Integrated quantum photonics

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“Information is physical”

R. Landauer

The processing of information is governed by the laws of physics.

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R. Landauer

The processing of information is governed by the laws of physics.

Quantum information

Challenges: from basic sciences

to emerging quantum technologies

- Fundamental physics:

  Test of non-locality, quantum contextuality

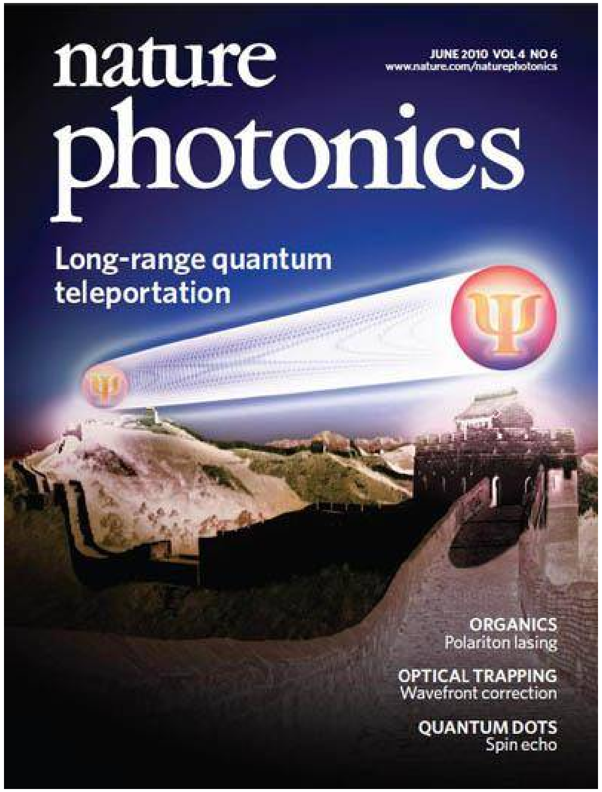
  Shed light on the boundary between classical and quantum world

  Exploiting quantum parallelism

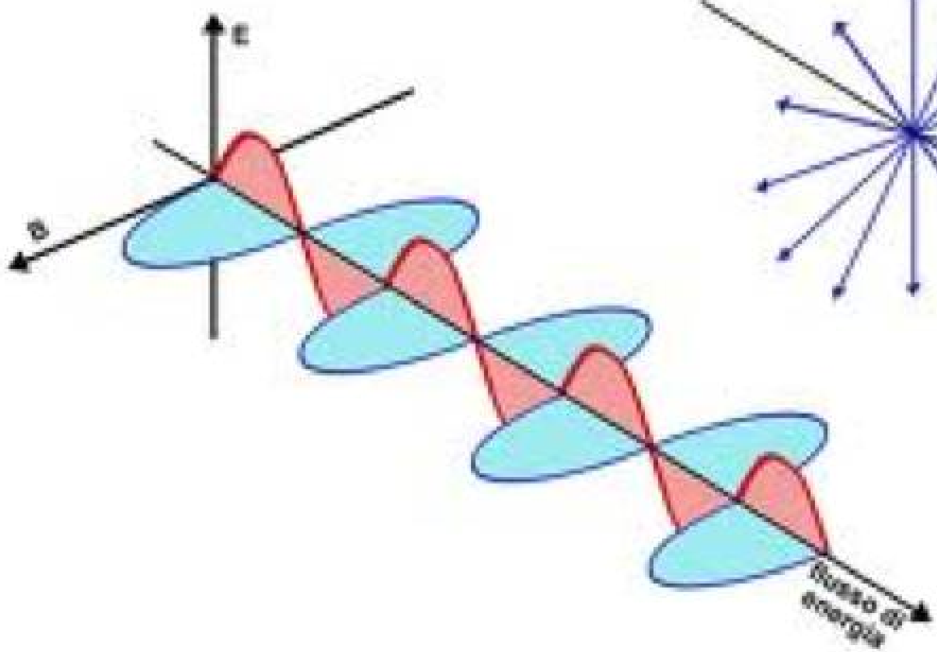
  to simulate quantum many-body systems

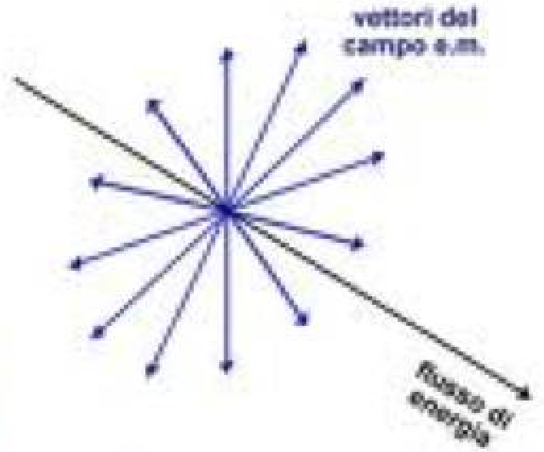
- New cryptographic protocols
- Quantum sensing: imaging,metrology
- Quantum computing

  quantum simulation



Polarization of light





Qubit → **Polarization of a single photon**

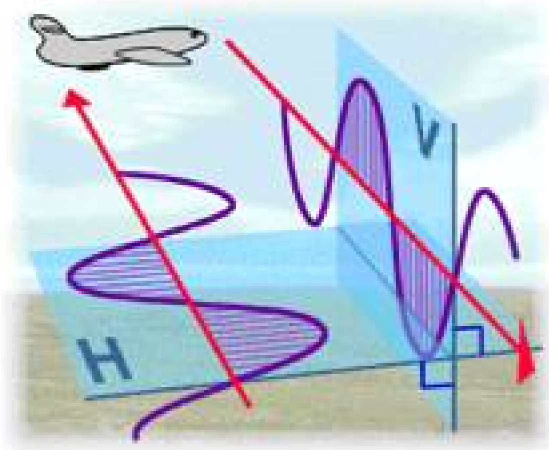
$$\alpha|0\rangle + \beta|1\rangle$$

$$\alpha|H\rangle + \beta|V\rangle$$

H: horizontal
V: vertical

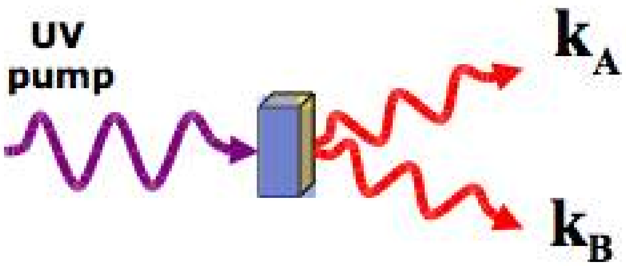
Polarization encoding of qubit

Polarization:
direction of oscillation
of the e.m. field

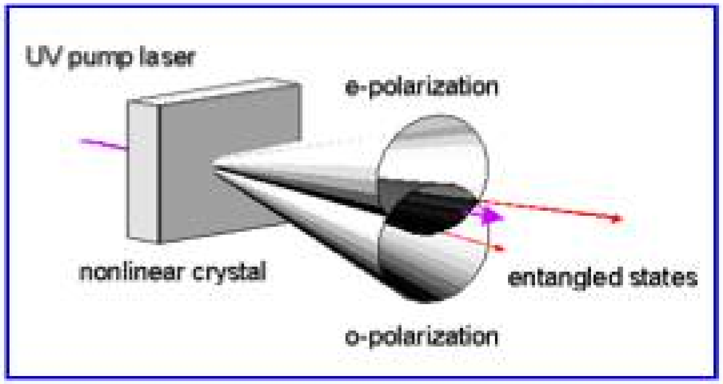


$$\alpha|0\rangle+\beta|1\rangle \longleftrightarrow \alpha|H\rangle+\beta|V\rangle$$

- Easy to manipulate: Waveplates and Polarizing Beam Splitters (PBSs)
- Easy to generate entangled states: Nonlinear crystals



- Many applications:
  - Quantum non-locality tests
  - Quantum cryptography
  - Quantum teleportation
  - Quantum metrology
  - Quantum computation
  - Simulation



$$|\psi^-\rangle = \frac{2}{\sqrt{2}}(|H\rangle|V\rangle - |V\rangle|H\rangle)$$

Integrated photonic quantum simulations

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

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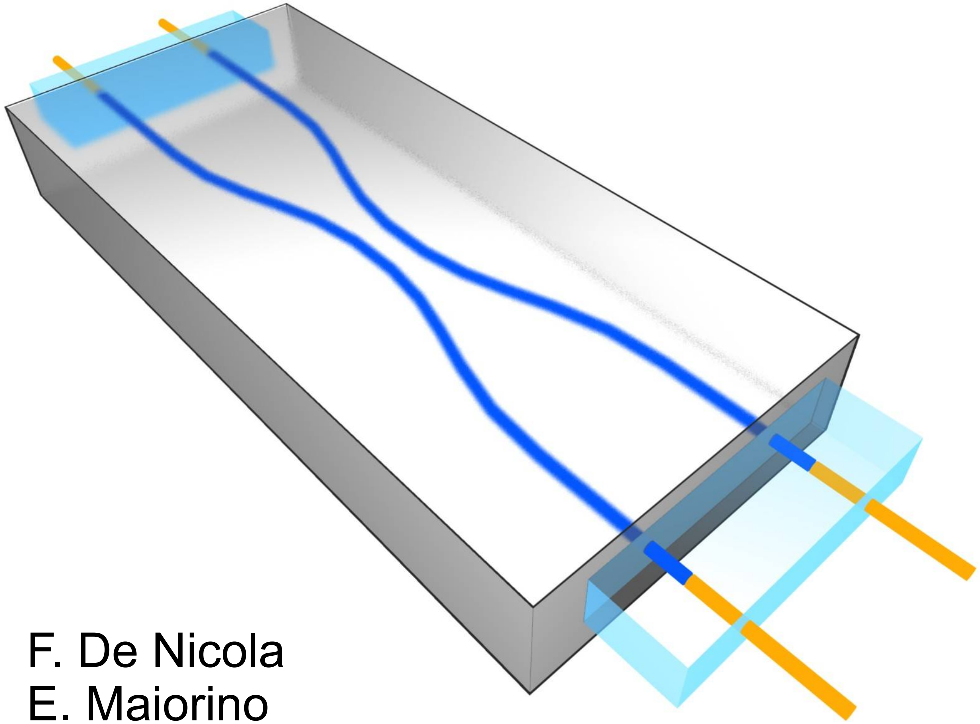
OTTICA



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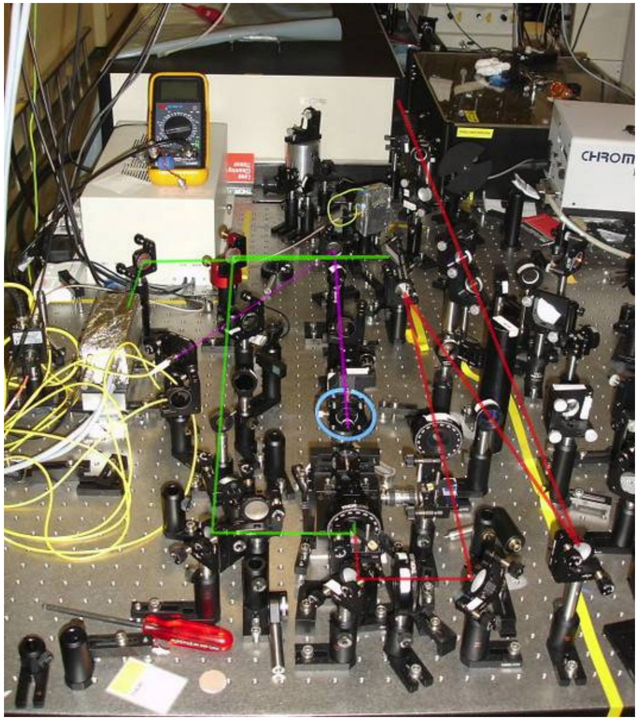
Integrated photonics:
Bulk optics limitations

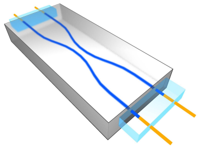
Photonic quantum technologies:
a promising experimental platform for quantum information processing

SETUP: COMPLEX OPTICAL INTERFEROMETERS

- ✓ Large physical size
- ✓ Low stability
- ✓ Difficulty to move forward applications outside laboratory



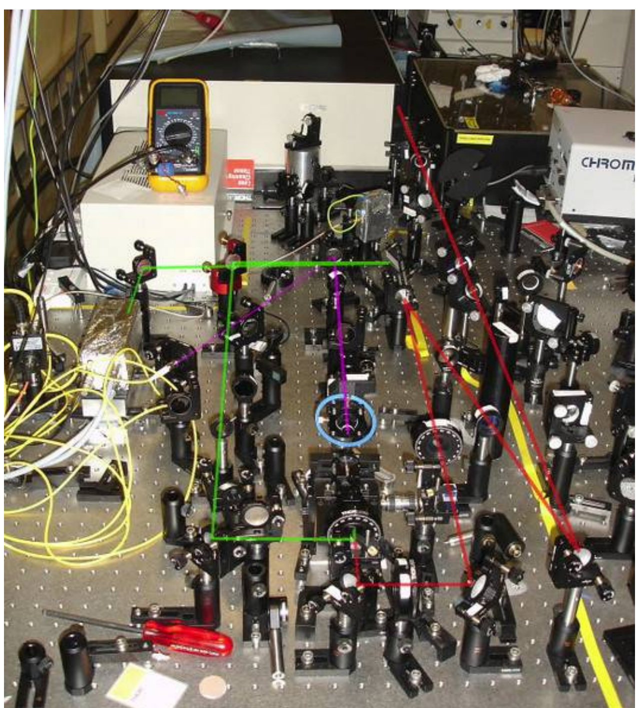
Possible solutions?



Integrated photonics: Bulk optics limitations

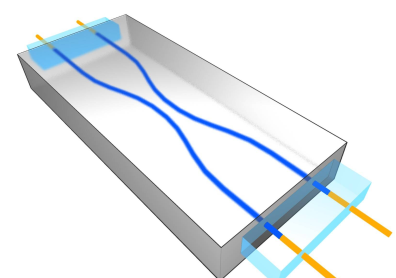
The main limitations of experiments realized with bulk optics are:

- ✓ Large physical size
- ✓ Low stability
- ✓ Difficulty to move forward applications outside laboratory



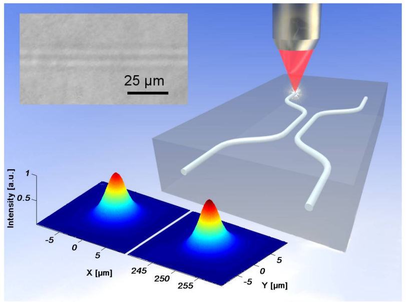
Possible solutions?

Integrated waveguide technology

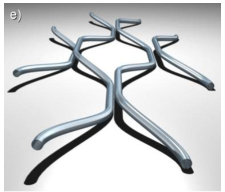


Summary

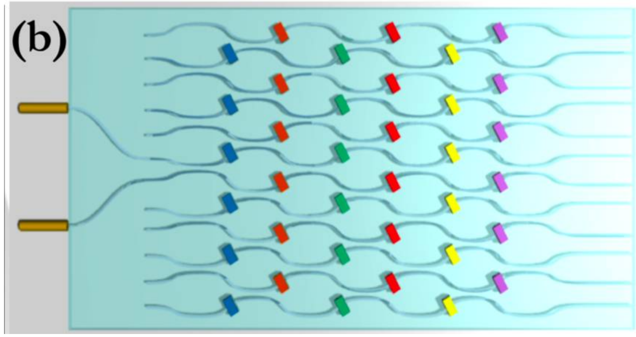
I) Laser writing techniques
First step: beamsplitters



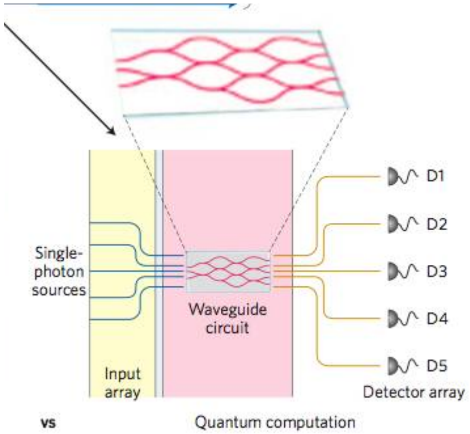
II) Ordered quantum walk



III) Simulation of disordered systems

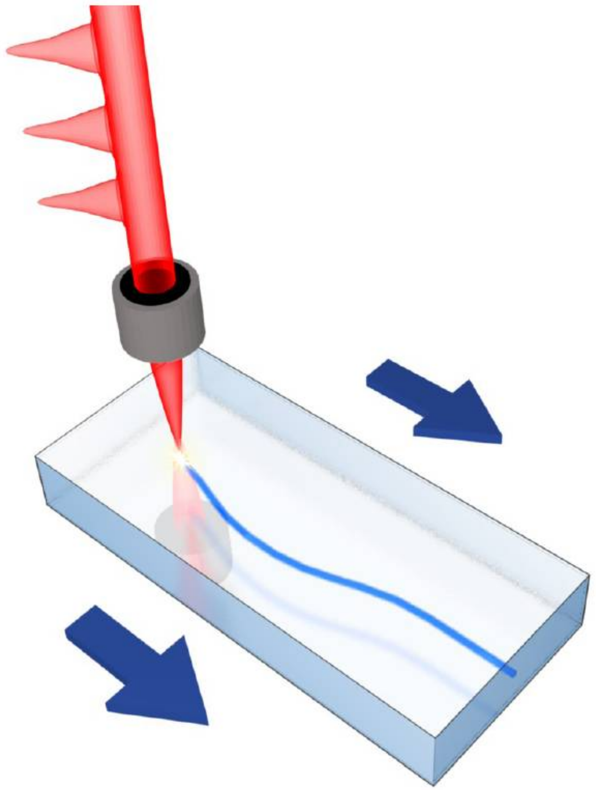


IV) Boson sampling

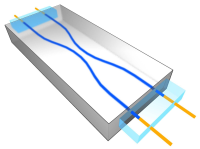


Integrated photonics: Femtosecond laser writing

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.



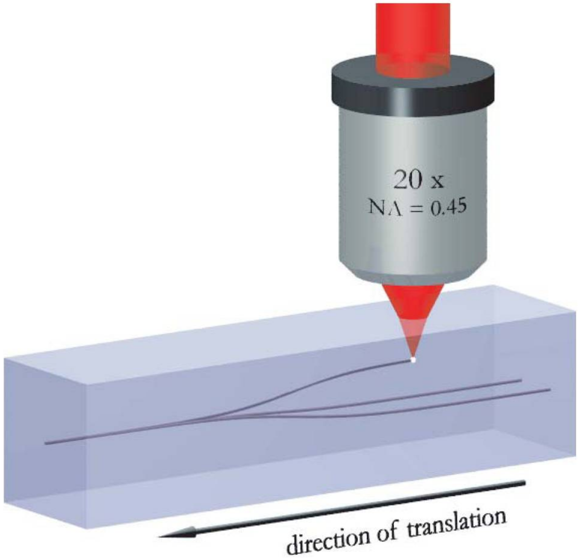
Femtosecond laser writing

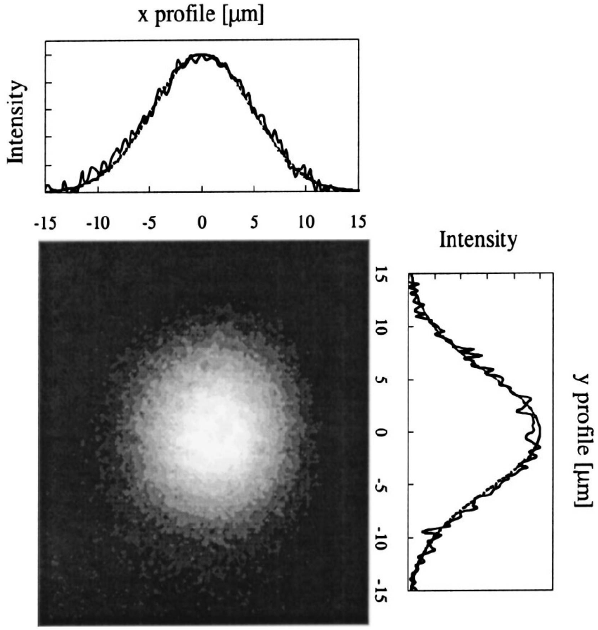
3-dimensional capabilities

Rapid device prototyping: writing speed =4 cm/s

Propagation of circular gaussian modes

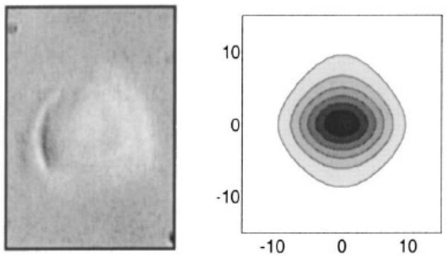
Characteristics:



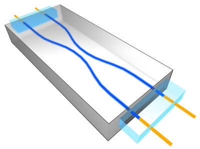


Circular waveguide transverse profile

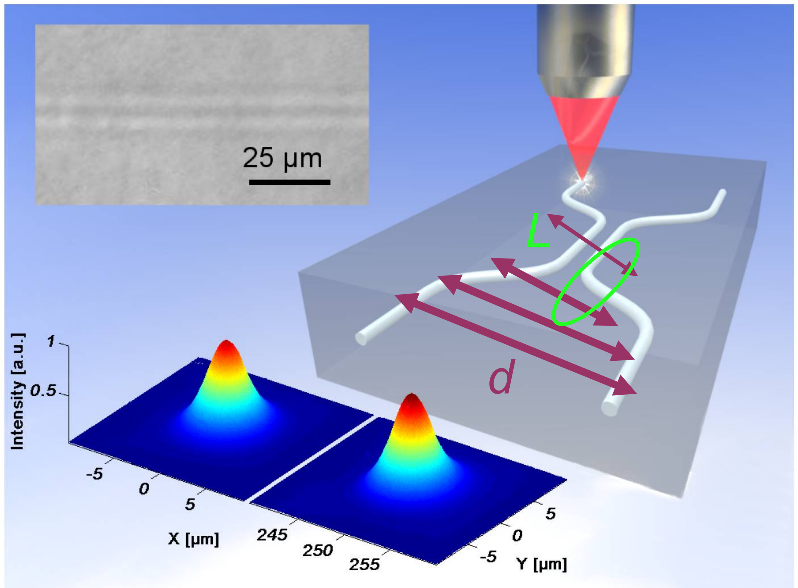
Low birefringence



SUITABLE TO SUPPORT ANY POLARIZATION STATE

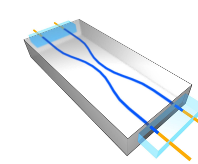


Integrated beam splitter



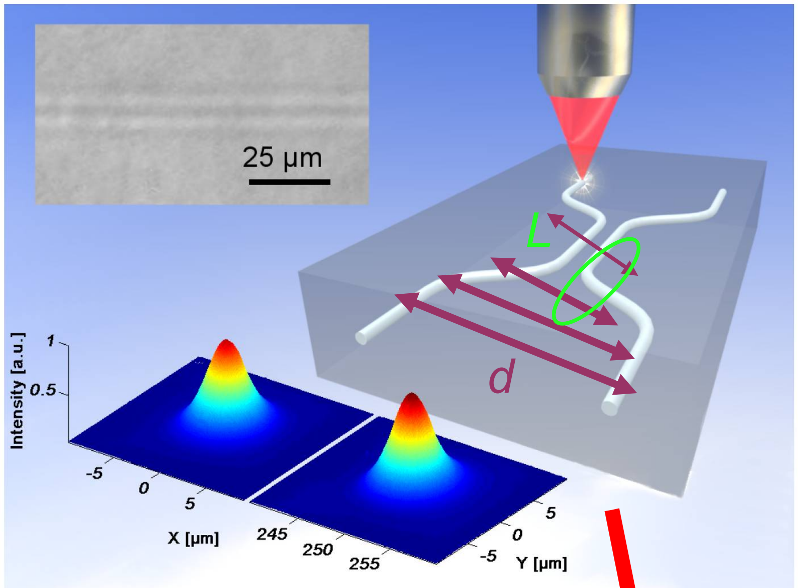
L: interaction region

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

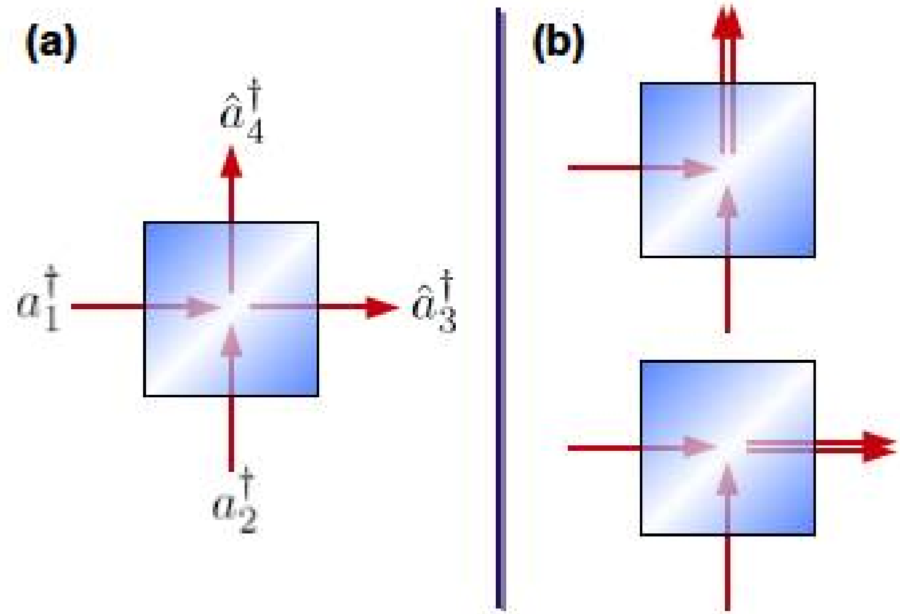


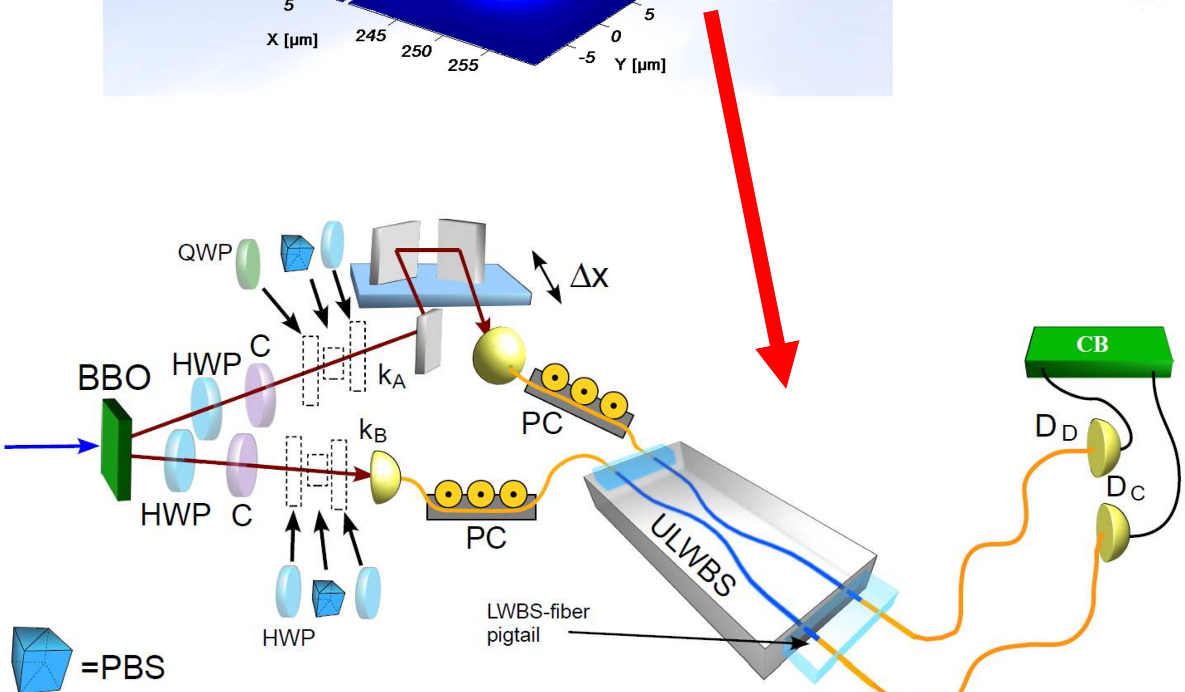
L. Sansoni *et al.* *Phys. Rev. Lett.* **105**, 200503 (2010)

Integrated beam splitter

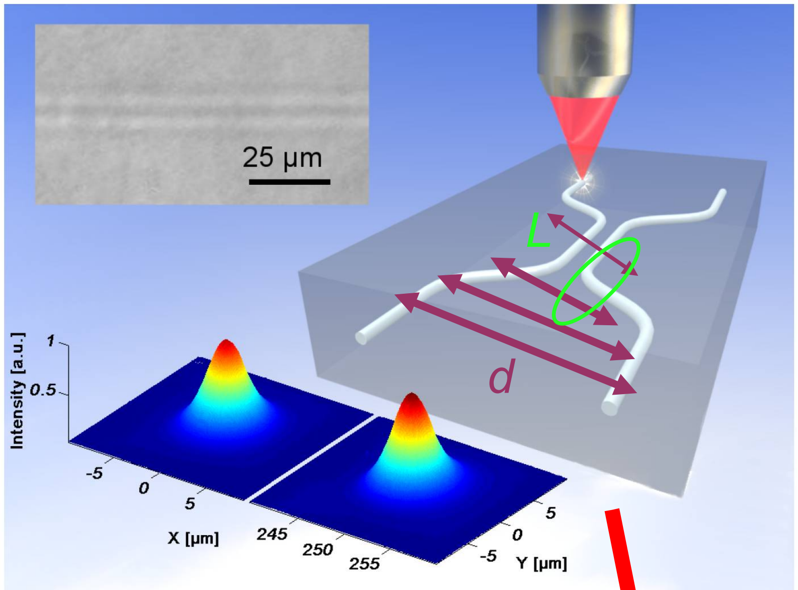


Indistinguishable photons: Bosonic coalescence

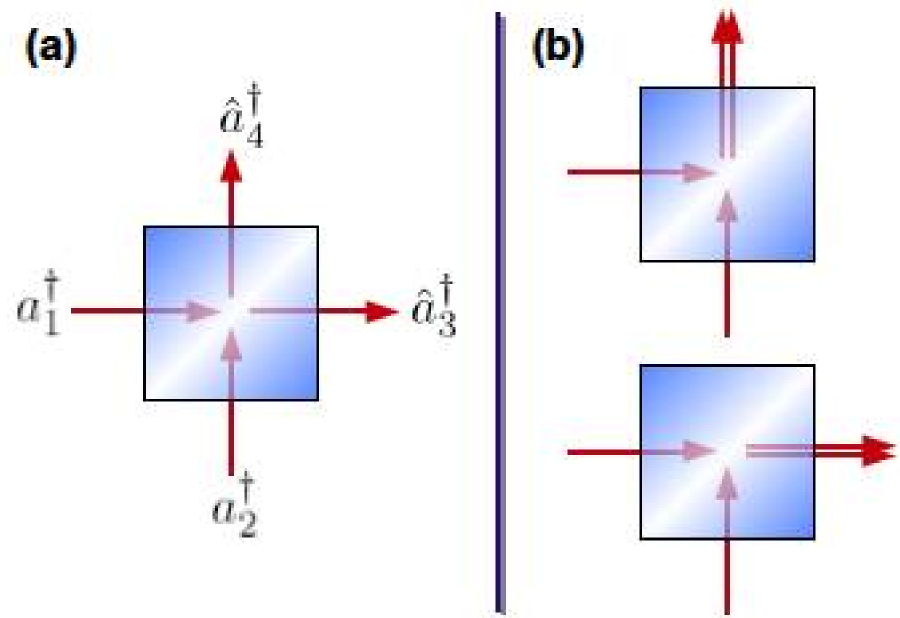


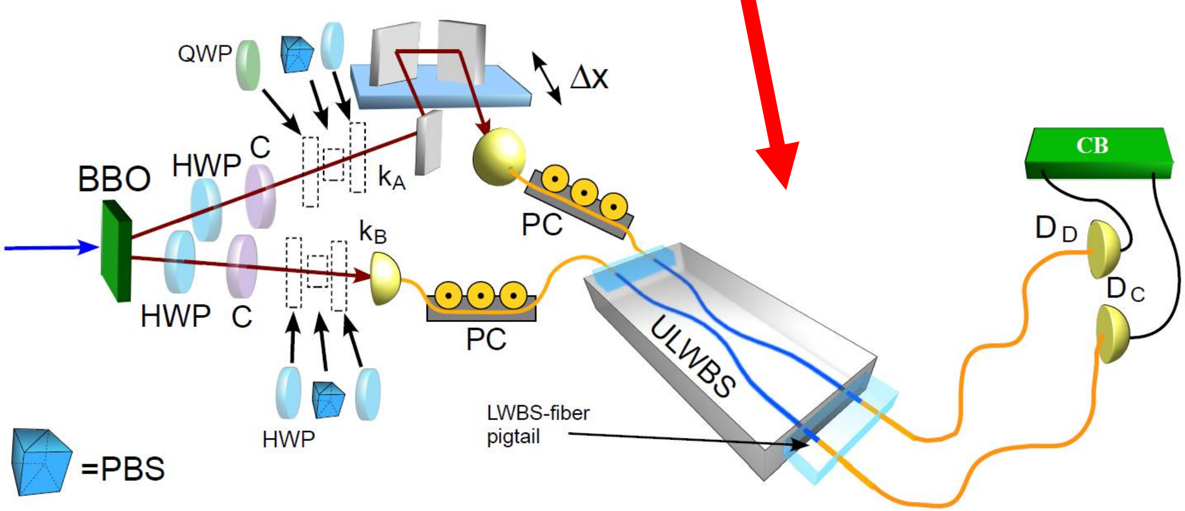


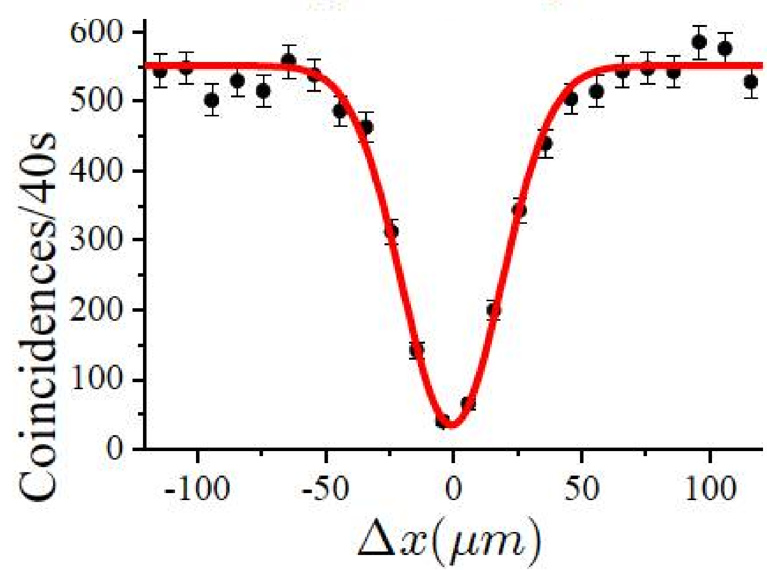
Integrated beam splitter



Indistinguishable photons: Bosonic coalescence







Two-photon entangled state on a beamsplitter...

The symmetry of two particles influences the output probability distribution

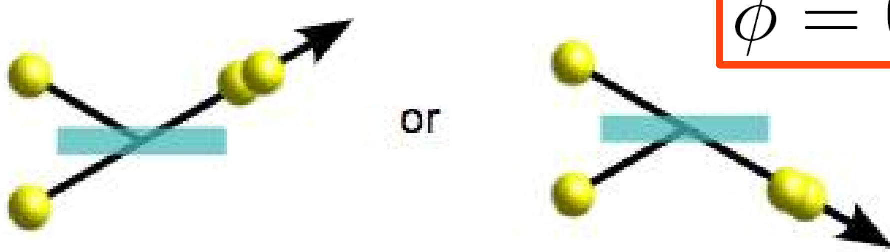
Polarization independent integrated beam splitter

Exploit <u>polarization entanglement</u> to simulate other particle statistics

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

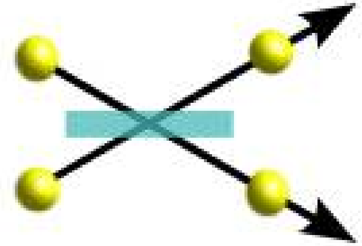
Bosons

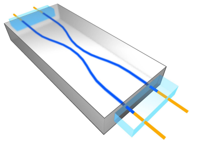
$\phi = 0$



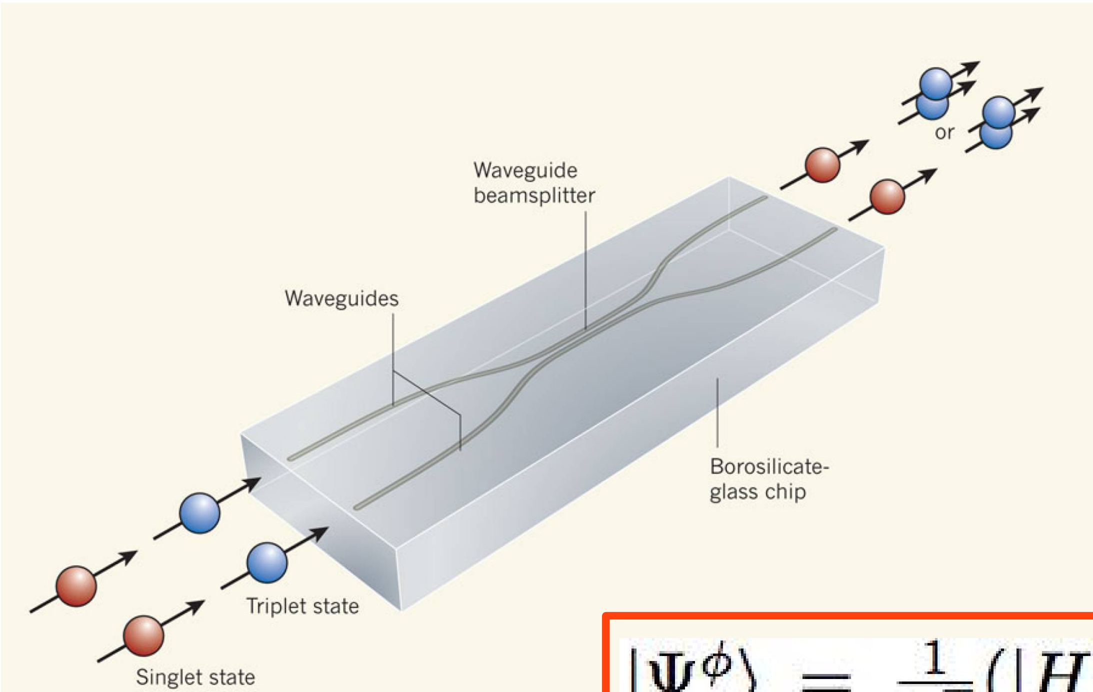
Fermions

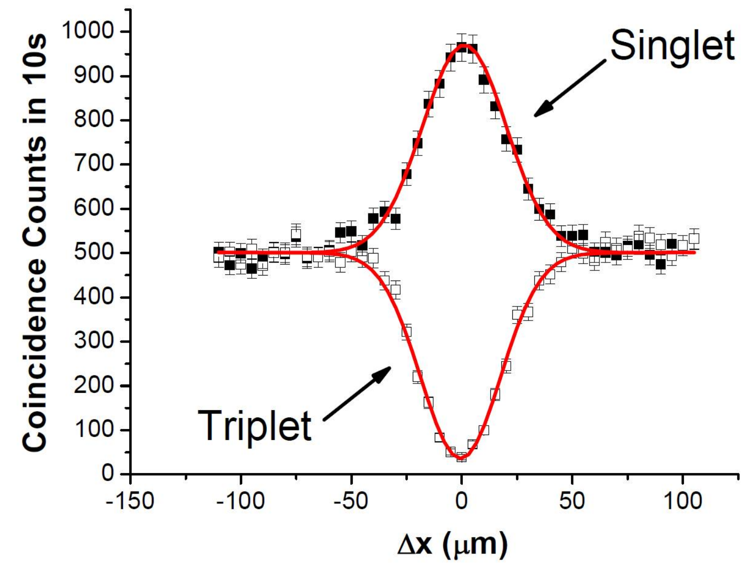
$\phi = \pi$





Polarization entanglement on a chip





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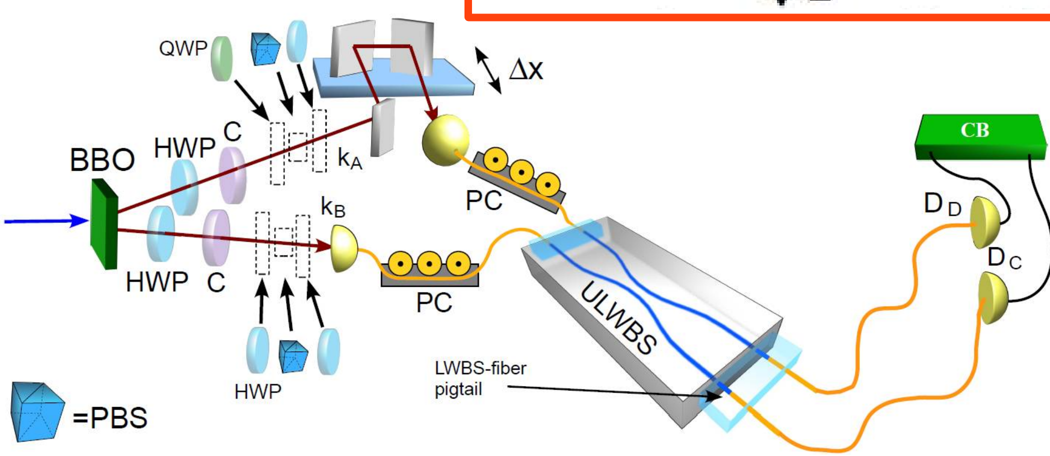
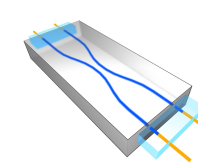


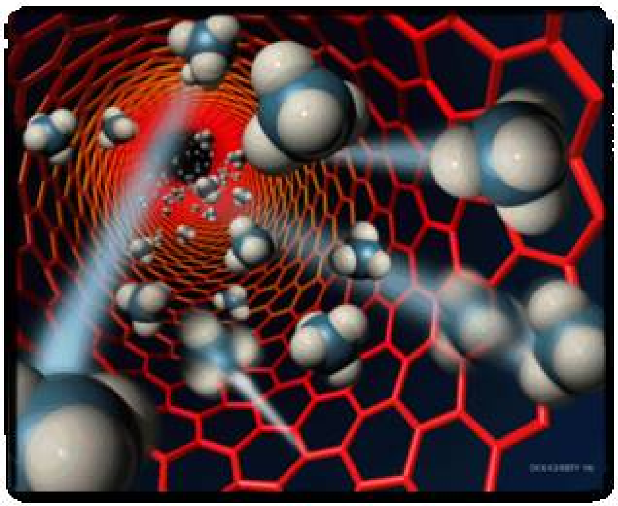
M. Lobino & J.L. O'Brien *News &Views* Nature (2011)

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



QUANTUM SIMULATION

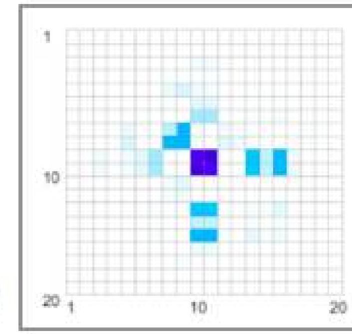
R. Feynman:
"To exploit quantum hardware to simulate quantum systems"



Quantum transport phenomena:

Transport over disordered systems

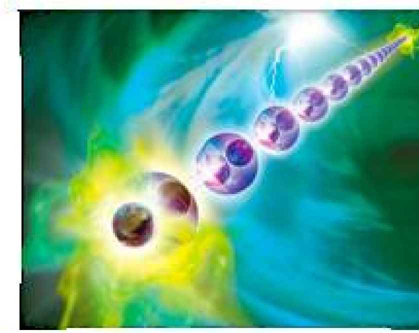
Anderson localization for bosons and fermions



Solid state physics:

Topological phenomena in quantum systems

Bound states



Fundamental physics:

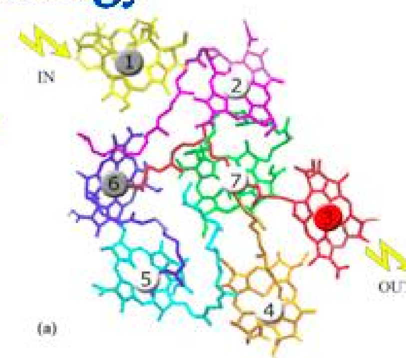
Quantum to classical transition

simulation of decoherence

Quantum biology:

Simulate dynamics of energy transfer process

Photosynthetic systems: quantum effects such as delocalized excitonic transport



QUANTUM SIMULATION VIA QUANTUM WALKS

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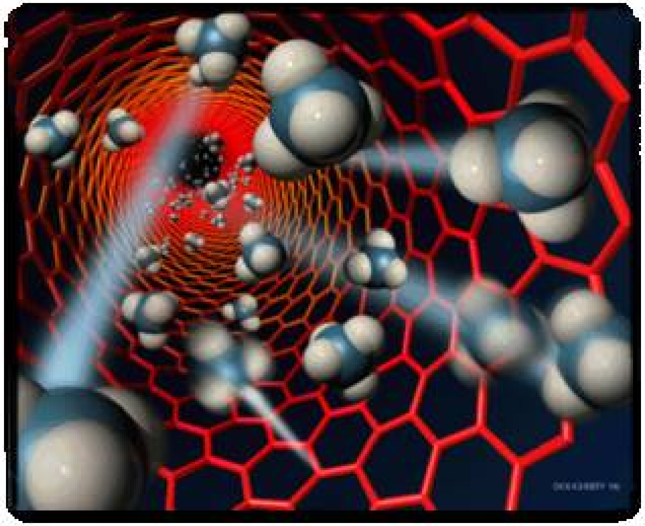
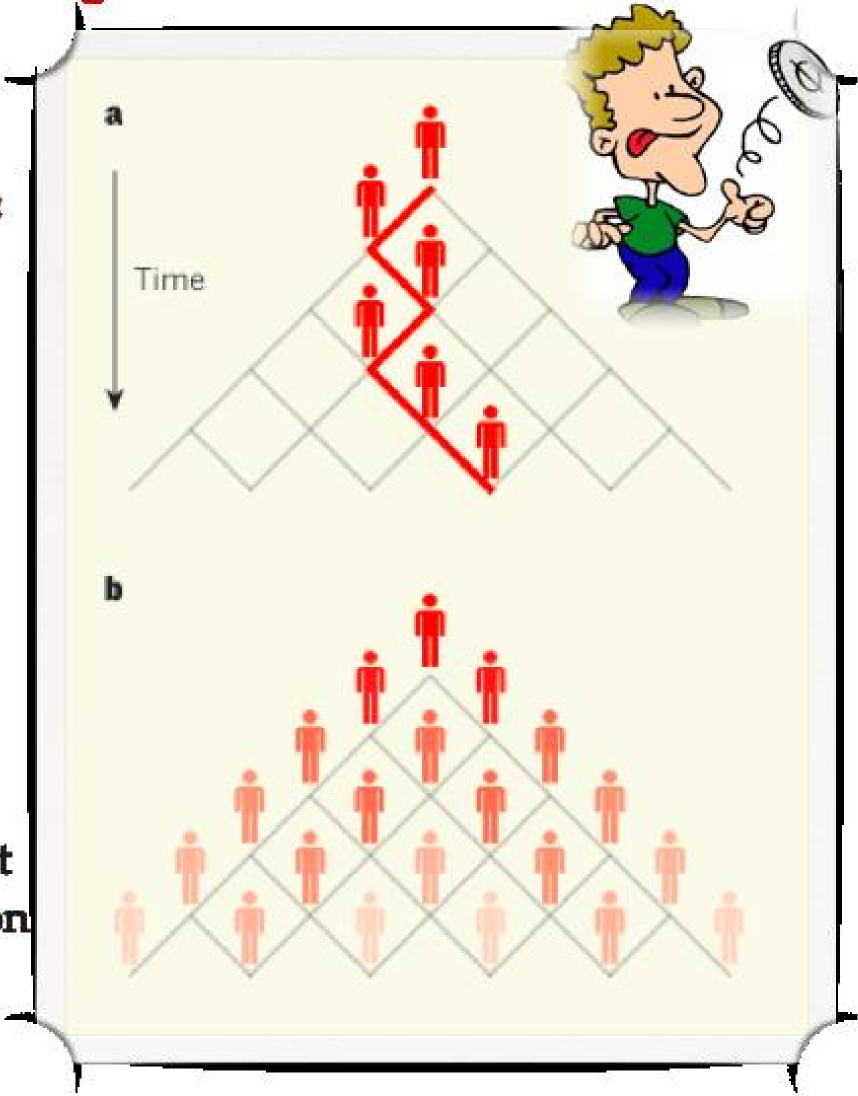


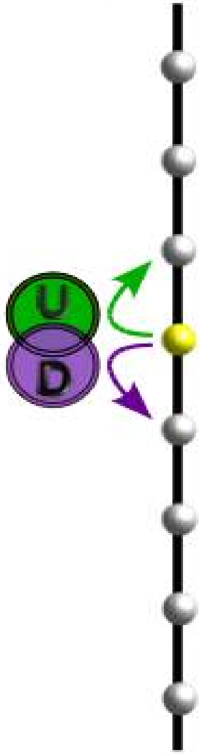
Realization of quantum simulation via quantum walks

Classical random walk:
a walker must make a choice (randomly) of moving either left or right at each step.

Quantum walk:
the walker uses a 'quantum coin' mechanism that allows it to move in a superposition of both left and right.



Discrete-time quantum walk



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

Quantum particles evolve on a graph, with their evolution governed by their internal quantum coin (QC) states

The walker in the position j is described by the quantum state |j>
The particle shifts up or down depending on the internal QC state |U> or |D>

Evolution: step operator

$$E = \sum_j |j-1\rangle\langle j| \otimes |U\rangle\langle U| + |j+1\rangle\langle j| \otimes |D\rangle\langle D|$$

Experimental platforms

Ion trap

F. Zahringer, et al.,
Phys. Rev. Lett. **104**, 100503 (2010)

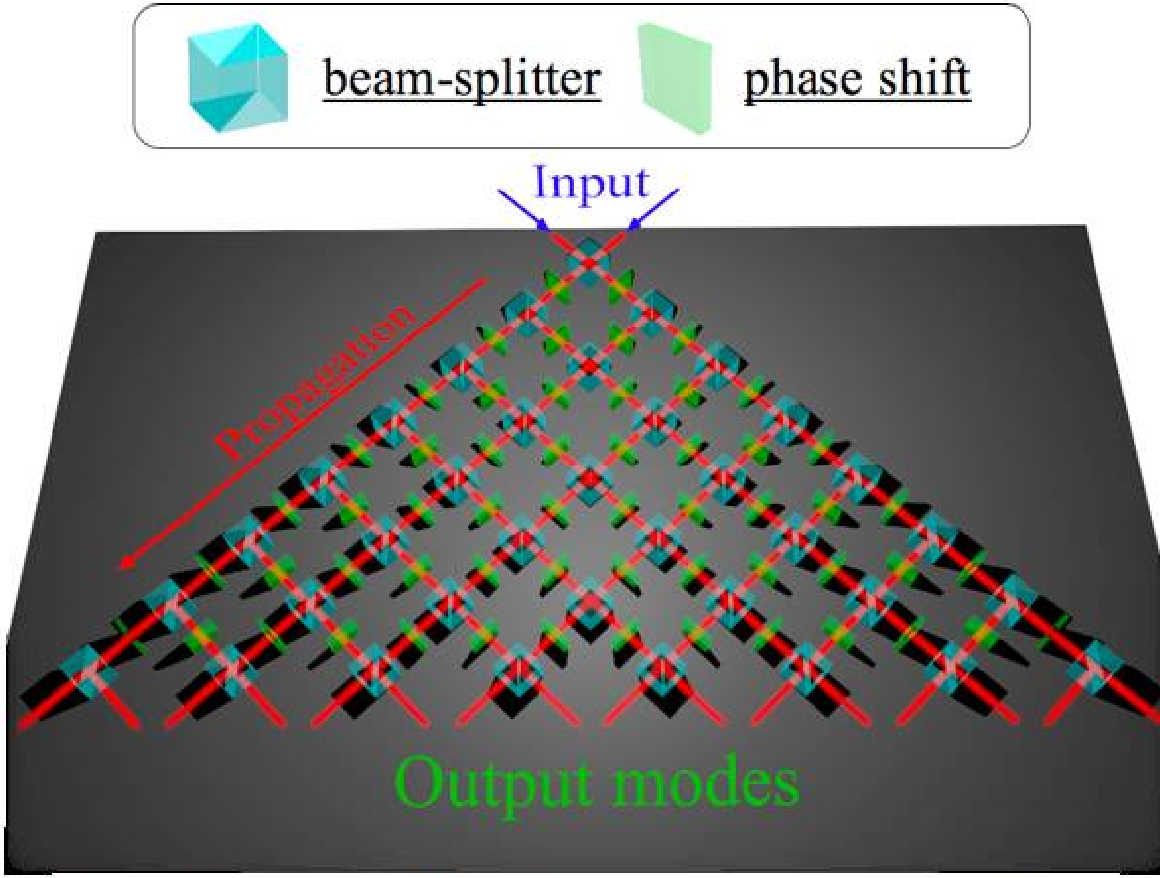
Fiber loops

A. Schreiber et al.,
Phys. Rev. Lett. **104**, 050502 (2010)
Phys. Rev. Lett. **106**, 180403 (2011)
Science **336**, 55 (2012)

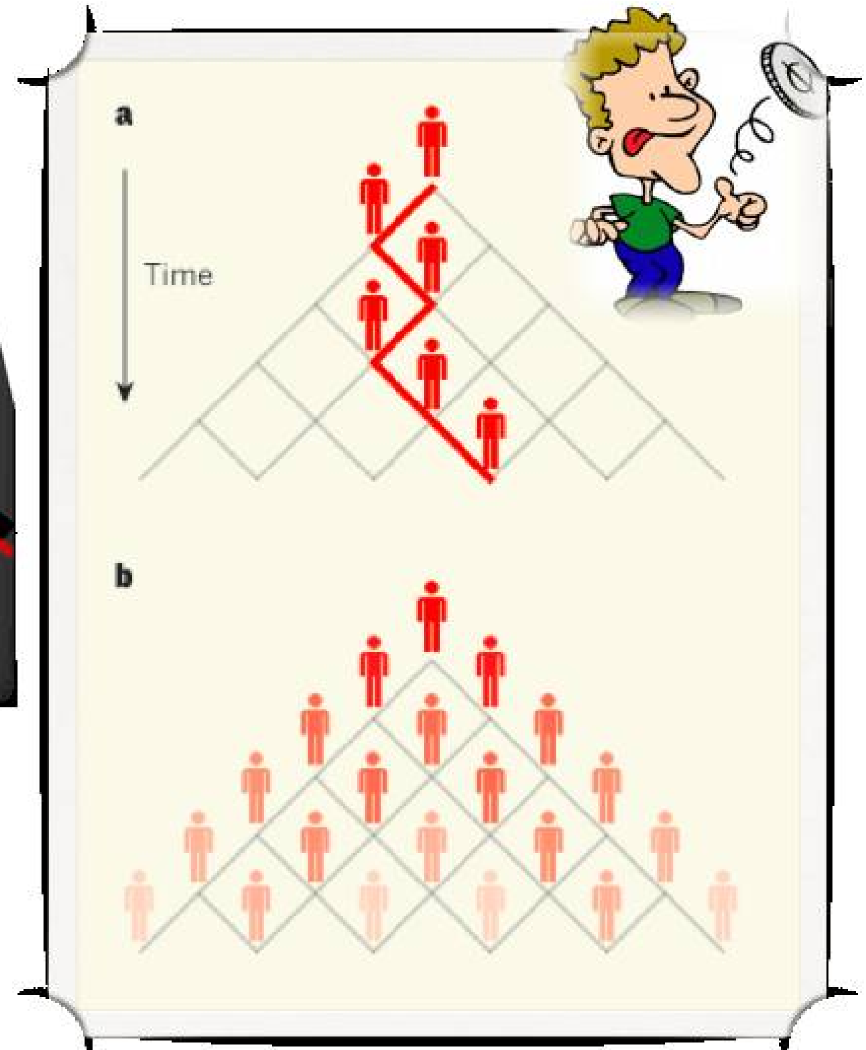
Coupled waveguides

A. Peruzzo, et al.,
Science **329**, 1500 (2010)
JCF Matthews, et al.,
ArXiv:1106.1166 (2011)

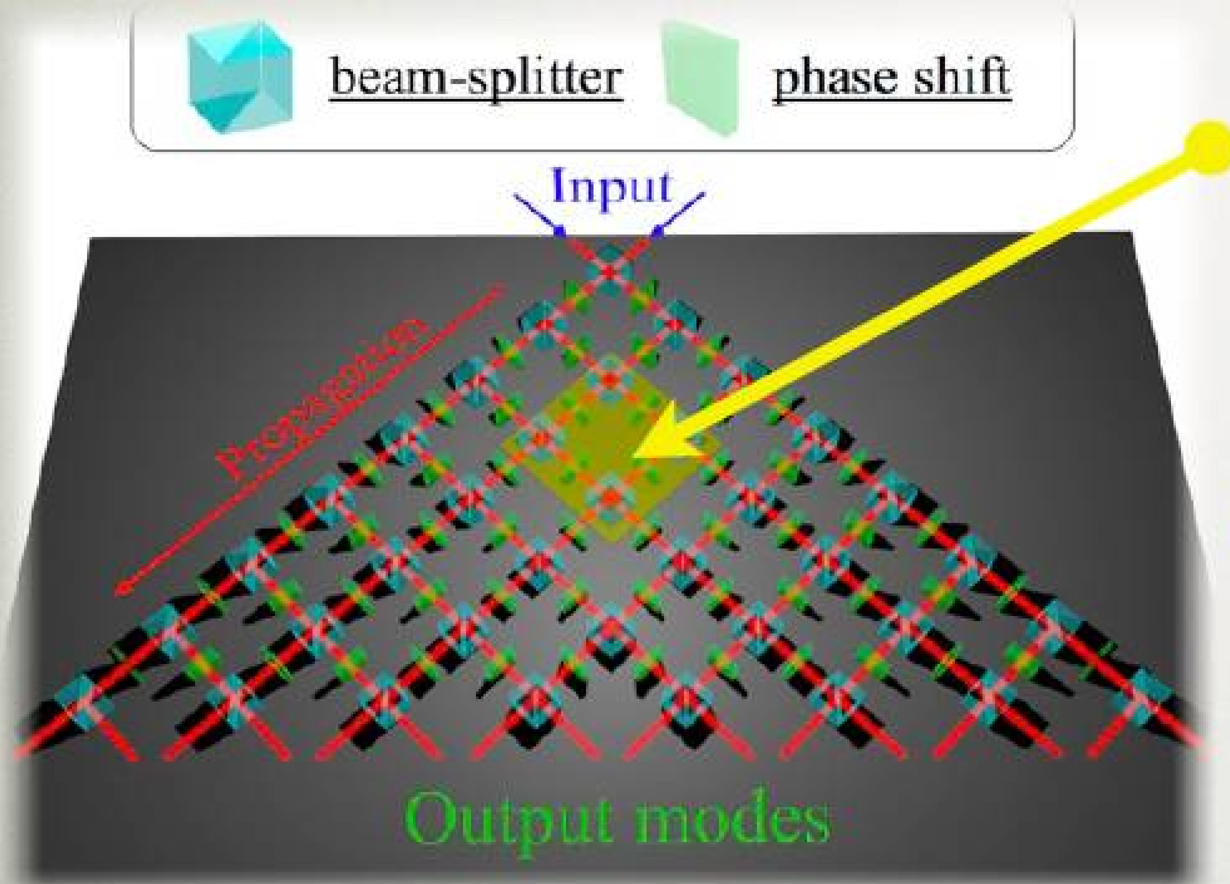
IMPLEMENTATION OF QUANTUM WALKS: OPTICAL SYSTEMS



Quantum walks: photons propagating along an arrays of beam splitters and phase shifters



QUANTUM WALKS VIA OPTICAL SYSTEMS



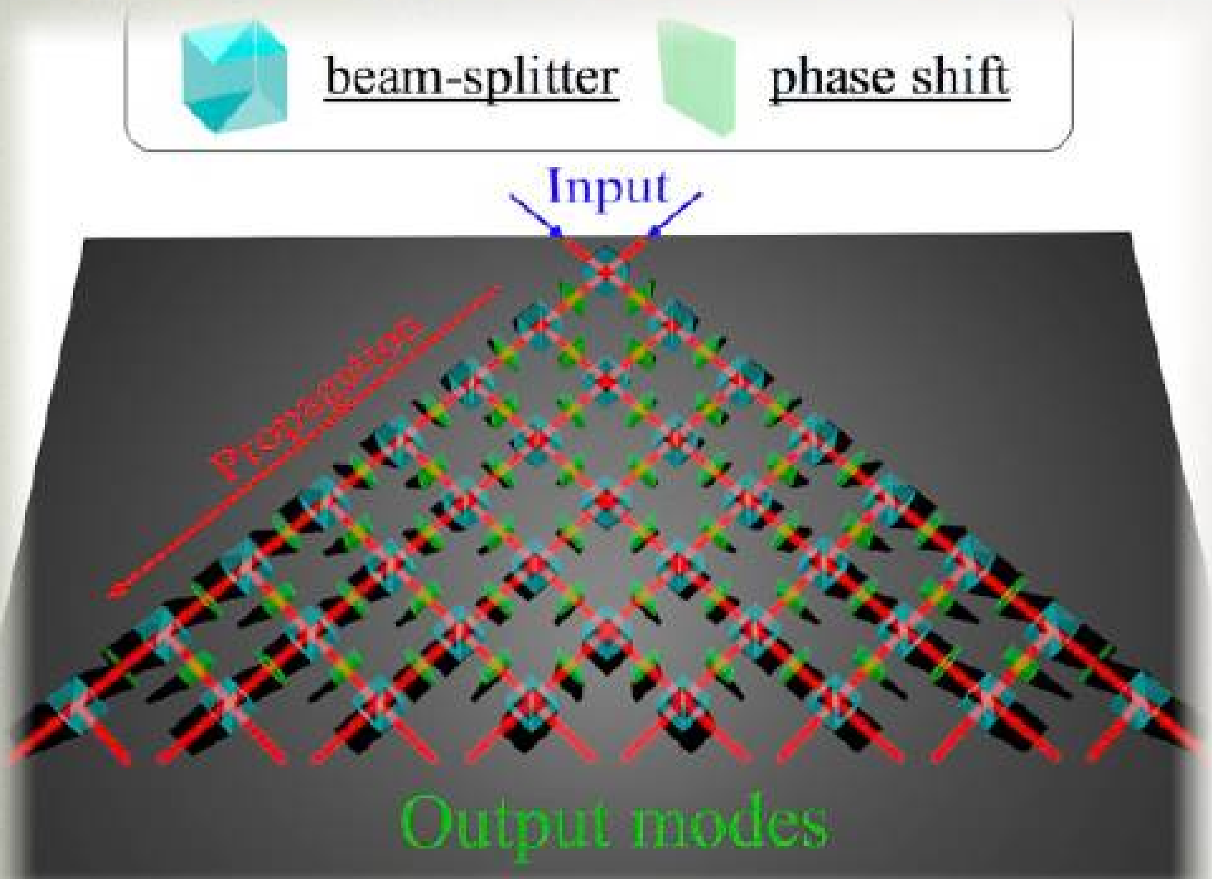
Quantum walks: photons propagating along an arrays of beam splitters and phase shifters

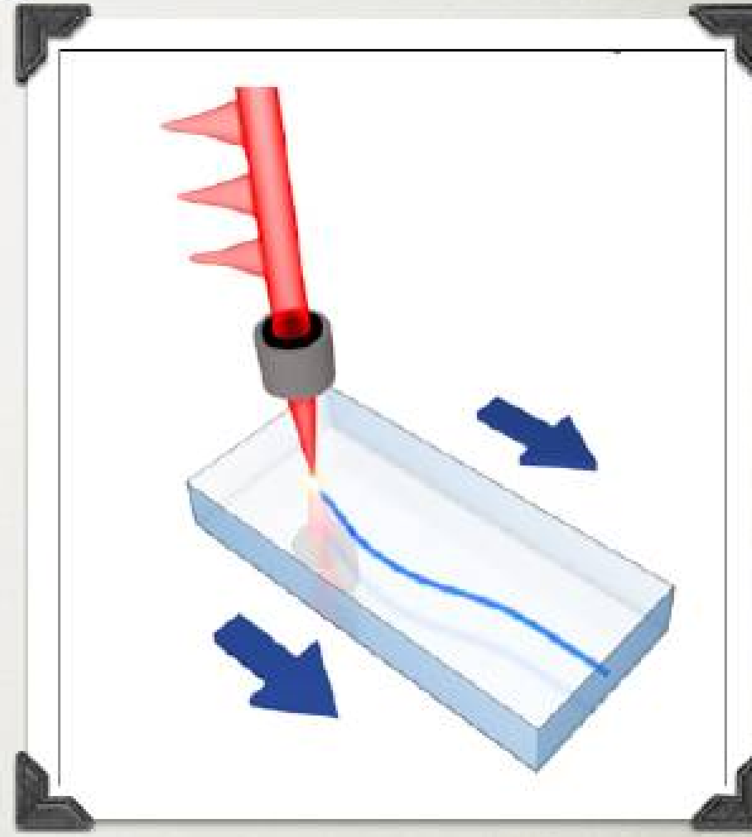
Limitations of experiments with bulk optics:

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

Large number of chained interferometers: impossible to realize by bulk optics!

THE SOLUTION: INTEGRATED PHOTONICS

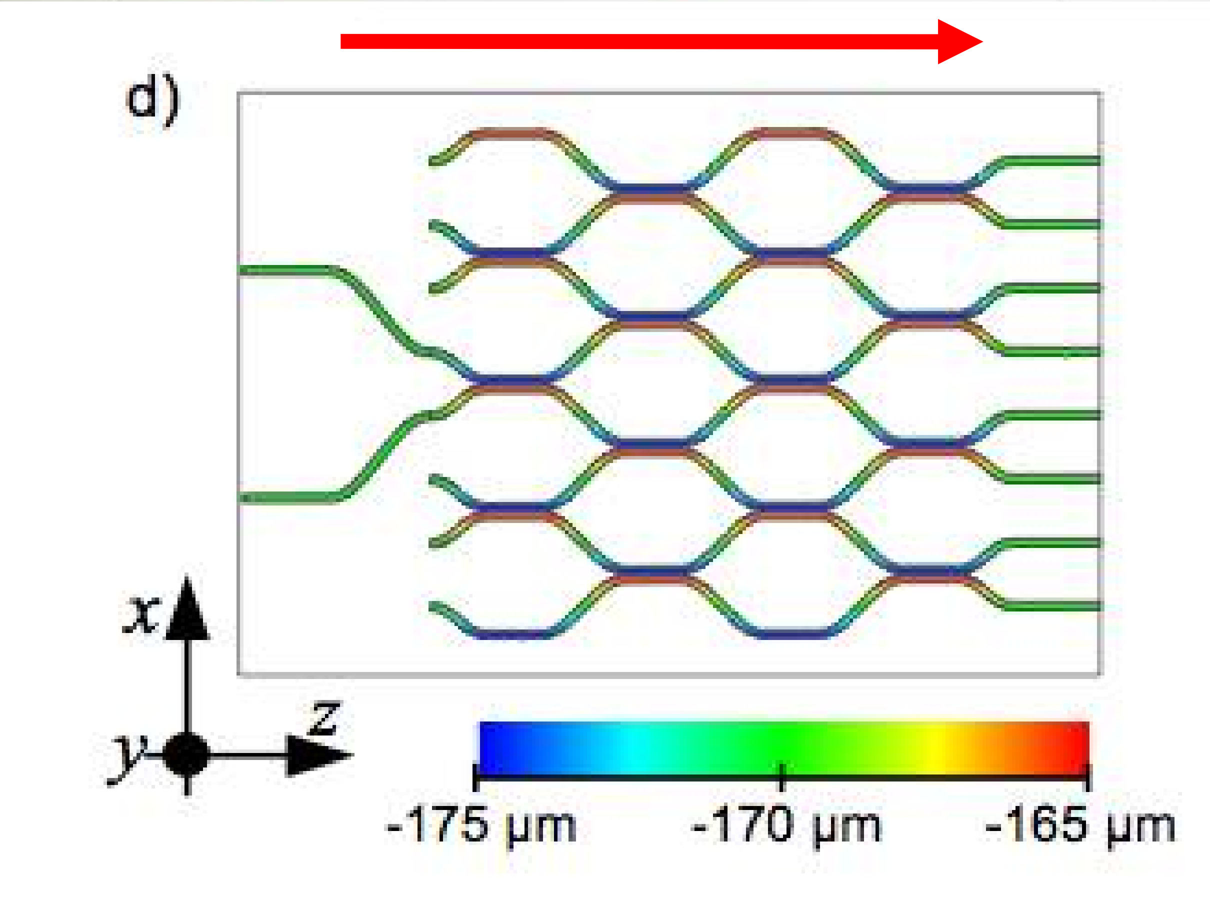


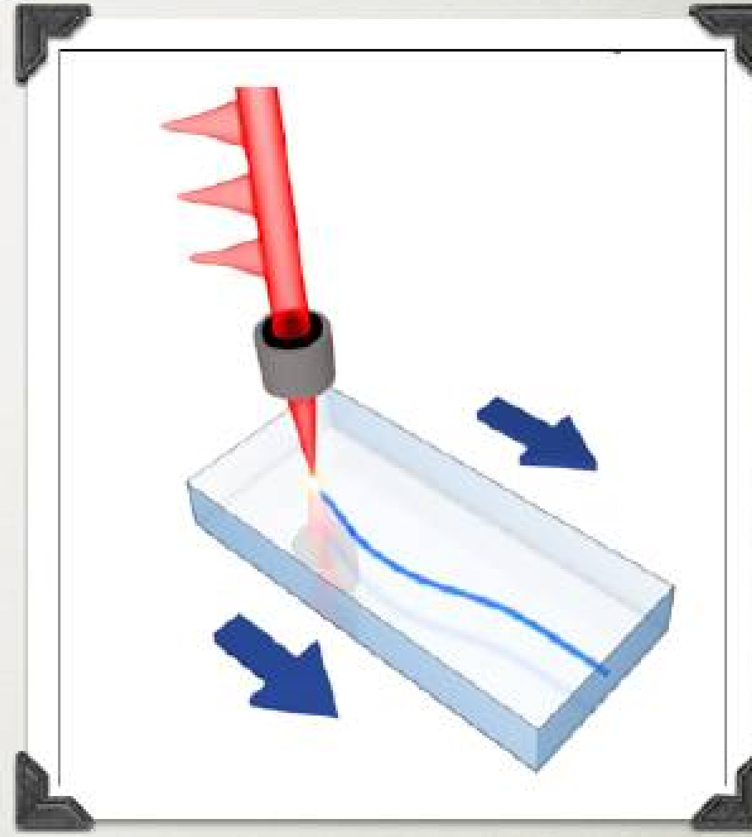


Laser writing technology:
unique capability to transmit any polarization state

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

THE SOLUTION: INTEGRATED PHOTONICS





Laser writing technology:
unique capability to transmit any polarization state

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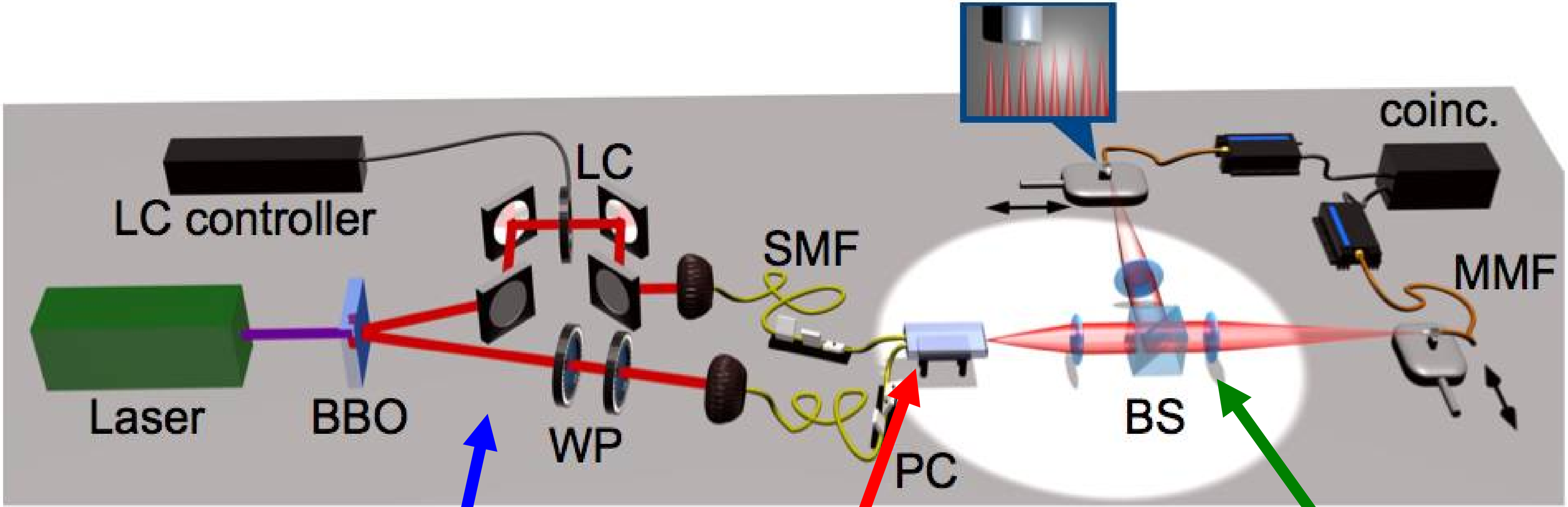
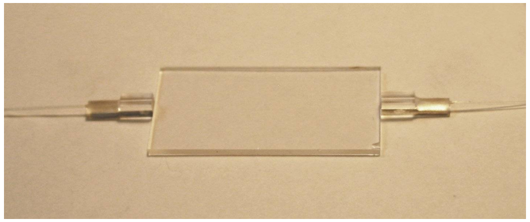
Two-particles quantum walk: experimental setup



BS array on a chip

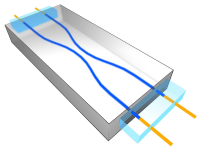


Eight output modes:

Measurement of coincidences between modes i and j

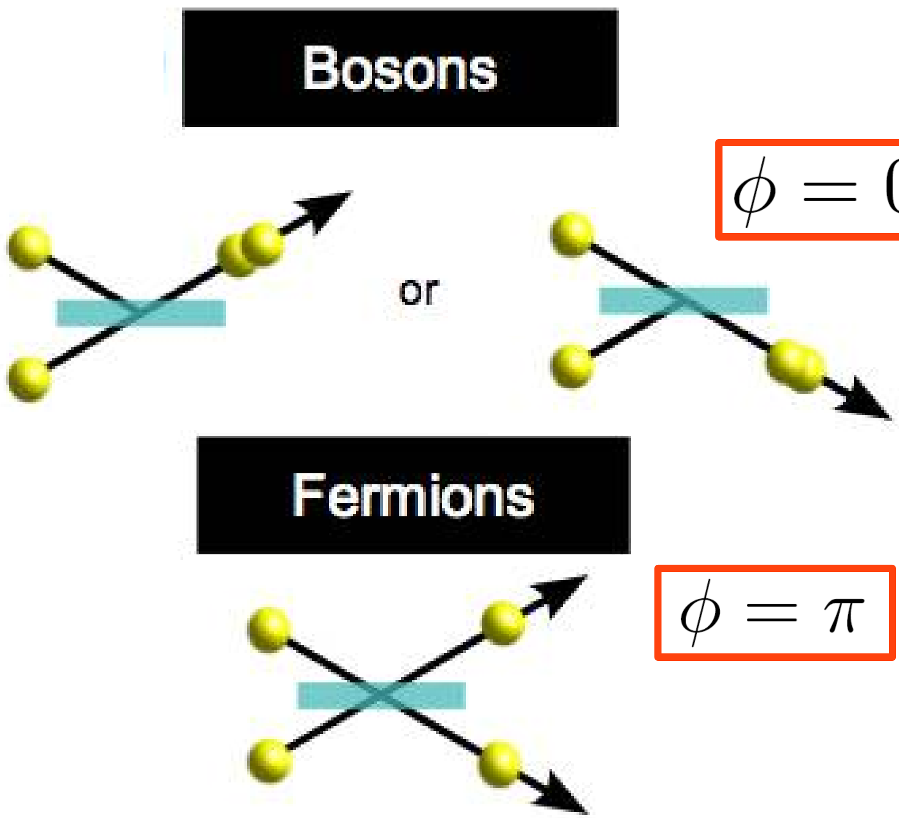
Generation of two-photon entangled states with different symmetries

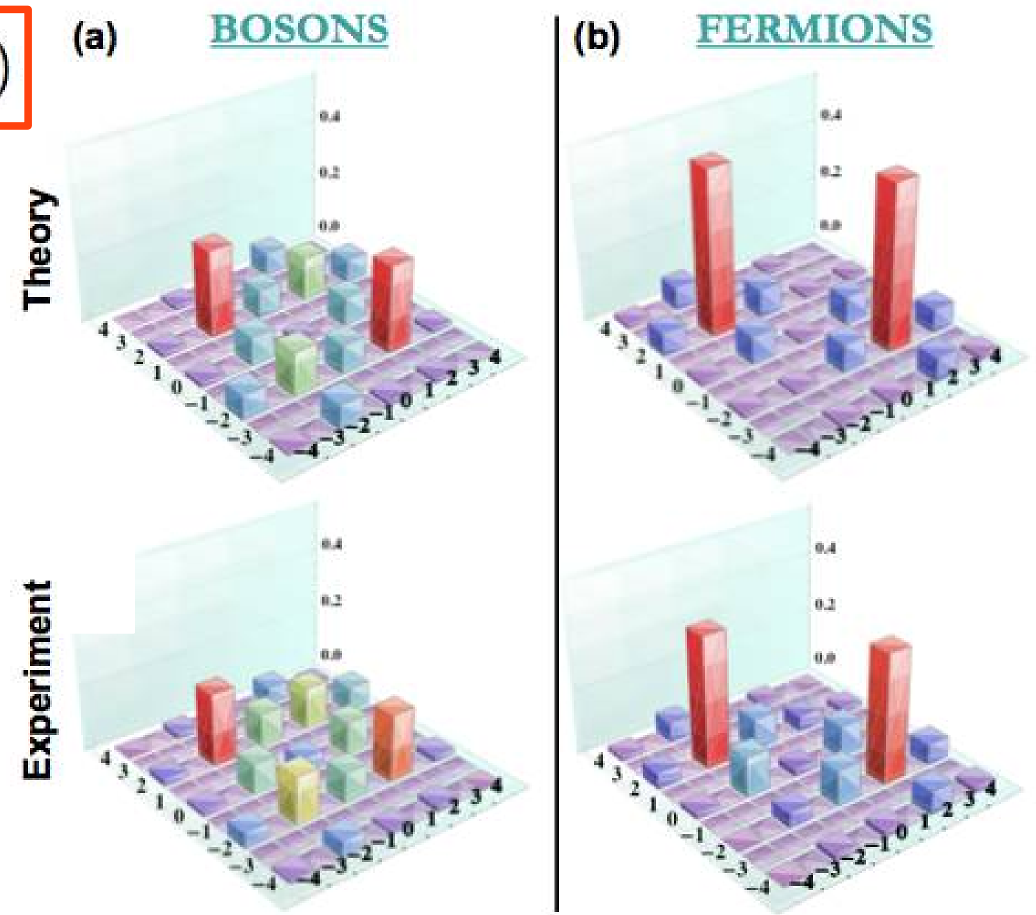
$$|\Psi^{\phi}\rangle = \frac{1}{\sqrt{2}}(|H\rangle_A|V\rangle_B + e^{i\phi}|V\rangle_A|H\rangle_B)$$



Two-particles quantum walk: results

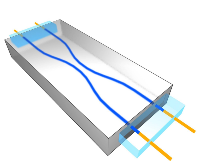
$$|\Psi^{\phi}\rangle = \frac{1}{\sqrt{2}}(|H\rangle_A|V\rangle_B + e^{i\phi}|V\rangle_A|H\rangle_B)$$



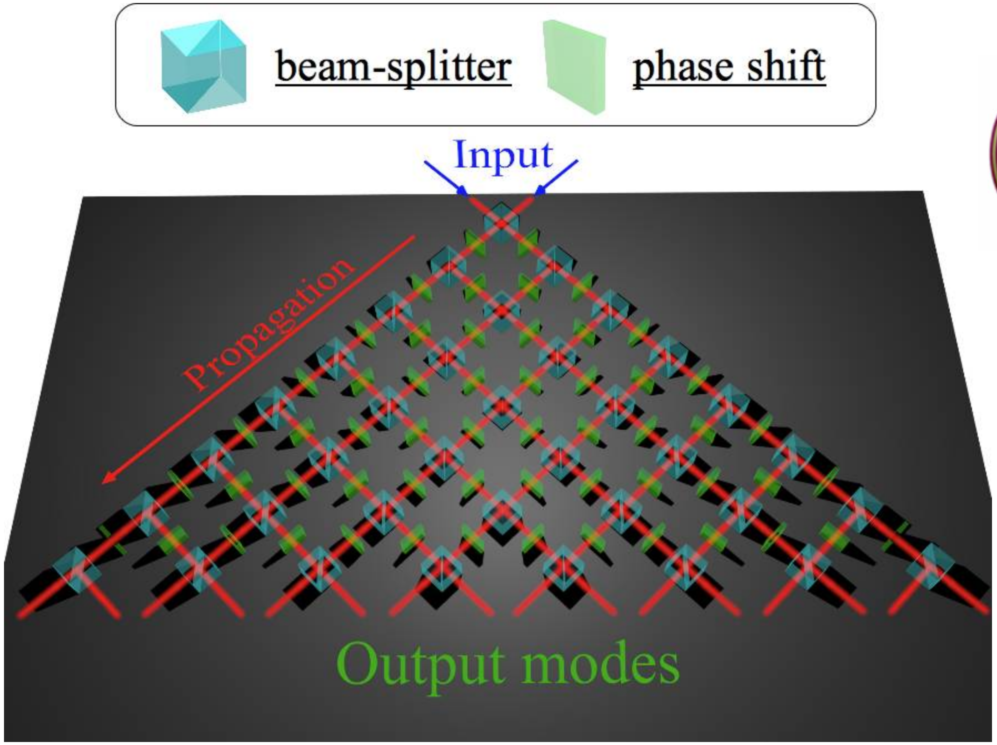


L. Sansoni, *et al.*, Phys, Rev, Lett, **108**, 010502 (2012)

See also: continuous quantum walk by J. Mathews, et al., Sc.. Reports **3**, 1539 (2013)



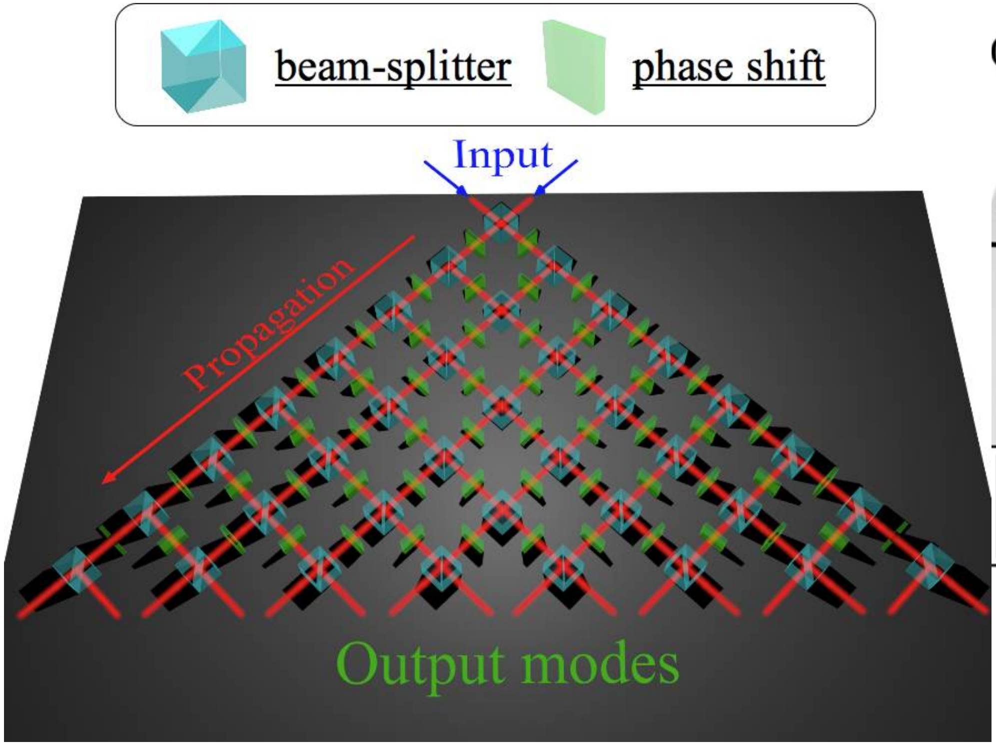
Simulation of disordered systems

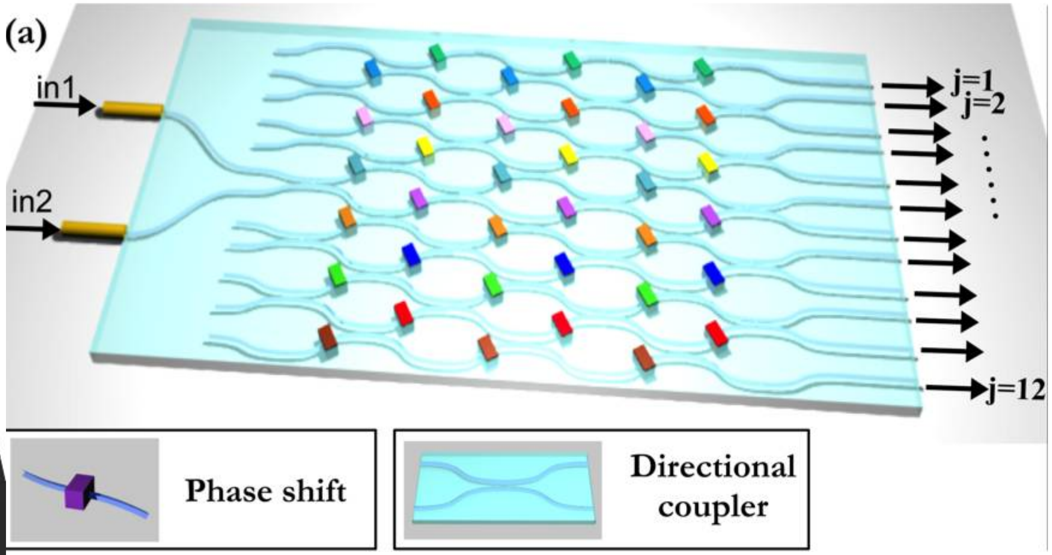


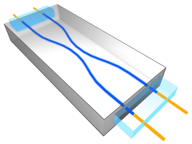
SCUOLA NORMALE SUPERIORE

R. Fazio
V. Giovannetti

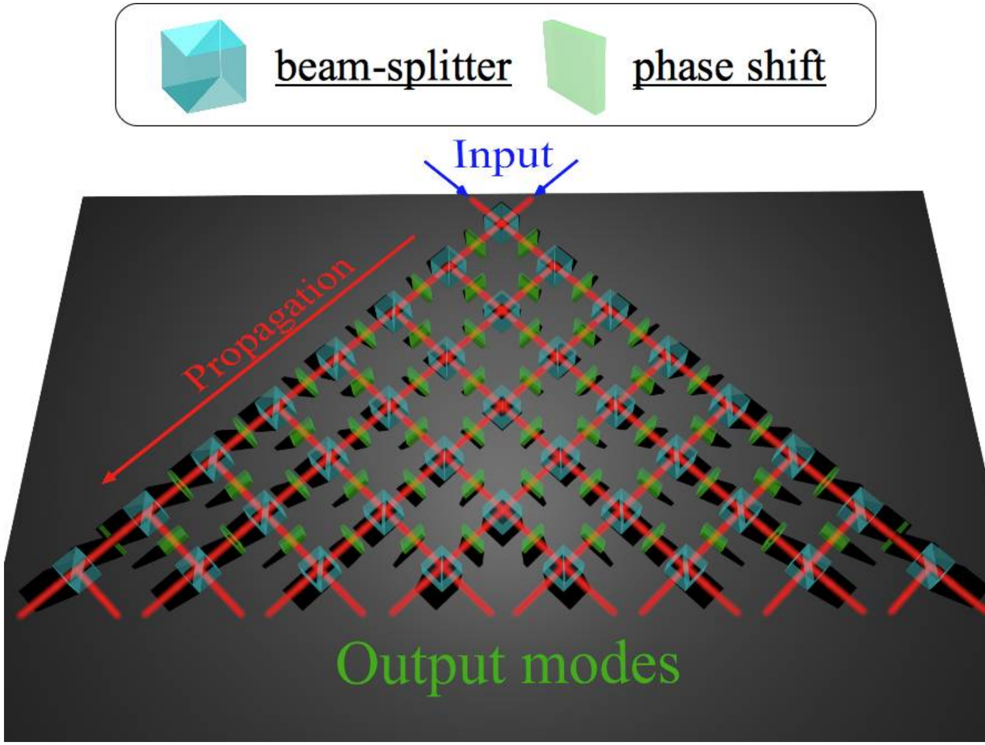
Simulation of disordered systems

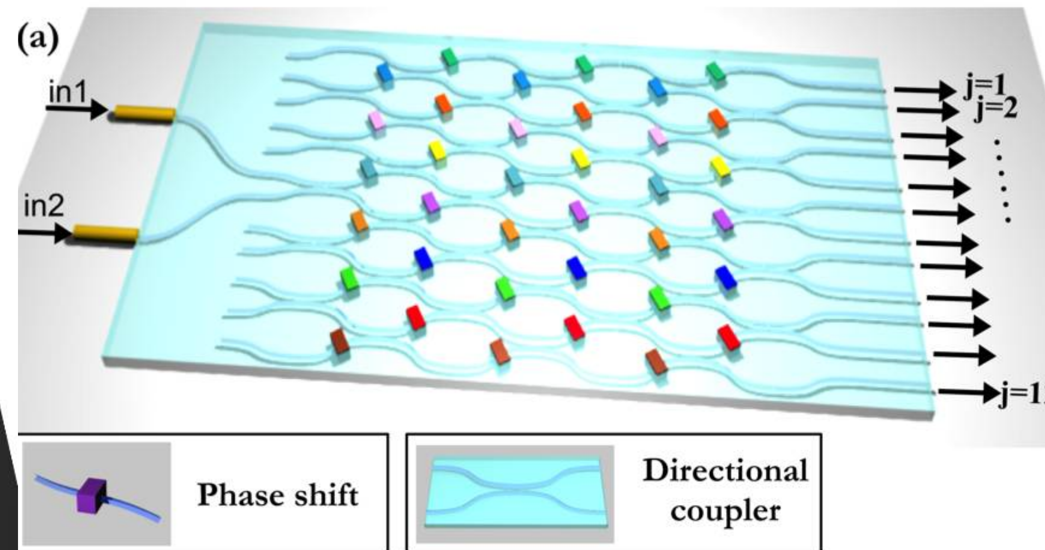




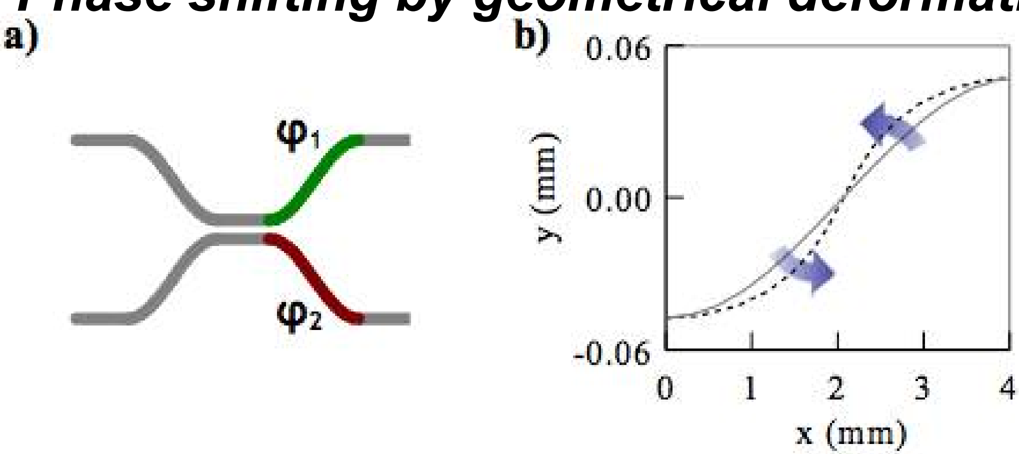


Simulation of disordered systems

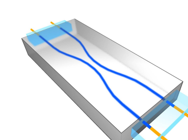




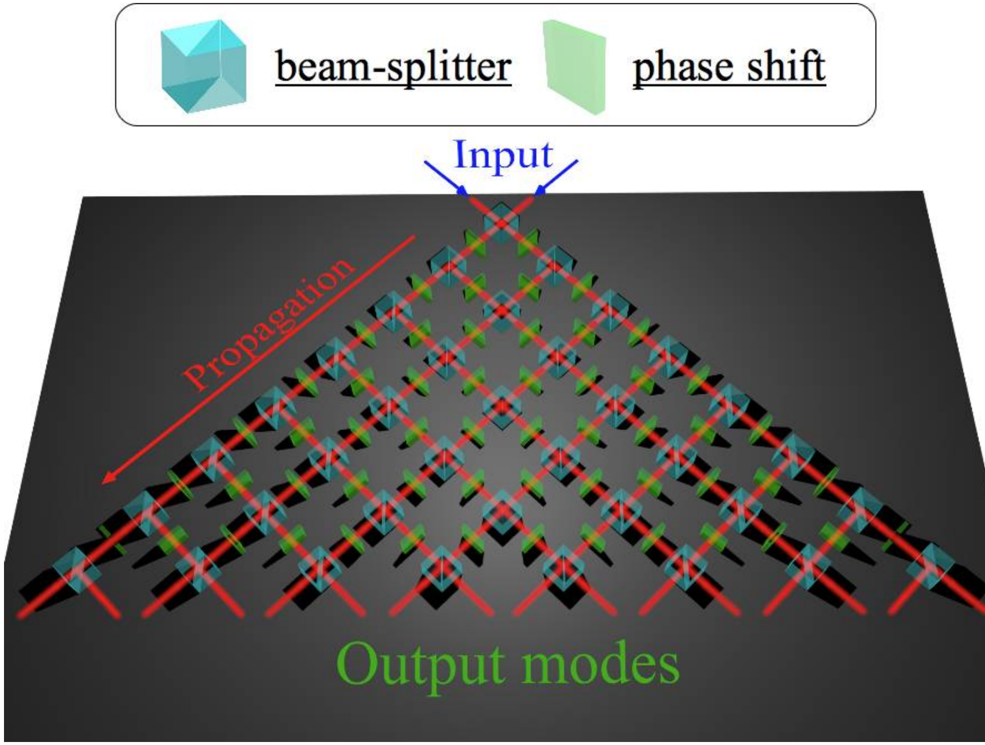
Phase shifting by geometrical deformation

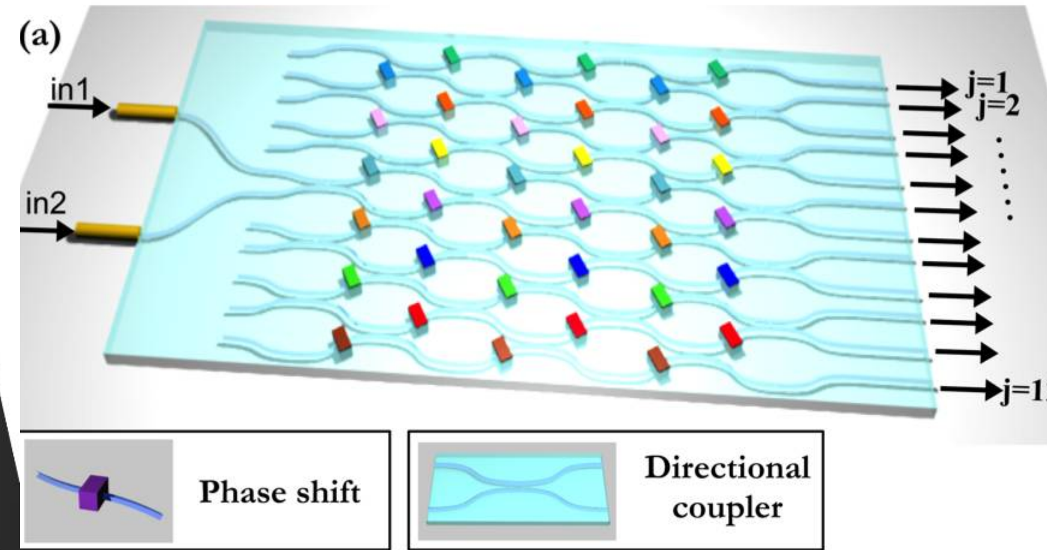


POLARIZATION INDEPENDENT



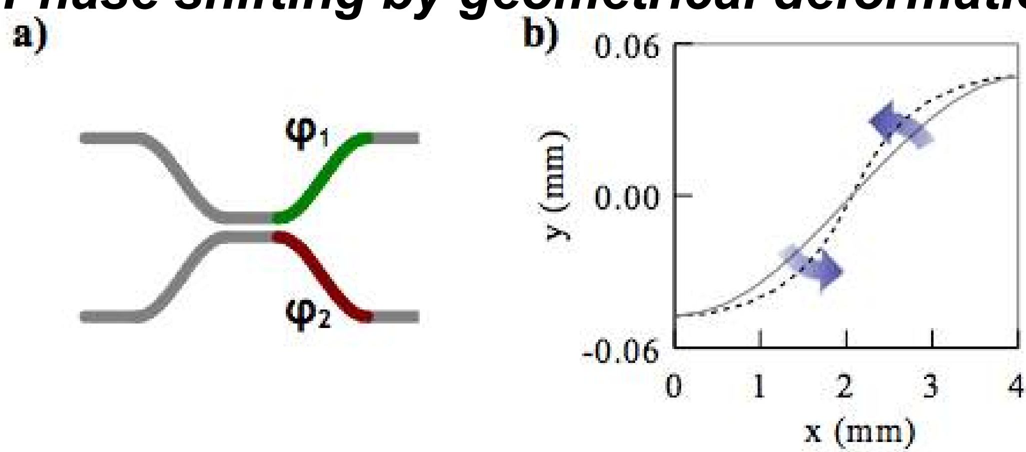
Simulation of disordered systems





.... FIRST EXPERIMENTS....

Phase shifting by geometrical deformation



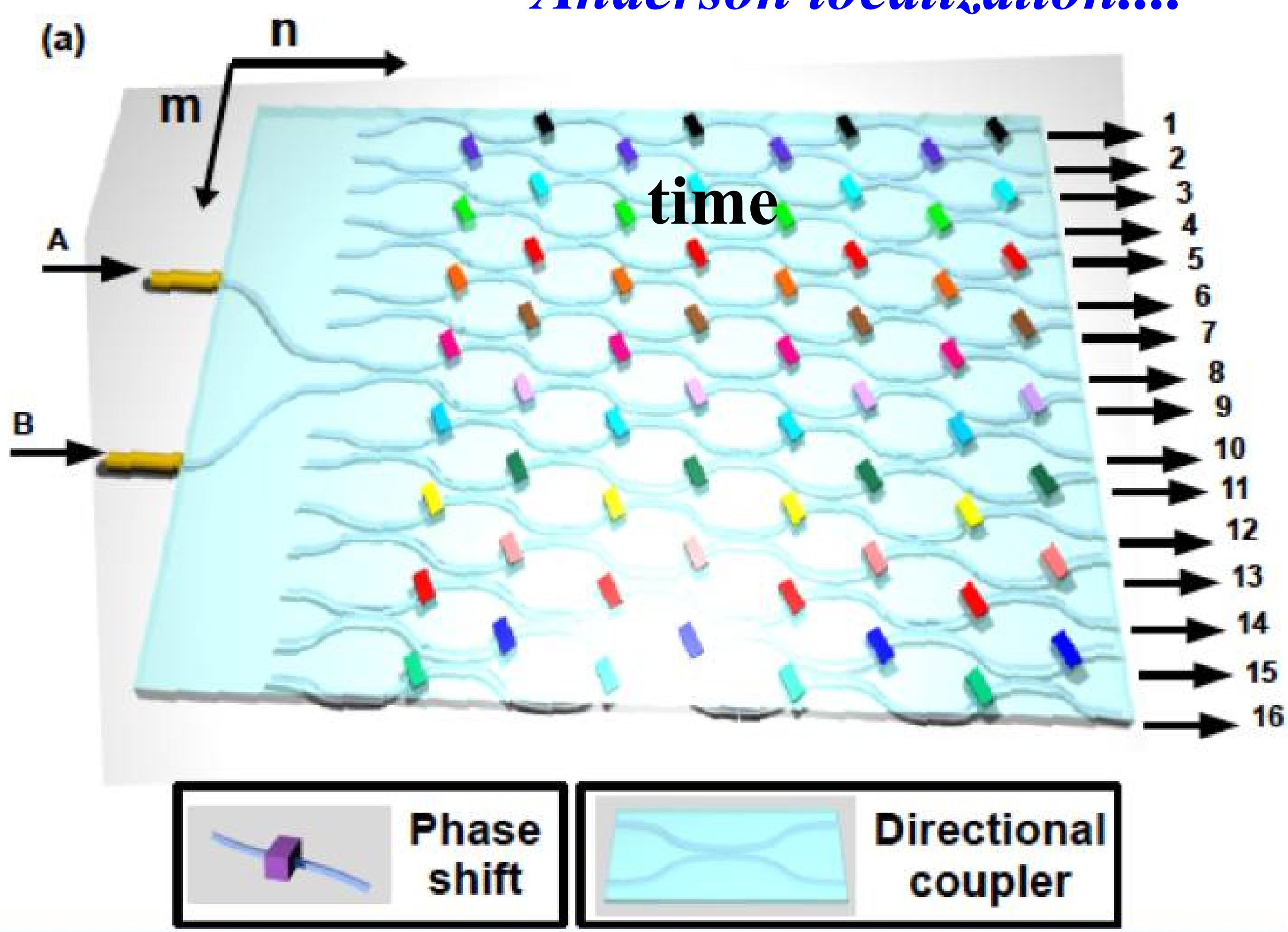
POLARIZATION INDEPENDENT

To simulate different types of disorders:

Simulation of static disorder

Disorder depends:
- on location
- but NOT on time

Anderson localization....



64 Beam splitters
64 phase-shifters
Polarization indiependent

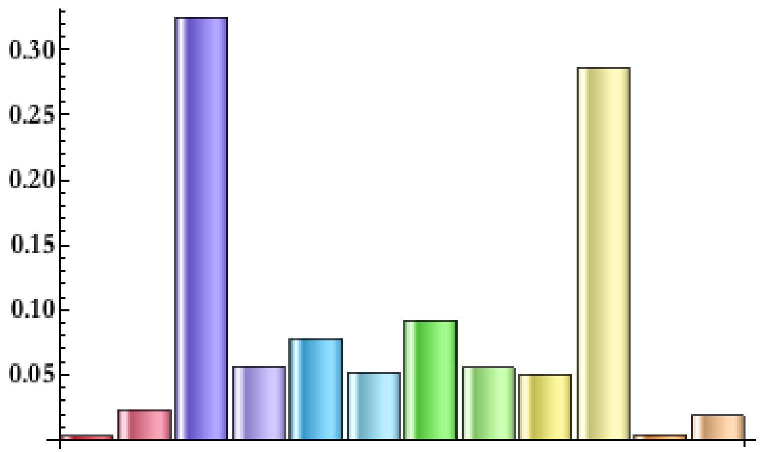
A. Crespi, R. Osellame, R. Ramponi, V. Giovannetti, R. Fazio, L. Sansoni, F. De Nicola, F. Sciarrino, and P. Mataloni, *Anderson localization of entangled photons in an integrated quantum walk*, Nature Photonics **7**, 322 (2013)

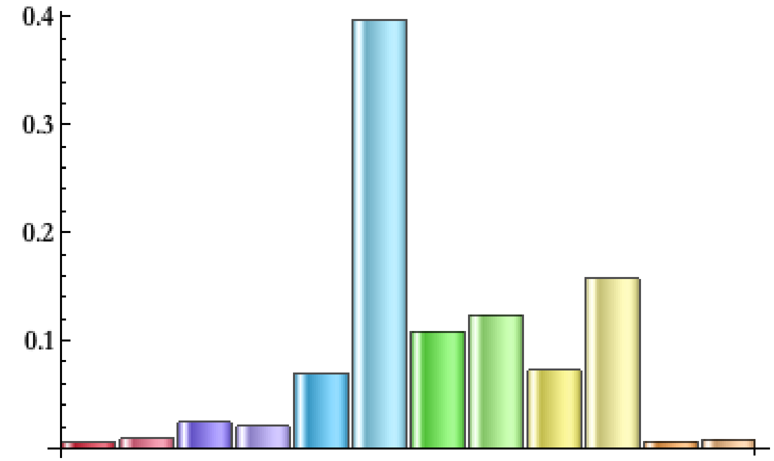
Simulation of disordered systems: Single particle quantum walk

Ordered system

Disordered system

Experiment

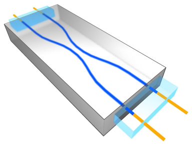




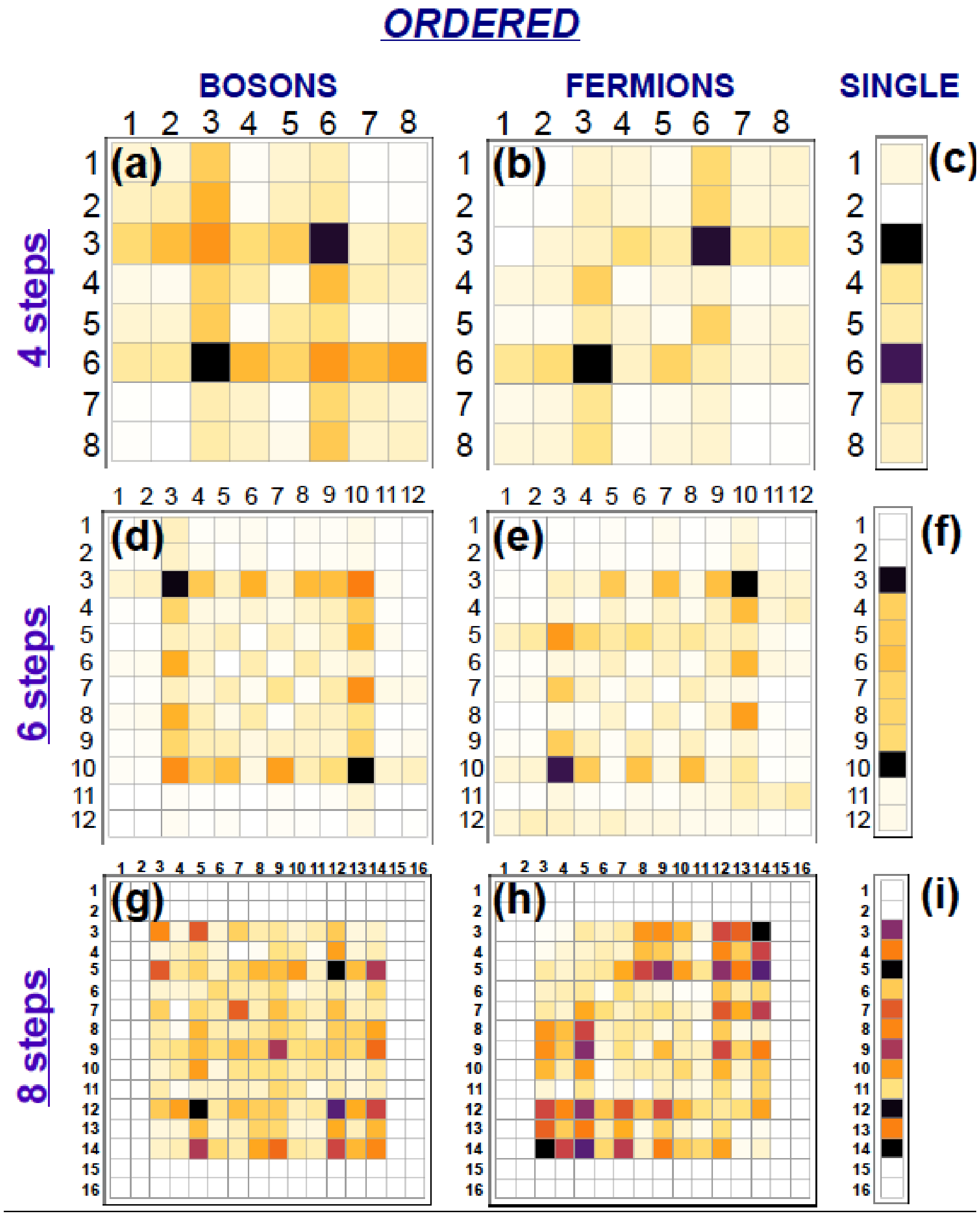
Experimentally observed by Silberhorn's group with fiber loops:
Phys. Rev. Lett. **106**, 180403 (2011).

Two-particle quantum walk with disordered systems:
… experiments missing so far...

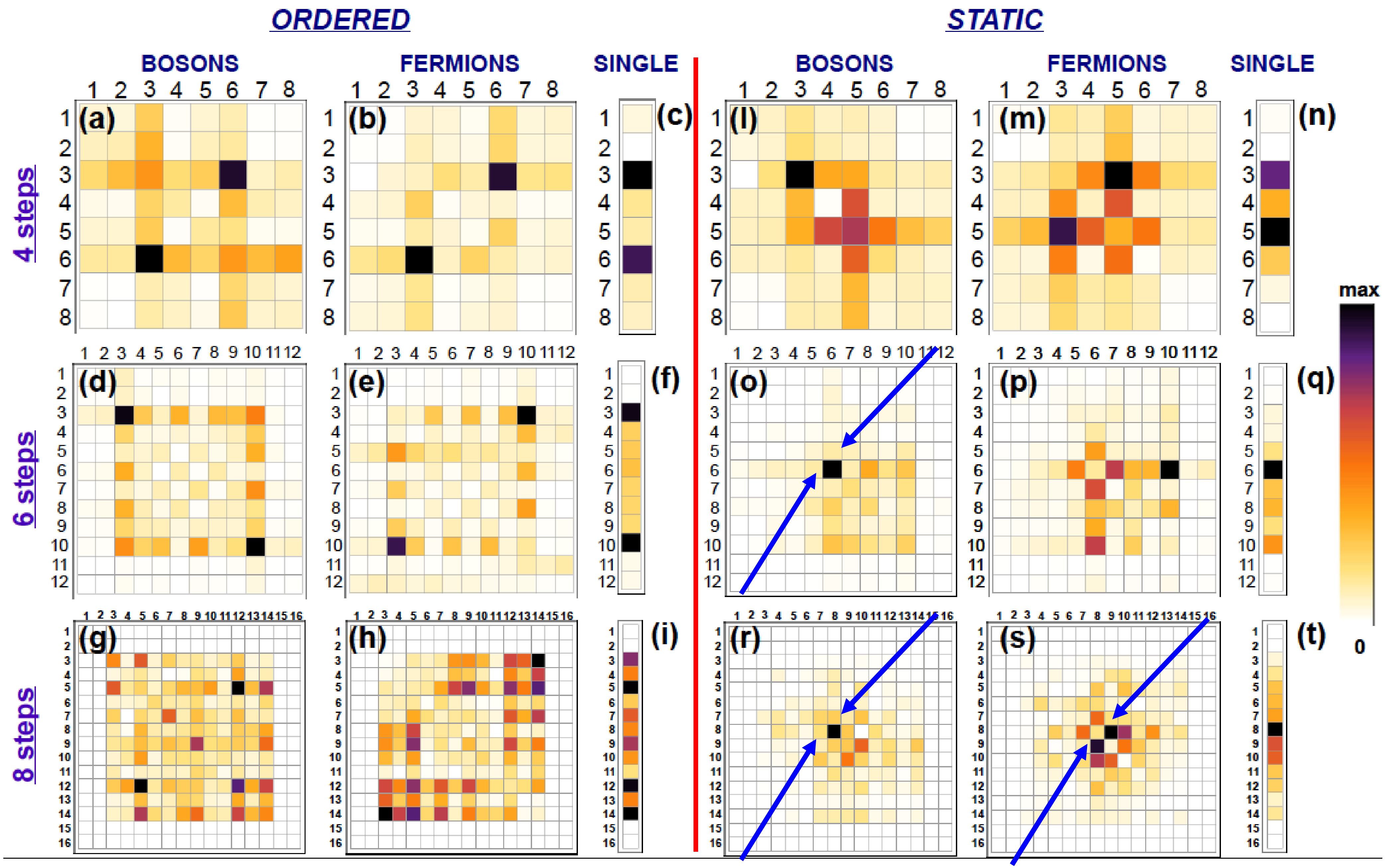
Theoretical investigation by Silberberg's group
Y. Lahini, et al., Phys. Rev. Lett. **105**, 163905 (2010).



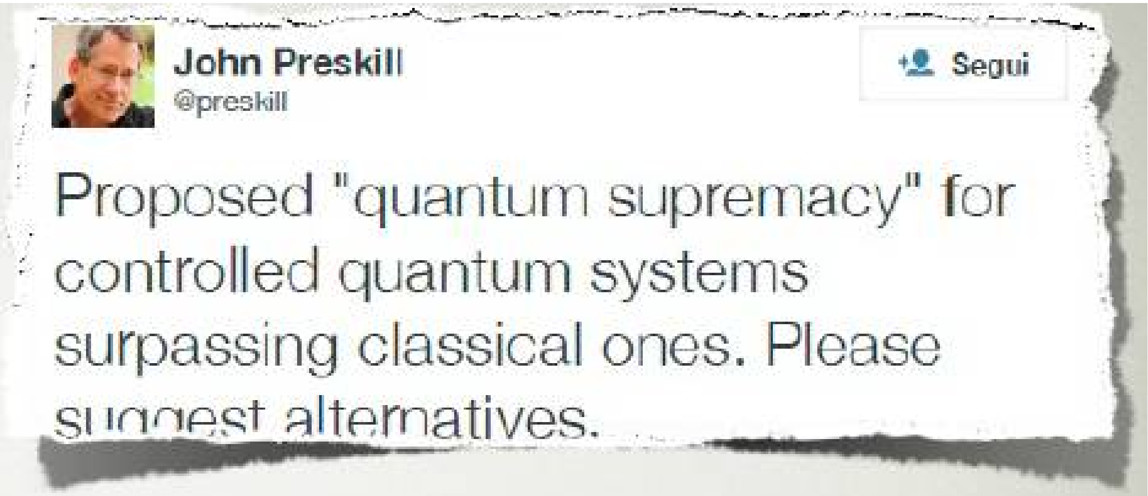
Ordered VS Static Quantum Walk: Experimental results



Ordered VS Static Quantum Walk: Experimental results



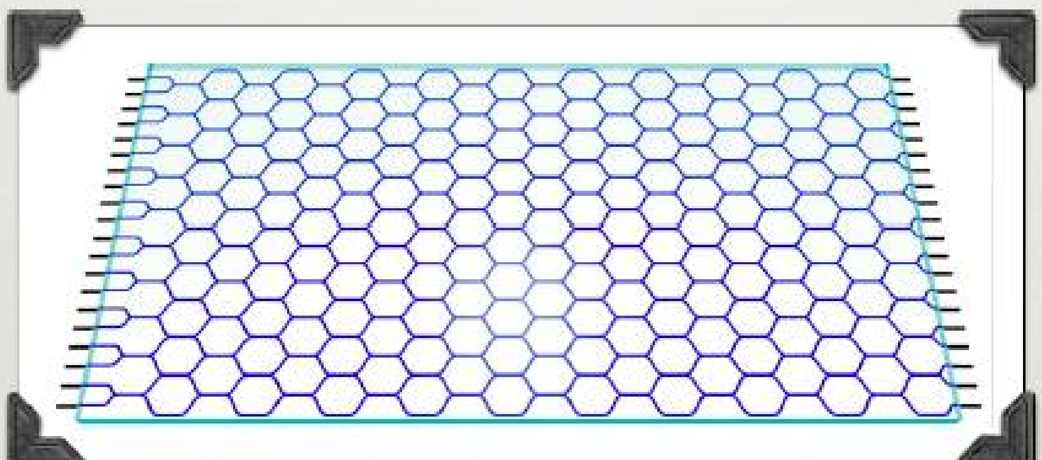
How to achieve QUANTUM SUPREMACY ??



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 ?

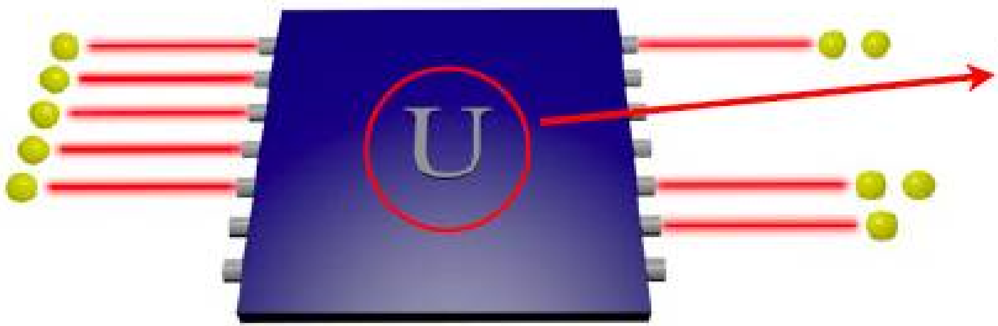
Answer: NO!!

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

The 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



Uniformly drawn

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

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

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

<u>classicaly hard</u>

input

output	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

The Boson Sampling

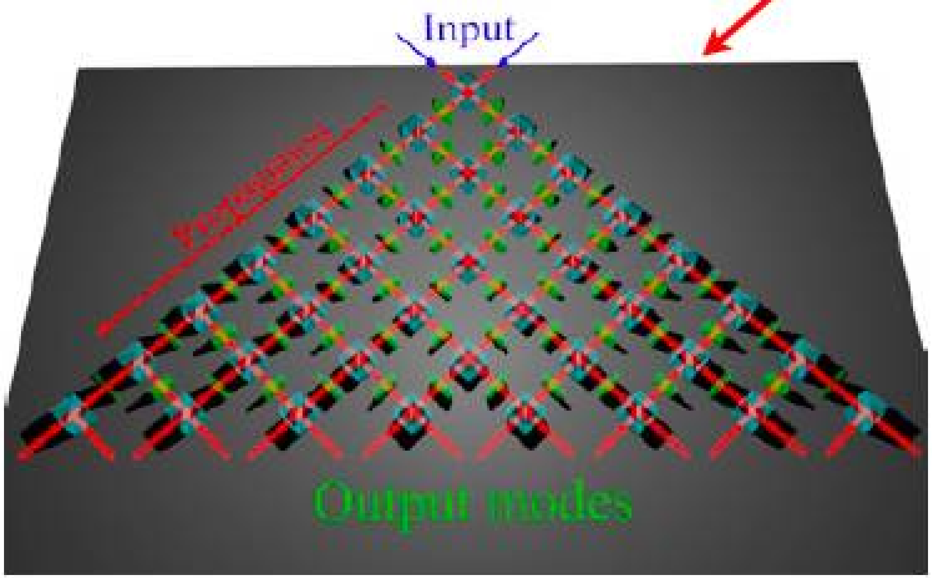
Photons naturally solve the BosonSampling problem

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

Required resources:

- Single-photon inputs
- Multimode interferometers
- Detection

n photons
m modes



Hard to implements with bulk optics

↓

Require a technological step recently available due to integrated photonics

Sapienza Università di Roma · Universidade Federal Fluminense · Consiglio Nazionale delle Ricerche · Politecnico Milano

University of Oxford · University of Southampton · University of London · Shanghai Jiao Tong University

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 $|\mathbf{T}\rangle$ 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

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]. Here, we demonstrate this model of computation using laser-written integrated quantum networks that were designed to implement unitary matrix transformations. We characterize the integrated devices using an *in situ* reconstruction method and observe three-photon interference[10–12] that leads to the boson-sampling output distribution. Our results set a benchmark for a type of quantum computer with the potential to outperform a conventional computer through the use of only a few photons and linear-optical elements[13].

More than a decade ago, Knill, Laflamme and Milburn (KLM) showed in their seminal work[14] that scalable photonic quantum computing is possible using only linear optical circuits, single-photon sources and detectors, and measurement-induced effective nonlinearities. The use of ancillary photons not only enables the heralding of successful gate operations[7,8], but also provides a basis for protocols in which probabilistic two-photon gates are teleported into a quantum circuit with high probability[15]. Despite impressive theoretical progress[16–19], the number of indistinguishable ancilla photons required for a universal optical quantum computer appears to be very challenging given current photonic quantum technology[20].

Several interesting intermediate models of quantum computation have been proposed recently[3–5]. Although they do not enable universal quantum computation, these models still provide a dramatic increase in computational speed for particular tasks. In contrast to the proposed KLM scheme, these models need neither entangling gate operations, adaptive measurements, nor ancilla photons, and are thus technically more feasible. The intermediate quantum computation model proposed by Aaronson and Arkhipov[6] seems to be extremely resource-efficient, as it utilizes the unique advantages of the mobility and bosonic nature of photons to solve the so-called sampling problems that are believed to be classically hard[13,21]. In general, sampling problems ask for random samples according to a specified probability distribution. The probability distributions and how they are specified depend on the problem class, such as the boson sampling problem considered in our work.

Here, we experimentally solve small instances of the boson-sampling problem by implementing Aaronson and Arkhipov's model of computation with non-interacting bosons, specifically 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

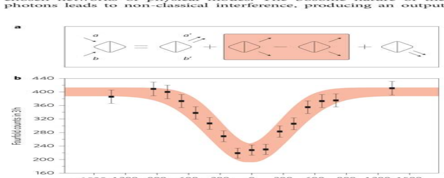


Figure 1 | Non-classical interference. a, Basic two-photon interference. When two indistinguishable photons enter a 50/50 beamsplitter, destructive interference of having both photons either transmitted or reflected (highlighted) leads to bunching such that both photons must be found together in one of the two output modes *a'* or *b'*. Therefore, the probability of finding two photons in different output modes is zero. This is described mathematically as the permanent of the 50/50 beamsplitter unitary. **b**, Example of experimental three-photon interference. Three photons were injected into input modes 3, 4 and 5 of one of our optical networks. We measured fourfold coincidence counts between a trigger detector and output modes 2, 4 and 5 of our device, while simultaneously delaying the input photons in modes 4 and 5. The dip shows a clear signature of genuine three-photon interference. The error for the experimental data follows a Poissonian distribution of the measured counts. The shaded area represents the Gaussian fit including errors.

[1]Faculty of Physics, University of Vienna, Boltzmanngasse 5, A-1090 Vienna, Austria, [2]Institute for Quantum Optics and Quantum Information, Austrian Academy of Sciences, Boltzmanngasse 3, A-1090 Vienna, Austria, [3]Institute of Applied Physics, Abbe Center of Photonics, Friedrich-Schiller Universität Jena, Max-Wien-Platz 1, D-07743 Jena, Germany. *e-mail: max.tillmann@univie.ac.at; walther-office@univie.ac.at

Massachusetts Institute of Technology · The University of Queensland, Australia

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

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

Photonic Boson Sampling in a Tunable Circuit

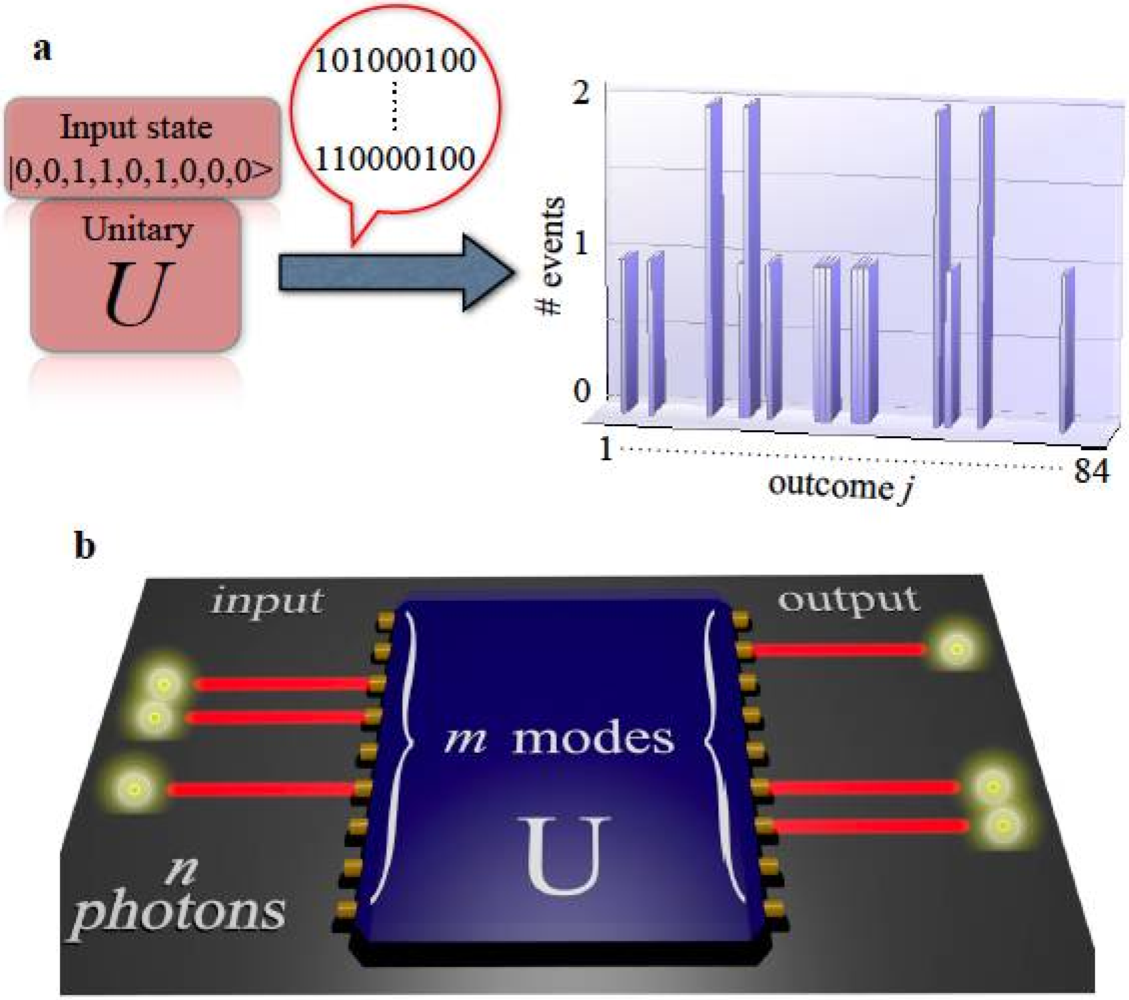
Matthew A. Broome,[1,2]* Alessandro Fedrizzi,[1,2] Saleh Rahimi-Keshari,[2] Justin Dove,[3] Scott Aaronson,[3] Timothy C. Ralph,[2] Andrew G. White[1,2]

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

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

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

Boson Sampling on a chip



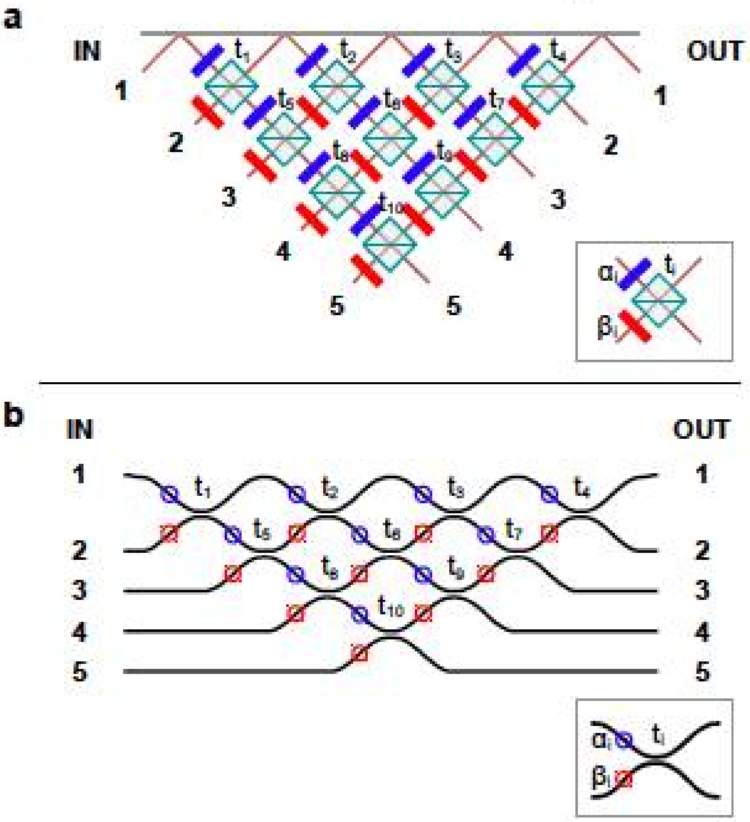
« Small-scale quantum computers made from an array of interconnected waveguides on a glass chip can now perform a task that is considered hard to undertake on a large scale by classical means. »

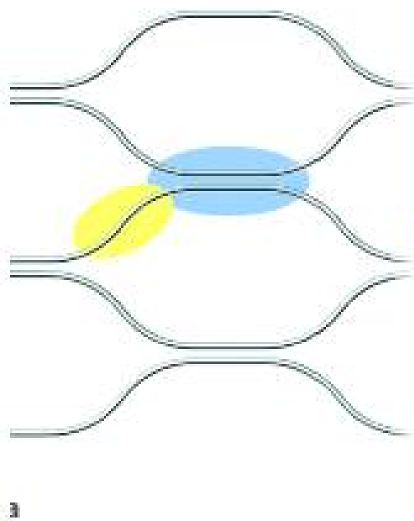
T. Ralph, News & Views, *Nature Photonics* **7**, 514 (2013)

Boson Sampling: chip

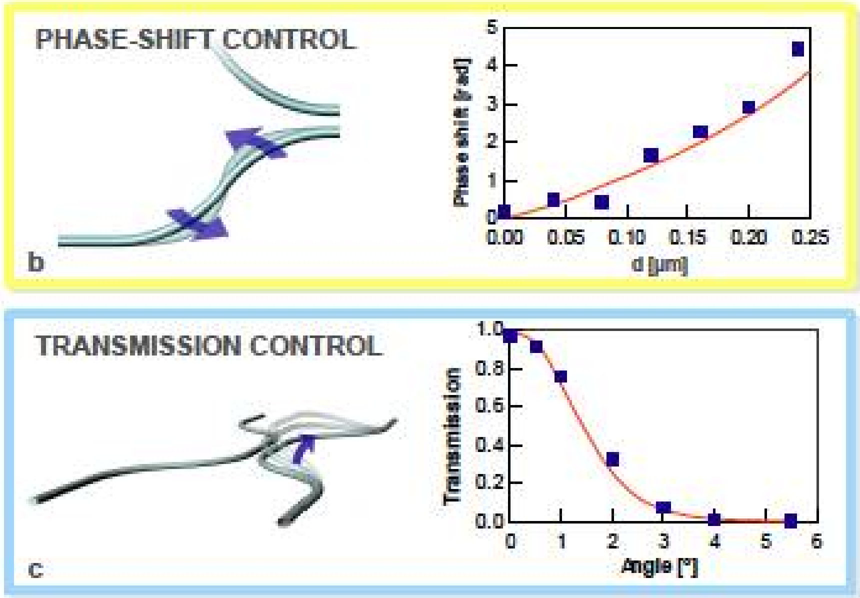
Requirement for Boson Sampling - design arbitrary interferometers → Requires independent control of phases and beam-splitter operation

Architecture for arbitrary unitary

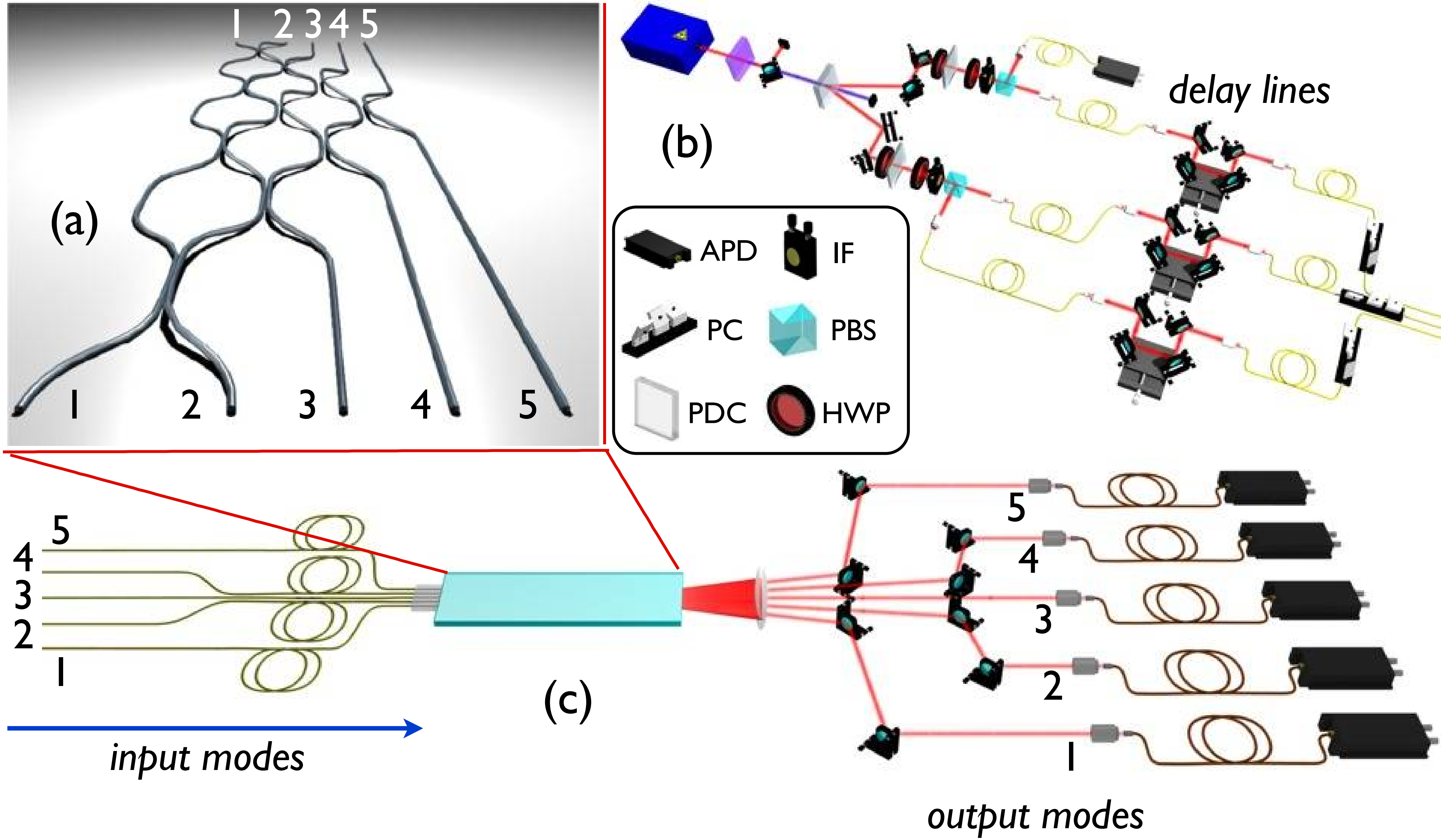




Fabrication process



Boson Sampling: apparatus

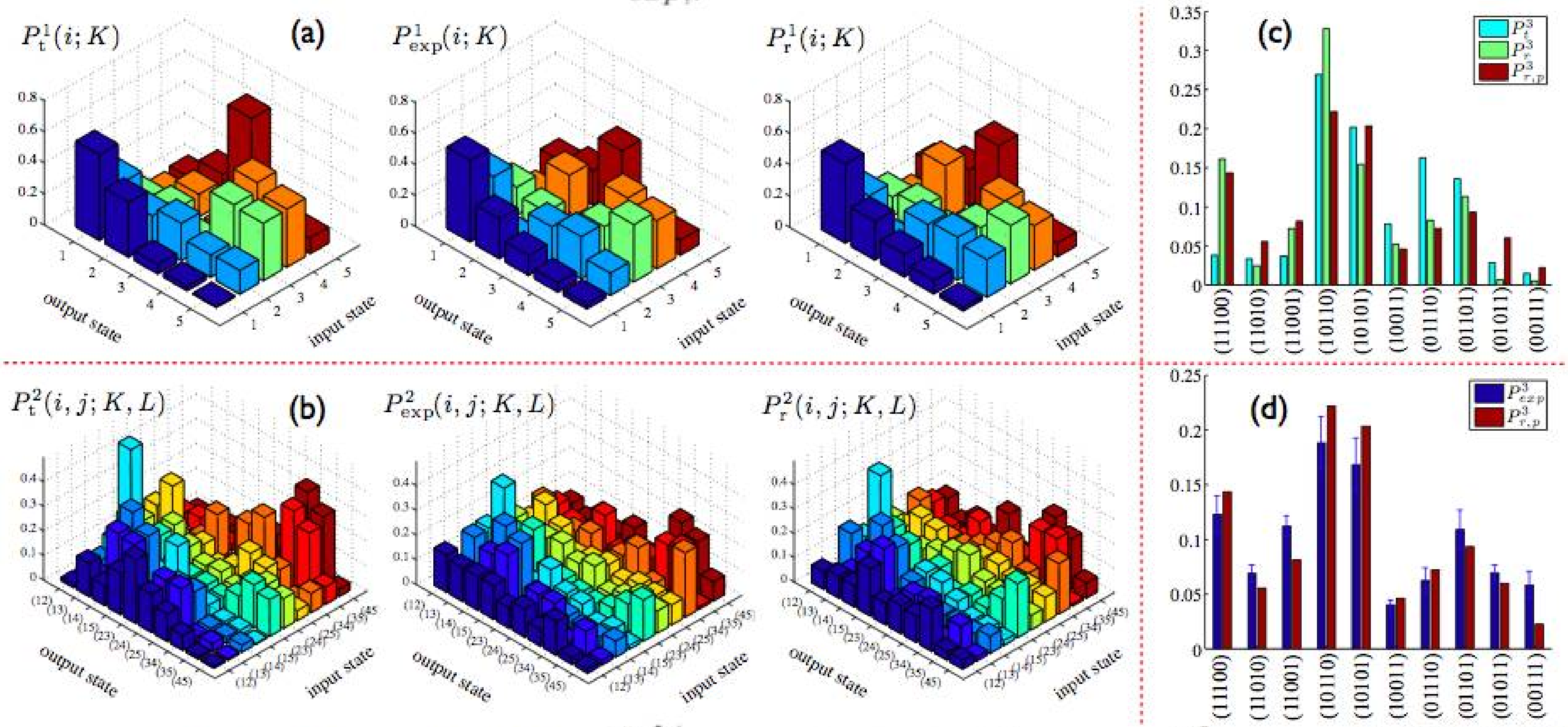


A. Crespi, R. Osellame, R. Ramponi, D. J. Brod, E. F. Galvao, N. Spagnolo, C. Vitelli, E. Maiorino, P. Mataloni, F. Sciarrino, *Integrated multimode interferometers with arbitrary designs for photonic boson sampling*, Nature Photonics 7, 545 (2013).

Experimental Boson Sampling

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

Three-photon probabilities



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

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

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

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

Validation of Boson Sampling....

Boson Sampling: hard problem with classical computer

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

Validation of Boson Sampling....

Boson Sampling: hard problem with classical computer

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

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

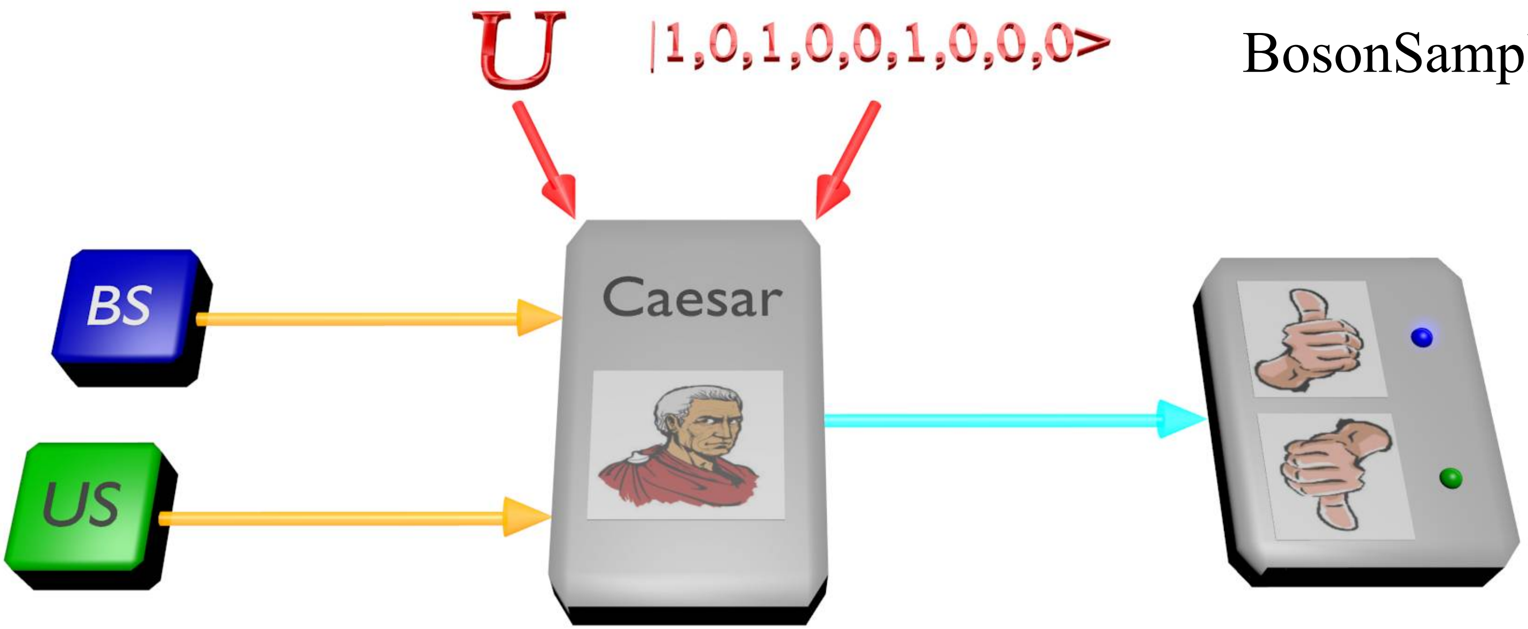
Dahlem Center for Complex Quantum Systems, Freie Universität Berlin, 14195 Berlin, Germany

C. Gogolin, M. Kliesch, L. Aolita, J. Eisert, arXiv:1306.3995 (2013)

Distinguishing Boson Sampling from Uniform

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

BosonSampling input



Validation stage

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

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

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

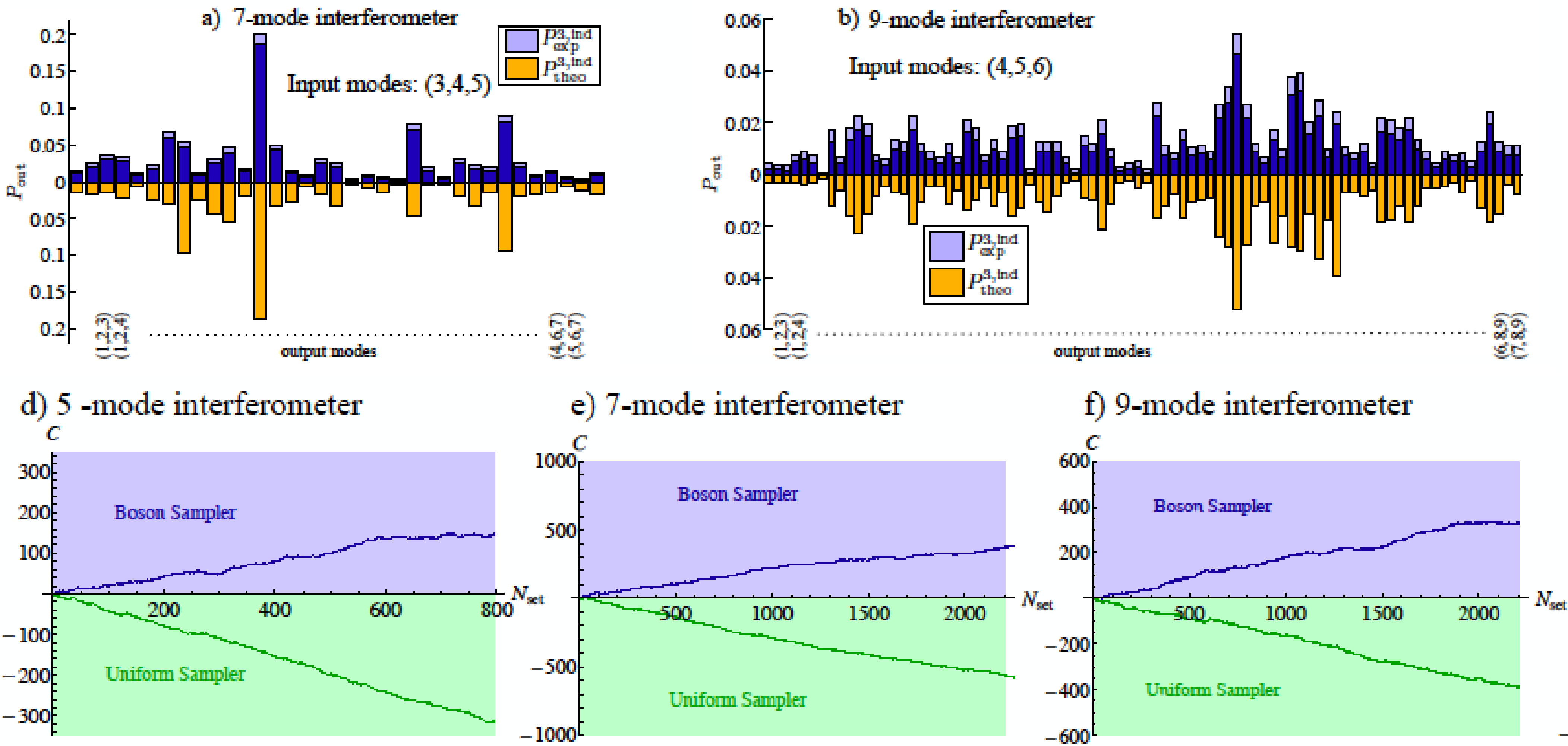
computationally efficient

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

Else UniformSampler

S. Aaronson and A. Arkhipov, arXiv:1309.7460 (2013)

Experimental Results - 1



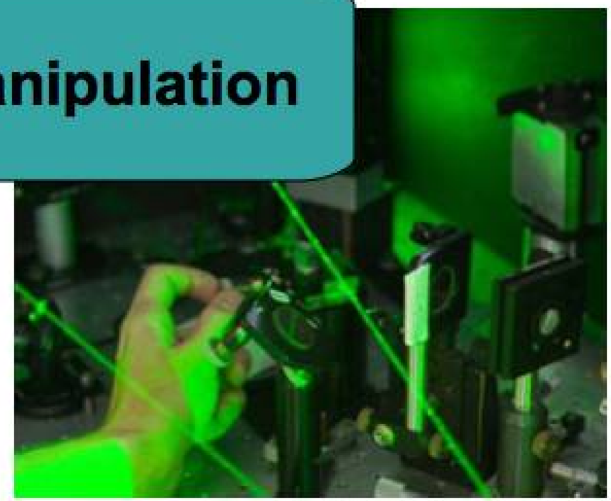
The BosonSampling distribution can be efficiently discriminated from the Uniform

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, arXiv:1311.1622 (2013)

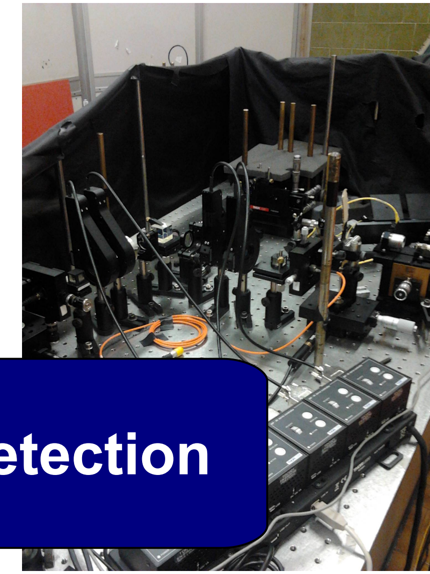
Integrated quantum photonics

Preparation

Manipulation



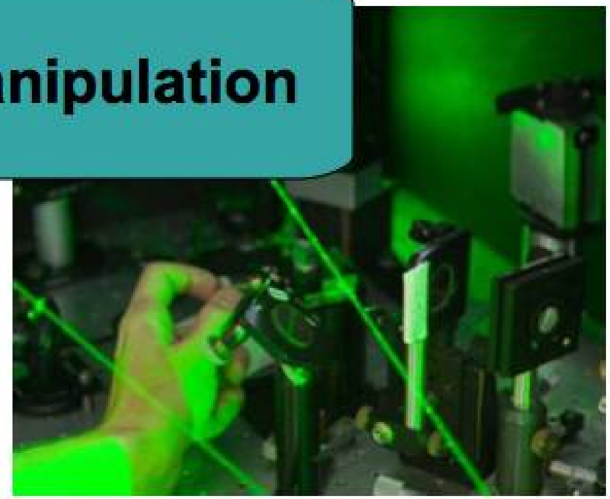
Detection



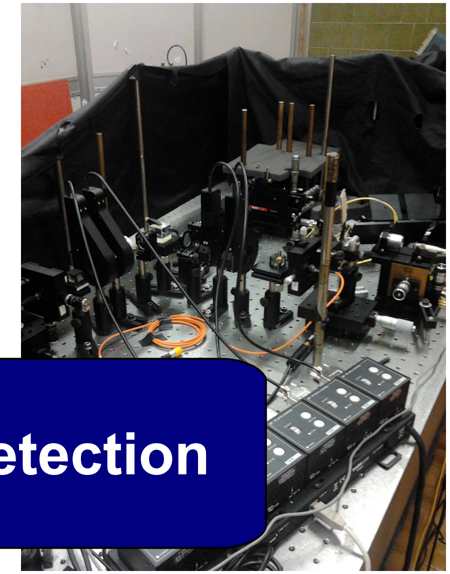
Integrated quantum photonics

Preparation

Manipulation

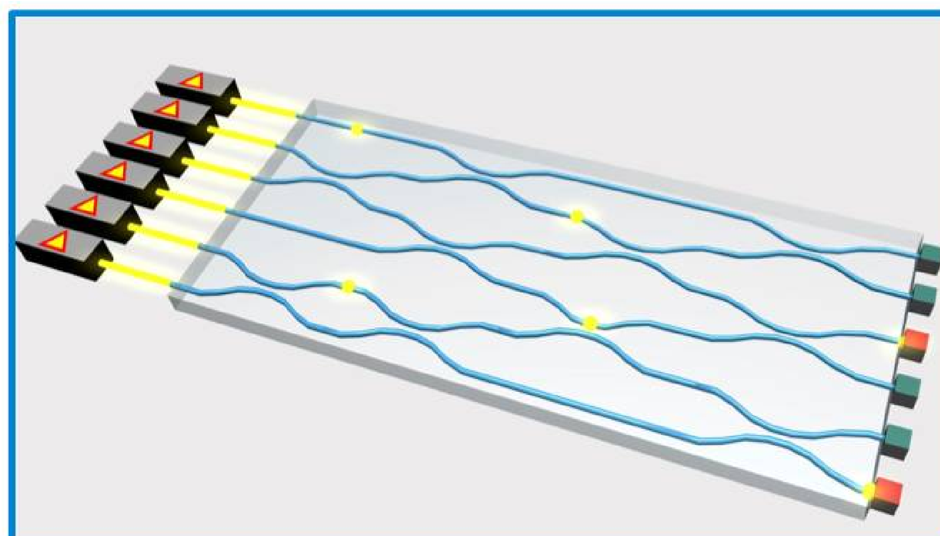


Detection



- Single photon sources
- Manipulation
- Single photon detectors

ON THE SAME CHIP



PICQUE

Marie Curie
Initial Training Network (ITN)

www.picque.eu

MARIE CURIE ACTIONS

PICQUE project:
« Photonic Integrated Compound Quantum Encoding »

seit 1558

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ADAPTICA

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SINGLE QUANTUM

SISTEMI FORMATIVI CONFINDUSTRIA

ma per seguir virtute e canoscenza
SISSA

Summary

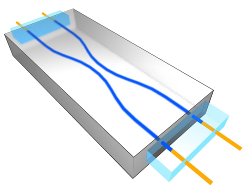
Integrated devices

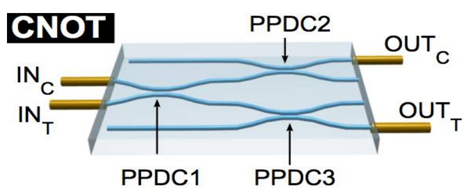
Polarization independent

Polarization dependent

Beam Splitter

CNOT





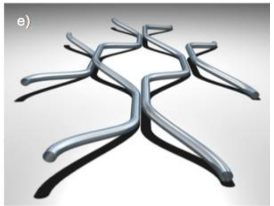
Phys. Rev. Lett. **105**, 200503 (2010)

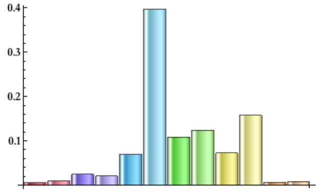
Nat. Comm. **2**, 566 (2011)

Quantum simulation

Ordered systems

Disordered Systems Phase Control





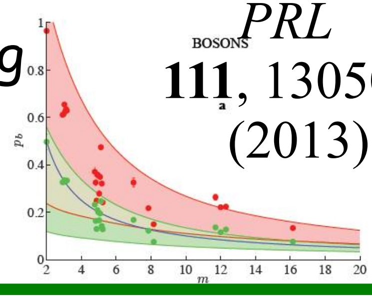
Phys. Rev. Lett. **108**, 010502 (2012)

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

Bosons Sampling and Birthday Paradox

Boson Sampling On chip

Nat. Phot. 7, 545 (2013)

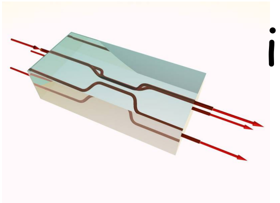


PRL **111**, 130503 (2013)

3D devices

Integrated tritter

Nat. Com. 4, 1606 (2013)



3d interferometry

Sc. Reports 2, 862 (2012)

www.3dquest.eu