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Noise-Induced Quantum Synchronization and Entanglement in a Quantum Analogue of Huygens' Clock

Bhavay Tyagi, Hao Li, Eric R. Bittner,* Andrei Piryatinski, and Carlos Silva-Acuña*

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08/2024

Asymmetry Amplification by a Nonadiabatic Passage through a Critical Point

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(Dated: August 29, 2024)

arXiv: 2408.15897
PRA: In Review

10/2024

Noise-induced synchronization in coupled quantum oscillators

Eric R. Bittner and Bhavay Tyagi
Department of Physics, University of Houston, Houston, Texas, 77204, United States. [a)]

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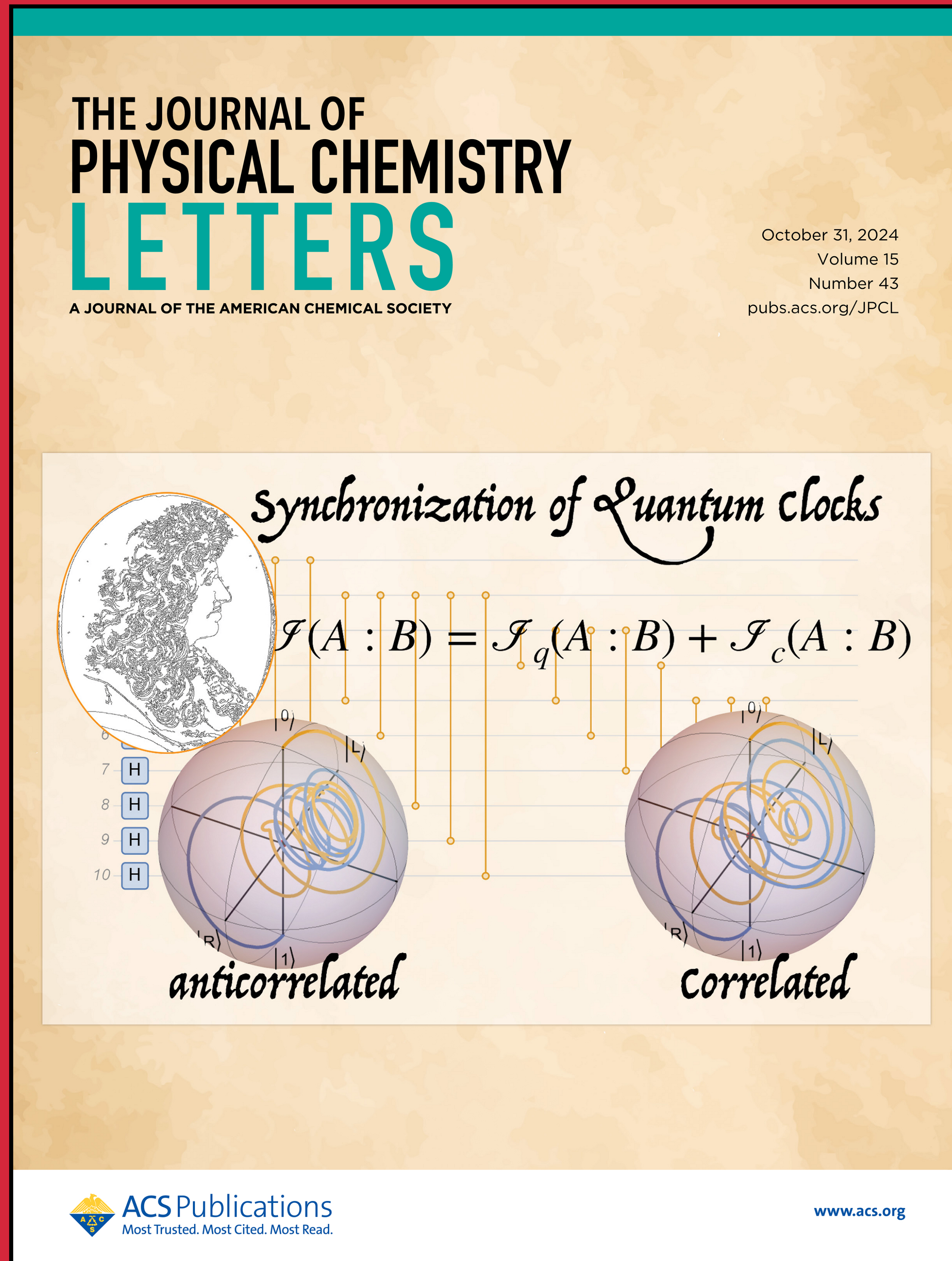
JCP: Accepted (02/2025)

Bhavay Tyagi
Advisor: Prof. Eric R. Bittner
Theoretical Chemical Physics Group

Physics Research Day 2025



A Big (sometimes solvable) Problem

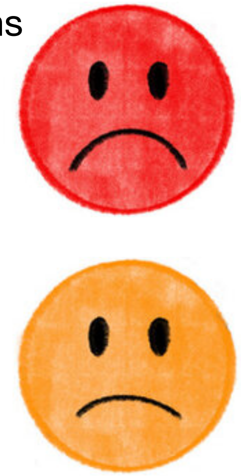
- The Problem: Decoherence

Thermal Fluctuations

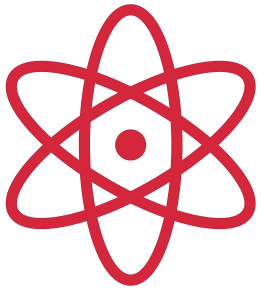
Nuclear, Electronic and Vibrational Fluctuations

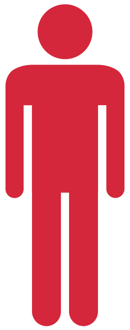
Even in the most ideal case

Vacuum and Fields Fluctuations



- The Want: To make our system robust against this or at least control it.





$\tau_P = 10^{-3}s$

$\tau_D = 10^{-6}s$ $\tau_D = 10^{-30}s$ $\tau_P = 100ms$

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A Big (sometimes solvable) Problem

- The Problem: Decoherence

- The Want: To make our system robust against this or at least control it.

- The Big Idea: What if this noisy environment is actually a ally.

- The Metrics of Success: Increased coherence time, understand transport of quantum excitations/information.

Correlated noise enhancement of coherence and fidelity in coupled qubits

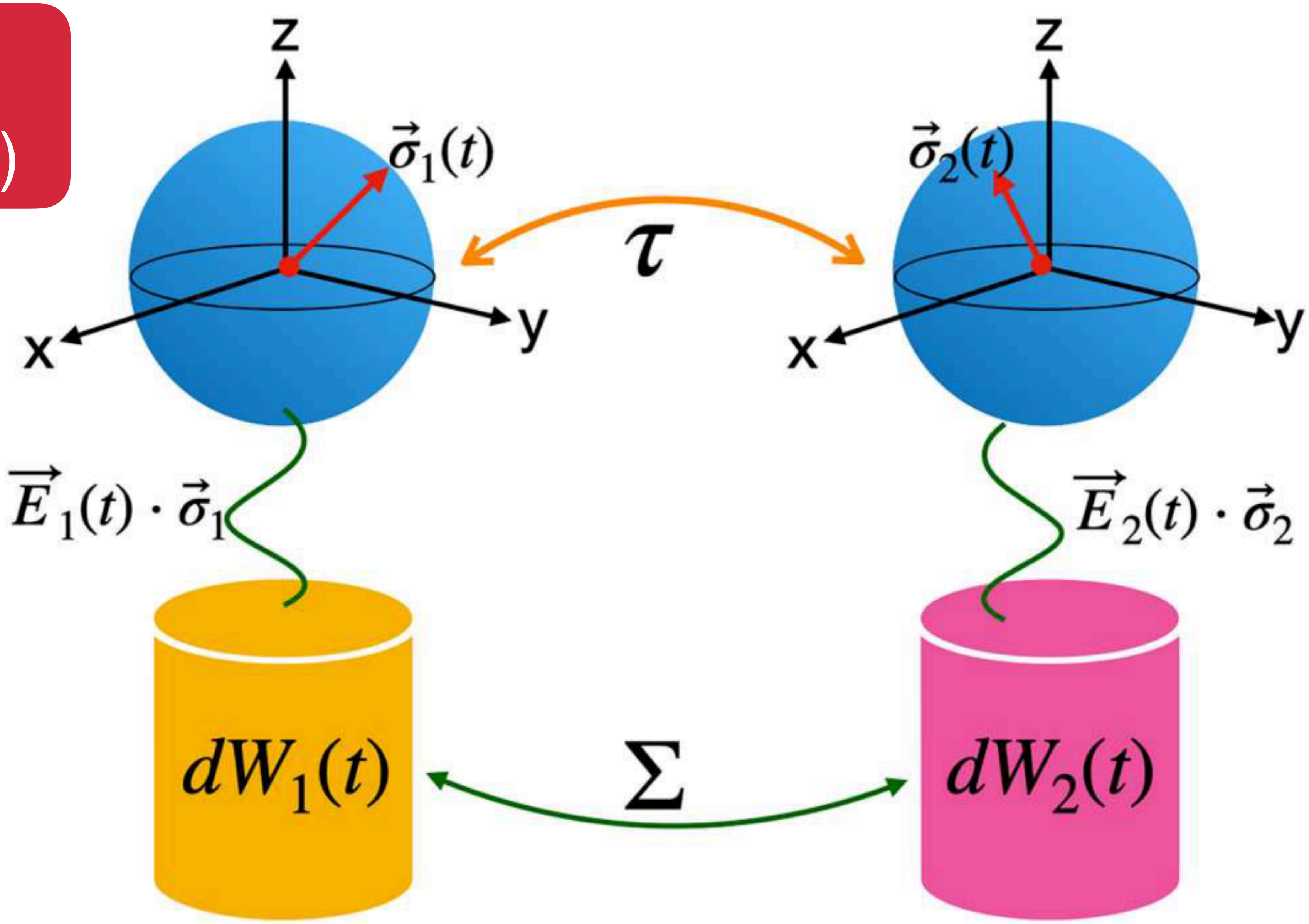
Eric R. Bittner[a,b], Hao Li[a], S. A. Shah[b,c], Carlos Silva-Acuña[d] and Andrei Piryatinski[c]

PHILOSOPHICAL MAGAZINE
2024, VOL. 104, NOS. 13–14, 630–646
https://doi.org/10.1080/14786435.2024.2341011

The Toy (Minimal, solvable) Model

$$H = H_S + H_{SE}$$

(The von Neumann Style)



$d\mathbf{E} = -\mathbf{A}\,.\,\mathbf{E}dt + \mathbf{B}\,.\,d\mathbf{W}$ (SDE: Ornstein-Uhlenbeck)

$\mathbf{\Sigma} dt \delta(t - t') = d\mathbf{W} \otimes d\mathbf{W}$ (correlation matrix)

Correlated noise enhancement of coherence and fidelity in coupled qubits

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The Toy (Minimal, solvable) Model

$H = H_S + H_{SE}$
(The von Neumann Style)

Unitary Evolution

Liouville-von Neumann Equation

$$\frac{d\rho_{SE}}{dt} = -i[H, \rho_{SE}] + \sum_i D_i(\rho_{SE})$$

Dissipation superoperator

$$D_i(\rho_{SE}) = L_i \rho_{SE} L_i^\dagger - \frac{1}{2}\{L_i^\dagger L_i, \rho_{SE}\} + L_i' \rho_{SE} L_i'^\dagger - \frac{1}{2}\{L_i'^\dagger L_i', \rho_{SE}\}$$

- $\xi = 0 \implies$ Uncorrelated Noise
- $\xi = -1 \implies$ Anti-correlated Noise
- $\xi = +1 \implies$ Correlated Noise

$$L_\pm = \sqrt{\frac{1 \pm \xi}{2}}(L_1 \pm L_2) \qquad L'_\pm = \sqrt{\frac{1 \pm \xi}{2}}(L'_1 \pm L'_2)$$

The correlation parameter!
$-1 \leq \xi \leq +1$

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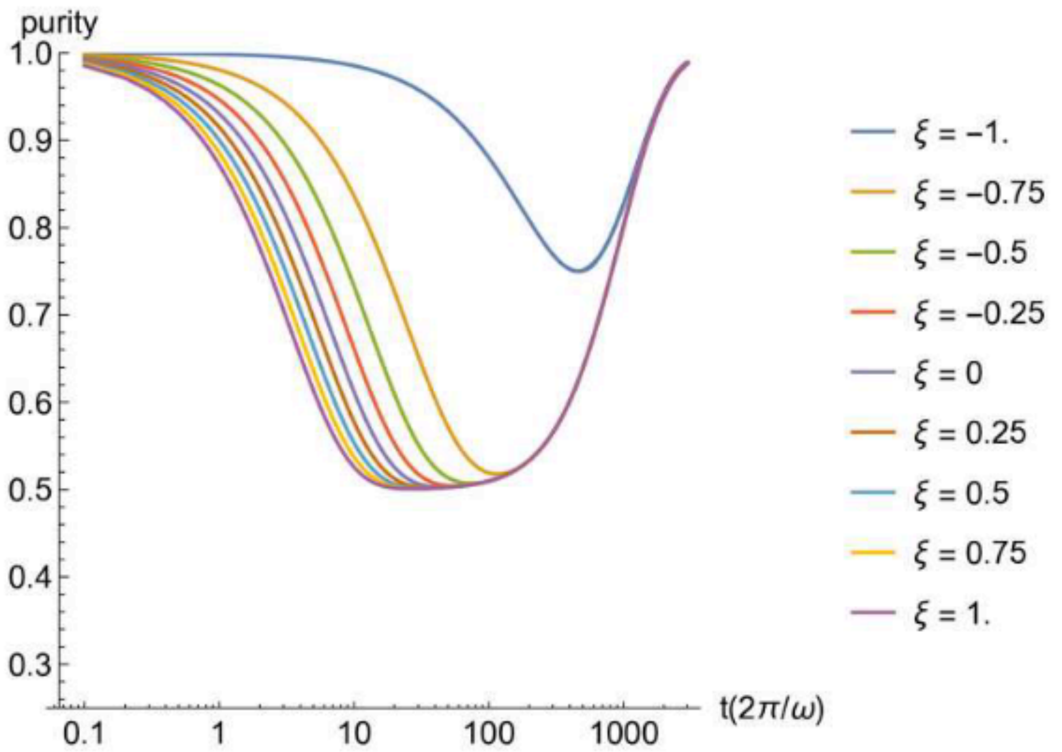
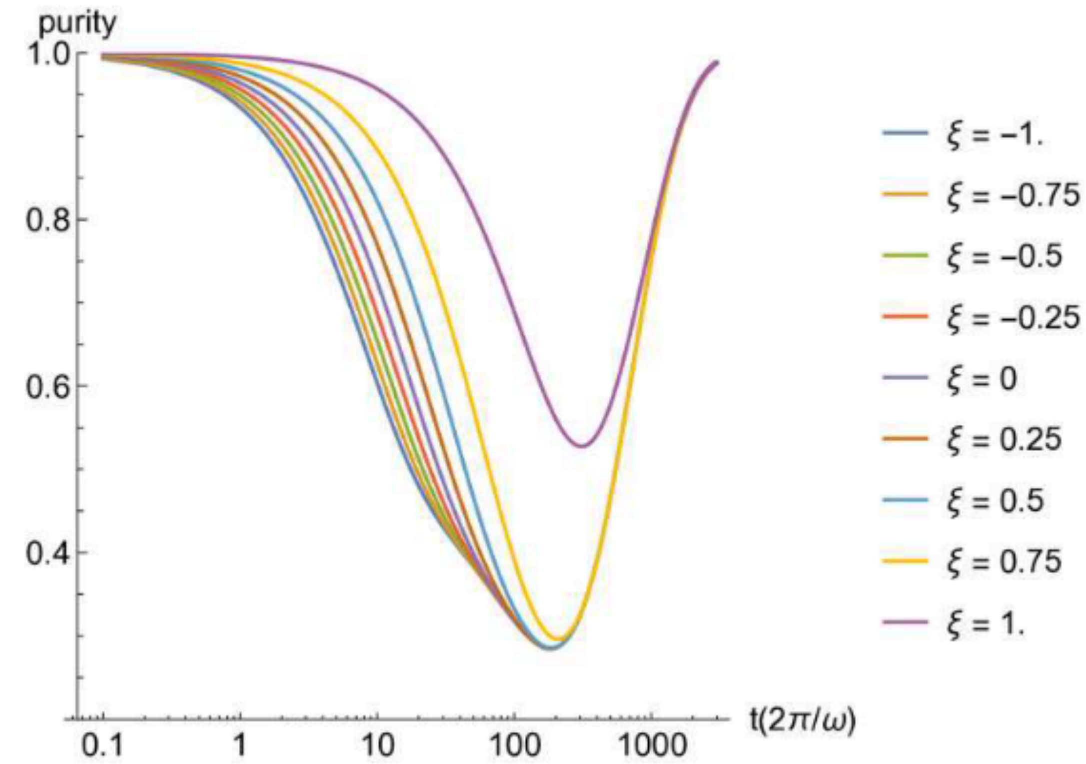
We see it, but wait…



$Tr(\rho^2)$



$$\Phi^+ = \frac{1}{2}(00 + 11)$$

Increased coherence time

$$\Psi^+ = \frac{1}{2}(01 + 10)$$

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Lets Re-search

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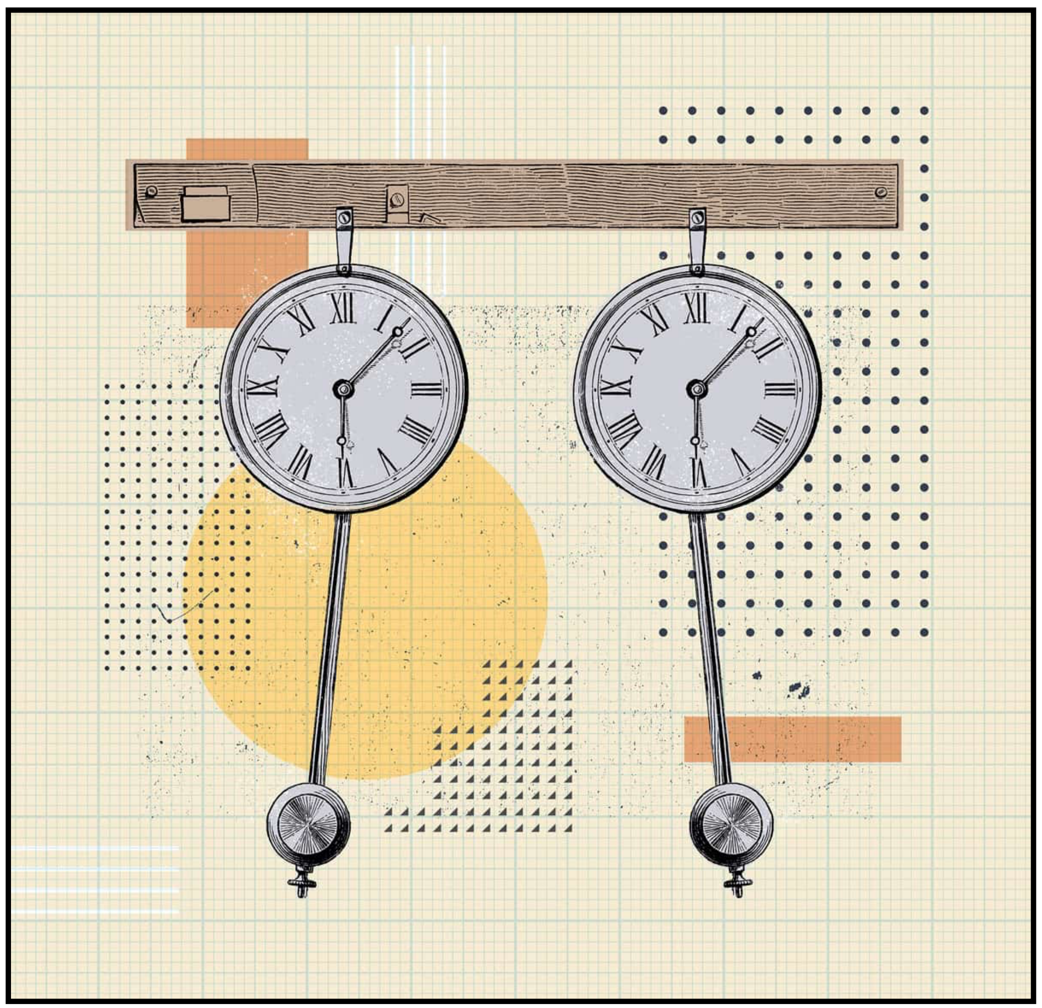

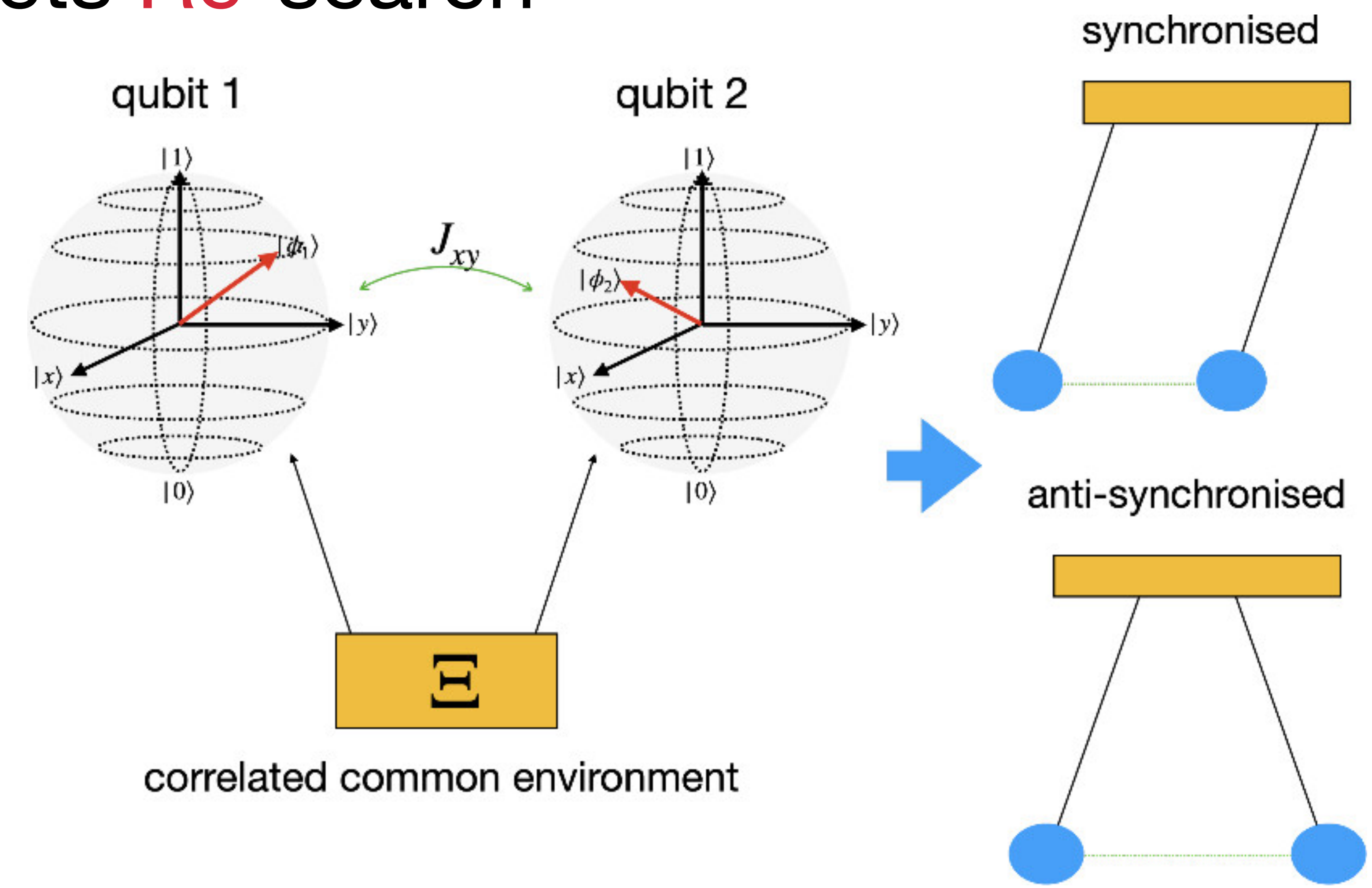

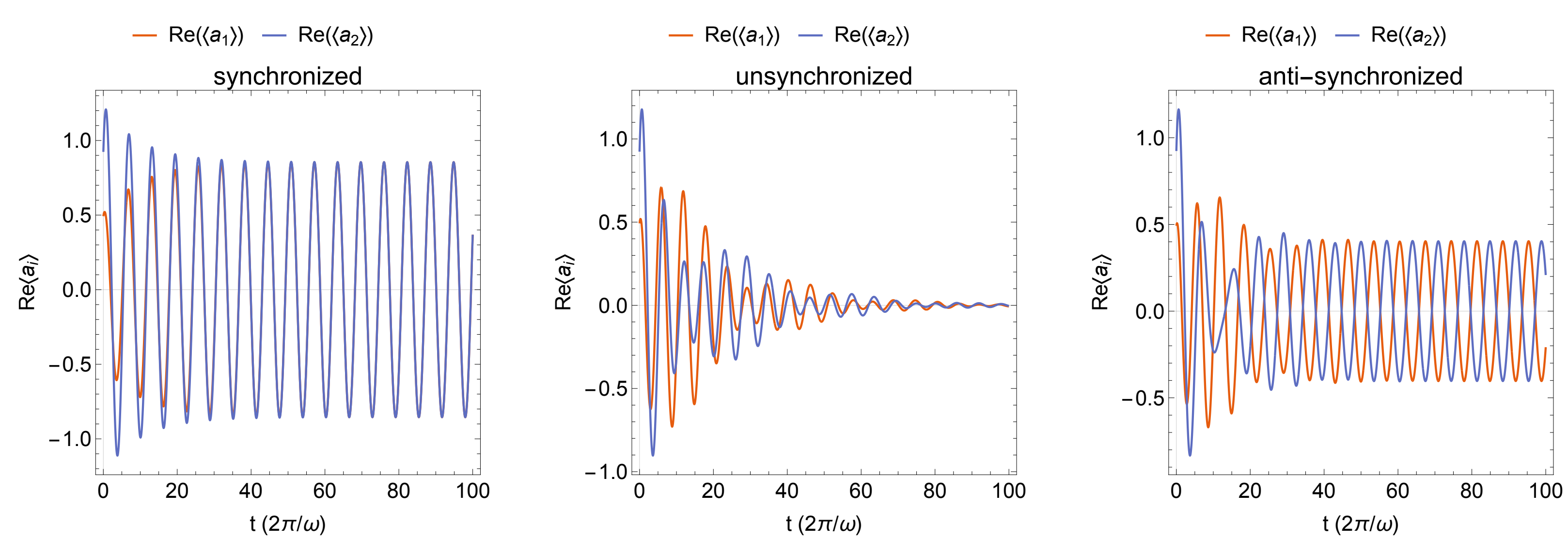

https://physicsworld.com/a/the-secret-of-the-synchronized-pendulums/

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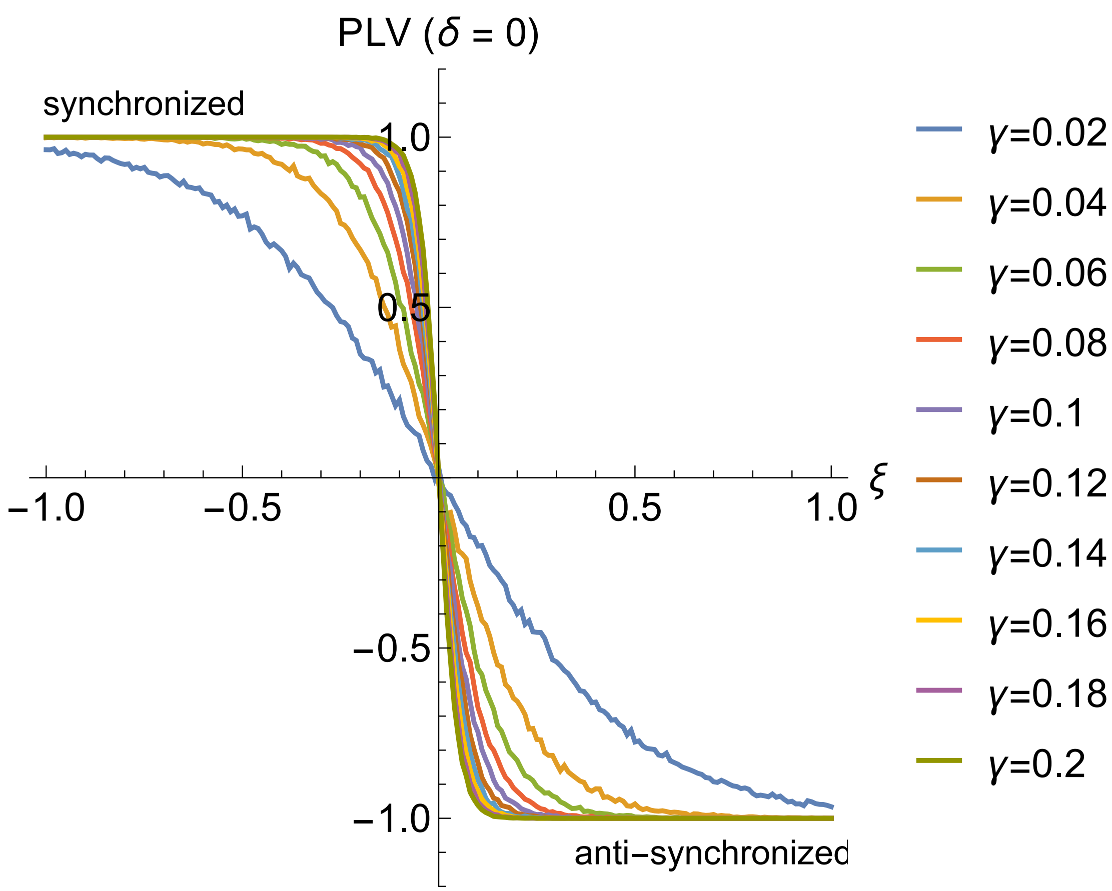
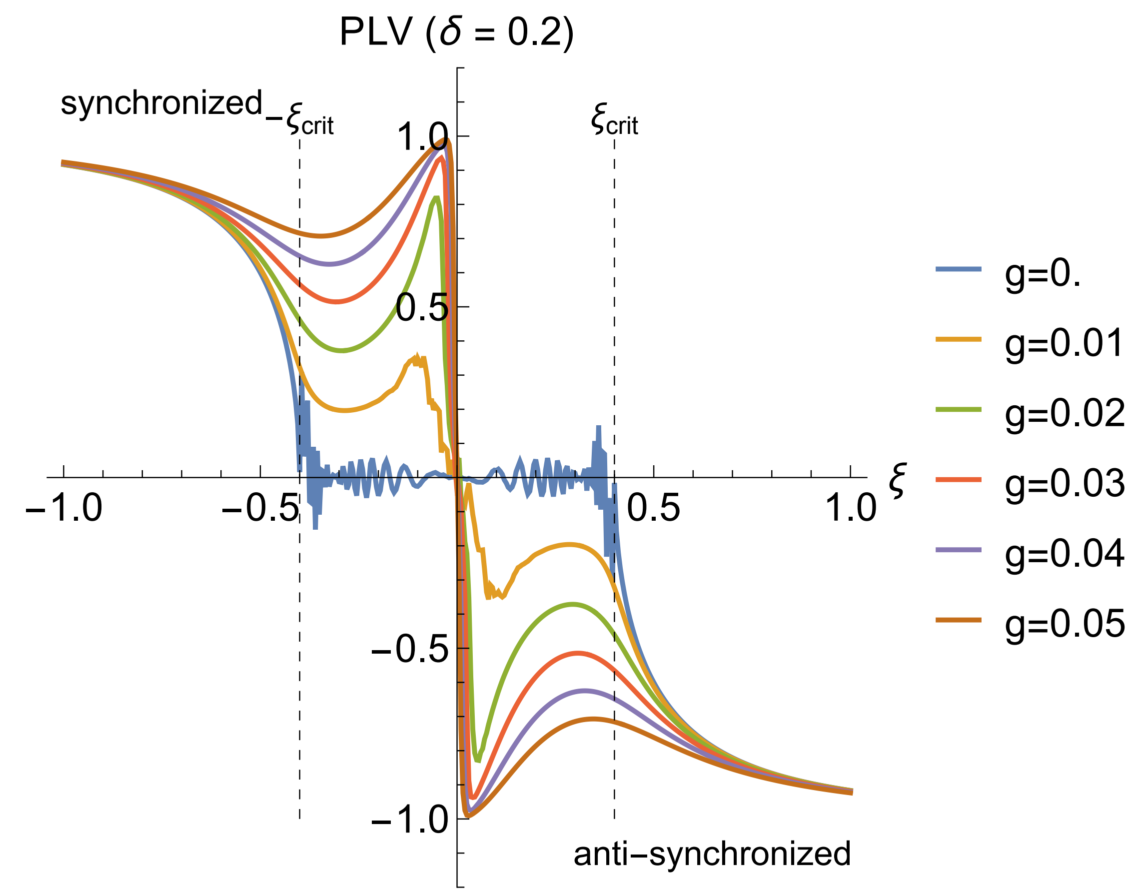
Oh really?





Oh that's cool!

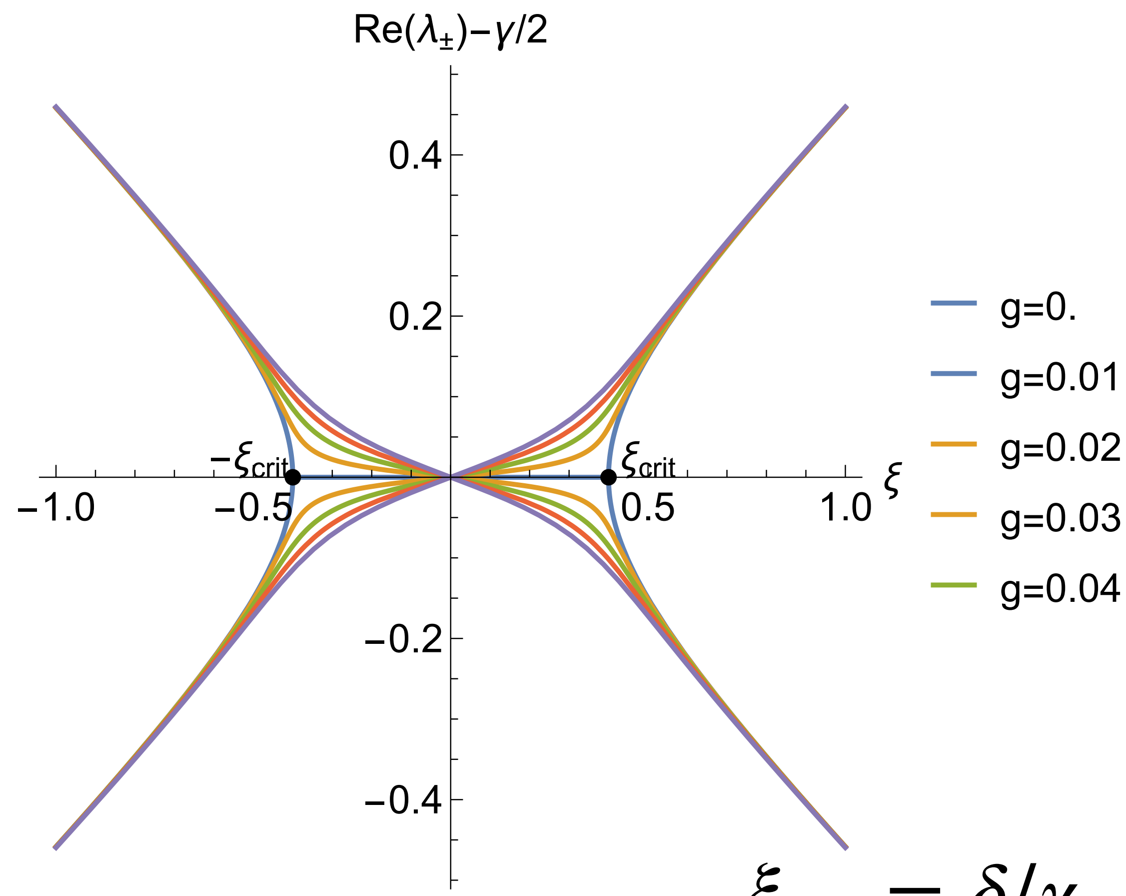
A novel and universal result.

$\mathscr{PT}$ symmetry breaking.

Decoherence free subspaces

What does the future hold?

- System on different topologies.
- Larger system size.
- ξ is emergent in finite dimensional systems.



$$\xi_{crit} = \delta/\gamma$$

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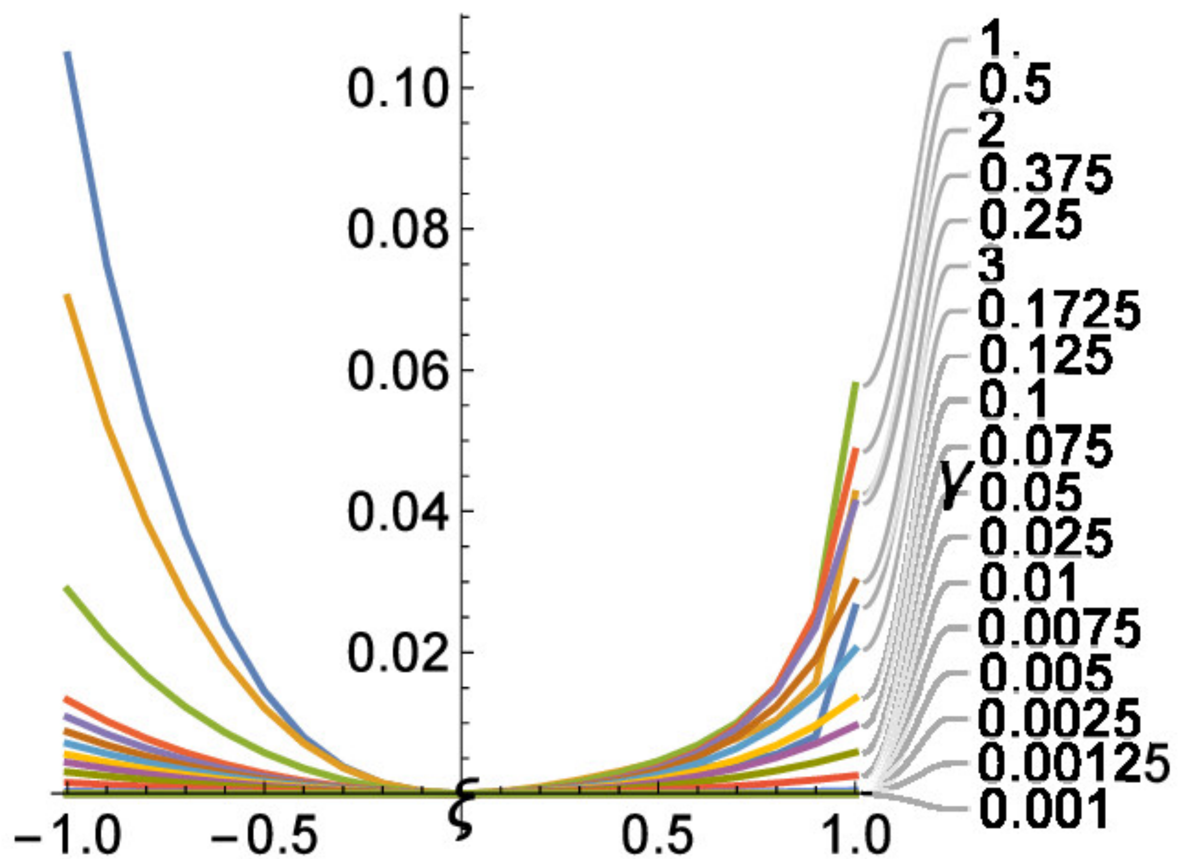
We did it, again!

$$\rho_{SE} \underset{\text{Long-time}}{\rightarrow} diag(\rho_{SE}) = \begin{pmatrix} ii & \times & \times\cdots & \times \\ \times & ii & \times\cdots & \times \\ \times & \times & ii\cdots & \times \\ \times & \times & \times\cdots & ii \end{pmatrix}$$

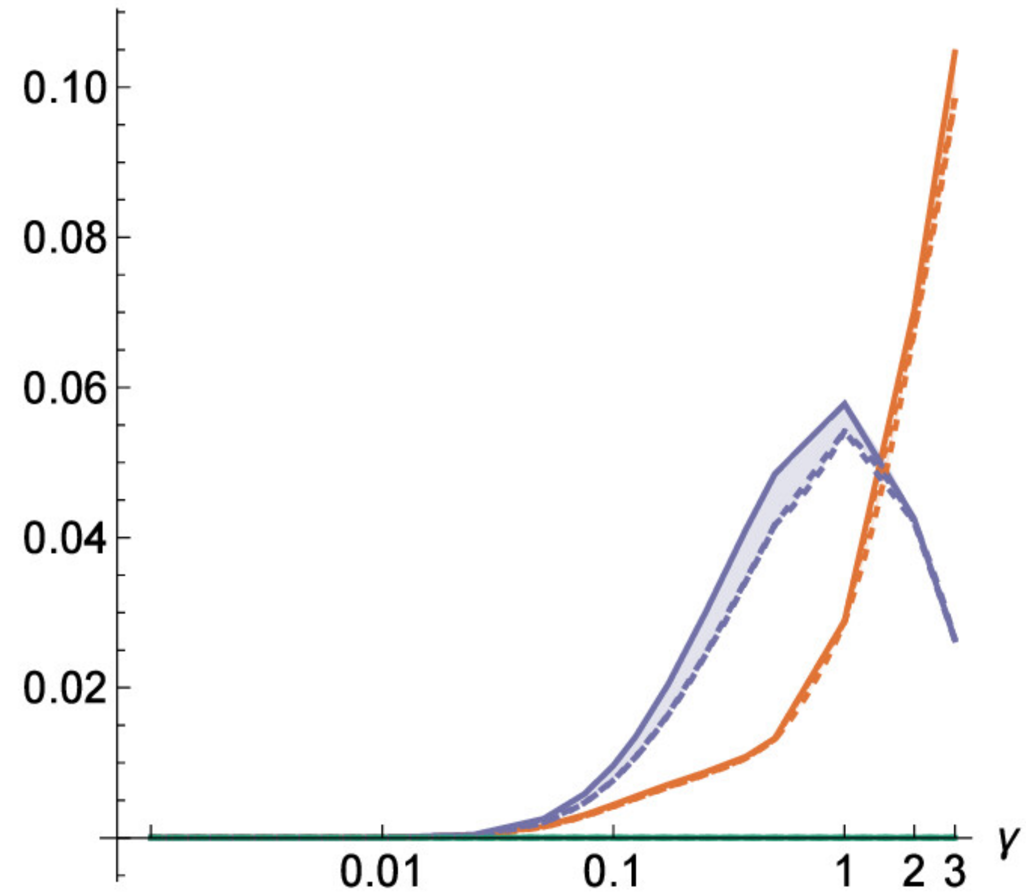
J_{xy}=0

I(A:B) $= S_A + S_B - S_{AB}$



J_{xy}=0

I(A|B) = Classical Correlations + Quantum Correlations



Decoherence (kind of) helped us.

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Oh that's way cooler!

A novel and universal result.

$$D_i(\rho_{SE}) = L_i\rho_{SE}L_i^\dagger - \frac{1}{2}\{L_i^\dagger L_i, \rho_{SE}\} + L_i'\rho_{SE}L_i'^\dagger - \frac{1}{2}\{L_i'^\dagger L_i', \rho_{SE}\}$$

$$L_\pm = \sqrt{\frac{1 \pm \xi}{2}} L_1 \pm L_2 \qquad L_\pm' = \sqrt{\frac{1 \pm \xi}{2}} L_1' \pm L_2'$$

- $\xi = 0 \implies$ Cross dissipation channels vanish.
- $\xi = -1 \implies$ Symmetric terms vanish.
- $\xi = +1 \implies$ Anti-symmetric terms vanish.

Quantum Noise-Cancelling Headphones

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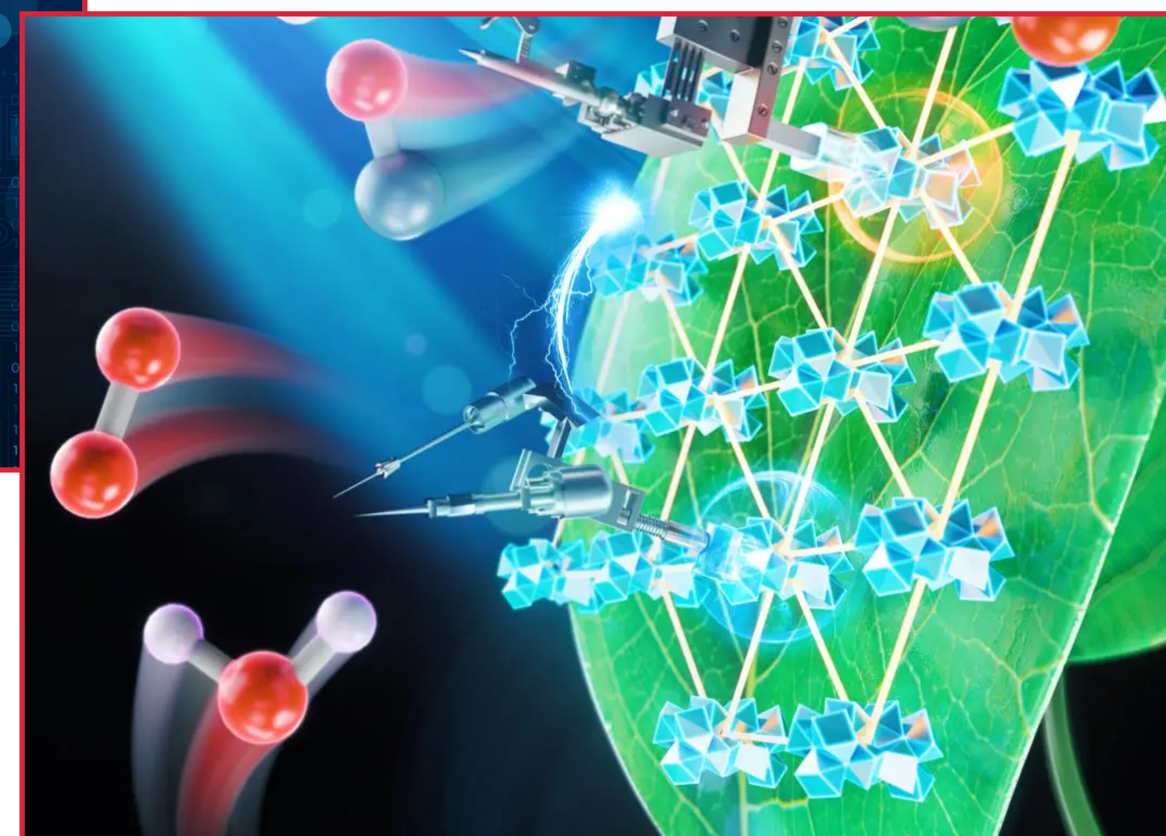
Real-world impact

https://www.einfochips.com/blog/quantum-computing-in-artificial-intelligence-around-the-corner/

"It is still an unending source of surprise for me how a few scribbles on a blackboard or on a piece of paper can change the course of human affairs."
- Stanislaw Ulam



Peter Allen/University of Chicago

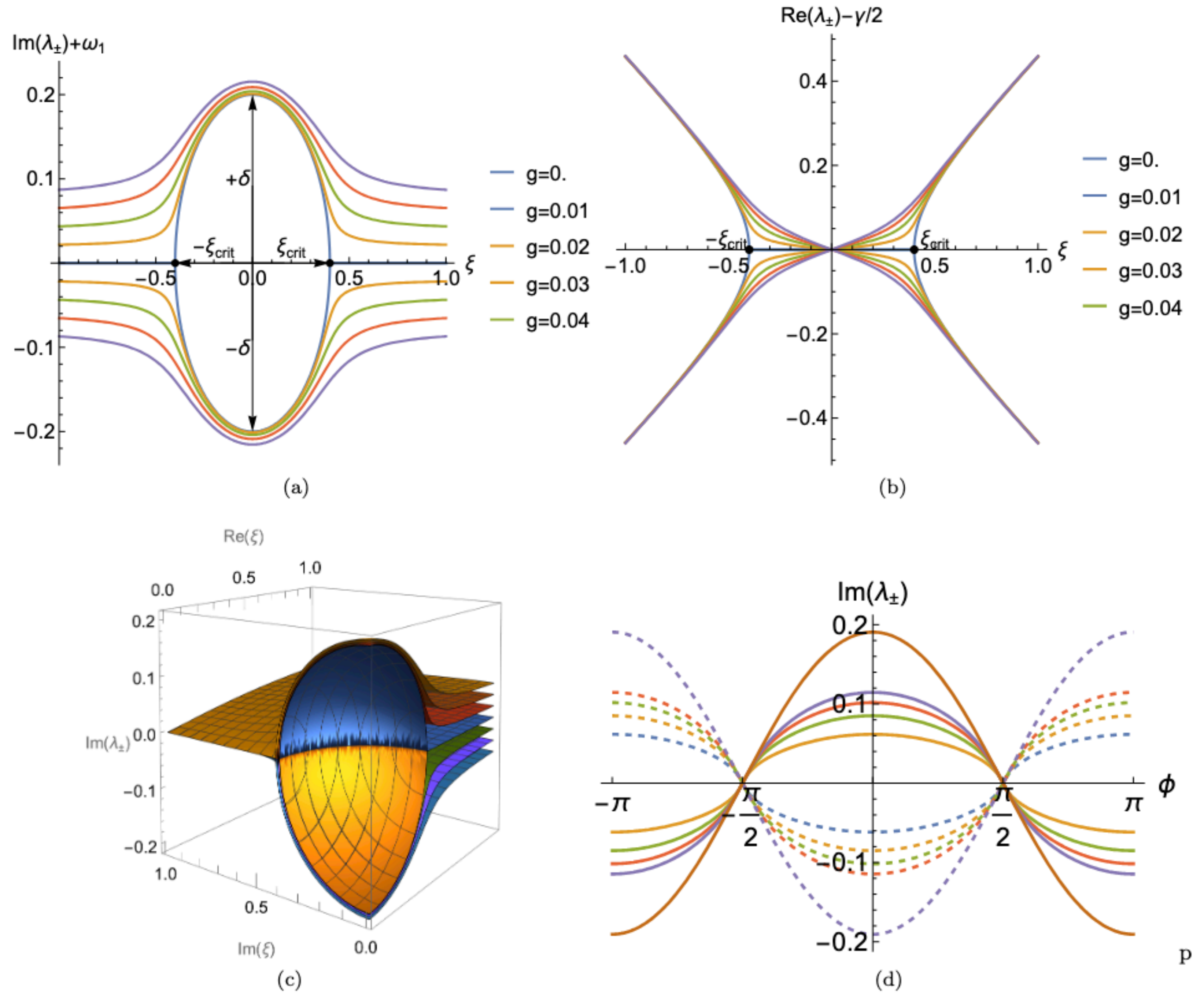
Thank you for your attention!

Back Up

$$\text{PLV} = \lim_{t_2 \to \infty} \frac{1}{t_2 - t_1} \text{Re} \left\langle \int_{t_1}^{t_2} e^{i(\phi_1(t) - \phi_2(t))} dt \right\rangle$$

$$D_\Pi(A \,|\, B) = I(A : B) - J_\Pi(A \,|\, B)$$

$$J_\Pi(A \,|\, B) = S(\rho_A) - S_\Pi(A \,|\, B)$$



p

FIG. 1. Imaginary (a) and Real (b) components of the eigenvalues of the non-Hermitian dynamical matrix in Eq. 19 for various parametric values: $\delta = \omega_1 - \omega_2 = 0.2$, $\gamma = 0.5$ and increasing values of exchange coupling $g = 0$ to $g = 0.04$ The system enters the spontaneous synchronized domain above the critical coupling $\xi_{crit} = \delta/\gamma$. (c) Analytical continuation of (b) onto the complex ξ-plane for showing the presence of a branch cut starting at $\pm i\xi_{crit}$. (d) Slice through (c) along $|\xi_{crit}|$ passing through the exceptional points at $\phi = \pm\pi/2$ for $g > 0$. Solid: Im(λ_+). Dashed: Im(λ_-).