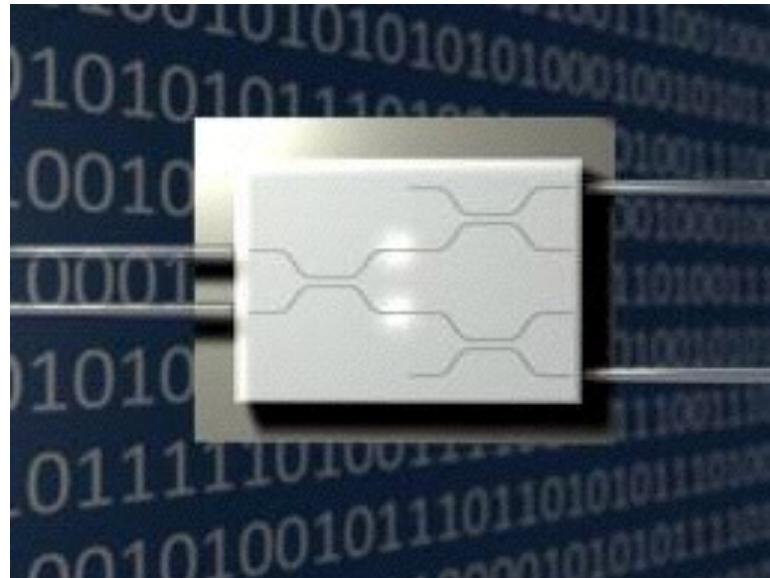




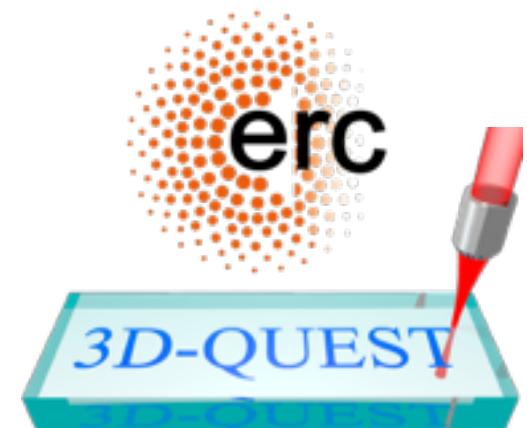
Lecture 3: Boson sampling



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Fabio Sciarrino

Dipartimento di Fisica,
“Sapienza” Università di Roma

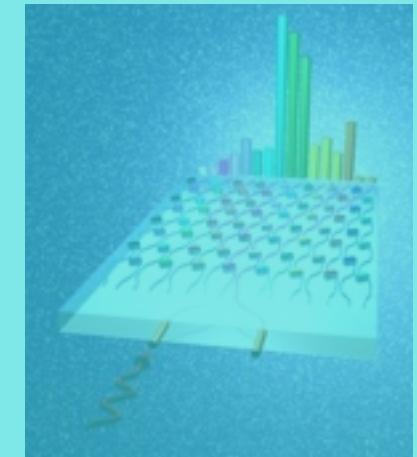


Quantum computation

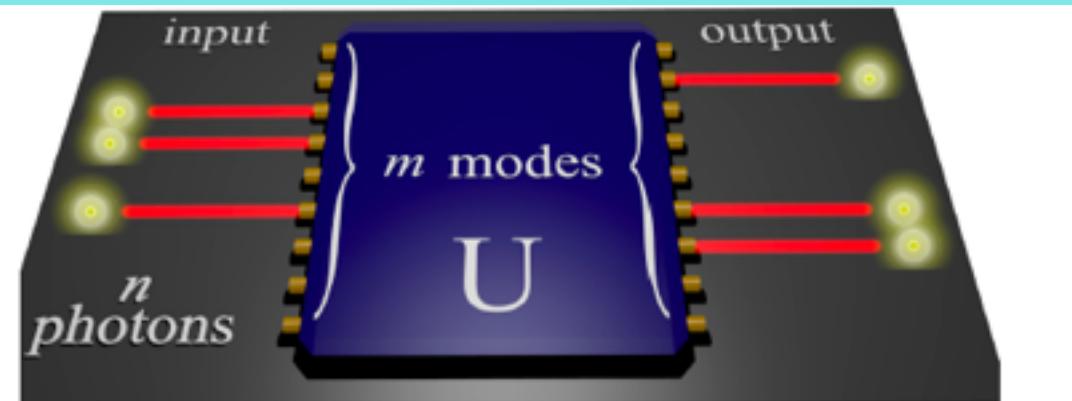


- logical gate
- quantum algorithms

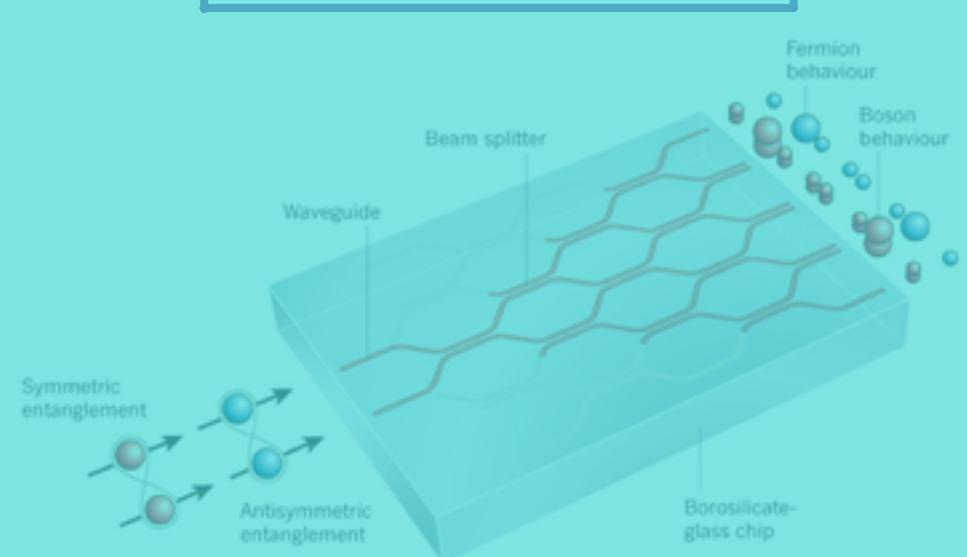
Quantum simulation



Boson Sampling



Quantum walk



HOW TO ACHIEVE QUANTUM SUPREMACY ??



John Preskill
@preskill

Segui

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

HOW TO ACHIEVE QUANTUM SUPREMACY ??



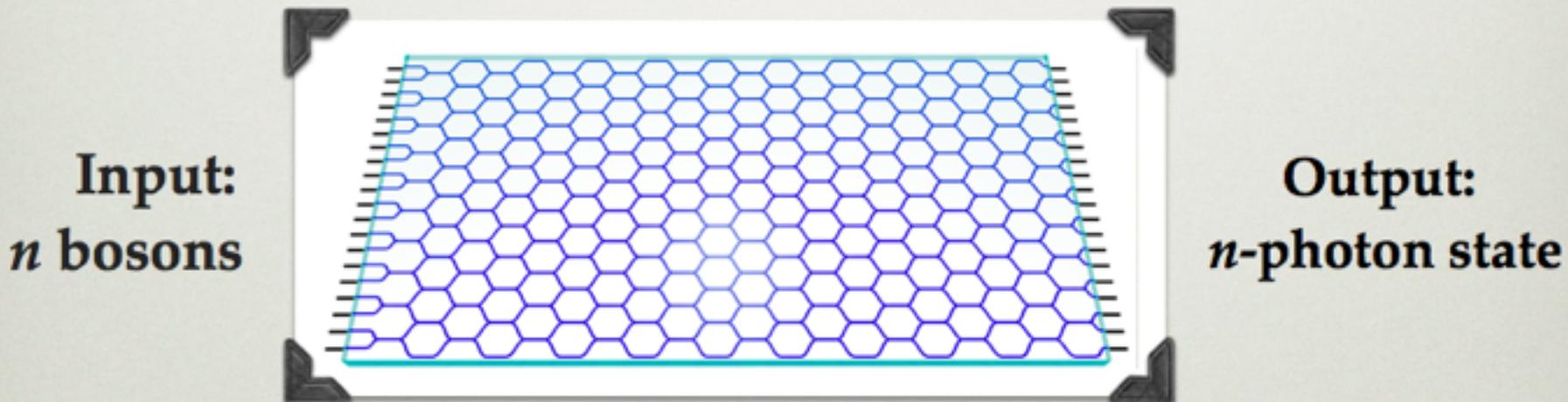
John Preskill
@preskill

Segui

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

BOSON SAMPLING

propagation on the chip with m modes



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

Answer: NO!!

HOW TO ACHIEVE QUANTUM SUPREMACY ??



John Preskill
@preskill

Segui

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

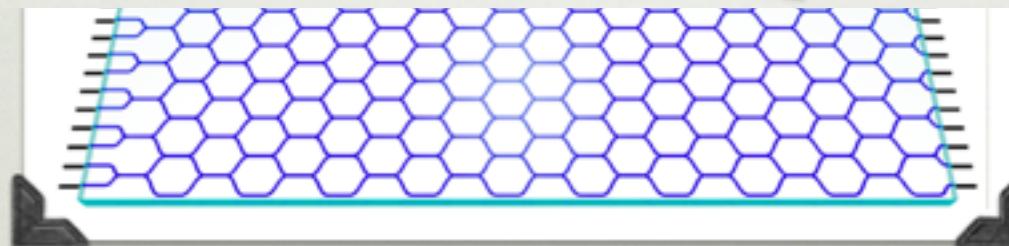
BOSON SAMPLING

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

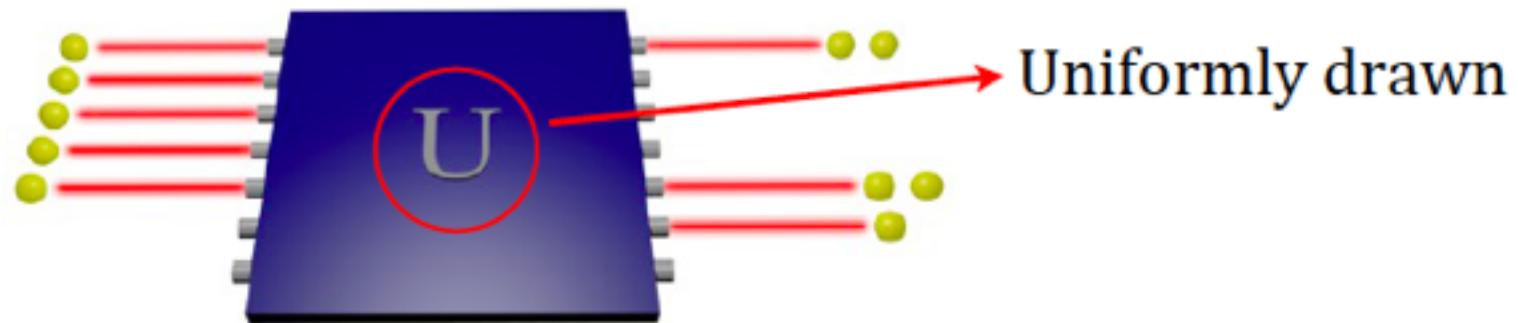
Can a classical computer efficiently simulate the distribution of the output mode numbers ?

Answer: NO!!

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 permanent of square matrices

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

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

classically hard

		input				
		0	1	1	0	1
output	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	1	-0.723 + 0.363i	0.087 - 0.09i	-0.076 - 0.155i	0.206 + 0.443i	-0.153 - 0.193i
	0	-0.092 + 0.045i	-0.148 - 0.645i	-0.588 + 0.184i	-0.369 - 0.086i	0.167 + 0.025i
0	0	0.318 - 0.009i	-0.144 - 0.594i	0.452 - 0.405i	0.037 + 0.387i	0.071 + 0.025i

EVOLUTION OF BOSONIC STATES IN LINEAR OPTICS

How does the transition amplitude links with the permanent?

U  Unitary evolution of the system, $m \times m$ matrix

$|T\rangle = |t_1, \dots, t_m\rangle$  Input n -photon state: $t_1 + \dots + t_m = n$

$|S\rangle = |s_1, \dots, s_m\rangle$  Output n -photon state: $s_1 + \dots + s_m = n$

EVOLUTION OF BOSONIC STATES IN LINEAR OPTICS

How does the transition amplitude links with the permanent?

$U \rightarrow$ Unitary evolution of the system, $m \times m$ matrix

$|T\rangle = |t_1, \dots, t_m\rangle \rightarrow$ Input n -photon state: $t_1 + \dots + t_m = n$

$|S\rangle = |s_1, \dots, s_m\rangle \rightarrow$ Output n -photon state: $s_1 + \dots + s_m = n$

Unitary evolution in the Hilbert space: \mathcal{H}_l with dimension: $l = \binom{m+n-1}{n}$

$n \times n$ matrix, composed by repeating:

$l =$ all possible combinations of n photons in m modes

(-) s_i times the i^{th} row of U
(-) t_j times the j^{th} column of U

$$\langle S | \varphi(U) | T \rangle = \frac{\text{per}(U_{S,T})}{\sqrt{s_1! \cdots s_m! t_1! \cdots t_m!}}$$

AN EXAMPLE OF BOSON SAMPLING

Input:

$$|1, 1, 1, 0, 0, 0, 0, 0\rangle$$

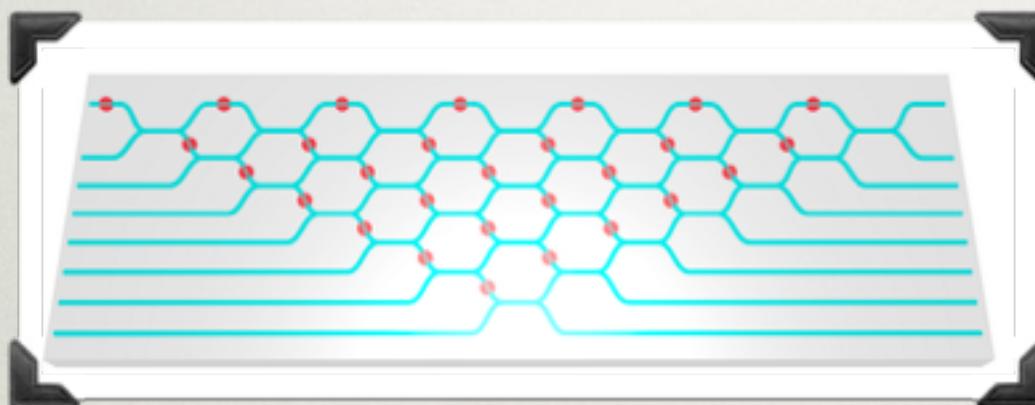
propagation on the chip
with $m=8$ modes



Output 3-photon state:

$$|s_1, s_2, \dots, s_m\rangle$$

$$\sum_{j=1}^m s_j = 3$$



possible outcomes

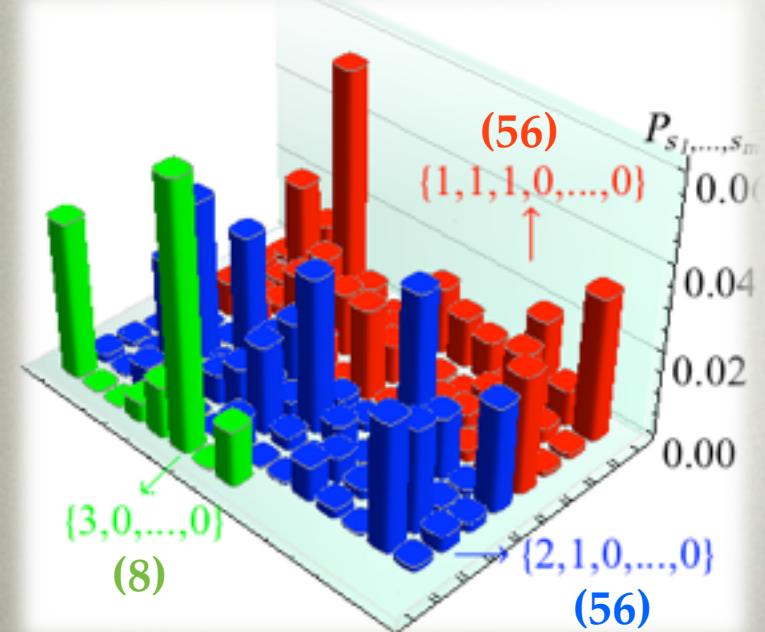
$$l = \binom{m+n-1}{n}$$

$$l = 120$$

$$P(s_1, \dots, s_m) = \text{per}(U)$$

$O(n!)$ elements

permanent of $n \times n$ matrix



COMPUTATIONAL COMPLEXITY OF THE PERMANENT

How complex is the calculation of the permanent of a $n \times n$ matrix?

Permanent, bosons

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



faster algorithms scale as $O(n^{2^n})$

No linear algebra rules
can be exploited to
simplify the calculation



No linear transformations can map the permanent to a determinant

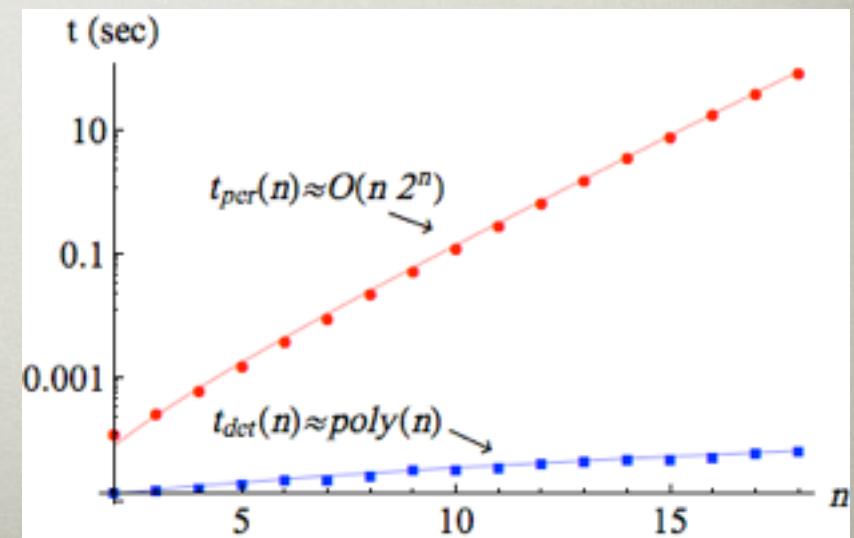
Determinant, fermions

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

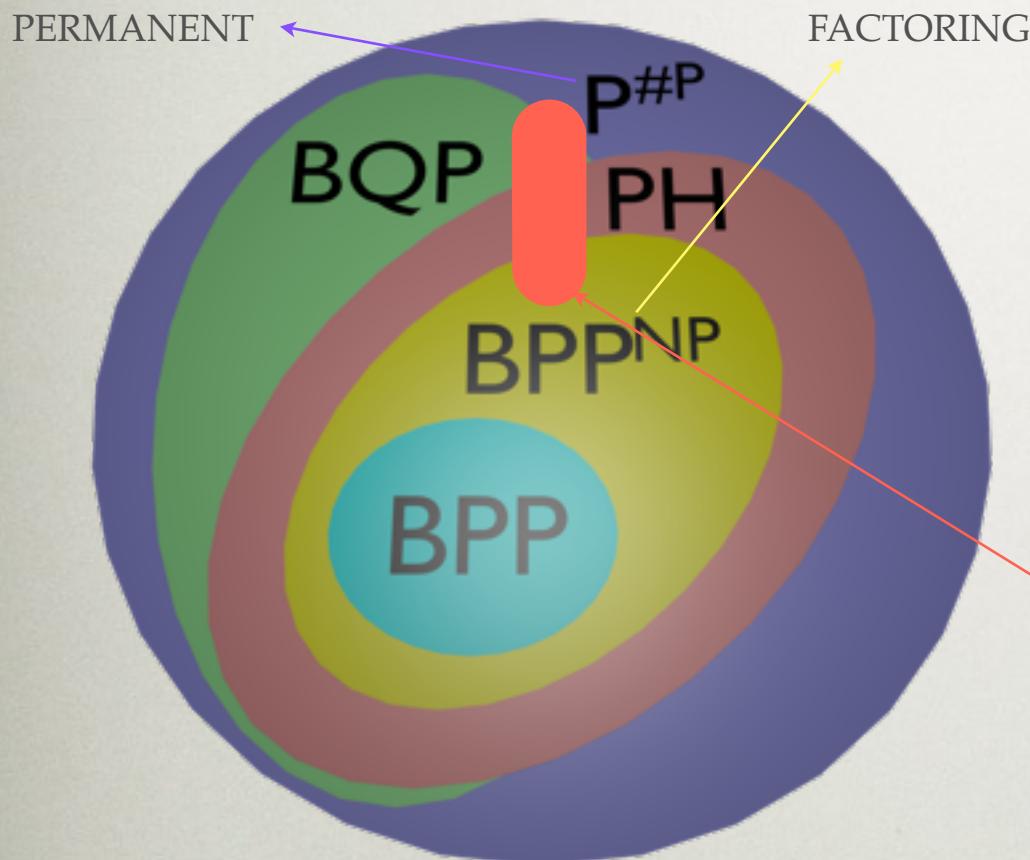


can be computed in $\text{poly}(n)$ time

The sgn permits the application of linear algebra theorems



APPROXIMATION OF THE PERMANENT COMPLEXITY CLASSES AND THE COLLAPSE OF THE POLYNOMIAL HIERARCHY



$\text{P}^{\#P}$: counting problems associated to decision ones in NP
 BQP : solvable in polynomial time by a quantum computer

PH : union of all classes in the polynomial hierarchy

BPP^{NP} : solvable in polynomial time by randomized algorithms with an oracle for a problem in NP

BPP : solvable in polynomial time by randomized algorithms

HARDNESS CONJECTURE (S. Aaronson and A. Arkhipov, Proceedings of ACM STOC 2011, 333-342)

If the Boson Sampling problem could be (even approximately) solved by a classical algorithm in $\text{poly}(n)$ times

Collapse of the polynomial hierarchy!

Based on two conjectures on the computational complexity of the permanent of a Gaussian matrix

#P COMPUTATIONAL COMPLEXITY AND THE PERMANENT

#P Class: includes the sets of counting problems associated to a decision problem in NP

Counts the number of solutions satisfying a certain constraint

Decision problems solvable with a non-deterministic Turing machine

Machine state and the tape symbol do not *uniquely* determine the next step of the machine

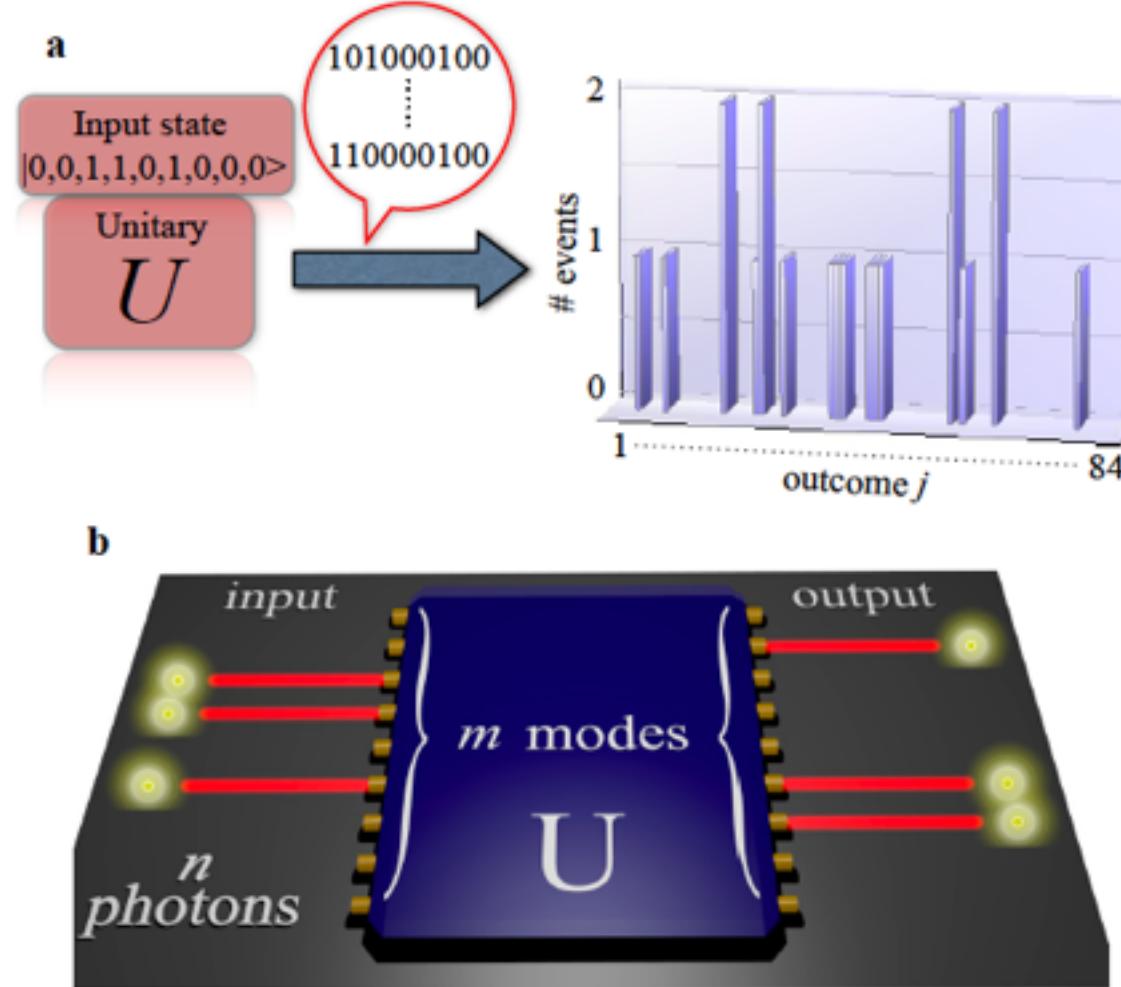
Turing machine where the transition rule is not *single-valued*

Permanent of a Matrix with N(0,1) gaussian entries: #P-hard problem

Permanent of a Matrix with {0,1} entries: #P-complete problem
(Valiant, 1979)

Every problem in #P can be reduced to the permanent of a {0,1} entries matrix in polynomial time

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. »

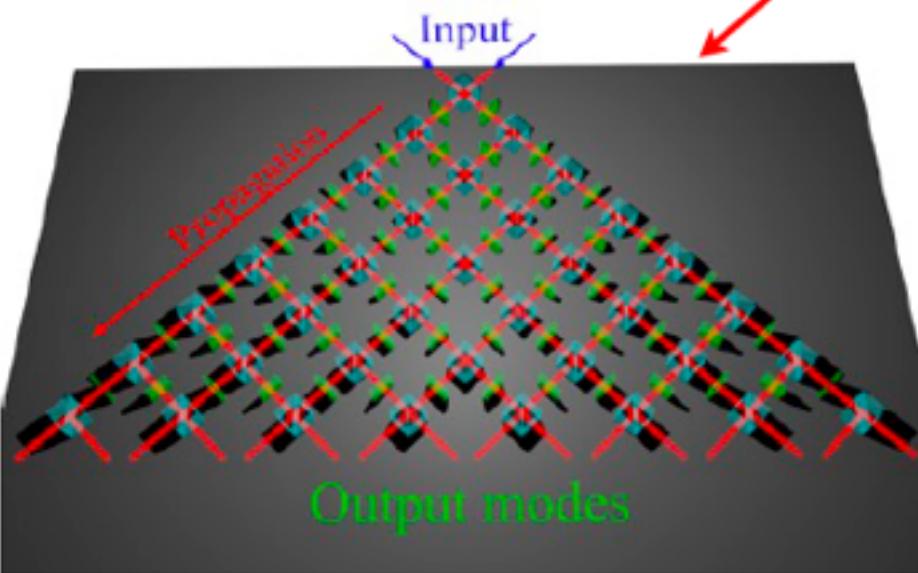
Boson Sampling

Photons naturally solve the BosonSampling problem

Experimental platform: photons in linear optical interferometers

Required resources:

n photons
 m modes



- Single-photon inputs
- Multimode interferometers
- Detection

Hard to implement with bulk optics

Require a technological step recently available due to integrated photonics



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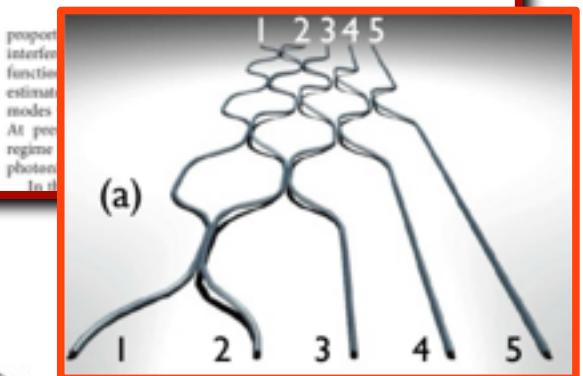
LETTERS

PUBLISHED ONLINE: XX XX 2013 | DOI: 10.1038/NPHOTON.2013.102

Integrated multimode interferometers with arbitrary designs for photonic boson sampling

Andrea Crespi^{1,2}, Roberto Osellame^{1,2*}, Roberta Ramponi^{1,2}, Daniel J. Brod³, Ernesto F. Galvão^{3*}, Nicolò Spagnolo⁴, Chiara Vitelli^{4,5}, Enrico Maiorino⁴, Paolo Mataloni⁴ and Fabio Sciarrino^{6**}

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 multipart interferometer naturally solve this so-called boson sampling problem¹, thereby motivating the development of technologies that enable precise control of multiphoton interference in large interferometers^{2–5}. Here, we use novel three-dimensional manufacturing techniques to achieve simultaneous control of all the parameters describing



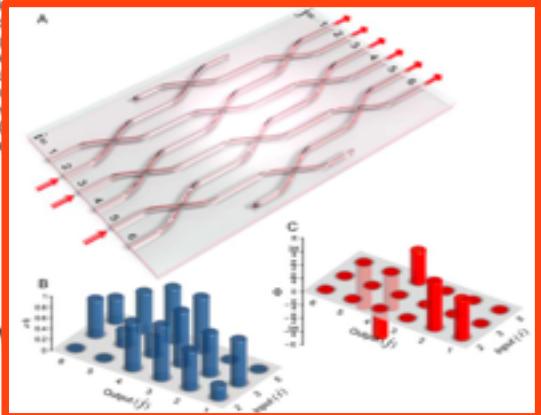
Boson Sampling on a Photonic Chip

Justin B. Spring,^{1*} Benjamin J. Micallef,² Peter C. Humphreys,³ W. Steven Kolthammer,³ Xian-Min Jin,^{1,2} Mario Barbieri,¹ Animesh Datta,¹ Nicholas Thomas-Peter,² Nathan K. Langford,^{1,2} Dmitry Kondyuk,⁴ James C. Gates,⁴ Brian J. Smith,² Peter G. R. Smith,² Ian A. Walmsley^{1*}

Although universal quantum computers ideally operate exponentially more efficiently than classical machines, devices motivate the demonstration of simpler, quantum speedup. We constructed a quantum bit output distribution resulting from the nonclassical photonic circuit, a problem thought to be exponentially hard for classical computation, boson sampling merely requires a quantum computer to implement. We benchmarked our device against a classical Monte Carlo simulation to assess sources of sampling inaccuracy. Scaling up to larger numbers of photons will enable quantum-enhanced computation.

Universal quantum computers acquire physical systems that are well isolated from the decohering effects of their environment, while at the same time allowing precise manipulation during computation. They also re-

15 FEBRUARY 2013



Massachusetts
Institute of
Technology



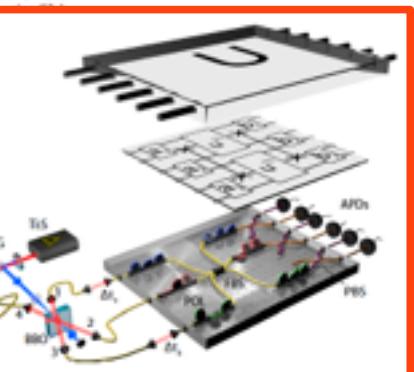
Photonic Boson Sampling in a Tunable Circuit

Matthew A. Broome,^{1,2*} Alessandro Fedrizzi,^{1,2} Saleh Rahimi-Keshari,² Justin Geva,³ Scott Aaronson,² Timothy C. Ralph,² Andrew G. White^{1,2}

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 (37)]. We present a result for this using planar graphs with

By analyzing the full interacting many-body system, we find that the algorithm performs the desired computation up to an error term that is small (37). Our analysis is based on a perturbation theory discussion that takes into account the fact that the graphs and the graphs are finite. By choosing the size and the number of vertices in the graph, we can ensure that the evolution time to be polynomial in n and g , the error in simulation is small.

15 FEBRUARY 2013



efficient computation or simulation if the number of qubits is large enough. This would be strongly contradicted by physical principles, such as the fact that it is impossible to simulate a universal quantum computer using a classical computer. Such a task is known as the ‘‘quantum supremacy’’ problem. In this work, we show that it is possible to implement a universal quantum computer using a photonic circuit, which is a much simpler task than building a universal quantum computer.

These results are realistic physical devices, then the question is whether they can be used to perform a universal computation. This is a difficult task because the computation must be performed on a realistic

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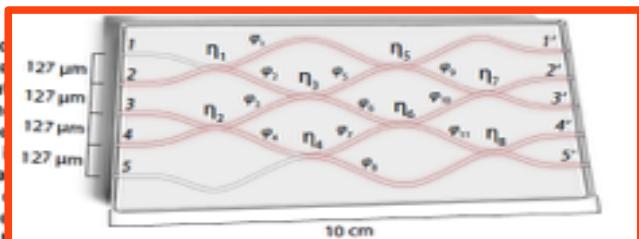
LETTERS

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

Experimental boson sampling

Max Tillmann^{1,2*}, Borivoje Dakic¹, René Heilmann³, Stefan Nolte³, Alexander Szameit³ and Philip Walther^{1,2*}

Universal quantum computers¹ promise a dramatic speedup over classical computers, but their full-size remains challenging². However, intermediate quantum computational models^{3–5} have been proposed that are not but can solve problems that are believed to be hard. Aaronson and Arkhipov⁶ have shown that of single photons in random optical networks can be a hard problem of sampling the bosonic output. Remarkably, this computation does not require multi-photon interactions^{7,8} or adiabatic feed-forward to



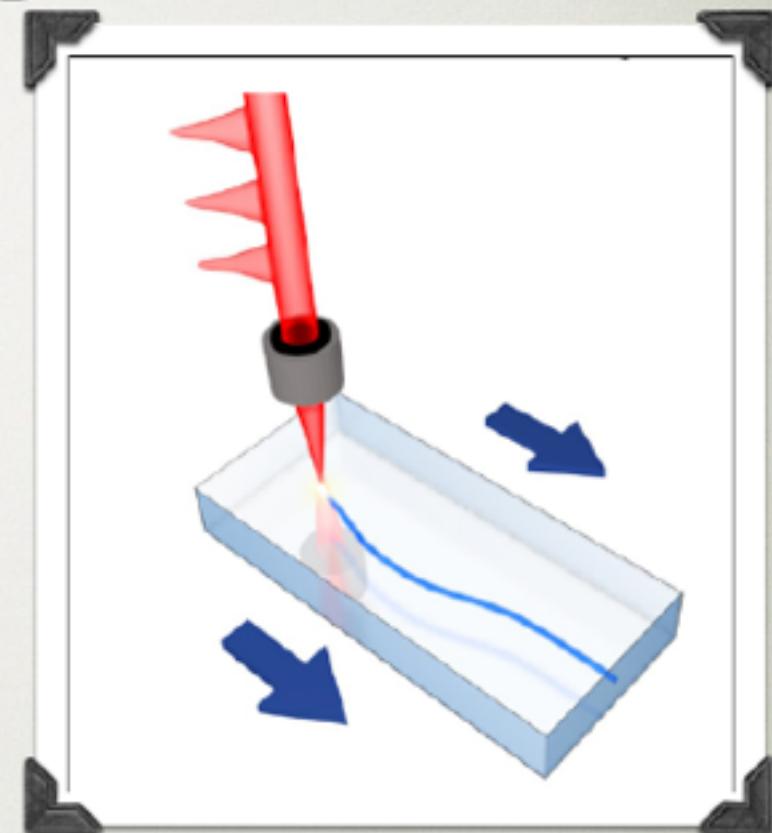
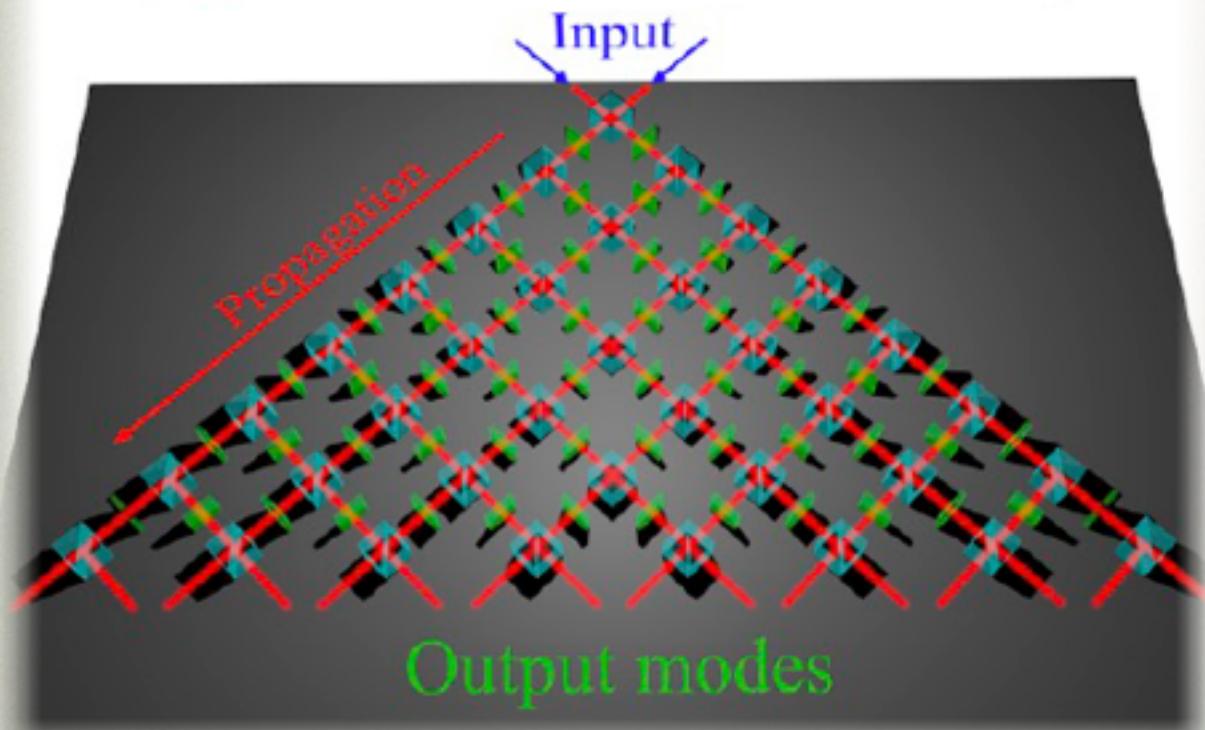
THE SOLUTION: INTEGRATED PHOTONICS



beam-splitter



phase shift



**Laser writing technology:
unique capability to transmit any polarization state**

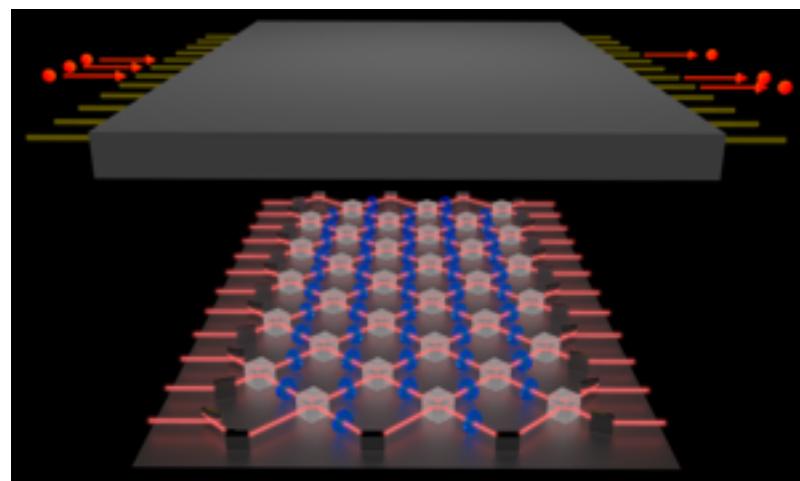
- Femtosecond pulse tightly focused in a glass
- Waveguides writing by translation of the sample

Boson Sampling: chip

Requirement for Boson Sampling - design arbitrary interferometers

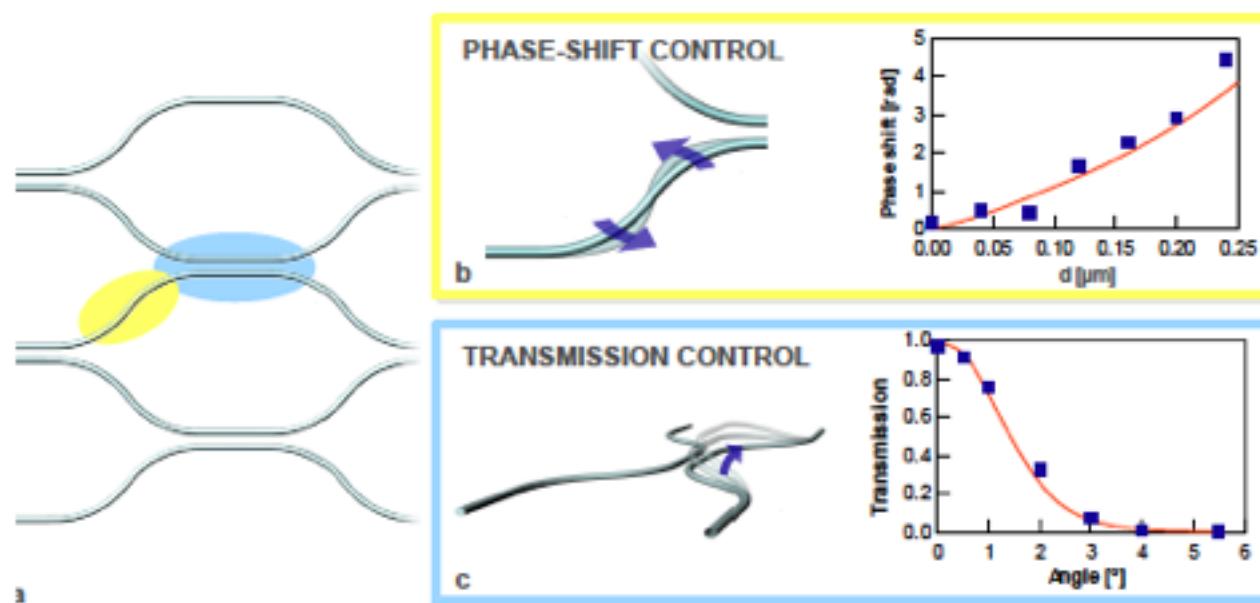


Requires independent control of phases and beam-splitter operation



b

Fabrication process



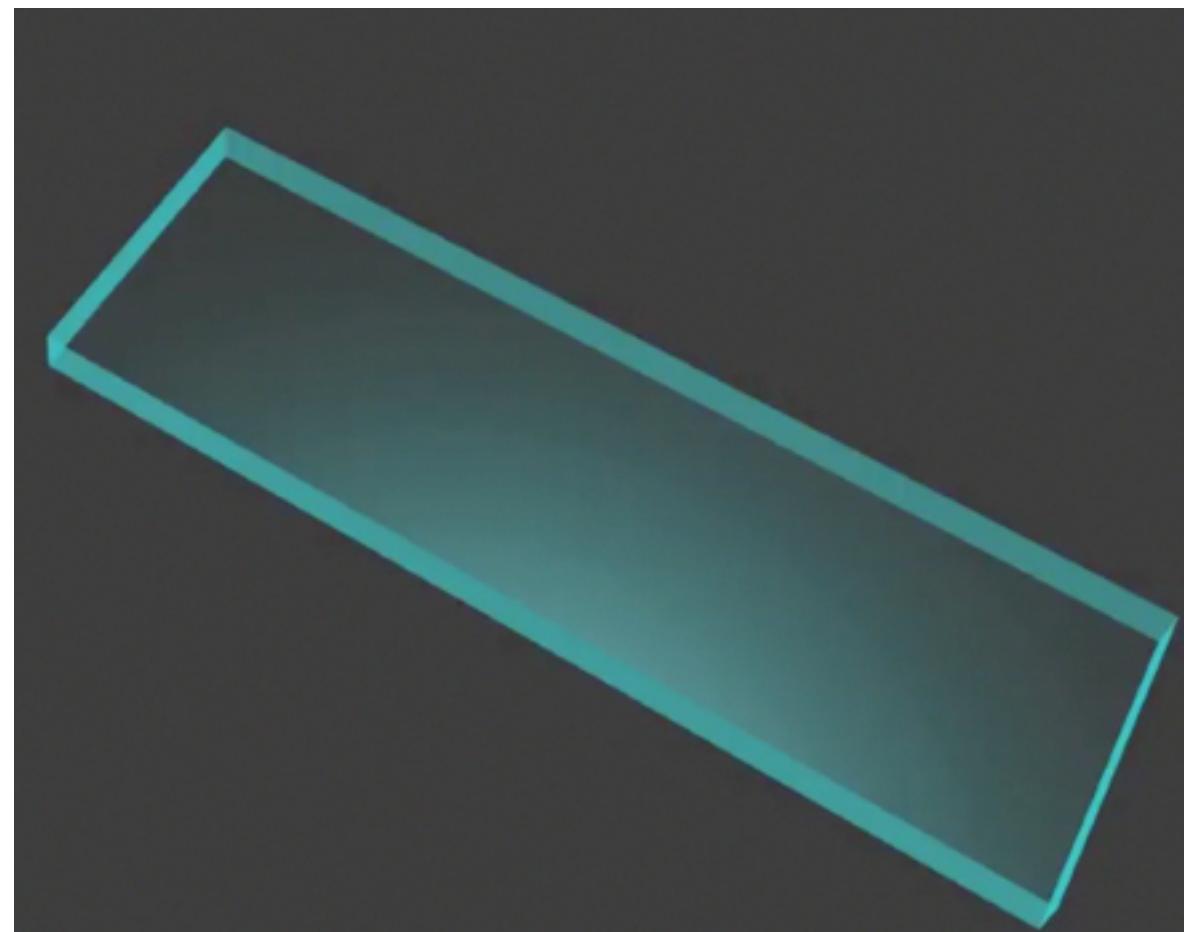
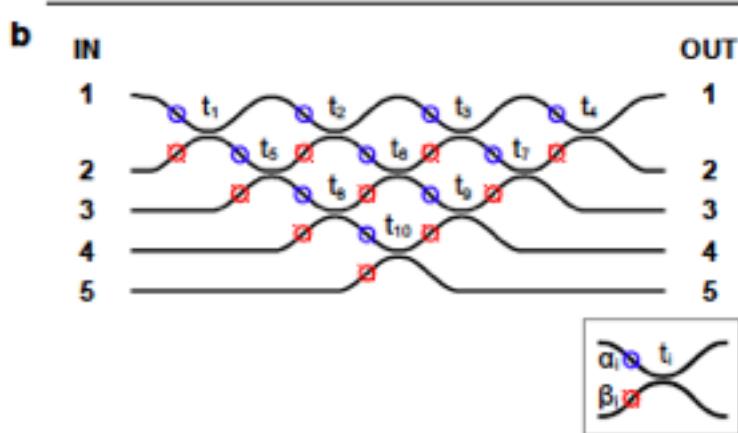
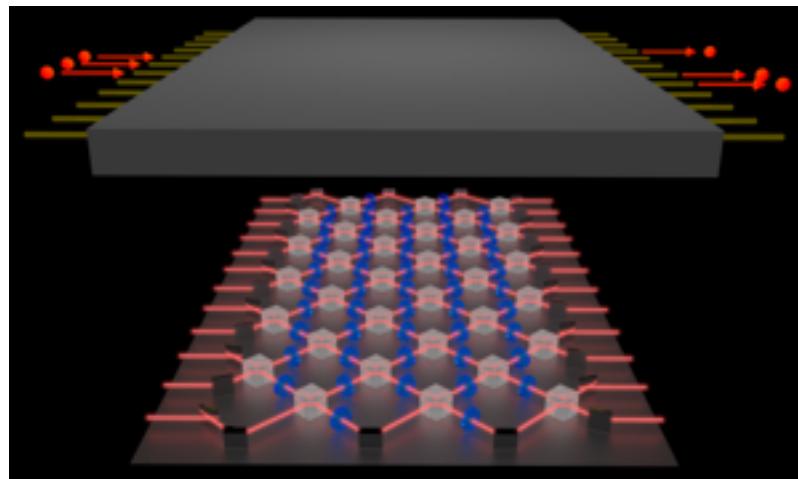
Reck, et al., *PRL* **73**, 58 (1994)

Boson Sampling: chip

Requirement for Boson Sampling - design arbitrary interferometers

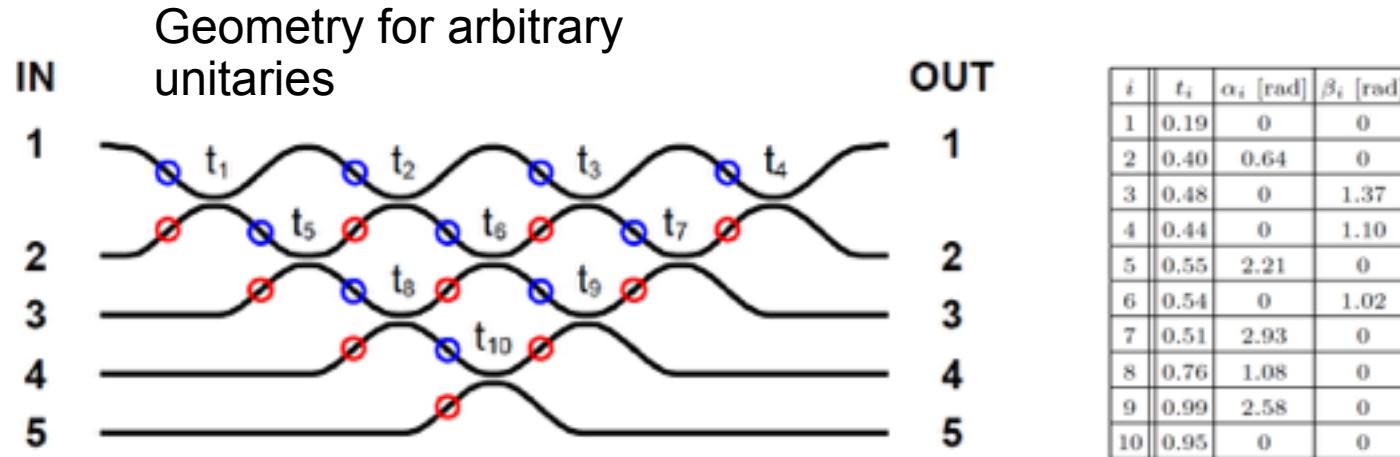


Requires independent control of phases and beam-splitter operation



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

Characterization of the unitary



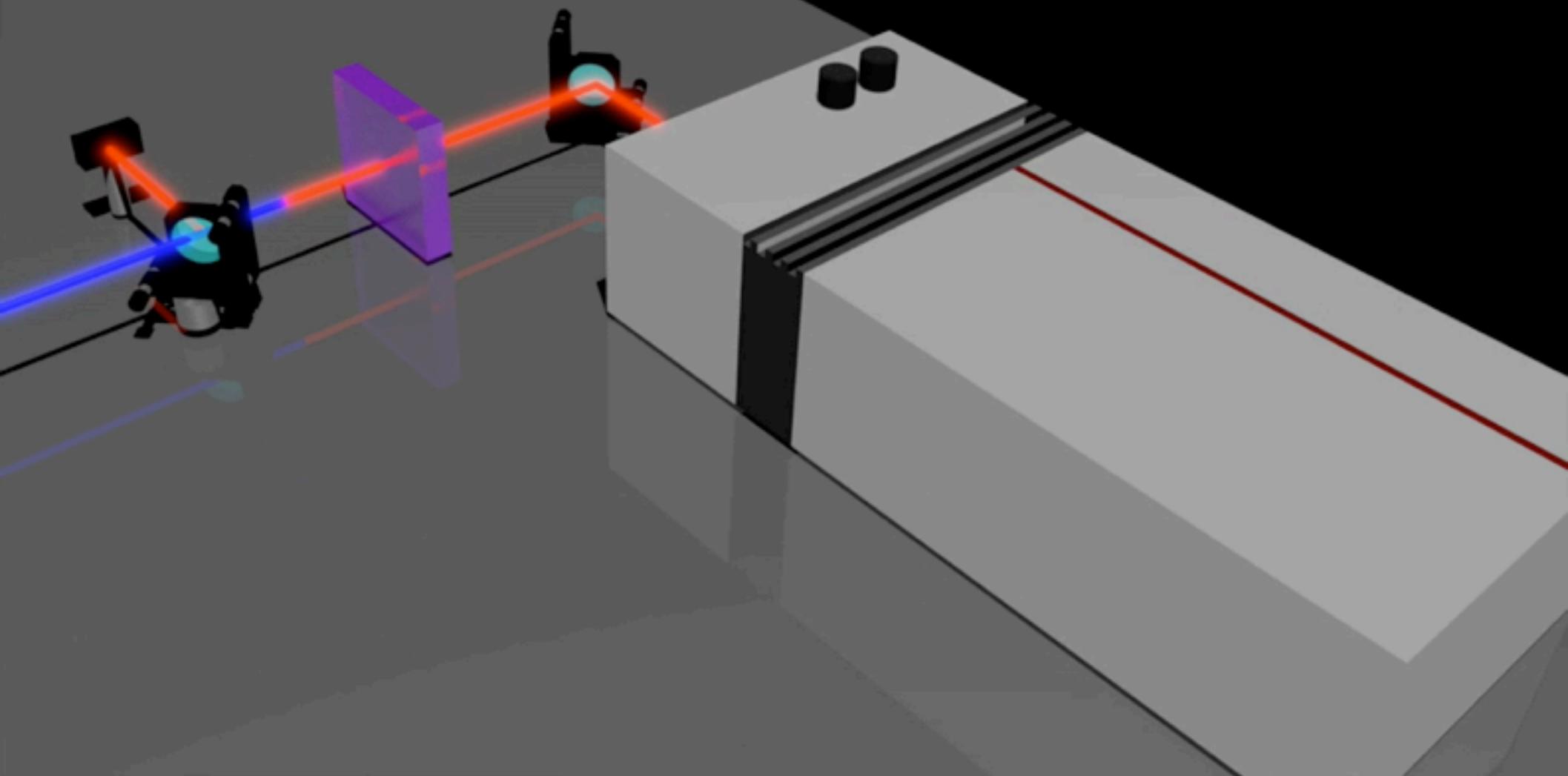
Randomly sampled matrix

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

Reconstructed matrix

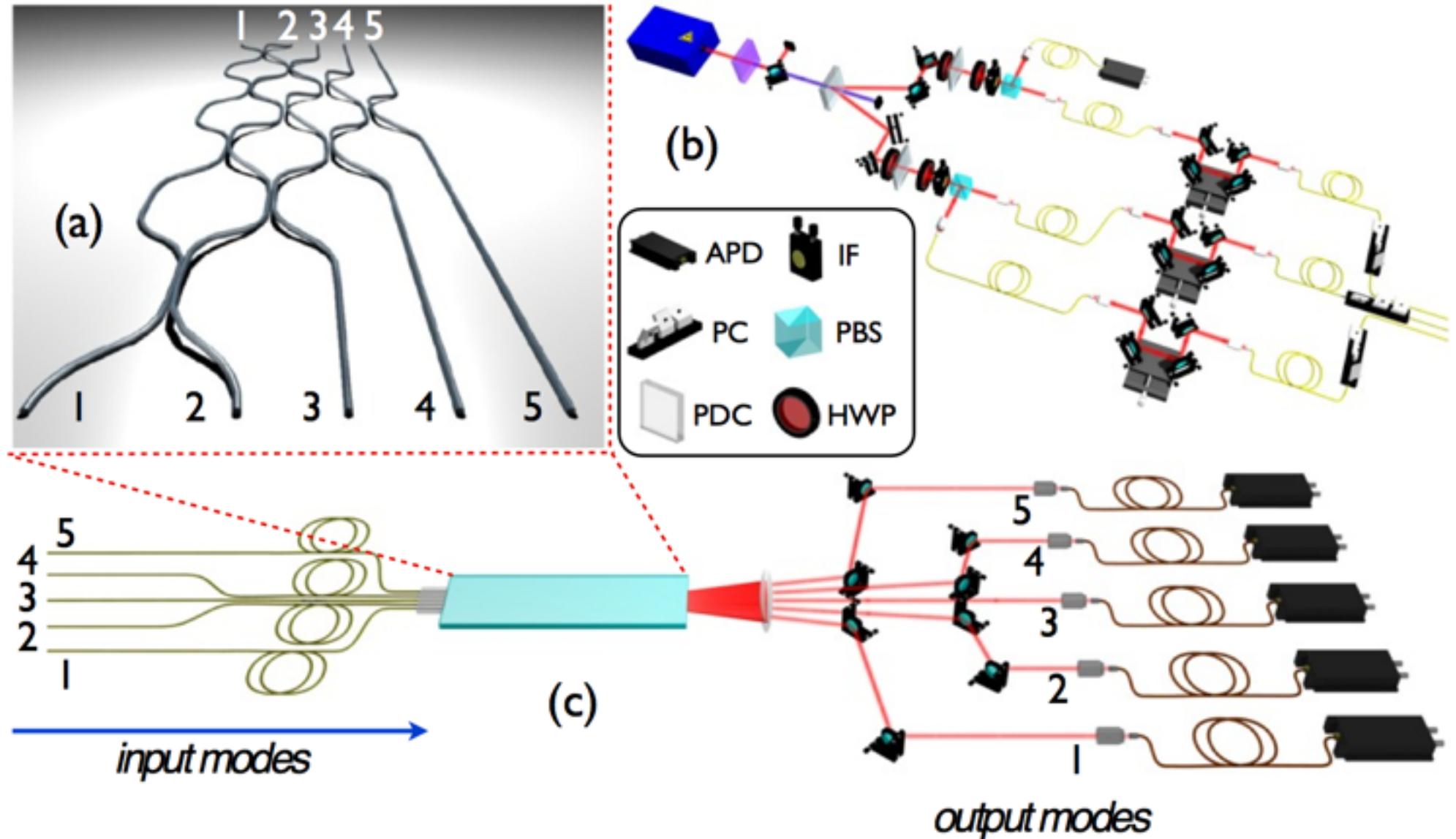
$$U^r = \begin{pmatrix} 0.37 & 0.007 + 0.151i & -0.164 - 0.31i & -0.442 + 0.138i & -0.702 + 0.099i \\ -0.109 - 0.465i & -0.013 - 0.585i & 0.121 + 0.381i & 0.076 - 0.134i & -0.474 - 0.147i \\ -0.677 + 0.18i & 0.134 - 0.027i & -0.283 - 0.133i & 0.036 + 0.498i & -0.206 - 0.319i \\ -0.039 + 0.24i & -0.08 - 0.572i & -0.496 - 0.046i & -0.475 - 0.22i & 0.265 + 0.125i \\ 0.262 + 0.133i & 0.09 - 0.524i & 0.479 - 0.377i & 0.055 + 0.486i & 0.143 + 0.007i \end{pmatrix}$$

Gate fidelity: $F = |Tr(U^t U^{r\dagger})|/5 = 0.95$.



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).

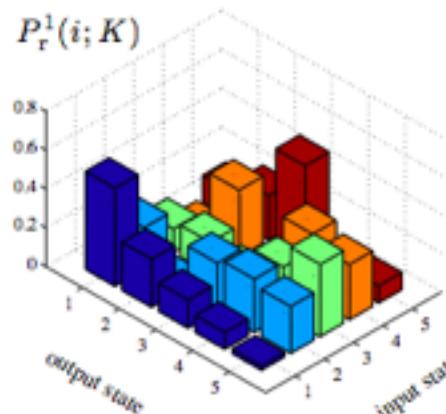
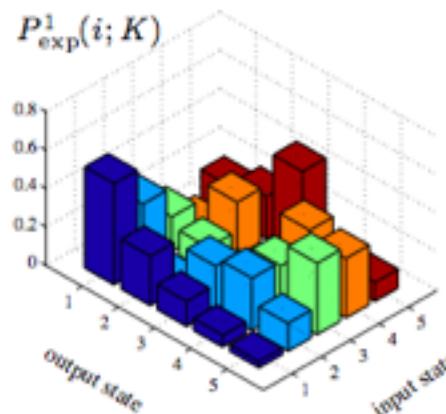
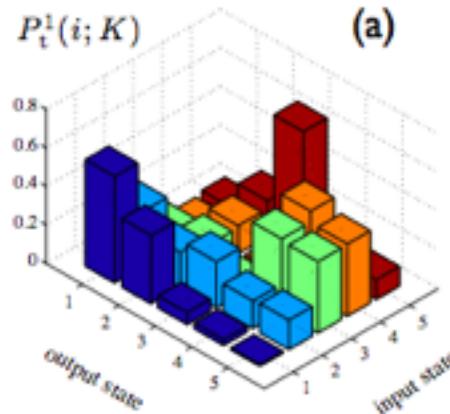
Boson Sampling: apparatus



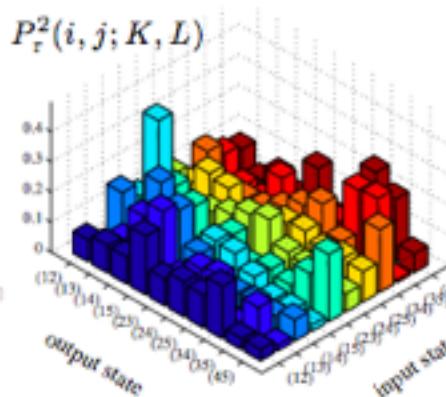
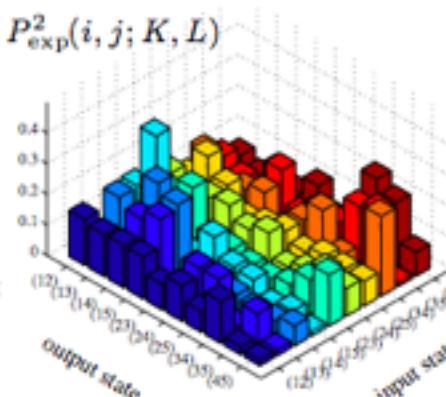
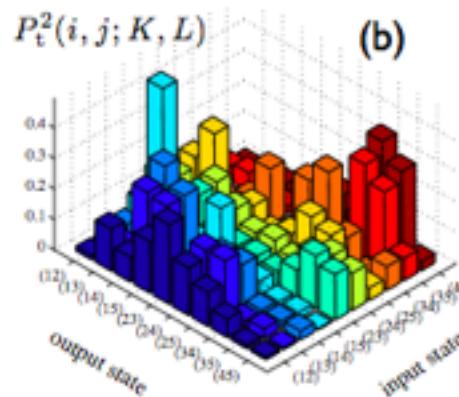
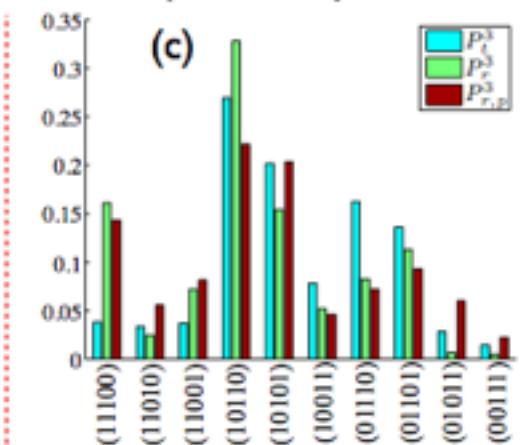
A. Crespi, R. Osellame, R. Ramponi, D. J. Brod, E. F. Galvao, N. Spagnolo, C. Vitelli, E. Maiorino, P. Mataloni, F. Sciarrino, *Integrated multimode interferometers with arbitrary designs for photonic boson sampling*, Nature Photonics 7, 545 (2013).

Experimental Boson Sampling

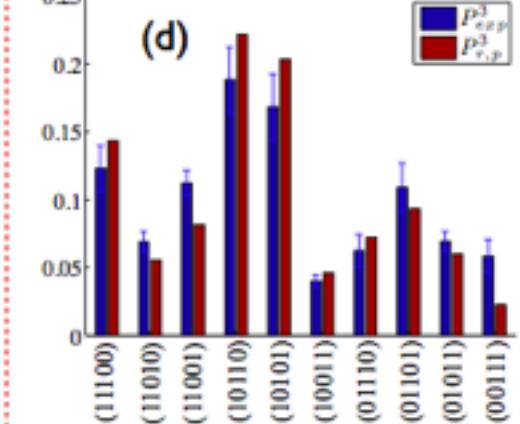
Single-photon probabilities $S_{exp,r}^1 = 0.990 \pm 0.005$



Three-photon probabilities



Two-photon probabilities $S_{exp,r}^2 = 0.977 \pm 0.027$



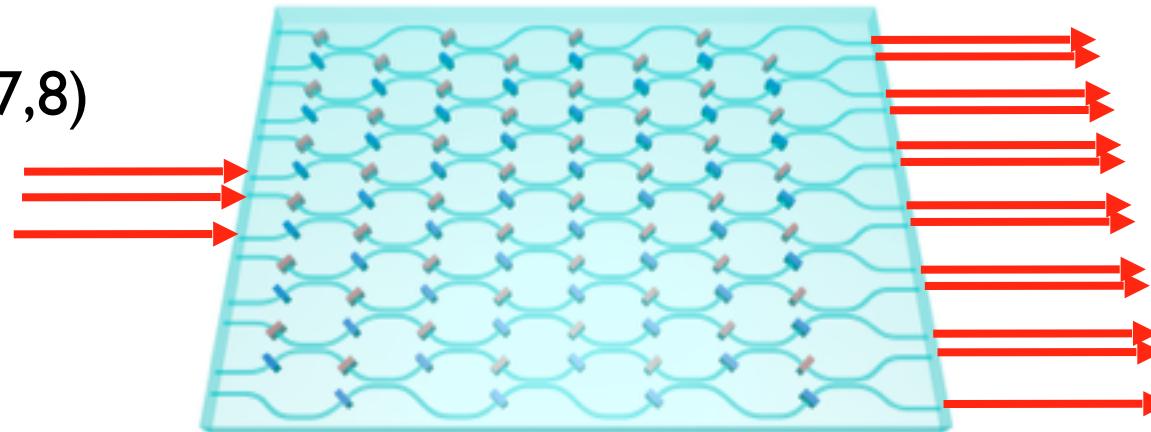
$S_{exp,rp}^3 = 0.983 \pm 0.045$

Good agreement between experimental data and the probabilities expected from the permanent formula:

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

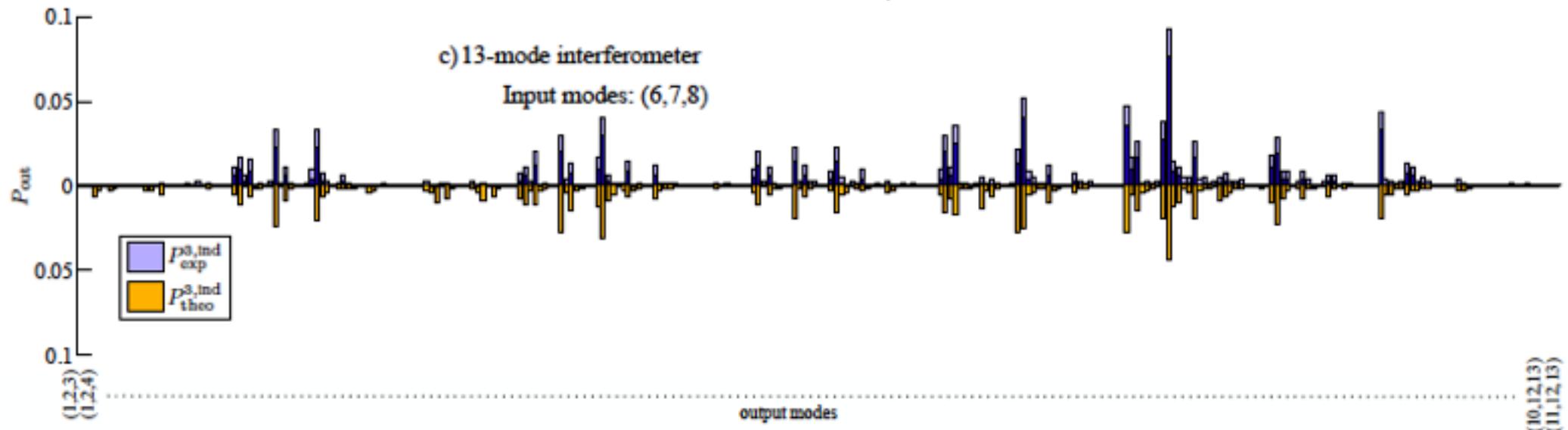
Boson Sampling in a 13-mode device

Input: (6,7,8)



Output: 286 different possible no-bunching configurations

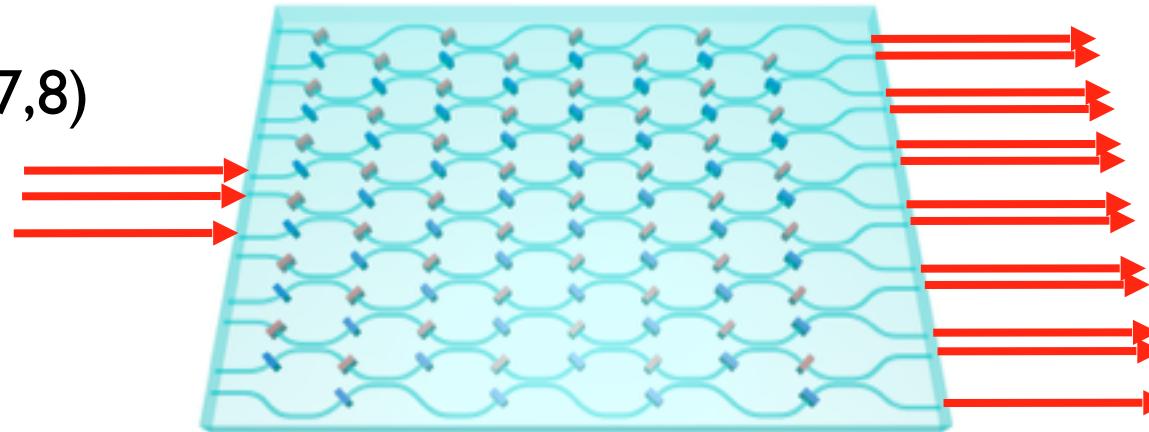
91 different fabrication phases



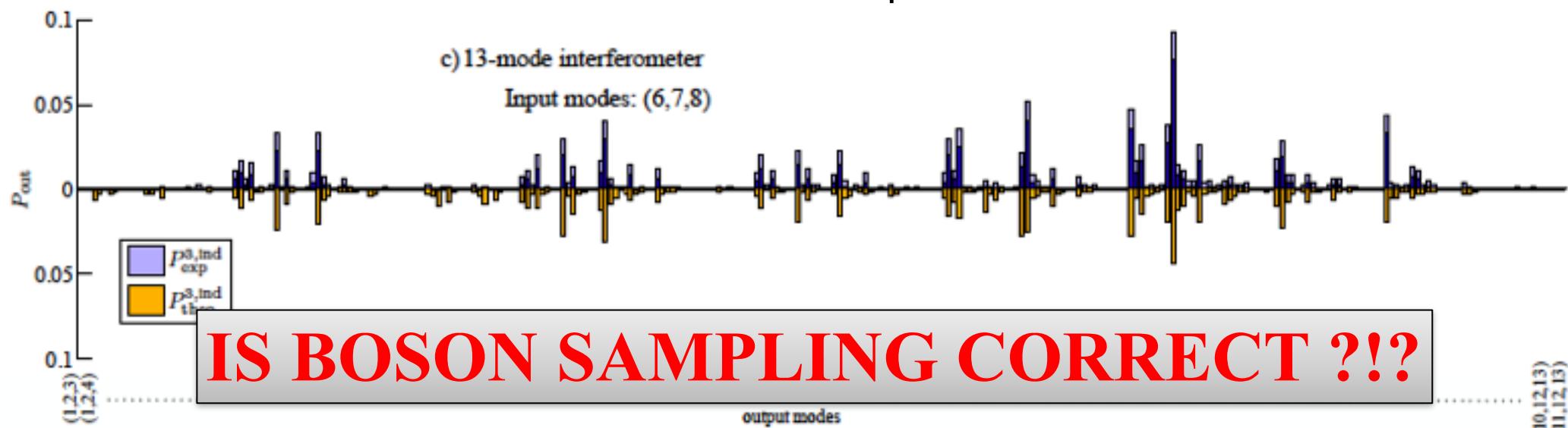
N. Spagnolo, C. Vitelli, M. Bentivegna, D. J. Brod, A. Crespi, F. Flamini, S. Giacomini, G. Milani, R. Ramponi, P. Mataloni, R. Osellame, E. F. Galvao, and F. Sciarrino, *Nature Photonics* **8**, 614 (2014)
Similar experiment in Bristol: J. Carolan, et al., *Nature Photonics* **8**, 619 (2014)

Boson Sampling in a 13-mode device

Input: (6,7,8)



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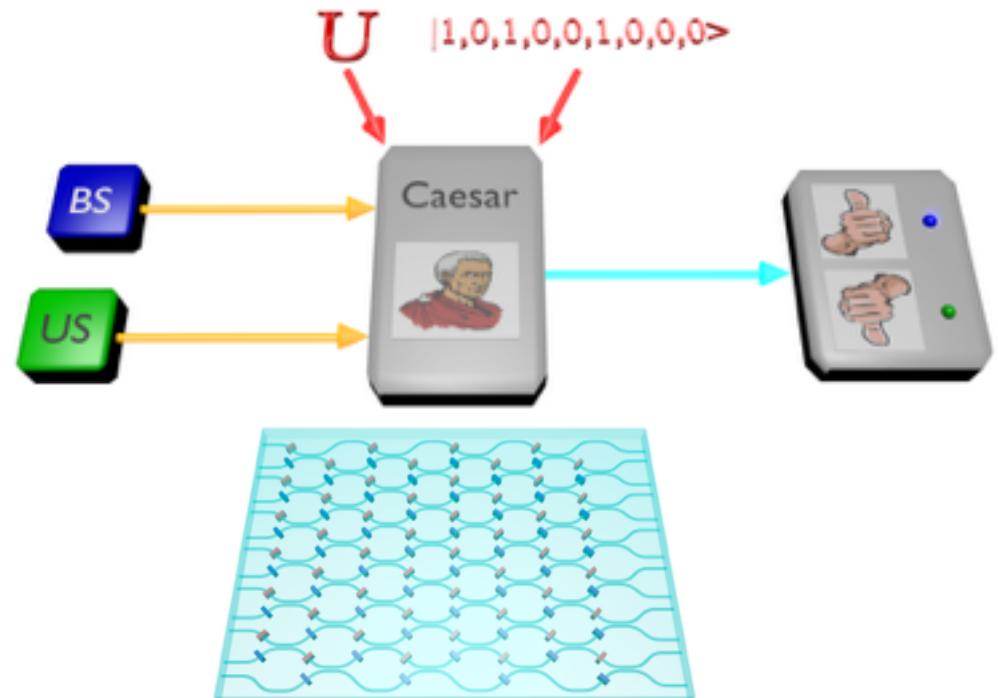
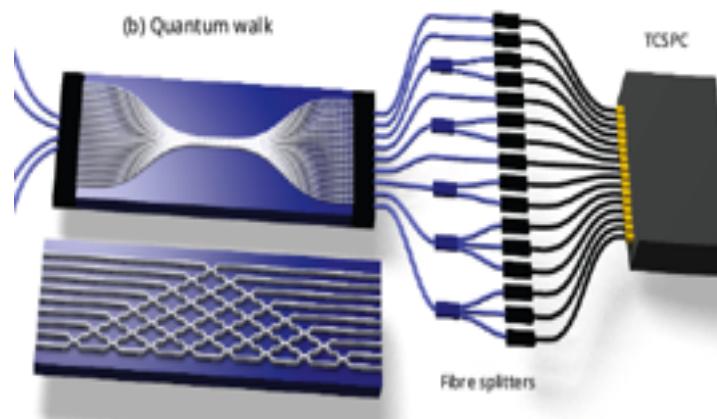
N. Spagnolo, C. Vitelli, M. Bentivegna, D. J. Brod, A. Crespi, F. Flamini, S. Giacomini, G. Milani, R. Ramponi, P. Mataloni, R. Osellame, E. F. Galvao, and F. Sciarrino, *Nature Photonics* **8**, 614 (2014)
Similar experiment in Bristol: J. Carolan, et al., *Nature Photonics* **8**, 619 (2014)

Validation of the Boson Sampling output

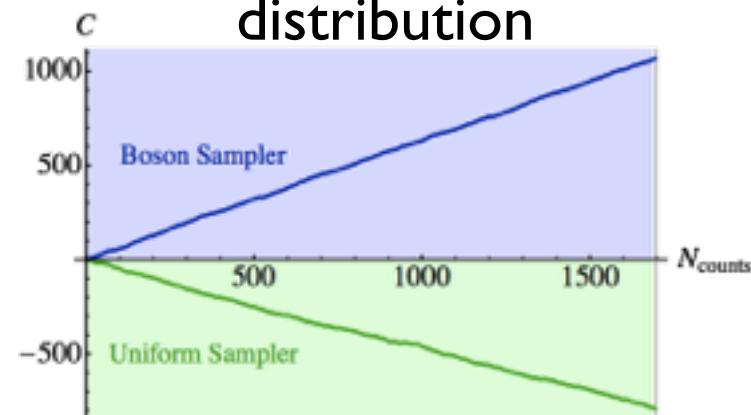
Boson Sampling:
hard problem with classical
computer

*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....

Boson Sampling: hard problem with classical computer

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

*Two sources of hard computability: permanent calculation and
the exponential growth of the Hilbert space*

Validation of Boson Sampling....

Boson Sampling: hard problem with classical computer

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

***Two sources of hard computability: permanent calculation and
the exponential growth of the Hilbert space***

Can we discriminate the Boson Sampling distribution from the Uniform Distribution efficiently, hence without requiring an exponential number of measurements ?

Boson-Sampling in the light of sample complexity

C. Gogolin, M. Kliesch, L. Aolita, and J. Eisert

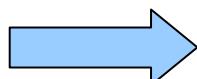
Dahlem Center for Complex Quantum Systems, Freie Universität Berlin, 14195 Berlin, Germany

Distinguishing Boson Sampling from Uniform

Can we discriminate the Boson Sampling distribution from the Uniform Distribution efficiently (hence without requiring an exponential number of measurements) ?

Black box settings:  no information on the system including the unitary

Symmetric algorithms:  decision depends only on the outcome frequencies and not on the labels of the collected samples

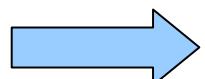
 the two distribution cannot be distinguished efficiently

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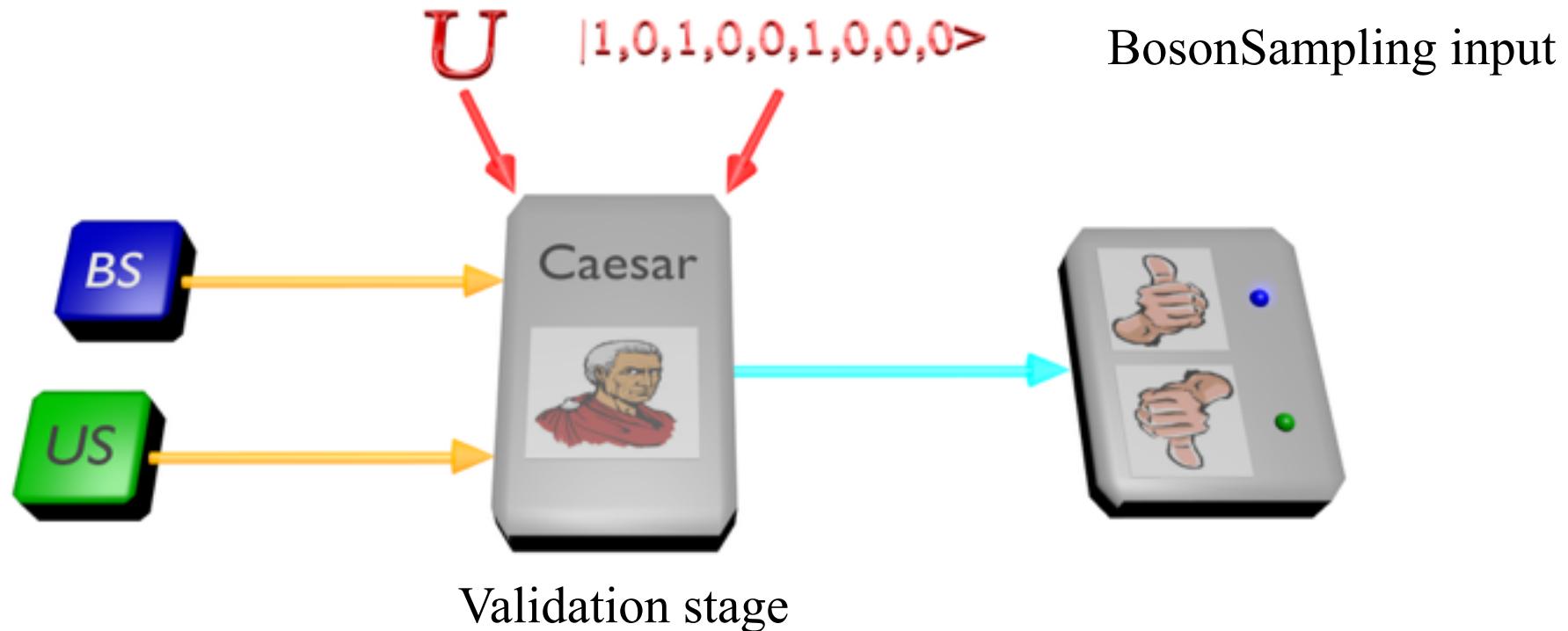
The unitary U and the input state are known problem parameters

  The adoption only of symmetric algorithms is too restrictive

Can we efficiently distinguishing the BosonSampling distribution from a Uniform distribution by exploiting information on the unitary?

Distinguishing Boson Sampling from Uniform

Can we efficiently distinguish the BosonSampling distribution from a Uniform distribution by exploiting information on the unitary?



The algorithm: for each outcome $T = \{t_1, t_2, \dots, t_n\}$, input $S = \{s_1, s_2, \dots, s_n\}$

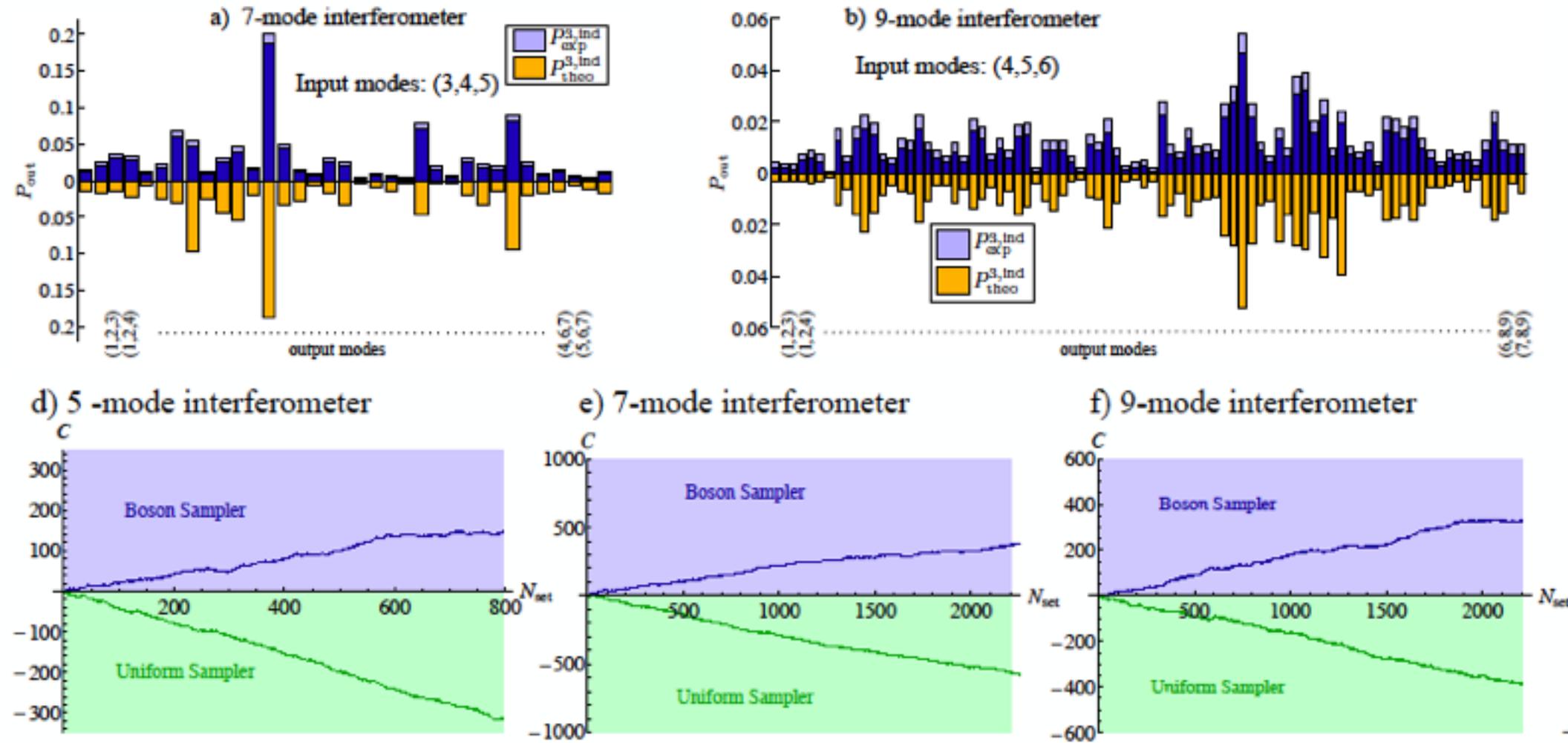
Define $A_{i,j} = U_{s_i, t_j}$.

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

If $P > \left(\frac{n}{m}\right)^n$ BosonSampling
Else UniformSampler

computationally efficient

Experimental Results - 1

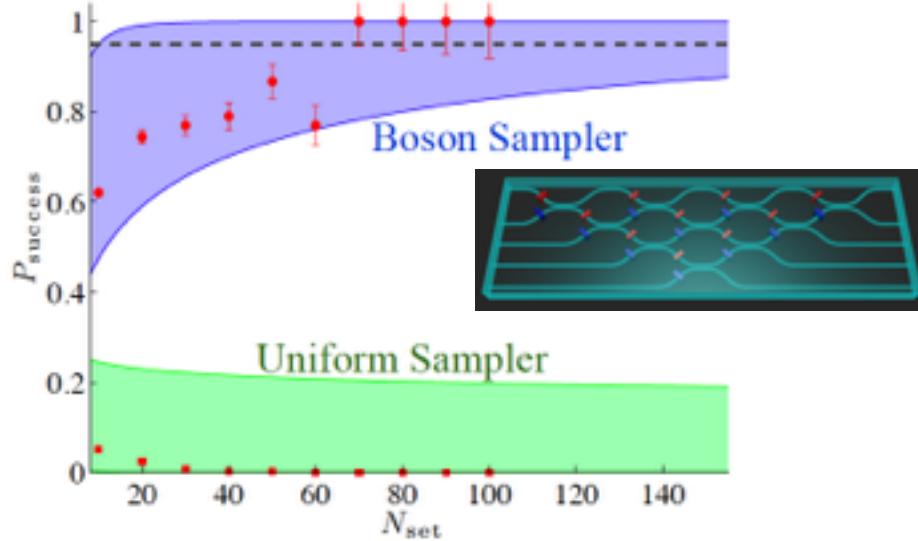


The BosonSampling distribution can be efficiently discriminated from the Uniform

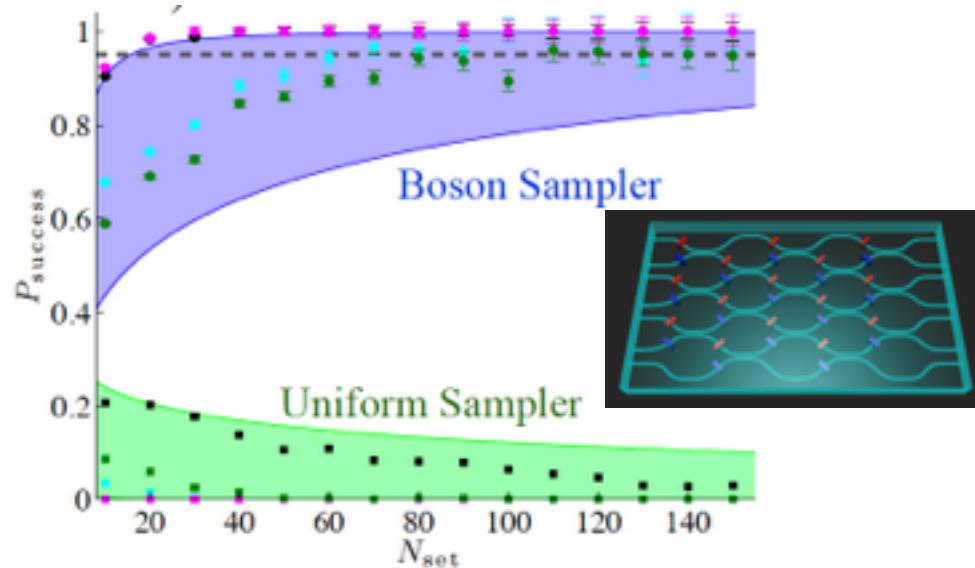
N. Spagnolo, C. Vitelli, M. Bentivegna, D. J. Brod, A. Crespi, F. Flamini, S. Giacomini, G. Milani, R. Ramponi, P. Mataloni, R. Osellame, E. F. Galvao, and F. Sciarrino, *Nature Photonics* **8**, 614 (2014)
Similar experiment in Bristol: J. Carolan, et al., *Nature Photonics* **8**, 619 (2014)

Experimental Results - 2

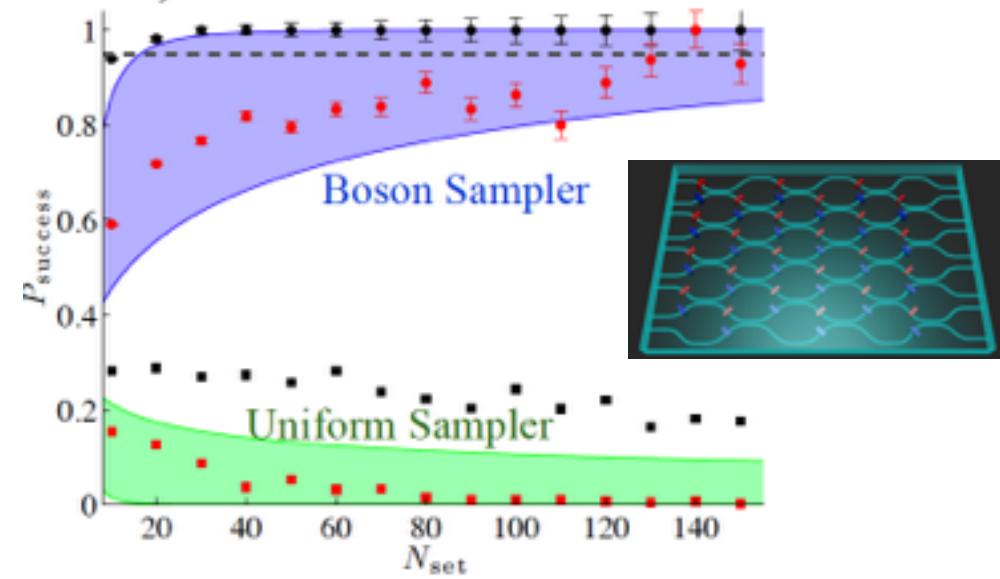
5-mode interferometer



7-mode interferometer



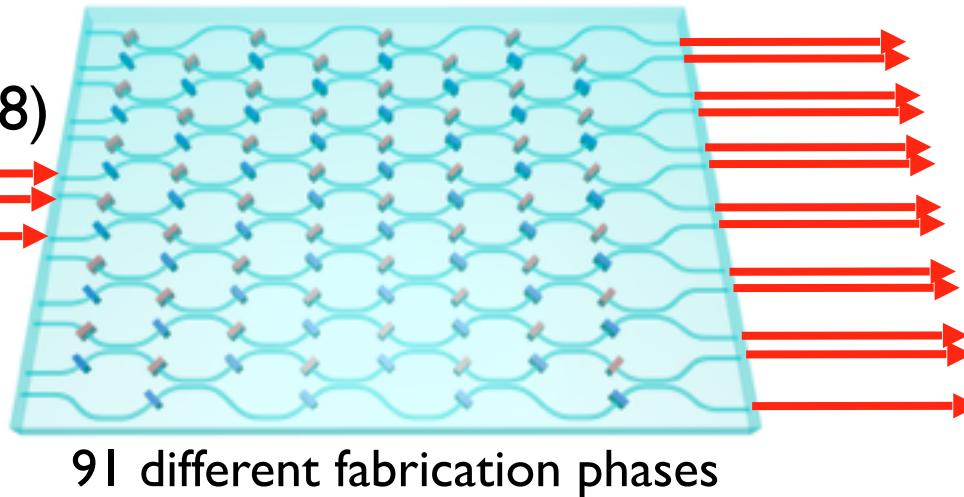
9-mode interferometer



>95% success probability achieved
with sample size of $N \sim 100$ data

Validation of Boson Sampling in a 13-mode device

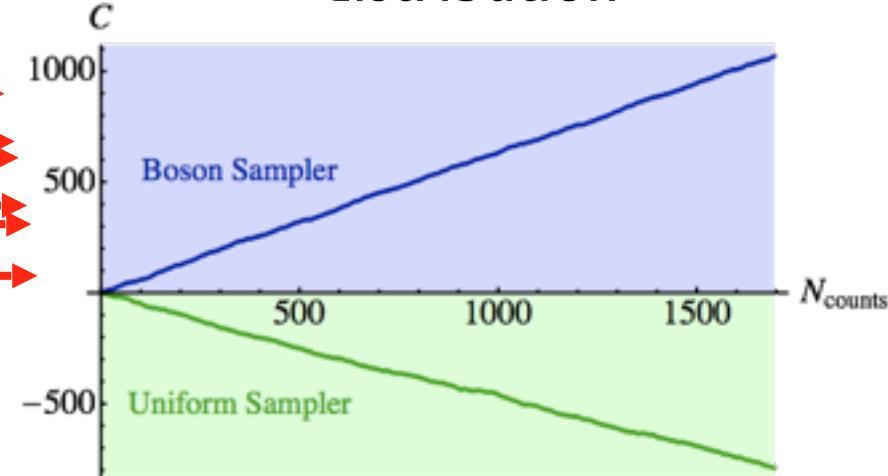
Input: (6,7,8)



91 different fabrication phases

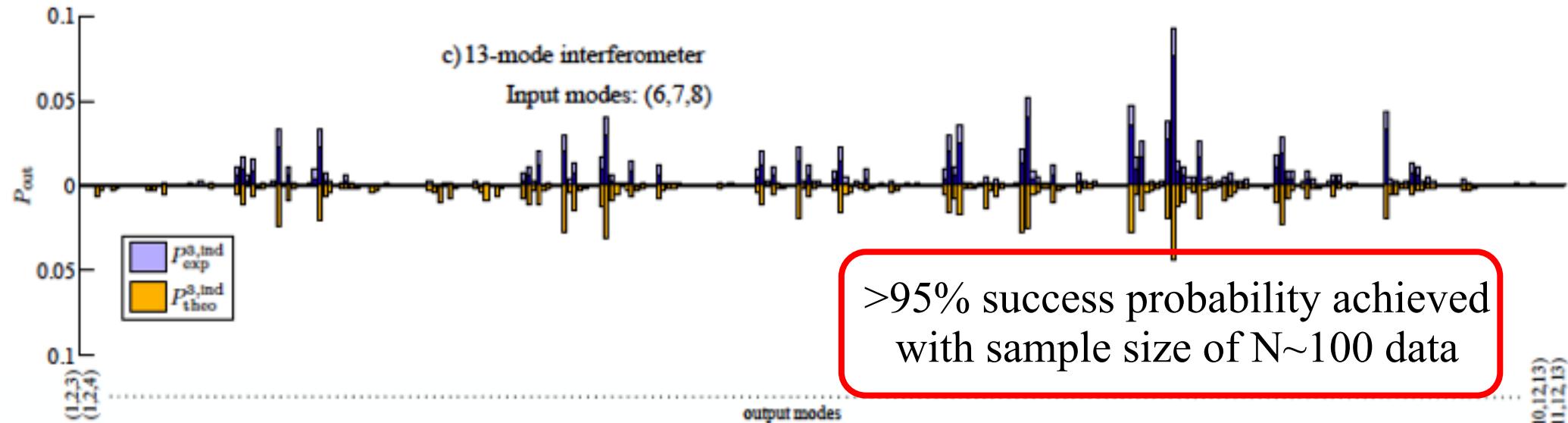
Output: 286 different possible no-bunching configurations

Validation against the uniform distribution



c) 13-mode interferometer

Input modes: (6,7,8)



(12,3)

(10,12,13)
(11,12,13)

Validation of Boson Sampling

What about other distributions?

- ▶ Uniform (simplest and most general case of non-informed-about-U distributions) can be ruled out efficiently
- ▶ What about validating against “smarter cheaters”?
 - Fermion Sampler
 - Classical Mockup Sampler

nature
photonics

LETTERS

PUBLISHED ONLINE: 22 JUNE 2014 | DOI: 10.1038/NPHOTON.2014.135

Experimental validation of photonic boson sampling

Nicolò Spagnolo¹, Chiara Vitelli^{1,2}, Marco Bentivegna¹, Daniel J. Brod³, Andrea Crespi^{4,5}, Fulvio Flamini¹, Sandro Giacomini¹, Giorgio Milani¹, Roberta Ramponi^{4,5}, Paolo Mataloni¹, Roberto Osellame^{4,5*}, Ernesto F. Galvão^{3*} and Fabio Sciarrino^{1*}

Distinguishing Boson Sampling from alternative distributions

Further Step: can we discriminate the BosonSampling distribution from Alternative distribution?

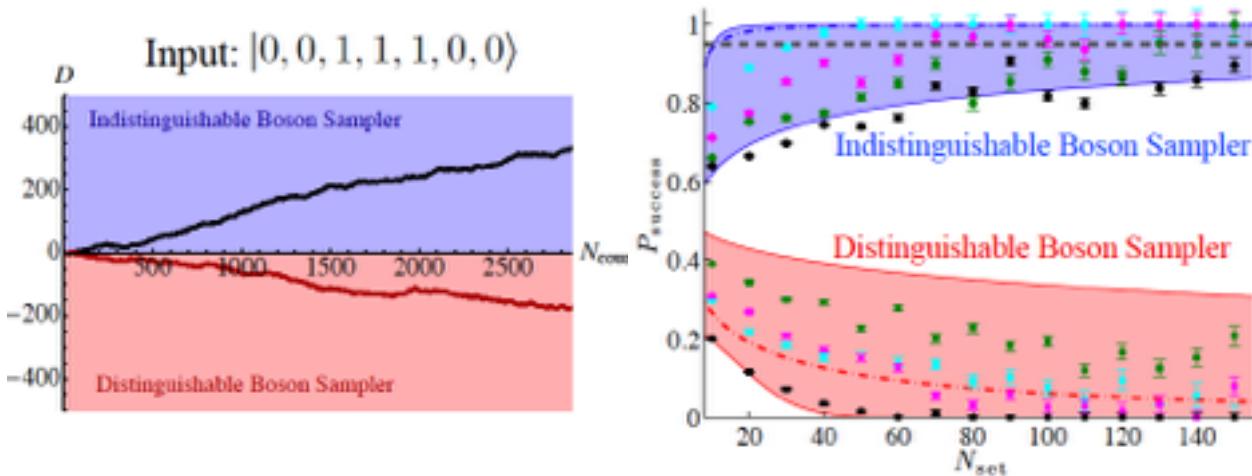
Example: Indistinguishable Bosons vs Distinguishable Bosons

Strategy: Compare outcome-by-outcome the probabilities between the two cases and assign the event (up to a threshold) to the cases with higher probability

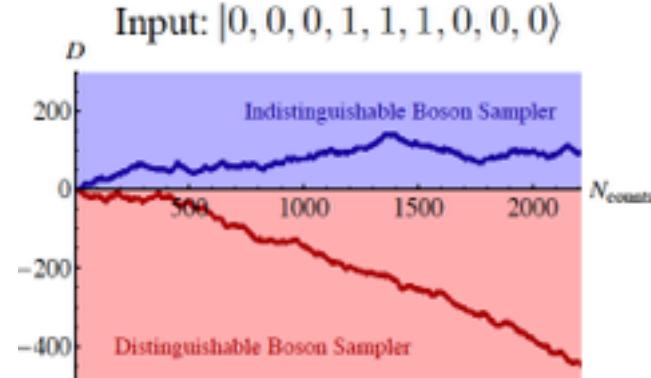
Requires calculating permanents

Does not require calculating the whole distribution

a) 7-mode interferometer



b) 9-mode interferometer



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, arXiv:1311.1622 (2013)
Nature Photonics (in press)

First experimental results with integrated photonics :

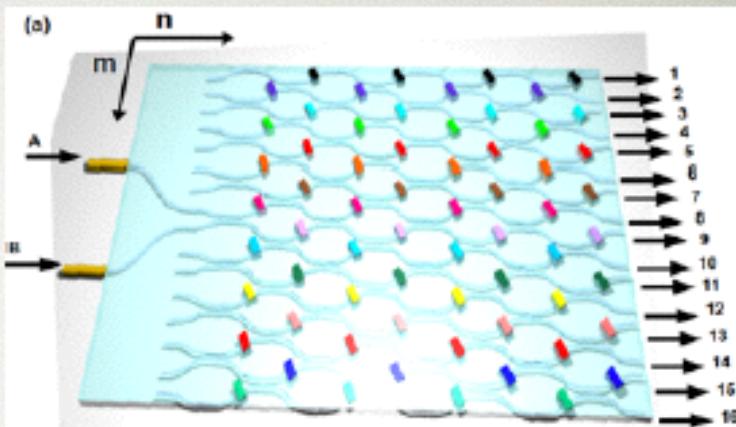
nature
photronics

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. Brod³, Ernesto F. Galvão^{3,*}, Nicolò Spagnolo⁴, Chiara Vitelli^{4,5}, Enrico Maiorino⁴, Paolo Mataloni⁴ 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

PRL 113, 100502 (2014)

PHYSICAL REVIEW LETTERS

week ending
3 SEPTEMBER 2014

Boson Sampling from a Gaussian State

A. P. Lund,¹ A. Laing,² S. Rahimi-Keshari,³ T. Rudolph,³ J. L. O'Brien,¹ and T. C. Ralph¹

¹Centre for Quantum Computation and Communication Technology, School of Mathematics and Physics, University of Queensland, Brisbane, Queensland 4272, Australia

²Centre for Quantum Photonics, H. H. Wills Physics Laboratory and Department of Electrical and Electronic Engineering, University of Bristol, Bristol BS8 1TQ, United Kingdom

³Optics Section, Mullard Laboratory, Imperial College London, London SW7 2AZ, United Kingdom

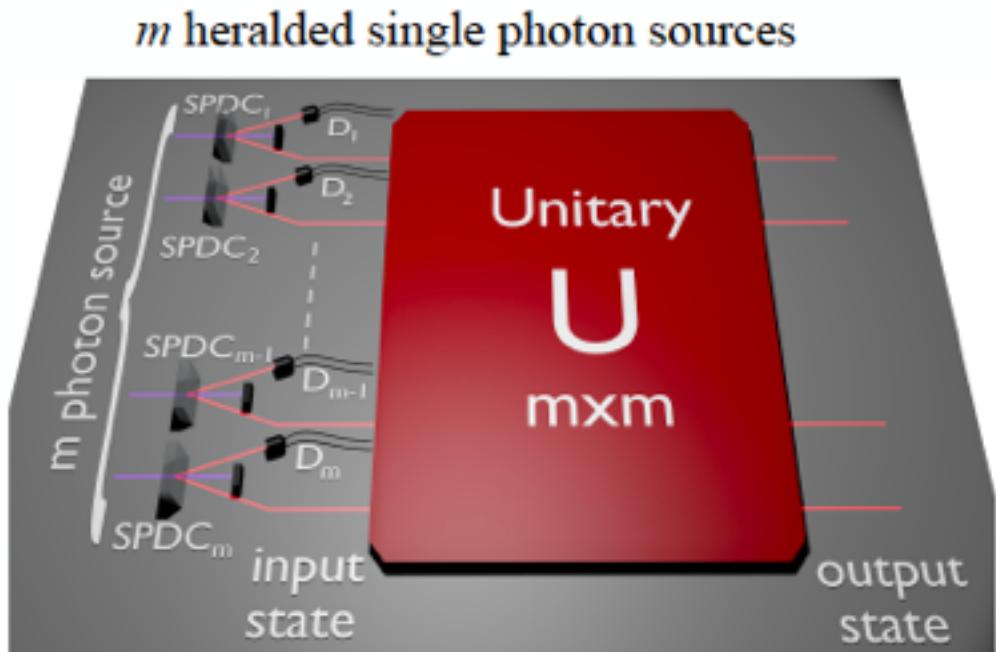
(Received 26 November 2013; revised manuscript received 21 March 2014; published 3 September 2014)

We pose a randomized boson sampling problem. Strong evidence exists that such a problem becomes intractable for 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 nondisruptive 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)



« Three things that I should've gotten around to years

ago

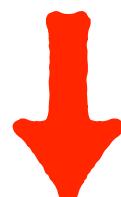
Twenty Reasons to Believe Oswald Acted Alone »

Scattershot BosonSampling: A new approach to scalable BosonSampling experiments

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

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

Scattershot Boson Sampling

p = probability of generating a photon pair in a single source
(typical values $p=0.01\text{-}0.015$)

Conventional Boson Sampling, n photons

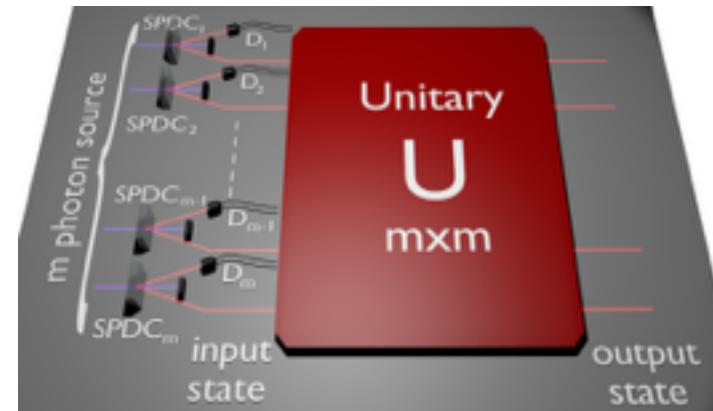
p^n probability of generating the n -photon input

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

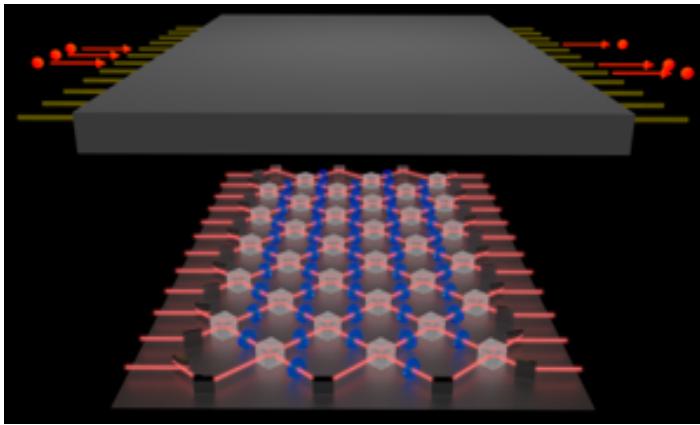
Total generation rate: $\sim p^n(1-p)^{m-n} \binom{m}{n}$



Hardness of Scattershot Boson Sampling: as hard as the conventional Boson Sampling

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

Scalability of down conversion



“Conventional” Boson Sampling

n bosons evolving in m modes,
random Unitary,
fixed input state

Sampling from the output distribution

Photonic implementations

based on parametric down-conversion sources

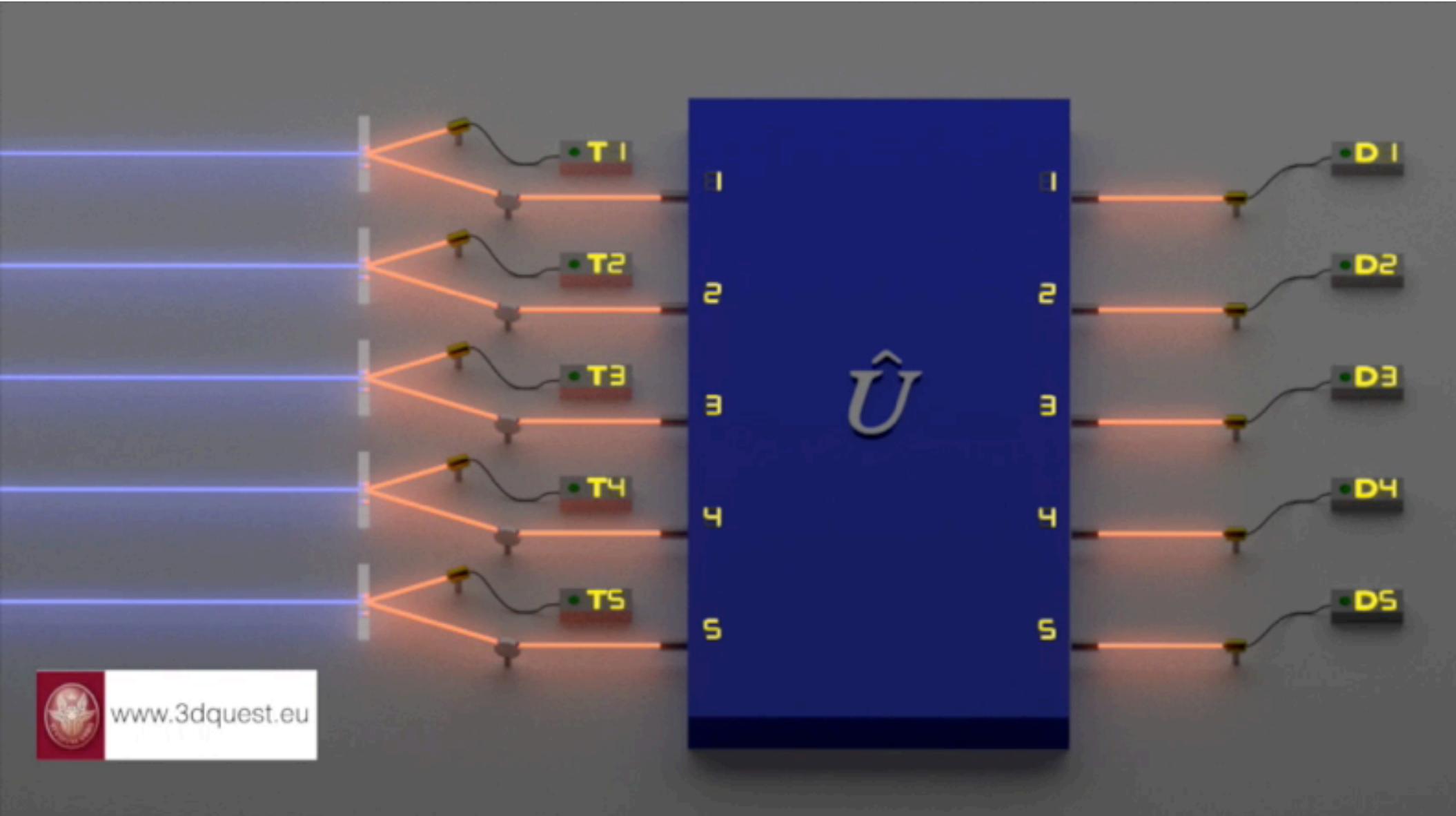
Probabilistic process

Probability of producing n photons
drops exponentially in n

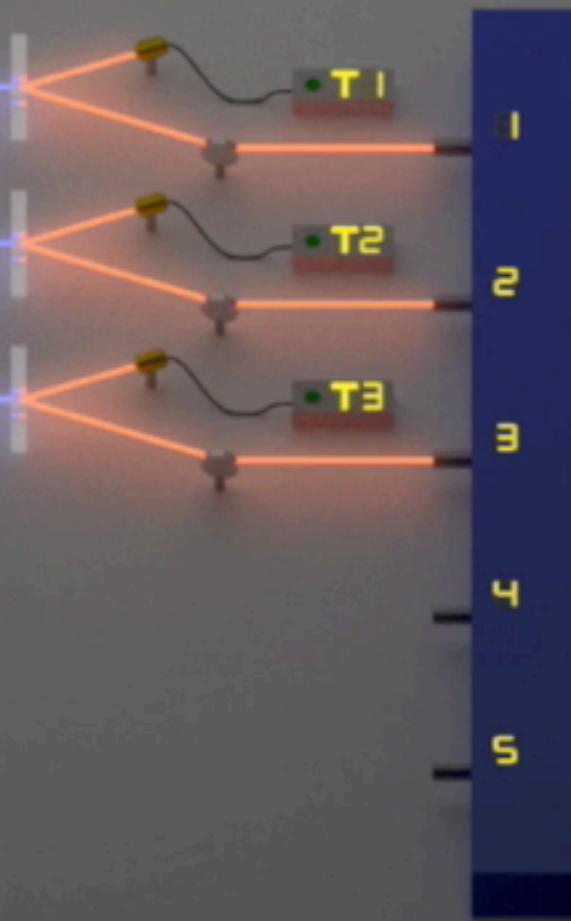
Low process efficiency, gain must be kept low
to prevent multi-photon events

Is it possible to devise a generalized Boson Sampling problem?

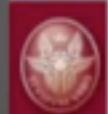
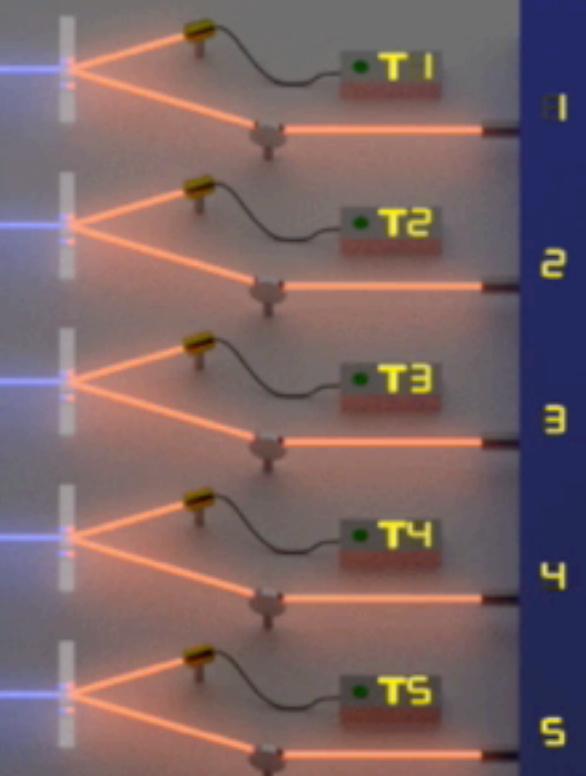
Same computational complexity of conventional Boson Sampling



BOSON SAMPLING



SCATTERSHOT BOSON SAMPLING



www.3dquest.eu

Generated events



Generated events



Experimental scattershot boson sampling

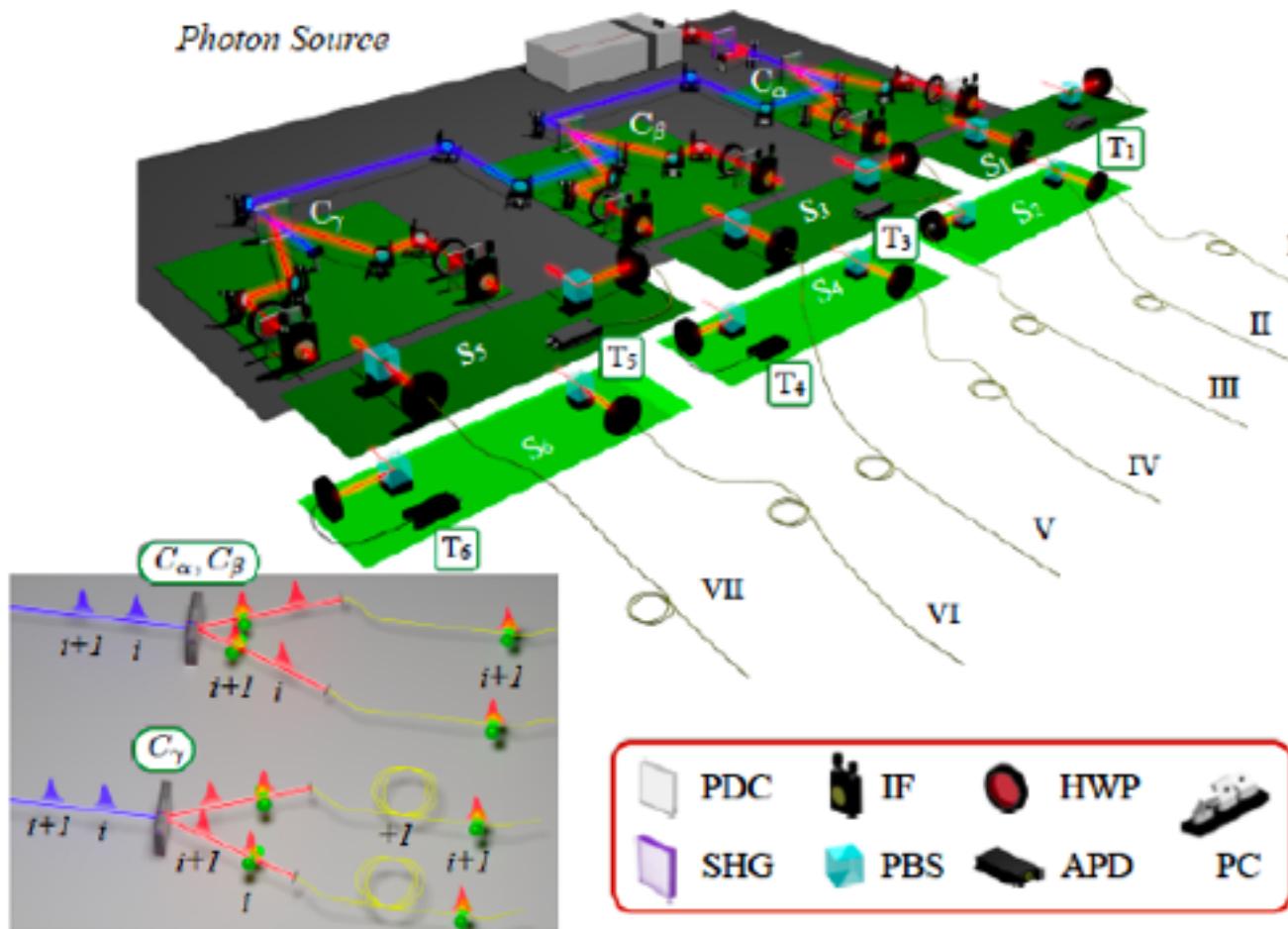
Photon source



Input state preparation



Chip and detection

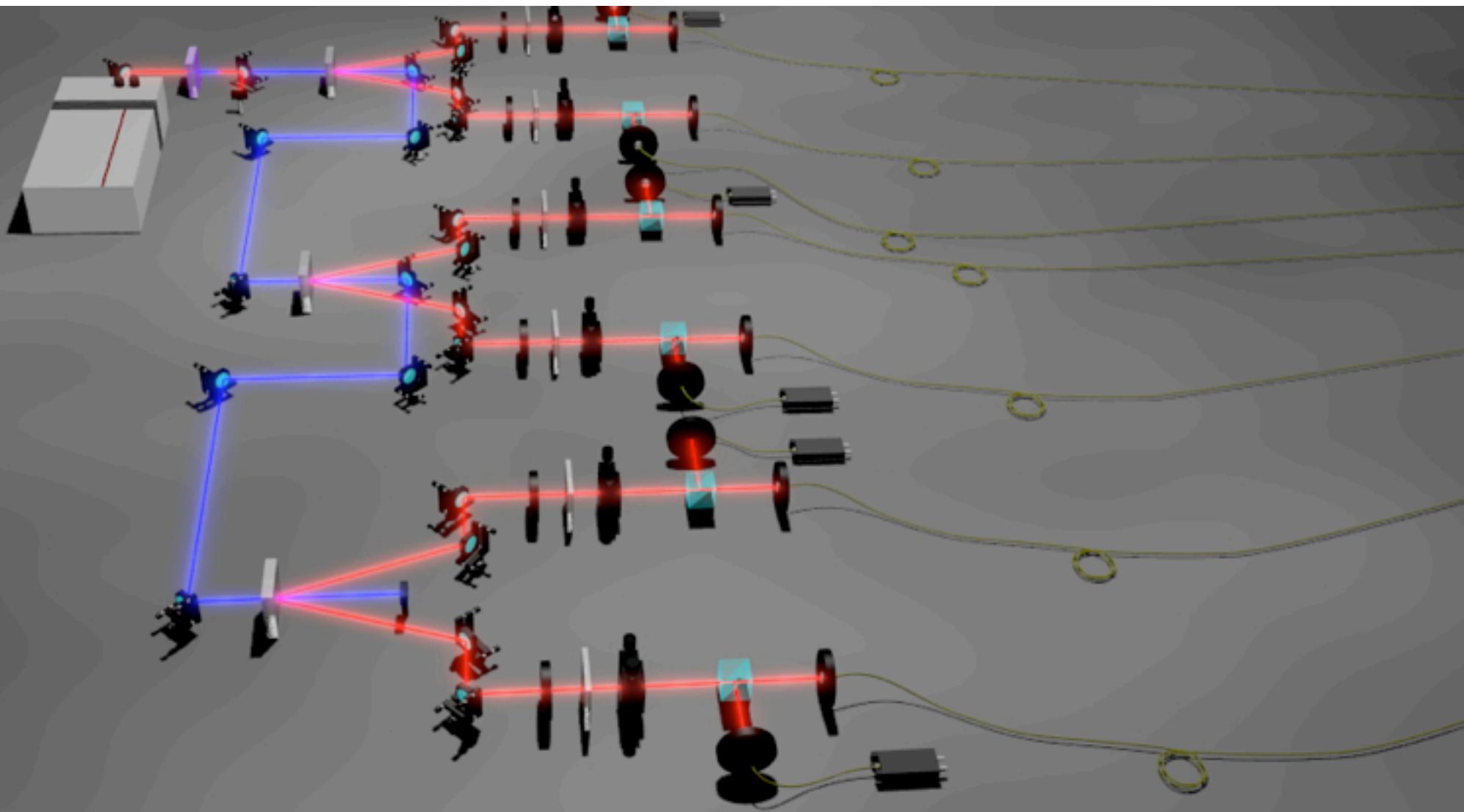


6 different parametric
down-conversion sources
(S₁-S₆)



3 physical crystals and
separation by polarization

Interference between photons
generated from two
subsequent laser pulses



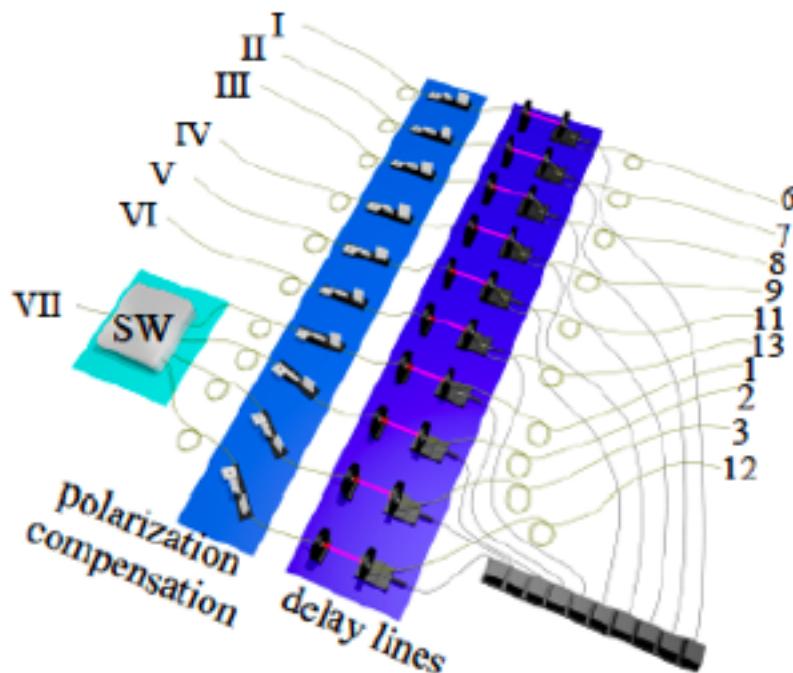
M. Bentivegna, N. Spagnolo, C. Vitelli, F. Flamini, N. Viggianiello, L. Latmiral, P. Mataloni, D. J. Brod, E. F. Galvao, A. Crespi, R. Ramponi, R. Osellame, and F. Sciarrino,
“Experimental scattershot boson sampling”, *Science Advances* **1**, e1400255 (2015).

Experimental setup: preparation

Photon source

Input state preparation

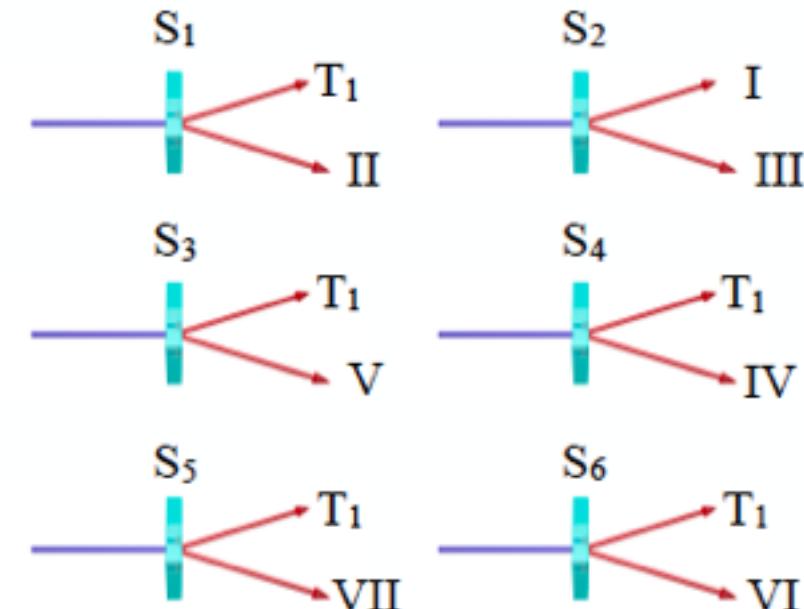
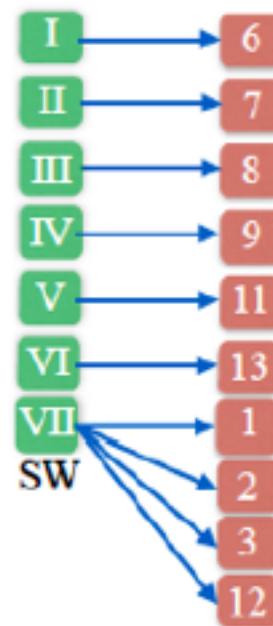
Chip and detection



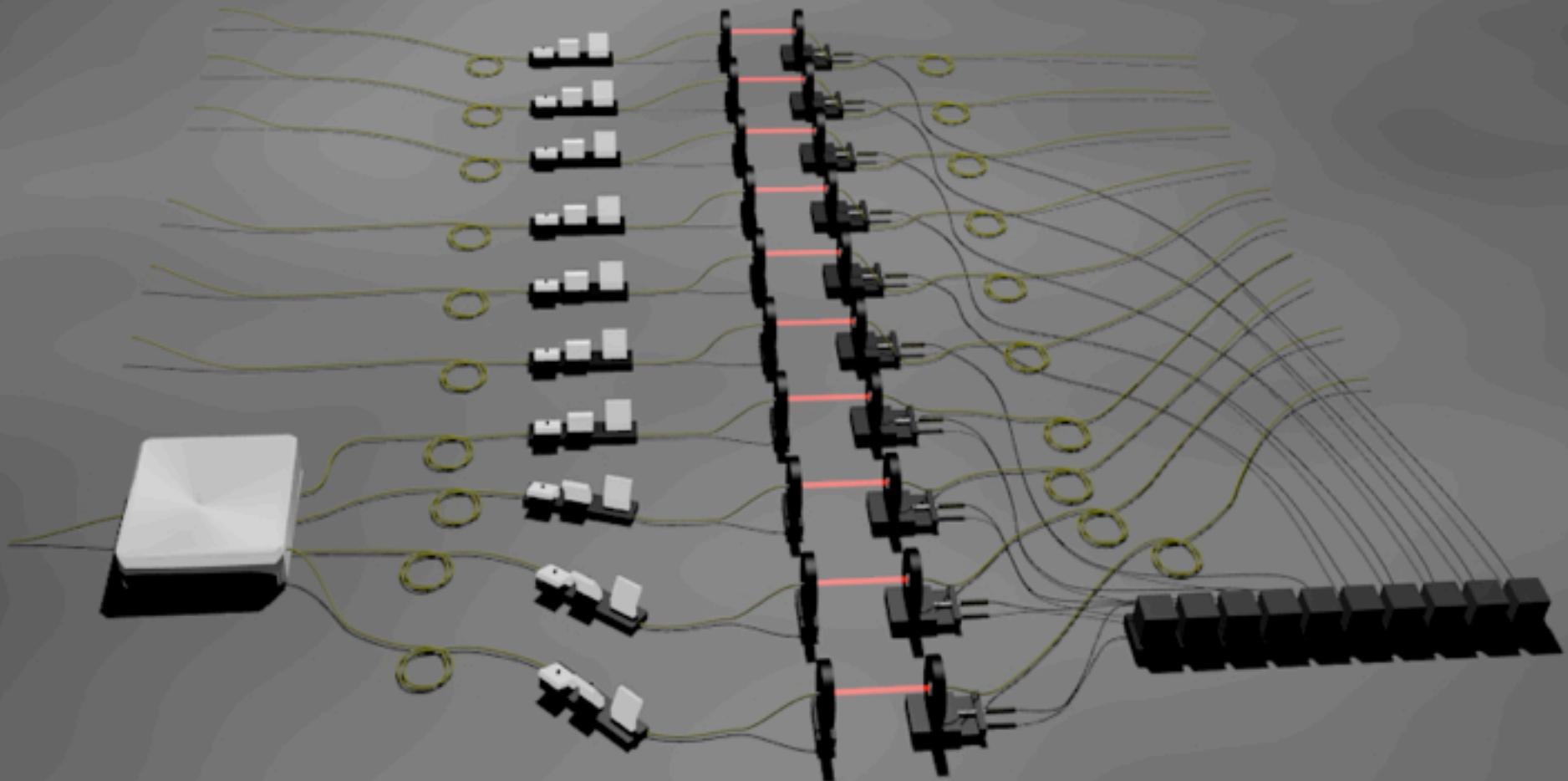
Three photon events:

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

Input state preparation



Input randomness further enhanced by sequential switching of photon VII



M. Bentivegna, N. Spagnolo, C. Vitelli, F. Flamini, N. Viggianiello, L. Latmiral, P. Mataloni, D. J. Brod, E. F. Galvao, A. Crespi, R. Ramponi, R. Osellame, and F. Sciarrino,
“Experimental scattershot boson sampling”, *Science Advances* **1**, e1400255 (2015).

Experimental setup: chip and detection

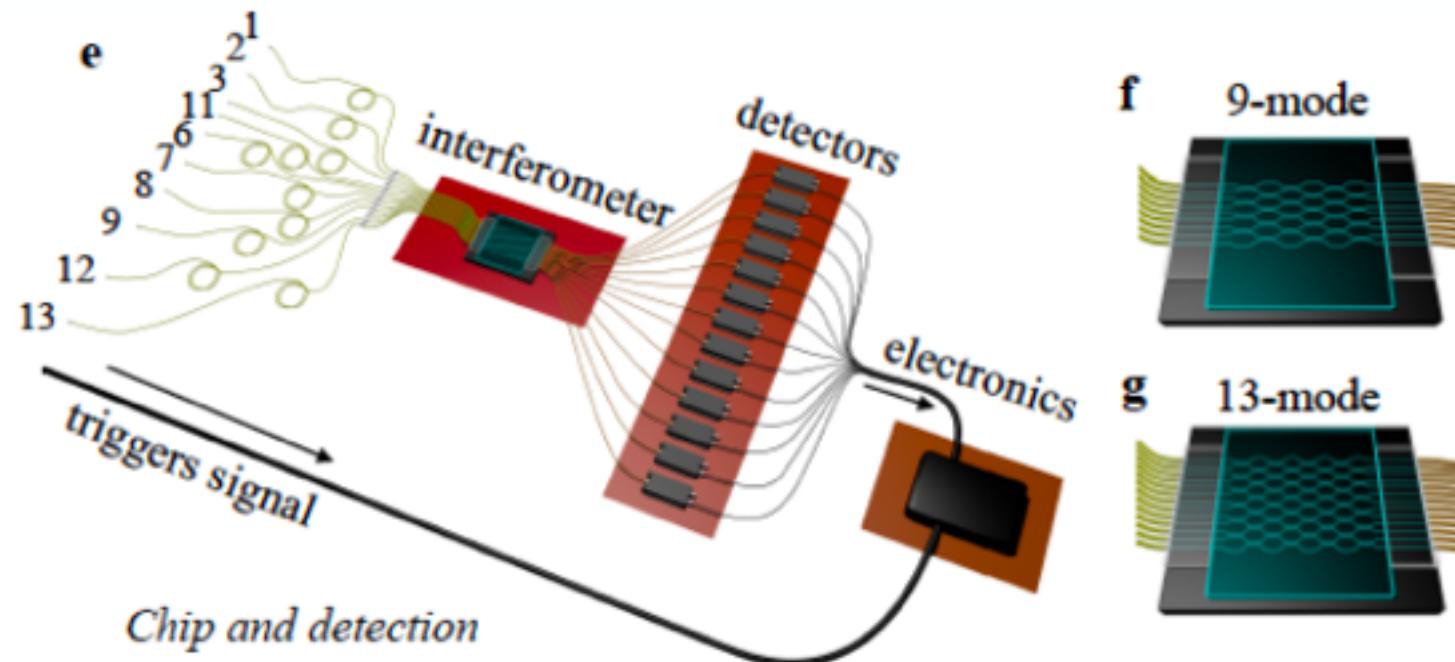
Photon source



Input state preparation



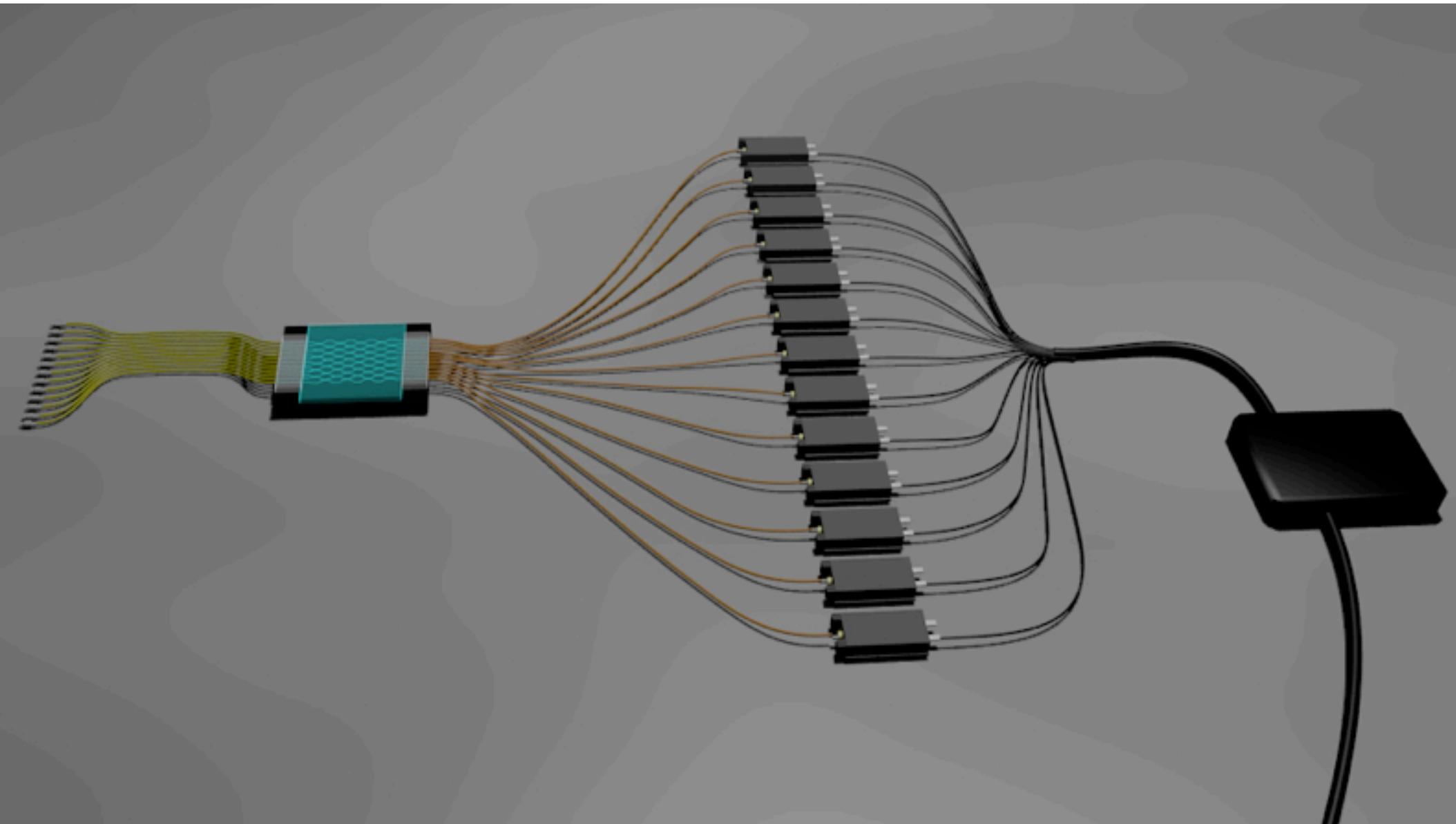
Chip and detection



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, N. Spagnolo, C. Vitelli, F. Flamini, N. Viggianiello, L. Latmiral, P. Mataloni, D. J. Brod, E. F. Galvao, A. Crespi, R. Ramponi, R. Osellame, and F. Sciarrino,
“Experimental scattershot boson sampling”, *Science Advances* **1**, e1400255 (2015).

Experimental setup: generation

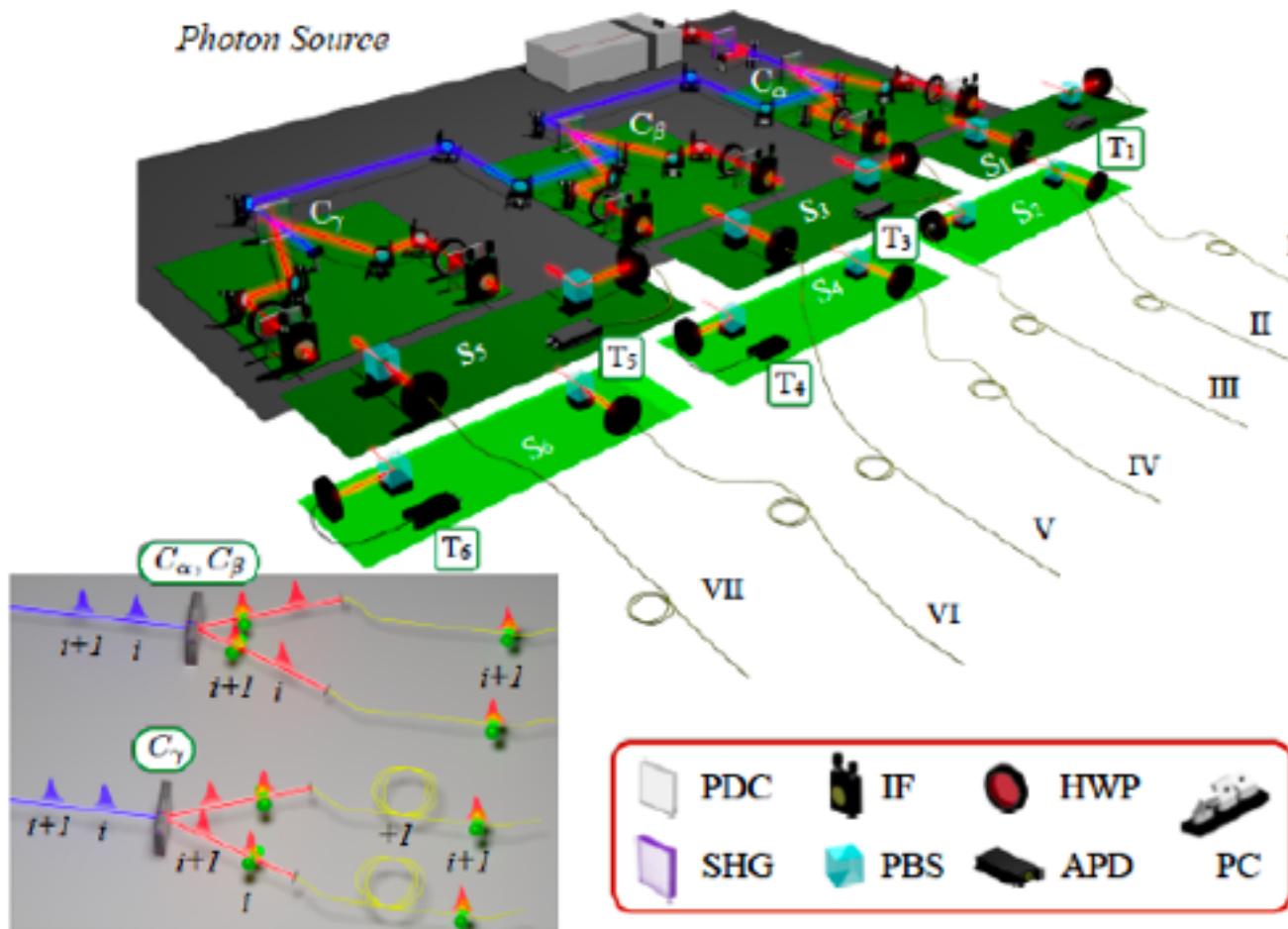
Photon source



Input state preparation



Chip and detection



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



3 physical crystals and
separation by polarization

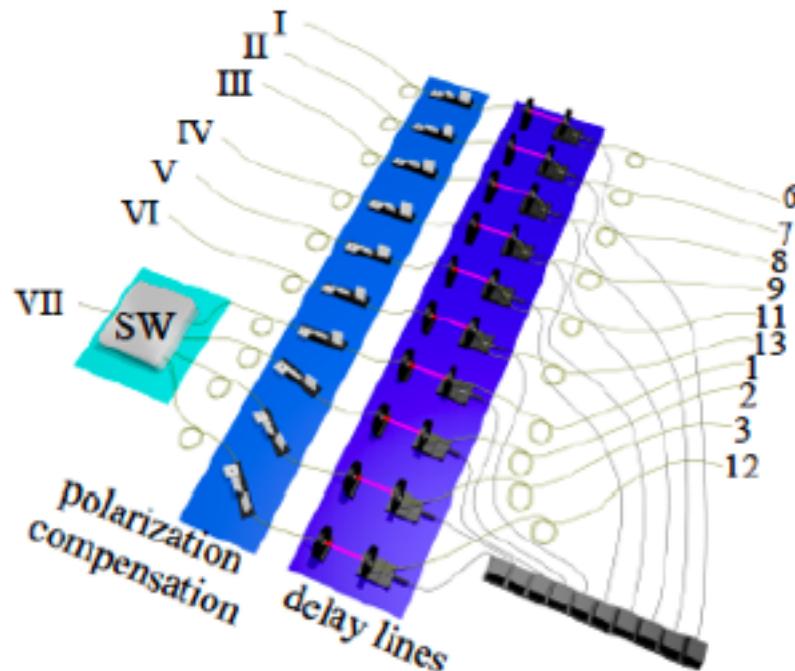
Interference between photons
generated from two
subsequent laser pulses

Experimental setup: preparation

Photon source

Input state preparation

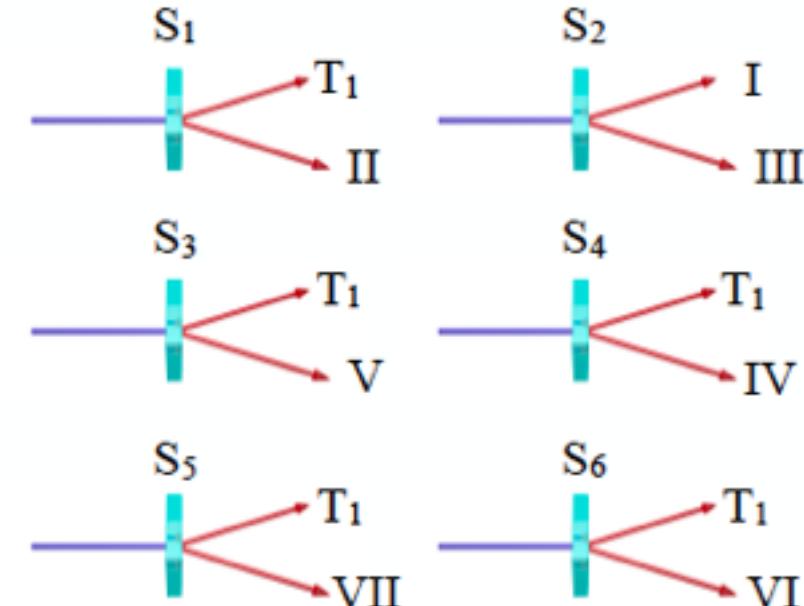
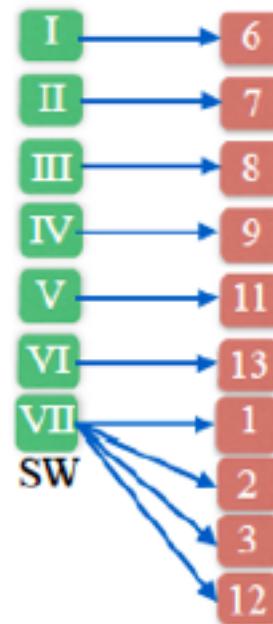
Chip and detection



Three photon events:

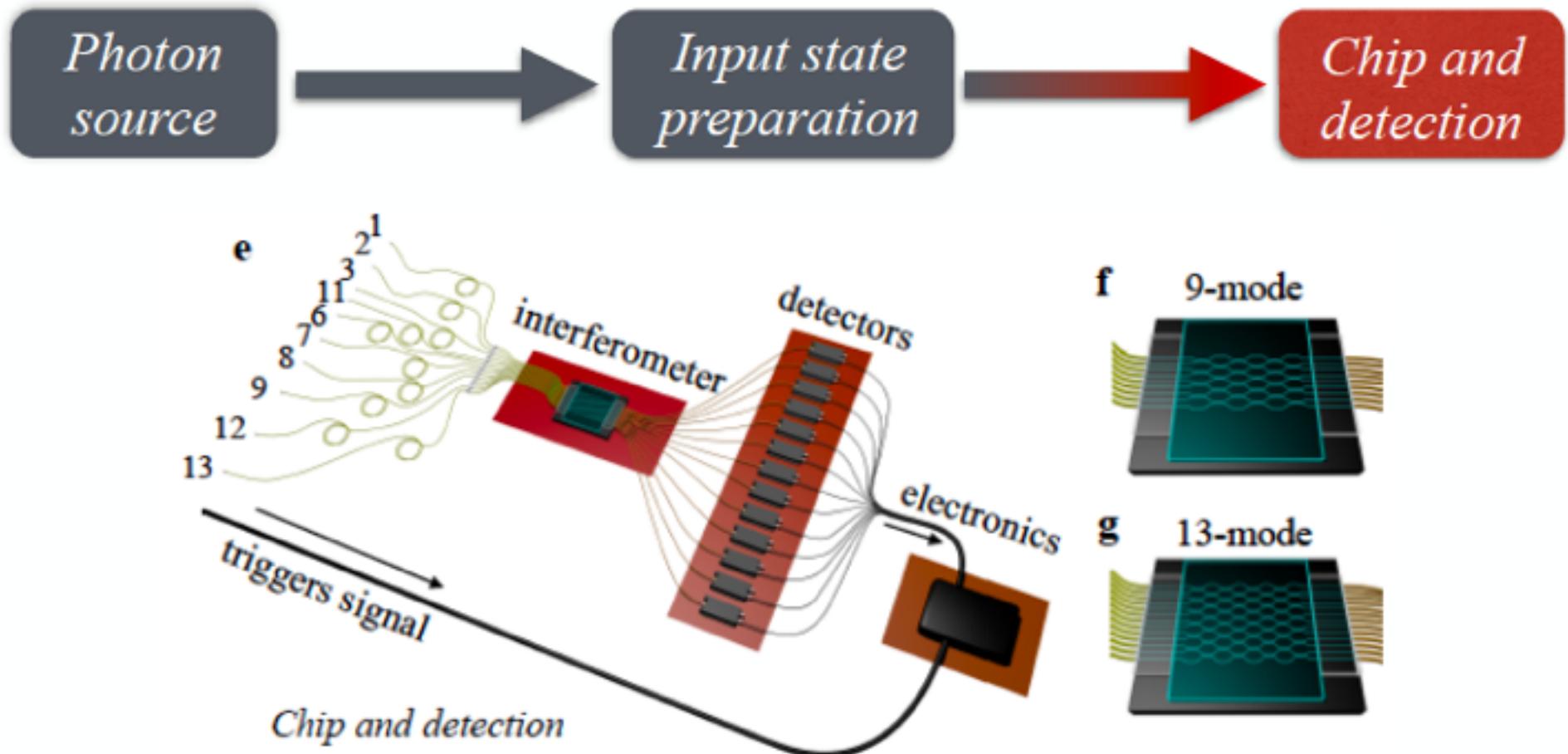
- 1) Photon I (input 6) [fixed]
- 2) Photon III (input 8) [fixed]
- 3) Random input heralded by T_i

Input state preparation



Input randomness further enhanced by sequential switching of photon VII

Experimental setup: chip and detection



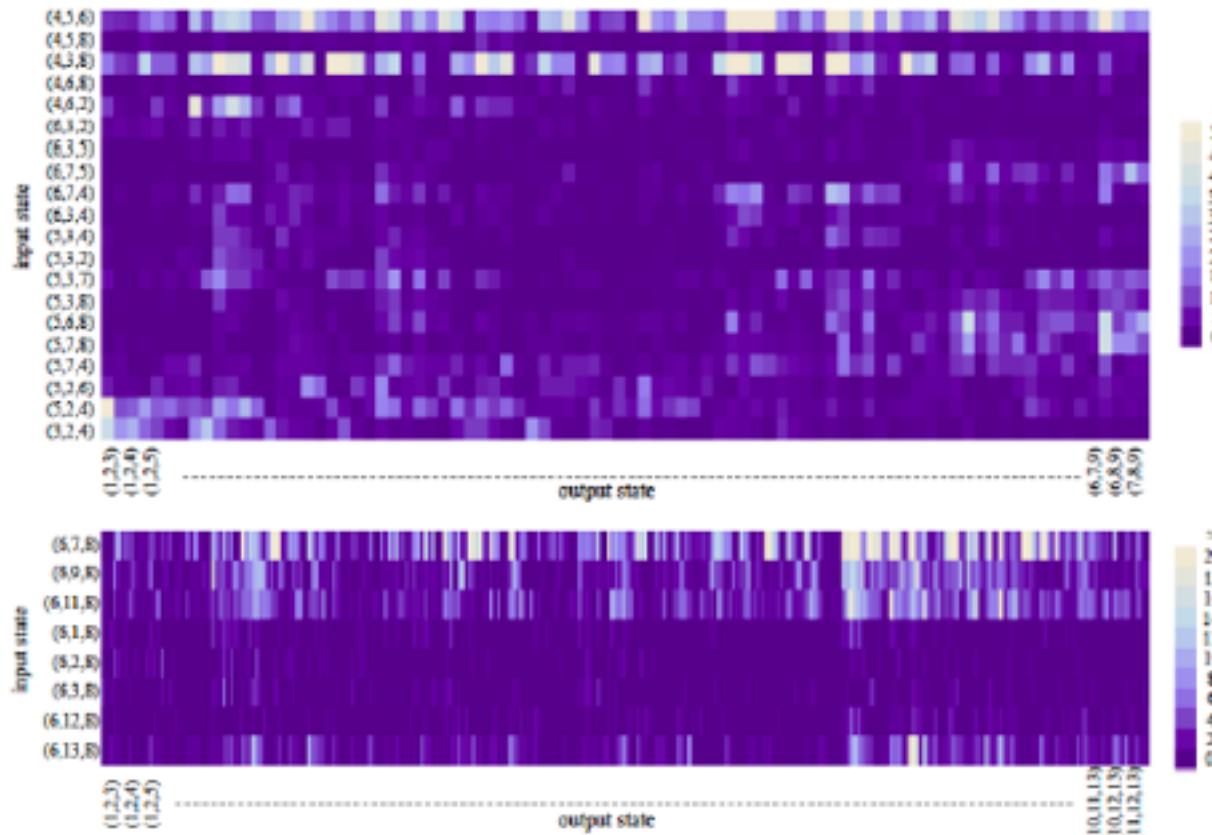
Evolution through $m=9$ and $m=13$ interferometers with random (but known) structure

Coincidence detection for:

Three-photon events with one heralding trigger
Two-photon events with two heralding triggers

Scattershot – sampling with random input

Three-photon events



9-mode interferometer

13-mode interferometer

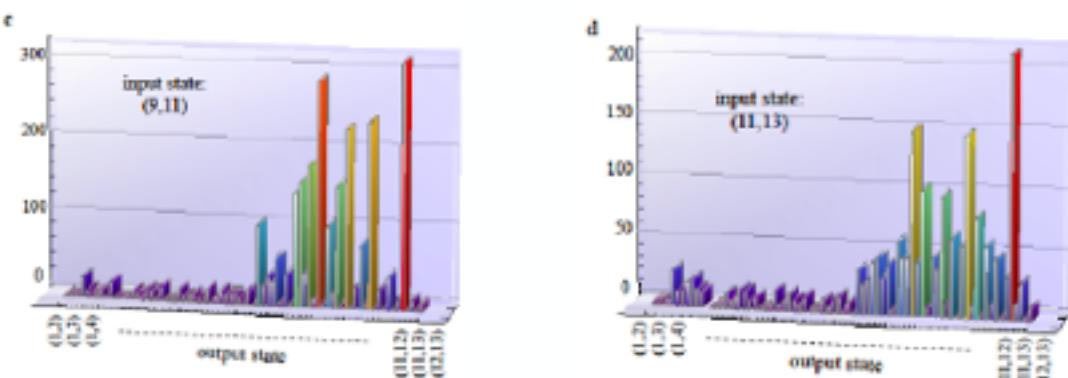
Number of input/output configurations

$m=9$ interferometer
2288 combinations

$m=13$ interferometer
1680 combinations

Few events per input/
output configurations

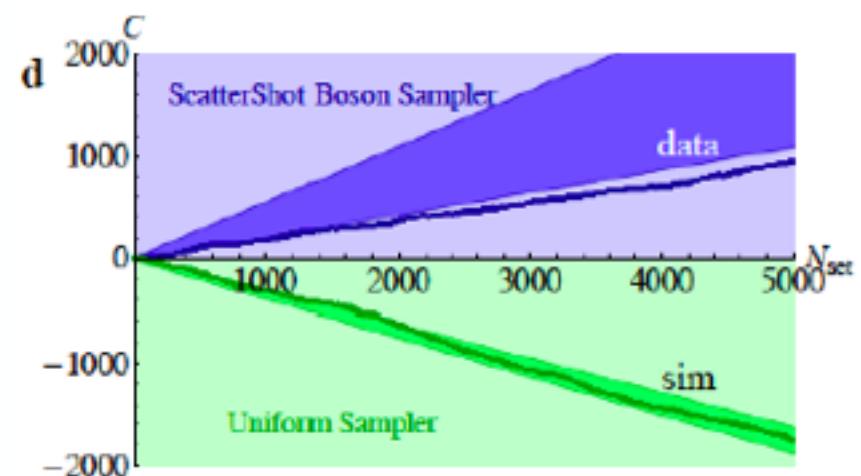
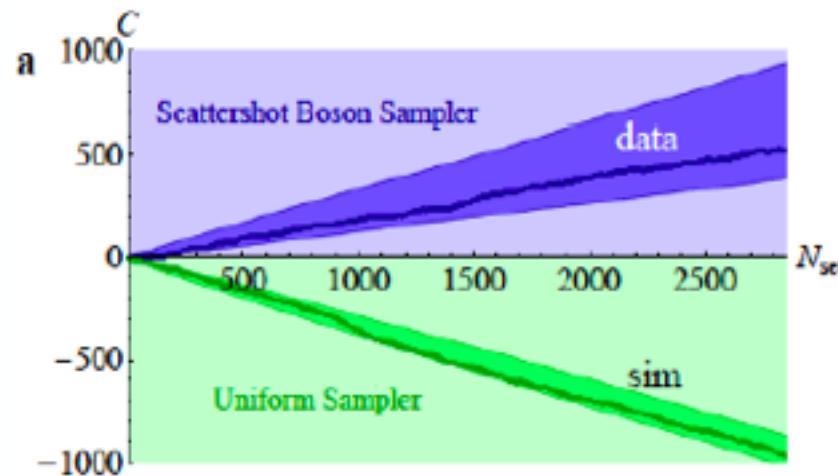
Two-photon events



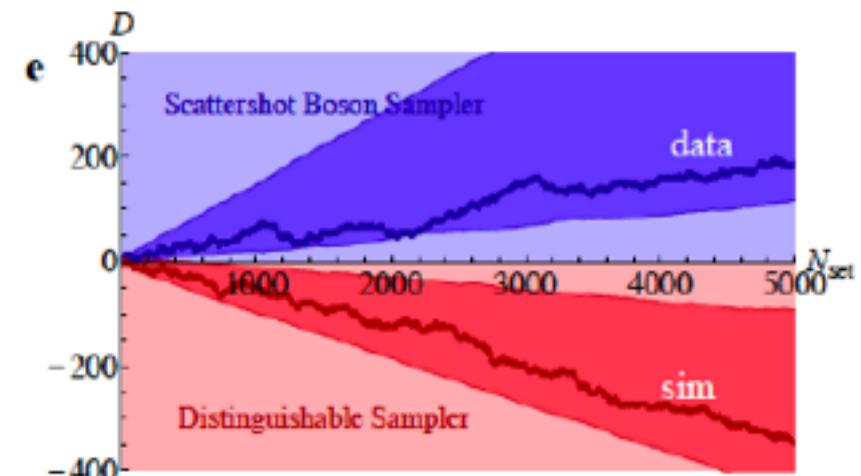
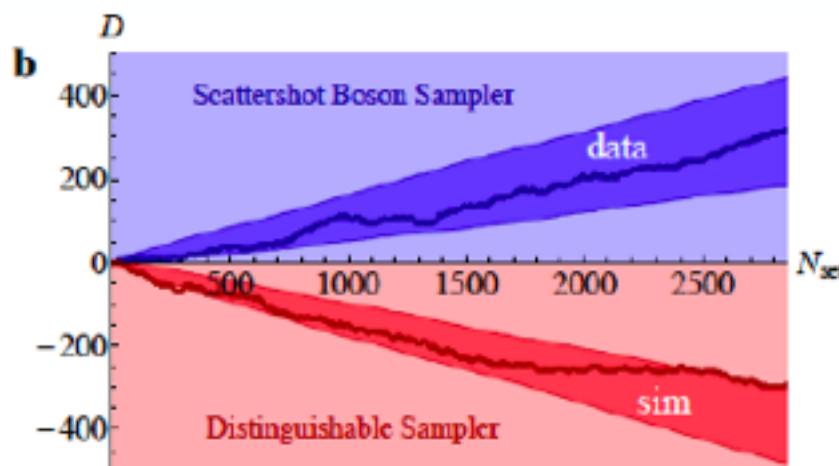
Data with three-photon and
two-photon input collected
simultaneously

Validation of Scattershot Boson Sampling

Validation against the uniform distribution with the Aaronson-Arkhipov test



Validation against distinguishable photons with shot-by-shot likelihood ratio test



Data can be validated against a first set of alternative hypothesis

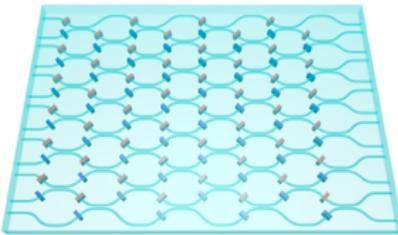
Witness of genuine multi-photon interference

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

Quantum certification of Boson Sampling..

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

Boson Sampling with random unitaries:
output states hard to predict..



Fourier matrices with m modes: $U_{l,q}^{Fou} = \frac{1}{\sqrt{m}} e^{i \frac{2\pi l q}{m}}$

Quantum suppression law (forbidden output state)
generalization of the Hong-Ou-Mandel effect to multiport device

1) Efficient approach for increasing n and m

- many output states are suppressed
- computationally easy to predict which states are suppressed

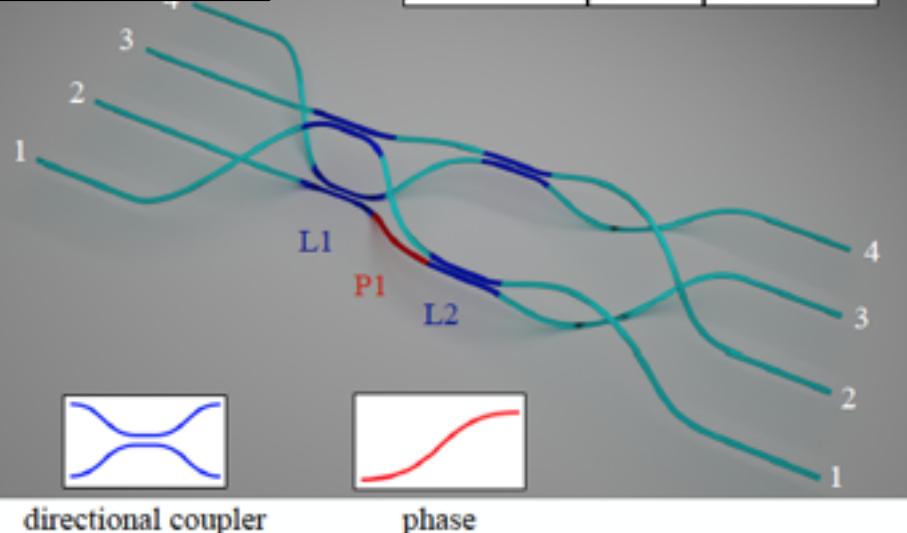
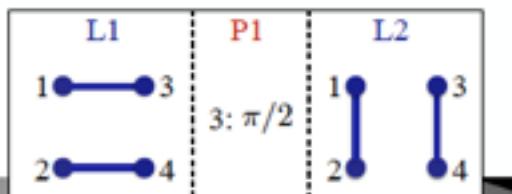
2) Stringent approach

- genuine n-photon quantum interference

Theoretical proposal - *Stringent and efficient assessment of Boson-Sampling devices*
M. Tichy, K. Mayer, A. Buchleitner, K. Mølmer, *PRL* **113**, 020502 (2014)

Implementation of Fast Fourier Transform with 3D-integrated photonics

4 modes
Fast Fourier
Transform



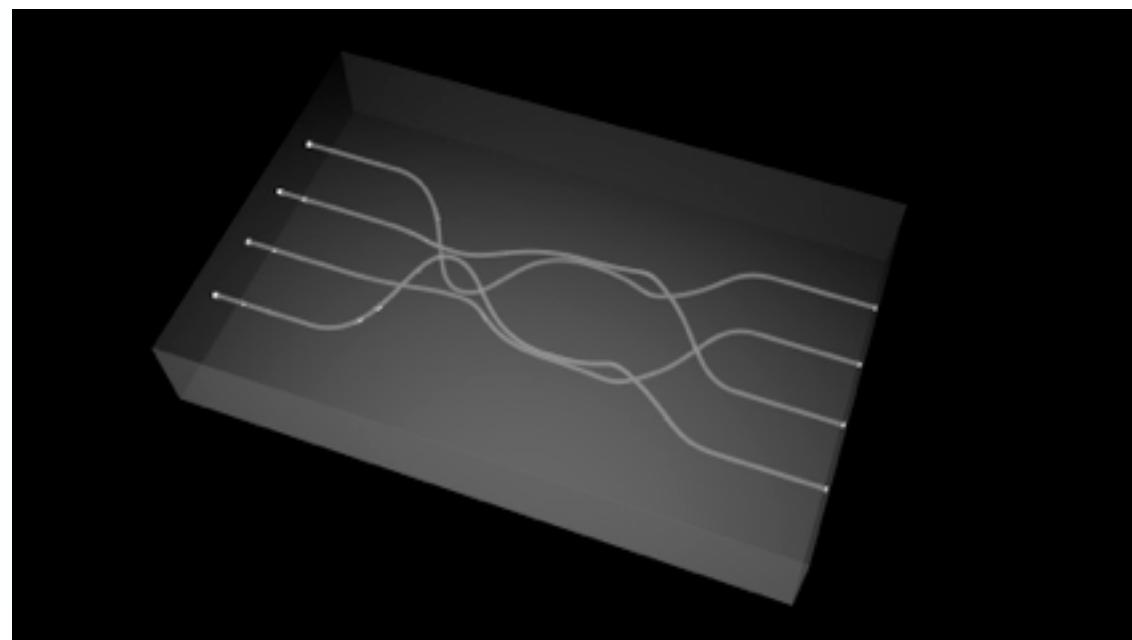
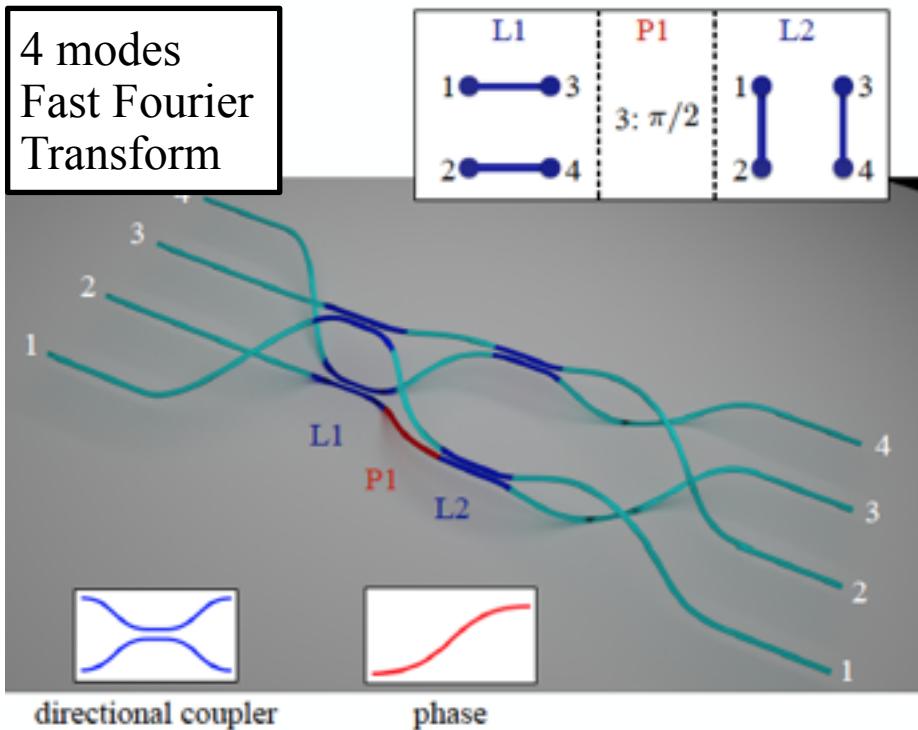
directional coupler



phase

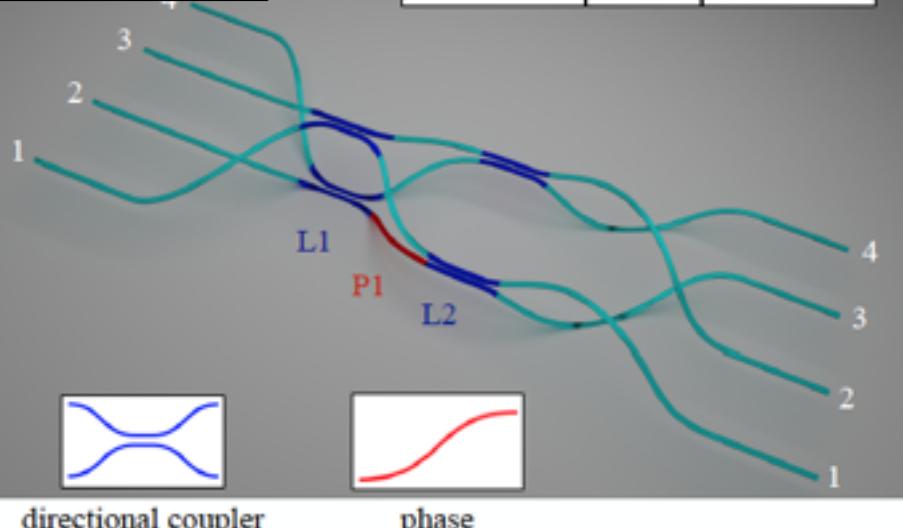
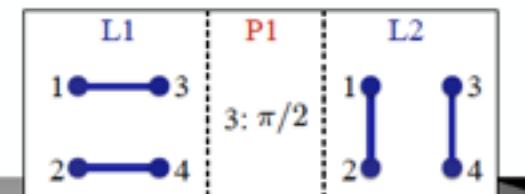
Crespi, Osellame, Ramponi, Bentivegna, Flaminii, Spagnolo, Viggianiello, Innocenti, Mataloni, and Sciarrino
Quantum suppression law in a 3-D photonic chip implementing the Fast Fourier Transform,
Nature Communications 7, 10469 (2016).

Implementation of Fast Fourier Transform with 3D-integrated photonics

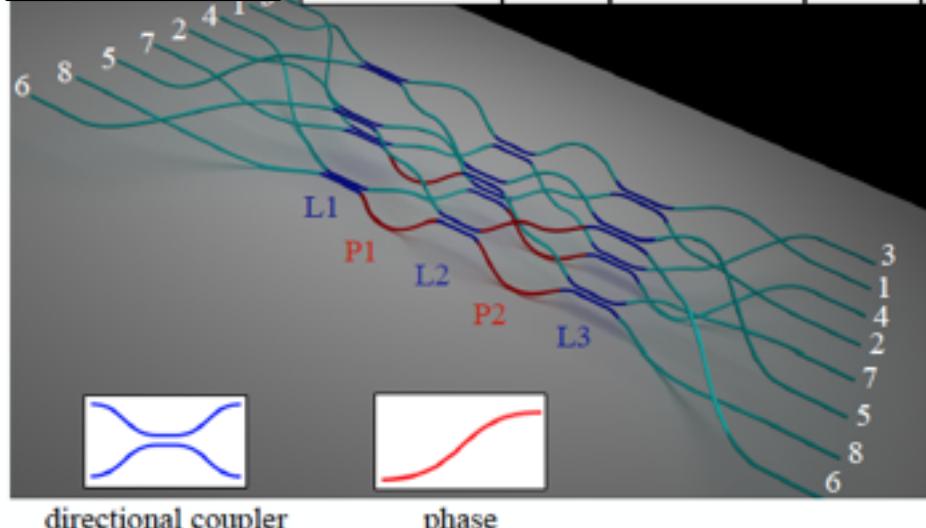
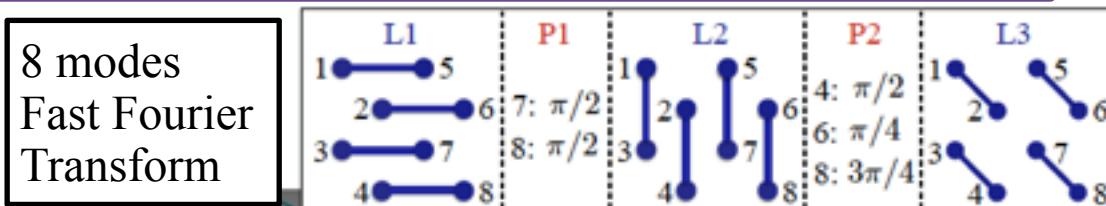


Implementation of Fast Fourier Transform with 3D-integrated photonics

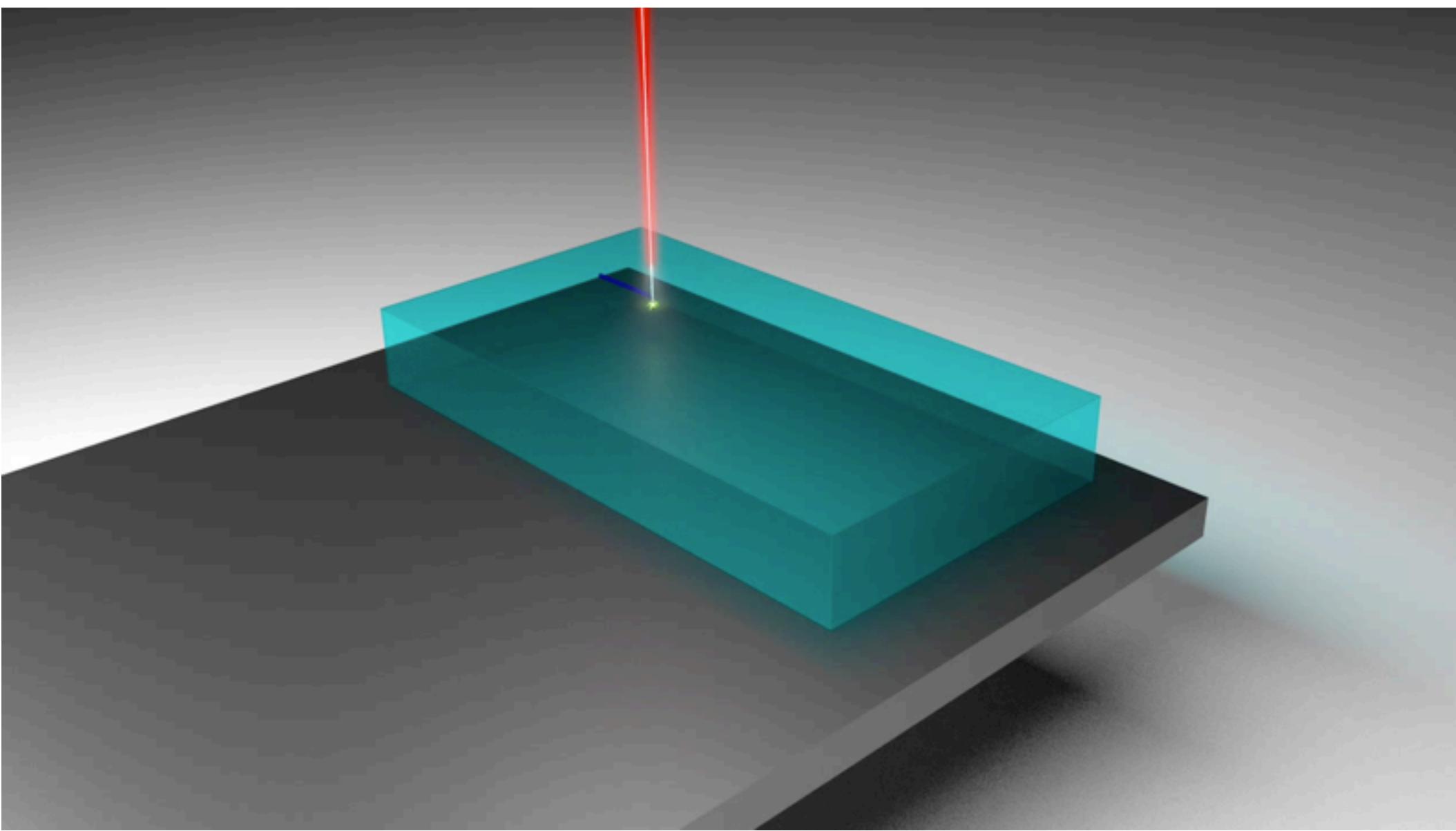
4 modes
Fast Fourier
Transform



8 modes
Fast Fourier
Transform

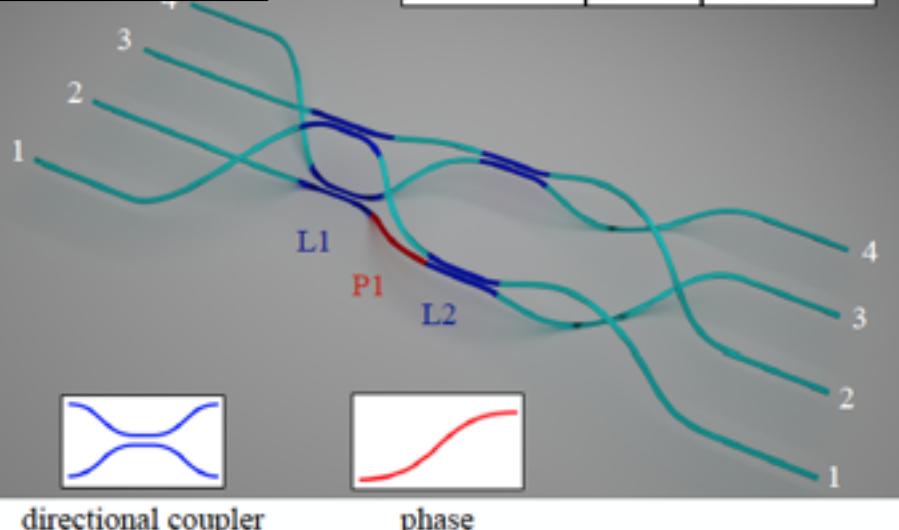
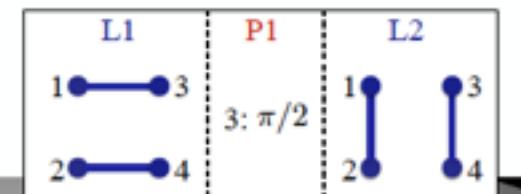


Scalable approach for the implementation of fast Fourier transform using 3-D photonic integrated interferometers fabricated via femtosecond laser writing technique.

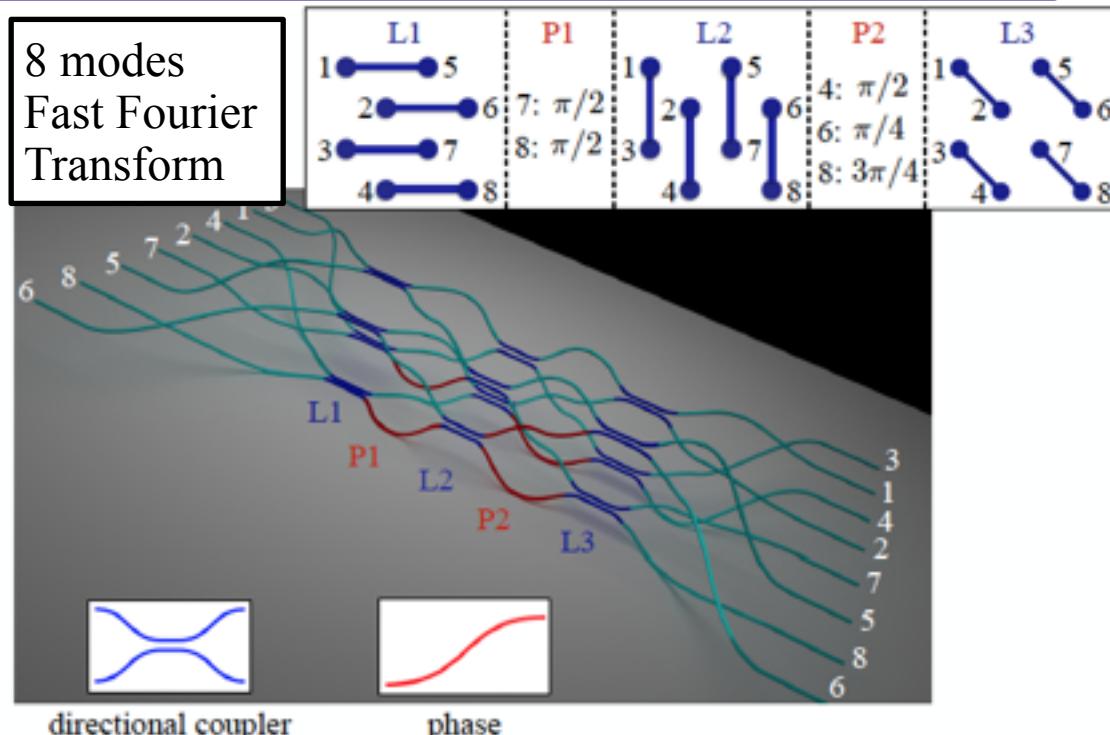


Implementation of Fast Fourier Transform with 3D-integrated photonics

4 modes
Fast Fourier
Transform

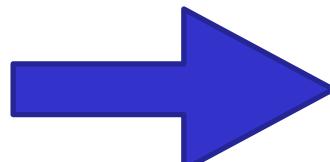


8 modes
Fast Fourier
Transform



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)

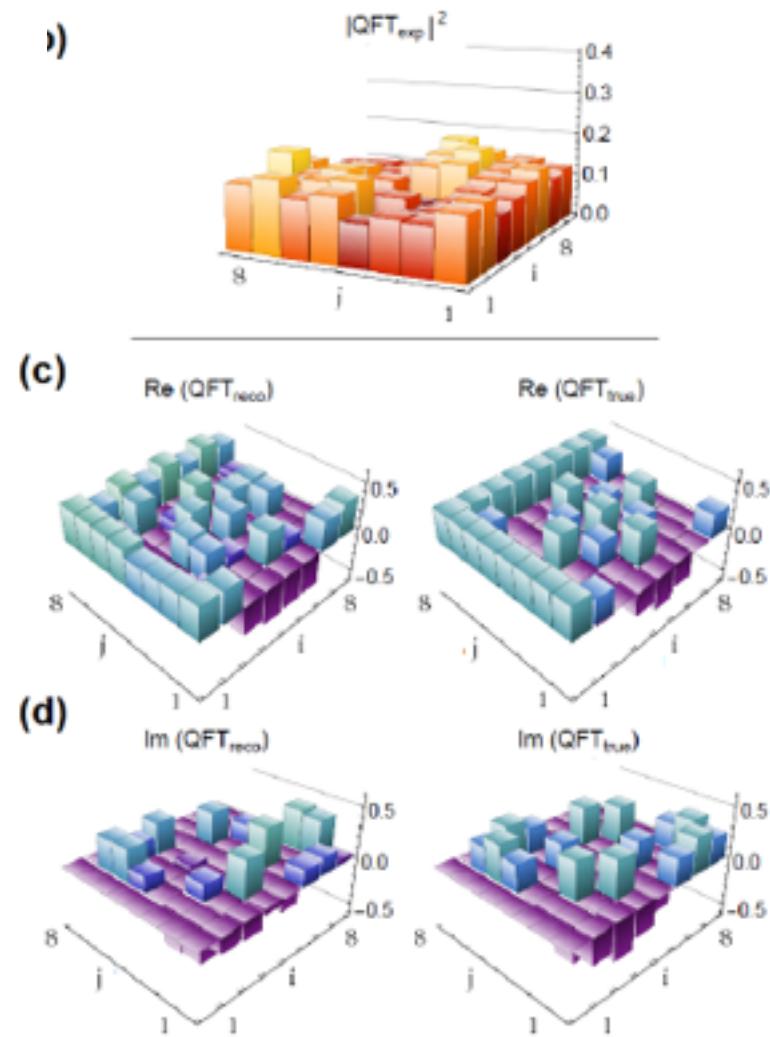
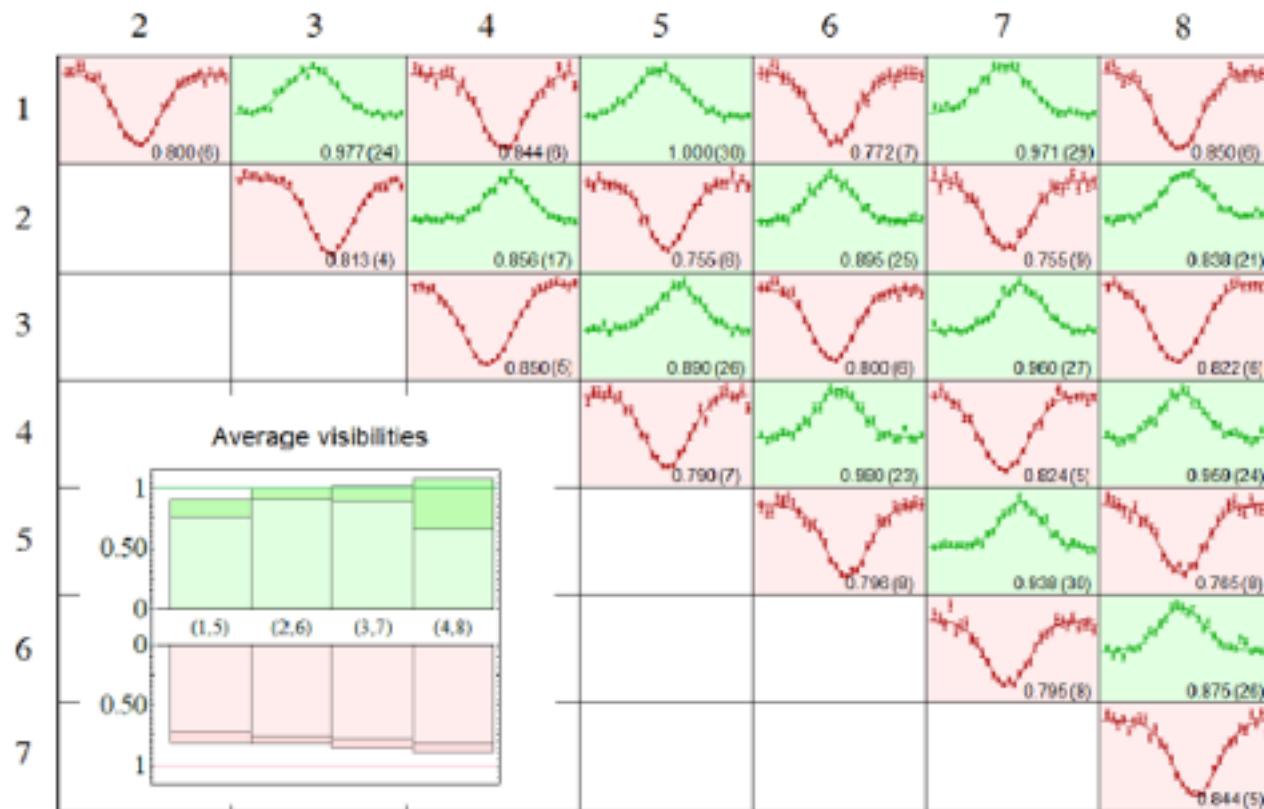


Quantum suppression law

Suppression of all output non-cyclic output states!

Quantum certification of Boson Sampling

$n=2$ photons over 8 modes Fast Fourier Transform

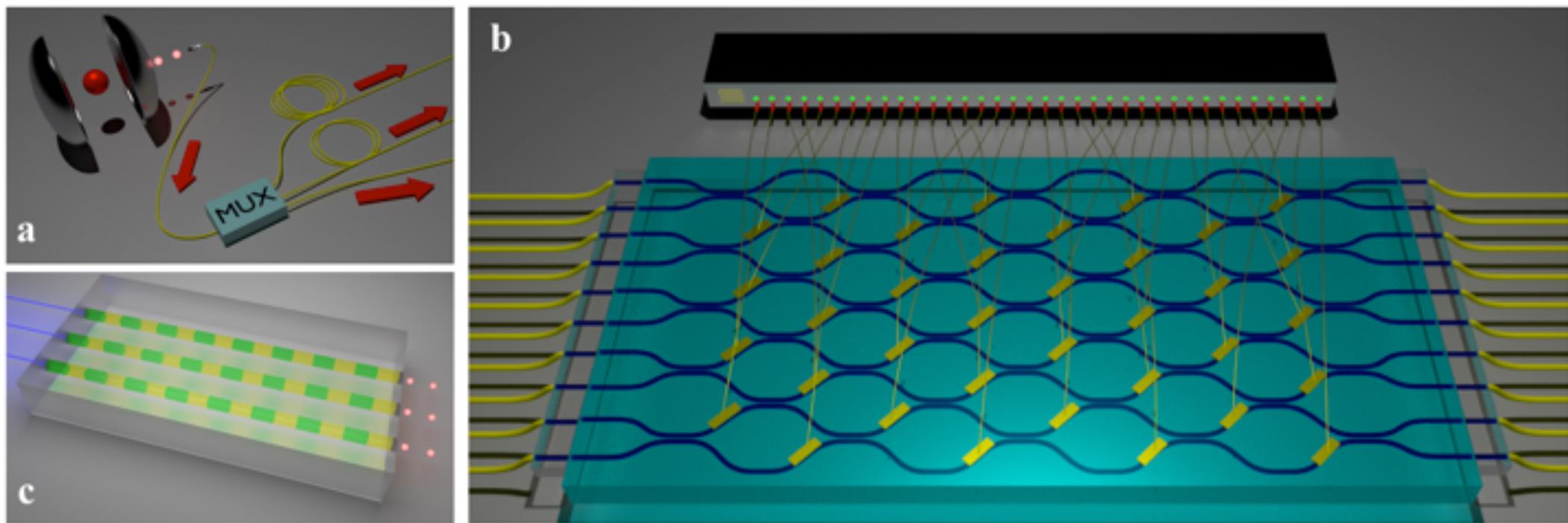


16 suppressed states over 28 output states

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

Paper	Group	Contents	Validation
Science 339, 794 (2013)	Brisbane, Boston	n=2,3 photons, m=6 modes - fiber	No
Science 339, 798 (2013)	Oxford	n=3 photons, m=6 modes + n=4 photons with (lower complexity) bunched input	No
Nat. Photon. 7, 540 (2013)	Vienna, Jena	n=3 photons, m=5 modes	No
Nat. Photon. 7, 548 (2013)	Roma, Milano, Niteroi	n=3 photons, m=5 modes Haar-Random unitary	No
PRL 111, 130503 (2013)	Roma, Milano, Niteroi	Bosonic Birthday paradox, and verification of full-bunching law	No
Nat. Photon. 8, 615 (2014)	Roma, Milano, Niteroi	n=3 photons, m=5,7,9,13 modes validation tests	Uniform distribution, distinguishable particles
Nat. Photon. 8, 621 (2014)	Bristol	n=3 + n=4,5 photons (subtracting bunching), m=21 qwalk n=3 photons in m=9 Haar Unitary	Uniform distribution, distinguishable particles
Phys. Rev. X 5, 041015 (2015)	Vienna, Jena	investigation on complexity with partial photon distinguishability, n=3 photons, m=5 modes	No
Science Advances 1, e1400255 (2015)	Roma, Milano, Niteroi	n=3 photons, m=9,13 modes scattershot of 8 input states	Uniform distribution, distinguishable particles
Science 349, 711 (2015)	Bristol	implementation of 6x6 fully reconfigurable circuit, Haar-random. n=3: zero-transmission in Fourier matrix n=6 with bunched input (2 modes)	Distinguishable particles
Nature Communications 7, 10469 (2016).	Roma, Milano	n=2 photons, m=4,8 modes suppression law in Fourier matrix with scalable 3D architecture	Distinguishable particles, mean-field state

Next platform... hybrid integrated quantum photonics



Near-optimal single-photon sources in the solid-state
arXiv: 1510.06499

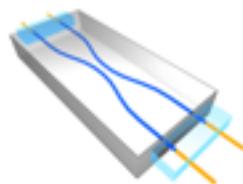
N. Somaschi^{1,}, V. Giesz^{1,*}, L. De Santis^{1,2*}, J. C. Loredo³, M. P. Almeida³, G. Hornecker^{4,5}, S. L. Portalupi¹, T. Grange^{4,5}, C. Anton¹, J. Demory¹, C. Gomez¹, I. Sagnes¹, N. D. Lanzillotti-Kimura¹, A. Lemaitre¹, A. Auffeves^{4,5}, A. G. White³, L. Lanco^{1,6} and P. Senellart^{1,7,*}*

Summary

Integrated devices

Polarization independent

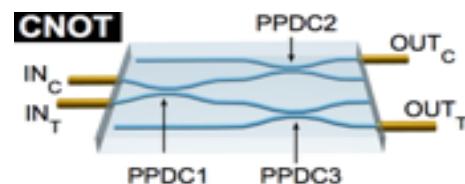
Beam Splitter



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

Polarization dependent

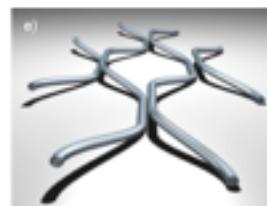
CNOT



Nat. Comm.
2, 566
(2011)

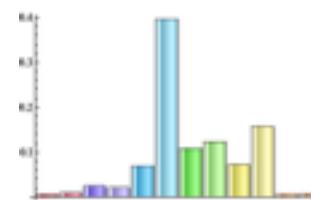
Quantum simulation

Ordered systems



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

Disordered Systems
Phase Control



Nat. Phot.
7, 322
(2013)



Bosons Sampling and Birthday Paradox

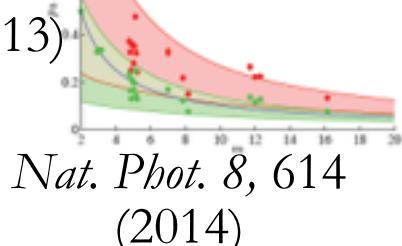
Boson Sampling
On chip

Nat. Phot. 7, 545 (2013)

Science Advances 1,
e1400255 (2015).

Validation

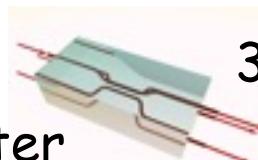
PRL
111, 130503
(2013)



3D devices

Integrated tritter

Nat. Com. 4, 1606
(2013)



3d interferometry
Sc. Reports 2,
862 (2012)

Integrated waveplates
Nat. Com. 5, 2549
(2014)

