Noise-assisted digital quantum simulation of open systems

José D. Guimarães, James Lim, Mikhail I. Vasilevskiy, Susana F. Huelga, Martin B. Plenio | 2022

Overview - Part I

- Use the intrinsic noise of NISQ devices as a resource for quantum computation.

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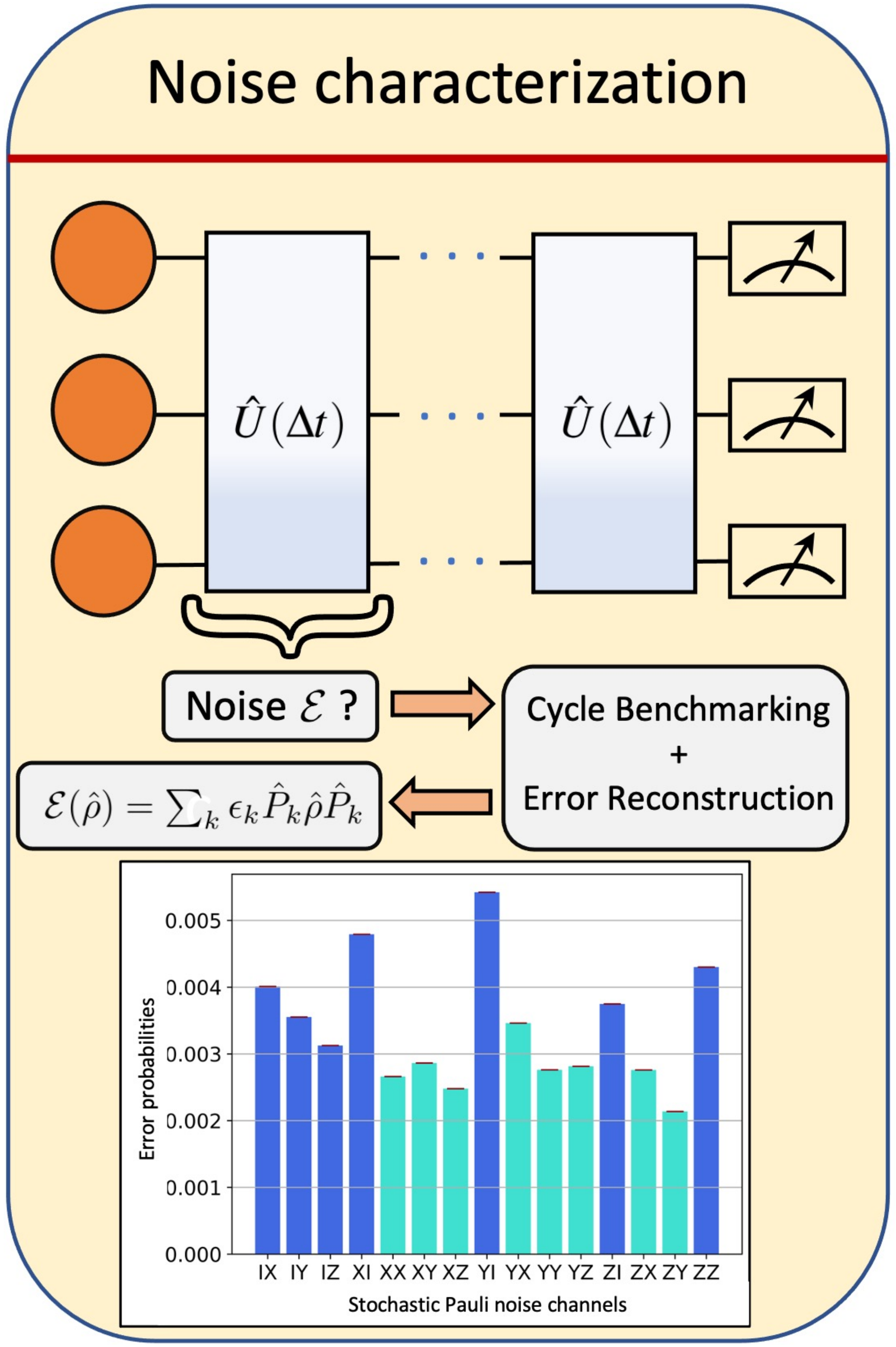
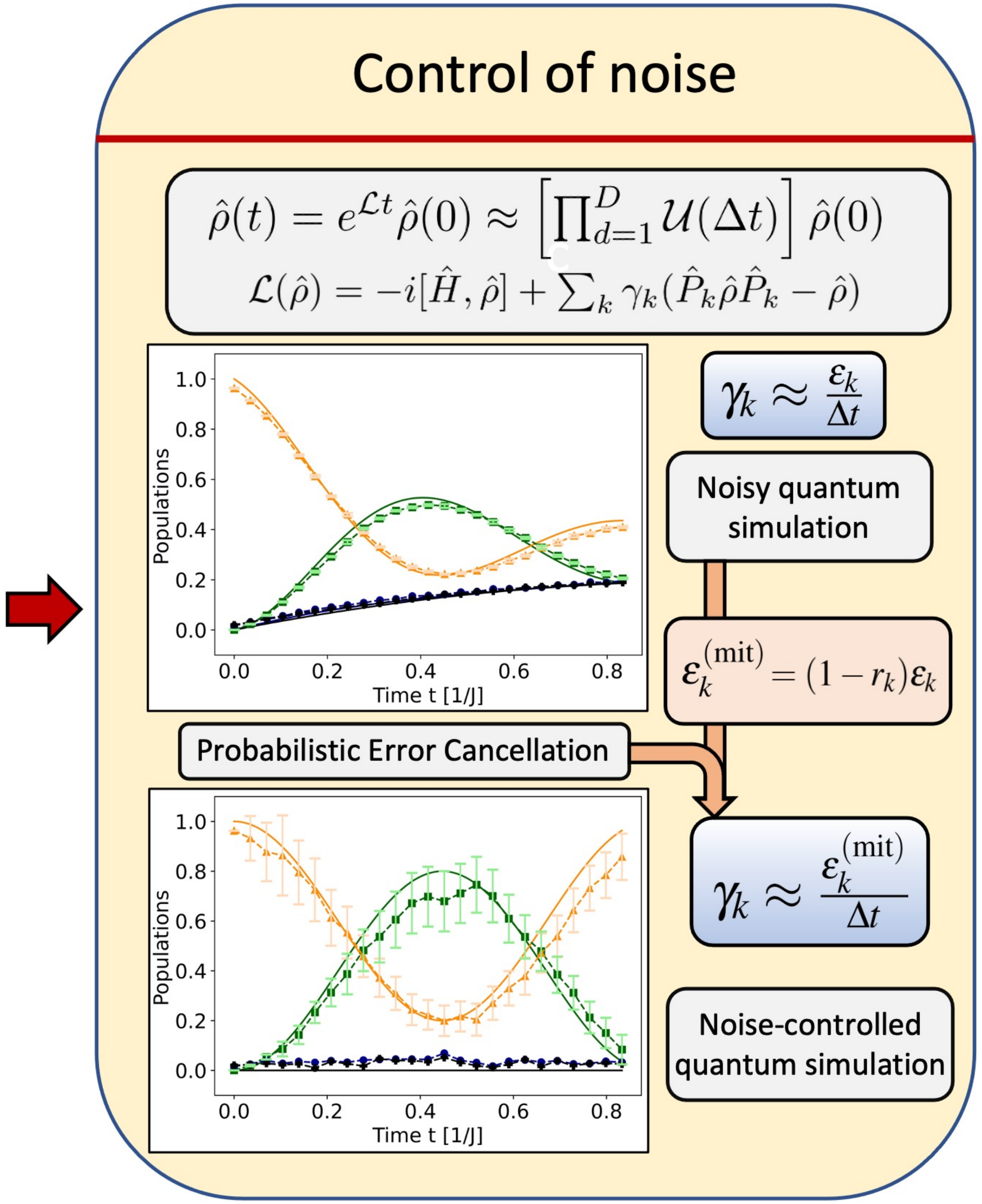
- The quantum hardware does not need to be changed in order to tune the decoherence rates;

Overview - Part II





Time-evolution via product formulas

- Time-evolution in the quantum computer,

Noiseless quantum computer: $e^{-i\hat{H}t}|\Psi(0)\rangle \approx \prod_{d=1}^{D} \hat{U}_k(\Delta t)|\Psi(0)\rangle,$ $\hat{U}_1(\Delta t) = \prod_{j=1}^{N} e^{-i\hat{H}_j\Delta t}, \quad \Delta t = t/D\,.$

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- Markovian noise.
- Weak noise over a Trotter iteration.

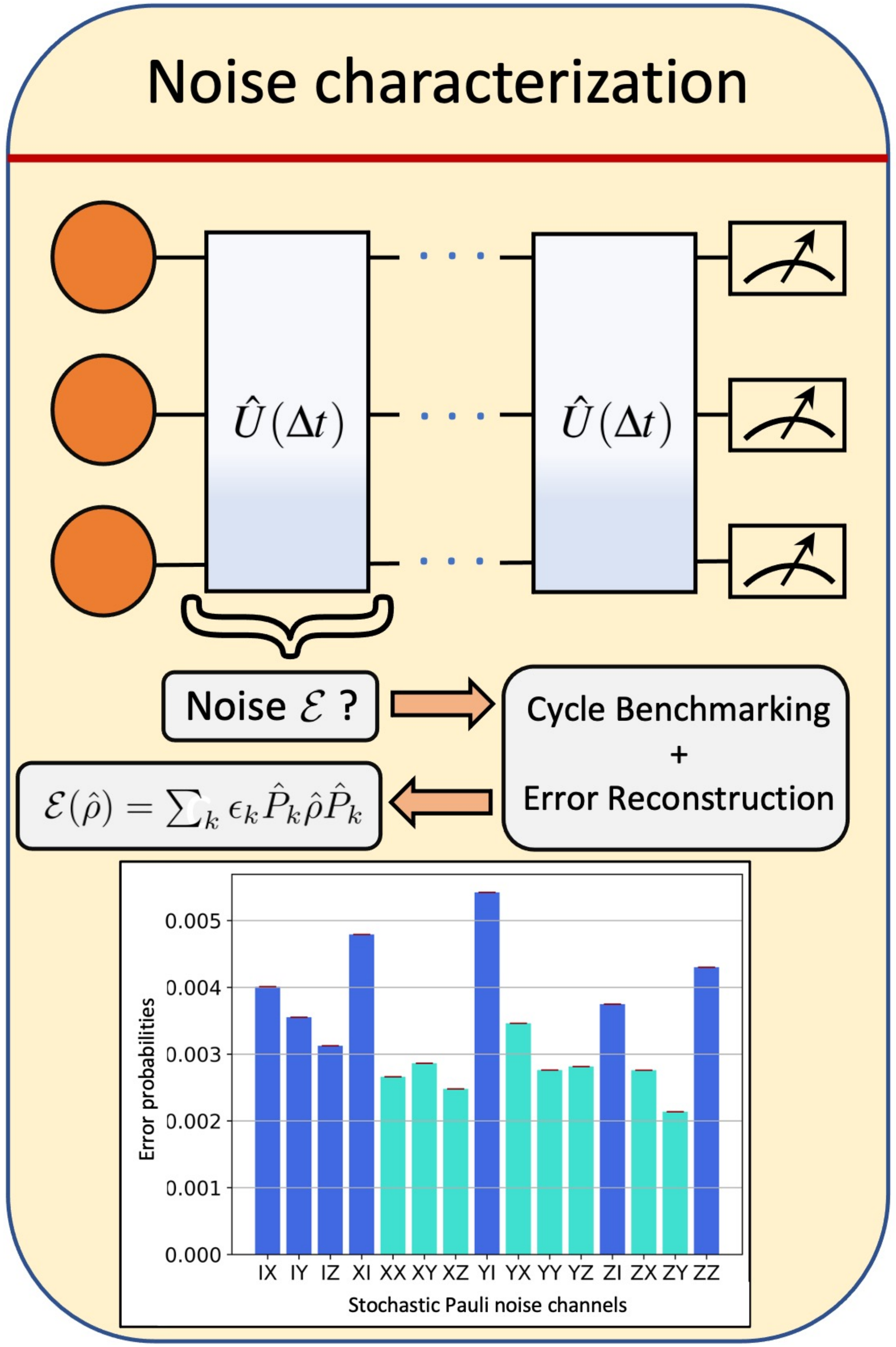
Noise characterization

CB + ER

Erhard, Alexander, et al. *Nature communications* 10.1 (2019): 1-7.

Flammia, Steven T., and Joel J. Wallman. *ACM Transactions on Quantum Computing* 1.1 (2020): 1-32.

K-qubit stochastic Pauli channel: $\mathscr{E}(\rho) = \sum_k \epsilon_k \hat{P}_k \rho \hat{P}_k$



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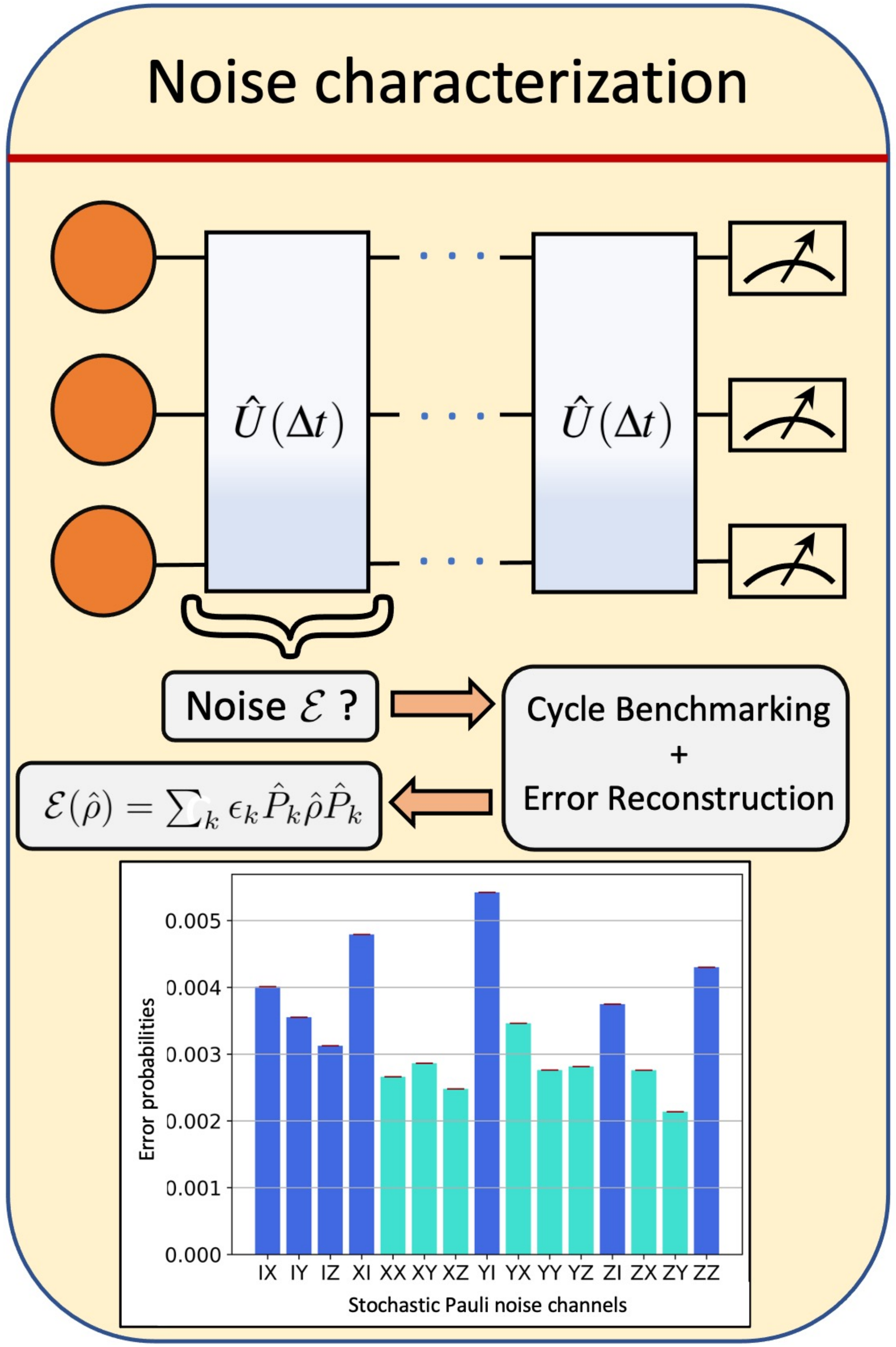
K=2: $\mathscr{E}_{m,m+1}^{(2)}(\hat{\rho}) = \mathscr{E}_m^{(1)}(\hat{\rho}) + \mathscr{E}_{m+1}^{(1)}(\hat{\rho})$

$+\epsilon_{XX} \hat{X}_m \hat{X}_{m+1} \hat{\rho} \hat{X}_m \hat{X}_{m+1}, + \epsilon_{XY} \hat{X}_m \hat{Y}_{m+1} \hat{\rho} \hat{X}_m \hat{Y}_{m+1} + \cdots$



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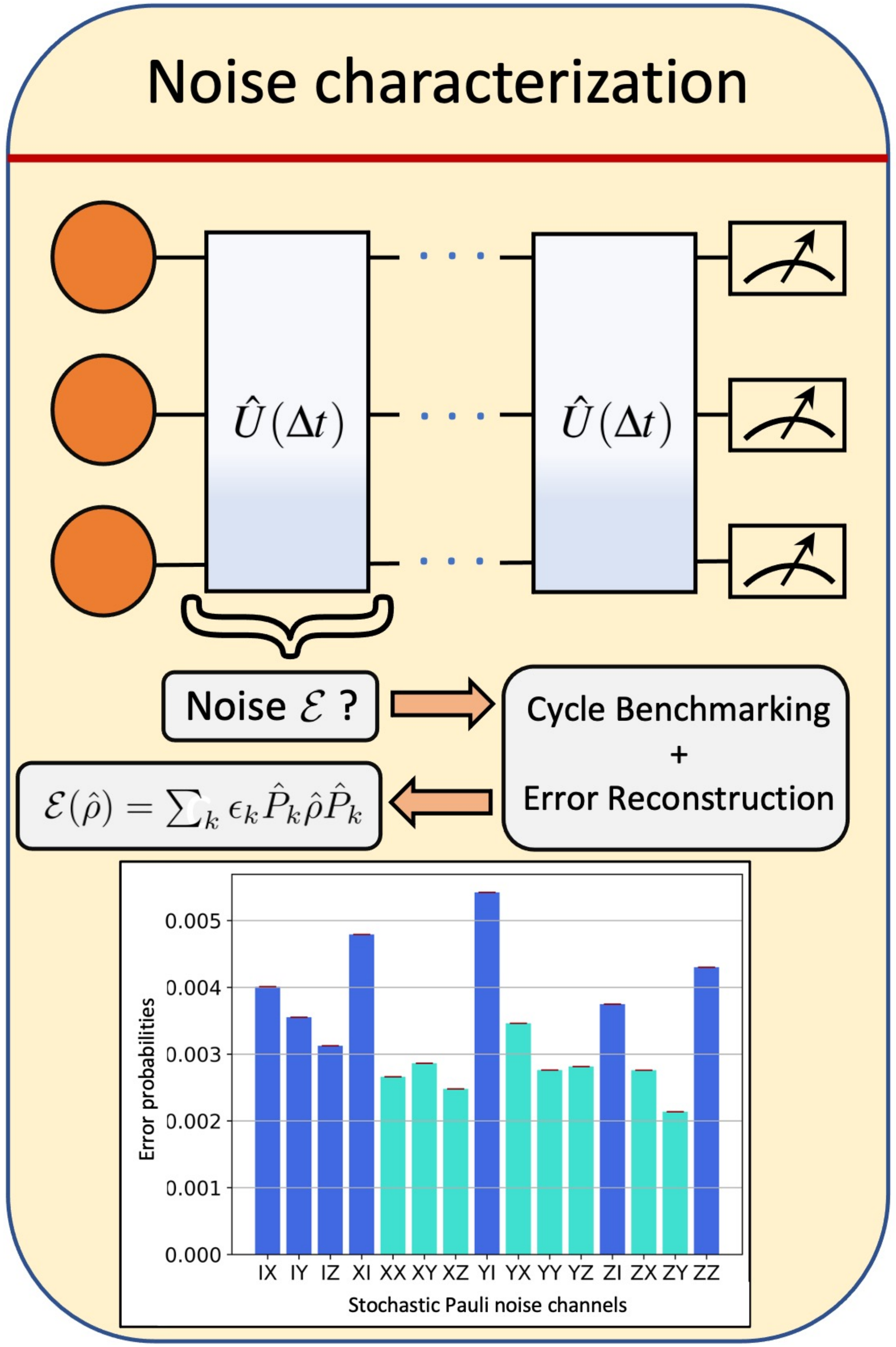
No need to characterize errors acting on more than K=2 nearest-neighbour qubits.



Hashim, Akel, et al. *arXiv preprint arXiv:2010.00215* (2020).
Wallman, Joel J., and Joseph Emerson. *Physical Review A* 94.5 (2016): 052325.

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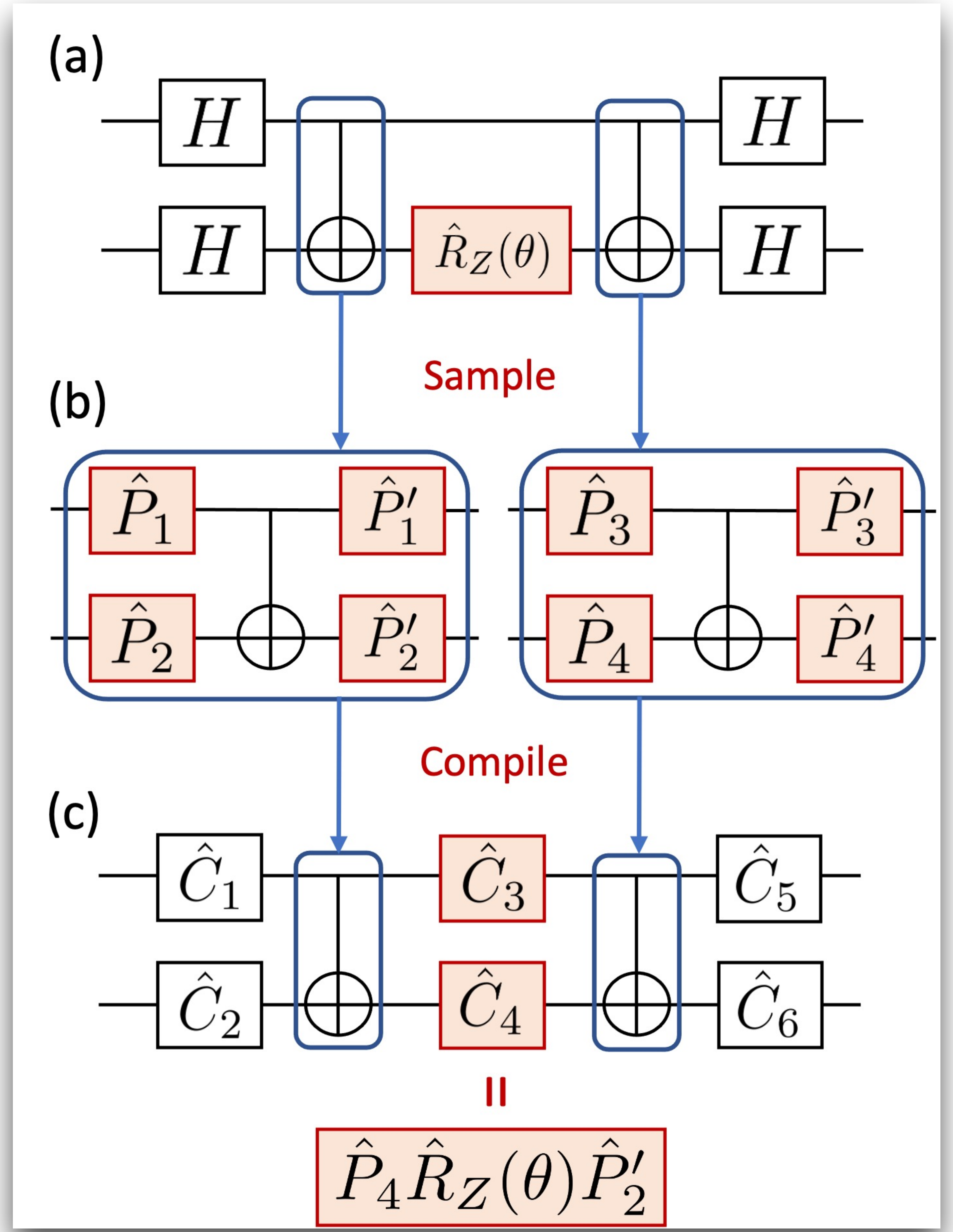
Randomized Compiling



$\hat{G} = \hat{P}'_k \hat{G} \hat{P}_k, \quad \hat{P}'_k = \hat{G} \hat{P}_k \hat{G}^\dagger$

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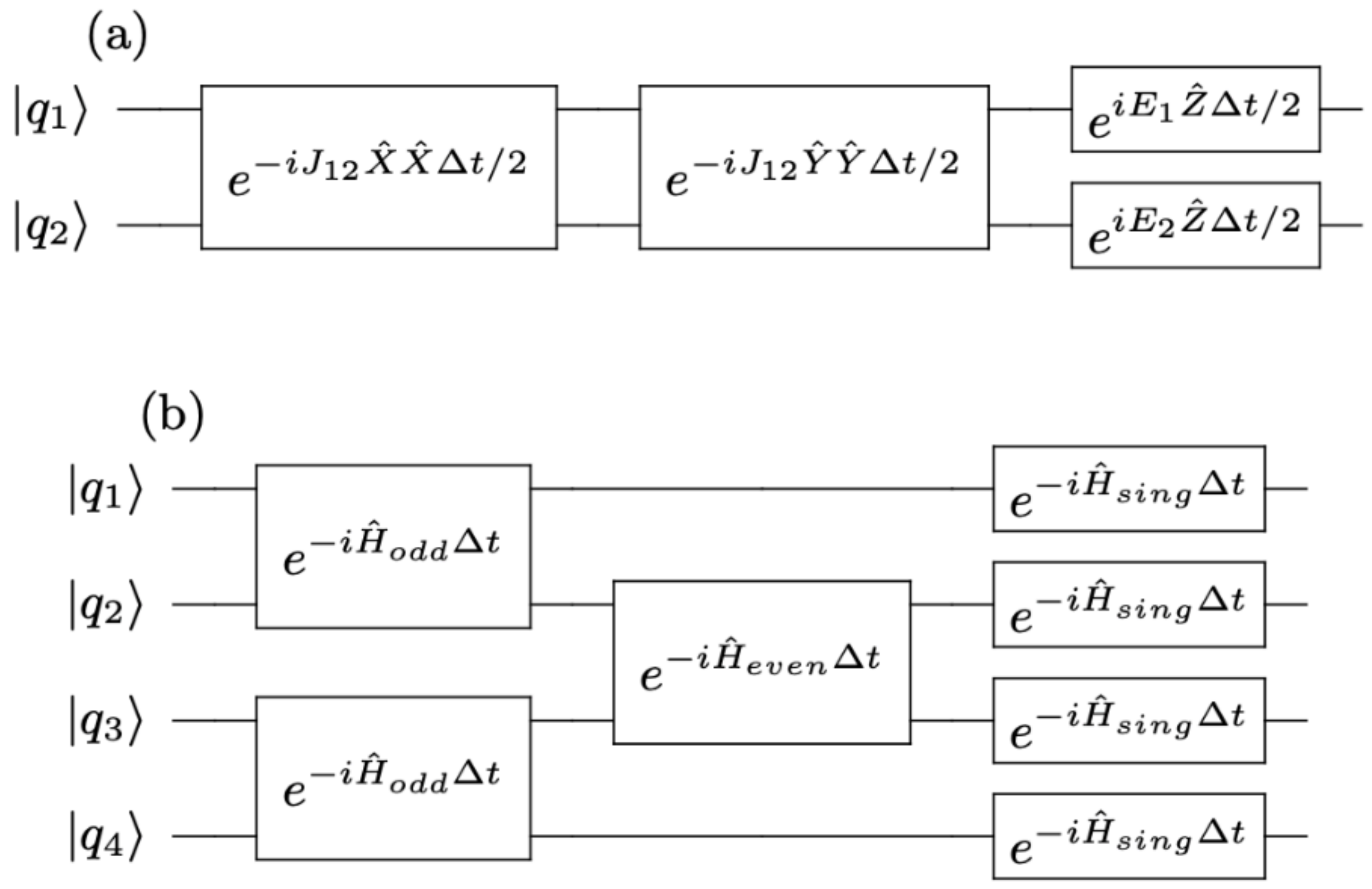
$$\mathscr{D}_{\text{stochastic}}[\hat{\rho}(t)] = \sum_{k=0}^{4^K-1} \gamma_k \left(\hat{P}_k \hat{\rho}(t) \hat{P}_k - \hat{\rho}(t)\right), \quad \gamma_k = \epsilon_k/\Delta t$$

K=2

Time-evolution via product formulas

$$\hat{H} = -\sum_{m=1}^{n} \frac{E_m}{2}\hat{Z}_m + \sum_{m=1}^{n-1} \frac{J_{m,m+1}}{2}(\hat{X}_m\hat{X}_{m+1} + \hat{Y}_m\hat{Y}_{m+1})$$



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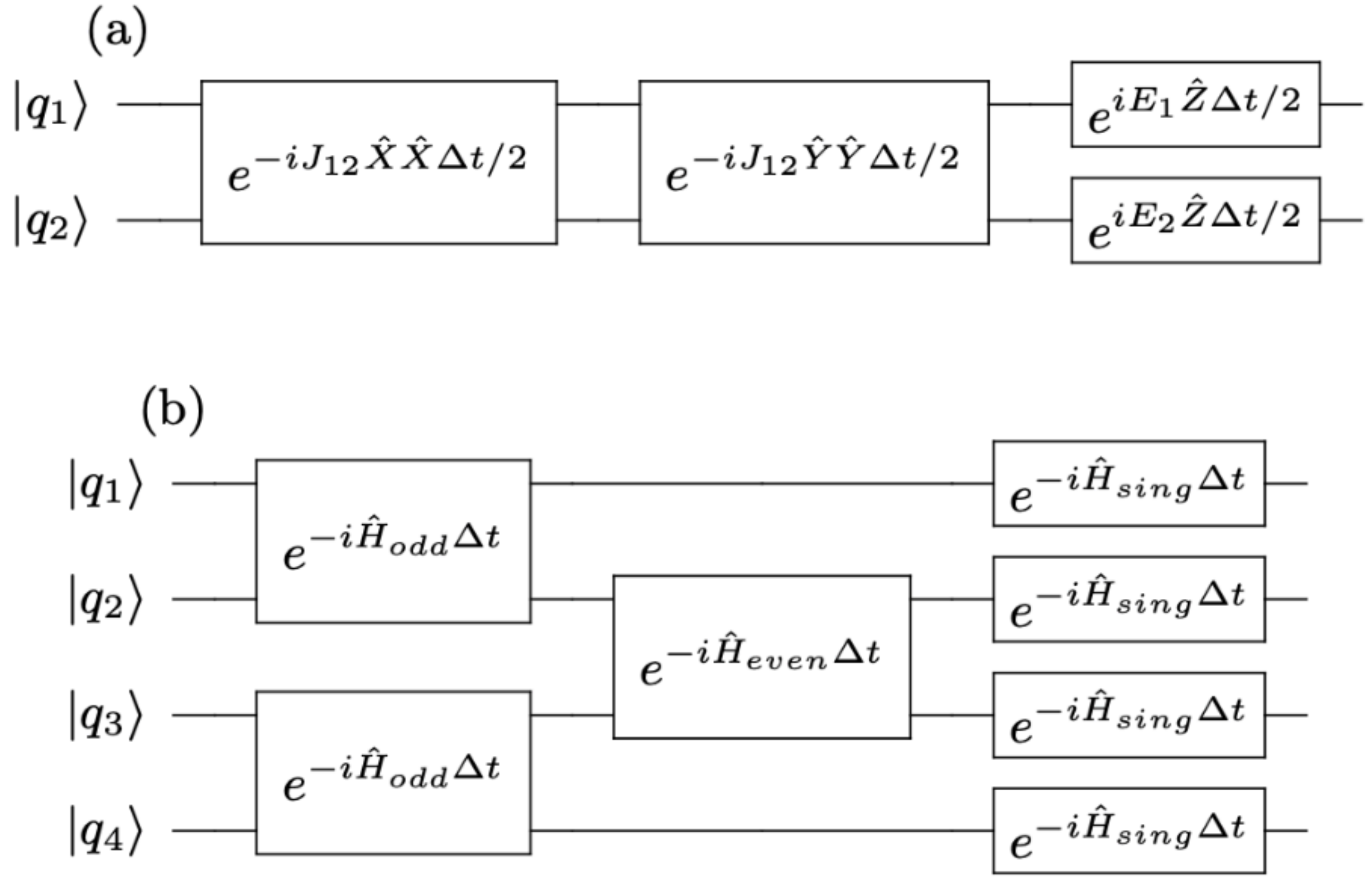
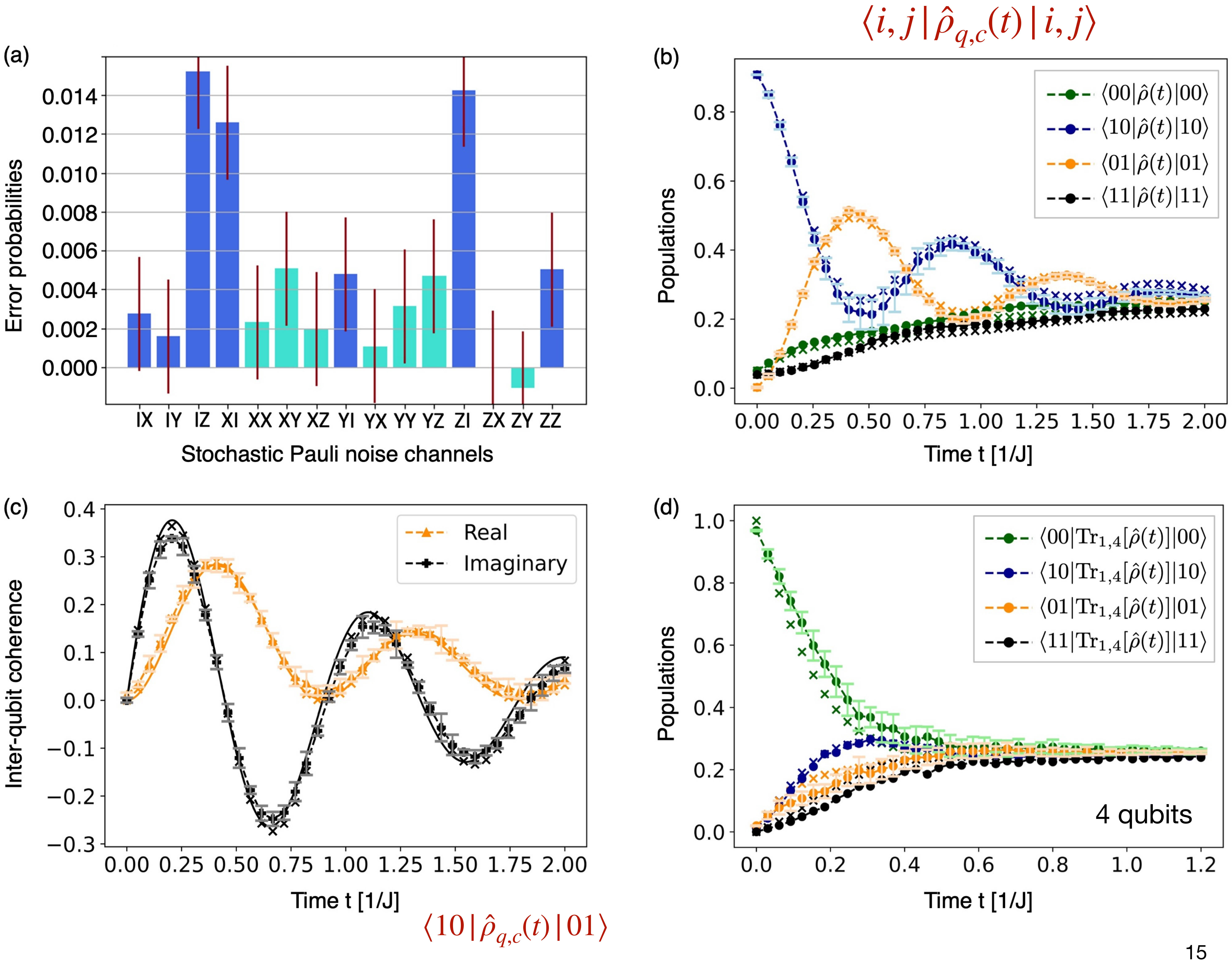
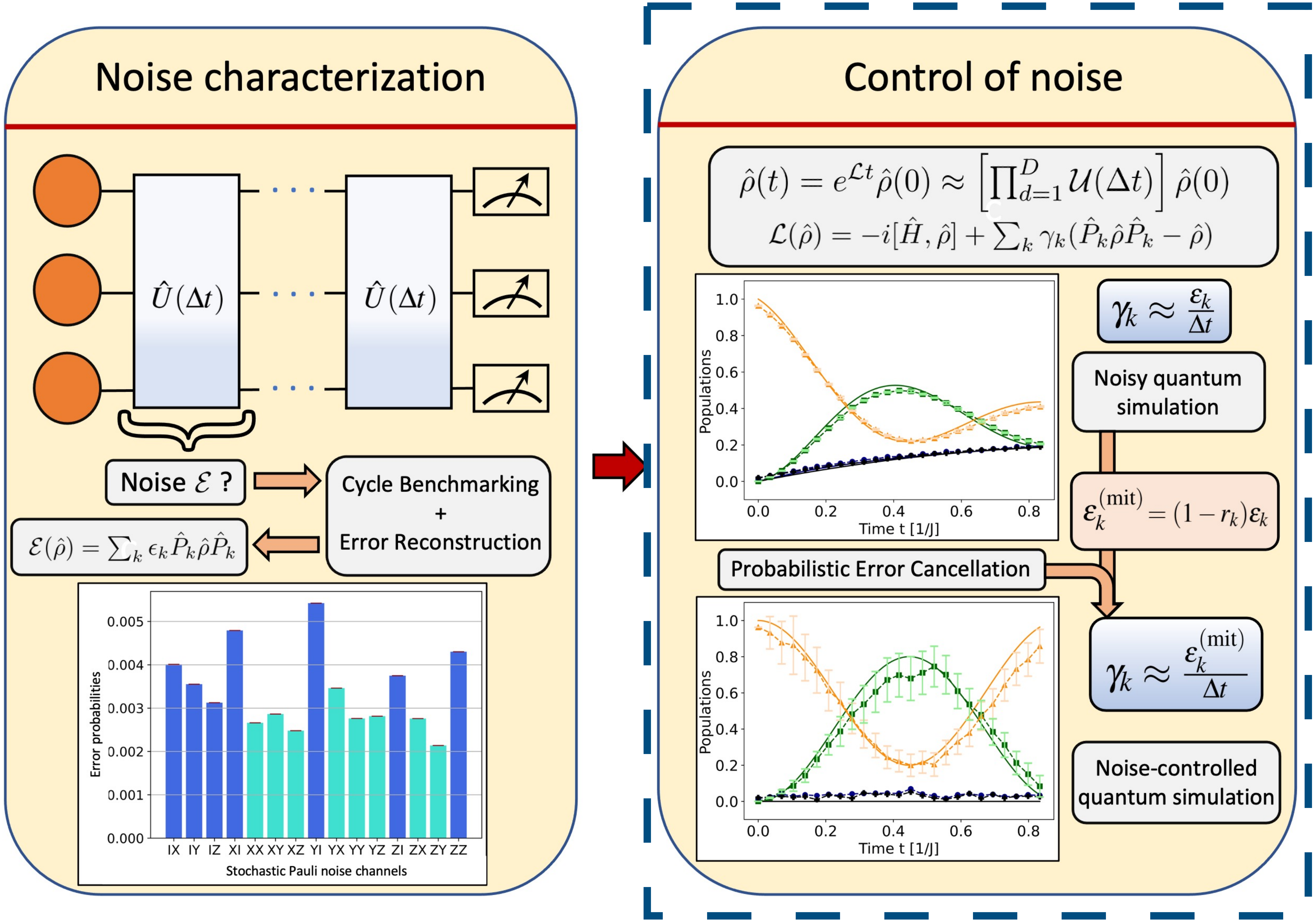




Control of noise



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$r_k \in [0,1]$

Probabilistic Error Cancelation

Endo, Suguru, Simon C. Benjamin, and Ying Li. *Physical Review X* 8.3 (2018): 031027.
Sun, Jinzhao, et al. *Physical Review Applied* 15.3 (2021): 034026.

Probabilistic Error Cancelation

Overview

- Probabilistically cancels Markovian noise to first order by inverting the noise channel.

Characterization of the noise channel acting in the circuit:

$$\mathscr{E}(\rho) = \epsilon_0 \rho + \sum_{k=1} \epsilon_k P_k \rho P_k$$

CPTP map

Inversion of the characterized stochastic Pauli channel:

$$\mathscr{E}^{-1}(\rho) = \epsilon_0' \rho - \sum_{k=1} \epsilon_k' P_k \rho P_k$$

Non-CP map

$$\epsilon_{k>0}' = r_k \epsilon_k$$

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Probabilistic application of Pauli gates

$$\mathscr{E}^{-1} = C \sum_{k=0} p_k \text{sign}(q_k) \mathscr{P}_k$$

$p_k = \epsilon'_k / C$

$C = \sum_{k=0} |q_k|$

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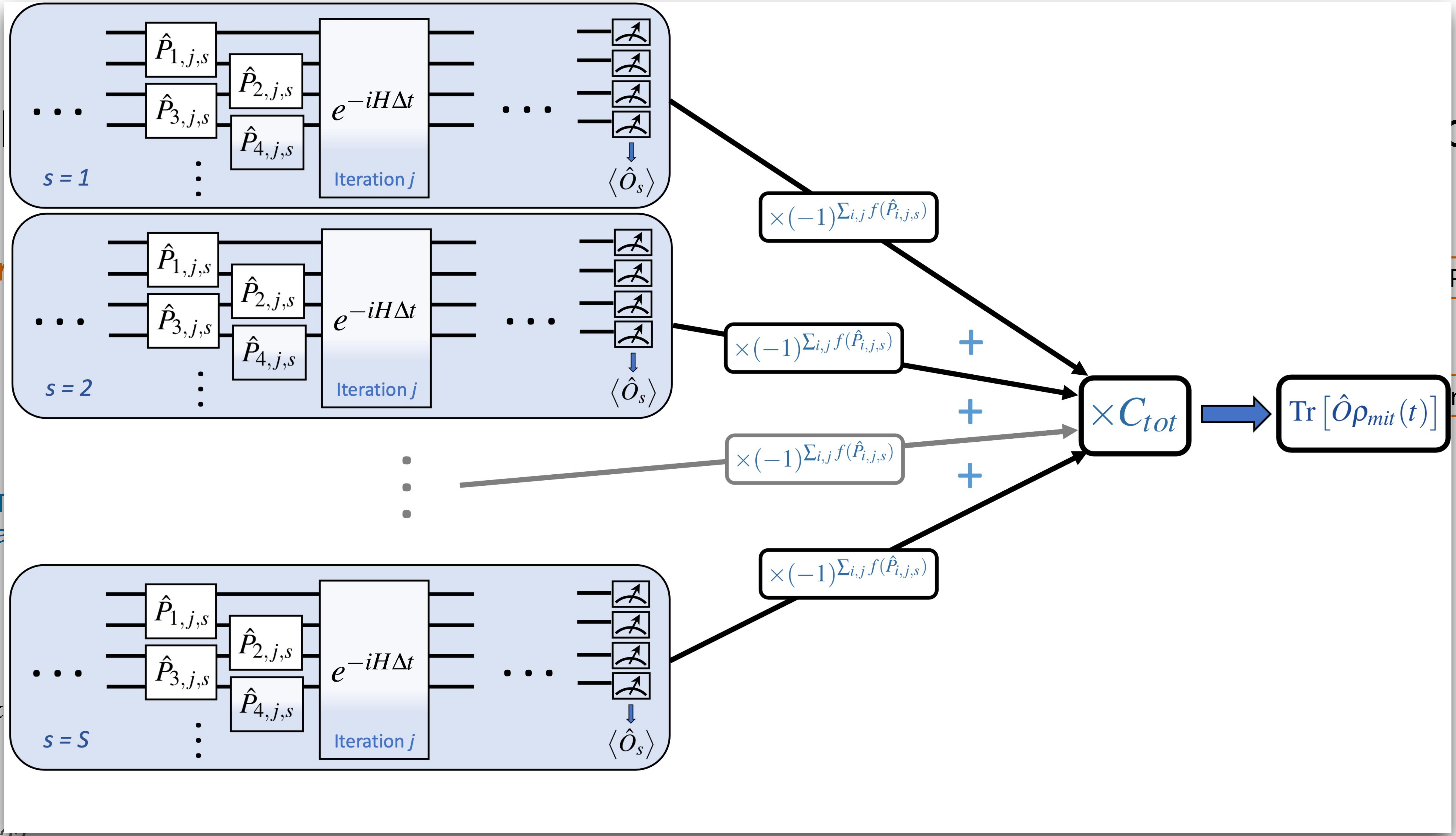
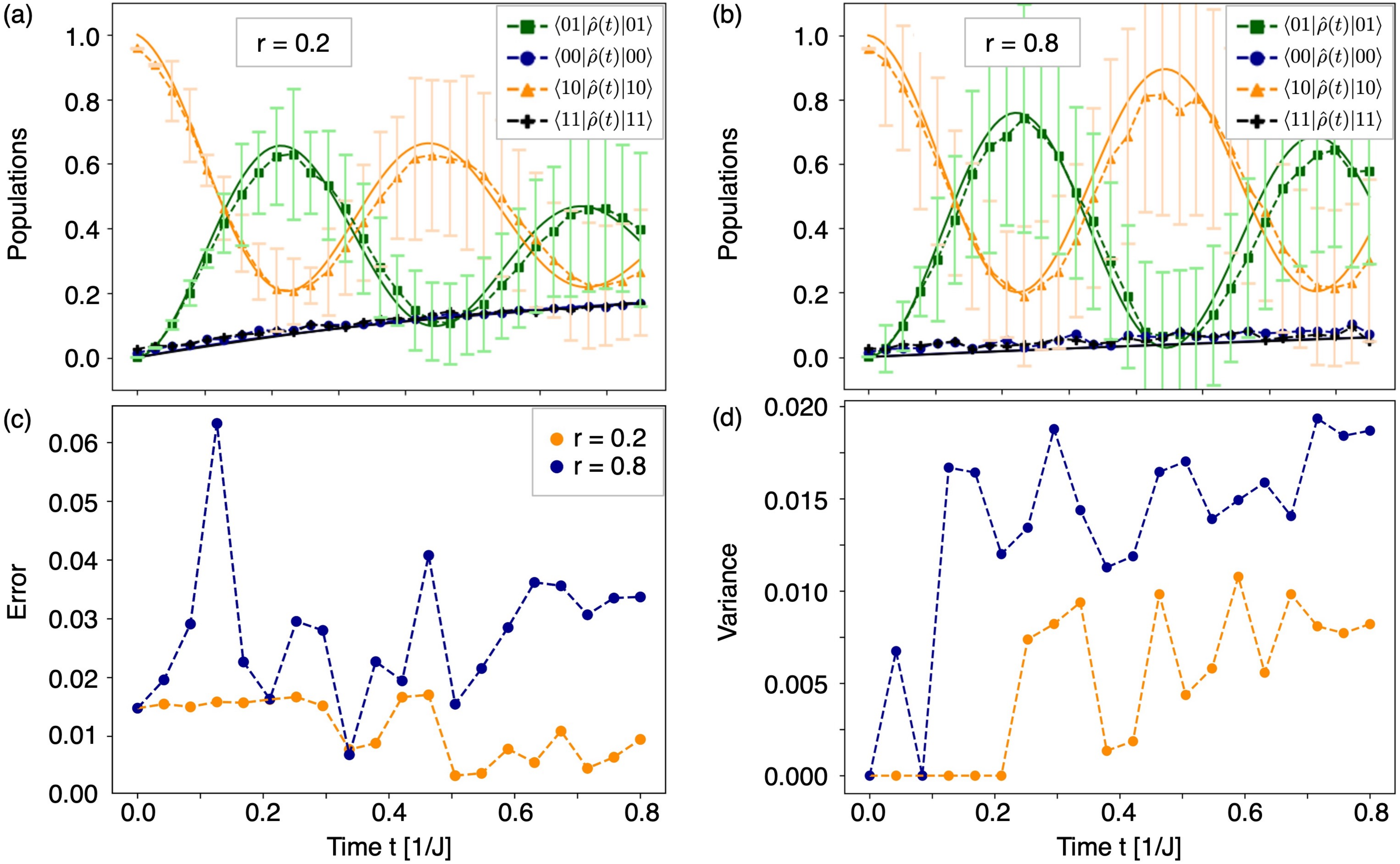


Implementation

$$\epsilon'_{k>0} = r\epsilon_k$$

$$C = \sum_{k=0} |q_k| = 1 + 2r \sum_{k=1} \epsilon_k$$



Partial Probabilistic Error Cancelation

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Partial Probabilistic Error Cancelation

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$$\Delta O_M \propto M^{-1} \Rightarrow \Delta O_M^{(\text{PEC})} \propto C_{\text{tot}}^2 M^{-1}$$

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For a Trotter-type circuit:

$$C_{tot}^2 \sim e^{\lambda n D \epsilon_r}$$

$$\epsilon_r = \sum_{k=1} \epsilon'_k = \sum_{k=1} r_k \epsilon_k$$

Decoherence rate control scheme

How can we control γ_k in the digital simulation without changing the hardware components?

Target decoherence rates Γ_k : $\mathscr{D}^{\text{(controlled)}}_{\text{stochastic}}[\hat{\rho}(t)] = \sum_{k=0}^{4^K-1} \Gamma_k \left(\hat{P}_k \hat{\rho}(t) \hat{P}_k - \hat{\rho}(t) \right)$

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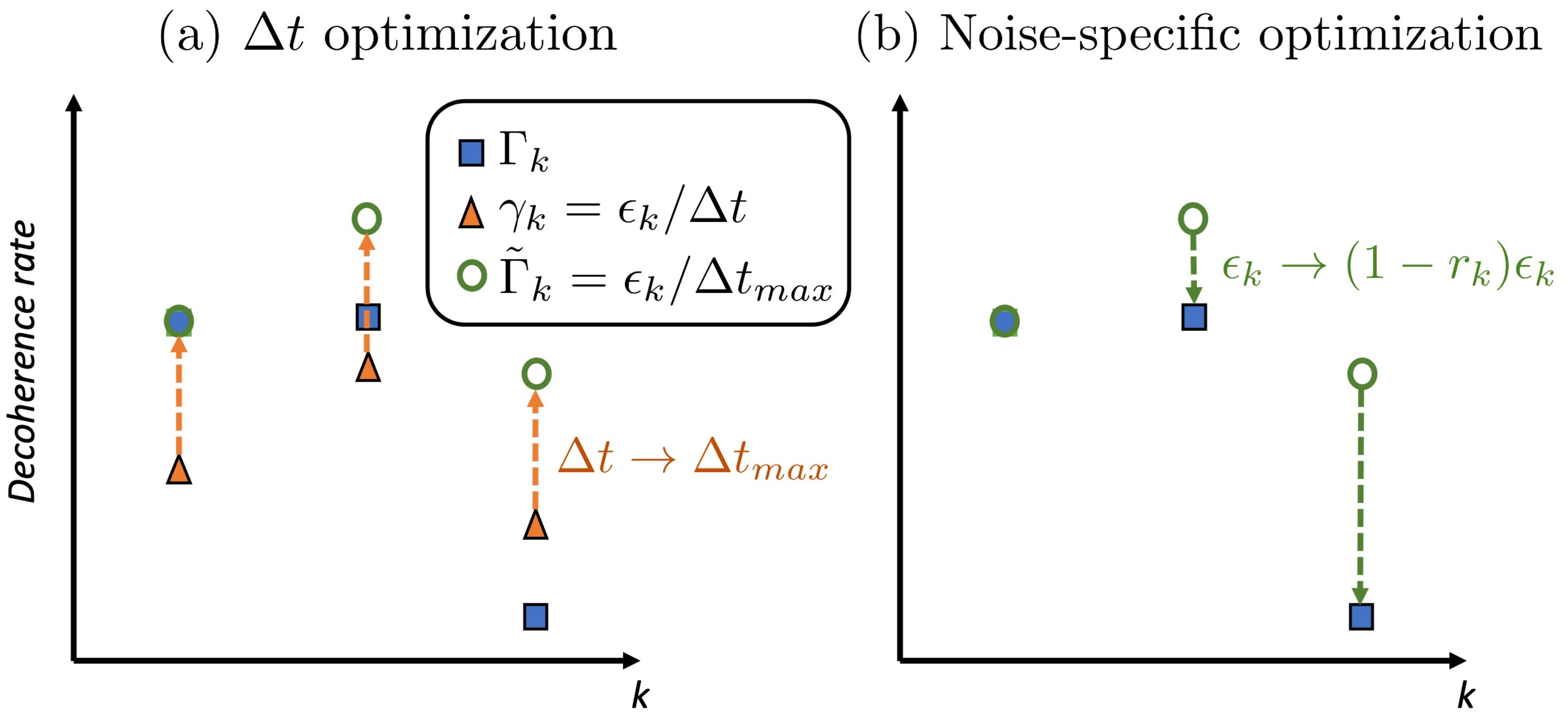

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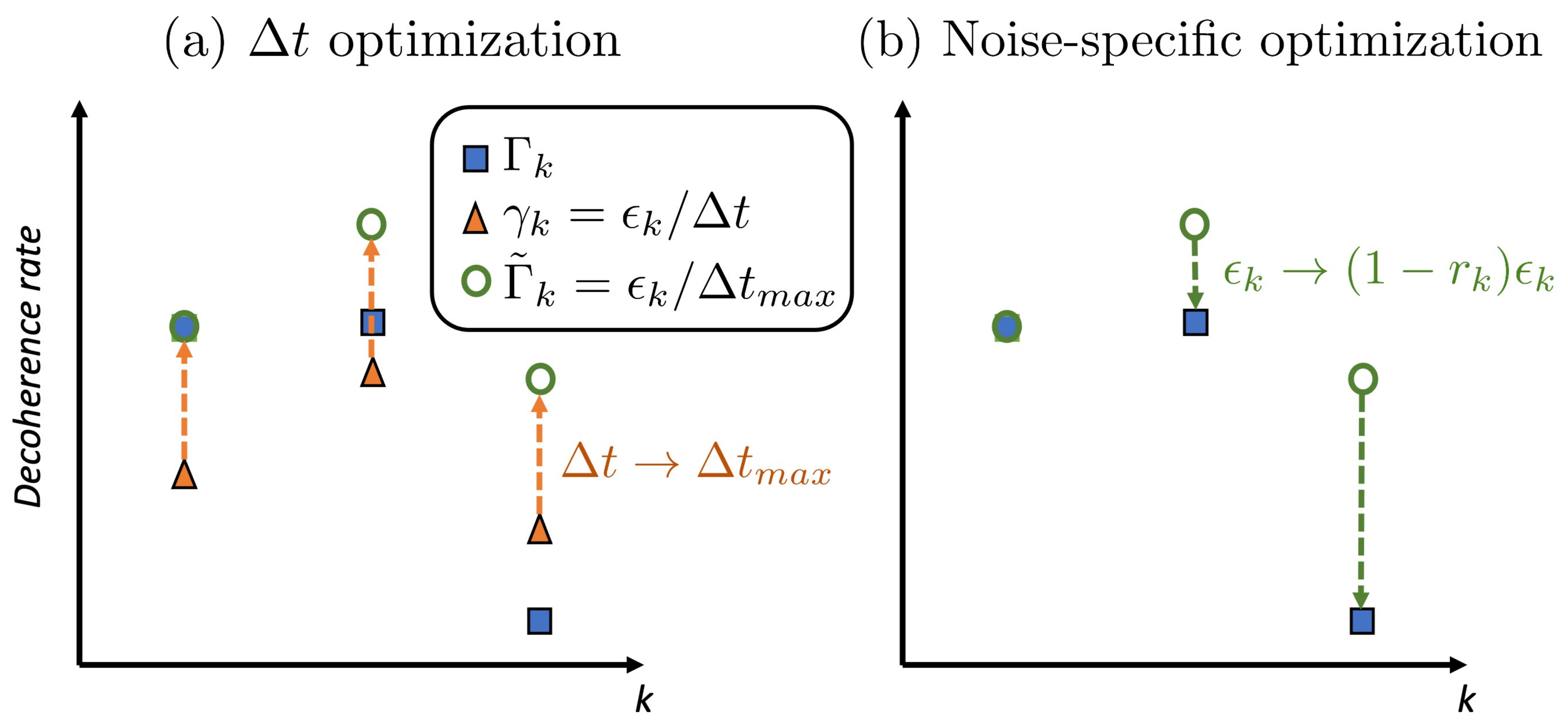

$$\Gamma_k = \epsilon_k (1 - r_k) / \Delta t_{max}$$

Limitations of the technique

Target decoherence rates Γ_k : $\Gamma_k = \epsilon_k(1 - r_k)/\Delta t$

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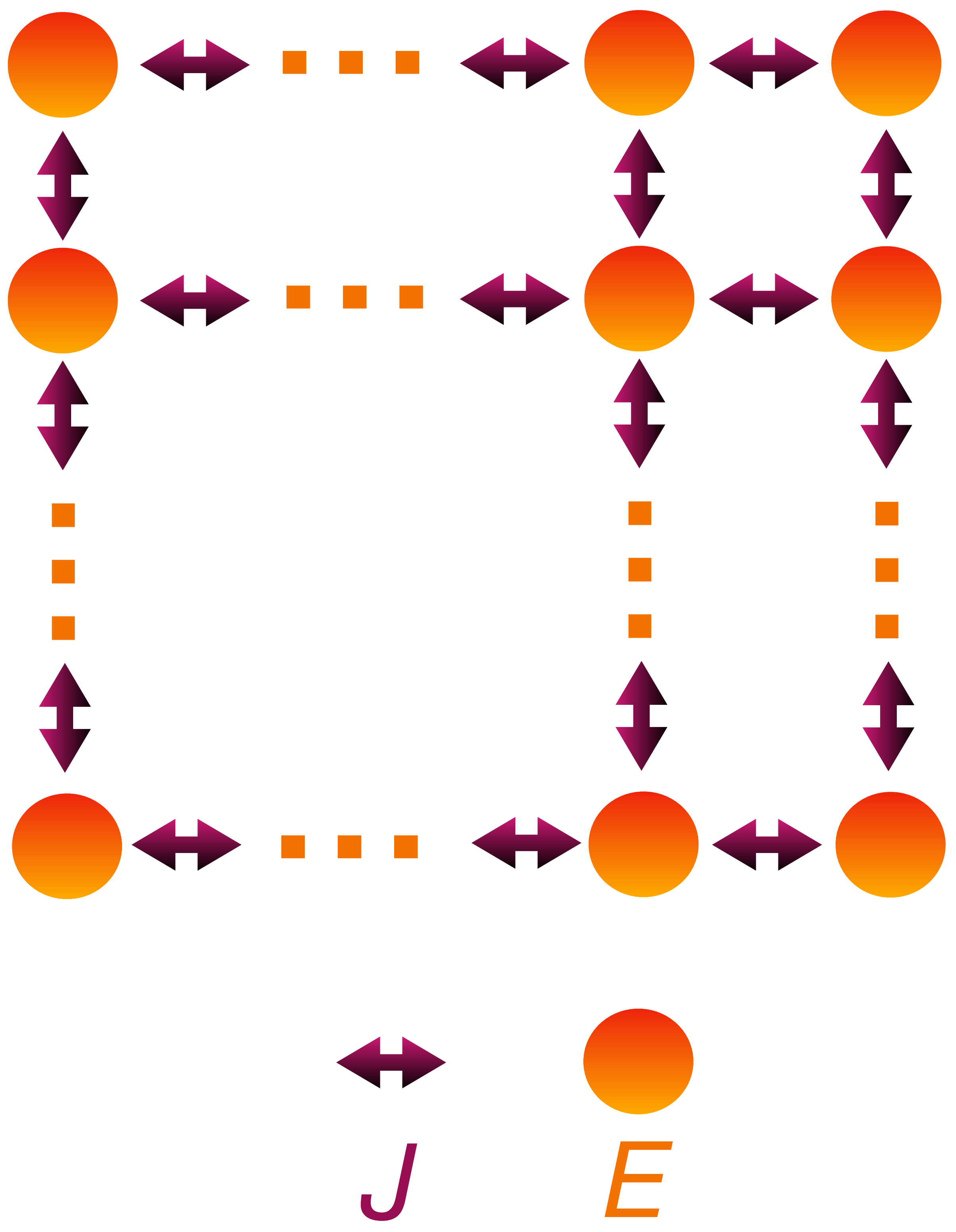

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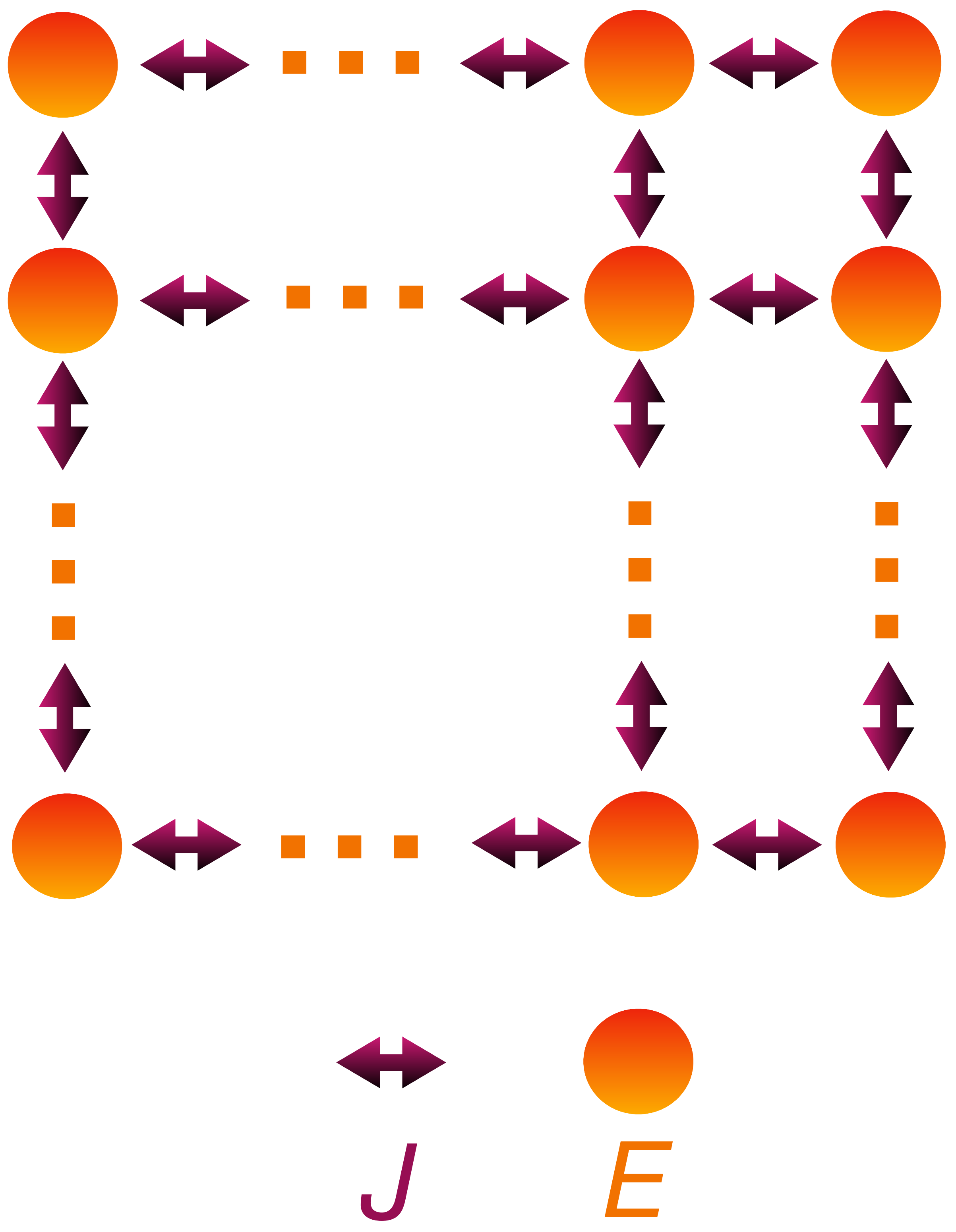
Childs, Andrew M., et al. Physical Review X 11.1 (2021): 011020.

$$D = O\left(\frac{n^d J(J+E)t^2}{\varepsilon_{\mathrm{Trot}}}\right)$$



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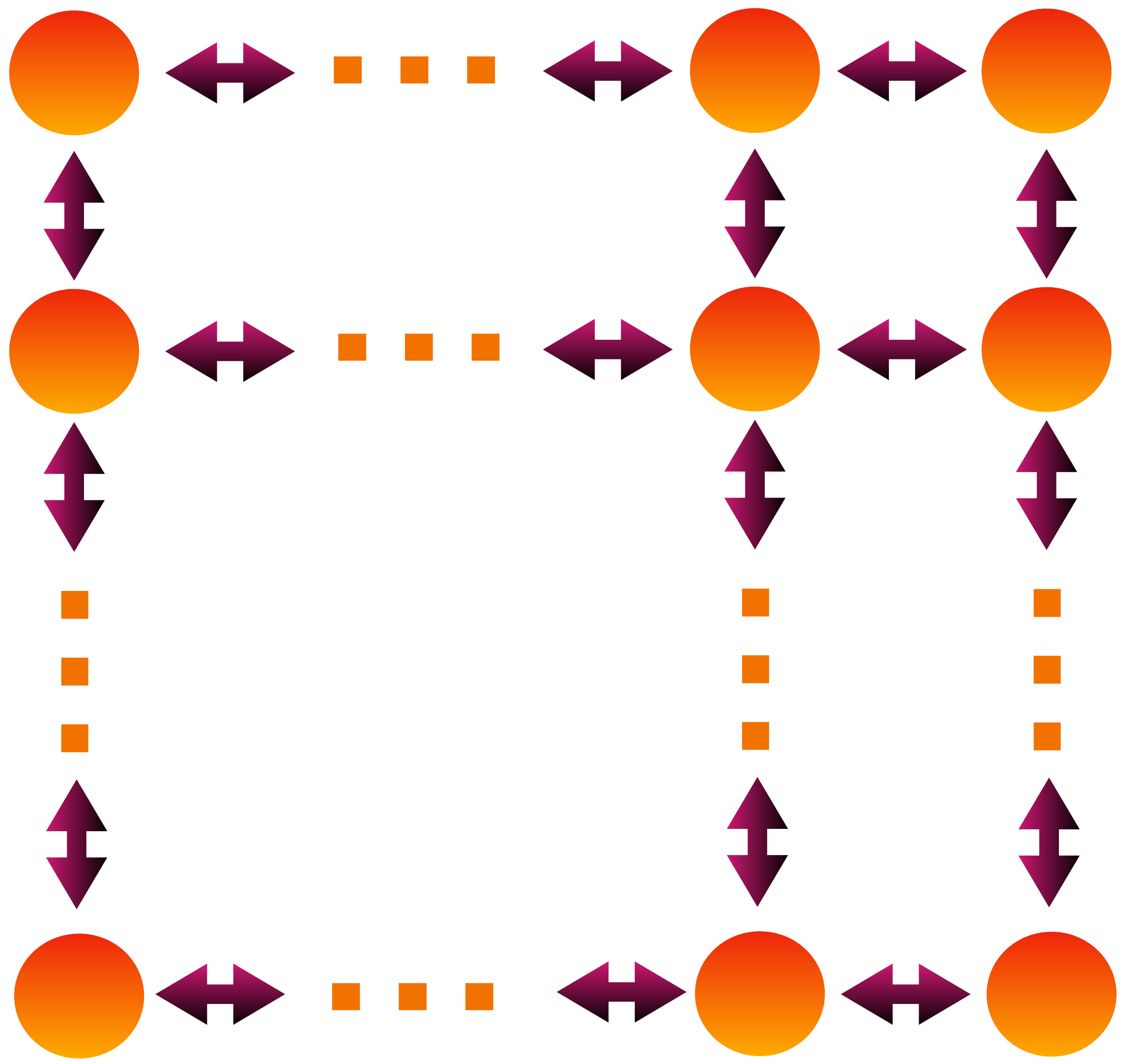

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$$\epsilon \lesssim O\left(\frac{\varepsilon_{\text{Trot}}\Gamma}{n^d J(J+E)t} + \frac{\varepsilon_{\text{Trot}}^2 \ln(M_{\max}^{(\text{NISQ})})}{2\lambda n^{2d+1} J^2 (J+E)^2 t^4}\right)$$

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Conclusion

Noise-assisted simulation

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- The quantum hardware does not need to be changed in order to tune the noise rate;
- Open quantum systems coupled to Markovian environments via stochastic Pauli noise channels with medium- or large-decoherence rates.

Note: Technique is not restricted only to stochastic Pauli channels

Conclusion

Noise-assisted simulation

- Applications: NISQ computers and quantum analog simulations.
- The quantum hardware does not need to be changed in order to tune the noise rate;
- Open quantum systems coupled to Markovian environments via stochastic Pauli noise channels with medium- or large-decoherence rates.
- Ongoing work: Generalization of this technique to simulate non-perturbative dynamics of open quantum systems.

Thank you for your attention!

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