Quantum Information on a chip

Fabio Sciarrino
Sapienza università di Roma

THE FRAMEWORK PROGRAMME FOR RESEARCH AND INNOVATION
HORIZON 2020
erc
3D-QUEST
QUCHIP
Quantum Simulation on a Photonic Chip
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MARIE CURIE ACTIONS

www.3dquest.eu
www.quantumlab.it

Quantum information

Challenges: from basic sciences

to emerging quantum technologies

- Fundamental physics:

  Test of non-locality, quantum contextuality

  Shed light on the boundary between classical and quantum world

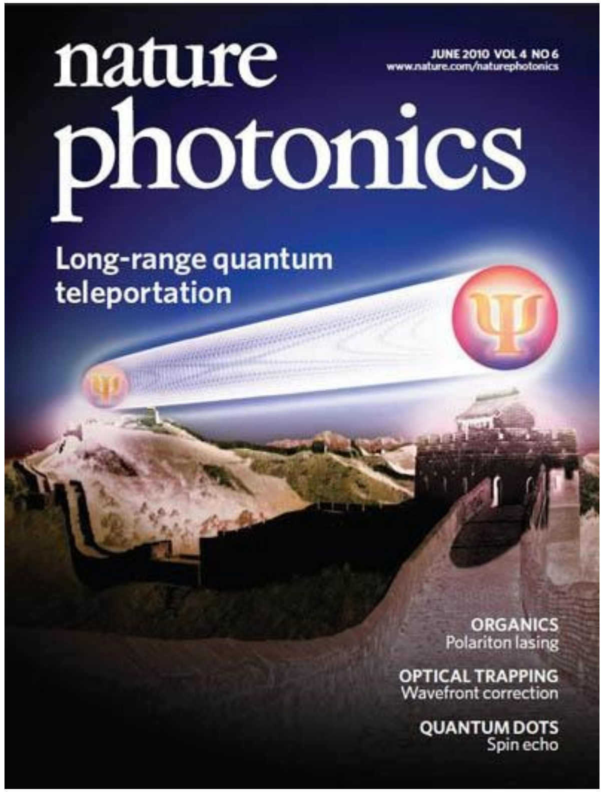
  Exploiting quantum parallelism

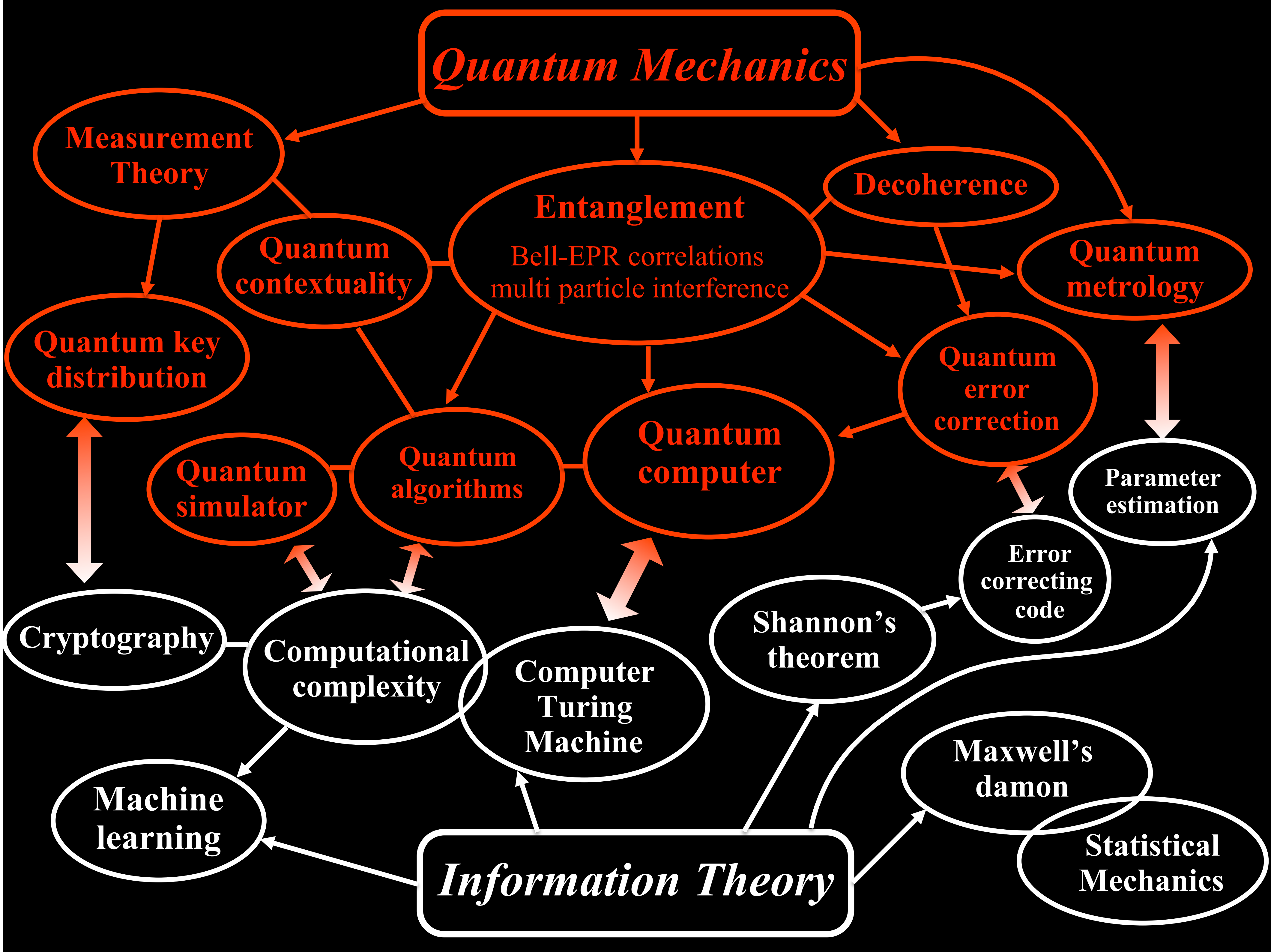
  to simulate quantum many-body systems

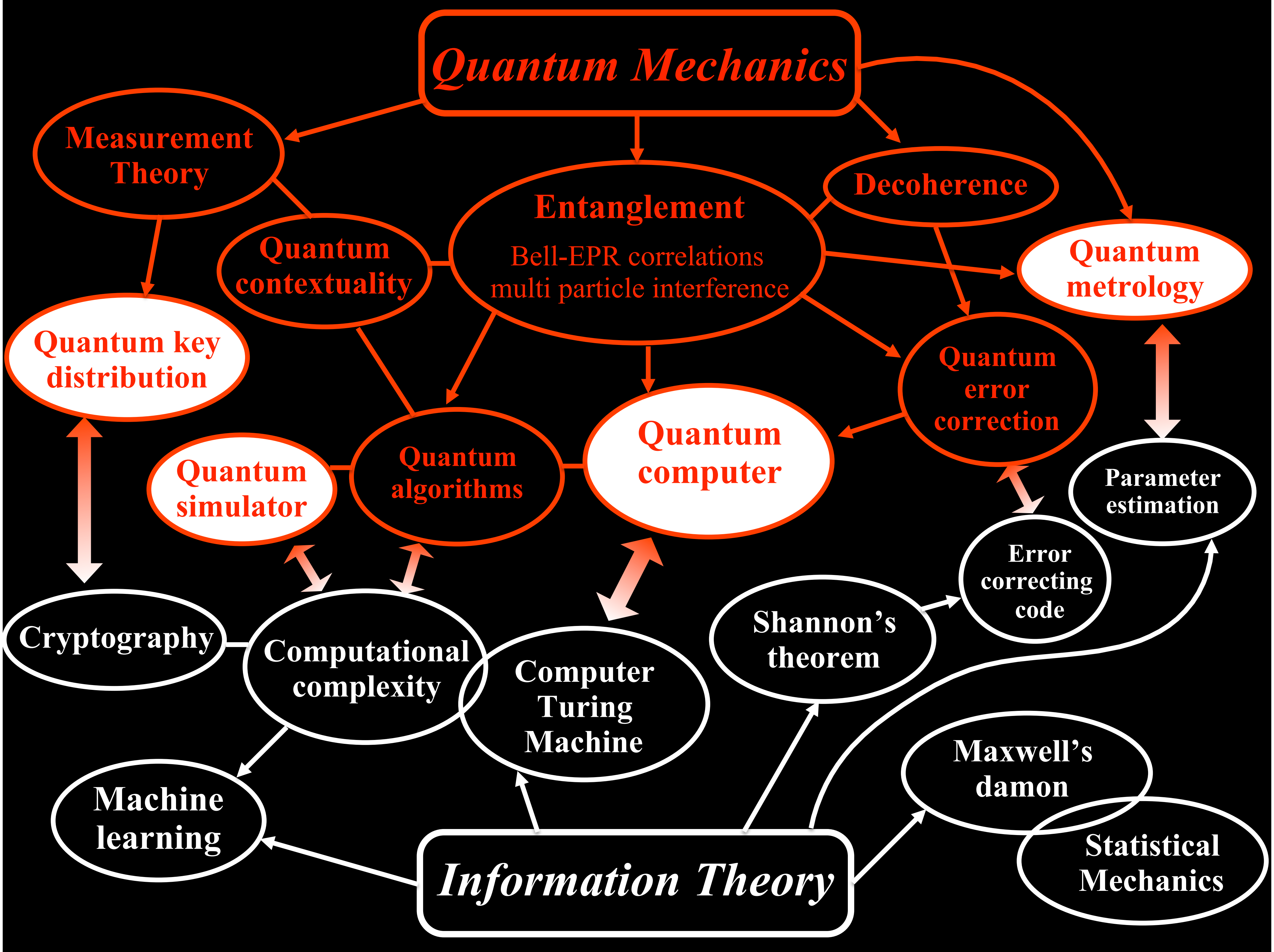
  - New cryptographic protocols

- Quantum sensing: imaging, metrology
- Quantum computing

  quantum simulation




Quantum Mechanics
Measurement Theory
Entanglement
Bell-EPR correlations
multi particle interference
Decoherence
Quantum contextuality
Quantum metrology
Quantum key distribution
Quantum error correction
Quantum computer
Quantum algorithms
Quantum simulator
Parameter estimation
Error correcting code
Cryptography
Computational complexity
Computer Turing Machine
Shannon's theorem
Maxwell's damon
Statistical Mechanics
Machine learning
Information Theory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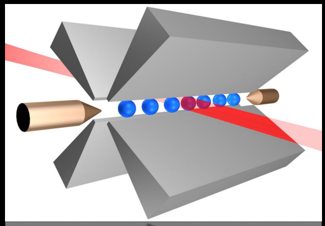
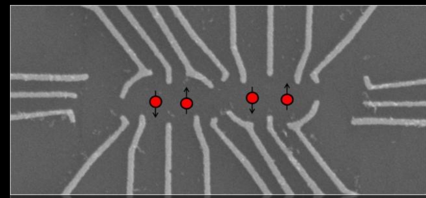
Implementation of Quantum Information

Trapped ions



Spin qubit



Single photons

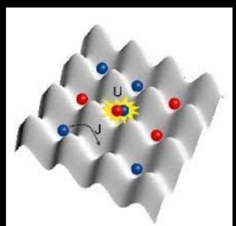
Quantum computation

Quantum simulation

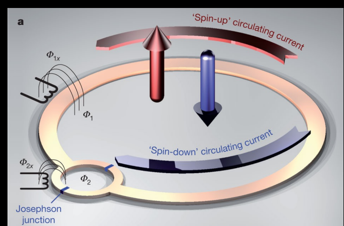
Quantum communication

Quantum metrology

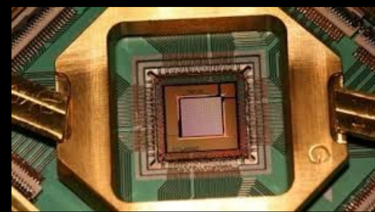
Foundations of Quantum Mechanics



Cold atoms in optical lattices



Superconducting qubits

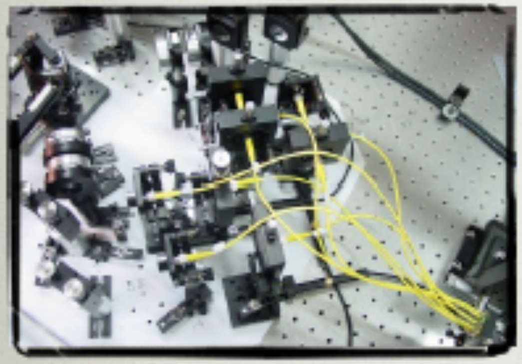


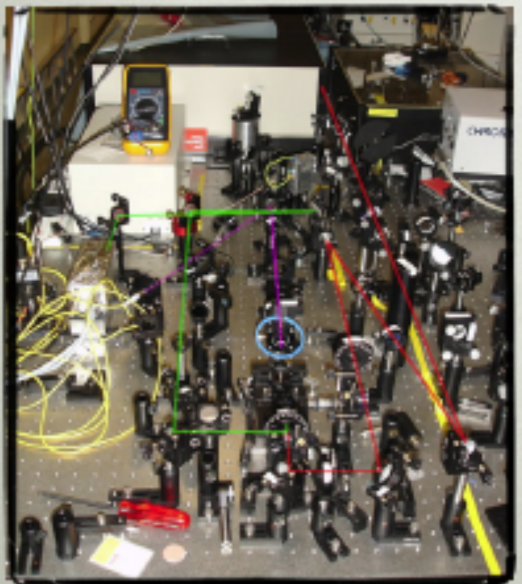
Quantum annealers

Quantum Optics: A benchmark for foundations of Quantum Mechanics and Quantum Technologies

- Test on the foundations of quantum mechanics
- Quantum cryptography and communication
- Quantum computing
- Quantum interferometry, metrology and sensing

Politecnico di Milano
IFN
CNR

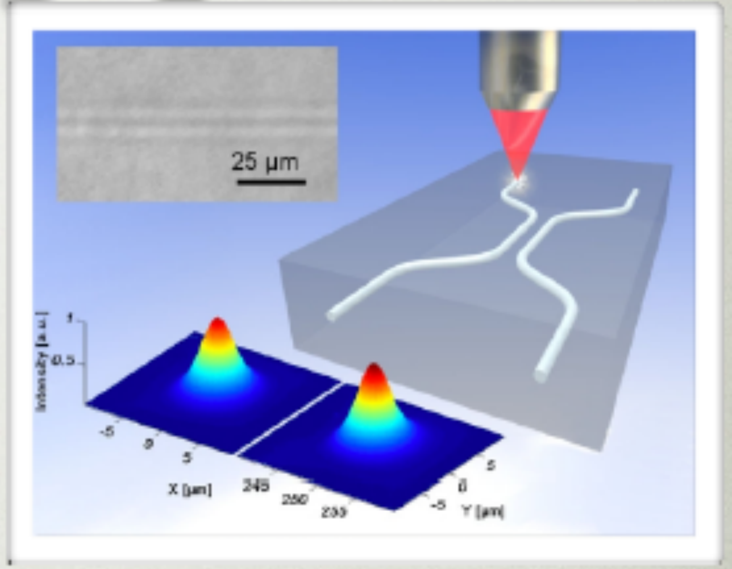




Limitations of experiments with bulk optics:

- Scalability
- Large physical size
- Low stability
- Costs...

Solution: Integrated waveguide technology

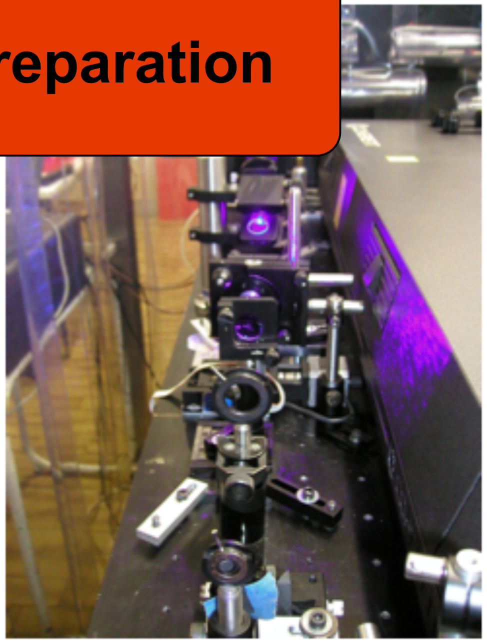


Integrated photonic circuits: Laser writing technique

- Femtosecond pulse tightly focused in a glass
- Waveguides writing by translation of the sample

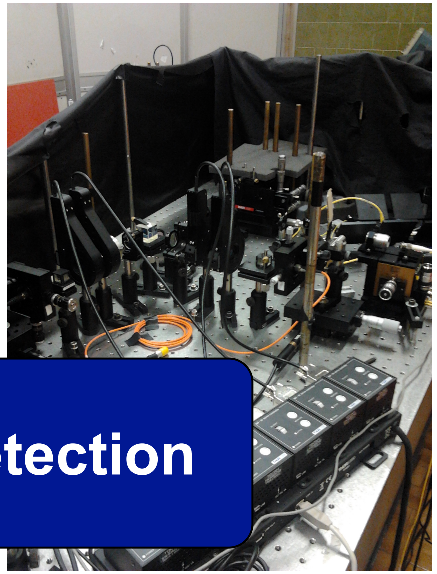
Integrated quantum photonics

Preparation



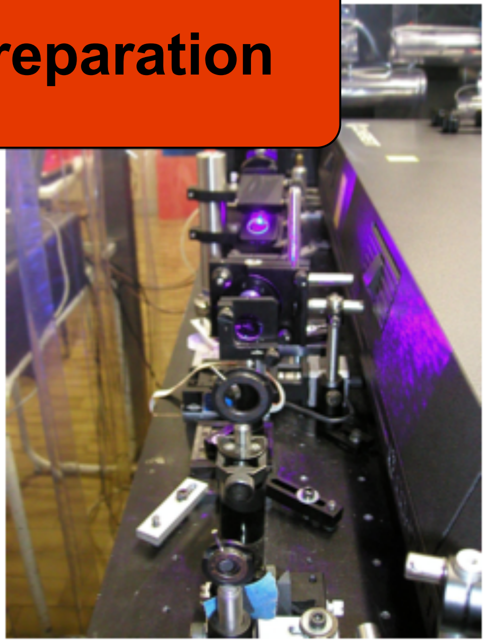
Manipulation

Detection



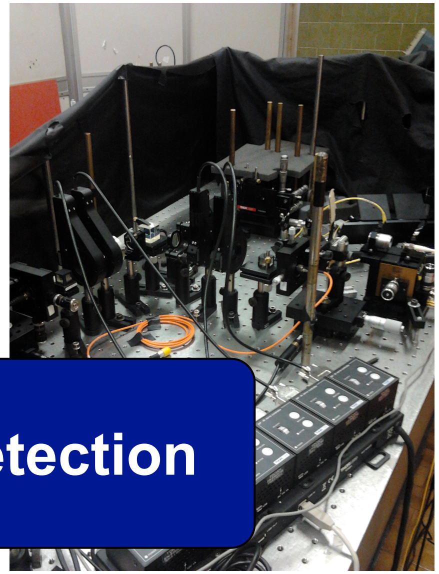
Integrated quantum photonics

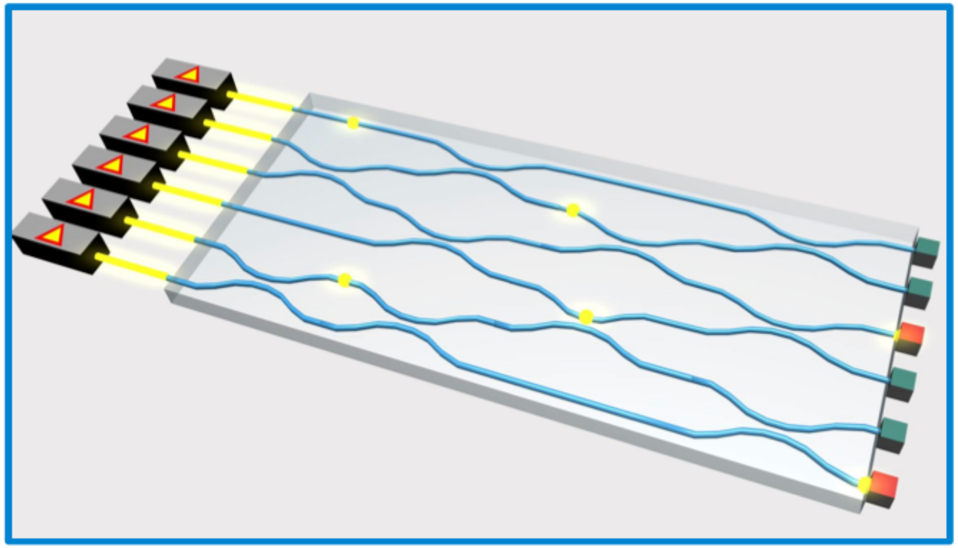
Preparation



Manipulation

Detection





- **Single photon sources**
- **Manipulation**
- **Single photon detectors**

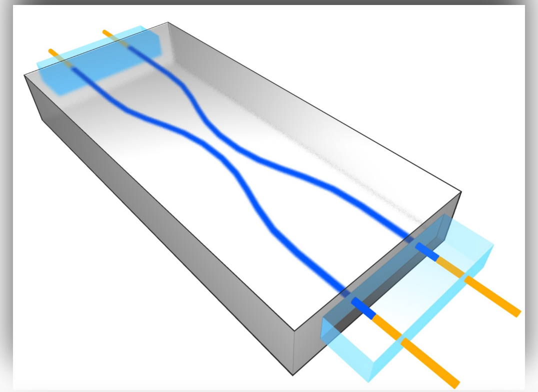
ON THE SAME CHIP

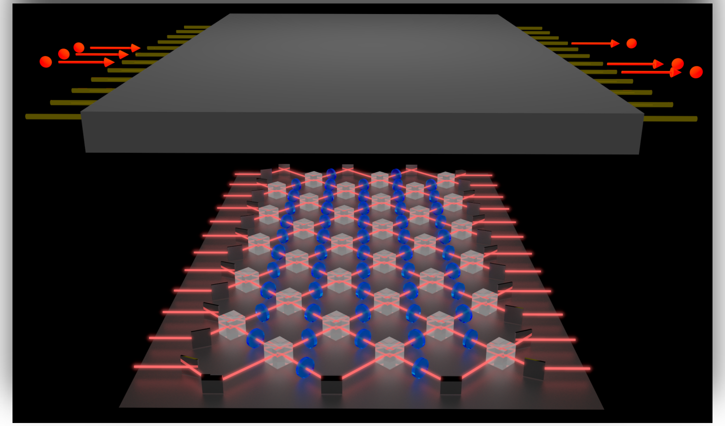
Outline

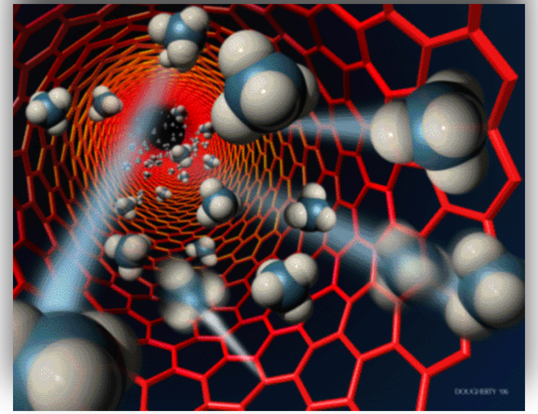
1. Integrated quantum circuits

2. Boson sampling

3. Quantum simulation via quantum walk





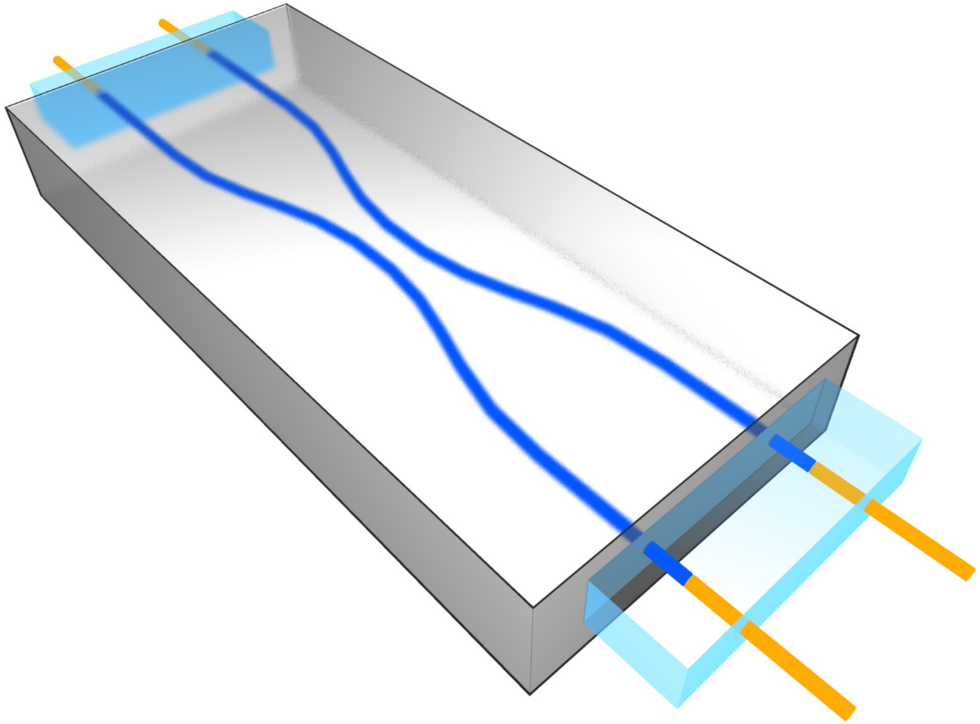


Integrated quantum photonics

In collaboration with Politecnico di Milano
and Istituto di Fotonica e Nanotecnologie - CNR

M. Ciampini
F. Flamini
G. Carvacho
A. Cuevas
A. Syed Rab
N. Viggianiello
I. Agresti
T. Giordani
E. Polino
M. Bentivegna
N. Spagnolo
P. Mataloni
F. Sciarrino

SAPIENZA
UNIVERSITÀ DI ROMA



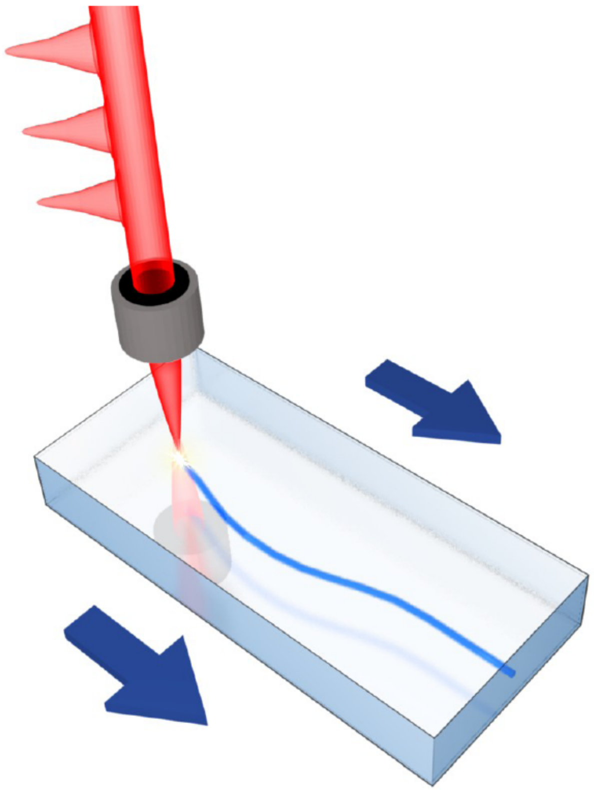
POLITECNICO
MILANO

ifn

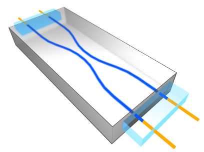
A. Crespi
G. Corrielli
I. Pitsios
R. Ramponi
R. Osellame

Integrated photonics: Femtosecond laser writing

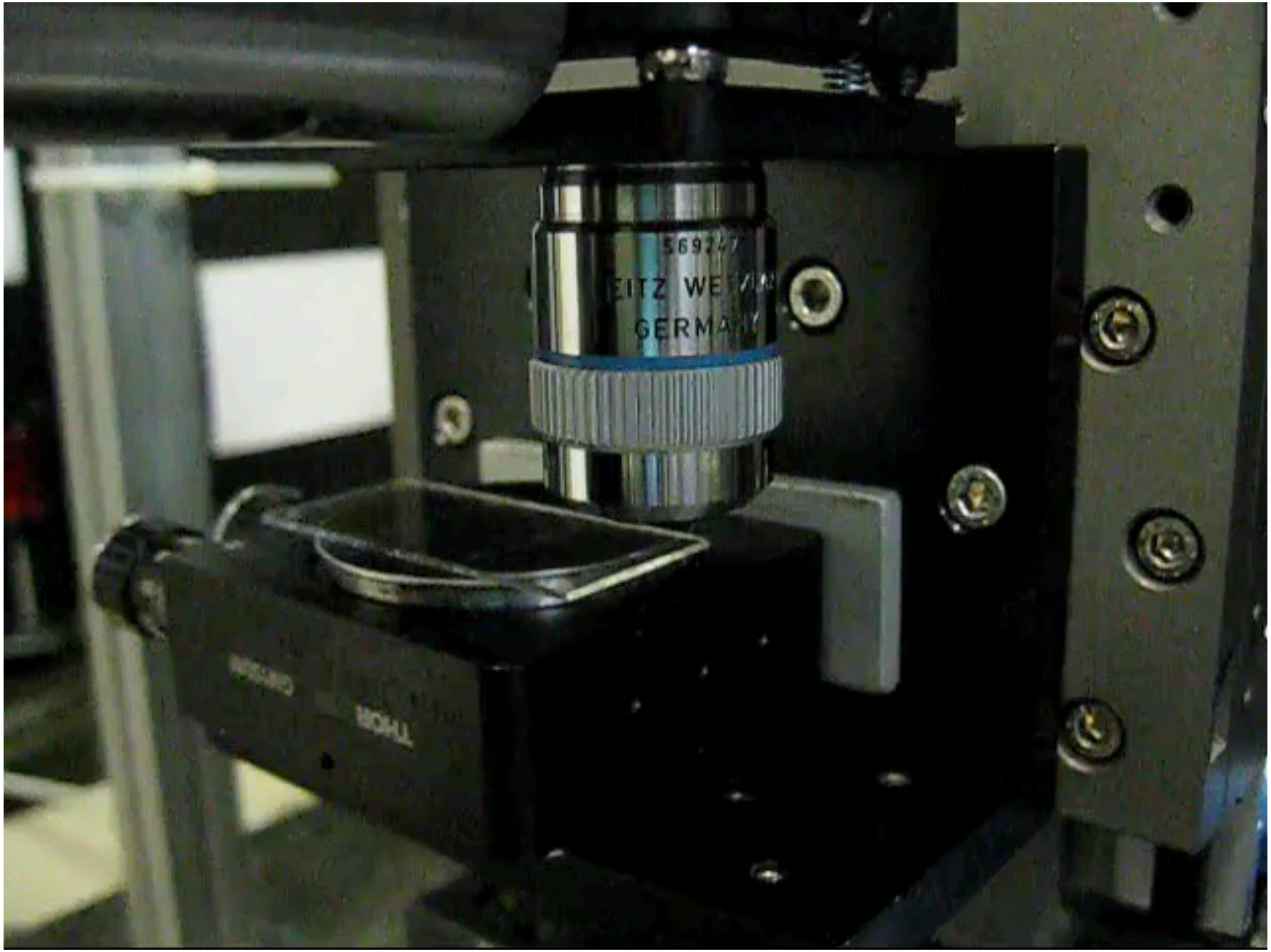
Laser writing technique for devices able to transmit polarization qubits



- 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.



Femtosecond laser writing

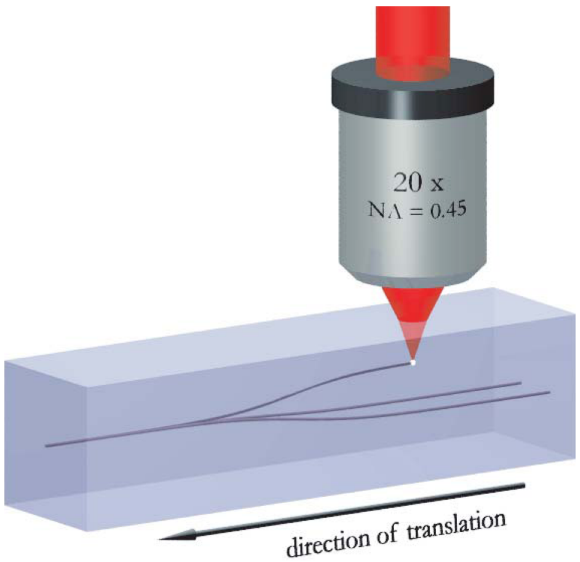


Femtosecond laser writing

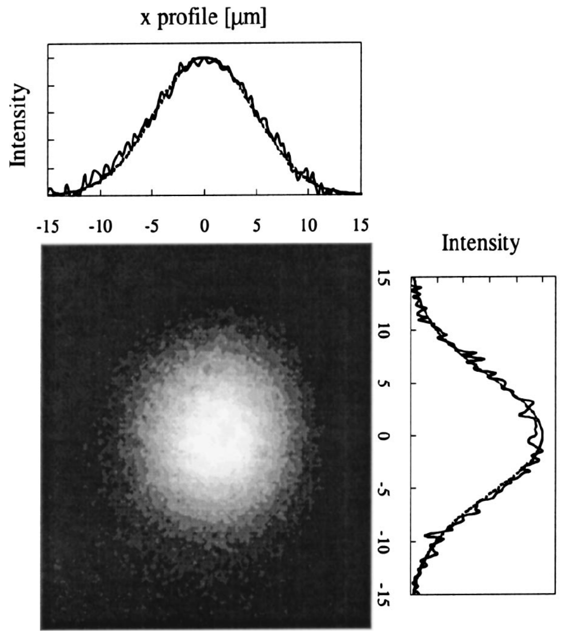
3-dimensional capabilities

Rapid device prototyping: writing speed =4 cm/s

Propagation of circular gaussian modes

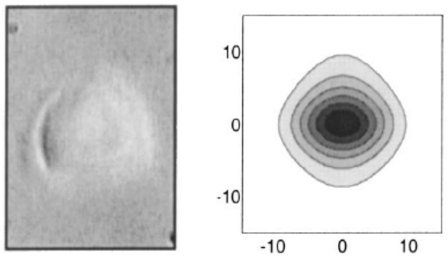


Characteristics:

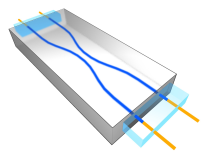


Circular waveguide transverse profile

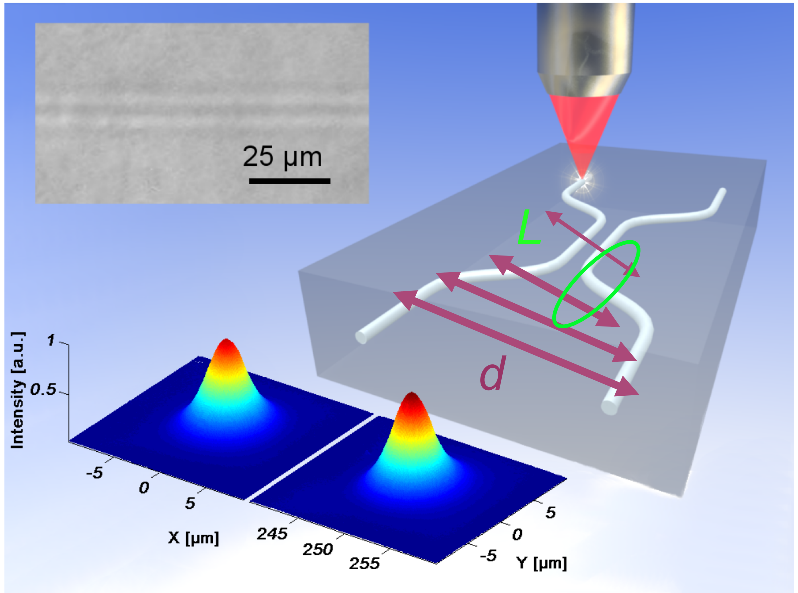
Low birefringence



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).



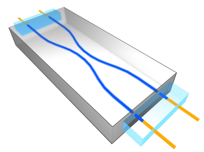
Integrated beam splitter



L: interaction region

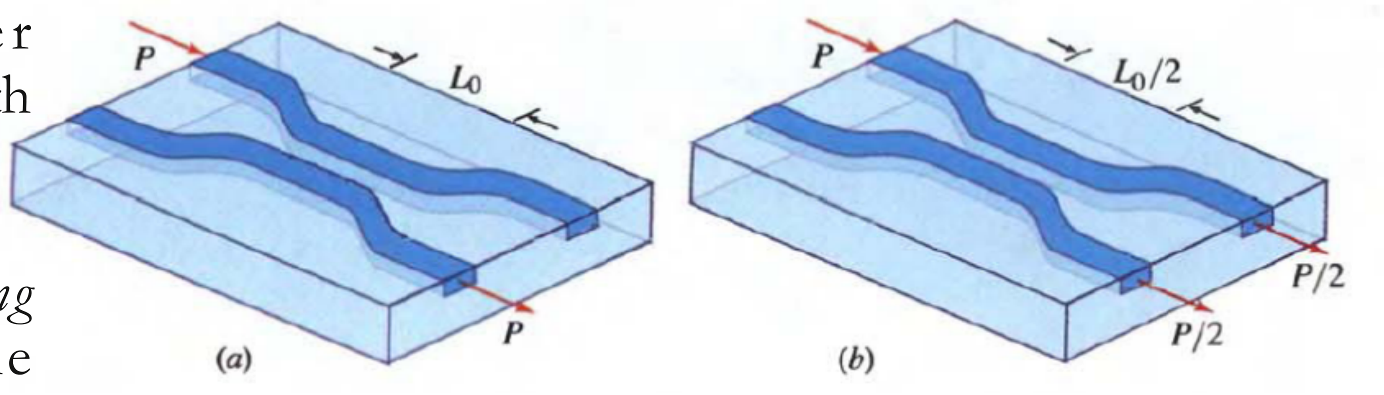
the coupling of the modes occurs also in the curved parts of the two waveguides

L. Sansoni *et al.* *Phys. Rev. Lett.* **105**, 200503 (2010)

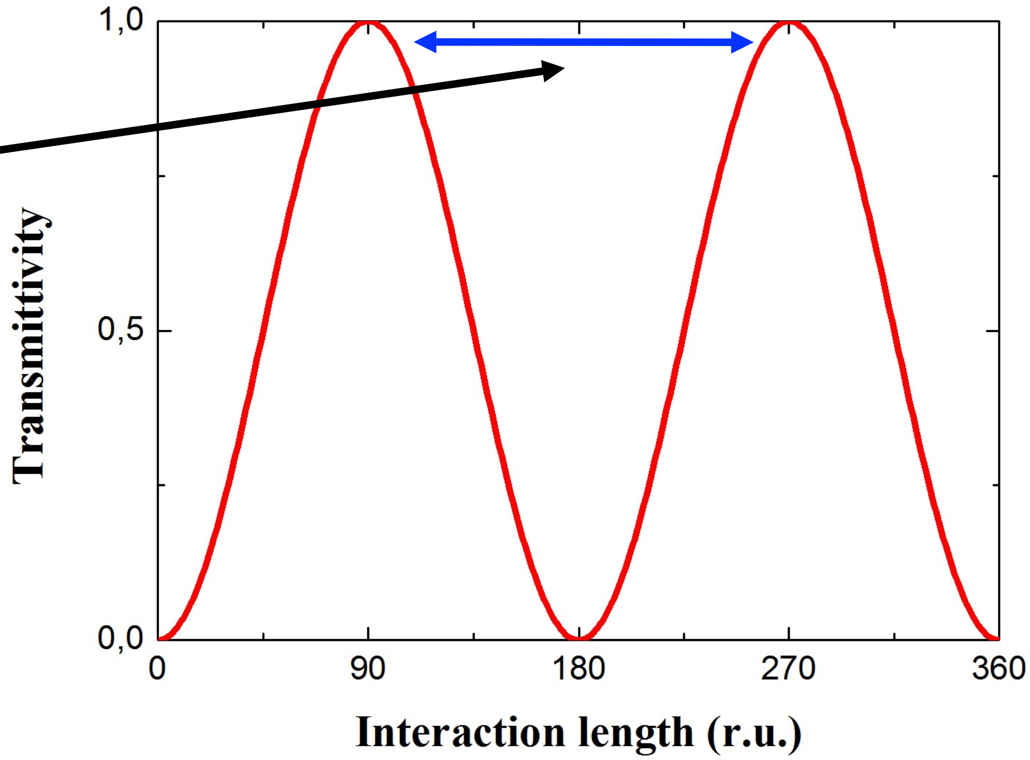


Tunability of the direction coupler transmission

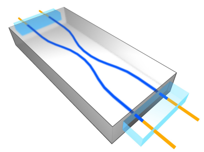
Optical power transfer follows a sinusoidal law with the interaction length.



Oscillation period (*beating period*) depends upon the coupling coefficient of the two guided modes.



Periodicity of the transmission depends from the *Effective index of refraction*



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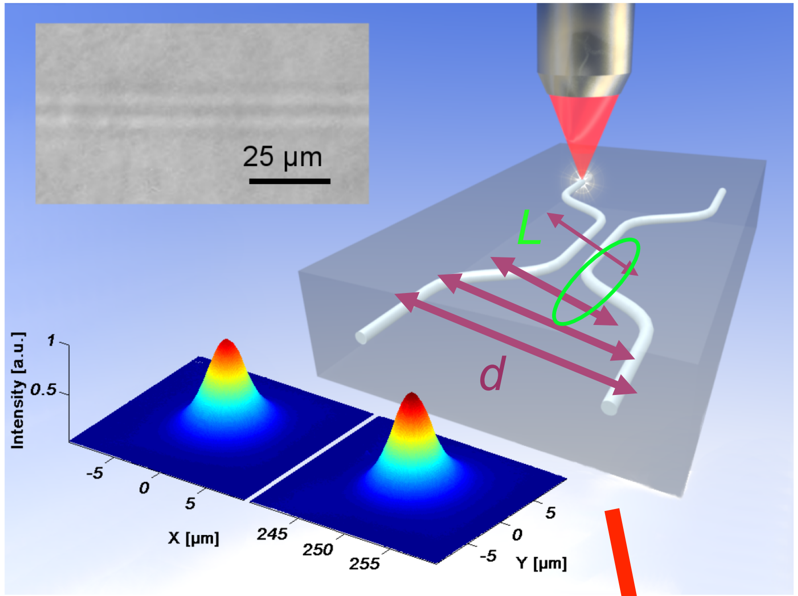
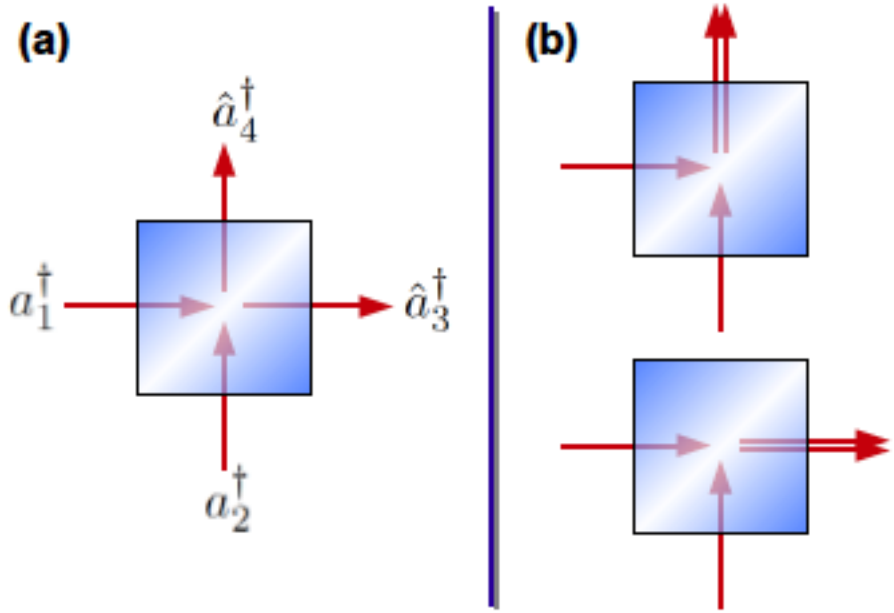
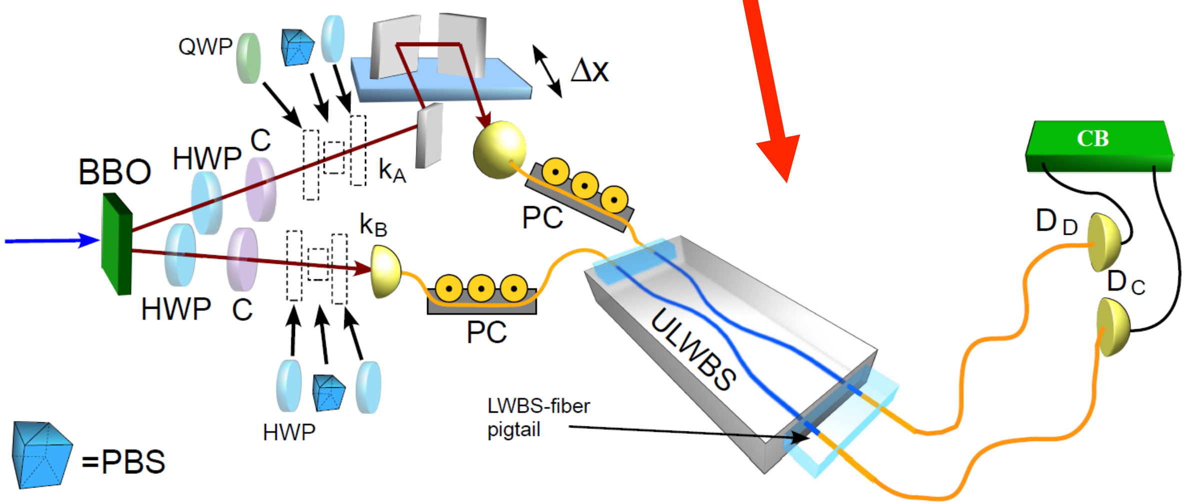
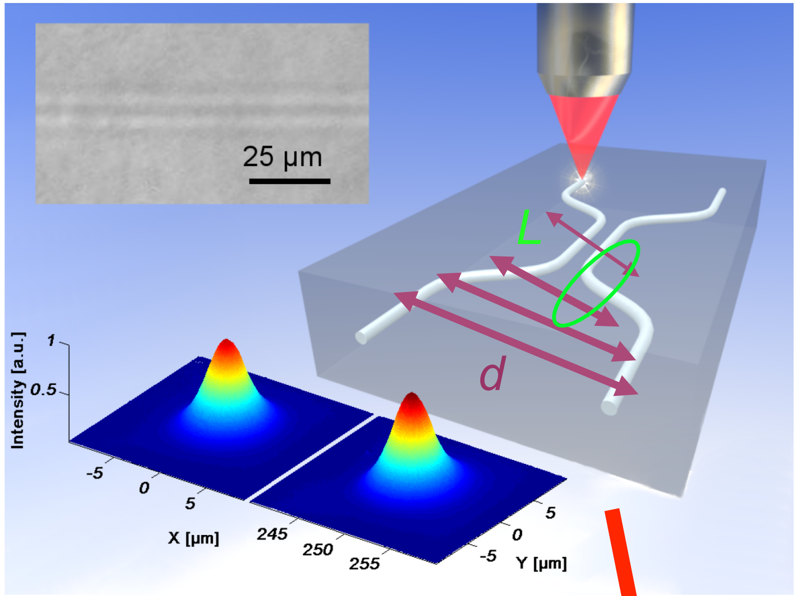


Indistinguishable photons: Bosonic coalescence

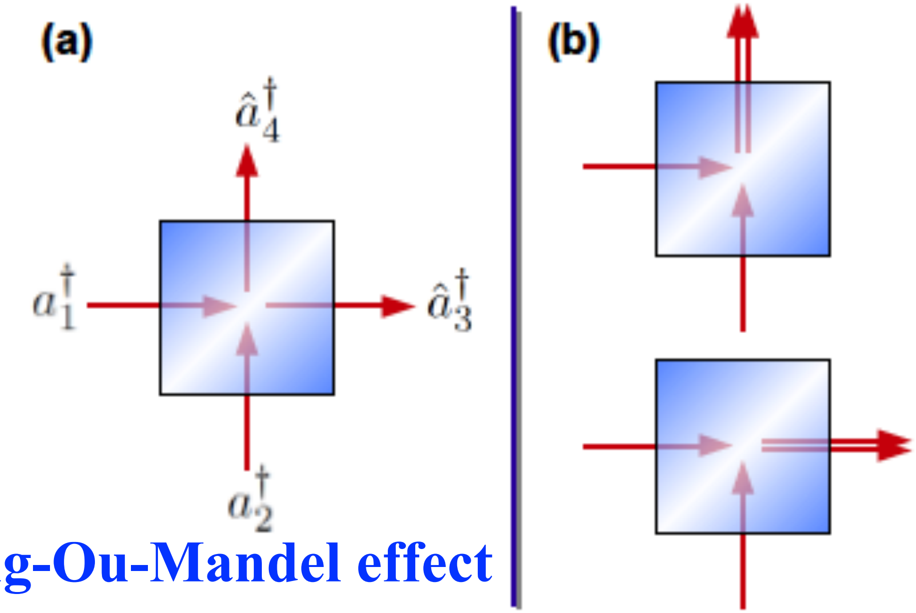




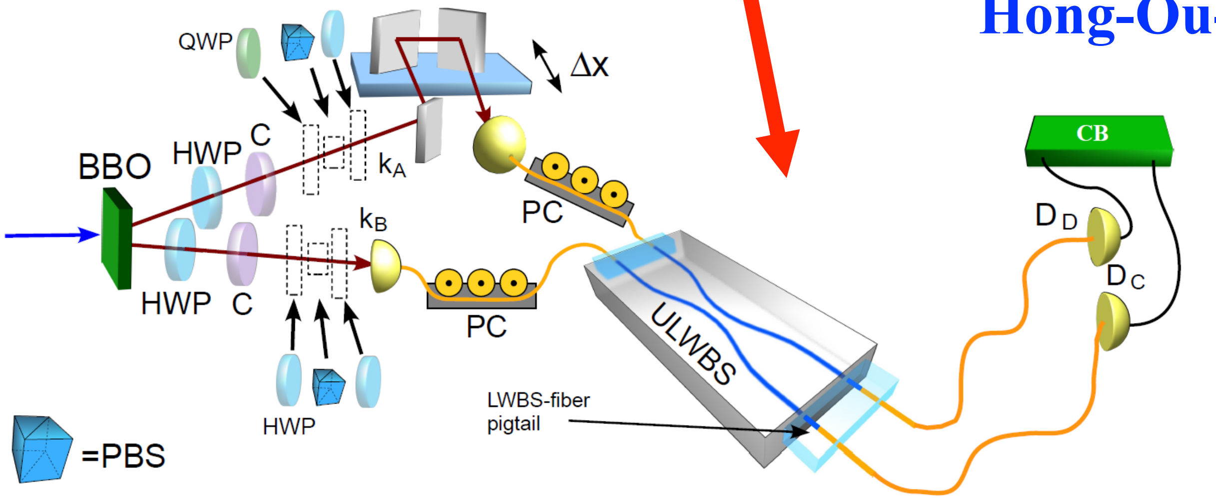
Integrated beam splitter

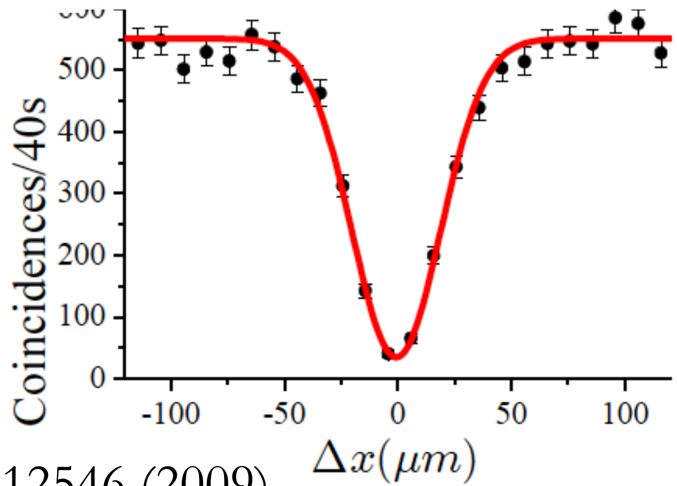


Indistinguishable photons: Bosonic coalescence



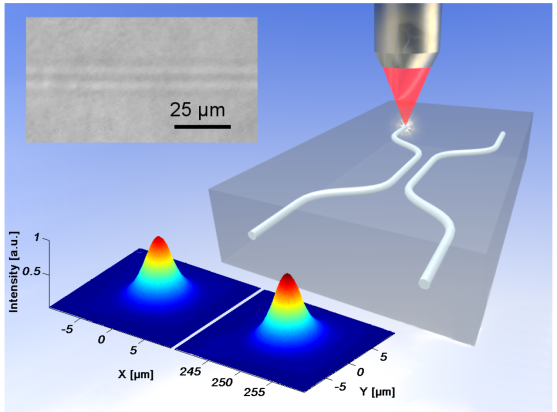
Hong-Ou-Mandel effect





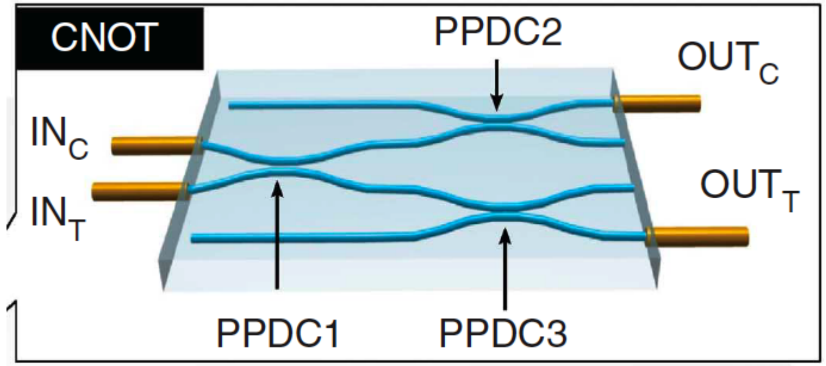
G. D. Marshall et al., *Opt. Express* **17**, 12546 (2009).
L. Sansoni *et al. Phys. Rev. Lett.* **105**, 200503 (2010)

Quantum logical gates



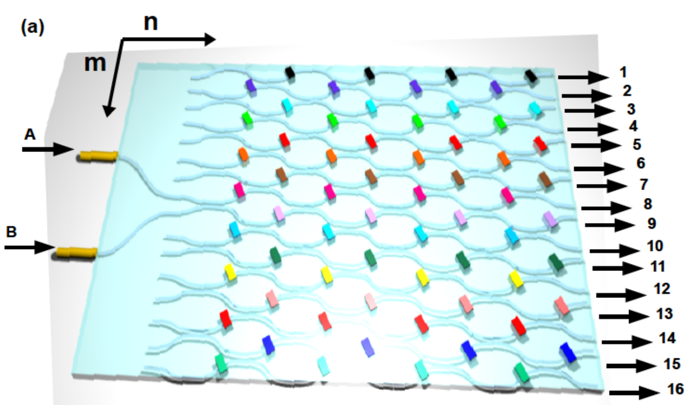
Directional coupler

L. Sansoni et al., Phys. Rev. Lett. 105, 200503 (2010)



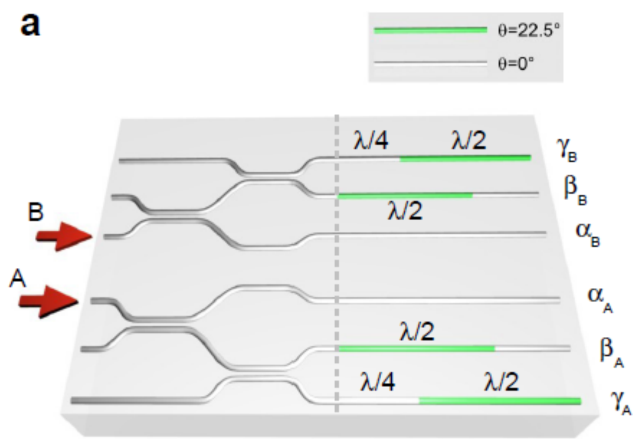
Partially polarizing and logical gate

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



Quantum walk and Anderson Localization

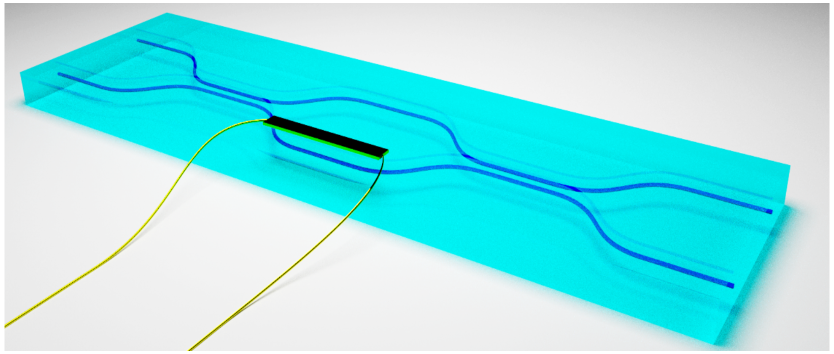
L. Sansoni et al., Phys. Rev. Lett. 108, 010502 (2012)
A. Crespi et al., Nat. Photon. 7, 322-328 (2013)



Tunable waveplate

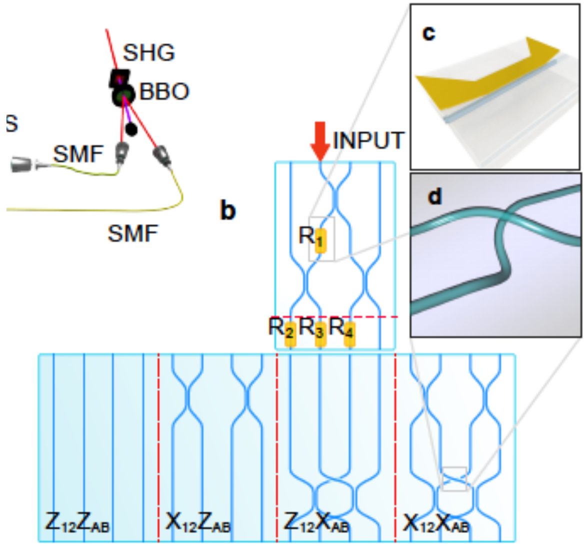
L. Corrielli et al., Nat. Comm. 5, 2549 (2014)

Reconfigurable devices



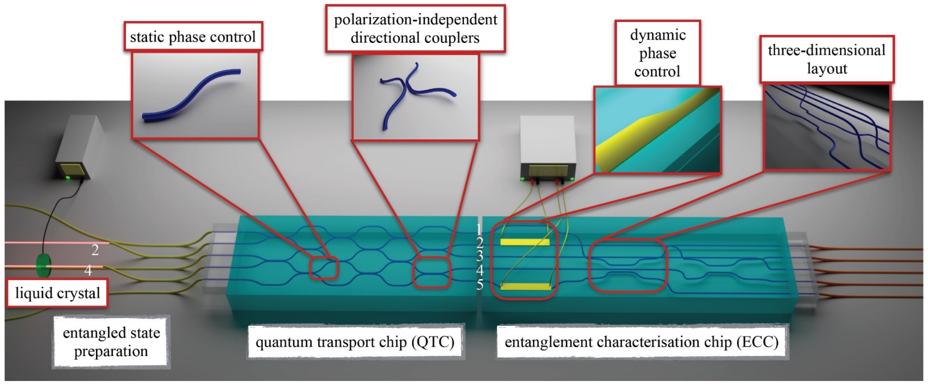
Reconfigurable interferometer

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



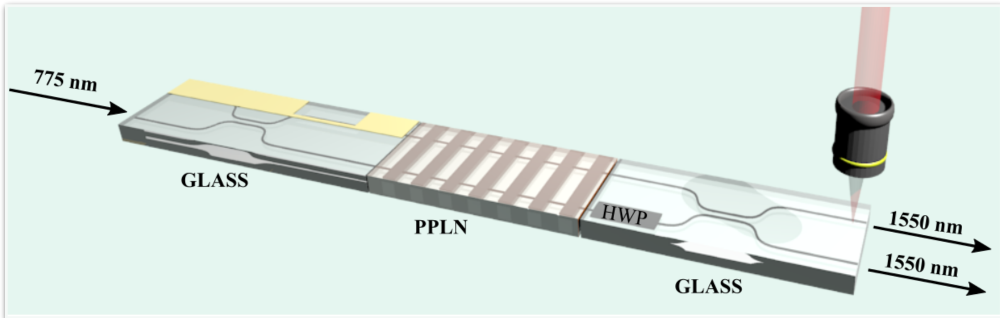
On chip quantum contextuality

A. Crespi et al., ACS photonics (in press)



Programmable simulator

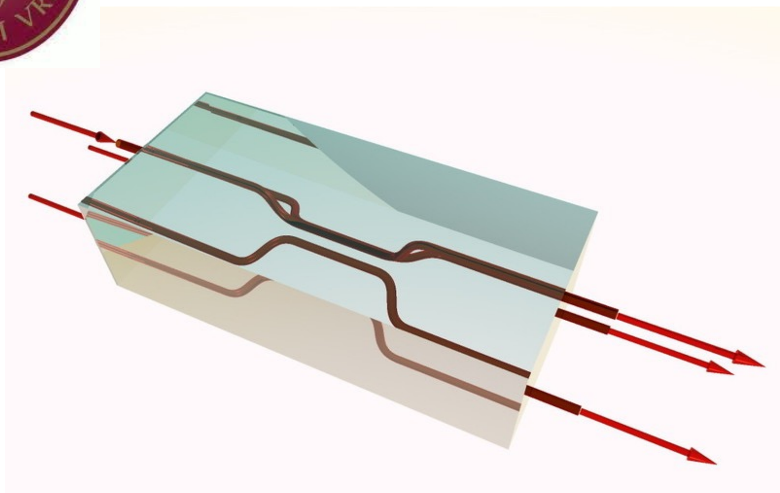
I. Pitsios, et al., Nature Communications (in press)



Integrated source of entangled pairs

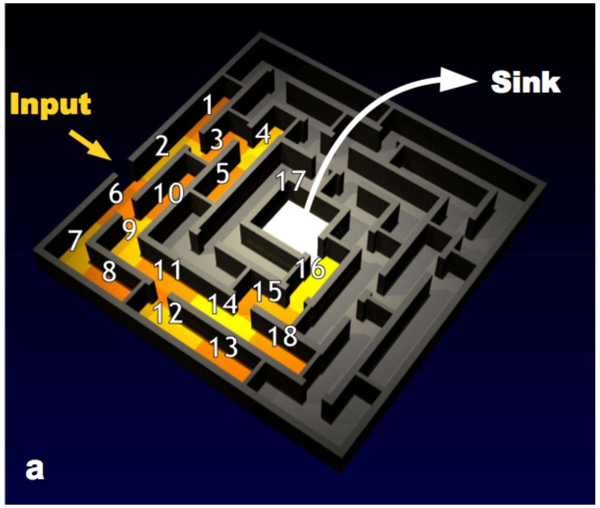
S. Rab, (in preparation)

3D devices



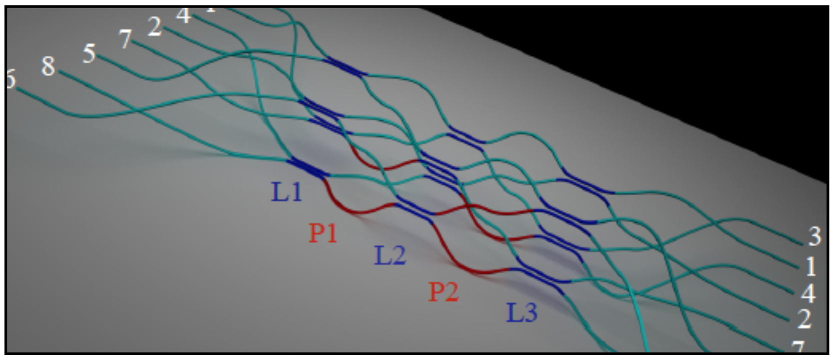
Integrated tritter

N. Spagnolo, et al., Nature Communications 4, 1606 (2013)



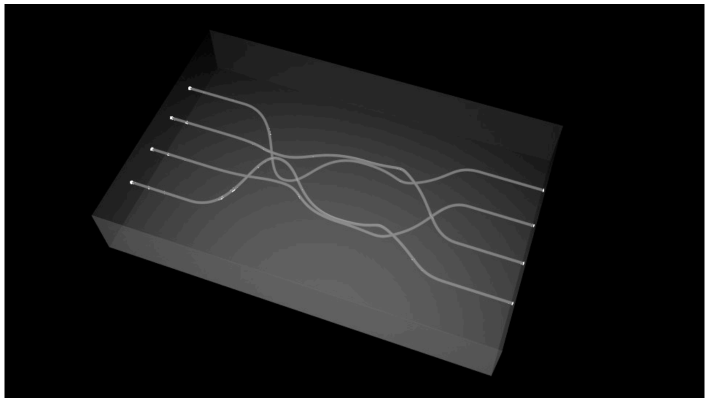
On chip quantum maze

F. Caruso et al., Nature Communications 7, 11682 (2016)



Fast fourier transform

A. Crespi, et al., Nature Communications 7, 10469 (2016)



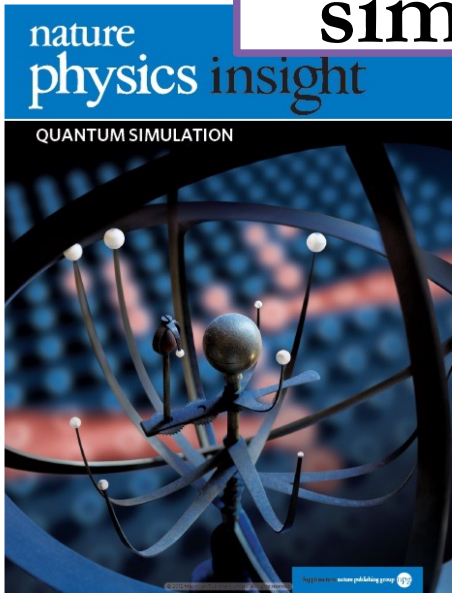
Sylvester interferometers

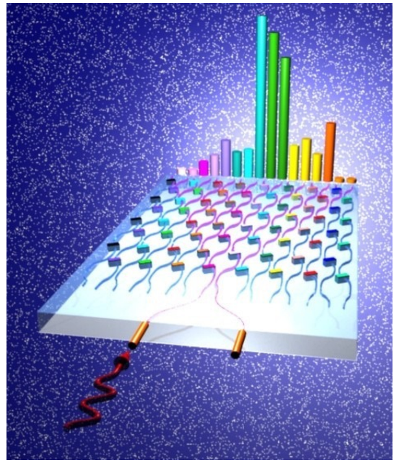
N. Viggianiello, et al., [arXiv:1705.08650].

Quantum computation

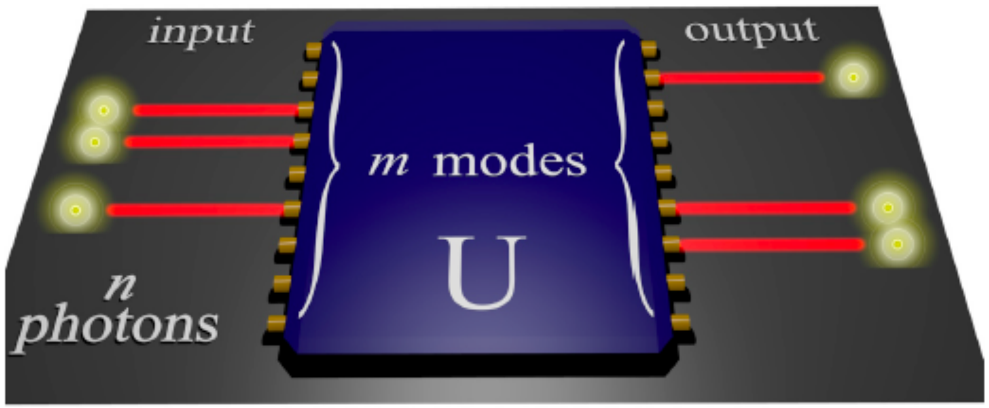
- logical gate
- quantum algorithms

Quantum simulation

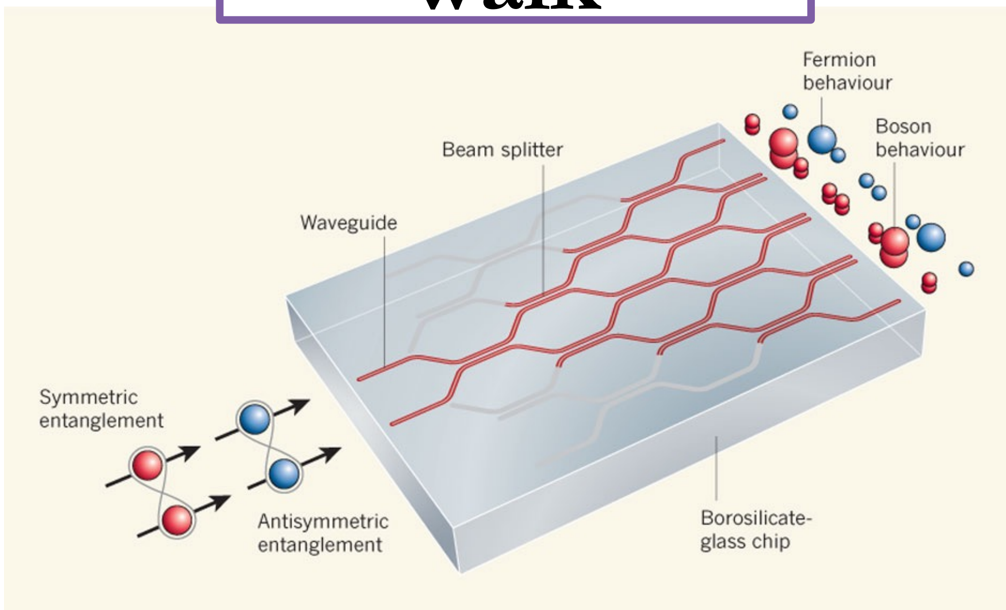




Boson Sampling

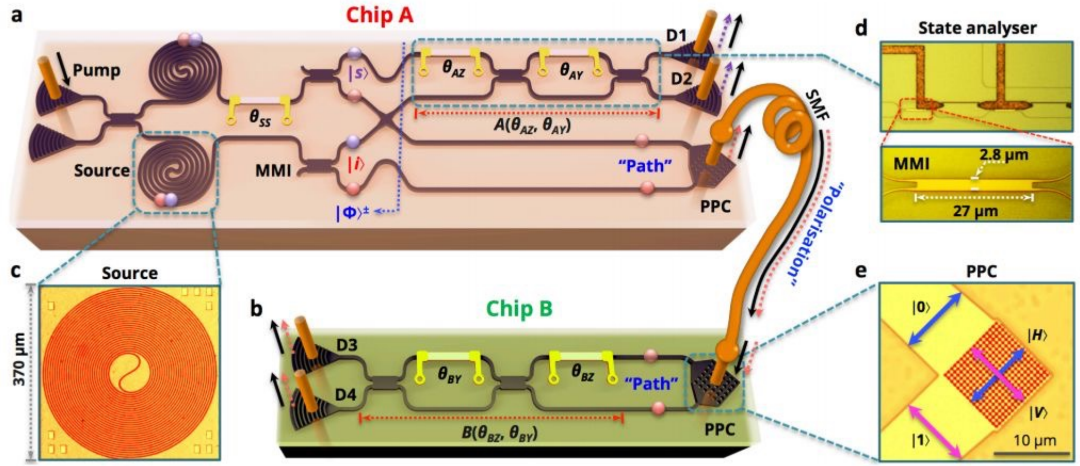


Quantum walk

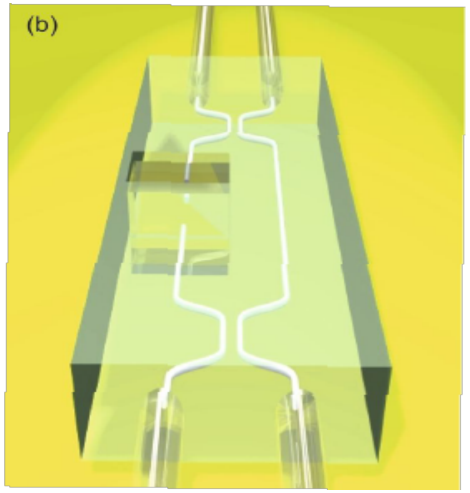


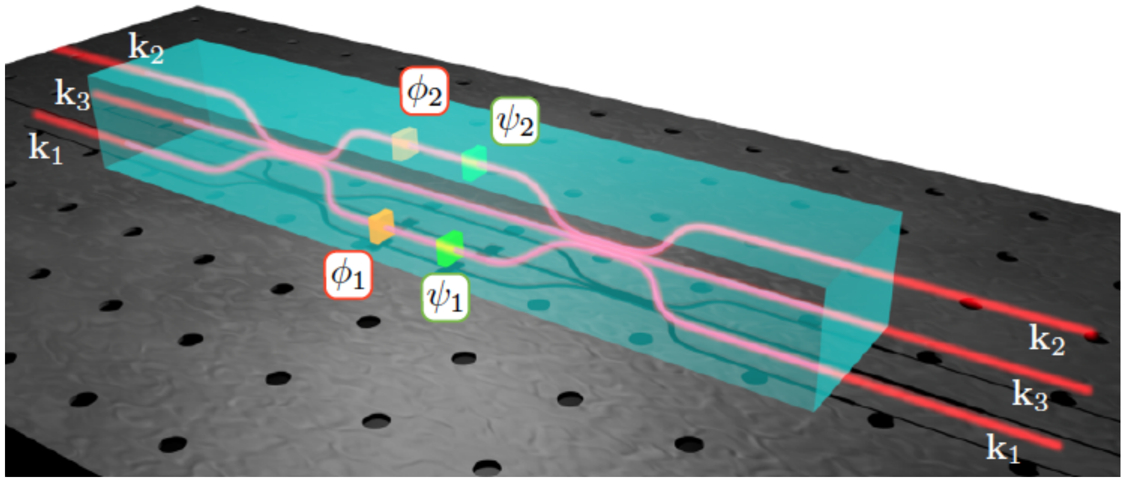
Quantum communication

Fundamental science



Quantum metrology and sensing

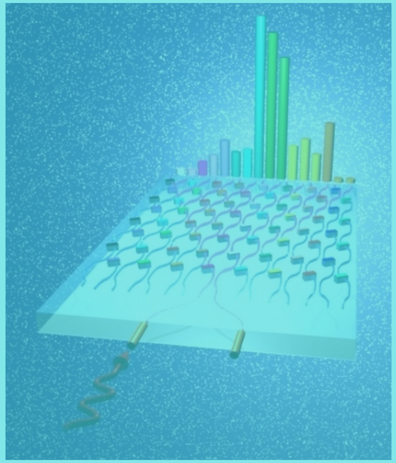




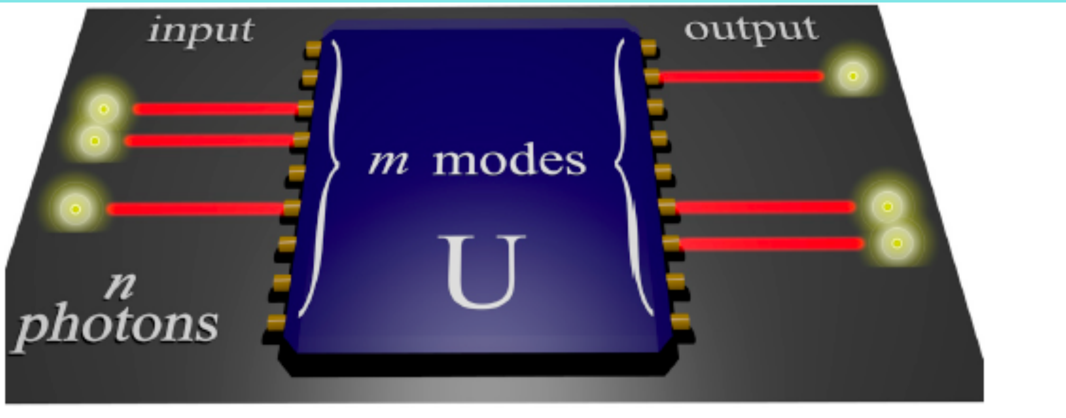
Quantum computation

- logical gate
- quantum algorithms

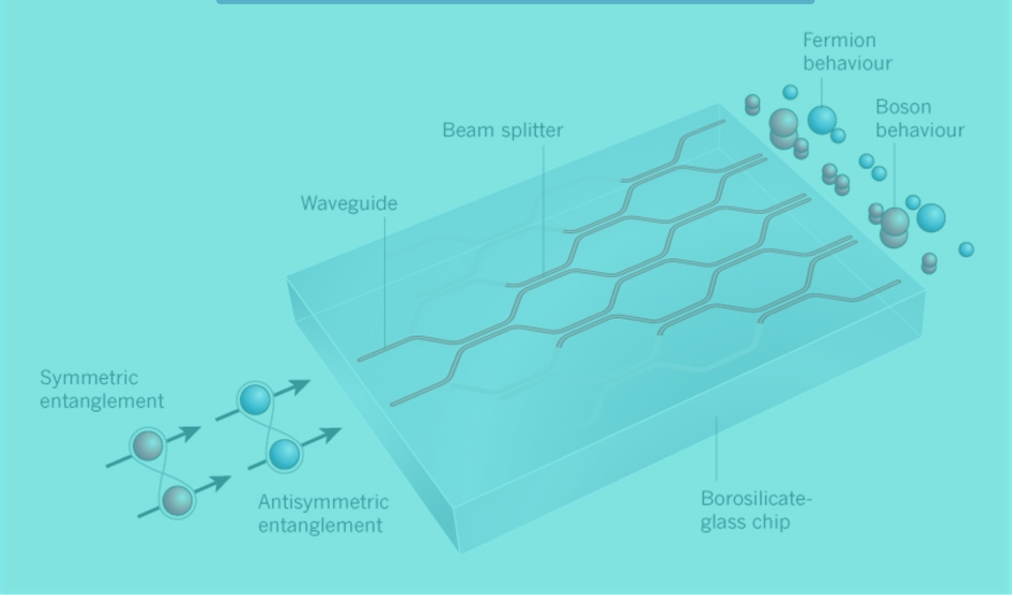
Quantum simulation



Boson Sampling

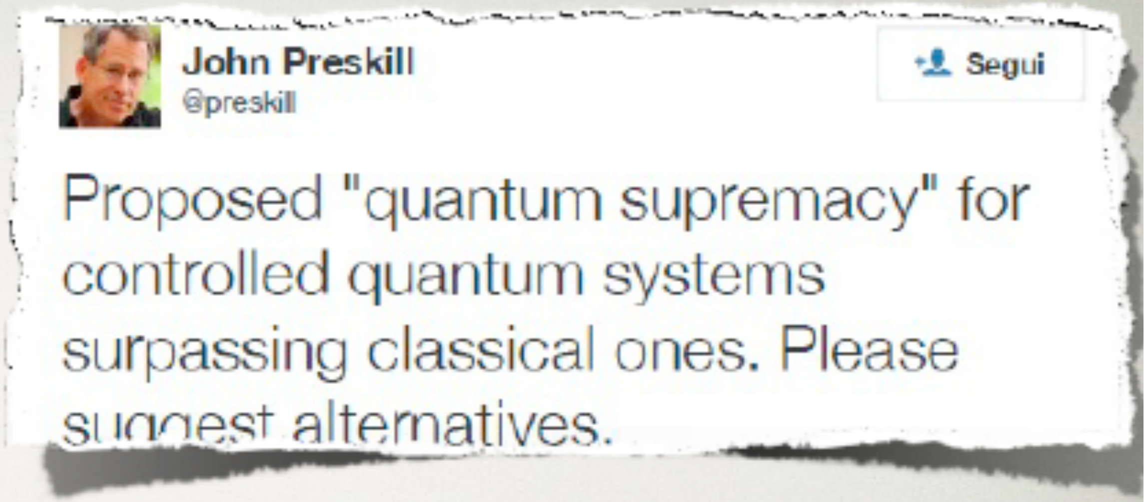


Quantum walk



How to achieve QUANTUM SUPREMACY ??

(QUANTUM ADVANTAGE)



How to achieve quantum supremacy ??

(quantum advantage)

John Preskill
@preskill
Segui

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.

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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 ≠ 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.

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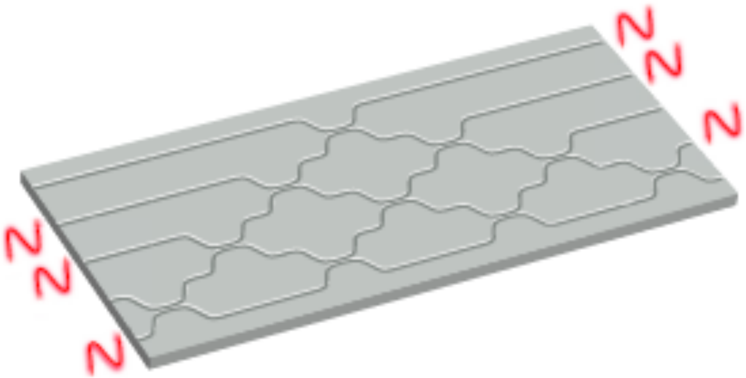
BOX 1

Boson sampling

Boson sampling[9] is a formalization of the problem of simulating non-interacting photons in linear optics; see Box 1 Figure below. n coincident photons are input into a linear-optical network on $m \gg n$ modes (usually generated at random), with detectors positioned at the output of the network. The challenge is to sample from the distribution on detection outcomes. Following the initial theoretical proposal of Aaronson and Arkhipov[9], several experimental groups quickly demonstrated small-scale examples of boson sampling experiments, with up to four coincident photons in up to six modes[46-49]. Subsequent work has experimentally validated boson sampling, in the sense of implementing statistical tests that distinguish the boson sampling distribution from other particular distributions[34,50]. The current records for implementation of arbitrary linear-optical transformations are six modes with up to six photons[51] or nine modes with up to five photons[34,50,52].

Initial boson-sampling experiments used single-photon sources based on spontaneous parametric downconversion. This is a randomized process that has inherently poor scaling with the number of photons, requiring exponential time in the number of photons for each valid experimental run. A variant of boson sampling known as 'scattershot' boson sampling has therefore been proposed. This uses many sources, each of which produces a photon with some small probability, and it is known in which modes a photon has been produced. Scattershot boson sampling has been implemented with 6 sources and 13 modes[53]. An alternative approach is to use a high-performance quantum dot source[52]. Challenges faced by experimental implementations of boson sampling include handling realistic levels of loss in the network, and the possibility of the development of more efficient classical sampling techniques.

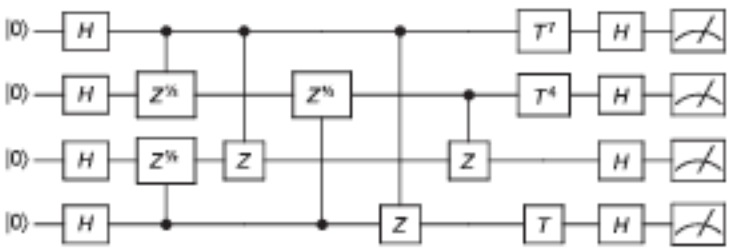


Box 1 Figure | Diagram of a boson sampling experiment. Photons (red waveforms) are injected on the left-hand side into a network of beamsplitters (shown black) that is set up to generate a random unitary transformation. Photons are detected on the right-hand side according to a probability distribution conjectured to be hard to sample from classically. Photonic modes are represented by lines, and beamsplitters are represented by two lines coming together, corresponding to directional couplers in an integrated photonic circuit.

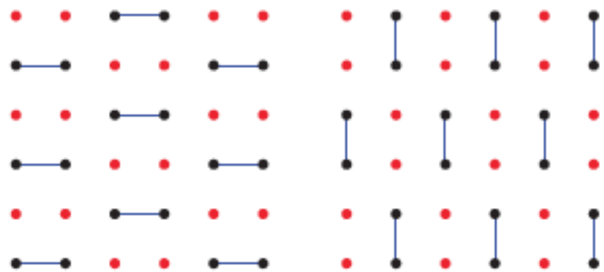
BOX 2

Random quantum circuits

Unlike boson sampling, some quantum-supremacy proposals remain within the standard quantum circuit model. In the model of commuting quantum circuits[10] known as IQP (instantaneous quantum polynomial-time), one considers circuits made up of gates that all commute, and in particular are all diagonal in the X basis; see Box 2 Figure below. Although these diagonal gates may act on the same qubit many times, as they all commute, in principle they could be applied simultaneously. The computational task is to sample from the distribution on measurement outcomes for a random circuit of this form, given a fixed input state. Such circuits are both potentially easier to implement than general quantum circuits and have appealing theoretical properties that make them simpler to analyse[11,18]. However, this very simplicity may make them easier to simulate classically too. Of course, one need not be restricted to commuting circuits to demonstrate supremacy. The quantum-AI group at Google has recently suggested an experiment based on superconducting qubits and non-commuting gates[12]. The proposal is to sample from the output distributions of random quantum circuits, of depth around 25, on a system of around 49 qubits arranged in a 2D square lattice structure (see Fig. 1). It has been suggested[12] that this should be hard to simulate, based on (a) the absence of any known simulation requiring less than a petabyte of storage, (b) IQP-style theoretical arguments[18] suggesting that larger versions of this system should be asymptotically hard to simulate, and (c) numerical evidence[12] that such circuits have properties that we would expect in hard-to-simulate distributions. If this experiment were successful, it would come very close to being out of reach of current classical simulation (or validation, for that matter) using current hardware and algorithms.



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.



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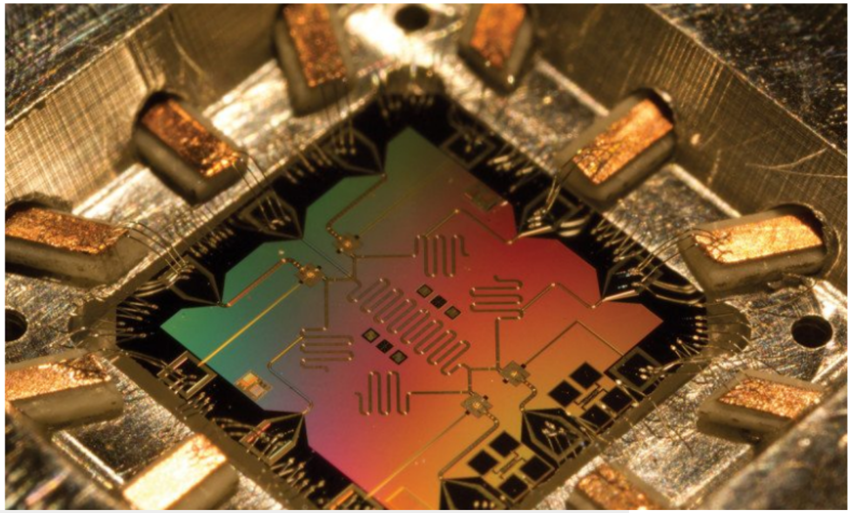
THIS WEEK 31 August 2016

Revealed: Google's plan for quantum computer supremacy

The field of quantum computing is undergoing a rapid shake-up, and engineers at Google have quietly set out a plan to dominate



MIT Technology Review

Intelligent Machines

Google Reveals Blueprint for Quantum Supremacy

The ability of quantum machines to outperform classical computers is called quantum supremacy. Now Google says it

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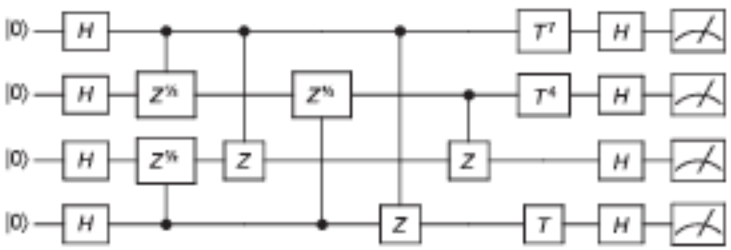

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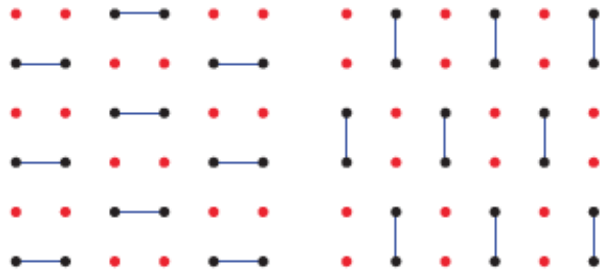

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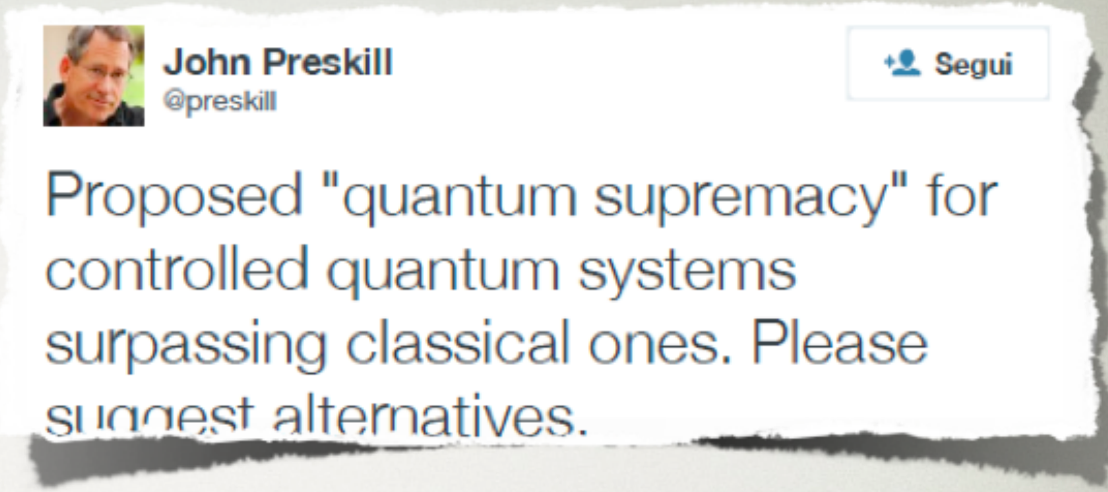
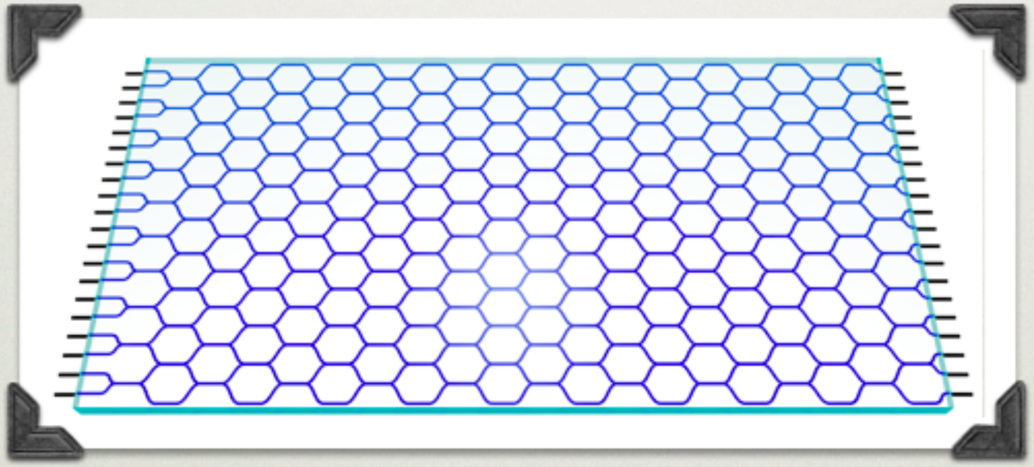


BOSON SAMPLING

propagation on the chip with m modes

Input:
***n* bosons**



Output:
***n*-photon 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)

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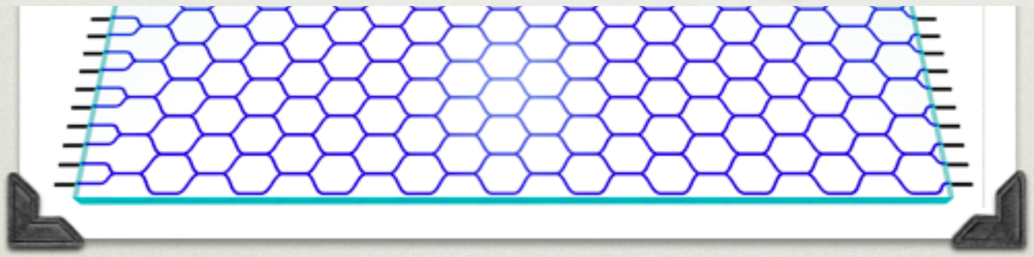
BOSON SAMPLING

The Extended Church-Turing (ECT) Thesis

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

Can we experimentally disproof the ECT thesis ?

***n* bosons**



***n*-photon state**

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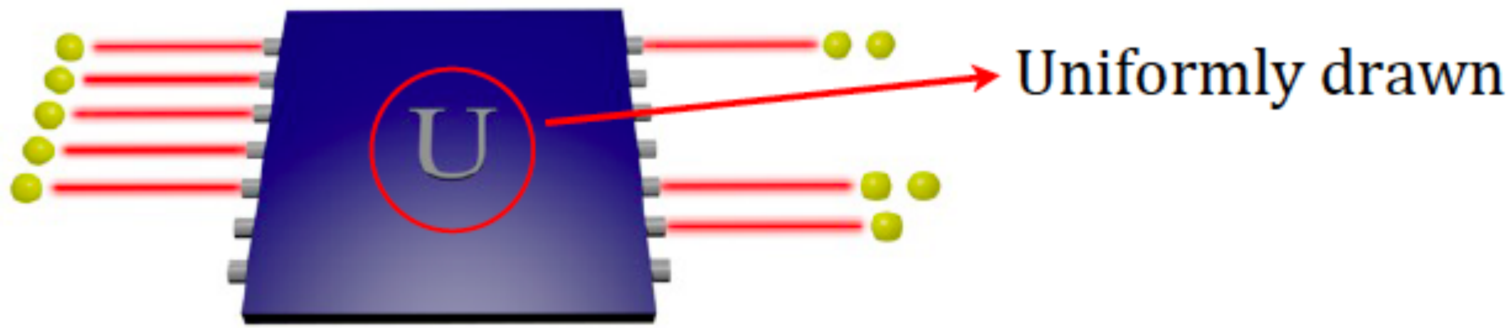
Arkhipov and Aaronson, The Computational Complexity of Linear Optics Proceedings of the Royal Society (2011)

Boson Sampling

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

n bosons
m modes



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

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

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

Boson Sampling

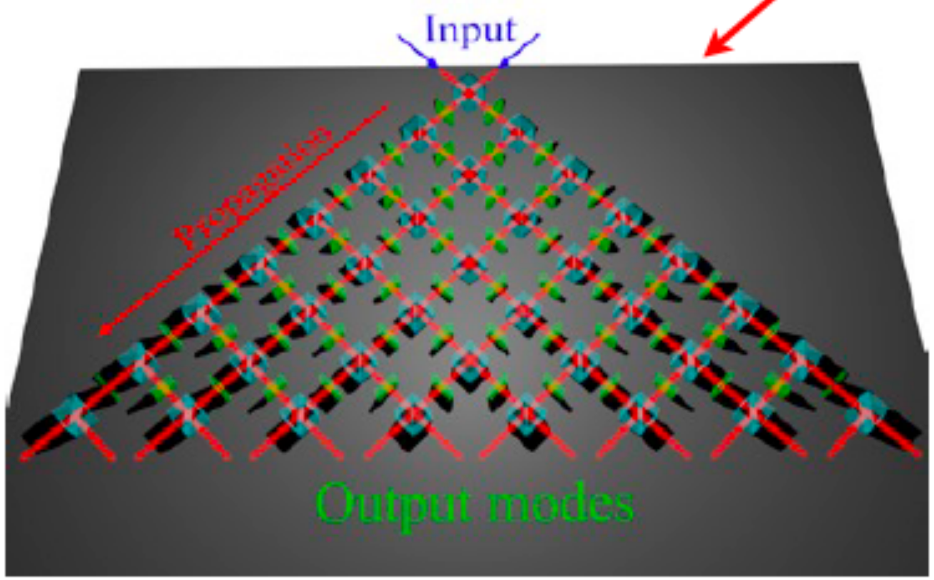
Photons naturally solve the BosonSampling problem

<u>Experimental platform</u>: 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

SAPIENZA Università di Roma

Universidade Federal Fluminense

Consiglio Nazionale delle Ricerche

Politecnico Milano

nature photonics LETTERS
PUBLISHED ONLINE: XX XX 2013 | DOI: 10.1038/NPHOTON.2013.112

Integrated multimode interferometers with arbitrary designs for photonic boson sampling

Andrea Crespi[1,2], Roberto Osellame[1,2]*, Roberta Ramponi[1,2], Daniel J. Brod[3], Ernesto F. Galvão[3]*, Nicolò Spagnolo[4], Chiara Vitelli[4,5], Enrico Maiorino[4], Paolo Mataloni[4] and Fabio Sciarrino[4]*

The evolution of bosons undergoing arbitrary linear unitary transformations quickly becomes hard to predict using classical computers as we increase the number of particles and modes. Photons propagating in a multiport interferometer naturally solve this so-called boson sampling problem[1], thereby motivating the development of technologies that enable precise control of multiphoton interference in large interferometers[2–4]. Here, we use novel three-dimensional manufacturing techniques to achieve simultaneous control of all the parameters describing

proportional to the permanent of a matrix associated with the interferometer (see Methods for details), and the permanent is a function that is notoriously hard to compute[10]. In ref. 1 it was estimated that a system of approximately 20 photons in $m \approx 400$ modes would already take noticeably long to simulate classically. Q4 At present, the most promising technology for achieving this regime involves inputting Fock states into multimode integrated photonic chips[2–4,11–13].

In this Letter we report on the experimental implementation of

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University of Southampton

UNIVERSITY OF LONDON

Shanghai Jiao Tong University

Boson Sampling on a Photonic Chip

Justin B. Spring,[1]* Benjamin J. Metcalf,[1] Peter C. Humphreys,[1] W. Steven Kolthammer,[1] Xian-Min Jin,[1,2] Marco Barbieri,[1] Animesh Datta,[1] Nicholas Thomas-Peter,[1] Nathan K. Langford,[1,3] Dmytro Kundys,[4] James C. Gates,[4] Brian J. Smith,[1] Peter G. R. Smith,[4] Ian A. Walmsley[1]*

Although universal quantum computers ideally solve problems such as factoring integers exponentially more efficiently than classical machines, the formidable challenges in building such devices motivate the demonstration of simpler, problem-specific algorithms that still promise a quantum speedup. We constructed a quantum boson-sampling machine (QBSM) to sample the output distribution resulting from the nonclassical interference of photons in an integrated photonic circuit, a problem thought to be exponentially hard to solve classically. Unlike universal quantum computation, boson sampling merely requires indistinguishable photons, linear state evolution, and detectors. We benchmarked our QBSM with three and four photons and analyzed sources of sampling inaccuracy. Scaling up to larger devices could offer the first definitive quantum-enhanced computation.

Universal quantum computers require physical systems that are well isolated from

unitary transformation U is thought to be exponentially hard to sample from classically (12). The

modes (18). Such circuits can be rapidly reconfigured to sample from a user-defined operation (19, 20). Importantly, boson sampling requires neither nonlinearities nor on-demand entanglement, which are substantial challenges in photonic universal quantum computation (21). This clears the way for experimental boson sampling with existing photonic technology, building on the extensively studied two-photon Hong-Ou-Mandel interference effect (22).

A QBSM (Fig. 1) samples the output distribution of a multiparticle bosonic quantum state $|\Psi_{out}\rangle$, prepared from a specified initial state $|\mathbf{T}\rangle$ and linear transformation Λ. Unavoidable losses in the system imply Λ will not be unitary, although lossy QBSMs can still surpass classical computation (12, 23). A trial begins with the input state $|\mathbf{T}\rangle = |T_1 \ldots T_M\rangle \propto \Pi_{i=1}^{M} (\hat{a}_i^\dagger)^{T_i} |0\rangle$, which describes $N = \sum_{i=1}^{M} T_i$ particles distributed in M input modes in the occupation-number representation. The output state $|\Psi_{out}\rangle$ is generated

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nature photonics LETTERS
PUBLISHED ONLINE: 12 MAY 2013 | DOI: 10.1038/NPHOTON.2013.102

Experimental boson sampling

Max Tillmann[1,2]*, Borivoje Dakić[1], René Heilmann[3], Stefan Nolte[3], Alexander Szameit[3] and Philip Walther[1,2]*

Universal quantum computers[1] promise a dramatic increase in speed over classical computers, but their full-size realization remains challenging[2]. However, intermediate quantum computational models[3–5] have been proposed that are not universal but can solve problems that are believed to be classically hard. Aaronson and Arkhipov[6] have shown that interference of single photons in random optical networks can solve the hard problem of sampling the bosonic output distribution. Remarkably, this computation does not require measurement-based interactions[7,8] or adaptive feed-forward techniques[9]

photons. Randomly chosen instances of this problem are strongly believed to be hard to solve by classical means. Instances of boson sampling can be realized with quantum systems composed of non-interacting photons that are processed through randomly chosen networks of physical modes. The bosonic nature of the photons leads to non-classical interference, producing an output

a

Massachusetts Institute of Technology

The University of Queensland Australia

To implement a circuit, the subgraphs representing circuit elements are connected by paths. Figure 4 depicts a graph corresponding to a simple two-qubit computation. Timing is important: Wave packets must meet on the vertical paths for interactions to occur. We achieve this by choosing the numbers of vertices on each of the segments in the graph appropriately, taking into account the different propagation speeds of the two wave packets [see section S4 of (32)]. In section S3.1 of (32), we present a refinement of our scheme using planar graphs with maximum degree four.

By analyzing the full $(n + 1)$–particle interacting many-body system, we prove that our algorithm performs the desired quantum computation up to an error term that can be made arbitrarily small (32). Our analysis goes beyond the scattering theory discussion presented above; we take into account the fact that both the wave packets and the graphs are finite. Specifically, we prove that by choosing the size of the wave packets, the number of vertices in the graph, and the total evolution time to be polynomial functions of both n and g, the error in simulating an n-qubit, g-gate

Photonic Boson Sampling in a Tunable Circuit

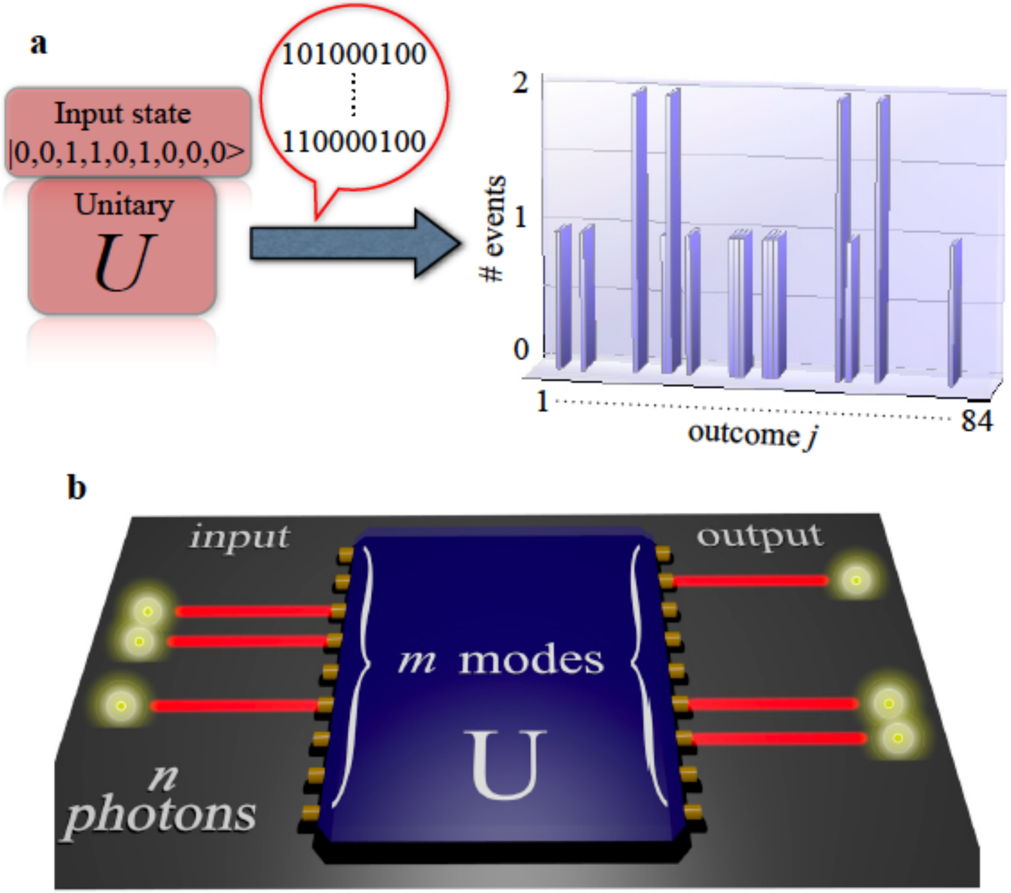
Matthew A. Broome,[1,2]* Alessandro Fedrizzi,[1,2] Saleh Rahimi-Keshari,[2] Justin Dove,[3] Scott Aaronson,[3] Timothy C. Ralph,[2] Andrew G. White[1,2]

Quantum computers are unnecessary for exponentially efficient computation or simulation if the Extended Church-Turing thesis is correct. The thesis would be strongly contradicted by physical devices that efficiently perform tasks believed to be intractable for classical computers. Such a task is boson sampling: sampling the output distributions of n bosons scattered by some passive, linear unitary process. We tested the central premise of boson sampling, experimentally verifying that three-photon scattering amplitudes are given by the permanents of submatrices generated from a unitary describing a six-mode integrated optical circuit. We find the protocol to be robust, working even with the unavoidable effects of photon loss, non-ideal sources, and imperfect detection. Scaling this to large numbers of photons should be a much simpler task than building a universal quantum computer.

A major motivation for scalable quantum computing is Shor's algorithm (1), which enables the efficient factoring of

puters are realistic physical devices, then the Extended Church-Turing (ECT) thesis—that any function efficiently computed on a realistic

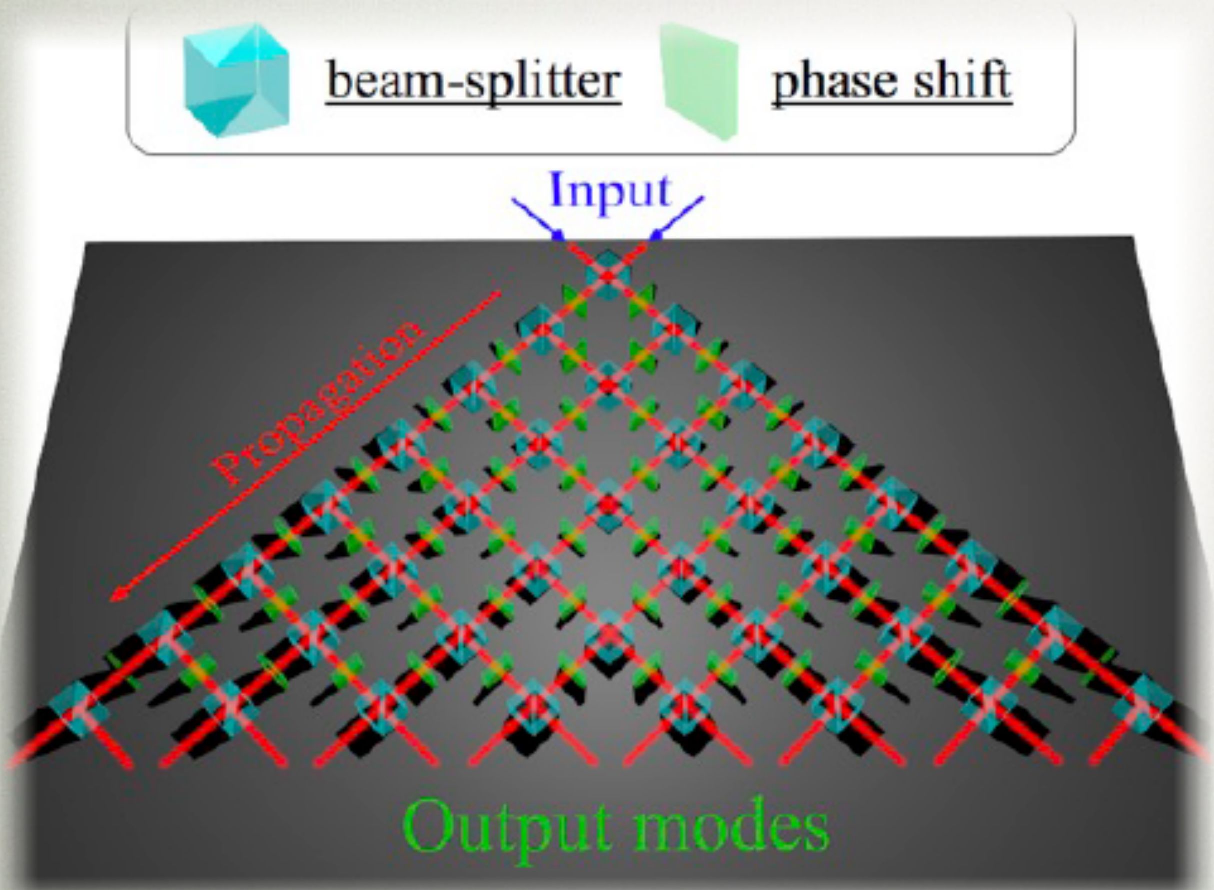
Boson Sampling

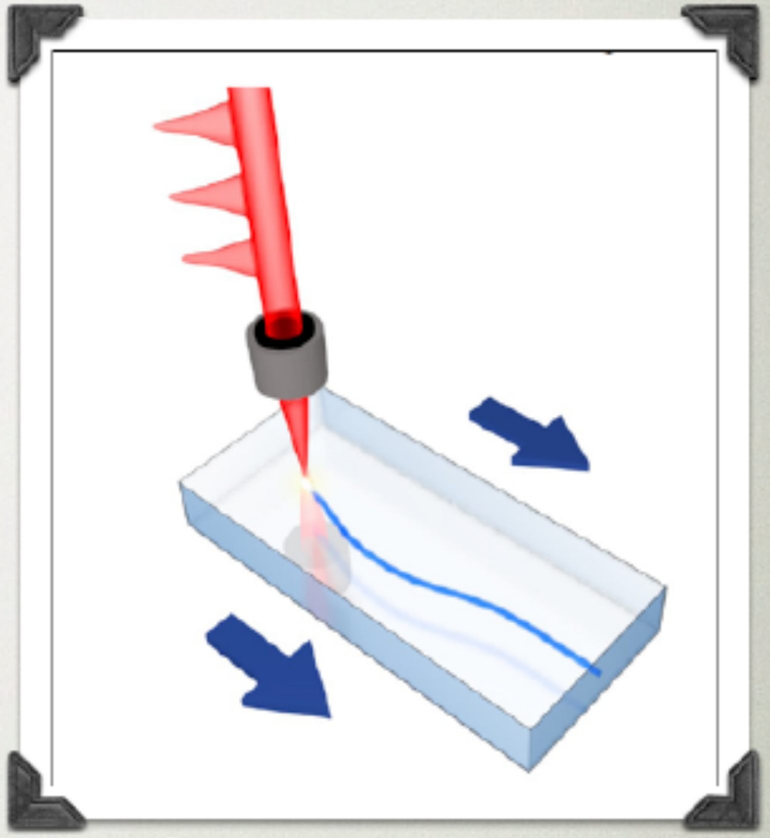


interconnected waveguides on a glass chip can now perform a task that is considerec

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

THE SOLUTION: INTEGRATED PHOTONICS



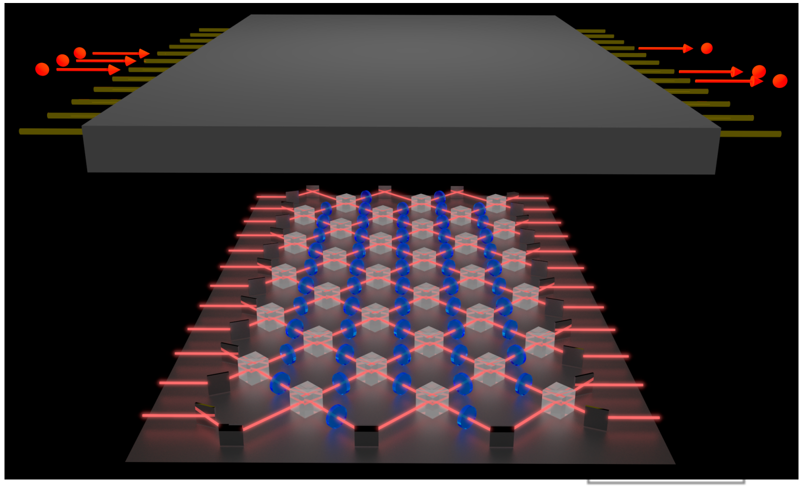


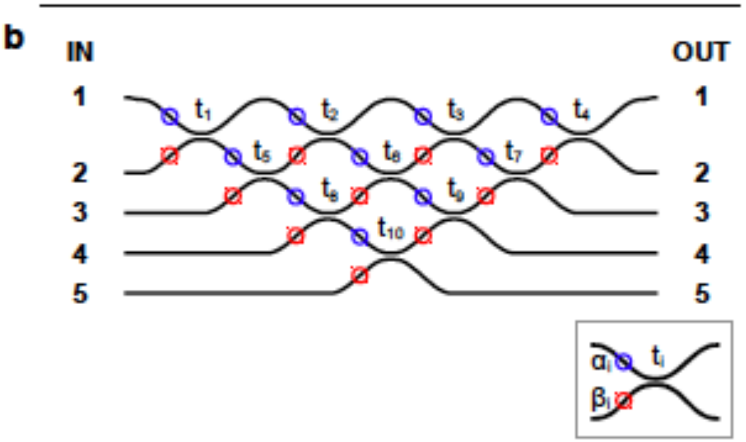
Laser writing technology:
unique capability to transmit any polarization state

- Femtosecond pulse tightly focused in a glass
- Waveguides writing by translation of the sample

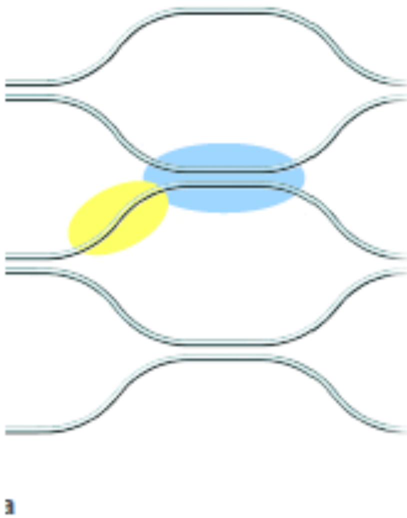
Boson Sampling: chip

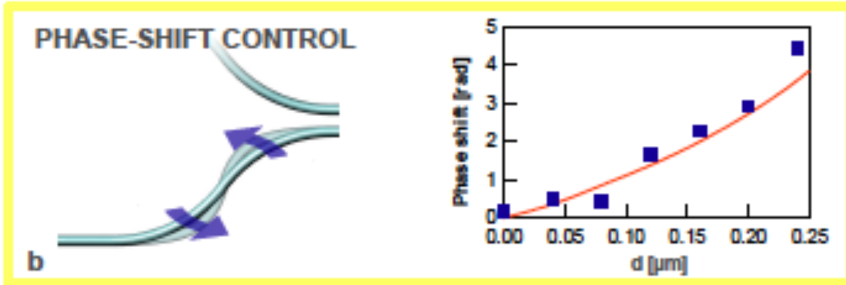
Requirement for Boson Sampling - design arbitrary interferometers → Requires independent control of phases and beam-splitter operation

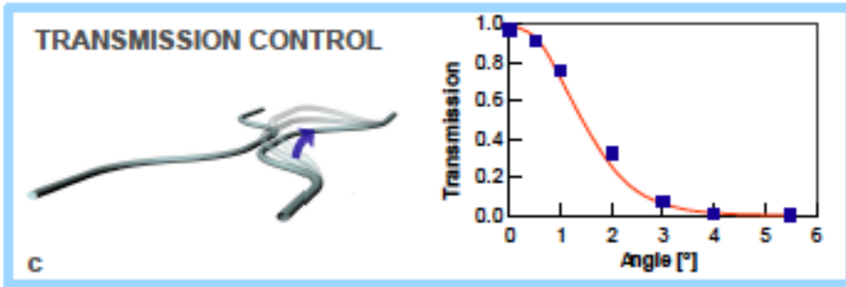




Fabrication process







Reck, et al., *PRL* **73**, 58 (1994)

Boson Sampling: chip

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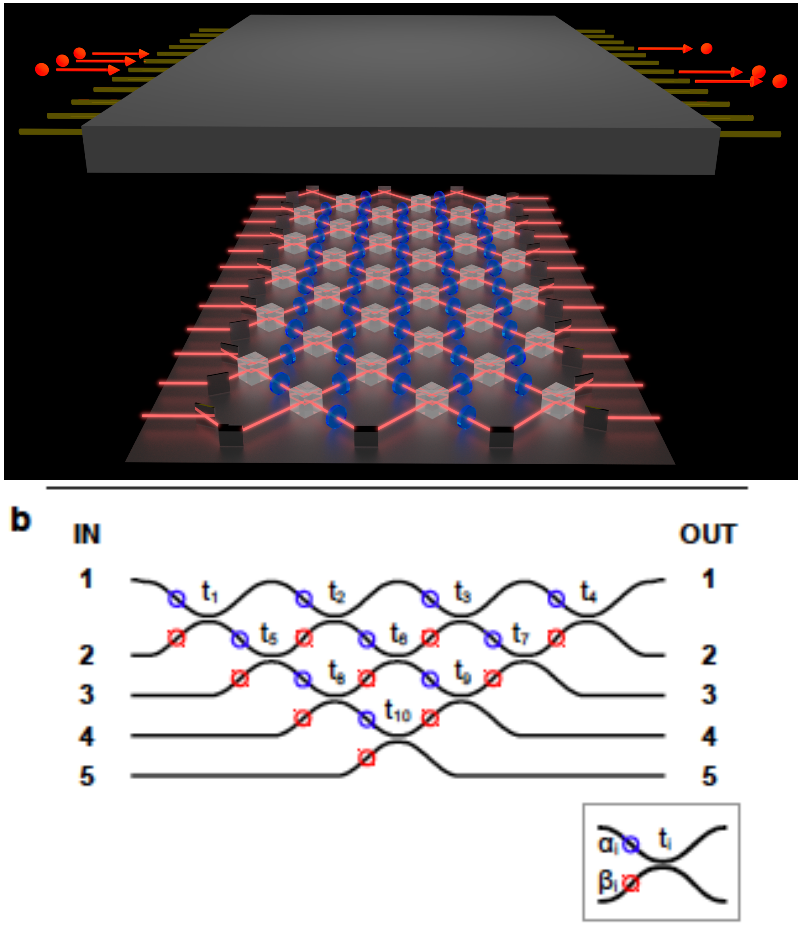
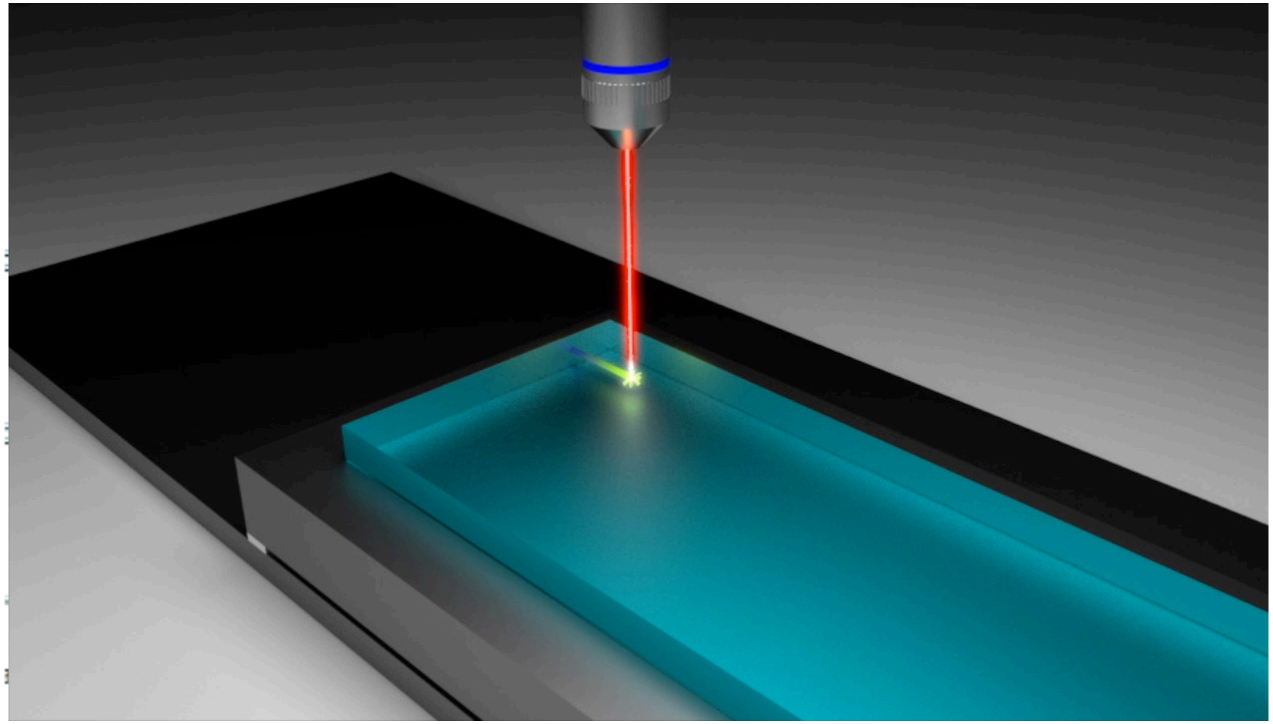
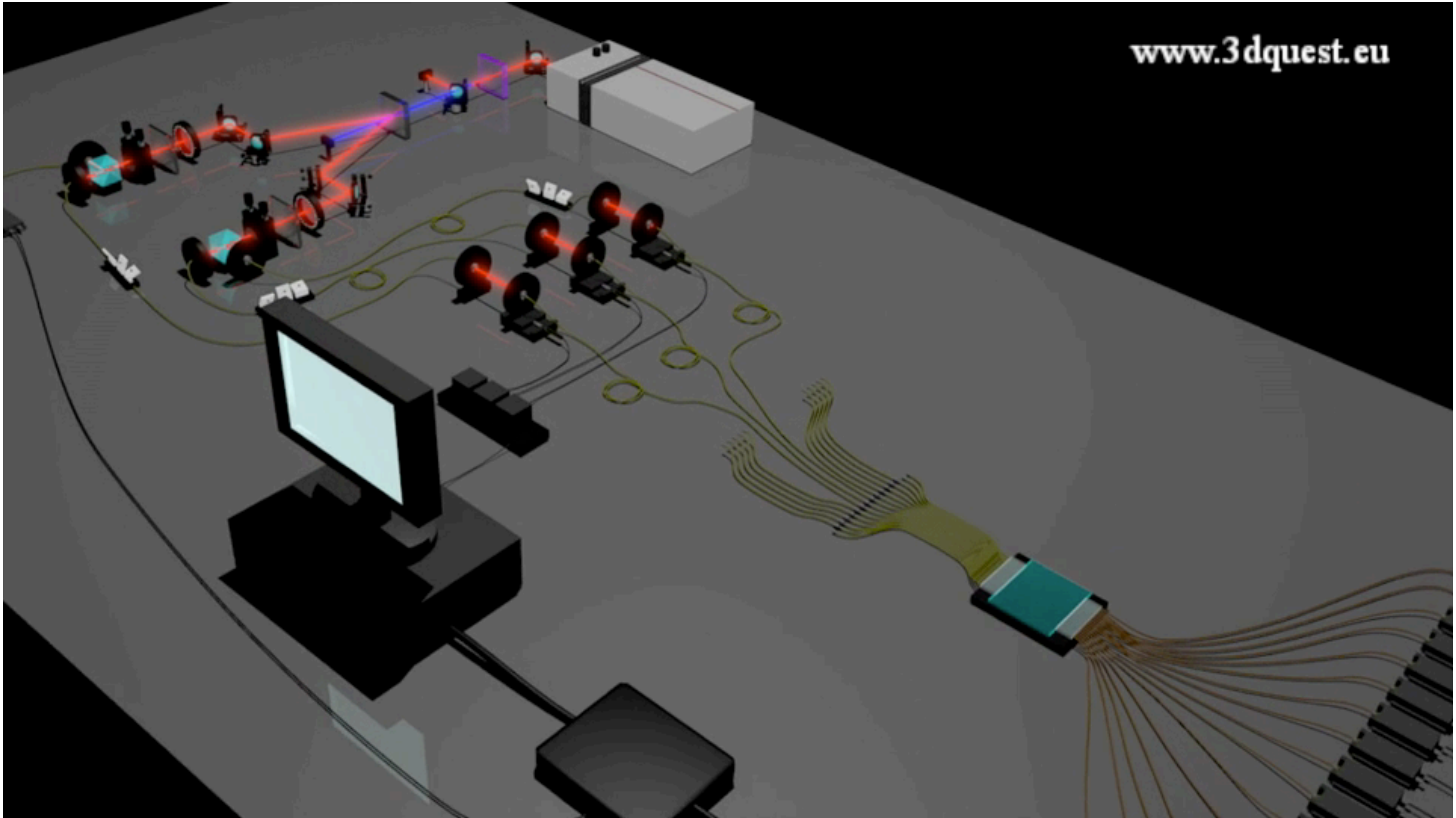
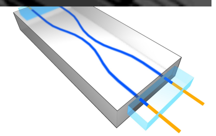




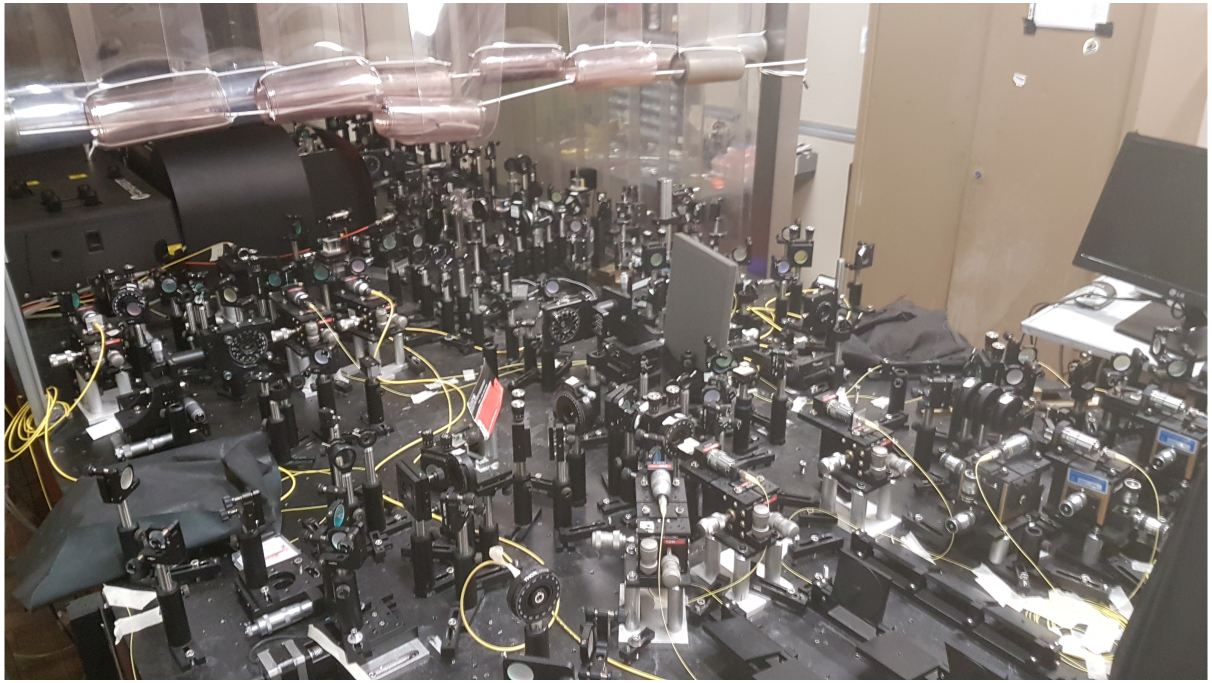
Reck, et al., *PRL* **73**, 58 (1994)

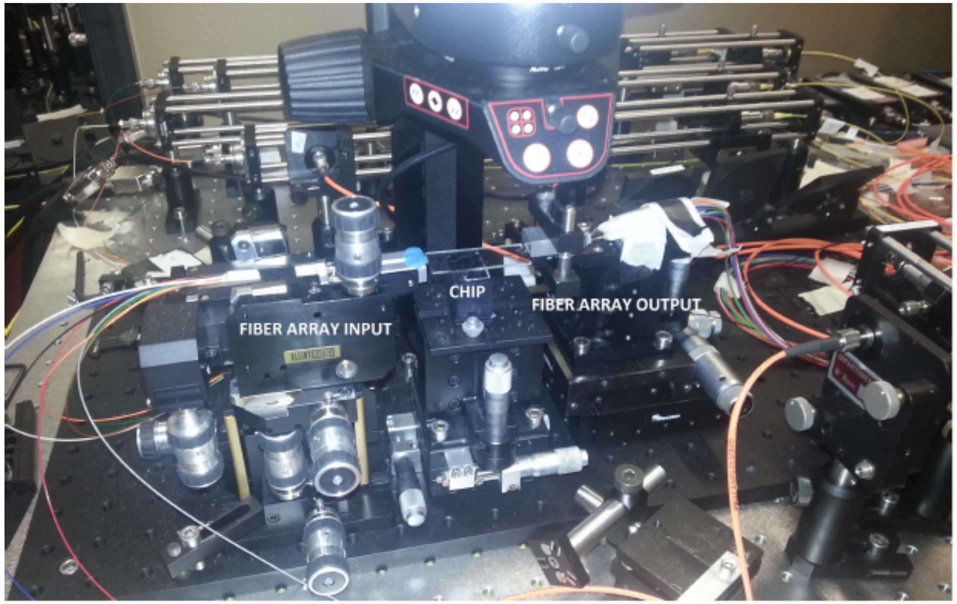
Boson sampling experiment….

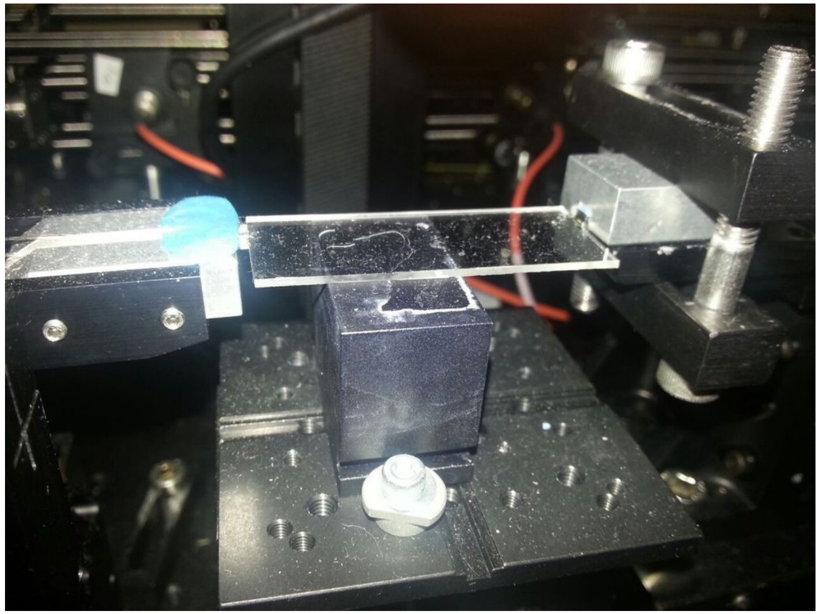




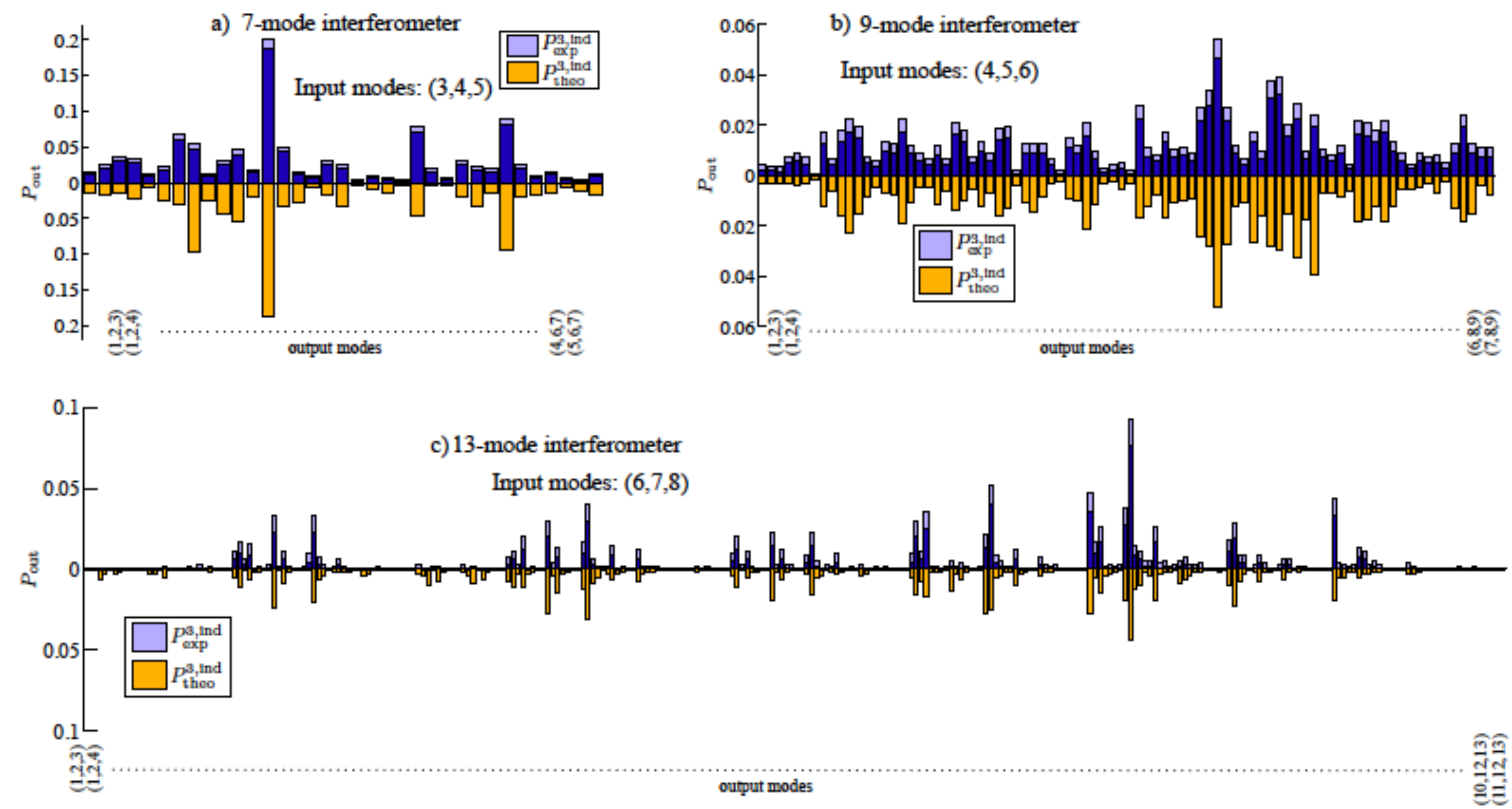
Boson sampling: the lab....







Experimental results with larger chips



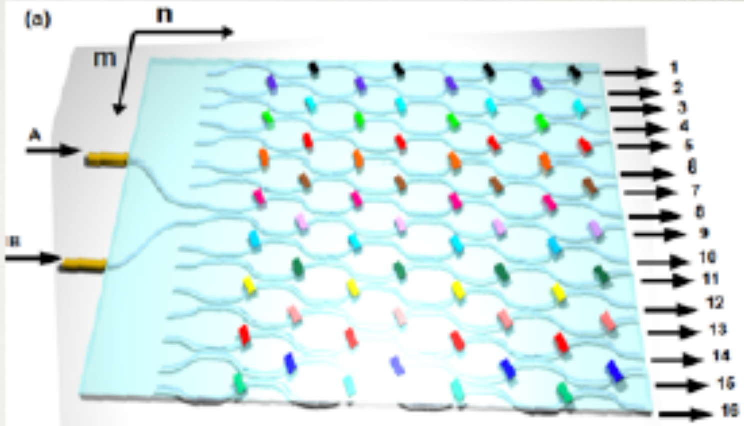
N. Spagnolo, C. Vitelli, M. Bentivegna, D. J. Brod, A. Crespi, F. Flamini, S. Giacomini, G. Milani, R. Ramponi, P. Mataloni, R. Osellame, E. F. Galvao, and F. Sciarrino, *Nature Photonics* **8**, 614 (2014)

First experimental results with integrated photonics :

nature photonics LETTERS
PUBLISHED ONLINE: 26 MAY 2013 | DOI: 10.1038/NPHOTON.2013.112

Integrated multimode interferometers with arbitrary designs for photonic boson sampling

Andrea Crespi[1,2], Roberto Osellame[1,2*], Roberta Ramponi[1,2], Daniel J. Brod[3], Ernesto F. Galvão[3*], Nicolò Spagnolo[4], Chiara Vitelli[4,5], Enrico Maiorino[4], Paolo Mataloni[4] and Fabio Sciarrino[4*]



The Extended Church-Turing (ECT) Thesis

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

Can we experimentally disproof the ECT thesis ?

GOAL: to achieve Boson Sampling with n=10-20 photons and m=100-200 modes

Open questions:

- How to increase the complexity of Boson sampling ?
- Does it exist simpler experimental schemes achieving a similar goal?
- How to certify the well-functioning of boson-sampling experiment?
. How realistic noise and imperfections affect the hardness claim?

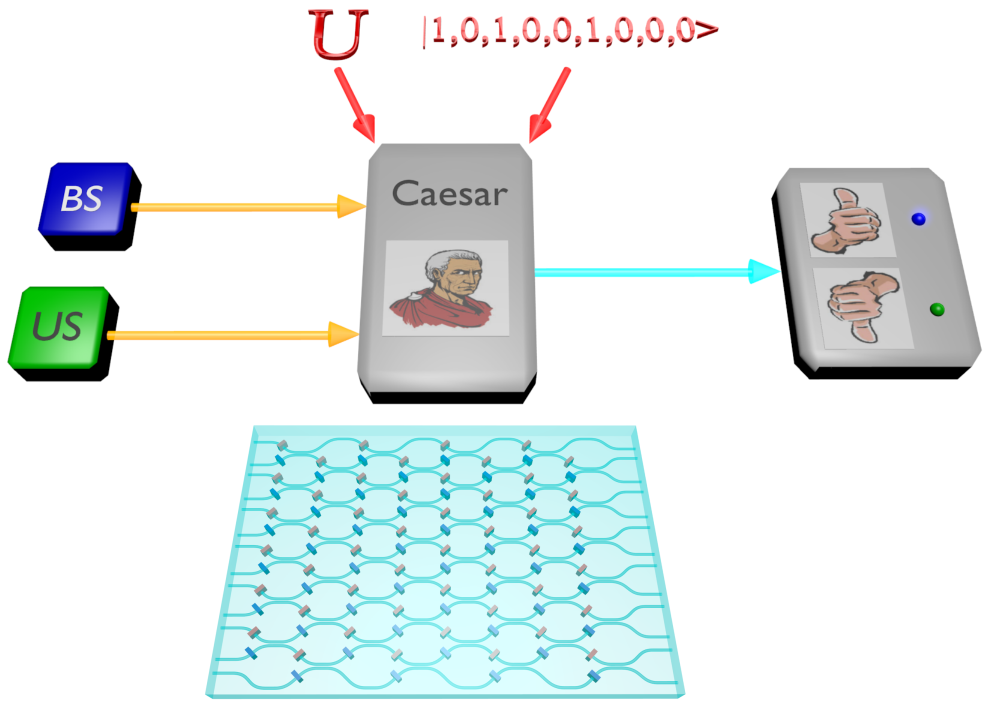
Challenges

- Single photon sources
- Manipulation on a chip
- Single photon detectors

Validation of the Boson Sampling output

Boson Sampling:
hard problem with classical computer

but may be very hard also to validate/certify!



N. Spagnolo, C. Vitelli, M. Bentivegna, D. J. Brod, A. Crespi, F. Flamini, S. Giacomini, G. Milani, R. Ramponi, P. Mataloni, R. Osellame, E. F. Galvao, and F. Sciarrino, *Nature Photonics* **8**, 614 (2014)
Similar experiment in Bristol: J. Carolan, et al., *Nature Photonics* **8**, 619 (2014)

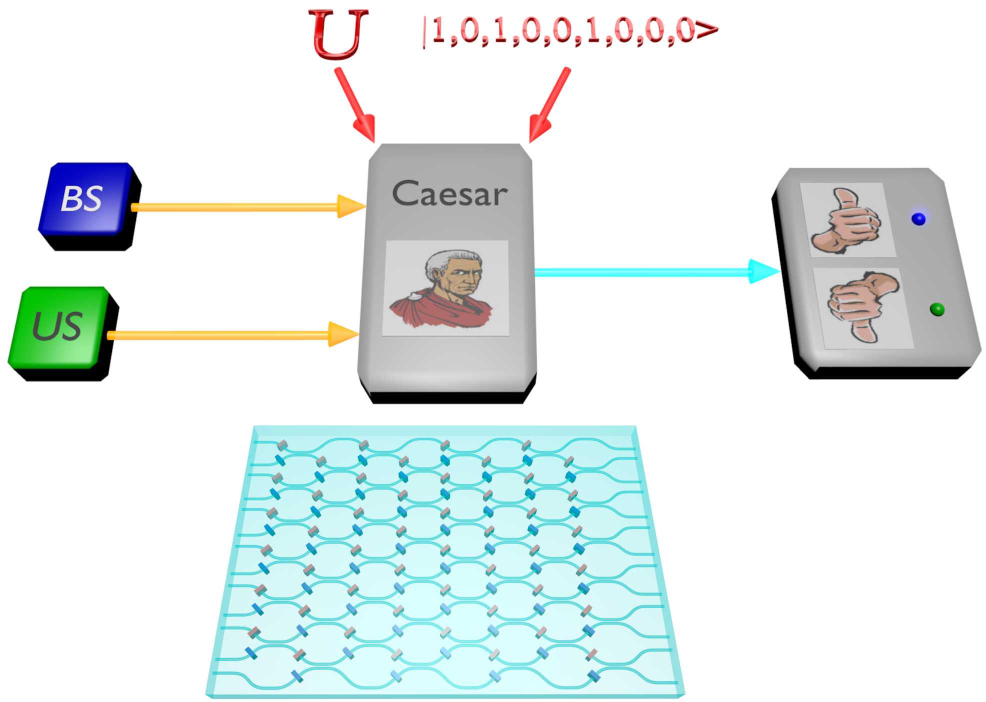
Validation of the Boson Sampling output

Boson Sampling:
hard problem with classical computer

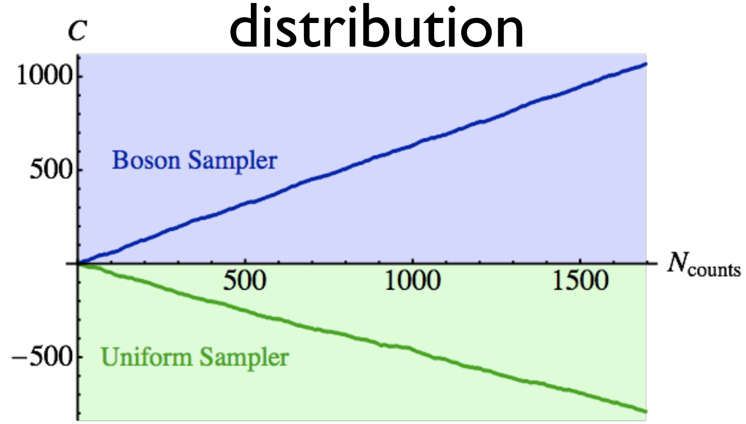
but may be very hard also to validate/certify!

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

First experiments based on Bayesian inference



Validation against the uniform distribution



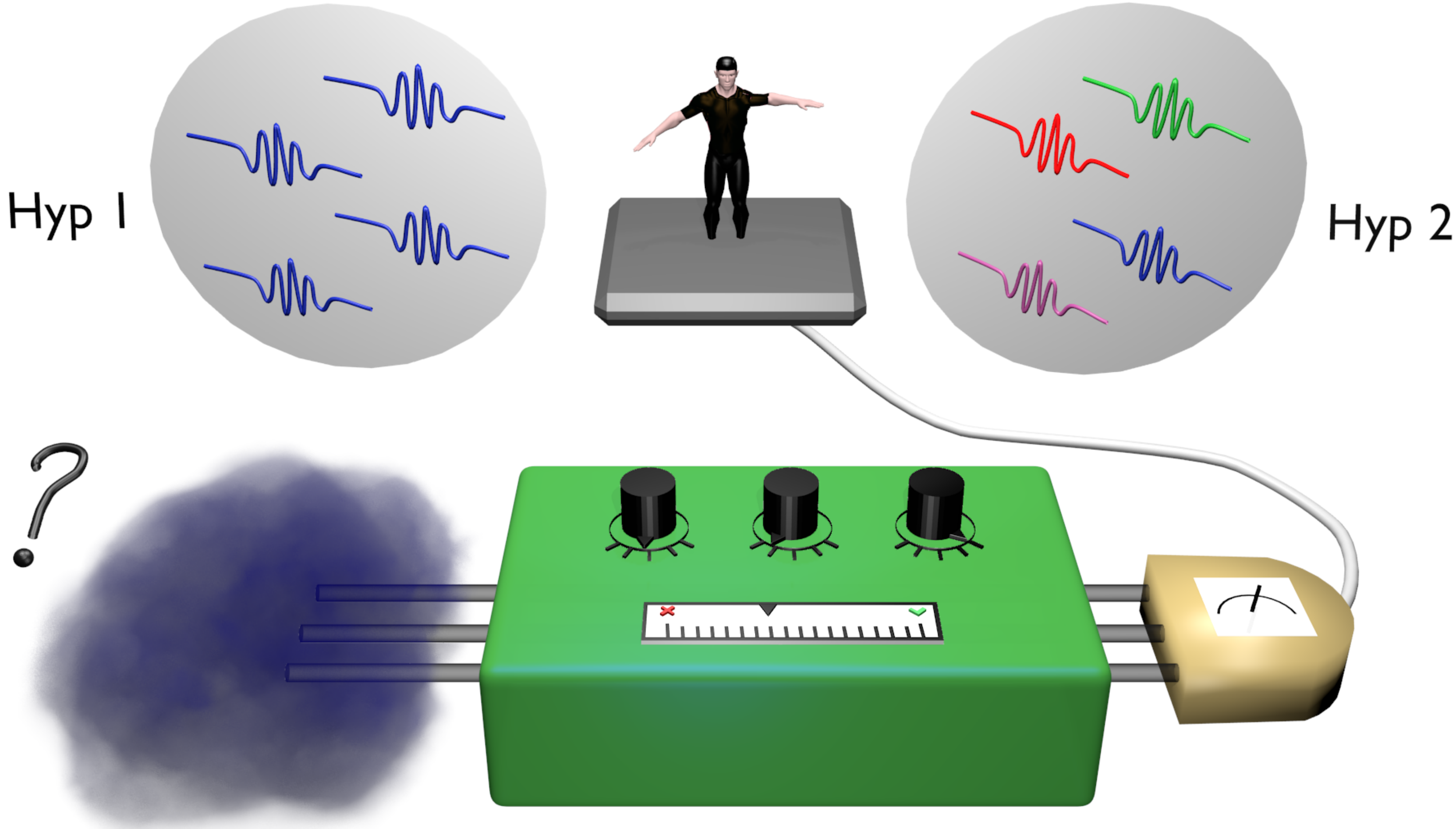
N. Spagnolo, C. Vitelli, M. Bentivegna, D. J. Brod, A. Crespi, F. Flamini, S. Giacomini, G. Milani, R. Ramponi, P. Mataloni, R. Osellame, E. F. Galvao, and F. Sciarrino, *Nature Photonics* **8**, 614 (2014)
Similar experiment in Bristol: J. Carolan, et al., *Nature Photonics* **8**, 619 (2014)

Witness of genuine multi-photon interference

Is it possible to derive a witness able to identify true-many photon interference occurring in Boson Sampling ?

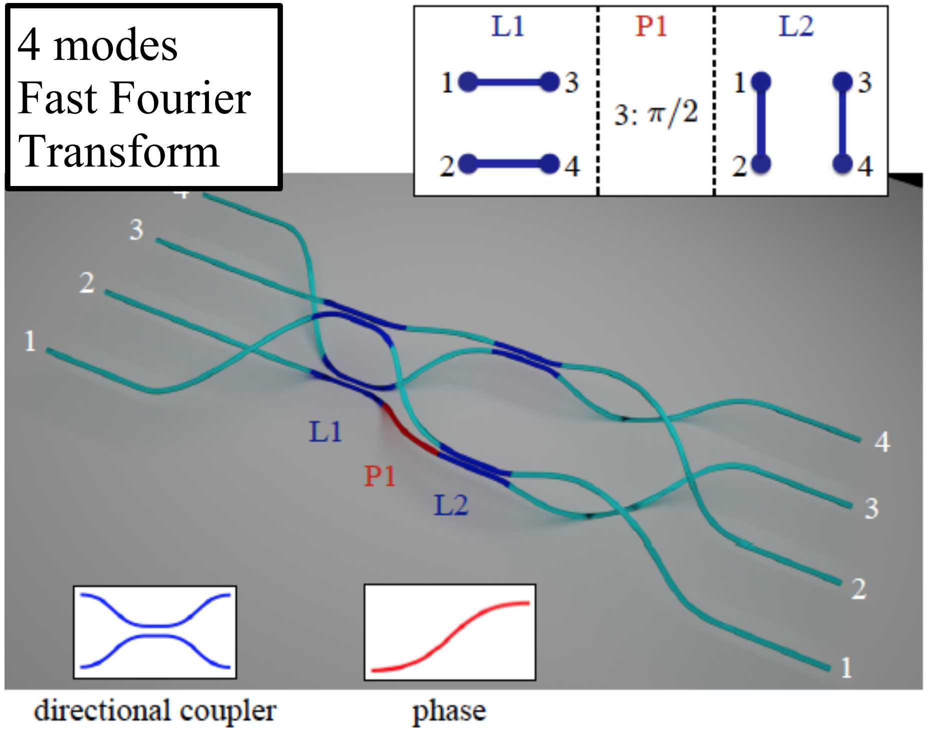
Witness of genuine multi-photon interference

Is it possible to derive a witness able to identify true-many photon interference occurring in Boson Sampling ?



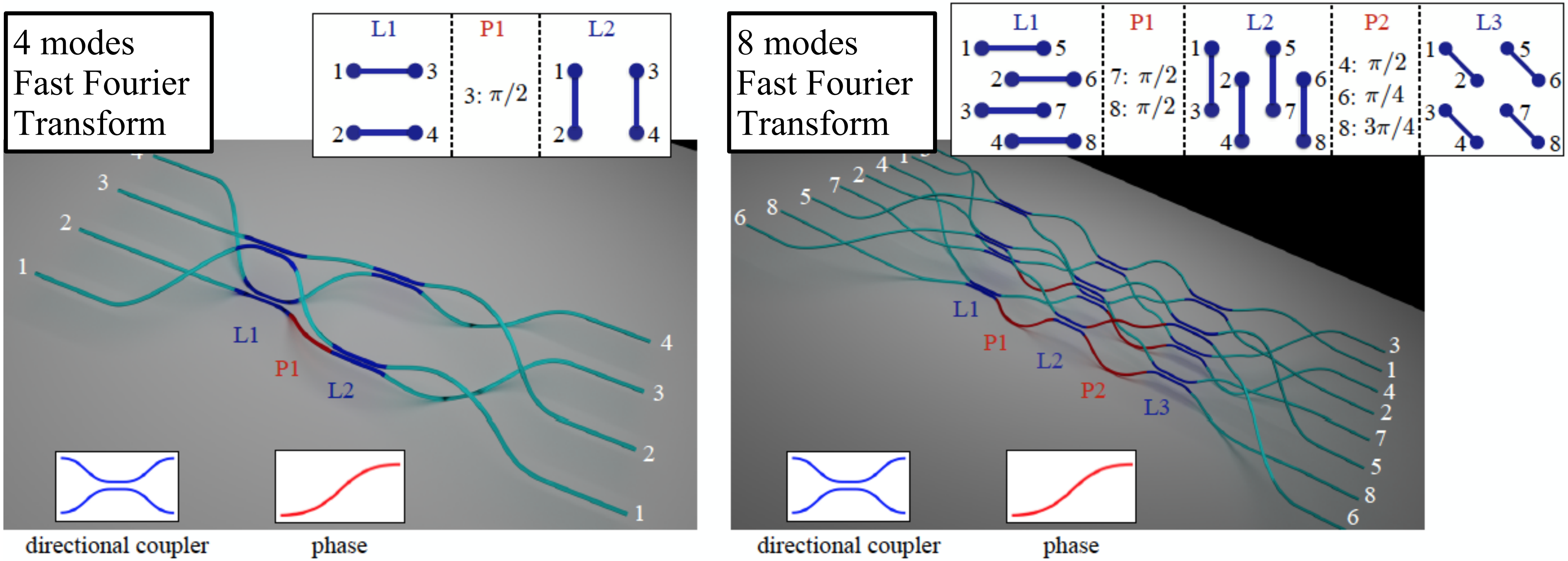
Which is the best device to discriminate between distinguishable and indistinguishable photons?

Implementation of Fast Fourier Transform with 3D-integrated photonics



Crespi, Osellame, Ramponi, Bentivegna, Flamini, Spagnolo, Viggianiello, Innocenti, Mataloni, and Sciarrino "Quantum suppression law in a 3-D photonic chip implementing the Fast Fourier Transform", *Nature Communications* **7**, 10469 (2016).

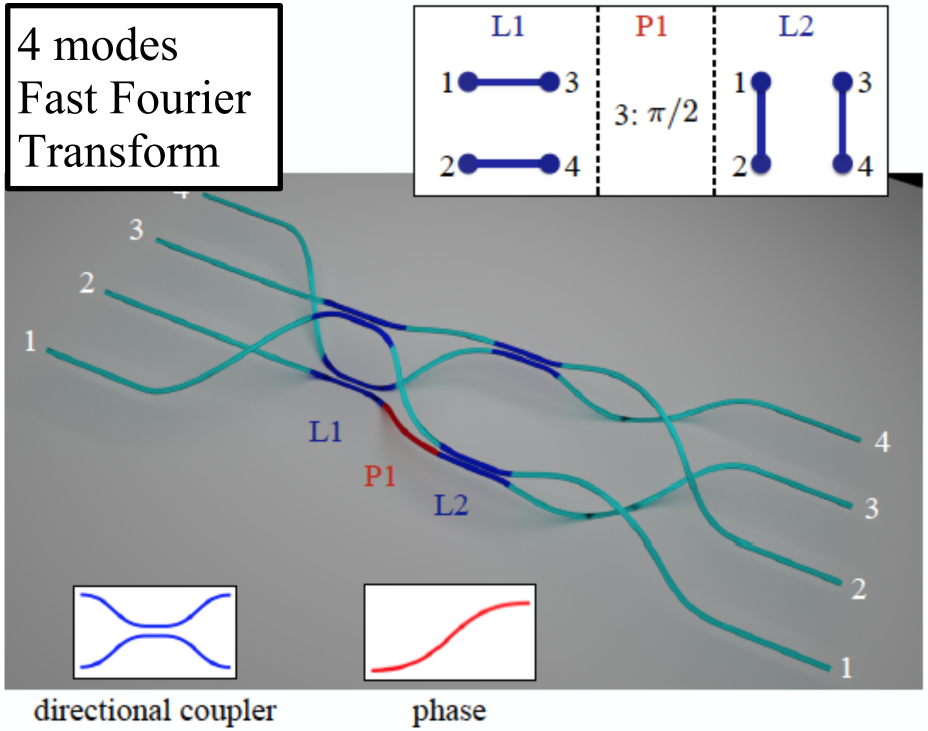
Implementation of Fast Fourier Transform with 3D-integrated photonics

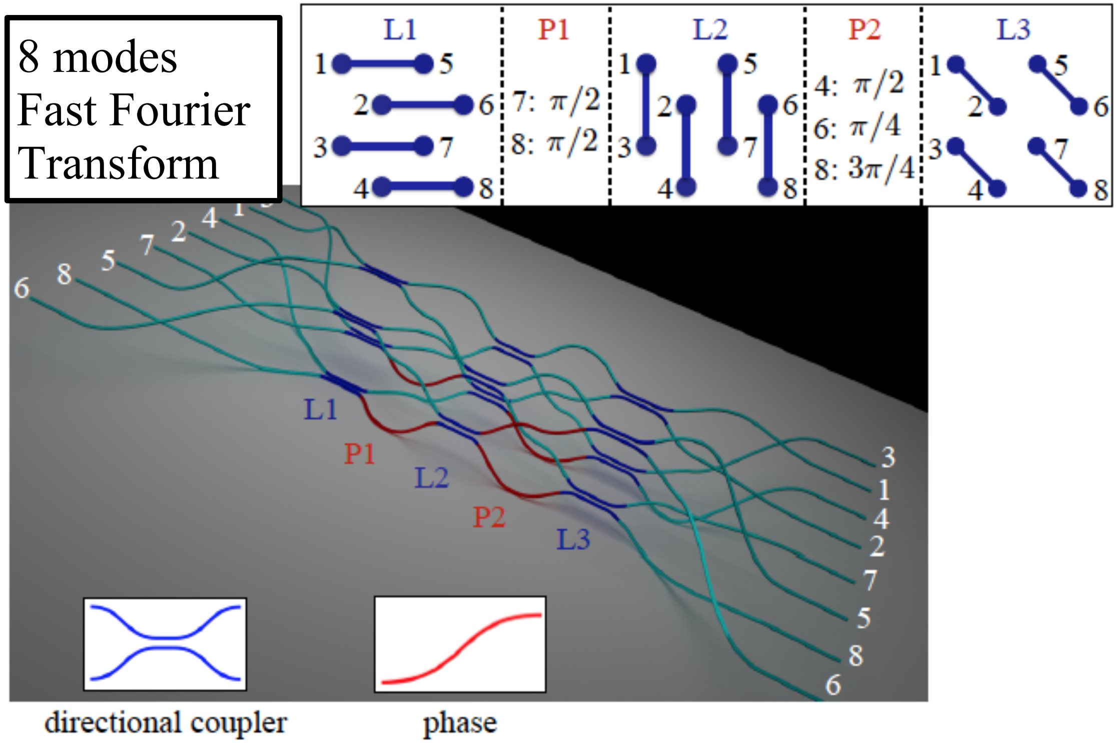


<u>Scalable approach</u> for the implementation of fast Fourier transform using 3-D photonic integrated interferometers fabricated via femtosecond laser writing technique.

Crespi, Osellame, Ramponi, Bentivegna, Flamini, Spagnolo, Viggianiello, Innocenti, Mataloni, and Sciarrino
Quantum suppression law in a 3-D photonic chip implementing the Fast Fourier Transform,
Nature Communications 7, 10469 (2016).

Implementation of Fast Fourier Transform with 3D-integrated photonics





Injection of cyclic input states

For n = 2 and m = 8 there are 4 possible (collision-free) cyclic inputs: (1,0,0,0,1,0,0,0), (0,1,0,0,0,1,0,0), (0,0,1,0,0,0,1,0), (0,0,0,1,0,0,0,1)

→

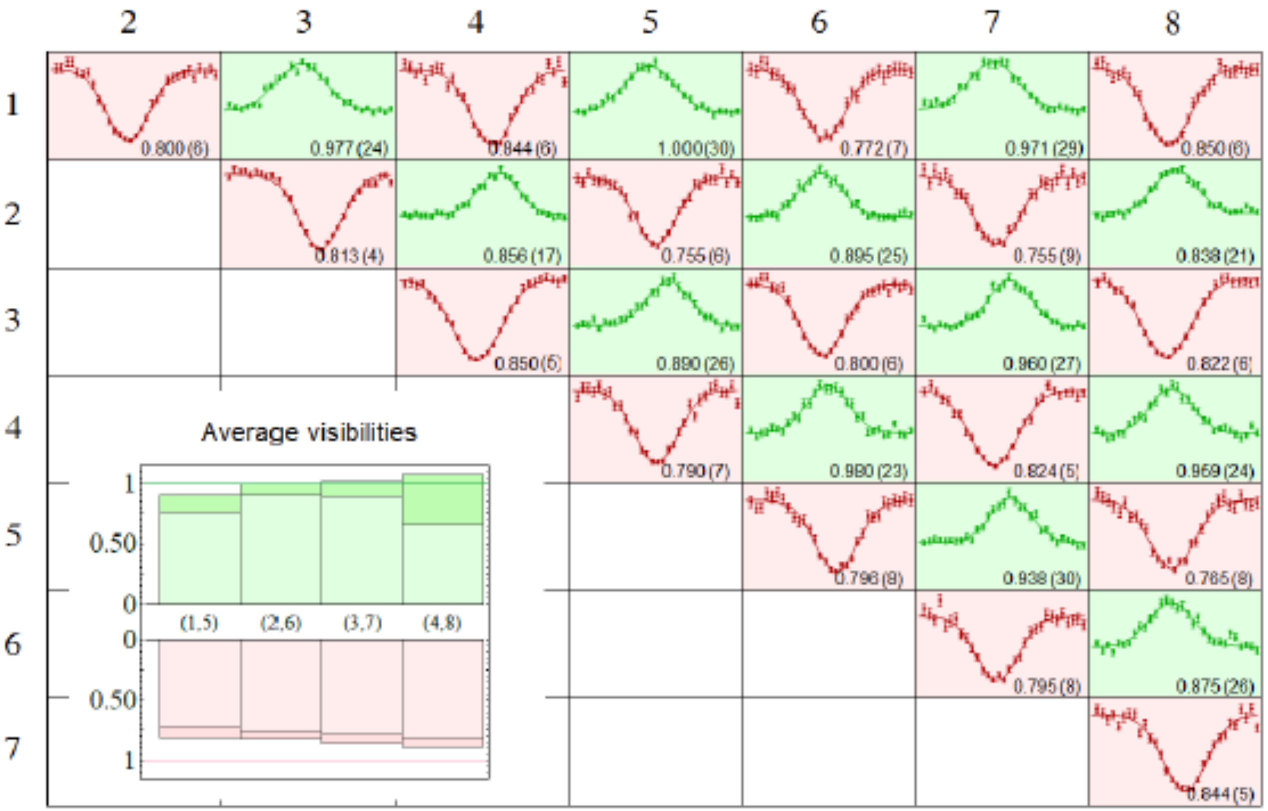
Quantum suppression law

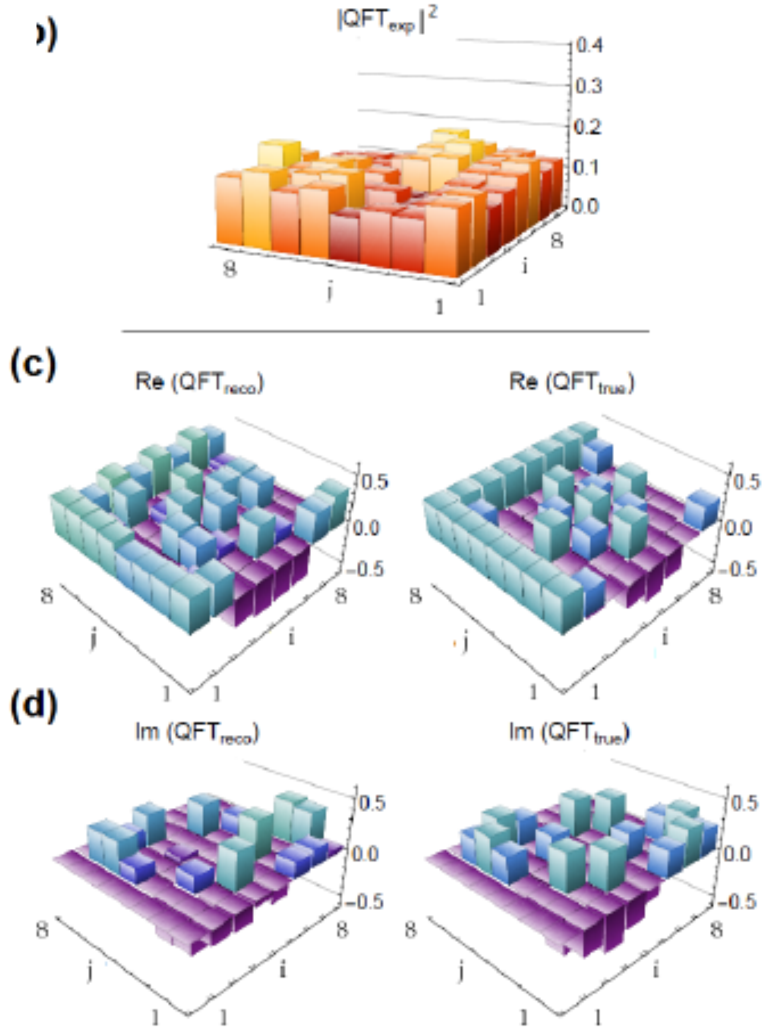
Suppression of all output non-cyclic output states!

Crespi, Osellame, Ramponi, Bentivegna, Flamini, Spagnolo, Viggianiello, Innocenti, Mataloni, and Sciarrino "Quantum suppression law in a 3-D photonic chip implementing the Fast Fourier Transform", *Nature Communications* **7**, 10469 (2016).

Quantum certification of Boson Sampling

n=2 photons over 8 modes Fast Fourier Transform





16 suppressed states over 28 output states

Quantum suppression of a large number of output states
with 4- and 8- mode optical circuits.

Scattershot Boson Sampling

PRL 113, 100502 (2014) PHYSICAL REVIEW LETTERS week ending 5 SEPTEMBER 2014

Boson Sampling from a Gaussian State

A. P. Lund,[1] A. Laing,[2] S. Rahimi-Keshari,[1] T. Rudolph,[3] J. L. O'Brien,[2] and T. C. Ralph[1]
[1]*Centre for Quantum Computation and Communication Technology, School of Mathematics and Physics, University of Queensland, Brisbane, Queensland 4072, Australia*
[2]*Centre for Quantum Photonics, H. H. Wills Physics Laboratory and Department of Electrical and Electronic Engineering, University of Bristol, Bristol BS8 1UB, United Kingdom*
[3]*Optics Section, Blackett Laboratory, Imperial College London, London SW7 2AZ, United Kingdom*
(Received 28 November 2013; revised manuscript received 21 March 2014; published 5 September 2014)

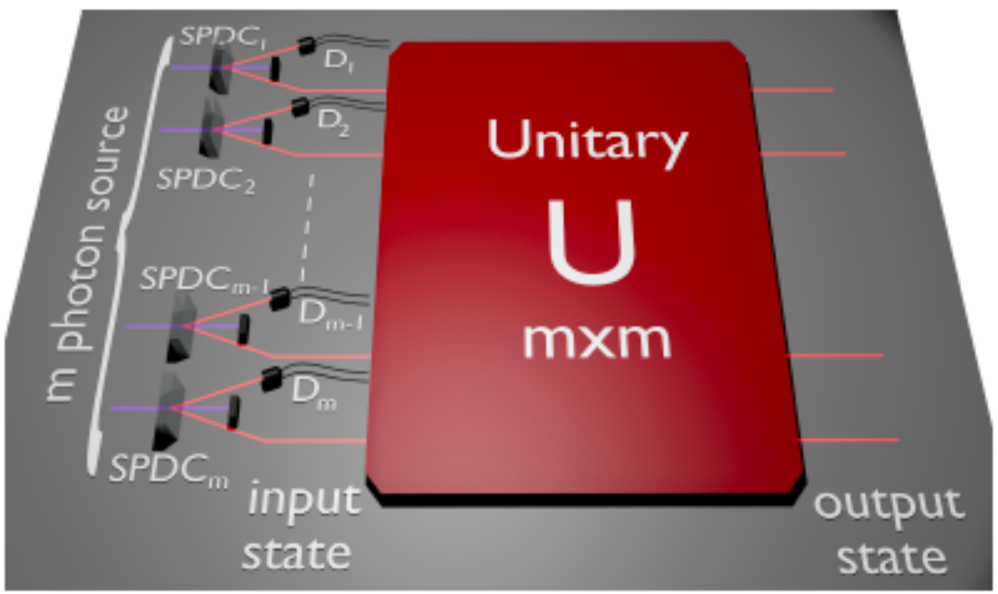
We pose a randomized boson-sampling problem. Strong evidence exists that such a problem becomes intractable on a classical computer as a function of the number of bosons. We describe a quantum optical processor that can solve this problem efficiently based on a Gaussian input state, a linear optical network, and nonadaptive photon counting measurements. All the elements required to build such a processor currently exist. The demonstration of such a device would provide empirical evidence that quantum computers can, indeed, outperform classical computers and could lead to applications.

DOI: 10.1103/PhysRevLett.113.100502 PACS numbers: 03.67.Lx, 03.67.Ac, 42.50.-p

A. P. Lund, A. Laing, S. Rahimi-Keshari, T. Rudolph, J. L. O'Brien, T. C. Ralph, Phys. Rev. Lett. 113, 100502 (2014)

Scott Aaronson's blog, acknowledged to S. Kolthammer, http://www.scottaaronson.com/blog/?p=1579

m heralded single photon sources



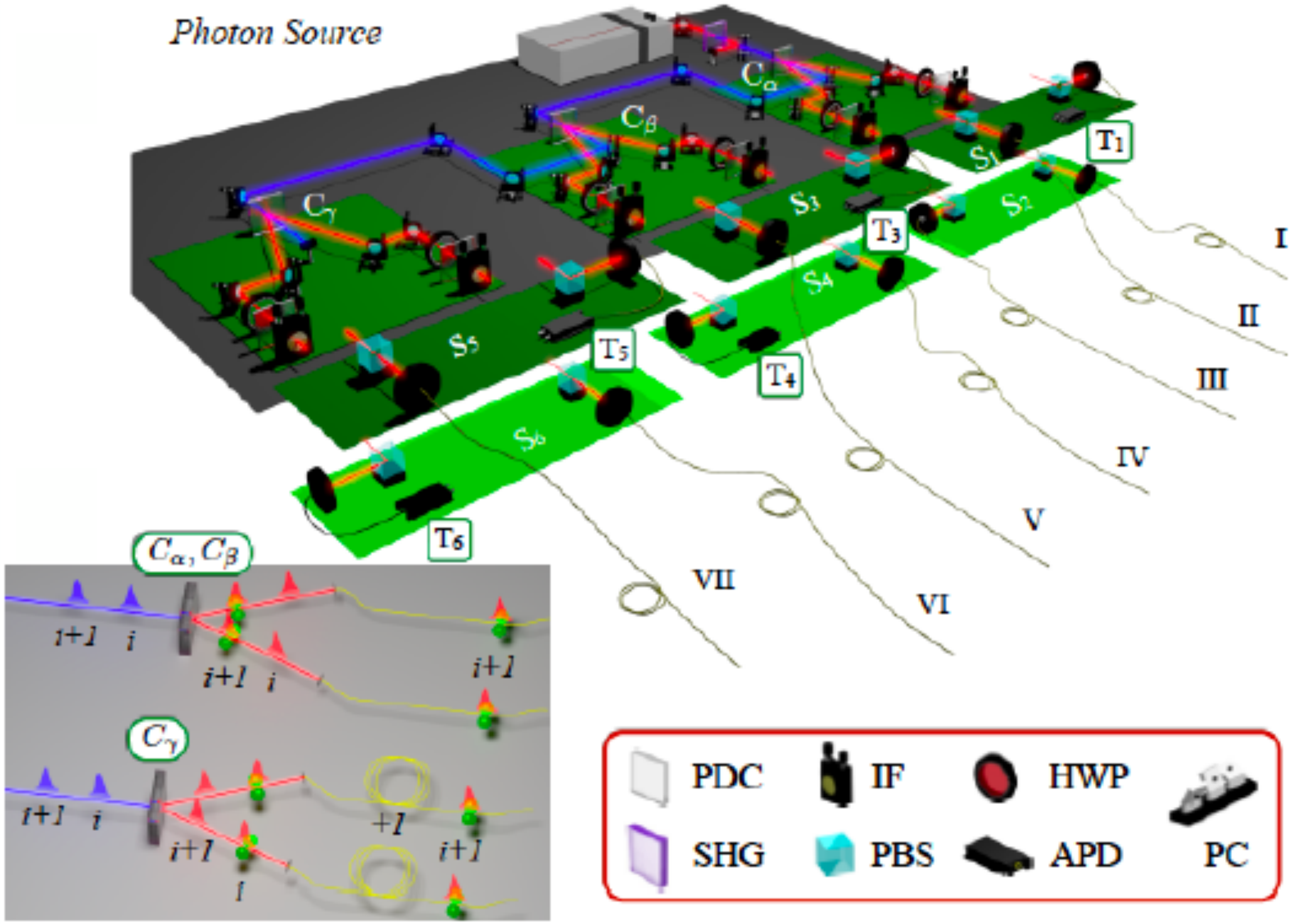
Generalization of Boson Sampling problem with computational complexity

Corresponds to sampling both from the *input* and the *output modes*

Potential huge increase of the brightness of the quantum hardware

Experimental scattershot boson sampling

Photon source → *Input state preparation* → *Chip and detection*



6 different parametric down-conversion sources (S_1-S_6)

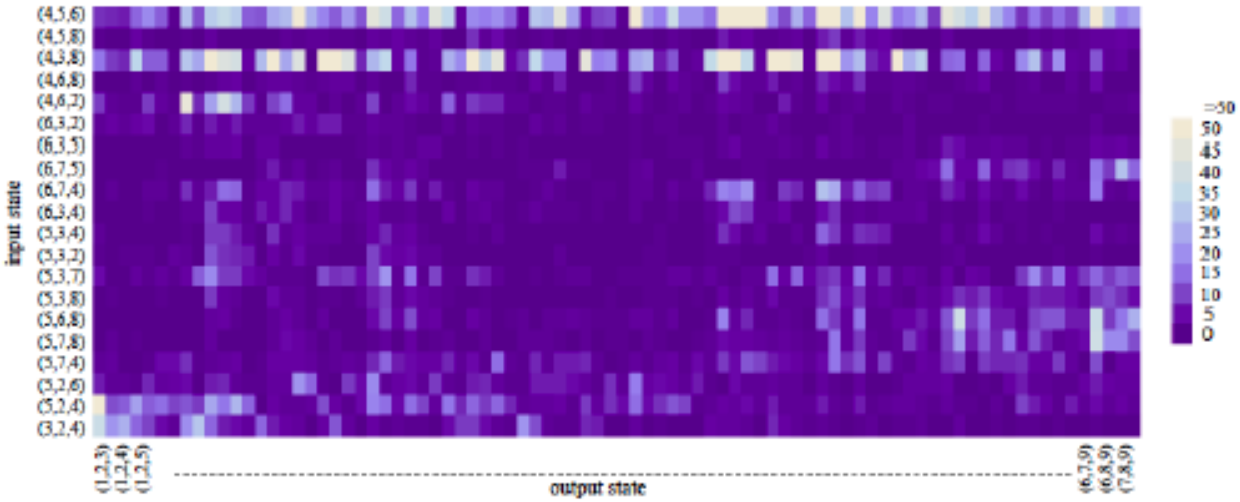
↕

3 physical crystals and separation by polarization

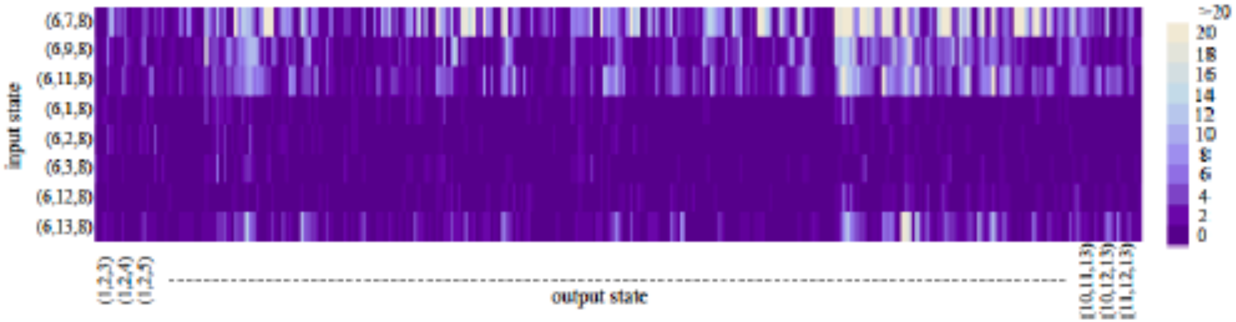
Interference between photons generated from two subsequent laser pulses

Experimental scattershot boson sampling

Three-photon events



9-mode interferometer



13-mode interferometer

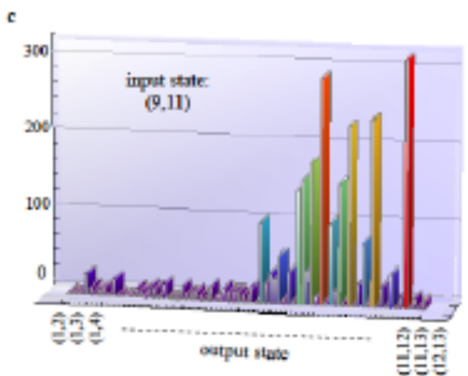
<u>Number of input/output configurations</u>

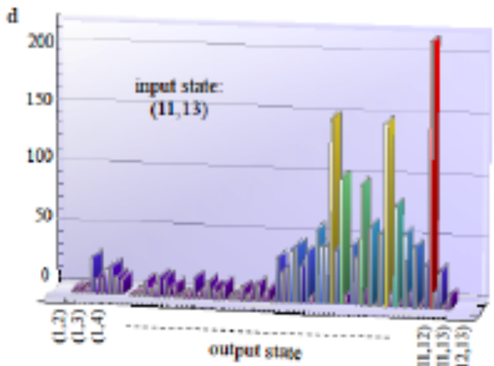
m=9 interferometer
2288 combinations

m=13 interferometer
1680 combinations

Few events per input/output configurations

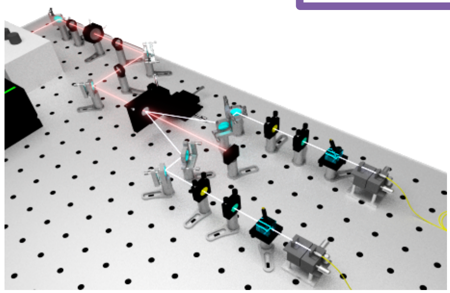
Two-photon events



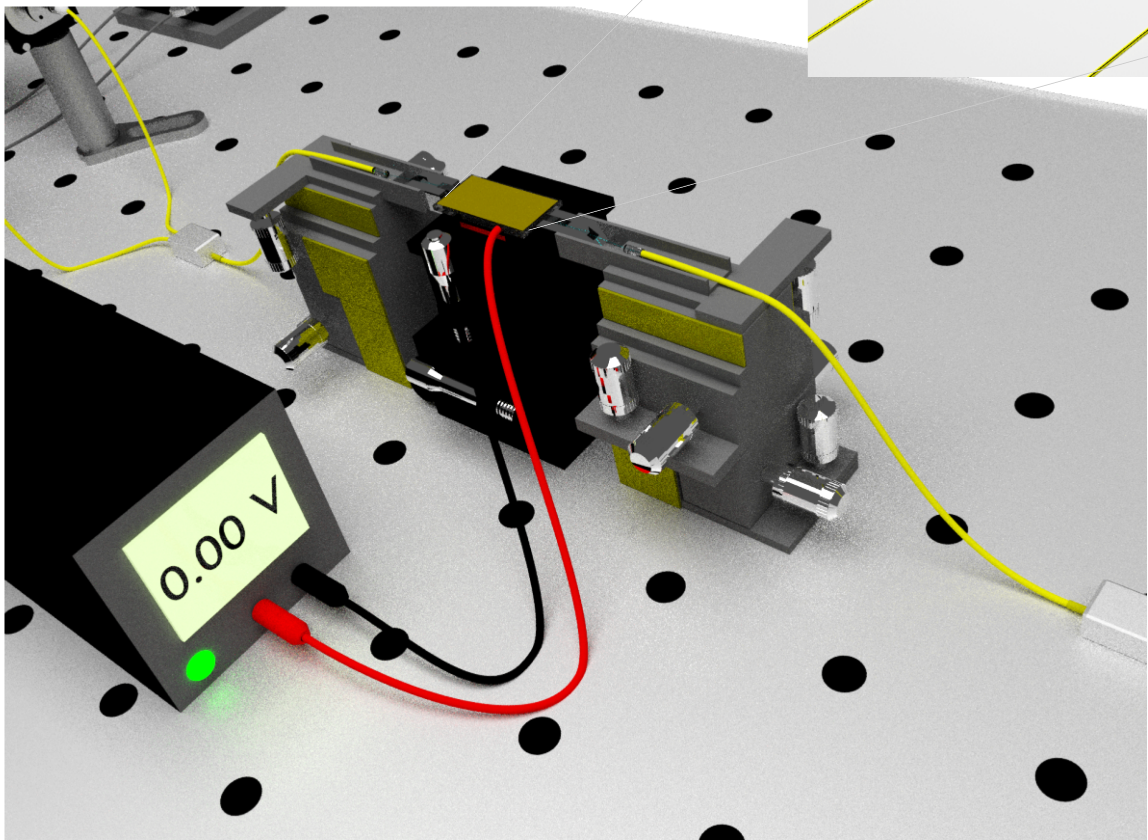


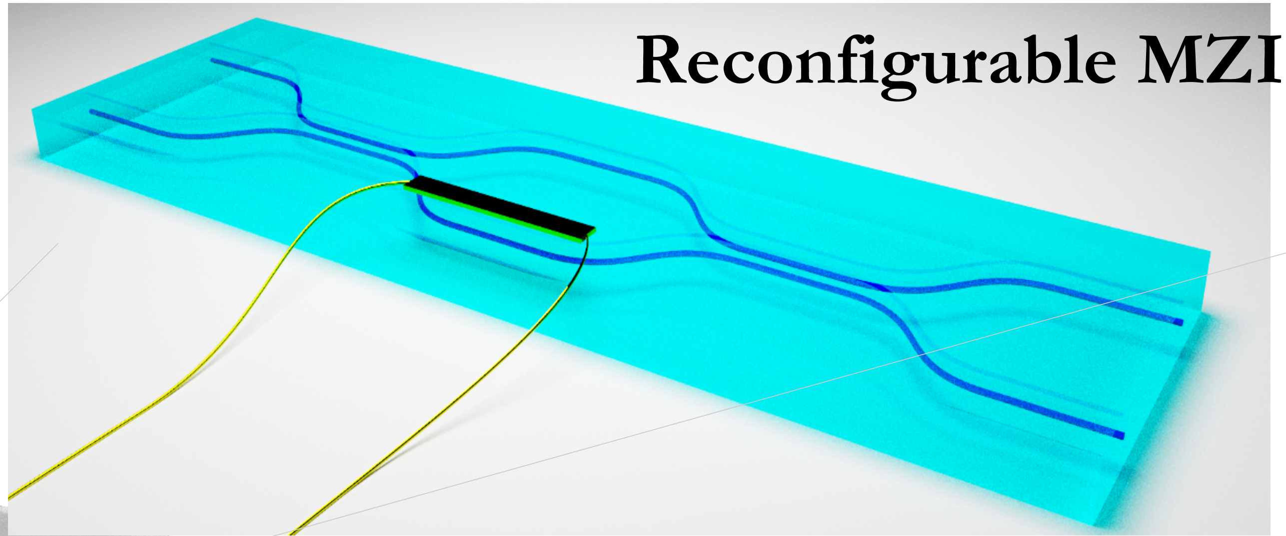
Data with three-photon and two-photon input collected simultaneously

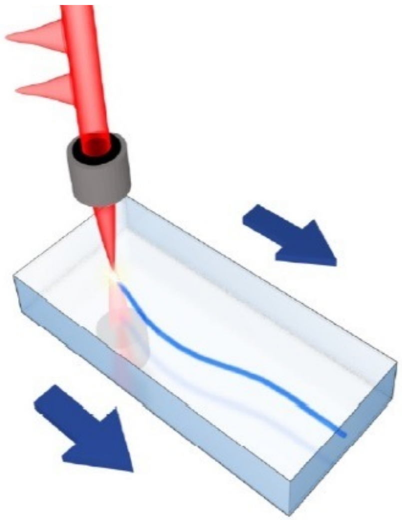
Integrated tunable circuits



Generation

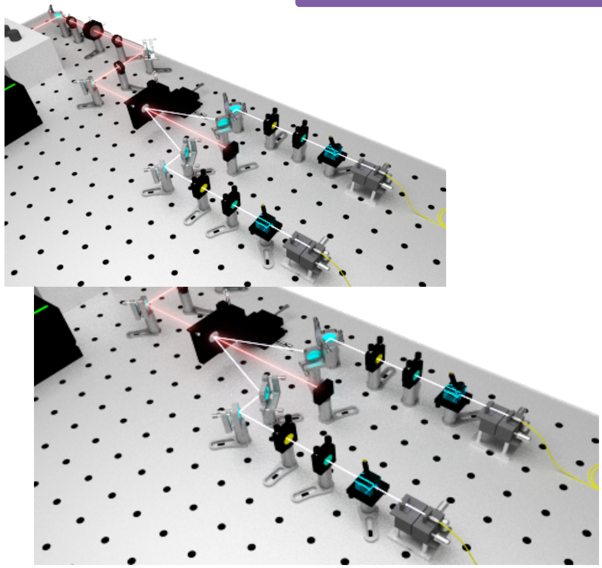




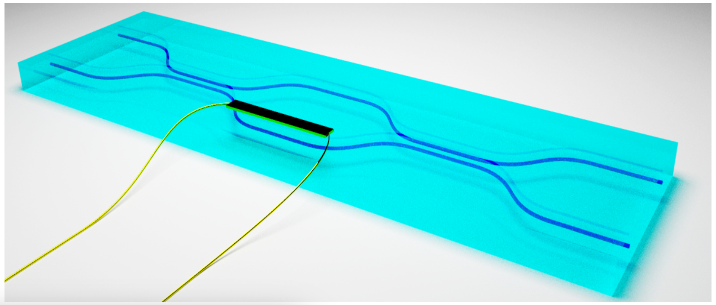


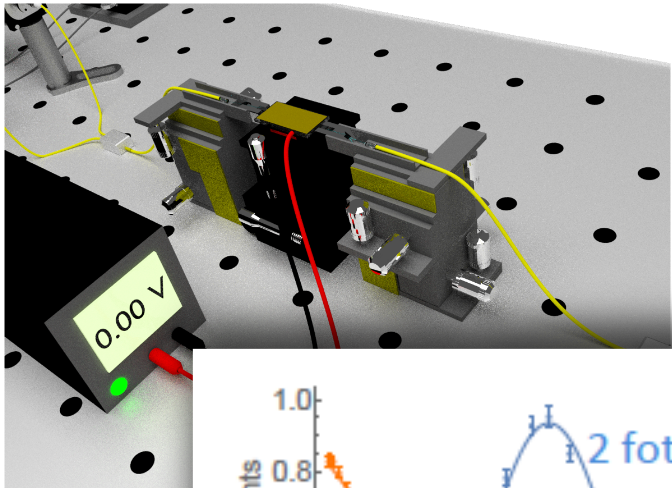
Femtosecond
laser writing technique

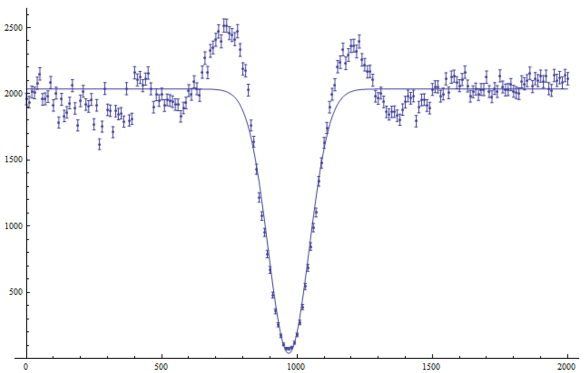
Integrated tunable circuits

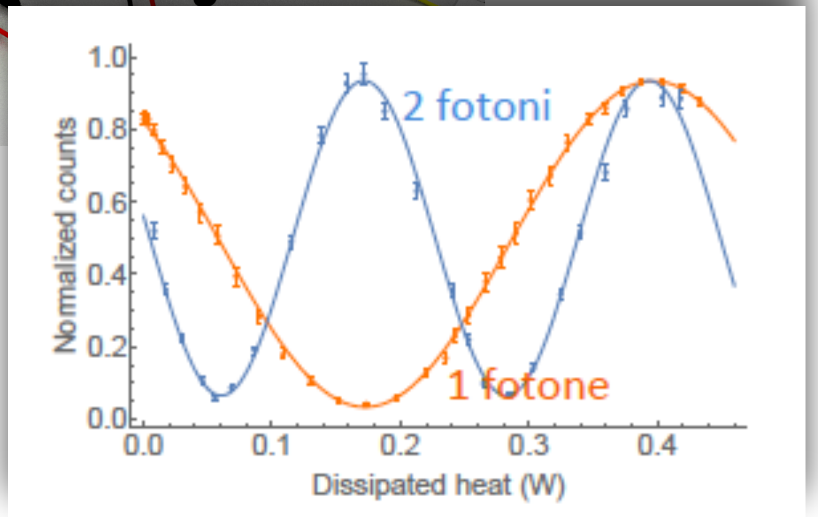


Reconfigurable MZI



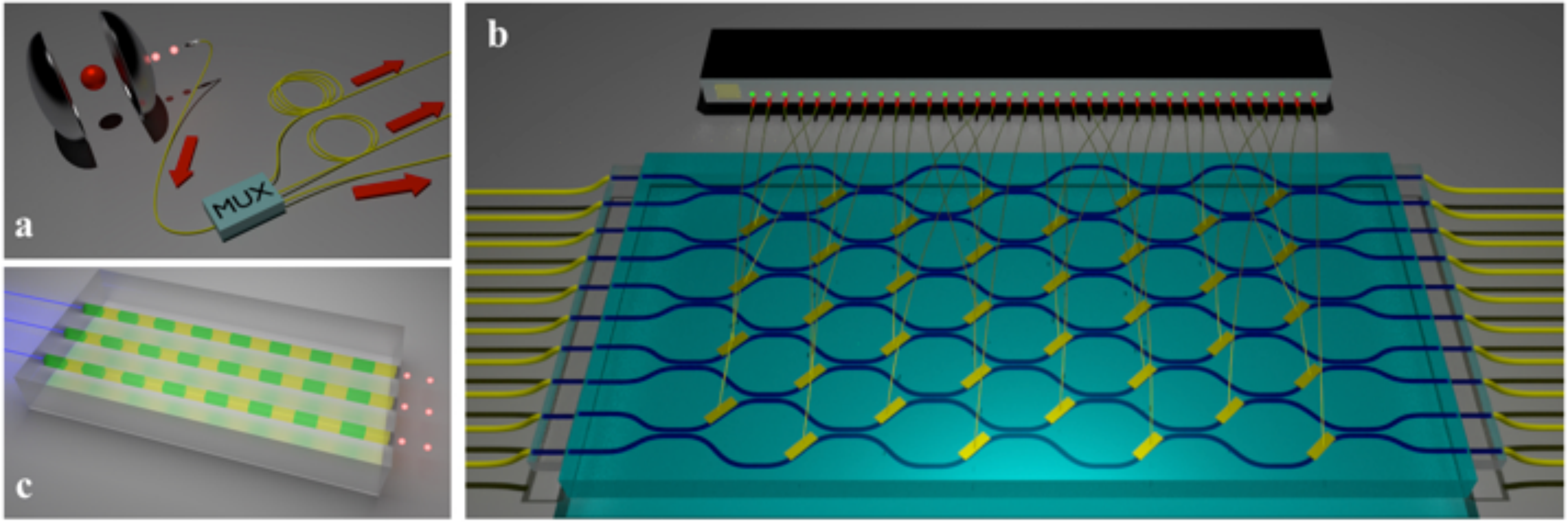






Thermally-Reconfigurable Quantum Photonic Circuits at Telecom Wavelength by Femtosecond Laser Micromachining”, F. Flamini, L. Magrini, A. Syed Rab, N. Spagnolo, V. D'Ambrosio, P. Mataloni, F. Sciarrino, T. Zandrini, A. Crespi, R.Ramponi, and R. Osellame, *Light: Science & Applications (Nature)* 4, e354 (2015)

Next platform…
hybrid integrated quantum photonics



Near-optimal single-photon sources in the solid-state

arXiv: 1510.06499

N. Somaschi[1,], V. Giesz[1,*], L. De Santis[1,2*], J. C. Loredo[3], M. P. Almeida[3], G. Hornecker[4,5], S. L. Portalupi[1], T. Grange[4,5], C. Anton[1], J. Demory[1], C. Gomez[1], I. Sagnes[1], N. D. Lanzillotti-Kimura[1], A. Lemaitre[1], A. Auffeves[4,5], A. G. White[3], L. Lanco[1,6] and P. Senellart[1,7,+]*

How far is Quantum Supremacy?

State-of-the-art

Other research teams

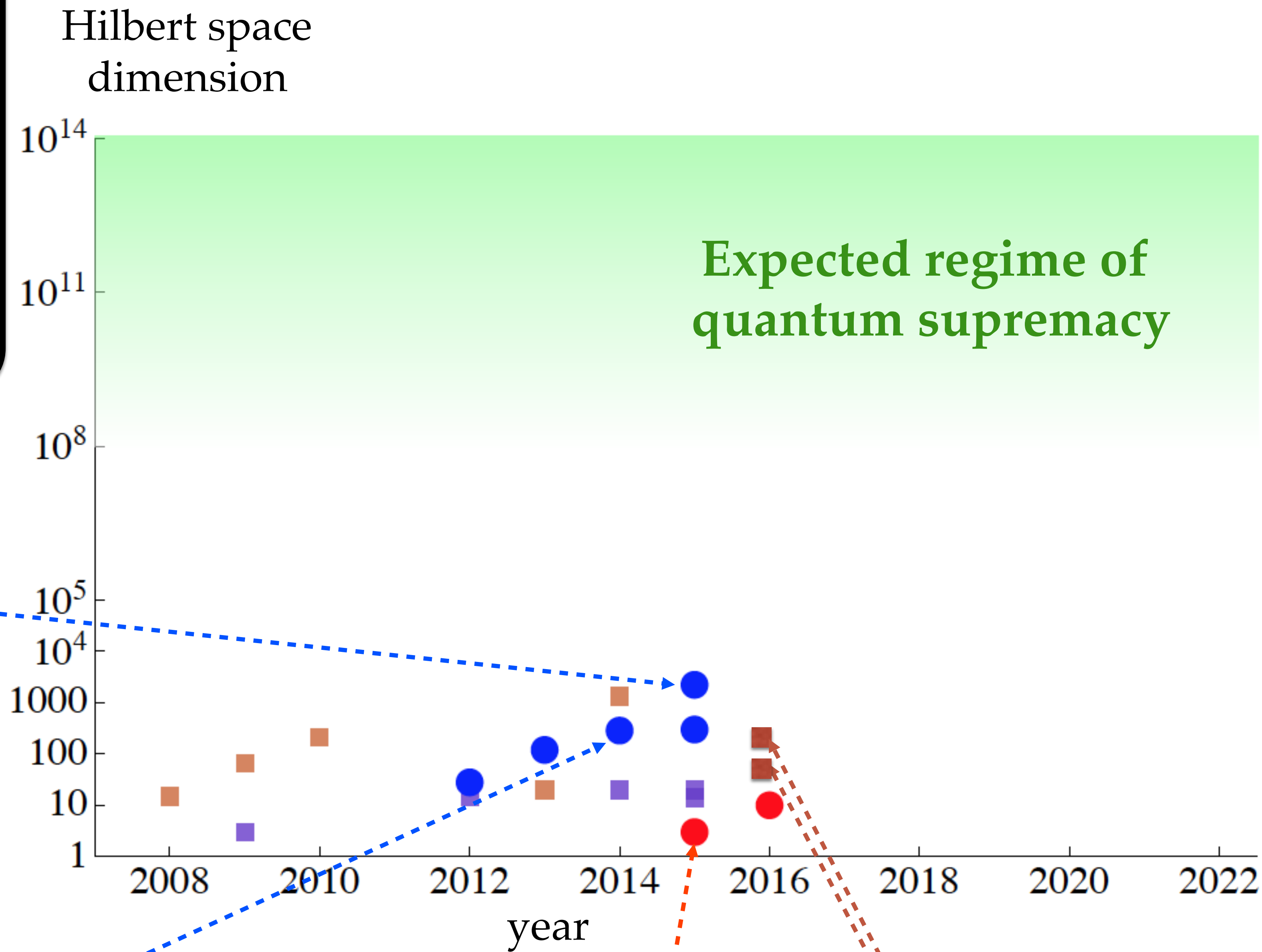
Static chip

Reconfigurable chip

Roma & Milano

Static

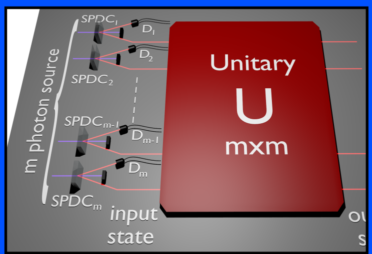
Reconfigurable



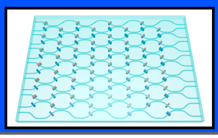
Science Advances (2015)

Scattershot Boson sampling

photons n=3
modes m=13



Nature Photonics (2014)

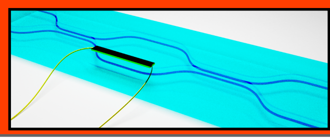


Boson sampling

n=3, m=13

Light Science & Applications (2015)

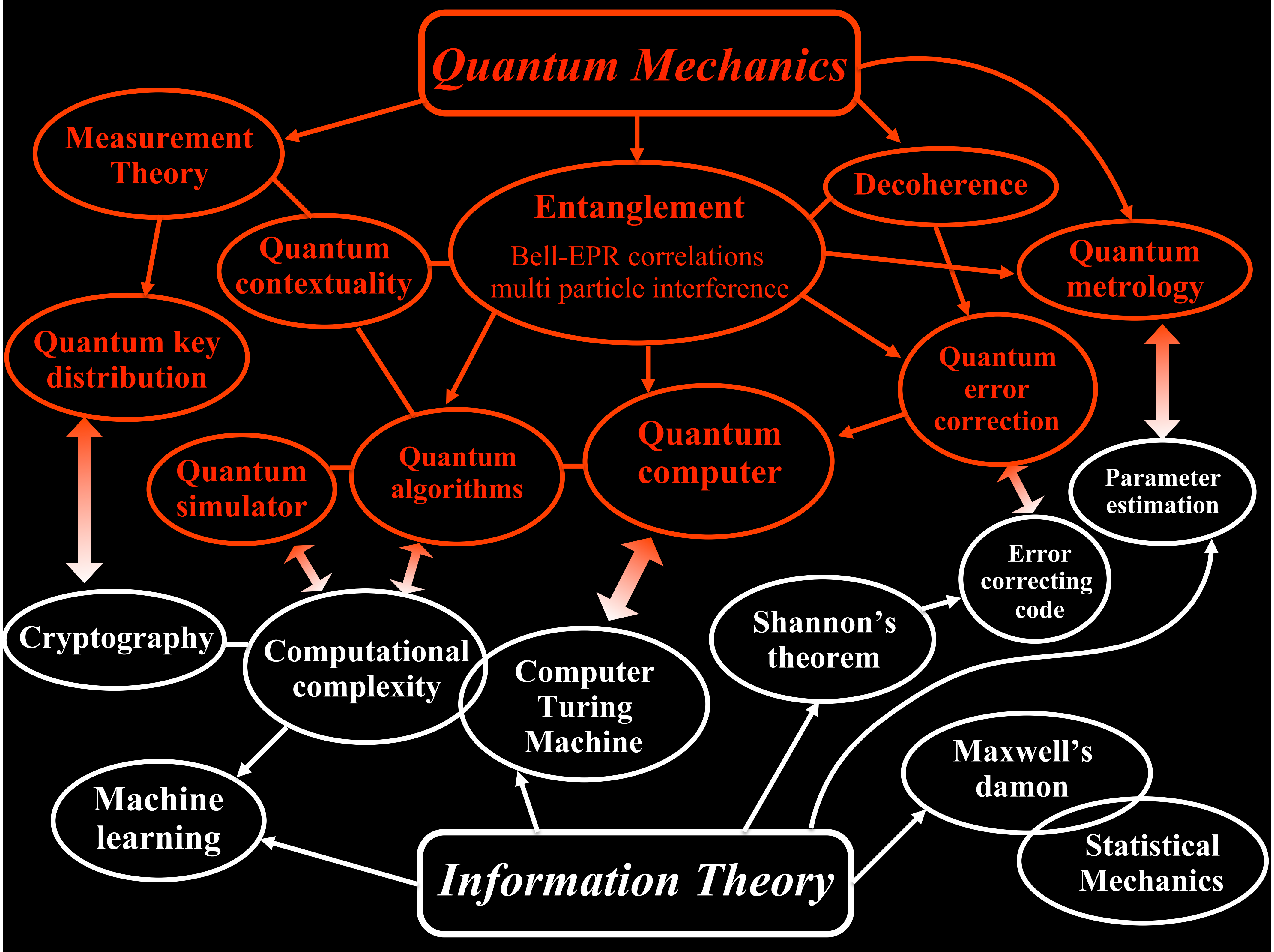
Reconfigurable chip



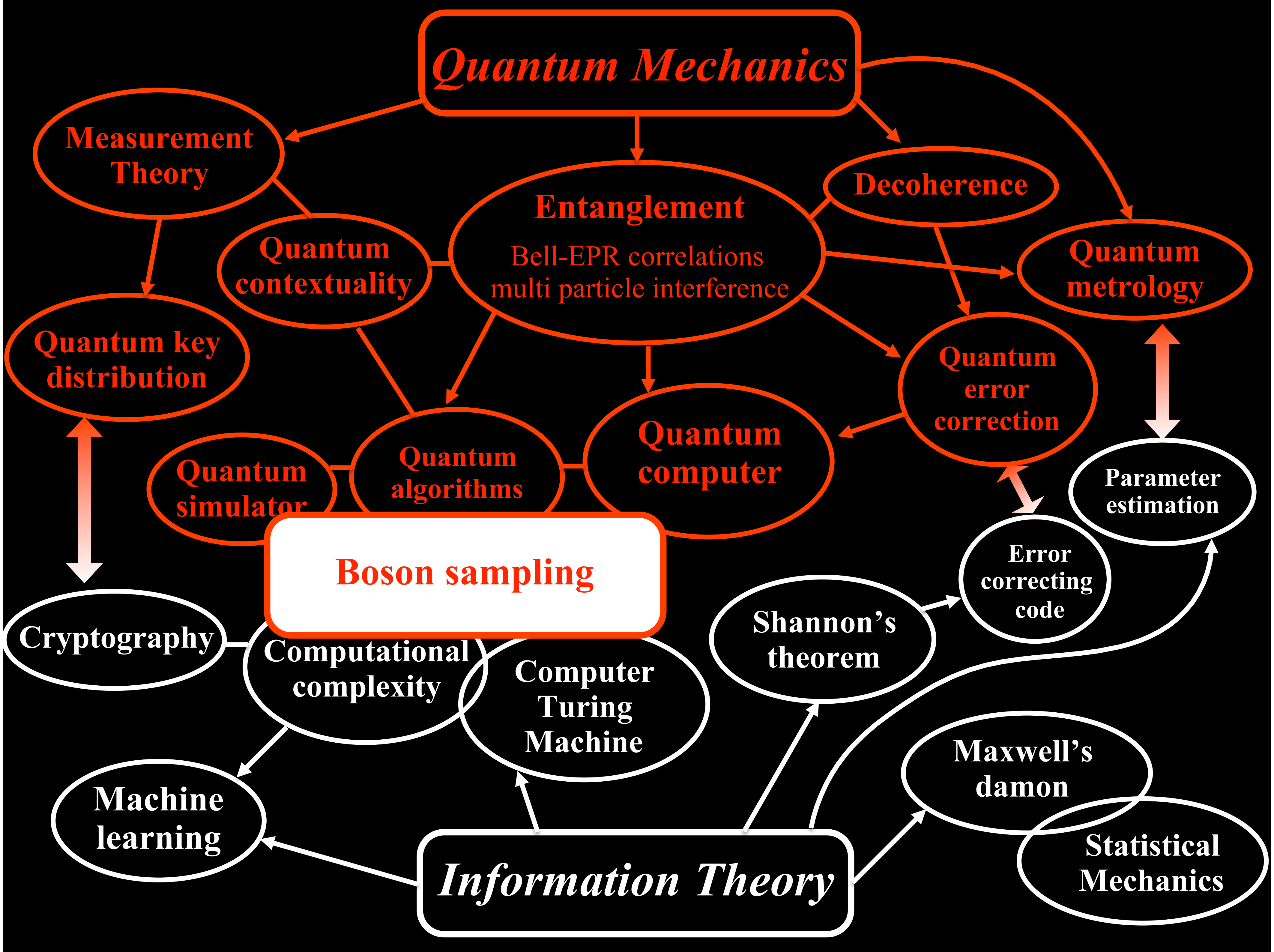
n=2, m=2

Quantum dot fiber network

1603.00054
1603.04127



Quantum Mechanics
Measurement Theory
Entanglement
Bell-EPR correlations
multi particle interference
Decoherence
Quantum contextuality
Quantum metrology
Quantum key distribution
Quantum error correction
Quantum computer
Quantum simulator
Quantum algorithms
Parameter estimation
Error correcting code
Cryptography
Computational complexity
Computer Turing Machine
Shannon's theorem
Maxwell's damon
Statistical Mechanics
Machine learning
Information Theory


Quantum Mechanics
Measurement Theory
Entanglement
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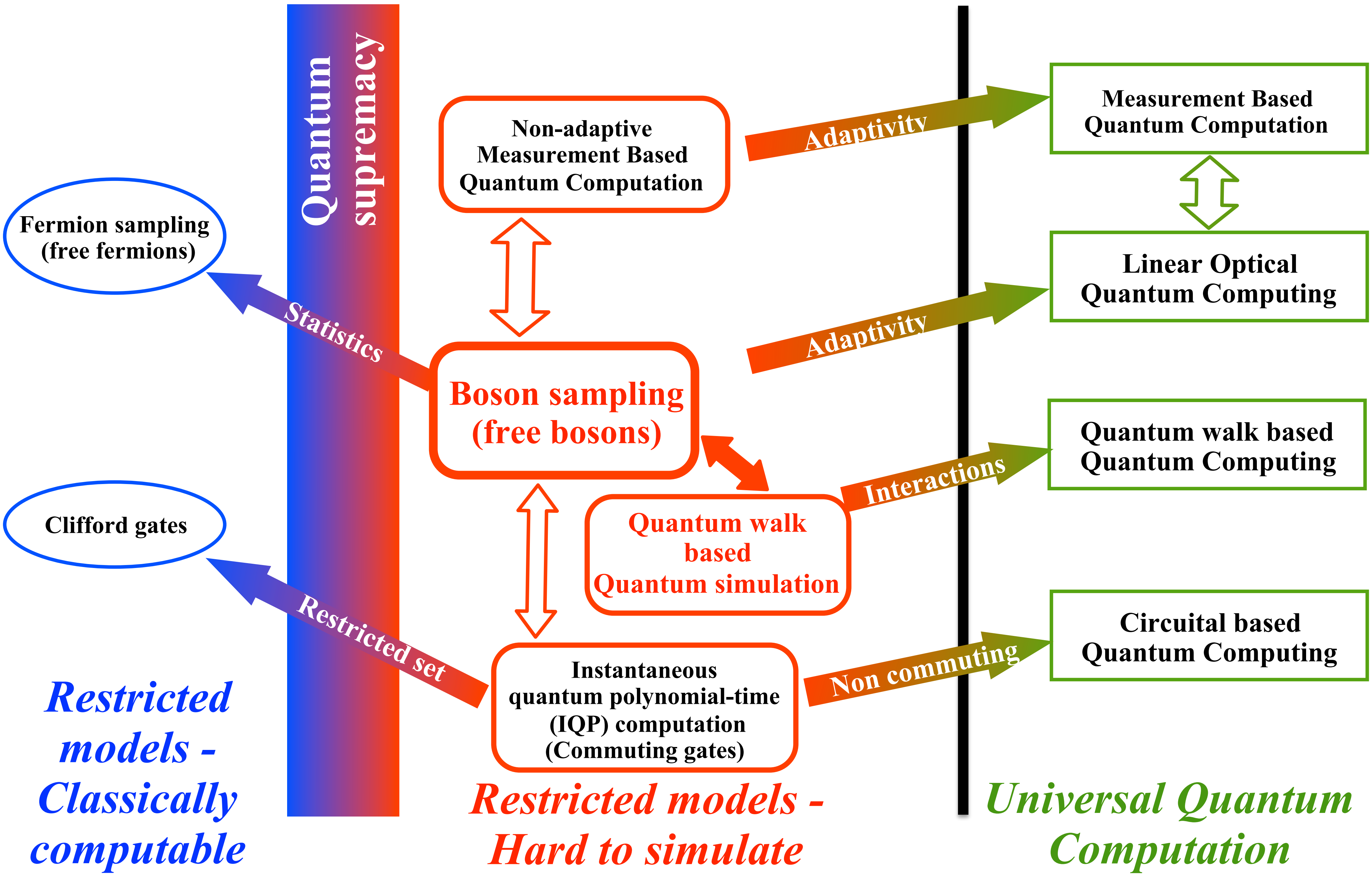
multi particle interference
Decoherence
Quantum contextuality
Quantum metrology
Quantum key distribution
Quantum error correction
Quantum simulator
Quantum algorithms
Quantum computer
Parameter estimation
Boson sampling
Error correcting code
Cryptography
Computational complexity
Computer Turing Machine
Shannon's theorem
Machine learning
Maxwell's damon
Statistical Mechanics
Information Theory

Boson Sampling

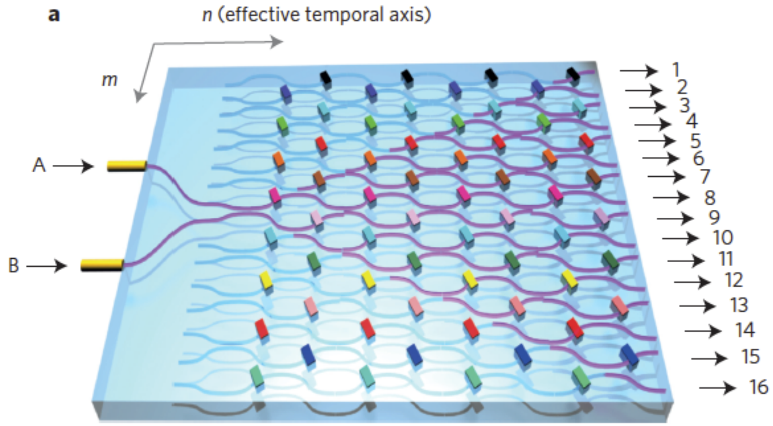
restricted models of Quantum Computation



Applications of Boson Sampling

QUANTUM WALKS

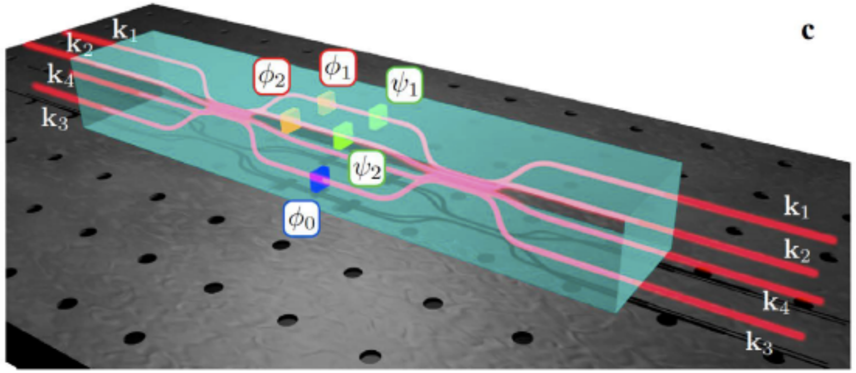
Multiparticle interference in quantum walks



Nature Photonics **7**, 322 (2013)

QUANTUM METROLOGY

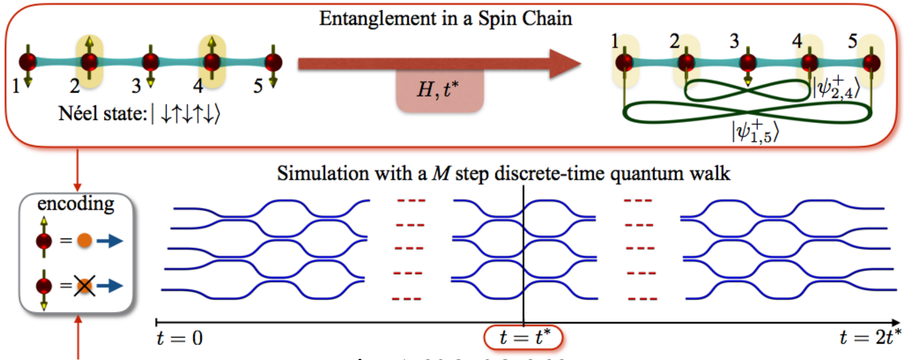
Quantum enhanced multiparameter estimation



Scientific Reports **6**, 28881 (2016)

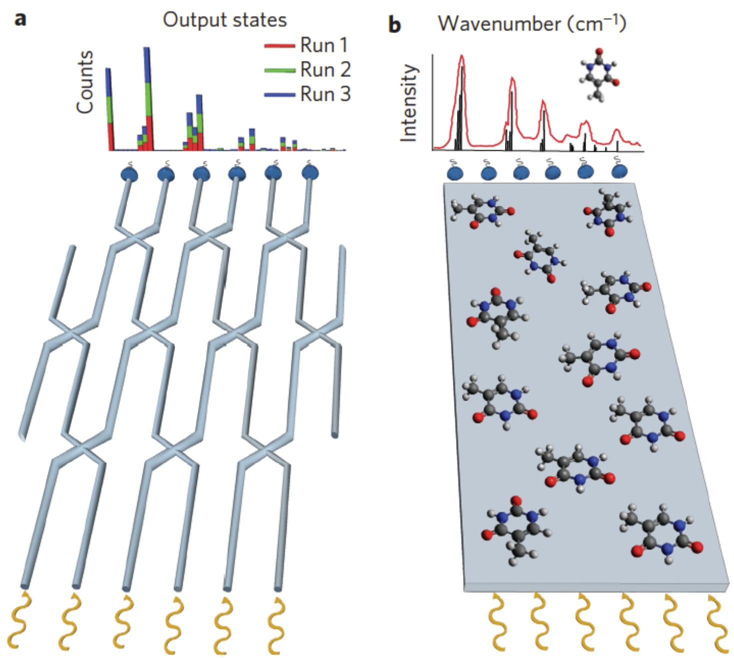
QUANTUM SIMULATION

Quantum simulation of spin systems



arXiv:1603.02669

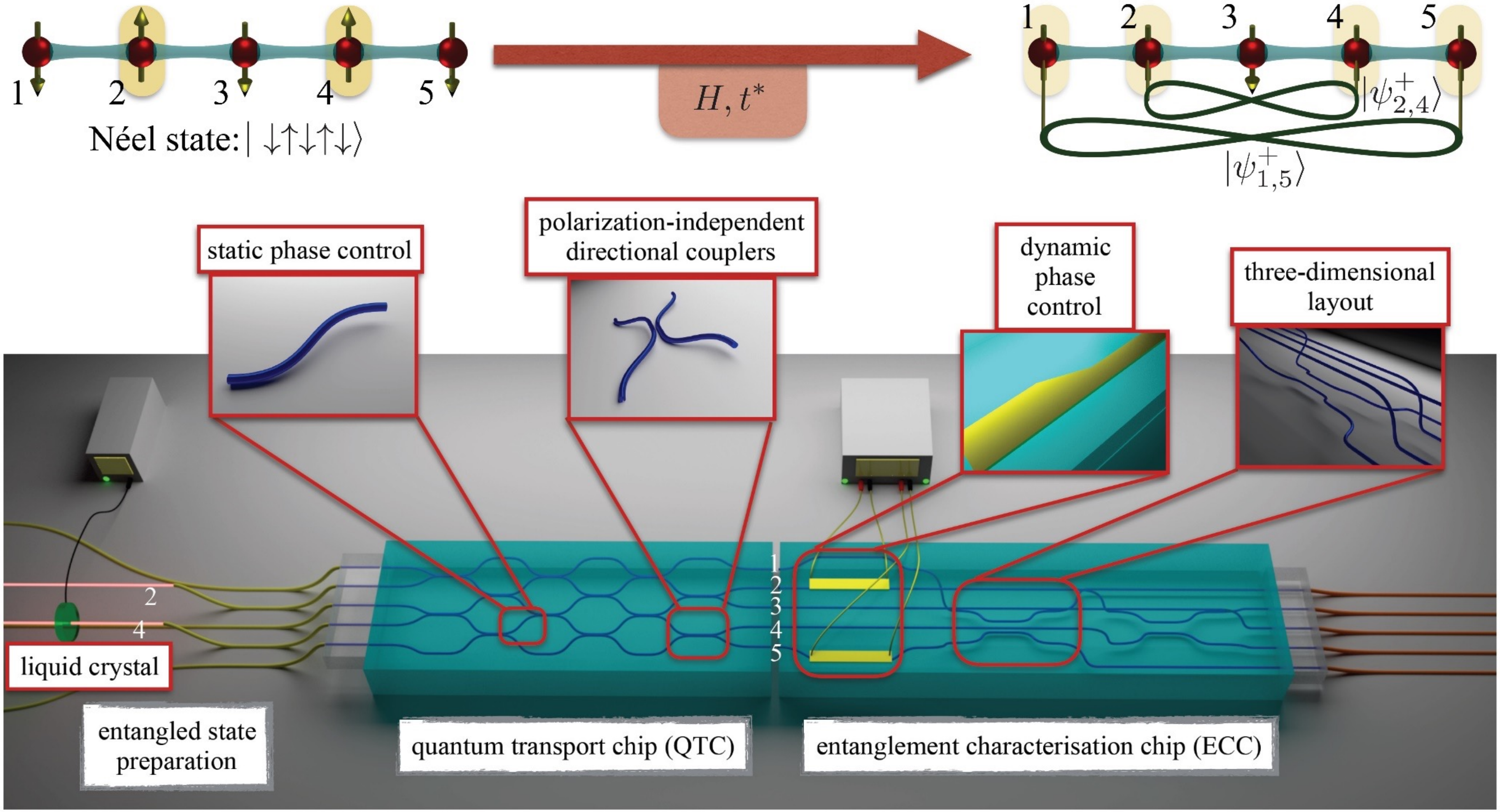
Quantum simulation of vibrionic spectra



Nature Physics **9**, 615 (2015)

Simulation of quantum transport

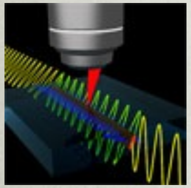
Entanglement generation after a spin chain quench



I. Pitsios, L. Banchi, A. S. Rab, M. Bentivegna, D. Caprara, A. Crespi, N. Spagnolo, S. Bose, P. Mataloni, R. Osellame, F. Sciarrino, arXiv:1603.02669

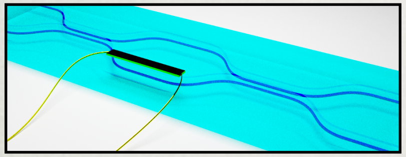
Integrated devices

Integrated waveplates



Nature Com.
5, 2549 (2014)

Controlled phase shifter

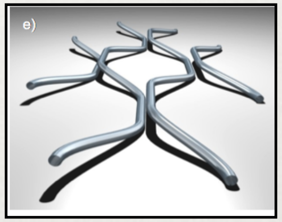


Light S&A (Nature)
4, e354 (2015)

Light S&A (Nature)
5, e16064 (2016)

Quantum simulation via quantum walk

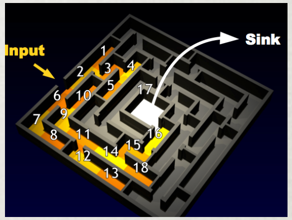
Ordered systems



Phys. Rev. Lett.
108, 010502 (2012)

Nature Photonics
7, 322 (2013)

Quantum transport



Nature Com.
6, 7706 (2015)

Phys. Rev. Lett.
114, 090201(2015)

Science Advances
1, e1500087 (2015)

Nature Com.
7, 11862 (2016)

Boson Sampling

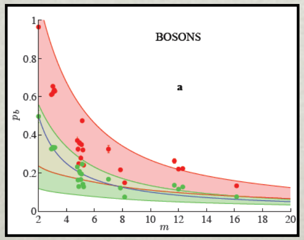
Boson Sampling On a chip

Nature Photonics
7, 545 (2013)

Phys. Rev. Lett.
111, 130503 (2013)

Nature Photonics
8, 614 (2014)

Scattershot Boson Sampling



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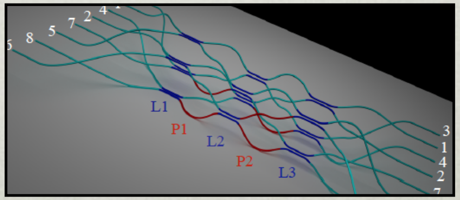
3D-Devices

Fourier matrix



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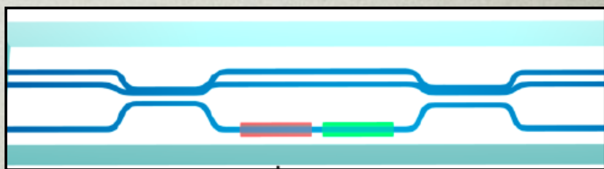

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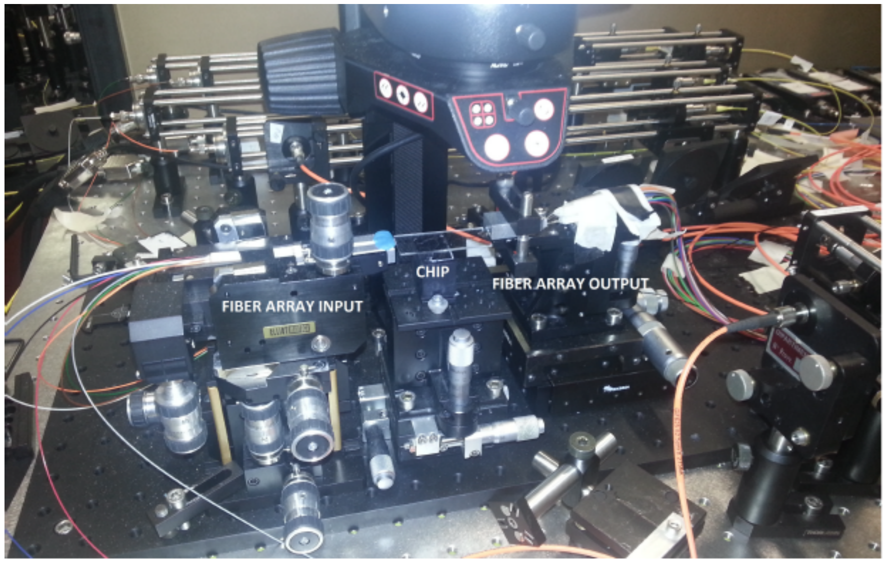

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3D-QUEST

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