Quantum Exceptional Points: challenges and opportunities

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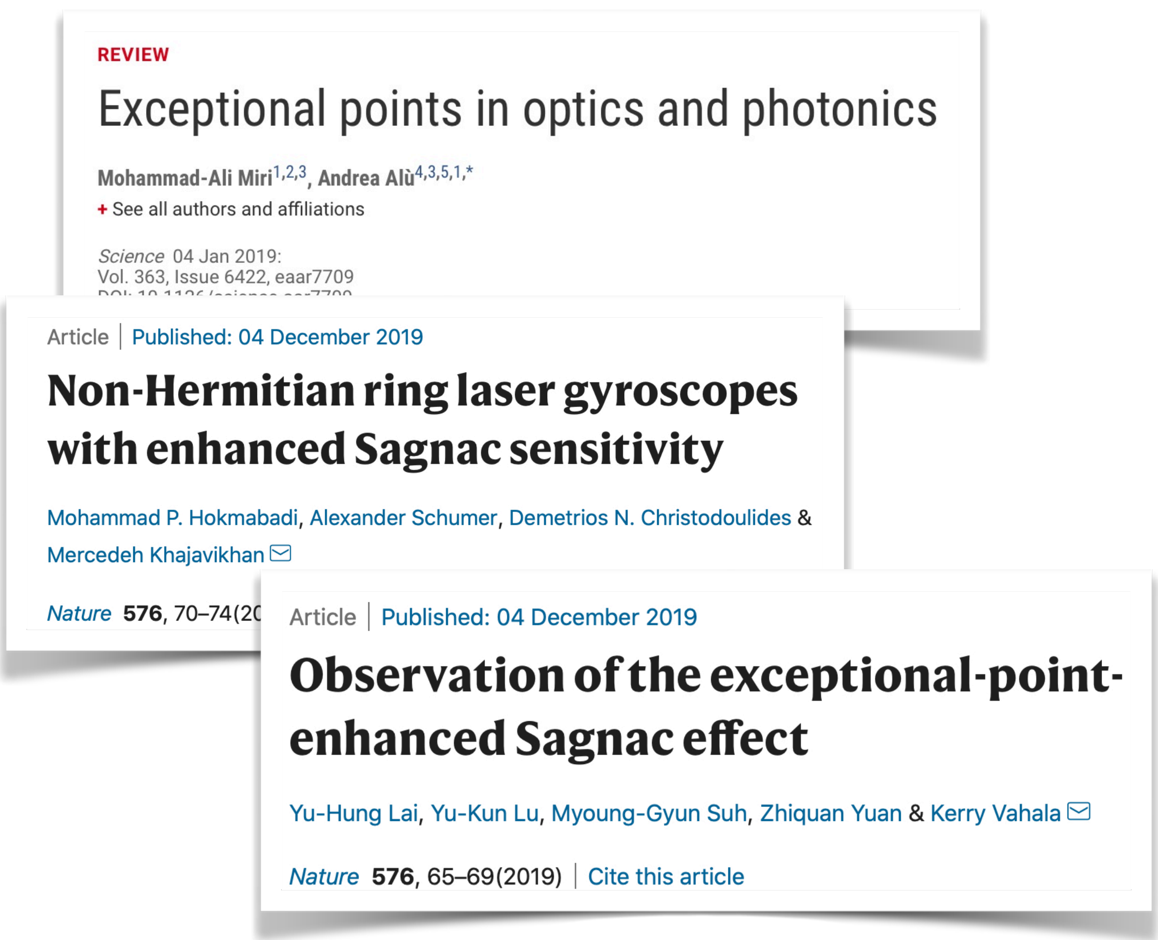
Indiana University - Purdue University Indianapolis (IUPUI)

Theory group: 3-4 doctoral, 1-2 undergrad, 1-3 high-school students
Work with experimentalists across different platforms.

What is (is not) non-Hermiticity?

- Coherent, non-unitary evolution: not Lindblad!
- Exceptional Points: degeneracies of non-Hermitian matrices.
- Classical EPs and their noise effects are understood.



REVIEW

Exceptional points in optics and photonics

Mohammad-Ali Miri[1,2,3], Andrea Alù[4,3,5,1,*]

+ See all authors and affiliations

Science 04 Jan 2019:
Vol. 363, Issue 6422, eaar7709

Article | Published: 04 December 2019

Non-Hermitian ring laser gyroscopes with enhanced Sagnac sensitivity

Mohammad P. Hokmabadi, Alexander Schumer, Demetrios N. Christodoulides & Mercedeh Khajavikhan

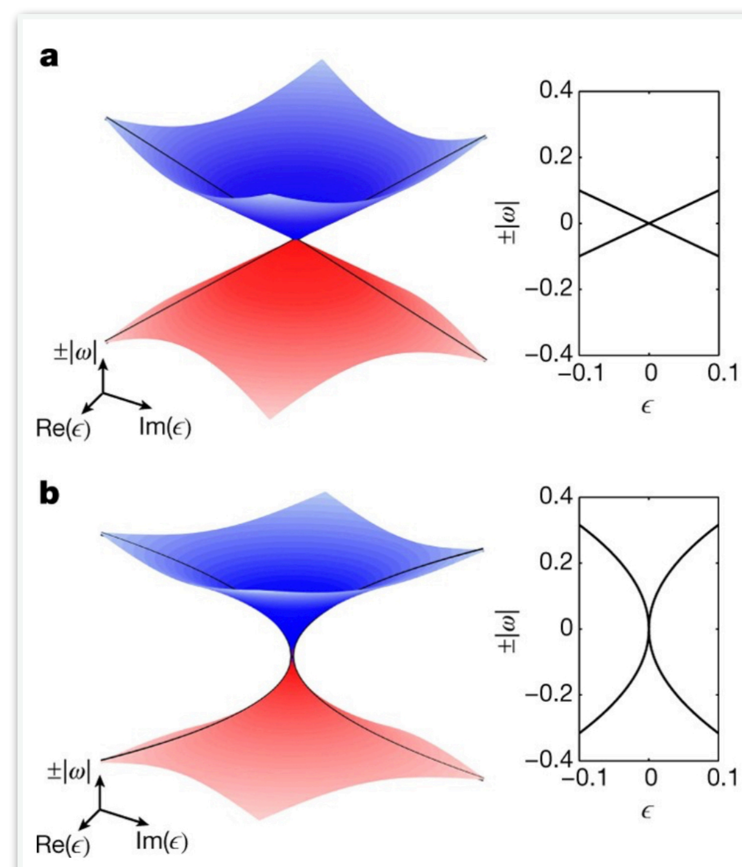
Nature **576**, 70–74(20

Article | Published: 04 December 2019

Observation of the exceptional-point-enhanced Sagnac effect

Yu-Hung Lai, Yu-Kun Lu, Myoung-Gyun Suh, Zhiquan Yuan & Kerry Vahala

Nature **576**, 65–69(2019) | Cite this article



$$\delta\omega \propto \epsilon$$

$$\delta\omega_{EP} \propto \epsilon^{1/2}$$

W. Chen et al., Nature **548**, 192 (2017)

What are "Quantum" Exceptional Points?

$$i\partial_t \boxed{A} = \boxed{B}\,\boxed{A} \quad ?$$

A: classical or quantum input and output.

B: classical or quantum "Hamiltonian".

EPs in coherent, non-unitary evolution.

A: quantum density matrix in Lindblad evolution.

B: Lindblad super-operator (with an extra i).

EP: critically damped (fastest) approach to steady-state.

?: Is this equation a correct description?

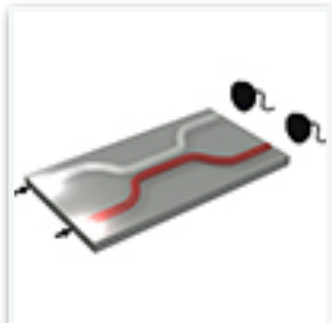
Can we make quantum EPs? Yes, across multiple platforms.

Roberto Leon

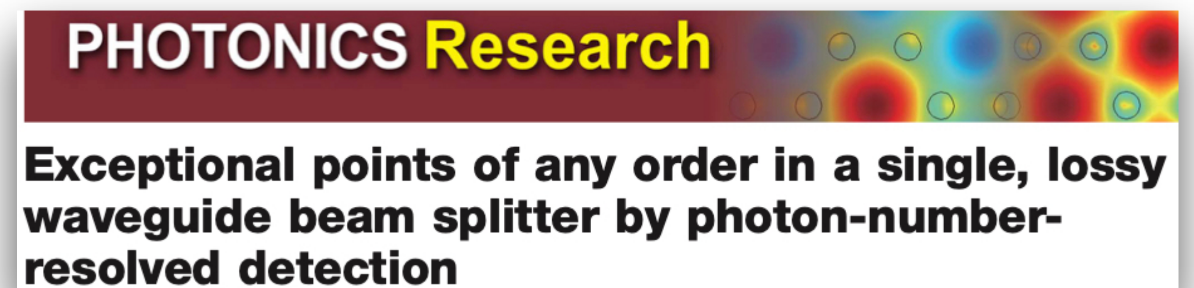
Quantum input A to "classical devices" B

Anthony Laing

Passive PT dimer



Use Fock input states;
Use number-resolved output.
Use tomography to measure density matrix.



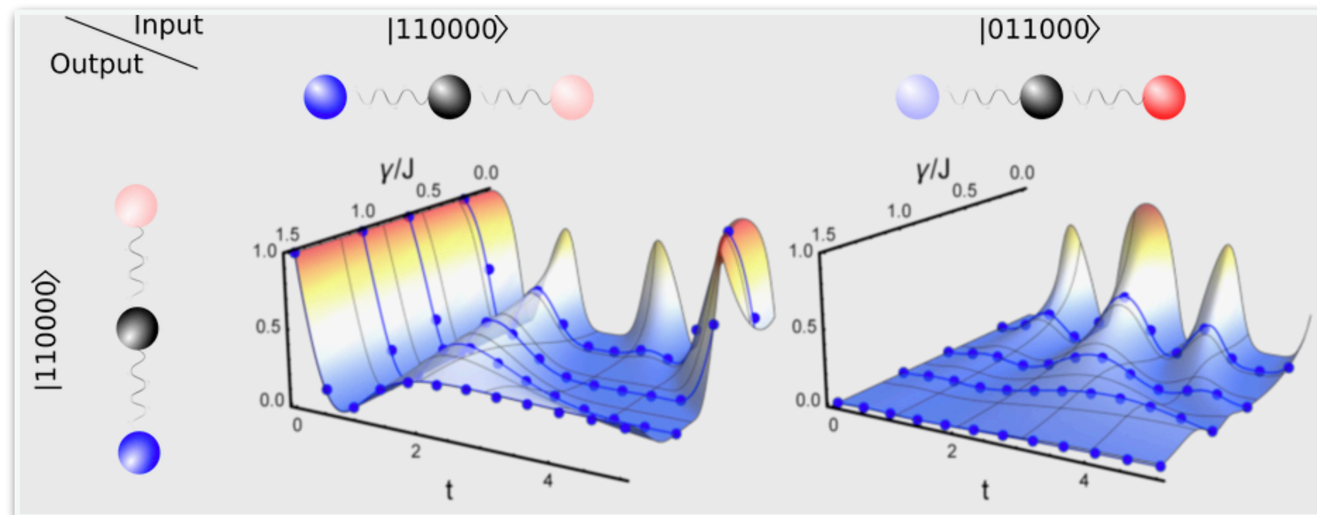
PHOTONICS Research

Exceptional points of any order in a single, lossy waveguide beam splitter by photon-number-resolved detection

Theory proposal: "quantum" EPs

Put in N-photon state in a dimer.
Measure number-resolved output.
Post-select to N-photon manifold.
Get a robust EP of order N+1.

RLM, YNJ Photonics Research 7, 862 (2019).



Unitary dilation for non-unitaries.

Multi-photon statistics in PT-trimer.
Thermalization, Lindblad simulations.

YNJ, AL Nature 557, 660 (2018); ongoing work.

“Quantum B”: minimal devices

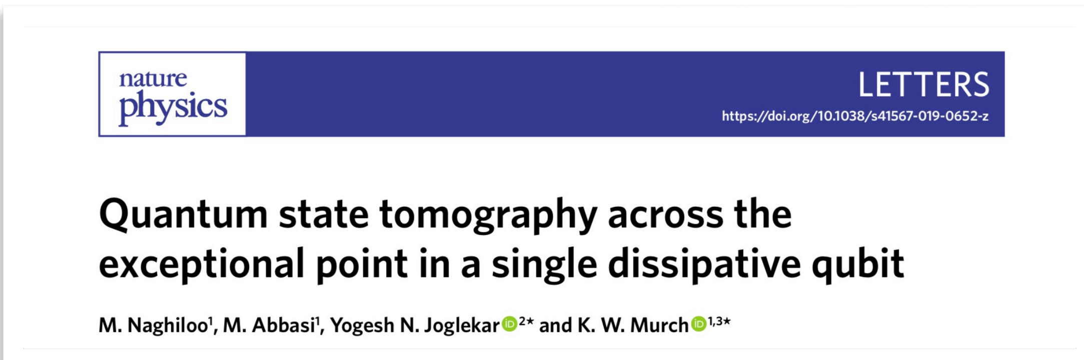
Kater Murch

$$\partial_t \rho = i[H_0, \rho] - \sum_k i\frac{\gamma_k}{2}\left[\{L_k^\dagger L_k, \rho\} + 2L_k\rho L_k^\dagger\right]$$

Lindblad description.

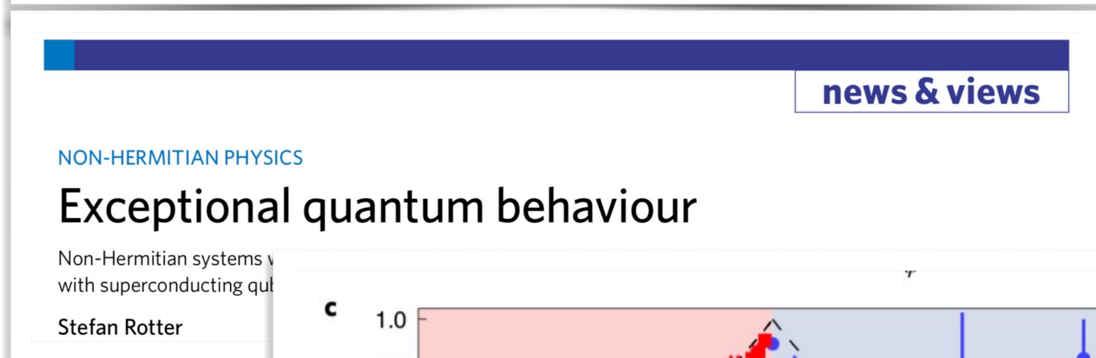
Ignore quantum jumps.

Post-select:å non-Hermitian B.


nature physics LETTERS
https://doi.org/10.1038/s41567-019-0652-z

Quantum state tomography across the exceptional point in a single dissipative qubit

M. Naghiloo[1], M. Abbasi[1], Yogesh N. Joglekar[2*] and K. W. Murch[1,3*]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NON-HERMITIAN PHYSICS

Exceptional quantum behaviour

Non-Hermitian systems …
with superconducting qu…

Stefan Rotter

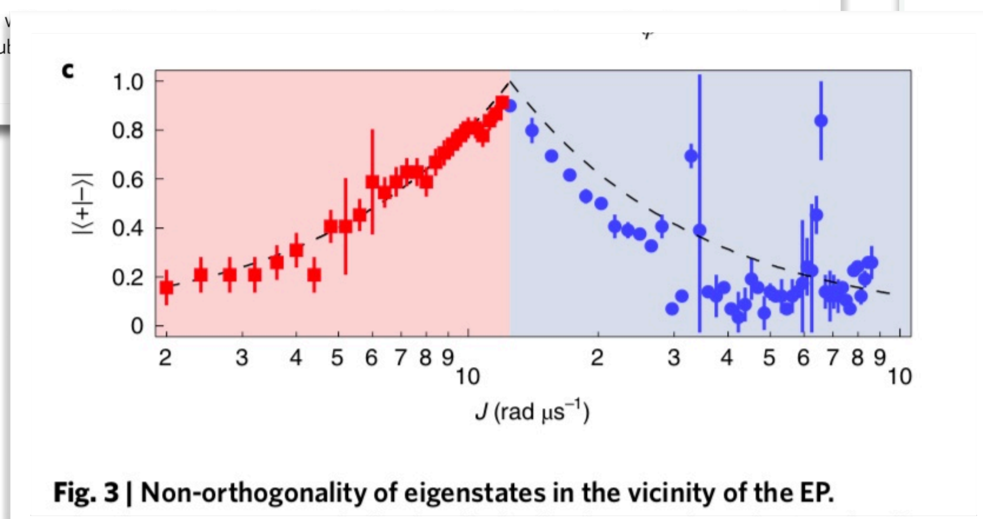
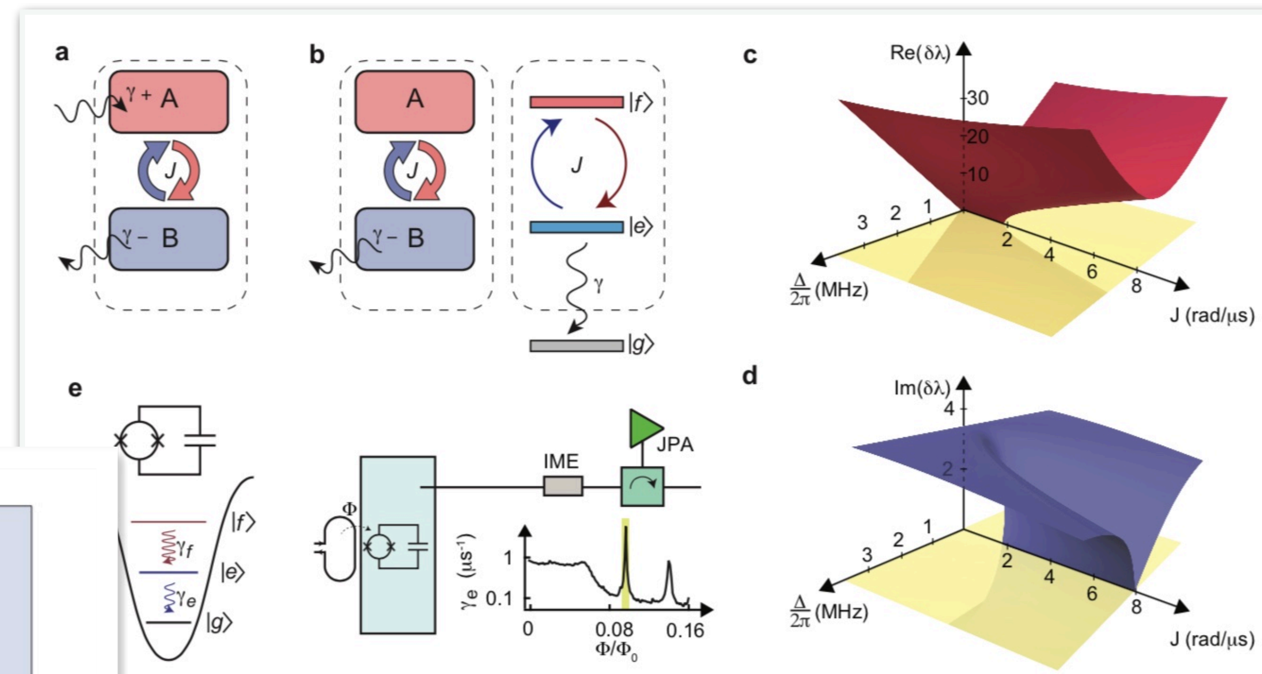


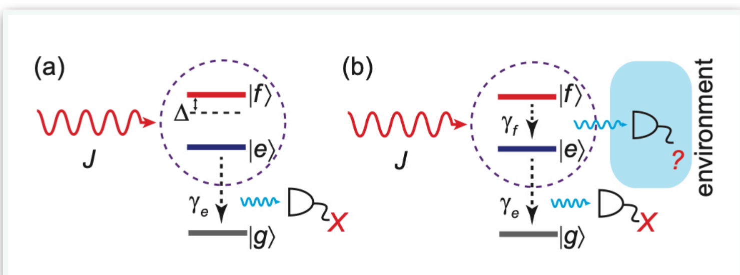
Fig. 3 | Non-orthogonality of eigenstates in the vicinity of the EP.

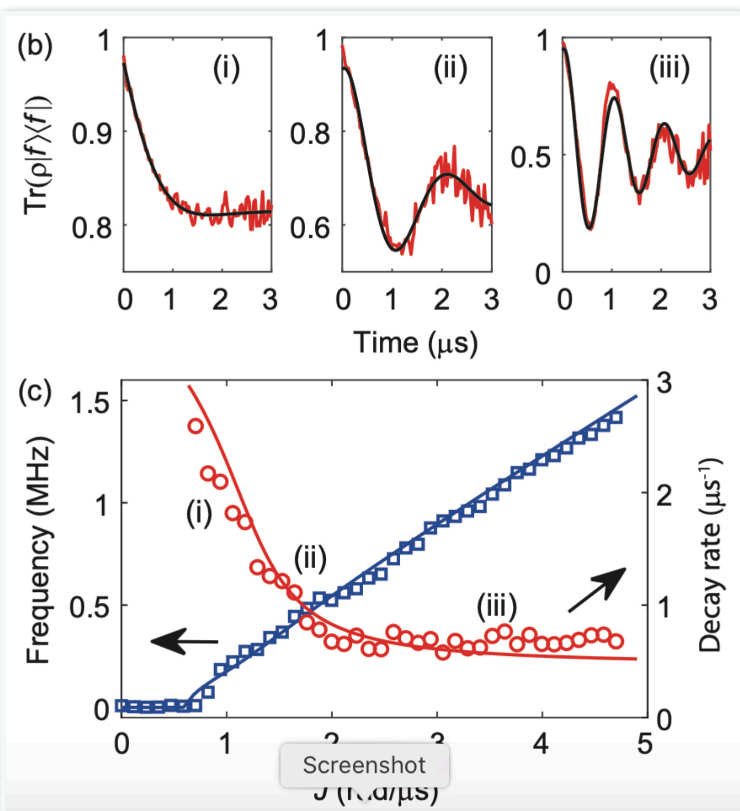


YNJ, KWM Nature Physics 15, 1232 (2019)

Lindblad EPs in minimal devices $(A = \rho, B = i\mathscr{L})$

$$\partial_t \rho(t) = i[H_0(t), \rho(t)] - i\frac{\gamma(t)}{2}\left[\{L_k^\dagger L_k, \rho\} - 2L_k \rho L^\dagger\right] = \mathscr{L}(t)\rho(t)$$





Density matrix reaches steady state.

L spectrum: $\{0, \lambda_k, \lambda_k^* \,|\, \Re\lambda_k < 0\}$

Underdamped or overdamped approach.

Fastest approach occurs at EP.

No post-selection, but decaying signal.

Unphysical density matrix eigenstates.

Encircling mode-switches not possible.

YNJ, KWM arXiv:2103.06274

Kater Murch

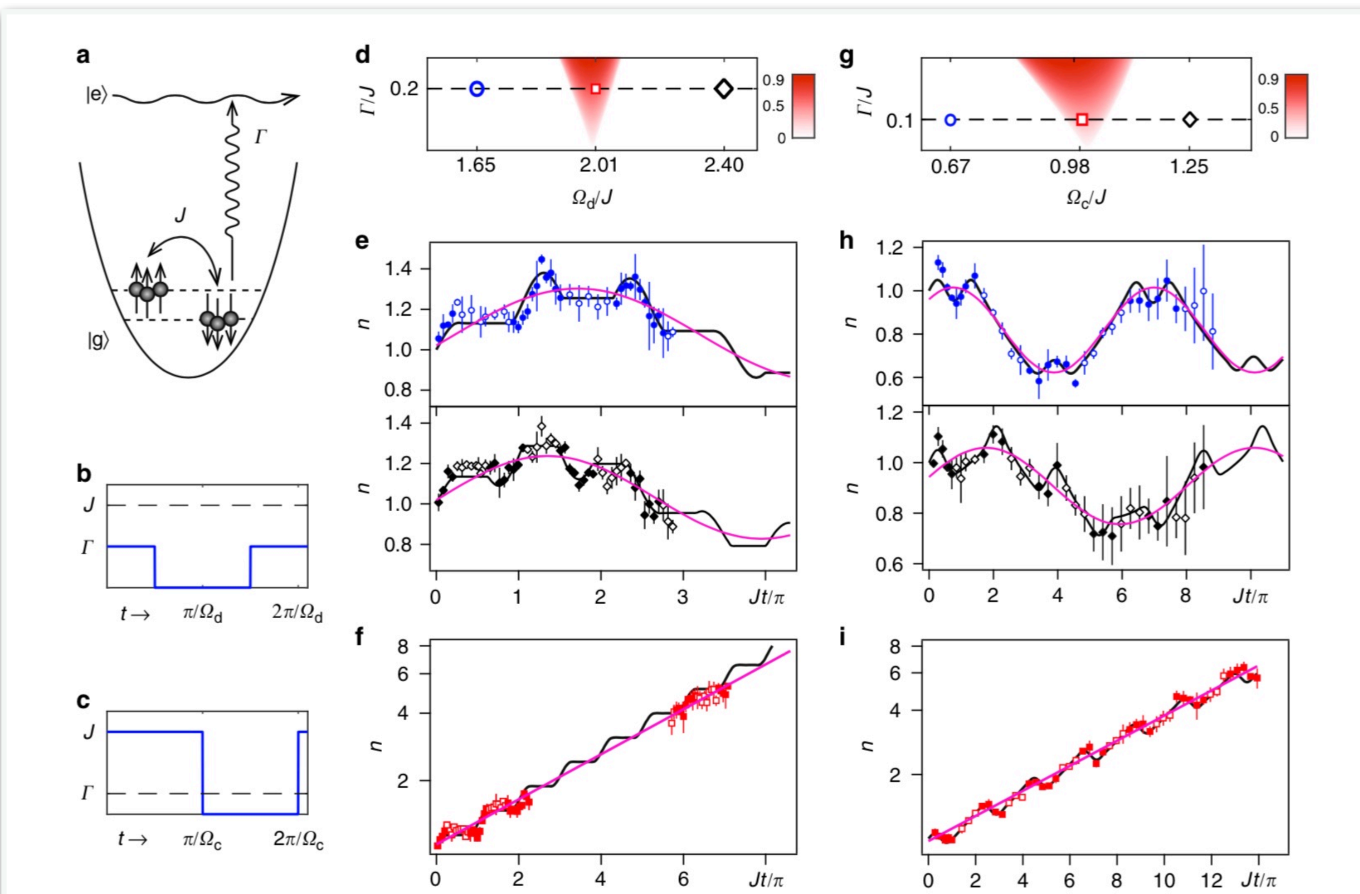
Le Luo

“Quantum B”: interacting materials

Hermitian systems with QPT (atoms, ions, Rydberg).

No tomography; introduce single-particle losses.

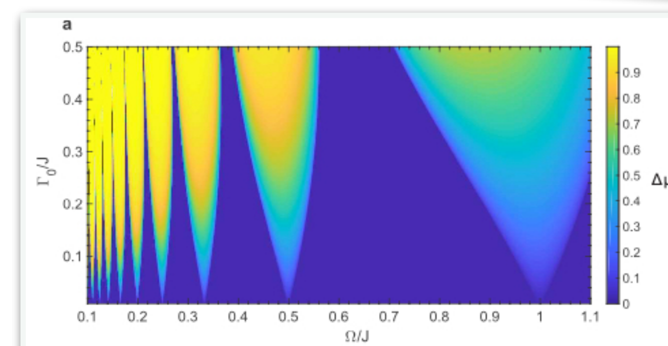
Time-periodic (Floquet) problem: EP contours.

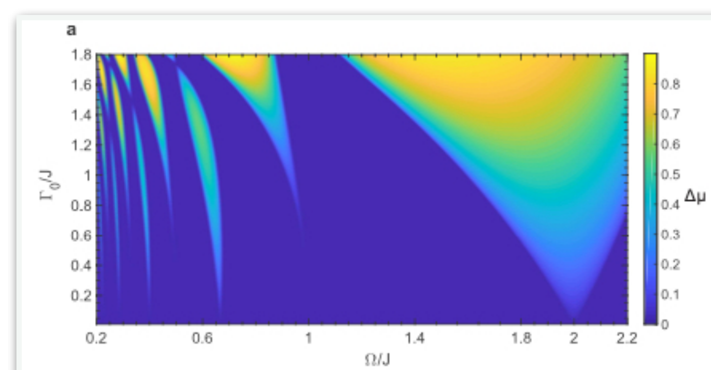


ARTICLE

https://doi.org/10.1038/s41467-019-08596-1 OPEN

Observation of parity-time symmetry breaking transitions in a dissipative Floquet system of ultracold atoms



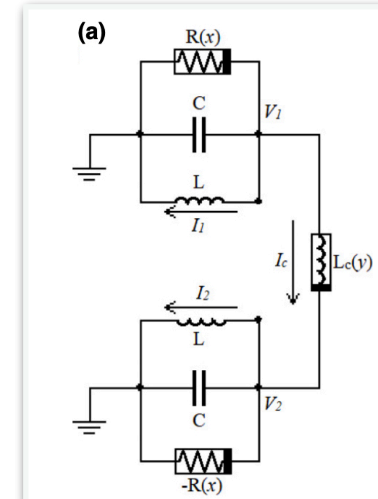


YJ et al., PRA 90, 040101 (2014) Theory.
YNJ, LL Nature Communications 10, 855 (2019).

Roberto Leon

Floquet engineering of EP contours

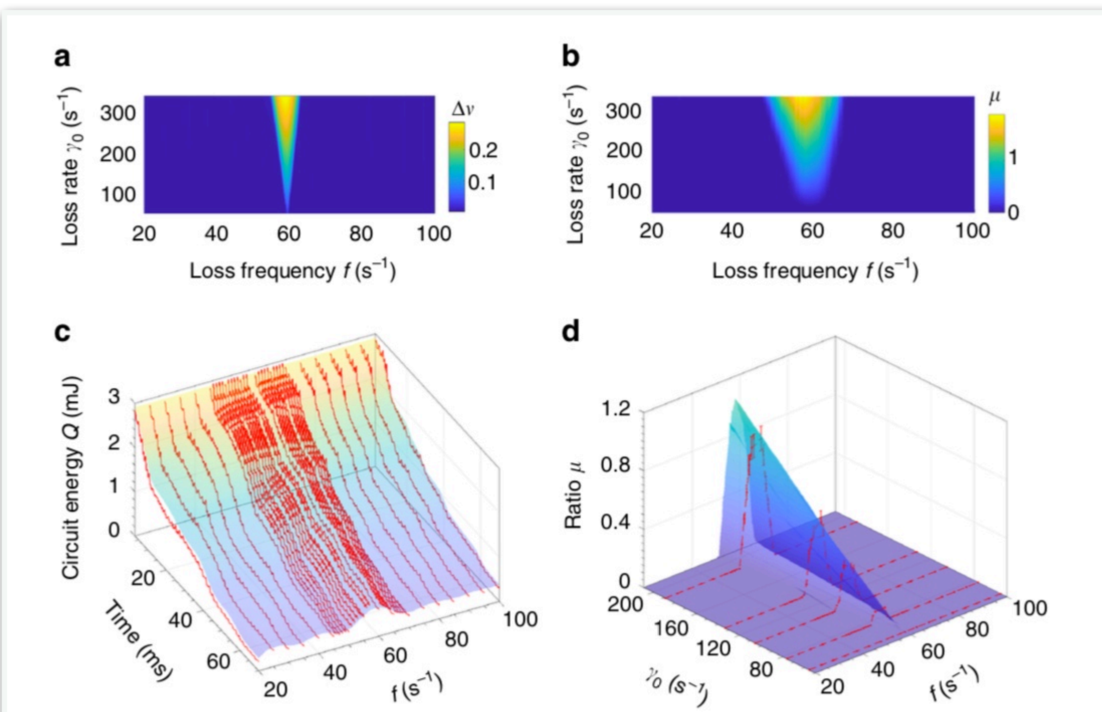
$$B(t) = H_0(t) + i\Gamma(t) = B(t+T) \text{ with } T = 2\pi/\Omega$$

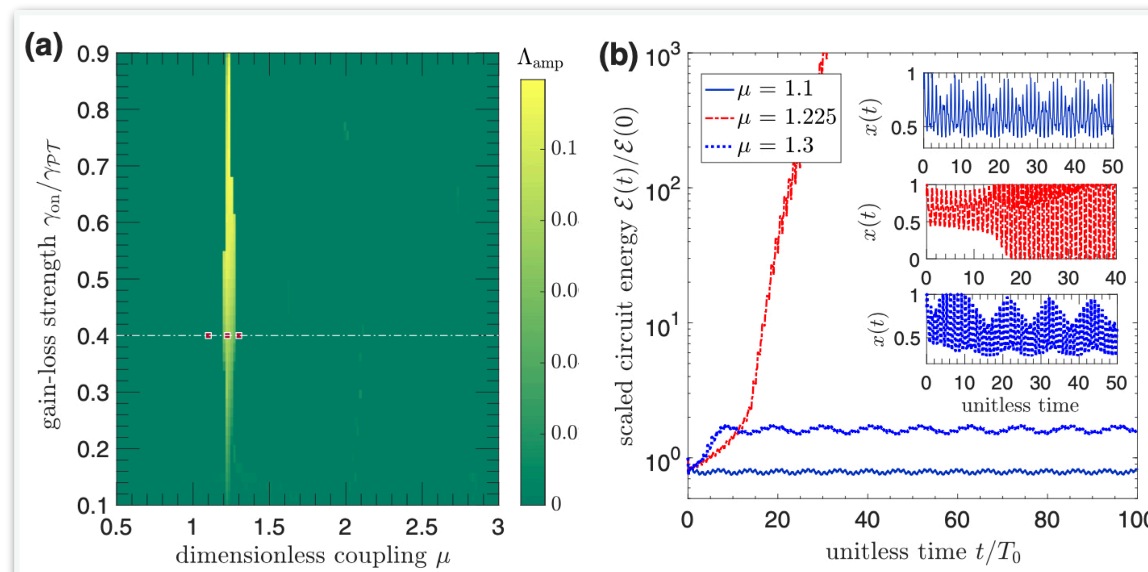


Static B: isolated EPs near $\Gamma \sim H_0$.

Time-periodic (Floquet) case: EPs become contours.

Valid in both classical and quantum domains.





PHYSICAL REVIEW RESEARCH **3**, 013135 (2021)

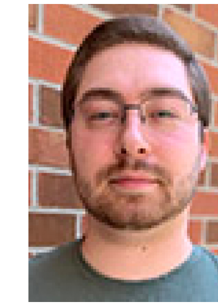
Parity-time symmetric systems with memory

Zachary A. Cochran[1] Avadh Saxena[2] and Yogesh N. Joglekar[1]

YJ, RLM Communications Physics 1, 88 (2018).

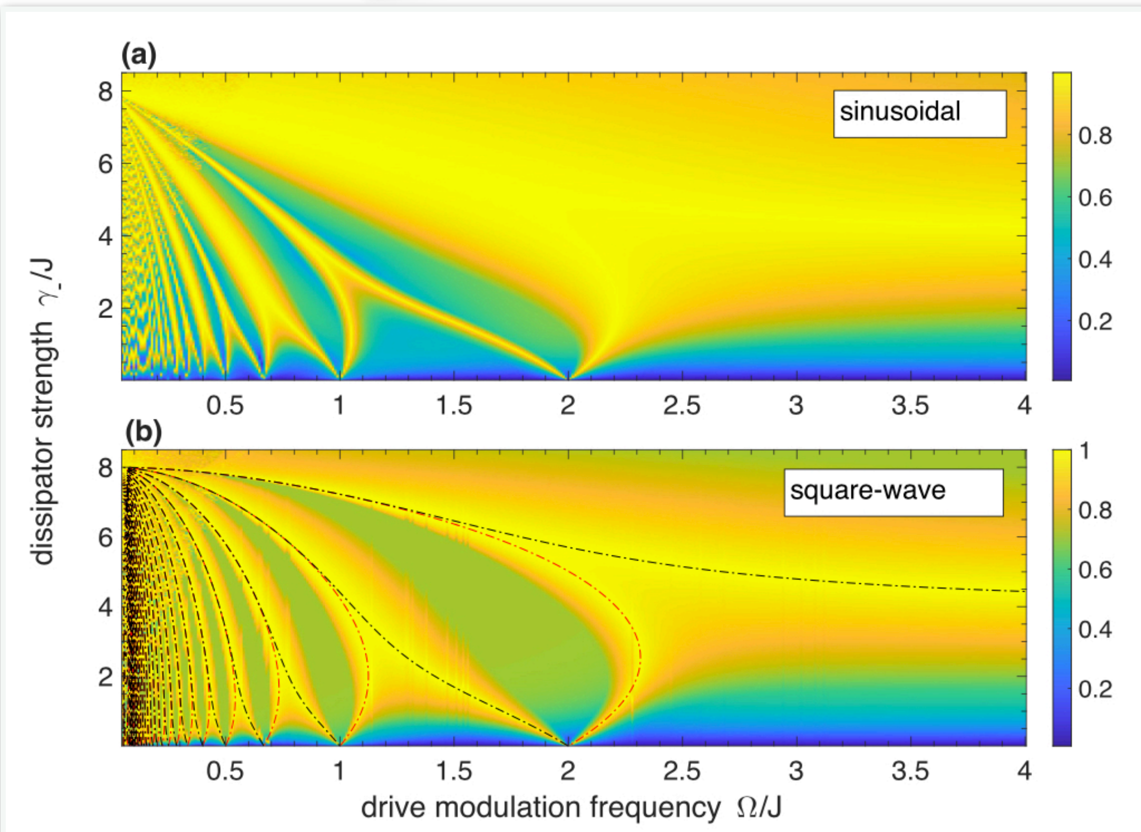
John Gunderson

Floquet engineering of Lindblad EP contours



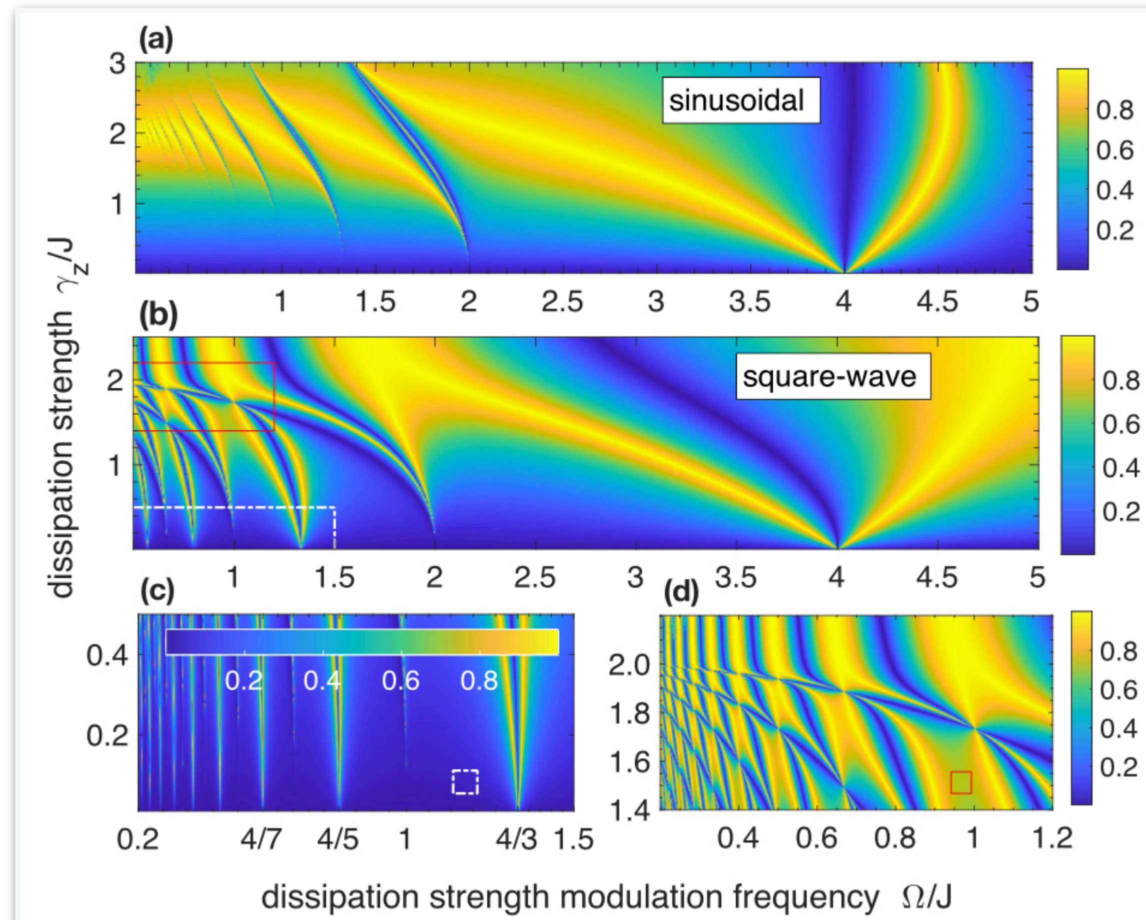
Jacob Muldoon

$$\mathscr{L}(t) = \mathscr{L}_0(t) + \Gamma(t) = \mathscr{L}(t+T) \text{ with } T = 2\pi/\Omega$$



Time-periodic drive for the qubit.

Time-periodic phase noise $\gamma_z(t)$



Also see poster by Akhil Kumar, IISER, Kolkata.

Gunderson, Jacob Muldoon, KWM, YJ PRA 103, 023718 (2021)

Q: Is this equation a correct description?

Manas Kulkarni

Archak Purkayastha

T=0 losses (allow quantum-jump elimination);
No gain (quantum noise in amplifier).

$$i\partial_t \boxed{A} = \boxed{B}\,\boxed{A} \quad + \text{noise-terms}$$

Classical: number ← → Quantum: $a^\dagger$

- ✗ Equation invalid at the operator level.
- ✓ Ok at quadrature level: EPs in H_{eff}.
- ✗ Not OK for correlations and intensity.

PHYSICAL REVIEW RESEARCH **2**, 043075 (2020)

Emergent $\mathcal{PT}$ symmetry in a double-quantum-dot circuit QED setup

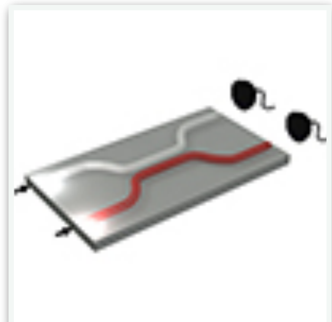
Archak Purkayastha,[1,*] Manas Kulkarni,[2,†] and Yogesh N. Joglekar[3,‡]

See: Archak Purkayastha (Today, 18:20)

Open Questions: Do quantum EPs lead to better sensors?
How can we realize many-body systems EPs?
What is the fate of entanglement dynamics across EPs?

Quantum input A to "classical devices" B

Passive PT dimer



$$A = |1_L\rangle \otimes |1_R\rangle$$

$$B = -J(|L\rangle\langle L| + |R\rangle\langle R|) - i\gamma|R\rangle\langle R|$$

2 photon HOM dip (post-selection)

Observation of PT-symmetric quantum interference

F. Klauck, L. Teuber, M. Ornigotti, M. Heinrich, S. Scheel & A. Szameit

Nature Photonics **13**, 883–887(2019) | Cite this article

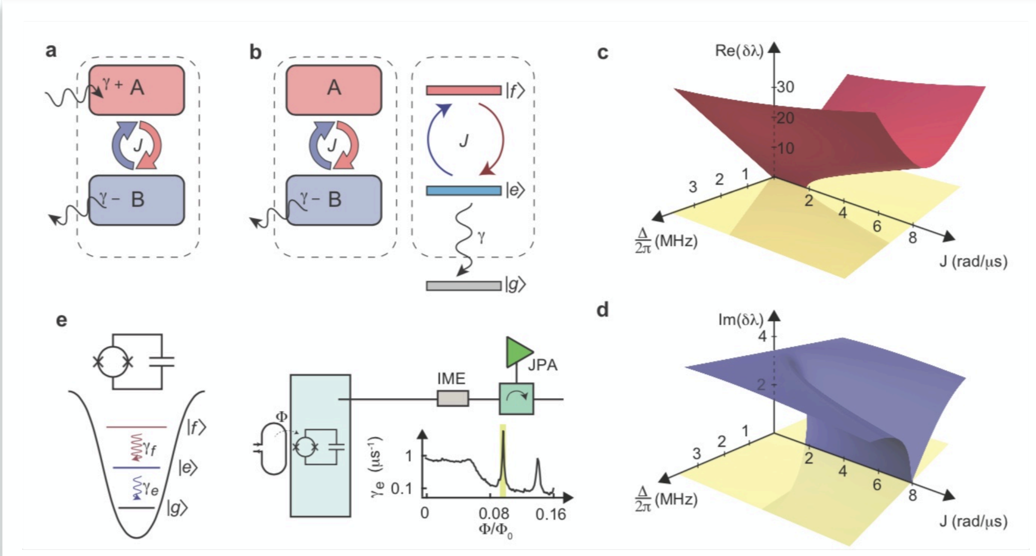
Drawbacks: Post-selection means reduced data sets.

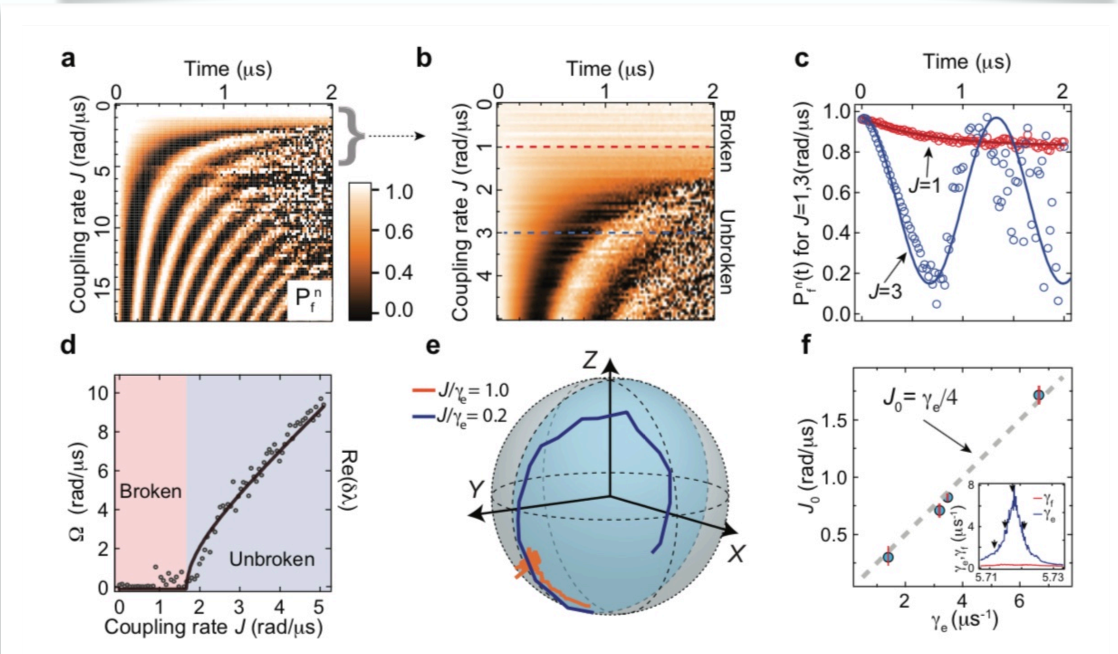
What happens if the quantum input is not Fock states?

Signatures of EPs in non-Gaussian initial states?

Kater Murch, Wash U

Quantum tomography across an EP





nature physics LETTERS https://doi.org/10.1038/s41567-019-0652-z

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news & views

NON-HERMITIAN PHYSICS

Exceptional quantum behaviour

Non-Hermitian systems with gain and loss give rise to exceptional points with exceptional properties. An experiment with superconducting qubits now offers a first step towards studying these singularities in the quantum domain.

Stefan Rotter

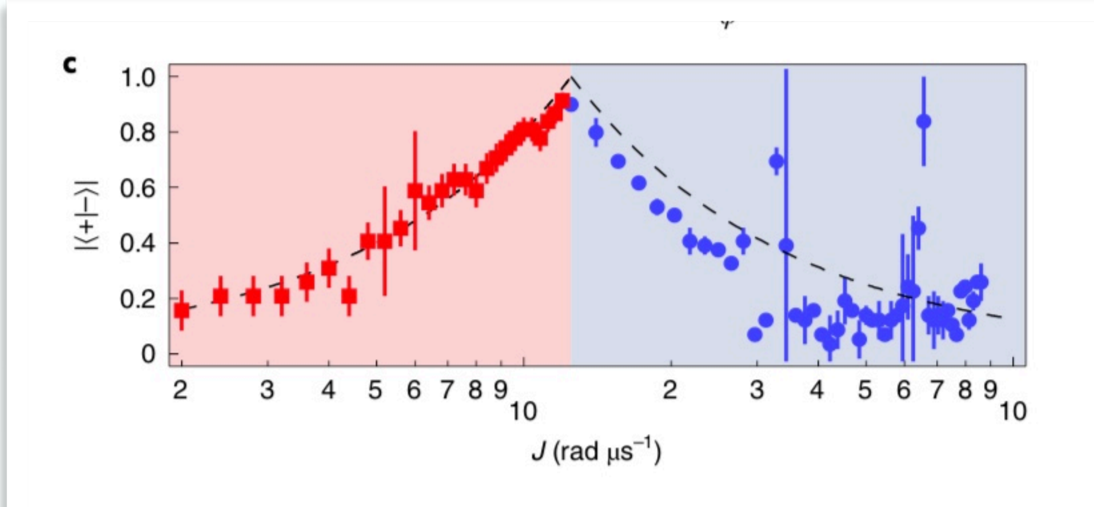


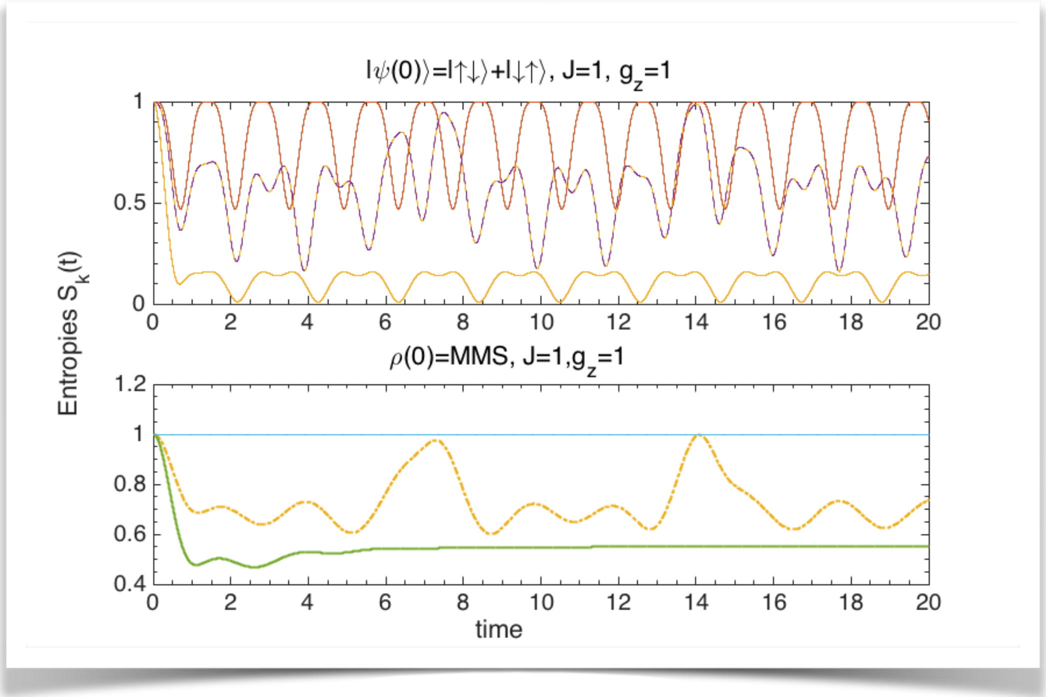
Fig. 3 | Non-orthogonality of eigenstates in the vicinity of the EP.

Post-selection on Lindblad gives non-Hermitian H

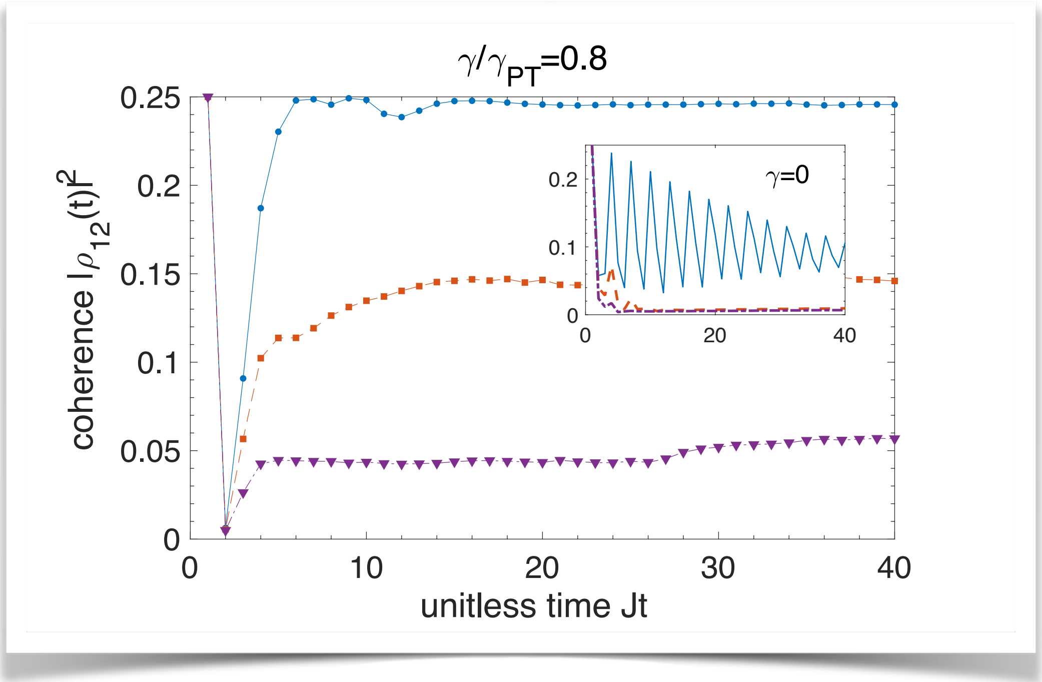
Non-Hermitian Quantum Simulations

- Interactions+non-Hermiticity: new entanglement dynamics.
- Decoherence vs. non-Hermiticity: new way to control.

$$H = -J(X_1 + X_2) + g_z Z_1 Z_2 - i\Gamma_1(1 - Z_1)/2$$



Lindblad + loss γ



Open question (we can potentially address):

New quantum phases from non-Hermitian interactions.