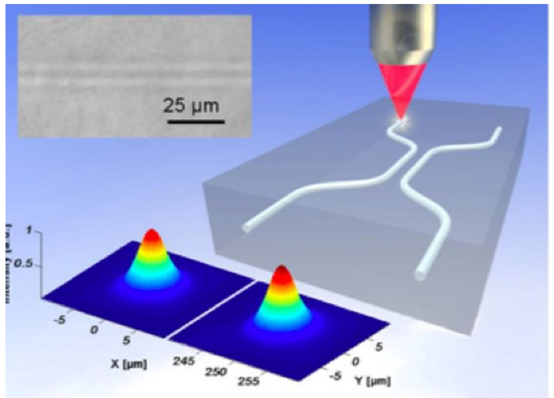

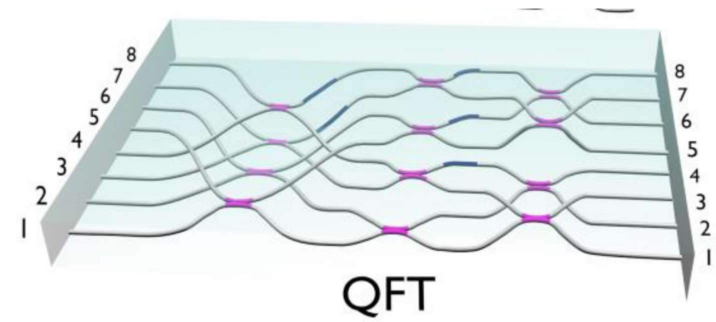

Journal Club: Quantum computational advantage experiments

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INTERNATIONAL IBERIAN NANOTECHNOLOGY LABORATORY

Instituto de Física
Universidade Federal Fluminense

European Research Council
Established by the European Commission

FCT
Fundação para a Ciência e a Tecnologia

Quantum and Linear Optical Computation (QLOC) group seminar, Jan. 27th, 2021

Quantum and Linear-Optical Computation group

- Welcome to new QPI PhD students!

- Rafael Wagner – supervisors Rui, Ernesto, Mikhail Vasilevskiy (Uminho) – coherence and contextuality
- Anita Camillini – supervisors Ernesto and Michael Belsley (Uminho) – scalable photonic q. computing
- Antonio Molero- supervisors Raffaele, Ernesto, Luís S. Barbosa – q. machine learning
- Angelos Bampounis - supervisors Rui, Pedro Patrício (Math, Uminho) – matchgates and magic states
- Raman Choudhary – supervisors Rui, Luís Paulo Santos – contextuality and q. advantage

Ernesto Galvão

(group leader)

Rui Soares Barbosa

(Staff Researcher)

Raffaele Santagati

(Affiliate)

Carlos Fernandes

(PhD student)

Michael Oliveira

(PhD student)

Filipa Peres

(PhD student)

Alexandra da Costa Alves

(Master's)

Tomás Souza

(Master's)

Ana Filipa Carvalho

(Master's)

Mafalda da Costa Alves

(Master's)

José Guimarães

(Master's)

António Pereira

(Master's)

Journal Club

- Informal talk and discussion on one or more recent interesting papers

- Papers I will focus on here:

- Quantum supremacy using a programmable superconducting processor – Arute et al., Nature **574**, 505 (2019) [Google Quantum AI team, leader John Martinis]

- Quantum computational advantage with photons - H. Wang *et al.*, Science 370 (6523), 1460 (Dec. 2020) [University of Science and Technology of China, leaders Chao-Yang Lu, Jian-Wei Pan]

A bit of background on the current status of different QC platforms

Quantum computation: current status

Ion Traps

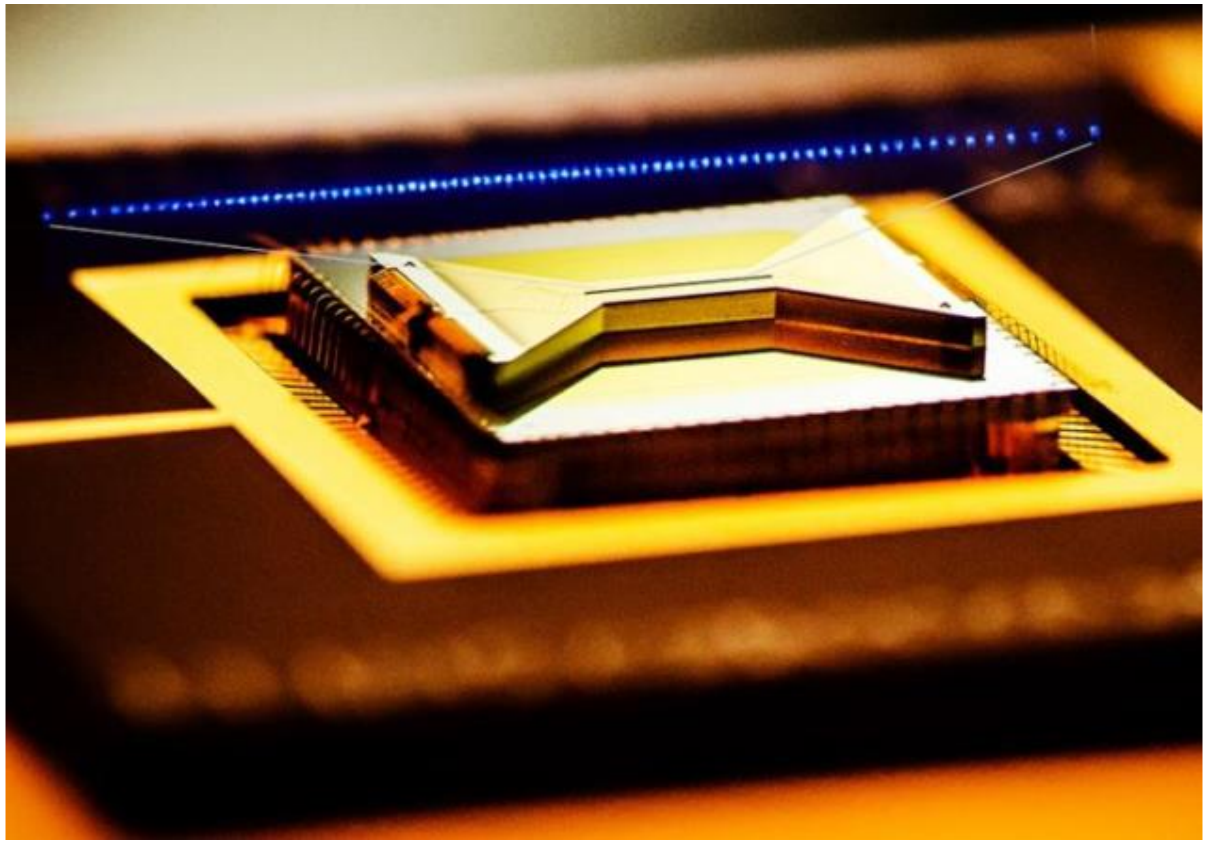
Few ions trapped in EM fields, addressed individually by lasers

- Electronic levels = qubits
- Motional degrees of freedom = qubit-qubit interactions
- Long history: atomic clocks. Extremely good gates, up to 32 qubits

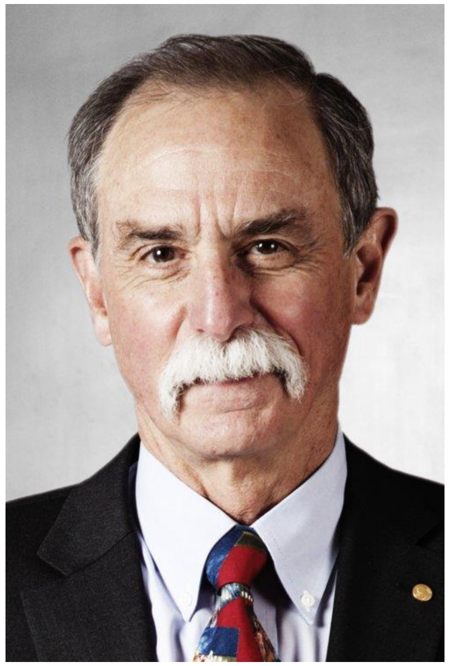
Key companies: IonQ (USA), Honeywell (USA), Alpine Q. Technologies (Austria)

Gossip: q. volume of 4 000 000 in IonQ press-release; Honeywell: 128

Q. Volume tutorial: https://pennylane.ai/qml/demos/quantum_volume.html



Montage: ion trap, trapped ions (IonQ)



This field gave Dave Wineland his 2012 Physics Nobel Prize

Quantum computation: current status

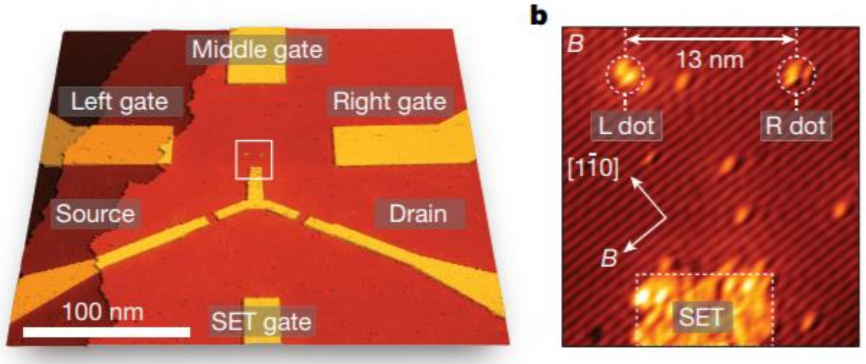
Anyons

Exotic statistics of excitations in 2D electron gases in solids

- 2020 witnessed experimental signatures of anyons
- Naturally robust against decoherence = destruction of superpositions due to external interference

Key companies: Microsoft

H. Bartolomei *et al.*, Science 368 (6487), 173 (2020)



Y. He et al., Nature 571, 371 (2019)

Electrons in solid state

Electron spin of phosphorus atoms in silicon

- Two-qubit gates demonstrated
- Could leverage existing Si industry processes for scaling up

Key companies: Silicon Quantum Computing (Australia)

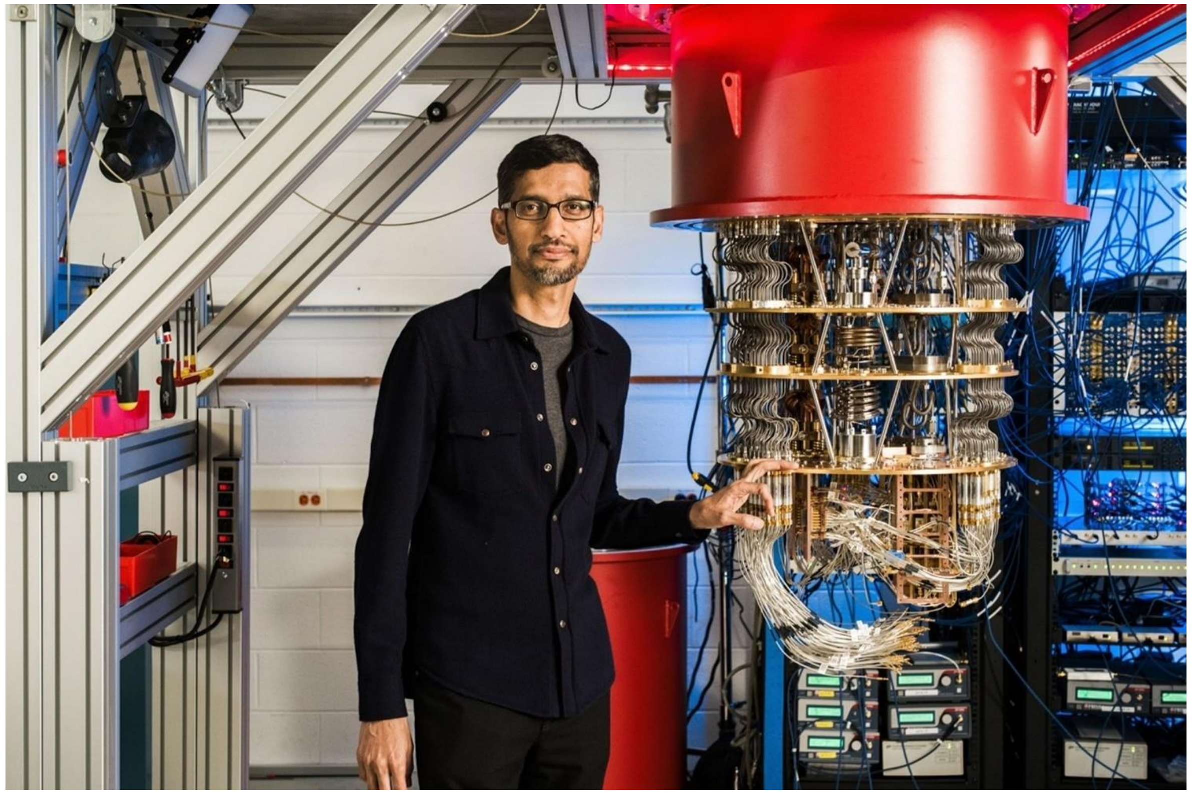
Quantum computation: current status

Superconducting chips

Superconductor dynamics is governed by QM. Transmon qubits (2007) can be coupled and read out, and are the basic units in QCs based on superconductors

- Up to 72 qubits, although noise so far prevents deep circuits
- Recent demonstration of quantum computational advantage by the Google Quantum AI team (2019)
- For hands-on experience on quantum computers: https://qiskit.org/ (IBM's SDK)

Key companies: IBM Q Experience, Google Quantum AI, Rigetti Computing, IQM



Google CEO Sundar Pichai with QC cryostat

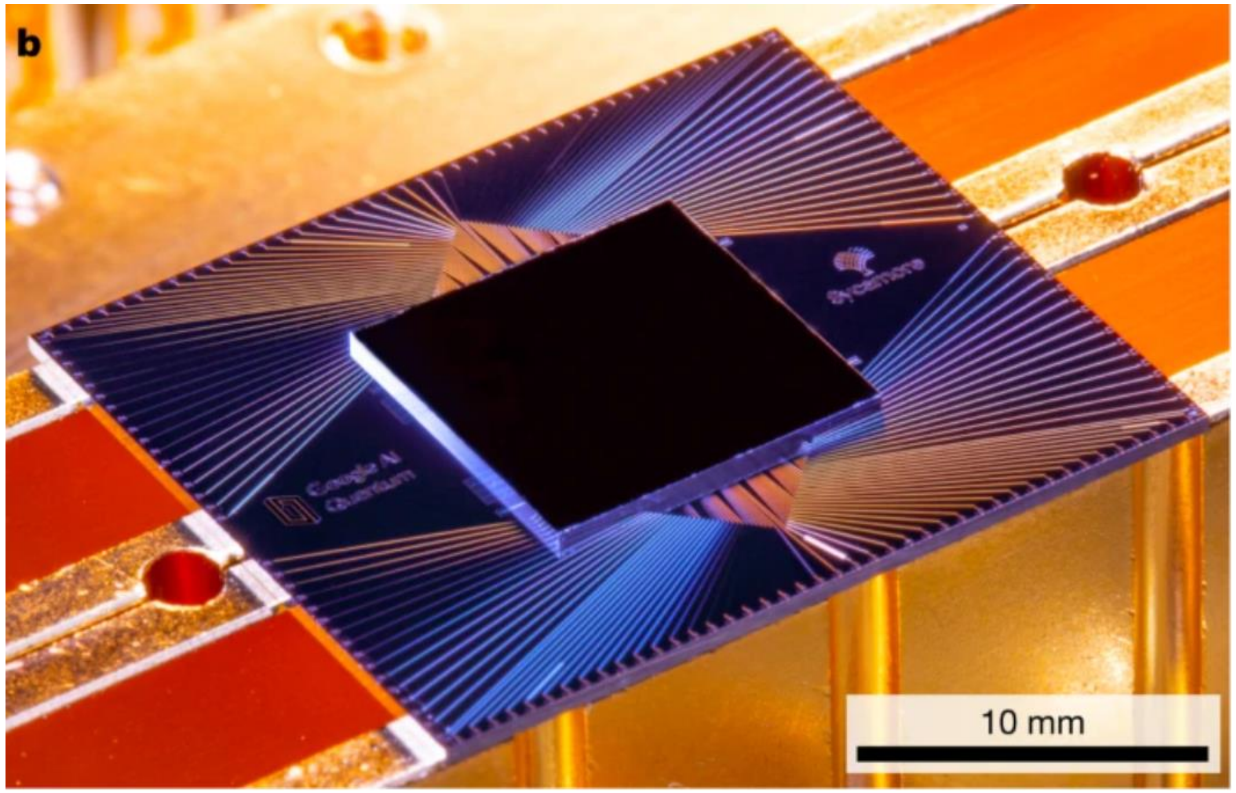


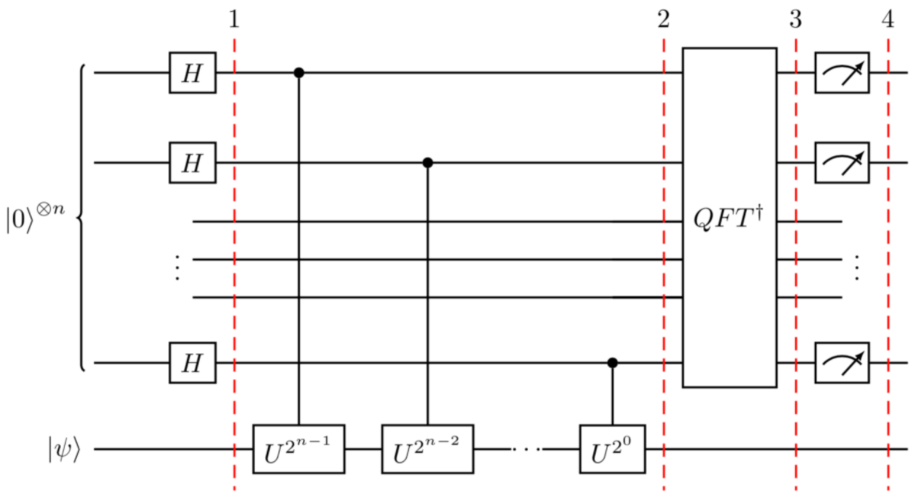
Image: Arute et al., Nature **574**, 505 (2019)

Quantum computation: current status

Theory:

- Scalable, error-corrected QCs will provide computational break-throughs in data security, optimization, materials science, q. chemistry, etc.

- Open problem: can we obtain practical advantage with near-term Noisy, Intermediate-Scale Quantum (NISQ) devices?



Experiment:

- Small-scale QC prototypes using various physical platforms
- Demonstrations of computational advantage for contrived, useless tasks
- Still no practical advantage over classical computers
- Still a long way towards error-correction & large scale QC

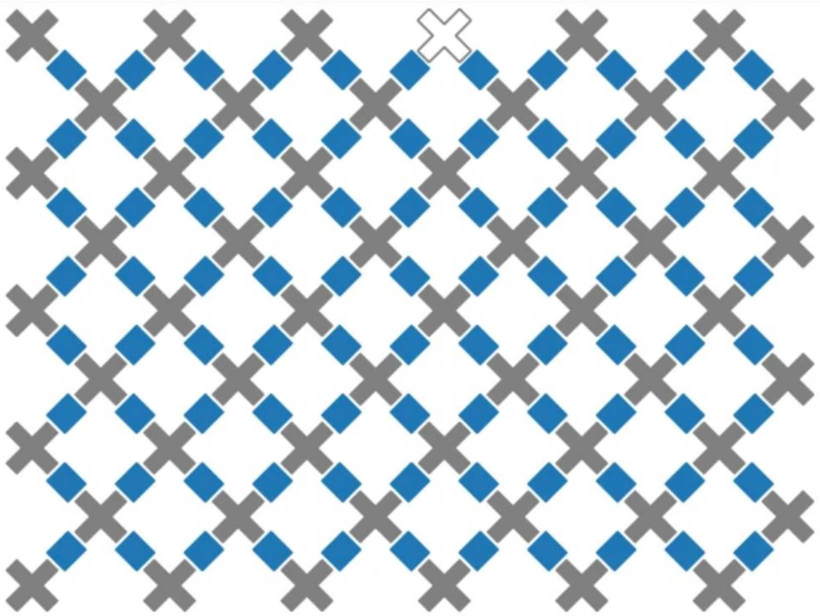
The Google Quantum AI quantum advantage experiment

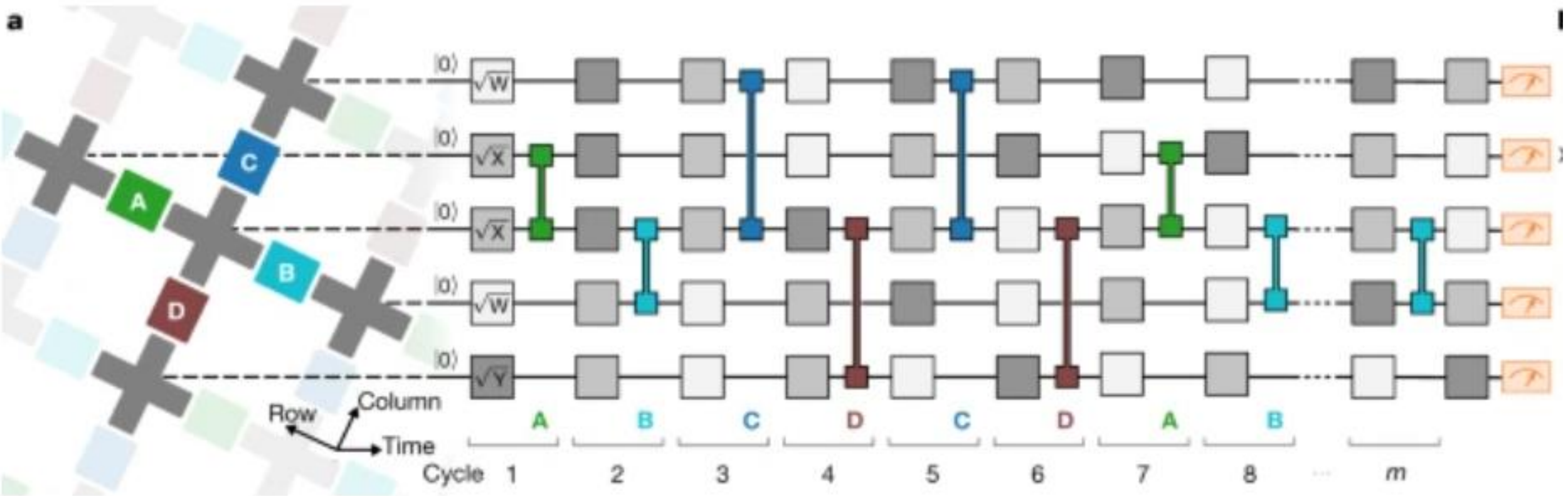
Google Quantum AI experiment (2019)

Images from: Arute *et al.*, Nature **574**, 505 (2019)

- 53 superconducting qubits, connected to nearest neighbors in square lattice

- Up to 20 cycles of randomly chosen one- and two-qubit gates (random = hard instance). 2-qubit gates tile sequentially, 1-qubit gates randomly picked from 3-gate set {sqrt(X), sqrt(Y), sqrt((X+Y)/sqrt(2))}





- 2-qubit gates: fSim
- 2 fSim gates (+ single qubit gates) give a CZ

$$\mathrm{fSim}(\theta,\phi) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(\theta) & -i\sin(\theta) & 0 \\ 0 & -i\sin(\theta) & \cos(\theta) & 0 \\ 0 & 0 & 0 & e^{-i\phi} \end{bmatrix}$$

- fSim gates chosen as they are harder than CZs to simulate using a Feynman path integral approach – circuits half as deep for the same simulation cost

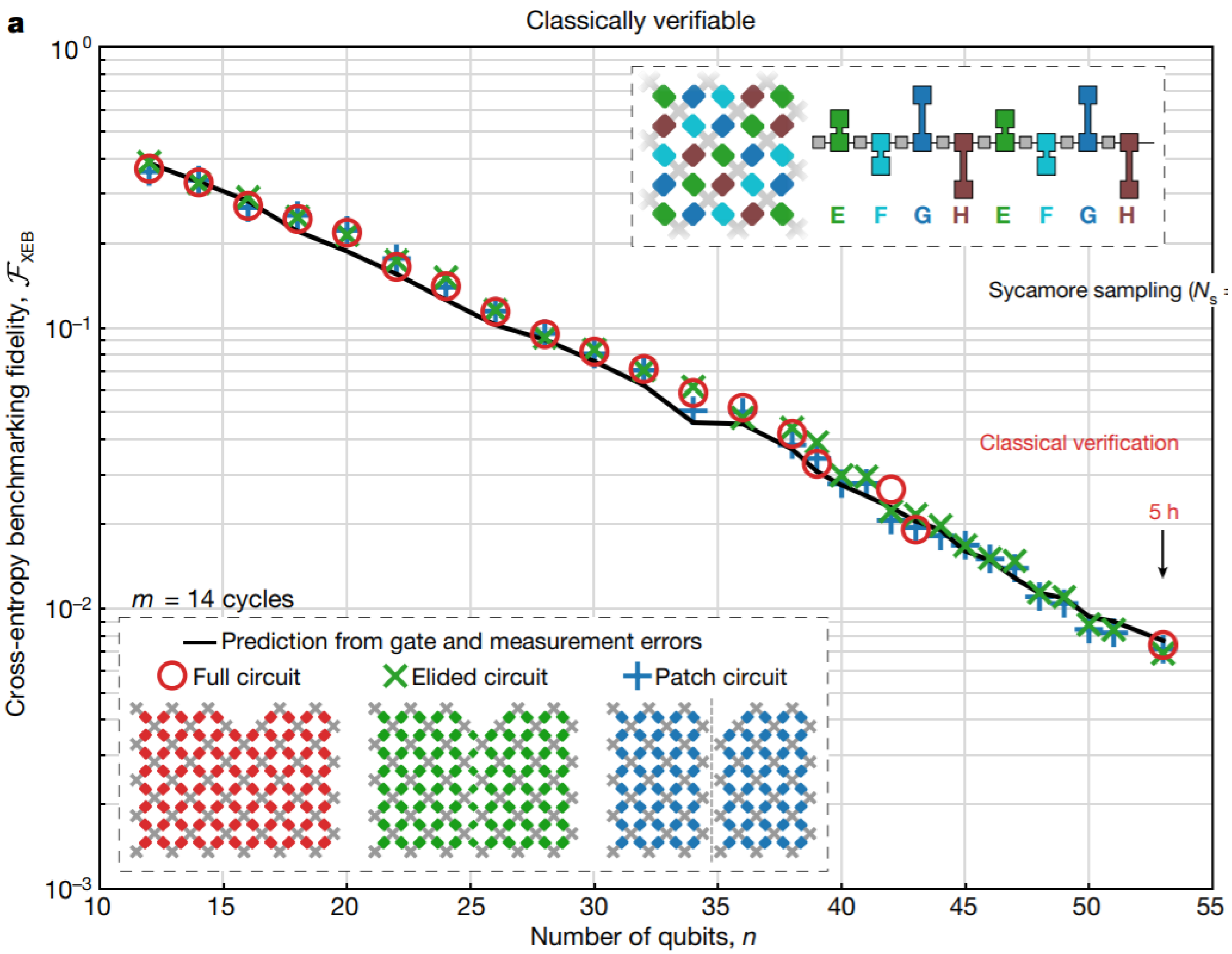
Google Quantum AI experiment (2019)

Images from: Arute *et al.*, Nature **574**, 505 (2019)

Device verification: use of cross-entropy fidelity

$$\mathcal{F}_{XEB} = 2^n \langle P(x_i) \rangle_i - 1$$

- P(x_i) are calculated probabilities of experimental outcomes
- F correlated with how often we sample high-probability outcomes
- F=1 for ideal distribution, F=0 for uniform distribution

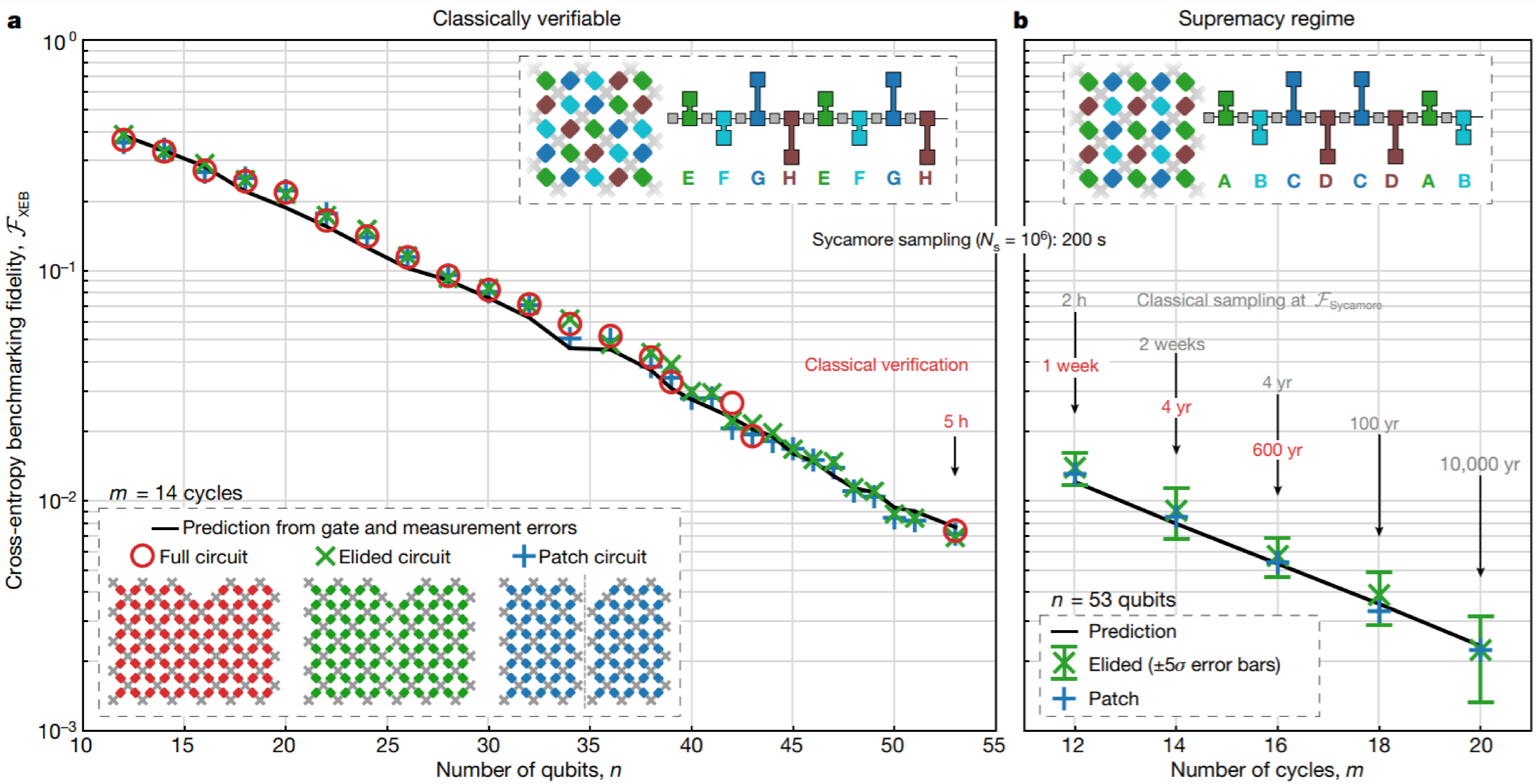


Test circuits can be simulated classically:

- Patch circuit: 2-qubit gates between two halves of computer not implemented.
- Elided circuit: only a few early 2-qubit gates are removed.

Google Quantum AI experiment (2019)

Images from: Arute *et al.*, Nature **574**, 505 (2019)



- Estimated simulation run-time of largest circuits on supercomputer: 10000 years
- Estimated energy cost: 1 petawatt hour
- IBM controversy: simulation possible in a few days?

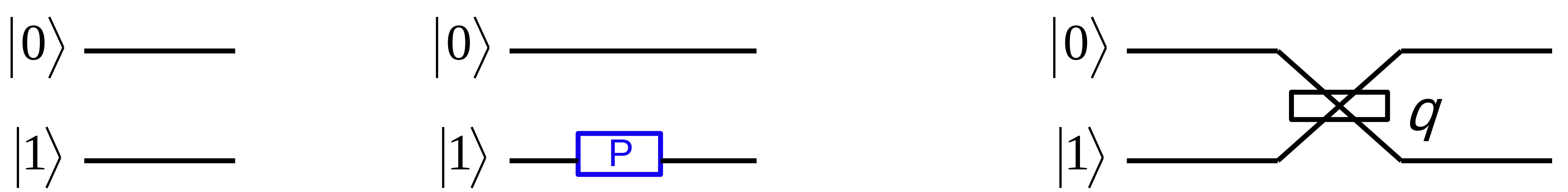
Quantum advantage with Gaussian Boson Sampling

Quantum computing with light – discrete variables

Path encodings

Dual-rail: single photon in two propagation modes, labelled 0/1

- arbitrary single-photon gates easy – beam splitters (BS) and phase shifters:



$$R(j) = \begin{pmatrix} 1 & 0 \\ 0 & e^{ij} \end{pmatrix} \qquad U(q) = \begin{pmatrix} \cos(q) & i\sin(q) \\ i\sin(q) & \cos(q) \end{pmatrix}$$

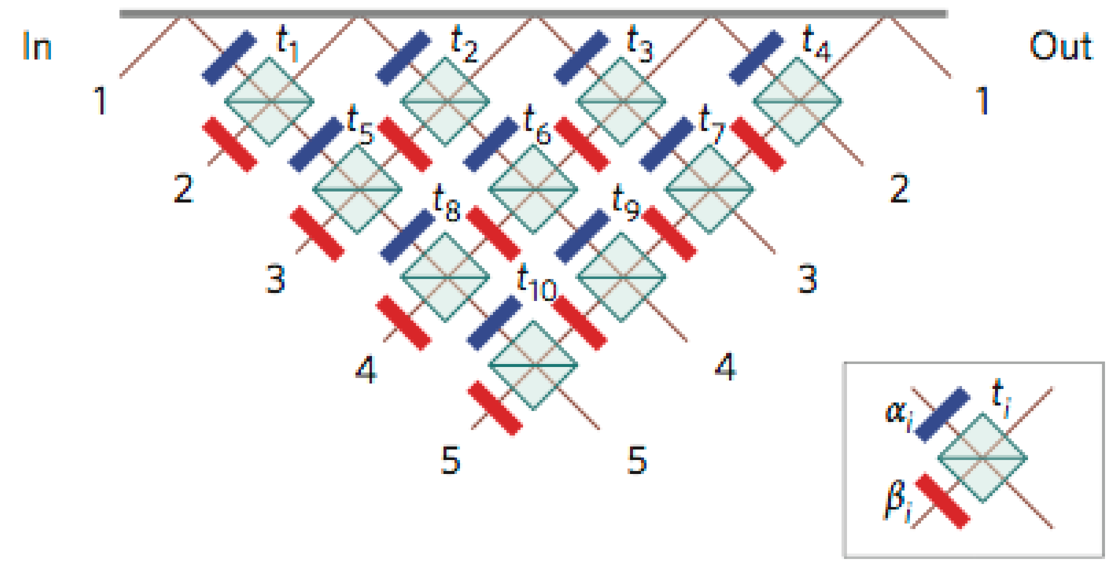
- Arbitrary single-qubit unitaries implementable with a BS and phase shifters

- The problem is two-qubit unitaries – how to make the two photons interact?

  - One way: medium with large cross-Kerr non-linearity (hard to do)
  - Measurement-induced non-linearities:
    key idea of **Knill-Laflamme-Milburn (KLM)** proposal

What kind of QC can we build with linear optical elements only?

Non-interacting photons in linear interferometers



- Input to output creation operators mapped by unitary:

$$a_k^+ \rightarrow \sum_j U_{j,k} a_j^+$$

- Any *m*-mode linear interferometer can be decomposed in
  - 2-mode beam splitters;
  - single-mode phase shifters.

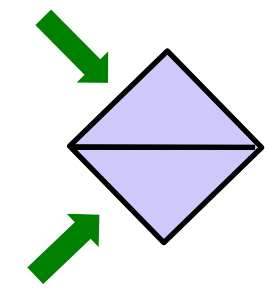
- Output probabilities given by permanents of matrices associated with *U:*
  - Example: the probability of an output of one photon per mode, with an input of one photon per mode, is:

$$p = \left|per(U)\right|^2$$

- The permanent is similar to the determinant, but with no negative signs. The calculation is intractable (*#P-hard*).

Example: Hong-Ou-Mandel effect

- Two identical photons simultaneously arrive at a beam splitter



- If the beam splitter is unbalanced, we have
  - *T*= transmissivity
  - *R*=reflectivity

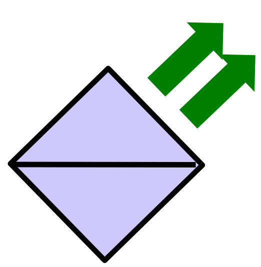
$$U = \begin{pmatrix} T & iR \\ iR & T \end{pmatrix}$$

- Probability that the two photons exit in different modes is

$$p = \left|per(U)\right|^2 = \left|T^2 - R^2\right|^2$$

Hong-Ou-Mandel effect: for balanced beam-splitter *T=R*, and *p=0*

Photons always leave the BS in the same mode:



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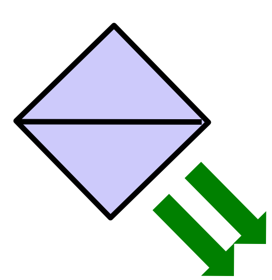
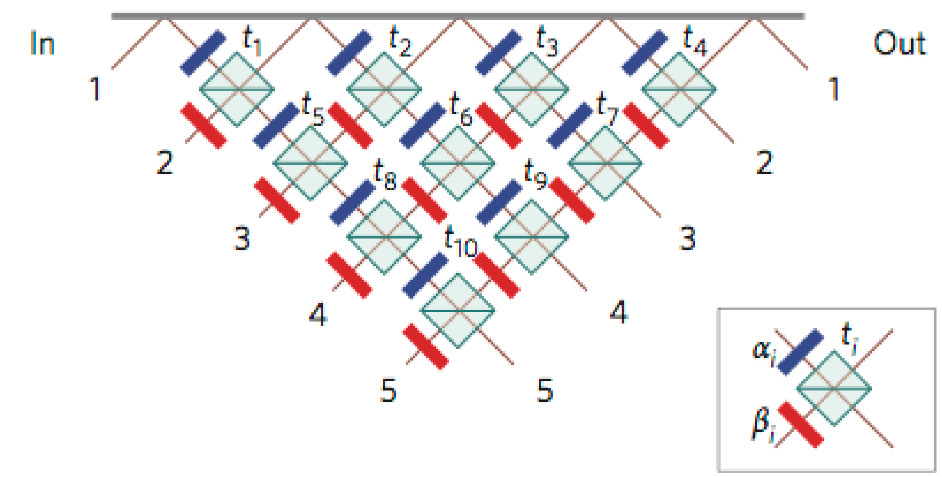


Photonic Boson Sampling

Aaronson/Arkhipov arxiv:1011.3245

- Given m-mode interferometer description U, sample from the output distribution of:

    1. Input of n indistinguishable photons;
    2. Multi-photon interference in interferometer;
    3. Yes/no detection at output modes.



- Classical exact simulation would imply a highly unlikely computational complexity result (“collapse of the polynomial hierarchy”)

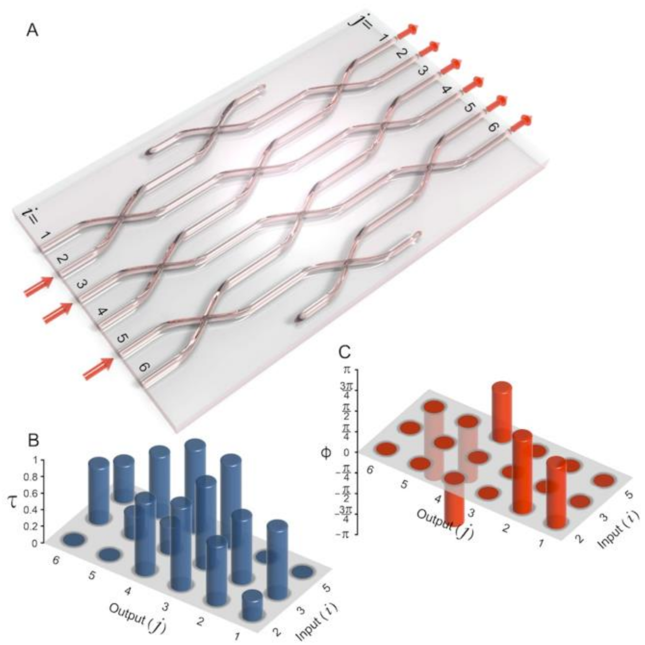
- **Even approximate simulation is hard**, modulo a couple of reasonable conjectures.

- **Advantages:** about 45 photons would be non-trivial to simulate. If we can add:
    - Intermediate photon measurements;
    - Ultra-fast reconfiguration of interferometer based on outcomes

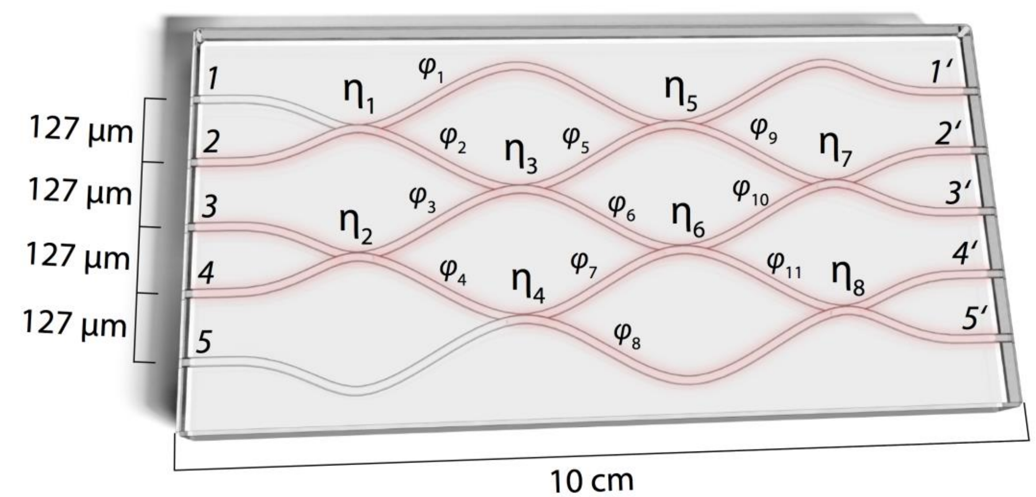
  we would have a universal photonic quantum computer.

- **Disadvantages**: it doesn’t solve a “useful” problem; certification can be difficult.

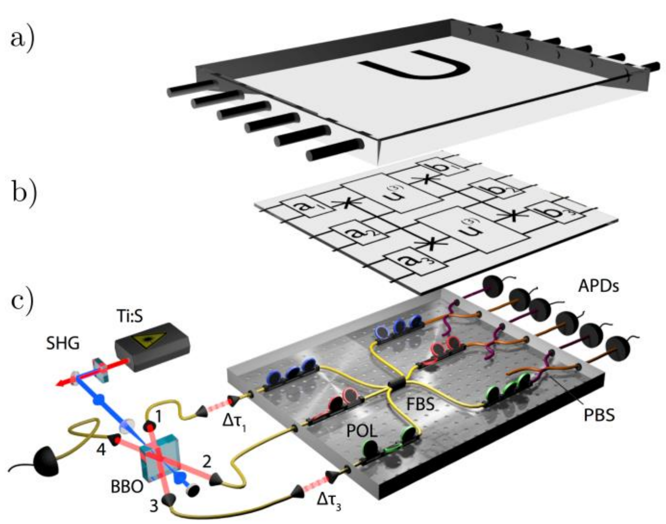
Experimental progress: first small-scale experiments (2013)



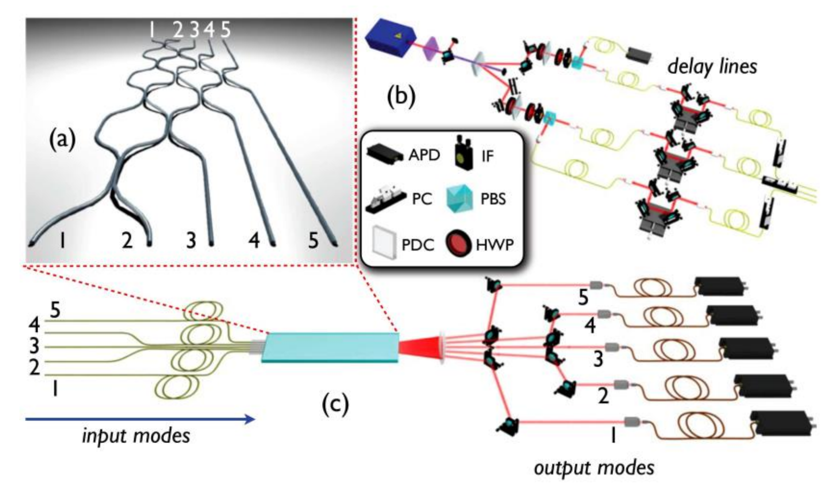
Spring et al., *Science* 339, 798 (2013) [Walmsley group]



Tillmann et al, *Nat. Photon.* 7, 540 (2013) [Walther group]



Broome et al., *Science* 339, 794 (2013) [White group]

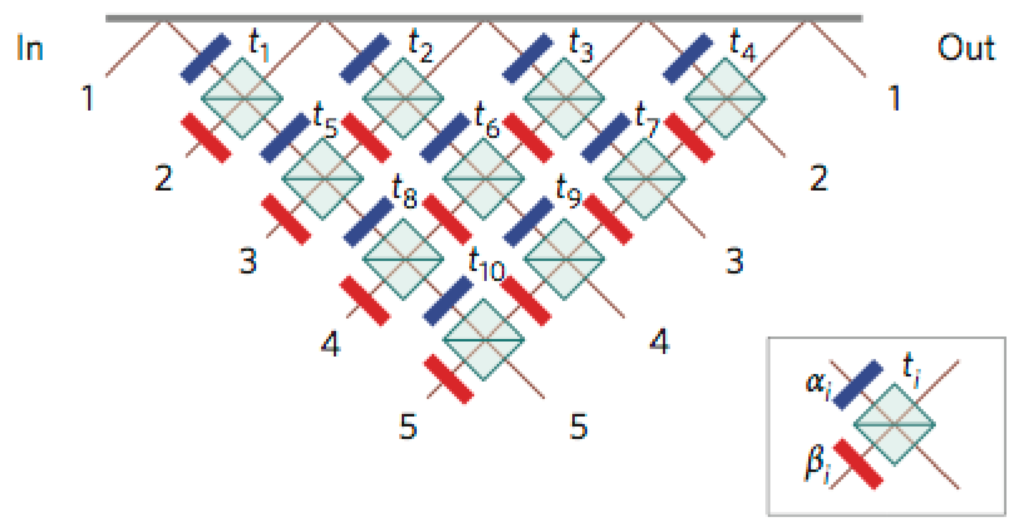


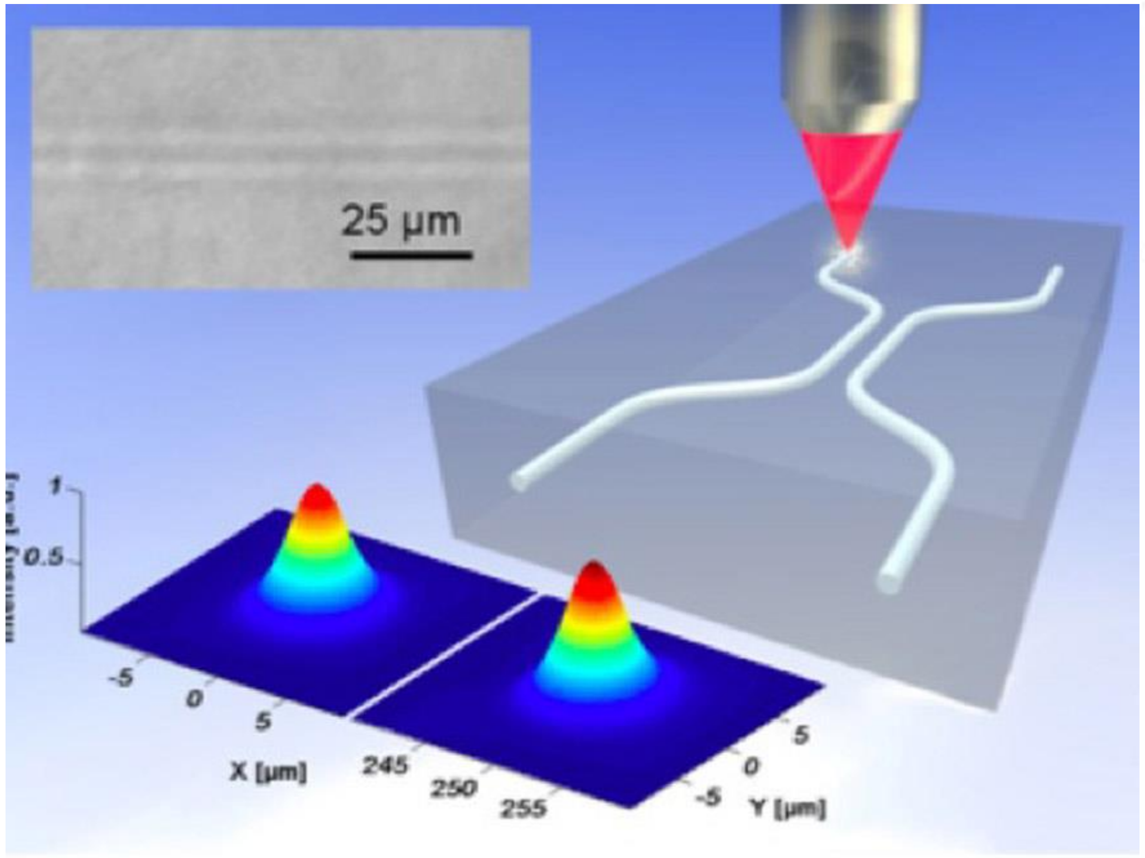
Crespi et al., *Nat. Photon.* 7, 545 (2013) [Sciarrino group]

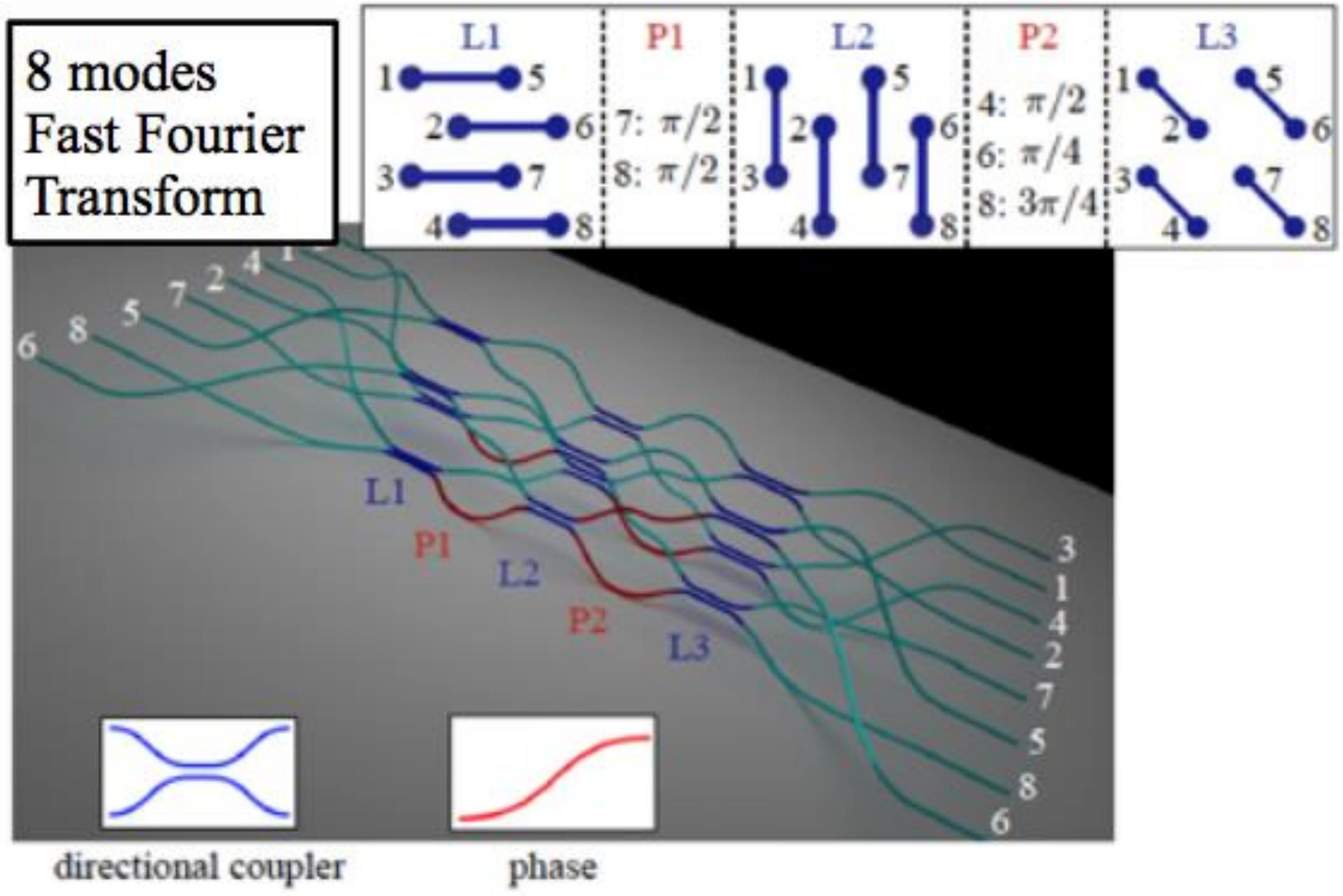
- Interference of 3,4 photons in integrated photonic chips with 5,6 modes
- Verified that probabilities are given in terms of permanents of 3x3 matrices

Integrated multi-mode interferometers

- **Challenge**: stability of complex interferometers
- **Solution**: integrated interferometers with waveguides inscribed with lasers in glass:
  - Beam splitting by evanescent-field coupling between close waveguides
  - Phase shifs implemented by differences in path length
  - 3D design technology

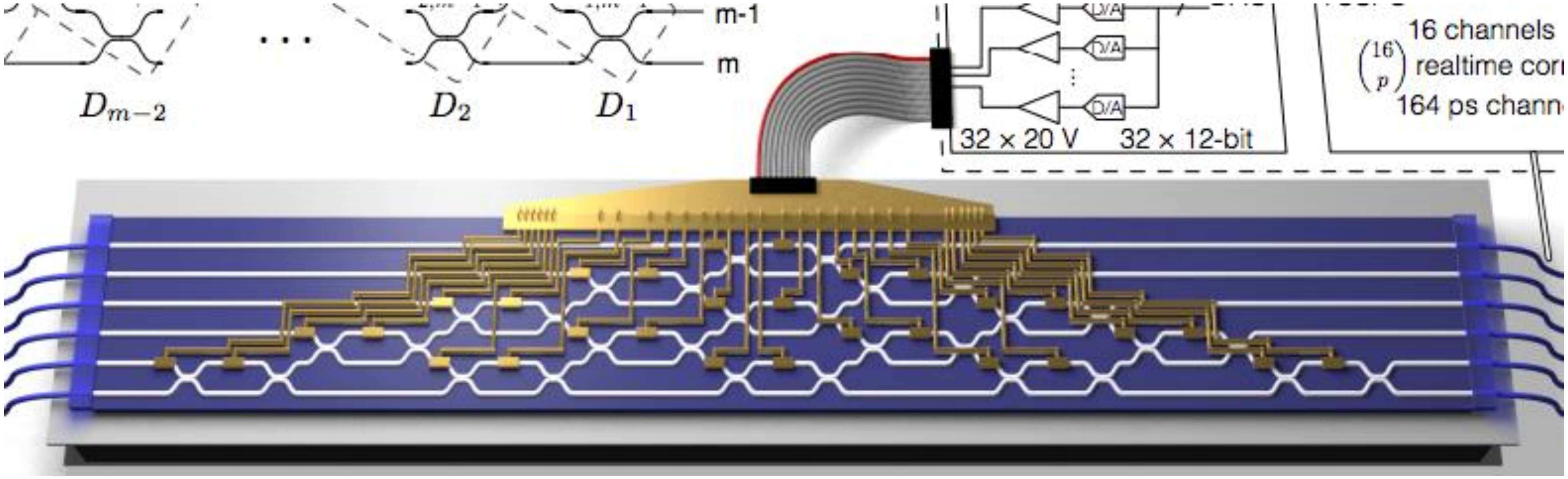






Experimental progress: reconfigurability (2015-)

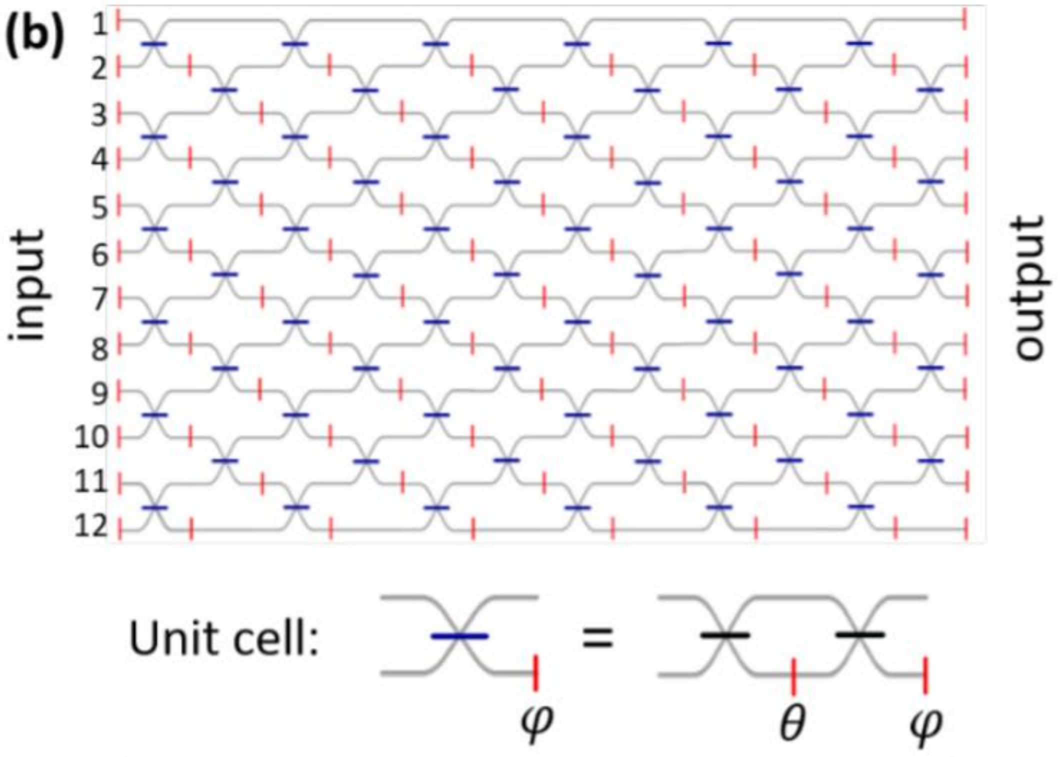
Fully reconfigurable 6-mode interferometer [Carolan *et al.*, *Science* 349, 711 (2015)]



- Full reconfigurability in seconds by thermo-optic phase shifters
- 6-photon boson sampling (only 15 events)
- Automated experiments

Universal 12-mode reconfigurable chip
[Taballione et al., arXiv:2012.05673]

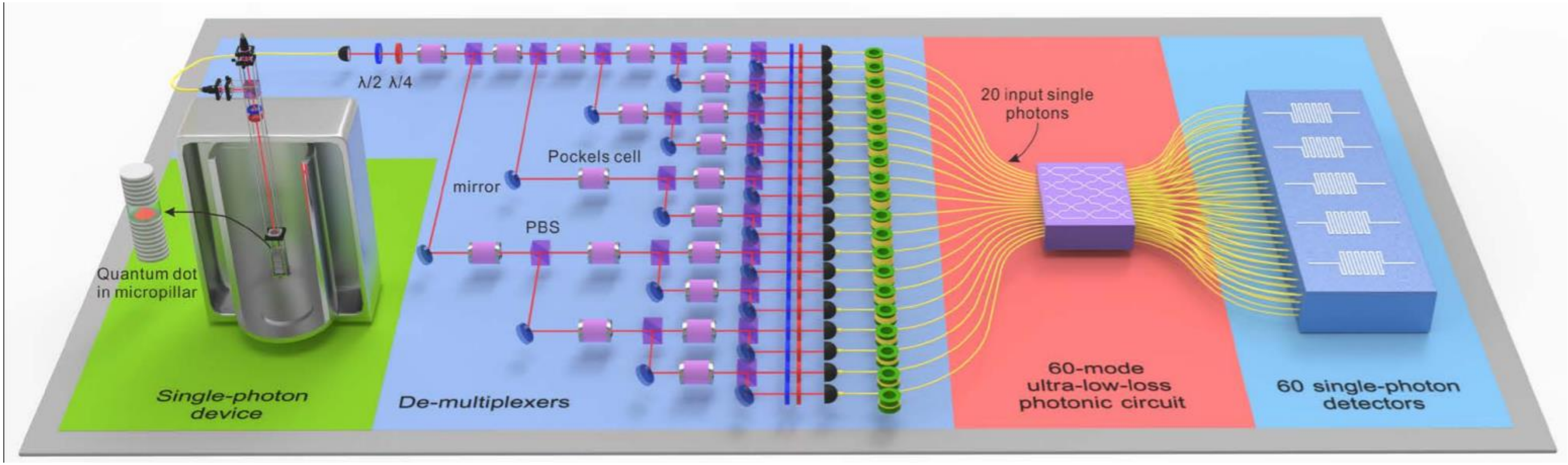
- Silicon nitrite
- 128 tunable thermo-optic phase shifters



Experimental progress: current state-of-the-art (2019)

- Boson Sampling experiment at University of Science and Technology of China (Chao-Yang Lu's group) - H. Wang *et al.*, Phys. Rev. Lett. 123, 250503 (2019)

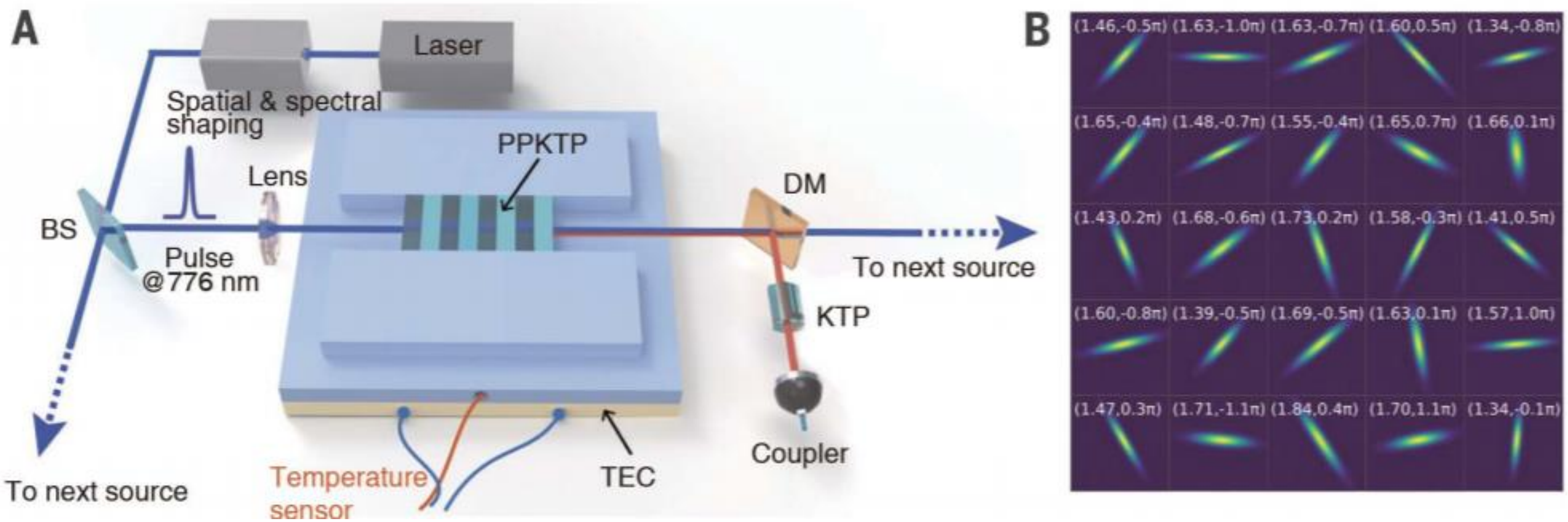
- quantum-dot micropillar, demultiplexed solid state source
- Up to 14 photons detected
- Still simulable on a conventional computer



Photonic quantum advantage: Gaussian boson sampling (2020)

- Gaussian Boson Sampling experiment @ Univ. of Science and Technology of China (Hefei) - H. Wang *et al.*, Science 370 (6523), 1460 (Dec. 2020)
- Gaussian Boson Sampling:
  - Input: squeezed, single-mode states (from PDC)
  - Probabilities given by **hafnians/Torontonians**, matrix functions related to permanents (and hard to compute classically)
  - Single-photon detection at the output

Source: 25 PDC non-linear crystals -> 25 two-mode squeezed states = 50 single-mode squeezed states



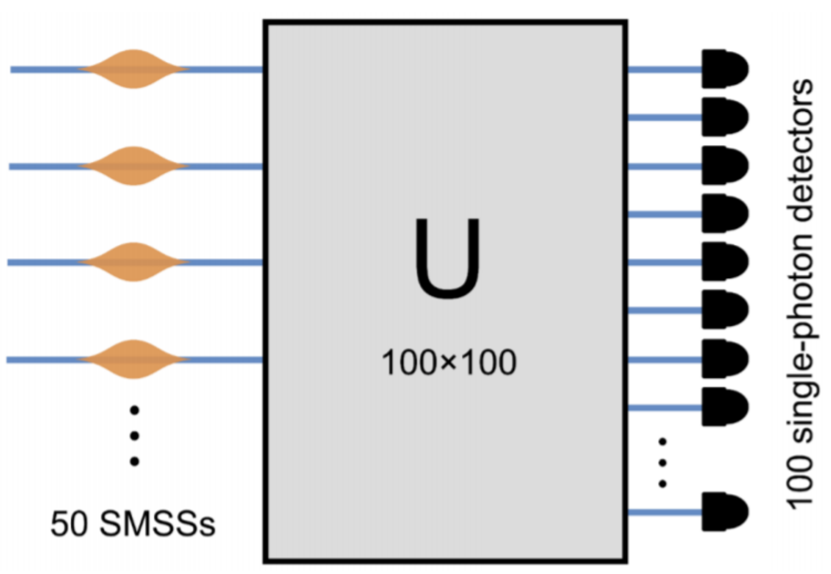
Photonic quantum advantage: Gaussian boson sampling (2020)

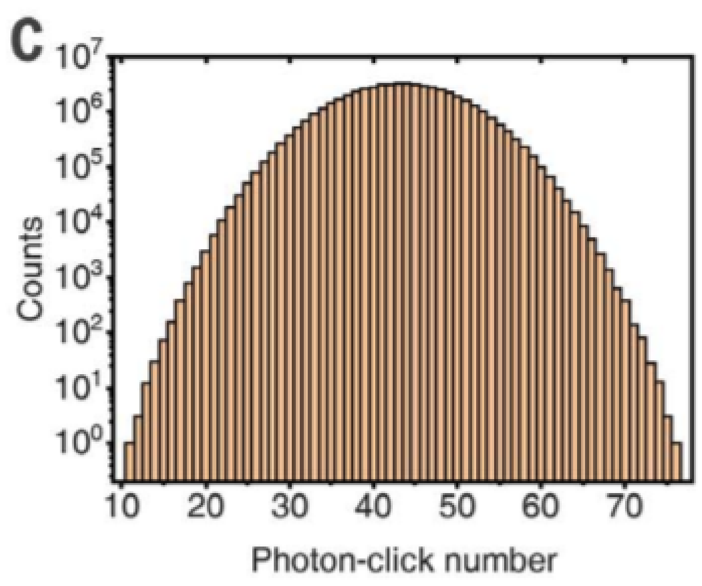
- Gaussian Boson Sampling experiment @ Univ. of Science and Technology of China (Hefei) - H. Wang *et al.*, Science 370 (6523), 1460 (Dec. 2020)

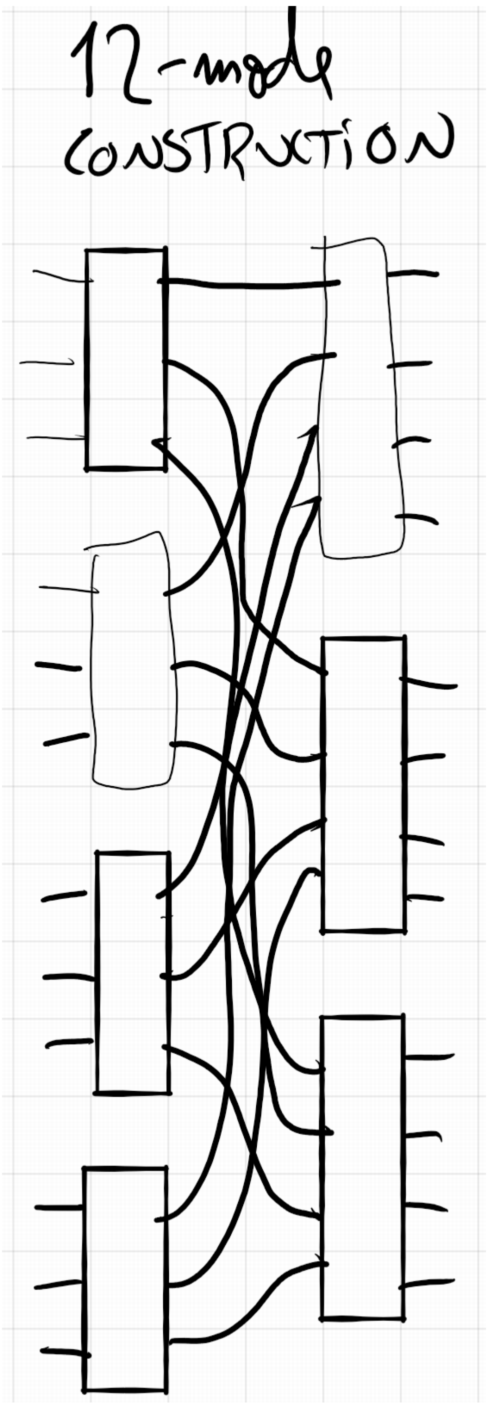
Interferometer

- Fully-connected, 50-spatial-mode interferometer= 100 hybrid modes (using H/V polarization)

- 50-path interferometer = 5 10-mode, fully connected chips, linked to 10, 5-mode fully connected chips. Result: full connectivity







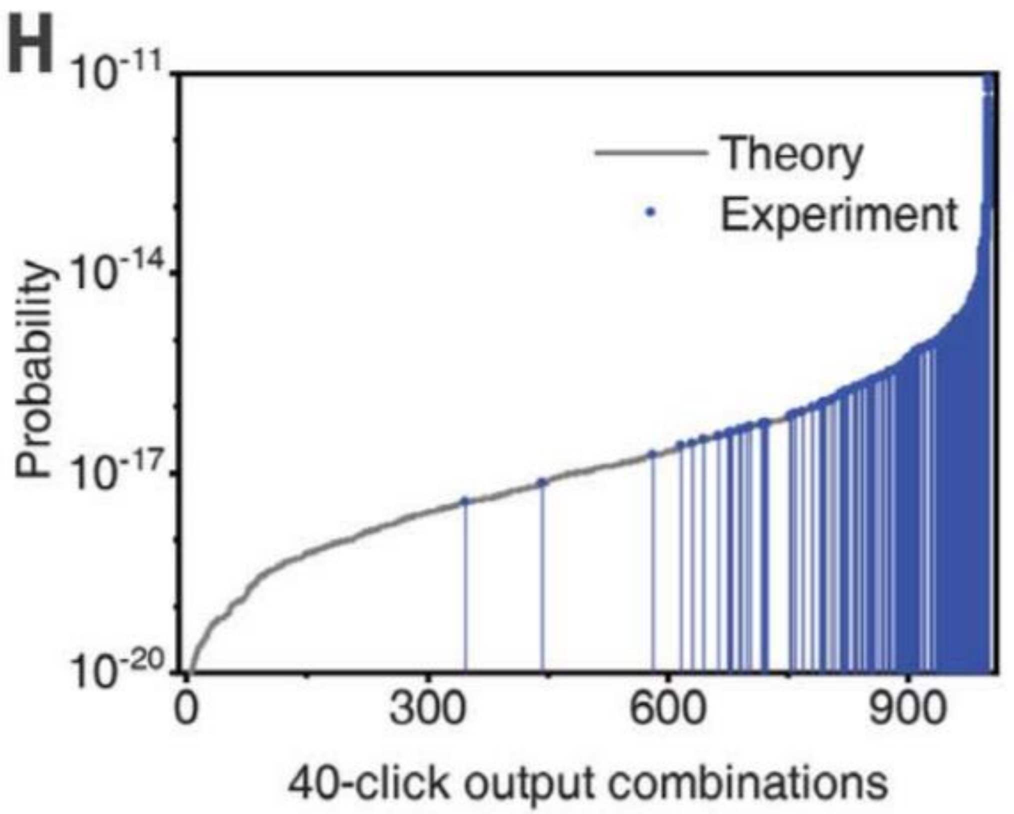
Photonic quantum advantage: Gaussian boson sampling (2020)

- Gaussian Boson Sampling experiment @ Univ. of Science and Technology of China (Hefei) - H. Wang *et al.*, Science 370 (6523), 1460 (Dec. 2020)

Device verification

- Validation tests against uniform distribution, and thermal distribution (distrib. tends to thermal if too many photons lost)

- Variation of the heavy-output generation (HOG) test – checking if events are mostly high-prob events (similar to cross-entropy test)



- Estimated classical simulation time: about 1 billion years on supercomputer

- Open questions:

  - improved classical simulation, “faking” events using supercomputer
  - Future: higher complexity regime, explore GBS’s applications: molecular simulations, graph theory problems

Thank you for your attention!