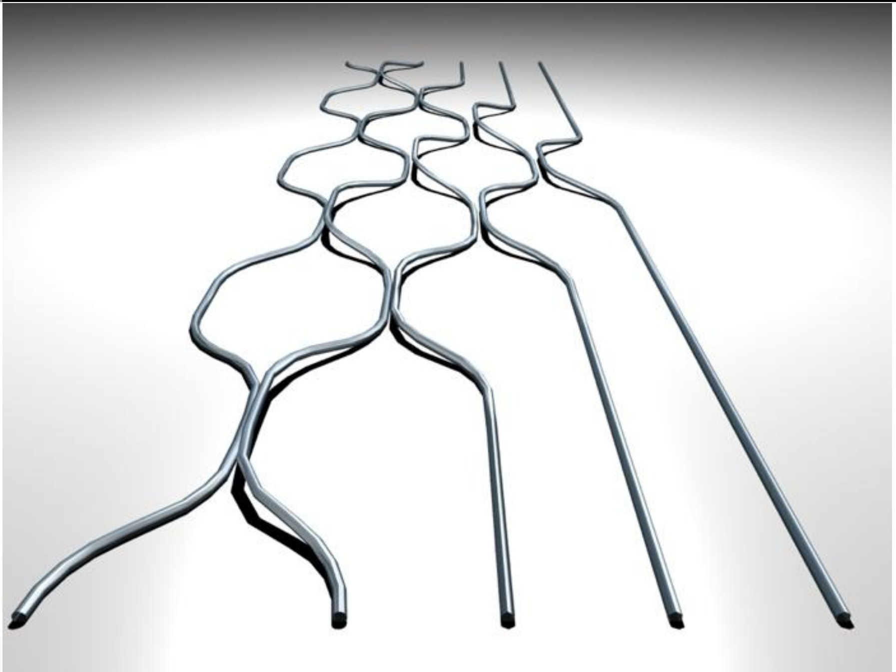


Boson Sampling with integrated photonics

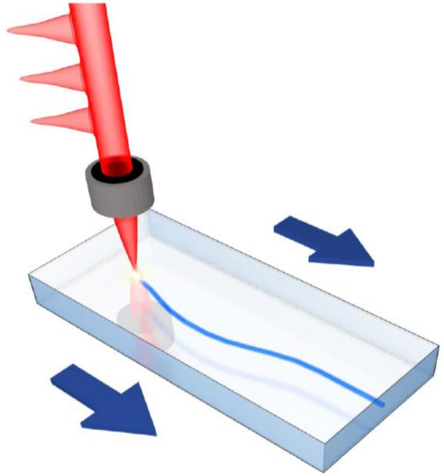
Paolo Mataloni

Dipartimento di Fisica,
Sapienza Università di Roma

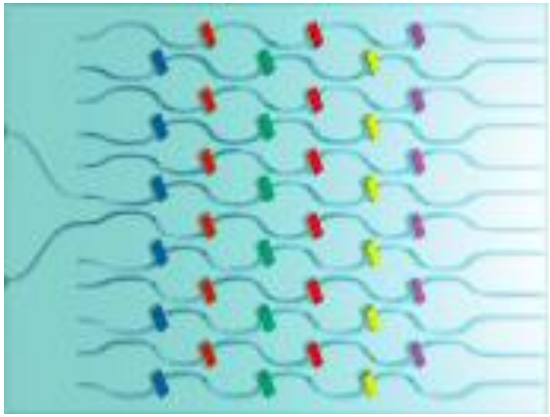
http:\\quantumoptics.phys.uniroma1.it

IQIS 2015, Monopoli, September 10, 2015

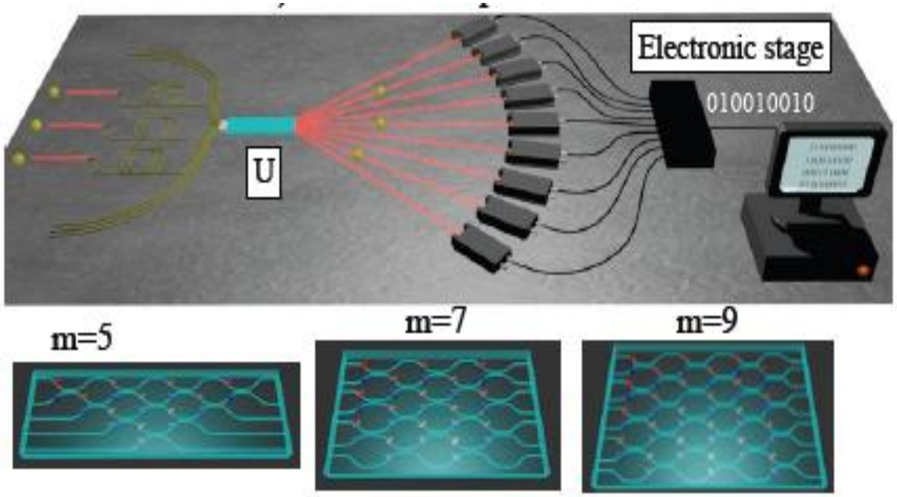
Summary



1) **Femtosecond laser writing: main features**



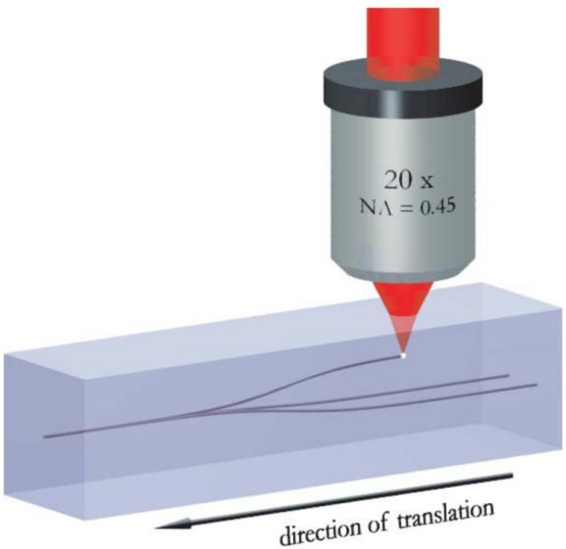
2) **Complex integrated photonics networks. Discrete quantum walks**



3) **BosonSampling: a promising route towards *Quantum Supremacy***

Femtosecond laser writing

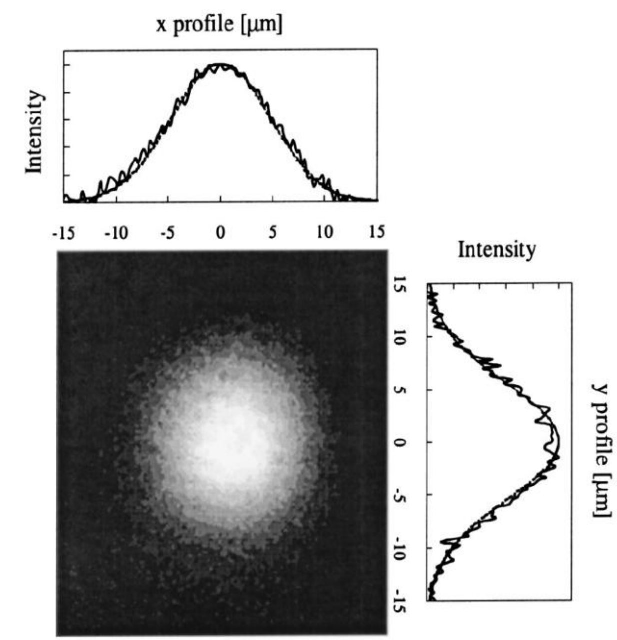
3-D capability



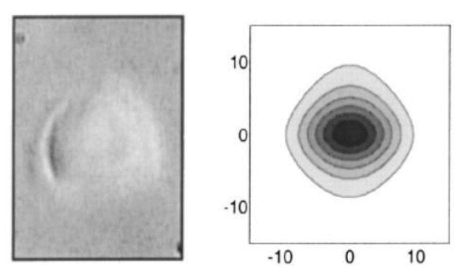
Rapid device prototyping:
writing speed = 4 cm/s

Main_features

Propagation of circular gaussian modes



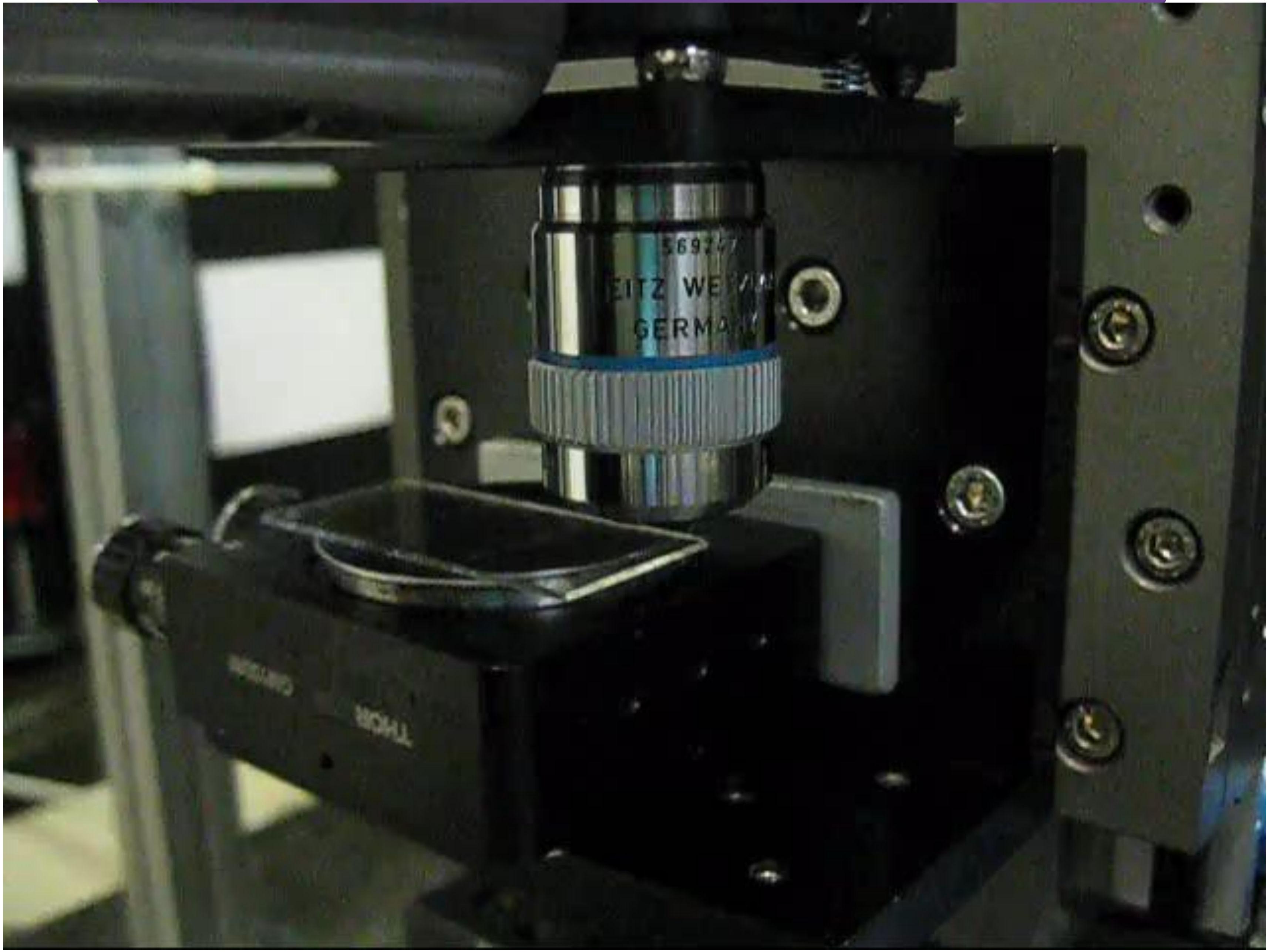
Circular waveguide transverse profile



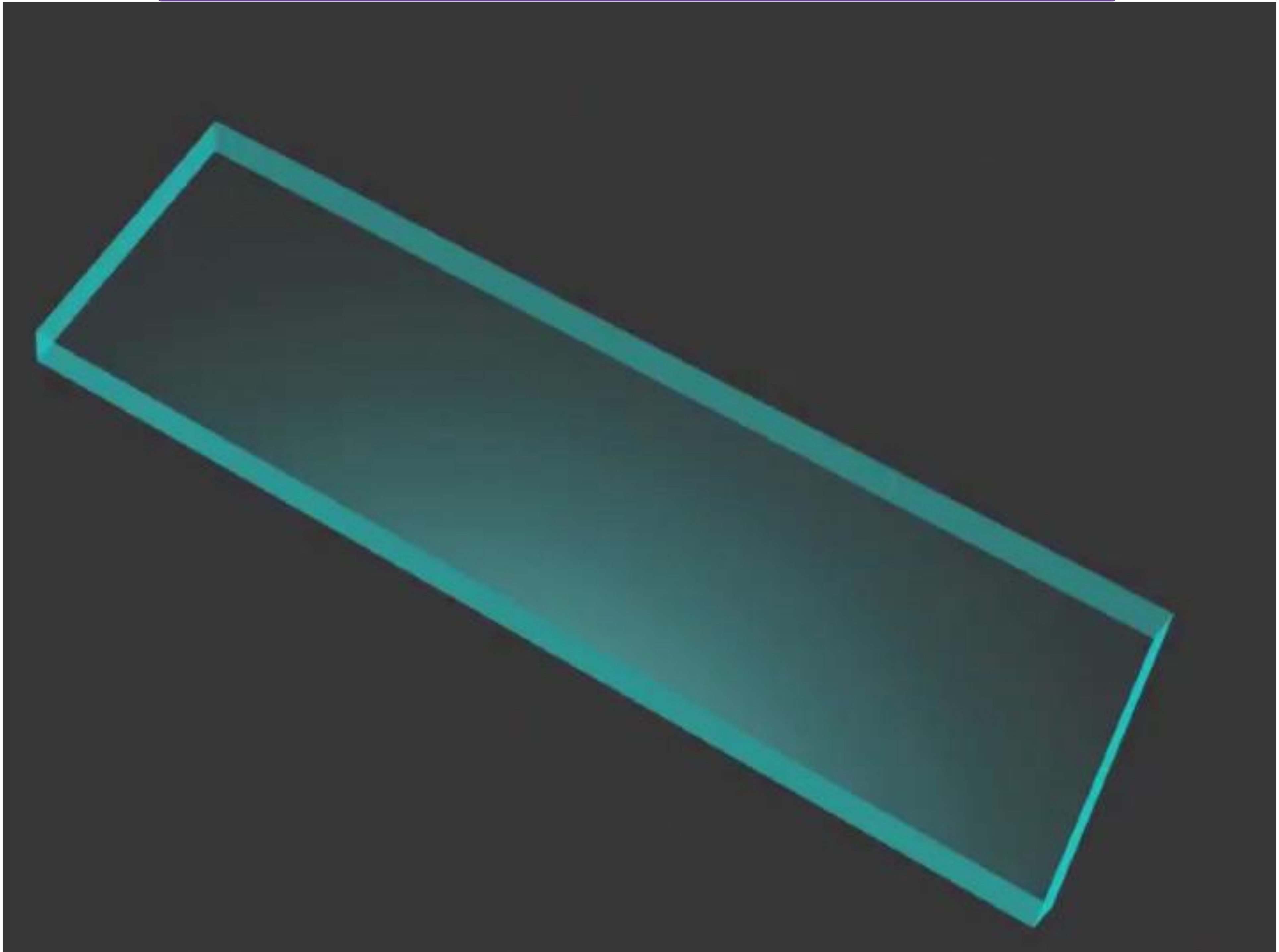
Low birefringence

ABLE TO SUPPORT ANY POLARIZATION STATE

Femtosecond laser writing

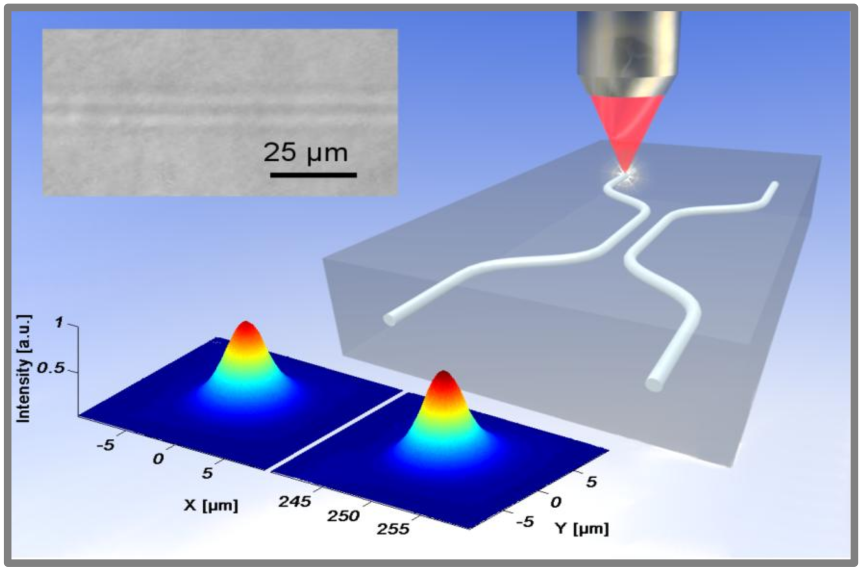


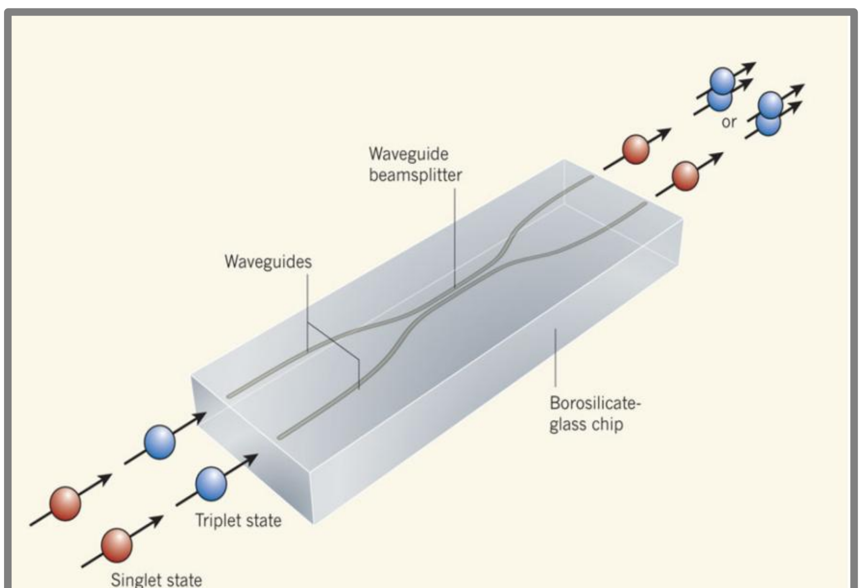
Femtosecond laser writing



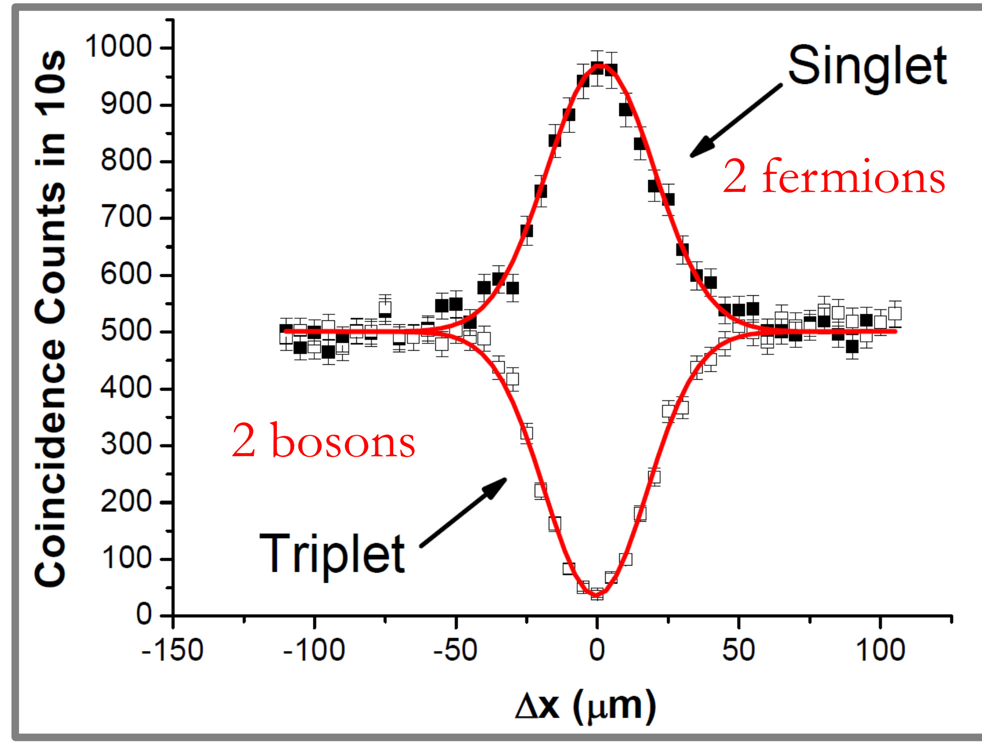
Integrated beam splitter

$$|\Psi^{\phi}\rangle = \frac{1}{\sqrt{2}}(|H\rangle_A|V\rangle_B + e^{i\phi}|V\rangle_A|H\rangle_B)$$





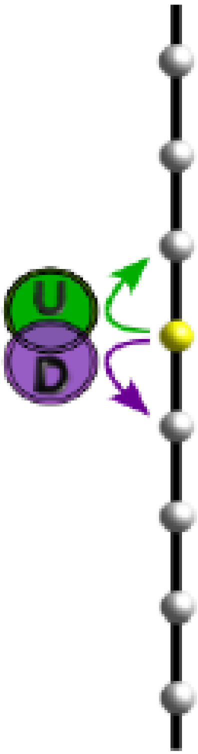
M. Lobino & J.L. O'Brien *News &Views* Nature (2011)



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

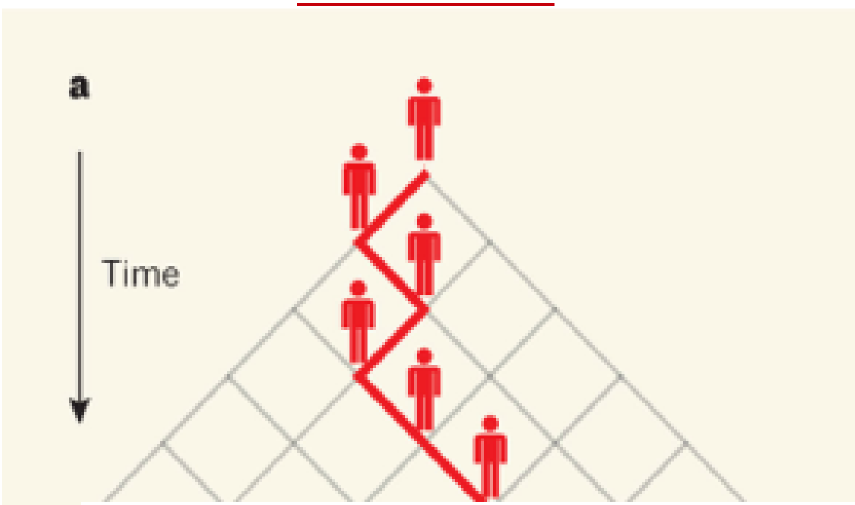
Goal: to realize complex integrated photonics structures of beam splitters.

Quantum Walk

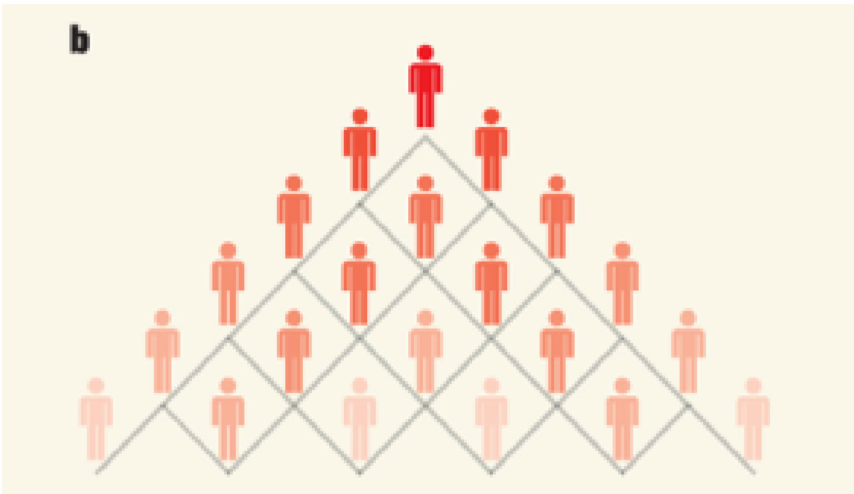


Quantum walk: extension of the classical random walk:
a walker on a lattice "jumping" between different sites with given probability

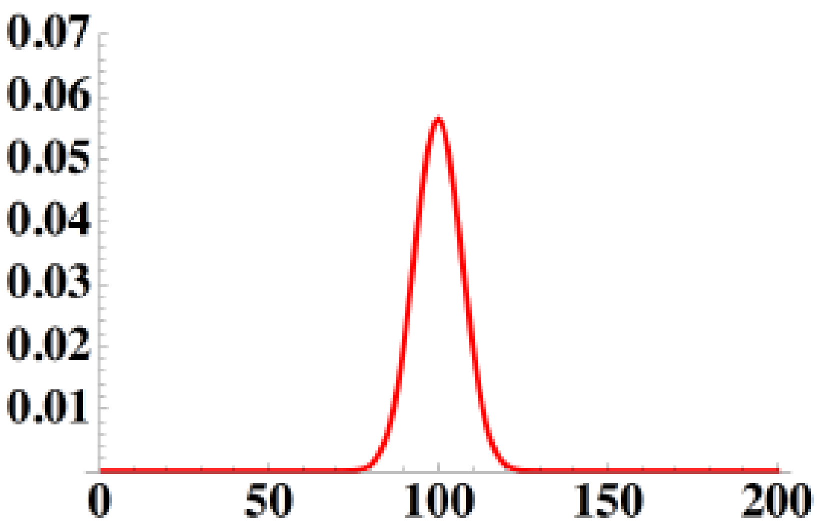
Classical

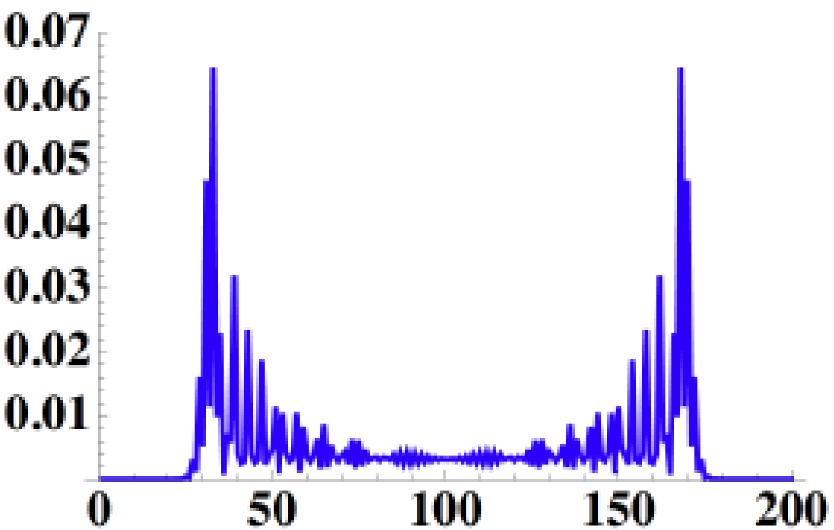


Quantum

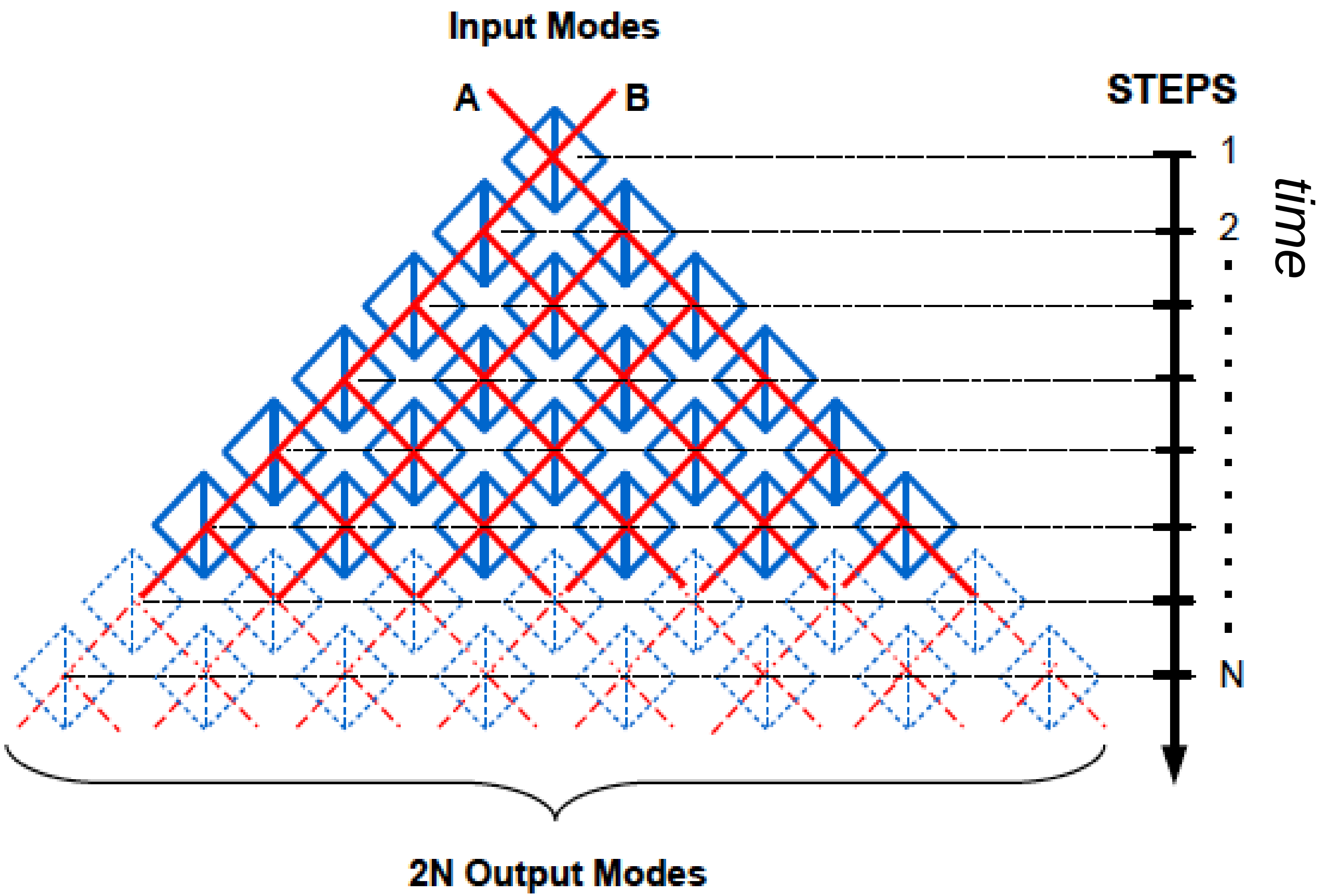


J. Matthews & M. Thompson, *News & Views Nature (2012)*





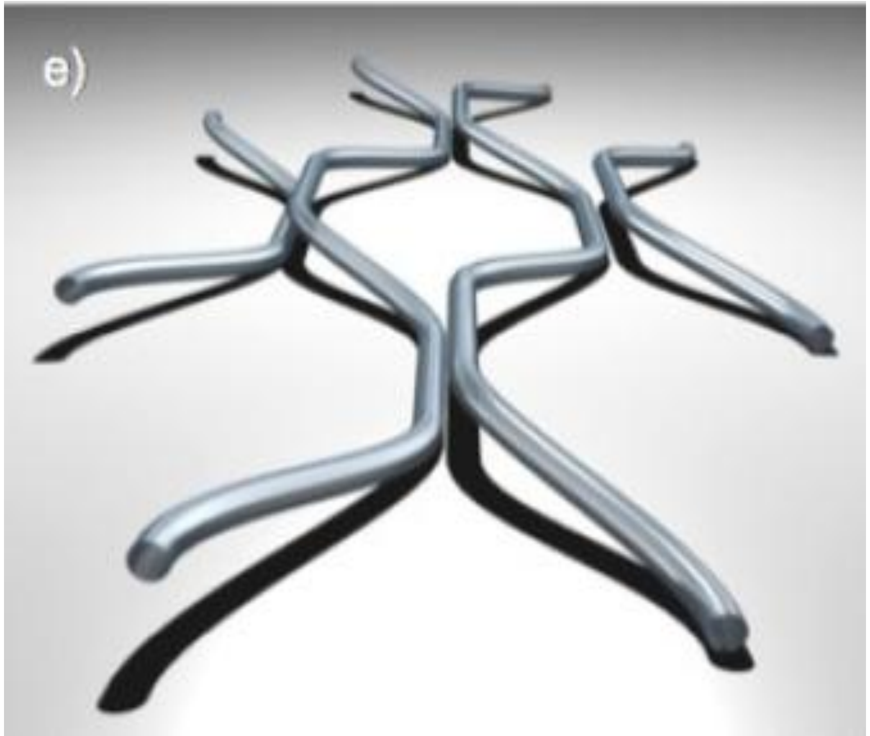
Implementing QW with photons



Discrete QW: realized by concatenating many beam splitters and phase shifters

Feasible with integrated photonic waveguides

Polarization independent QW



- Polarization independent lattices made possible by 3D writing capability
- Path lengths controlled up to few nanometers

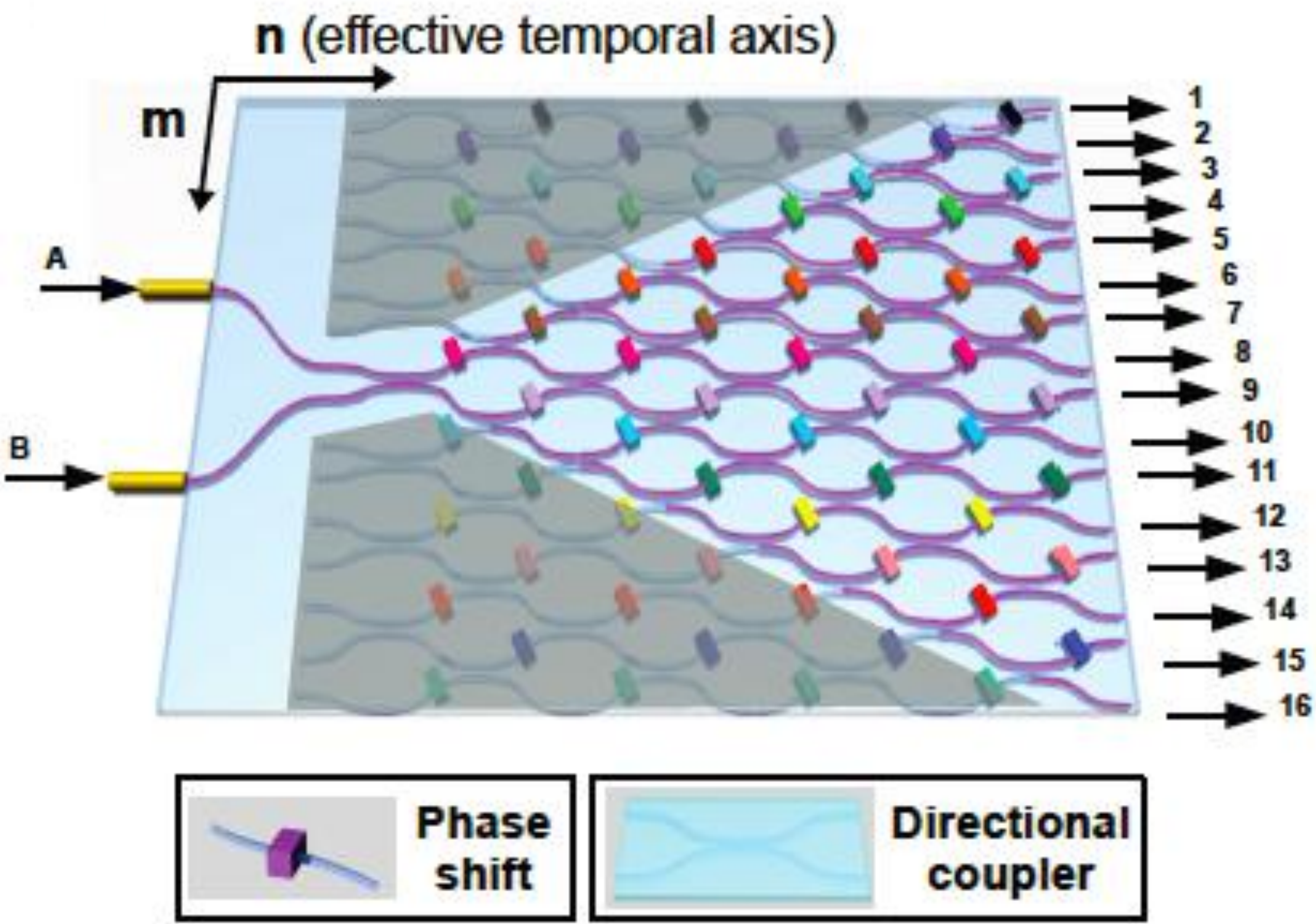
L. Sansoni, *et al.*, Phys, Rev, Lett, **108**, 010502 (2012)

Main QW realizations

Ordered QW → ***Study the statistics of bosonic/fermionic wavefunction***
PRL (2012)

Disordered QW depending
- on site
- but NOT on time

→ ***Anderson localization of the quantum particle wavefunction***
Nat Photon (2013)



Up to 16 output modes and 64 polarization independent BSs and phase-shifters

On chip BS array

The BosonSampling problem

HOW TO ACHIEVE QUANTUM SUPREMACY ??

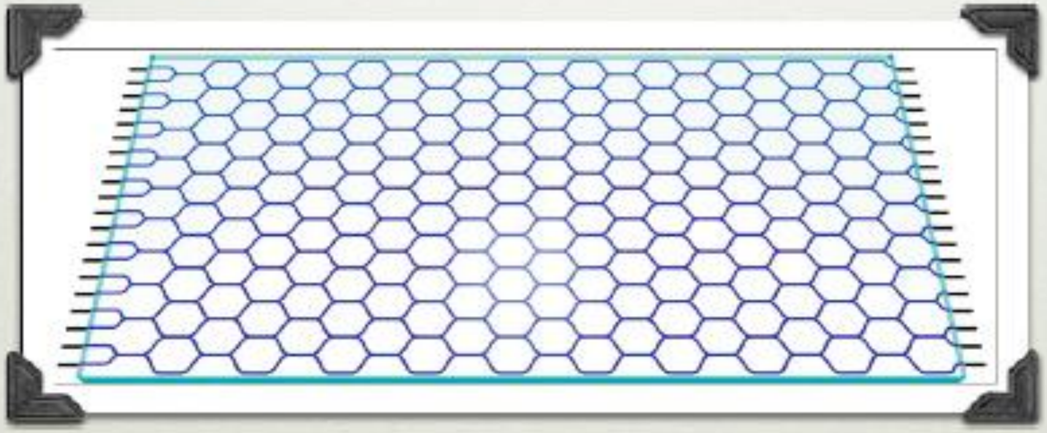
John Preskill
@preskill
Segui

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

BOSON SAMPLING

propagation on the chip with m modes →

Input:
n **bosons**



Output:
n**-photon state**

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

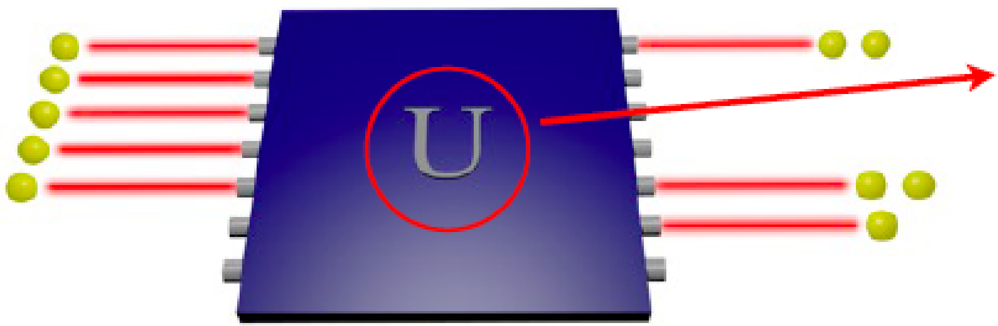
Answer: NO!!

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

BosonSampling

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



Uniformly drawn

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

BosonSampling

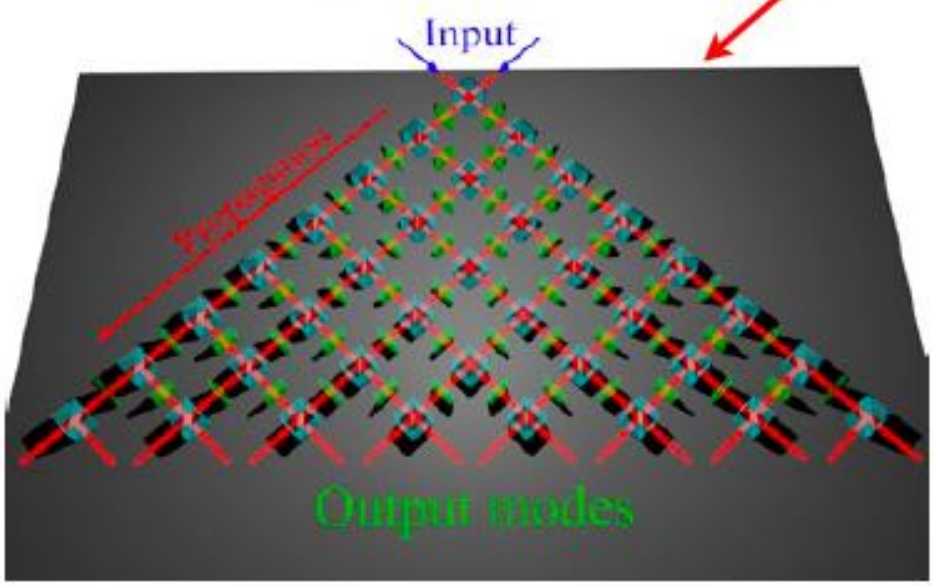
Photons naturally solve the BosonSampling problem

<u>Experimental platform</u>: photons in linear optical interferometers

Required resources:

- Single-photon inputs
- Multimode interferometers
- Detection

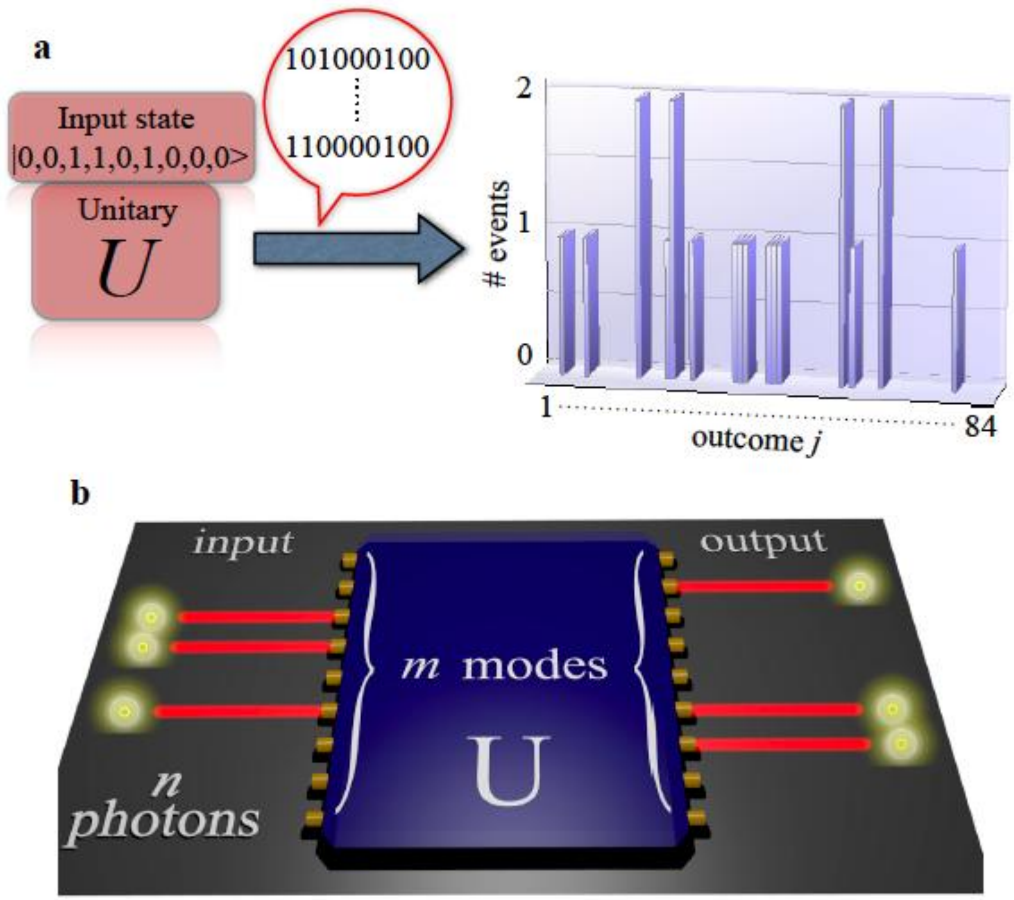
n photons
m modes



Hard to implements with bulk optics

Require a technological step recently available due to integrated photonics

BosonSampling



« 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)

BosonSampling

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. 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

University of Oxford · 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

15 FEBRUARY 2013 VOL 339 SCIENCE www.sciencemag.org

universität wien · seit 1558

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 ...

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.

15 FEBRUARY 2013 VOL 339 SCIENCE www.sciencemag.org

... trarily small constant [section S5 of (32)]. For example, for the Bose-Hubbard model and for ...

... primes. The presumed difficulty of this task is the basis of the majority of today's public-key en- ...

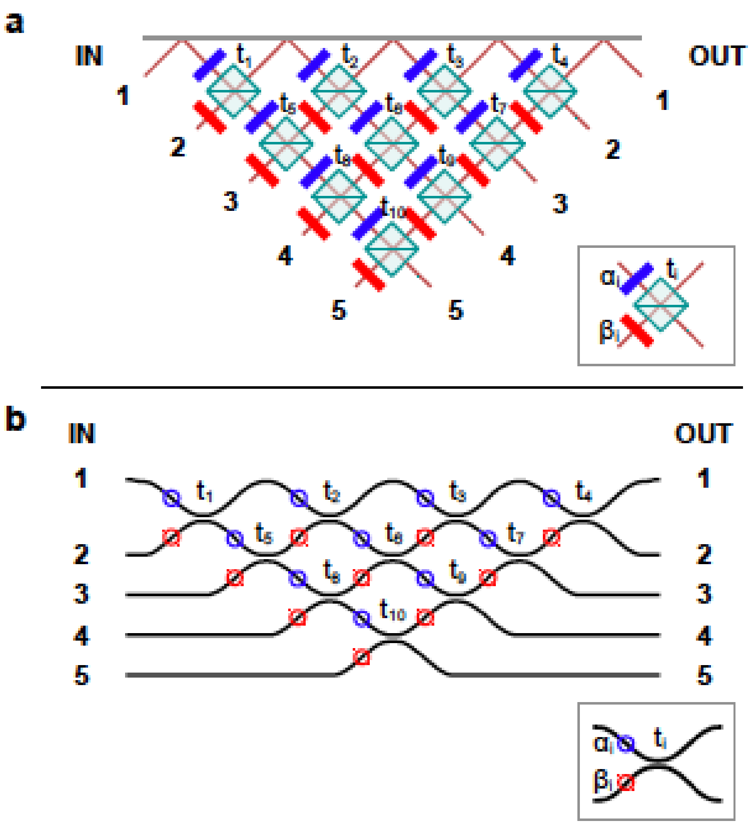
... on a probabilistic Turing machine—means that a classical efficient factoring algorithm exists.

BosonSampling: the chip

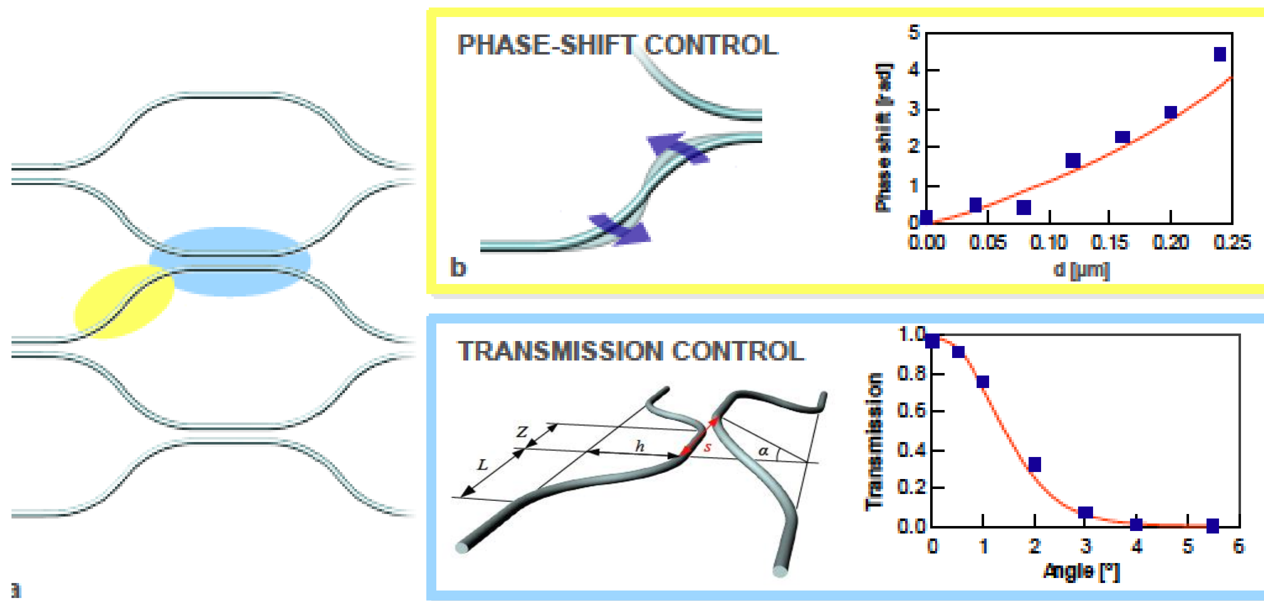
Requirement for Boson Sampling - design arbitrary interferometers

Requires independent control of phases and beam-splitter operation

Architecture for arbitrary unitary

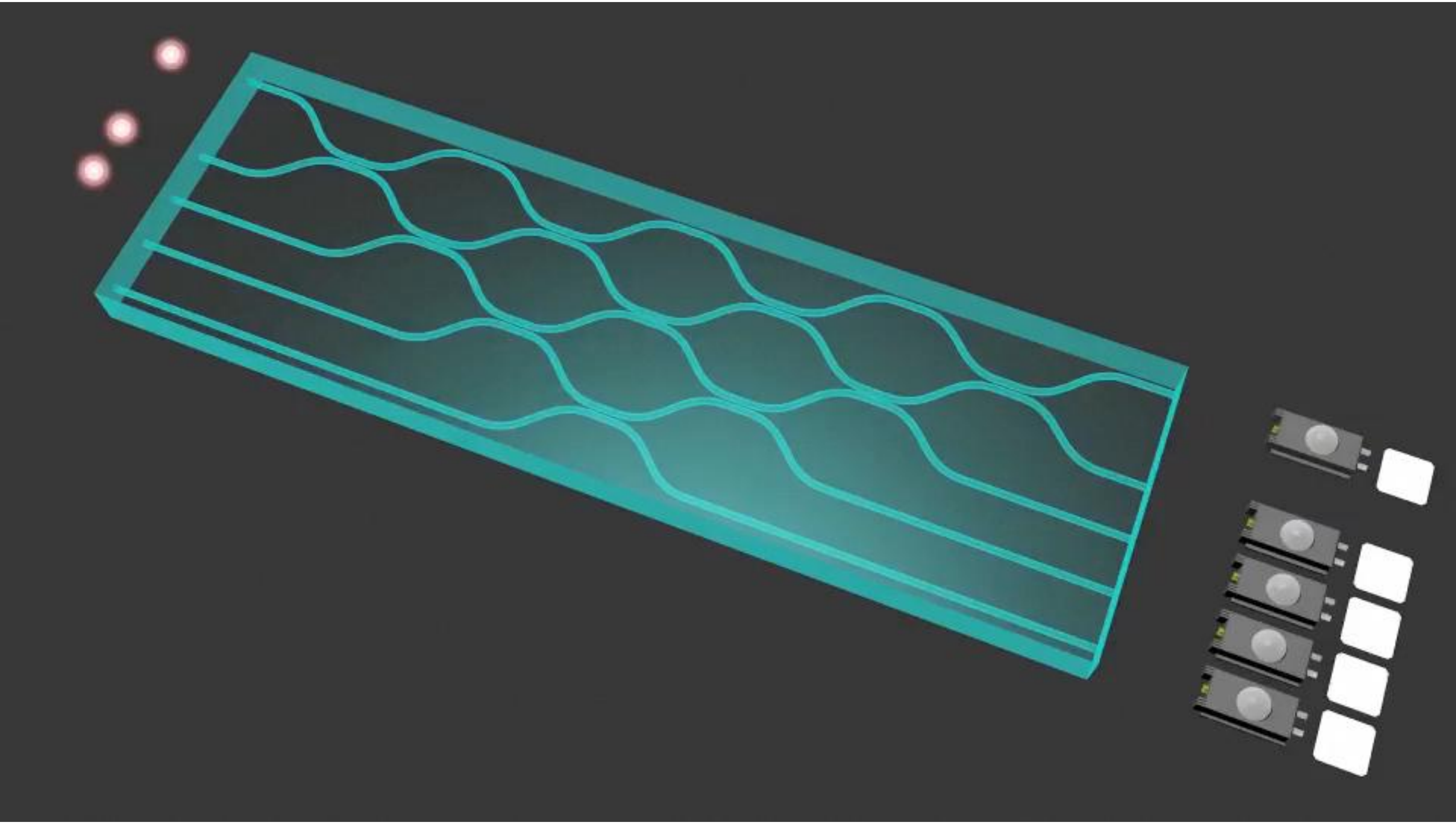


Fabrication process

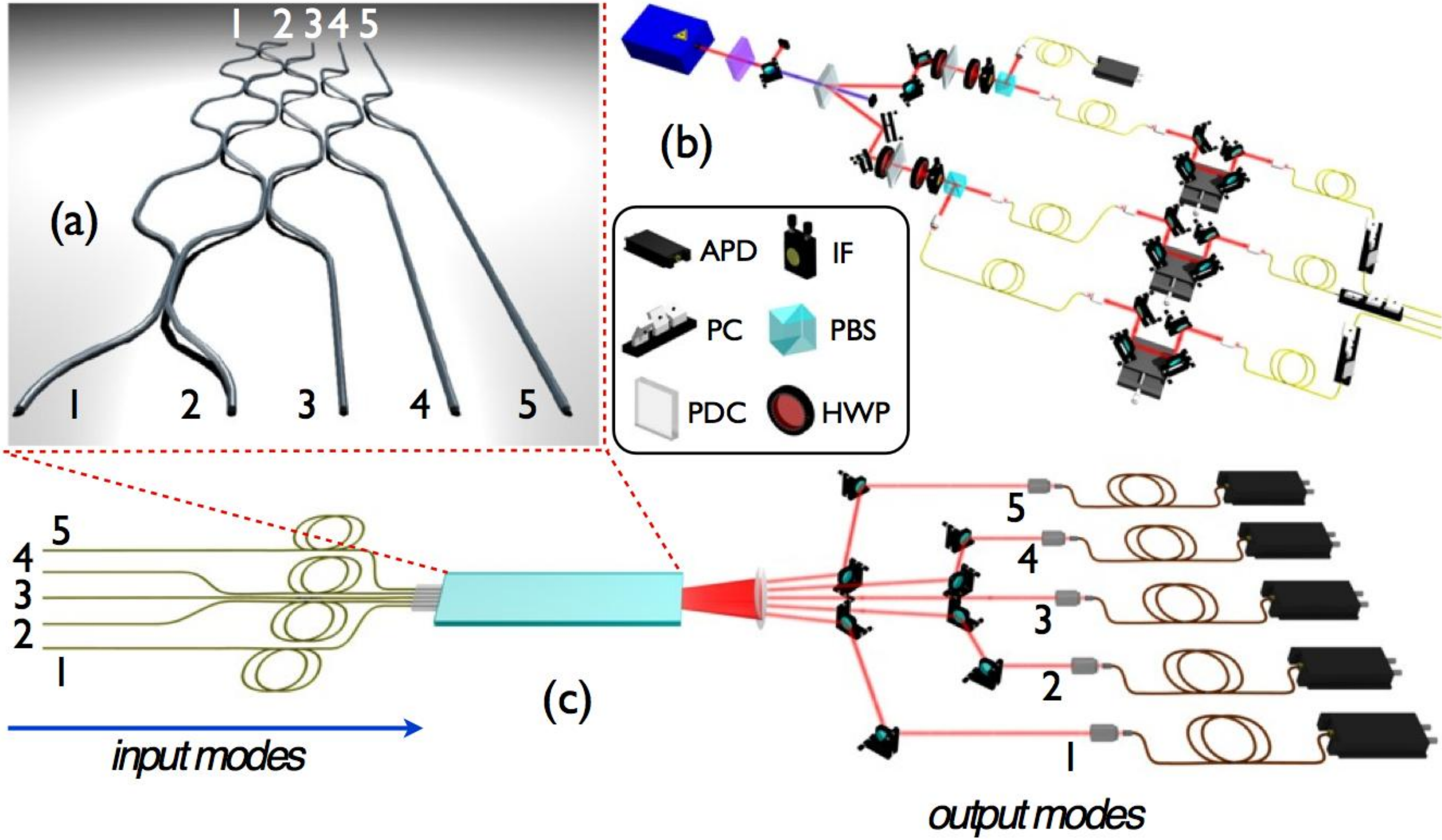


A. Crespi, et al., *Nature Photonics* **7**, 545 (2013)

BosonSampling



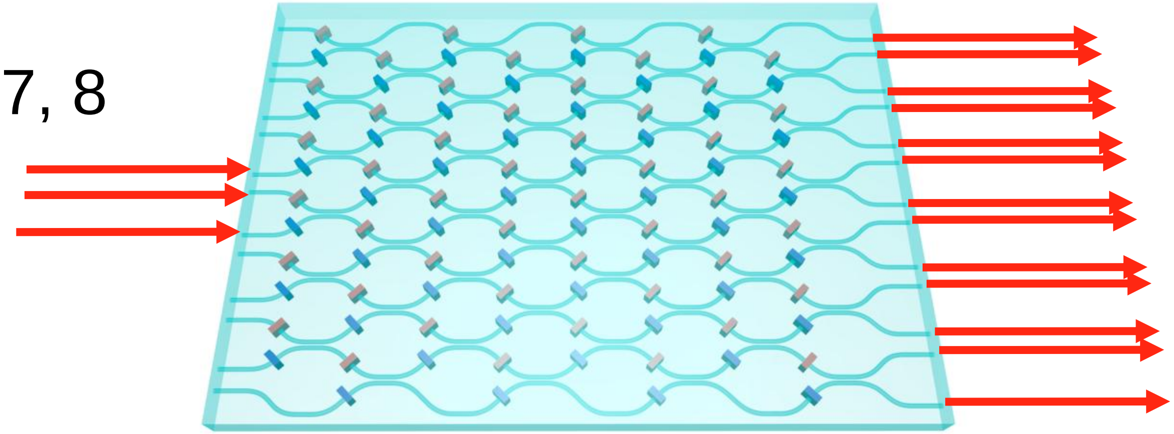
BosonSampling: the setup



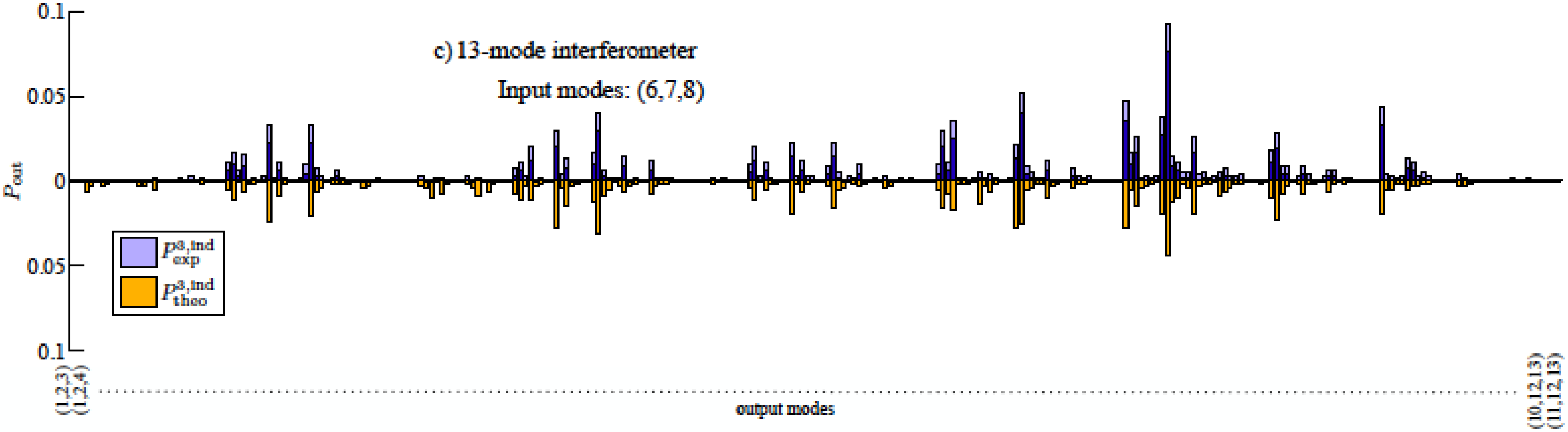
A. Crespi, et al., *Nature Photonics* **7**, 545 (2013)

Up to 13 mode systems investigated

Input: 6, 7, 8



Output: 286 different possible no-bunching configurations



N. Spagnolo, et al., *Nature Photonics*, ***8***, *615* (2014)

Validation of BosonSampling

Can Boson Sampling be validated?

It has been argued that due to the high complexity, BosonSampling output in the hard-computational regime cannot be distinguished from the random output of a uniform distribution

C. Gogolin et al. *arXiv:1306.3995*

The Theorists' Answer

For each single registered event, which identifies the output state, calculate the quantity

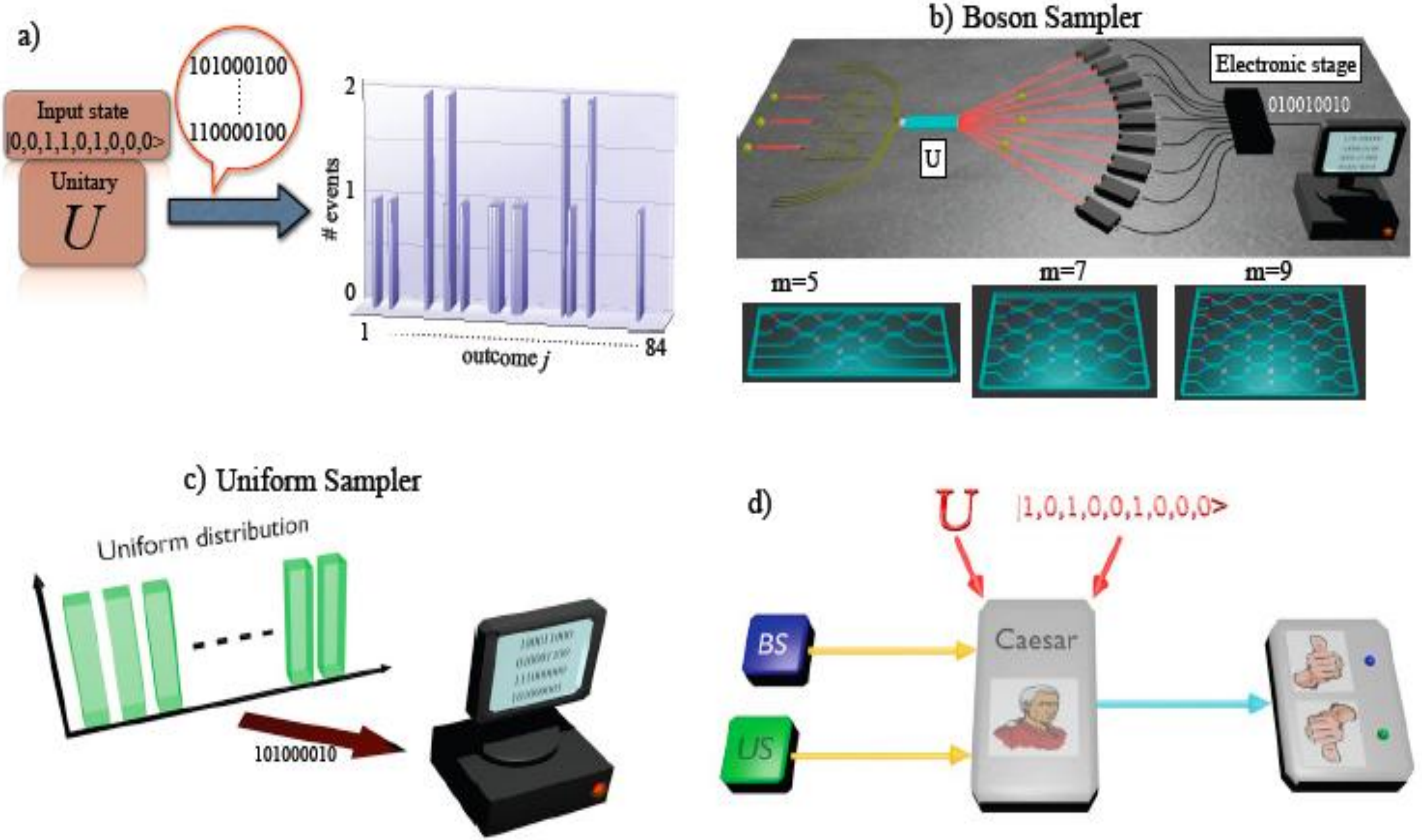
$$P = \prod_{i=1}^{n} \sum_{j=1}^{n} |A_{i,j}|^2$$

whith $A_{i,j}$ = submatrix of U depening on the input and output states, and compare this value to its counterpart for a uniform distribution Pu .

If P > Pu, you can guess that the single event has been produced by a BosonSampler

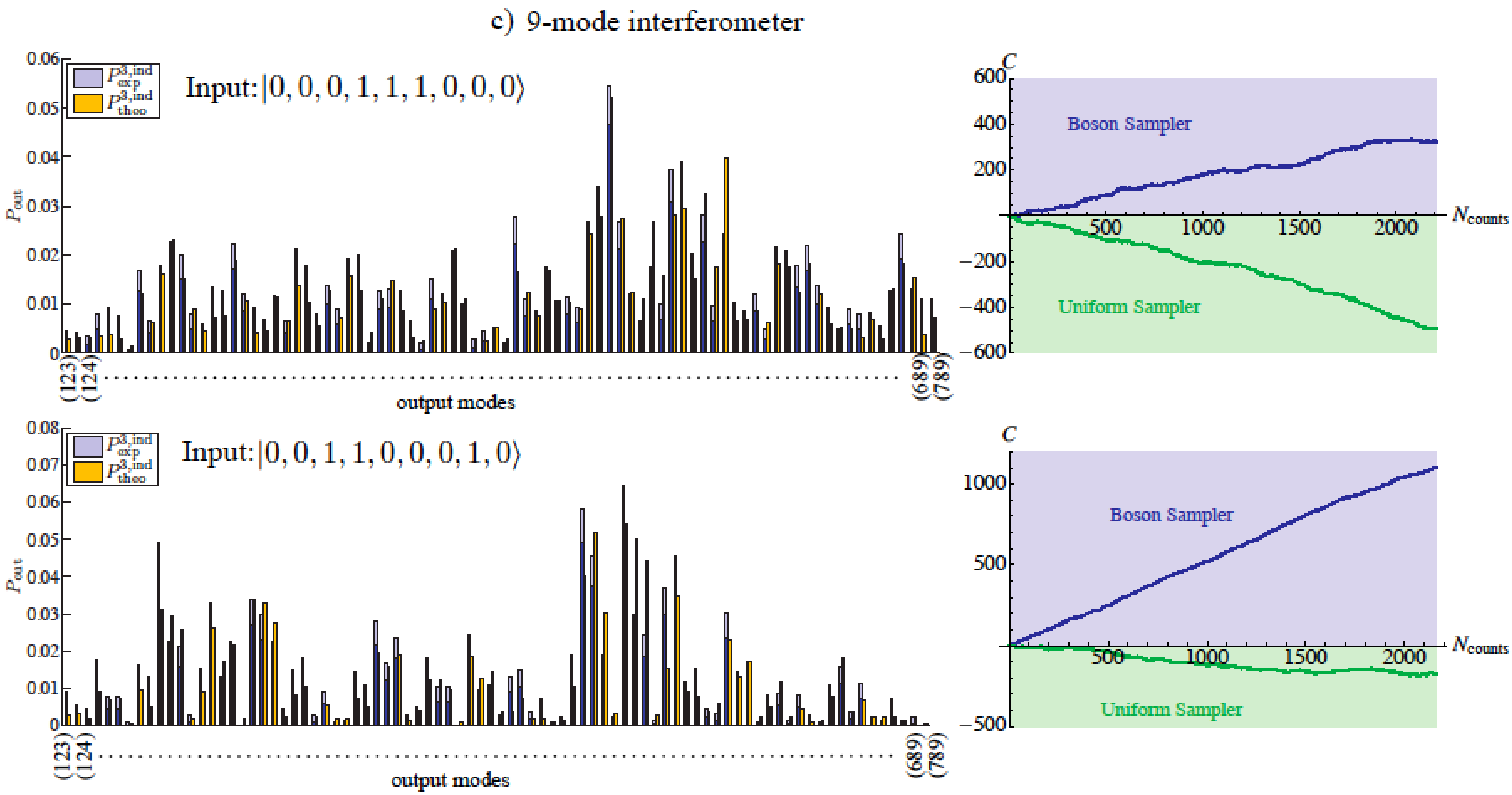
S. Aaronson et al. *arXiv:1309.7460*

Validation of BosonSampling



N. Spagnolo, et al., *Nature Photonics*, ***8****, 615* (2014)

Validation of BosonSampling with 9 modes



N. Spagnolo, et al., *Nature Photonics*, ***8***, *615* (2014)

Towards Quantum Supremacy

The extended Church-Turing (ECT) Thesis:
Everything feasibly computable in the physical world is feasibly co
(probabilistic) Turing machine

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

Open questions

- *Measure BS complexity*
- *Other equivalent experimental schemes*
- *Certify the functioning of a BS experiment*
- *How noise/imperfections affect a complex BS*

Challenges

- *Efficient single photon sour*
- *Reconfigurable photonic cir*
- *Efficient single photon dete*

Scattershot BosonSampling

p = probability of generating a photon pair in a single source
(typical values *p*=0.01-0.015)

p^n probability of generating the *n*-photon input

Scattershot Boson Sampling, n-photon term

$p^n(1-p)^{m-n}$ probability of generating one of the *n*-photon input configurations

$\binom{m}{n}$ number of possible output configurations

Total generation rate: $\sim p^n(1-p)^{m-n}\binom{m}{n}$

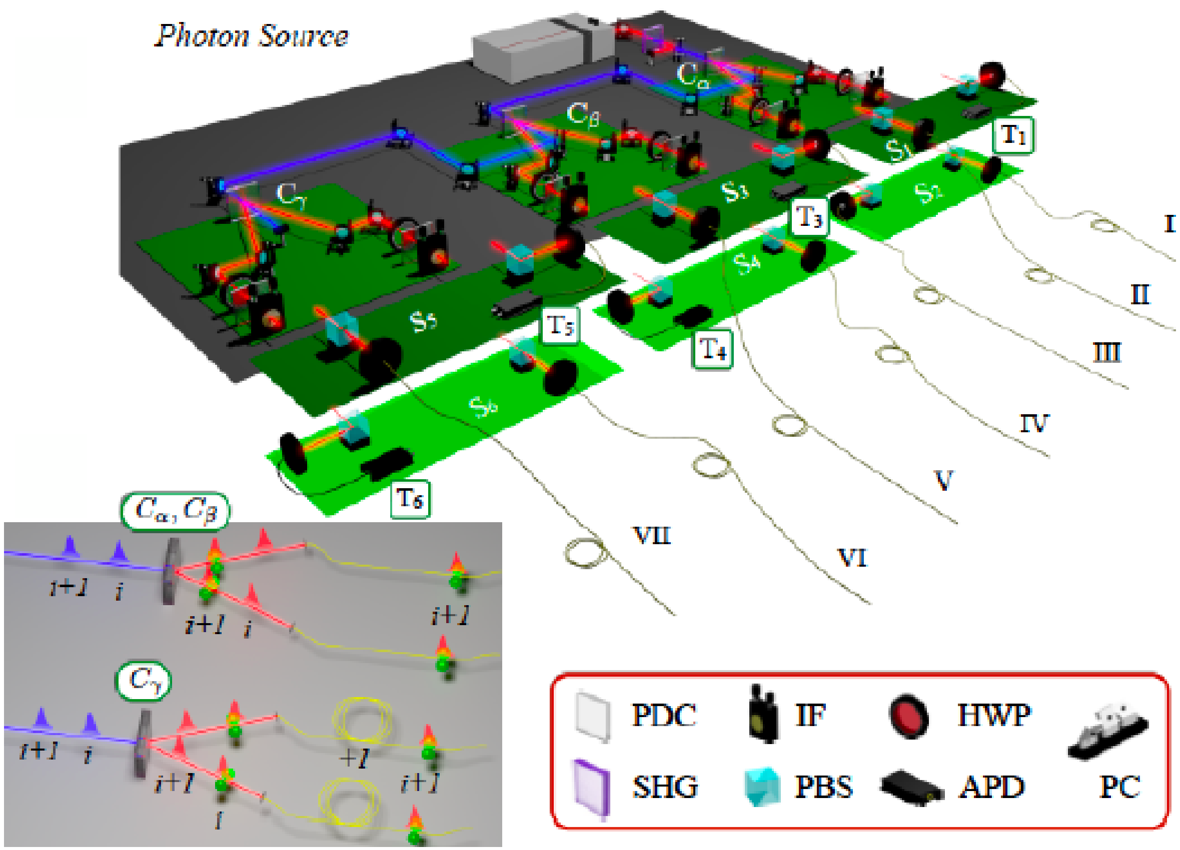
Sample both from the *input* and the *output modes* → **Potentially huge increase of the brightness of the quantum hardware**

See Niko Viggianiello's Poster on Scattershot BosonSampling!!!

Scattershot BosonSampling: generation

Experimental setup - 1

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



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

↕

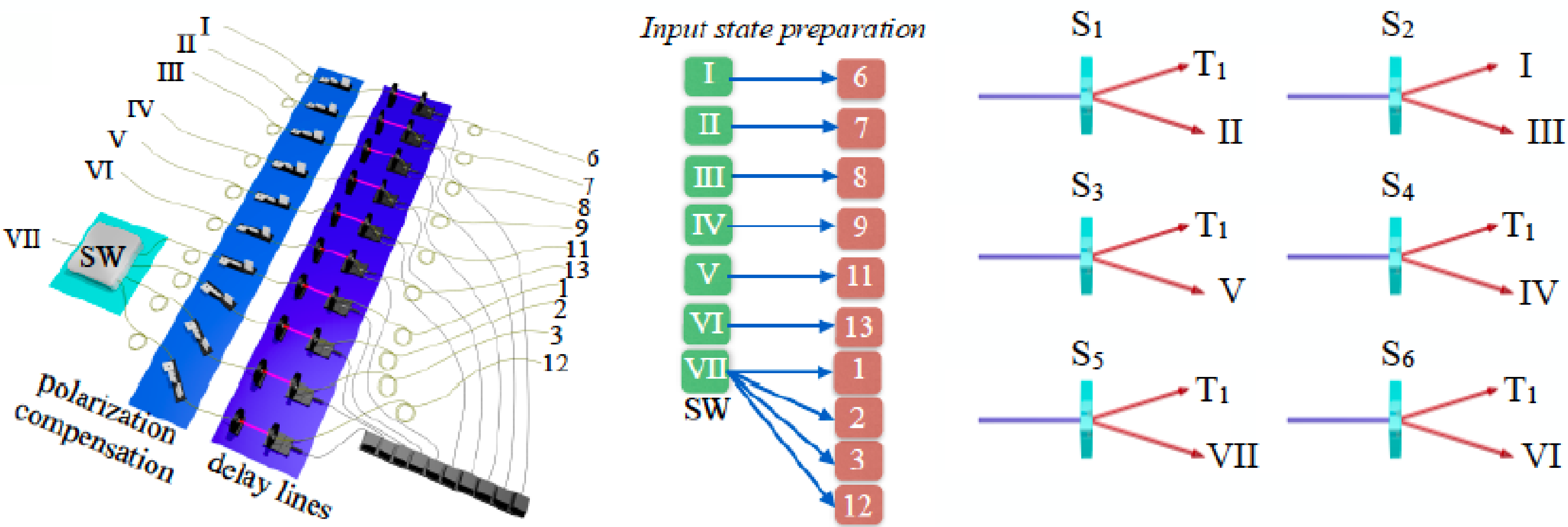
3 physical crystals and separation by polarization

Interference between photons generated from two subsequent laser pulses

M. Bentivegna, et al., *Science Advances*, ***1***, *e1400255* (2015)

Scattershot BosonSampling: preparation

Experimental setup - 2



Three photon events:

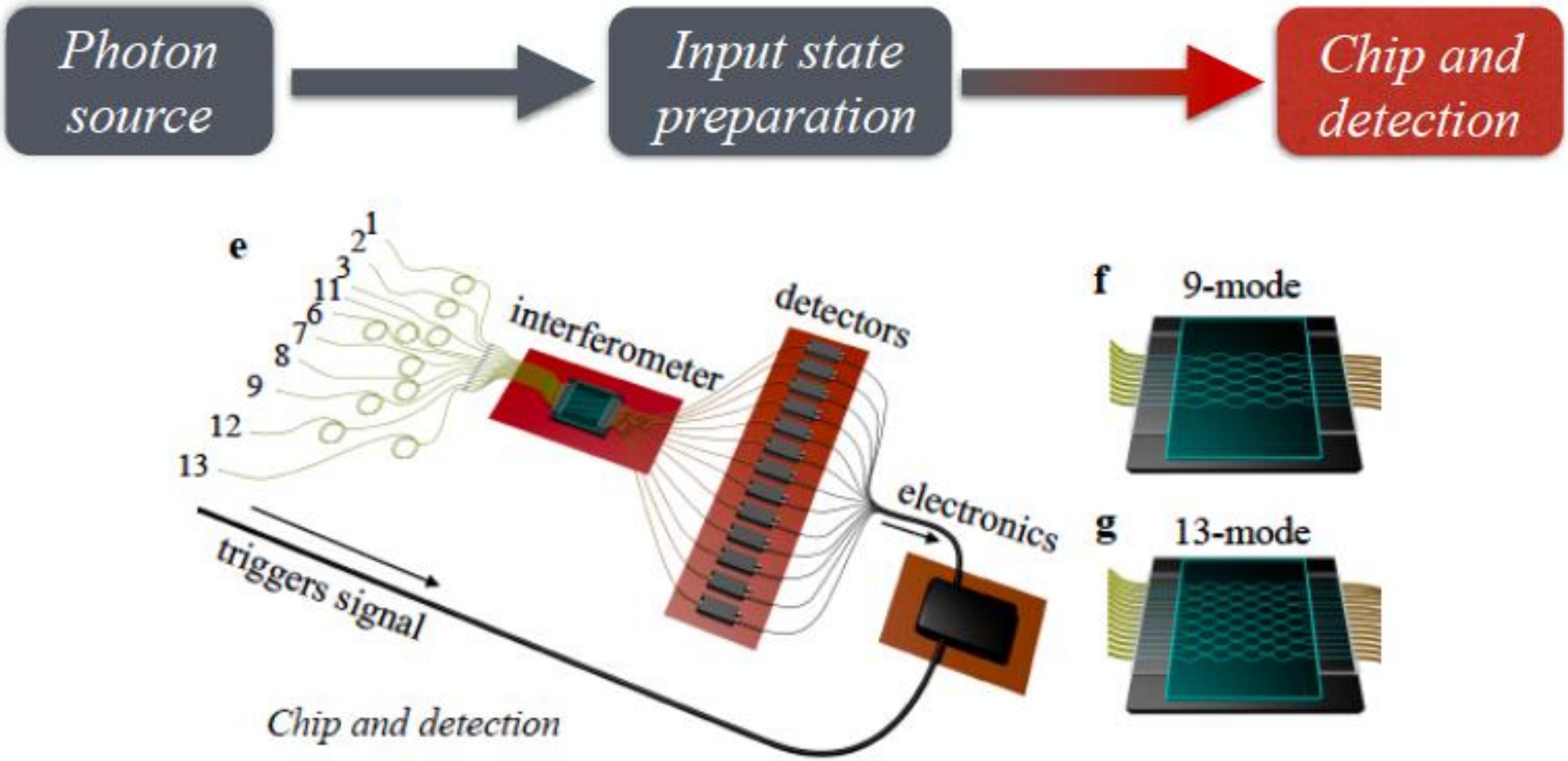
1) Photon I (input 6) [fixed]
2) Photon III (input 8) [fixed]
3) Random input heralded by T_i

Input randomness further enhanced by sequential switching of photon VII

M. Bentivegna, et al., *Science Advances*, ***1***, *e1400255* (2015)

Scattershot BS: chip and detection

Experimental setup - 3



Evolution through m=9 and m=13 interferometers with random (but known) structure

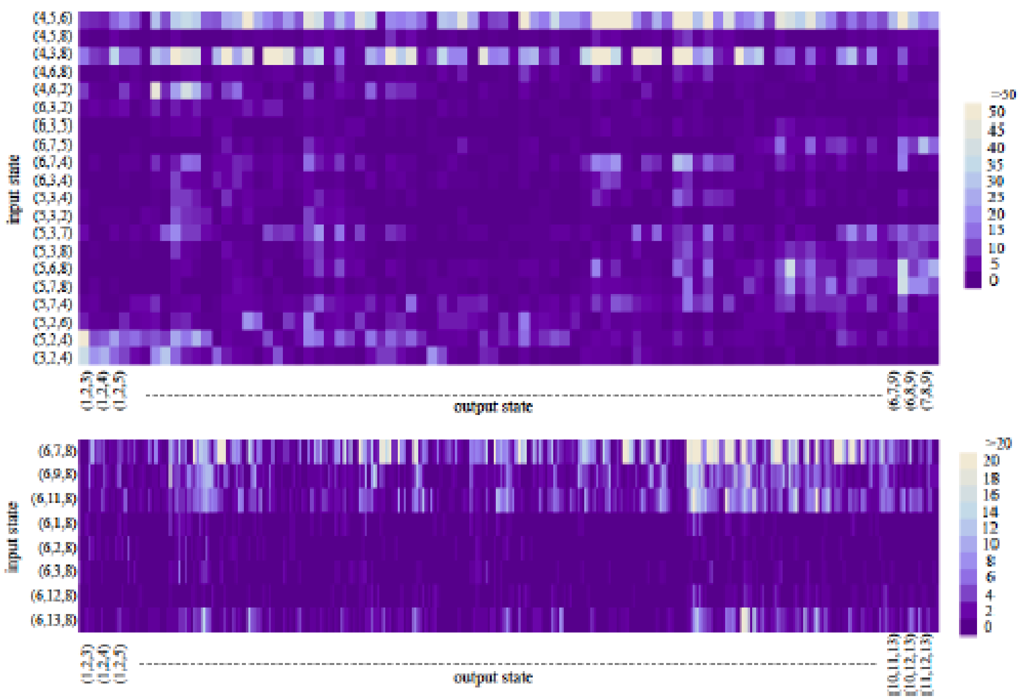
Coincidence detection for:
- Three-photon events with one heralding trigger
- Two-photon events with two heralding triggers

M. Bentivegna, et al., *Science Advances*, ***1***, *e1400255* (2015)

Scattershot BS: random input

Scattershot - sampling with random input

Three-photon events



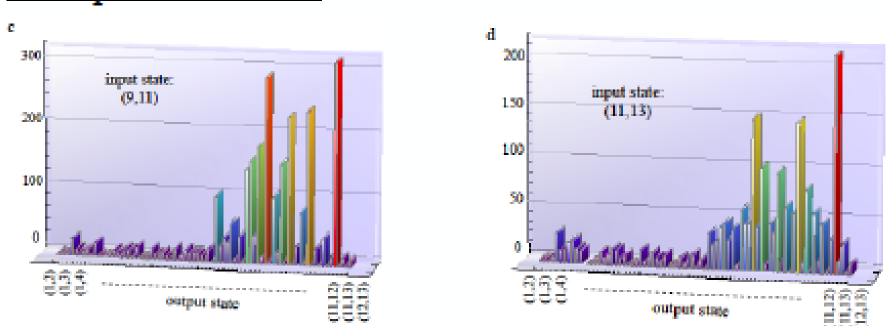
Number of input/output configurations

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

M. Bentivegna, et al., *Science Advances*, ***1***, *e1400255* (2015)

Implementing the Fast Fourier Transform

Boson Sampling experiments pose serious problem of certification of the result's correctness in the computationally-hard regime.

Use 3-D photonic chips to test true n-photon interference in a multimode device [by M.C. Tichy *et al.* (Phys. Rev. Lett., 2014)].

Proposal based on the suppression of specific output configurations in an interferometer implementing an n^p -dimensional Quantum Fourier Transform (QFT) matrix.

Generalization of the 2-photon/2-modes Hong-Ou-Mandel (HOM) effect, used to test a wide range of photonic platforms.

A. Crespi, et al., *arXiv: 1508.00782v1* (2015)

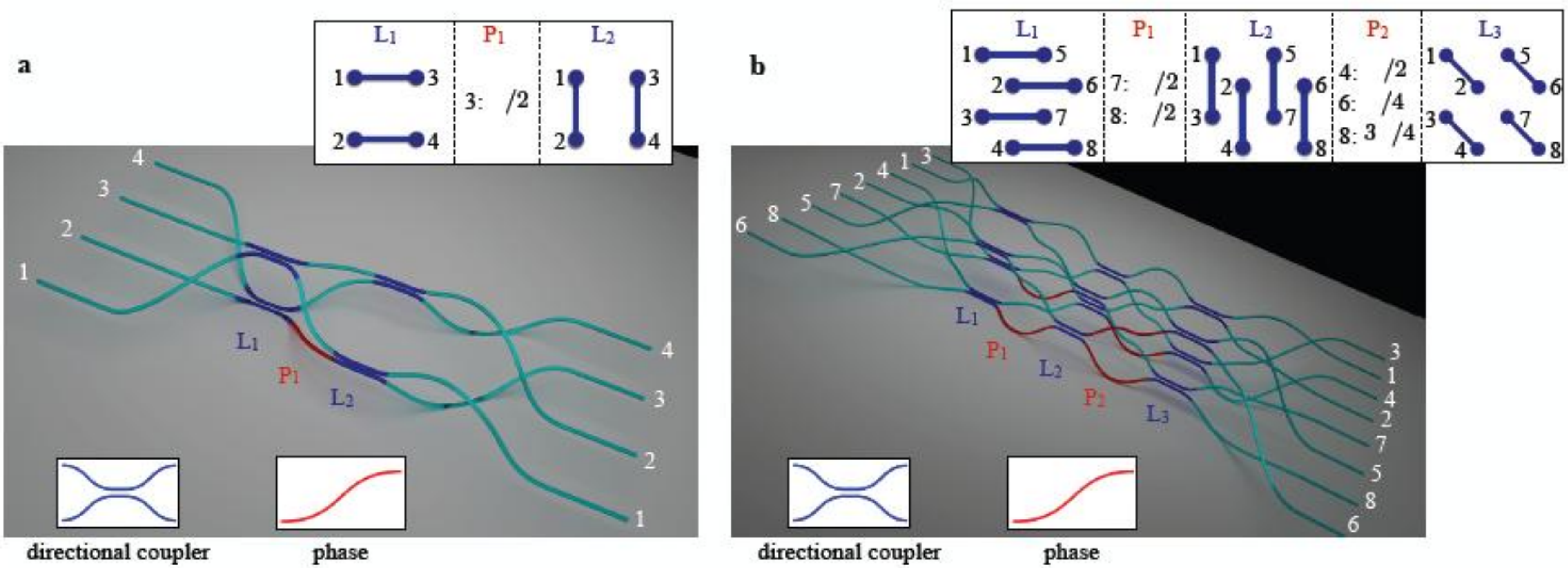
Quantum Fourier Transform in a 3D chip

Quantum interference in multimode interferometers may determine suppression of a large fraction of the output configurations.

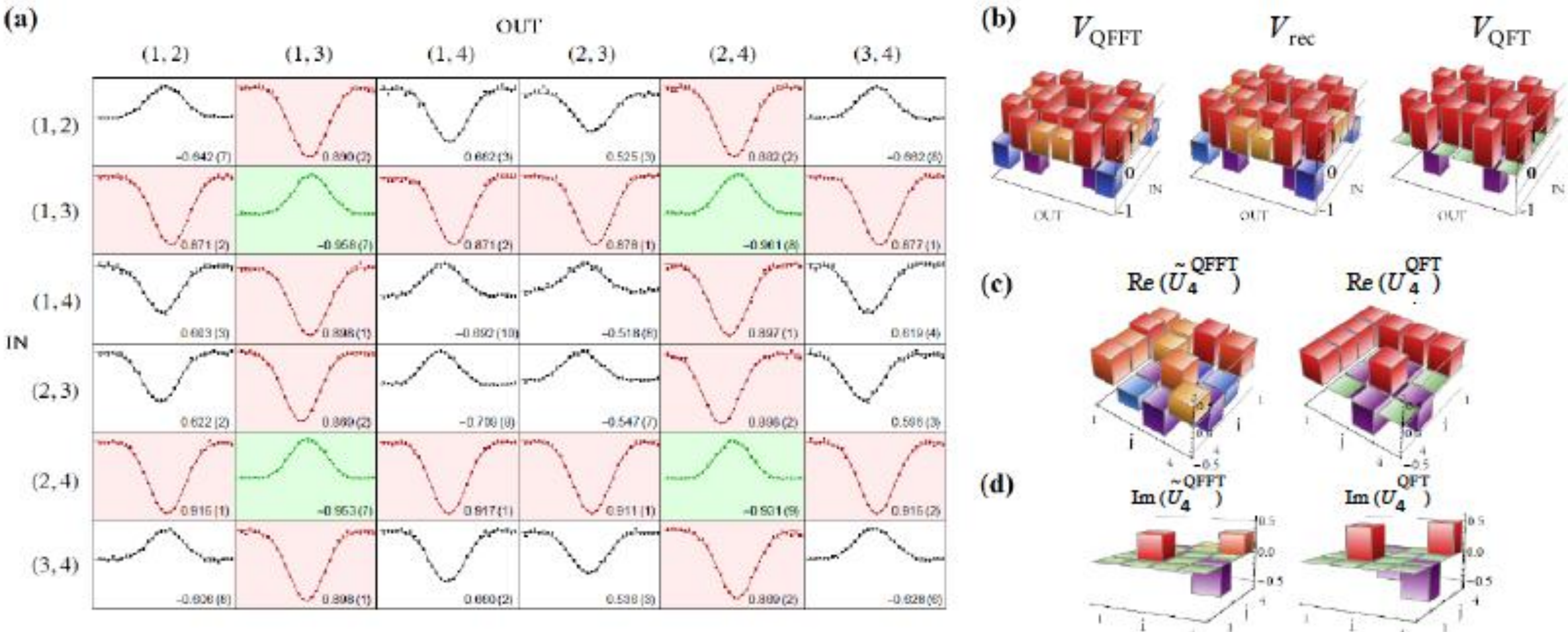
Study the evolution of particular input states through the network implementing the QFT described by the unitary matrix:

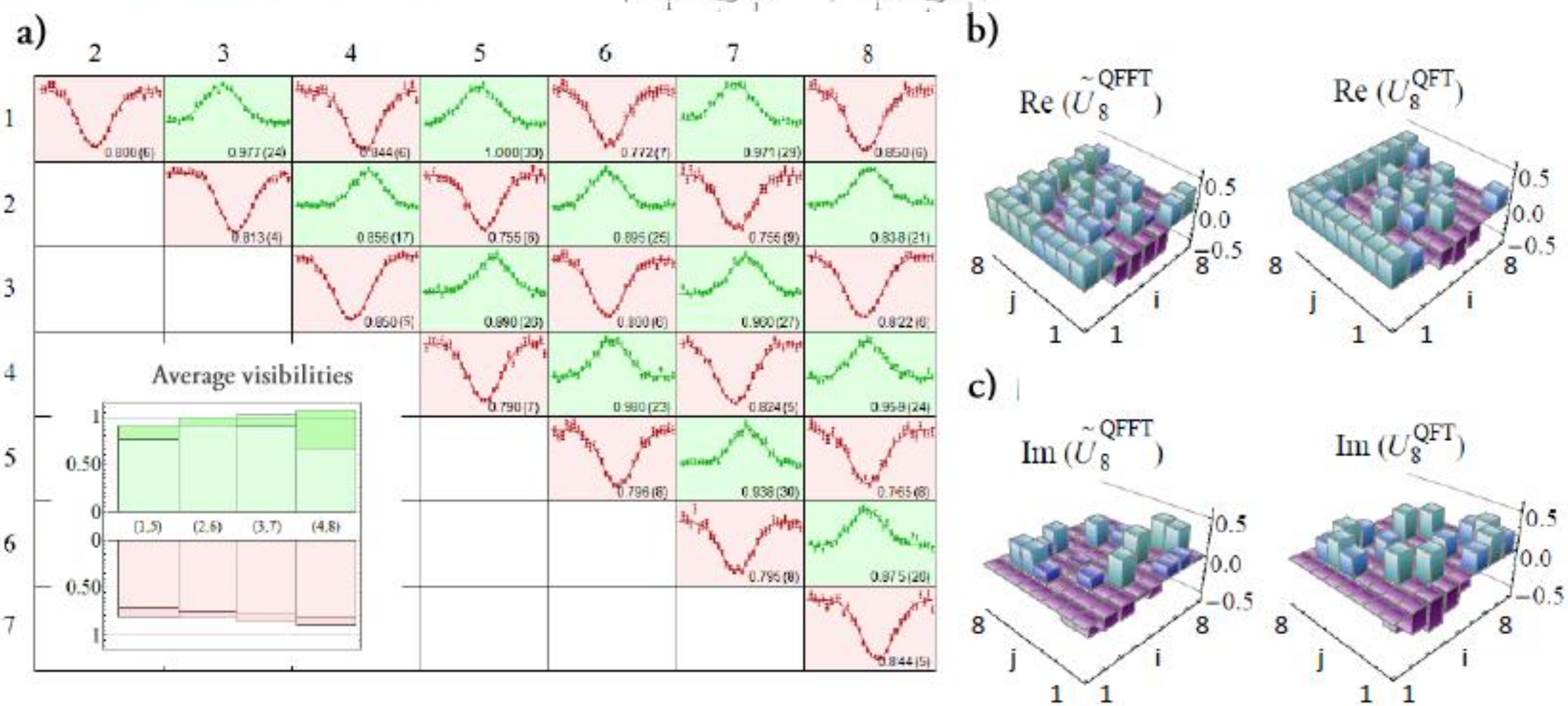
$$U_{l,q}^{\mathrm{QFT}} = \frac{1}{\sqrt{m}} e^{i \frac{2\pi l q}{m}}$$

Test performed with 2 photon and 4- and 8- mode interferometers



Quantum suppression law in a 3D chip





A. Crespi, et al., *arXiv: 1508.00782v1* (2015)

Conclusions

- Flexibility of waveguide integrated circuits (in particular 3D capabilities of fsec laser writing).
- Potential for quantum simulations and quantum walks (2 non-interacting bosons/fermions)
- BosonSampling (proof-of-principle test, validation, scattershot BS, Quantum Suppression Law)

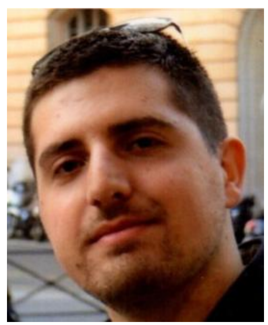
Fabio Sciarrino

3D-QUEST

Nicolò Spagnolo
Postdoc

Marco Bentivegna
PhD student

Fulvio Flammini
PhD student



Niko Viggianiello
PhD student

Sandro Giacomini
Giorgio Milani

Chiara Vitelli
Postdoc (now at Authority per l'Energia)

SAPIENZA UNIVERSITÀ DI ROMA
FUTURO IN RICERCA
SEVENTH FRAMEWORK PROGRAMME
chist-era
QUCHIP
QWAD
PICQUE MARIE CURIE ACTIONS
WWW.PICQUE.EU