IBS Conference on *Flatbands*

Novel Phenomena in Photonic Flatband Lattices

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Collaborators:

IBS: Prof. S. Flach, Prof. B.-J. Yang, Dr. J.-W. Rhim,

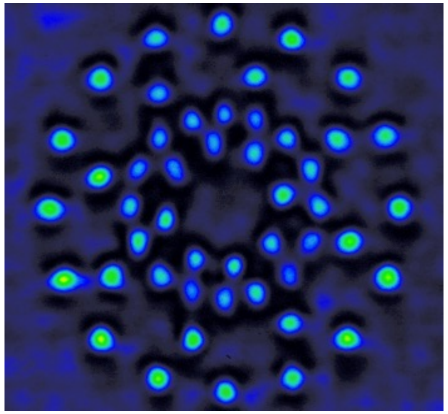
Dr. D. Leykam, Dr. C. Danieli

19th Aug 2021

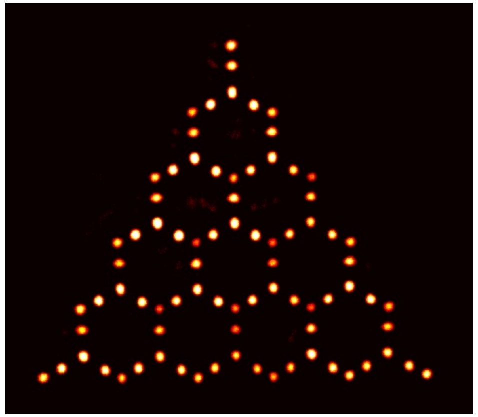
Outline

Introduction - flatband systems

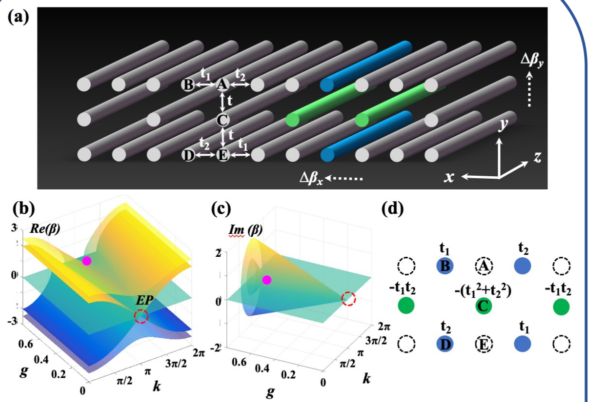
Our work (design and demonstration)



Unconventional flatband localization



Square-root higher-order topological insulators

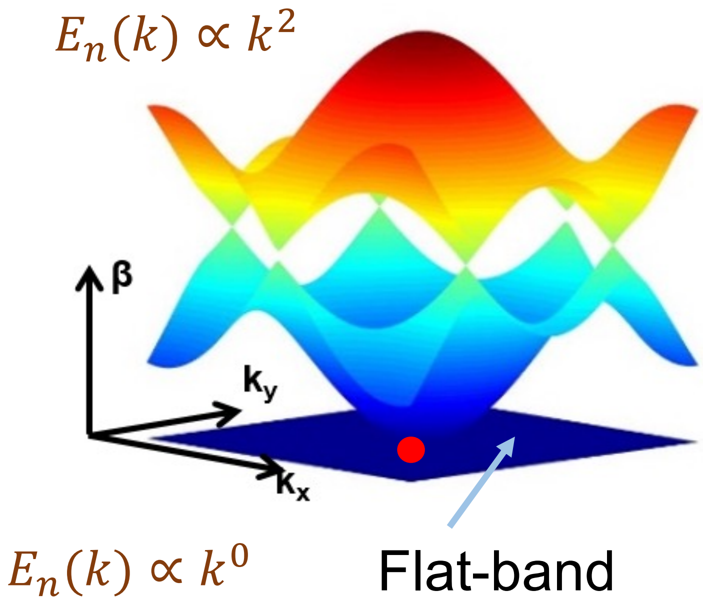


Landau-Zener Bloch oscillations in Non-Hermitian flatband lattices

Flat bands（FB）

- A completely dispersionless band
- Zero group velocity

in tight-binding models

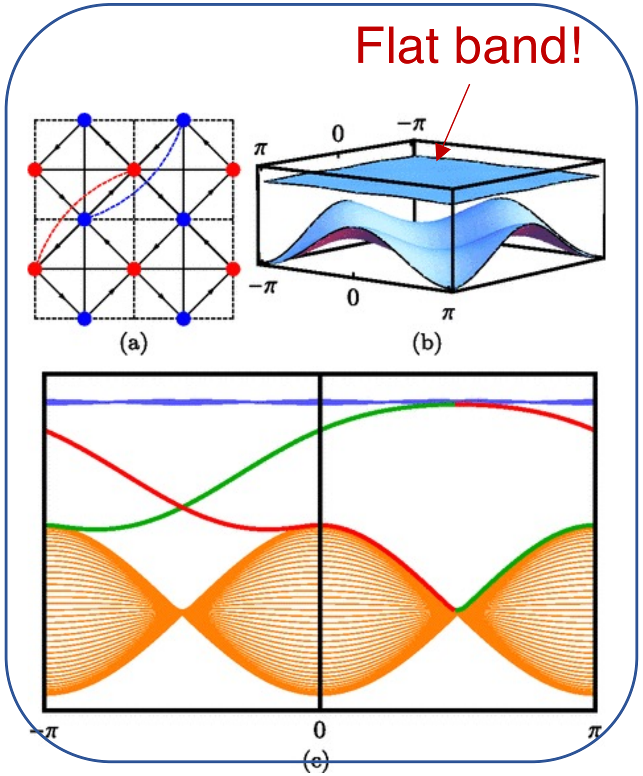


Flat bands: extremely sensitive to perturbation

novel strongly correlated many-body physics

Flatband Physics

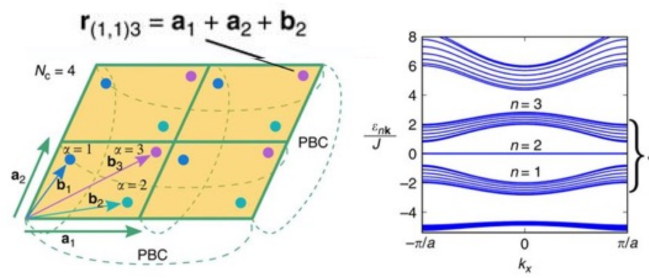
Nontrivial Topology



Fractional Quantum Hall States

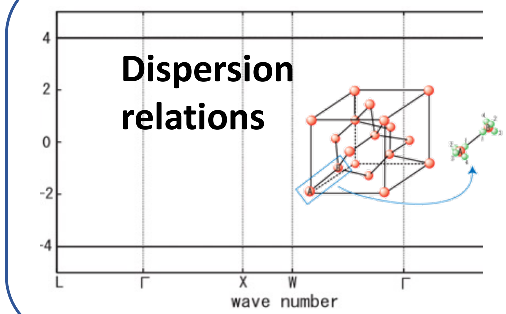
E. Tang, et al. PRL (2011)
K. Sun, et al. PRL (2011)
T Neupert, et al. PRL (2011)

Flatband superfluidity



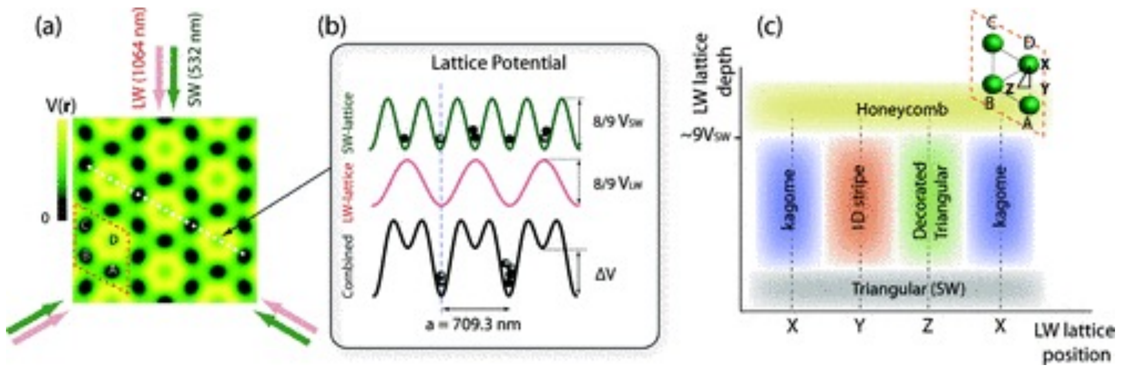
S. Peotta et al., Nat. Commun. (2015)

Inverse Anderson Transition



M. Goda et al., PRL (2006)

Ultracold atomic condensates

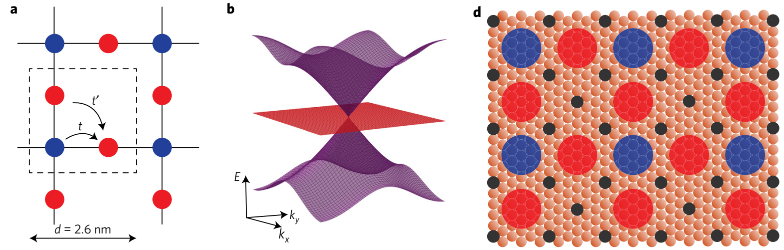


high critical temperature

G.-B. Jo, et al. PRL (2012)

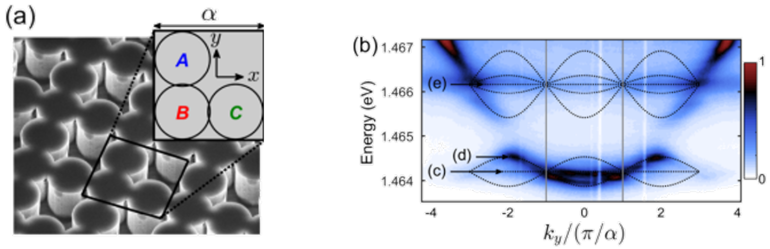
Flatband Systems

Electrons



M. R. Slot, et al., Nat. Phys. (2017)

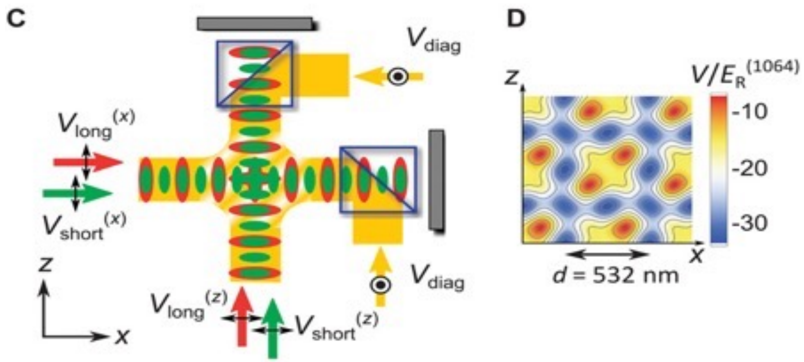
Polaritons



Scanning electron microscope image

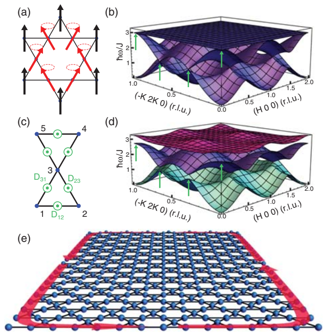
C. E. Whittaker et al., PRL (2018)

Bose-Einstein Condensates



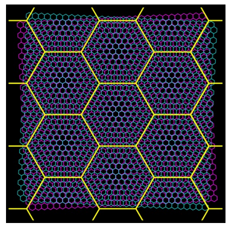
S. Taie, et al., Sci. Adv. (2015)

Realistic Materials



R. Chisnell, et al., PRL (2015)

Magic-angle graphene

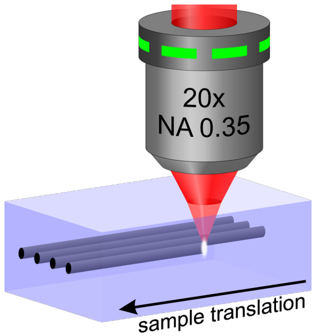


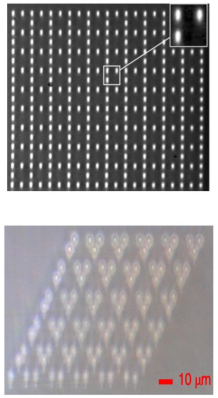
Fundamental physical origin of Mott-insulators

Nature 556, 80 (2018)
Nature 556, 43 (2018)

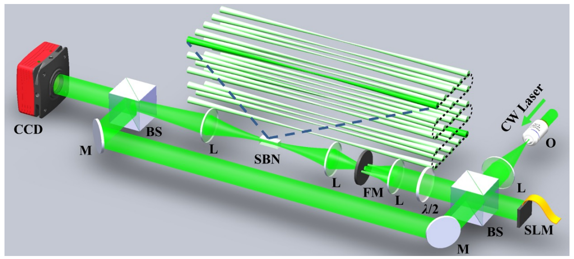
Photonic flat bands

Photonic lattices



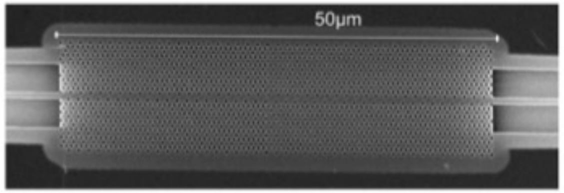


Phys. Rev. Lett. 2015 Nat. Photon. 2019



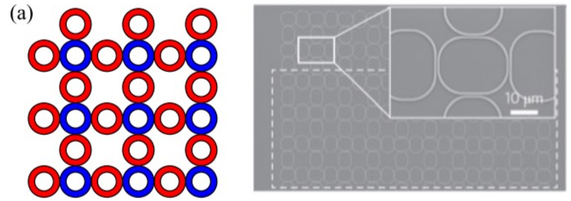
Nanophononics (2020)

Photonic crystals



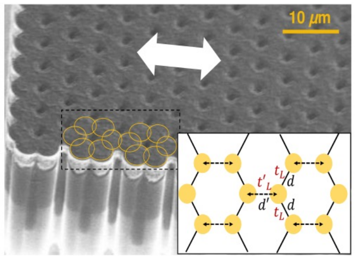
Opt. Lett. (2017)

Coupled resonator lattices



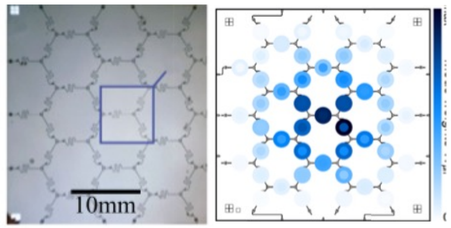
Nat. Photonics (2013)

Photonic micropillars



Phys. Rev. X 2019

Microwave circuit QED



Phys. Rev. X (2016)

- ☐ **A fine-tuned platform:**
  precise control and monitoring (including phase)
- ☐ **Directly observe wave dynamics using classical light waves**

see recent reviews

Leykam, Andreanov, Flach, Adv Phys X 3, 1473052(2018)

Leykam, S. Flach, APL Photonics 3, 070901 (2018)

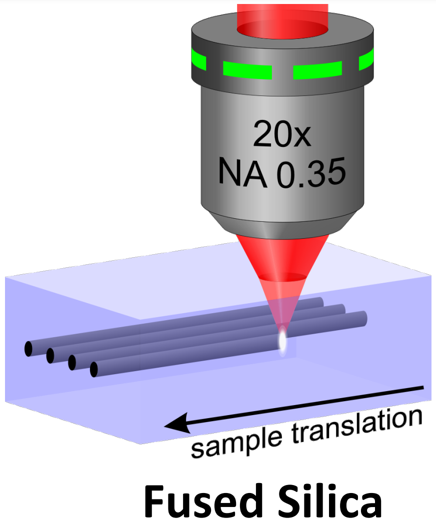
Tang, Song, …, Xu, Leykam, Chen. Nanophononics, 9, 1161 (2020)

R. A. Vicencio, Adv Phys X 6, 1878057 (2021)

How to create FB photonic lattices ?

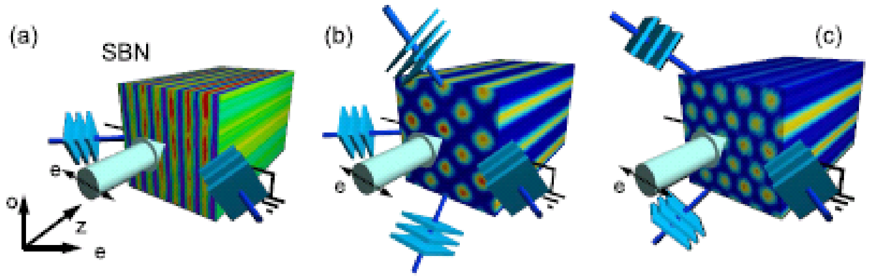
Femtosecond laser written technique (permanent)

Pertsch et al, OL 04
Szameit et al, OL 08
……



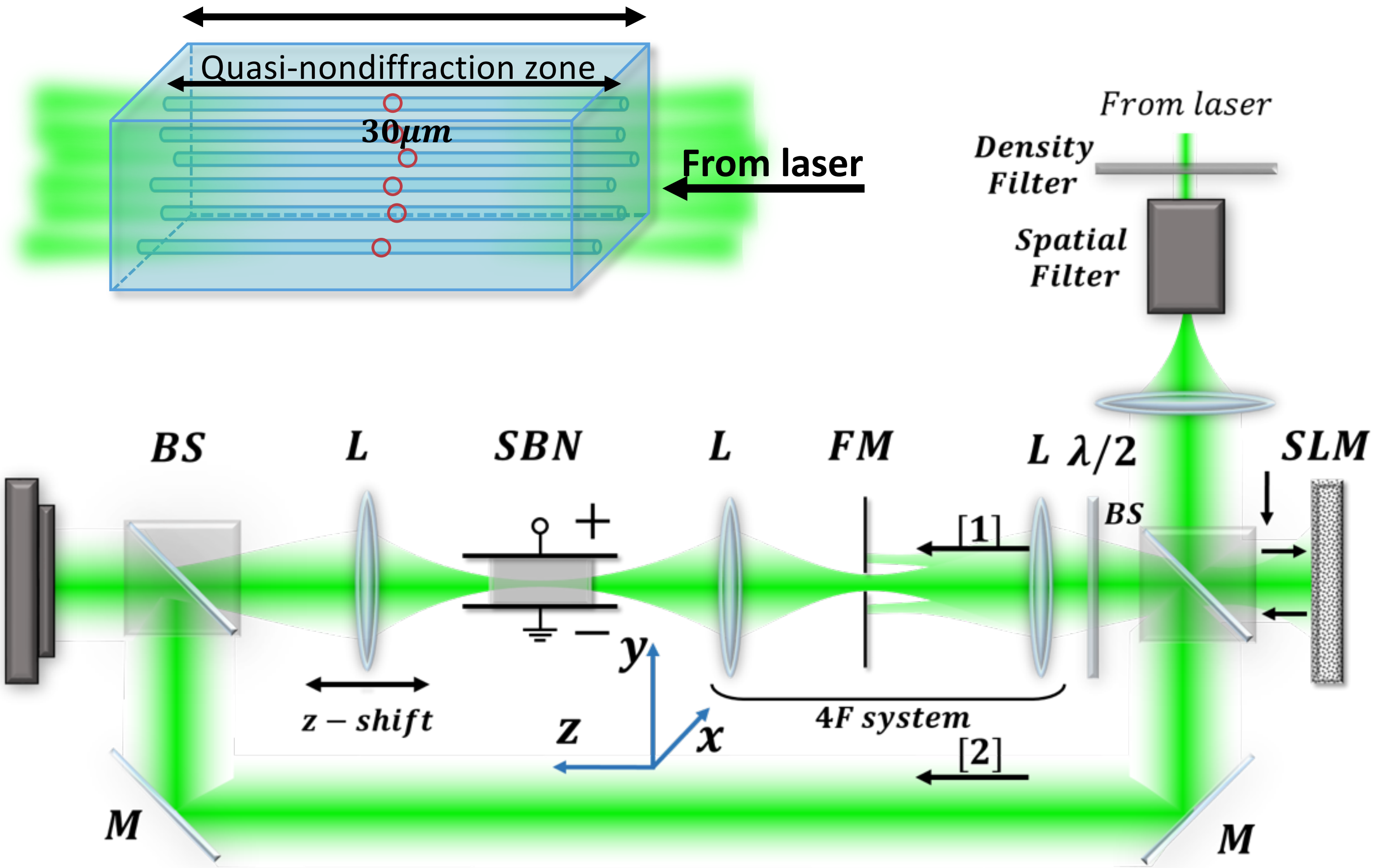
Multiple-beam interference technique (reconfigurable)

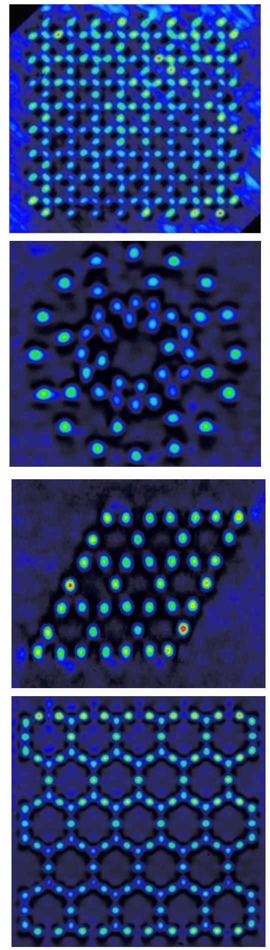
Efremidis et al., PRE (2002)
Fleischer et al. PRL;Nature (2003).
Neshev et al, OL (2003).
Cohen et al, Nature (2005).
……



How to create FB photonic lattices ?

Site to site cw-laser writing technique for bounded lattices (reconfigurable)

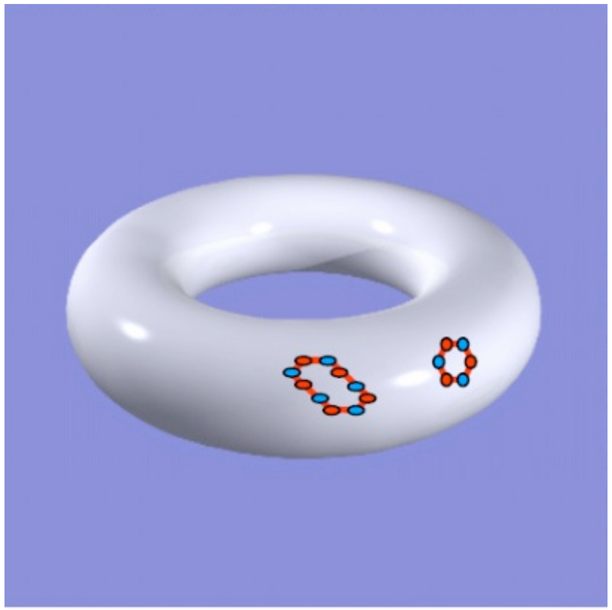




Motivation

Can we design a 2D photonic lattice to represent a 3D torus structure?

- Periodic boundary condition
- Nontrivial loop states
- Real-space topology



PHYSICAL REVIEW LETTERS

Unconventional Flatband Line States in Photonic Lieb Lattices

Shiqi Xia, Ajith Ramachandran, Shiqiang Xia, Denghui Li, Xiuying Liu, Liqin Tang, Yi Hu, Daohong Song, Jingjun Xu, Daniel Leykam, Sergej Flach, and Zhigang Chen

Phys. Rev. Lett. **121**, 263902 – Published 28 December 2018

ADVANCED OPTICAL MATERIALS

Communication

Flatband Line States in Photonic Super-Honeycomb Lattices

Wenchao Yan, Hua Zhong, Daohong Song, Yiqi Zhang, Shiqi Xia, Liqin Tang, Daniel Leykam, Zhigang Chen

First published: 30 March 2020 | https://doi.org/10.1002/adom.201902174 |

PHYSICAL REVIEW LETTERS

Direct Observation of Flatband Loop States Arising from Nontrivial Real-Space Topology

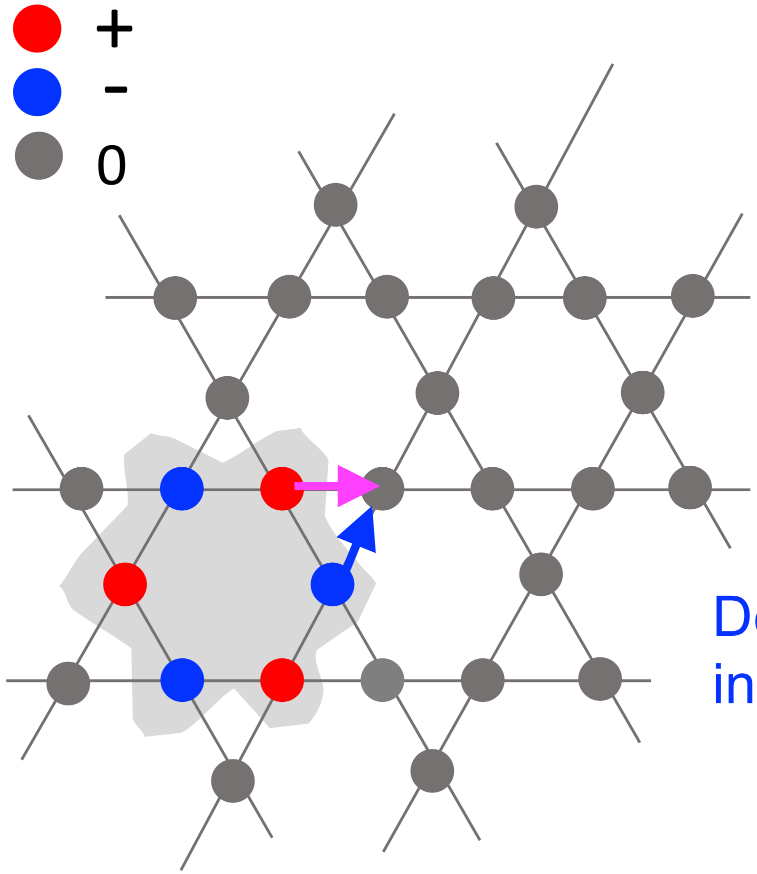
Jina Ma, Jun-Won Rhim, Liqin Tang, Shiqi Xia, Haiping Wang, Xiuyan Zheng, Shiqiang Xia, Daohong Song, Yi Hu, Yigang Li, Bohm-Jung Yang, Daniel Leykam, and Zhigang Chen

Phys. Rev. Lett. **124**, 183901 – Published 4 May 2020

Compact Localized State (CLS)

Flat band → CLS

Kagome lattice



Destructive interference

Aoki, Ando, Matsumura, Phys. Rev. B (1996)

Bodyfelt, Leykam, Danieli, Yu, Flach, Phys. Rev. Lett. (2014)

Demonstration of CLS in Photonic lattices

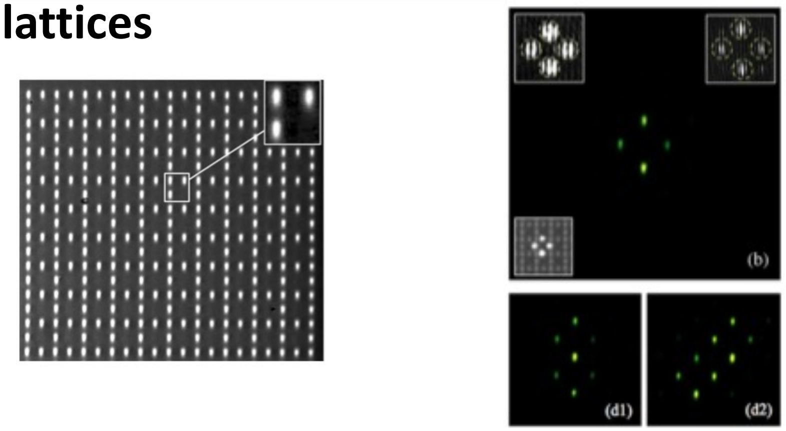
- Lieb lattices:
  R. A. Vicencio, et al., PRL. (2015);
  S. Mukherjee, et al., PRL. (2015)
  S. Xia , et al., OL. (2016)

- Kagome lattices:
  Y. Zong et al. OE. (2016);

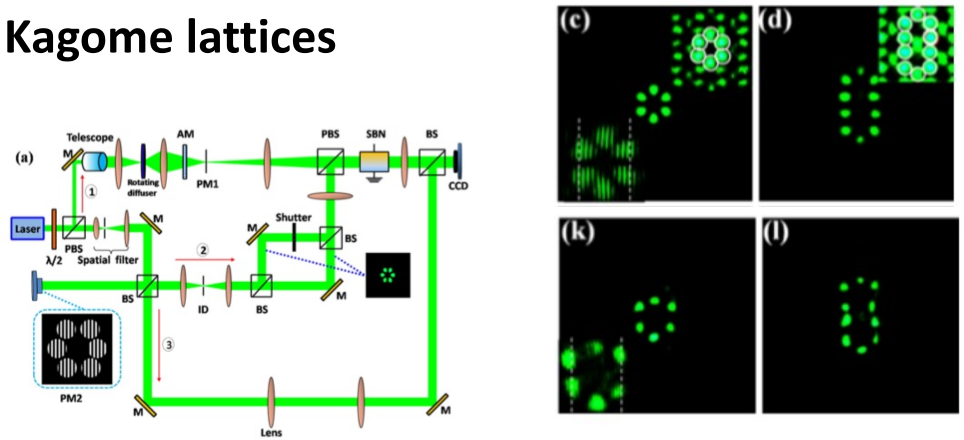
- Rhombic lattices
  S. Mukherjee, et al. OL (2015) ;
  OL(2017); Nat Commun (2017);
  PRL(2018)
  S. Xia, et al., APL Photon.(2020);
  S. Longhi, OL (2014) ; OL (2019) ;
  R. Khomeriki, et al. PRL (2016)

… …

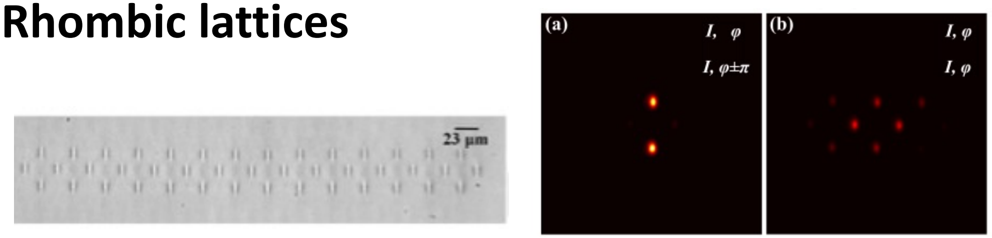
Lieb lattices



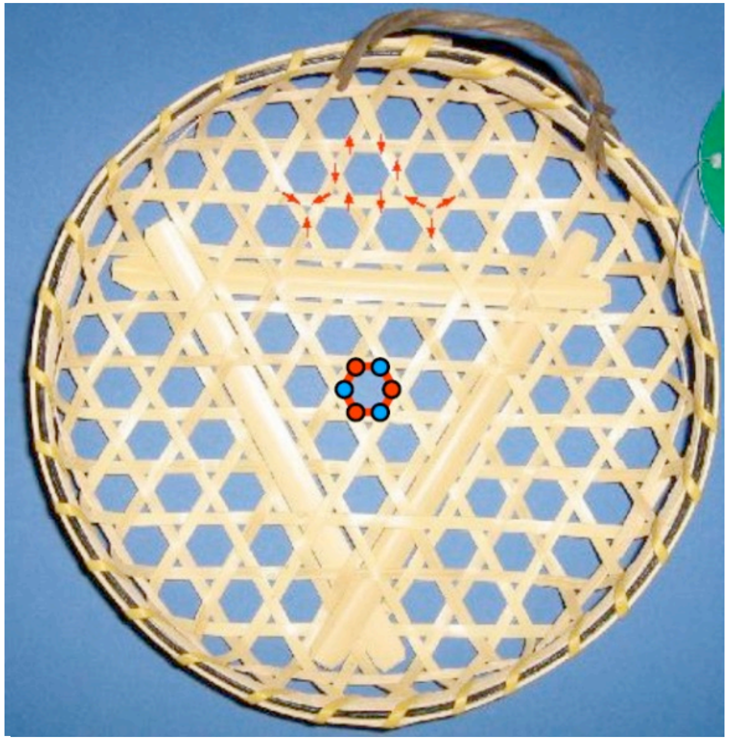
Kagome lattices



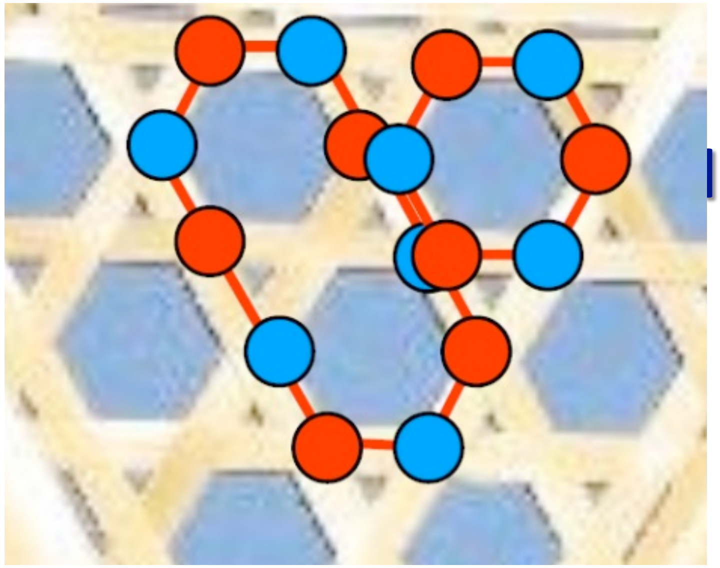
Rhombic lattices



CLSs incomplete?



Elementary hexagon



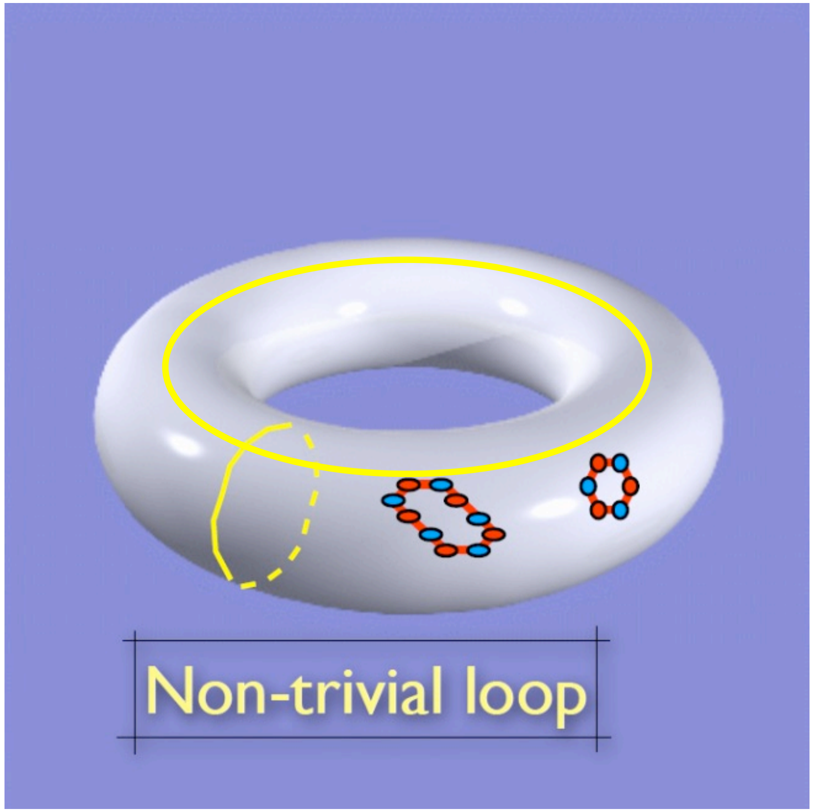
No all CLSs are independent

Bergman, Wu, Balents, PRB 78, 125104 (2008)

Ramachandran, Andreanov, Flach, PRB 96, 161104(R) (2017).

J.-W. Rhim, B.-J. Yang, PRB 99, 045107 (2019)

Why are CLSs incomplete?



- On torus with N unit cells, find N-1 linearly independent states

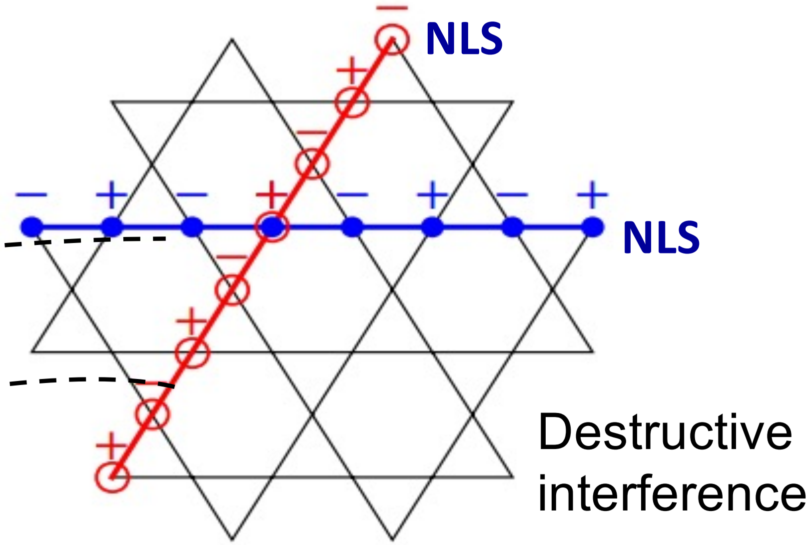
- Where is the missing state?

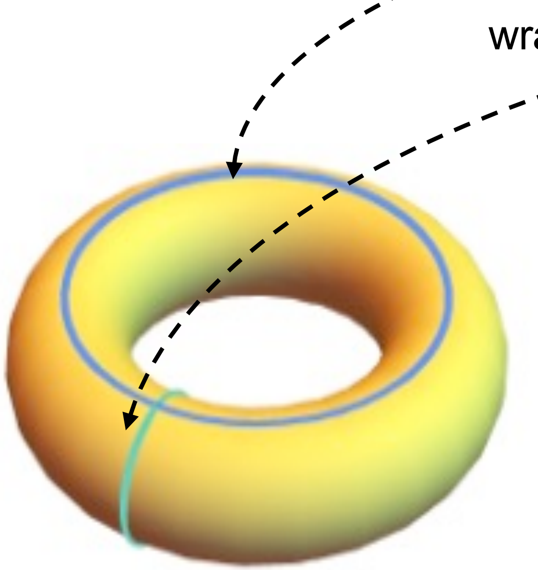
Answer:

- Two non-contractible loops formed on the torus.
- Total states: N+1 states
- This requires another band to touch the flat band.

- Non-contractible loops states(NLS) is not equal to CLS in topology
- real space topology

NLSs in Kagome



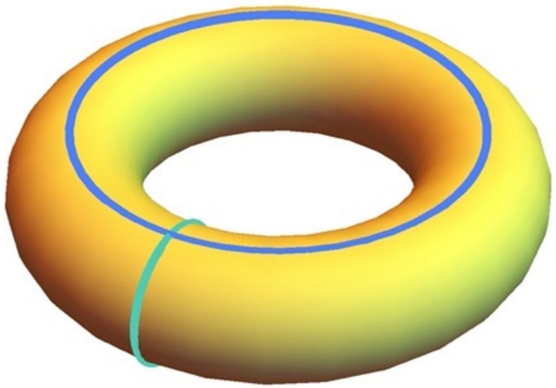


- Two non-contractible loops can be formed on the torus.

Non-trivial loop

Question

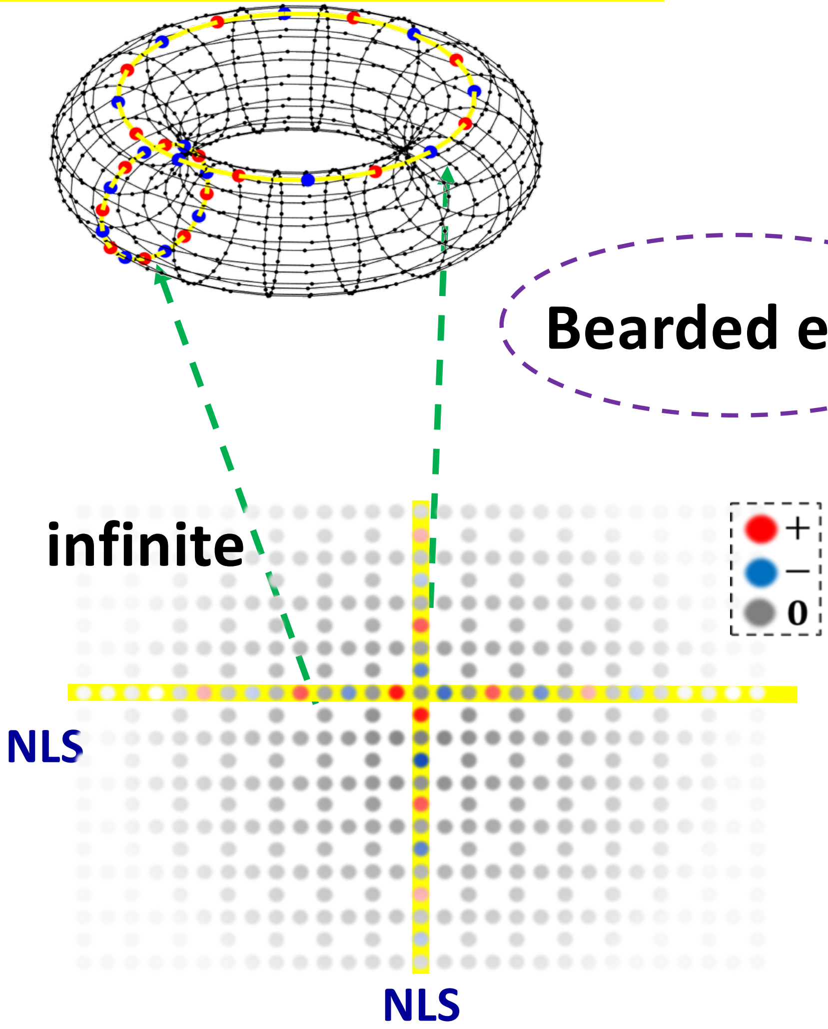
Such **NLSs** exist in principle only in the infinite flat-band lattices, or forming noncontractible loops on a torus.



What happens at the open boundary?

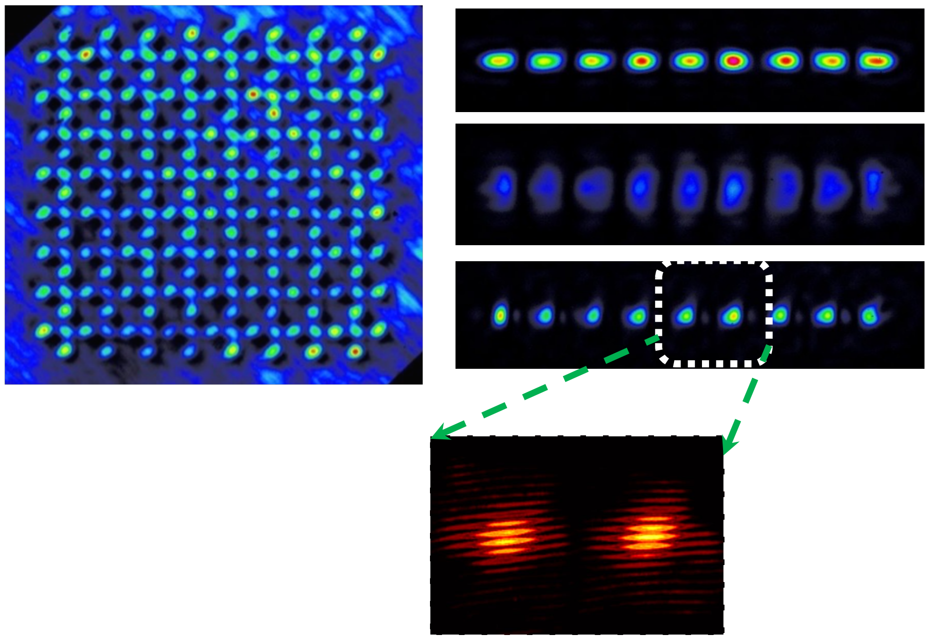
Unconventional line localization in truncated Lieb

Non-contractible loop states



Boundary dependence

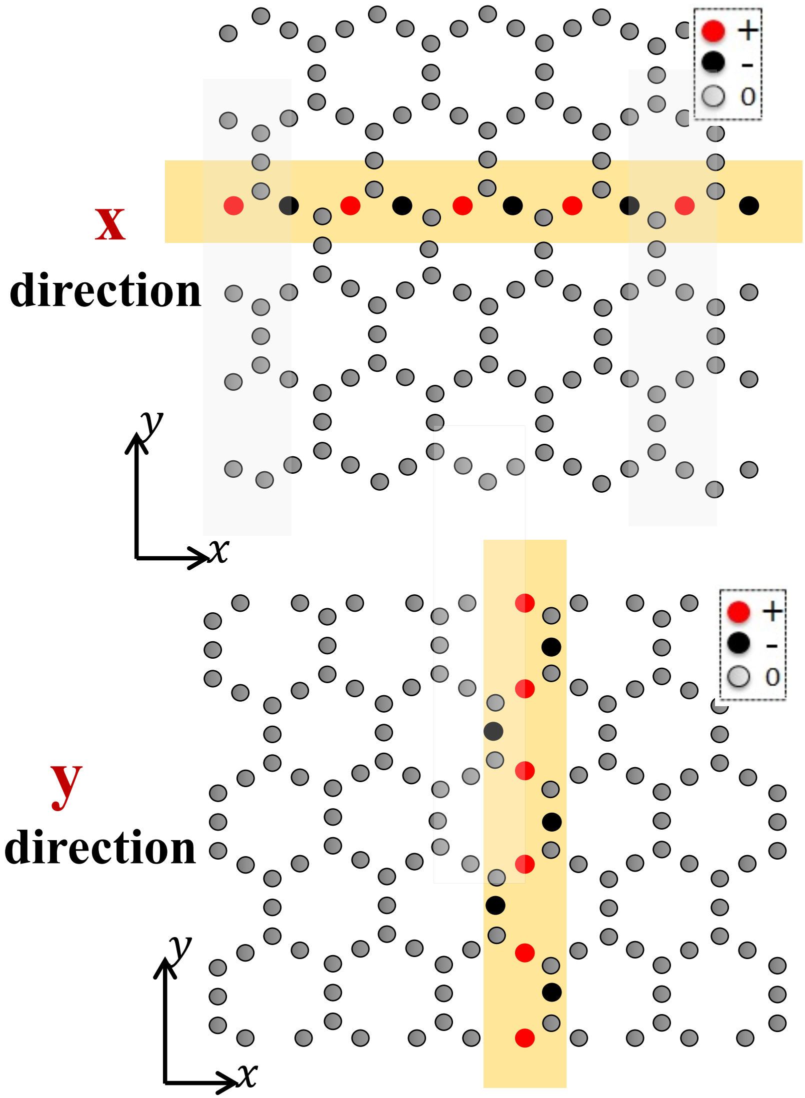
Bearded edges



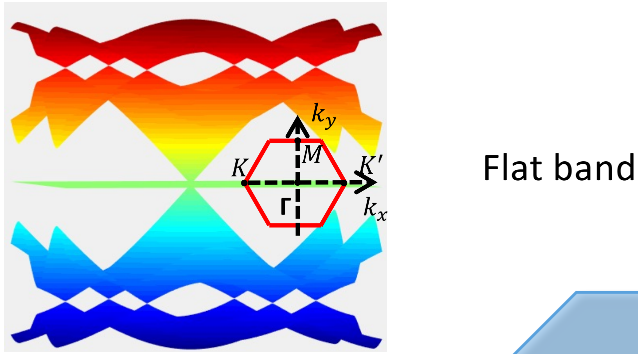
out-of-phase

Xia, …, Song, Leykam, Flach, Chen, Phys. Rev. Lett. (2018)

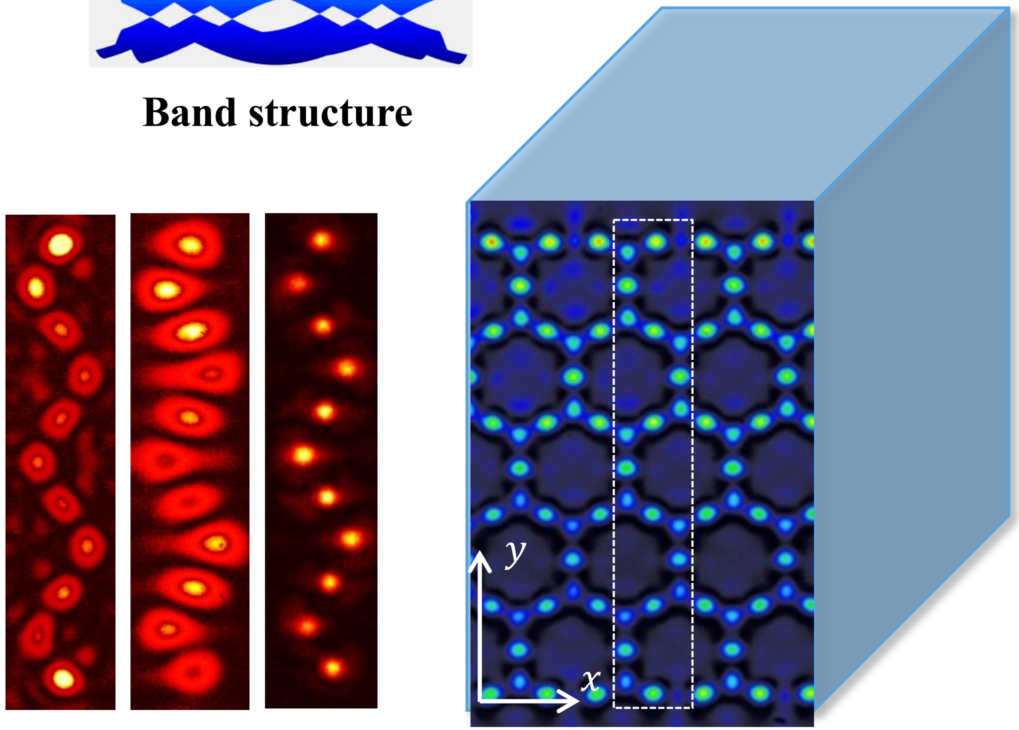
FB Localization in truncated Super-honeycomb



In k space



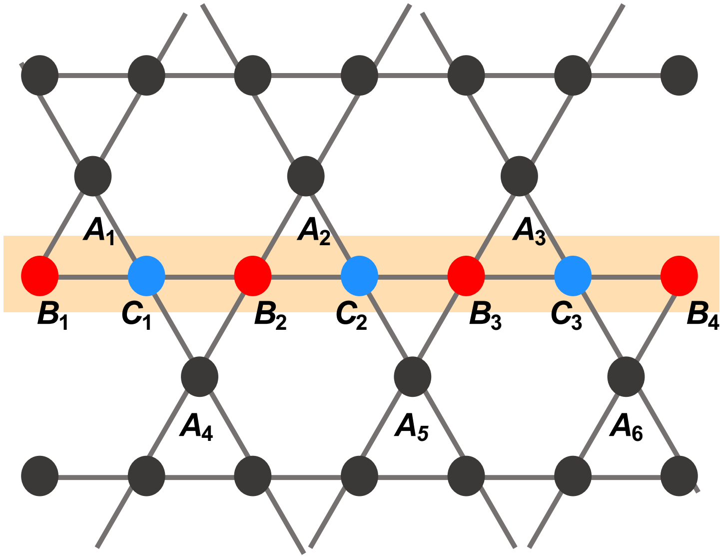
Band structure



Unconventional flatband line localization

Yan, …, Song, …, Tang, Leykam, Chen. Adv. Opt. Mater. 8, 1902174,(2020)

Truncated Kagome lattice



line state:

$$|\psi_{LS}\rangle = c_0\left(|B_1\rangle - |C_1\rangle + |B_2\rangle - |C_2\rangle + |B_3\rangle - |C_3\rangle + |B_4\rangle\right)$$

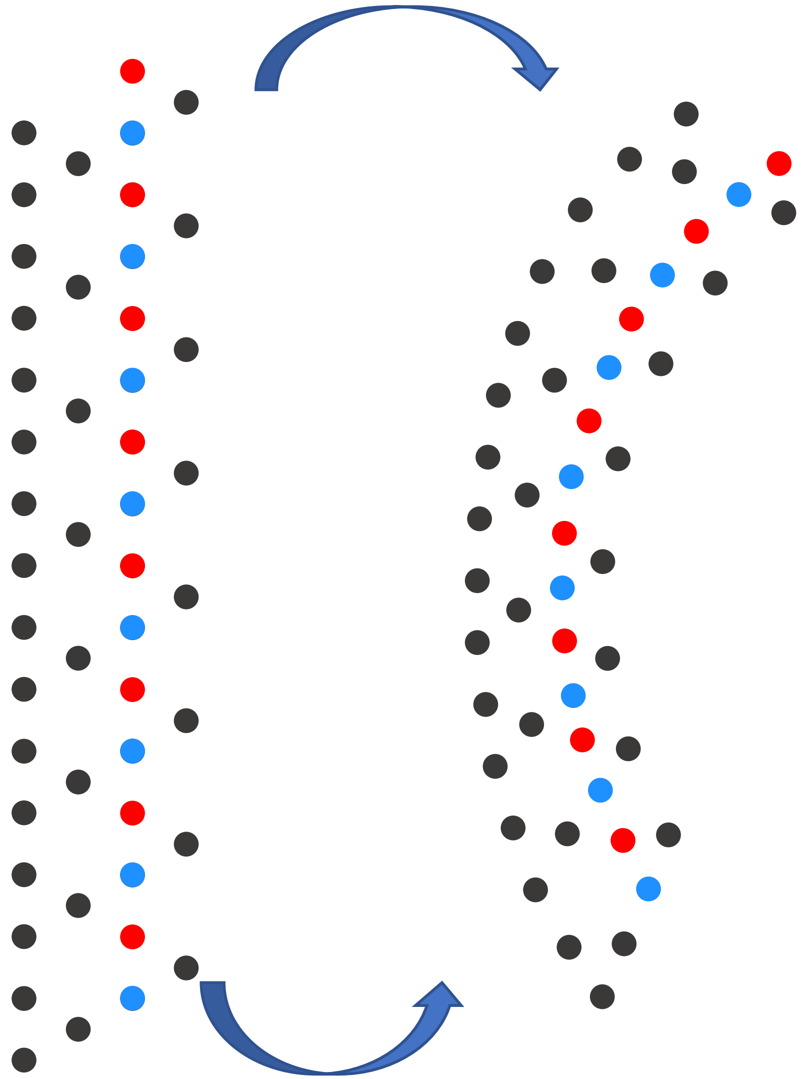
applying the Hamiltonian to this line state:

$$H_k|\psi_{LS}\rangle = c_0 t\left(-|B_1\rangle + 2|C_1\rangle - 2|B_2\rangle + 2|C_2\rangle - 2|B_3\rangle + 2|C_3\rangle - |B_4\rangle\right)$$

$\langle\psi_{LS}|H_k|\psi_{LS}\rangle$: **not equal to a constant**

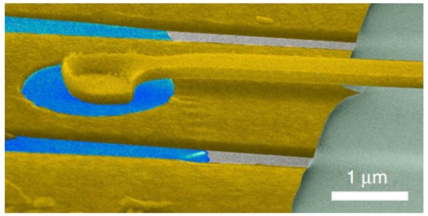
$|\psi_{LS}\rangle$: **not an eigenmode with open boundary condition**

Corbino-Kagome geometry

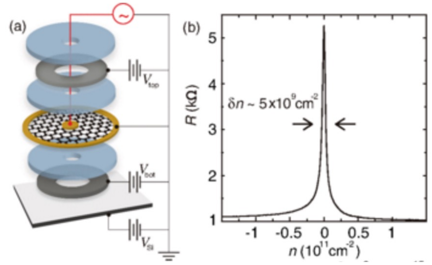


Kagome ribbon

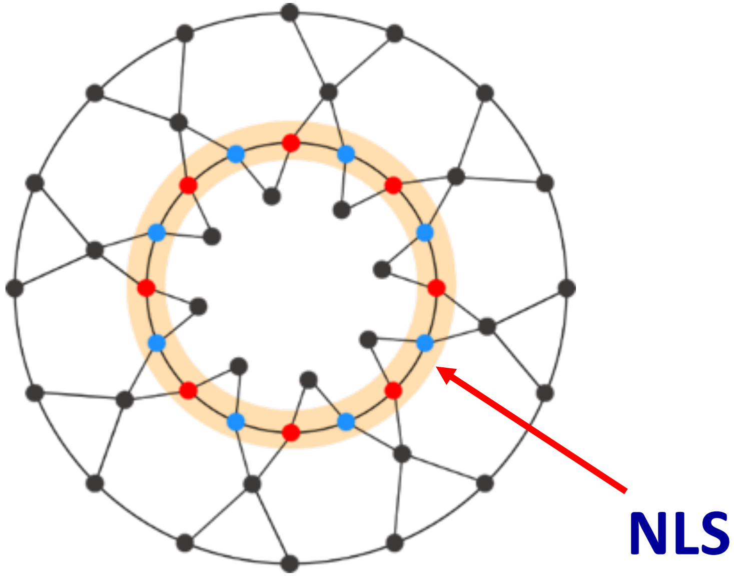
Wrap



M. Kumar,et.al., Nat. Commun. (2018)



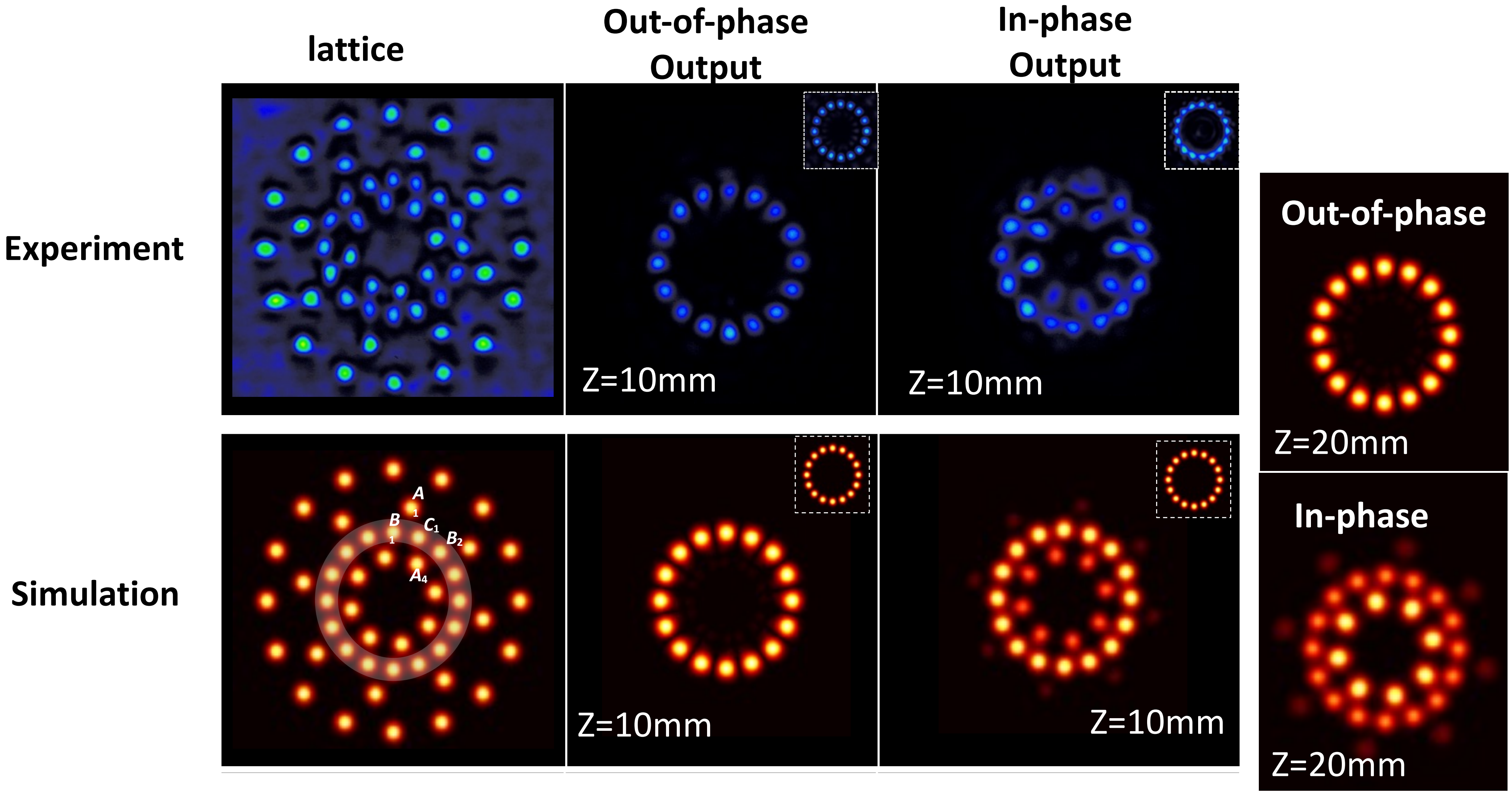
Y. Zeng,et.al., PRL (2018).



Corbino-Kagome

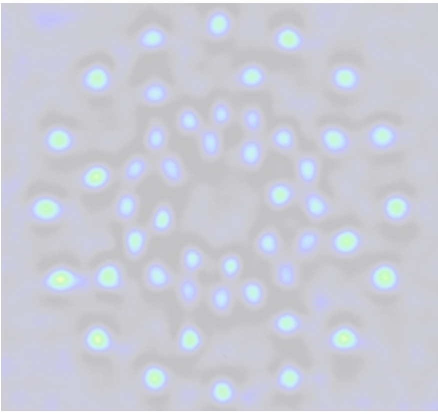
Demonstration of NLS in Corbino-Kagome lattices

J. Ma, J.-W. Rhim, L. Tang, …, B.-J. Yang, D. Leykam, Z. Chen. Phys. Rev. Lett. 124, 183901(2020).

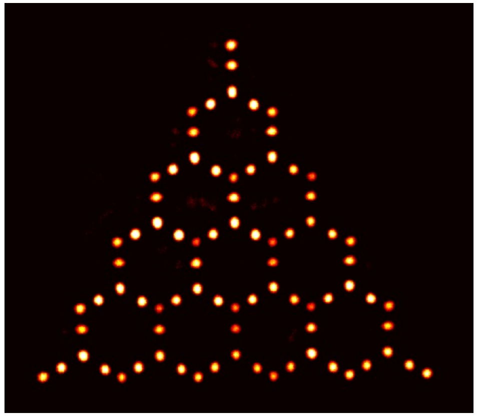


Direct observation of the NLS – real space topology

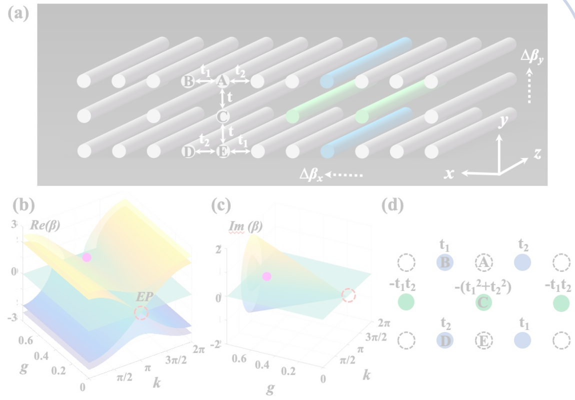
Outline



Unconventional flatband localization



Photonic square-root higher-order topological insulators



Landau-Zener Bloch oscillations in Non-Hermitian flatband lattices

Realization of second-order photonic square-root topological insulators

WENCHAO YAN[1], DAOHONG SONG[1,2*], SHIQI XIA[1], JUNFANG XIE[1], LIQIN TANG[1], JINGJUN XU[1,2] AND ZHIGANG CHEN[1-4]

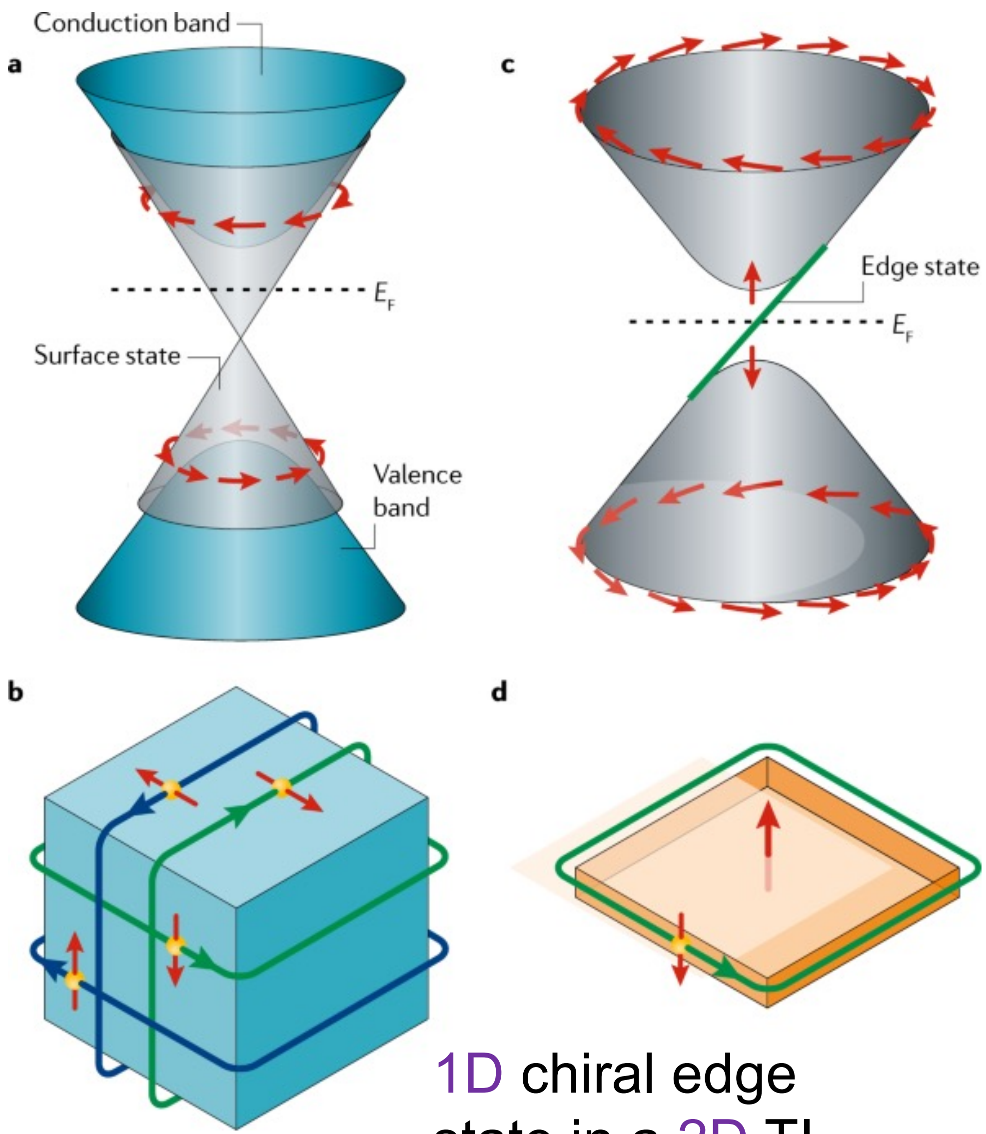
[1]*Key Laboratory of Weak-Light Nonlinear Photonics, Ministry of Education, TEDA Institute of Applied Physics and School of Physics, Nankai University, Tianjin 300457, China*

[2]*Collaborative Innovation Center of Extreme Optics, Shanxi University, Taiyuan, Shanxi 030006, China*

[3]*Department of Physics and Astronomy, San Francisco State University, San Francisco, California 94132, USA*

Conventional topological insulators

(D-1) dimensional boundary states in a **D**-dimensional gapped bulk

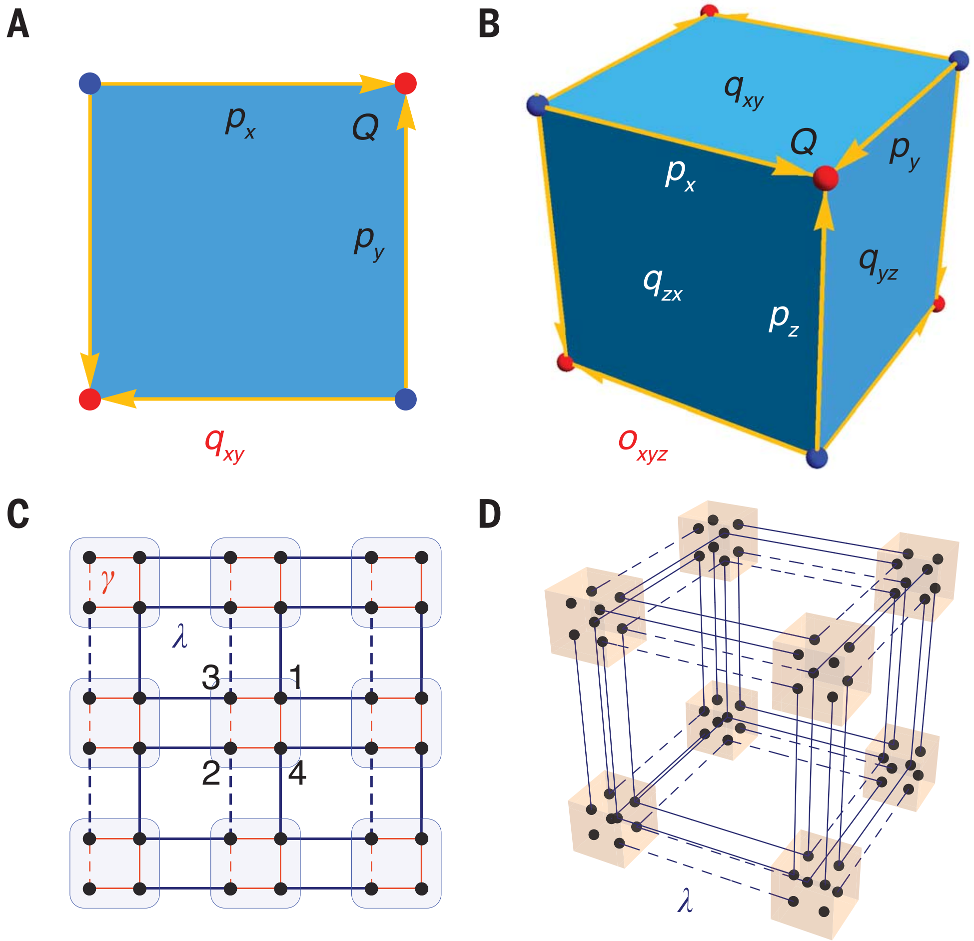


2D surface state in a 3D TI

1D chiral edge state in a 2D TI

Tokura, Yasuda, Tsukazaki.
Nat. Rev. Phys. 1,126 (2019)

Higher-order topological insulators (HOTI)



(D-n) dimensional gapless boundary states in a **D**-dimensional gapped bulk

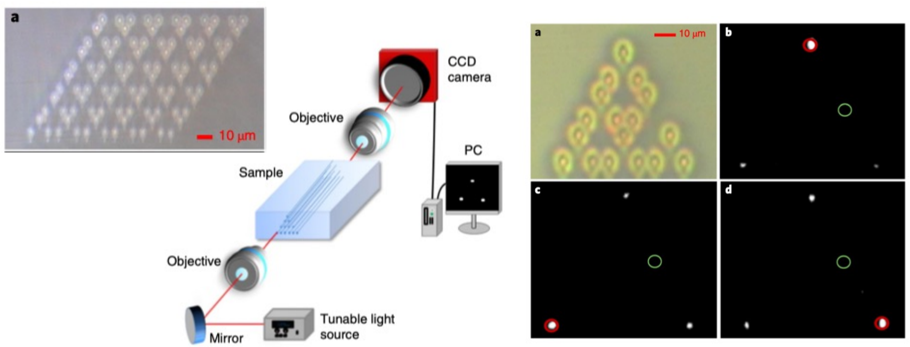
(n-th) order HOTI
(n≥ 2)

0D corner states in a 2D or 3D TIs

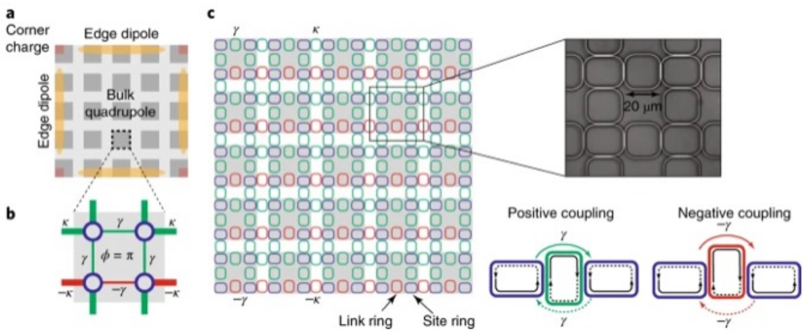
W. A. Benalcazar, et al. Science, 357,61 (2017)

Experimental Demonstration of HOTIs

Photonic HOTIs

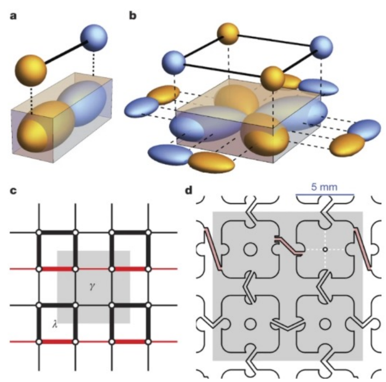


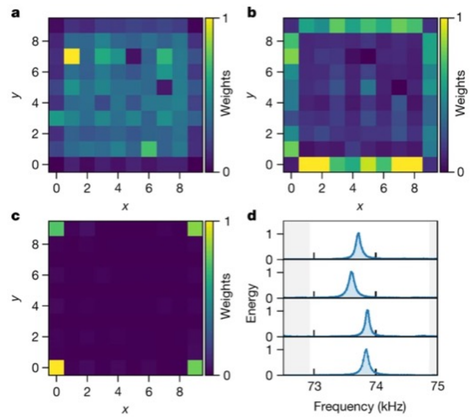
A.E. Hassan, et al. Nat. Photonics **13**, 697 (2019)



S. Mittal, et al. Nat. Photonics **13**, 692 (2019)

Acoustics HOTIs





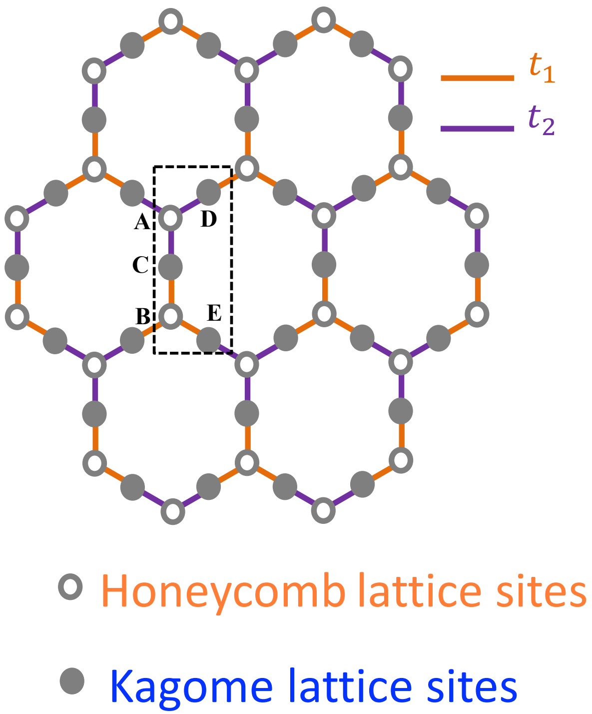
M. Serra-Garcia, et al. Nature 555, 342 (2018)

H. Xue, et al. Nature Materials 18, 108 (2019)
X. Ni, et al. Nature Materials 18, 113 (2019)

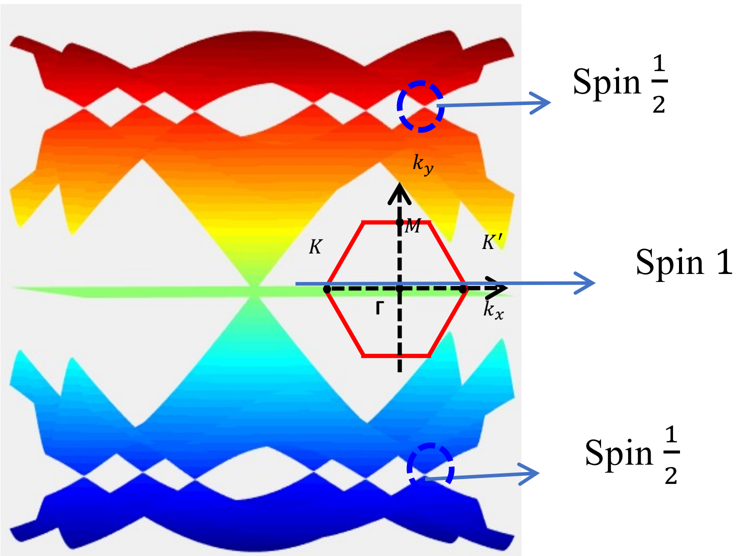
Other systems

HOTI in bismuth: F. Schindler, et al. Nature Physics 14, 918 (2018)
HOTI in electric circuits: S. Imhof, et al. Nature Physics 14, 925 (2018)

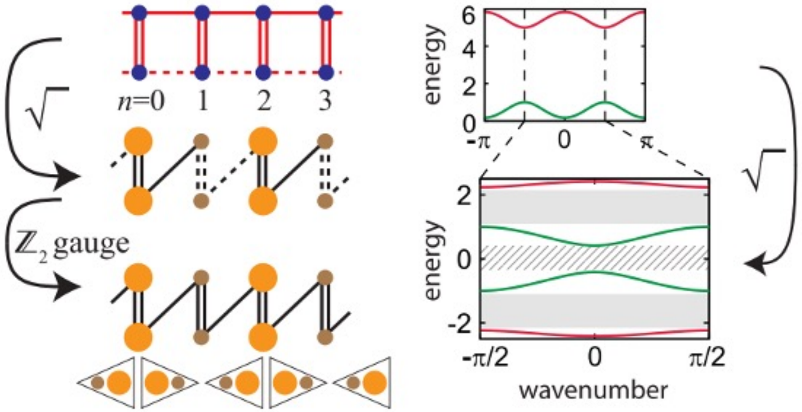
Super-honeycomb Lattices(SHCLs)



Flat band



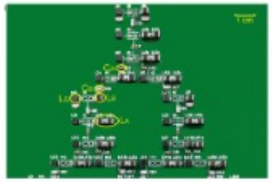
Motivation: Photonic Square-root HOTIs



Phys. Rev. B. 95, 165109(2017).

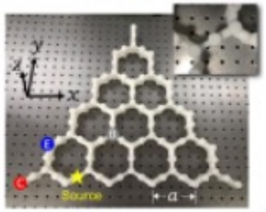
Electric circuits

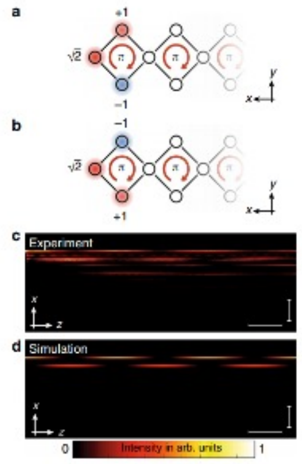
Nano Lett. 20, 7566 (2020)



Acoustics

Phys. Rev. B. 102, 180102 (2020)

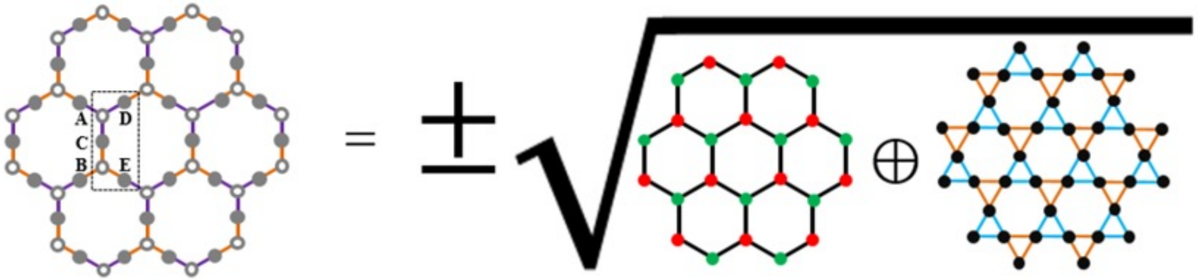




Nat. Commun.11, 907 (2020)

- inherited from the nontrivial square root of its parent lattice Hamiltonian

Square root Hamiltonian



The Hamiltonian of SHCL:

$$H_{\boldsymbol{k}} = \begin{pmatrix} O_{2,2} & \Phi_{\boldsymbol{k}}^{\dagger} \\ \Phi_{k} & O_{3,3} \end{pmatrix}$$

Here $O_{l,m}$ represents the $l\times m$ zero matrix, the $\Phi_{\boldsymbol{k}}$ is the 3×2 matrix:

$$\Phi_{\boldsymbol{k}} = \begin{pmatrix} t_1 & t_2 \\ t_1 & t_2 e^{-i\boldsymbol{k}\cdot\boldsymbol{a1}} \\ t_1 & t_2 e^{-i\boldsymbol{k}\cdot\boldsymbol{a2}} \end{pmatrix}$$

Next, we take a square of Hamiltonian:

$$[H_k]^2 = \begin{pmatrix} h_k^{(H)} & O_{2,3} \\ O_{3,2} & h_k^{(K)} \end{pmatrix},$$

Where

$$\boxed{h_k^{(H)} = \Phi_{\boldsymbol{k}}^{\dagger}\,\Phi_k}$$

is the 2×2 matrix ,and

$$\boxed{h_k^{(K)} = \Phi_k \Phi_{\boldsymbol{k}}^{\dagger}}$$

is the 3×3 matrix

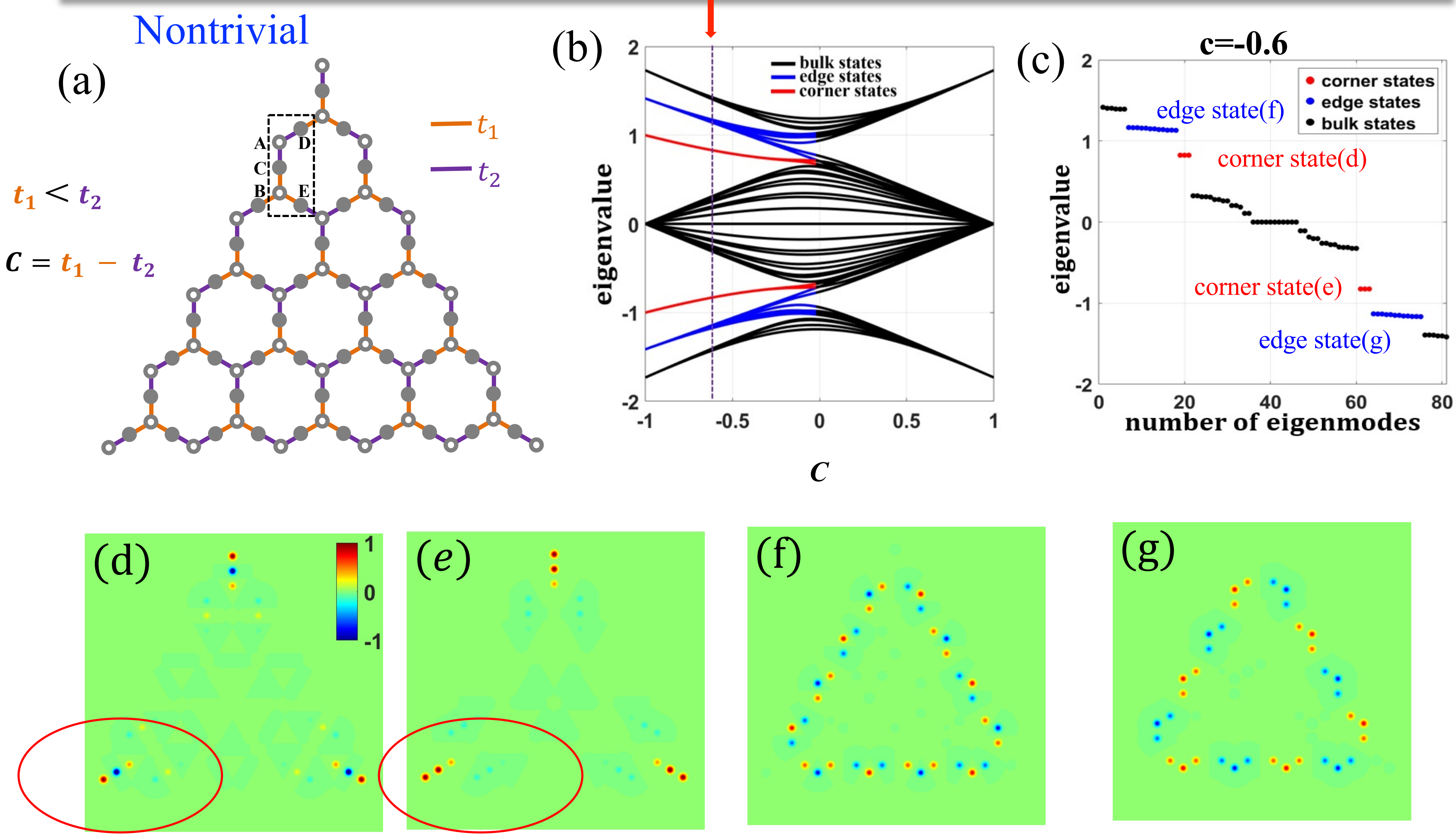
the HCL with different sublattice on-site potentials

the breathing Kagome lattice with different coupling.

t_1, t_2 : hopping strength

Mizoguchi , Kuno , Hatsugai, Phys. Rev. A. 102, 033527 (2020)

Corner states in SHCL (Square root HOTIs)



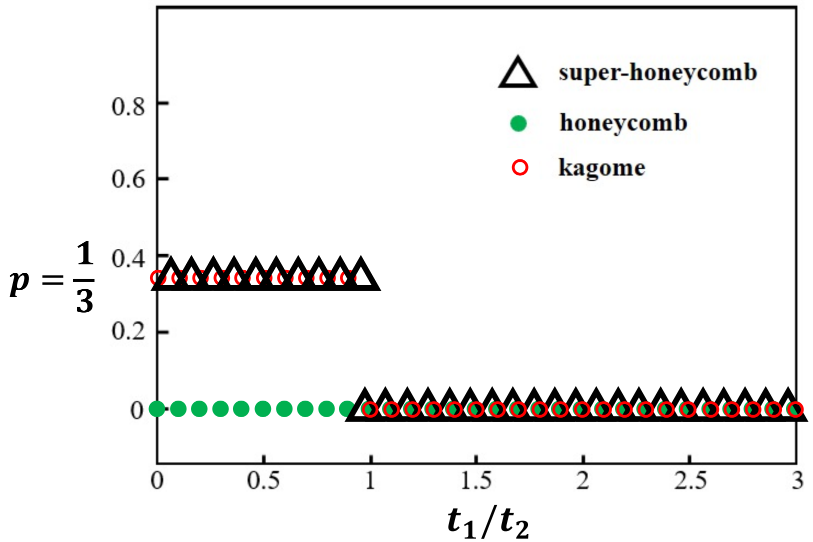
corner state (out of phase)

corner state (in phase)

edge state (out of phase)

edge state (in phase)

Square root topological property



Use the bulk polarization as a topological invariant

$$2\pi p_n = arg\theta_{\mathrm{n}}(K) \ (\mathrm{mod}\ 2\pi)$$

where

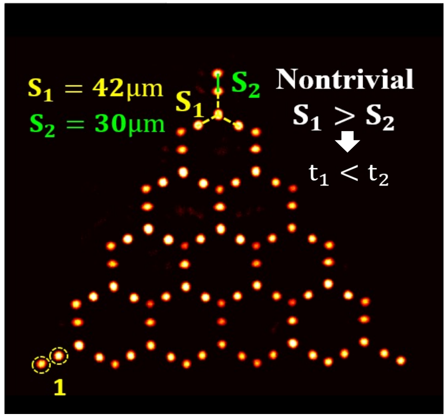
$$\theta_{\mathrm{n}}(\boldsymbol{k}) = \boldsymbol{u}_n^{\dagger}(\boldsymbol{k}) \cdot (U_{\boldsymbol{k}} \boldsymbol{u}_{\mathrm{n}}(\boldsymbol{k}))$$

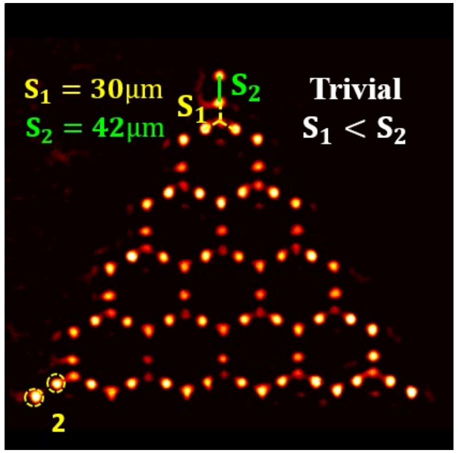
The topological property of corner states in SHCL is inherited from breathing Kagome model

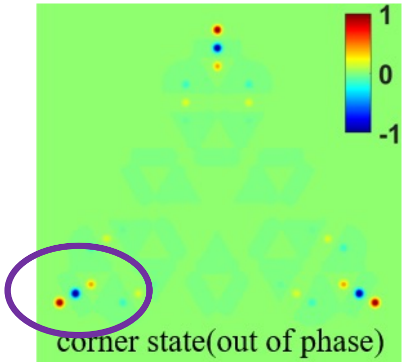
Mizoguchi , Kuno , Hatsugai, Phys. Rev. A. 102, 033527 (2020)

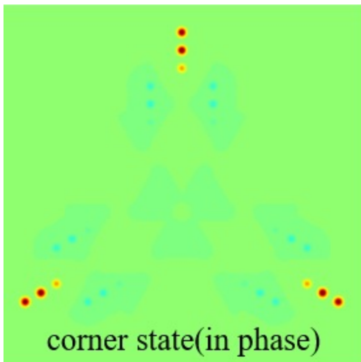
Experimental observation-two kinds of corner states

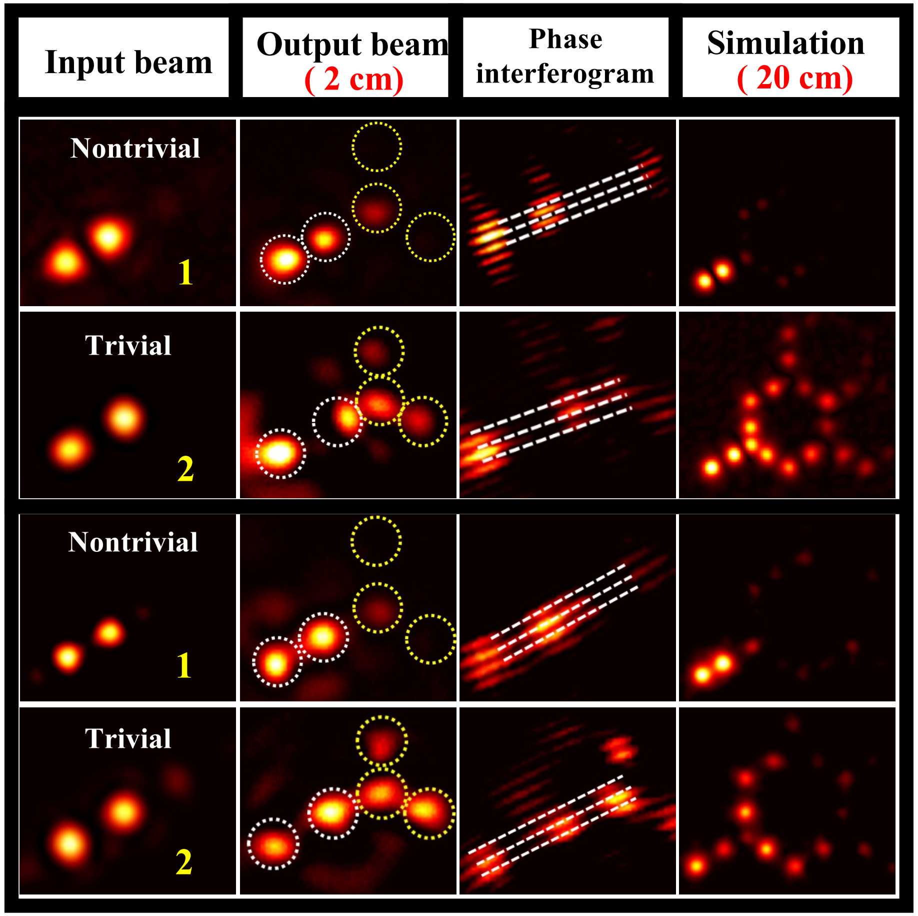
Experimental lattices



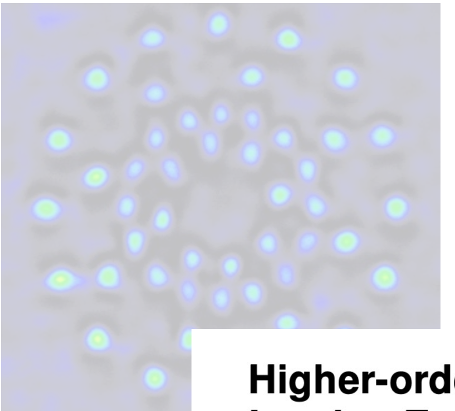








Outline

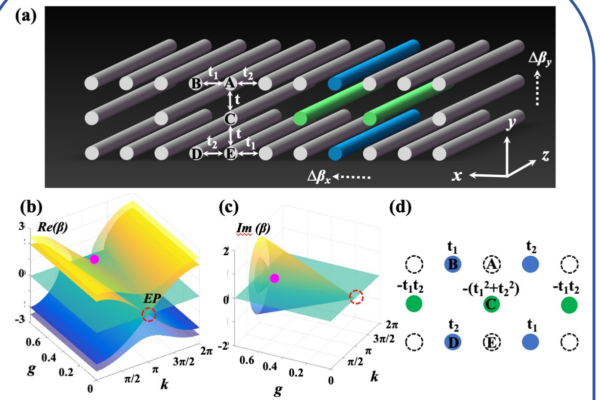


Unconven
loc

Higher-order exceptional point and Landau-Zener Bloch oscillations in driven non-Hermitian photonic Lieb lattices

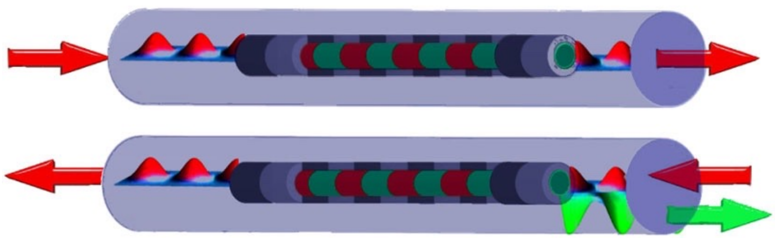
SHIQIANG XIA,[1,2] CARLO DANIELI,[3] YINGYING ZHANG,[1] XINGDONG ZHAO,[1,5] HAI LU,[1] LIQIN TANG,[2,*] DENGHUI LI,[2] DAOHONG SONG,[2] AND ZHIGANG CHEN[2,4]

[1] *Engineering Laboratory for Optoelectronic Technology and Advanced Manufacturing, School of Physics, Henan Normal University, Xinxiang, Henan 453007, China*
[2] *The MOE Key Laboratory of Weak-Light Nonlinear Photonics, TEDA Applied Physics Institute and School of Physics, Nankai University, Tianjin 300457, China*
[3] *Max Planck Institute for the Physics of Complex Systems, Nothnitzer Straße 38, 01187 Dresden, Germany*
[4] *Department of Physics and Astronomy, San Francisco State University, San Francisco, California 94132, USA*

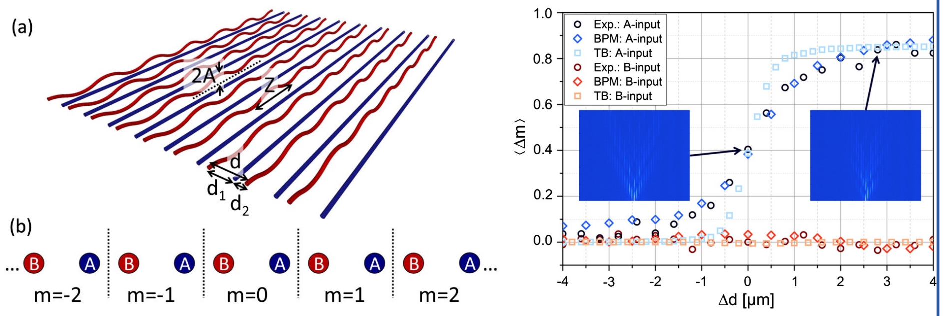


Landau-Zener Bloch oscillations in Non-Hermitian flatband lattices

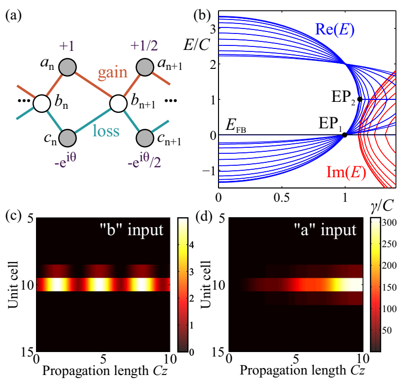
Flatbands in non-Hermitian systems



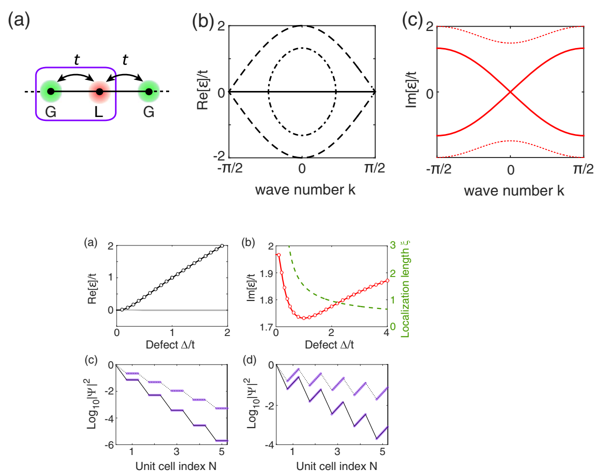
Phys. Rev. Lett. 106, 213901 (2011)



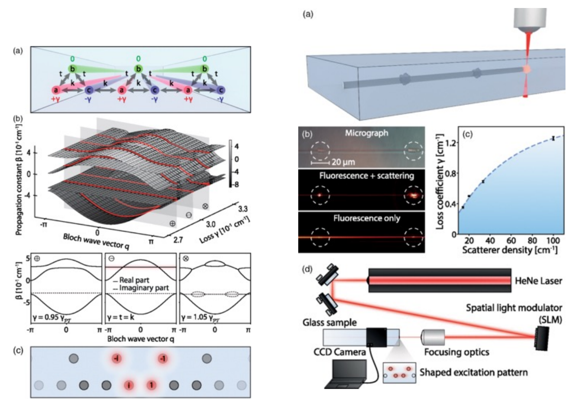
Phys. Rev. Lett. 115, 040402 (2015)



D. Leykam et al.
Phys. Rev. B 96, 064305 (2017)



Phys. Rev. Lett. 120, 093901 (2018)



Phys. Rev. Lett. 123, 183601 (2019)

Bloch Oscillation with Flatbands

PRL **116,** 245301 (2016) PHYSICAL REVIEW LETTERS week ending 17 JUNE 2016

Landau-Zener Bloch Oscillations with Perturbed Flat Bands

Ramaz Khomeriki[1,2] and Sergej Flach[2,3]

PHYSICAL REVIEW A **103**, 023721 (2021)

Stable Bloch oscillations and Landau-Zener tunneling in a non-Hermitian $\mathcal{PT}$-symmetric flat-band lattice

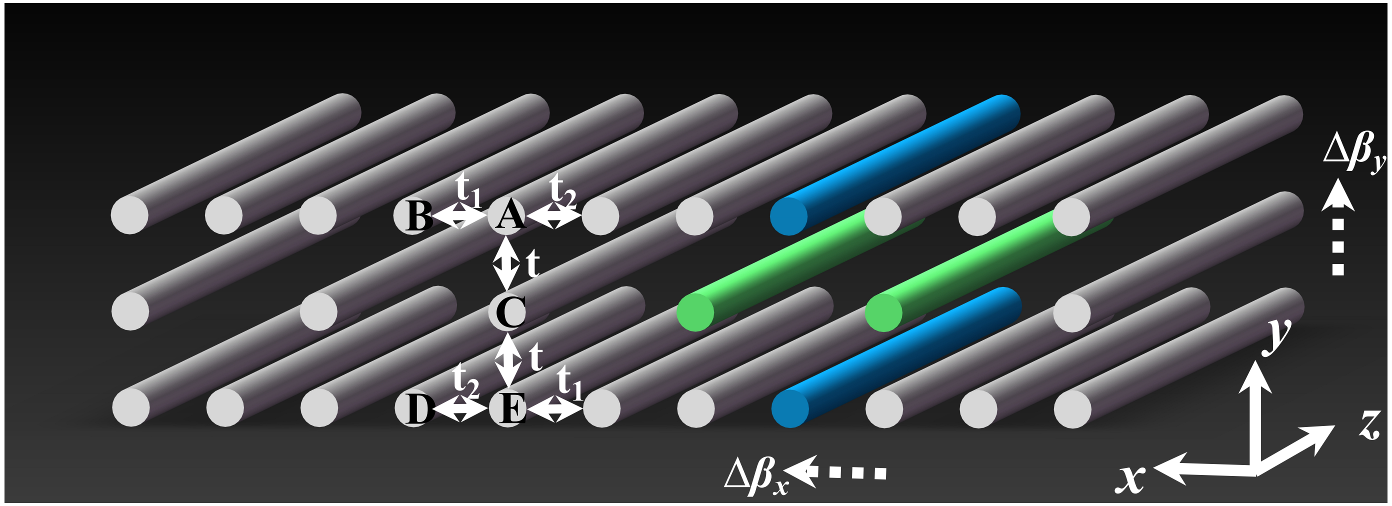
J. Ramya Parkavi,[1] V. K. Chandrasekar,[1] and M. Lakshmanan[2]

Phys. Rev. Lett. 116, 245301 (2016)
arXiv:1706.01107 (2017)

Phys. Rev. A 103, 023721 (2021).

Phys. Rev. Lett. 103, 123601 (2009)
Sci. Rep. 5, 1 (2015)
Nat. Commun. 7, 1–6 (2016)

PT Lieb ribbon with external field



$t = 1$

$t_1 = t(1+ig)$

$t_2 = t(1-ig)$

g : non-Hermitian parameter

Hamiltonian in the tight-binding approximation

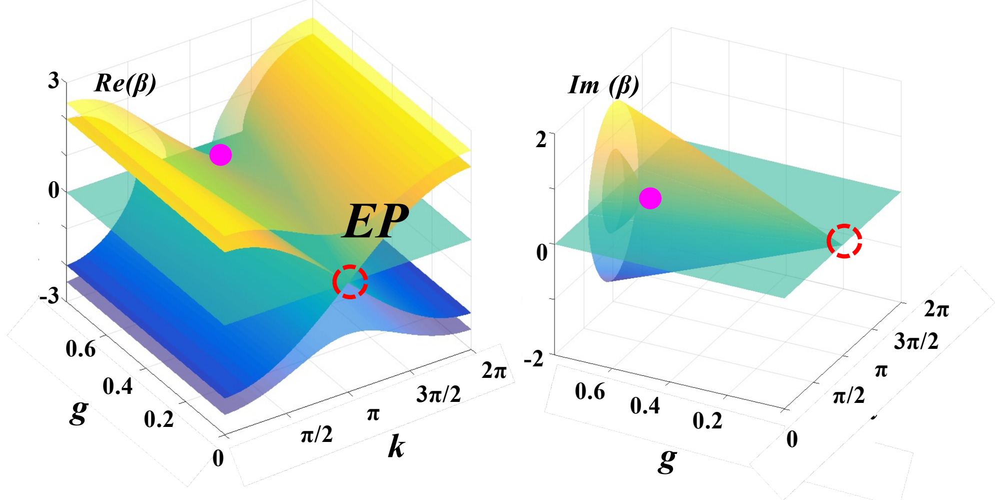
$$H = \sum_n -\left(t_1 a_n^\dagger b_n + t_2 a_n^\dagger b_{n-1} + t a_n^\dagger c_n + t_2 e_n^\dagger d_n + t_1 e_n^\dagger d_{n-1} + t e_n^\dagger c_n + h.c.\right)$$

$$+ \boxed{\Delta\beta_y}\left(a_n^\dagger a_n + b_n^\dagger b_n - d_n^\dagger d_n - e_n^\dagger e_n\right)$$

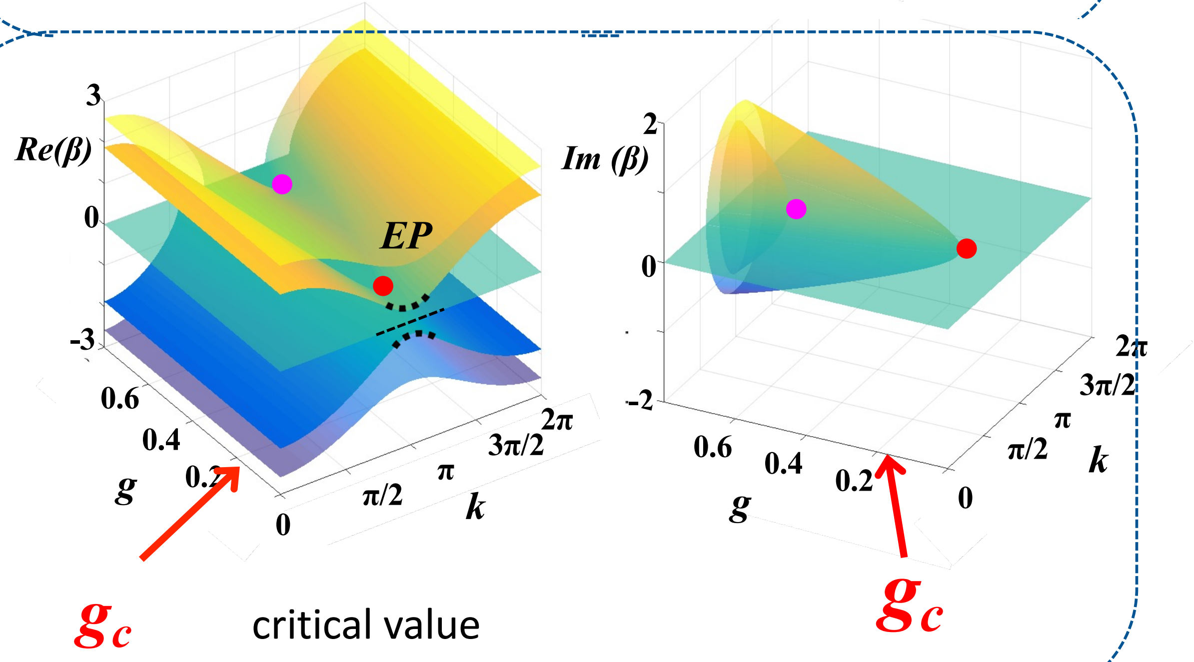
$$+ n\boxed{\Delta\beta_x}\left(a_n^\dagger a_n + b_n^\dagger b_n + c_n^\dagger c_n + d_n^\dagger d_n + e_n^\dagger e_n\right) + \frac{\boxed{\Delta\beta_x}}{2}\left(b_n^\dagger b_n + d_n^\dagger d_n\right)$$

unbroken PT phase or completely real spectra?

Spectrum without/with external field

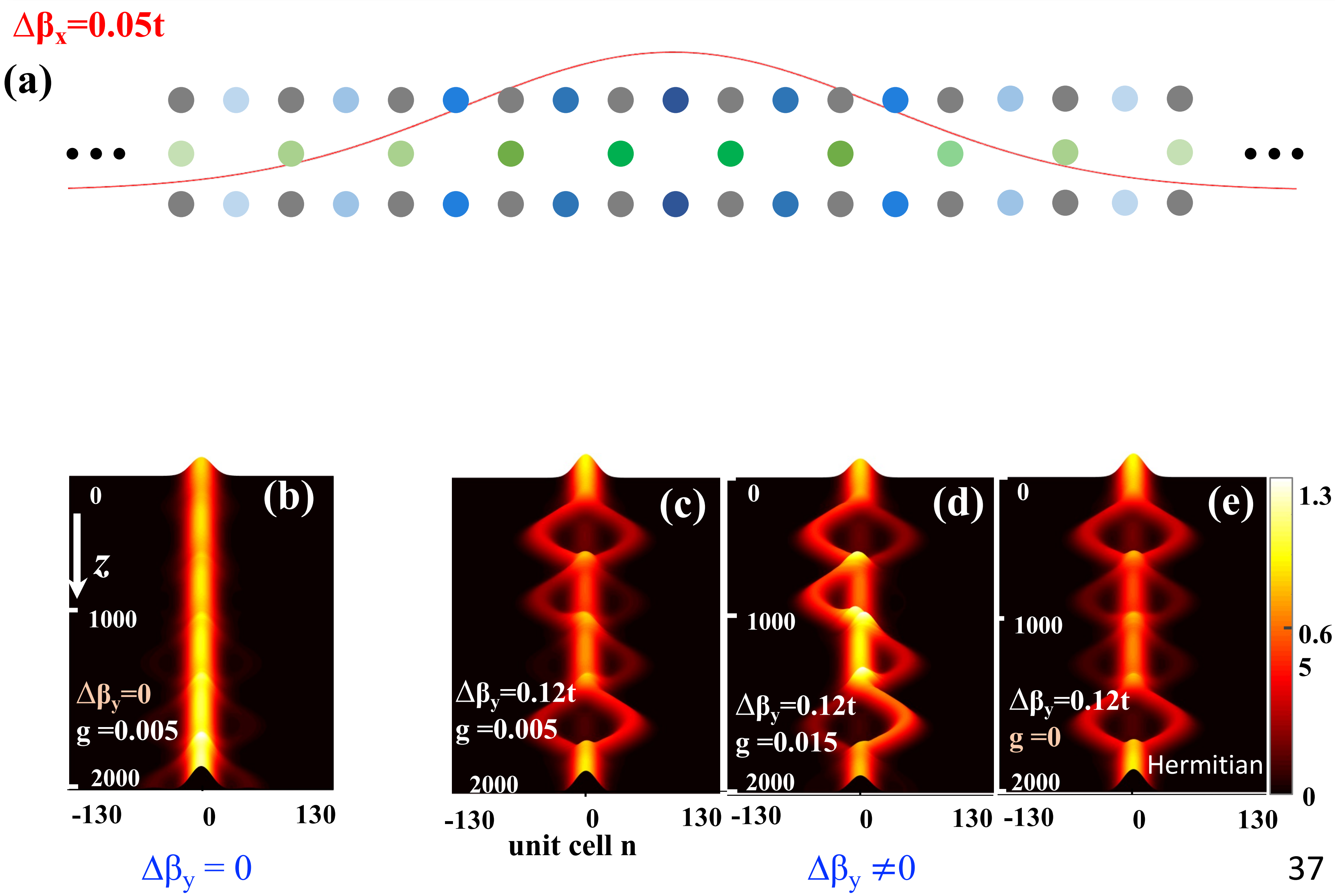


$\Delta\beta_y = 0$

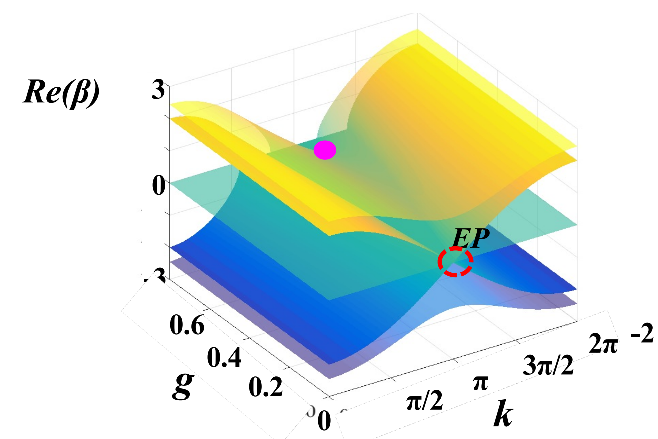


$\Delta\beta_y \neq 0$

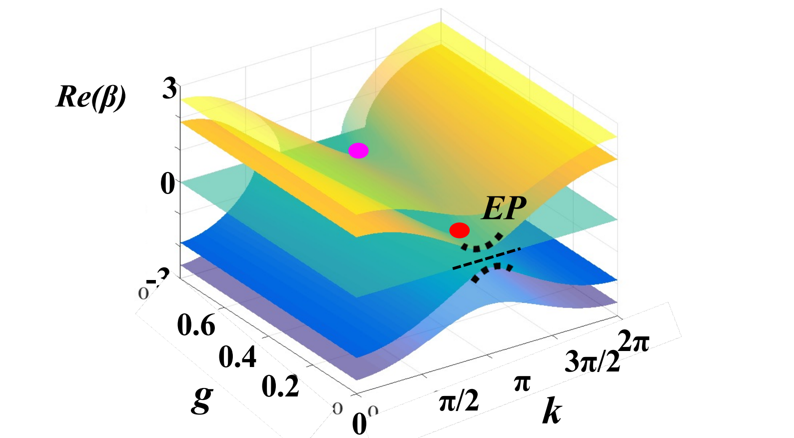
Flatband Landau-Zener-Bloch Oscillation



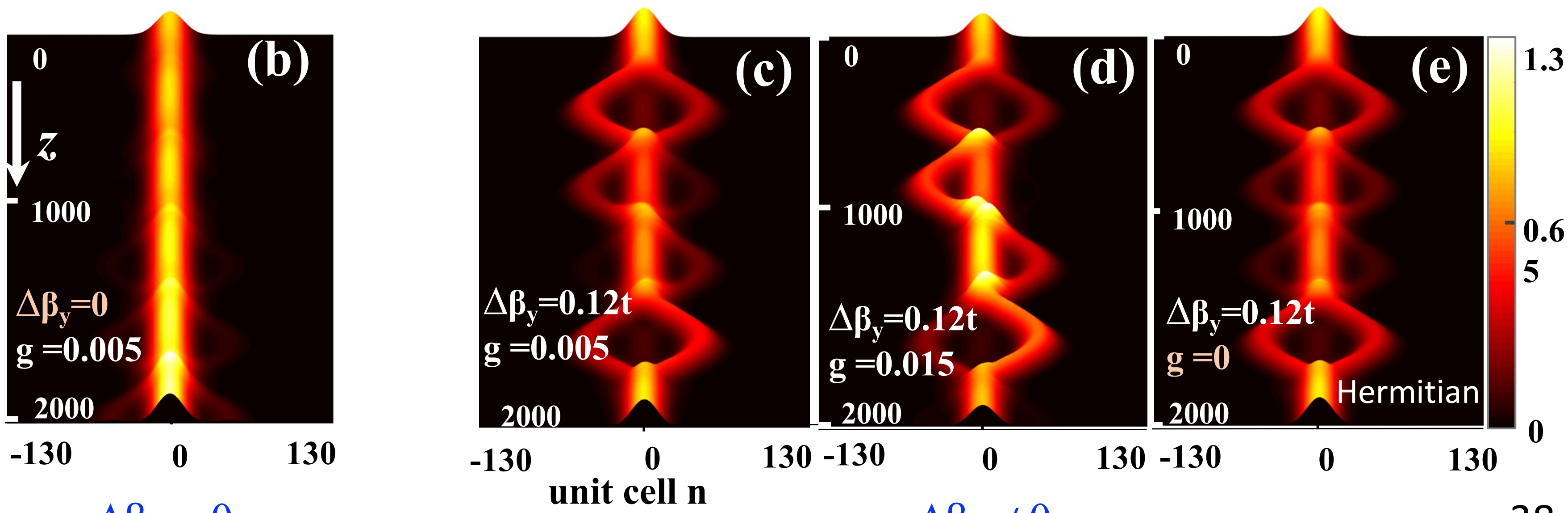
Flatband Landau-Zener-Bloch Oscillation



$\Delta\beta_y = 0$



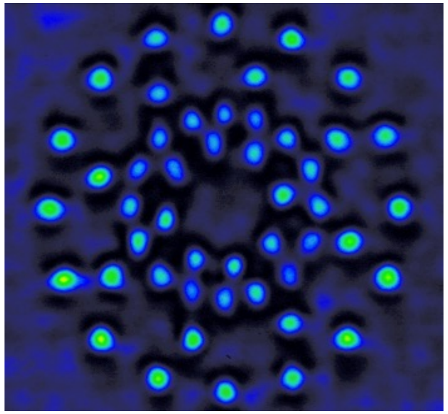
$\Delta\beta_y \neq 0$



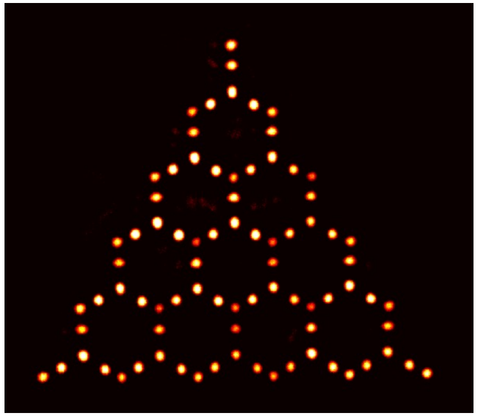
$\Delta\beta_y = 0$

$\Delta\beta_y \neq 0$

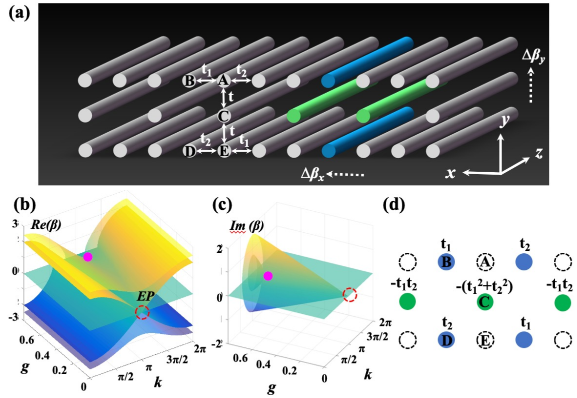
Summary



Unconventional flatband localization



Photonic square-root higher-order topological insulators



Landau-Zener Bloch oscillations in Non-Hermitian flatband lattices

Collaborators:

IBS: Prof. S. Flach, Prof. B.-J. Yang, Dr. J.-W. Rhim, Dr. D. Leykam, Dr. C. Danieli

Thank You !

tanya@nankai.edu.cn