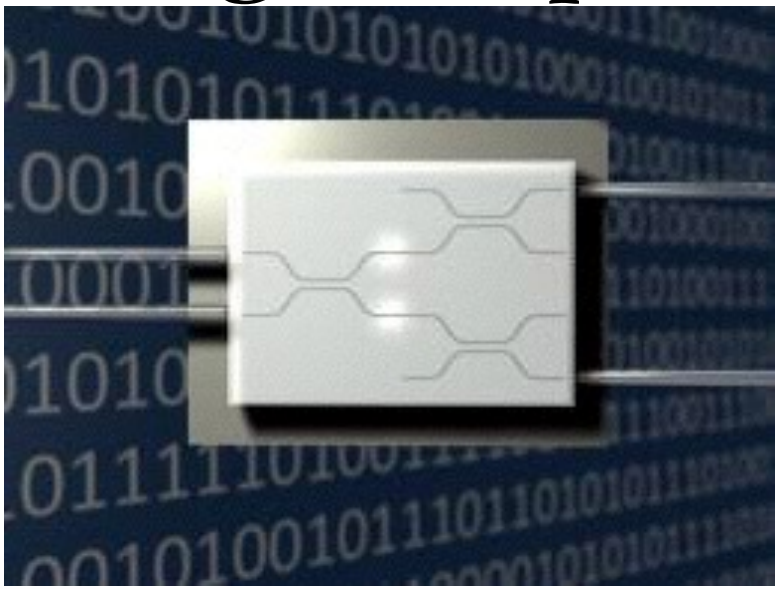
Lecture 2: Quantum walk with integrated photonics

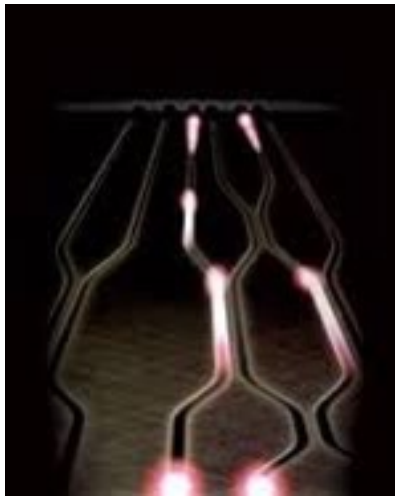


SAPIENZA
UNIVERSITÀ DI ROMA

Fabio Sciarrino

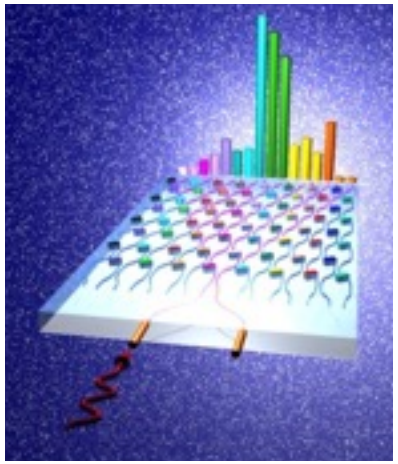
Dipartimento di Fisica,
"Sapienza" Università di Roma

Quantum computation

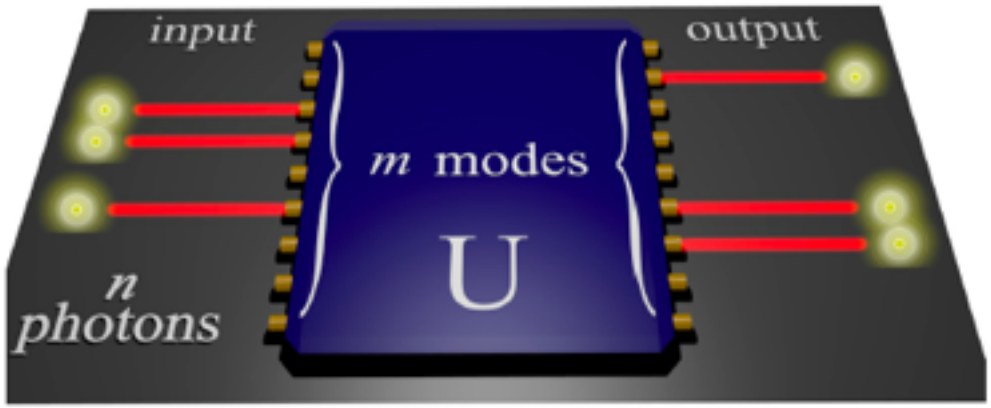


- logical gate
- quantum algorithms

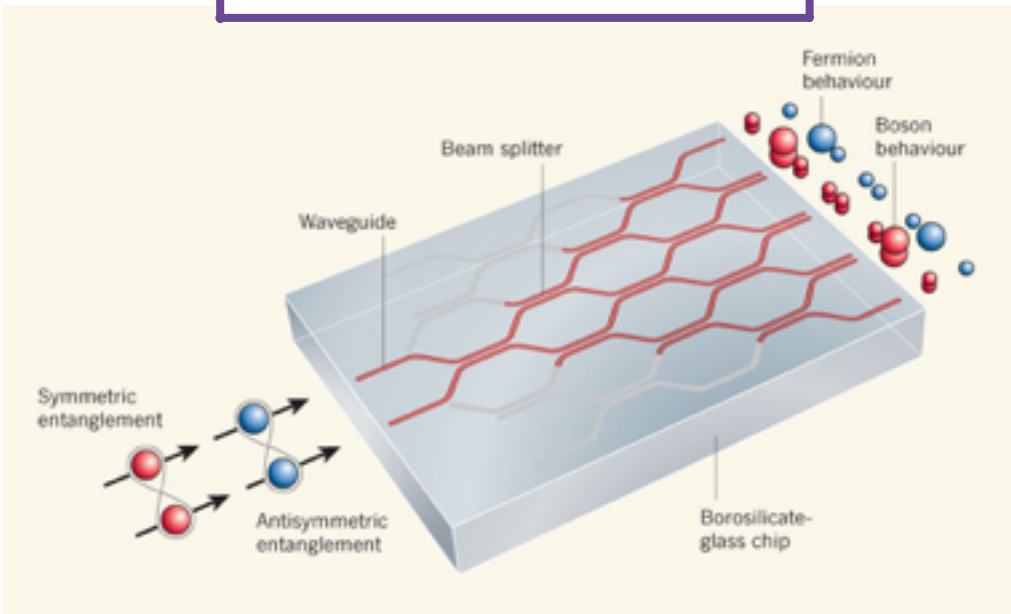
Quantum simulation



Boson Sampling

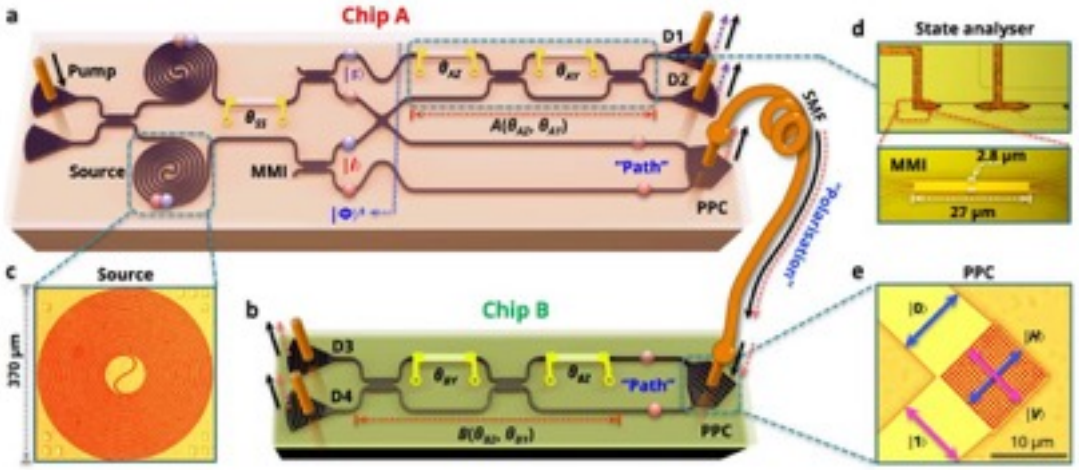


Quantum walk

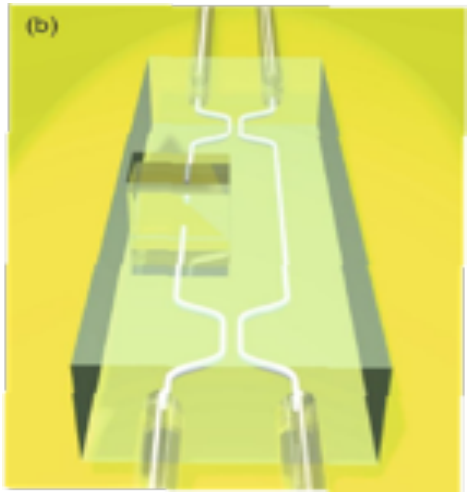


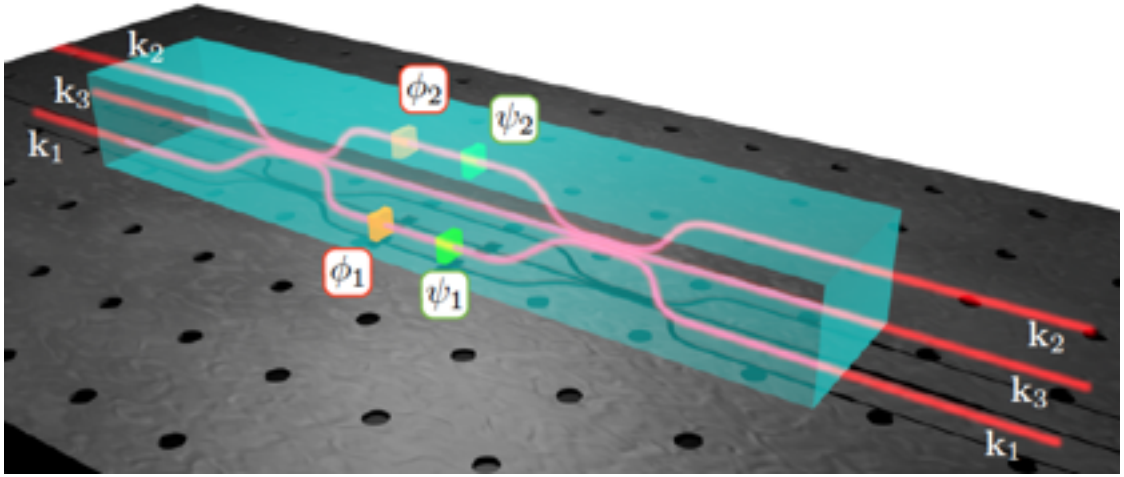
Quantum communication

Fundamental science



Quantum metrology and sensing

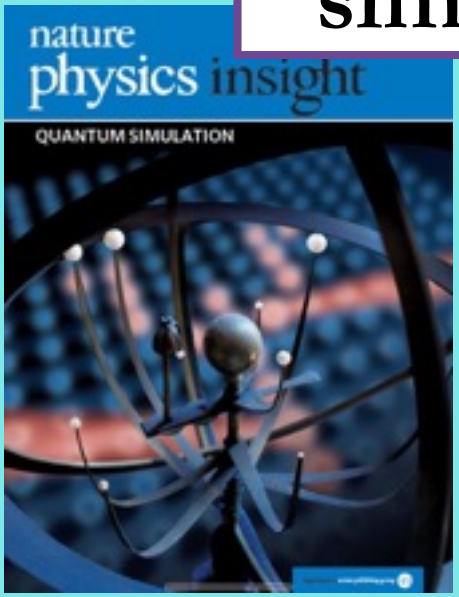


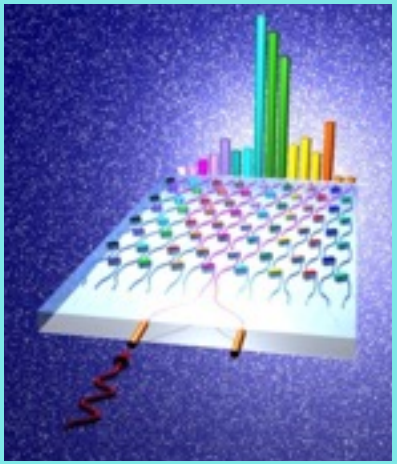


Quantum computation

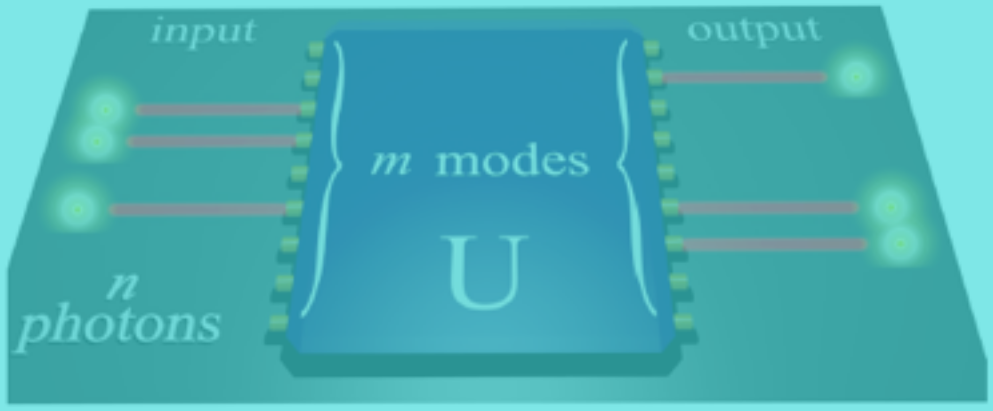
- logical gate
- quantum algorithms

Quantum simulation

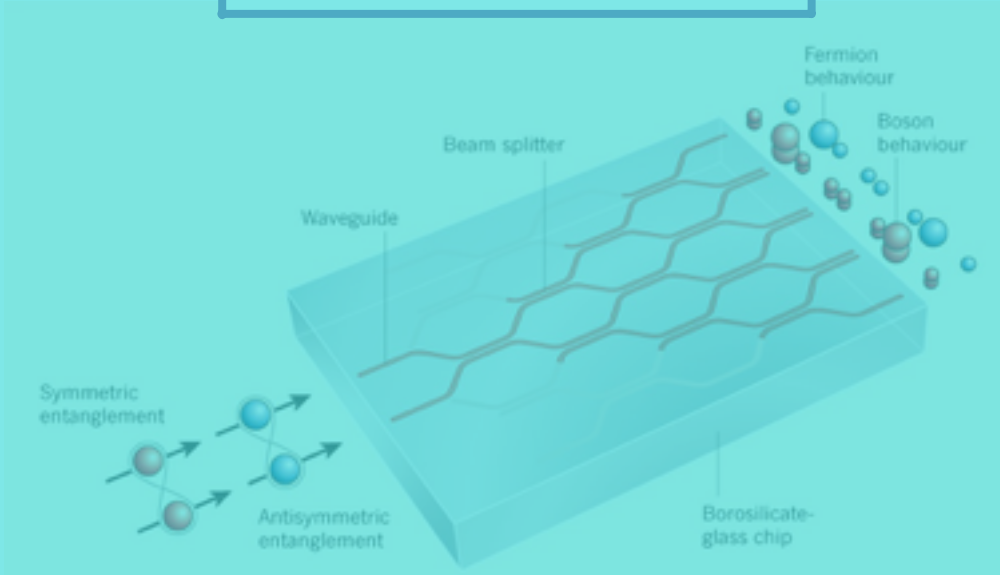




Boson Sampling

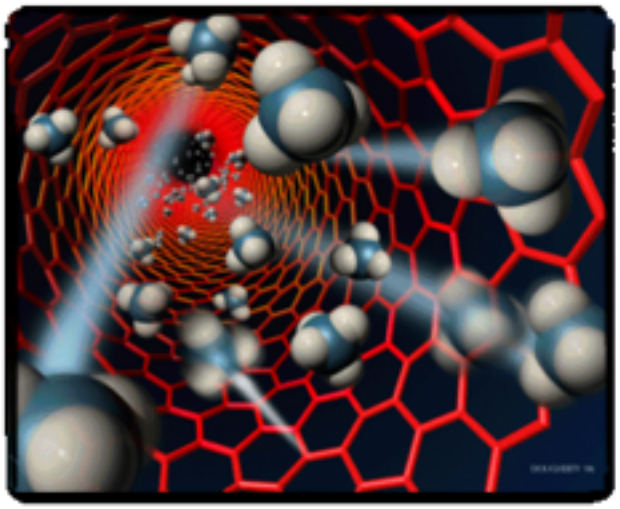


Quantum walk



QUANTUM SIMULATION

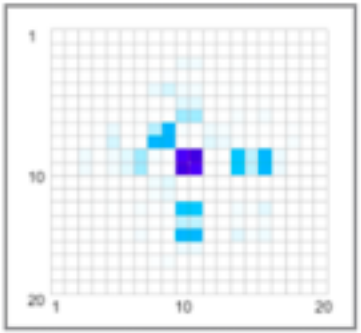
R. Feynman:
"To exploit quantum hardware to simulate quantum systems"



Quantum transport phenomena:

Transport over disordered systems

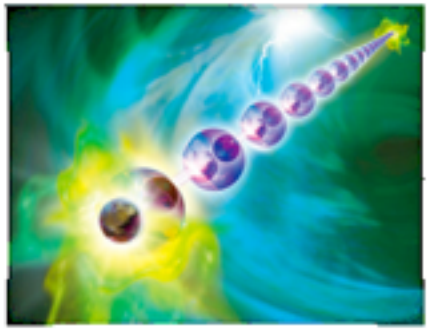
Anderson localization for bosons and fermions



Solid state physics:

Topological phenomena in quantum systems

Bound states



Fundamental physics:

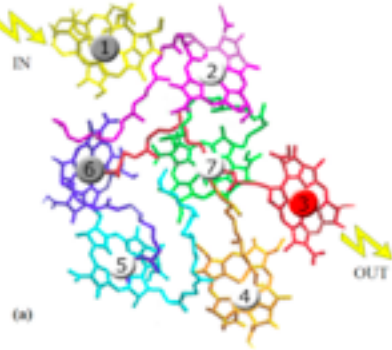
Quantum to classical transition

simulation of decoherence

Quantum biology:

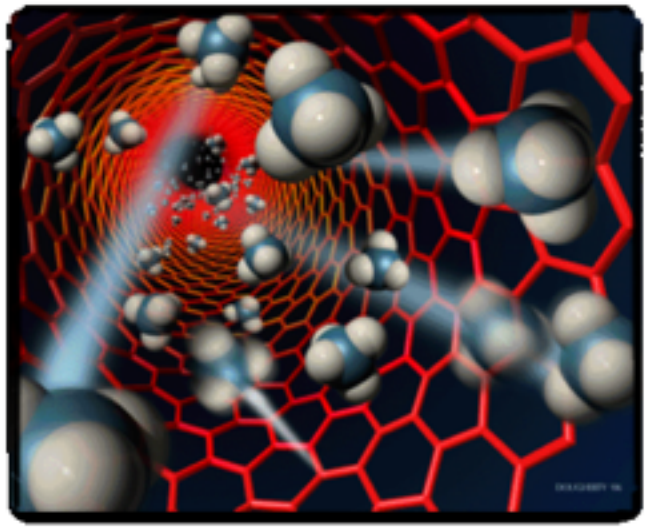
Simulate dynamics of energy transfer process

Photosynthetic systems: quantum effects such as delocalized excitonic transport



QUANTUM SIMULATION VIA QUANTUM WALKS

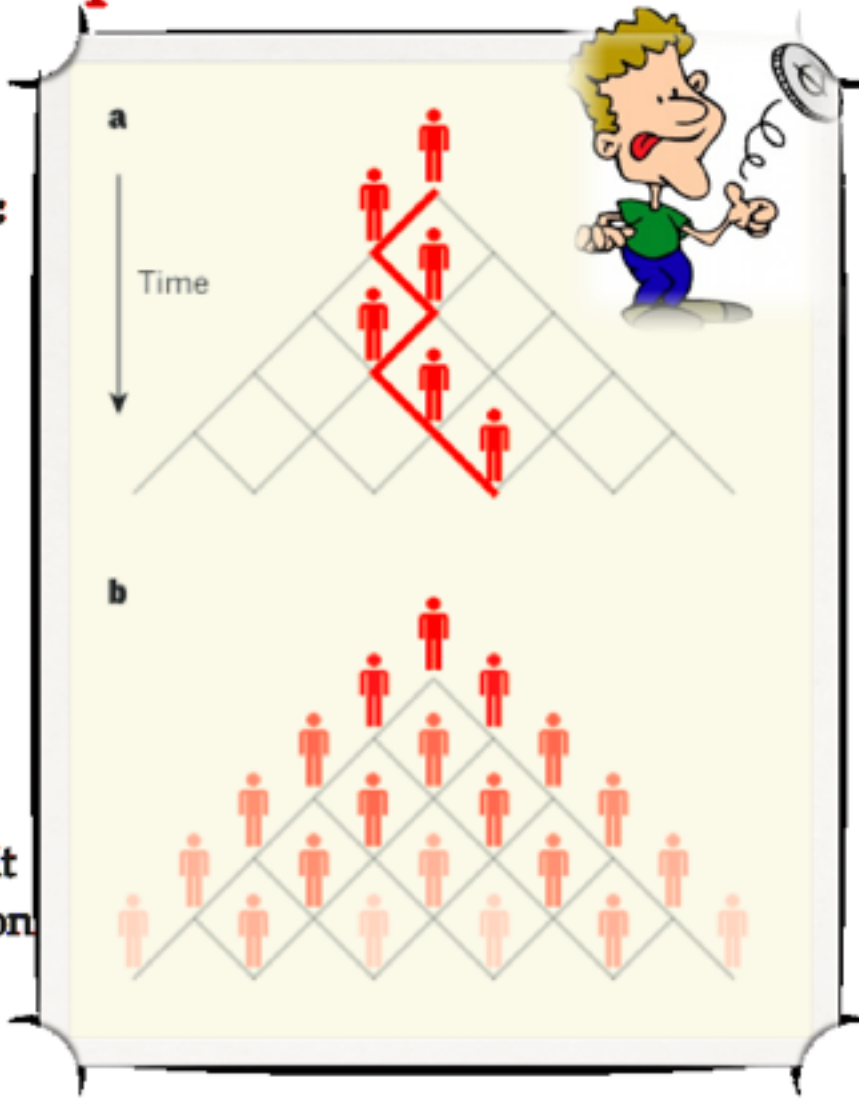
R. Feynman:
"To exploit quantum hardware to simulate quantum systems"



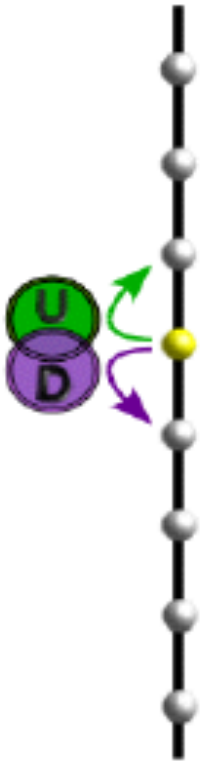
Realization of quantum simulation via quantum walks

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.



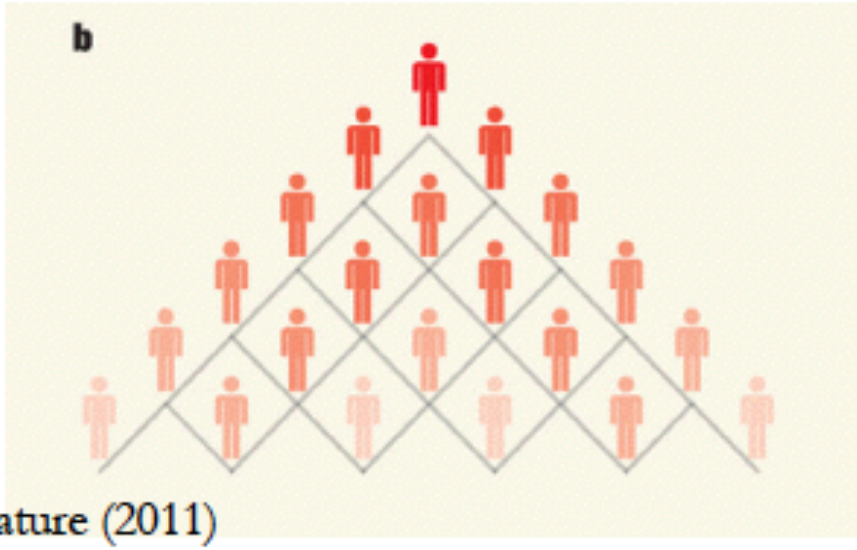
Discrete-time quantum walk



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

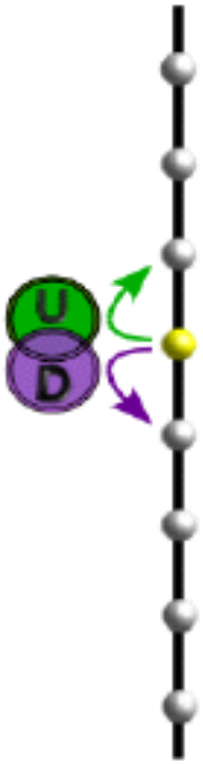
Classical

Quantum



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

Discrete-time quantum walk



Quantum walk: extension of the classical random walk:
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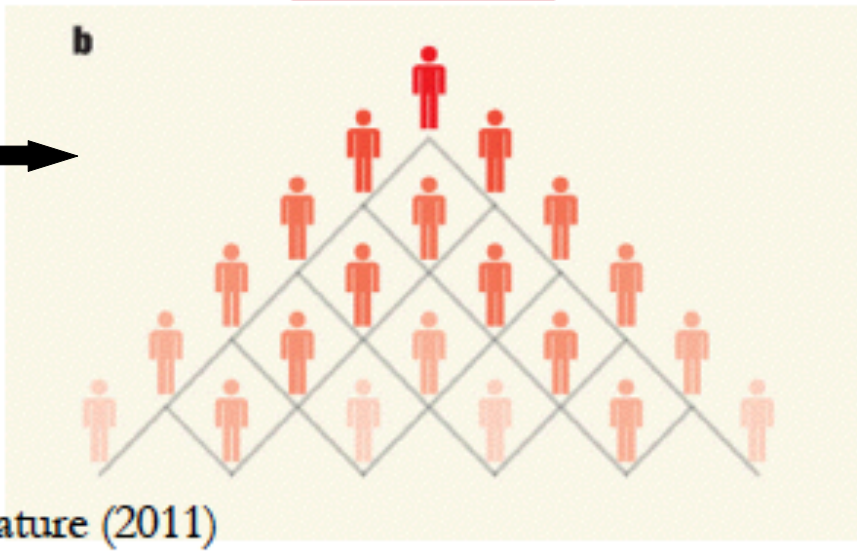
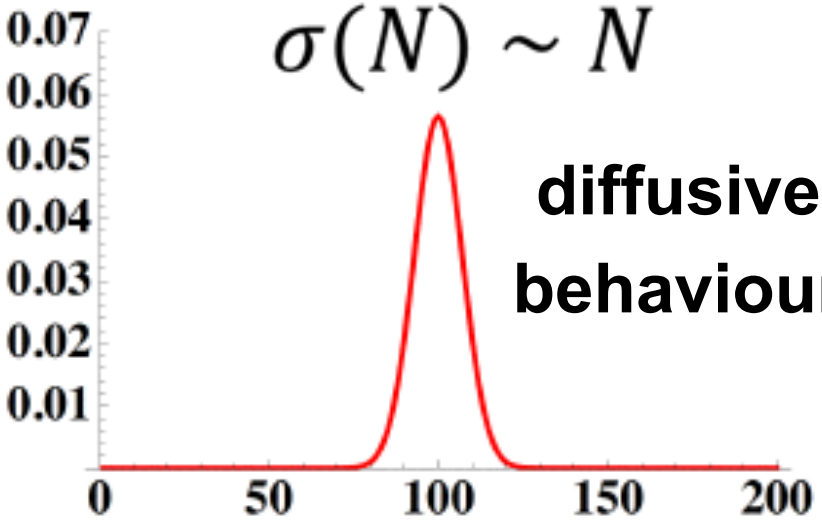
Classical

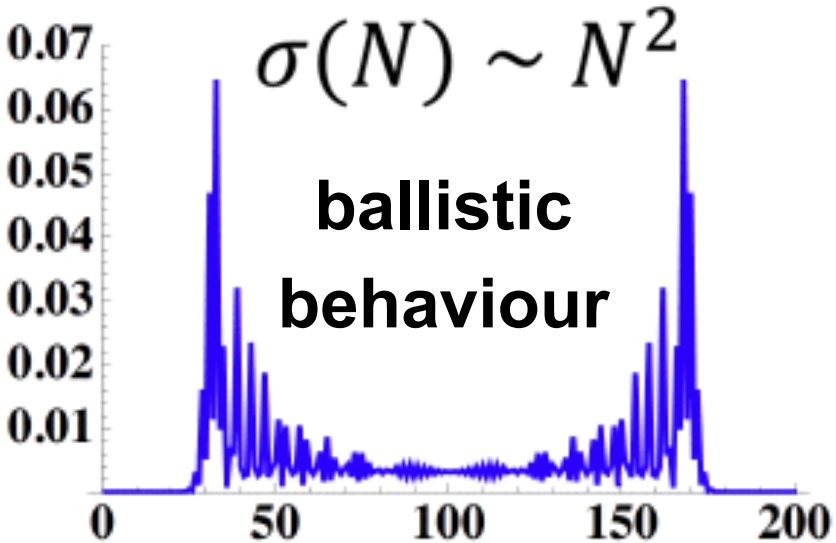
Quantum



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

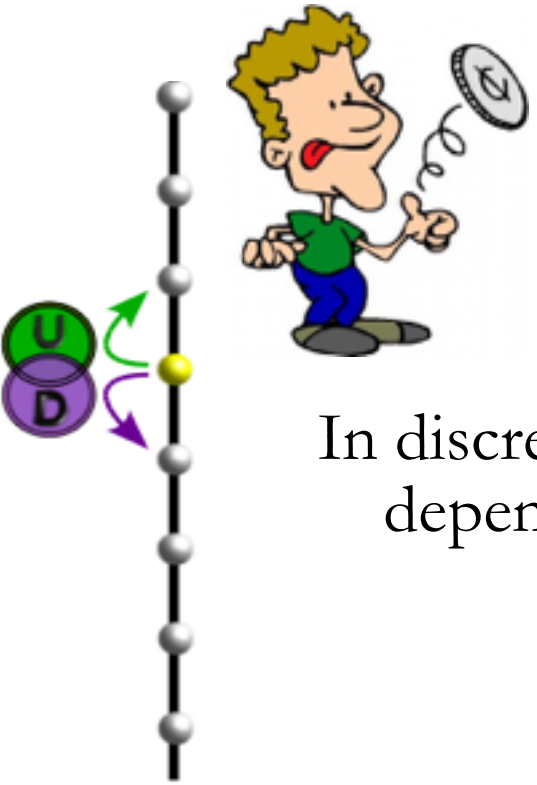


diffusive behaviour



ballistic behaviour

First applications: Quantum walk



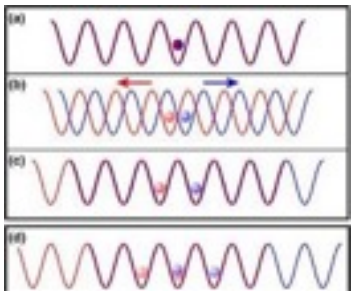
Quantum walk:
extension of the classical random walk
a walker on a lattice "jumping"
between different sites with given probability

In discrete quantum walk one or more quantum particles moves depending from by their internal quantum coin (QC) states

Experimental platforms

Ion trap

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



Single atom

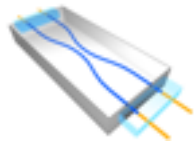
M. Karski,, et al.,
Science **325**, 174 (2009).

Coupled waveguides

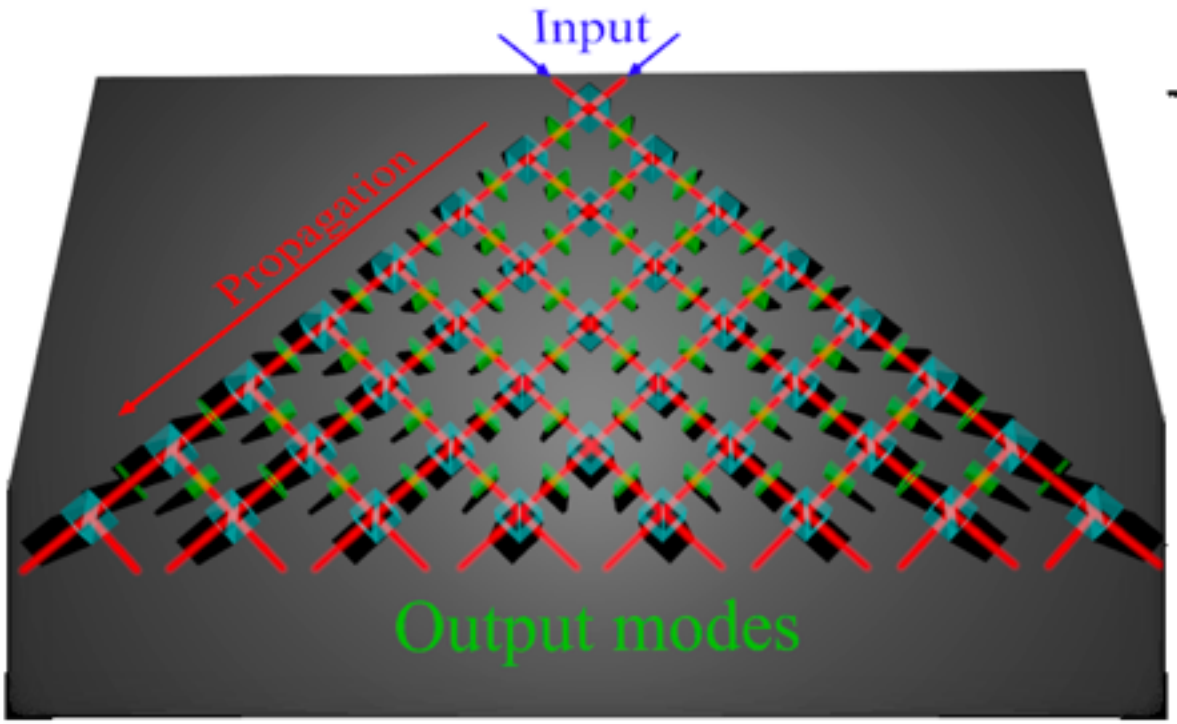
A. Peruzzo, et al.,
Science **329**, 1500 (2010)

Fiber loops

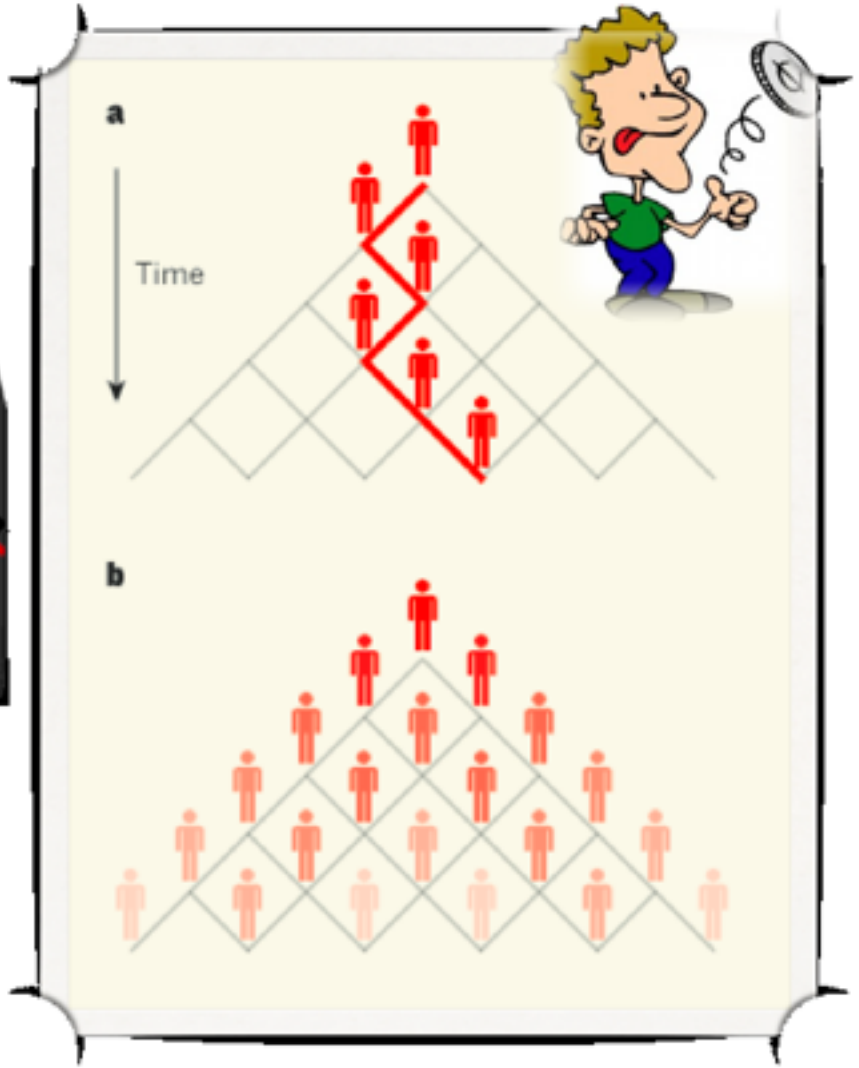
A. Schreiber et al.,
Phys. Rev. Lett. **104**, 050502 (2010).



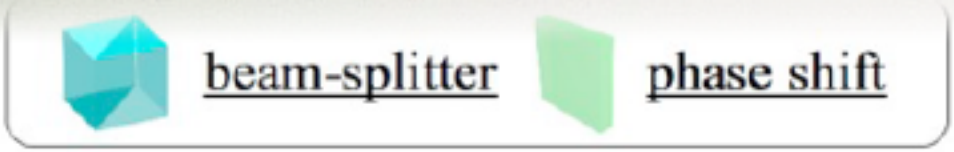
IMPLEMENTATION OF QUANTUM WALKS: OPTICAL SYSTEMS

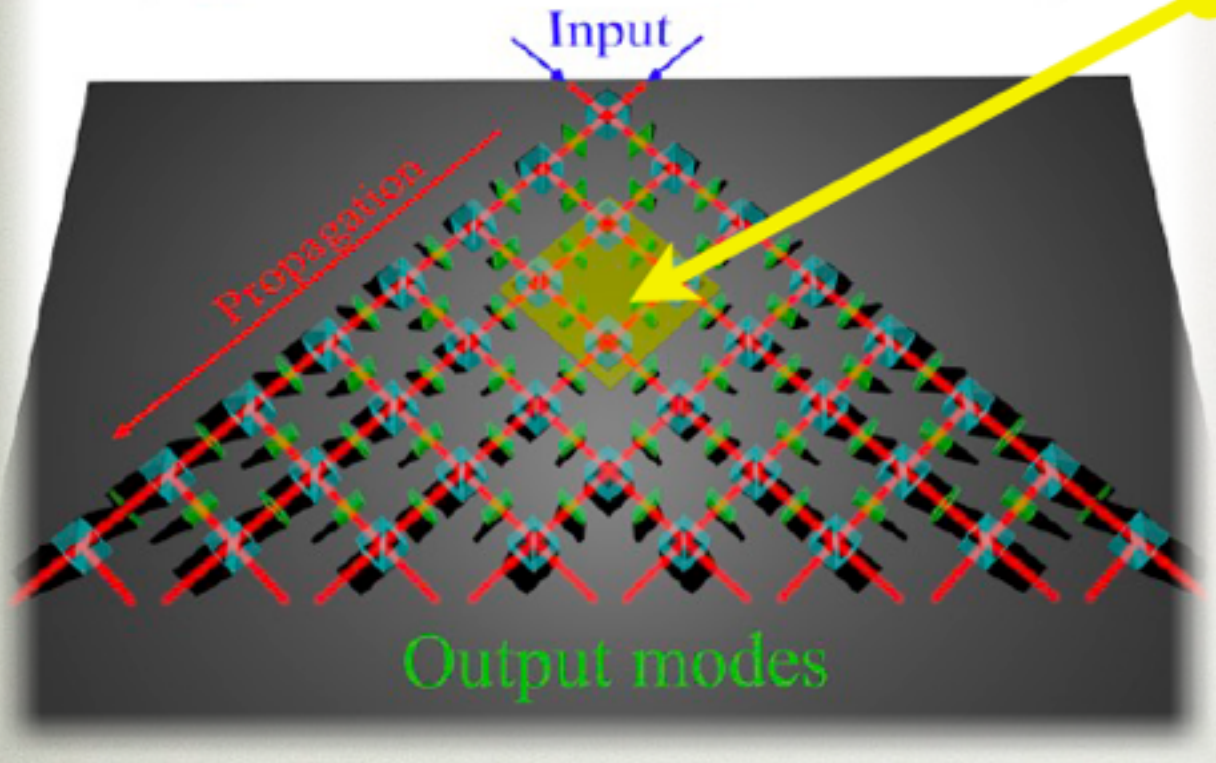


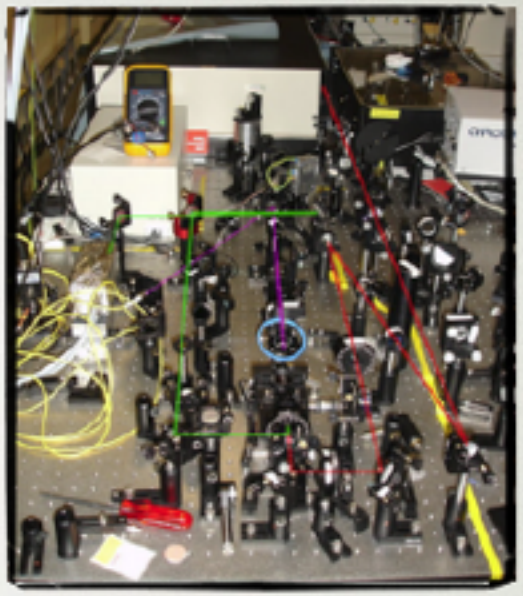
Quantum walks: photons propagating along an arrays of beam splitters and phase shifters



QUANTUM WALKS VIA OPTICAL SYSTEMS







Limitations of experiments with bulk optics:

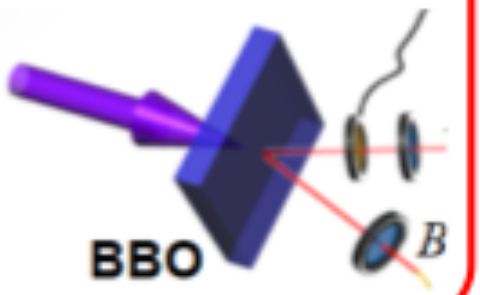
- **Scalability**
- **Large physical size**
- **Low stability**
- **Costs...**

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

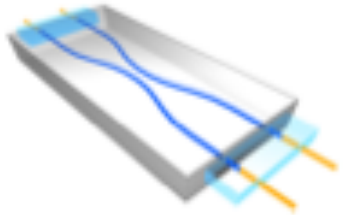
Large number of chained interferometers: impossible to realize by bulk optics!

Photonic implementation of quantum walks

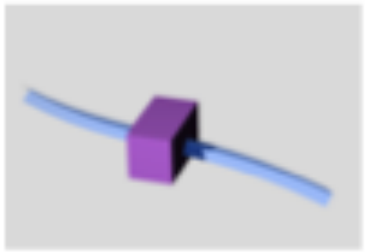
Single photons



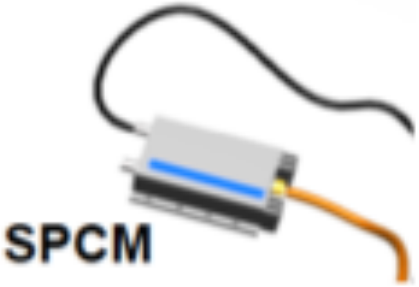
Beam splitters

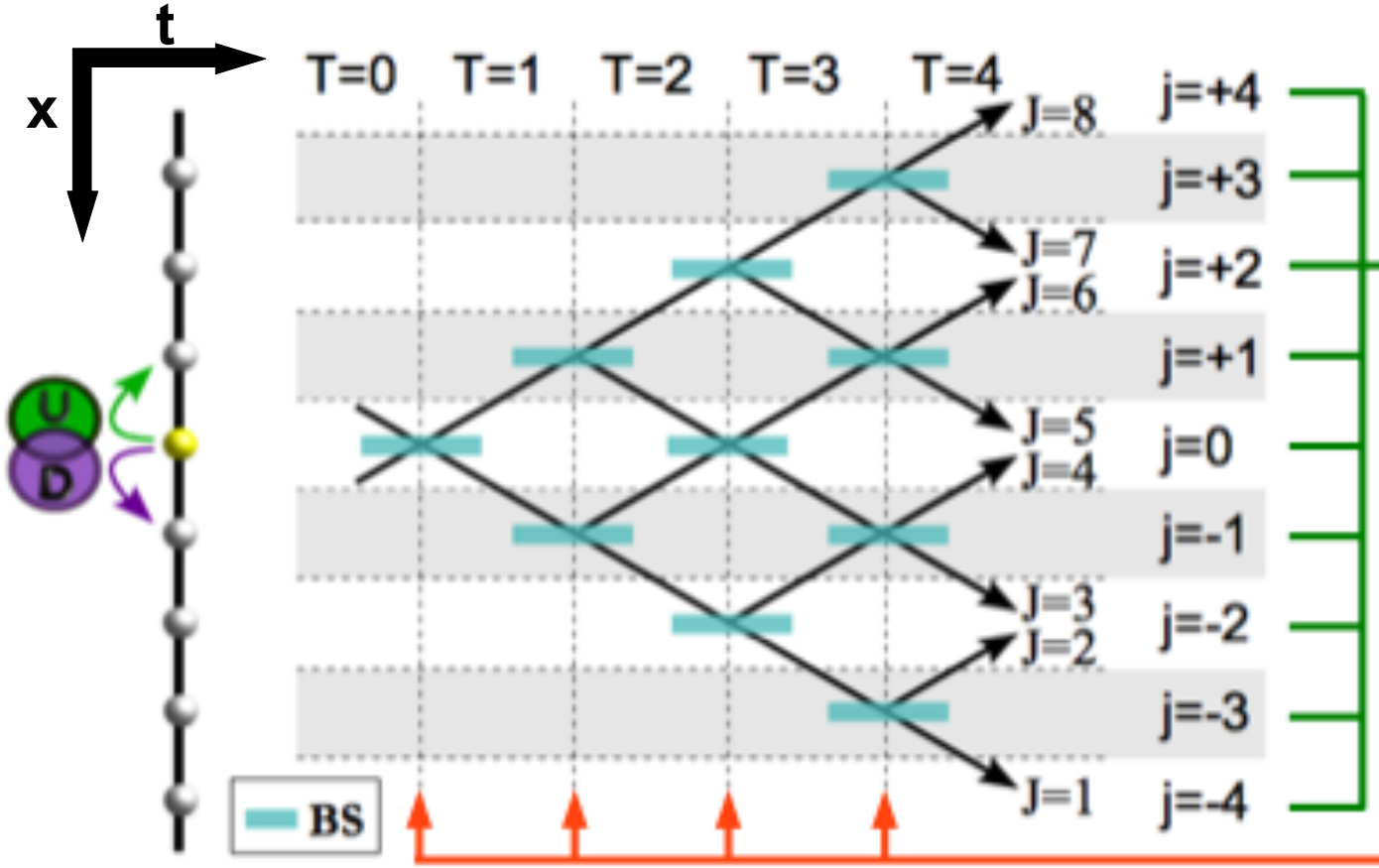


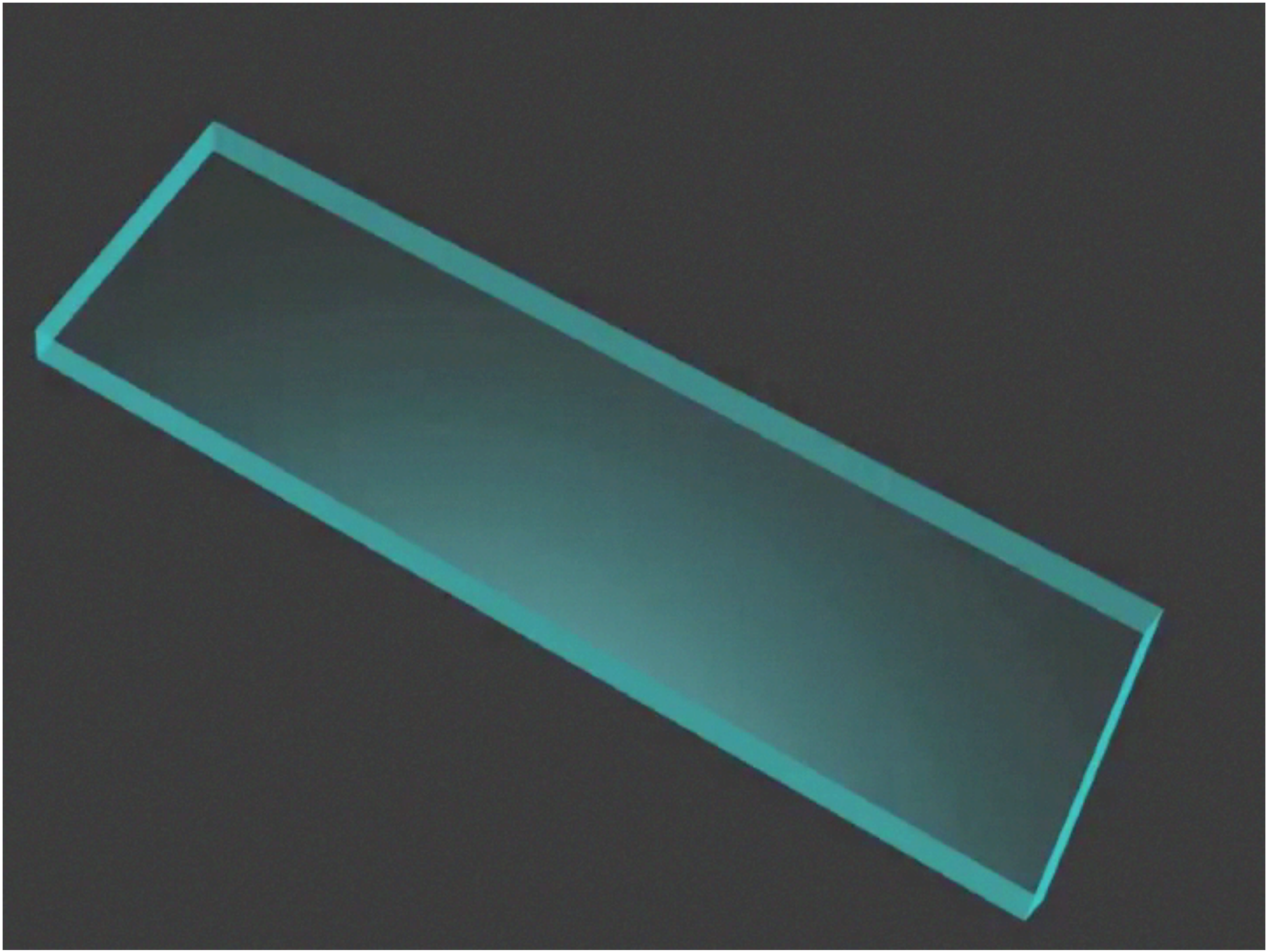
Phase shifters



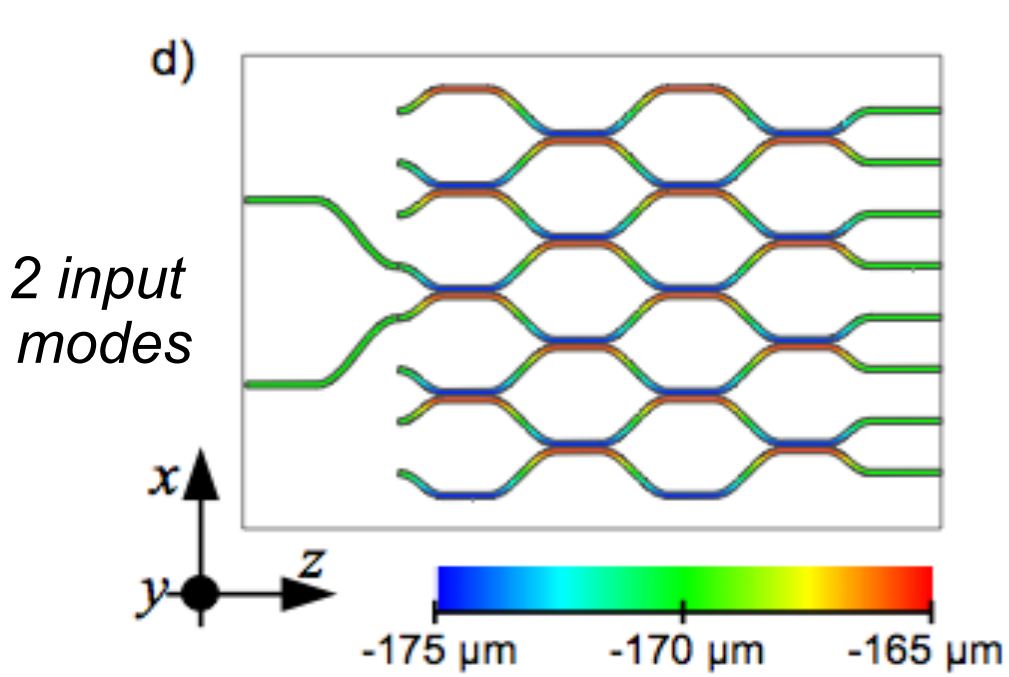
Photodetectors

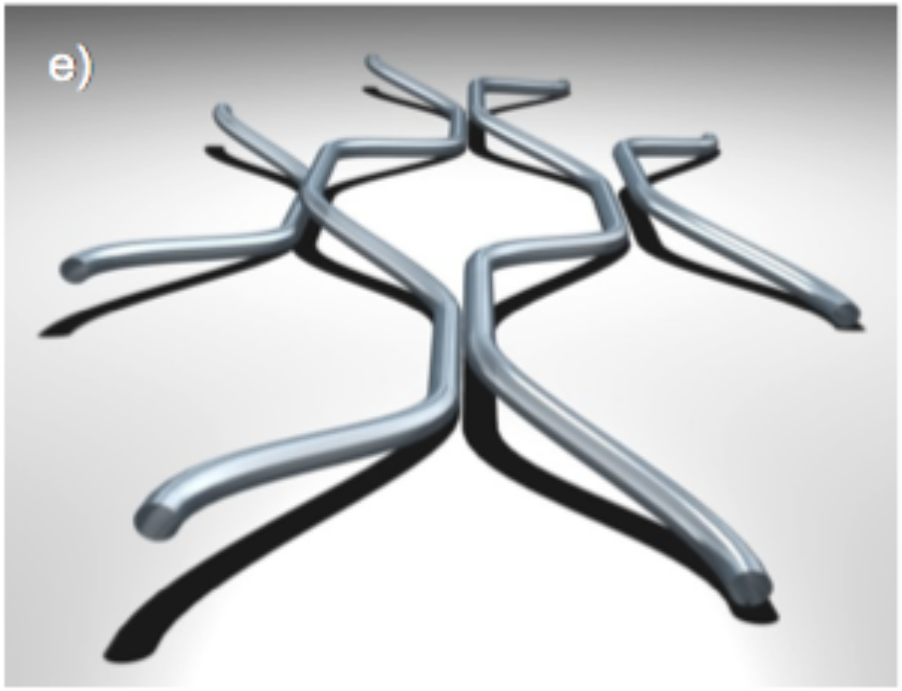






Beamsplitter arrays via 3D chip

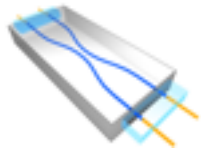




- 16 3D-beamsplitters with balanced reflectivities $R_H = R_V = 49\%$ able to support any polarization state

- Control path lengths up to few nanometers:
  all interferometers with phase difference betwen the two arms set equal to 0

- Stable operation of the BS arrays: length 32 mm, width about 1 mm

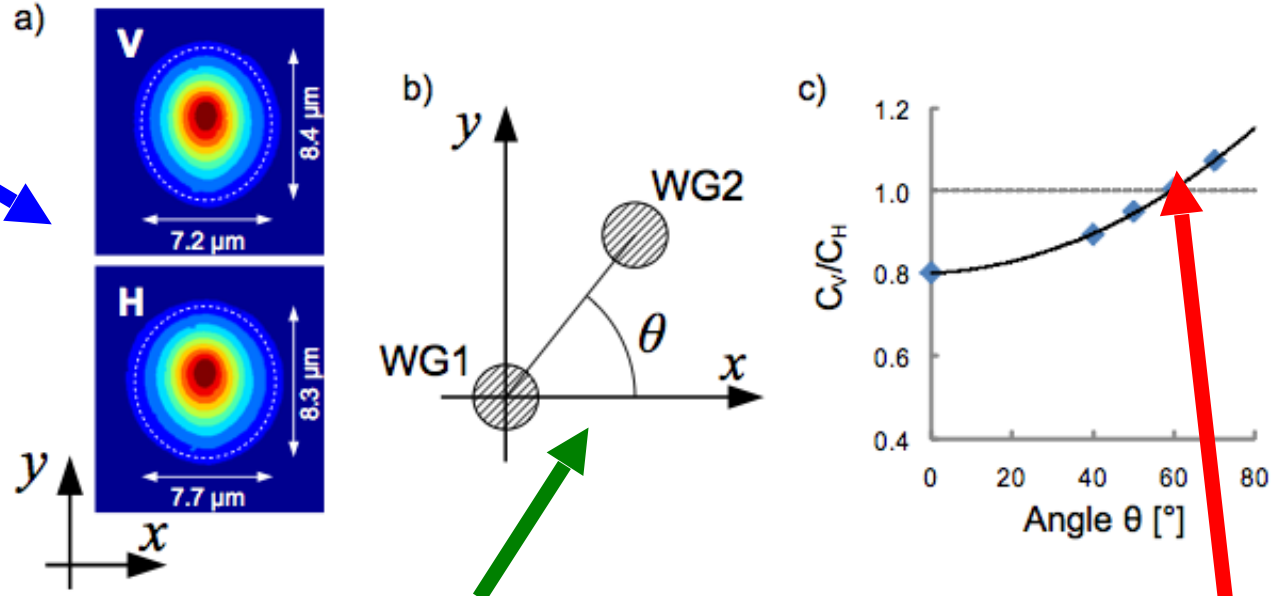


L. Sansoni, *et al.*, Phys, Rev, Lett, **108**, 010502 (2012)

Improving the on-chip devices: 3D architecture

- Previous results: $R_H = 0.49$, $R_V = 0.58$

  along the y axis the V polarized mode slightly greater than the H polarized one



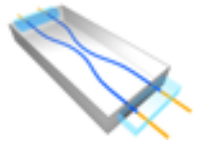
- Tight control on the reflectivities for the two polarizations:

  3 D architecture:

  Depending on the angle of the geometry, different coupling for the polarization H and V

$R_H = R_V$

- **High-balancement between the different polarizations**

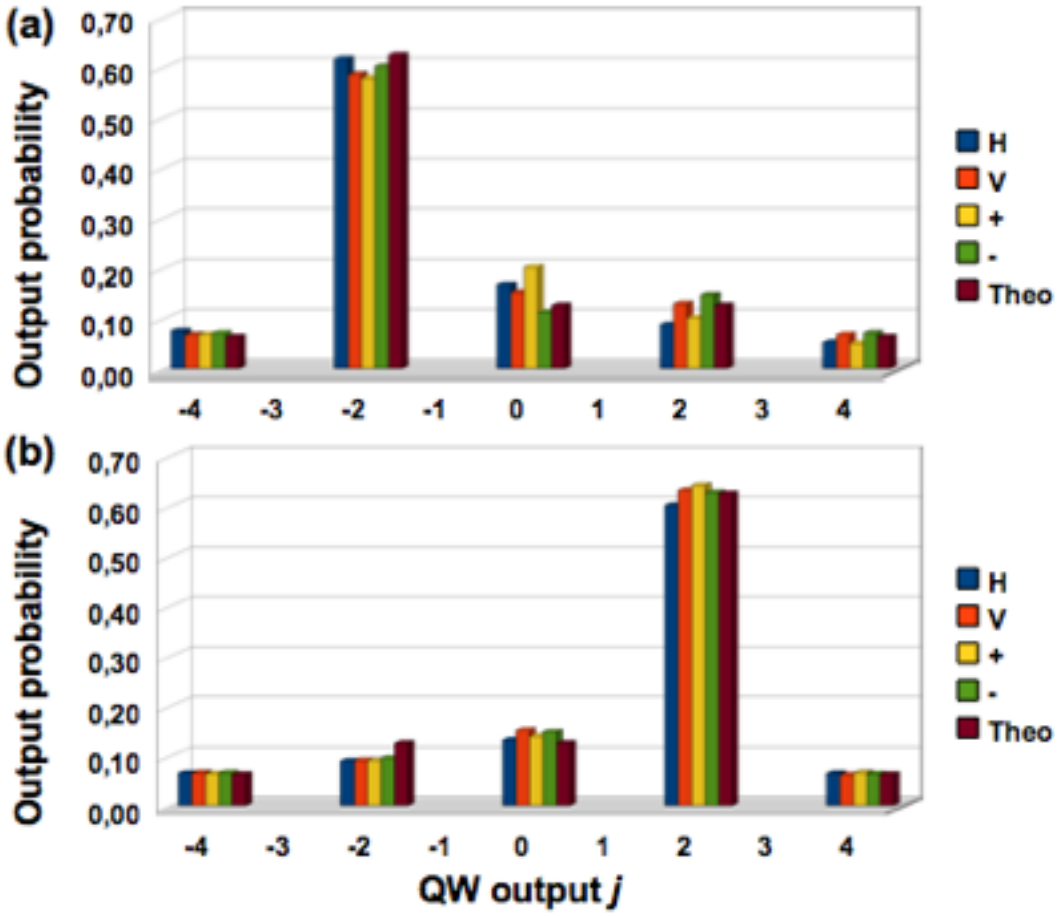


Single-particle quantum walk

We inject a single photon
in the BS array

We observe the same quantum walk
independently of the polarization state

GOAL: to exploit the polarization degree of freedom in order to inject different entangled states of two photons



Two-particle quantum walk

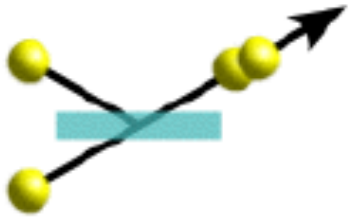
The symmetry of two travelling quantum walkers influences the output probability distribution

Polarization independent integrated beam splitter

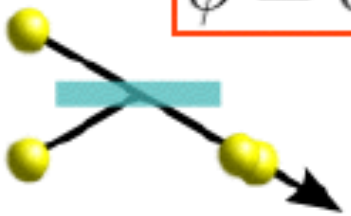
Exploit polarization entanglement to change the symmetry of two-particle wavefunction

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

Bosons

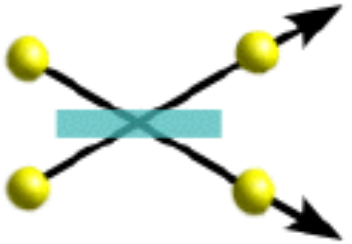


or

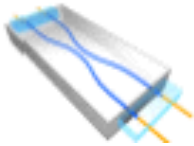


$\phi = 0$

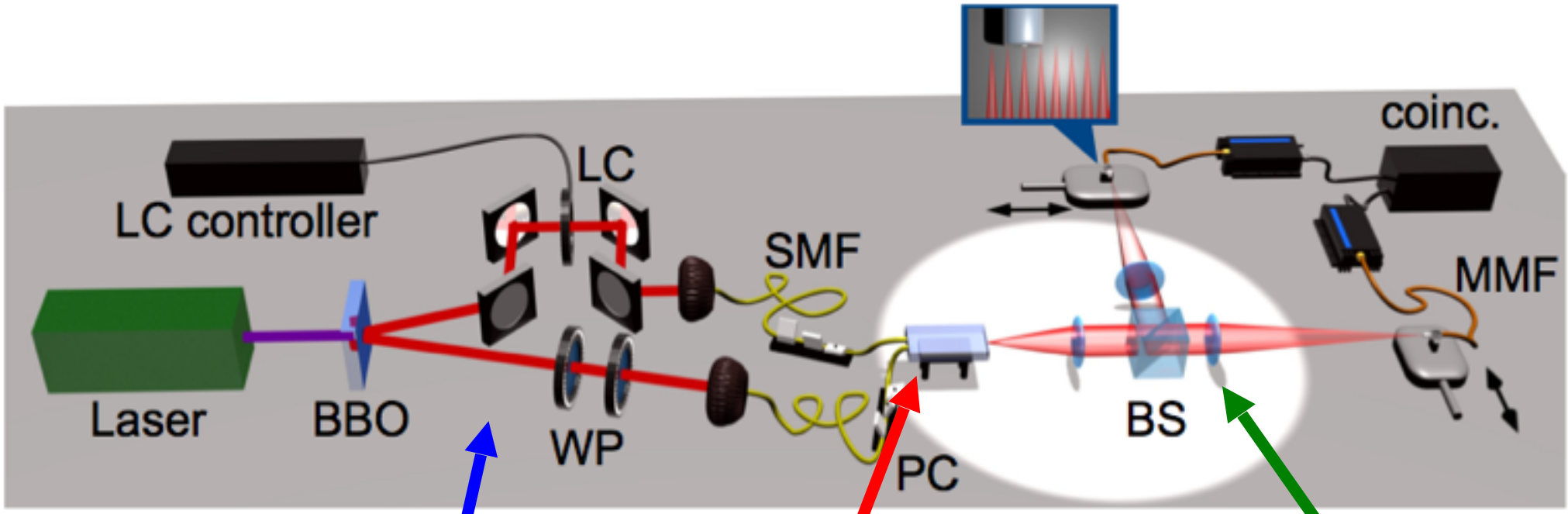
Fermions



$\phi = \pi$



Two-particles quantum walk: experimental setup



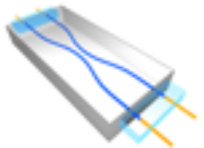
BS array on a chip

Generation of two-photon entangled states with different symmetries

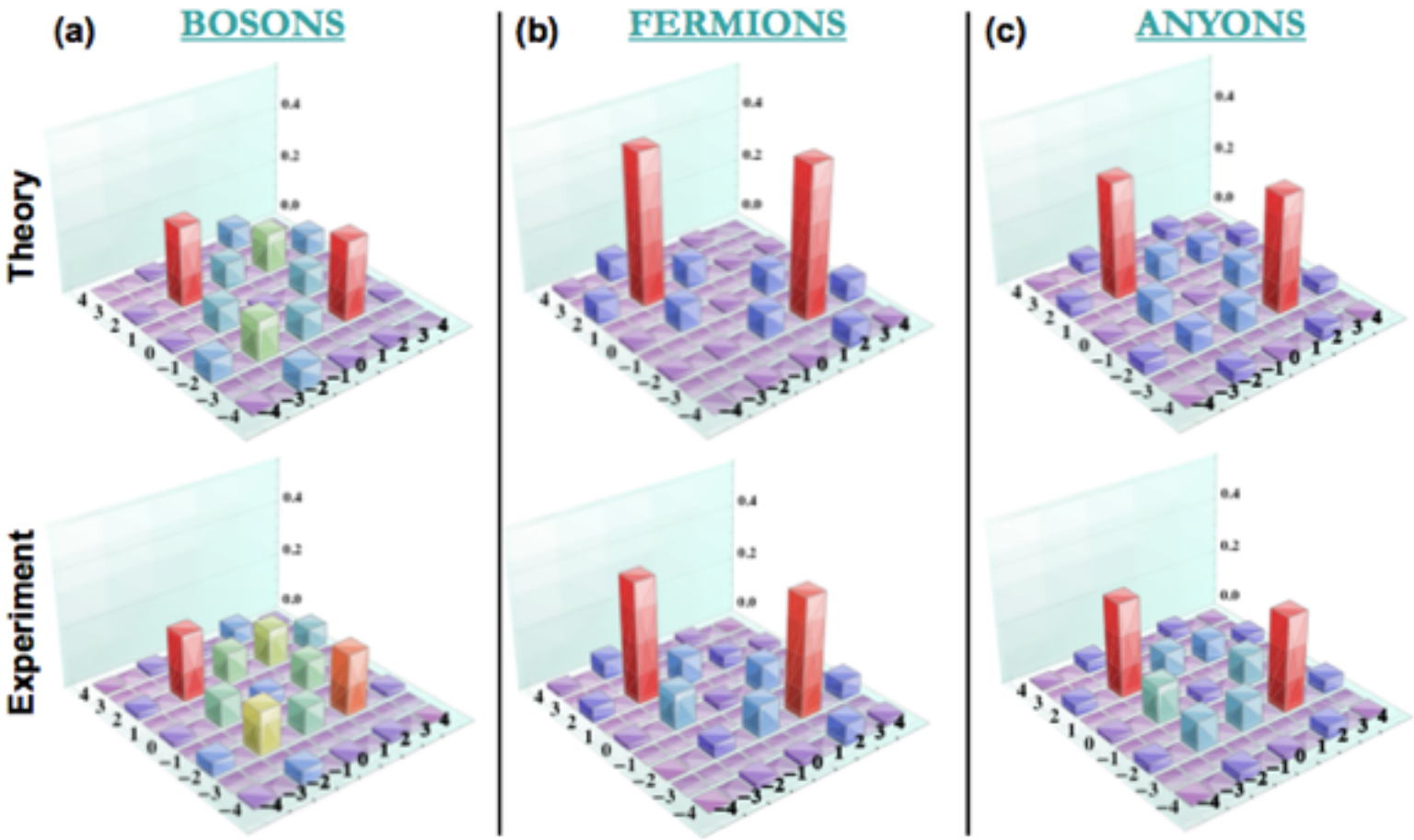
Eight output modes:

Measurement of coincidences between modes i and j

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



Two-particles quantum walk: results



Similarities between theory and experiment

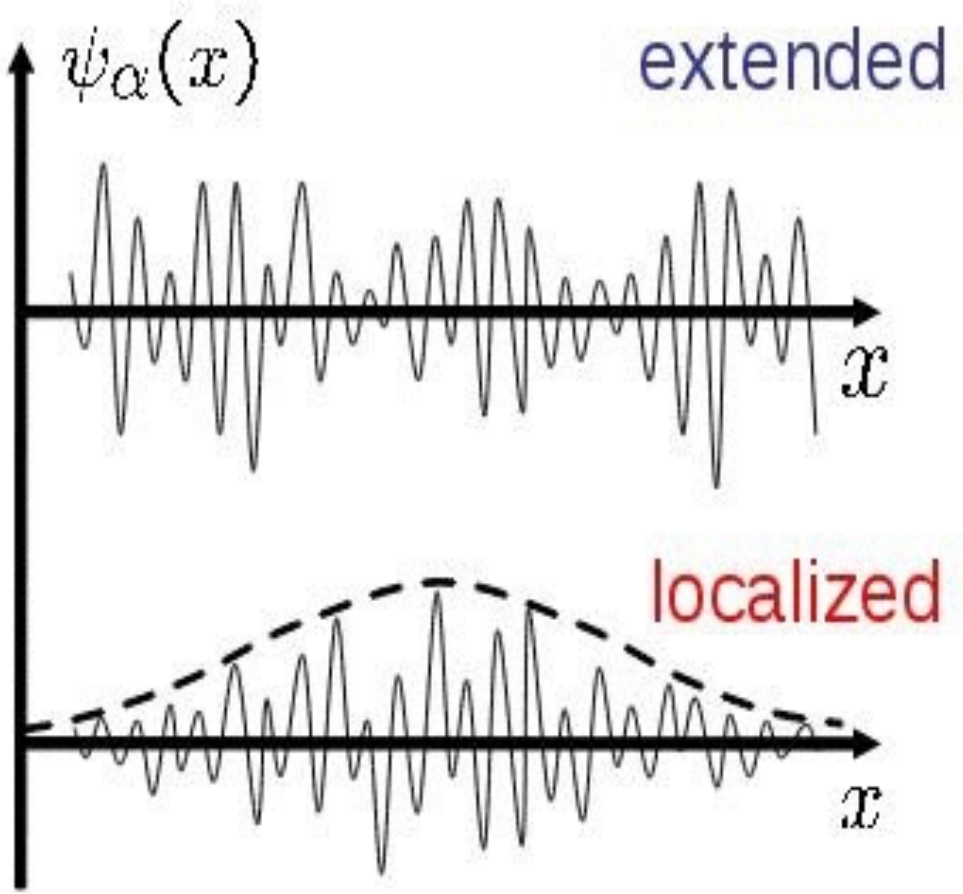
S = 0.982 ± 0.002 **S = 0.973 ± 0.002** **S = 0.987 ± 0.002**

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

See also: continuous quantum walk by J. Mathews, et al., arXiv: 1106.1166

Anderson localization

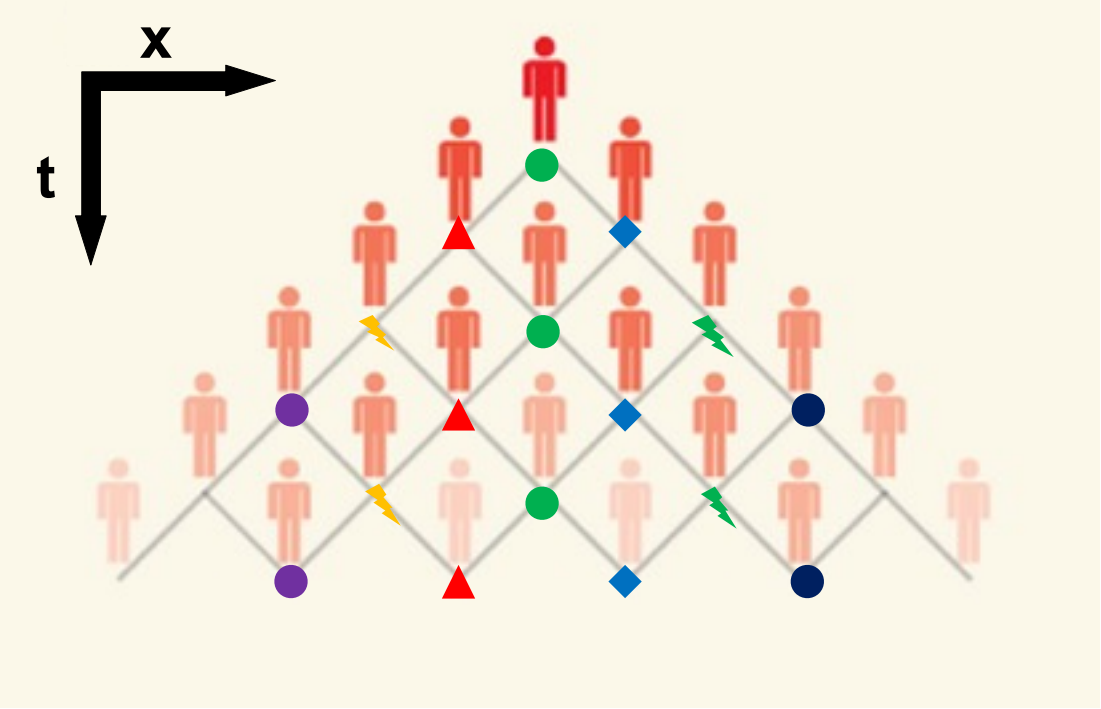
- Anderson, 1958: electrons in disordered media do not diffuse!
- To date, Anderson localization is used to model metal-insulator transitions.



P. W. Anderson, “Absence of diffusion in certain random lattices,” *Physical review*, vol. 109, no. 5, p. 1492, 1958

Simulating Anderson localization with a QW

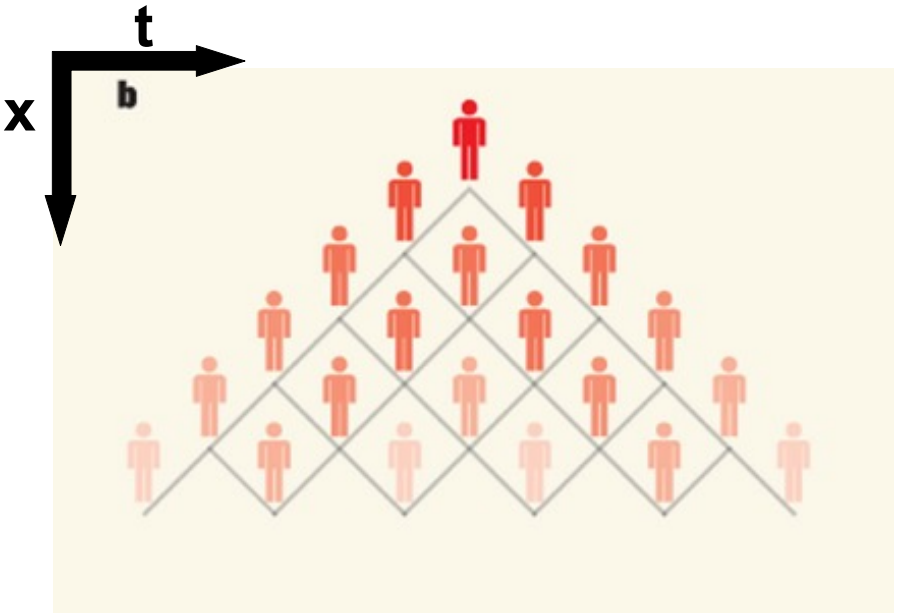
- Disordered medium → Static random noise in the QW
- Noise → Loss of quadratic spread
- Ergodicity → Possibility to average over different noise configurations

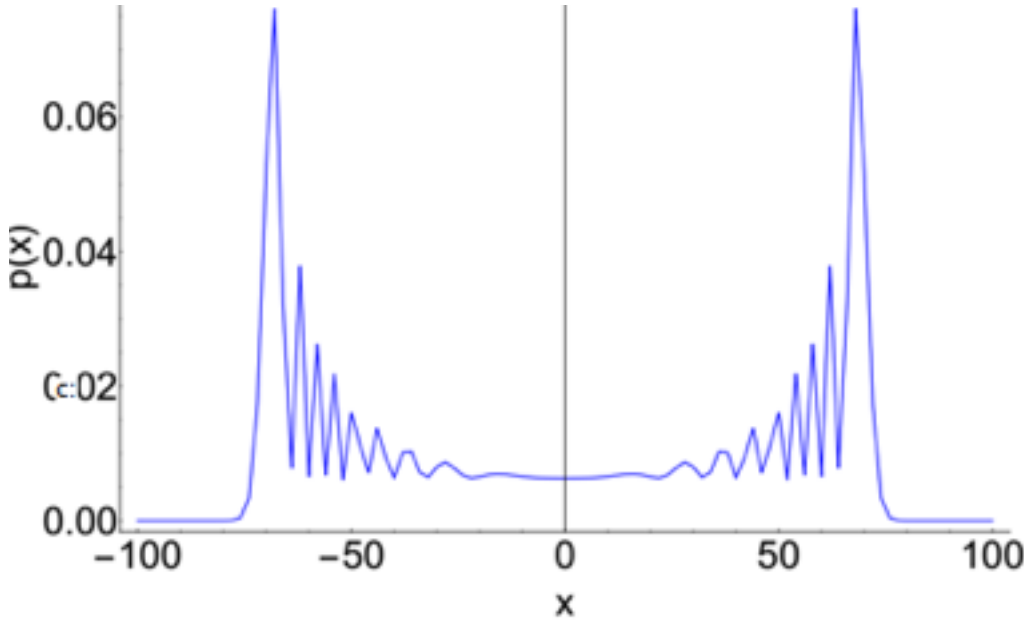


Simulating Anderson localization with a QW

1 particle QW

- Noiseless case: ballistic behaviour

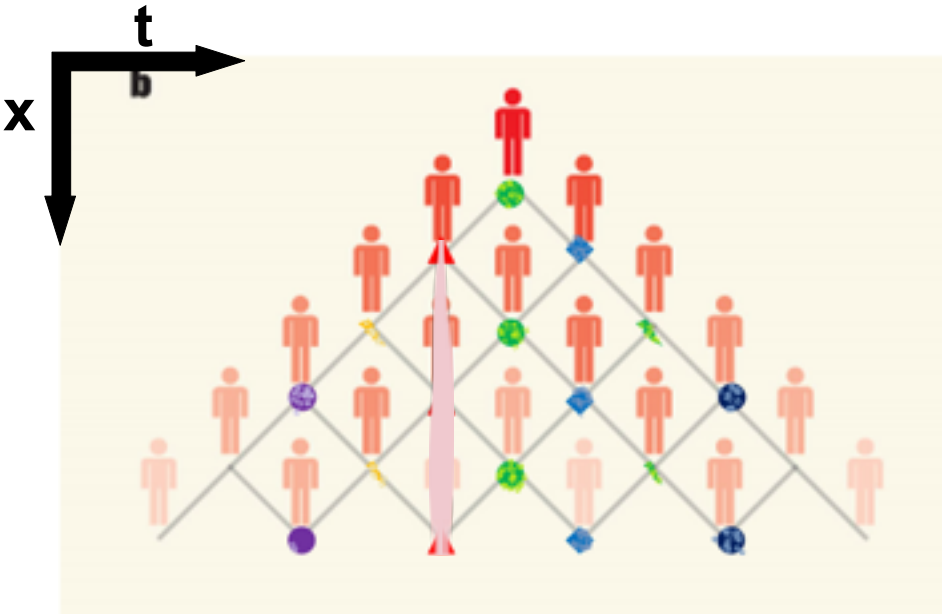


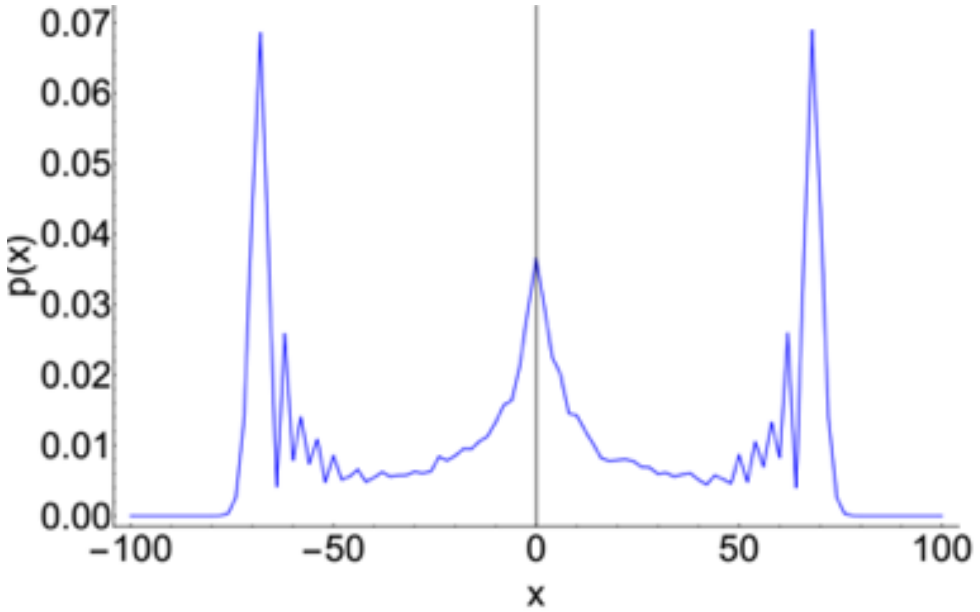


Simulating Anderson localization with a QW

1 particle QW

- Introducing noise

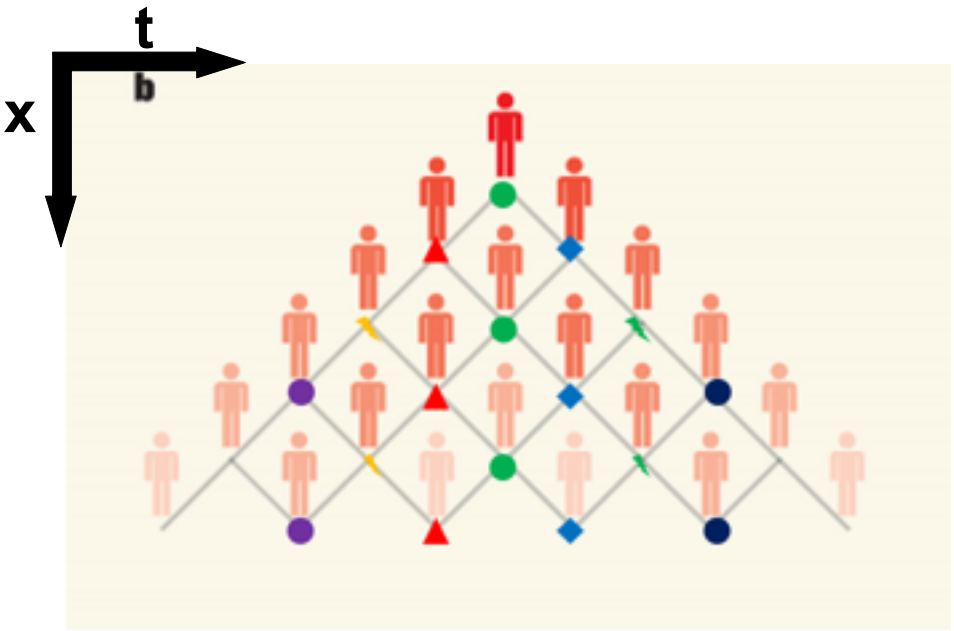


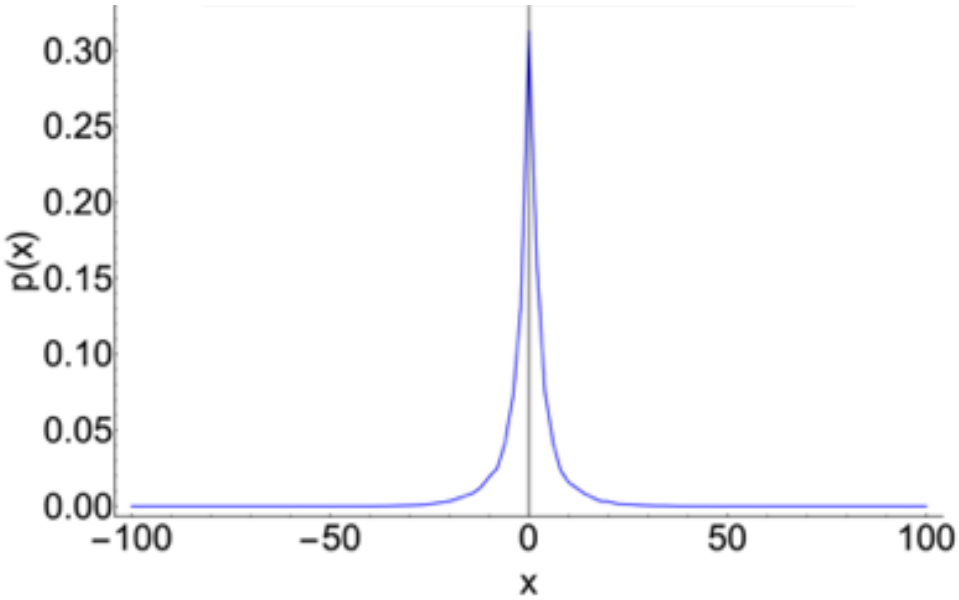


Simulating Anderson localization with a QW

1 particle QW

- Anderson localization



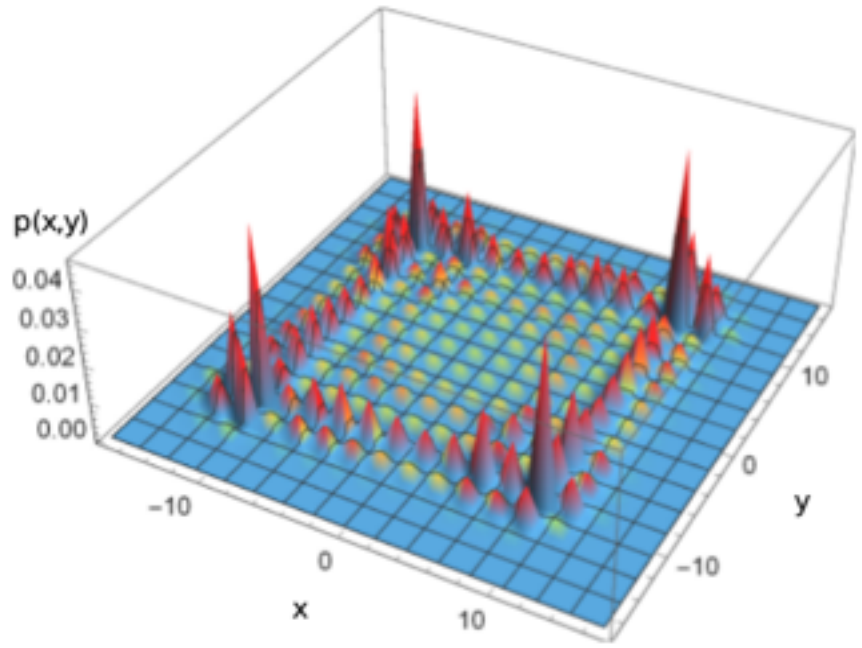


Diffusion is completely suppressed.
The decay is exponential with respect to the classical case

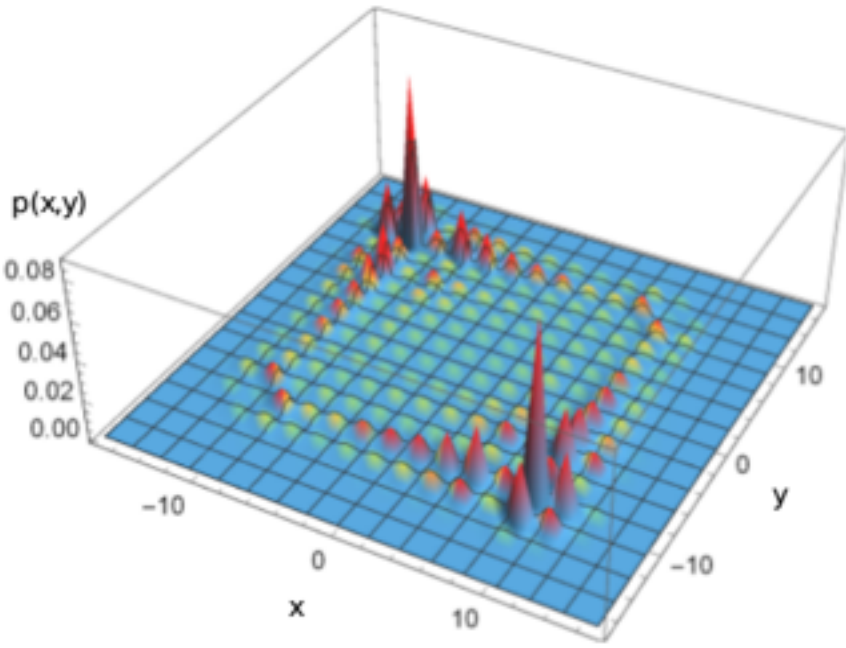
Simulating Anderson localization with a QW

2 particles QW

- Bosonic statistics: bunching
- Fermionic statistics: antibunching



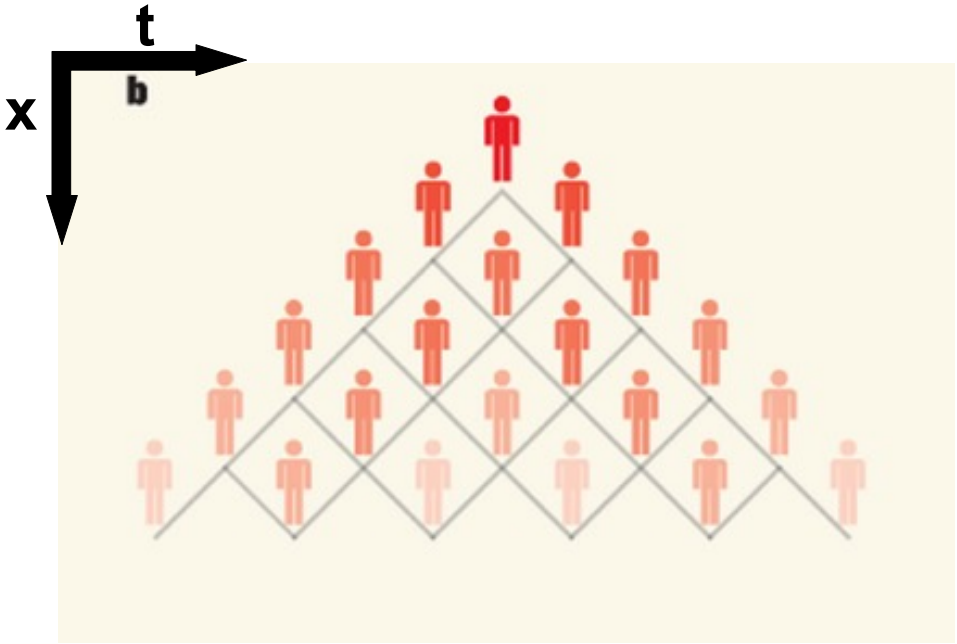
(a)



(b)

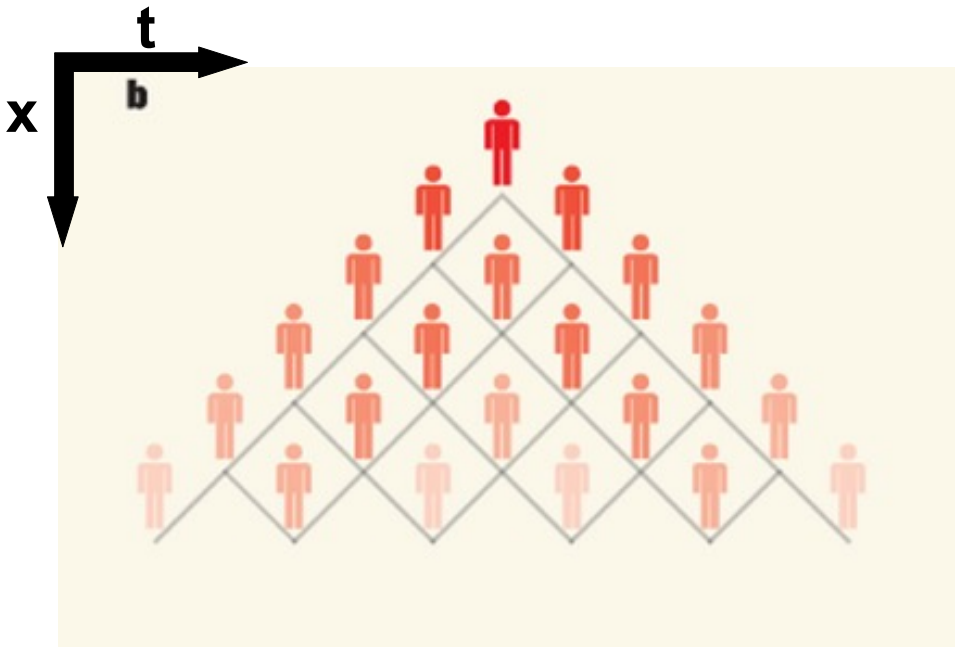
Photonic Quantum Walks

Time is mapped at every step of the walker

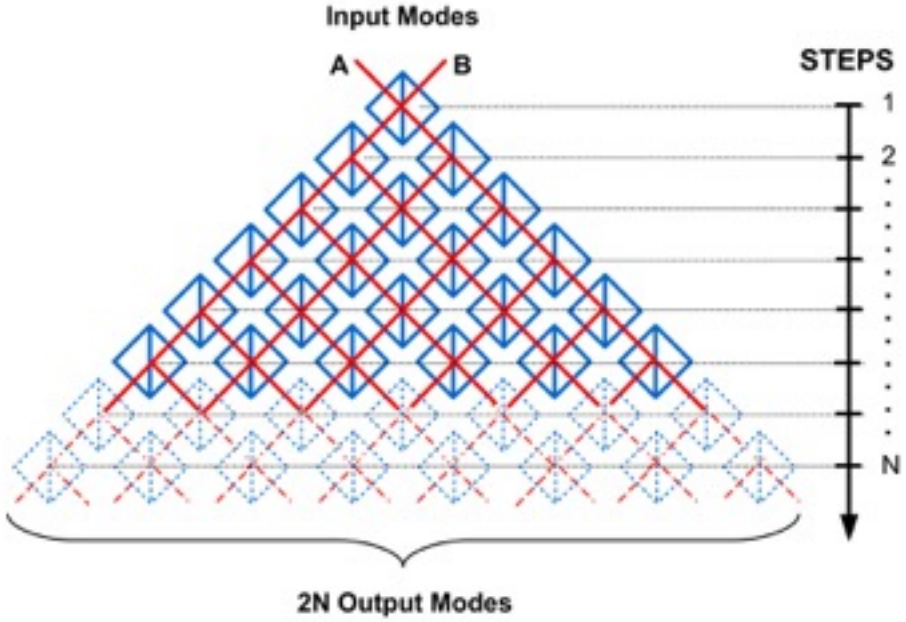


Photonic Quantum Walks

Time is mapped at every step of the walker

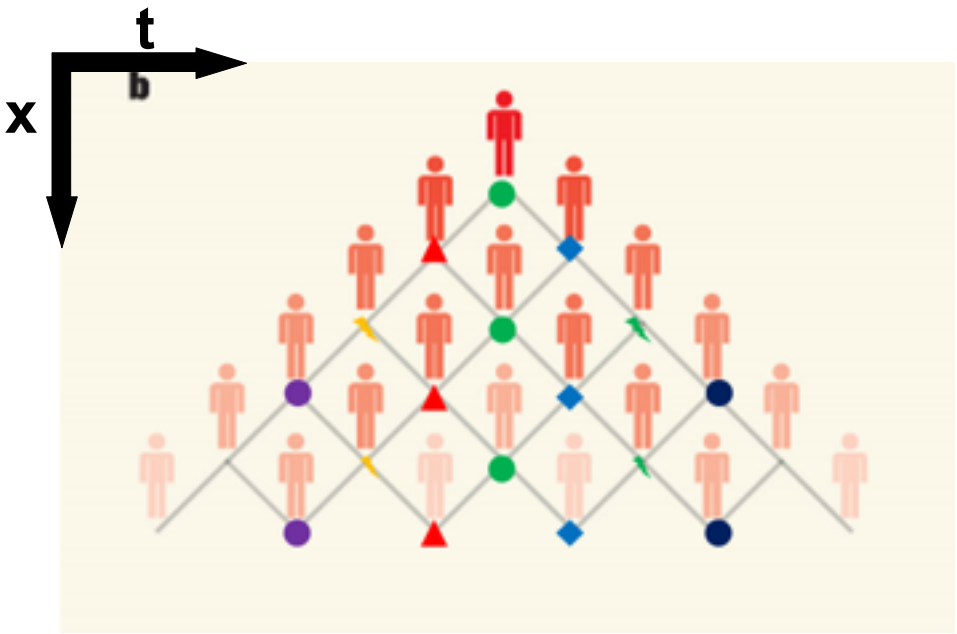


Photonic QW → Cascade of Mach-Zehnder interferometers (MZI). MZIs act both as coin and displacement operators

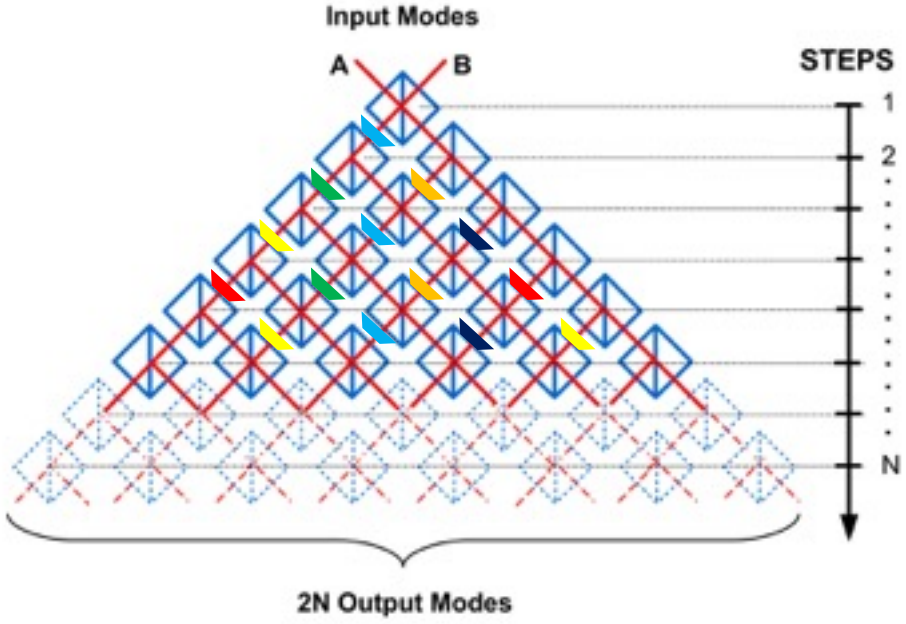


Photonic Quantum Walks

Time is mapped at every step of the walker

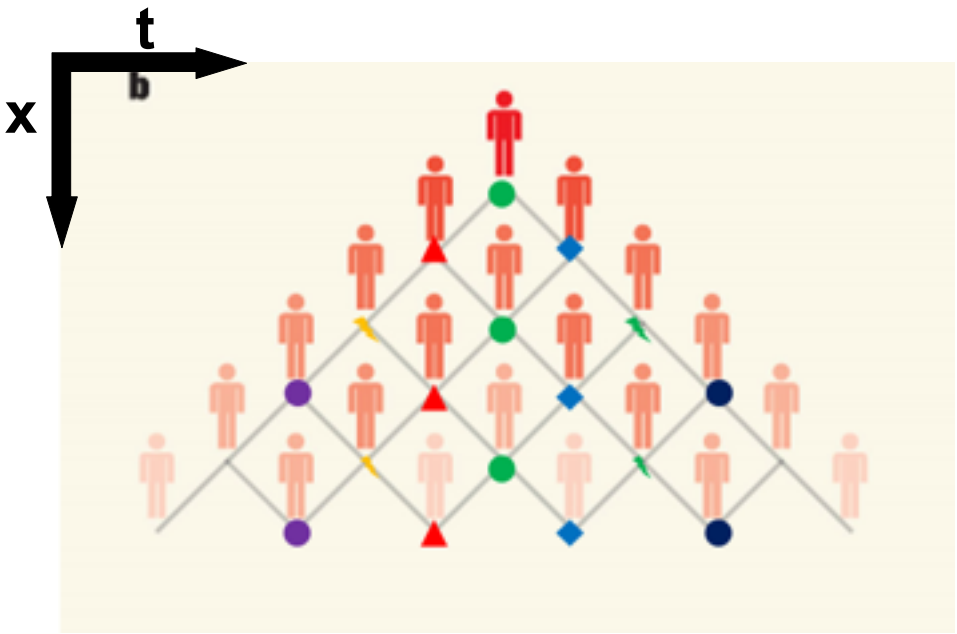


Noise is introduced by unbalancing each beam-splitter in the MZIs, i.e. adding a phase shift



Photonic Quantum Walks

Time is mapped at every step of the walker



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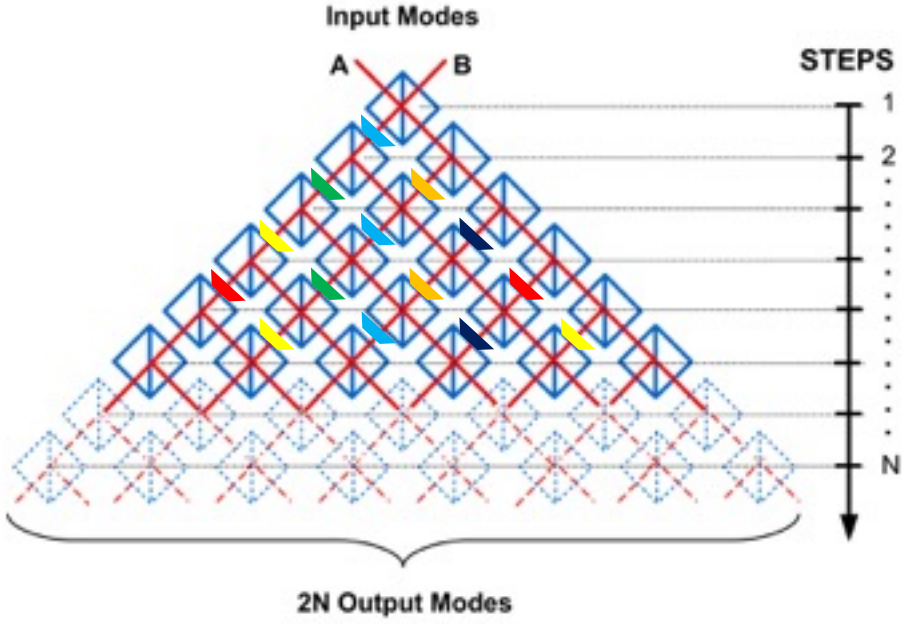
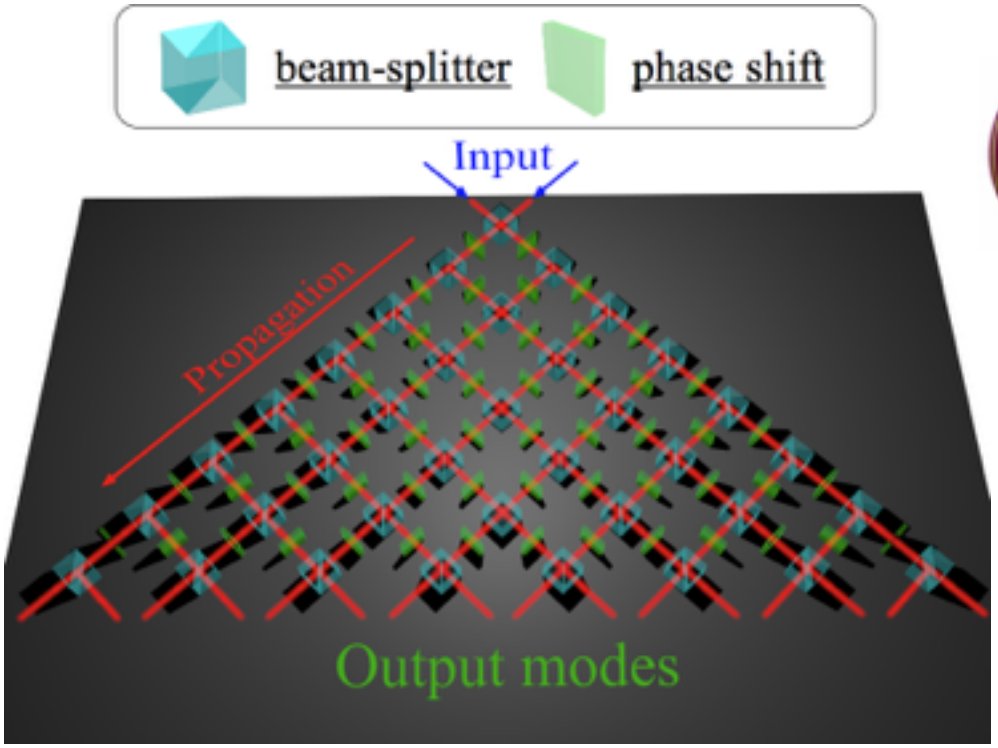


Simulation of disordered systems



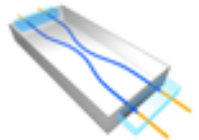
SAPIENZA
UNIVERSITÀ DI ROMA

POLITECNICO
MILANO

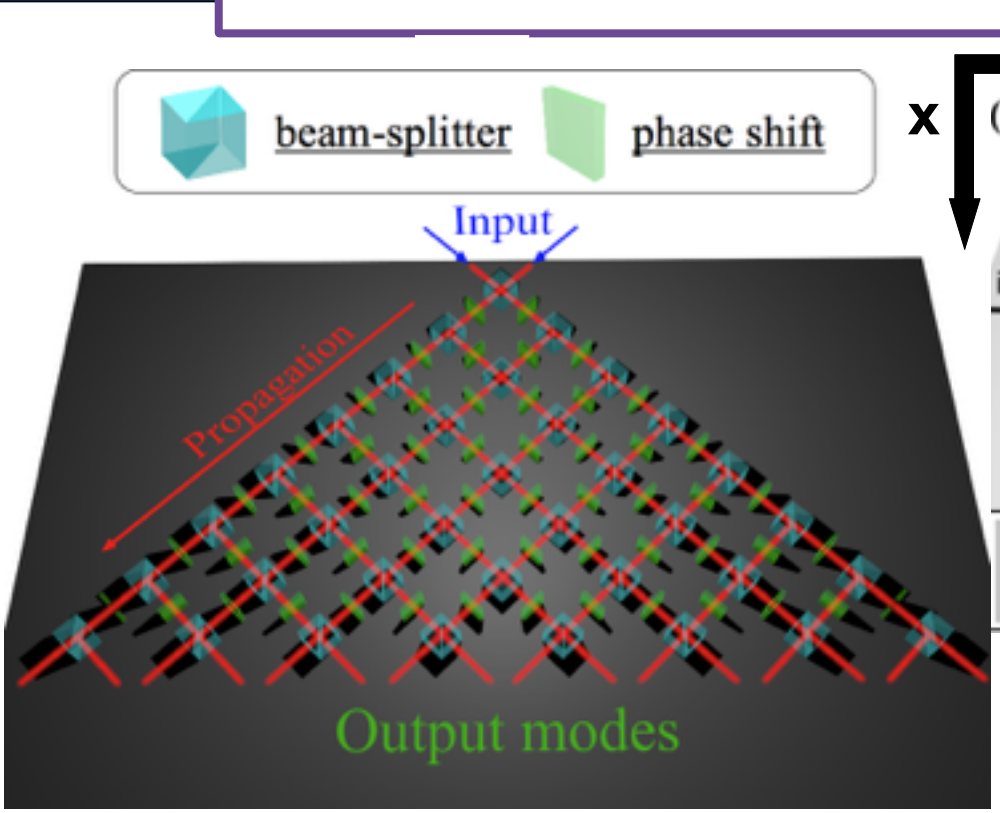
SCUOLA
NORMALE
SUPERIORE

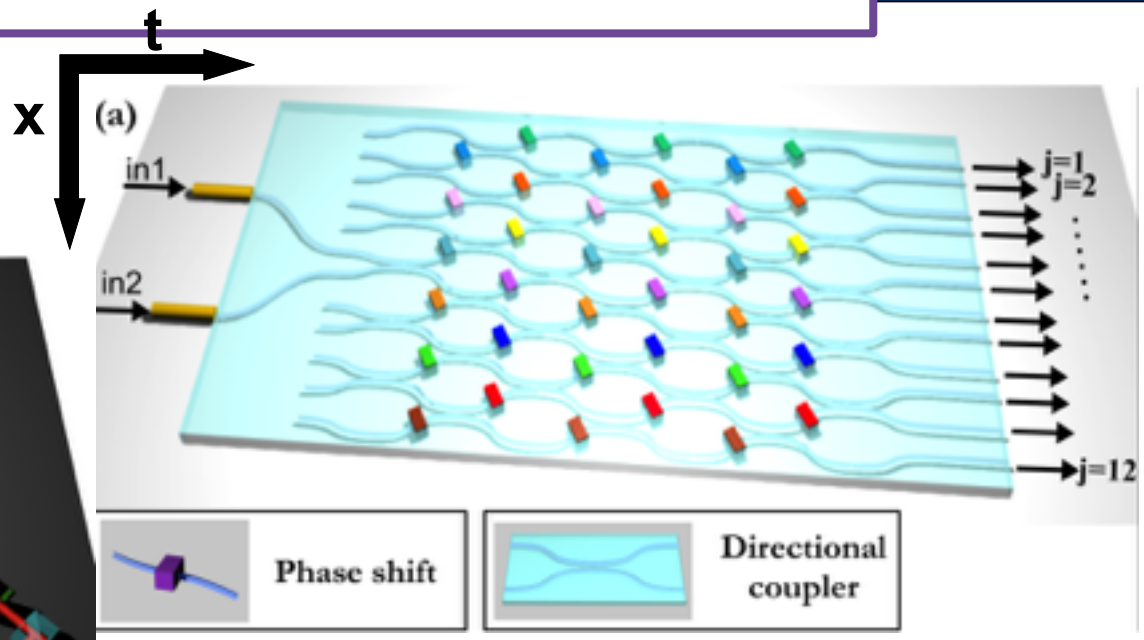
ifn

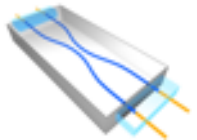
R. Fazio
V. Giovannetti



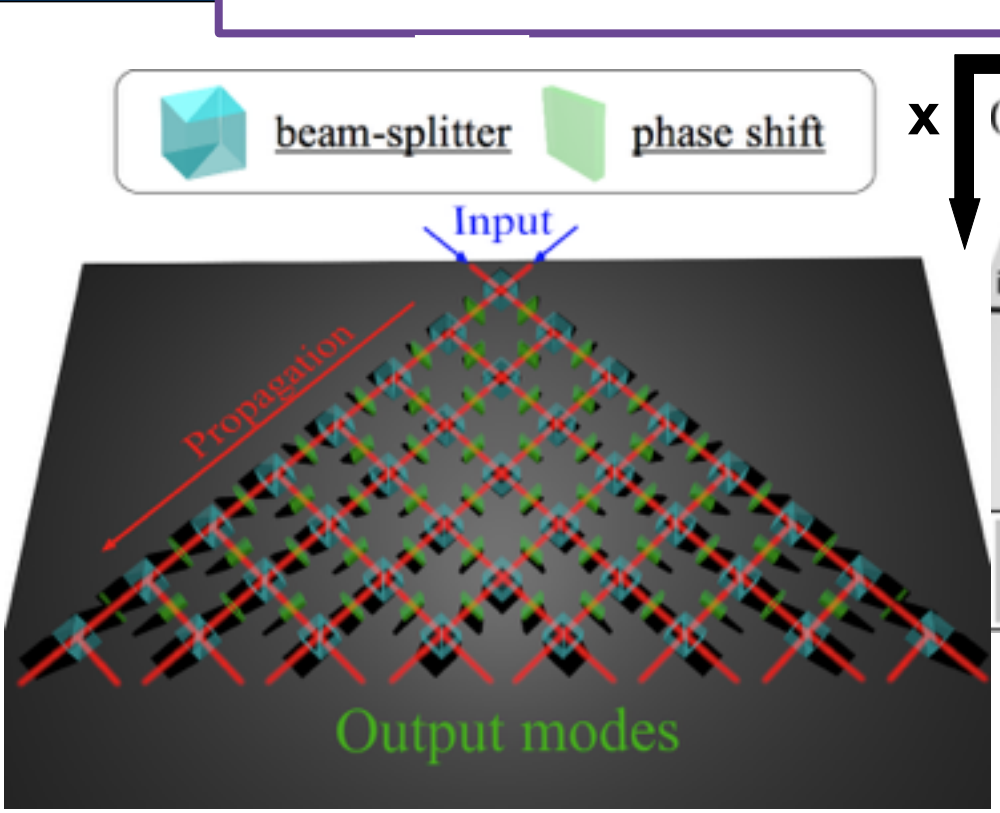
Simulation of disordered systems

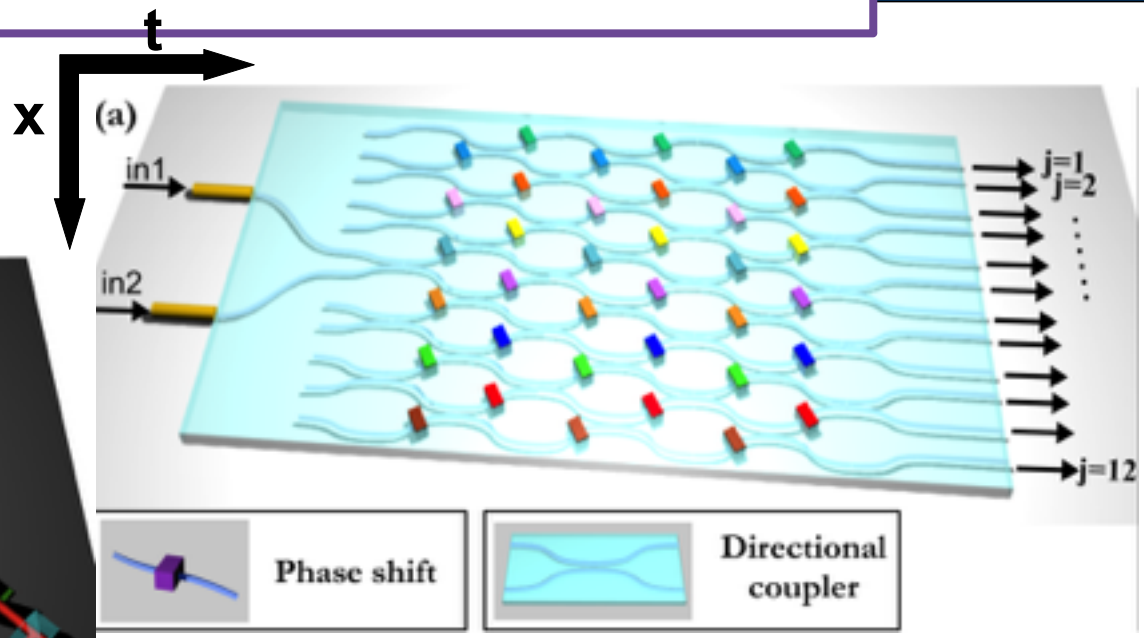




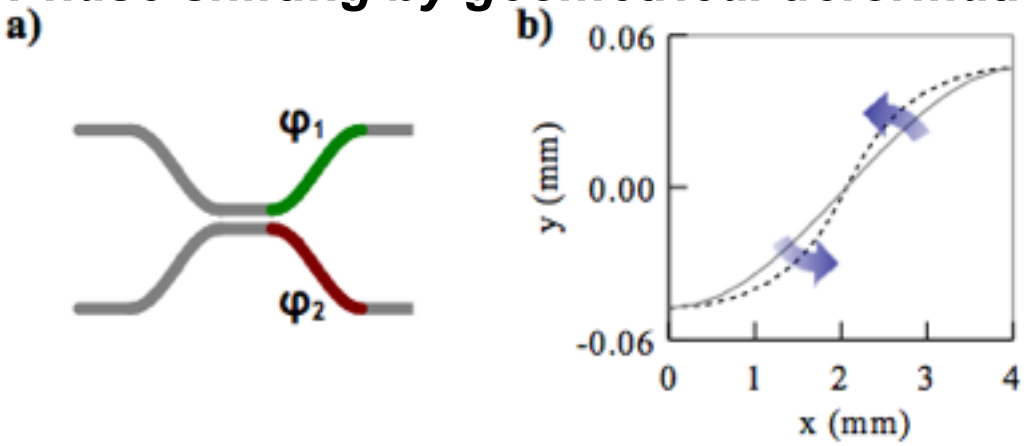


Simulation of disordered systems

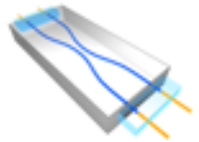




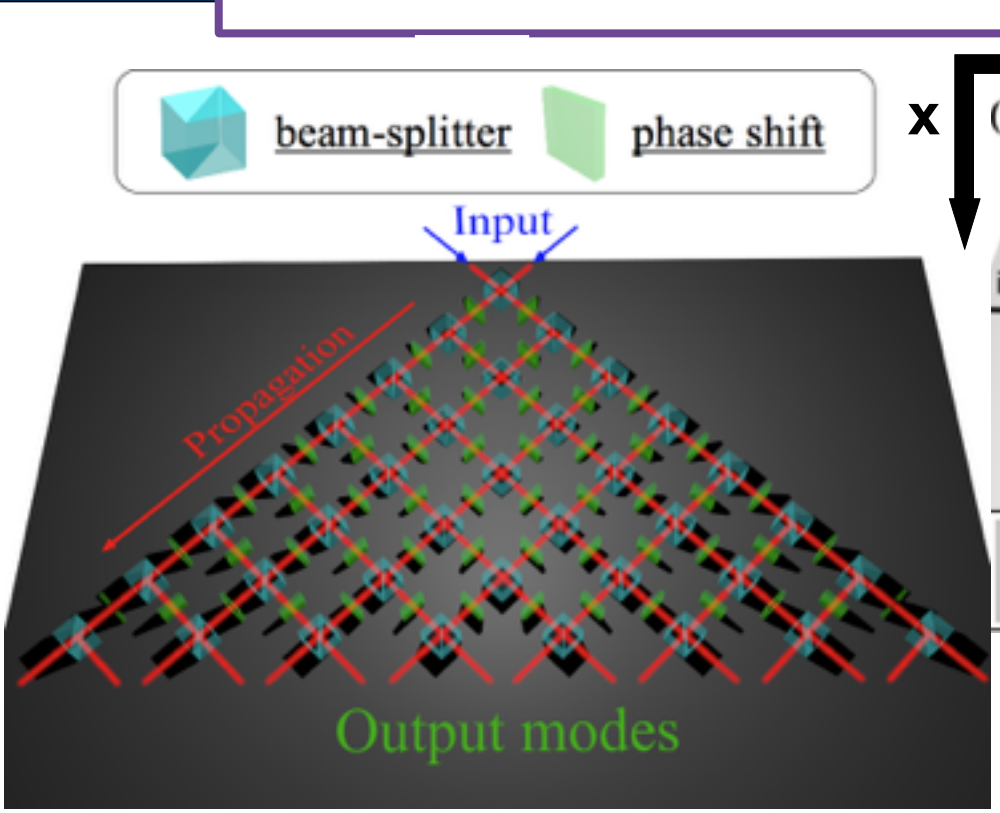
Phase shifting by geometrical deformation

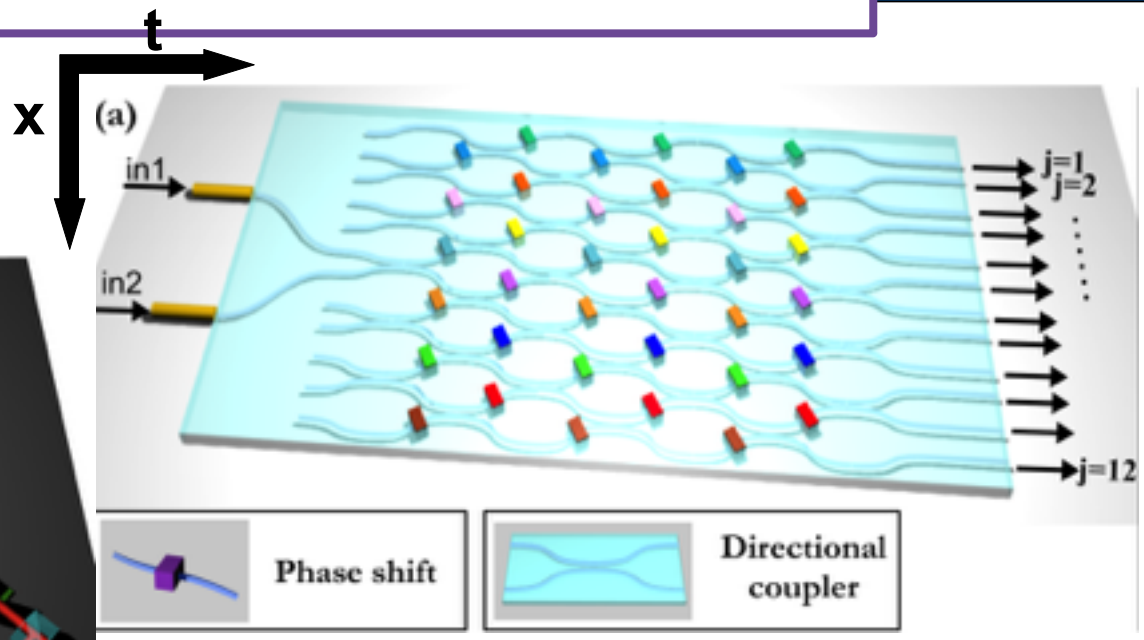


POLARIZATION INDEPENDENT



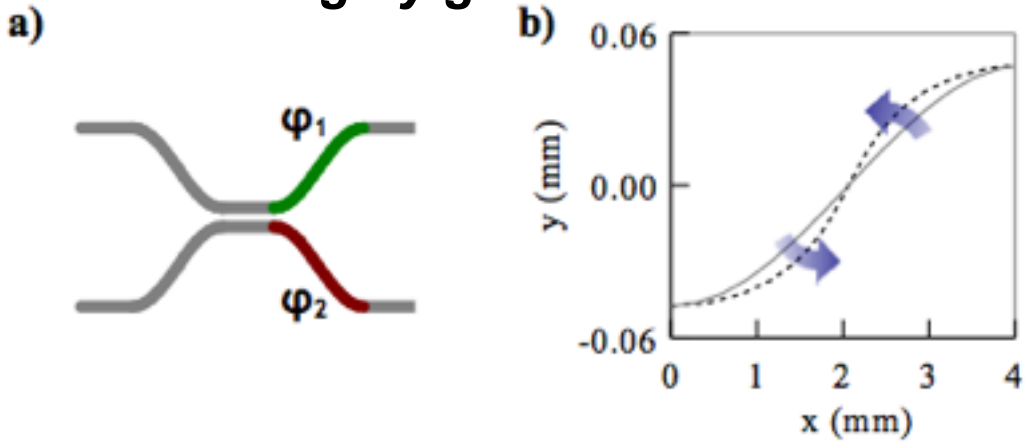
Simulation of disordered systems

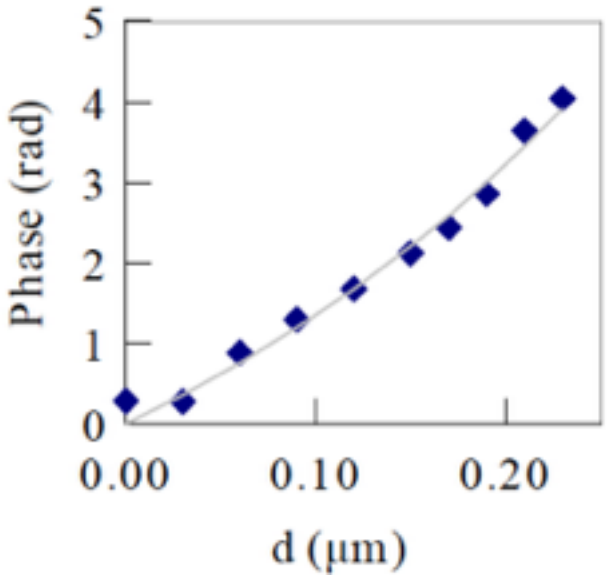




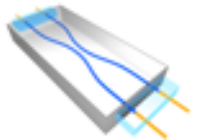
Phase shifting by geometrical deformation

Phase-shifter versus deformation





POLARIZATION INDEPENDENT

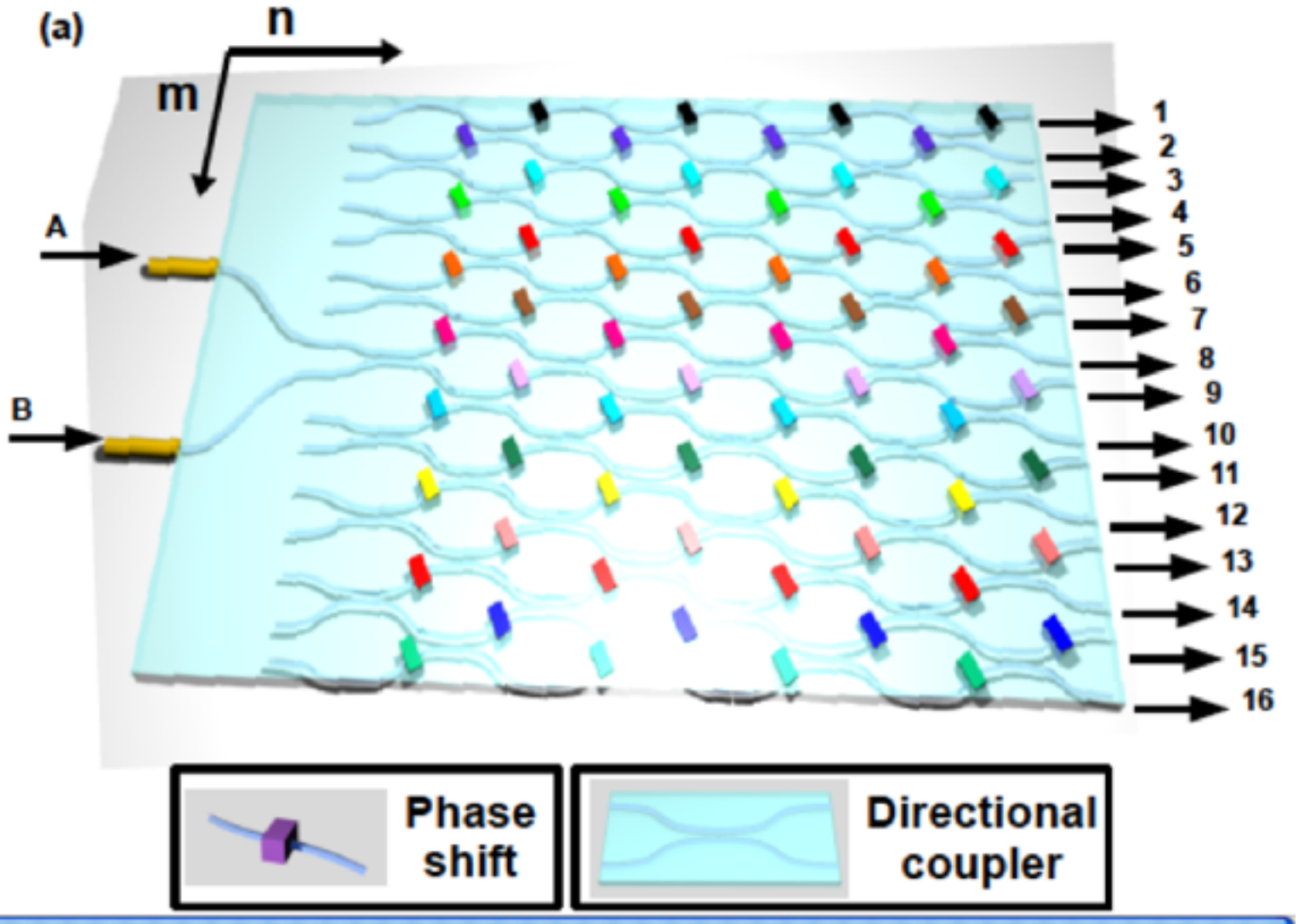


Simulation of static disorder

Disorder depends:
- from location
- but NOT from time

Anderson localication....

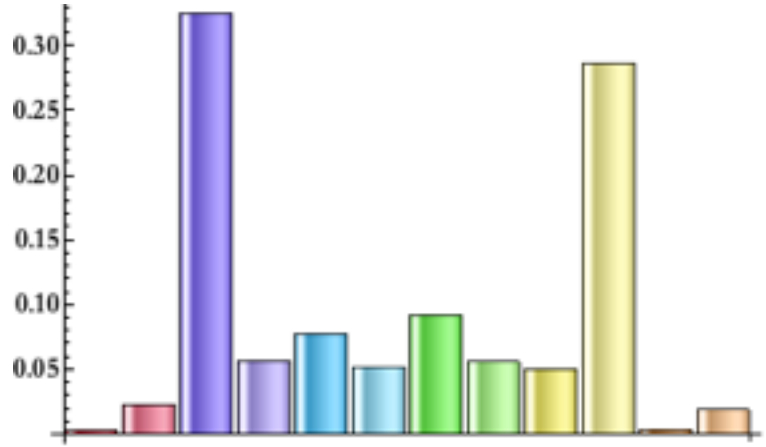
64 Beam splitters
64 phase-shifters
Polarization independent



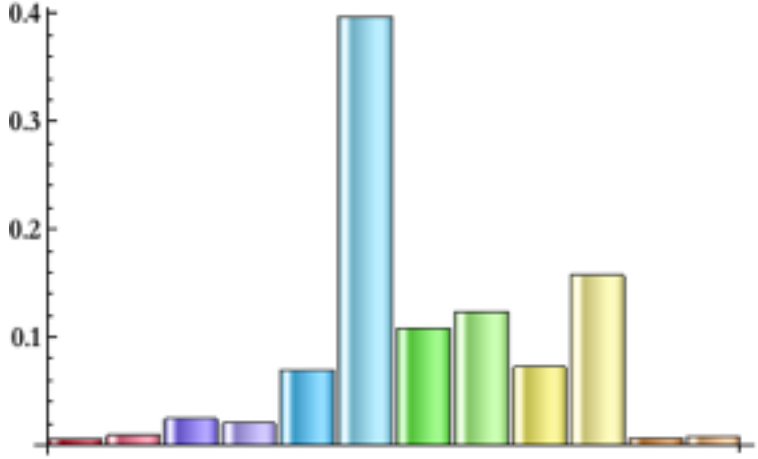
Simulation of disordered systems: Single particle quantum walk

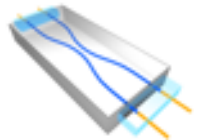
Experiment

Ordered system



Disordered system

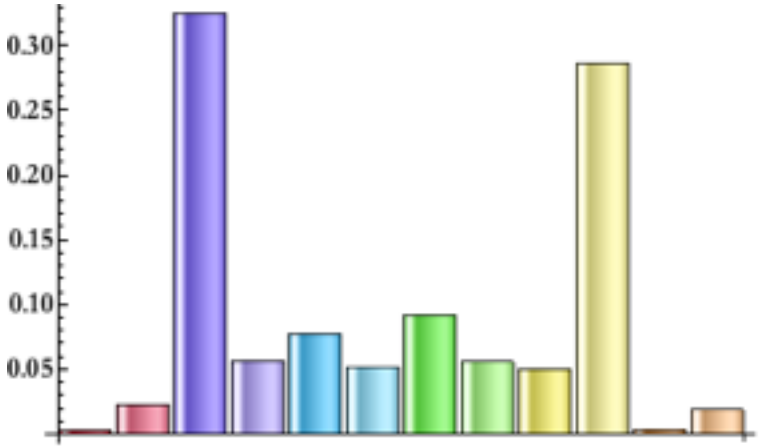




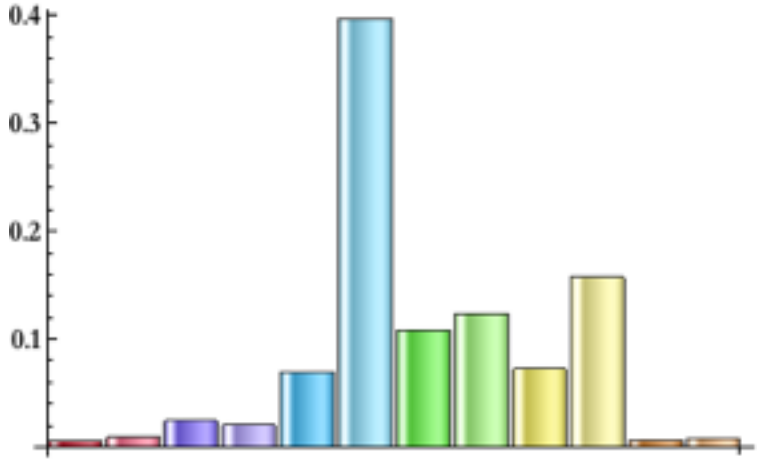
Simulation of disordered systems: Single particle quantum walk

Experiment

Ordered system



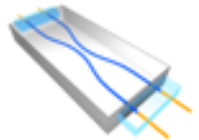
Disordered system



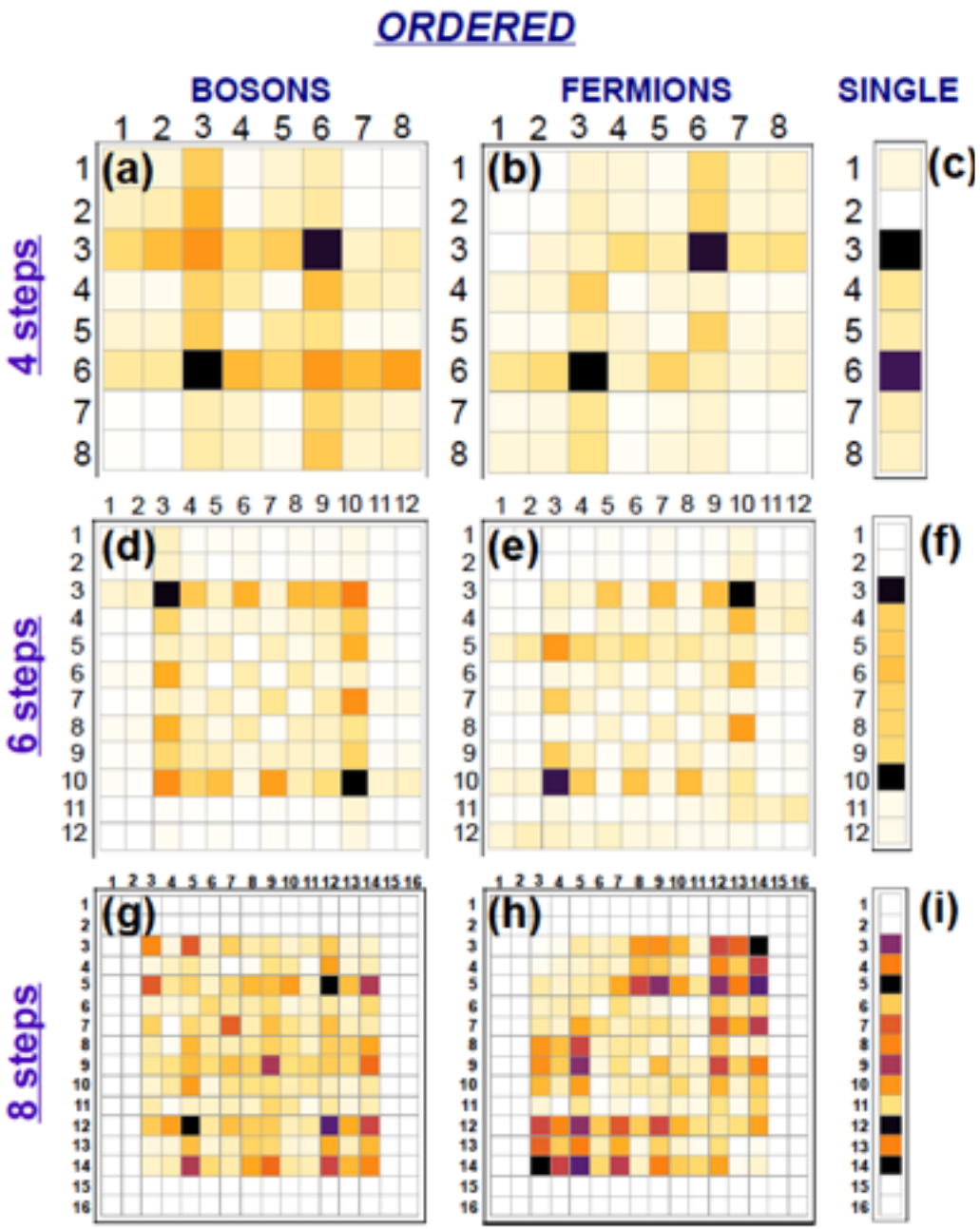
Experimentally observed by Silberhorn's group with fiber loops:
Phys. Rev. Lett. **106**, 180403 (2011).

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

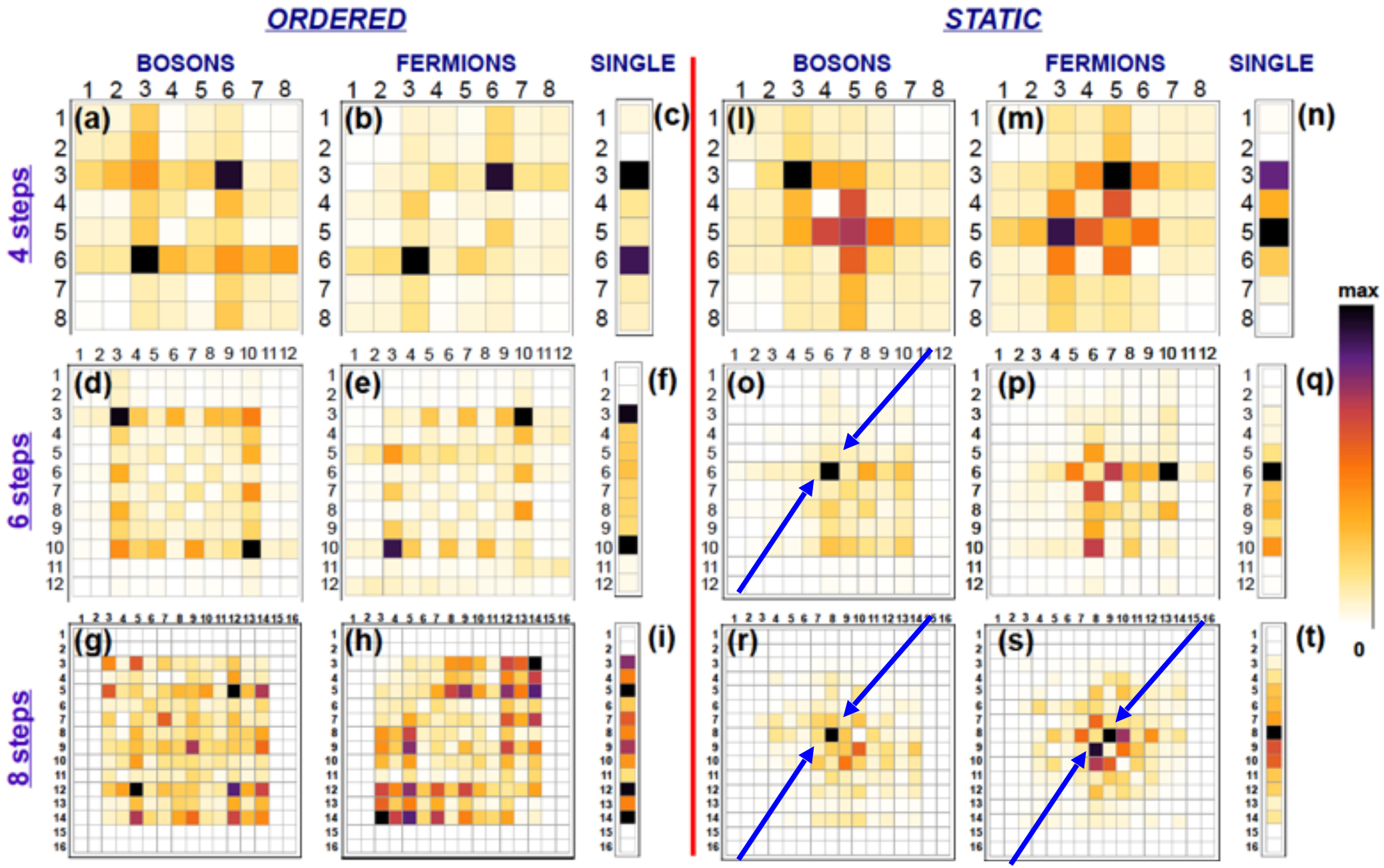
Theoretical investigation by Silberberg's group
Y. Lahini, et al., Phys. Rev. Lett. **105**, 163905 (2010).



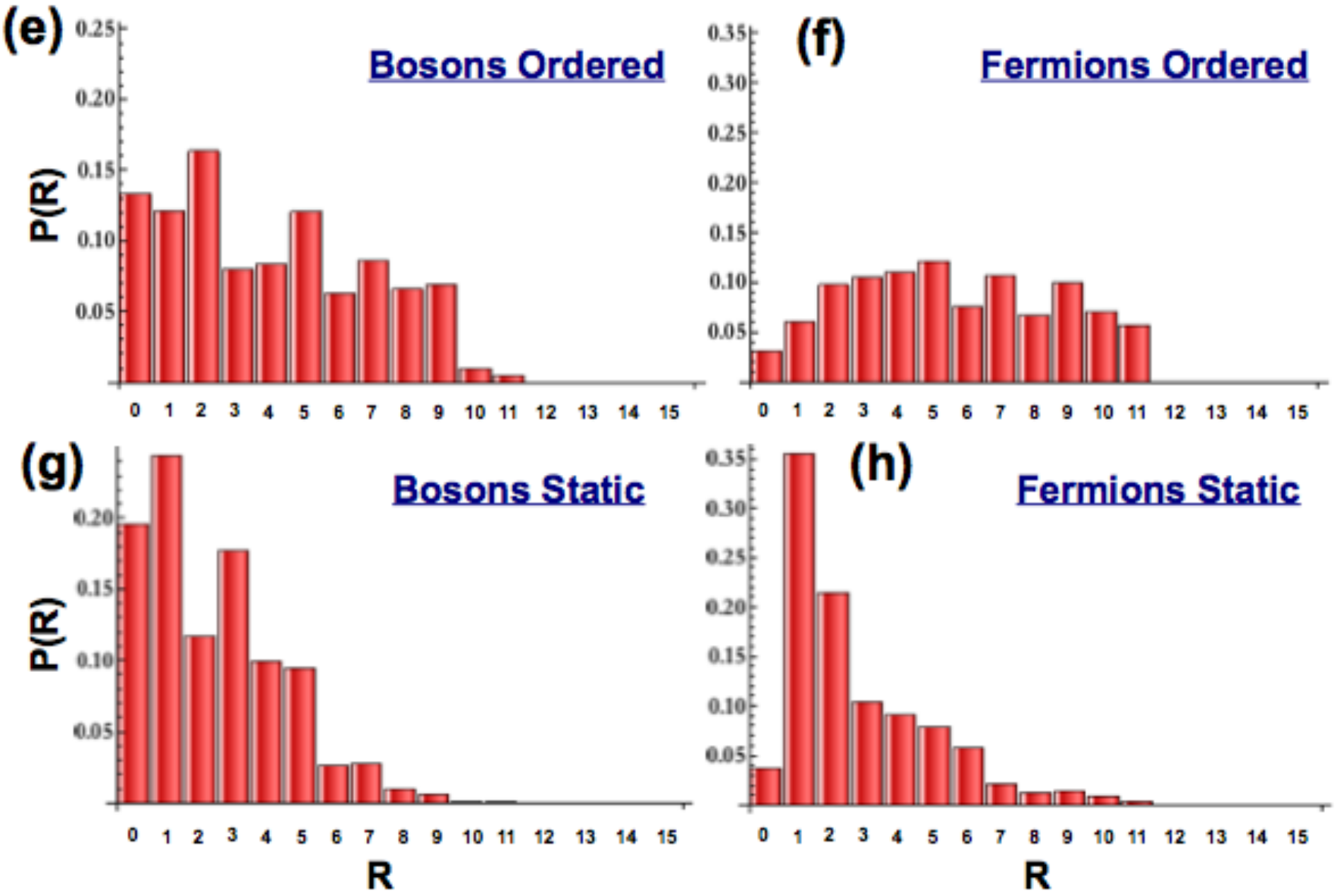
Ordered VS Static Quantum Walk: Experimental results



Ordered VS Static Quantum Walk: Experimental results



Ordered VS Static Quantum Walk: Experimental results



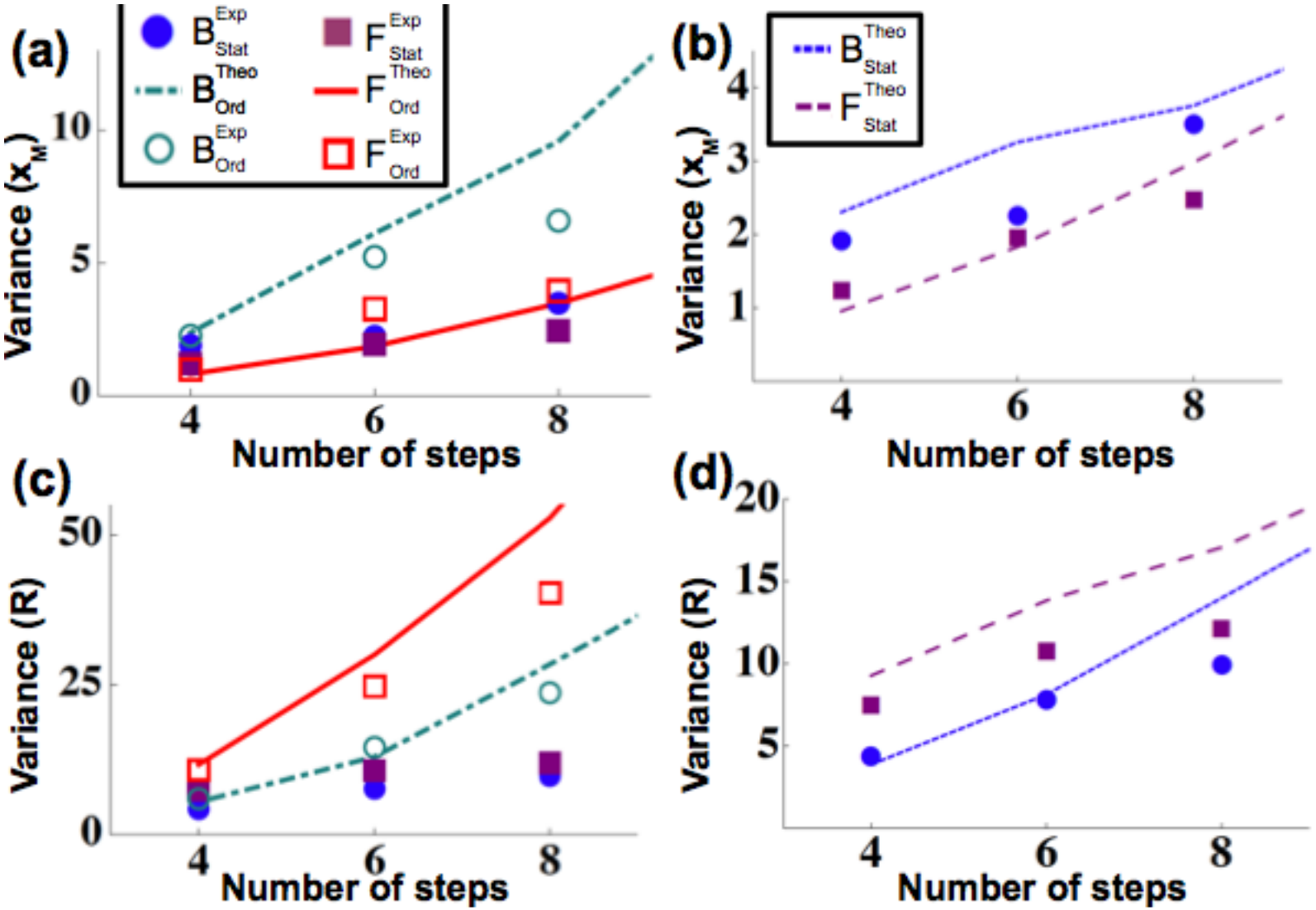
Ordered versus static quantum walk: Experimental results

***Mean* distance**

(j+k)/2

Relative distance

Abs(j-k)

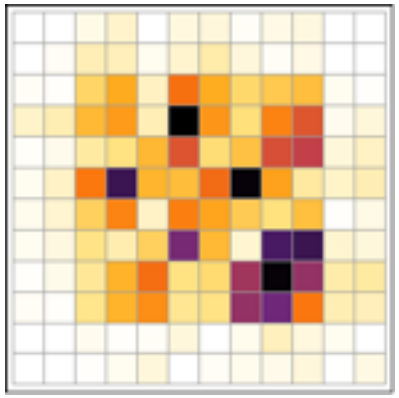


A. Crespi, R. Osellame, R. Ramponi, V. Giovannetti, R. Fazio, L. Sansoni, F. De Nicola, F. Sciarrino, P. Mataloni, Anderson localization of entangled photons in an integrated quantum walk, *Nature Photonics* **7**, 322 (2013).

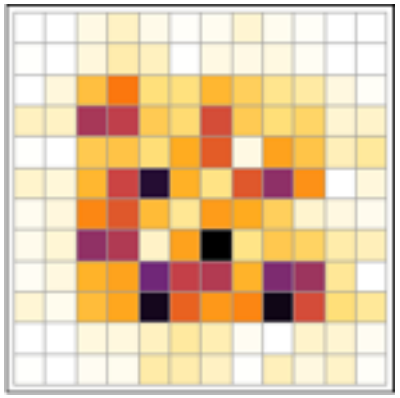
Simulation of other disordered systems

Disorder depends:
- from time
- from location

BOSONS

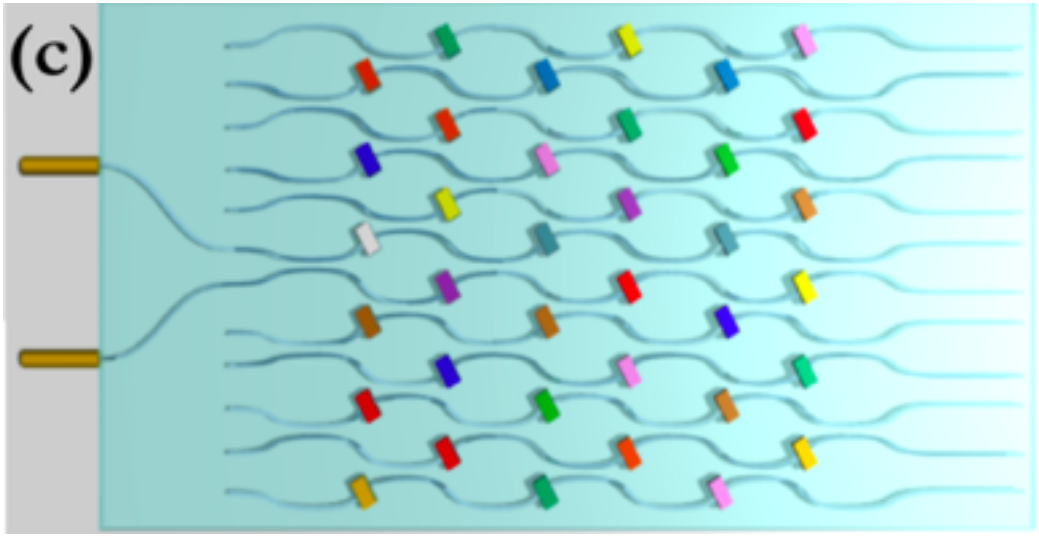


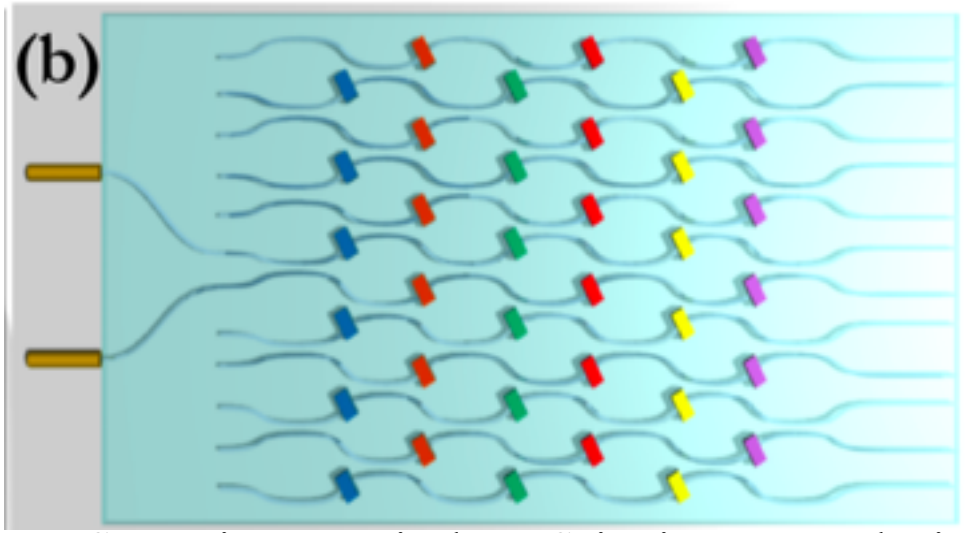
FERMIONS



Disorder depends:
- from time
- but NOT from location

Classical random walk distributions....





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

Simulation of dynamic disorder: Single- & two-particle quantum walks

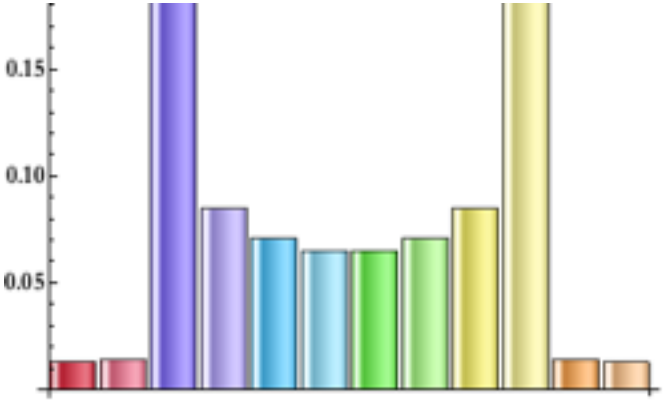
Ordered systems

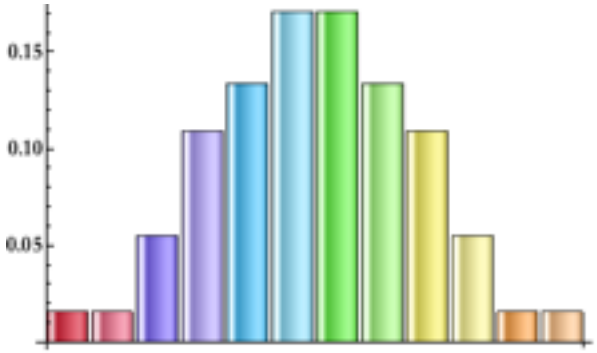
Disordered systems

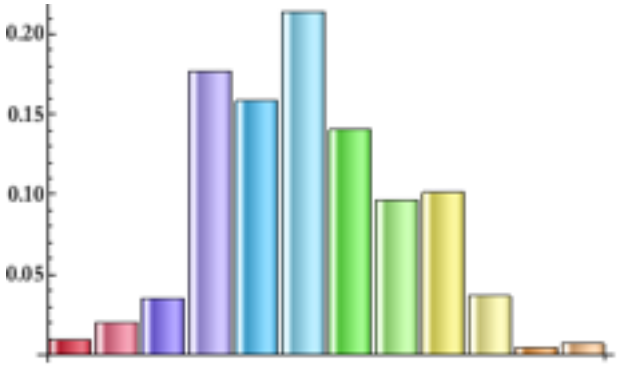
Theory

Experiment

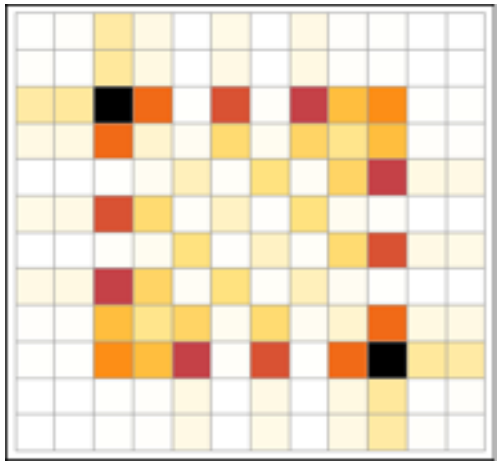
SINGLE

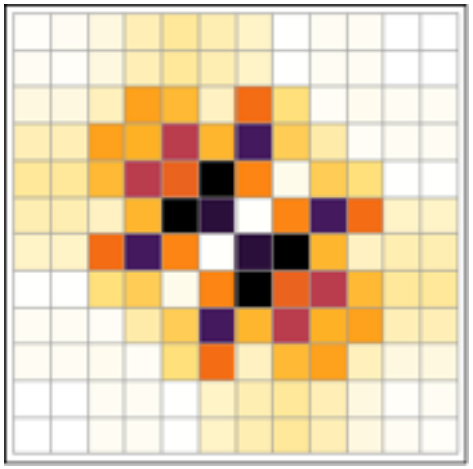


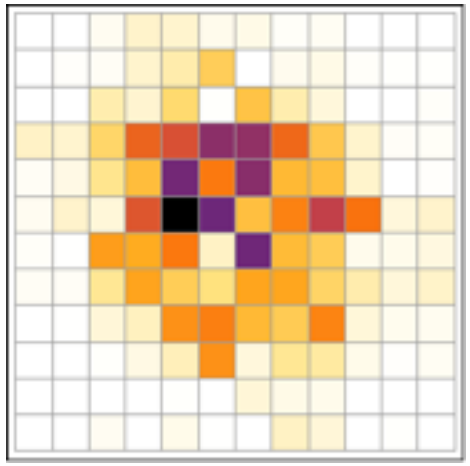




BOSONS



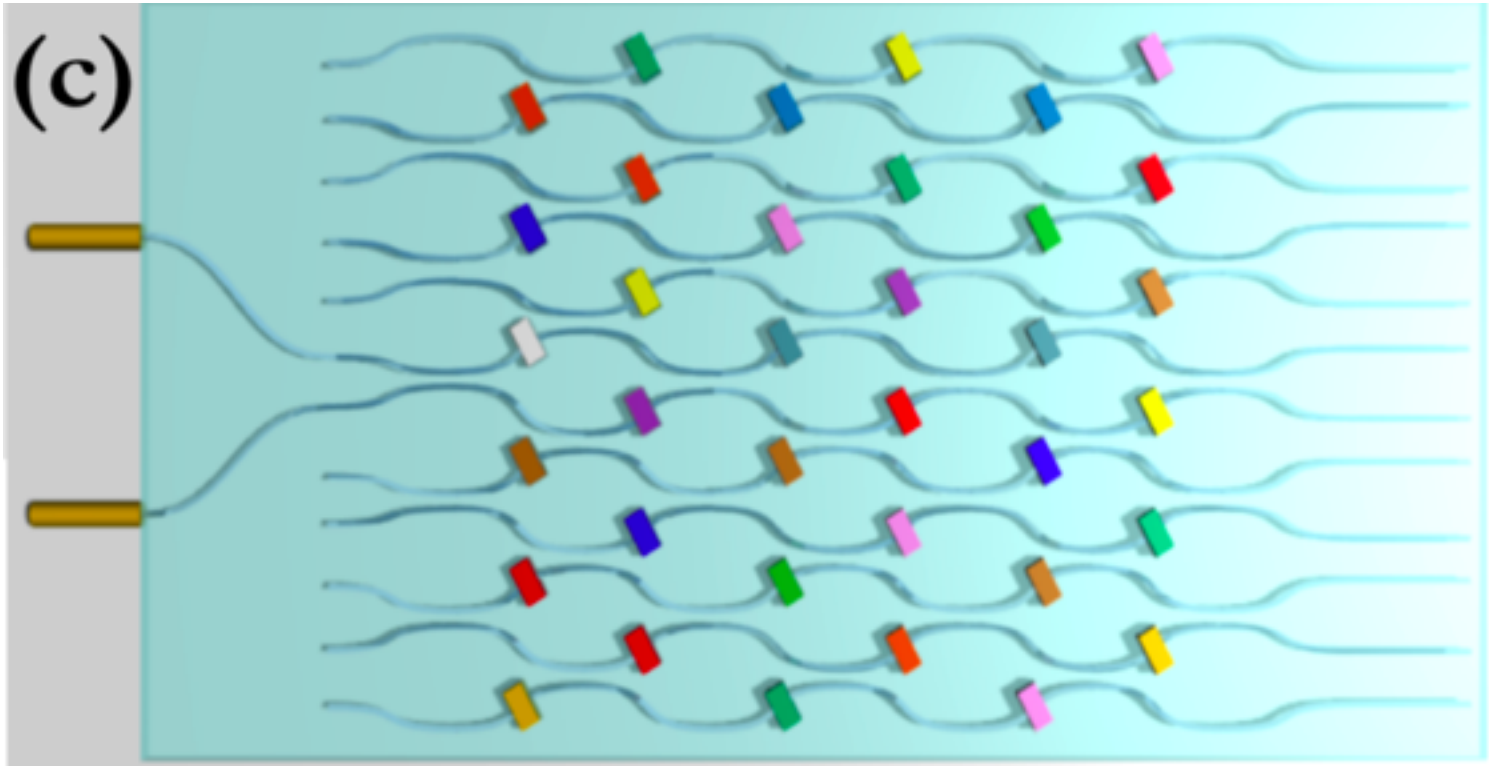




Simulation of fluctuating disorder

Disorder depends:
- from time
- from location

time



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Simulation of fluctuating disorder: Single- & two-particle quantum walks

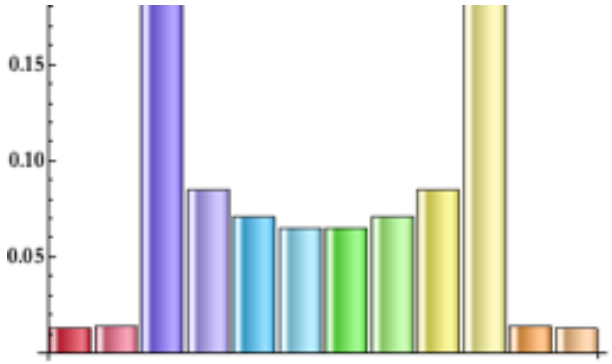
Contour plot of probability

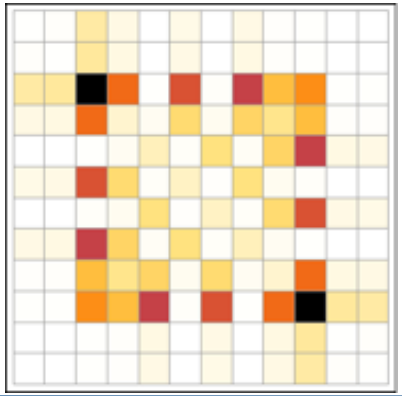
SINGLE

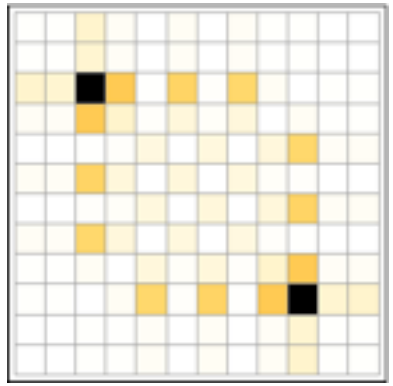
BOSONS

FERMIONS

ORDERED

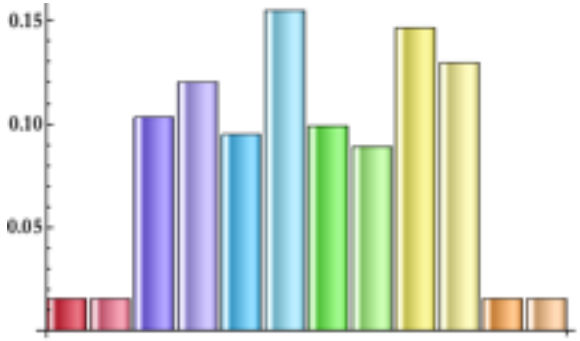


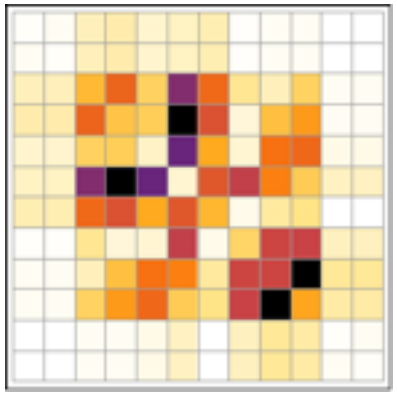


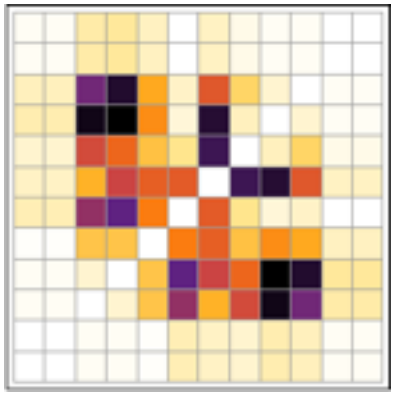


FLUCTUATING

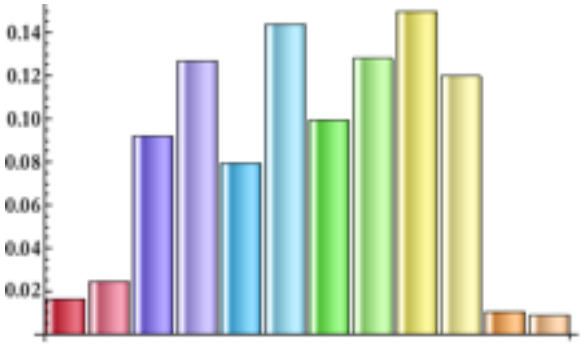
Theory

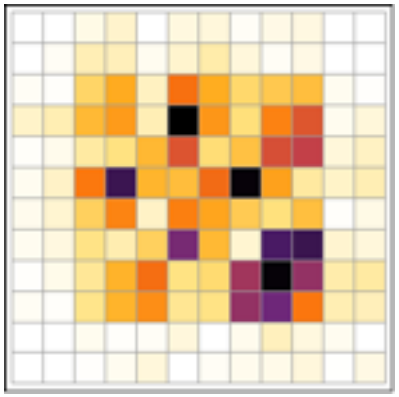


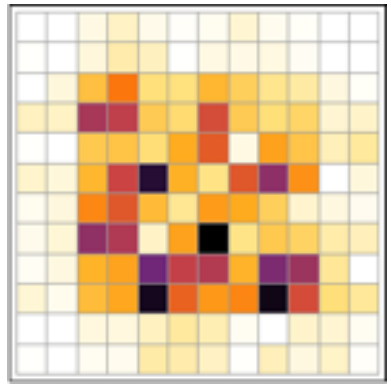


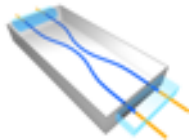


Experiment

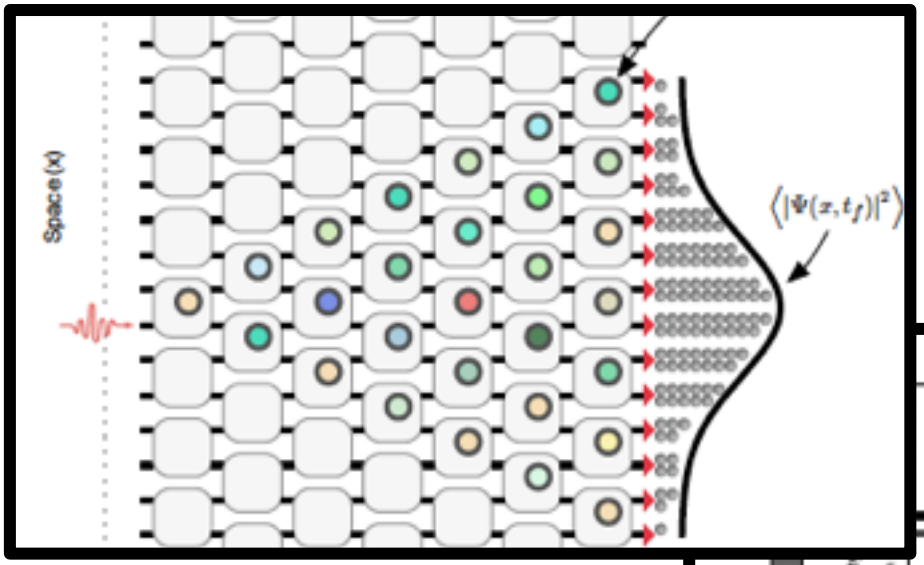


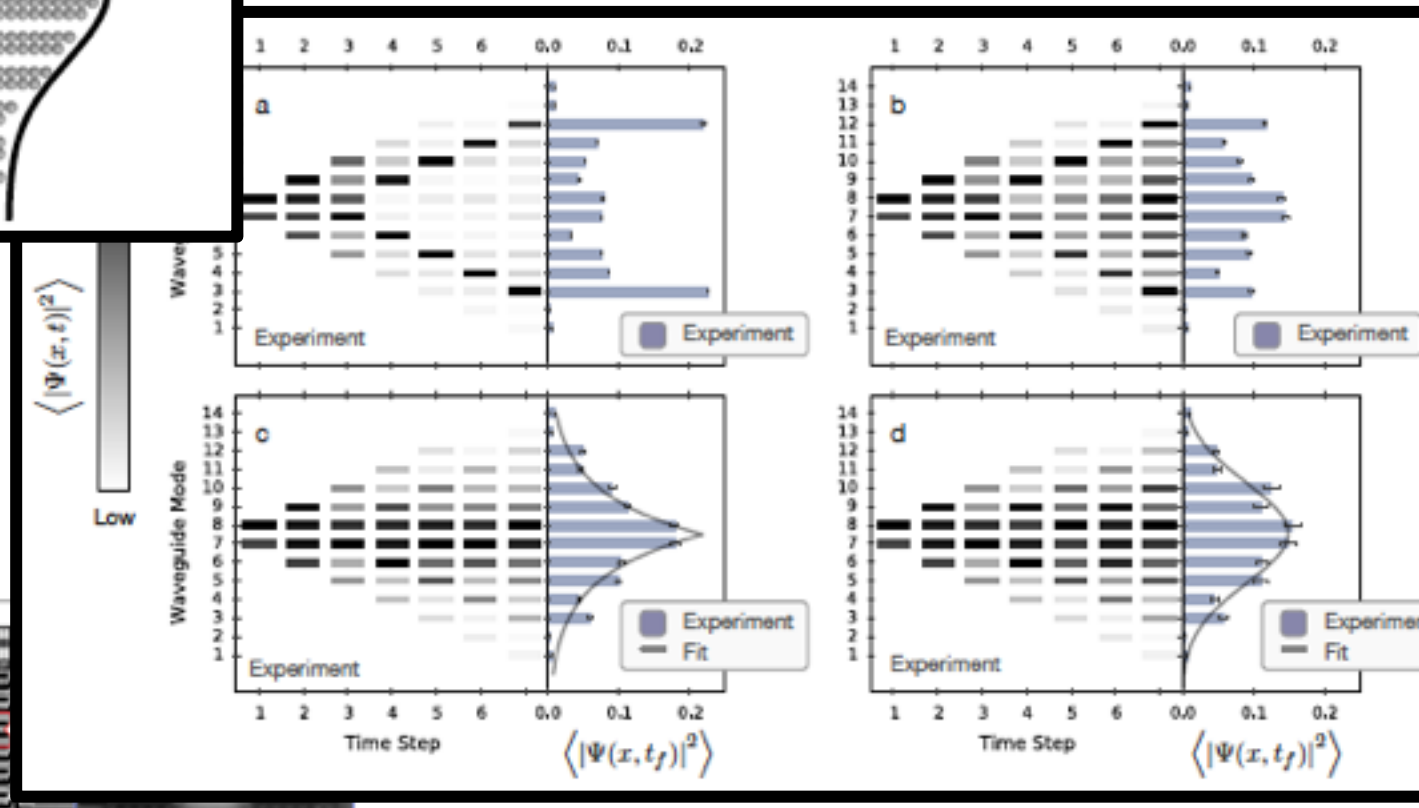




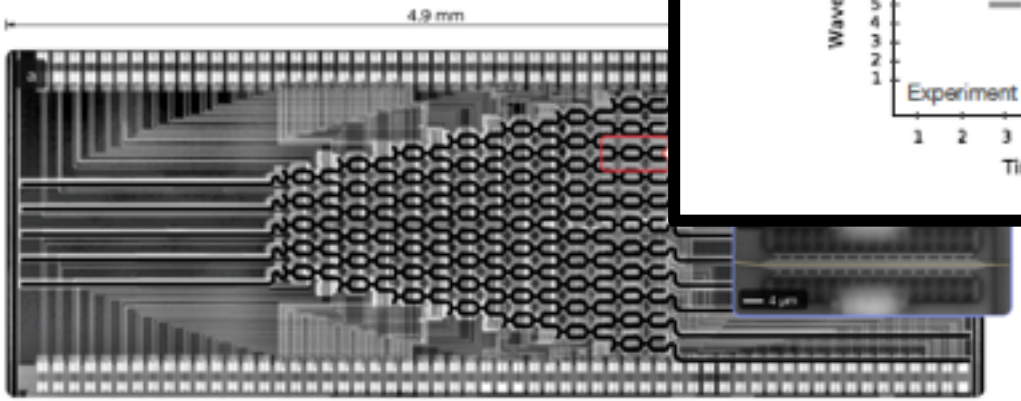


Transport simulations in a programmable nanophotonic processor





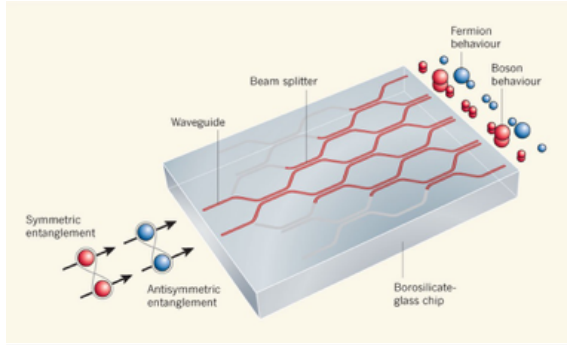
Massachusetts Institute of Technology

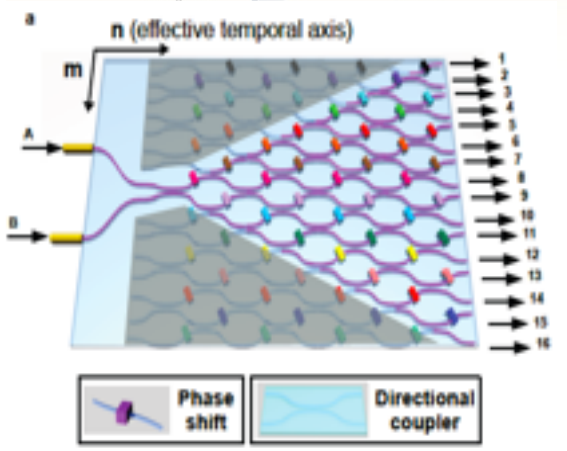


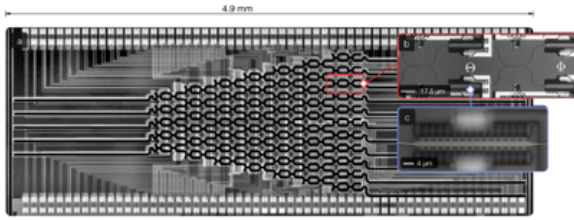
N.C. Harris, et al., quant-ph/1507.0340

State of the art: discrete quantum walk on chip

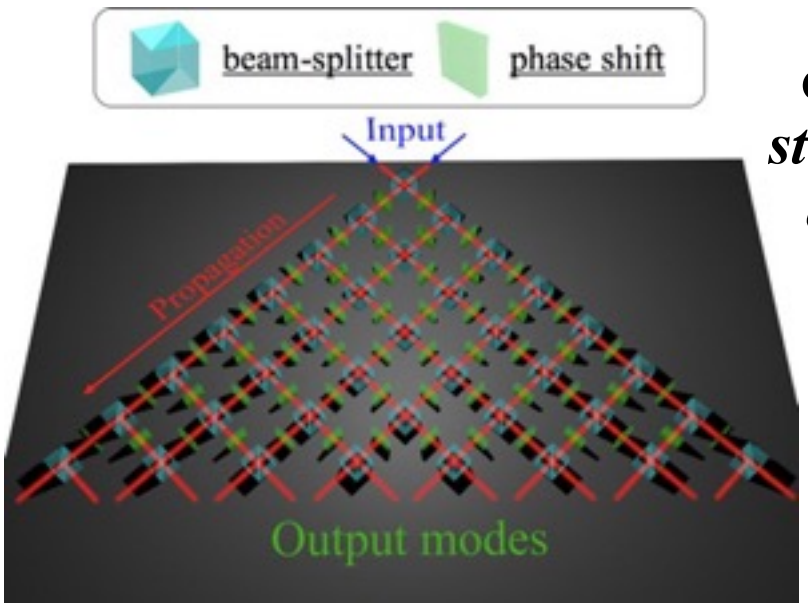
Content	Group Year	Light	Platform
Two-particle bosonic-fermionic quantum walk via integrated photonics	Roma, Milano 2012	2 entangled photons	Laser written circuit
Anderson localization of entangled photons in an integrated quantum walk	Roma, Milano, Pisa 2013	2 entangled photons	Laser written circuit
On the experimental verification of quantum complexity of linear optics	Bristol 2014	3 photons	Silica on Silicon
Bosonic transport simulations in a large-scale programmable nanophotonic processor	MIT 2015	attenuated coherent light	Silicon on insulator



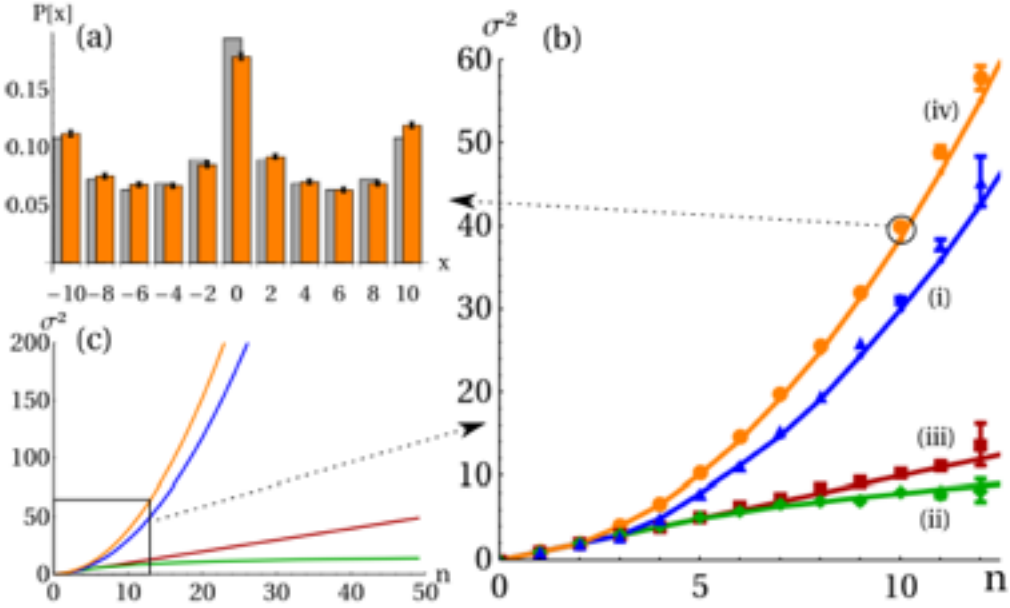




Discrete quantum walks



Discrete coupling: ***stroboscopic evolution***



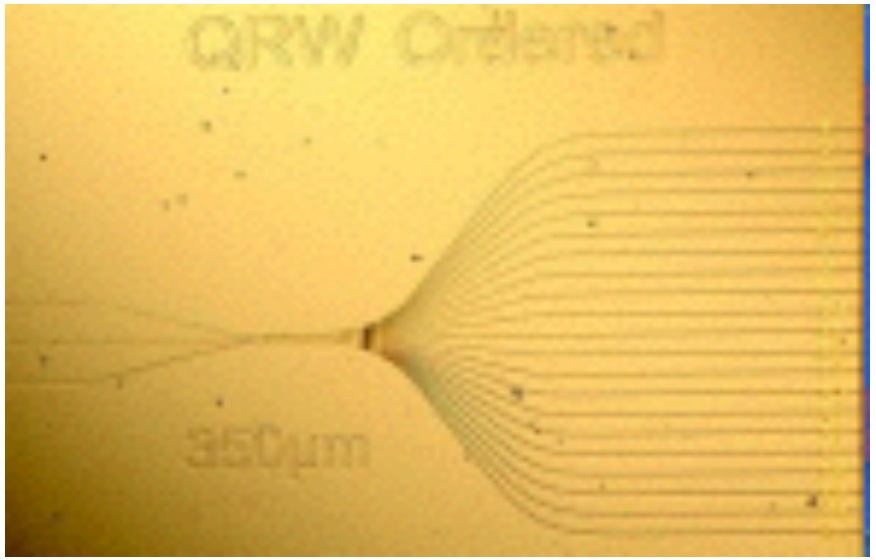
Continuous quantum walks

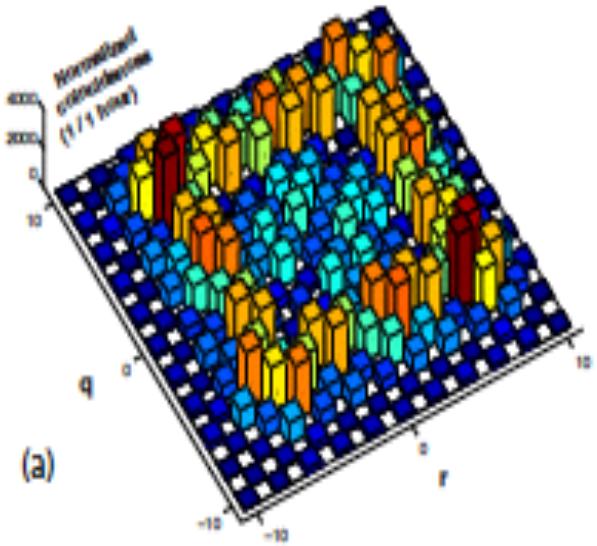
Continuous coupling

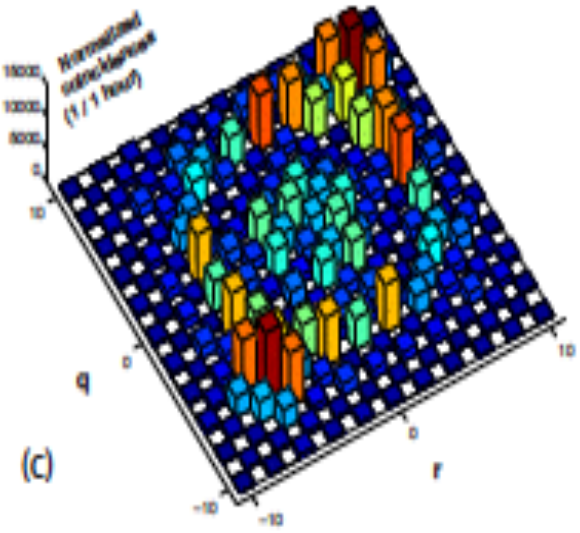
Photons propagating through the coupled waveguide array are modelled assuming nearest neighbour interaction with the Hamiltonian for coupled oscillators

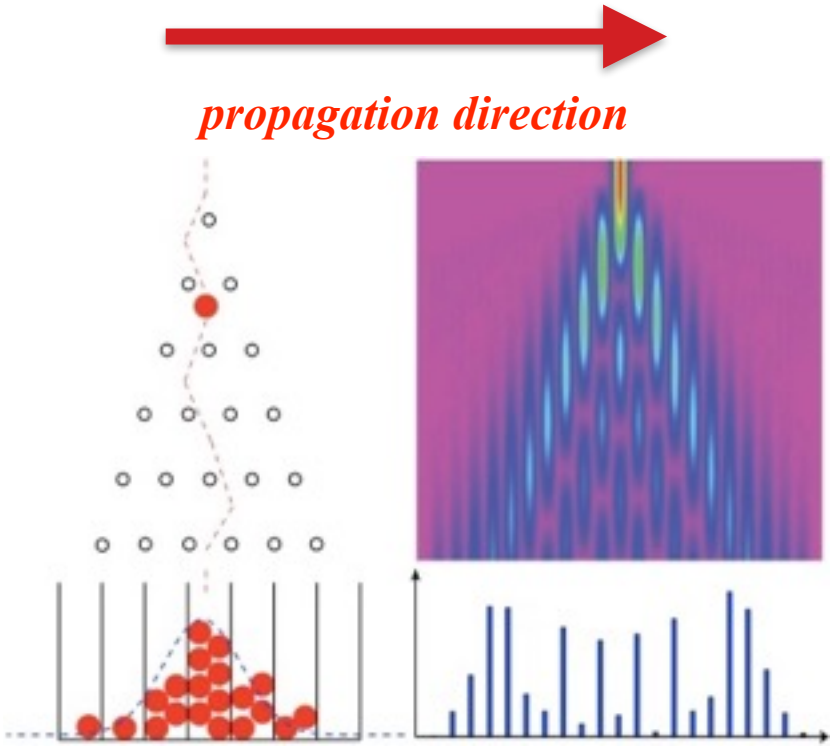
$$\hat{H} = \sum_{j=1}^{N} \left[\beta_j a_j^\dagger a_j + C_{j,j-1} a_{j-1}^\dagger a_j + C_{j,j+1} a_{j+1}^\dagger a_j \right]$$

First continuous quantum walk









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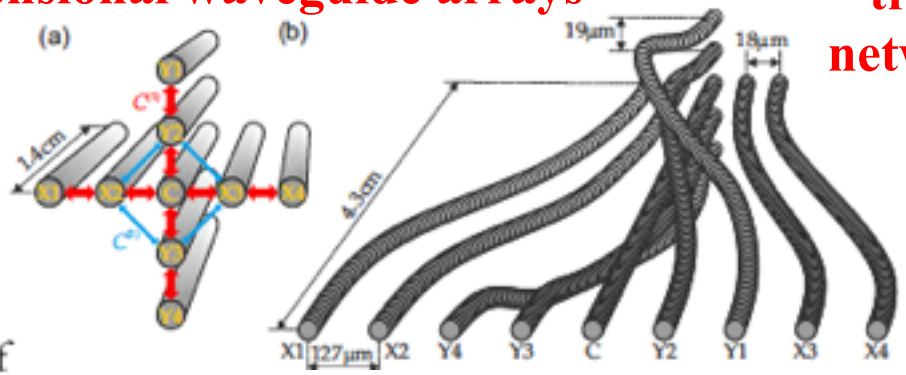
A. Peruzzo et al. Science (2010)
Continuous QW of 2 correlated photons

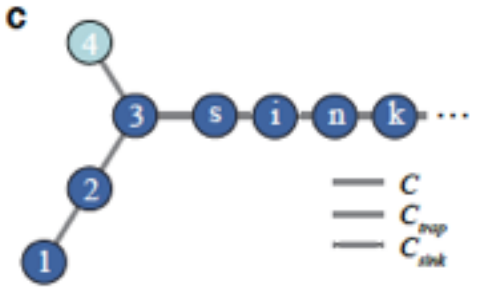
Continuous quantum walks in 2D structure

"Quantum walks of correlated photon pairs in two-dimensional waveguide arrays"



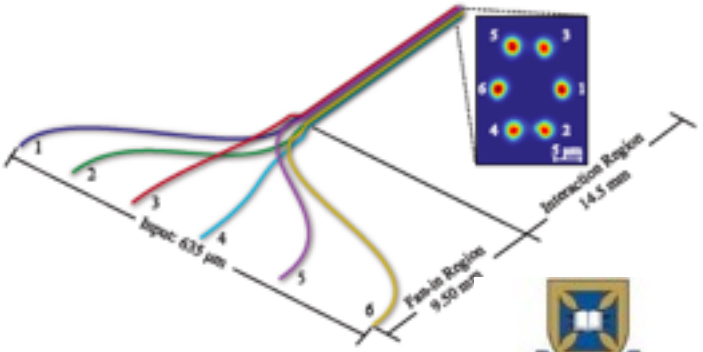
Phys. Rev. Lett. 112, 143604 (2014)

"Enhancing quantum transport in a photonic network using controllable decoherence"



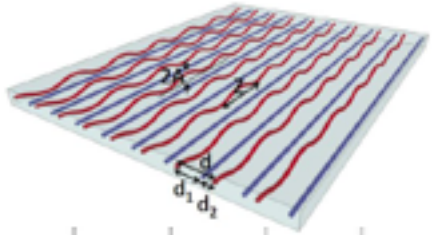
arXiv:1504.06152

"Two-photon quantum walks in an elliptical direct-write waveguide array"

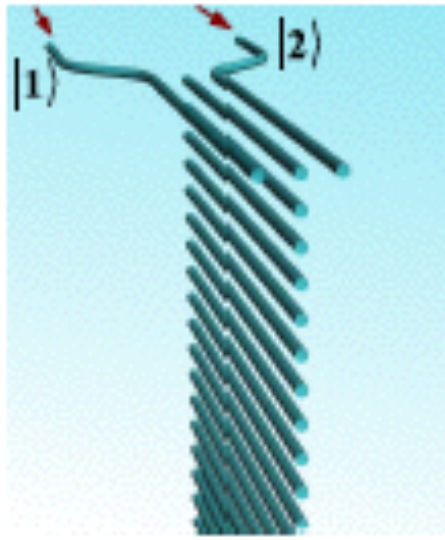


New J. Phys. 13 (2011)

"Particle Statistics Affects Quantum Decay and Fano Interference"

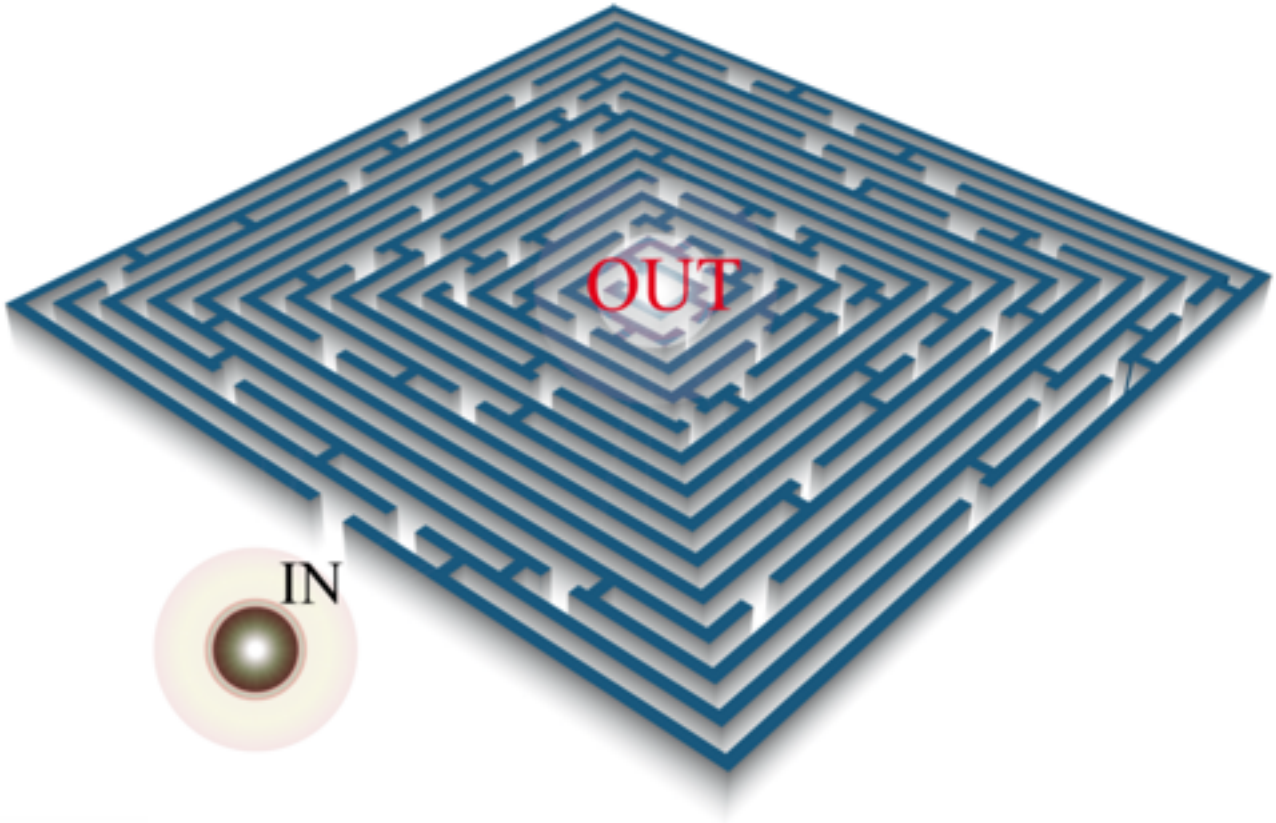


arXiv:1408.2191



Phys. Rev. Lett. 114, 090201 (2015).

Fast Escape from Quantum Mazes in Integrated Photonics



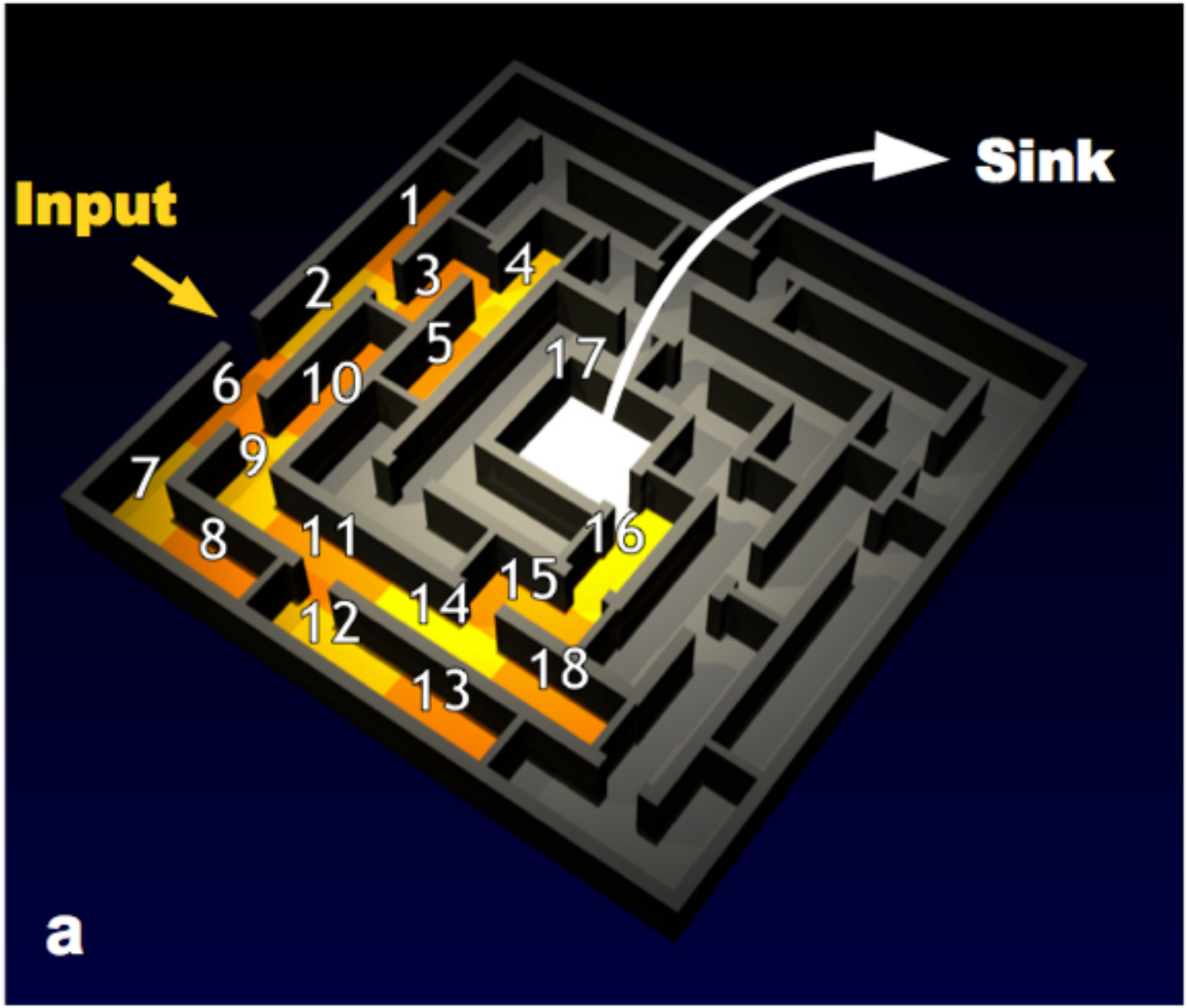
SAPIENZA
UNIVERSITÀ DI ROMA

INO-CNR
ISTITUTO
NAZIONALE DI
OTTICA

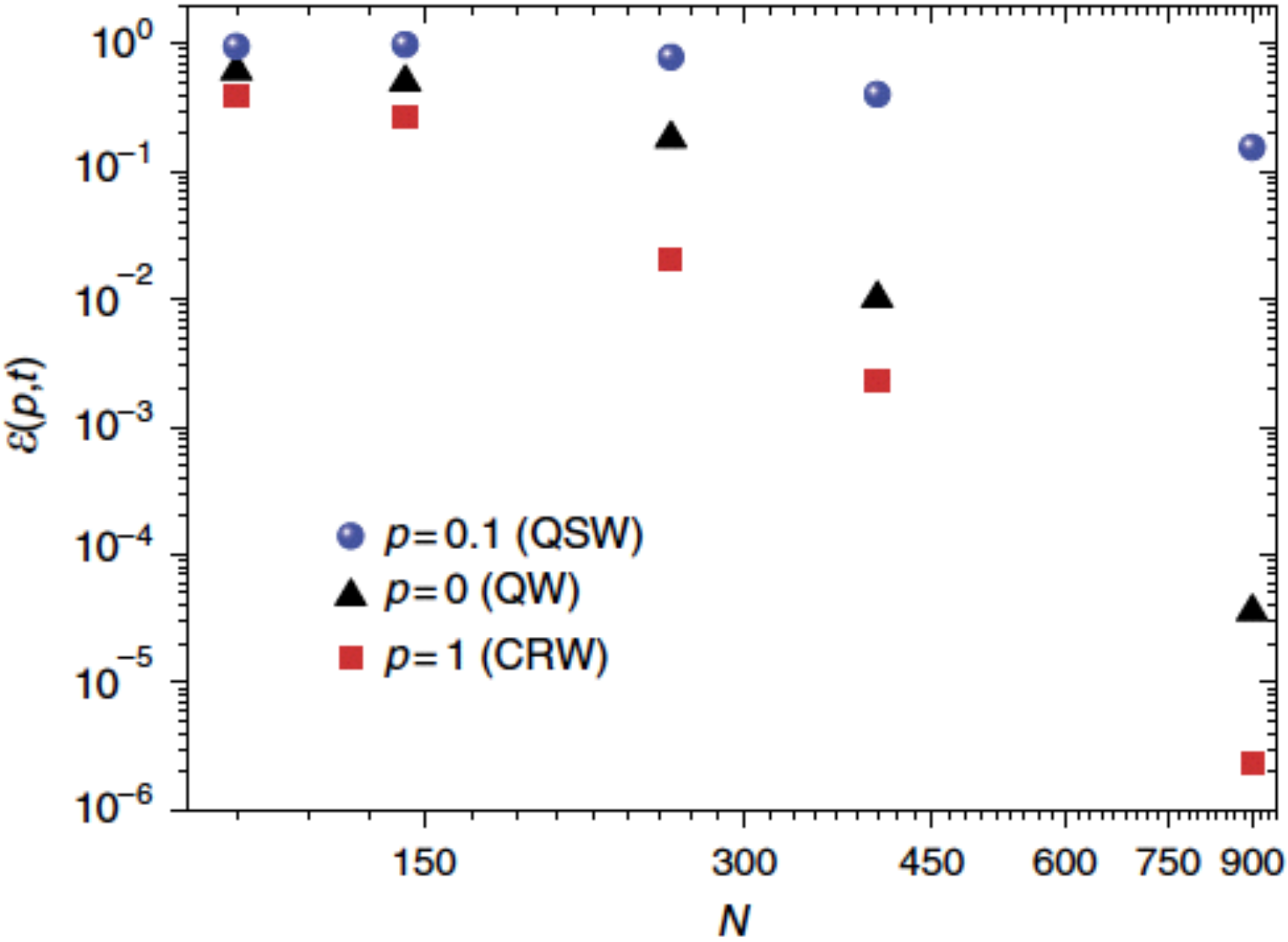
GOAL: to demonstrate how a quantum walker can efficiently reach the output of a maze by partially suppressing the presence of interference.

F. Caruso, A. Crespi, A. G. Ciriolo, F. Sciarrino, R. Osellame,
Fast escape of a quantum walker from an integrated photonic maze,
Nature Communications 7, 11682 (2016).

Fast Escape from Quantum Mazes in Integrated Photonics



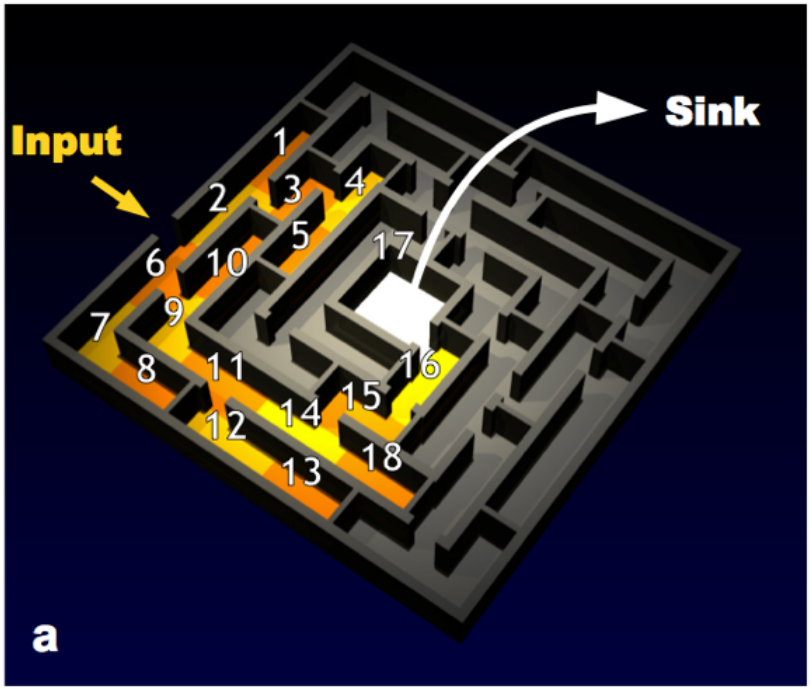
Fast Escape from Quantum Mazes in Integrated Photonics

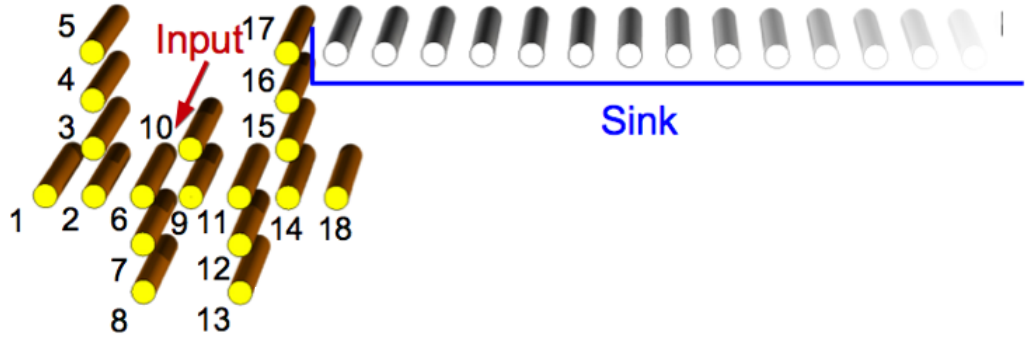


N number of nodes in the maze

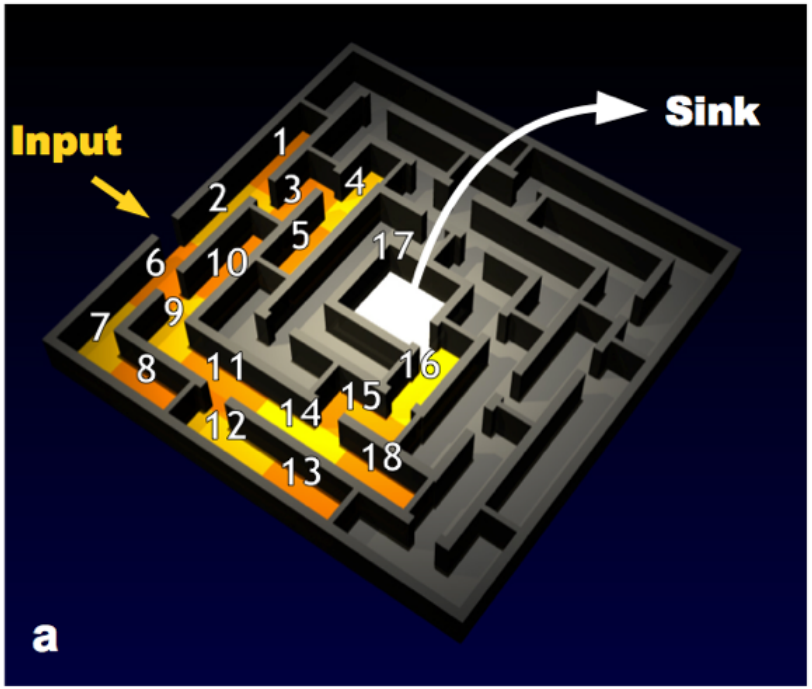
Transport efficiency for different sizes. Transfer efficiency *E(p,t)* versus the size *N* of the maze, for a time scale *t* linearly increasing with *N*. For a maze with *N*=900 nodes, the optimal mixing $p_C=0.1$ provides a transfer efficiency that is about five orders of magnitude larger than the perfectly coherent (quantum, that is, *p=0*) and fully noisy (classical, that is, *p=1*) regimes.

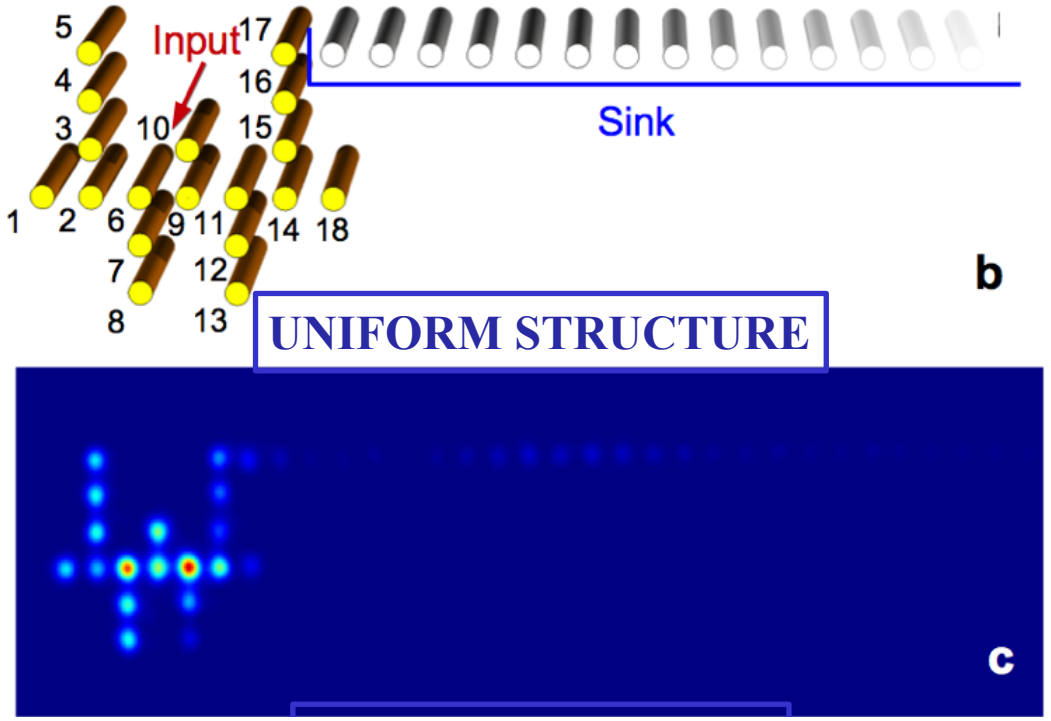
Fast Escape from Quantum Mazes in Integrated Photonics



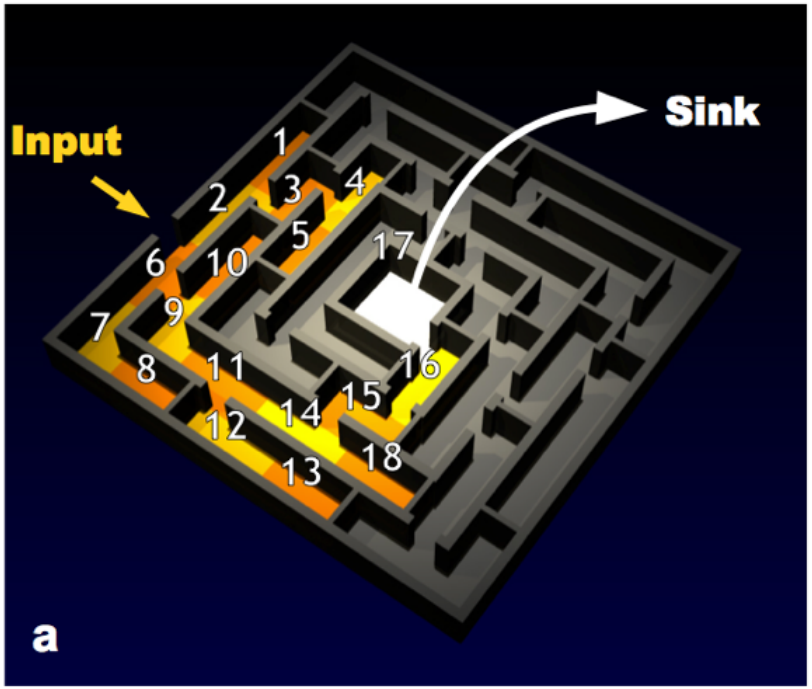


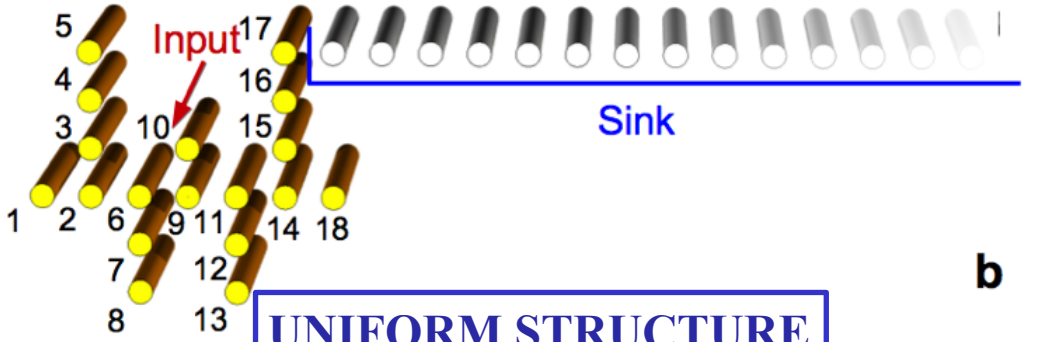
Fast Escape from Quantum Mazes in Integrated Photonics





Fast Escape from Quantum Mazes in Integrated Photonics

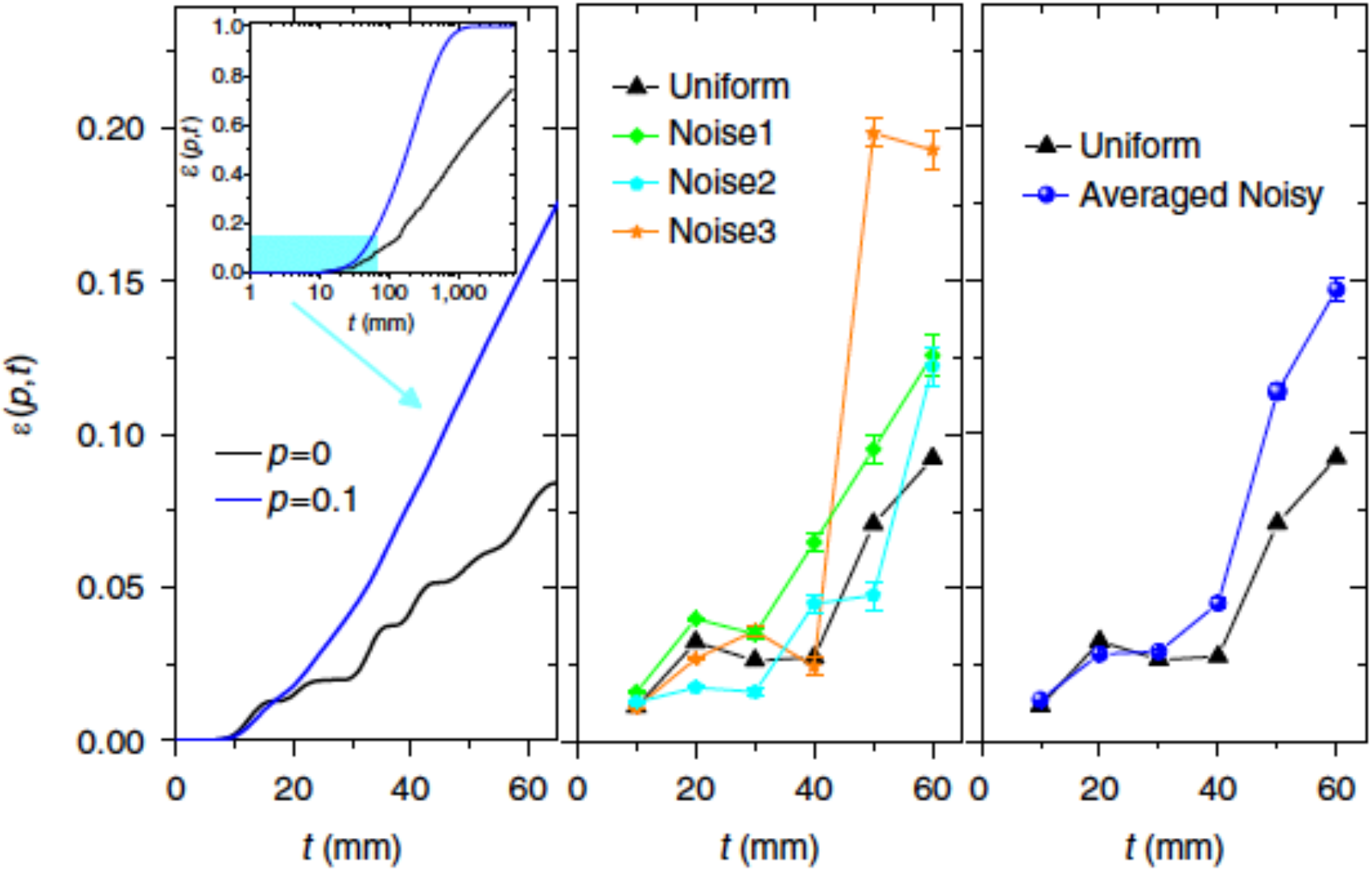




UNIFORM STRUCTURE

NOISY STRUCTURE

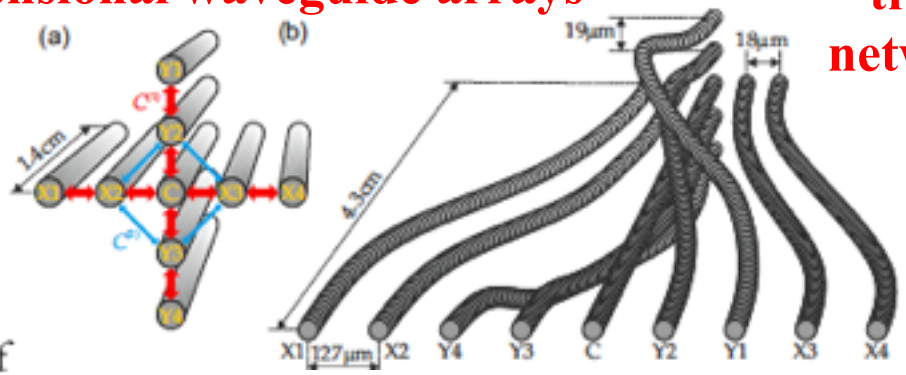
Fast Escape from Quantum Mazes in Integrated Photonics



Role of noise in the transfer efficiency time evolution.

Continuous quantum walks in 2D structure

"Quantum walks of correlated photon pairs in two-dimensional waveguide arrays"



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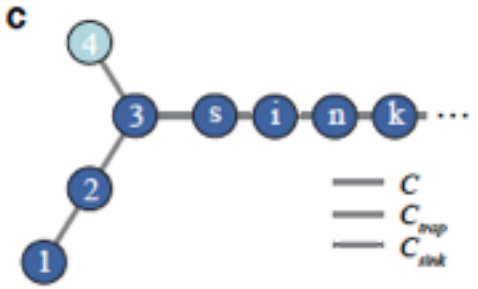

arXiv:1504.06152

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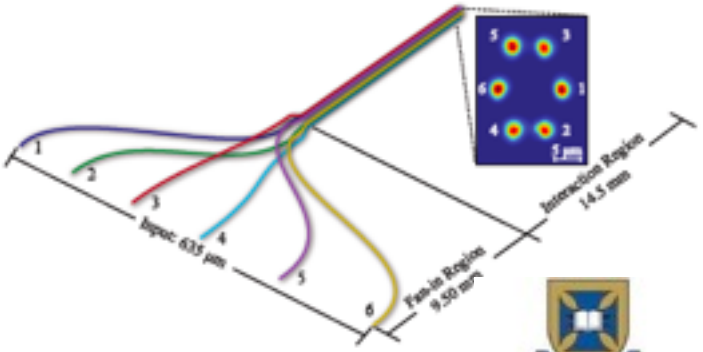

New J. Phys. 13 (2011)

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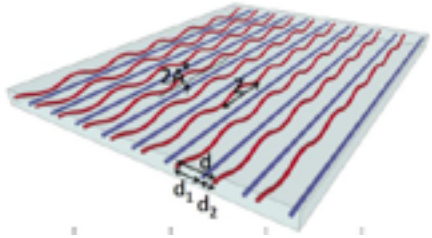
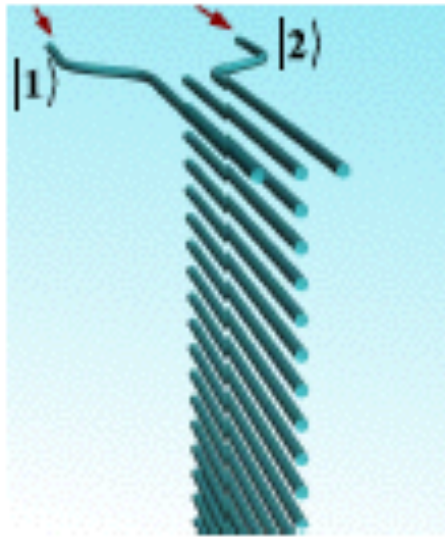
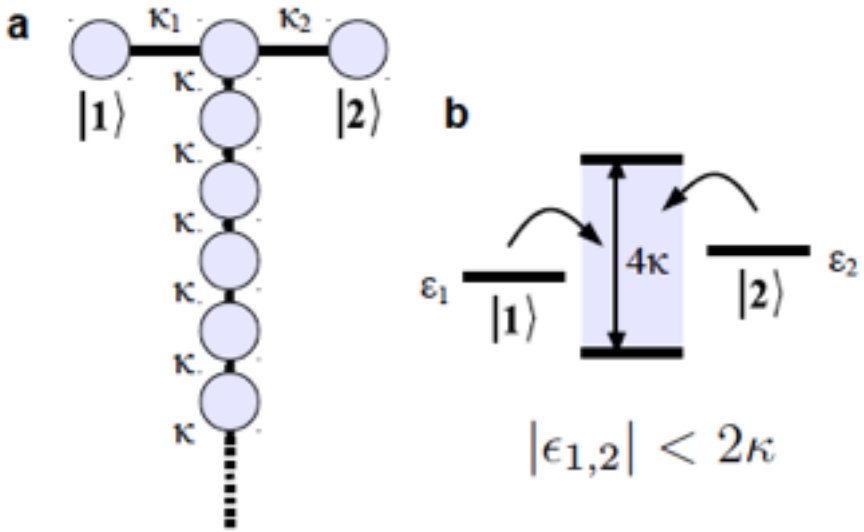


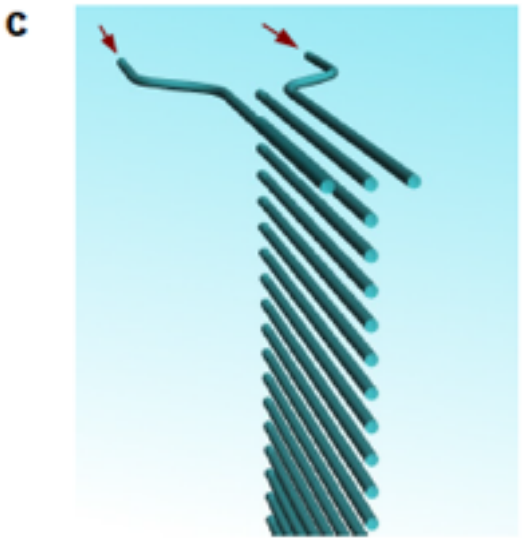
arXiv:1408.2191



Phys. Rev. Lett. 114, 090201 (2015).

Fano resonances: effects of particle statistics





Quantum decay of an excited state to a continuum is a general problem in fundamental physics.

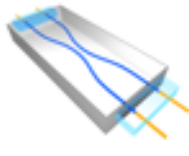
When multiple paths are possible for this decay, quantum interference may produce non-trivial phenomena such as Fano resonances and bound states with energy in the continuum.

Simulation with photonics lattice

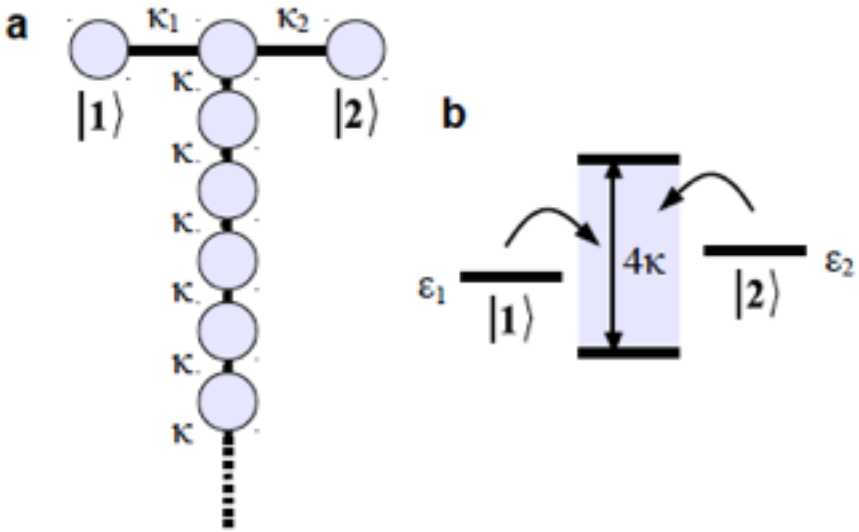
Single particle experiments:

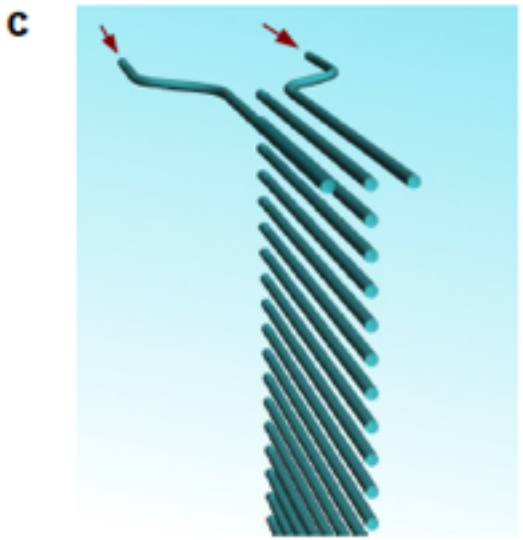
Y. Plotnik, O. Peleg, F. Dreisow, M. Heinrich, S. Nolte, A. Szameit, and M. Segev, *Phys. Rev. Lett.* **107**, 183901 (2011).

S. Weimann, Y. Xu, R. Keil, A. E. Mirosh- nichenko, S. Nolte, A. A. Sukhorukov, A. Szameit, and Y. S. Kivshar, *Phys. Rev. Lett.* **111**, 240403 (2013).



Fano resonances: effects of particle statistics

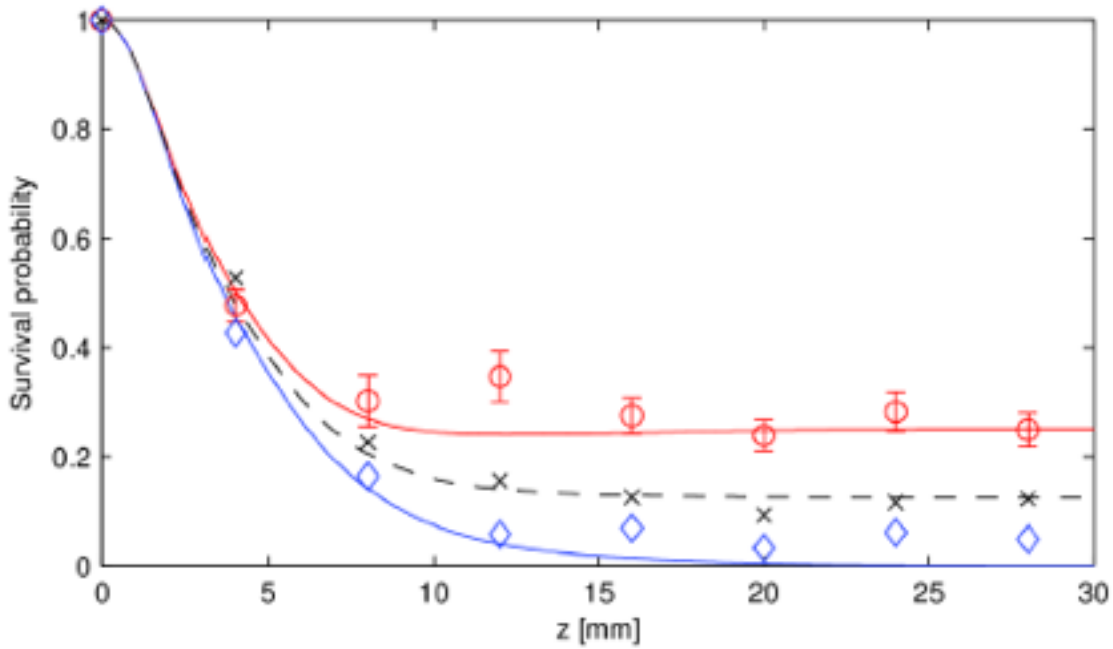




We experimentally investigate the multi-particle case, by studying the propagation of two-photon states in engineered photonic lattices.

The particle statistics, either bosonic or fermionic, of the particles strongly affects the decay process.

The Fano resonance, when two discrete levels are coupled to a continuum, is suppressed in the fermionic case.



A. Crespi, R. Osellame, S. Longhi, A. Ciamei, L. Sansoni, P. Mataloni, F. Sciarrino (in preparation)

State of the art: continuous quantum walk on chip

Content	Group/Year	Light	Platform
Quantum walks of correlated particles	Bristol, Rehovot 2010	2 photons	SiON, Lithography
Two-photon quantum walks in an elliptical direct-write waveguide array	Queensland, Macquarie 2011	2 photons	Laser written circuit
Observing fermionic statistics with photons in arbitrary processes	Bristol 2013	2 entangled photons	SiON, Lithography
Three-photon bosonic coalescence in an integrated tritter	Milano, Roma 2013	3 photons	Laser written circuit
Particle Statistics Affects Quantum Decay and Fano Interference	Milano, Roma 2015	2 entangled photons	Laser written circuit
Quantum walks of correlated photon pairs in two-dimensional waveguide arrays	Bristol, Jena 2014	2 photons	Laser written circuit
Enhancing quantum transport in a photonic network using controllable decoherence	Queensland, Jena 2015	2 photons	Laser written circuit
Realization of Quantum Walks with Negligible Decoherence in Waveguide Lattices	Rehovot 2008	coherent light	AlGaAs, e-beam lithography
Transport and Anderson localization in disordered two-dimensional photonic lattices	Haifa 2007	coherent light	Optical induction in SBN
Photonic realization of the quantum Rabi model	Milano 2012	coherent light	Laser written circuit
Photonic Floquet topological insulators	Haifa, Jena 2013	coherent light	Laser written circuit
Experimental simulation of charge conservation violation and Majorana dynamics	Jena, Innsbruck, Singapore, 2014	coherent light	Laser written circuit
Fast Escape from Quantum Mazes in Integrated Photonics	Milano, Roma 2015	coherent light	Laser written circuit