QUANDELA

Variational quantum algorithms implemented on a general-purpose single-photon-based quantum computing platform

Alexia Salavrakos

QTML - 22 November 2023

@Quandela_SAS
@AlexiaSalavra

About Quandela

Founded in 2017
Spin off from Pascale Senellart's group at C2N
(CNRS & Paris-Saclay University)

Today:
80 people, with >50 scientists and engineers
New funding round announced on November 7

Quandela Scientific Advisory Board

R&D Centers

C2N - Palaiseau

Massy

Production Centers

IPVF - Palaiseau

Massy

Paris-Saclay
Munich
Barcelona
Cambridge

Collaboration between many teams

A general-purpose single-photon-based quantum computing platform

Nicolas Maring,[1] Andreas Fyrillas,[1,*] Mathias Pont,[1,2,*] Edouard Ivanov,[1,*] Petr Stepanov,[1] Nico Margaria,[1] William Hease,[1] Anton Pishchagin,[1] Thi Huong Au,[1] Sébastien Boissier,[1] Eric Bertasi,[1] Aurélien Baert,[1] Mario Valdivia,[1] Marie Billard,[1] Ozan Acar,[1] Alexandre Brieussel,[1] Rawad Mezher,[1] Stephen C. Wein,[1] Alexia Salavrakos,[1] Patrick Sinnott,[1] Dario A. Fioretto,[2] Pierre-Emmanuel Emeriau,[1] Nadia Belabas,[2] Shane Mansfield,[1] Pascale Senellart,[2] Jean Senellart,[1] and Niccolo Somaschi[1]

[1] *Quandela, 7 Rue Léonard de Vinci, 91300 Massy, France*
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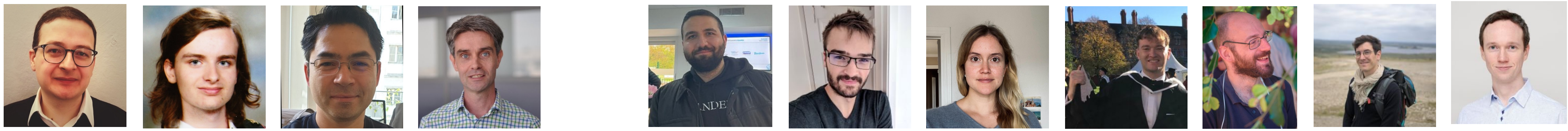
(Dated: June 2, 2023)

arXiv:2306.00874



Many of us are used to working with kets $|\psi\rangle$ and matrices U…

How do we implement protocols in practice?

What are the challenges that can arise?

Outline

1. Experimental setup
2. Photonic quantum computing
3. Demonstrations of variational quantum algorithms

Ascella Quantum Computing Platform

Ascella Quantum Computing Platform

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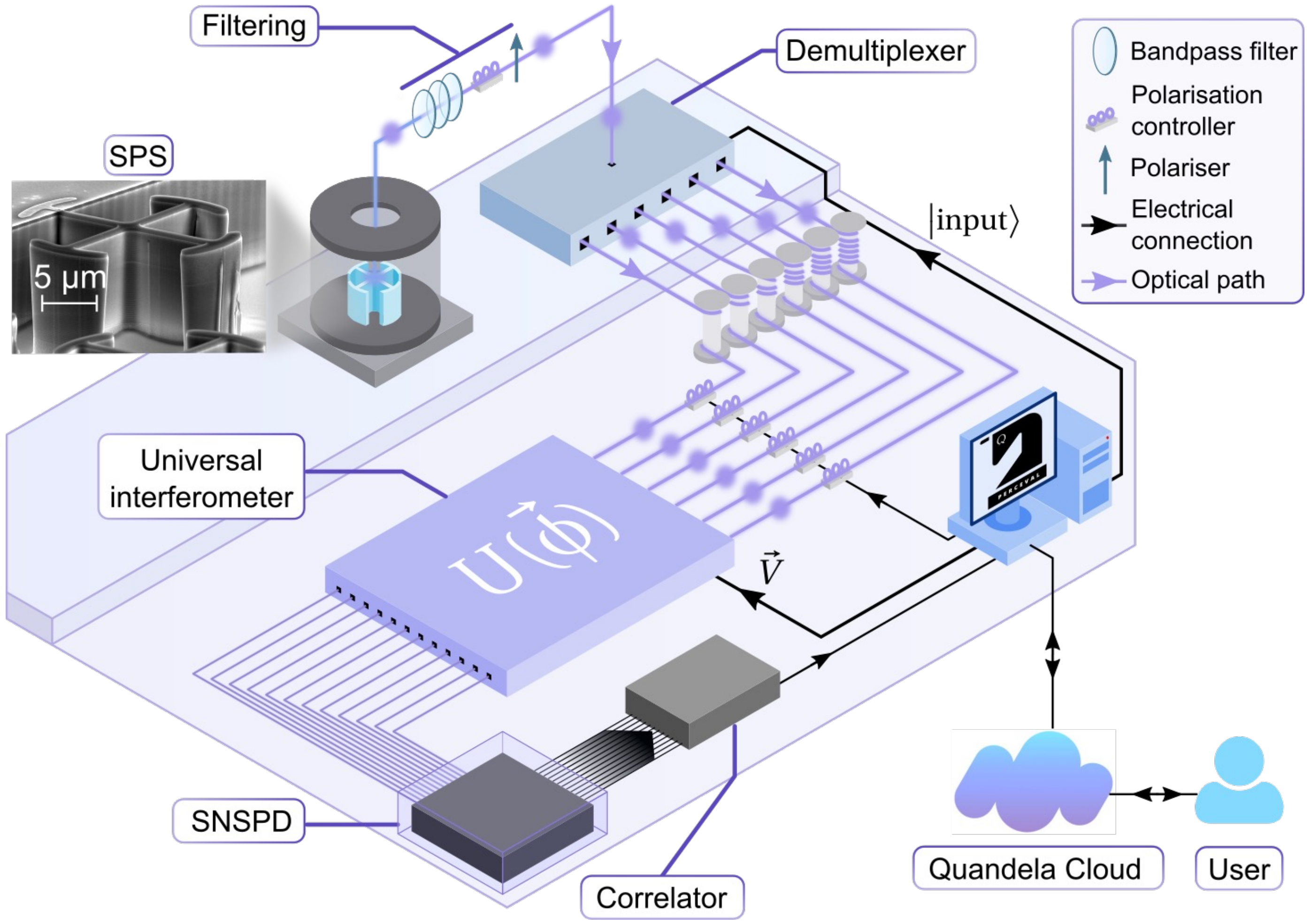
Ascella Quantum Computing Platform



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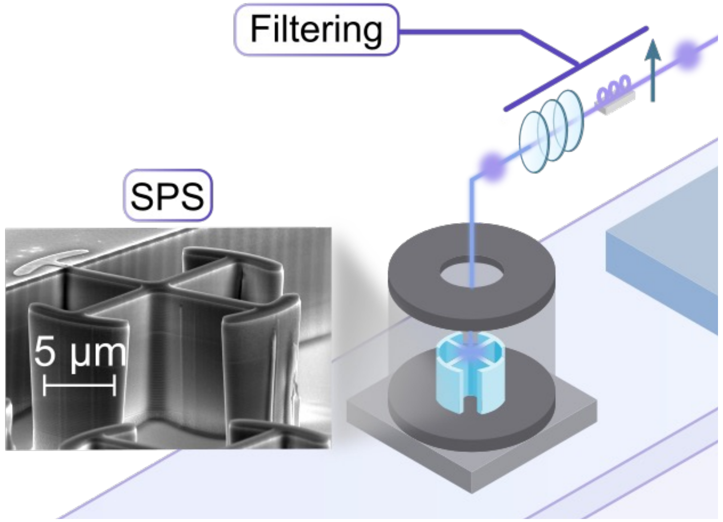
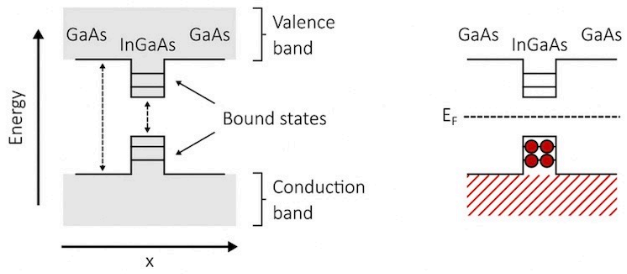
Photon source

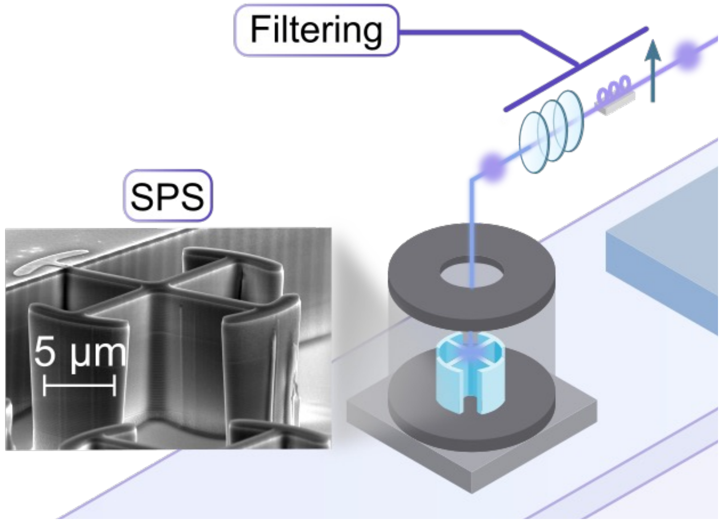


Quantum dot

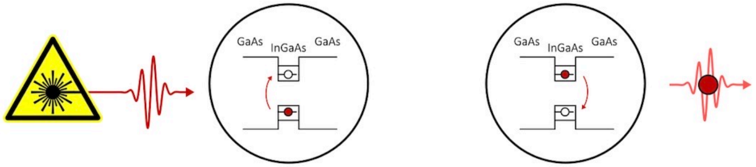


In micropillar cavity

Photon source



Quantum dot



In micropillar cavity

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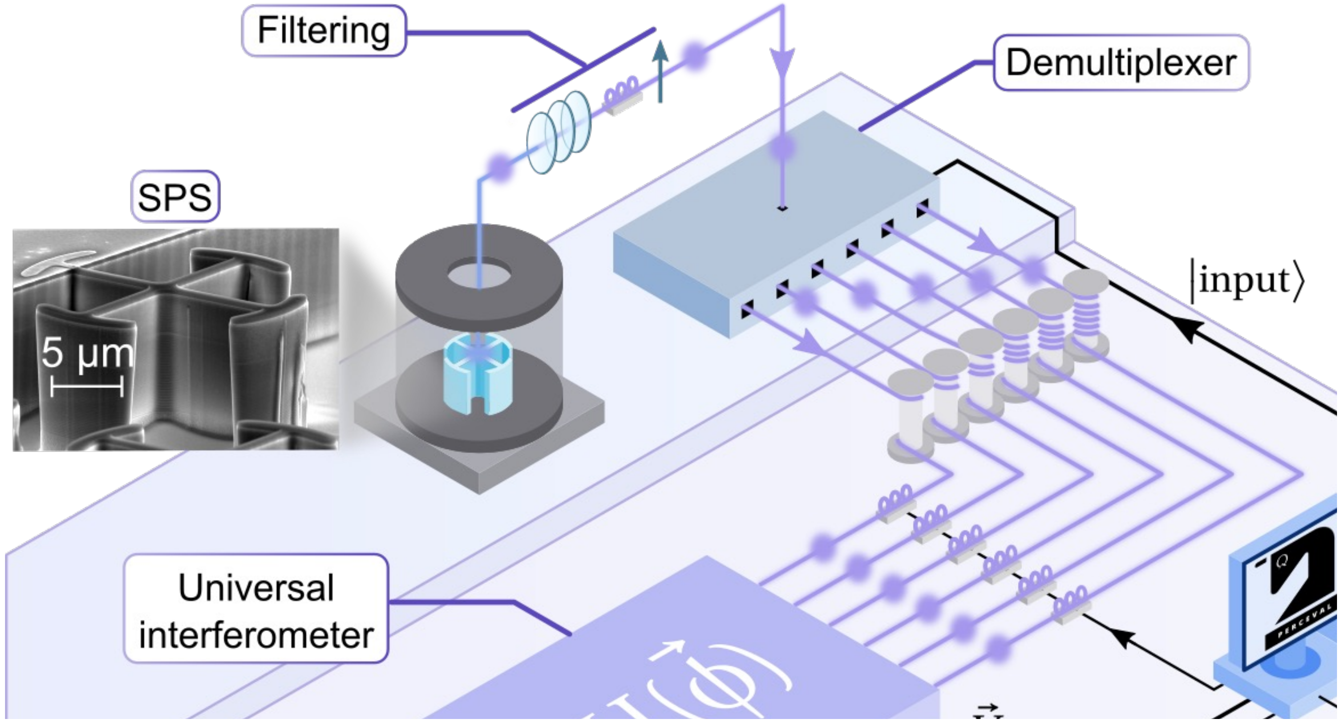
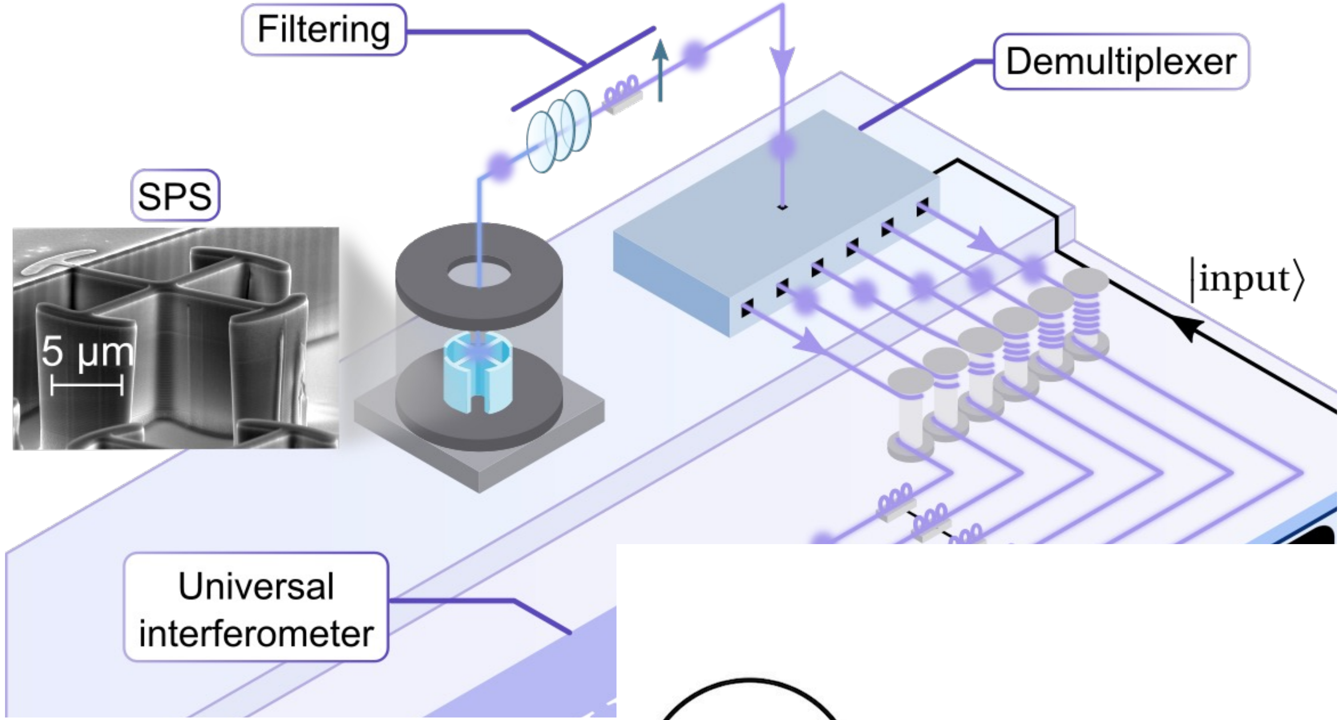
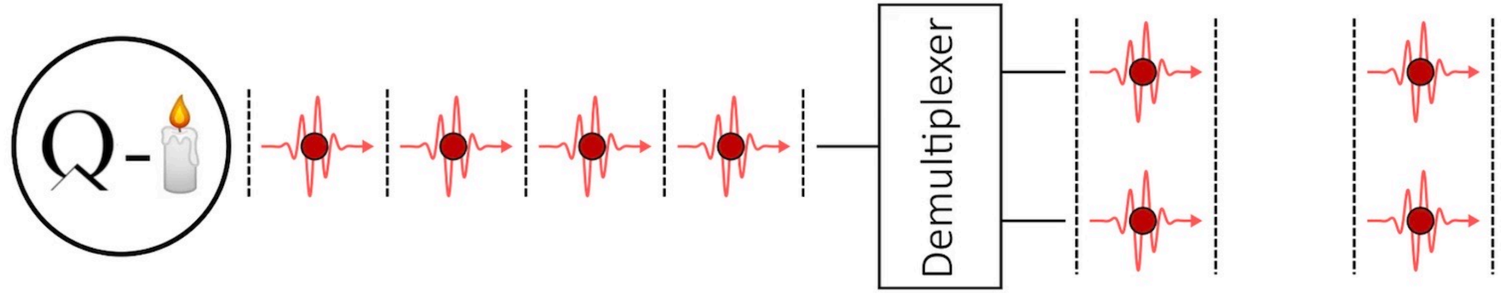
Demultiplexer



Demultiplexer





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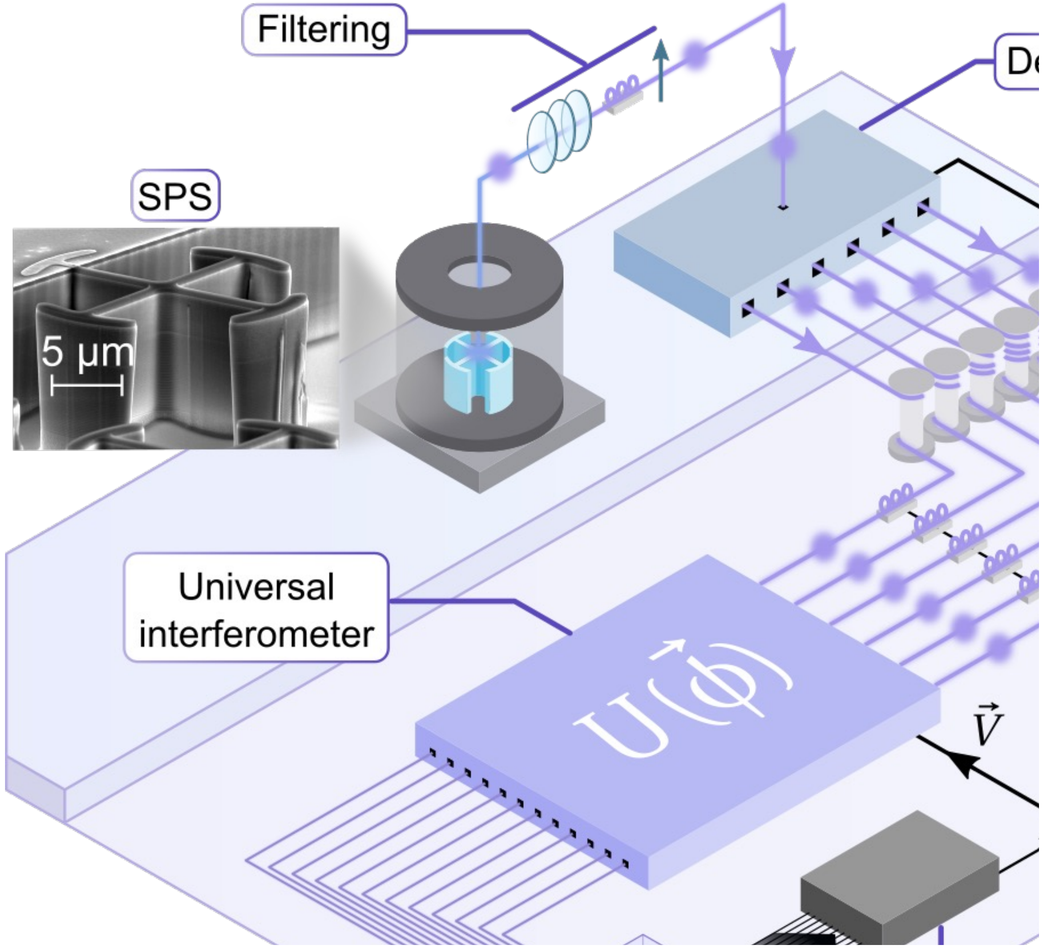
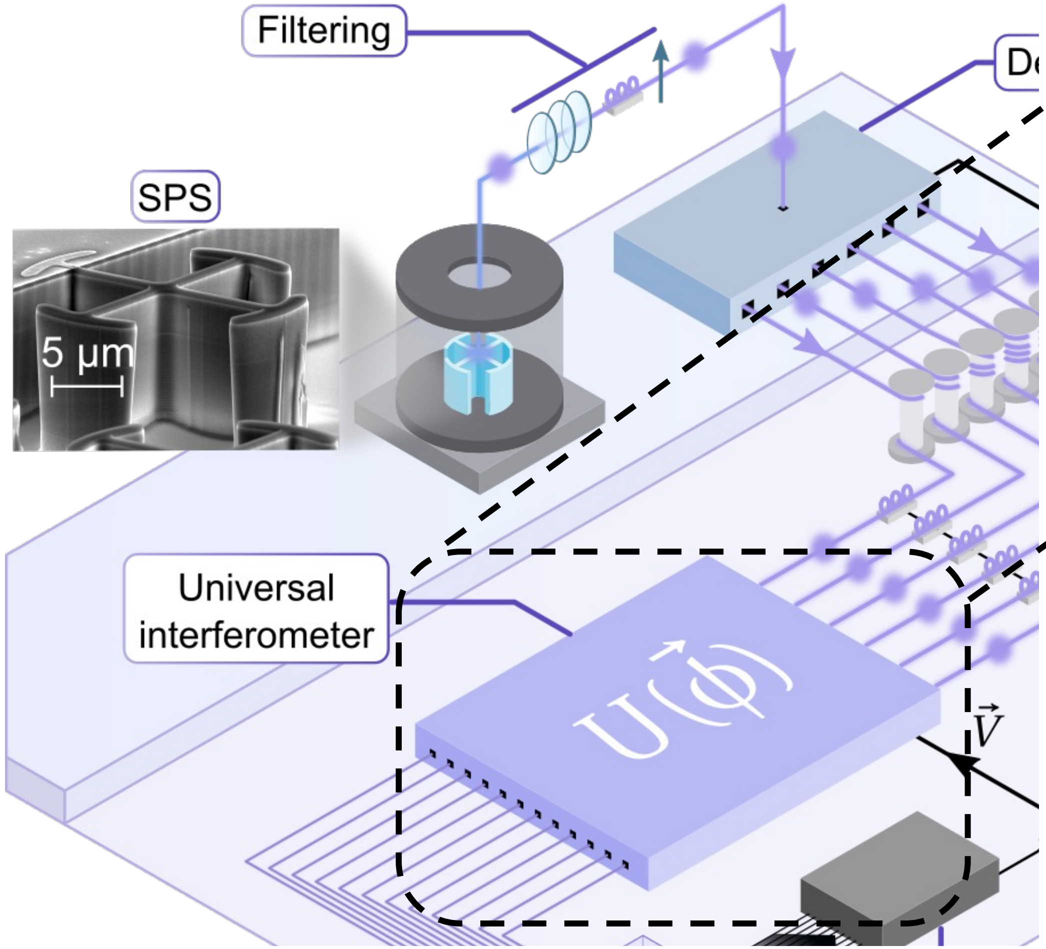
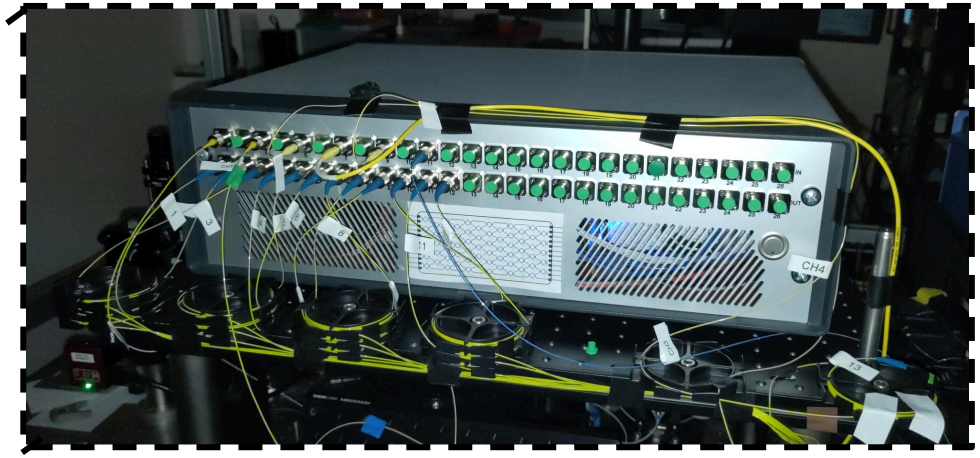
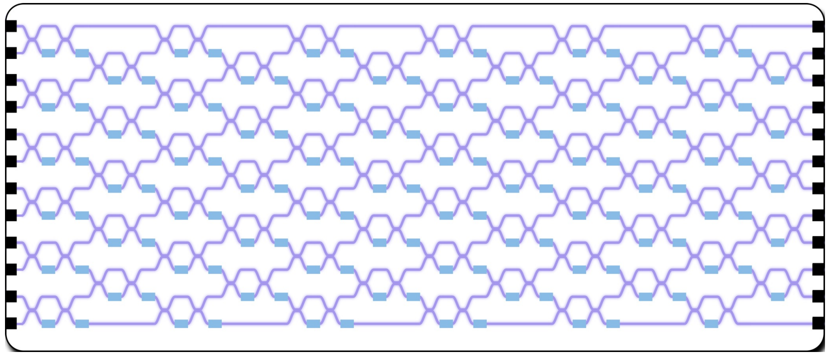
Photonic circuit



Photonic circuit







12 x 12 fully reconfigurable universal interferometer

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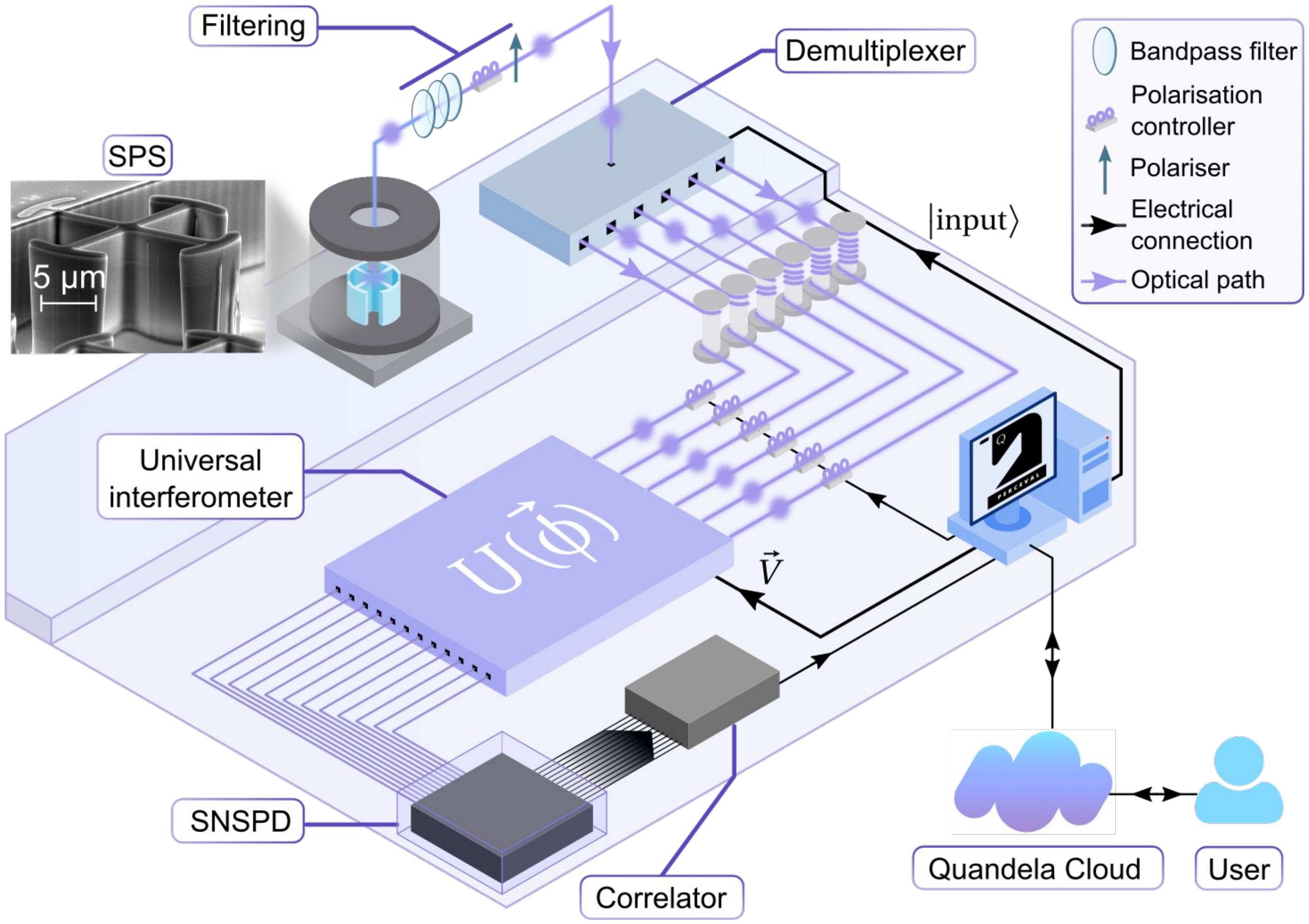
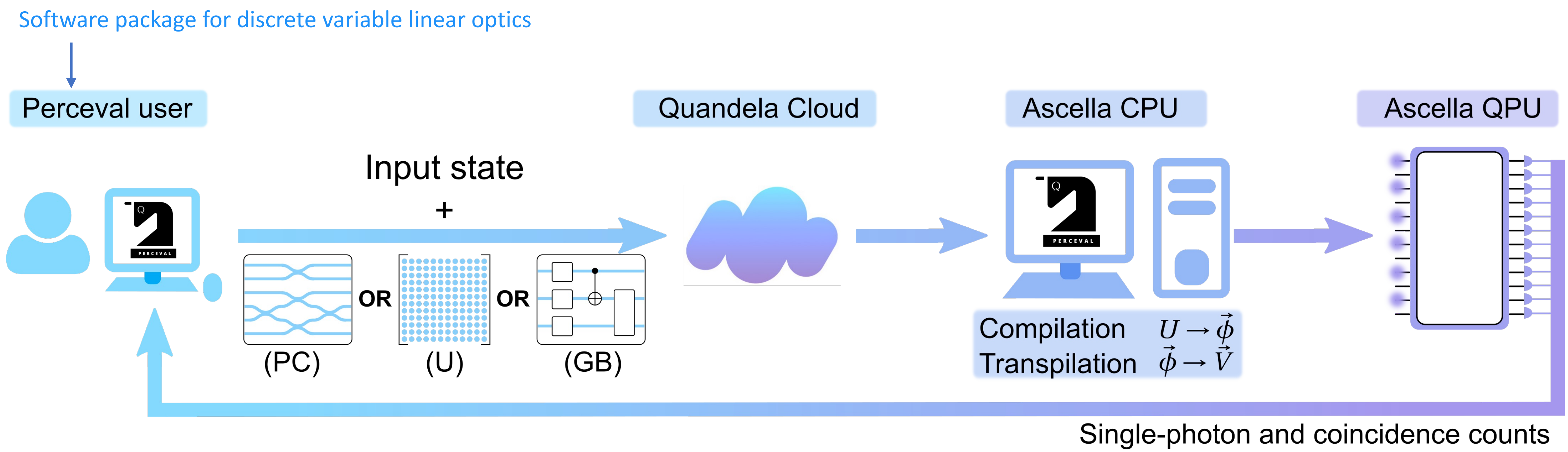
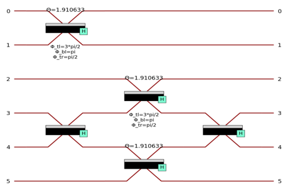
Ascella Quantum Computing Platform



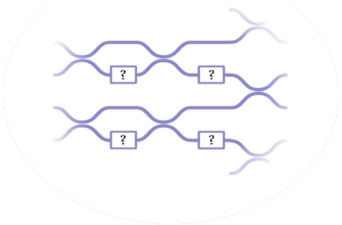
Computation process

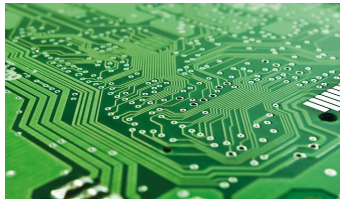


Compilation and transpilation



$$\hat{U}$$

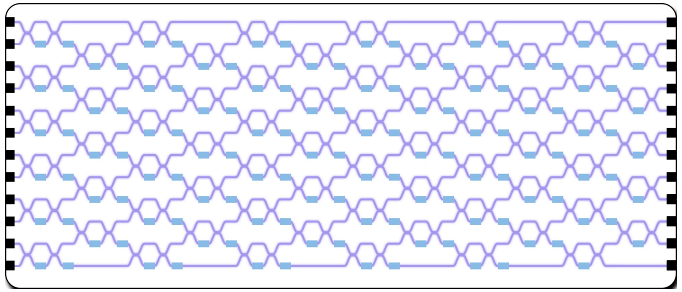




Circuit → Unitary matrix → Phases → Voltages

Compilation (Circuit → Unitary matrix → Phases)

Transpilation (Phases → Voltages)



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*

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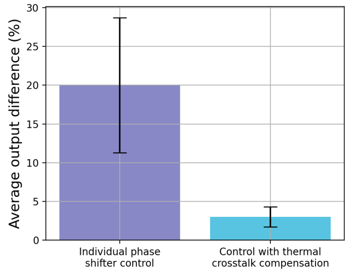
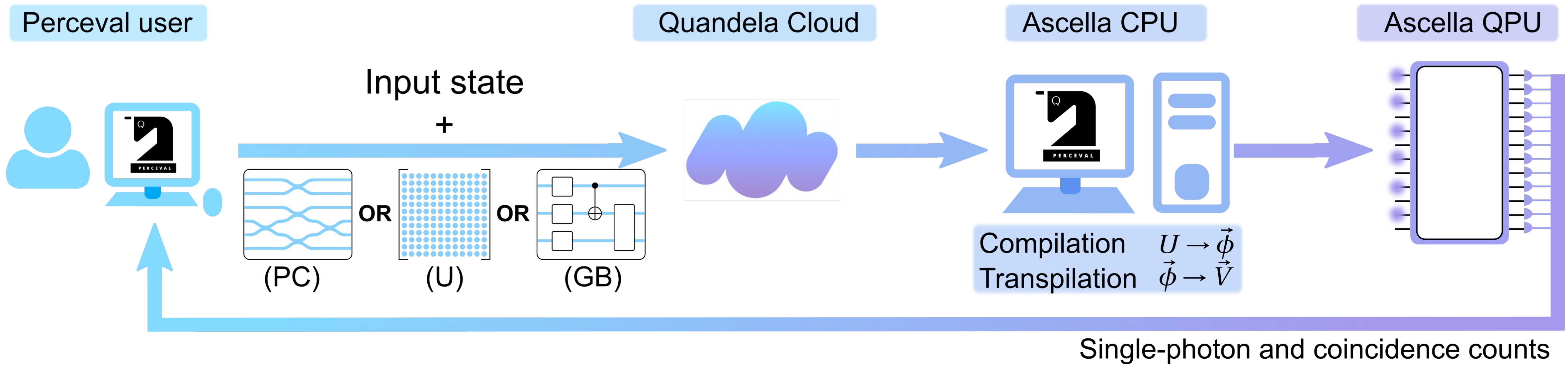


arXiv:2310.15349

"ML for Q"

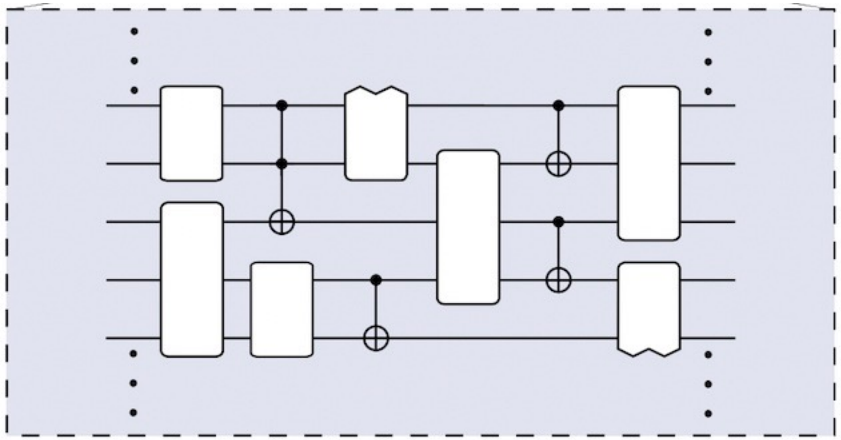
Computation process



Photonic quantum computing

Computation models

We are used to the qubit quantum circuit model, especially in QML



M. Cerezo et al. Nature Reviews Physics 3, 625-644 (2021)

Computation models

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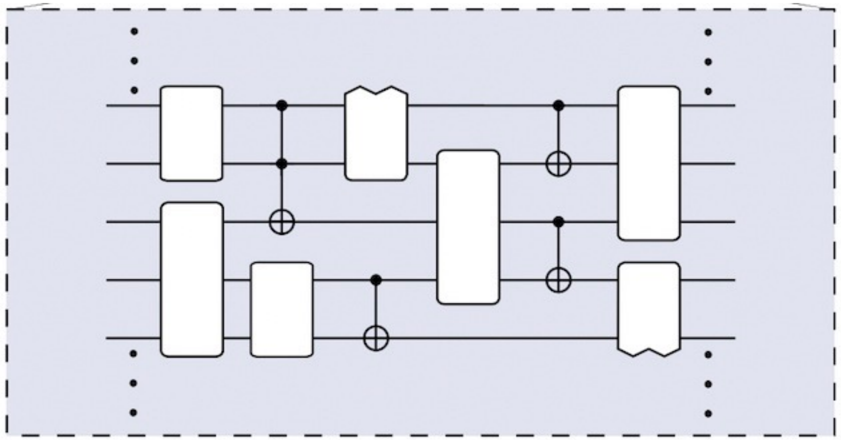
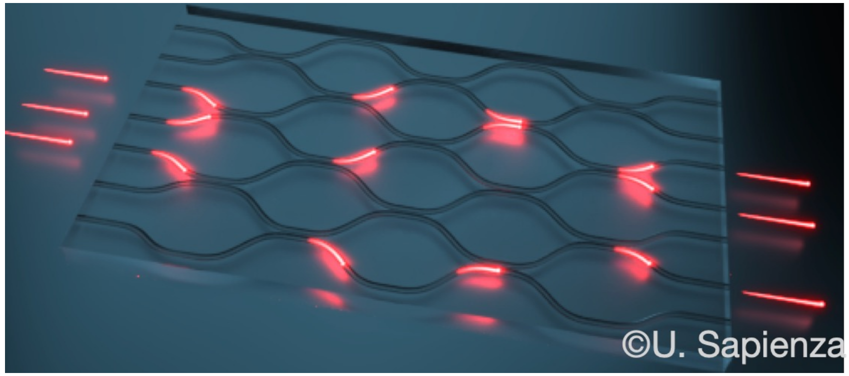


M. Cerezo et al. Nature Reviews Physics 3, 625-644 (2021)

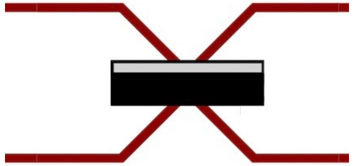
How do we proceed with photonic hardware?



Linear optics framework

$|n_1, n_2, \dots, n_i, \dots, n_m\rangle$ 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

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

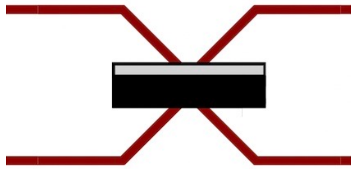
+ source and detectors

Recall: used in Boson Sampling (Aaronson and Arkhipov, #P hard)

Linear optics framework

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

Beamsplitter



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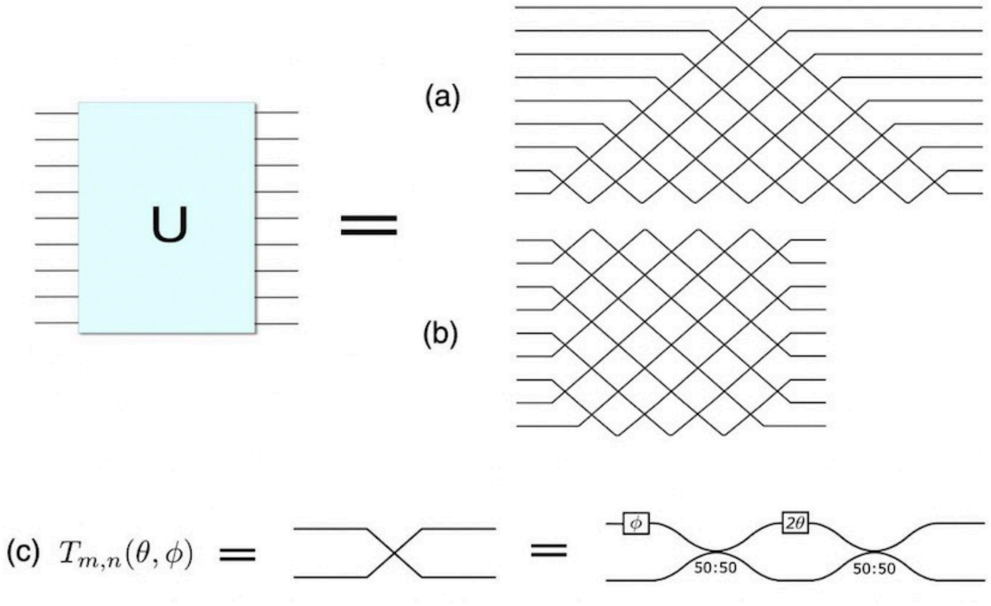
Phase shifter

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

+ source and detectors

Recall: used in Boson Sampling (Aaronson and Arkhipov, #P hard)

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



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

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

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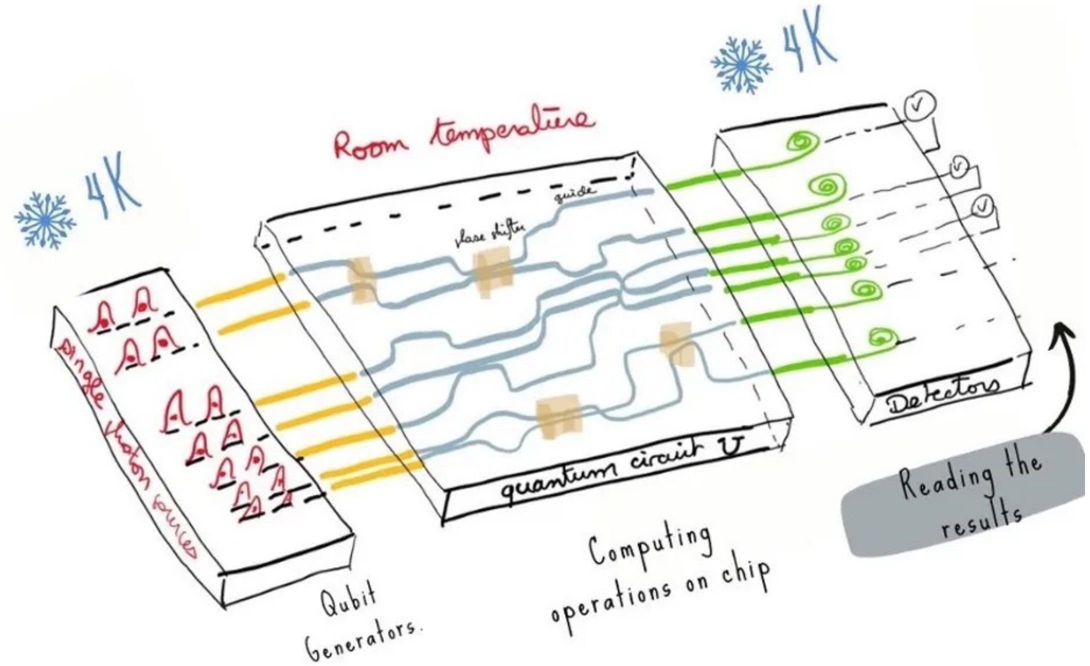
Photon number resolution



Detectors: ideally photon number resolving

Output states such as $|0210301\rangle$

Current technology: threshold detectors

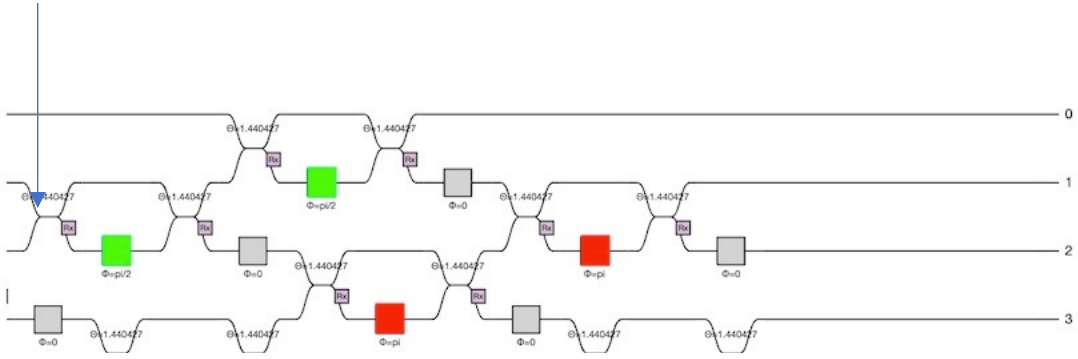
Indicates click or no click

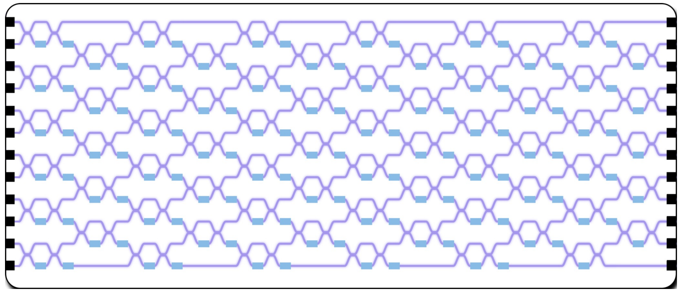
Output states such as $|0110101\rangle$

Pseudo photon number resolution

As a temporary solution we can use **pseudo PNR**

PPNR: use additional modes and detectors and redirect photons through beamsplitters





Define mapping

111000000000 → 003000000000

101001000000 → 002001000000

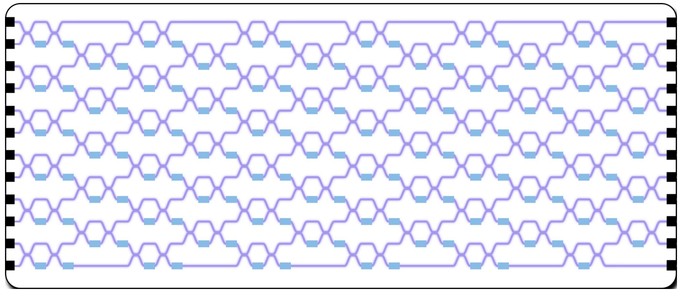
100011000000 → 001011000000

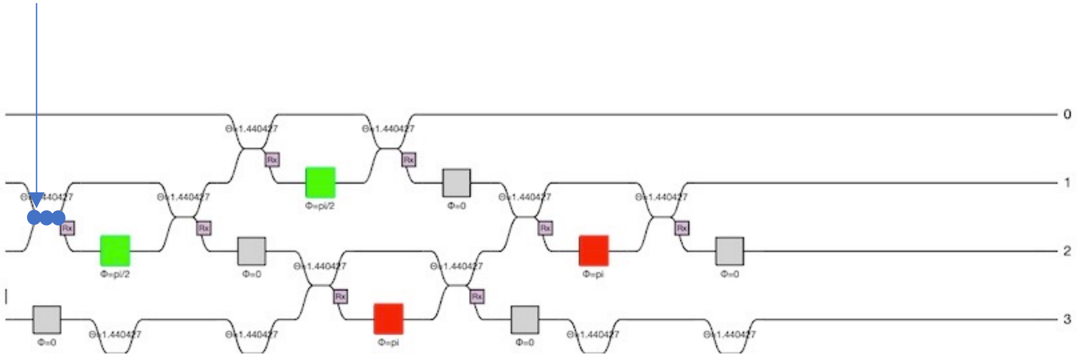
…

Pseudo photon number resolution

As a temporary solution we can use **pseudo PNR**

PPNR: use additional modes and detectors and redirect photons through beamsplitters





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	…	

Pseudo photon number resolution

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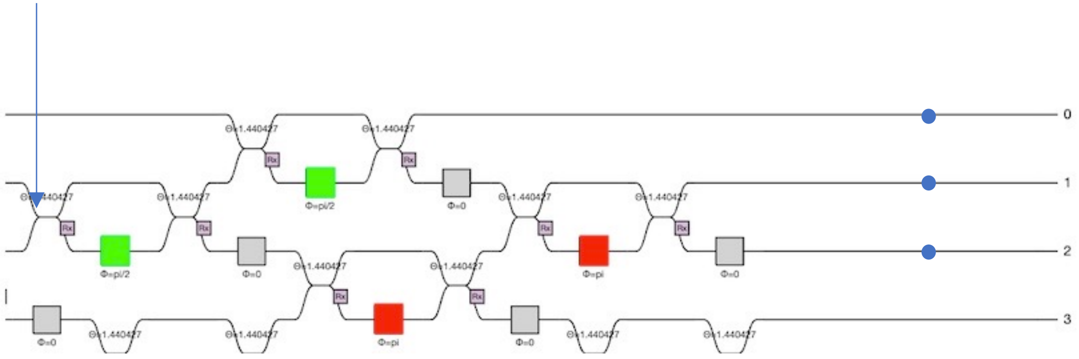
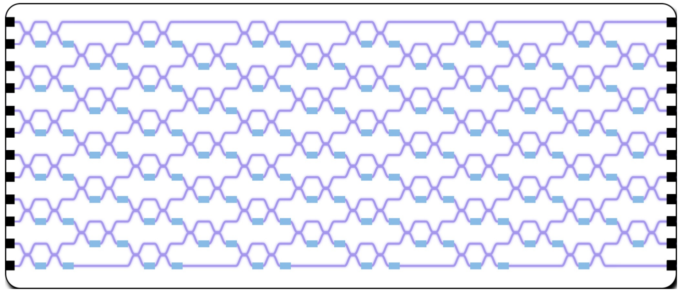




Define mapping

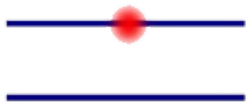
111000000000	→	003000000000
101001000000	→	002001000000
100011000000	→	001011000000
	…	

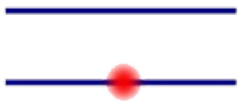
Qubits and logical gates with linear optics

Choose an encoding

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

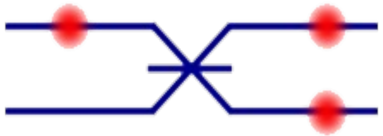
Dual rail





One qubit gates

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



Beamsplitter

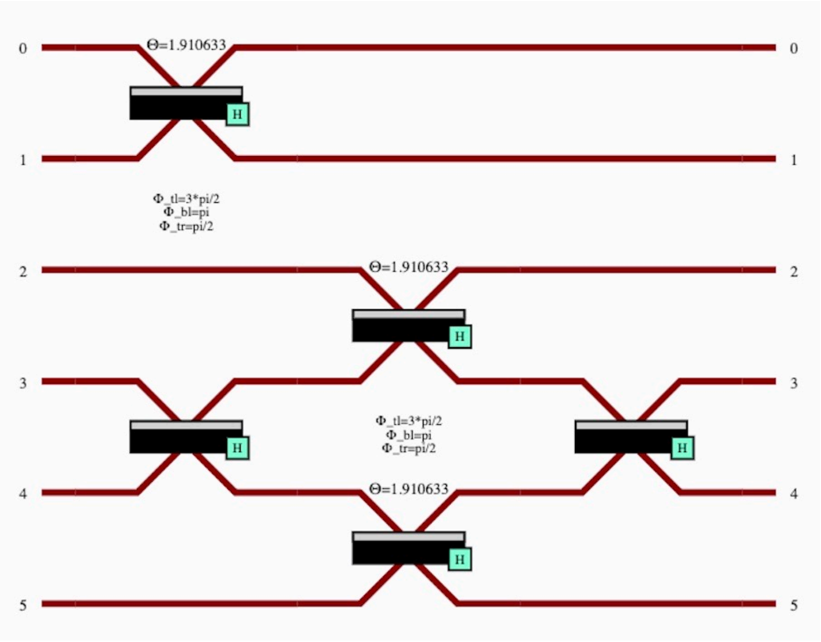
Qubits and logical gates with linear optics

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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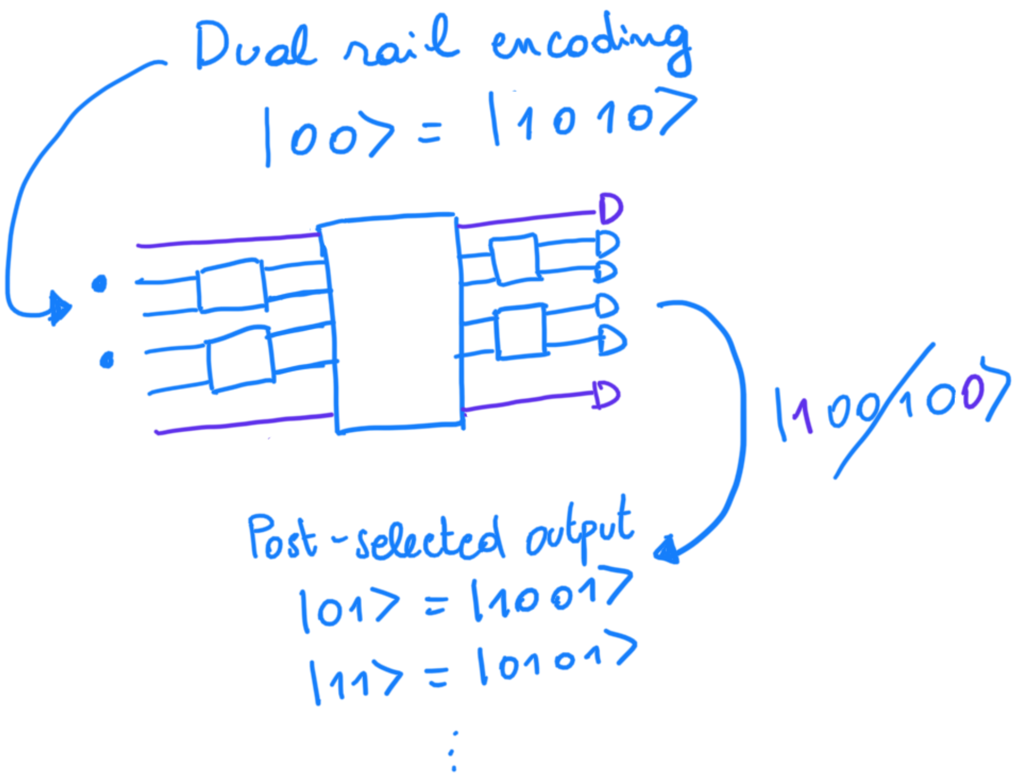
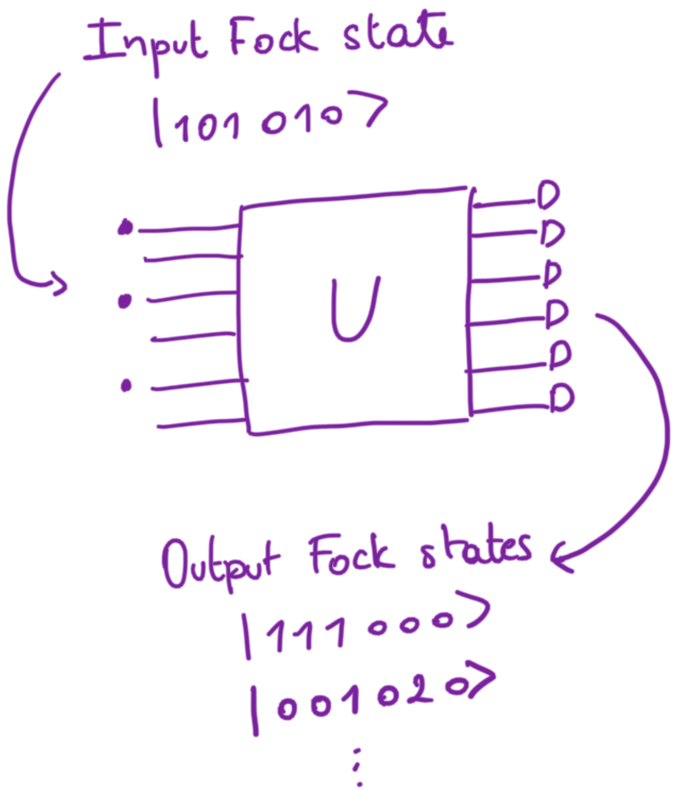
Approaches on our device

Qubit circuit based



Photonic native



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Challenges - algorithms

Post-selected gates: non-deterministic computation

PNR detectors not yet available: reduced output space

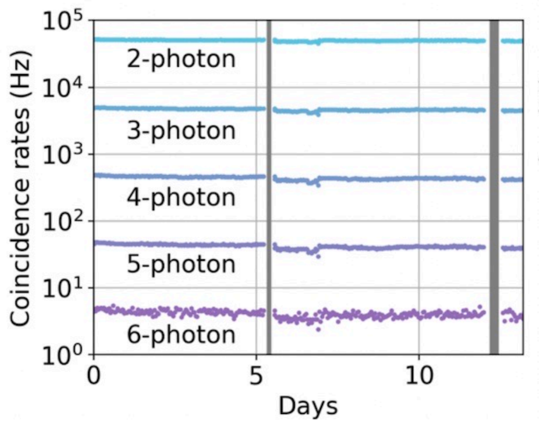
Optimization in QML: little research in parameter shift rules for linear optics

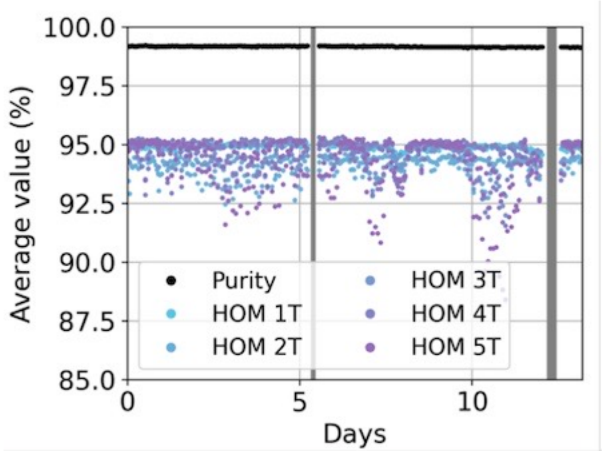
Challenges - hardware

Photon loss is main source of noise: total efficiency 8%

Indistinguishability of the photons: ~ 94%

Single-photon purity: > 99%

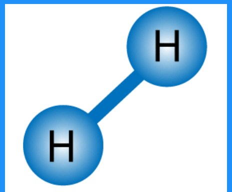




Approaches on our device

Qubit circuit based

Variational quantum eigensolver



Photonic native

Variational quantum classifier

VQE experiment

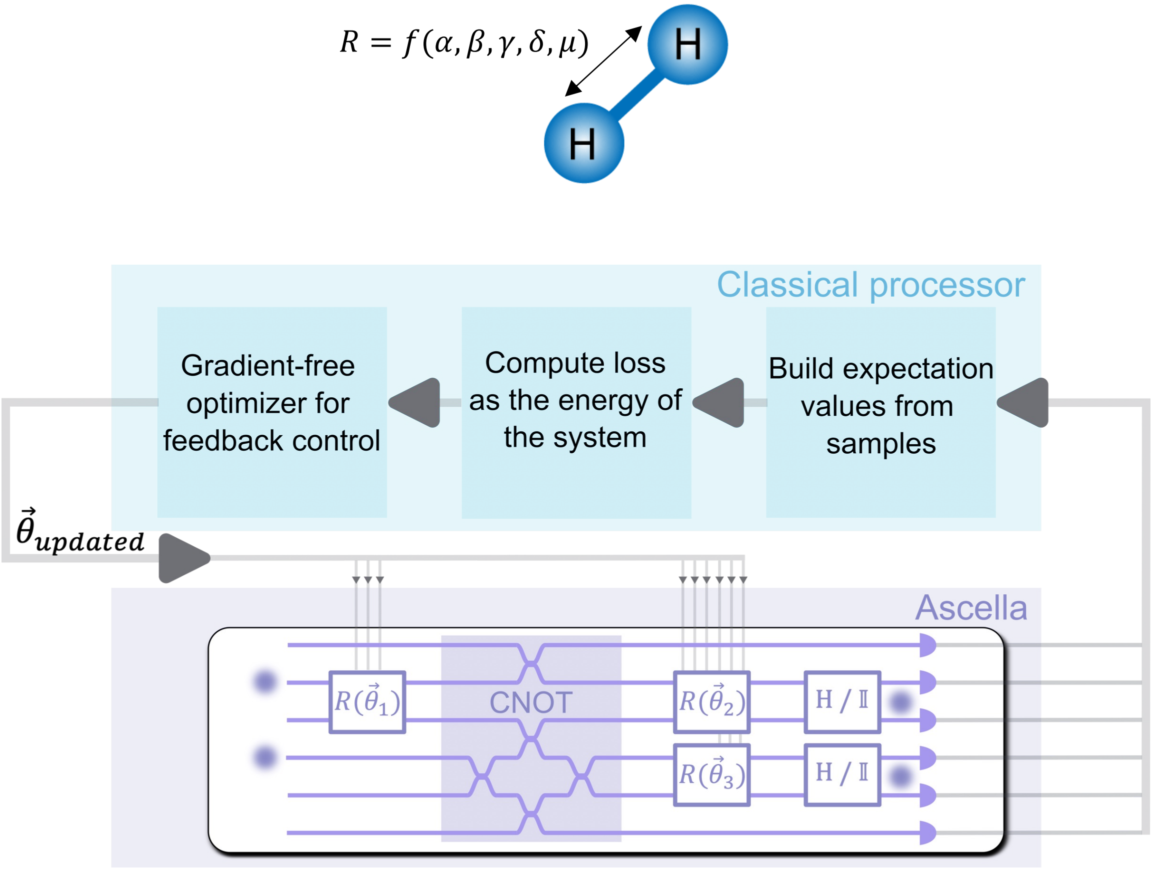
VQE results

We consider the H2 molecule with effective Hamiltonian $\widehat{H} = \alpha\mathbb{I}\mathbb{I} + \beta \mathrm{Z}\mathbb{I} + \gamma\mathbb{I}\mathrm{Z} + \delta\mathrm{ZZ} + \mu\mathrm{XX}$

Circuit prepares an ansatz state of two qubits:

- dual rail encoding
- post-selected CNOT gate

Error mitigation scheme inspired from D. Lee et al. *Optica* 9, 88-95 (2022)



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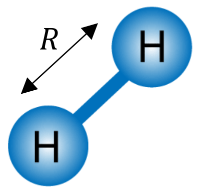
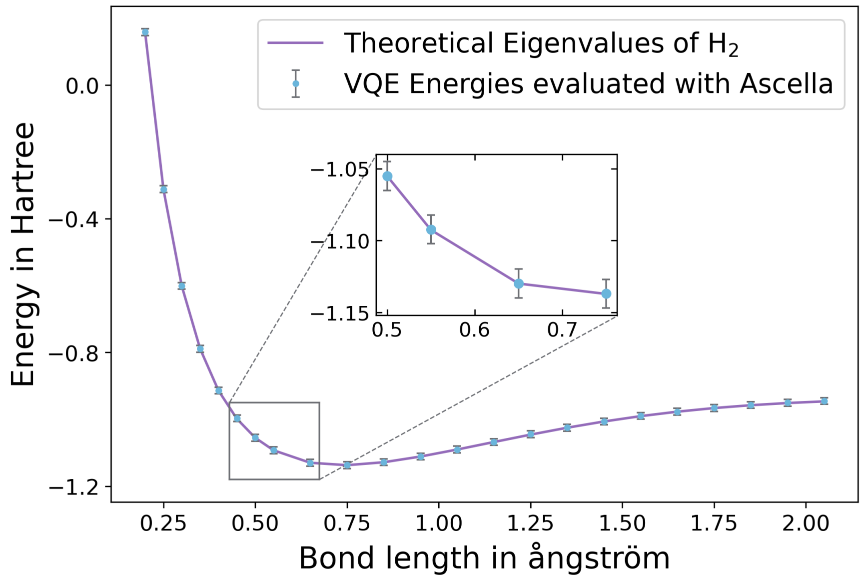
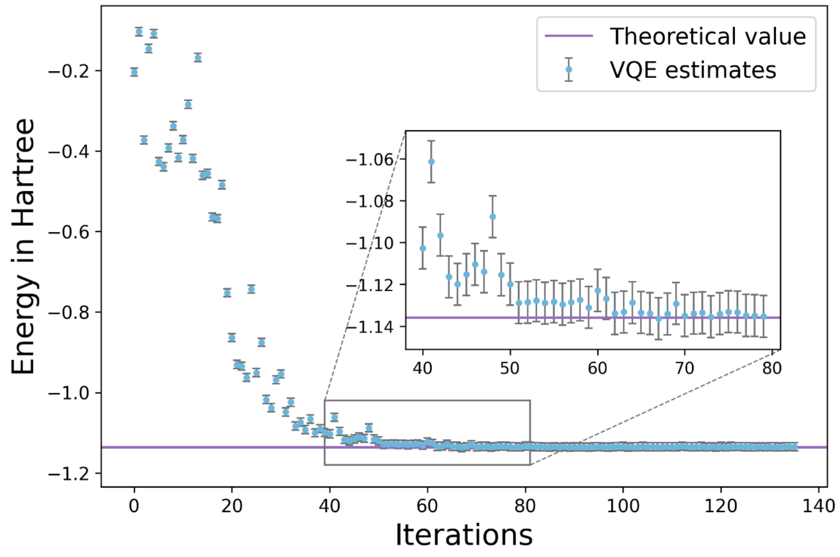
VQE results



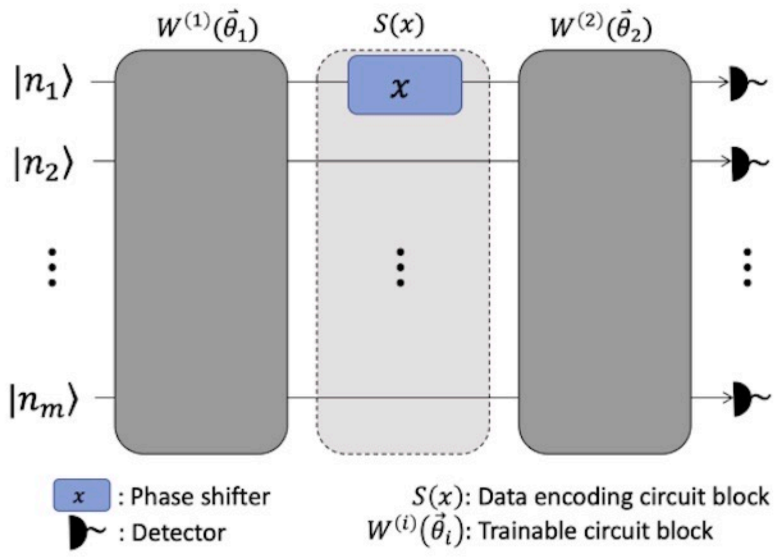




Variational quantum classifier

Variational quantum classification algorithm

Fock-space based classifier proposed in [1]



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

Resulting model:

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

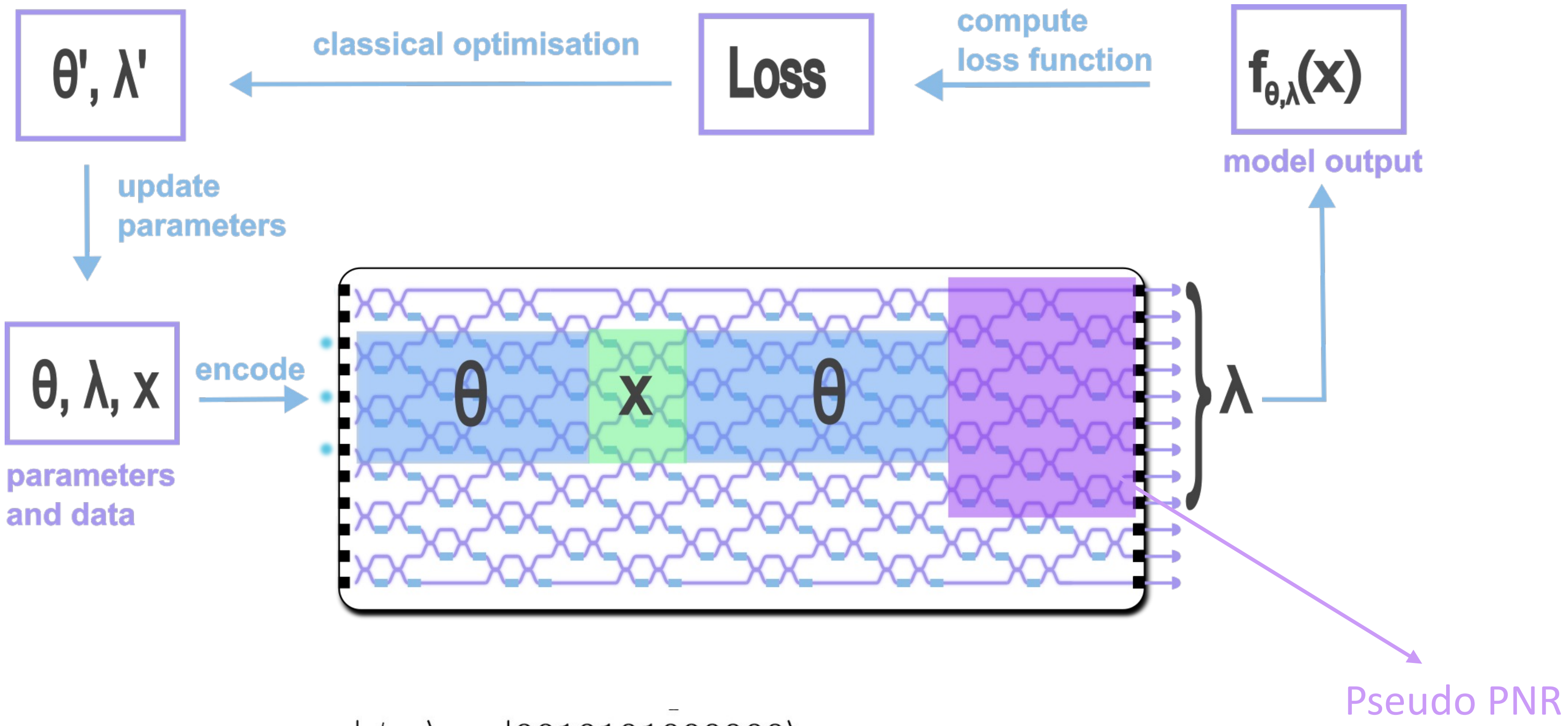
Unitary from the circuit

Observable

Defined in Fock space:

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

Variational quantum classification algorithm

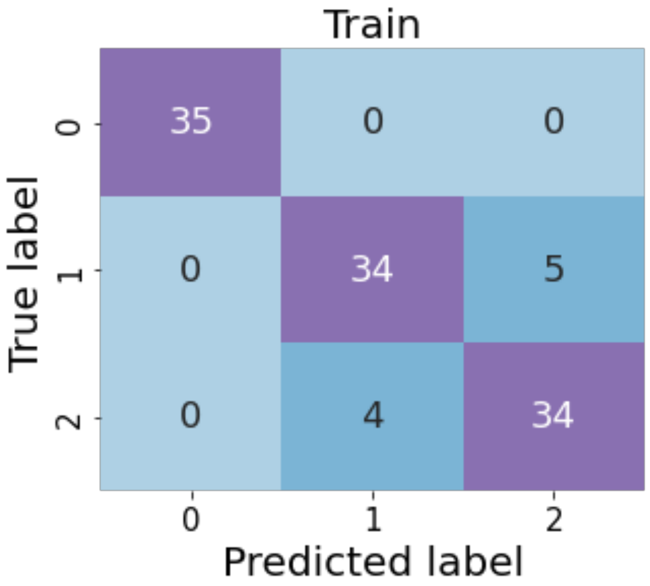


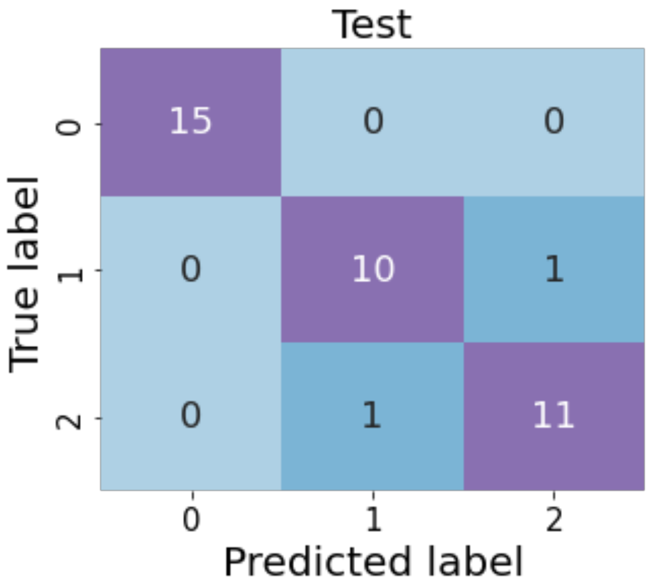
Input Fock state $|\psi_{in}\rangle = |0010101000000\rangle$

Variational quantum classifier: results

Classifying Fisher's iris dataset:

- 150 data points
- 4 dimensions
- 3 classes



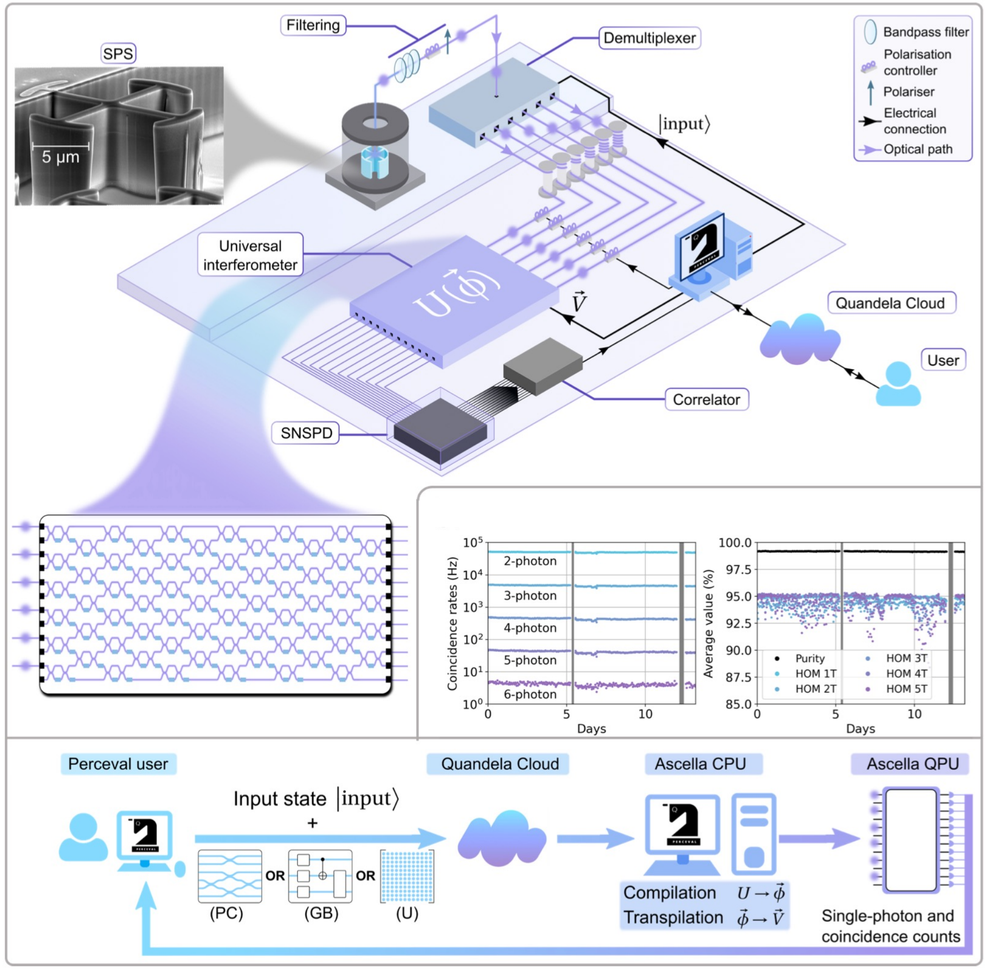


Conclusions

Highlights

- First device of its kind based on single photons
- Available online on the cloud
- Versatility:
  - VQA demonstration
  - Benchmarking
  - Other protocols

arXiv:2306.00874



Open questions and future work

Experimental directions:

- Near term optimization of each component in setup
- PNR detectors
- Towards measurement based QC
  - GHZ state generation
  - Linear cluster states directly from the source [1]

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)

[1] N. Coste, D.A. Fioretto, N. Belabas, et al. *Nat. Photon.* **17**, 582–587 (2023)

Open questions and future work

Experimental directions:

- Near term optimization of each component in setup
- PNR detectors
- Towards measurement based QC
  - GHZ state generation
  - Linear cluster states directly from the source [1]

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]
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Variational algorithms:

- Optimization and gradient evaluation
- Compilation of qubit circuits to photonic circuits
- Inductive bias of linear optics?

[1] N. Coste, D.A. Fioretto, N. Belabas, et al. *Nat. Photon.* **17**, 582–587 (2023)

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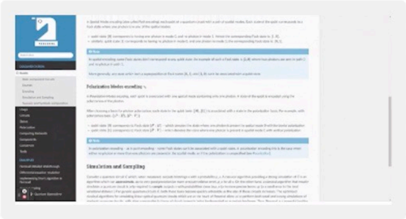

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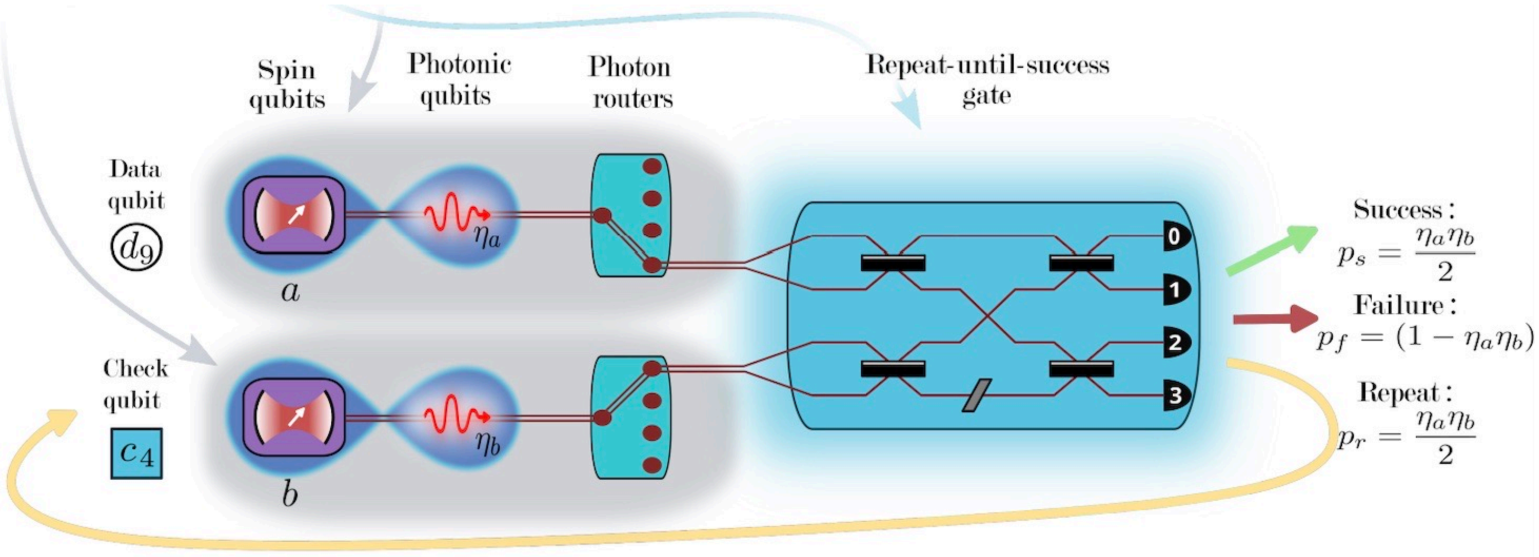
Appendix

Hybrid 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]
[1]Quandela, 7 Rue Léonard de Vinci, 91300 Massy, France
[2]Sorbonne Université, CNRS, LIP6, F-75005 Paris, France



VQE error mitigation scheme

Error mitigation scheme inspired from [1]

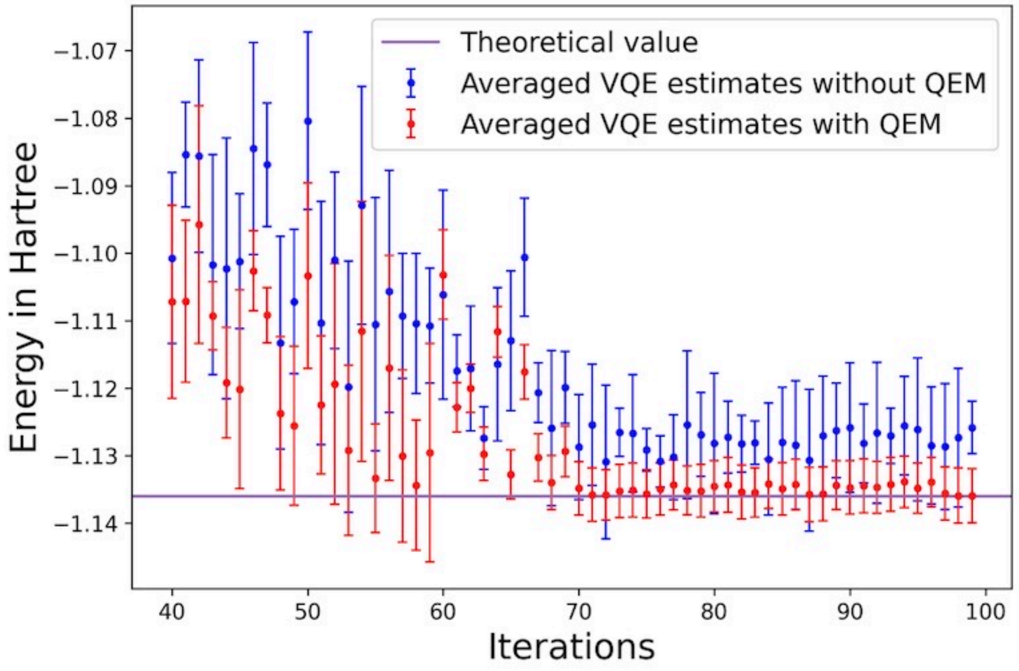
State preparation and measurement (SPAM) errors

Correct probability distribution $q = \Gamma_b p$

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

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

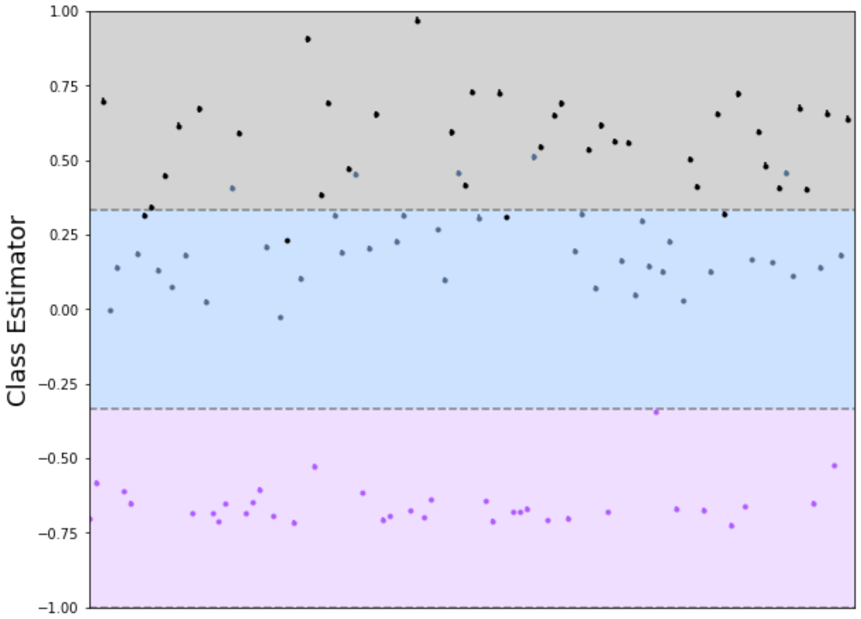
$$\Gamma_{XX} = \begin{bmatrix} 9.99999951e-01 & 2.47148265e-02 & 2.47148265e-02 & 1.24580719e-09 \\ 2.39578331e-08 & 9.50570344e-01 & 1.18422748e-09 & 2.39578331e-08 \\ 2.39578331e-08 & 1.18422748e-09 & 9.50570344e-01 & 2.39578331e-08 \\ 1.24580731e-09 & 2.47148287e-02 & 2.47148287e-02 & 9.99999951e-01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



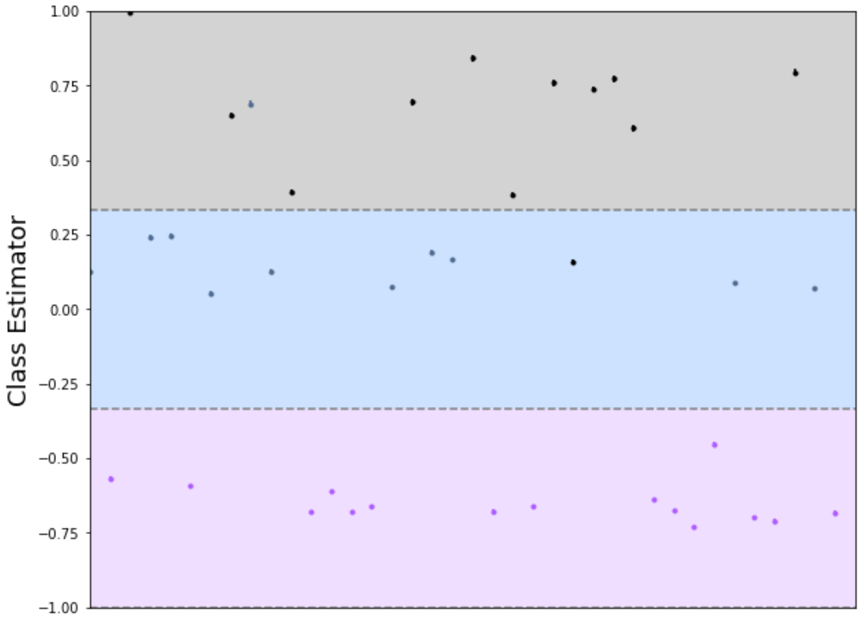
[1] D. Lee et al. *Optica* 9, 88-95 (2022)

Variational quantum classifier: results

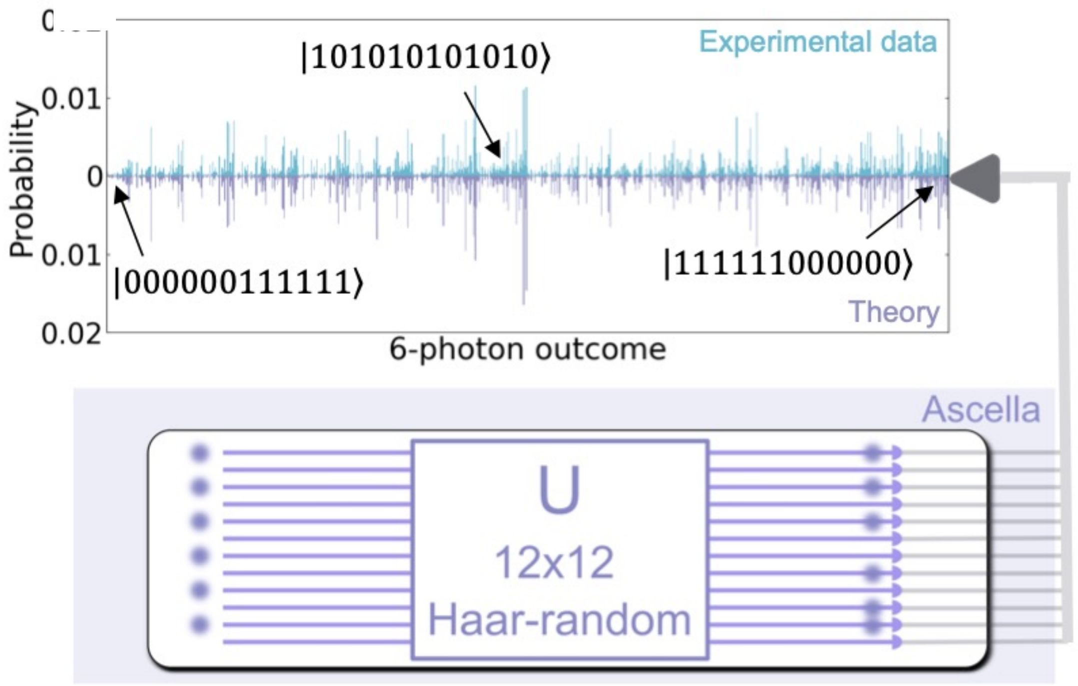
Train set

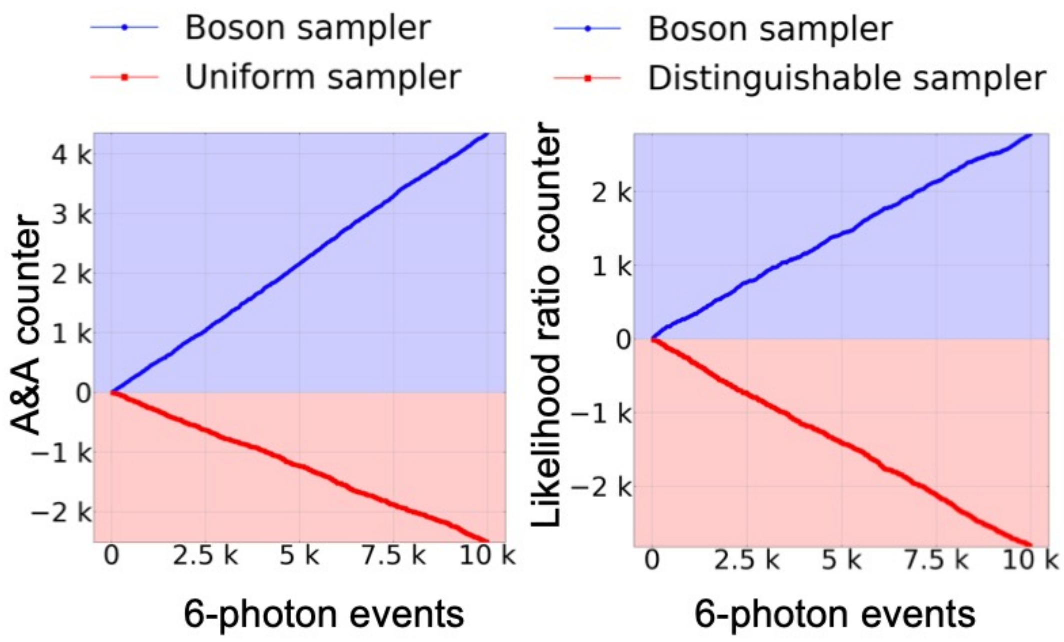


Test set



Boson Sampling: on-chip implementation





- Aaronson & Arkhipov counter
- Likelihood ratio counter

Distinguishers between uniform and observed output distributions which validate the experiment

Benchmarking: average gate fidelities

Initial pure state $|\psi\rangle$ → Target state $U|\psi\rangle$
Final state ρ

$$T = \begin{pmatrix} 1 & 0 \\ 0 & e^{i\frac{\pi}{4}} \end{pmatrix} \qquad \mathrm{CNOT} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix}$$

$$\mathrm{Toffoli} = \begin{pmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 \\ 0 & 0 & 0 & 0 & 1 & 0 \end{pmatrix}$$

State fidelity: $\mathcal{F}_\psi(U) = \langle\psi|U^\dagger \rho U|\psi\rangle$

F_{avg} is state fidelity averaged over the Haar measure

Platform (device)	**Gate**	**Number of Qubits**	**F_{avg} (%)**
Quandela (Ascella)	**T-gate**	**1**	**99.6±0.1**
	CNOT	**2**	**93.8±0.6**
	Toffoli	**3**	**86±1.2**

IonQ (ionq.qpu)	T-Gate	1	99.6±1
	CNOT	2	91.7±1.7
	Toffoli	3	90±3.1
Rigetti (rigetti.aspen-11)	T-Gate	1	88.7±1
	CNOT	2	71.2±1.5
IBM (Quito or Belem)	T-Gate	1	96±1.5
	CNOT	2	86.4±1.5

R. Mezher and S. Wein, Direct computing of the average gate fidelity of any gate, *In preparation*, 2023.

Generating GHZ states: towards MBQC

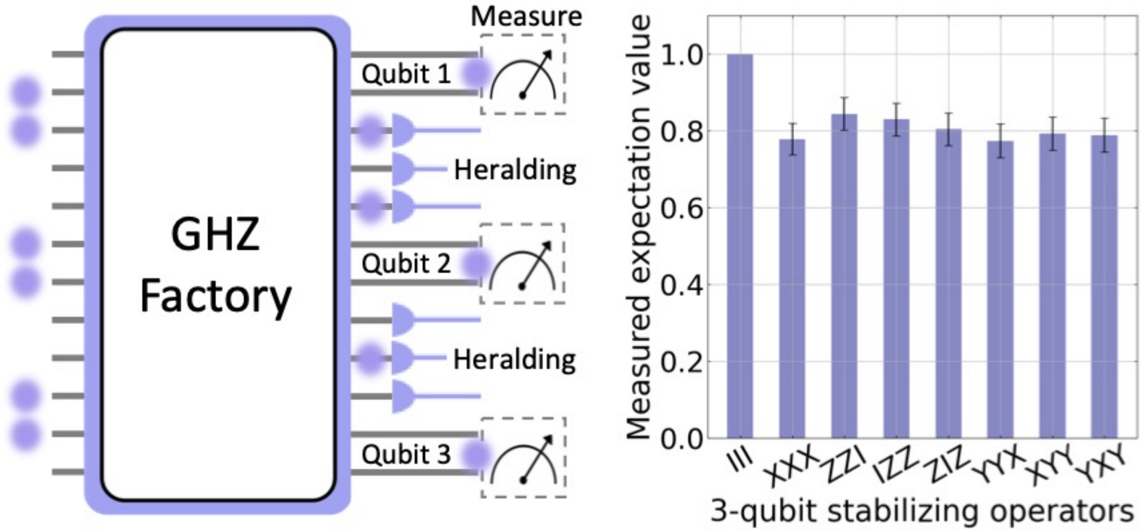
Not scalable to work with probabilistic 2-qubit gates

Solution: MBQC

Requires, e.g., construction of graph states, which can be built up of:

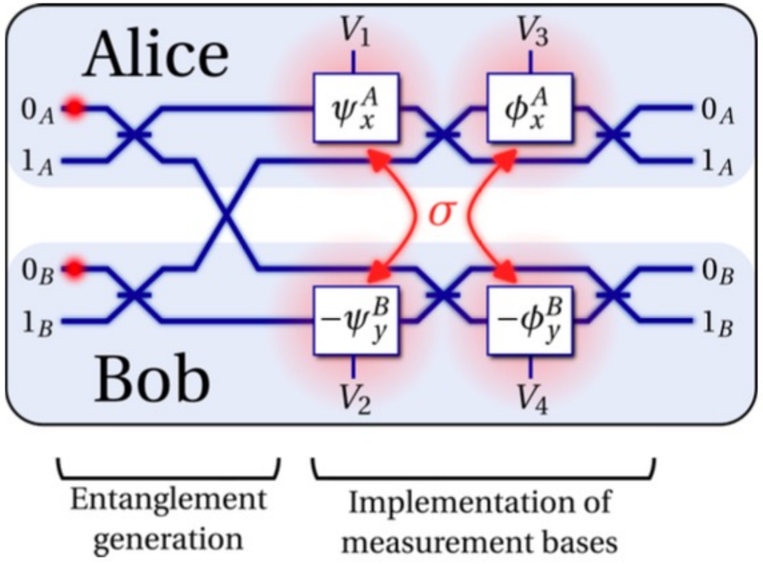
- Small entangled states such as GHZ states
- Fusion operations such as Bell measurements

In principle MBQC can be achieved with small constant depth of probabilistic operations



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 $F_{\mathrm{GHZ}_3^+} = 0.82 \pm 0.04$.

A CHSH Bell test

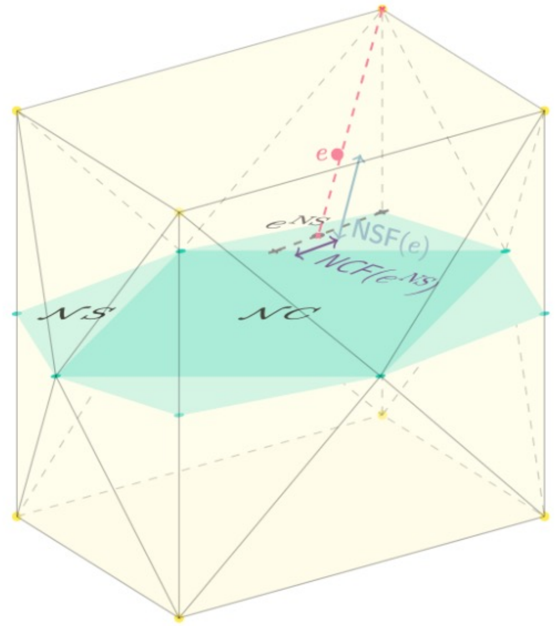


in\out	(0,0)	(0,1)	(1,0)	(1,1)
(a,b)	0.418	0.083	0.084	0.415
(a,b')	0.090	0.416	0.410	0.084
(a',b)	0.085	0.418	0.418	0.079
(a',b')	0.077	0.429	0.423	0.071

- CF ≈ 0.34
- Tsirelson bound: CF ≈ 0.41
- Observed signalling: $\sigma^{emp} < 0.05$
- Estimated unsharpness: $\eta^{emp} < 0.001$

- For randomness certification, sharpness and determinism are irrelevant
- Crucial only to establish CF $> \sigma$

- This is the starting point for a protocol to certify the generation of private unpredictable randomness



arXiv:2301.03536
arXiv:2310.19383