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Hermitian Bulk – Non-Hermitian Boundary Correspondence

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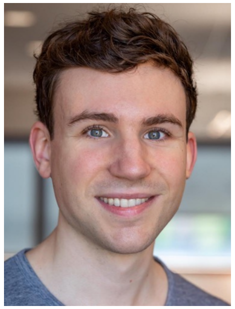
PRX Quantum 4, 030315 (2023)

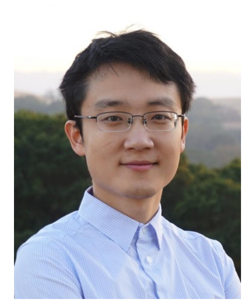
arXiv:2405.10015

PRX Quantum 4, 030315 (2023)



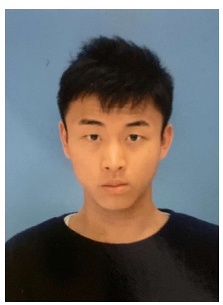
Frank Schindler
(Princeton → Imperial College London)

Kaiyuan Gu
(Princeton)



Biao Lian
(Princeton)

arXiv:2405.10015



Shu Hamanaka (Kyoto)

Tsuneya Yoshida (Kyoto)

Outline

1. Introduction

2. Non-Hermitian topology (review)

3. Hermitian bulk – non-Hermitian boundary correspondence

4. Non-Hermitian topology in Hermitian topological matter

Non-Hermitian physics

Despite the enormous success, the existing framework of topological phases is **confined to Hermitian systems at equilibrium**.

→ **Richer properties appear in non-Hermitian systems!**

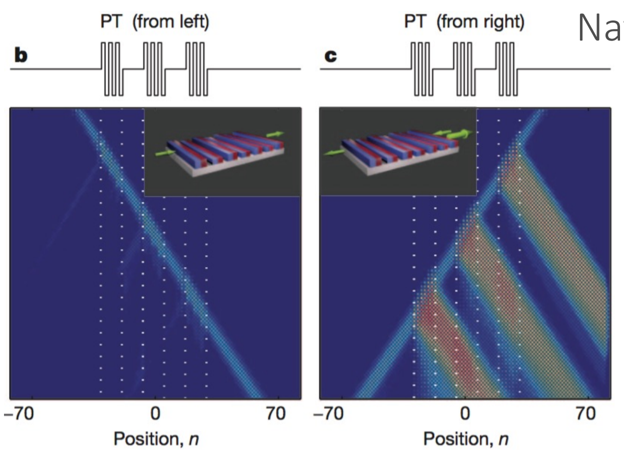
☆ Non-Hermiticity arises from **dissipation**, i.e., exchanges of energy or particles with an environment.

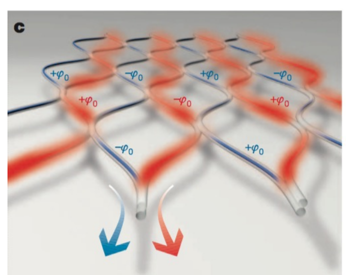
El-Ganainy *et al.*, Nat. Phys. **14**, 11 (2018)

- **Photonic lattices with gain/loss**

Unidirectional light transport

Regensburger *et al.*, Nature **488**, 167 (2012)

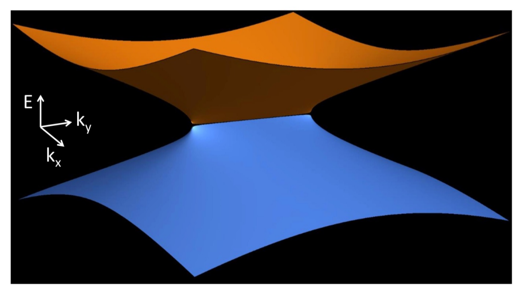


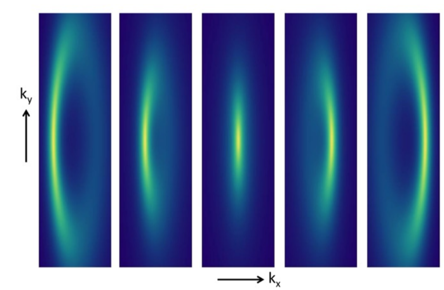


- **Finite-lifetime quasiparticles**

Bulk Fermi arc due to non-Hermitian self-energy

Kozii & Fu, arXiv: 1708.05841

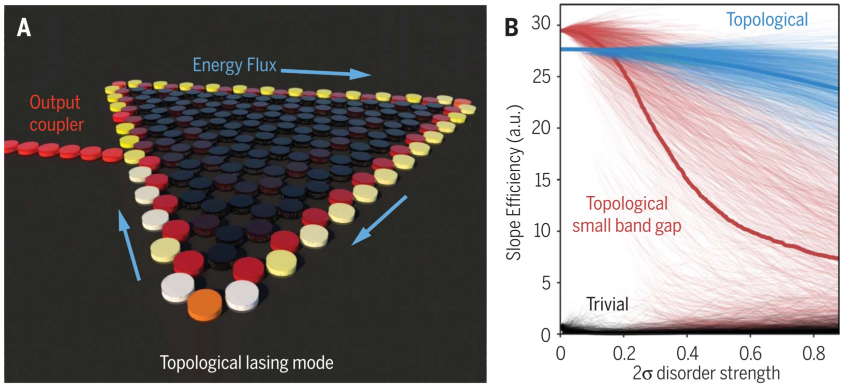




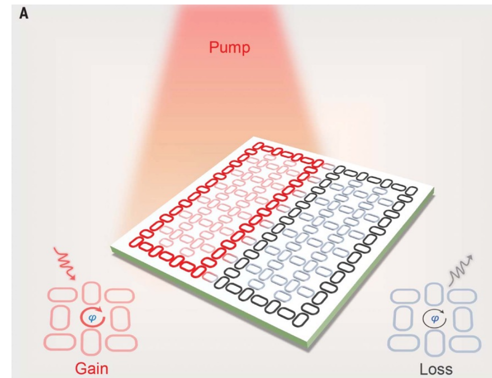
Non-Hermitian topological systems

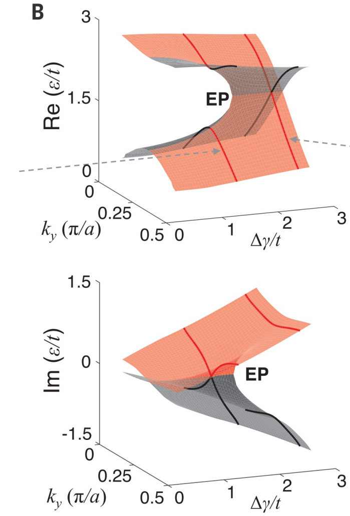
• Topological laser

New laser with high efficiency due to the **interplay of non-Hermiticity and topology**.



Bandres *et al.*, Science **359**, eaar4005 (2018)

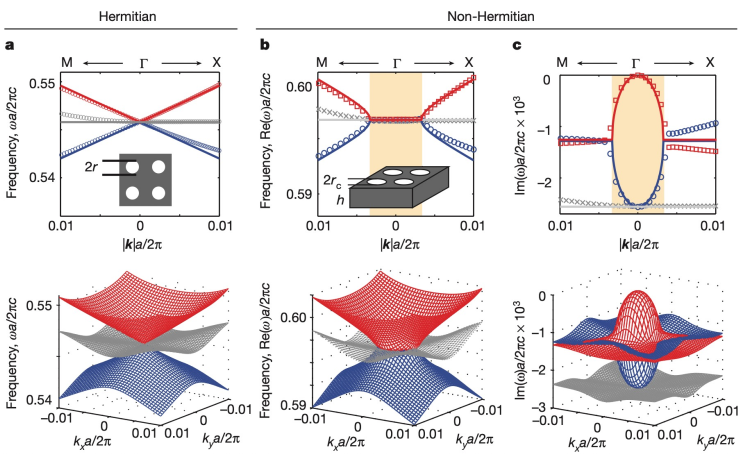




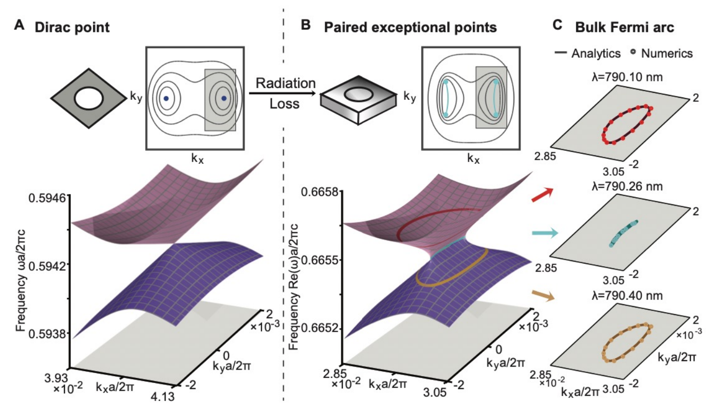
Zhao *et al.*, Science **365**, 1163 (2019)

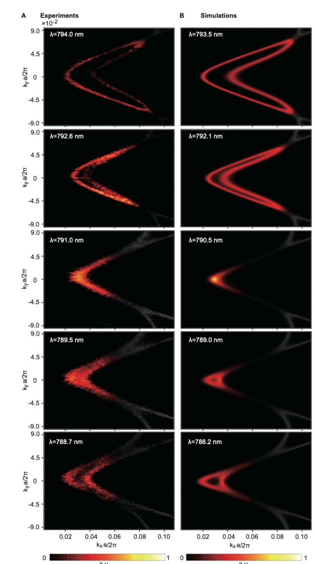
• Exceptional point

Nondiagonalizable gapless point (Jordan matrix)



Zhen *et al.*, Nature **525**, 354 (2015)





Zhou *et al.*, Science **359**, 1009 (2018)

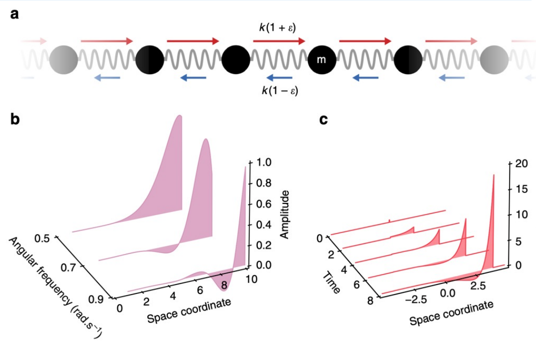
Non-Hermitian skin effect

☆ Non-Hermitian skin effect

Lee, PRL **116**, 133903 (2016); Yao & Wang, PRL **121**, 086803 (2018); Kunst *et al.*, PRL **121**, 026808 (2018)

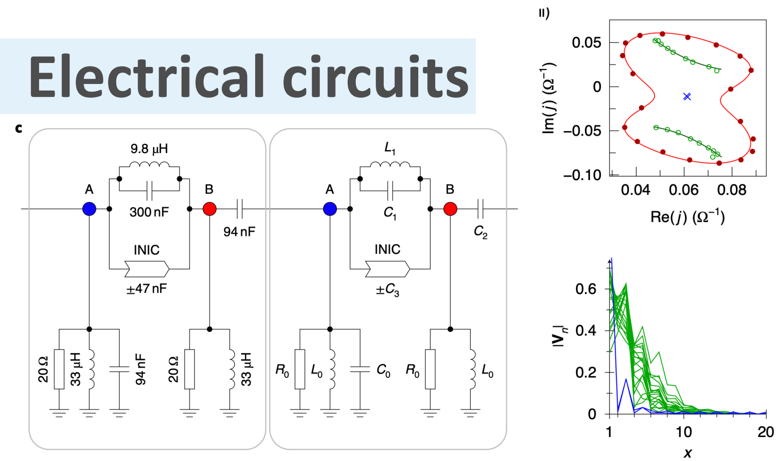
Localization of an extensive number of eigenmodes due to non-Hermitian topology

- **Mechanical metamaterials**



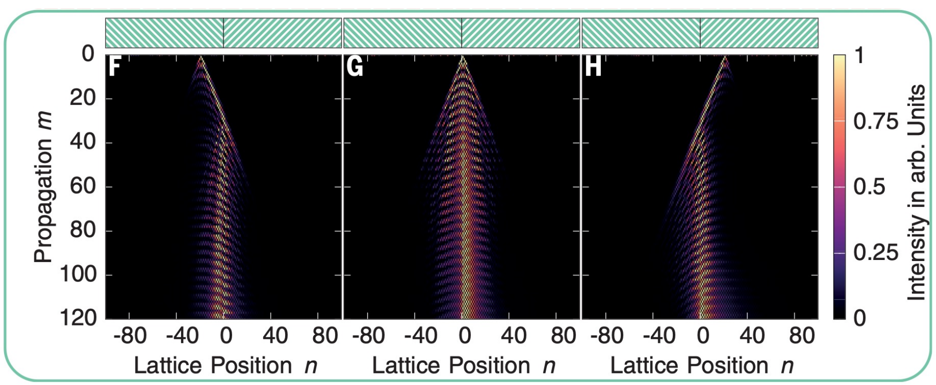
Brandenbourger *et al.*, Nat. Commun. **10**, 4608 (2019)

- **Electrical circuits**



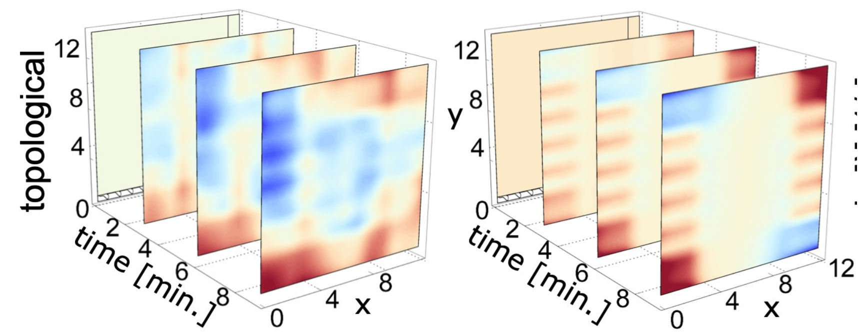
Helbig *et al.*, Nat. Phys. **16**, 747 (2020)

- **Photonic lattice**



Weidemann *et al.*, Science **368**, 311 (2020)

- **Active matter**



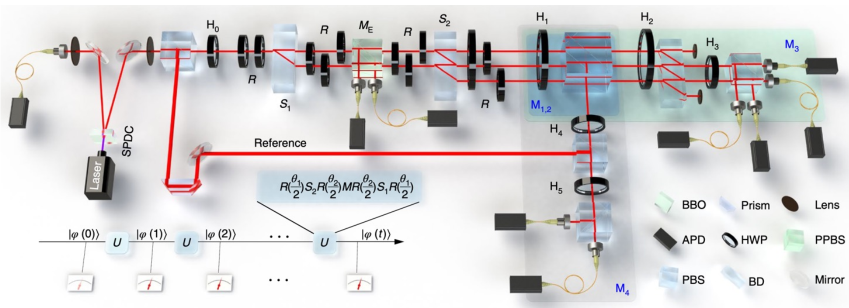
Palacios *et al.*, Nat. Commun. **12**, 4691 (2021)

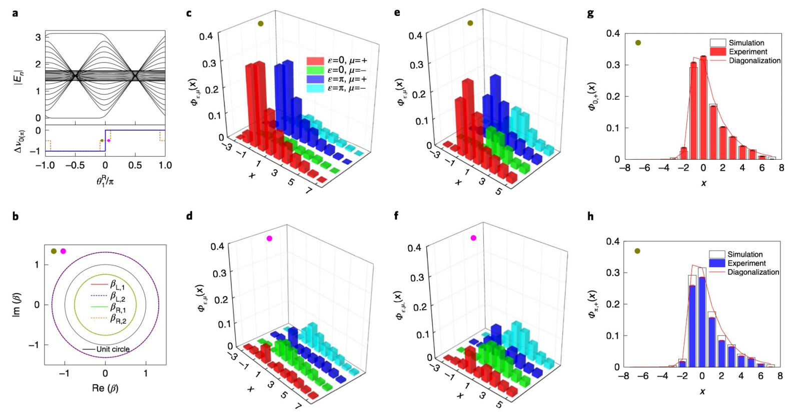
Skin effect in quantum physics

Skin effect has been observed also in recent quantum experiments.

- **Quantum walk (single photons)**

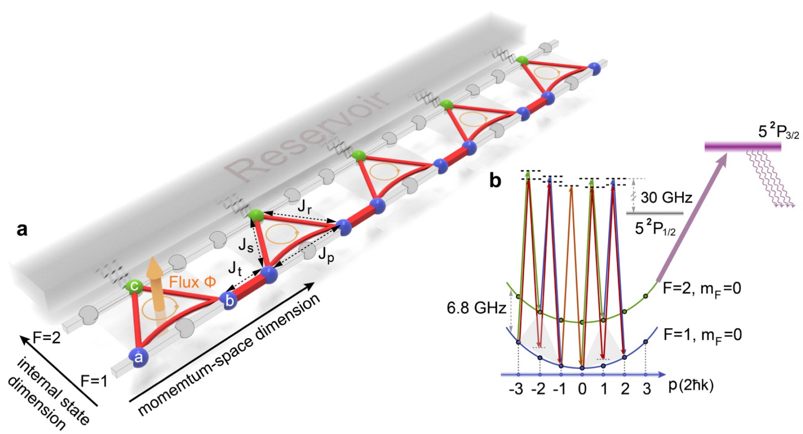
Xiao *et al.*, Nat. Phys. **16**, 761 (2020)

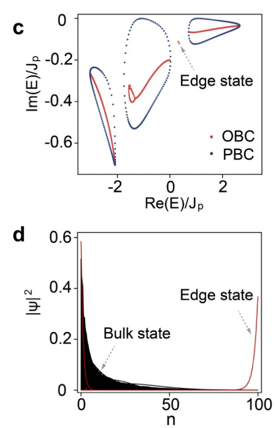


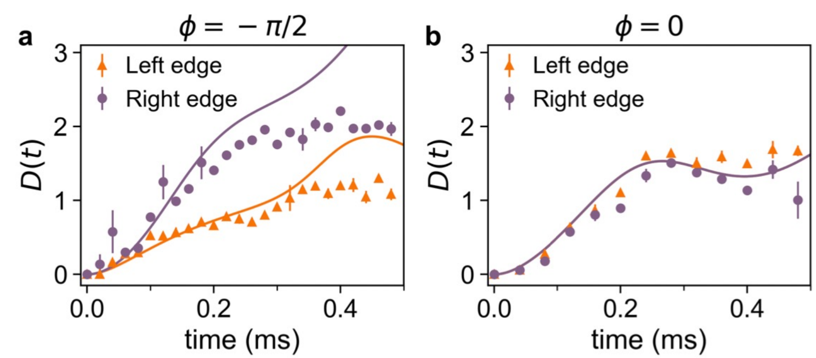


- **Ultracold atoms**

Liang *et al.*, PRL **129**, 070401 (2022)







Skin effect in quantum physics

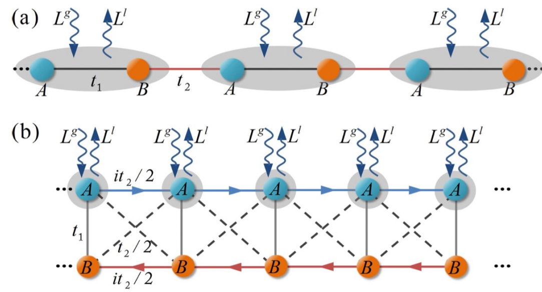
Non-Hermitian topology is relevant even to more generic open quantum systems that are not characterized by Hamiltonians.

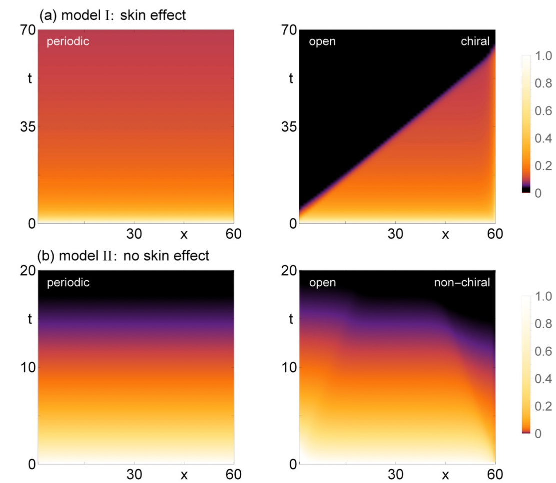
Song, Yao & Wang, PRL **123**, 170401 (2019)

- **Master equation**

$$d\hat{\rho}/dt = \underline{\mathcal{L}}\hat{\rho}$$

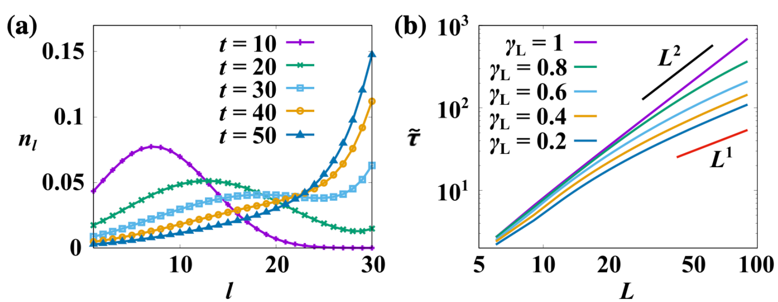
Non-Hermitian superoperator (Liouvillian)

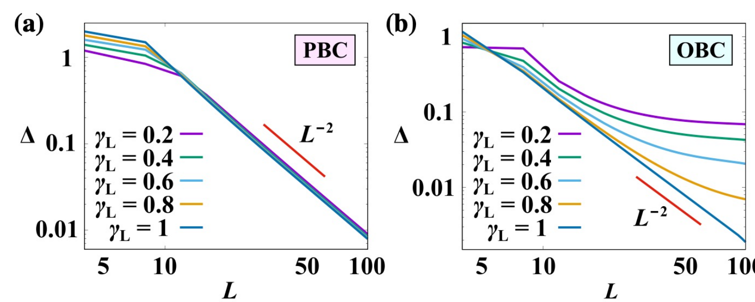




Chiral damping due to the skin effect

Slowdown of relaxation due to the skin effect





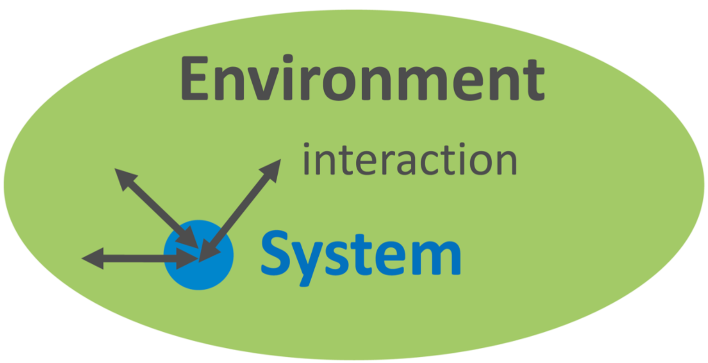
Haga *et al.*, PRL **127**, 070402 (2021); Mori *et al.*, PRL **125**, 230604 (2020)

Motivation

Non-Hermiticity gives rise to unique topological phases that have no Hermitian counterparts.

Meanwhile, open systems can be embedded in larger closed systems.

→ **Can we connect intrinsic non-Hermitian topology with Hermitian topology?**



Results (1)

We find a new topological correspondence between Hermitian bulk and non-Hermitian boundary.

***d*-dim Hermitian bulk** ··········· **(*d*-1)-dim non-Hermitian boundary**

Topological boundary modes + non-Hermiticity (dissipation)

→ intrinsic non-Hermitian topology

New boundary phenomena:

– corner skin effect of chiral edge modes

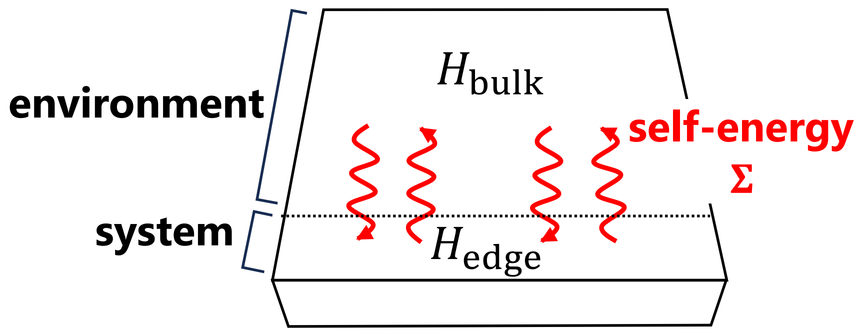
– chiral hinge modes due to non-Hermiticity

Schindler, Gu, Lian & **Kawabata**, PRX Quantum **4**, 030315 (2023)

cf. Nakamura, Inaka, Okuma & Sato, PRL **131**, 256602 (2023)

Results (2)

We develop the same correspondence even in Hermitian topological insulators (without non-Hermicity)



The self-energy captures the particle exchange between the bulk and boundary, and detects Hermitian topology in the bulk and non-Hermitian topology at the boundary.

Hamanaka, Yoshida & **Kawabata**, arXiv:2405.10015

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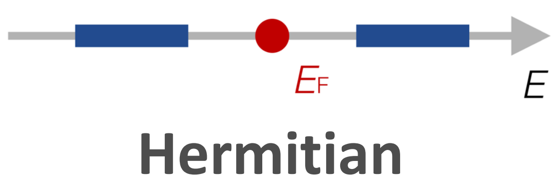
Complex-energy gaps (1)

An “**energy gap”** is needed to define a topological phase.

However, a non-Hermitian extension of an **“energy gap”** is nontrivial since the **spectrum is complex**.



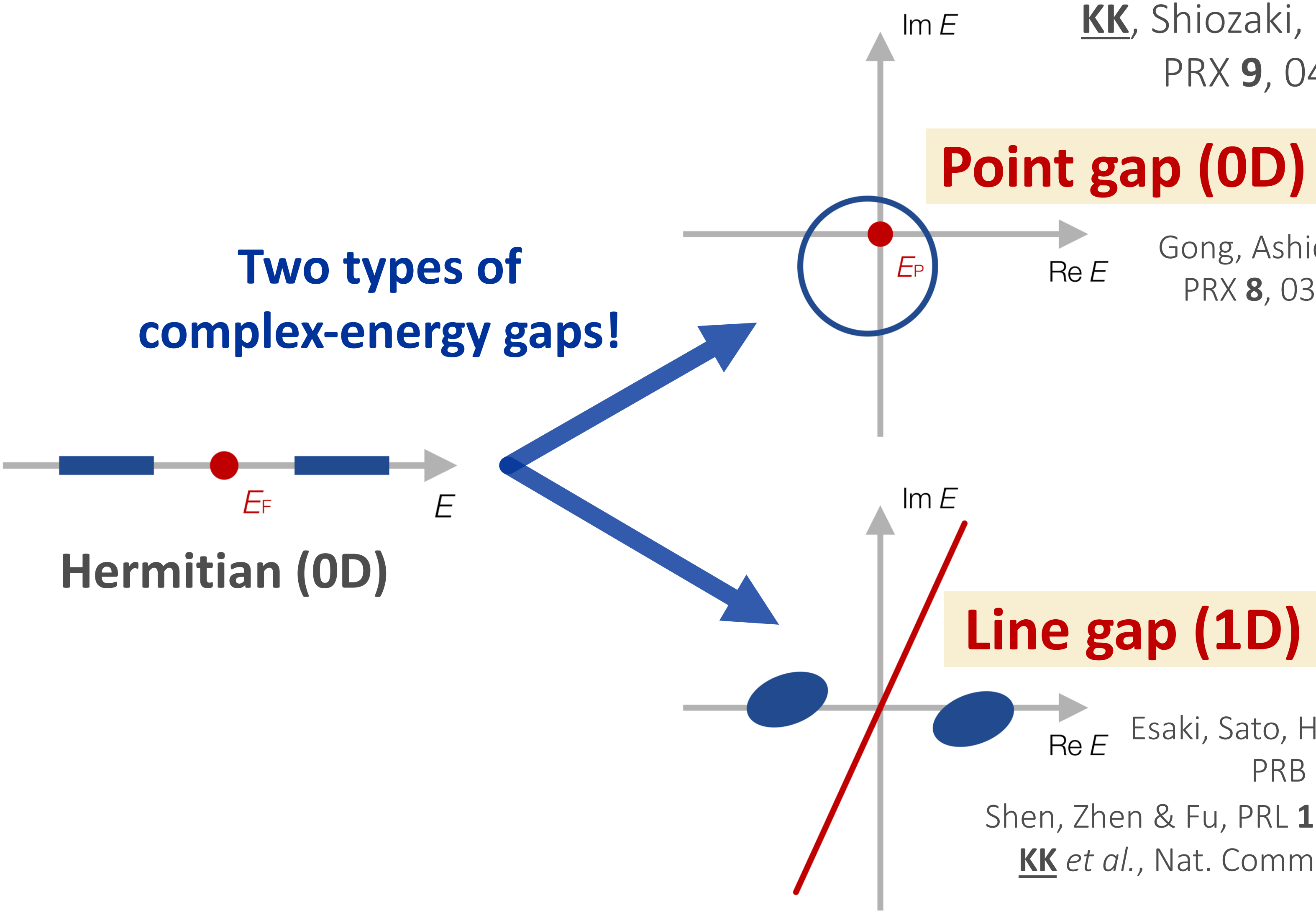
Energy gap in Hermitian systems:

- Energy regions where states are **forbidden to be present**.
- They **should be point-like (0D)** since the **real spectrum is 1D**.

→ Since the **complex spectrum is 2D (real and imaginary)**, such vacant regions can be **either 0D or 1D**!

Complex-energy gaps (2)

KK, Shiozaki, Ueda & Sato, PRX **9**, 041015 (2019)



Gong, Ashida, **KK** *et al.*, PRX **8**, 031079 (2018)

Esaki, Sato, Hasebe & Kohmoto, PRB **84**, 205128 (2011)
Shen, Zhen & Fu, PRL **120**, 146402 (2018)
KK *et al.*, Nat. Commun. **10**, 297 (2019)

NOTE: The definition that should be adopted depends on the individual physical situations that we are interested in.

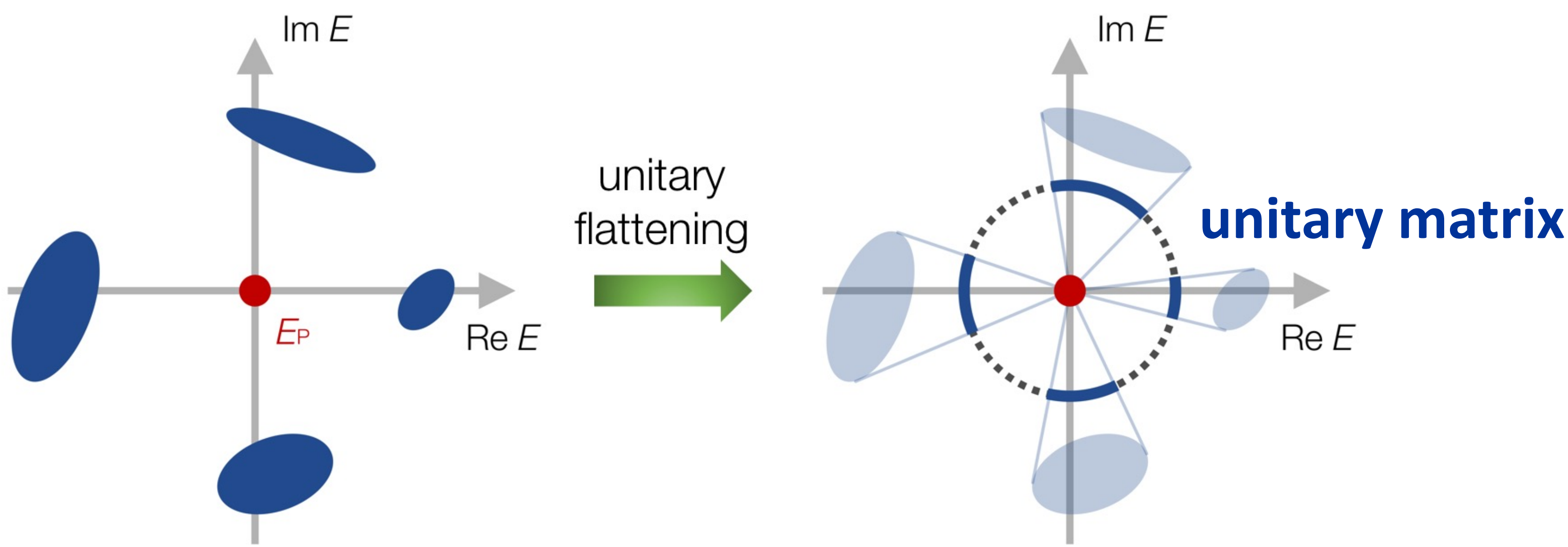
Point gap: unitary flattening

Unitary flattening for a point gap:

A non-Hermitian Hamiltonian with a **point gap** can be continuously deformed into a **unitary matrix** while having symmetry and the point gap.

non-Hermitian H ⟷ unitary U ⟷ **Hermitian** $\begin{pmatrix} 0 & U \\ U^\dagger & 0 \end{pmatrix}$

Classification is well established!



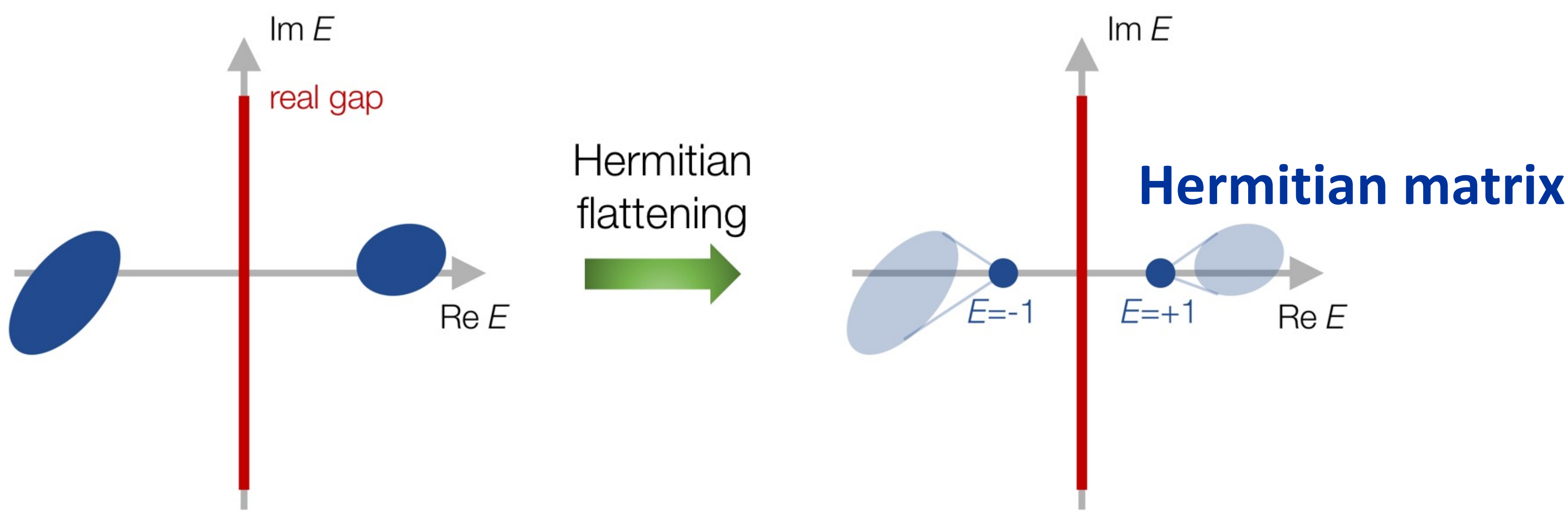
Line gap: Hermitian flattening

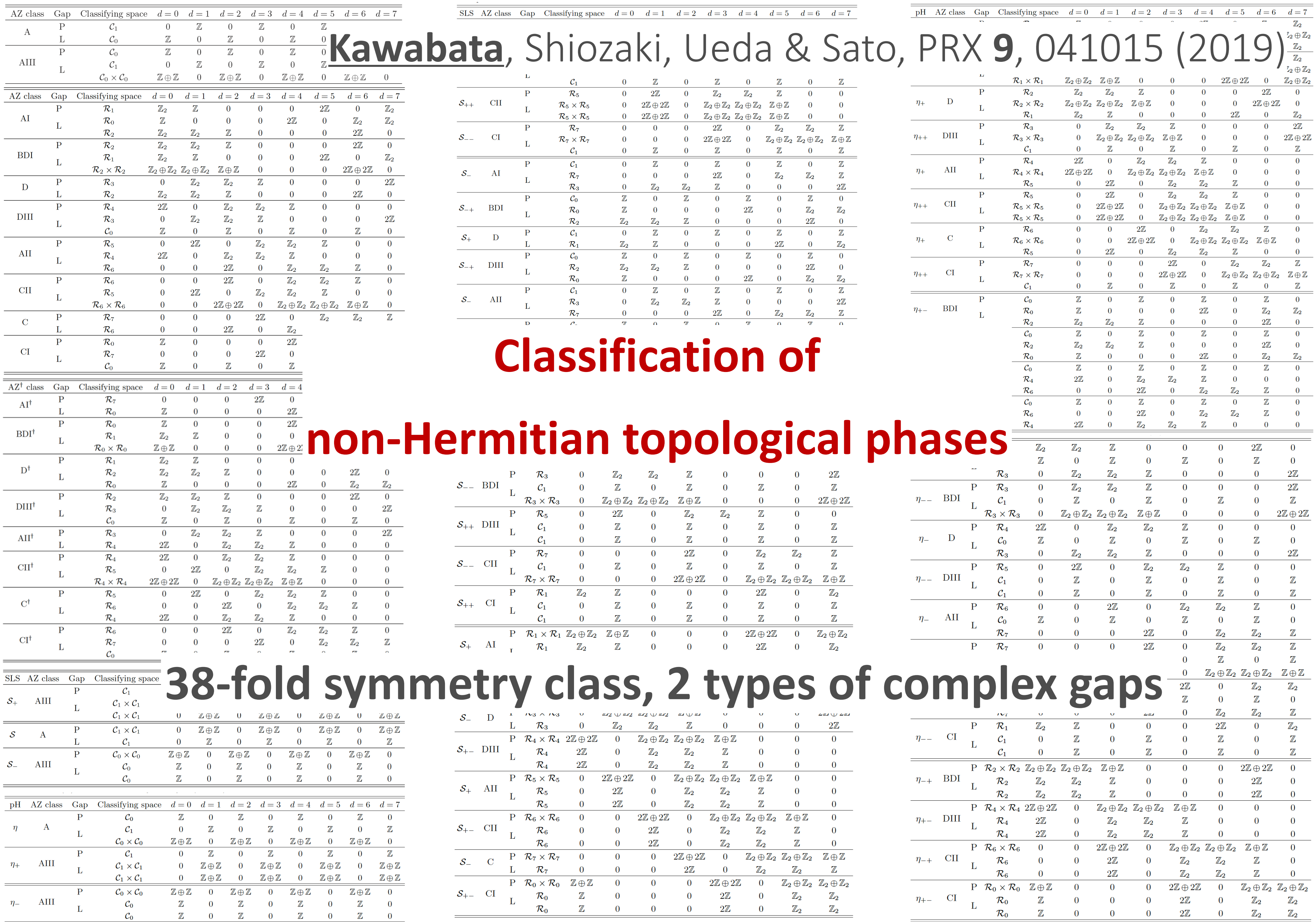
Hermitian flattening for a line gap:

A non-Hermitian Hamiltonian with a **line gap** can be continuously deformed into a **Hermitian matrix** while having symmetry and the line gap.

non-Hermitian H ⟷ **Hermitian** $\tilde{H}$

Classification is well established!





Kawabata, Shiozaki, Ueda & Sato, PRX **9**, 041015 (2019)

Classification of non-Hermitian topological phases

38-fold symmetry class, 2 types of complex gaps

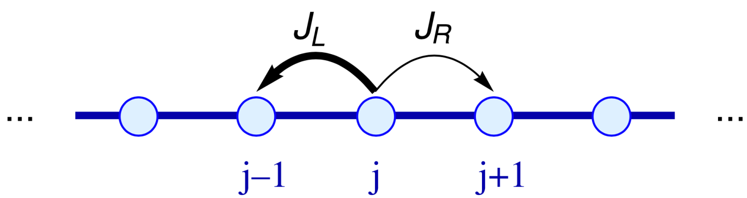
Intrinsic non-Hermitian topology

Line-gap topology: stability of Hermitian topology against non-Hermiticity

⟷ **Point-gap topology: intrinsic non-Hermitian topology**

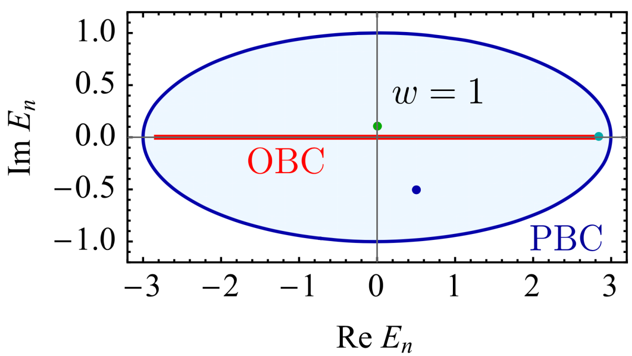
- **Hatano-Nelson model** Hatano & Nelson, PRL **77**, 570 (1996)

asymmetric hopping



$$\hat{H}_{\mathrm{HN}} = \sum_i \left(J_{\mathrm{R}} \hat{c}_{i+1}^\dagger \hat{c}_i + J_{\mathrm{L}} \hat{c}_i^\dagger \hat{c}_{i+1} \right)$$

$$H_{\mathrm{HN}}(k) = J_{\mathrm{R}} e^{\mathrm{i}k} + J_{\mathrm{L}} e^{-\mathrm{i}k}$$



Winding of complex energy!

$$W(E) := \oint \frac{dk}{2\pi \mathrm{i}} \frac{d}{dk} \log\det\left(H(k) - E\right)$$

(ill-defined in Hermitian systems)

Gong, Ashida, **KK** *et al.*, PRX **8**, 031079 (2018)

☆ **Skin effect: bulk-boundary correspondence for point-gap topology**

Emergence of an extensive number of boundary modes!

Okuma, **KK**, Shiozaki & Sato, PRL **124**, 086801 (2020); Zhang, Yang & Fang, PRL **125**, 126402 (2020)

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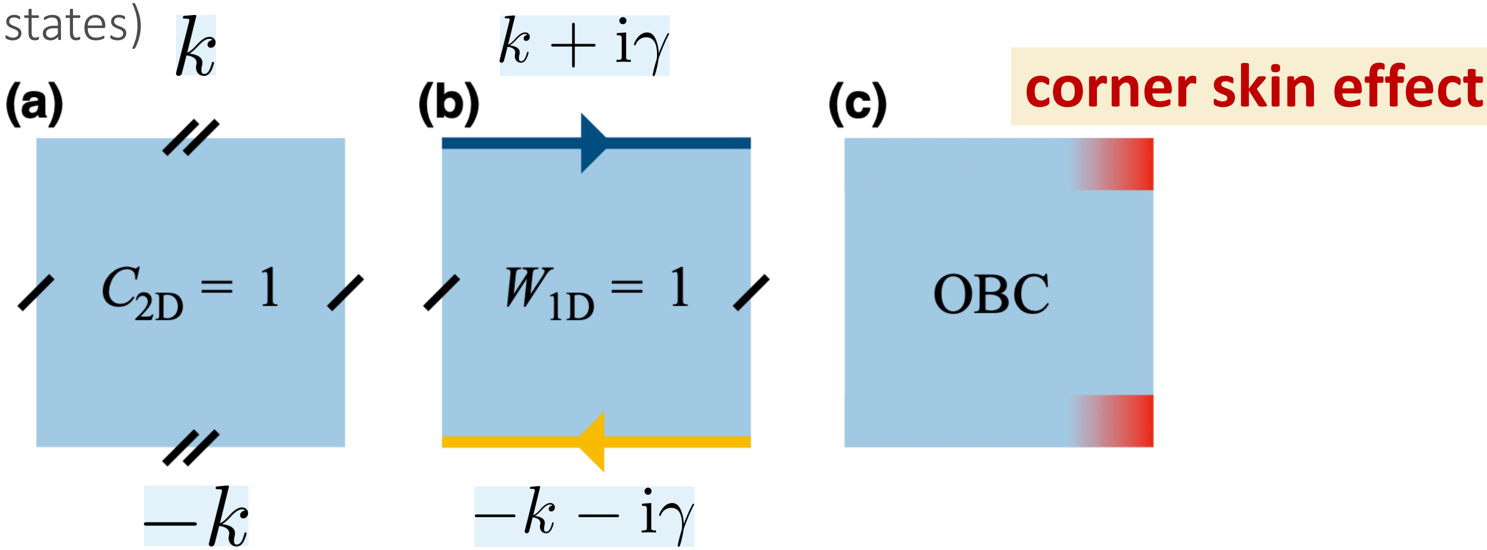
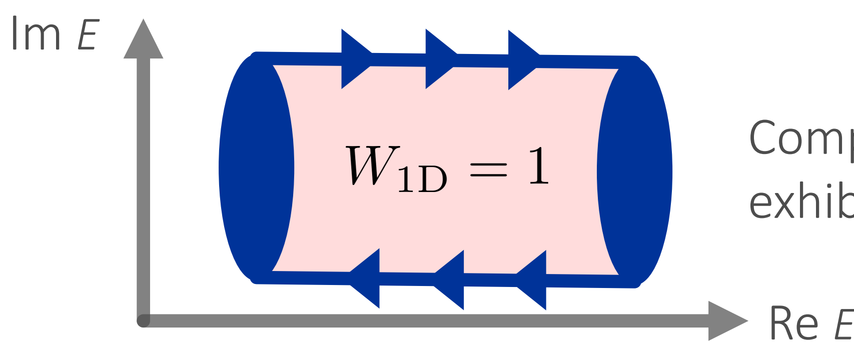
Non-Hermitian chiral edge modes

☆ **Chiral edge modes in 2D topological insulators exhibit 1D non-Hermitian topology and skin effect!**

(chiral edge states)



(add gain/loss at boundaries)

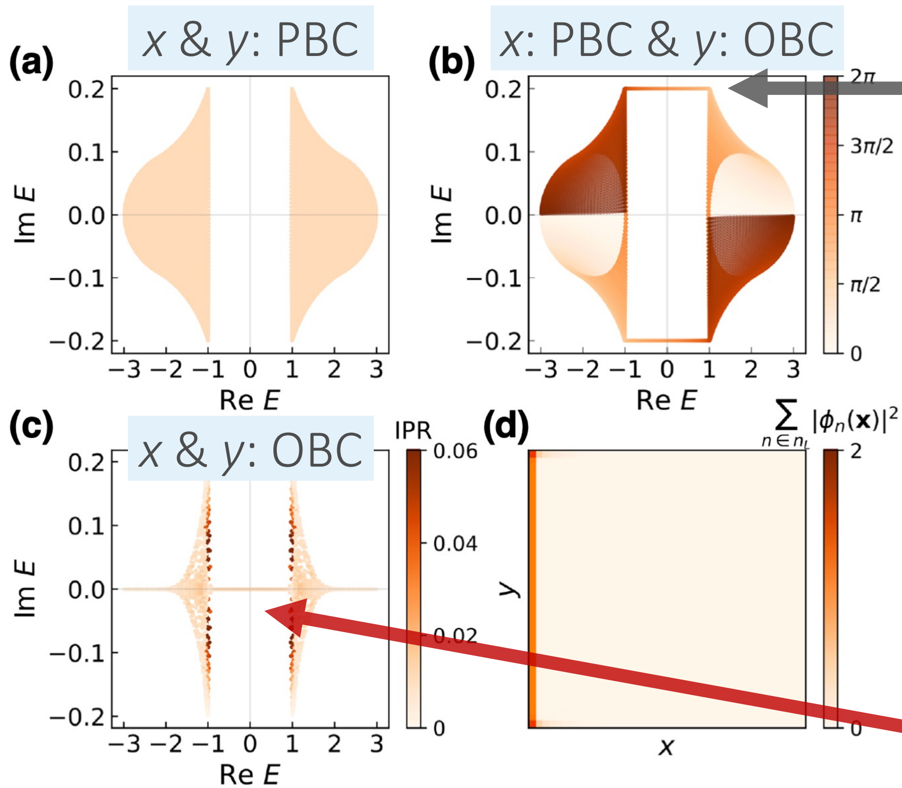


Complex chiral edge modes exhibit the spectral winding

Non-Hermitian Chern insulator

cf. **Kawabata** *et al.*, PRB **98**, 165148 (2018)

$$H(\boldsymbol{k}) = (m + t\cos k_x + t\cos k_y)\,\sigma_x + (t\sin k_x + \mathrm{i}\gamma)\,\sigma_y + (t\sin k_y)\,\sigma_z$$



chiral edge states

$\sin k_x + \mathrm{i}\gamma$

$$C_{\mathrm{2D}} = W_{\mathrm{1D}}$$

(can be shown in the presence of pseudo inversion symmetry)

New type of corner skin effect

– We can realize boundary non-Hermitian topology by a non-Hermitian perturbation only at the boundary.

cf. Nakamura, Inaka, Okuma & Sato, PRL **131**, 256602 (2023)

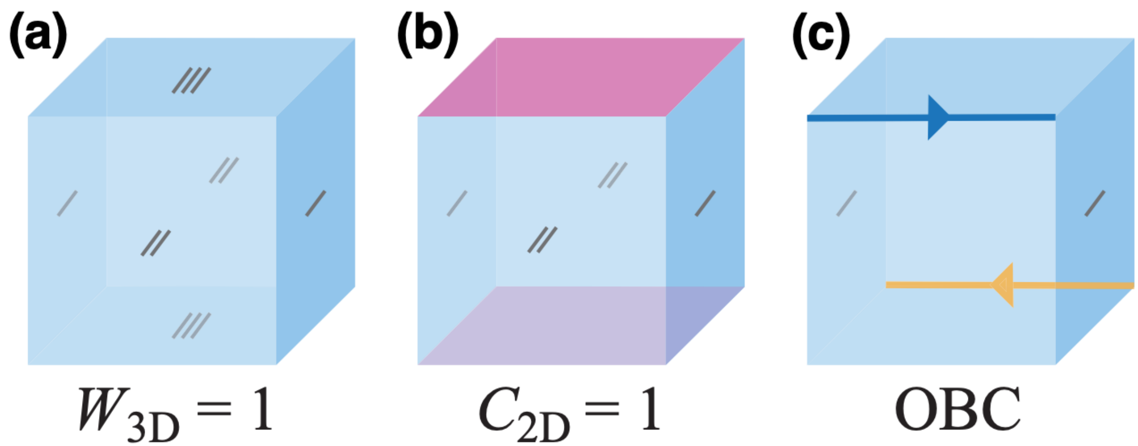
Non-Hermitian Dirac surface modes

☆ **Dirac surface states in 3D topological insulators exhibit 2D non-Hermitian topology and chiral hinge states!**

(non-Hermitian Dirac surface states)

$$k_x\sigma_x + k_y\sigma_y + \mathrm{i}\gamma k_x$$

2D point-gap topology



chiral hinge states $\mathrm{i}\gamma k_x$

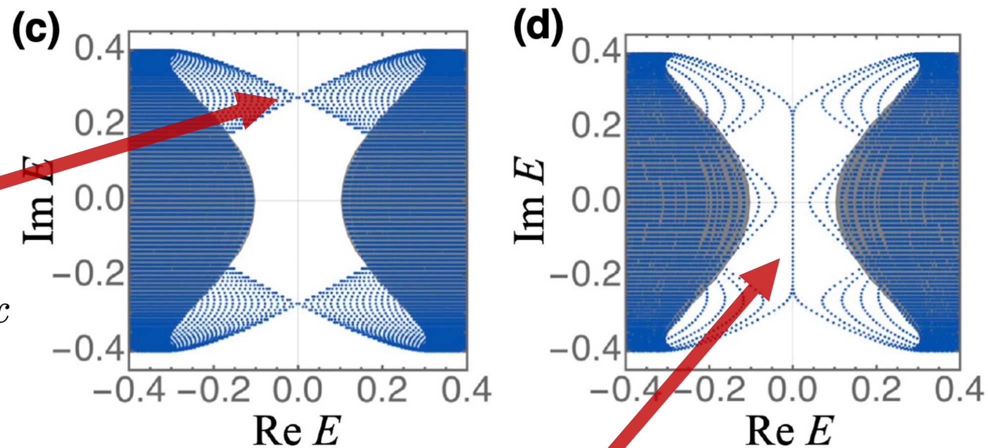
$$W_{3D} = C_{2D}$$

(3D Hermitian bulk) **(2D non-Hermitian boundary)**

Non-Hermitian 3D topological insulator

$$H(\boldsymbol{k}) = (m + t_1 \cos k_x + t_1 \cos k_y + t_1 \cos k_z)\,\tau_y + t_2 (\sigma_x \sin k_x + \sigma_y \sin k_y + \sigma_z \sin k_z)\,\tau_x + \delta (\cos k_x + \cos k_y)\,\sigma_y \tau_y + \underline{\mathrm{i}\gamma \sin k_x}$$

x & *y*: PBC, *z*: OBC   *x*: PBC, *y* & *z*: OBC



Dirac surface states

$$k_x \sigma_x + k_y \sigma_y + \mathrm{i}\gamma k_x$$

chiral hinge states! $\mathrm{i}\gamma k_x$

New type of second-order topological insulator induced by non-Hermiticity!

Classification

☆ **We classify possible non-Hermitian boundary topology for all the tenfold classes of topological insulators.**

Different non-Hermitian boundary phenomena appear for different symmetry classes and spatial dimensions.

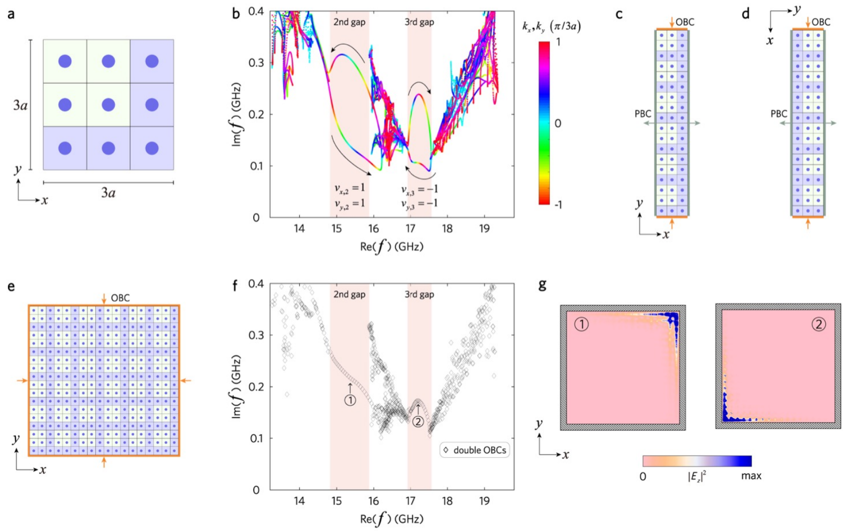
$d=2$ Line-gap topology		$d=1$ Point-gap topology	
H class	Invariant	NH class	Invariant (with $\mathcal{I}^\dagger$)
A ($\mathbb{Z}$)	$C \in \mathbb{Z}$	A ($\mathbb{Z}$)	$W(E_F) = C$ (mod 2)
D ($\mathbb{Z}$)	$C \in \mathbb{Z}$	D ($\mathbb{Z}_2$)	...
		D† ($\mathbb{Z}$)	$W(0) = C$ (mod 2)
DIII ($\mathbb{Z}_2$)	$\nu \in \{0,1\}$	DIII† ($\mathbb{Z}_2$)	$\nu(0) = \nu$
AII ($\mathbb{Z}_2$)	$\nu \in \{0,1\}$	AII ($2\mathbb{Z}$)	$W(E_F) = 2\nu$ (mod 4)
		AII† ($\mathbb{Z}_2$)	$\nu(E_F) = \nu$
C ($2\mathbb{Z}$)	$C \in 2\mathbb{Z}$	C† ($2\mathbb{Z}$)	$W(0) = C$ (mod 4)

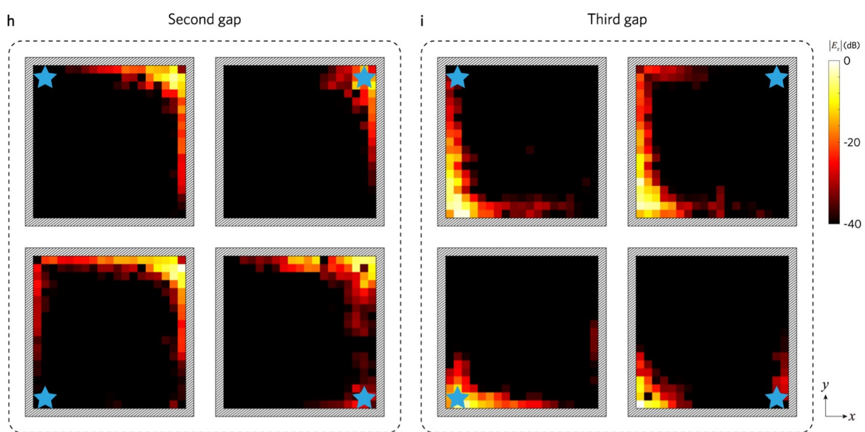
$d=3$ Line-gap topology		$d=2$ Point-gap topology	
H class	Invariant	NH class	Invariant (with $\mathcal{I}^\dagger$)
AIII ($\mathbb{Z}$)	$W \in \mathbb{Z}$	AIII ($\mathbb{Z}$)	$C(0) = W$ (mod 2)
DIII ($\mathbb{Z}$)	$W \in \mathbb{Z}$	DIII ($\mathbb{Z}_2$)	...
		DIII† ($\mathbb{Z}$)	$C(0) = W$ (mod 2)
AII ($\mathbb{Z}_2$)	$\nu \in \{0,1\}$	AII† ($\mathbb{Z}_2$)	$\nu(E_F) = \nu$
CII ($\mathbb{Z}_2$)	$\nu \in \{0,1\}$	CII ($2\mathbb{Z}$)	$C(0) = 2\nu$ (mod 4)
		CII† ($\mathbb{Z}_2$)	$\nu(0) = \nu$
CI ($2\mathbb{Z}$)	$W \in 2\mathbb{Z}$	CI† ($2\mathbb{Z}$)	$C(0) = W$ (mod 4)

cf. Nakamura, Bessho & Sato, PRL **132**, 136401 (2024)

Experiments

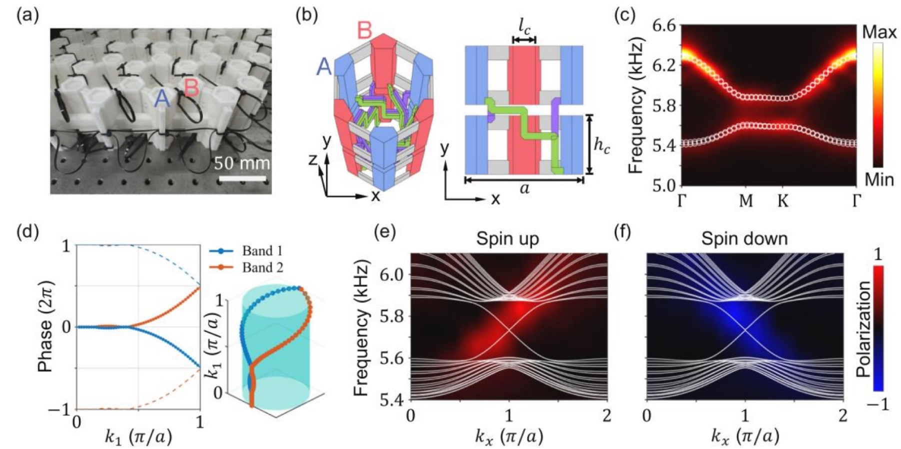
Photonic crystal

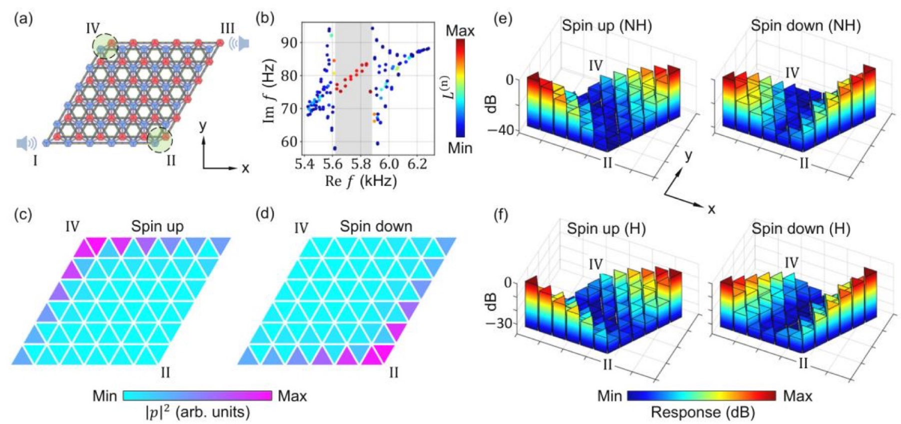




Liu *et al.*, Phys. Rev. Lett. **132**, 113802 (2024)

Phononic crystal



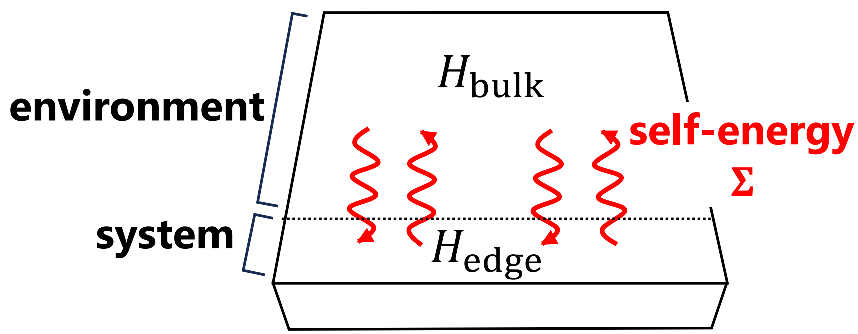


Wu *et al.* arXiv:2312.12060

So far, we have realized non-Hermitian topology by explicitly adding non-Hermiticity to the boundaries.

→ **We develop the Hermitian bulk – non-Hermitian boundary correspondence even in Hermitian topological insulators.**

(no dissipation)



Although no dissipation is added externally, the coupling between the bulk and boundary leads to non-Hermitian topology!

Outline

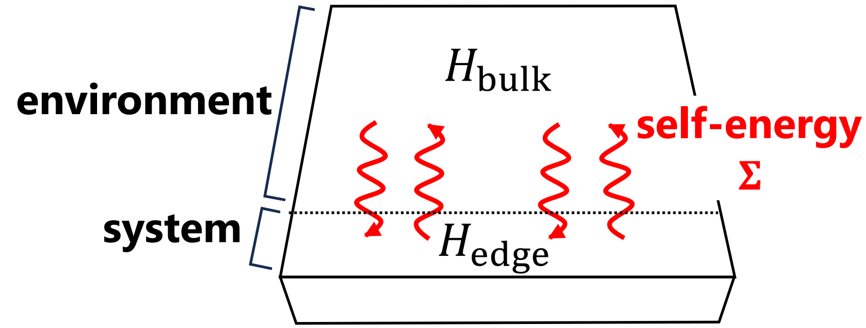
1. Introduction

2. Non-Hermitian topology (review)

3. Hermitian bulk – non-Hermitian boundary correspondence

4. Non-Hermitian topology in Hermitian topological matter

Non-Hermitian self-energy



Single-particle Hermitian Hamiltonian:

$$H = \begin{pmatrix} H_{\mathrm{bulk}} & T \\ T^{\dagger} & H_{\mathrm{edge}} \end{pmatrix}$$

Single-particle Schrödinger equation:

$$H \begin{pmatrix} |\psi_{\mathrm{bulk}}\rangle \\ |\psi_{\mathrm{edge}}\rangle \end{pmatrix} = (E + \mathrm{i}\eta) \begin{pmatrix} |\psi_{\mathrm{bulk}}\rangle \\ |\psi_{\mathrm{edge}}\rangle \end{pmatrix}$$

→ **Effective non-Hermitian Hamiltonian at the boundary:**

$$H_{\mathrm{eff}}(E) = H_{\mathrm{edge}} + \underline{\Sigma(E)}$$

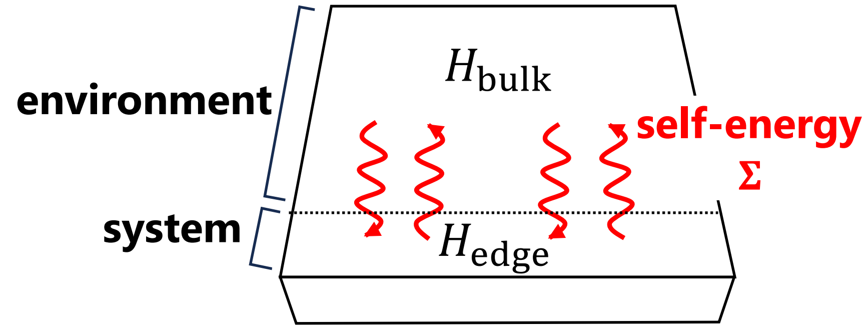
self-energy $\Sigma(E) := T^{\dagger} (E + \mathrm{i}\eta - H_{\mathrm{bulk}})^{-1} T$

☆ Self-energy is generally non-Hermitian and captures the particle exchange between the bulk and boundary.

Non-Hermitian self-energy

Single-particle Hermitian Hamiltonian:

$$H = \begin{pmatrix} H_{\mathrm{bulk}} & T \\ T^{\dagger} & H_{\mathrm{edge}} \end{pmatrix}$$



Single-particle Schrödinger equation:

H

Topology of the original Hermitian Hamiltonian should leave an imprint on that of the effective non-Hermitian Hamiltonian at the boundary!

$$H_{\mathrm{eff}}(E) = H_{\mathrm{edge}} + \underline{\Sigma(E)}$$

self-energy $\Sigma(E) := T^{\dagger}\left(E + i\eta - H_{\mathrm{bulk}}\right)^{-1} T$

☆ Self-energy is generally non-Hermitian and captures the particle exchange between the bulk and boundary.

Su-Schrieffer-Heeger model (1)

SSH model: $H_{\mathrm{SSH}}(k) = (v + t\cos k)\,\sigma_x + (t\sin k)\,\sigma_y$

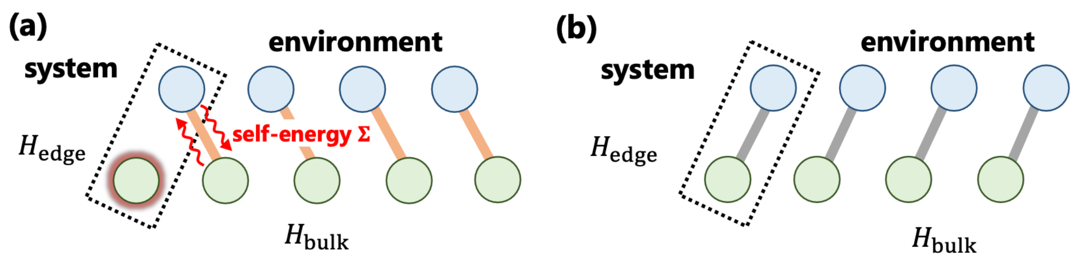
→ edge mode $|\psi_0\rangle \propto \sum_x \left(-\frac{v}{t}\right)^x |x\rangle \otimes \begin{pmatrix}1\\0\end{pmatrix}$ (top. phase: $|v/t| < 1$)

0D self-energy between the bulk and edge:

$$\Sigma(E) = \begin{pmatrix} 0 & 0 \\ 0 & -\mathrm{i}\pi\left(t^2 - v^2\right)\delta(E)\,\theta(t-v) \end{pmatrix}$$

chiral symmetry: $\sigma_z H_{\mathrm{SSH}}(k)\,\sigma_z = -H_{\mathrm{SSH}}(k)$

→ $\sigma_z H_{\mathrm{eff}}^{\dagger}(E=0)\,\sigma_z = -H_{\mathrm{eff}}(E=0)$

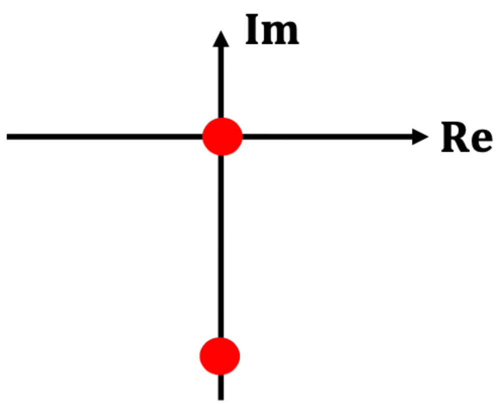


Su-Schrieffer-Heeger model (2)

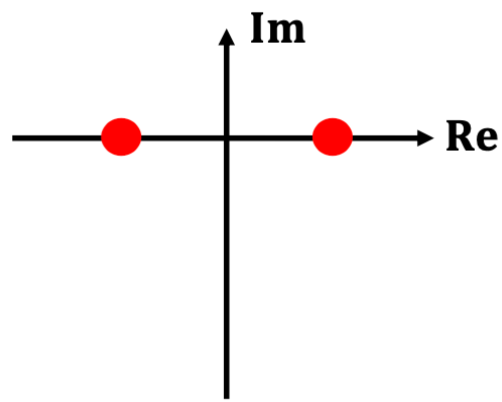
$$\Sigma(E) = \begin{pmatrix} 0 & 0 \\ 0 & -i\pi\left(t^2 - v^2\right)\delta(E)\,\theta(t-v) \end{pmatrix}$$

topological **trivial**

(c)



(d)



$$H_{\mathrm{eff}}(E=0) = v\sigma_x + \Sigma(E=0)$$

exhibits point-gap topology in 0D protected by chiral symmetry

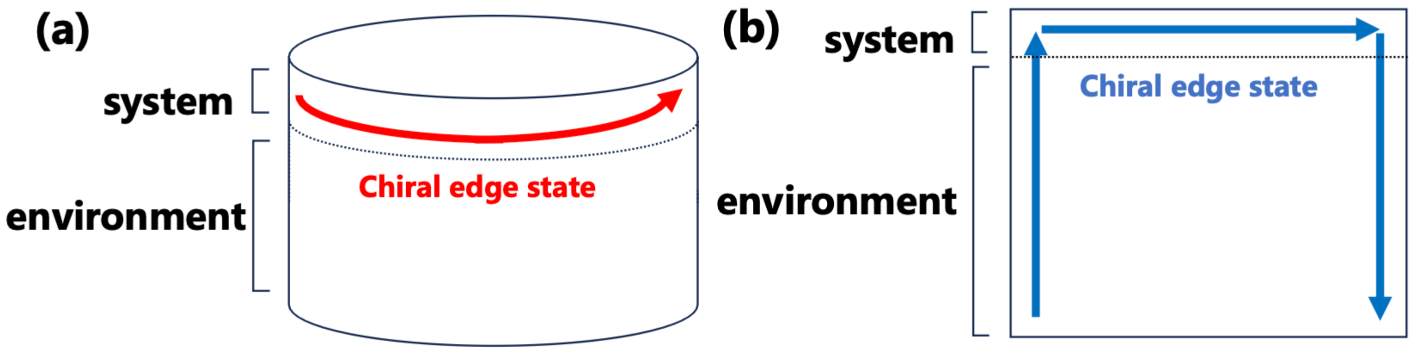
(0th Chern number of $iH_{\mathrm{eff}}\sigma_z$)

ensures the persistence of zero modes

Chern insulator (1)

$$H_{\mathrm{Chern}}\left(\boldsymbol{k}\right) = \left(t\sin k_x\right)\sigma_x + \left(t\sin k_y\right)\sigma_y + \left(m + t\cos k_x + t\cos k_y\right)\sigma_z$$

(1st) Chern number: $C_1 = \begin{cases} \mathrm{sgn}\left(m/t\right) & \left(|m/t| < 2\right) \\ 0 & \left(|m/t| > 2\right) \end{cases}$



1D self-energy between the bulk and edge:

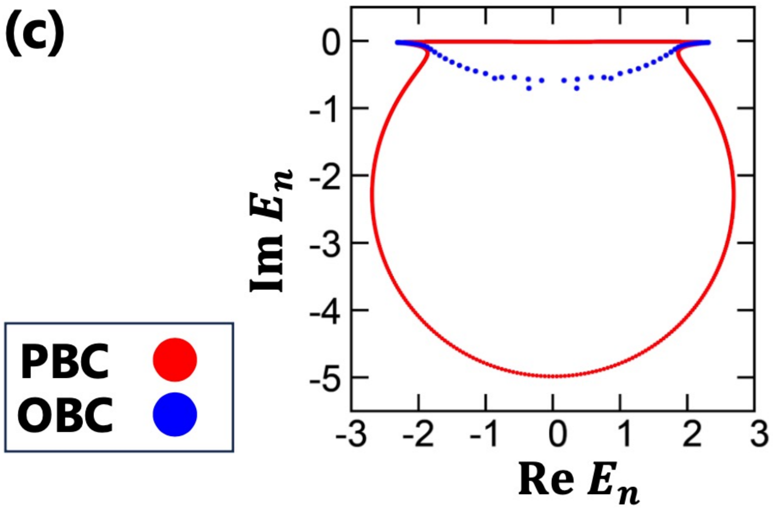
$$\Sigma\left(E, k_y\right) = \frac{t^2 - \left(m + t\cos k_y\right)^2}{2\left(E + \mathrm{i}\eta - t\sin k_y\right)}\left(\sigma_0 - \sigma_y\right)$$

$$H_{\mathrm{eff}}\left(E, k_y\right) = \left(t\sin k_y\right)\sigma_y + \left(m + t\cos k_y\right)\sigma_z + \Sigma\left(E, k_y\right)$$

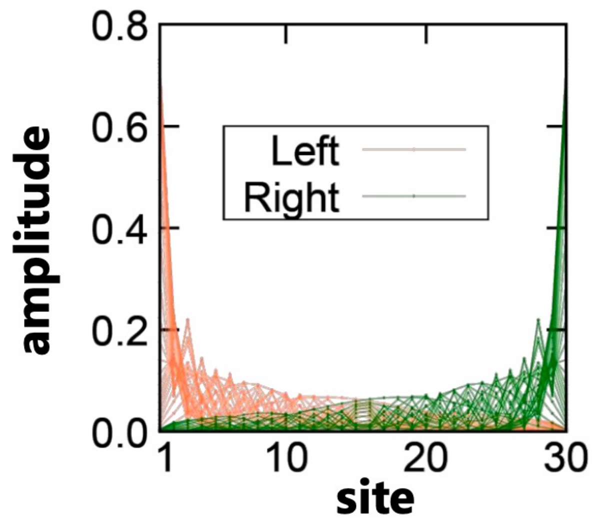
Chern insulator (2)

The complex spectrum of H_{eff} exhibits winding.
(i.e., 1D point-gap topology)

(c)



(d)

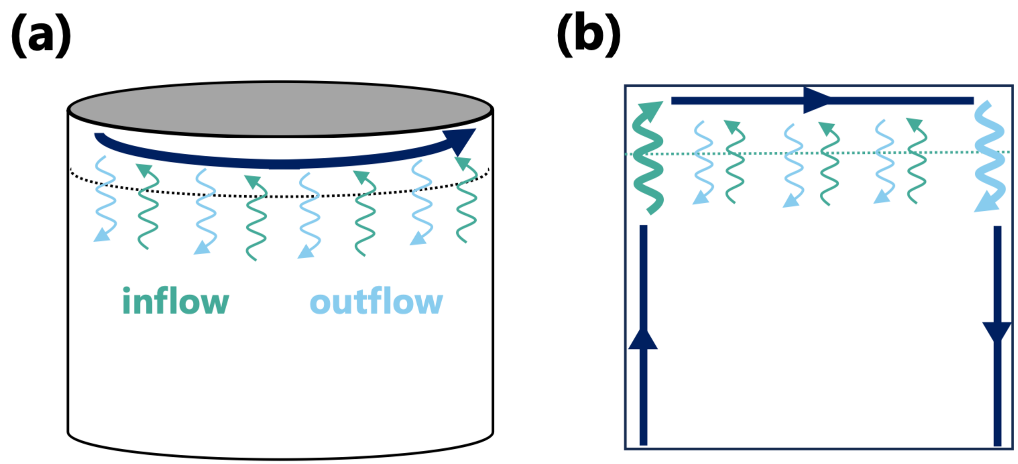


As a consequence of the point-gap topology,
H_{eff} also exhibits the non-Hermitian skin effect.
(localized at the corners)

Skin current (1)

What is a physical consequence of the point-gap topology and skin effect in the effective boundary non-Hermitian Hamiltonian?

→ **Skin effect of the chiral edge modes results in the localized current distributions.**

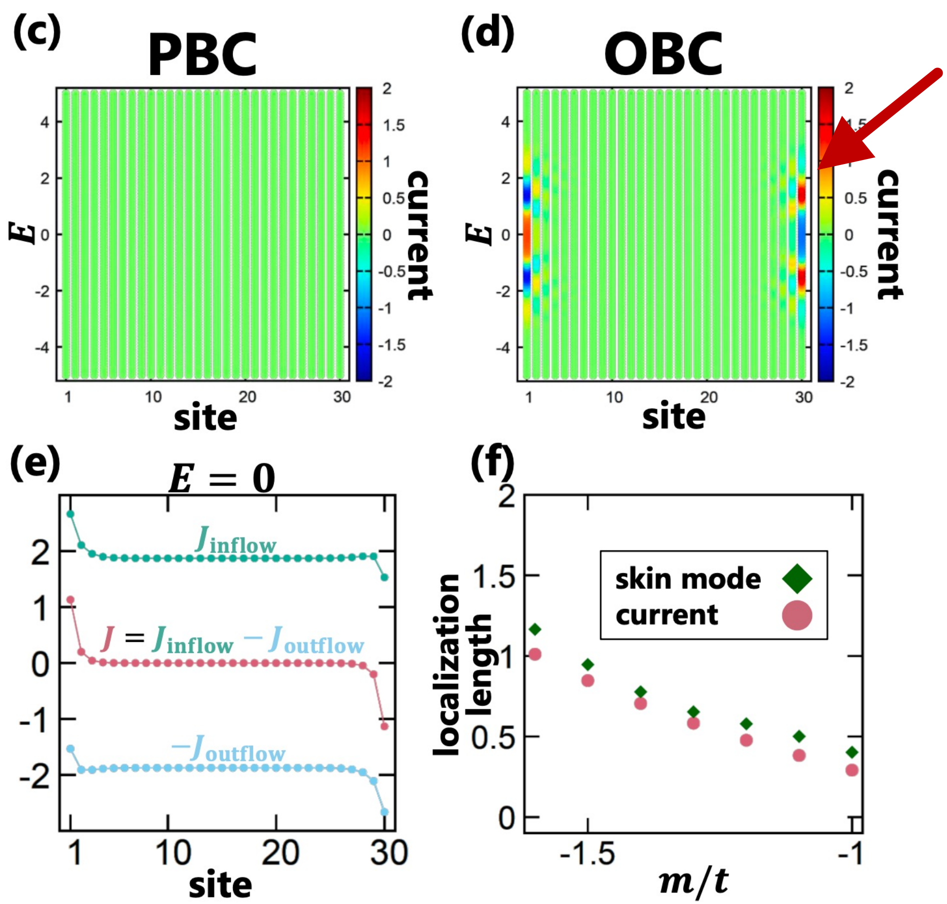


– **Inflow** from the bulk to the edge at one corner

– **Outflow** from the bulk to the edge at the other corner

Skin current (2)

E-resolved current: $J(E) = -\left[H_{\mathrm{edge}}, G_{\mathrm{edge}}(E)\right] - \left[H_{\mathrm{edge}}, G_{\mathrm{edge}}(E)\right]^{\dagger}$



Localized current arises only under the OBC

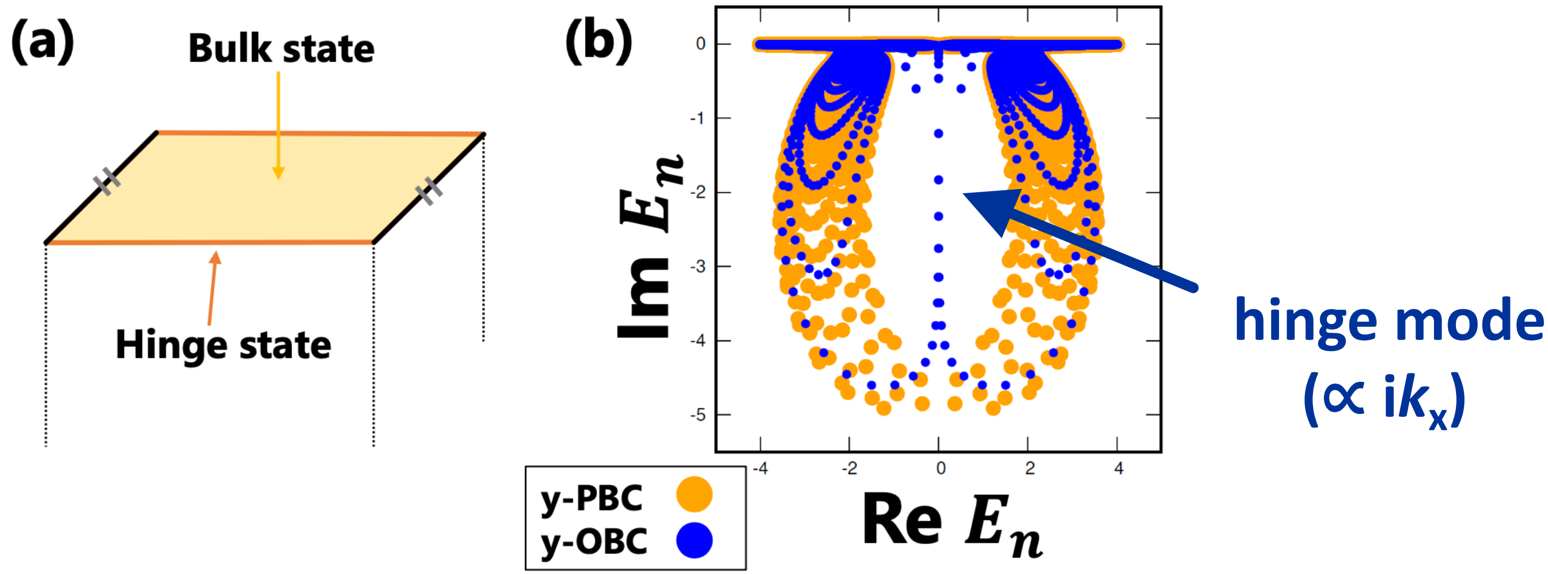
Localized current due to the skin effect

$J_y \simeq j_1 e^{-y/\xi} - j_2 e^{-(L-y)/\xi}$

ξ: localization length of skin mode

Three dimensions

3D topological insulator:
$$H_{\mathrm{3DTI}}(\boldsymbol{k}) = (m + t\cos k_x + t\cos k_y + t\cos k_z)\,\tau_y + (t\sin k_x)\,\sigma_x\tau_x + (t\sin k_y)\,\sigma_y\tau_x + (t\sin k_z)\,\sigma_z\tau_x + \delta\,(\cos k_x + \cos k_y)\,\sigma_y\tau_y$$



H_{eff} exhibits 2D point-gap topology, leading to the chiral hinge modes!

(1st Chern number of $iH_{\mathrm{eff}}\sigma_z$)

Classification

When the original Hermitian Hamiltonians respect AZ symmetry, the effective non-Hermitian Hamiltonians H_{eff} respect AZ† symmetry.

→ **H_{eff} can generally exhibit point-gap topology**

skin effect

hinge mode

AZ class	TRS	PHS	CS	$d=1$	$d=2$	$d=3$
A	0	0	0	0	$\mathbb{Z}^*$	0
AIII	0	0	1	$\mathbb{Z}$	0	$\mathbb{Z}$
AI	+1	0	0	0	0	0
BDI	+1	+1	1	$\mathbb{Z}$	0	0
D	0	+1	0	$\mathbb{Z}_2$	$\mathbb{Z}^*$	0
DIII	−1	+1	1	$\mathbb{Z}_2$	$\mathbb{Z}_2^*$	$\mathbb{Z}^{**}$
AII	−1	0	0	0	$\mathbb{Z}_2^*$	$\mathbb{Z}_2^*$
CII	−1	−1	1	$2\mathbb{Z}$	0	$\mathbb{Z}_2$
C	0	−1	0	0	$2\mathbb{Z}^*$	0
CI	+1	−1	1	0	0	$2\mathbb{Z}$

cf. Nakamura, Bessho & Sato, PRL **132**, 136401 (2024)

Summary

PRX Quantum 4, 030315 (2023)

arXiv:2405.10015

- We establish the topological correspondence between the Hermitian bulk and non-Hermitian boundary.
- We find new boundary physics, such as corner skin effect of chiral edge modes and chiral hinge modes due to non-Hermiticity.
- We develop this correspondence even in Hermitian topological insulators.