In this work, the global white-noise model is proved from first principles. The adherence of NISQ hardware to the global white-noise model is used to perform noise mitigation using CLAssical White-noise Extrapolation (CLAWE).

I. GLOBAL WHITE-NOISE MODEL

Universal quantum computation involves the encoding of algorithms into sequences of local gates. The noise processes in Noisy Intermediate-Scale Quantum (NISQ) hardware do not exhibit such locality, resulting in qubit crosstalk [1–25].

This non-locality suggests a global description of the average noise dynamics. The global white-noise model [26–29] presumes that the noise dynamics associated with entangling operations [30–66] can be approximated by depolarizing events that span the entire Hilbert space (Figure 1). The global white-noise model is now derived from first principles using quantum channel technology.

A. Introduction to Superoperators

Rigorously treating noise dynamics requires a density matrix representation [67–69], because the evolution of open quantum systems generates mixed quantum states. Vector representations cannot describe such processes, as they only characterize pure quantum states: $|\psi\rangle$.

Mixed quantum states have interacted with unknown degrees of freedom. They are composed of an ensemble of pure states $\{|\psi_k\rangle\}$, with observational probabilities $\{\alpha_k\}$. The corresponding density matrix is the following:

$$\rho_{\text{mixed}} = \sum_k \alpha_k |\psi_k\rangle\langle\psi_k|$$  \hspace{1cm} (I.1)

In the density matrix representation, $d \times d$-dimensional operators that act on wavefunctions, generalize to $d^2 \times d^2$-dimensional quantum channels known as superoperators. Each superoperator can be represented by sets of Kraus operators $\{M_k\}$ [70]:

$$\hat{\mathcal{E}} = \sum_{k=1}^\mathcal{K} M_k \otimes M_k^\dagger$$  \hspace{1cm} (I.2)

Meaningful density matrices are positive semi-definite, with $\text{Tr}(\rho) = 1$. To map such density matrices onto one another, superoperators must be completely positive and trace-preserving (CPTP): $\sum_k M_k M_k^\dagger = 1$ [71].

In this work, hat-notation is reserved for the action of superoperators in matrix representation:

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B. The Depolarizing Channel

Depolarization results in the mixing of a quantum state with the infinite temperature Gibbs state, one for which all micro-states are equally likely [72]. Such processes are described by the $n$-qubit depolarizing channel:

$$\hat{\mathcal{D}}_{\epsilon,n} \rho = (1 - \epsilon) \rho + \epsilon \mathcal{I}_n$$  \hspace{1cm} (I.5)

where $\mathcal{I}_n = 1/2^n$ is the infinite temperature state (ITS) and $\epsilon$ is the noise strength.

The repeated action of the depolarizing channel is the following:

$$\hat{\mathcal{D}}_{\epsilon,n}^k \rho = (1 - \epsilon)^k \rho + f(\epsilon, k) \mathcal{I}_n$$  \hspace{1cm} (I.6)

$$f(\epsilon, k) = \epsilon \sum_{n=0}^{k-1} (1 - \epsilon)^n$$  \hspace{1cm} (I.7)

The input state is suppressed exponentially, indicating a signal-to-noise problem. After its qubits are saturated by the ITS, a Quantum Processing Unit (QPU) can no longer perform meaningful computation (Figure 2).

C. Proving the Global White-Noise Model

A QPU is composed of qubits coupled to the environment and a measurement apparatus:
\mathcal{H}_{\text{QPU}} = \mathcal{H}_{\text{env}} \otimes \mathcal{H}_0 \otimes \mathcal{H}_{\text{app}} \quad (I.8)

In the QPU’s expanded Hilbert space, noise dynamics map onto unitary time evolution [73].

Consider a QPU that performs digital computations with CNOT gates. It is examined throughout a quantum computation obeying the computational cycle:

(I.) \textit{state preparation}: The qubits are prepared in a pure initial state.

(II.) \textit{quantum computation}: The target computation is performed by applying CNOT gates to the qubits.

(III.) \textit{measurement}: An observable on \(\mathcal{H}_0\) is measured.

The computational cycle is repeated \(N_m\) times. Within the QPU, the entire computation is described by unitary evolution for time \(t_{\text{exp}} = N_m t_{\text{cycle}}\):

\[
\rho_{\text{QPU}}^{(t)} = \hat{U}_{\text{QPU}}^{(t)} \rho_{\text{QPU}}^{(0)} \quad (I.9)
\]

A location metric is required to identify the occurrence of CNOT gates in a computation. In this work, the \textit{scalar depth} (\(\chi\)) is used: the number of entangling operations applied after state preparation.

The state of the QPU during the computation can be parametrized by the scalar depth \(\chi(t)\):

\[
\rho_{\text{QPU}}^{(t)} \to \rho_{\text{QPU}}[\chi(t)] \quad (I.10)
\]

The qubits will be acted on by the \(\chi^{th}\) CNOT gate at times \(\{t_s\}\) satisfying \(\chi(t_s) = \chi'\). The state of the QPU at times \(\{t_s\}\) defines a set of \textit{encountering states}:

\[
\rho_{\text{QPU}}^{(t_s)}[\chi'] \equiv \rho_{\text{QPU}}[\chi'(t_k)] \quad (I.11)
\]

Encountering states at times \(t_i\) and \(t_k\) are related by unitary evolution on \(\mathcal{H}_{\text{QPU}}\), represented by \textit{encountering transformations}:

\[
\hat{U}_{ik} = \hat{U}_{ik}^{(t_i)} \hat{U}_{ik}^{(t_k)} \quad (I.12)
\]

\[
\rho_{\text{QPU}}^{(t_i)}[\chi'] = \hat{U}_{ik} \rho_{\text{QPU}}^{(t_k)}[\chi'] \quad (I.13)
\]

The action of the \(\chi^{th}\) CNOT gate on the encountering states is treated with quantum channel technology. The native CNOT gate coupling qubits \(i, j\) is the following:

\[
\hat{C}^{ij}_\chi = \hat{E}_\chi \hat{C}^{ij}_x \quad (I.14)
\]

\(\hat{E}_\chi\) is a superoperator describing the noise dynamics of the native gate. \(\hat{C}^{ij}_x\) is the ideal CNOT gate.

To treat the noise dynamics in a unitary fashion, a \textit{Stinespring dilation} [74] is performed:

\[
\mathcal{H}_\chi \to \mathcal{H}_{\text{QPU}}, \quad \hat{E}_\chi \to \hat{V}_\chi, \hat{\xi} \quad (I.15)
\]

\(\hat{V}_\chi\) is a \textit{unital homomorphism} that takes \(\mathcal{H}_\chi \to \mathcal{H}_{\text{QPU}}\). \(\hat{\xi}\) is a unitary transformation acting on \(\mathcal{H}_{\text{QPU}}\).

The action of \(\hat{C}^{ij}_\chi\) on the \(k^{th}\) encountering state is as follows:

\[
\rho_{\text{QPU}}^{(t_k)}[\chi'] + 1 = \hat{V}_\chi \hat{C}^{ij}_x \hat{V}_k \rho_{\text{QPU}}^{(t_k)}[\chi'] \quad (I.16)
\]

The expectation value of \(O_q\) is obtained by averaging the contributions of the encountering states:

\[
\langle O_q \rangle = \frac{1}{N_m} \sum_{k=1}^{N_m} \text{Tr}_{\text{QPU}} \left[ \hat{V}_\chi \hat{C}^{ij}_x \hat{U}_k \rho_{\text{QPU}}^{(t_k)}[\chi'] \right] O_q \quad (I.17)
\]

In the second line, \(\rho_{\text{QPU}}^{(t_k)}[\chi']\) is expressed in terms of an encountering transformation on \(\rho_{\text{QPU}}^{(t_k)}[\chi']\).

In the ideal limit, the target computation is applied identically for all cycles. This implies the following:

\[
\langle O_q \rangle_{U_{ik}^{\text{ideal}}} = 0 \quad (I.18)
\]

\(U_{k1} U_{k1}^\dagger\) is now inserted into Equation I.17:

\[
\langle O_q \rangle = \frac{1}{N_m} \sum_{k=1}^{N_m} \text{Tr}_{\text{QPU}} \left[ U_{ki}^\dagger \left\{ \hat{V}_\chi \hat{C}^{ij}_x \hat{U}_k \rho_{\text{QPU}}^{(t_k)}[\chi'] \right\} U_{k1} O_{k1} \right] \quad (I.19)
\]

This allows Equation I.19 to be expressed as follows:

\[
\langle O_q \rangle \approx \frac{1}{N_m} \sum_{k=1}^{N_m} \text{Tr}_{\text{QPU}} \left[ \hat{U}_{k1}^\dagger \hat{V}_\chi \hat{U}_k \hat{C}^{ij}_x \rho_{\text{QPU}}^{(t_k)}[\chi'] \right] O_{k1} \quad (I.20)
\]
Note the following identity [75]:

\[ \mathcal{E}^{\text{vno}} \rho = \int dU \hat{U} \hat{\rho} \hat{U}^{\dagger} \rho = (1 - \epsilon) \rho + \epsilon \mathcal{J}_n \quad \text{(I.21)} \]

Applying this relation yields the following:

\[ \langle O_n \rangle \sim \int dU Tr_{\text{phys}} \left[ \left\{ \hat{U} \hat{V}_U \hat{U}^{\dagger} \hat{C}_x^{ij} \rho_U^{(i)} [\mathcal{X}] \right\} O_n \right] = Tr_{\text{phys}} \left[ \left\{ (1 - \epsilon_g) \hat{C}_x^{ij} \rho_n [\mathcal{X}] + \epsilon_g \mathcal{J}_n \right\} O_n \right] \quad \text{(I.22)} \]

The averaged noise dynamics of the CNOT gate approximate a global depolarizing channel with global noise strength \( \epsilon_g \).

The noise dynamics of the CNOT gate can be modified using noise tailoring (NT) algorithms (Appendix I).

## II. CLASSICAL WHITE-NOISE EXTRAPOLATION

The objective of CLAssical White-noise Extrapolation (CLAWE) [29], is the extraction of ideal observables from their noisy counterparts. This extraction requires the noise dynamics to obey the global white-noise model.

### A. Model-Based Extrapolation

CLAWE is a model-based extrapolation algorithm. Model-based extrapolation [76–79] can be represented schematically in three stages:

1. **Modeling**: Find a suitable model that describes a class of systems \( \{ \mathcal{P}_n \} \), using parameters \( \{ \lambda_n \} \). The model must relate accessible observables to target observables: \( \{ O_n^{\text{acc}} \} \rightarrow \{ O_n^{\text{tar}} \} \).

2. **Calibration**: Determine the model parameters \( \{ \lambda_n^{\text{acc}} \} \) for a system \( \mathcal{P}_{\text{phys}} \), by measuring calibration observables \( \{ O_n^{\text{cal}} \} \).

3. **Extrapolation**: Use the model to estimate target observables of \( \mathcal{P}_{\text{phys}} \).

#### I. Modeling

**Model Inversion**: It is possible to exactly invert the global white-noise model due to the unitary invariance of the depolarizing channel:

\[ \hat{D}_{\epsilon,n} \hat{U} \hat{\rho} = \hat{U} \hat{D}_{\epsilon,n} \rho \quad \text{(II.1)} \]

Consider a target computation of scalar depth \( \chi \): \( U_\chi \). There are \( \chi \) global depolarizing channels dressing the ideal gates, which can be moved to the end of the computation, such that they act on the perfect output state:

\[ \rho_n = (1 - \epsilon_g)^\chi \hat{U}_\chi \hat{\rho} + f(\epsilon_g, \chi) \mathcal{J}_n. \quad \text{(II.2)} \]

This relation can be used to express a noisy observable in terms of its infinite temperature value \( \Omega_{\text{ITS}} = \text{Tr}[\mathcal{J}_n O] \):

\[ \langle O_n \rangle = (1 - \epsilon_g)^\chi \text{Tr}[\hat{U}_\chi \hat{\rho}] + f(\epsilon_g, \chi) \text{Tr}[\mathcal{J}_n O] \]

\[ = (1 - \epsilon_g)^\chi \text{Tr}[\hat{\rho} \hat{U}_\chi^\dagger] + f(\epsilon_g, \chi) \text{Tr}[\mathcal{J}_n O] \]

\[ = (1 - \epsilon_g)^\chi \langle O_n \rangle + f(\epsilon_g, \chi) \Omega_{\text{ITS}} \]

Apply the geometric sum formula to \( f(\epsilon_g, \chi) \) (Equation 1.7), to isolate the ideal observable \( \langle O_n \rangle \):

\[ \langle O_n \rangle - \Omega_{\text{ITS}} = (1 - \epsilon_g)^\chi \langle O_n \rangle - \Omega_{\text{ITS}} \]

To obtain a simple relation, the rescaled observable is defined \( \Omega \equiv O - \Omega_{\text{ITS}} x \Omega_n \):

\[ \langle \Omega_n \rangle = (1 - \epsilon_g)^\chi \langle O_n \rangle \]

#### 2. Calibration

A calibrating unitary is a secondary computation that mimics the noise dynamics of the primary computation. It must have a calibrating observable: a quantity whose ideal observable \( \langle O_n \rangle \) is known for a calibration state \( \hat{\rho}_n \).

To obtain \( \langle O_n \rangle \), the calibrating observable is measured after applying the calibrating unitary to \( \hat{\rho}_n \). Taking the ratio of the noisy observable to the ideal observable after rescaling, yields the contamination \( \mathcal{C}(\chi_c) \):

\[ \mathcal{C}(\chi_c) = \frac{\langle O_n \rangle}{\langle \Omega_n \rangle} \quad \text{(II.6)} \]

The secondary global noise strength is given in terms of the contamination:

\[ \epsilon_g^\chi = 1 - \mathcal{C}(\chi_c)^{1/\chi_c} \quad \text{(II.7)} \]

#### 3. Extrapolation

The ideal map is the estimate of the ideal observable obtained from CLAWE:

\[ \langle O_n^{\text{map}} \rangle = (1 - \epsilon_g^\chi)^\chi \langle O_n \rangle \]

\[ \langle O_n^{\text{map}} \rangle = (1 - \epsilon_g^\chi)^\chi (1 - \epsilon_g)^\chi \langle O_n \rangle \]

The viability of CLAWE is determined by the ratio of the ideal map to the ideal observable:
The ratio scales super-polynomially as the scalar depth increases. The ideal map becomes unstable beyond the gate cutoff: \( \chi \sim O(1/\epsilon_g) \). This comes as a result of the depolarizing channel’s signal-to-noise problem.

**B. Calibration Algorithms**

In the following algorithms, motion-reversal \((\hat{U} \hat{U}^\dagger)\) of the target computation is used as the calibrating unitary [26].

1. **Variant I**

An implicit assumption of Equation II.5 is that \( \epsilon_g \) is relatively constant during the course of the computation. The Variant I calibration algorithm is designed to extract this constant, by applying motion-reversal in powers of the target computation (Figure 3):

\[
\{ \hat{U}_X^k \hat{U}_X^k \} \text{ for } \forall k, \text{ from } 1 \text{ to } N_c \quad (\text{II.11})
\]

2. **Variant II**

The Variant II calibration algorithm partitions the target computation into unitary fragments \( \chi_i \) [26]:

\[
U_X \to U_{X_{N_p}} \cdots U_{X_2} U_{X_1} \quad (\text{II.12})
\]

Throughout a computation, \( \epsilon_g \) will modulate across the unitary fragments. This allows \( \epsilon_g \) to be modeled as a global noise vector \( \vec{\epsilon}_g = \{ \epsilon_{g1}, \ldots, \epsilon_{gN_p} \} \).

**Memory Window**: Calibrating the unitary fragments in a vacuum will not capture the true noise dynamics of \( U_X \). The qubits retain memory of past interactions with the environment. The noise dynamics of a unitary fragment depend on those of its predecessors.

Due to quantum memory loss, this dependence can be mimicked by a memory window: a portion of the unitary fragment’s predecessors. Applying the memory window to the calibration state will imprint noise dynamics onto a memory state (Figure 4).

After constructing the memory state, motion-reversal is performed to generate \( \epsilon_{g4} \). Repeating this procedure for every unitary fragment yields \( \epsilon_{g4} \).

The ideal map is the following:

\[
(\Omega_{m_n}^{\text{map}}) = \left( 1 - \epsilon_{g1}^2 \right) \cdots \left( 1 - \epsilon_{gN_p}^2 \right)^{\chi_{N_p}} (\Omega_n) \quad (\text{II.13})
\]
Computations that exhibit quantum speedups are those \( \in \text{BQP} \) and \( \notin \text{BPP} \) [98].

**Local quantum simulation** is a computation thought to be \( \notin \text{BPP} \) [99–104]. Calculating the time evolution of an \( n \)-qubit system involves multiplying \( 2^n \times 2^n \) matrices. Because classical algorithms manipulate matrix elements, computing the dynamics will take exponential time:

\[
time-complexity \sim O(2^{2n)^2} \quad \text{(III.2)}
\]

Seth Lloyd proved that local quantum simulation is \( \in \text{BQP} \) by deriving the Product Formula Algorithm (PFA) [100]. It is tailored to \( k \)-local theories [115], which have interactions coupling \( \leq k \) qubits:

\[
H = \sum_{\sigma=1}^{N_i} H_{\sigma} \quad \text{(III.3)}
\]

The PFA applies a Trotter-Suzuki expansion [116–118] to the evolution operator:

\[
e^{-iHt} \approx \left( \prod_{\sigma=1}^{N_i} e^{-iH_\sigma t/n_\sigma} \right)^{n_t} \quad \text{(III.4)}
\]

Approximating the dynamics to accuracy \( \epsilon \) will take the following time:

\[
\text{time-complexity} \sim N_i A^k t^2/\epsilon \quad \text{(III.5)}
\]

This will scale polynomially, provided \( N_i \sim \text{poly}(n) \) and \( k \sim \text{polylog}(n) \). For such theories, the PFA generates an exponential quantum speedup over classical approaches.

**B. Simulating the Fermi-Hubbard Model on a Quantum Computer**

The benchmark computations involve digital quantum simulation using the PFA.

1. Simulation Prescription

The benchmark computations require time-dependent quantum simulation of the Fermi-Hubbard Model:

\[
H_f(t) = -h(t) \left\{ \sigma_x^2 + \sigma_y^2 \right\} + \frac{u(t)}{2} \sigma_z^1 \otimes \sigma_z^2 \quad \text{(III.6)}
\]

The Hamiltonian becomes dimensionless when rescaled with \( h(t) \). The dimensionless interaction is \( \tilde{u}(t) = u(t)/h(t) \); the Hamiltonian time-evolves to:

\[
\hat{H}_f(t) = -\left\{ \sigma_x^2 + \sigma_y^2 \right\} + \frac{\tilde{u}(t)}{2} \sigma_z^1 \otimes \sigma_z^2 \quad \text{(III.7)}
\]

The initial state is prepared with a pair of Hadamard gates (Figure 5):

\[
|\psi_{\text{ini}}\rangle = \left\{ \left| 0 \right\rangle + \left| 1 \right\rangle \right\}/\sqrt{2} \otimes \left\{ \left| 0 \right\rangle + \left| 1 \right\rangle \right\}/\sqrt{2} \quad \text{(III.8)}
\]

2. Computation Parameters

**Theoretical Result:** To compute the theoretical result, quantum simulation is performed numerically.

The digitization error is estimated by perturbing terms in the PFA. Each PFA step contains 3 units, of which two mutually commute (Figure 5). As such, there are \( 4^k \) total permutations for the \( k \)-th PFA step.

3. Electronic Overlap Dynamics

The presence of electrons occupying shared lattice sites is indicated by the electronic overlap:

\[
E_o = |00\rangle\langle 00| + |11\rangle\langle 11| \quad \text{(III.9)}
\]

The electronic overlap is measured during quantum simulation of the Fermi-Hubbard Model.

a. NISQ Computation

**QPU Interfacing:** The IBMQ-Vigo is accessed via Qiskit, which enables preparation of quantum circuits within an intuitive framework [119]. Quantum circuits are packaged into a job object, and sent to the QPU. Each job object can contain up to 75 individual circuits.

**Data Acquisition:** The benchmark computation requires 10 quantum circuits. The circuits are evaluated with a single call to the IBMQ-Vigo. A bootstrap algorithm [120–122] is run on the measurements to generate the electronic overlap and its uncertainty.

b. ZNE Noise Mitigation

ZNE is used to establish a performance baseline for CLAWE.

ZNE is performed with a polynomial fit and a Richardson extrapolation.

In both approaches, errors are modulated using the quartic-cycle noise amplification (QCNA) prescription. QCNA amplifies the noise dynamics by injecting pairs of CNOT gates in four rounds of computation (Figure 6). In this work, a \((7\times7)\)-QCNA is utilized: \( \chi \rightarrow 7\chi \).
ZNE Viability: ZNE is designed to treat computations that remain within the PNR after error amplification is performed. Applying \((\times 7)\)-QCNA to the PFA-expansion probes noise dynamics outside of the PNR \((\chi: 20 \rightarrow 140)\):

\[
\text{IBMQ-Vigo: } \chi_{\text{PNR}} \approx 111 \quad (\text{III.10})
\]

As such, ZNE should reliably correct \(7/10\) time-steps.

Polynomial Fit: Performing ZNE with a third-order polynomial fit demonstrates theoretical agreement for \(2/10\) points (Figure 7).

Richardson Extrapolation: Performing ZNE with a second-order Richardson extrapolation demonstrates theoretical agreement for \(6/10\) points (Figure 8).

c. CLAWE Noise Mitigation

Variant I and Variant II are applied to the electronic overlap computation.

Variant I: Performing Variant I demonstrates theoretical agreement for \(8/10\) points (Figure 9).

Variant II: Performing Variant II demonstrates theoretical agreement for \(8/10\) points (Figure 10).

Variant I Calibration: The global noise strength is used to perform extrapolation (Figure 11).

Variant II Calibration: The global noise vector is used to perform extrapolation (Figure 12).

4. Rényi Entropy Dynamics

The Rényi entropy is measured during quantum simulation of the Fermi-Hubbard Model.

\[ H = H_\uparrow \otimes H_\downarrow \quad (\text{III.11}) \]

For a state \(\rho\), the *reduced density matrix* for each electron spin species is obtained by applying a *partial trace*:

\[ \rho_\uparrow = \text{Tr}_\downarrow [\rho] \quad (\text{III.12}) \]
\[ \rho_\downarrow = \text{Tr}_\uparrow [\rho] \quad (\text{III.13}) \]

The Rényi entropy of \(\rho_\uparrow\) is the following:

\[ S(\rho_\uparrow) = -\frac{1}{2} \log \left\{ \text{Tr} (\rho_\uparrow^2) \right\} \quad (\text{III.14}) \]

b. NISQ Computation

The Rényi entropy can be computed using the *Bell-Basis Algorithm* (BBA) [123].

Bell-Basis Algorithm: Quantum simulation is applied to two copies of the initial state. The quantum stage of the BBA is applied using a CNOT gate between the spin-up qubits (Figure 5).

Data Acquisition: The Rényi entropy computation requires \(10\) quantum circuits, which are evaluated with a single call to the IBMQ-Santiago. A bootstrap algorithm is run to generate the Rényi entropy and its uncertainty.

c. ZNE Noise Mitigation

ZNE is applied to the Rényi entropy computation.

Polynomial Fit: Performing ZNE with a third-order polynomial fit demonstrates theoretical agreement for \(1/10\) points (Figure 13).
Richardson Extrapolation: Performing ZNE with a second-order Richardson extrapolation demonstrates theoretical agreement for 4/10 points (Figure 14).

d. CLAWE Noise Mitigation

Variant I and Variant II are applied to the Rényi entropy computation.

Variant I: Performing Variant I demonstrates theoretical agreement for 3/10 points (Figure 15).

Variant II: Performing Variant II demonstrates theoretical agreement for 7/10 points (Figure 16).

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Those who wait on the Lord shall renew their strength; they shall mount up with wings like eagles, they shall run and not be weary, they shall walk and not faint.

-Isaiah 40:31

—AMDG—

APPENDIX

I. Noise Tailoring Algorithms

Coarse-grained decoupling [124–127] can be used to alter noise dynamics using gate-level control. Oliver Kern, Gernot Alber, and Dima Shepelyansky first demonstrated this using Pauli Random Error Correction (PAREC) [124].

In PAREC, the computational frame is toggled during a computation by inserting randomized pairs of Pauli operations. This leaves the computation logically equivalent. Toggling the computational frame generates a dynamical decoupling-like effect without the need for rapid time-modulation [128].

The NT algorithm used in this work is Randomized Compiling (RC0) [126]. RCo applies coarse-grained decoupling across a sequence of circuits.

FIG. 6. Error-amplified dynamics (gray), are extrapolated to the zero-noise solution.

FIG. 7. The ZNE polynomial fit (red) is compared with the theoretical result (indigo) for the electronic overlap.

FIG. 8. The ZNE Richardson extrapolation (golden) is compared with the theoretical result (indigo) for the electronic overlap.
FIG. 9. Variant I (red) is compared with the theoretical result (indigo) for the electronic overlap.

FIG. 10. Variant II (golden) is compared with the theoretical result (indigo) for the electronic overlap.

FIG. 11. The global noise strength (red) is shown alongside its mean value (blue).

FIG. 12. The global noise vector (purple) is shown alongside its mean value (blue).

FIG. 13. The ZNE polynomial fit (red) is compared with the theoretical result (blue) for the Rényi entropy.

FIG. 14. The ZNE Richardson extrapolation (golden) is compared with the theoretical result (blue) for the Rényi entropy.

FIG. 15. Variant I (red) is compared with the theoretical result (blue) for the Rényi entropy.

FIG. 16. Variant II (golden) is compared with the theoretical result (blue) for the Rényi entropy.
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