Quantum Walks and Wavepacket Dynamics on a Lattice with Twisted Photons

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A Naples, Rome, Ottawa Collaboration

Cardano et al., Science Advances 1, e1500087 (2015).

Presented at Photonics North, June 9-11, Ottawa ON Canada

Quantum Simulator (A Sort of Quantum Computer)

Quantum simulator: simulation of a complex quantum system by means of another simpler and well controlled quantum system

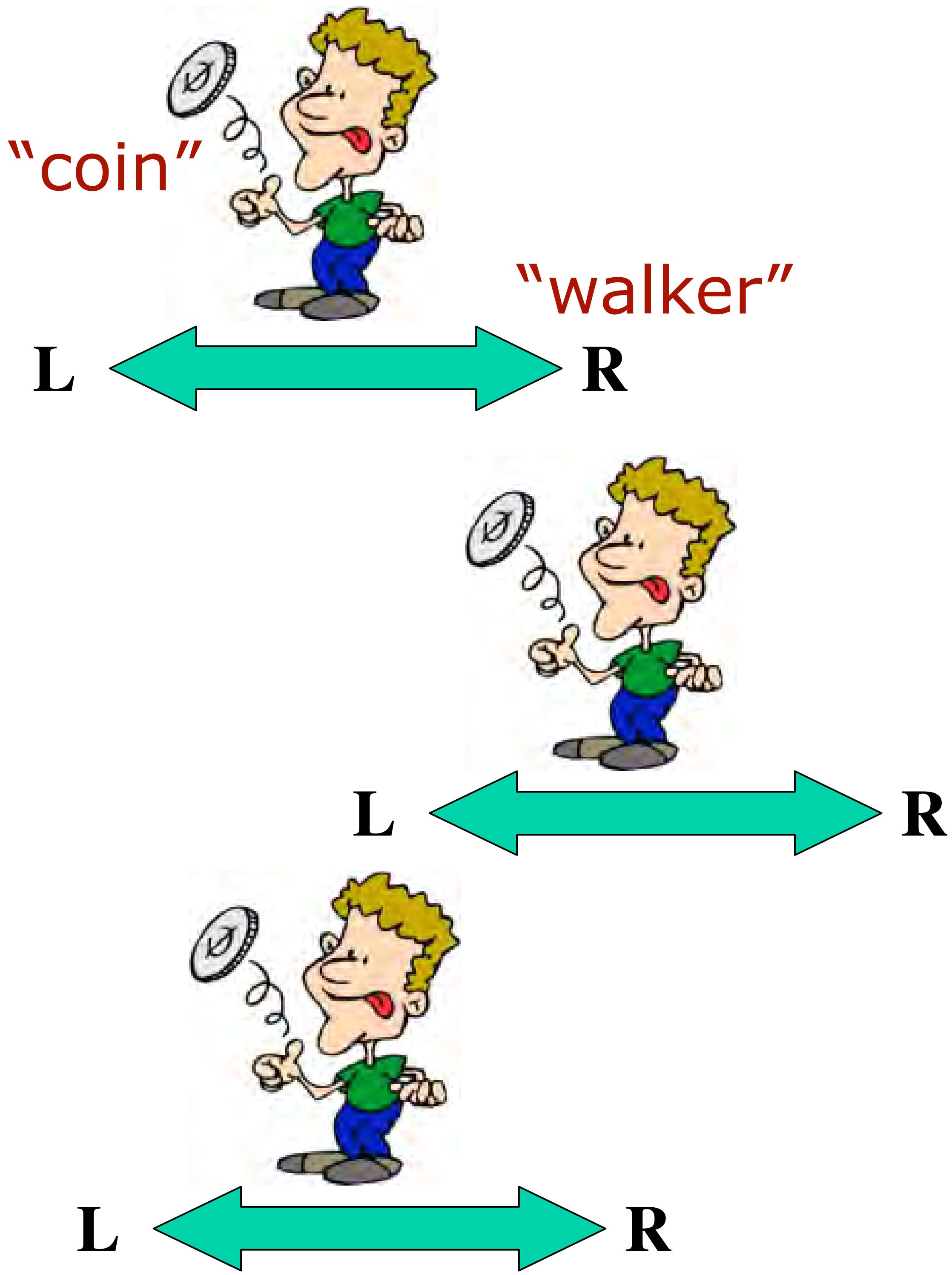
Proposed by Feynman and investigated by many

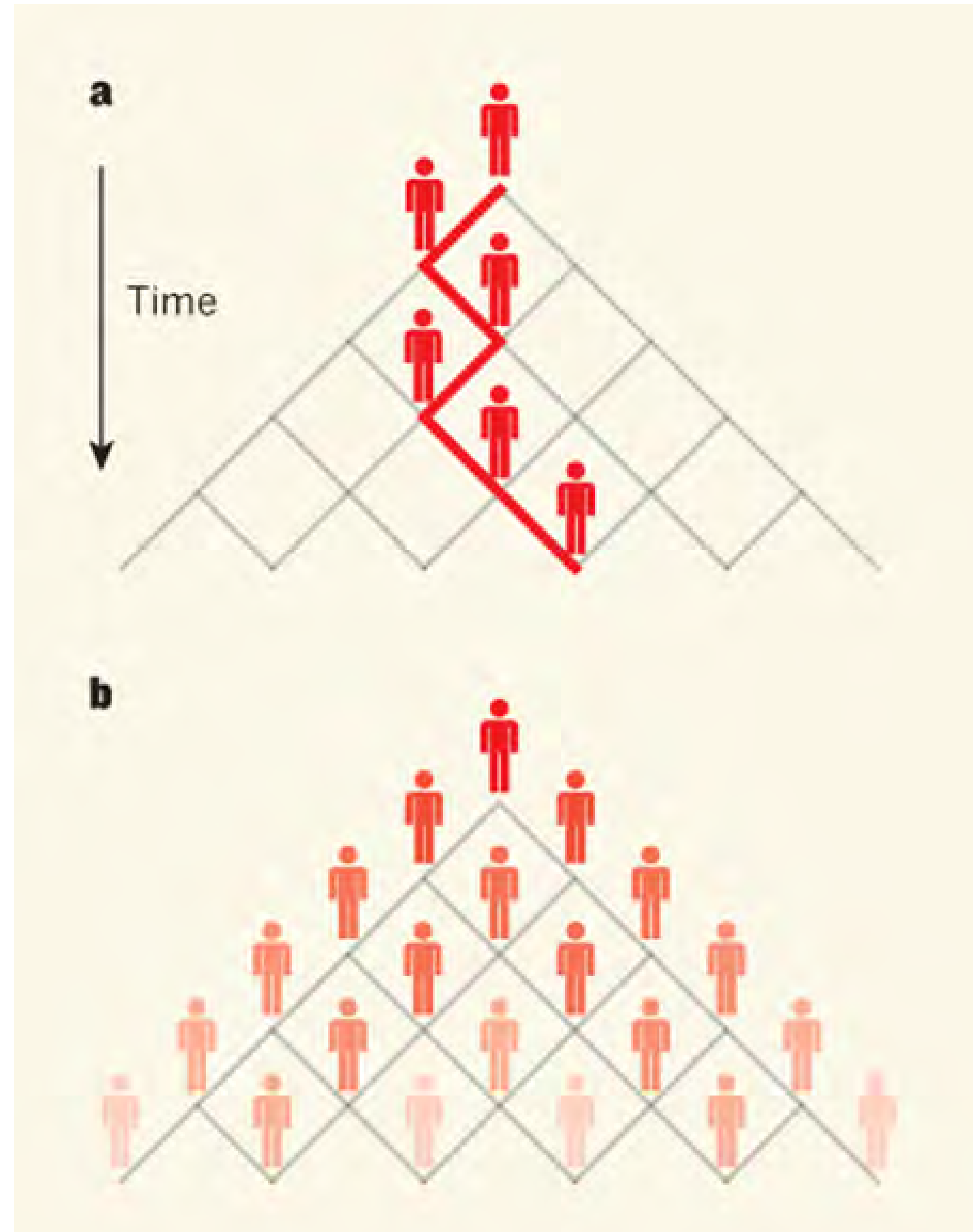
Quantum walk (quantum version of the random walk) is a key example of a quantum simulator

We describe our implementation of the quantum walk simulator

R. Feynman, Simulating physics with computers. Int. J. Theor. Phys. 21, 467–488 (1982).
A. Aspuru-Guzik, P. Walther, Photonic quantum simulators. Nat. Phys. 8, 285–291 (2012).
J. Kempe, Quantumrandom walks: An introductory overview. Contemp. Phys. 44, 307–327 (2003).
P. L. Knight, E. Roldán, J. E. Sipe, Quantum walk on the line as an interference phenomenon, Phys. Rev. A 68, 020301 (2003).

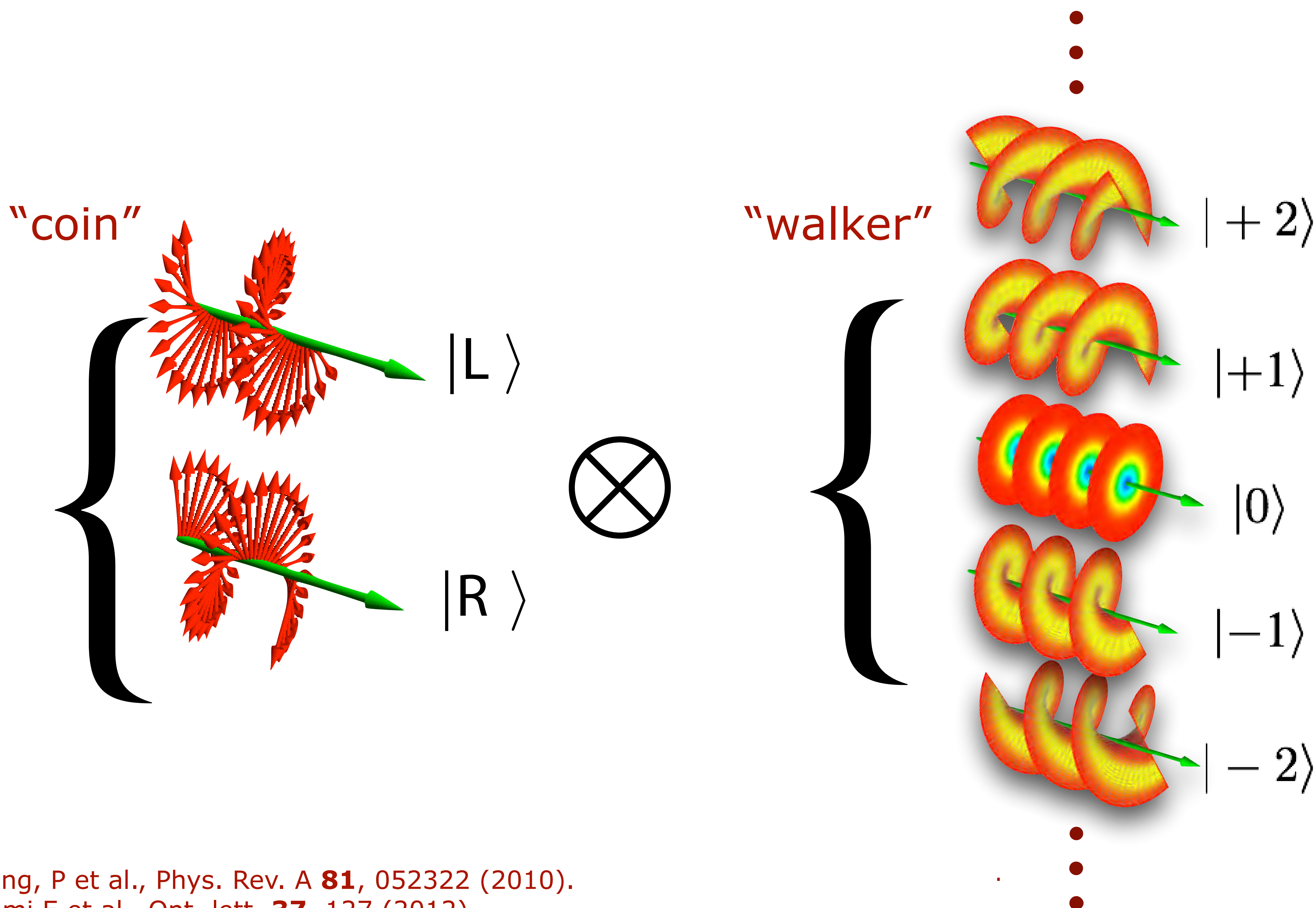
Classical and Quantum Random Walks





Matthews, JCF & Thompson MG, Nature **484**, 47 (2012)

We Use OAM as a Novel "Walker"

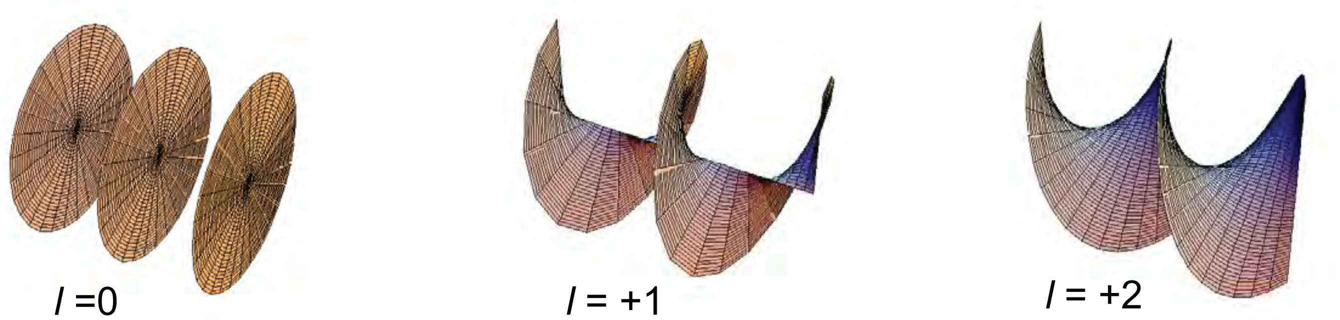


Zhang, P et al., Phys. Rev. A **81**, 052322 (2010).
Karimi E et al., Opt. lett. **37**, 127 (2012).
Goyal, SK et al., Phys. Rev. Lett. **110**, 263602 (2013)

What Are the Orbital Angular Momentum (OAM) States of Light?

- Light can carry spin angular momentum (SAM) by means of its circular polarization.
- Light can also carry orbital angular momentum (OAM) by means of the phase winding of the optical wavefront.
- A well-known example are the Laguerre-Gauss modes. These modes contain a phase factor of $\exp(il\varphi)$ and carry angular momentum of $\hbar l$ per photon. (Here φ is the azimuthal coordinate.)

Phase-front structure of some OAM states



See, for instance, A.M. Yao and M.J. Padgett, Advances in Photonics 3, 161 (2011).

Laguerre-Gauss Modes

The paraxial approximation to the Helmholtz equation $(\nabla^2 + k^2)E(\boldsymbol{k}) = 0$ gives the paraxial wave equation which is written in the cartesian coordinate system as

$$\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + 2ik\frac{\partial}{\partial z}\right) E(x, y, z) = 0. \tag{1}$$

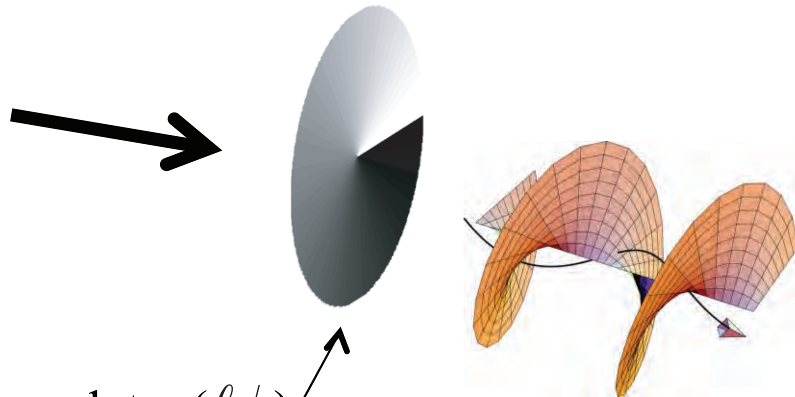
The paraxial wave equation is satisfied by the Laguerre-Gaussian modes, a family of orthogonal modes that have a well defined orbital angular momentum. The field amplitude $LG_p^l(\rho, \phi, z)$ of a normalized Laguerre-Gaussian modes is given by

$$\begin{aligned} LG_p^l(\rho, \phi, z) = & \sqrt{\frac{2p!}{\pi(|l| + p)!}} \frac{1}{w(z)} \left[\frac{\sqrt{2}\rho}{w(z)}\right]^{|l|} L_p^l \left[\frac{2\rho^2}{w^2(z)}\right] \\ & \times \exp\left[-\frac{\rho^2}{w^2(z)}\right] \exp\left[-\frac{ik^2\rho^2 z}{2(z^2 + z_R^2)}\right] \exp\left[i(2p + |l| + 1)\tan^{-1}\left(\frac{z}{z_R}\right)\right] e^{-il\phi}, \end{aligned} \tag{2}$$

where k is the wave-vector magnitude of the field, z_R the Rayleigh range, $w(z)$ the radius of the beam at z, l is the azimuthal quantum number, and p is the radial quantum number. L_p^l is the associated Laguerre polynomial.

How to create a beam carrying orbital angular momentum?

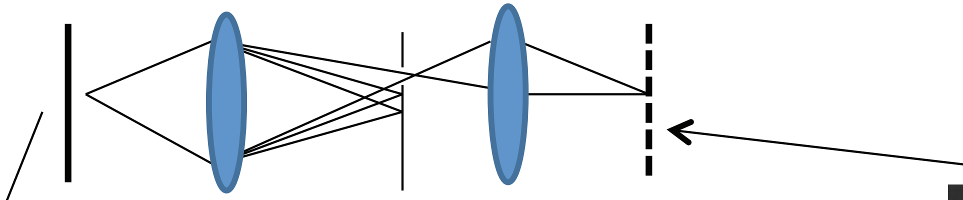
Pass beam through a spiral phase plate



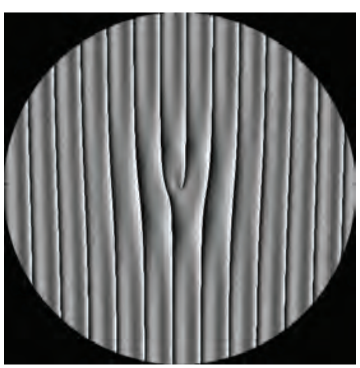
$e^{i\ell\phi}$

Spiral phase plate $(\ell\phi)$

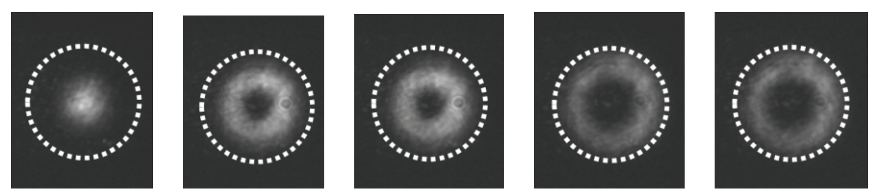
Use a spatial light modulator acting as a computer generated hologram (more versatile)



LG



Laguerre-Gauss

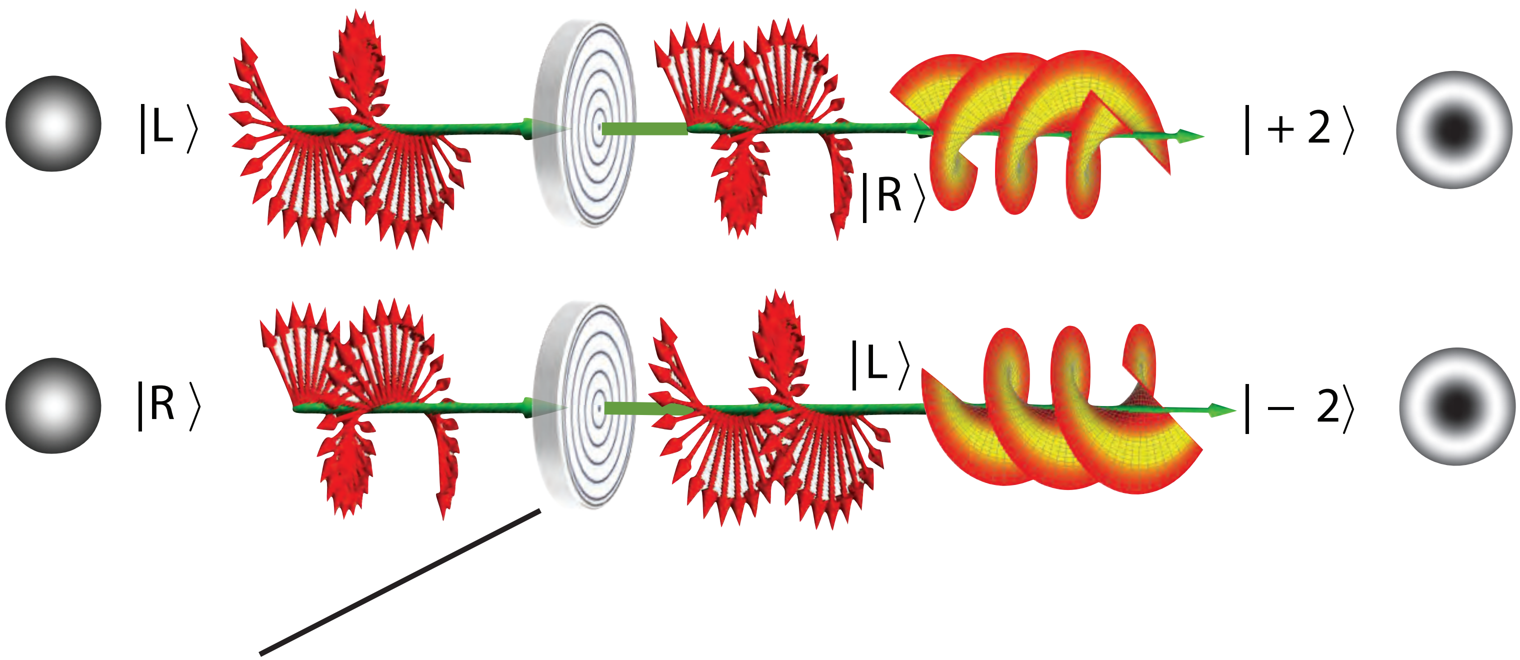


Exact solution to simultaneous intensity and phase masking with a single phase-only hologram, E. Bolduc, N. Bent, E. Santamato, E. Karimi, and R. W. Boyd, Optics Letters 38, 3546 (2013).

Photonic q-Plates: A Quantum Interface

Spin angular momentum can be transferred to OAM through use of a q-plate

Ability to change basis of encoding useful for quantum information processing

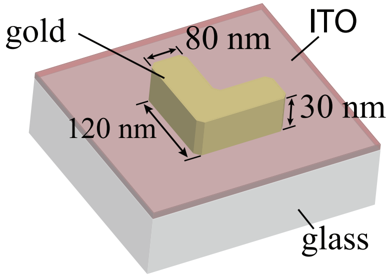


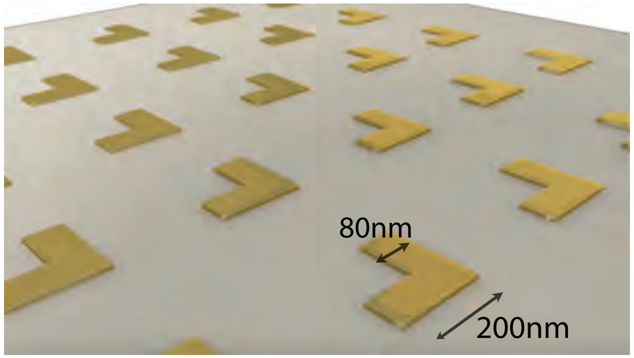
q-plate. Usually a carefully constructed liquid-crystal cell

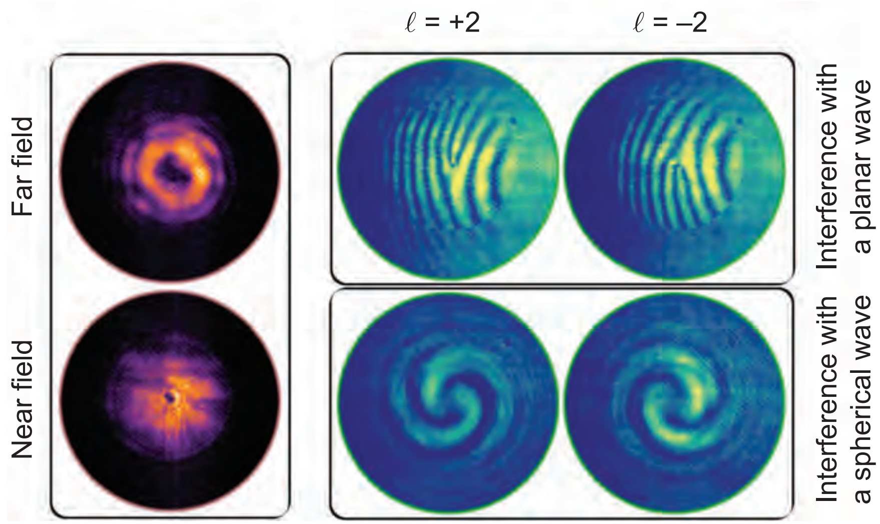
Marrucci et al., PRL 96, 163905 (2006)
Karimi et al., APL 98, 231124 (2009)

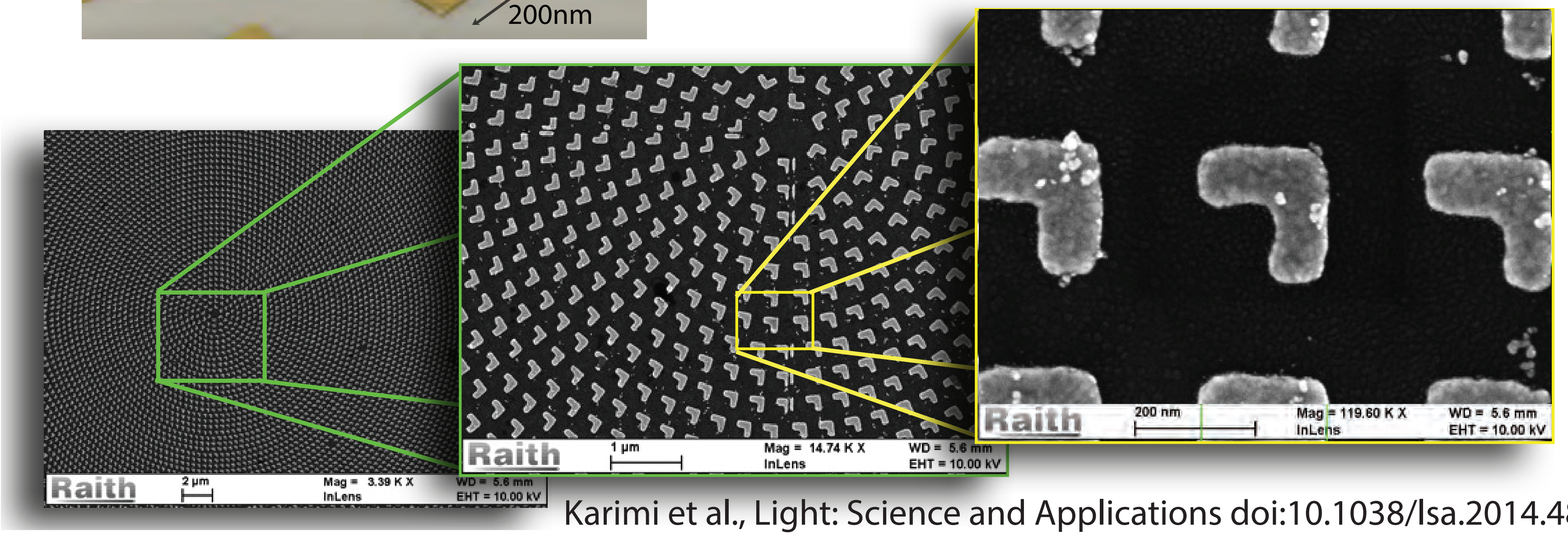
Fabrication of a Nano-Scale q-Plate

- A q-plate is a device that converts spin angular momentum into orbital angular momentum.
- It functions as a quantum interface.
- Fabricated device is only 30-nm thick and thus suitable for use in integrated quantum circuits.



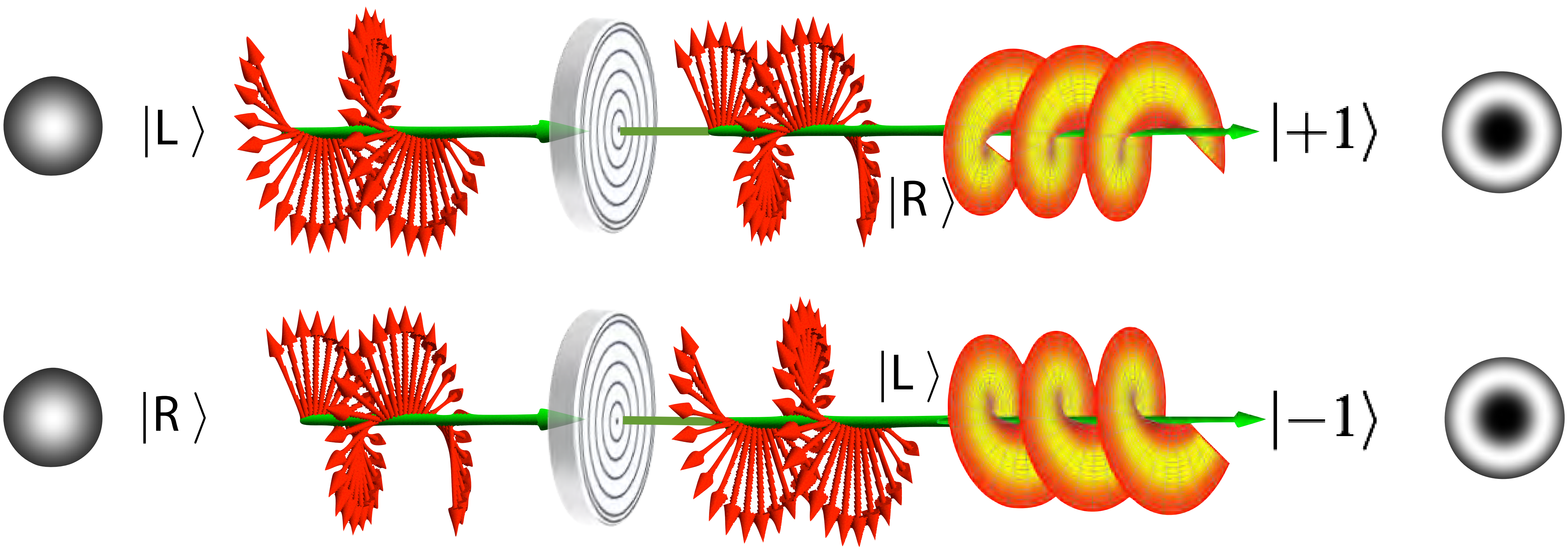






Karimi et al., Light: Science and Applications doi:10.1038/lsa.2014.48 (2014)

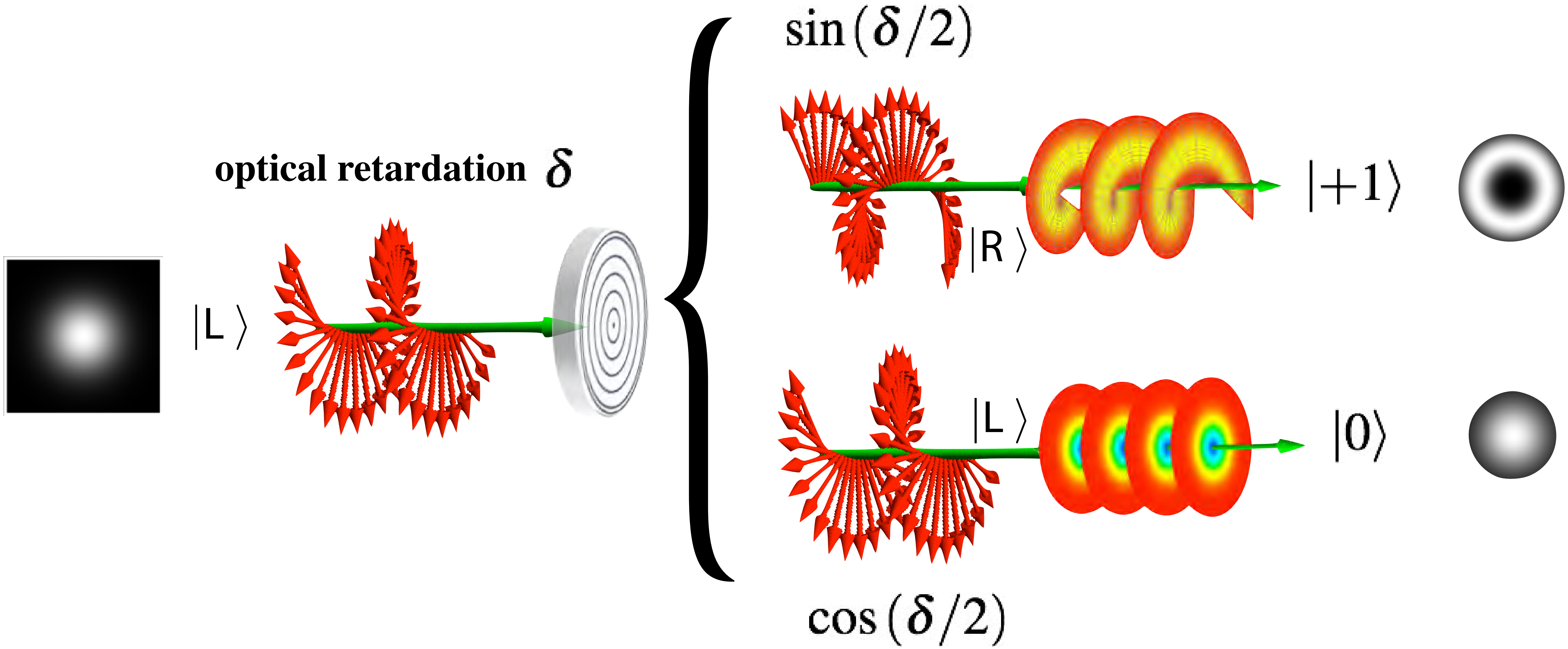
We use a q-plate to couple SAM with OAM



Marrucci, L et al, PRL **96**, 163905 (2006).
Karimi, E et al., APL, **98**, 231124 (2009).

We can control the statistics of the “walking”

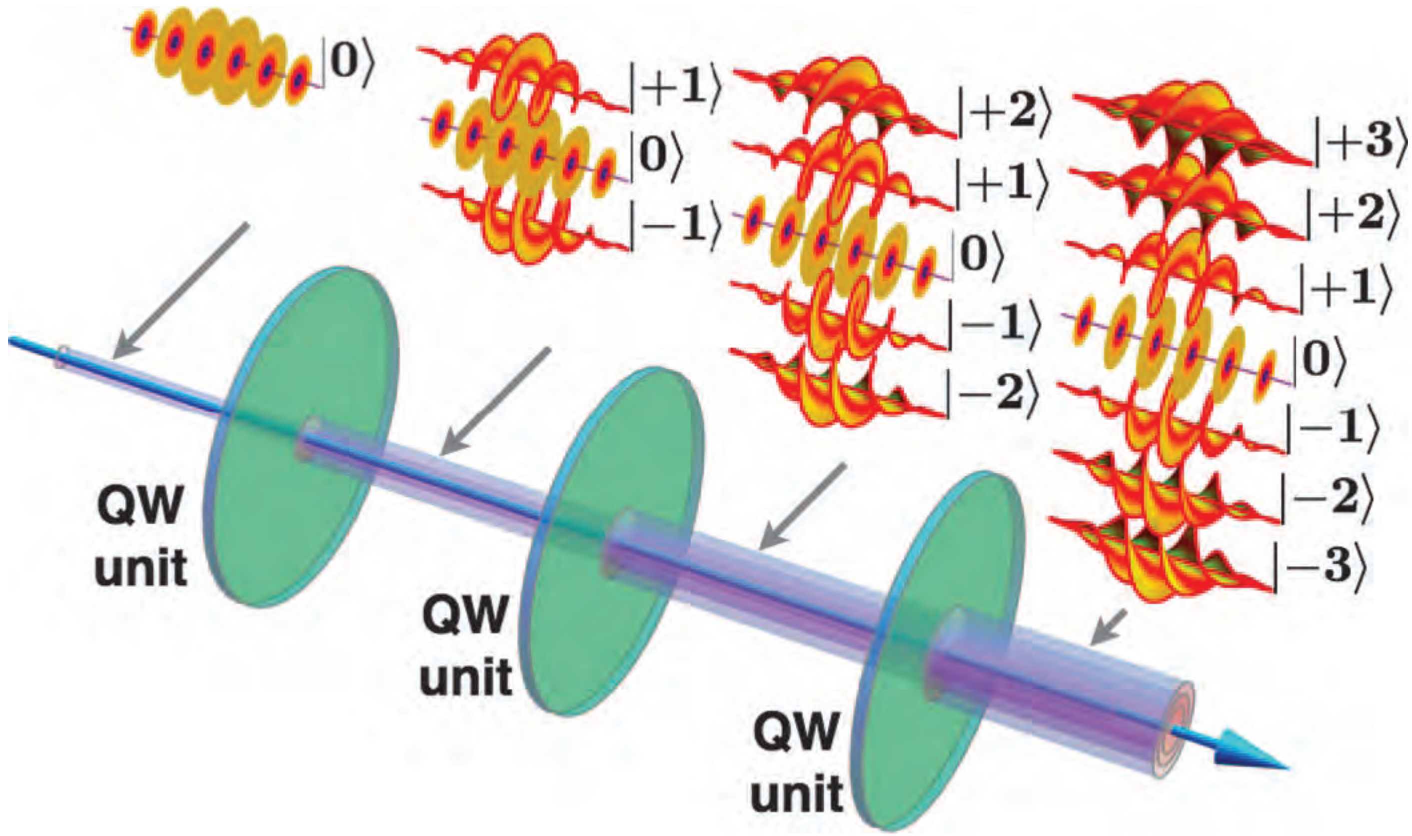
- We control the retardation δ of the q-plate by changing the applied voltage.
- We thus control the fraction of the time that the walker stands still (instead of walking).



Marrucci, L et al, PRL **96**, 163905 (2006).
Karimi, E et al., APL, **98**, 231124 (2009).

Our Quantum Walk Protocol

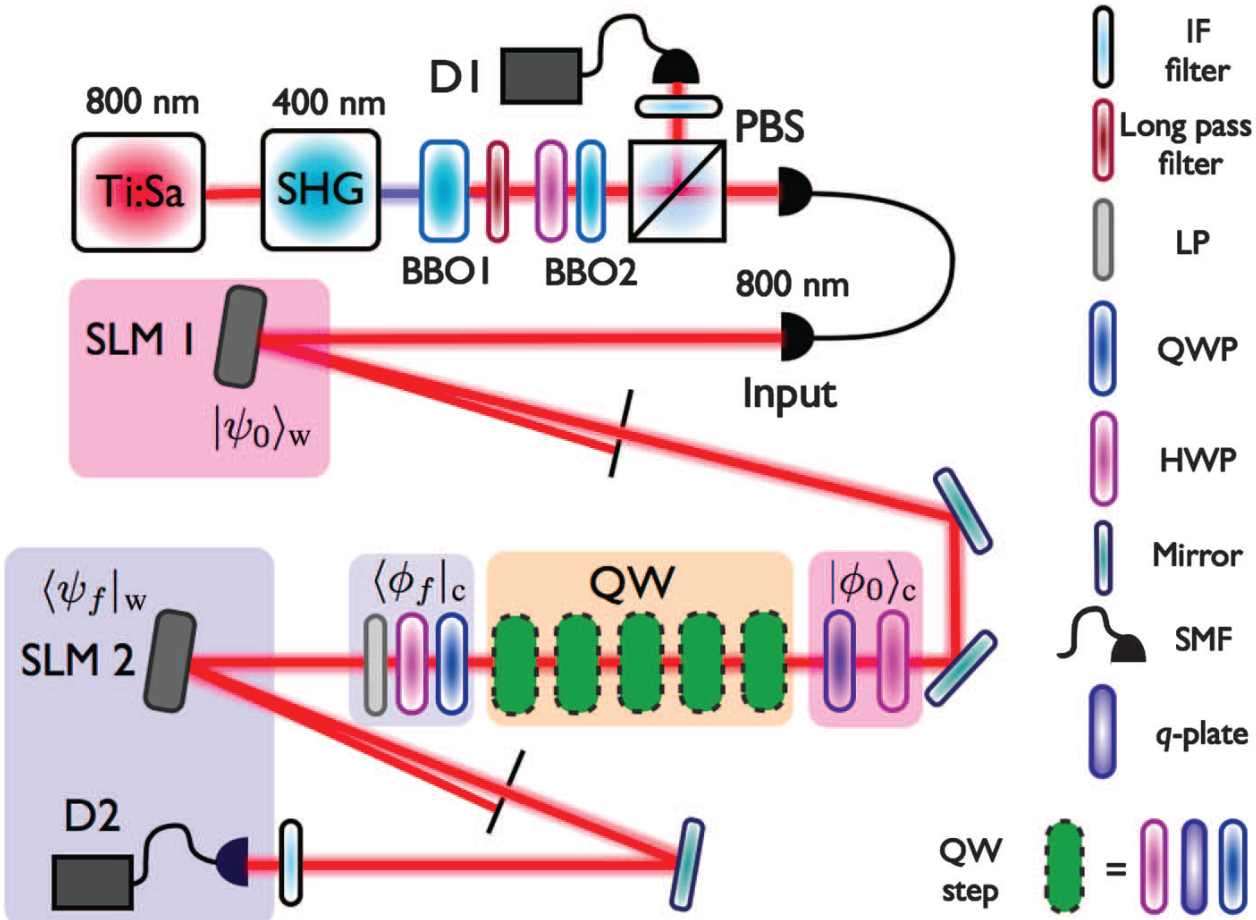
- Quantum Walk in the OAM Space of a Single Photon



- In each Quantum Walk Unit:
  - Polarization of the photon acts as a "coin." Linearly polarized light has 50/50 chance of being RHC (LHC) polarized
  - OAM of the photon increases or decreases depending on the measured polarization state

Cardano et al., Science Advances 1, e1500087 (2015).

Our Experimental Setup



Each quantum walk (QW) step entails passing through a combination of a

- Quarter-wave plate: Converts incident circular polarization to linear
- q-plate: Induces a polarization-dependent change in OAM
- Half-wave plate: Undoes change in polarization due to q-plate

Cardano et al., Science Advances 1, e1500087 (2015).

Quantum Walk Results

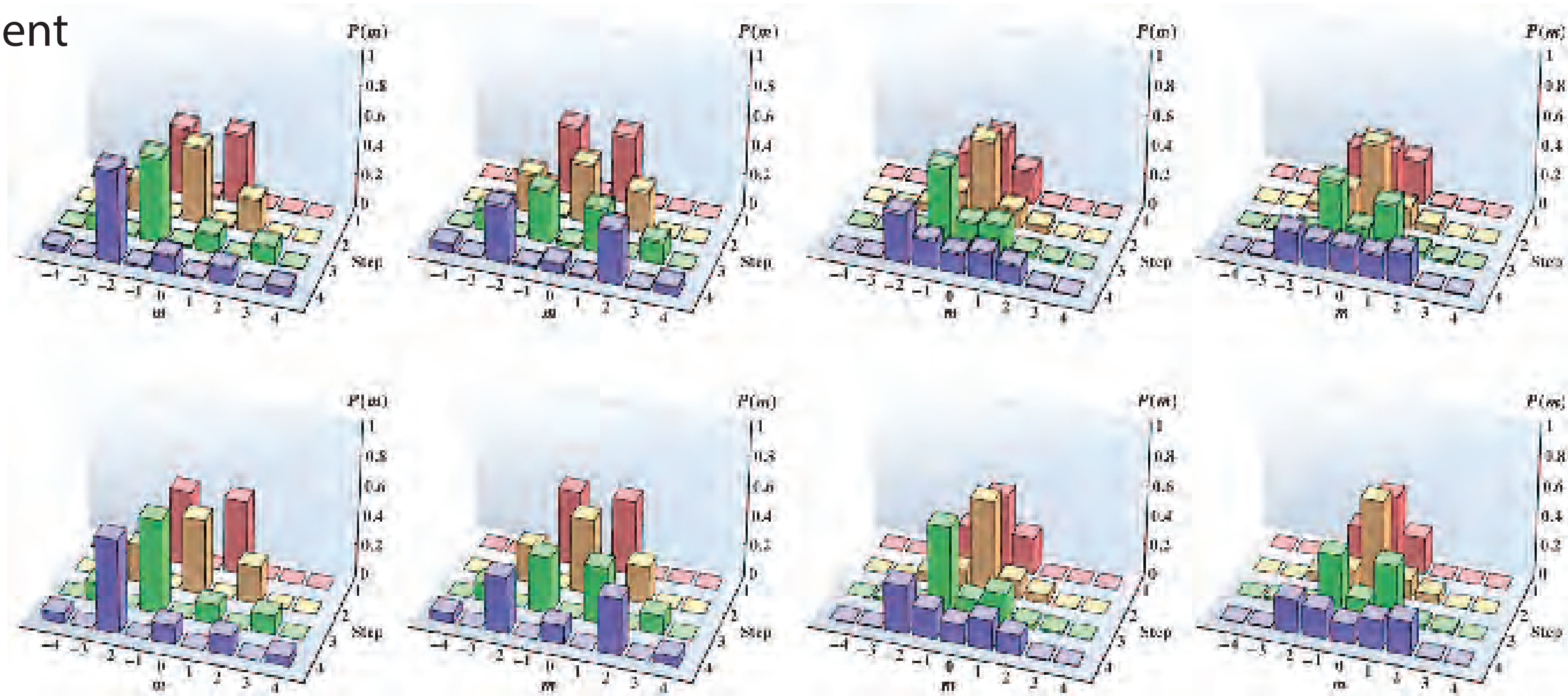
- Input is a single photon with m=0.

$\delta = \pi$, standard quantum walk — $\delta = \pi/2$, hybrid quantum walk

circ pol input | lin pol input | circ pol input | lin pol input

Experiment

Theory



- Theory and experiment agree with a "similarity" of at least 98%. Show only experiment in further visuals.

Cardano et al., Science Advances 1, e1500087 (2015).

Quantum Walk Experimental Results

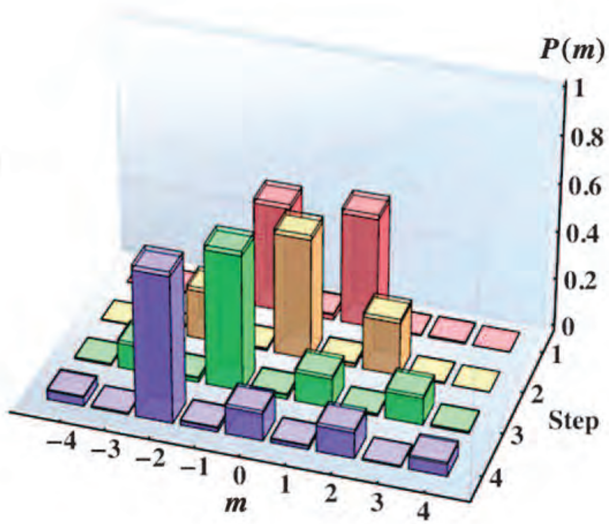
Input is a single photon with m=0.

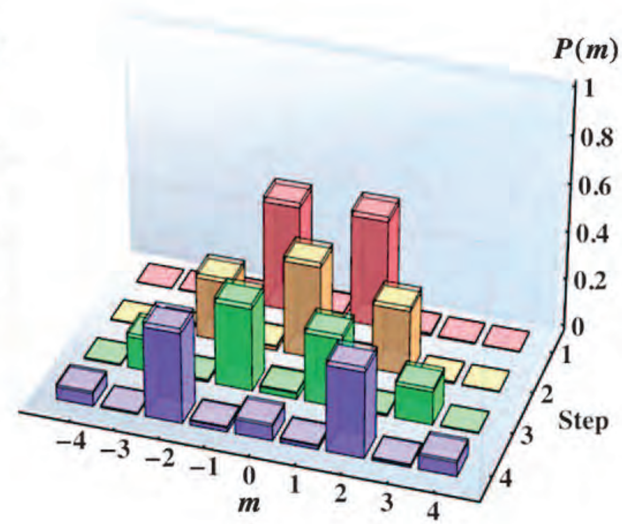
circ pol input (centred at negative m)

lin pol input (centred at m = 0)

$\delta = \pi$, standard quantum walk

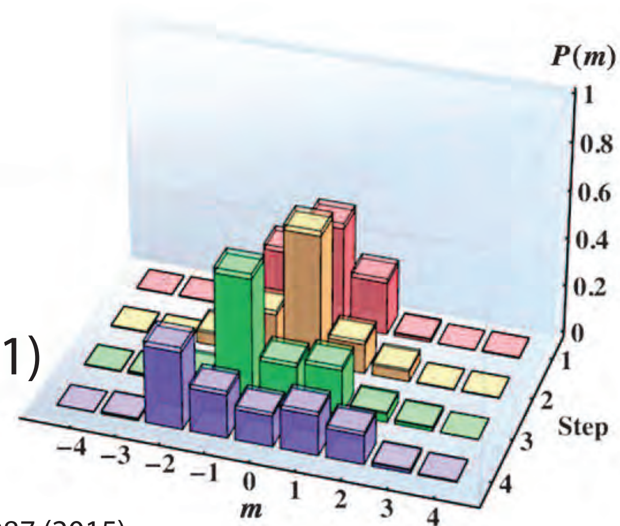
(m changes by +/- 1)

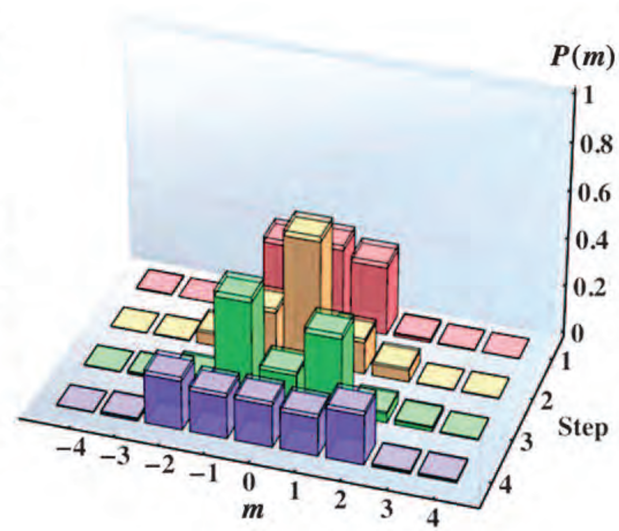




$\delta = \pi/2$, hybrid quantum walk

(m changes by 0, +/- 1)



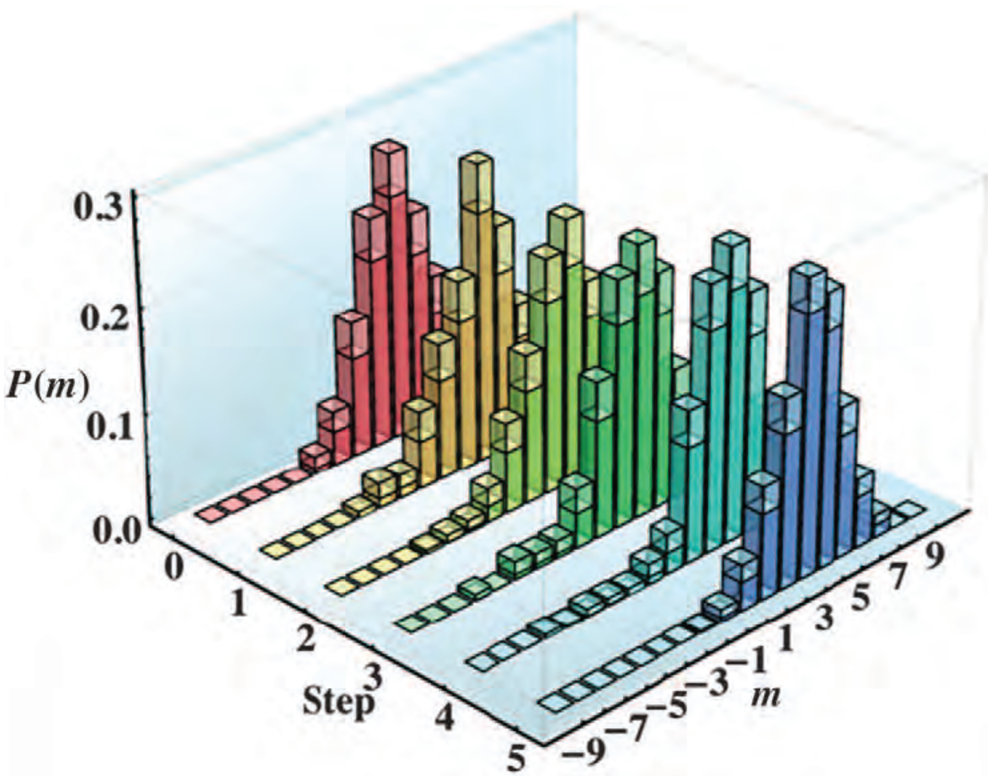


Cardano et al., Science Advances 1, e1500087 (2015).

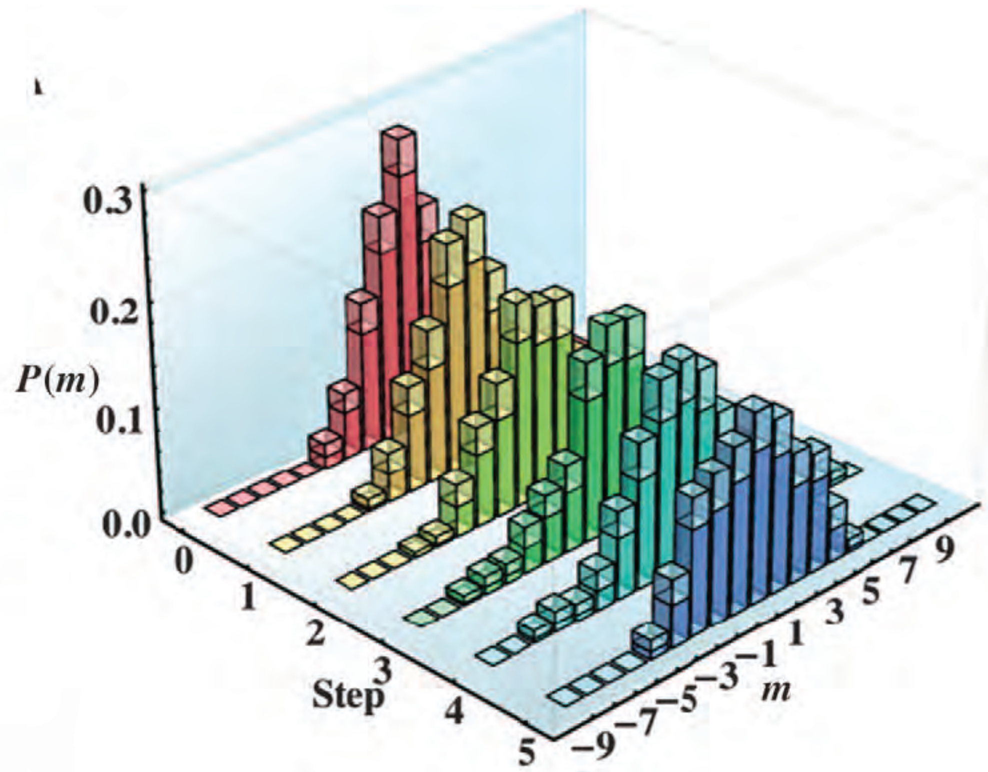
Quantum Simulation of Wavepacket Evolution

Input is a one-photon Gaussian wave packet, for two different sets of parameters

Wavepacket "propagates"



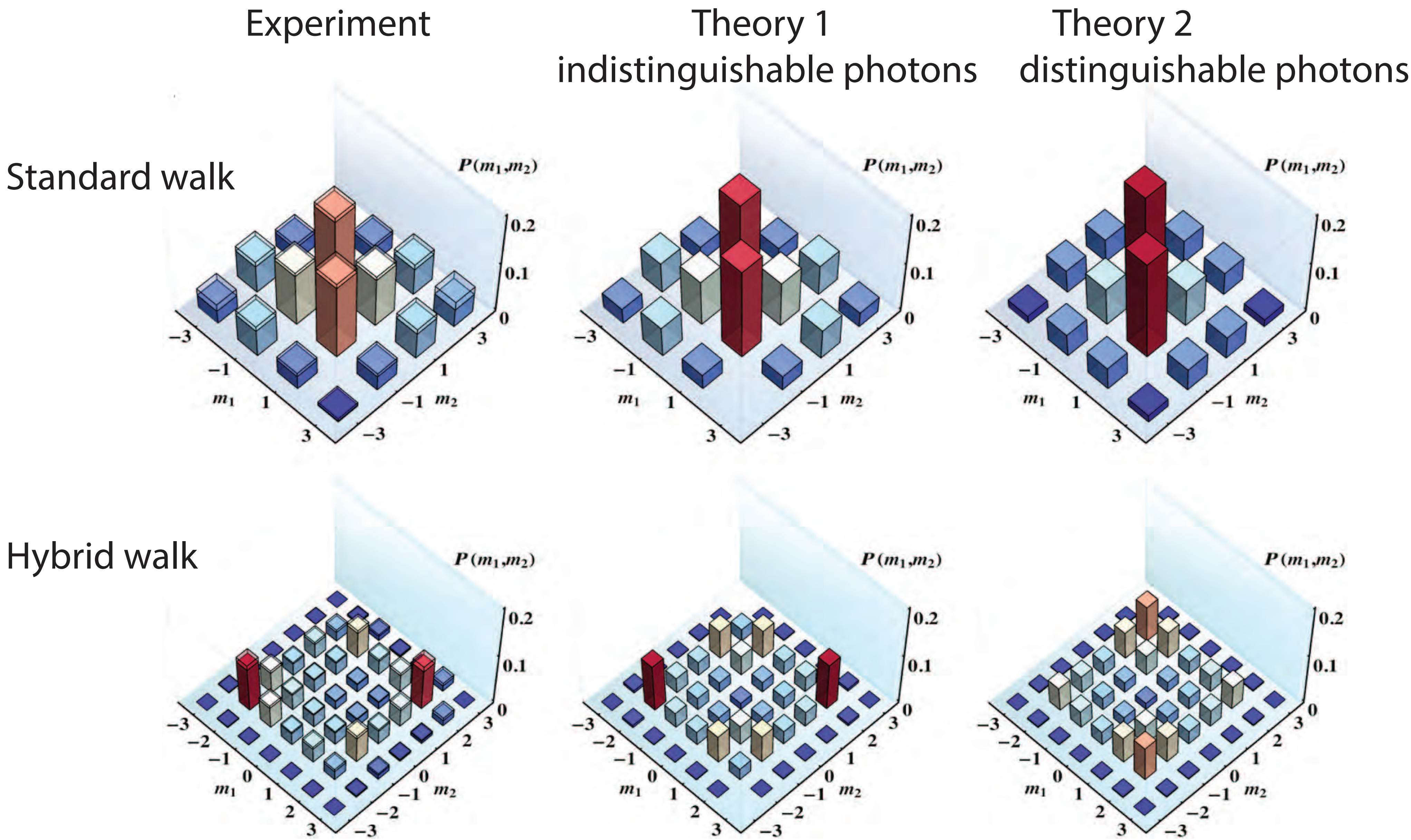
Wavepacket "spreads"



Cardano et al., Science Advances, e1500087 (2015).

Two-Photon Quantum Walk

Input is a two-photon state with $m_1=m_2=0$.



Cardano et al., Science Advances, e1500087 (2015).

Conclusions

We have implemented quantum walk for both one-photon and two-photon input states.

Also implemented a quantum simulator for wavepacket evolution.

Our method entails the coupling of the internal degrees of freedom (SAM and OAM) of a single photon or biphoton.

We thus do not require interferometric alignment of our setup.

Moreover, the resources required for our protocol (number of waveplates, etc.) scales only linearly with the number of steps in the quantum walk