Thermal/Ground State Preparation for Near-Term Devices using System-Bath Coupling dynamics

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Bridging the Gap Between NISQ and FTQC
IPAM

*(**Ding**, Zhan, Preskill, Lin, arXiv:2508.05703)*
*(Wang, **Ding**, arXiv:2512.03457)*

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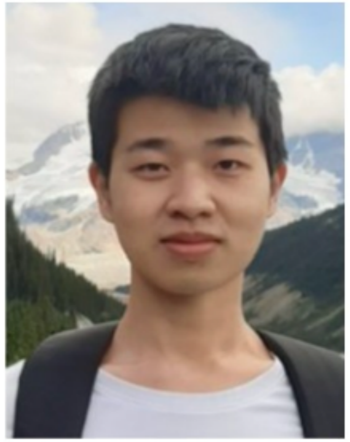
Collaborators:



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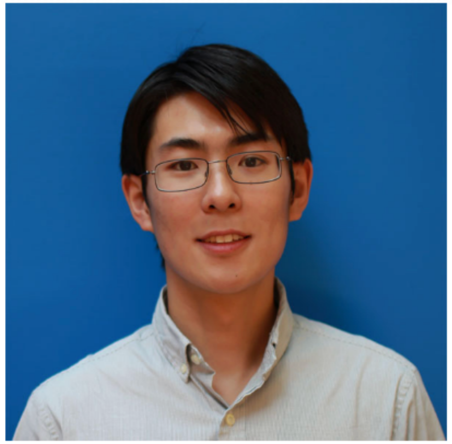

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(***Ding***, *Zhan, Preskill, Lin, arXiv:2508.05703*)

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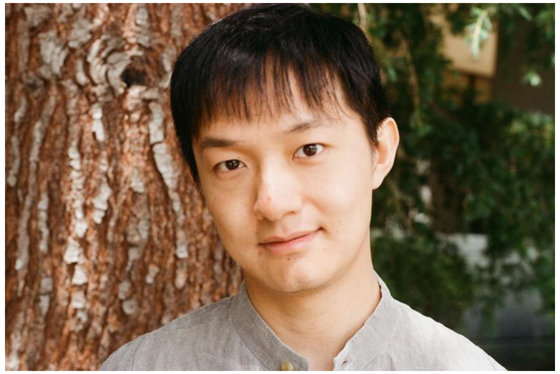
(*Wang,* ***Ding****, arXiv:2512.03457*)



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(***Ding***, *Lin, Yang, Zhang, arXiv:2510.07439*)

Outline

- Introduction
- Weak system-bath interaction algorithm
- Beyond Lindblad dynamics

Quantum ground and thermal state preparation

Given a Hamiltonian H and inverse temperature β, prepare

$\exp(-itH)$

$$\sigma_\beta = \frac{\exp(-\beta H)}{\mathrm{Tr}\left(\exp(-\beta H)\right)}.$$

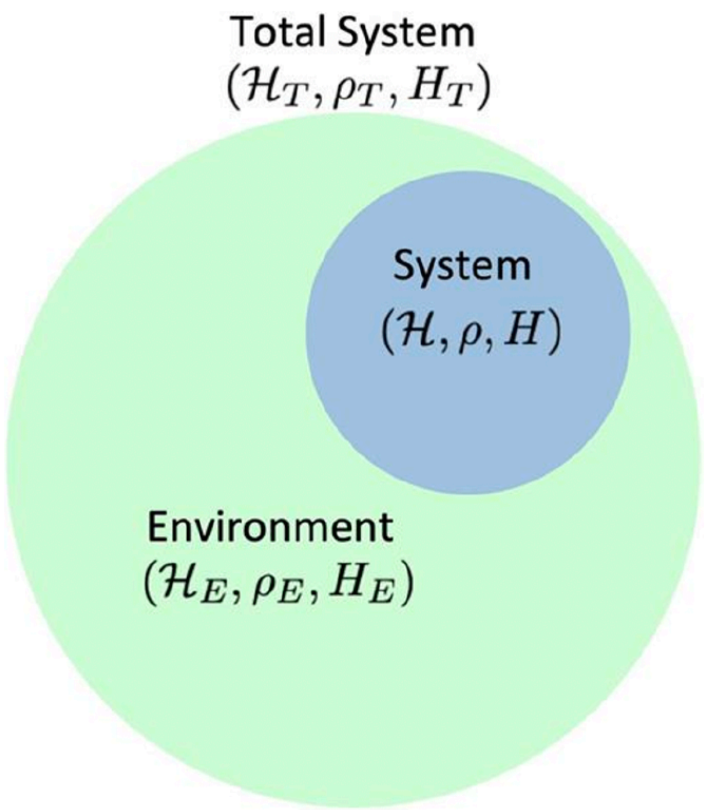
Thermal state

When $\beta \to \infty,\ \sigma_\beta \to \left|\psi_0\right\rangle\left\langle\psi_0\right|.$

Ground state

e.g. Prepare the initial state for phase estimation using $\exp(-itH)$.

Open quantum system



- $\rho_S(t) = \Phi(\rho_S(0)) := \mathrm{Tr}_E\left(\exp(-iH_T t)\rho_S(0) \otimes \rho_E \exp(iH_T t)\right)$ (interacting with bath+trace out)
- $\rho_S(t) \to \sigma_\beta, \quad t \to \infty$ Nature thermalizes fast.

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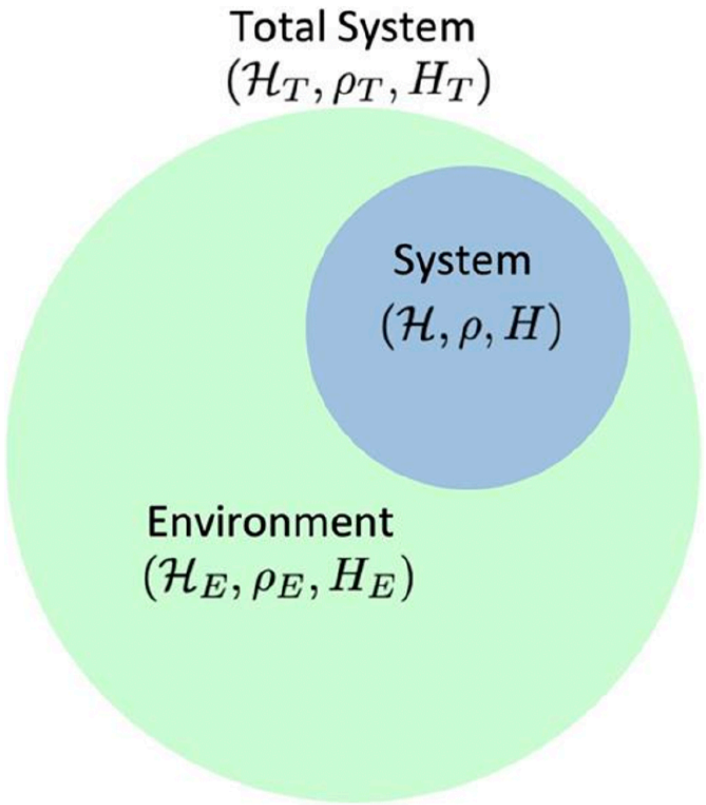

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- $\rho_S(t) \to \sigma_\beta, \quad t \to \infty$ Nature thermalizes fast.

Q: How to design an algorithm working as a fridge?

First attempt: Lindblad dynamics

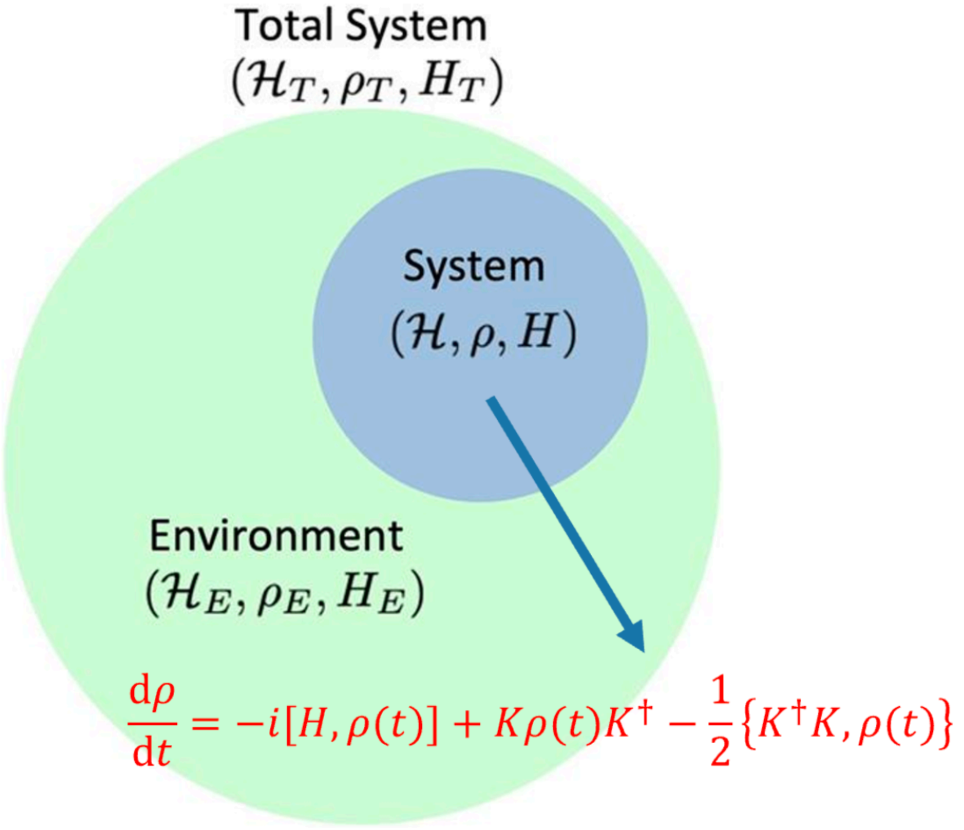
$$\frac{\mathrm{d}\rho}{\mathrm{d}t} = \mathcal{L}[\rho] = \underbrace{-i[G,\rho]}_{\text{coherent}} + \sum_a \underbrace{K_a \rho K_a^\dagger}_{\text{transition}} - \frac{1}{2}\underbrace{\left\{K_a^\dagger K_a, \rho\right\}}_{\text{dissipation}}$$

System-bath interaction

Weak interaction between system and bath

Born-Markov-Secular approximation

Lindblad dynamics



(Lindblad, CMP 1976) (Gorini-Kossakowski-Sudarshan, JMP 1976)

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System-bath interaction

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~~Born-Markov-Secular approximation~~

Lindblad dynamics

As an algorithm tool with provable guarantees

[CKBG, arXiv:2303.18224] [CKG, arXiv:2311.09207]

[CKBG, Nature, 2025]

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Lindblad dynamics

[CKBG, arXiv:2303.18224] [CKG, arXiv:2311.09207]

[CKBG, Nature, 2025]

Numerous progress toward end-to-end complexity guarantee:

- Correct fixed point: [RWW, Quantum, 2023], [**D**CL, PRR, 2023], [GCDK, arXiv:2405.20322], [JI, arXiv:2406.16023], [**D**LL, CMP, 2025], ……
- Efficient simulation: [CW, ICALP 2017], [LW, ICALP 2023], [**D**LL, PRX Quantum, 2024], [CLLY, Quantum, 2024], [KWIY, arXiv:2412.19453], [HSDS, arXiv:2506.04321] …
- Mixing time guarantee: [BCGL, PRL, 2023], [KACR, CMP, 2024],[RFA, arXiv:2411.04885, 2024], [SMBB, arXiv:2501.01412], [RFA, STOC, 2025], [TZ, PRX Quantum, 2025], [Z**D**HG et al, PRX, 2025], [BC, arXiv:2510.08533]…..

Simulation of Lindblad dynamics

$$\frac{\mathrm{d}\rho}{\mathrm{d}t} = \mathcal{L}[\rho] = \underbrace{-i[G,\rho]}_{\text{coherent}} + \sum_a \underbrace{K_a \rho K_a^\dagger}_{\text{transition}} - \underbrace{\frac{1}{2}\left\{K_a^\dagger K_a, \rho\right\}}_{\text{dissipation}}$$

- Provide oracles: $\exp(-iH\tau)$ and block encodings $\left\{\mathcal{U}_{A_a}\right\}_a$

→ Block encodings G, $\left\{K_a\right\}_a$ $\quad K_a = \int_{-\infty}^{\infty} f(t)\exp(-iHt)A_a\exp(iHt)\mathrm{d}t$

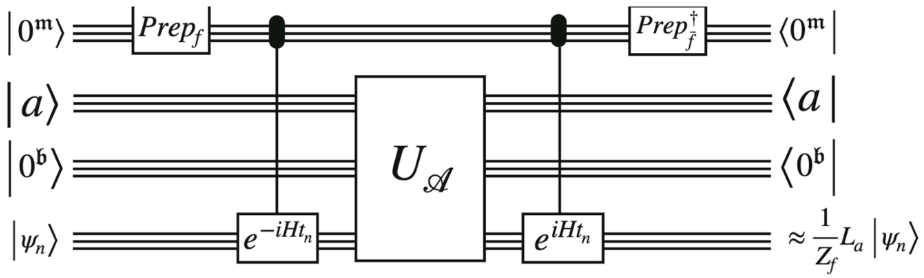
→ Lindblad simulation: $\rho(T)$ $\quad \mathcal{O}(T\mathrm{polylog}(1/\epsilon))$ query complexity

[CW, ICALP 2017], [LW, ICALP 2023], [CKBG, arXiv:2303.18224], [**D**LL, CMP, 2024], …

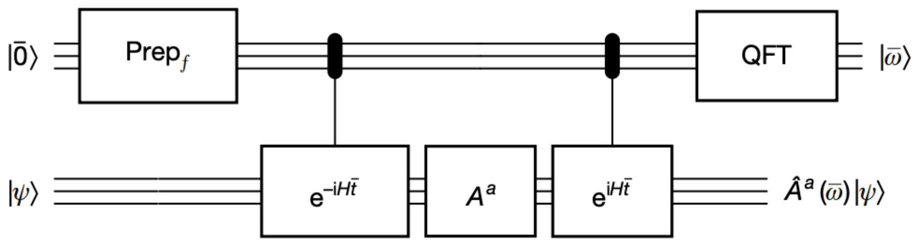
Block encoding of the jump operator:

$$\frac{\mathrm{d}\rho}{\mathrm{d}t} = \mathcal{L}[\rho] = \underbrace{-i[G, \rho]}_{\text{coherent}} + \sum_{a} \underbrace{K_a \rho K_a^\dagger}_{\text{transition}} - \frac{1}{2} \underbrace{\left\{ K_a^\dagger K_a, \rho \right\}}_{\text{dissipation}}$$

- Provide oracles: $\exp(-iH\tau)$ and block encodings $\left\{ \mathscr{U}_{A_a} \right\}_a$



(DLL, CMP, 2024)



(CKBG, Nature, 2025)

Block encodings
$G, \left\{ K_a \right\}_a$

Requires LCU, multi-control/ backward Hamiltonian simulation, QFT, ..

Our thought:

$$\frac{\mathrm{d}\rho}{\mathrm{d}t} = \mathcal{L}[\rho] = \underbrace{-i[G,\rho]}_{\text{coherent}} + \sum_a \underbrace{K_a \rho K_a^\dagger}_{\text{transition}} - \underbrace{\frac{1}{2}\left\{K_a^\dagger K_a, \rho\right\}}_{\text{dissipation}}$$

System-bath interaction

~~Born-Markov Secular approximation~~

Lindblad dynamics

As an algorithm tool

Q: Can we find a simpler algorithm that is more suitable for near-term devices while preserves rigorous guarantees ?

Our thought:

$$\frac{d\rho}{dt} = \mathcal{L}[\rho] = \underbrace{-i[G,\rho]}_{\text{coherent}} + \sum_a \underbrace{K_a \rho K_a^\dagger}_{\text{transition}} - \frac{1}{2}\underbrace{\left\{K_a^\dagger K_a, \rho\right\}}_{\text{dissipation}}$$

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As an algorithm tool

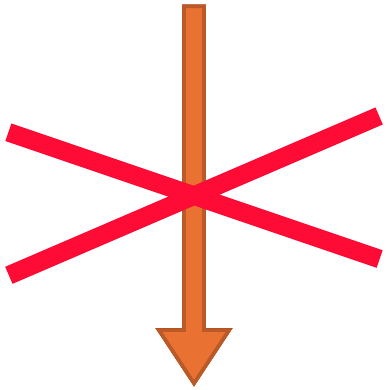
Q: Can we find a simpler algorithm that is more suitable for near-term devices while preserves rigorous guarantees ?

Yes, (**Ding**, Zhan, Preskill, Lin, arXiv:2508.05703)

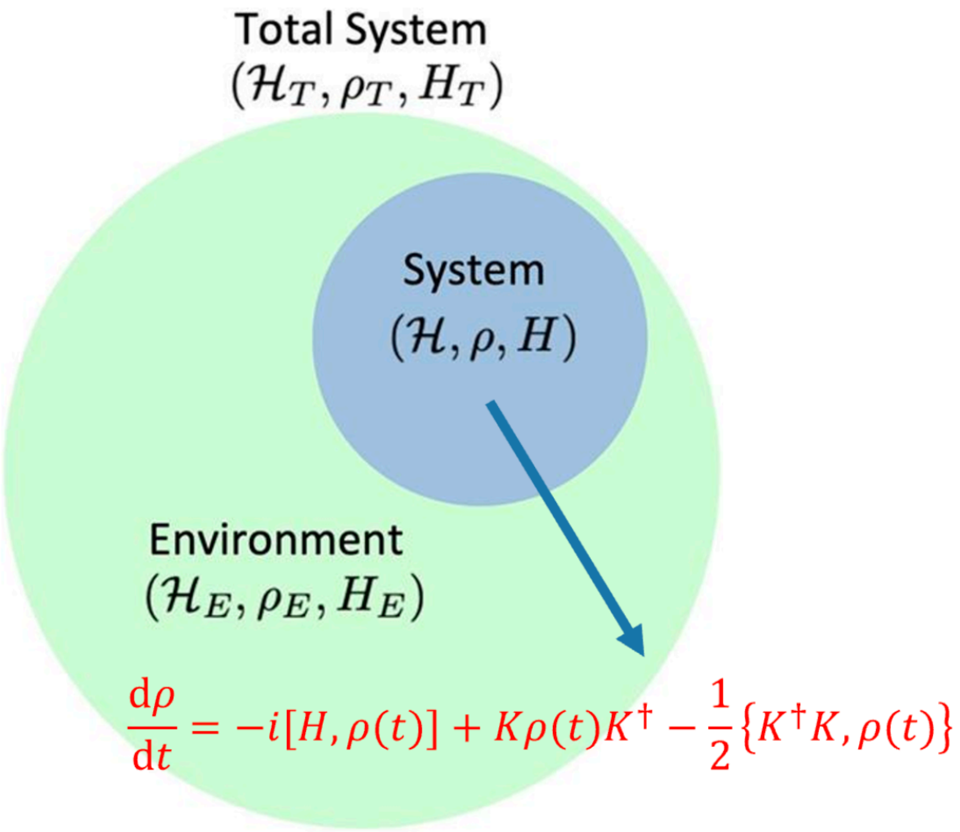
Interaction system: an algorithm

$$\rho_S(t) = \Phi(\rho_S(0)) := \mathrm{Tr}\left(\exp(-iH_T t)\rho_S(0) \otimes \rho_E \exp(iH_T t)\right)$$

System-bath
interaction model as an algorithm tool



Lindblad dynamics



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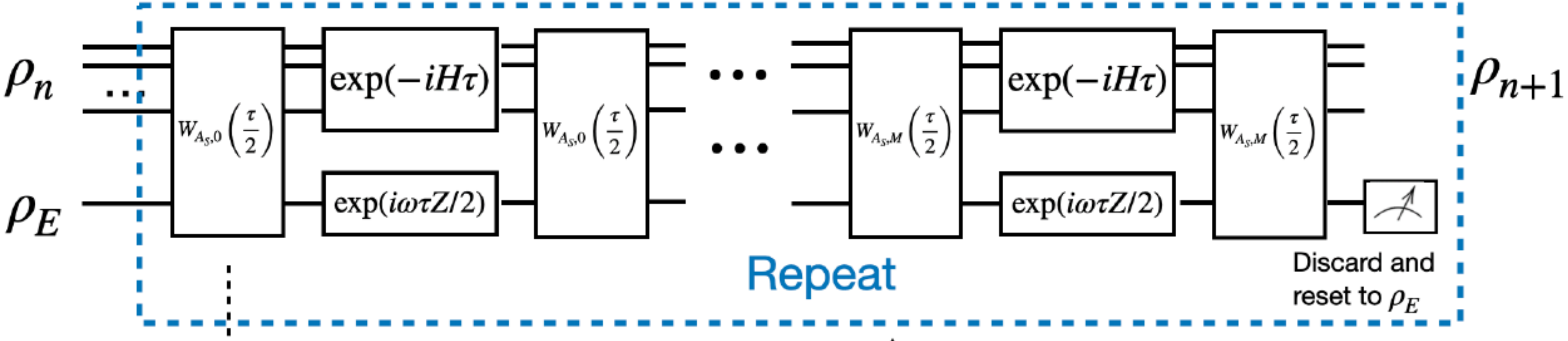
Interaction system

(**Ding**, Zhan, Preskill, Lin, arxiv:2508.05703)

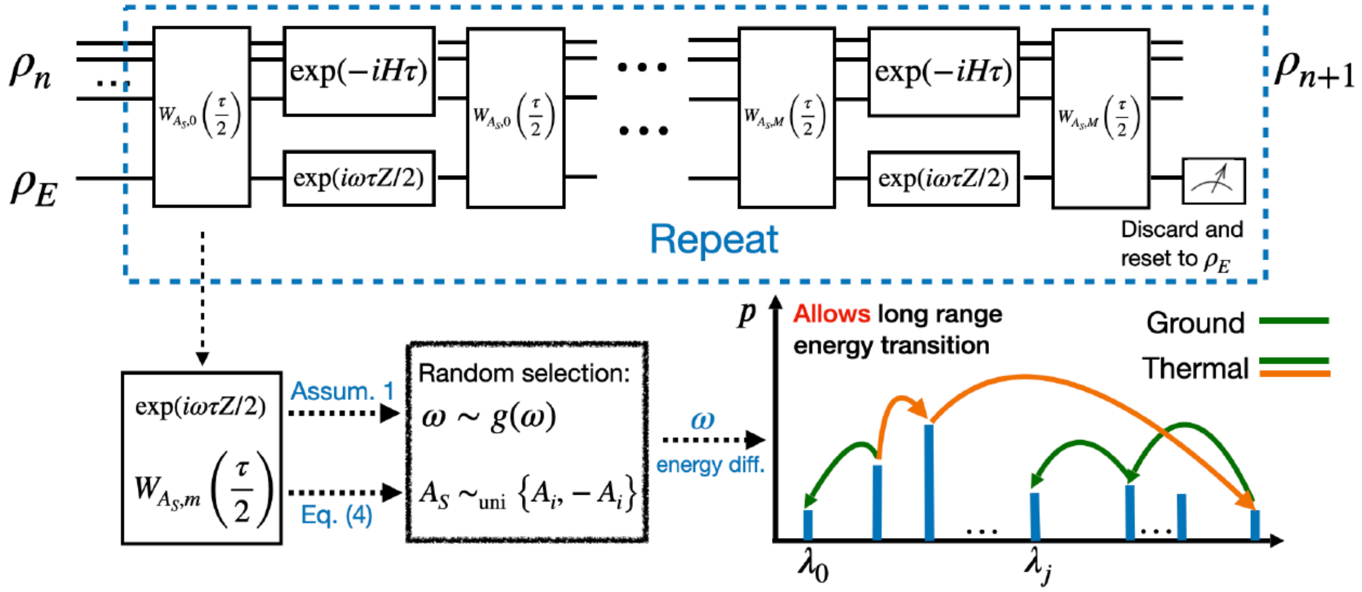


- Iteration algorithm: $\rho_{n+1} = \Phi(\rho_n) := \mathrm{Tr}_E\left(\exp(-iH_{\mathrm{tot}}T)\rho_n \otimes \rho_E \exp(iH_{\mathrm{tot}}T)\right)$
- Single ancilla qubit (representing bath) with tracing out (no success prob. problem).
- No controlled Hamiltonian simulation $\exp(-iHt)$.
- The simulation cost of Φ is dominated by the Hamiltonian simulation $\exp(-iHt)$.

$$\Phi^n(\rho_0) \to_{n\to\infty} \sigma_\beta, \quad \forall \rho_0$$

Interaction system

*(**Ding**, Zhan, Preskill, Lin, arxiv:2508.05703)*



- System-bath interaction: $\rho_{n+1} = \Phi(\rho_n) := \mathrm{Tr}_E\left(\exp(-iH_{\text{tot}}T)\rho_n \otimes \rho_E \exp(iH_{\text{tot}}T)\right)$

Single ancilla bath

- Time-dependent Hamiltonian: $H_{\text{tot}}(t) = H + \boxed{\left(-\frac{\omega}{2}Z_E\right)} + \Gamma f(t)\boxed{\left(A_S \otimes |0\rangle\langle 1| + A_S^\dagger \otimes |1\rangle\langle 0|\right)}$

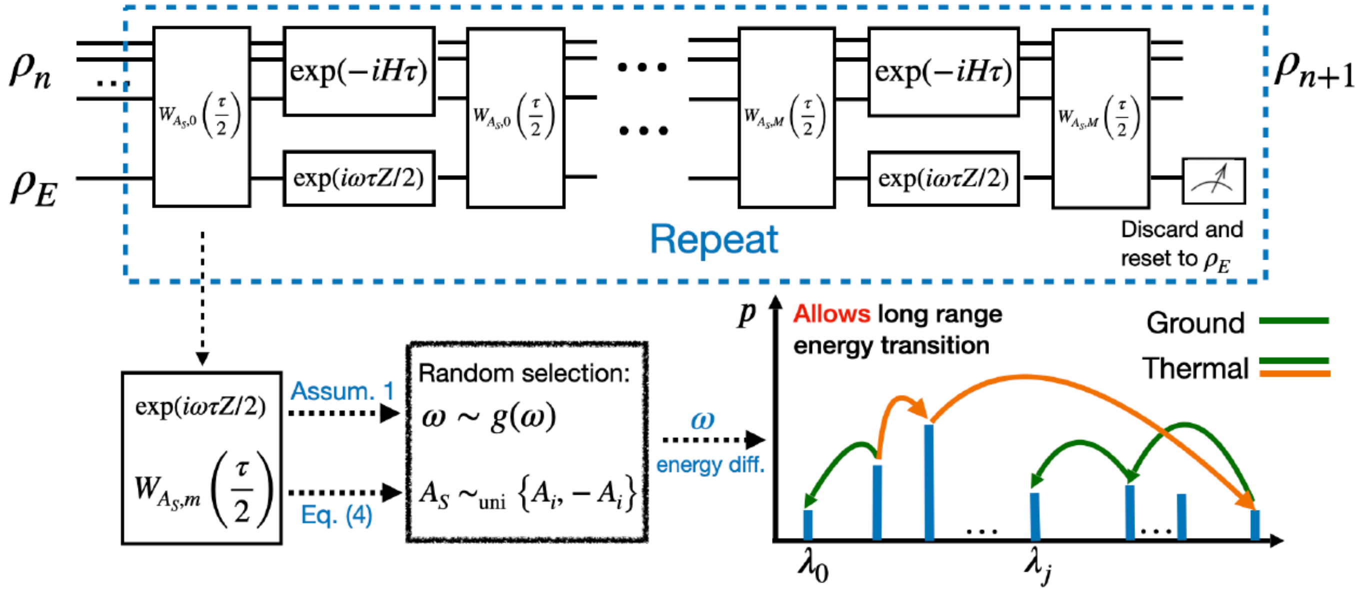
Local system-bath interaction

- Bath starts with inverse temperature β: $\rho_E \propto \exp(\omega\beta/2Z_E)$

A_S: local coupling operator

Interaction system

(**Ding**, Zhan, Preskill, Lin, arxiv:2508.05703)



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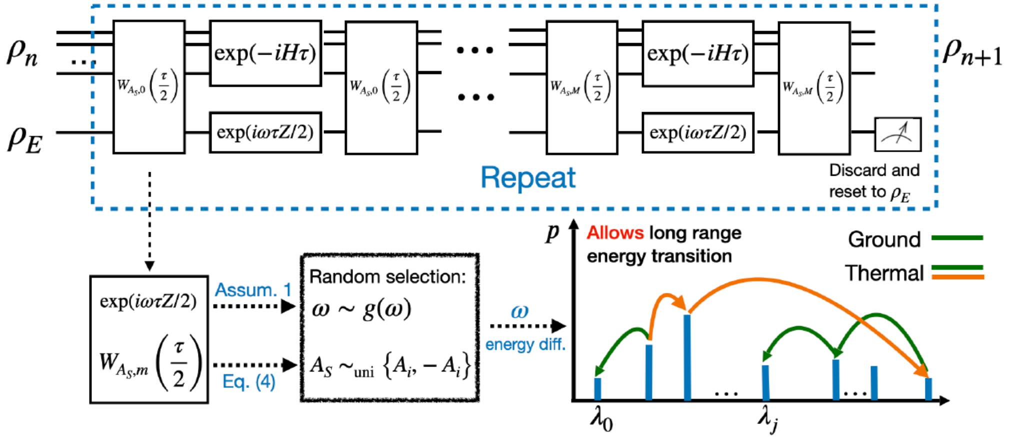
- Bath starts with inverse temperature β: $\rho_E \propto \exp(\omega\beta/2Z_E)$ Bath initializes at temperature β^{-1}

Choice of parameters



- $H_{\text{tot}}(t) = H + \left(-\frac{\omega}{2} Z_E\right) + \Gamma f(t)\left(A_S \otimes |0\rangle\langle 1| + A_S^\dagger \otimes |1\rangle\langle 0|\right)$

- $\rho_E \propto \exp(\omega\beta/2 Z_E)$

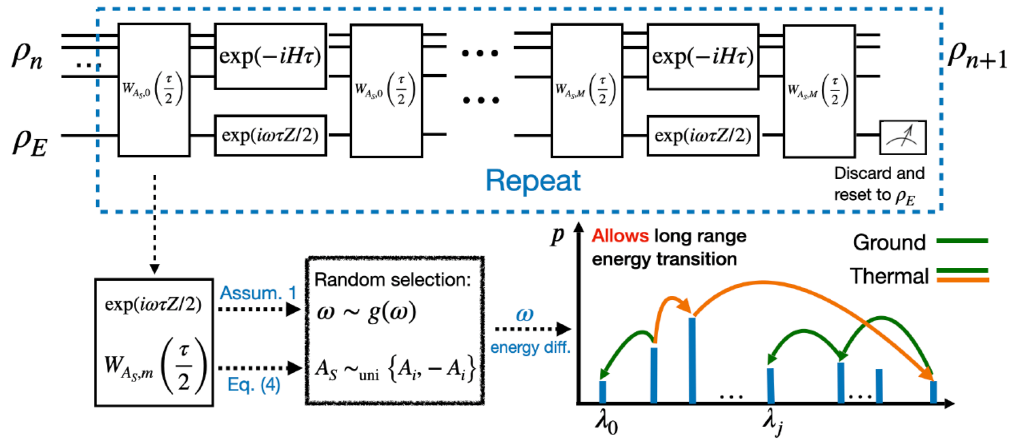
- Gaussian interaction function:

$$f(t) = \frac{1}{(2\pi)^{1/4}\sigma} \exp\left(-\frac{t^2}{4\sigma^2}\right), \quad \sigma \gg 1$$

Note: Gaussian f is a technical requirement. This is inspired by [CKBG, 2023], [CKG, 2023].

In practice, we can choose a constant interaction : $f(t) = \frac{1}{T}\mathbf{1}_{t \le T}$ for simplicity.

Choice of parameters



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- ω uniformly chosen from $[0,2\|H\|]$. (Distribution is flexible)

Approximates the allowed energy transition in each step.

Choice of parameters

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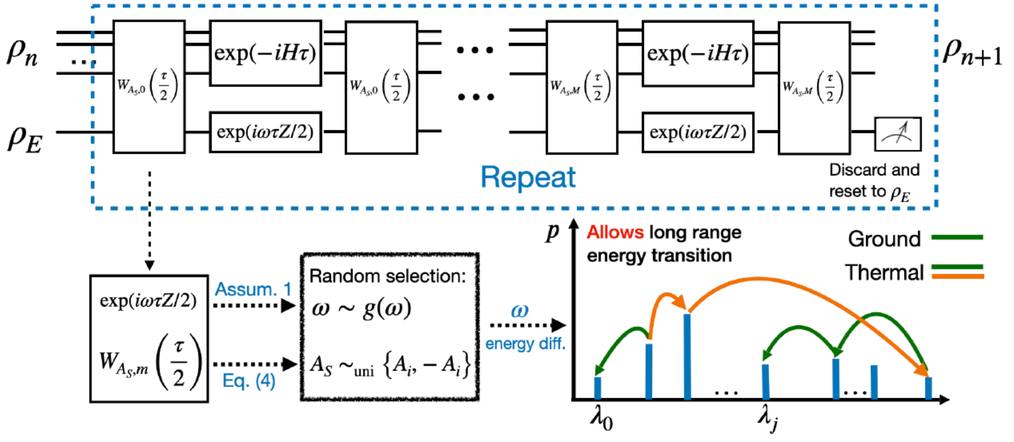

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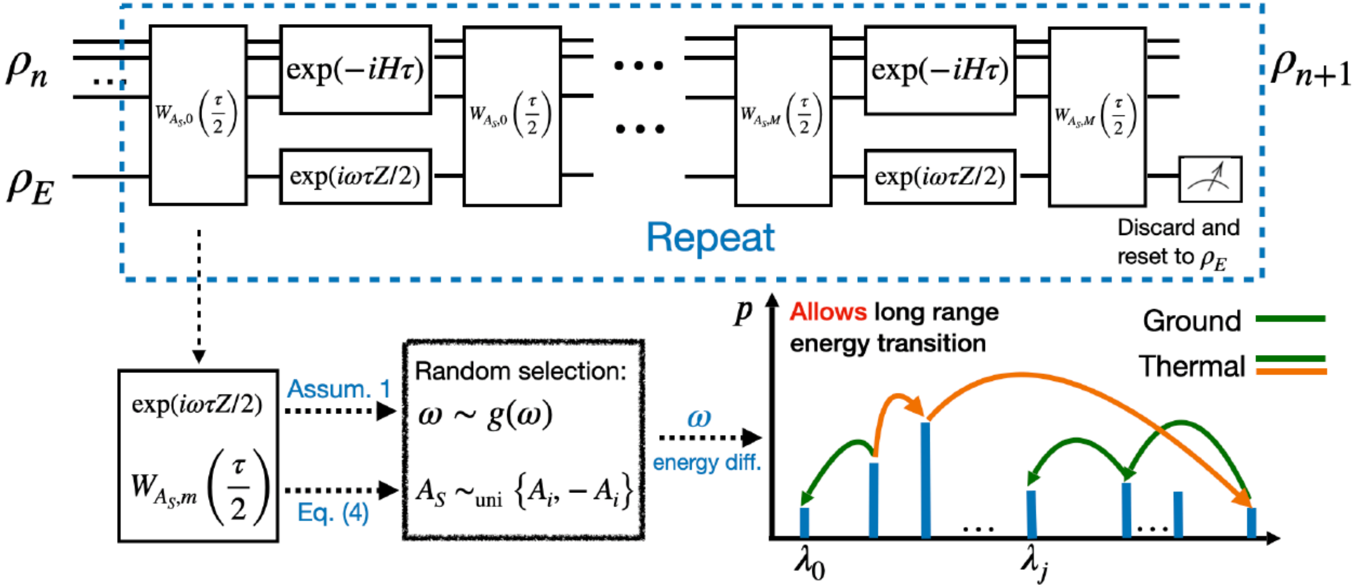
- A_S randomly chosen from a proper set. (Ex. Single Pauli set, Single creation/annihilation set)



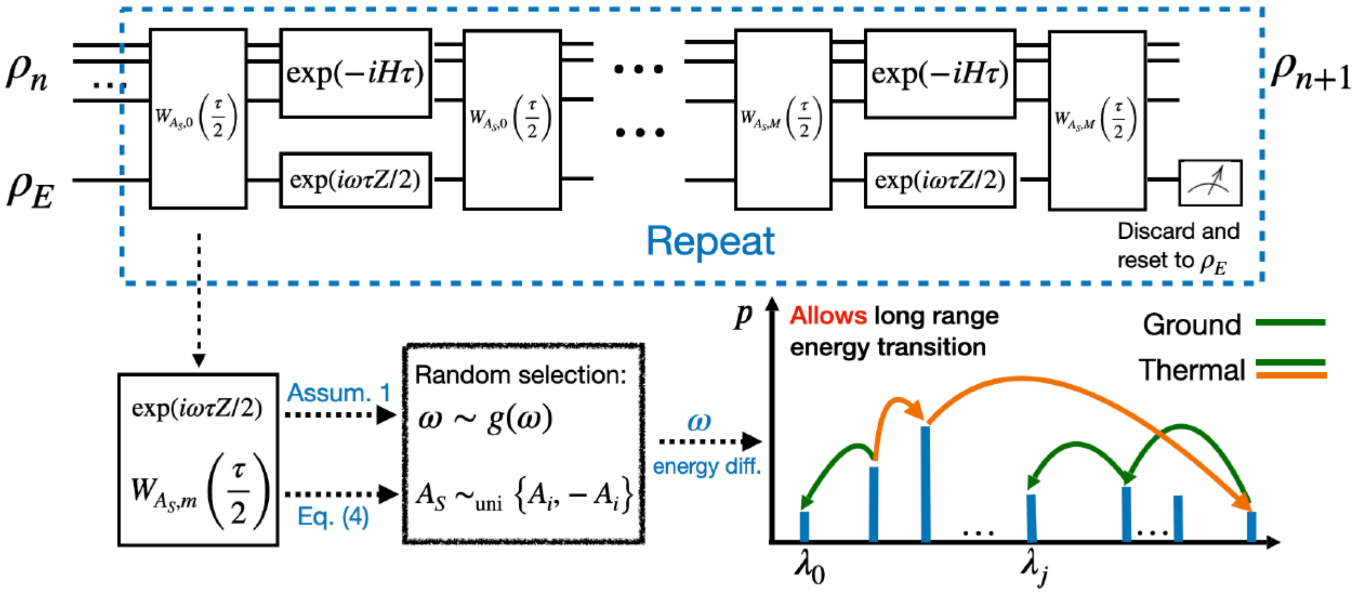
- System-bath interaction: $\rho_{n+1} = \Phi(\rho_n) := \mathrm{Tr}_E\left(\exp(-iH_{\mathrm{tot}}T)\rho_n \otimes \rho_E \exp(iH_{\mathrm{tot}}T)\right)$

Simulation is equivalent to Hamiltonian simulation + trace out

If we use second order Trotter for Hamiltonian simulation

Complexity: $\mathcal{O}(T^{3/2}/\epsilon^{1/2})$

Single ancilla;
No need to construct jump operator;
No controlled/backward Hamiltonian evolution



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Simulation is equivalent to Hamiltonian simulation + trace out

If we use second order Trotter for Hamiltonian simulation

End-to-end complexity: $\mathcal{O}(T^{3/2}/\epsilon^{1/2}) \times \tau_{\text{mix}}$

Single simulation time and mixing time

Integer mixing time

$$\tau_{\text{mix},\Phi}(\epsilon) = \min\left\{ t \in \mathbb{N} \,\middle|\, \sup_{\rho} \|\Phi^t(\rho) - \rho_{\text{fix}}(\Phi)\|_1 \le \epsilon \right\}$$

Theoretical guarantee:

(**Ding**, Zhan, Preskill, Lin, arxiv:2508.05703)
(Slezak, Sandi, Alhambra, Franca, Rouze, arxiv:2601.16154)

End-to-end complexity: Efficiency preparation of the target state

$$\rho_{n+1} = \Phi(\rho_n) := \mathrm{Tr}_E\left(\exp(-iH_{\mathrm{tot}}T)\rho_n \otimes \rho_E \exp(iH_{\mathrm{tot}}T)\right)$$

Theorem 1: Given finite β, to prepare σ_β up to ϵ-trace distance, we need

$$\text{Total } H\text{-simulation time} = \mathrm{poly}\left(\beta, N, 1/\epsilon\right)$$

after choosing
$\sigma = \Omega(\epsilon^{-1}), \quad T \sim \sigma, \quad \Gamma = \mathcal{O}(\epsilon)$

e.g. weak-interacting system, 1D local, high temp local

Theorem 2: We assume H has a spectral gap Δ. To prepare σ_∞ up to ϵ-trace distance, we need

$$\text{Total } H\text{-simulation time} = \mathrm{poly}\left(\Delta^{-1}, N, 1/\epsilon\right)$$

after choosing
$\sigma = \Omega(\Delta^{-1}), \quad T \sim \sigma, \quad \Gamma = \mathcal{O}(\epsilon)$

e.g. free fermion

Theoretical guarantee:

(***Ding***, *Zhan, Preskill, Lin, arxiv:2508.05703)*

(Slezak, Sandi, Alhambra, Franca, Rouze, arxiv:2601.16154)

End-to-end complexity: Efficiency preparation of the target state

Theorem 1

$\Gamma = \mathcal{O}(\epsilon)$

Theorem 2

distance, w

High-level proof idea:

- Weak coupling regime $\Gamma = \mathcal{O}(\epsilon)$:

$$\Phi(\rho) = \rho + \Gamma^2 \mathscr{L}_{\mathrm{Lind}}(\rho) + \Gamma^4(\,\cdot\,) \approx \exp(\mathscr{L}\Gamma^2)\rho$$

Step 1: Demonstrate $\mathscr{L}$ preserves the target state

- $\tau_{\mathrm{mix}} \sim t_{\mathrm{min}}(\mathscr{L})\Gamma^2$

Step 2: Calculate the mixing time of $\mathscr{L}$ (independent of σ, Γ)

Total H-simulation time $= \mathrm{poly}\left(\Delta^{-1}, N, 1/\epsilon\right)$ after choosing $\sigma = \Omega(\Delta^{-1}), \quad T \sim \sigma, \quad \Gamma = \mathcal{O}(\epsilon)$

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Interaction system: an algorithm

- System-bath interaction: $\rho_{n+1} = \Phi(\rho_n) := \mathrm{Tr}_E\left(\exp(-iH_{\mathrm{tot}}T)\rho_n \otimes \rho_E \exp(iH_{\mathrm{tot}}T)\right)$
- Time-dependent Hamiltonian: $H_{\mathrm{tot}}(t) = H + \left(-\frac{\omega}{2}Z_E\right) + \Gamma f(t)\left(A_S \otimes \left|0\right\rangle\left\langle 1\right| + A_S^\dagger \otimes \left|1\right\rangle\left\langle 0\right|\right)$

$$f(t) = \frac{1}{(2\pi)^{1/4}\sigma}\exp\left(-\frac{t^2}{4\sigma^2}\right), \quad \sigma \gg 1$$

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$$f(t) = \frac{1}{(2\pi)^{1/4}\sigma}\exp\left(-\frac{t^2}{4\sigma^2}\right), \quad \sigma \gg 1$$

Weak interaction regime: Require $\Gamma \ll 1$

$\Rightarrow$ $\Phi(\rho) \approx \exp(\mathscr{L}\Gamma^2)\rho$

Pros: Theoretically simple

Cons: Slow mixing ($\tau_{\mathrm{mix}} \sim \Gamma^{-2}$)

*(**Ding**, Zhan, Preskill, Lin, arXiv:2508.05703)*

Interaction system: an algorithm

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$$f(t) = \frac{1}{(2\pi)^{1/4}\sigma}\exp\left(-\frac{t^2}{4\sigma^2}\right), \quad \sigma \gg 1$$

Beyond Lindblad dynamics: $\Gamma = \Theta(1)$

Higher order terms

$$\Phi_\Gamma \rho = \rho + \underbrace{\underbrace{\Gamma^2 \mathcal{L}_{\mathrm{Lind}}(\rho)}_{\text{Previous works}} \boxed{+\Gamma^4(\dots)}}_{\text{Our analysis}}$$

$\Rightarrow$ $\Phi(\sigma_\beta) \approx \sigma_\beta$

Pros: faster mixing

*(Wang, **Ding**, arXiv/2512.03457)*

Interaction system: an algorithm

- System-bath interaction: $\rho_{n+1} = \Phi(\rho_n) := \mathrm{Tr}_E\left(\exp(-iH_{\text{tot}}T)\rho_n \otimes \rho_E \exp(iH_{\text{tot}}T)\right)$
- Time-dependent Hamiltonian: $H_{\text{tot}}(t) = H + \left(-\frac{\omega}{2}Z_E\right) + \Gamma f(t)\left(A_S \otimes |0\rangle\langle 1| + A_S^\dagger \otimes |1\rangle\langle 0|\right)$

$$f(t) = \frac{1}{(2\pi)^{1/4}\sigma}\exp\left(-\frac{t^2}{4\sigma^2}\right), \quad \sigma \gg 1$$

Beyond Lindblad dynamics: $\Gamma = \Theta(1)$

$\Rightarrow$ $\Phi(\sigma_\beta) \approx \sigma_\beta$

Optimal simulation cost $\sim \mathcal{O}(T\tau_{\text{mix}}) = \mathcal{O}(\sigma\tau_{\text{mix}})$

- Large Γ reduces the cost ($\tau_{\text{mix}} \sim \Gamma^{-2}$)

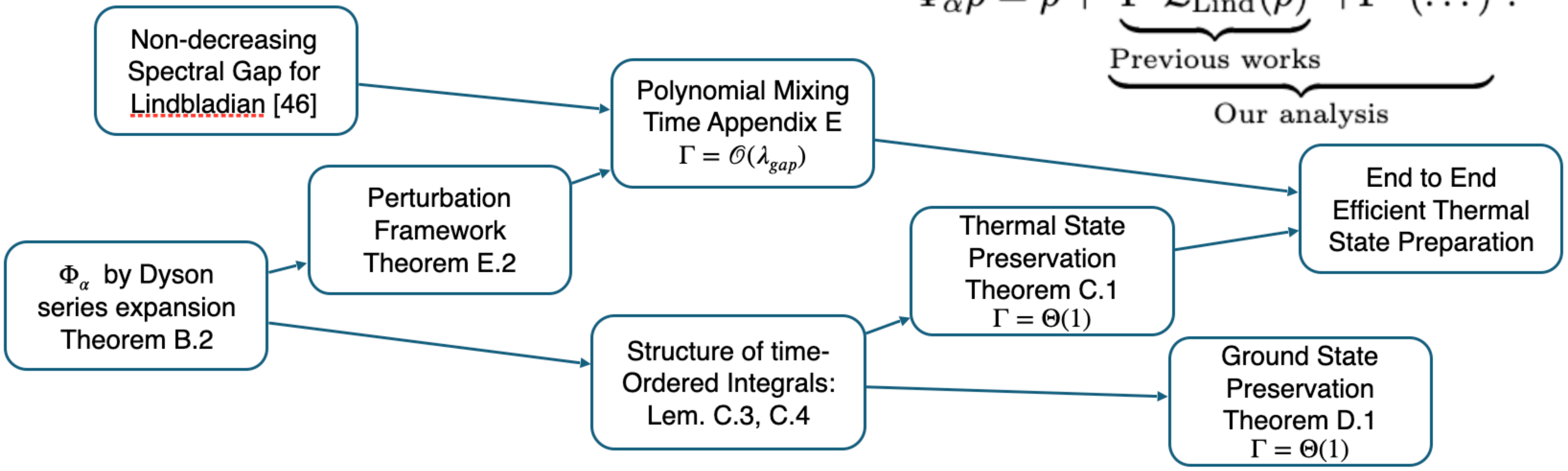
e.g. weak-interacting system, 1D local, high temp local

$\text{Cost} \sim \sigma^2/\epsilon^2 \rightarrow \text{Cost} \sim \sigma^2$

[SSAFR,2026] *(Wang, **Ding**, arXiv/2512.03457)*

Interaction system: an algorithm

$$\Phi_\alpha \rho = \underbrace{\rho + \underbrace{\Gamma^2 \mathcal{L}_{\mathrm{Lind}}(\rho)}_{\text{Previous works}} + \Gamma^4 (\dots)}_{\text{Our analysis}} .$$



Beyond Lindblad dynamics: $\Gamma = \Theta(1)$

$$\Rightarrow \quad \Phi(\sigma_\beta) \approx \sigma_\beta$$

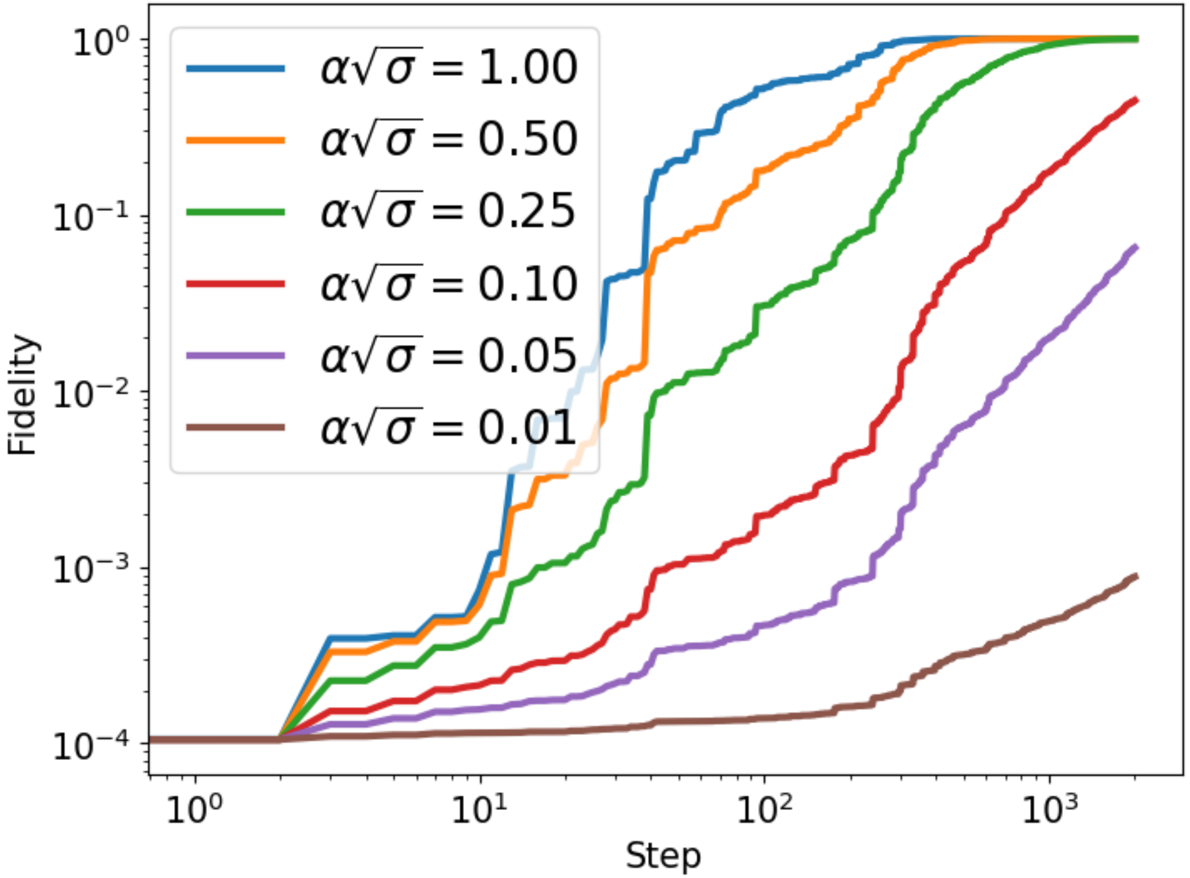
- Large Γ reduces the cost ($\tau_{\mathrm{mix}} \sim \Gamma^{-2}$)
- Open quantum system based state preparation algorithm can theoretically go beyond Lindblad dynamics

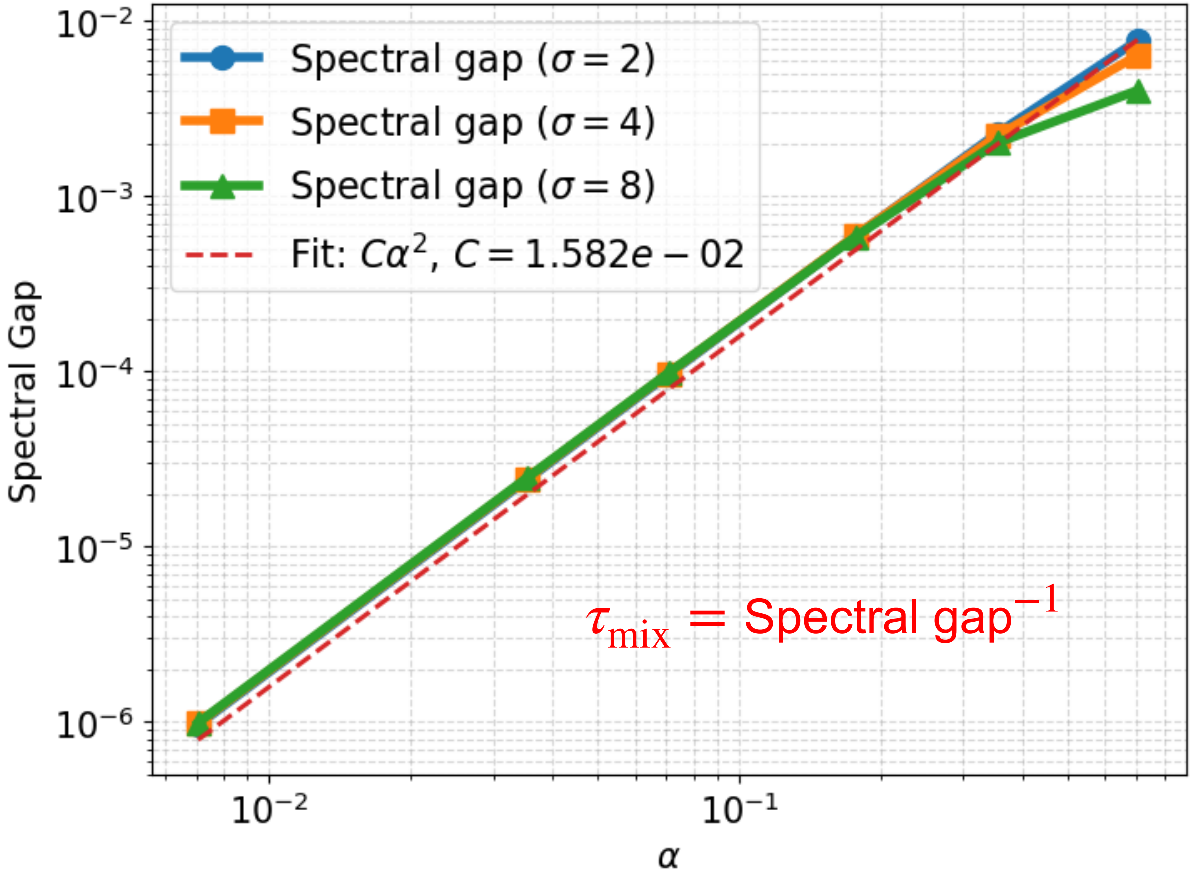
*(Wang, **Ding**, arXiv/2512.03457)*

1-D Hubbard model (4 qubits)

$$\Gamma = \alpha\sqrt{\sigma}$$

$$\hat{H} = -t\sum_{i,\sigma}\left(\hat{c}^\dagger_{i,\sigma}\hat{c}_{i+1,\sigma} + \hat{c}^\dagger_{i+1,\sigma}\hat{c}_{i,\sigma}\right) + U\sum_i \hat{n}_{i\uparrow}\hat{n}_{i\downarrow}$$

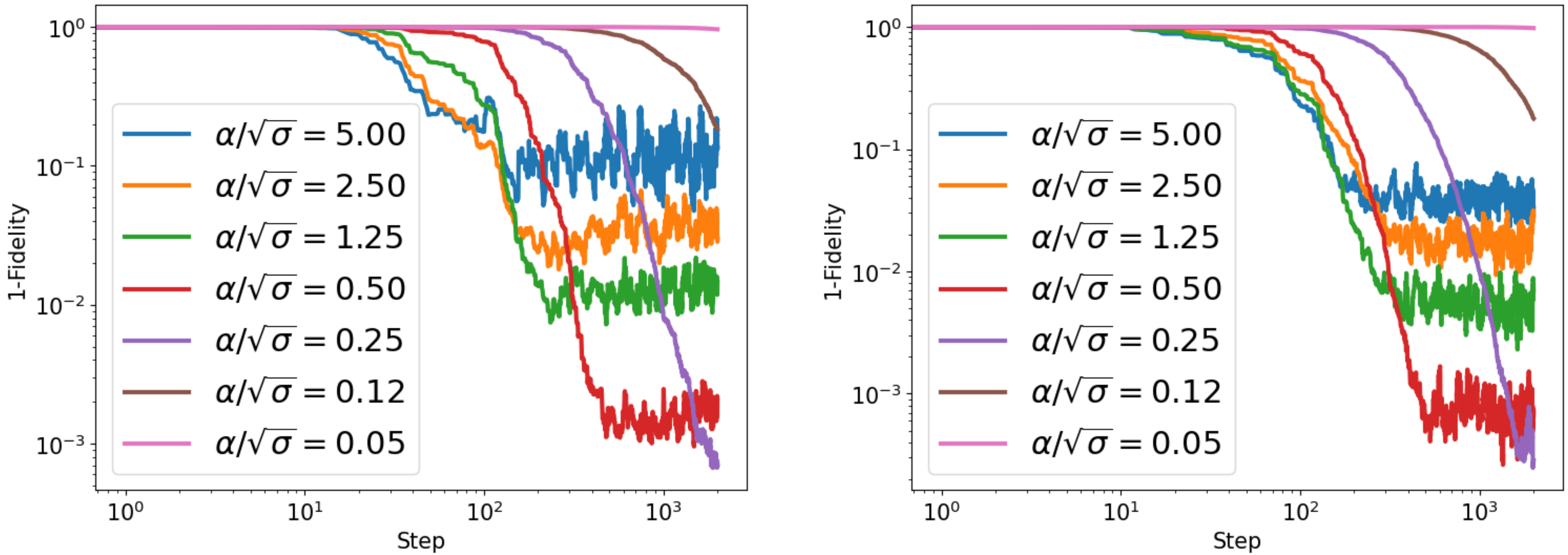




Might allow strong coupling?

$$H_{\text{tot}}(t) = H + \left(-\frac{\omega}{2}Z_E\right) + \Gamma \ldots,$$ Theory: $\Gamma = \Theta(1)$, Numerical: $\Gamma = \Theta(\sigma)$ $(\sigma \gg 1)$

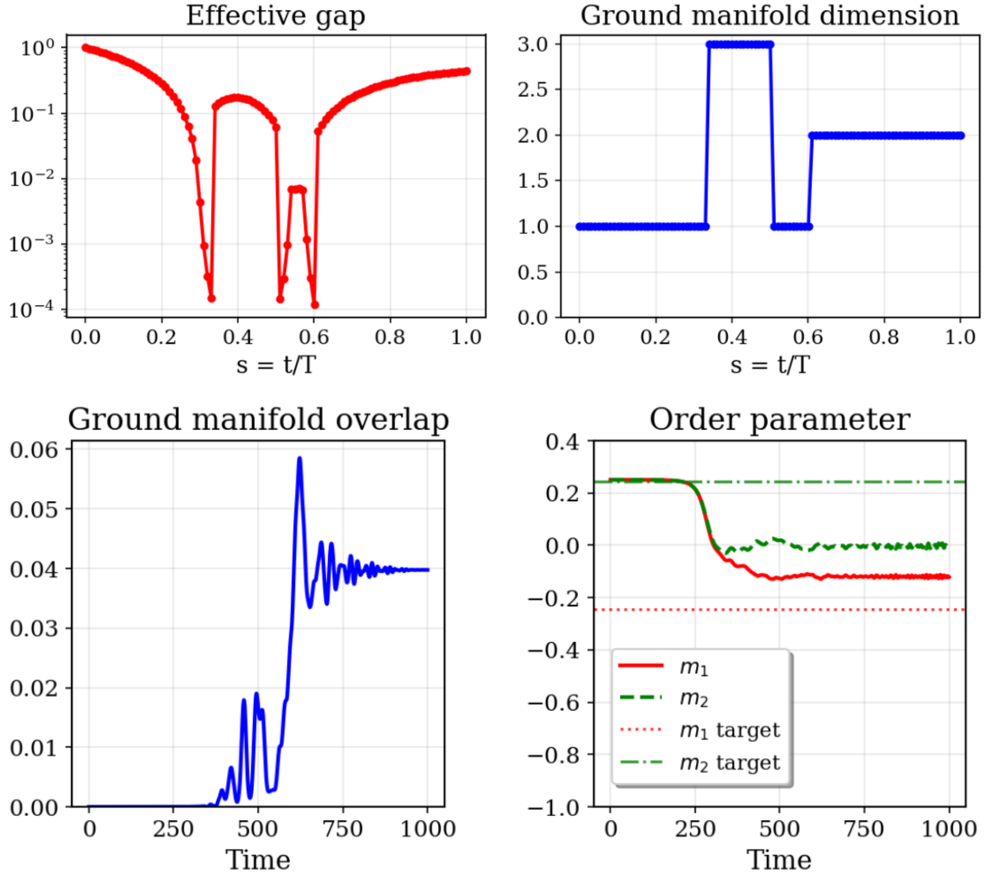
TFIM-8 model $\Gamma/\sigma = \alpha/\sqrt{\sigma}$ Hubbard-4 model



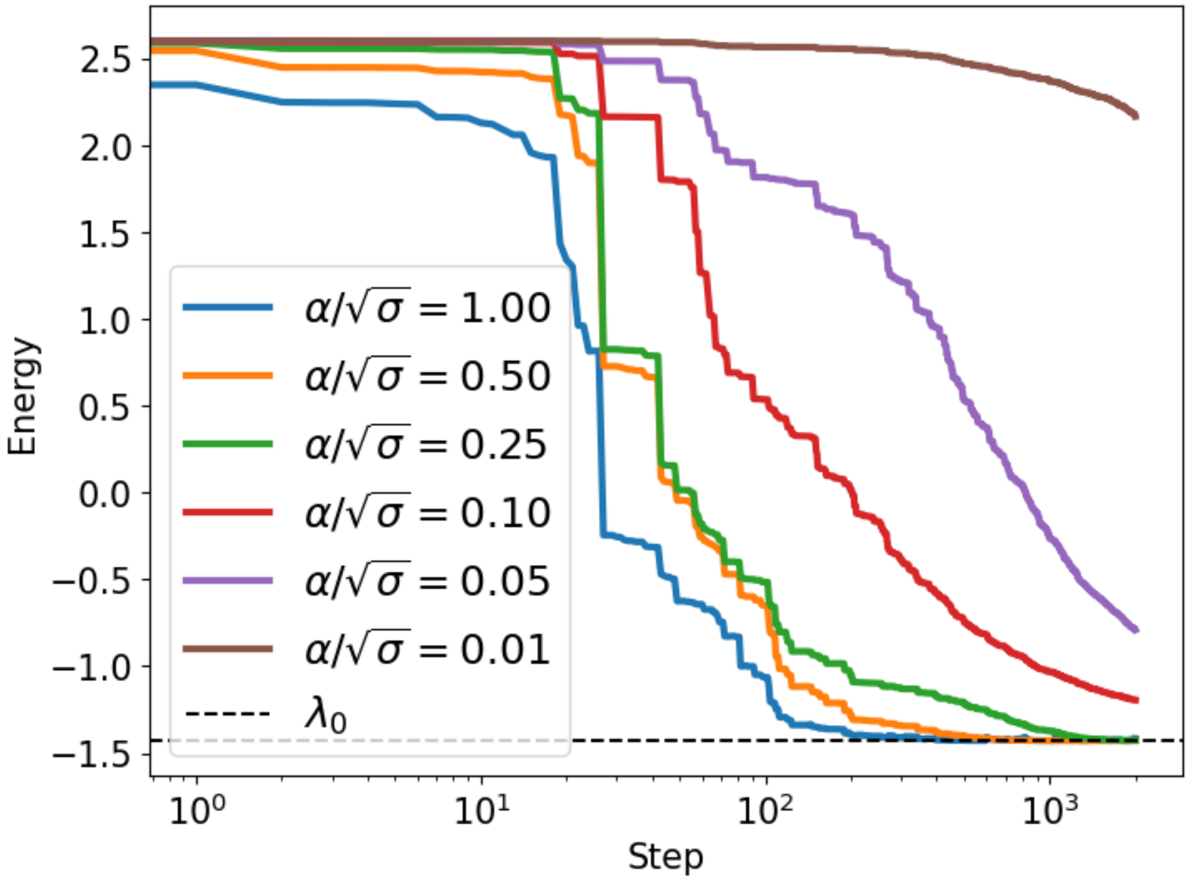
ANNNI model

$$H_{\mathrm{ANNNI}} = \frac{J_1}{4}\sum_i Z_i Z_{i+1} + \frac{J_2}{4}\sum_i Z_i Z_{i+2} - \frac{\Gamma}{2}\sum_i X_i$$

Adiabatic fails



Our algorithm

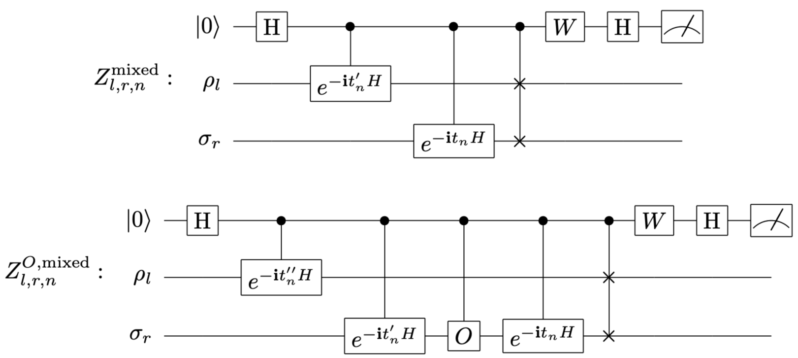


[ZDHG et al, PRX, 2026]

Low energy subspace characterization:

(**Ding**, Lin, Yang, Zhang, arXiv:2510.07439)

Trial state: $\{\rho_i\}_i^k$



$\xrightarrow{\text{Data collection}}$

$$\left\{Z_{i,j}(t_n, t_n')\right\}_n \approx \left\{\mathrm{Tr}\left(\rho_i \exp(-iHt_n)\rho_j \exp(-iHt_n')\right)\right\}_n$$

$$\left\{Z_{i,j}(t_n, t_n', t_n'')\right\}_n \approx \left\{\mathrm{Tr}\left(\rho_i \exp(-it_n H)O \exp(-it_n' H)\rho_j \exp(-it_n'' H)\right)\right\}_n$$

Tensor based

$\longrightarrow$

classical post-processing

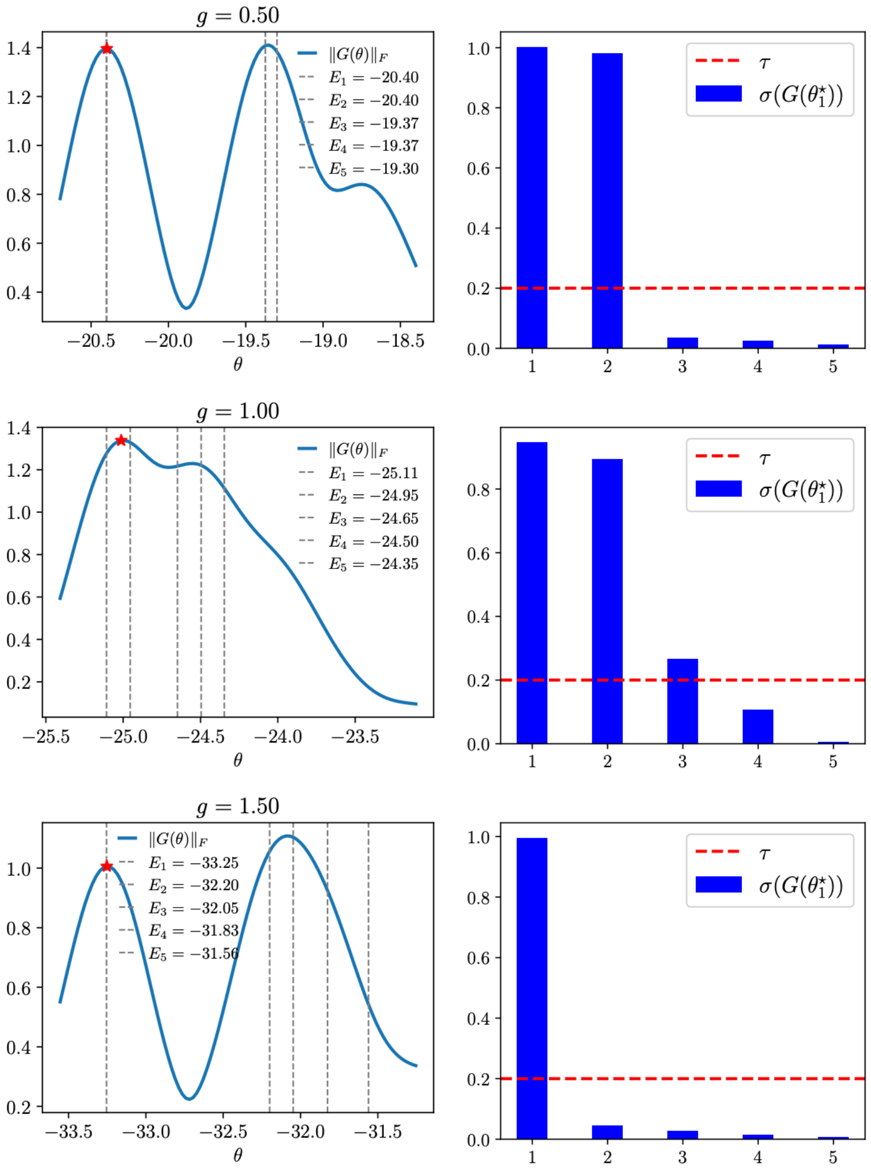
1.Ground state energy or low excited state energy.

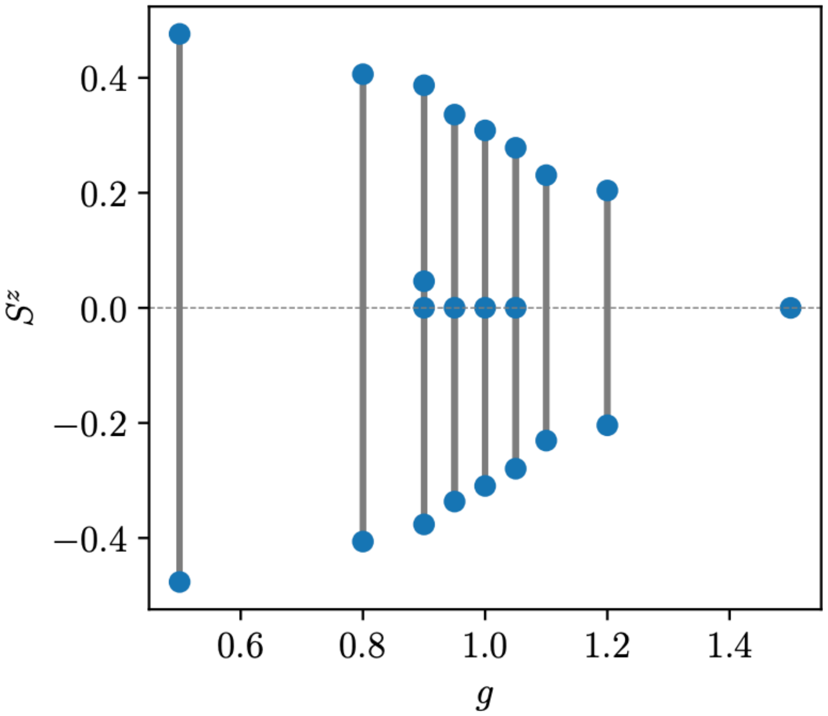
2.Multiplicity of ground/low energy subspace.

3.Physical observables of low energy subspace.

$$H = -\sum_{i=1}^{N_{\text{spin}}-1} Z_i Z_{i+1} - g \sum_{i=1}^{N_{\text{spin}}} X_i \, ,$$

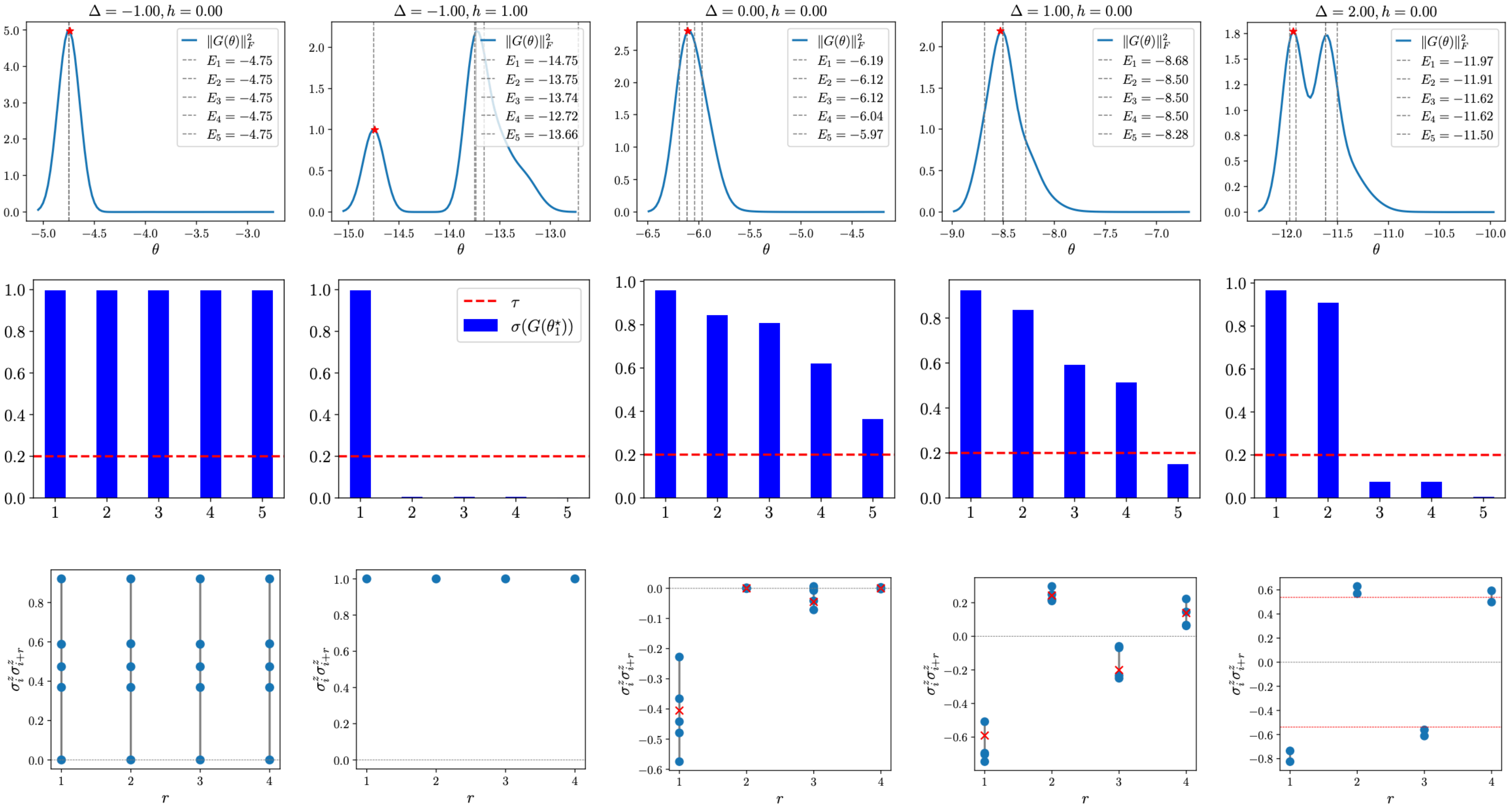
*(**Ding**, Lin, Yang, Zhang, arXiv:2510.07439)*





$$H = \sum_{i=1}^{N_{\text{spin}}-1} (X_i X_{i+1} + Y_i Y_{i+1} + \Delta Z_i Z_{i+1}) + h \sum_{i=1}^{N_{\text{spin}}} Z_i.$$

*(**Ding**, Lin, Yang, Zhang, arXiv:2510.07439)*



(a) FM, isotropic (b) FM, polarized (c) Gapless, XY (d) Gapless, Heisenberg (e) AFM

Future

(**Ding**, Zhan, Preskill, Lin, arXiv:2508.05703)
(Wang, **Ding**, arXiv:2512.03457)

- . EFTQC implementation

Simulation is equivalent to Hamiltonian simulation + trace out

can be replaced with repeated interaction

Noise robustness? Noise contraction in thermalization/cooling

- . Algorithm improvement:

Our result: $\sigma \sim \beta/\epsilon$ (similar to [CKBG, 2023]) $\xrightarrow[\text{In practice}]{}$ $\sigma = \Omega(1)$ or $\log(1/\epsilon)$?

Variational implementation

Choice of parameters and A_S are flexible

Global spectral gap ∝ local spectral gap

Combining with other quantum computing algorithms

(**Ding**, Lin, Yang, Zhang, arXiv:2510.07439)