Quantum simulations of parity-time symmetric Hamiltonians

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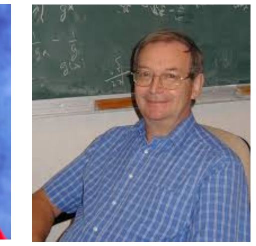
Indianapolis area High-School Students

Outline

1. PT Hamiltonians: history.
2. PT = classical systems with “balanced” gain-loss.
3. Unitary dilation: simulate a quantum PT system.
4. Bosonic correlations.
5. Entropy evolution, quantum information evolution.
6. Conclusions.
7. Other examples: ultra cold gas, electrical circuits

Jorge Cham, Nature Physics 2015

Introduction: PT (quantum) theory

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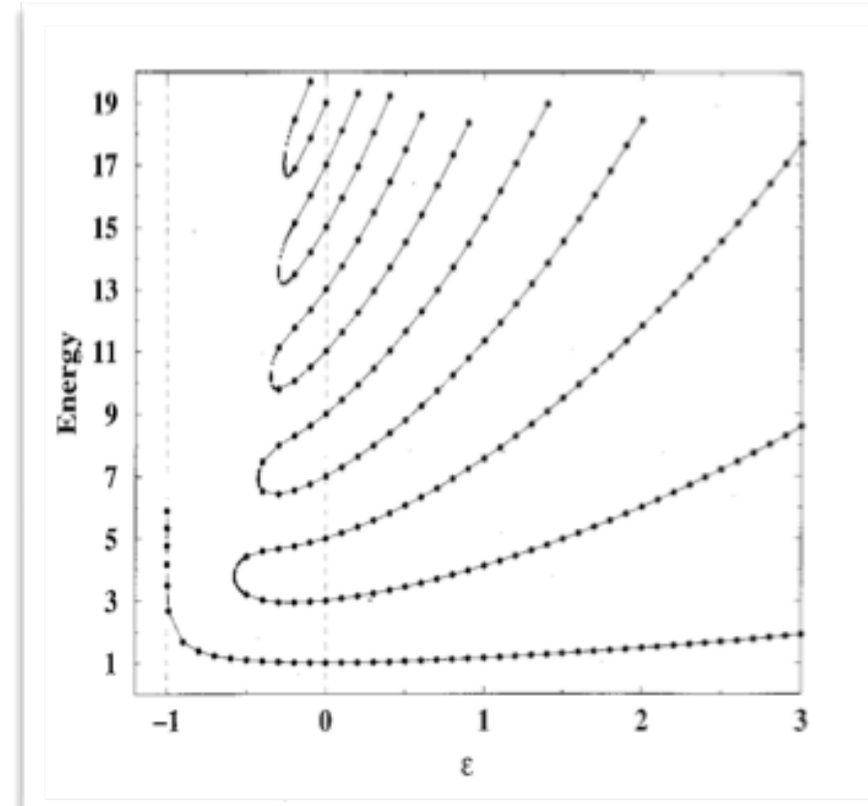
Continuum models: $-\partial_x^2 + x^2 (ix)^\epsilon$

- Hermitian, PT kinetic energy term
- Non-Hermitian, PT-symmetric potential
- Real spectra for “small” non-Hermiticity
- Complex eigenvalues for “large” non-H



$$H = -J\sigma_x + i\Gamma\sigma_z/2,$$
$$\lambda_\pm = \pm\sqrt{J^2 - \Gamma^2/4}$$

PT symmetry breaking: emergence of complex conjugate eigenvalues.

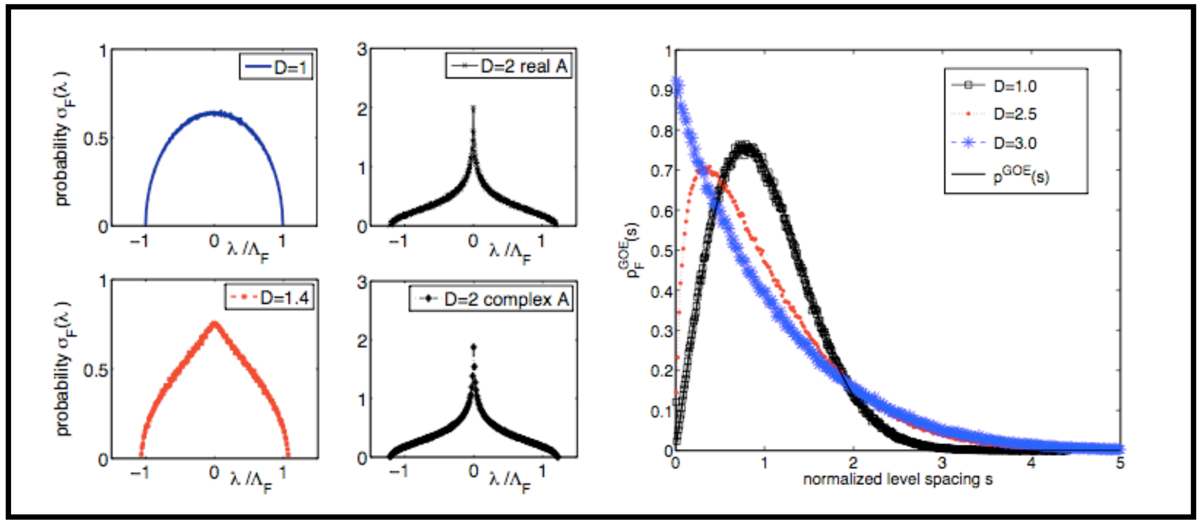
Real Eigenvalues: so what’s next ?

Carl Bender 1998 PRL

Introduction: PT (quantum) theory

Option 1: develop consistent quantum theory

- Similarity transform ("CPT") to make H self-adjoint.
- Get unitary evolution: *claim fundamental theory.*
- Can define "PT" thermo, quantum brachistochrone etc.
- *Pseudo-Hermitian random matrices: interesting properties.*
- *Obtain "constants of motion" i.e. all intertwining operators*



PRE 83, 031122 (2011)

M. Znojil Ali Mostafazadeh

Introduction: PT (quantum) theory

Consistent quantum theory: at what cost?

- Procedure valid only in PT-symmetric region.
- Intertwining operators depend on H.
- *Observables* in the theory *depend on H.*
- Continuum models: x, p no longer "observables".
- Discrete models: S_k no longer "observables".
- Local version violates no-signaling principle.

Y-C Lee et al, PRL 112, 1330404 (2014)

What is the second option?

Option 2: effective model for open systems

Demetrios Christodoulides

Schrodinger equation : paraxial approximation to ME

real potential: index of refraction n(x)

imaginary potential: gain or loss, complex n*(-x)=n(x)

LETTERS nature physics
PUBLISHED ONLINE: 24 JANUARY 2010 | DOI:10.1038/NPHYS1515

Observation of parity–time symmetry in optics

Christian E. Rüter[1], Konstantinos G. Makris[2], Ramy El-Ganainy[2], Demetrios N. Christodoulides[2], Mordechai Segev[3] and Detlef Kip[1]*

904 (2008) PHYSICAL REVIEW LETTERS 14 M

Beam Dynamics in $\mathcal{PT}$ Symmetric Optical Lattices

K. G. Makris, R. El-Ganainy, and D. N. Christodoulides
College of Optics & Photonics-CREOL, University of Central Florida, Orlando, Florida 32816, USA

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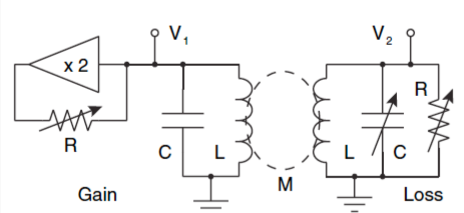
SCHINDLER, LI, ZHENG, ELLIS, AND KOTTOS



PHYSICAL REVIEW A 84, 040101(R) (2011)

Experimental study of active *LRC* circuits with $\mathcal{PT}$ symmetries

Joseph Schindler, Ang Li, Mei C. Zheng, F. M. Ellis, and Tsampikos Kottos
Department of Physics, Wesleyan University, Middletown, Connecticut 06459, USA

(Received 28 June 2011; revised manuscript received 31 August 2011; published 13 October 2011)

PRL 103, 093902 (2009) PHYSICAL REVIEW LETTERS 28

Observation of $\mathcal{PT}$-Symmetry Breaking in Complex Optical Potentials

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(Received 29 April 2009; published 27 August 2009)

Observation of $\mathcal{PT}$ phase transition in a simple mechanical system

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[2]*Blackett Laboratory, Imperial College, London SW7 2AZ, UK*

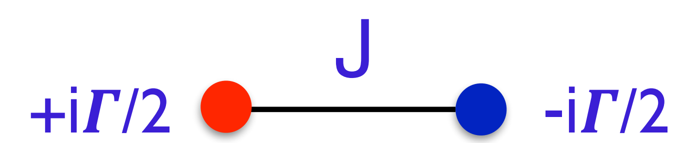
(Dated: June 22, 2012)

If a Hamilto
real, in which
eigenvalues ar

PT: (classical) balanced gain and loss

PT systems = balanced gain and loss

$$|\psi(t)\rangle = e^{-iH_{PT}t}|\psi(0)\rangle$$
$$\langle\psi(t)|\psi(t)\rangle \neq \langle\psi(0)|\psi(0)\rangle$$



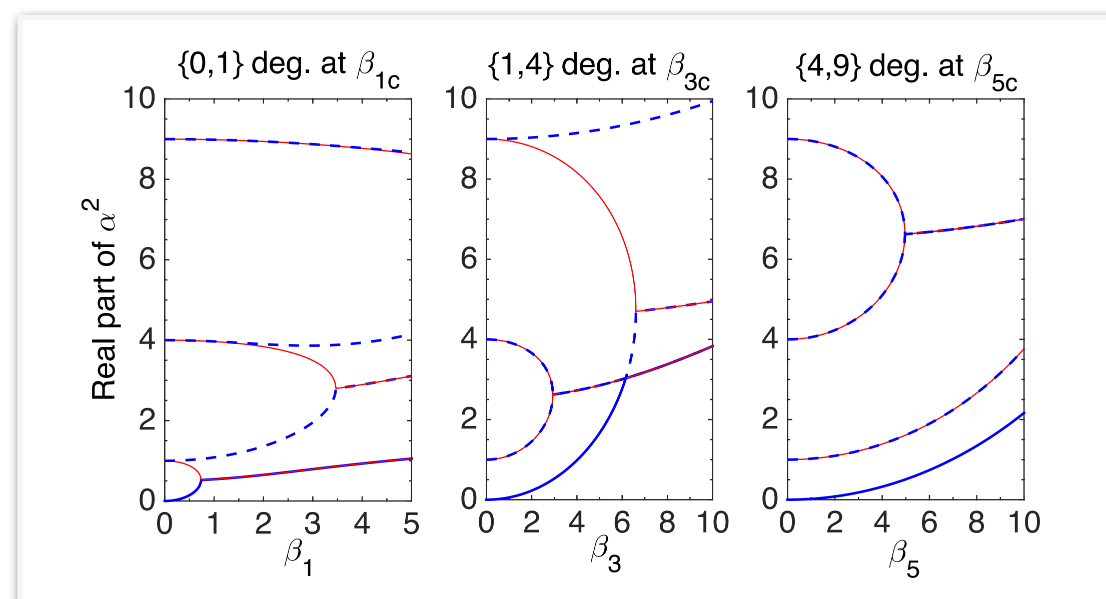
$$H_{PT} = -J\sigma_x + i\Gamma\sigma_z/2$$

$$\lambda_\pm = \sqrt{J^2 - \Gamma^2/4}$$

PTS (real): intensity oscillations, PT eigenfunctions

EP(degenerate): power-law growth.

PTB (complex): exponential growth, not eigenfunctions of PT

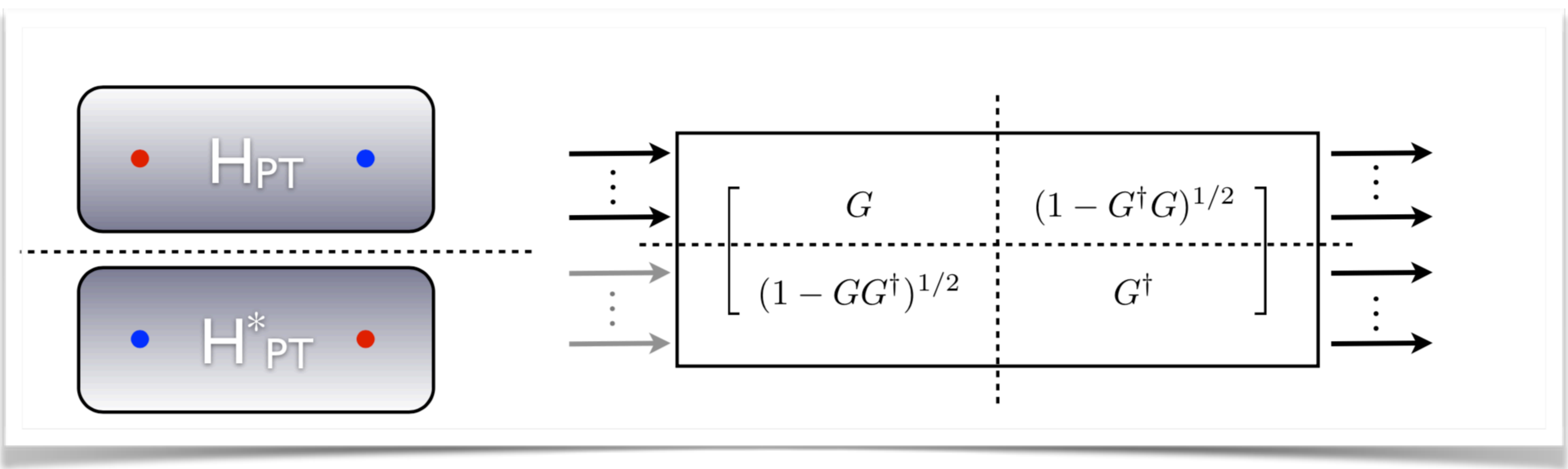


Typical flow of Re[Eigenvalues] vs. non-Hermiticity

Quantum simulations of PT systems

- Optics: loss linear, but gain non-linear, random ✗
- Simulate gain-loss Hamiltonian (CTQW) ???
- Simulate loss-only Hamiltonian: quantum possible ✓
- Simulate time-evolution operator (DTQW) ✓

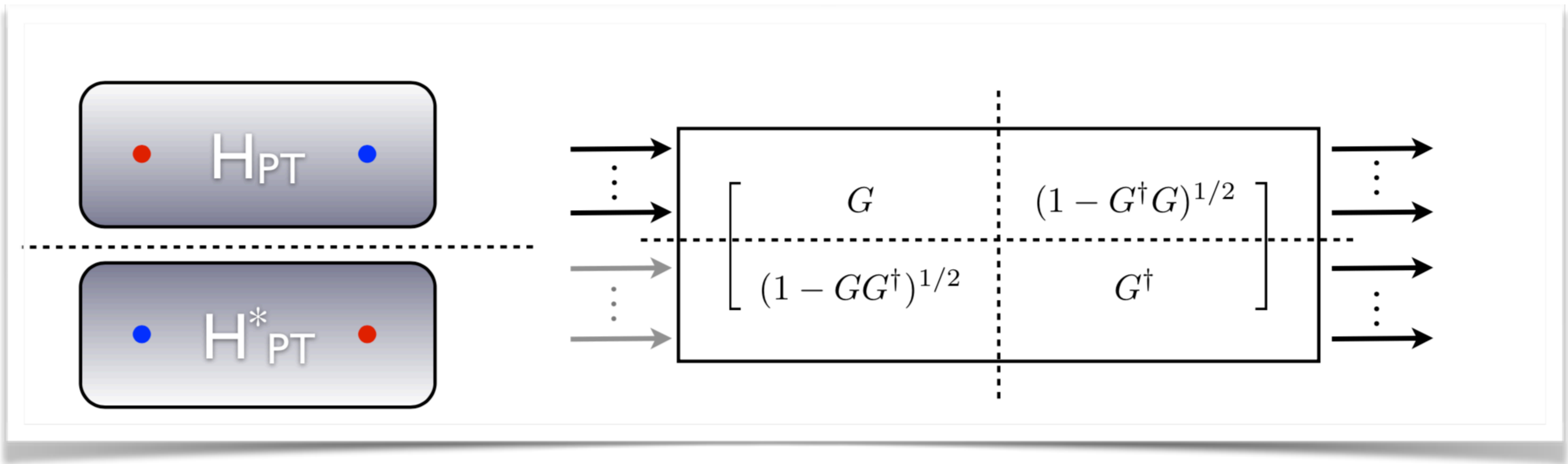
$$G_{PT}(t) = \exp(-iH_{PT}t) \neq G^{\dagger^{-1}}_{PT}(t)$$



H. Obuse, P. Xue et al., Nat. Phys. 2017

Nature 557, 660 (2018)

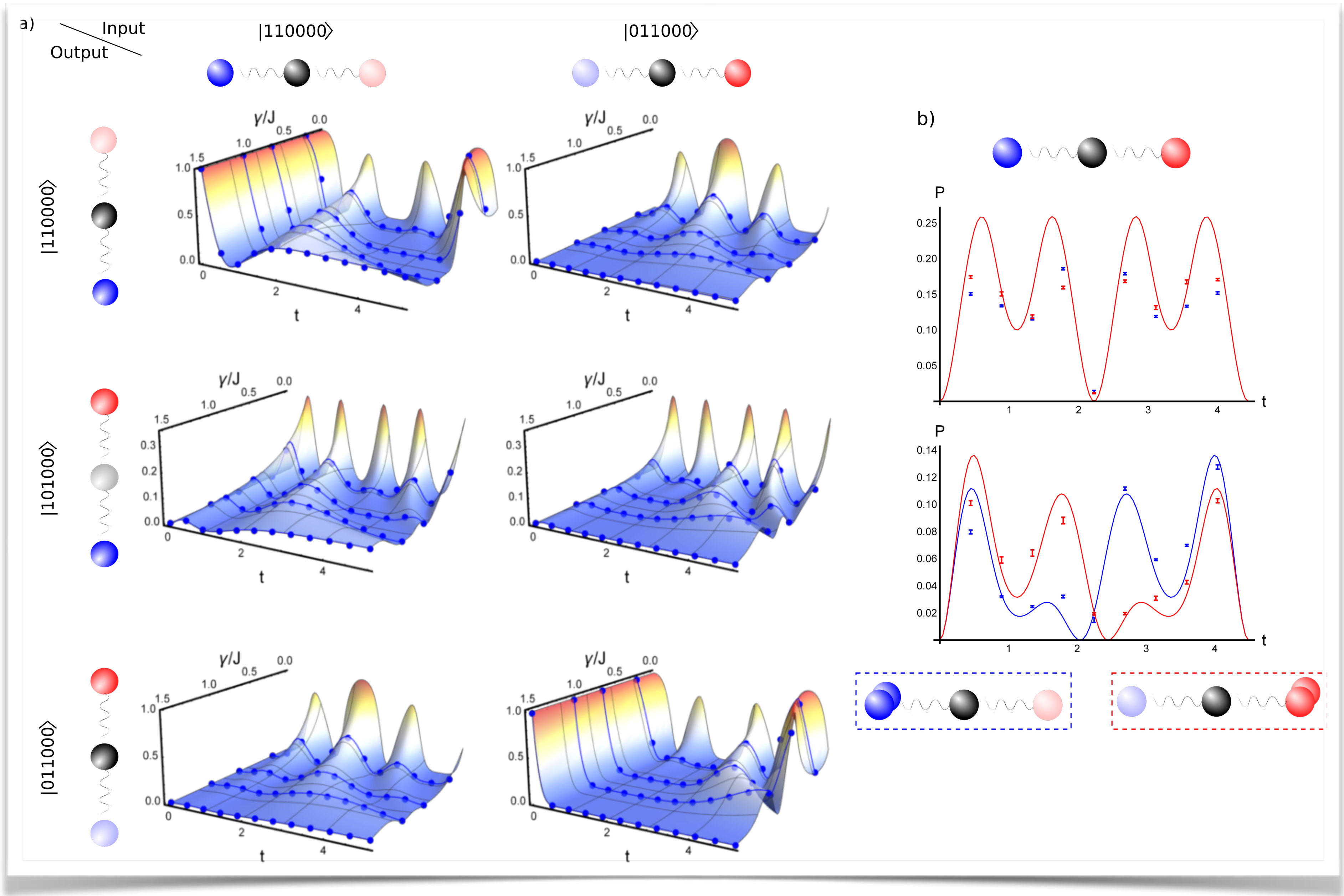
Unitary dilation approach to quantum simulation



- Applicable in both PT symmetric + broken regimes.
- Use 2m x 2m unitary for m-dimensional PT system.
- Not a Naimark or other Hamiltonian dilation.
- Measure coincidences, or full density matrix.
- Obtain quantum information properties.

U. Gunther et al. PRL 101, 230404 (2008)
K. Kawabata et al. PRL 119, 190401 (2017)

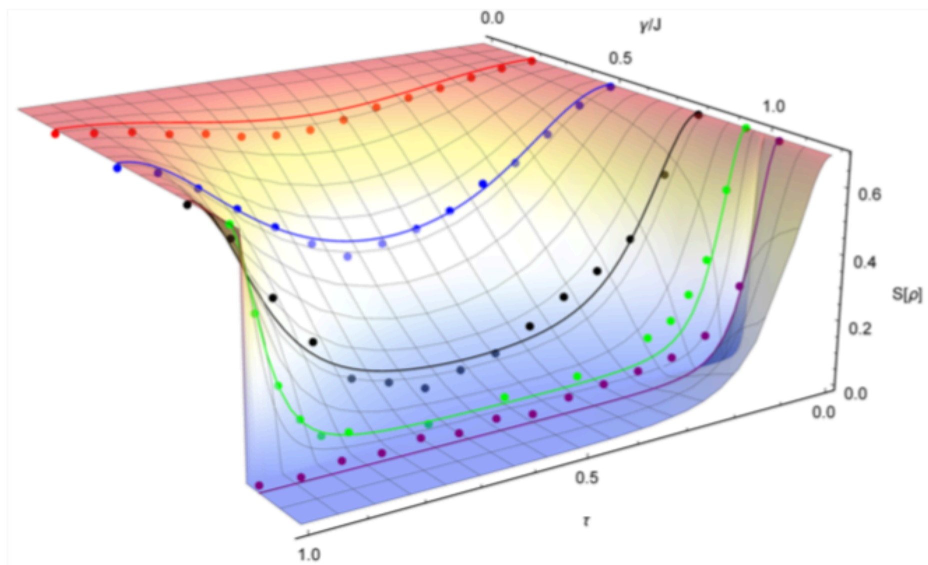
Bosonic correlation results



Gain loss "interchangeable" in PT symmetric phase
Gain loss distinct in the PT broken phase

N. Maraviglia, A. Harter, …., Y.N.J., Anthony Laing, in preparation

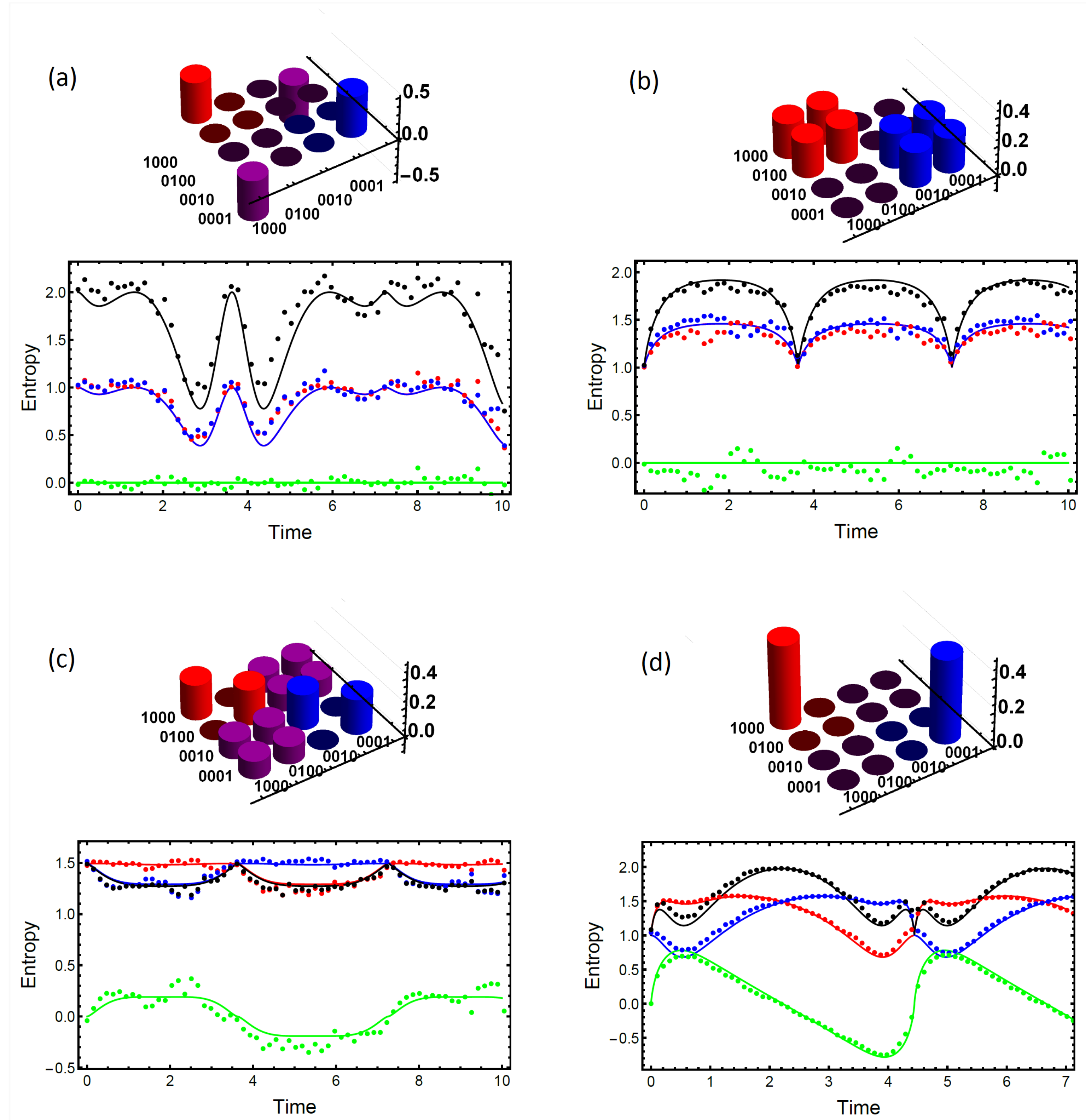
Quantum information across PT transition



Access to all phases.

Entropy is oscillatory or steady state.

Q Information metrics show similar behavior.

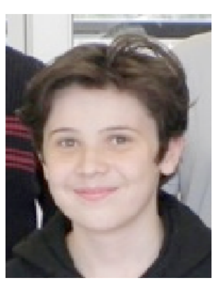


K. Kawabata et al. PRL 119, 190401 (2017)

N. Maraviglia, A. Harter, …., Y.N.J., Anthony Laing, in preparation

Conclusions and Outlook

- Unitary dilation allows quantum simulation.
- Q: Hamiltonian realizations? Lossy-system realizations?
- Highly accessible to young kids!


PRA 83, 030103(R) (2010).
PRA 84, 024103 (2011).
PRA 84, 043826 (2011).
PRA 87, 044101 (2013).
PRA 89, 030102(R) (2014).




PHHQP 2020

Yogesh Joglekar and Avadh Saxena

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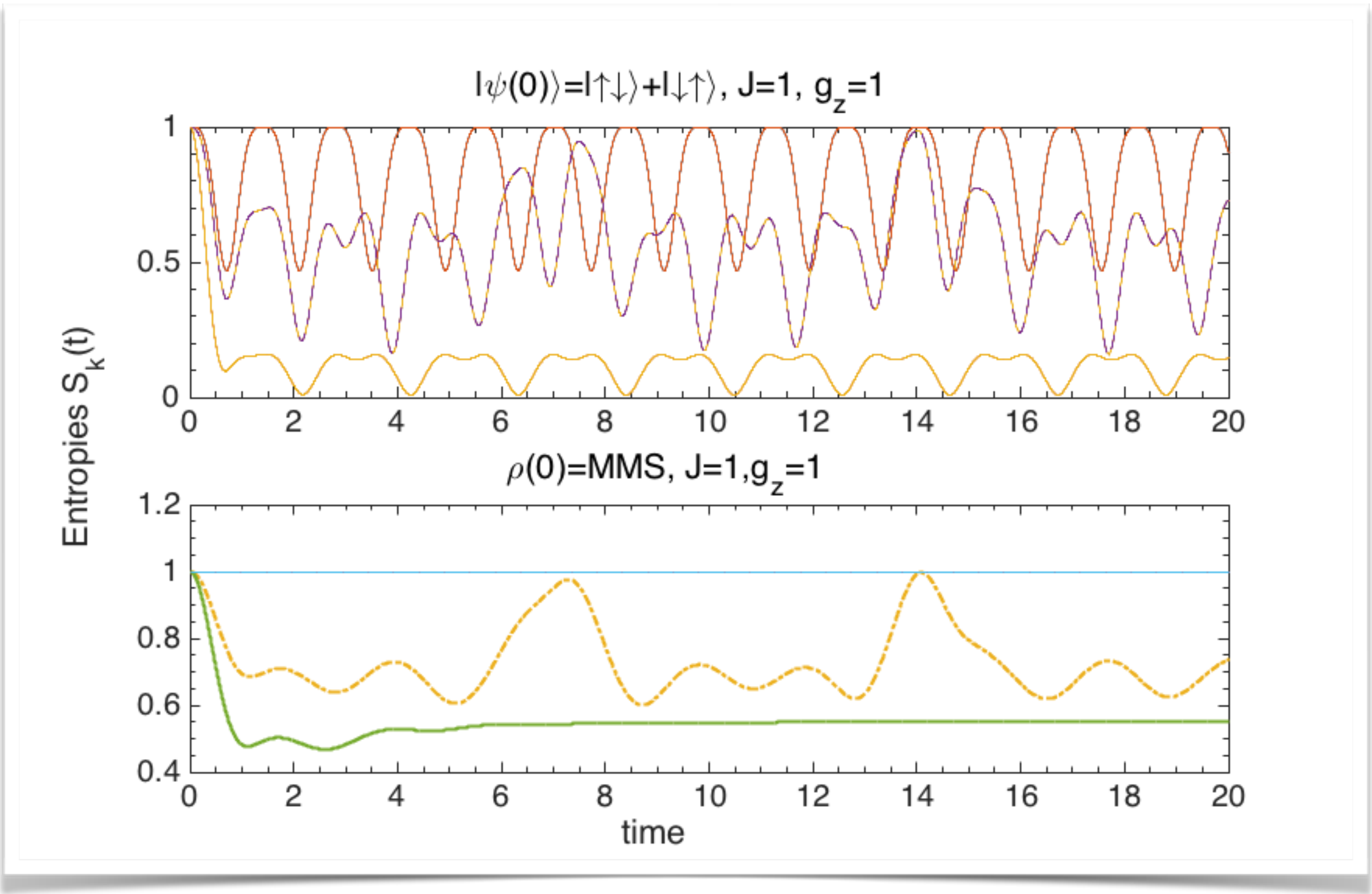
Quantum entanglement in coupled qubits: proposal

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



“Passive” PT systems = neutral and localized loss

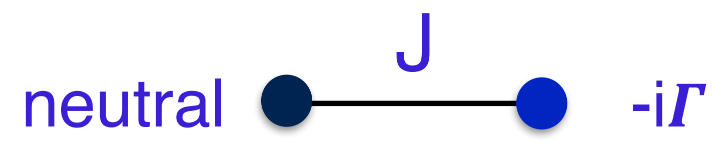
PTS: decay-rate increases with Γ.

PT transition: fastest decay.

PTB: decay-rate *decreases with* Γ.

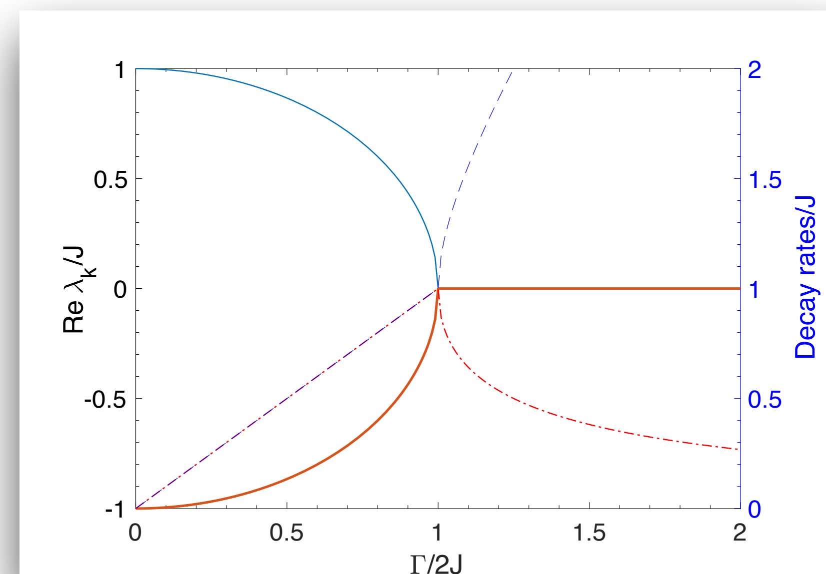
Scaled norm shows oscillatory to exponential time dependence.

gain-loss = localized loss



$$H = -J\sigma_x - i\Gamma|\uparrow\rangle\langle\uparrow|$$

$$\lambda_\pm = -i\Gamma/2 \pm \sqrt{J^2 - \Gamma^2/4}$$

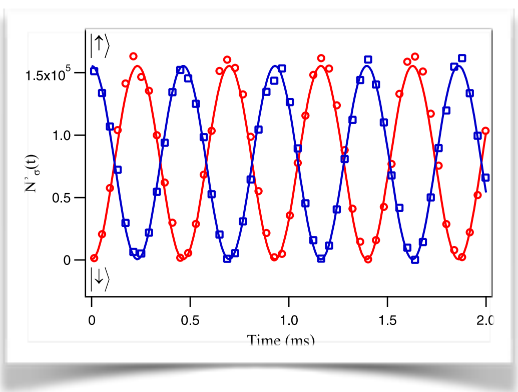


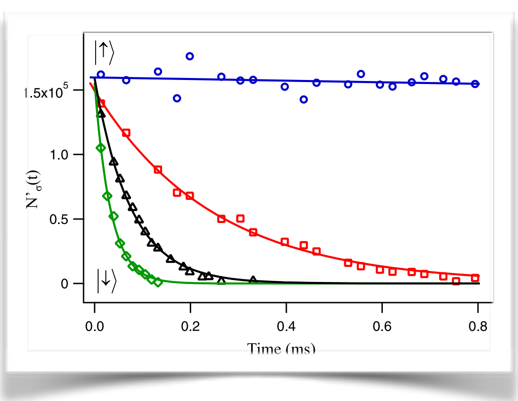
Passive PT: quantum realizations possible arxiv:1608.05061

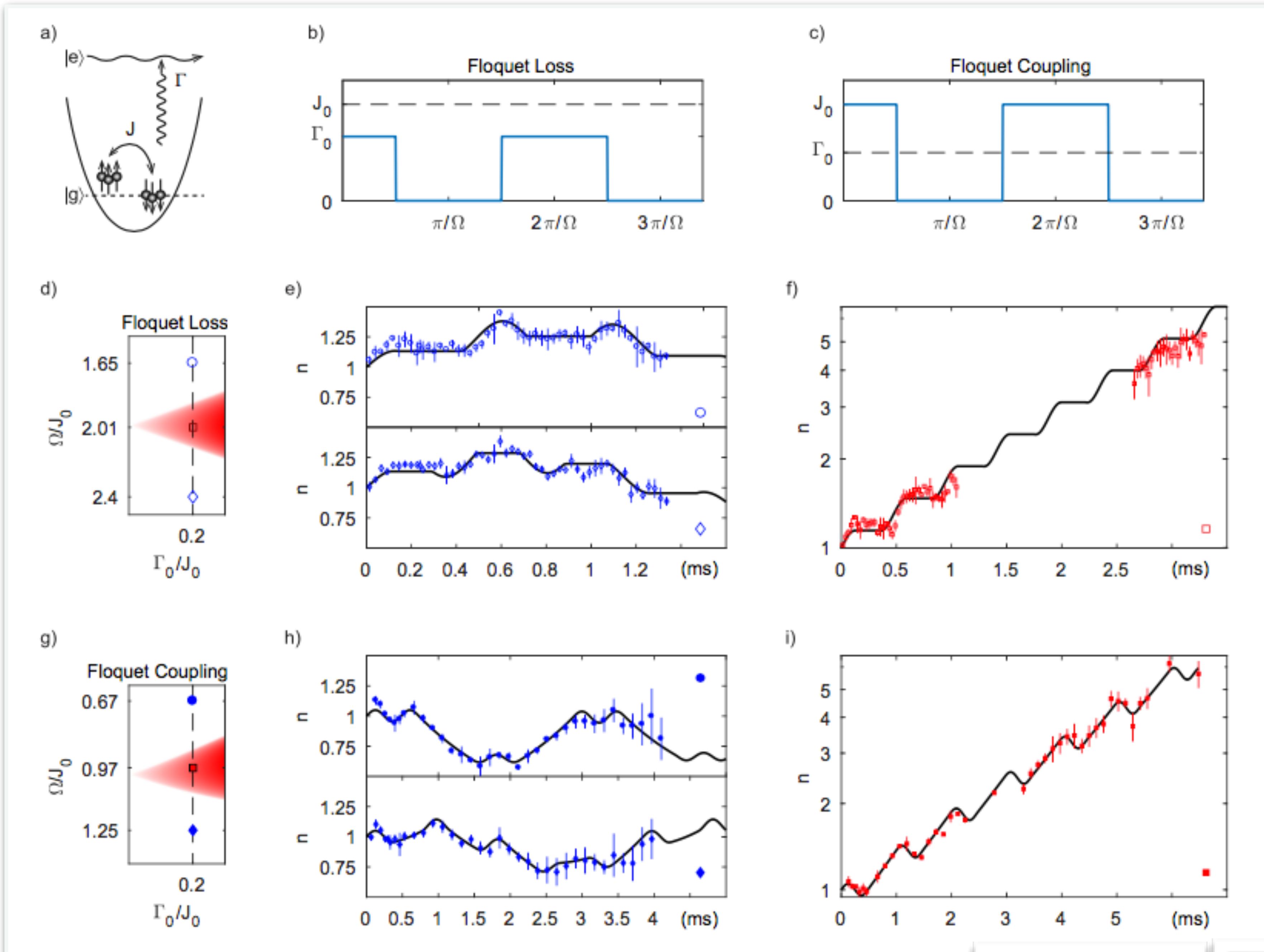
Floquet PT-breaking in a ultra cold gas (^6Li)

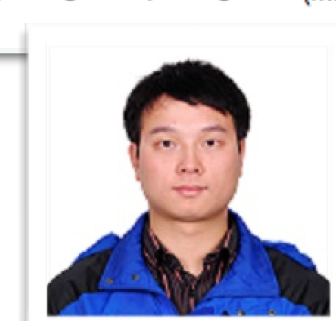
~0.16M ^6Li

@ T_f = 10 μK





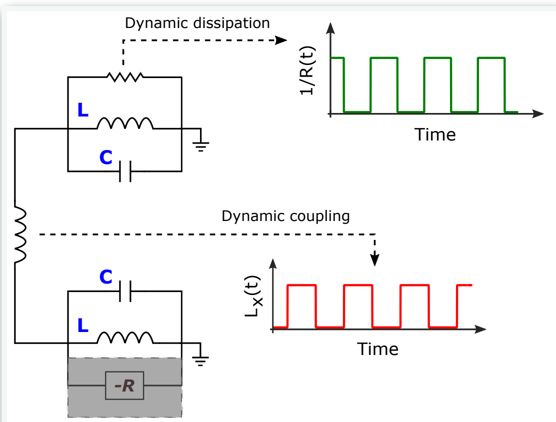


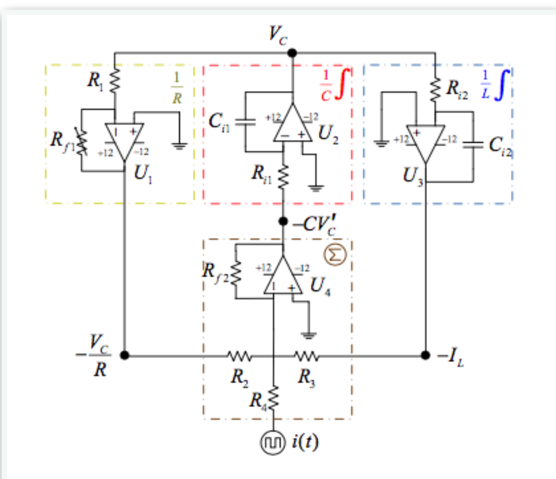


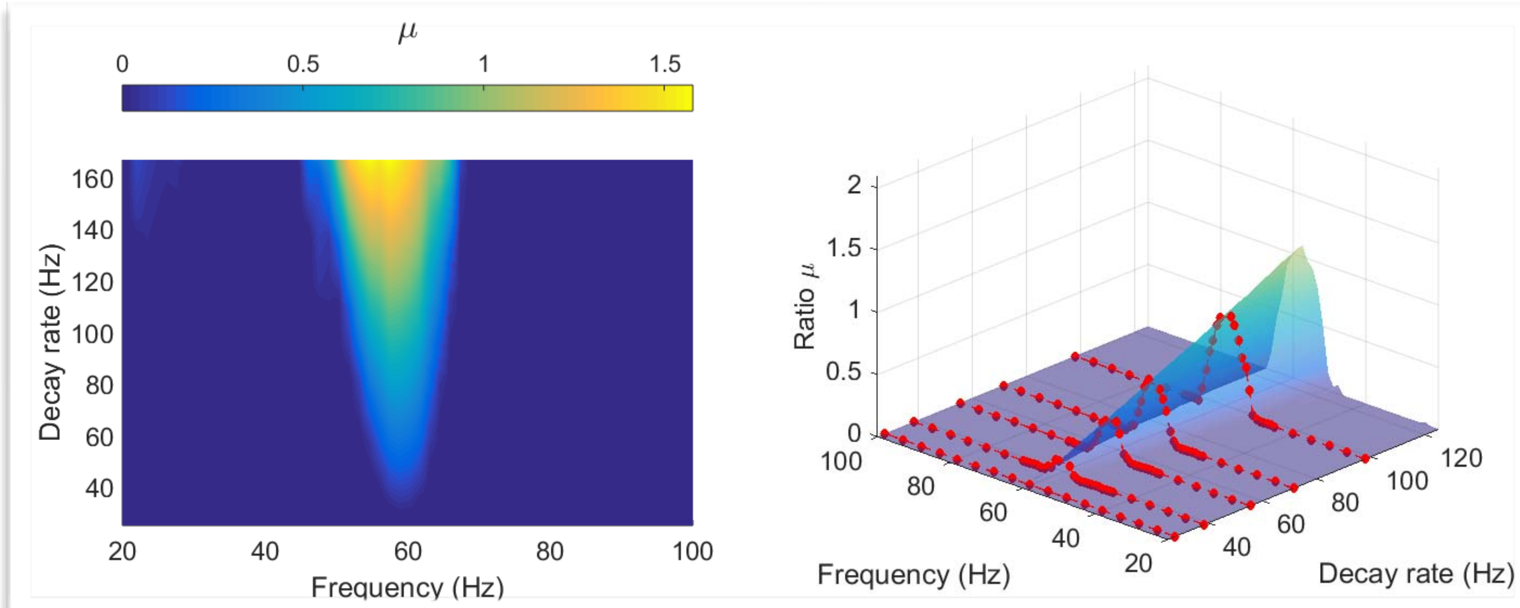
Access PT transitions with minimal loss!

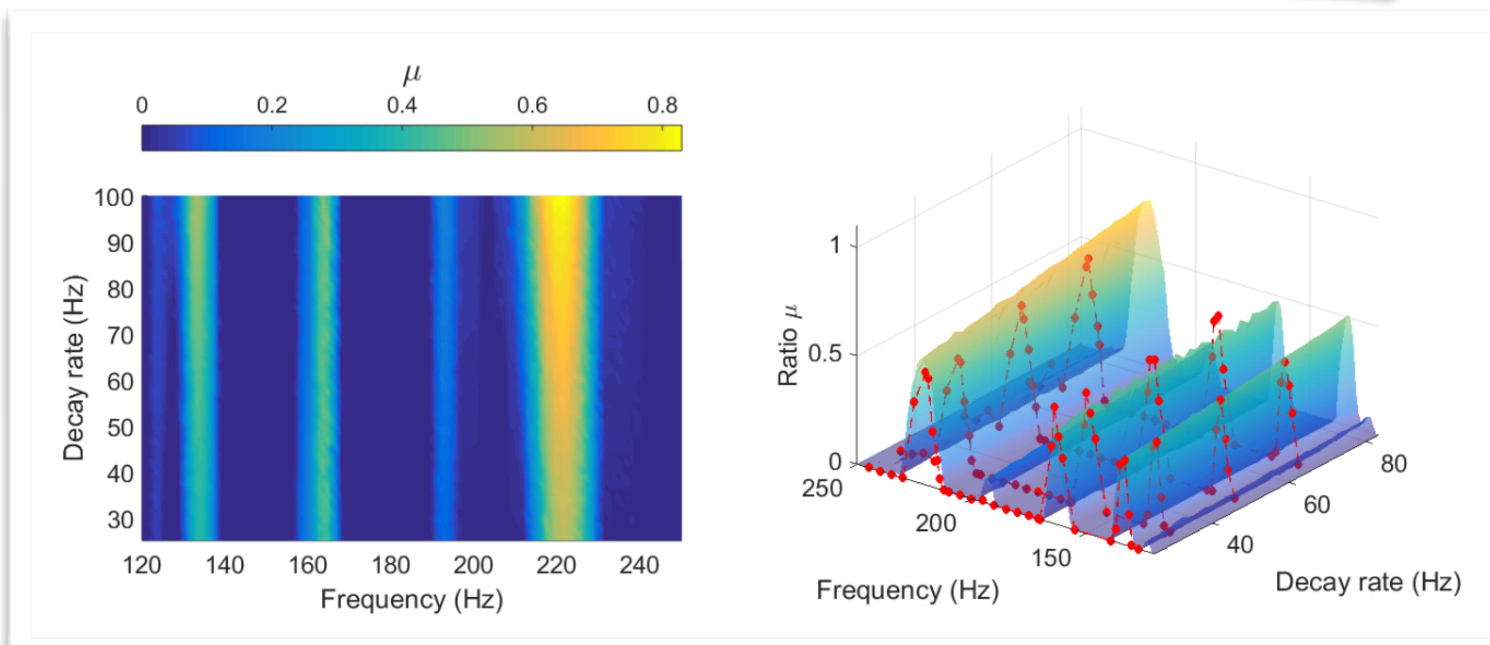
arXiv:1805.08393

PT transitions in synthetic electrical circuits









Nonlinearities in dissipation or time-delays possible

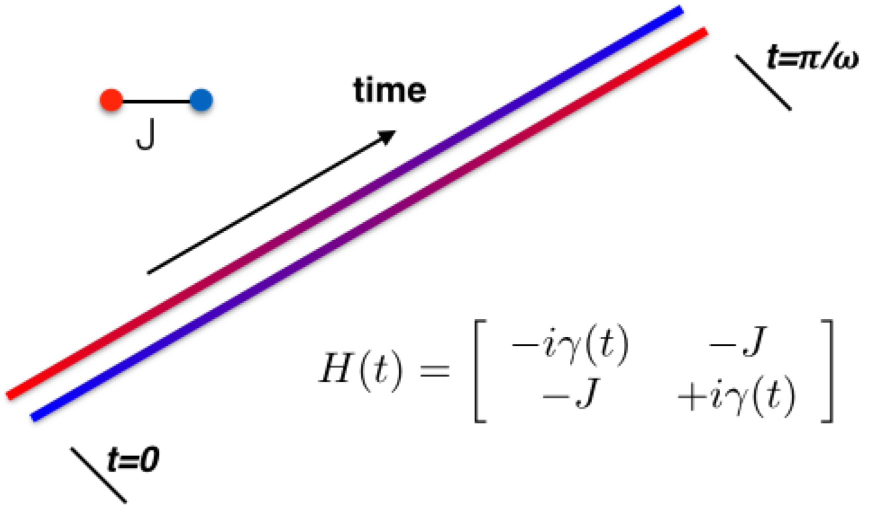
PRA 90, 040101(R) (2014)
PRA 92, 042103 (2015)

(Passive) PT Floquet model

Static case: single PT transition.

High frequencies ω: no PT breaking.

Resonance: PTB for small gain-loss.



$$H(t) = \begin{bmatrix} -i\gamma(t) & -J \\ -J & +i\gamma(t) \end{bmatrix}$$

$$H = -J\sigma_x + i\Gamma(t)\sigma_z/2$$

$$i\Gamma(t) = i\Gamma_0 \mathrm{Square}(\Omega t)$$