Quantum walks (QWs) of correlated photons in engineered photonic lattices

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2025/01/15

Content

Quantum Simulation (QS)

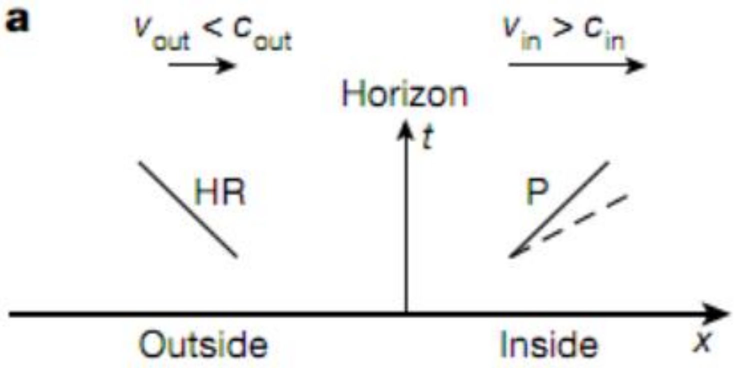
Richard Feynman

One could employ a controllable quantum system to mimic other quantum systems to dispose of these intractable problems

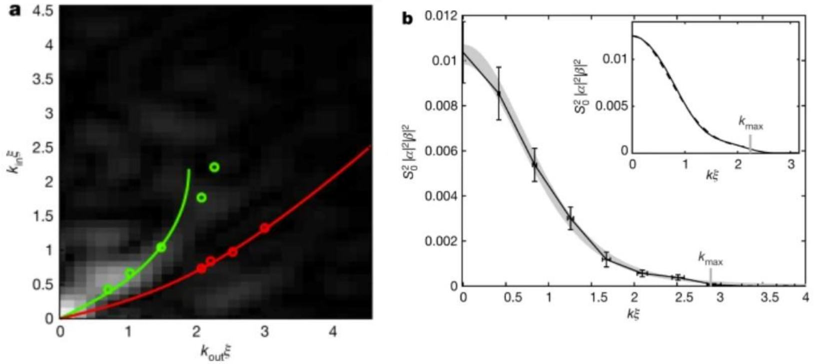
■ Quantum computation

■ Hawking Radiation

■ Hawking radiation using QS



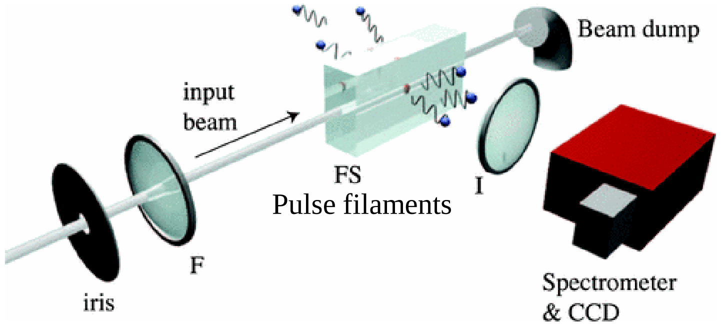
Bose-Einstein Condensate (BEC)



Nature 569, 688 (2019)

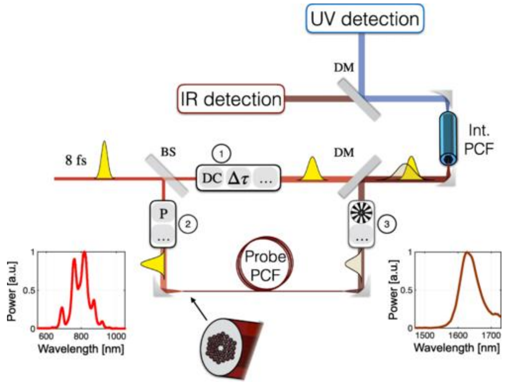
Photonic Quantum Simulation

- Spontaneous Hawking radiation



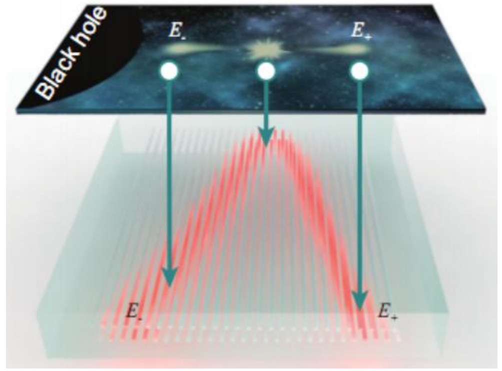
Phys. Rev. Lett. 105, 203901 (2010)

- Stimulated Hawking radiation



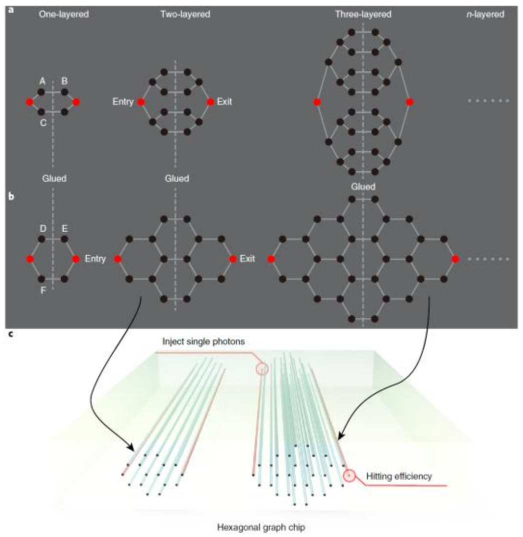
Phys. Rev. Lett. 122, 010404 (2019)

- Dirac particle separation



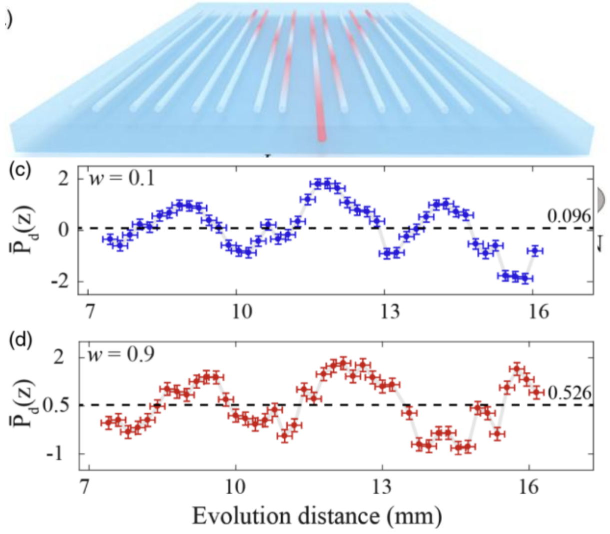
National Science Rev. 7,1476 (2020)

- Quantum fast hitting



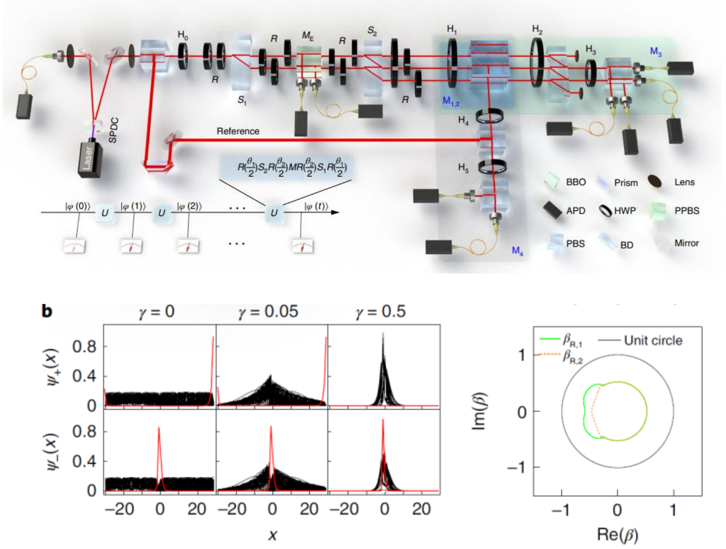
Nat. Photon 12, 754 (2018)

- Topological physics



Phys. Rev. Lett. 122, 193903 (2019)

- Non-Hermitian physics

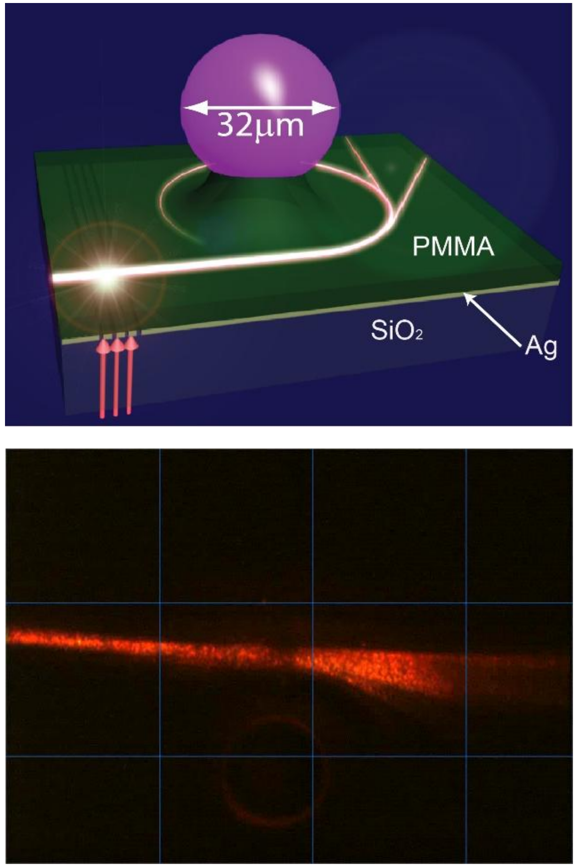


Nat. Physics 16, 761 (2020)

On-chip Photonic Simulation @ our group

- Black hole-like cavity

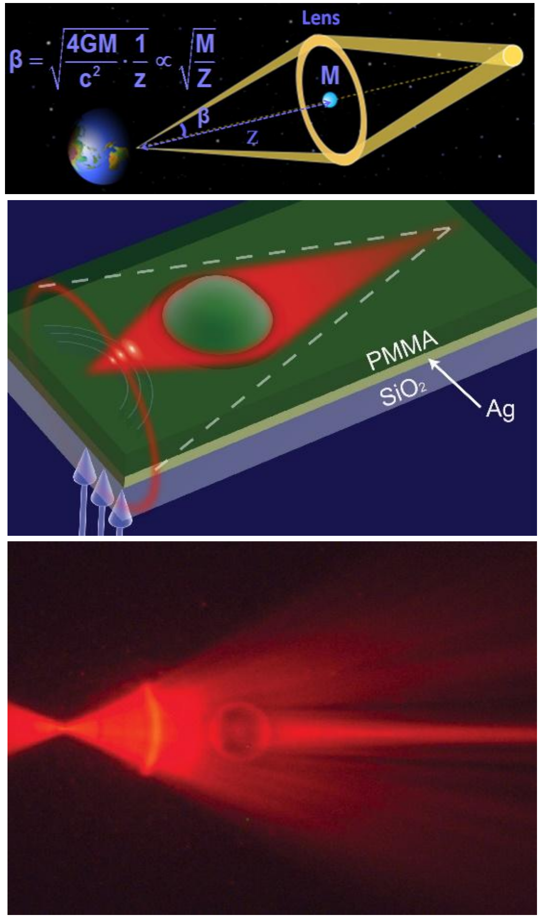
$$n(r) \propto 1/r^2$$



Nat. Photon 7,903 (2013)

- Einstein ring

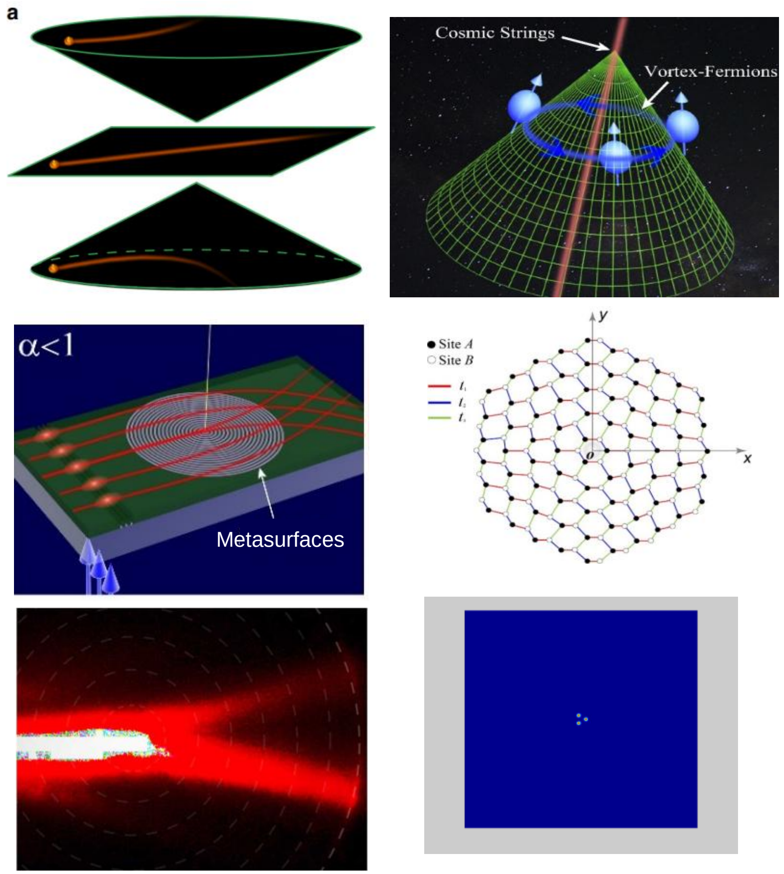
$$n(r) \propto a/(1+(r/r_c)^b)$$



Nat. Commun. 7,10747 (2016)

- Cosmic string

$$n = \begin{bmatrix} n_r & 0 \\ 0 & n_\theta \end{bmatrix} \quad \alpha = n_r/n_\theta$$

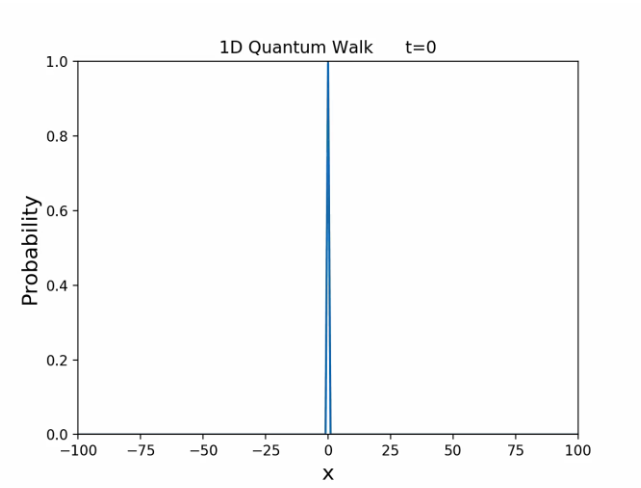


Nat. Commun. 9,4271 (2018)

Light Sci. Appl.11, 243 (2022）

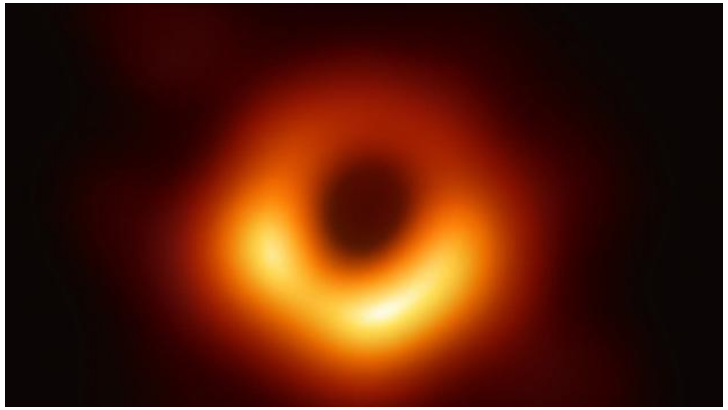
QWs using photonic lattices

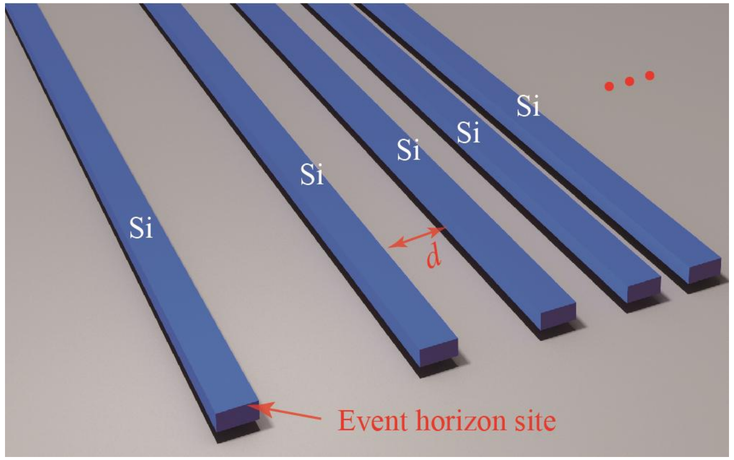
QWs & silicon photonics



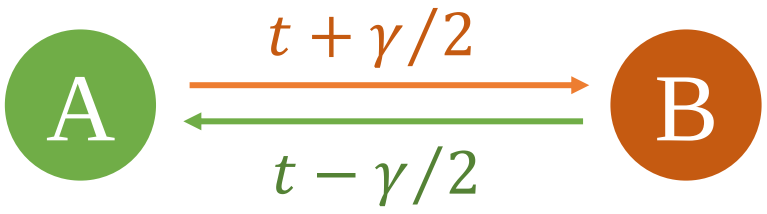
CMOS fabrication

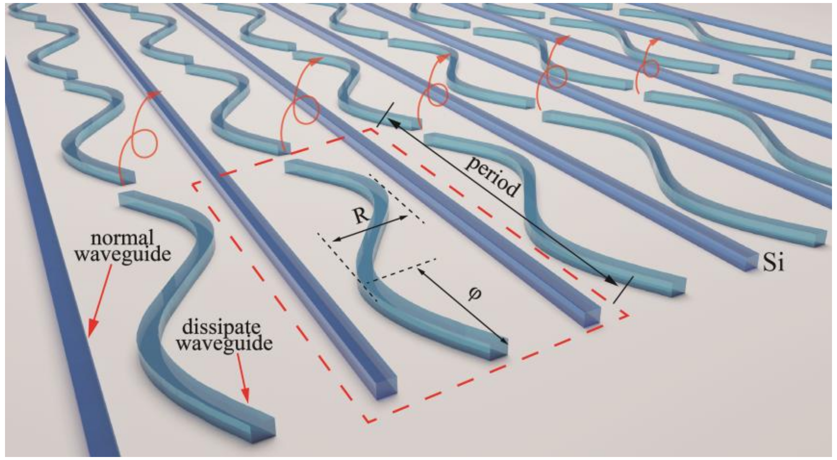
QWs in curved space





QWs in non-Hermitian system



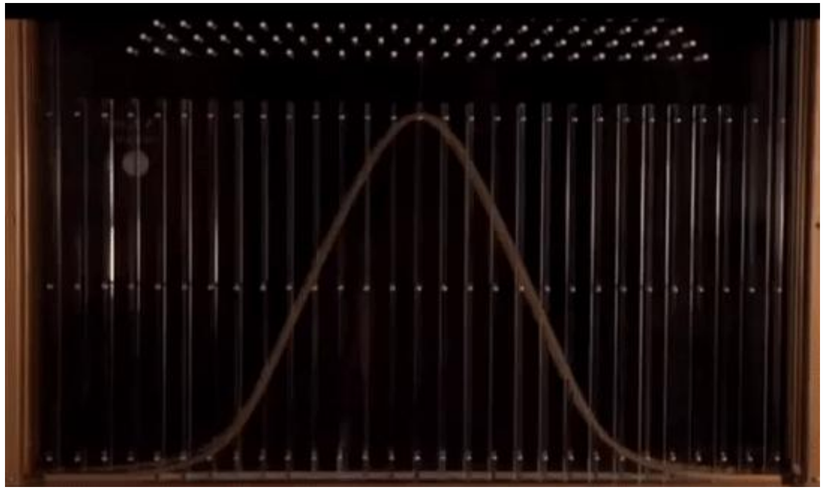


Content

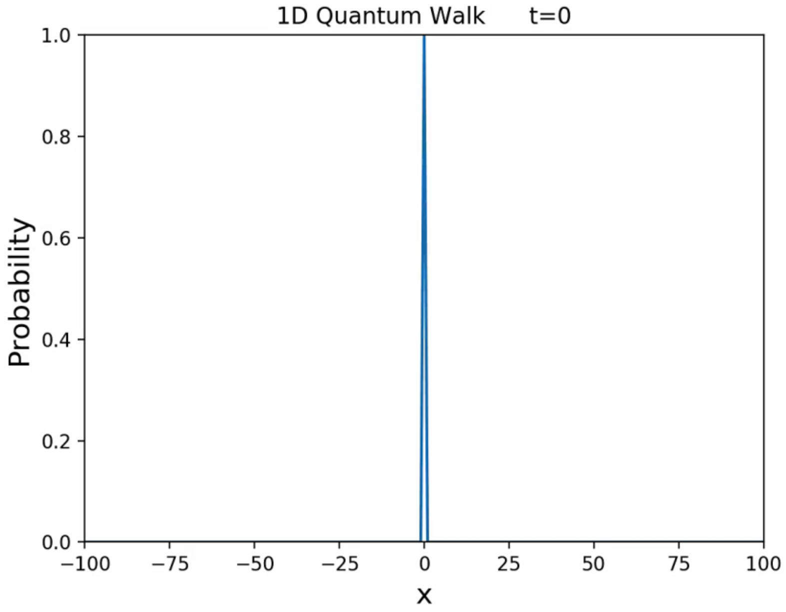
QWs in curved space

Motivation: What about quantum walks in curved space?

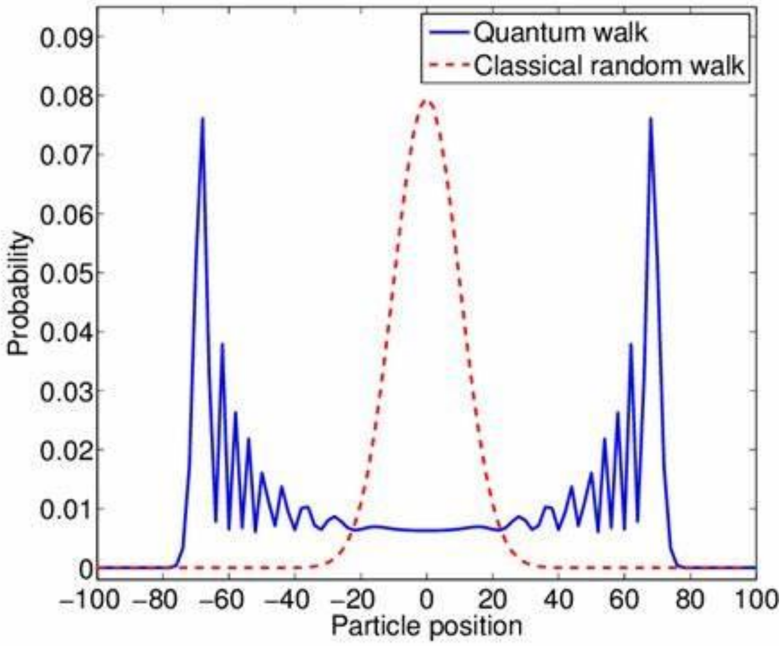
- Classical random walk



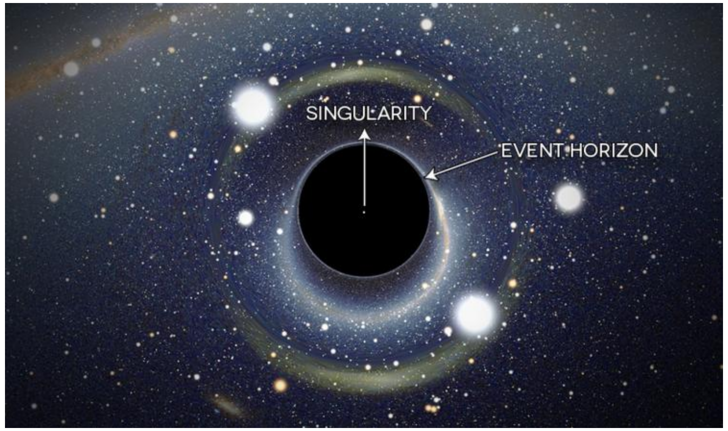
- Quantum walk



- The comparison

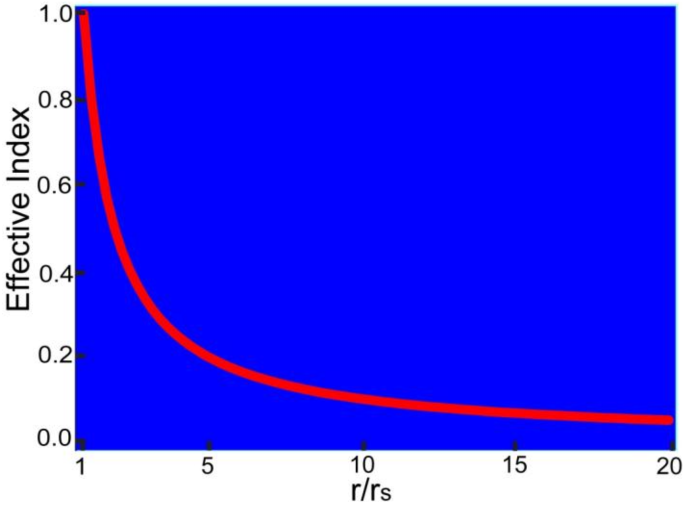


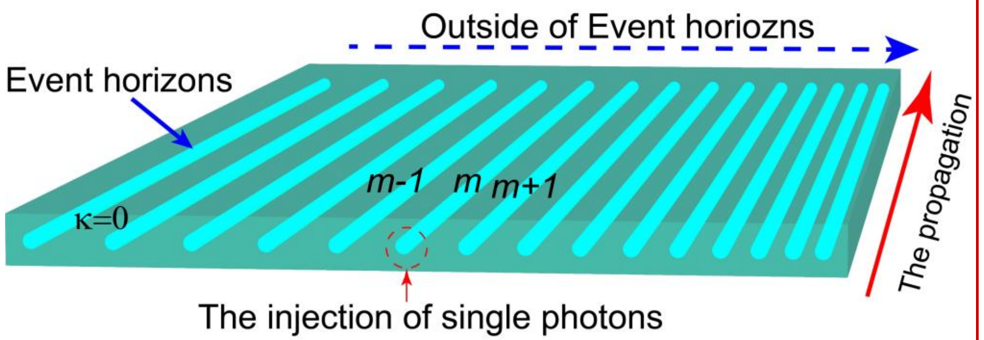
Synthetic horizons using photonic lattices



Metric: $ds^2 = -(\alpha r)^2 dt^2 + dr^2$

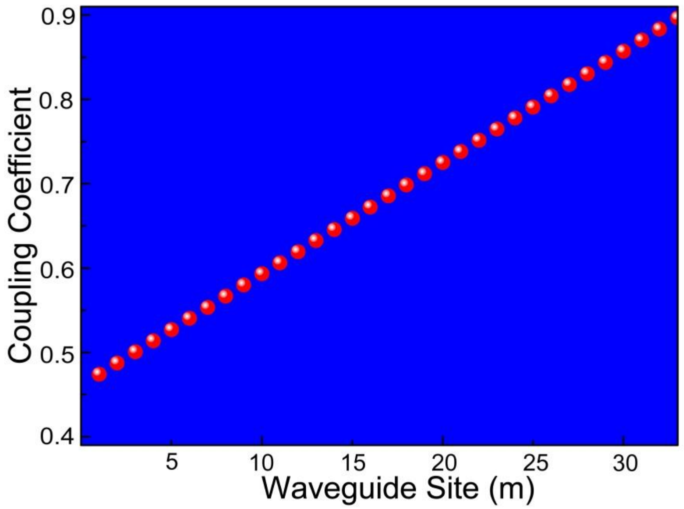
Velocity: $v = dr/dt \propto r$



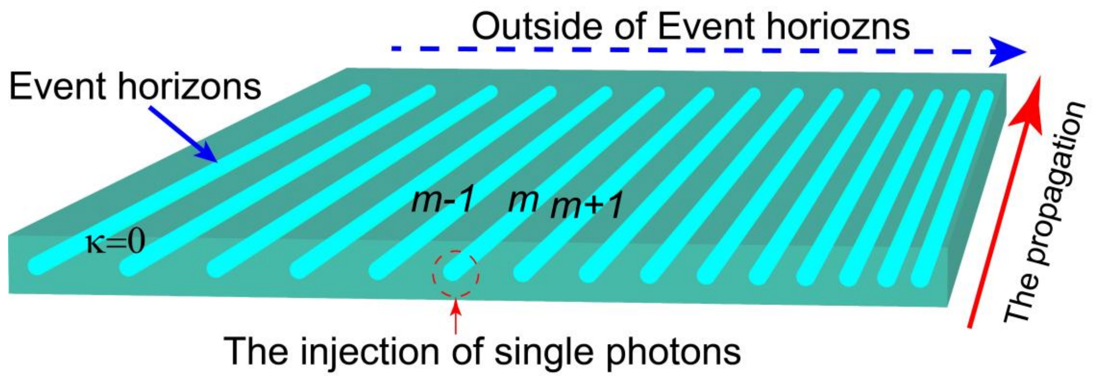


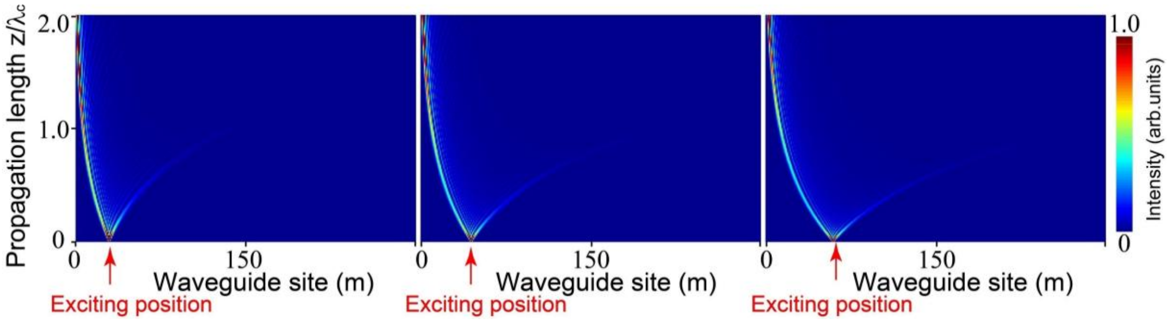
Velocity: $v \propto \kappa$

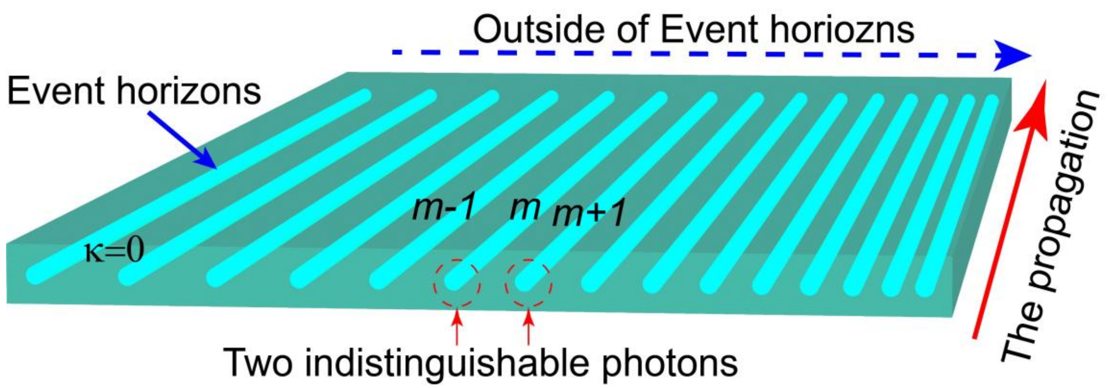
Coupling coefficients: $\kappa(m) \propto \alpha m$



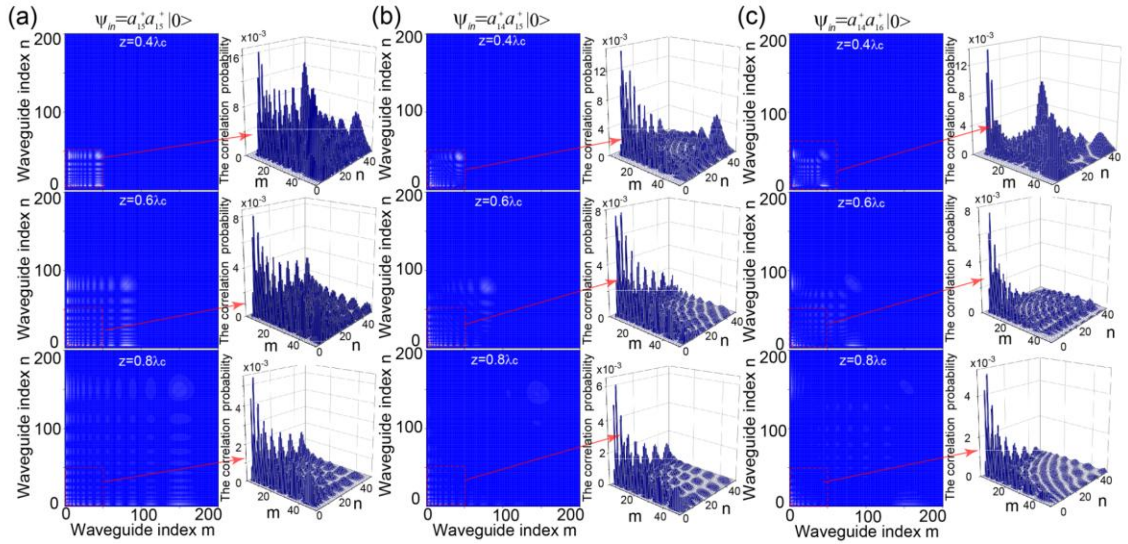
Trapping photons by synthetic horizons







Space correlation spectrum



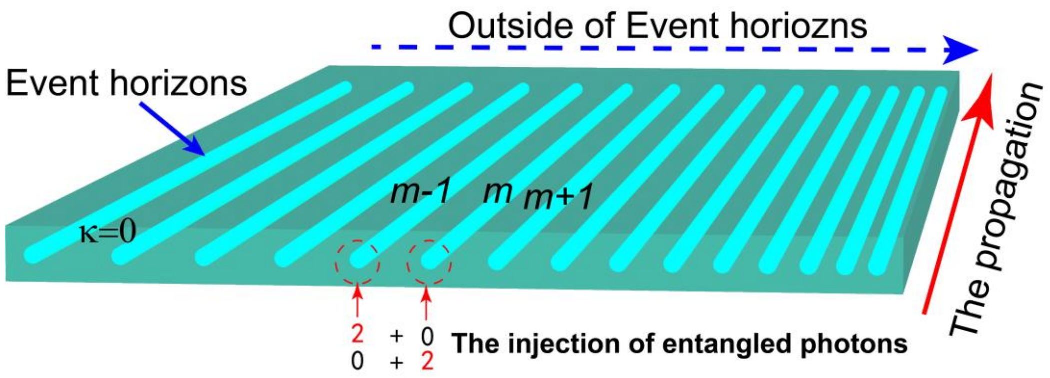
Green Function: $U_{mn} = \frac{1}{2\pi}\int_{-\pi}^{\pi} dq exp\left\{inq - i2m \cdot arctan\left[tanh\left(arctanh\left[tan\frac{q}{2}\right] - \frac{\kappa z}{2}\right)\right] - i\beta_0 z\right\}$

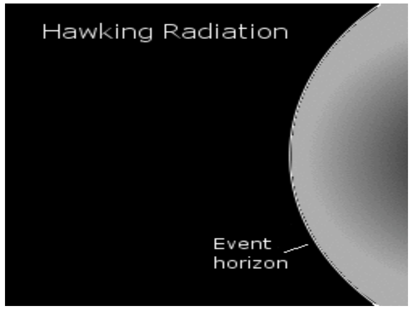
when $\kappa z/2 \gg 1$, the simplified Green Function:

$$U_{mn} = \boldsymbol{\delta}(\boldsymbol{n}) exp(im\pi/2 - i\beta_0 z)$$

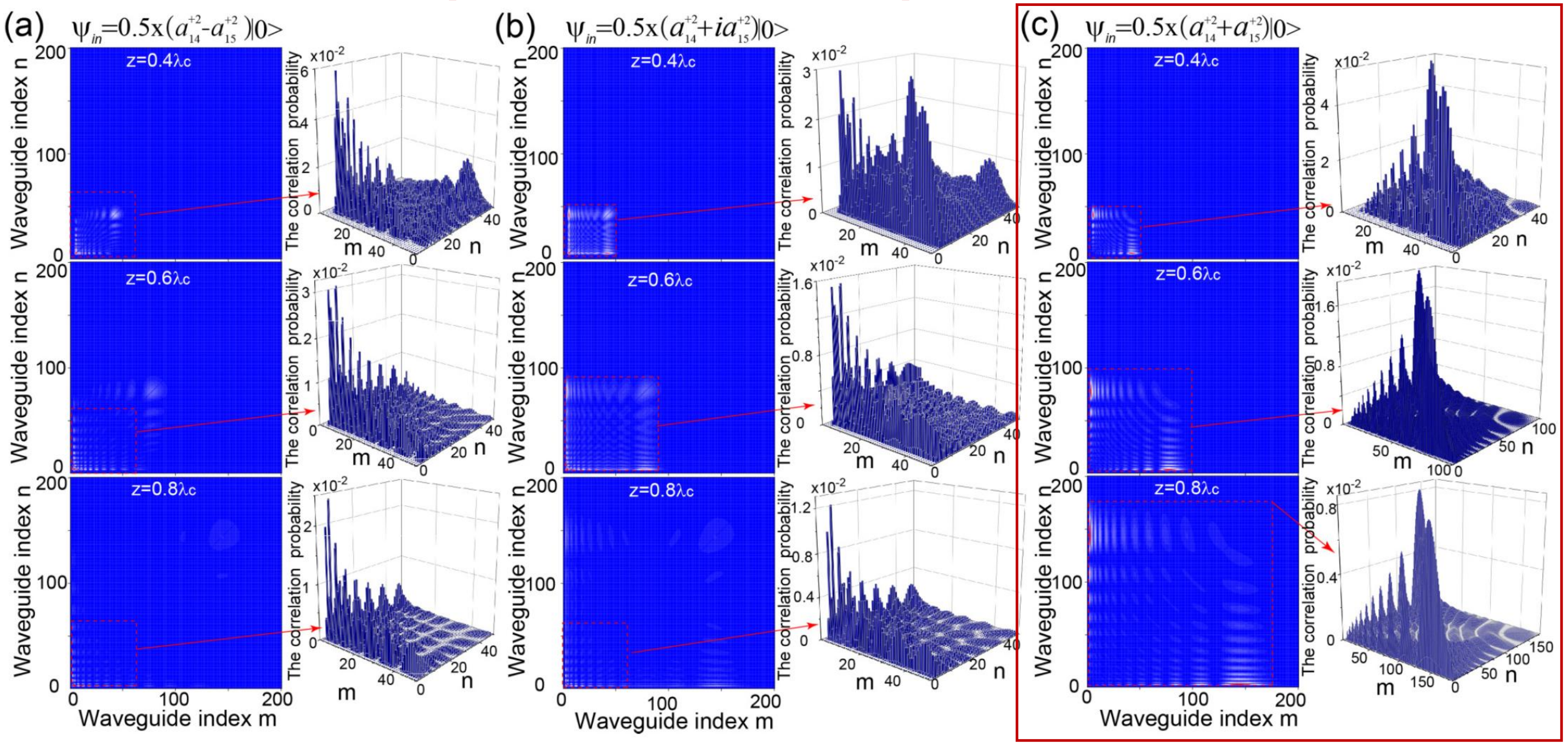
Chong Sheng*,…, Shi-Ning Zhu, Hui Liu*, Phys. Rev. A 103, 099703 (2021)

Photons escape cause by quantum inferences





Space correlation spectrum

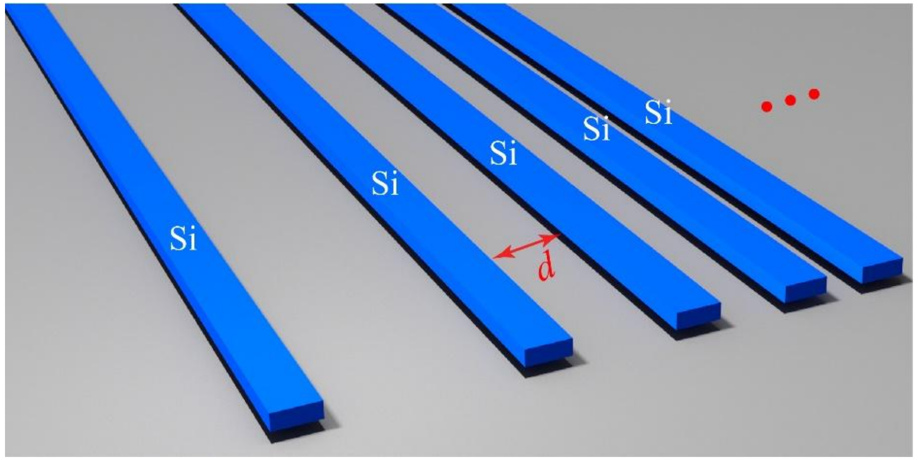


Photon escape caused by **quantum interference**

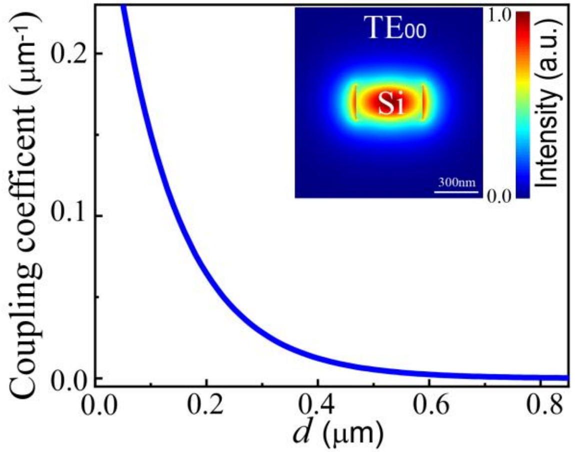
Chong Sheng*,…, Shi-Ning Zhu, Hui Liu*, Phys. Rev. A 103, 099703 (2021)

Experimental demonstration

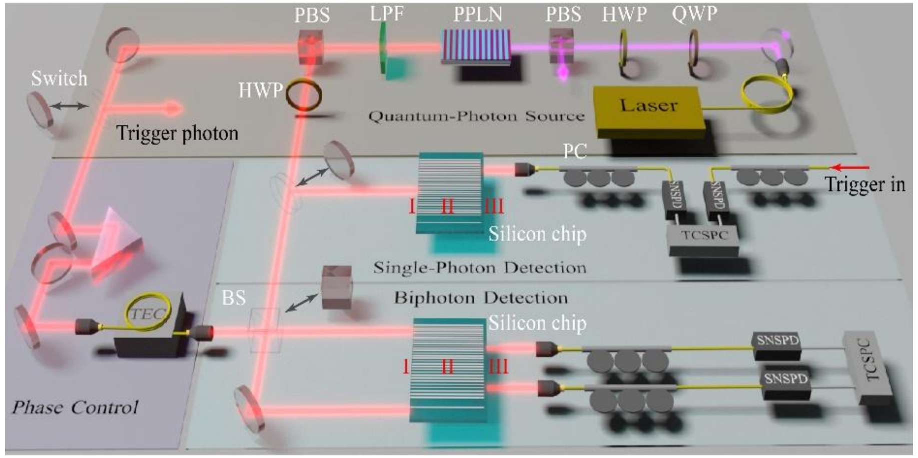
■ Nonuniform silicon lattices



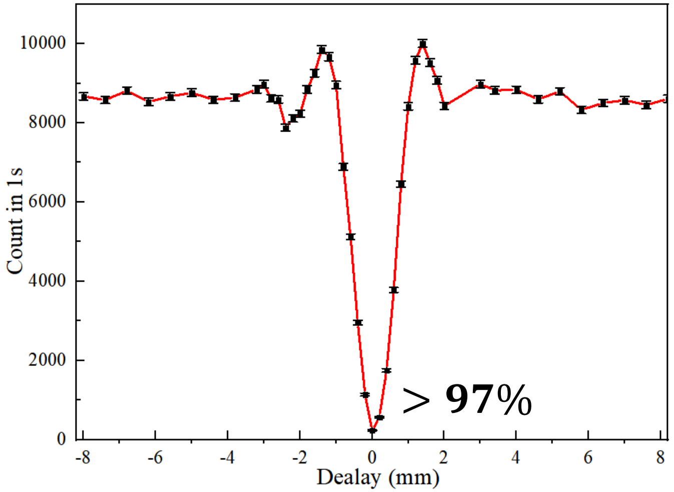
■ Coupling coefficients



■ Experimental setup



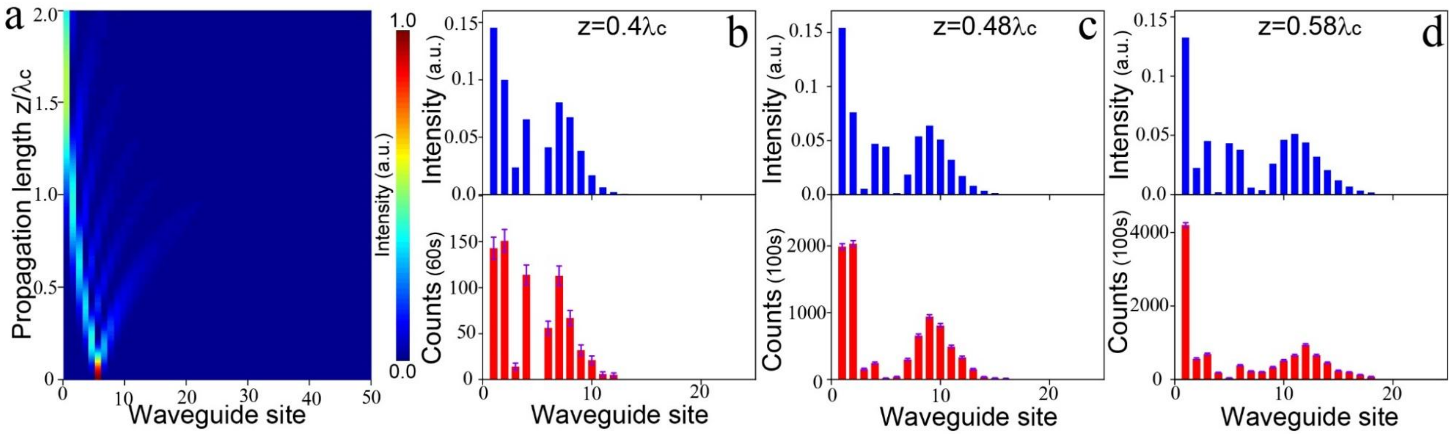
■ Quantum light sources



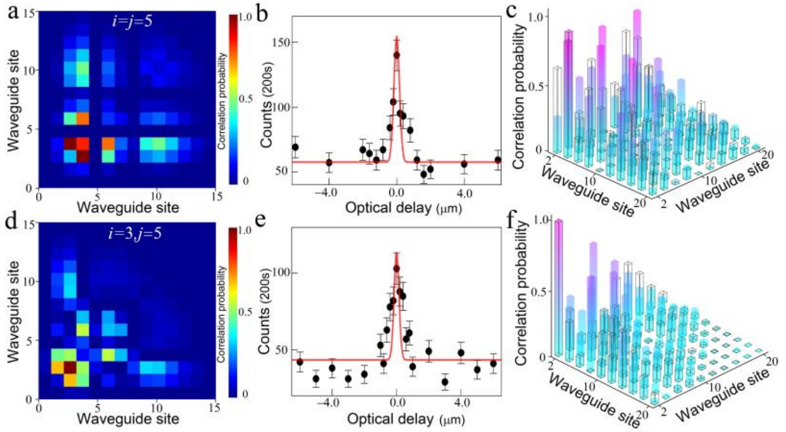
Runqiu He, Yule Zhao, Chong Sheng*,…, Shi-Ning Zhu, Hui Liu*, Phys. Rev. Research 6, 013233 (2024)

Experimental demonstration

- Single photons

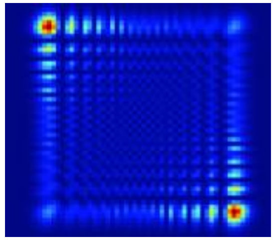


- Two indistinguishable photons

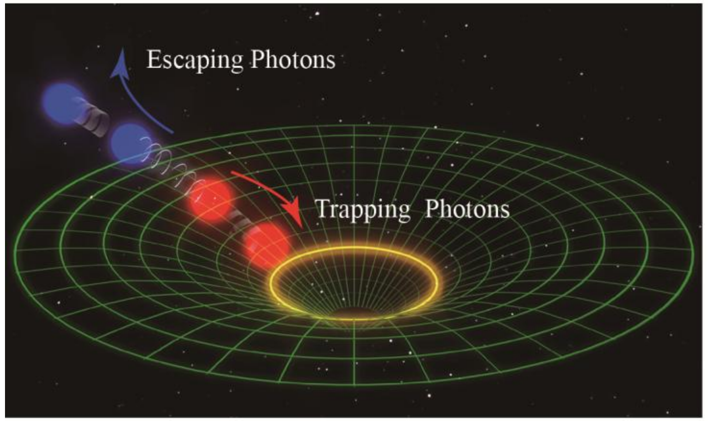


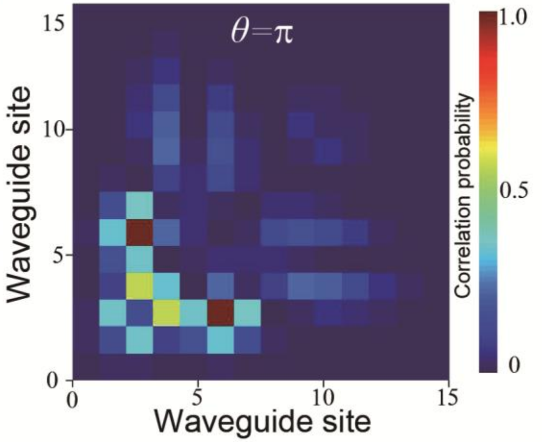
- Entangled photons

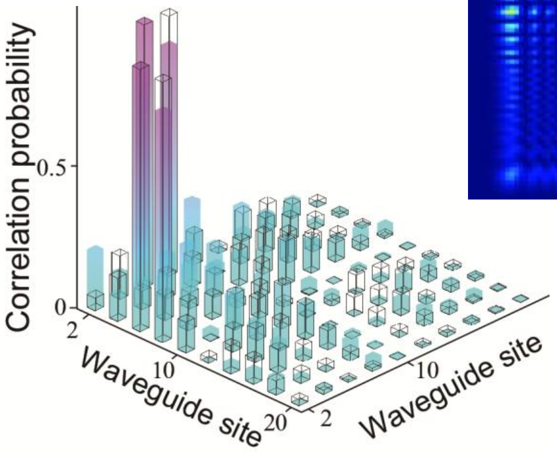
Antibunching



Photons Escape







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Content

I. Research Background.

II. QWs in the emulated curved space.

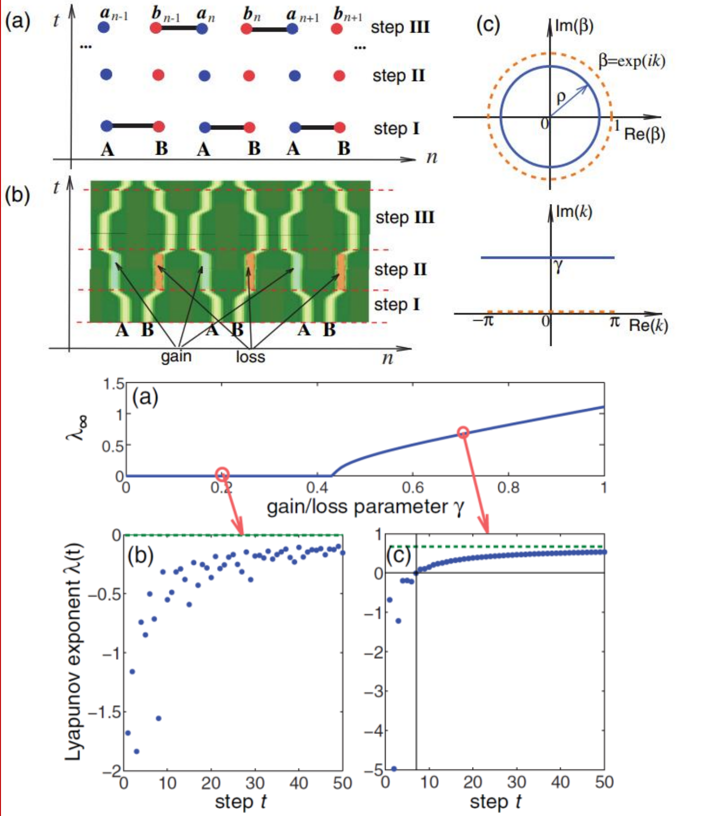
III. QWs in non-Hermitian photonic lattices.

IV. Brief Summary.

Non-Hermitian optics: QWs

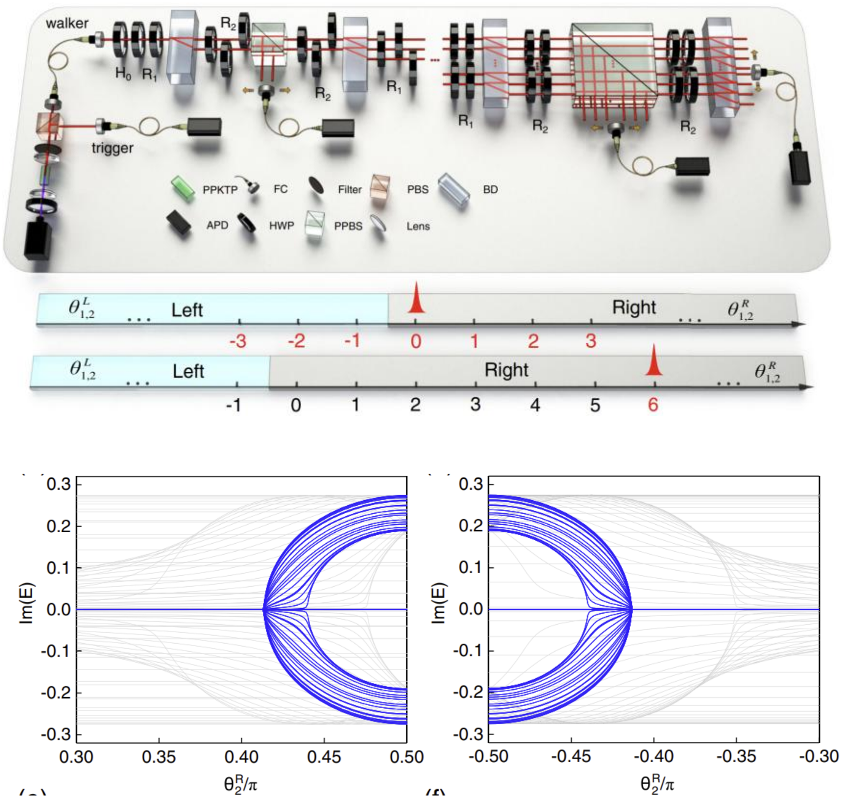
Motivation: entropy in non-Hermitian photonic lattices ?

Parity-time phase transition



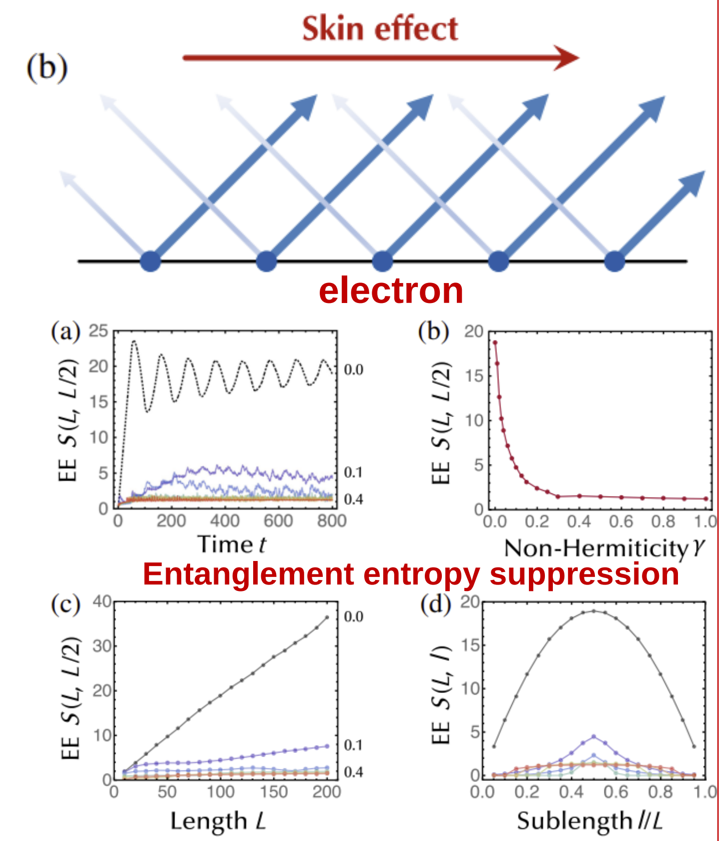
Opt. Lett. 44, 5804 (2019)

Exceptional point



Phys. Rev. Lett. 126, 230402 (2021)

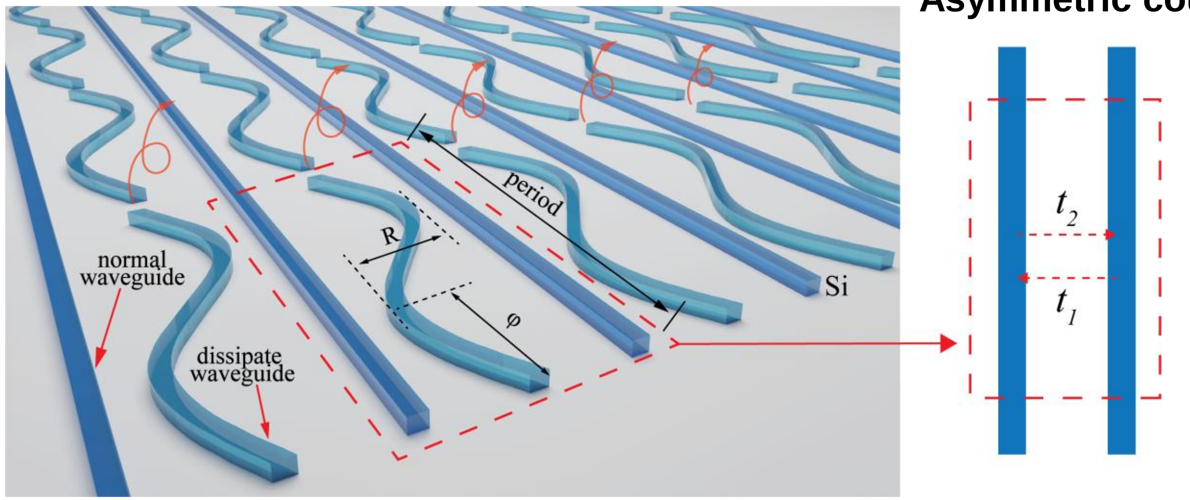
Multiparticle entropy



Phys. Rev. X 13, 021002 (2023)

Non-Hermitian photonic lattices

Asymmetric coupling

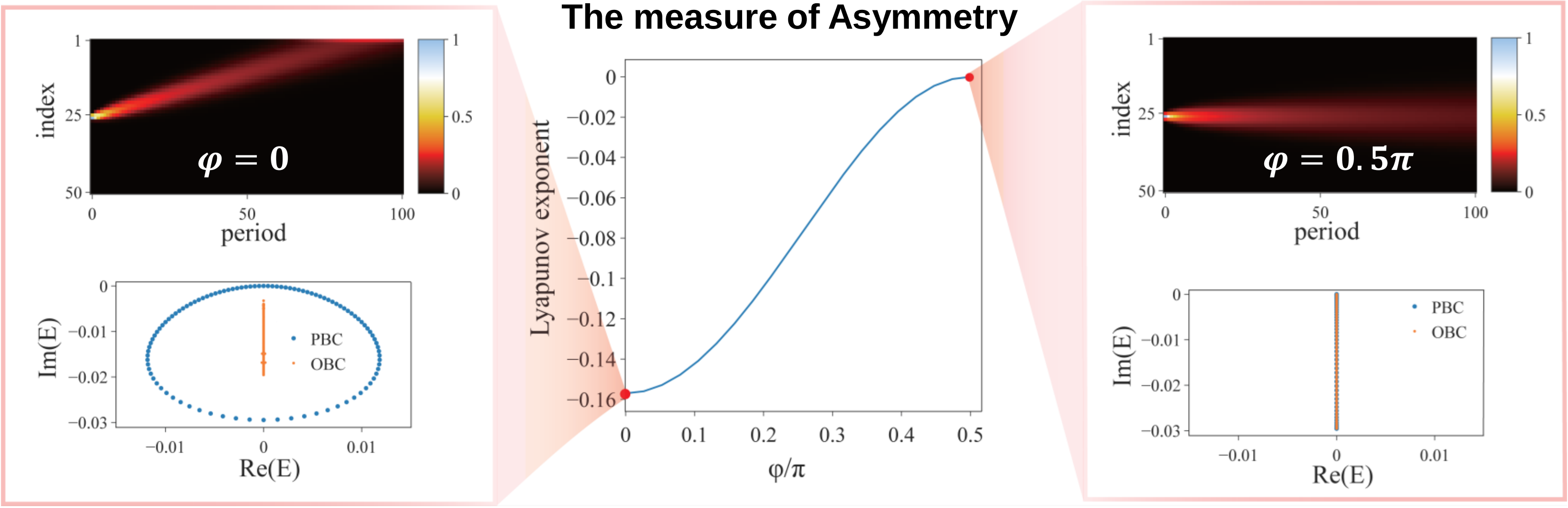


The modulation by the auxiliary waveguide:

$$R\sin(\omega t+\varphi)$$

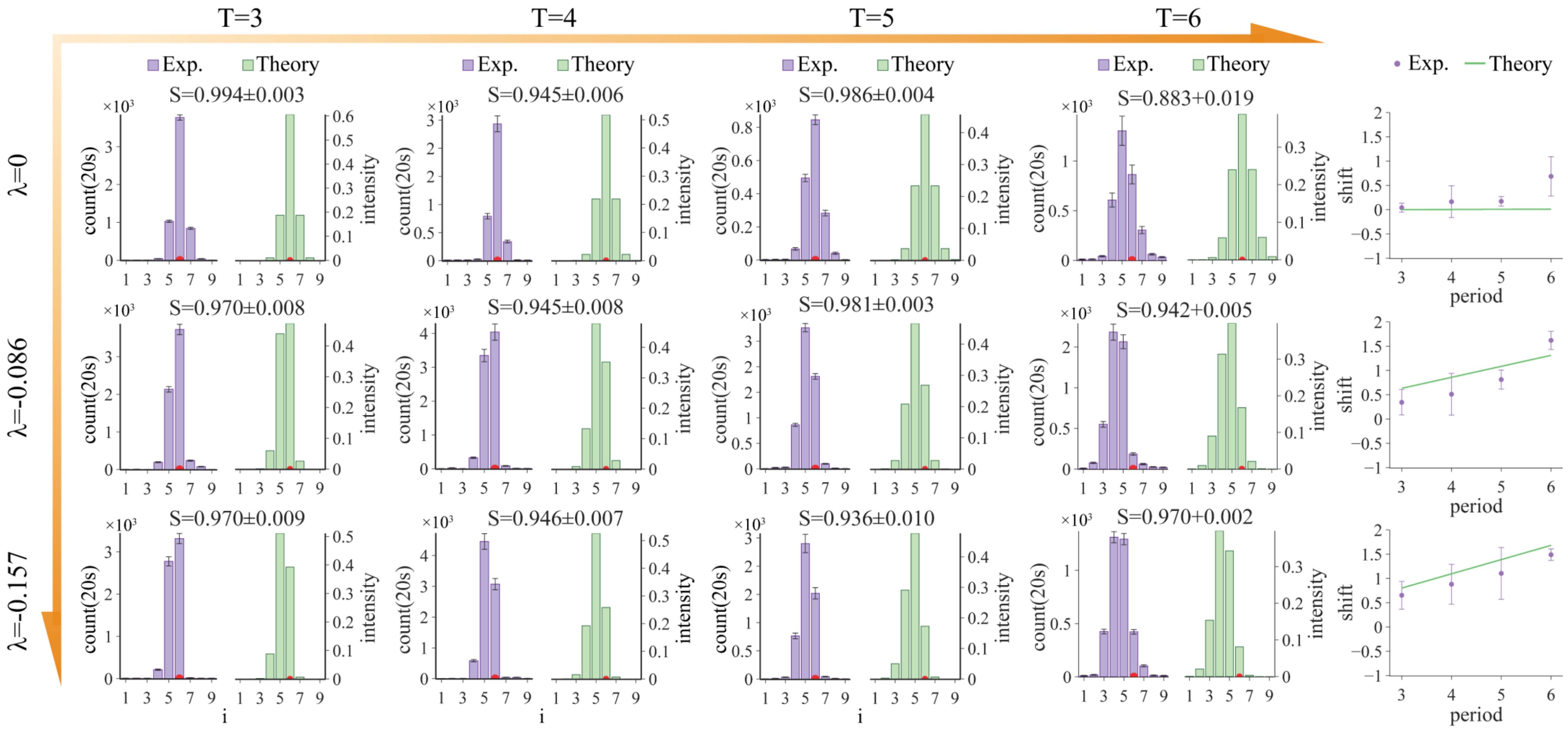
The relevance of the Lyapunov exponent to the geometric phase (φ)

The measure of Asymmetry



QWs of single photons

The unidirectional behavior vs. Lyapunov exponents and evolution periods



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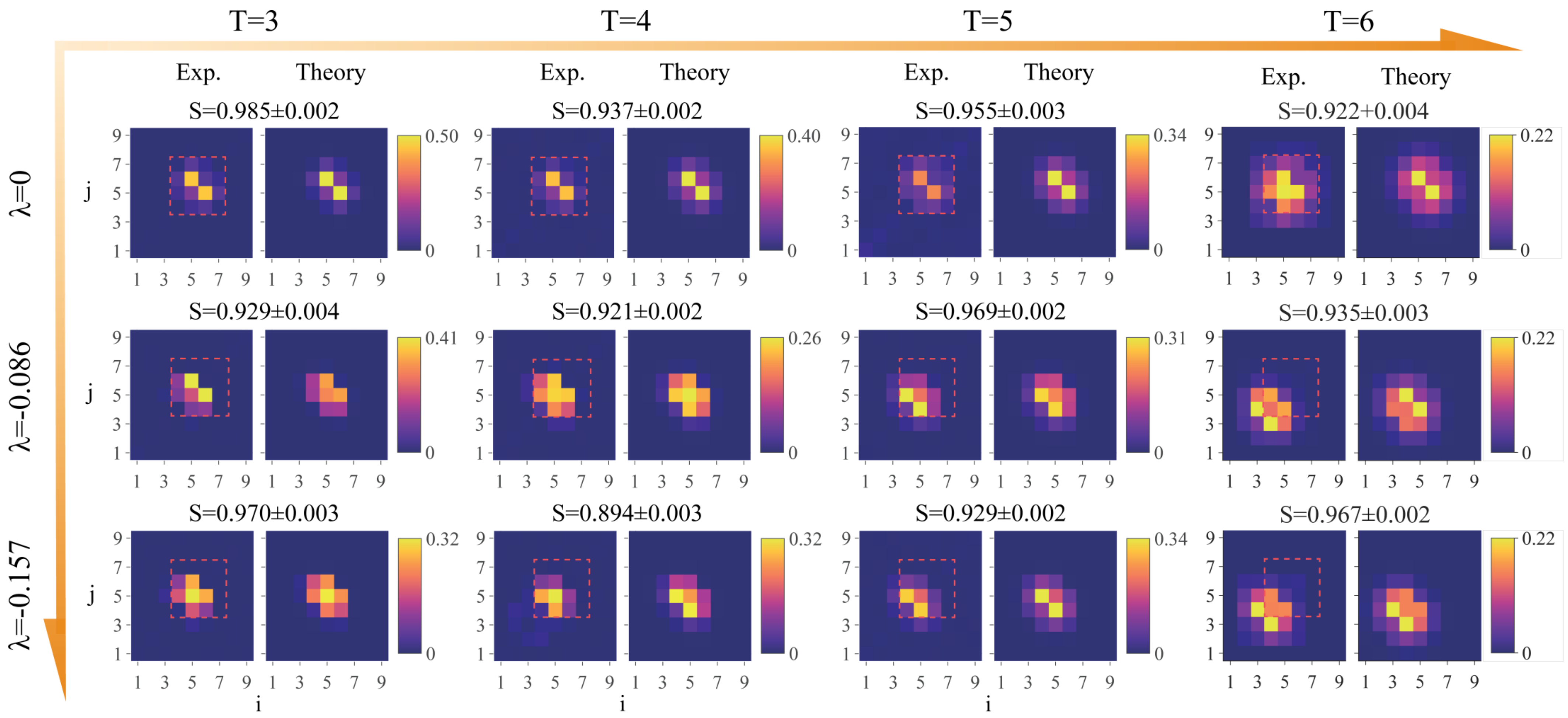
QWs of two indistinguishable photons

The coincident distribution vs. Lyapunov exponents and evolution periods



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Lindblad master equation

$$\dot{\rho}_{tot} = -i\left[\hat{H}_{tot}, \rho_{tot}\right], \hat{H}_{tot} = \hat{H}_S + \hat{H}_E + \hat{V}$$

- Trace over the environment
- Born approximation

Born-Markov master equation

$$\dot{\rho}(t) = -iTr_E\left[V(t), \rho_{tot}(0)\right] - \int_0^t dt Tr_E\left[V(t), \left[V(t_1), \rho_{tot}(t_1)\right]\right]$$

- Rotating wave approximation
- Single mode approximation
- Ignore inter-coupling between auxiliary WGs

Lindblad master equation

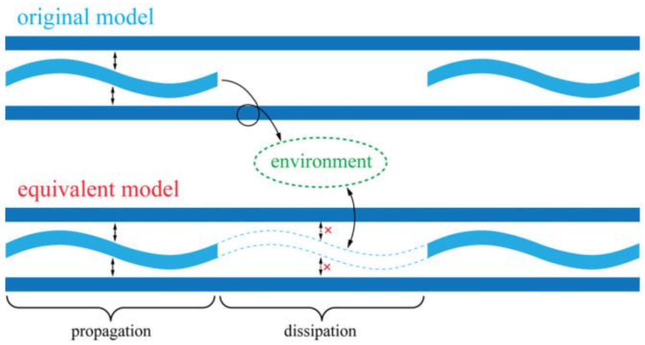
$$\dot{\rho} = -i\left[H', \rho\right] + \sum_i D[\sqrt{2}a_i]\rho(t), H' = -\Delta\omega \sum_i a_i^\dagger a_i$$

$$\rho = c_0|0\rangle\langle 0| + \sum_n c_{n,1}|1_n\rangle\langle 0| + \sum_j c_{j,2}|0\rangle\langle 1_j| + \sum_{n,j} c_{n,j,3}|1_n\rangle\langle 1_j| + \sum_{n,m} c_{n,m,4}|2_{n,m}\rangle\langle 0|$$

$$+ \sum_{j,l} c_{j,l,5}|0\rangle\langle 2_{j,l}| + \sum_{n,m,j} c_{n,m,j,6}|2_{n,m}\rangle\langle 1_j| + \sum_{n,j,l} c_{n,j,l,7}|1_n\rangle\langle 2_{j,l}| + \sum_{n,m,j,l} c_{n,m,j,l,8}|2_{n,m}\rangle\langle 2_{j,l}|.$$

Second-order Rényi entropy

$$S_2 = -\log \mathrm{Tr}\rho_A^2$$



$$H_S = \beta_0 \sum_i a_i^\dagger a_i$$

$$H_E = \sum_k \omega_k b_k^\dagger b_k$$

assumption for the loss process in our system

$$V = \sum_{k,i}\left(g_k b_k + g_k b_k^\dagger\right)\left(a_i + a_i^\dagger\right)$$

Effective non-Hermitian Hamiltonian under semi-classical limit

$$H'_{eff} = H' - i\sum_i a_i^\dagger a_i$$

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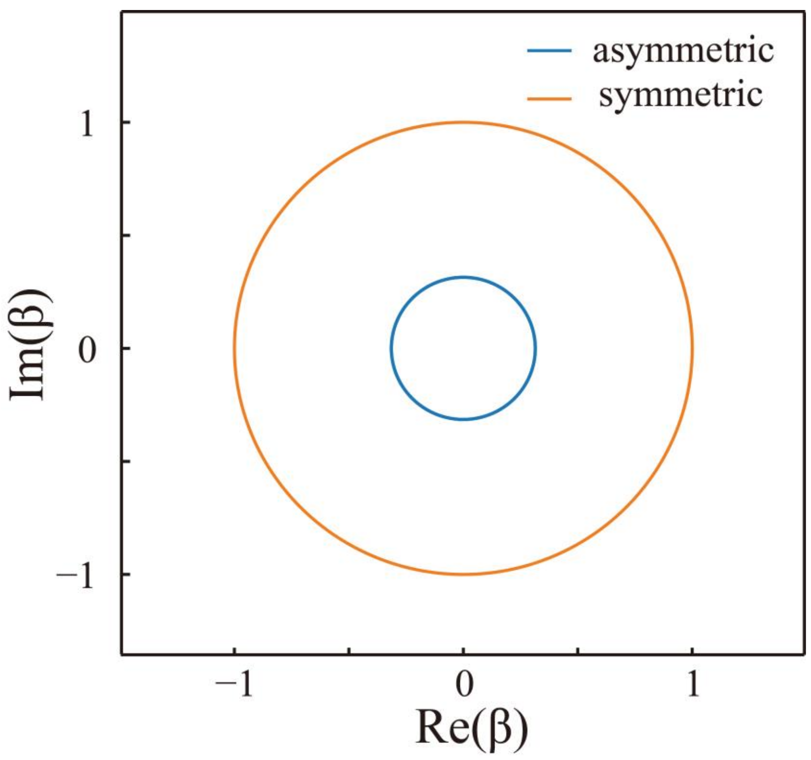
Entanglement entropy and skin effect

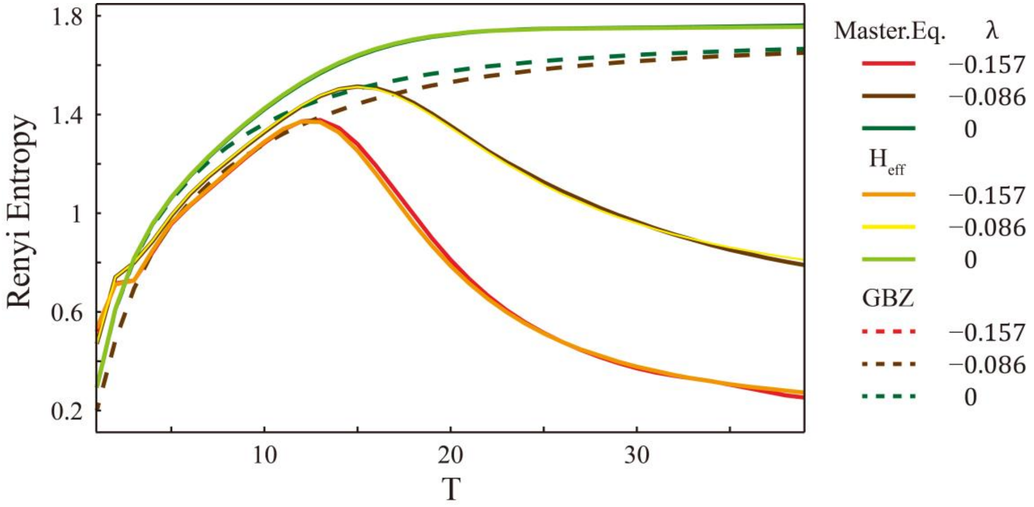
Generalized Brillouin zone

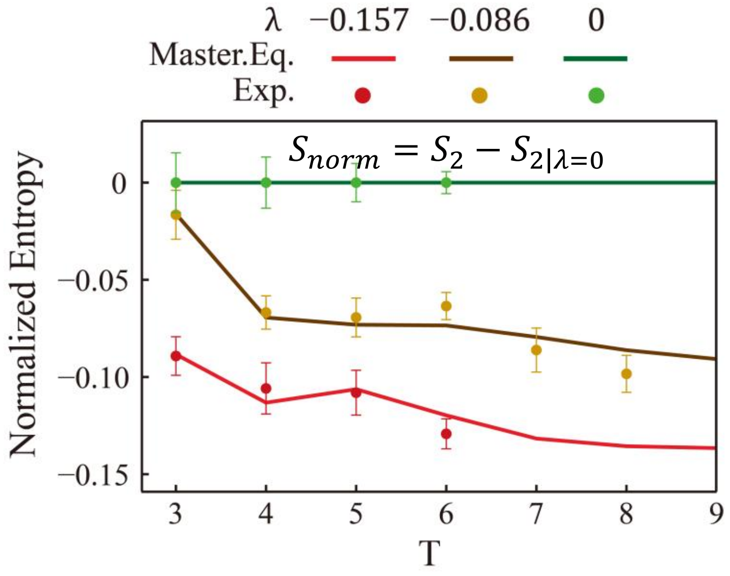


$$\bar{H} = S H_{\text{eff}} S^{-1}, \quad S = \text{diag}\{e^{-1g}, e^{-2g}, e^{-3g}, \ldots, e^{-ng}\}$$

The GBZ circle as $e^{g} = |\beta_{1(2)}|$

Rényi entropy suppressed by the skin effect





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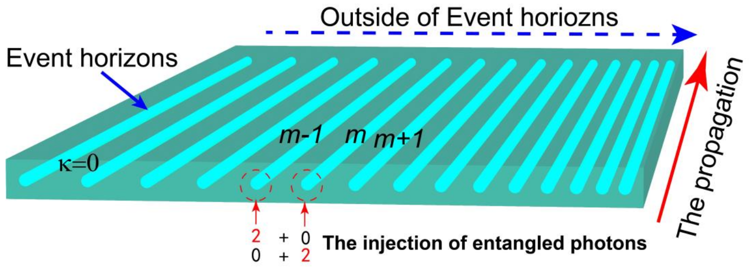
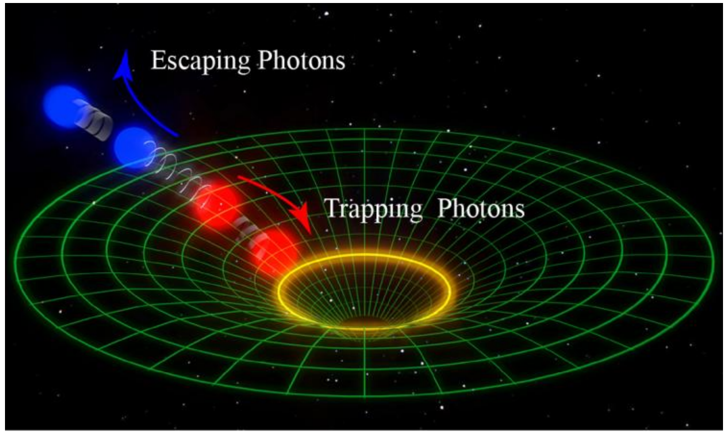
Content

Conclusion and Prospect

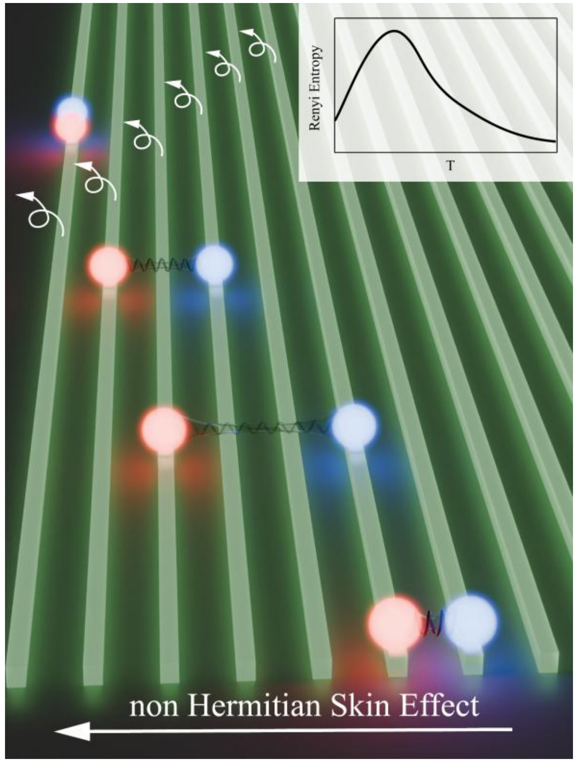
Photonic lattices are a promising platform for quantum simulation.

Relativity



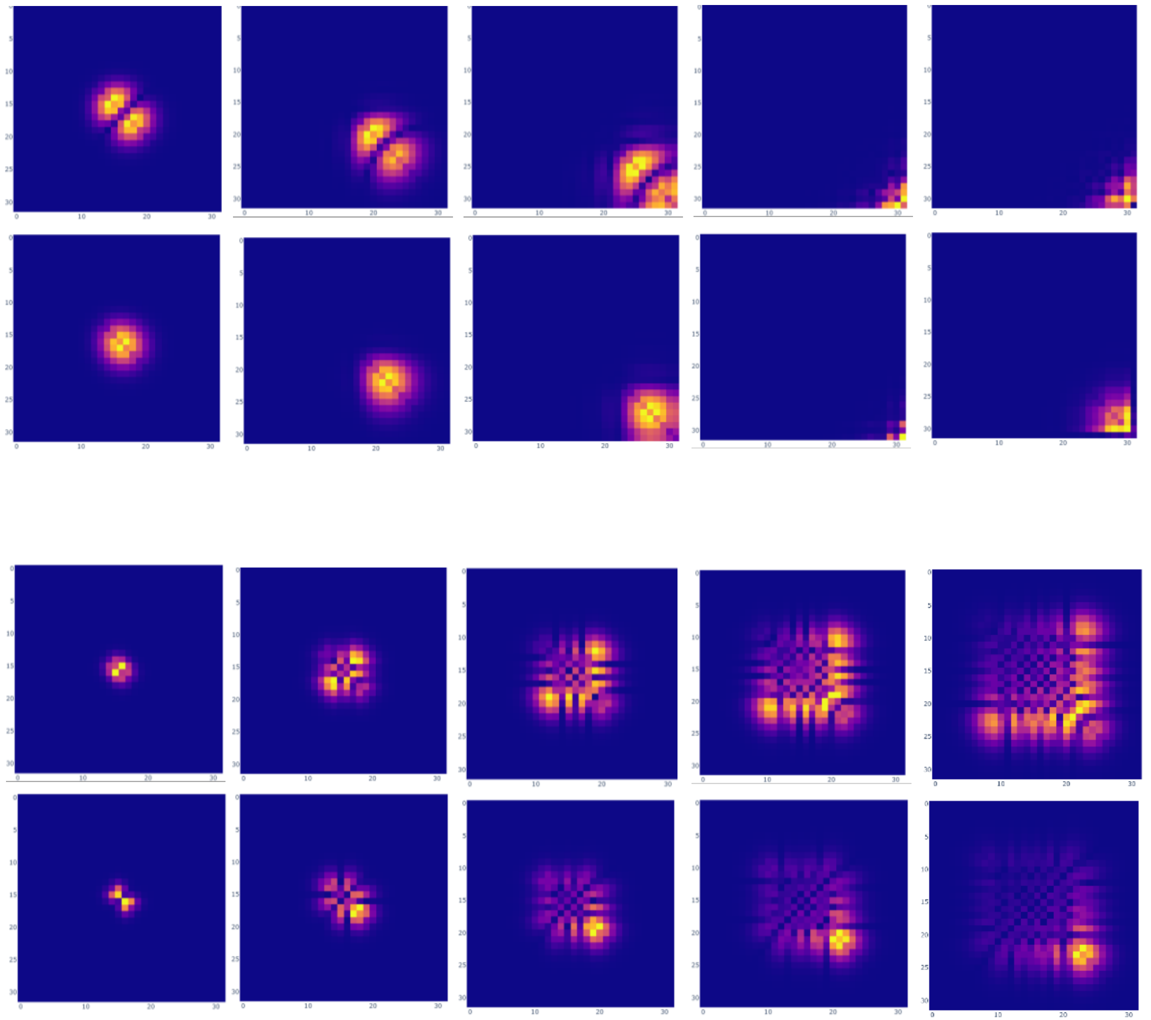


Non-Hermitian physics



Conclusion and Prospect

time



Weak skin effect
- NOON $\varphi = 0$ — Fermion-like
- NOON $\varphi = \pi$ — Boson-like

✓

Strong skin effect
- NOON $\varphi = 0$ — Fermion-like
- NOON $\varphi = \pi$ — Boson-like

✗

Collaborators

Prof. Shining Zhu @ Nanjing University

Prof. Hui Liu @ Nanjing University

Prof. Yanxiao Gong @ Nanjing University

Prof. Kun Ding @ Fudan University

Prof. Liangliang Lu @ Nanjing Normal University

Dr. Runqiu He@ Nanjing University

Dr. Yule Zhao @ Nanjing University

Dr. Mingyuan Gao @ Nanjing University

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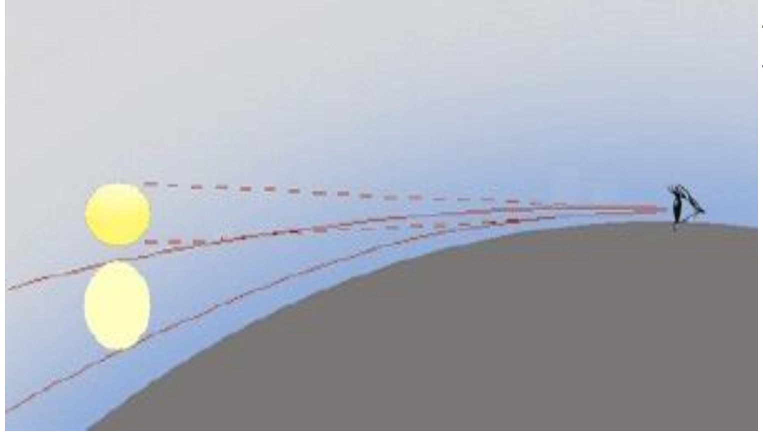
Ministry of Science and Technology of the People's Republic of China

国家自然科学基金委员会
NSFC

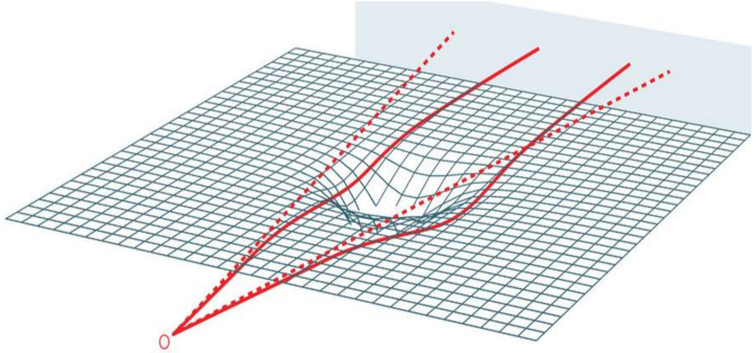
Thanks! Welcome for discussion!

Transformation Optics



Maxwell Equations

$$\nabla \times \vec{E} = -\boldsymbol{\mu}(\boldsymbol{r}).\,\partial\vec{H}/\partial t$$
$$\nabla \times \vec{H} = \boldsymbol{\varepsilon}(\boldsymbol{r}).\,\partial\vec{E}/\partial t$$



Einstein Equations

$$R_{uv} - \frac{1}{2}\mathbf{g}_{uv}R = -\frac{8\pi G}{c^4}T_{uv}$$

Metamaterials

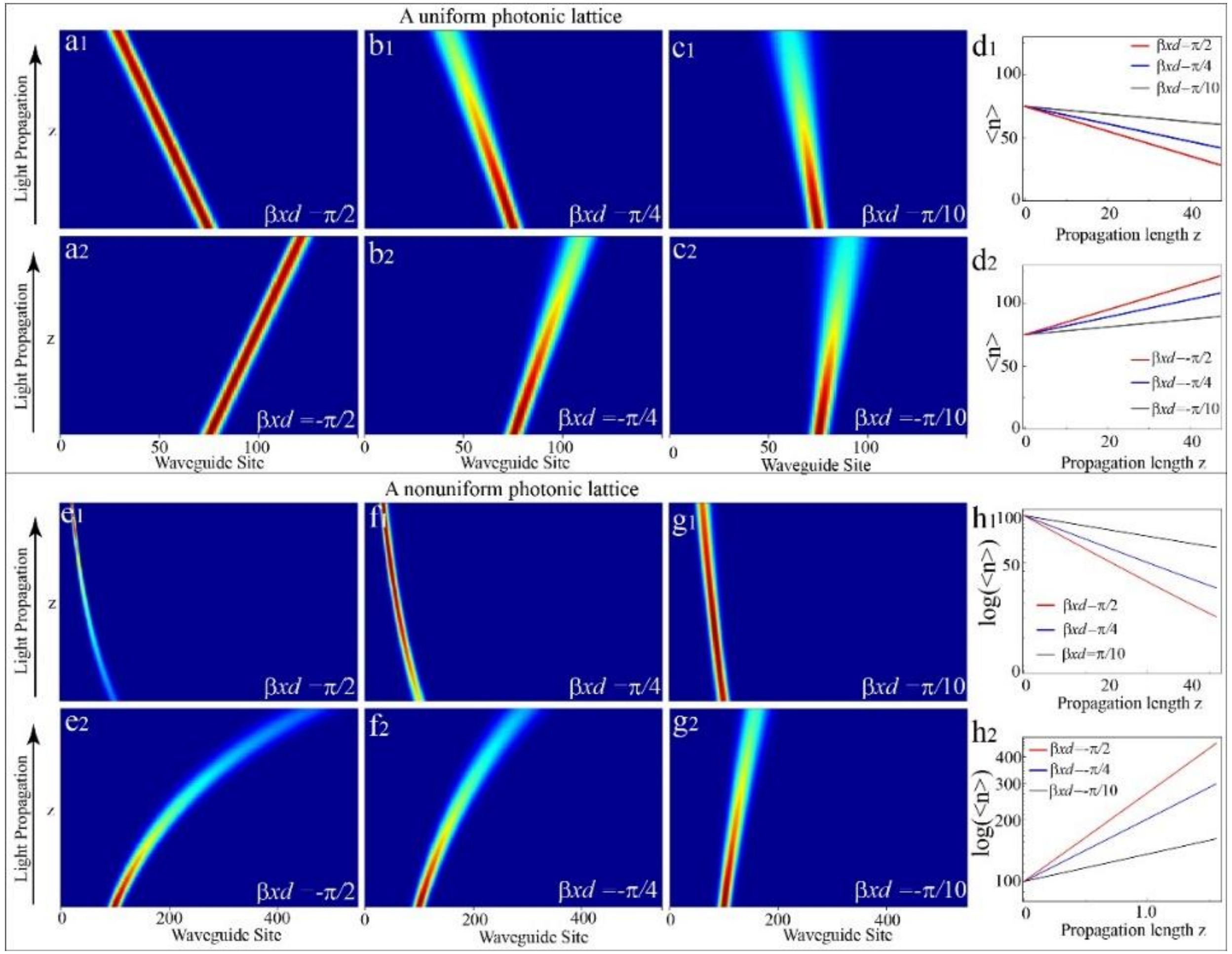
IEEE Trans. Microwave Theory Tech. 47, 2075 (1999)

Transformation Optics

The relation of material parameters and metrics in curved space:

$$\boldsymbol{\varepsilon_{ij}} = \boldsymbol{\mu_{ij}} = \mp\frac{\sqrt{-\mathbf{g}}}{\mathbf{g_{00}}}\mathbf{g}^{ij}, \boldsymbol{w_i} = \frac{\mathbf{g_{0i}}}{\mathbf{g_{00}}}$$

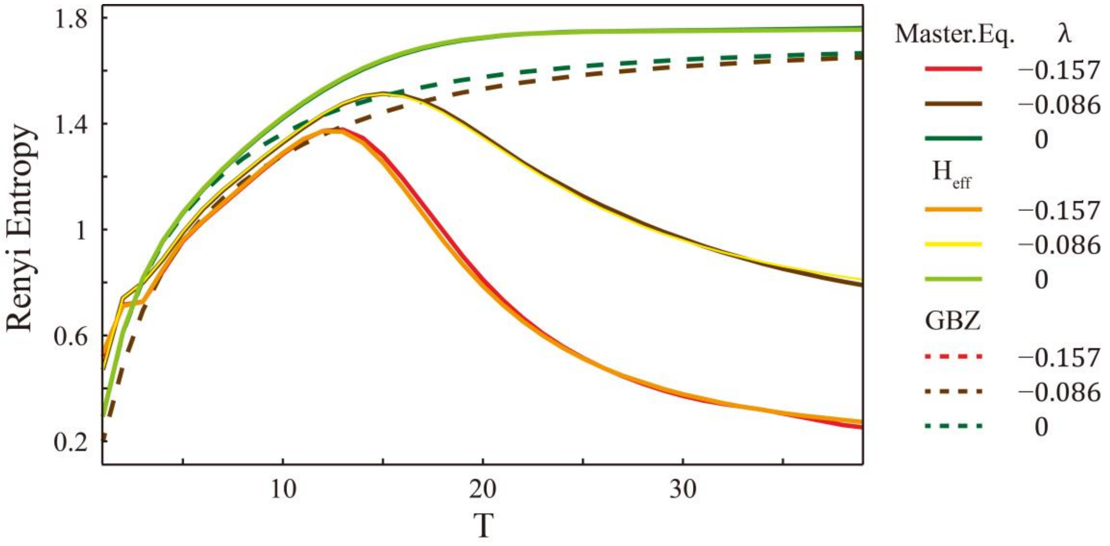
Phys. Rev. 118, 1396 (1960); Gene.Relativity .Grav. 2, 247 (1971); New.J.Phys. 8, 247 (2006).



The dynamics of single-photon wave packet in photonic waveguide lattice can be described by a set of coupled discrete Schrodinger equations, which is derived from Schrodinger-type paraxial wave equation by employing the tight-binding mode:

$$i\,\partial\varphi_m/\partial z = \beta_0\varphi_m - \kappa_m\varphi_{m-1} - \kappa_{m+1}\varphi_{m+1}$$

In experiments, the lattice system has total sites N = 9.



■ Coupling coefficients