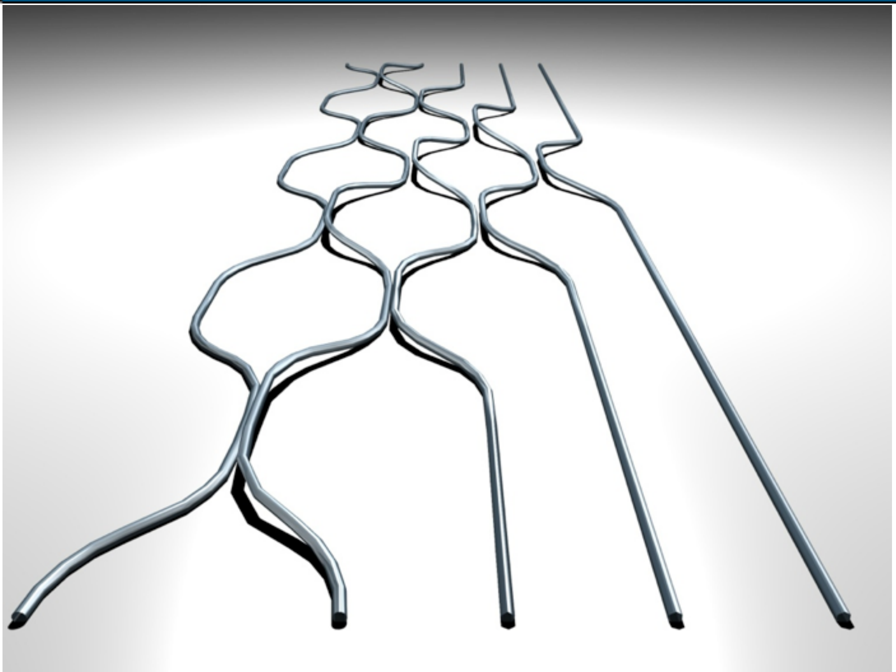

Simulating quantum phenomena through integrated photonic circuits

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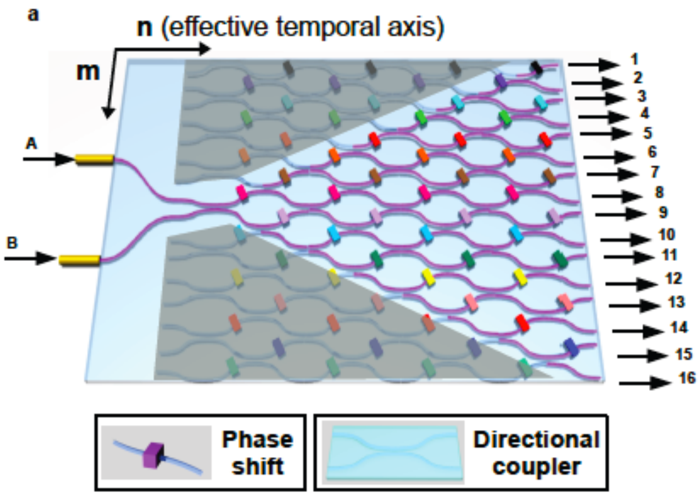
Sapienza Università di Roma

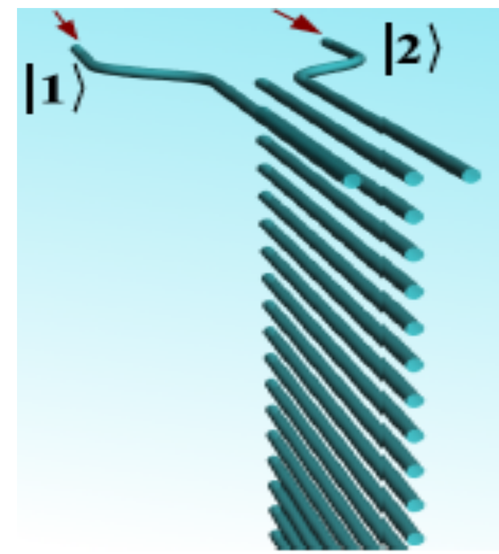
http:\\quantumoptics.phys.uniroma1.it

What Next, Firenze, May 6, 2015

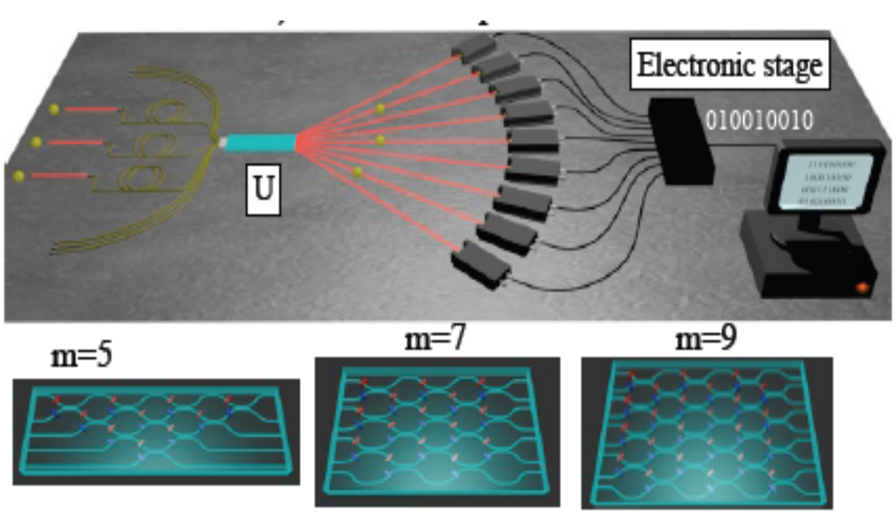
Summary



1) Anderson localization of two non-interacting bosons/fermions via quantum walks



2) Study the role of particle statistics in quantum decay in a continuum and Fano resonances



3) Boson Sampling: a promising route towards *Quantum Supremacy*

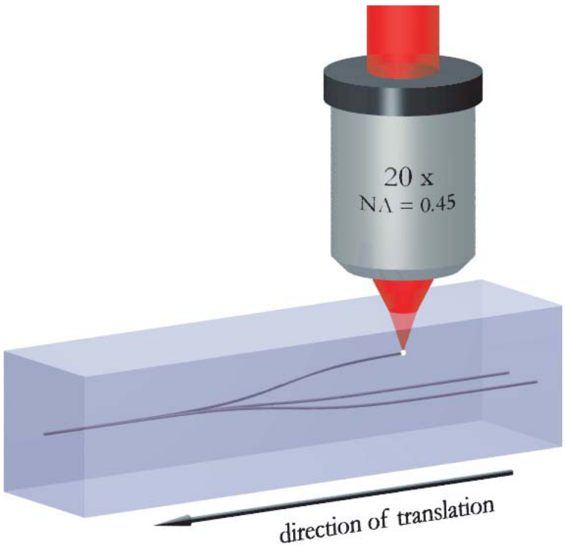
Femtosecond laser writing

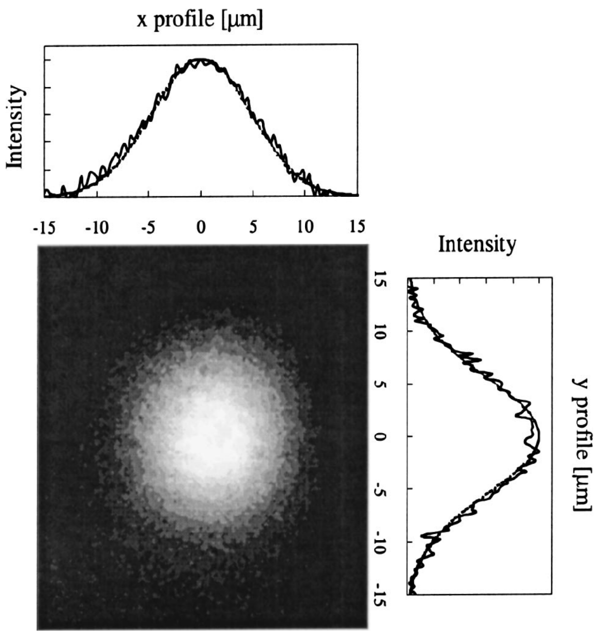
3-D capability

Rapid device prototyping:
writing speed = 4 cm/s

Propagation of circular gaussian modes

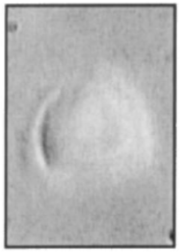
Main features

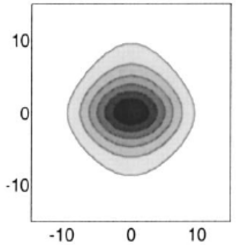




Circular waveguide transverse profile

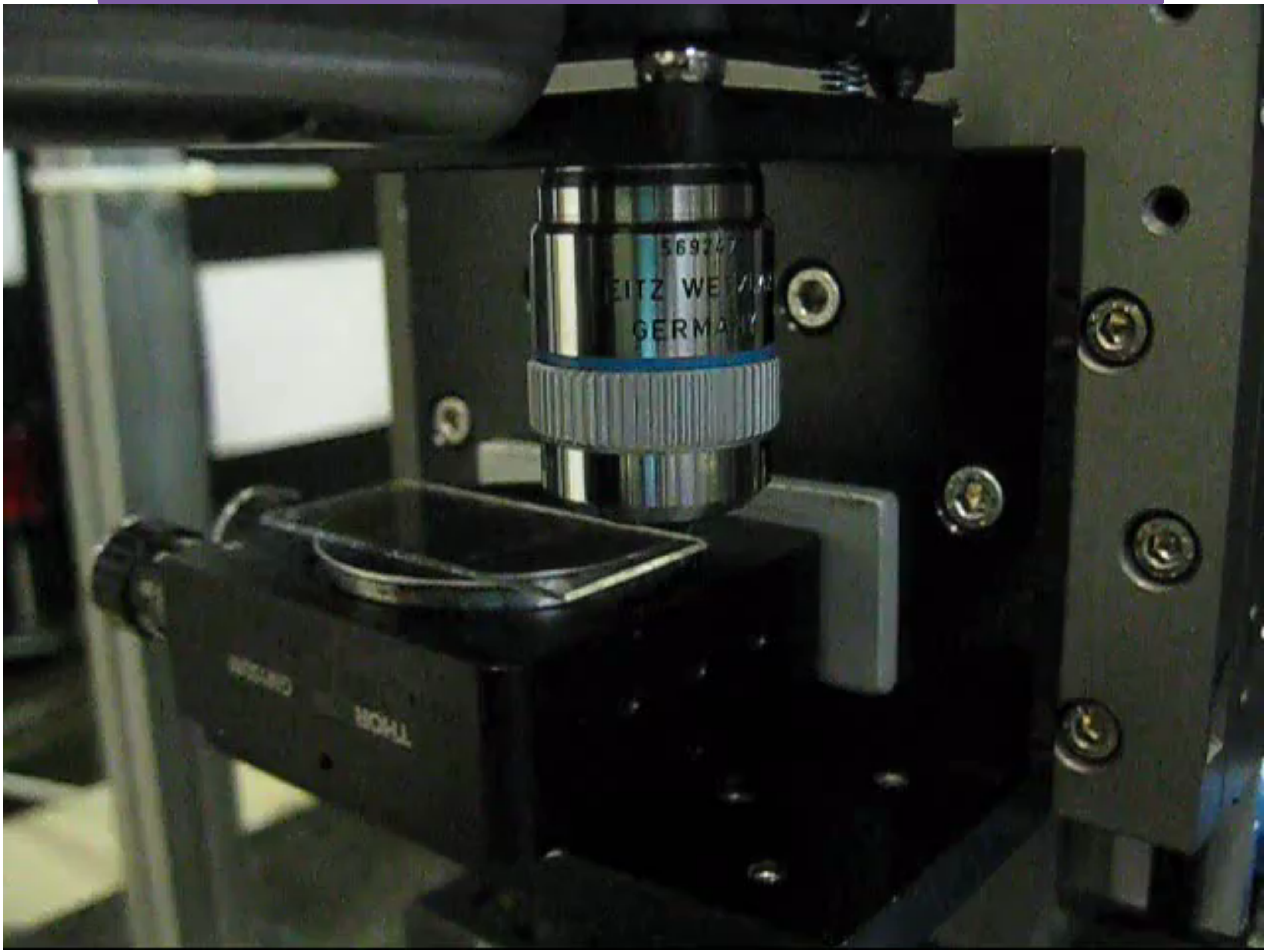
Low birefringence



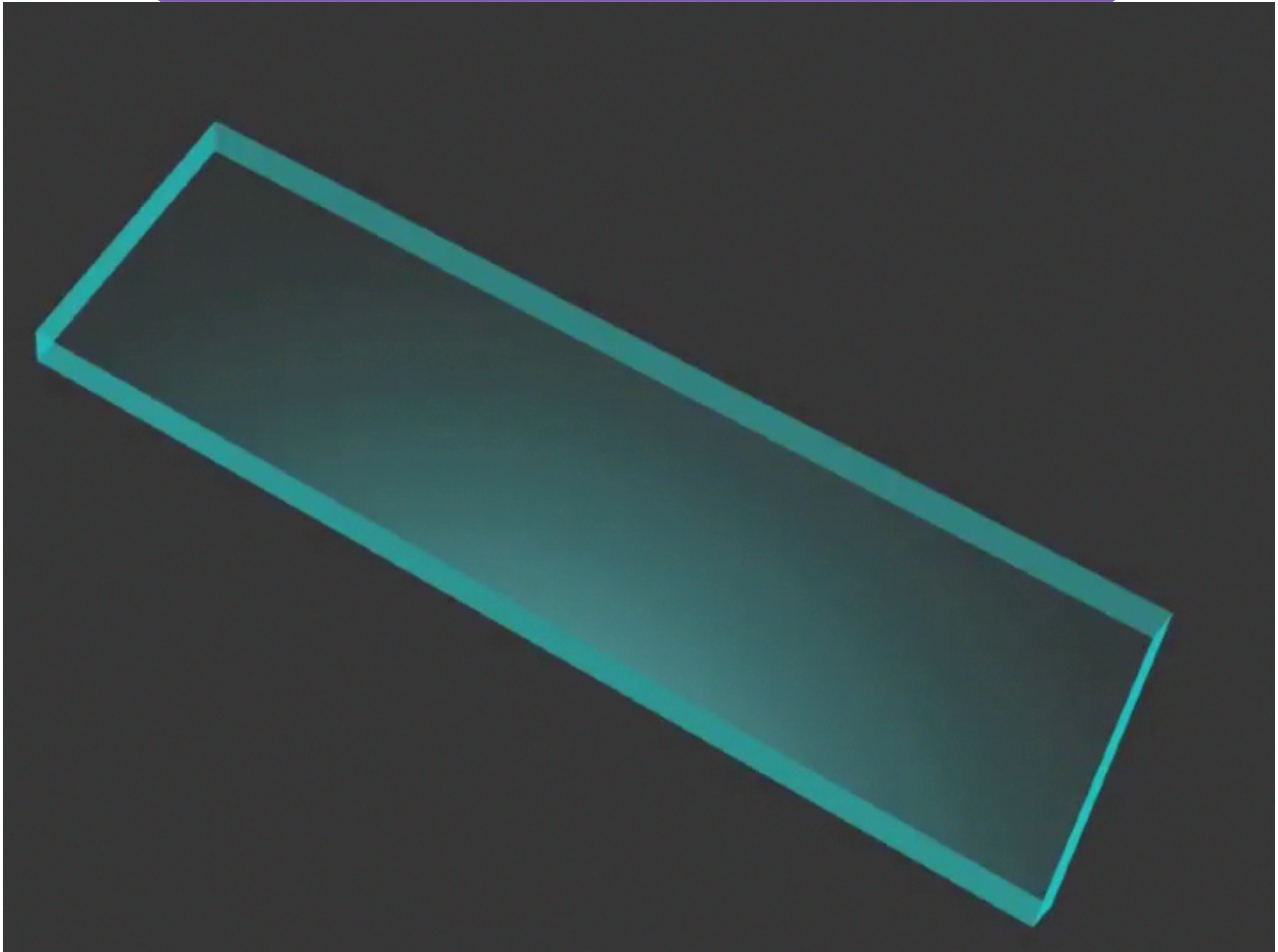


ABLE TO SUPPORT ANY POLARIZATION STATE

Femtosecond laser writing

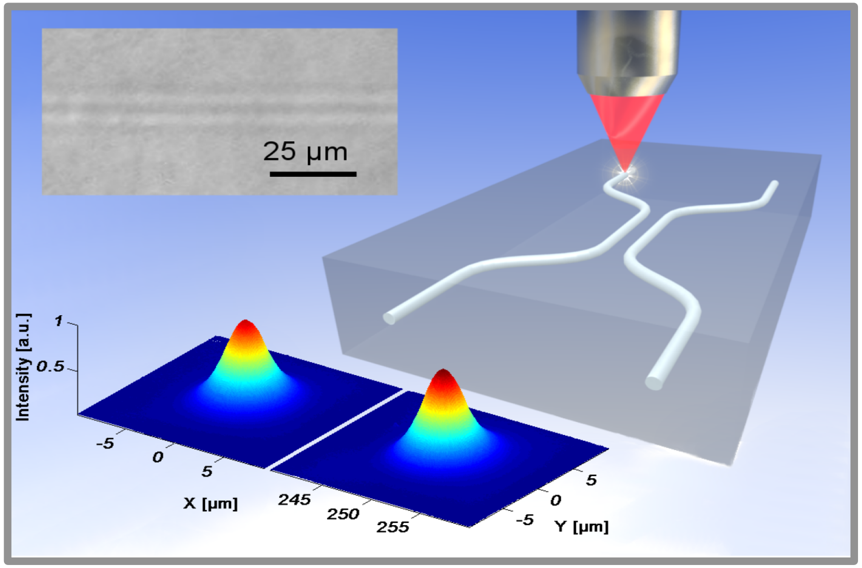


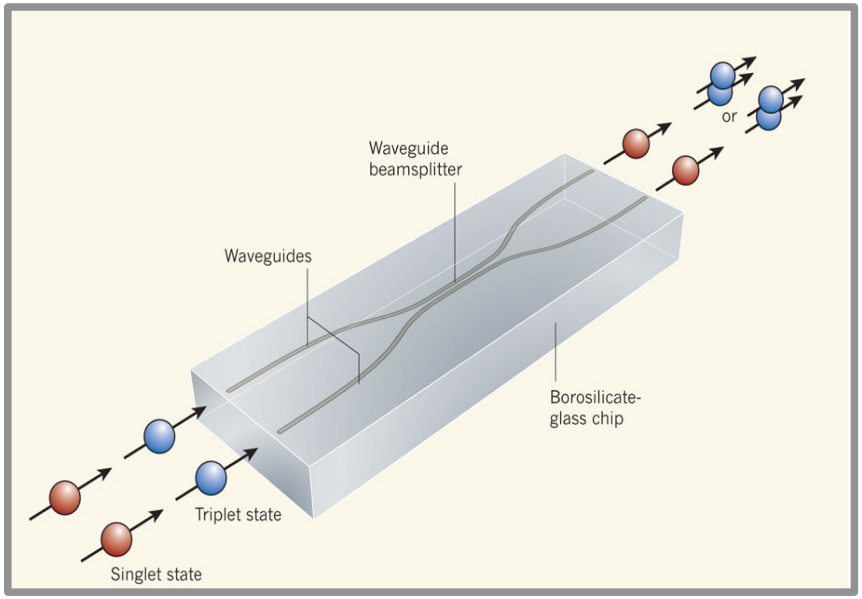
Femtosecond laser writing



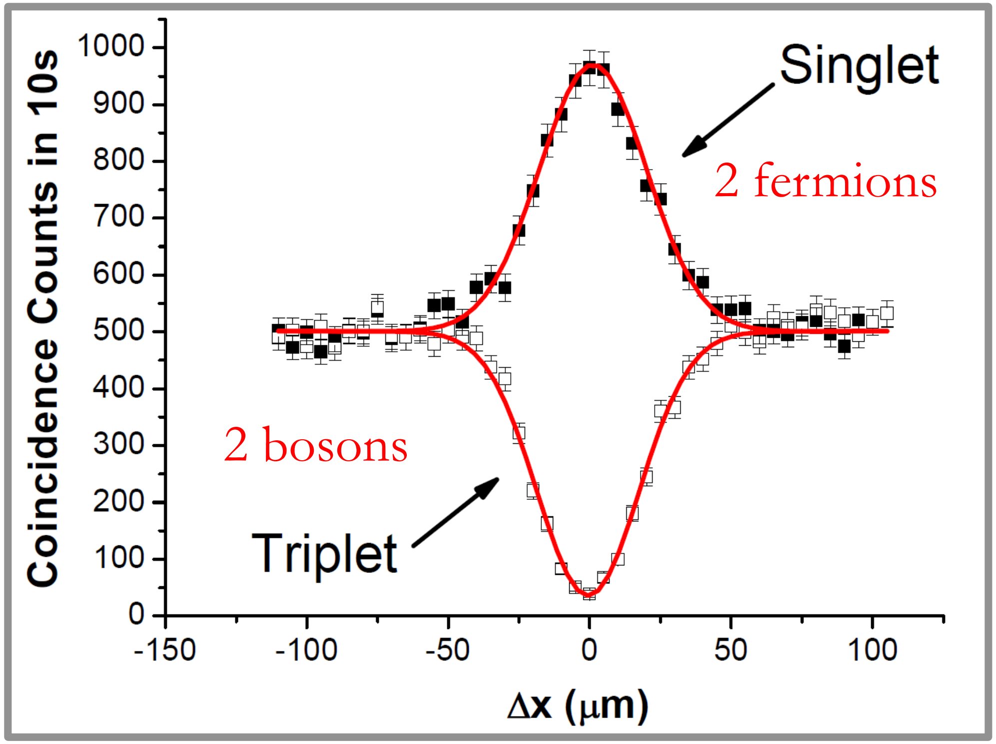
Integrated beam splitter

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





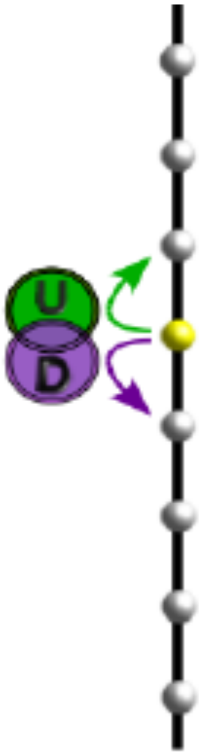
M. Lobino & J.L. O'Brien *News &Views* Nature (2011)



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

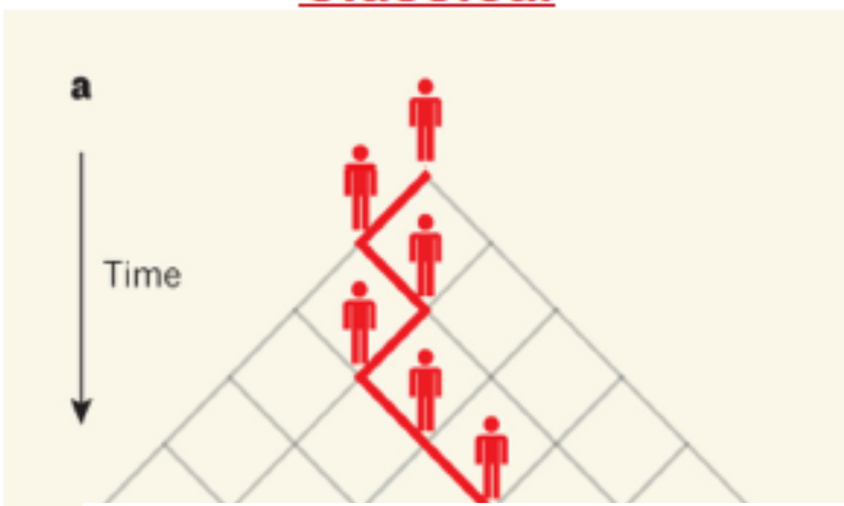
Goal: to simulate the dynamics of non-interacting bosons/fermions in complex interferometric structures

Quantum Walk



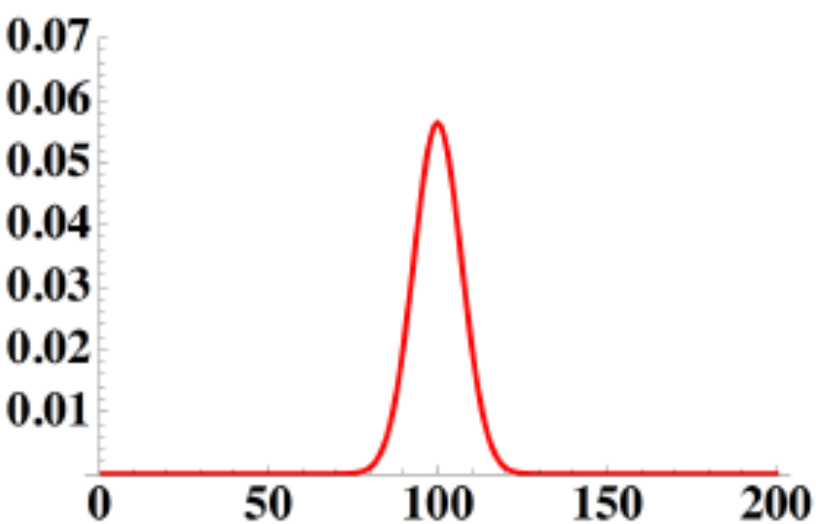
Quantum walk: extension of the classical random walk:
a walker on a lattice "jumping" between different sites with given probability

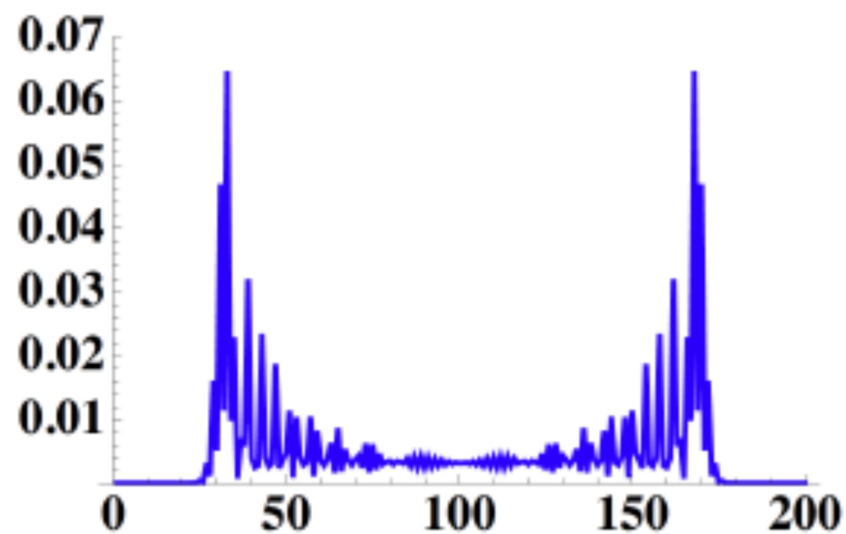
Classical



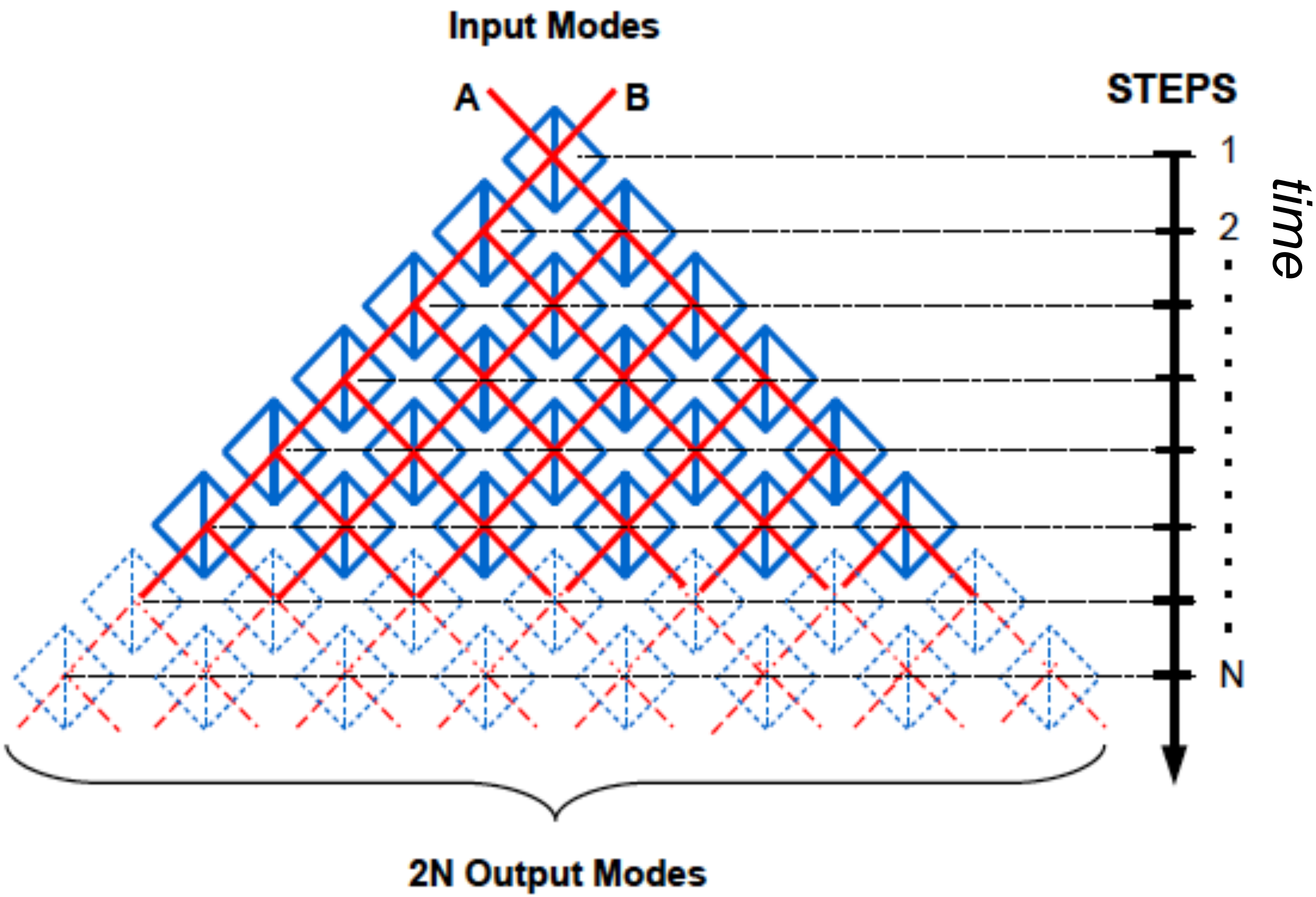
Quantum

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

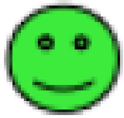




Implementing QW with photons

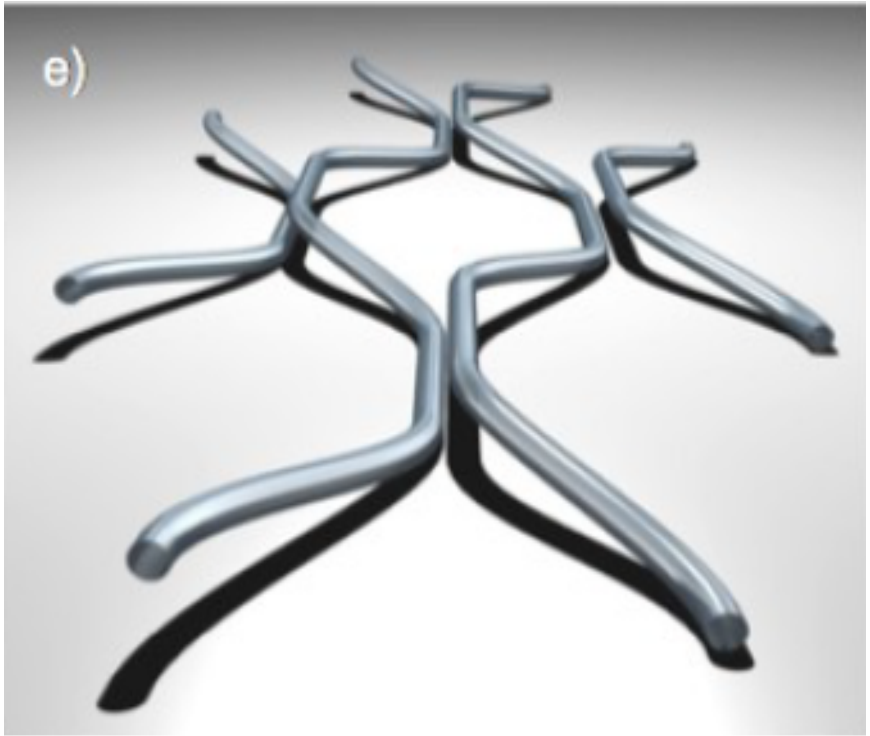


Discrete QW: realized by concatenating many beam splitters and phase shifters



Feasible with integrated photonic waveguides

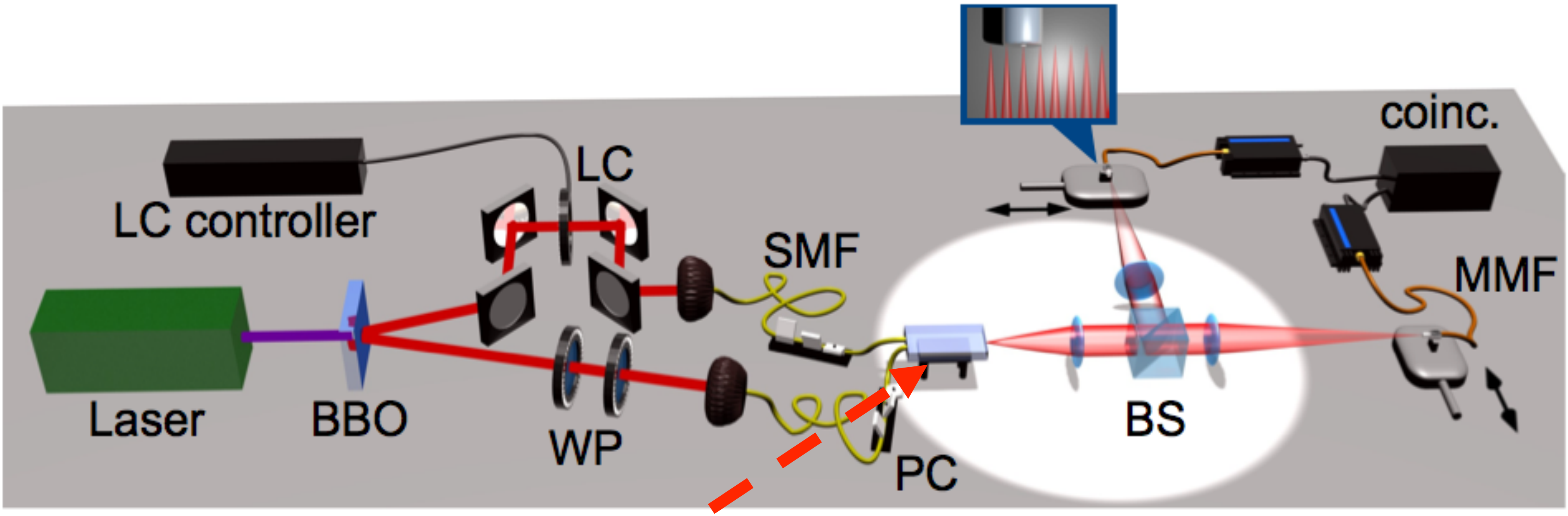
Polarization independent QW



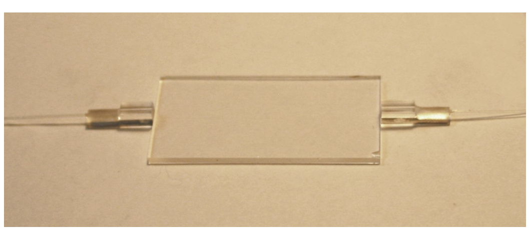
- Polarization independent lattices made possible by 3D writing capability
- Path lengths controlled up to few nanometers

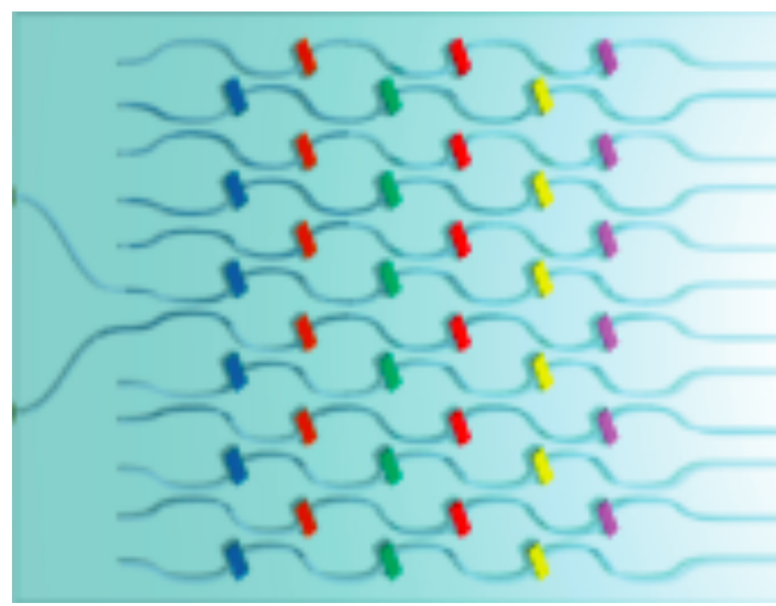
L. Sansoni, *et al.*, Phys, Rev, Lett, **108**, 010502 (2012)

QW experiment



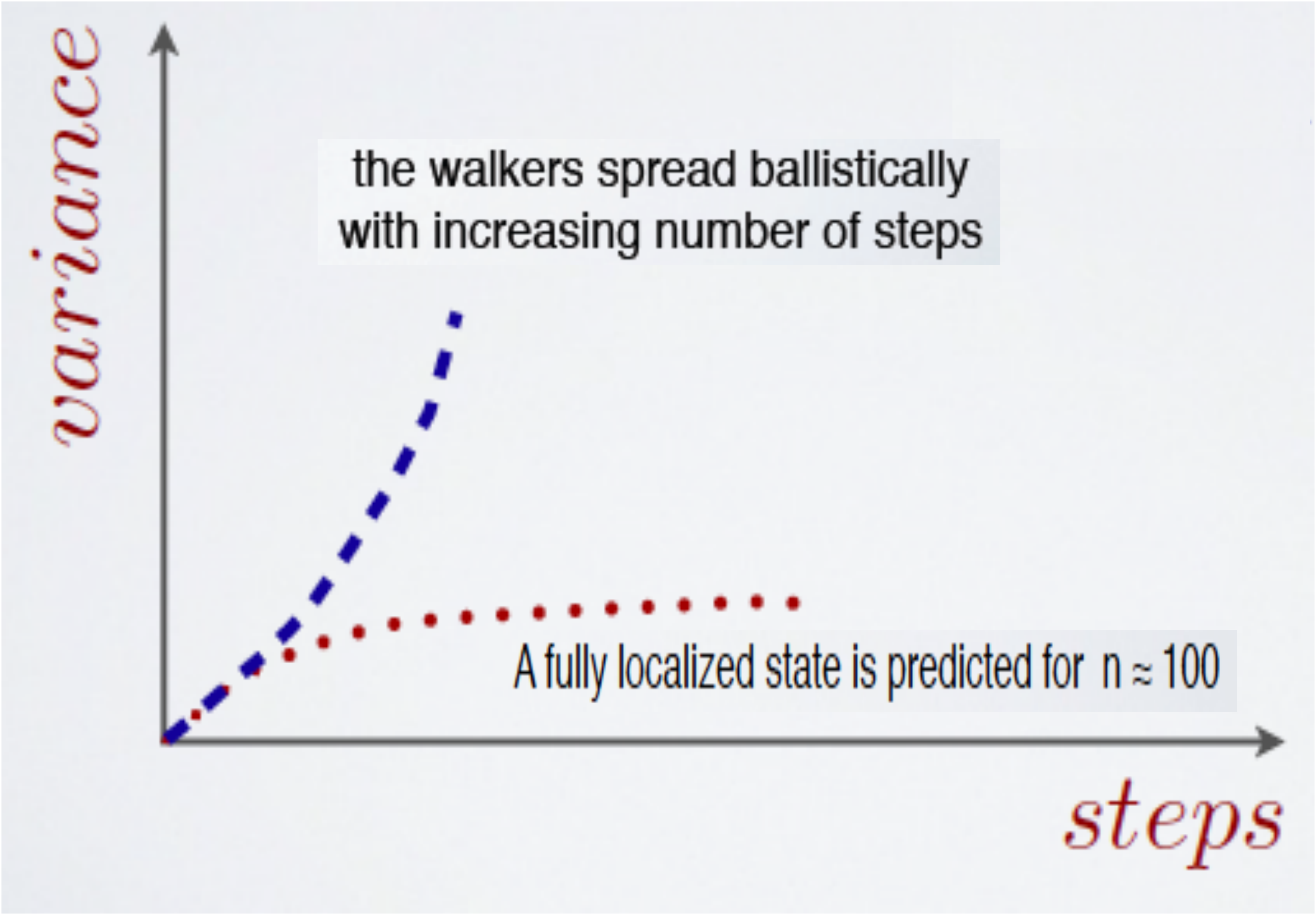
On chip BS array





Ordered & Disordered QWs

Study the pure role of symmetries by different phase maps used in different diffusion processes of two non-interacting bosons/fermions

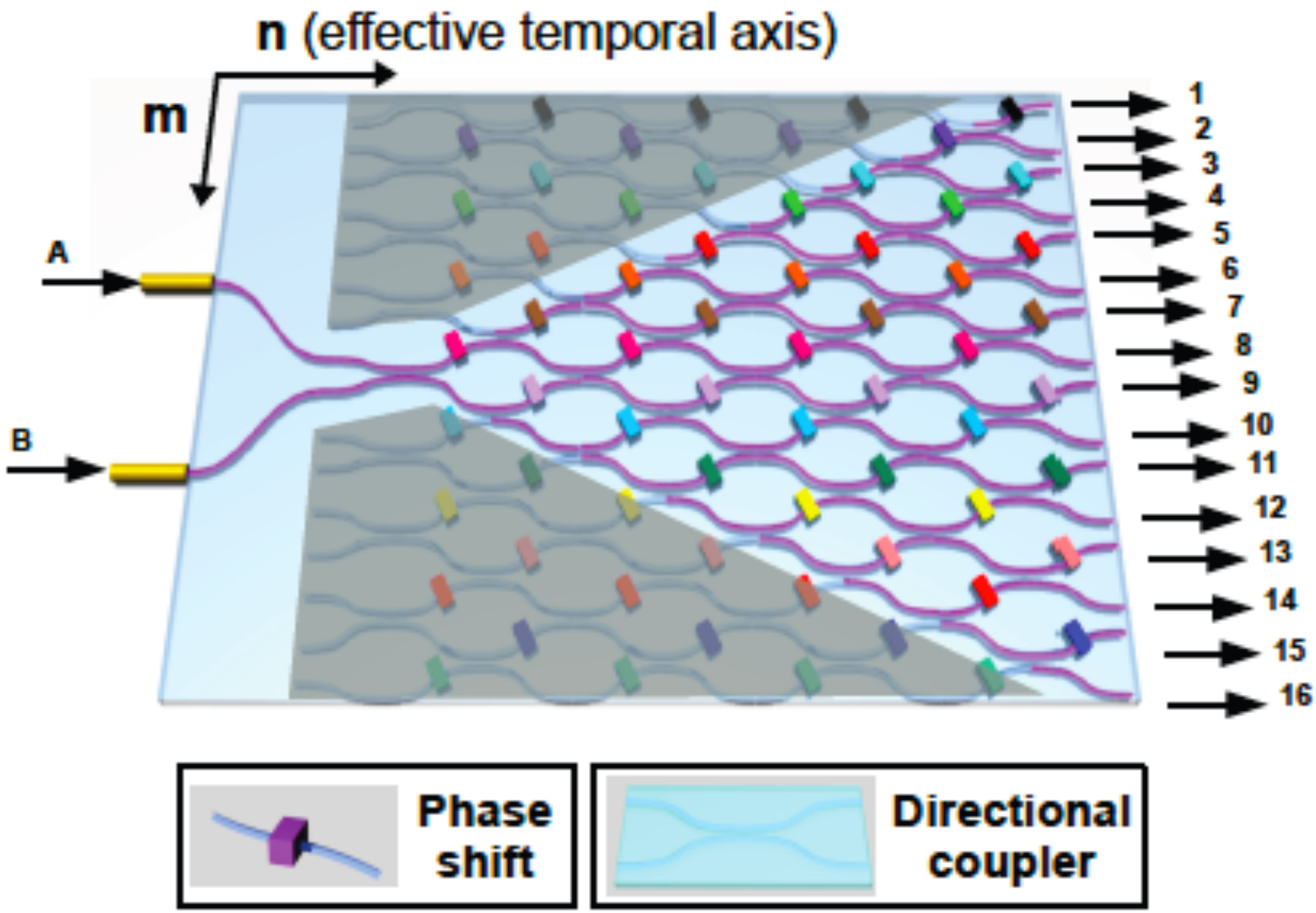


Static disorder

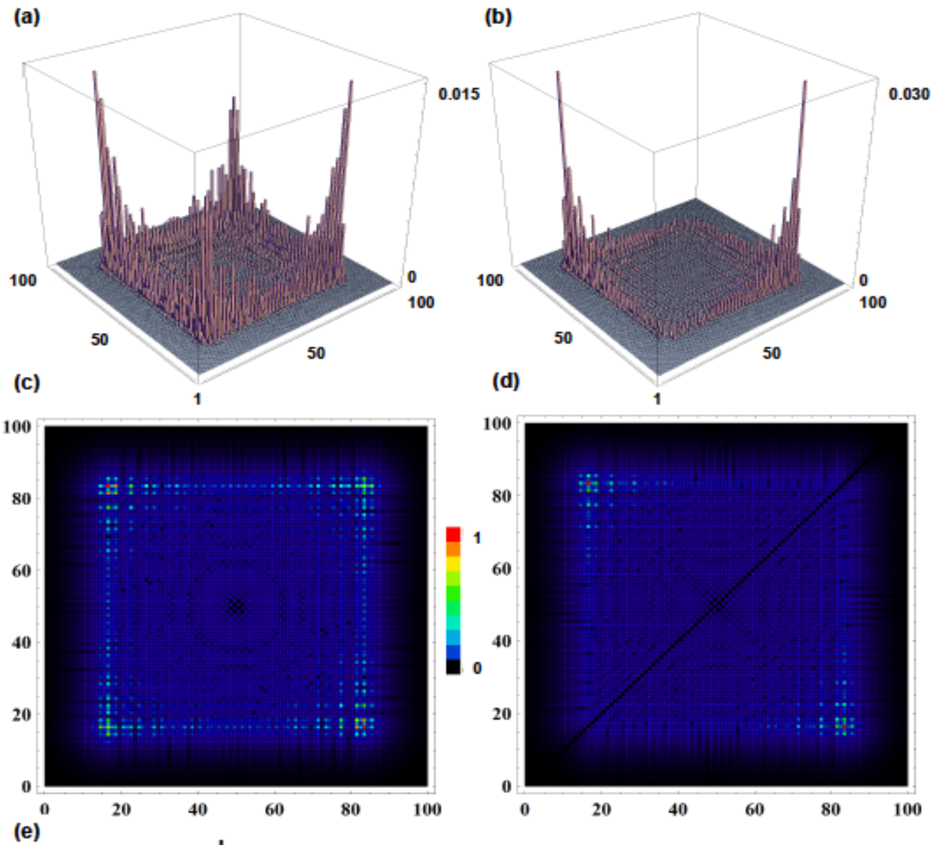
Disorder depending
- on site
- but NOT on time

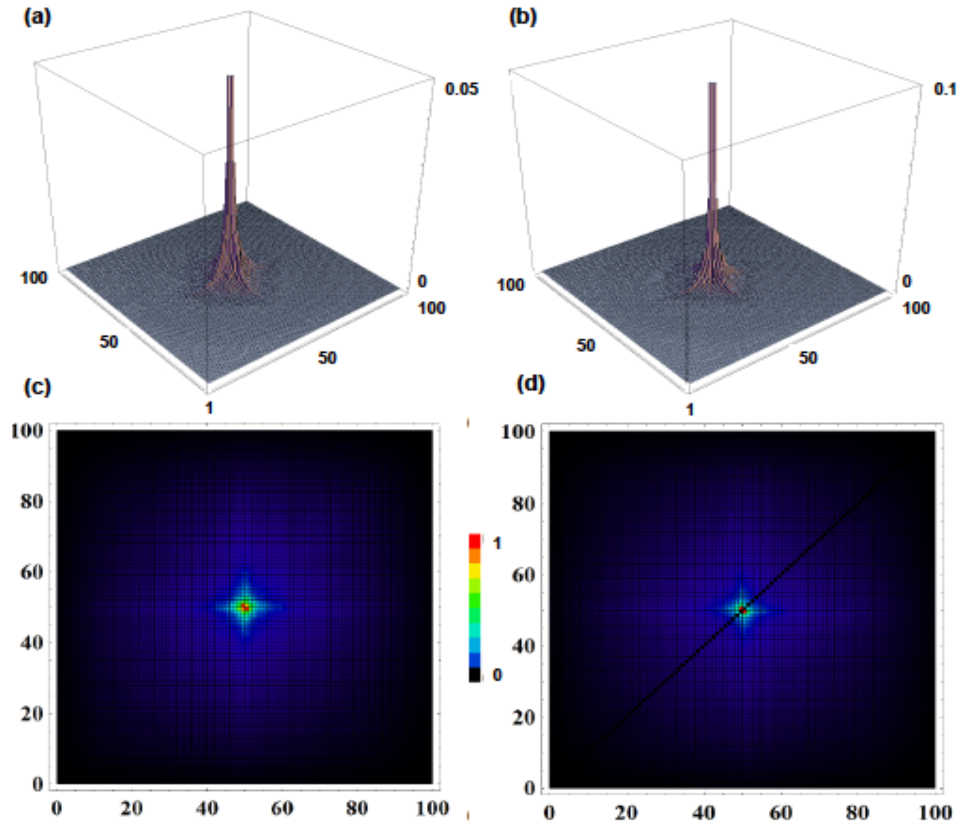
Anderson localization of the quantum particle wavefunction

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



2-particle QW: theoretical distribution





2 Bosons **2 Fermions**

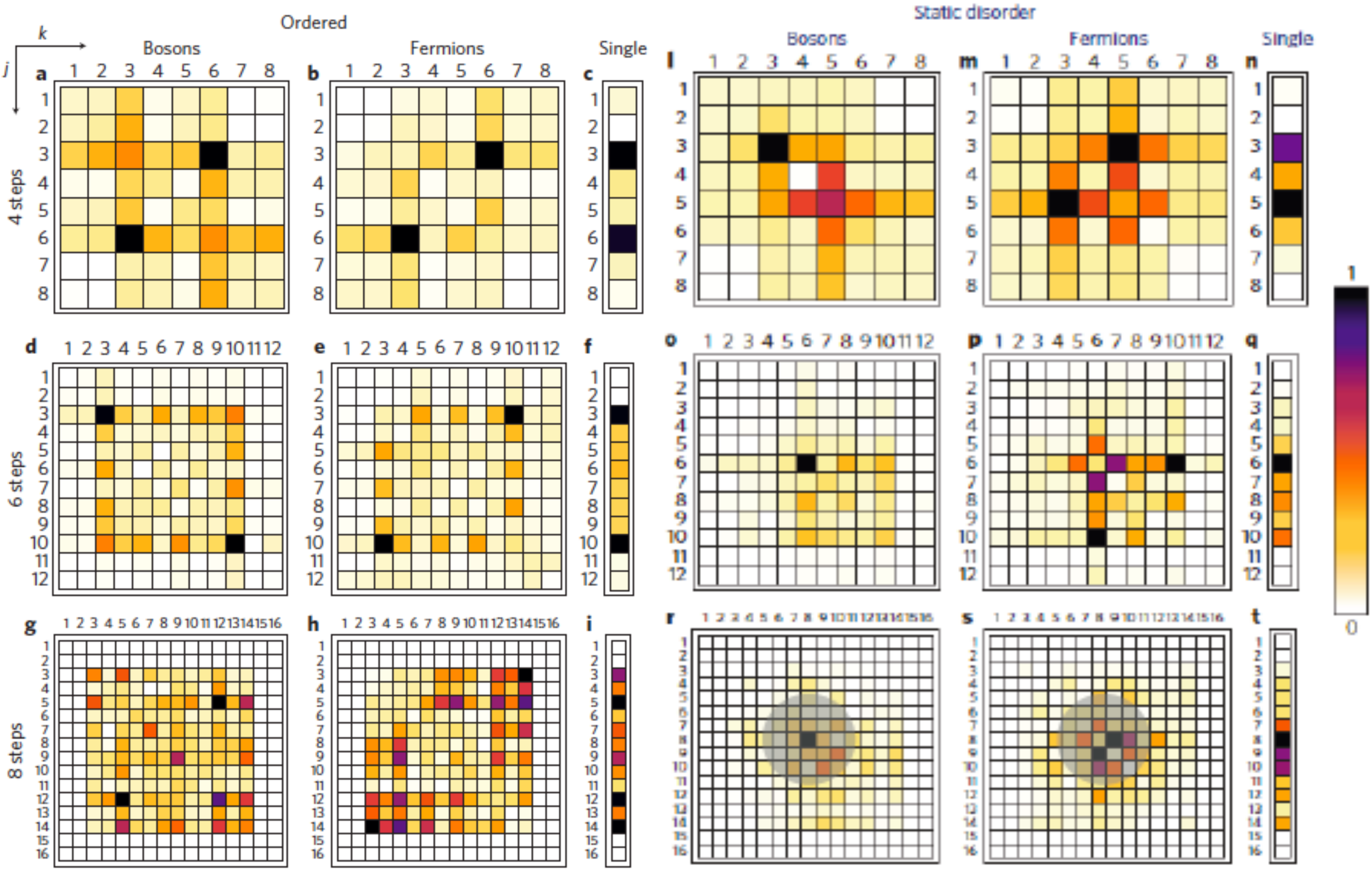
Ordered QW (50 steps)

2 Bosons **2 Fermions**

Static disordered QW (50 steps)

F. De Nicola, *et al.*, *Phys. Rev. A*, **89**, 032322 (2014)

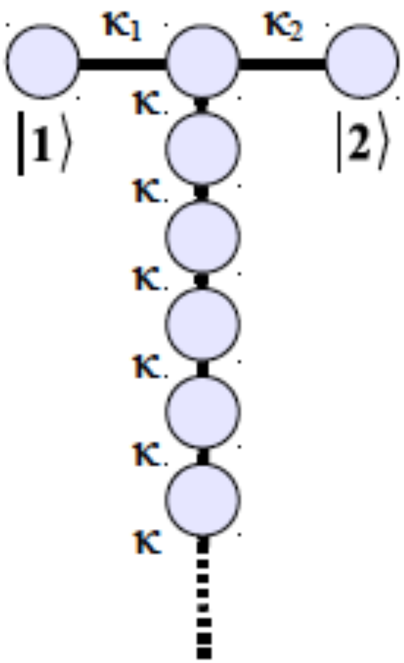
2-particle QW: exp. results

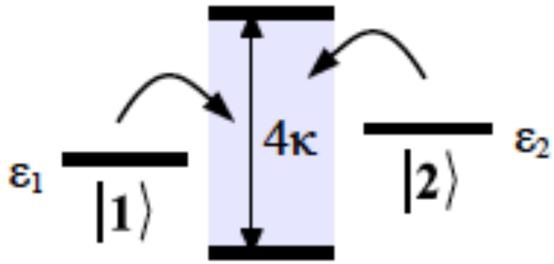


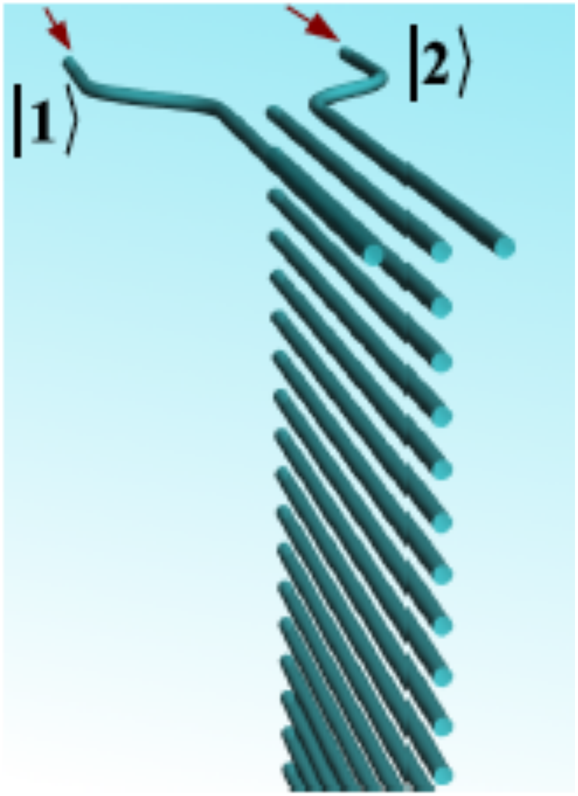
A. Crespi, *et al.*, *Nature Photonics*, **7**, 322 (2013)

Quantum decay and Fano resonances

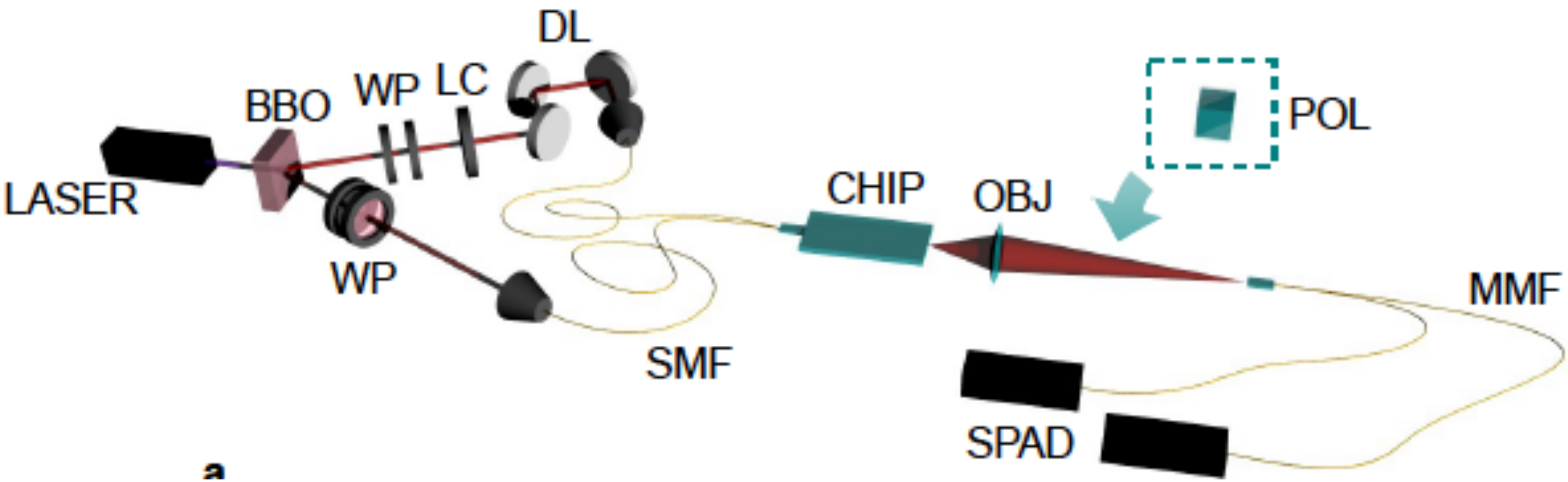
Investigate the decay process of two non-interacting particles (bosons/fermions) to a common continuum.
Probe properly engineered lattices with 2-photon states.
Insight on Fano interference and bound states in the continuum.

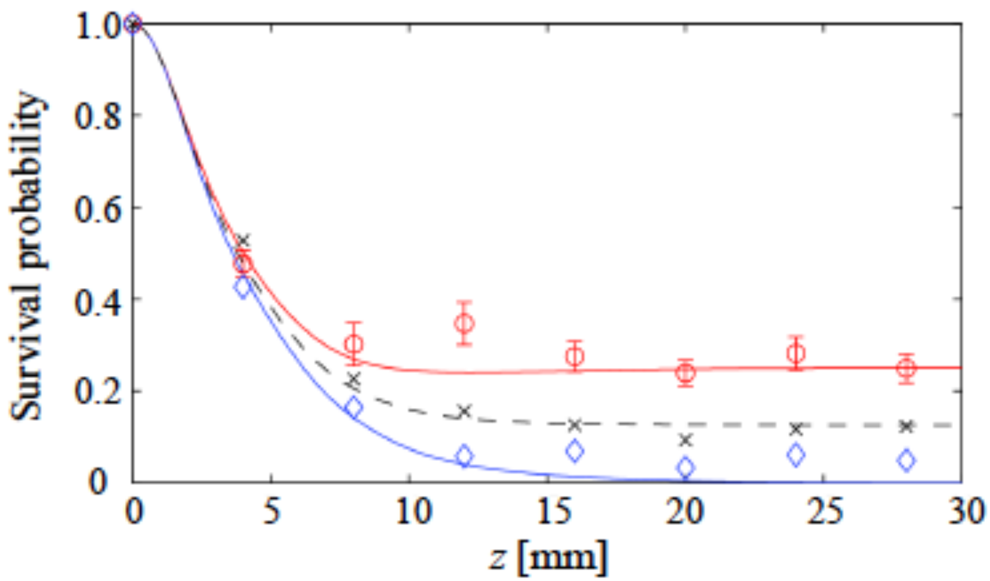


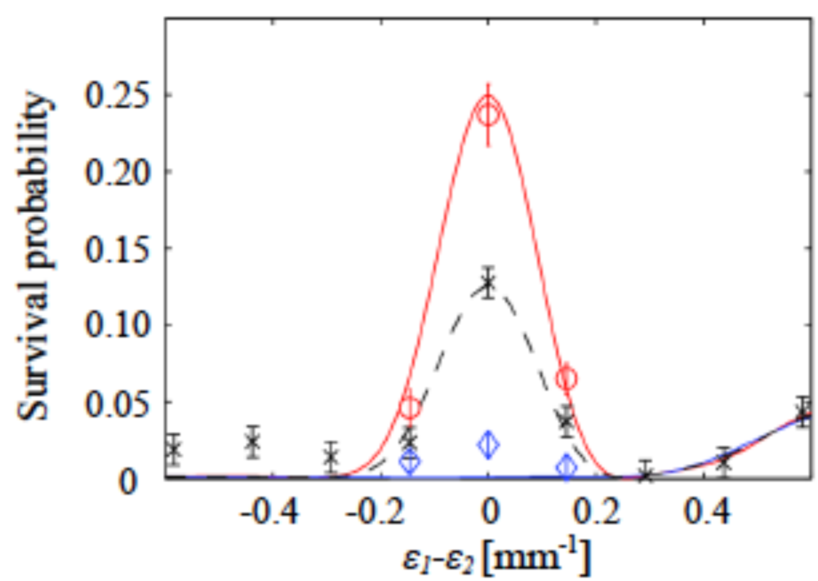




Fano resonances with 2-bosons & fermions



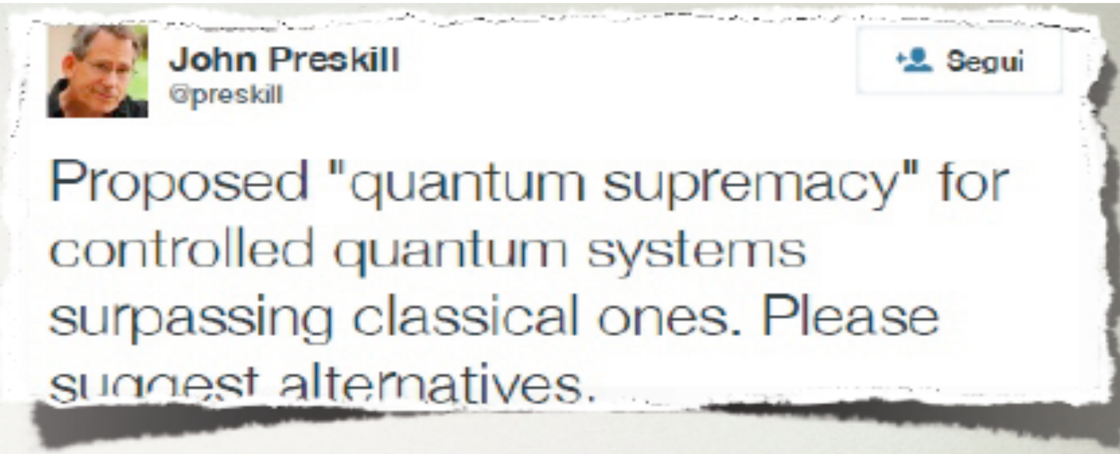




A. Crespi, *et al.*, *Phys. Rev. Lett.* 114, 090201 (2015)

The BosonSampling problem

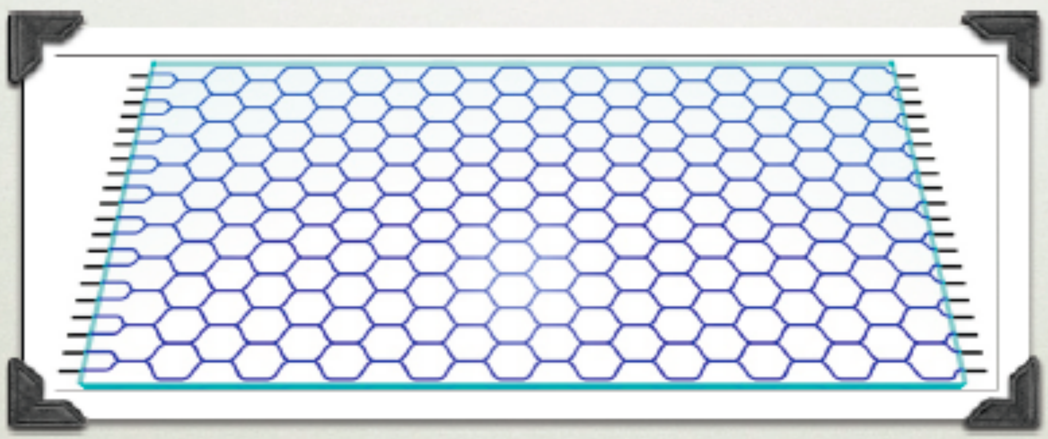
HOW TO ACHIEVE QUANTUM SUPREMACY ??



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)

BosonSampling

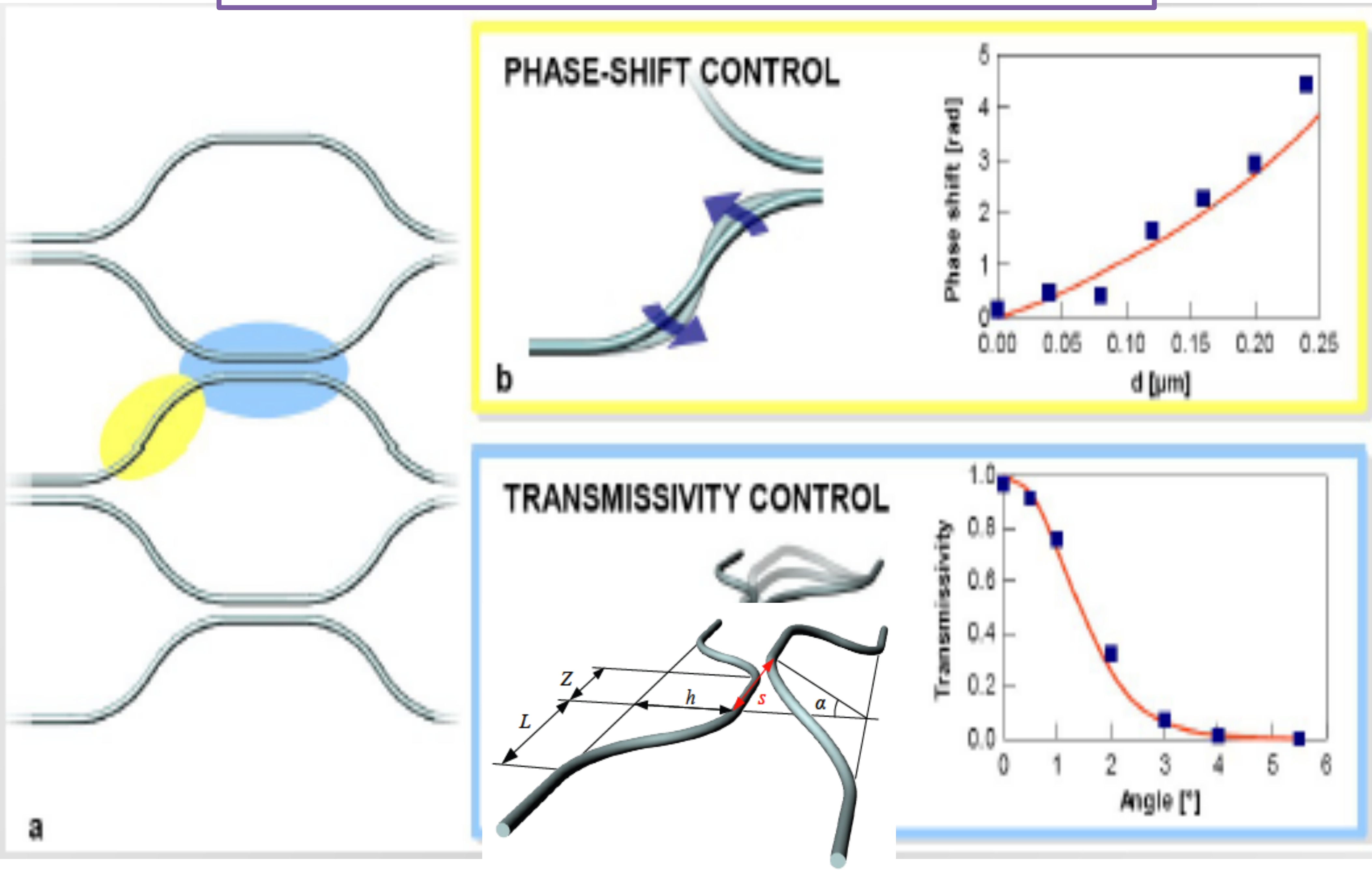
Complex network of linear optical elements described by a m x m unitary transformation U.
Evidence of the advantage of quantum over classical computers.

For a large enough number of photons (n ≈ 10) and modes (m ≈ 100) 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)

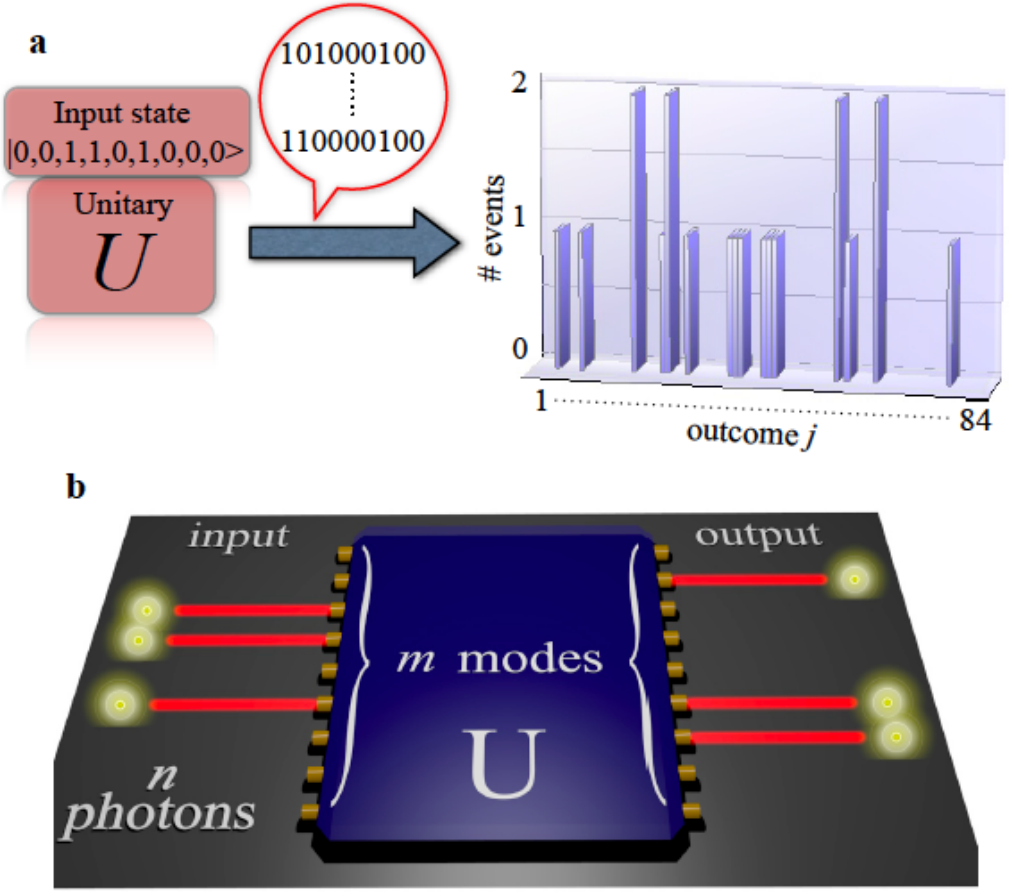
Natural choice: photons evolving through linear interferometers

Our approach: control ϕ and T



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

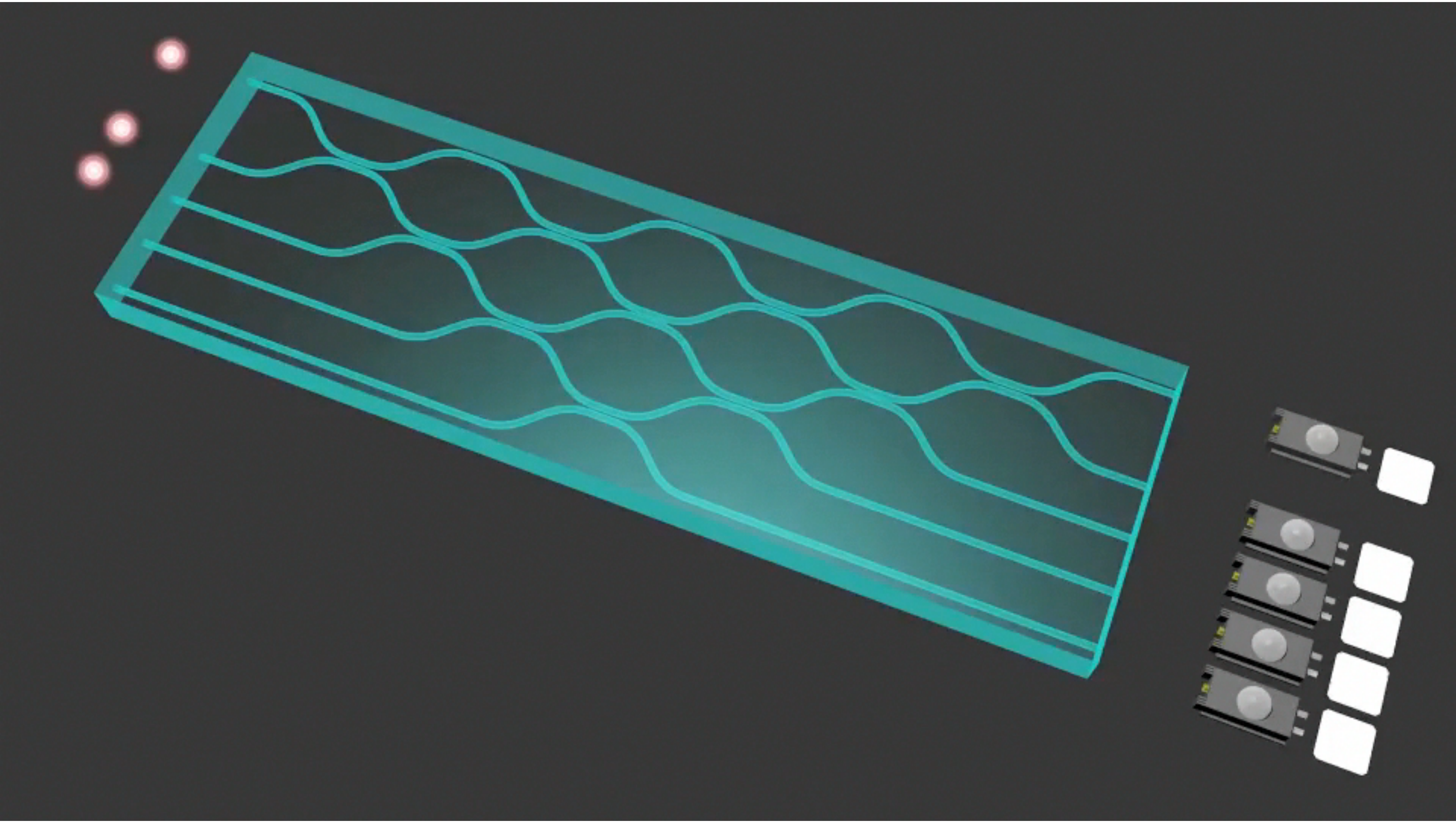
Boson Sampling



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

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

Boson Sampling



Validation of BosonSampling

Can Boson Sampling be validated?

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

C. Gogolin et al. *arXiv:1306.3995*

The Theorists' Answer

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

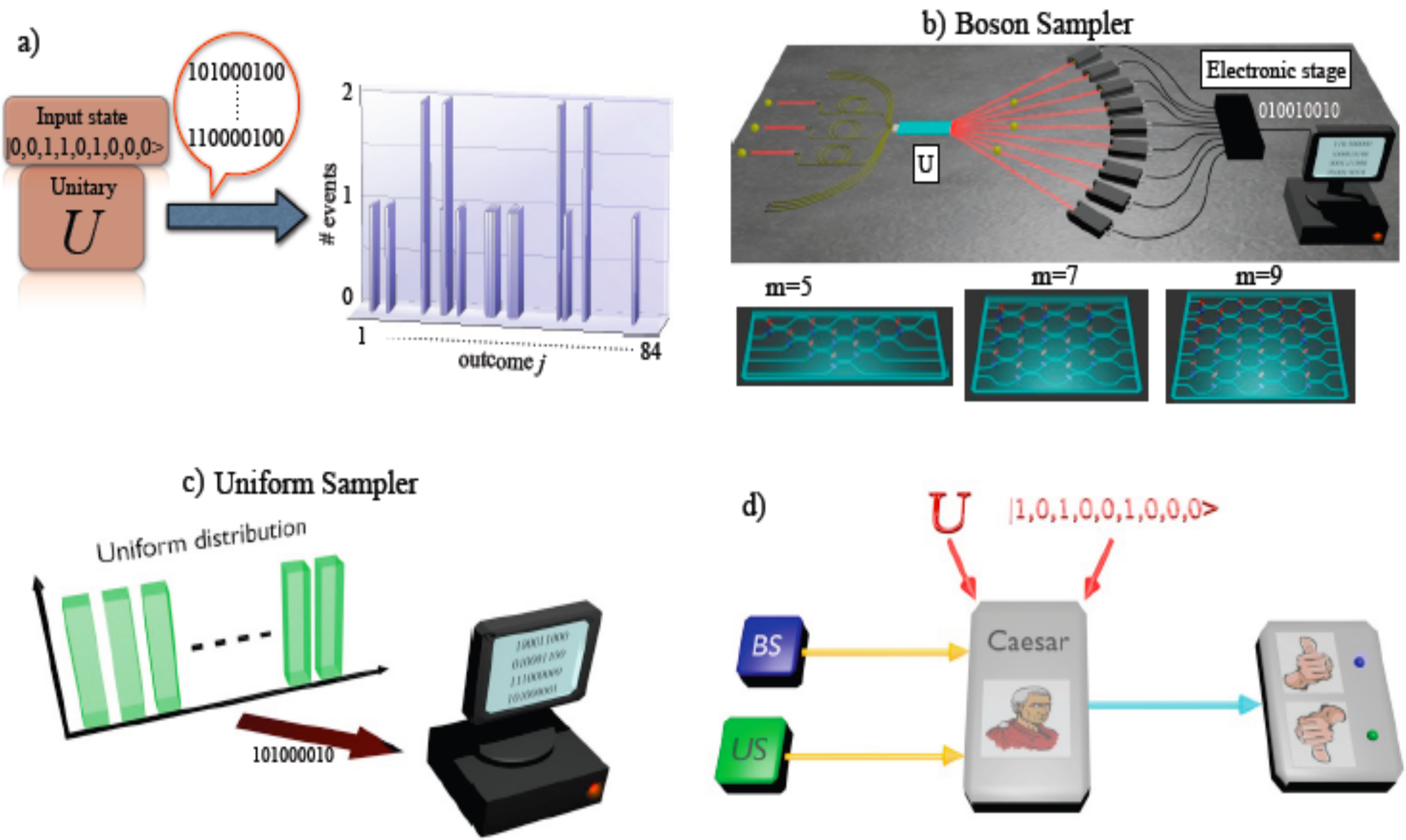
$$P = \prod_{i=1}^{n} \sum_{j=1}^{n} |A_{i,j}|^2$$

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

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

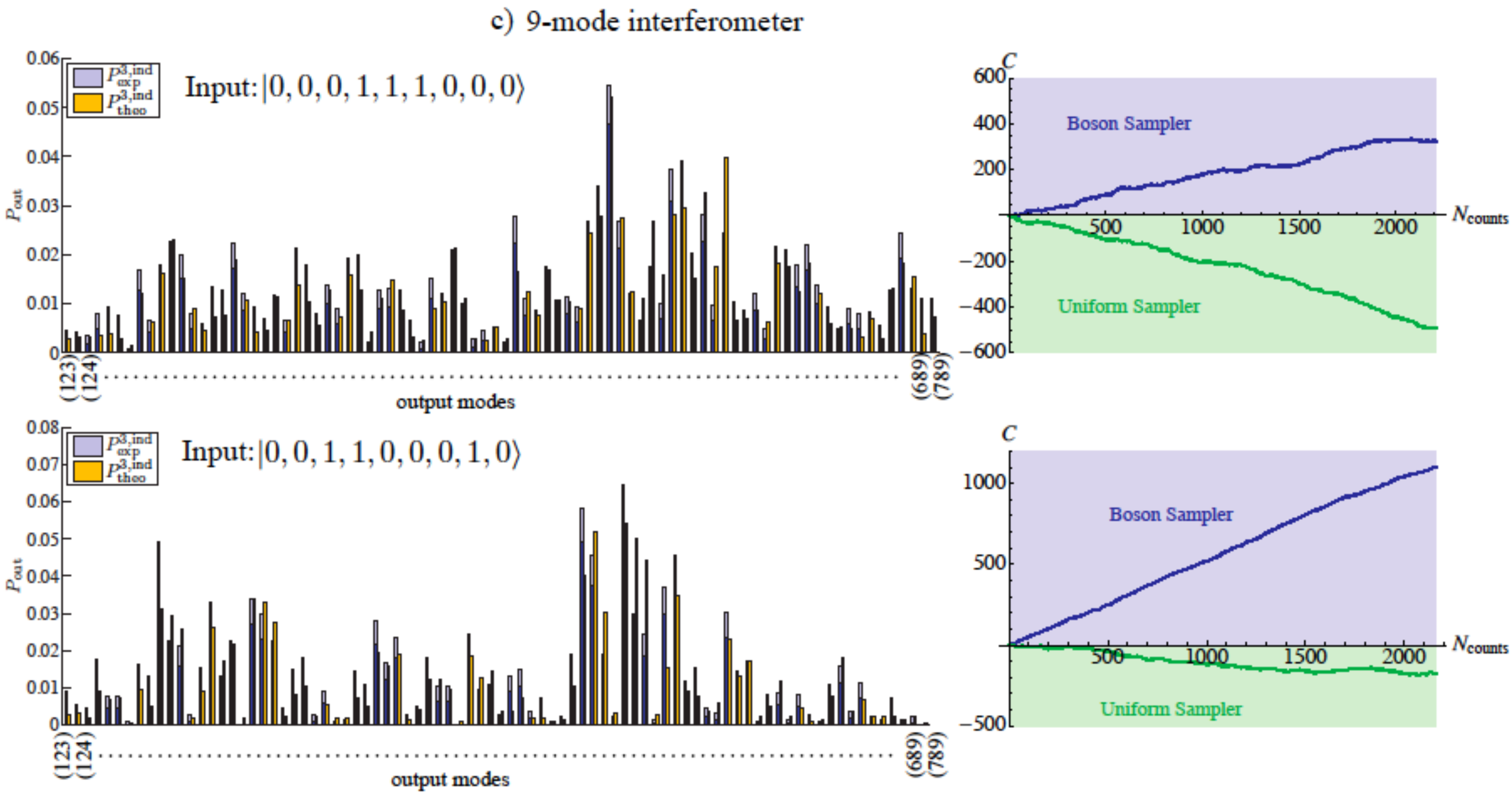
S. Aaronson et al. *arXiv:1309.7460*

Validation of BosonSampling



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

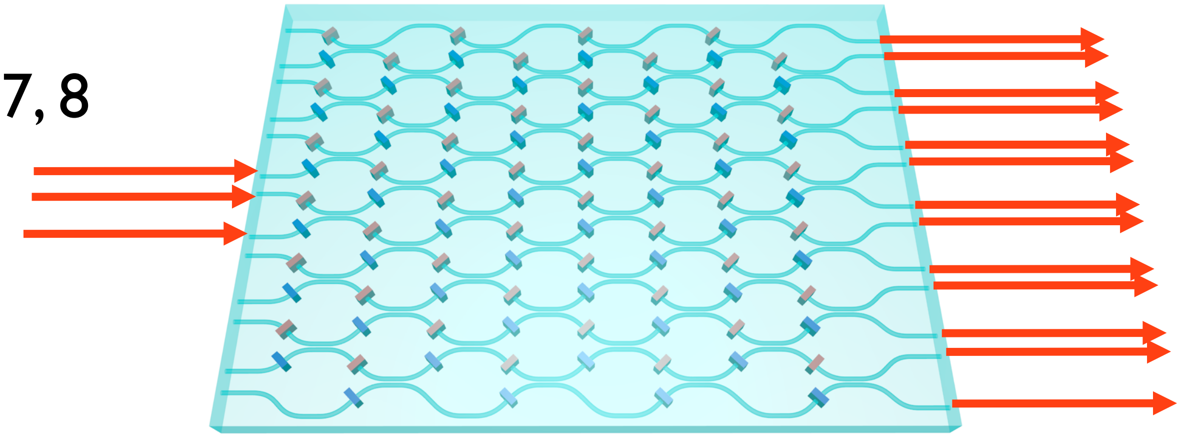
Validation of BosonSampling with 9 modes



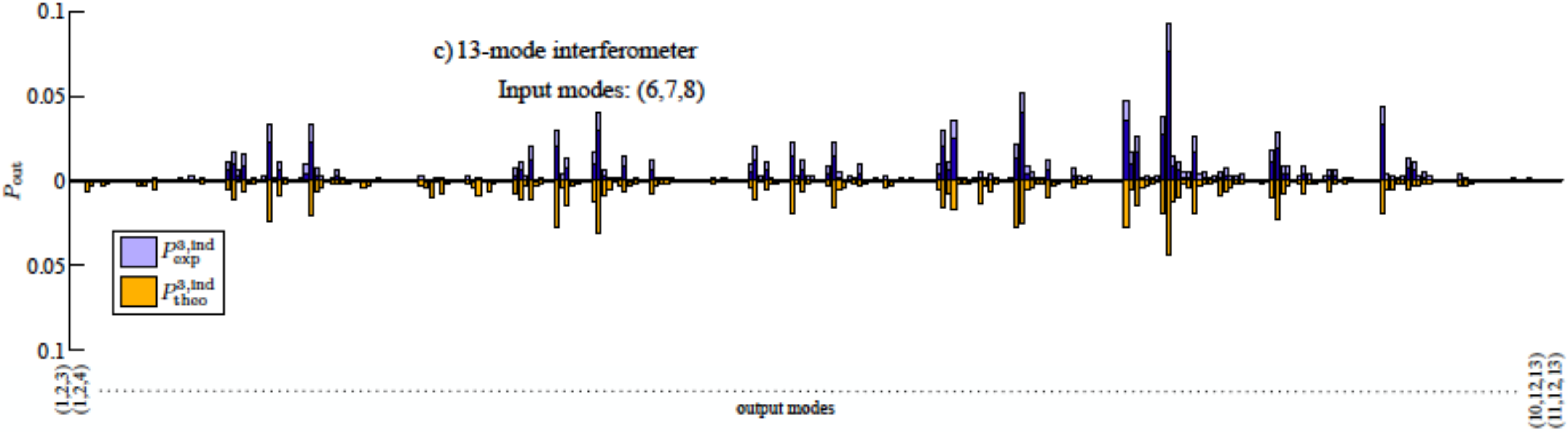
N. Spagnolo, et al., *Nature Photonics, **8**, 615* (2014)

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

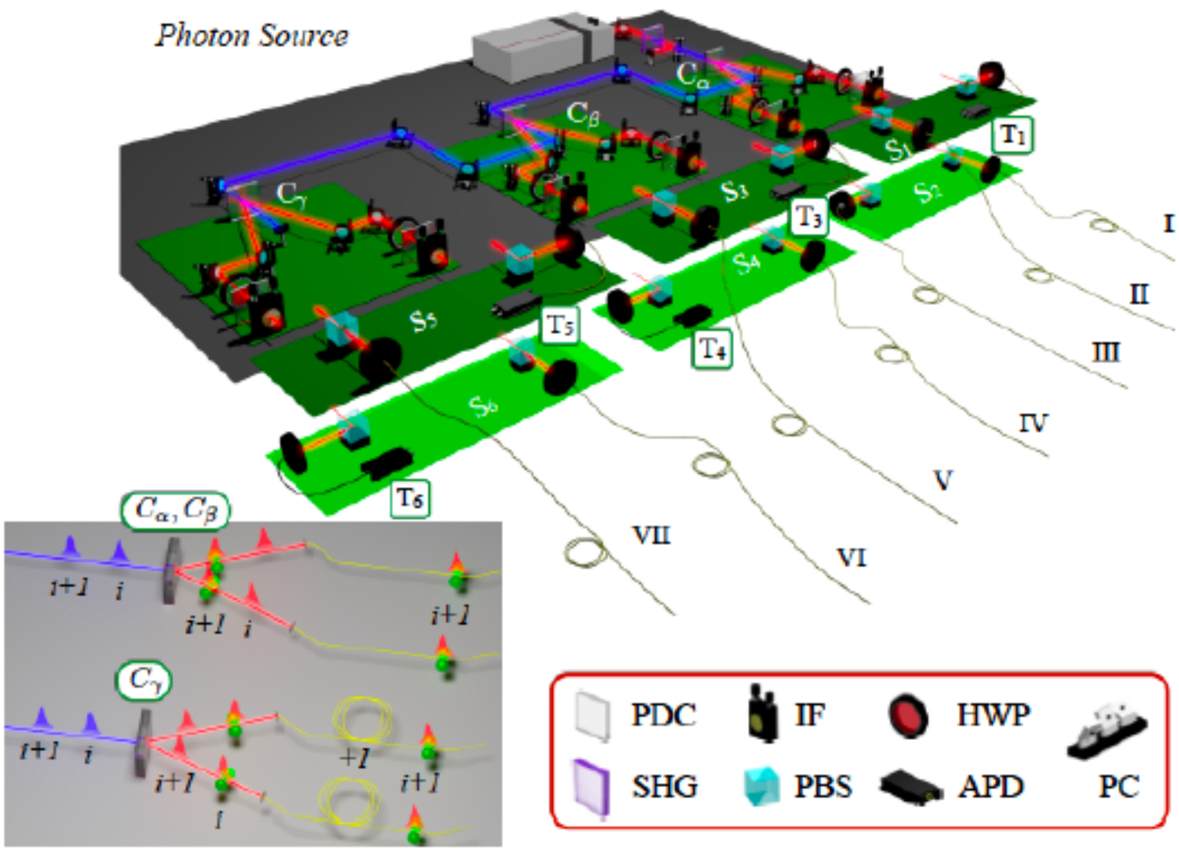
Total generation rate: $\sim p^n(1-p)^{m-n}\binom{m}{n}$

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

Scattershot BosonSampling: generation

Experimental setup - 1

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



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

↕

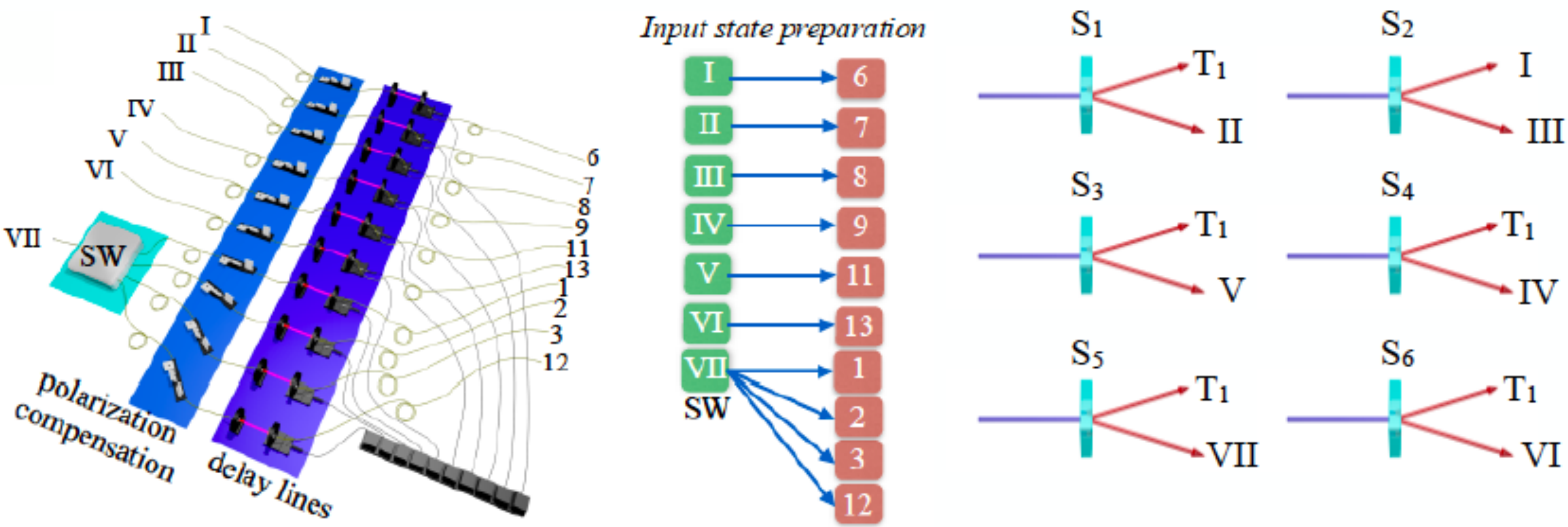
3 physical crystals and separation by polarization

Interference between photons generated from two subsequent laser pulses

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

Scattershot BosonSampling: preparation

Experimental setup - 2



Three photon events:

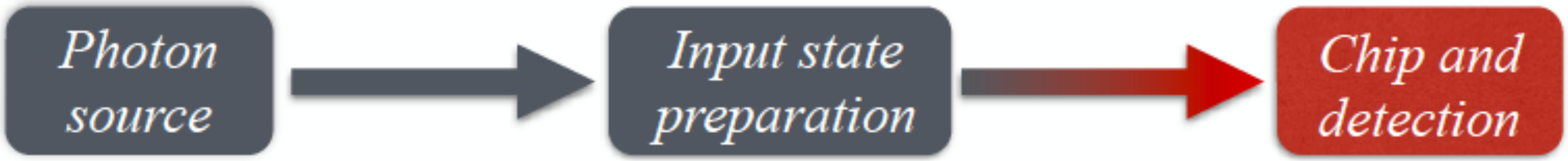
1) Photon I (input 6) [fixed]
2) Photon III (input 8) [fixed]
3) Random input heralded by T_i

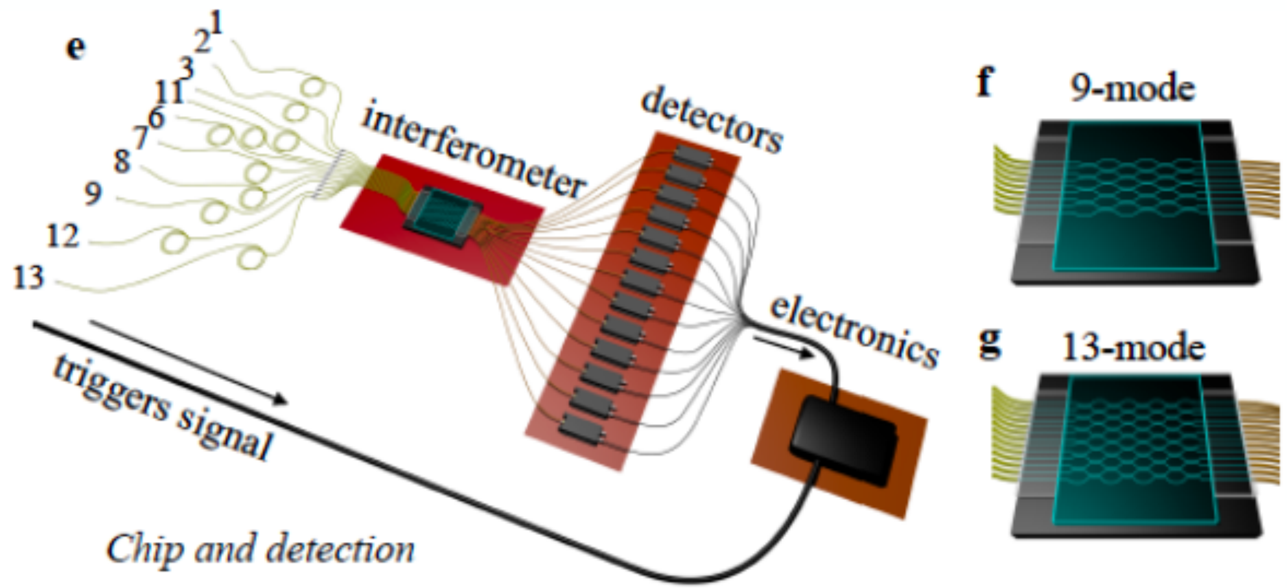
Input randomness further enhanced by sequential switching of photon VII

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

Scattershot BS: chip and detection

Experimental setup - 3





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

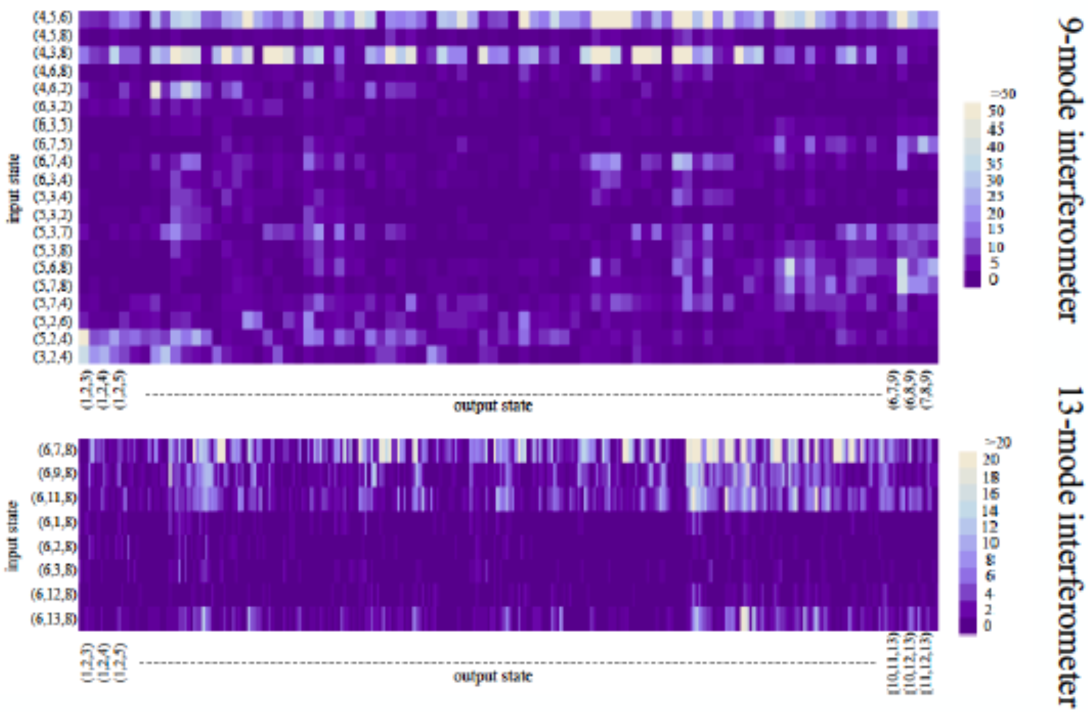
Coincidence detection for:
- Three-photon events with one heralding trigger
- Two-photon events with two heralding triggers

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

Scattershot BS: random input

Scattershot - sampling with random input

Three-photon events



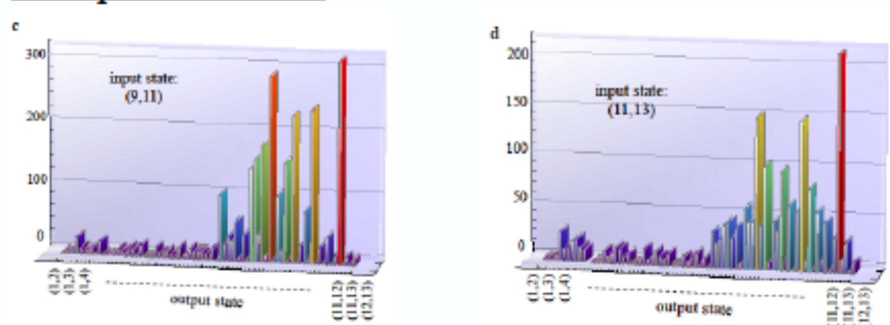
Number of input/output configurations

m=9 interferometer
2288 combinations

m=13 interferometer
1680 combinations

Few events per input/output configurations

Two-photon events



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

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

Conclusions

- Flexibility of waveguide integrated circuits
  (in particular 3D capabilities of fsec laser writing).

- Potential for quantum simulations and quantum walks
  (2 non-interacting bosons/fermions)

- Decay in a continuum of 2-bosonic/fermionic particles decay

- BosonSampling proof-of-principle tests

Thank you!

Fabio Sciarrino

Nicolò Spagnolo
Postdoc

Chiara Vitelli
Postdoc

Marco Bentivegna
PhD student

Fulvio Flammini
PhD student

Linda Sansoni
Post-doc (now in Paderborn)

Niko Viggianiello
Sandro Giacomini
Giorgio Milani