Engineering topological non-Hermitian quantum and photonic matter with modulated losses

Jose Lado

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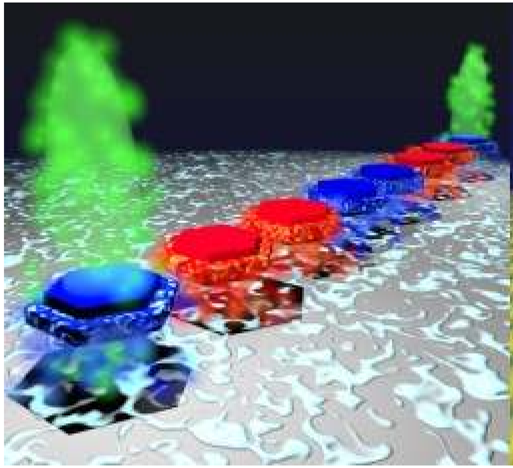
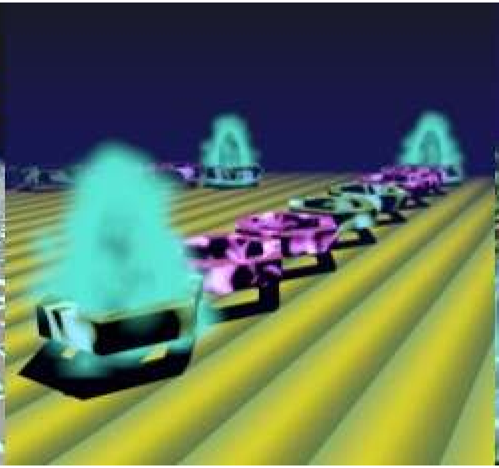
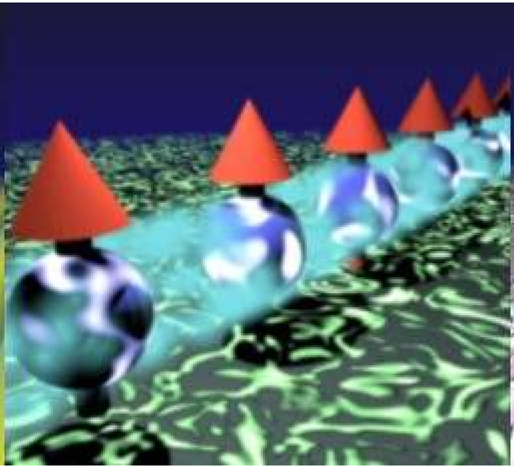
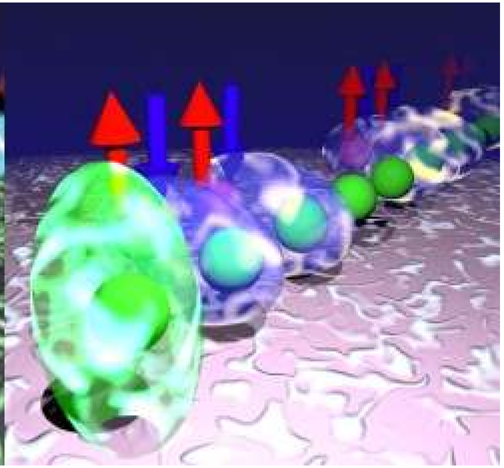

Phys. Rev. Research 6, 023004 (2024)


Nature Materials 24, 1393–1399 (2025)

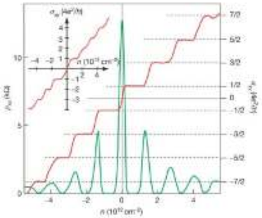

Phys. Rev. Lett. 130, 100401 (2023)


Phys. Rev. Lett. 134, 116605 (2025)

Quantum Correlated Light and Matter, Finland
November 5th 2025

Topological matter

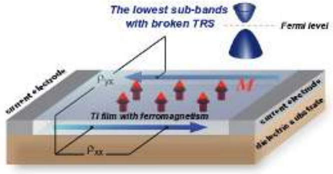
Quantum Hall effect



graphene

Nature 438, 197-200 (2005)

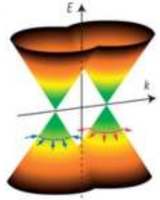
Quantum Anomalous Hall effect



Cr-doped $(Bi,Sb)_2Te_3$

Science 340.6129 (2013): 167-170

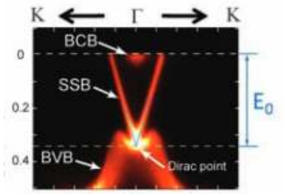
Weyl semimetal



TaAs

Nature Physics 11, 724–727 (2015)

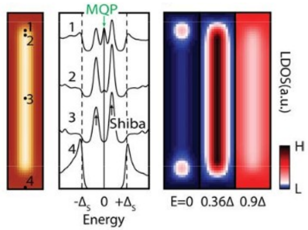
Quantum Spin Hall effect



Bi_2Se_3

Science 325.5937 (2009): 178-181

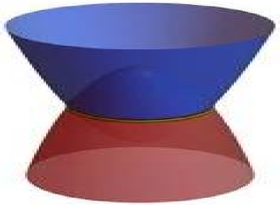
Topological superconductor



Fe@Pb

Science 346.6209 (2014): 602-607

Nodal line semimetals



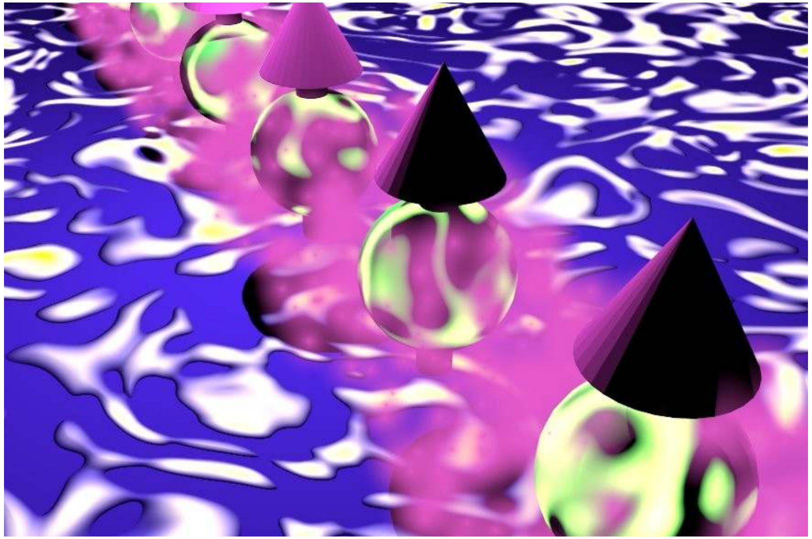
Mg_3Bi_2

Advanced Science 6.4 (2019): 1800897

All these states are described by effective isolated single-particle Hamiltonians

Two major challenges in topological matter

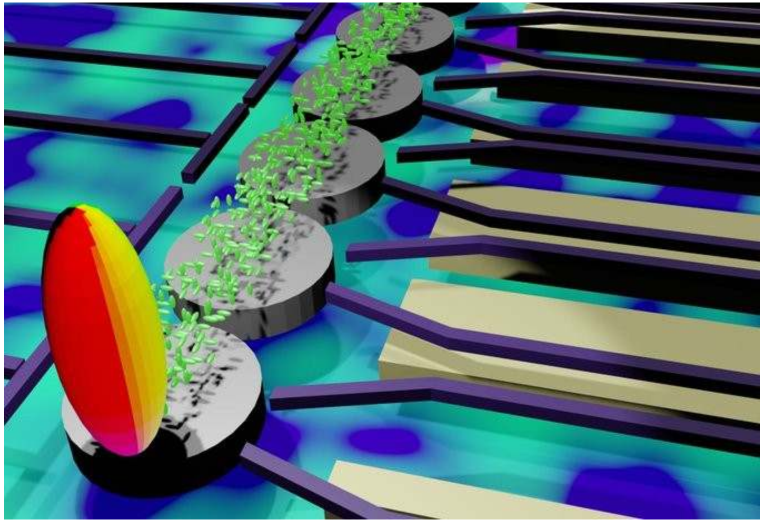
Many-body interactions



Interacting topological matter

Rep. Prog. Phys. 81 116501 (2018)

Coupling to the environment

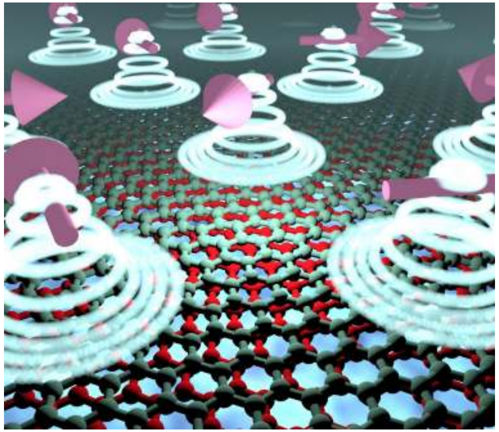


Non-Hermitian topological matter

Rev. Mod. Phys. 93, 015005 (2021)

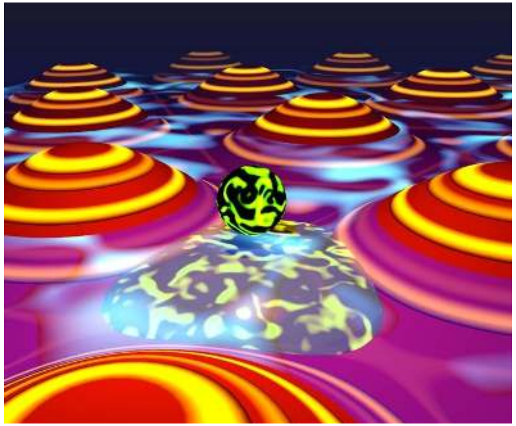
Many-body quantum matter

Quantum spin liquids



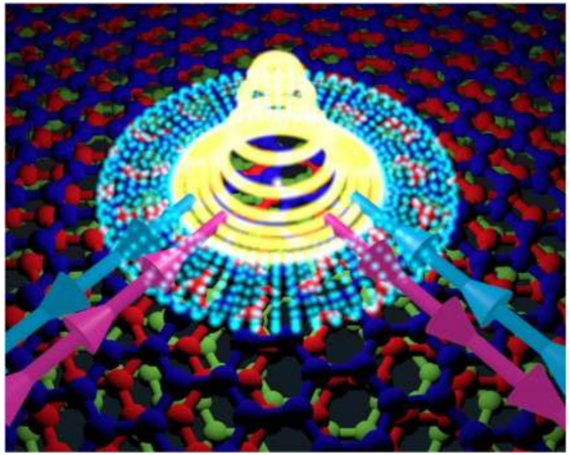
Reports on Progress in Physics 80.1 (2016): 016502
Rep. Prog. Phys. 80, 016502 (2017)
Rev. Mod. Phys. 88, 041002 (2016)
Nature Physics 17, 1154–1161 (2021)

Fractional Chern insulators



Phys. Rev. Lett. 106, 236804 (2011)
Phys. Rev. X 1, 021014 (2011)
Nature Materials 24, 1042–1048 (2025)
Nature 622, 69–73 (2023)

Parafermions

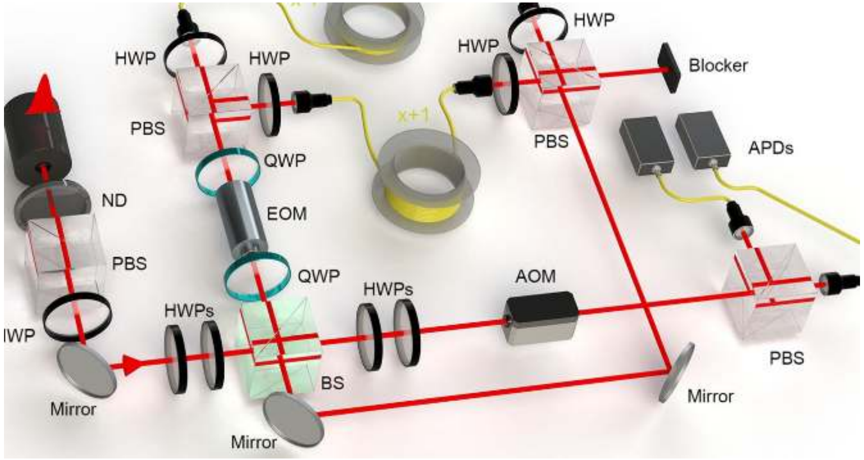


Ann Review of Cond Mat Phys 7, 119-139 (2016)
Phys. Rev. X 12, 021057 (2022)

Many-body quantum matter represents an exciting critically open challenge

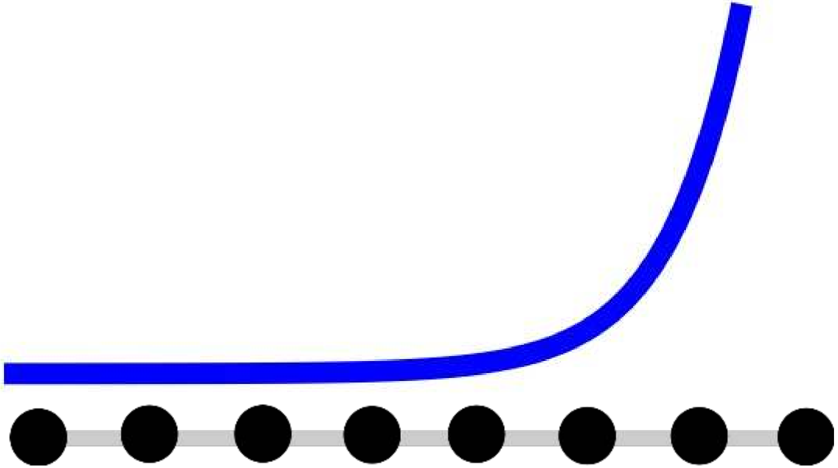
Non-Hermitian quantum matter

Non-Hermitian topology



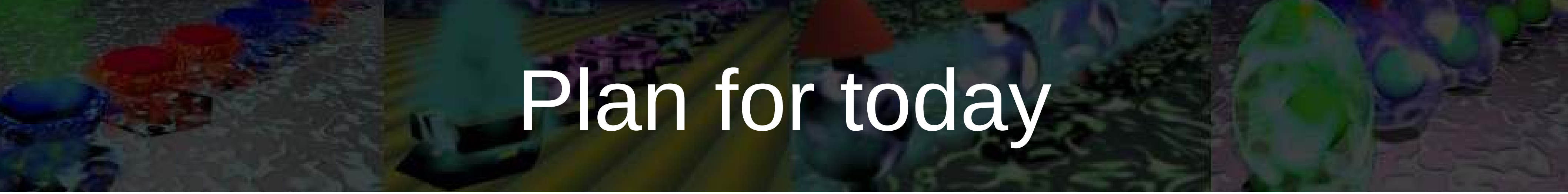
Nat Comm 13, 3229 (2022)

Non-Hermitian skin effect



Phys. Rev. Lett. 129, 070401 (2022)

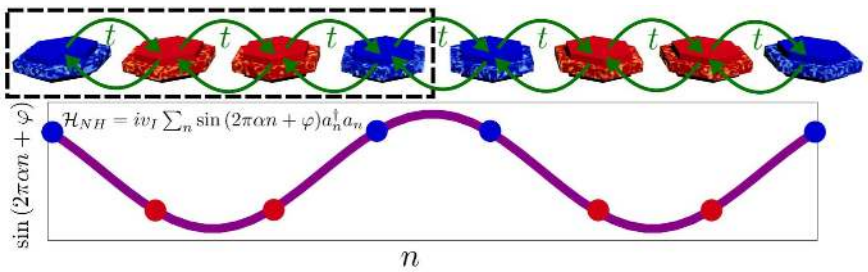
Non-Hermitian quantum matter opens exciting new possibilities in emergent phenomena



Plan for today

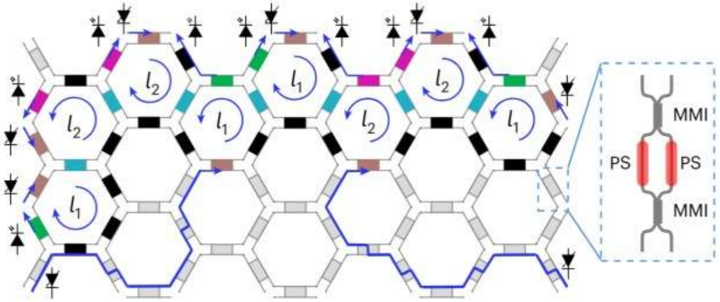
Non-Hermitian quasiperiodic topology from modulated losses

Phys. Rev. Research 6, 023004 (2024)



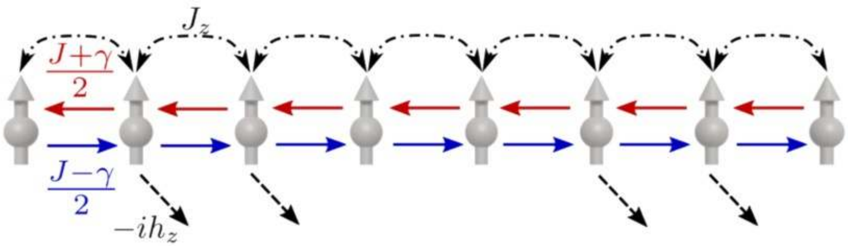
Experimental realization of non-Hermitian topology from modulated losses

Nature Materials 24, 1393–1399 (2025)



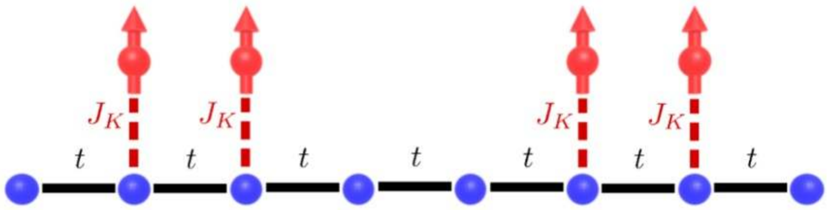
Dynamical correlators for non-Hermitian many-body topology

Phys. Rev. Lett. 130, 100401 (2023)

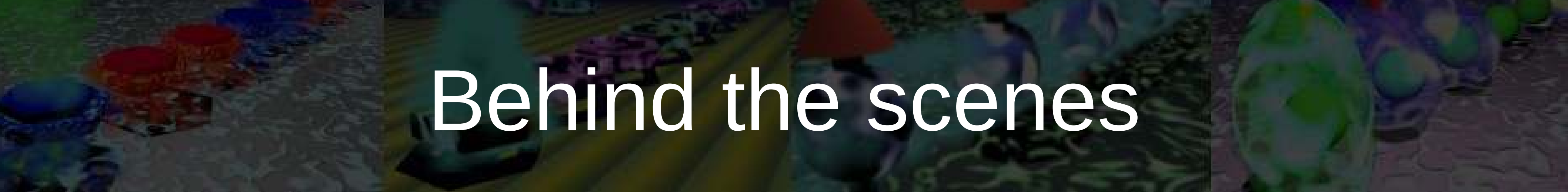


Topological modes in a Kondo lattice emerging from non-Hermitian topology

Phys. Rev. Lett. 134, 116605 (2025)



Behind the scenes



Non-Hermitian quasiperiodic topology from modulated losses

Phys. Rev. Research 6, 023004 (2024)

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Experimental realization of non-Hermitian topology from modulated losses

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Fei Song

Guangze Chen

Topological modes in a Kondo lattice emerging from non-Hermitian topology

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Zina Lippo

Guangze Chen

Elizabeth Pereira

How does non-Hermiticity appear in a Hamiltonian?

Coupling a system to an environment

Full Hamiltonian of the system

$$H_{\text{full}} = \begin{pmatrix} H_0 & \Gamma \\ \Gamma^\dagger & H_{\text{env}} \end{pmatrix}$$

Selfenergy

$$\Sigma_{\text{env}} = \Gamma(\omega - H_{\text{env}})^{-1}\Gamma^\dagger$$

Green's function of the coupled system

$$G_0 = (\omega - H_0 - \Sigma_{\text{env}})^{-1}$$

Coupling a system to an environment

Full Hamiltonian of the system

$$H_{\rm full} = \begin{pmatrix} H_0 & \Gamma \\ \Gamma^\dagger & H_{\rm env} \end{pmatrix}$$

Effective Hamiltonian associated to the Green's function

$$H_0^{eff} = H_0 + \frac{1}{2}(\Sigma_{\rm env} + \Sigma_{\rm env}^\dagger) + \frac{1}{2}(\Sigma_{\rm env} - \Sigma_{\rm env}^\dagger)$$

Hermitian renormalization

Non-Hermitian environment induced terms

Coupling a system to an environment

Full Hamiltonian of the system

$$H_{\text{full}} = \begin{pmatrix} H_0 & \Gamma \\ \Gamma^\dagger & H_{\text{env}} \end{pmatrix}$$

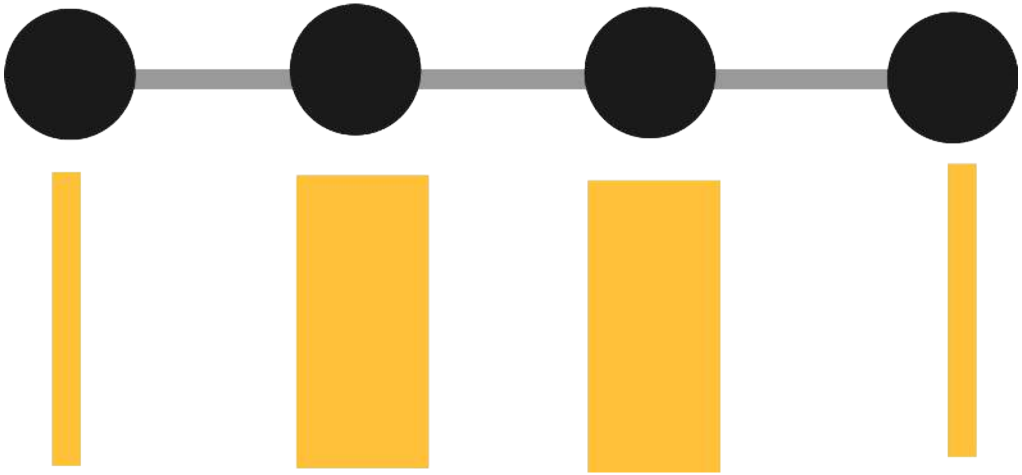
Effective Hamiltonian associated to the Green's function

$$H_0^{eff} = \bar{H}_0 + H_0^{NH}$$

Hermitian terms

Non-Hermitian terms

Non-Hermiticity in resonators



Single-mode resonator

Environment

$$g_n = \mathrm{Im}(\Sigma_n)$$

Environment selfenergy

Hopping

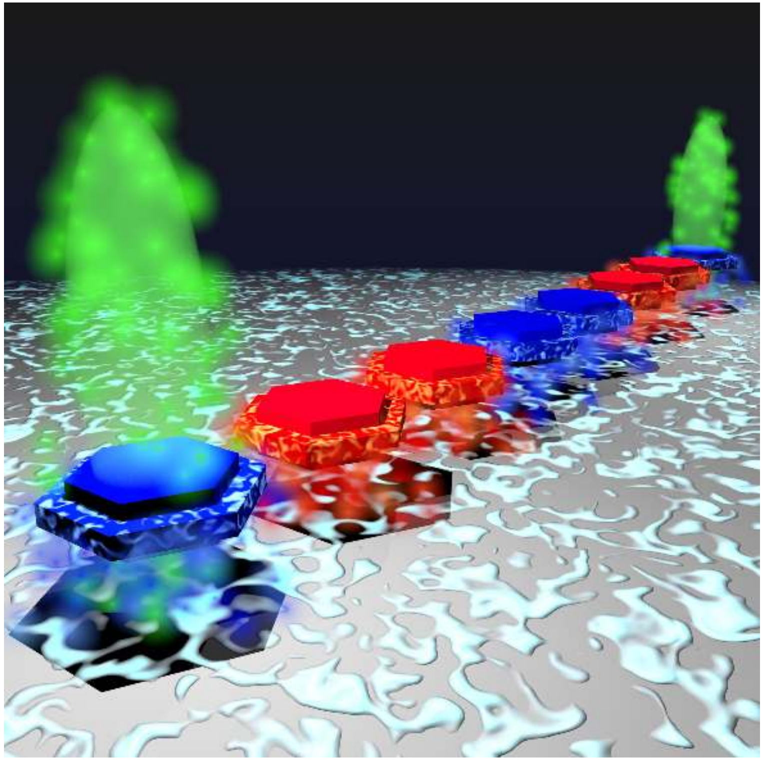
Imaginary onsite energy

$$H = c_n^\dagger c_{n+1} + c_{n+1}^\dagger c_n + i g_n c_n^\dagger c_n$$

<u>Coupling to an environment generates non-Hermitian terms in an effective Hamiltonian</u>

Topology and criticality in a non-Hermitian quasicrystal

Non-Hermitian topology and criticality from modulated losses



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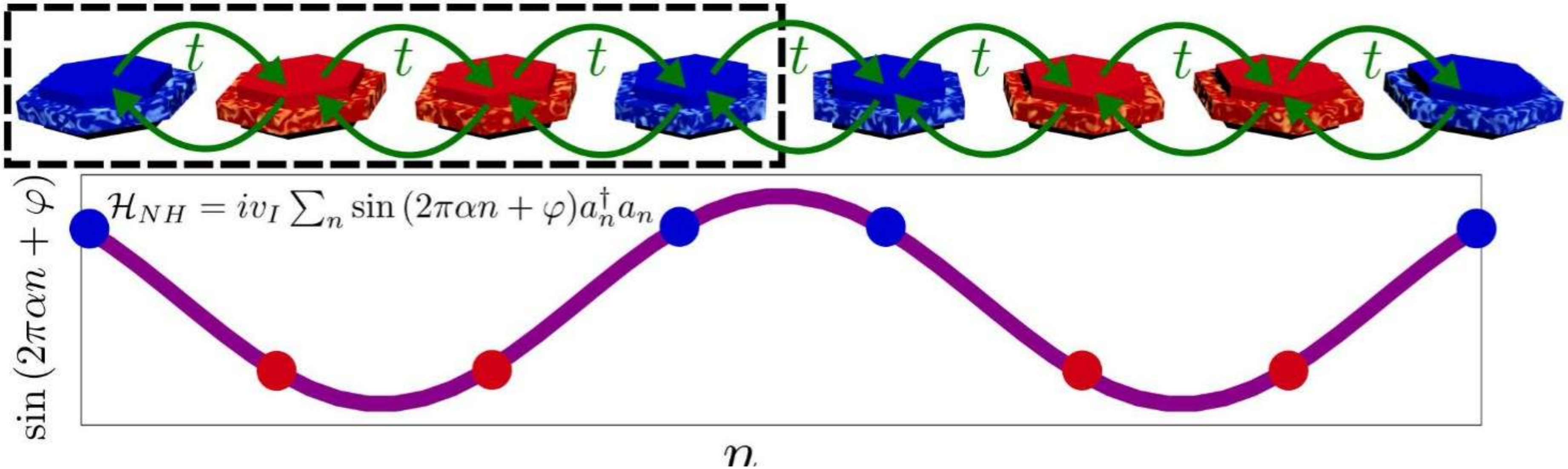
Resonator with modulated losses

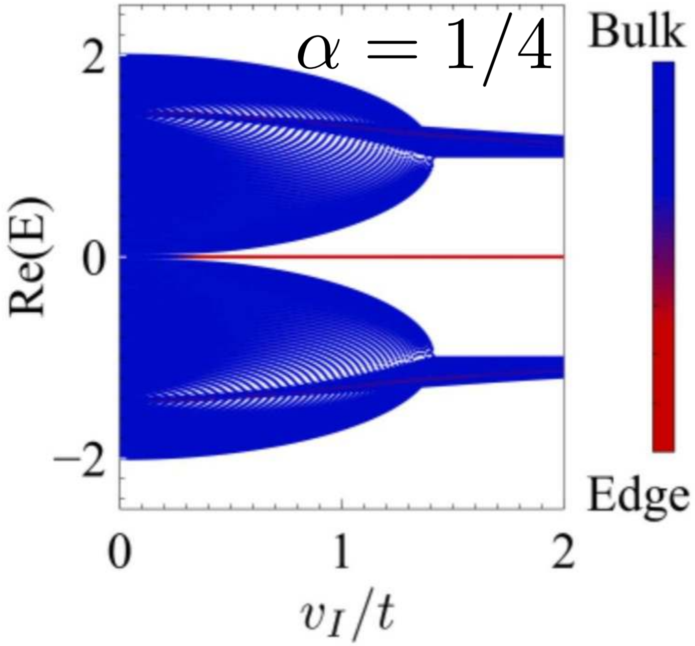


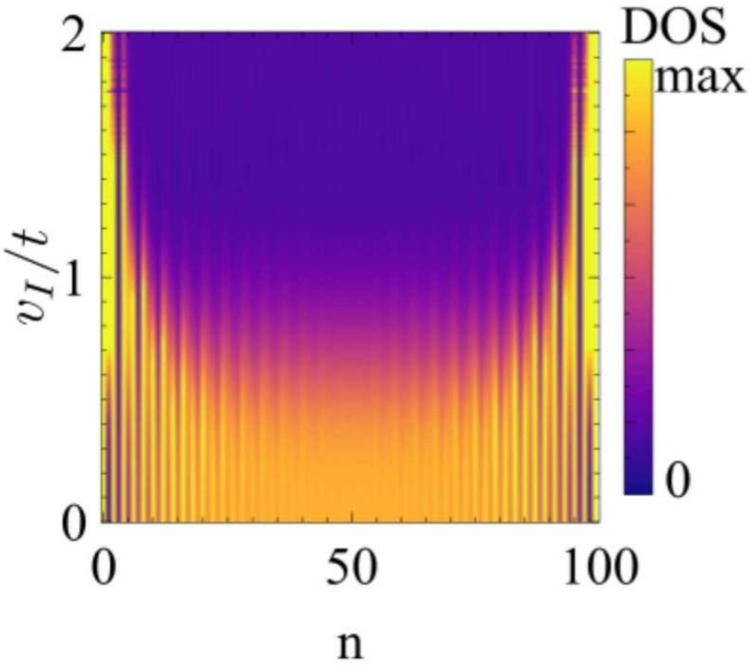
$$H = t\sum_{n=0}^{N-2}\left(a_n^\dagger a_{n+1} + h.c.\right) + i\sum_{n=0}^{N-1} v_I \sin(2\pi n\alpha + \varphi) a_n^\dagger a_n$$

There is a continuum family of models with modulated losses featuring topological modes

Topological edge modes from periodic modulated losses

$$H = t\sum_{n=0}^{N-2}\left(a_n^\dagger a_{n+1} + h.c.\right) + i\sum_{n=0}^{N-1} v_I \sin(2\pi n\alpha + \varphi)a_n^\dagger a_n$$

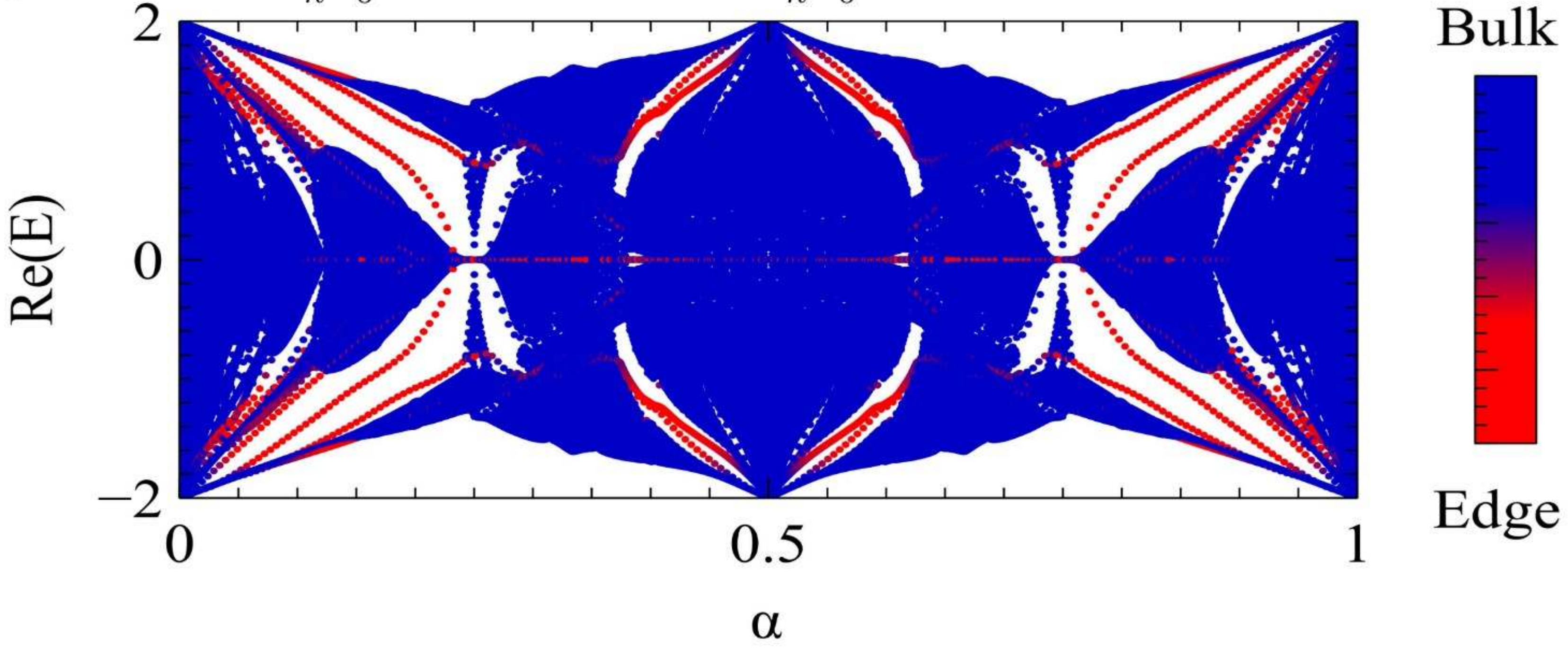




There is a continuum family of models with modulated losses featuring topological modes

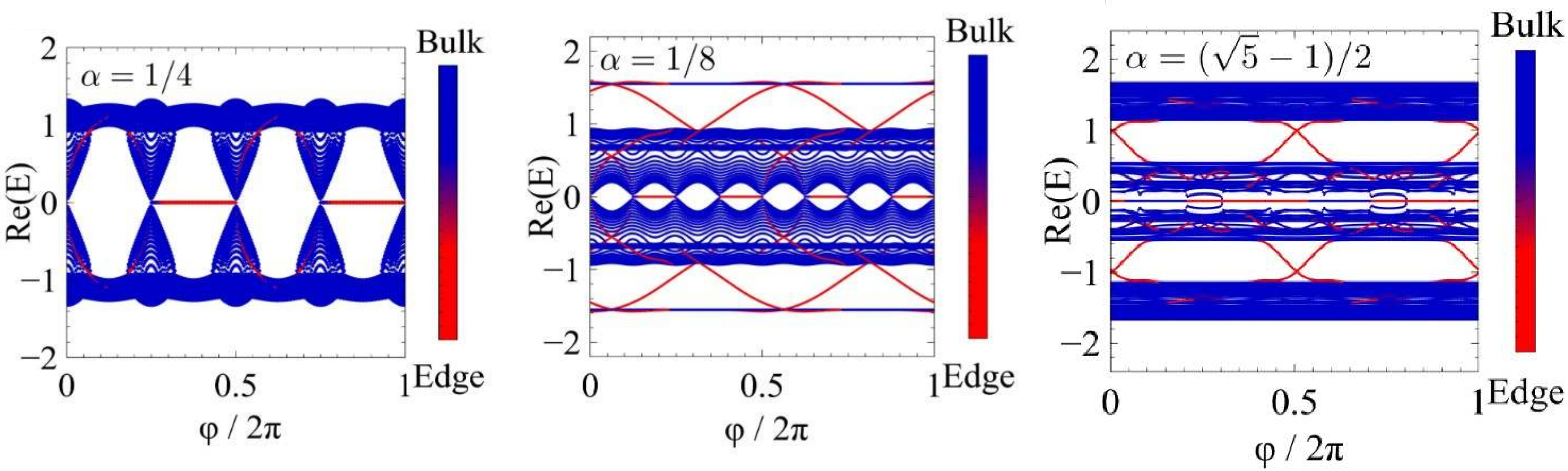
A quasiperiodic family of topological modes from modulated losses

$$H = t\sum_{n=0}^{N-2}\left(a_n^\dagger a_{n+1} + h.c.\right) + i\sum_{n=0}^{N-1} v_I \sin(2\pi n\alpha + \varphi)a_n^\dagger a_n$$



There is a continuum family of models with modulated losses featuring topological modes

A quasiperiodic family of topological modes from modulated losses



$$H = t\sum_{n=0}^{N-2}\left(a_n^\dagger a_{n+1} + h.c.\right) + i\sum_{n=0}^{N-1} v_I \sin(2\pi n\alpha + \varphi)a_n^\dagger a_n$$

There is a continuum family of models with modulated losses featuring topological modes

The impact of disorder in non-Hermitian topological modes

Two types of disorder

Resonance frequency   Loss

$$H_D = w_R \sum_n \chi_{n,R} a_n^\dagger a_n + i w_I \sum_n \chi_{n,I} a_n^\dagger a_n$$

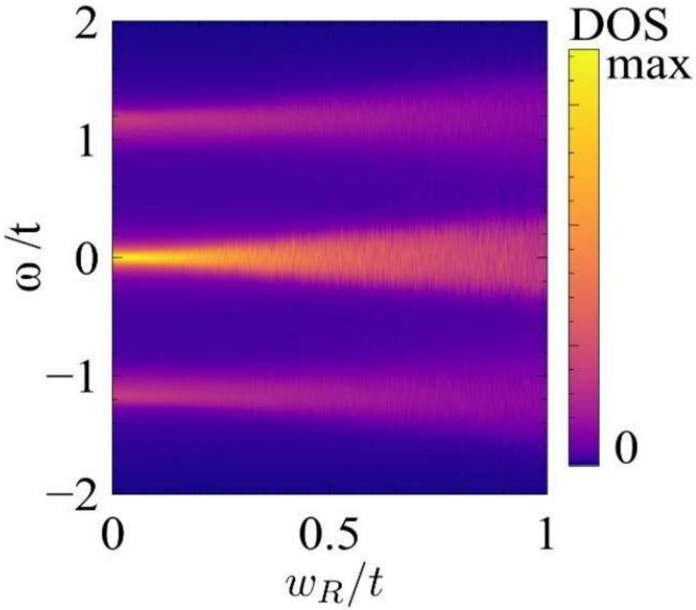
NH topological modes are

<u>Fragile to real freq. disorder</u>

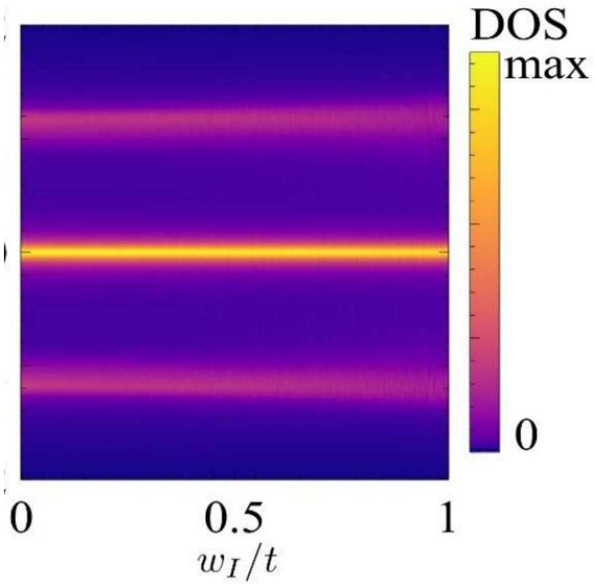
<u>Robust to loss disorder</u>

Phys. Rev. Research 6, 023004 (2024)

Res. freq. disorder



Loss disorder



Generalized Hermitian and non-Hermitian model

Phys. Rev. Research 6, 023004 (2024)

$$H = t\sum_{n=0}^{N-2}\left(a_n^\dagger a_{n+1} + h.c.\right)$$

Kinetic energy

$$+\sum_{n=0}^{N-1}(v_R + iv_I)\sin(2\pi n\alpha + \varphi)a_n^\dagger a_n$$

Resonant frequency and loss

Two limiting cases

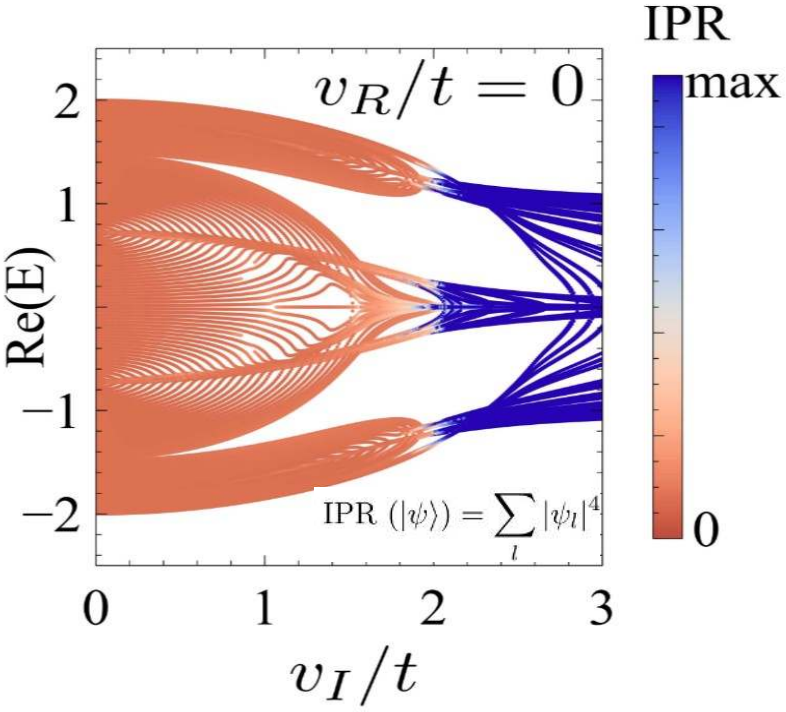
$v_I = 0$ Aubry-Andre-Harper model (Hermitian, equivalent to a quantum Hall state)

$v_R = 0$ Non-Hermitian AAH (in general not mapable to a quantum Hall state)

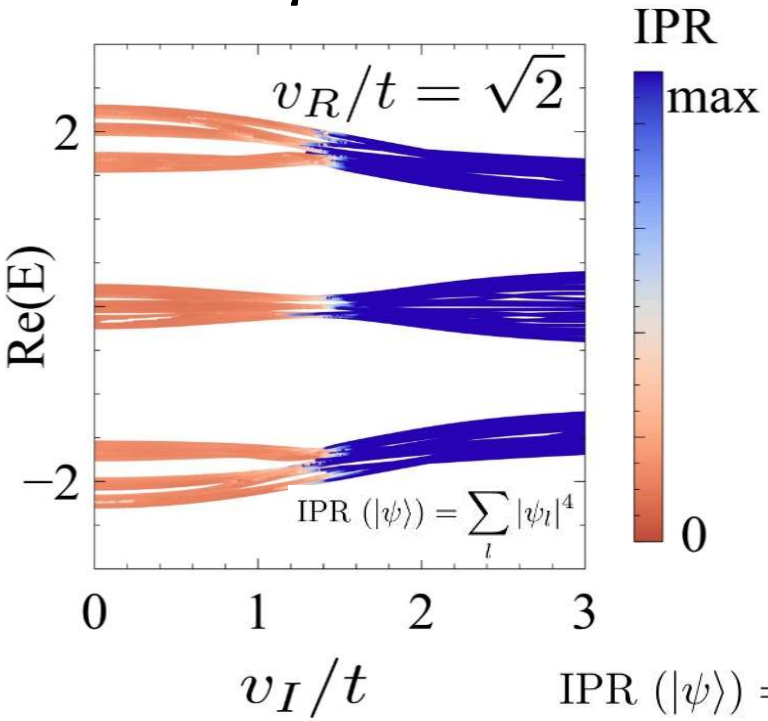
Do modulated losses yield phenomena analogous to the modulated frequencies?

Non-Hermitian localization-dellocalization transition

Imaginary AAH



Complex AAH

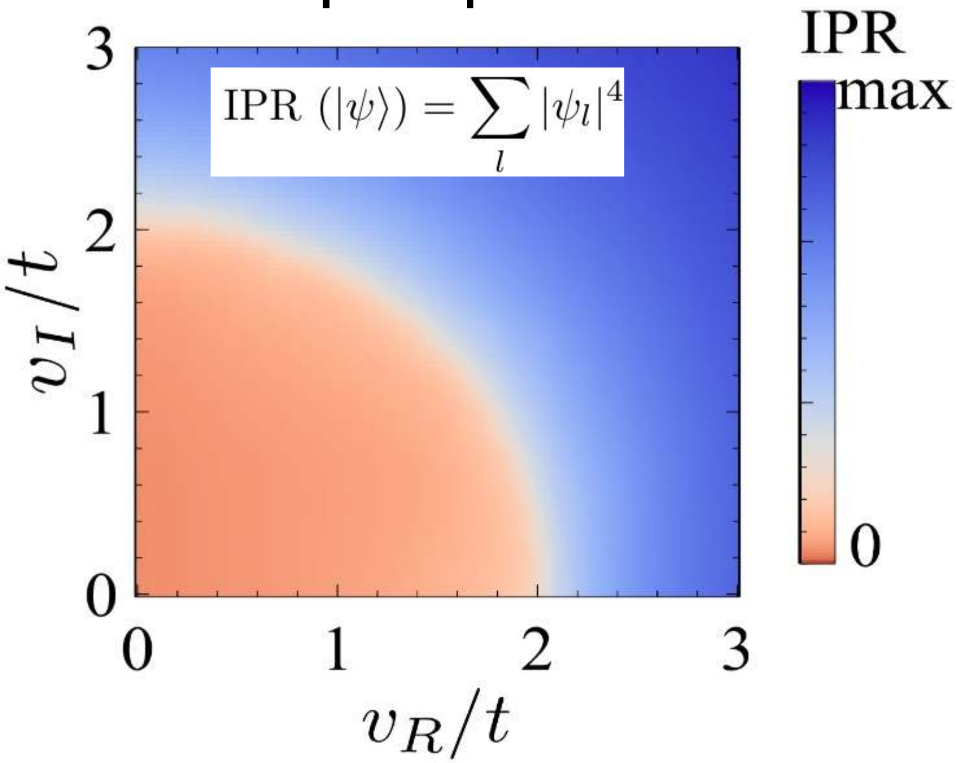


$$\mathrm{IPR}\,(|\psi\rangle) = \sum_l |\psi_l|^4$$

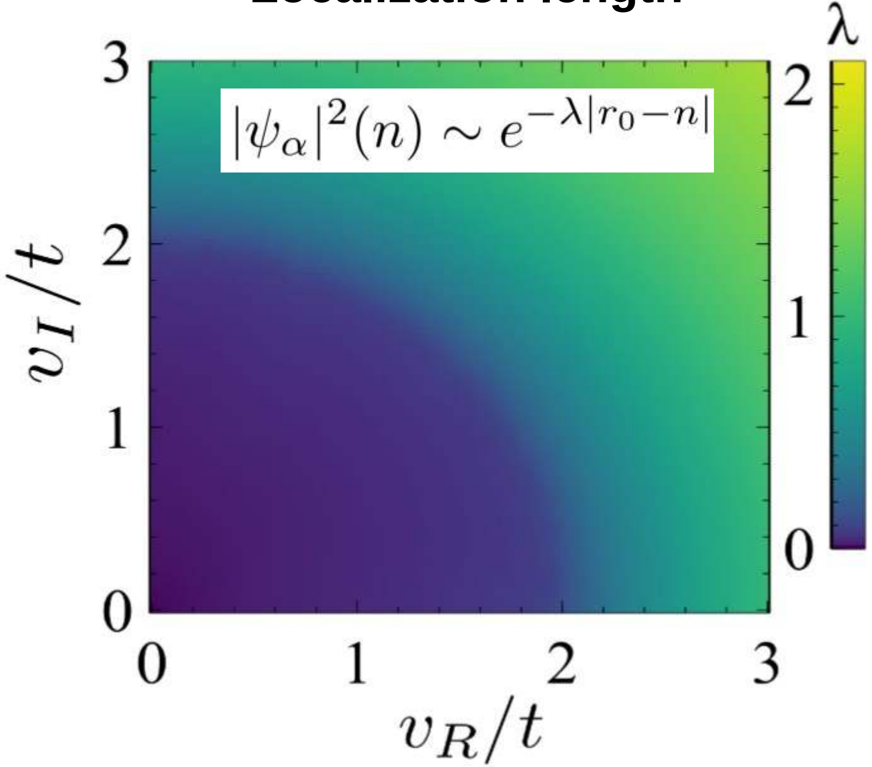
A localization of all states simultaneously appears in the generalized non-Hermitian model

Tunable localization-dellocalization

Inverse participation ratio



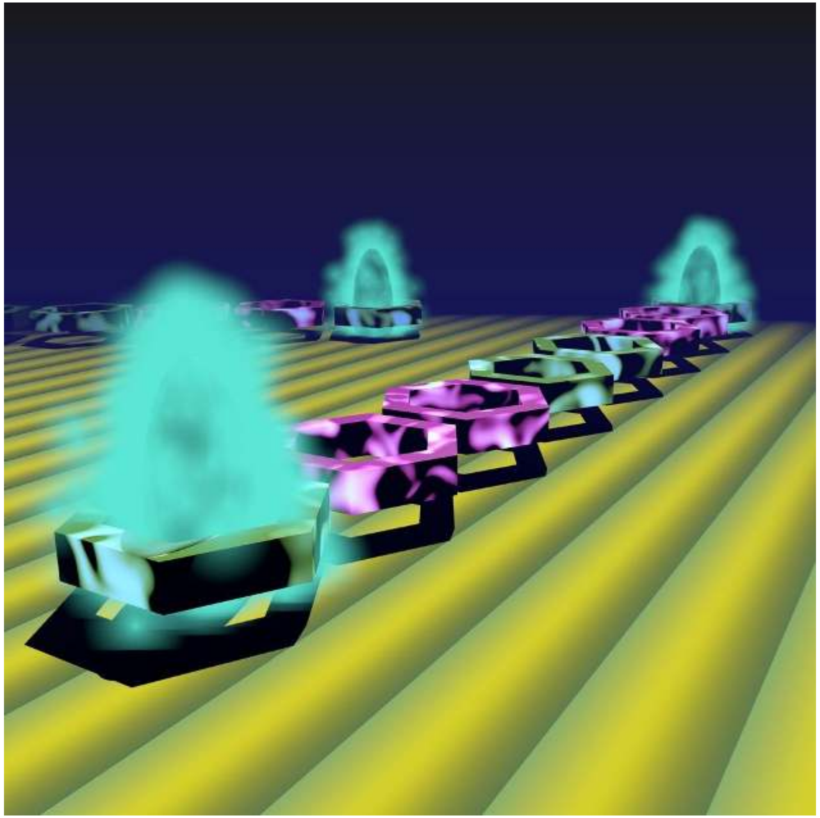
Localization length



A localization of all states simultaneously appears in the generalized non-Hermitian model

Experimental realization of topological modes in non-Hermitian photonic resonators

Experimental realization of non-Hermitian topology from modulated losses



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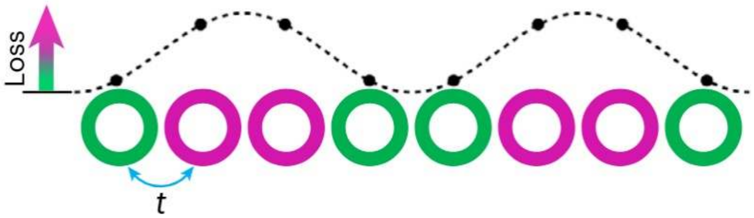
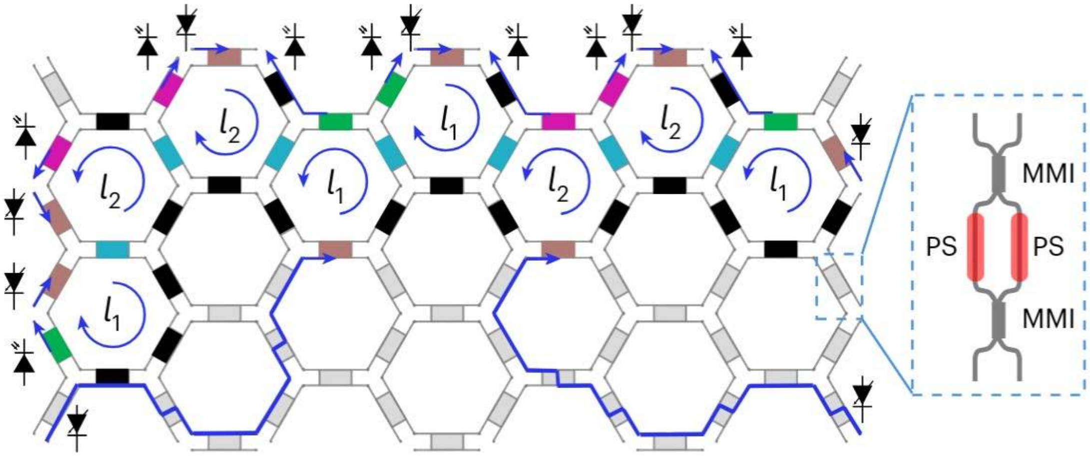
Nature Materials 24, 1393–1399 (2025)

Integrated silicon photonics as a platform for tunable non-Hermitian matter

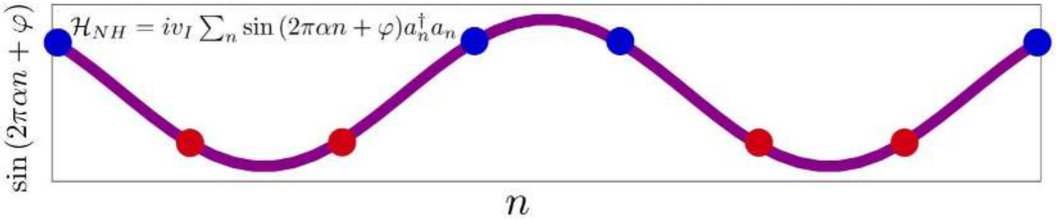
Nature Materials 24, 1393–1399 (2025)

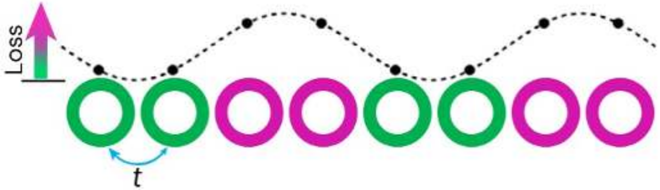


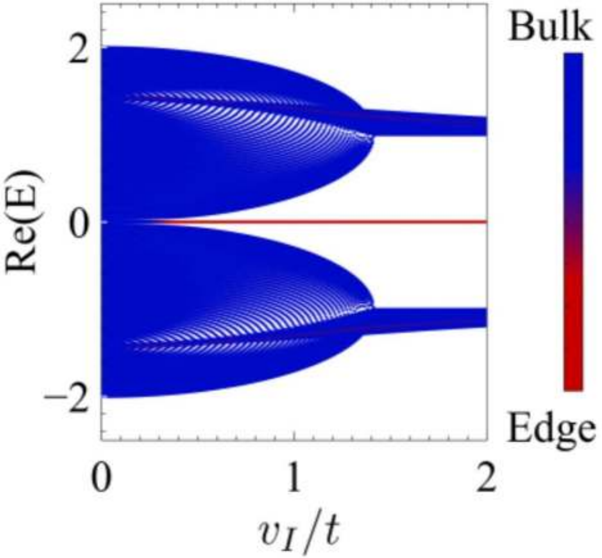


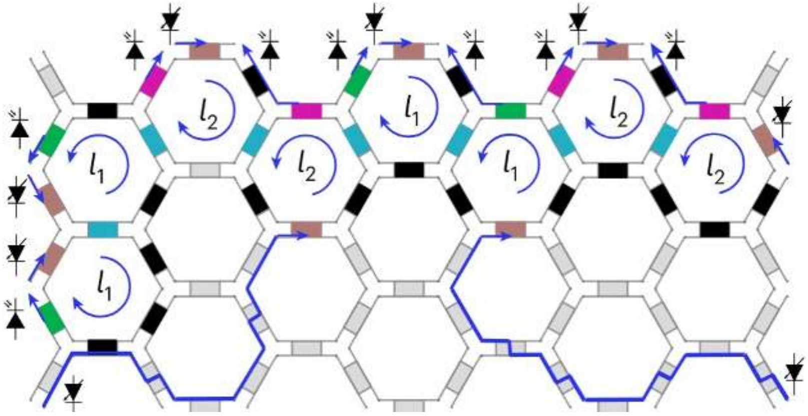
Programmable integrated photonic resonators enable creating controllable photonic lattice with tunable couplings and losses

Realizing a commensurate non-Hermitian topological model





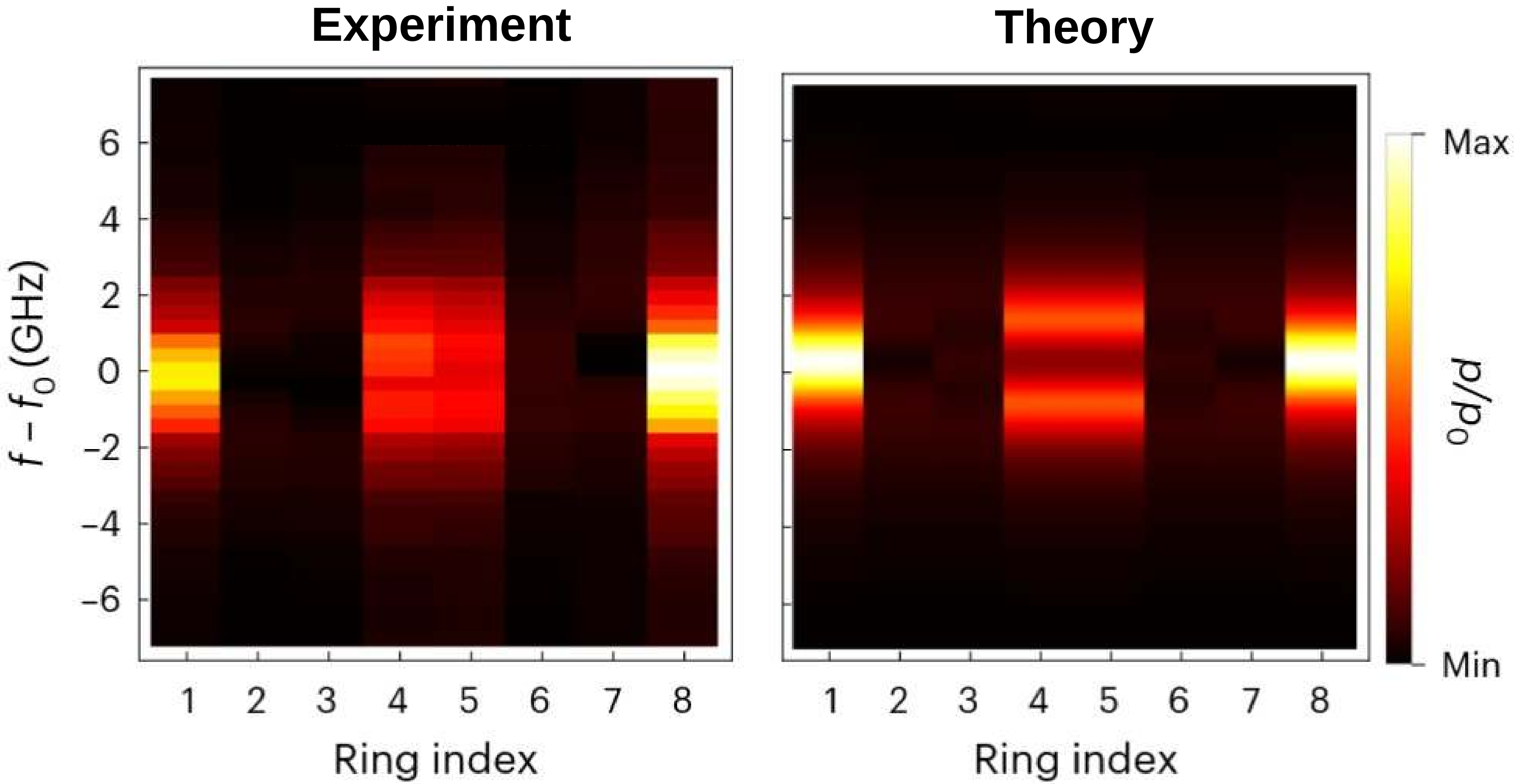




Nature Materials 24, 1393–1399 (2025)

By creating a chain with sites featuring modulated losses, we can create a topological model

Non-Hermitian topological modes from modulated losses



Integrated photonics allows to create topological modes stemming solely from modulated losses

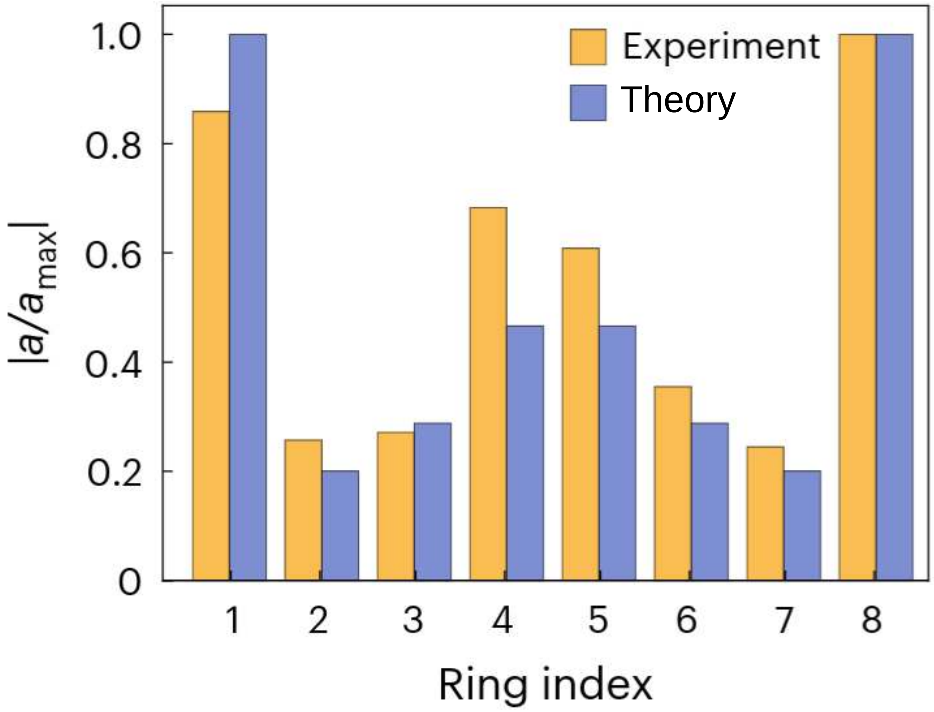
Nature Materials 24, 1393–1399 (2025)

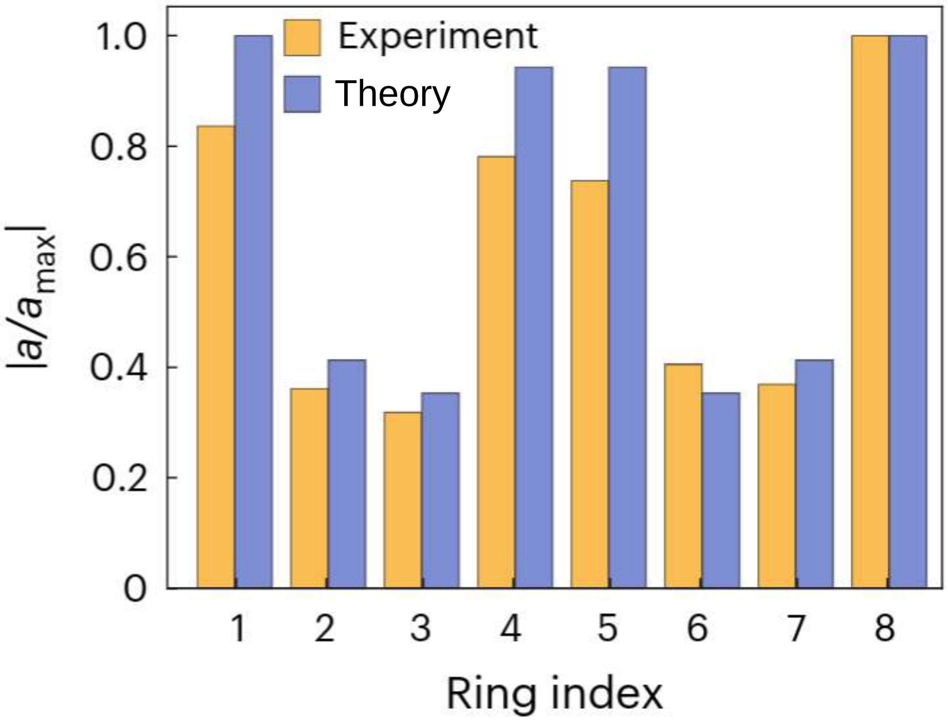
Theory-experiment comparison between modes

Mode #1

Nature Materials 24, 1393–1399 (2025)

Mode #2

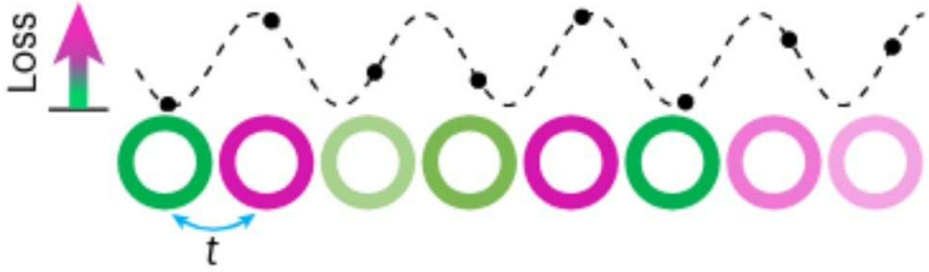




For short chains, the topological edge modes hybridize, leading to similar modes in theory and experiment

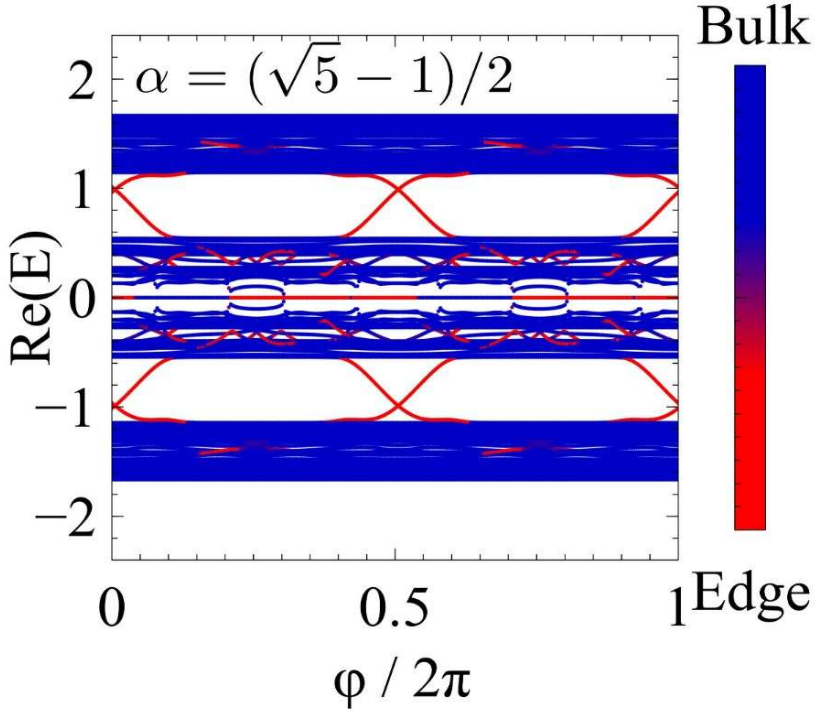
Engineering a quasiperiodic non-Hermitian photonics

Non-Hermitian quasicrystal



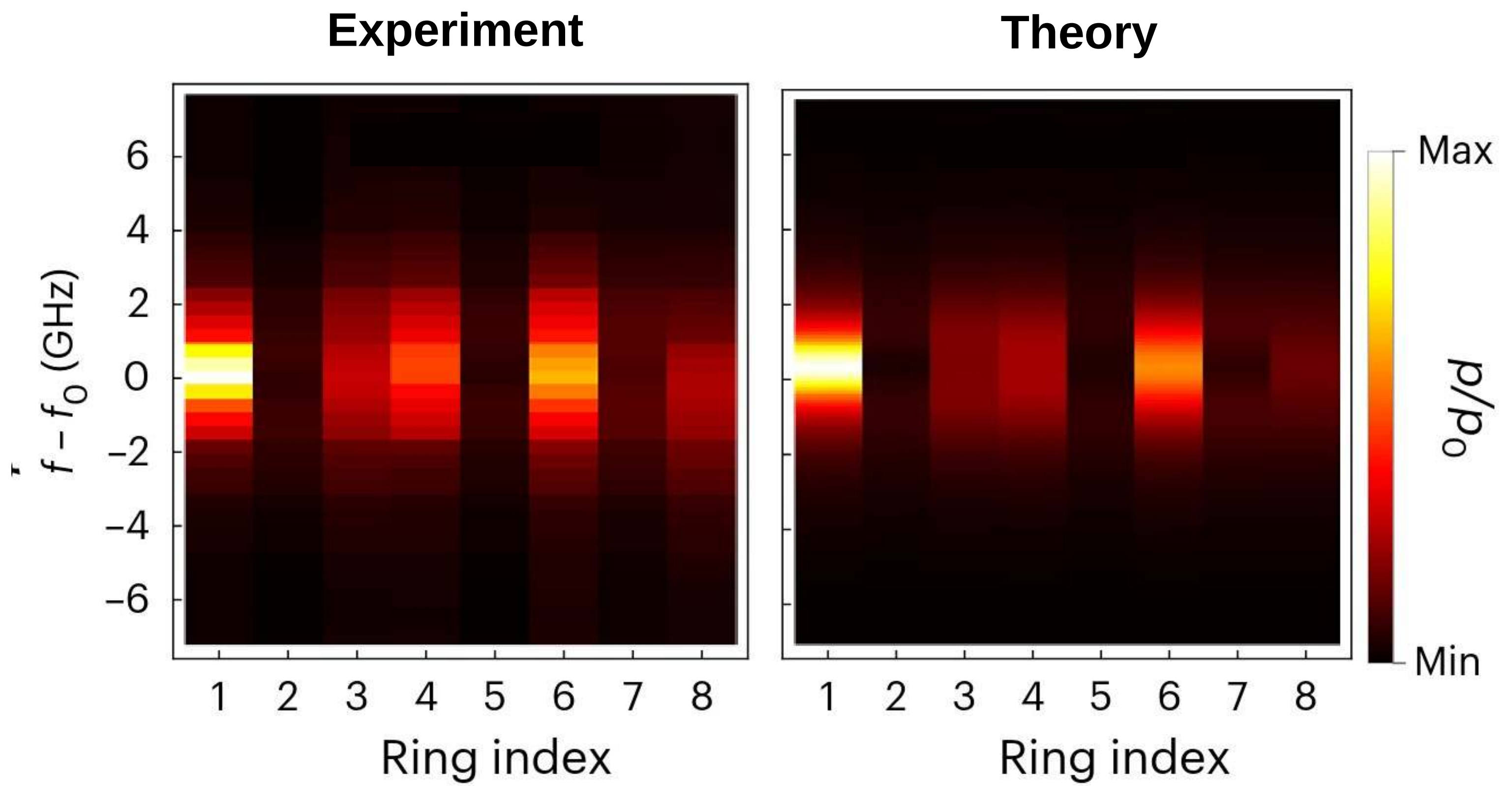
$$H = t\sum_{n=0}^{N-2}\left(a_n^\dagger a_{n+1} + h.c.\right) + i\sum_{n=0}^{N-1} v_I \sin(2\pi n\alpha + \varphi) a_n^\dagger a_n$$

Non-Hermitian spectra



Can we engineer non-Hermitian quasiperiodic systems with integrated photonics

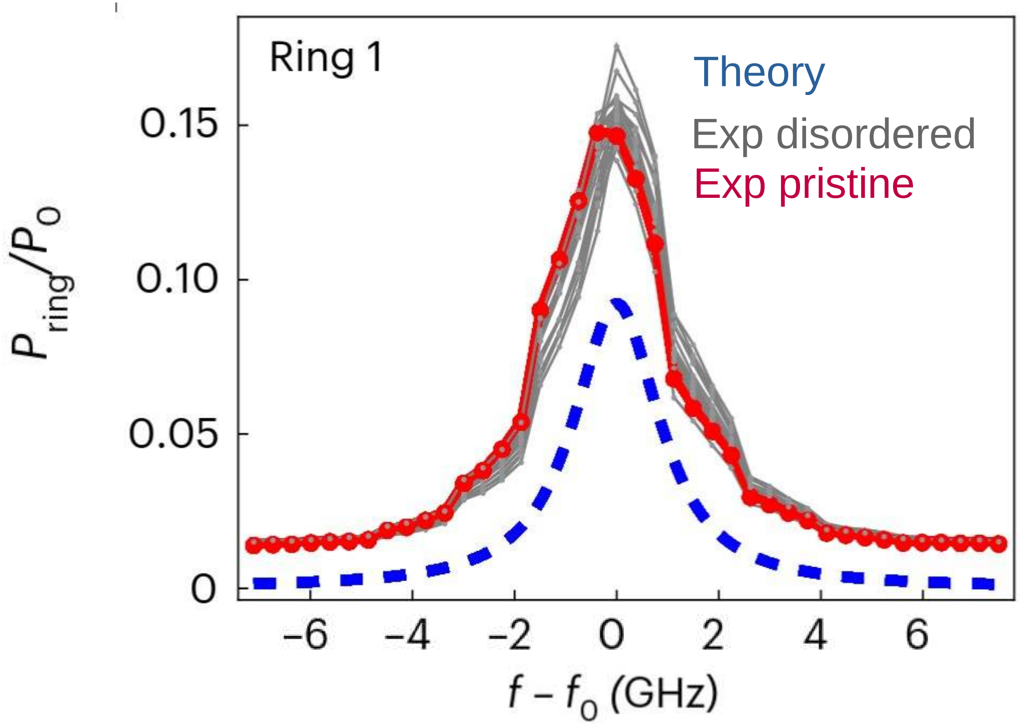
Engineering a quasiperiodic non-Hermitian photonics



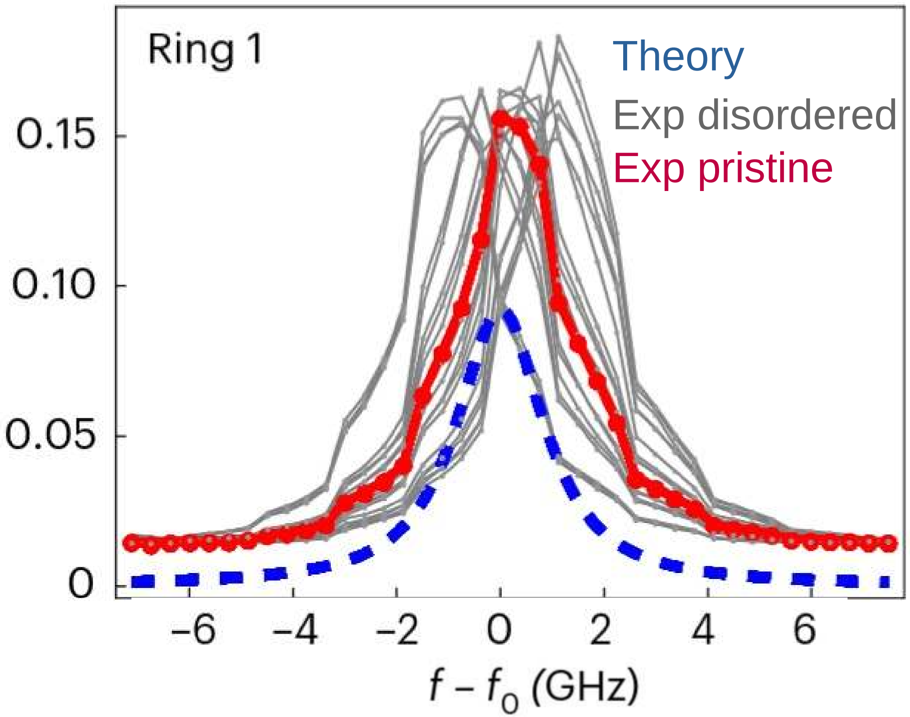
Finite-size quasiperiodic non-Hermitian models can be engineered with integrated photonics

Impact of disorder in topological non-Hermitian modes

Disorder in the loss



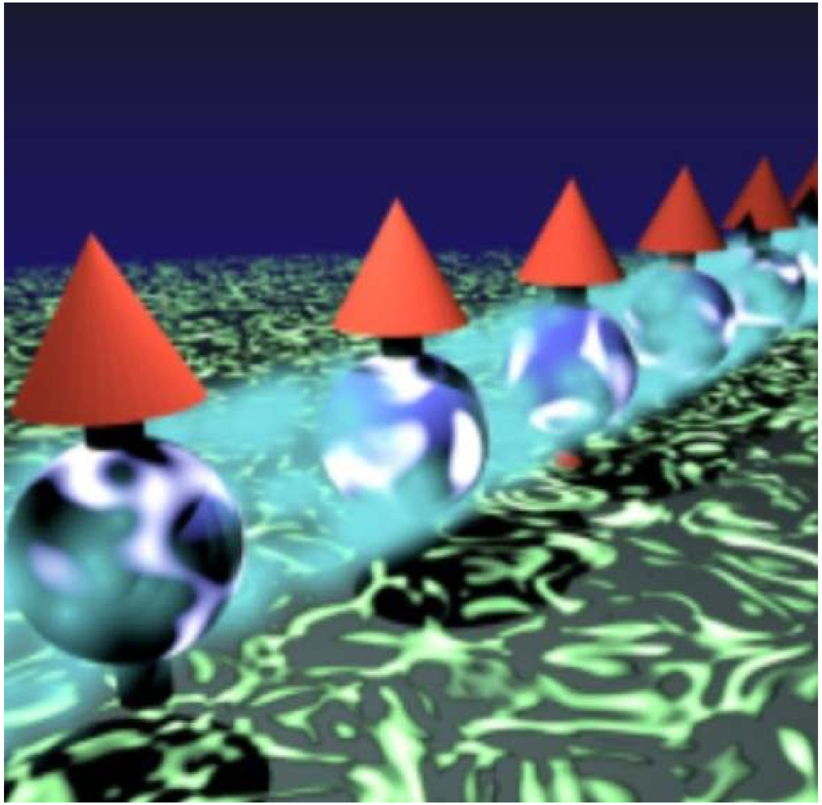
Disorder in the resonance frequency



Topological modes are robust to loss disorder, but not disorder in the resonance frequency

Dynamical correlators in topological interacting non-Hermitian systems

Topological excitations in non-Hermitian quantum many-body models

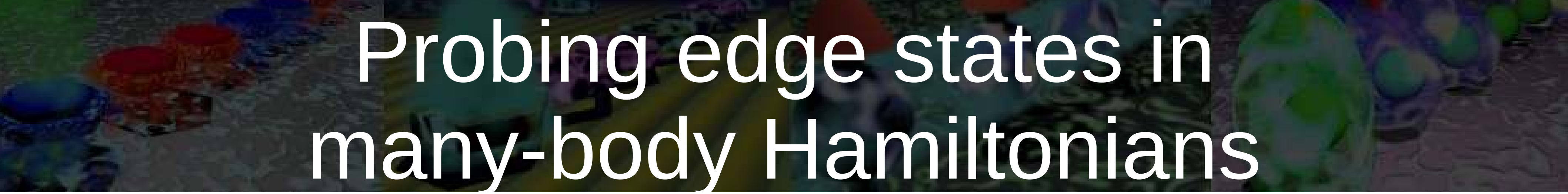


Guangze Chen

Fei Song

Phys. Rev. Lett. 130, 100401 (2023)

Probing edge states in many-body Hamiltonians



Dynamical correlator (for single particle electron excitations)

$$A(\omega, n) = \langle \Omega | c_n \delta(\omega - (\mathcal{H} - E_0)) c_n^\dagger | \Omega \rangle$$

for fermionic/bosonic models

Dynamical correlator (for spin excitations)

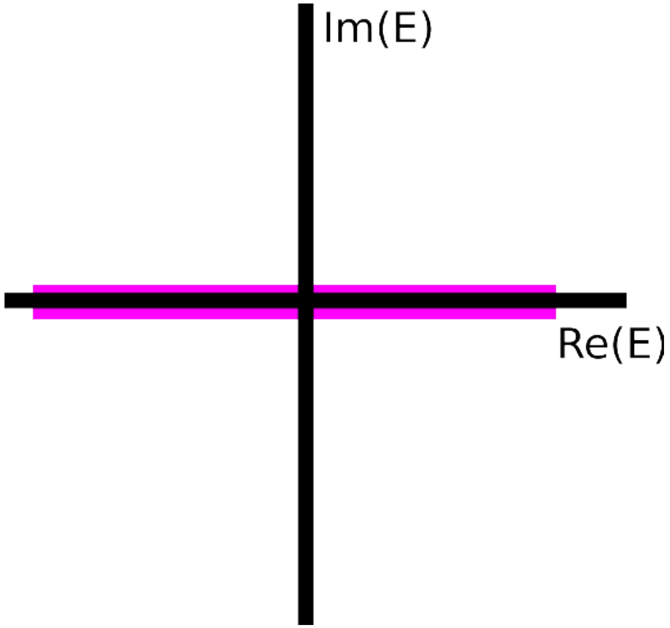
$$A(\omega, n) = \langle \Omega | S_n^+ \delta(\omega - (\mathcal{H} - E_0)) S_n^- | \Omega \rangle$$

for spin models

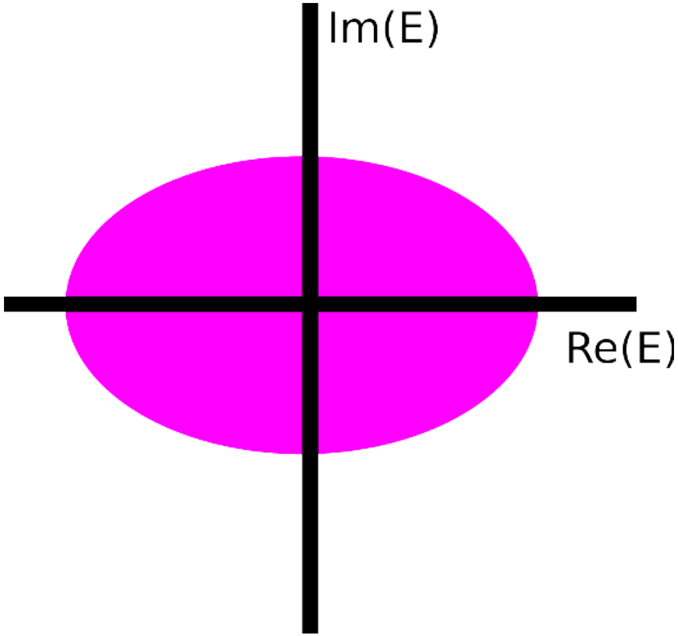
How can we probe topological modes in many-body interacting non-Hermitian systems?

A first challenge: dynamical correlators in non-Hermitian matter

In the Hermitian case



In the non-Hermitian case



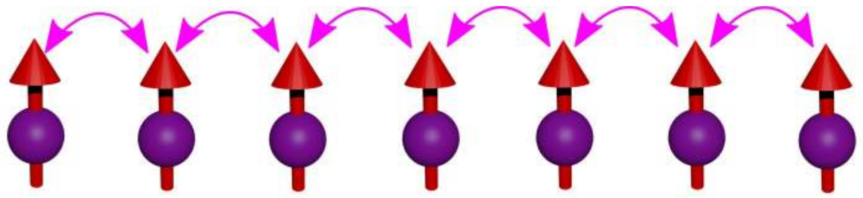
In the non-Hermitian case, dynamical correlators are defined in the complex energy plane

A second challenge:
The problem of many-body dimensionality

In a many-body problem, the size of our vectors grows as

2^L where L is the number of sites

$$\mathcal{H} = \sum_{\langle ij \rangle} J \vec{S}_i \cdot \vec{S}_j$$



A typical wavefunction is written as

$$|\Psi\rangle = \sum c_{s_1,s_2,\ldots,s_L} |s_1, s_2, \ldots s_L\rangle$$

We need to determine in total 2^L coefficients

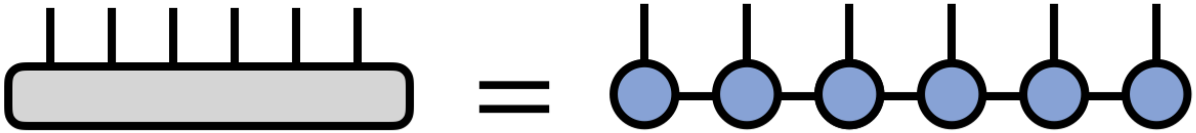
Is there an efficient way of storing so many coefficients?

State compression with tensor-networks

Annals of Physics 326, 96 (2011)

Given a many-body wavefunction, we can parametrice the components as

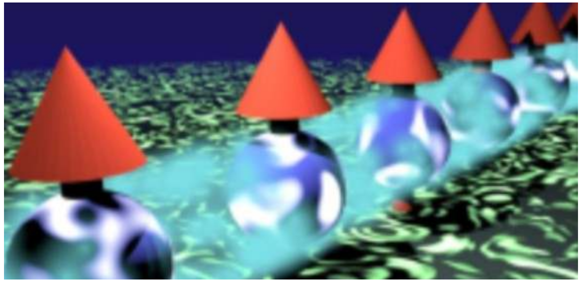
$$|\Psi\rangle = \sum_{\{s\}} \left[M_1^{(s_1)} M_2^{(s_2)} \cdots M_N^{(s_N)} \right] |s_1 s_2 \dots s_N\rangle$$



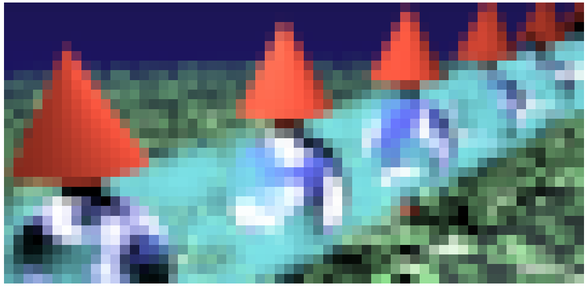
Matrix product state

The previous representation allows drastically reducing the memory required to store a state

Real wavefunction



Tensor network wavefunction

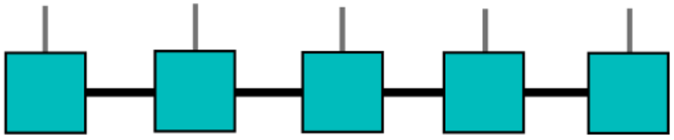


Exponentially large algebra with tensor networks

Tensor network allow to (approximately) operate in exponentially large vector spaces

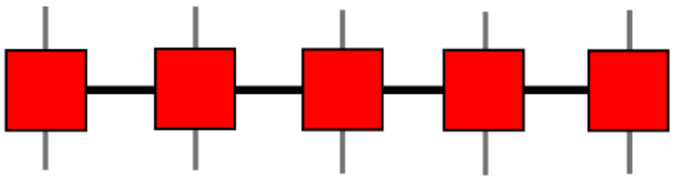
vector

$$|\Psi\rangle \equiv$$

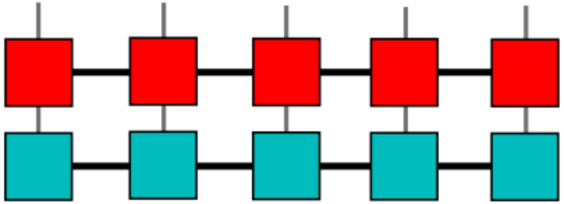


matrix

$$\hat{A} \equiv$$



$$|\Psi_2\rangle = \hat{A}|\Psi_1\rangle \equiv$$



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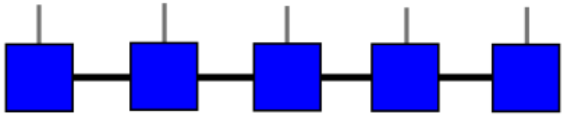
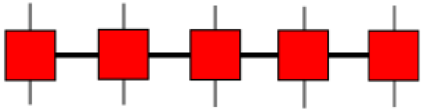


$$\hat{A}_3 = \hat{A}_1 + \hat{A}_2 \equiv$$



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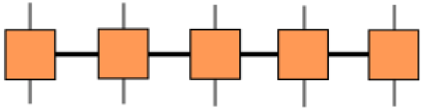

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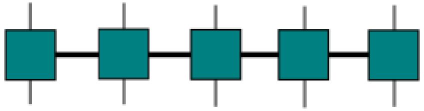
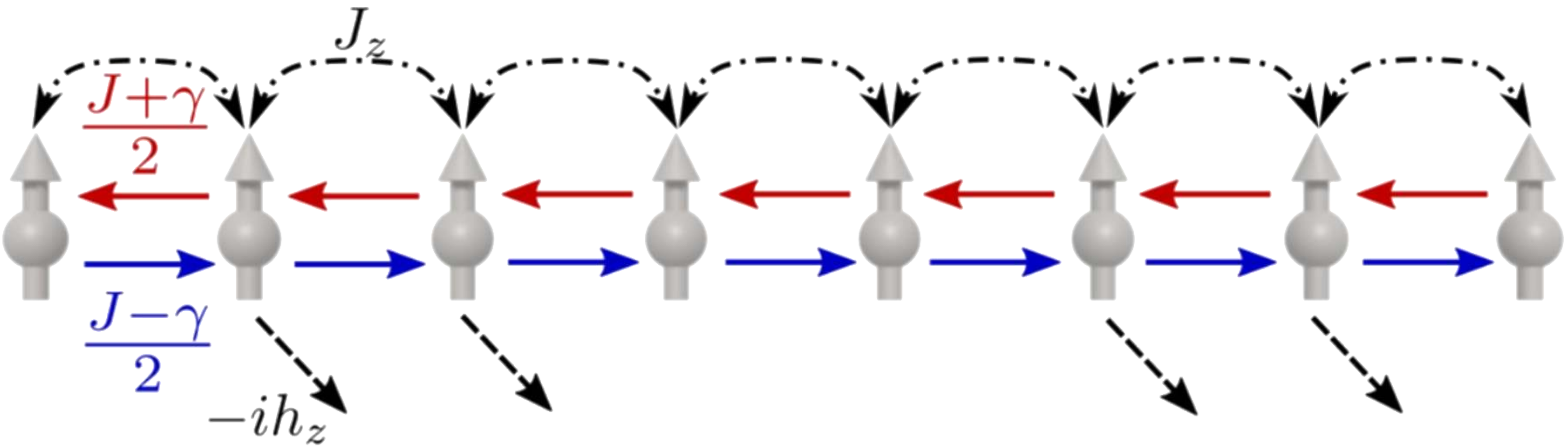


A non-Hermitian quantum many-body model



$$\tilde{H} = \sum_{l=1}^{L-1}\left(\frac{J+\gamma}{2}c_l^\dagger c_{l+1} + \frac{J-\gamma}{2}c_{l+1}^\dagger c_l + J_z\left(c_l^\dagger c_l - \frac{1}{2}\right)\left(c_{l+1}^\dagger c_{l+1} - \frac{1}{2}\right)\right) + \sum_{l=1}^{L} ih_l^z\left(c_l^\dagger c_l - \frac{1}{2}\right)$$

Drives skin effect　　　　Many-body interaction　　　　Local loss

Dynamical correlator of a topological non-Hermitian model

We take the following non-Hermitian model

$$\tilde{H} = \sum_{l=1}^{L-1} \left(\frac{J+\gamma}{2} c_l^\dagger c_{l+1} + \frac{J-\gamma}{2} c_{l+1}^\dagger c_l + J_z \left(c_l^\dagger c_l - \frac{1}{2} \right) \left(c_{l+1}^\dagger c_{l+1} - \frac{1}{2} \right) \right) + \sum_{l=1}^{L} i h_l^z \left(c_l^\dagger c_l - \frac{1}{2} \right)$$

Drives skin effect

Many-body interaction

Local loss

Full dynamical correlator

$$\mathrm{S}(\omega, l) = \left\langle \mathrm{GS_L} \left| c_l \delta^2 \left(\omega + E_{\mathrm{GS}} - H \right) c_l^\dagger \right| \mathrm{GS_R} \right\rangle + \left\langle \mathrm{GS_L} \left| c_l^\dagger \delta^2 \left(\omega + E_{\mathrm{GS}} - H \right) c_l \right| \mathrm{GS_R} \right\rangle$$

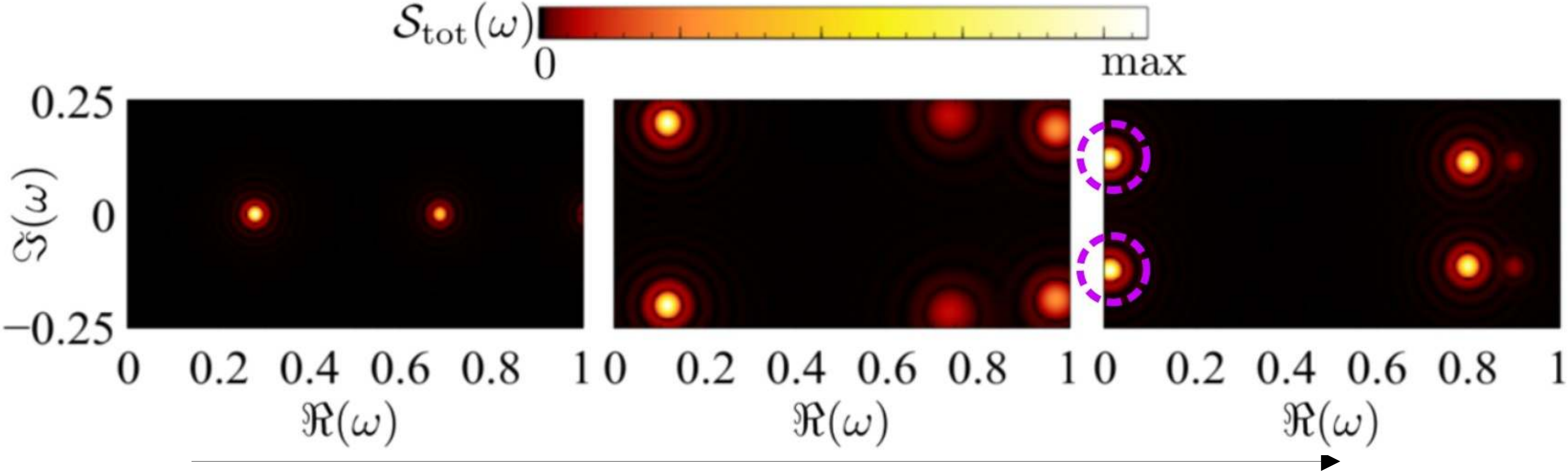
Integrated in the imaginary axis

(equivalent to the Hermitian one)

$$\tilde{\rho}(E \in \mathbb{R}, l) = \left| \int \mathcal{S}(E + iy, l) dy \right|$$

Topological degeneracies in a dynamical correlator

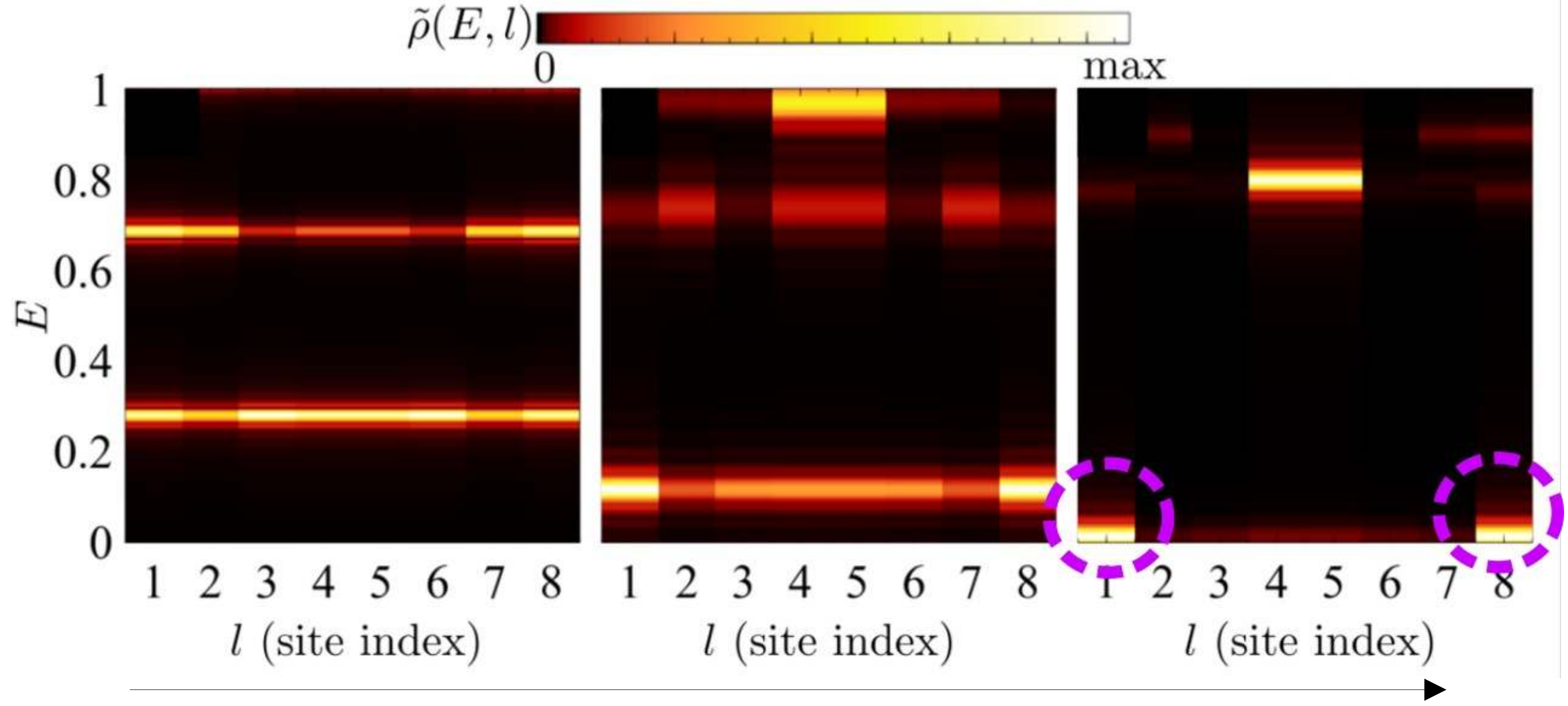
Total structure factor $\tilde{S}_{\text{tot}}(\omega) = \left| \sum_{l=1}^{L} \mathcal{S}(\omega, l) \right|$



Increasing topological gap

As the topological gap gets bigger, degeneracies at zero real frequency emerge

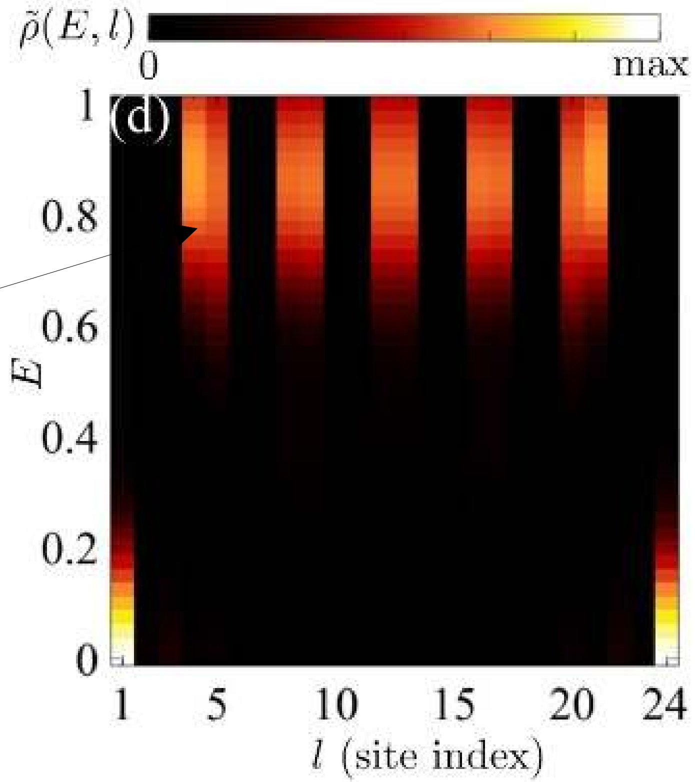
Topological modes in the local dynamical correlator



Increasing topological gap

As the topological gap gets bigger, edge modes at zero real frequency emerge

Non-Hermitian topological modes



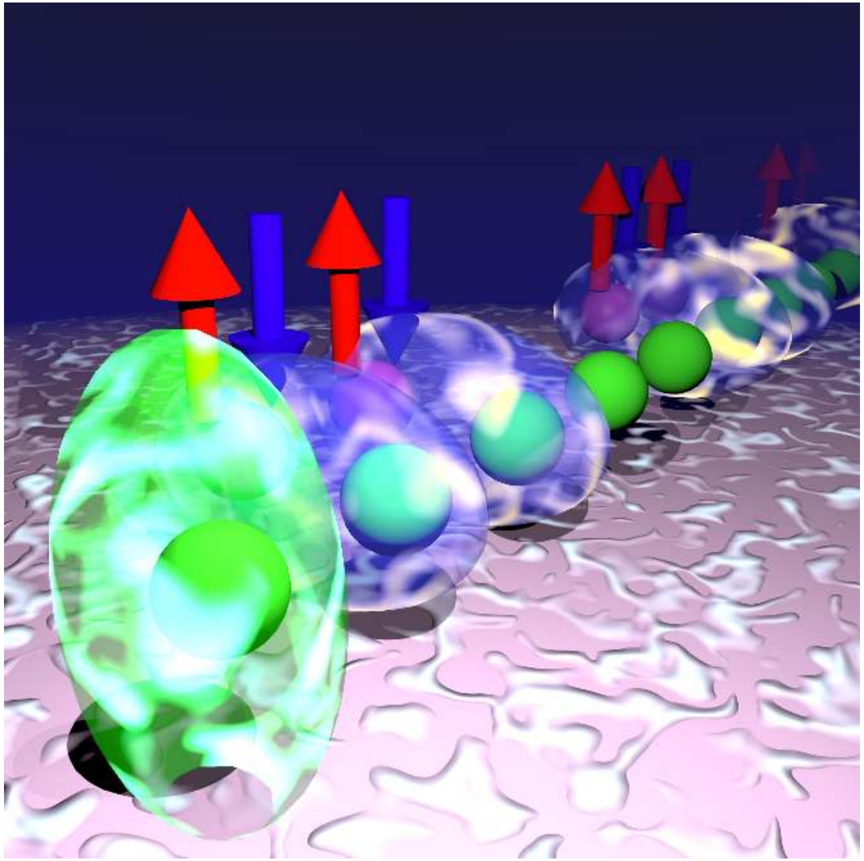
Bulk modes

Edge modes

The non-Hermitian dynamical correlator allows visualizing the topological modes

Non-Hermitian topological modes in a topological Kondo insulator

Non-Hermitian topology in a many-body Hermitian Kondo lattice



Zina Lippo

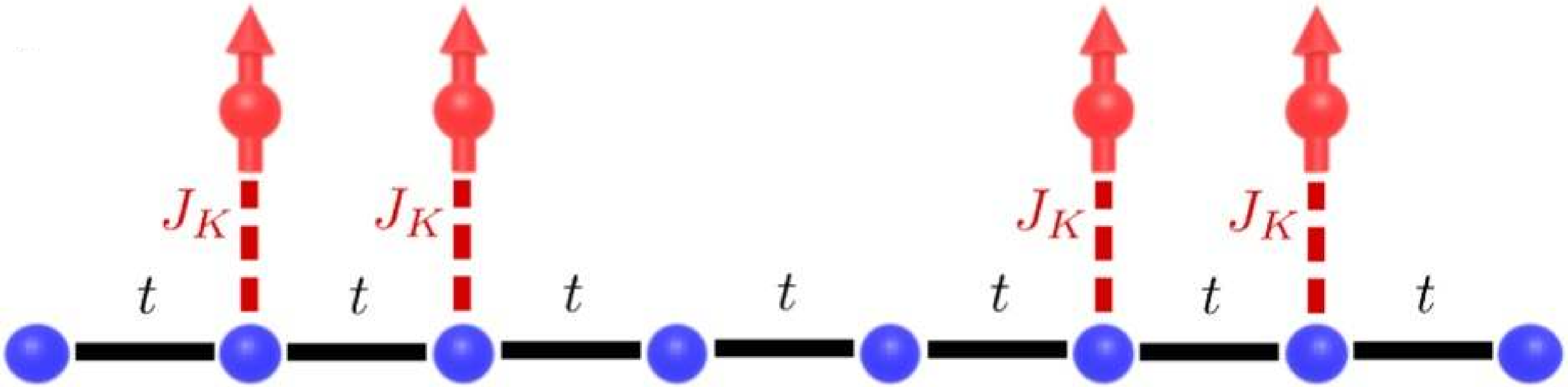
Elizabeth Pereira

Guangze Chen

Phys. Rev. Lett. 134, 116605 (2025)

A minimal topological Kondo insulator

Phys. Rev. Lett. 134, 116605 (2025)



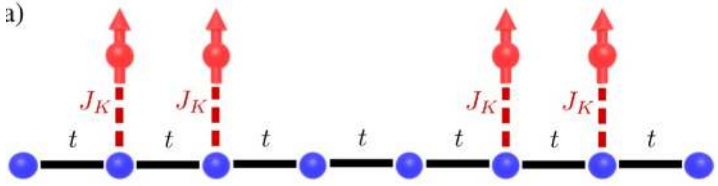
$$\mathcal{H} = t \sum_{s,n=1}^{N-1} \left(c^\dagger_{n+1,s} c_{n,s} + \mathrm{H.c.} \right) + J_K \sum_{\substack{s,s',\alpha \\ n \in n_K}} c^\dagger_{n,s} \sigma^\alpha_{ss'} c_{n,s'} S^\alpha_n$$

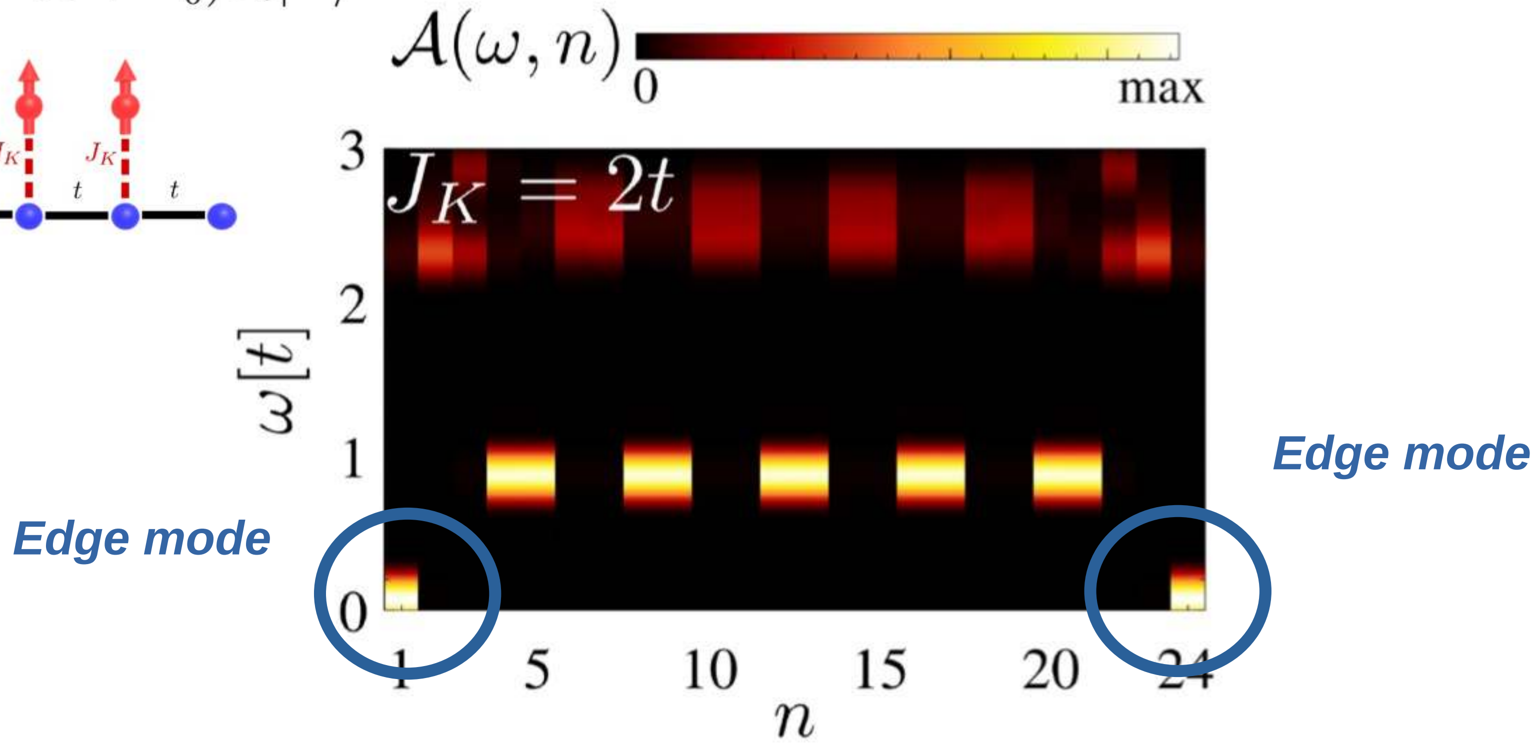
An engineered Kondo lattice model gives rise to a topological many-body state

Topological modes in a Kondo lattice

$$\mathcal{A}(\omega, n) = \langle \Omega | c_n \delta(\omega - \mathcal{H} + E_0) c_n^\dagger | \Omega \rangle$$

Phys. Rev. Lett. 134, 116605 (2025)



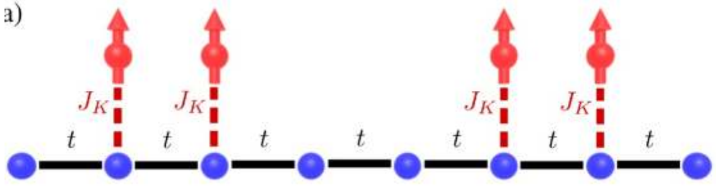


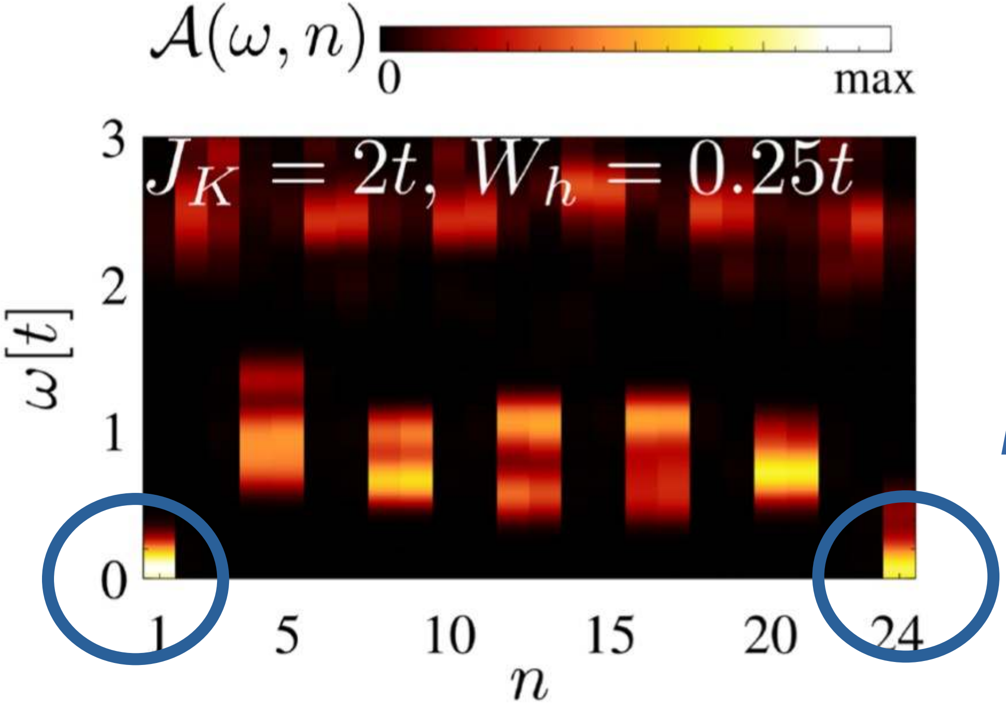
An engineered Kondo lattice model gives rise to a topological many-body state

Robustness of topological modes in a Kondo lattice

$$\mathcal{A}(\omega, n) = \langle \Omega | c_n \delta(\omega - \mathcal{H} + E_0) c_n^\dagger | \Omega \rangle$$

Phys. Rev. Lett. 134, 116605 (2025)





Edge mode

Edge mode

The topological modes are robust to the presence of disorder in the Kondo couplings

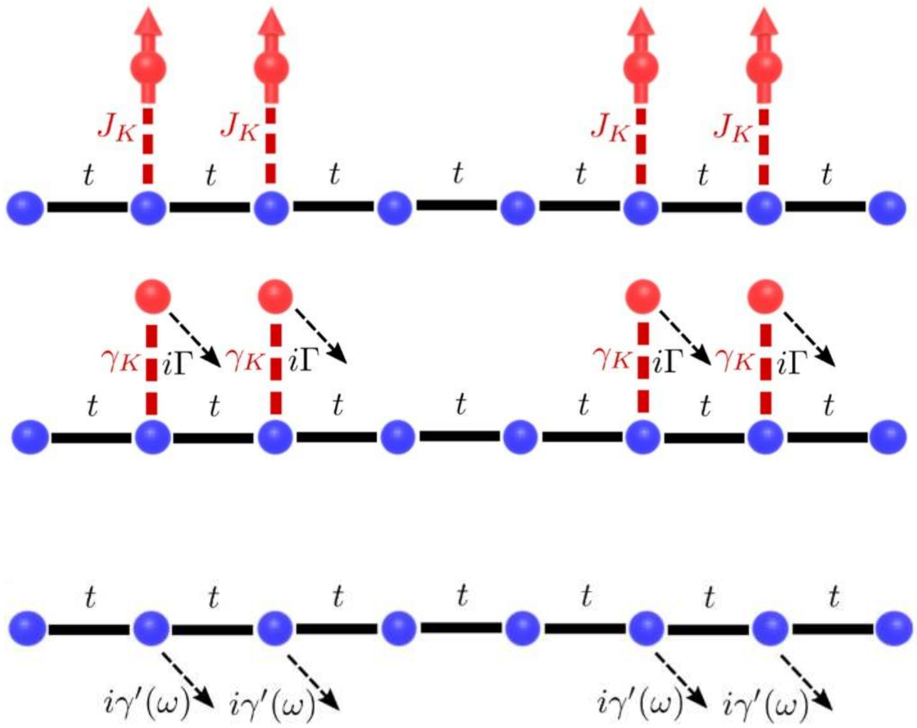
From Hermitian many-body to non-Hermitian single body

Phys. Rev. Lett. 134, 116605 (2025)

Locally modulated Kondo lattice

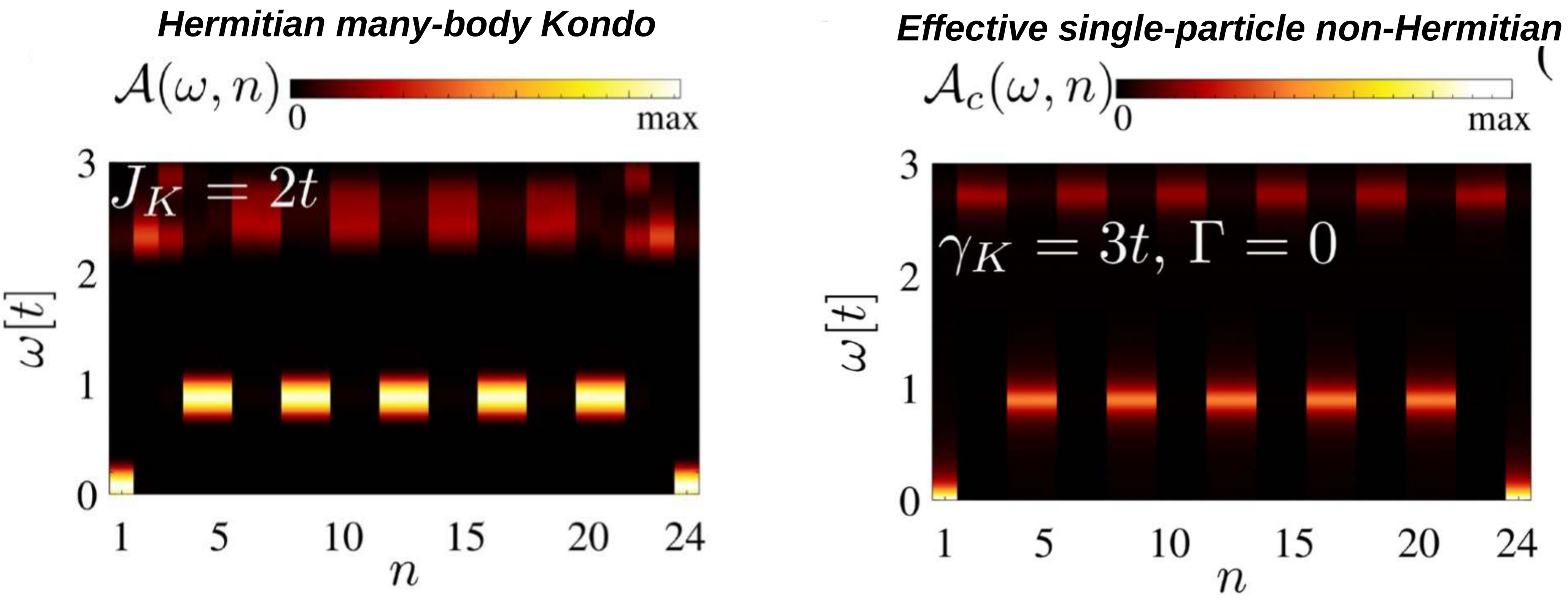
Locally modulated self-energy

Locally modulated losses



A Hermitian many-body model can be mapped to a topological non-Hermitian single particle topological model

Comparison between full many-body and effective non-Hermitian model



Spectral properties of the many-body model are captured with the effective non-Hermitian model

The topological invariants of a many-body Kondo lattice

Phys. Rev. Lett. 134, 116605 (2025)

Twisted periodic Kondo Hamiltonian

$$\mathcal{H}^{\text{pump}}(\phi) = t \sum_{s,n=1}^{N-1} \left(c_{n+1,s}^{\dagger} c_{n,s} + \text{H.c.} \right) + \sum_{s} \left(e^{i\phi} c_{N,s}^{\dagger} c_{1,s} + \text{H.c.} \right) + J_K \sum_{\substack{s,s',\alpha \\ n \in n_K}} c_{n,s}^{\dagger} \sigma_{ss'}^{\alpha} c_{n,s'} S_n^{\alpha}.$$

Correlation matrix

$$\bar{\Xi}_{ij}(\phi) = \frac{1}{2} \sum_{s} \langle \Omega_{\phi} | c_{is}^{\dagger} c_{js} | \Omega_{\phi} \rangle$$

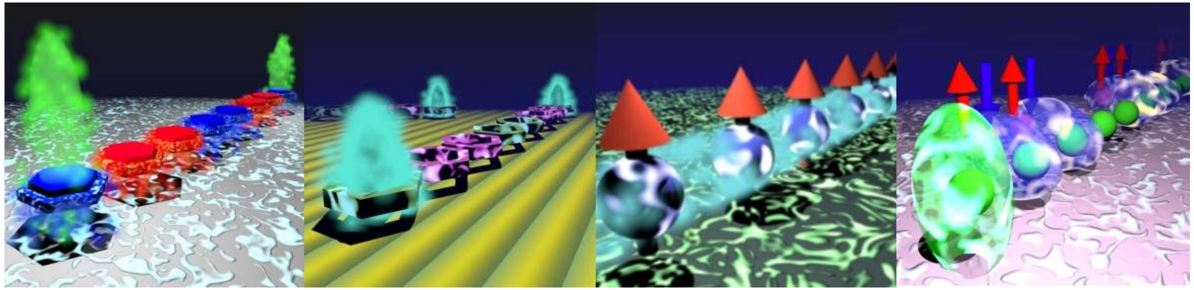
Kondo lattice topological invariant from corr mat. eigenvectors

$$\Phi = i \int_{\phi=0}^{2\pi} \sum_{\bar{\chi}_{\phi} > \Delta} \langle \bar{v}_{\phi} | \partial_{\phi} | \bar{v}_{\phi} \rangle d\phi$$

The topological invariant of the many-body Kondo lattice can be obtained
from the correlation matrix, yielding the same classification as the non-Hermitian invariant

Take home

Non-Hermitian topological modes can be engineered with controlled modulated coupling to an environment, both in the single particle and many-body limits



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