Exponentially tighter limitations for quantum error mitigation

QTech Berlin 2024

Johannes Jakob Meyer

Freie Universität Berlin

Motivation

ADVANTAGES
Quantum computers offer advantages, e.g. for sampling or factoring

Can we translate this potential into practical applications?

NEAR-TERM PROPOSALS
There are many proposals for near-term applications where error correction is not possible.

One fundamental ingredient is the computation of **expectation values**.

ERROR MITIGATION
Before the advent of full error correction, can we somehow **mitigate** the impact of noise on the computed expectation values?

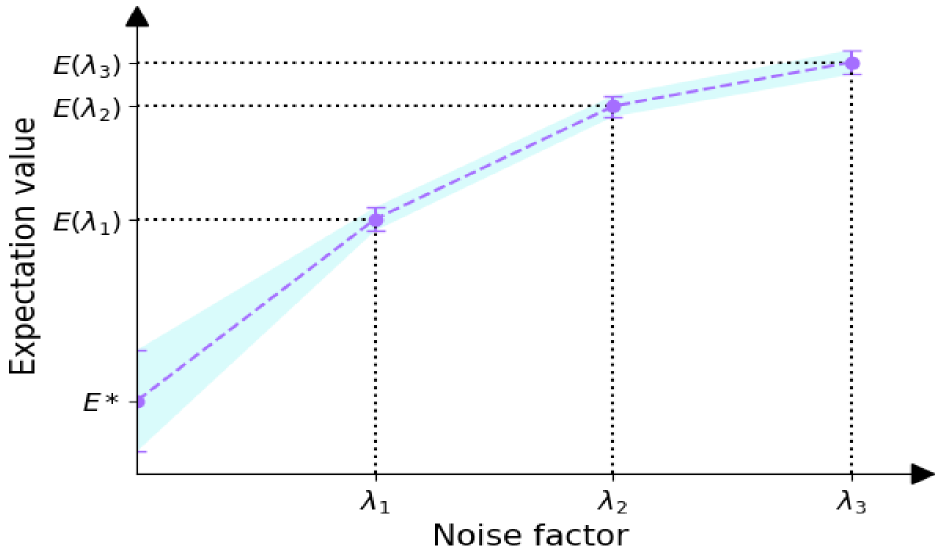
Error Mitigation

KEY IDEA

Can we gather more data and use it to classically „undo“ the noise?

ZERO NOISE EXTRAPOLATION[1]

- Increase noise level by adding superfluous operations
- Compute expectation values at different noise levels
- Fit the curve and extrapolate to zero noise



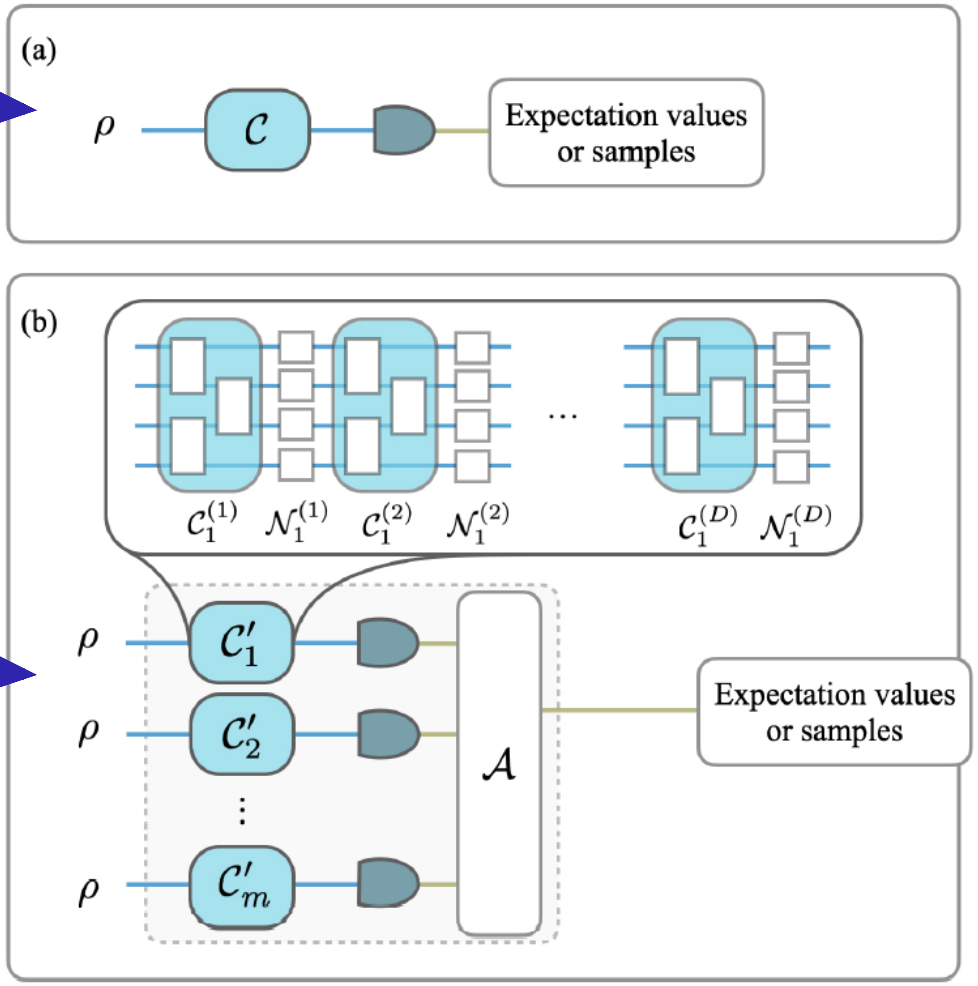
2

[1]Li and Benjamin, Phys. Rev. X 7, 021050 (2017). [2]Majumdar et al., IEEE Int. Conf. Quant. Comp. Eng. (2023)

Error Mitigation

IDEAL CASE
We run a target circuit on an input state and obtain the desired output

ERROR MITIGATION ABSTRACTION
We run a number of noisy circuits on the input state and post-process their outputs into a prediction



cf. Takagi et al., npj QI 8(1), 114 (2022); Takagi et al., PRL 131(21), 210602 (2023); Tsubouchi et al., PRL 131(21), 210601 (2023).

Limitations on Error Mitigation

LOCAL DEPOLARIZING NOISE
Pushes quantum states towards the maximally mixed state exponentially fast in depth[1]

WE SHOW THAT
For many circuits, this effect is drastically amplified, even in log-log depth

We need exponential-in-depth resources for quantum error mitigation[2,3]

We need exponential-in-depth and in-qubit-count resources for quantum error mitigation

$$N \geq \exp(O(D))$$

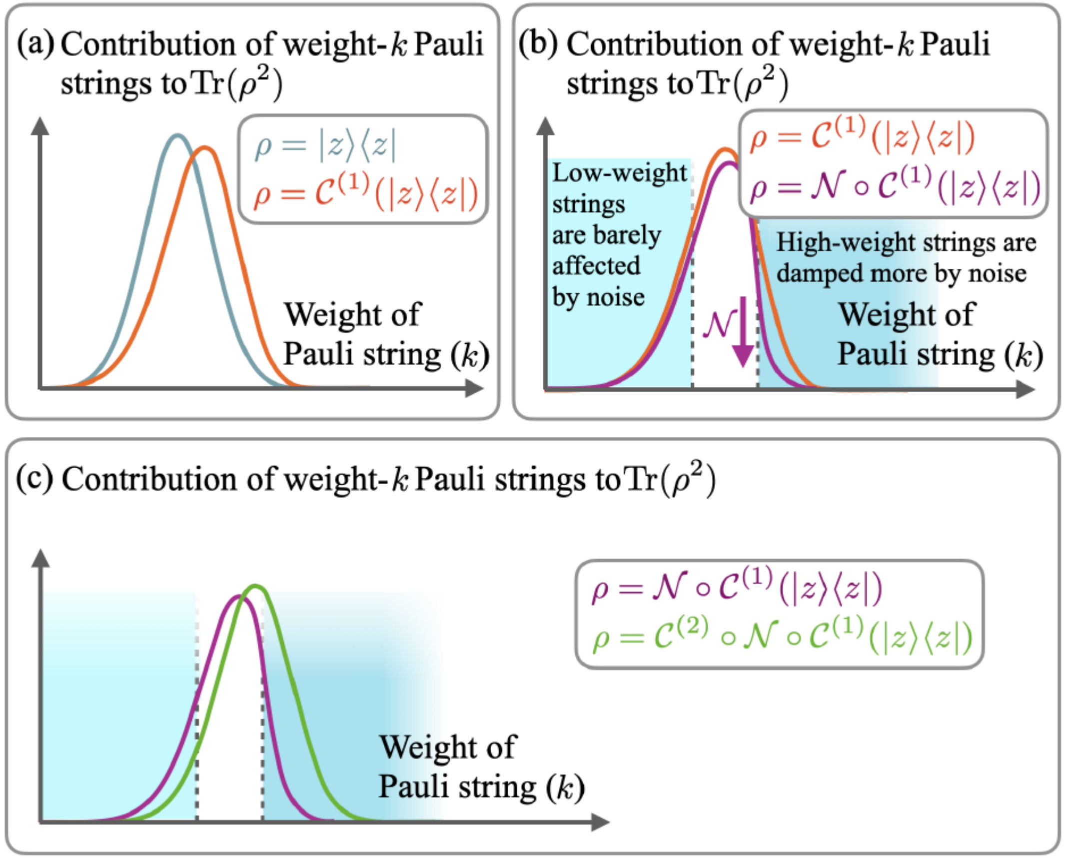
$$N \geq \exp(O(nD))$$

[1]Müller-Hermes et al., JMP 57(2) (2016). [2]Takagi et al., PRL, 131(21), 210602 (2023) [3]Tsubouchi et al., PRL 131(21), 210601 (2023).

Key proof idea

Bound relative entropy by Rényi 2 relative entropy, the log-purity

Purity is given by the 2-norm of coefficients of the Pauli expansion



High weight Paulis decay fast, but low weight Paulis inhibit decay with system size

Add dynamics[1] that re-shuffle the coefficients, increasing the weight of the Paulis

[1]Cleve et al., Quant. Inf. Comp. 16(9-10), 0721 (2016)

What now?

- Our work shows that error mitigation is not scalable and does not work for all circuits
- Obstructions already appear at log-log depth
- There could, however, still be schemes that work well in practice for a given system and circuit

Error mitigation can still help,
but **error correction**
is what we really need

Thank you for your attention.

johannesjakobmeyer.com

@jj_xyz

nature > nature physics > articles > article

Article | Open access | Published: 25 July 2024

Exponentially tighter bounds on limitations of quantum error mitigation

Article

Slides