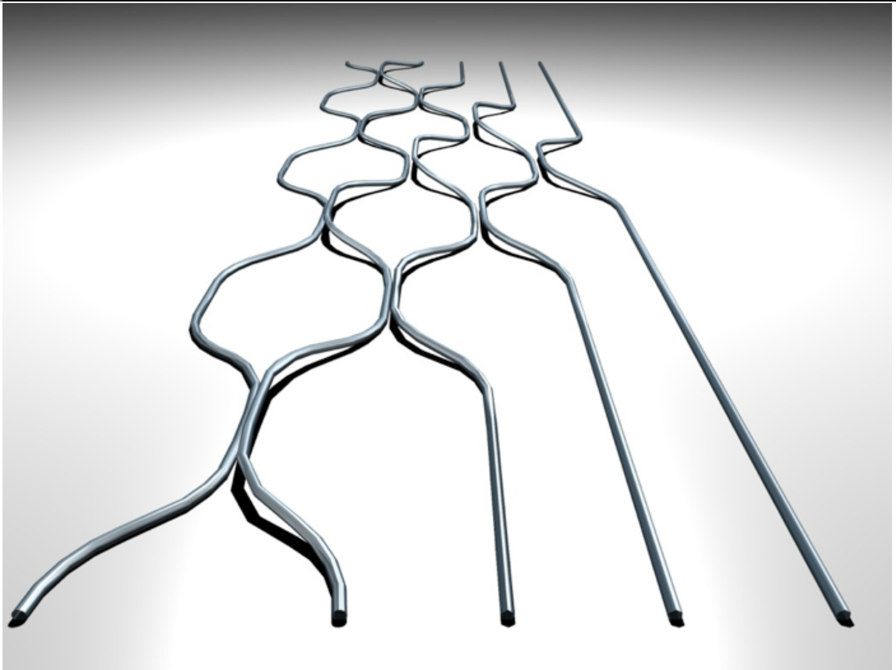

Integrated waveguide photonics circuits for quantum simulation and beyond

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Dipartimento di Fisica,
Sapienza Università di Roma

http:\\quantumoptics.phys.uniroma1.it

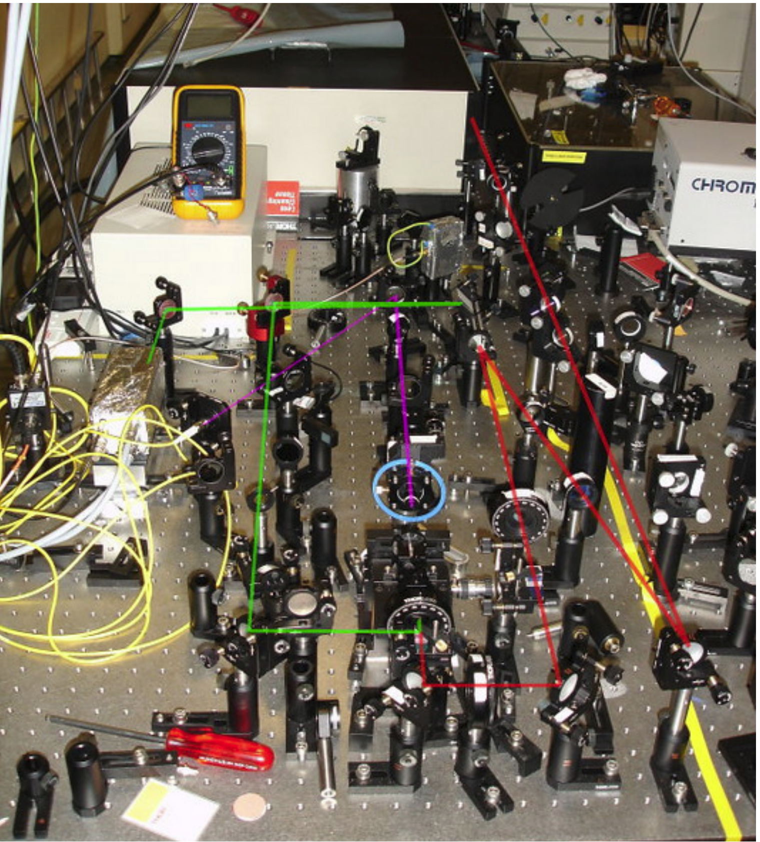
Dipartimento di Fisica Pavia, 25 Febbraio 2016

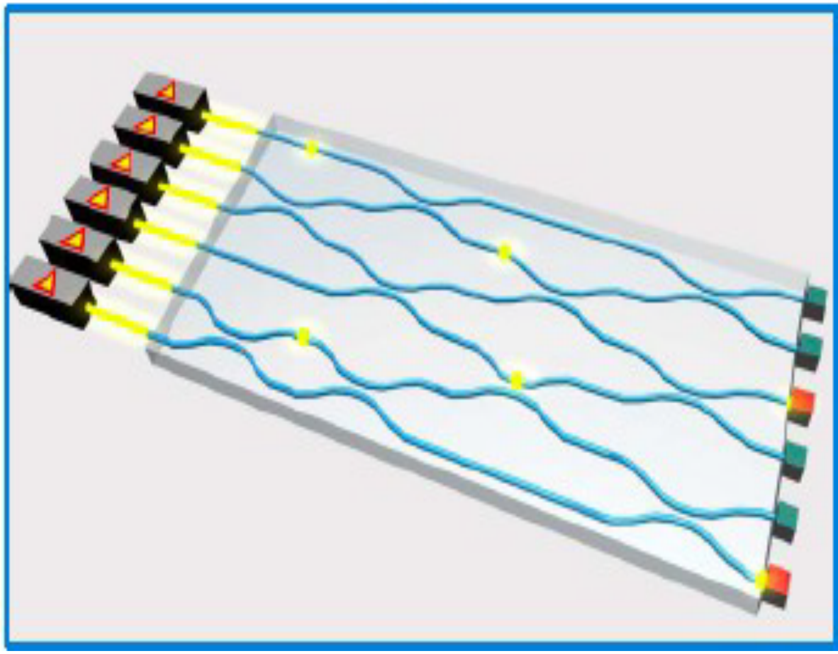
Integrated photonic quantum circuits

A new scenario for photonic quantum information processing

Complex optical setup affected by:

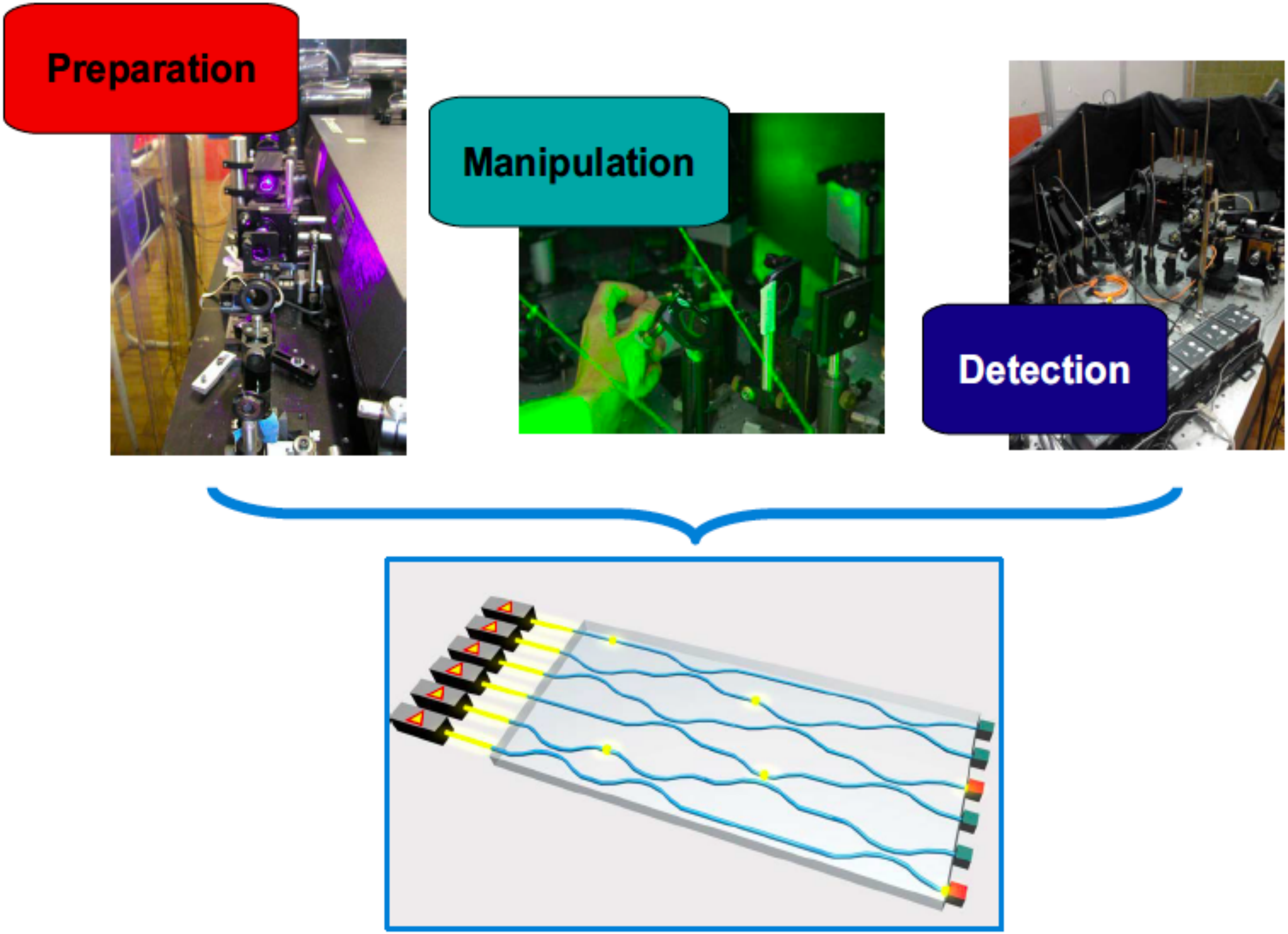
✓ Large physical size
✓ Low stability
✓ Difficulty to move forward applications outside laboratory





A. Politi et al., Science 320, 646 (2008)

On-chip integrated setup



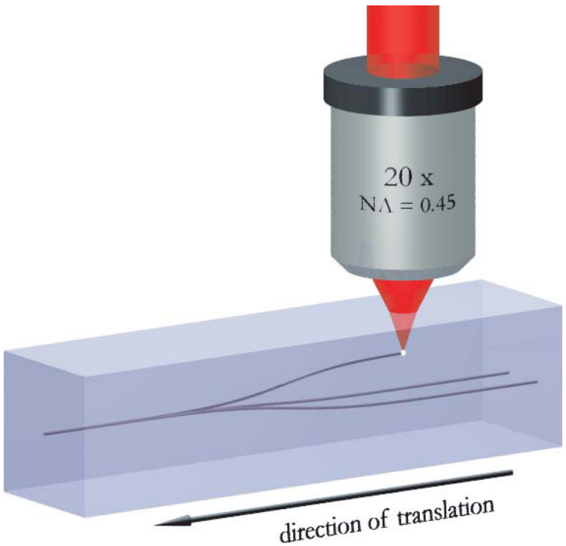
Femtosecond laser writing

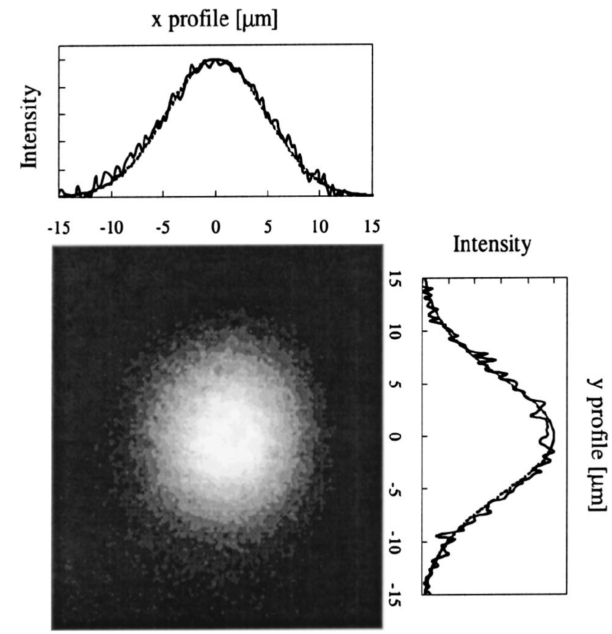
3-D capability

Rapid device prototyping:
writing speed = 4 cm/s

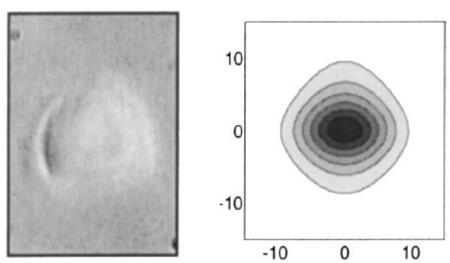
Propagation of circular
gaussian modes

Main features





Circular waveguide
transverse profile

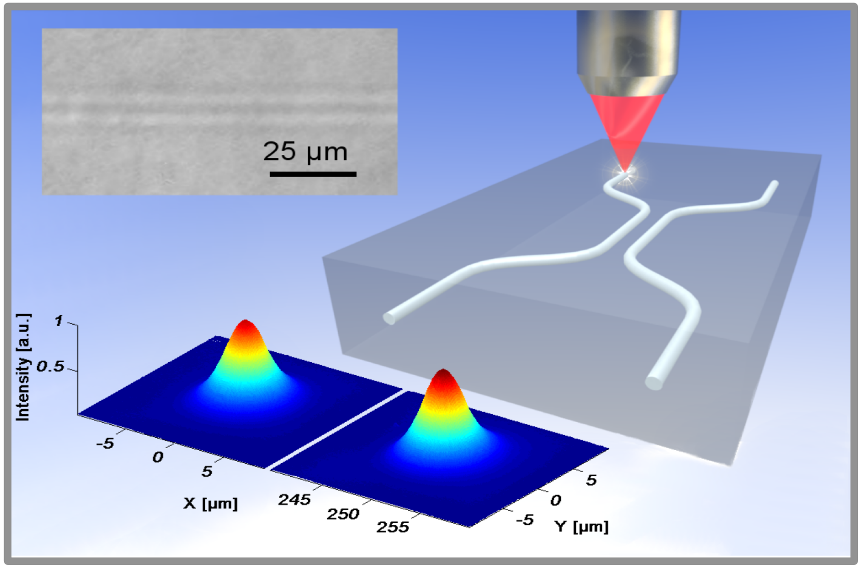


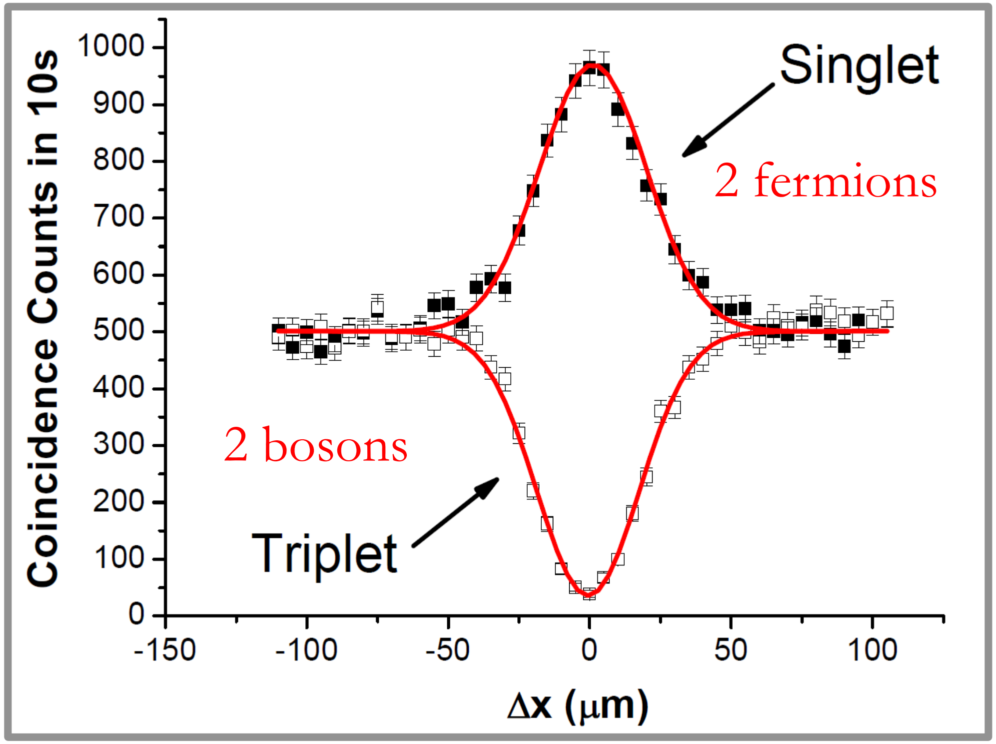
Low birefringence

ABLE TO SUPPORT ANY POLARIZATION STATE

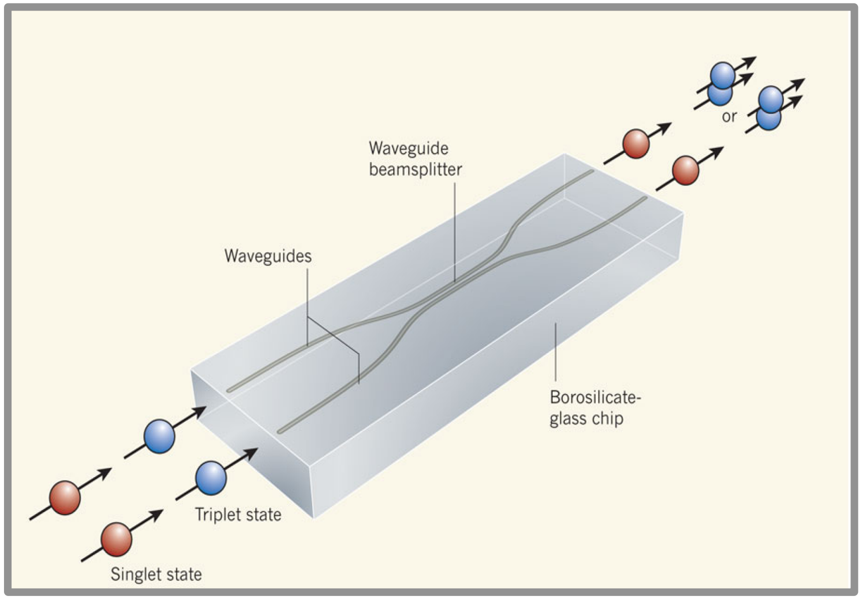
On-chip integrated directional coupler

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





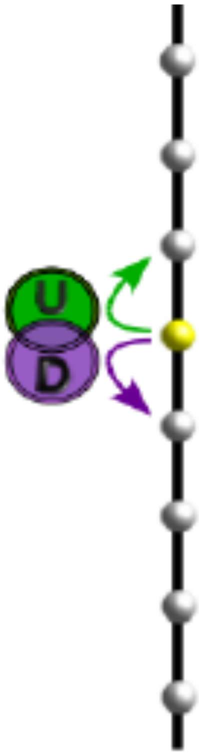
L. Sansoni *et al. Phys. Rev. Lett.* **105**, 200503 (2010)



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

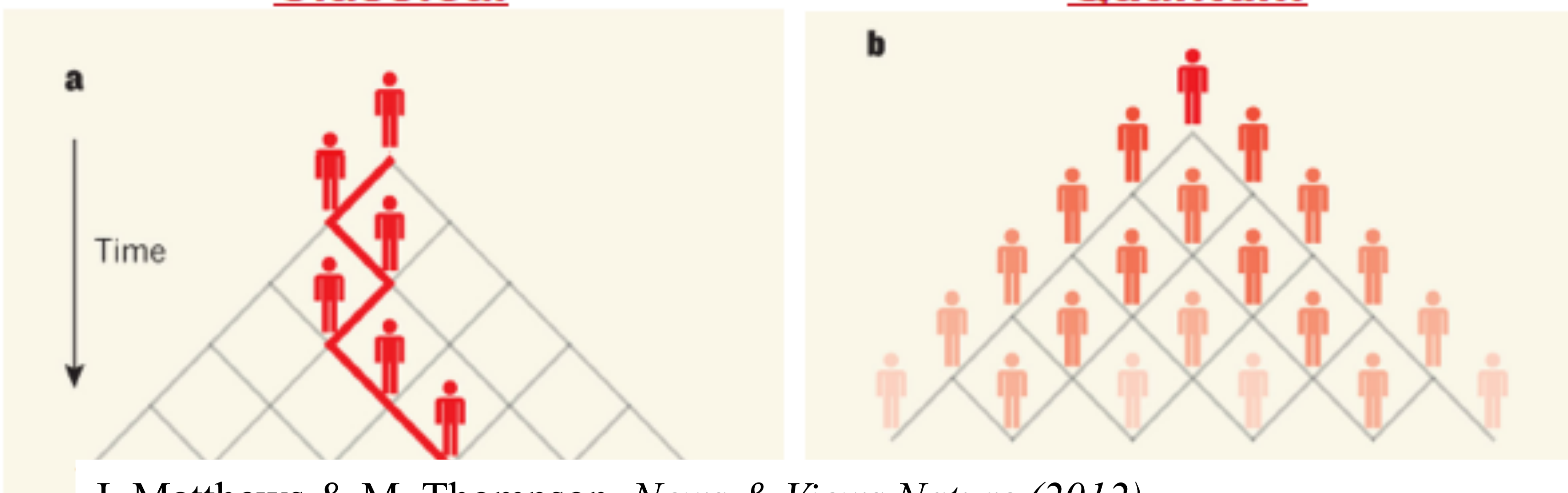
Goal: simulate the dynamics of non-interacting bosons/fermions in complex interferometric structures

Discrete time Quantum Walk

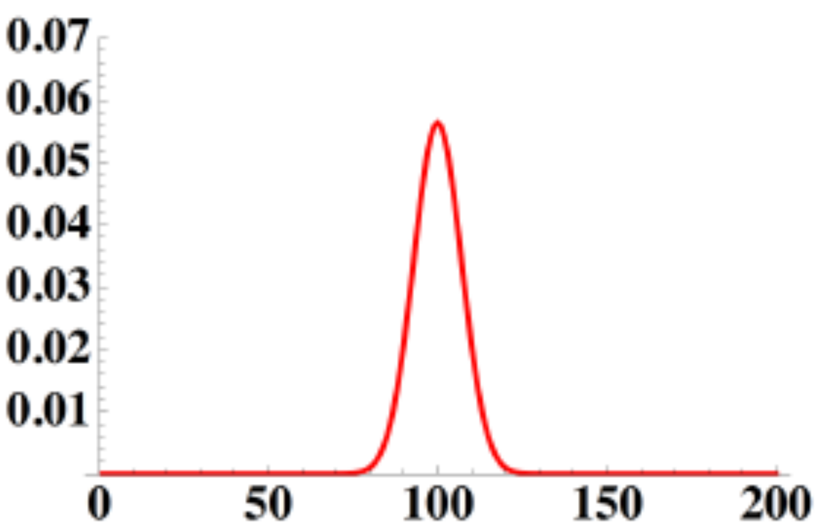


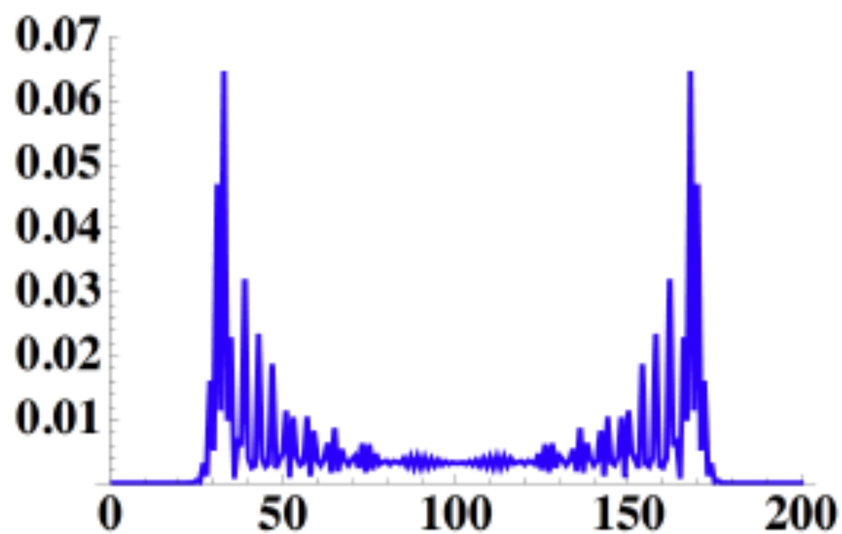
Quantum walk: extension of the classical random walk:
a walker on a lattice "jumping" between different sites with given probability

Classical **Quantum**

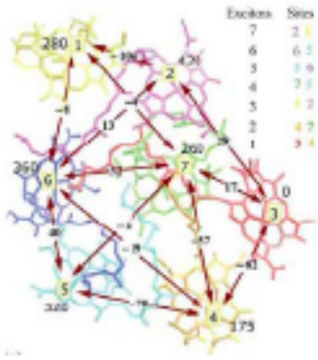


J. Matthews & M. Thompson, *News & Views Nature (2012)*





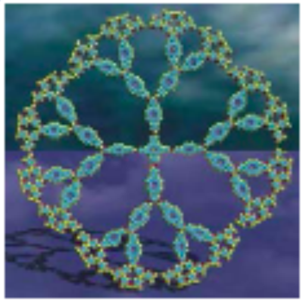
Why Quantum Walks?



Energy transfer: within photosynthetic systems can display quantum effects such as delocalized excitonic transport which can be simulated by QW.

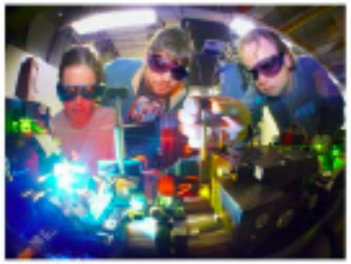
Controlled transition from Classical to Quantum: QW can be employed for testing the transition from the quantum to the classical world by applying a controlled degree of decoherence.

QW?

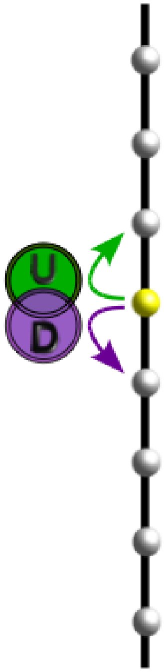


Light-harvesting molecule is efficient at concentrating light at its center as quantum walk reaches the target vertex exponentially faster than a classical walk: because of destructive interference between the paths that point backward, toward the leaves.

Faster quantum Computation: It has been theoretically proven that QWs allow the speed-up of search algorithms



Discrete time Quantum Walk



In a discrete Quantum Walk one or more quantum particles evolve on a graph with their evolution governed by their internal quantum coin (QC) states

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

Walk evolution described by the operator:

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

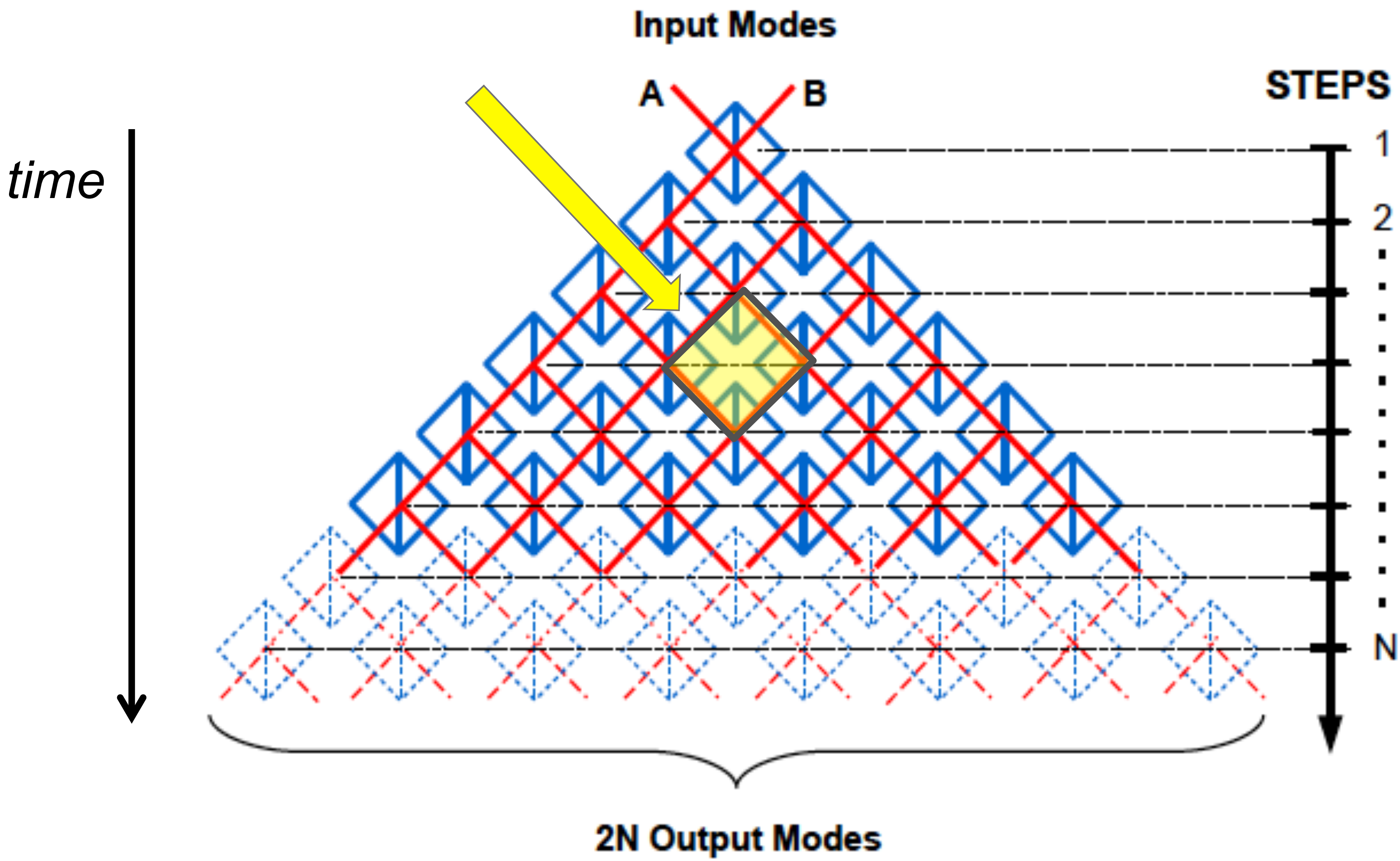
Experimental platforms:

Ion trap
F. Zahringer *et al.*,
*PRL **104** 100503 (2010)*

Fiber loops
A. Schreiber *et al.*,
*PRL **104** 050502 (2010)*
2D QW: Science (2012)

Coupled waveguides
A. Peruzzo *et al.*,
*Science **329** 1500 (2010)*

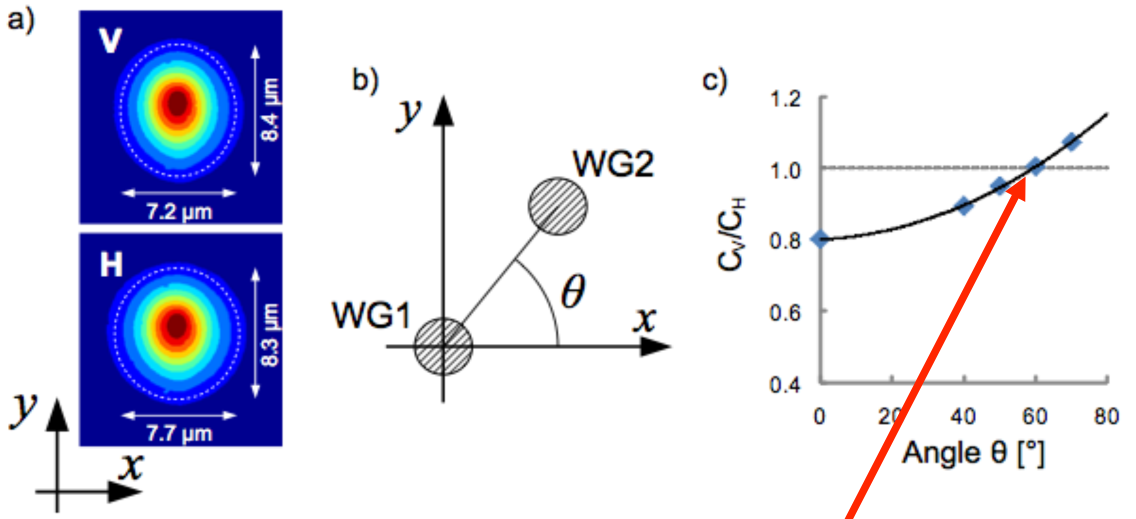
Photonic QW

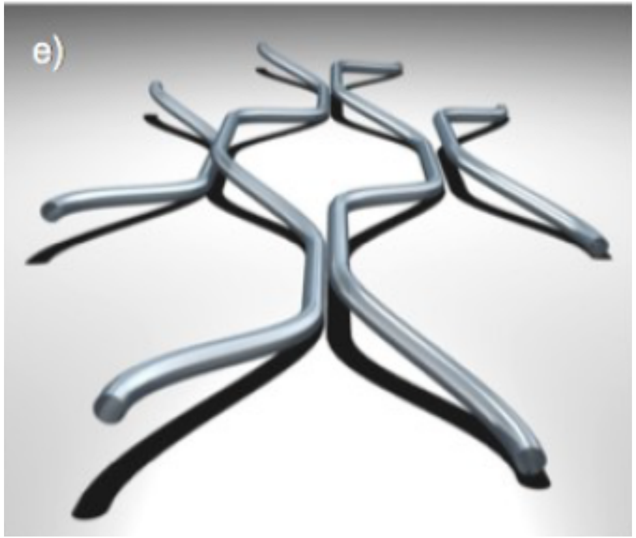


Feasible with integrated photonic waveguides

Polarization independent QW

V-mode slightly larger than the H-mode along the y axis:
Use 3D capability to improve the on-chip devices





$R_H = R_V$

- 3D array of beamsplitters with balanced reflectivities $R_H = R_V = 49\%$ able to support any polarization state.
- Path lengths controlled up to few nanometers: complete control of phase difference.

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

2-particle QW

The symmetry of two travelling quantum walkers influences the output probability distribution

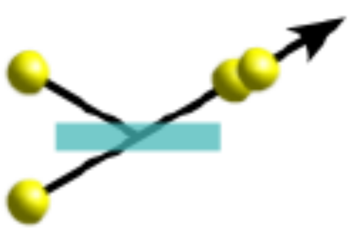
Polarization independent integrated beam splitter

Exploit polarization entanglement to change the symmetry of two-particle wavefunction

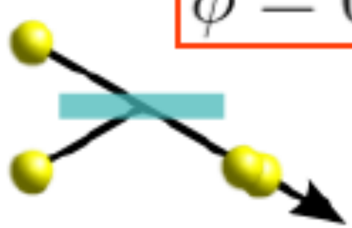
$$|\Psi^{\phi}\rangle = \frac{1}{\sqrt{2}}(|H\rangle_A|V\rangle_B + e^{i\phi}|V\rangle_A|H\rangle_B)$$

Bosons

$\phi = 0$

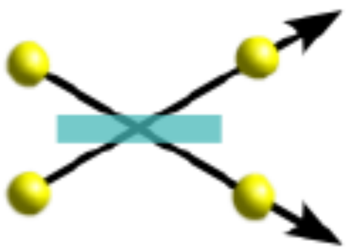


or

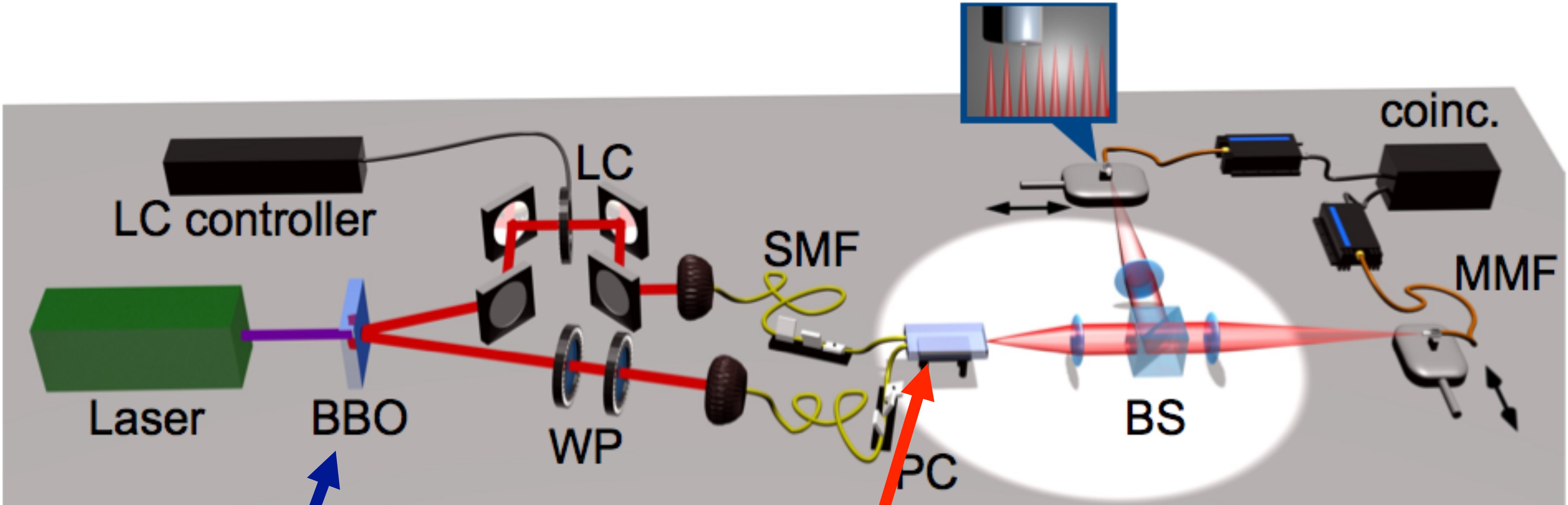


Fermions

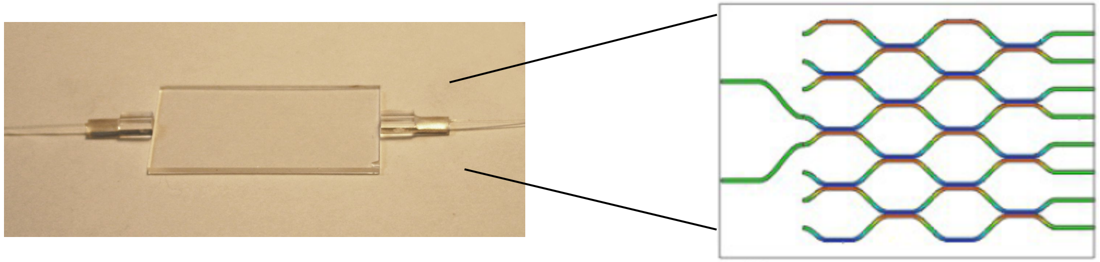
$\phi = \pi$



The experiment



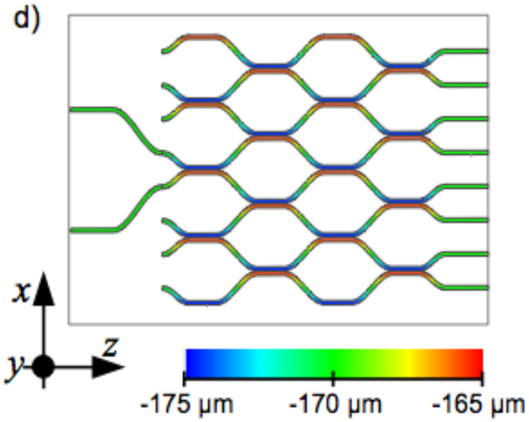
On chip BS array

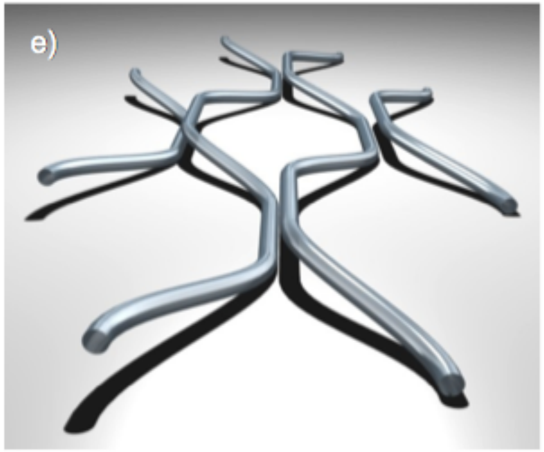


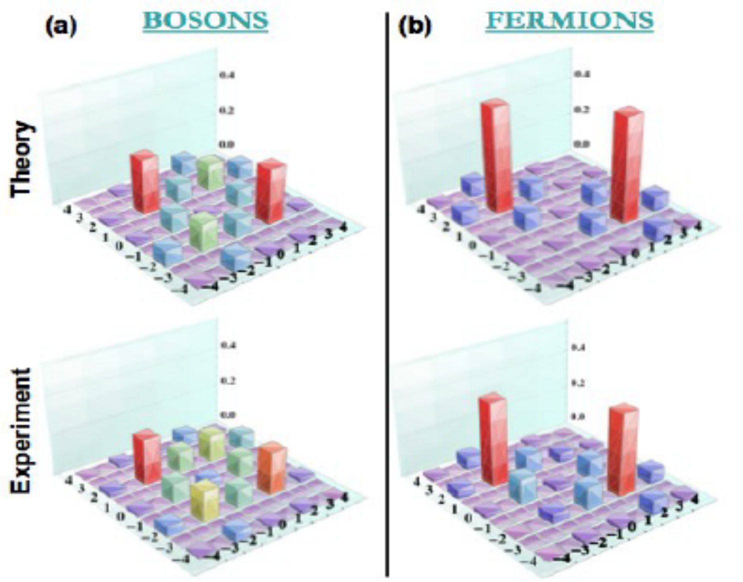
2-photon entangled states with different symmetries

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

Integrated Quantum Walk

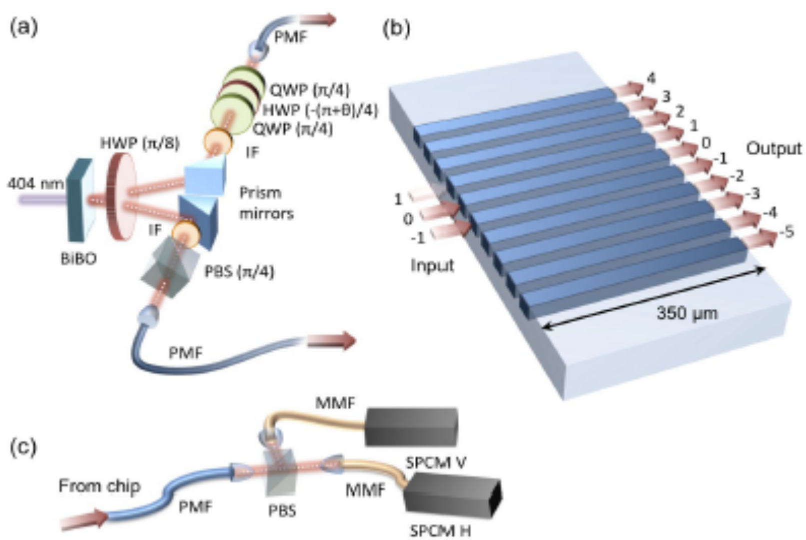






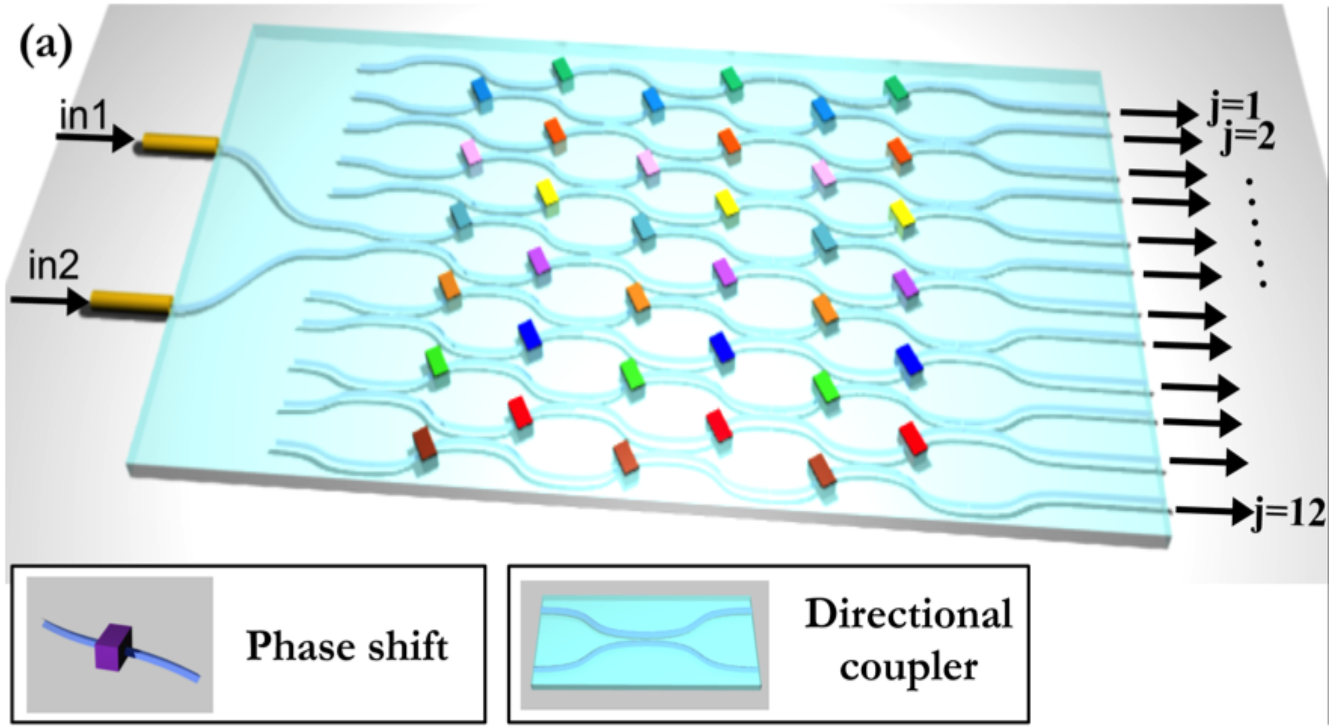
L. Sansoni et al. PRL (2012)
Discrete time QW. Mimic bosonic/fermionic behaviour using two entangled photons

S = 0.982 ± 0.002 **S = 0.973 ± 0.002**

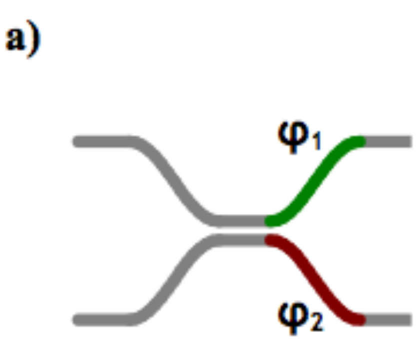


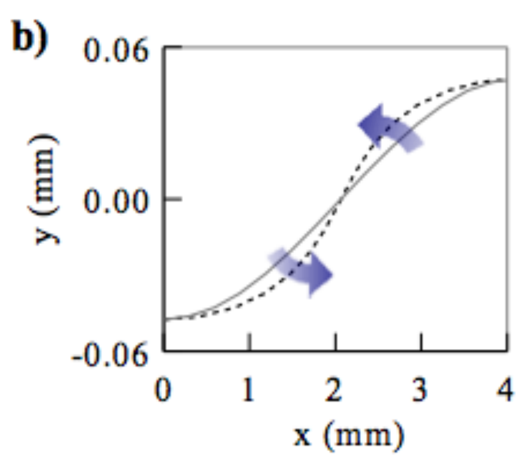
J.C.F. Matthews et al. Sci. Rep. (2013)
Simulation of fermionic statistics

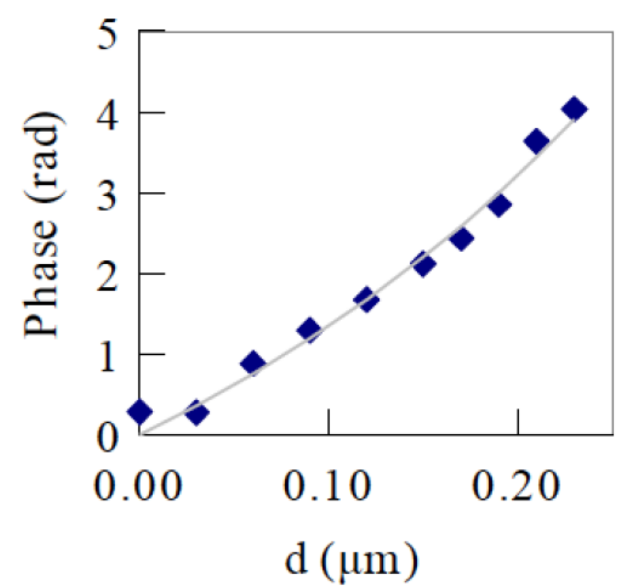
Disorder control in a QW



Phase shift induced by path variation



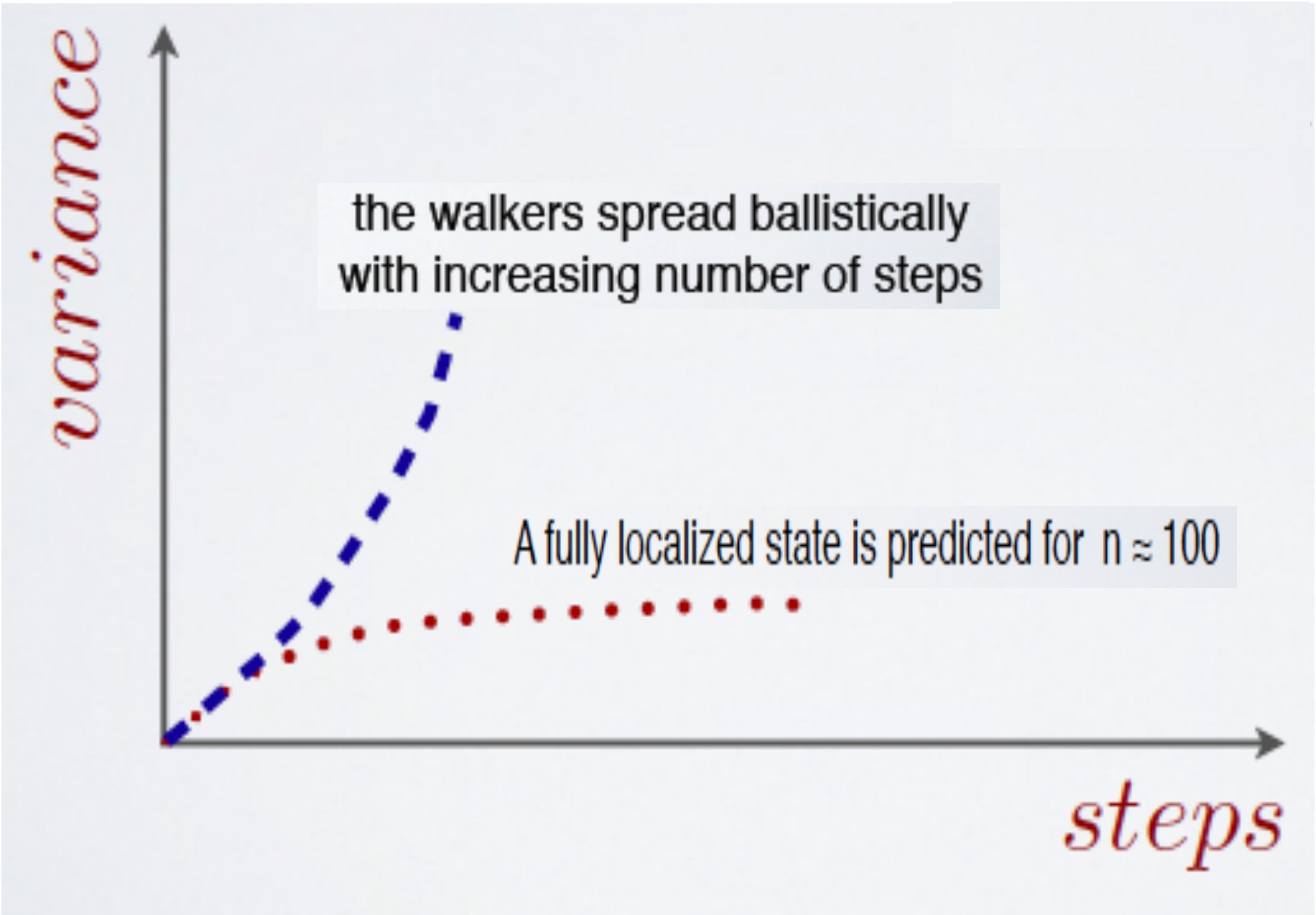




Ordered vs. disordered lattices

By realizing different phase maps the pure role of symmetries in different diffusion processes of two non-interacting bosons/fermions may be investigated.

Measure the variance of the distribution

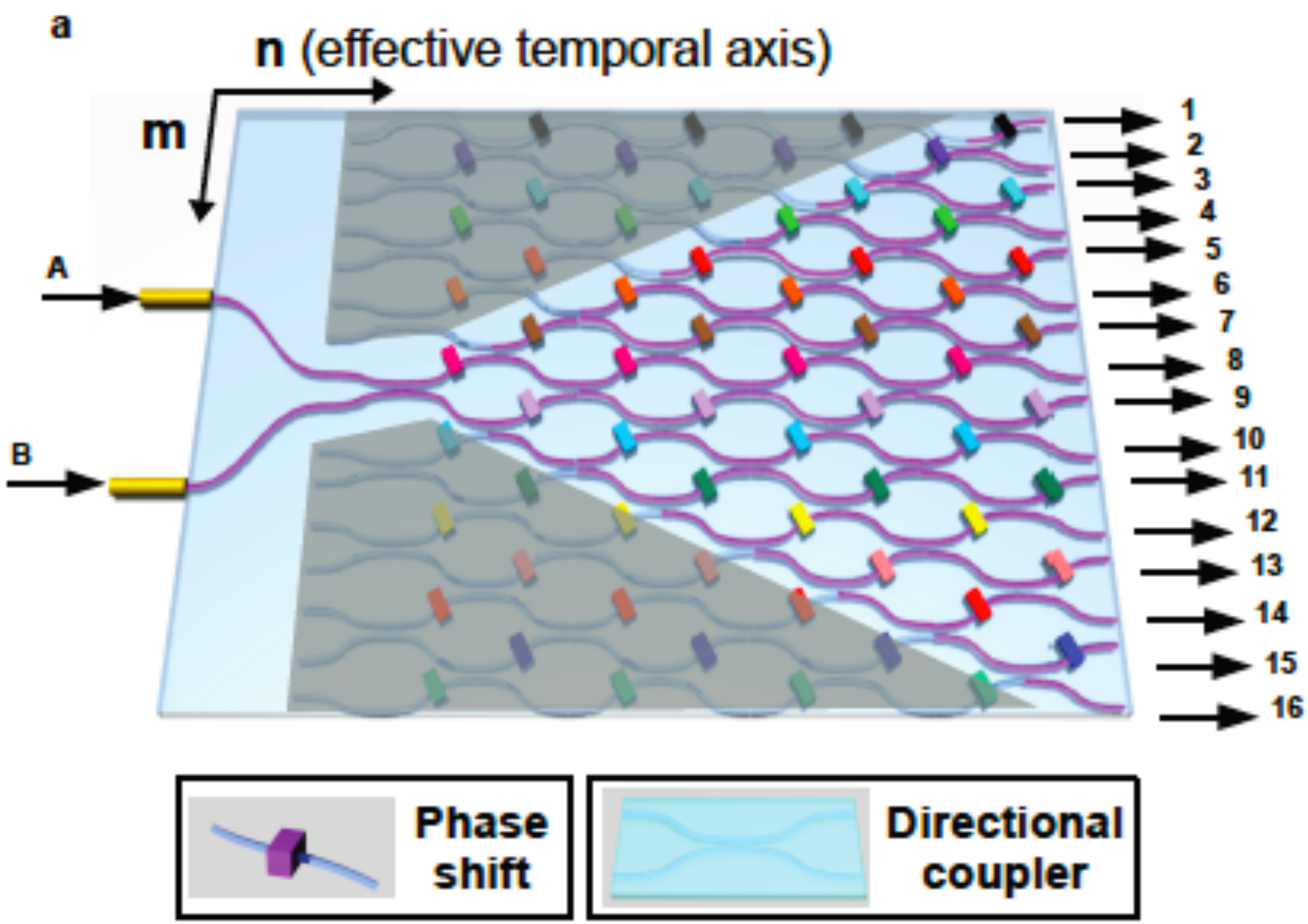


Static disorder

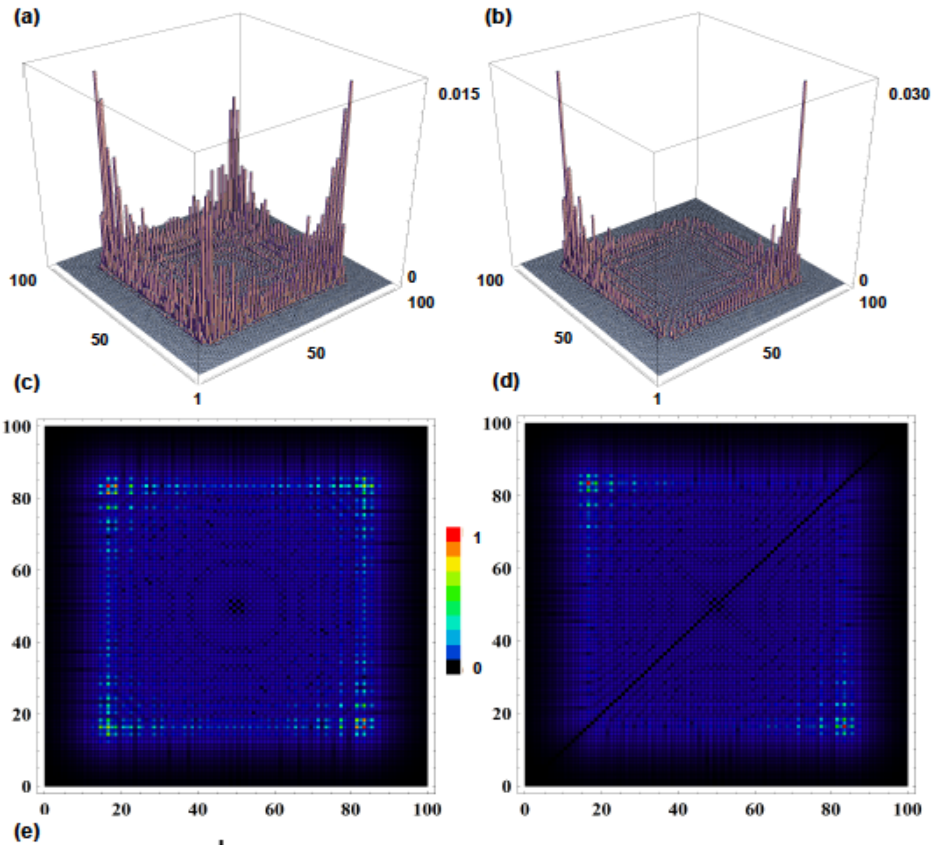
Disorder depending
- on site
- but NOT on time

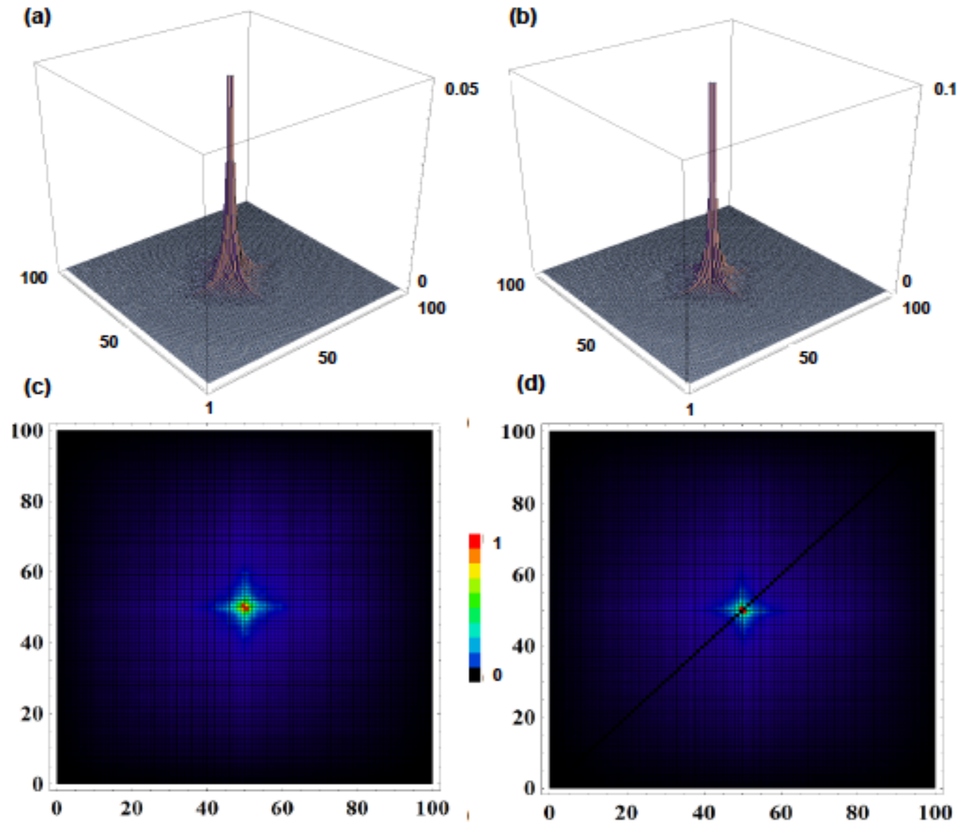
→ ***Anderson localization of the quantum particle wavefunction***

Up to 64 polarization independent BSs and phase-shifters



2-particle QW: theoretical distributions





2 Bosons **2 Fermions**

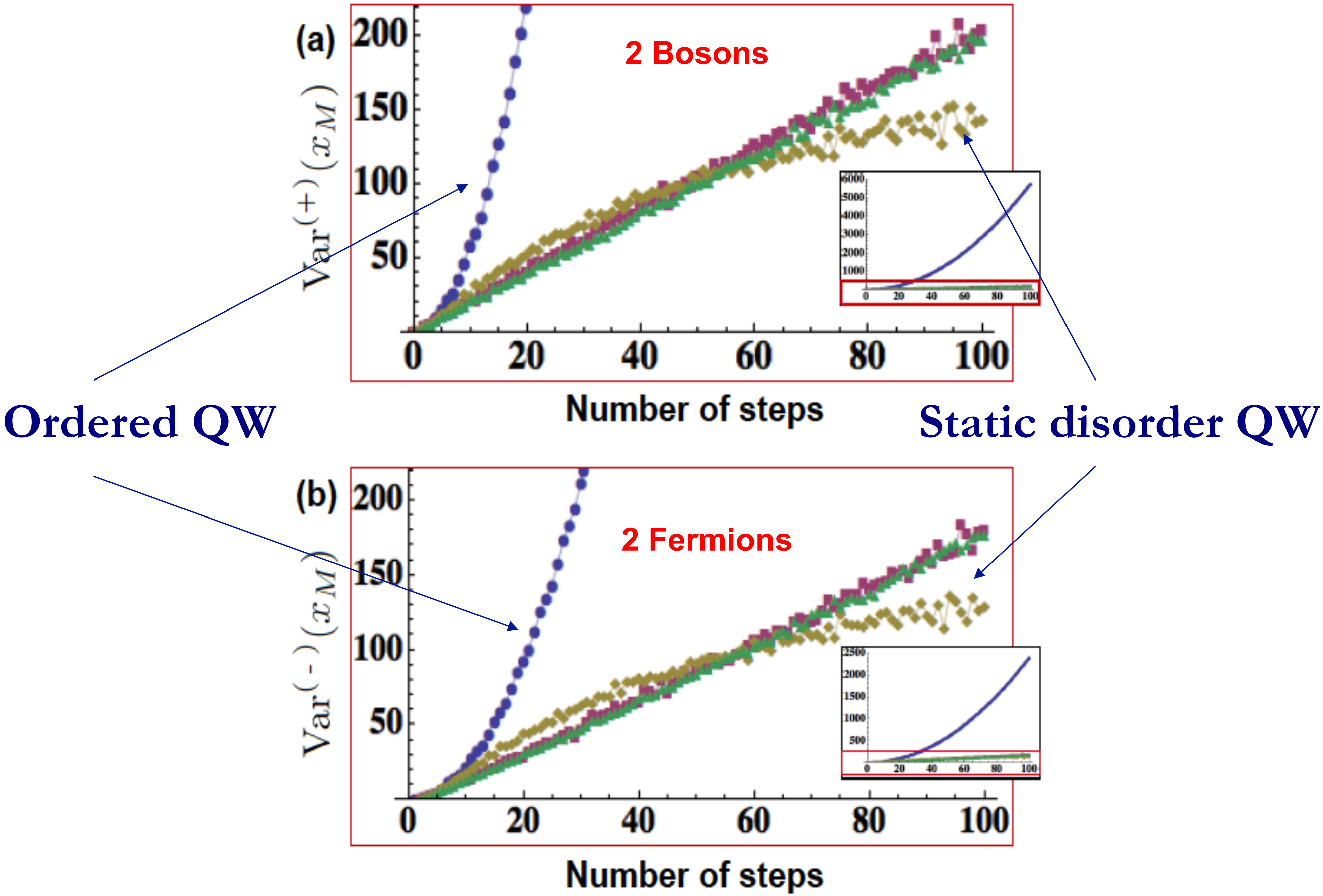
Ordered QW (50 steps)

2 Bosons **2 Fermions**

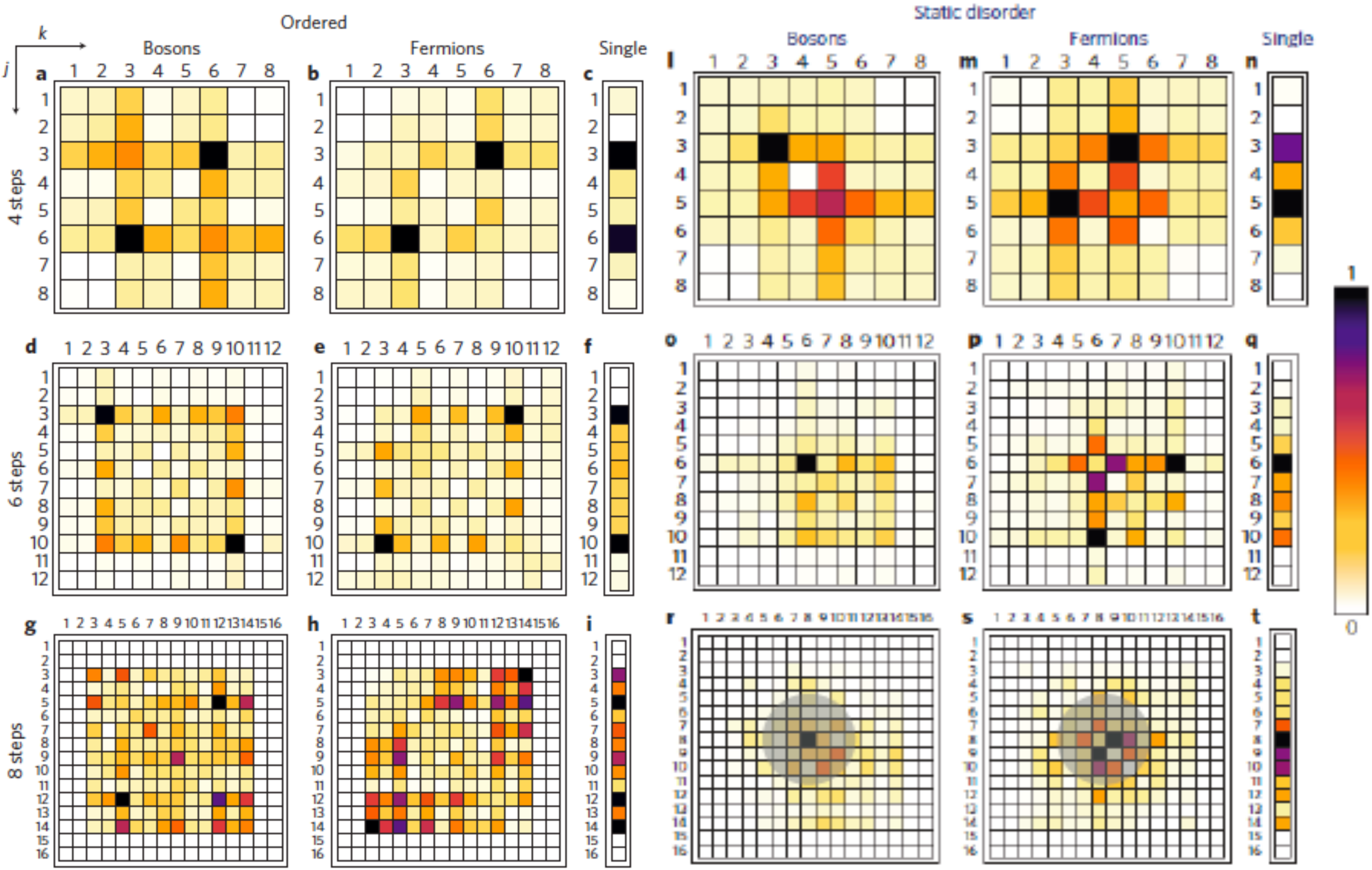
Static disordered QW (50 steps)

F. De Nicola, *et al.*, Phys, Rev, A, **108**, 012102 (2014)

2-particle QW: variance of distributions



2-particle QW: exp. results



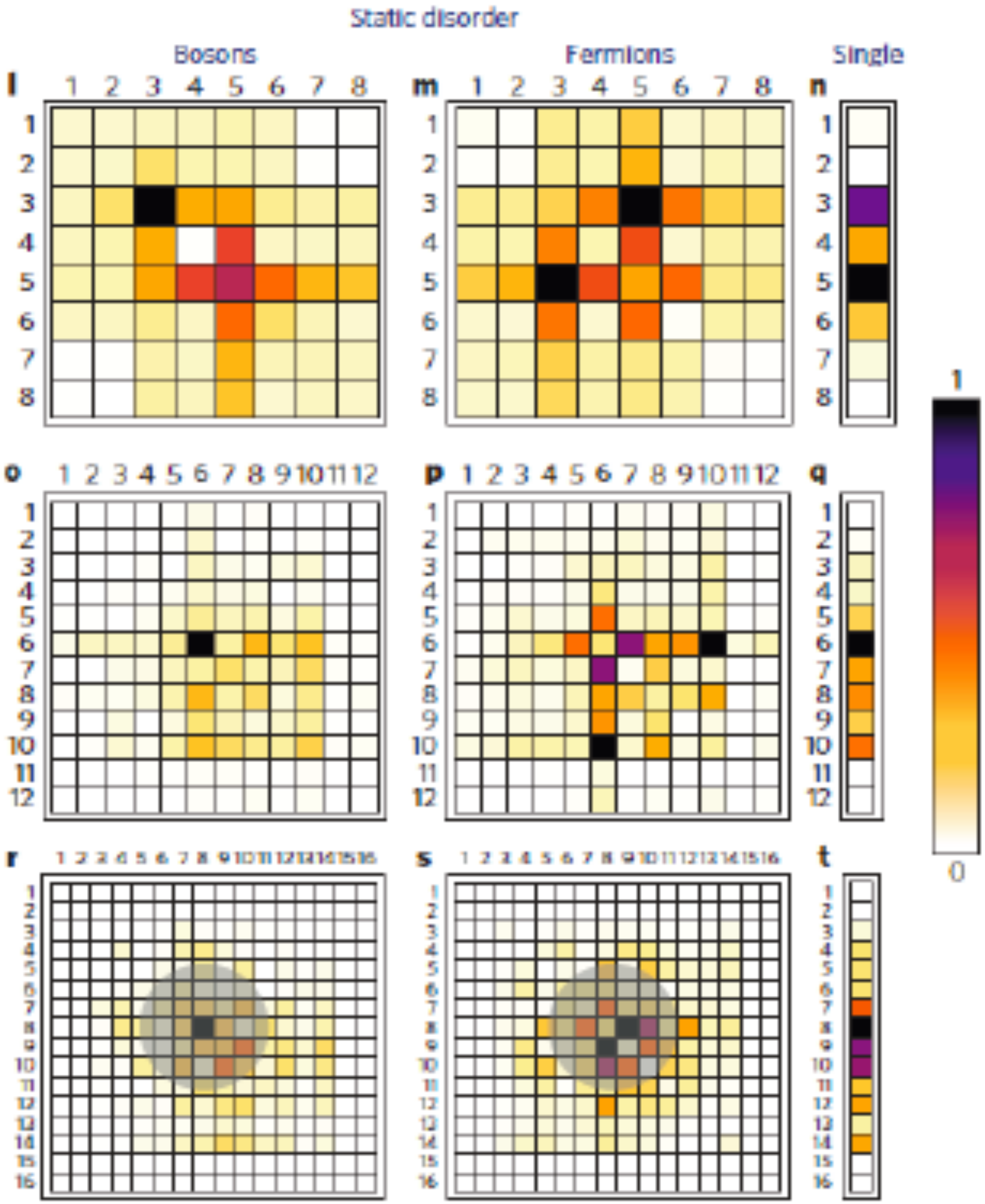
A. Crespi, *et al.*, *Nature Photonics*, **7**, 322 (2013)

Localization evolution

4-time steps

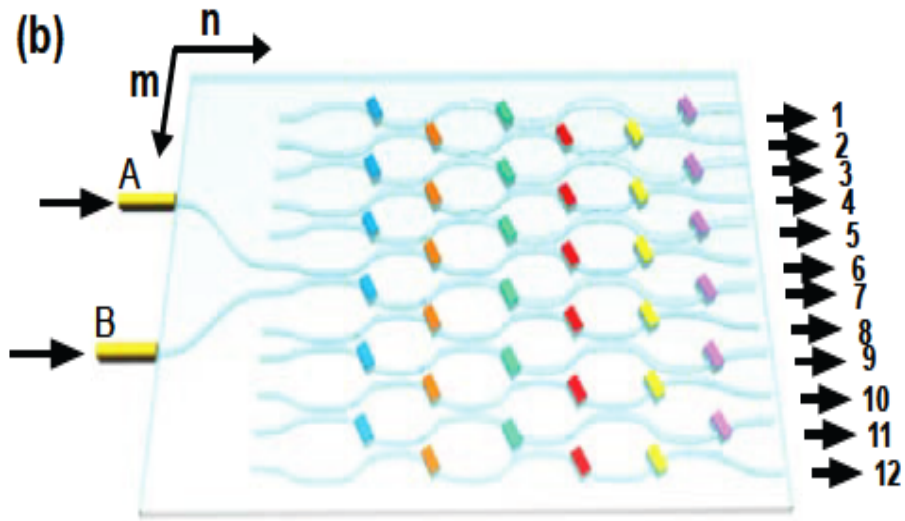
6-time steps

8-time steps



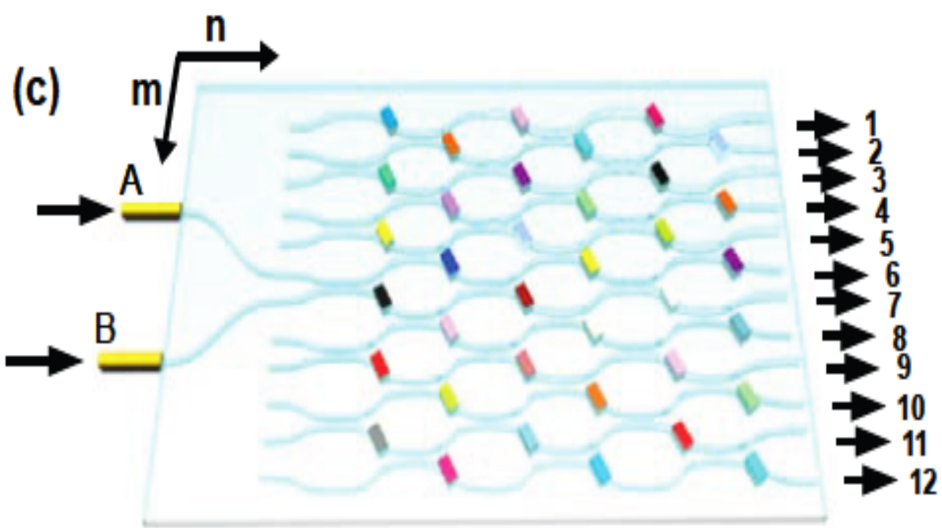
Other disordered systems

Dynamic disorder : depending on time but NOT on site

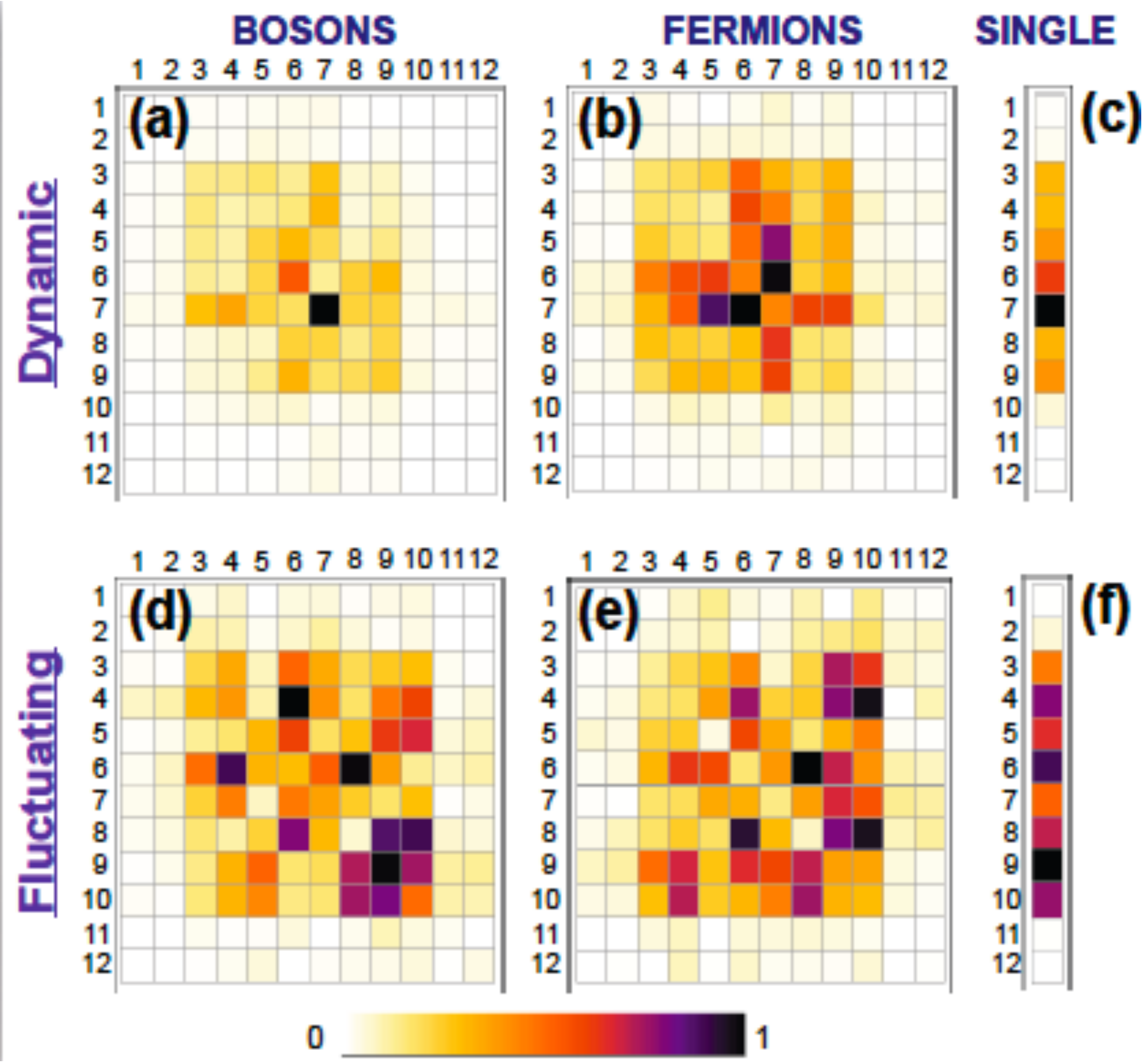


Classical random walk distribution

Fluctuating disorder: depending BOTH on time and on site



Other disordered systems



The onset of dynamic disorder actually quenches the Anderson localization effects, and the distribution is far less localized. The system evolution at long times converges to a diffusion process.

A. Crespi, *et al.*, *Nature Photonics*, 7, 322 (2013)

Towards Quantum Supremacy: BosonSampling

How to achieve quantum supremacy ??

John Preskill
@preskill
Segui

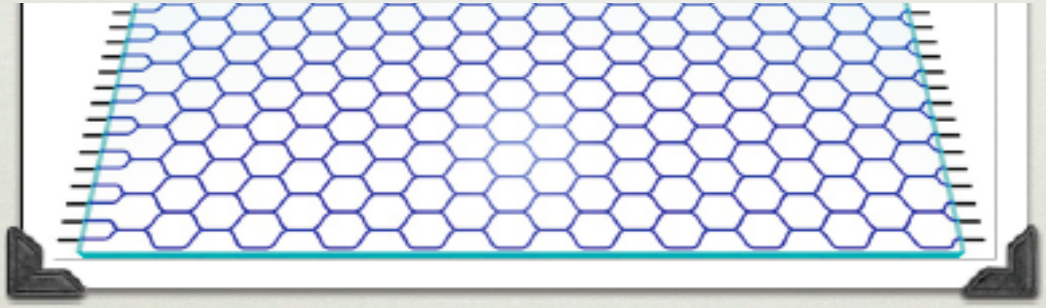
Proposed "quantum supremacy" for controlled quantum systems surpassing classical ones. Please suggest alternatives.

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 ?

Input:
n bosons



Output:
n-photon state

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

Answer: NO!!

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

BosonSampling

Complex network of linear optical elements described by a m x m unitary transformation U.
Evidence of the advantage of quantum over classical computers.

Need for:
(i) input of photons in a Fock state
(ii) unitary evolution implemented by beam splitters and phase shifters
(iii) simultaneous photon-counting measurement of all modes

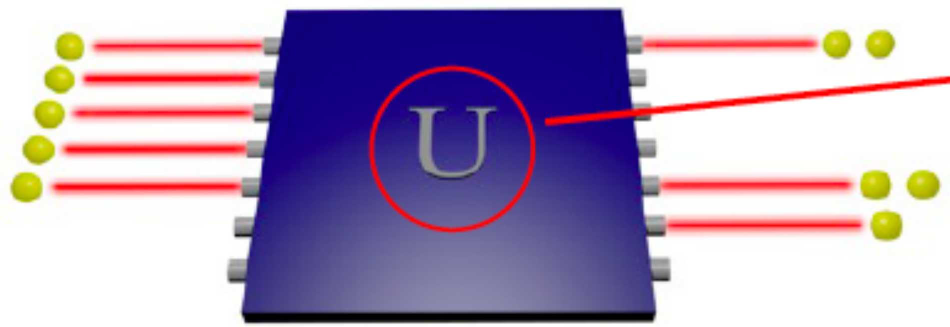
For a large enough number of photons (10-20) and modes (100-200) classical simulation starts to be inefficient

- Permanent of the matrix: computationally hard problem (simulated by the evolution of noninteracting <u>bosons</u>)
- Determinant of the matrix: calculated in a polinomial time (<u>fermion</u> output probabilities)

BosonSampling

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

n bosons
m modes



Uniformly drawn

Why? Transition amplitudes are related to the permanent of square matrices

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

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

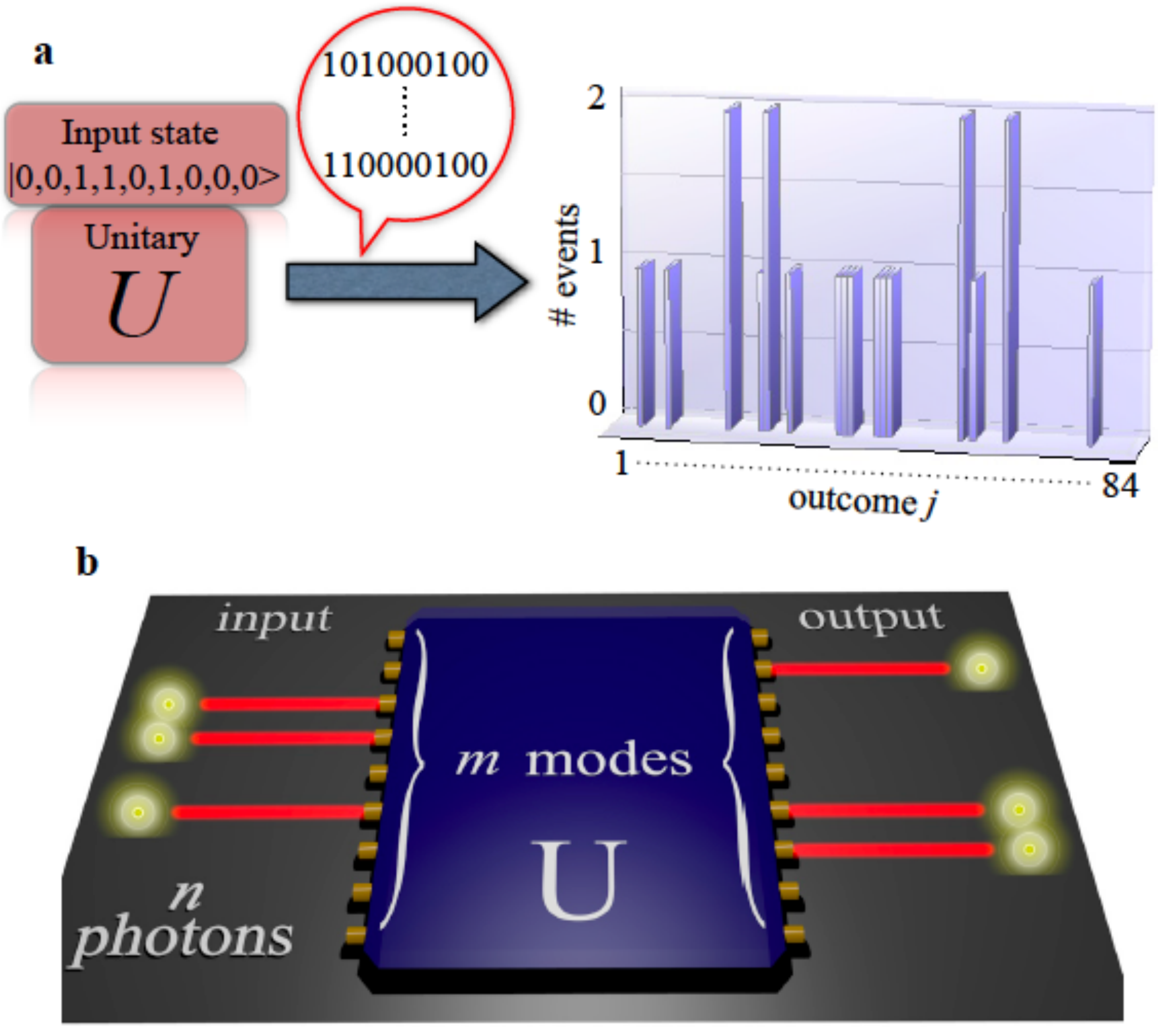
classicaly hard

input

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

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

BosonSampling



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

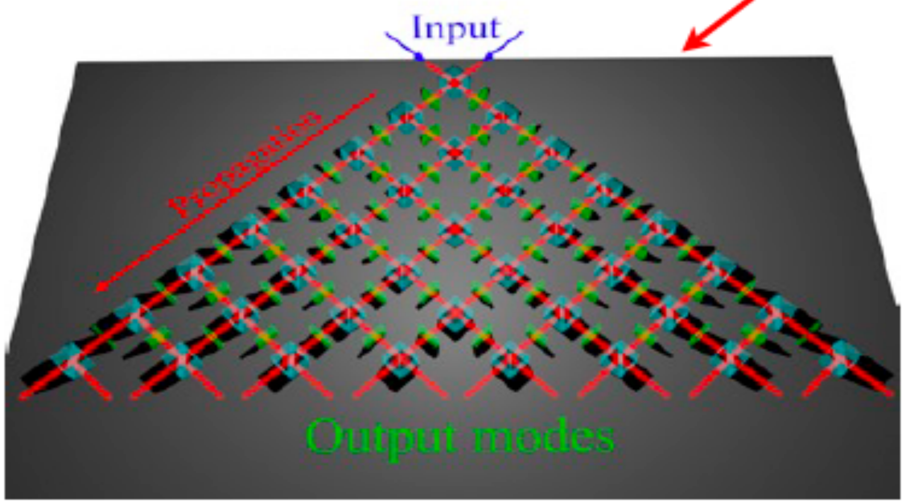
Quantum optics for Boson Sampling

Photons naturally solve the BosonSampling problem

Experimental platform: photons in linear optical interferometers

Required resources:
- Single-photon inputs
- Multimode interferometers
- Detection

n photons
m modes



Hard to implements with bulk optics

Require a technological step recently available due to integrated photonics

Need:

- **High-quality multiport devices performing random unitaries with controllable characteristis**
- **Unitary reconstruction capability**

BosonSampling: an overview

SAPIENZA UNIVERSITÀ DI ROMA

Universidade Federal Fluminense

Consiglio Nazionale delle Ricerche

POLITECNICO MILANO

UNIVERSITY OF OXFORD

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SHANGHAI JIAO TONG UNIVERSITY 1896

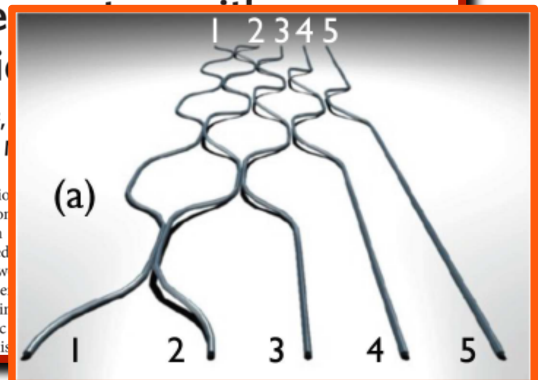
nature photonics LETTERS
PUBLISHED ONLINE: XX XX 2013 | DOI: 10.1038/NPHOTON.2013.112

Integrated multimode interfe... arbitrary designs for photoni...

Andrea Crespi[1,2], Roberto Osellame[1,2]*, Roberta Ramponi[1,2], ...
Nicolò Spagnolo[4], Chiara Vitelli[4,5], Enrico Maiorino[4], Paolo ...

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

proportio... interferom... function... estimated... modes w... At prese... regime i... photonic... In this...



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. Sm...

Although universal quantum computers ideally solve problems such ... exponentially more efficiently than classical machines, the formidab... devices motivate the demonstration of simpler, problem-specific alg... quantum speedup. We constructed a quantum boson-sampling mach... output distribution resulting from the nonclassical interference of p... photonic circuit, a problem thought to be exponentially hard to solv... quantum computation, boson sampling merely requires indistinguish... evolution, and detectors. We benchmarked our QBSM with three an... sources of sampling inaccuracy. Scaling up to larger devices could ... quantum-enhanced computation.

Universal quantum computers require physical systems that are well isolated from ... unitary transforma... nentially hard to sa...

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 photon-

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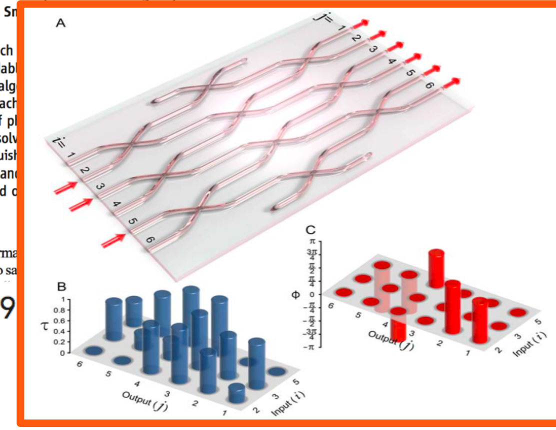

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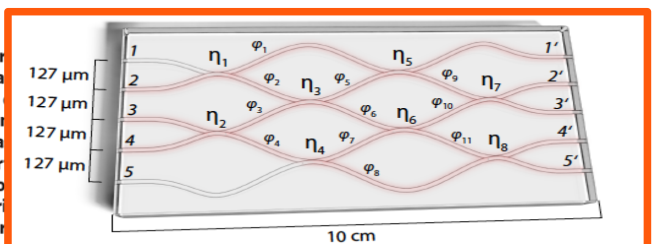
nature photonics LETTERS
PUBLISHED ONLINE: 12 MAY 2013 | DOI: 10.1038/NPHOTON.2013.102

Experimental boson sampling

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

Universal quantum computers[1] promise a dramatic incr... speed over classical computers, but their full-size rea... remains challenging[2]. However, intermediate quantum ... tational models[3-5] have been proposed that are not u... but can solve problems that are believed to be cla... hard. Aaronson and Arkhipov[6] have shown that inter... of single photons in random optical networks can so... hard problem of sampling the bosonic output distri... Remarkably, this computation does not require measur... based interactions[7,8] or adaptive feed-forward techn...



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

Photonic Boson Sampling in a Tunable Circuit

Matthew A. Broome,[1,2] ...
Scott Aaronson,[3] Timot...

Quantum computers are ... Extended Church-Turing ... devices that efficiently p... is boson sampling: samp... unitary process. We test... three-photon scattering ... unitary describing a six-... even with the unavoidab... Scaling this to large num... quantum computer.

▲ major motivati... primes. The presumed di... basis of the majority of ...

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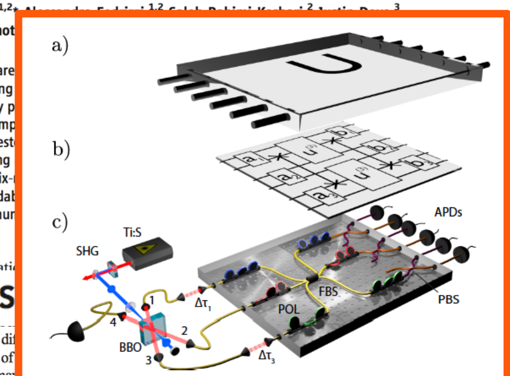
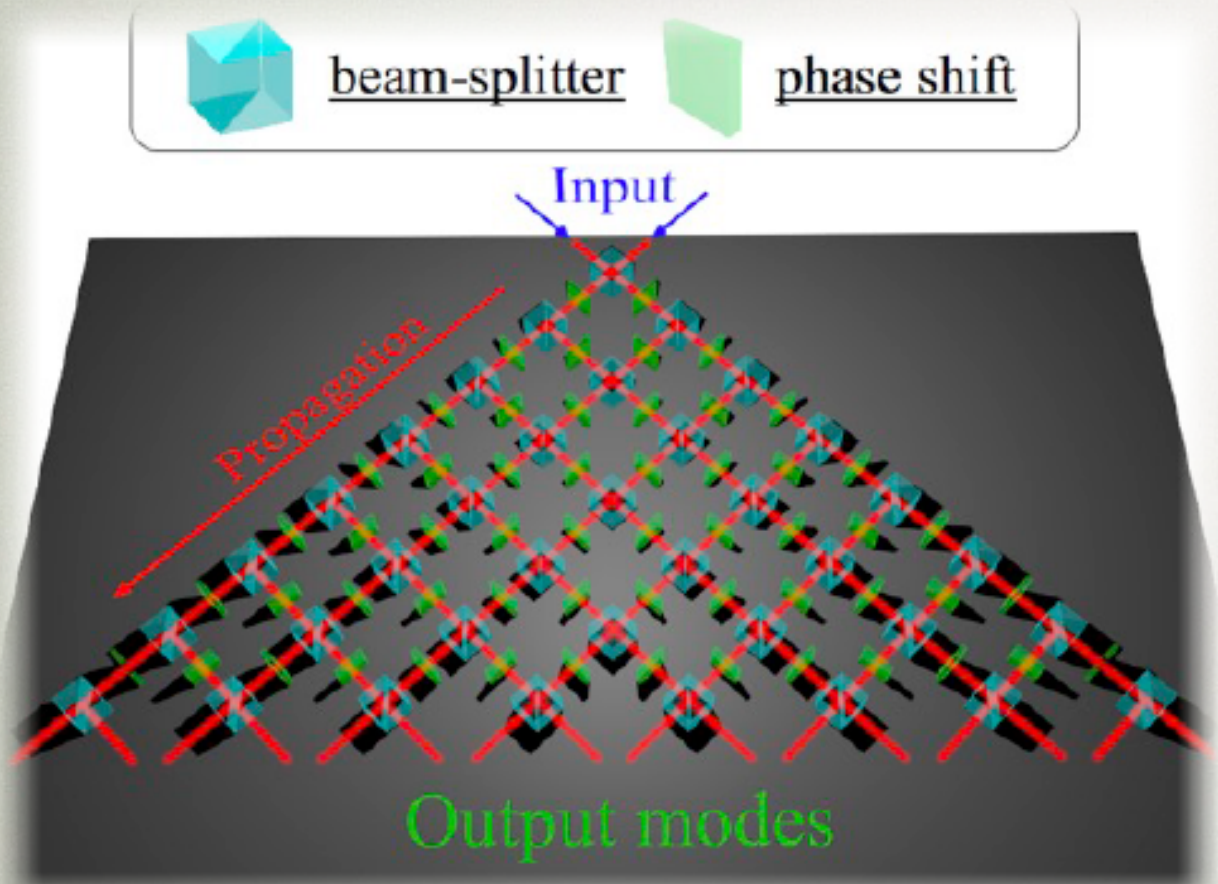
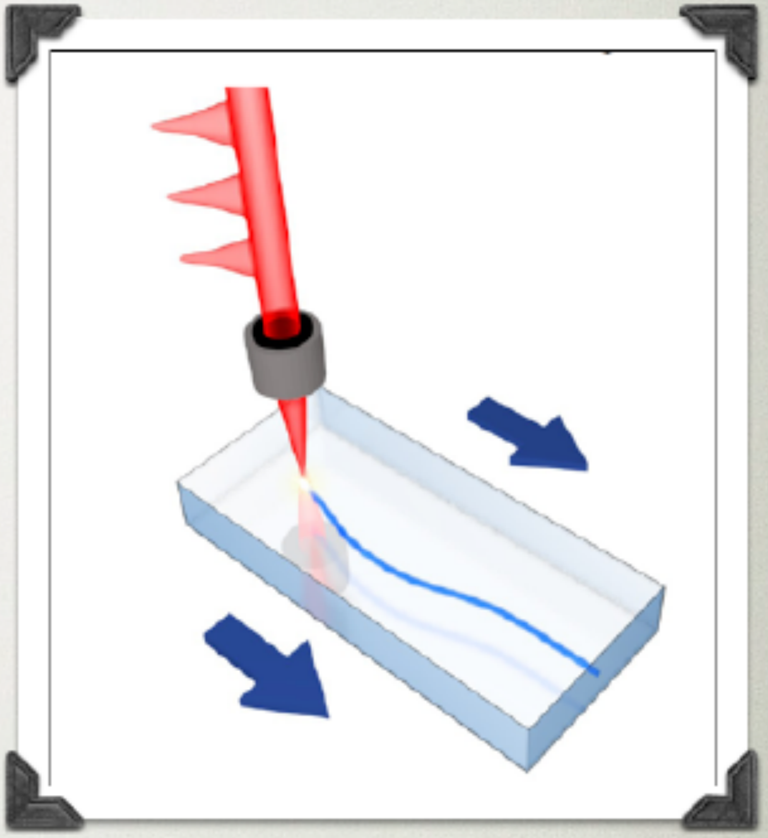


Paper	Group	Contents	Validation
Science 339, 794 (2013)	Brisbane, Boston	n=2,3 photons, m=6 modes - fiber optics	No
Science 339, 798 (2013)	Oxford	n=3 photons, m=6 modes + n=4 photons with (lower complexity) bunched input	No
Nat. Photon. 7, 540 (2013)	Vienna, Jena	n=3 photons, m=5 modes	No
Nat. Photon. 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
Nat. Commun. 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

THE SOLUTION: INTEGRATED PHOTONICS



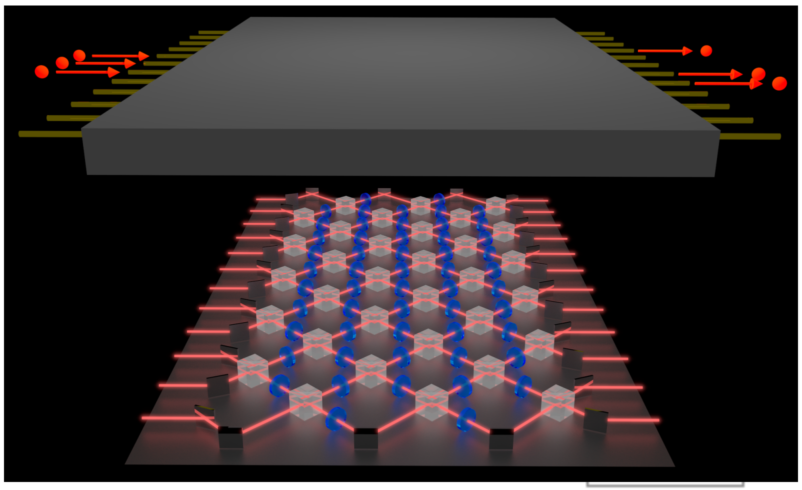


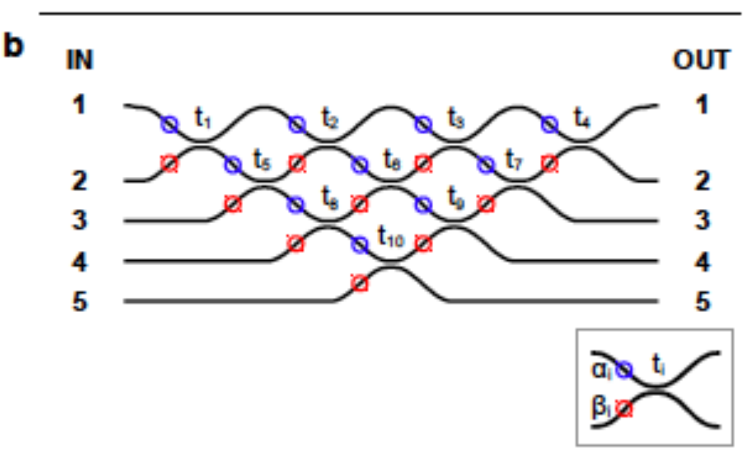
Laser writing technology:
unique capability to transmit any polarization state

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

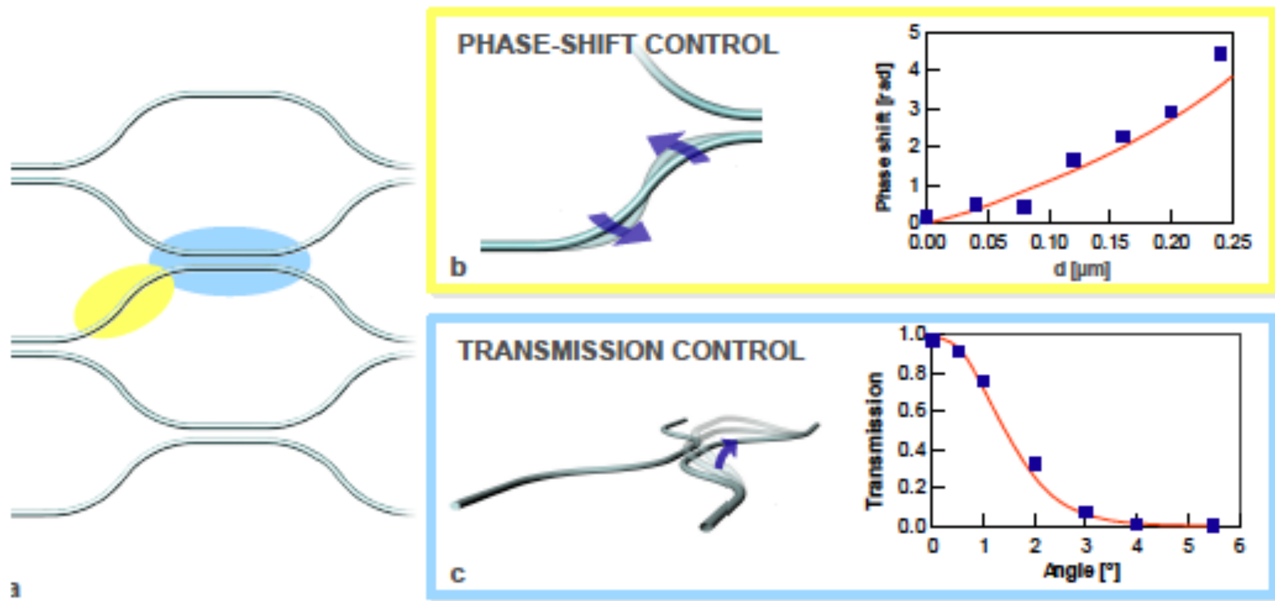
Our approach: controlling ϕ and T

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





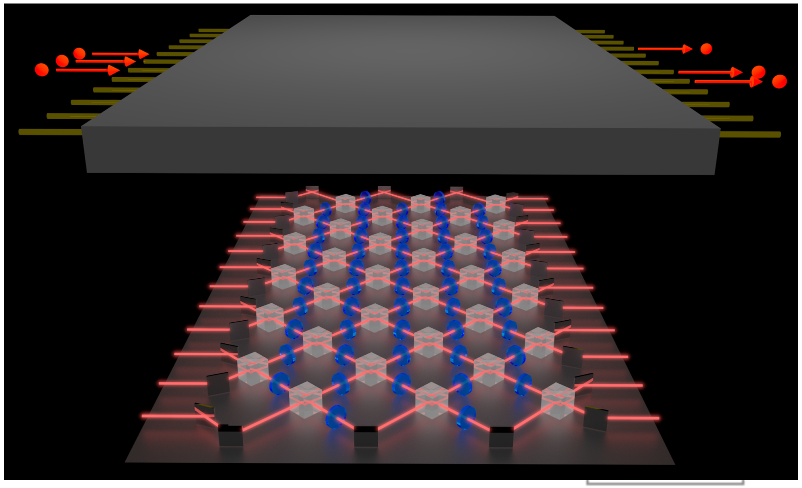
Fabrication process

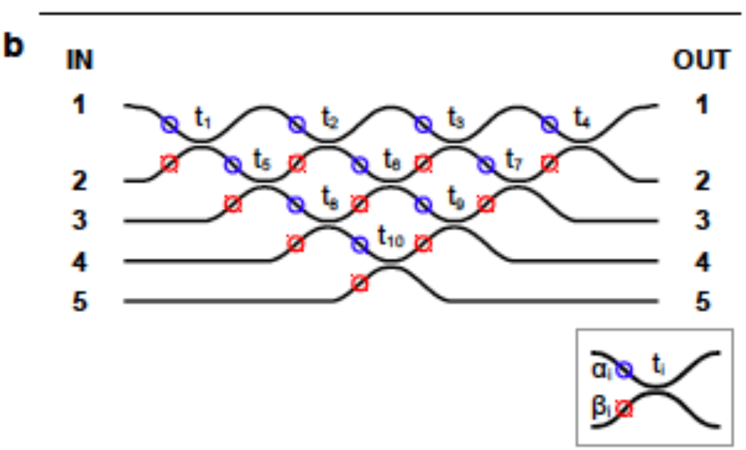


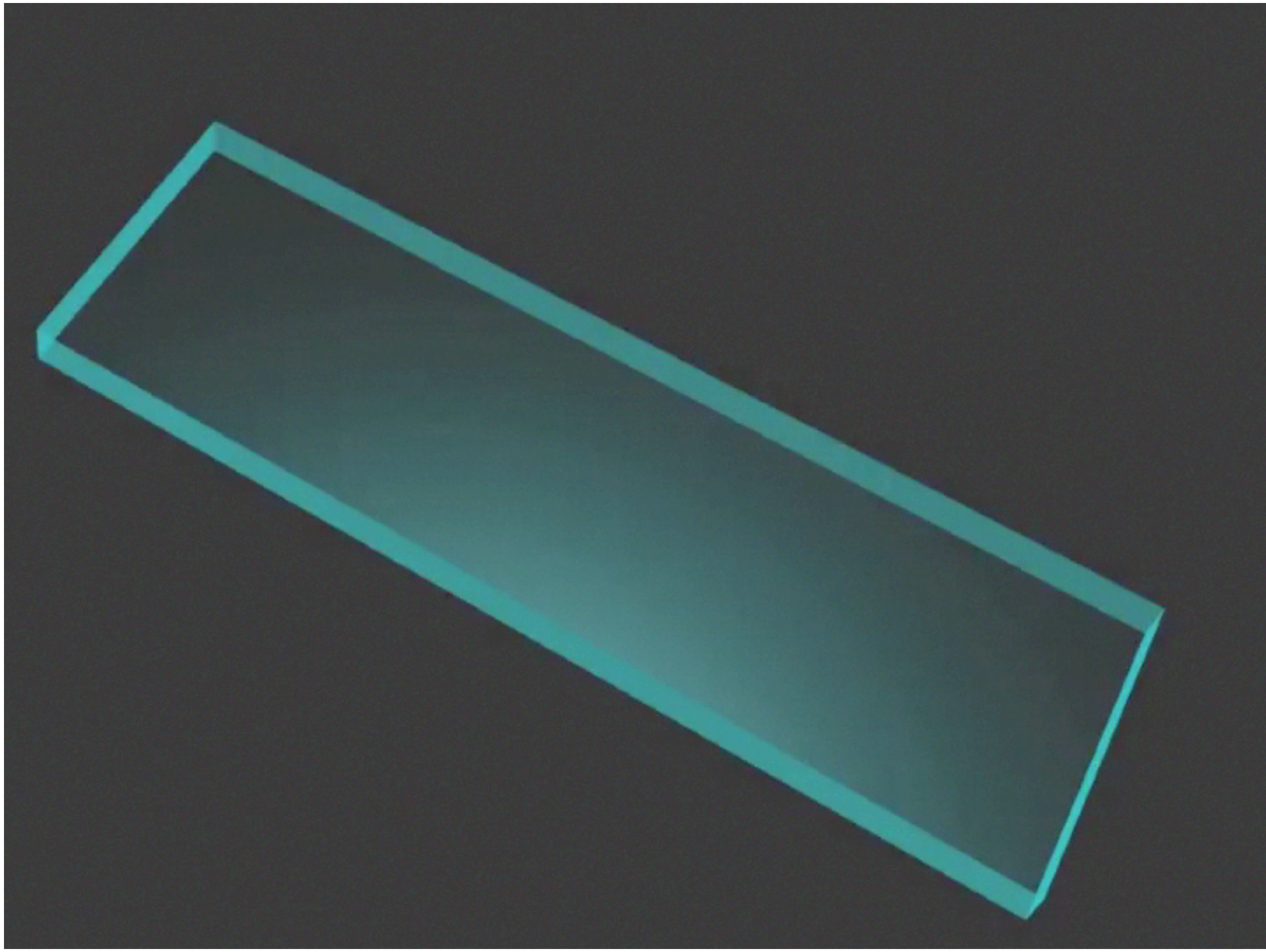
The chip

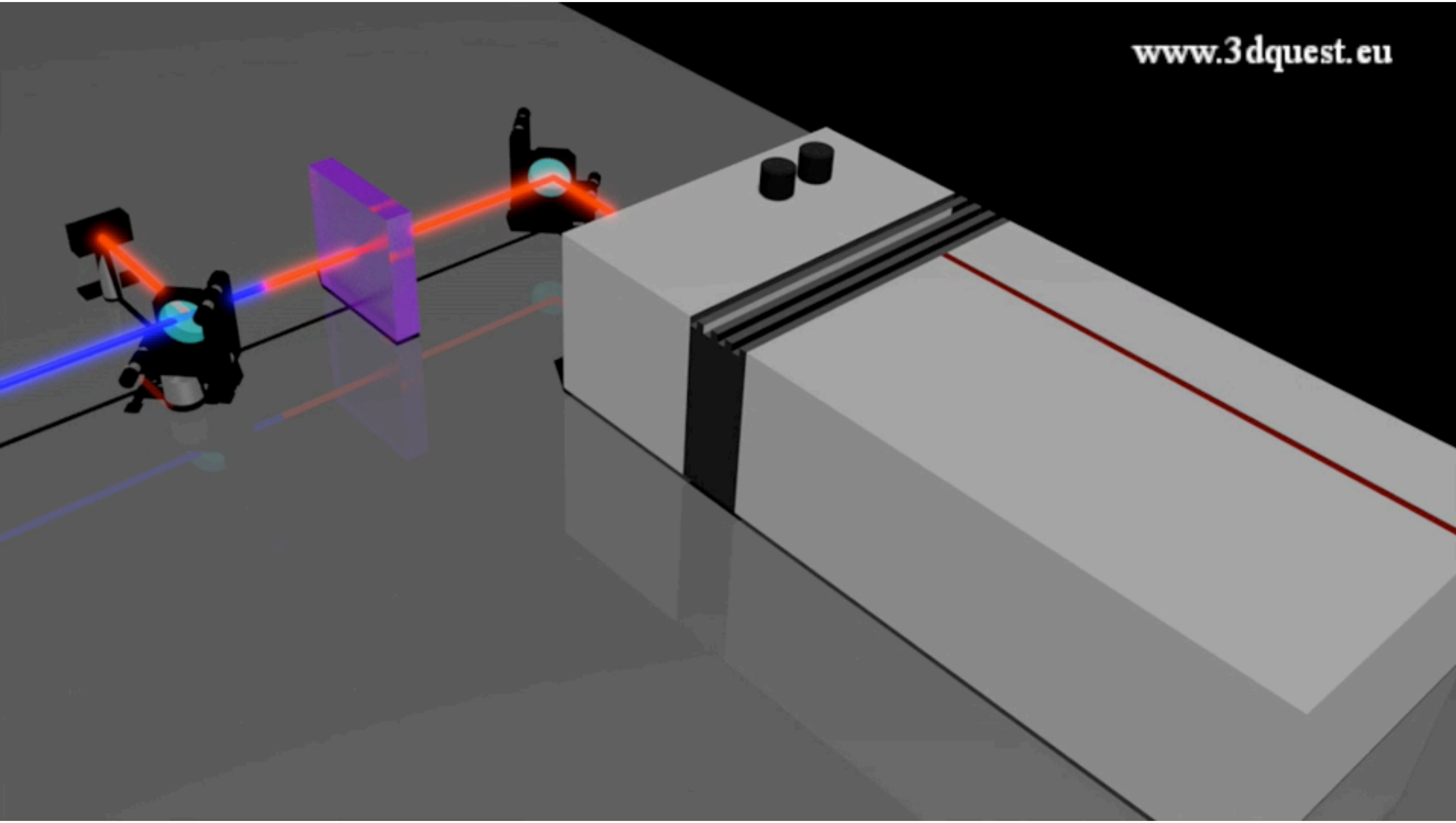
Requirement for Boson Sampling - design arbitrary interferometers

Requires independent control of phases and beam-splitter operation

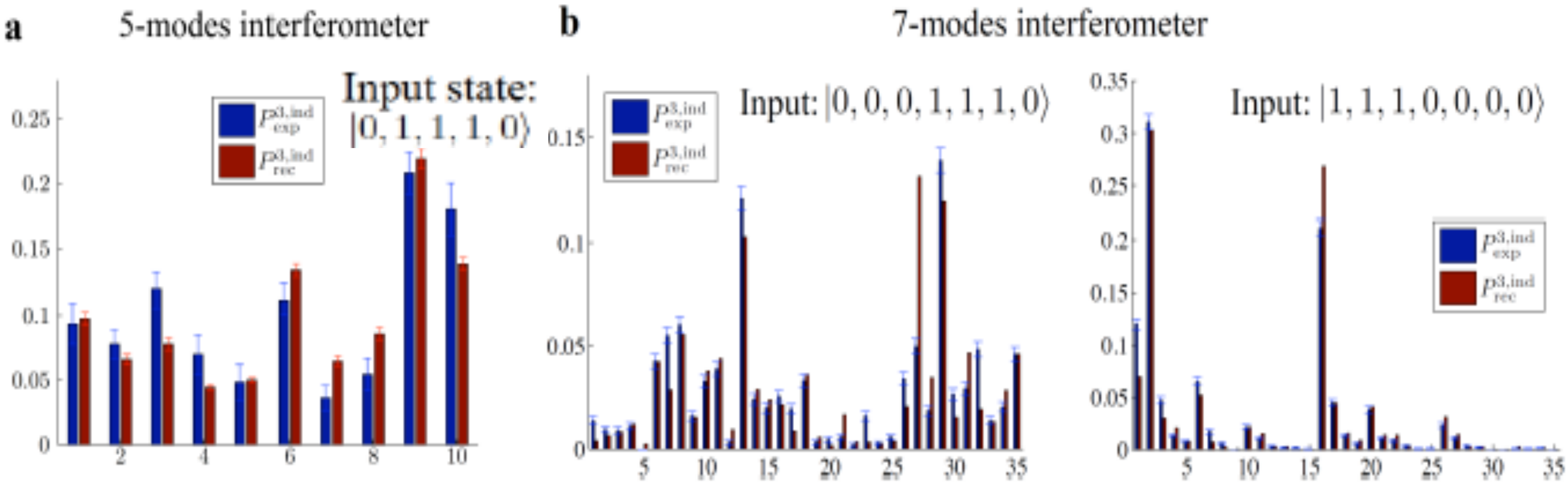







www.3dquest.eu

3 photons, 5 and 7 modes



$$D_{exp,\,sp} = 0.105 \pm 0.024$$

$$D_{exp,\,sp} = 0.122 \pm 0.037$$

Partial distinguishability of the photons taken into account

- Confirmation of Permanent formula
- Upgraded to a higher number of modes

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

Can Boson Sampling be validated?

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

C. Gogolin et al. *arXiv:1306.3995*

The Theorists' Answer

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

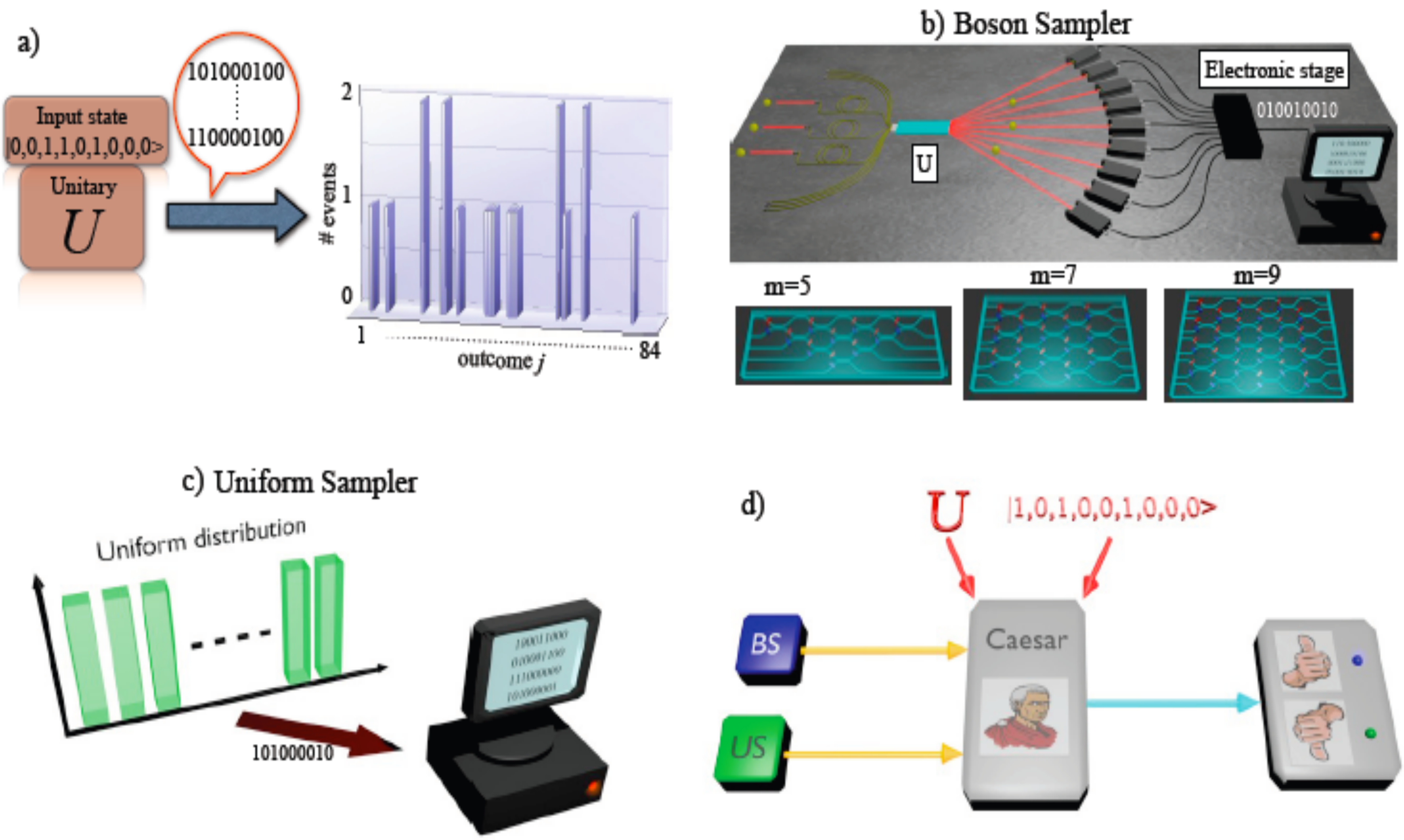
$$P = \prod_{i=1}^{n} \sum_{j=1}^{n} |A_{i,j}|^2$$

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

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

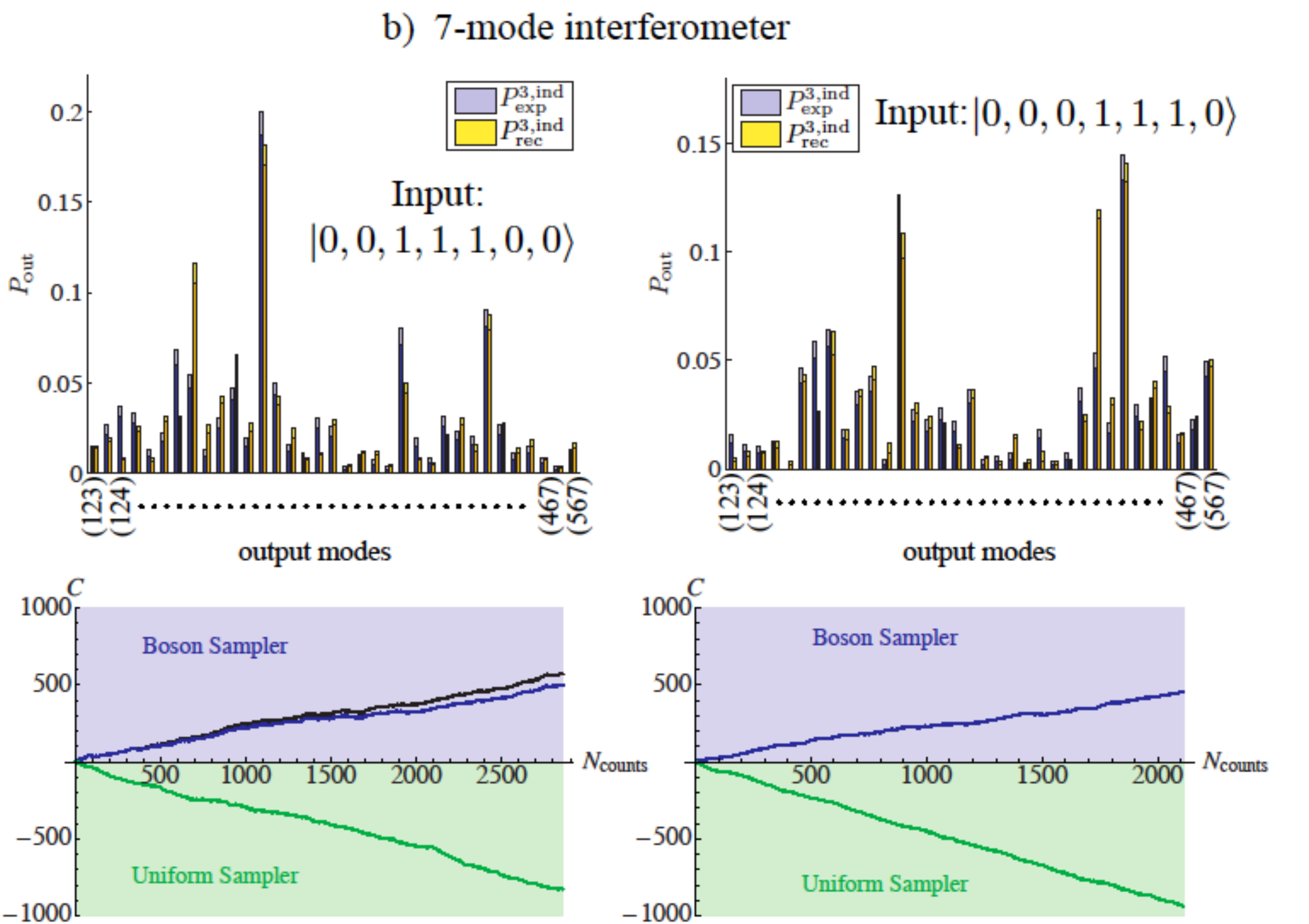
S. Aaronson et al. *arXiv:1309.7460*

Validation of BosonSampling



N. Spagnolo,et al., *Nature Photonics* **8**, 614 (2014)
Similar experiment in Bristol: J. Carolan, et al., *Nature Photonics* **8**, 619 (2014)

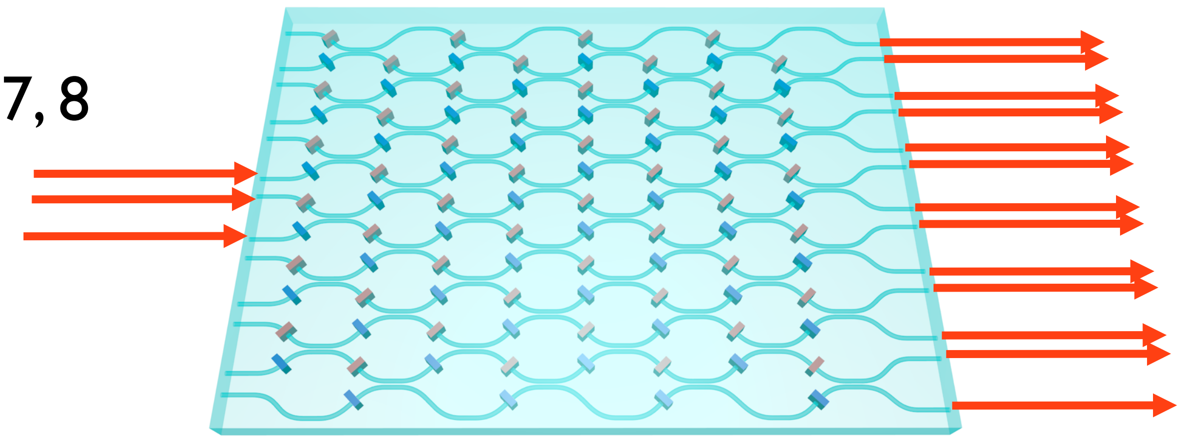
Experimental proof of validation, 7 modes



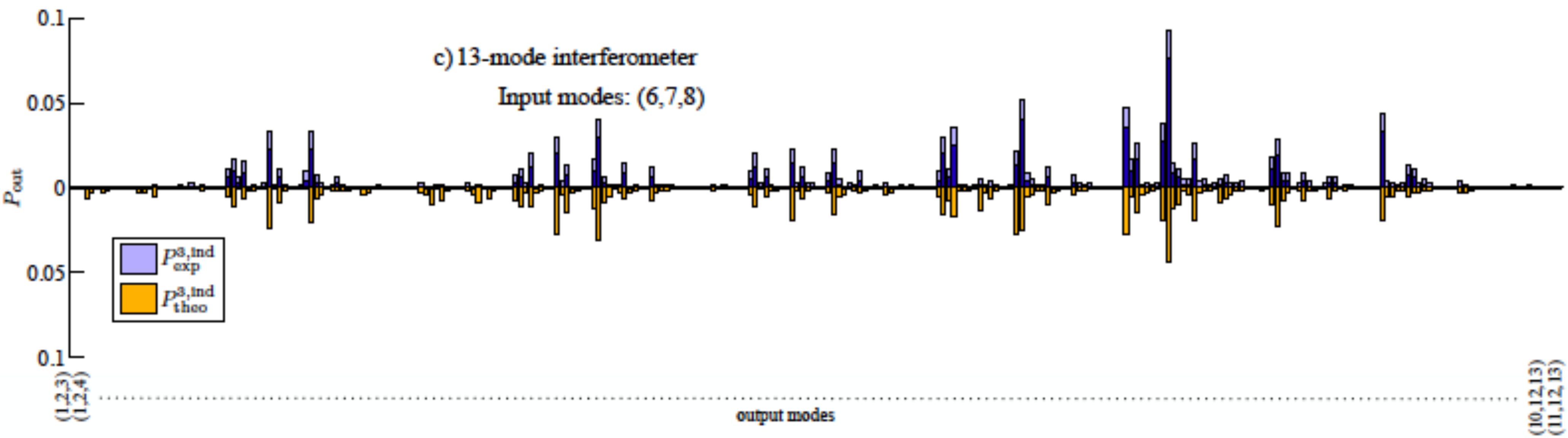
N. Spagnolo,et al., *Nature Photonics* **8**, 614 (2014)

BosonSampling in a 13 mode system

Input: 6, 7, 8



Output: 286 different possible no-bunching configurations



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

Towards Quantum Supremacy

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

Open questions

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

Challenges

- *Efficient single photon sources*
- *Reconfigurable photonic circuits*
- *Efficient single photon detectors*

Scattershot BosonSampling

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

p^n probability of generating the n-photon input

Scattershot Boson Sampling, n-photon term

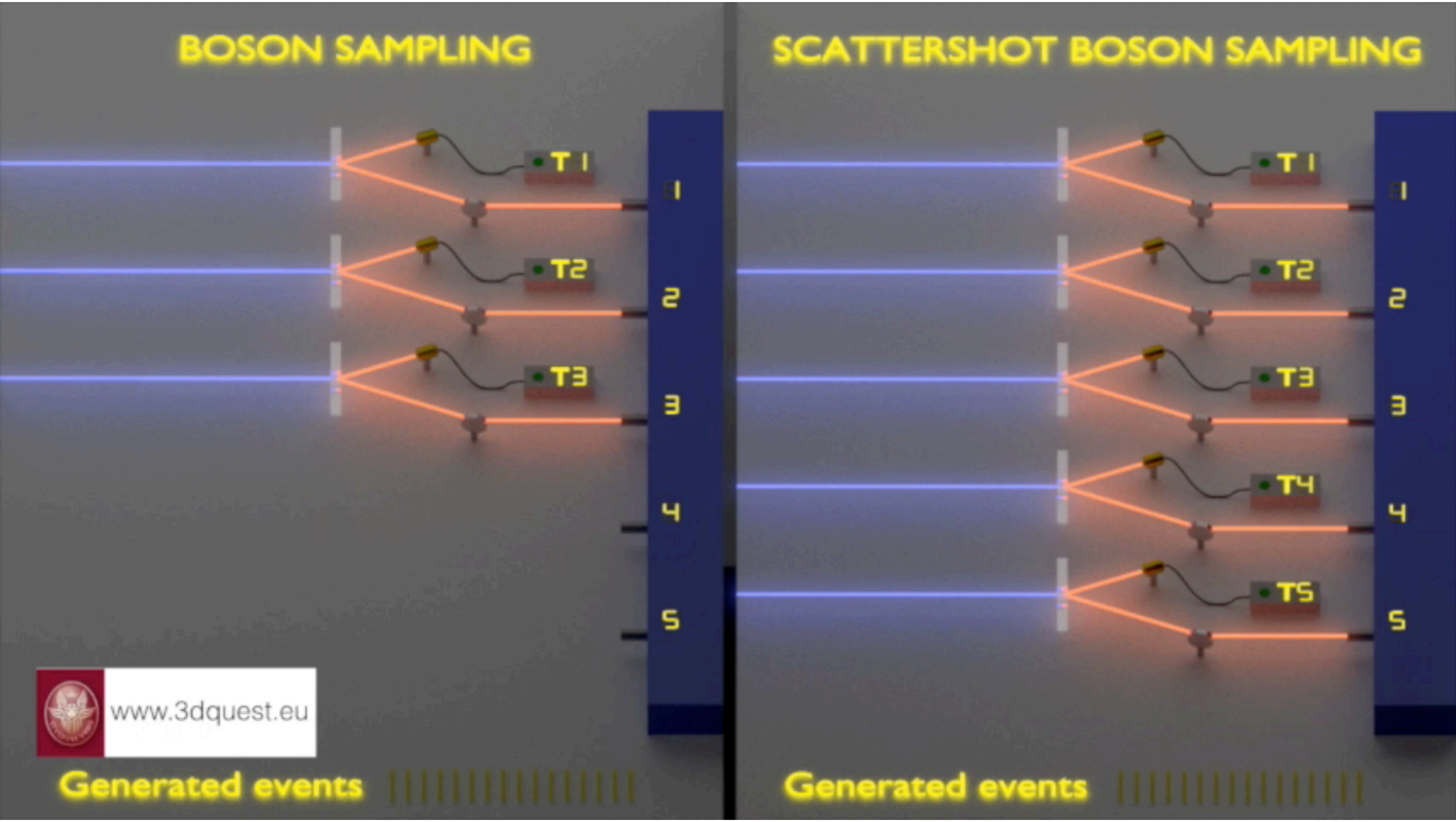
$p^n(1-p)^{m-n}$ probability of generating one of the n-photon input configurations

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

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

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

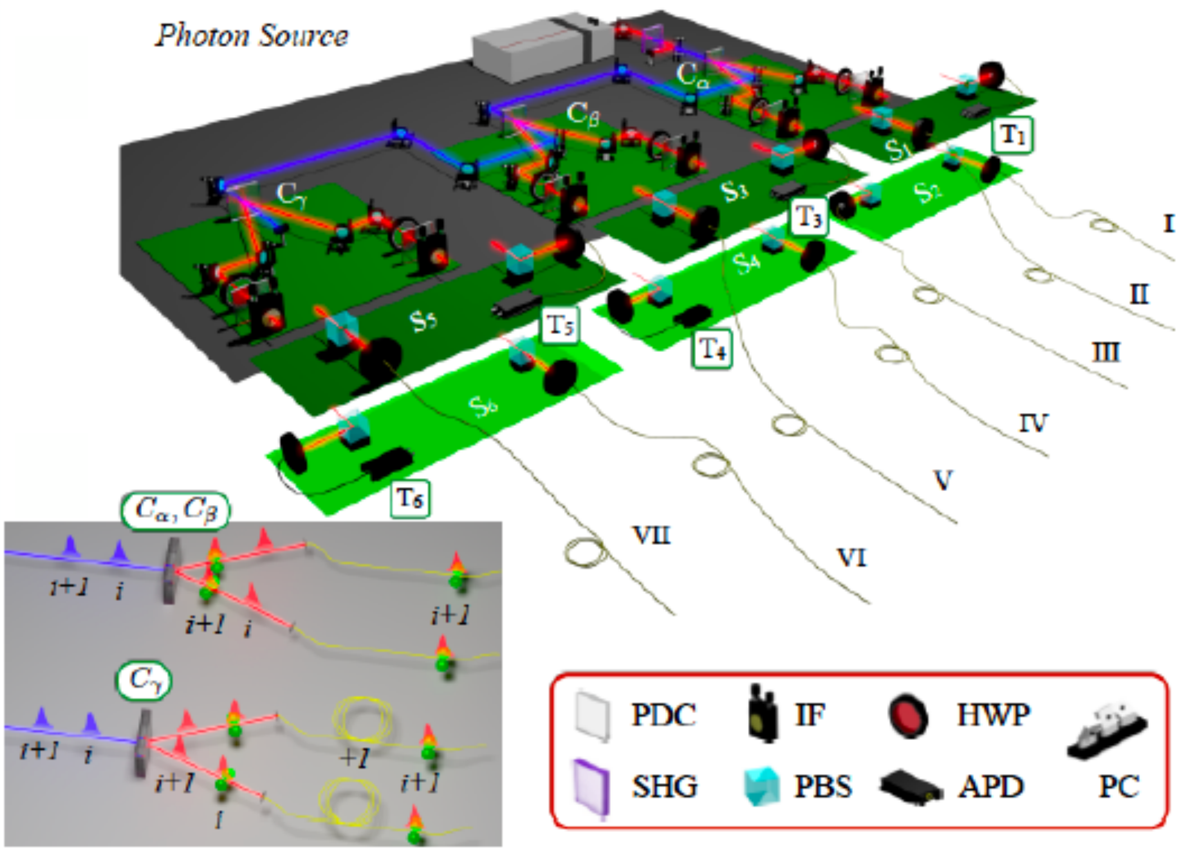
Scattershot BosonSampling



Scattershot BosonSampling: generation

Experimental setup - 1

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



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

↕

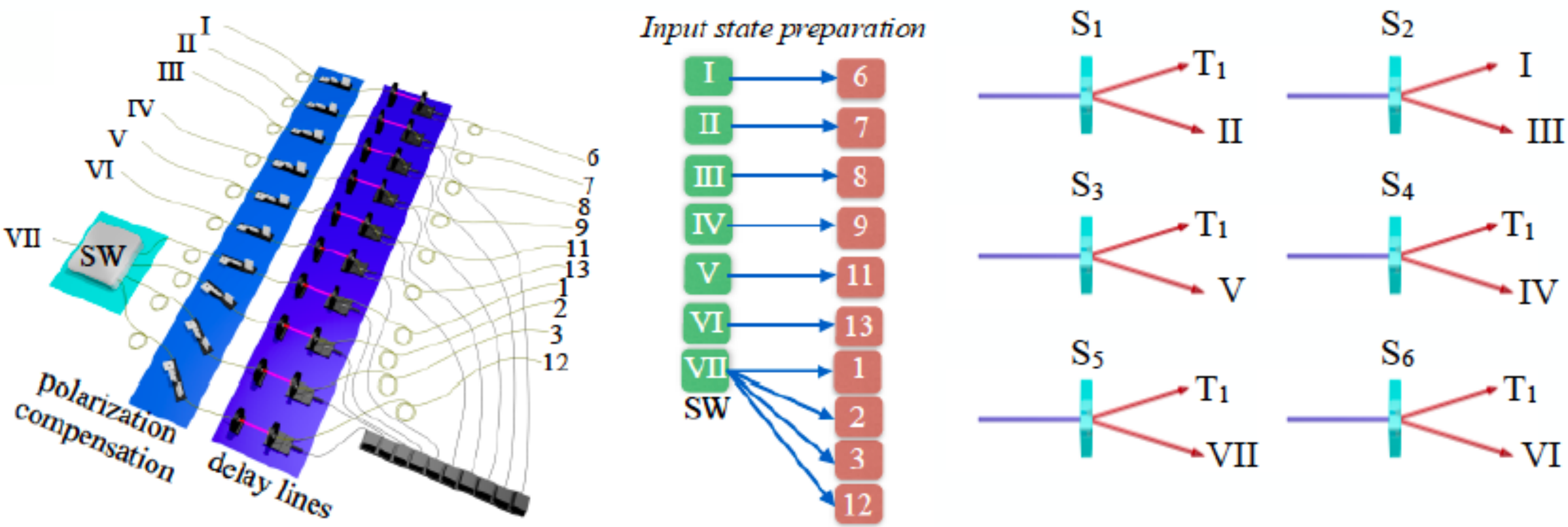
3 physical crystals and separation by polarization

Interference between photons generated from two subsequent laser pulses

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

Scattershot BosonSampling: preparation

Experimental setup - 2



Three photon events:

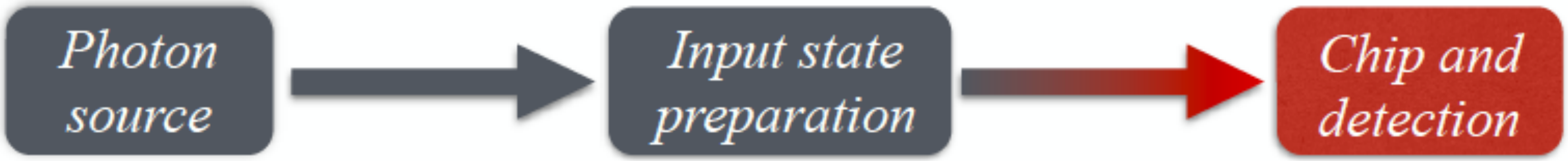
1) Photon I (input 6) [fixed]
2) Photon III (input 8) [fixed]
3) Random input heralded by T_i

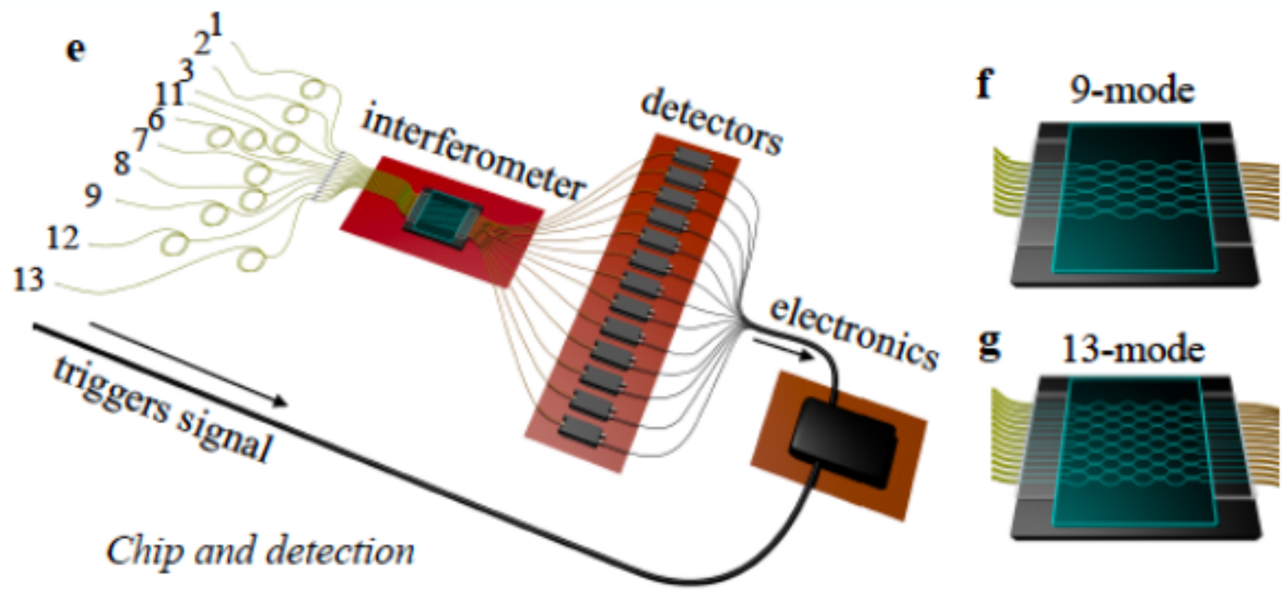
Input randomness further enhanced by sequential switching of photon VII

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

Scattershot BS: chip and detection

Experimental setup - 3



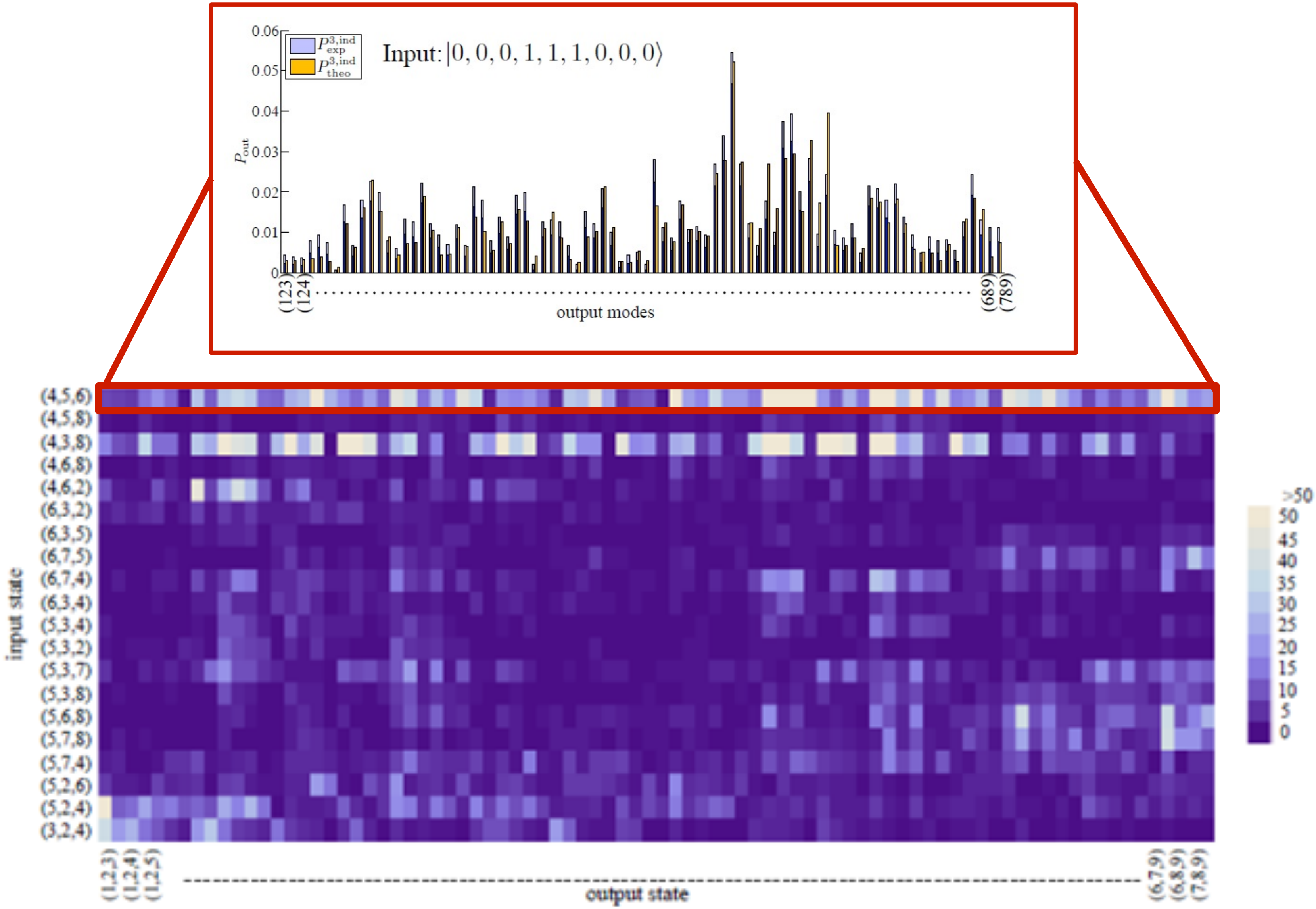


Evolution through m=9 and m=13 interferometers with random (but known) structure

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

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

Scattershot BS: random input



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

Certification of many-body interference

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

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

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

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

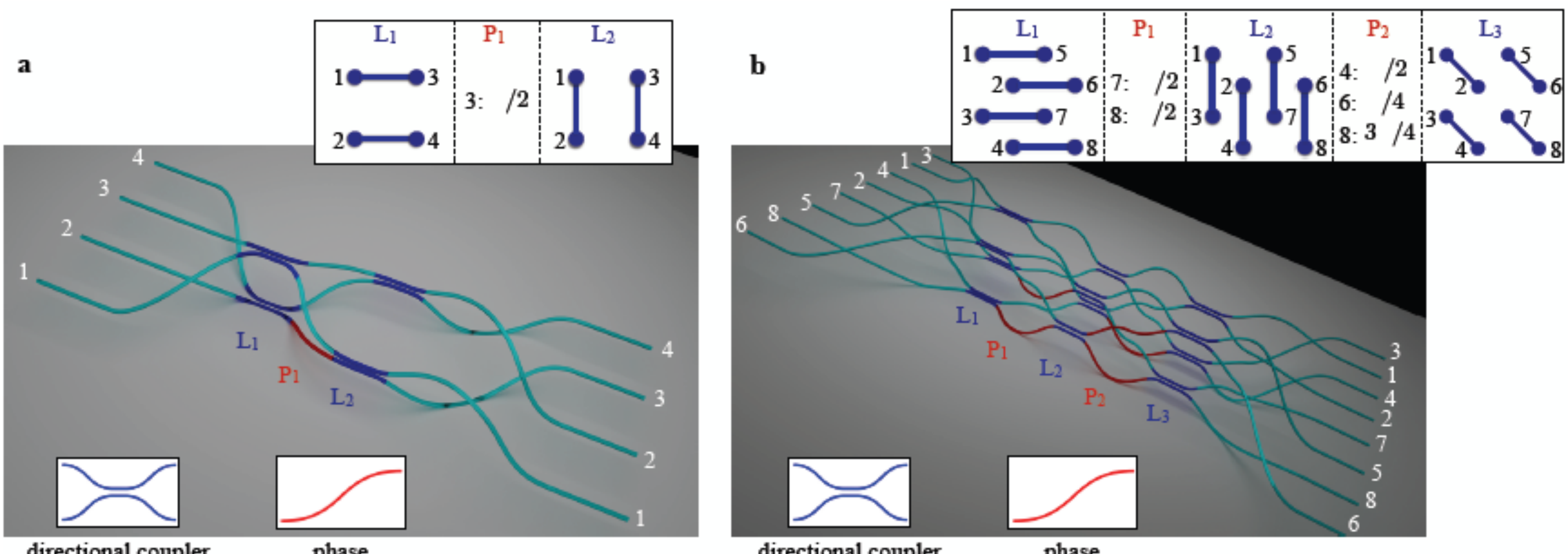
Quantum Fourier Transform in a 3D chip

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

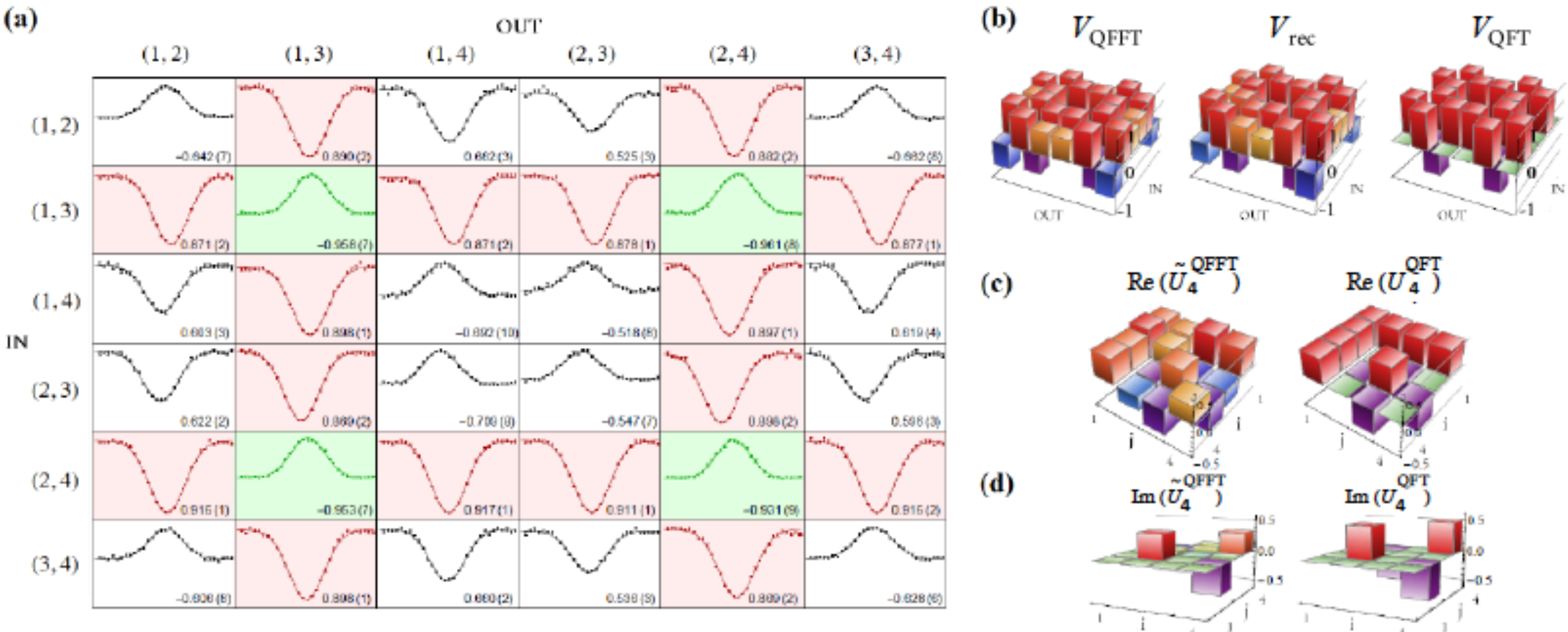
Study the evolution of particular input states through the network implementing the QFT described by the unitary matrix:

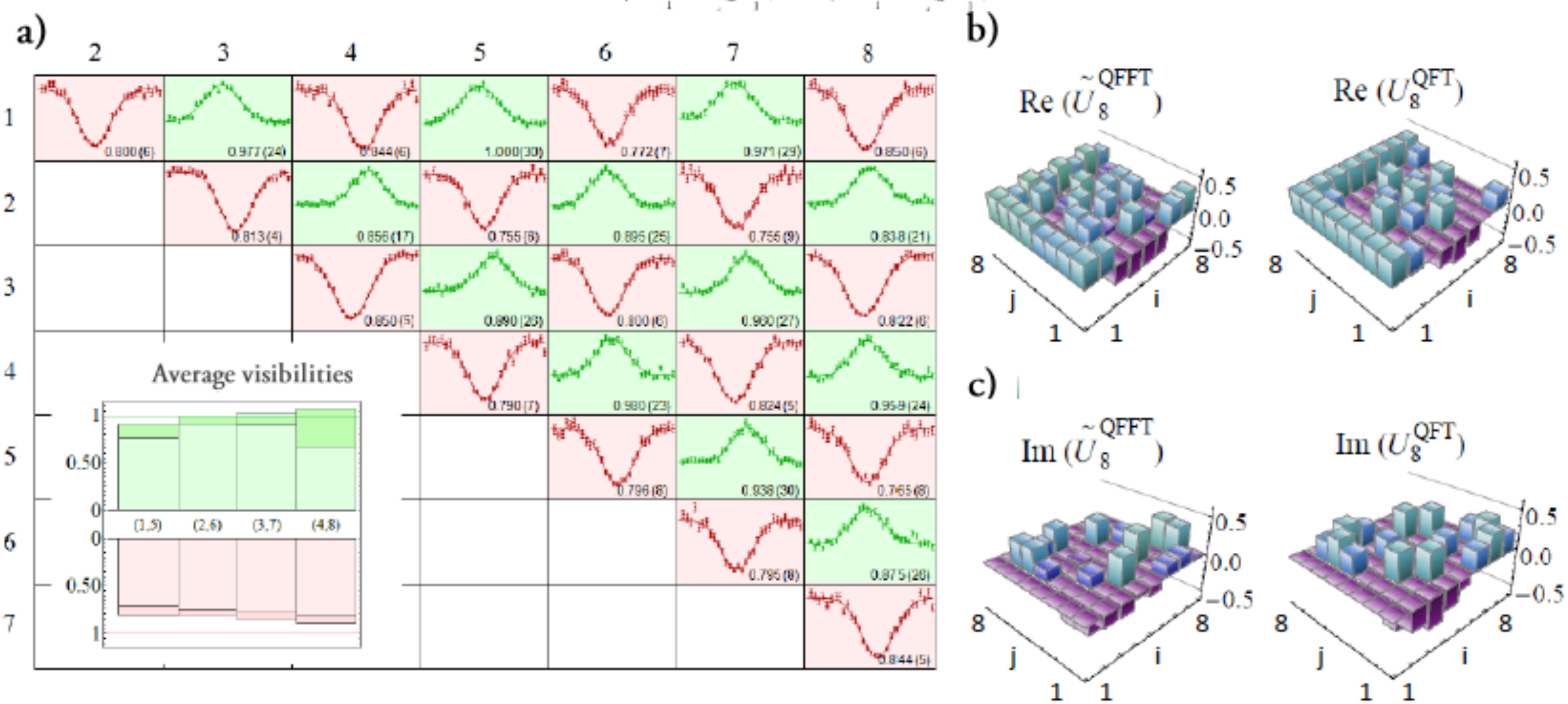
$$U_{l,q}^{\mathrm{QFT}} = \frac{1}{\sqrt{m}} e^{i\,\frac{2\pi l q}{m}}$$

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



Quantum suppression law in a 3D chip





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

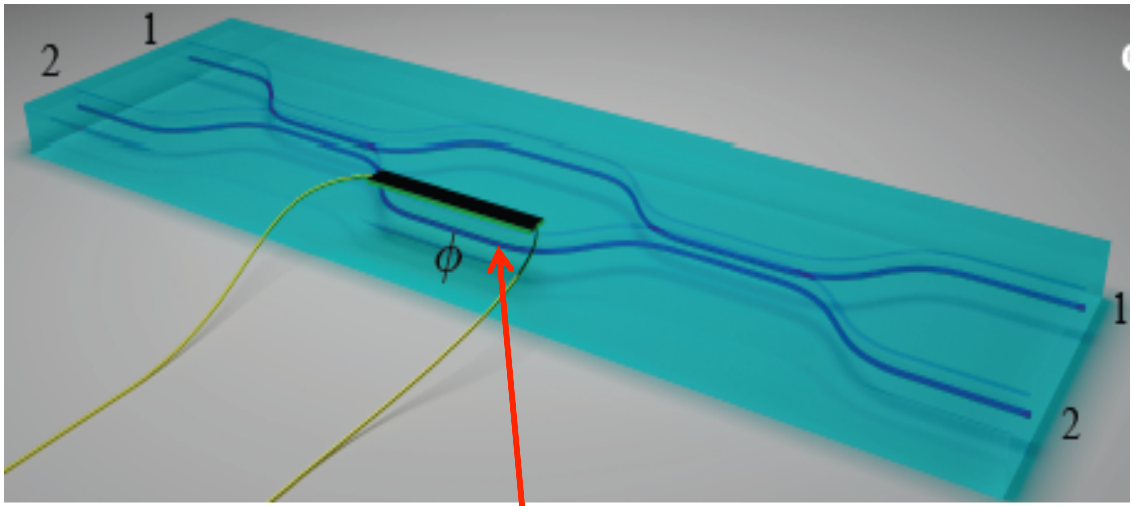
Building blocks of integrated photonics

- Directional coupler (BS)
- Mach – Zehnder interferometer
- Phase shifter
- Polarizing directional coupler (PBS)
- Waveplate (HWP, QWP)

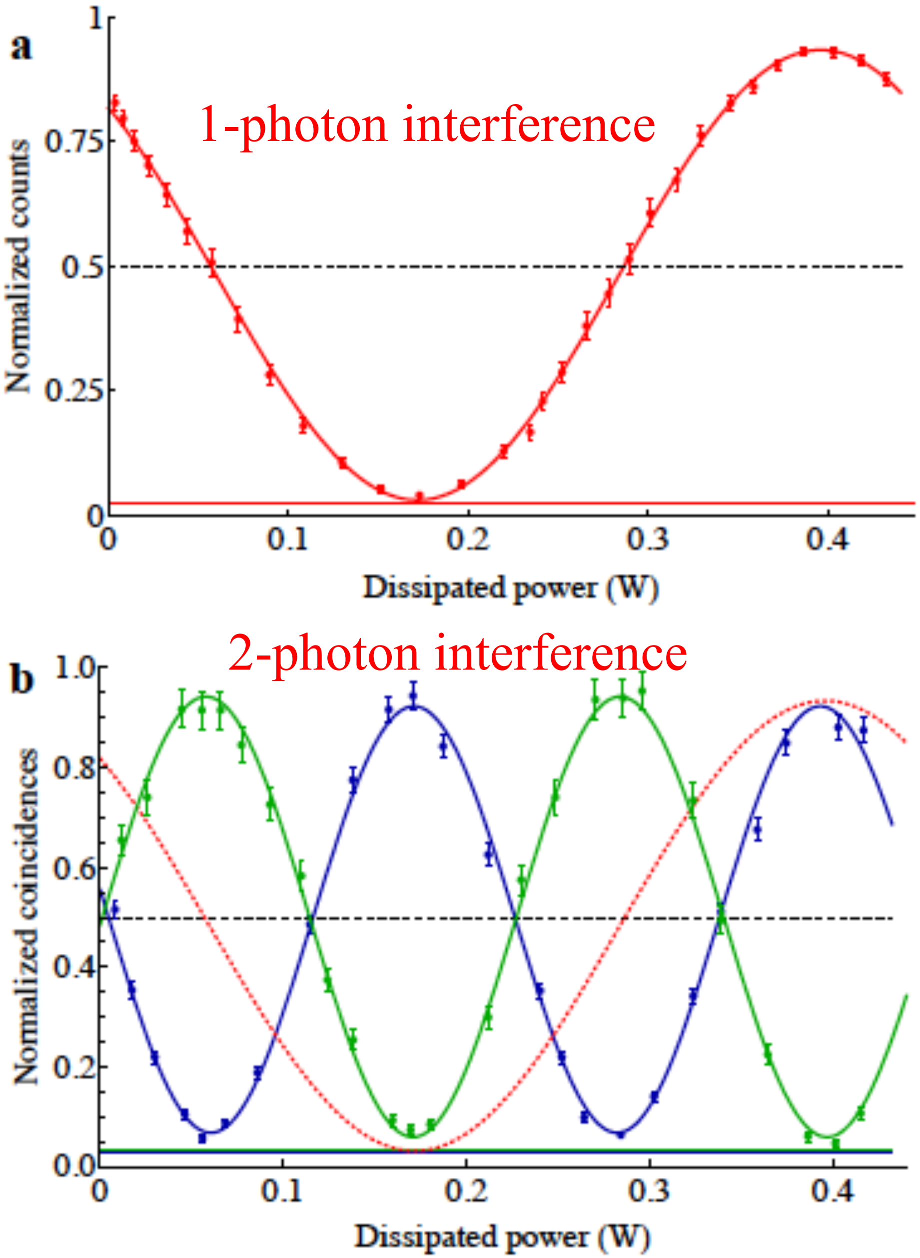
Use with single- or multi-photon states, with path and/or polarization qubit encoding

Two-arm interferometer – Phase shifter

Mach-Zehnder interferometer



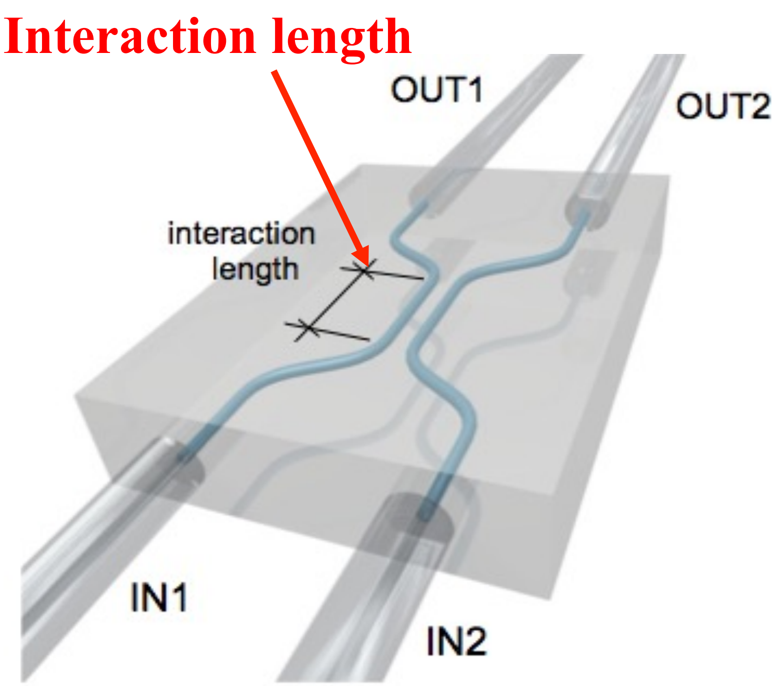
Phase ϕ changed by electric thermistor

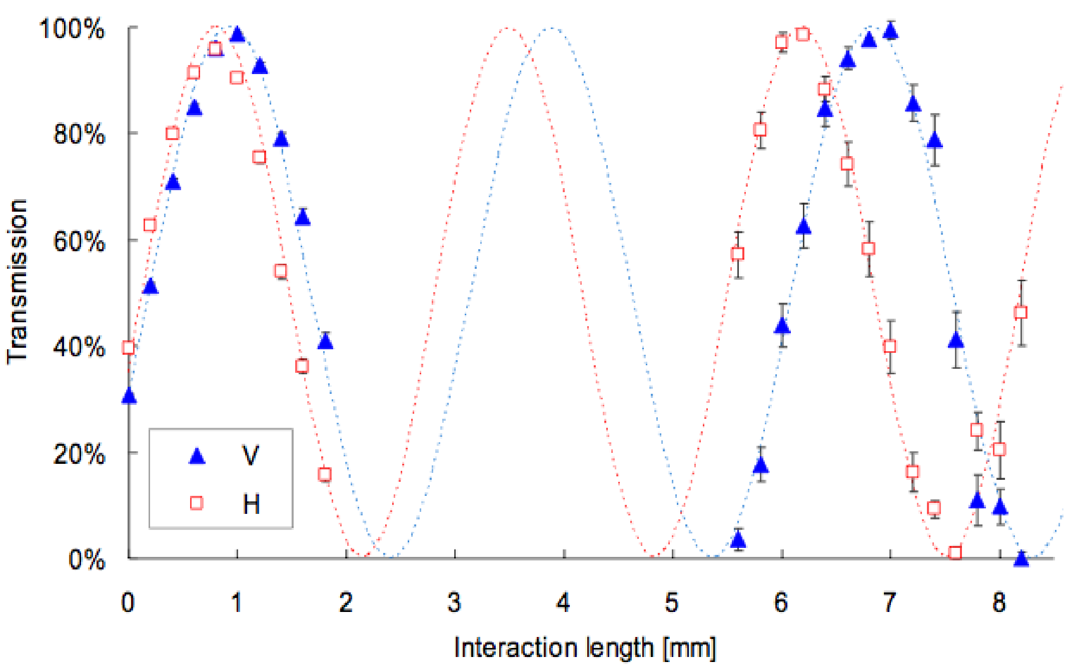


F. Flammini *et al.* Light: Science&Applications, 4, e354 (2015)

Polarizing beam splitter

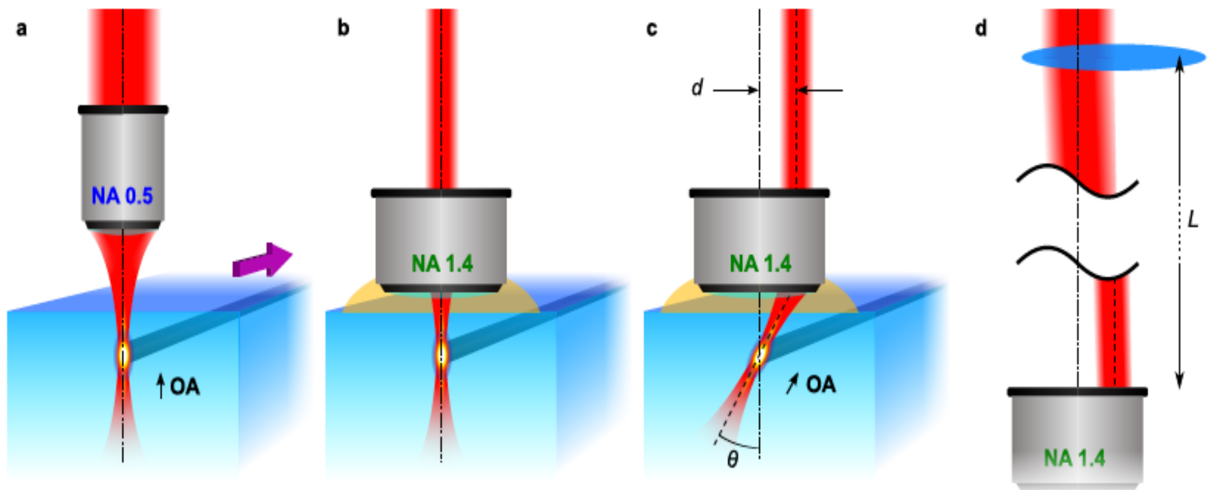
Different periodicities for H and V polarization deriving from residual asimmetry of waveguides.
Useful to realize polarization depedent devices (PPDC)

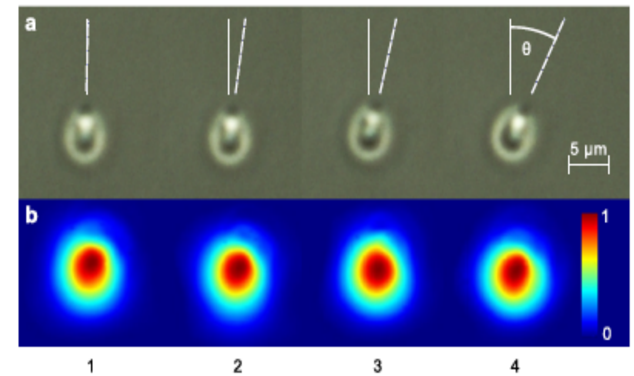




A. Crespi *et al. Nature Comm.* ***2****, 566* (2011)

Integrated waveplates

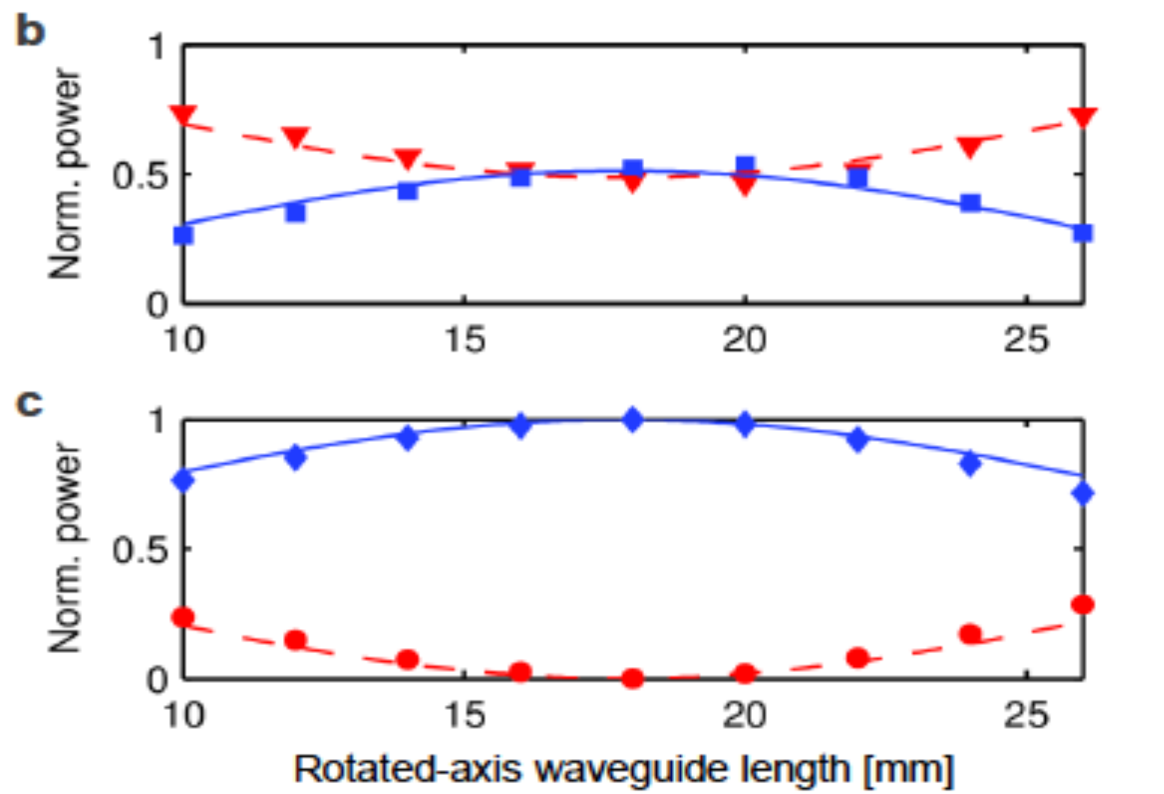




Fabrication

Input: H/V

Input: D/A



G. Corrielli *et al.*, Nat. Commun., 5, 4249 (2014)

2-photon hyperentanglement

Entangling two photons in many degrees of freedom: alternative to distributing the qubits between many particles (multiphoton entanglement)

$$|\Psi_N\rangle = |Bell_1\rangle \otimes |Bell_2\rangle \dots \otimes |Bell_N\rangle$$

N = # of degrees of freedom

$|Bell_i\rangle$:

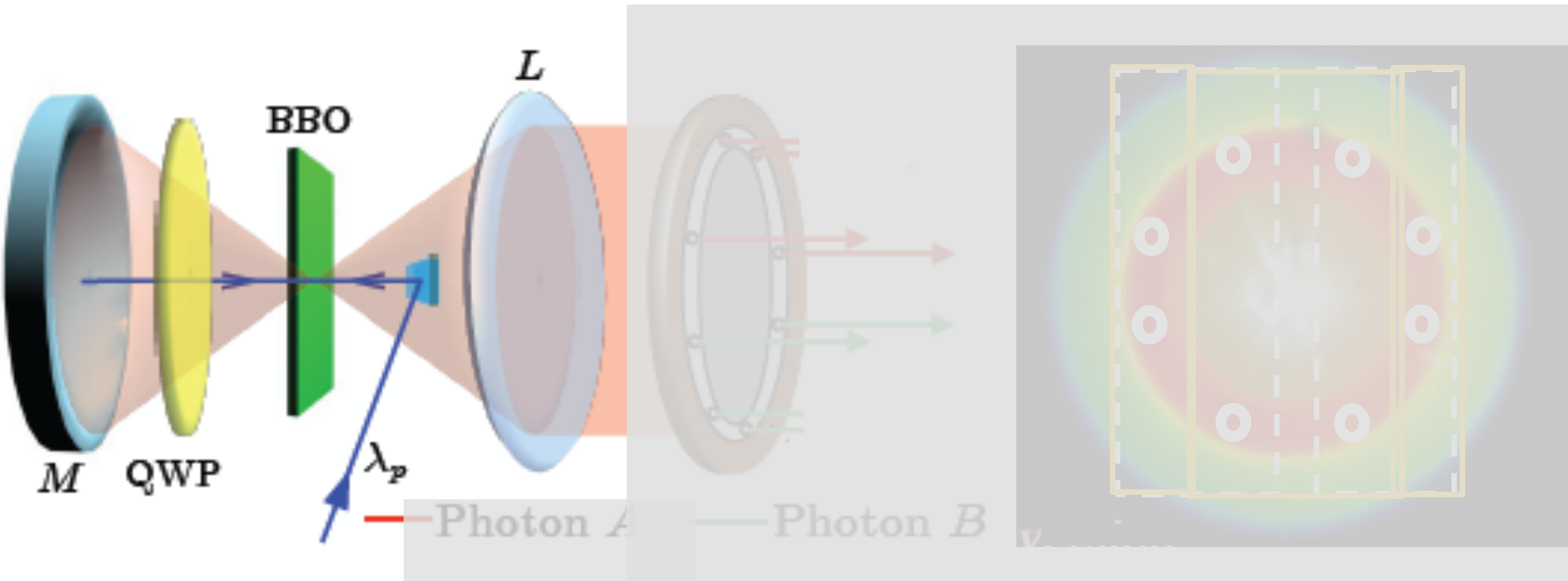
$$|\Phi^{\pm}\rangle = \frac{1}{\sqrt{2}}\left[|00\rangle \pm |11\rangle\right]$$

$$|\Psi^{\pm}\rangle = \frac{1}{\sqrt{2}}\left[|01\rangle \pm |10\rangle\right]$$

- Less decoherence with respect to *n*-photon entanglement.
- Detection efficiency, scaling as η^N, is constant when growing the size of the state.
- Exponential growing of resources but higher repetition in the state detection/generation rate.
- Used for advanced tasks of quantum information : Bell State Analysis, superdense coding, one-way quantum computation, advanced tests of quantum nonlocality, multipartite entangled states…

Path-polarization hyperentanglement

Use path and polarization of 2 photons to create 4/6 qubits)

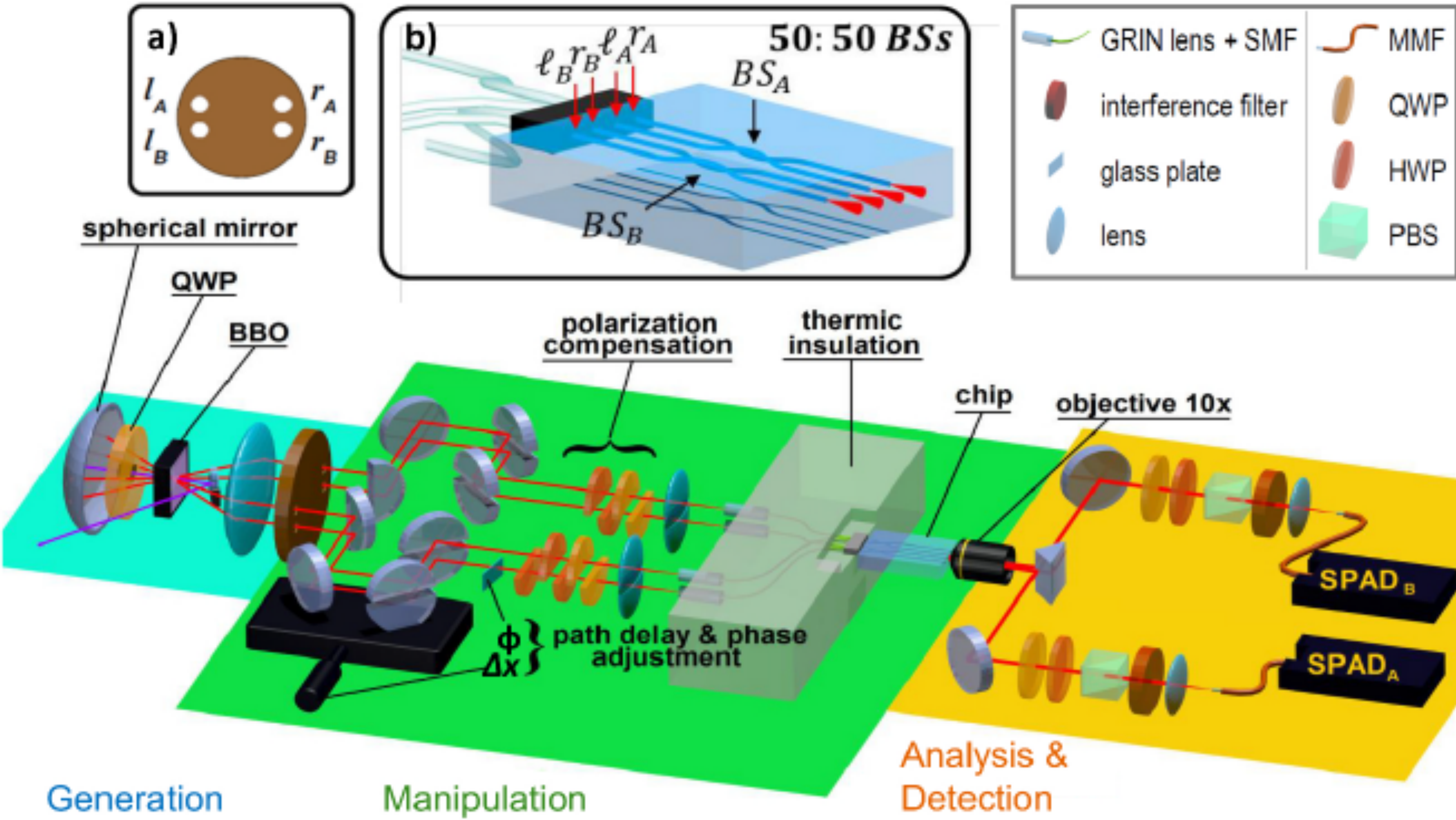


$$HE_6 = \frac{1}{\sqrt{2}}\left[|H_A H_B\rangle - |V_A V_B\rangle\right] \otimes \frac{1}{\sqrt{2}}\left[|l_A r_B\rangle + |r_A l_B\rangle\right] \otimes \frac{1}{\sqrt{2}}\left[|E_A E_B\rangle + |I_A I_B\rangle\right]$$

2 photons → 4 qubits

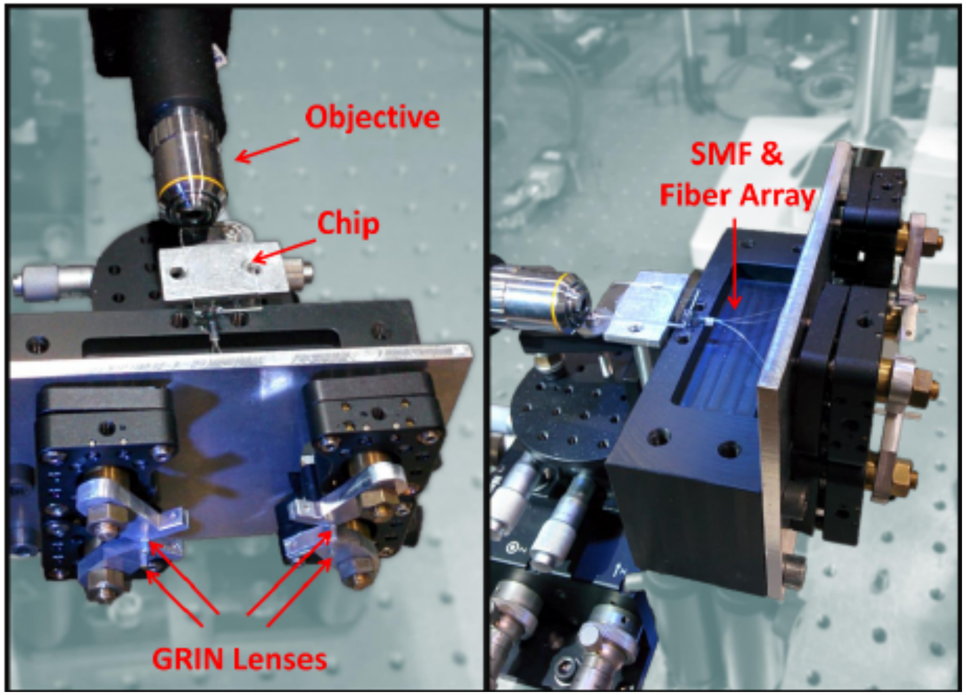
R. Ceccarelli et al., *Phys. Rev. Lett.*, 103, 160401 (2009)

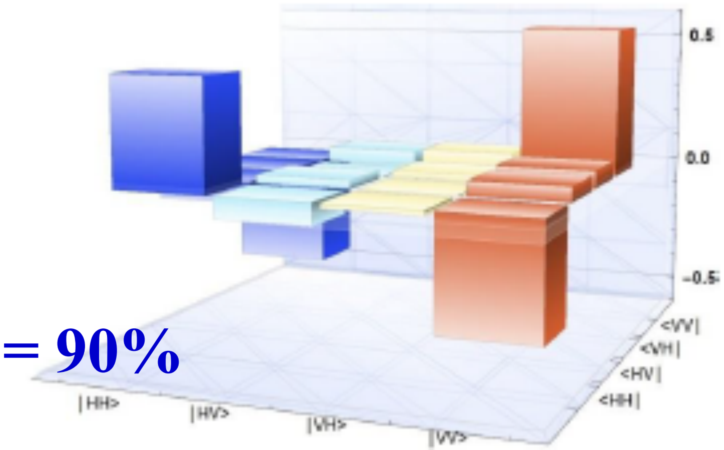
Hyperentanglement on a chip



M. Ciampini et al., *Light Science & Applications (to appear)*

Hyperentanglement on a chip

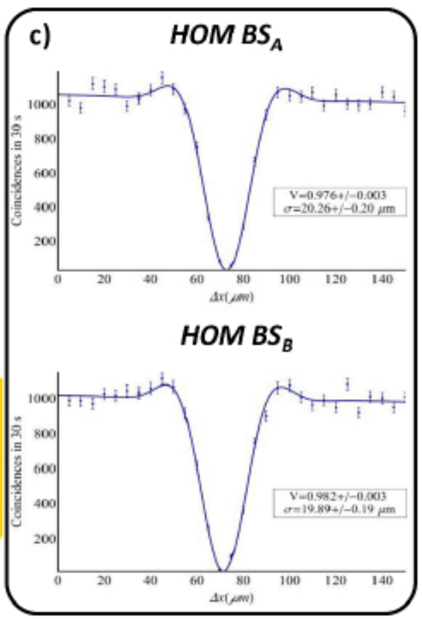


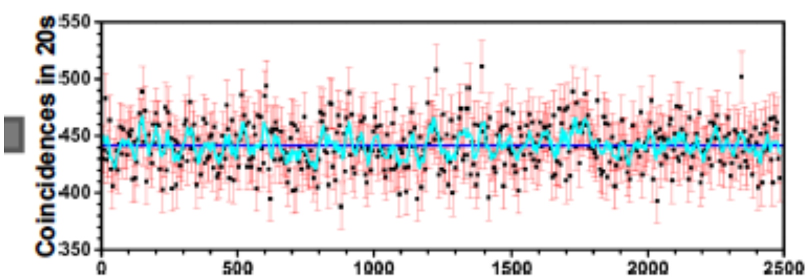


F = 90%

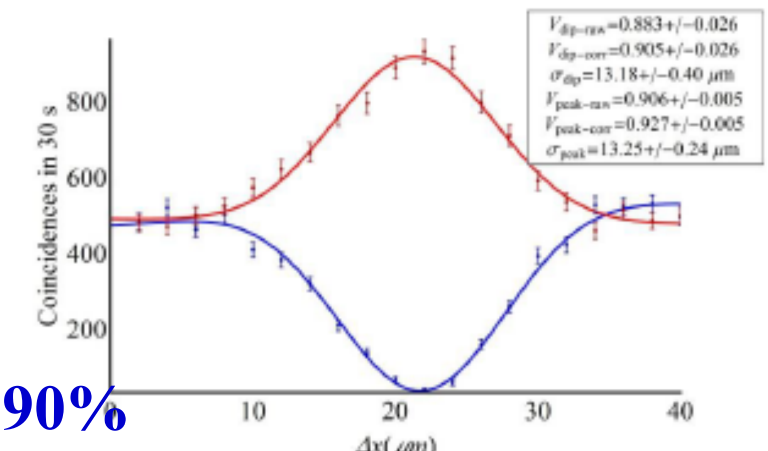
$$|l_A r_B\rangle \otimes \frac{1}{\sqrt{2}}(|H_A H_B\rangle - |V_A V_B\rangle)$$

Test separately polarization and path entanglement





Good phase stability



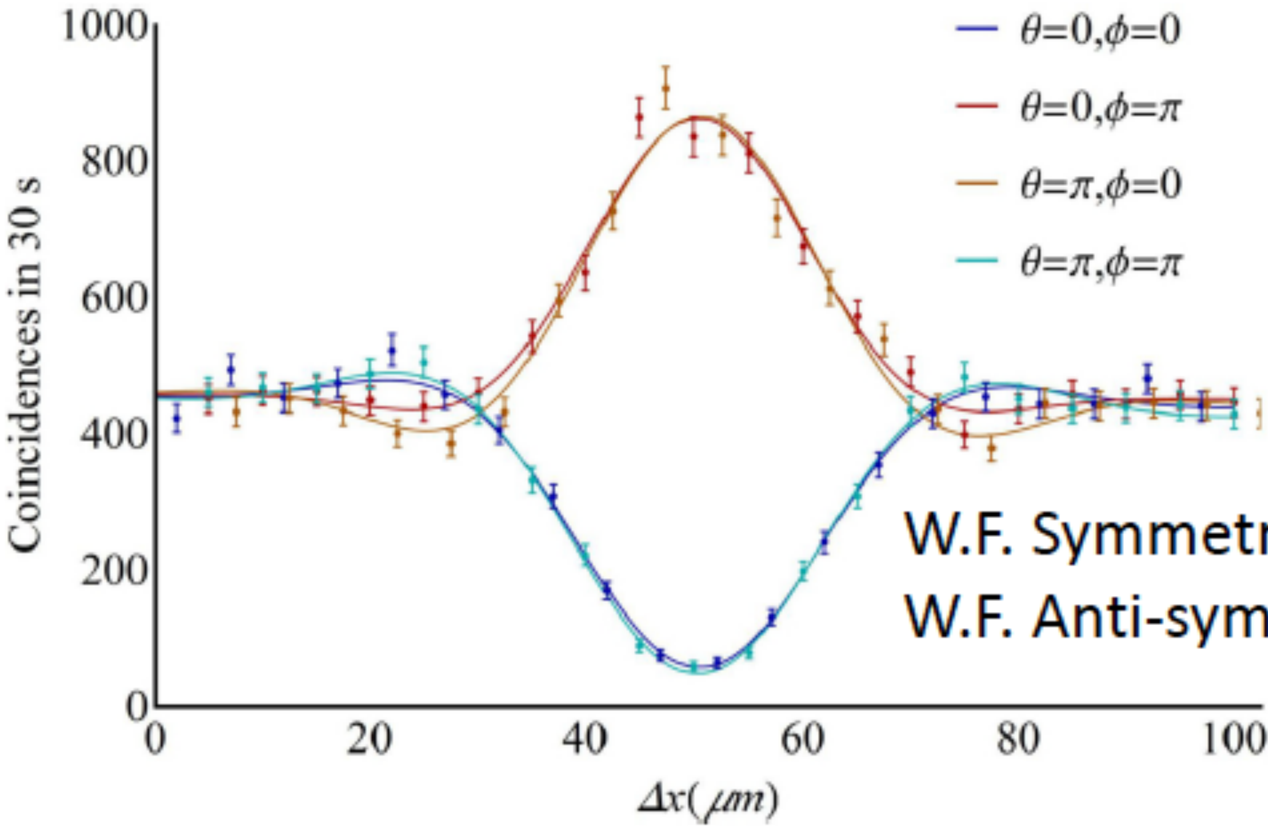
V > 90%

$$|H_A H_B\rangle \otimes \frac{1}{\sqrt{2}}(|l_A r_B\rangle + e^{i\phi}|r_A l_B\rangle)$$

Hyperentanglement measurements

Hyperentangled state interference:

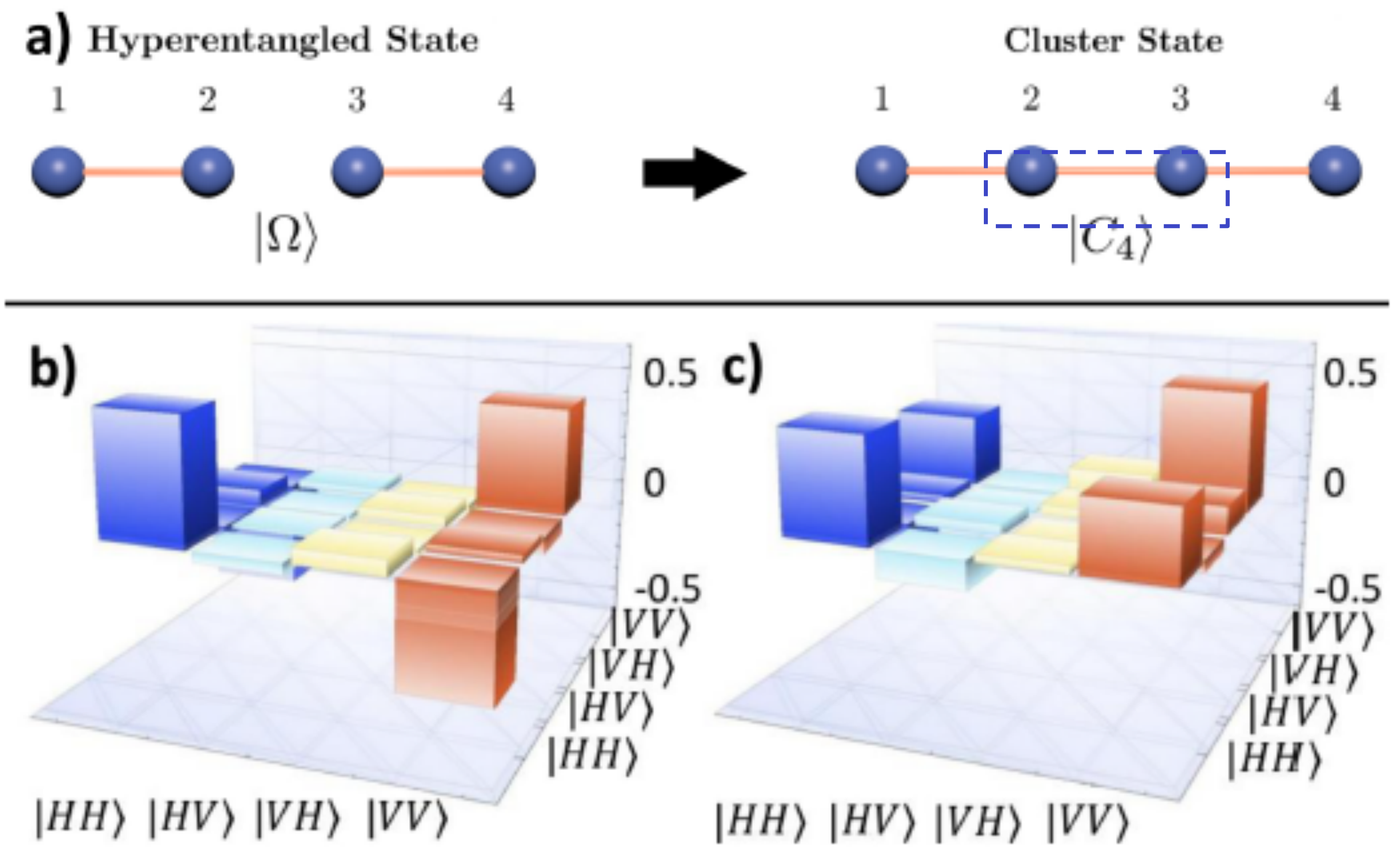
$$|\Omega\rangle = \frac{1}{2}\left(|HH\rangle_{AB} + e^{i\phi}|VV\rangle_{AB}\right) \otimes \left(|rl\rangle_{AB} + e^{i\theta}|lr\rangle_{AB}\right)$$



W.F. Symmetric -> **bosonic** behaviour

W.F. Anti-symmetric-> **fermionic** behaviour

Hyperentangled cluster states



$$F_{\Phi-} = 0.91 \pm 0.10, \qquad C_{\Phi-} = 0.88 \pm 0.08,$$
$$F_{\Phi+} = 0.83 \pm 0.11, \qquad C_{\Phi+} = 0.91 \pm 0.08.$$

$$|C_4\rangle = \frac{1}{2}(|H_a r_A H_B l_B\rangle + |V_a r_A B_B l_B\rangle + |H_a l_A H_B r_B\rangle - |V_a l_A V_B r_B\rangle)$$

$|C_4>$ realized by a HW on mode r_A acting as a Control Phase (CP).
90% fidelity measured for the states ψ_+ and ψ_- on pairs $l_A r_B$ and $r_A l_B$.

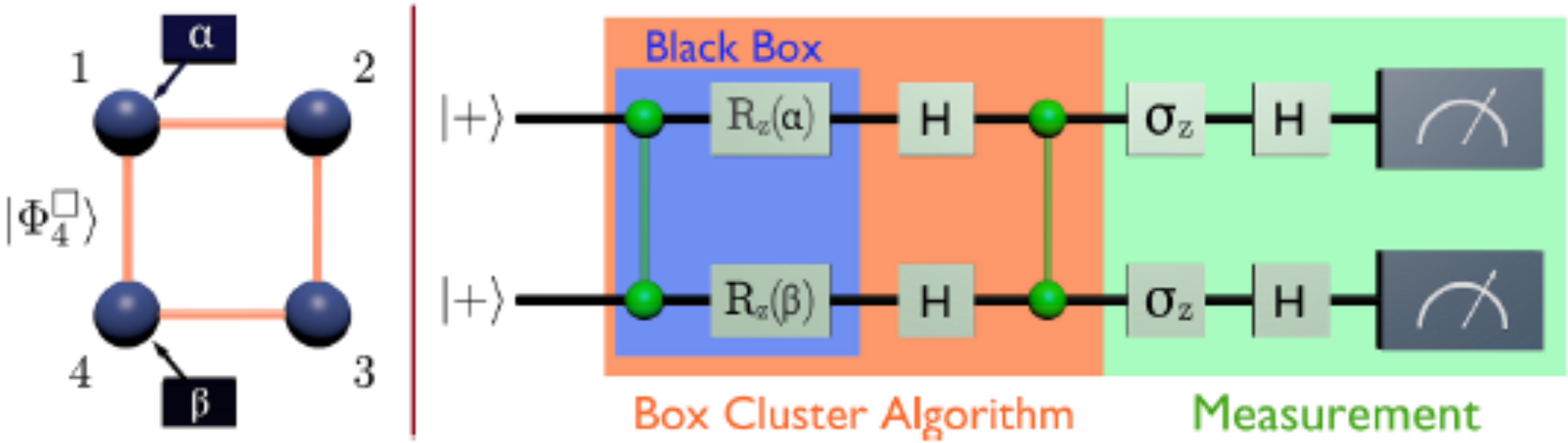
Cluster state measurements

$Z_A Z_B$	$+0.940 \pm 0.028$
$X_A X_B z_A$	-0.860 ± 0.030
$X_A X_B z_B$	$+0.860 \pm 0.030$
$z_A z_B$	-0.990 ± 0.007
$Z_A x_A x_B$	$+0.8092 \pm 0.036$
$Z_B x_A x_B$	$+0.8081 \pm 0.035$

Use multipartite entanglement witness:

$$W = 0.5(4 - Z_A Z_B - Z_A x_A x_B + X_A z_A X_B + z_A z_B - x_A Z_B x_B - X_A X_B z_B) = -0.634 \pm 0.036$$

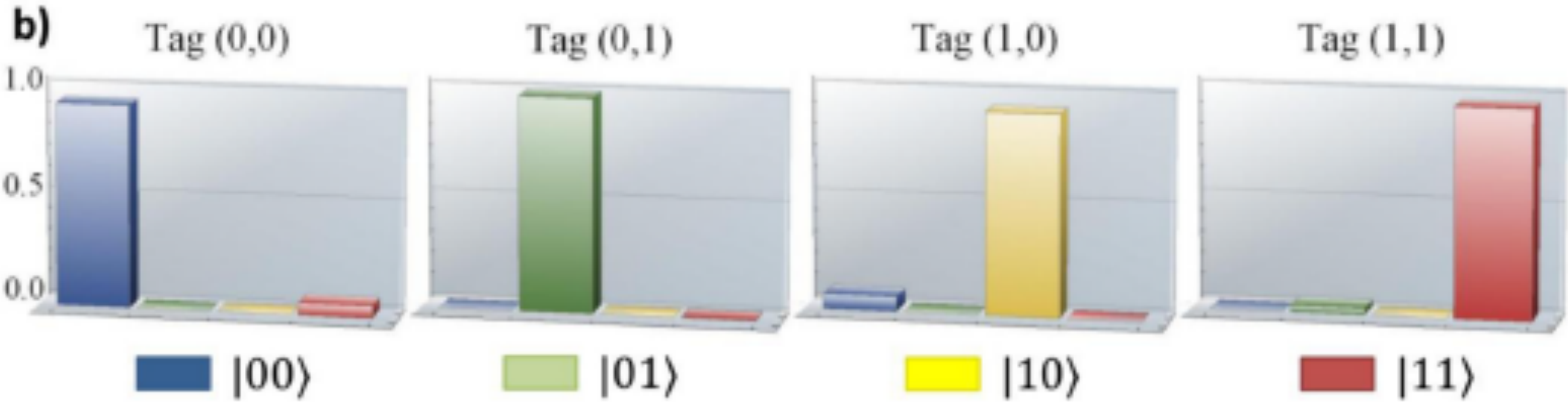
Grover's search algorithm



Have 2^M elements encoded in M qubits and a black box (oracle) tagging one of them by changing its sign.
Goal: identify the tagged item by a repeated query to the black box.
Classical: $2^M/2$ calculations
Grover: $\sqrt{(2^M)}$ operations

Four qubit box cluster states composed by the path (k) and polarization (π) qubits, labelled in the order (1, 2, 3, 4) = (k_B, π_A, k_A, π_B,).
Measure qubits 1 and 4 on the bases α and β.
Information processed and read on qubits 2 and 3.

Grover's algorithm: results



Outcome probability for different tagged items

Probabilistic algorithm (depends on postselection):
Average probability = 0.960 ± 0.007 (average rate: 17 Hz)

Deterministic algorithm (passive feed-forward)
Average probability = 0.964 ± 0.003 (average rate: 68 Hz)

Challenges, perspectives.....

- Increase number of modes (limitation: bending losses of laser written waveguides)
- Active reconfiguration of Unitaries
- Novel 3D structures for more complex circuits
- Exponential growth of quantum complexity
- More complex circuits including PBSs, waveplates, active phase shifters enabling state manipulation and analysis on a chip
- Integrate hyperentanglement source inside the chip.
- High efficiency single photon detectors
- Higher number of photons

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3D-QUEST

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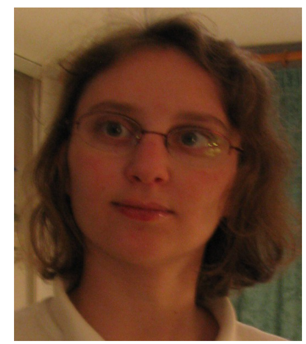

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SAPIENZA
UNIVERSITÀ DI ROMA

FUTURO IN RICERCA

SEVENTH FRAMEWORK PROGRAMME

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QUCHIP

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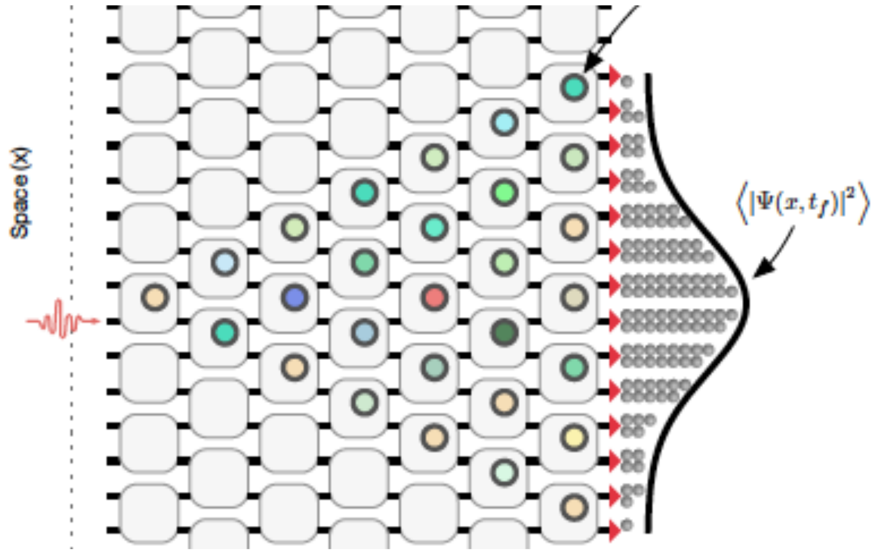
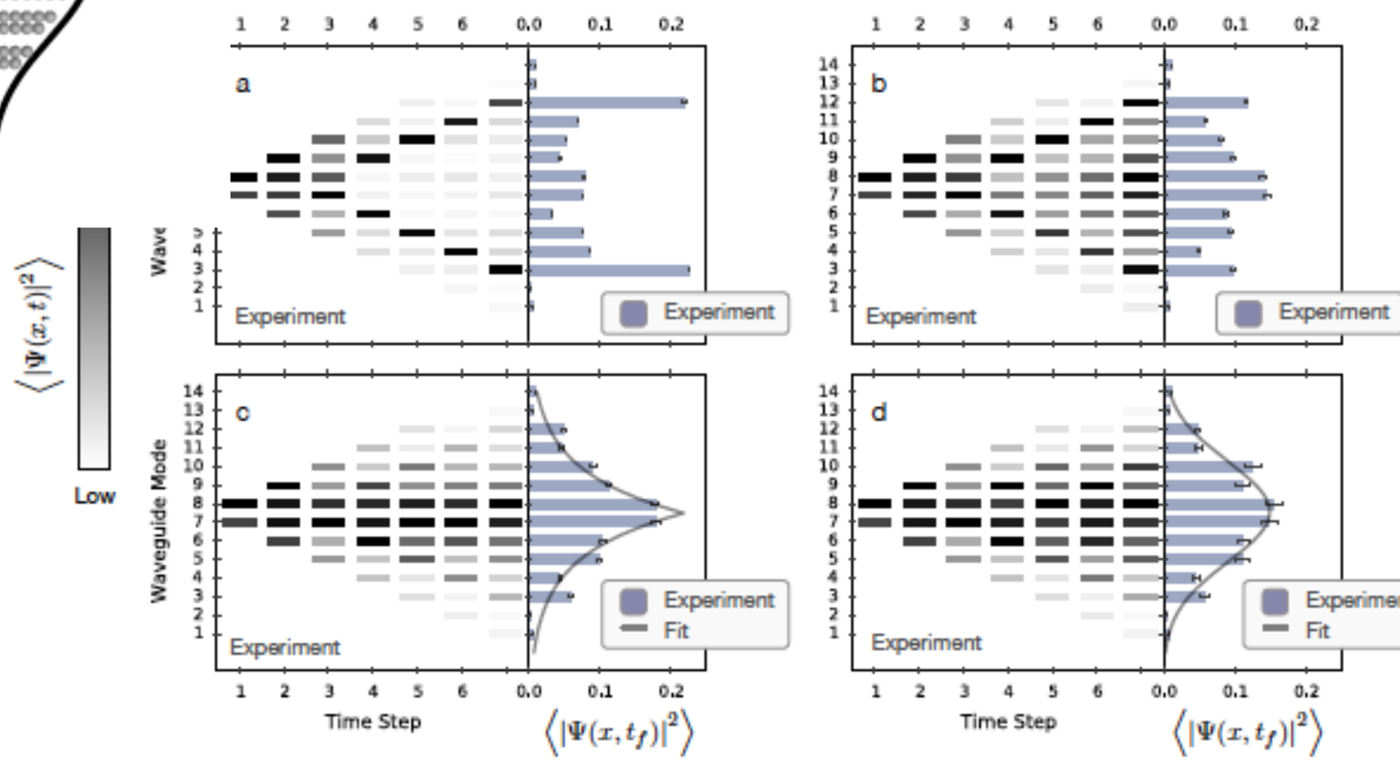
Bosonic transport simulation in a programmable processor





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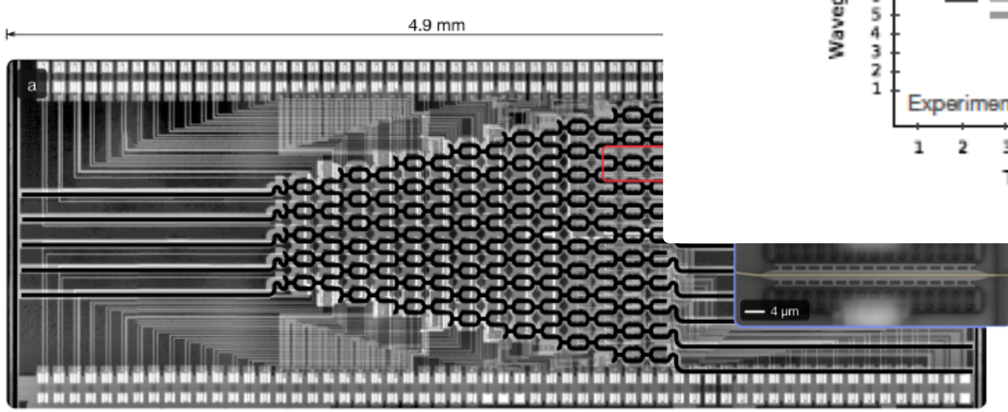
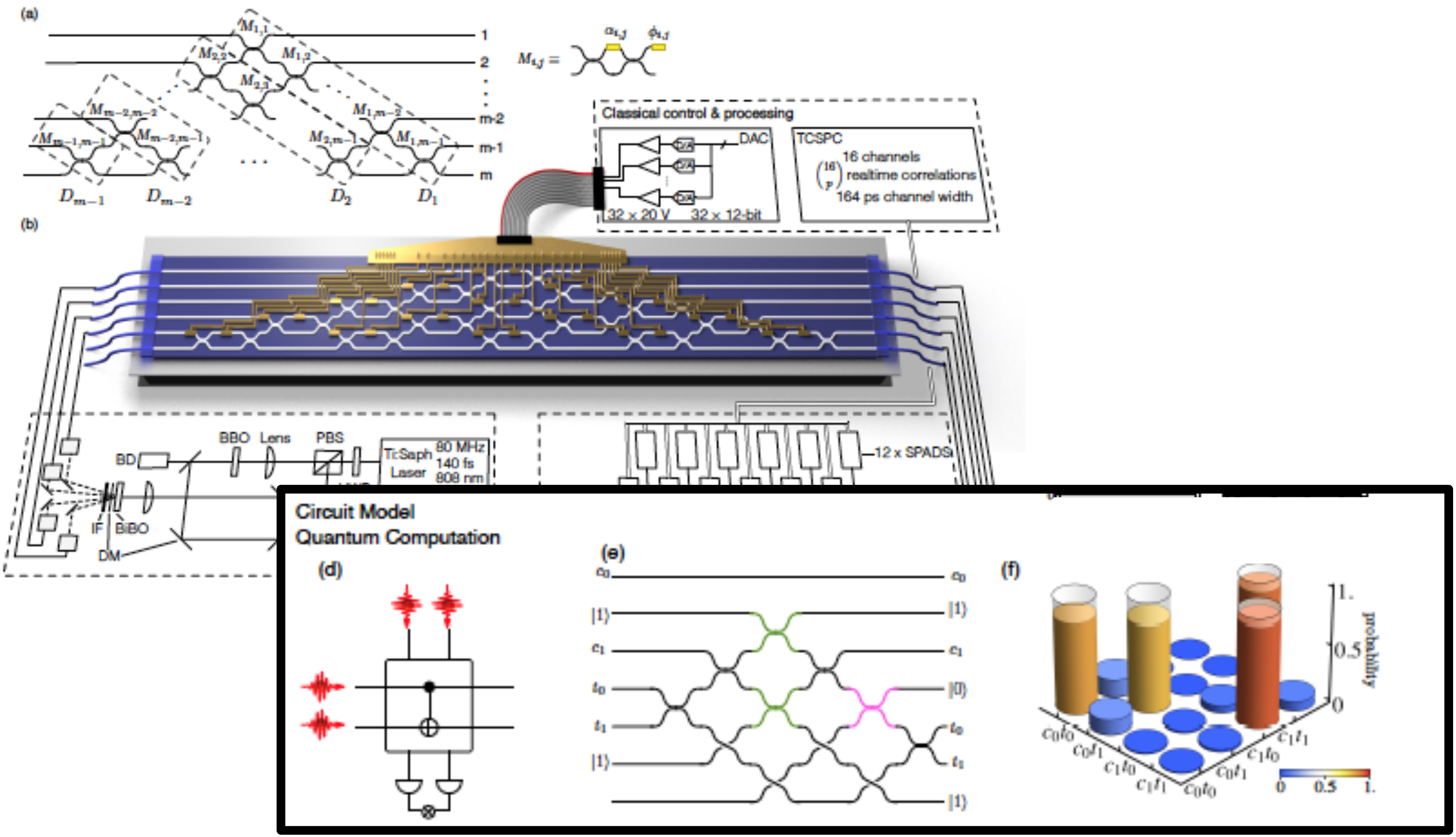


N. C. Harris, *et al.*, (2015)

Universal linear optics



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J. Carolan, *et al.*, *Science* (2015)