University of BRISTOL

QET Labs

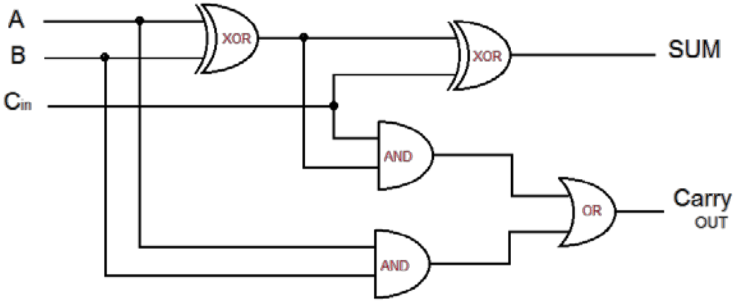
Quantum Computing:

From one qubit to infinity.

Jeremy C. Adcock & Caterina Vigliar

Quantum computation on quantum bits

Full adder logic circuit



n bits can store a number up to *2ⁿ*

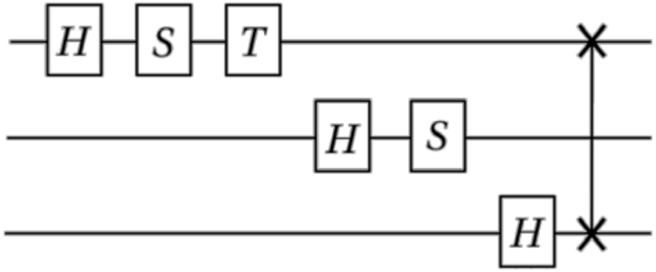
$0 \; or \; 1$

BIN DEC

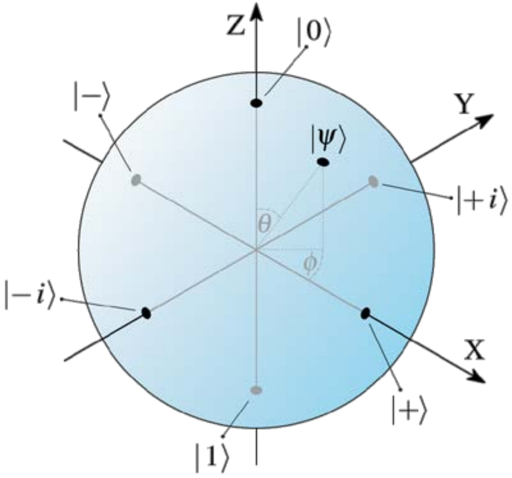
$01011010 = 80$

	128	64	32	16	8	4	2	1
Binary	0	1	0	1	1	0	1	0
Decimal	64 + 16 + 8 + 2 = 80							

Quantum Fourier transform quantum circuit



n qubits access a *2ⁿ* dimensional space



Superposition!

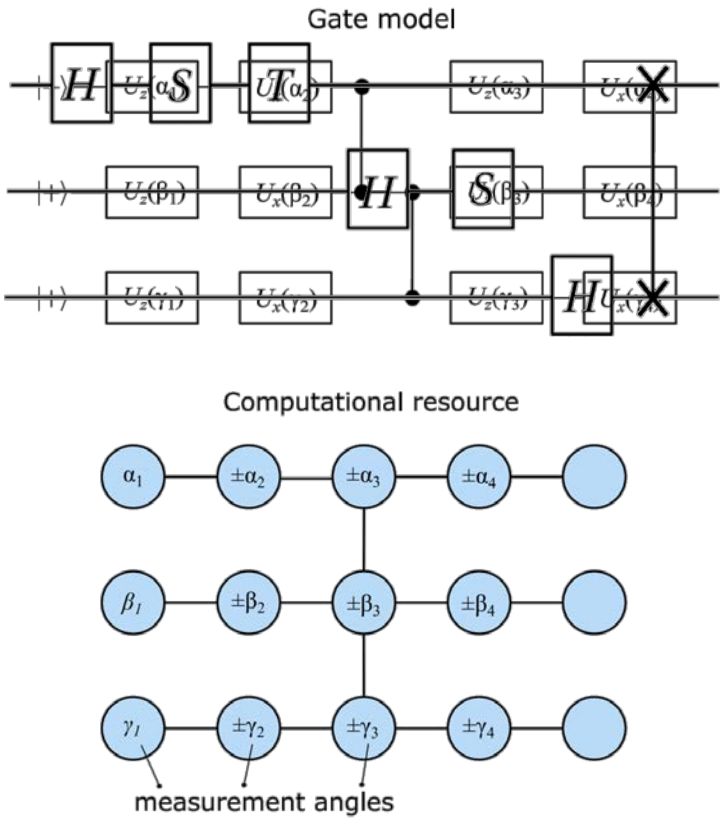
$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

Entanglement!

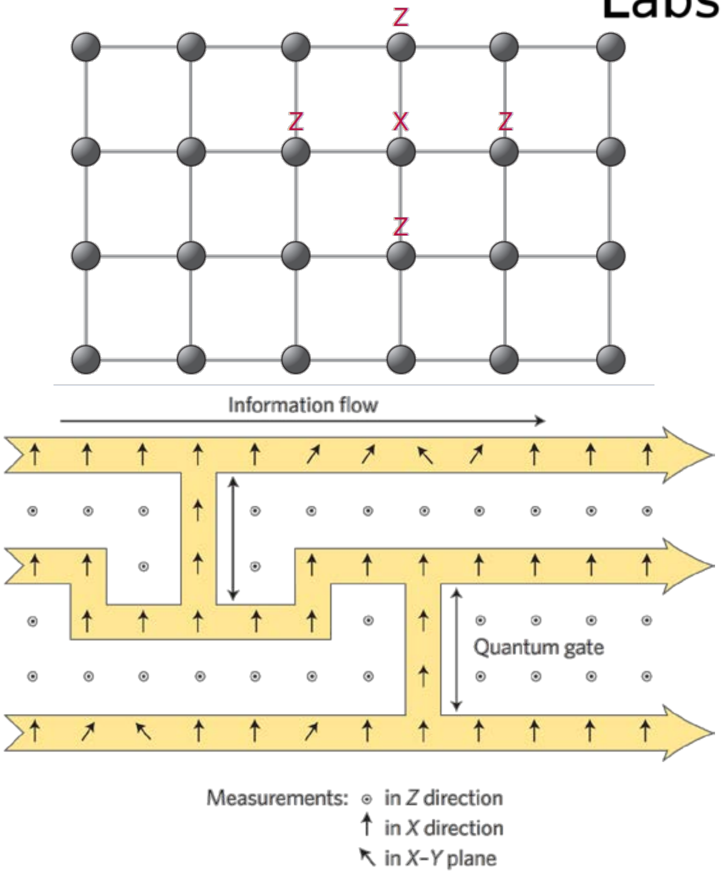
$$|\Phi^+\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle)$$

…But measurement only reveals a single bit-string!

Modern quantum computer architecture



Daniel E. Browne and Terry Rudolph. "Resource-efficient linear optical quantum computation." *Physical Review Letters* 95.1 (2005): 010501.

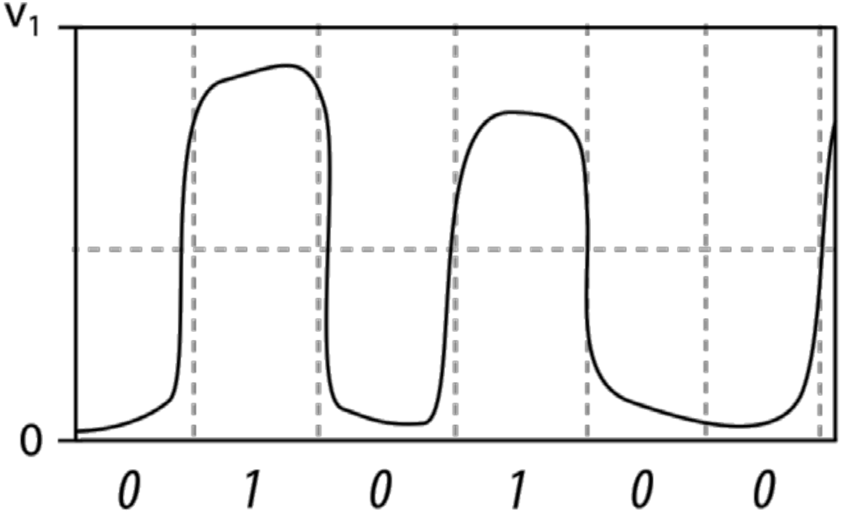


Hans J. Briegel et al. "Measurement-based quantum computation." *Nature Physics*, 5.1 (2009): 19

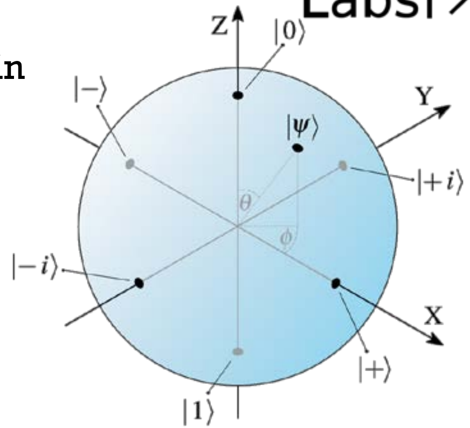
Quantum error correction

QET Labs

Digital errors within a threshold
can always be corrected

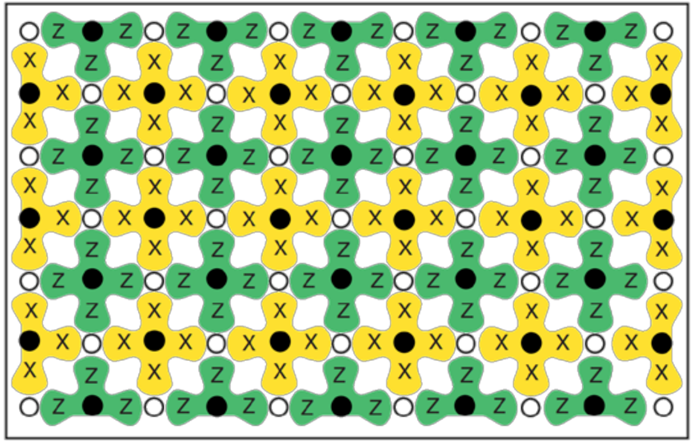


..but quantum states live in
a continuous space!



$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

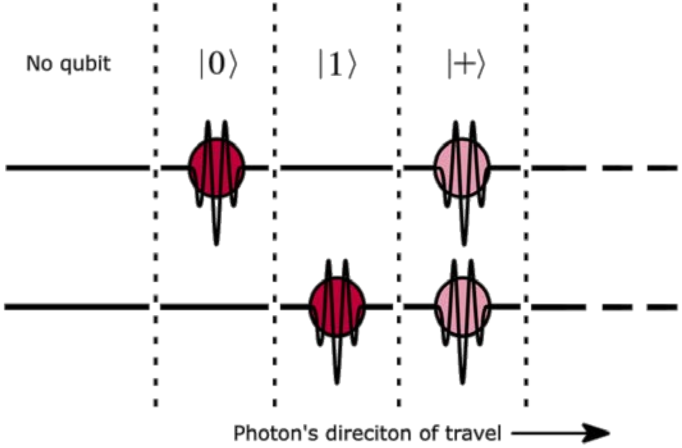
Amazingly, topological properties of entangled states can be used to correct errors, below a certain threshold!



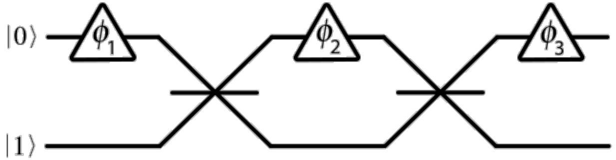
Austin G. Fowler et al. "Surface codes: Towards practical large-scale quantum computation." *Physical Review A* 86.3 (2012): 032324.

Photonic qubits

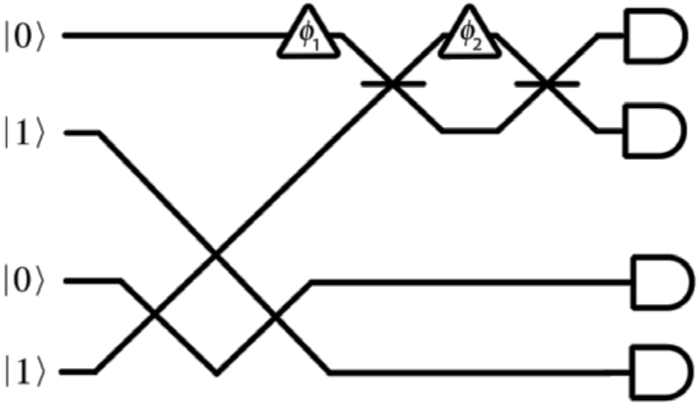
‘Dual-rail’ qubits

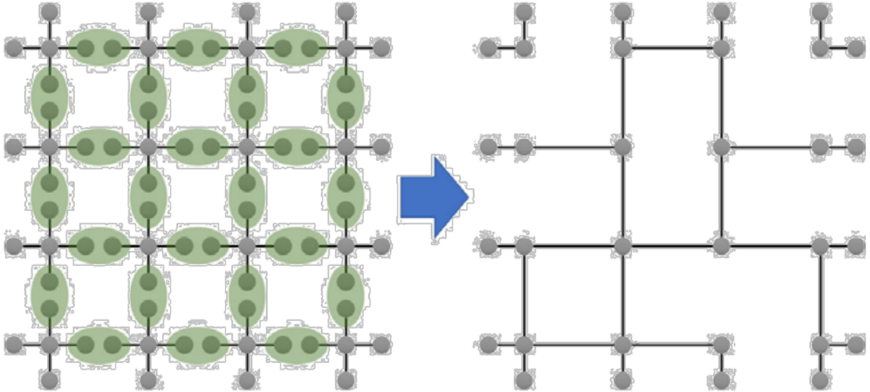


Single-qubit gate



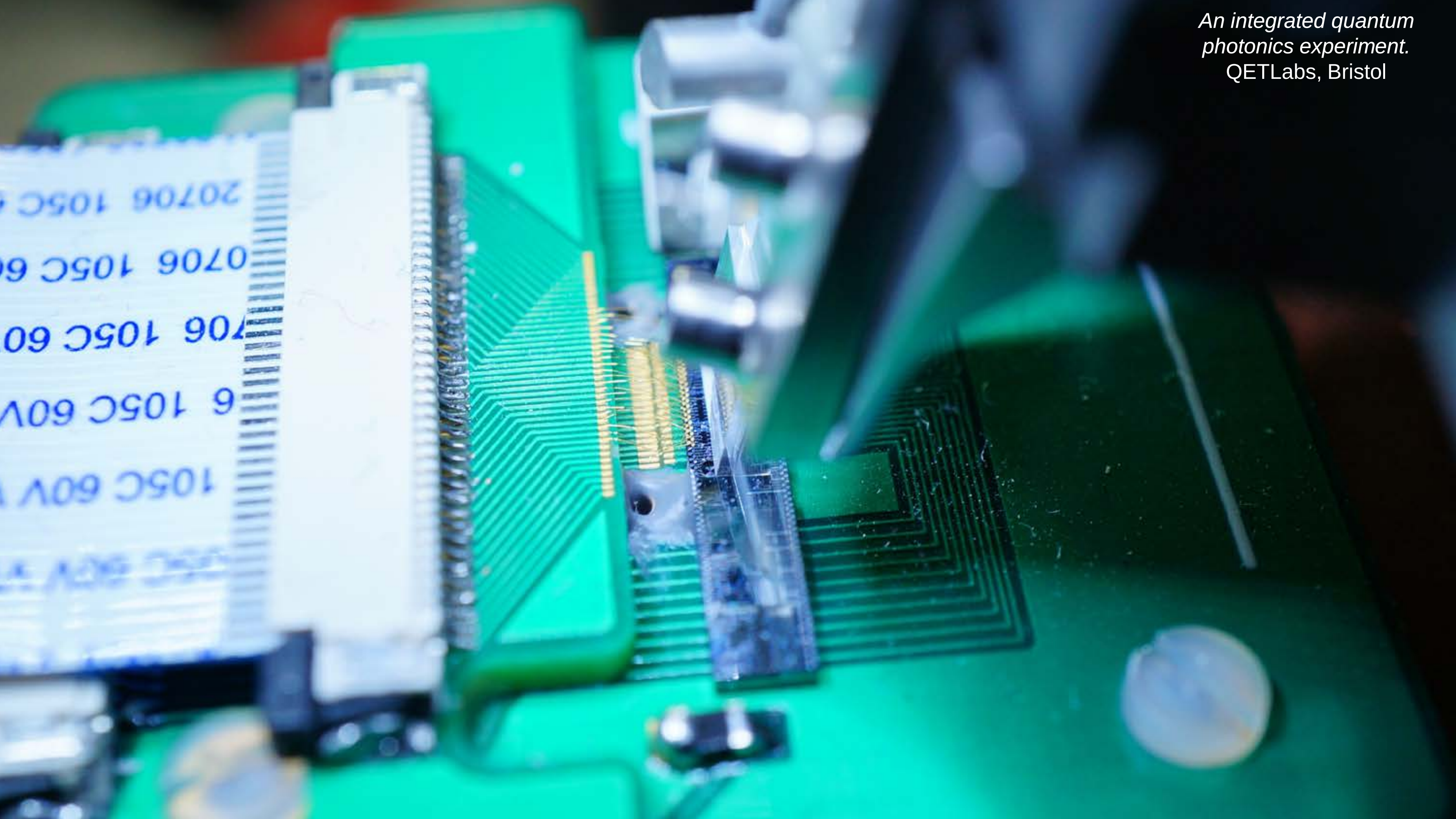
Heralded two-qubit gate: *Fusion*





Pant, Mihir, et al. "Percolation thresholds for photonic quantum computing." *Nature communications* 10.1 (2019): 1070.

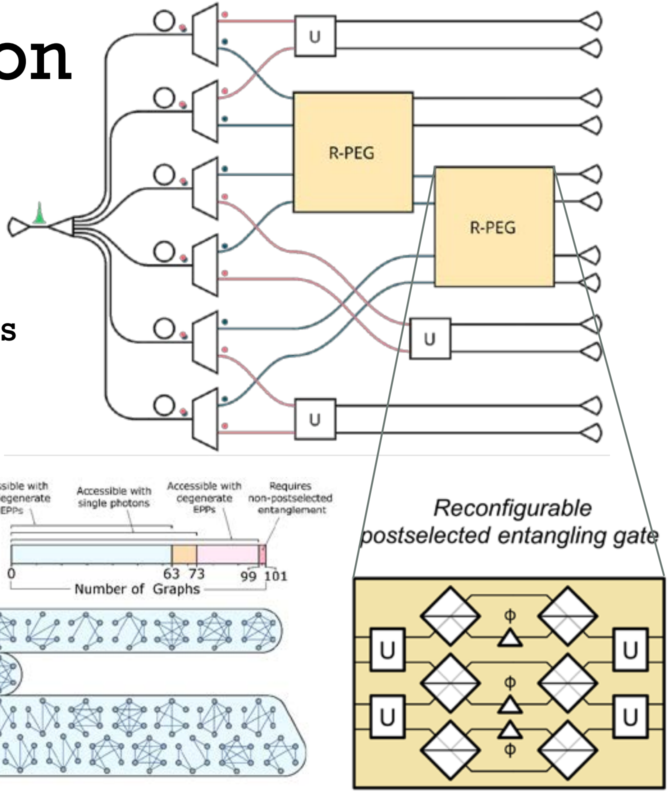
A bulk optics quantum photonics experiment.
Max-Plack Institute, Munich

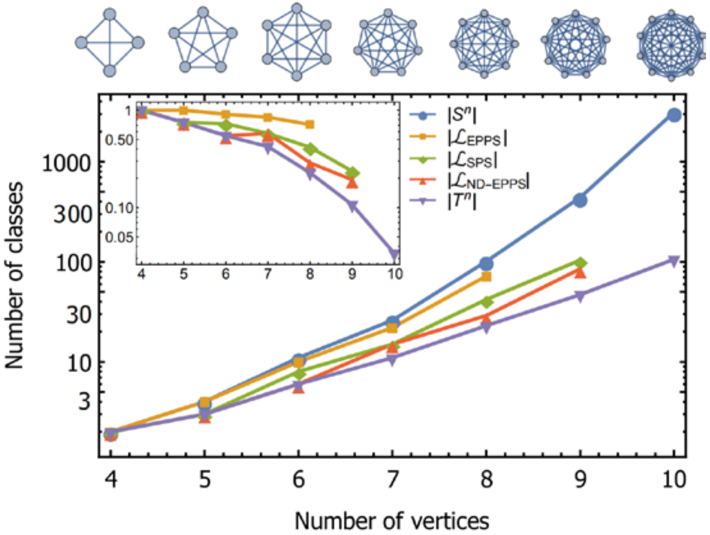


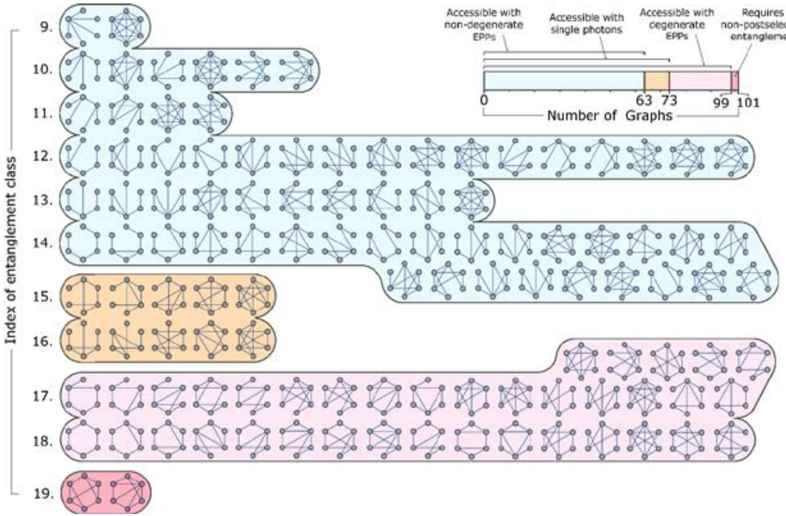
An integrated quantum photonics experiment.
QETLabs, Bristol

The end of the road for postselection

- Postselection enables testing of quantum photonic technology
  - But is not scalable
- We find new limitations: *most* entanglement is out of reach
- We also find new reconfigurable graph state generator experiments
  - Mapping the end of the road of postselected experiments



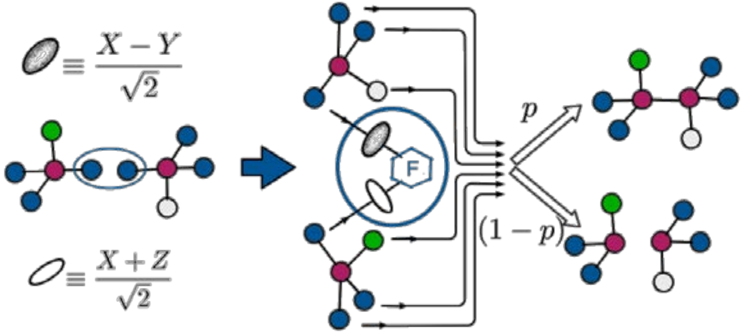


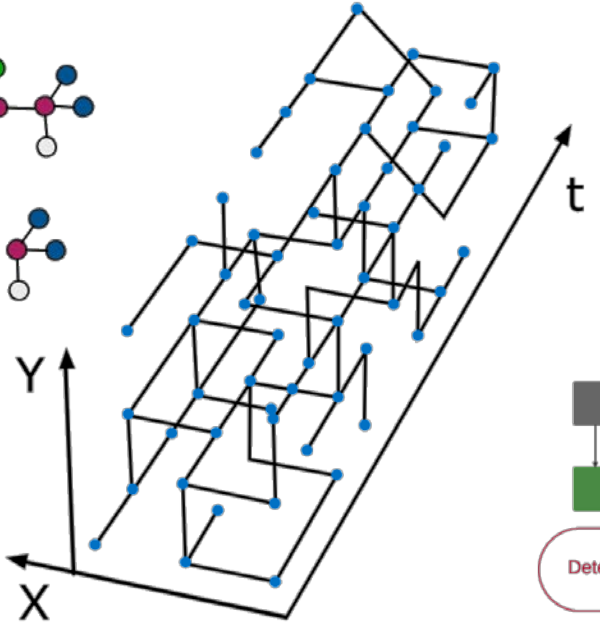


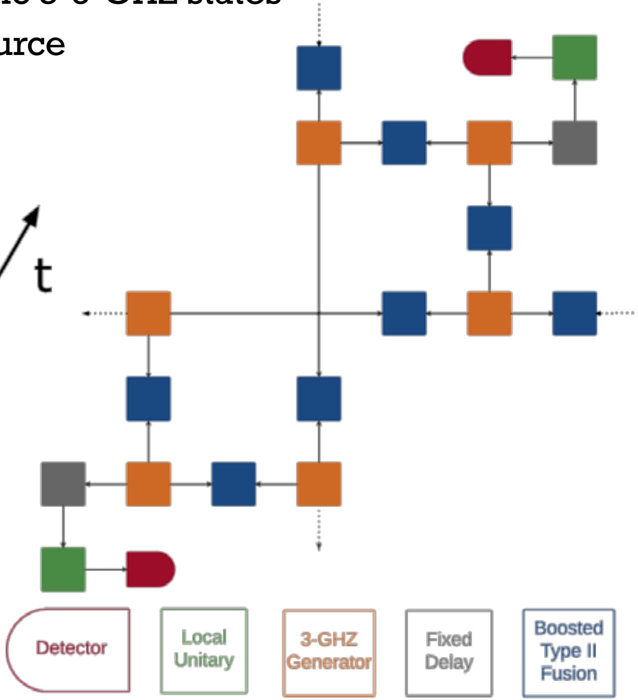
Jeremy C. Adcock et al. "Hard limits on the postselectability of optical graph states." *Quantum Science and Technology* 4.1 (2018): 015010.

The photonic quantum computer architecture

- How can we generate a resource state for universal quantum computation using linear optics?
  - A ‘ballistic’ approach is taken
- Photons sources and gates are multiplexed to produce deterministic 3-5-GHZ states
- Probabilistic gates then generate an imperfect, but universal, resource



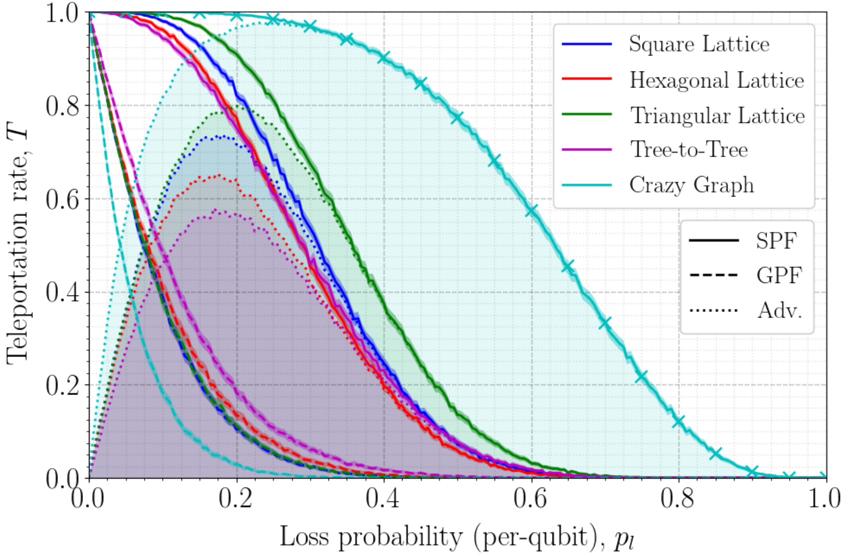


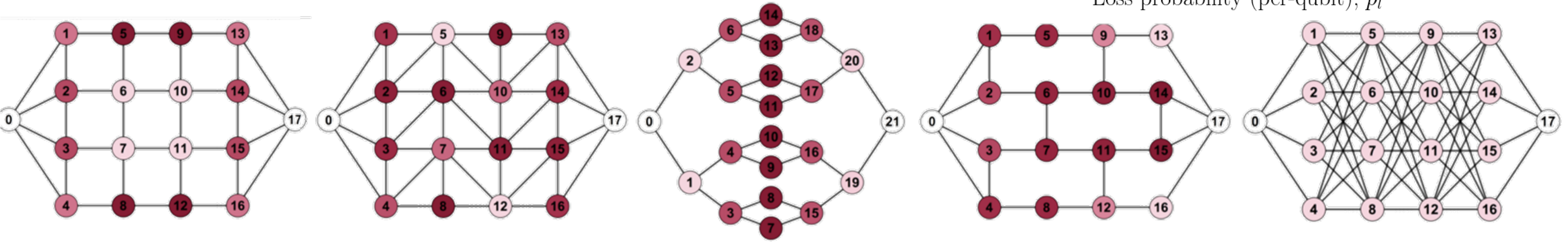


Terry Rudolph "Why I am optimistic about the silicon-photonic route to quantum computing." *APL Photonics* 2.3 (2017): 030901.
Mercedes Gimeno-Segovia et al. "From three-photon GHZ states to ballistic universal quantum computation." *Physical review letters* 115.2 (2015): 020502.

Improving the architecture

- Physical lattice simulations of thousands of qubits
    - Stable for modest numbers of ‘alive’ qubits
    - Low complexity co-processing
- Photon loss can be tolerated up to ~10%
    - Previously unsolved!
    - Different resource states have different tolerances
- Improvements to the percolation thresholds for universal quantum resource states





Pant, Mihir, et al. "Percolation thresholds for photonic quantum computing." *Nature communications* 10.1 (2019): 1070.
Sam Morley-Short et al. "Loss-tolerant teleportation on large stabilizer states." *Quantum Science and Technology* 4 (2018) 025014.
Sam Morley-Short et al. "Physical-depth requirements for generating universal photonic cluster states." *Quantum Science and Technology* 3.1 (2017): 015005.

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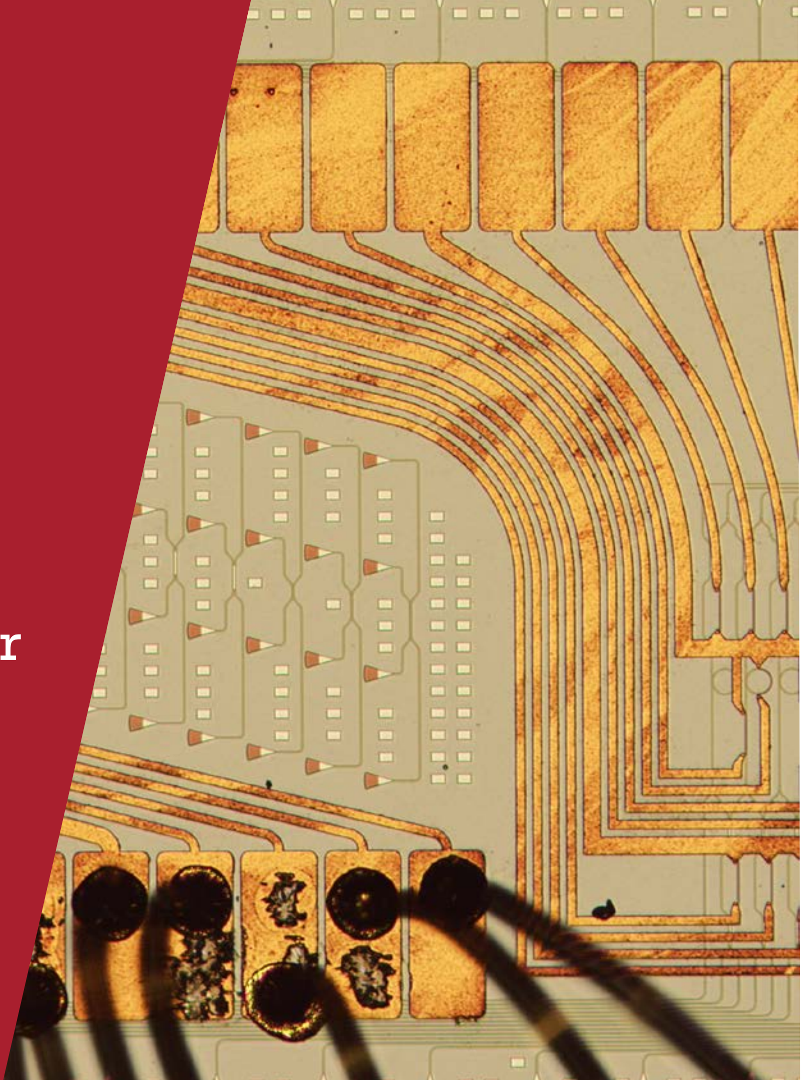
Thank you!

Up next:

Implementations of quantum photonic processing on silicon with Caterina Vigliar



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From one photon to infinity.

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University of BRISTOL

QET Labs

Quantum Computing:

From one photon to *(almost)* infinity.

Jeremy C. Adcock & Caterina Vigliar

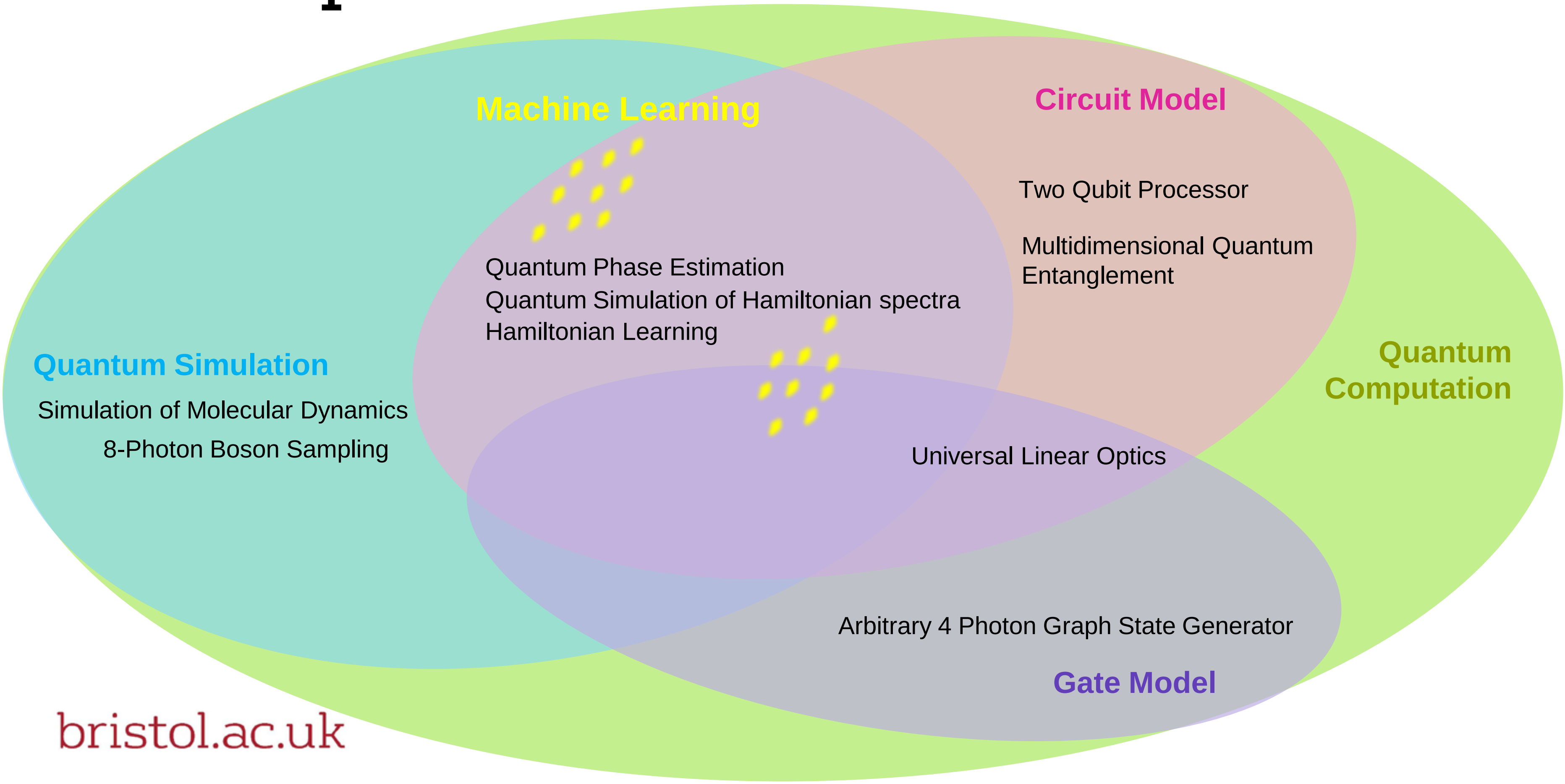
Quantum Computing:

From one photon to ~~(almost) infinity~~.

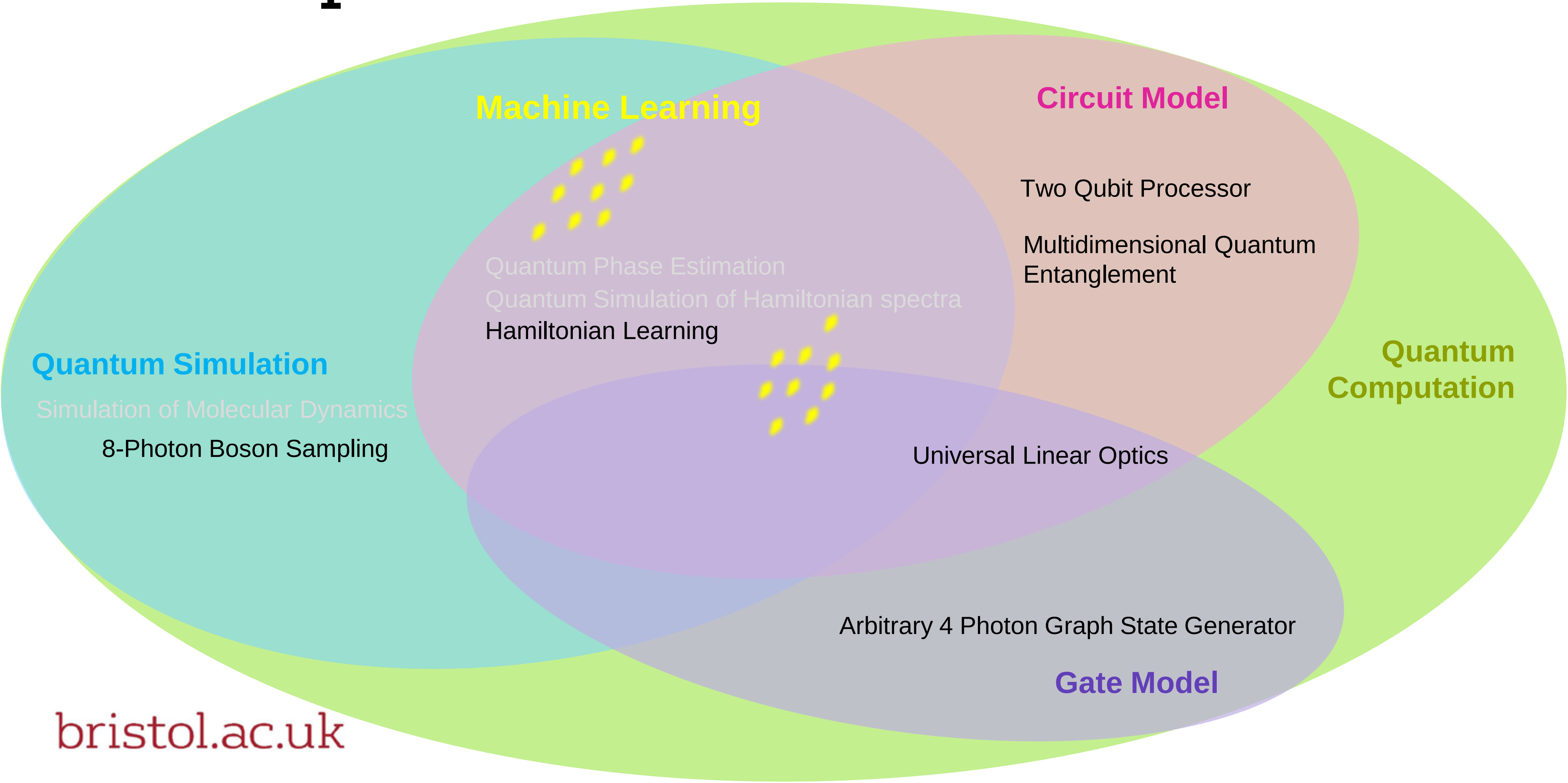
(8 photons)

Jeremy C. Adcock & Caterina Vigliar

Bristol Experiments



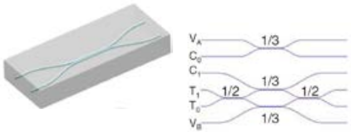
Bristol Experiments



Bristol Experiments (The Past)

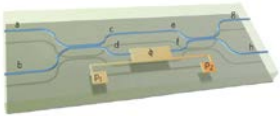
2008

A. Politi et al., Science 320, 646.

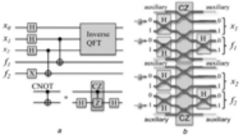


2009

J. C. F. Matthews et al., Nature Photonics 3, 346.

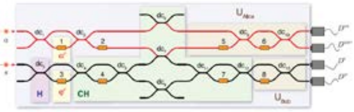


A.Politi, J. C. F. Matthews, et al., Science 325, 1221.



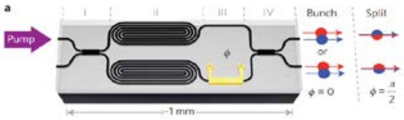
2012

P. J. Shadbolt et al., Nat. Photonics 6, 45.



2013

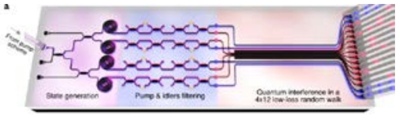
J. W. Silverstone et al., Nature photonics 8, 104.



Quantum Photonic Programme Grant

… …

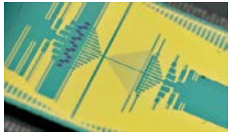
Bristol Experiments (Present)



2018 -2019

S. Paesani et al., arXiv:1812.03158 [quant-ph].

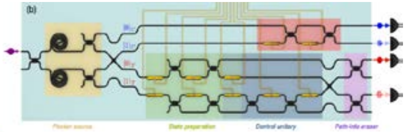
Jeremy Adcock et al. arXiv:1811.03023 [quant-ph].



2018

J. Wang, S. Paesani et al., Science.

Xiaogang Qiang et al., Nature Photonics.

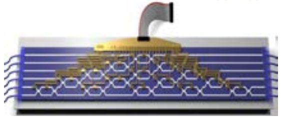


2017

J. Wang, S. Paesani, R. Santagati et al., Nature Physics,
PRL & Science Advances.

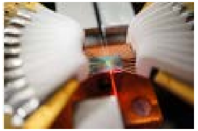
2015

Jacques Carolan et al., Science.

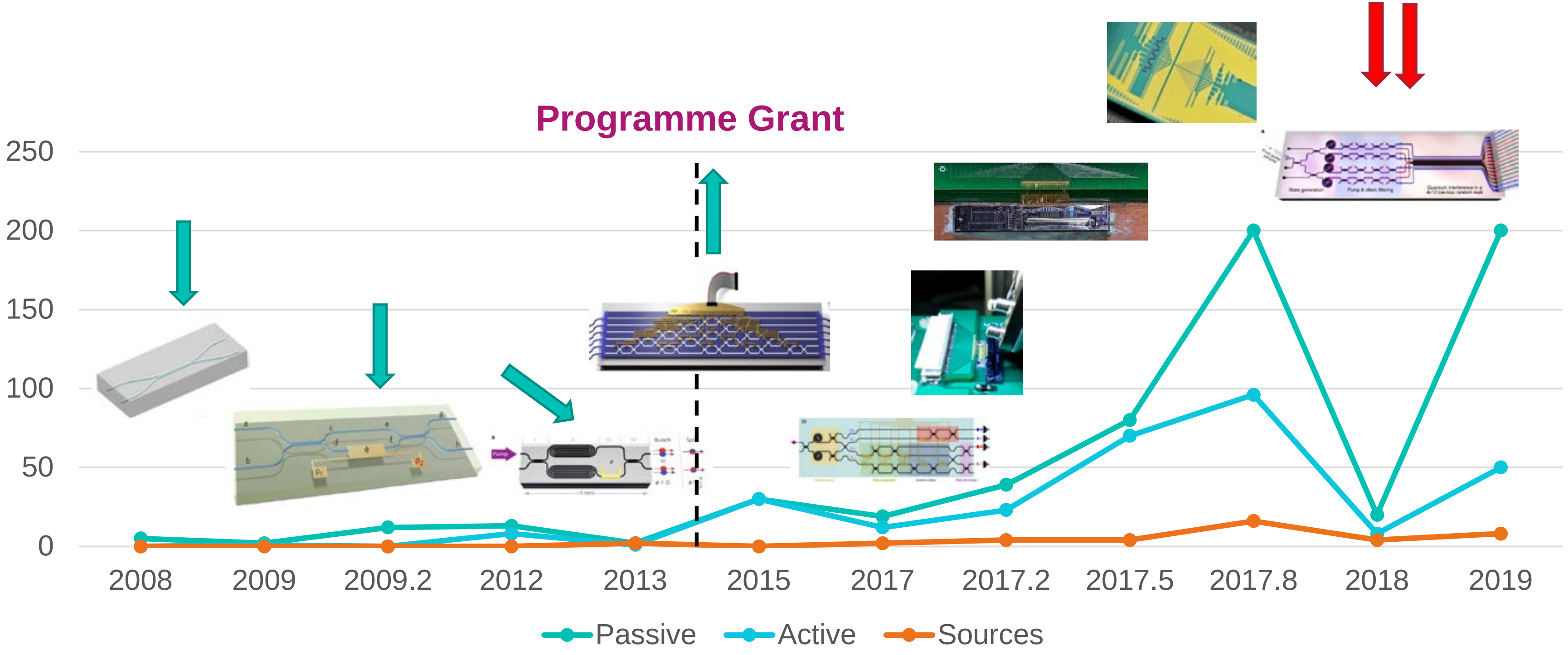


2014

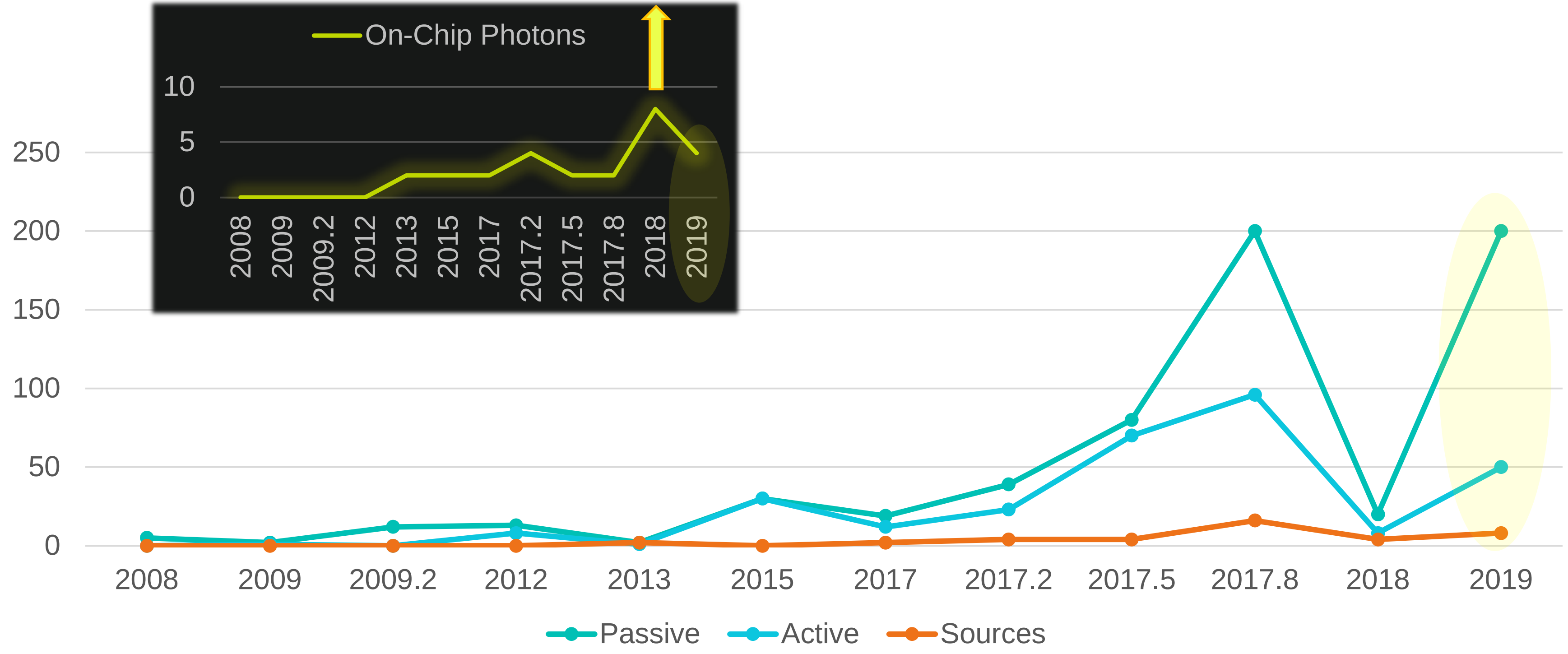
J. W. Silverstone et al., Integrated Photonics Research, Silicon and Nanophotonics.



Number of Components in Time

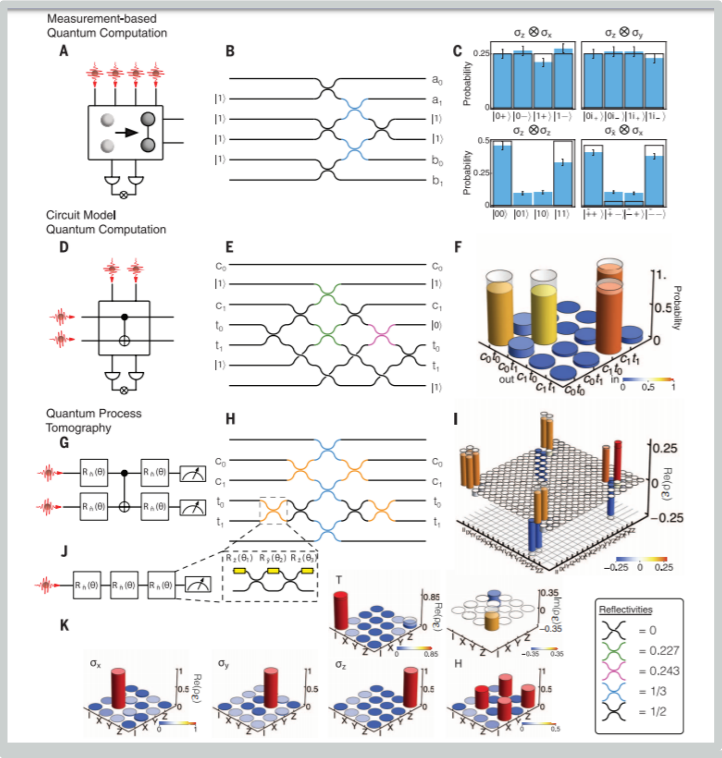


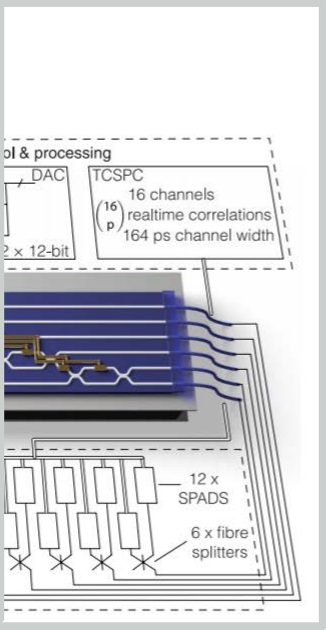
Number of Components in Time



Universal Linear Optics

Implement all possible linear optical protocols up to the size of the circuit.





THE DEVICE

- Six-mode universal system with 30 reconfigurable thermo-optic phase shifters.
- Input of up to six (off chip) photons.
- Measurements with a 12-single-photon detector system.

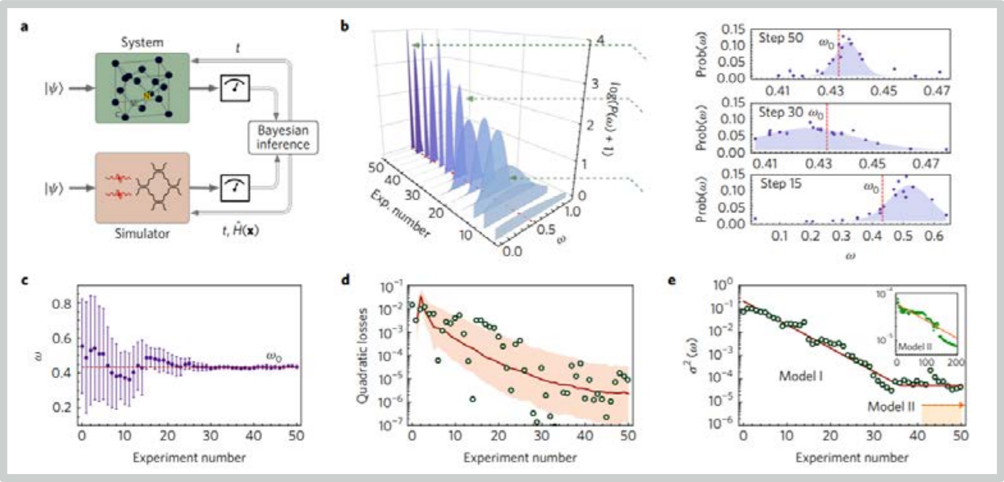
QUANTUM PROTOCOLS

- Heralded quantum logic and entangling gates.
- Boson sampling with verification tests.
- Six-dimensional complex Hadamards.
- 100 Haar random unitaries with an average fidelity of 0.999 ± 0.001.

Jacques Carolan, C. Harrold, C. Sparrow, E. Martín-López, N. J. Russell, J. W. Silverstone, P. J. Shadbolt, N. Matsuda, M. Oguma, M. Itoh, G. D. Marshall, M. G. Thompson, J. C. F. Matthews, T. Hashimoto, J. L. O'Brien, A. Laing. SCIENCE, 14 AUGUST 2015 , VOL 349 ISSUE 6249.

Experimental quantum Hamiltonian learning

Learn the Hamiltonian of an electron spin in a diamond NV center.



THE SYSTEM

- Interface two different quantum systems through a classical channel.
  - Silicon-photonics quantum simulator.
  - Electron spin in a diamond nitrogen–vacancy centre.

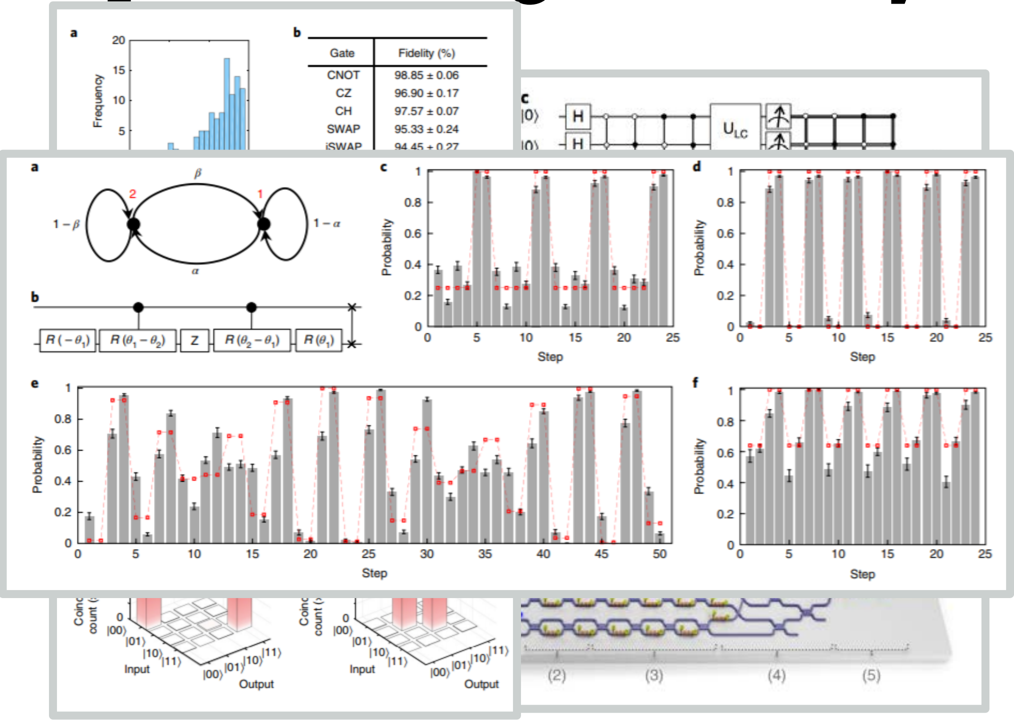
QUANTUM PROTOCOLS

- Algorithm of characterisation of quantum systems, based on Machine Learning enhanced by a quantum simulator.

- Learn the Hamiltonian of the quantum system via Bayesian inference.
- Learn the salient Hamiltonian parameter with an uncertainty of approximately 10^-5.
- Saturation in the learning algorithm suggests Model Learning.

J. Wang, S. Paesani, R. Santagati, S. Knauer, A. A. Gentile, N. Wiebe, M. Petruzzella , J. L. O'Brien, J. G. Rarity, A. Laing and M. G. Thompson.
NATURE PHYSICS, VOL 13, JUNE 2017.

Large-scale silicon quantum photonics implementing arbitrary two-qubit processing



THE DEVICE

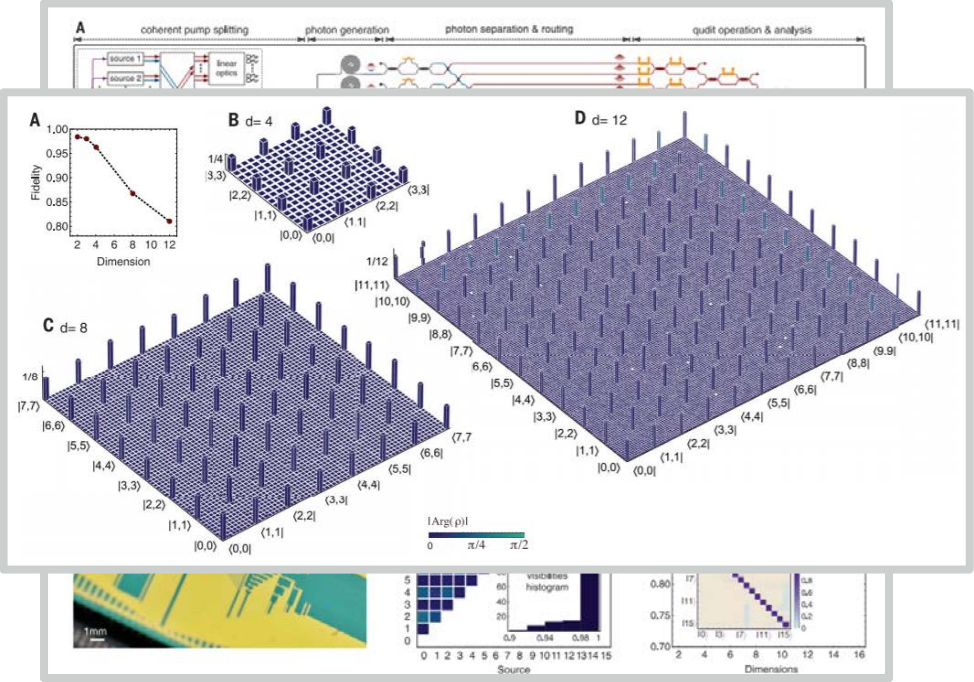
- Fully programmable two-qubit quantum processor, enabling universal two-qubit quantum information processing in optics.
- More than 200 photonic components, 4 on-chip sources for generation of 2 on-chip photons.

QUANTUM PROTOCOLS

- Implement 98 different two-qubit unitary operations (average quantum process fidelity of $93.2 \pm 4.5\%$).
- Experimental realization of a two-qubit quantum approximate optimization algorithm.
- Efficient simulation of Szegedy directed quantum walks.

Xiaogang Qiang, Xiaoqi Zhou, Jianwei Wang, Callum M. Wilkes, Thomas Loke, Sean O'Gara, Laurent Kling, Graham D. Marshall, Raffaele Santagati, Timothy C. Ralph, Jingbo B. Wang, Jeremy L. O'Brien, Mark G. Thompson and Jonathan C. F. Matthews. Nature Photonics, VOL 12, SEPTEMBER 2018, 534–539.

Multidimensional quantum entanglement with large-scale integrated optics



THE DEVICE

- A programmable bipartite entangled system with dimensions up to 15 × 15.
- More than 550 photonic components on a single chip, including 16 identical photon-pair sources.

QUANTUM PROTOCOLS

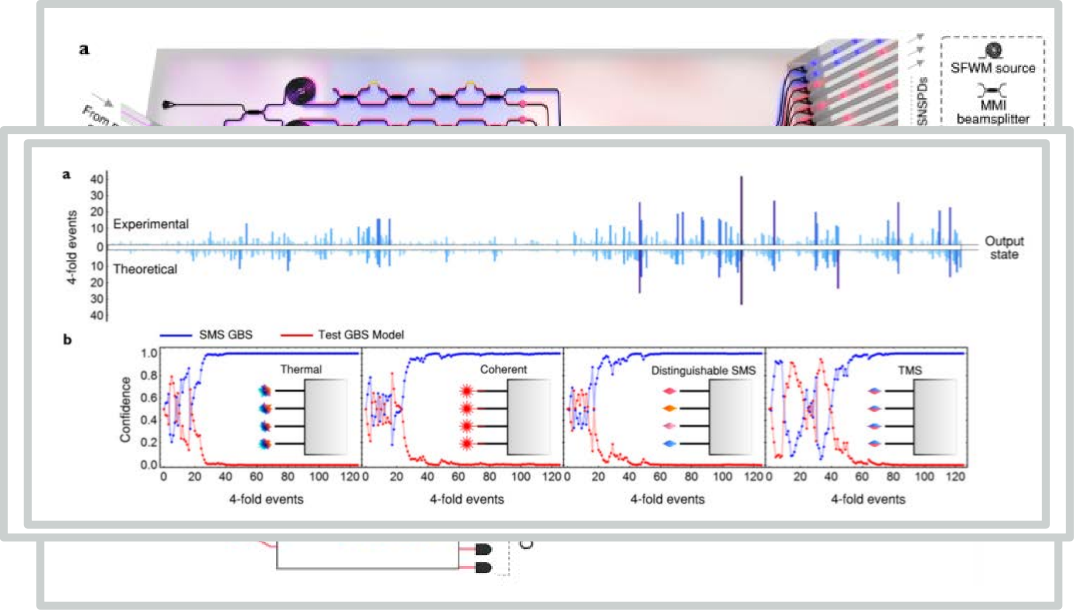
- High precision in the control of bipartite multidimensional entangled states.
- Quantum State Tomographies.
- Certification of system dimensionality.
- Multidimensional Bell Tests.

- Previously unexplored quantum applications:
  - quantum randomness expansion,
  - self-testing on multidimensional states.

J. Wang, S. Paesani, Y. Ding, R. Santagati, P. Skrzypczyk, A. Salavrakos, J. Tura, R. Augusiak, L. Mančinska, D. Bacco, D. Bonneau, J. W. Silverstone, Q. Gong, A. Acín, K. Rottwitt, L. K. Oxenløwe, J. L. O'Brien, A. Laing, M. G. Thompson. SCIENCE 360, 285–291 (2018).

Generation and sampling of quantum states of light in a silicon chip

Processing many photons



THE DEVICE

- 12-mode interferometer (Random Walk).
- 4 heralded photons, generating and processing quantum states of light with up to eight photons.

QUANTUM PROTOCOLS

- Quantum sampling algorithms: Scattershot, Gaussian and Standard Boson Sampling protocols in the same silicon chip.
- Benchmark a quantum algorithm for calculating molecular vibronic spectra.

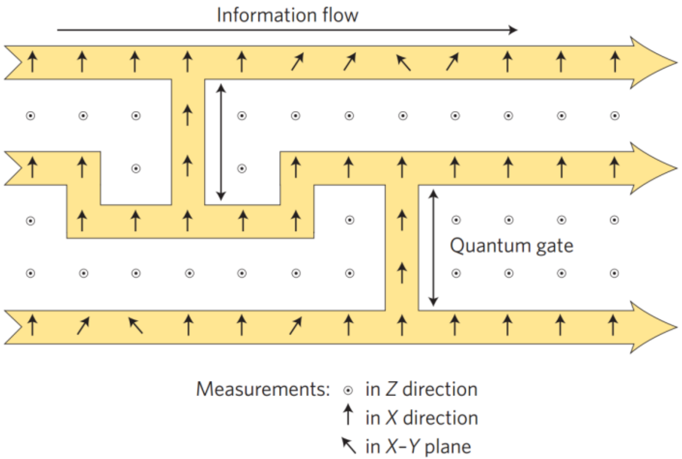
S. Paesani, Y. Ding, R. Santagati, L. Chakhmakhchyan, C. Vigliar, K. Rottwitt, L. K. Oxenløwe, J. Wang, M. G. Thompson and A. Laing. arXiv:1812.03158 [quant-ph].

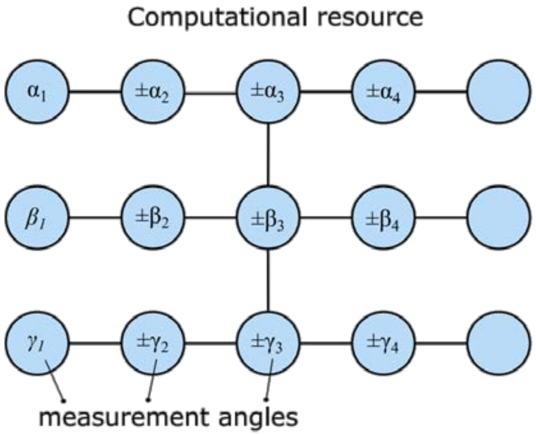
One-Way Quantum Computing

ENTANGLED RESOURCE

ONE-DIRECTIONAL INFORMATION FLOW

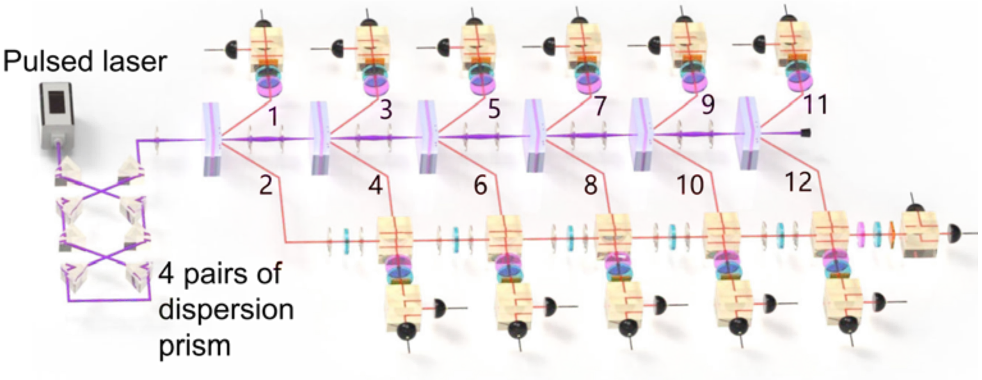
SINGLE QUBIT MEASUREMENTS



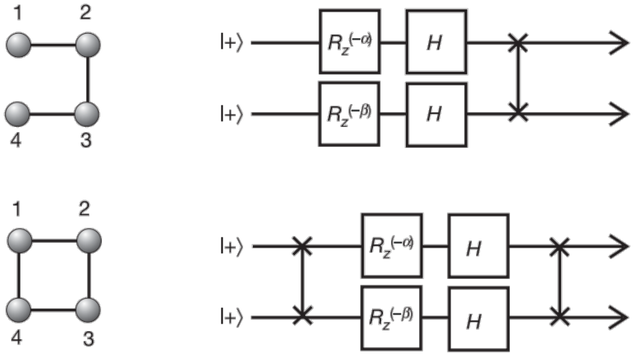


Raussendorf, R. & Briegel, H. J. A one-way quantum computer. Physical Review Letters 86, 5188 (2001).

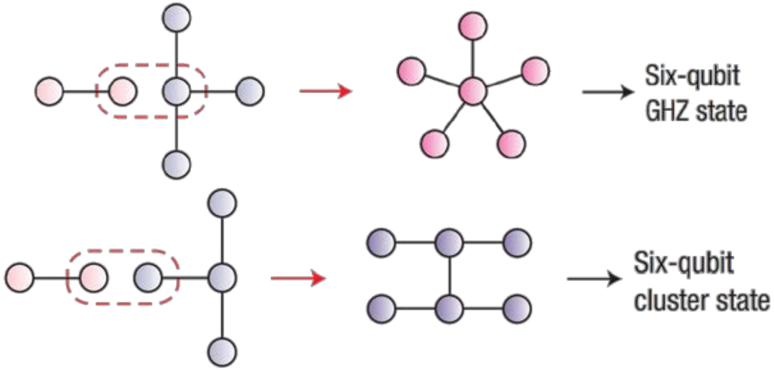
Daniel E. Browne and Terry Rudolph. "Resource-efficient linear optical quantum computation." Physical Review Letters 95.1 (2005): 010501.



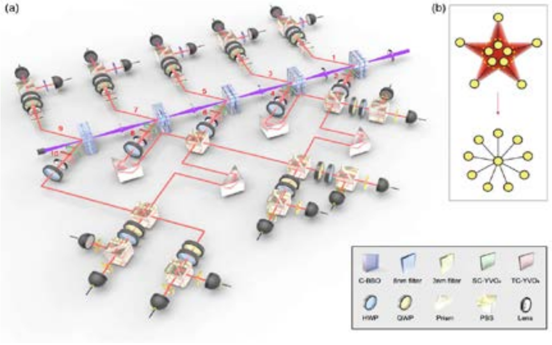
Zhong, Han-Sen, et al. "12-photon entanglement and scalable scattershot boson sampling" Physical review letters 121.25 (2018): 250505



Walther, Philip, et al. "Experimental one-way quantum computing." *Nature* 434.7030 (2005): 169.

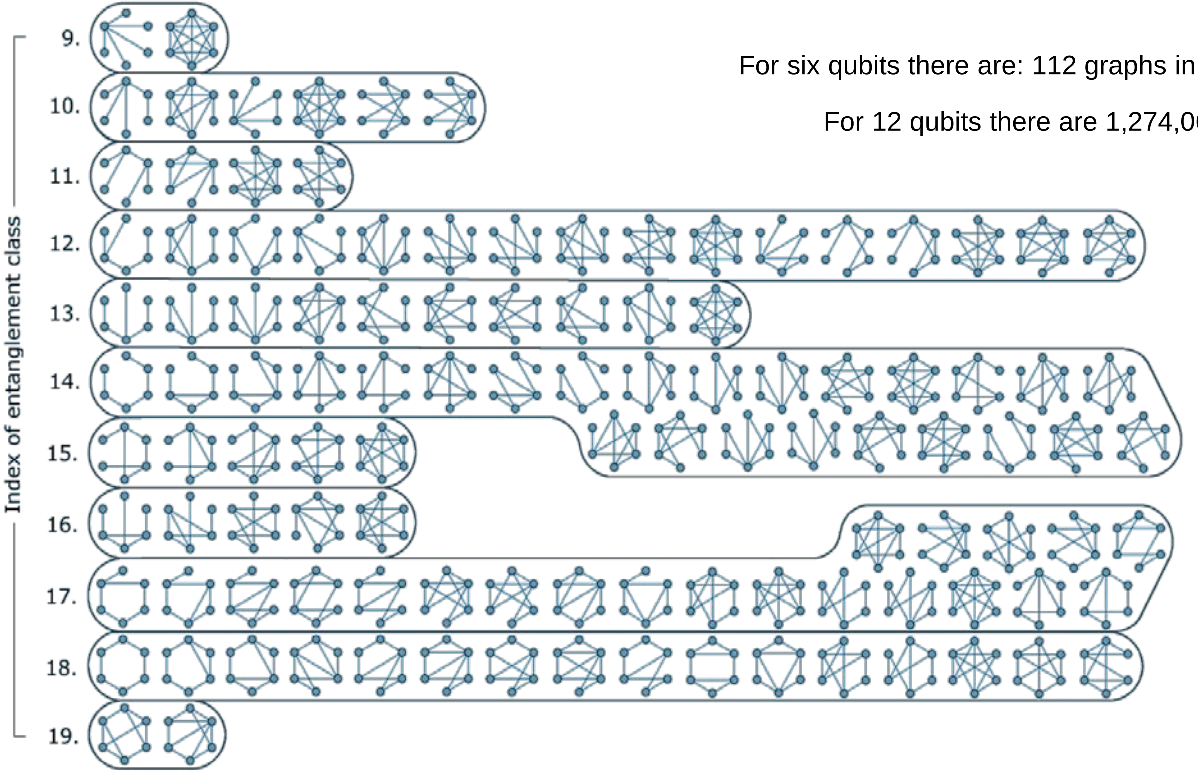


Lu, Chao-Yang, et al. "Experimental entanglement of six photons in graph states." Nature physics 3.2 (2007): 91.



Wang, Xi-Lin et al., , Phys. Rev. Lett.,117, 21 (2016)

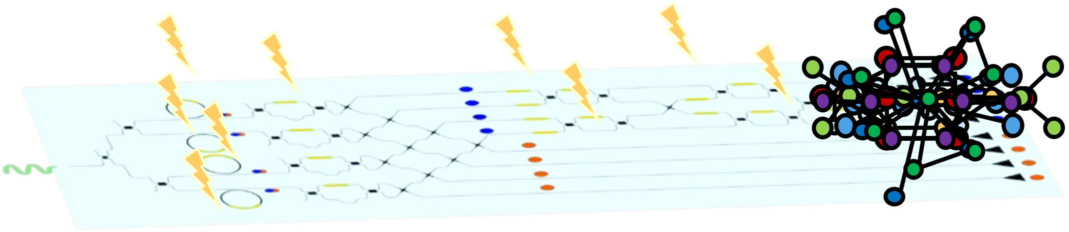
But there is much more…



For six qubits there are: 112 graphs in 11 classes.

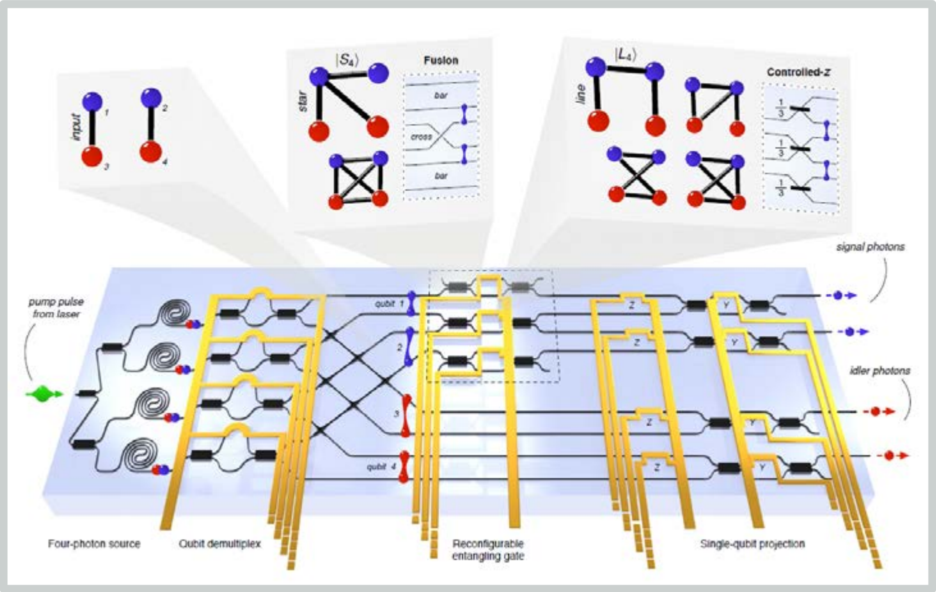
For 12 qubits there are 1,274,068 **classes**.

Programmable graph generator



Programmable four-photon graph states on a silicon chip

Processing arbitrary graph states



THE DEVICE

- All the 4-qubit graph state classes.
- 39 passive optical components, 23 active components 4 integrated sources.
- Generation and manipulation of 4 entangled photons.

J. C. Adcock, C. Vigliar, R. Santagati, J. W. Silverstone and M. G. Thompson. arXiv:1811.03023 [quant-ph].

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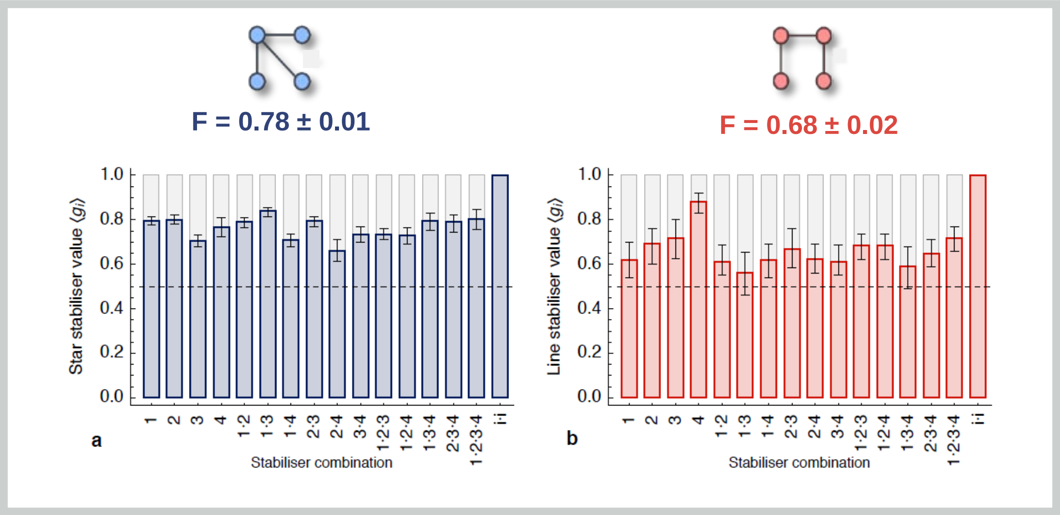
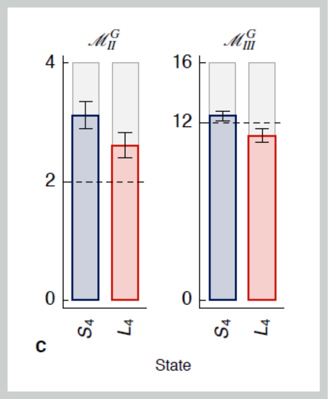


QUANTUM PROTOCOLS

- Generation of both star- and line-type graph states.
- Basic measurement-based protocols.
- Measure heralded interference of on-chip four photons.
- Multipartite Bell Tests.



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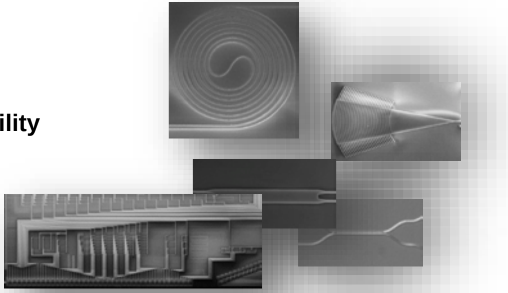
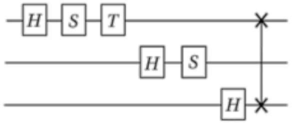
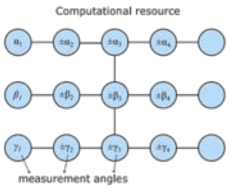
Quantum Computing



Hardware

Stability
Quick Reconfigurability
High Density



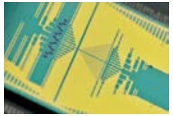


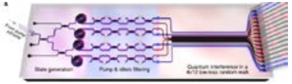
Software

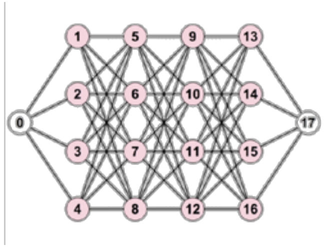
Circuit Model
Gate Model

Operational Tests

5-500 integrated components
8 on-chip photons
Hilbert space dimension from 4 to ~2000







Future Research

More complex circuits
Larger Hilbert Spaces
Error Correction
Fast modulators for feed-forward

Thank you!

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