Boson sampling with integrated photonics

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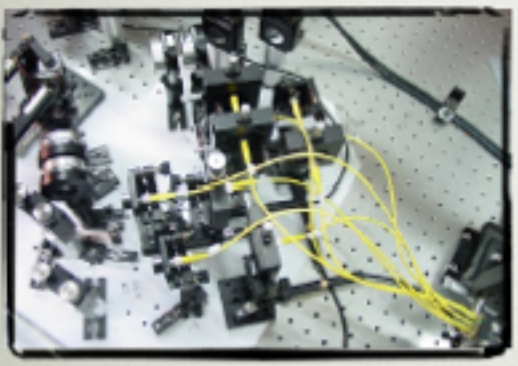
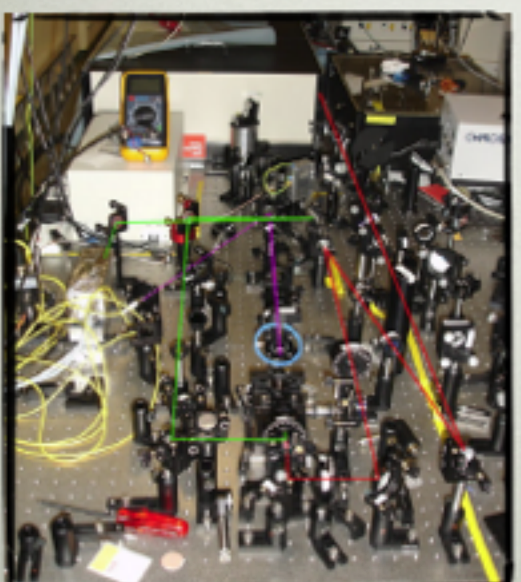
Quantum Optics: A benchmark for foundations of Quantum Mechanics and Quantum Technologies

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

Politecnico di Milano IFN CNR

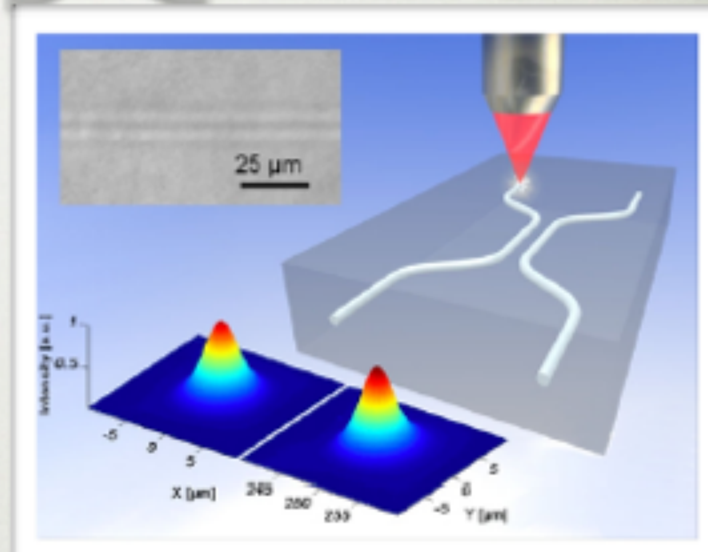




Limitations of experiments with bulk optics:

- 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 photonic quantum simulations

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

N. Spagnolo
C. Vitelli
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P. Mataloni
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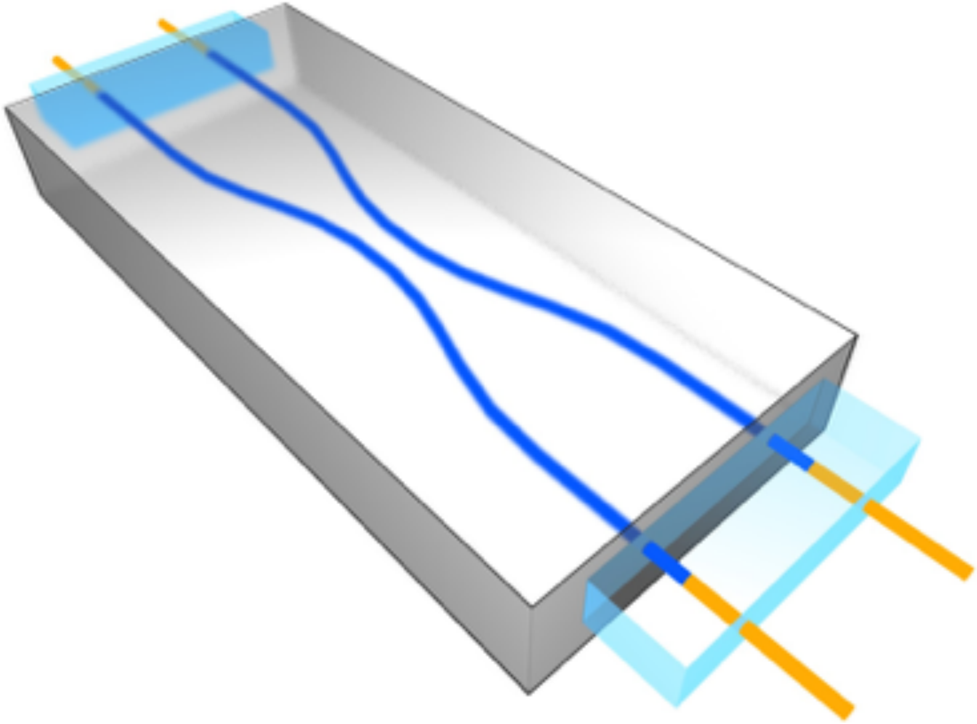

SAPIENZA
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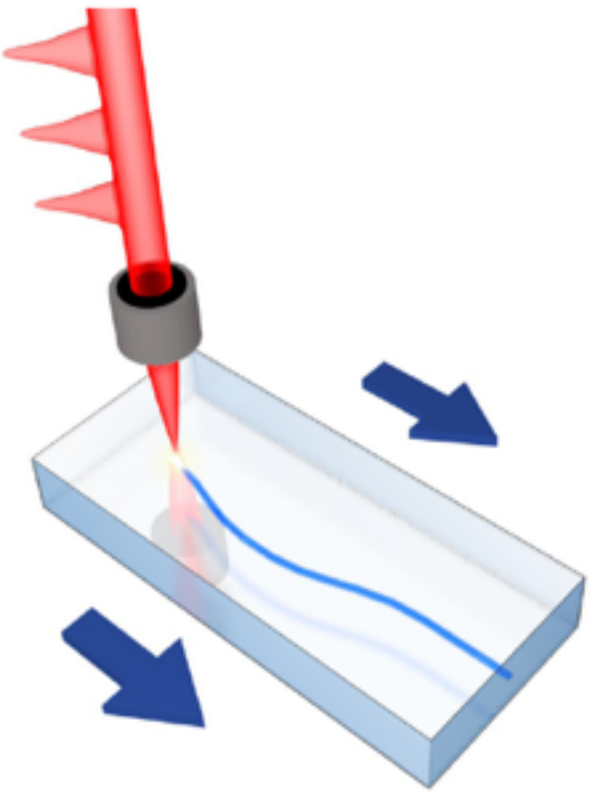
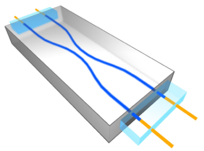
A. Crespi
R. Ramponi
R. Osellame

Integrated photonics: Femtosecond laser writing

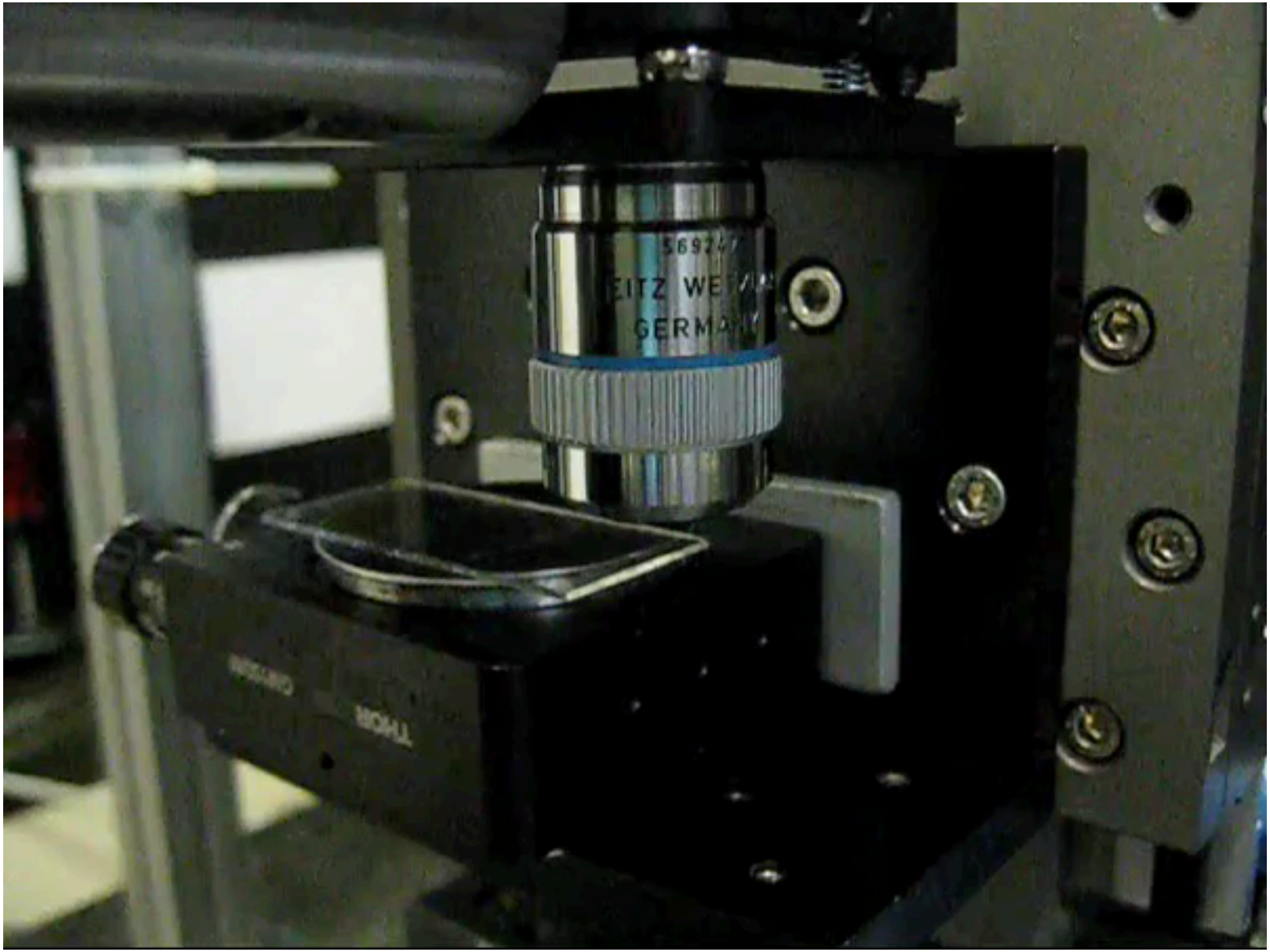
Laser writing technique for devices able to transmit polarization qubits



- ➢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.

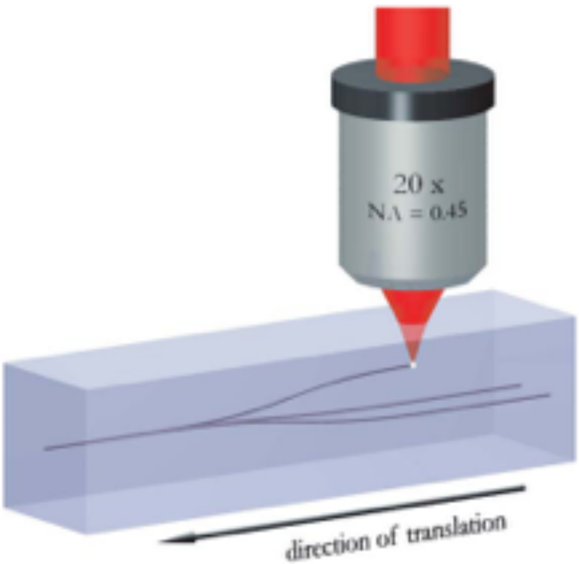


Femtosecond laser writing



Femtosecond laser writing

3-dimensional capabilities



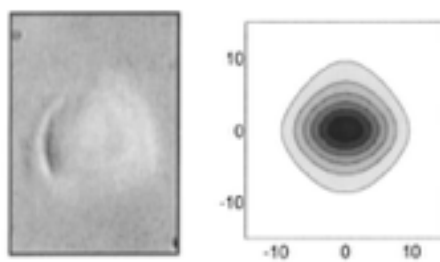
Rapid device prototyping: writing speed =4 cm/s

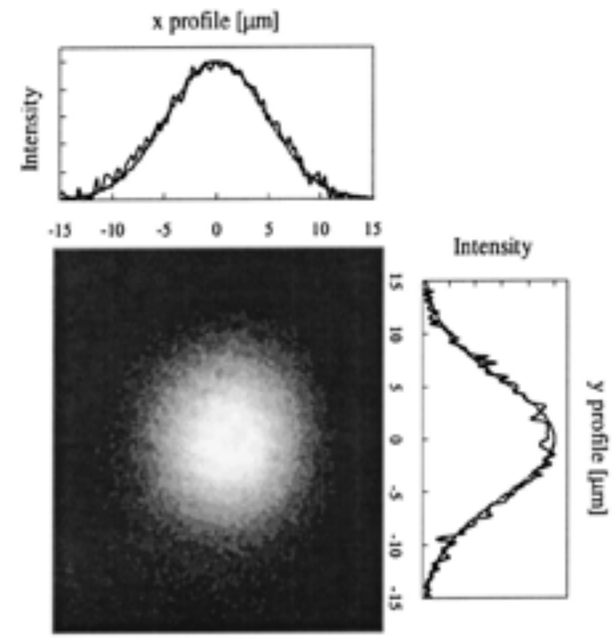
Propagation of circular gaussian modes

Characteristics:

Circular waveguide transverse profile

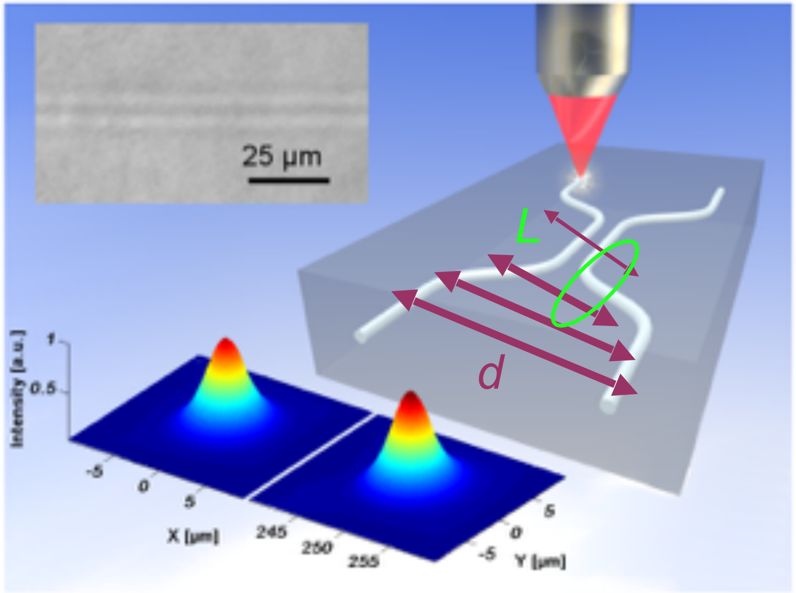
Low birefringence





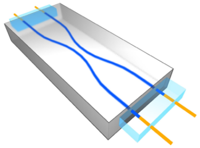
R. R. Gattass and E. Mazur, Nat. Photon. 2, 219 (2008).
G. Della Valle, R. Osellame, and P. Laporta, J. Opt. A 11, 013001 (2009).

Integrated beam splitter



L: interaction region

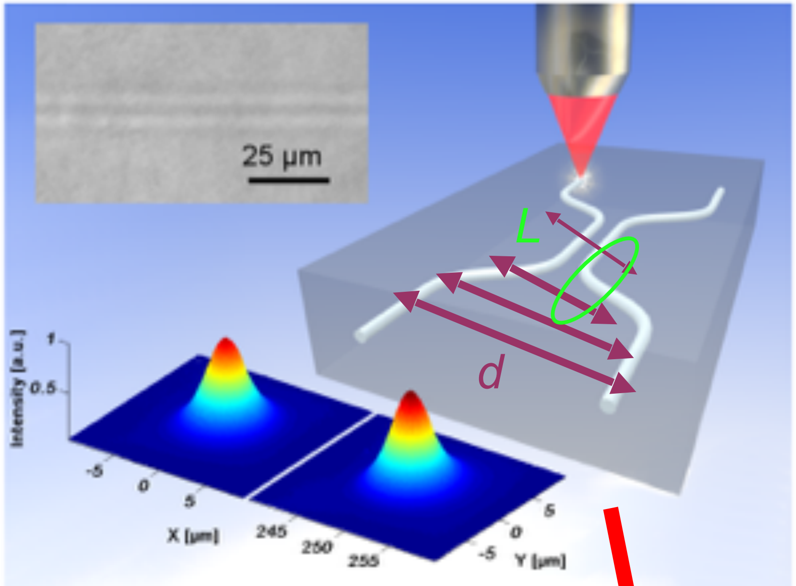
the coupling of the modes occurs also in the curved parts of the two waveguides

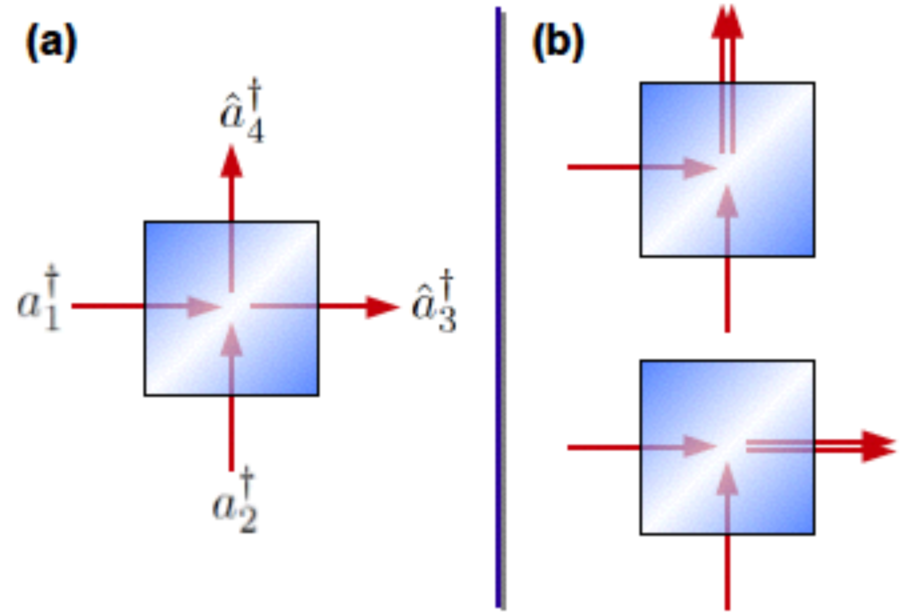


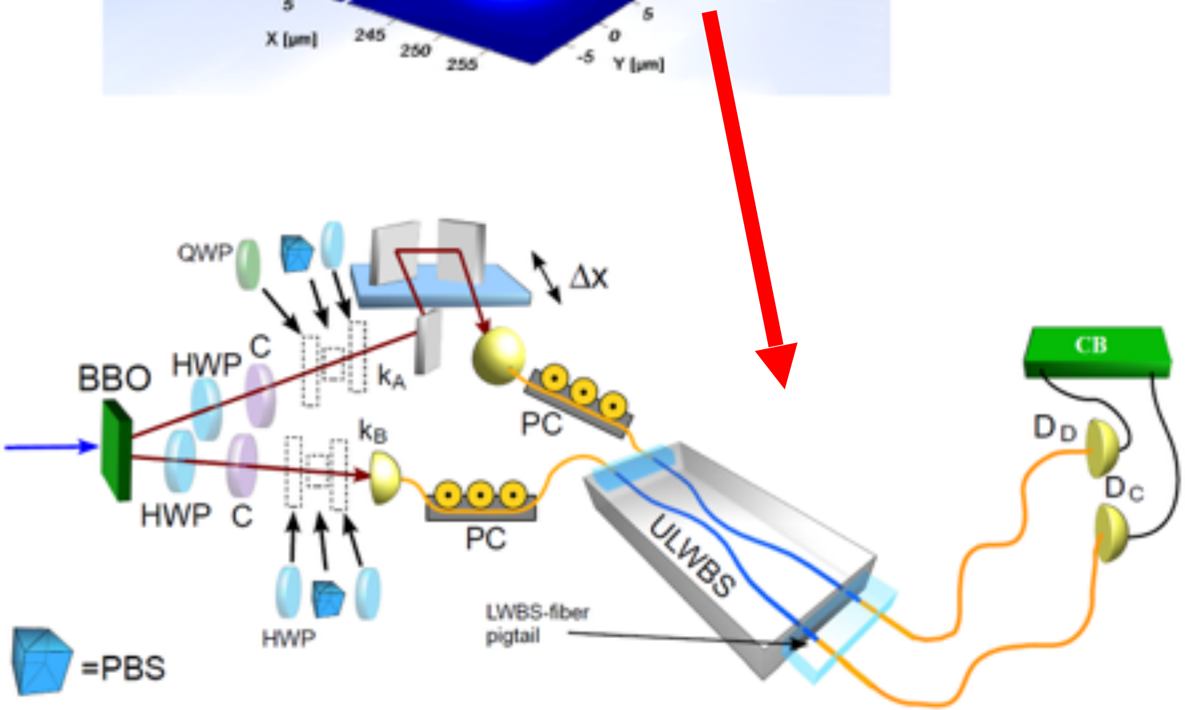
L. Sansoni *et al. Phys. Rev. Lett.* **105**, 200503 (2010)

Integrated beam splitter

Indistinguishable photons: Bosonic coalescence

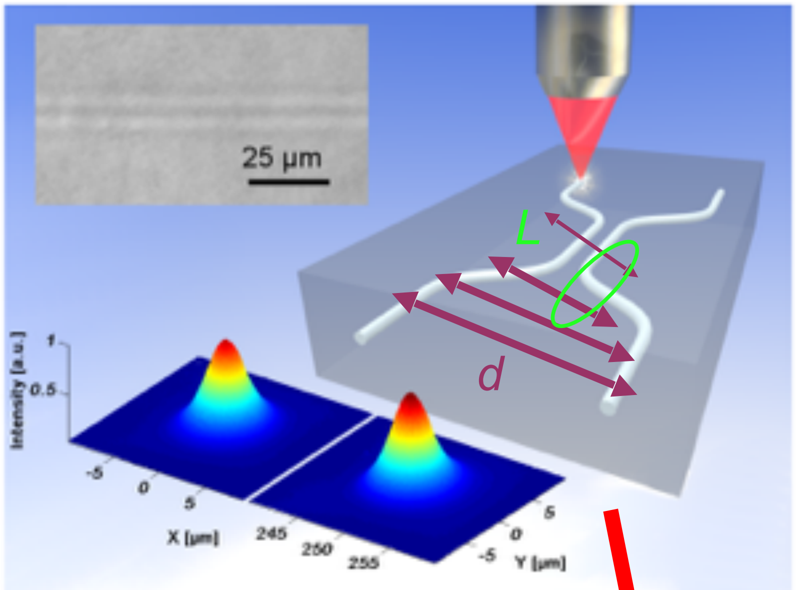


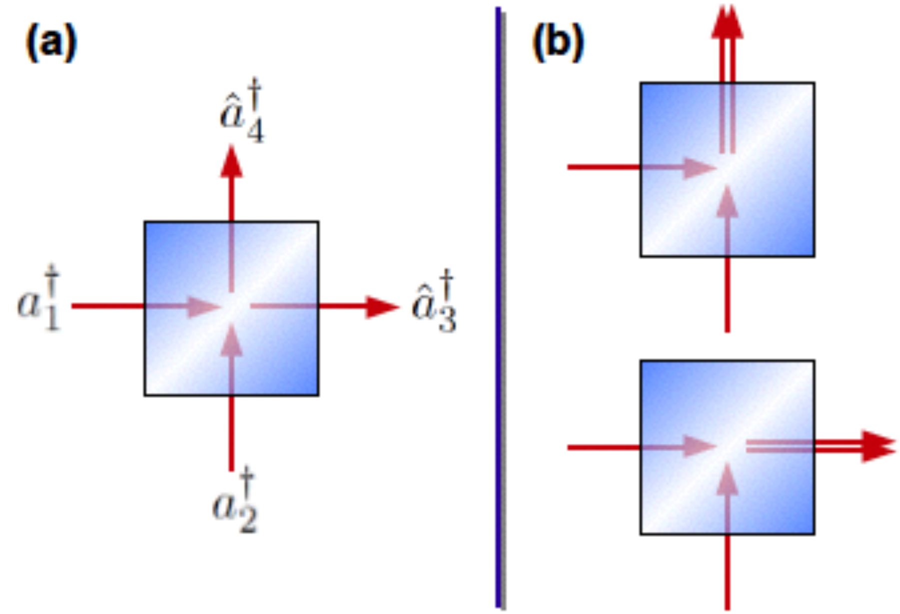


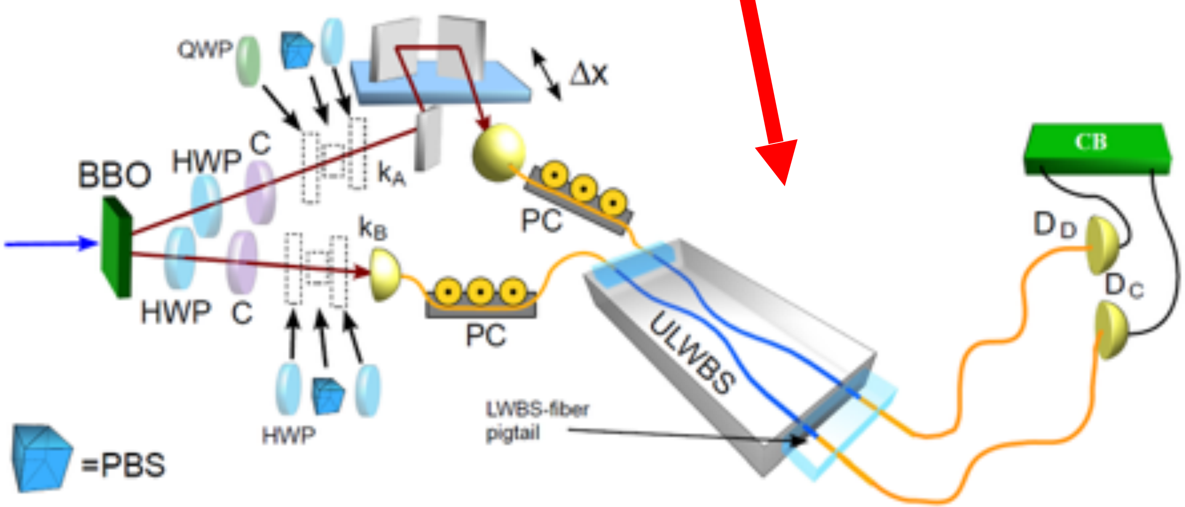


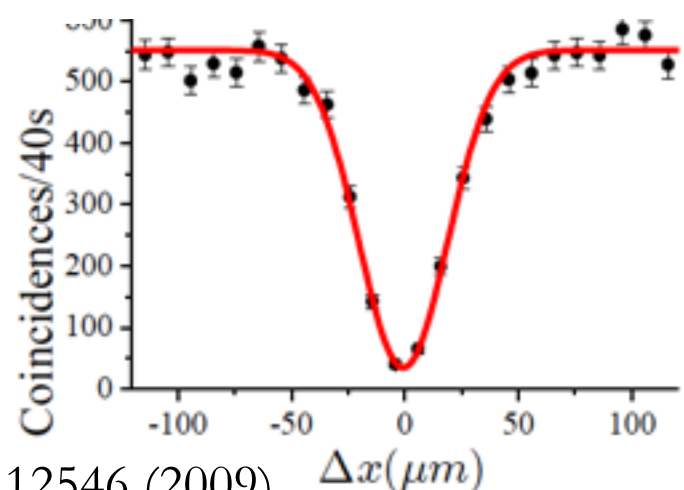
Integrated beam splitter

Indistinguishable photons: Bosonic coalescence



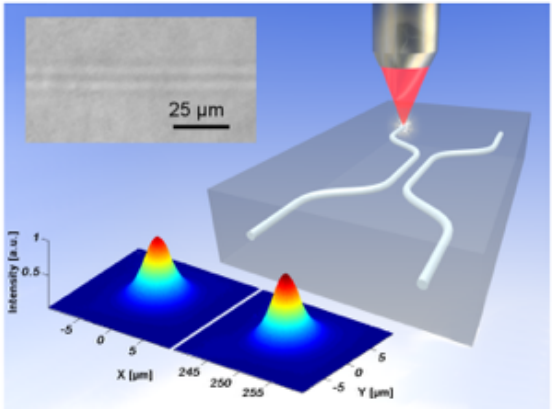






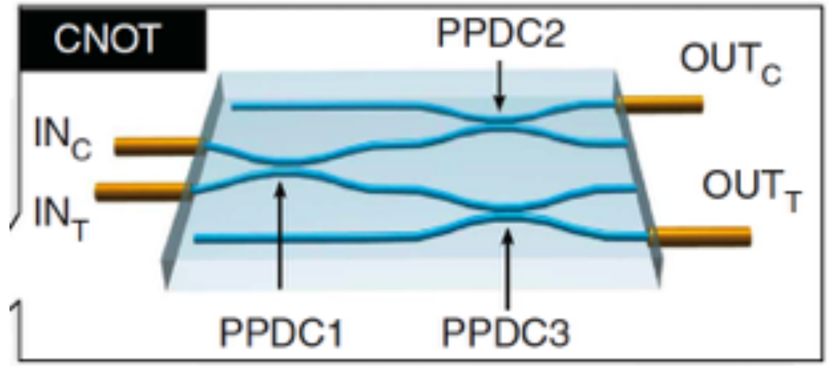
G. D. Marshall et al., *Opt. Express* **17**, 12546 (2009).

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



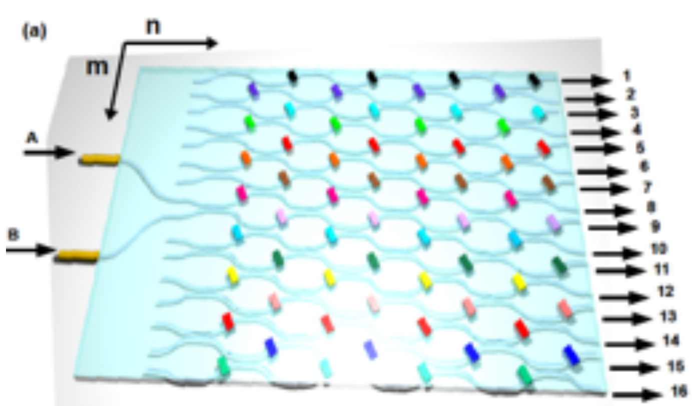
Directional coupler

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



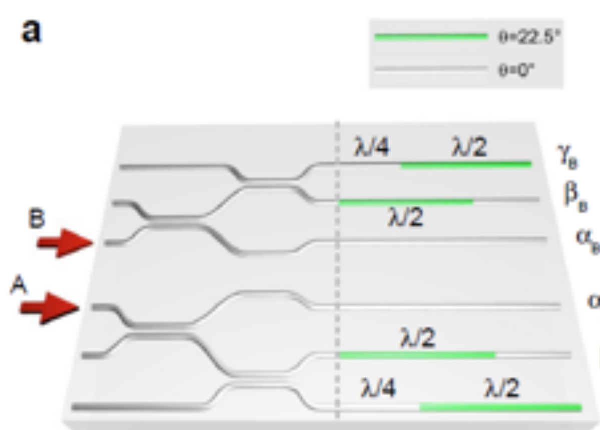
Partially polarizing and logical gate

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



Quantum walk and Anderson Localization

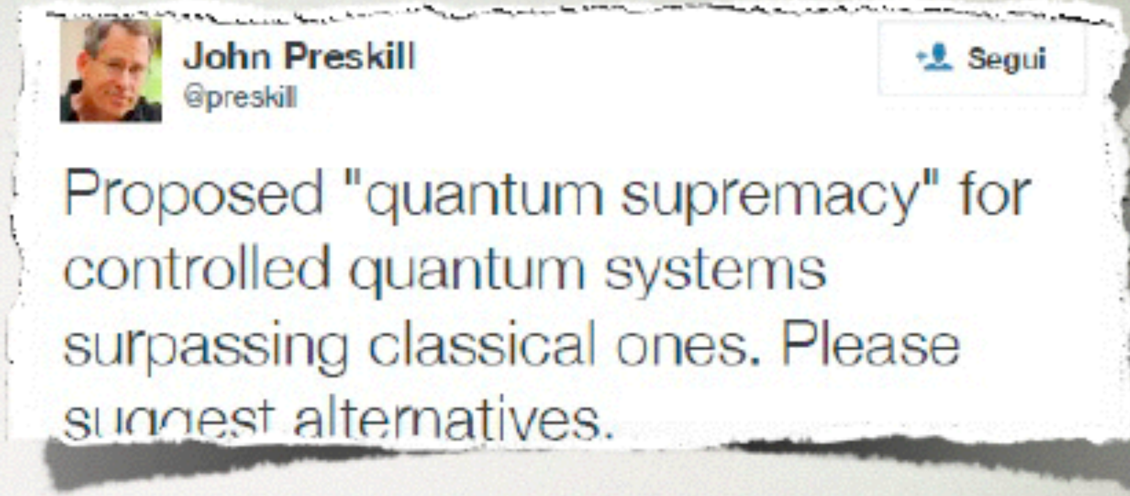
L. Sansoni et al., Phys. Rev. Lett. 108, 010502 (2012)
A. Crespi et al., Nat. Photon. 7, 322-328 (2013)



Tunable waveplate

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

How to achieve QUANTUM SUPREMACY ??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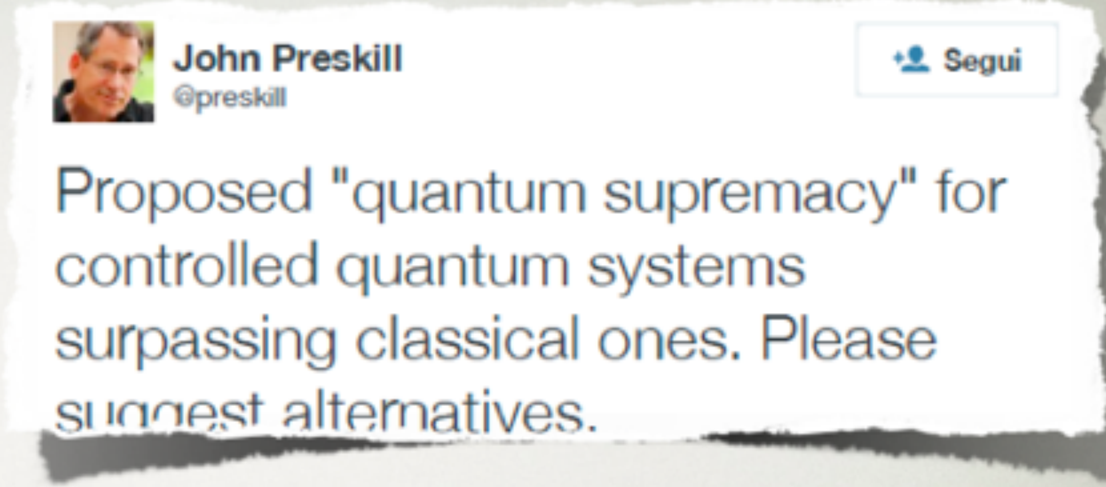
@preskill
Segui

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

How to achieve QUANTUM SUPREMACY ??


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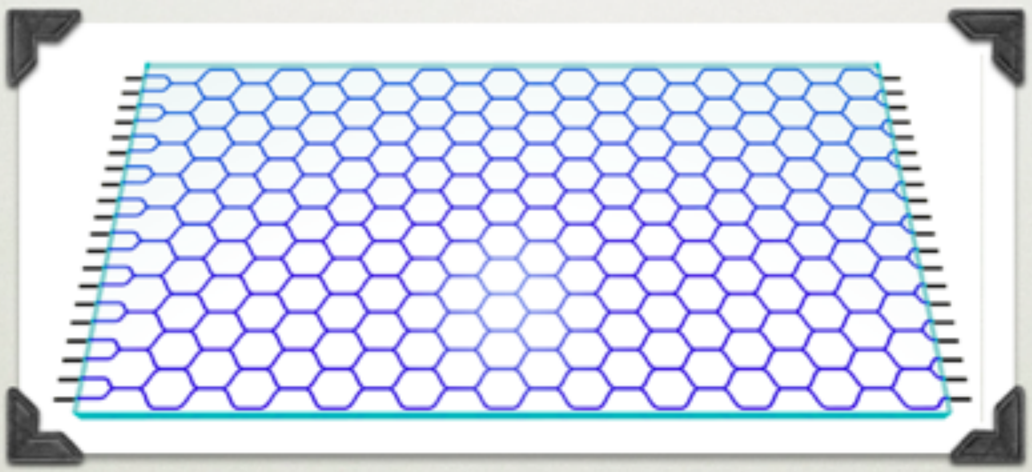
Proposed "quantum supremacy" for controlled quantum systems surpassing classical ones. Please suggest alternatives.

BOSON SAMPLING

propagation on the chip with m modes

Input:
***n* bosons**



Output:
***n*-photon state**

Can a classical computer 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)

How to achieve QUANTUM SUPREMACY ??

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

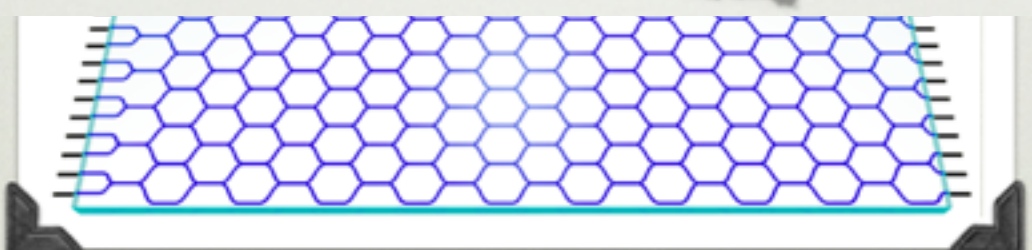
BOSON SAMPLING

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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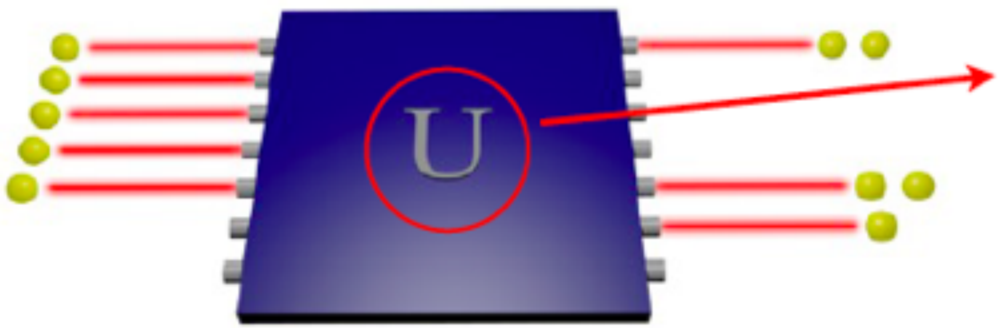
Boson Sampling

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 permanent of square matrices

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

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

classicaly hard

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

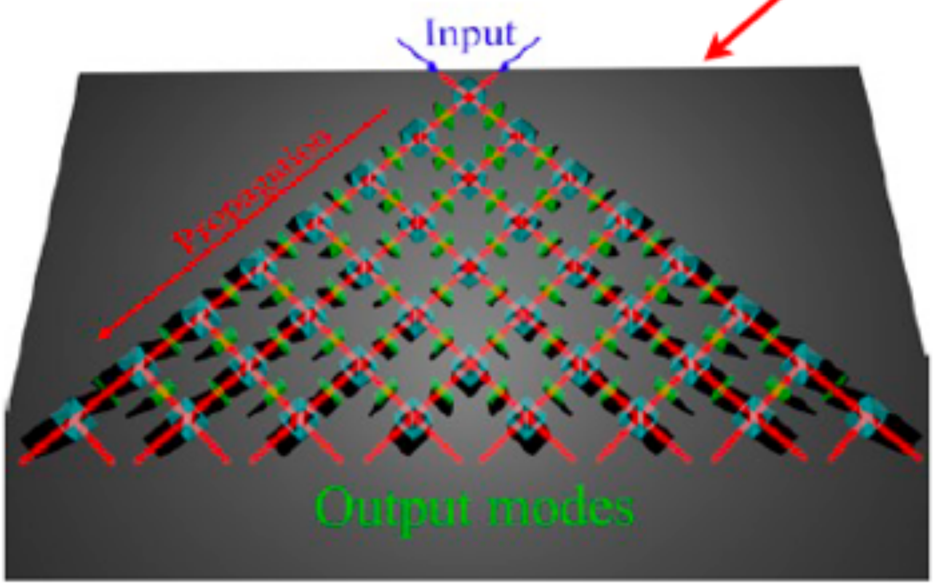
Photons naturally solve the BosonSampling problem

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

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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

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 $|T\rangle$ 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 $|T\rangle = |T_1 \ldots T_M\rangle = \Pi_{i=1}^{M} (\hat{A}_i^\dagger)^{T_i}|0\rangle$, 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
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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

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

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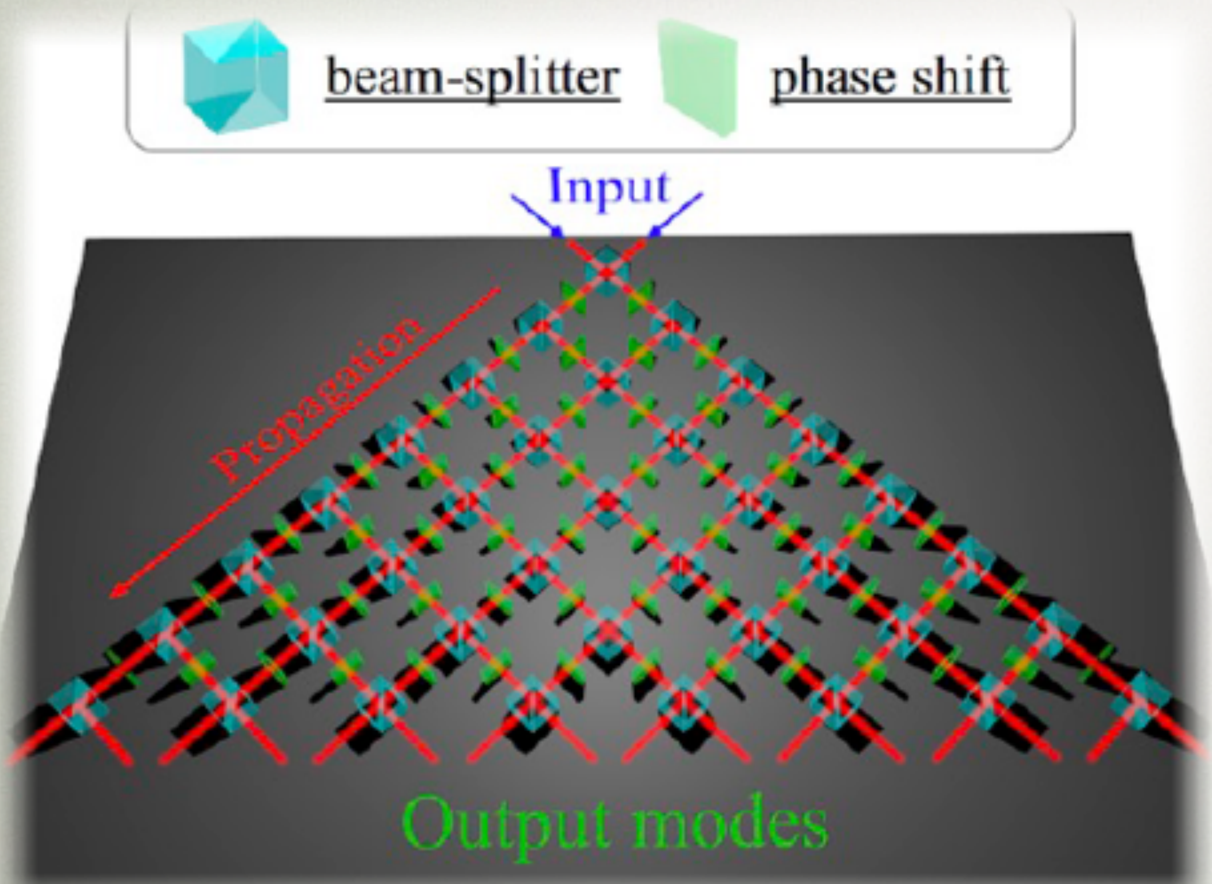
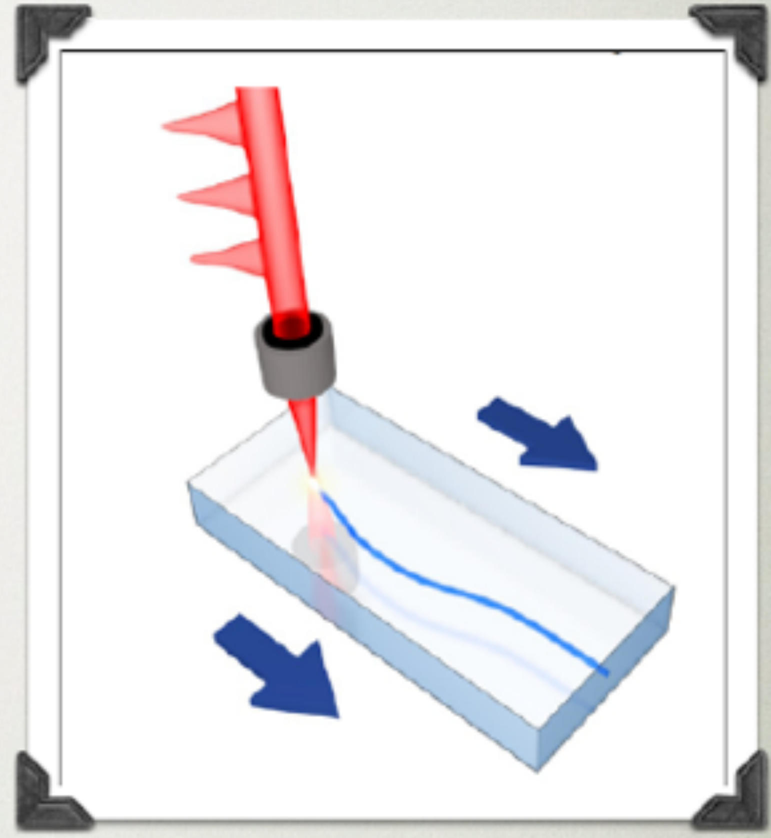
THE SOLUTION: INTEGRATED PHOTONICS

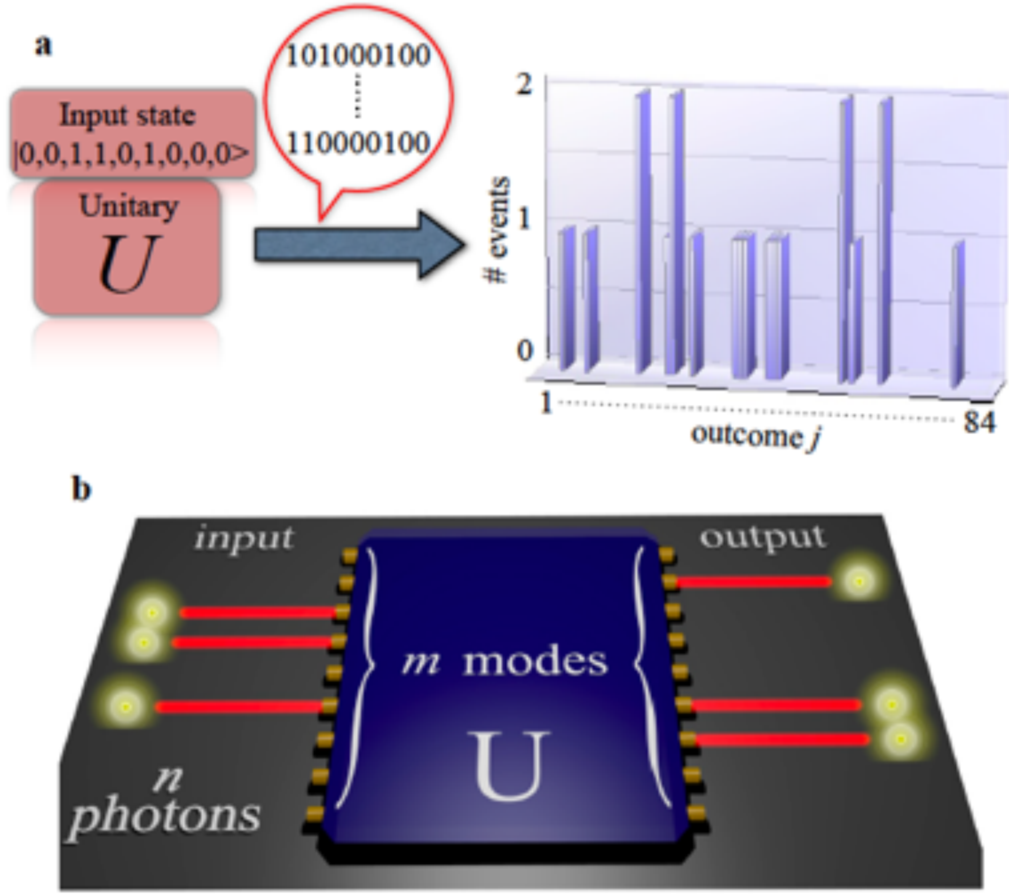




Laser writing technology:
unique capability to transmit any polarization state

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

Boson Sampling



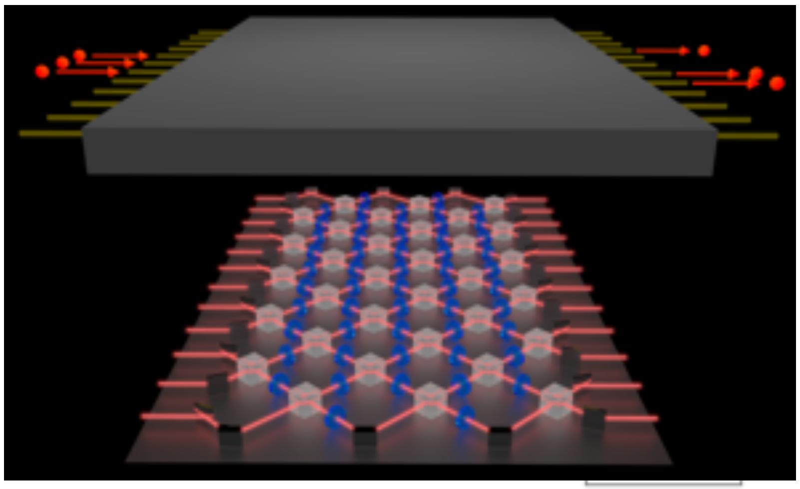
« Small-scale quantum computers made from an array of interconnected waveguides on a glass chip can now perform a task that is considered hard to undertake on a large scale by classical means. »

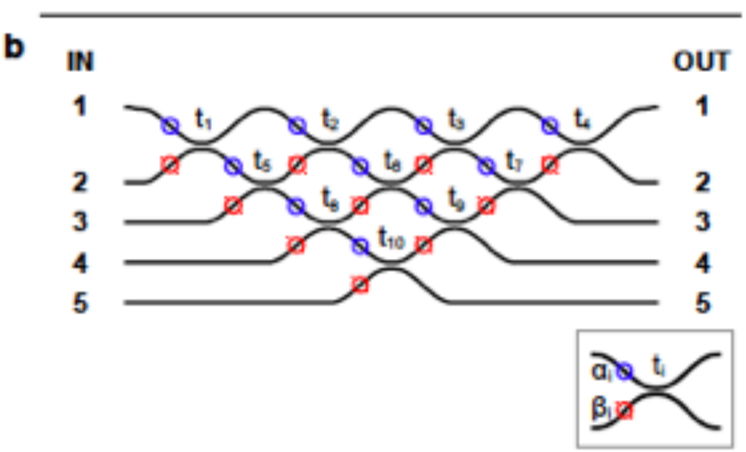
T. Ralph, News & Views, *Nature Photonics* **7**, 514 (2013)

Boson Sampling: chip

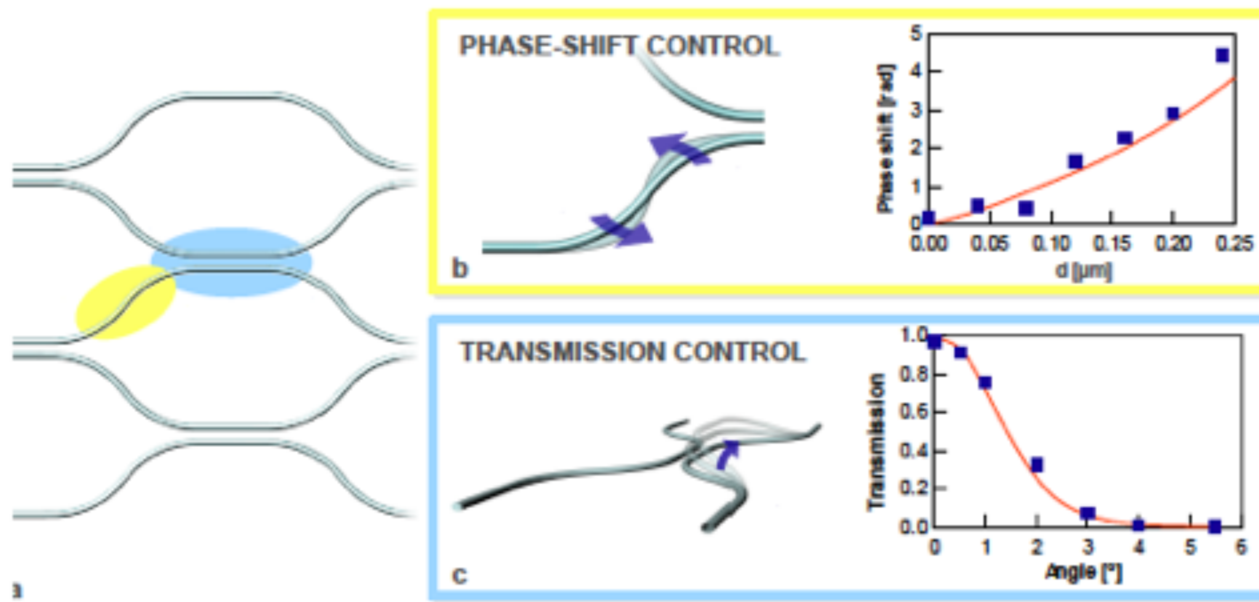
Requirement for Boson Sampling - design arbitrary interferometers

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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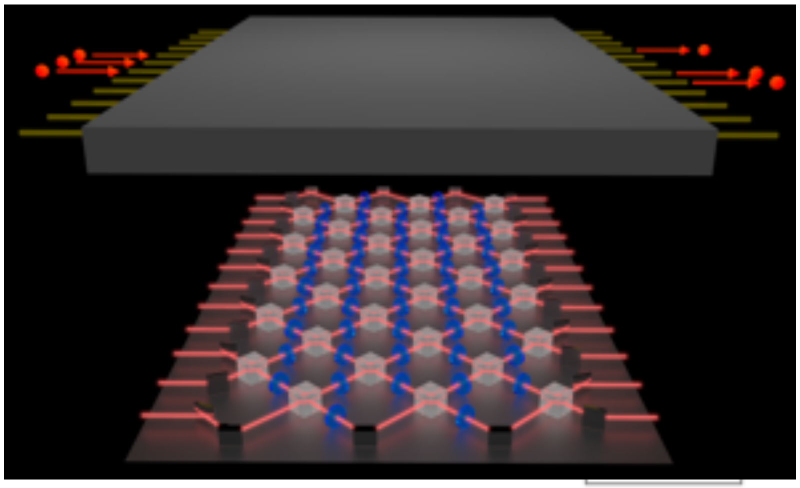
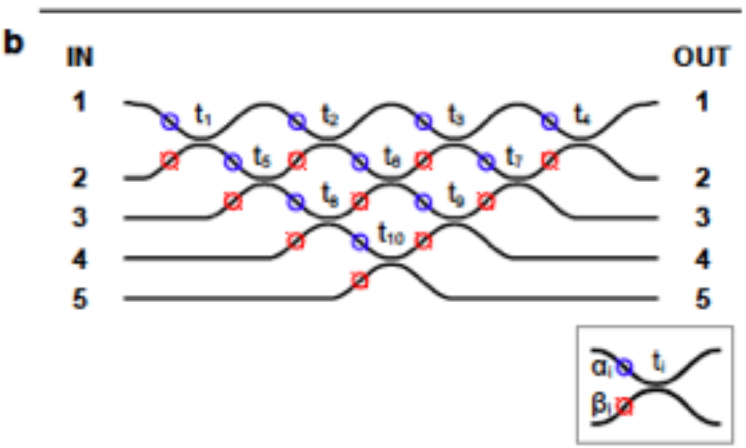
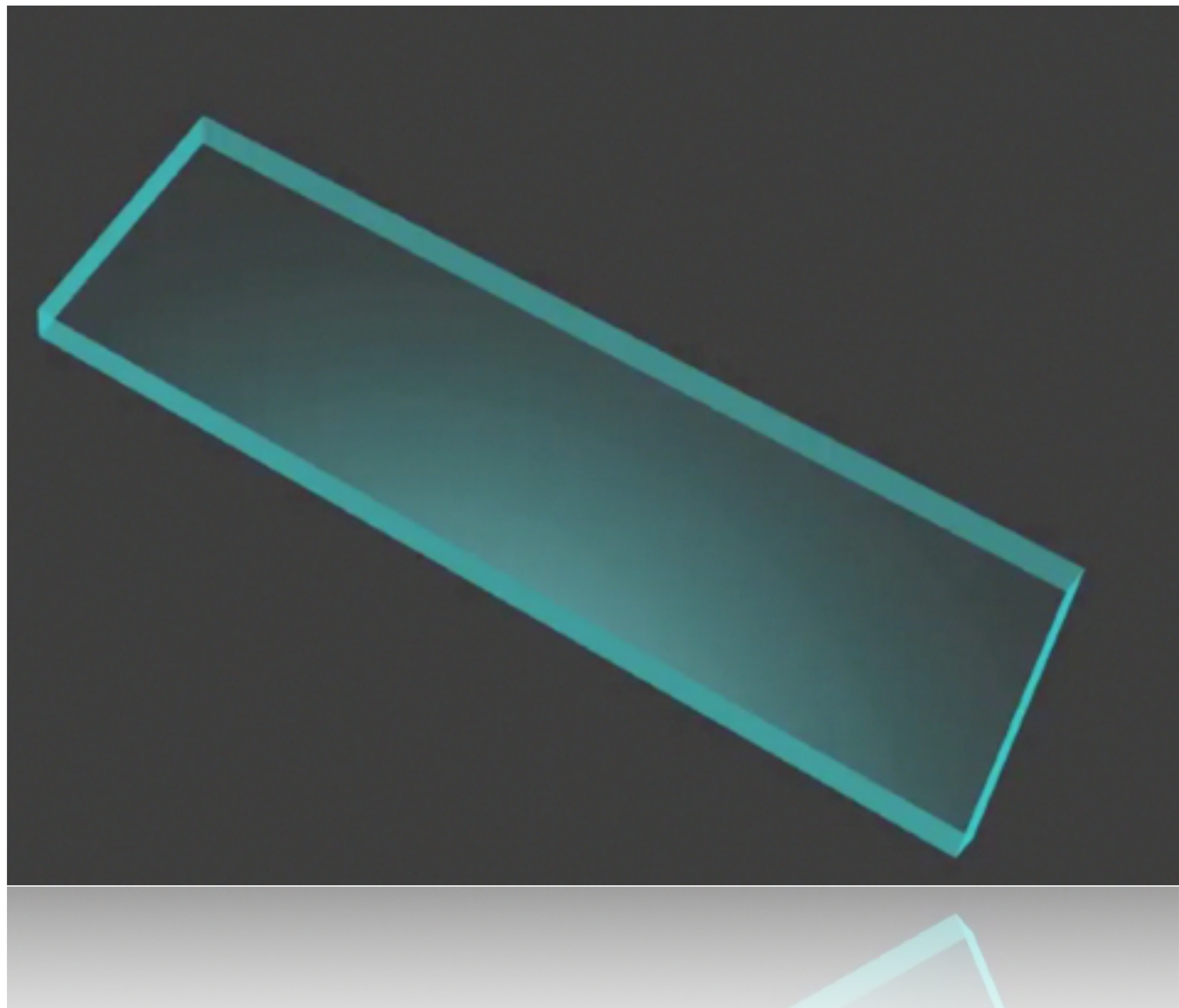
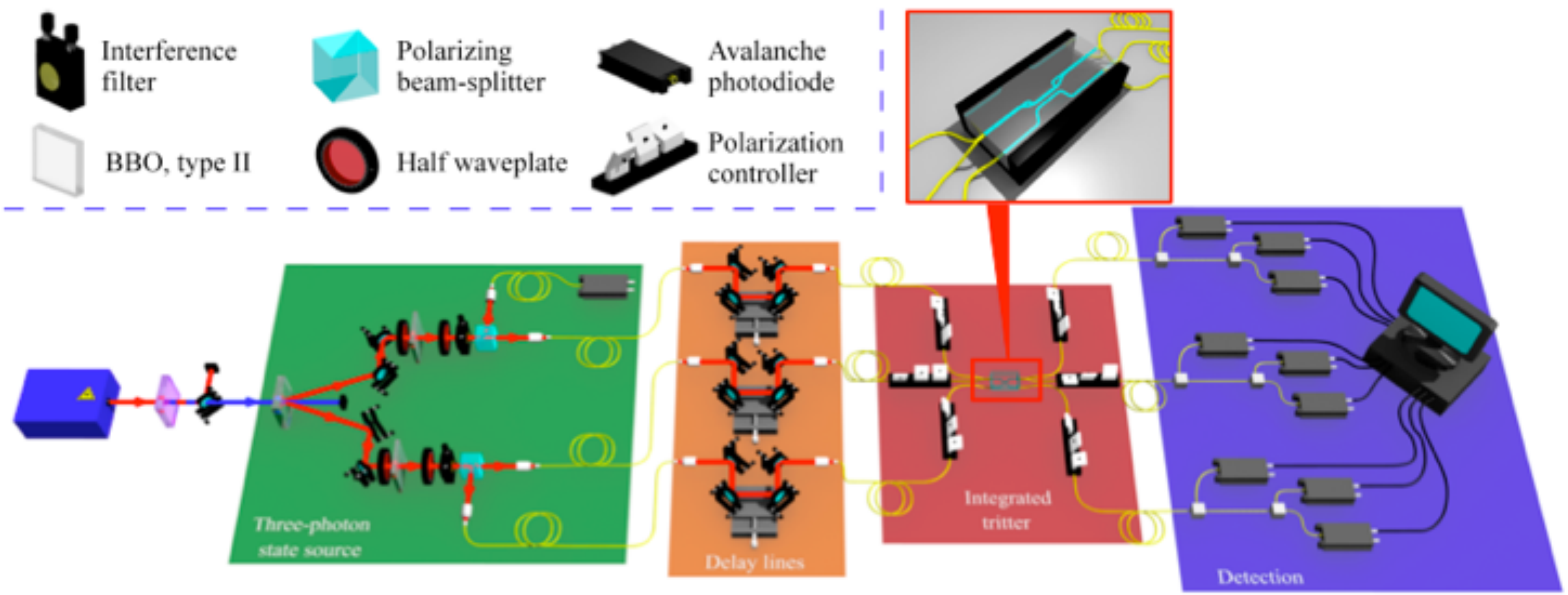




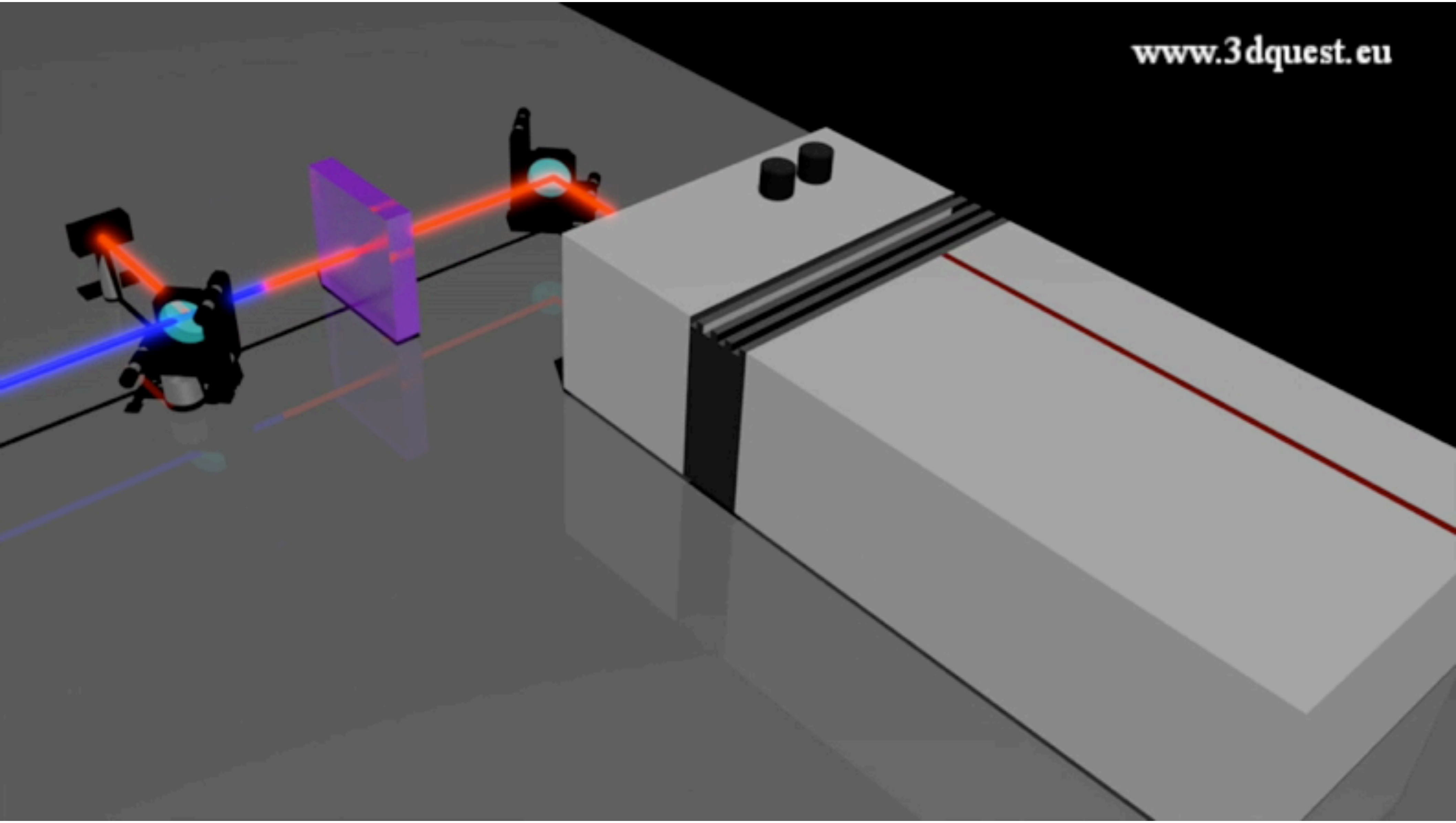
Reck, et al., *PRL* **73**, 58 (1994)



Boson Sampling in a 13-mode device



A. Crespi, R. Osellame, R. Ramponi, D. J. Brod, E. F. Galvao, N. Spagnolo, C. Vitelli, E. Maiorino, P. Mataloni, F. Sciarrino, *Integrated multimode interferometers with arbitrary designs for photonic boson sampling*, Nature Photonics 7, 545 (2013).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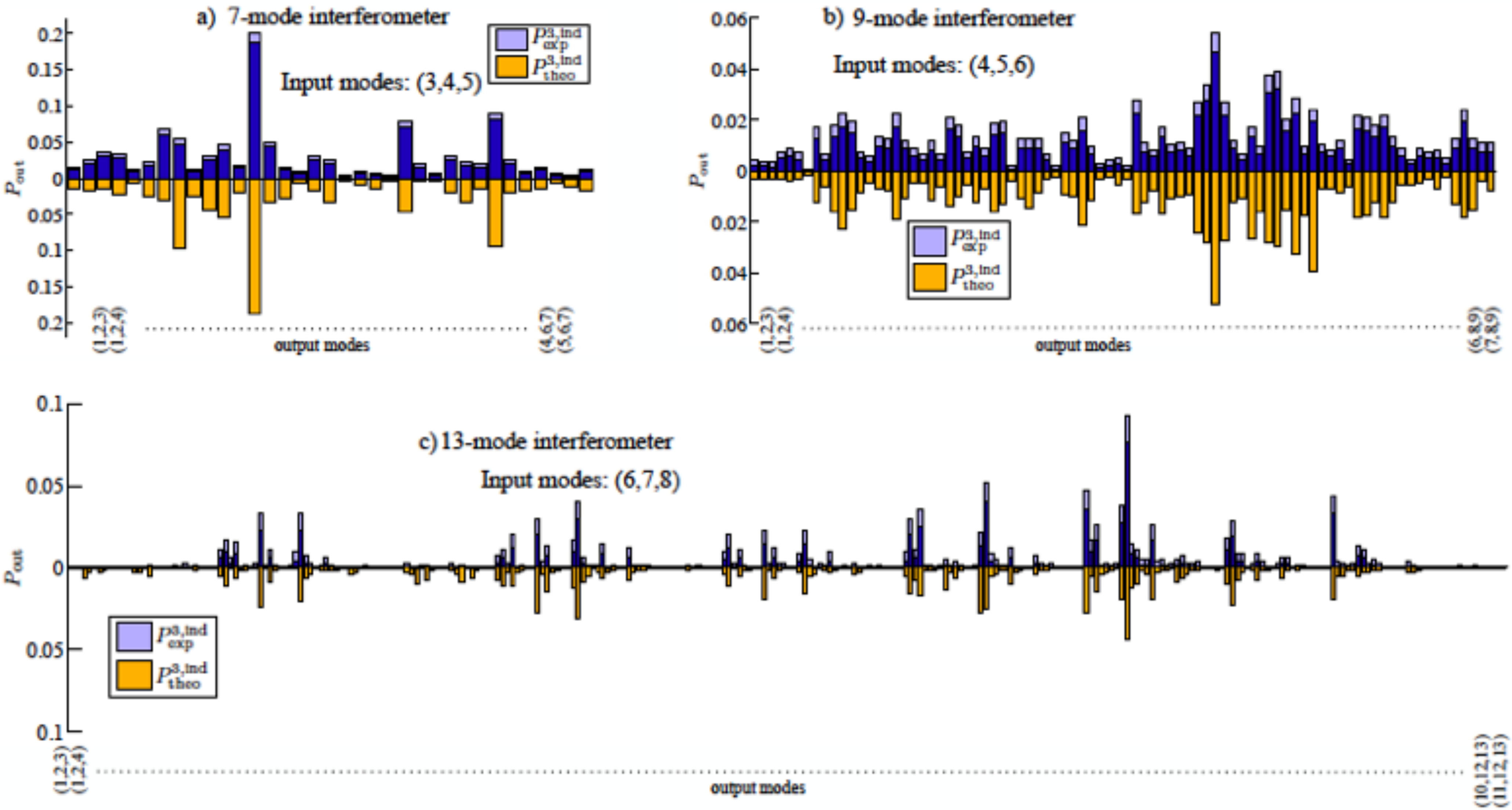
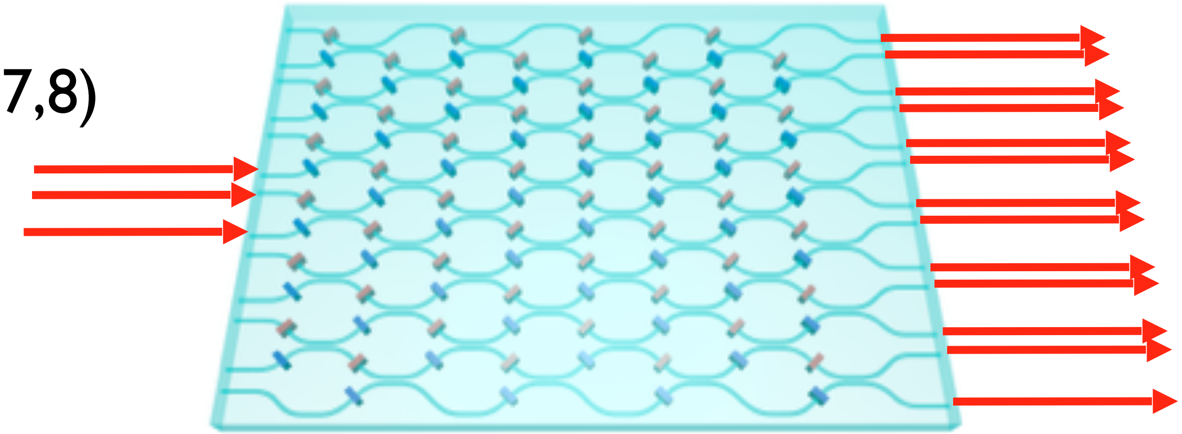
Boson Sampling in a 7 and 9-mode device



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)

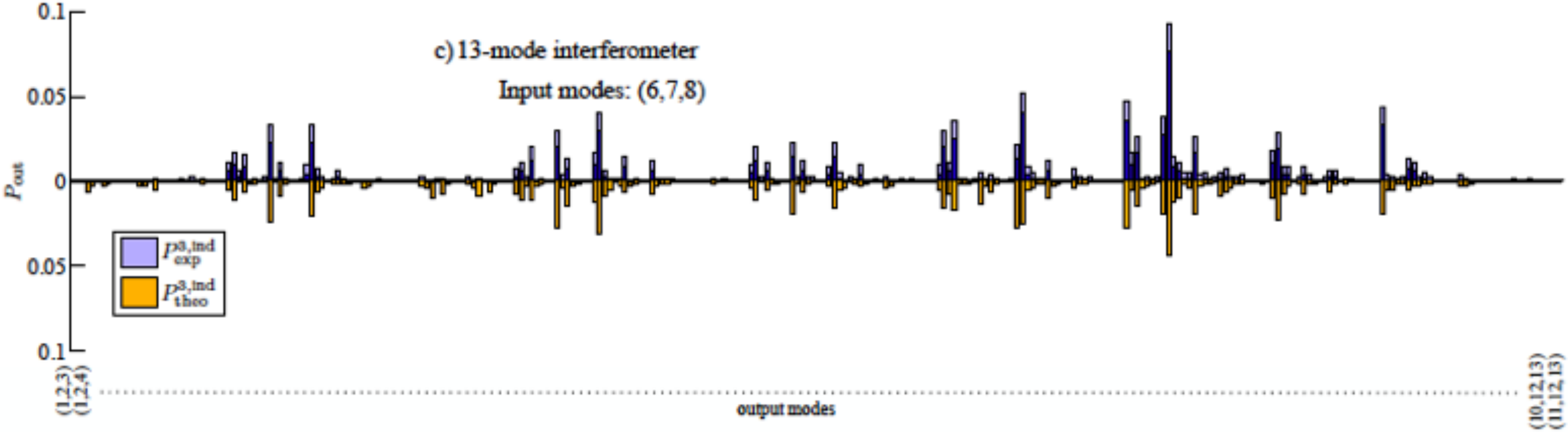
Boson Sampling in a 13-mode device

Input: (6,7,8)



Output: 286 different possible no-bunching configurations

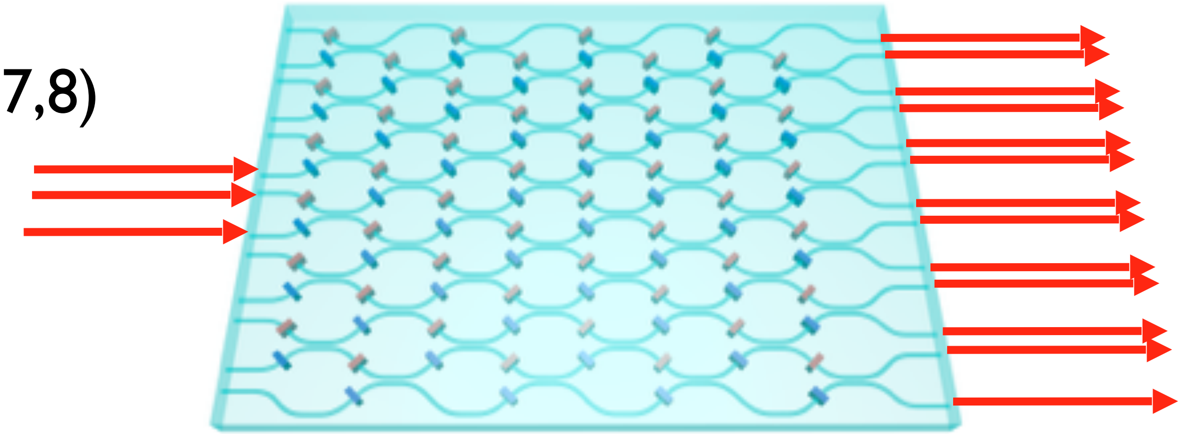
91 different fabrication phases



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)

Boson Sampling in a 13-mode device

Input: (6,7,8)



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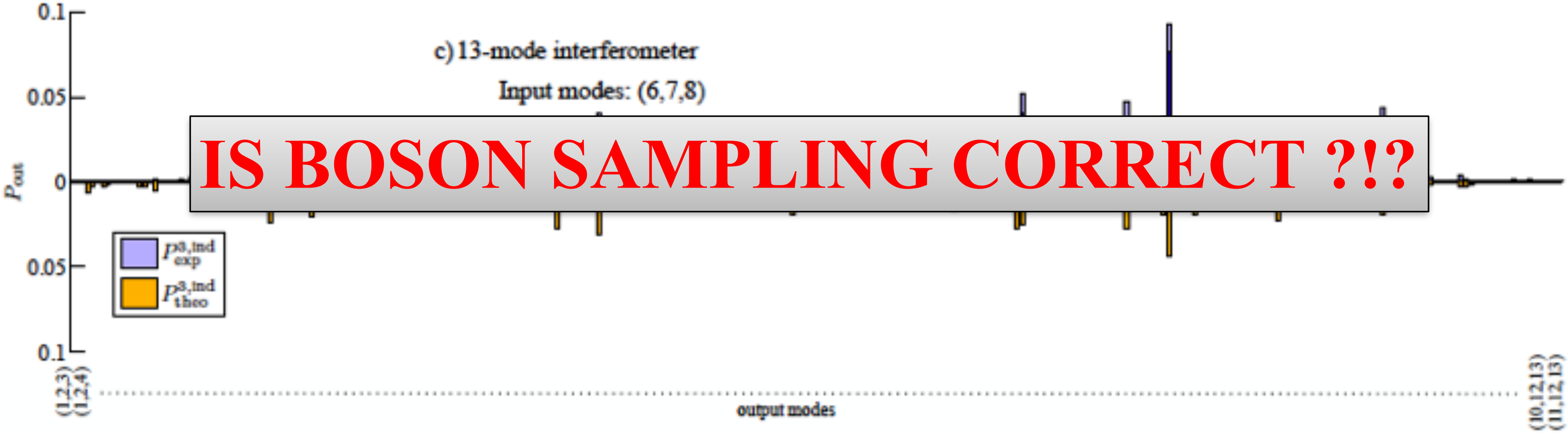


IS BOSON SAMPLING CORRECT ?!?

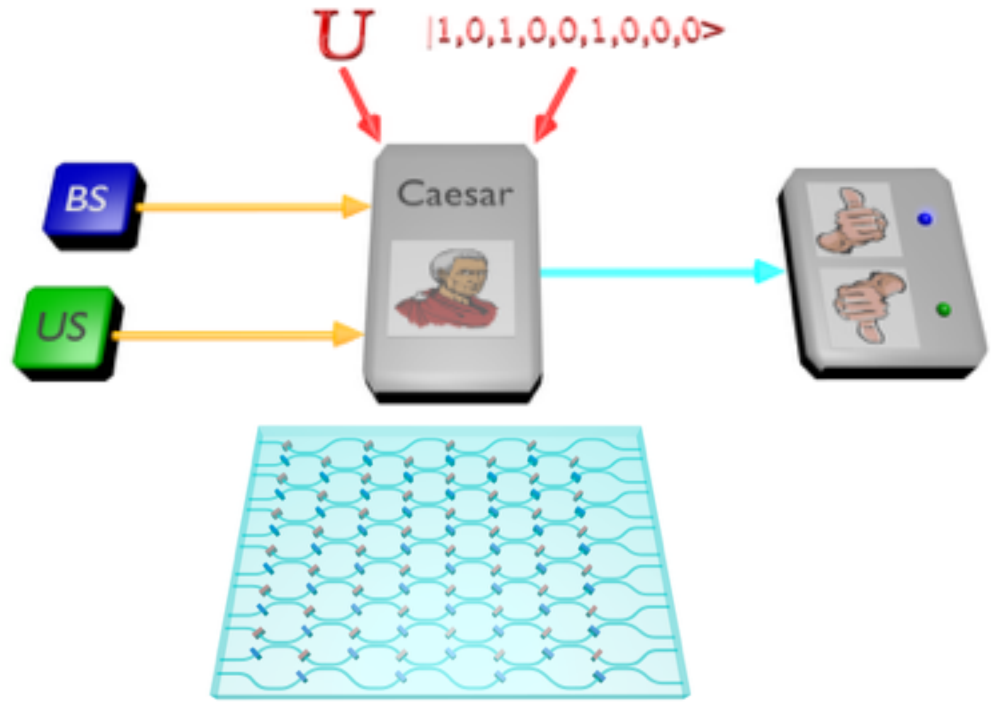
N. Spagnolo, C. Vitelli, M. Bentivegna, D. J. Brod, A. Crespi, F. Flamini, S. Giacomini, G. Milani, R. Ramponi, P. Mataloni, R. Osellame, E. F. Galvao, and F. Sciarrino, *Nature Photonics* **8**, 614 (2014)
Similar experiment in Bristol: J. Carolan, et al., *Nature Photonics* **8**, 619 (2014)

Validation of the Boson Sampling output

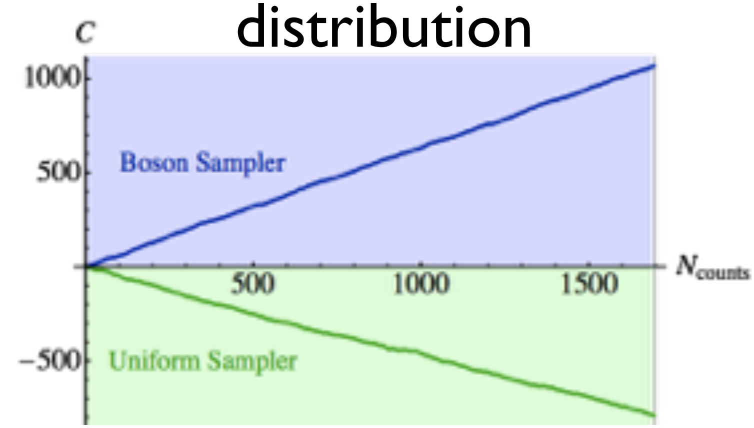
Boson Sampling:
hard problem with classical computer

but may be very hard also to validate/certify!

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



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)

Validation of Boson Sampling

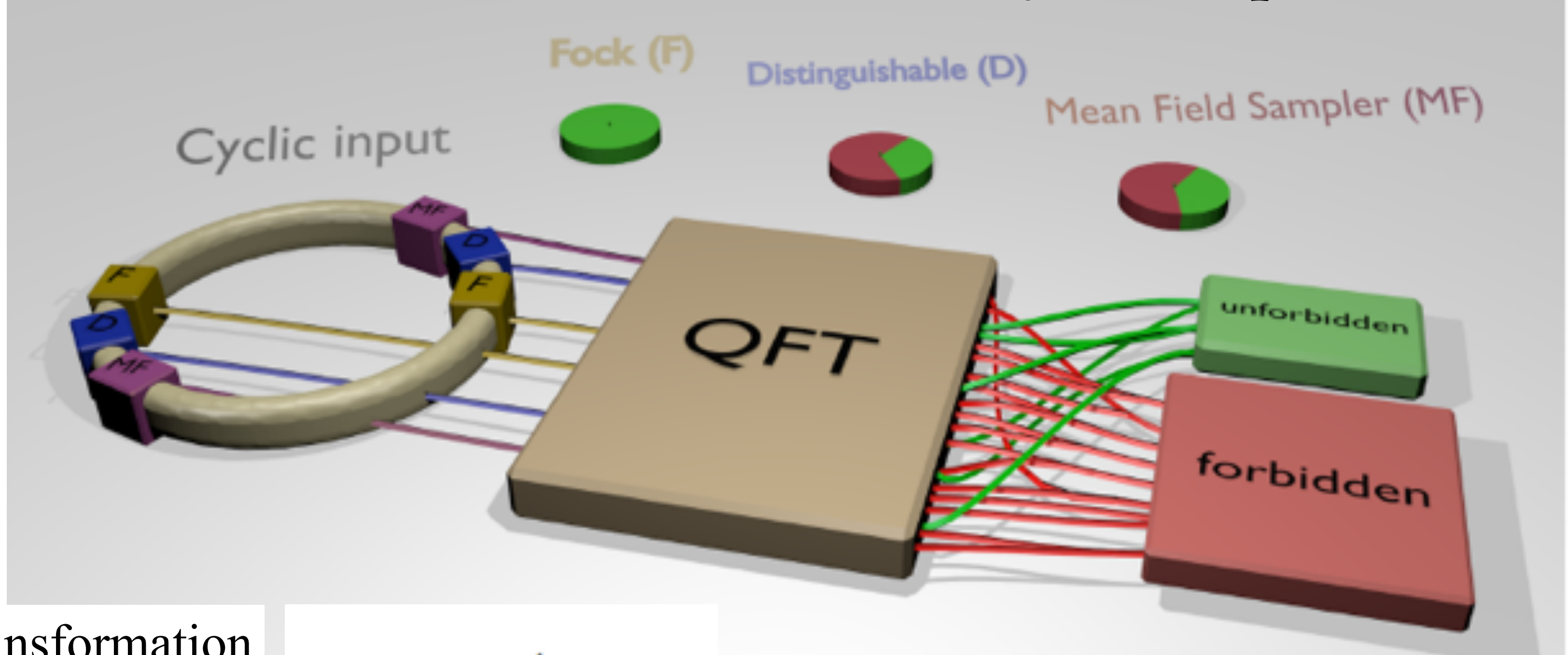
Conclusions – What Next?

- Row Norm Estimator can efficiently validate against trivial distributions
- The validation test works even if
  - low n,m case
  - $m < n^{5.1}$
  - experimental imperfections
- Efficient validation against distributions which do make use of information about U is still unexplored

New proposals: - *Stringent and efficient assessment of Boson-Sampling devices*
M. Tichy, K. Mayer, A. Buchleitner, K. Mølmer, *PRL* **113**, 020502 (2014)
- *Photon clouding with ordered quantum walk*
J. Carolan, et al., arxiv:1311.2913

Quantum certification via Fourier Transform

Fraction of forbidden non-cyclic output states



Unitary transformation

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

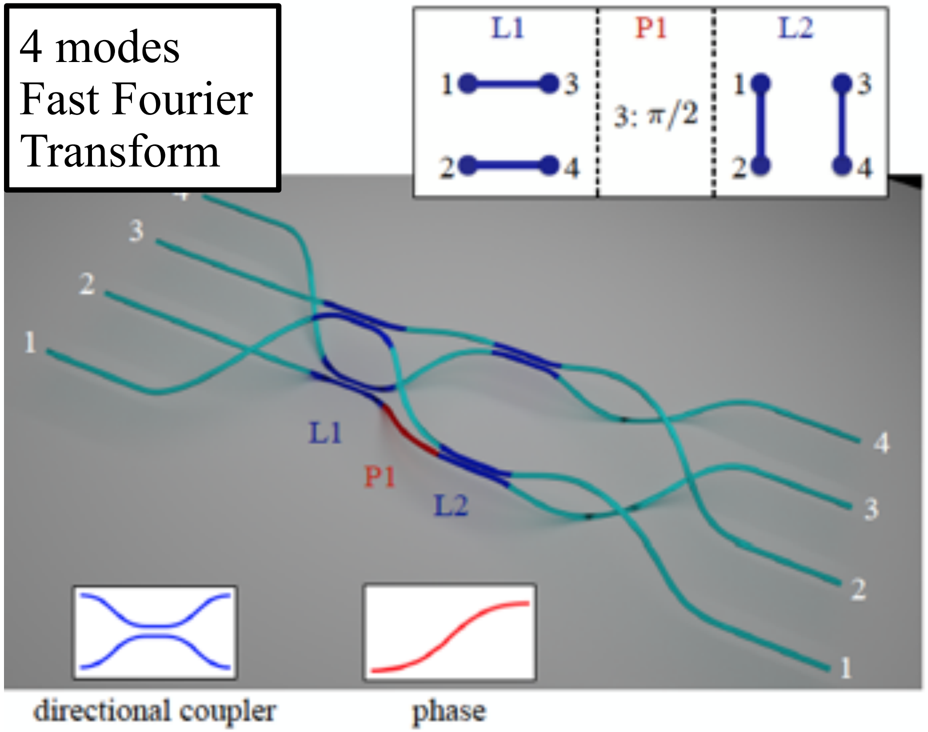
Injection of cyclic input states

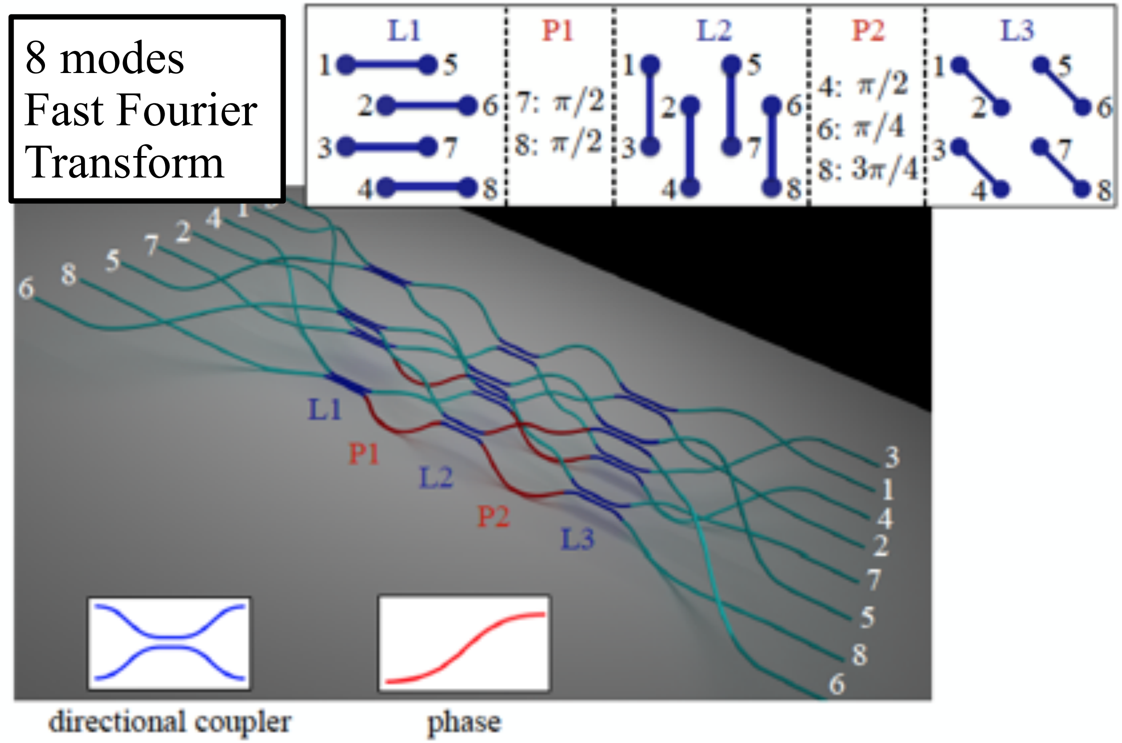
For n = 2 and m = 8 there are 4 possible (collision-free) cyclic inputs: (1,0,0,0,1,0,0,0), (0,1,0,0,0,1,0,0), (0,0,1,0,0,0,1,0), (0,0,0,1,0,0,0,1)

Quantum suppression law

Suppression of all output non-cyclic output states!

Implementation of Fast Fourier Transform with 3D-integrated photonics



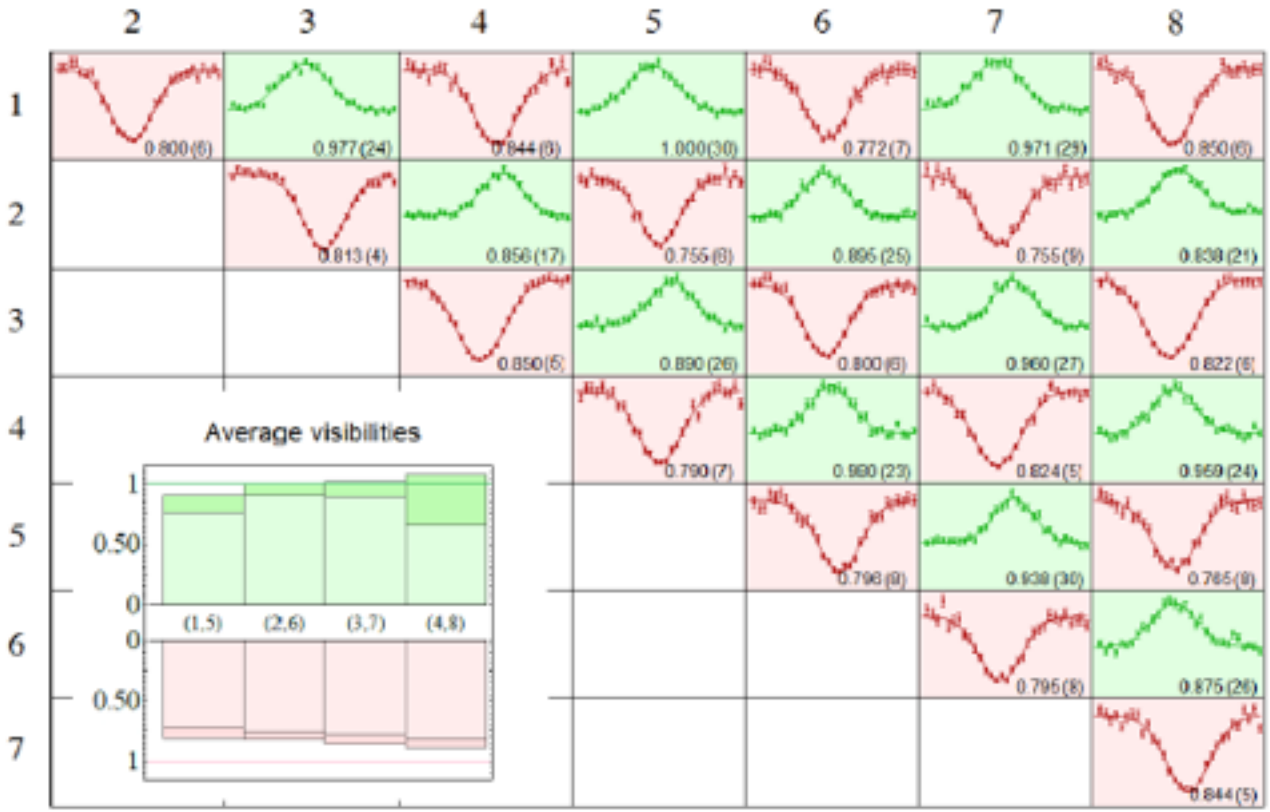


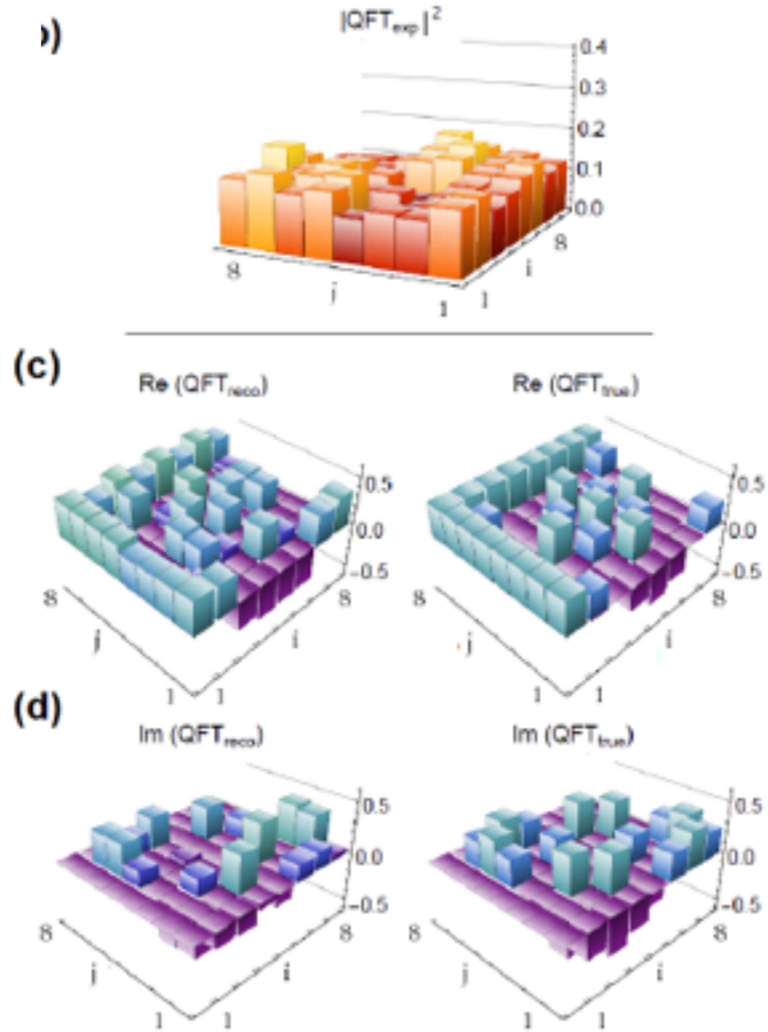
<u>Scalable approach</u> for the implementation of fast Fourier transform using 3-D photonic integrated interferometers fabricated via femtosecond laser writing technique.

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, arXiv:1508.0078

Quantum certification of Boson Sampling

n=2 photons over 8 modes Fast Fourier Transform





16 suppressed states over 28 output states

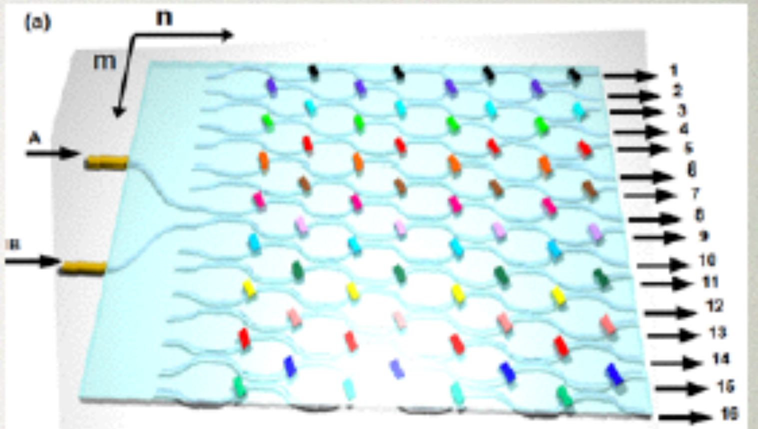
Quantum suppression of a large number of output states with 4- and 8- mode optical circuits: the experimental results demonstrate genuine quantum interference between the injected photons

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

Scattershot Boson Sampling


PHYSICAL REVIEW LETTERS

Boson Sampling from a Gaussian State

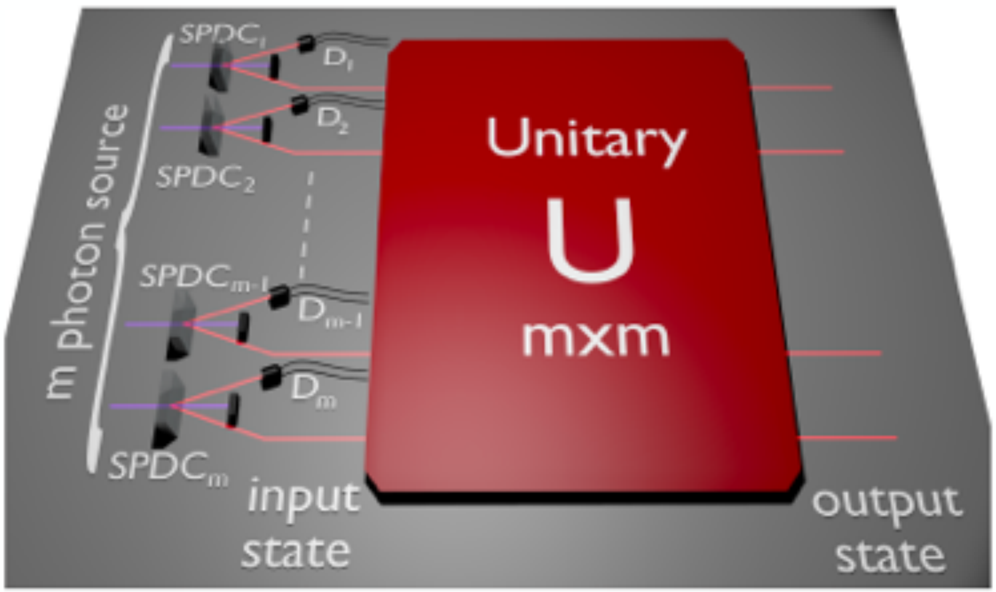
A. P. Lund, A. Laing, S. Rahimi-Keshari, T. Rudolph, J. L. O'Brien, and T. C. Ralph

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

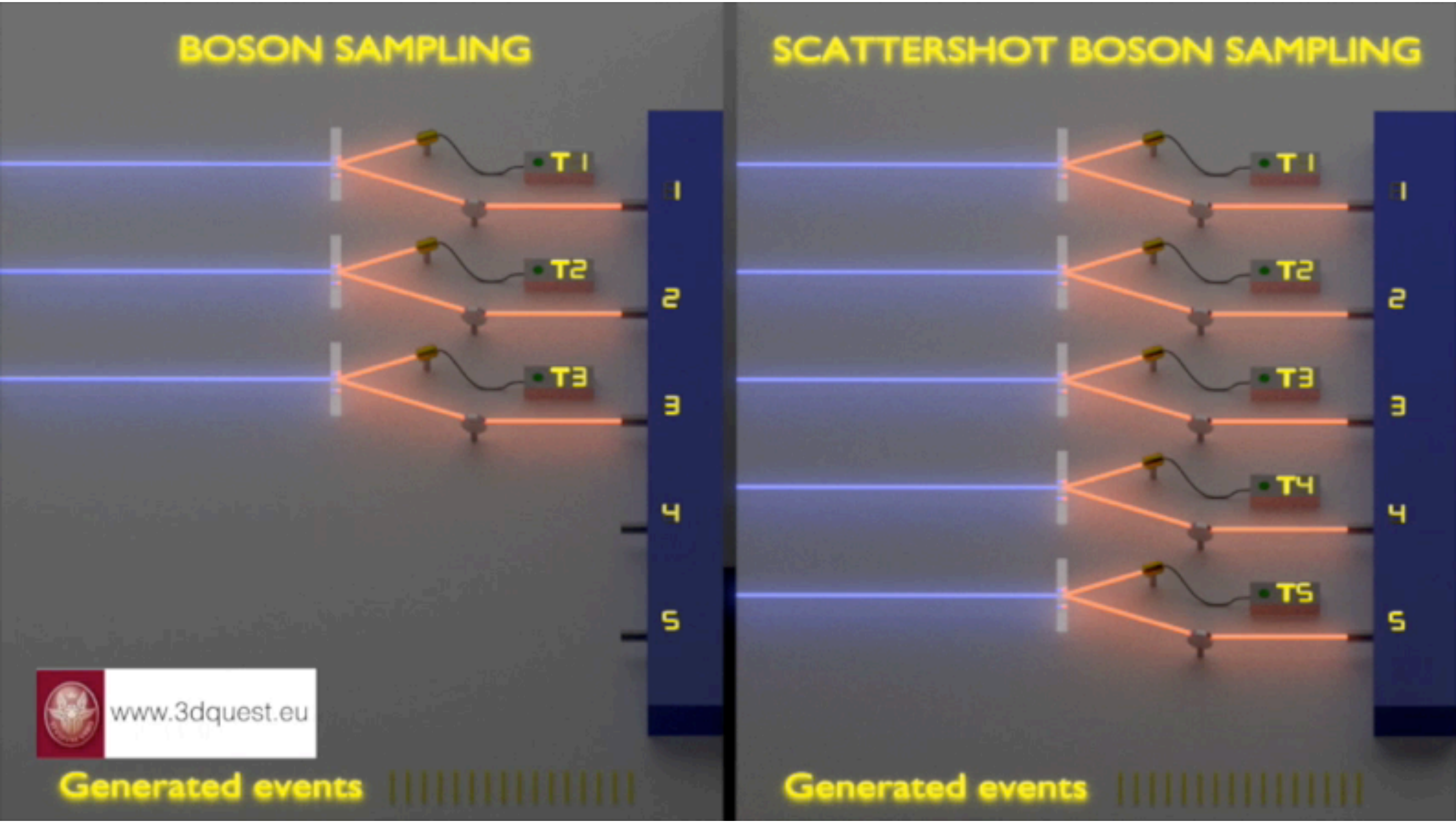
Generalization of Boson Sampling problem with computational complexity

m heralded single photon sources



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

Potential huge increase of the brightness of the quantum hardware



BOSON SAMPLING
SCATTERSHOT BOSON SAMPLING
T1
T2
T3
T4
T5
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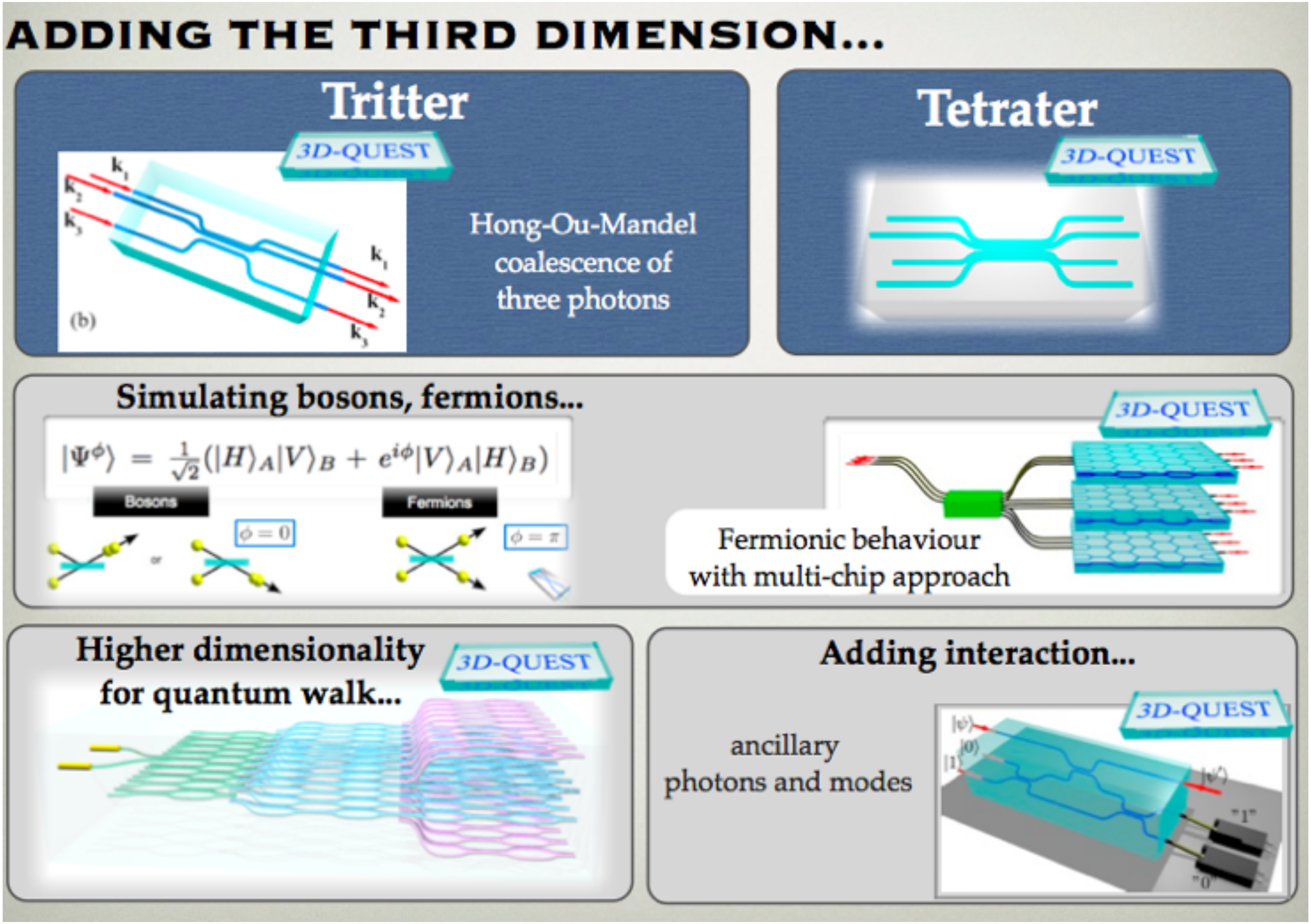
Generated events

Integrated quantum simulations…next steps

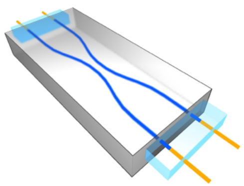


Summary

Integrated devices

Polarization independent

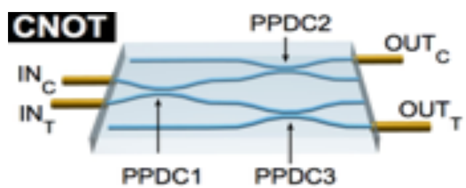
Beam Splitter



Phys. Rev. Lett. **105**, 200503 (2010)

Polarization dependent

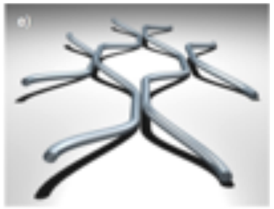
CNOT



Nat. Comm. **2**, 566 (2011)

Quantum simulation

Ordered systems



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

Disordered Systems Phase Control

Nat. Phot. *7*, 322 (2013)

Bosons Sampling and Birthday Paradox

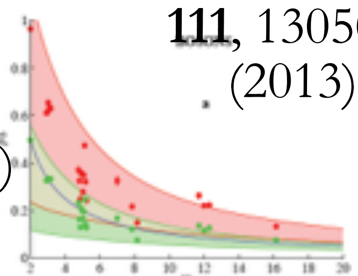
Boson Sampling On chip

Nat. Phot. 7, 545 (2013)

Science Advances 1, e1400255 (2015).

Validation

PRL **111**, 130503 (2013)

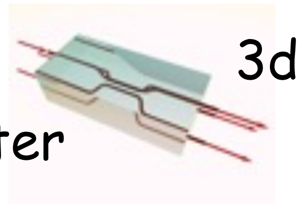


Nat. Phot. 8, 614 (2014)

3D devices

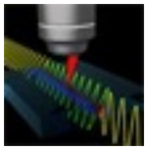
Integrated tritter

Nat. Com. 4, 1606 (2013)



3d interferometry

Sc. Reports 2, 862 (2012)



Integrated waveplates

Nat. Com. 5, 2549 (2014)