QUANTUM LAB

Quantum Information Lab
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SAPIENZA UNIVERSITÀ DI ROMA

Quantum advantage with integrated photonics

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HORIZON 2020

Phoqusing

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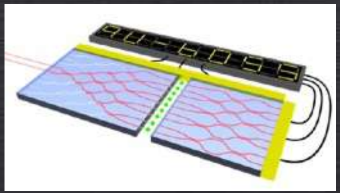


How to achieve quantum supremacy (advantage)?

John Preskill
@preskill

Proposed "quantum supremacy" for controlled quantum systems surpassing classical ones. Please suggest alternatives.

Nature Special Issue on "Quantum software"

REVIEW

doi:10.1038/nature23458

Quantum computational supremacy

Aram W. Harrow[1] & Ashley Montanaro[2]

The field of quantum algorithms aims to find ways to speed up the solution of computational problems by using a quantum computer. A key milestone in this field will be when a universal quantum computer performs a computational task that is beyond the capability of any classical computer, an event known as quantum supremacy. This would be easier to achieve experimentally than full-scale quantum computing, but involves new theoretical challenges. Here we present the leading proposals to achieve quantum supremacy, and discuss how we can reliably compare the power of a classical computer to the power of a quantum computer.

[1]Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA. [2]School of Mathematics, University of Bristol, Bristol BS8 1TW, UK.

BOX 1

Boson sampling

Box 1 Figure | Diagram of a boson sampling e
(red waveforms) are injected on the left-hand s
beamsplitters (shown black) that is set up to ge
transformation. Photons are detected on the rig
to a probability distribution conjectured to be h
classically. Photonic modes are represented by
are represented by two lines coming together, c
directional couplers in an integrated photonic c

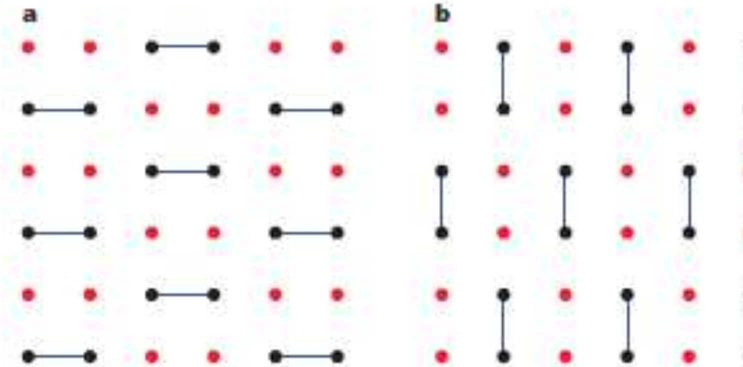
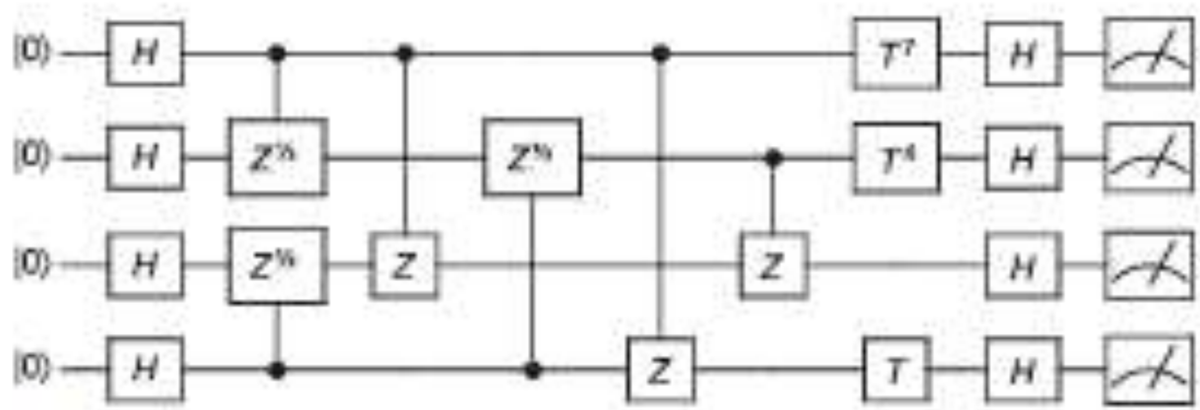


Figure 1 | A 2D lattice of superconducting qubits proposed as a way to demonstrate quantum supremacy. Panels **a** and **b** depict the condition of the lattice at two illustrative timesteps. At each timestep, two-qubit gates (blue) are applied across some pairs of neighbouring qubits, and random one-qubit gates (red) are applied on other qubits. This experiment was proposed[12] by the quantum-AI group at Google; see Box 2 for more details.

BOX 2

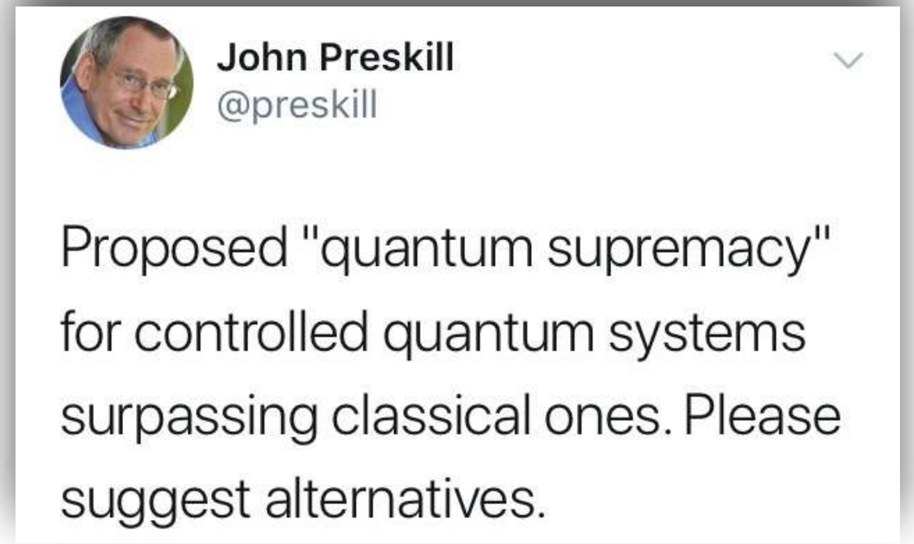
Random quantum circuits



Box 2 Figure | Example of an IQP circuit. Between two columns of Hadamard gates (H) is a collection of diagonal gates (T and controlled-$\sqrt{Z}$). Although these diagonal gates may act on the same qubit many times

How to achieve quantum supremacy?

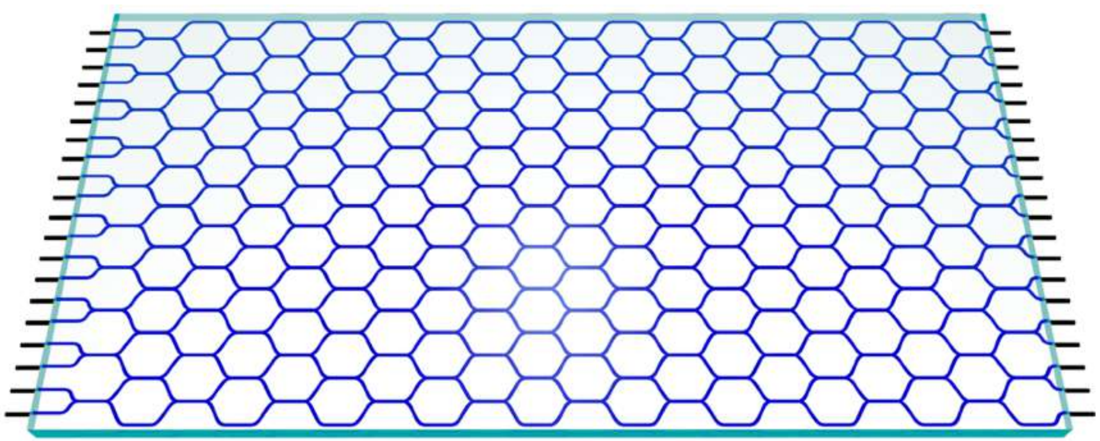
(Quantum advantage)



BOSON SAMPLING

propagation on *m* optical modes

Input n bosons



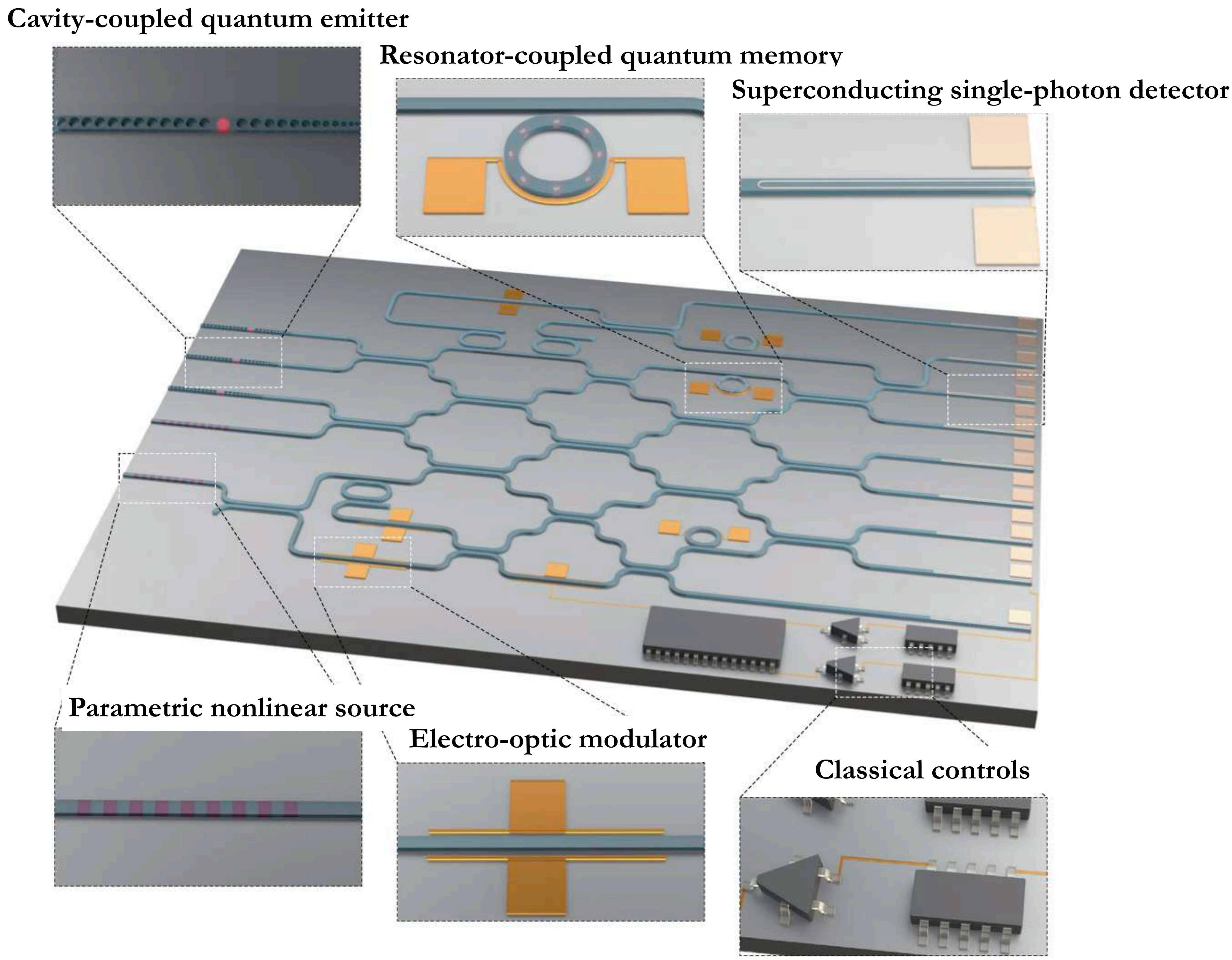
Sampling output state

Can a classical computer efficiently simulate the distribution of the output mode numbers?

Answer: No!

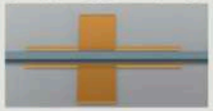
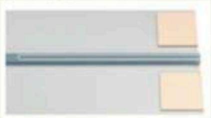
Arkhipov and Aaronson, "The computational complexity of linear optics", Proceedings of the Royal Society (2011)

Quantum photonic integrated circuit architecture



Quantum photonic integrated circuit architecture

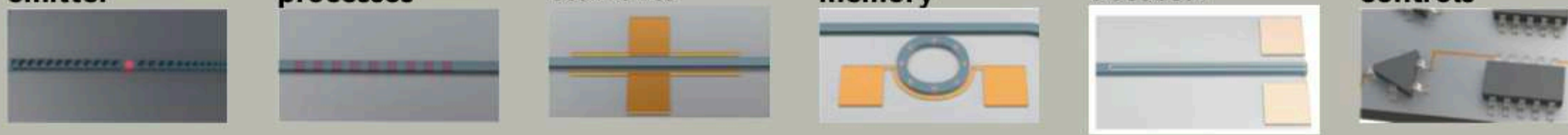
Quantum photonic integrated circuits (qPICs) can be monolithically, hybrid or heterogeneously integrated and can harness the current progress of classical photonic integration platforms

Devices	Quantum photonic use cases									
	Memory-based repeater	Cluster-state repeater	One-way QC	Trapped-ion-based QC	QKD	Quantum imaging	Squeezed light sensing	Boson sampling	N00N-state sensing	QRNG
Quantum emitter 	R	R	R	O	O	O	NA	R	O	O
Nonlinear processes 	O	R	R	O	O	R	R	R	O	O
Circuit elements 	R	R	R	R	R	R	R	R	R	R
Quantum memory 	R	O	R	NA	O	NA	NA	NA	NA	NA
Single-photon emitter 	R	R	R	O	R	R	R	R	R	R
Classical circuits 	R	R	R	R	R	R	R	R	R	R

R: required, NA: not available, O: optional

Photonic integration platforms: technological maturity

Overview of several photonic integration platforms
categorized by their level of technological maturity



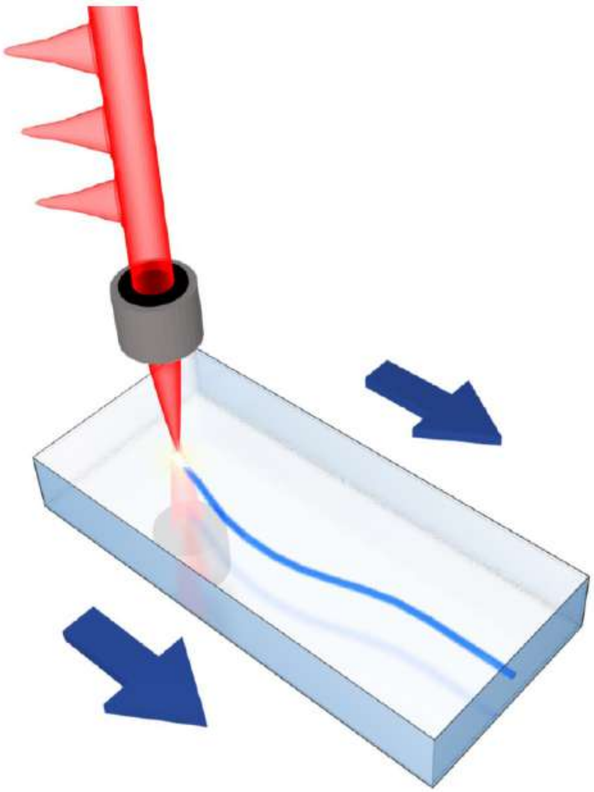
Platform	Quantum emitter	Nonlinear processes	Circuit elements	Quantum memory	Single-photon detector	Classical controls
Silicon	E	D	D	E	D	D
Silica	E	P	D	E	P	P
Silicon nitride	P	D	D	E	P	D
Aluminium nitride	P	D	D	E	P	P
Silicon carbide	D	P	P	D	P	D
Lithium niobate	P	D	P	E	P	P
Diamond	D	P	P	D	P	E
III-V semiconductors	D	P	D	P	P	D
Polymers	E	E	P	NA	E	P
Tantalum pentoxide	NA	E	P	NA	P	P

D: development stage
E: early/explorative stage
NA: not available
P: proof-of-principle stage

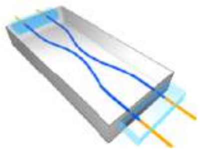
"The potential and global outlook of integrated photonics for quantum technologies"

Emanuele Pelucchi, Giorgos Fagas, Igor Aharonovich, Dirk Englund, Eden Figueroa, Qihuang Gong, Hübel Hannes, Jin Liu , Chao-Yang Lu, Nobuyuki Matsuda, Jian-Wei Pan, Florian Schreck, Fabio Sciarrino, Christine Silberhorn, Jianwei Wang and Klaus D. Jöns (Nature Physics Review, in press)

Femtosecond laser writing

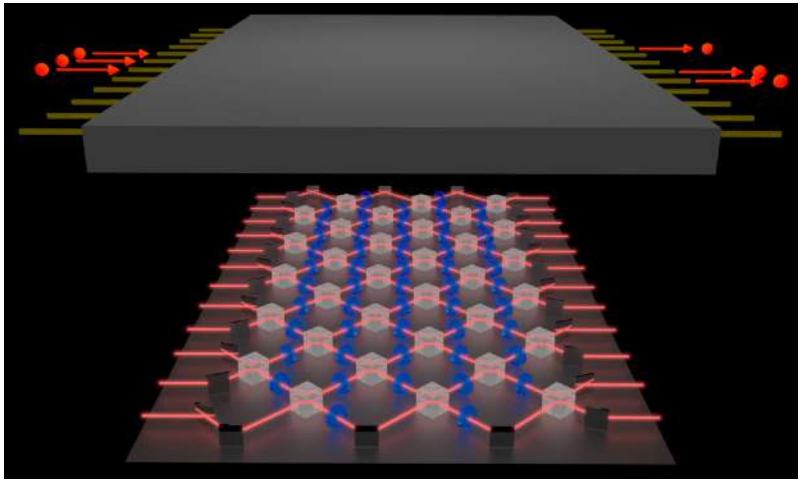


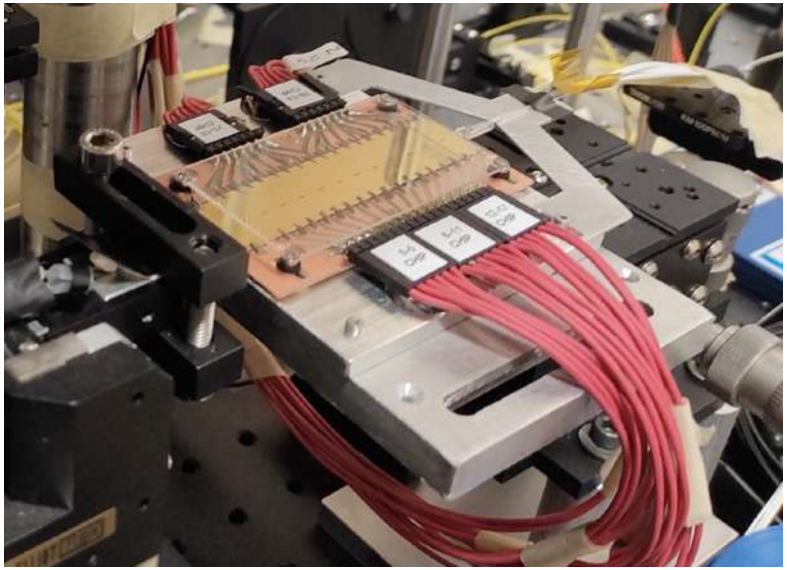
- Femtosecond pulse tightly focused in a glass
- Combination of multiphoton absorption and avalanche ionization induces *permanent and localized refractive index increase* in transparent materials
- Waveguides are fabricated in the bulk of the substrate by translation of the sample at constant velocity with respect to the laser beam, along the desired path.



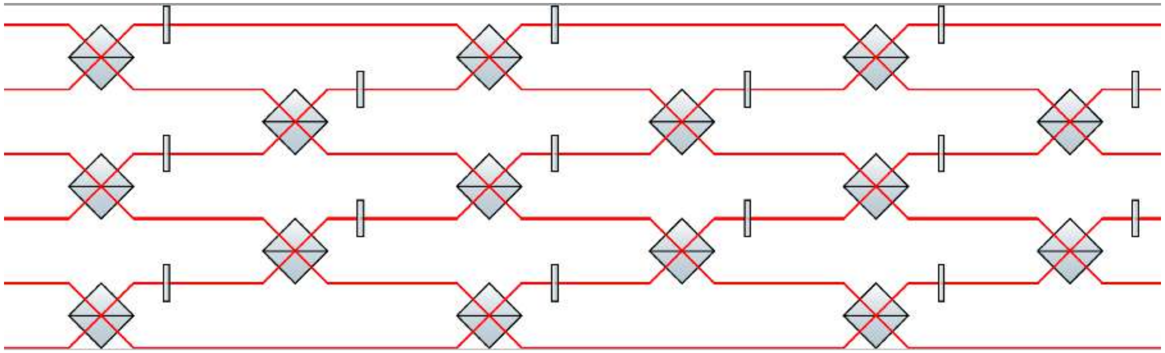
Boson Sampling: Universal programmable device

Requirement for Boson Sampling - design arbitrary interferometers → Requires independent control of phases and beam-splitter operation





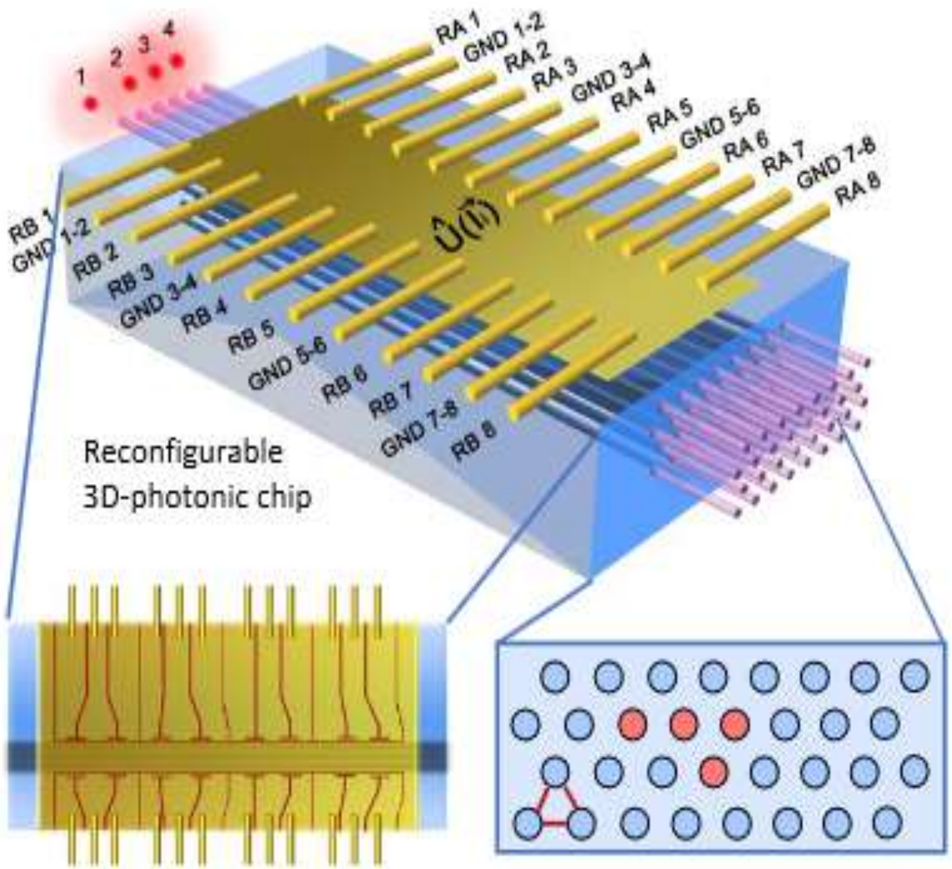
DISCRETE-COMPONENTS LAYOUT

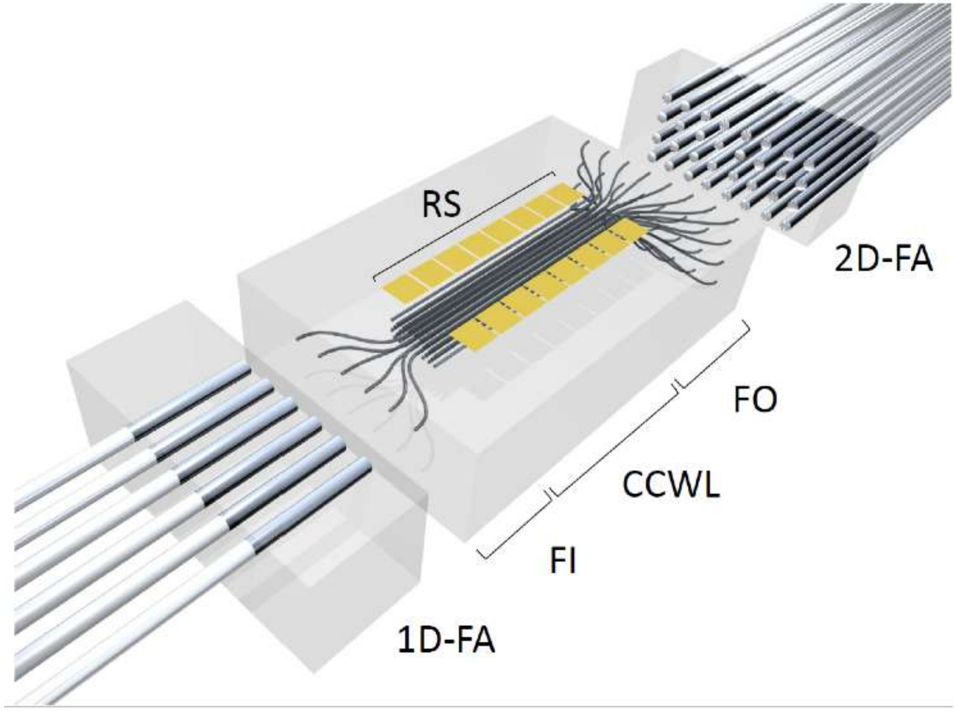


- 6-mode universal photonic integrated chip
- 33 heaters
- Experiment ongoing

3D continuously coupled integrated photonic device

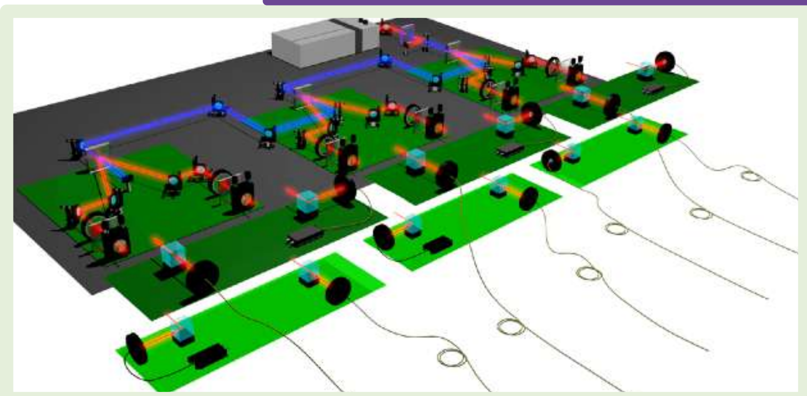
- 32 modes linear interferometer
- 16 heaters on the top surface
- 6 modes 1D fan-in (FI) and input fiber array (FA)
- 32 modes 2D rectangular fan-out (FO) and 2D-fiber array



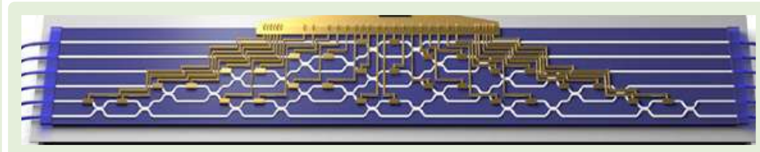


Hoch, et al., *npj Quantum Information* **8**, 55 (2022)

State-of-art on Boson Sampling



Scattershot Boson Sampling



Reconfigurable circuits

- *Phys. Rev. Lett.* **120**
- *Phys. Rev. Lett.* **121**

- *Nat. Commun.* **7**

2018

2017

2016

2015

- *Science* **349**
- *Sci. Adv.* **1**
- *Phys. Rev. X* **5**

2014

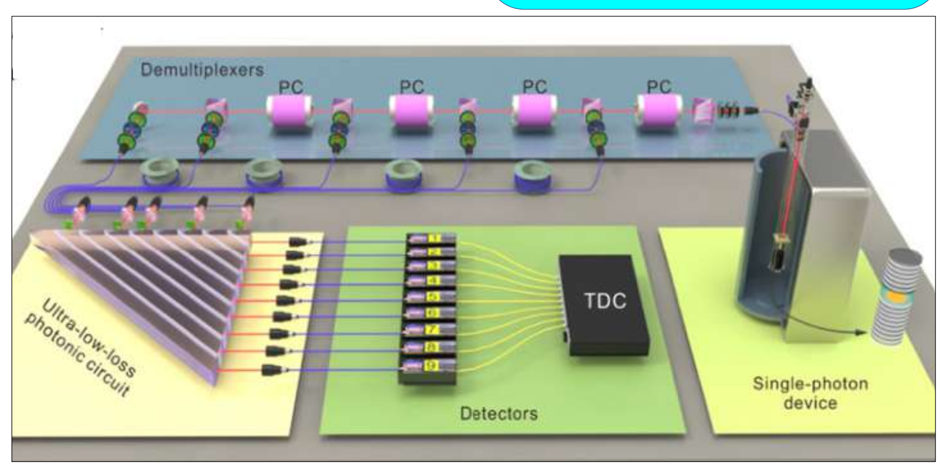
2013

- *Science* **339**
- *Science* **339**
- *Nat. Photon.* **7**
- *Nat. Photon.* **7**

- *Nat. Photon.* **8**
- *Nat. Photon.* **8**

Bright-source Boson Sampling based on Quantum Dot

- *Nat. Photon.* **11**
- *Nat. Photon.* **12**
- *Phys. Rev. Lett.* **118**
- *Phys. Rev. Lett.* **118**

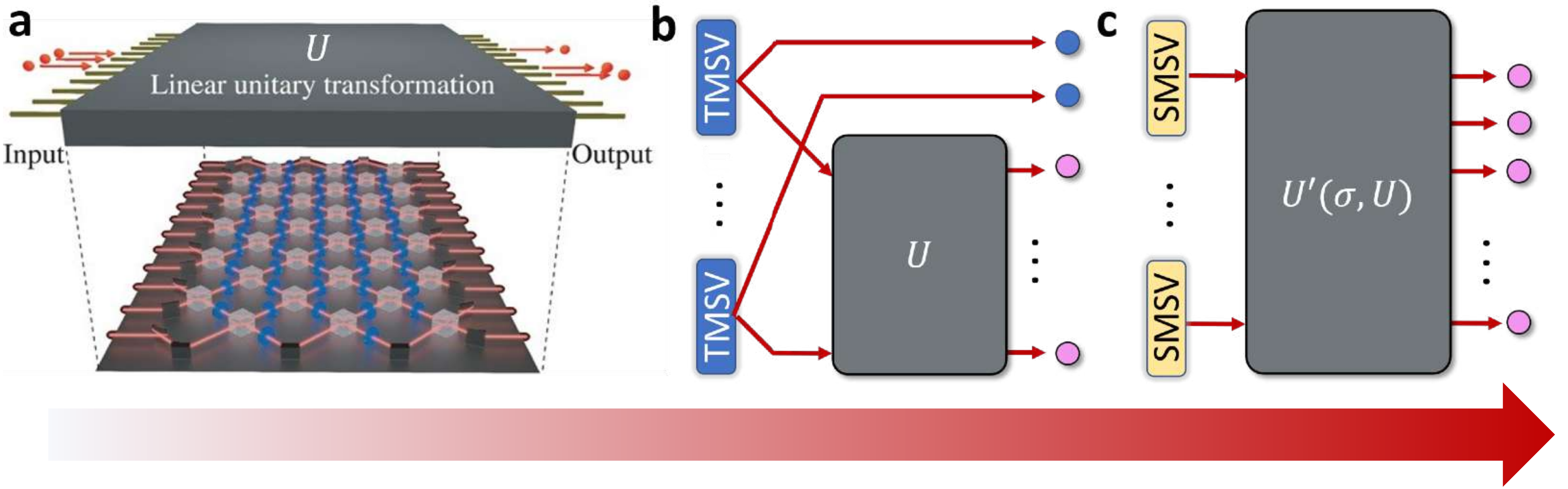


Boson Sampling: the concept

Aaronson & Arkhipov (2011)

Variants of Boson Sampling

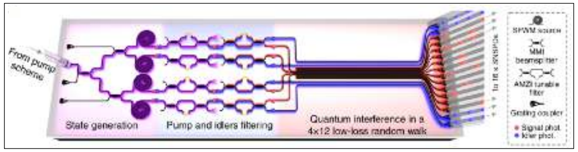
Standard Boson Sampling | **Scattershot Boson Sampling** | **Gaussian Boson Sampling**



Increasing sample rate

State-of-art on Boson Sampling

Paesani et al. Nat. Phys 15, 925–929 (2019)

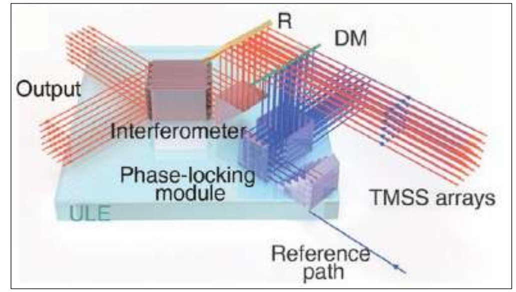


On chip Boson Sampling

2019

Quantum Advantage Via Gaussian Boson Sampling

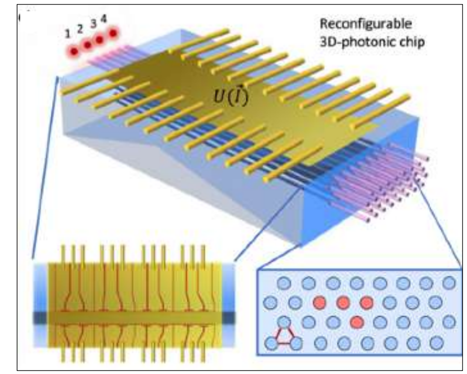
Zhong et al. Science 370, 6523 (2020)



2020

3D-Boson Sampling

Hoch et al. npj Quantum Inf. 8, 55 (2022)

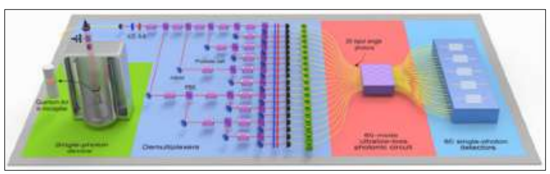


2021

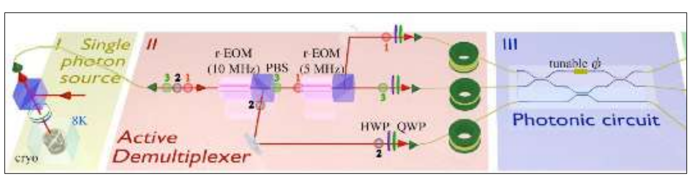
2022

Quantum dot based Boson Sampling

Wang et al. Phys. Rev. Lett. 123, 250503 (2019)

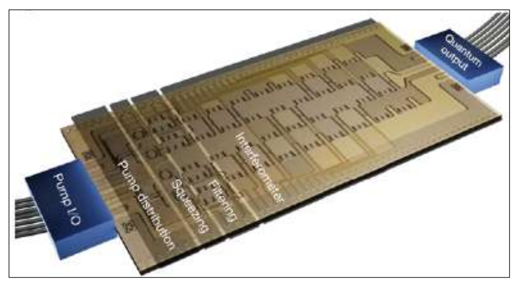


Antón et al. Optica 6, 1471-1477 (2019)

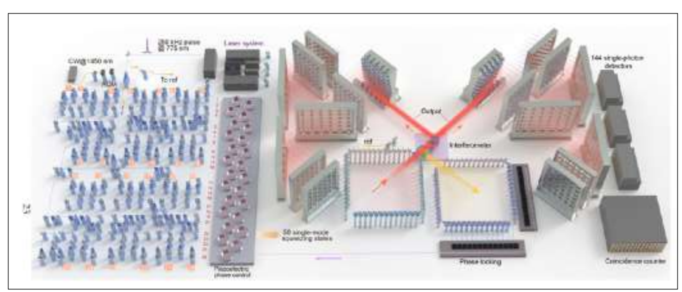


On chip Gaussian Boson Sampling

Arrazola et al. Nature 591, 54–60 (2021)



Zhong et al. Phys. Rev. Lett. 127, 180502 (2021)



Gaussian Boson Sampling

[Submitted on 3 Dec 2020]

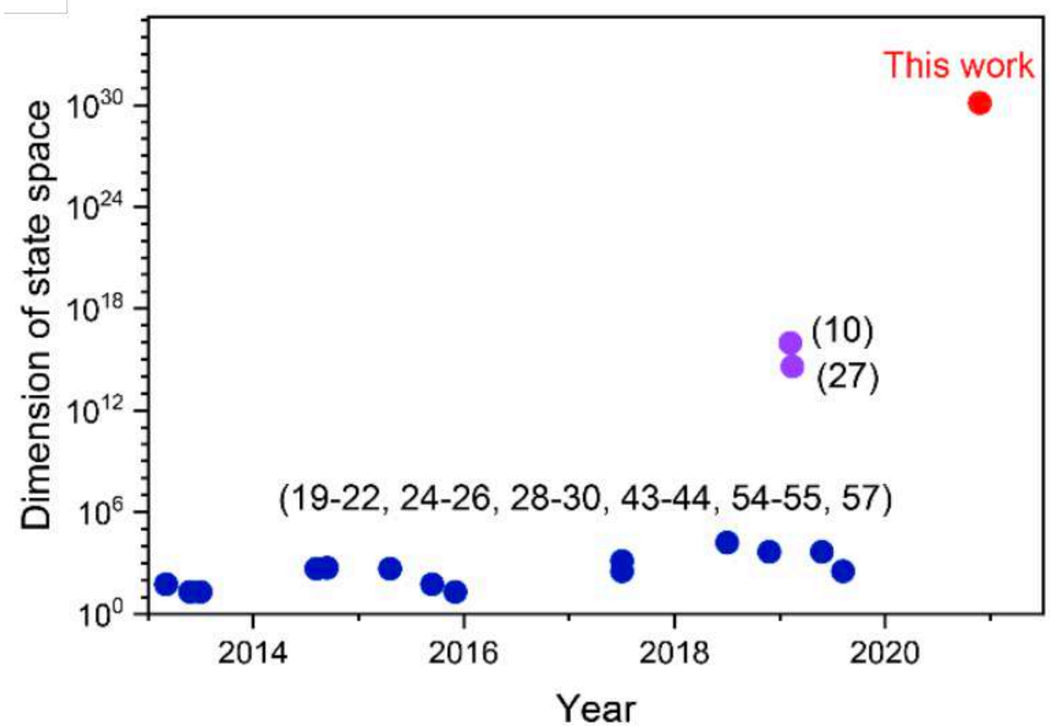
Quantum computational advantage using photons

Han-Sen Zhong, Hui Wang, Yu-Hao Deng, Ming-Cheng Chen, Li-Chao Peng, Yi-Han Luo, Jian Qin, Dian Wu, Xing Ding, Yi Hu, Peng Hu, Xiao-Yan Yang, Wei-Jun Zhang, Hao Li, Yuxuan Li, Xiao Jiang, Lin Gan, Guangwen Yang, Lixing You, Zhen Wang, Li Li, Nai-Le Liu, Chao-Yang Lu, Jian-Wei Pan

Gaussian boson sampling exploits squeezed states to provide a highly efficient way to demonstrate quantum computational advantage. We perform experiments with 50 input single-mode squeezed states with high indistinguishability and squeezing parameters, which are fed into a 100-mode ultralow-loss interferometer with full connectivity and random transformation, and sampled using 100 high-efficiency single-photon detectors. The whole optical set-up is phase-locked to maintain a high coherence between the superposition of all photon number states. We observe up to 76 output photon-clicks, which yield an output state space dimension of 10^{30} and a sampling rate that is 10^{14} faster than using the state-of-the-art simulation strategy and supercomputers. The obtained samples are validated against various hypotheses including using thermal states, distinguishable photons, and uniform distribution.

JIUZHANG

- 50 input single-mode squeezed states
- 100-mode ultraslow-loss interferometer
- 100 high efficiency single-photon detectors



Zhong et al. *Science* **370**, 6523 (2020)

Gaussian Boson Sampling

Article

Quantum computational advantage with a programmable photonic processor

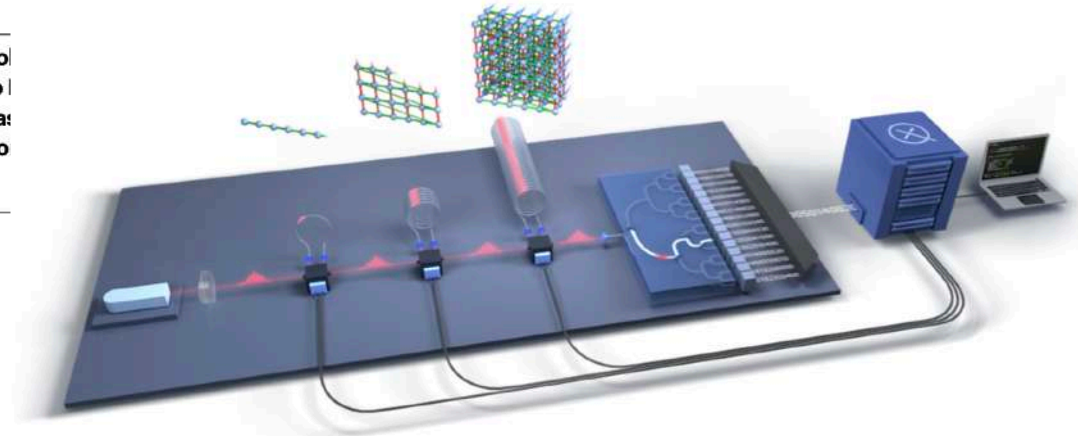
https://doi.org/10.1038/s41586-022-04725-x

Received: 12 November 2021

Accepted: 5 April 2022

Published online: 1 June 2022

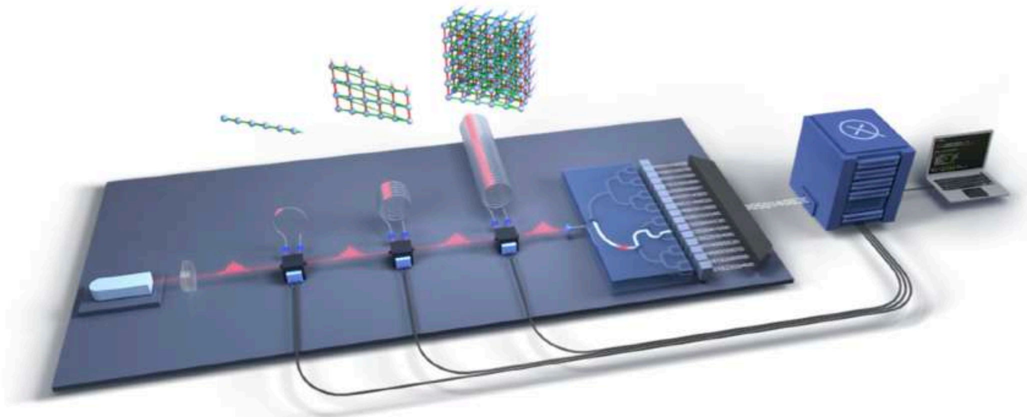
Lars S. Madsen[1,3], Fabian Laudenbach[1,3], Mo
Trevor Vincent[1], Jacob F. F. Bulmer[1], Filippo
Matthew J. Collins[1], Adriana E. Lita[2], Thoma
Matteo Menotti[1], Ish Dhand[1], Zachary Verno

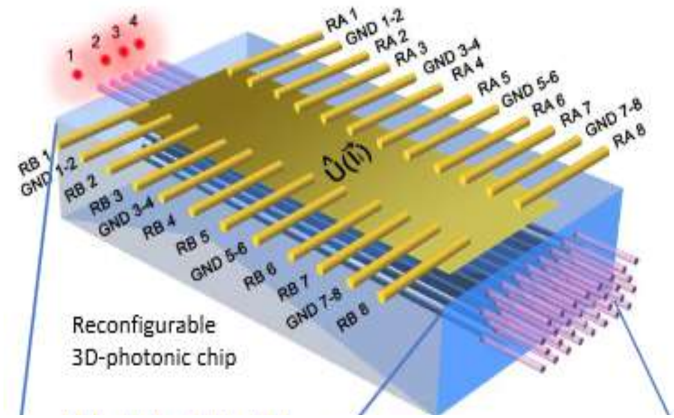


Key Features

- Cloud accessible with quantum-computational-advantage-level performance.
- A quantum light source, with adjustable brightness, emits trains of up to 288 squeezed-state qubits.
- Contains a fully programmable loop-based interferometer, synthesizing a large entangled state suitable for Gaussian Boson Sampling.
- Reprogrammable — dynamically program the gate parameters according to your own task.
- High-speed processing and readout by true photon-number-resolving detectors.

Challenges on Boson Sampling and variants

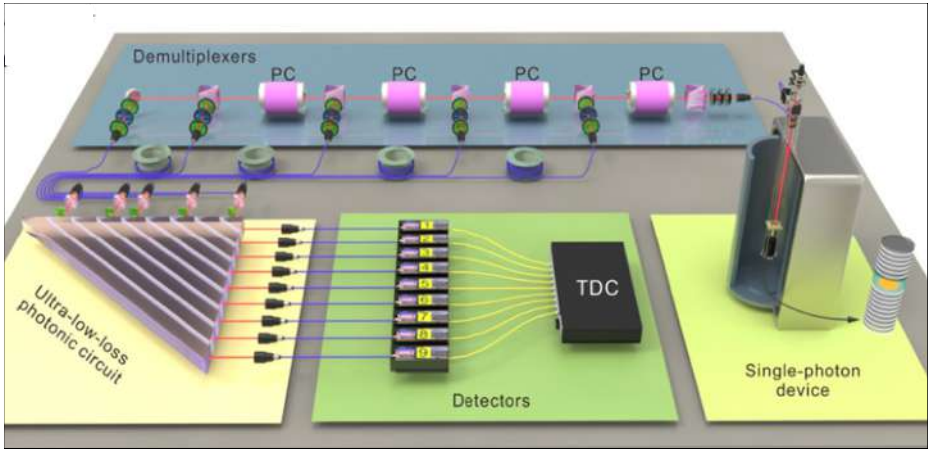




Technological challenges:
- Single photon sources
- Manipulation on a chip
- Large arrays of single photon detectors

TARGETS:
More photons
More optical modes
Alternative schemes

Open questions:
- Variant schemes
- Applications: how to exploit it within hybrid algorithms?
- How noise and imperfections affect the hardness claim?
- *How to certify the well functioning of Boson Sampling?*



Boson Sampling: potential applications

For proving quantum advantage

REPORT

Quantum computational advantage using photons

Han-Sen Zhong[1,2,*], Hui Wang[1,2,*], Yu-Hao Deng[1,2,*], Ming-Cheng Chen[1,2,*], Li-Chao Peng[1,2], Yi-Han Luo[1,...]
+ See all authors and affiliations

Science 18 Dec 2020:
Vol. 370, Issue 6523, pp. 1460-1463
DOI: 10.1126/science.abe8770

Article | Figures & Data | Info & Metrics | eLetters | PDF

A light approach to quantum advantage

For solving computational problems

PHYSICAL REVIEW A **98**, 032310 (2018)

Gaussian boson sampling for perfect matchings of arbitrary graphs

Kamil Brádler,[*] Pierre-Luc Dallaire-Demers, Patrick Rebentrost, Daiqin Su,[†] and Christian Weedbrook
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(Received 1 March 2018; published 10 September 2018)

A famously hard graph problem with a broad range of applications is computing the number of perfect matchings, that is, the number of unique and complete pairings of the vertices of a graph. We propose a method to estimate the number of perfect matchings of undirected graphs based on the relation between Gaussian boson sampling and graph theory. The probability of measuring zero or one photons in each output mode is directly related to the hafnian of the adjacency matrix, and thus to the number of perfect matchings of a graph. We present encodings of the adjacency matrix of a graph into a Gaussian state and show strategies to boost the sampling success probability for the studied graphs. With our method, a Gaussian boson sampling device can be used to estimate the number of perfect matchings significantly faster and with lower-energy consumption compared to a classical computer.

DOI: 10.1103/PhysRevA.98.032310

For quantum simulation

Article | Open Access | Published: 07 August 2017

Vibronic Boson Sampling: Generalized Gaussian Boson Sampling for Molecular Vibronic Spectra at Finite Temperature

Joonsuk Huh & Man-Hong Yung

Scientific Reports 7, Article number: 7462 (2017) | Cite this article

PHYSICAL REVIEW LETTERS **121**, 030503 (2018)

Using Gaussian Boson Sampling to Find Dense Subgraphs

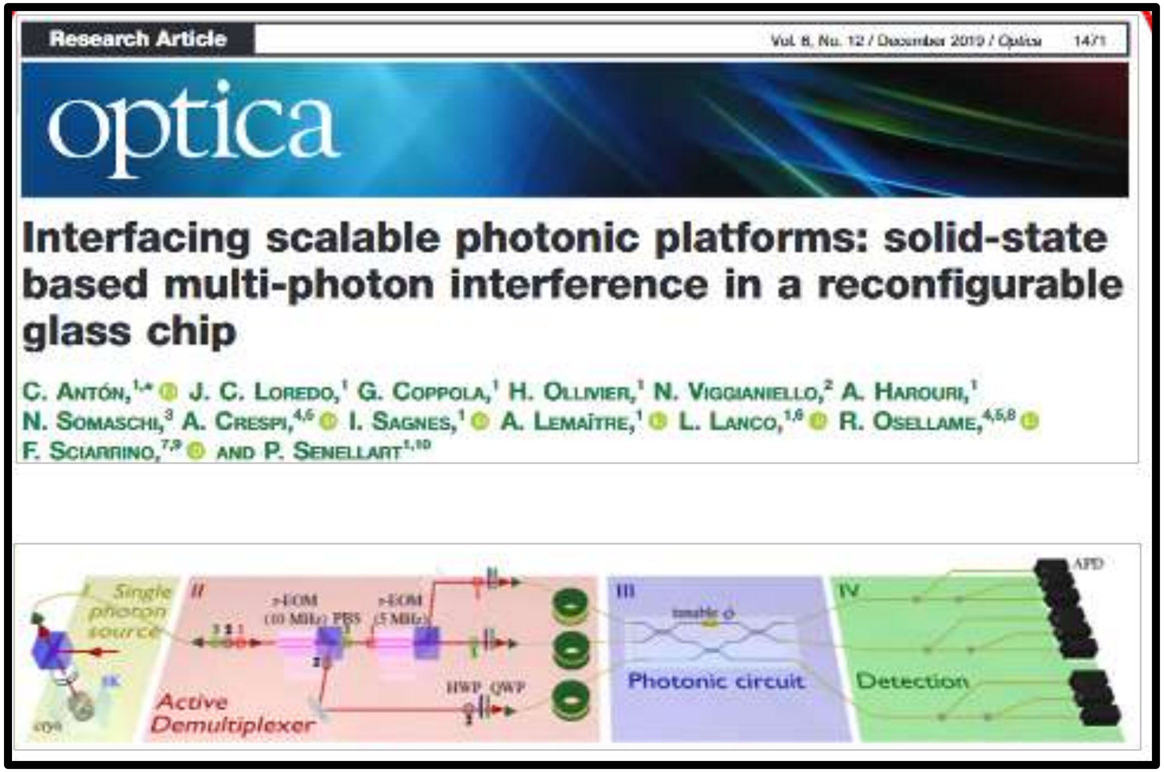
Juan Miguel Arrazola[*] and Thomas R. Bromley[†]
Xanadu, 372 Richmond Street W, Toronto, Ontario M5V 1X6, Canada

(Received 5 April 2018; revised manuscript received 14 May 2018; published 19 July 2018)

Boson sampling devices are a prime candidate for exhibiting quantum supremacy, yet their application for solving problems of practical interest is less well understood. Here we show that Gaussian boson sampling (GBS) can be used for dense subgraph identification. Focusing on the NP-hard densest k-subgraph problem, we find that stochastic algorithms are enhanced through GBS, which selects dense subgraphs with high probability. These findings rely on a link between graph density and the number of perfect matchings—enumerated by the Hafnian—which is the relevant quantity determining sampling probabilities in GBS. We test our findings by constructing GBS-enhanced versions of the random search and simulated annealing algorithms and apply them through numerical simulations of GBS to identify the densest subgraph of a 30 vertex graph.

DOI: 10.1103/PhysRevLett.121.030503

Hybrid integrated platform


Research Article Vol. 6, No. 12 / December 2019 / Optica 1471
optica

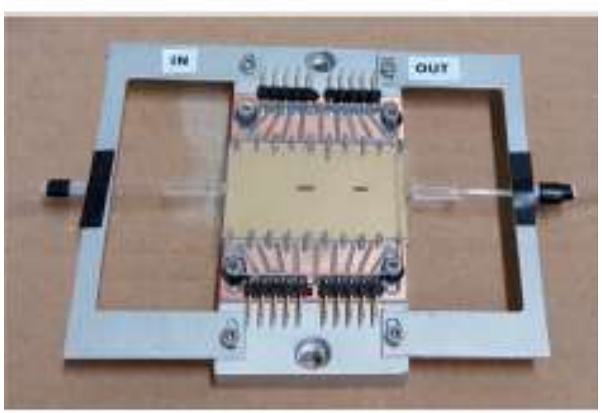
Interfacing scalable photonic platforms: solid-state based multi-photon interference in a reconfigurable glass chip

C. Antón,[1,*] J. C. Loredo,[1] G. Coppola,[1] H. Ollivier,[1] N. Viggianiello,[2] A. Harouri,[1] N. Somaschi,[3] A. Crespi,[4,6] I. Sagnes,[1] A. Lemaître,[1] L. Lanco,[1,8] R. Osellame,[4,5,8] F. Sciarrino,[7,9] and P. Senellart[1,10]

Merging in the same platform:

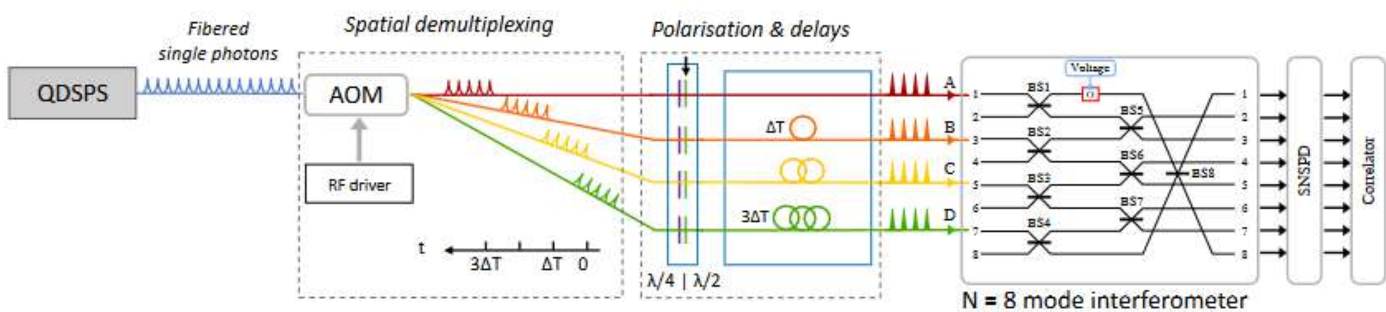
- quantum dot based sources
- integrated reconfigurable photonics

arXiv > quant-ph > arXiv:2201.13333



Quantifying n-photon indistinguishability with a cyclic integrated interferometer*

Mathias Pont,[1,†] Riccardo Albiero,[2,3,†] Sarah E. Thomas,[1,†] Nicolò Spagnolo,[4] Francesco Ceccarelli,[3] Giacomo Corrielli,[3] Alexandre Brieussel,[5] Niccolo Somaschi,[5] Hêlio Huet,[1] Abdelmounaim Harouri,[1] Aristide Lemaître,[1] Isabelle Sagnes,[1] Nadia Belabas,[1] Fabio Sciarrino,[4] Roberto Osellame,[3] Pascale Senellart,[1] and Andrea Crespi[2,3]



Hybrid integrated platform

POLITECNICO MILANO 1863

Quandela

Centre de Nanosciences & de Nanotechnologies C2N

UNIVERSITÀ DI PAVIA

The GHZ Circuit

Path-encoded 4-qubit GHZ states
Probabilistic generator

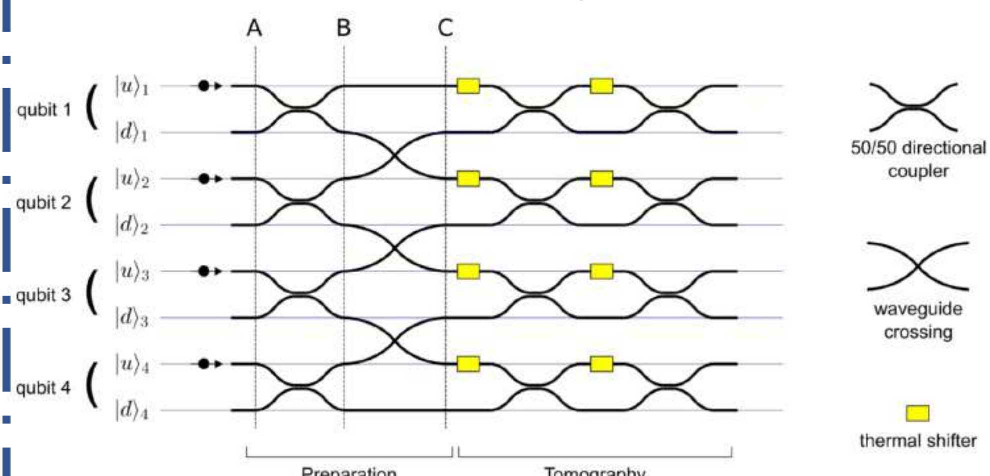
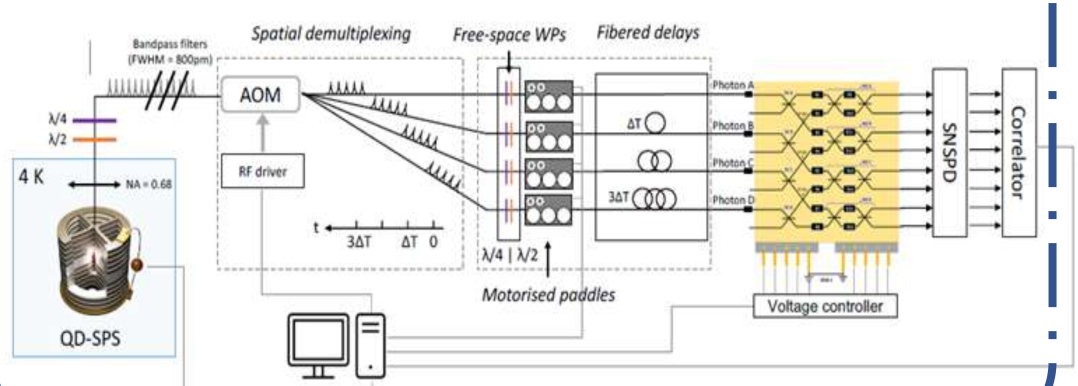


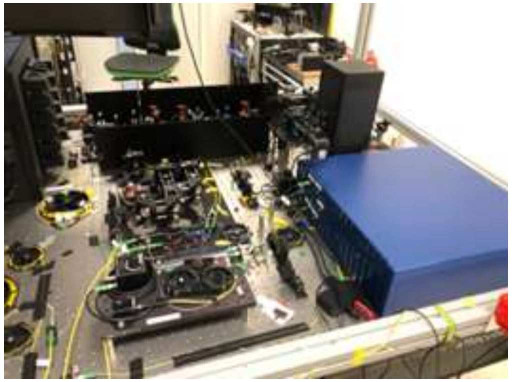
Figure 1

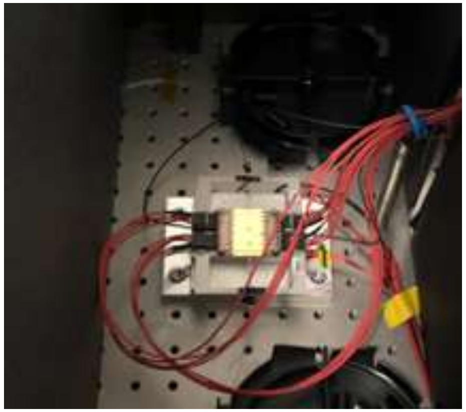
$$|\psi\rangle = \frac{|d_1u_2d_3u_4\rangle + e^{i\theta}|u_1d_2u_3d_4\rangle}{\sqrt{2}} = \frac{|0101\rangle + e^{i\theta}|1010\rangle}{\sqrt{2}}$$

- conditioned to the presence of one and only one photon per qubit

Experimental Setup







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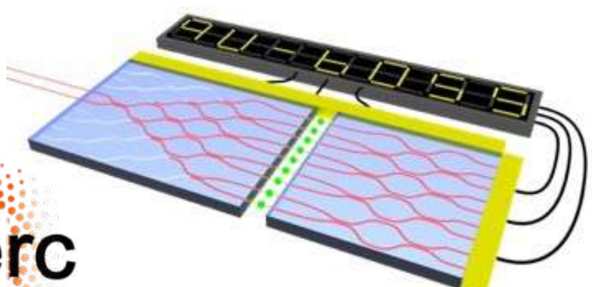

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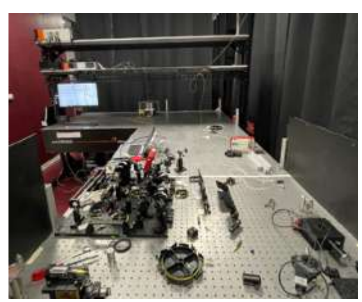
BOSON SAMPLING WITH INTEGRATED PHOTONICS

QUANTUM INTEGRATED OPTICAL SIMULATION

QUANTUM DOT SOURCES



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PHOTONICS OF SPIN–ORBIT OPTICAL PHENOMENA

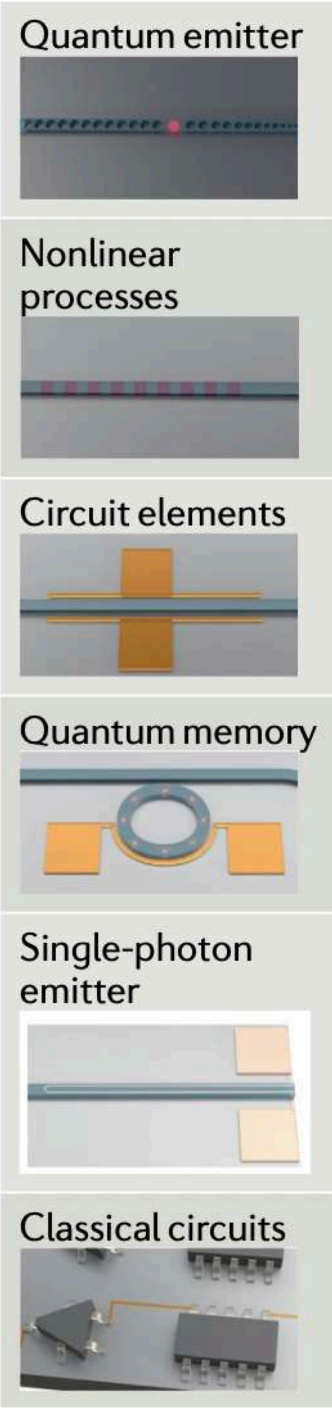
QUANTUM COMMUNICATIONS

MULTIPHASE INTEGRATED INTERFEROMETRY

Roadmap for integrated quantum photonics

Key points

- Photonic quantum technologies have reached a number of important milestones in the last 20 years, culminating with the recent demonstrations of quantum advantage and space-to-ground quantum communication.
- Scalability remains a strong challenge across all platforms, but photonic quantum technologies can benefit from the parallel developments in classical photonic integration.
- More research is required as multiple challenges reside in the intrinsically hybrid nature of integrated photonic platforms, which require a variety of multiple materials, device design and integration strategies.
- The complex innovation cycle for integrated photonic quantum technologies requires investments, the resolution of specific technological challenges, the development of the necessary infrastructure and further structuring towards a mature ecosystem.
- There is an increasing demand for scientists and engineers with substantial knowledge of both quantum mechanics and its technological applications.



“The potential and global outlook of integrated photonics for quantum technologies”

Emanuele Pelucchi, Giorgos Fagas, Igor Aharonovich, Dirk Englund, Eden Figueroa, Qihuang Gong, Hübel Hannes, Jin Liu , Chao-Yang Lu, Nobuyuki Matsuda, Jian-Wei Pan, Florian Schreck, Fabio Sciarrino, Christine Silberhorn, Jianwei Wang and Klaus D. Jöns, *Nature Reviews Physics* **4,** 194-208 (2022)