Simulating Open Quantum Systems and Their Environments with Matrix Product States

Grazia Di Bello

Università degli Studi di Napoli Federico II

INFN Napoli
Istituto Nazionale di Fisica Nucleare
Sezione di Napoli

cost
EUROPEAN COOPERATION
IN SCIENCE & TECHNOLOGY

Funded by
the European Union

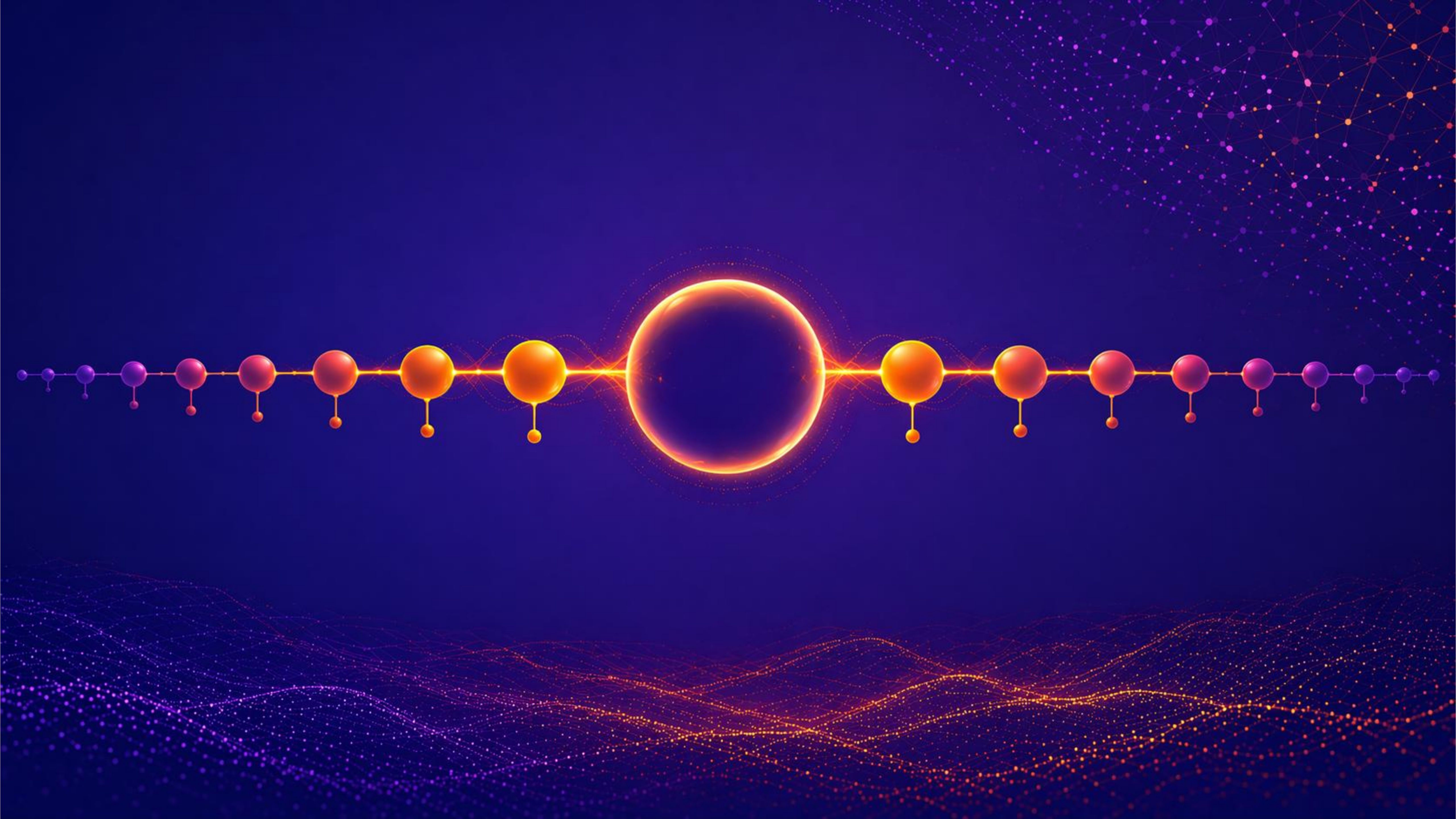
QOpen
Many-body Open Quantum Systems

COST Action CA24109 – QOpen

https://cost.eu

https://qopen.eu/

COST (European Cooperation in Science and Technology) is a funding agency for research and innovation networks. Our Actions help connect research initiatives across Europe and enable scientists to grow their ideas by sharing them with their peers. This boosts their research, career and innovation.



Simulating Open Quantum Systems and Their Environments with Matrix Product States

LISBON

Grazia Di Bello

Università degli Studi di Napoli Federico II

INFN Napoli
Istituto Nazionale di Fisica Nucleare
Sezione di Napoli

cost
EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

Funded by the European Union

QOpen
Many-body Open Quantum Systems

COST Action CA24109 – QOpen

https://cost.eu

https://qopen.eu/

COST (European Cooperation in Science and Technology) is a funding agency for research and innovation networks. Our Actions help connect research initiatives across Europe and enable scientists to grow their ideas by sharing them with their peers. This boosts their research, career and innovation.

Open quantum systems models

Qubit–boson models & explicit dissipation

GDB, et al., Eur. Phys. J. Plus 138, 135 (2023).

Open quantum systems models

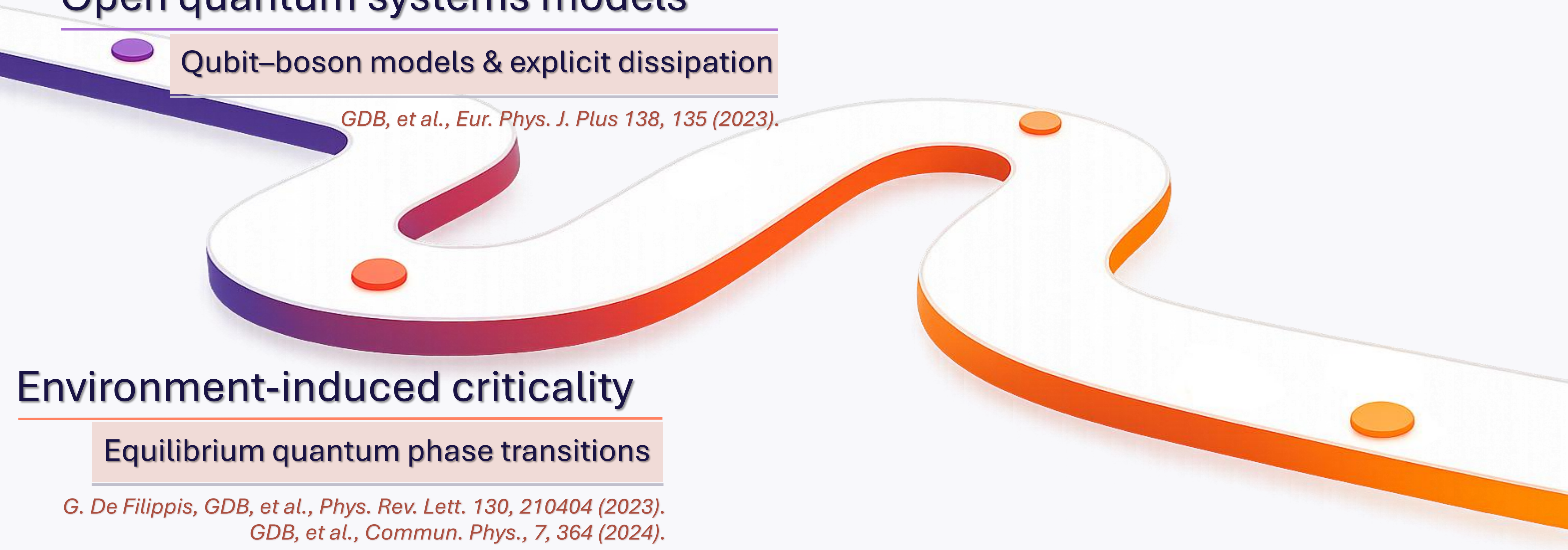
Qubit–boson models & explicit dissipation

GDB, et al., Eur. Phys. J. Plus 138, 135 (2023).

Environment-induced criticality

Equilibrium quantum phase transitions

G. De Filippis, GDB, et al., Phys. Rev. Lett. 130, 210404 (2023).
GDB, et al., Commun. Phys., 7, 364 (2024).



Open quantum systems models

Qubit–boson models & explicit dissipation

GDB, et al., Eur. Phys. J. Plus 138, 135 (2023).

Environment-induced criticality

Equilibrium quantum phase transitions

G. De Filippis, GDB, et al., Phys. Rev. Lett. 130, 210404 (2023).
GDB, et al., Commun. Phys., 7, 364 (2024).

Applications: work extraction & sensing

Ergotropy & quantum Fisher information

GDB, et al., Quantum Sci. Technol. 10, 015049 (2024).
F. Formicola, GDB, et al., Phys. Rev. Res. 7, 043086 (2025).
D. Parlato, GDB, et al., Phys. Rev. B 112, 224314 (2025).

Applications: work extraction & sensing

Ergotropy & quantum Fisher information

GDB, et al., Quantum Sci. Technol. 10, 015049 (2024).
F. Formicola, GDB, et al., Phys. Rev. Res. 7, 043086 (2025).
D. Parlato, GDB, et al., Phys. Rev. B 112, 224314 (2025).

Open quantum systems models

Qubit–boson models & explicit dissipation

GDB, et al., Eur. Phys. J. Plus 138, 135 (2023).

Environment-induced criticality

Equilibrium quantum phase transitions

G. De Filippis, GDB, et al., Phys. Rev. Lett. 130, 210404 (2023).
GDB, et al., Commun. Phys., 7, 364 (2024).

Recent past: non-equilibrium effects

Kibble-Zurek mechanism & quantum Mpemba effect

T. Pirozzi, GDB, et al., arXiv:2603.16709 (2026).
P. Chirico, GDB, et al., arXiv:2603.17565 (2026).

Open quantum systems models

Qubit–boson models & explicit dissipation

GDB, et al., Eur. Phys. J. Plus 138, 135 (2023).

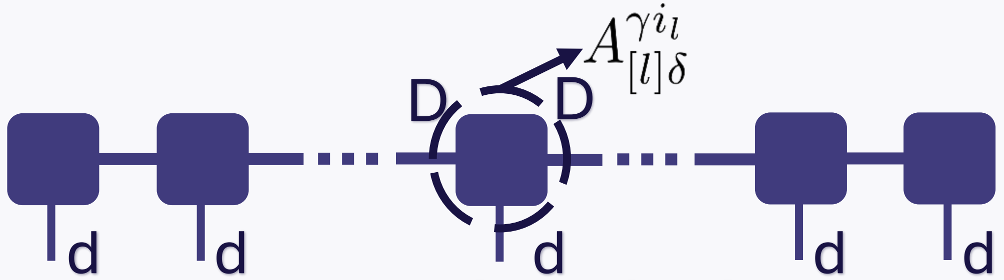
SIMULATING OPEN QUANTUM SYSTEMS

SIMULATING OPEN QUANTUM SYSTEMS

- no exact solution in general
- perturbative methods fail at strong coupling
- exact diagonalization is not scalable

SIMULATING OPEN QUANTUM SYSTEMS

- no exact solution in general
- perturbative methods fail at strong coupling
- exact diagonalization is not scalable



MATRIX PRODUCT STATE

[M. C. Bañuls, Annu. Rev. Condens. Matter Phys., 14, 173-191 (2023).]

$S_{\mathcal{N}/2} \leq \log(D)$

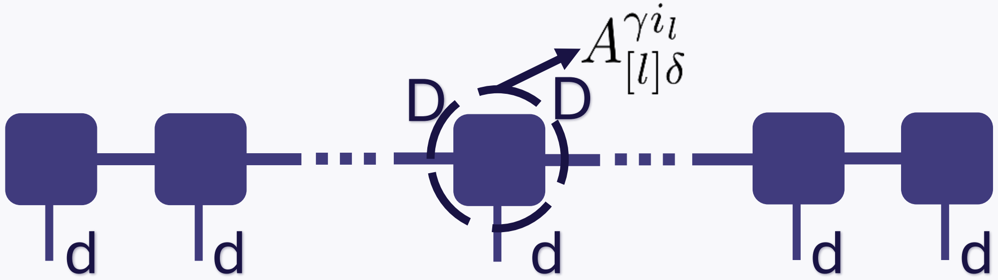
$\mathcal{N} D^2 d$ params

Ground state search (DMRG) and time evolution (TDVP)

Numerical effort correlates to entanglement

SIMULATING OPEN QUANTUM SYSTEMS

- no exact solution in general
- perturbative methods fail at strong coupling
- exact diagonalization is not scalable



MATRIX PRODUCT STATE

[M. C. Bañuls, Annu. Rev. Condens. Matter Phys., 14, 173-191 (2023).]

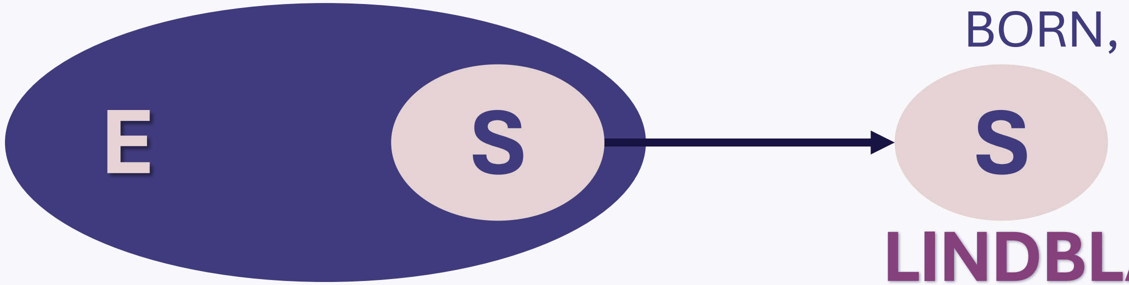
$S_{\mathcal{N}/2} \leq \log(D)$

$\mathcal{N} D^2 d$ params

Ground state search (DMRG) and time evolution (TDVP)

Numerical effort correlates to entanglement

BORN, MARKOV, SECULAR APPROX



$$\dot{\rho}(t) = \mathcal{L}\left[\rho(t)\right]$$

LINDBLAD MASTER EQUATION

[H. P. Breuer, & F. Petruccione, OUP Oxford (2002).]

MPS-based methods

MPS-based methods

Ground state search

[U. Schollwock, Ann. Phys., 326, 96192 (2011).]

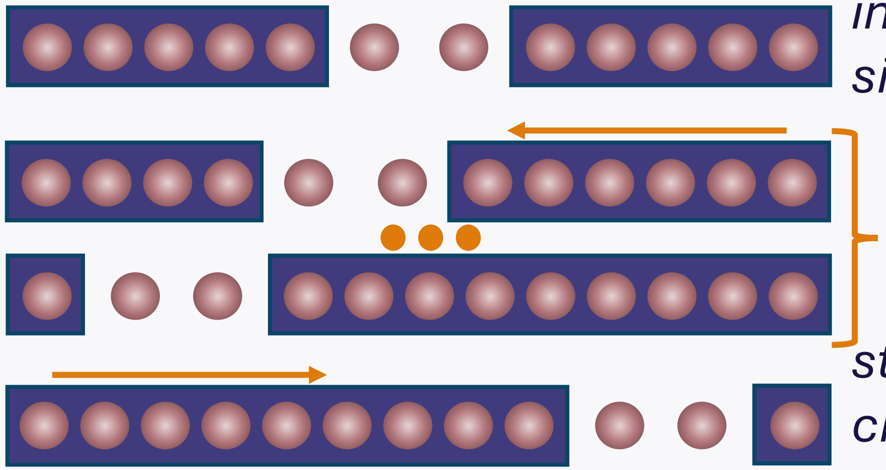
DMRG

MPS-based methods

Ground state search

[U. Schollwock, Ann. Phys., 326, 96192 (2011).]

DMRG



initial infinite-size warm-up

half sweep

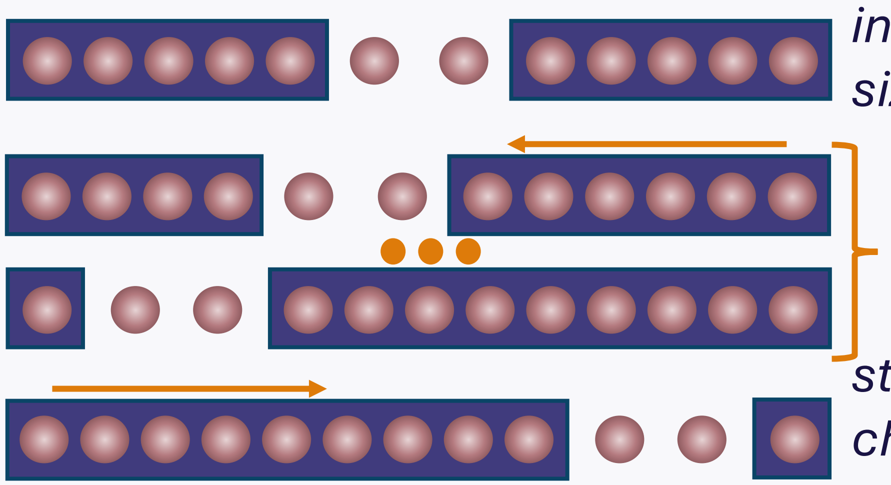
stop if energy change below a tolerance

MPS-based methods

Ground state search

[U. Schollwock, Ann. Phys., 326, 96192 (2011).]

DMRG



initial infinite-size warm-up

half sweep

stop if energy change below a tolerance

Time-dependent evolution

[J.Haegeman, et al., Phys. Rev. Lett., 107, 070601 (2011).]

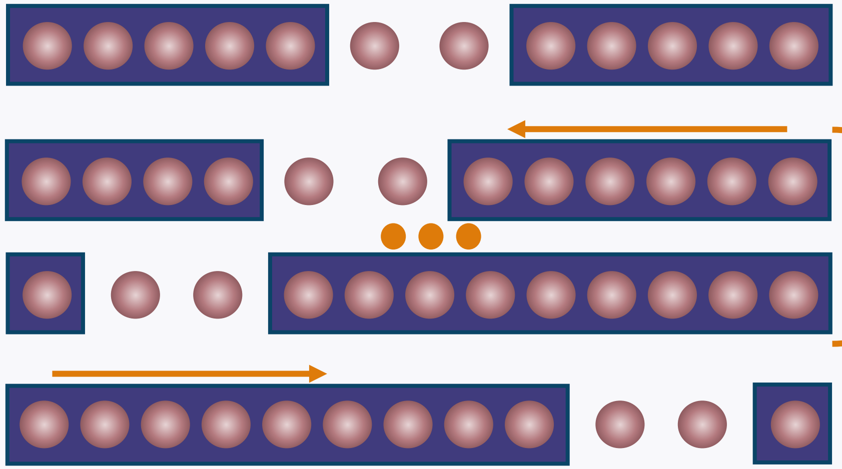
TDVP

MPS-based methods

Ground state search

[U. Schollwock, Ann. Phys., 326, 96192 (2011).]

DMRG



initial infinite-size warm-up

half sweep

stop if energy change below a tolerance

Time-dependent evolution

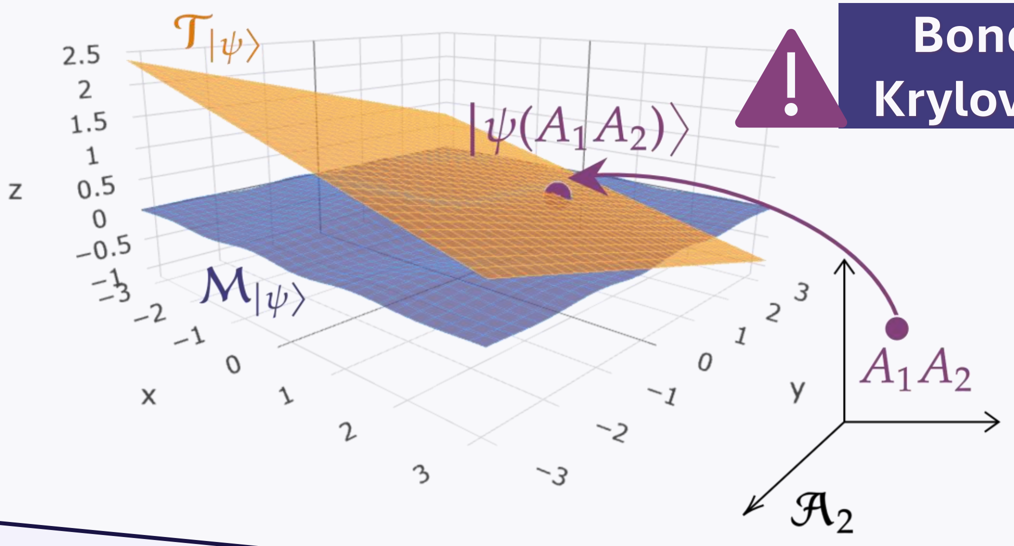
[J.Haegeman, et al., Phys. Rev. Lett., 107, 070601 (2011).]

TDVP

- Bigger time-step than W^I and W^{II}
- Time-step error $O(dt^3)$

$$-i\frac{d}{dt}|\psi\rangle = \hat{P}_{T_{|\psi\rangle}} H |\psi\rangle$$

Bond dim Krylov cutoff



HOW TO MODEL DISSIPATION

HOW TO MODEL DISSIPATION

$$H = \frac{p^2}{2M} + V(q) + \frac{1}{2}\sum_{\alpha=1}^{N}\left\{\frac{p_\alpha^2}{m_\alpha} + m_\alpha\omega_\alpha^2\left(x_\alpha - q\frac{c_\alpha}{m_\alpha\omega_\alpha^2}\right)^2\right\}$$

HOW TO MODEL DISSIPATION

$$H = \underbrace{\frac{p^2}{2M} + V(q)}_{H_S} + \frac{1}{2}\sum_{\alpha=1}^{N}\left\{\frac{p_\alpha^2}{m_\alpha} + m_\alpha\omega_\alpha^2\left(x_\alpha - q\frac{c_\alpha}{m_\alpha\omega_\alpha^2}\right)^2\right\}$$

H_S Particle in a potential

HOW TO MODEL DISSIPATION

$$H = \underbrace{\frac{p^2}{2M} + V(q)}_{H_S} + \frac{1}{2}\sum_{\alpha=1}^{N}\left\{\frac{p_\alpha^2}{m_\alpha} + m_\alpha\omega_\alpha^2\left(x_\alpha - q\underbrace{\frac{c_\alpha}{m_\alpha\omega_\alpha^2}}\right)^2\right\}$$

H_S Particle in a potential

$x_\alpha^{eq}(q)$ Linear coupling and dissipation

HOW TO MODEL DISSIPATION

$$H = \underbrace{\frac{p^2}{2M} + V(q)}_{H_S} + \frac{1}{2}\sum_{\alpha=1}^{N}\left\{\frac{p_\alpha^2}{m_\alpha} + m_\alpha\omega_\alpha^2\left(x_\alpha - \underbrace{q\frac{c_\alpha}{m_\alpha\omega_\alpha^2}}_{x_\alpha^{eq}(q)}\right)^2\right\}$$

Caldeira-Leggett model

H_S Particle in a potential

$x_\alpha^{eq}(q)$ Linear coupling and dissipation

HOW TO MODEL DISSIPATION

$$H = \underbrace{\frac{p^2}{2M} + V(q)}_{H_S} + \frac{1}{2}\sum_{\alpha=1}^{N}\left\{\frac{p_\alpha^2}{m_\alpha} + m_\alpha\omega_\alpha^2\left(x_\alpha - \underbrace{q\frac{c_\alpha}{m_\alpha\omega_\alpha^2}}_{x_\alpha^{eq}(q)}\right)^2\right\}$$

Caldeira-Leggett model

H_S Particle in a potential

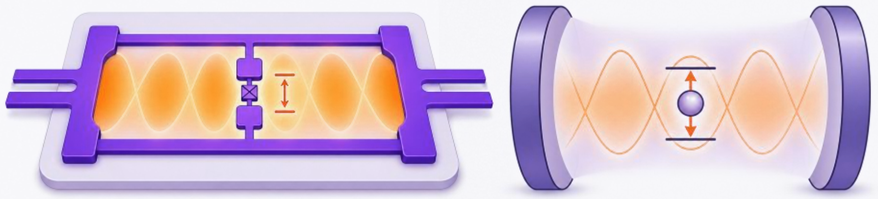
$x_\alpha^{eq}(q)$ Linear coupling and dissipation

$$J(\omega) = \frac{\pi}{2}\sum_{\alpha=1}^{N}\frac{c_\alpha^2}{m_\alpha\omega_\alpha}\delta\left(\omega-\omega_\alpha\right) \underset{N\to\infty}{\longrightarrow} \alpha\omega^s\omega_c^{1-s}\Theta\left(\omega_c-\omega\right)$$

Bath spectral density linked to the dissipation rates

MODELS

Target platforms

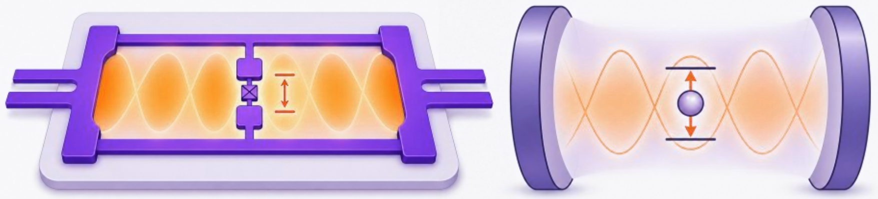


Circuit- and cavity-QED Hamiltonians

[G. Beaulieu, et al., PRX Quantum 6, 020301 (2025).]
[L. Garbe, et al., Phys. Rev. Lett. 124, 120504 (2020).]
[R.-H. Zheng, et al., Phys. Rev. Lett. 131, 113601 (2023).]
[Y. Liu, et al., Phys. Rev. Lett. 130, 173601 (2023).]

MODELS

Target platforms

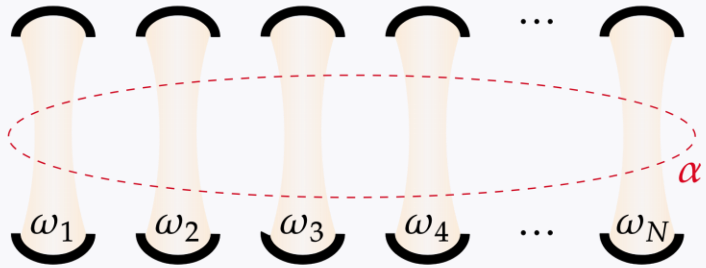


Circuit- and cavity-QED Hamiltonians

[G. Beaulieu, et al., PRX Quantum 6, 020301 (2025).]
[L. Garbe, et al., Phys. Rev. Lett. 124, 120504 (2020).]
[R.-H. Zheng, et al., Phys. Rev. Lett. 131, 113601 (2023).]
[Y. Liu, et al., Phys. Rev. Lett. 130, 173601 (2023).]

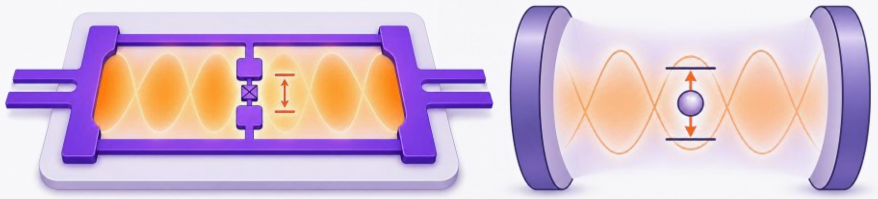
Non-Markovian challenges

Memory backflow • device noise



MODELS

Target platforms

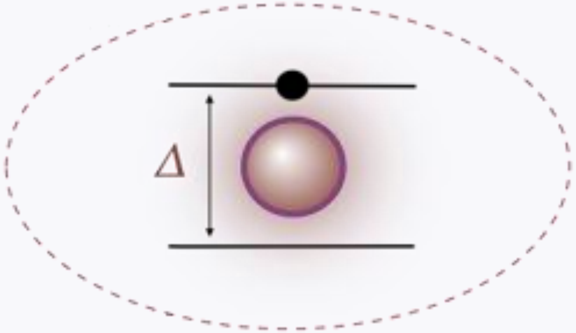


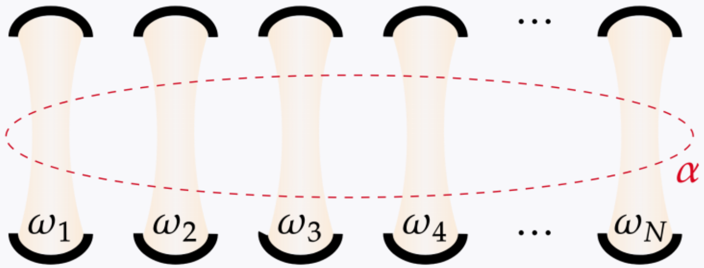
Circuit- and cavity-QED Hamiltonians

[G. Beaulieu, et al., PRX Quantum 6, 020301 (2025).]
[L. Garbe, et al., Phys. Rev. Lett. 124, 120504 (2020).]
[R.-H. Zheng, et al., Phys. Rev. Lett. 131, 113601 (2023).]
[Y. Liu, et al., Phys. Rev. Lett. 130, 173601 (2023).]

Non-Markovian challenges

Memory backflow • device noise



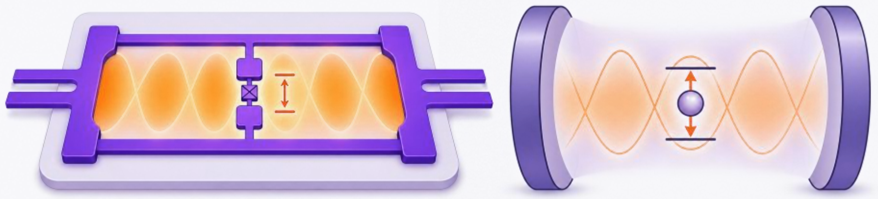


SPIN-BOSON MODEL (SBM)

1 qubit + N harmonic oscillators

MODELS

Target platforms

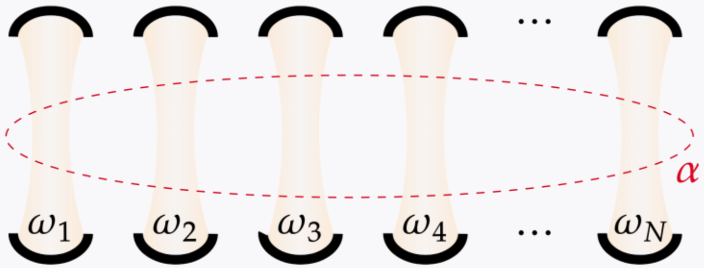


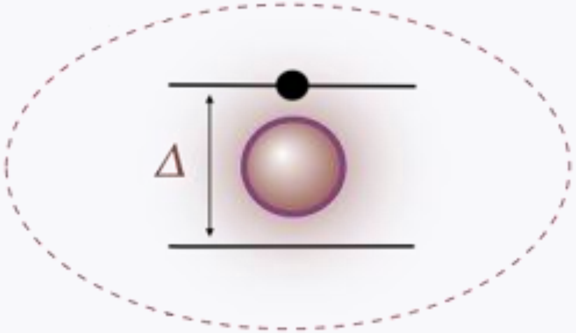
Circuit- and cavity-QED Hamiltonians

[G. Beaulieu, et al., PRX Quantum 6, 020301 (2025).]
[L. Garbe, et al., Phys. Rev. Lett. 124, 120504 (2020).]
[R.-H. Zheng, et al., Phys. Rev. Lett. 131, 113601 (2023).]
[Y. Liu, et al., Phys. Rev. Lett. 130, 173601 (2023).]

Non-Markovian challenges

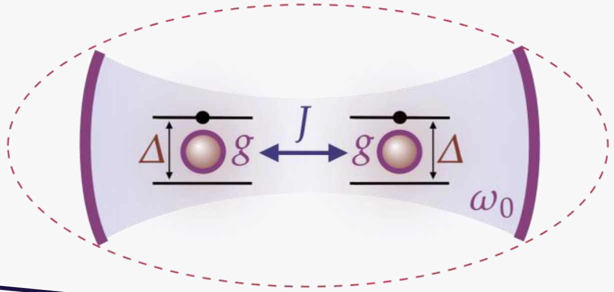
Memory backflow • device noise





SPIN-BOSON MODEL (SBM)

1 qubit + N harmonic oscillators



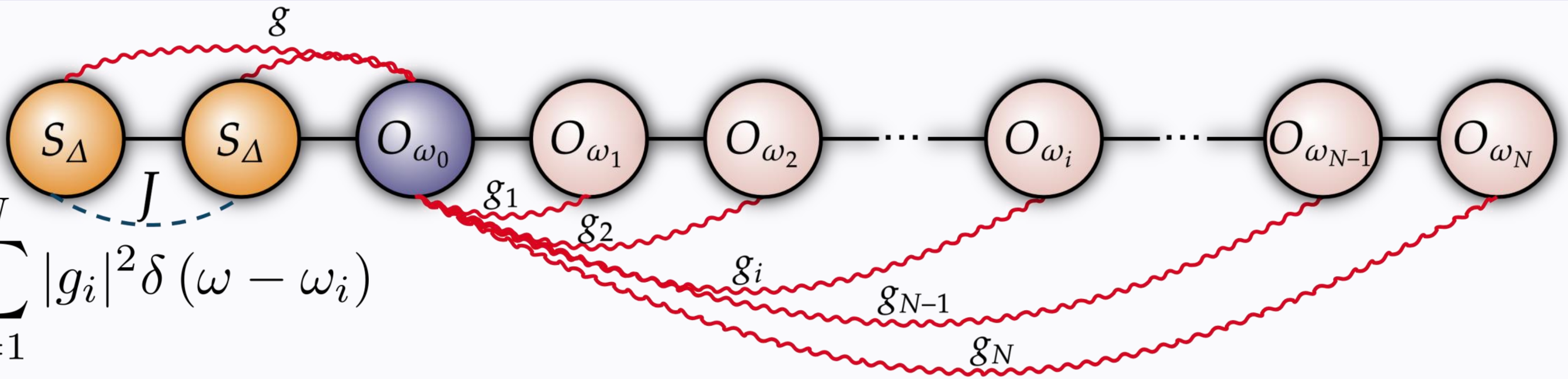
QUANTUM RABI MODEL (QRM)

1 or 2 qubits + cavity + N harmonic oscillators

How to set MPS sites

How to set MPS sites

Example:
two-qubit
Rabi model



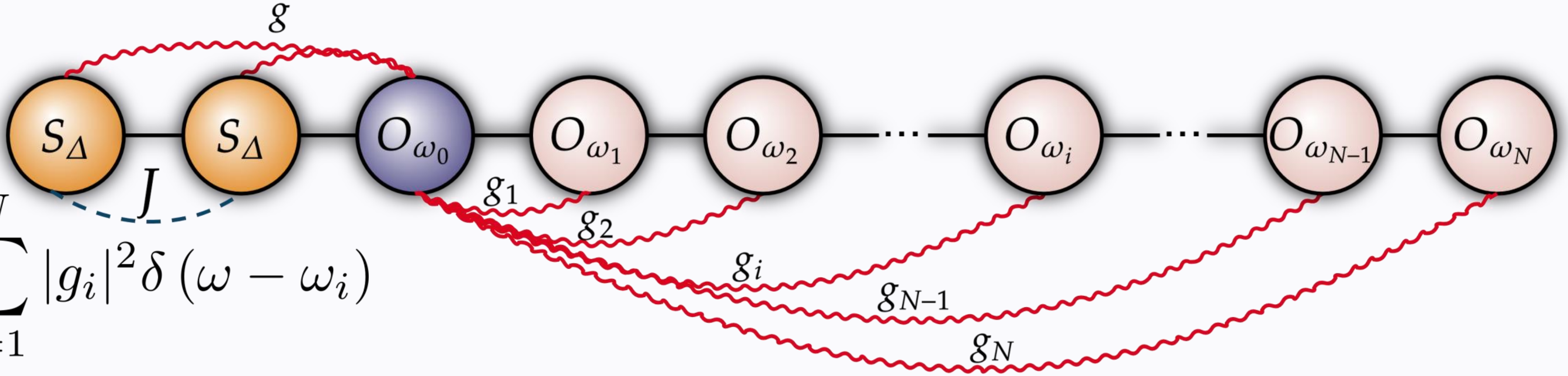
$$J(\omega) = \sum_{i=1}^{N} |g_i|^2 \delta(\omega - \omega_i)$$

$$\longrightarrow \alpha \omega^s \omega_c^{1-s} f(\omega_c)$$

How to set MPS sites

Example:

two-qubit Rabi model



$$J(\omega) = \sum_{i=1}^{N} |g_i|^2 \delta(\omega - \omega_i)$$

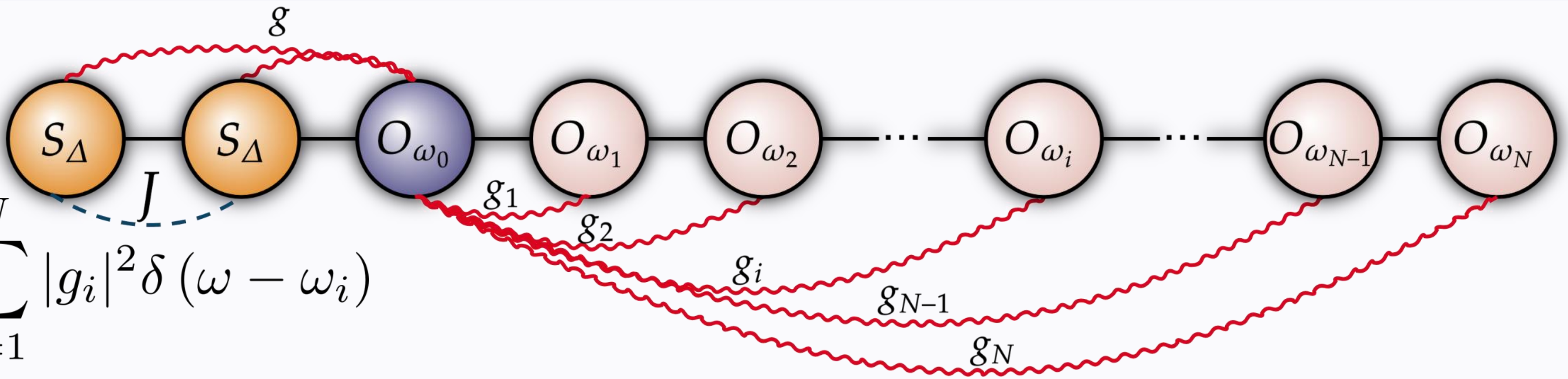
$$\longrightarrow \alpha \omega^s \omega_c^{1-s} f(\omega_c)$$

Wavefunction of the compound

$$|\psi(0)\rangle = (\alpha |\uparrow\uparrow\rangle + \beta |\uparrow\downarrow\rangle + \gamma |\downarrow\uparrow\rangle + \delta |\downarrow\downarrow\rangle) \otimes \sum_{n=0}^{n_{osc}} c_n |n\rangle \otimes |n_1, \ldots, n_N\rangle$$

How to set MPS sites

Example:
two-qubit
Rabi model



$$J(\omega) = \sum_{i=1}^{N} |g_i|^2 \delta(\omega - \omega_i)$$

$$\longrightarrow \alpha \omega^s \omega_c^{1-s} f(\omega_c)$$

Wavefunction of the compound

$$|\psi(0)\rangle = (\alpha |\uparrow\uparrow\rangle + \beta |\uparrow\downarrow\rangle + \gamma |\downarrow\uparrow\rangle + \delta |\downarrow\downarrow\rangle) \otimes \sum_{n=0}^{n_{osc}} c_n |n\rangle \otimes |n_1, \ldots, n_N\rangle$$

Direct access to interactions and bath observables

Environment-induced criticality

Equilibrium quantum phase transitions

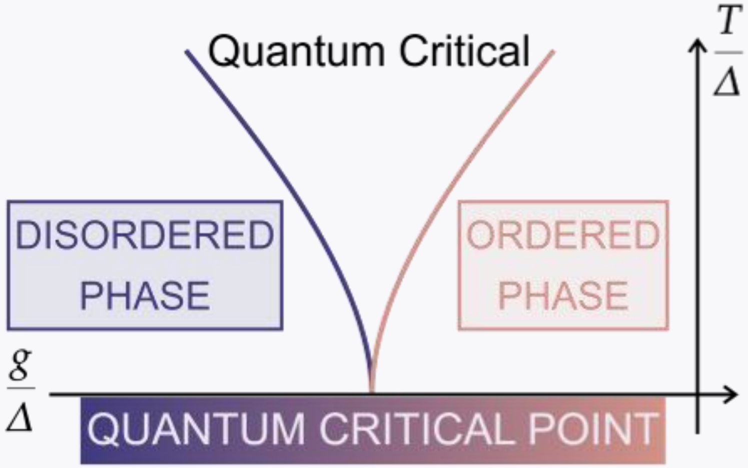
G. De Filippis, GDB, et al., Phys. Rev. Lett. 130, 210404 (2023).
GDB, et al., Commun. Phys., 7, 364 (2024).

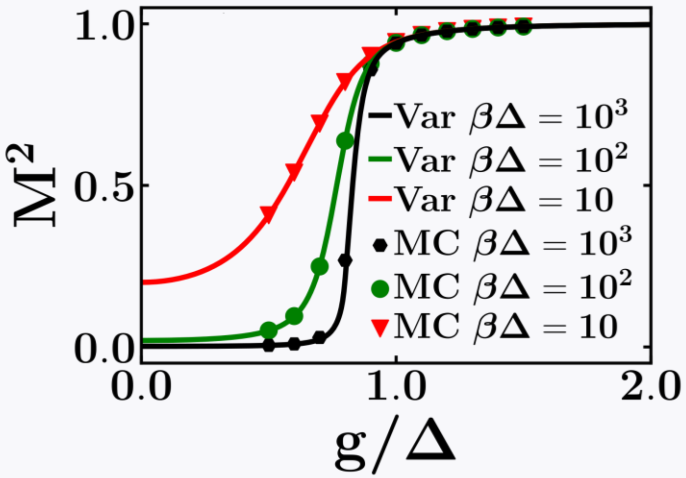
EQUILIBRIUM QUANTUM PHASE TRANSITIONS (QPTs)

G. De Filippis, GDB, et al., Phys. Rev. Lett. 130, 210404 (2023).

EQUILIBRIUM QUANTUM PHASE TRANSITIONS (QPTs)

EQUILIBRIUM



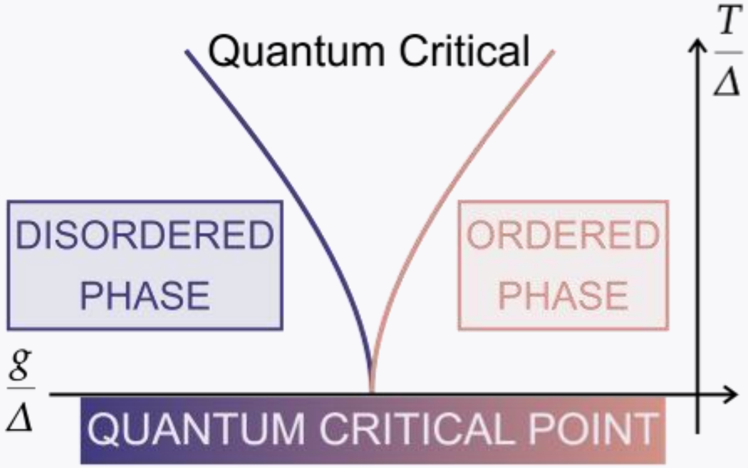


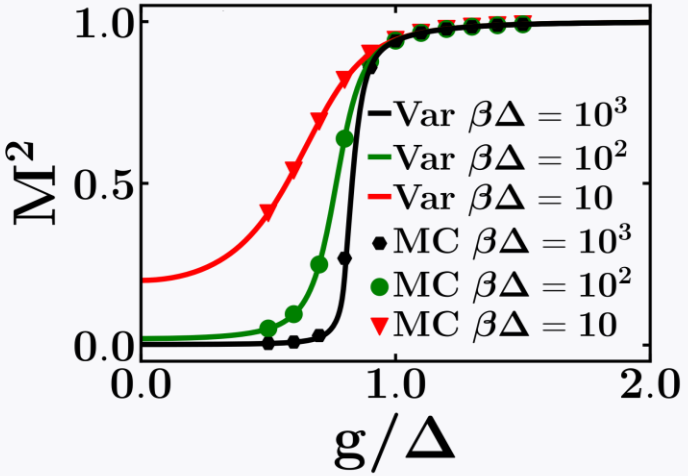
Squared magnetization signals the transition in the open QRM

G. De Filippis, GDB, et al., Phys. Rev. Lett. 130, 210404 (2023).

EQUILIBRIUM QUANTUM PHASE TRANSITIONS (QPTs)

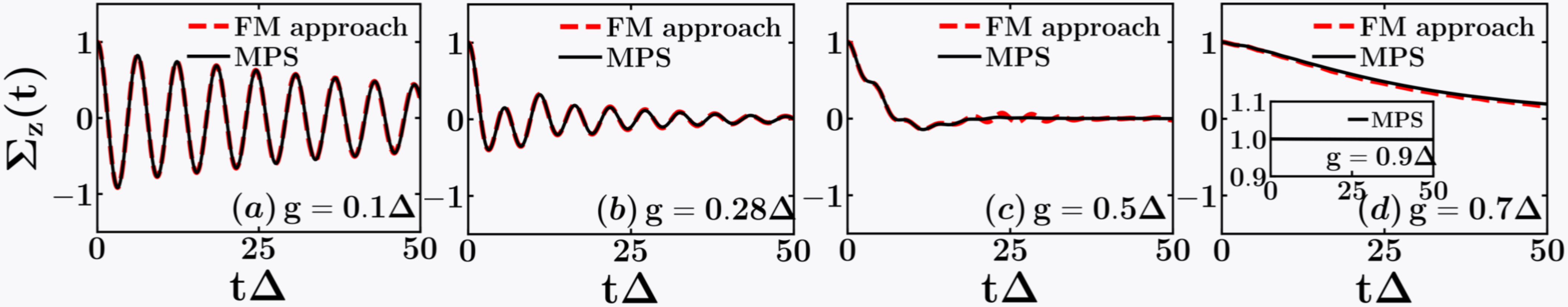
EQUILIBRIUM





Squared magnetization signals the transition in the open QRM

OUT OF EQUILIBRIUM

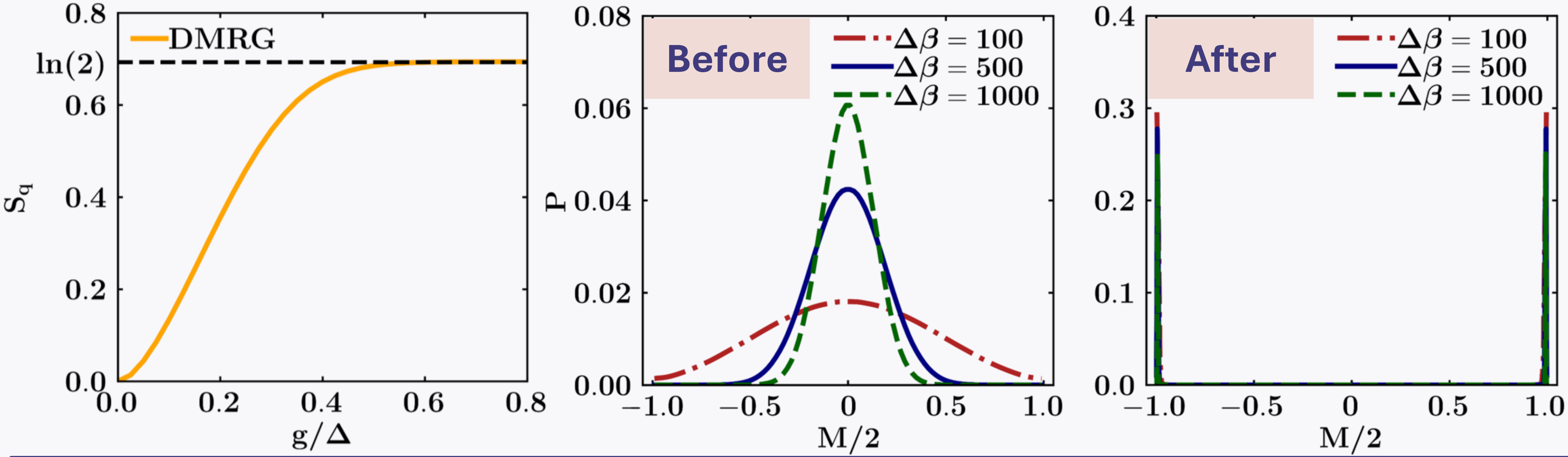


Rabi oscillations → exponential decay → no relaxation at the transition

G. De Filippis, GDB, et al., Phys. Rev. Lett. 130, 210404 (2023).

GDB, et al., Commun. Phys., 7, 364 (2024).

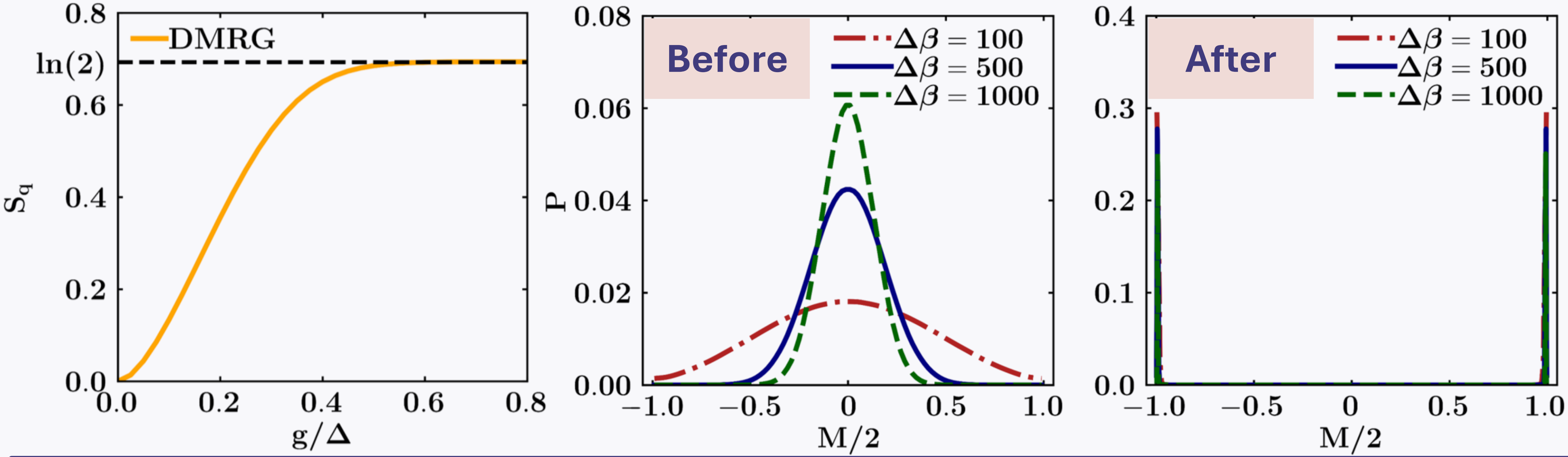
2-QUBIT CASE: EQUILIBRIUM



Two degenerate states post-transition from entanglement and magnetization distribution

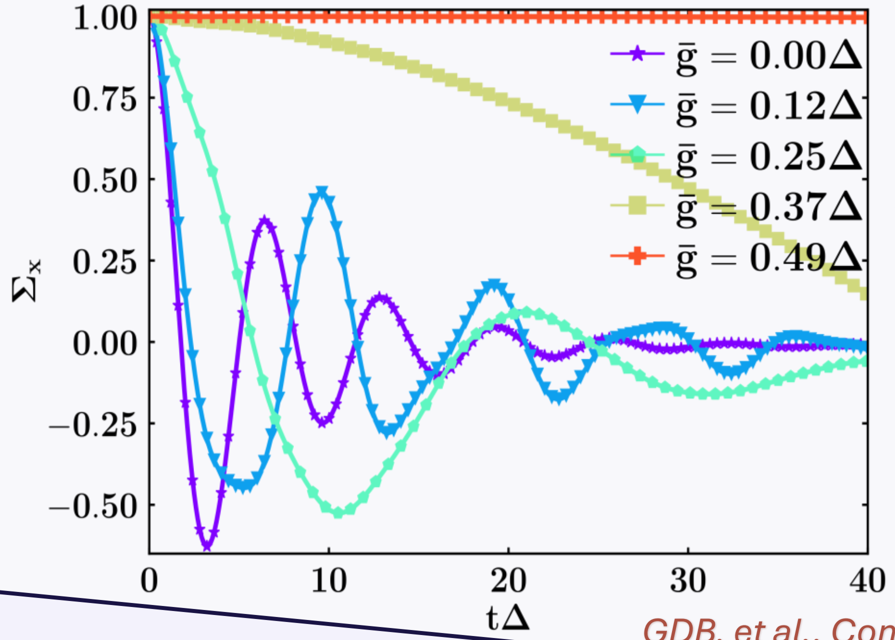
GDB, et al., Commun. Phys., 7, 364 (2024).

2-QUBIT CASE: EQUILIBRIUM



Two degenerate states post-transition from entanglement and magnetization distribution

2-QUBIT CASE: OUT OF EQUILIBRIUM - OSCILLATOR



Oscillator behavior resembles the qubits one

GDB, et al., Commun. Phys., 7, 364 (2024).

RELATED IDEA: Dynamical quantum phase transitions

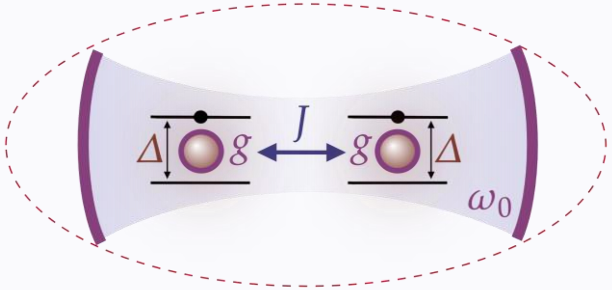
[M. Heyl, Europhys. Lett., 125, 26001 (2019).]

GDB, et al., Commun. Phys., 7, 364 (2024).

RELATED IDEA: Dynamical quantum phase transitions

[M. Heyl, Europhys. Lett., 125, 26001 (2019).]

INITIALIZATION

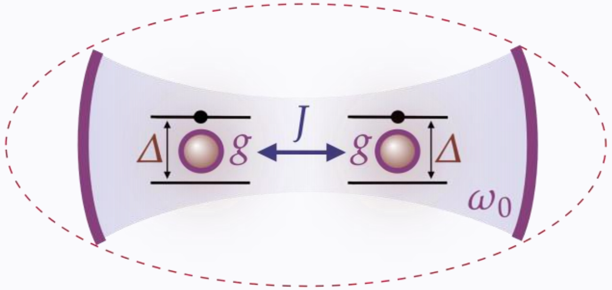


$$|\psi(0)\rangle = |GS\rangle_S \otimes |0, \ldots, 0\rangle_E$$

RELATED IDEA: Dynamical quantum phase transitions

[M. Heyl, Europhys. Lett., 125, 26001 (2019).]

INITIALIZATION



$$|\psi(0)\rangle = |GS\rangle_S \otimes |0,\ldots,0\rangle_E$$

HAMILTONIAN QUENCH

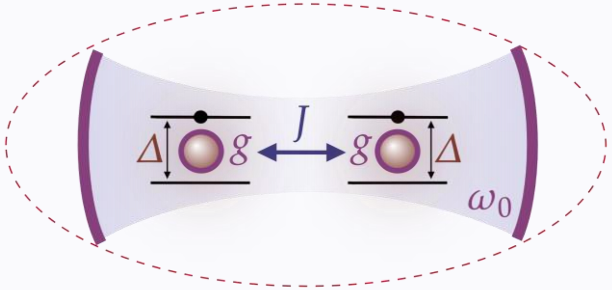
$$\begin{cases} H\big|_{g=0} \equiv H_0 \\ H\big|_{g\neq 0} \equiv H \end{cases}$$

GDB, et al., Commun. Phys., 7, 364 (2024).

RELATED IDEA: Dynamical quantum phase transitions

[M. Heyl, Europhys. Lett., 125, 26001 (2019).]

INITIALIZATION

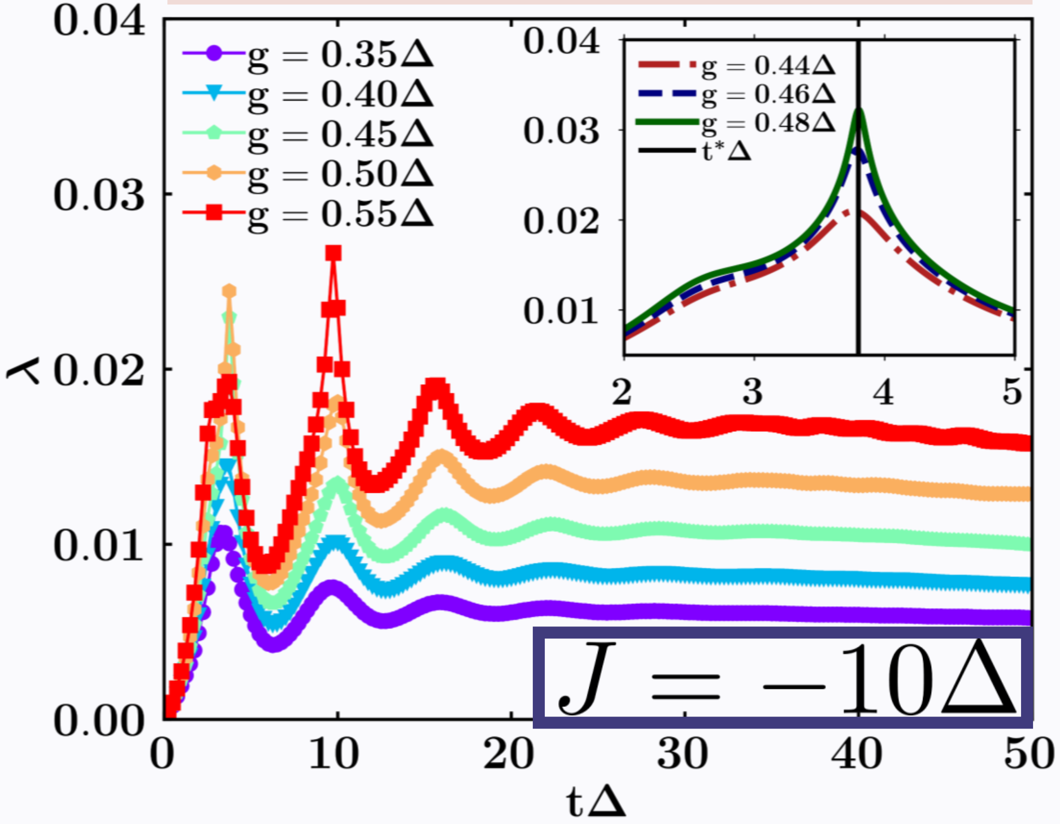


$$|\psi(0)\rangle = |GS\rangle_S \otimes |0, \ldots, 0\rangle_E$$

HAMILTONIAN QUENCH

$$\begin{cases} H\big|_{g=0} \equiv H_0 \\ H\big|_{g\neq 0} \equiv H \end{cases}$$

LOSCHMIDT ECHO RATE FUNCTION TIME EVOLUTION



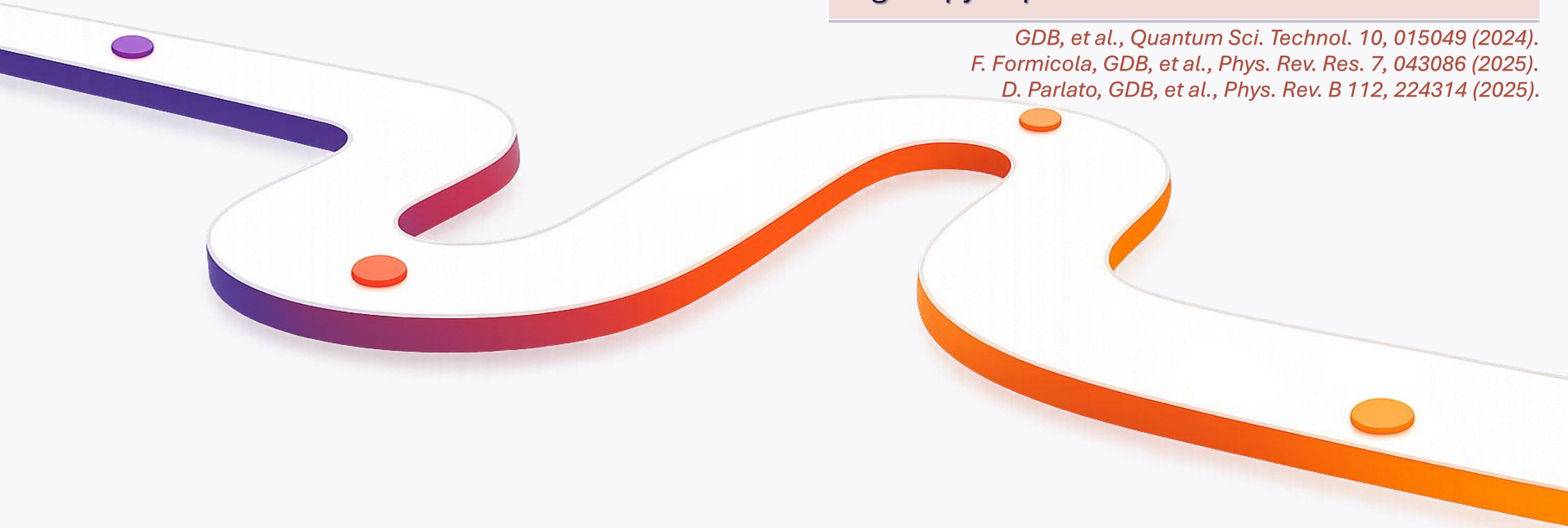
Rate function kinks towards the **dynamical transition (DQPT)** in the **same parameter range** as QPT

GDB, et al., Commun. Phys., 7, 364 (2024).

Applications: work extraction & sensing

Ergotropy & quantum Fisher information

GDB, et al., Quantum Sci. Technol. 10, 015049 (2024).
F. Formicola, GDB, et al., Phys. Rev. Res. 7, 043086 (2025).
D. Parlato, GDB, et al., Phys. Rev. B 112, 224314 (2025).



WORK EXTRACTION

[F. Campaioli, et al., Rev. Mod. Phys., 96, 031001 (2024).]

WORK EXTRACTION

[F. Campaioli, et al., Rev. Mod. Phys., 96, 031001 (2024).]

ERGOTROPY

Maximum extractable work

$$\mathcal{E} = \max_{U \in \mathcal{U}(d)} \left\{ \mathrm{tr}(H\rho) - \mathrm{tr}\left(U\rho U^{\dagger} H\right) \right\}$$

[A. Allahverdyan, et al., Europhys. Lett., 67, 565 (2004).]

WORK EXTRACTION

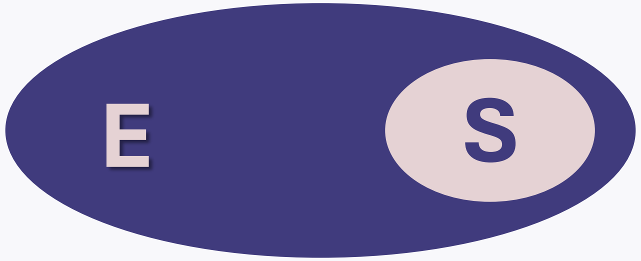
[F. Campaioli, et al., Rev. Mod. Phys., 96, 031001 (2024).]

ERGOTROPY

Maximum extractable work

$$\mathcal{E} = \max_{U \in \mathcal{U}(d)} \left\{ \mathrm{tr}(H\rho) - \mathrm{tr}\left(U\rho U^\dagger H\right) \right\}$$

[A. Allahverdyan, et al., Europhys. Lett., 67, 565 (2004).]



WORK EXTRACTION

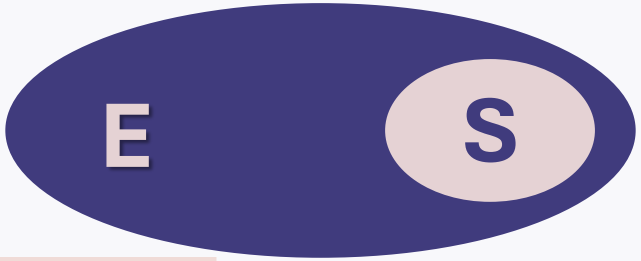
[F. Campaioli, et al., Rev. Mod. Phys., 96, 031001 (2024).]

ERGOTROPY

Maximum extractable work

$$\mathcal{E} = \max_{U \in \mathcal{U}(d)} \left\{ \mathrm{tr}(H\rho) - \mathrm{tr}\left(U\rho U^{\dagger} H\right) \right\}$$

[A. Allahverdyan, et al., Europhys. Lett., 67, 565 (2004).]



Switch-off: turning off environment interactions

$$\mathcal{E}_{so} = \mathcal{E}_{sys} - \Delta_{so}$$

[I. Kosuke, and T. Miyadera, arXiv:1711.02322 (2017).]

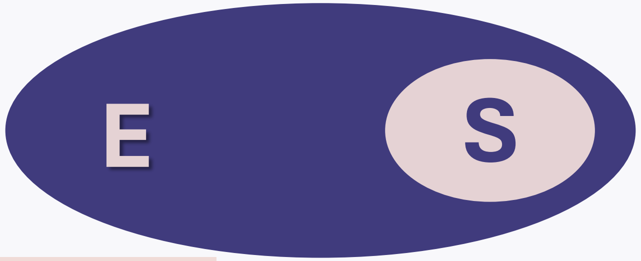
WORK EXTRACTION

[F. Campaioli, et al., Rev. Mod. Phys., 96, 031001 (2024).]

ERGOTROPY
Maximum extractable work

$$\mathcal{E} = \max_{U \in \mathcal{U}(d)} \left\{ \mathrm{tr}(H\rho) - \mathrm{tr}\left(U\rho U^{\dagger} H\right) \right\}$$

[A. Allahverdyan, et al., Europhys. Lett., 67, 565 (2004).]



Switch-off: turning off environment interactions

$$\mathcal{E}_{so} = \mathcal{E}_{sys} - \Delta_{so}$$

[I. Kosuke, and T. Miyadera, arXiv:1711.02322 (2017).]

Local: acting only on the system

$$\mathcal{E}_{S} = \max_{U_S \in \mathcal{U}(d_S)} \left\{ \mathrm{tr}(H_{SE}\rho_{SE}) - \mathrm{tr}\left(U_S \rho_{SE} U_S^{\dagger} H_{SE}\right) \right\}$$

[R. Salvia, et al., Phys. Rev. A, 107, 01240 (2023).]

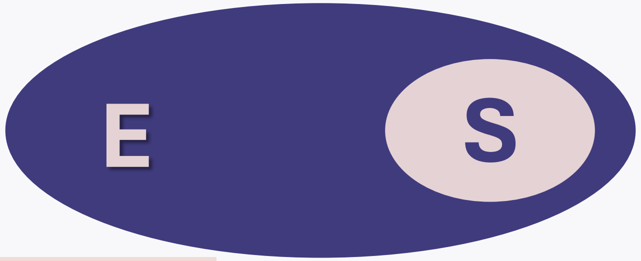
WORK EXTRACTION

[F. Campaioli, et al., Rev. Mod. Phys., 96, 031001 (2024).]

ERGOTROPY
Maximum extractable work

$$\mathcal{E} = \max_{U \in \mathcal{U}(d)} \left\{ \mathrm{tr}(H\rho) - \mathrm{tr}\left(U\rho U^\dagger H\right) \right\}$$

[A. Allahverdyan, et al., Europhys. Lett., 67, 565 (2004).]



Switch-off: turning off environment interactions

$$\mathcal{E}_{so} = \mathcal{E}_{sys} - \Delta_{so}$$

[I. Kosuke, and T. Miyadera, arXiv:1711.02322 (2017).]

Local: acting only on the system

$$\mathcal{E}_S = \max_{U_S \in \mathcal{U}(d_S)} \left\{ \mathrm{tr}(H_{SE}\rho_{SE}) - \mathrm{tr}\left(U_S \rho_{SE} U_S^\dagger H_{SE}\right) \right\}$$

[R. Salvia, et al., Phys. Rev. A, 107, 01240 (2023).]

Fluctuations: work quasi-probability distribution

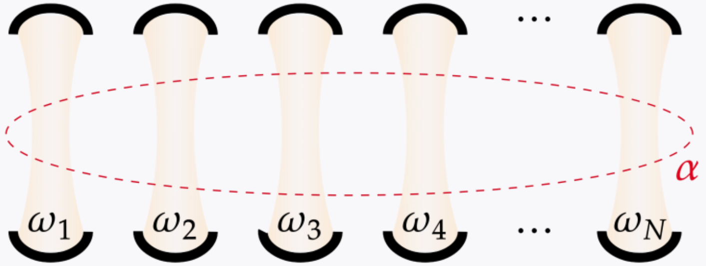
$$\sigma^2(t) = \langle w^2 \rangle - \langle w \rangle^2$$

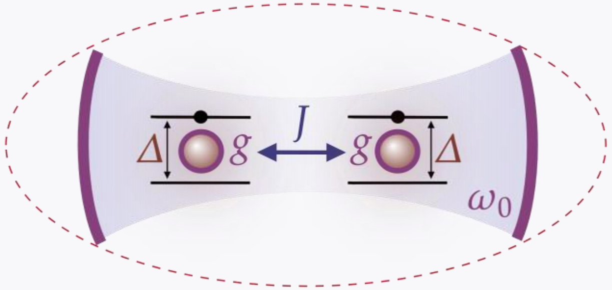
[G. Francica, Phys. Rev. E, 105, 014101 (2022).]

LOCAL ERGOTROPY ACROSS THE QPT

GDB, et al., Quantum Sci. Technol. 10, 015049 (2024).

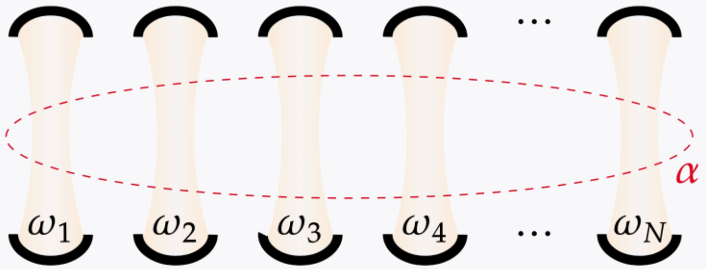
LOCAL ERGOTROPY ACROSS THE QPT

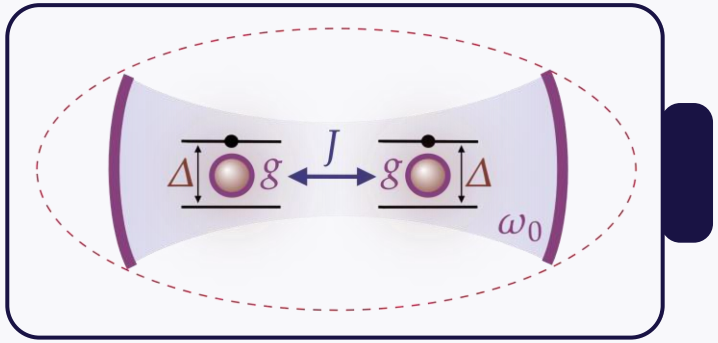




GDB, et al., Quantum Sci. Technol. 10, 015049 (2024).

LOCAL ERGOTROPY ACROSS THE QPT





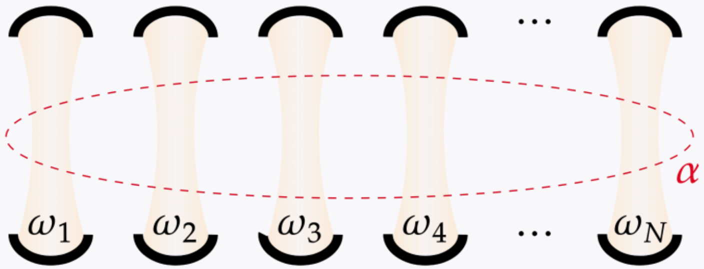
OPEN QUANTUM BATTERY

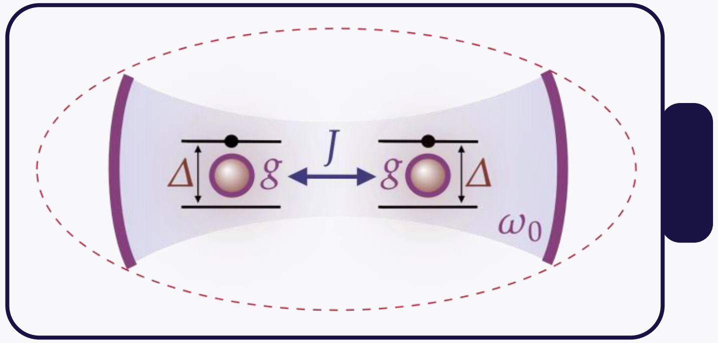
$$|\psi(0)\rangle = |GS\rangle_{DMRG}$$

Initial ground state of entire system

GDB, et al., Quantum Sci. Technol. 10, 015049 (2024).

LOCAL ERGOTROPY ACROSS THE QPT

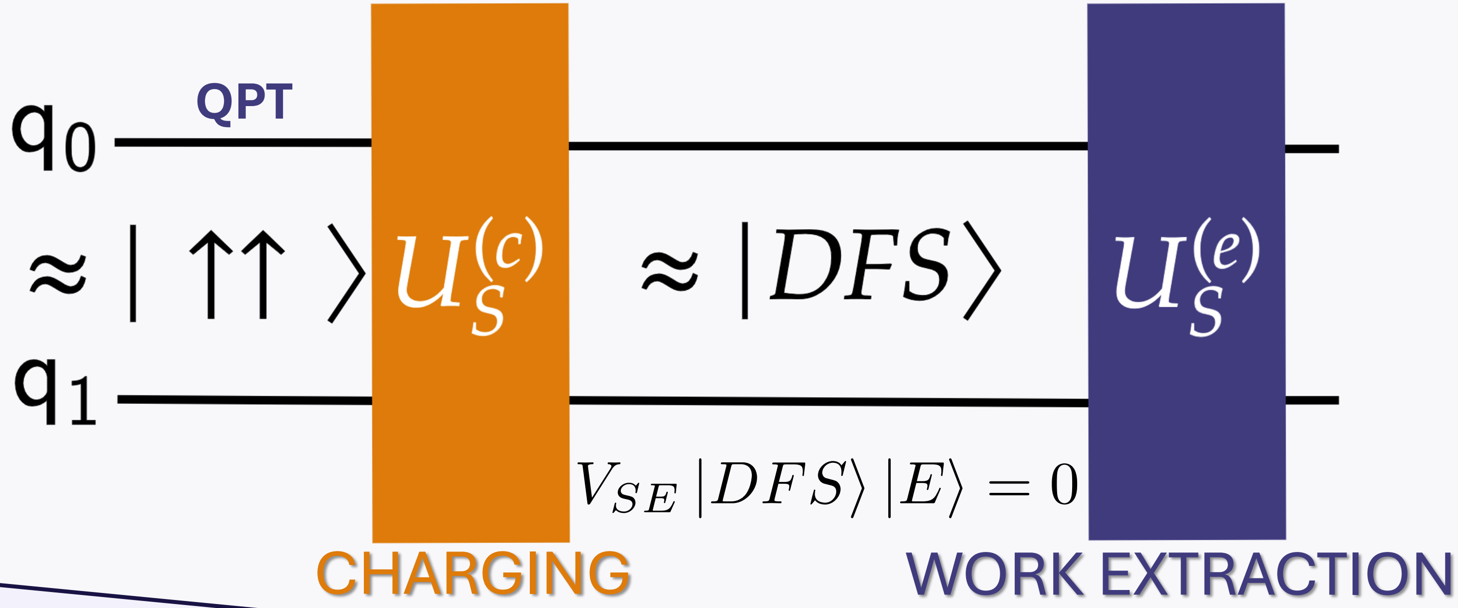




OPEN QUANTUM BATTERY

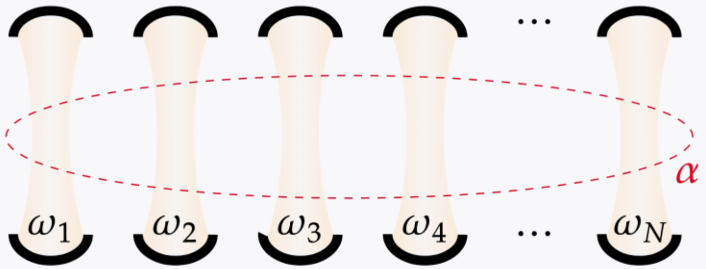
$$|\psi(0)\rangle = |GS\rangle_{DMRG}$$

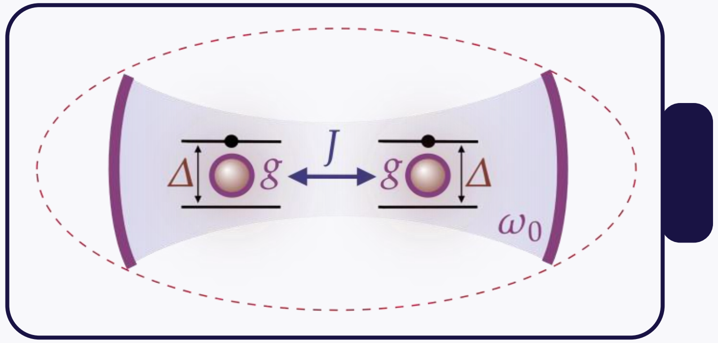
Initial ground state of entire system



GDB, et al., Quantum Sci. Technol. 10, 015049 (2024).

LOCAL ERGOTROPY ACROSS THE QPT

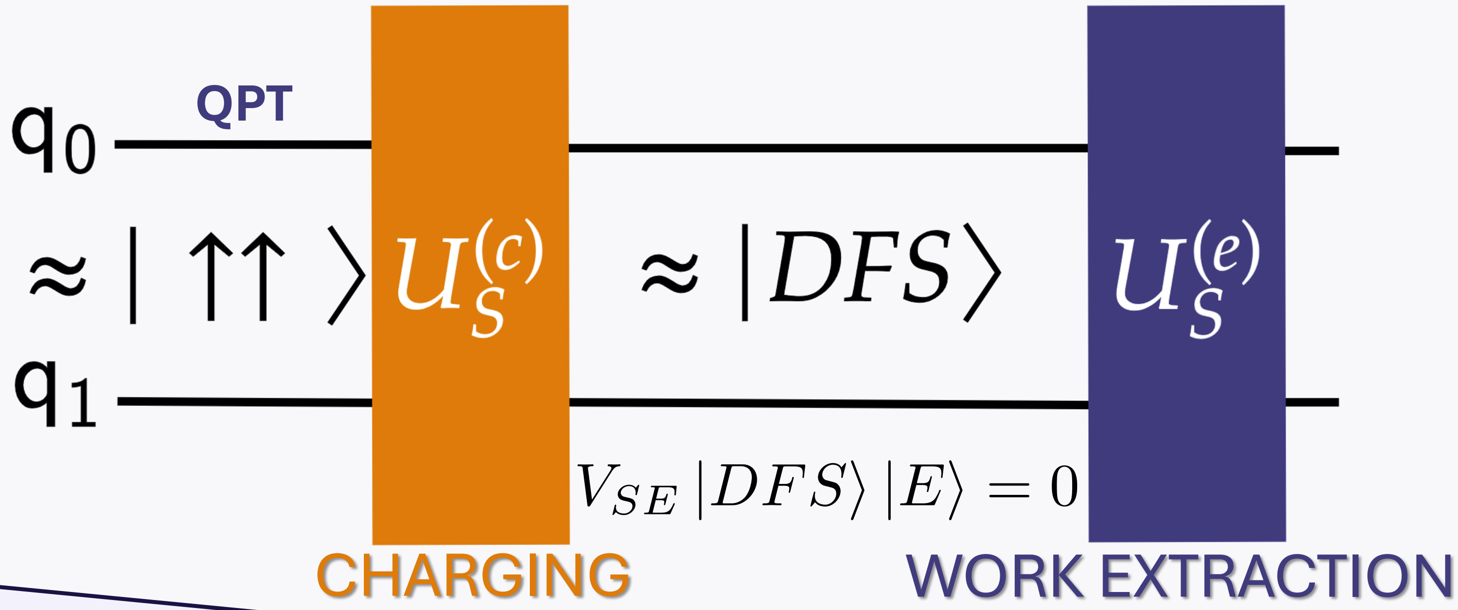


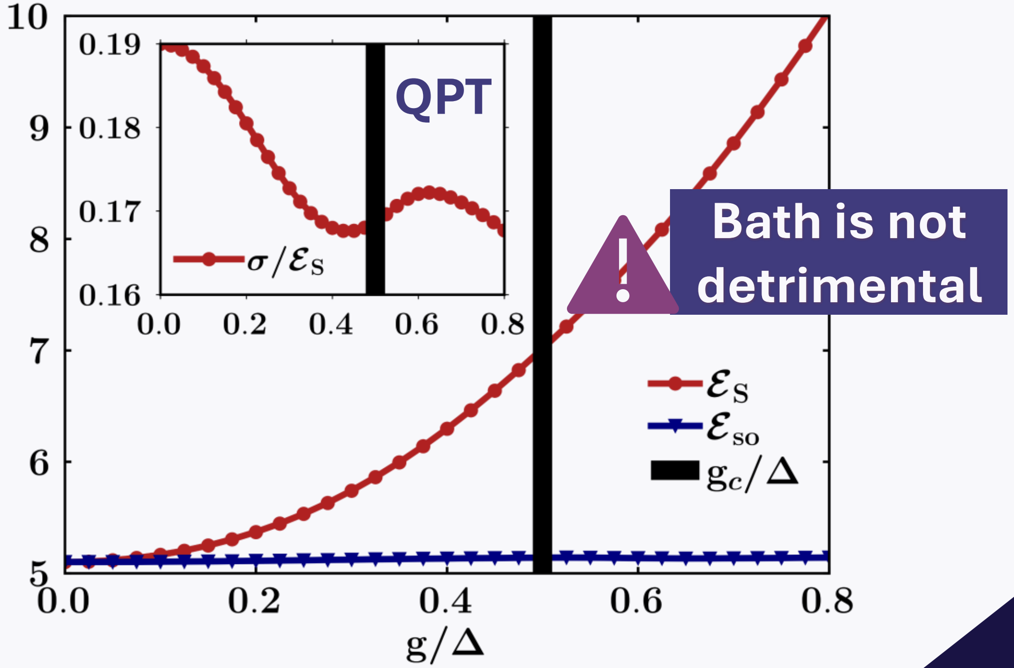


OPEN QUANTUM BATTERY

$$|\psi(0)\rangle = |GS\rangle_{DMRG}$$

Initial ground state of entire system





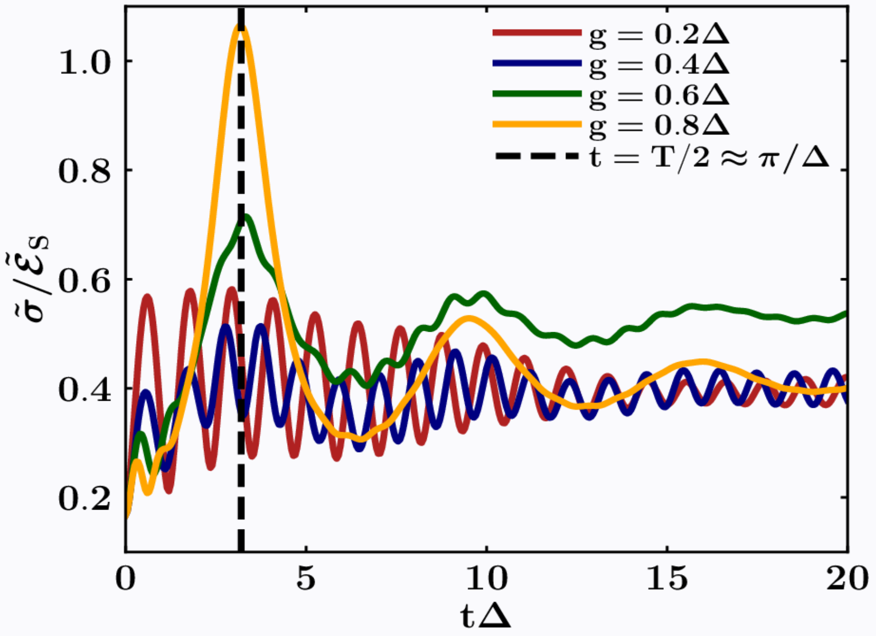
GDB, et al., Quantum Sci. Technol. 10, 015049 (2024).

AGNOSTIC PROTOCOL	BAYESIAN OPTIMIZED PROTOCOL

GDB, et al., *Quantum Sci. Technol.* 10, 015049 (2024).

AGNOSTIC PROTOCOL

apply $U_S^{(e)} = U_S^{(c)\dagger}$



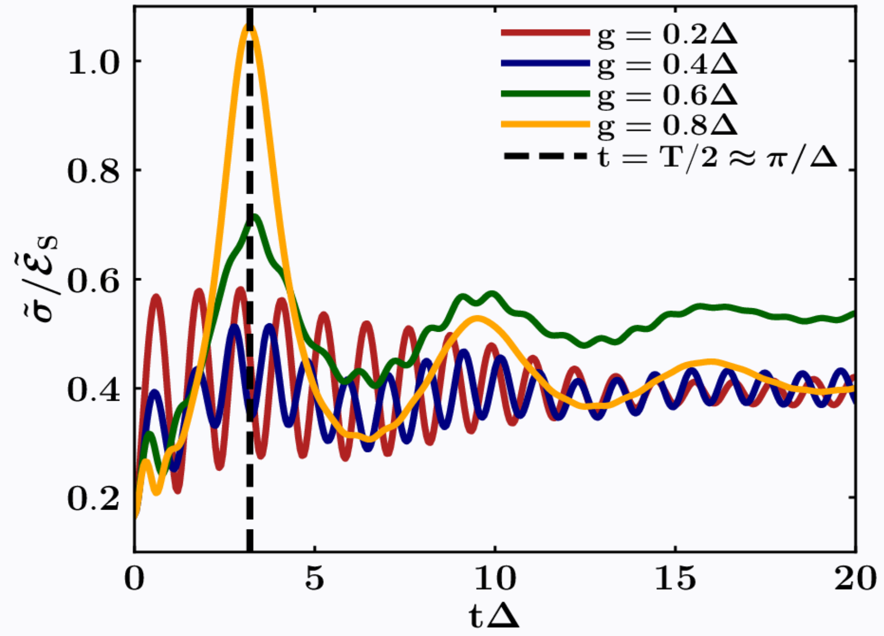
Relative fluctuations provide a QPT marker
Oscillations at ω_0 (cavity-bath) and $|J|$ (qubits)

BAYESIAN OPTIMIZED PROTOCOL

GDB, et al., Quantum Sci. Technol. 10, 015049 (2024).

AGNOSTIC PROTOCOL

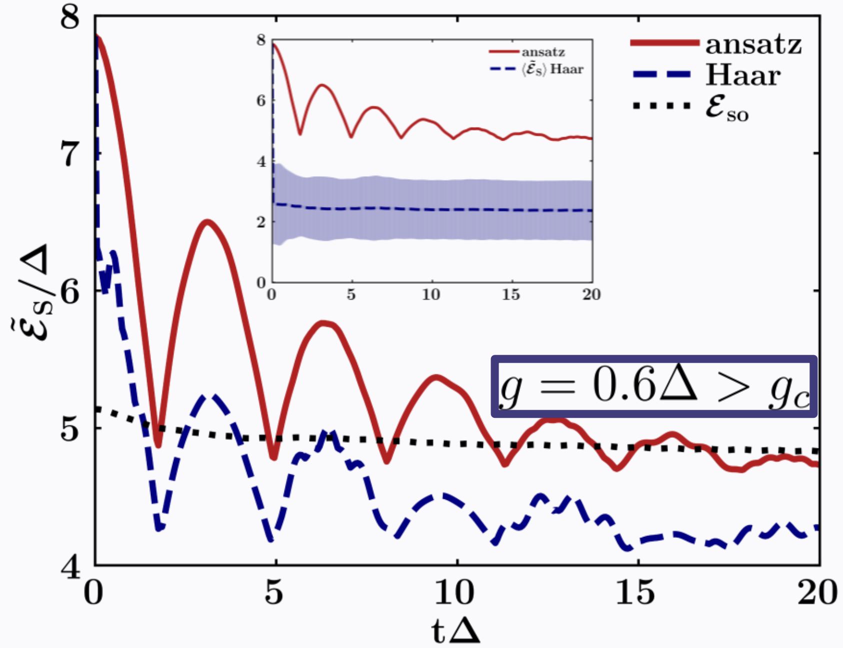
apply $U_S^{(e)} = U_S^{(c)\dagger}$



Relative fluctuations provide a QPT marker
Oscillations at ω_0 (cavity-bath) and $|J|$ (qubits)

BAYESIAN OPTIMIZED PROTOCOL

apply $U_S^{(e)} = U_S'(\bar{\theta}, \bar{\phi})\, U_S^{(c)\dagger}$



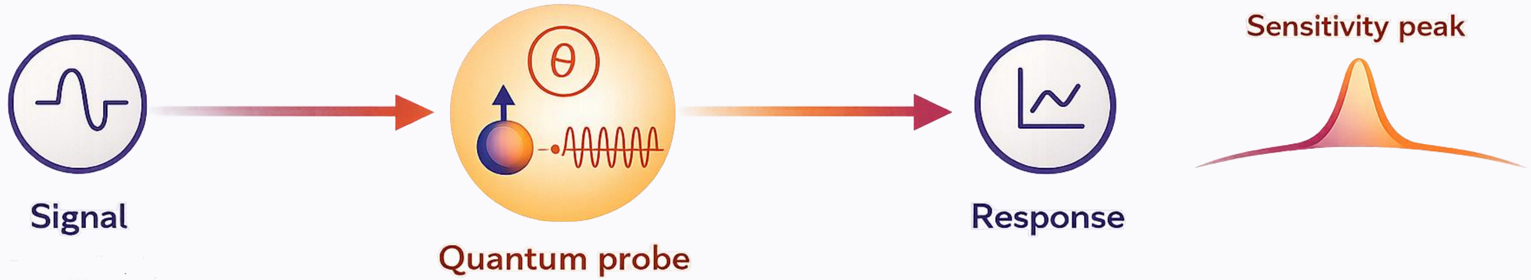
Bath rephasing improves the ergotropy performance
It outperforms Haar unitaries
and approaches ε_{SO} at long times

GDB, et al., Quantum Sci. Technol. 10, 015049 (2024).

QUANTUM FISHER INFORMATION (QFI) PROBING NON-MARKOVIANITY AND CRITICALITY

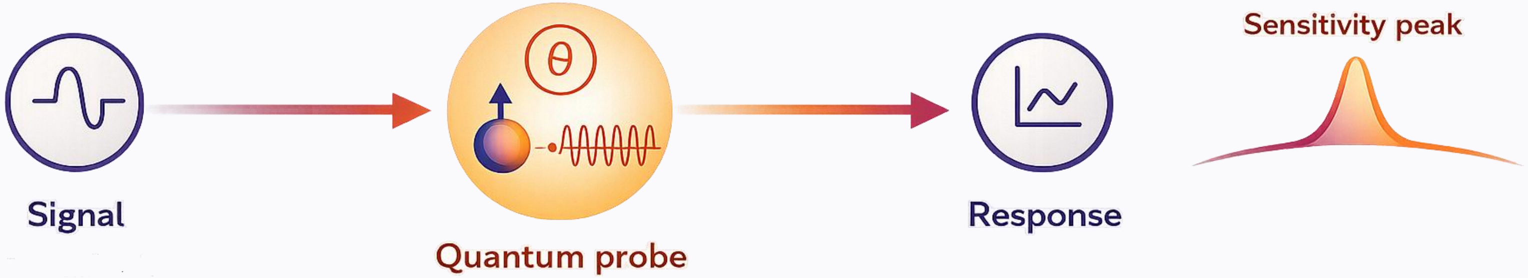
QUANTUM FISHER INFORMATION (QFI) PROBING NON-MARKOVIANITY AND CRITICALITY

QUANTUM SENSING
Estimate a parameter from the probe response



QUANTUM FISHER INFORMATION (QFI) PROBING NON-MARKOVIANITY AND CRITICALITY

QUANTUM SENSING
Estimate a parameter from the probe response



Large QFI = enhanced sensitivity to **small parameter changes**

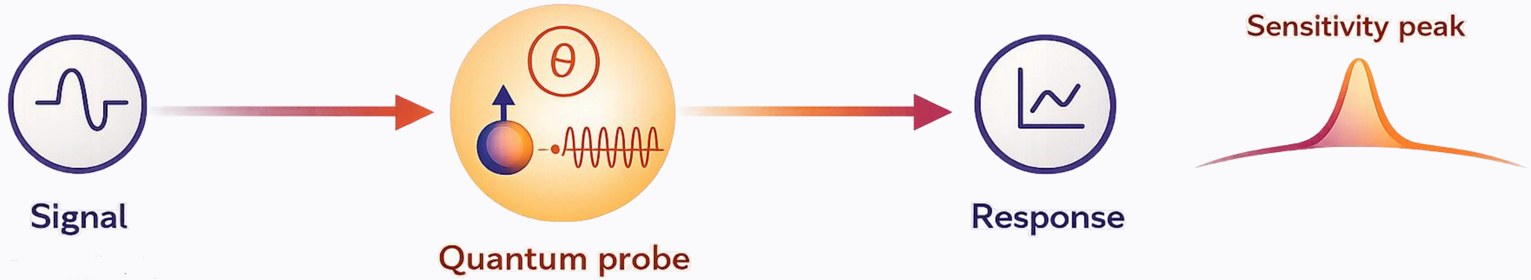
Cramér-Rao bound

$$\mathrm{var}_\theta \geq \frac{1}{(\#\mathrm{meas.})F_\theta(\rho(\theta))}$$

[J. Liu, et al., J. Phys. A: Math. Theor. 53, 023001 (2019).]

QUANTUM FISHER INFORMATION (QFI) PROBING NON-MARKOVIANITY AND CRITICALITY

QUANTUM SENSING
Estimate a parameter from the probe response



Large QFI = enhanced sensitivity to **small parameter changes**

Cramér-Rao bound

$$\mathrm{var}_\theta \geq \frac{1}{(\#\mathrm{meas.}) F_\theta(\rho(\theta))}$$

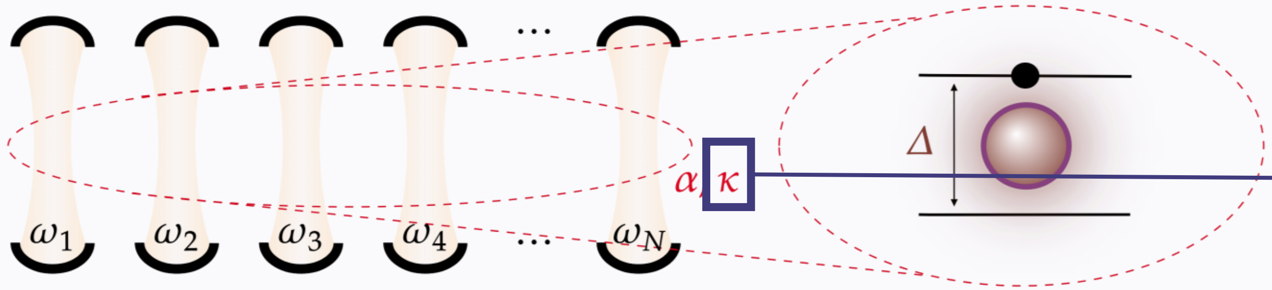
[J. Liu, et al., J. Phys. A: Math. Theor. 53, 023001 (2019).]

WHAT DO WE ASK?
- ❑ Is QFI a **marker of quantum phase transitions**?
- ❑ Is it **robust to dephasing** noise?
- ❑ Can its dynamics reveal **non-Markovianity**?

QFI to probe criticality and non-Markovianity

D. Parlato, GDB, et al., Phys. Rev. B 112, 224314 (2025).

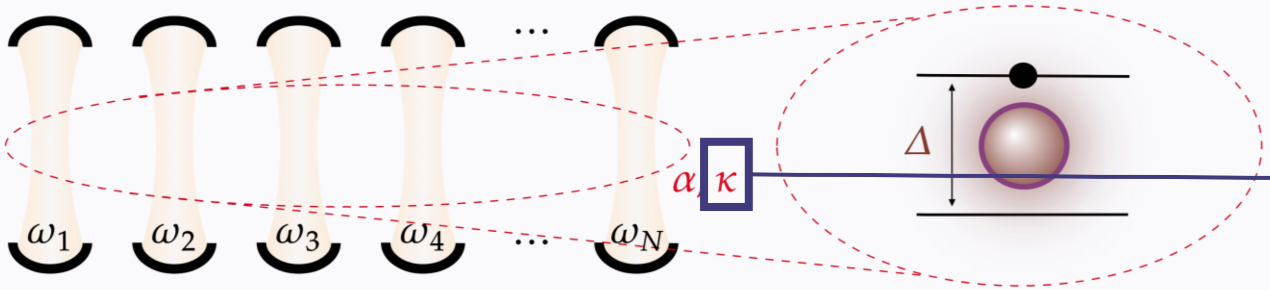
MODEL



Dephasing noise κ modifies the transition in SBM

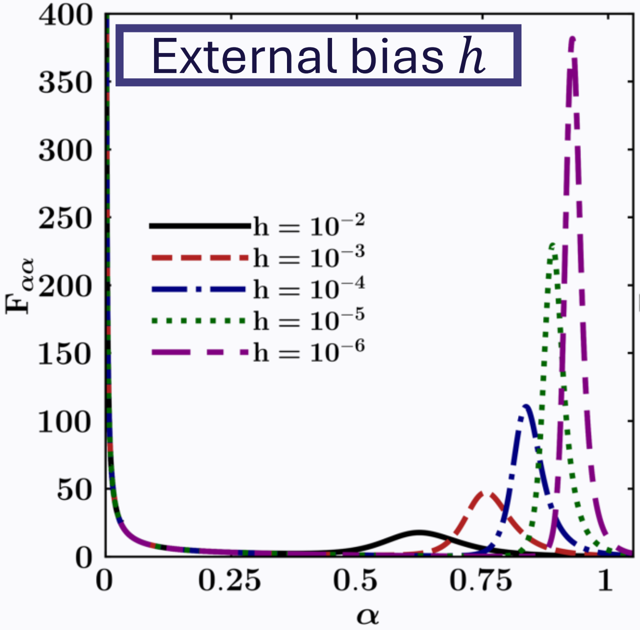
D. Parlato, GDB, et al., Phys. Rev. B 112, 224314 (2025).

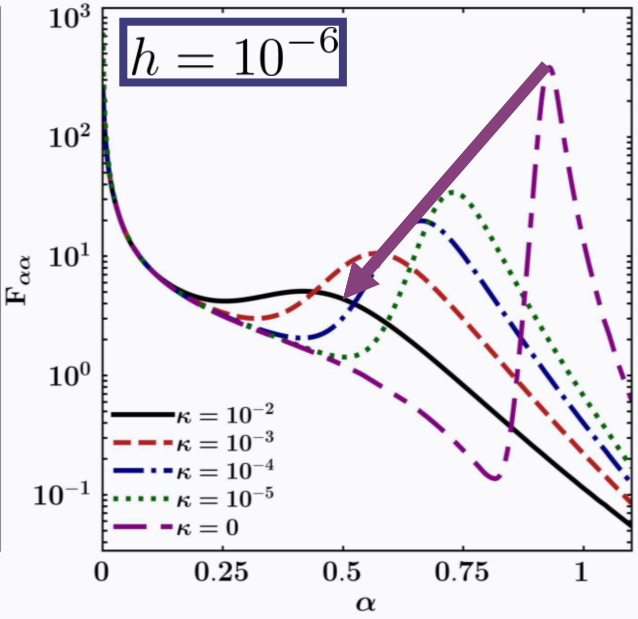
MODEL



Dephasing noise κ modifies the transition in SBM

QFI peaks at CRITICAL COUPLING

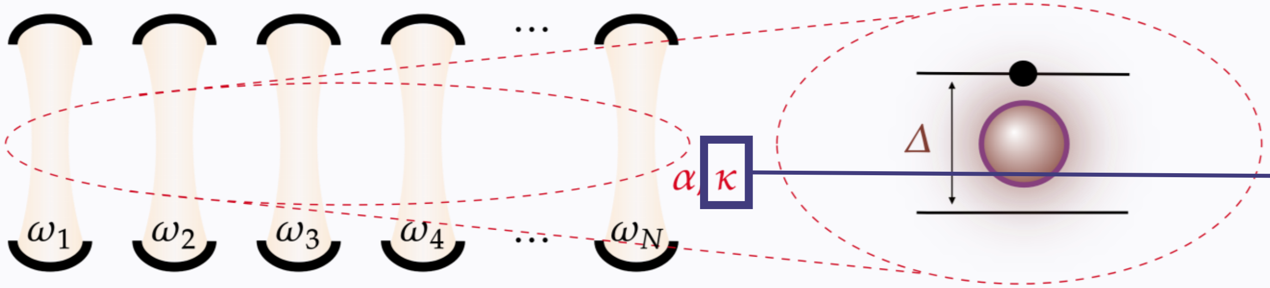




⚠ **Dephasing reduces sensitivity**

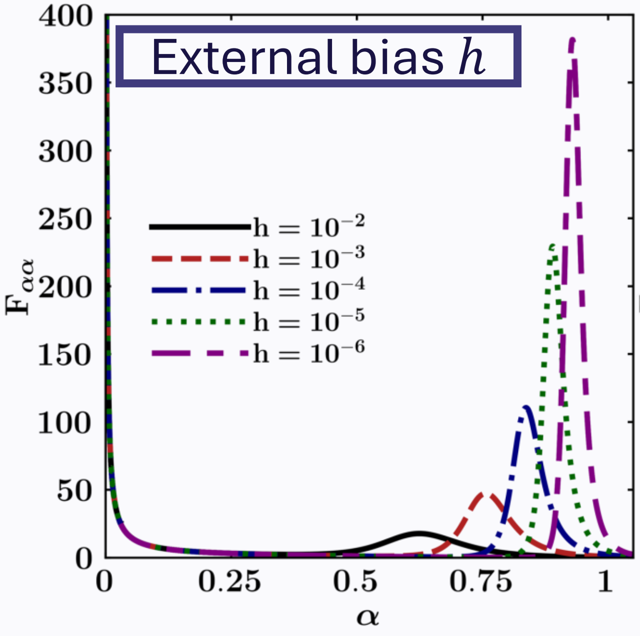
D. Parlato, GDB, et al., Phys. Rev. B 112, 224314 (2025).

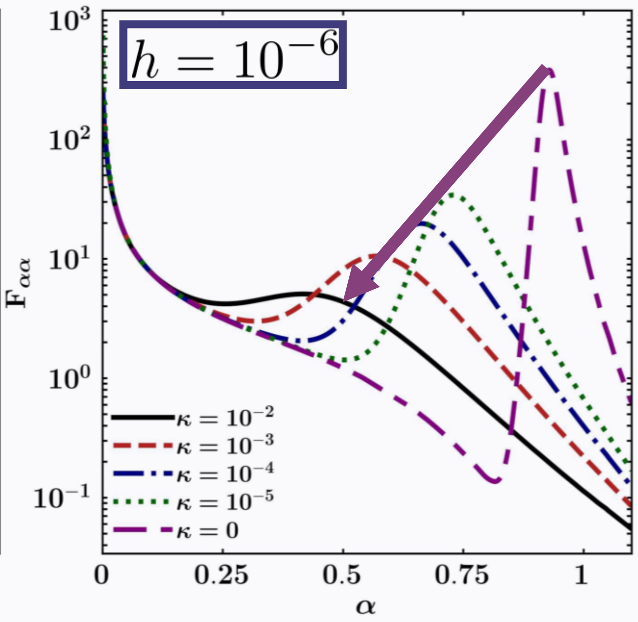
MODEL



Dephasing noise κ modifies the transition in SBM

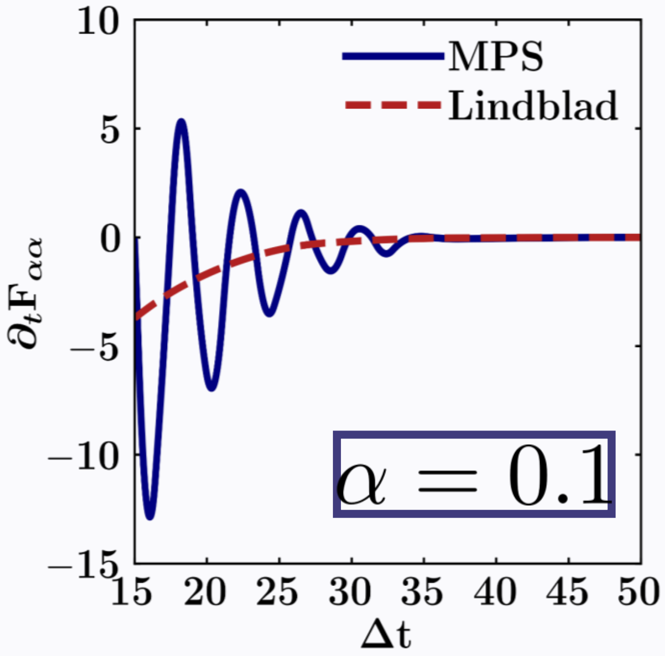
QFI peaks at CRITICAL COUPLING





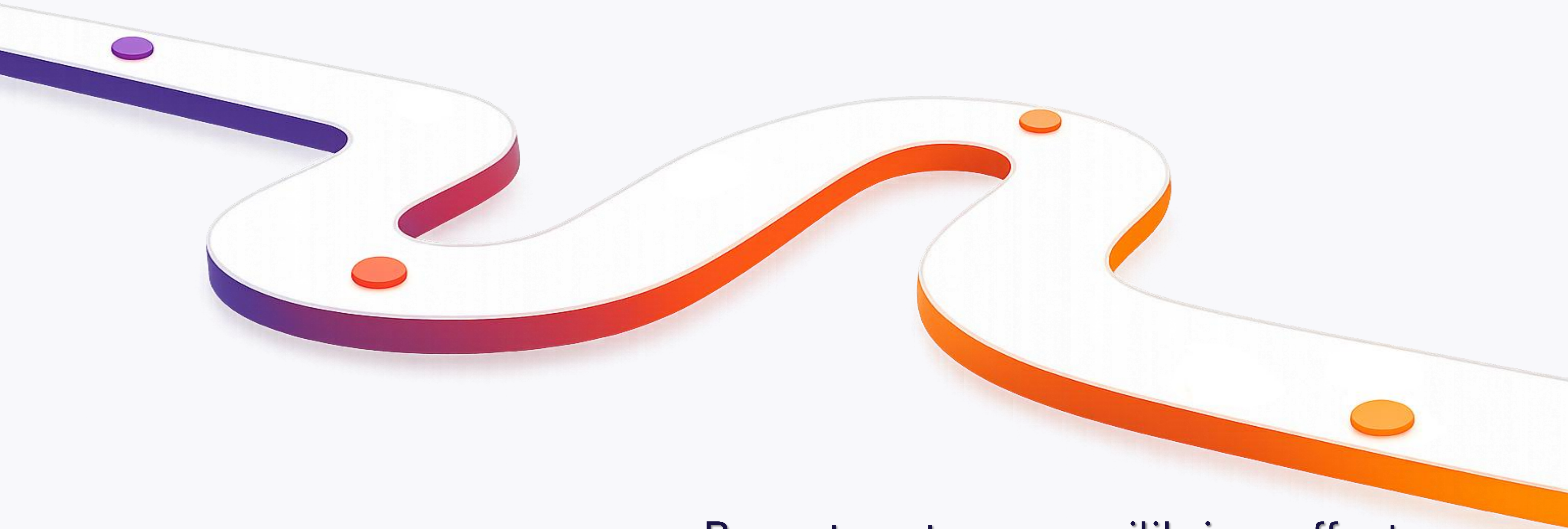
Dephasing reduces sensitivity

QFI FLUX reveals MEMORY EFFECTS



Lindblad = Markovian
Matrix product state = continuous **exchange** of information

D. Parlato, GDB, et al., Phys. Rev. B 112, 224314 (2025).



Recent past: non-equilibrium effects

Kibble-Zurek mechanism & quantum Mpemba effect

T. Pirozzi, GDB, et al., arXiv:2603.16709 (2026).
P. Chirico, GDB, et al., arXiv:2603.17565 (2026).

KIBBLE–ZUREK MECHANISM (KZM) IN THE OPEN QRB

T. Pirozzi, GDB, et al., arXiv:2603.16709 (2026).

KIBBLE–ZUREK MECHANISM (KZM) IN THE OPEN QRB

Main idea

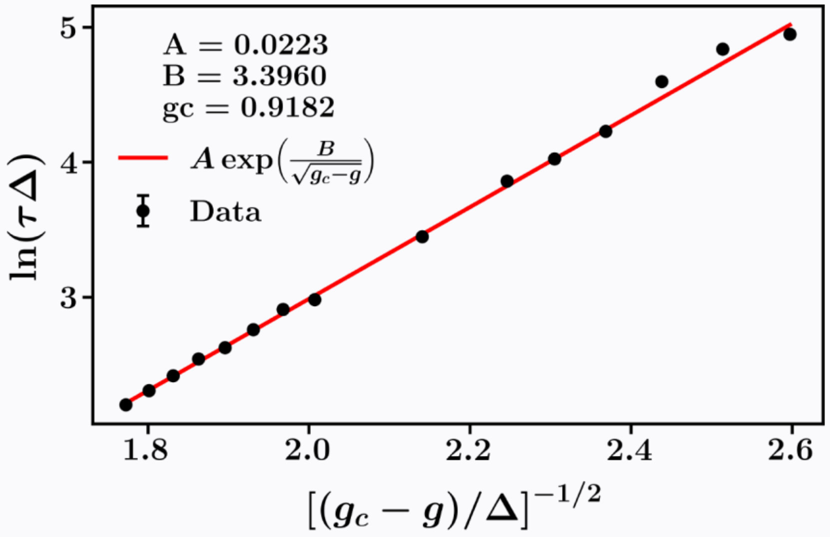
Environment does not simply destroy adiabaticity: in the non-Markovian regime, it shapes the critical universality class and preserves KZ scaling

T. Pirozzi, GDB, et al., arXiv:2603.16709 (2026).

KIBBLE–ZUREK MECHANISM (KZM) IN THE OPEN QRB

Main idea

Environment does not simply destroy adiabaticity: in the non-Markovian regime, it shapes the critical universality class and preserves KZ scaling



BKT transition

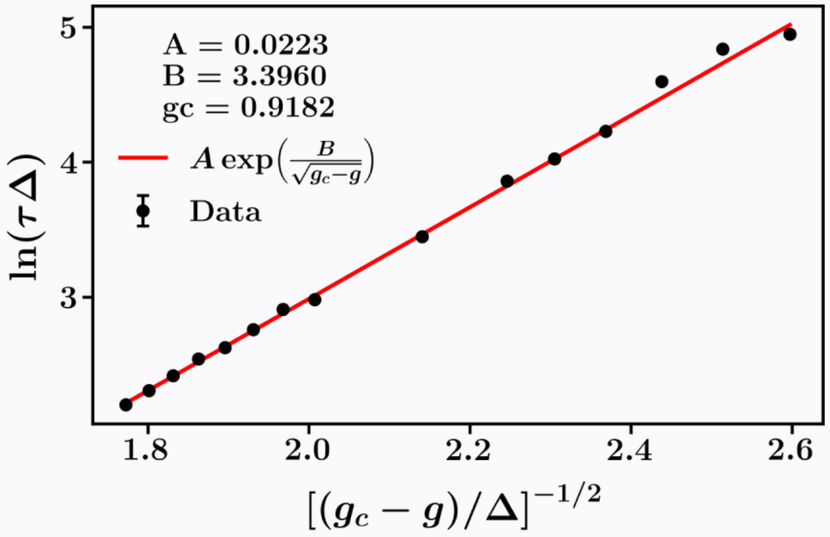
Relaxation-time
divergence confirms
BKT criticality

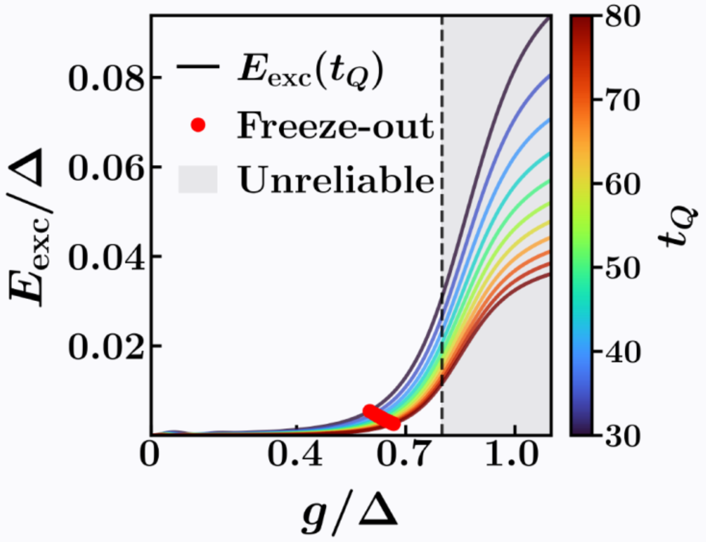
T. Pirozzi, GDB, et al., arXiv:2603.16709 (2026).

KIBBLE–ZUREK MECHANISM (KZM) IN THE OPEN QRB

Main idea

Environment does not simply destroy adiabaticity: in the non-Markovian regime, it shapes the critical universality class and preserves KZ scaling





BKT transition

Relaxation-time divergence confirms **BKT criticality**

Adiabatic breakdown

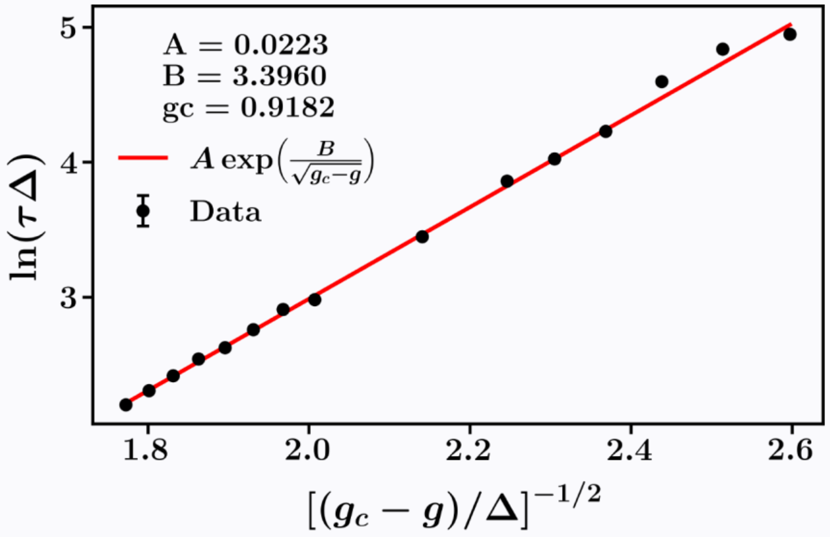
Crossing the critical point induces **freeze-out** and **loss of adiabaticity**

T. Pirozzi, GDB, et al., arXiv:2603.16709 (2026).

KIBBLE–ZUREK MECHANISM (KZM) IN THE OPEN QRB

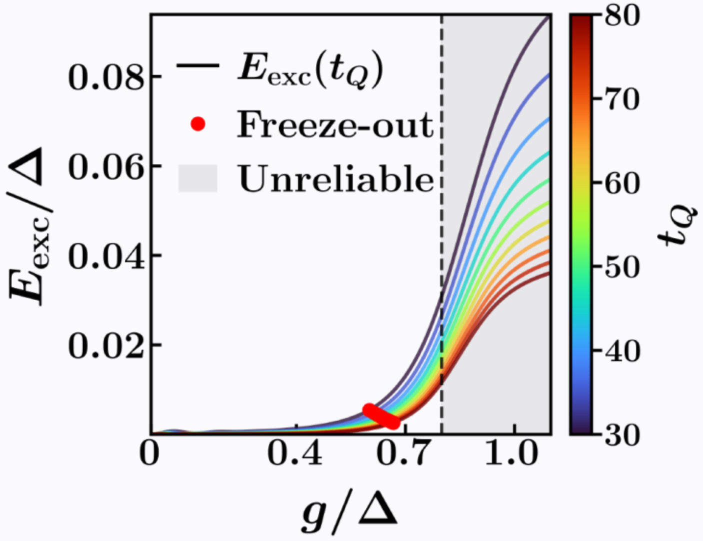
Main idea

Environment does not simply destroy adiabaticity: in the non-Markovian regime, it shapes the critical universality class and preserves KZ scaling



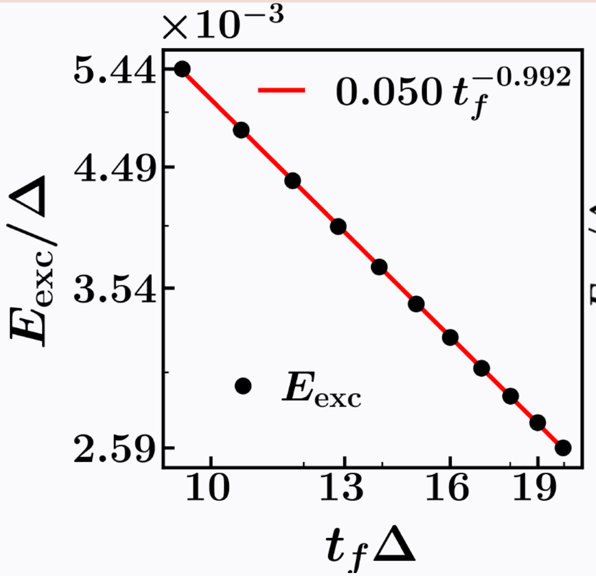
BKT transition

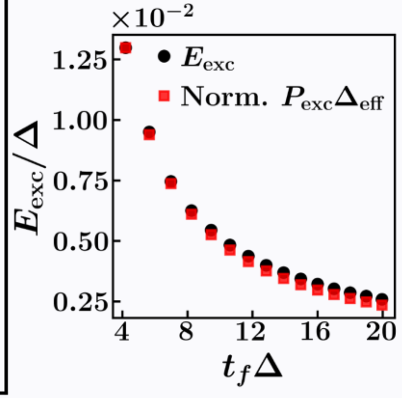
Relaxation-time divergence confirms **BKT criticality**



Adiabatic breakdown

Crossing the critical point induces **freeze-out** and **loss of adiabaticity**





KZM scaling + effective TLS

Universal excitation scaling follows from an effective **Landau–Zener** picture

T. Pirozzi, GDB, et al., arXiv:2603.16709 (2026).

QUANTUM MPEMBA EFFECT BEYOND WEAK COUPLING IN THE SBM

P. Chirico, GDB, et al., arXiv:2603.17565 (2026).

QUANTUM MPEMBA EFFECT BEYOND WEAK COUPLING IN THE SBM

Main idea

A state farther from equilibrium can relax faster (QUANTUM MPEMBA EFFECT) when the initial-state geometry selects a faster relaxation pathway

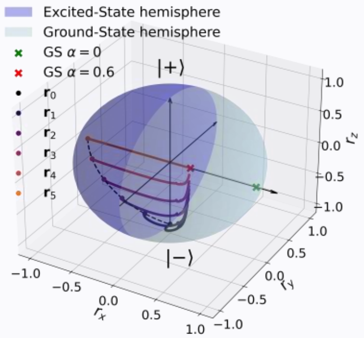
P. Chirico, GDB, et al., arXiv:2603.17565 (2026).

QUANTUM MPEMBA EFFECT BEYOND WEAK COUPLING IN THE SBM

Main idea

A state farther from equilibrium can relax faster (QUANTUM MPEMBA EFFECT) when the initial-state geometry selects a faster relaxation pathway

What we need



Initial states related by rotations

$$S(\rho||\rho_{ss}) = \mathrm{Tr}\left[\rho\left(\ln\rho - \ln\rho_{ss}\right)\right]$$

Relaxation quantified by relative entropy

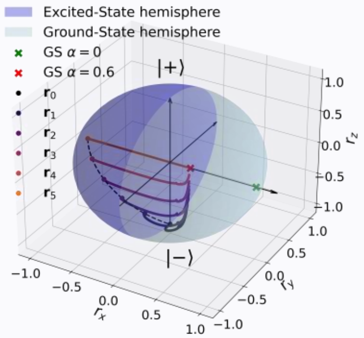
P. Chirico, GDB, et al., arXiv:2603.17565 (2026).

QUANTUM MPEMBA EFFECT BEYOND WEAK COUPLING IN THE SBM

Main idea

A state farther from equilibrium can relax faster (QUANTUM MPEMBA EFFECT) when the initial-state geometry selects a faster relaxation pathway

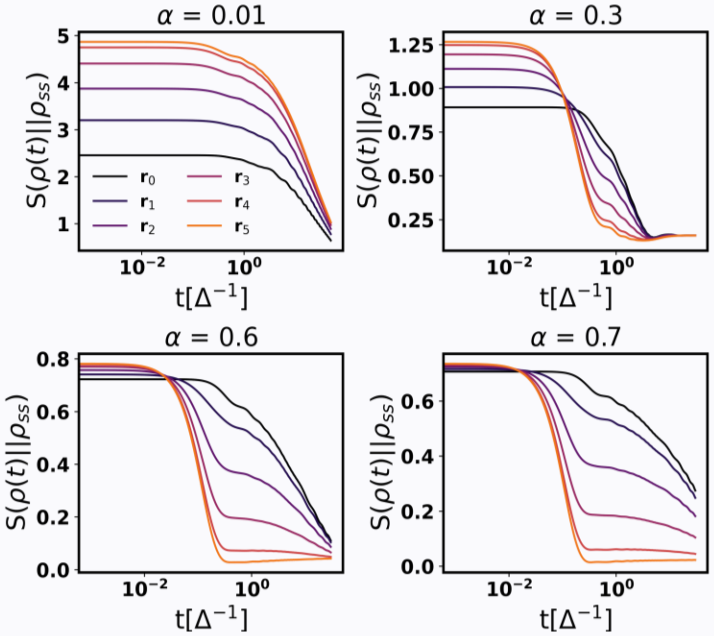
What we need



Initial states related by rotations

$$S(\rho||\rho_{ss}) = \mathrm{Tr}\left[\rho\left(\ln\rho - \ln\rho_{ss}\right)\right]$$

Relaxation quantified by relative entropy



Curve crossings mark the Mpemba effect; stronger coupling makes the separation clearer.

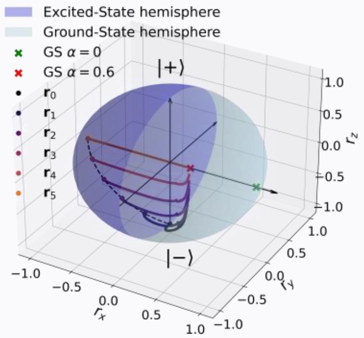
P. Chirico, GDB, et al., arXiv:2603.17565 (2026).

QUANTUM MPEMBA EFFECT BEYOND WEAK COUPLING IN THE SBM

Main idea

A state farther from equilibrium can relax faster (QUANTUM MPEMBA EFFECT) when the initial-state geometry selects a faster relaxation pathway

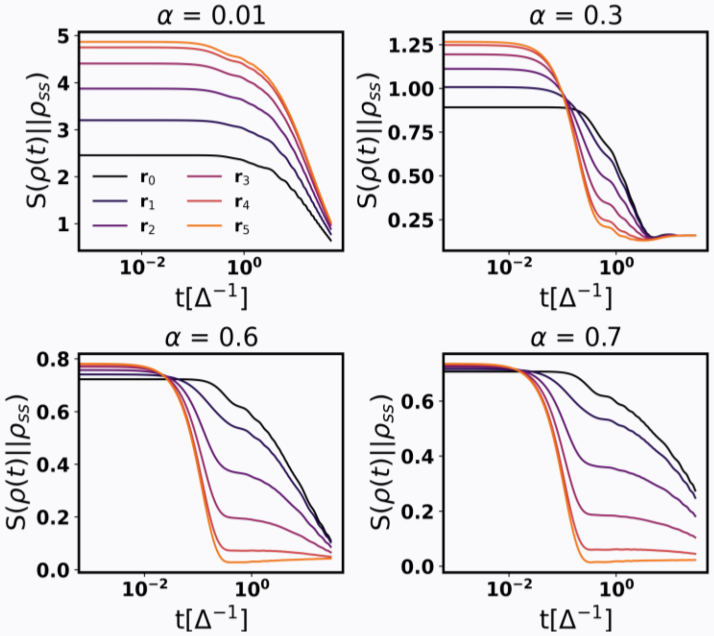
What we need



Initial states related by rotations

$$S(\rho||\rho_{ss}) = \mathrm{Tr}\left[\rho\left(\ln\rho - \ln\rho_{ss}\right)\right]$$

Relaxation quantified by relative entropy



Curve crossings mark the Mpemba effect; stronger coupling makes the separation clearer.

What we find

- The effect has a geometric structure on the Bloch sphere
- At zero temperature it is restored by increasing coupling α (for low α you need high temperature)
- Larger α → stronger effect

P. Chirico, GDB, et al., arXiv:2603.17565 (2026).

CONCLUSIONS

CONCLUSIONS

MPS to simulate open quantum systems beyond weak-coupling and Markovian approximations

Outcome: *by treating system and bath explicitly, we access reduced dynamics, bath observables, and system–environment interactions.*

CONCLUSIONS

MPS to simulate open quantum systems beyond weak-coupling and Markovian approximations

Outcome: *by treating system and bath explicitly, we access reduced dynamics, bath observables, and system–environment interactions.*

Criticality

- Environment induces and shapes QPTs and DQPTs

CONCLUSIONS

MPS to simulate open quantum systems beyond weak-coupling and Markovian approximations

Outcome: *by treating system and bath explicitly, we access reduced dynamics, bath observables, and system–environment interactions.*

Criticality

- Environment induces and shapes QPTs and DQPTs

Dynamics

- Explicit environments reveal DQPTs, KZM scaling, and Mpemba relaxation

CONCLUSIONS

MPS to simulate open quantum systems beyond weak-coupling and Markovian approximations

Outcome: *by treating system and bath explicitly, we access reduced dynamics, bath observables, and system–environment interactions.*

Criticality

- Environment induces and shapes QPTs and DQPTs

Dynamics

- Explicit environments reveal DQPTs, KZM scaling, and Mpemba relaxation

Applications

- Ergotropy: system-environment interaction as a resource for work extraction
- QFI: criticality as a resource for sensing and memory effects

INFN NAPOLI
Istituto Nazionale di Fisica Nucleare
Sezione di Napoli

Università degli Studi di Napoli
Federico II

INFN NAPOLI
Istituto Nazionale di Fisica Nucleare
Sezione di Napoli

UNIVERSITÀ DEGLI STUDI DI NAPOLI
FEDERICO II



C. A. Perroni, G. De Filippis, A. de Candia

INFN NAPOLI
Istituto Nazionale di Fisica Nucleare
Sezione di Napoli

UNIVERSITÀ DEGLI STUDI DI NAPOLI
FEDERICO II

C. A. Perroni, G. De Filippis, A. de Candia

F. Pavan,
F. G. Capone,
F. Formicola,
D. Parlato,
P. Chirico,
F. Tafuri,
T. Pirozzi

Thank you