東南大學 SOUTHEAST UNIVERSITY

Non-Unitary quantum walks with single photons

Peng Xue

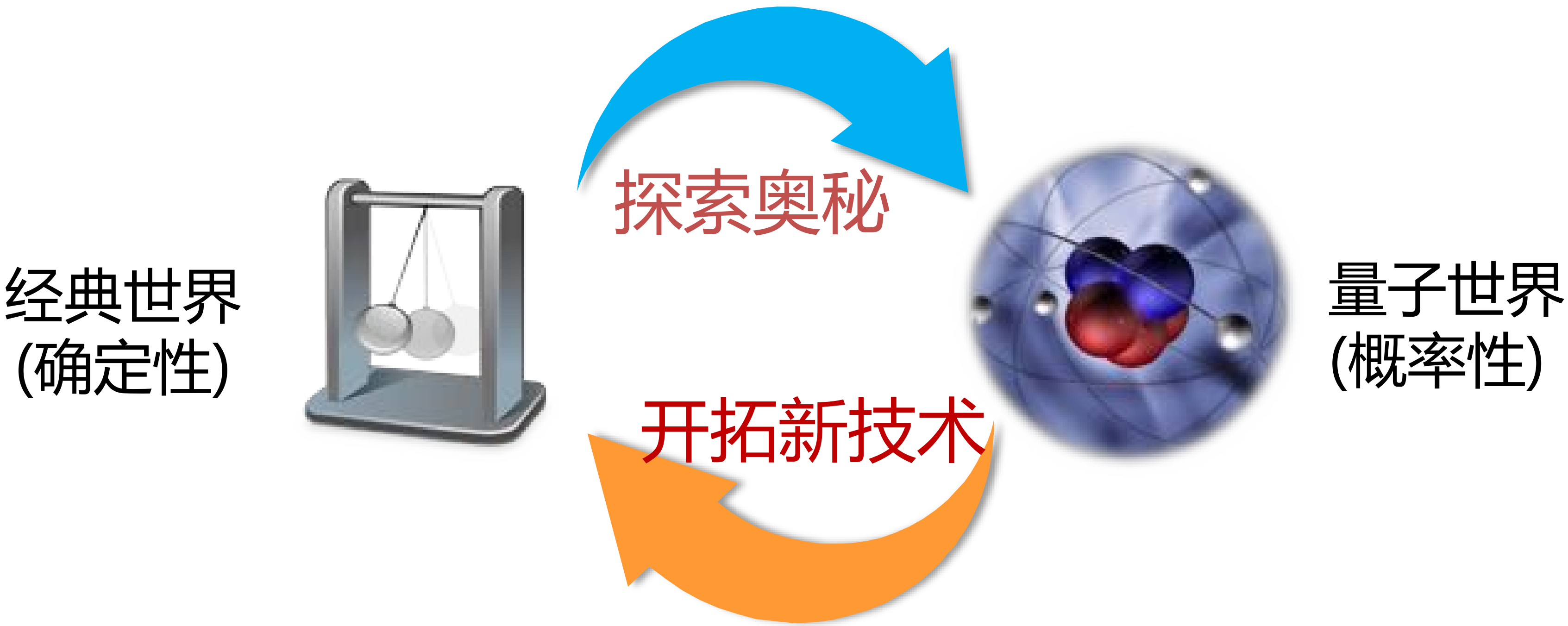
Physics Department, Southeast University

Nanjing, China

Outline

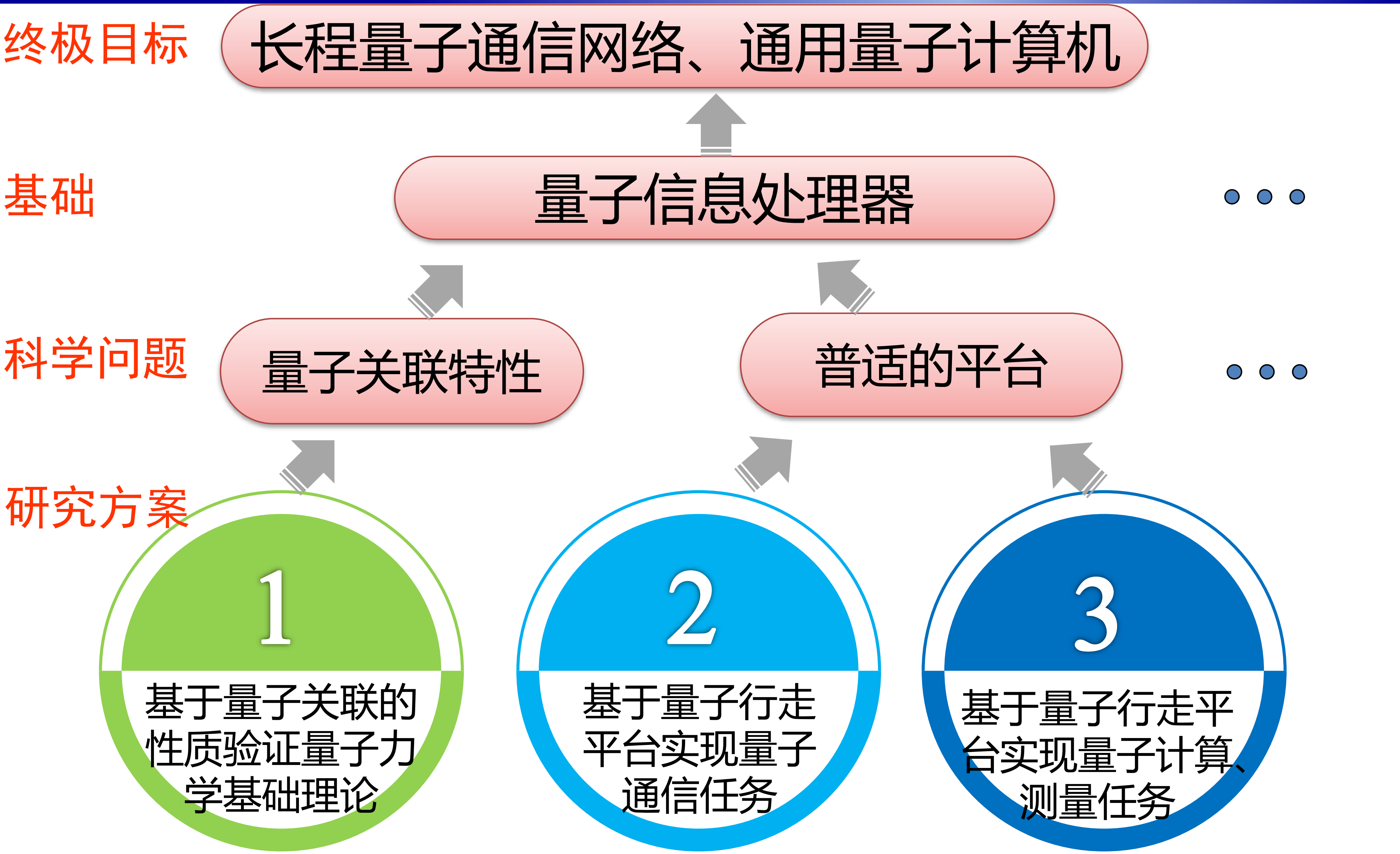
- A brief review of quantum walks (QWs)
- Parity-time (PT) symmetric quantum walks
- Experimental implementation of PT symmetric QWs with single photons
- Observation of Floquet topological phase in PT symmetric QWs
- Detection of topological invariances of non-unitary

方向



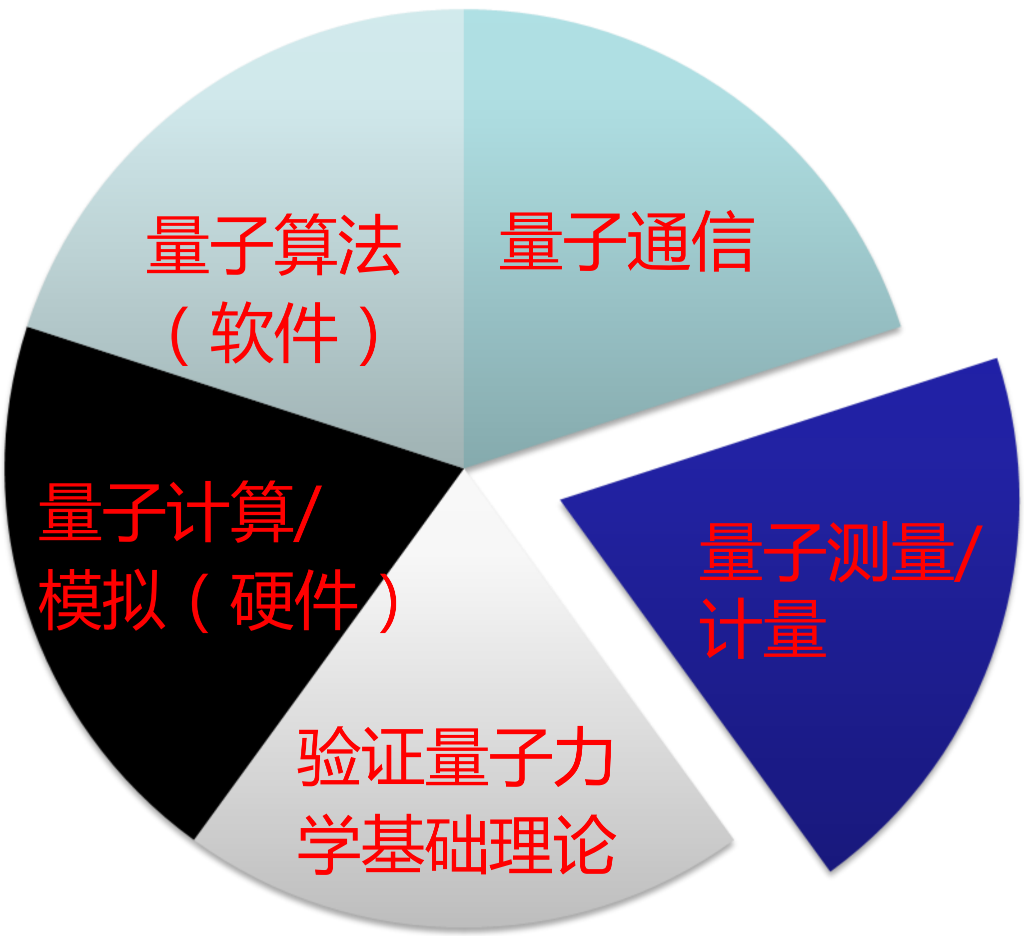
研究方向：量子信息学---量子力学与信息科学相融合的新兴交叉学科

研究目标：量子关联特性的研究，量子信息处理器的设计和开发


终极目标
长程量子通信网络、通用量子计算机
基础
量子信息处理器
···
科学问题
量子关联特性
普适的平台
···
研究方案
1
基于量子关联的性质验证量子力学基础理论
2
基于量子行走平台实现量子通信任务
3
基于量子行走平台实现量子计算、测量任务

量子行走

量子行走：



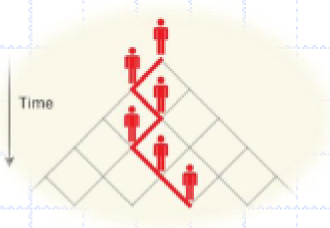
- 量子关联特性+随机行走→量子行走
- 量子信息扩散传播与恢复
- 量子测量
- 量子算法
- 量子态工程
- 量子态操控

结论：量子行走提供了普适的量子信息处理平台

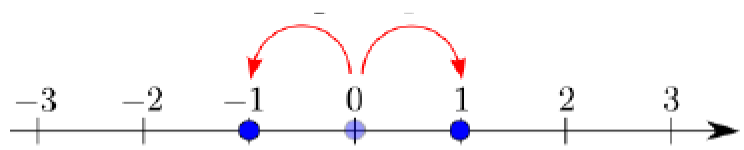
Quantum Walk (QW)

- A QW generalizes random walks in the quantum world. Both the walker and coin are quantum particles.

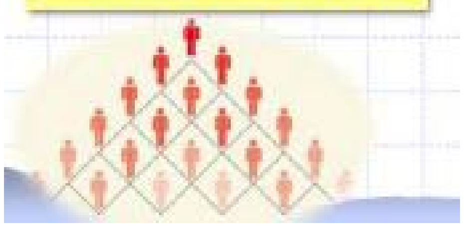
Random walk



Walkers move to right (left) with probability 1/2

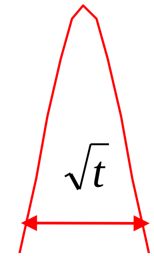


Quantum walk



- Walker: a particle whose motion is confined to one dimensional lattice;
- Coin: a qubit ---any two-level system
- Coin evolution operation: single qubit rotation
- Conditional shift operation: evolution of the interaction between walker and coin

Classical vs quantum walk



•Running a RW on the line
results in a probability distribution like:

Random Walks

- Probabilities
- Different paths adds up
- Diffusion
- Spread slowly

$$\sigma \sim \sqrt{t}$$

Quantum Walks

- Probability amplitudes
- Different paths interfere
- Wave propagation
- Spread fast

$$\sigma \sim t$$

while for RW to root of time.

量子行走

1

基于量子行走平台验证量子力学基础理论

- 验证熵的量子互文性和信息损失，PRL（2017）；Optica（2017）
- 验证量子非定域性和互文性的关系，PRL（2016）
- 验证加强型最小不确定关系，PRA（2016）；OE（2017）
- LG不等式与宏观实在性，PRA（2017）；OE（2017）；PRA RC（2018）
- 量子关联的度量，PRA（2012）；PRA(2017)
- 多体纠缠态制备并研究其量子关联，PRA（2012）

2

基于量子行走平台实现量子通信任务

- 周期性量子行走的实验实现，PRL（2015）；PRA（2017）
- 多体现象的量子模拟，NJP（2015）；PRA（2015）
- 量子信息处理平台，PRA（2014）；PRA（2013）
- 高维量子行走的物理实现，PRL（2009）；PRA（2014）

3

基于量子行走平台实现量子计算任务

- 宇称时间对称的量子行走中观测拓扑边界态，Nat. Phys.(2017)
- 直接探测非幺正量子行走的拓扑不变量，PRL（2017）
- 实验构建广义测量，PRL（2015）
- 实验实现最小体系的量子算法，OE（2015）；PRA（2017）
- 量子态路由器的方案，PRA（2014）
- 普适量子计算的方案，PRL（2006）

量子行走

1

- 验证熵的量子互文性和信息损失，**PRL**（2017）；**Optica**（2017）
- 验证量子非定域性和互文性的关系，**PRL**（2016）

nature physics

ARTICLES

PUBLISHED ONLINE: 31 JULY 2017 | DOI: 10.1038/NPHYS4204

Observation of topological edge states in parity–time-symmetric quantum walks

L. Xiao[1], X. Zhan[1], Z. H. Bian[1], K. K. Wang[1], X. Zhang[1], X. P. Wang[1], J. Li[1], K. Mochizuki[2], D. Kim[2], N. Kawakami[3], W. Yi[4,5], H. Obuse[2], B. C. Sanders[5,6,7,8] and P. Xue[1,9]*

3

基于量子行走平台实现量子计算任务

- 宇称时间对称的量子行走中观测拓扑边界态，**Nat. Phys.**（2017）
- 直接探测非幺正量子行走的拓扑不变量，**PRL**（2017）
- 实验构建广义测量，**PRL**（2015）
- 实验实现最小体系的量子算法，OE（2015）；PRA（2017）
- 量子态路由器的方案，PRA（2014）
- 普适量子计算的方案，**PRL**（2006）

量子行走

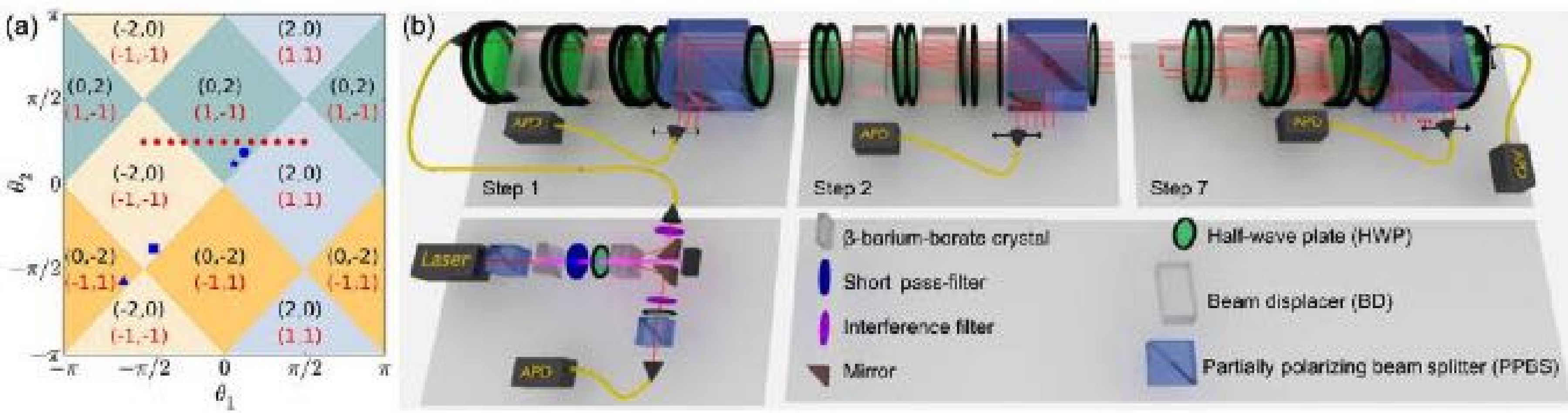
1

- 验证熵的量子互文性和信息损失，**PRL**（2017）；**Optica**（2017）

PRL 119, 130501 (2017) PHYSICAL REVIEW LETTERS week ending 29 SEPTEMBER 2017

Detecting Topological Invariants in Nonunitary Discrete-Time Quantum Walks

Xiang Zhan,[1] Lei Xiao,[1] Zhihao Bian,[1] Kunkun Wang,[1] Xingze Qiu,[2,3] Barry C. Sanders,[3,4,5,6] Wei Yi,[2,3,*] and Peng Xue[1,7,†]

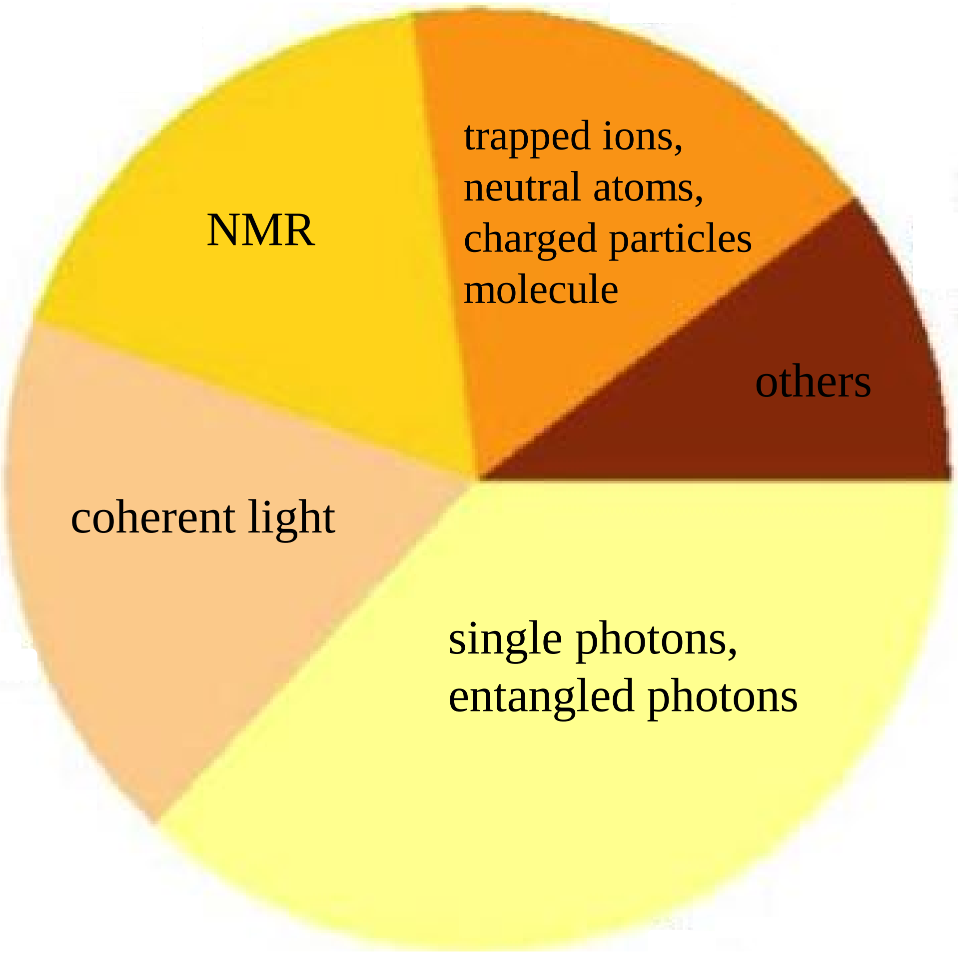


3

基于量子行走平台实现量子计算任务

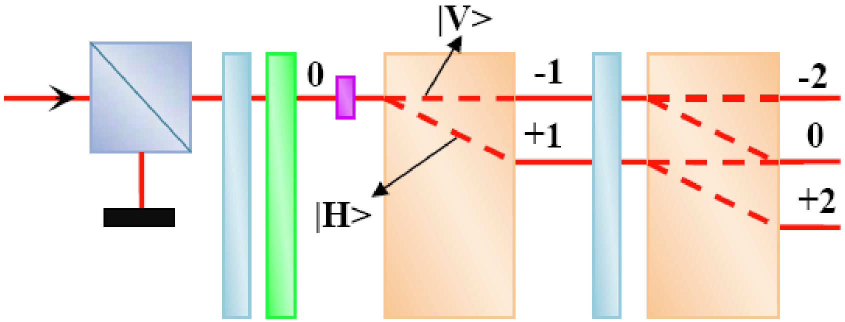
- 直接探测非幺正量子行走的拓扑不变量，**PRL**（2017）
- 实验构建广义测量，**PRL**（2015）
- 实验实现最小体系的量子算法，OE（2015）；PRA（2017）
- 量子态路由器的方案，PRA（2014）
- 普适量子计算的方案，**PRL**（2006）

Previous Breakthrough Experimental Results on QWs



Realizing discrete-time QWs with single photons

- Coin: polarizations of single photons
- Walker: spatial modes of single photons



- Conditional position shift: birefringent beam displacers (BDs) to build cascaded interferometer network
- Coin flipping: wave-plate sets

Ref: PX, X. Zhan, and Z. H. Bian, Sci. Rep. 4, 4825 (2014);

Ref: PX, H. Qin, B. Tang, and B. C. Sanders, New J. Phys. 16, 053009 (2014);

Ref: PX et al., Phys. Rev. Lett. 114, 140502 (2015);

Ref: Z. H. Bian, J. Li, H. Qin, X. Zhan, R. Zhang, B. C. Sanders, and PX, Phys. Rev. Lett. 114, 203602 (2015);

Ref: PX et al., Phys. Rev. A 92, 042316 (2015);

Ref: Z. H. Bian, J. Li, X. Zhan, J. Twamley, and PX, Phys. Rev. A 95, 052338 (2017);

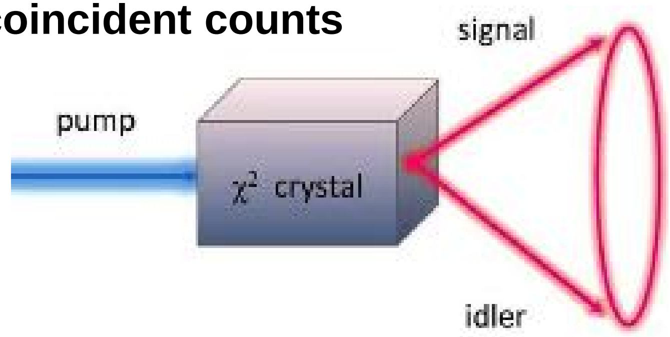
Ref: X. Zhan, L. Xiao, Z. H. Bian, K. K. Wang, X. Z. Qiu, B. C. Sanders, W. Yi and PX, Phys. Rev. Lett. 119, 130501 (2017);

Ref: L. Xiao et al, Nature Physics 13, 1117–1123 (2017).

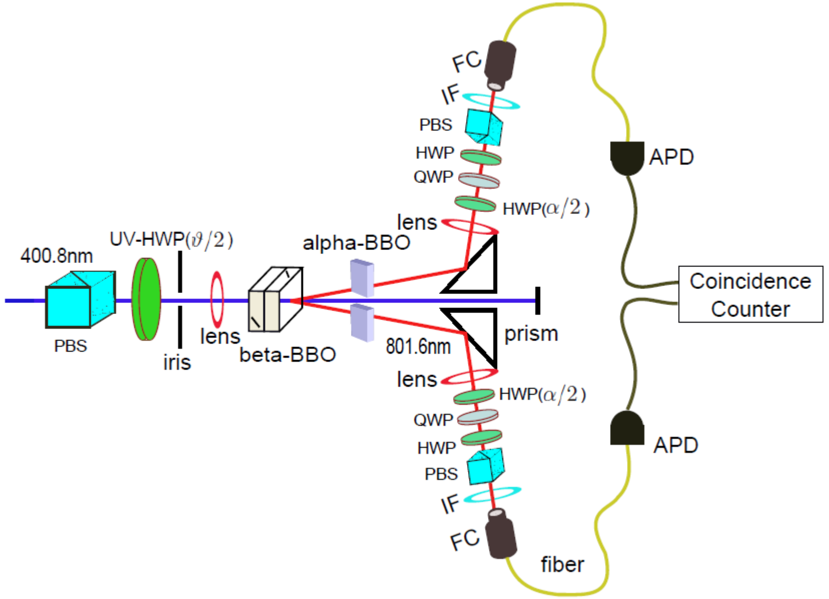
Methods

- **For single-photon source:** pairs of photons are generated via type-I SPDC. By triggering on one photon the other is prepared into a single-photon state.

single photon @800nm, 12000/s coincident counts



0.5mm-thick BBO crystals cut at 29.41°



- **For measurements:** photons are detected using avalanche photo-diodes (APD) with 7ns time window (dead time 40ns).

- **For BD interferometer network:** The optical axes of BDs are cut so the vertically polarized light is directly transmitted and horizontal light undergoes a displacement into a neighboring mode.

Optical axes of BDs are aligned to ensure high visibility (99.8% for each step).

PT-symmetric QWs

Motivation:

•Studying open quantum systems;

•Observing PT symmetry in real quantum regime (in the single photon level): the eigenenergies of the underlying system can be real even in non-Hermitian settings;

•Realizing and investigating Floquet topological phases (FTPs) driven by PT-symmetric QWs.

Ref: L. Xiao, X. Zhan, Z. H. Bian. K. K. Wang, X. Zhang, X. P. Wang, J. Li, K. Mochizuli, D. Kim, N. Kawakami, W. Yi, H. Obuse, B. C. Sanders, and PX, Nature Physics 13, 1117–1123 (2017)

- Non-unitary QWs with alternating gain and loss possess PT-symmetry **Ref: K. Mochizuki, D. Kim, and H. Obuse, Phys. Rev. A 93, 062116 (2016)**

$$U_{gl} = GSC(\theta_2(x))G^{-1}SC(\theta_1(x))$$

$$S = \sum_x |x\rangle\langle x+1| \otimes |0\rangle\langle 0| + |x\rangle\langle x-1| \otimes |1\rangle\langle 1|$$

$$C(\theta(x)) = \sum_x |x\rangle\langle x| \otimes \begin{pmatrix} \cos\theta(x) & \sin\theta(x) \\ \sin\theta(x) & -\cos\theta(x) \end{pmatrix} \qquad G = \sum_x |x\rangle\langle x| \otimes \begin{pmatrix} g & 0 \\ 0 & g^{-1} \end{pmatrix}$$

- Non-unitary QW with alternating less loss and more loss

Ref: L. Xiao et al, Nature Physics 13, 1117–1123 (2017).

$$U_{ll} = LSC(\theta_2(x))L'SC(\theta_1(x))$$

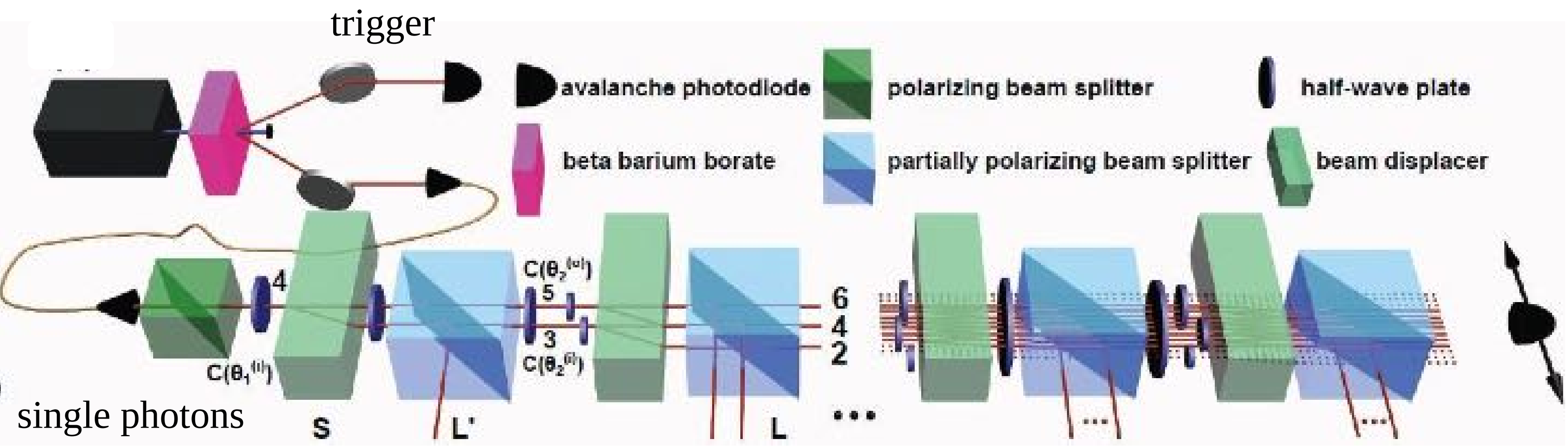
$$L = \sum_x |x\rangle\langle x| \otimes \begin{pmatrix} l_1 & 0 \\ 0 & l_2 \end{pmatrix} \qquad L' = \sum_x |x\rangle\langle x| \otimes \begin{pmatrix} l_2 & 0 \\ 0 & l_1 \end{pmatrix}$$

- Relation

By choosing $g = \sqrt{l_1/l_2}$

$$\boxed{C_o U_{ll} = U_{gl}} \qquad C_o = 1/(l_1 l_2) = e^{-\varepsilon_0}$$

Experimental realization of PT-symmetric QWs with single photons

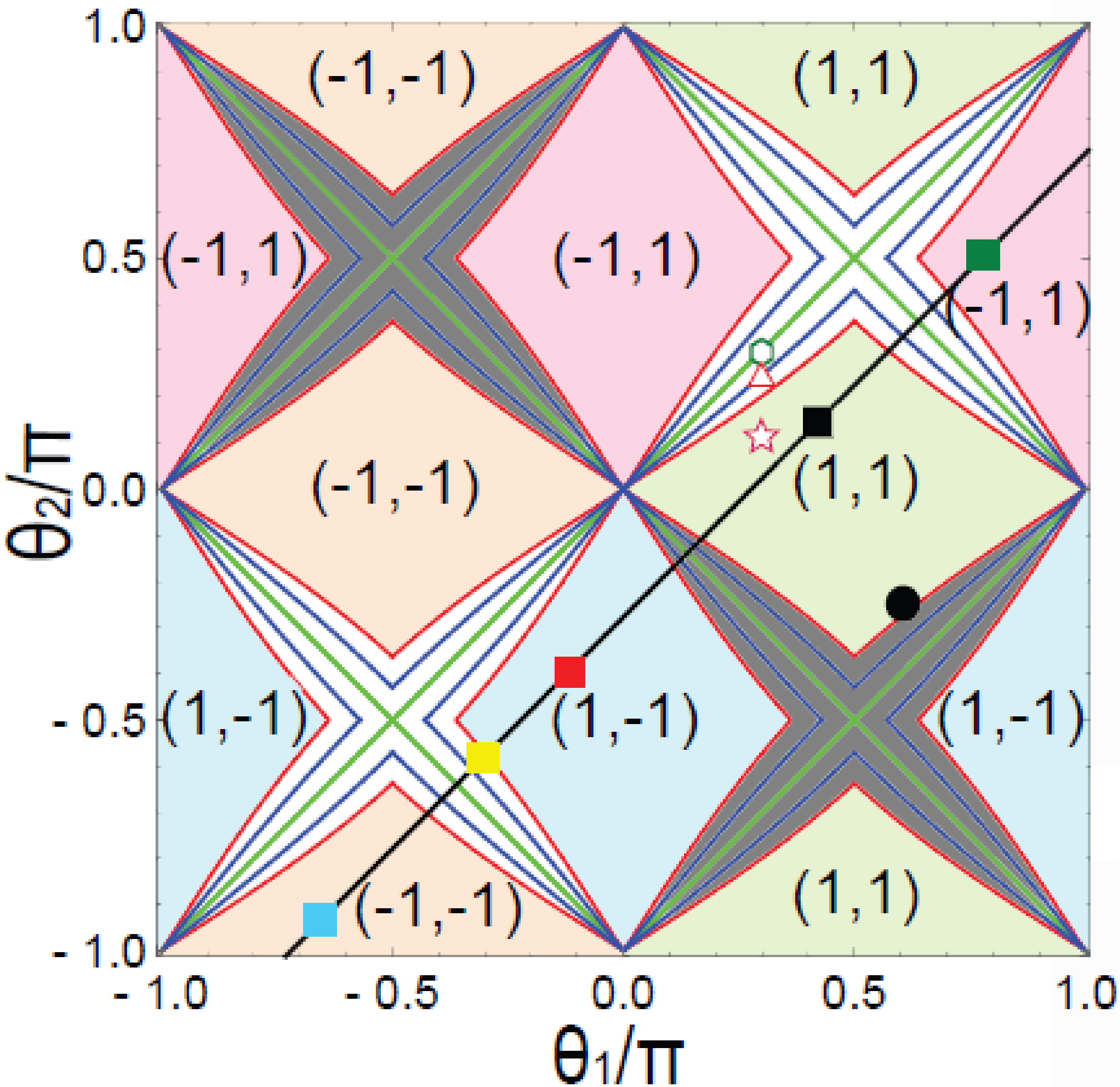


The polarization-dependent loss operator *L* is realized by a partially polarizing beam splitter (PPBS) with the transmissivity of horizontally and vertically polarized photons (l_1^2, l_2^2). L' is realized by a Sandwich-type HWP (@45^o)-PPBS-HWP (@45^o).

Conditional position shift: BDs

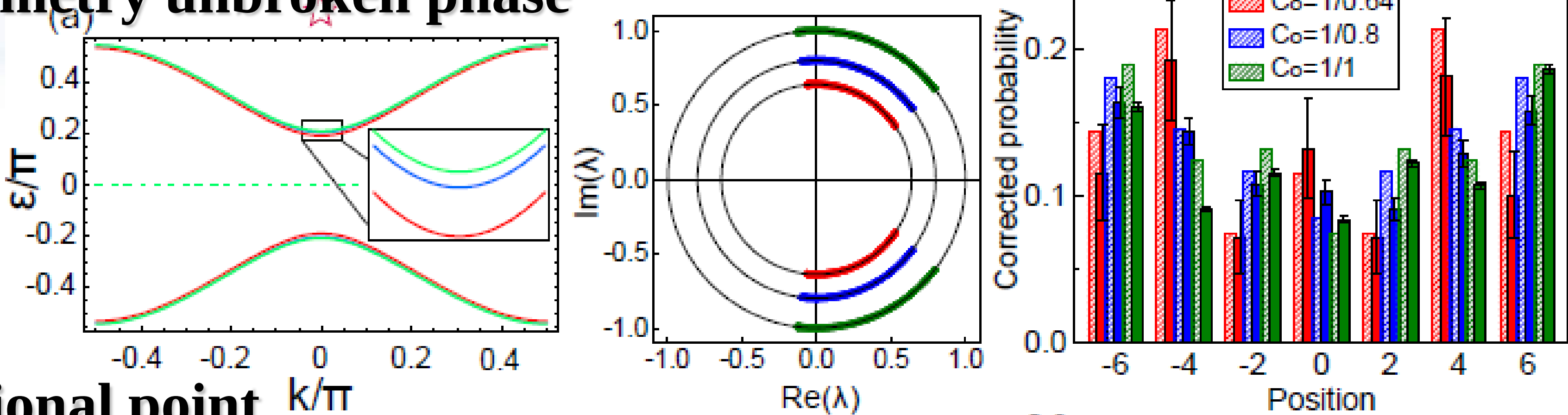
Coin flipping: WPs

Phase diagram

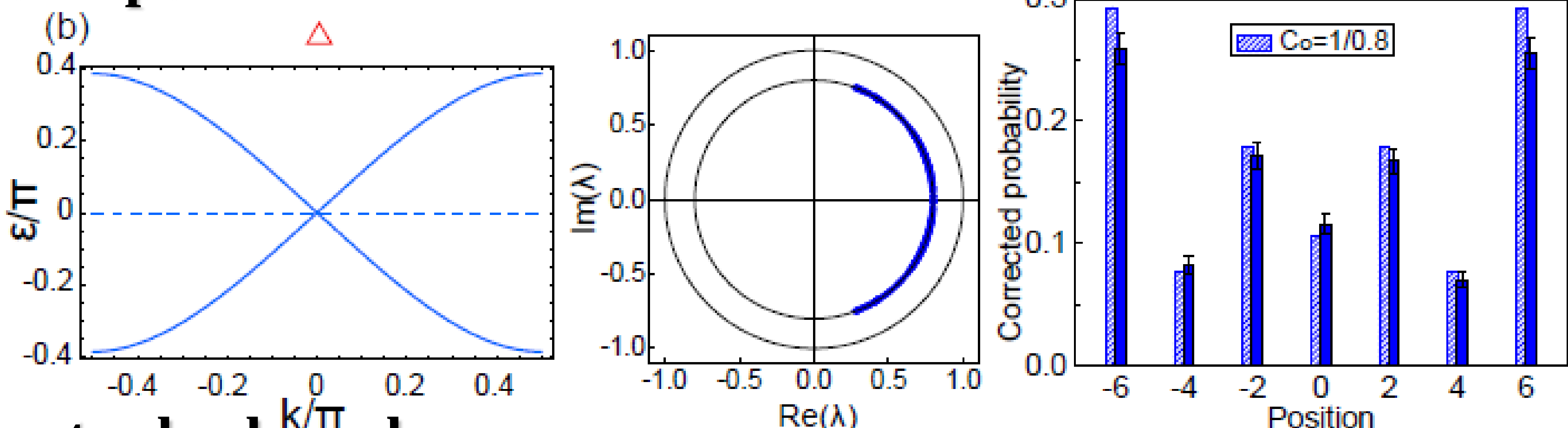


- White and grey areas represent broken PT symmetry phases. Real parts of quasienergies are 0 or π.
- Green, blue and red curves represent the boundaries of areas for different loss parameters
- Compared to unitary QW the area where the topological numbers are ill-defined extends from a line to finite region and the area depends on the loss parameters.

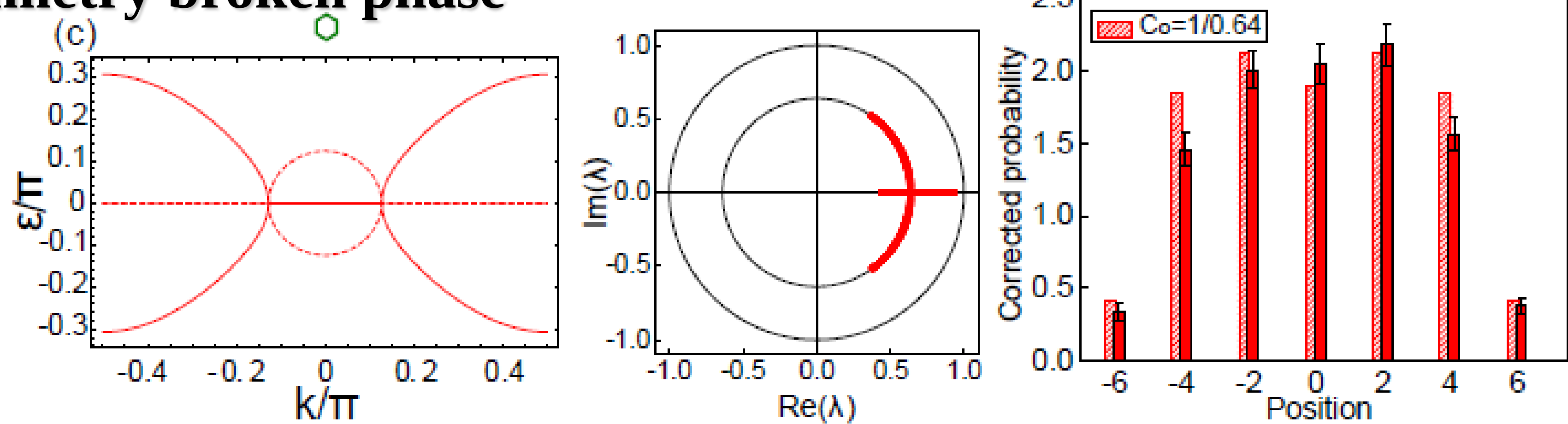
PT symmetry unbroken phase



Exceptional point

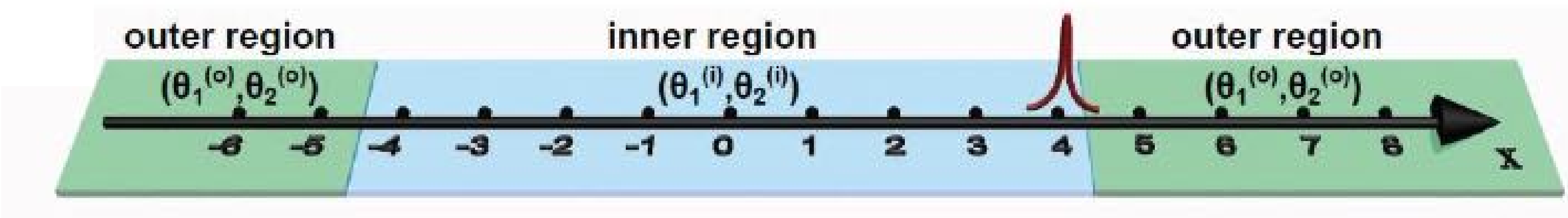


PT symmetry broken phase

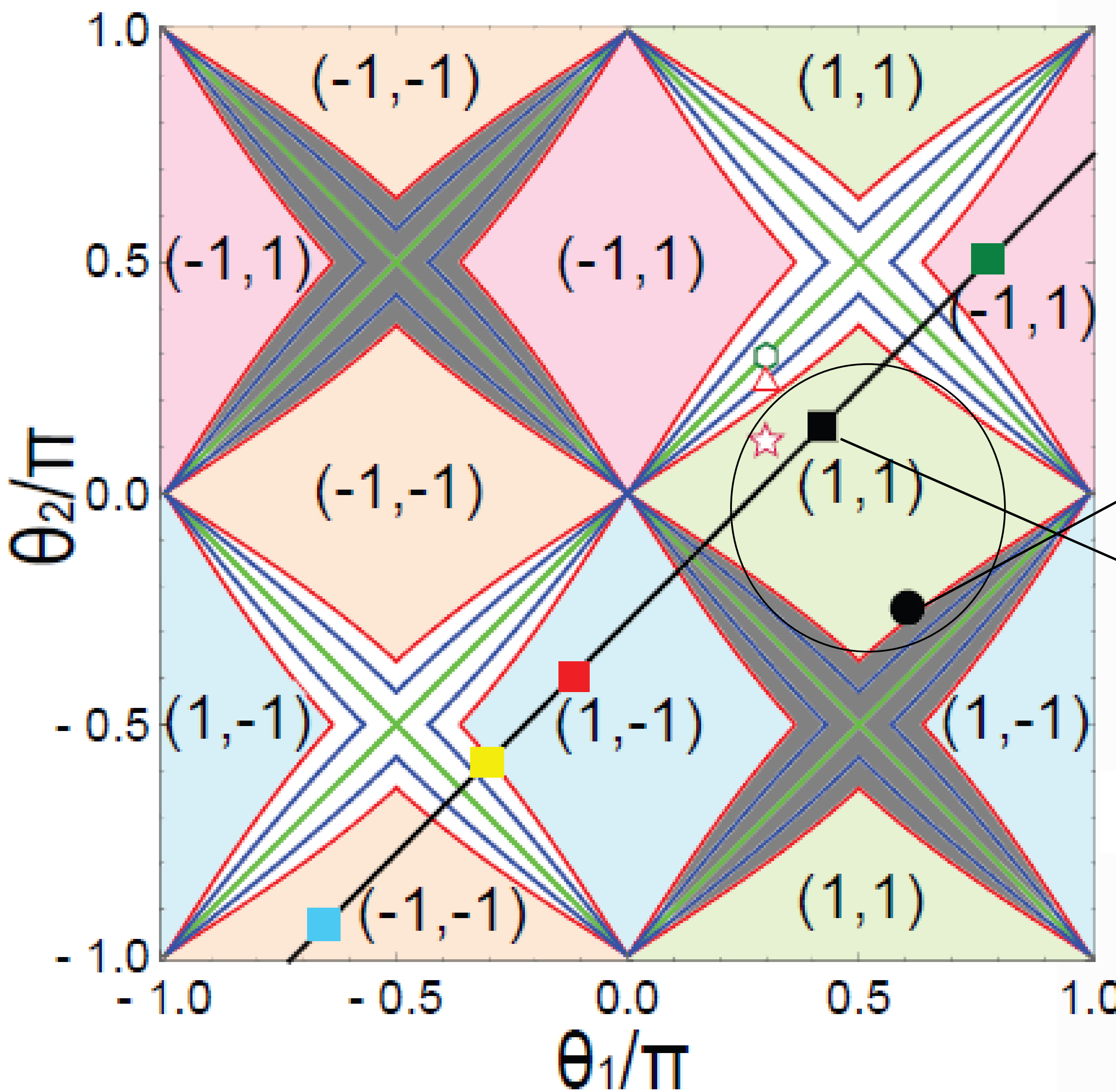


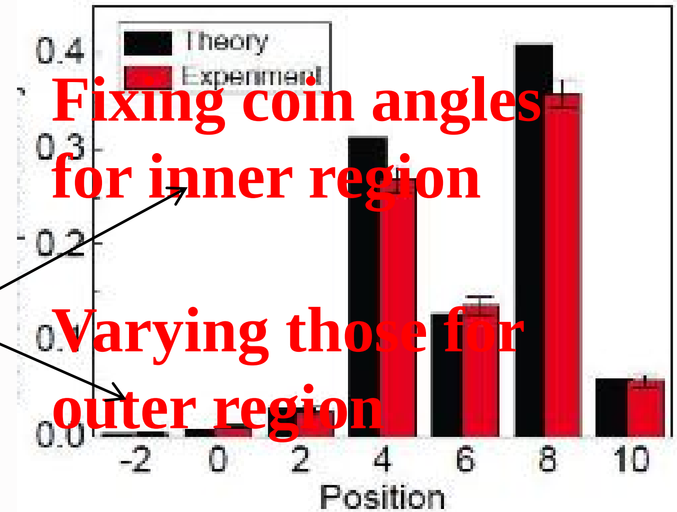
FTPs driven by PT-symmetric QWs

- Unitary QWs possess chiral symmetry, time-reversal symmetry, and particle-hole symmetry.
- PT-symmetric (non-unitary) QWs possess partial chiral symmetry, PT symmetry, and particle-hole symmetry.
- A similar FTP exists.
- In an inhomogeneous system, topological edge states originating from FTP would appear at interfaces between regions with different topological numbers.
- We probe these edge states by creating boundaries in the system.



No edge state



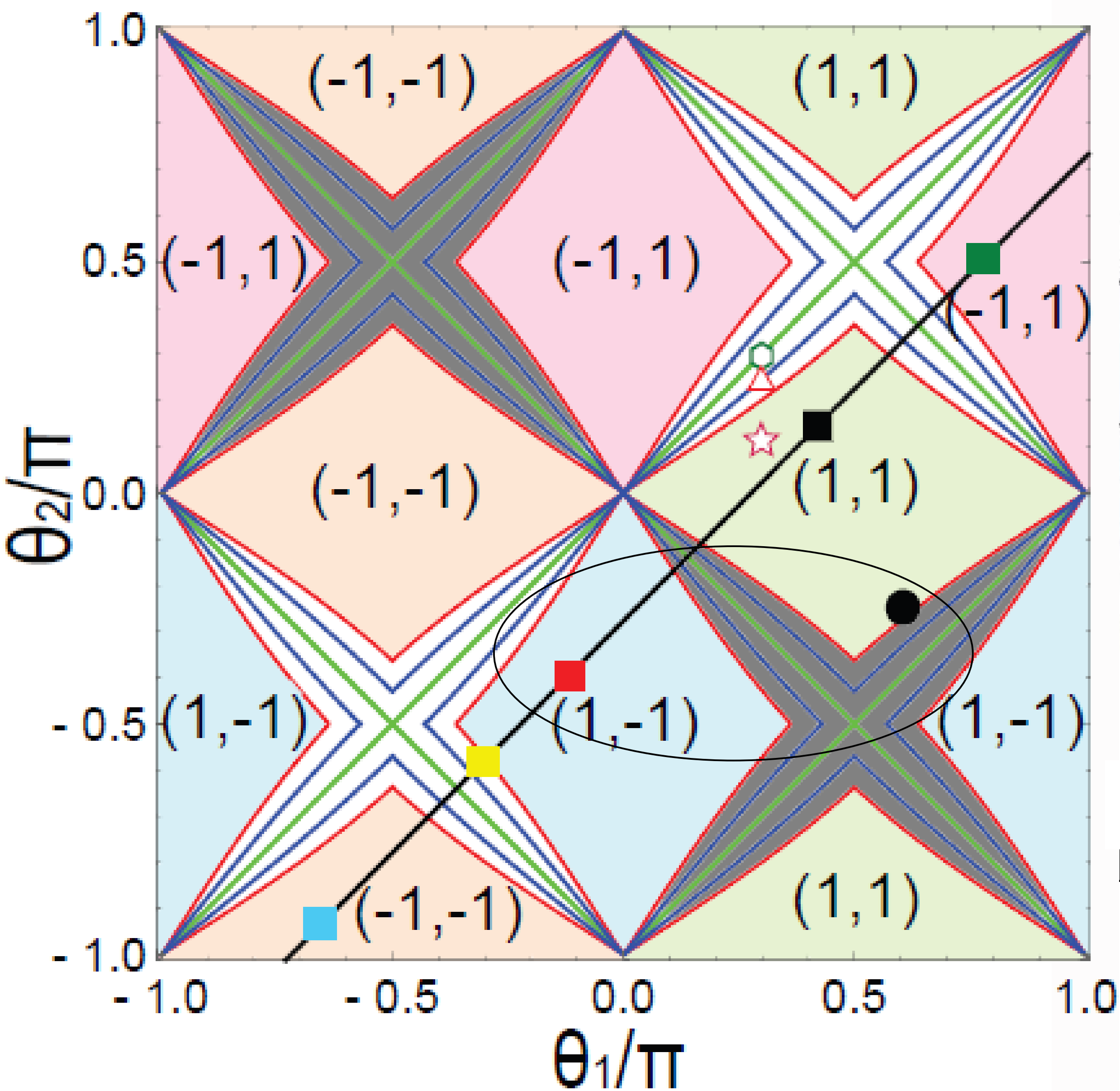


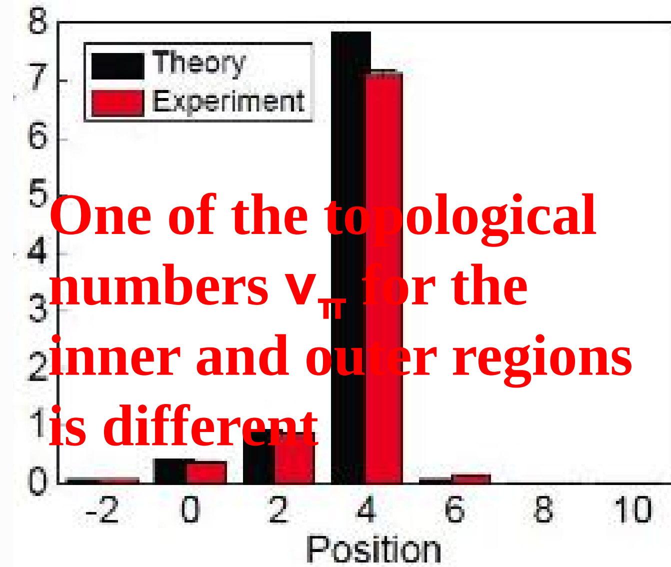
ons belong to the

al numbers.

distributions

One kind of edge states (Re(ε)=π)



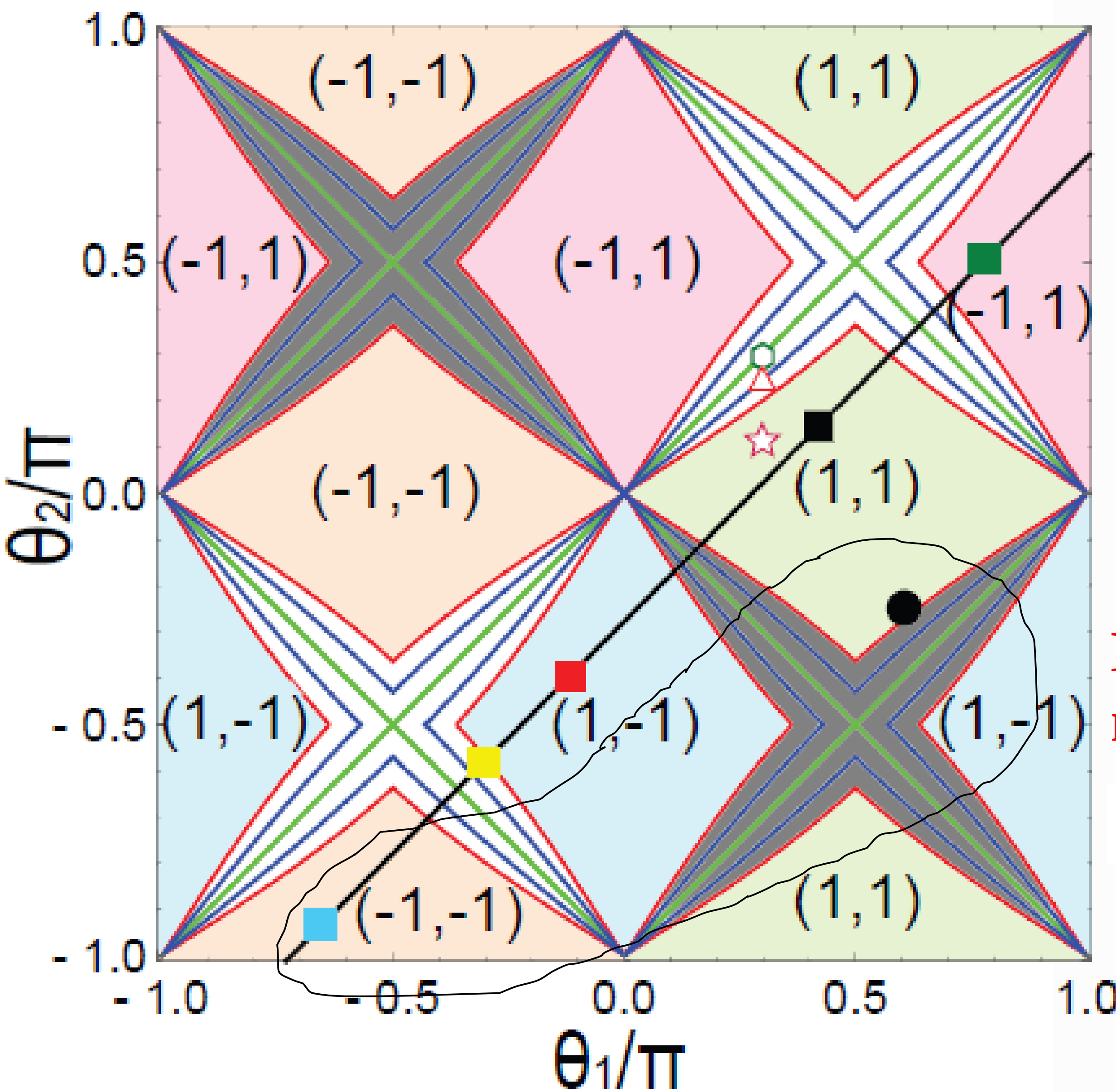


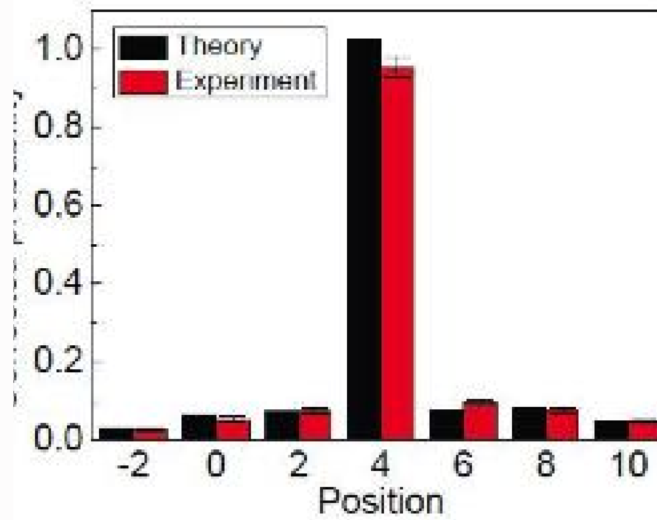
One of the topological numbers ν_π for the inner and outer regions is different

=4.

probability as the

Two kinds of edge states





e(ε)=0 and π.

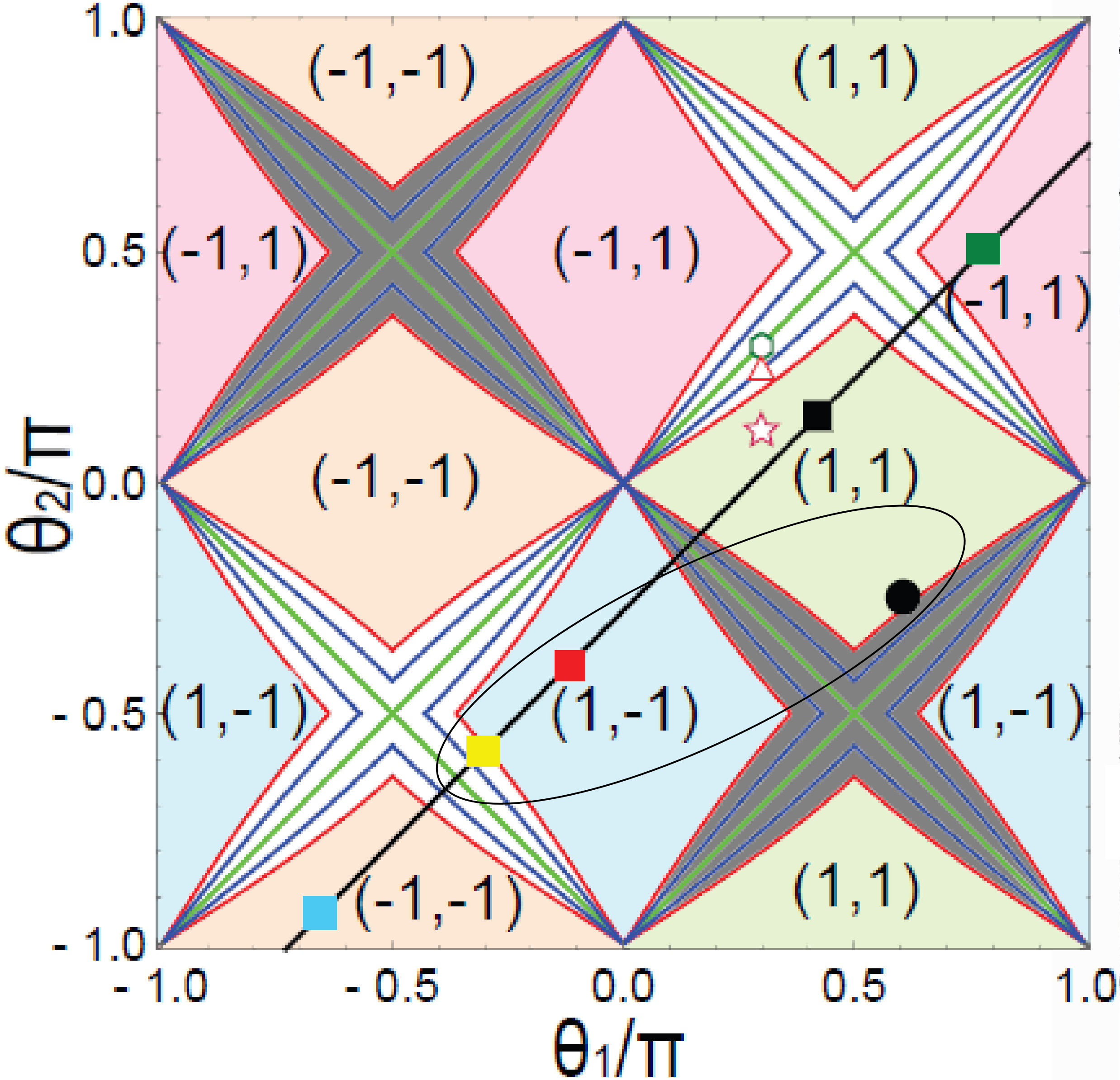
Both topological numbers are different

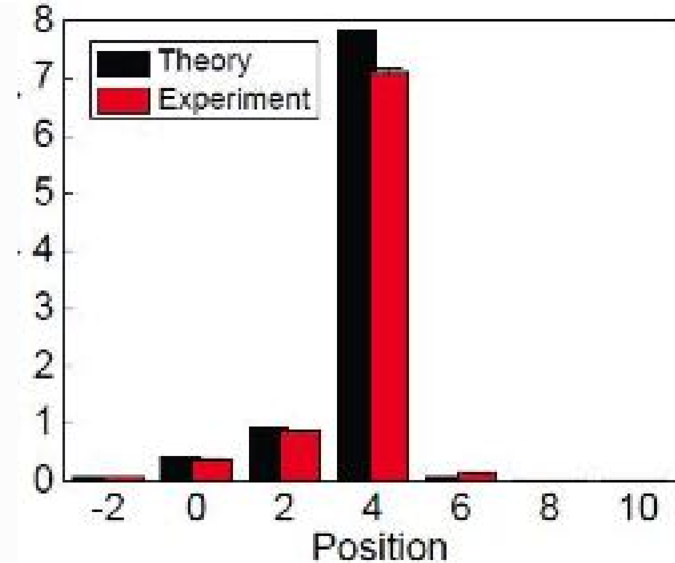
ne. The largest

or 6 is oscillating with

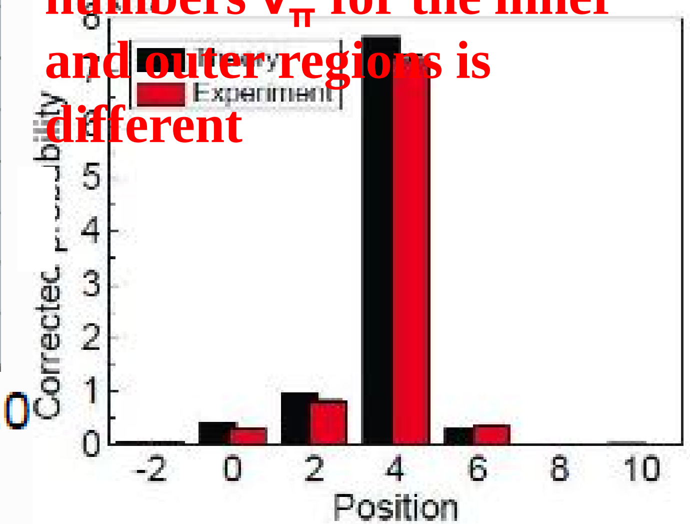
ture of the existence

Edge states are robust to symmetry-preserving small perturbations





One of the topological numbers v_π for the inner and outer regions is different

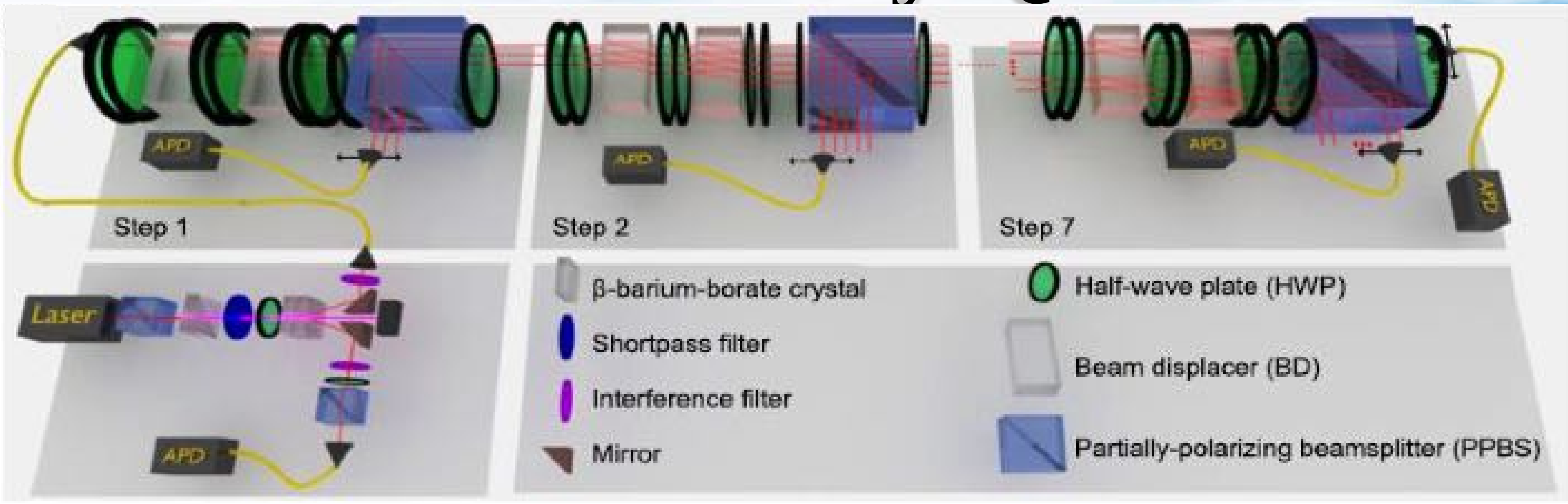


Detecting topological invariants

- We extend PT symmetric QW to general non-unitary QW and report the experimental detection of bulk topological invariants in non-unitary QWs with single photons.
- The non-unitarity of the quantum dynamics is enforced by periodically performing partial measurements, which effectively introduces loss to the dynamics.
- The topological invariant of the non-unitary QW is manifested in the quantized average displacement of the walker.
- We further demonstrate the robustness of the measurement scheme of the topological invariants against symmetry preserving disorder such as static disorder.

Ref: X. Zhan, L. Xiao, Z. H. Bian, K. K. Wang, X. Z. Qiu, B. C. Sanders, W. Yi and PX, Phys. Rev. Lett. 119, 130501 (2017)

Non-unitary QWs



Double-step unitary QWs:

$$U' = R(\tfrac{\theta_1}{2})SR(\theta_2)SR(\tfrac{\theta_1}{2})$$

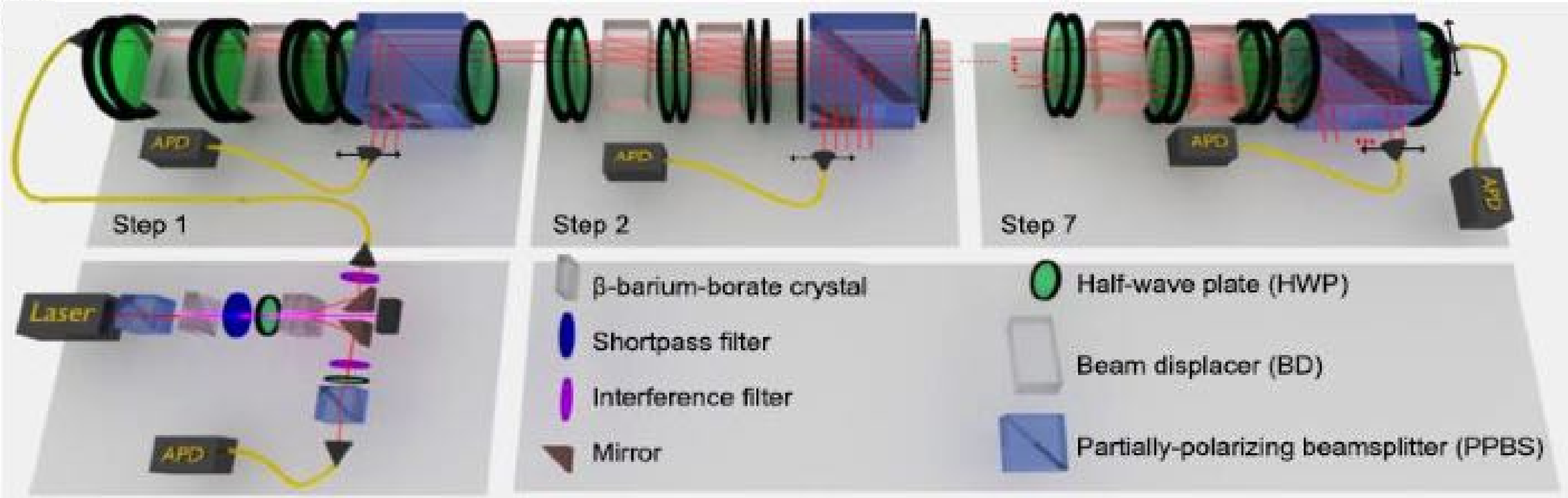
Non-unitarity is enforced by performing the partial measurement, which effectively introduces loss to the dynamics.

$$\begin{cases} M = \mathbb{1}_{\mathrm{w}} \otimes \left(|+\rangle\langle+| + \sqrt{1-p}\,|-\rangle\langle-| \right) \\ M_e = \mathbb{1}_{\mathrm{w}} \otimes \sqrt{p}\,|-\rangle\langle-| \end{cases}$$

Non-unitary QWs in different time frame:

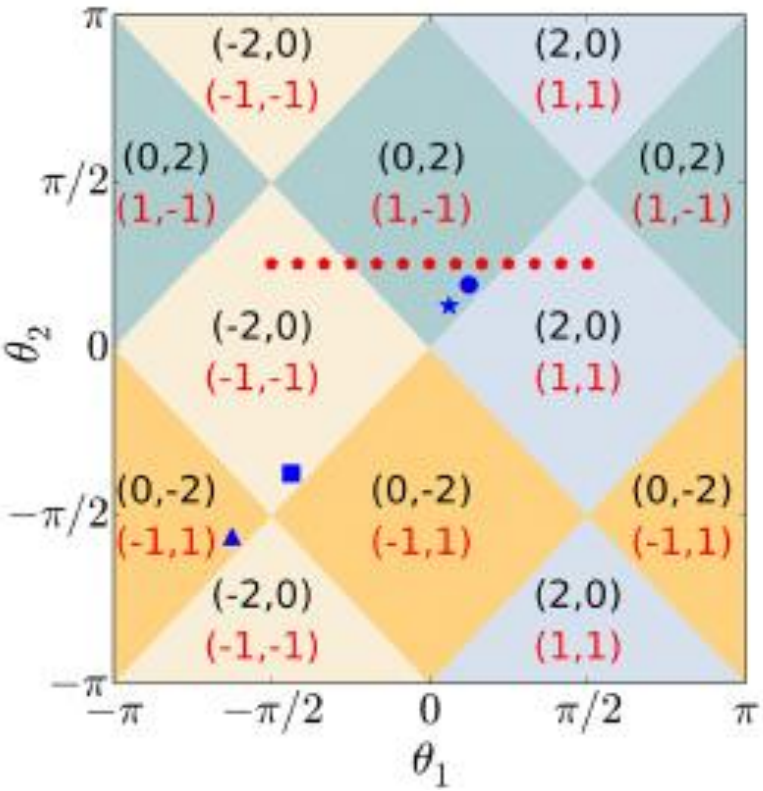
$$\begin{cases} \widetilde{U}' = MU' \\ \widetilde{U}'' = MR(\tfrac{\theta_2}{2})SR(\theta_1)SR(\tfrac{\theta_2}{2}) \end{cases}$$

Non-unitary QWs



- The initial coin state is |+>.
- Coin flipping can be realized by two HWPs with certain setting angles depending on coin parameters
- Shift operator is implemented by a BD.
- The partial measurement operator Me is realized by a sandwich-type setup involving two HWPs and a partially polarizing beamsplitter (PPBS) with the transmissivity of horizontally and vertically polarized photons $(T_{\mathrm{H}}, T_{\mathrm{V}}) = (1, 1-p)$
- Photons in |-> are reflected by the PPBS with a probability *p*, and then detected by APD. The remaining photons continue the QW dynamics after another polarization rotation via the second HWP, until they are detected and lost from the system.

Topological invariants of the non-unitary QWs



Phase diagram

- We consider a double-step QW under the Floquet operator

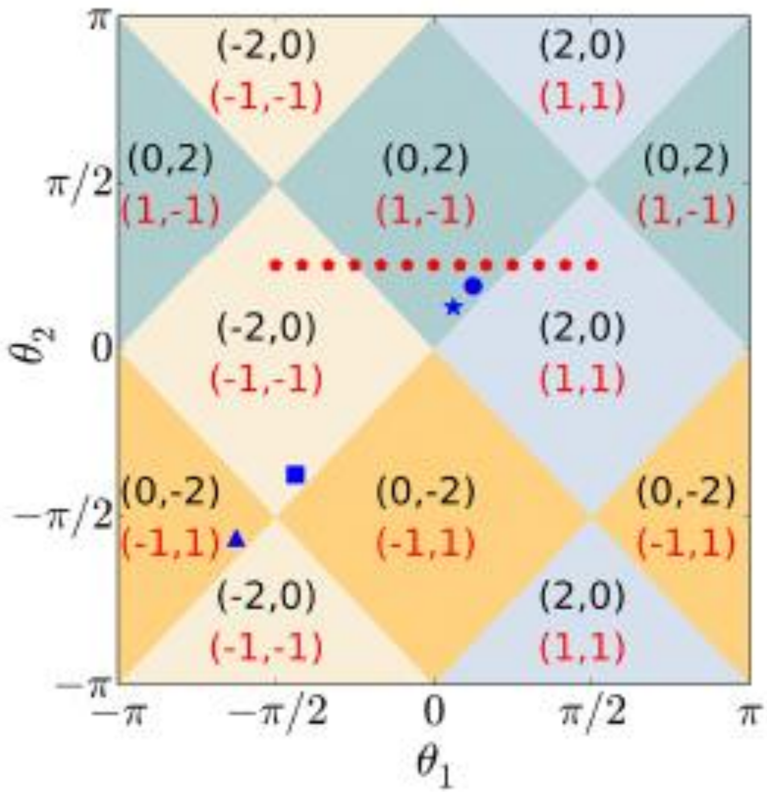
$$\tilde{U}' = M R\left(\frac{\theta_1}{2}\right) S R\left(\theta_2\right) S R\left(\frac{\theta_1}{2}\right)$$

- When p=0 QW is unitary. The topological invariant of the FTP is the winding number defined as

$$\nu = -\frac{1}{2\pi}\int_{-\pi}^{\pi} dk \left(\boldsymbol{n} \times \frac{\partial \boldsymbol{n}}{\partial k}\right)_x$$

- When p is not 0, the Floquet operator $\tilde{U}'$ becomes non-unitary, we can still define the effective non-Hermitian Hamiltonian.
- The topological invariant can be generalized as the winding number associated with the number of times the vector Re(n) winds around the x-axis as k goes through the first Brillouin zone.
- Here n is direction of the spinor eigenstates.

Displacement and dwell time



average displacement of the walker distribution:

$$\langle \Delta x \rangle = \sum_x \sum_{t'=1}^{\infty} x P_{\mathrm{th}}(x,t')$$

average dwell time, which characterizes the expected lifetime of the walker before it is measured and lost

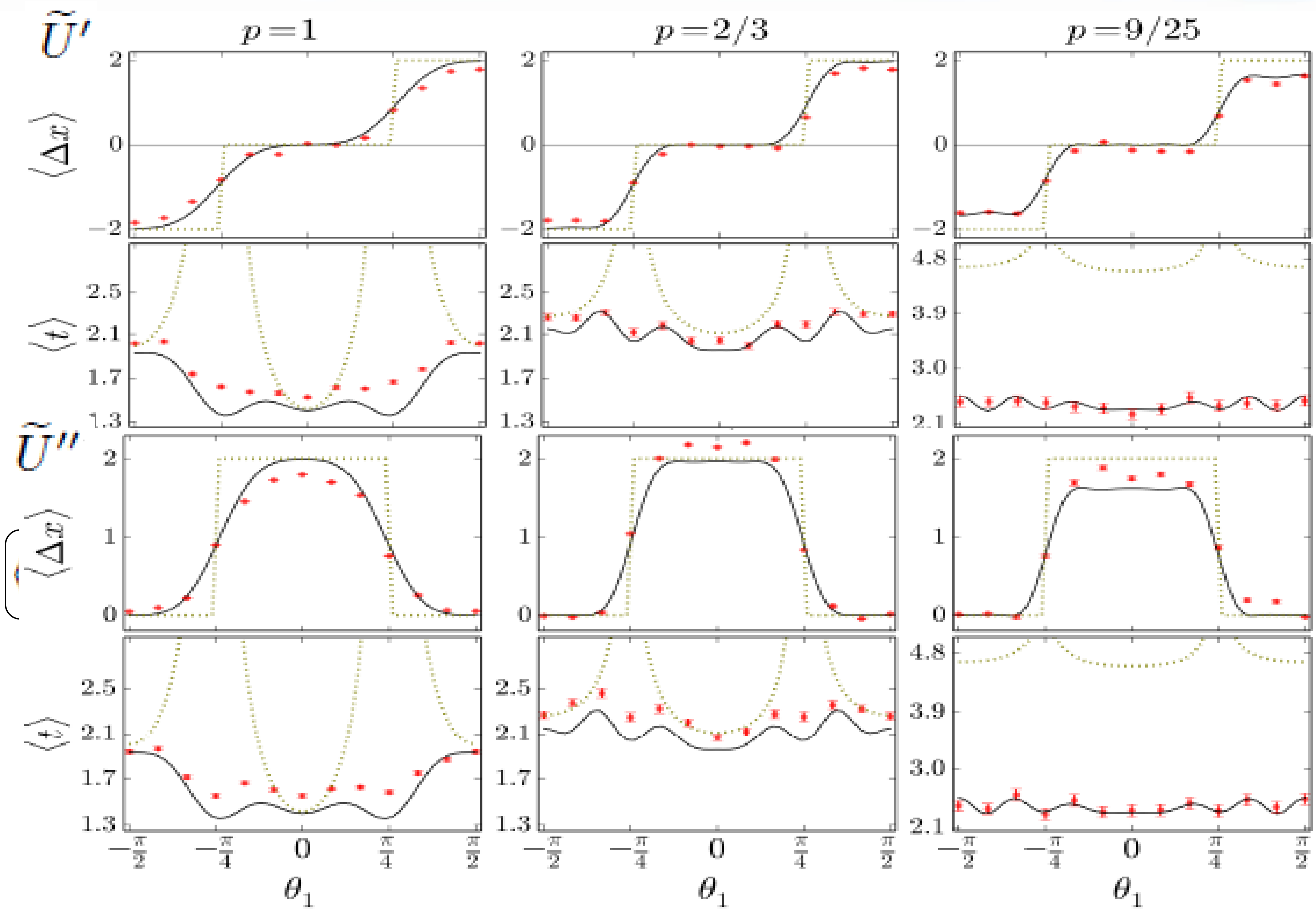
$$\langle t \rangle = \sum_x \sum_{t'=1}^{\infty} t' P_{\mathrm{th}}(x,t')$$

$$P_{\mathrm{th}}(x,t) = \langle \psi_{t-1} | \bar{U}'^{\dagger} M_e^{\dagger} (|x\rangle \langle x| \otimes \mathbb{1}_c) M_e \bar{U}' |\psi_{t-1}\rangle$$

- A non-unitary QW also supports FTP and a given FTP typically features two distinct topological invariants.

- The topological invariant of the non-unitary QW is manifested in the quantized average displacement of the walker.

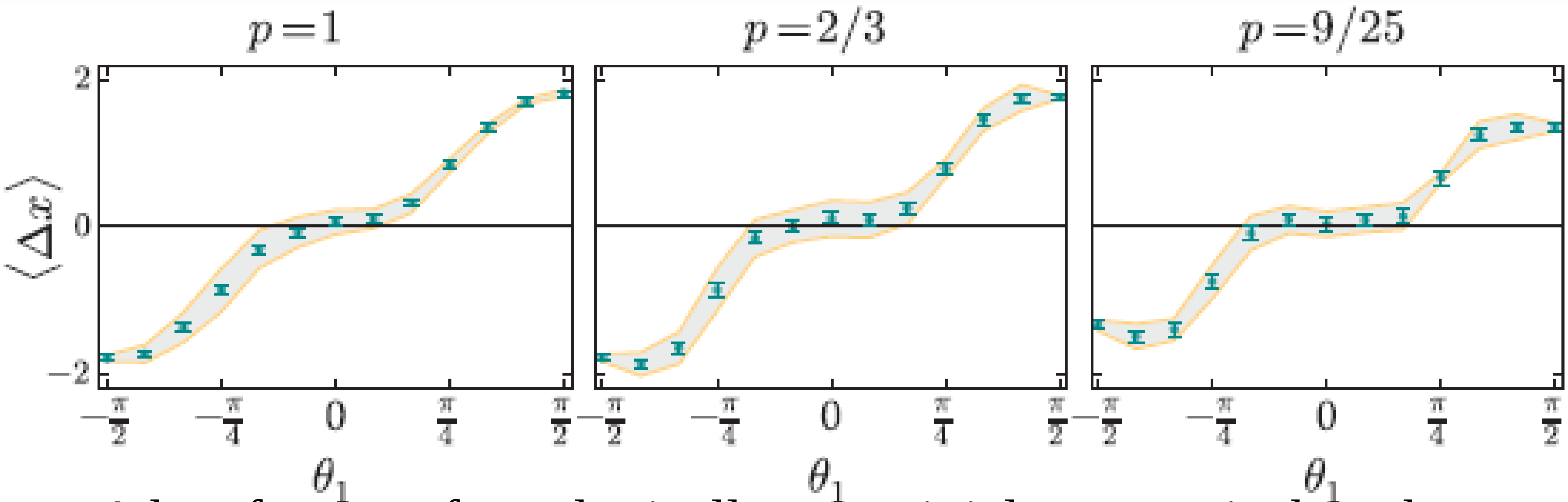
Displacement and dwell time



ıpt

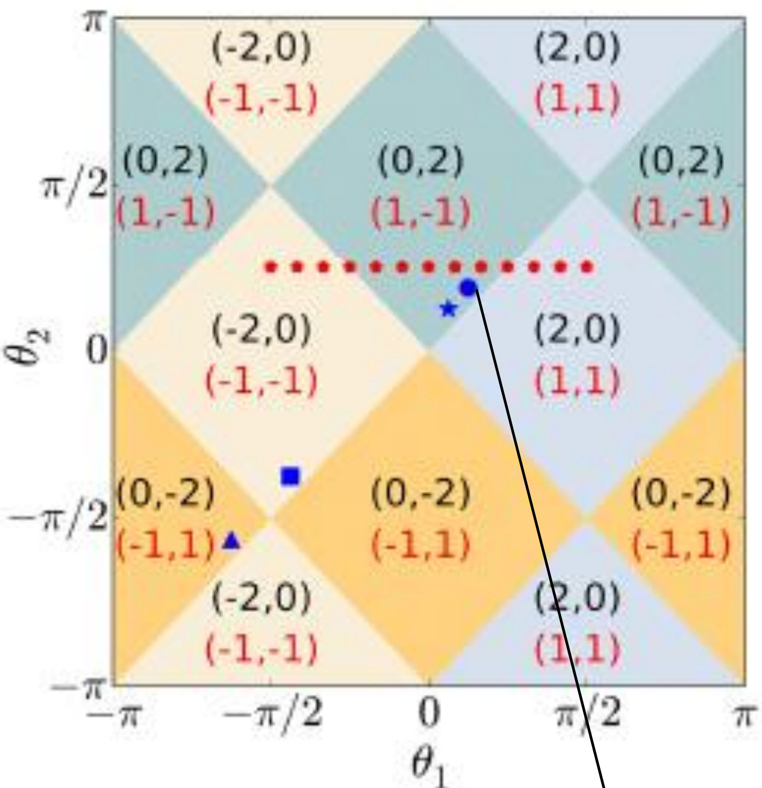
:h

Robustness against disorder



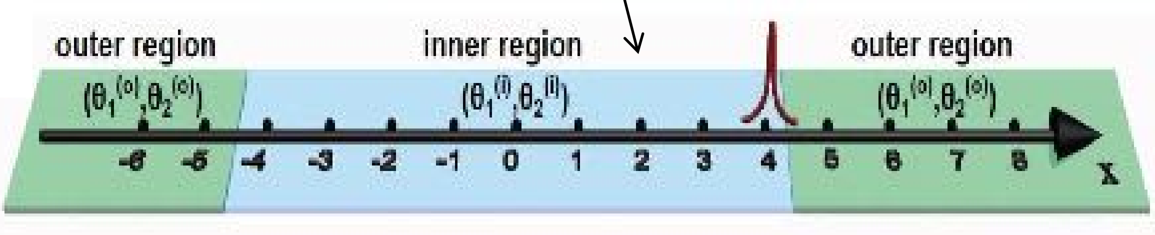
- A key feature of topologically non-trivial systems is the robustness of the topological properties against small perturbations.
- Figures show average displacements for 5-step QWs with static disordered rotation angles $\theta_{1,2}+\delta\theta$, where $\delta\theta$ is unique for each position and chosen from the intervals [-π/20, -π/20].
- The mean values of the average displacements are still quantized, which confirms the robustness of the measurement scheme against symmetry preserving static disorder.

Observation of edge states



- To confirm the non-trivial topological properties of the non-unitary QW, we create regions with distinct topological invariants and probe the existence of edge states via peaked probability distribution at the boundaries.

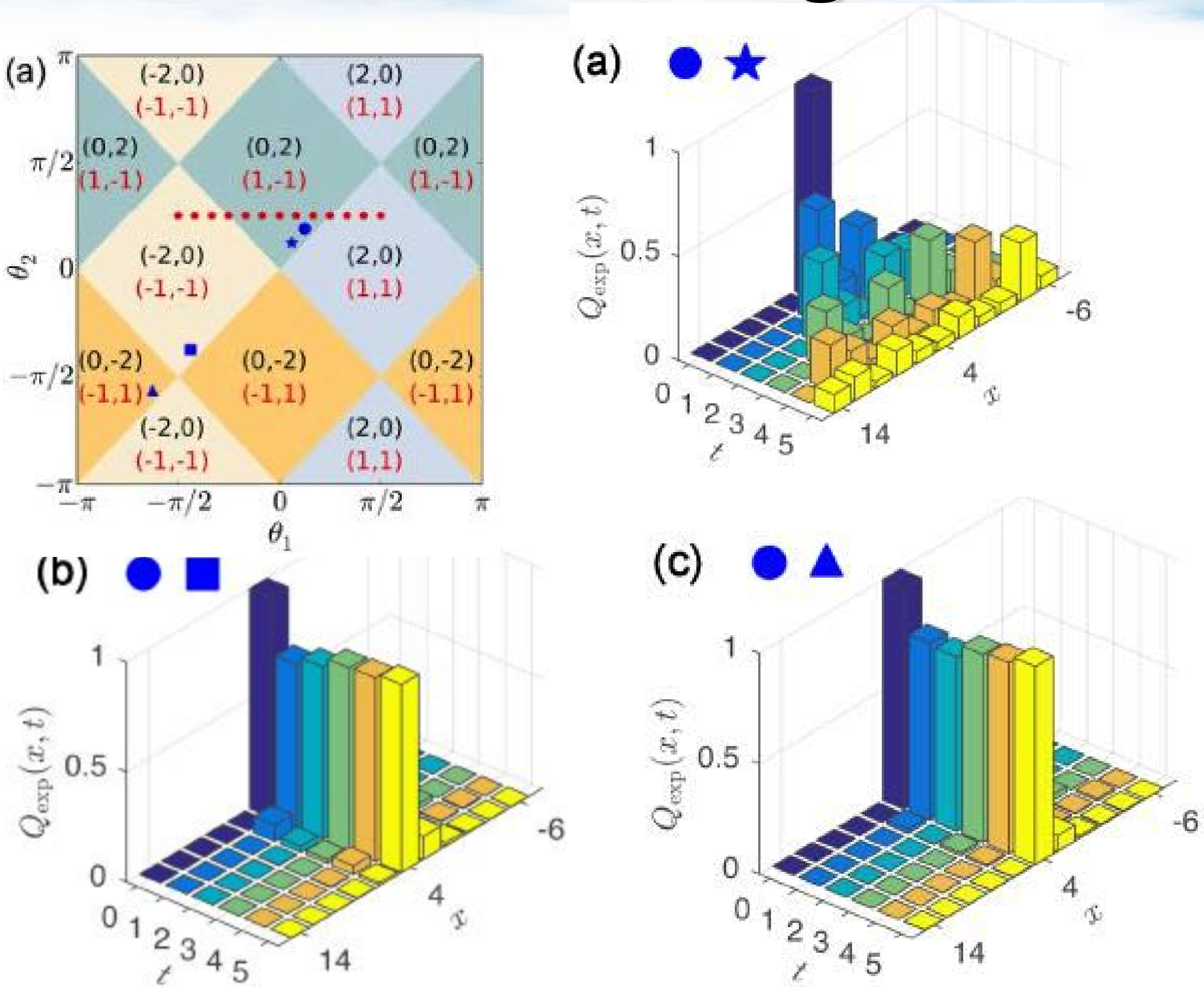
- The boundaries can be created by making the coin parameters spatially inhomogeneous. We fix the coin parameters for inner region and change those for outer region.



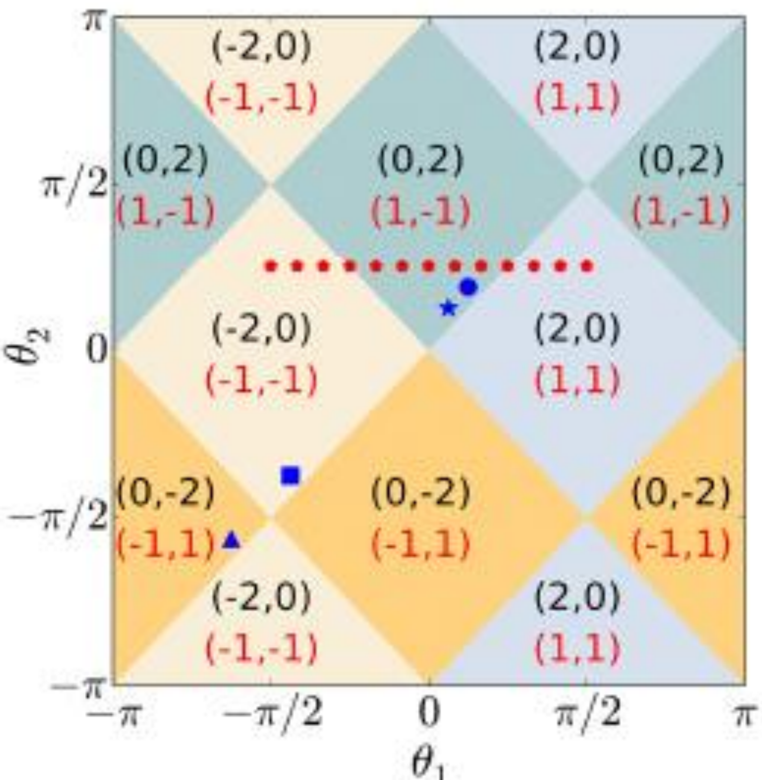
$$Q_{\rm th}(x,t) = |\langle x|\psi_t\rangle|^2/|\langle\psi_t|\psi_t\rangle|^2$$

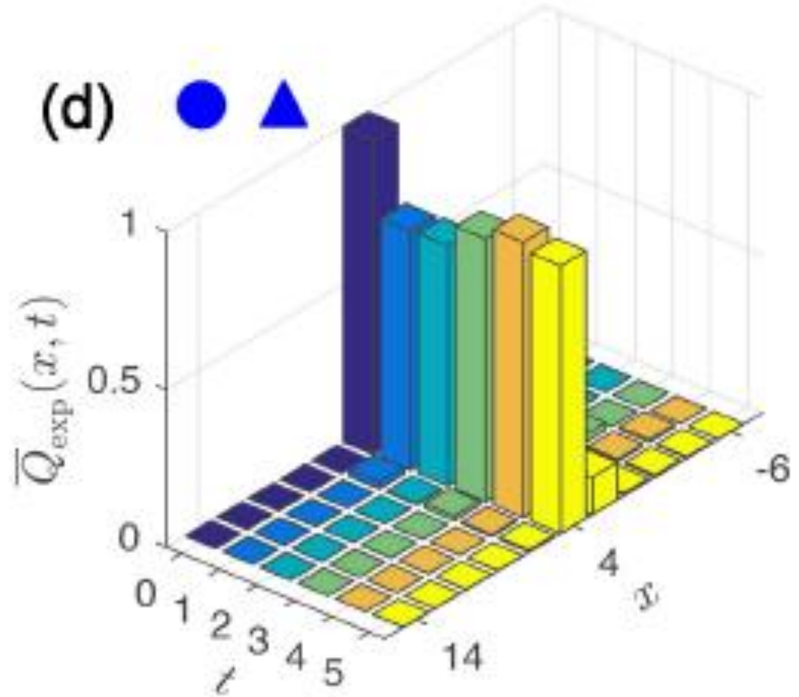
$$Q_{\rm exp}(x,t) = N_{\rm T}(x,t)/\sum_{x'} N_{\rm T}(x',t)$$

Observation of edge states



Observation of edge states





- The edge states are robust against static disorder.
- The experimental results of the mean values of the probabilities of QWs with static disorder introduced to both regions.
- An enhanced peak in position distribution is still observed near the boundary between the regions up to 5 steps, which confirms the robustness of edge state against static disorder.

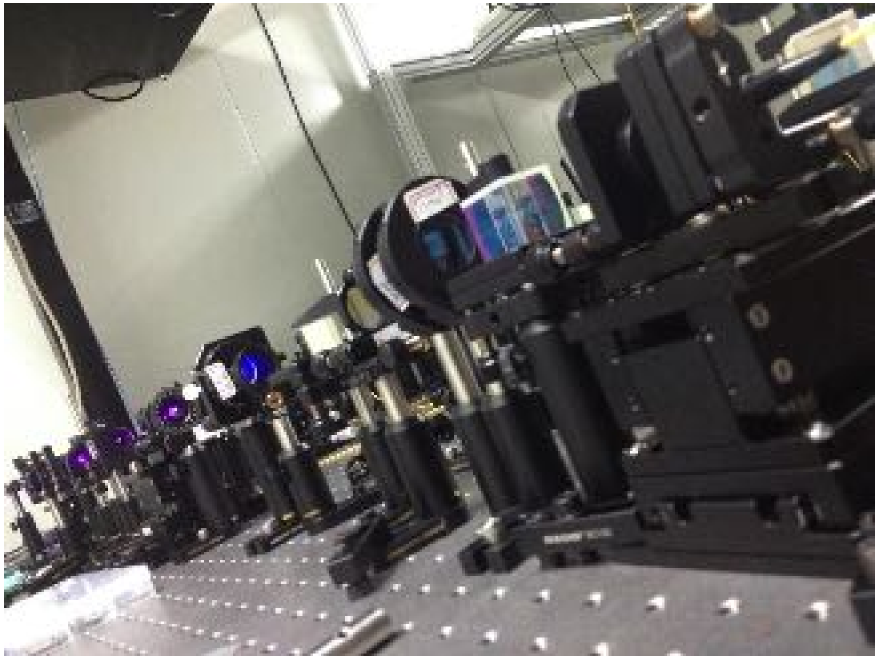
Summary

- Experimentally realize PT-symmetric QW in the single photon level with alternating loss instead of gain-loss
- Observation of Floquet topological phase in PT symmetric QW
- Evolution is non-unitary. Edge states are PT-symmetry broken states. The quasienergies of edge states are complex.
- Detection of topological invariants of non-unitary QWs.

Collaborators:

Experiment:

Lei Xiao, Xiang Zhan, Zhihao Bian, Kunkun Wang, Xin Zhang, Xiaoping Wang, Jian Li @ Southeast Univ.;



Theory:

Hideaki Obuse's group @ Hokkaido Univ.

Wei Yi's group @ Univ. of Sci. and Tech. of China

Barry C. Sanders @ Univ. of Calgary

Thank you for your attention…