Quantum walk with integrated photonics

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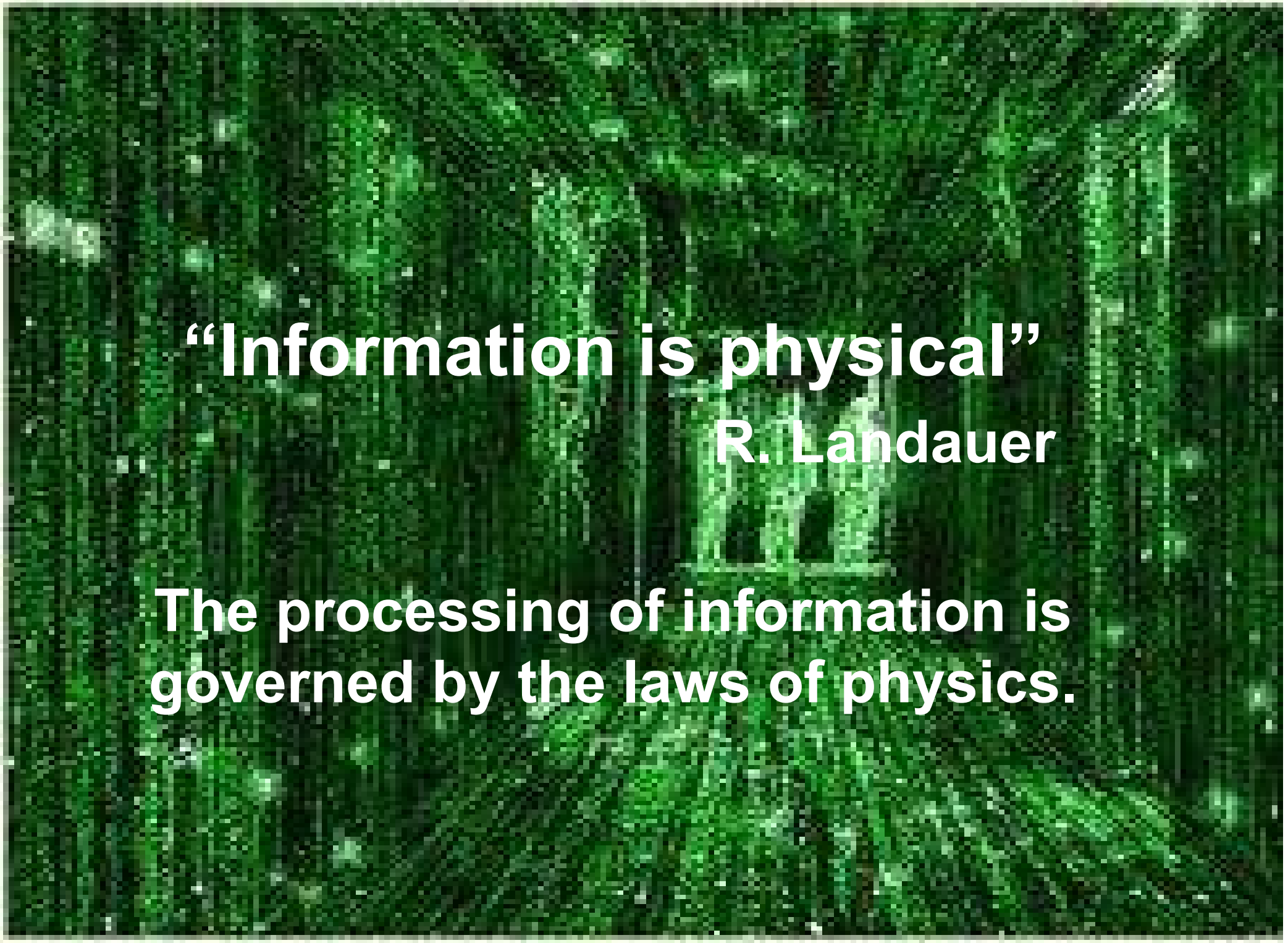


“Information is physical”

R. Landauer

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

Quantum information

Challenges: **from basic sciences**

to emerging quantum technologies

- Fundamental physics:

  Test of non-locality, quantum contextuality

  Shed light on the boundary between classical and quantum world

  Exploiting quantum parallelism

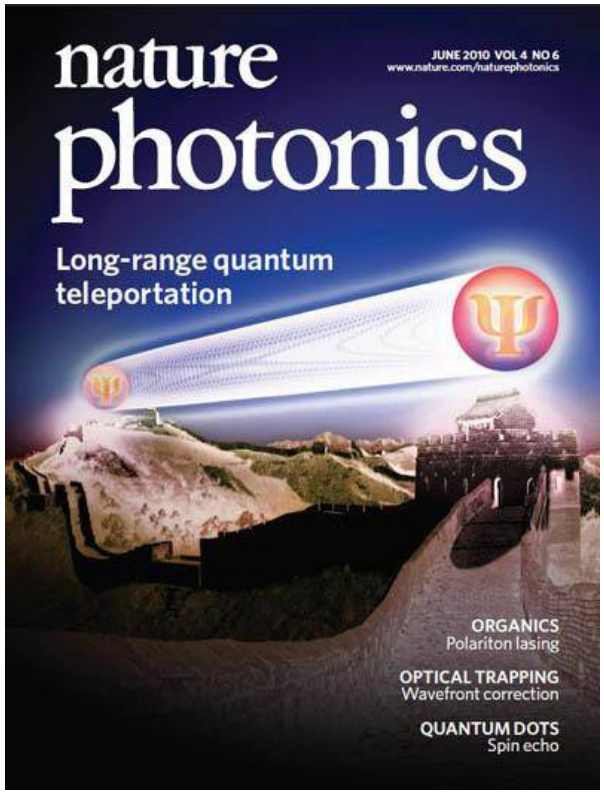
  to simulate quantum many-body systems

  - New cryptographic protocols

- Quantum sensing: imaging,metrology

- Quantum computing

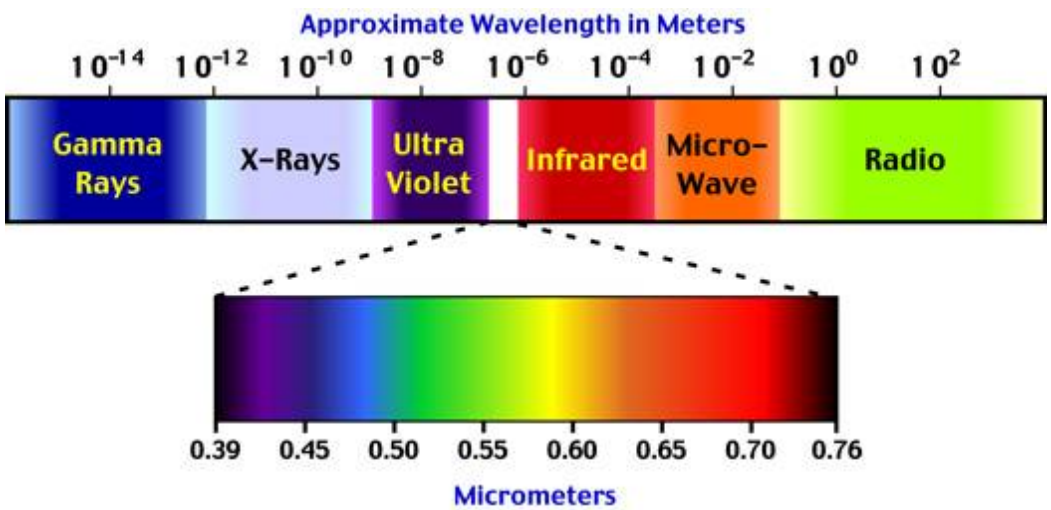
  quantum simulation

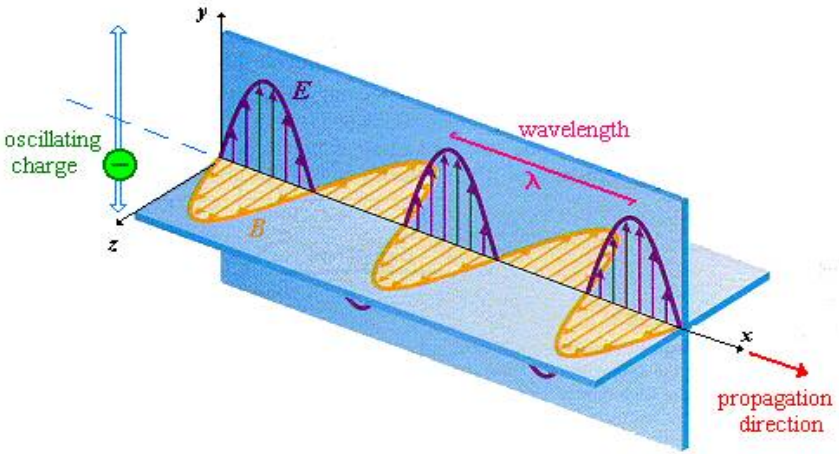


How to encode qubit with light ?

Optics for Quantum Information

Suitable hardware for quantum communication





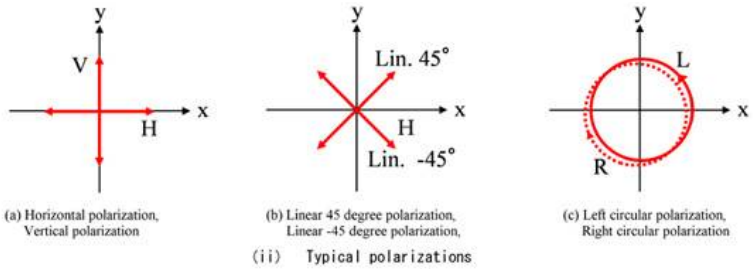
Photon: quantum of the electromagnetic field

Photoelectric effect – Einstein (1905)

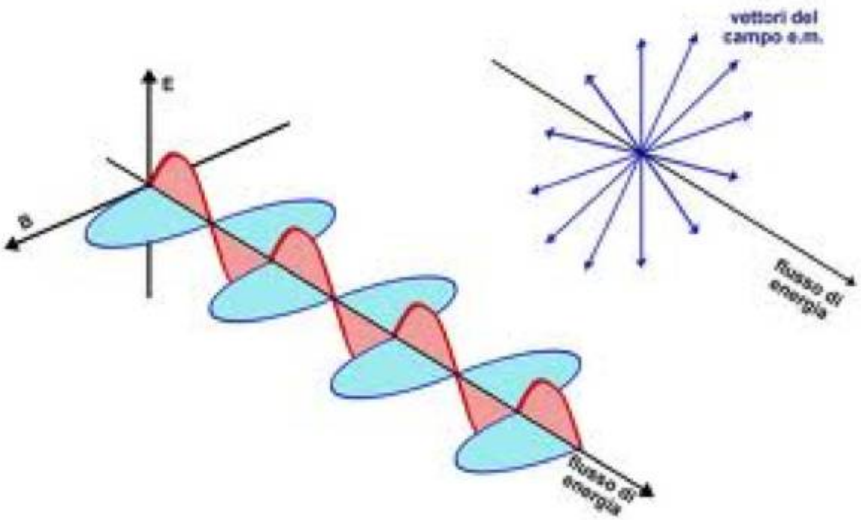
Qubit encoded into photon's degrees of freedom

Examples:

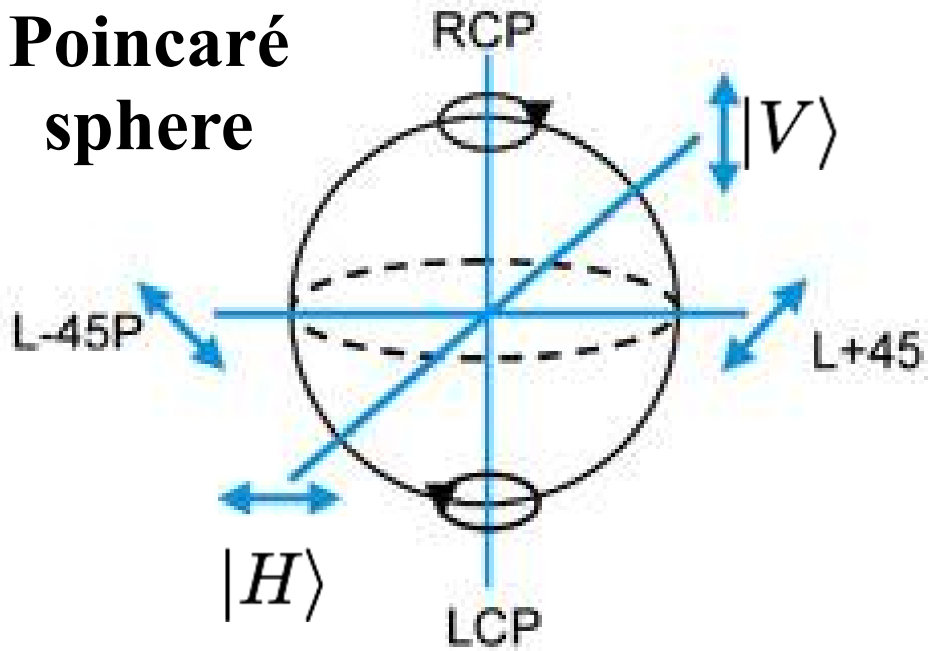
- Single photon polarization
- Spatial mode
- Time bin
- ...



Polarization of light



Poincaré sphere



Qubit

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

Polarization of a single photon

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

H: horizontal
V: vertical

Quantum Optics for Quantum Information Processing

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

  Polarization of a single photon:

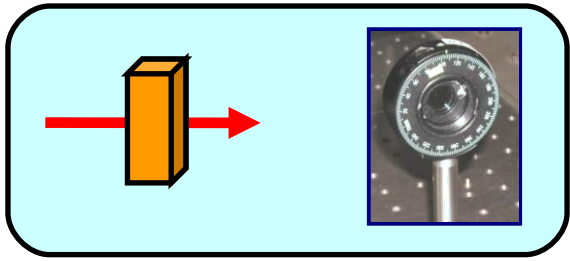
  H: horizontal polarization

  V: vertical polarization

  Mode of the electromagnetic field (k,wavelength)

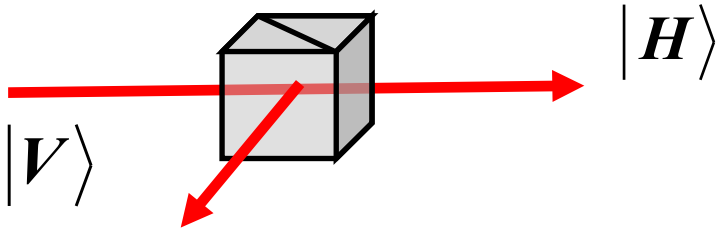
- Logic gate acting on a single qubit

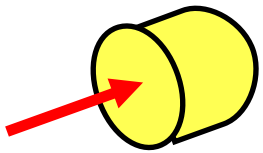
  Rotation of the polarization: waveplates

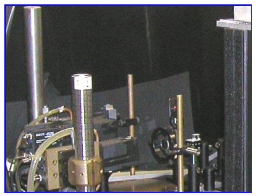


- Measurement of the qubit:

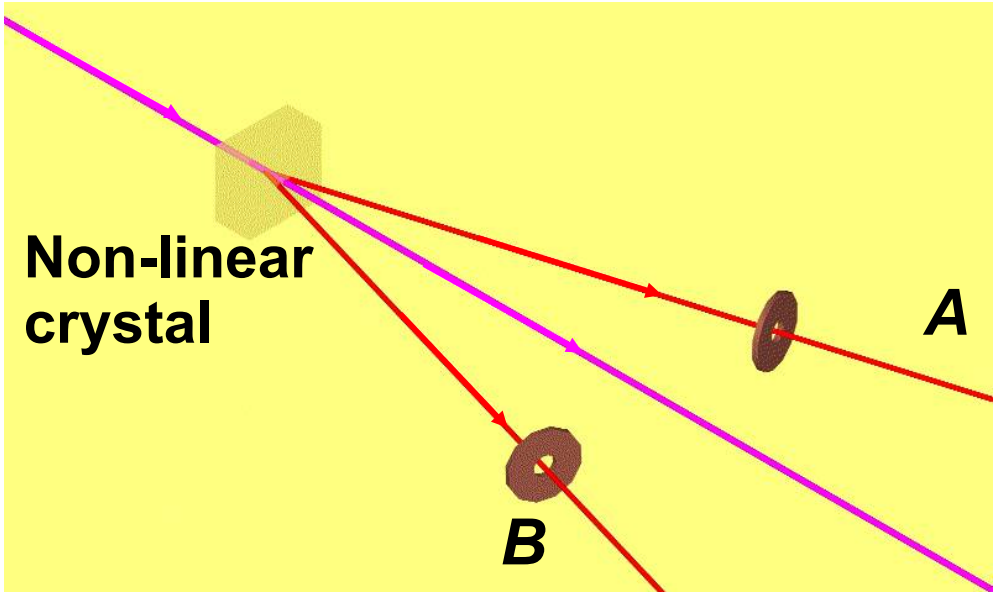
  polarizing beam splitter Single photon detectors

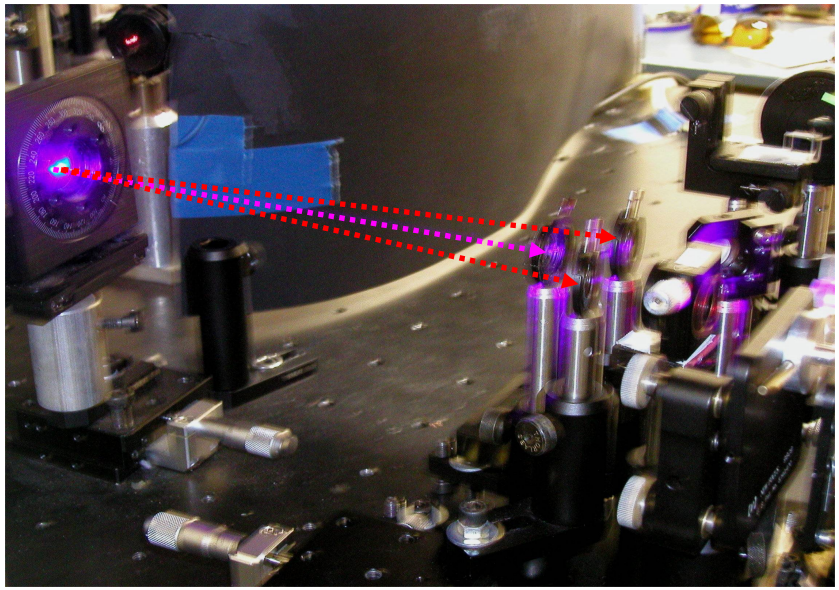


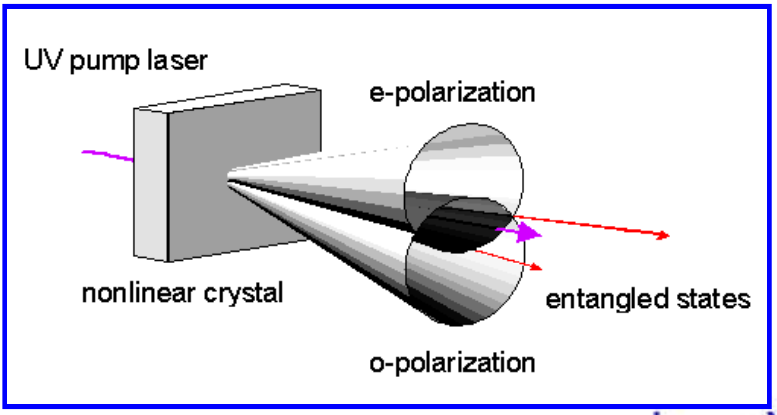




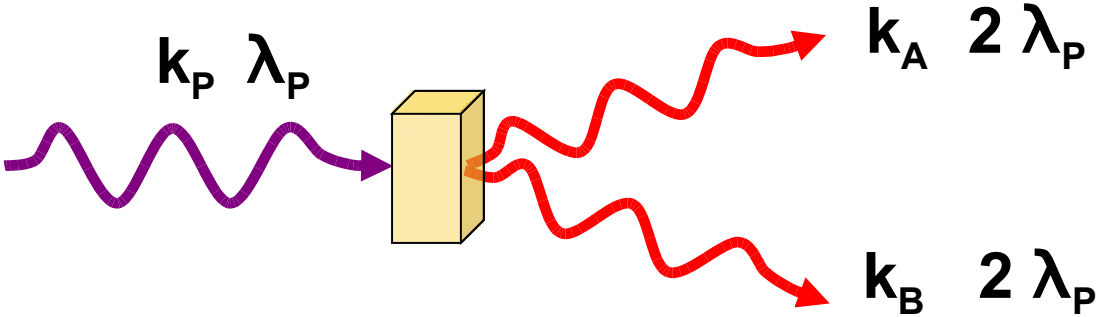
Generation of entangled states







Pumping laser

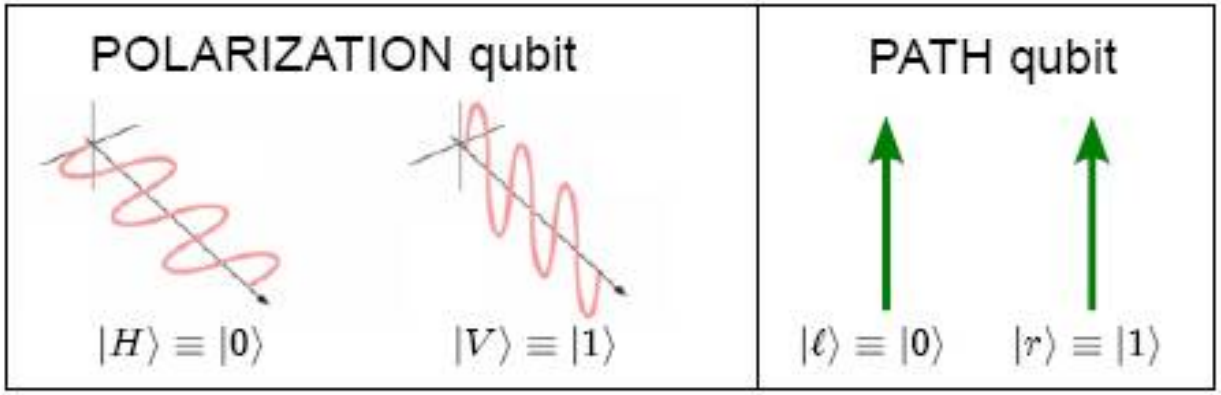


$$|\psi^-\rangle = \frac{1}{\sqrt{2}}\left(|H\rangle|V\rangle - |V\rangle|H\rangle\right)$$

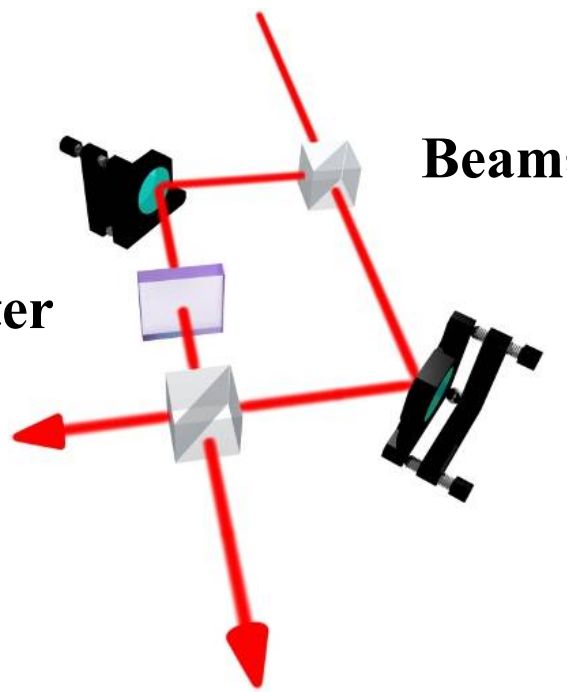
For more details: next talk by Harald Weinfurter

Implementation via path encoding

Qubit realization with photons



Manipulation: beamsplitters and phase-shifters



Problem!

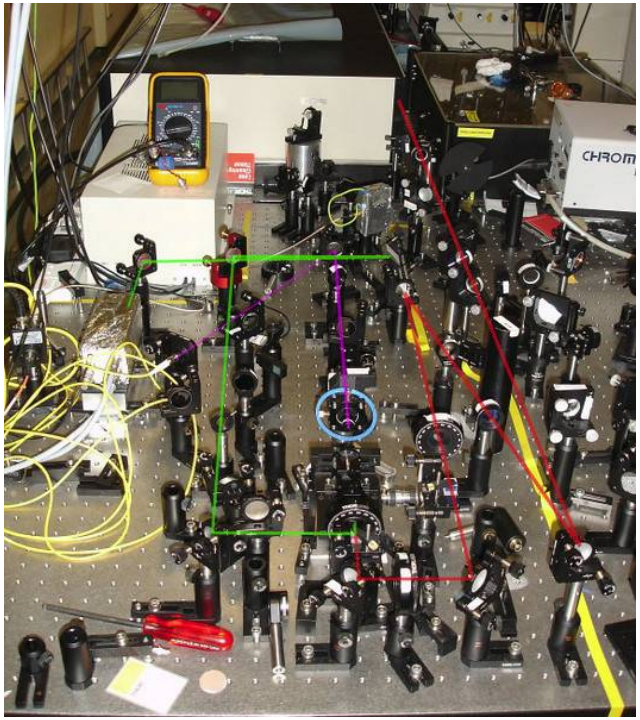
...Phase-stability of the interferometer...

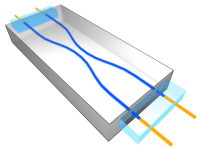
Integrated photonics: Bulk optics limitations

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

SETUP: COMPLEX OPTICAL INTERFEROMETERS

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



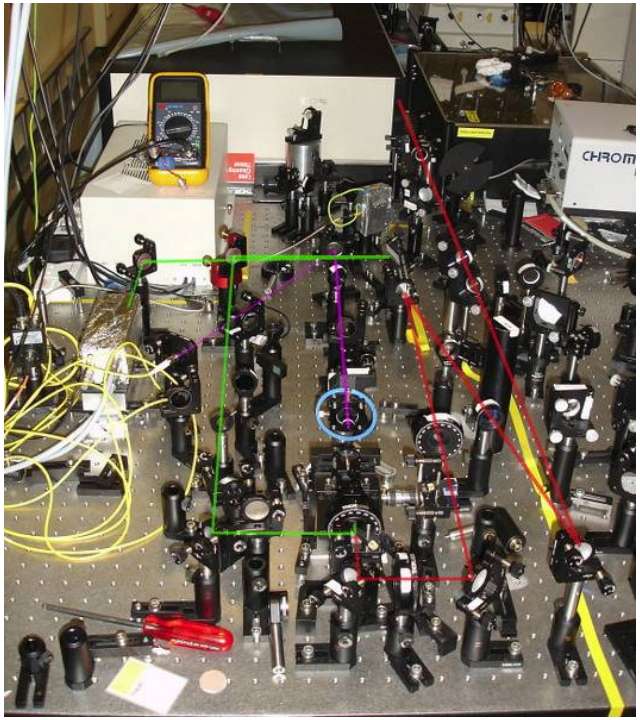


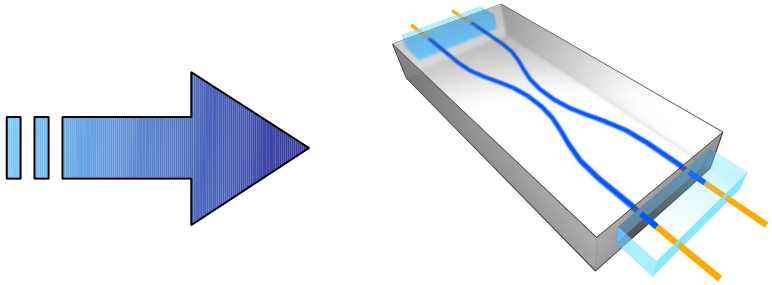
Integrated photonics: Bulk optics limitations

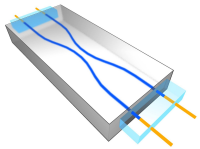
The main limitations of experiments realized with bulk optics are:

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

Possible solutions? Integrated waveguide technology

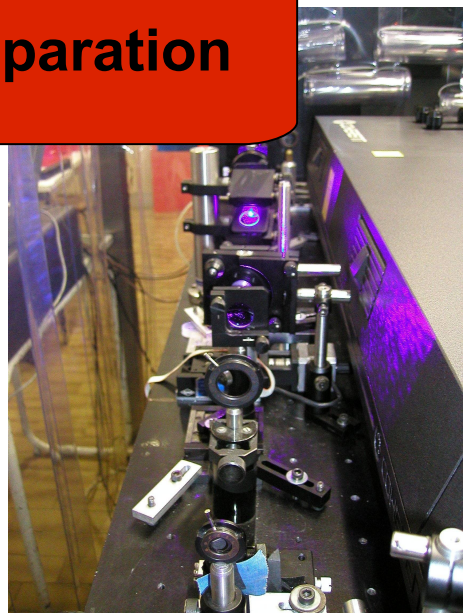




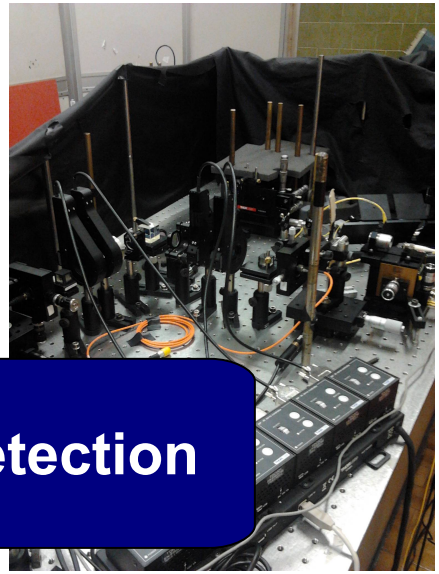


Integrated quantum photonics

Preparation



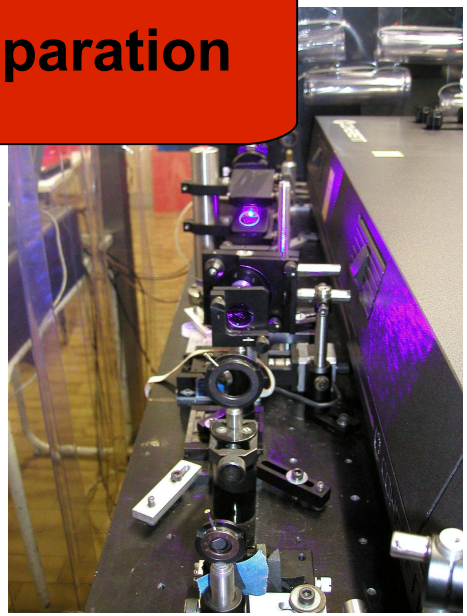
Manipulation



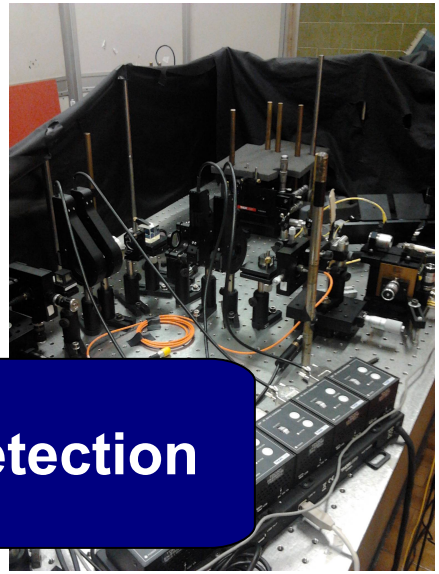
Detection

Integrated quantum photonics

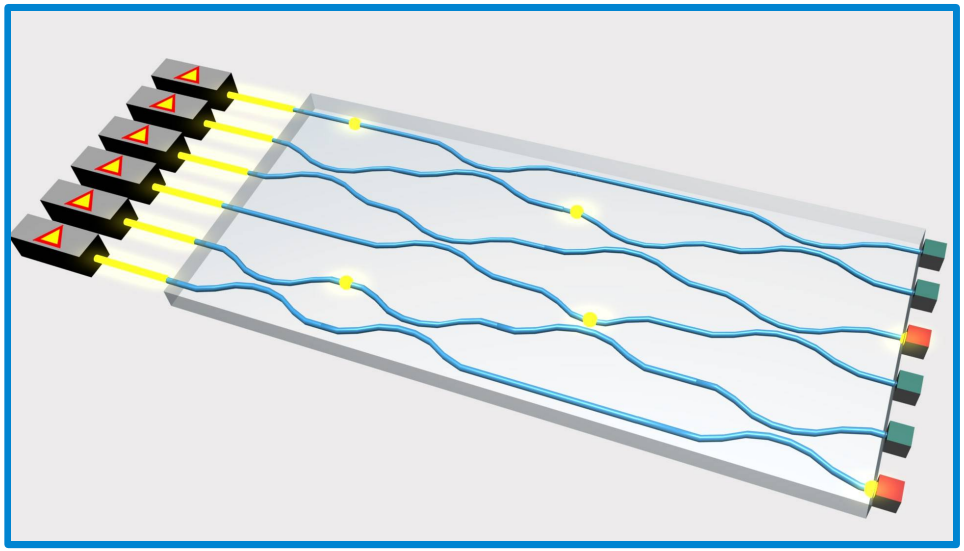
Preparation



Manipulation

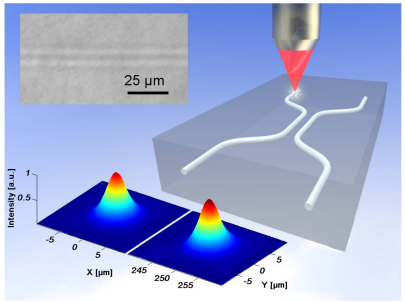


Detection

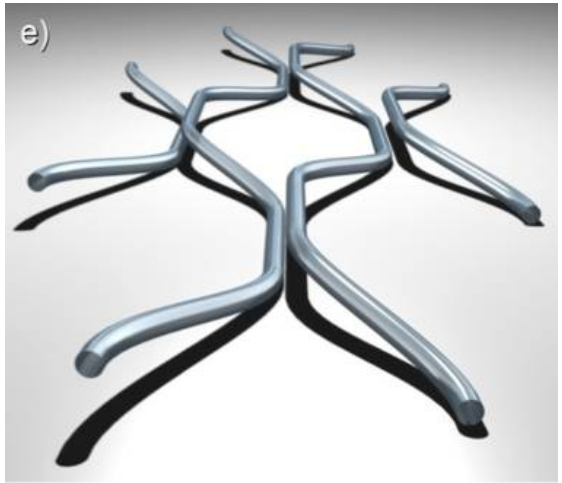


Summary

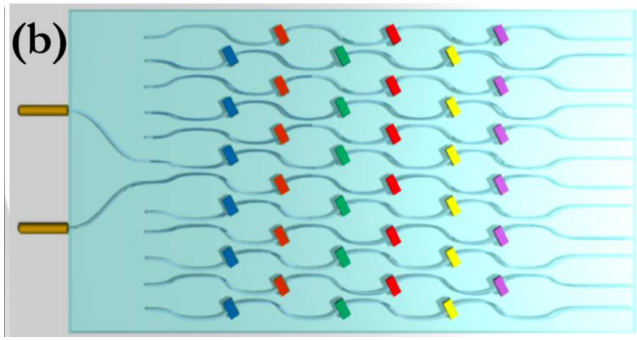
I) Laser writing techniques
First step: beamsplitters



II) Quantum walk



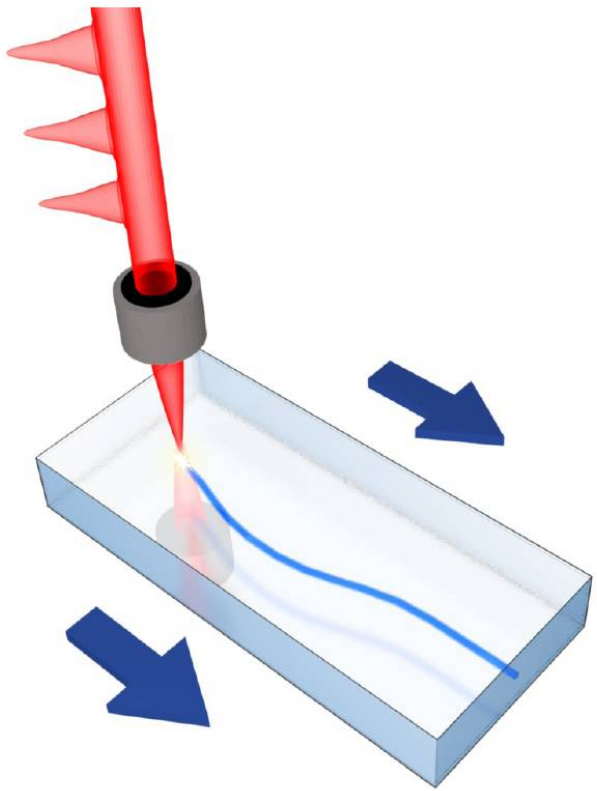
III) Simulation of disordered systems



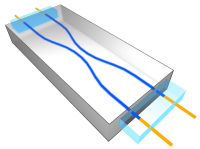
Femtosecond laser writing

What about polarization encoding?

Laser writing technique for devices able to transmit polarization qubits



- Femtosecond pulse tightly focused in a glass
- Combination of multiphoton absorption and avalanche ionization induces *permanent and localized refractive index increase* in transparent materials
- Waveguides are fabricated in the bulk of the substrate by translation of the sample at constant velocity with respect to the laser beam, along the desired path.



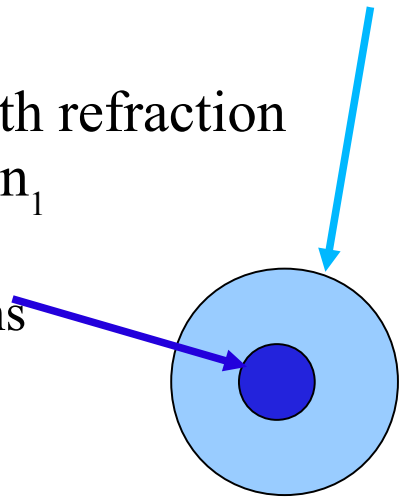
How to guide light on a chip ?

Fiber optics: guiding of light

Total internal reflection:

- *Cladding* with refraction index n_1
- *Core* with refraction index $n_2 > n_1$

Diameter few microns



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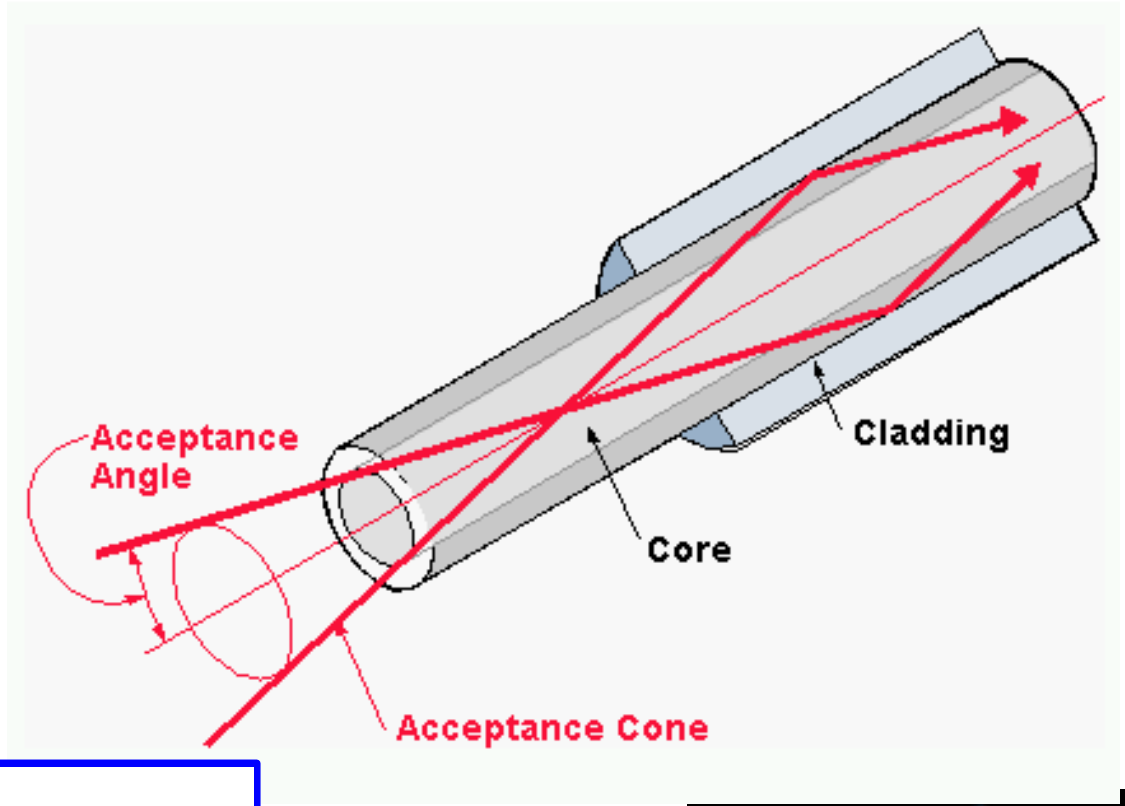

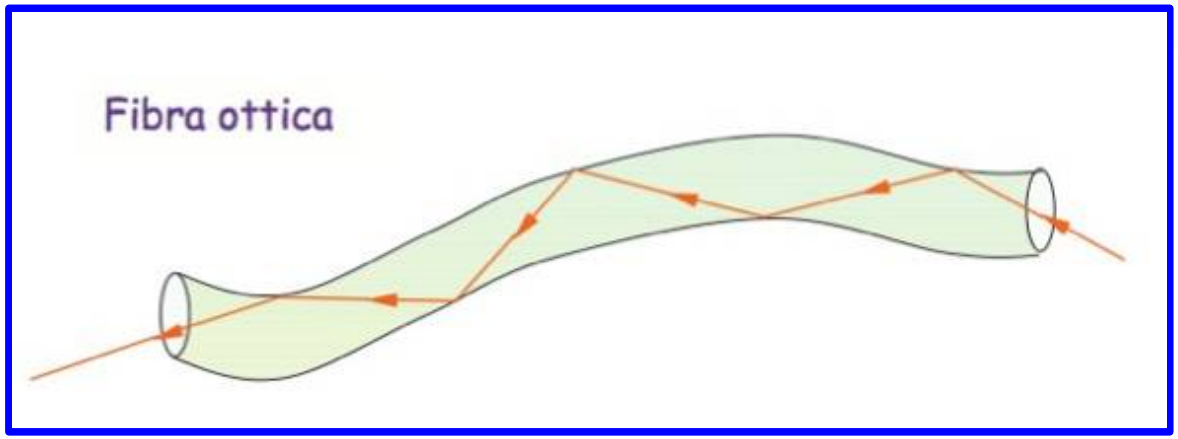

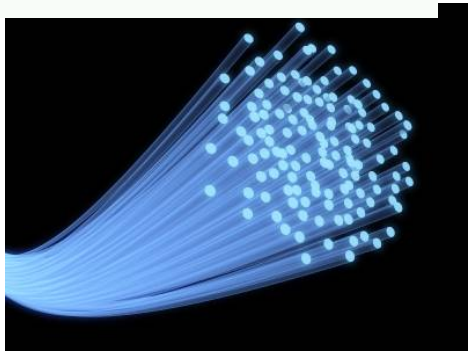

Integrated photonic quantum circuits

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

A. Crespi
R. Ramponi
R. Osellame

L. Sansoni
N. Spagnolo
C. Vitelli
P. Mataloni
F. Sciarrino

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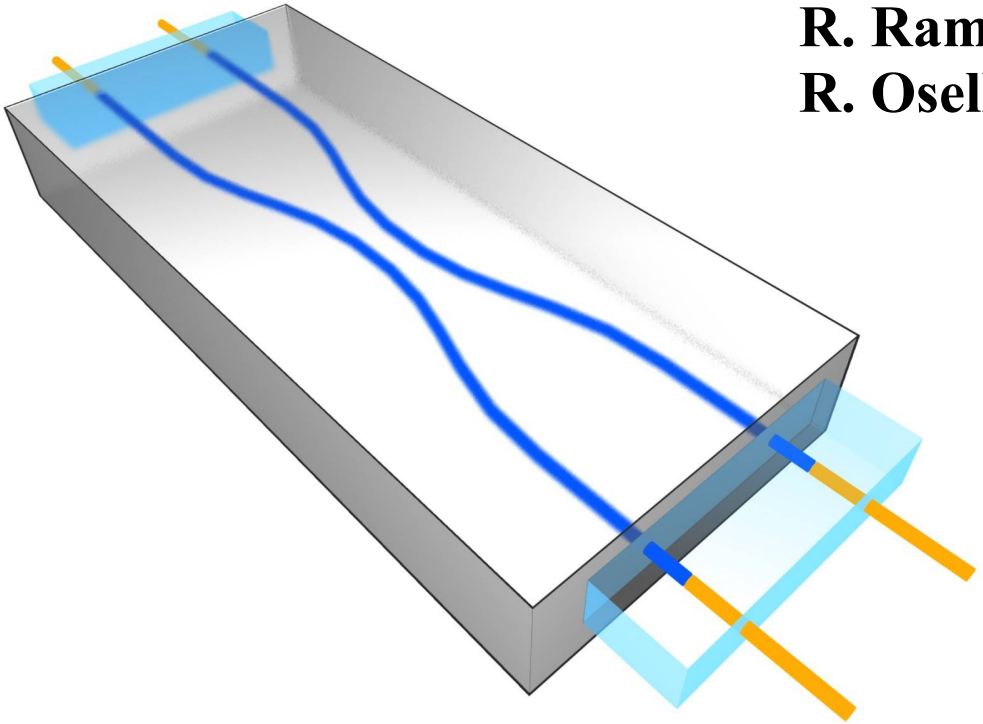
UNIVERSITÀ DI ROMA

INO-CNR
ISTITUTO
NAZIONALE DI
OTTICA

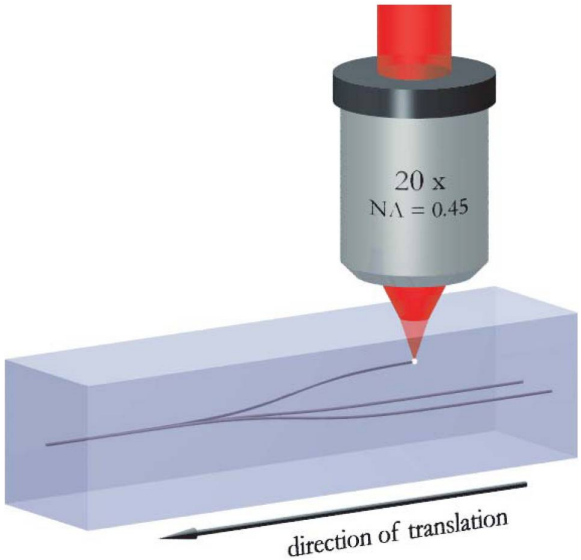


Femtosecond laser writing

3-dimensional capabilities

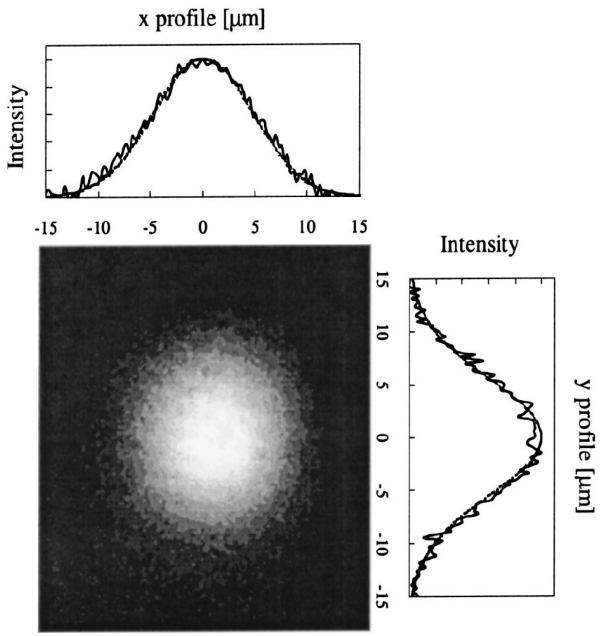
Rapid device prototyping: writing speed =4 cm/s

Propagation of circular gaussian modes

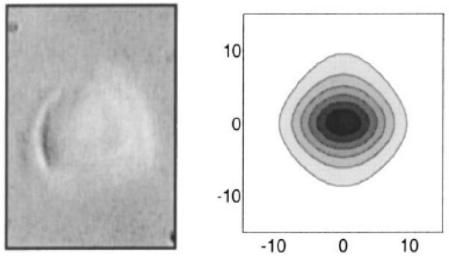


Characteristics:

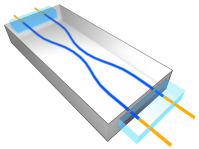
Circular waveguide transverse profile



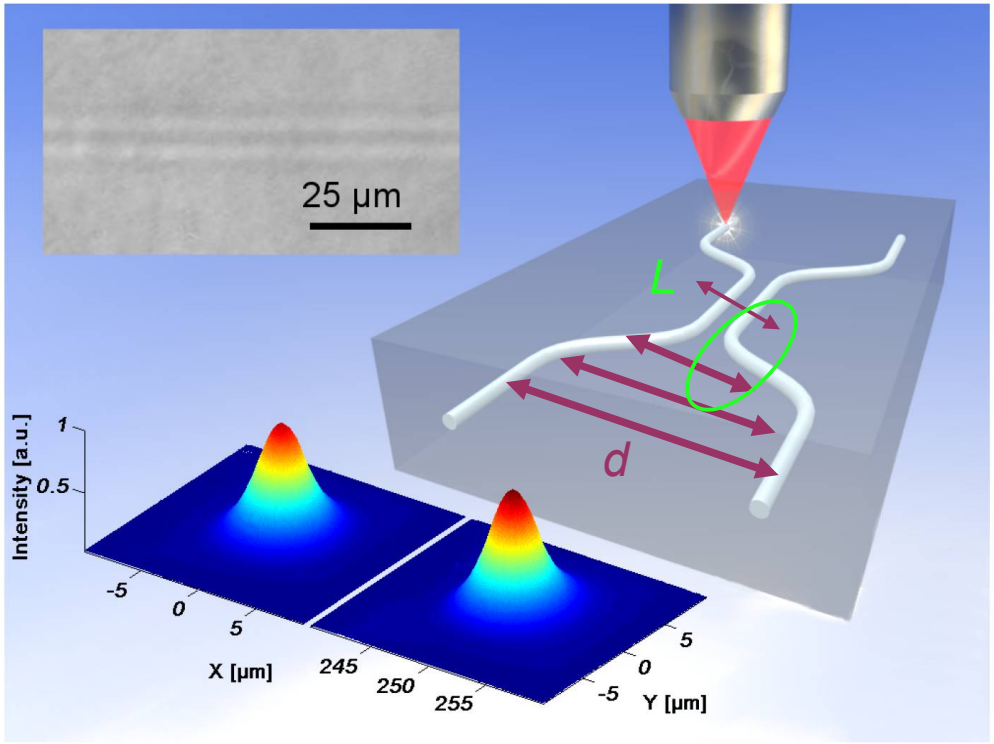
Low birefringence



SUITABLE TO SUPPORT ANY POLARIZATION STATE



Integrated beam splitter



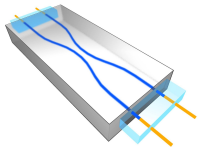
Substrate of borosilicate glass
(no birefringence observed)

Femtosecond infrared laser: λ=*1030nm*
Pulses: *300fs*, 1W
Repetition rate 1 MHz

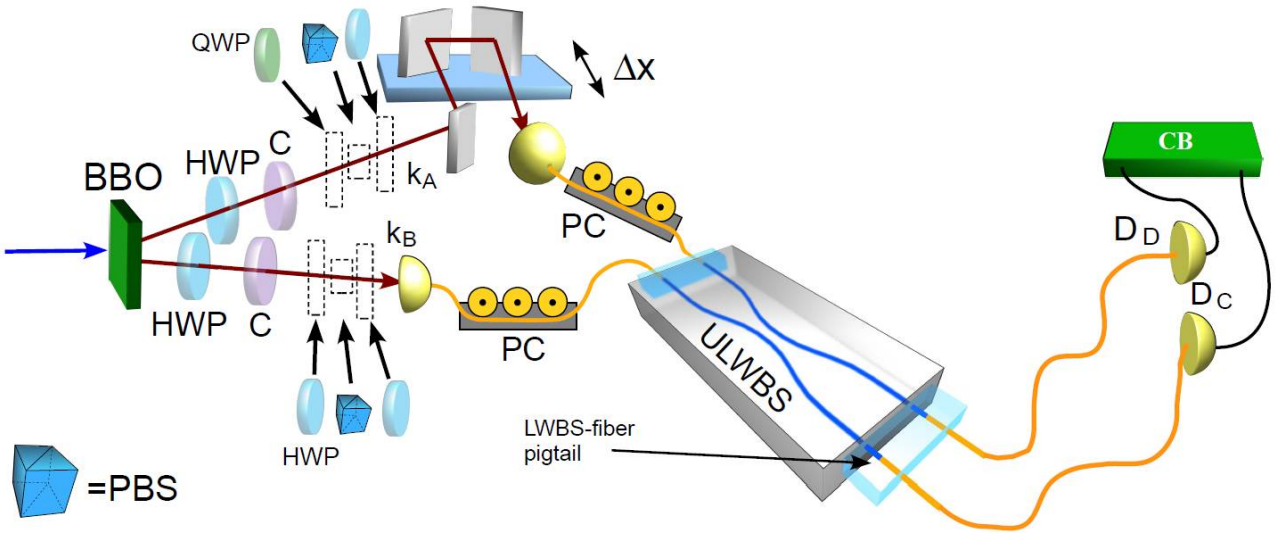
L: interaction region

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

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

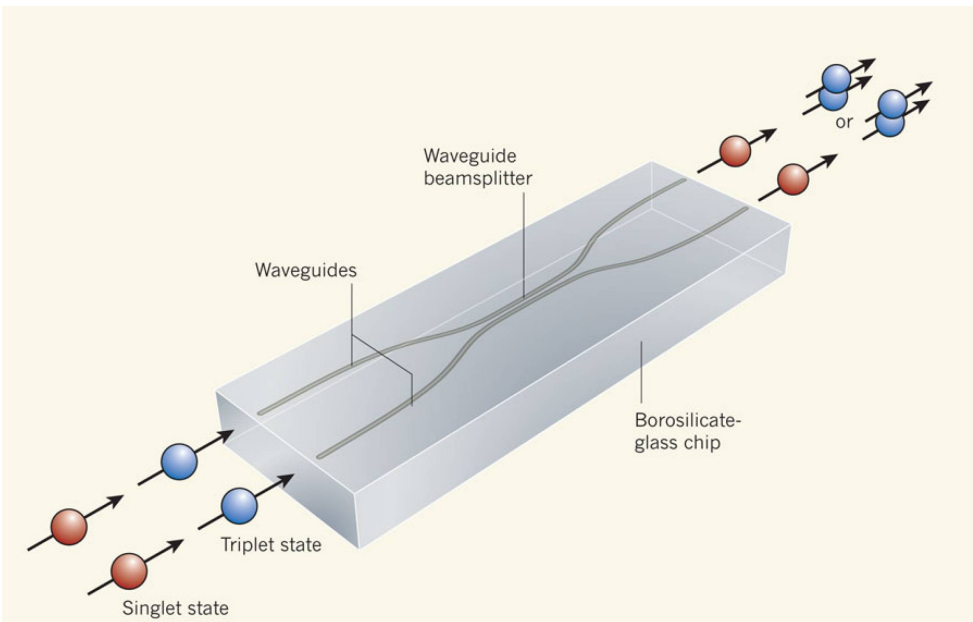


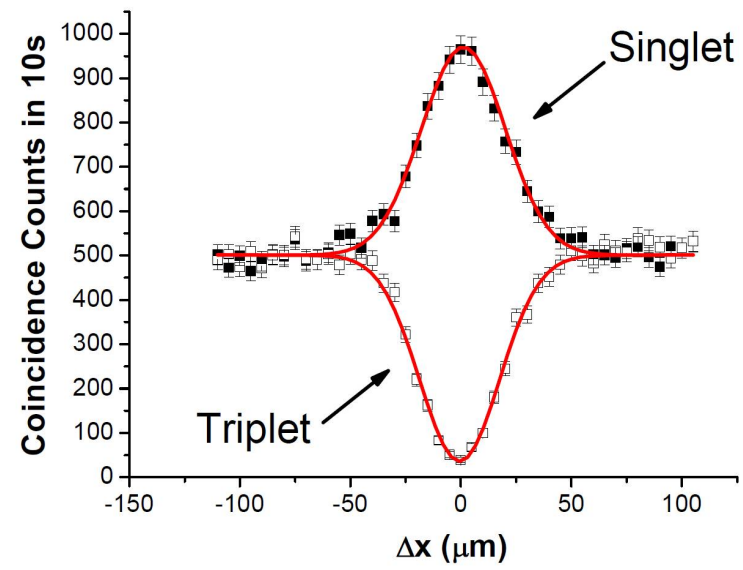
Polarization entanglement on a chip



$$V_{|\Psi-\rangle} = 0.930 \pm 0.005$$

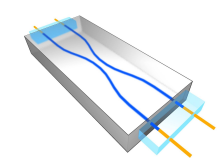
$$V_{|Tripl\rangle} = 0.928 \pm 0.007$$





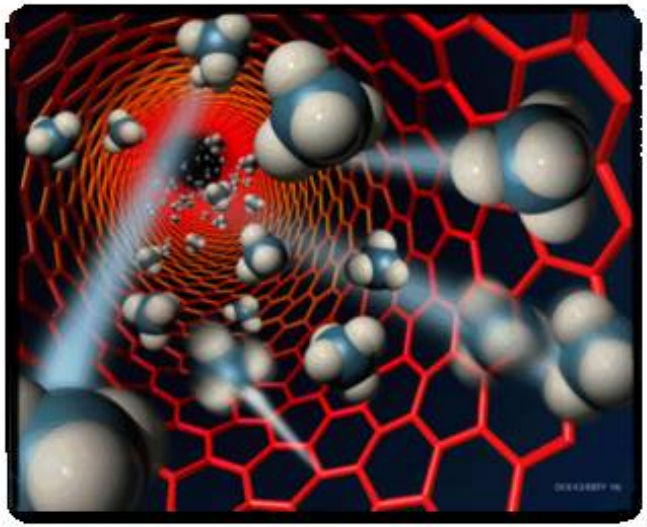
M. Lobino & J.L. O'Brien *News &Views* Nature (2011)

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



QUANTUM SIMULATION VIA QUANTUM WALKS

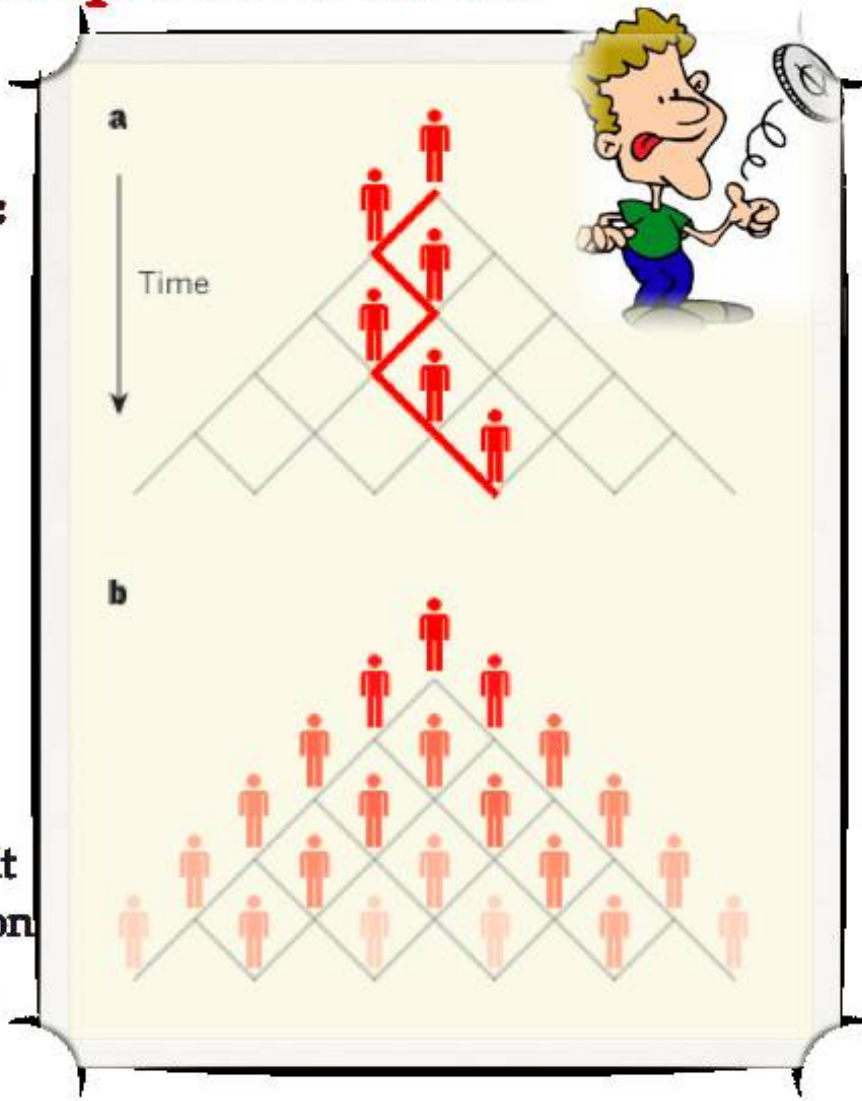
R. Feynman:
"To exploit quantum hardware to simulate quantum systems"



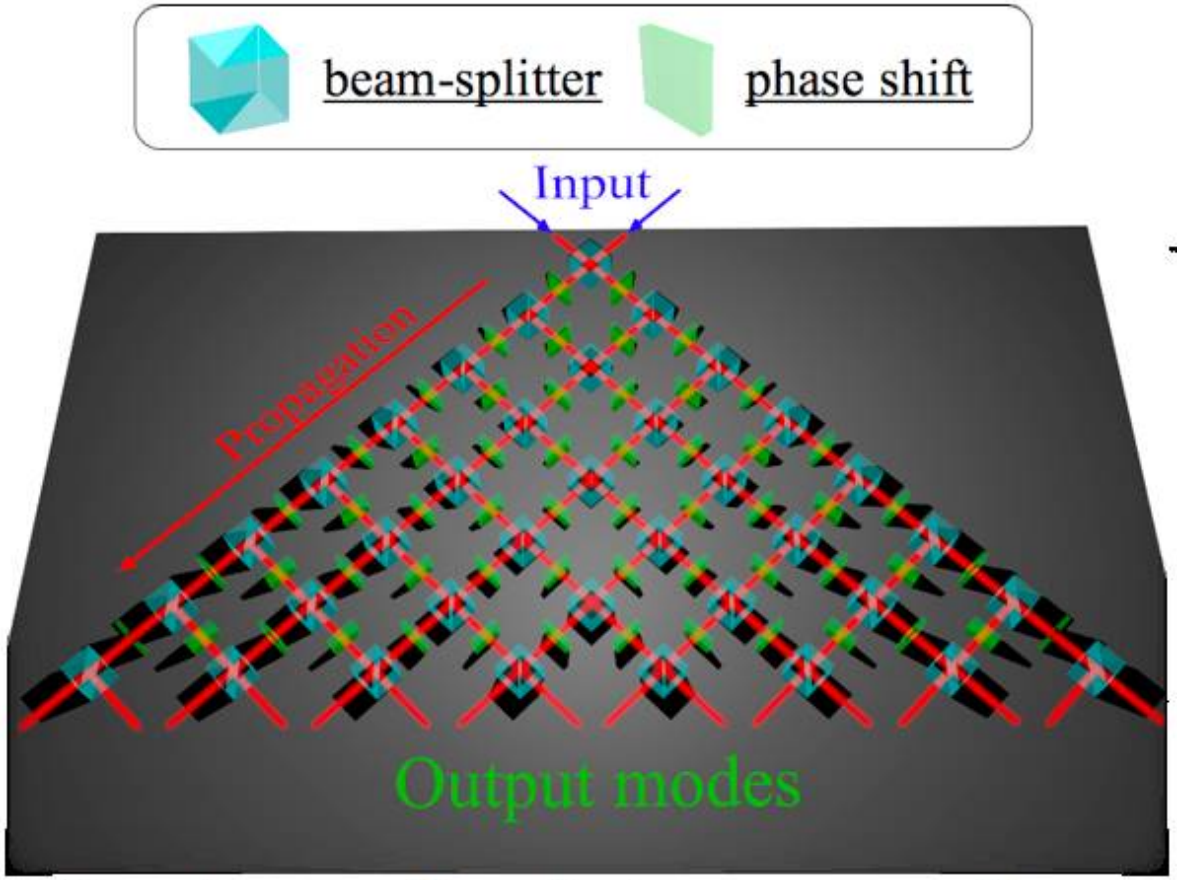
Realization of quantum simulation via quantum walks

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

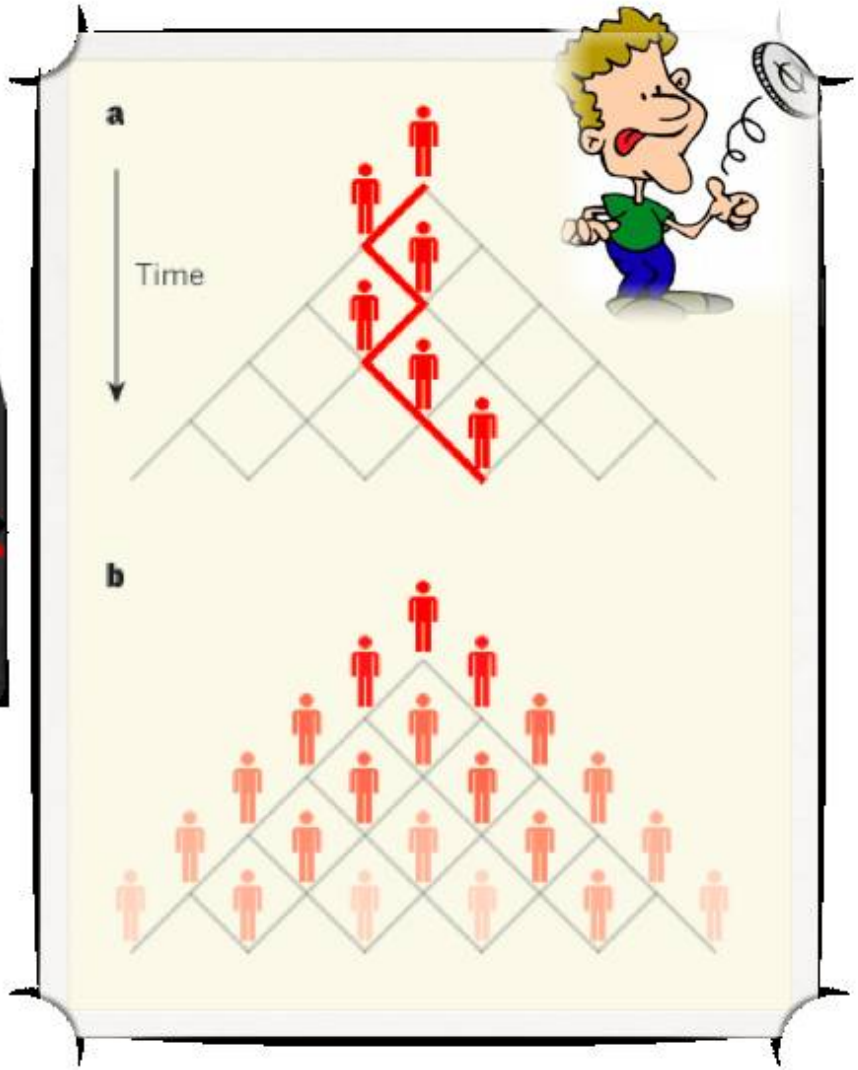
Quantum walk: the walker uses a 'quantum coin' mechanism that allows it to move in a superposition of both left and right.



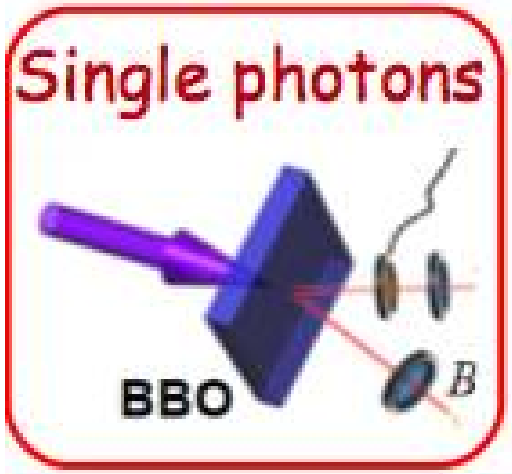
IMPLEMENTATION OF QUANTUM WALKS: OPTICAL SYSTEMS

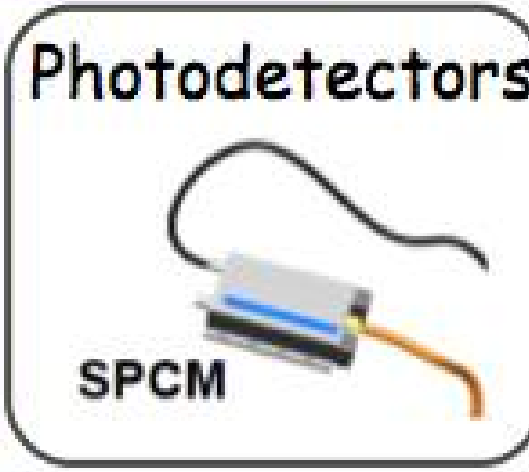


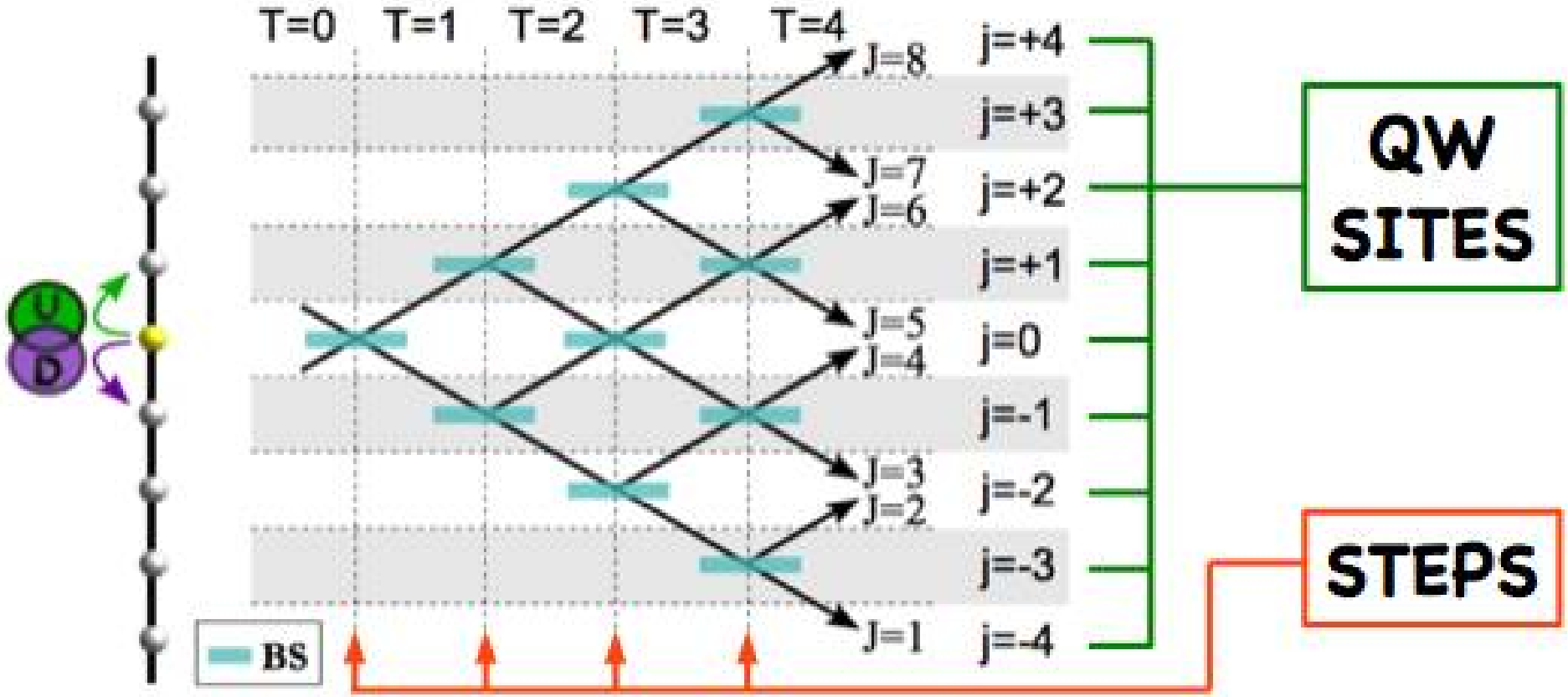
Quantum walks: photons propagating along an arrays of beam splitters and phase shifters



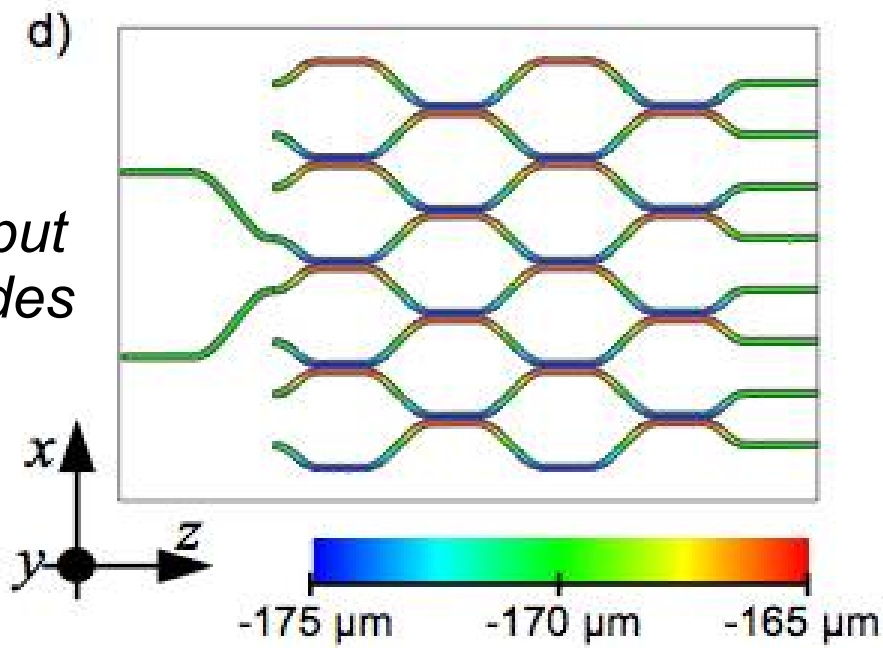
Photonic implementation of quantum walks







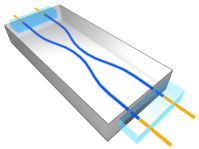
Beamsplitter arrays



- 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)

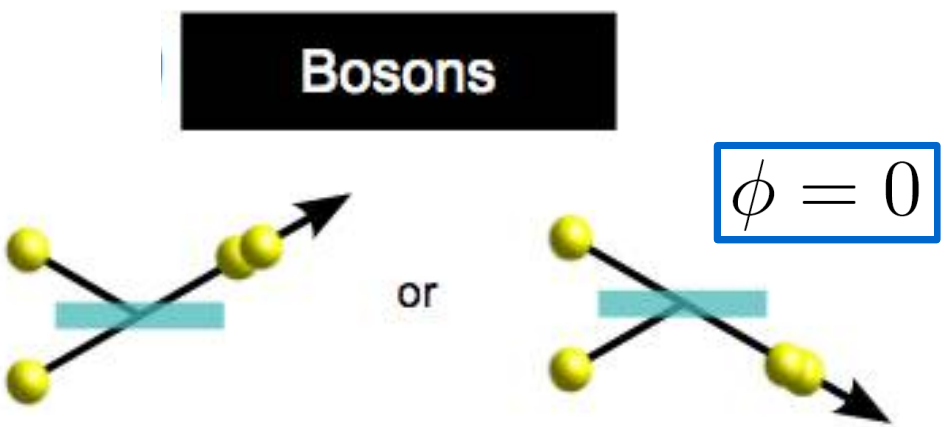
Quantum walk with two particles..

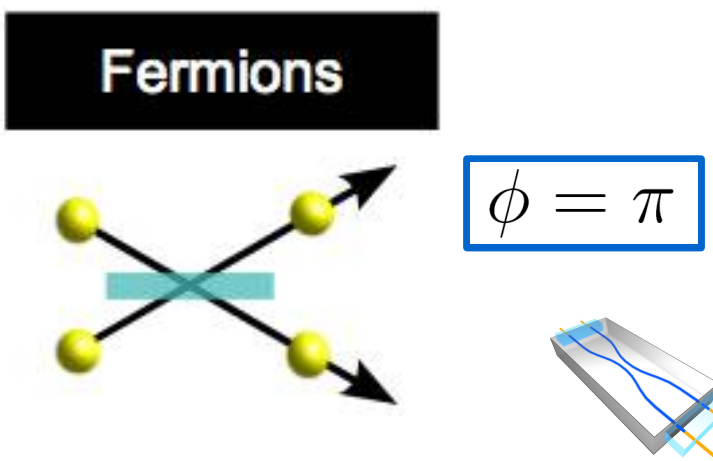
If two simultaneous quantum walkers travel their symmetry must influence the output probability distribution

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

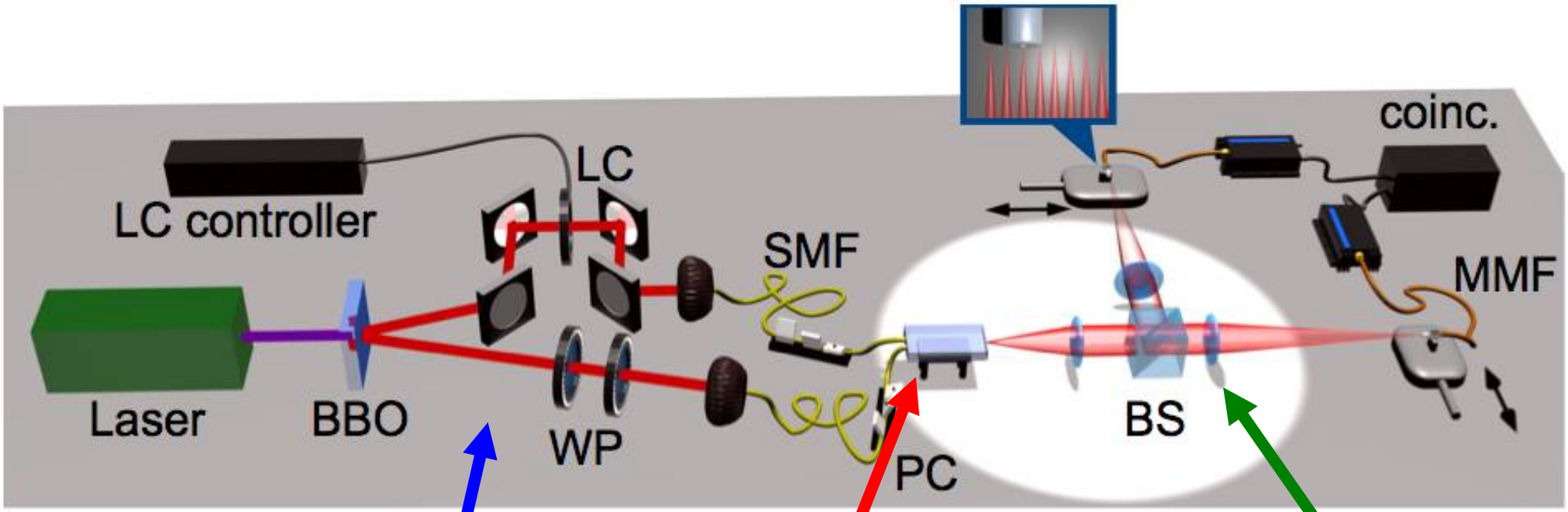
By changing the symmetry of entanglement we can simulate the quantum dynamics of the walks of two particles with bosonic or fermionic statistic.

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





Two-particles quantum walk: experimental setup



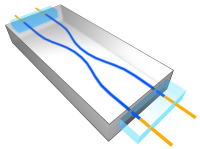
BS array on a chip

Eight output modes:

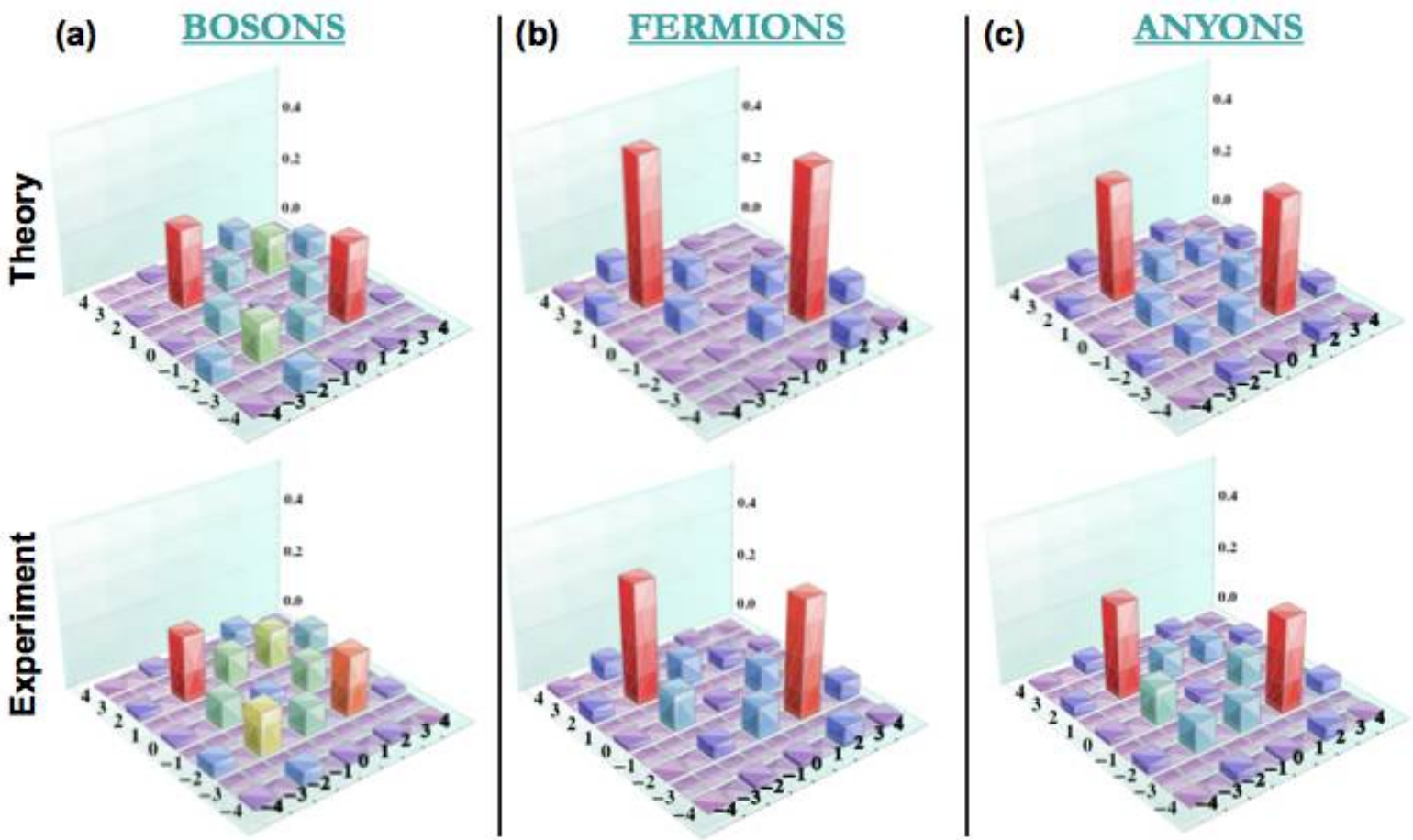
Generation of two-photon entangled states with different symmetries

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



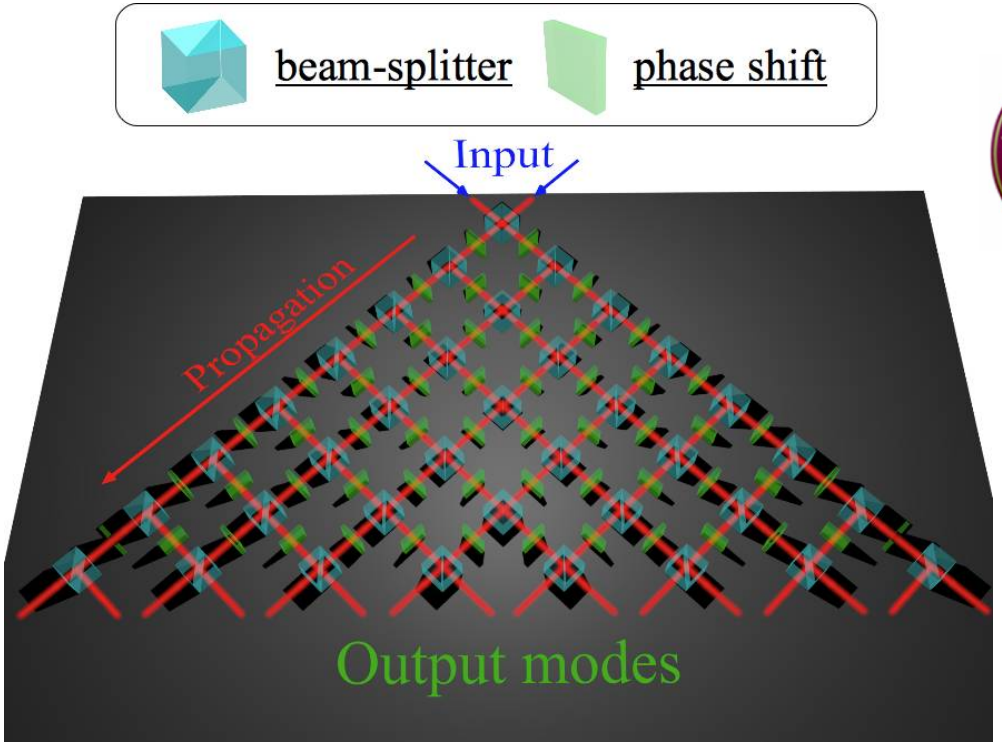
Similarities between theory and experiment

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

Simulation of disordered systems



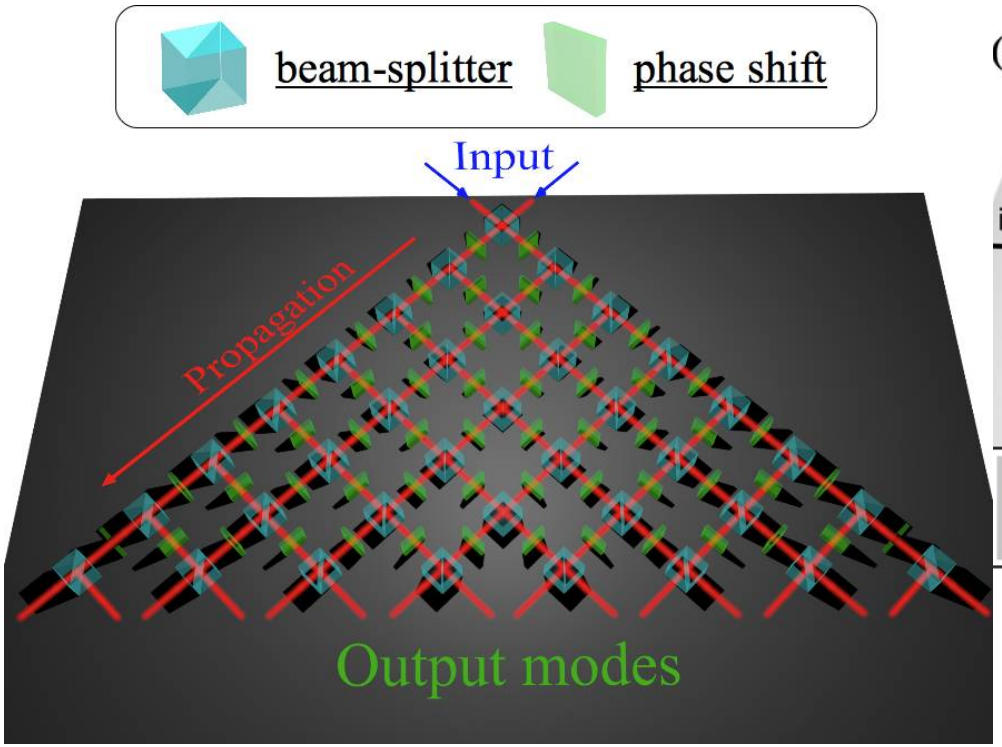
SAPIENZA
UNIVERSITÀ DI ROMA

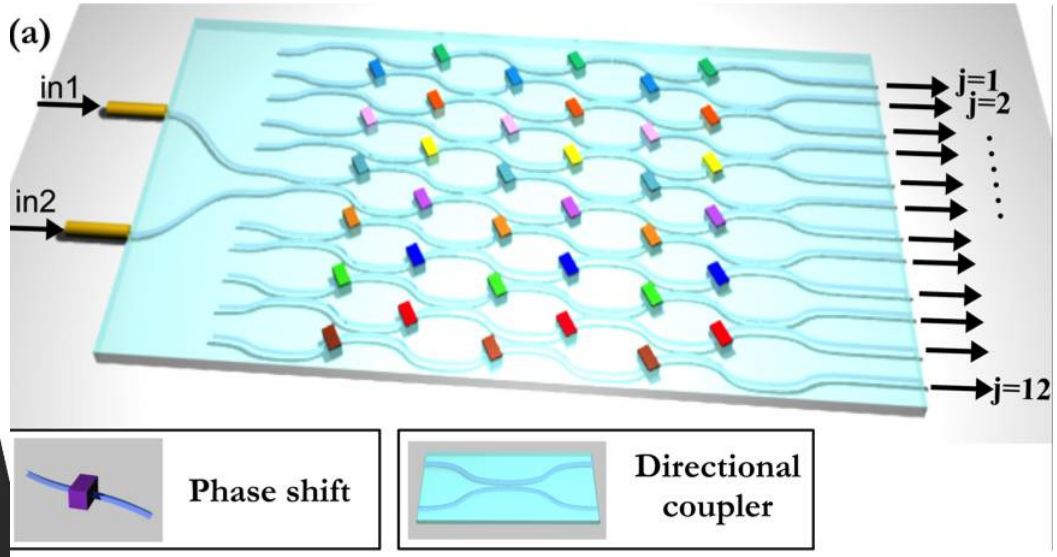
POLITECNICO MILANO

SCUOLA NORMALE SUPERIORE

R. Fazio
V. Giovannetti

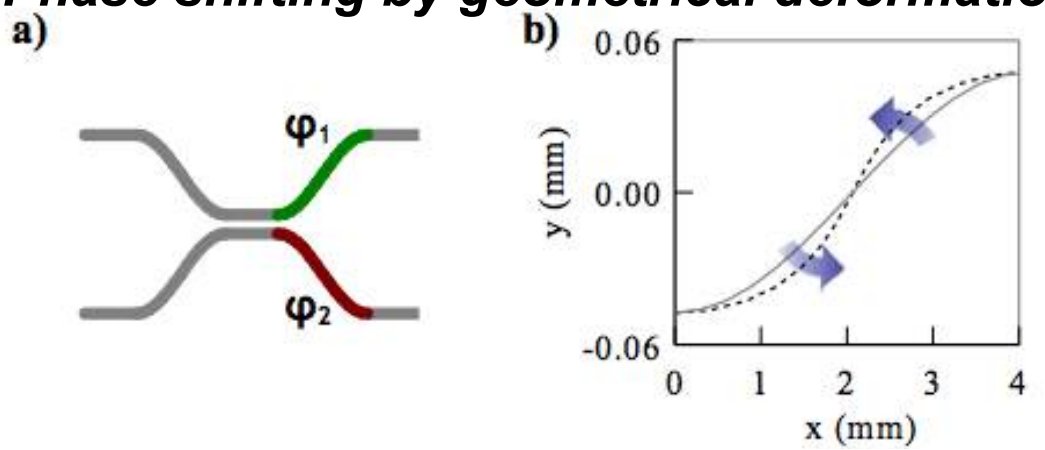
Simulation of disordered systems





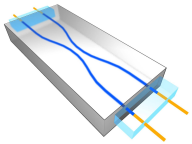
.... FIRST EXPERIMENTS....

Phase shifting by geometrical deformation



To simulate different types of disorders:

POLARIZATION INDEPENDENT

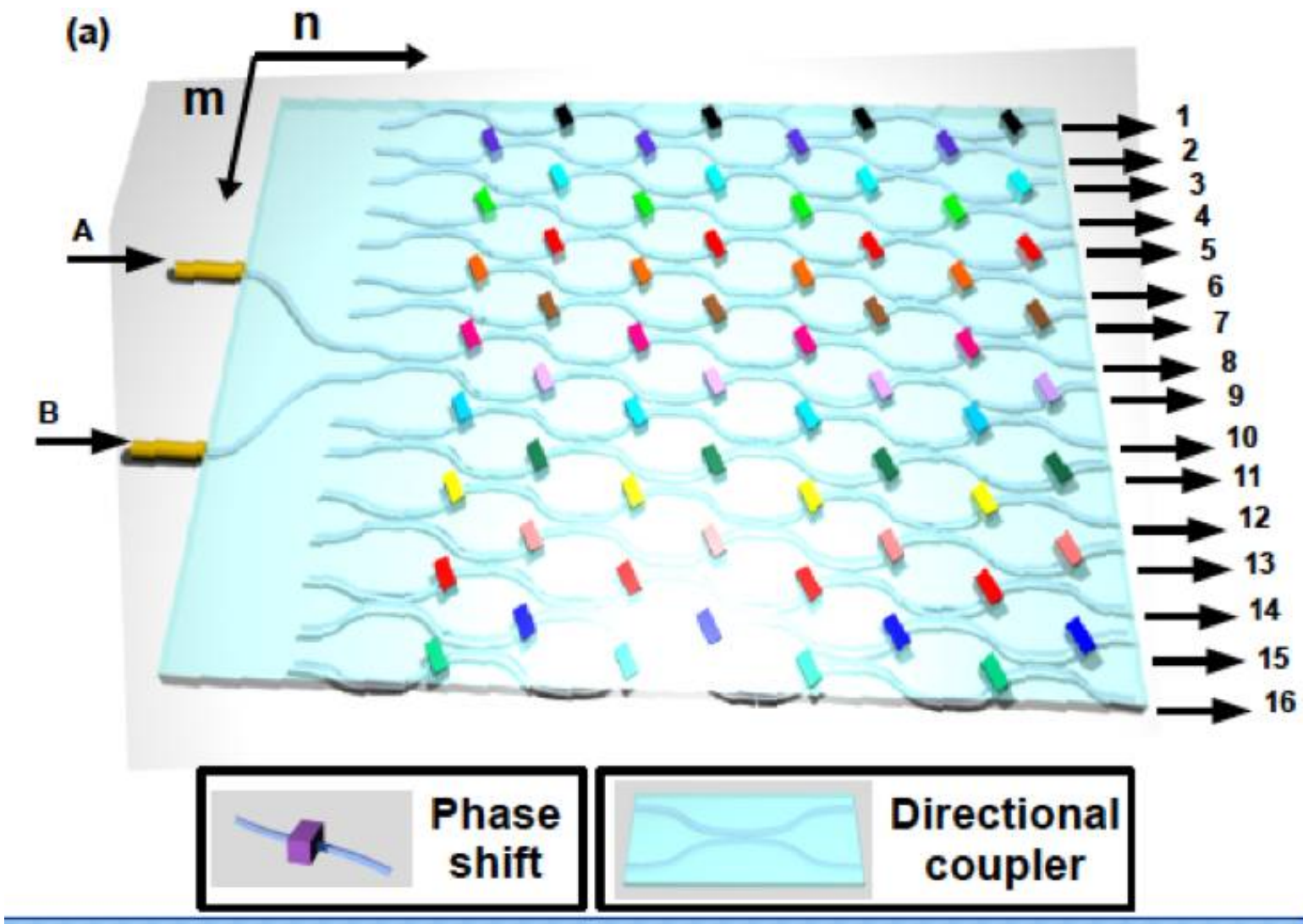


Simulation of static disorder

Disorder depends:
- from location
- but NOT from time

Anderson localication....

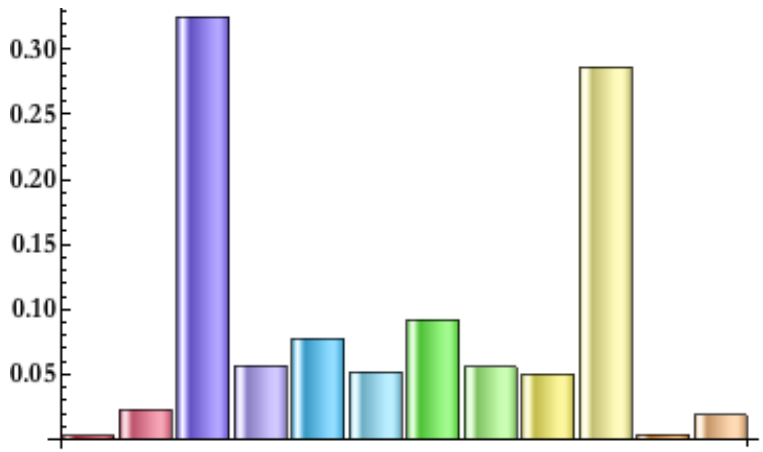
64 Beam splitters
64 phase-shifters
Polarization indiependent



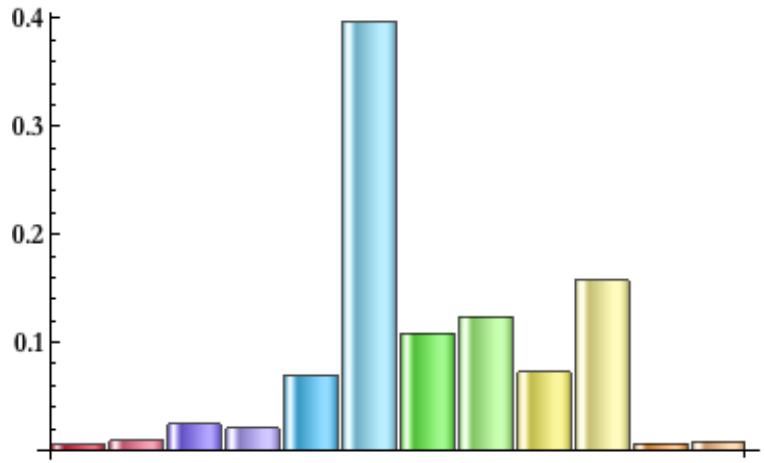
Simulation of disordered systems: Single particle quantum walk

Experiment

Ordered system



Disordered system

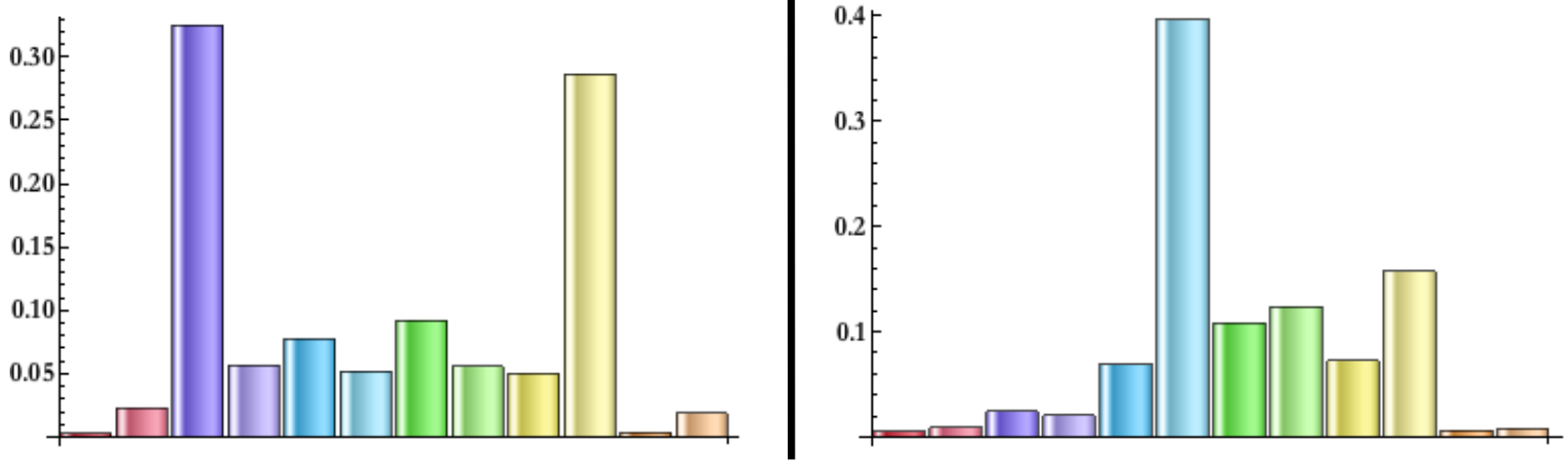


Simulation of disordered systems: Single particle quantum walk

Ordered system

Disordered system

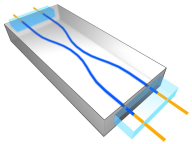
Experiment



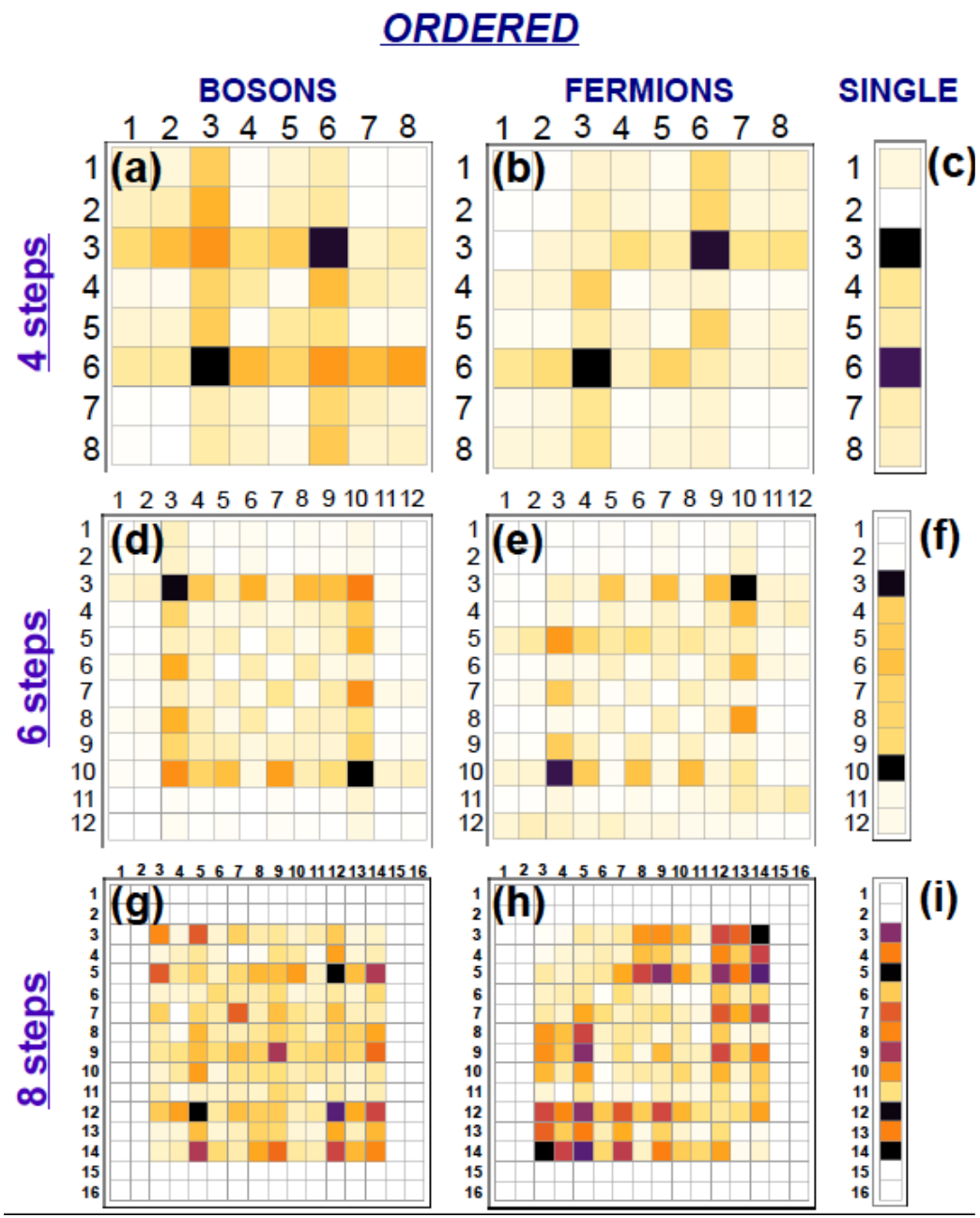
Experimentally observed by Silberhorn's group with fiber loops:
Phys. Rev. Lett. **106**, 180403 (2011).

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

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



Ordered VS Static Quantum Walk: Experimental results

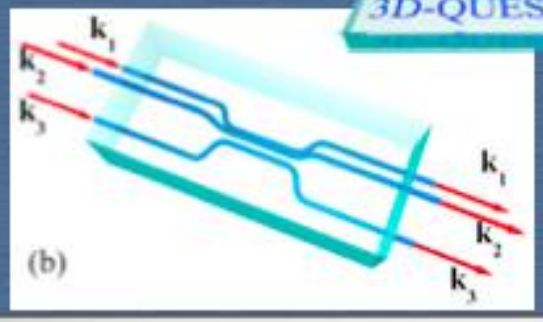


Integrated quantum simulations....

ADDING THE THIRD DIMENSION...

Tritter

3D-QUEST



Hong-Ou-Mandel coalescence of three photons

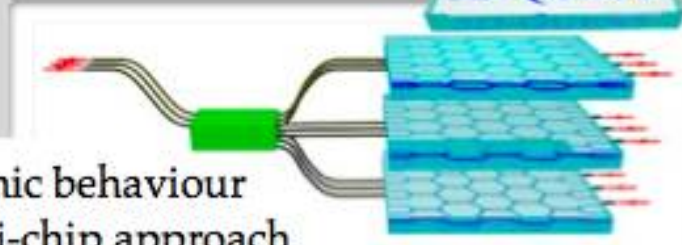
Tetrater

3D-QUEST

Simulating bosons, fermions...

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

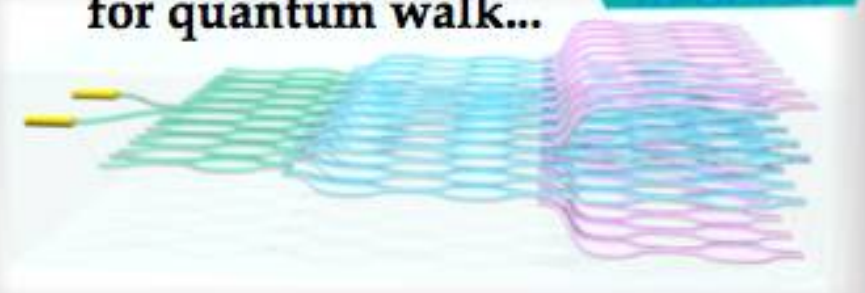
3D-QUEST



Fermionic behaviour with multi-chip approach

Higher dimensionality for quantum walk...

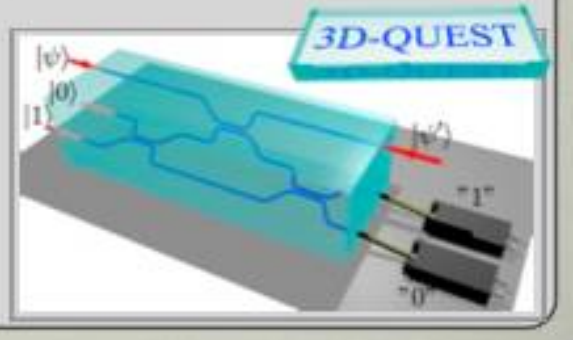
3D-QUEST



Adding interaction...

ancillary photons and modes

3D-QUEST



The tritter: a three-mode splitter

Three-dimensional femtosecond laser-writing → extension to three modes of a beam-splitter

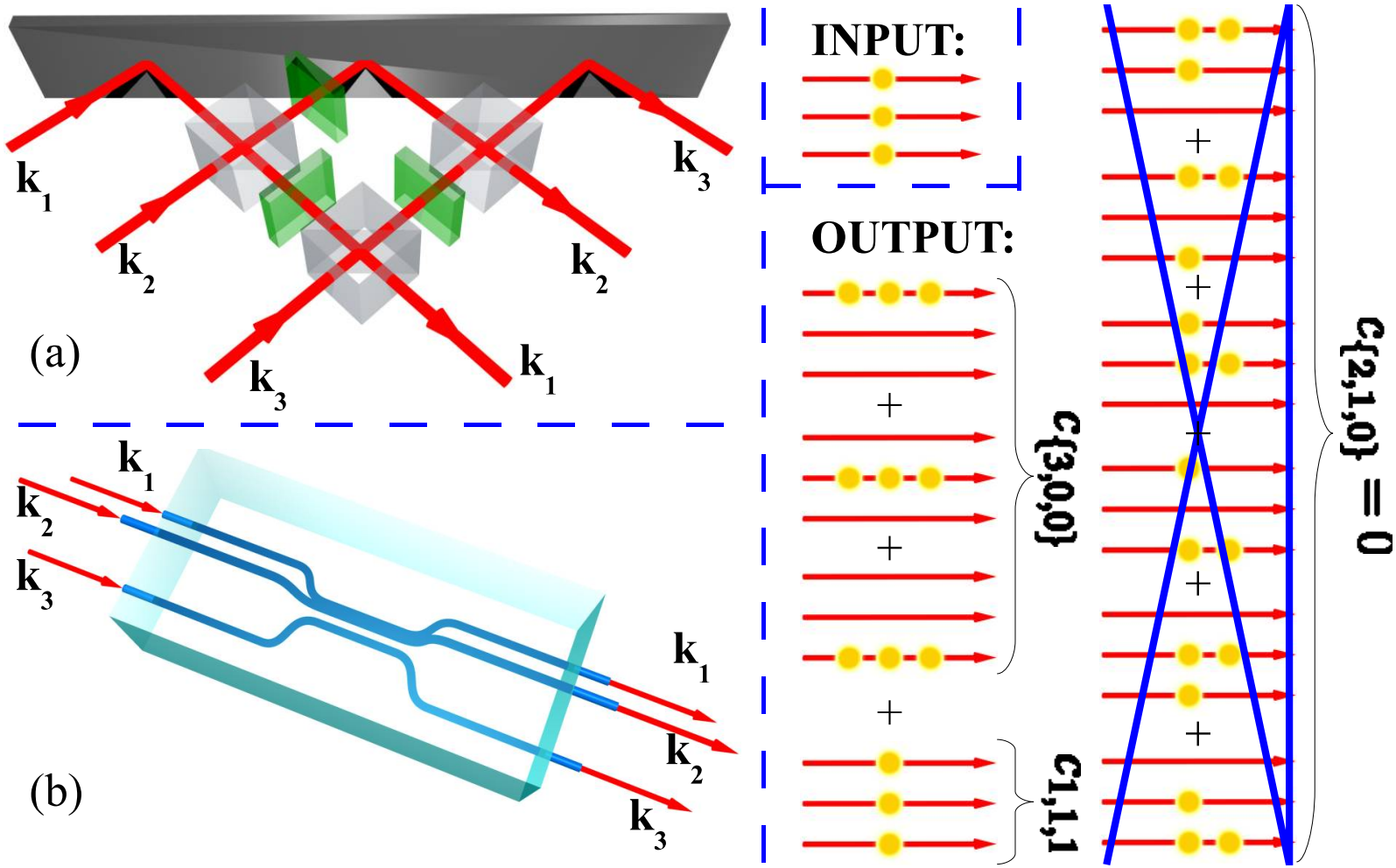
Simple integrated structure

↓

Simultaneous interference of the three modes

↓

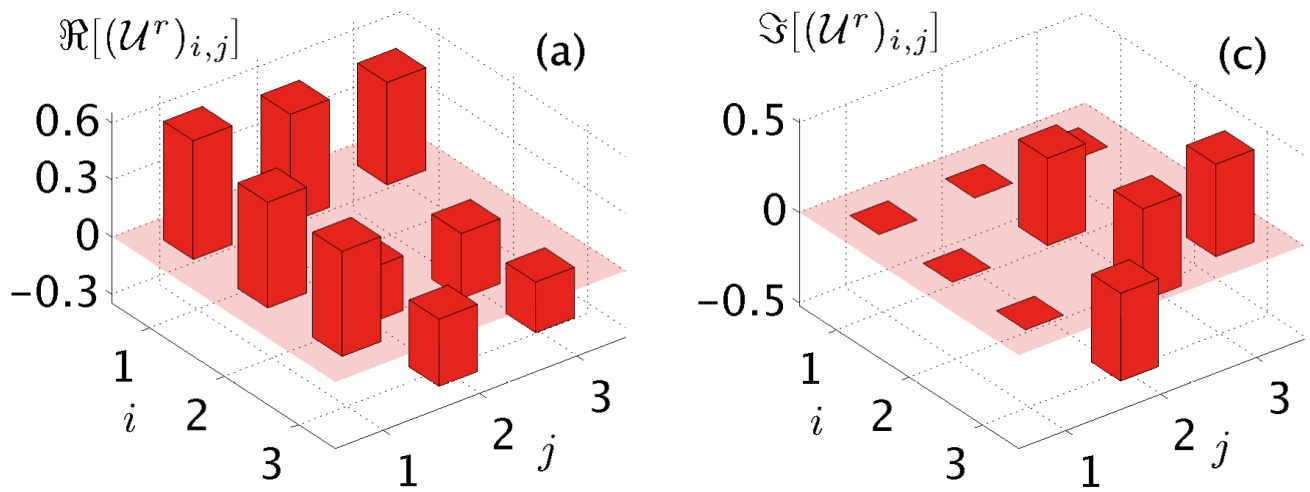
Exploring three-photon interference



The tritter: a three-mode splitter

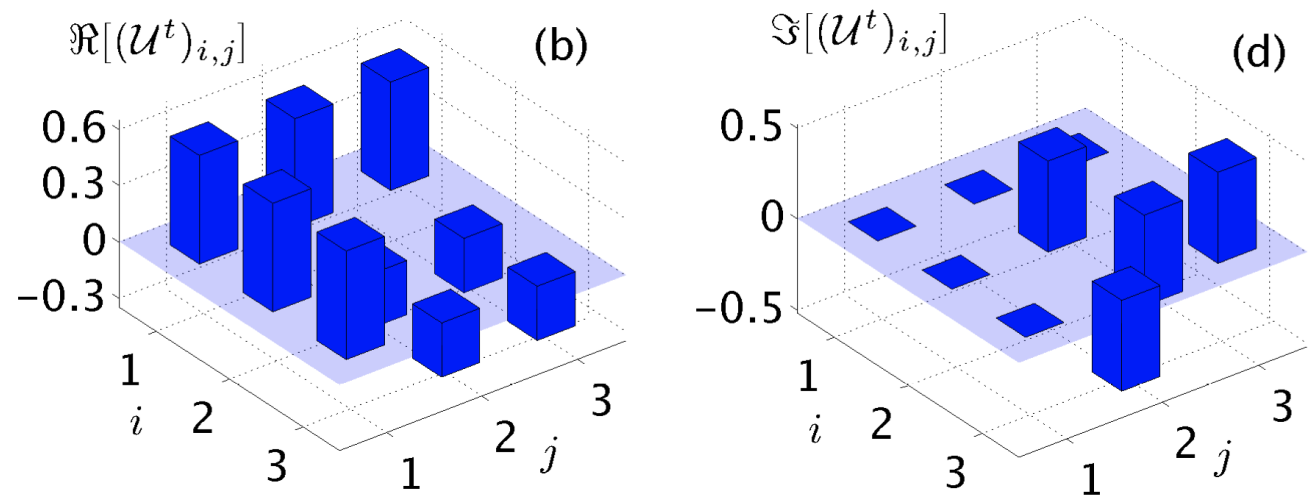
Tritter by femtosecond laser-writing

Experiment



Characterization of the tritter by single photon and two photon measurements

Theory

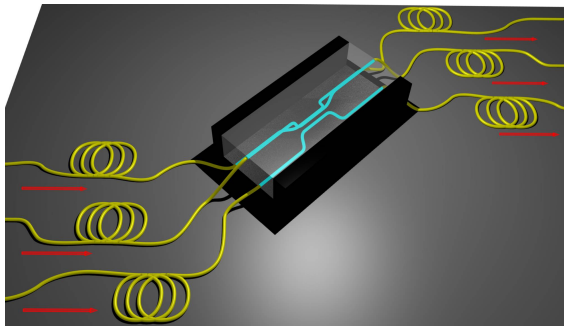


$$S = 0.973 \pm 0.001$$

High correspondence between the ideal and the reconstructed device

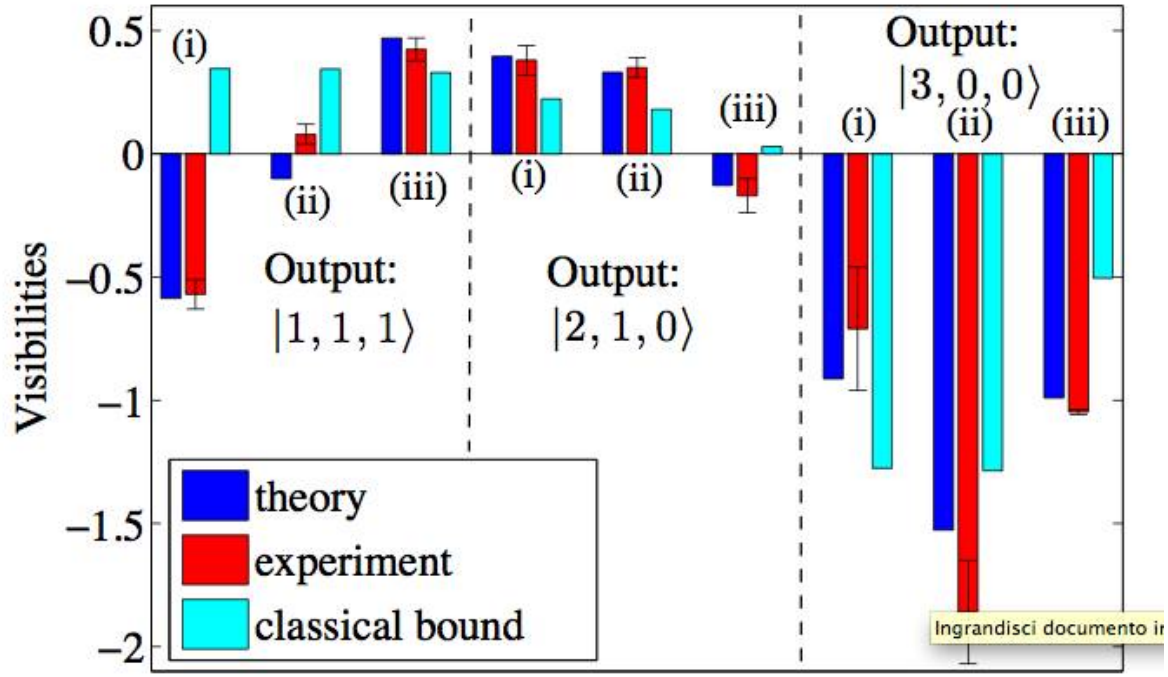
Photonic coalescence of 3 photons

Experimental three-photon bosonic coalescence



Three-photon input state: $|1,1,1\rangle$

Model taking into account the reconstructed tritter matrix and photon distinguishability

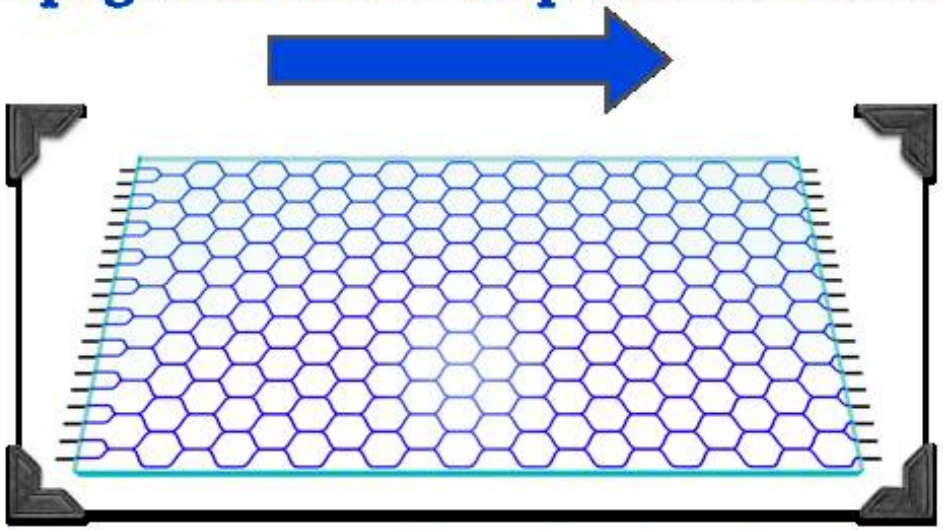


Visibilities outperform the classical bound for coherent state inputs

N. Spagnolo, C. Vitelli, L. Aparo, P. Mataloni, F. Sciarrino, A. Crespi, R. Ramponi, R. Osellame, *Three-photon bosonic coalescence in an integrated tritter*, [arXiv:1210.6935]

propagation on the chip with *m* modes

Input:
***n* photons**

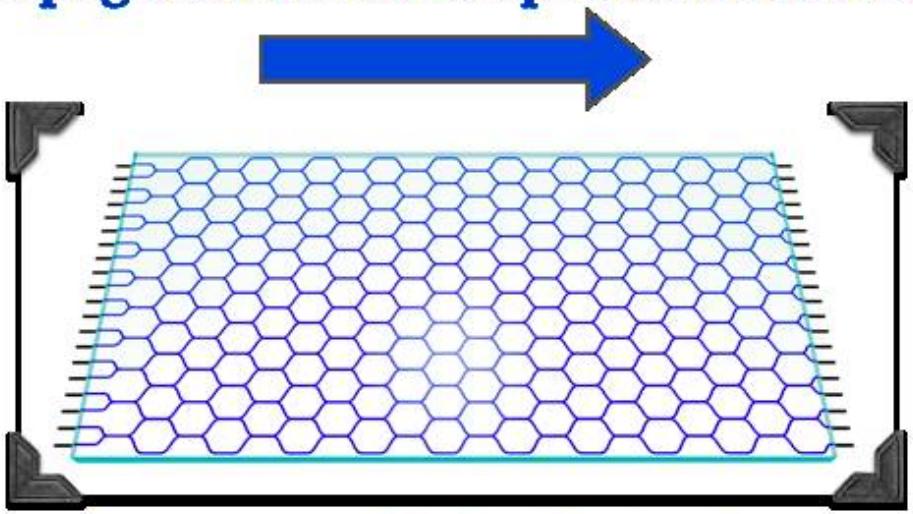


Output:
***n*-photon state**

Can a classical computer efficiently simulate these experiments ?

propagation on the chip with *m* modes

Input:
***n* photons**



Output:
***n*-photon state**

Can a classical computer efficiently simulate our experiments ?

Answer: NO!!

WHY: the permanents of n x n matrices must be calculated

Permanent of a matrix: hard to calculate with a classical computer

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

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

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

Conclusions and perspectives

- Beamsplitter able to support polarization encoded qubit
- Polarization sensitive devices
- Quantum walk with two-particles in different entangled states: simulation of Anderson localization

Circuits with 3-dimensional geometries

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

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

Quantum walk:

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

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3D-QUEST
SEVENTH FRAMEWORK PROGRAMME
SAPIENZA UNIVERSITÀ DI ROMA
FUTURO IN RICERCA