Classical and quantum properties of vector beams

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“Wits”

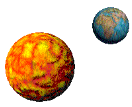
Tingye Li studied here

Angular momentum of light can be separated into two forms

$$j = (l \pm \sigma)\hbar$$

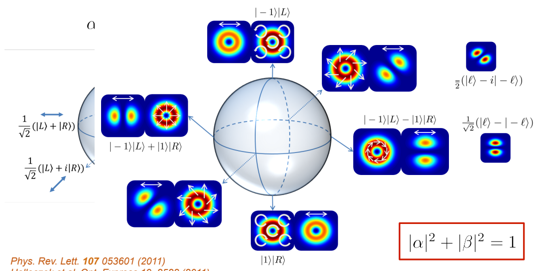
Spin Angular Momentum

Orbital Angular Momentum



Vector states of light can be mapped on a higher-order Poincaré sphere

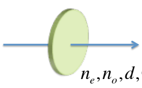
$$|U\rangle = \alpha|-\ell\rangle|L\rangle + \beta|\ell\rangle|R\rangle$$



$$\boxed{|\alpha|^2 + |\beta|^2 = 1}$$

Phys. Rev. Lett. **107** *053601 (2011)*
Holleczek et al. Opt. Express 19, 2528 (2011)

Using the *Geometric phase* we can create vector beams

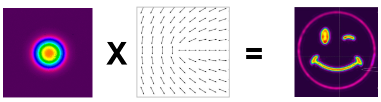


n_e, n_o, d, Φ

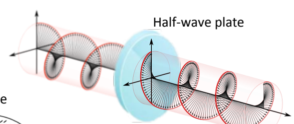
(Anisotropic media)
“extra” phase delay
called **geometric** phase

$$\delta = \left(\frac{n_e + n_o}{2}\right)\frac{2\pi}{\lambda}d \pm 2\Phi$$

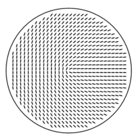
Geometric Phase



For example, spin-orbit coupling using a geometric phase element with an azimuthal phase variation



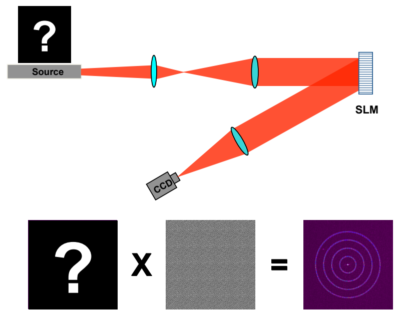
q-plate



$$\begin{pmatrix} \cos 2q\theta & \sin 2q\theta \\ \sin 2q\theta & -\cos 2q\theta \end{pmatrix}$$

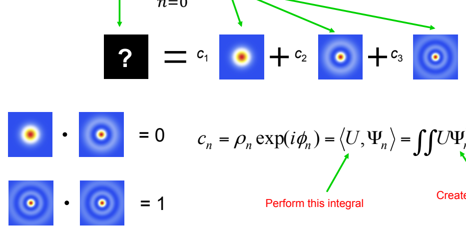
$$\boxed{\begin{matrix} |\ell, L\rangle \rightarrow |\ell + 2q, R\rangle \\ |\ell, R\rangle \rightarrow |\ell - 2q, L\rangle \end{matrix}}$$

Can we use the SLM as a digital tool for the analysis of optical fields and single photons?



The idea is to expand the unknown field into an orthonormal basis and find the unknown coefficients

$$U = \sum_{n=0}^{\infty} c_n \Psi_n$$

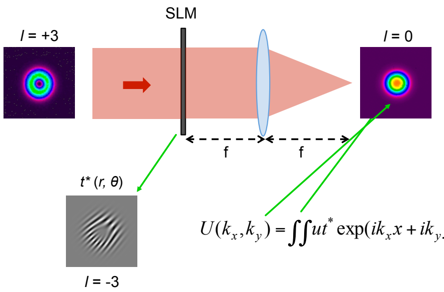


$$c_n = \rho_n \exp(i\phi_n) = \langle U, \Psi_n \rangle = \iint U \Psi_n^* dxdy$$

Perform this integral

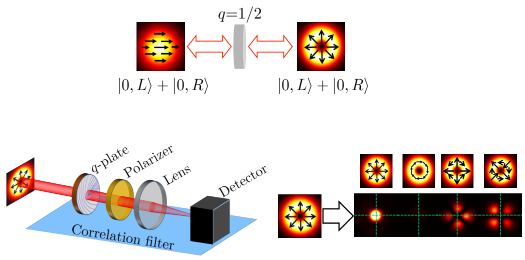
Create these modes

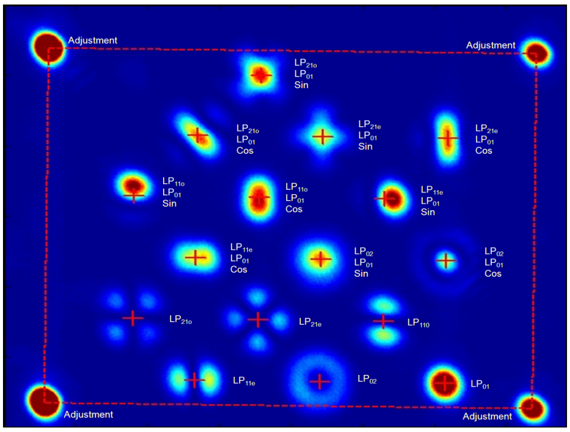
We can pass an unknown field through a match filter to find the inner product



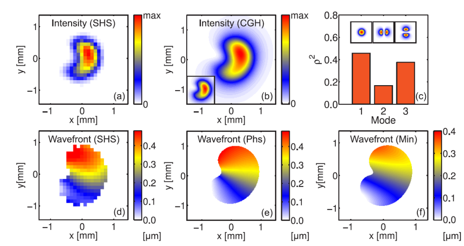
$$U(k_x, k_y) = \iint ut^* \exp(ik_x x + ik_y y) dxdy$$

Vector modes can also be sorted using the modal decomposition tool



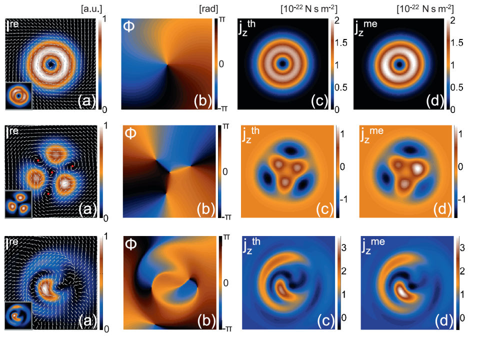


Determining the wavefront of light for scalar, vector and vortex beams



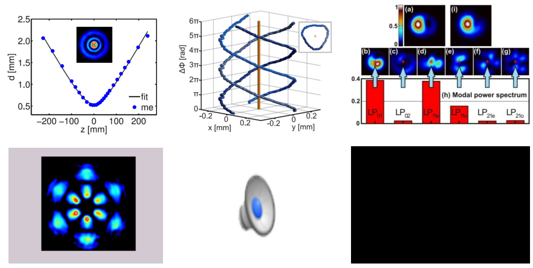
Applied Optics **52**, 5312 (2013)
Optics Express **20**,19714 (2012)

Determining the orbital angular momentum density of light



New J. Physics **15**, 073025 (2013)

Any physical property of the field can be measured; here are some examples

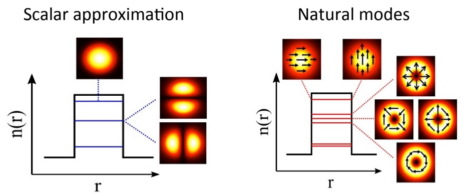


Applied Optics **53**, 5924 (2014)
Optics Express **21**,165 (2013)
Optics Letters **38**, 3429 (2013)

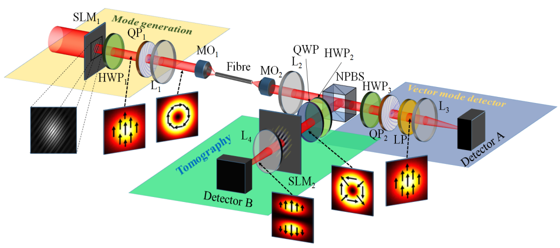
J. Optics **17**, 035617 (2015)
Optics Express **22**, 14031 (2014)
Optics Express **22**, 17553 (2014)

Optics Letters **40**, 435 (2015)
Optics Letters **39**, 704 (2014)

Vector vortex modes are eigenmodes of optical fibres

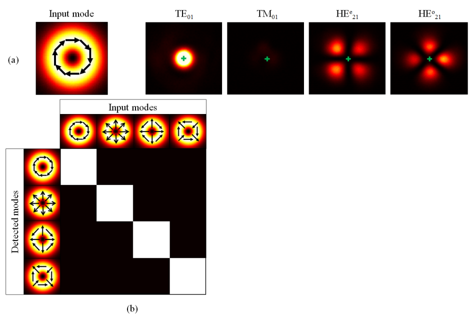


We can excite pure fibre modes with vector beams

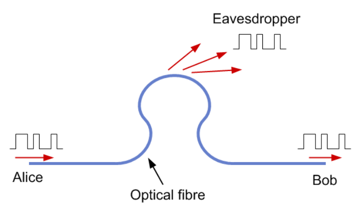


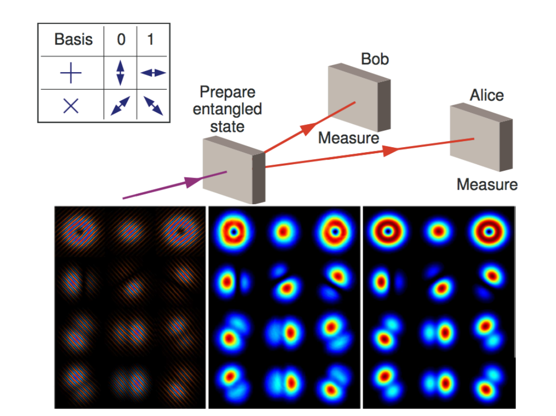
Optics Express **23**, 17330 (2015)

We have a new basis for information encoding



"fast" is not enough … we want it to be fundamentally secure too

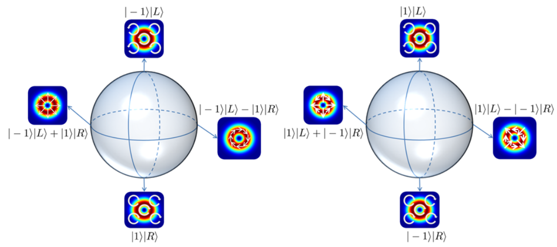




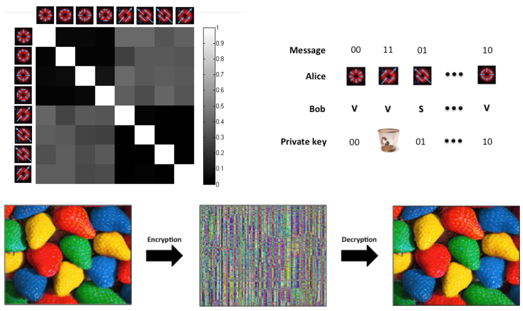
By combining degrees of freedom, we create a larger encoding space

$$\{|R\rangle,|L\rangle\} \longleftarrow \text{Polarization} \otimes \text{OAM} \longrightarrow \{|-\ell\rangle,|\ell\rangle\}$$

$$\{|-\ell,R\rangle,|\ell,R\rangle,|-\ell,L\rangle,|\ell,L\rangle\}$$

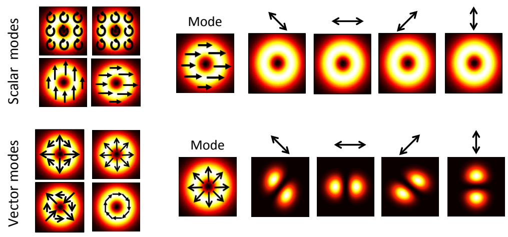


QKD with hybrid states holds promise for encoding information

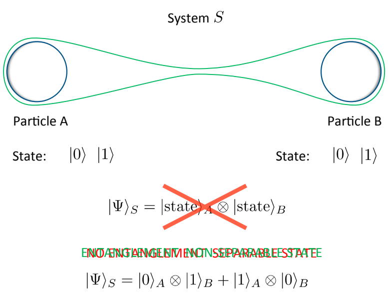


arXiv: 1612.09261 (2016)

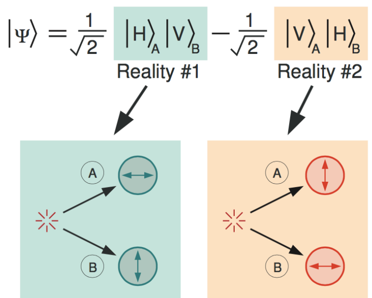
Vector vortex modes have inhomogeneous polarization distributions



We are interested primarily in entangled photonic states

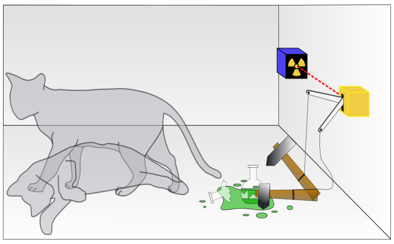


Multiple realities exist as super-positions … in this example as maximally entangled Bell states with polarisation



Entangled particles share information until they are measured

$$|Cat\rangle = |dead\rangle + |alive\rangle$$



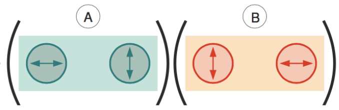
Or by "scattering" the entanglement can be destroyed, producing separable states

$$|\Psi\rangle = \frac{1}{2}|H\rangle_A|V\rangle_B - \frac{1}{2}|H\rangle_A|H\rangle_B + \frac{1}{2}|V\rangle_A|V\rangle_B - \frac{1}{2}|V\rangle_A|H\rangle_B$$

... can be factored (separated)

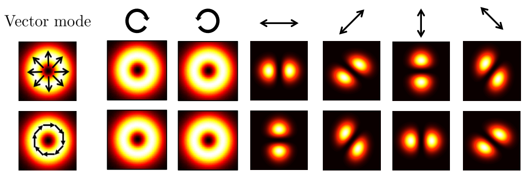
$$|\Psi\rangle = \frac{1}{2}\left(|H\rangle_A + |V\rangle_A\right)\left(|H\rangle_B - |V\rangle_B\right)$$

$|\psi\rangle = \frac{1}{2}$



Separability $\Rightarrow$ Not entangled

Non-separability is not unique to quantum mechanics!



Vector vortex beam

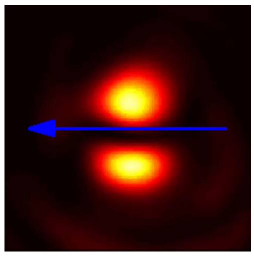
$$|\Psi\rangle = |\ell\rangle_1|R\rangle_2 + |\text{-}\ell\rangle_1|L\rangle_2$$

Equivalent?

Quantum entangled state

$$|\Psi\rangle = |\ell\rangle_1|\text{-}\ell\rangle_2 + |\text{-}\ell\rangle_1|\ell\rangle_2$$

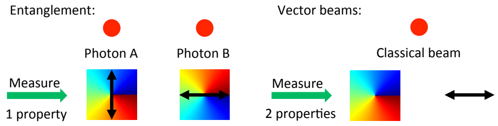
A measurement on one degree of freedom affects the outcome of the other



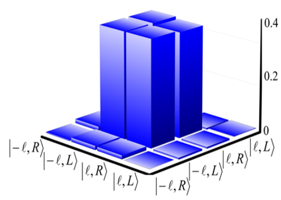
Doesn't this reminds us of quantum entanglement?

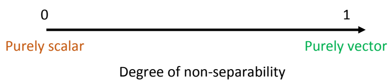
Entanglement: $|\psi\rangle_{AB} = |\ell\rangle_A|-\ell\rangle_B + |-\ell\rangle_A|\ell\rangle_B$

Vector beams: $|\psi\rangle = |\ell\rangle|R\rangle + |-\ell\rangle|L\rangle$

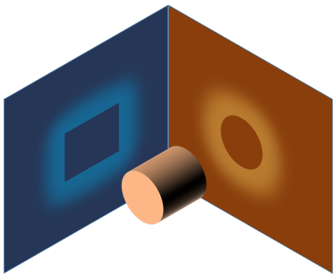


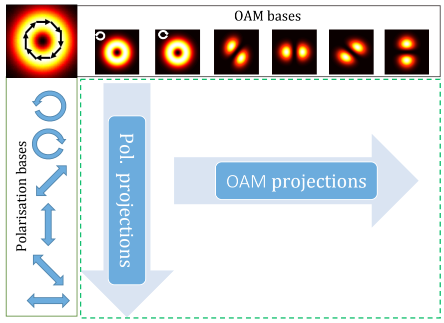
Can we use quantum tools to describe vector beams?



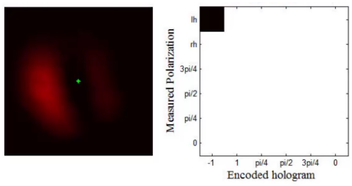


We perform a state tomography to reconstruct the density matrix



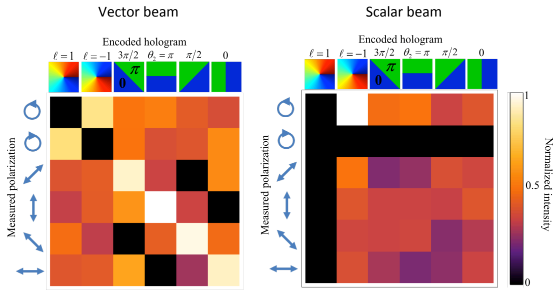


Full state tomography of the output beam



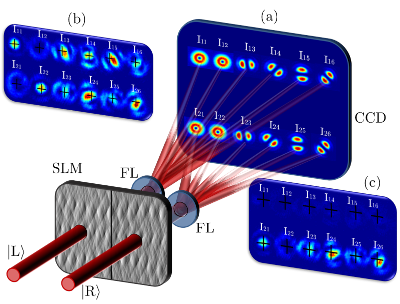
Phys. Rev. A **92** 023833 (2015)

Our tomography measurements reveal the vector or scalar nature of the field



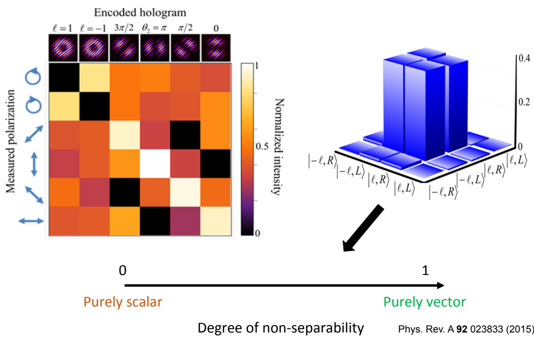
Phys. Rev. A **92** 023833 (2015)

This can all be done in a single shot by multiplexing the light



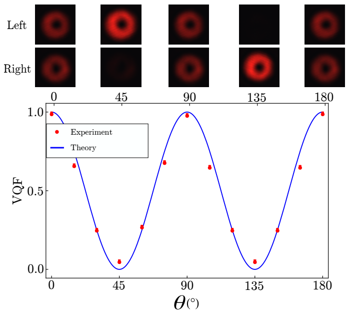
Optics Letters **41**, 3407 (2016)

Quantifying non-separability: vectorness

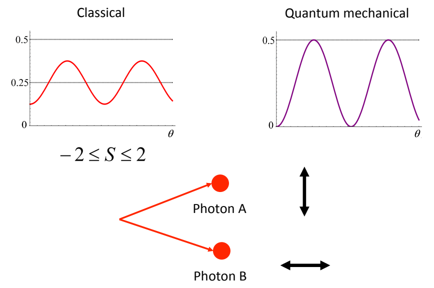


Phys. Rev. A **92** 023833 (2015)

We confirm the approach using a "tunable" vectorness

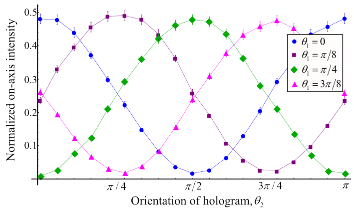


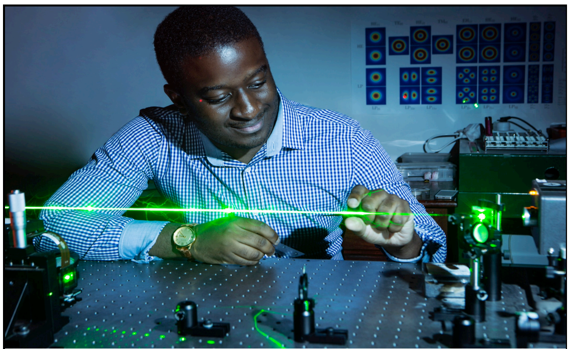
Bell inequality distinguishes classical & quantum correlations



Vector beams violate the Bell inequality?

$S = 2.72 \pm 0.01$

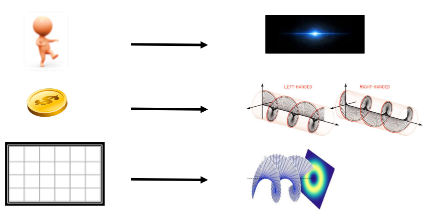




Classical entanglement?

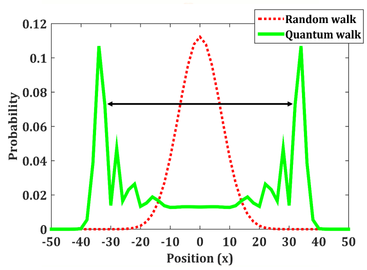
But can we harness it?

Walking non-separable classical light

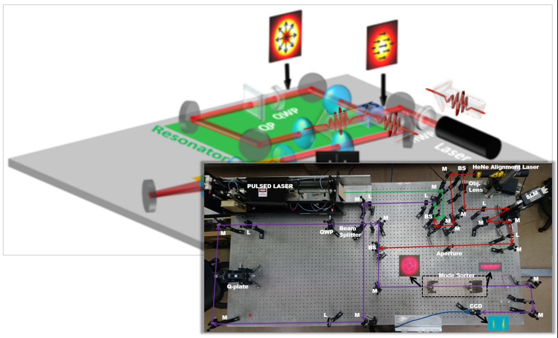


PRL **110**, 263602 (2013)

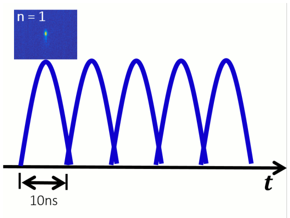
Easy to tell which from the walker distribution … quantum is exponentially faster pace



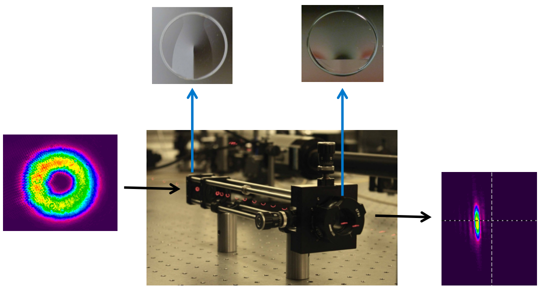
This is how the walk looks experimentally



Selecting the right step is a little more tricky: a matter of timing

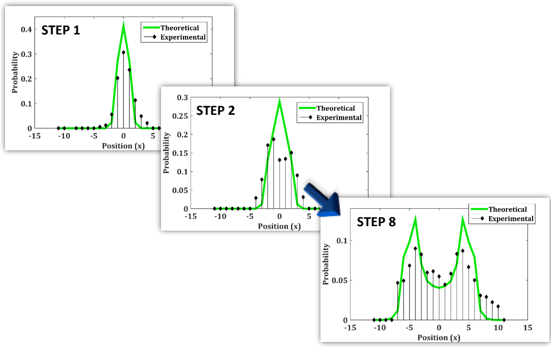


Detection is achieved by unwrapping our phase, mapping OAM to positions

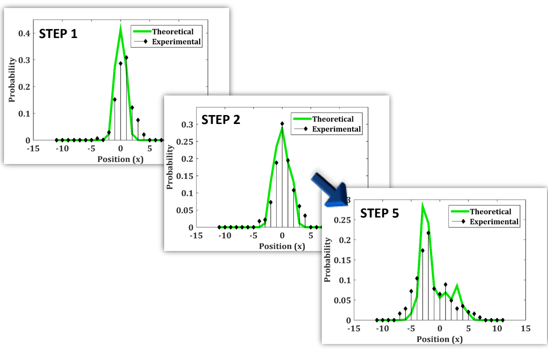


PRL **105**, 153601 (2010).

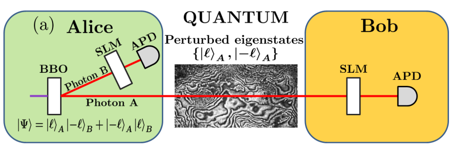
We have demonstrated a quantum walk with twisted classical light



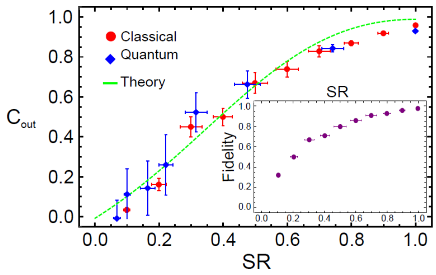
and playing with our symmetry…



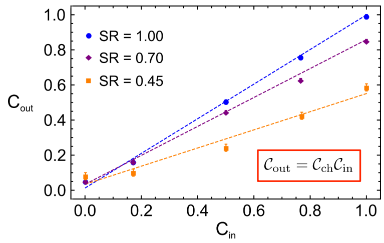
Blurring the classical-quantum divide



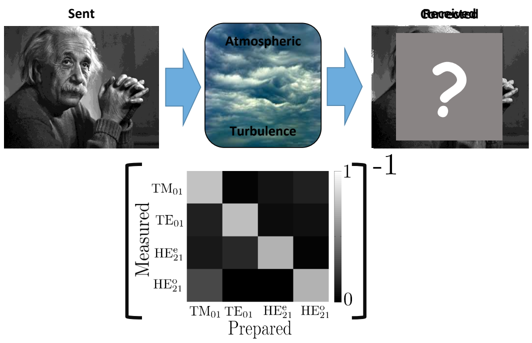
Nature can't distinguish between the decay of non-separable classical states and quantum entangled states



By the Choi- Jamiolkowski Isomorphism, there is a 1:1 correspondence between the state and the channel

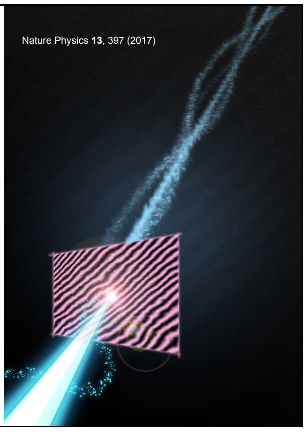


Real-time quantum error correction with classical light



Quantum error correction

Using classical fields



Thank You

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