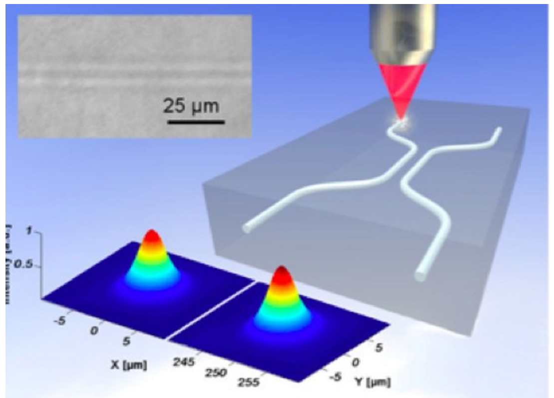
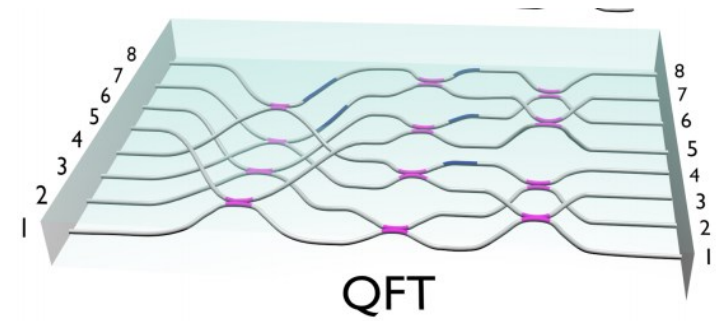




Recent progress in photonic quantum computation

Ernesto F. Galvão

Research group leader
Quantum and Linear-Optical Computation
International Iberian Nanotechnology Laboratory
Braga, Portugal

& Associate Professor (on leave)
Physics Department
Universidade Federal Fluminense - Niterói, Brazil

INTERNATIONAL IBERIAN NANOTECHNOLOGY LABORATORY

INSTITUTO DE FÍSICA
Universidade Federal Fluminense

European Research Council

FCT Fundação para a Ciência e a Tecnologia

IV Quantum Computing Workshop – UFSC – October 28th, 2021

Quantum and Linear-Optical Computation group

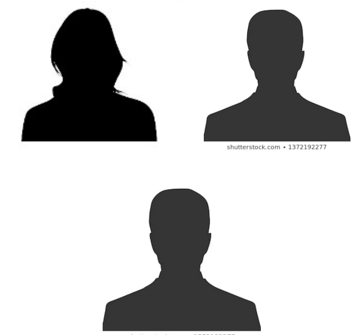
International Iberian Nanotechnology Laboratory (INL)
- Inter-governmental Lab in Braga, Portugal
- Member states: Spain, Portugal
- RTO – Research and Technology Organization
- About 450 staff/associates
- Food and environment monitoring, renewable energy, health, ICT, quantum materials, q. computation

Quantum and Linear-Optical Computation group

- Established at INL in July, 2019. Research lines:

- Principles enabling photonic quantum computation
- Information processing with integrated photonic chips
- Resources in different models of quantum computation

Secured funding for
3 postdocs



+5 recently admitted PhD students

Anita Camillini

Raman Chaudhary

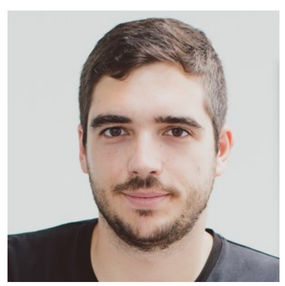
Angelos Bampounis

Rafael Wagner

Antonio Molero

Ernesto Galvão

(Group leader)



Rui Soares Barbosa

(Staff Researcher)

Carlos Fernandes

(PhD student)

Michael Oliveira

(PhD student)

Filipa Peres

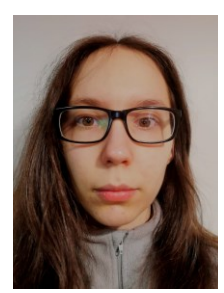
(PhD student)

Alexandra da Costa Alves

(Master's)

Ana Filipa Carvalho

(Master's)



Mafalda da Costa Alves

(Master's)

José Guimarães

(Master's)

António Pereira

(Master's)

Outline

- Quantum computer platforms: current state-of-play
- Quantum advantage: towards useful QC
- Photonic quantum computation
  - Boson sampling devices
  - Q. advantage from Gaussian Boson Sampling
- Photonic route towards scalable QC

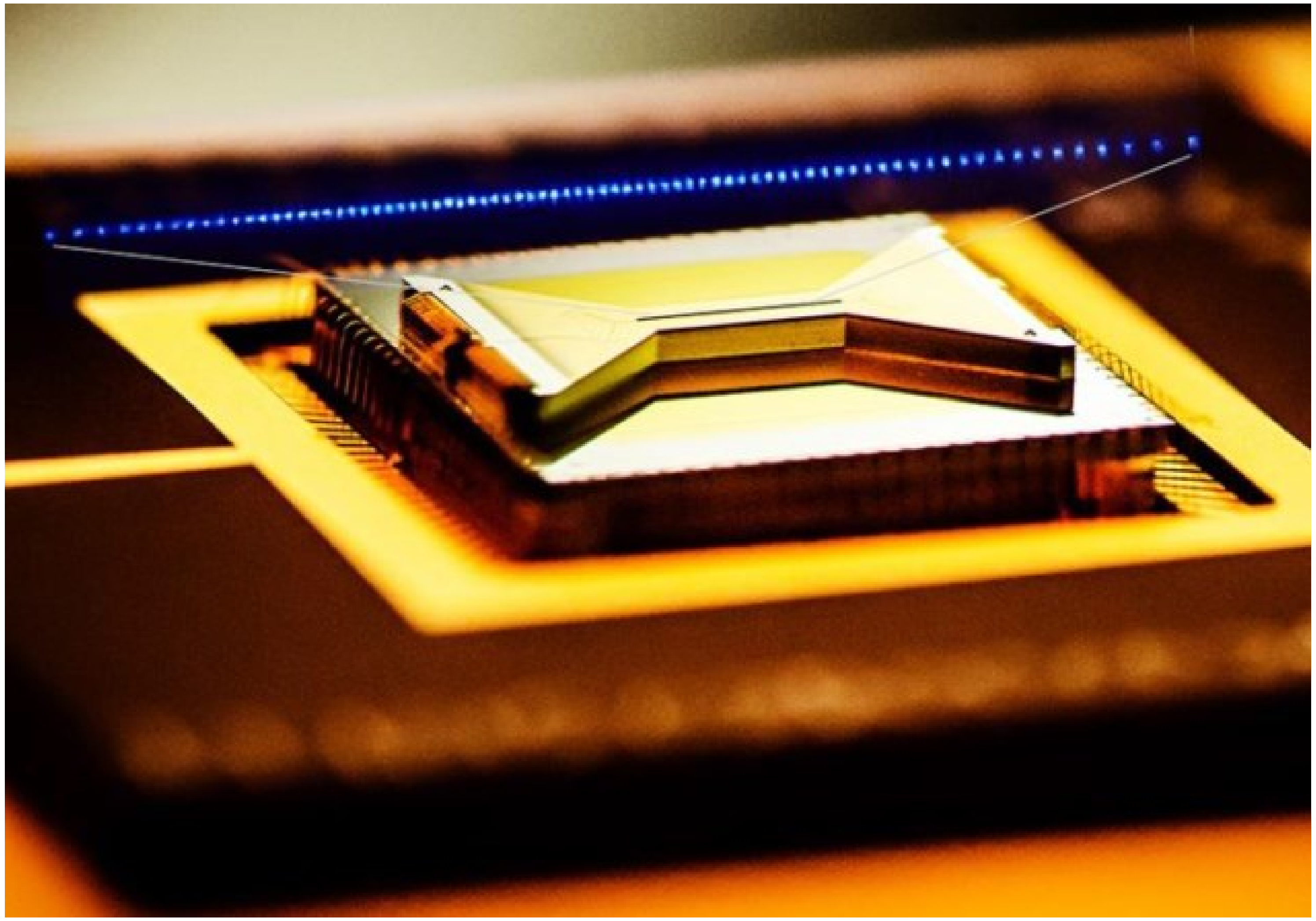
Quantum computation: current status

Ion Traps

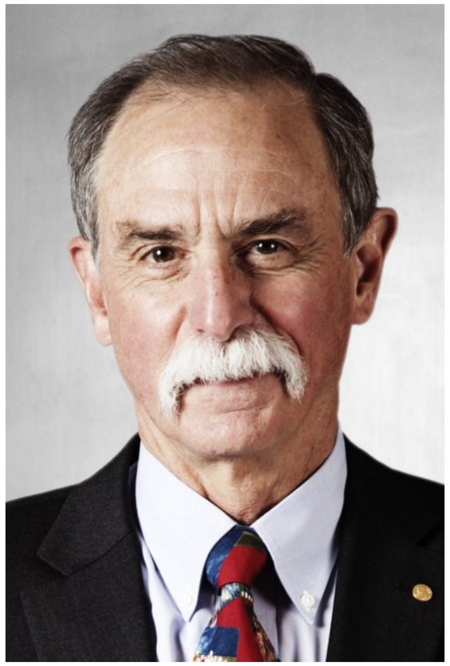
Few ions trapped in EM fields, addressed individually by lasers

- 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)



Montage: ion trap, trapped ions (IonQ) – set to become first “pure” QC company floating in the stock market, valuation > US$ 2 billion



This field gave Dave Wineland his 2012 Physics Nobel Prize

Quantum computation: current status

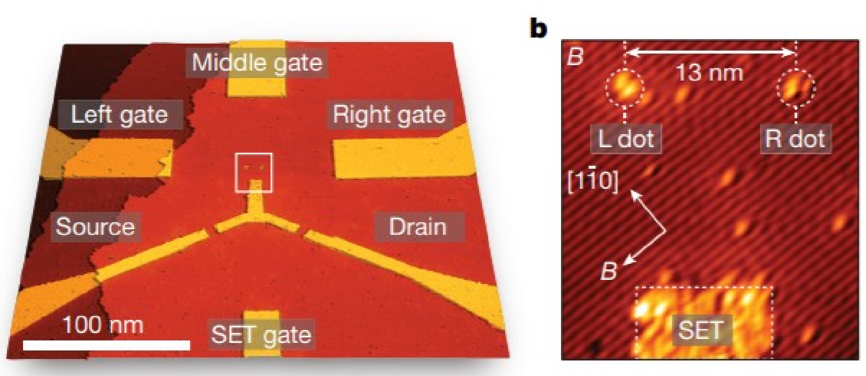
Anyons

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)

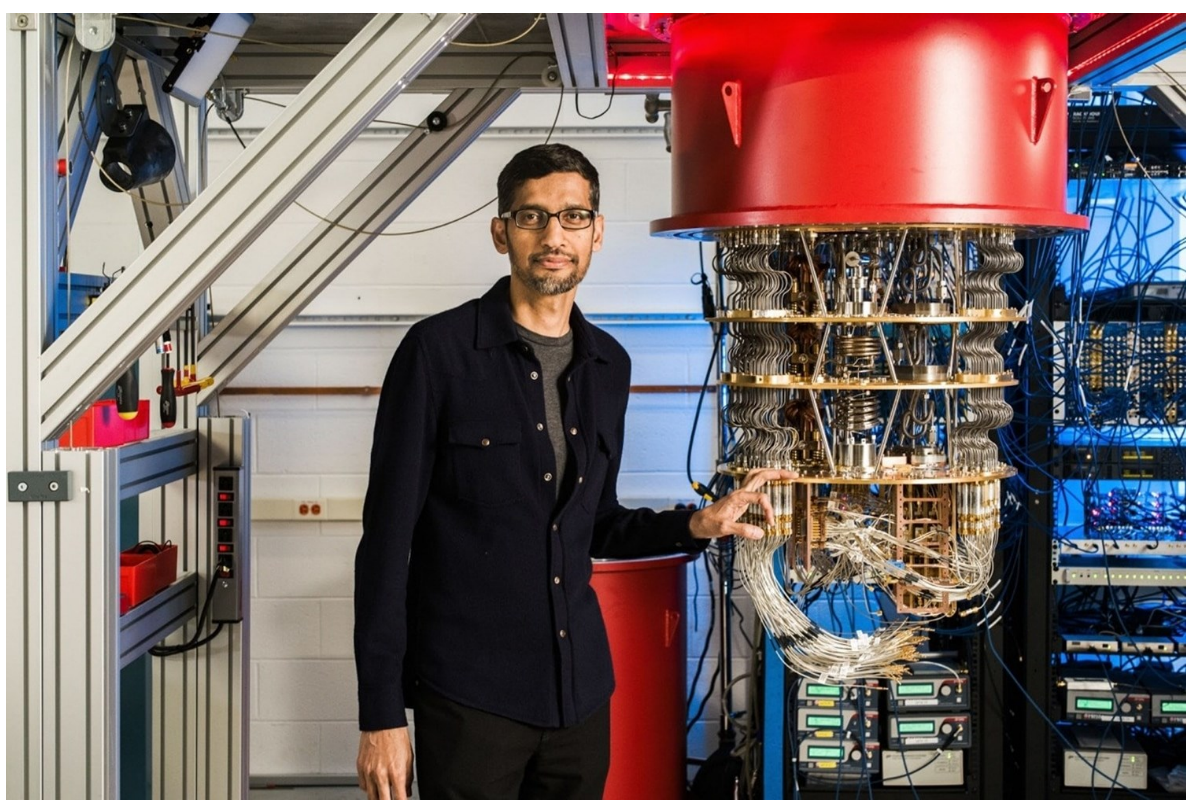
Quantum computation: current status

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

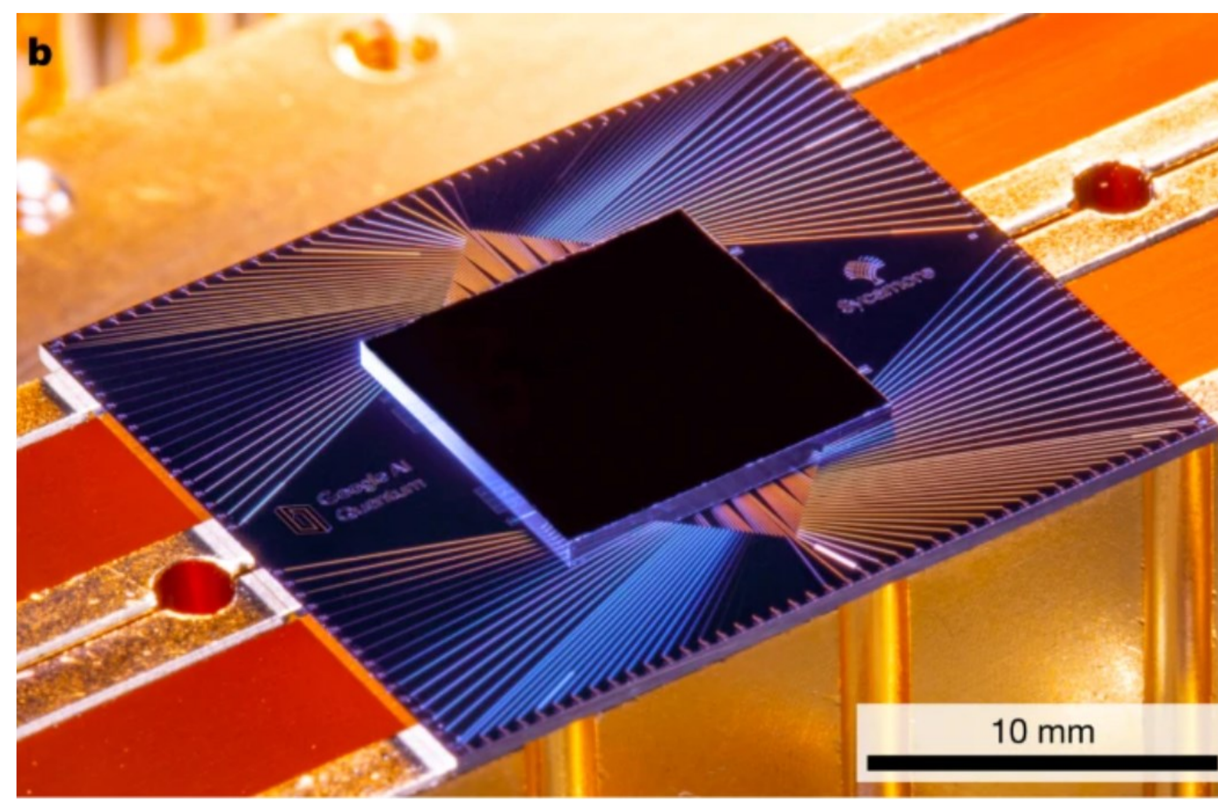
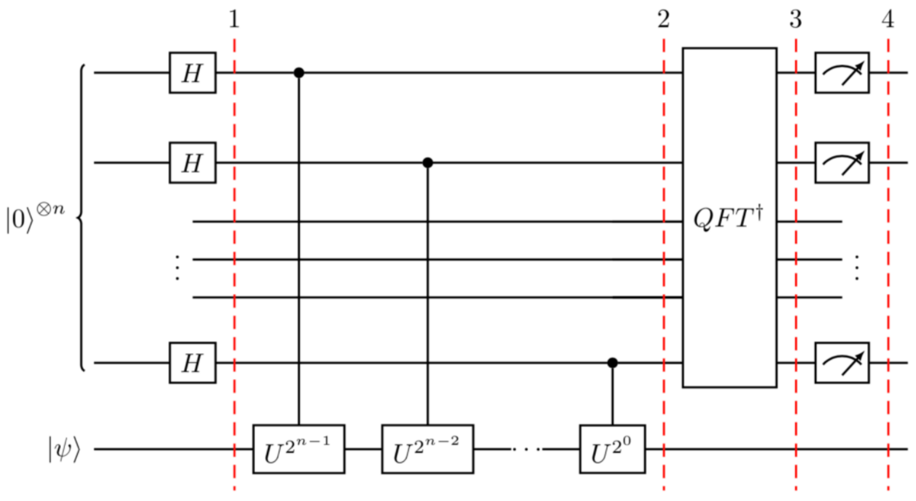


Image: Arute et al., Nature **574**, 505 (2019)

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:

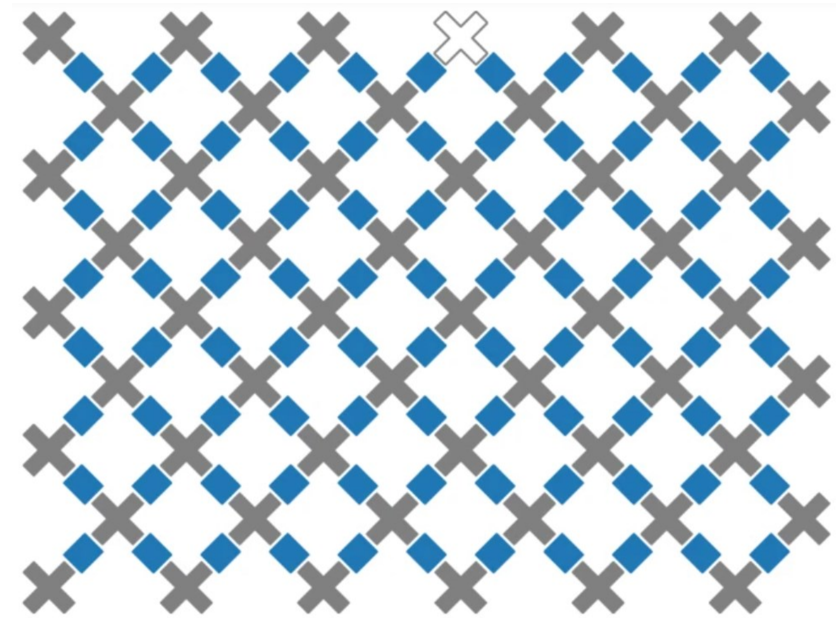
- Small-scale QC prototypes using various physical platforms
- Demonstrations of computational advantage for contrived, useless tasks
- Still no practical advantage over classical computers
- Still a long way towards error-correction & large scale QC

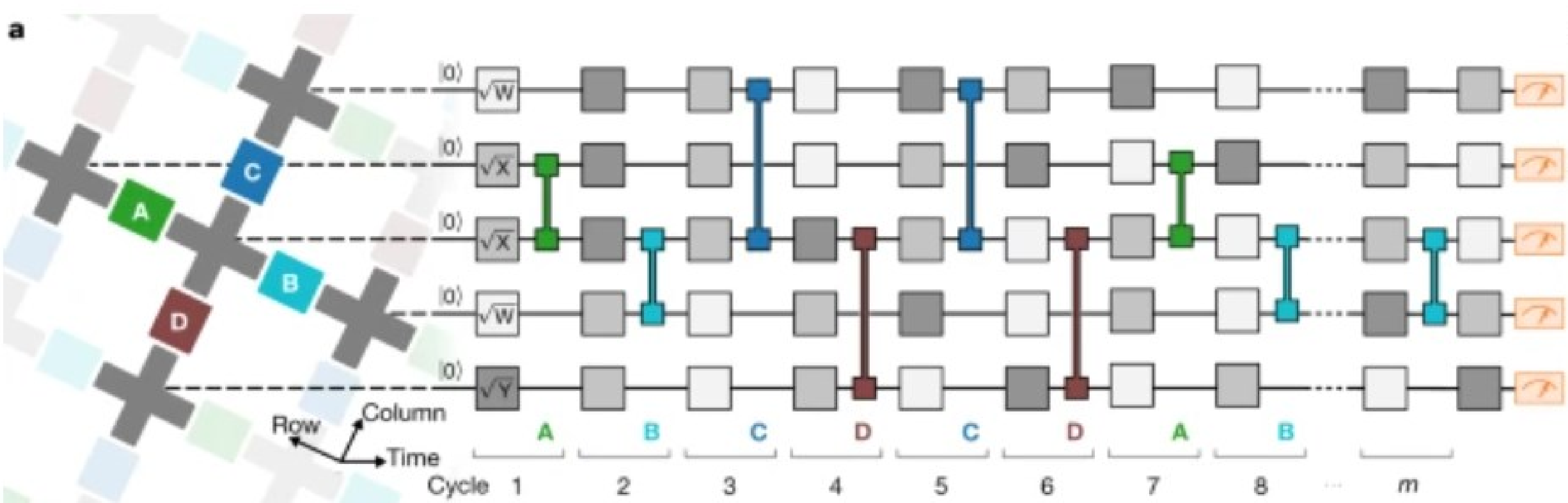
Google Quantum AI experiment (2019)

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

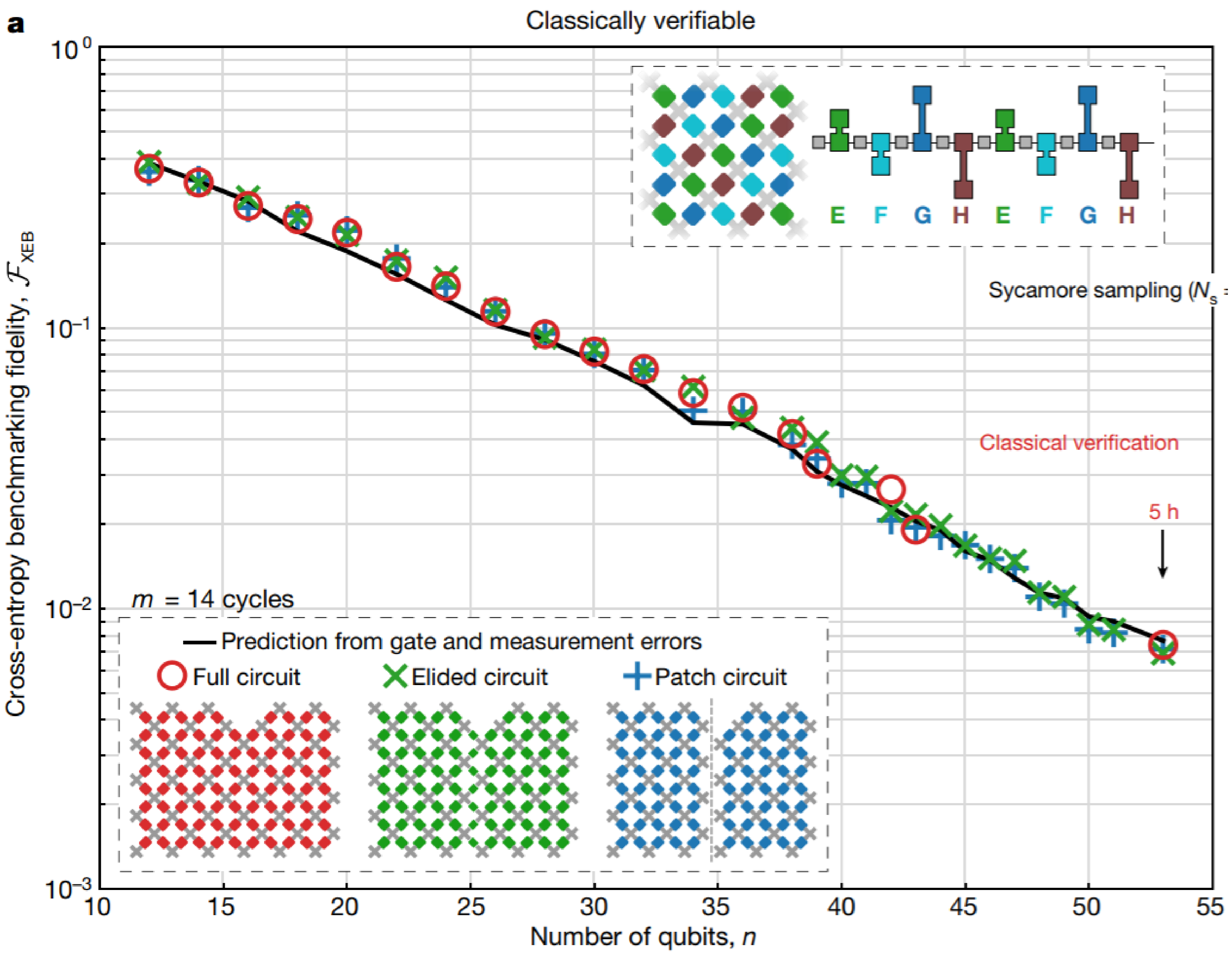
Google Quantum AI experiment (2019)

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

Device verification: use of cross-entropy fidelity

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

- 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

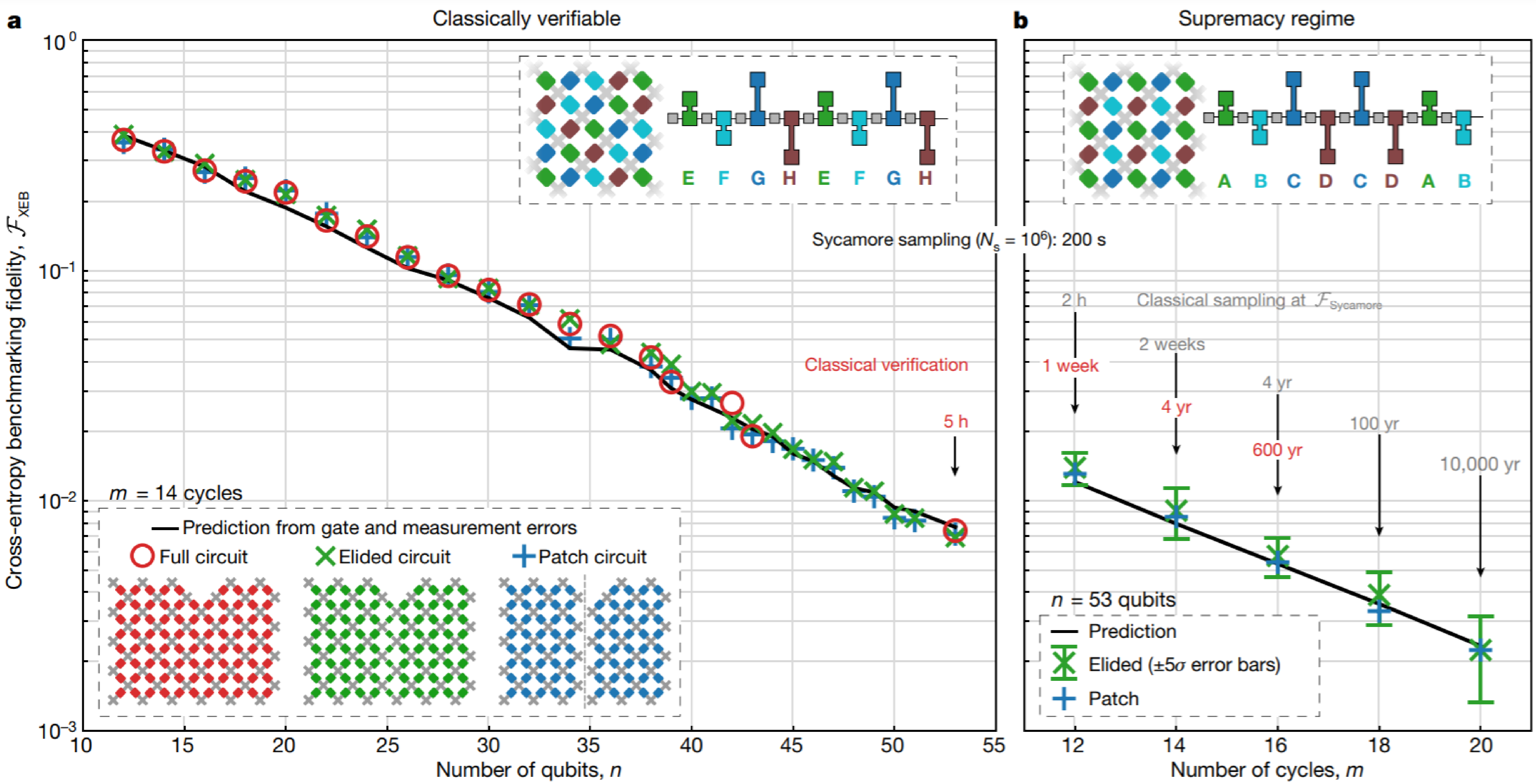


Test circuits can be simulated classically:

- 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?

Google Quantum AI experiment (2019)

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

Closing the "Quantum Supremacy" Gap: Achieving Real-Time Simulation of a Random Quantum Circuit Using a New Sunway Supercomputer

Yong (Alexander) Liu[1,3], Xin (Lucy) Liu[1,3], Fang (Nancy) Li[1,3], Haohuan Fu[2,3], Yuling Yang[1,3], Jiawei Song[1,3], Pengpeng Zhao[1,3], Zhen Wang[1,3], Dajia Peng[1,3], Huarong Chen[1,3], Chu Guo[4], Heliang Huang[4], Wenzhao Wu[3], and Dexun Chen[2,3]

[1]*Zhejiang Lab, Hangzhou, China*
[2]*Tsinghua University, Beijing, China*
[3]*National Supercomputing Center in Wuxi, Wuxi, China*
[4]*Shanghai Research Center for Quantum Sciences, Shanghai China*

October 28, 2021

Abstract

We develop a high-performance tensor-based simulator for random quantum circuits(RQCs) on the new Sunway supercomputer. Our major innovations include: (1) a near-optimal slicing scheme, and a path-optimization strategy that considers both complexity and compute density; (2) a three-level parallelization scheme that scales to about 42 million cores; (3) a fused permutation and multiplication design that improves the compute efficiency for a wide range of tensor contraction scenarios; and (4) a mixed-precision scheme to further improve the performance. Our simulator effectively expands the scope of simulatable RQCs to include the 10×10(qubits)$\times$(1+40+1)(depth) circuit, with a sustained performance of 1.2 Eflops (single-precision), or 4.4 Eflops (mixed-precision)as a new milestone for classical simulation of quantum circuits; and reduces the simulation sampling time of Google Sycamore to 304 seconds, from the previously claimed 10,000 years.

- 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?

Follow-up: Zuchongzhi chips (2020)

arXiv:2106.14734, **arXiv:2109.03494**

- Superconducting chips at University of Science and Technology of China (Shanghai), led by Jian-Wei Pan

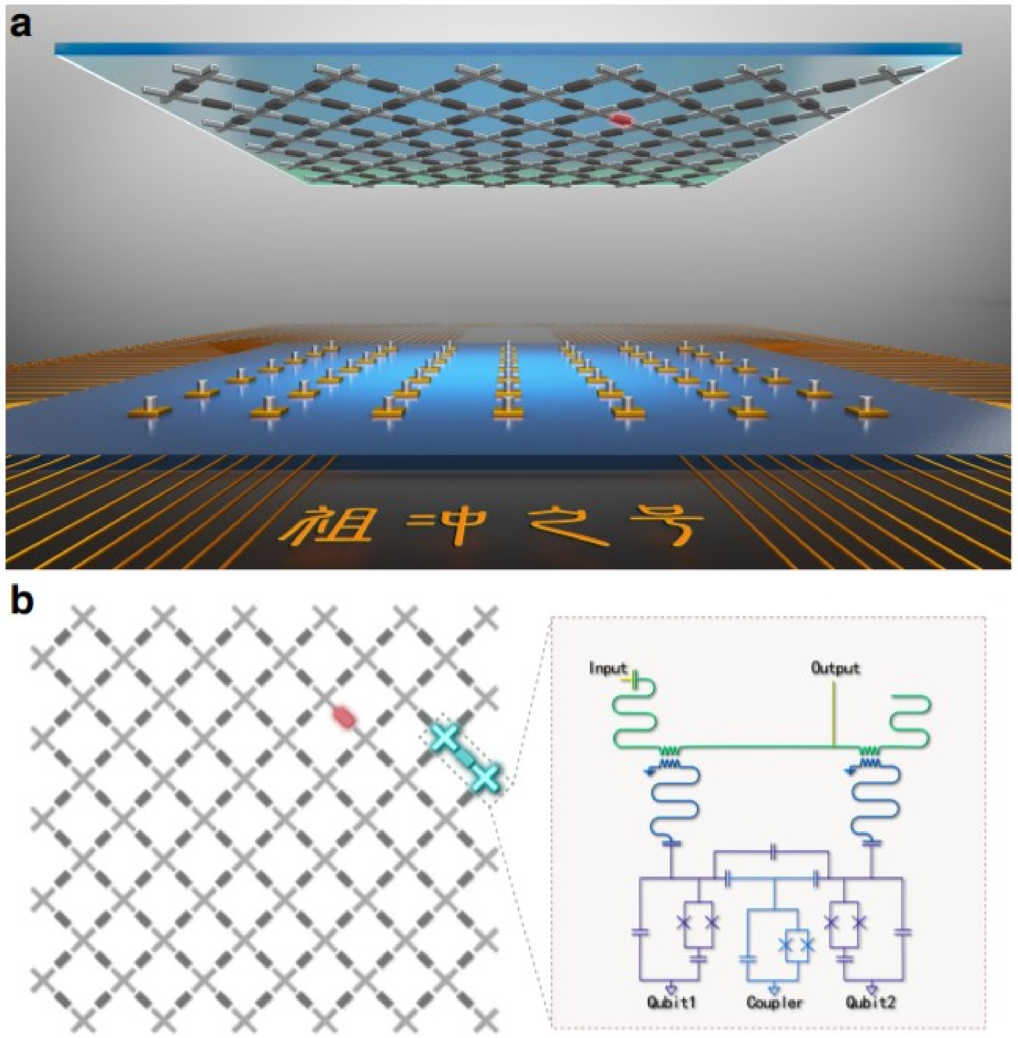
- Same connectivity, similar random circuits

- Zuchongzhi 1.0 – 56 qubits, 20 cycles

\- Simulation estimated to take 8 years on supercomputer

- Zuchongzhi 2.1 – 66 qubits, 24 cycles

\- Simulation estimated to take $4.8*10^4$ years



Zuchongzhi 2.1 chip, from arXiv:2109.03494

Follow-up: computational chemistry on Sycamore (2020)

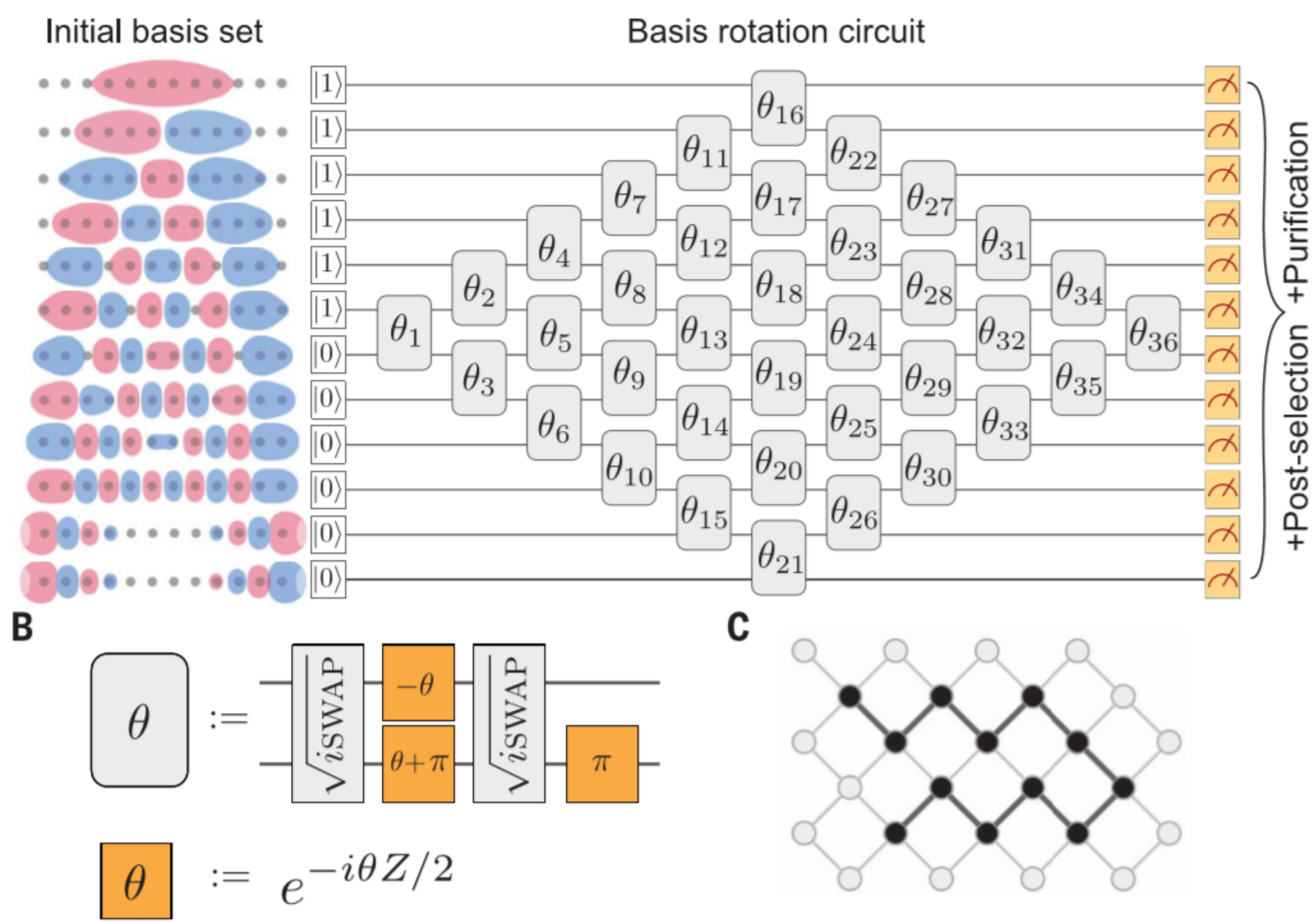
Rubin *et al.*, Science 369, 1084–1089 (2020)

- Application: ground-state energy estimation using variational methods – variational quantum eigensolver (VQE) using Hartree-Fock technique
- Demonstration on Sycamore: [Rubin *et al.*, Science 369, 1084–1089 (2020)]

- Quantum simulation of H chain (up to 12 atoms), and diazine ($C_4H_4N_2$) isomerization

- Right: Hartree-Fock orbitals of H12 mapped onto qubits. Variational circuit optimized to minimize energy, mean-field approximation

- In some cases, chemical accuracy achieved



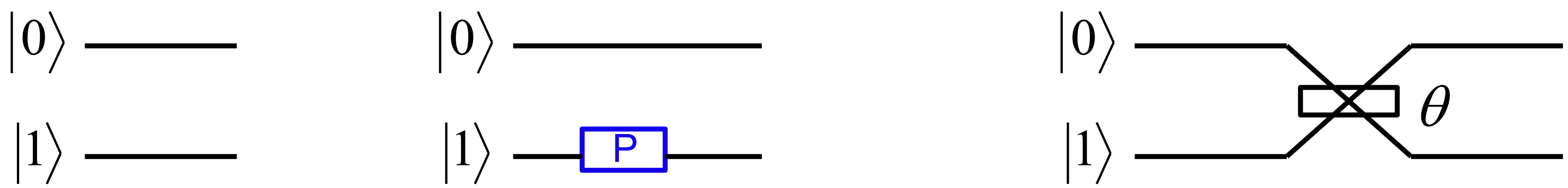
- Still simulable, but demonstration of error mitigation and calibration techniques. Step towards larger-scale simulators

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:



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

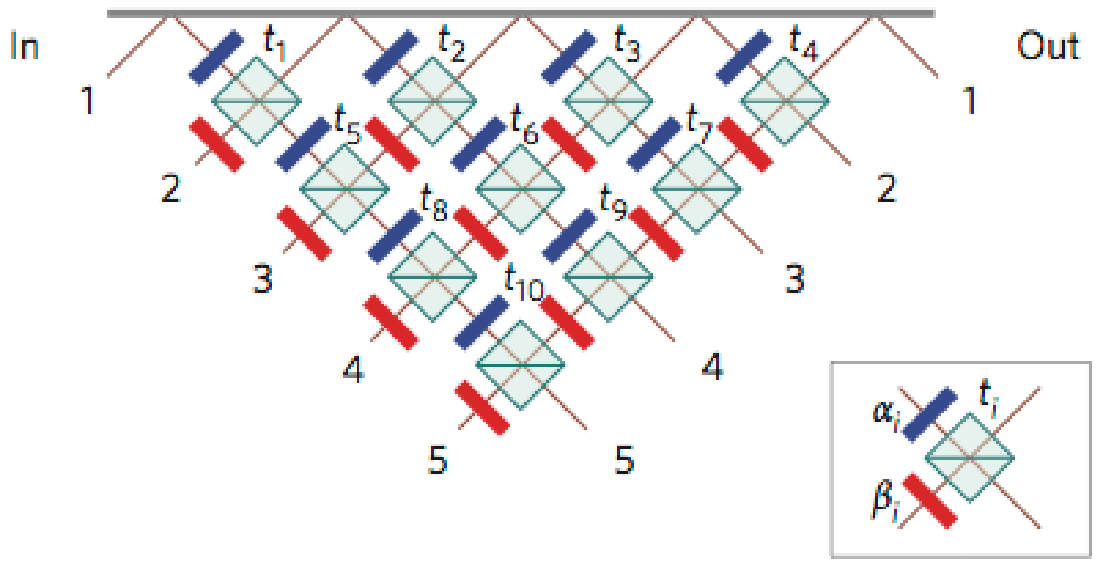
- Arbitrary single-qubit unitaries implementable with a BS and phase shifters

- 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?

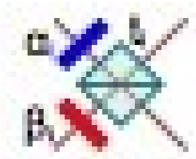
Non-interacting photons in linear interferometers



- 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.



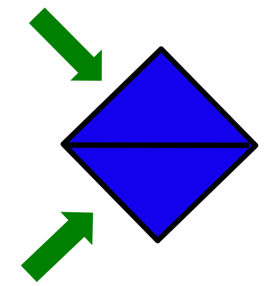
- Output probabilities given by permanents of matrices associated with *U:*
  - Example: the probability of an output of one photon per mode, with an input of one photon per mode, is:

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

- 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

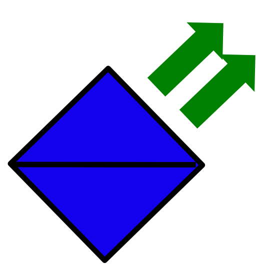
$$U = \begin{pmatrix} T & iR \\ iR & T \end{pmatrix}$$

- Probability that the two photons exit in different modes is

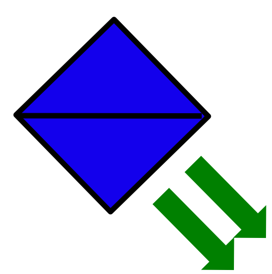
$$p = \left|per(U)\right|^2 = \left|T^2 - R^2\right|^2$$

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

Photons always leave the BS in the same mode:



or

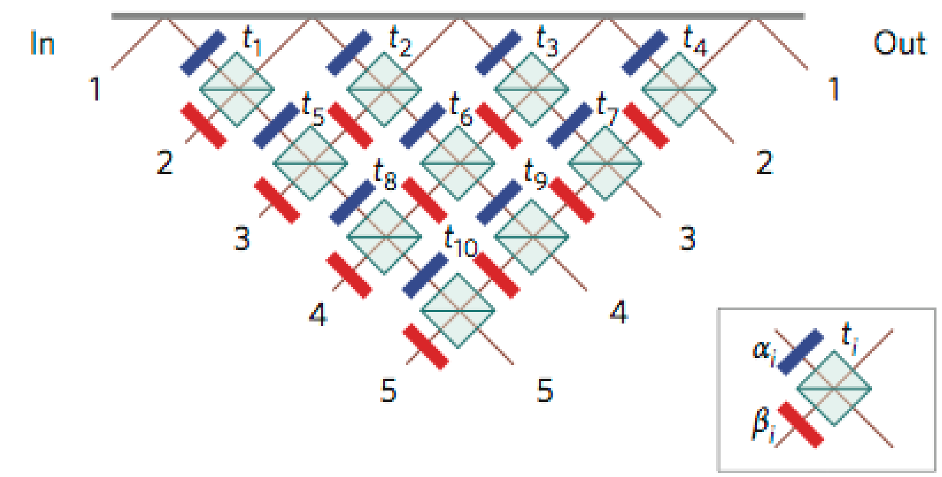


Photonic Boson Sampling

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.



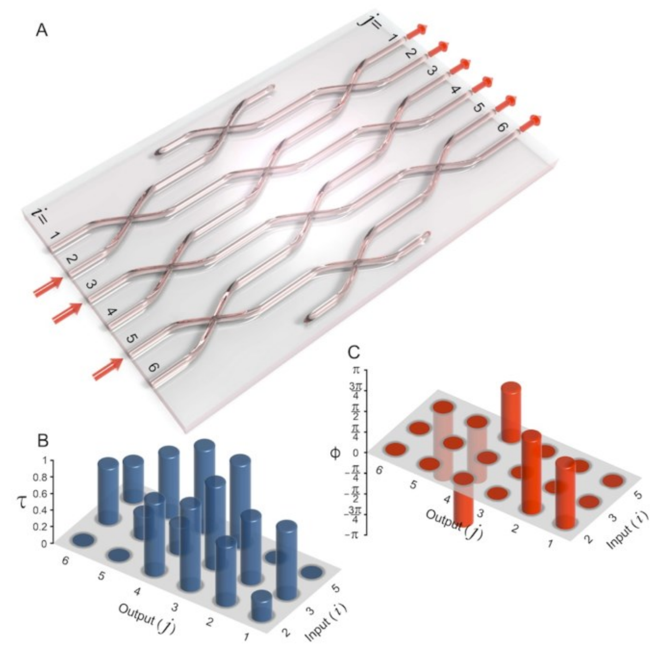
- Classical exact simulation would imply a highly unlikely computational complexity result (“collapse of the polynomial hierarchy”)

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

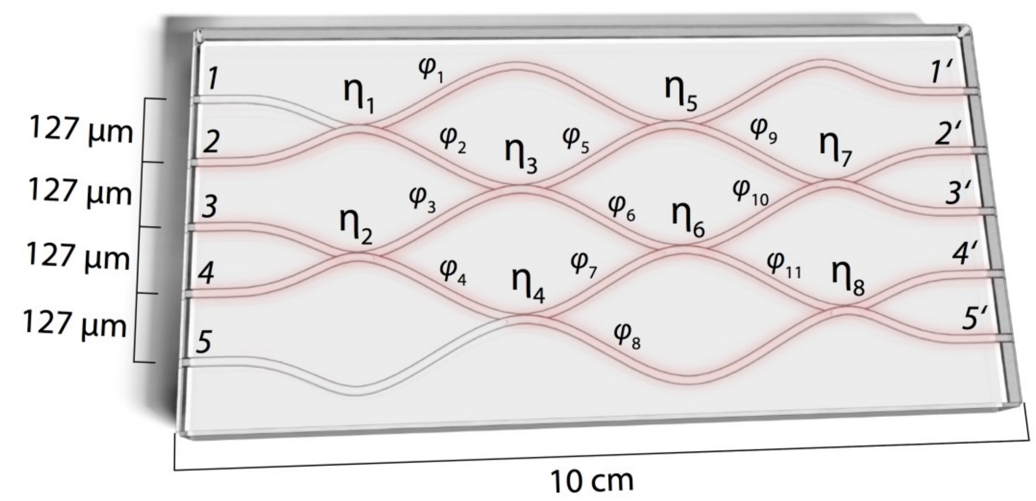
- **Advantages:** about 45 photons would be non-trivial to simulate. Step towards reconfigurable, universal photonic quantum computation

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

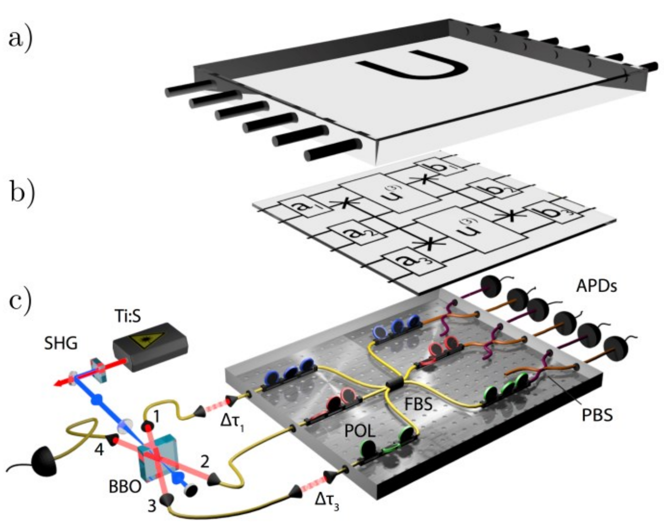
Experimental progress: first small-scale experiments (2013)



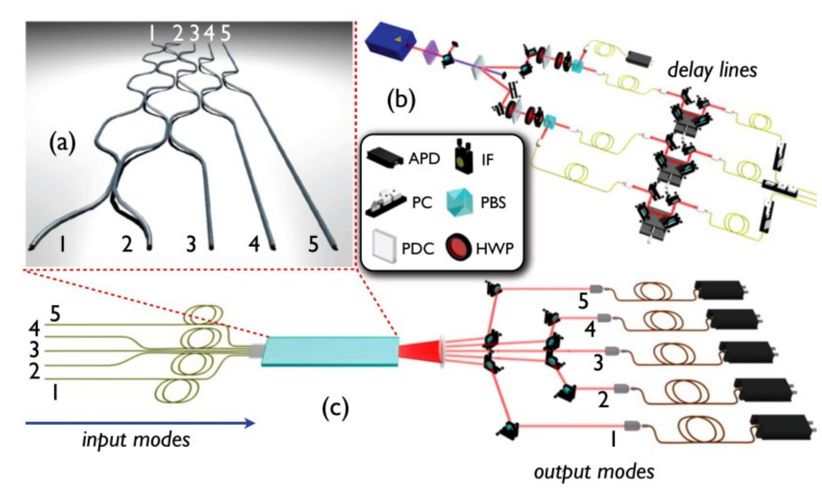
Spring et al., *Science* 339, 798 (2013) [Walmsley group]



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



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



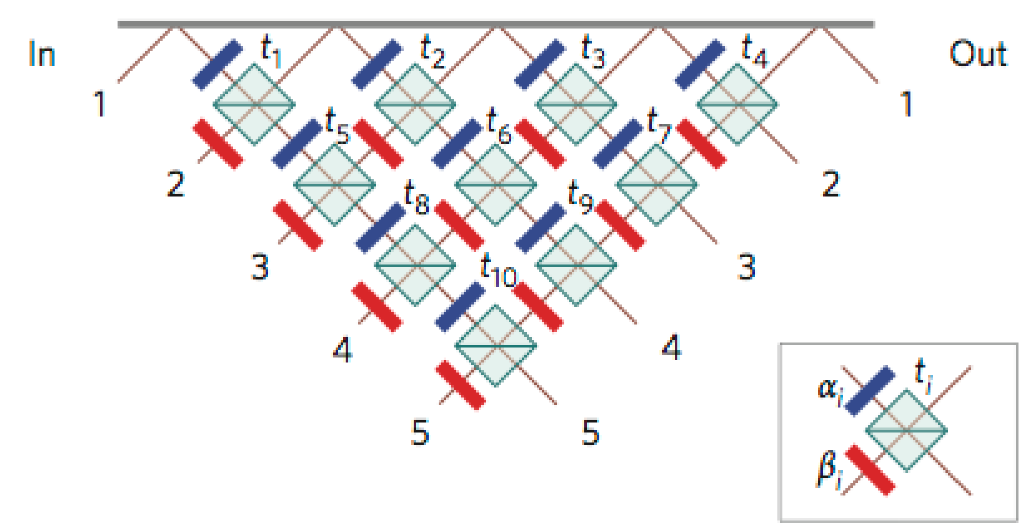
Crespi et al., *Nat. Photon.* 7, 545 (2013) [Sciarrino group]

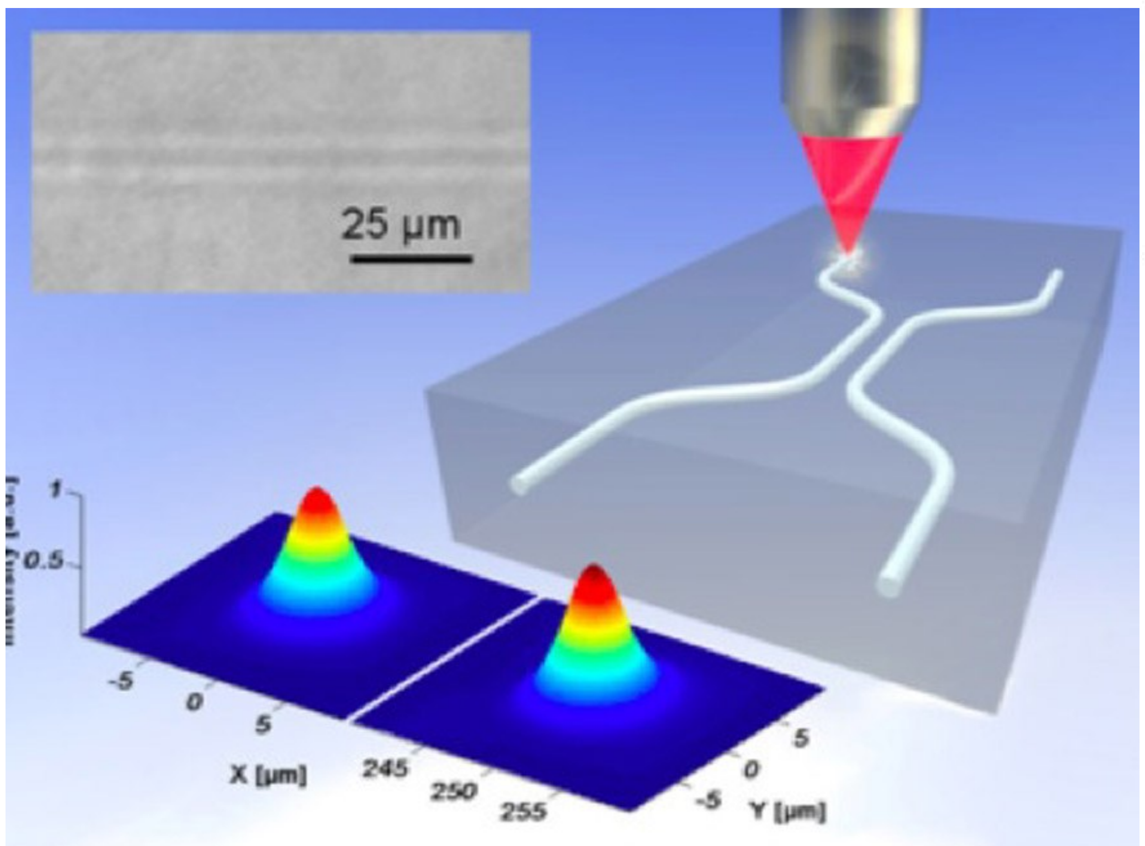
- Interference of 3,4 photons in integrated photonic chips with 5,6 modes
- Verified that probabilities are given in terms of permanents of 3x3 matrices

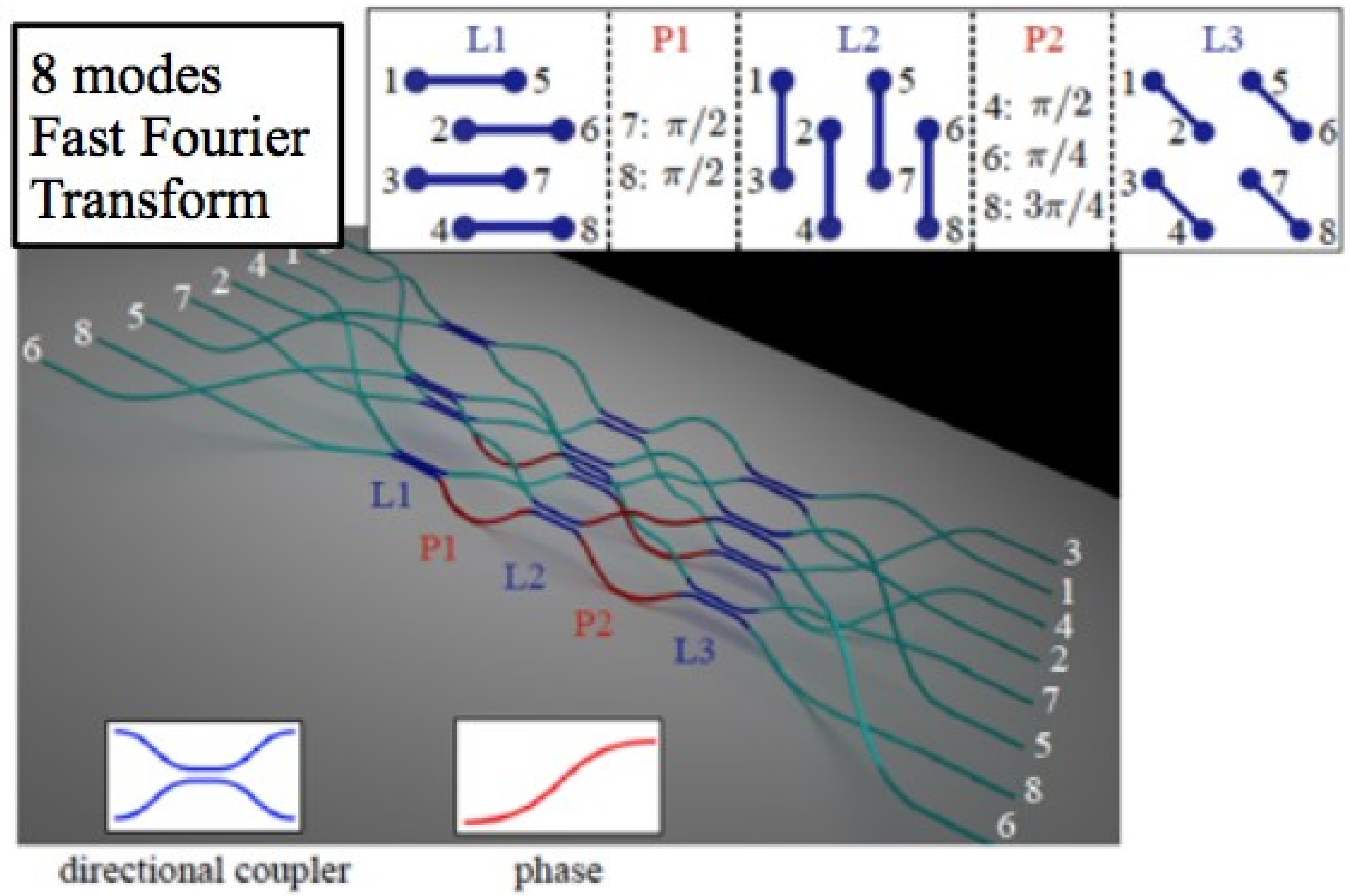
Integrated multi-mode interferometers

- **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

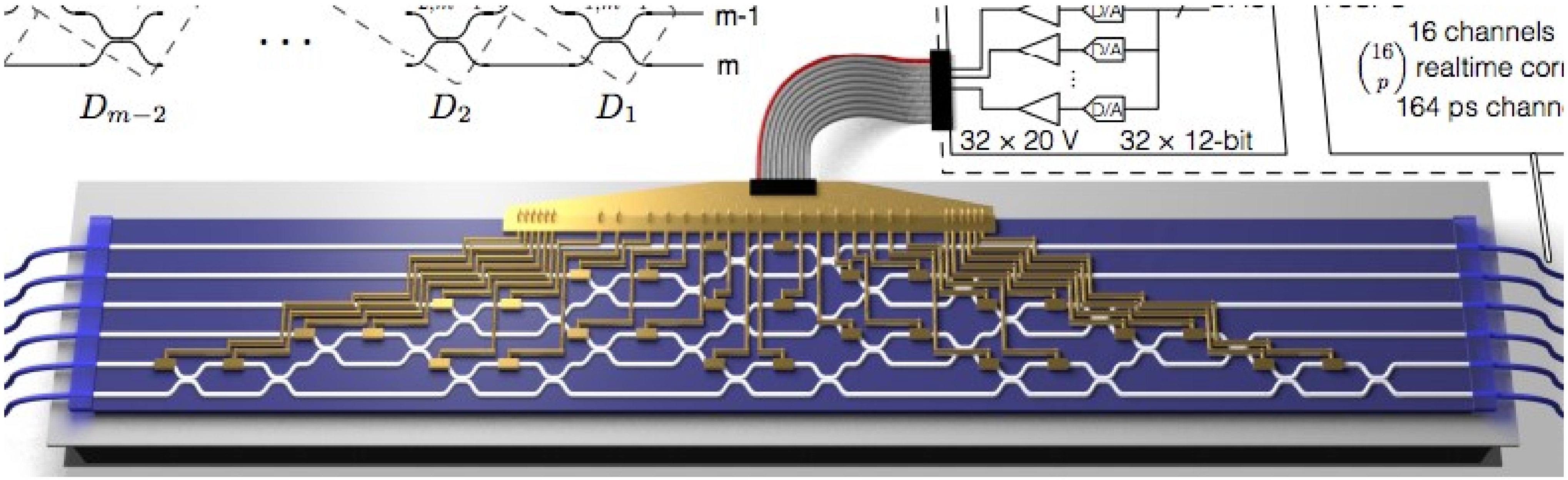






Experimental progress: reconfigurability (2015-)

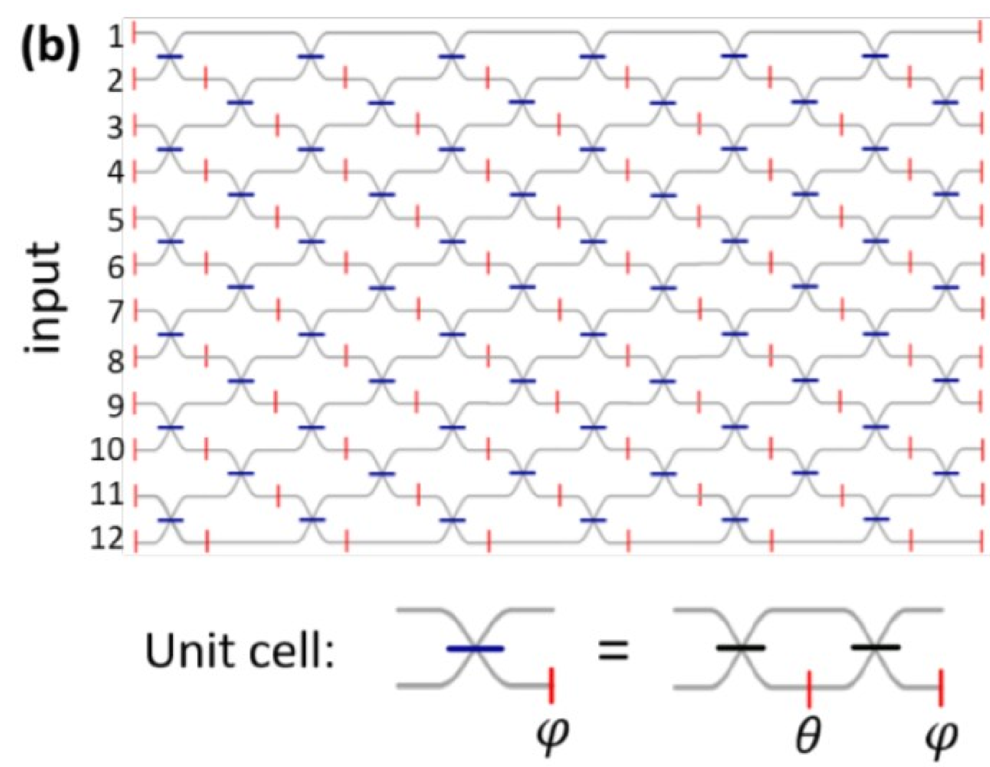
Fully reconfigurable 6-mode interferometer [Carolan *et al.*, *Science* 349, 711 (2015)]



- 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., Materials for Quantum Technology 1 (3), 035002 (2021)]

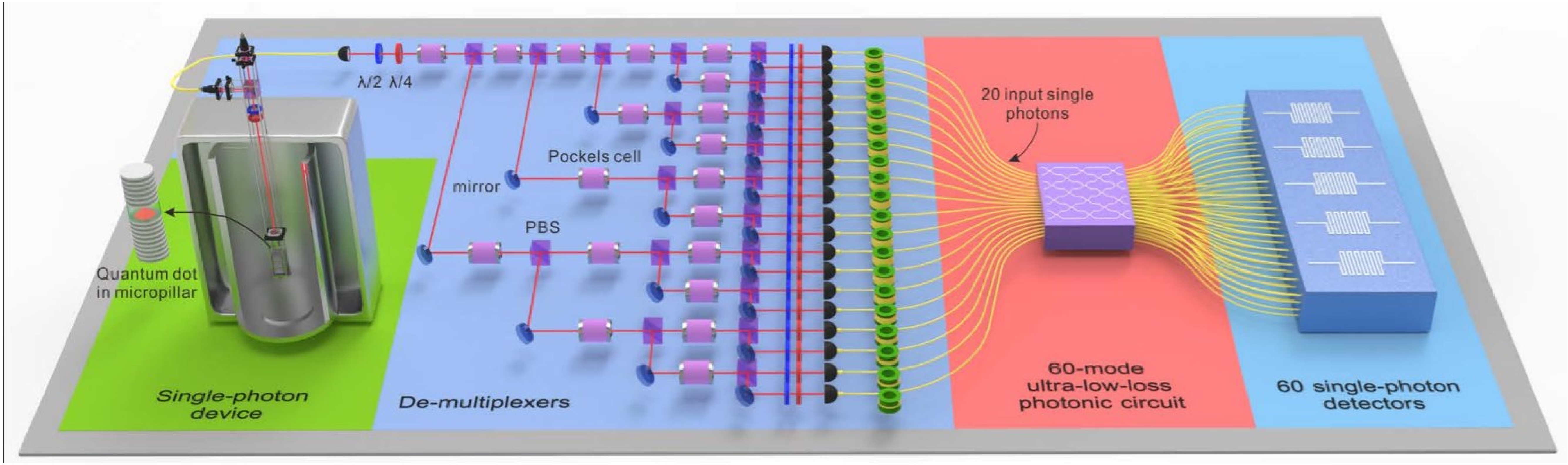
- Silicon nitrite
- 128 tunable thermo-optic phase shifters



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 (2020-21)

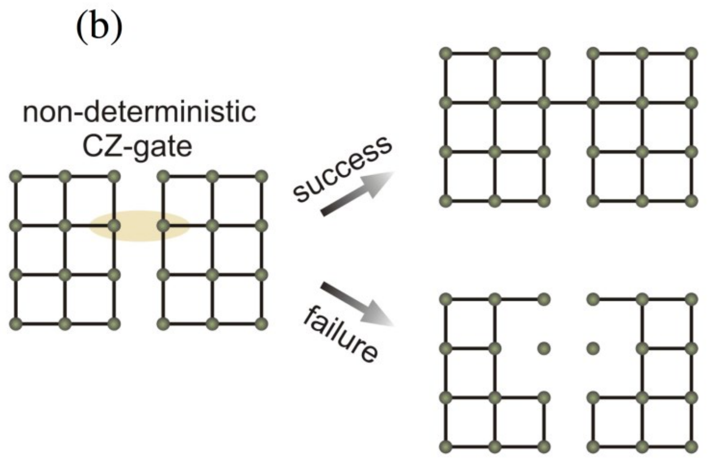
- Gaussian Boson Sampling experiment @ Univ. of Science and Technology of China (Hefei) - H. Wang *et al.*, Science 370 (6523), 1460 (Dec. 2020), preprint arXiv:2106.15534 [quant-ph]

- GBS is a variation of boson sampling using squeezed light as inputs (higher event rate)
- Up to 73 photons, 100 modes
- v2: up to 113 photons, 144 modes (June 2021)
- Simulation on supercomputer estimated to be **10^{24} times slower**

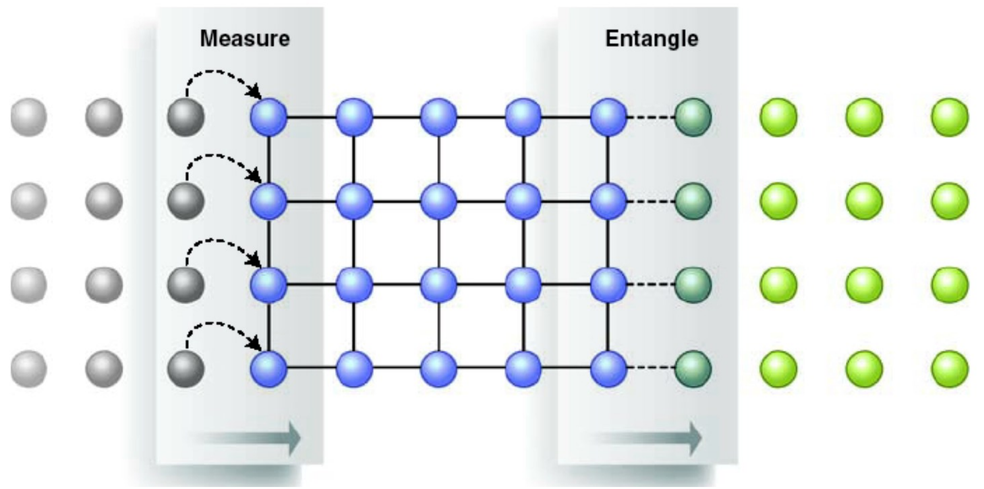
- Open questions:
  - improved classical simulation, “faking” events using supercomputer
  - Future: higher complexity regime, encoding qubits into continuous variables for scalable computation (Gottesman-Kitaev-Preskill encoding) – approach of Canadian company Xanadu

Growing photonic cluster states for MBQC

- Using one-way model to advantage: building large resource states from probabilistic operations; at once or on the go



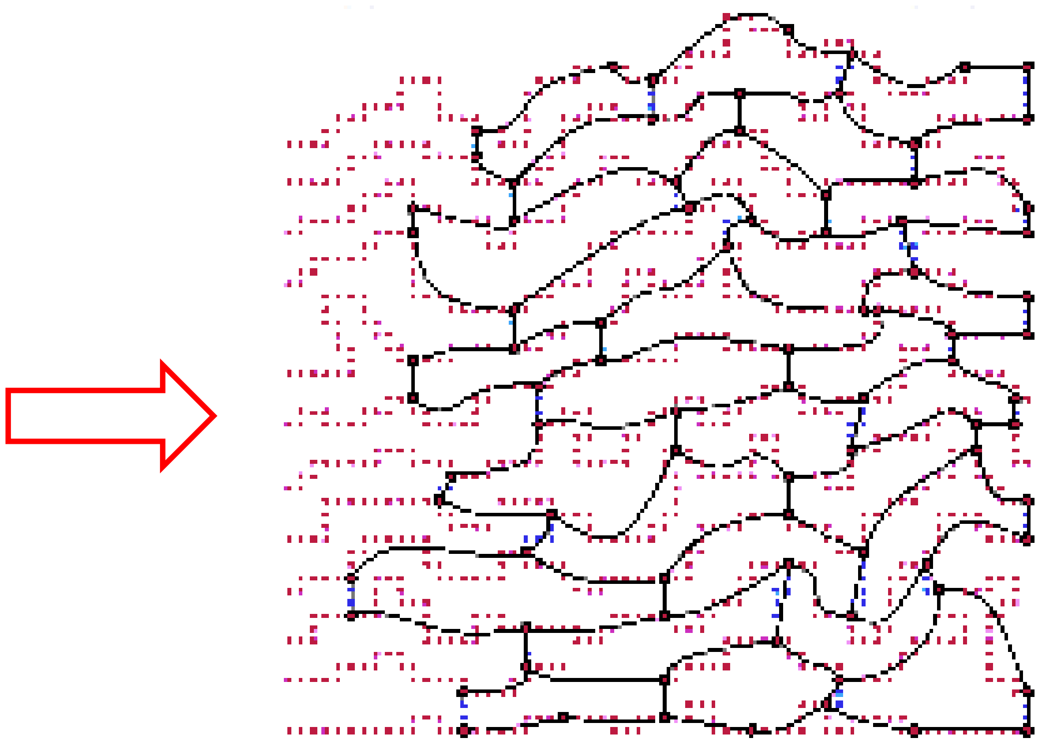
from: Briegel *et al., Nat. Phys.* 5 (1), 19 (2009)



from: O'Brien, Science 318, 1467 (2007)

- Schemes for adapting imperfect clusters for MBQC

(a) initial faulty square lattice

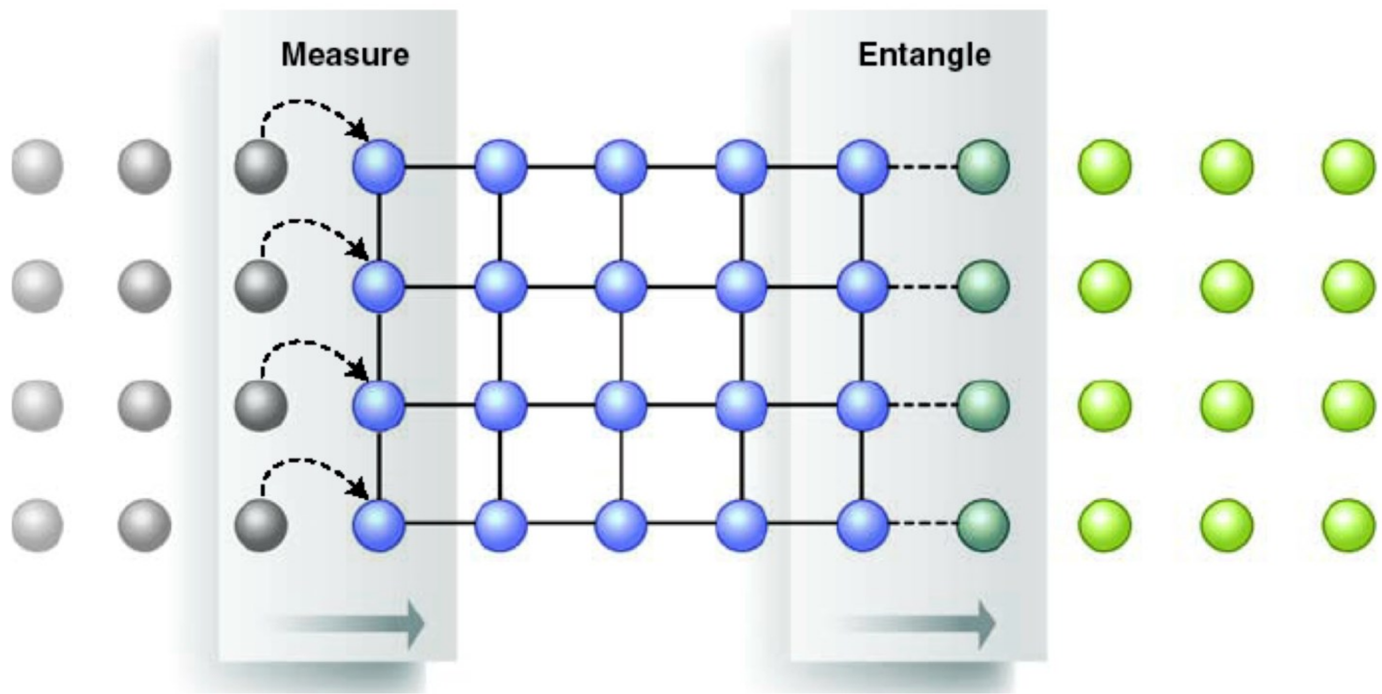


(f) deletion and contraction (Q.1 & Q.2)

from: Browne *et al., New J. Phys.* 10, 023010 (2008)

Universal QC with measurement-based quantum computation

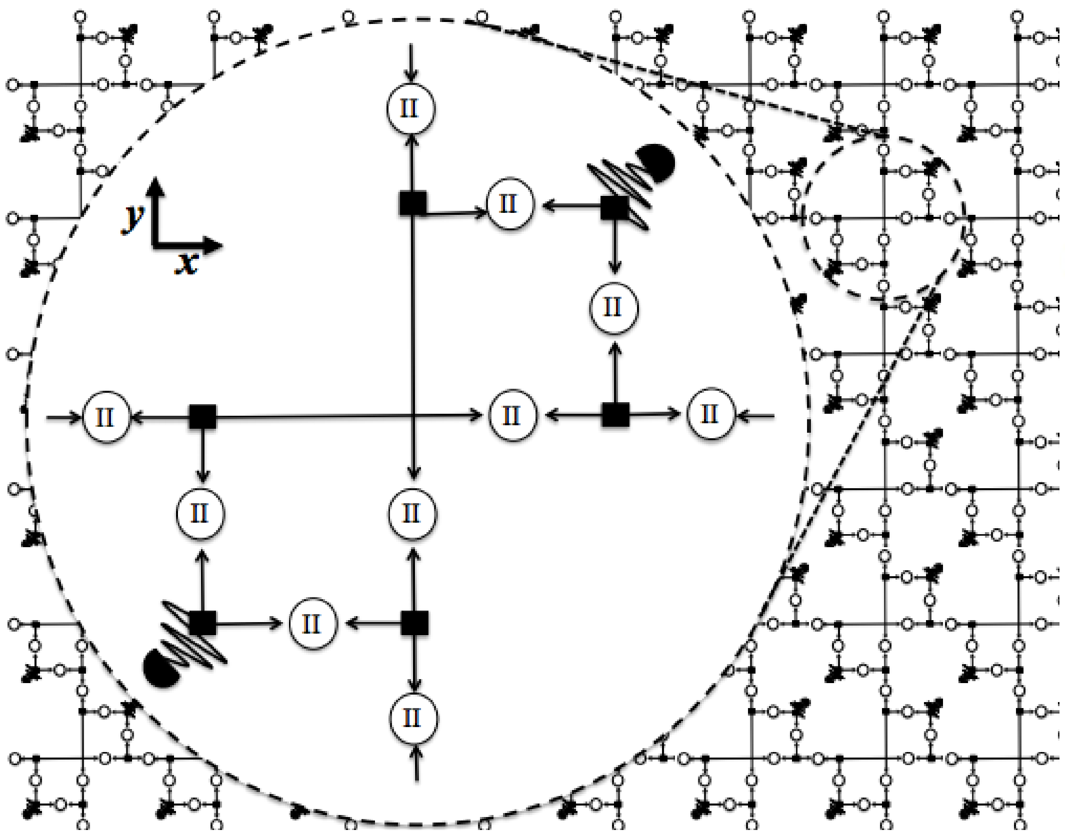
- Measurement-based quantum computation (MBQC) relies only on
  - entangling gates;
  - adaptive single-qubit measurements.
- Teleportation-based gates – states are teleported (and transformed) step by step

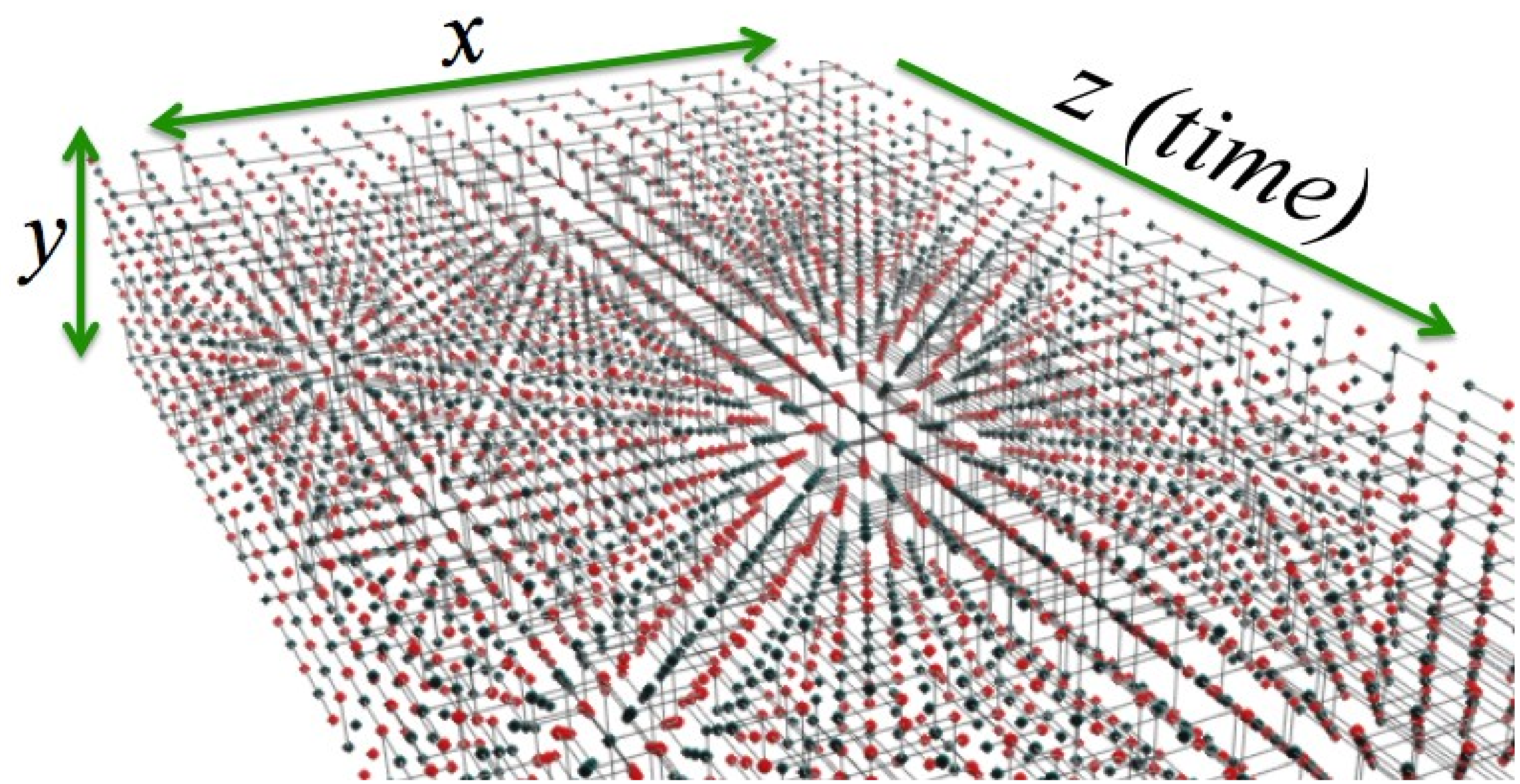


from: O'Brien, *Science* 318, 1467 (2007)

- MBQC is uniquely suited to photonic quantum computation:
  - Photons fly away fast…
  - …so they are stored for short times, measured, and information teleported to fresh photons.
- Approach being pursued by US company PsiQuantum (> 3 billion US$ valuation)

Universal QC with measurement-based quantum computation

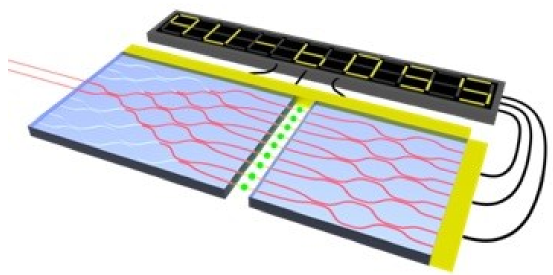




- MBQC using 3-photon GHZ-state sources on-chip: [Rudolph, arXiv:160708535]
  - (2+1)-dimensional architecture
  - probabilistic entangling gates sufficient, if above percolation threshold (essential use of error correction)
  - adaptive single-qubit measurements (delay lines)

- Key advantages: room-temperature chips (small cryo units for e.g. detectors), compatible with major chip foundry techniques, i.e. potentially scalable

INL in 2 EC-funded projects on photonic quantum computation



ERC Advanced Grant QU-BOSS ("Quantum advantage via non-linear Boson Sampling")
2020-2025

- PI: Fabio Sciarrino (Univ. of Rome, La Sapienza)
- Partners: Istituto de Fotonica e Nanotecnologie (IFN-CNR – Milan), INL

Phoqusing
Photonics Quantum Sampling Machine

H2020 FETOPEN PHOQUSING ("Photonic Quantum Sampling Machine")

2020-2024

- PI: Fabio Sciarrino (Univ. of Rome, La Sapienza)
- Partners: CNR (IT), CNRS (FR), Sorbonne Univ. (FR), Veriqloud (FR), QuiX BV (NL), INL

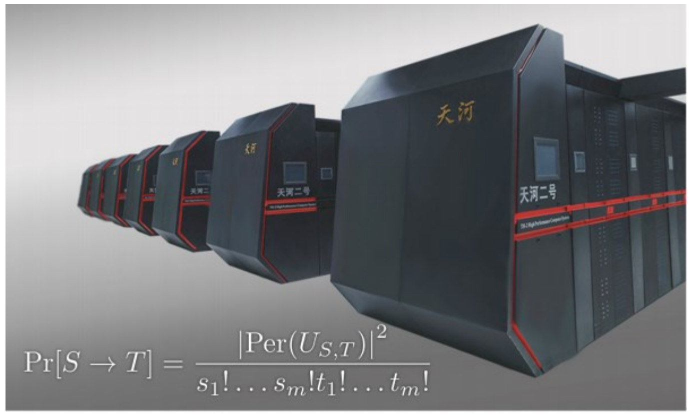
- Development of complex linear and non-linear interferometers
  - Theoretical characterization of photonic indistinguishability, resources such as contextuality and coherence
  - Scalability of photonic QC, MBQC ideas
- Noisy, Intermediate-Scale Quantum (NISQ) computational applications: variational algorithms, randomness manipulation, cryptography, quantum chemistry

Conclusion

- Q. computers promise extreme computational speed-up for many problems

… and they're already much faster than supercomputers at some contrived tasks

VS



- Q. computational advantage has (arguably) been demonstrated using superconducting chips and photonic systems

- Next steps:

  - Practical applications in small-scale q. simulation, optimization, graph theory
  - Scientific, technological, and engineering challenges to scale up QCs and incorporate quantum error correction for general applicability

Thank you for your attention!