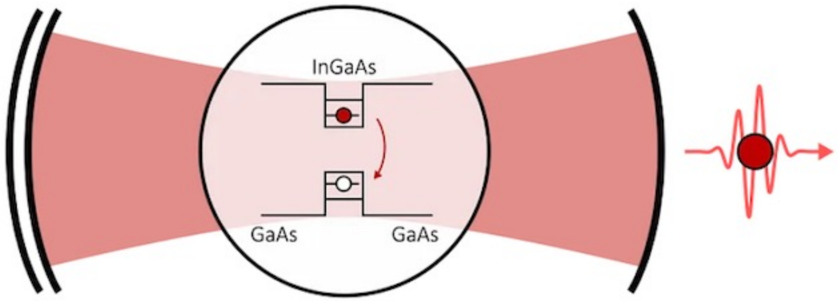
Quantum dots as single photon sources

Quantum dot in micropillar cavity





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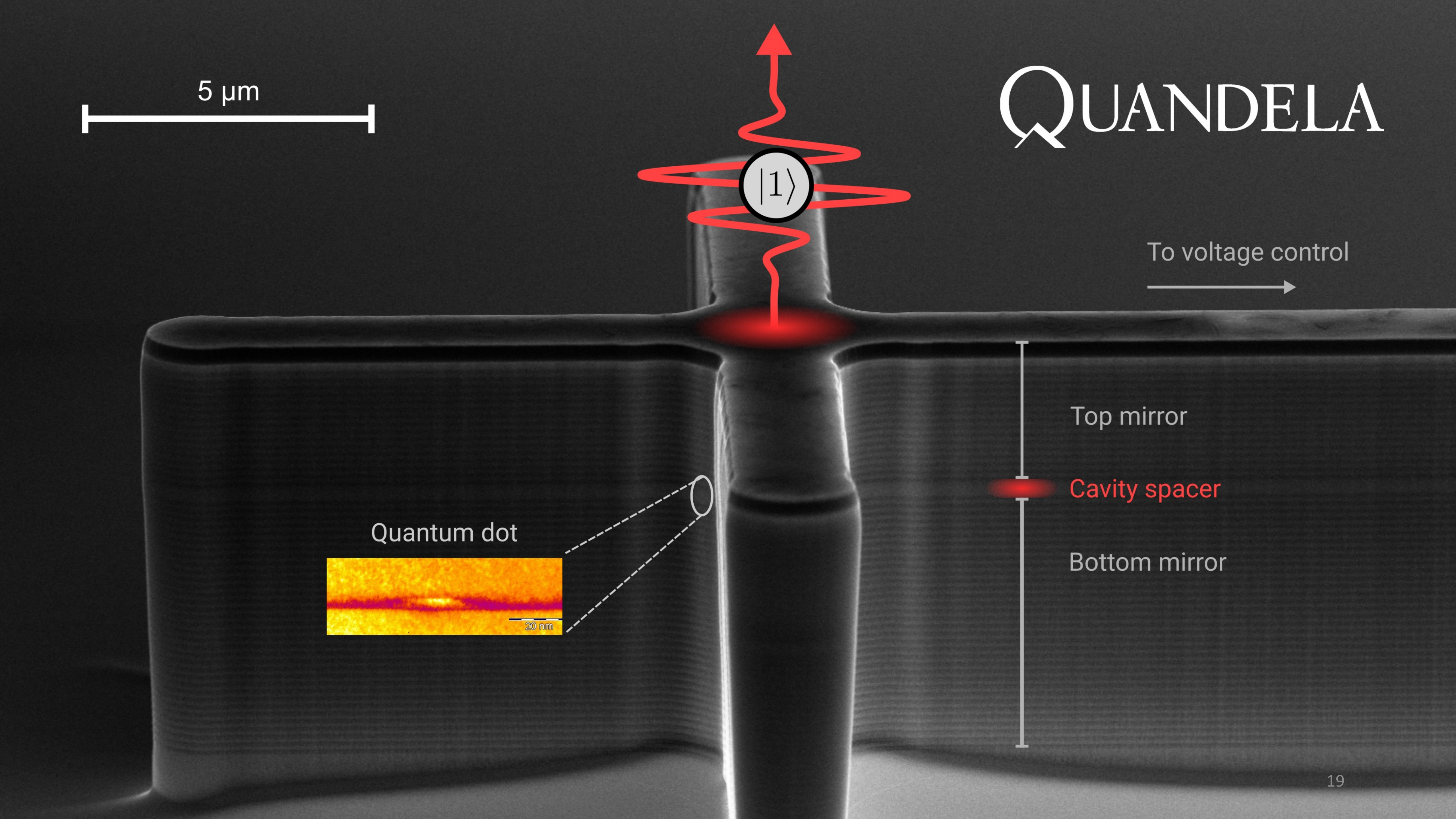
5 µm
$|1\rangle$
To voltage control
Top mirror
Cavity spacer
Bottom mirror
Quantum dot
20 nm

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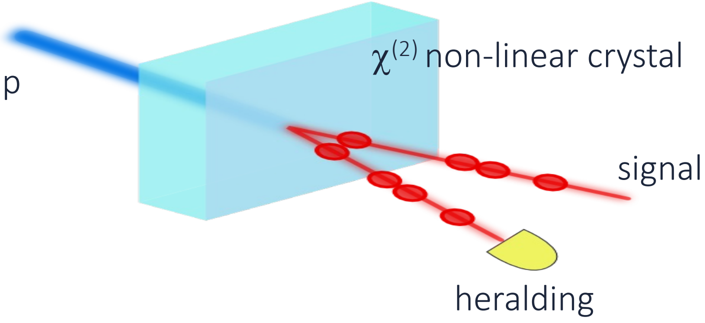
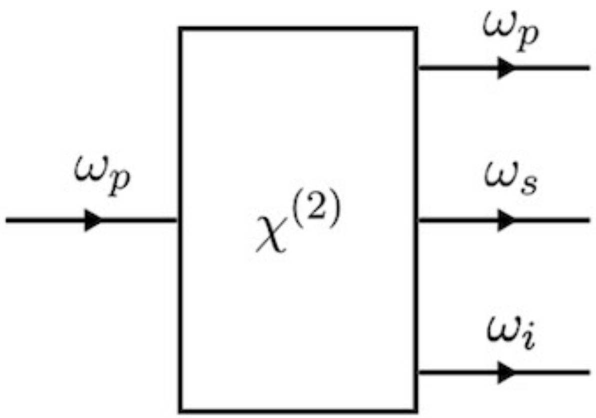
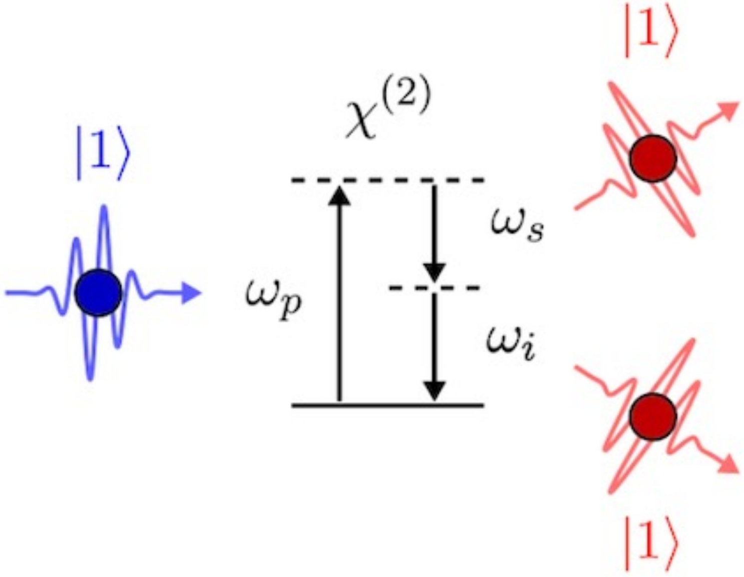
SPDC sources

SPDC: Spontaneous Parametric Down Conversion







Materials with large $\chi(2)$
LiNbO3
KTiOPO4
AlN

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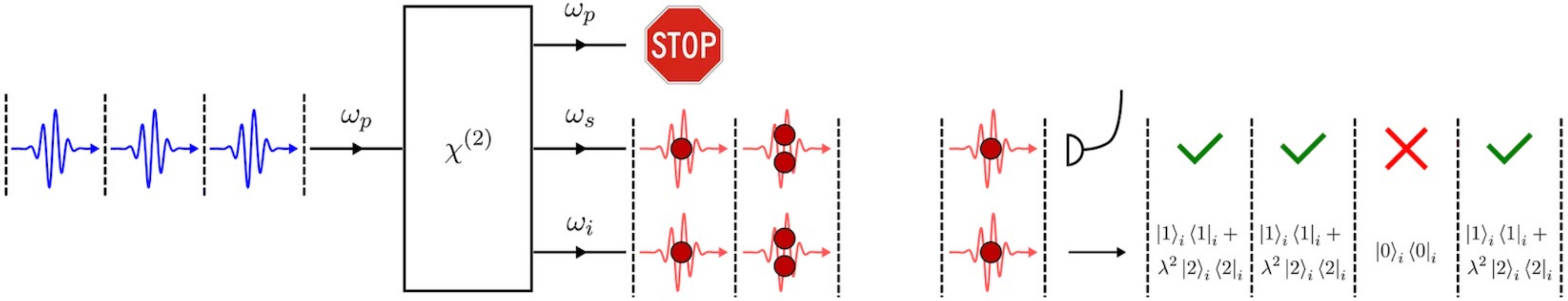
SPDC sources



Depends on $\chi(2)$ and laser power

Emitted state

$$|\Psi\rangle \approx |0\rangle_s |0\rangle_i + \lambda |1\rangle_s |1\rangle_i + \lambda^2 |2\rangle_s |2\rangle_i$$

After detection of signal photon

$$\rho_i \approx |1\rangle_i \langle 1|_i + \lambda^2 |2\rangle_i \langle 2|_i$$

$$g^{(2)} \approx \frac{2P(2)}{P(1)^2} \approx \frac{2\lambda^2}{1} = 2\lambda^2$$

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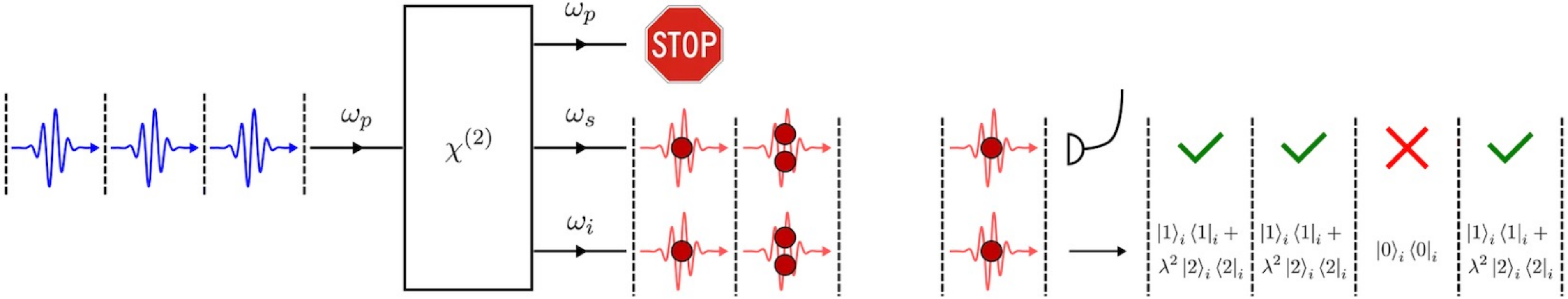
SPDC sources



Depends on $\chi(2)$ and laser power

Emitted state

$$|\Psi\rangle \approx |0\rangle_s |0\rangle_i + \lambda |1\rangle_s |1\rangle_i + \lambda^2 |2\rangle_s |2\rangle_i$$

After detection of signal photon

$$\rho_i \approx |1\rangle_i \langle 1|_i + \lambda^2 |2\rangle_i \langle 2|_i$$

$$g^{(2)} \approx \frac{2P(2)}{P(1)^2} \approx \frac{2\lambda^2}{1} = 2\lambda^2$$

Trade-off

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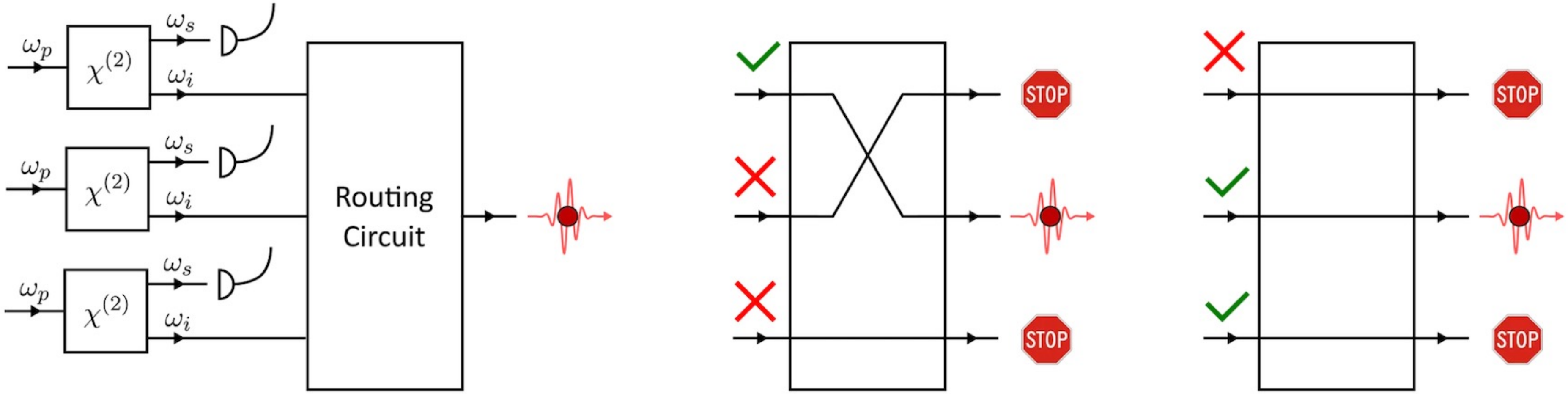
Multiplexing

Spatial multiplexing



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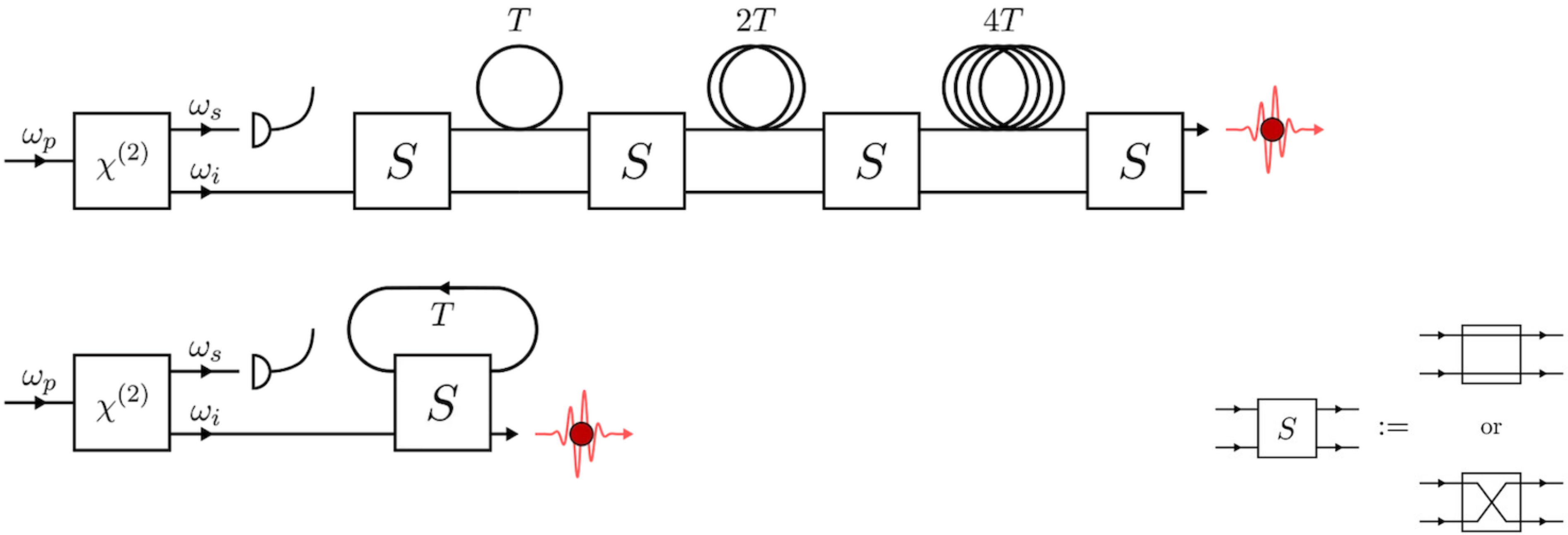
Multiplexing

Temporal multiplexing



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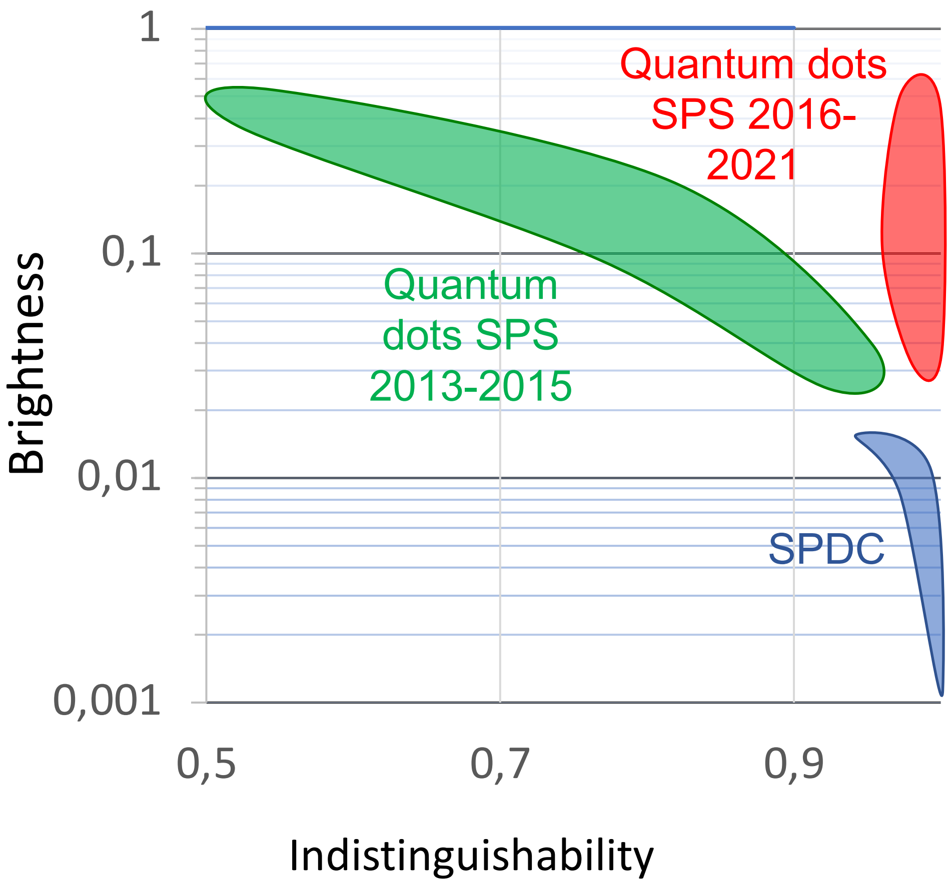
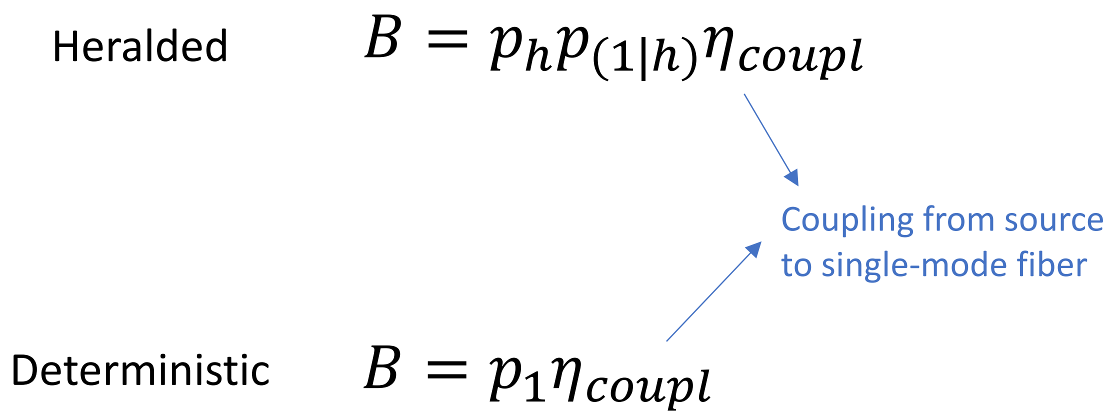
Single photon sources



Brightness metric



Heralded $B = p_h p_{(1|h)} \eta_{coupl}$

Deterministic $B = p_1 \eta_{coupl}$

Coupling from source to single-mode fiber

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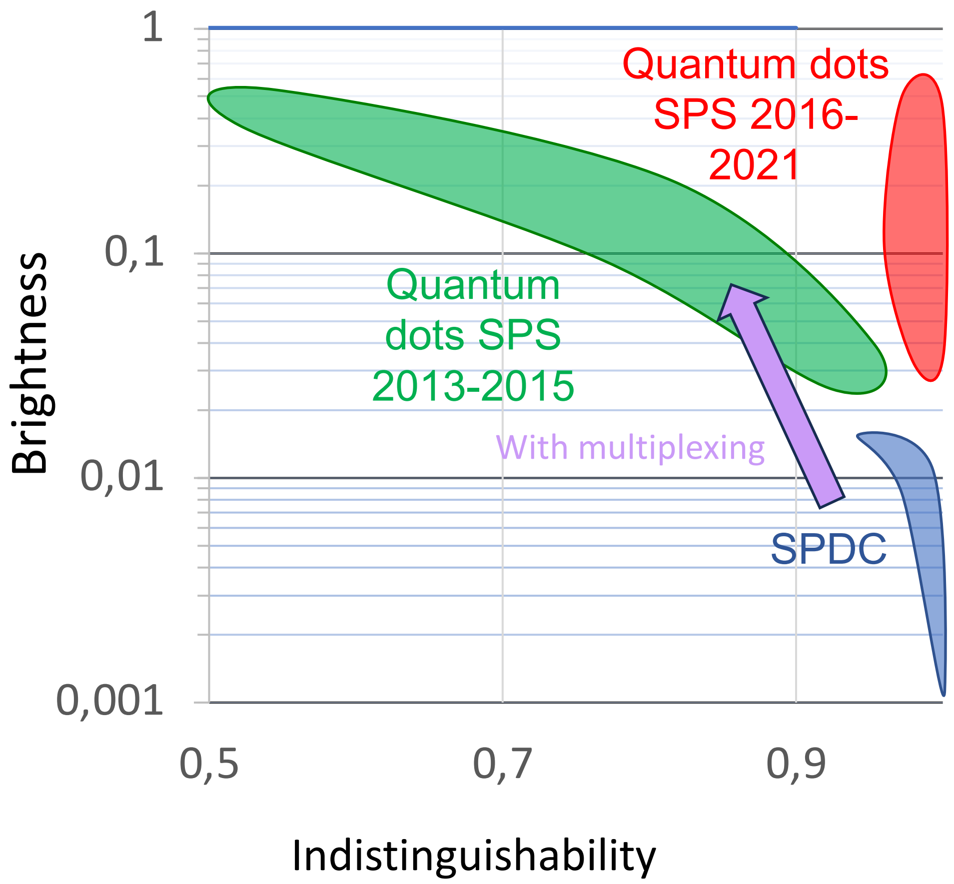
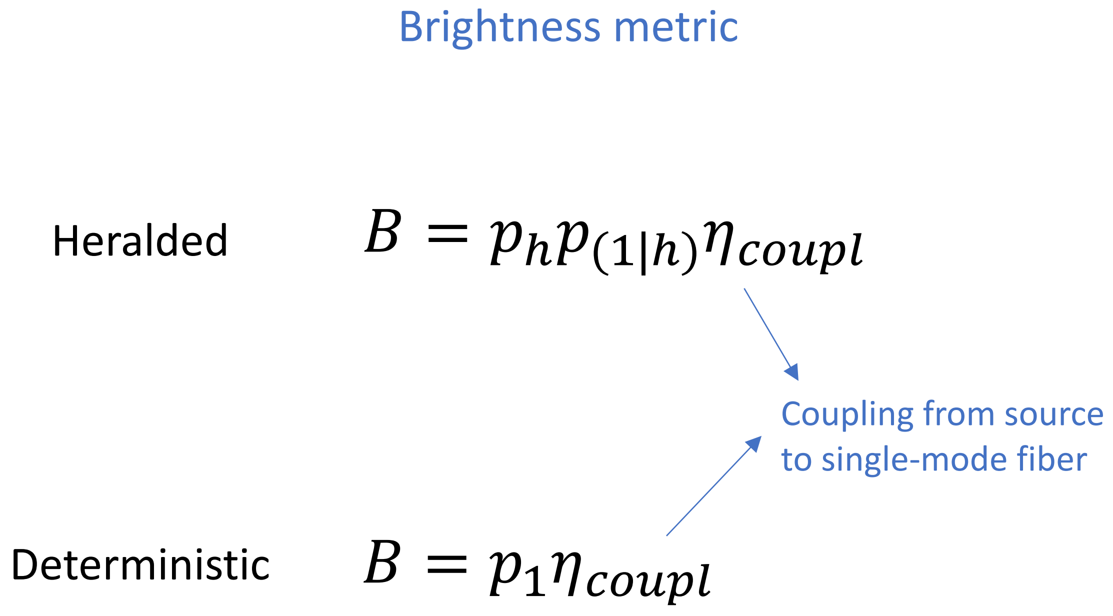
Single photon sources





Brightness metric

Heralded $$B = p_h p_{(1|h)} \eta_{coupl}$$

Deterministic $$B = p_1 \eta_{coupl}$$

Coupling from source to single-mode fiber

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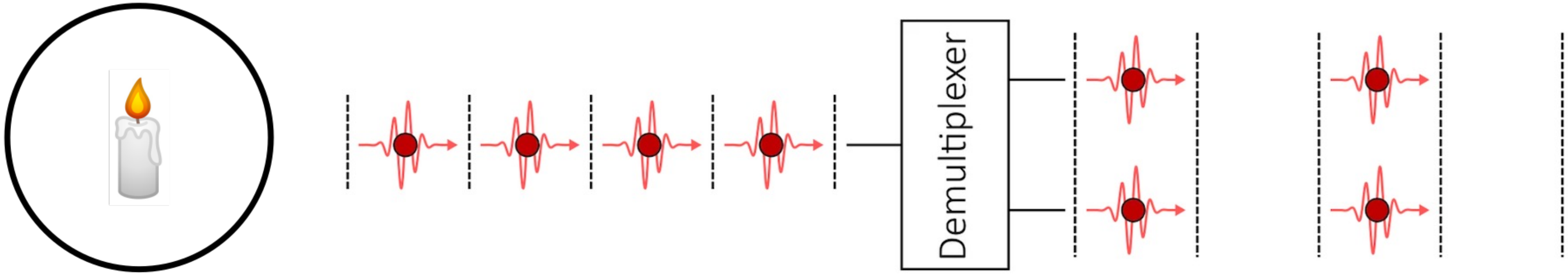
Demultiplexer for deterministic sources



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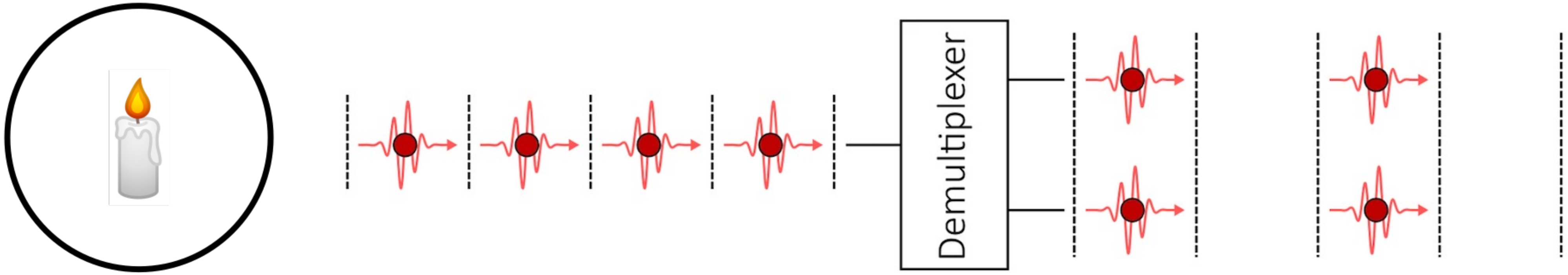
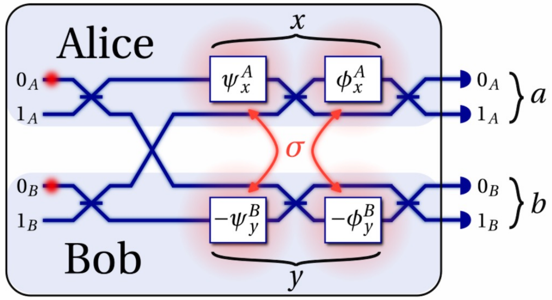
Demultiplexer for deterministic sources





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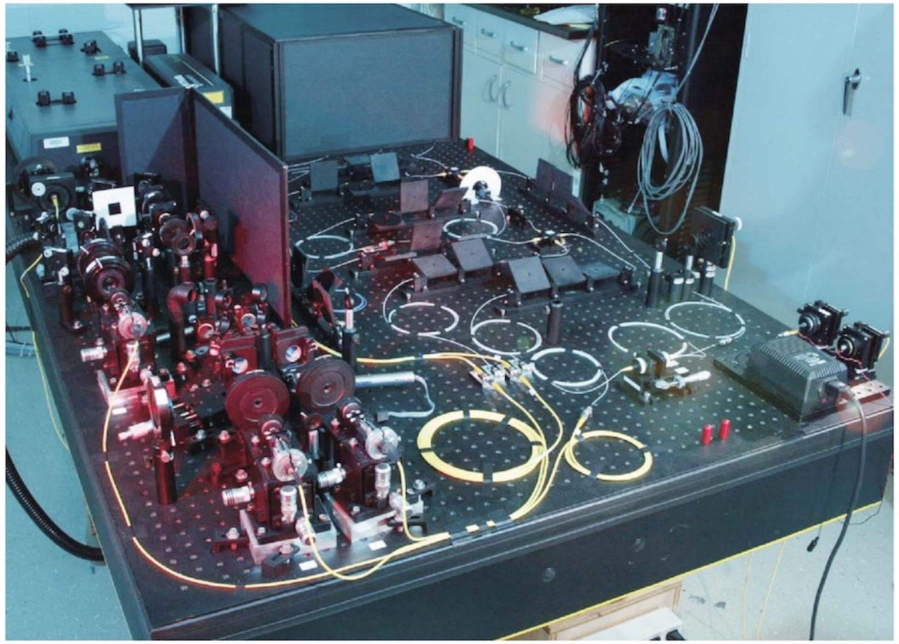
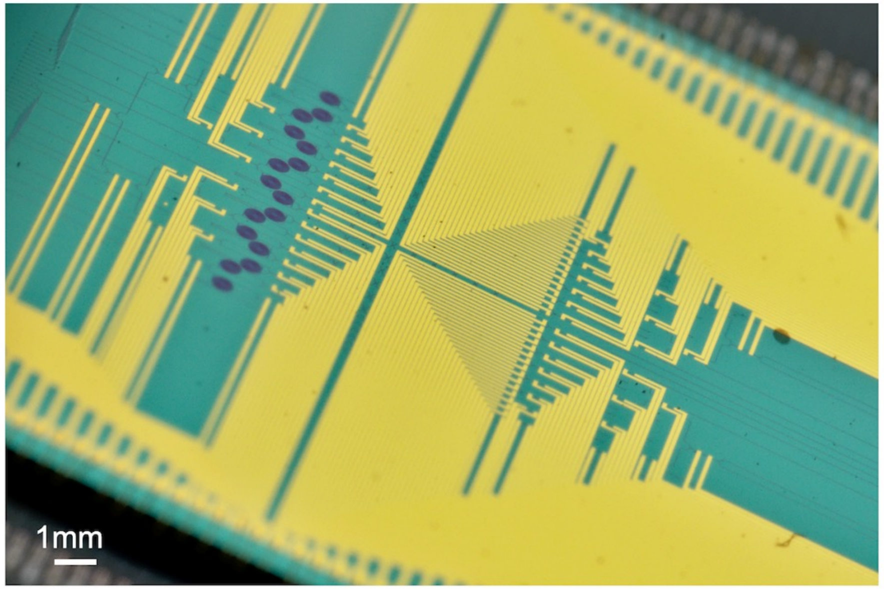
Photonic integrated chips





J. Wang et al. Science 360 (2018)

T. B. Pittman et al. Johns Hopkins APL Technical Digest 25 2 (2004)

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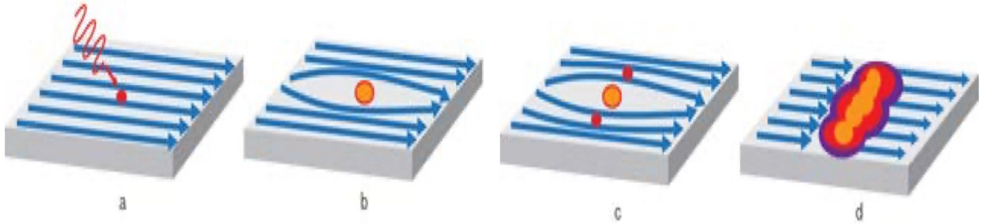
Photon detectors

Superconducting Nanowire Single Photon Detector (SNSPD)



> 95% single photon detection

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Photon detectors

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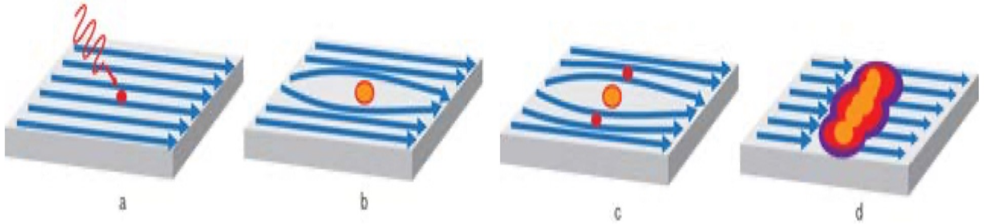

> 95% single photon detection

Photon number resolution (PNR)

Ideally: **PNR detectors**

Output states such as $|0210301\rangle$

Current technology: **threshold detectors**

Indicates click or no click

Output states such as $|0110101\rangle$

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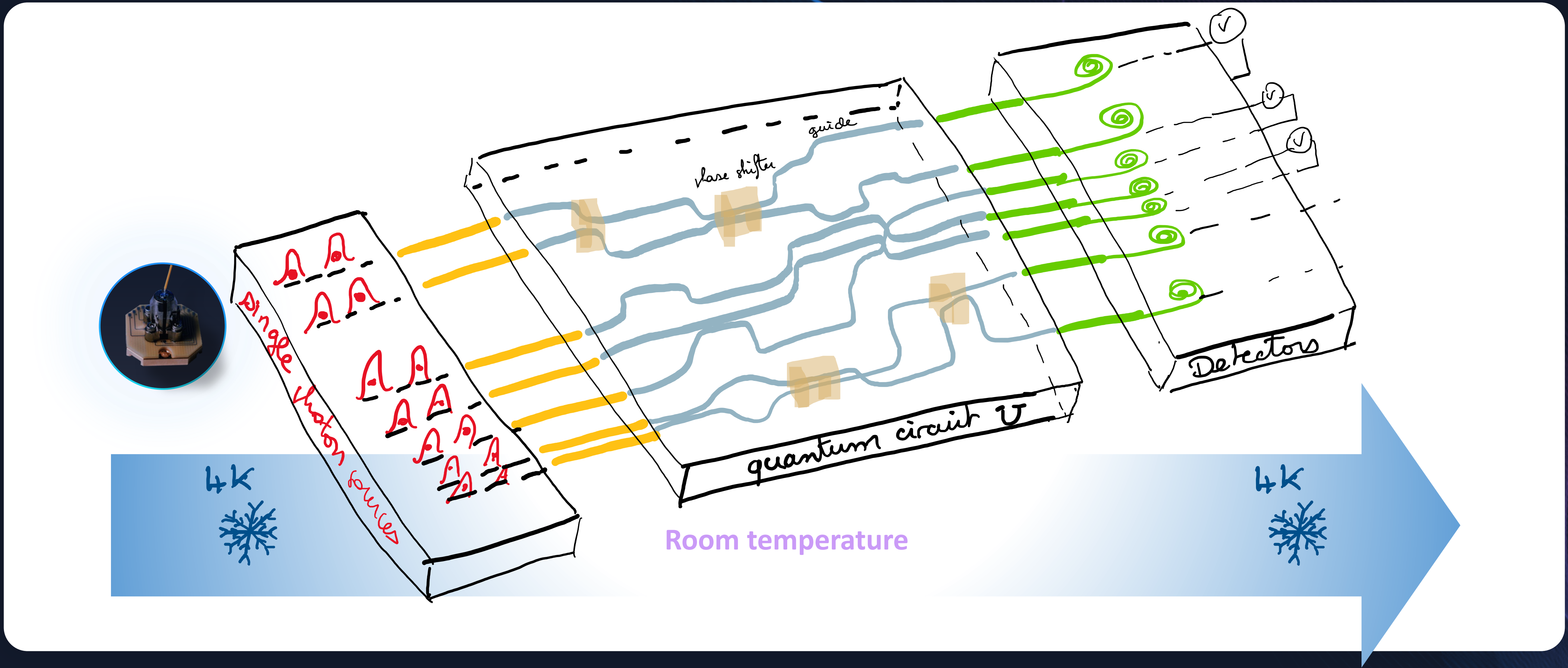
Near-term processors



Room temperature

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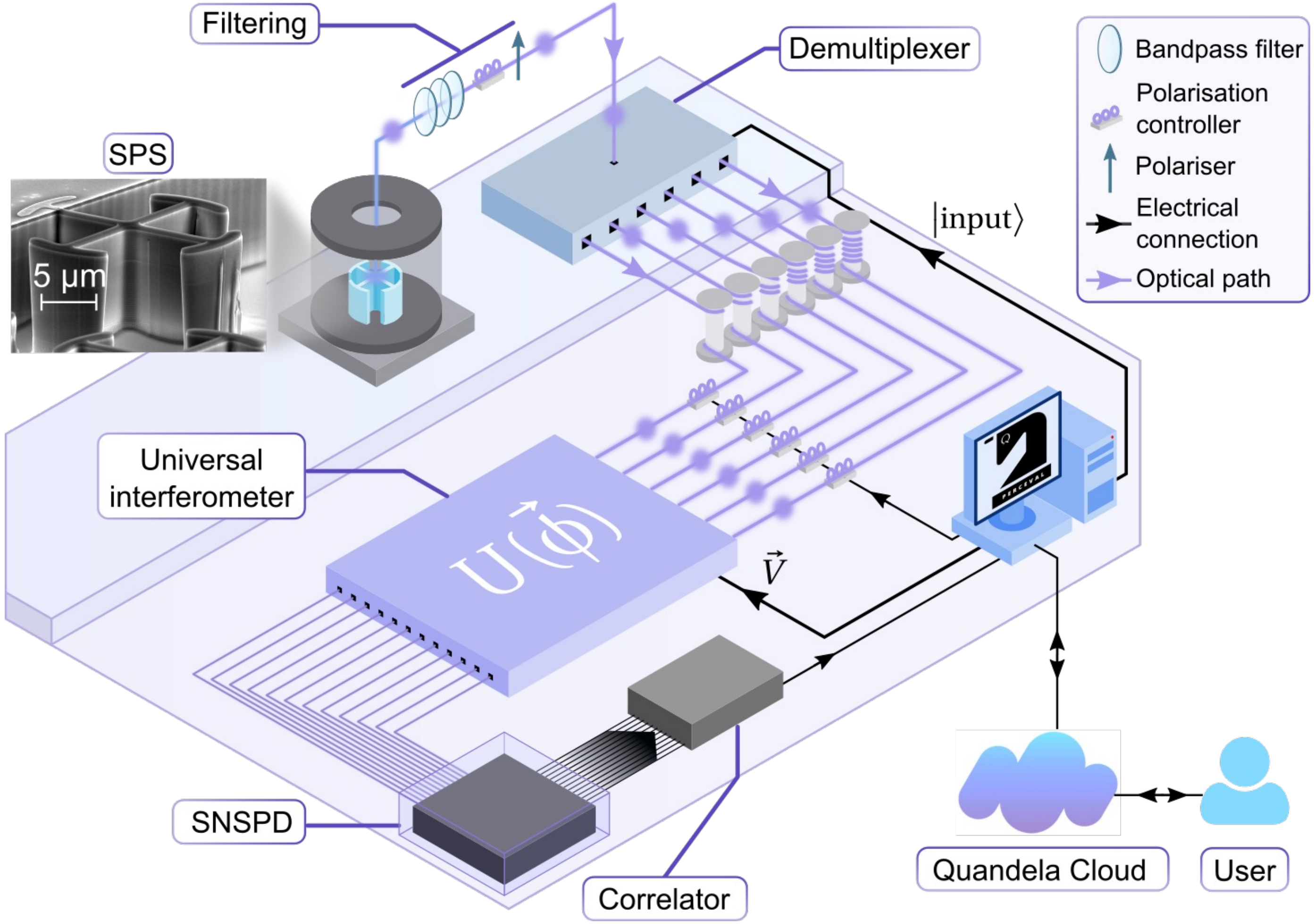
Ascella Quantum Computing Platform



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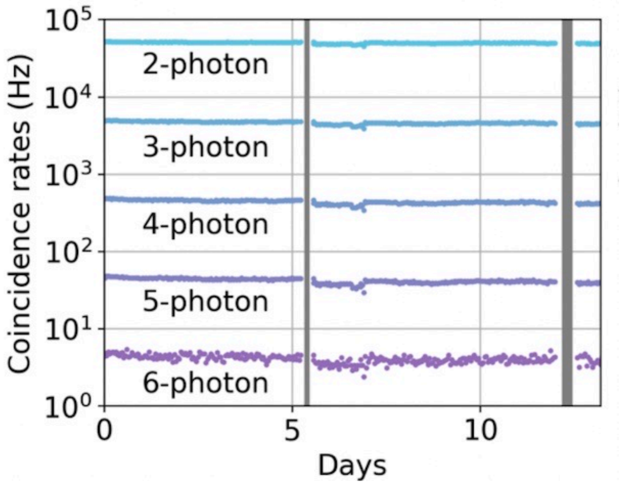
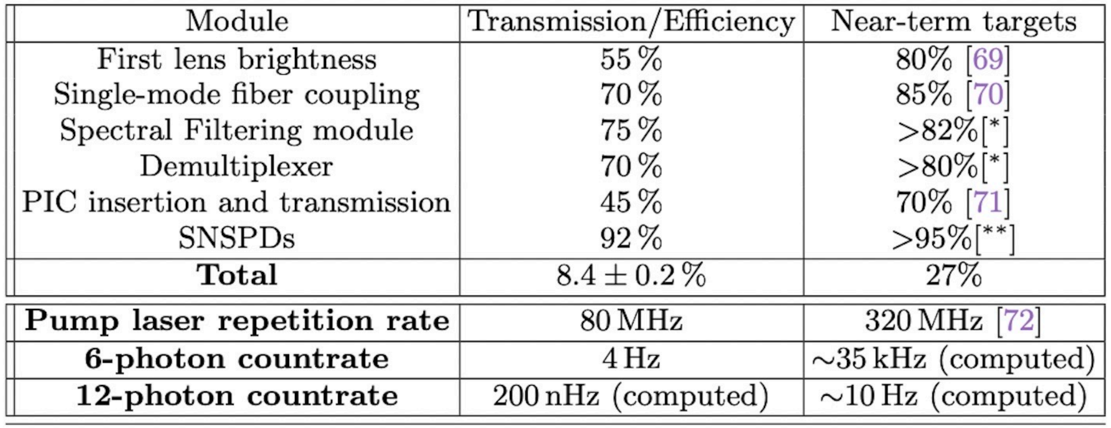
Photon loss happens throughout the setup

- Main source of noise
- Affects the whole circuit
- Exponential scaling with number of photons in an experiment





Module	Transmission/Efficiency	Near-term targets
First lens brightness	55 %	80% [69]
Single-mode fiber coupling	70 %	85% [70]
Spectral Filtering module	75 %	>82%[*]
Demultiplexer	70 %	>80%[*]
PIC insertion and transmission	45 %	70% [71]
SNSPDs	92 %	>95%[**]
Total	8.4 ± 0.2 %	27%
Pump laser repetition rate	80 MHz	320 MHz [72]
6-photon countrate	4 Hz	~35 kHz (computed)
12-photon countrate	200 nHz (computed)	~10 Hz (computed)

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QUIZZ

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Linear optical quantum computing

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What do we mean by linear optics?

- Discrete variable linear optical quantum computing (DVLOQC) uses beam splitters and phase shifters on an input of single photons to perform quantum computing.
- Fock state of n photons in a single mode : $|n\rangle$
- Fock state on m modes: $|n_1,\ldots,n_m\rangle$

$|1,0,1,0,1,1\rangle$

Input Fock state

$|1,2,0,1,0,0\rangle$

Output Fock state

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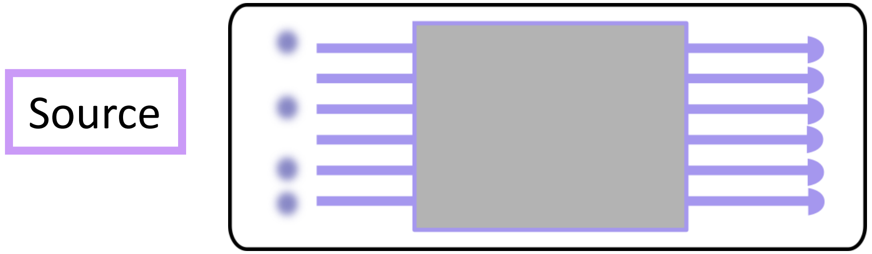
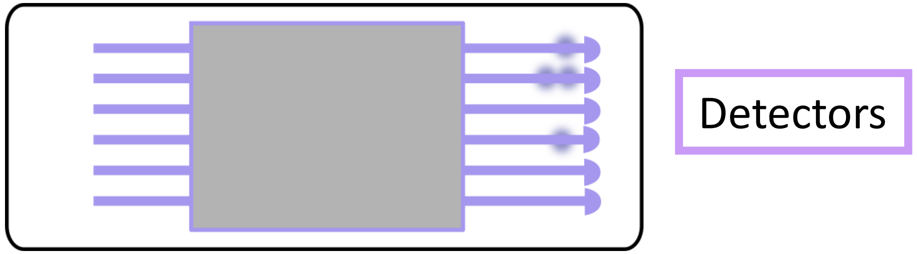


$|1,0,1,0,1,1\rangle$

Input Fock state



$|1,2,0,1,0,0\rangle$

Output Fock state

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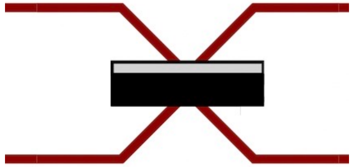
What do we mean by linear optics?

- Linear optical transformation on m modes $U \in U(m)$.
- Linear optical transformations are made of beam splitters (BS) which are $U(2)$ transformations (phases) and phase shifters (PS) which are $U(1)$ transformations.

Beamsplitter



$$\begin{bmatrix} e^{i(\phi_{tl}+\phi_{tr})}\cos\left(\frac{\theta}{2}\right) & ie^{i(\phi_{bl}+\phi_{tr})}\sin\left(\frac{\theta}{2}\right) \\ ie^{i(\phi_{tl}+\phi_{br})}\sin\left(\frac{\theta}{2}\right) & e^{i(\phi_{bl}+\phi_{br})}\cos\left(\frac{\theta}{2}\right) \end{bmatrix}$$

Phase shifter

$$\left[e^{i\phi}\right]$$

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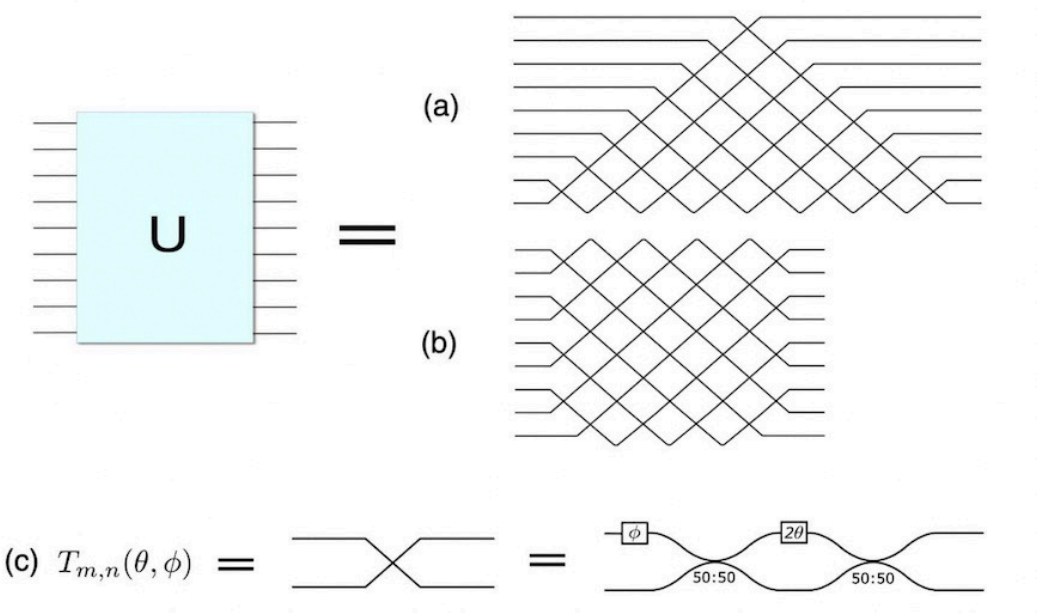
Implementing unitary transformations

Theorem by Reck et al. : for any $U \in U(m)$, there exists an m-mode linear optical circuit implementing it

Scattering mxm unitary matrix implemented with m(m-1)/2 beam splitters



M. Reck et al. *Physical Review Letters* 73, 58 (1994)

W. R. Clements et al. *Optica* 3, 12 (2016)

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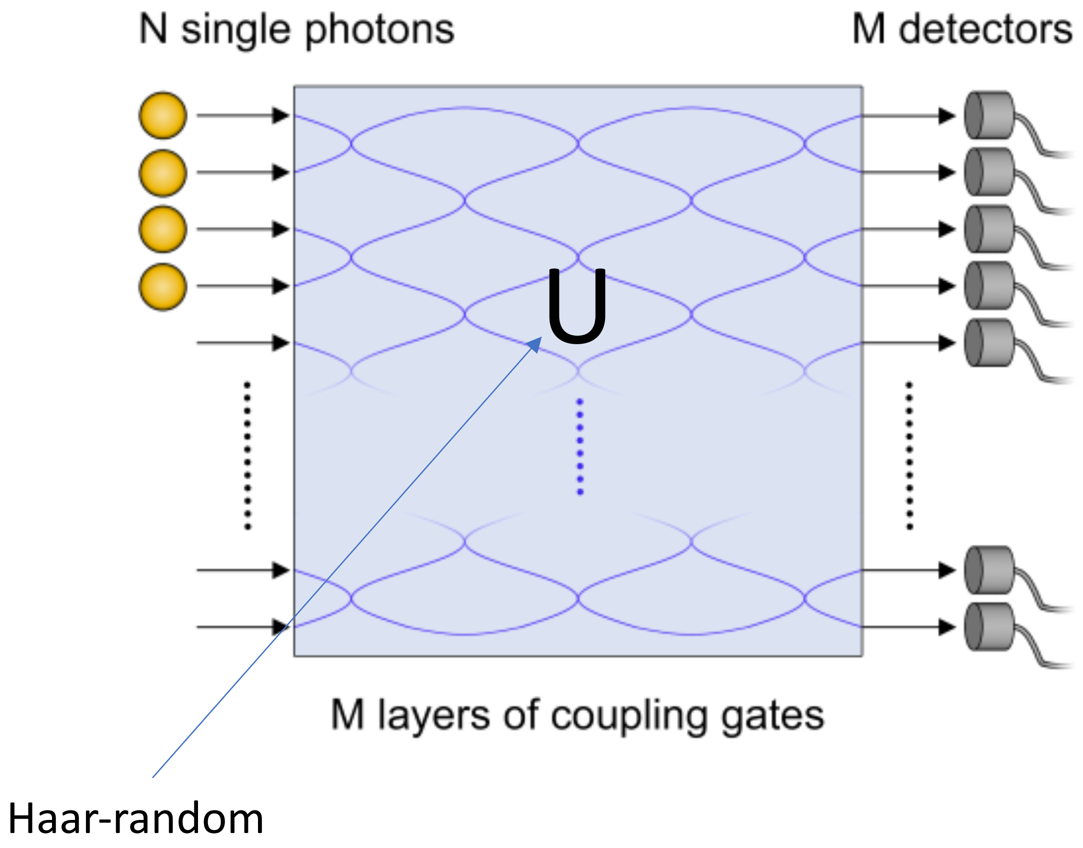
Boson Sampling



- The probability to measure an output state$|s_1, \dots s_m\rangle$ is given by $|\alpha_s|^2/s_1!\dots s_m!\, n_1!\dots n_m!$
- It can be shown that $|\alpha_s|^2$ =$|Per(U_{S,N})|^2$, $U_{S,N}$ submatrix of U determined by $S = (s_1, \dots, s_m)$ rows and N= $(n_1, \dots, n_m)$ column
- If A is an n×n matrix, $Per(A) = \sum_{\sigma\in S_n} \prod_{i=1}^{n} A_{i\sigma(i)}$
- Easy rule: like the determinant but with + signs everywhere
- The permanent, unlike the determinant, is hard to compute (best classical algorithms scale as O($n2^n$))

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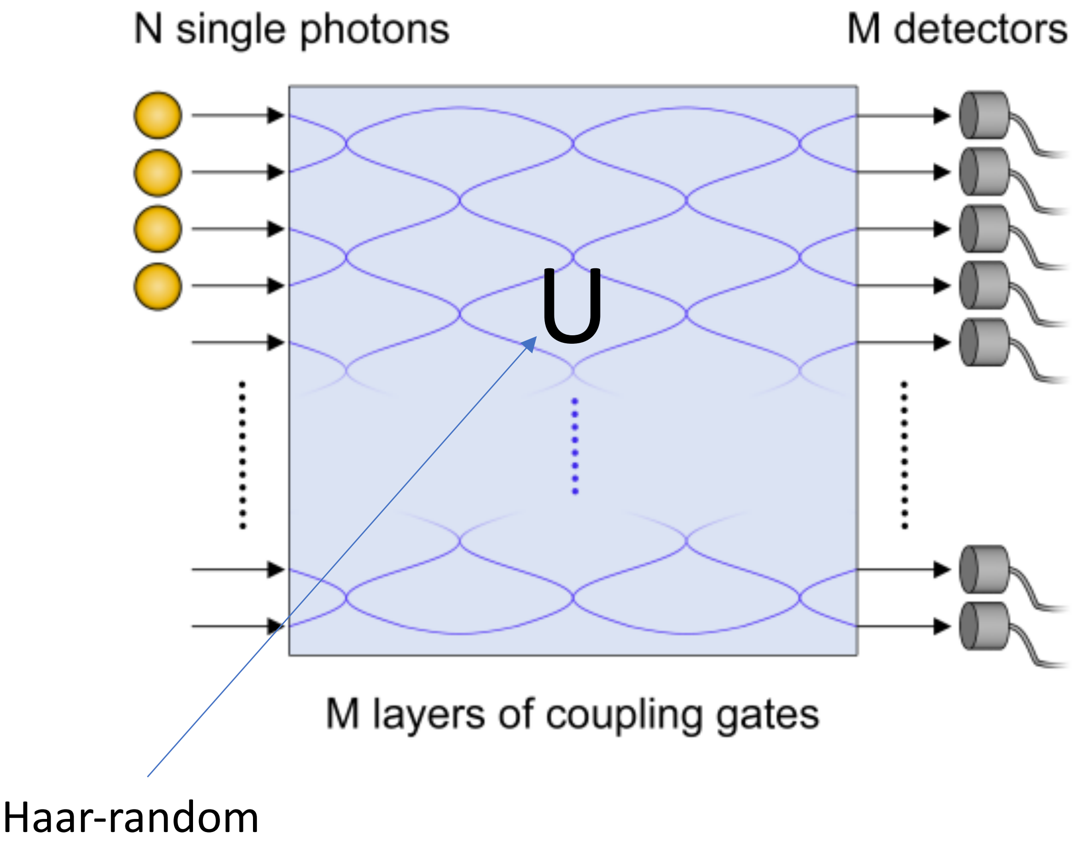
Boson Sampling



- Boson sampling task: sample from the output probability distribution of a DVLOQC circuit
- More specifically, sample outputs S from P(S)
- With P(S) ∝ $|Perm(U_{T,S})|^2$
- Hard to do classically, conditioned on some widely believed complexity theory conjectures

→ Near term demonstration of quantum advantage
→ Task may not be useful

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Boson Sampling

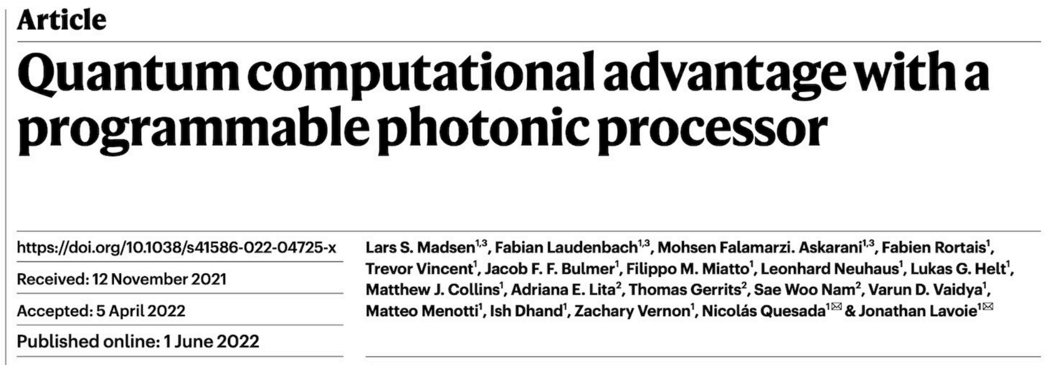
Gaussian Boson Sampling defined in continuous variable framework

RESEARCH

QUANTUM COMPUTING

Quantum computational advantage using photons

Han-Sen Zhong[1,2]*, Hui Wang[1,2]*, Yu-Hao Deng[1,2]*, Ming-Cheng Chen[1,2]*, Li-Chao Peng[1,2], Yi-Han Luo[1,2], Jian Qin[1,2], Dian Wu[1,2], Xing Ding[1,2], Yi Hu[1,2], Peng Hu[3], Xiao-Yan Yang[3], Wei-Jun Zhang[3], Hao Li[3], Yuxuan Li[4], Xiao Jiang[1,2], Lin Gan[4], Guangwen Yang[4], Lixing You[3], Zhen Wang[3], Li Li[1,2], Nai-Le Liu[1,2], Chao-Yang Lu[1,2]†, Jian-Wei Pan[1,2]†



Article

Quantum computational advantage with a programmable photonic processor

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Lars S. Madsen[1,3], Fabian Laudenbach[1,3], Mohsen Falamarzi. Askarani[1,3], Fabien Rortais[1], Trevor Vincent[1], Jacob F. F. Bulmer[1], Filippo M. Miatto[1], Leonhard Neuhaus[1], Lukas G. Helt[1], Matthew J. Collins[1], Adriana E. Lita[2], Thomas Gerrits[2], Sae Woo Nam[2], Varun D. Vaidya[1], Matteo Menotti[1], Ish Dhand[1], Zachary Vernon[1], Nicolás Quesada[1]✉ & Jonathan Lavoie[1]✉

Original Boson Sampling article

The Computational Complexity of Linear Optics

Scott Aaronson* Alex Arkhipov†

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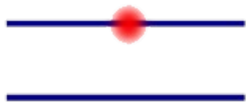
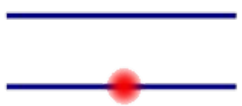
Qubits and logical gates with linear optics

Choose an encoding

$|0\rangle_{qubit} \coloneqq |1,0\rangle$ $\qquad$ $|1\rangle_{qubit} \coloneqq |0,1\rangle$

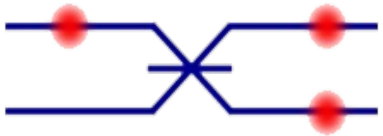
Dual rail





One qubit gates

$|0\rangle \rightarrow |0\rangle + |1\rangle$



Beamsplitter

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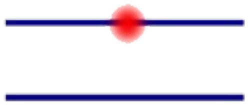
Qubits and logical gates with linear optics

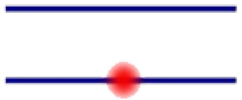
Choose an encoding

$|0\rangle_{qubit} \coloneqq |1,0\rangle$

$|1\rangle_{qubit} \coloneqq |0,1\rangle$

Dual rail

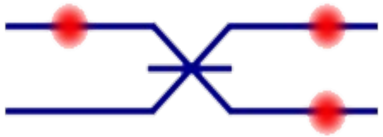




Other encodings are possible, like polarization

One qubit gates

$|0\rangle \rightarrow |0\rangle + |1\rangle$



Beamsplitter

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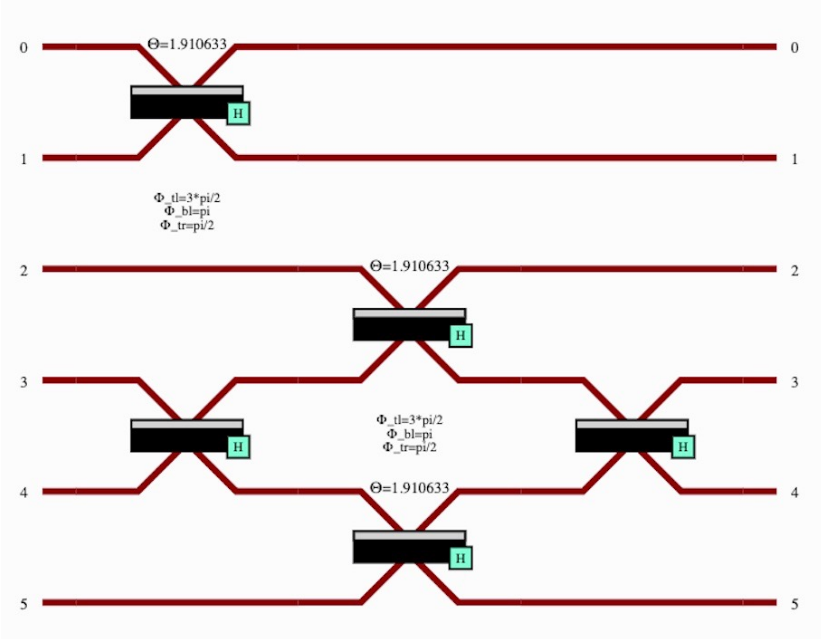
Qubits and logical gates with linear optics

However, some two-qubit gates cannot be achieved deterministically with passive linear optics

Options:

- Nonlinearities (materials unavailable)
- Post-selection (probabilistic)
- Heralding (probabilistic)
- Feedforward

Example: post-selected CNOT gate



Ralph, Timothy C., et al. *Physical Review A* 65.6 (2002): 062324.

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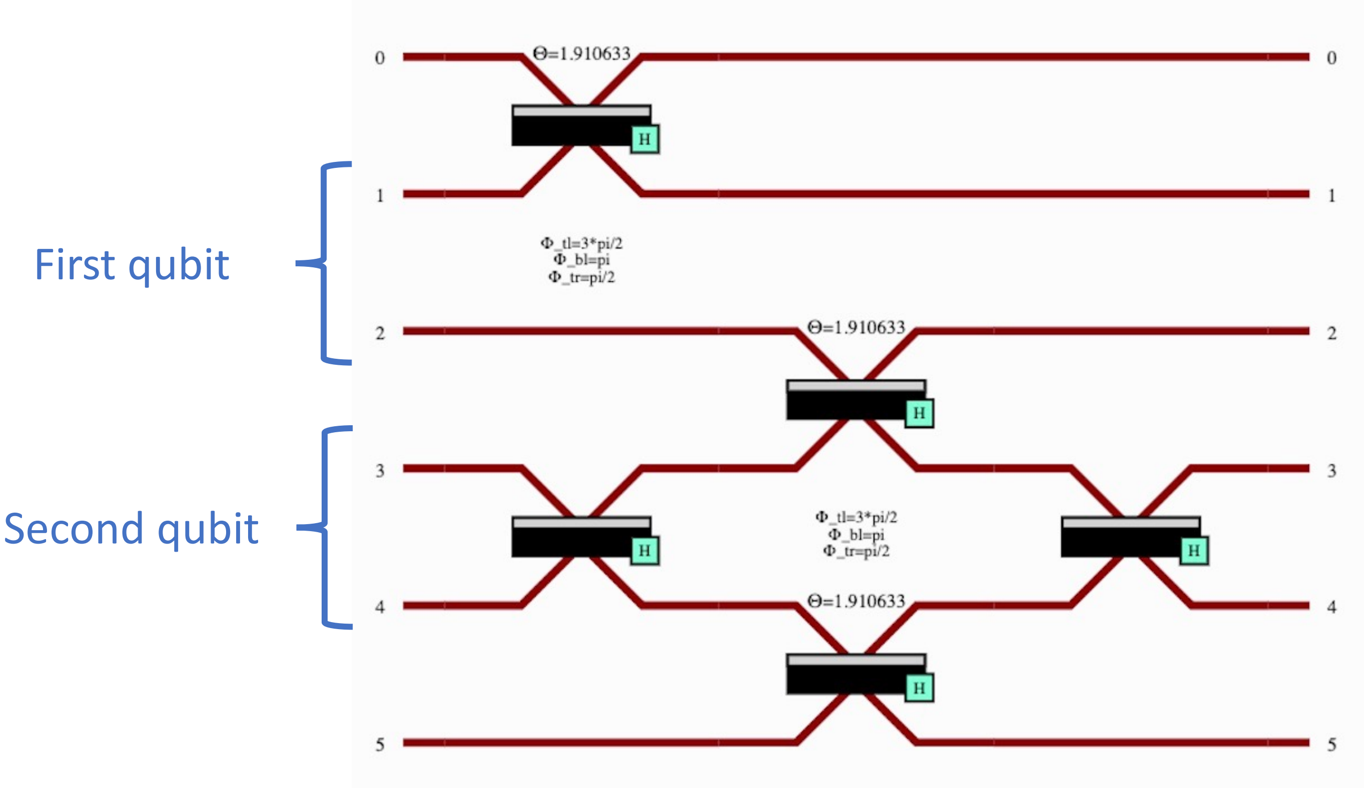
CNOT gate: exercise



Can you convince yourself that

$$|00\rangle \rightarrow |00\rangle$$
$$|01\rangle \rightarrow |01\rangle$$
$$|10\rangle \rightarrow |11\rangle$$
$$|11\rangle \rightarrow |10\rangle$$

?

What is the probability of success?

Ralph, Timothy C., et al. *Physical Review A* 65.6 (2002): 062324.

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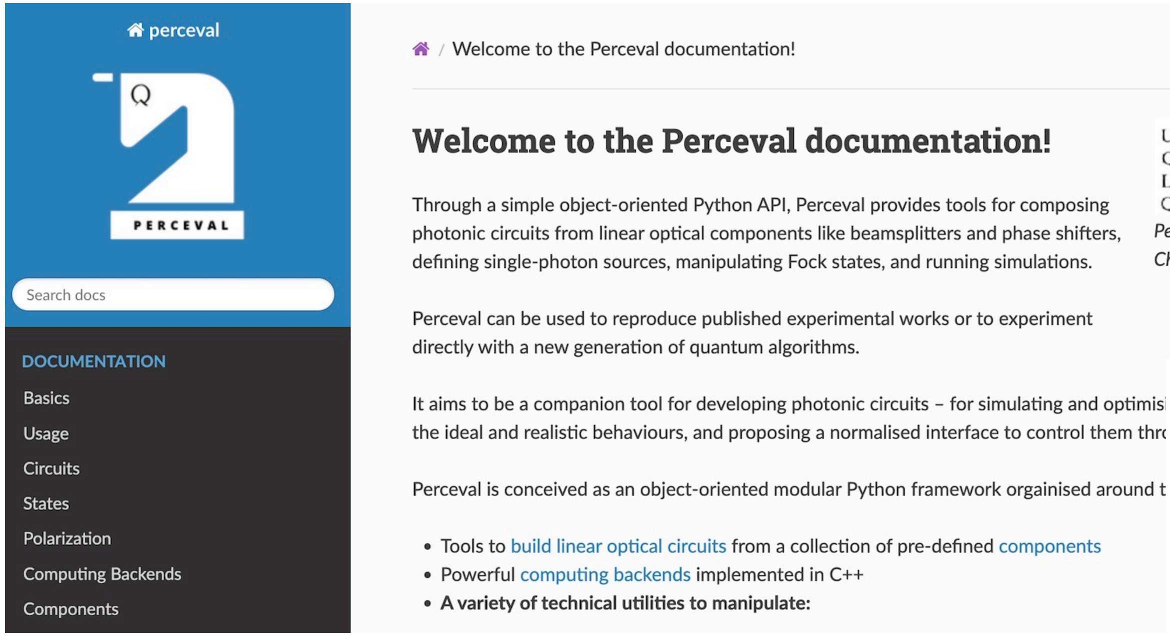
Simulation of LOQC – tutorial Thursday afternoon



Welcome to the Perceval documentation!

Une si granz clartez i vint
Qu'ausi perdirent les chandoiles
Lor clarté come les estoiles
Quant li solauz lieve ou la lune.

Perceval, the Story of the Grail – Chrétien de Troyes (circa 1180)

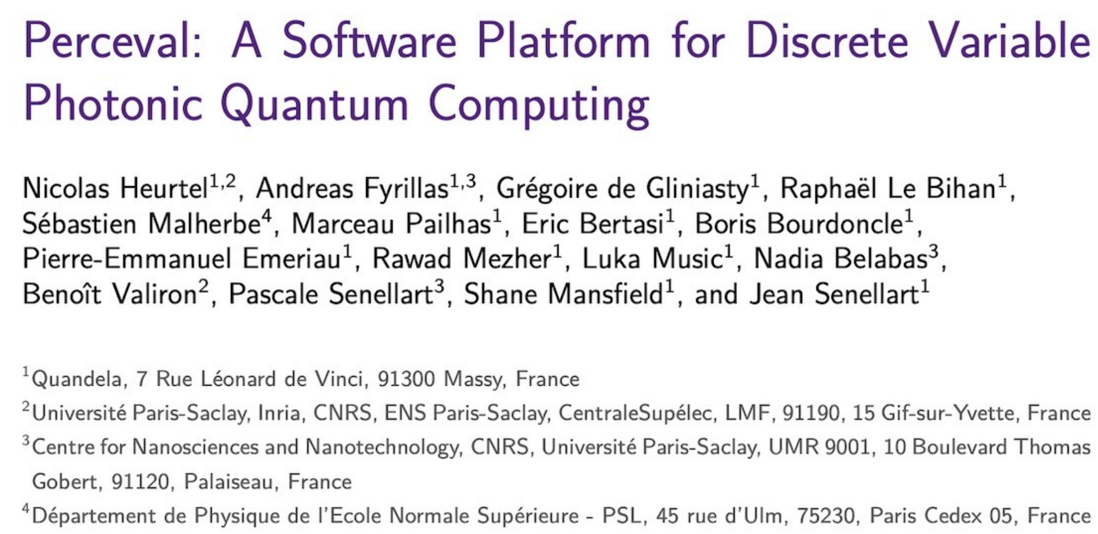
Through a simple object-oriented Python API, Perceval provides tools for composing photonic circuits from linear optical components like beamsplitters and phase shifters, defining single-photon sources, manipulating Fock states, and running simulations.

Perceval can be used to reproduce published experimental works or to experiment directly with a new generation of quantum algorithms.

It aims to be a companion tool for developing photonic circuits – for simulating and optimis
the ideal and realistic behaviours, and proposing a normalised interface to control them thro

Perceval is conceived as an object-oriented modular Python framework orgainised around t

- Tools to build linear optical circuits from a collection of pre-defined components
- Powerful computing backends implemented in C++
- **A variety of technical utilities to manipulate:**



Perceval: A Software Platform for Discrete Variable Photonic Quantum Computing

Nicolas Heurtel[1,2], Andreas Fyrillas[1,3], Grégoire de Gliniasty[1], Raphaël Le Bihan[1], Sébastien Malherbe[4], Marceau Pailhas[1], Eric Bertasi[1], Boris Bourdoncle[1], Pierre-Emmanuel Emeriau[1], Rawad Mezher[1], Luka Music[1], Nadia Belabas[3], Benoît Valiron[2], Pascale Senellart[3], Shane Mansfield[1], and Jean Senellart[1]

[1] Quandela, 7 Rue Léonard de Vinci, 91300 Massy, France
[2] Université Paris-Saclay, Inria, CNRS, ENS Paris-Saclay, CentraleSupélec, LMF, 91190, 15 Gif-sur-Yvette, France
[3] Centre for Nanosciences and Nanotechnology, CNRS, Université Paris-Saclay, UMR 9001, 10 Boulevard Thomas Gobert, 91120, Palaiseau, France
[4] Département de Physique de l'Ecole Normale Supérieure - PSL, 45 rue d'Ulm, 75230, Paris Cedex 05, France

```
pip install perceval-quandela
import perceval as pcvl
```

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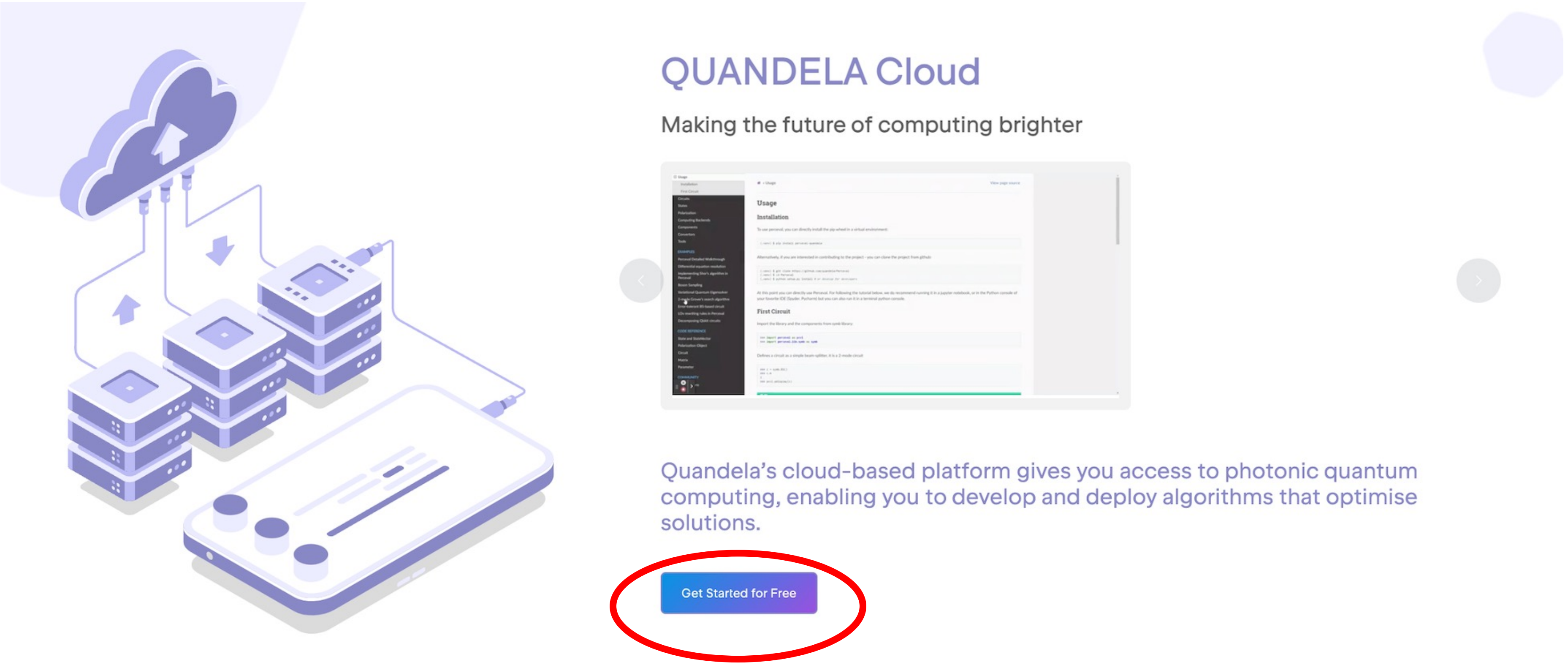
Simulation of LOQC – tutorial Thursday afternoon

Make an account on cloud.quandela.com



QUANDELA Cloud

Making the future of computing brighter

Quandela's cloud-based platform gives you access to photonic quantum computing, enabling you to develop and deploy algorithms that optimise solutions.

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QUIZZ

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Let’s sum up

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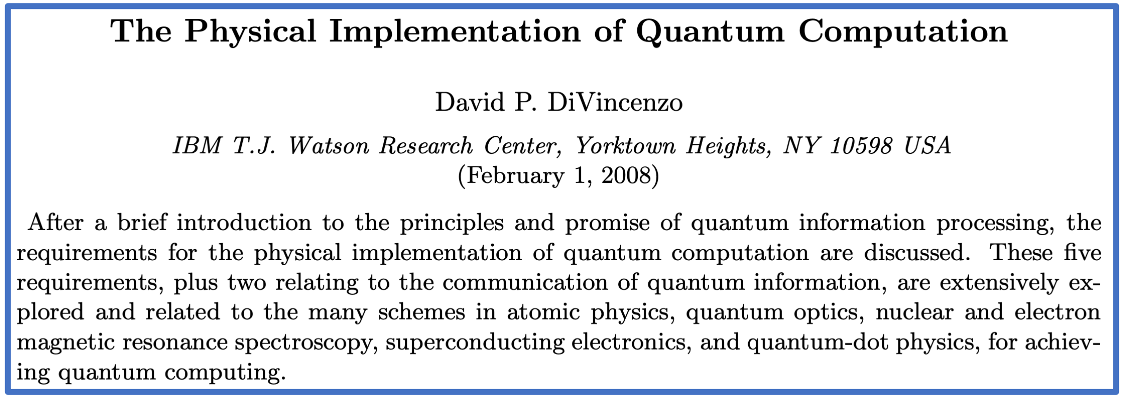
DiVincenzo’s criteria for a quantum computer

1. A **scalable** physical system with **well characterized qubits**
2. The ability to **initialize** the state of the qubits
3. **Long decoherence** times
4. A "**universal**" set of quantum gates
5. A qubit-specific **measurement capability**



The Physical Implementation of Quantum Computation

David P. DiVincenzo

IBM T.J. Watson Research Center, Yorktown Heights, NY 10598 USA
(February 1, 2008)

After a brief introduction to the principles and promise of quantum information processing, the requirements for the physical implementation of quantum computation are discussed. These five requirements, plus two relating to the communication of quantum information, are extensively explored and related to the many schemes in atomic physics, quantum optics, nuclear and electron magnetic resonance spectroscopy, superconducting electronics, and quantum-dot physics, for achieving quantum computing.

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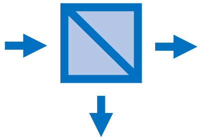
DiVincenzo's criteria for a quantum computer

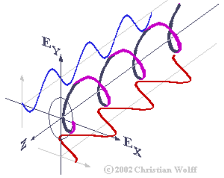
- A scalable physical system with well characterized qubits :
  - ➢ A qubit = a single photon
  - ➢ Many degrees of freedom to encode

- The ability to initialize the state of the qubits :
  - ➢ Many degrees of freedom to encode

✓ Path

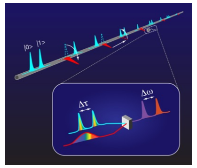


✓ Polarization

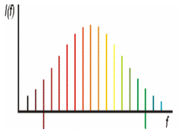


✓ OAM

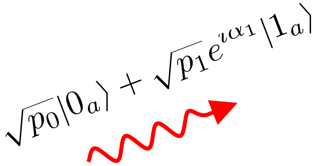
✓ Time



✓ Energy



✓ Photon number



$$\sqrt{p_0}|0_a\rangle + \sqrt{p_1}e^{i\alpha_1}|1_a\rangle$$

- Long decoherence times
  - ➢ No decoherence in *transparent* media

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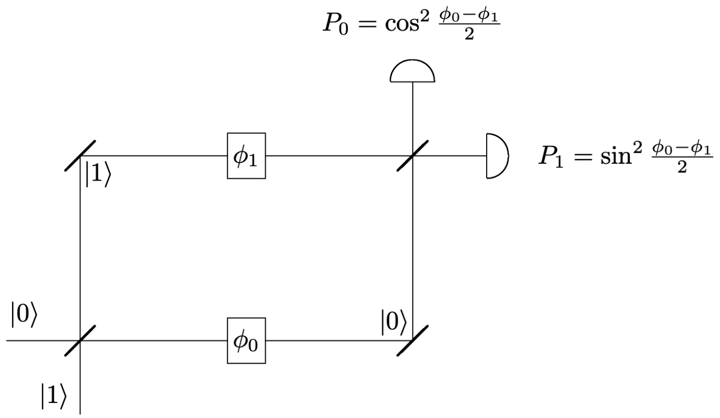
DiVincenzo’s criteria for a quantum computer

- A "universal" set of quantum gates
  - Single qubit gates very easy to implement



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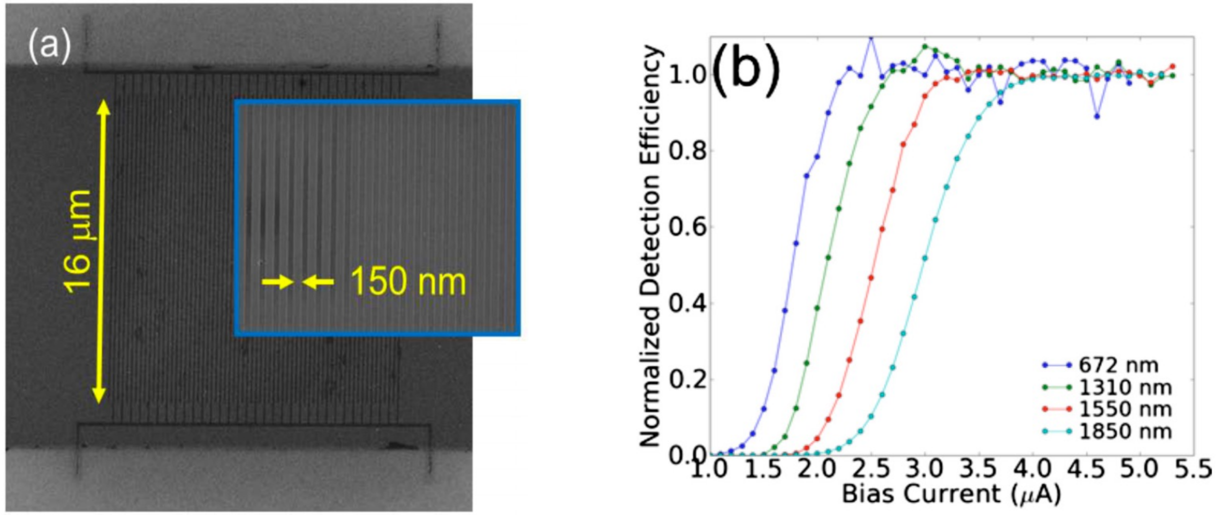
DiVincenzo's criteria for a quantum computer

- A qubit-specific measurement capability
  - ➢ Superconducting single photon detectors



Commercially available – System efficiency > 90%

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DiVincenzo’s criteria for a quantum computer

- A "universal" set of quantum gates
  - Two qubit gates are trickier
  - Photon entanglement with interaction through non-linear materials (e.g. AC Kerr effect) is extremely challenging
  - Knill, Laflamme and Milburn removed the need of strong non-linearities by showing that photon interference + photon measurement can induce photon entangling interactions
  - Browne and Rudolph showed that this could be done with HOM-type interference (see later) instead of Mach-Zehnder-type interference, removing the need for phase stability -> fusion gates
  - Further developments integrate these ideas in the MBQC framework

A scheme for efficient quantum computation with linear optics

E. Knill*, R. Laflamme* & G. J. Milburn†

* Los Alamos National Laboratory, MS B265, Los Alamos, New Mexico 87545, USA
† Centre for Quantum Computer Technology, University of Queensland, St. Lucia, Australia

Resource-Efficient Linear Optical Quantum Computation

Daniel E. Browne[1,2] and Terry Rudolph[1,3]

From Three-Photon Greenberger-Horne-Zeilinger States to Ballistic Universal Quantum Computation

Mercedes Gimeno-Segovia,[1,*] Pete Shadbolt,[1] Dan E. Browne,[2] and Terry Rudolph[1]

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Knill Laflamme Milburn (KLM) scheme

Scheme for a universal quantum computer with LO elements, single-photon sources and photon detectors:

- Qubit encoding, state measurement, single qubit gates
- Post-selected CNOT / CZ gates
- Gate teleportation for near-deterministic gates
  - Prepare entangled state with gate already applied offline
  - Teleport into circuit
  - Prepare many probabilistic gates with n-photon state
  - Success rate $\frac{n^2}{(n+1)^2}$

Article | Published: 04 January 2001

A scheme for efficient quantum computation with linear optics

E. Knill, R. Laflamme & G. J. Milburn

Nature **409**, 46–52 (2001) | Cite this article

Linear optical quantum computing with photonic qubits

Pieter Kok, W. J. Munro, Kae Nemoto, T. C. Ralph, Jonathan P. Dowling, and G. J. Milburn
Rev. Mod. Phys. **79**, 135 – Published 24 January 2007

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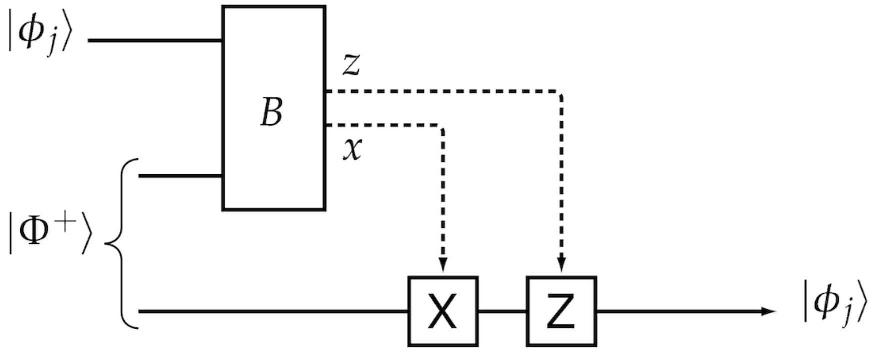
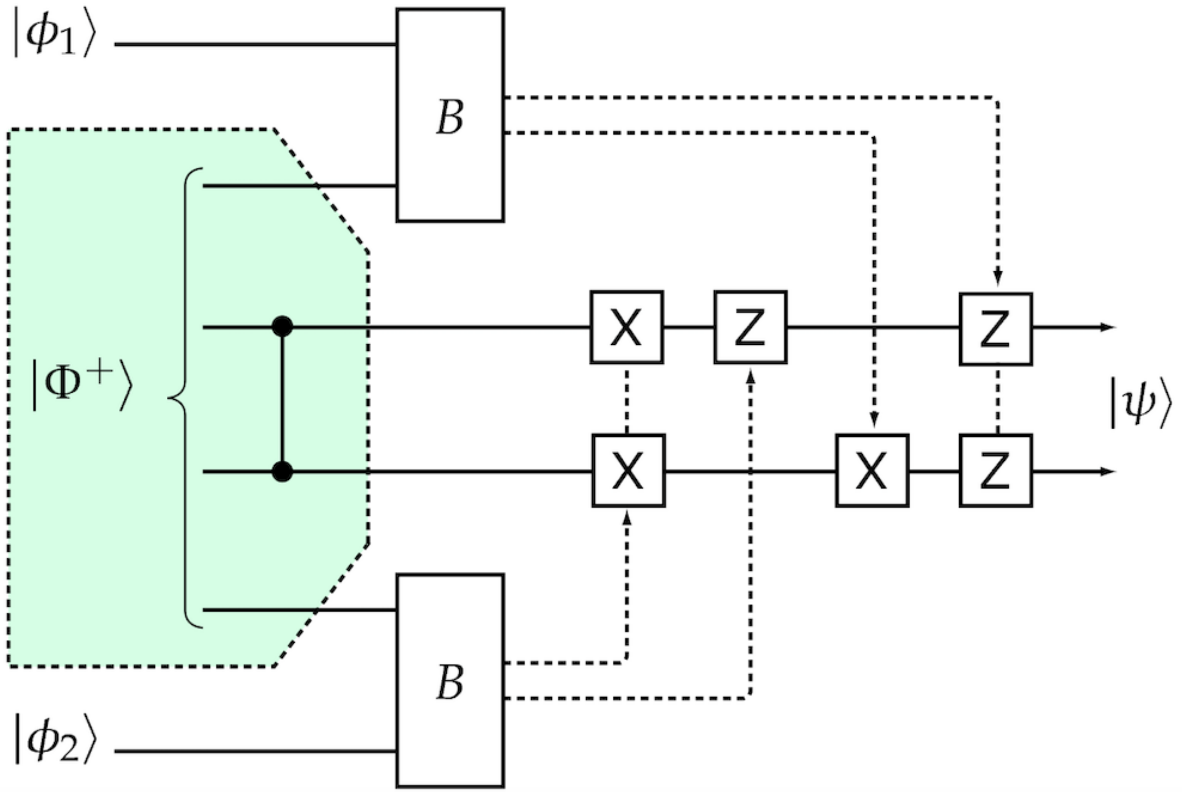
Knill Laflamme Milburn (KLM) scheme



Teleportation circuit



Teleport CZ gate $|\psi\rangle = U_{CZ}|\phi_1\rangle|\phi_2\rangle$

P. Kok et al. Rev. Mod. Phys. 79, 135 (2007)

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Advantages / inconvenients summary

✓

- Long coherence
- Connectivity
- 4K to room temperature
- Connection with network
- Single-qubit gates

✗

- Photon loss
- Source efficiency
- Two-qubit gates

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Designing algorithms with linear optics

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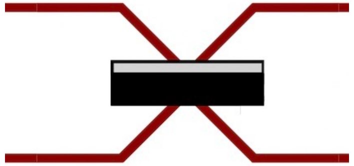
Let’s go back to a simple linear optical setup

$|n_1, n_2, \dots, n_i, \dots, n_m\rangle$ Fock state with n_i photons in mode *i*

Beamsplitter



$$\begin{bmatrix} e^{i(\phi_{tl}+\phi_{tr})}\cos\left(\frac{\theta}{2}\right) & ie^{i(\phi_{bl}+\phi_{tr})}\sin\left(\frac{\theta}{2}\right) \\ ie^{i(\phi_{tl}+\phi_{br})}\sin\left(\frac{\theta}{2}\right) & e^{i(\phi_{bl}+\phi_{br})}\cos\left(\frac{\theta}{2}\right) \end{bmatrix}$$

Phase shifter

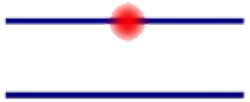
$$\begin{bmatrix} e^{i\phi} \end{bmatrix}$$

+ source and detectors

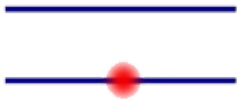
Qubit encoding

Dual rail

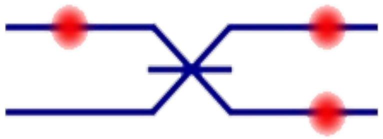
$|0\rangle_{qubit} \coloneqq |1, 0\rangle$



$|1\rangle_{qubit} \coloneqq |0, 1\rangle$



$|0\rangle \rightarrow |0\rangle + |1\rangle$



Beamsplitter

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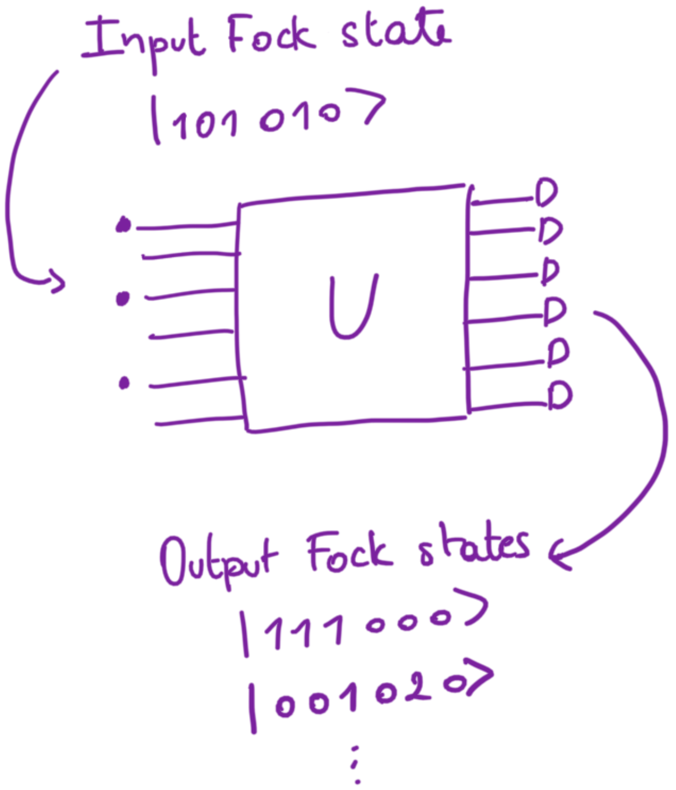
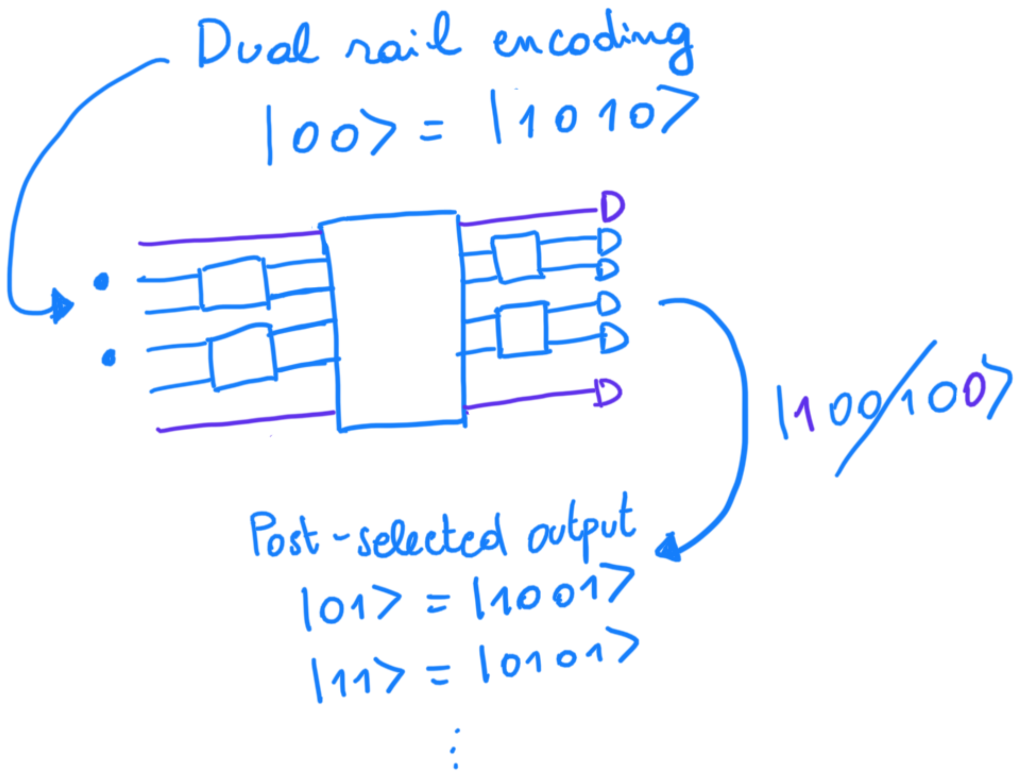
Near term algorithm design: two approaches

Photonic native



Qubit circuit based



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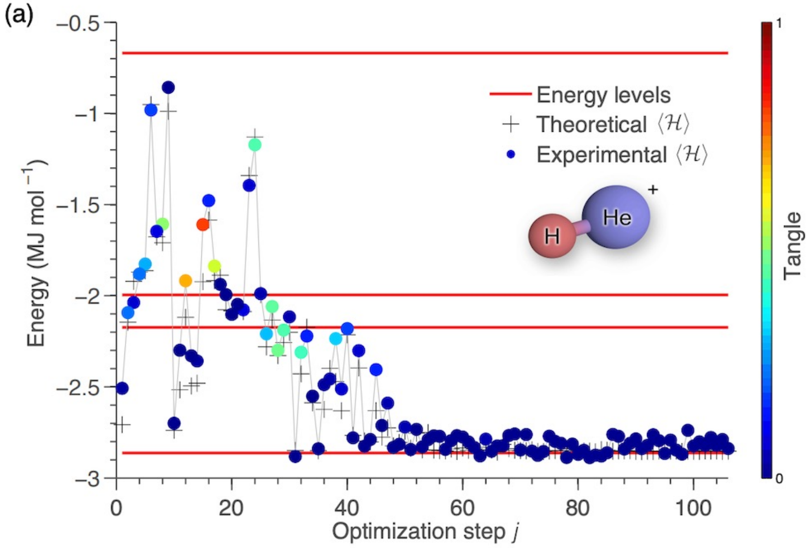
Algorithm example: Variational Quantum Eigensolver (VQE)

- Variational quantum algorithms are a type of hybrid quantum-classical algorithm
- A computation is usually run on a quantum circuit (*ansatz*) with parameters that can be optimised
- The optimisation procedure is done on a classical computer



A. Peruzzo et al. Nature Communications, 5:4213, (2014)

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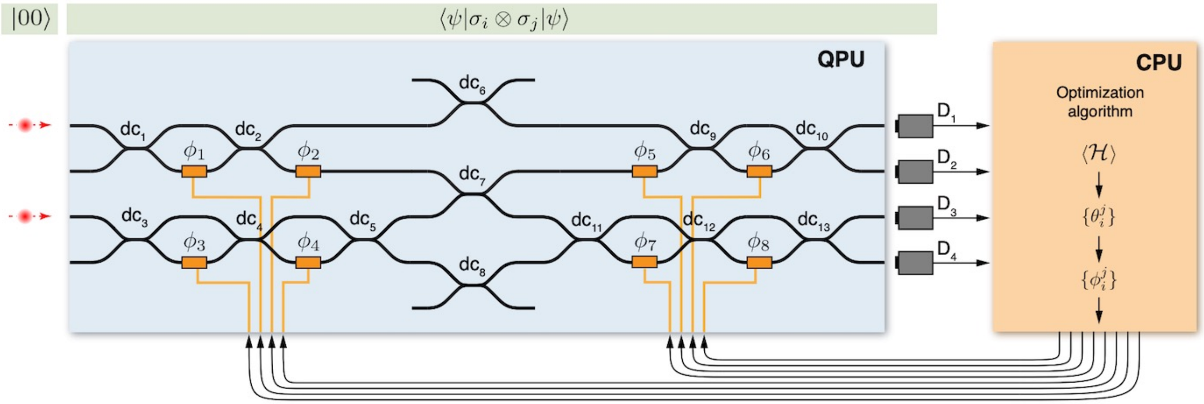
Algorithm example: Variational Quantum Eigensolver (VQE)

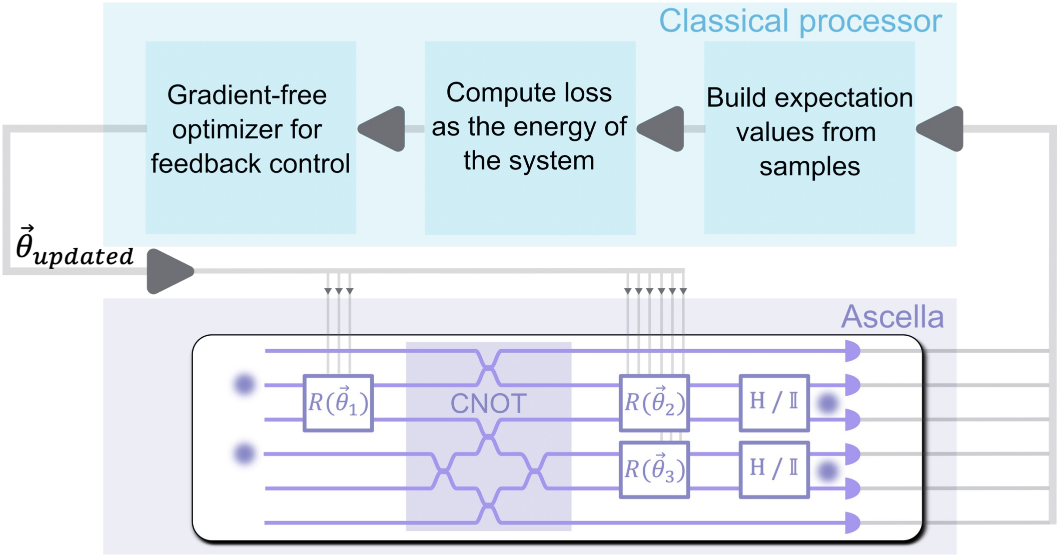
A variational eigenvalue solver on a photonic quantum processor

Alberto Peruzzo ✉, Jarrod McClean, Peter Shadbolt, Man-Hong Yung, Xiao-Qi Zhou, Peter J. Love, Alán Aspuru-Guzik ✉ & Jeremy L. O'Brien ✉

A versatile single-photon-based quantum computing platform

Nicolas Maring, Andreas Fyrillas, Mathias Pont, Edouard Ivanov, Petr Stepanov, Nico Margaria, William Hease, Anton Pishchagin, Aristide Lemaître, Isabelle Sagnes, Thi Huong Au, Sébastien Boissier, Eric Bertasi, Aurélien Baert, Mario Valdivia, Marie Billard, Ozan Acar, Alexandre Brieussel, Rawad Mezher, Stephen C. Wein, Alexia Salavrakos, Patrick Sinnott, Dario A. Fioretto, Pierre-Emmanuel Emeriau, Nadia Belabas, Shane Mansfield, Pascale Senellart, Jean Senellart ✉ & Niccolo Somaschi ✉





Classical processor

Gradient-free optimizer for feedback control

Compute loss as the energy of the system

Build expectation values from samples

$\vec{\theta}_{updated}$

Ascella

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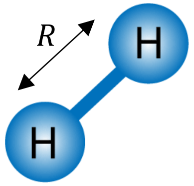
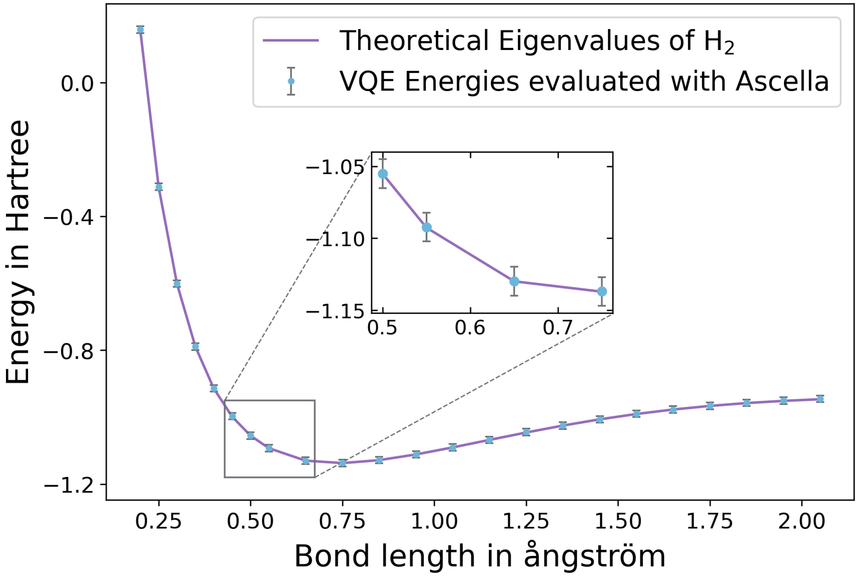
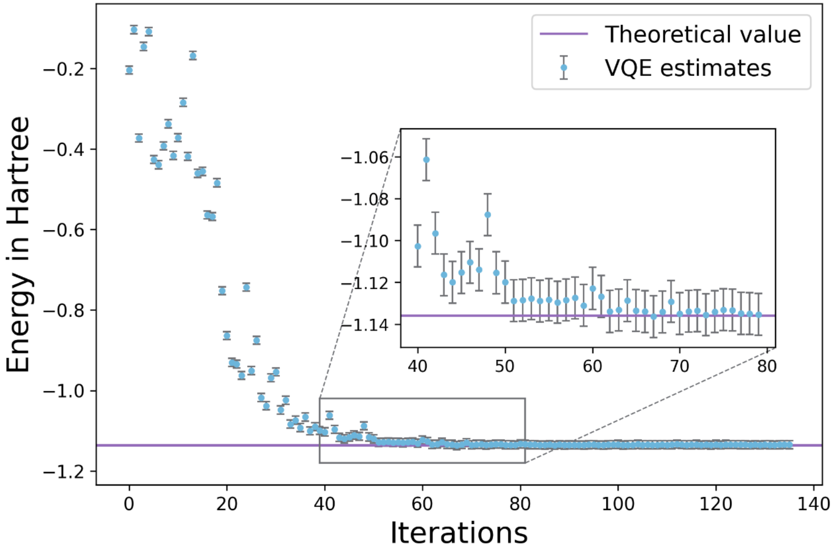
Algorithm example: Variational Quantum Eigensolver (VQE)







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Algorithm example: variational quantum classifier

- Variational framework is the same as VQE
- Here, the ansatz computes the model, which is a function of the variational parameters θ
- For a dataset $(\overrightarrow{x_i}, y_i)$ where $\overrightarrow{x_i}$ are the data points and y_i the labels, the loss function is of the form

$$L = \sum_i d(f_\theta(x_i), y_i)$$

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$$L = \sum_i d(\underbrace{f_\theta(x_i)}_{\text{model output}}, \underbrace{y_i}_{\text{label}})$$

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$$L = \sum_i d(\underset{\text{model output}}{f_\theta(x_i)}, \underset{\text{label}}{y_i}) \longrightarrow \text{minimise}$$

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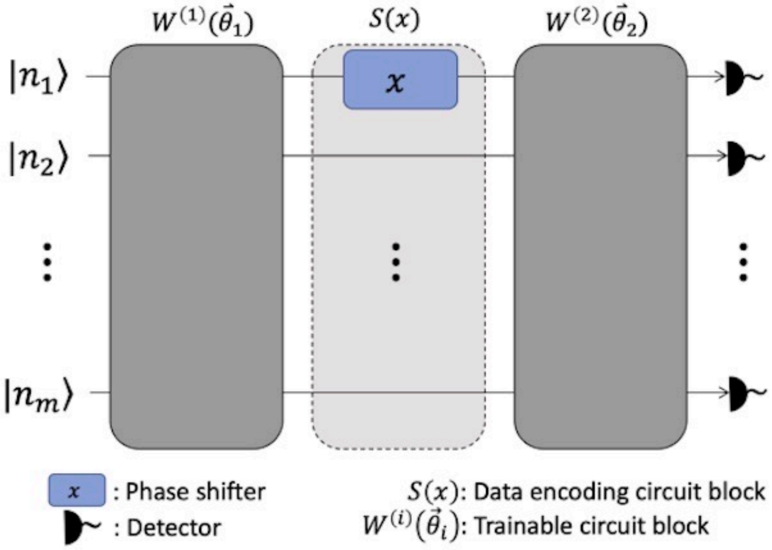
Algorithm example: variational quantum classifier

Fock-space based quantum neural network (QNN)



[1] B. Y. Gan, D. Leykam, and D. G. Angelakis. *EPJ Quantum Technol*. 9, 16 (2022)

Resulting model:

$$f^{(n)}(x,\boldsymbol{\Theta},\boldsymbol{\lambda}) = \left\langle \mathbf{n}^{(i)} \middle| \mathcal{U}^{\dagger}(x,\boldsymbol{\Theta})\mathcal{M}(\boldsymbol{\lambda})\mathcal{U}(x,\boldsymbol{\Theta}) \middle| \mathbf{n}^{(i)} \right\rangle$$

Unitary from the circuit

Observable

Defined in Fock space:

$$\left|\mathbf{n}^{(i)}\right\rangle = \left|n_1^{(i)}, n_2^{(i)}, \ldots, n_m^{(i)}\right\rangle$$

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Algorithm example: variational quantum classifier

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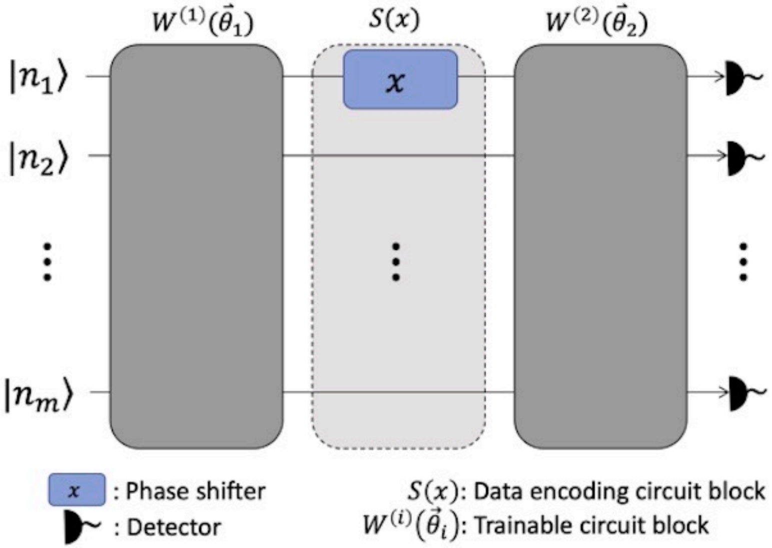
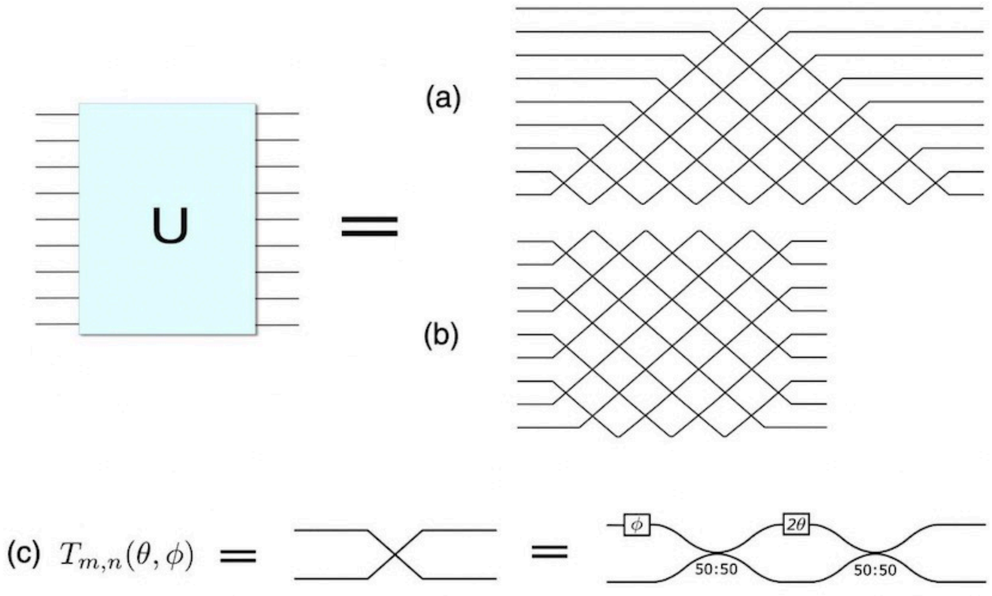


[1] B. Y. Gan, D. Leykam, and D. G. Angelakis. *EPJ Quantum Technol*. 9, 16 (2022)

Recall Clements / Reck decompositions:



M. Reck et al. *Physical Review Letters* 73, 58 (1994)

W. R. Clements et al. *Optica* 3, 12 (2016)

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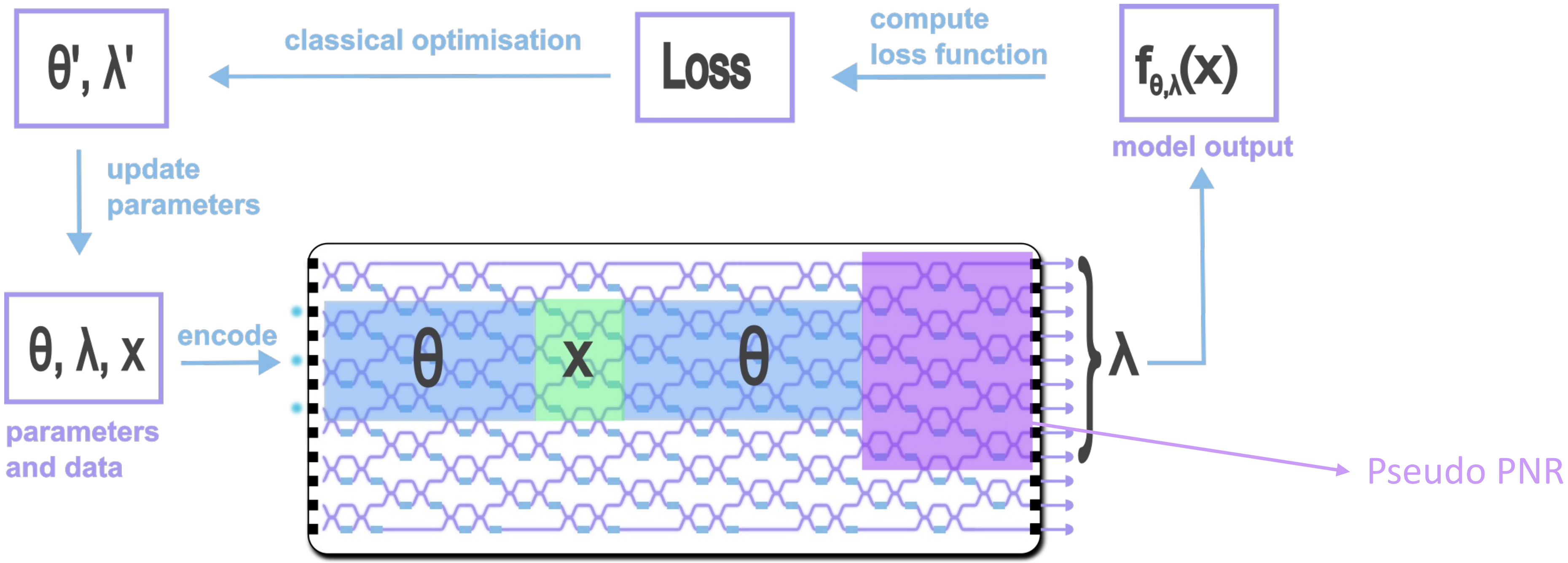
Algorithm example: variational quantum classifier



θ', λ'

classical optimisation

Loss

compute loss function

$f_{\theta,\lambda}(x)$

model output

update parameters

θ, λ, x

encode

parameters and data

Pseudo PNR

Input Fock state $|\psi_{in}\rangle = |0010101000000\rangle$

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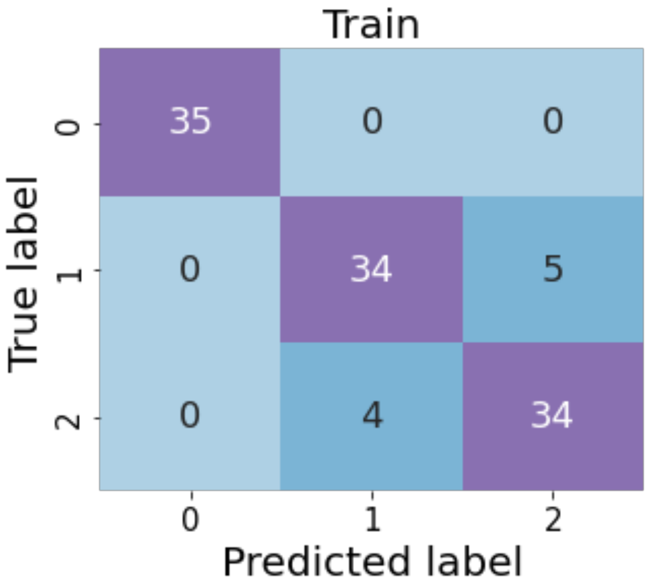
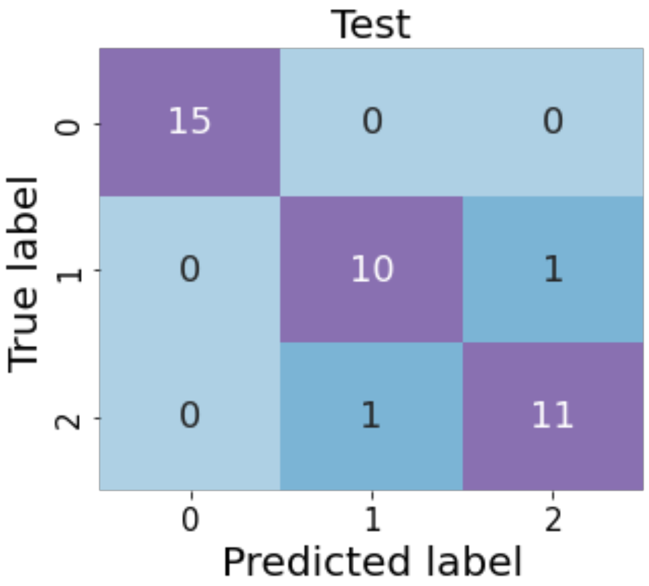
Variational quantum classifier: results

Classifying Fisher’s iris dataset:
- 150 data points
- 4 dimensions
- 3 classes



Train

True label \ Predicted label	0	1	2
0	35	0	0
1	0	34	5
2	0	4	34



Test

True label \ Predicted label	0	1	2
0	15	0	0
1	0	10	1
2	0	1	11

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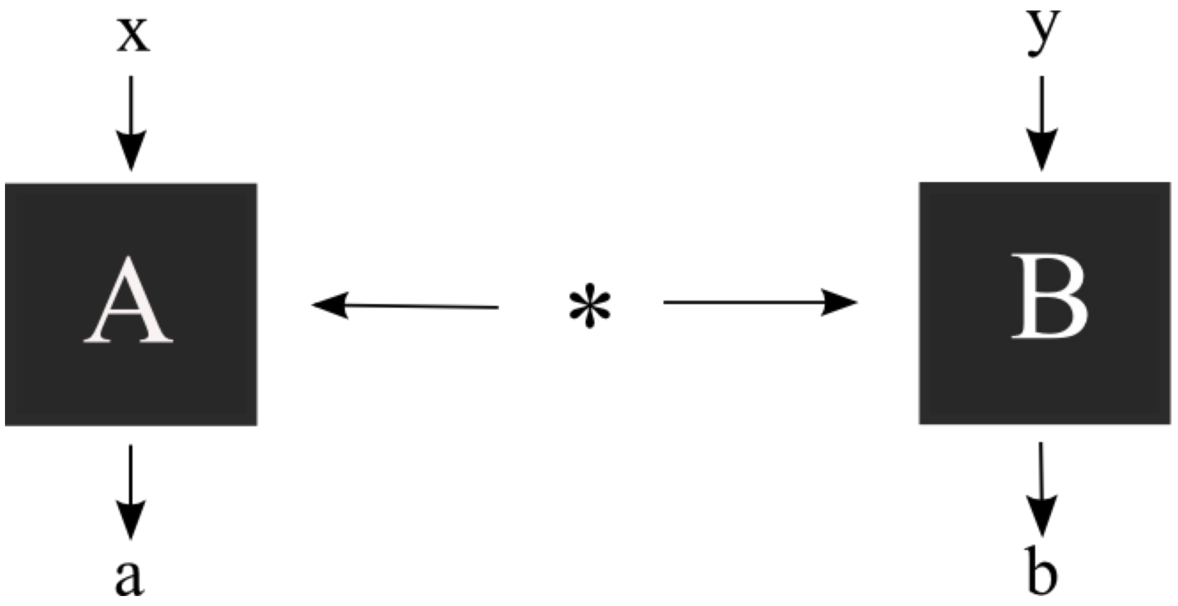
Algorithm example: Bell test



With classical resources, the CHSH inequality is bounded by 2

With quantum resources, it can reach up to 2√2

$$\mathcal{B}_{\text{CHSH}} = \langle A_1 B_1 \rangle + \langle A_1 B_2 \rangle + \langle A_2 B_1 \rangle - \langle A_2 B_2 \rangle \leq 2$$

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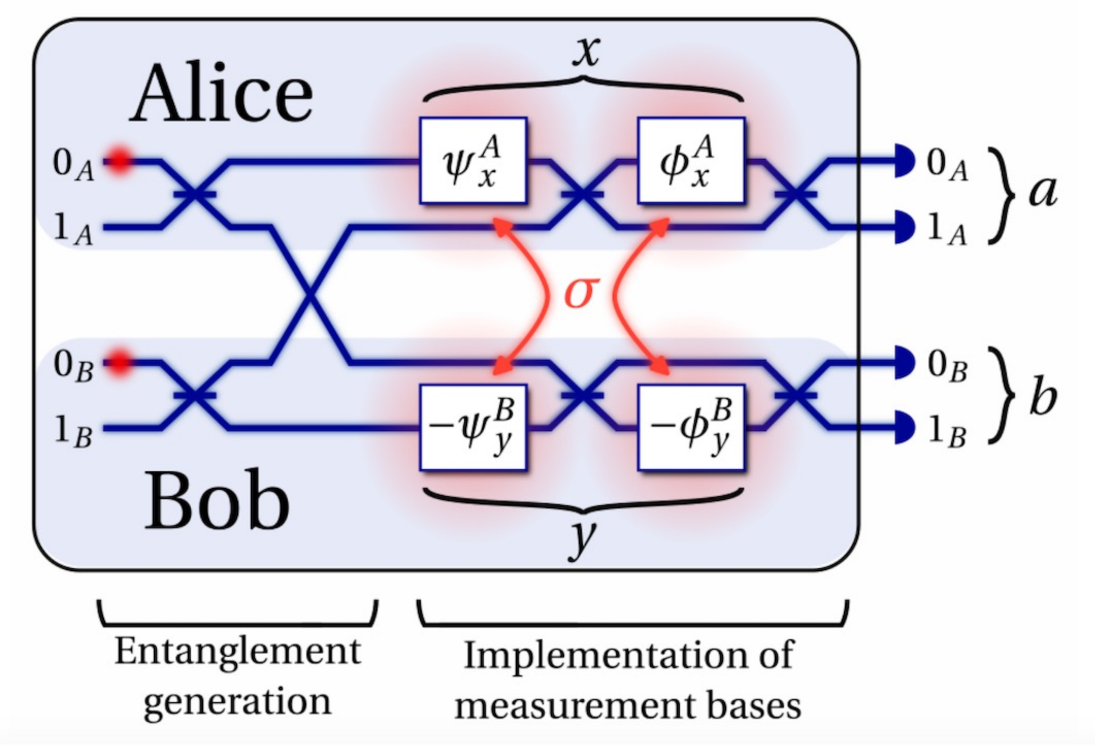

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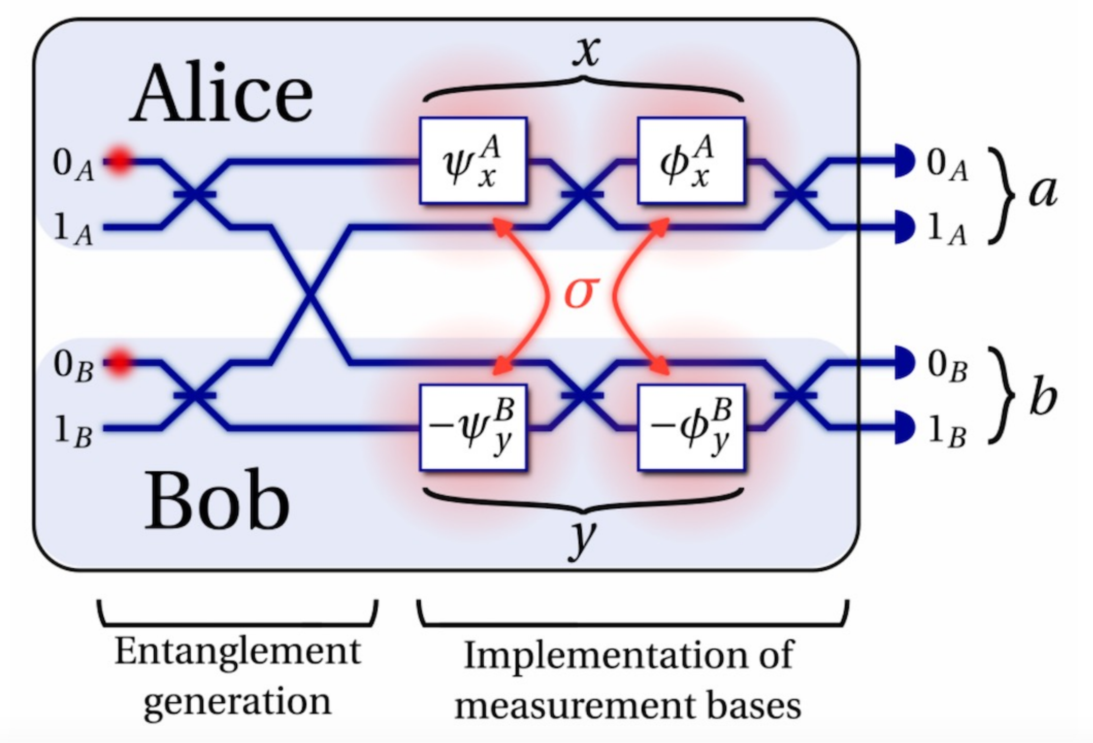

$$\frac{|01\rangle + |10\rangle}{\sqrt{2}}$$

Phases are functions of input x and y

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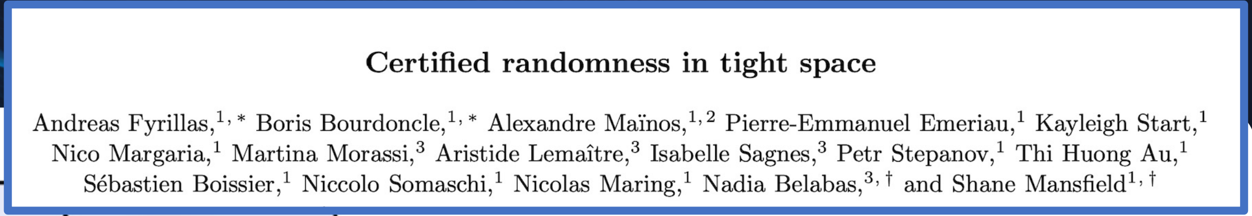
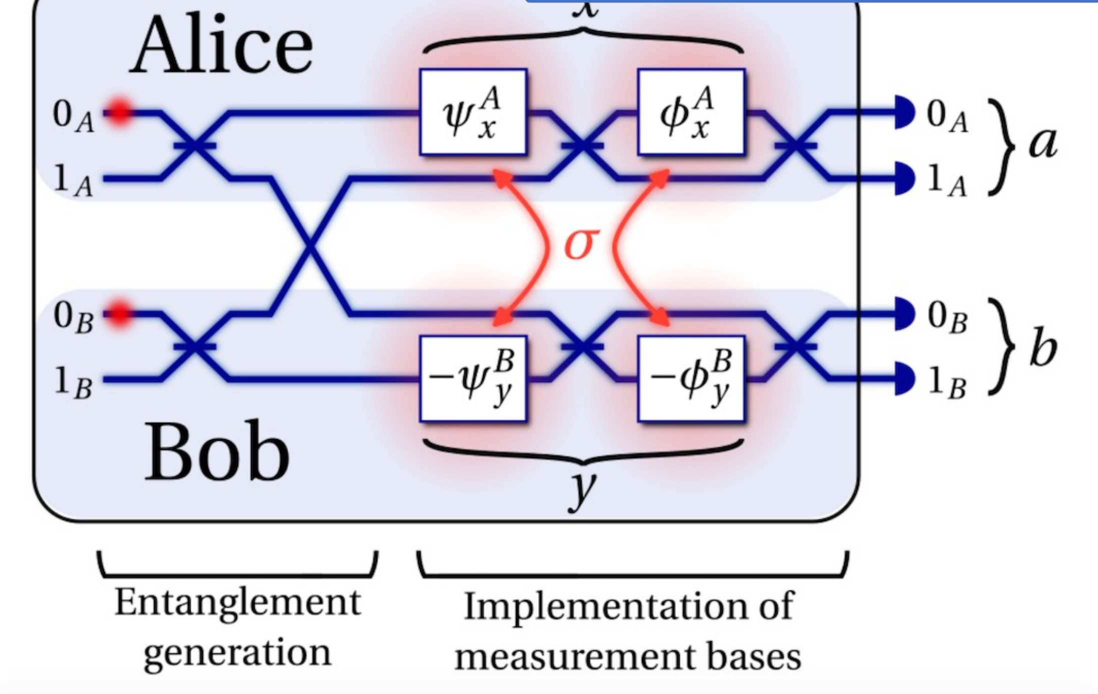
Algorithm example: Bell test



Certified randomness in tight space

Andreas Fyrillas,[1,*] Boris Bourdoncle,[1,*] Alexandre Maïnos,[1,2] Pierre-Emmanuel Emeriau,[1] Kayleigh Start,[1] Nico Margaria,[1] Martina Morassi,[3] Aristide Lemaître,[3] Isabelle Sagnes,[3] Petr Stepanov,[1] Thi Huong Au,[1] Sébastien Boissier,[1] Niccolo Somaschi,[1] Nicolas Maring,[1] Nadia Belabas,[3,†] and Shane Mansfield[1,†]



$$\frac{|01\rangle + |10\rangle}{\sqrt{2}}$$

Phases are functions of input x and y

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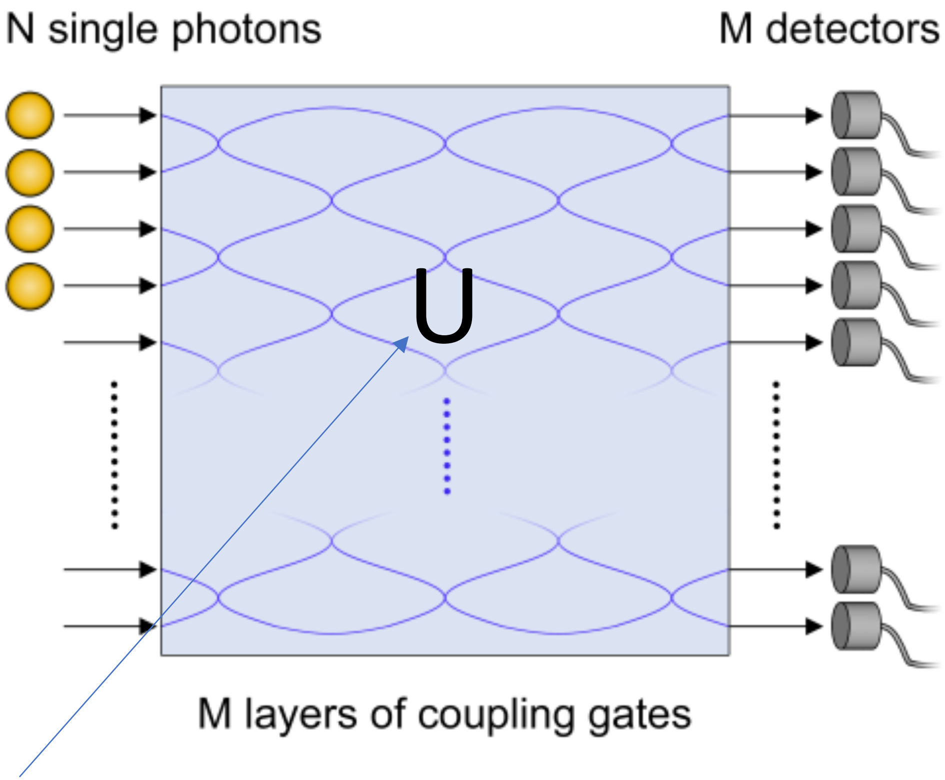
Algorithm example: solving graph problems



Haar-random

P(S) ∝ $|Perm(U_{S,N})|^2$

- The probability to measure an output state$|s_1, \dots s_m\rangle$ is given by $|\alpha_s|^2/s_1!\dots s_m! n_1!\dots n_m!$
- It can be shown that $|\alpha_s|^2$ =$|Per(U_{S,N})|^2$, $U_{S,N}$ submatrix of U determined by $S = (s_1, \dots., s_m)$ rows and N= $(n_1, \dots., n_m)$ column
- If A is an n×n matrix, $Per(A) = \sum_{\sigma\in S_n}\prod_{i=1}^{n} A_{i\sigma(i)}$
- Easy rule: like the determinant but with + signs everywhere
- The permanent, unlike the determinant, is hard to compute (best classical algorithms scale as O($n2^n$))

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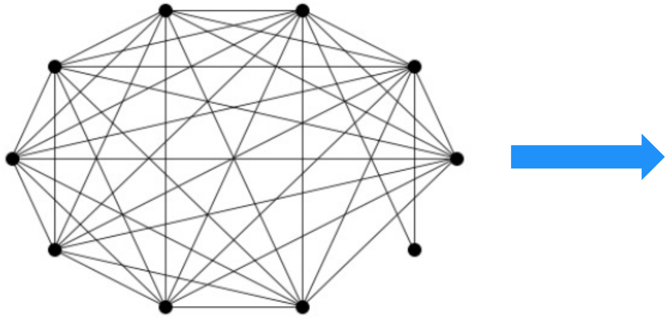
Algorithm example: solving graph problems

Adjacency matrix of a graph

If two vertices are connected in the graph you get a 1 in the adjacency matrix, otherwise a 0

Several graph problems can be related to the properties of the adjacency matrix



$$A = \begin{pmatrix} 0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 \\ 1 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 0 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 0 & 1 & 1 & 1 & 1 & 1 & 0 \\ 1 & 1 & 1 & 1 & 0 & 1 & 1 & 1 & 1 & 0 \\ 1 & 1 & 1 & 1 & 1 & 0 & 1 & 1 & 1 & 0 \\ 1 & 1 & 1 & 1 & 1 & 1 & 0 & 1 & 1 & 0 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 & 1 & 0 \\ 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 0 & 0 \\ 0 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{pmatrix}$$

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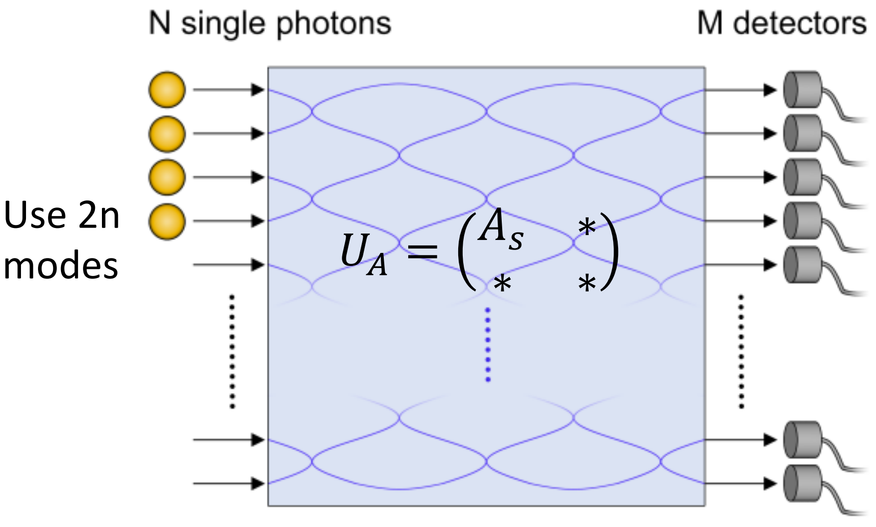
Algorithm example: solving graph problems

Step 1: We scale down the adjacency matrix using singular value decomposition

$$A_s := \frac{1}{s} A$$

Step 2: Use the ***unitary dilation theorem*** to embed A_s onto a larger unitary matrix U_A. If A is an $n \times n$ matrix, **U_A is a $2n \times 2n$ matrix**

$$\boxed{U_A := \begin{pmatrix} A_s & * \\ * & * \end{pmatrix}}$$



$$U_A = \begin{pmatrix} A_s & * \\ * & * \end{pmatrix}$$

$$\mathrm{p}(\boldsymbol{n_{out}} \,|\, \boldsymbol{n_{in}}) \propto |\mathrm{Per}(A_s)|^2$$

$$\propto \frac{1}{s^{2n}} |\mathrm{Per}(A)|^2$$

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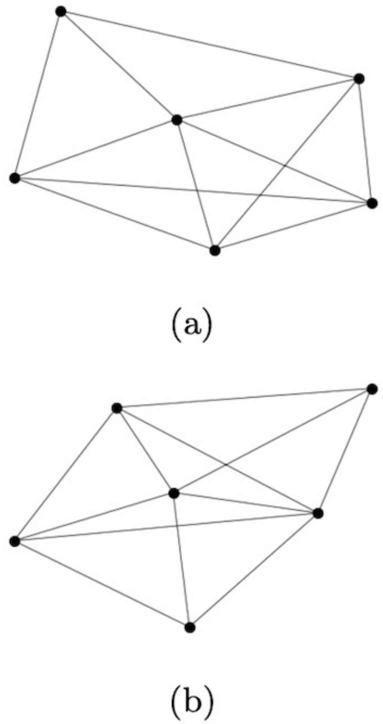
Algorithm example: solving graph problems

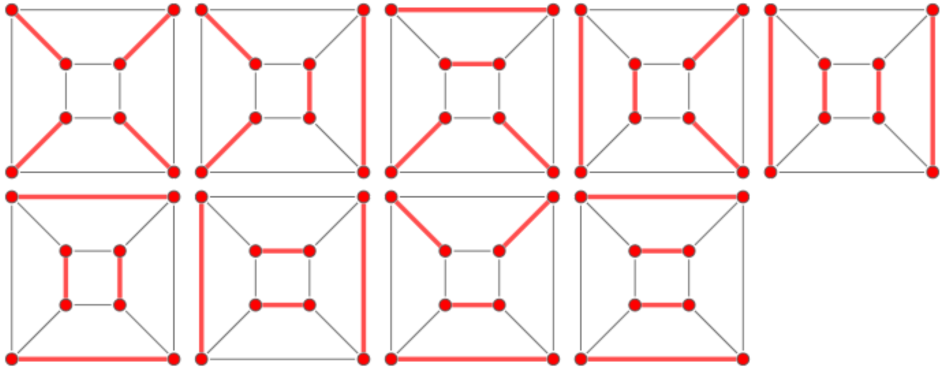
Solving graph problems with single photons and linear optics

Rawad Mezher, Ana Filipa Carvalho, and Shane Mansfield
Phys. Rev. A **108**, 032405 – Published 6 September 2023

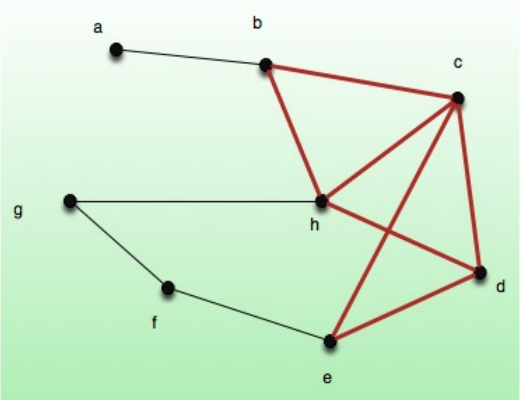
Graph isomorphism: compare permanents of adjacency matrices



Number of perfect matchings: $\sqrt{Per(A)}$



Densest subgraph identification



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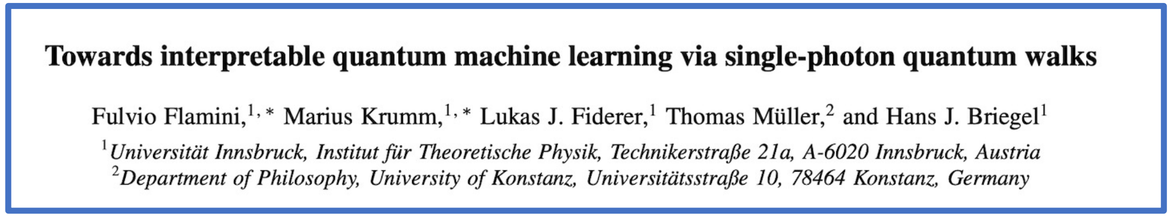
References: reinforcement learning on photonic circuits

Experimental quantum speed-up in reinforcement learning agents

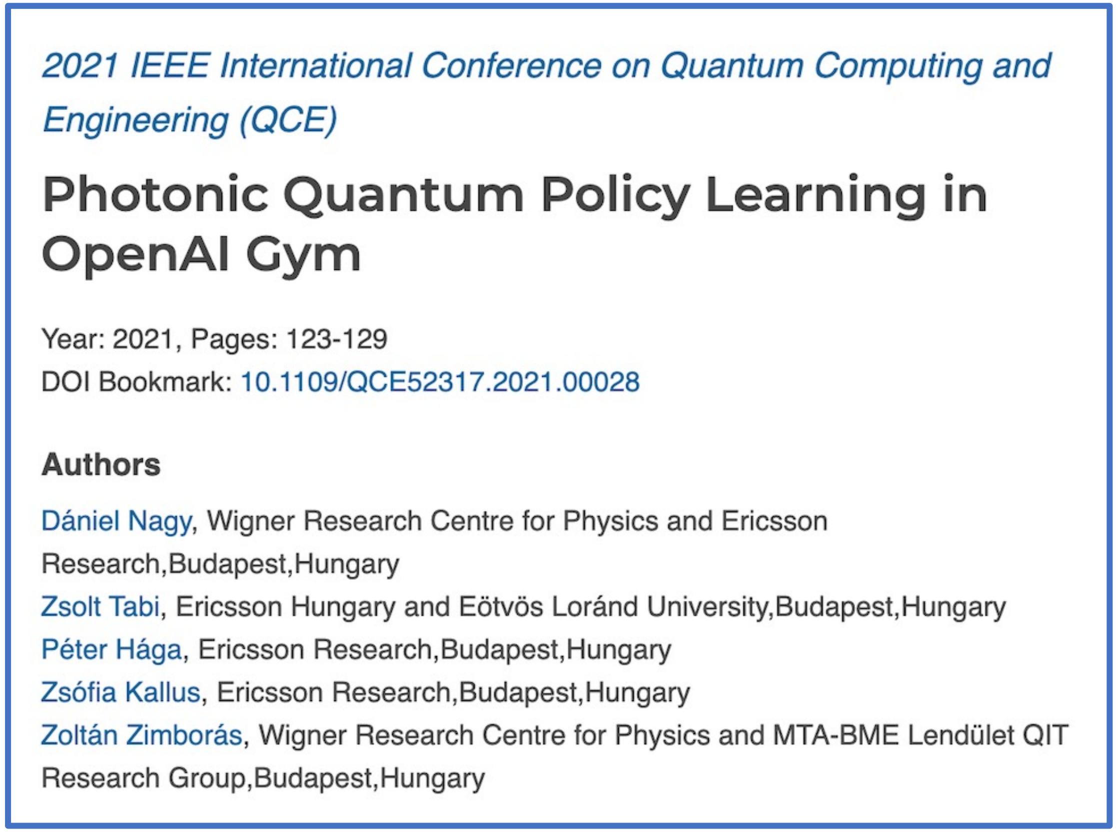
V. Saggio ✉, B. E. Asenbeck, A. Hamann, T. Strömberg, P. Schiansky, V. Dunjko, N. Friis, N. C. Harris, M. Hochberg, D. Englund, S. Wölk, H. J. Briegel & P. Walther ✉



Towards interpretable quantum machine learning via single-photon quantum walks

Fulvio Flamini,[1,*] Marius Krumm,[1,*] Lukas J. Fiderer,[1] Thomas Müller,[2] and Hans J. Briegel[1]

[1] *Universität Innsbruck, Institut für Theoretische Physik, Technikerstraße 21a, A-6020 Innsbruck, Austria*
[2] *Department of Philosophy, University of Konstanz, Universitätsstraße 10, 78464 Konstanz, Germany*



2021 IEEE International Conference on Quantum Computing and Engineering (QCE)

Photonic Quantum Policy Learning in OpenAI Gym

Year: 2021, Pages: 123-129
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References: reinforcement learning on photonic circuits

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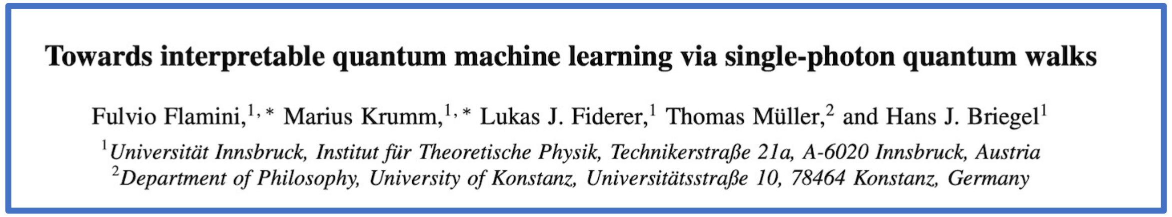

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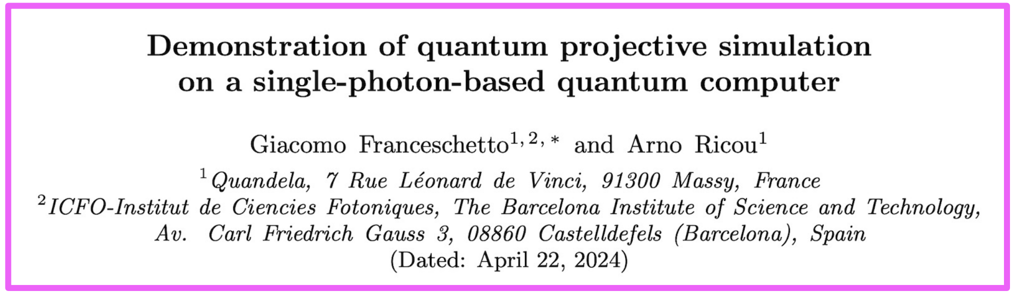
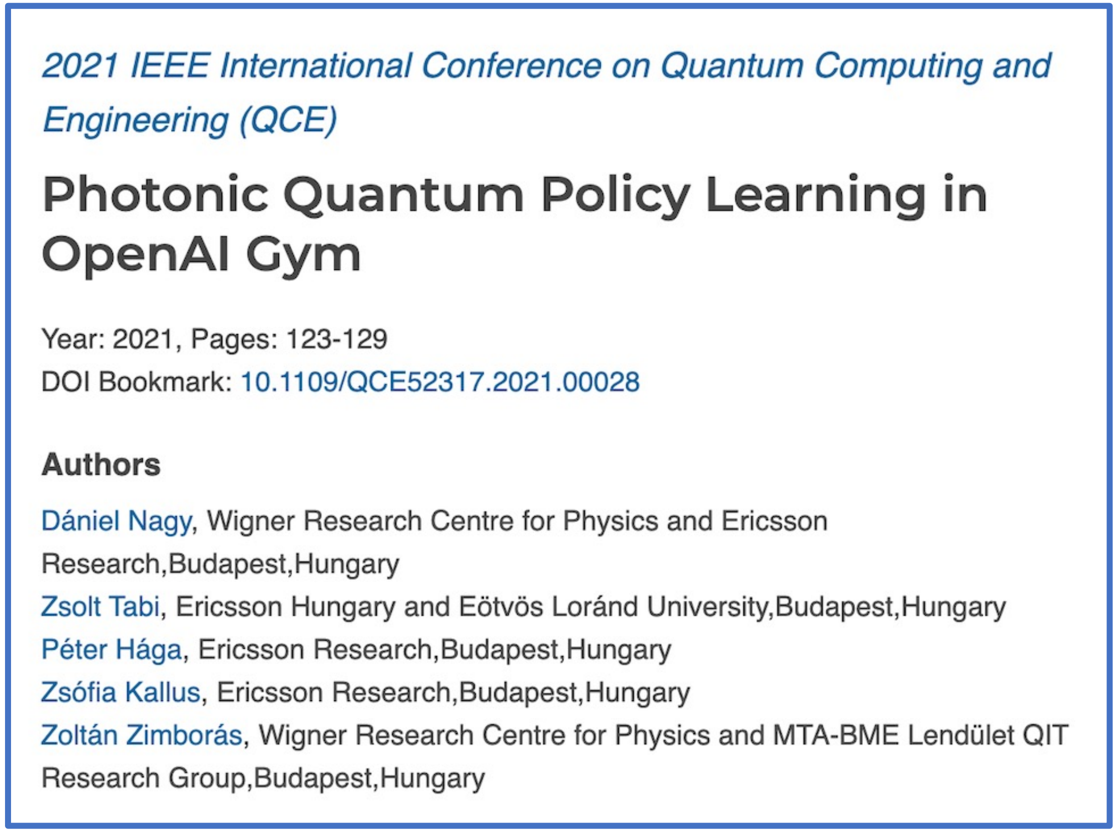


Demonstration of quantum projective simulation on a single-photon-based quantum computer

Giacomo Franceschetto[1,2,*] and Arno Ricou[1]

[1] *Quandela, 7 Rue Léonard de Vinci, 91300 Massy, France*
[2] *ICFO-Institut de Ciencies Fotoniques, The Barcelona Institute of Science and Technology, Av. Carl Friedrich Gauss 3, 08860 Castelldefels (Barcelona), Spain*
(Dated: April 22, 2024)



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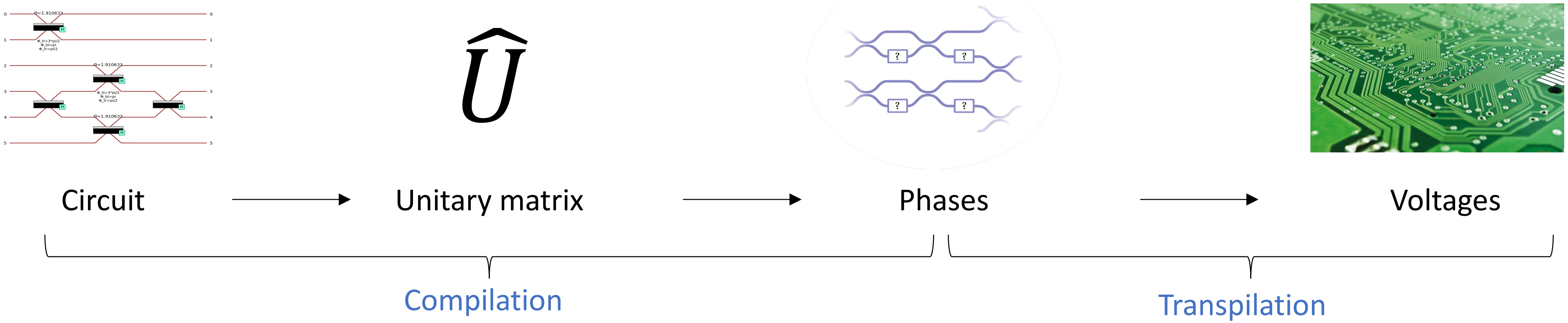

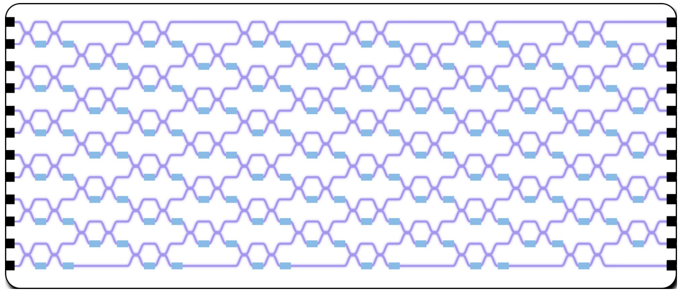

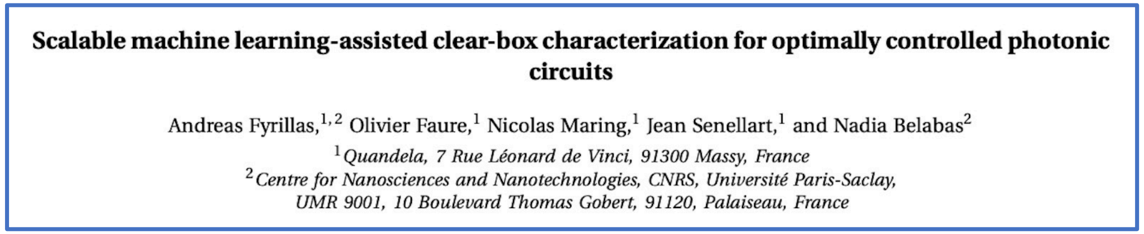

Scalable machine learning-assisted clear-box characterization for optimally controlled photonic circuits

Andreas Fyrillas,[1,2] Olivier Faure,[1] Nicolas Maring,[1] Jean Senellart,[1] and Nadia Belabas[2]
[1] *Quandela, 7 Rue Léonard de Vinci, 91300 Massy, France*
[2] *Centre for Nanosciences and Nanotechnologies, CNRS, Université Paris-Saclay, UMR 9001, 10 Boulevard Thomas Gobert, 91120, Palaiseau, France*

arXiv:2310.15349

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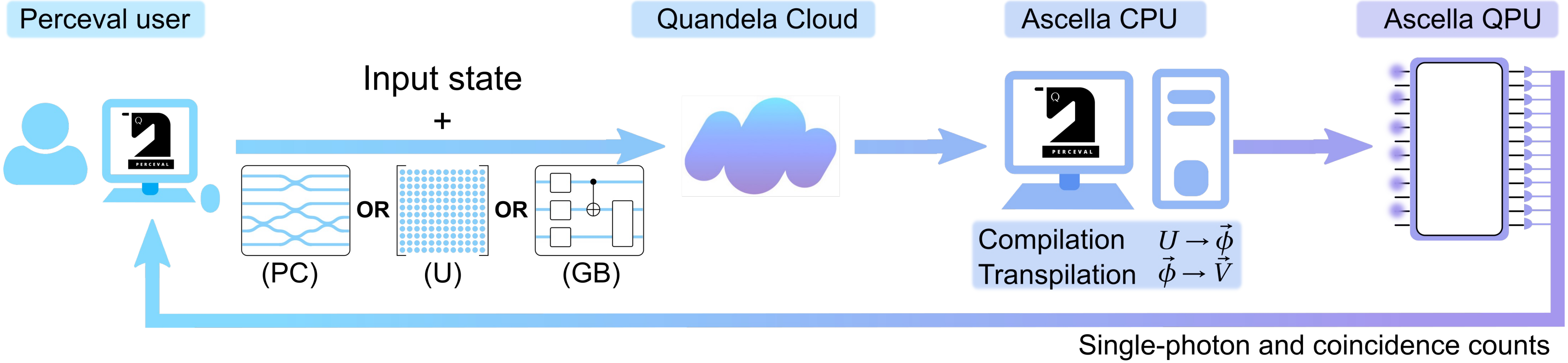
Cloud computing



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Qiskit to Perceval converter

A Qiskit QuantumCircuit can be converted to an equivalent Perceval Processor using QiskitConverter

```
>>> import qiskit
>>> from perceval.converters import QiskitConverter
>>> from perceval.components import catalog
>>> # Create a Quantum Circuit (the following is pure Qiskit syntax):
>>> qc = qiskit.QuantumCircuit(2)
>>> qc.h(0)
>>> qc.cx(0, 1)
>>> print(qc.draw())
     ┌───┐     
q_0: ┤ H ├──■──
     └───┘┌─┴─┐
q_1: ─────┤ X ├
          └───┘

>>> # Then convert the Quantum Circuit with Perceval QiskitConvertor
>>> qiskit_convertor = QiskitConverter(catalog)
>>> perceval_processor = qiskit_convertor.convert(qc)
```

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VQE error mitigation scheme

Error mitigation scheme inspired from [1]

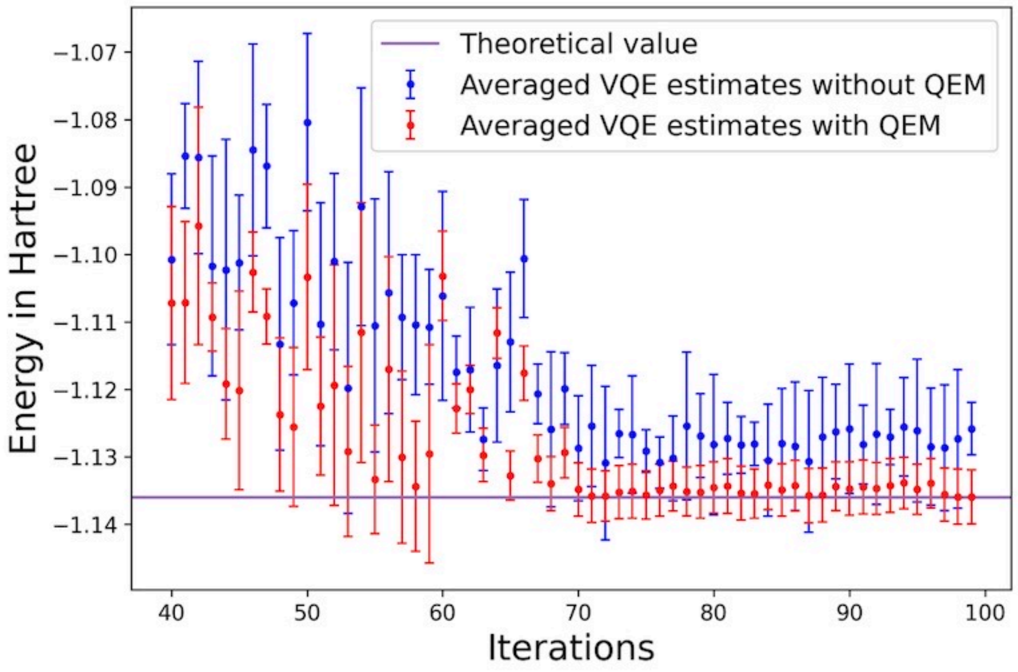
State preparation and measurement (SPAM) errors

Correct probability distribution $q = \Gamma_b p$

Evaluate right before experiment $(\Gamma_b)_{ij} = |\langle\psi|_i^b \, b \, |\psi\rangle_j^b|^2$

$$\Gamma_{ZZ} = \begin{bmatrix} 9.99999952e-01 & 3.09568451e-02 & 3.09568451e-02 & 1.54929555e-09 \\ 2.34741773e-08 & 9.38086308e-01 & 1.45337301e-09 & 2.34741773e-08 \\ 2.34741773e-08 & 1.45337301e-09 & 9.38086308e-01 & 2.34741773e-08 \\ 1.54929555e-09 & 3.09568451e-02 & 3.09568451e-02 & 9.99999952e-01 \end{bmatrix}$$

$$\Gamma_{XX} = \begin{bmatrix} 9.99999951e-01 & 2.47148265e-02 & 2.47148265e-02 & 1.24580719e-09 \\ 2.39578331e-08 & 9.50570344e-01 & 1.18422748e-09 & 2.39578331e-08 \\ 2.39578331e-08 & 1.18422748e-09 & 9.50570344e-01 & 2.39578331e-08 \\ 1.24580731e-09 & 2.47148287e-02 & 2.47148287e-02 & 9.99999951e-01 \end{bmatrix}$$



[1] D. Lee et al. *Optica* 9, 88-95 (2022)

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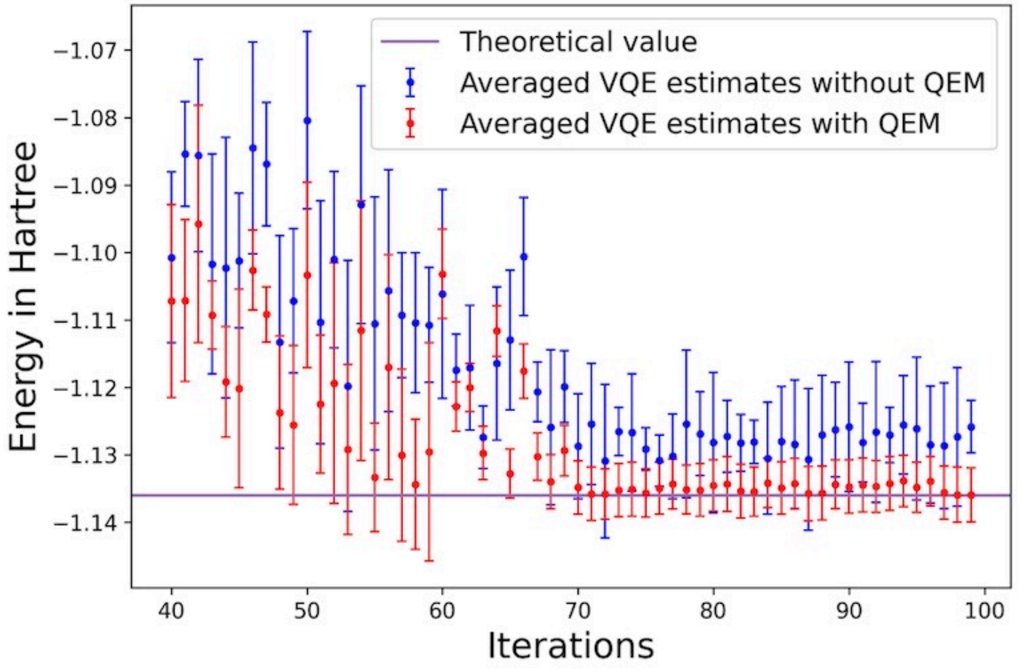

New results on QEM for photon loss coming out in May (J. Mills and R. Mezher, in preparation)

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QUIZZ

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Measurement-based quantum computing and photonics

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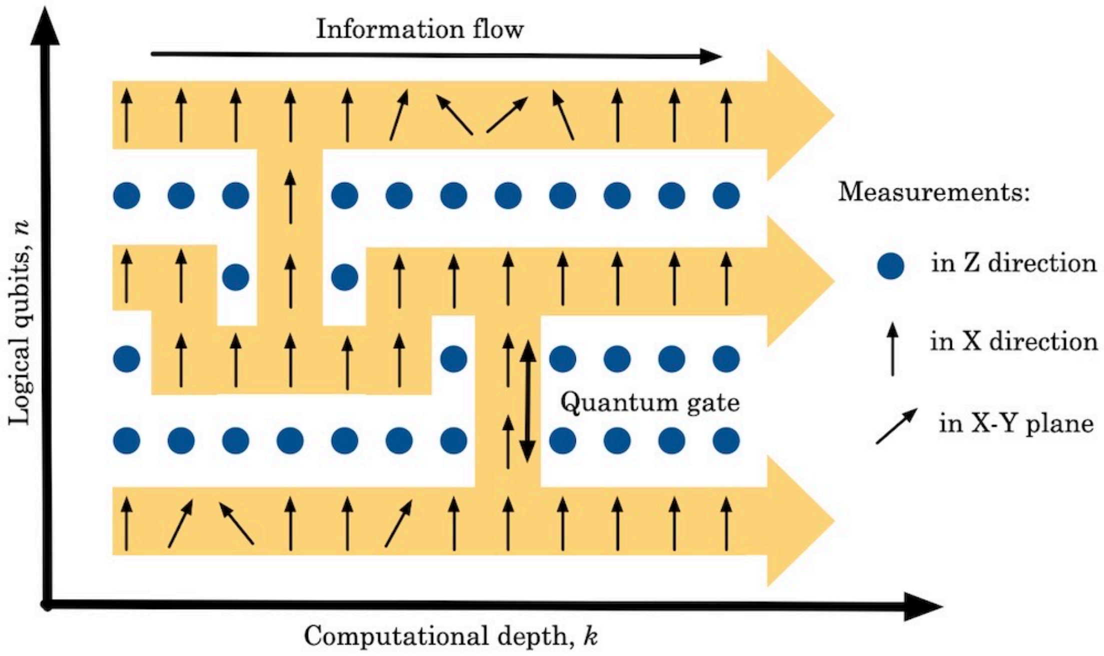
Photonic platforms – scaling proposals

Measurement based quantum computing (MBQC)



Proposed by R. Raussendorf and H. J. Briegel in *A One-Way Quantum Computer* (2001)

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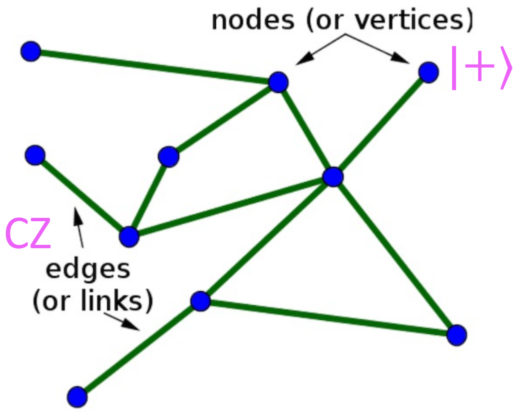
MBQC is based on graph states

- **Circuit model:**
  - Evolve unitarily qubits through a circuit by applying on the qubits the gates one-by-one
  - Measure (read-out) at the end to convert quantum information to classical

- **MBQC model:**
  - Start with a large entangled state consisting of multiple qubits (also called resource state, cluster state)
  - Make single-qubit measurements in suitably chosen bases
  - Apply corrections to make it deterministic



Petros Wallden. Lectures http://pwallden.gr/courseiqc.asp

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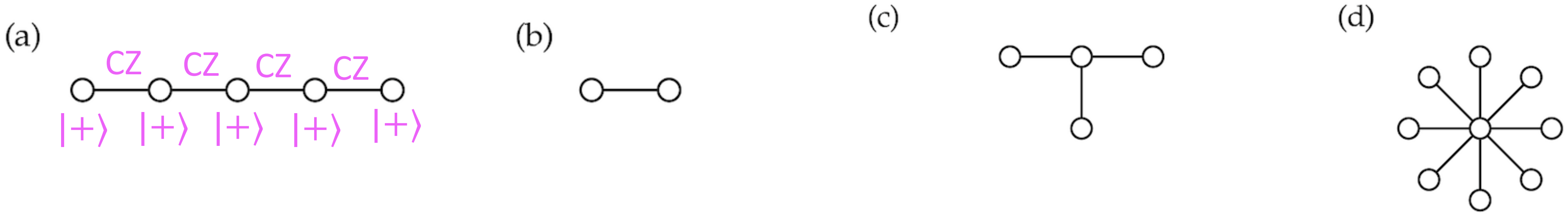

P. Kok et al. Rev. Mod. Phys. 79, 135 (2007)

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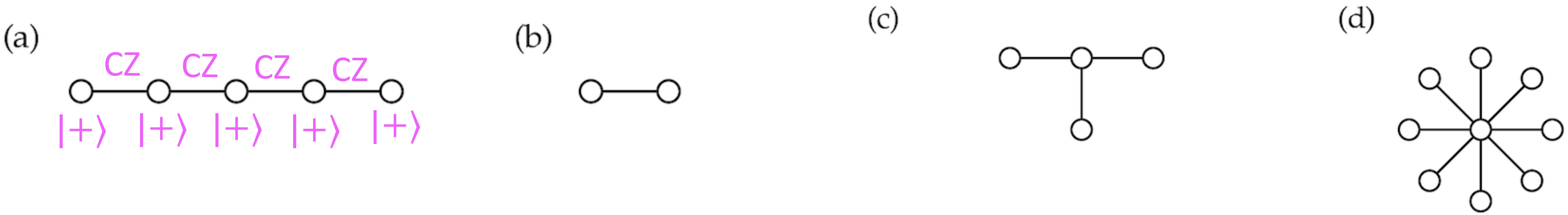
What are (b), (c) and (d) equivalent to?



P. Kok et al. Rev. Mod. Phys. 79, 135 (2007)

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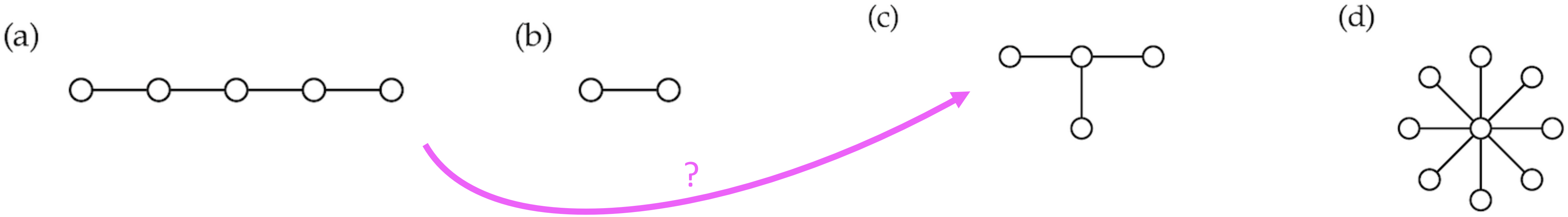
  - Make single-qubit measurements in suitably chosen bases
  - Apply corrections to make it deterministic

Z meas: removes qubit and severs all bonds with cluster
X meas: removes qubit and transfers all the bonds



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MBQC is universal

MBQC is universal and equivalent to circuit model

Milestone

Measurement-based quantum computation on cluster states

Robert Raussendorf, Daniel E. Browne, and Hans J. Briegel
Phys. Rev. A **68**, 022312 – Published 25 August 2003

Based on set of $J(\theta) = \frac{1}{\sqrt{2}}\begin{pmatrix} 1 & e^{i\theta} \\ 1 & -e^{i\theta} \end{pmatrix}$ gates for all θ and CZ gates which is universal

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MBQC is universal

Milestone

Measurement-based quantum computation on cluster states

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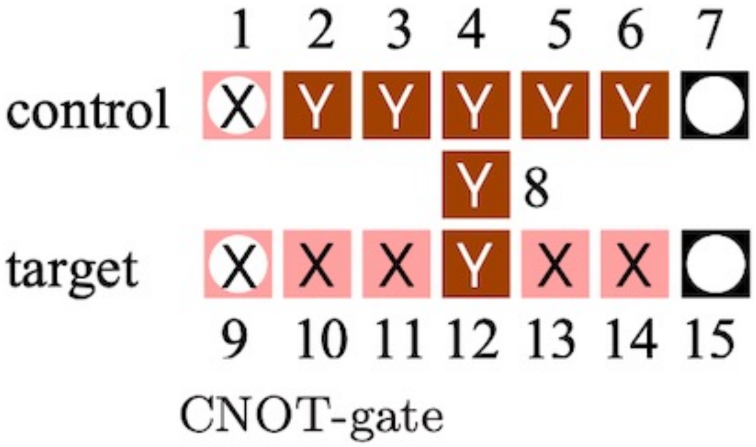
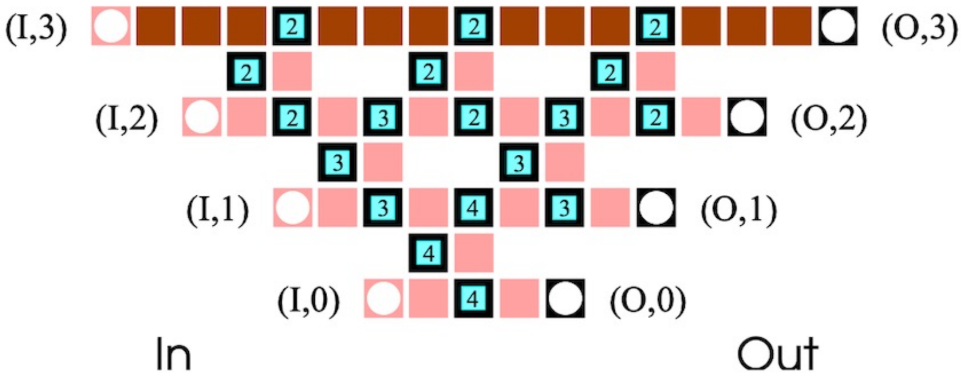
Phys. Rev. A **68**, 022312 – Published 25 August 2003

Nice examples in the paper like how to do the quantum Fourier transform in MBQC





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MBQC examples for variational algorithms

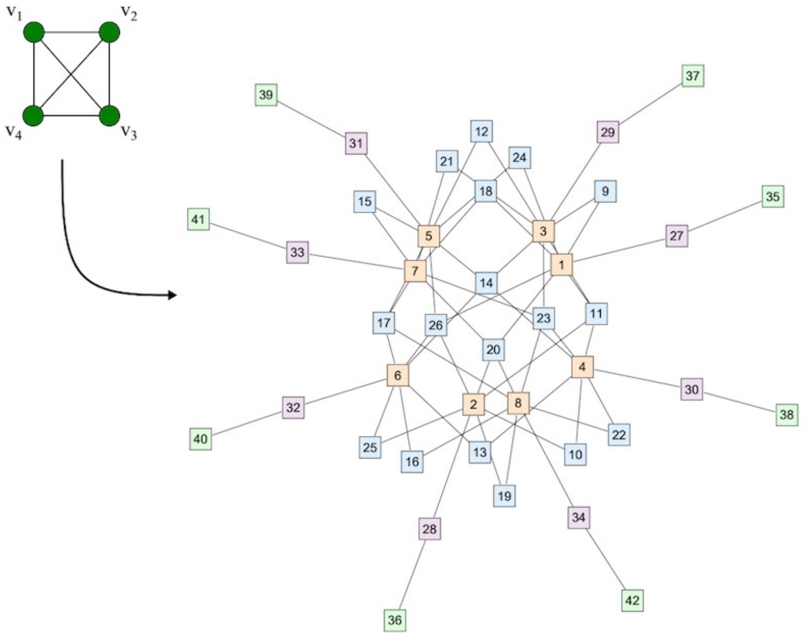
Native measurement-based quantum approximate optimization algorithm applied to the Max K-Cut problem

Massimiliano Proietti, Filippo Cerocchi, and Massimiliano Dispenza
Phys. Rev. A **106**, 022437 – Published 30 August 2022

Variational measurement-based quantum computation for generative modeling

Arunava Majumder[1], Marius Krumm[1], Tina Radkohl[1], Hendrik Poulsen Nautrup[1], Sofiene Jerbi[2], and Hans J. Briegel[1]

[1]Institute for Theoretical Physics, University of Innsbruck, Technikerstr. 21a, A-6020 Innsbruck, Austria
[2]Dahlem Center for Complex Quantum Systems, Freie Universität Berlin, Berlin, Germany



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Measurement based proposal for photonics

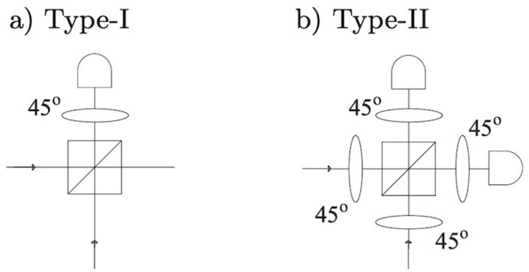
Resource-Efficient Linear Optical Quantum Computation

Daniel E. Browne and Terry Rudolph
Phys. Rev. Lett. **95**, 010501 – Published 27 June 2005

Improvement on KLM proposal for a linear optical quantum computer

Using MBQC framework

Introducing fusion mechanisms that allow for the construction of cluster states



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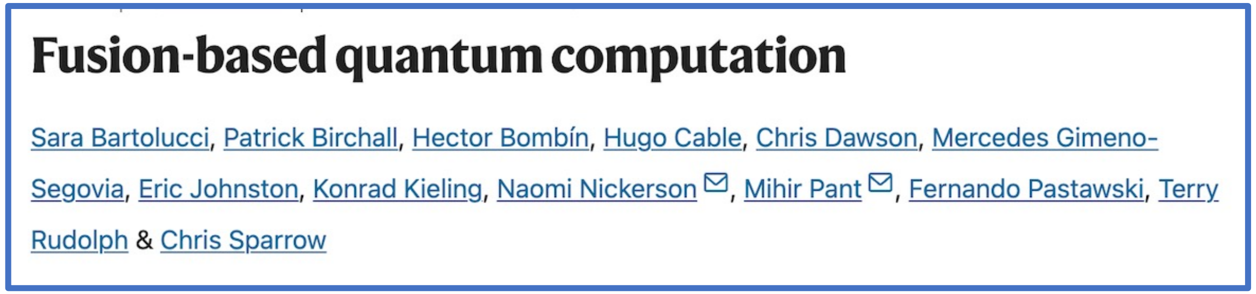
Measurement based proposal for photonics



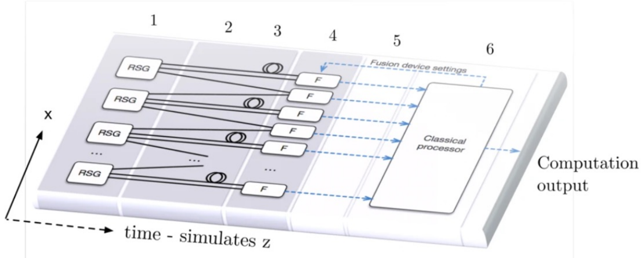
Fusion-based quantum computation

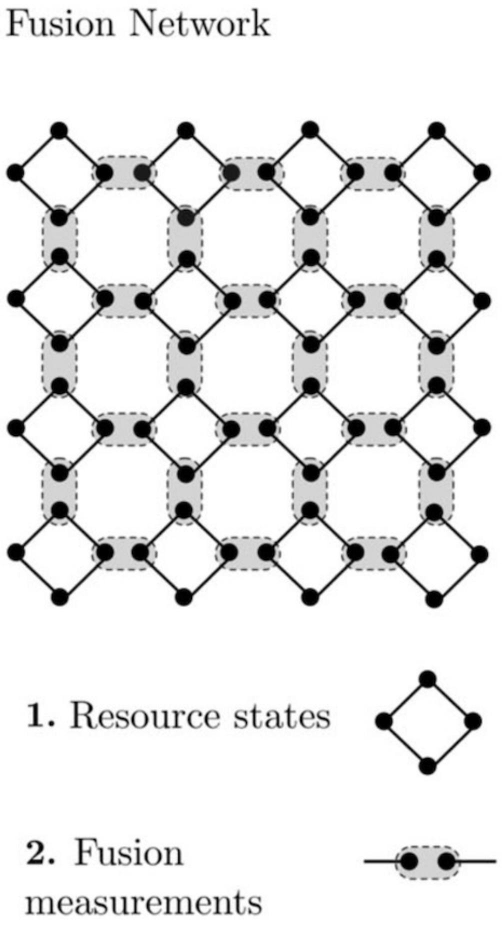
Sara Bartolucci, Patrick Birchall, Hector Bombín, Hugo Cable, Chris Dawson, Mercedes Gimeno-Segovia, Eric Johnston, Konrad Kieling, Naomi Nickerson ✉, Mihir Pant ✉, Fernando Pastawski, Terry Rudolph & Chris Sparrow

Proposal by PsiQuantum

Compared to MBQC it already integrates fault tolerance

Proposal comes with photonic hardware as well





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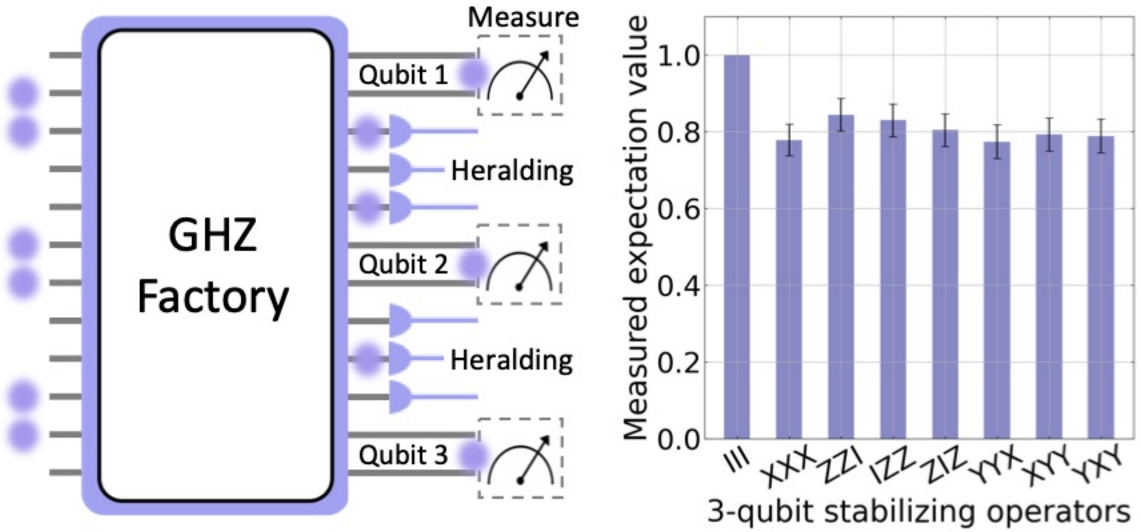
Paths for graph state generation: GHZ states



Heralded generation of 3-photon GHZ states. Measured expectation values of the stabilizing operators of the heralded 3-photon GHZ state $|\mathrm{GHZ}_3^+\rangle$ yielding a fidelity of $F_{\mathrm{GHZ}_3^+} = 0.82 \pm 0.04$.

Generate small GHZ states
Add fusion operations

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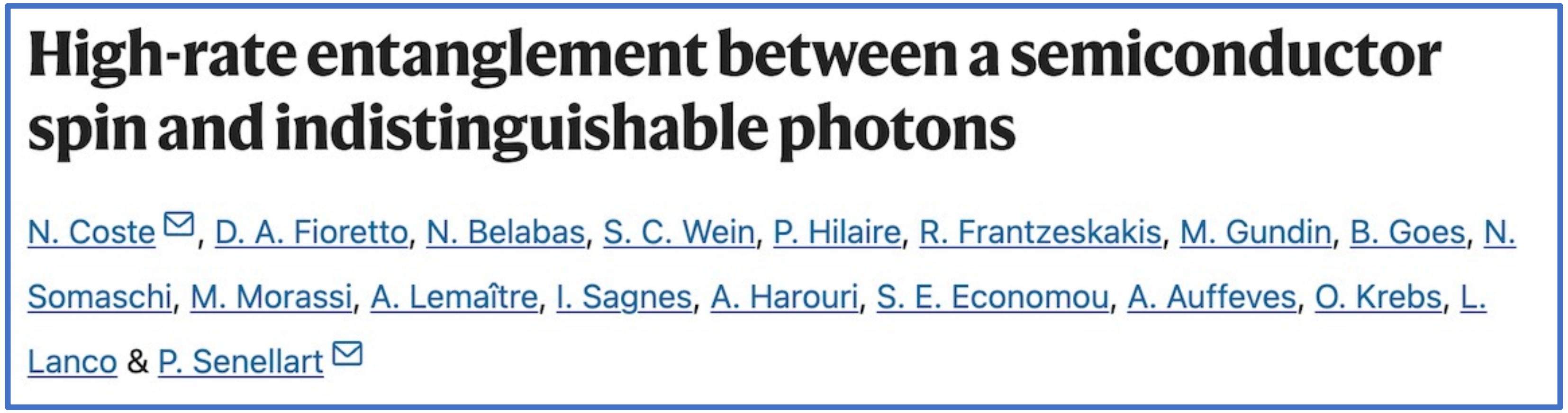
Paths for graph state generation: from the source



High-rate entanglement between a semiconductor spin and indistinguishable photons

N. Coste, D. A. Fioretto, N. Belabas, S. C. Wein, P. Hilaire, R. Frantzeskakis, M. Gundin, B. Goes, N. Somaschi, M. Morassi, A. Lemaître, I. Sagnes, A. Harouri, S. E. Economou, A. Auffeves, O. Krebs, L. Lanco & P. Senellart

Proposal for Pulsed On-Demand Sources of Photonic Cluster State Strings

Netanel H. Lindner and Terry Rudolph
Phys. Rev. Lett. **103**, 113602 – Published 8 September 2009

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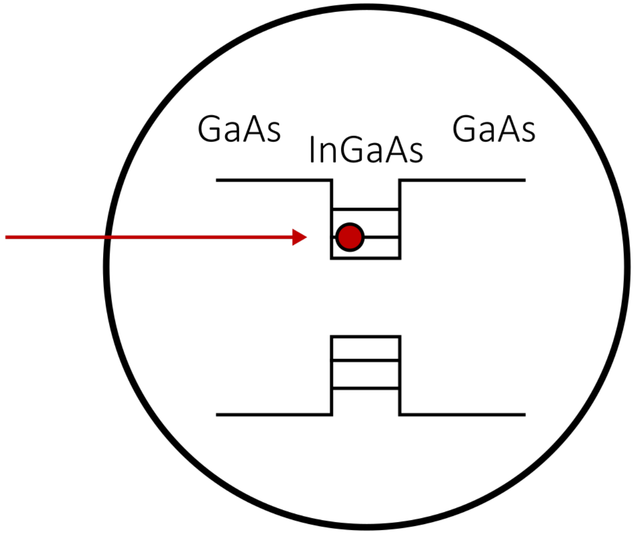

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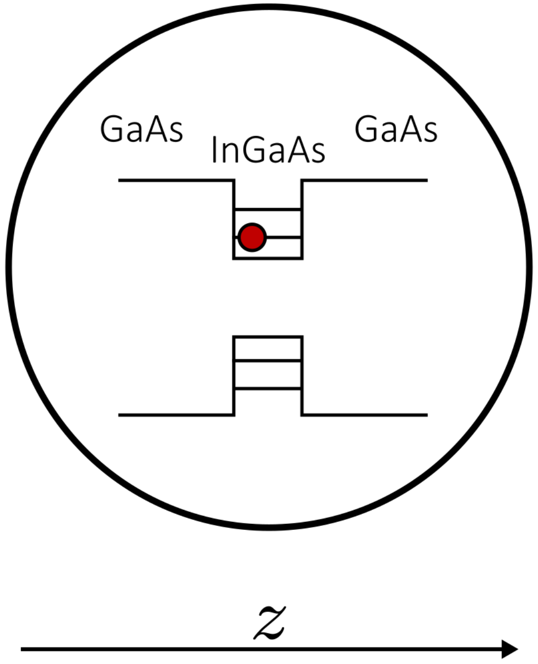
Paths for graph state generation: from the source



spin basis: $|{\downarrow_z}\rangle\,,|{\uparrow_z}\rangle$

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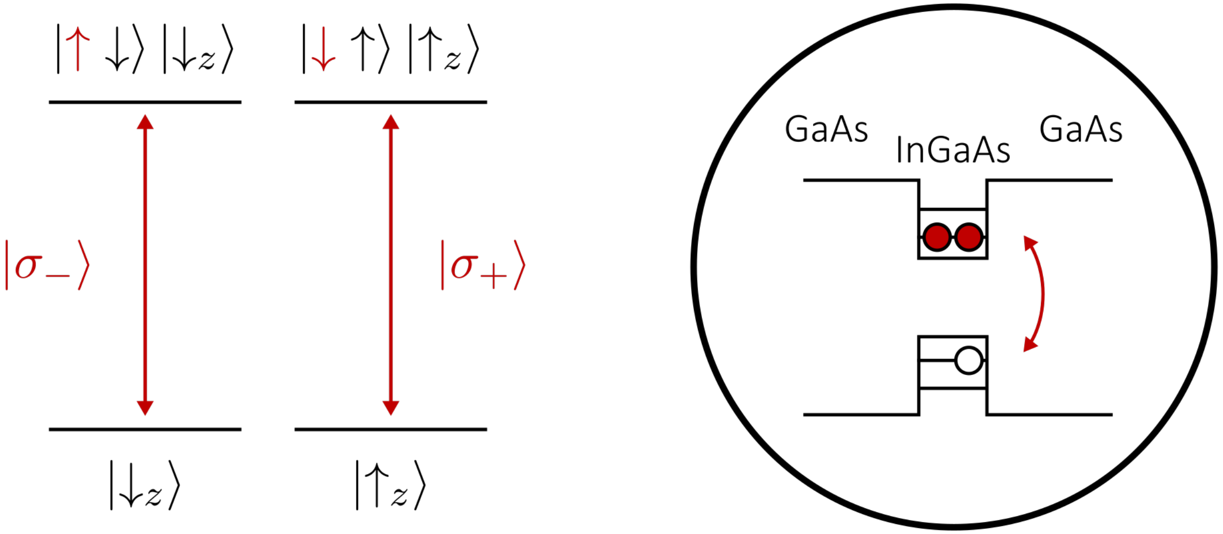

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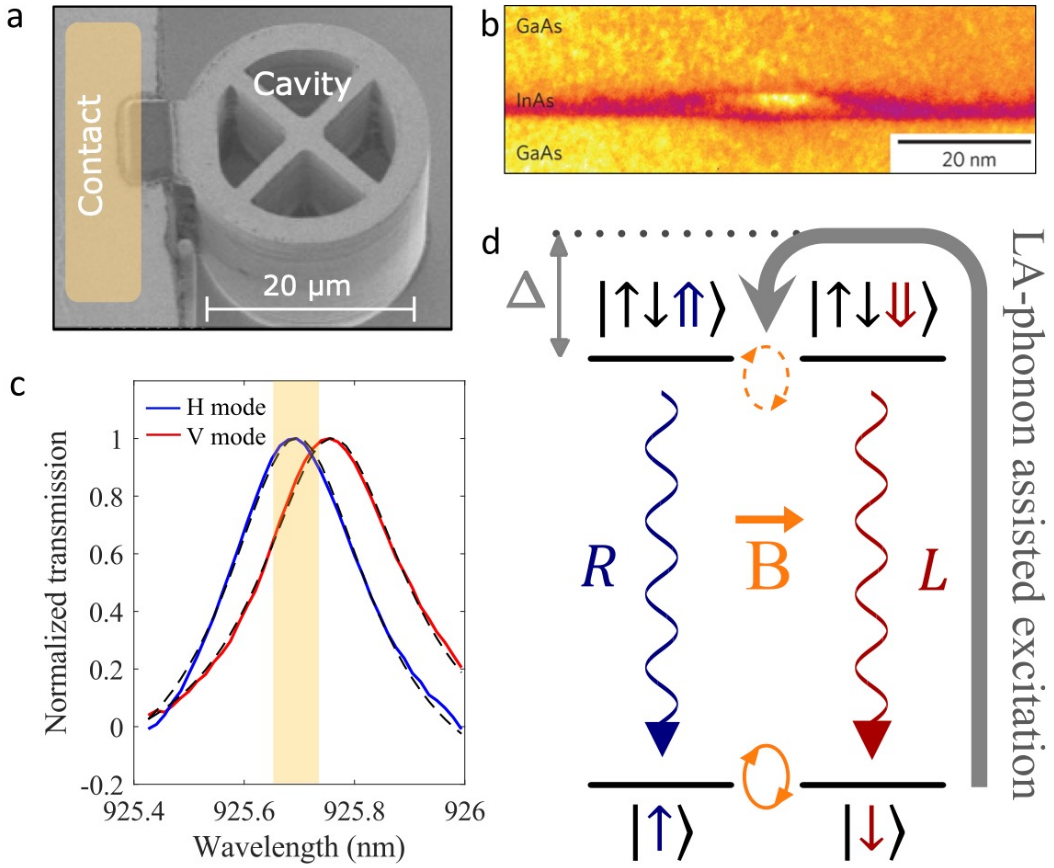

N. Coste et al., Nat. Photon. 17, 582 (2023)

$$|\uparrow\rangle|R\rangle + |\downarrow\rangle|L\rangle$$

Spin-photon entanglement

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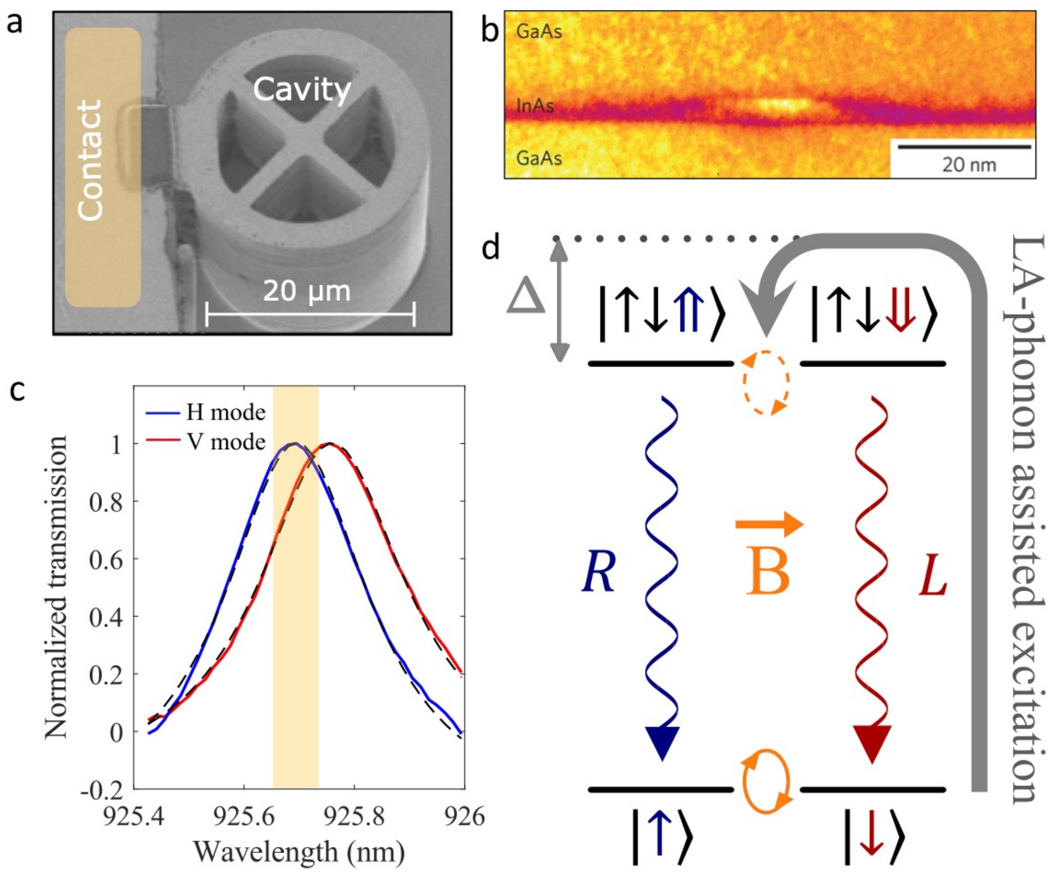

N. Coste et al., Nat. Photon. 17, 582 (2023)

$$|\uparrow\rangle|R\rangle + |\downarrow\rangle|L\rangle$$

$^{\pi}/_{2}$ spin-gate

$$\frac{|\uparrow\rangle + |\downarrow\rangle}{\sqrt{2}}|R\rangle + \frac{|\uparrow\rangle - |\downarrow\rangle}{\sqrt{2}}|L\rangle$$

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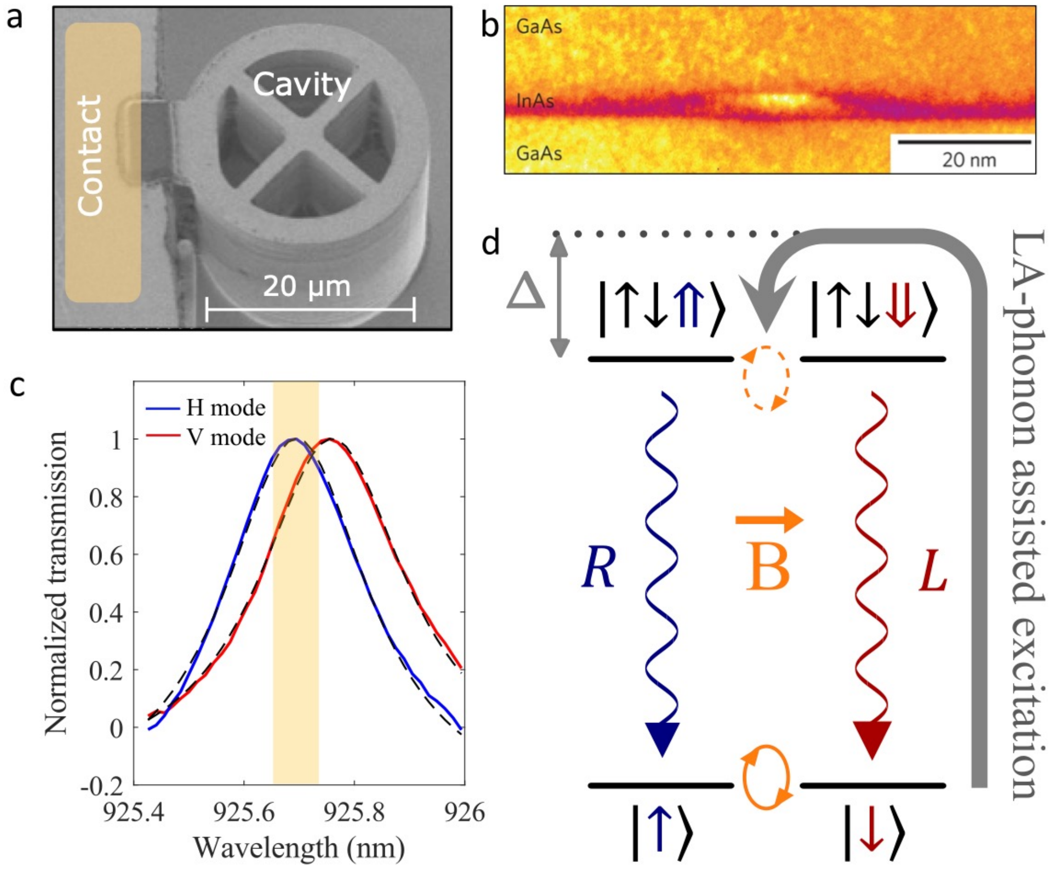

N. Coste et al., Nat. Photon. 17, 582 (2023)

$$|\uparrow\rangle|R\rangle + |\downarrow\rangle|L\rangle$$

$^{\pi}/_{2}$ spin-gate

$$-i|\uparrow\rangle|V\rangle + |\downarrow\rangle|H\rangle$$

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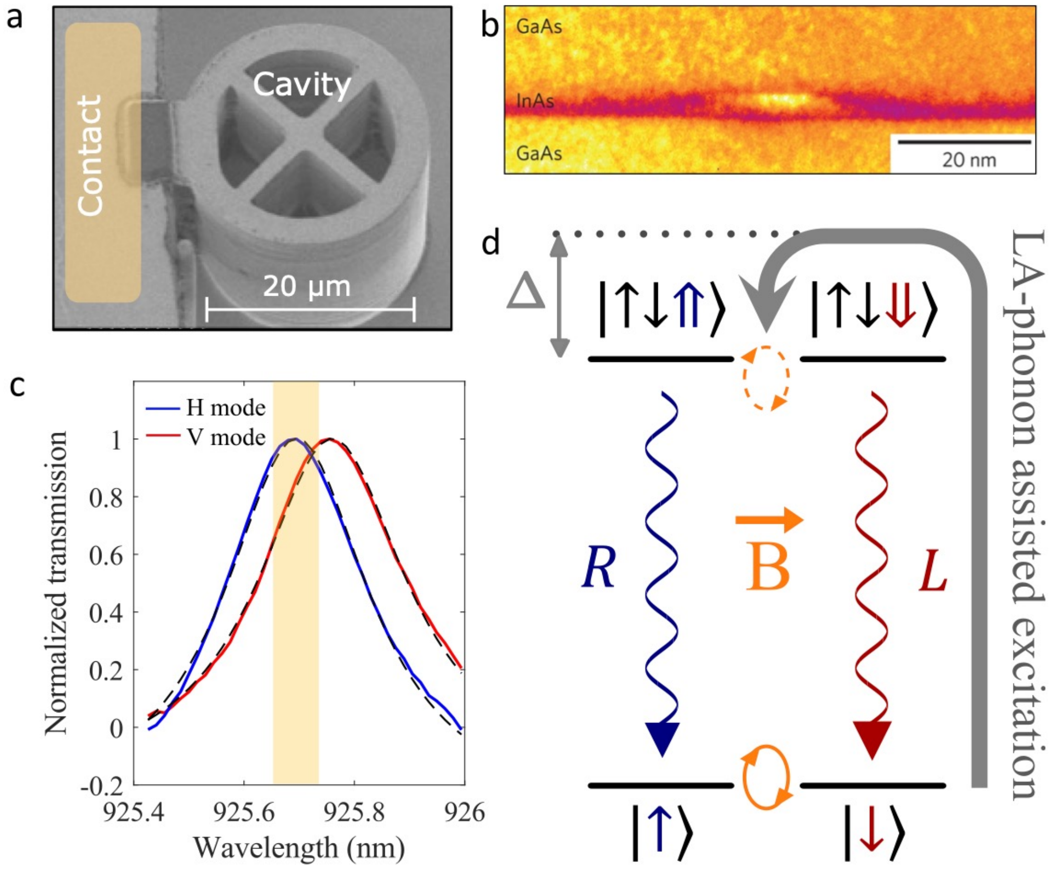

N. Coste et al., Nat. Photon. 17, 582 (2023)

$$|\uparrow\rangle|R\rangle + |\downarrow\rangle|L\rangle$$

$^{\pi}/_{2}$ spin-gate

$$-i|\uparrow\rangle|V\rangle + |\downarrow\rangle|H\rangle$$

Excitation H

$$-i|\uparrow\rangle|V\rangle|R\rangle + |\downarrow\rangle|H\rangle|L\rangle$$

…

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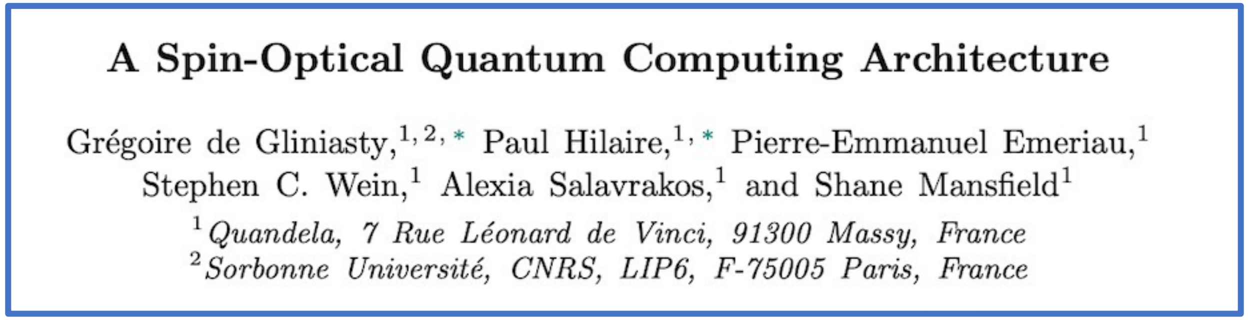
Fault tolerant architecture proposal: SPOQC



A Spin-Optical Quantum Computing Architecture

Grégoire de Gliniasty,[1,2,*] Paul Hilaire,[1,*] Pierre-Emmanuel Emeriau,[1]
Stephen C. Wein,[1] Alexia Salavrakos,[1] and Shane Mansfield[1]
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[2] *Sorbonne Université, CNRS, LIP6, F-75005 Paris, France*

General intuition:

- Strategies like FBQC can be achieved with many quantum dots
- Why not leverage those dots as carriers of quantum information?
- Trade-off between all-photonic and all-matter based approaches

- Using spins of quantum dots as qubits
- Using spin-entangled photon to perform 2-qubit gates

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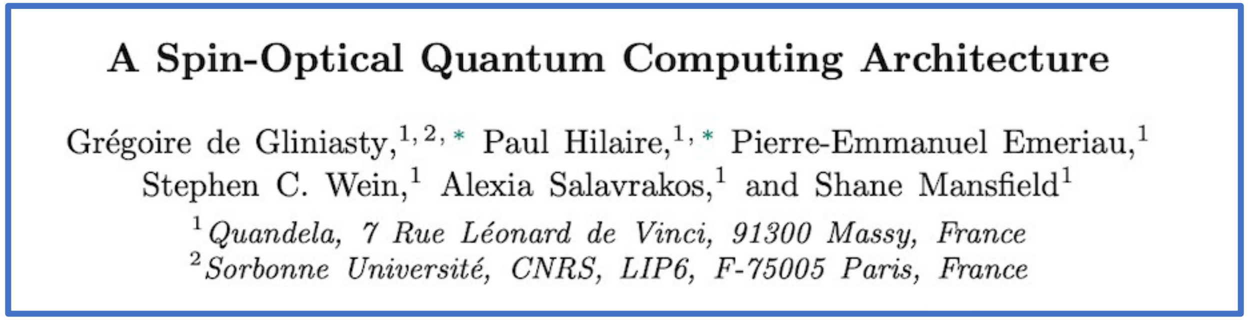
Fault tolerant architecture proposal: SPOQC



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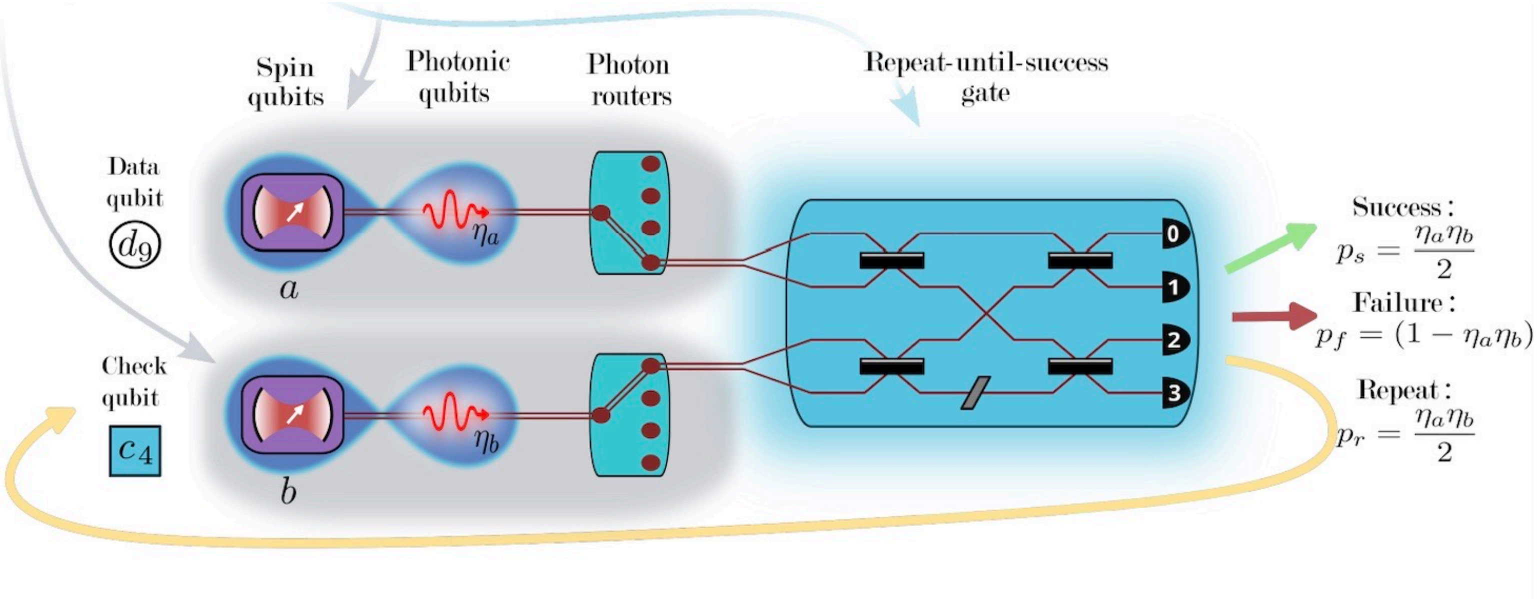

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QUIZZ

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Conclusions

- Near term photonic quantum computing:
    - LOQC (linear optics)
    - Boson Sampling
    - Variational and boson-sampling-based algorithms

- Medium term photonic quantum computing:
    - MBQC and other schemes

- Really cool resource to know more: Mercedes Gimeno-Segovia’s PhD thesis