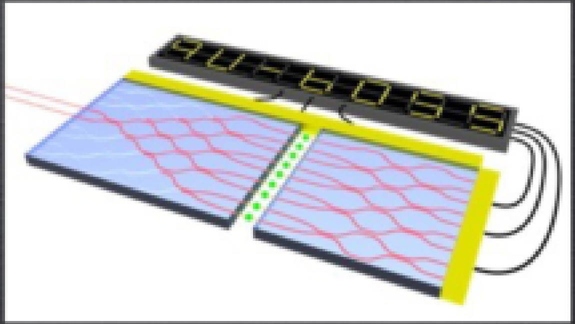
# THE QUEST OF QUANTUM ADVANTAGE WITH A PHOTONICS PLATFORM

FABIO SCIARRINO
SAPIENZA UNIVERSITÀ DI ROMA

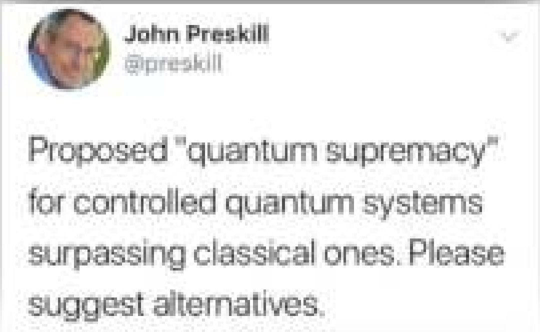


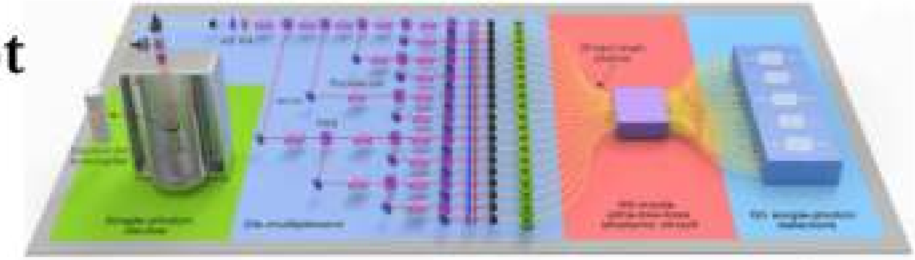
*www.quantumlab.it*

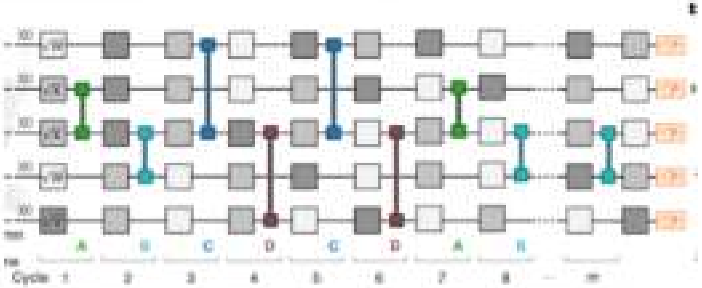
*Twitter: @FabioSciarrino*

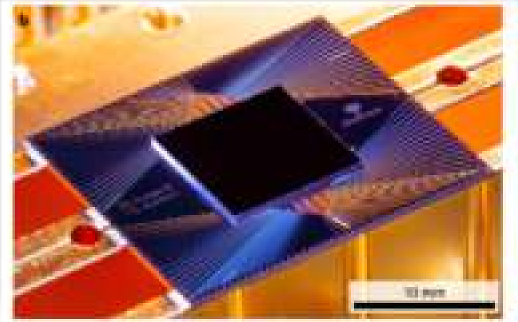
# Outline

## To explore the quantum boundaries from a computational perspective







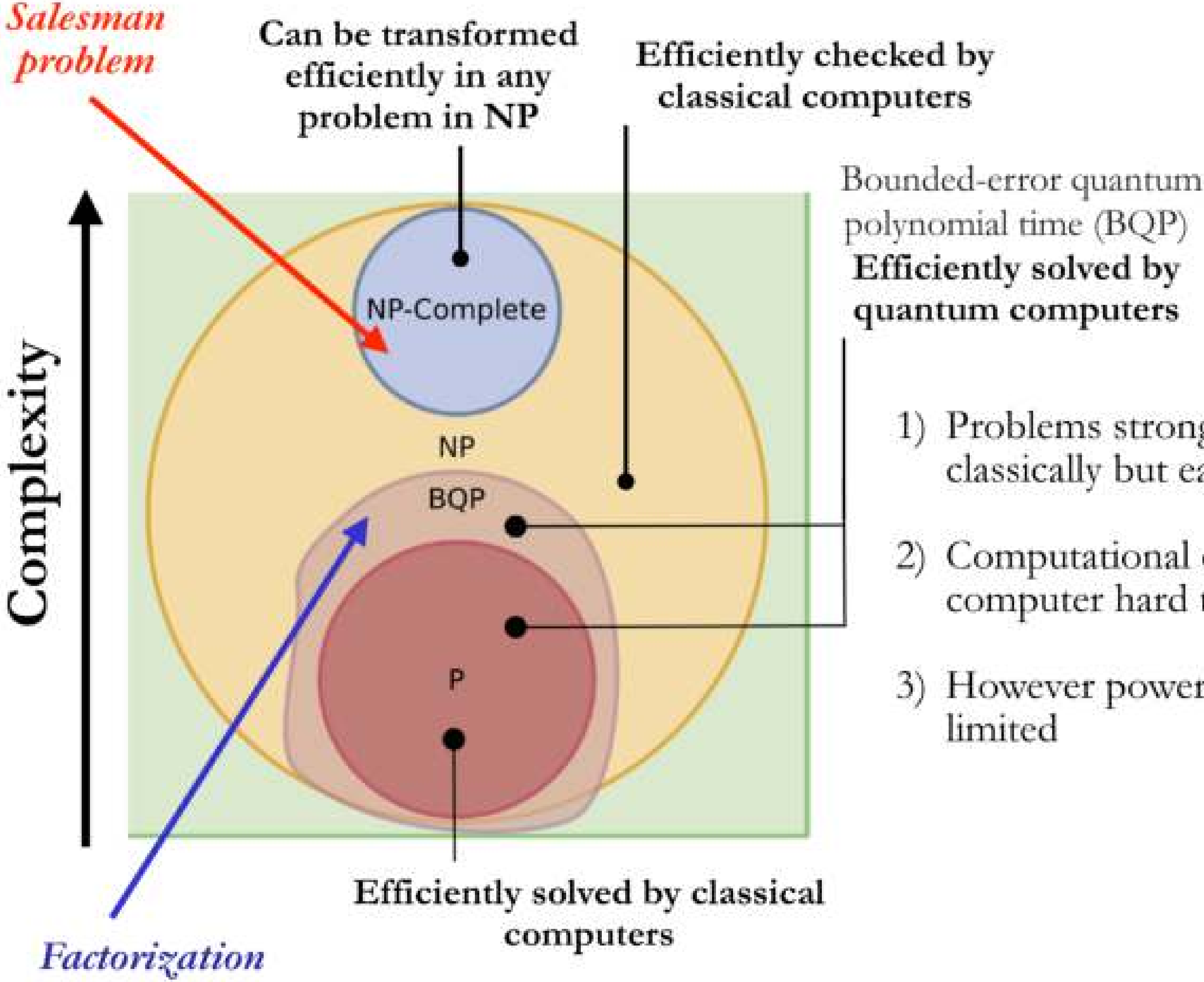
1. Quantum supremacy - the concept
2. Photonics approach:

   Boson Sampling

3. Integrated quantum photonics
4. Implementation of Boson Sampling
5. Perspectives

# Computational complexity classes

## The power of quantum computing




1) Problems strongly believed to be hard classically but easy for quantum computers
2) Computational complexity theory: quantum computer hard to simulate classically
3) However power of quantum computing is limited

# The challenge of quantum computing

1) Qubits must interact strongly with one another in order to elaborate information

2) Qubits should not interact with the environment

3) We must have full control on the interaction between the qubits and full measurement capability

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## How to address noise?

Quantum error correction - several sophisticated schemes

↓

Scalability possibile if errors below some thresholds

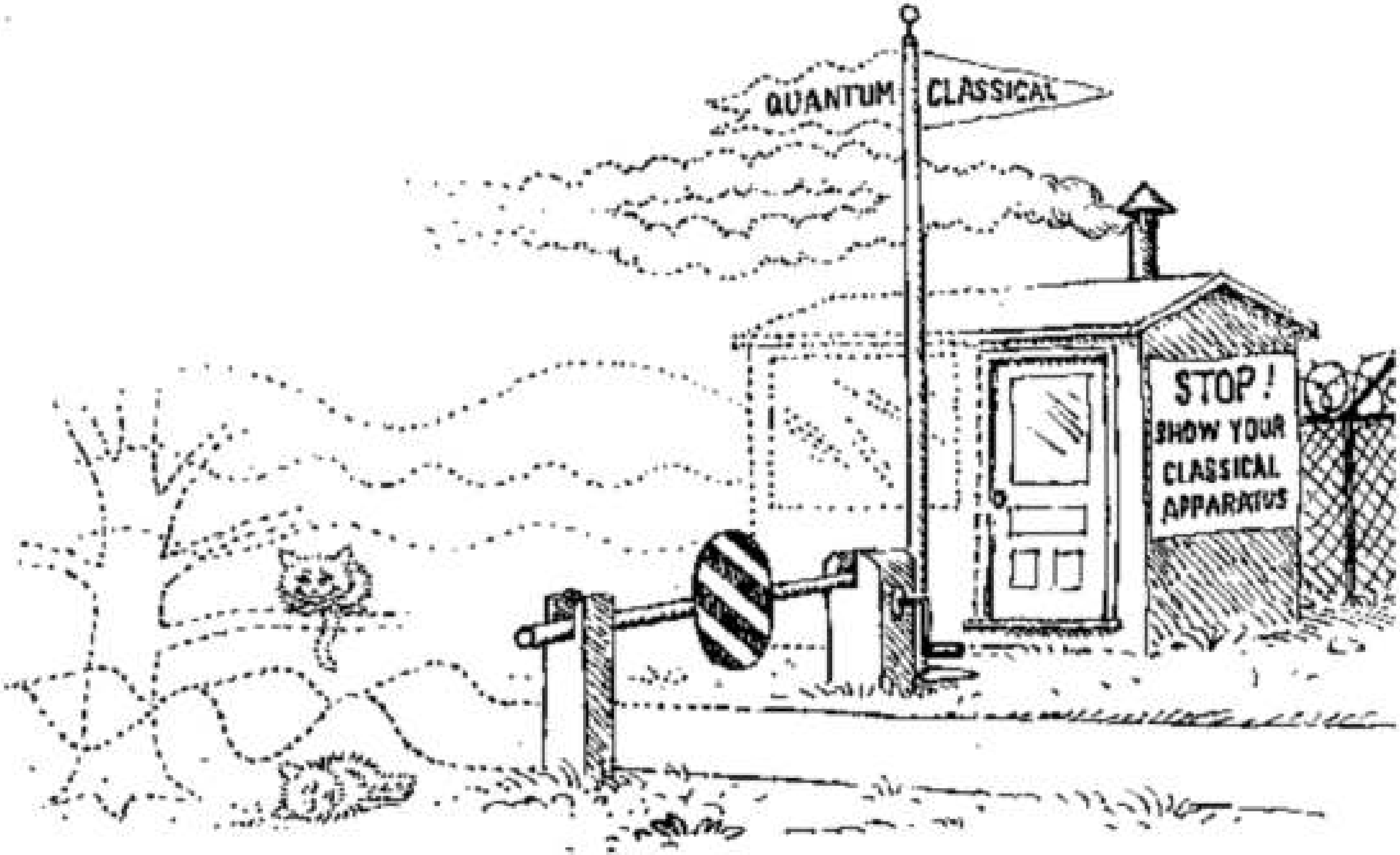
↓

Very large overhead of the number of qubit and number of gates

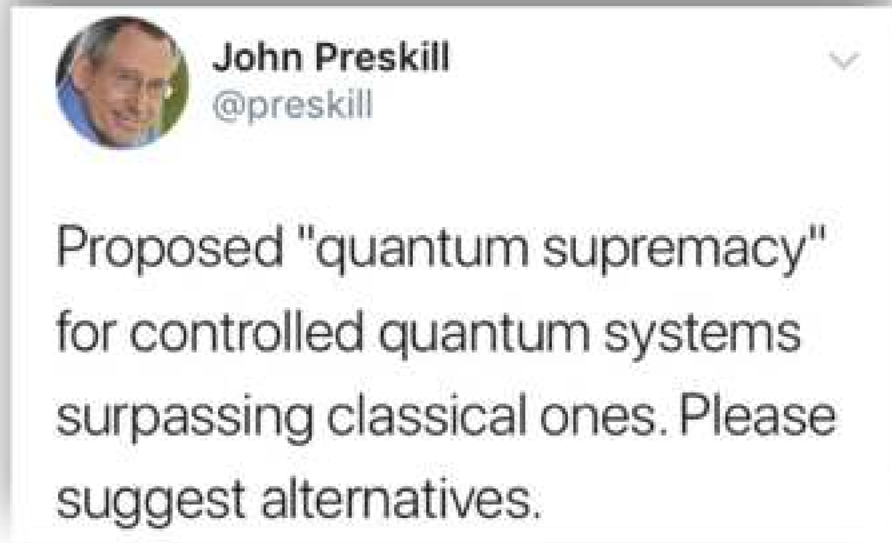
# The challenge

Can a quantum system be engineered to perform a computation in a *large enough computational Hilbert* space and with a *low enough error rate* to provide a **quantum speedup**?

Can we formulate a problem that is *hard for a classical computer* but *easy for a quantum computer*?



# *How to achieve quantum supremacy?*


John Preskill
@preskill

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

# *How to achieve quantum supremacy?*

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@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.

# The Extended Church-Turing Thesis

*Everything feasibly computable in the physical world is feasibly computable by a (probabilistic) Turing machine.*

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## ~~The Extended Church-Turing Thesis~~

*~~Everything feasibly computable in the physical world is feasibly computable by a (probabilistic) Turing machine.~~*

**Not valid anymore**

*Nature Special Issue on "Quantum software"*

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As a goal, quantum supremacy[1] is unlike most algorithmic tasks because it is defined not in terms of a particular problem to be solved but in terms of what classical computers cannot do. This is like the situation in cryptography, where the goal is not only for the authorized parties to perform some task, but to do so in a way that restricts the capabilities of unauthorized parties. Understanding the fundamental limitations of computation is the remit of the theory of computational complexity[2]. A basic goal of this theory is to classify problems (such as integer factorization) into complexity classes (such as the famous classes P and NP), and then to prove rigorously that these classes are unequal. In the cases of both cryptography and quantum supremacy, computational complexity theory is a very long way from being able to prove the conjectured computational limitations unconditionally. Just as we cannot yet prove that $P \neq NP$, we currently cannot unconditionally prove that quantum mechanics cannot be simulated classically. Instead, claims of quantum supremacy will need to rely on assumptions based on complexity theory, which in turn can be justified heuristically.

Segui

...uantum supremacy" for
...antum systems
...assical ones. Please
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# Quantum supremacy: How to device an experimental demonstration?

In order to achieve quantum supremacy/advantage the following key ingredients are necessary:

1) To identify a **computational problem** whose complexity scales exponentially with classical hardware but only polynomially when using quantum devices

2) **Classical benchmarking:** to address this problem with the best classical algorithm so as to find the threshold to be beaten for a claim of quantum advantage

3) **Experimental implementation**: to implement the quantum instance on a system large enough to surpass the classical threshold

4) **Validation**: to develop suitable tools to validate the correctness of the output.

# Is quantum supremacy the right name?

Nature | Vol 576 | 12 December 2019 | 213

Readers respond

## Correspondence

### Groundwater: a call to action

As we embark on the United Nations 'decade of action' (see go.nature.com/2opvyi3), and as this week's UN COP25 Climate Change Conference concludes in Madrid, let's remember the crucial contribution of groundwater to climate resilience and sustainable development.

Besides sustaining drinking water and ecosystems worldwide, groundwater acts as a subsurface sponge for floods. It is a resource against drought and for natural climate solutions that sequester soil carbon. And it is crucial for sustainable development because it enables food security and lifts rural populations out of poverty.

However, these essential benefits are being undermined by the long-term depletion, contamination and salinization of groundwater (see, for example, I. E. M. de Graaf *et al.* *Nature* **574**, 90–94; 2019).

In our view, groundwater needs to be monitored and managed with greater rigour on regional and global scales so that it can be used more effectively to boost climate adaptation and sustainable development. As members of a global group of scientists and practitioners, we have issued a call to action to international and national governmental and non-governmental agencies, development organizations,

### Evaluating Italy's ranking boom

The president and vice-presiden[t] of the Italian National Agency for the Evaluation of Universities and Research Institutes (ANVUR) claim that Italy's rise in international research-impact rankings is a real effect (P. Miccoli and R. I. Rumiati *Nature* **574**, 486; 2019), and not (as we have argued) the result of Italian scholars citing one another's articles more heavily (see *Nature* http://doi.org/dcgj; 2019). We question their evidence for this claim.

First, they say that scientific productivity in Italy has risen in the past decade, possibly stimulated by the introduction of performance-related university funding. More articles are indeed being published, but the yearly growth rate of Italy's scientific production has in fact slowed down since the introduction of performance-related targets in 2012, according to ANVUR's own statistics (see go.nature.com/34ms9n; in Italian).

Second, they state that ANVUR recognizes the importance of correcting gaming behaviours, including self-citation. They point out that, in an evaluation of 2011–14 work, the agency established a criterion for 'downgrading' papers in which self-citation exceeded a given threshold. ANVUR's own reports, however, show that this downgrading was

### We'll take 'quantum advantage'

We take issue with the use of 'supremacy' when referring to quantum computers that can out-calculate even the fastest supercomputers (F. Arute *et al.* *Nature* **574**, 505–510; 2019). We consider it irresponsible to override the historical context of this descriptor, which risks sustaining divisions in race, gender and class. We call for the community to use 'quantum advantage' instead.

The community claims that quantum supremacy is a technical term with a specified meaning. However, any technical justification for this descriptor could get swamped as it enters the public arena after the intense media coverage of the past few months.

In our view, 'supremacy' has overtones of violence, neocolonialism and racism through its association with 'white supremacy'. Inherently violent language has crept into other branches of science as well — in human and robotic spaceflight, for example, terms such as 'conquest', 'colonization' and 'settlement' evoke the *terra nullius* arguments of settler colonialism and must be contextualized against ongoing issues of neocolonialism.

Instead, quantum computing should be an open arena and an inspiration for a new generation of scientists.

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## Quantum Dominance, Hegemony, and Superiority

December 19th, 2019

Yay! I'm now a Fellow of the ACM. Along with my fellow new inductee Peter Shor, who I hear is a real up-and-comer in the quantum computing field. I will seek to use this awesome responsibility to steer the ACM along the path of good rather than evil.

https://www.scottaaronson.com/blog/

**WSJ | OPINION**

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OPINION | REVIEW & OUTLOOK

# *Achieving Quantum Wokeness*

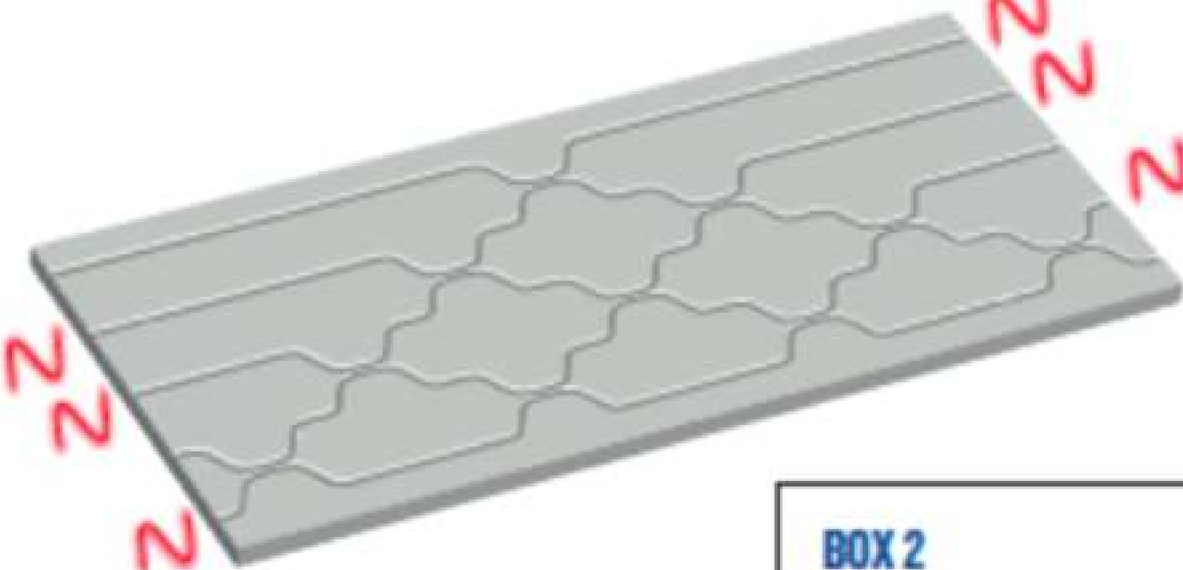
Political correctness barges into a computer science breakthrough

**Anima Anandkumar (hiring at #NeurIPS2019)** @An... · 27 dic 2019

Read my latest blog post detailing recent events around naming of #quantumsupremacy and parallels it shares with #neurips name change. Also cluelessness of privileged men like @sapinker and Aaronson

**BOX 1**

# Boson sampling



**Box 1 Figure | Diagram of a boson sampling e**
(red waveforms) are injected on the left-hand si
beamsplitters (shown black) that is set up to ge
transformation. Photons are detected on the ri
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

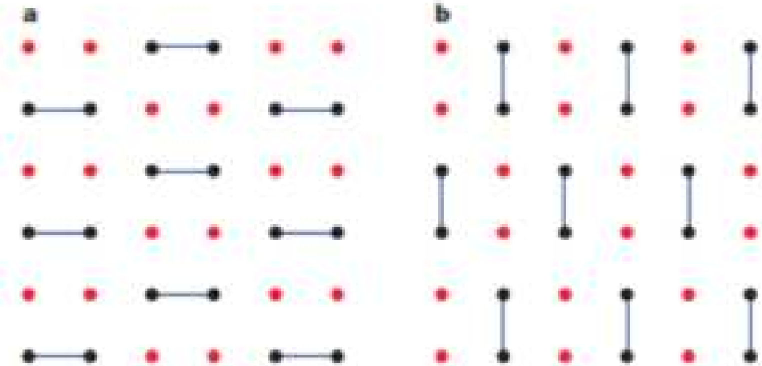
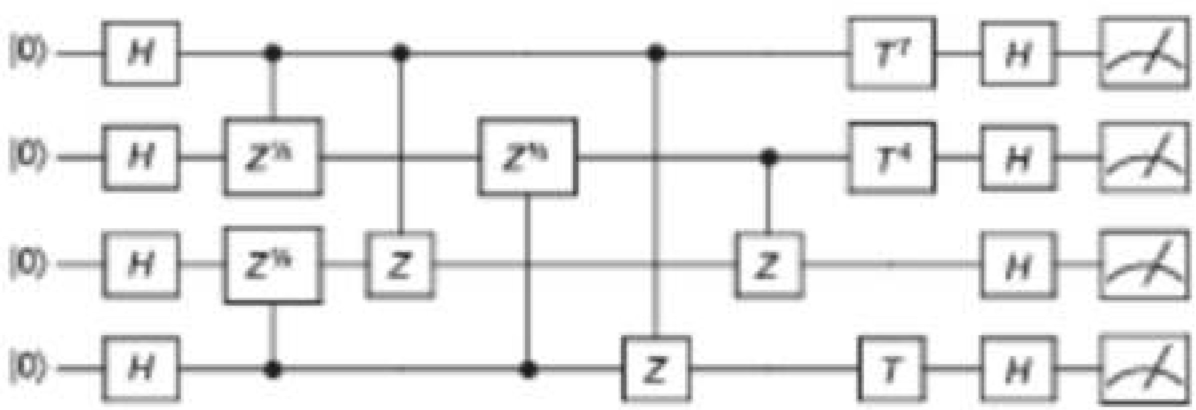



**Figure 1 | A 2D lattice of superconducting qubits proposed as a way to demonstrate quantum supremacy.** Panels **a** and **b** depict the condition of the lattice at two illustrative timesteps. At each timestep, two-qubit gates (blue) are applied across some pairs of neighbouring qubits, and random 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.

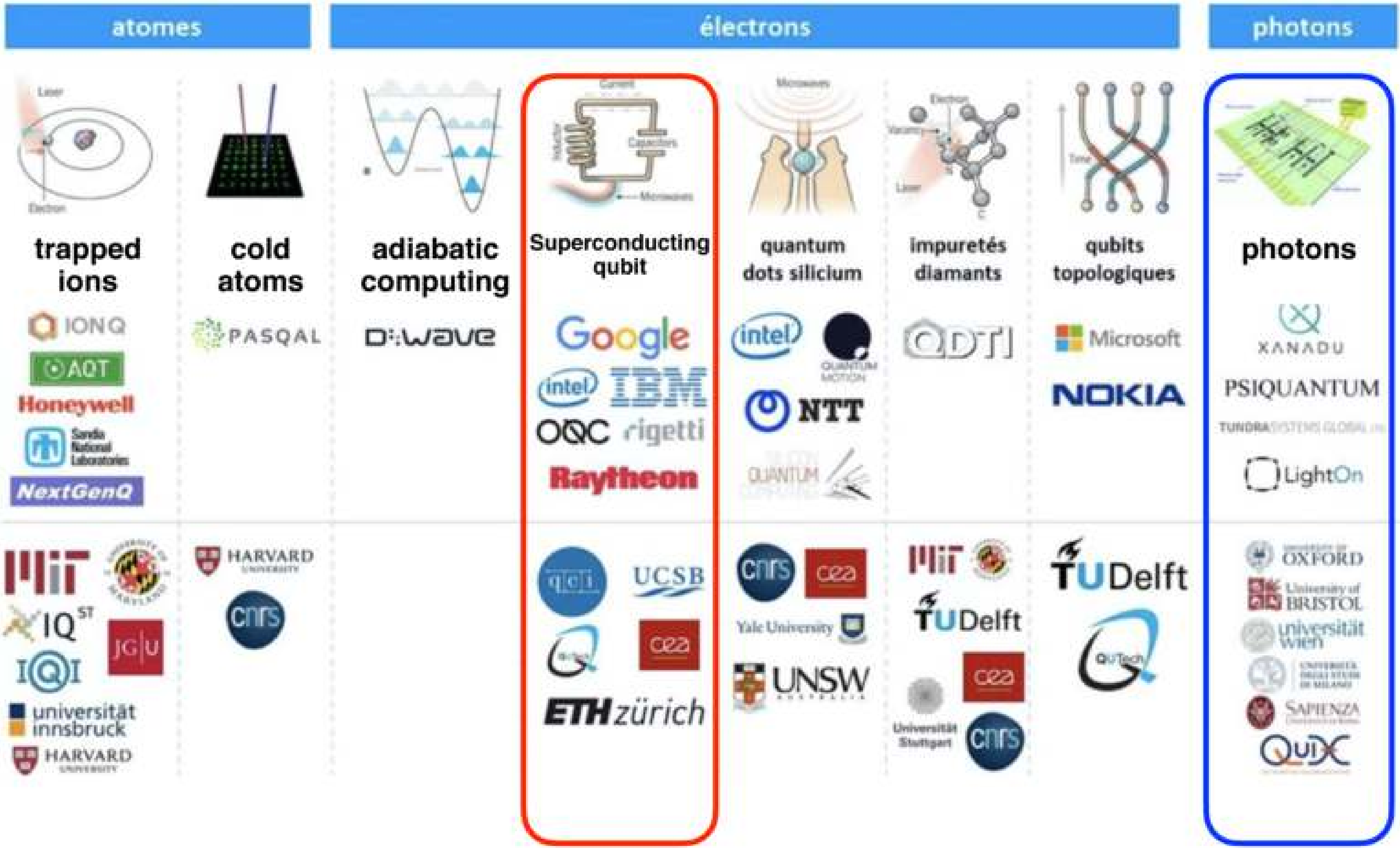
**BOX 2**

# Random quantum circuits



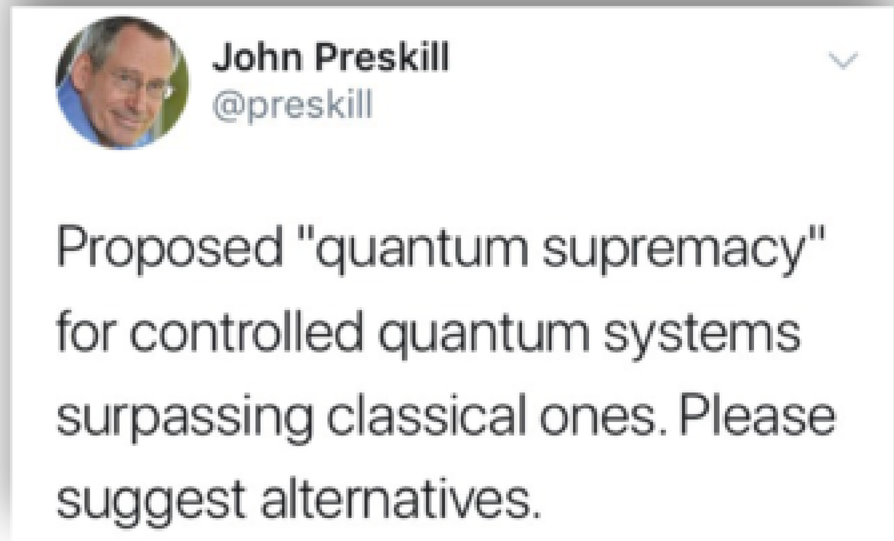

**Box 2 Figure | Example of an IQP circuit.** Between two columns of Hadamard gates (*H*) is a collection of diagonal gates (*T* and controlled-$\sqrt{Z}$). Although these diagonal gates may act on the same qubit many times

# Current platforms and worldwide effort



# *How to achieve quantum supremacy?*

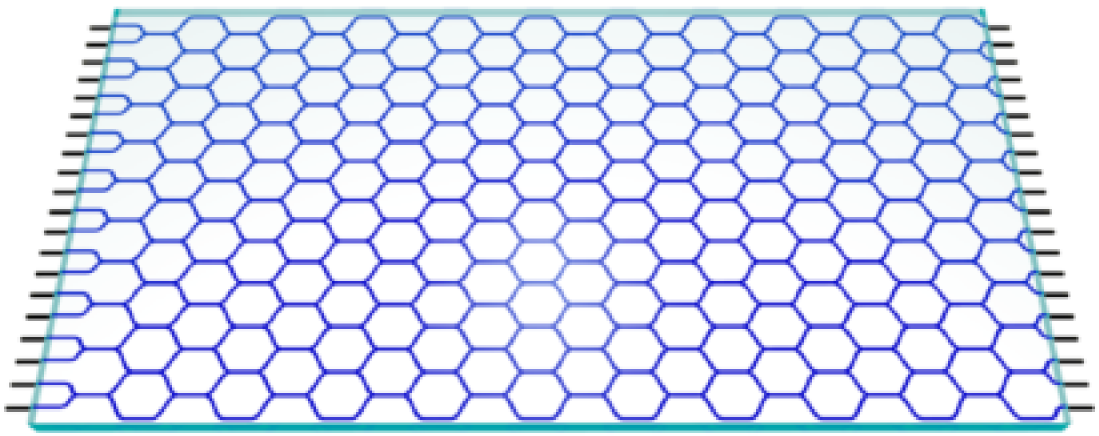
*(Quantum advantage)*




## 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)

# Boson Sampling

Sampling the output distribution (*even approximately*) of non-interacting bosons evolving through a linear network is hard to do with classical resources


Why? Transition amplitudes are related to the <u>permanent</u> of square matrices

$$\langle T|U_F|S\rangle = \frac{\mathrm{Per}(U_{S,T})}{\sqrt{s_1!\dots s_m! t_1!\dots t_m!}}$$

$$\mathrm{Per}(A) = \sum_{\sigma\in S_n}\prod_{i=1}^{n} a_{i,\sigma_i}$$

<u>classicaly hard</u>

input

$$\text{output}\quad \begin{array}{c c} & \begin{array}{ccccc} 0 & 1 & 1 & 0 & 1 \end{array} \\ \begin{array}{c} 0 \\ 1 \\ 1 \\ 1 \\ 0 \end{array} & \begin{pmatrix} 0.212 & -0.018+0.165i & -0.238-0.18i & -0.429+0.32i & -0.715+0.2i \\ -0.193-0.388i & -0.045-0.379i & 0.19+0.311i & 0.328-0.269i & -0.594+0.03i \\ -0.723+0.363i & 0.087-0.09i & -0.076-0.155i & 0.206+0.443i & -0.153-0.193i \\ -0.092+0.045i & -0.148-0.645i & -0.588+0.184i & -0.369-0.086i & 0.167+0.025i \\ 0.318-0.009i & -0.144-0.594i & 0.452-0.405i & 0.037+0.387i & 0.071+0.025i \end{pmatrix} \end{array}$$

S. Aaronson and A. Arkhipov, Proceedings of the 43rd Annual ACM Symposium on Theory of Computing, 333–342

# Boson Sampling

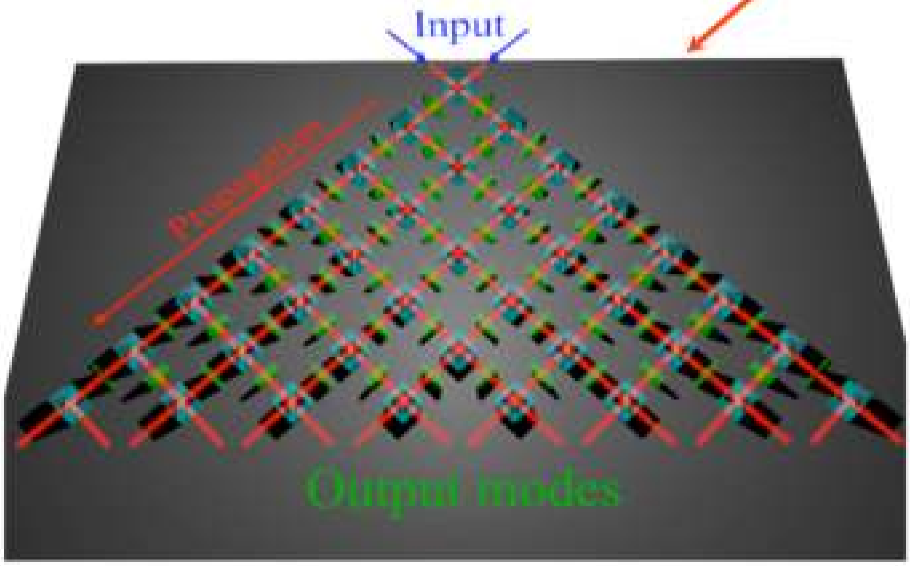
Photons naturally solve the BosonSampling problem

Experimental platform: photons in linear optical interferometers

Required resources:

- Single-photon inputs
- Multimode interferometers
- Detection

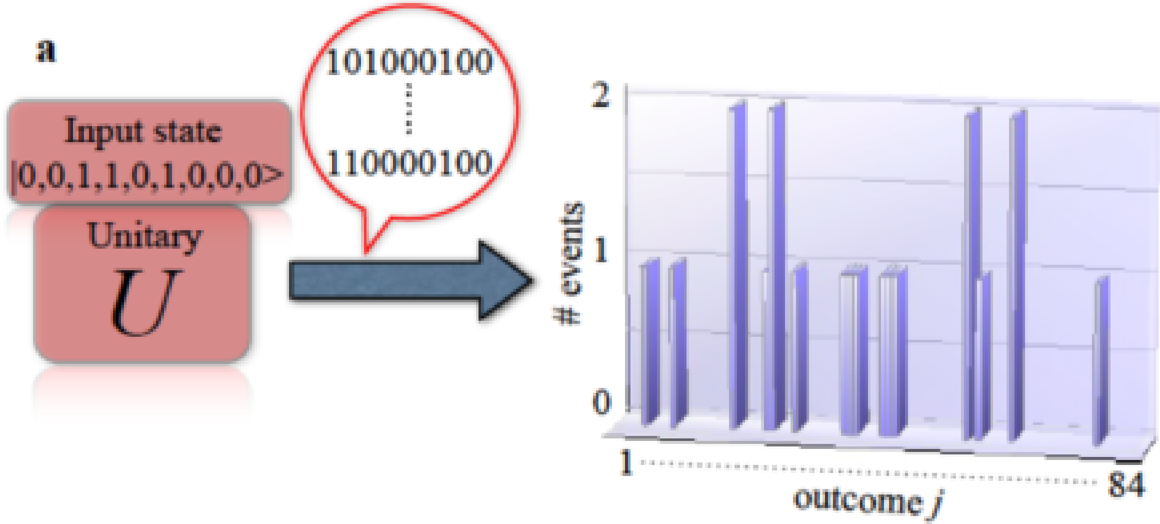
n photons
m modes

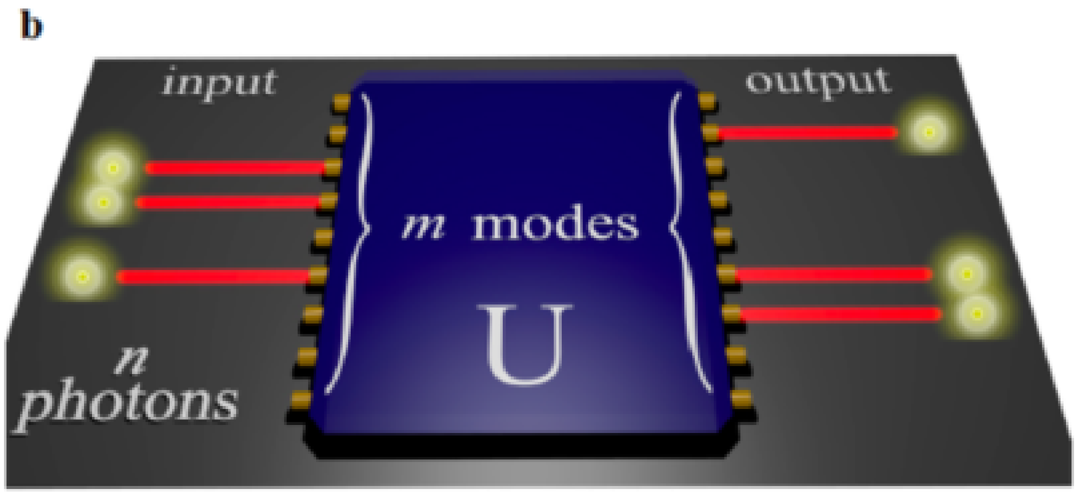



Hard to implements with bulk optics

Require a technological step recently available due to integrated photonics

# Boson Sampling



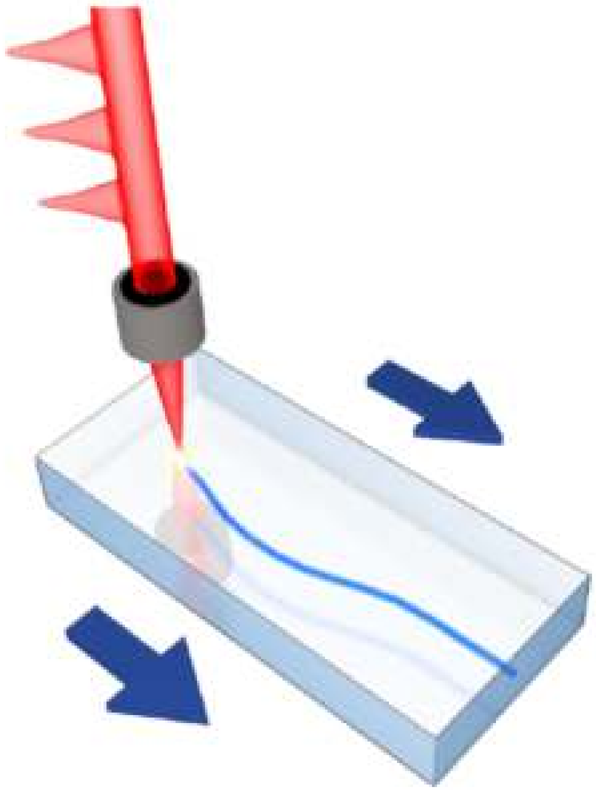




« Small-scale quantum computers made from an array of interconnected waveguides on a glass chip can now perform a task that is considered hard to undertake on a large scale by classical means. »

T. Ralph, News & Views, *Nature Photonics* **7**, 514 (2013)

# Integrated photonics: Femtosecond laser writing

## Laser writing technique for devices able to transmit polarization qubits

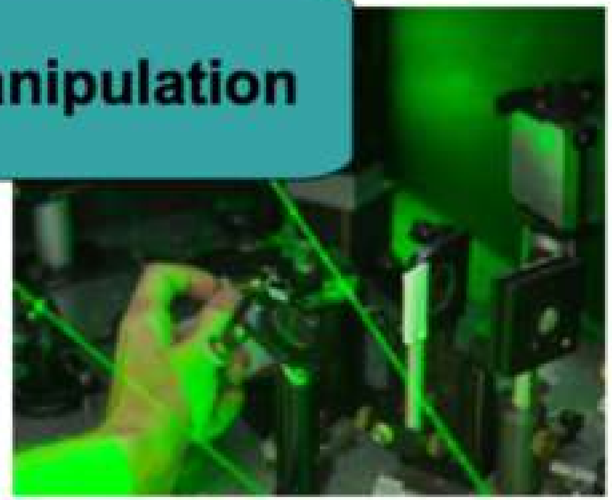


- Femtosecond pulse tightly focused in a glass
- Combination of multiphoton absorption and avalanche ionization induces *permanent and localized refractive index increase* in transparent materials
- Waveguides are fabricated in the bulk of the substrate by translation of the sample at constant velocity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

# Integrated quantum photonics

**Preparation**

**Manipulation**



**Detection**

# Integrated quantum photonics

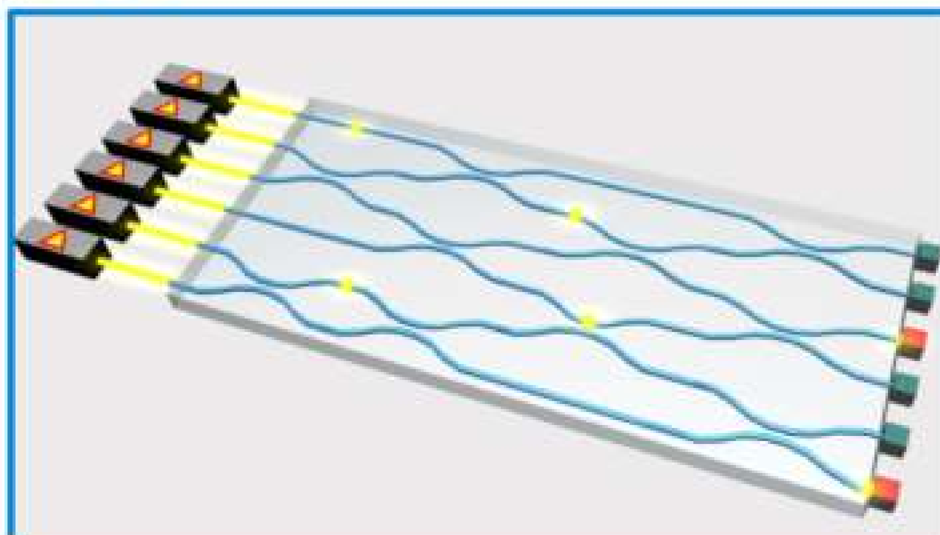
**Preparation**

**Manipulation**

**Detection**

- Single photon sources
- Manipulation
- Single photon detectors

ON THE SAME CHIP

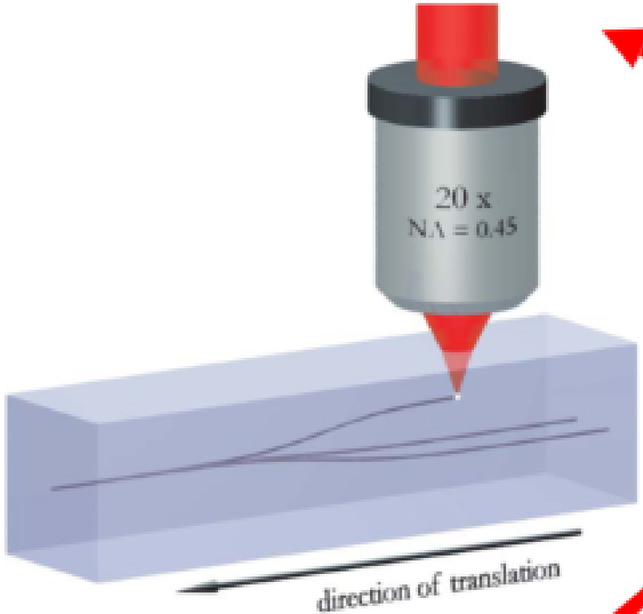


# Femtosecond laser writing

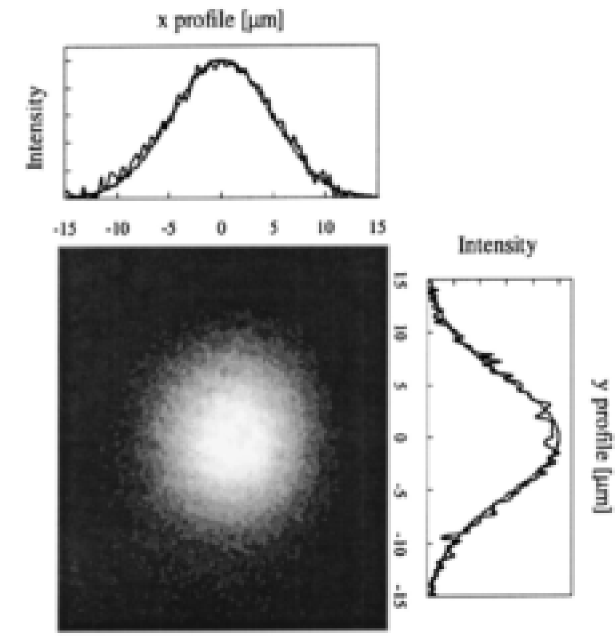
3-dimensional capabilities

Rapid device prototyping: writing speed =4 cm/s

Propagation of circular gaussian modes

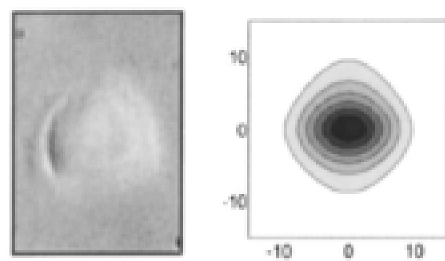



**Characteristics:**




Low birefringence

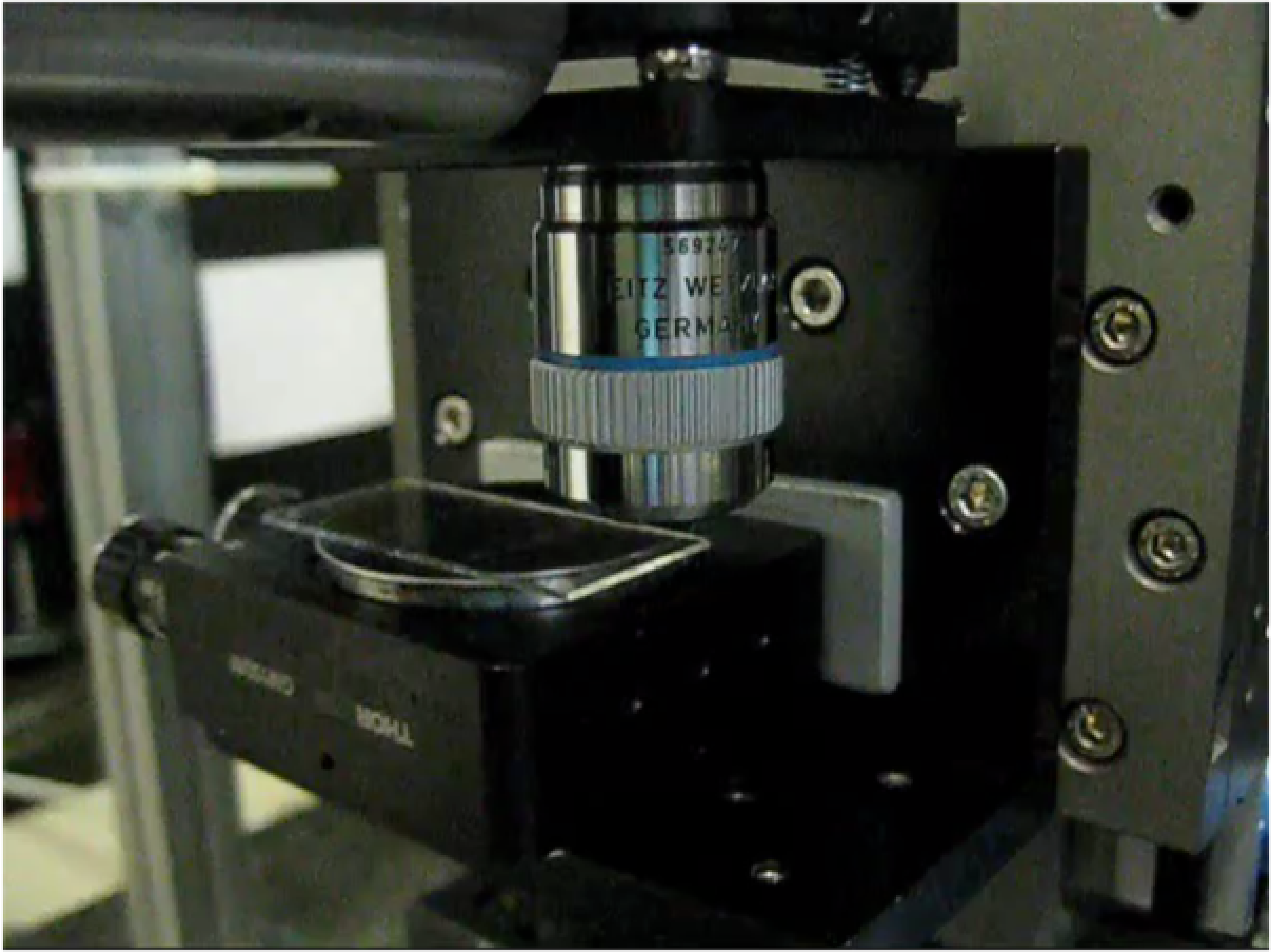
Circular waveguide transverse profile





R. R. Gattass and E. Mazur, *Nat. Photon.* **2**, 219 (2008)
G. Della Valle, R. Osellame, and P. Laporta, *J. Opt. A* **11**, 013001 (2009)

# Femtosecond laser writing



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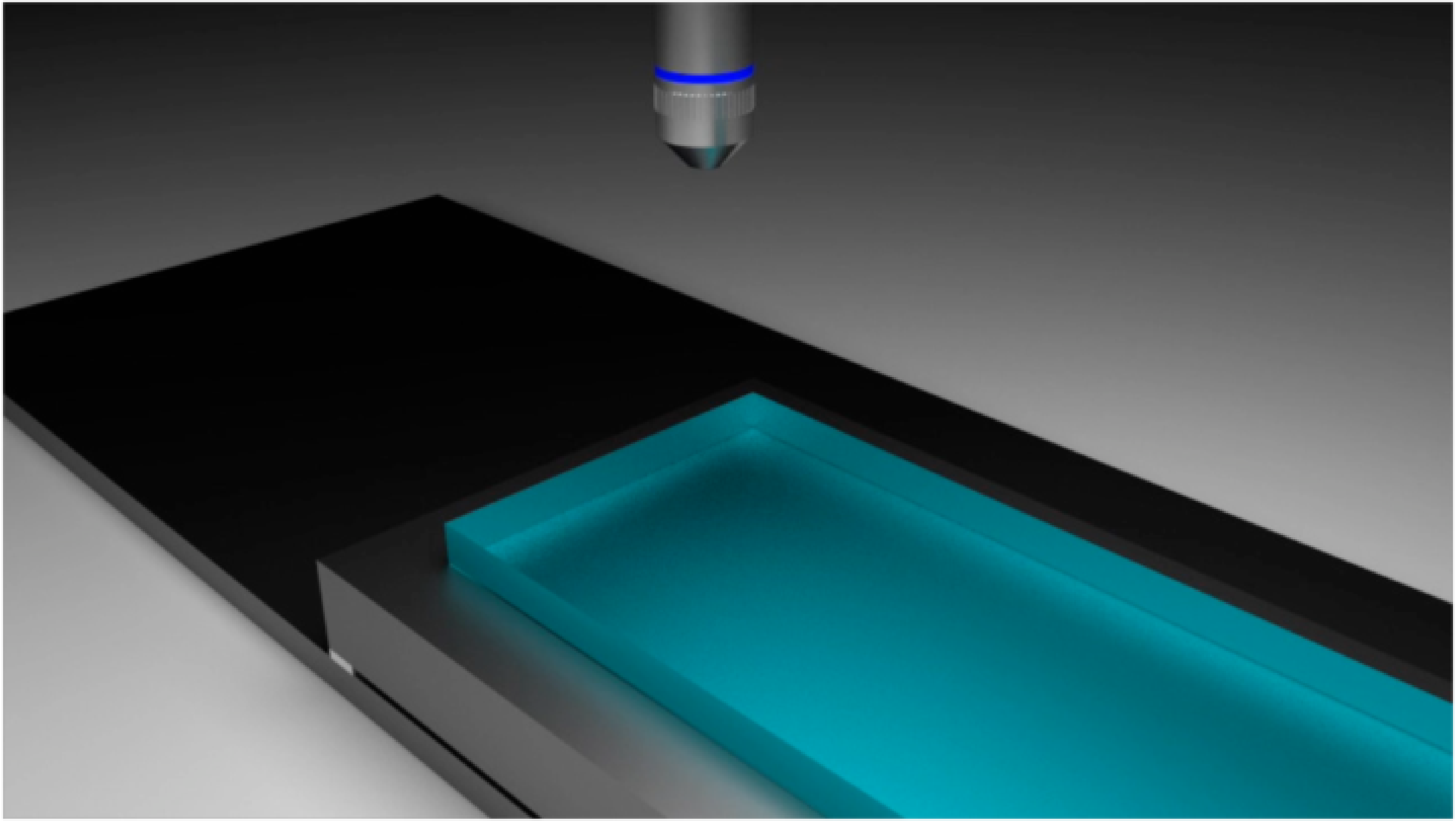
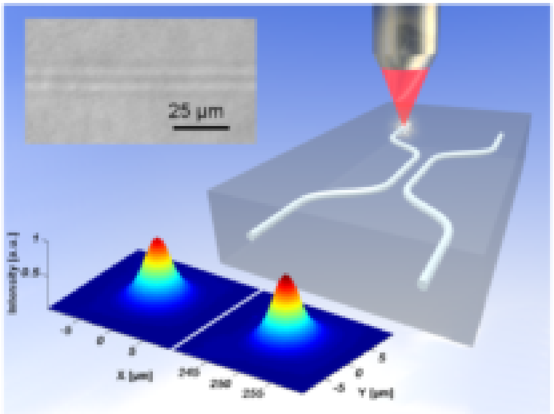
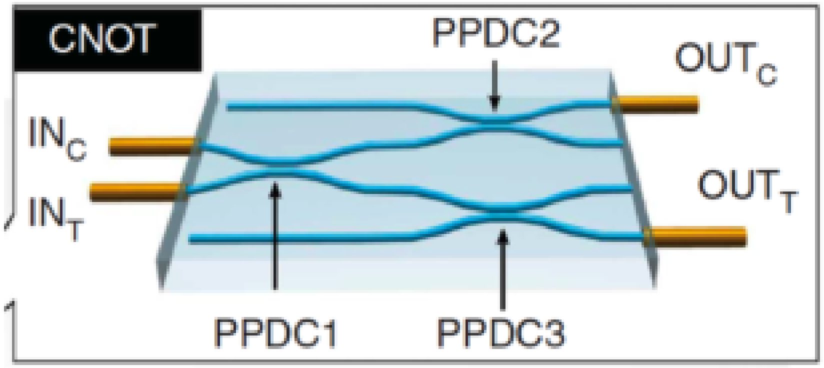


# Quantum logical gates



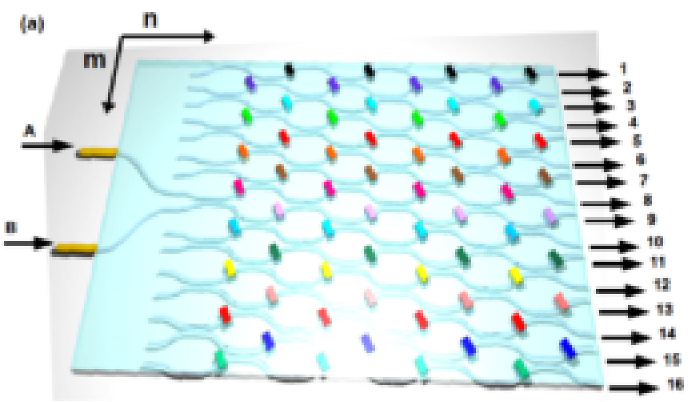

**Directional coupler**

L. Sansoni et al., *Phys. Rev. Lett.* (2010)



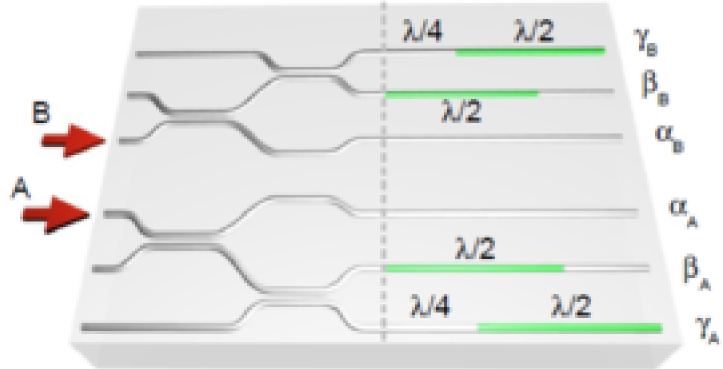

**Partially polarizing and logical gate**

L. Corrielli et al., *Nat. Comm.* **5**, 2549 (2014);




**Quantum walk**
**Anderson Localization**

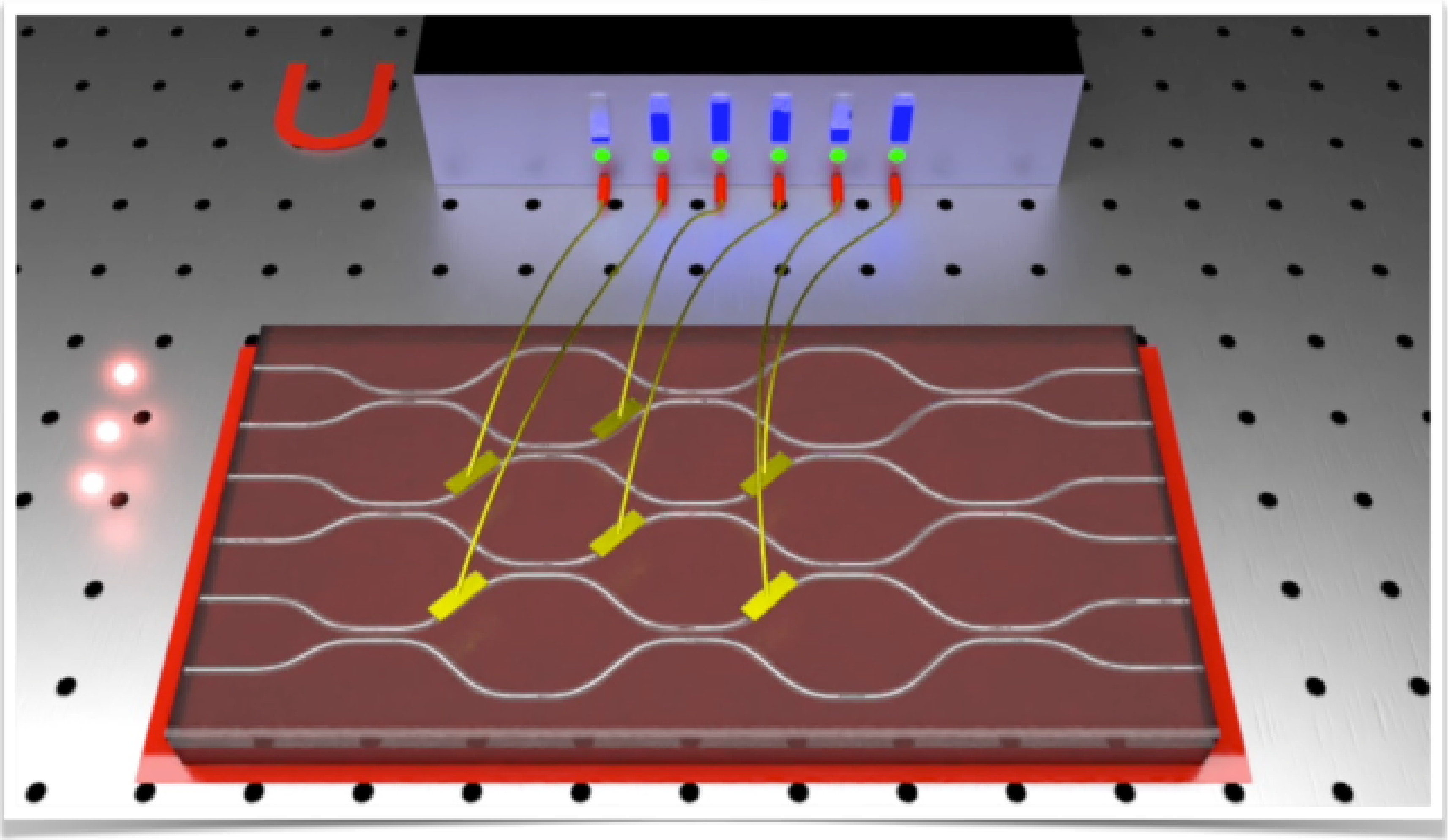
L. Sansoni et al., *Phys. Rev. Lett.* **108**, 010502 (2012);
A. Crespi et al., *Nat. Photon.* **7**, 322-328 (2013)



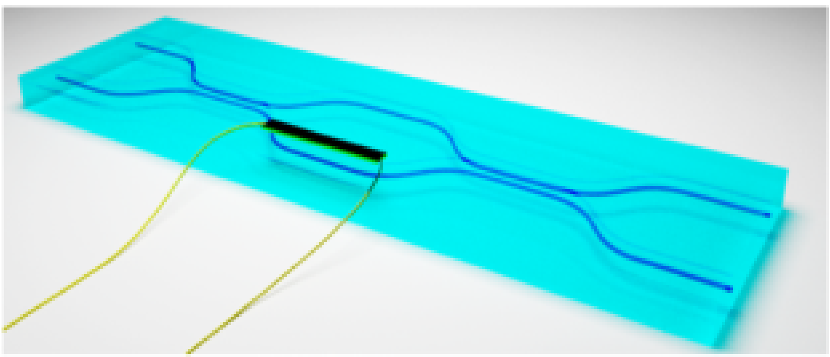

**Tunable waveplate**

A. Crespi et al., *Nat. Comm.* **2**, 566 (2011)

# Reconfigurability of photonics chip

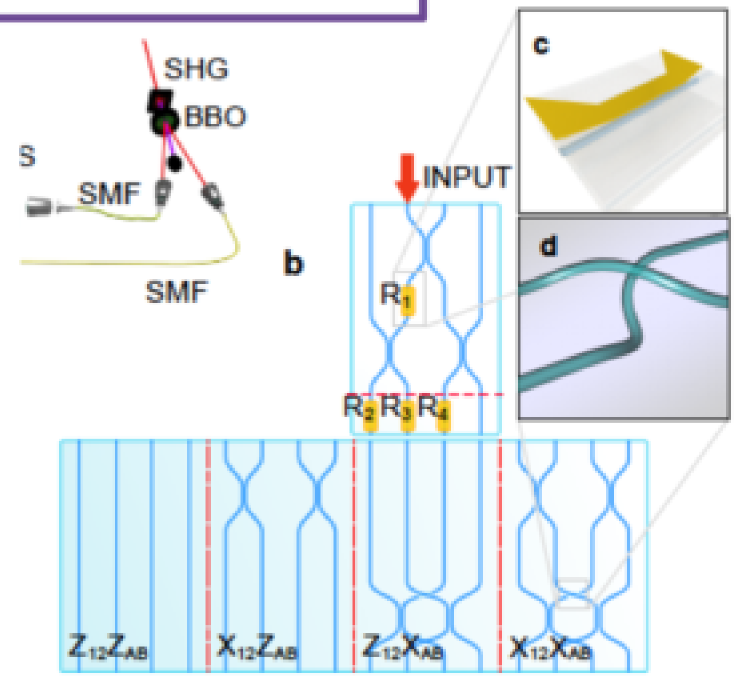


# Reconfigurable devices



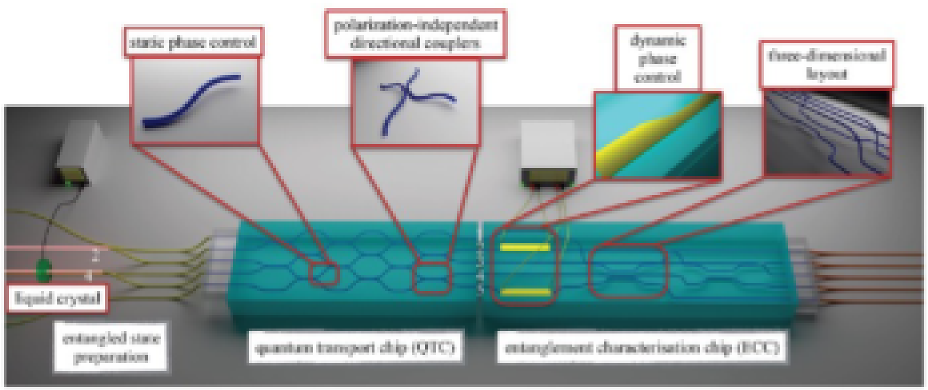
**Reconfigurable interferometer**

F. Flamini, et al. *Light: Science & Applications* 4, e354 (2015)



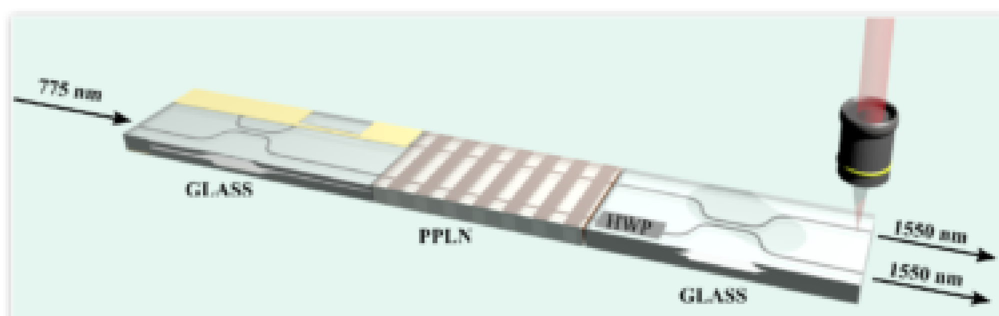

**On chip quantum contextuality**

A. Crespi et al., *ACS photonics* **4**, 2807 (2017)




**Programmable simulator**

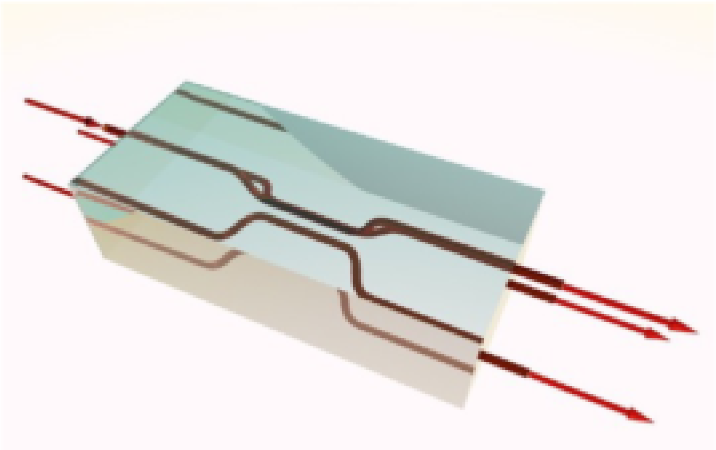
I. Pitsios, et al., *Nat. Comm.* **8**, 1569 (2017)

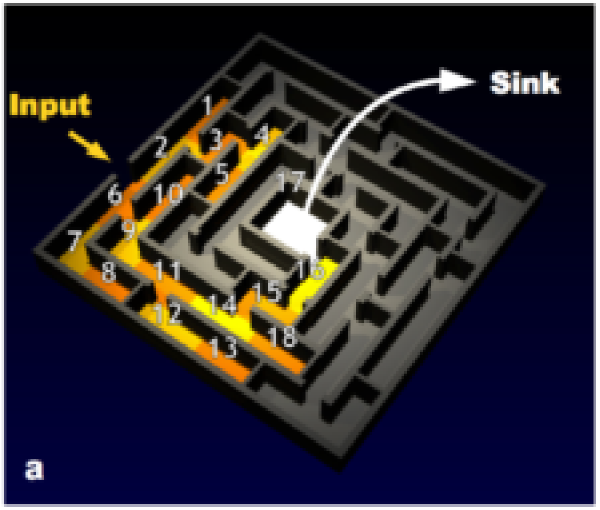



**Integrated source of entangled pairs**

A. Atzeni et al., *Optica* **5**, 311(2018)

# 3D-devices



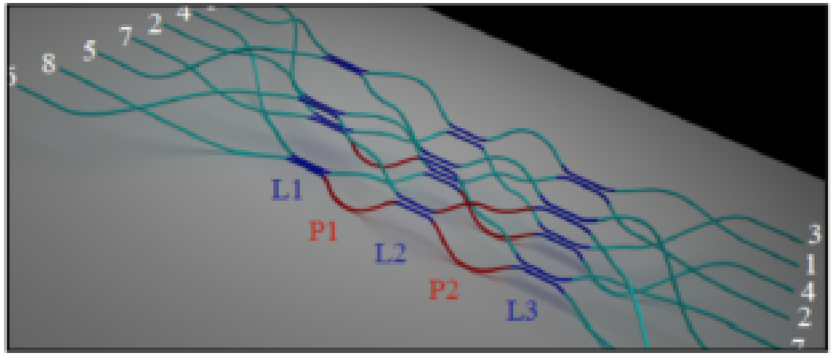



**Integrated tritter**

N. Spagnolo, et al., *Nat. Comm.* **4**, 1606 (2013);

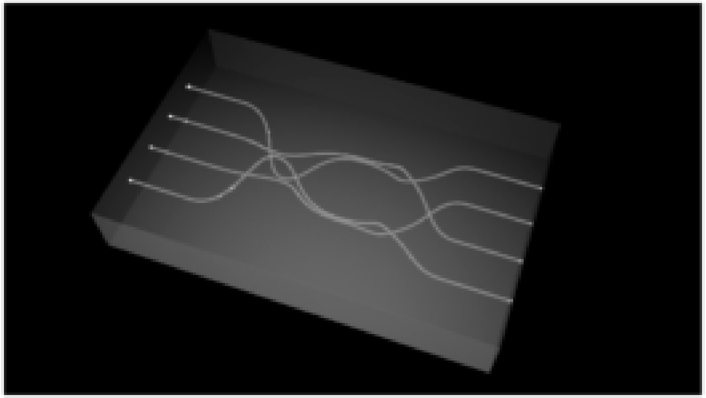
**On chip quantum maze**

F. Caruso et al., *Nat. Comm.* **7**, 11682 (2016)




**Fast Fourier transform**

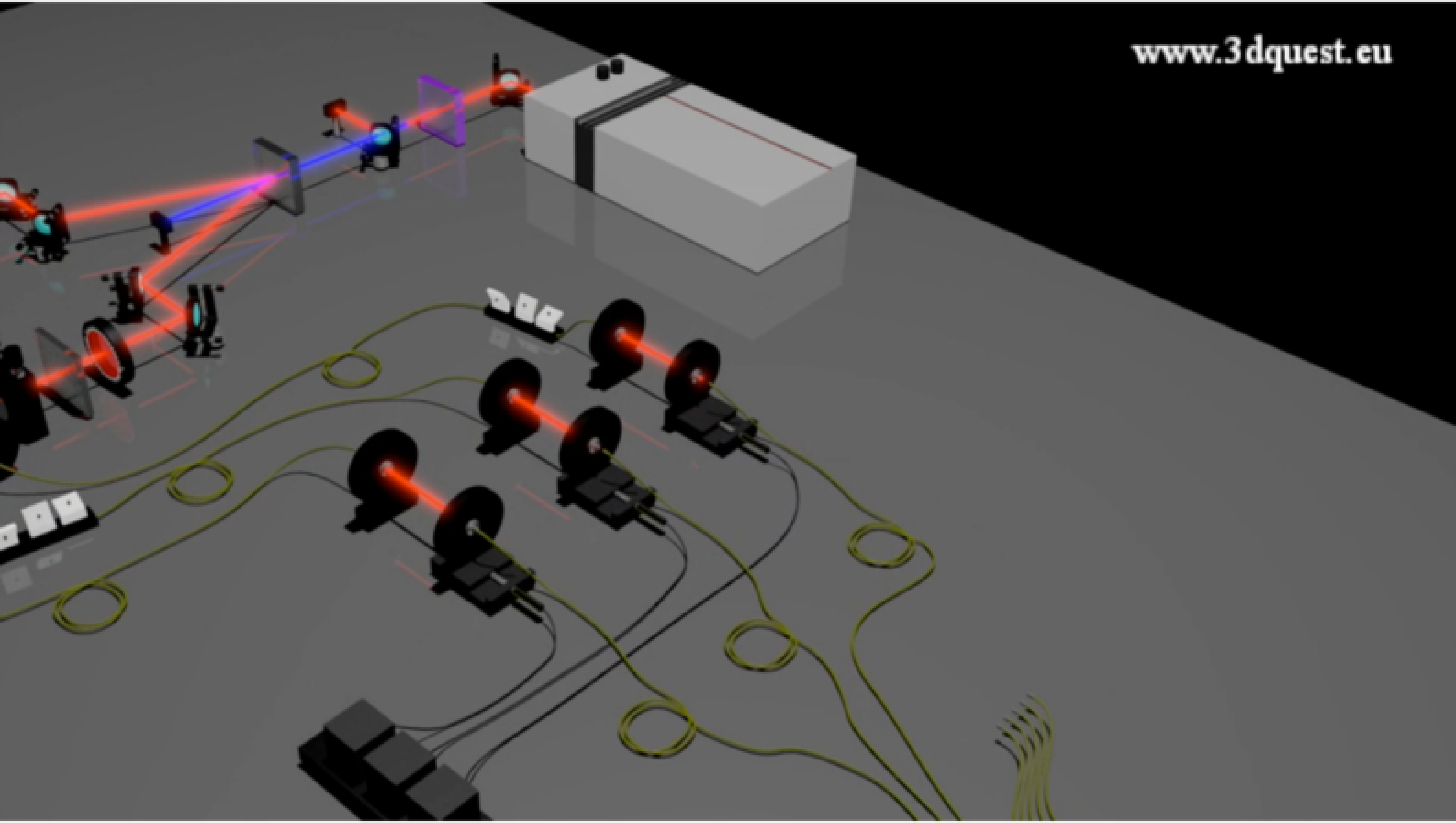
A. Crespi, et al., *Nat. Comm.* **7**, 10469 (2016)



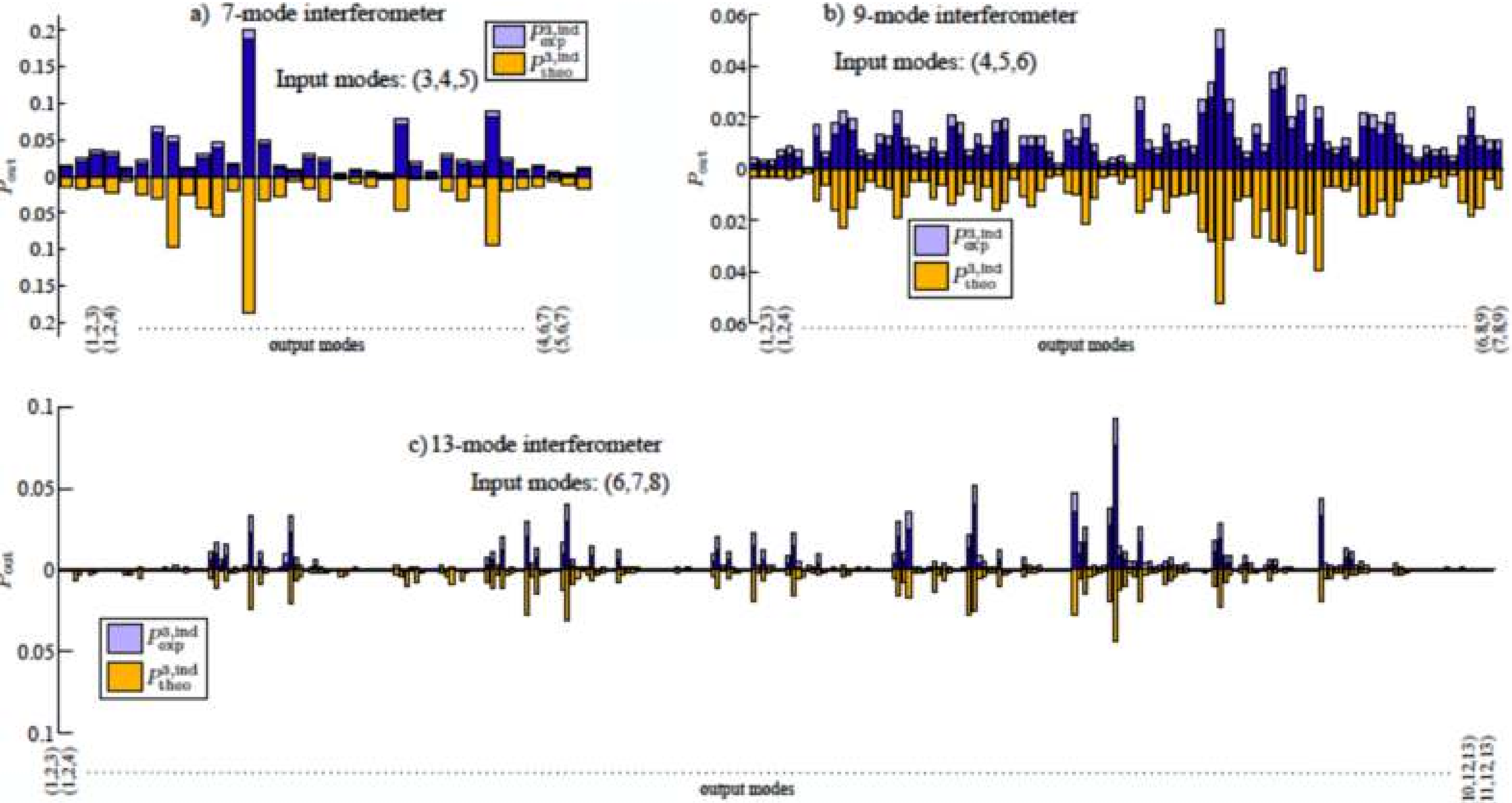
**Sylvester interferometers**

N. Viggianiello et al., *New Journal Physics* (2018)

# Boson sampling experiment

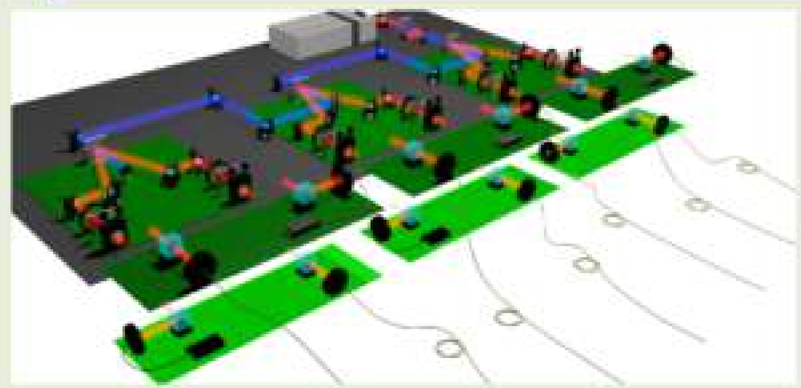


# Experimental results with different chips

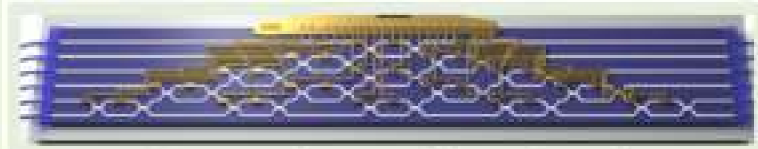



N. Spagnolo, et al., *Nature Photonics* **8**, 614 (2014)

# State-of-art on Boson Sampling



Scattershot
Boson Sampling



Reconfigurable circuits

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

2013

2014

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

2015

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

2016

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

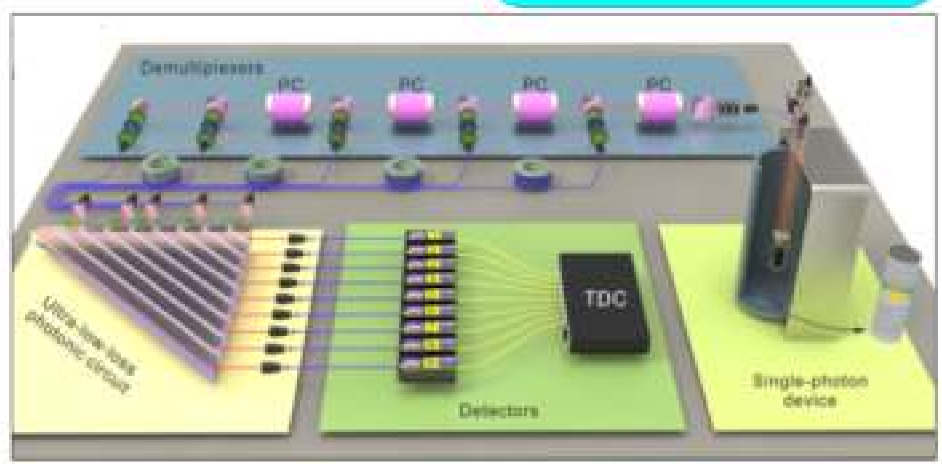
2017

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

2018

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

Bright-source
Boson Sampling
based on Quantum Dot




Boson Sampling: the concept
Aaronson & Arkhipov (2011)

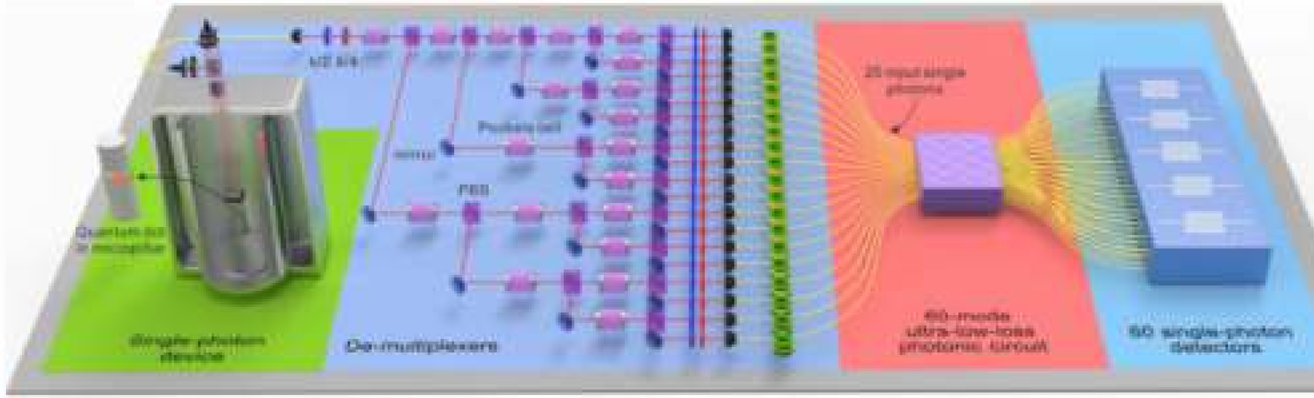
# Last contribution from China..

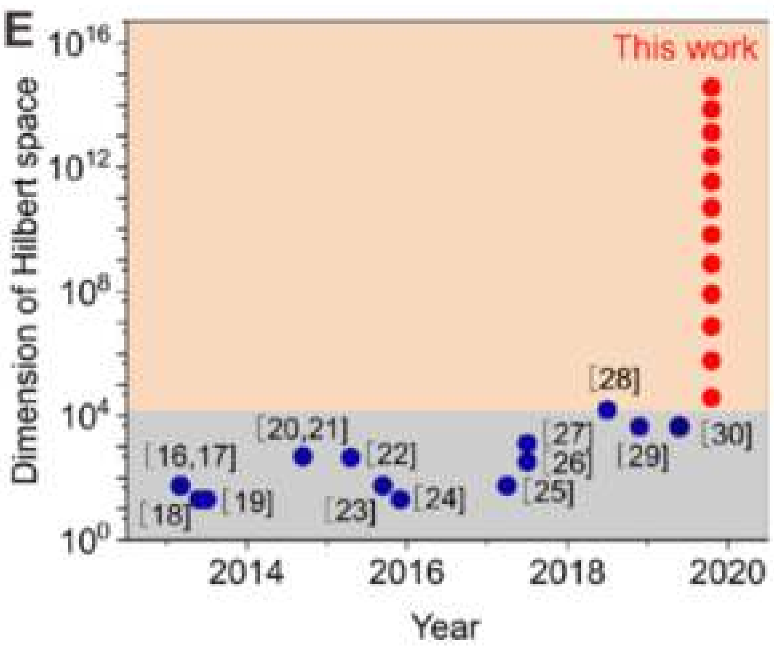
PHYSICAL REVIEW LETTERS **123**, 250503 (2019)

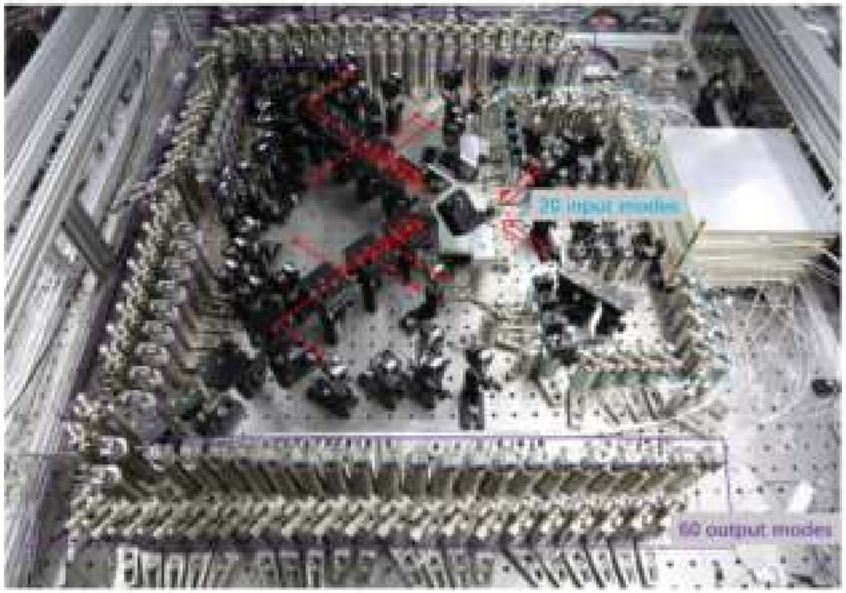
Editors' Suggestion | Featured in Physics

**Boson Sampling with 20 Input Photons and a 60-Mode Interferometer in a $10^{14}$-Dimensional Hilbert Space**

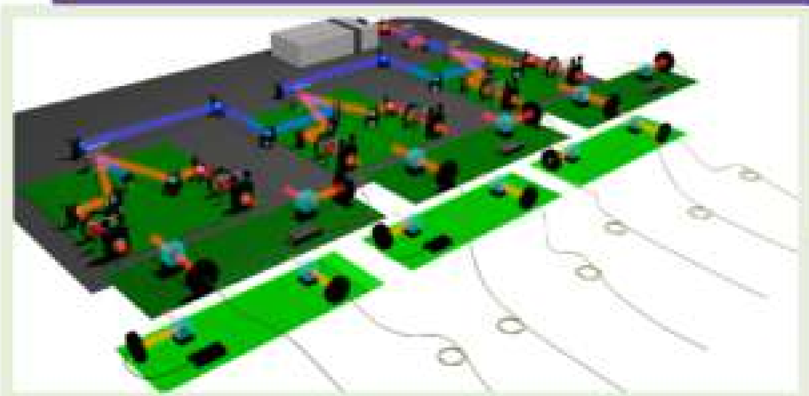
Pan's group in Hefei/Shangai

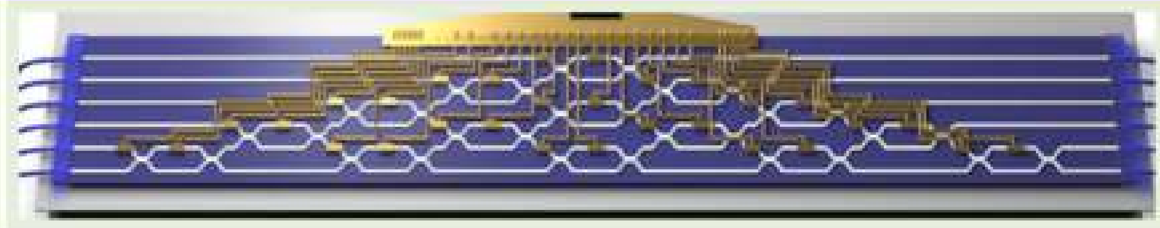


# A global perspective on Boson Sampling

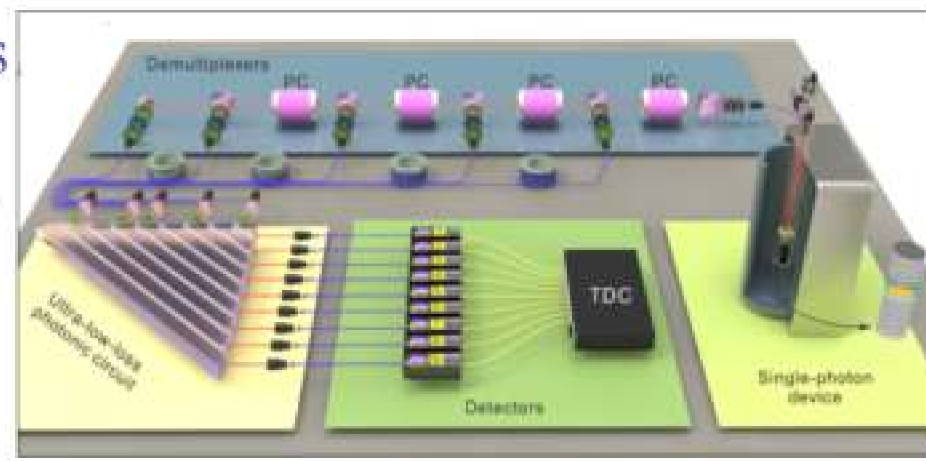




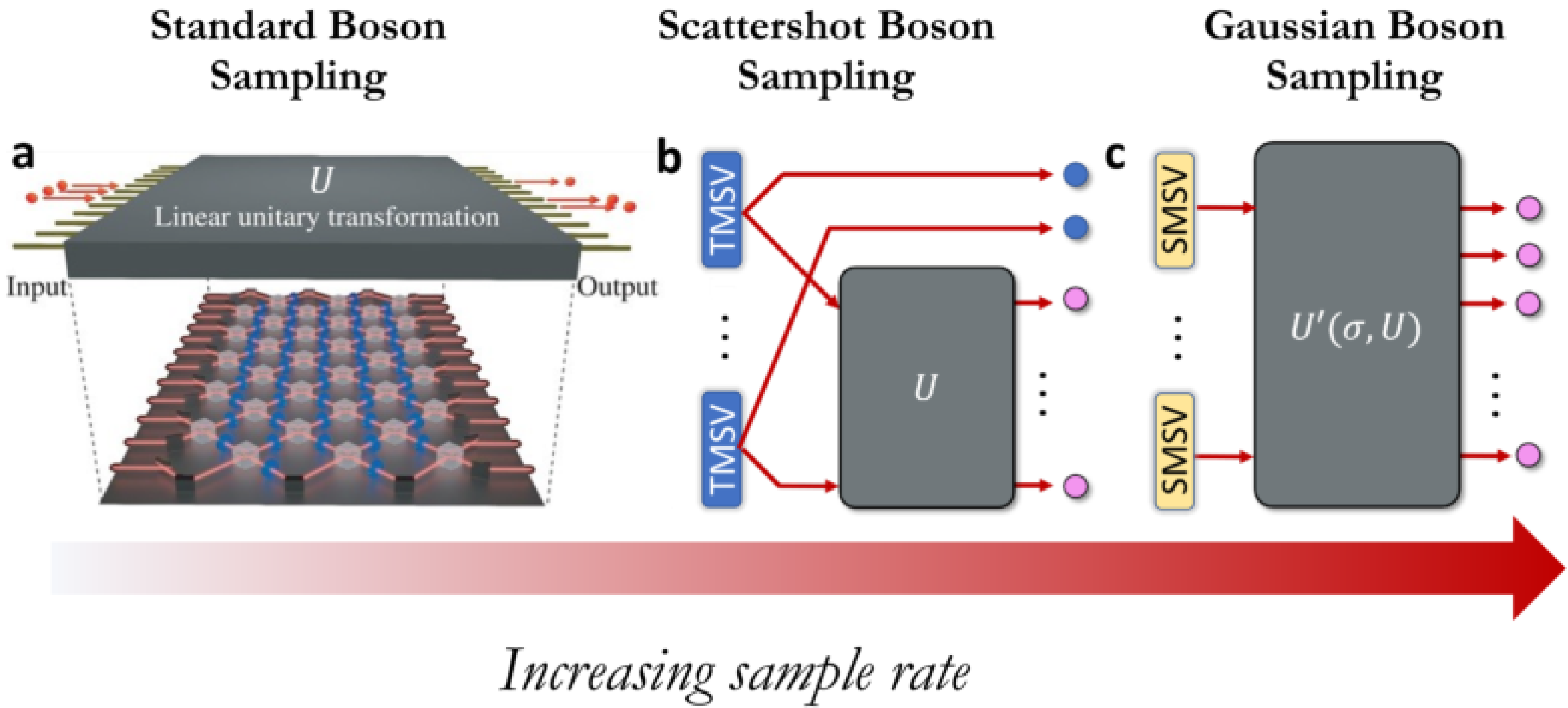
**TARGETS:**
**More photons**
**More optical modes**
**Alternative schemes**

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

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



# Variants of Boson Sampling



[Submitted on 3 Dec 2020]

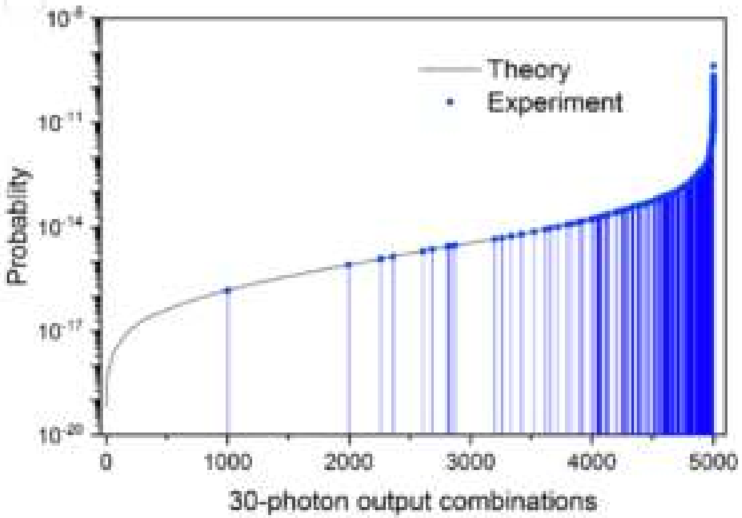
## Quantum computational advantage using photons

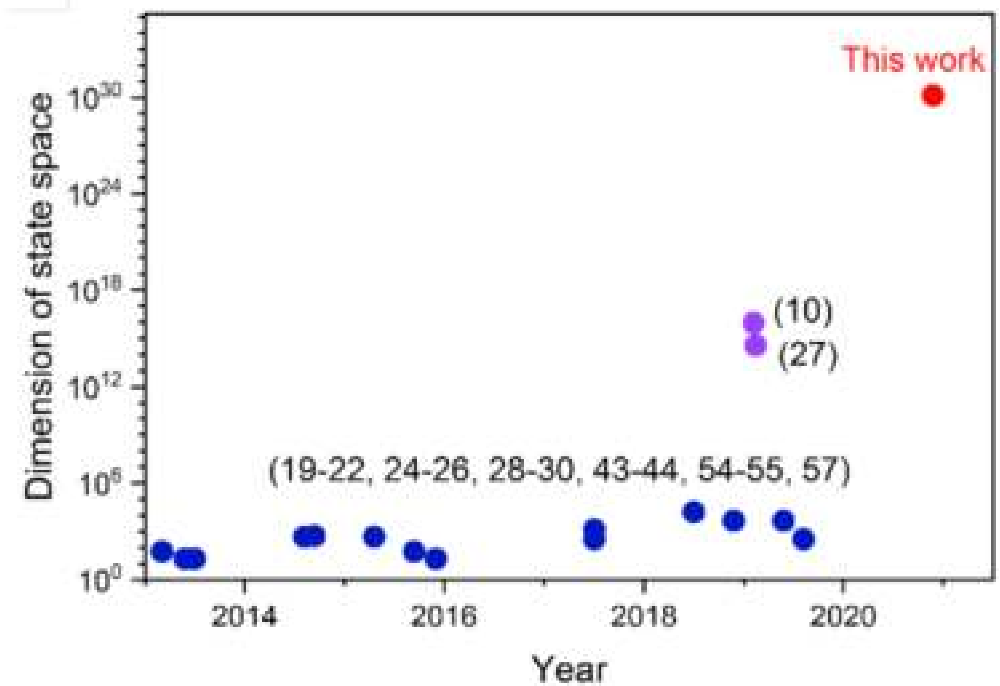
Han-Sen Zhong, Hui Wang, Yu-Hao Deng, Ming-Cheng Chen, Li-Chao Peng, Yi-Han Luo, Jian Qin, Dian Wu, Xing Ding, Yi Hu, Peng Hu, Xiao-Yan Yang, Wei-Jun Zhang, Hao Li, Yuxuan Li, Xiao Jiang, Lin Gan, Guangwen Yang, Lixing You, Zhen Wang, Li Li, Nai-Le Liu, Chao-Yang Lu, Jian-Wei Pan

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.

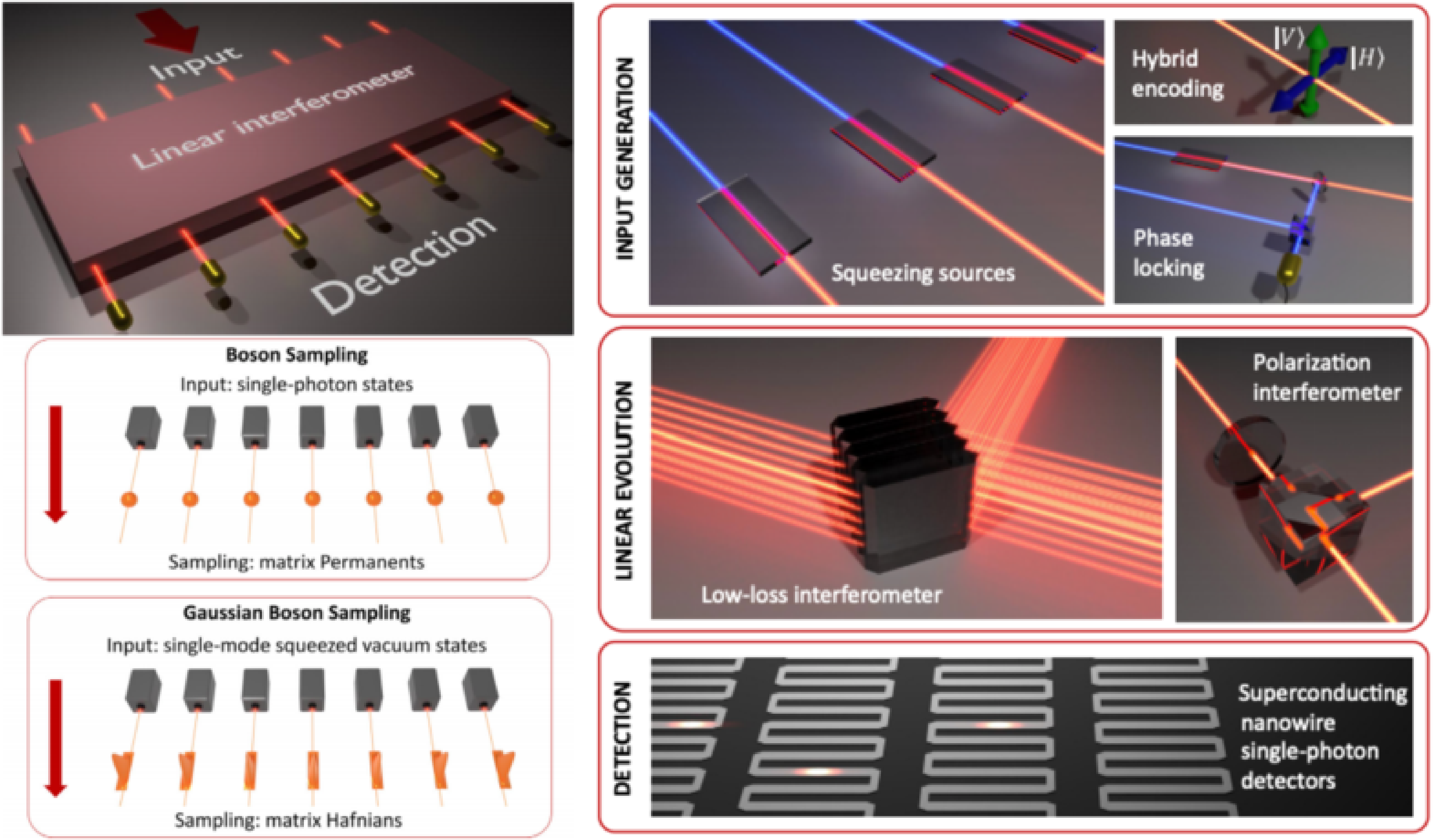
# JIUZHANG

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



# Gaussian Boson Sampling

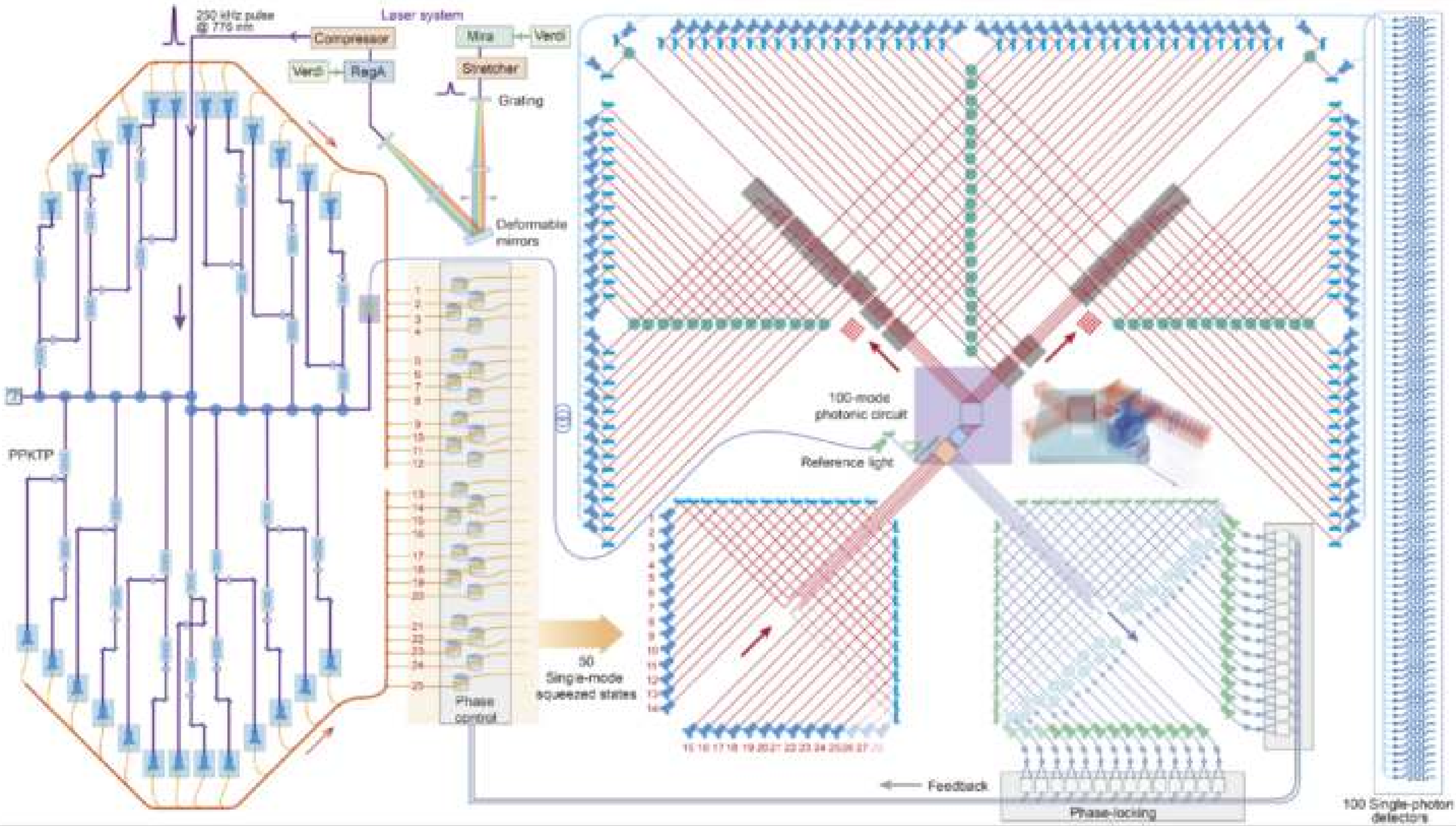



F. Sciarrino, and N. Spagnolo, "The race towards quantum computational advantage: milestone photonic experiment", *Science Bulletin* (2021)

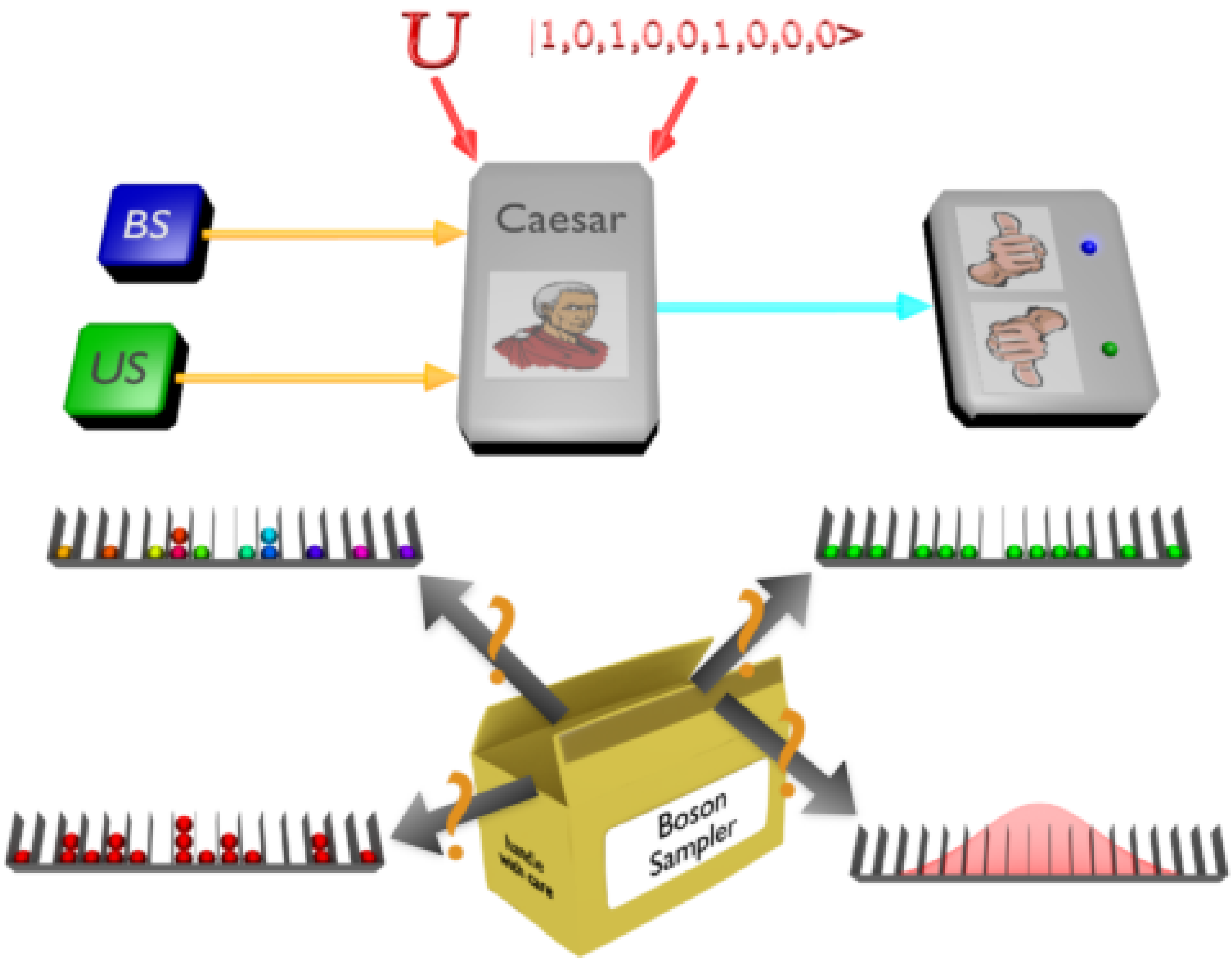
# Gaussian Boson Sampling: setup

- Phase-locked setup
- Up to 76 output photon-clicks
- Output state dimension ~10^30

Sampling rate that is ~10^14 faster
Than using the state-of-the-art simulation
strategy and supercomputers



# Validation of Boson Sampling




**Boson Sampling:**
hard problem with classical computer

*but may be very hard also to validate/certify!*

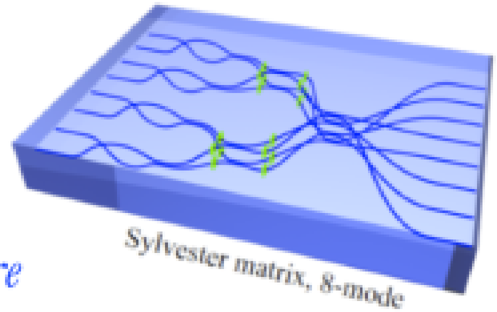
*We need to develop different methodologies to validate/certify the output*

# Validation: hierarchy of tests

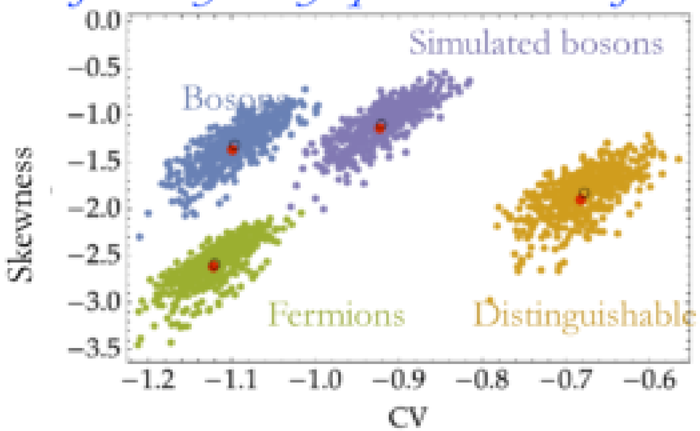
## Physical approach

*Interference in ordered structure*

Crespi, et al., *Nat. Commun.* 7, 10469 (2016)

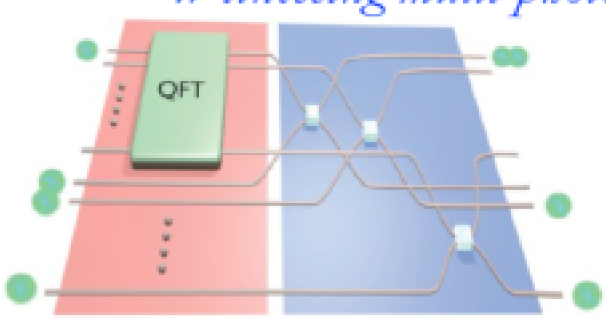



*Statistical signature of many-body quantum interference*




Giordani, et al., *Nature Photonics* **12**, 173 (2018)

*Witnessing multi photon interference*




Brod, et al., *Phys. Rev. Lett.* **122**, 063602 (2019)

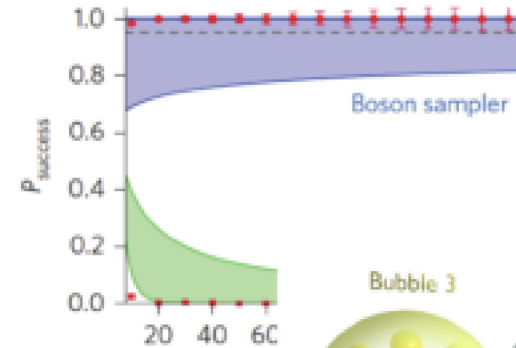
***Stringent assessment***

## Computational approach

*Bayesian inference*

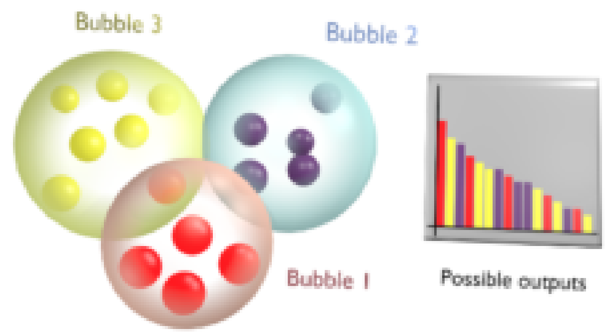
N. Spagnolo, et al., *Nat. Photon.* **8**, 615 (2014)

J. Carolan, et al., *Nat. Photon.* **8**, 621 (2014)




M. Bentivegna, et al., *IJQI* **12**, 1560028 (2014)

*Pattern classifications*




Agresti et al, *Physical Review X* **9**, 011013 (2019)

*Neural networks*

Flamini, et al., *QST* (2019)

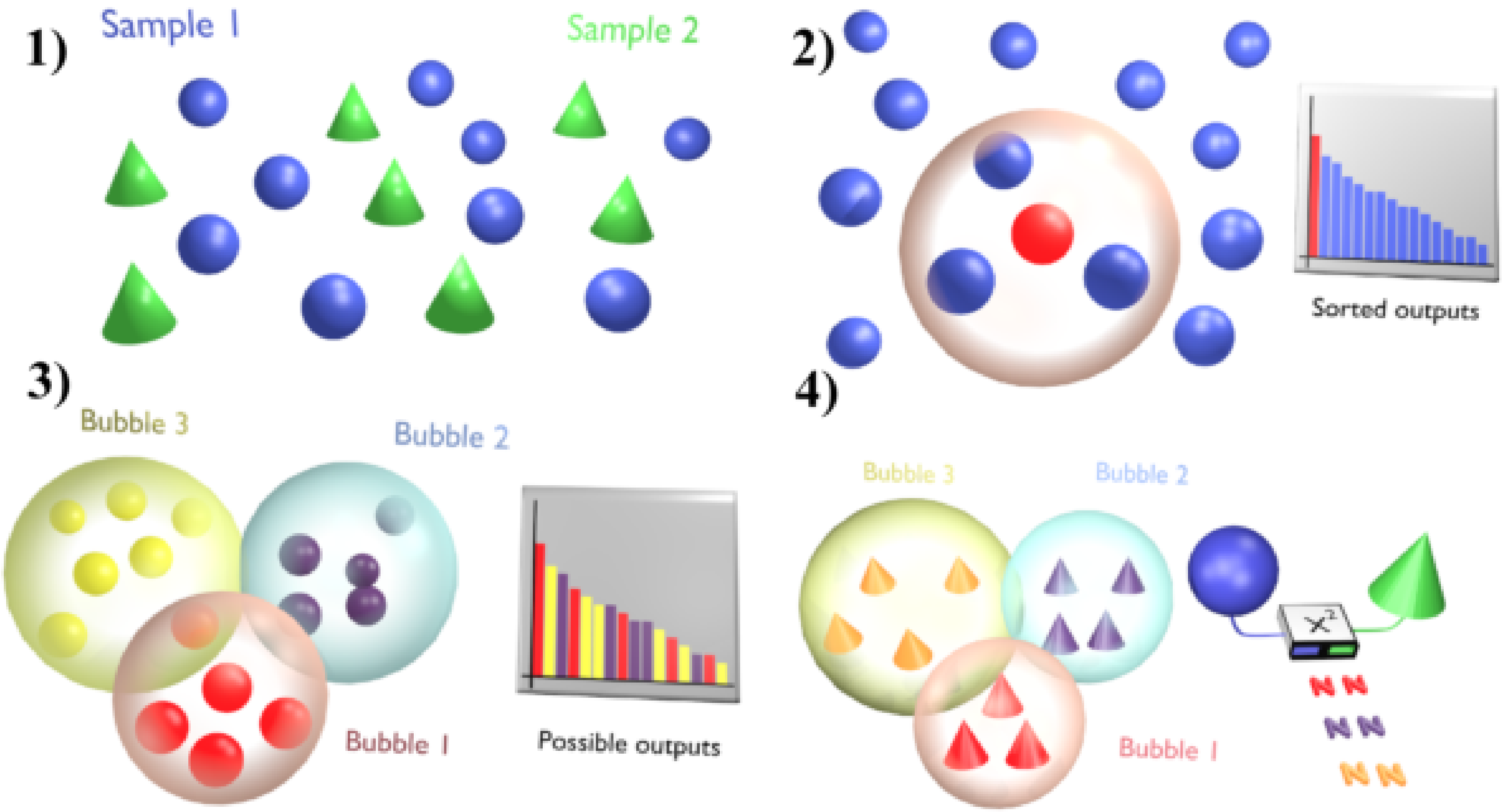
**Machine learning techniques**

***Efficient certification***

# Validation: pattern recognition techniques

First Goal: to benchmark boson sampling versus trusted boson samplers
or other fake measured distributions

**Techniques inspired by pattern recognition: hierarchical clustering**
**k-means clustering**




Sapienza Università di Roma
Microsoft
Consiglio Nazionale delle Ricerche

I. Agresti, N. Viggianiello, F. Flamini, N. Spagnolo, A. Crespi, R. Osellame, N. Wiebe, and F. Sciarrino, "Pattern recognition techniques for Boson Sampling validation", *Physical Review X* **9**, 011013 (2019)

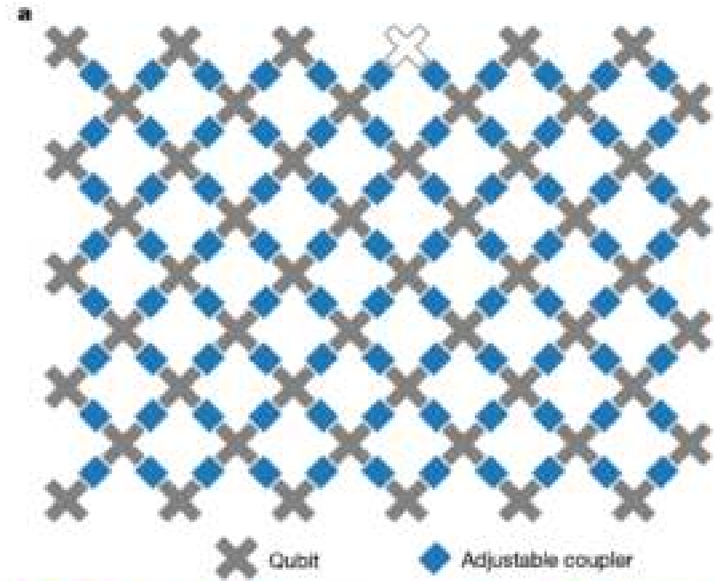
# Quantum Supremacy: reported by Google..

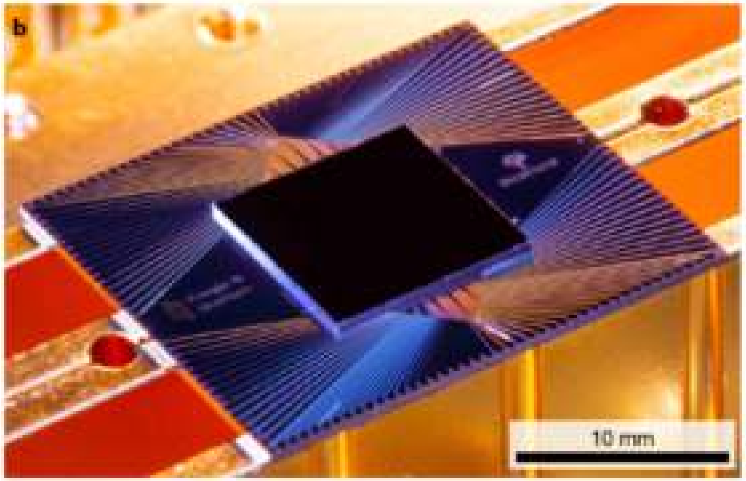
nature
International journal of science

Article | Published: 23 October 2019

## Quantum supremacy using a programmable superconducting processor

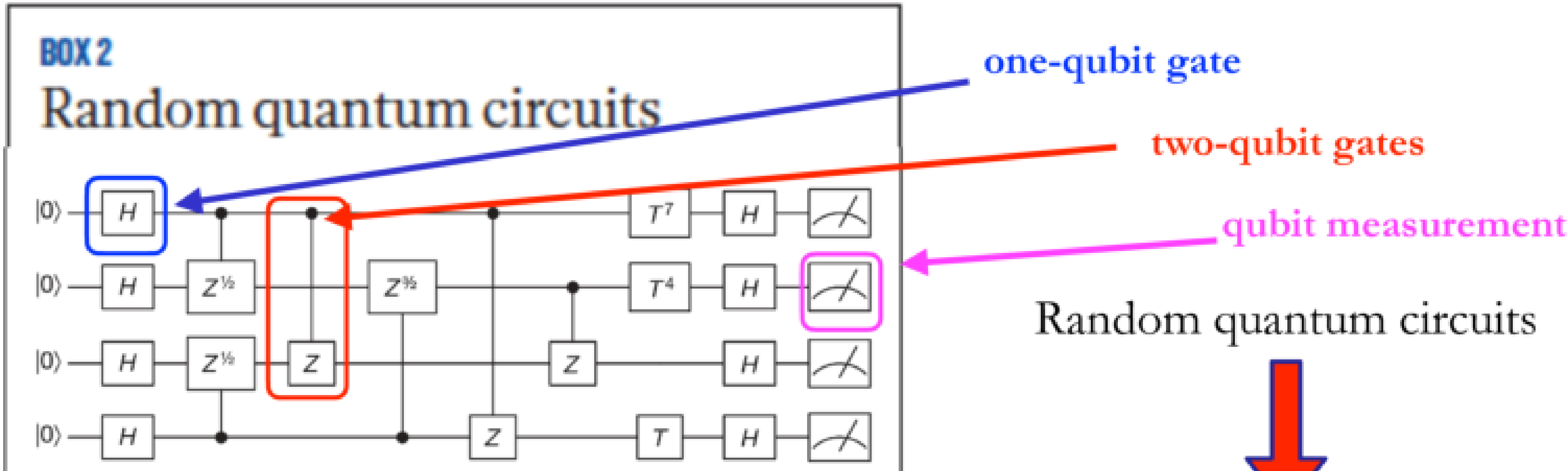
Frank Arute, Kunal Arya, [...] John M. Martinis




*Nature* **574**, 505 (2019)

# Google approach: 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 they all commute, so in principle could be applied simultaneously.

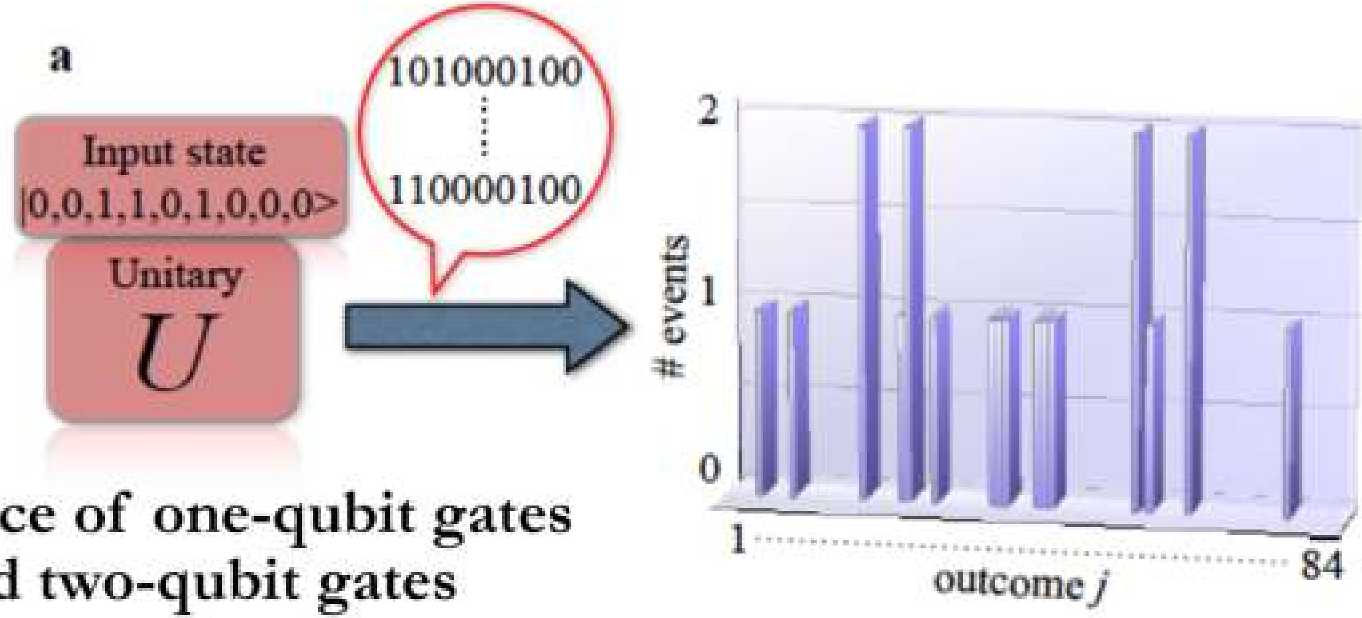
Random quantum circuits

No symmetry to simplify classical simulation

I) To entangle a set of qubits by repeated application of single-qubit and two-qubit logical gates ($m$ cycles).

II) Sampling the quantum circuit's output produces a set of bitstrings, for example {0000101, 1011100, …}

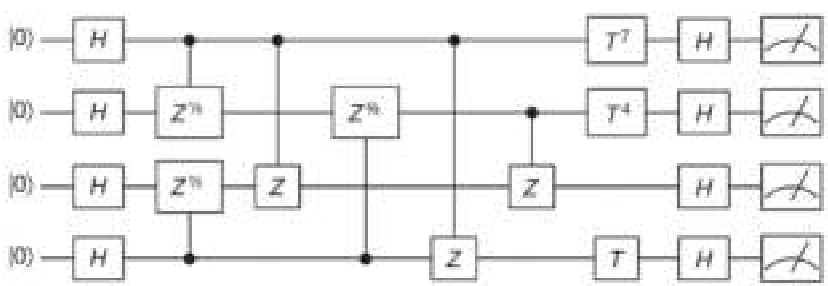
# Google approach: random quantum circuits



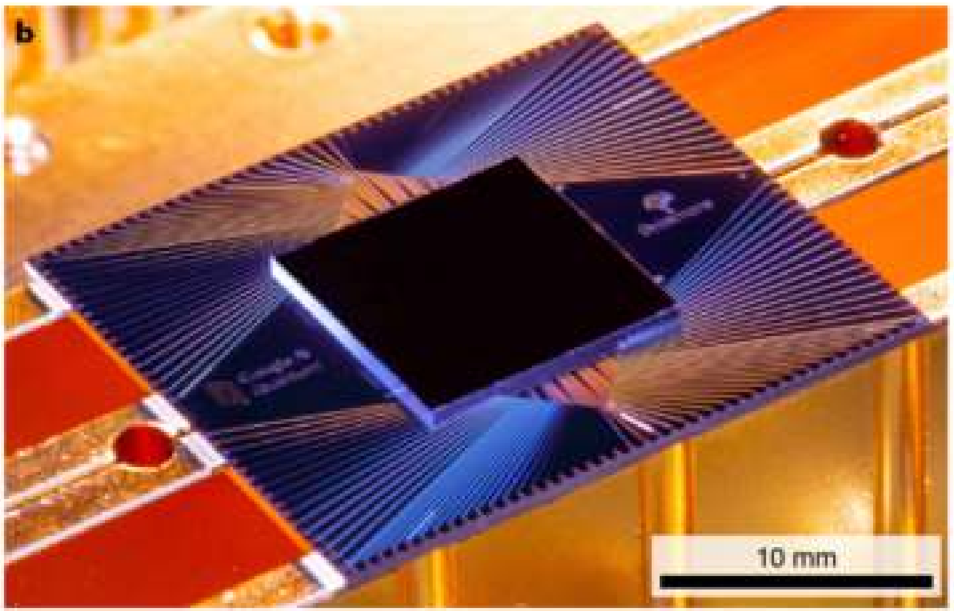

sequence of one-qubit gates
and two-qubit gates

**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 they all commute, so in principle could be applied simultaneously.



# Why is these experiments are significant?

## COMPUTER SCIENCE

*The extended Church–Turing thesis asserts that any 'reasonable' model of computation can be efficiently simulated by a Turing machine.*

**These experiments suggests that finally the quantum computation violates this assertion.**

## PHYSICS

*Quantum works for complex systems: : no additional decoherence physics observed when increasing the number of qubits*

**Capability to handle a huge Hilbert space**

## QUANTUM ENGINEERING

*Development of large quantum hardware with high performances*

**Possibility to implement quantum error correction - no unexpected limitation on the scaling**

# 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
*Xanadu, 372 Richmond Street West, Toronto, Ontario, Canada M5V 1X6*

(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

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

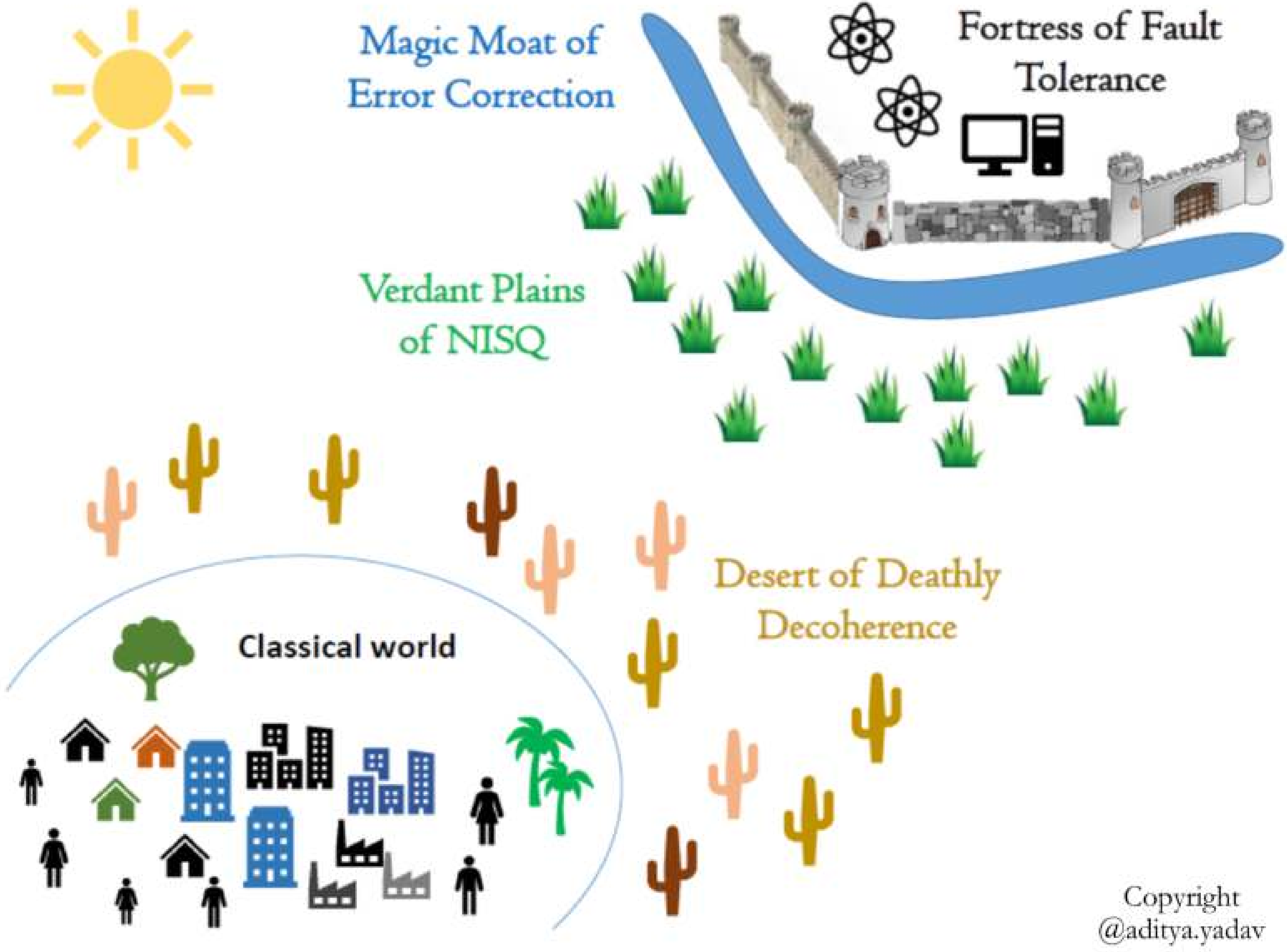
## For quantum simulation

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


Magic Moat of
Error Correction
Fortress of Fault
Tolerance
Verdant Plains
of NISQ
Desert of Deathly
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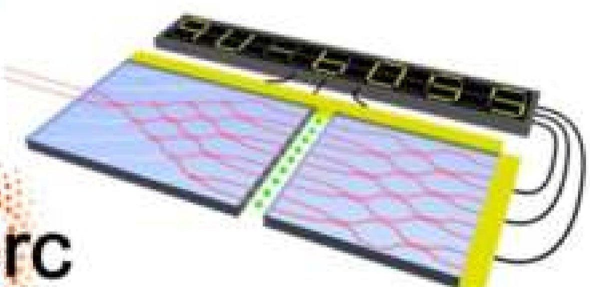

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