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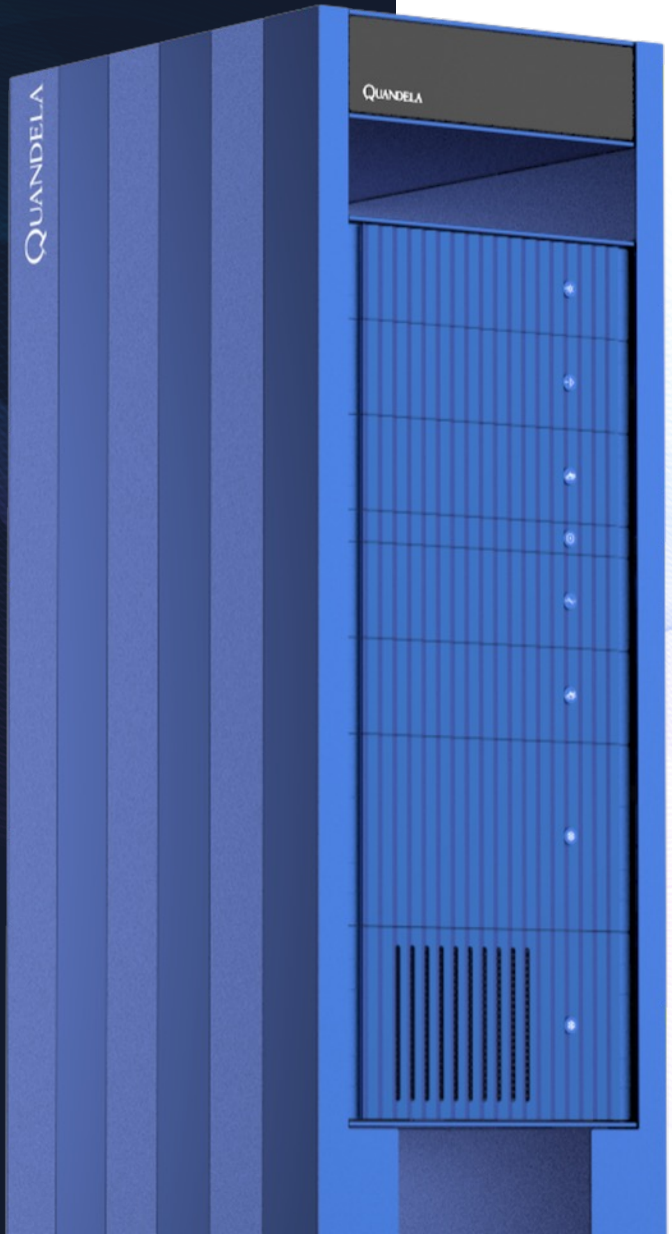
Testing contextuality on a general-purpose single-photon-based quantum computing platform

Shane Mansfield



arXiv:2306.00874, arXiv:2301.03536
Workshop on Samson's Springer Volume
UCL, 18th Sep 2023

Quandela
Presentation

Quandela Scientific Advisory Board

Founded in 2017
>80 People

>50 Scientists and Engineers
algorithms, semiconductors, optical technologies, CS

R&D Centers

C2N - Palaiseau

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Massy

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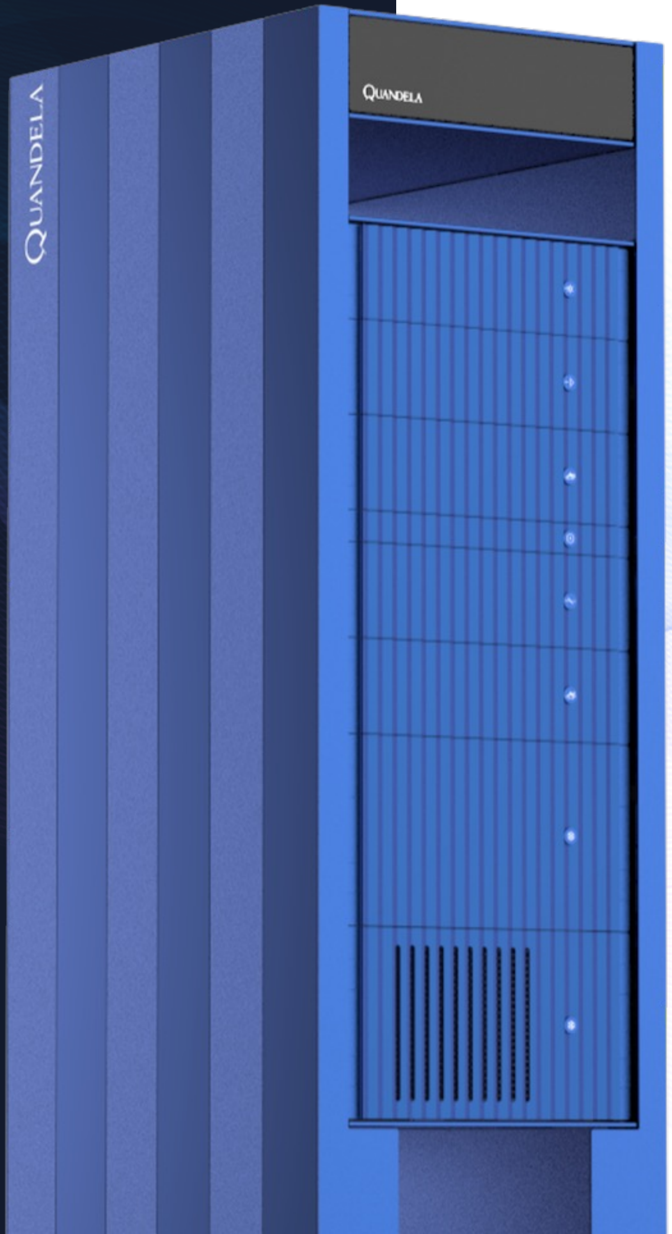
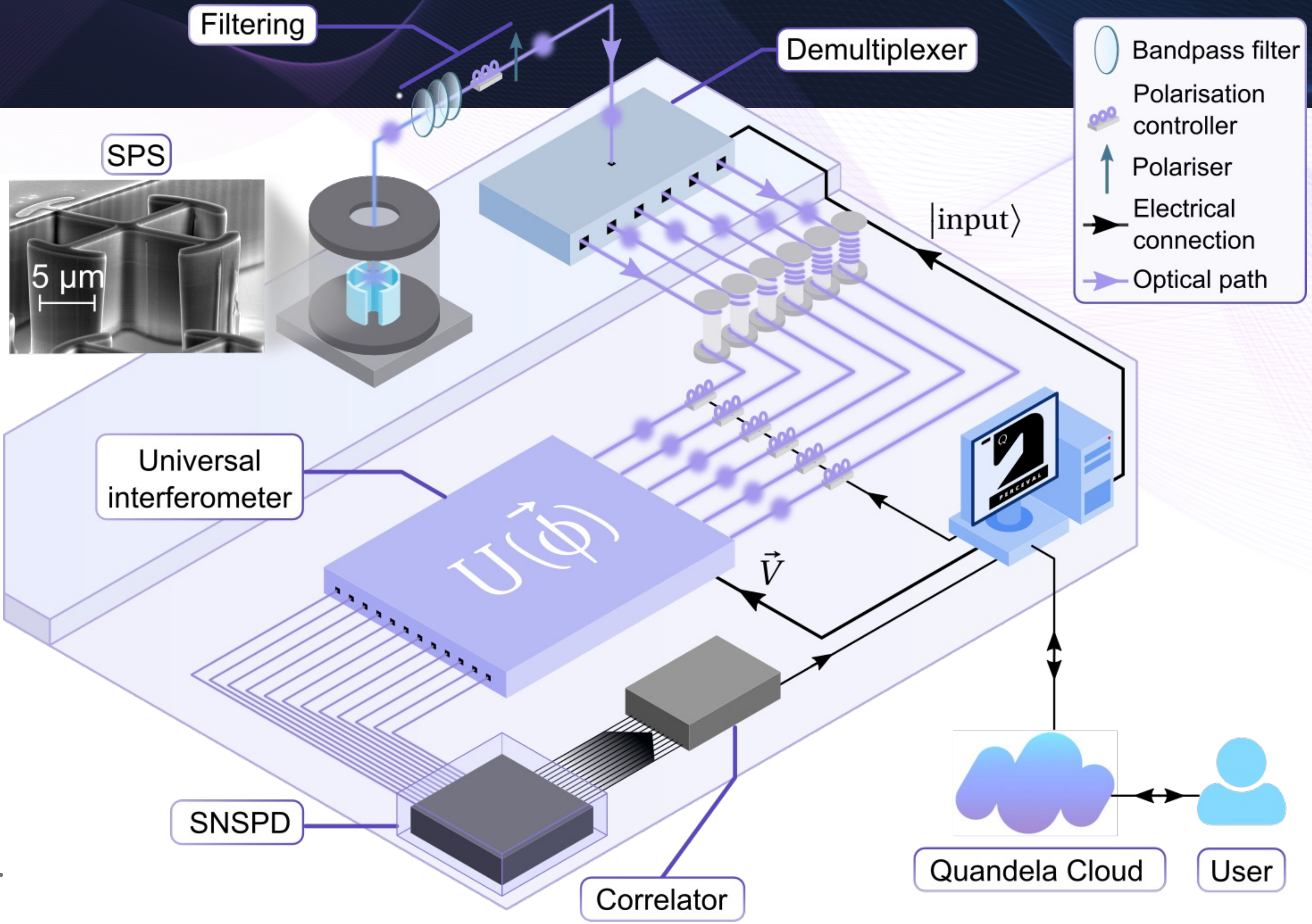
Ascella Quantum Processor



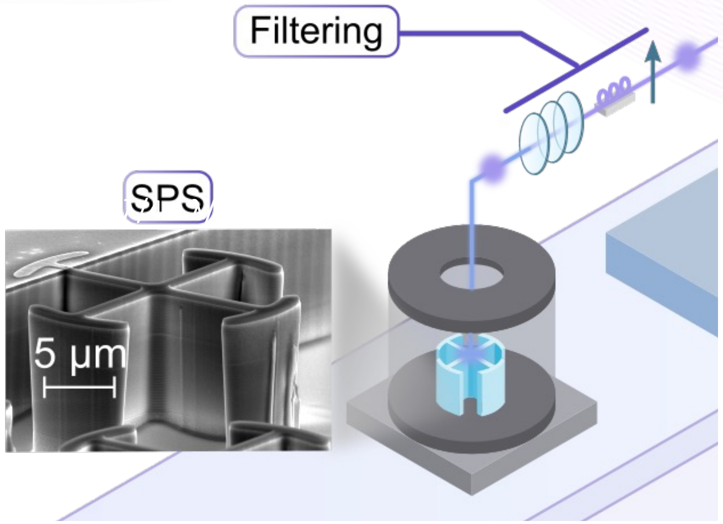
Ascella

Quantum Computing Platform



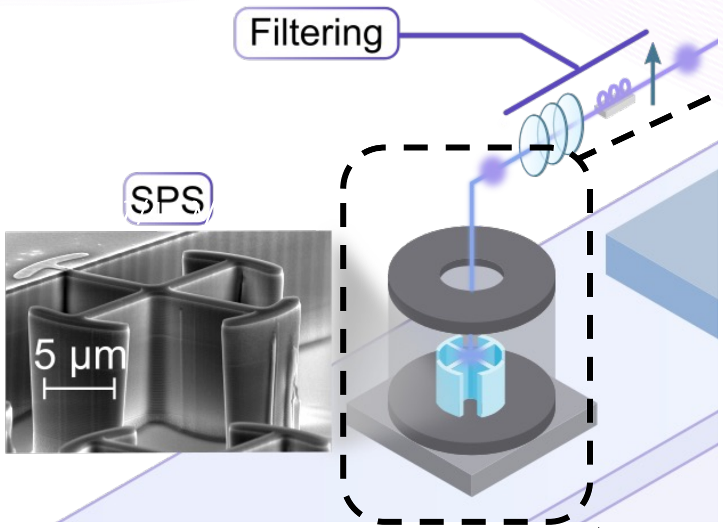
arXiv:2306.00874

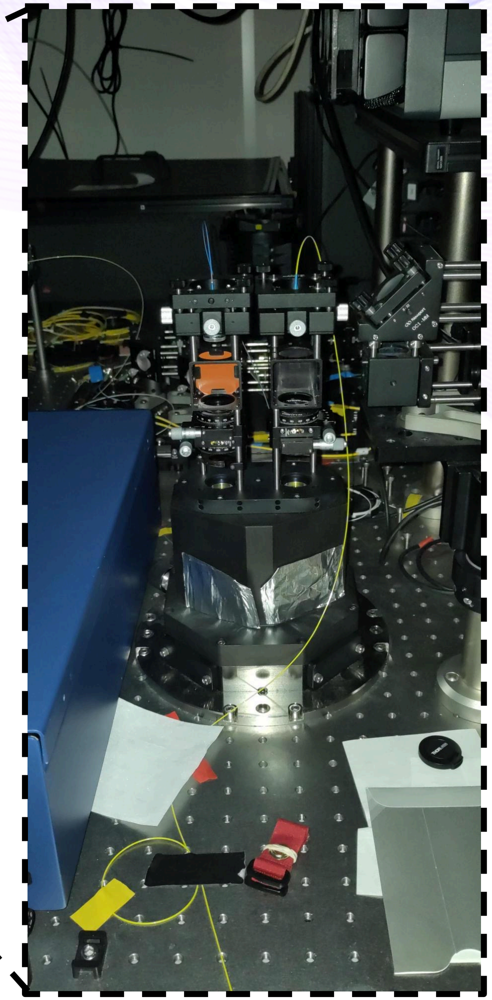
Virtual Lab Tour
The Photon Source



Virtual Lab Tour

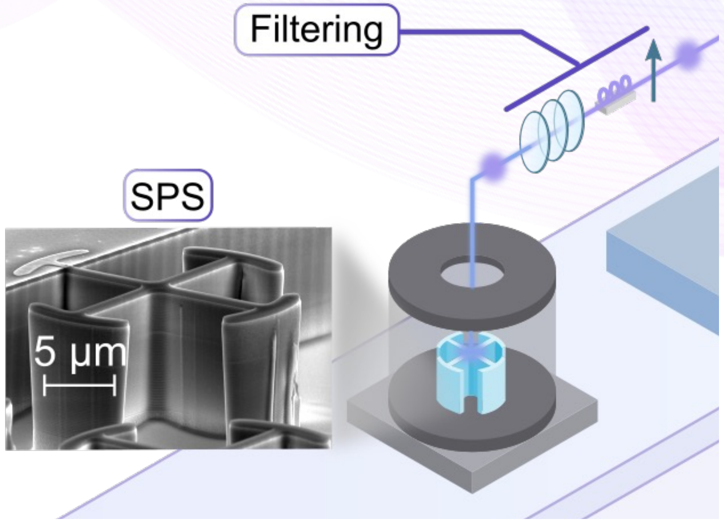
The Photon Source





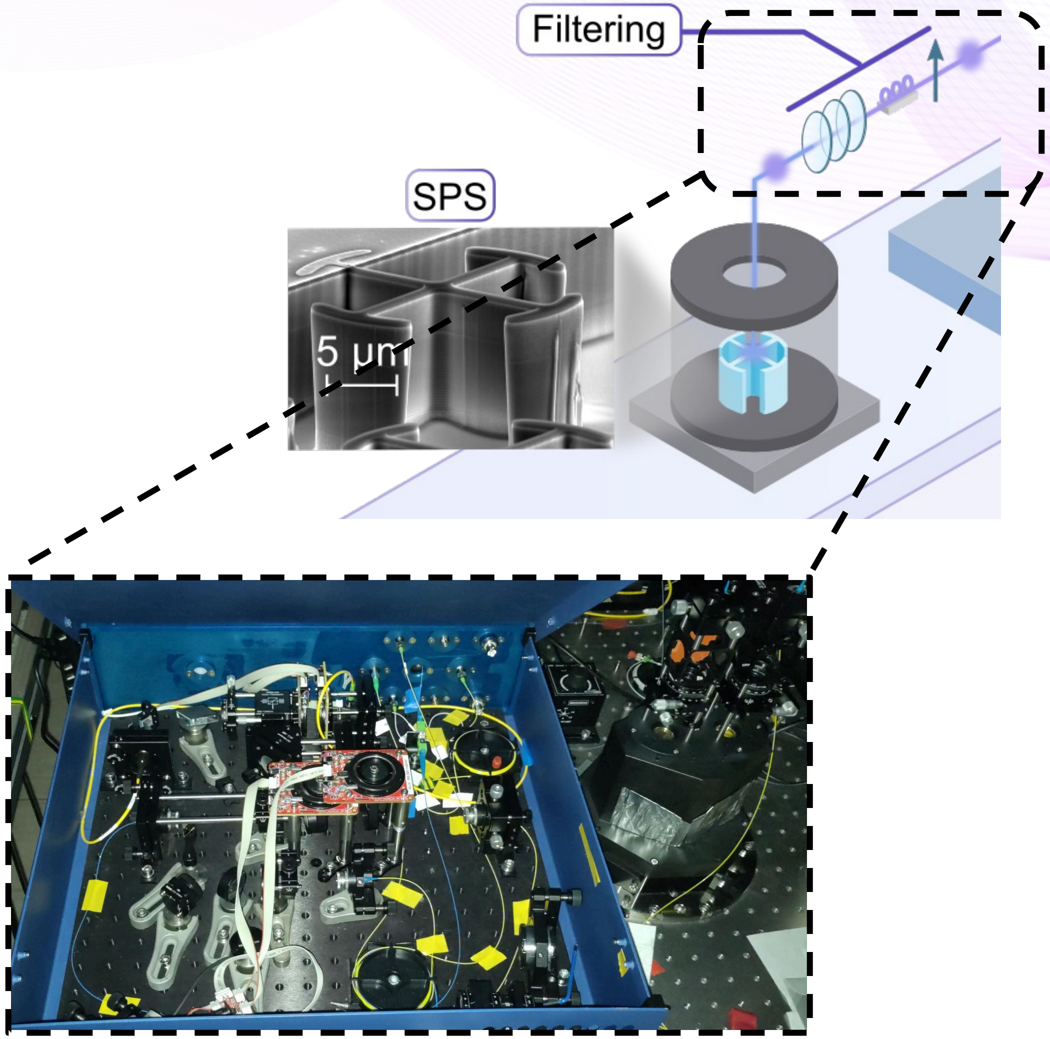
Virtual Lab Tour

Filtering

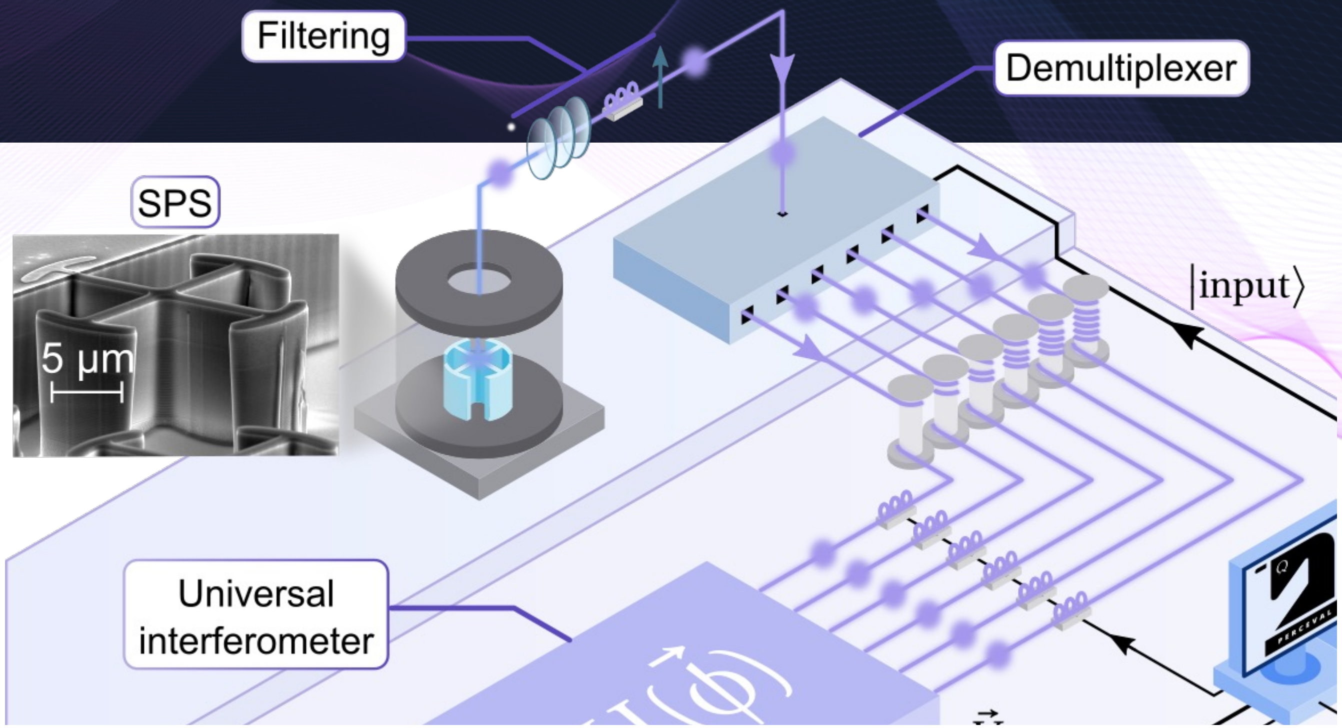


Virtual Lab Tour

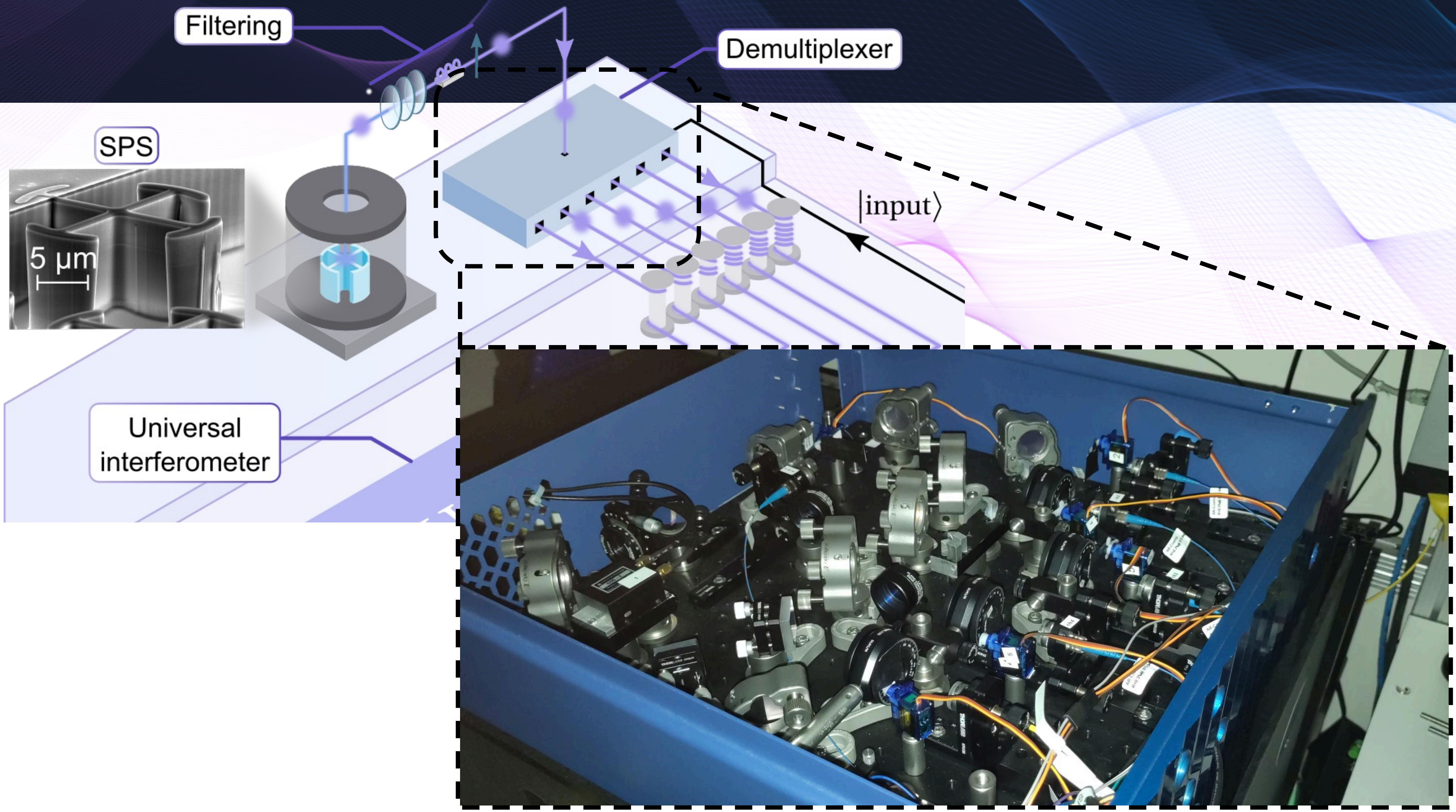
Filtering



Virtual Lab Tour
Demultiplexer

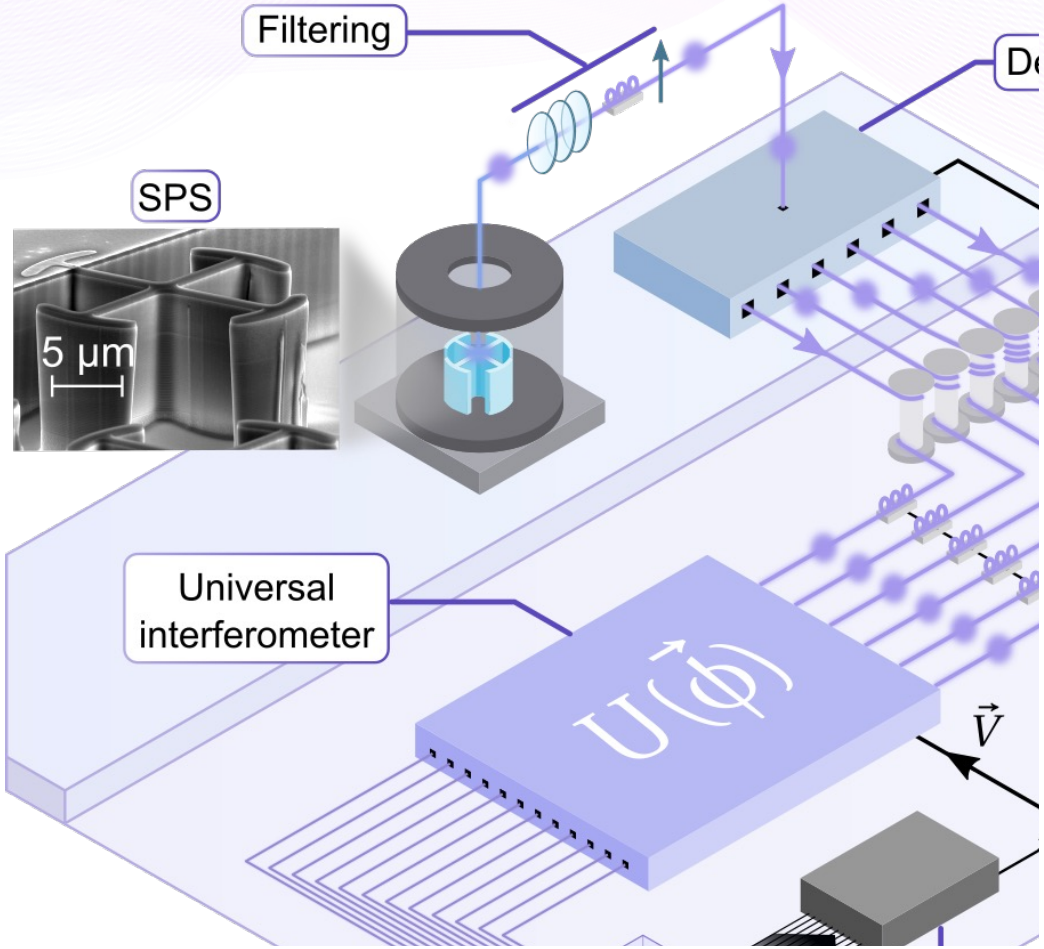


Virtual Lab Tour
Demultiplexer

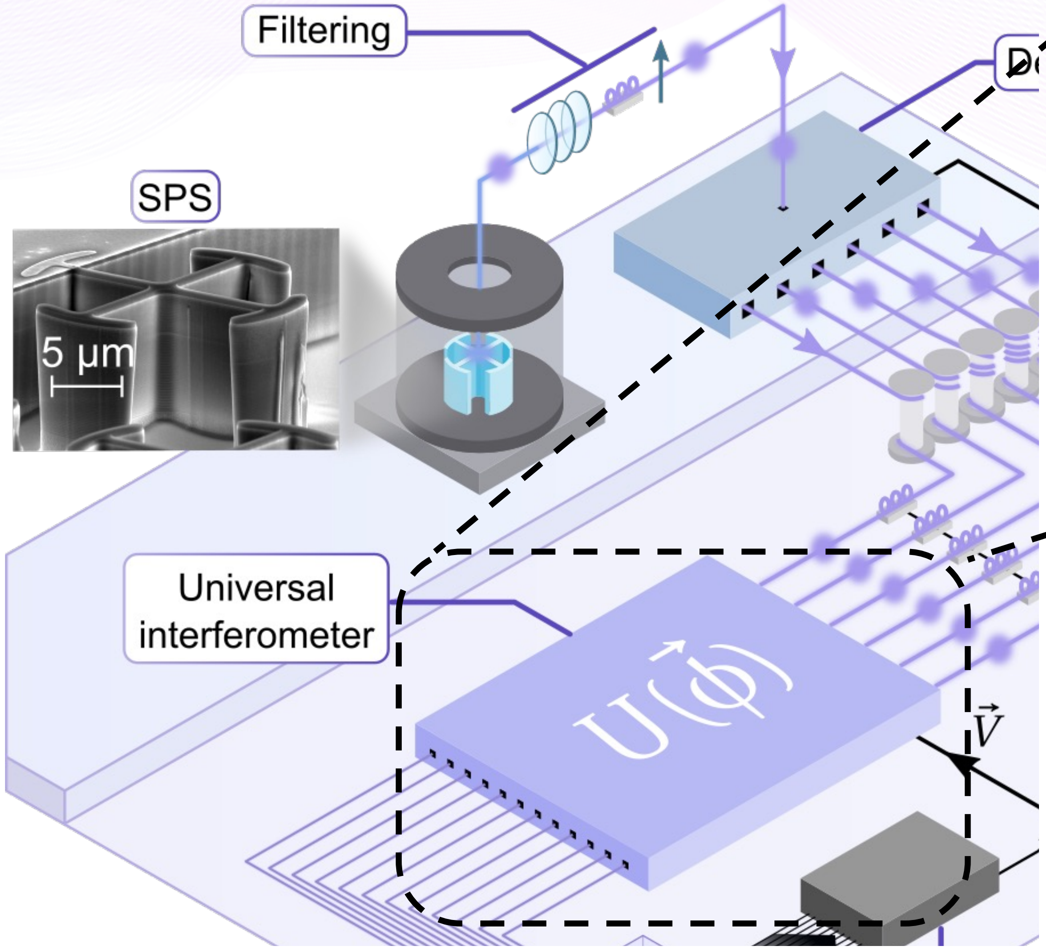


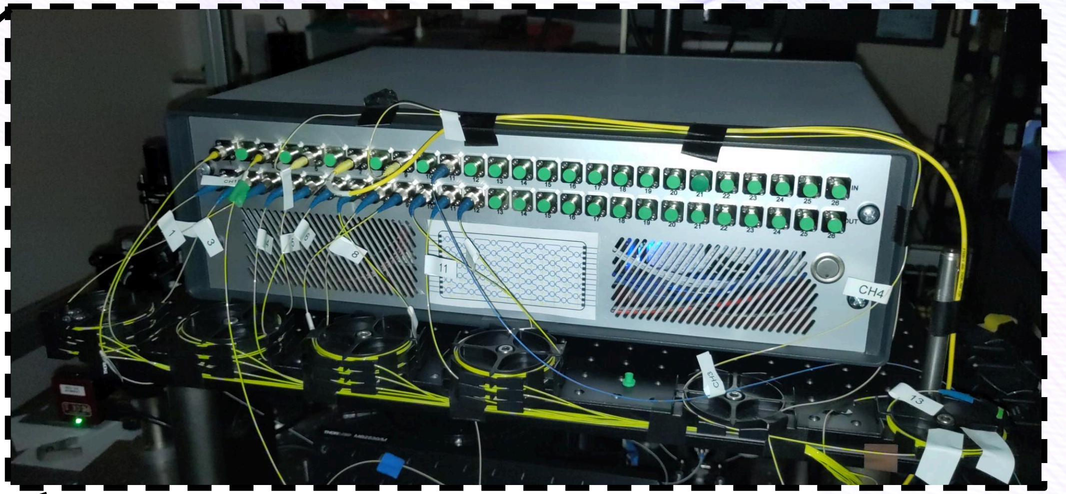
Virtual Lab Tour

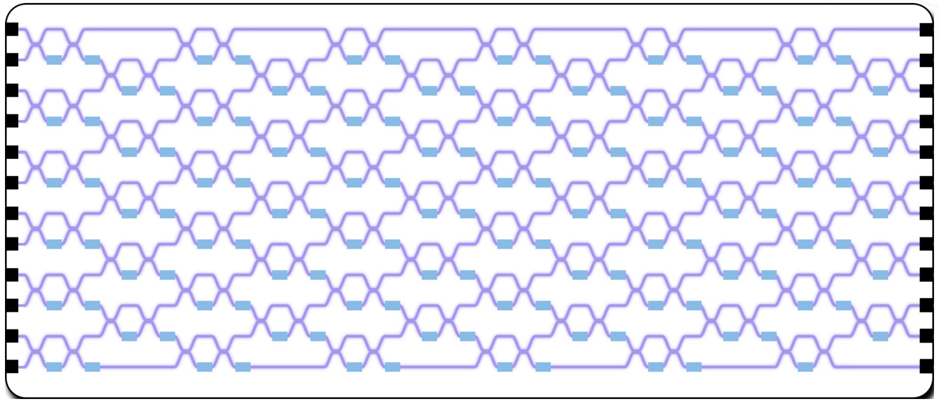
Photonic Circuit



Virtual Lab Tour
Photonic Circuit







12 x 12 fully reconfigurable universal interferometer

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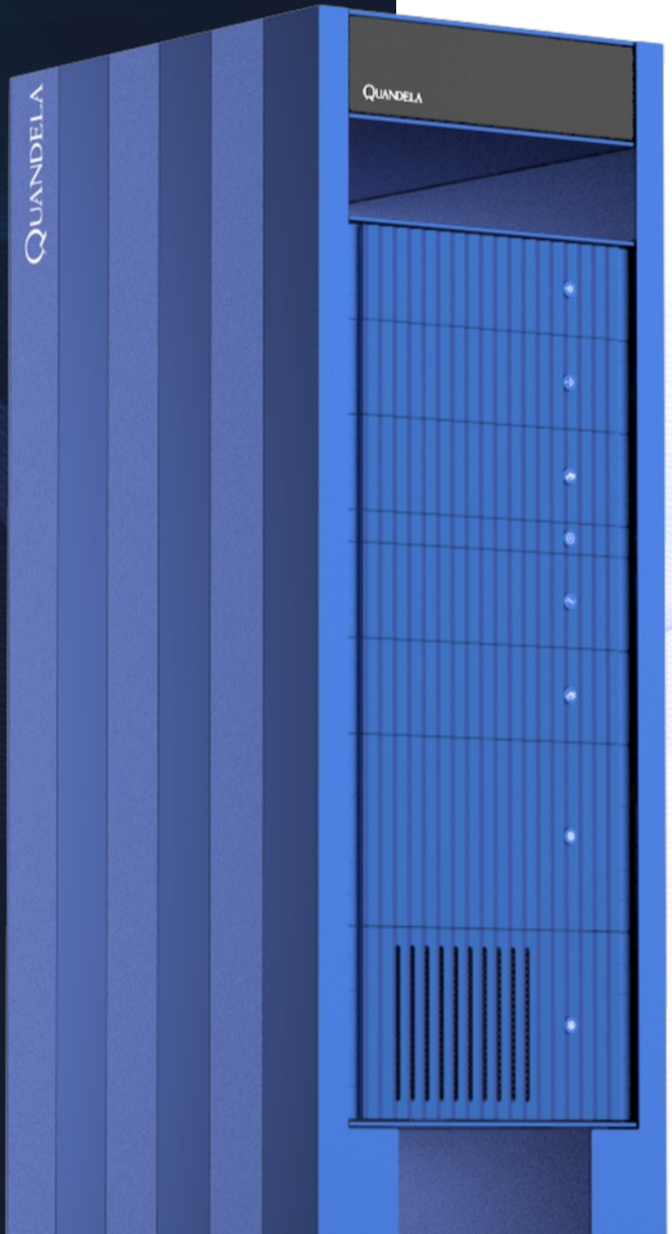
Some Notions of Photonic Quantum Computing



Photonic Operations
Second Quantisation Description

- Fock state with n_{ki} photons in mode k_i

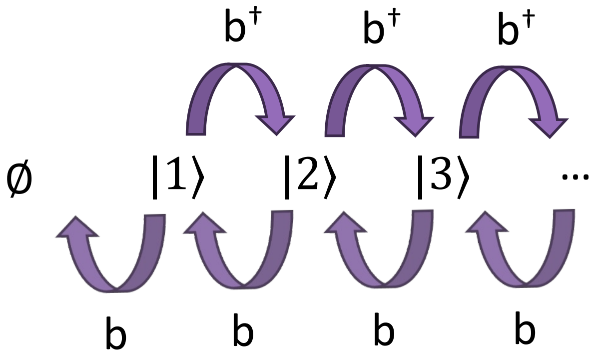
$$|n_{\mathbf{k}_1}, n_{\mathbf{k}_2}, .. n_{\mathbf{k}_i} \ldots\rangle$$

- Creation operator $b^\dagger_{\mathbf{k}_l}$:

$$b^\dagger_{\mathbf{k}_l}|n_{\mathbf{k}_1}, n_{\mathbf{k}_2}, n_{\mathbf{k}_3} \ldots n_{\mathbf{k}_l}, \ldots\rangle = \sqrt{n_{\mathbf{k}_l}+1}|n_{\mathbf{k}_1}, n_{\mathbf{k}_2}, n_{\mathbf{k}_3} \ldots n_{\mathbf{k}_l}+1, \ldots\rangle$$

- Annihilation operator $b_{\mathbf{k}_l}$:

$$b_{\mathbf{k}_l}|n_{\mathbf{k}_1}, n_{\mathbf{k}_2}, n_{\mathbf{k}_3} \ldots n_{\mathbf{k}_l}, \ldots\rangle = \sqrt{n_{\mathbf{k}_l}}|n_{\mathbf{k}_1}, n_{\mathbf{k}_2}, n_{\mathbf{k}_3} \ldots n_{\mathbf{k}_l}-1, \ldots\rangle$$



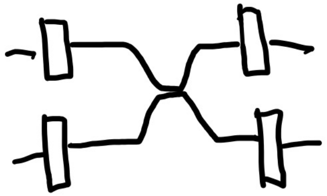
- Identity on 2 modes

$$\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}\begin{pmatrix} b_0^+ \\ b_1^+ \end{pmatrix}$$

- Phase shift

$$e^{i\phi}$$

- Beam splitter



General

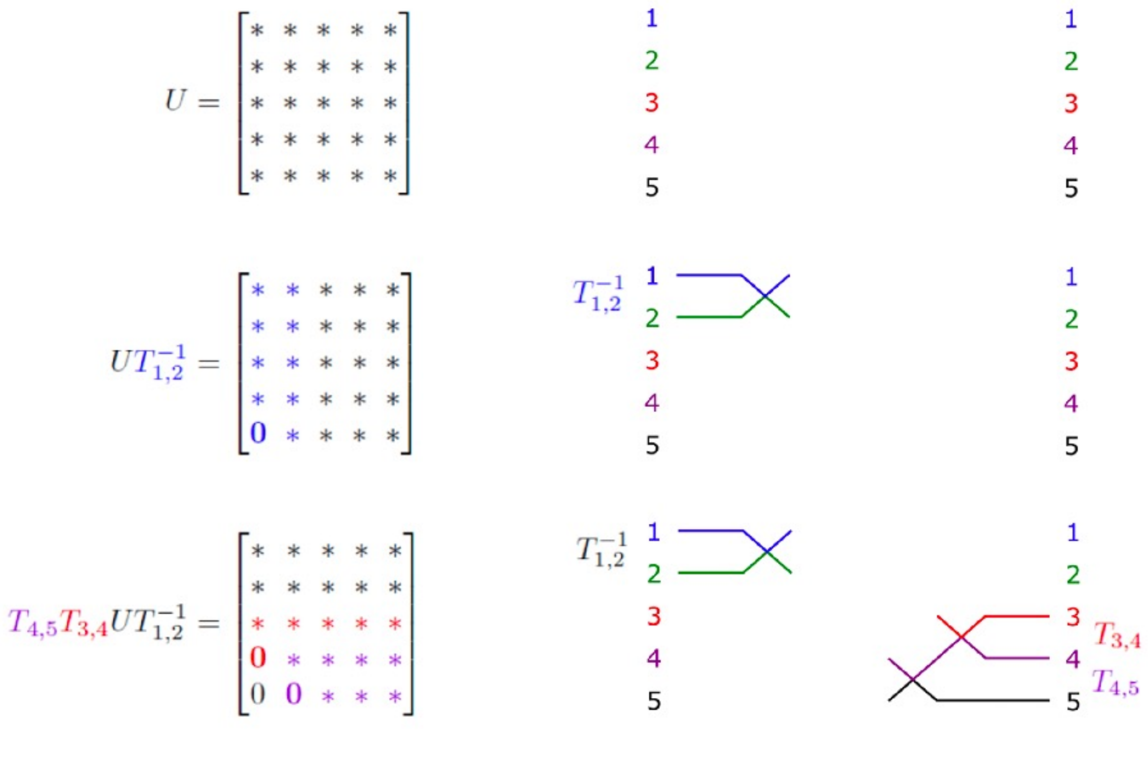
$$\begin{bmatrix} e^{i(\phi_{tl}+\phi_{tr})}\cos\left(\frac{\theta}{2}\right) & e^{i(\phi_{bl}+\phi_{tr})}\sin\left(\frac{\theta}{2}\right) \\ e^{i(\phi_{tl}+\phi_{br})}\sin\left(\frac{\theta}{2}\right) & -e^{i(\phi_{bl}+\phi_{br})}\cos\left(\frac{\theta}{2}\right) \end{bmatrix}$$

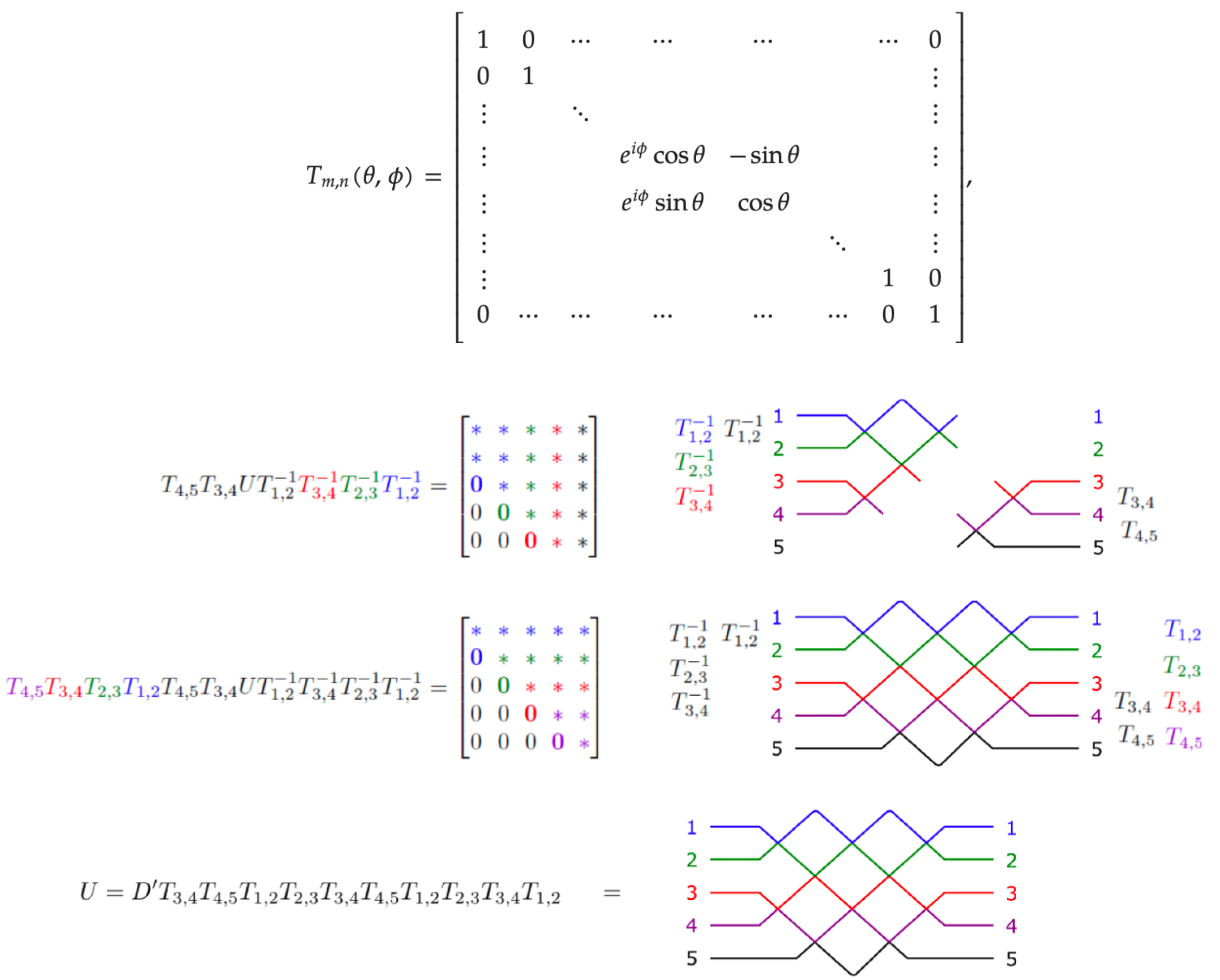
No phases

$$\hat{U}_{\mathrm{BS}}(\theta) = \begin{matrix} & |1,0\rangle & |0,1\rangle \\ \langle 1,0| & \cos\left(\frac{\theta}{2}\right) & i\sin\left(\frac{\theta}{2}\right) \\ \langle 0,1| & i\sin\left(\frac{\theta}{2}\right) & \cos\left(\frac{\theta}{2}\right) \end{matrix}$$

Universal interferometer

Linear Optical Implementation of an Arbitrary Unitary via Normal Form



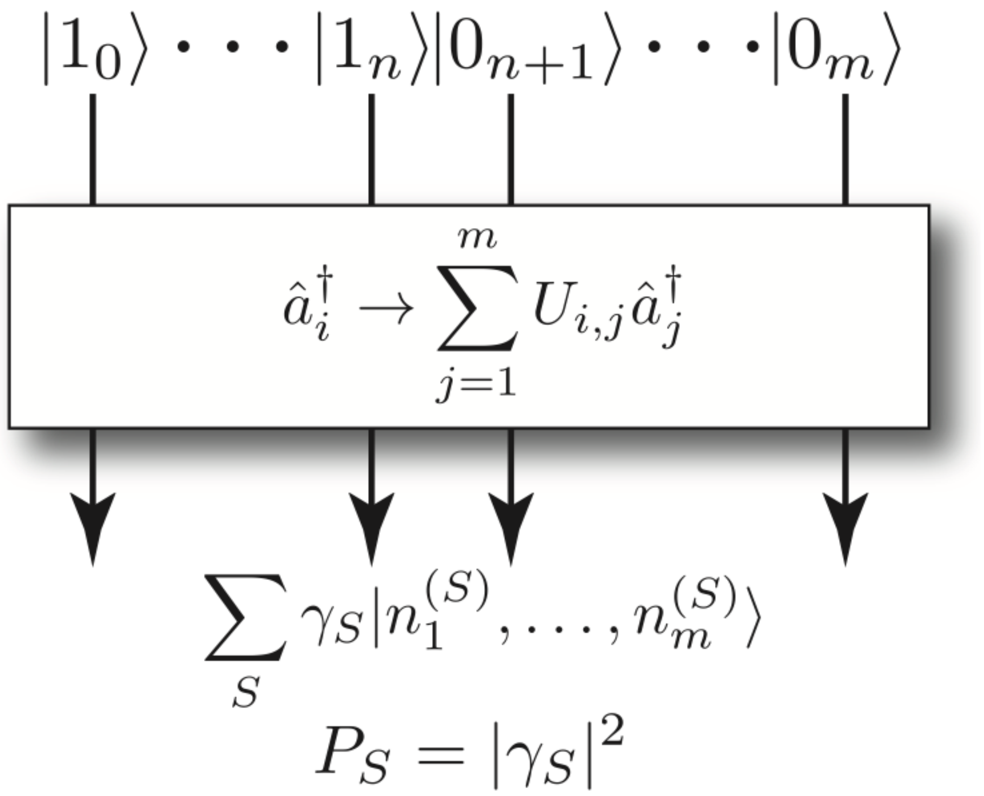


Clements, William R., et al. "Optimal design for universal multiport interferometers." *Optica* 3.12 (2016): 1460-1465.

Based on an earlier work:
Reck, Michael, et al. "Experimental realization of any discrete unitary operator." *Physical review letters* 73.1 (1994): 58.

Boson Sampling

Linear Optics is #P-hard to Exactly Simulate



$$
\begin{aligned}
|\psi_{\text{in}}\rangle &= |1_1, \ldots, 1_n, 0_{n+1}, \ldots, 0_m\rangle \\
&= \hat{a}_1^\dagger \ldots \hat{a}_n^\dagger \, |0_1, \ldots, 0_m\rangle\,,
\end{aligned}
$$

$$\hat{U}\hat{a}_i^\dagger\hat{U}^\dagger = \sum_{j=1}^{m} U_{i,j}\hat{a}_j^\dagger,$$

$$\gamma_S = \frac{\text{Per}(U_S)}{\sqrt{n_1^{(S)}! \ldots n_m^{(S)}!}},$$

Gard, Bryan T., et al. "An introduction to boson-sampling." From atomic to mesoscale: The role of quantum coherence in systems of various complexities. 2015. 167-192.

Ascella
With Universal Interferometer

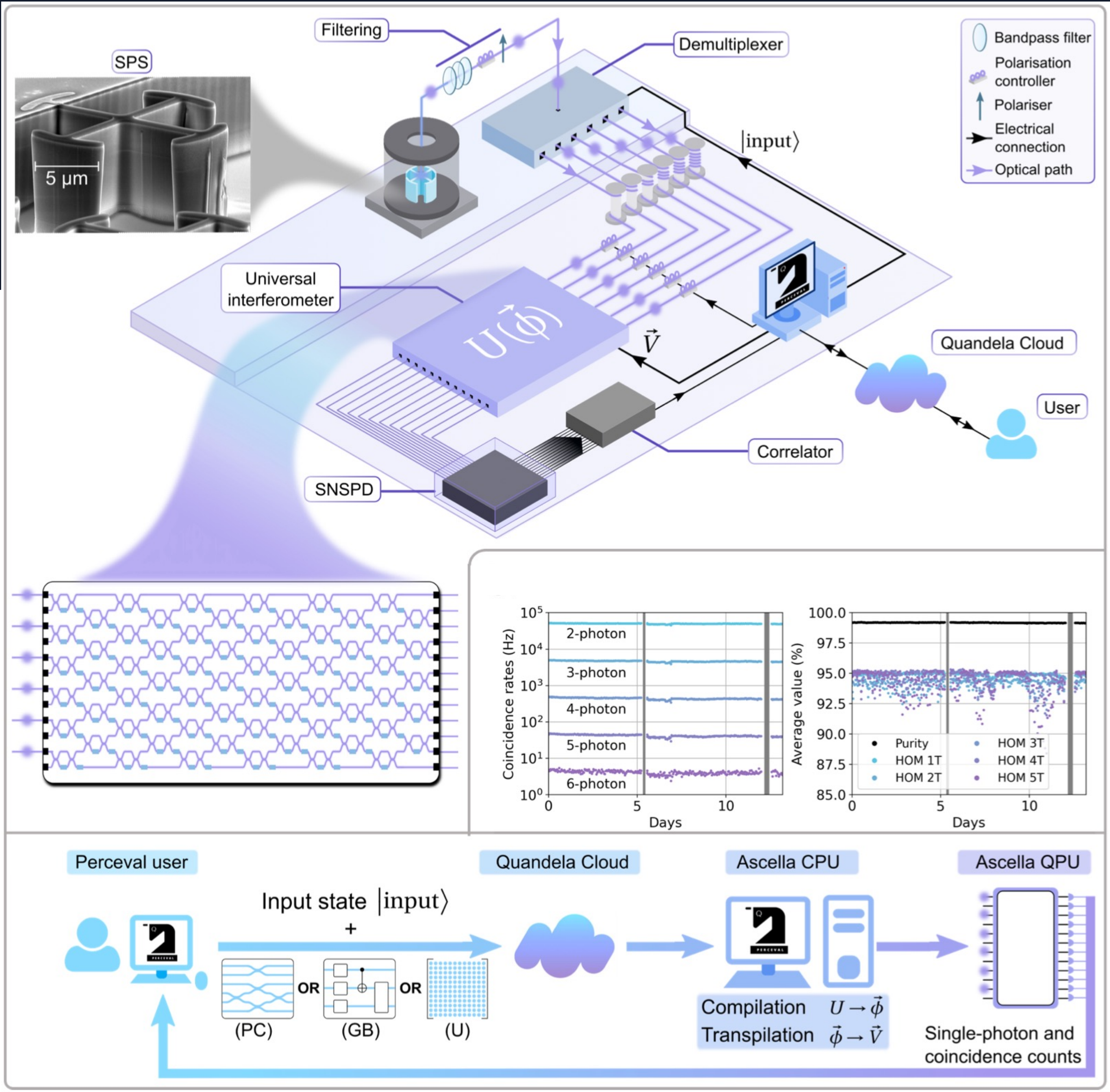
User input

- Fock state
- Unitary / Photonic Circuit (PC) / Gate-based Quantum Circuit (GB)

PC and GB can first be compiled to a unitary

User output

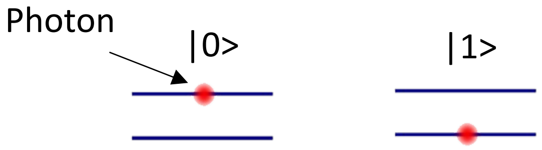
Coincidence counts

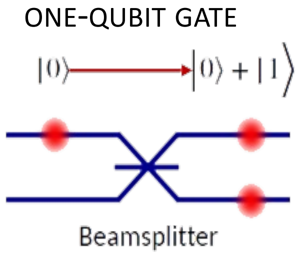


Qubits & Logic Gates

Postselection, Heralding and Active Linear Optics

Dual-rail Qubit Encoding



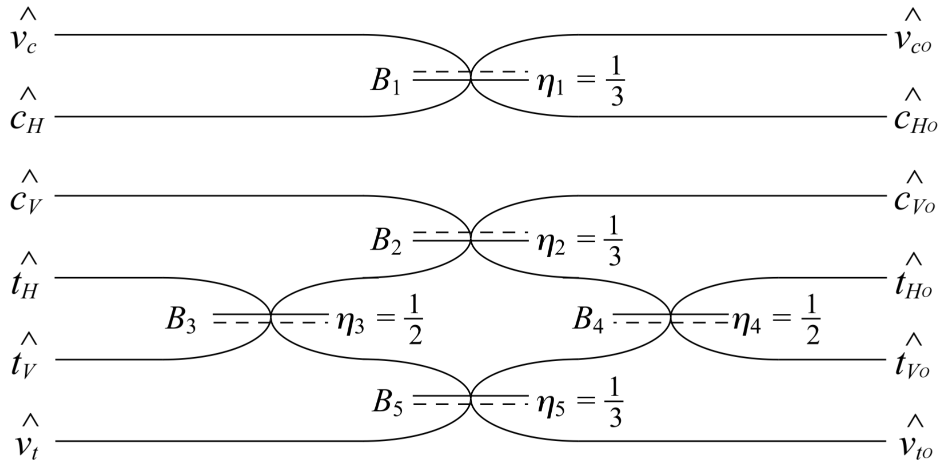


But 2-qubit gates cannot be achieved deterministically with passive linear optics

Requires:

- Nonlinearities (materials unavailable)
- Postselection (probabilistic)
- Heralding (probabilistic)
- Feedforward

Basic Example: Postselected CNOT

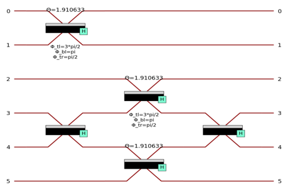


$$
\begin{aligned}
|\phi\rangle_{out} &= (\alpha\, c^\dagger_{H_O} t^\dagger_{H_O} + \beta\, c^\dagger_{H_O} t^\dagger_{V_O} + \gamma\, c^\dagger_{V_O} t^\dagger_{H_O} + \delta\, c^\dagger_{V_O} t^\dagger_{V_O})|0000\rangle|00\rangle \\
&= \frac{1}{3}\{\alpha|HH\rangle + \beta|HV\rangle + \gamma|VV\rangle + \delta|VH\rangle \\
&\quad +\sqrt{2}(\alpha+\beta)|0100\rangle|10\rangle + \sqrt{2}(\alpha-\beta)|0000\rangle|11\rangle + (\alpha+\beta)|1100\rangle|00\rangle \\
&\quad +(\alpha-\beta)|1000\rangle|01\rangle + \alpha|0010\rangle|10\rangle + \beta|0001\rangle|10\rangle \\
&\quad -(\gamma+\delta)|0200\rangle|00\rangle - (\gamma-\delta)|0100\rangle|01\rangle + \gamma|0020\rangle|00\rangle \\
&\quad +(\gamma-\delta)|0010\rangle|01\rangle + (\gamma+\delta)|0011\rangle|00\rangle + (\gamma-\delta)|0001\rangle|01\rangle + \delta|0002\rangle|00\rangle\}
\end{aligned}
$$

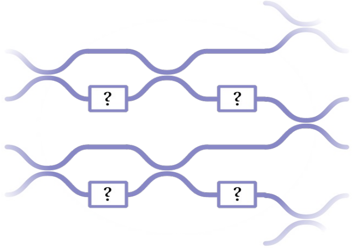
Ralph, Timothy C., et al. "Linear optical controlled-NOT gate in the coincidence basis." Physical Review A 65.6 (2002): 062324.

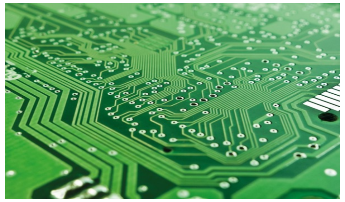
Ascella: Compilation & Transpilation

With Machine Learning to Offset Hardware Imperfections



$\hat{U}$

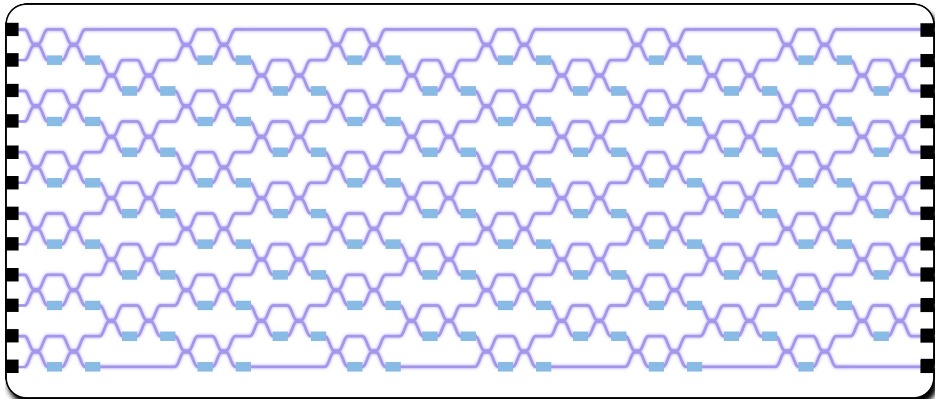




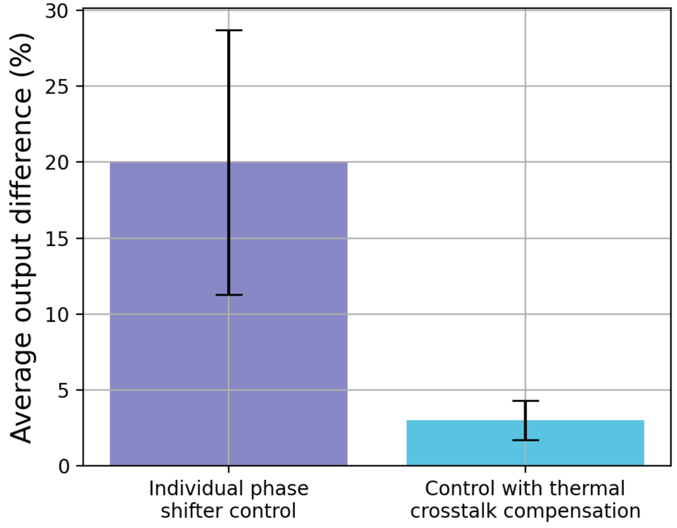
Circuit → Unitary matrix → Phases → Voltages

Compilation (Circuit → Unitary matrix → Phases)

Transpilation (Phases → Voltages)



- 12 x 12 fully reconfigurable universal interferometer
- 126 physical phase shifters
- 132 directional couplers



Standard approach Machine learning

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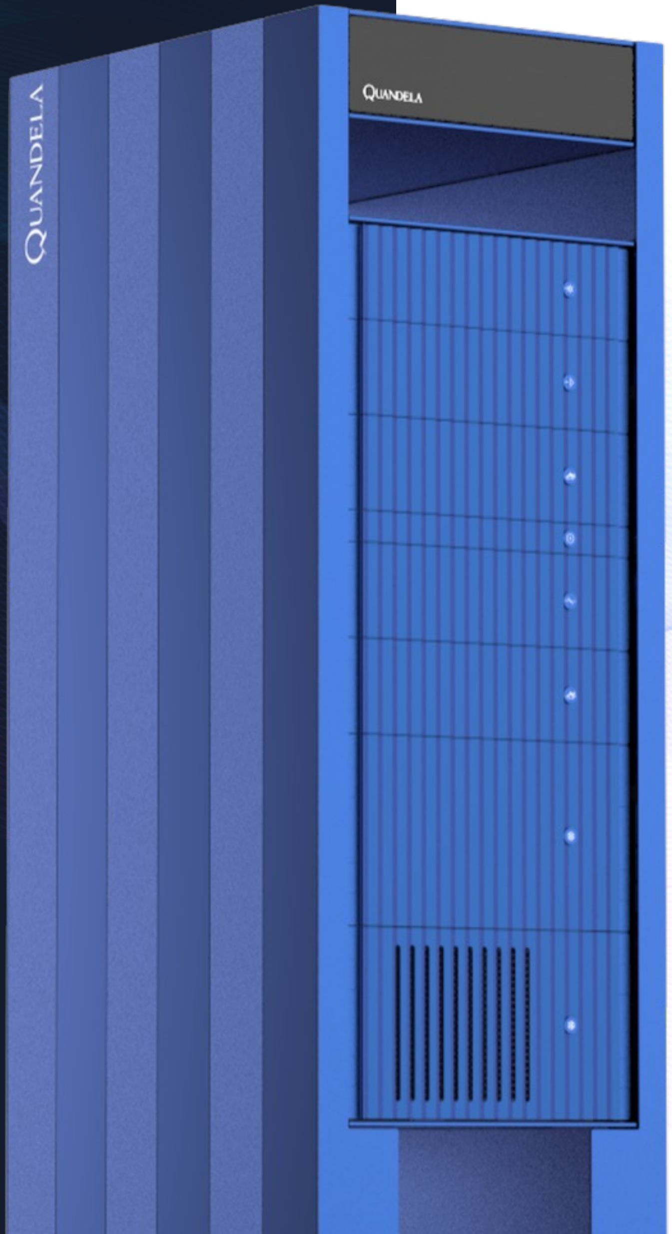
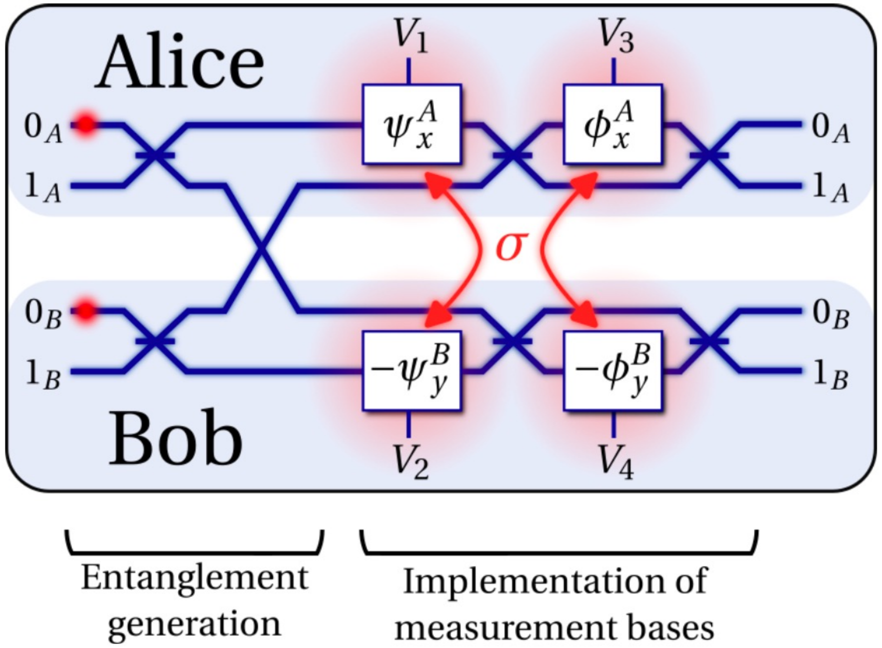
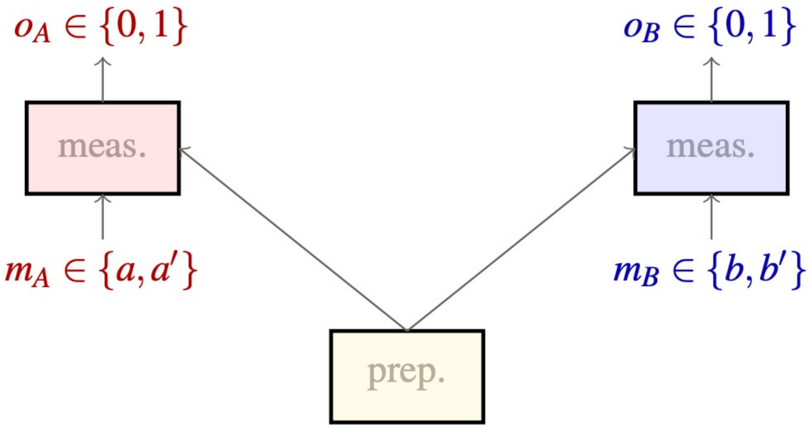
Testing Contextuality



Bell-CHSH Scenario

A Contextuality Test



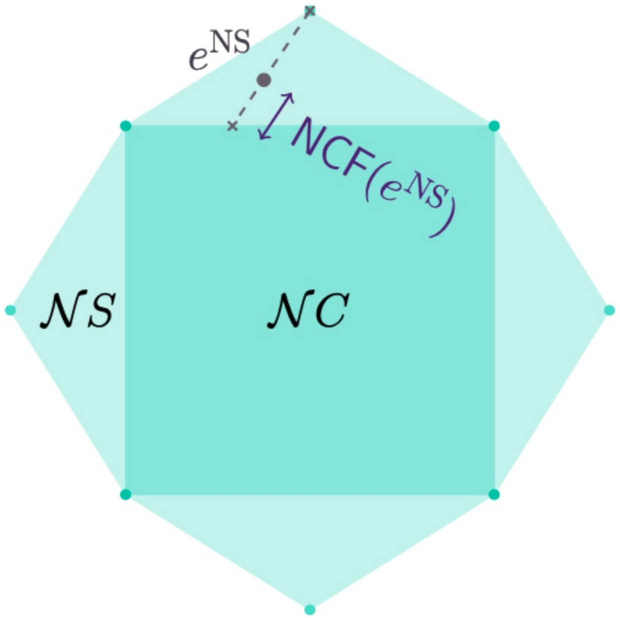


in\out	(0,0)	(0,1)	(1,0)	(1,1)
(a,b)	1/2	0	0	1/2
(a,b')	1/2	0	0	1/2
(a',b)	1/2	0	0	1/2
(a',b')	0	1/2	1/2	0

Not the actual experimental data yet…

Quantifying Contextuality

Contextual Fraction



$$e = \mathsf{NCF}(e)\, e^{NC} + \mathsf{CF}(e)\, e^{SC}$$

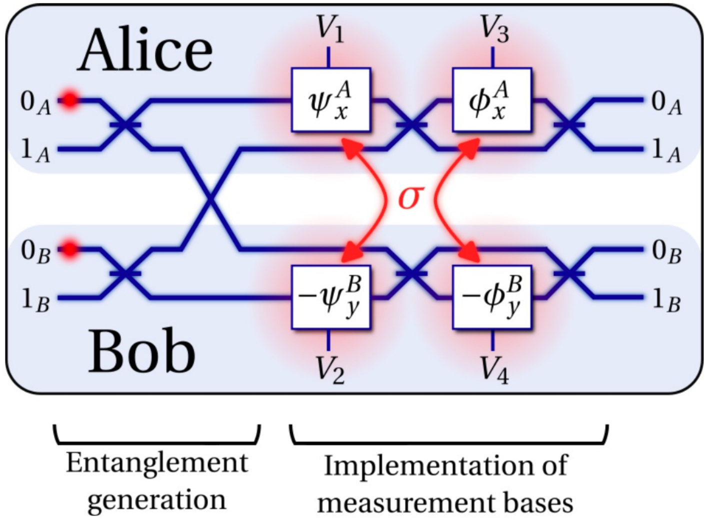
- CF Corresponds to the normalised violation of an optimal Bell inequality
- Master inequality for witnessing contextuality

$$\mathsf{CF}(e) > 0$$

Abramsky, Samson, and Adam Brandenburger. "The sheaf-theoretic structure of non-locality and contextuality." New Journal of Physics 13.11 (2011): 113036.
Abramsky, Samson, Rui Soares Barbosa, and Shane Mansfield. "Contextual fraction as a measure of contextuality." Physical review letters 119.5 (2017): 050504

Quantifying Contextuality

On Actual Empirical Data



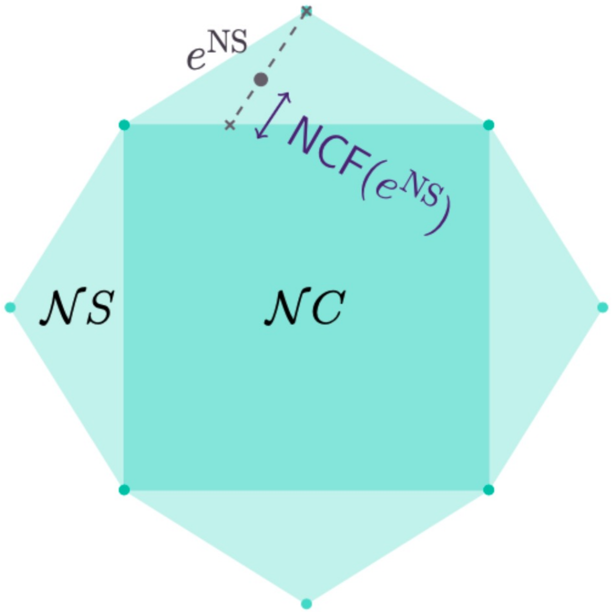
in\out	(0,0)	(0,1)	(1,0)	(1,1)
(a,b)	0.418	0.083	0.084	0.415
(a,b')	0.090	0.416	0.410	0.084
(a',b)	0.085	0.418	0.418	0.079
(a',b')	0.077	0.429	0.423	0.071

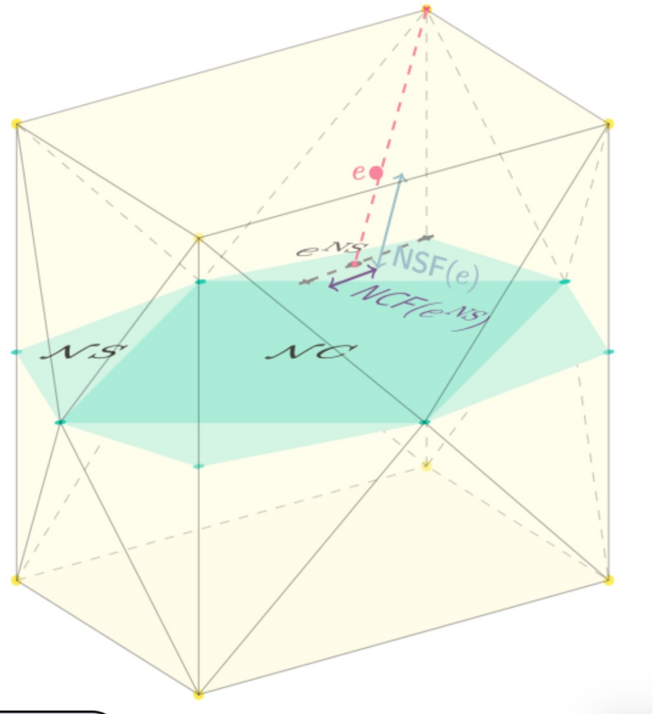
- CF ≈ 0.34
- Tsirelson bound: CF ≈ 0.41

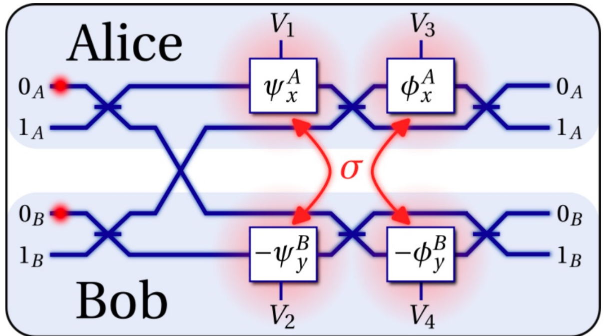
Fyrillas et al., arXiv:2301.03536

Non-ideal data

The Signalling Fraction







- Empirical behaviour can be signalling
- Due to experimental cross-talk
- Or finite statistics

- Analogous to the *contextual fraction*, we introduce a *signalling fraction**

$$e = NSF(e)e^{NS} + SF(e)e'$$

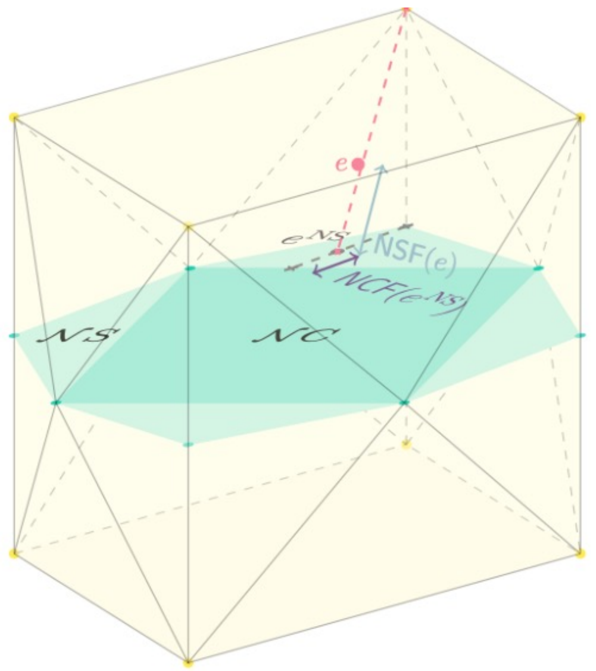
- Observed signalling: $SF < 0.05$

*From unpublished work with Samson and Rui

Contextuality in the Presence of Signalling

What does it all mean?

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



What does it all mean?

- Contextuality rules out hidden variable realisations which are
  1. Deterministic
  2. Non-signalling for each hidden variable (i.e. hidden variables are *global* assignments)
- In the presence of signalling we should relax 2
- A new assumption is always required to relate empirical signalling to hidden variable signalling

$$\sigma^{HV} = f(SF(e)) > SF(e)$$

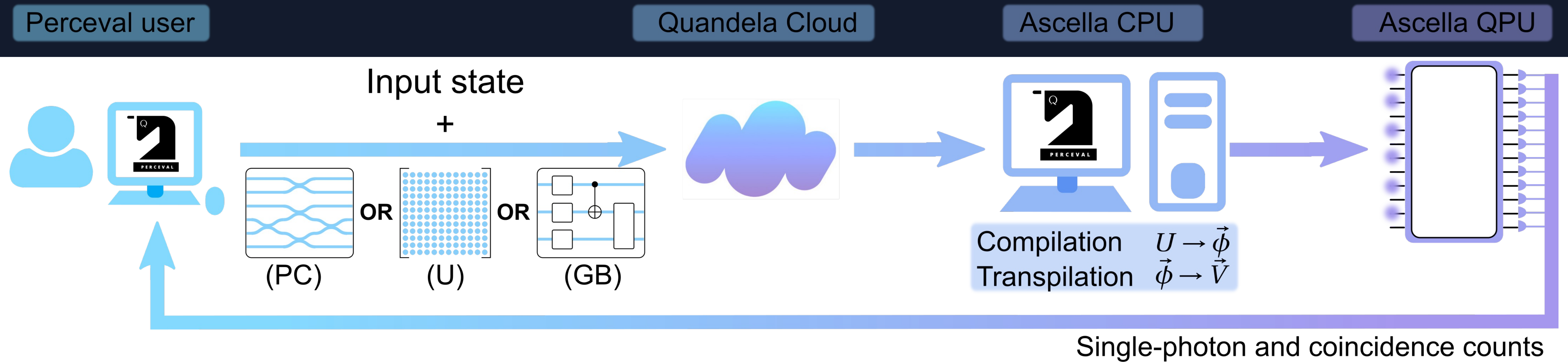
- Contextuality-by-default analysis (Dzafharov, Kujala et al.) quantifies very differently but essentially sets $f = Id$
- Sufficient condition to rule out relaxed hidden variable realisations:

$$CF(e) > \sigma^{HV}$$

Vallée, Kim et al. *in preparation*

Experimenting with Ascella

Free access



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