Entering the quantum utility era:

how to best mitigate noise on quantum computers?

Sabrina Maniscalco
Algorithmiq Ltd

algorithmiq

Scalable tensor-network error mitigation for near-term quantum computing

Sergei Filippov,[1] Matea Leahy,[1,2] Matteo A. C. Rossi,[1] and Guillermo García-Pérez[1]

[1]*Algorithmiq Ltd, Kanavakatu 3 C, FI-00160 Helsinki, Finland*

[2]*Trinity Quantum Alliance, Unit 16, Trinity Technology and Enterprise Centre, Pearse Street, D02 YN67, Dublin 2, Ireland*

Until fault-tolerance becomes implementable at scale, quantum computing will heavily rely on noise mitigation techniques. While methods such as zero noise extrapolation with probabilistic error amplification (ZNE-PEA) and probabilistic error cancellation (PEC) have been successfully tested on hardware recently, their scalability to larger circuits may be limited. Here, we introduce the tensor-network error mitigation (TEM) algorithm, which acts in post-processing to correct the

arXiv:2307.11740v2

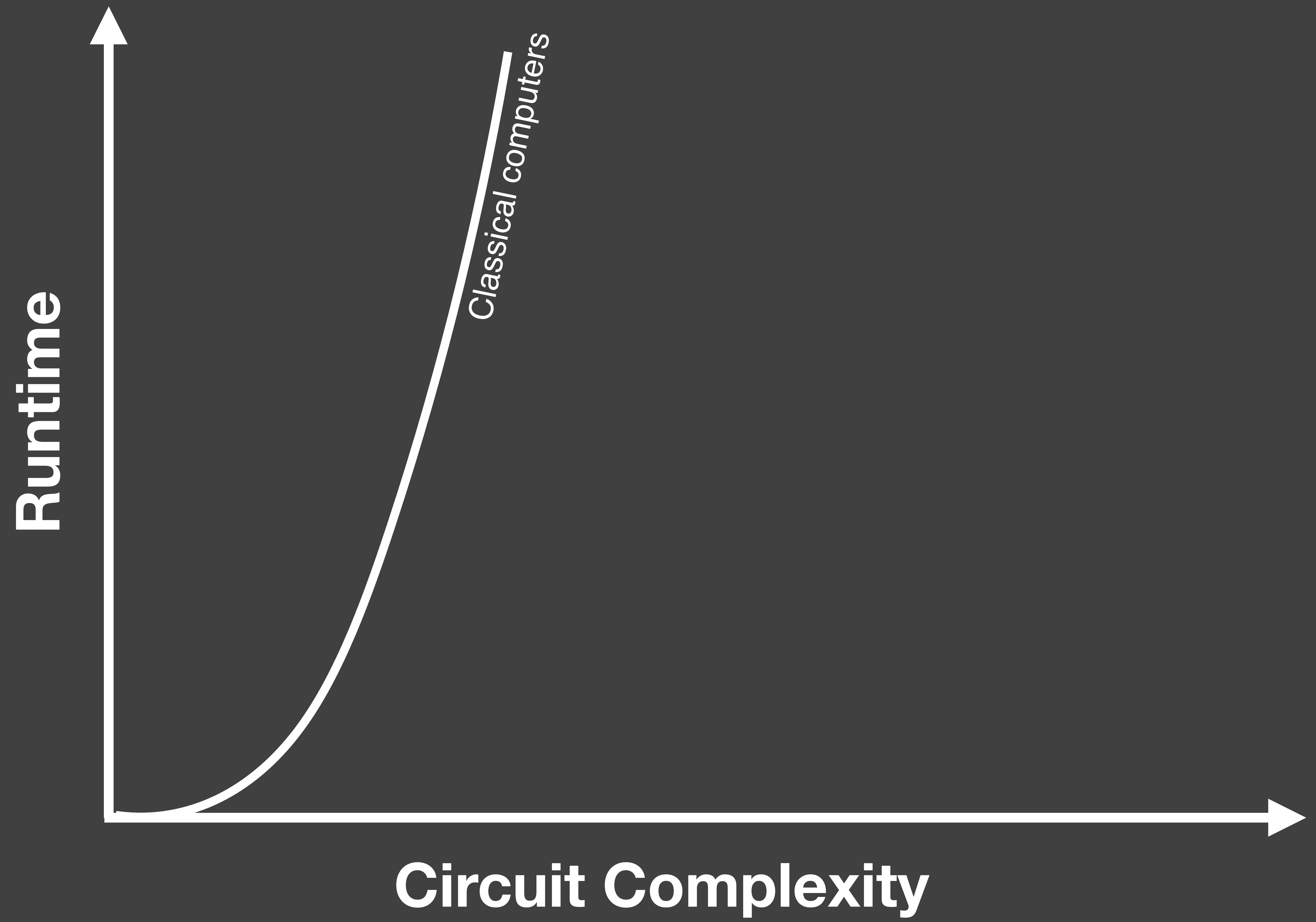


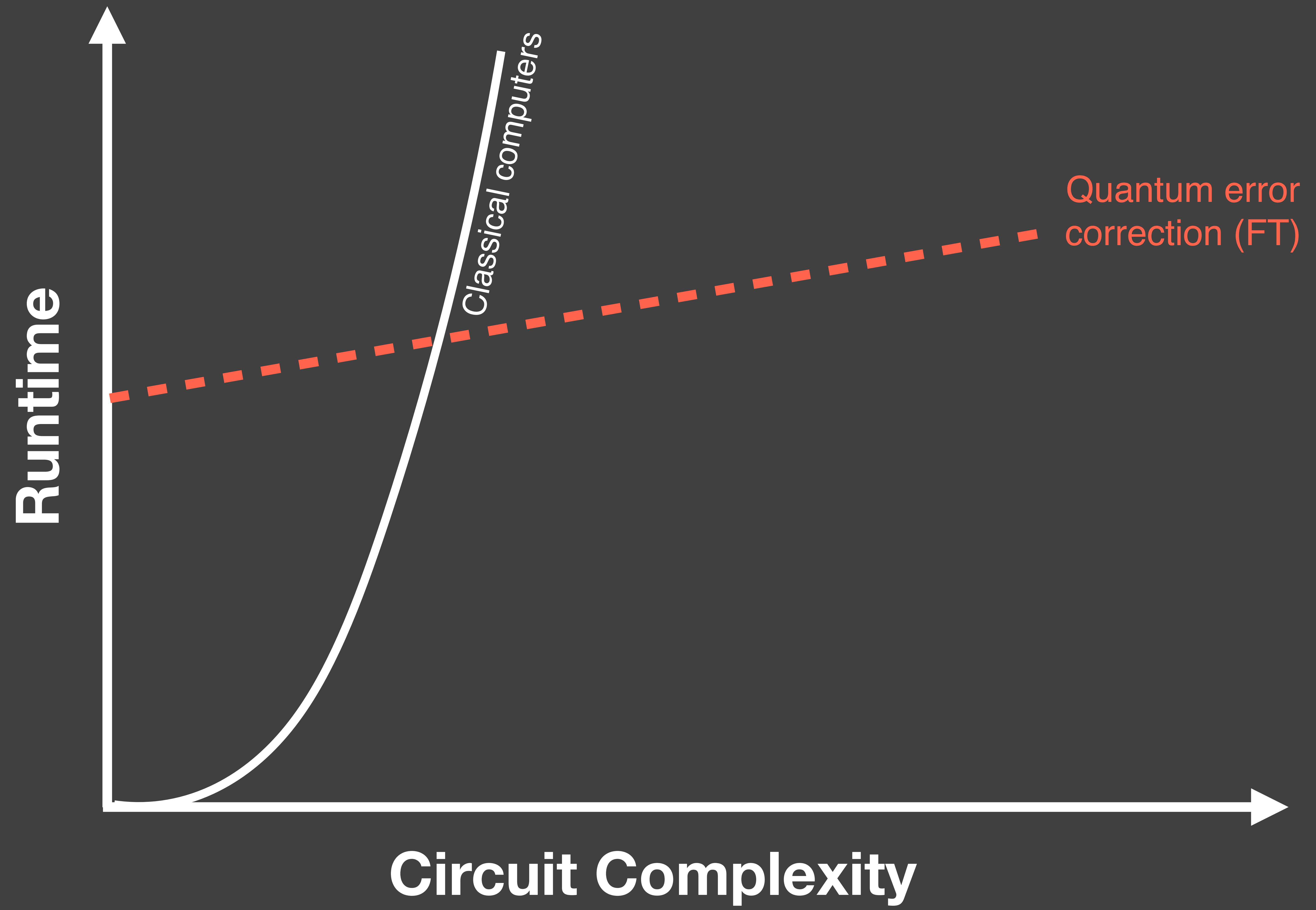

algorithmiq

Noise Mitigation for near-term QC

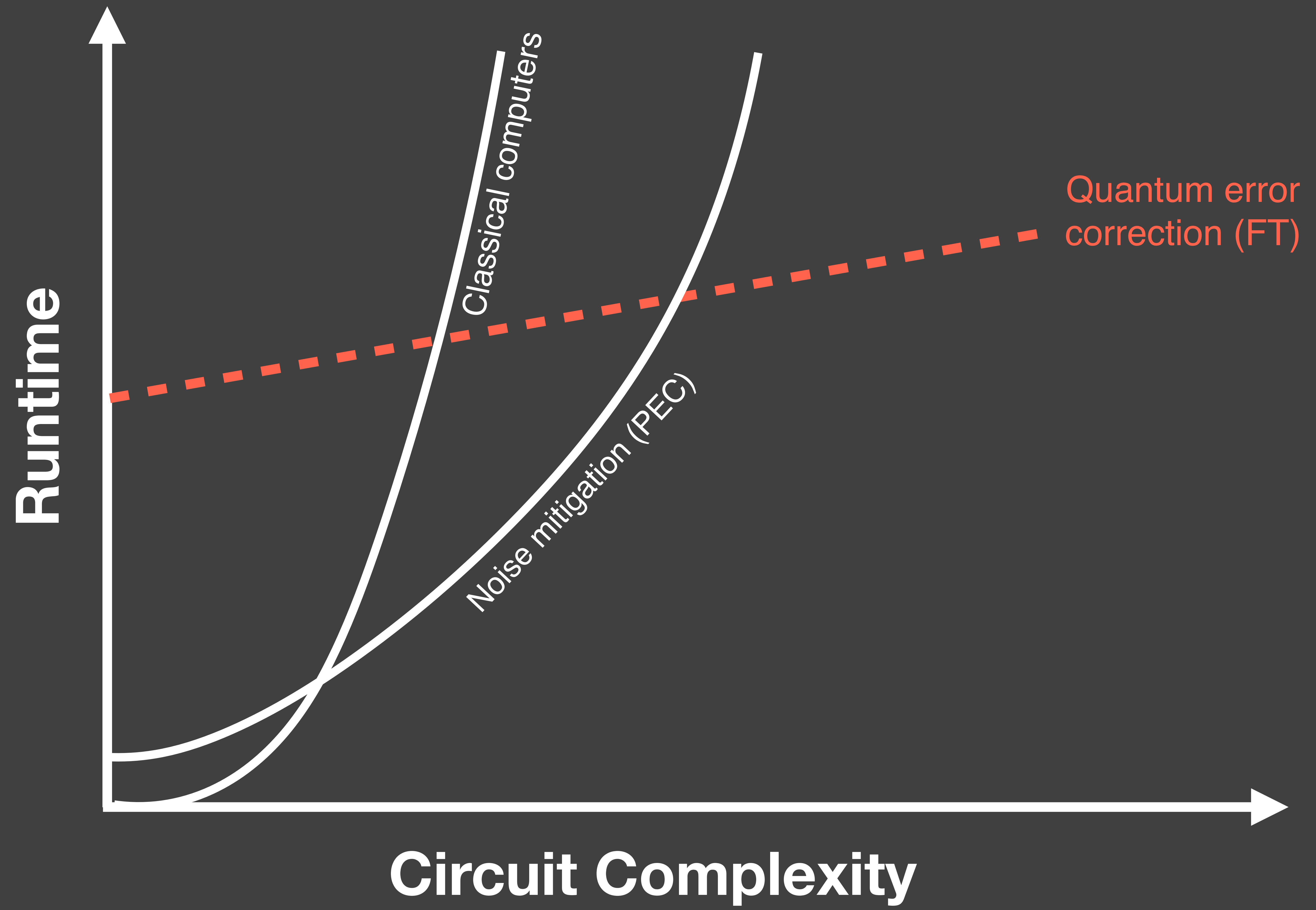
a.k.a.

Living with "exponentially hard"

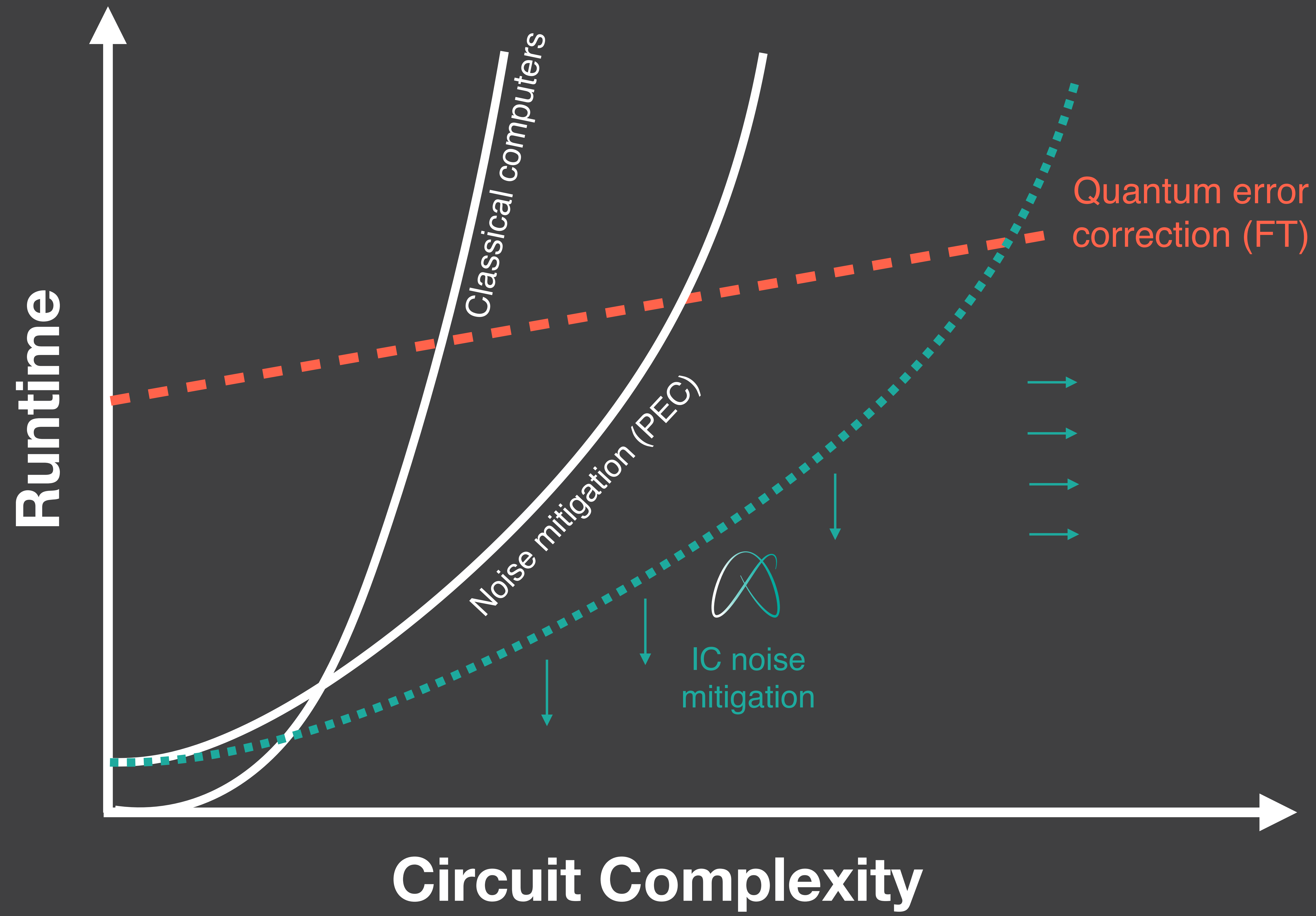

Runtime
Classical computers
Circuit Complexity



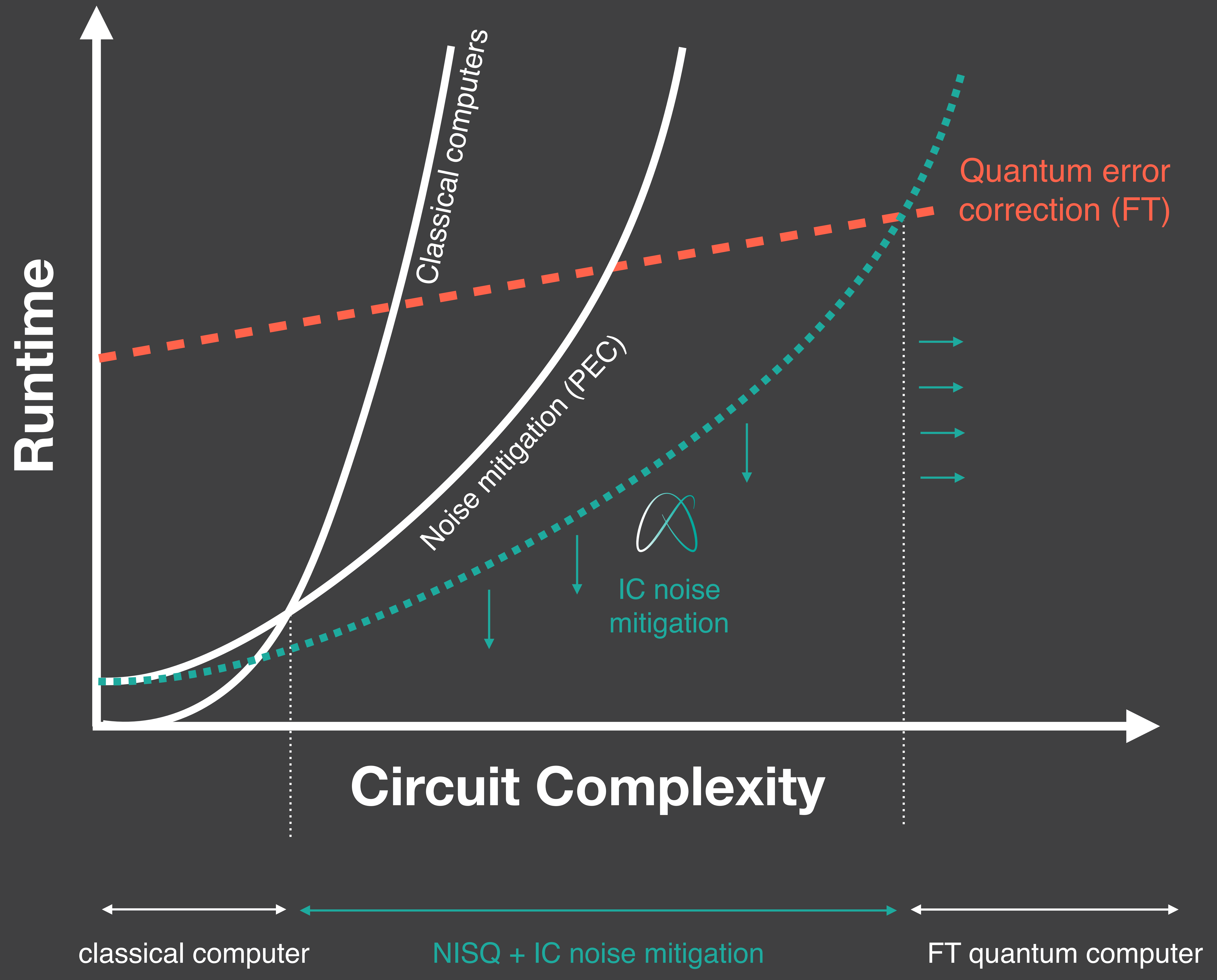
algorithmiq



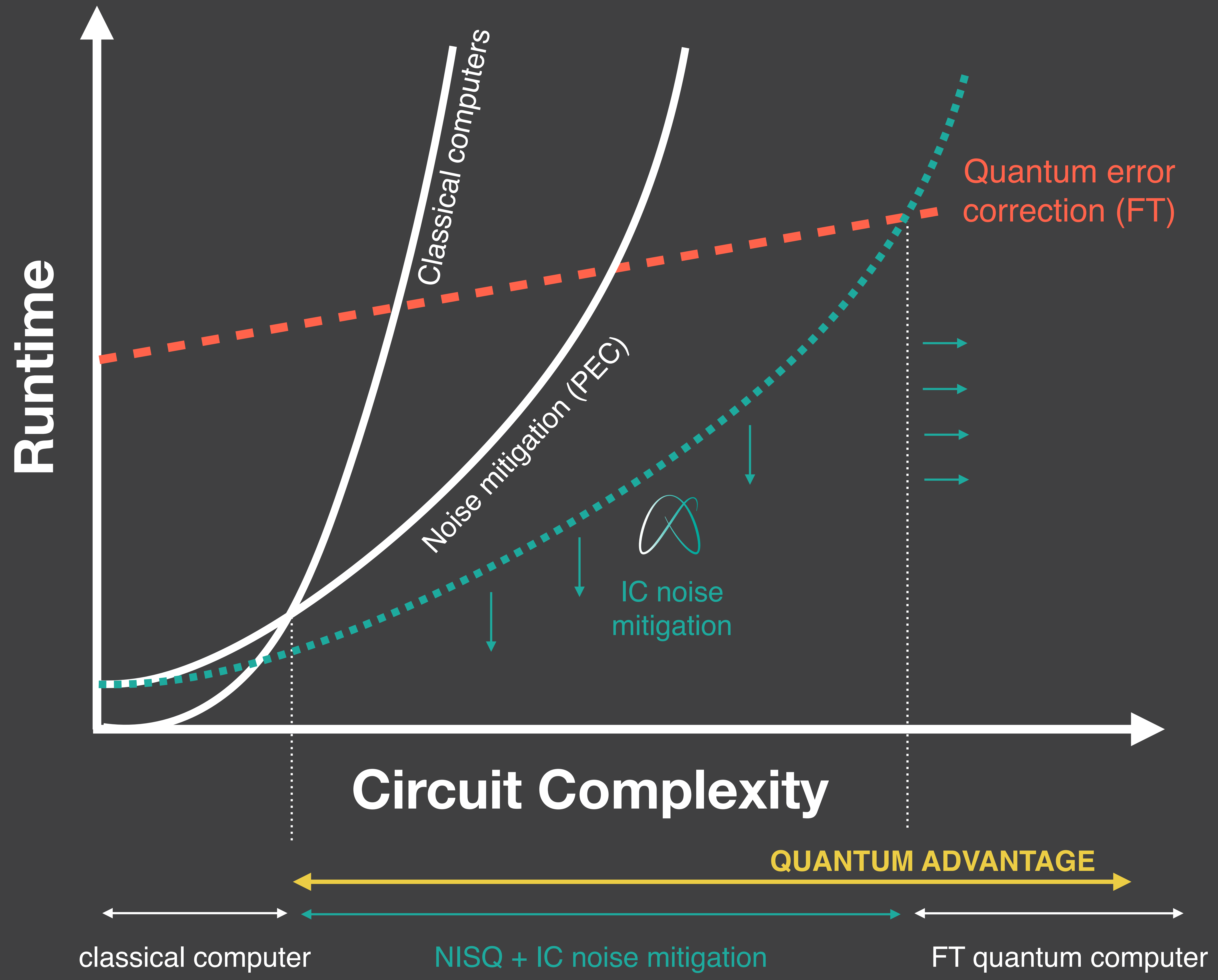
algorithmiq



algorithmiq



algorithmiq



algorithmiq

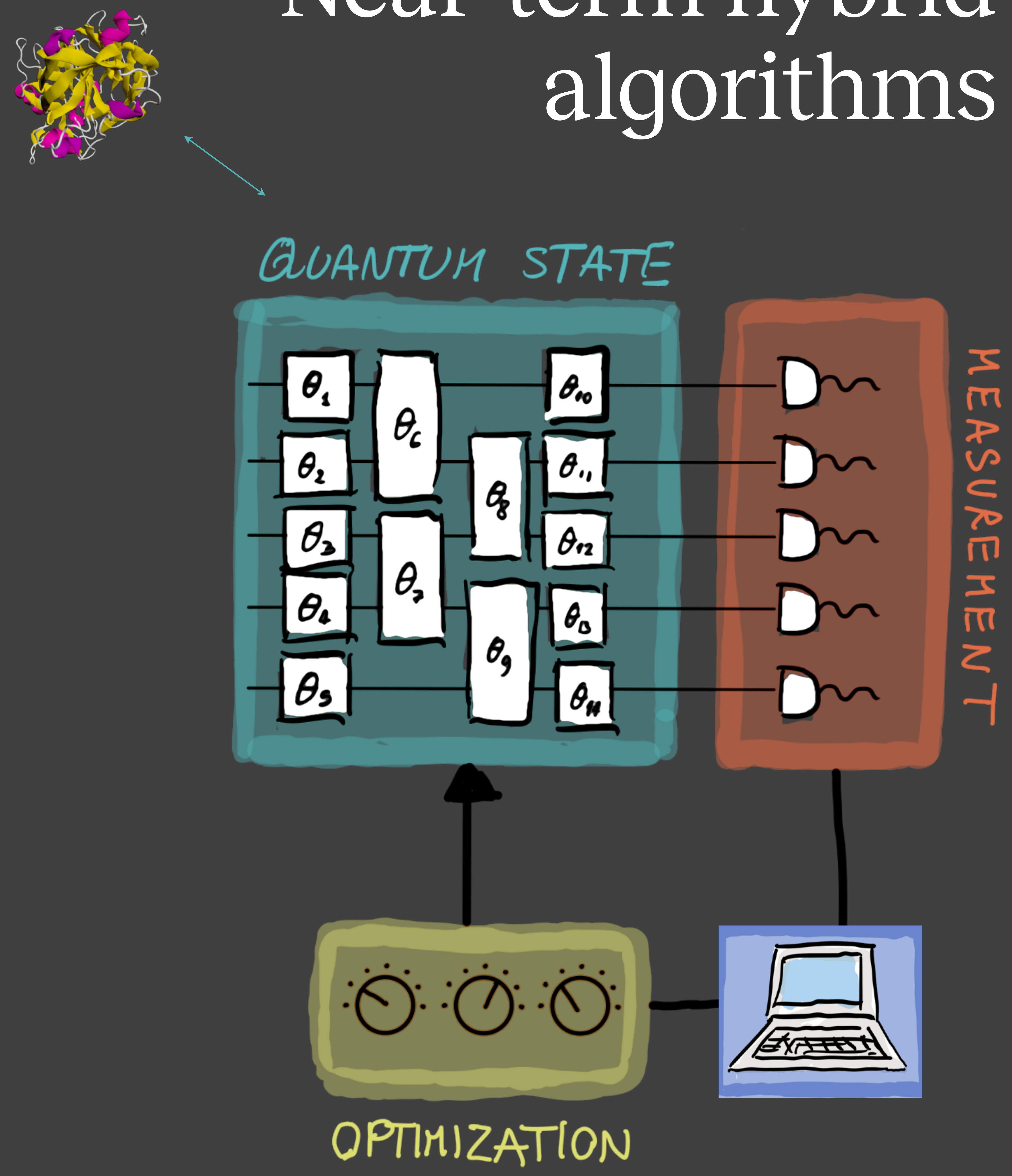
"Exponentially hard" is bad.

"Exponentially hard" is bad.

But how about the exponent?

what can we do with, say 200, "very good" qubits?

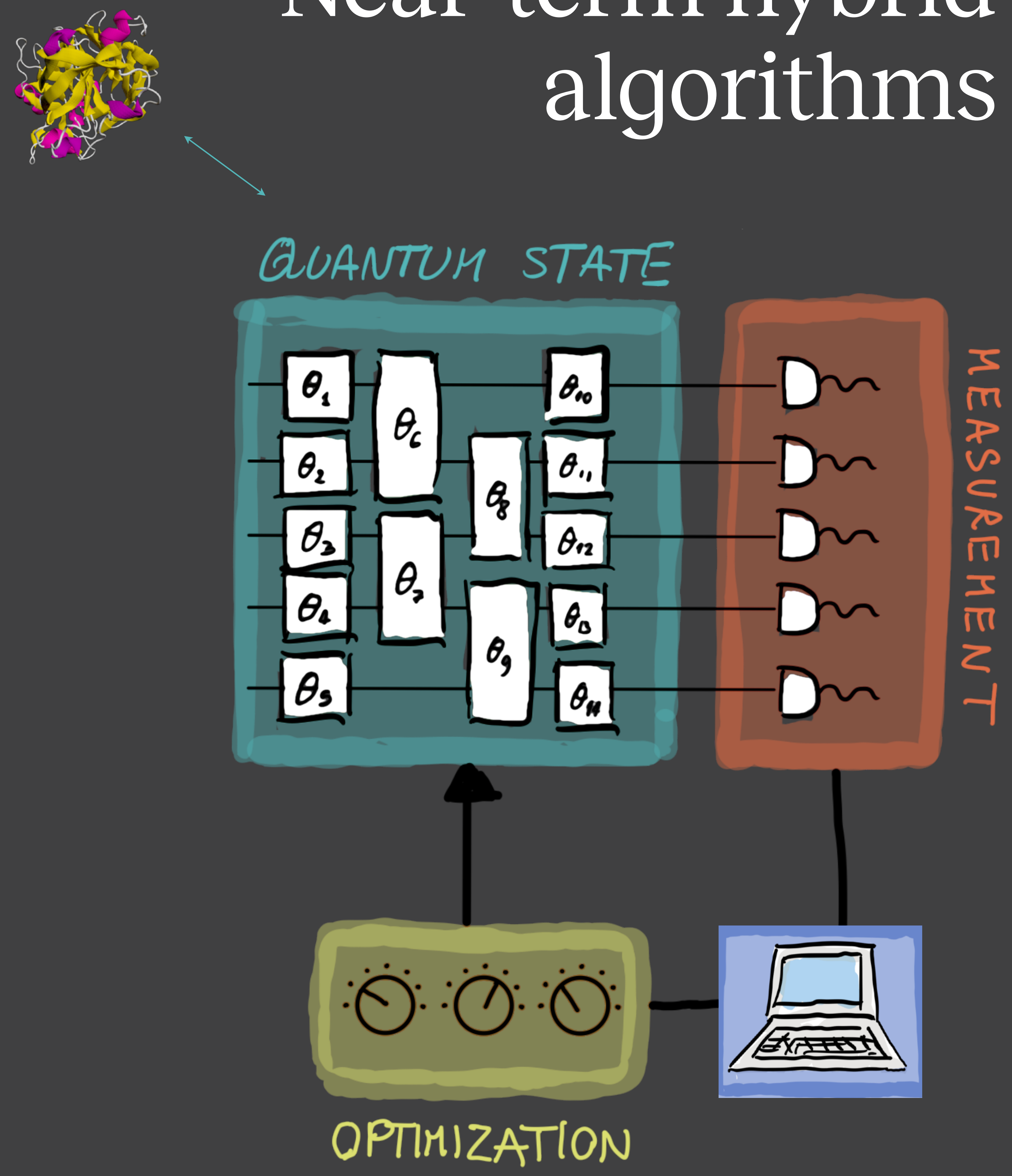
Near-term hybrid algorithms



Challenges

algorithmiq

Near-term hybrid algorithms

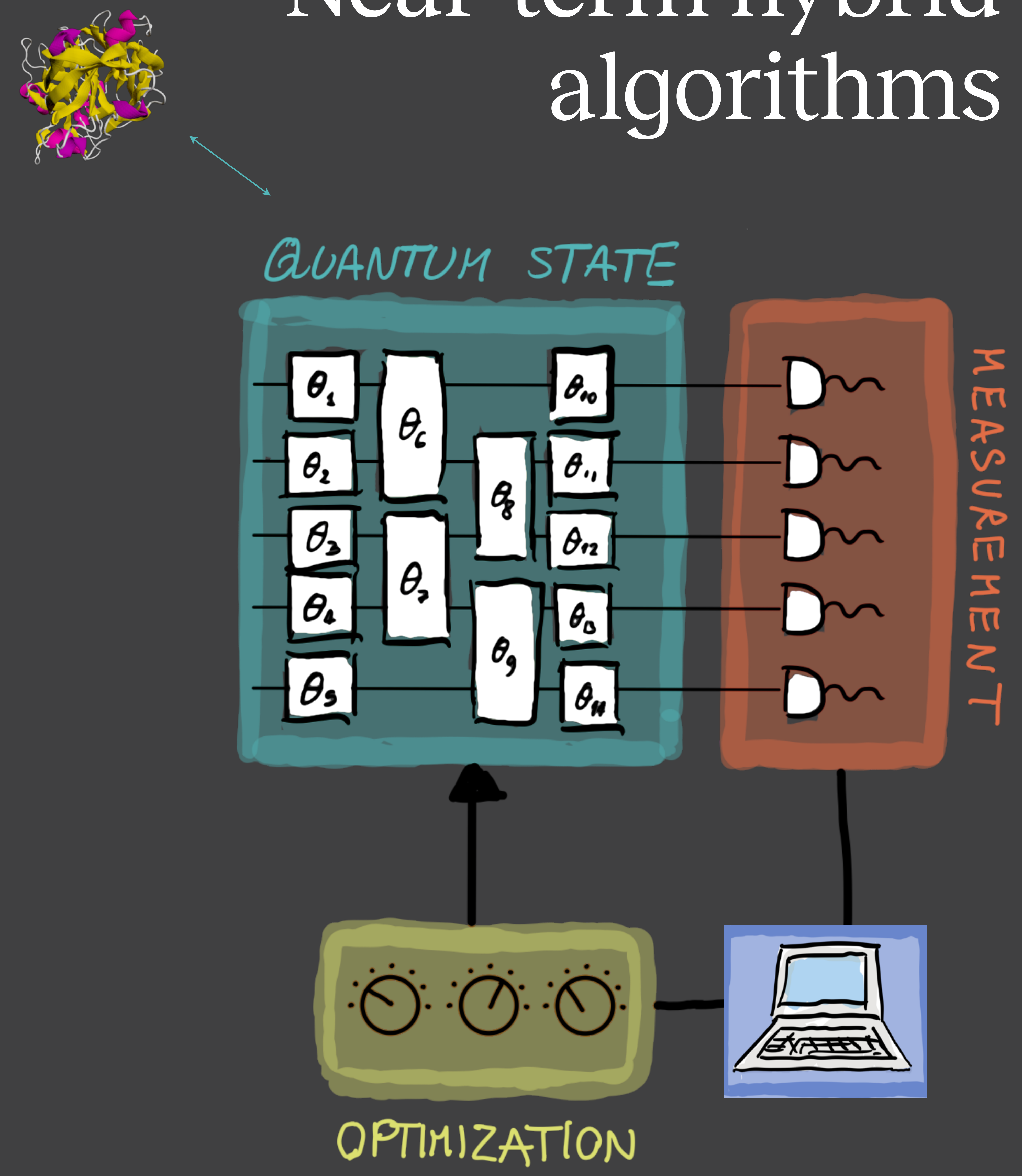


algorithmiq

Challenges

- Measurement stage is time-consuming
- Hilbert space is a big space
- Noise biases the results
- Qubits are a scarce resource

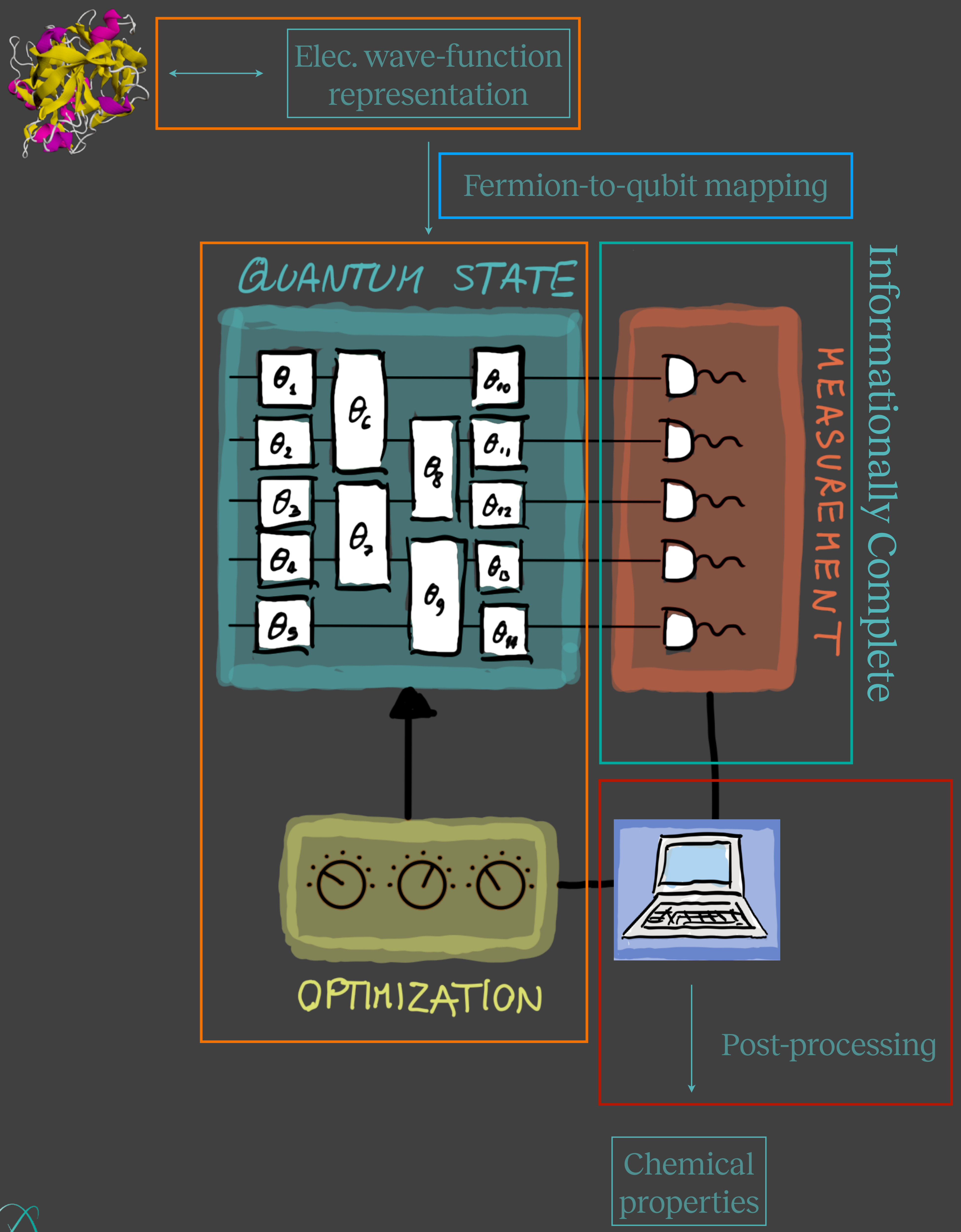
Near-term hybrid algorithms



Challenges

- Measurement stage is time-consuming
- Hilbert space is a big space
- Noise biases the results
- Qubits are a scarce resource

4 problems,
1 solution



algorithmiq

List of papers

- PRX Quantum **2**, 040342 (2021)
- 2208.07817
- 2212.10262 in press in Phys. Rev. Research
- 2212.09713, PRX Quantum **4**, 030314 (2023)
- 2212.09719
- 2212.11405
- 2207.01360
- 2212.10225
- 2307.11740

Unlocking practical quantum advantage

with near-term quantum computers

algorithmiq

Requires changing the way we measure

algorithmiq

QUANTUM

ADVANTAGE

IN NEAR-TERM QC

CAN BE ACHIEVED

WITH IC GENERALISED

MEASUREMENTS

algorithmiq

Adaptive
IC POVM

CAN BE

LEMENTED

AR-TERM

NTUM

PUTERS

They are a SCALABLE measurement strategy

algorithmiq

They are a SCALABLE measurement strategy

they ENABLE otherwise unrealistic hybrid techniques

algorithmiq

They are a SCALABLE measurement strategy

they ENABLE otherwise unrealistic hybrid techniques

We can estimate the mean value of any observable with the same IC data

algorithmiq

PRX QUANTUM 2, 040342 (2021)

Learning to Measure: Adaptive Informationally Complete Generalized Measurements for Quantum Algorithms

Guillermo García-Pérez,[1,2,3,4,*] Matteo A.C. Rossi,[3,5,6] Boris Sokolov,[1,3,4] Francesco Tacchino,[7] Panagiotis Kl. Barkoutsos,[7] Guglielmo Mazzola,[7] Ivano Tavernelli,[7] and Sabrina Maniscalco[1,3,5,6]




algorithmiq

Adaptive POVM implementations and measurement error mitigation strategies

adaptive measurement techniques tailored for variational quantum algorithms on near-term small and noisy devices.

arXiv: 2208.11030



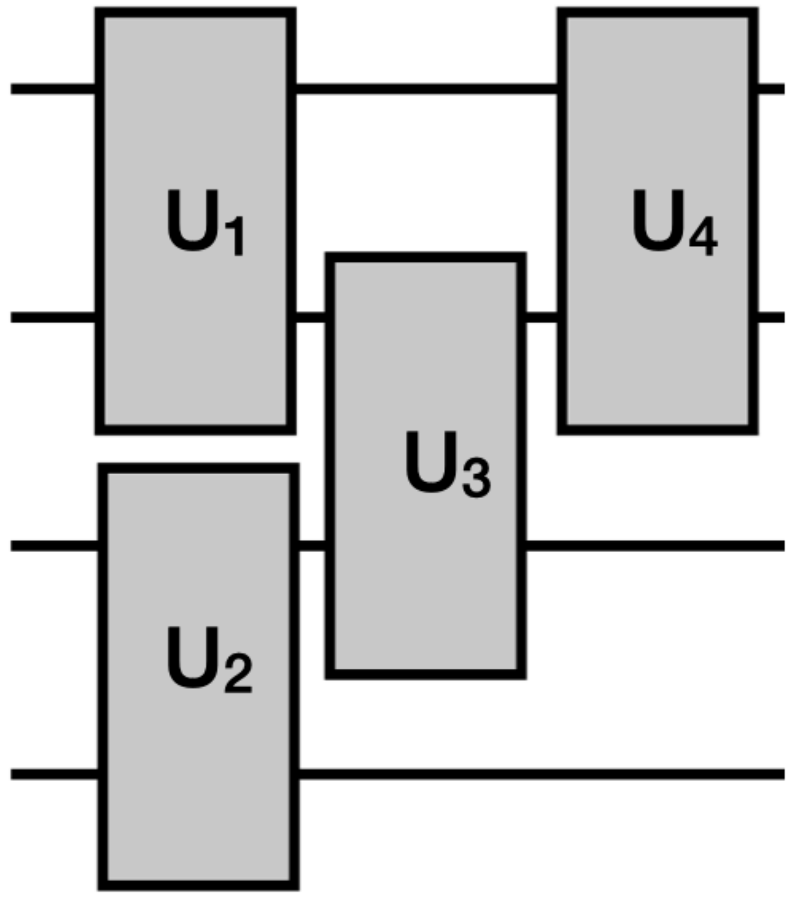




algorithmiq

WINNING THE NOISE BATTLE

algorithmiq

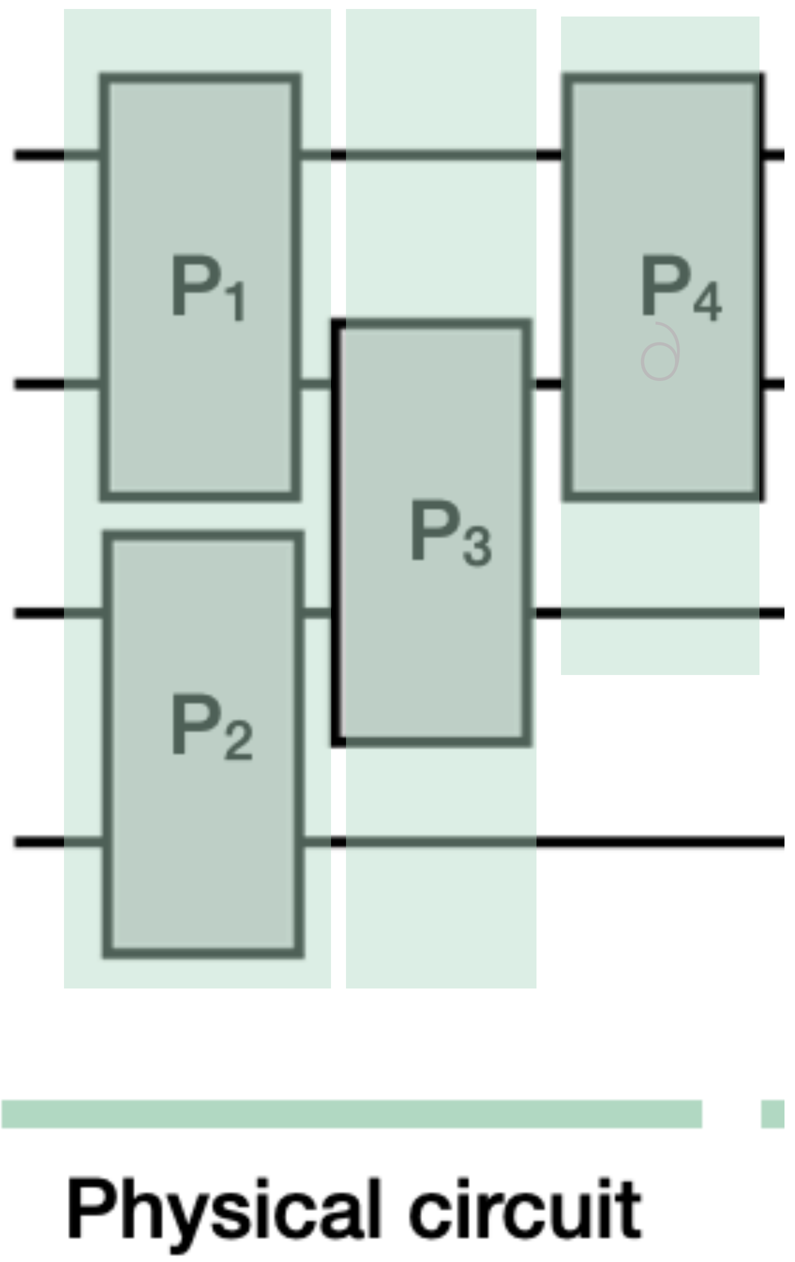


Ideal circuit

Noise mitigation

Characterised noise

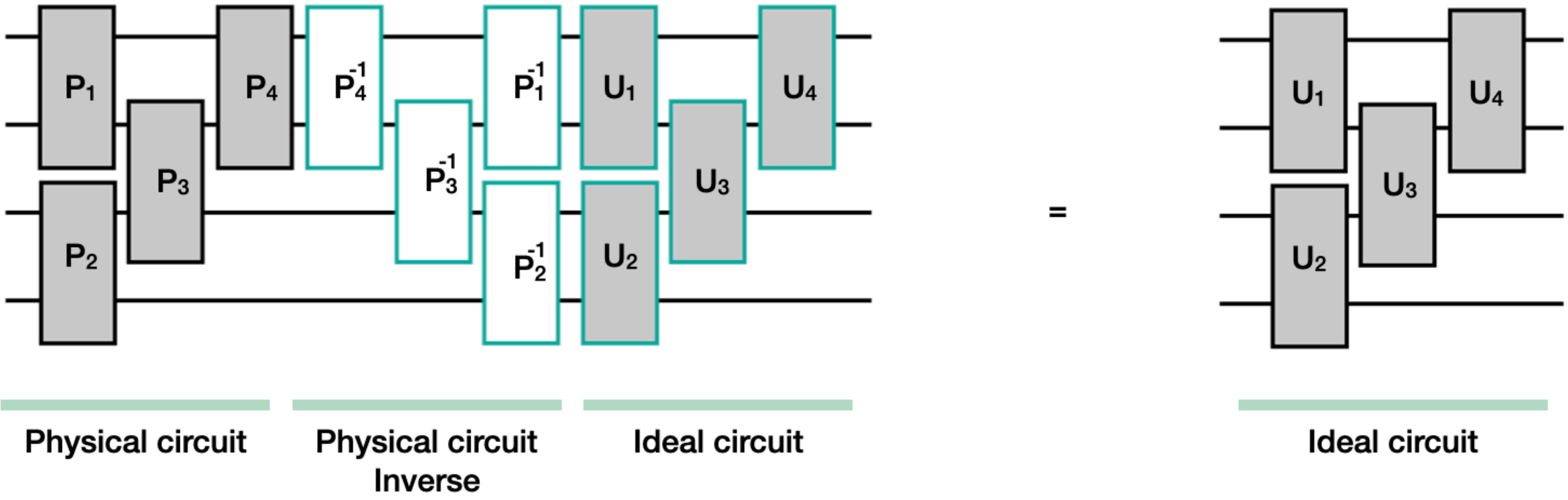
algorithmiq



Noise mitigation

Characterised noise

algorithmiq



Noise mitigation

Characterised noise

algorithmiq

2 state-of-the-art noise mitigation methods relying on noise characterization

algorithmiq

2 state-of-the-art noise mitigation methods relying on noise characterization

PEC

PEC represents a noise-free circuit as a quasiprobability distribution of the randomised noisy ones at the expense of a measurement overhead

(which quantitatively shows the increase in the measurement outcomes needed to get the same precision in estimation of observables).

K. Temme, S. Bravyi, and J. M. Gambetta, Phys. Rev. Lett. 119, 180509 (2017)
E. Van Den Berg, Z. K. Minev, A. Kandala, and K. Temme, Nature Physics (2023)
C. Piveteau, D. Sutter, and S. Woerner, npj Quantum Information 8, 12 (2022)

2 state-of-the-art noise mitigation methods relying on noise characterization

PEC

PEC represents a noise-free circuit as a quasiprobability distribution of the randomised noisy ones at the expense of a measurement overhead

(which quantitatively shows the increase in the measurement outcomes needed to get the same precision in estimation of observables).

K. Temme, S. Bravyi, and J. M. Gambetta, Phys. Rev. Lett. 119, 180509 (2017)
E. Van Den Berg, Z. K. Minev, A. Kandala, and K. Temme, Nature Physics (2023)
C. Piveteau, D. Sutter, and S. Woerner, npj Quantum Information 8, 12 (2022)

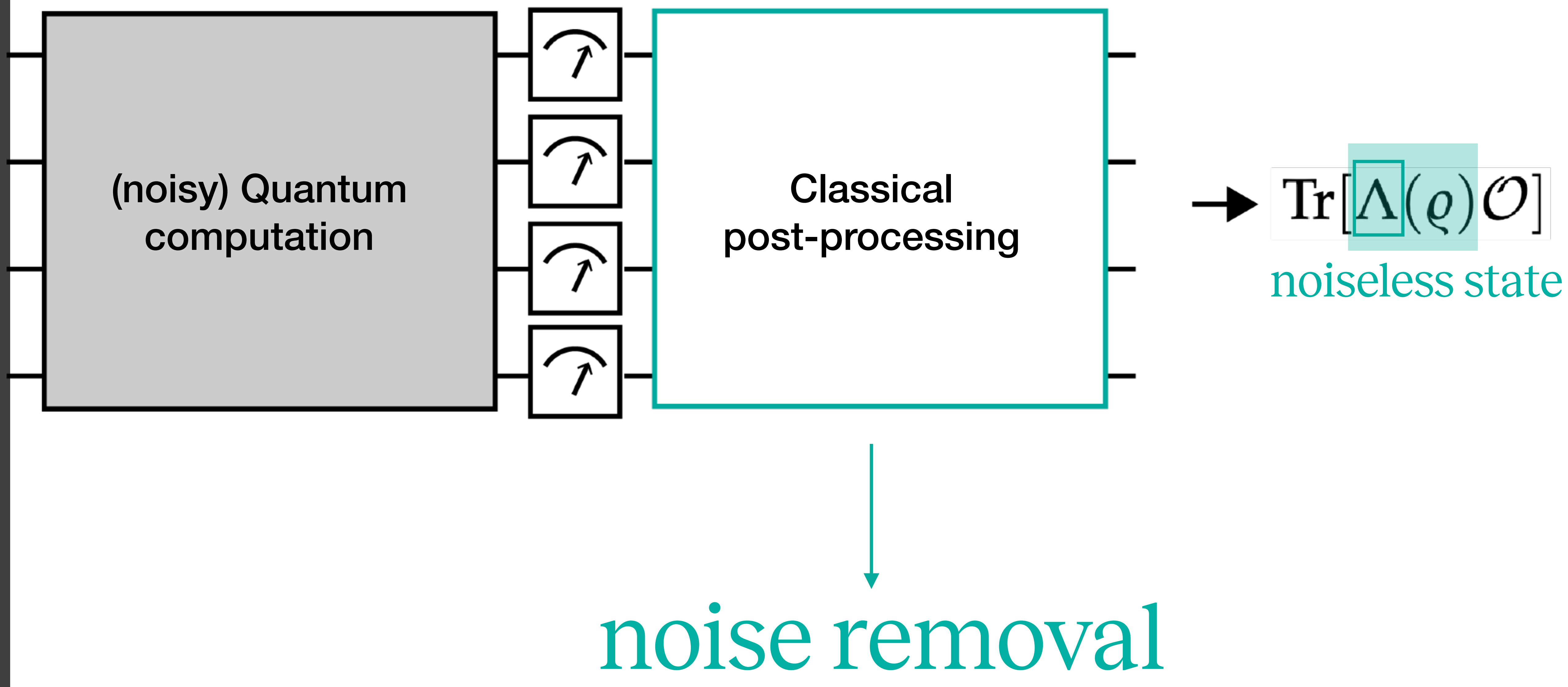
ZNE-PEA

The ZNE-PEA intentionally increases the strength of the characterised noise by sampling gates from a true probability distribution, thus avoiding the measurement overhead but suffering from a potential bias in the estimated quantities and extrapolation instabilities for large circuit depths.

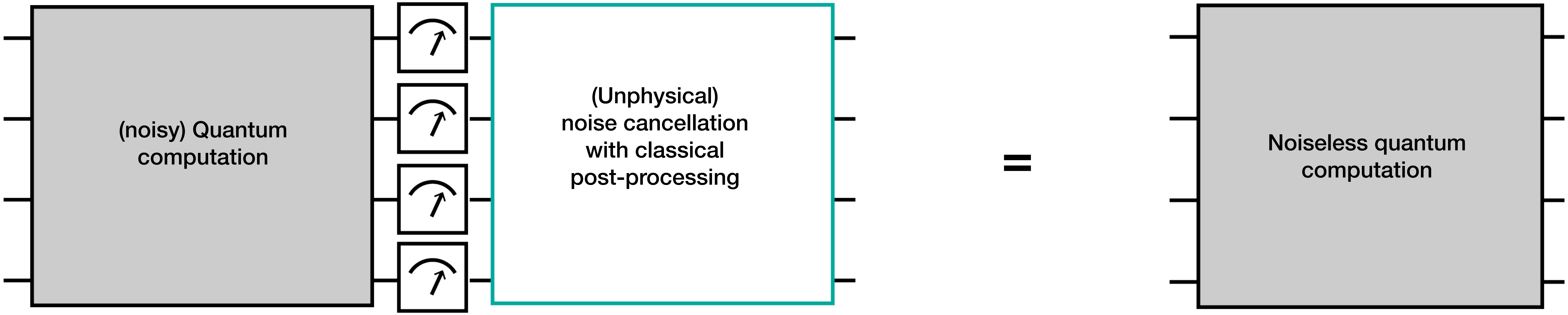
Y. Kim, A. Eddins, S. Anand, K. X. Wei, E. Van Den Berg, S. Rosenblatt, H. Nayfeh, Y. Wu, M. Zale, K. Temme, et al., Nature 618, 500 (2023).

The goal - the Algo way

estimate physical properties of a modified state corresponding to the result of a virtual transformation applied on the state of a quantum processor

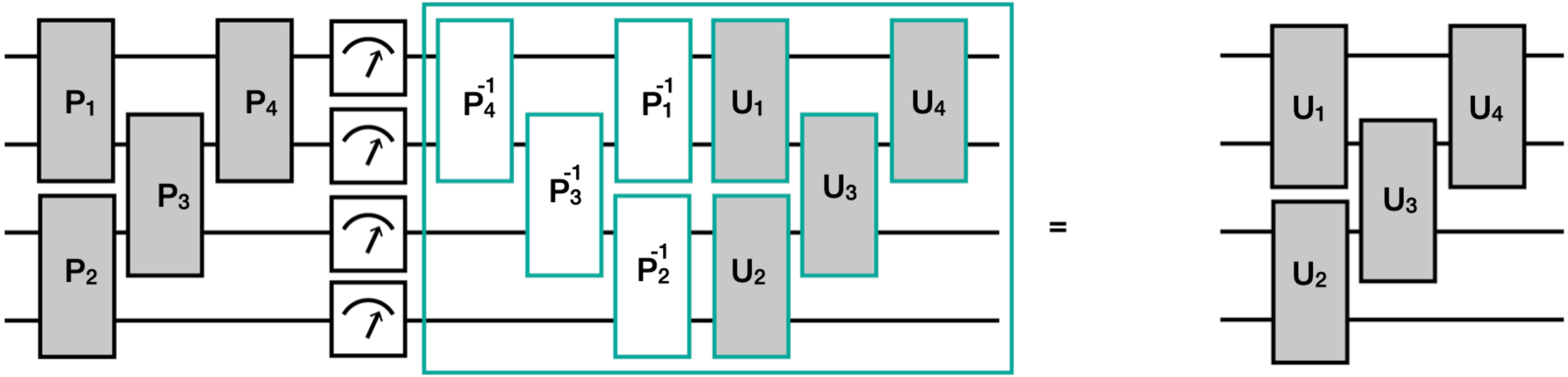


algorithmiq



Noise mitigation

Characterised noise



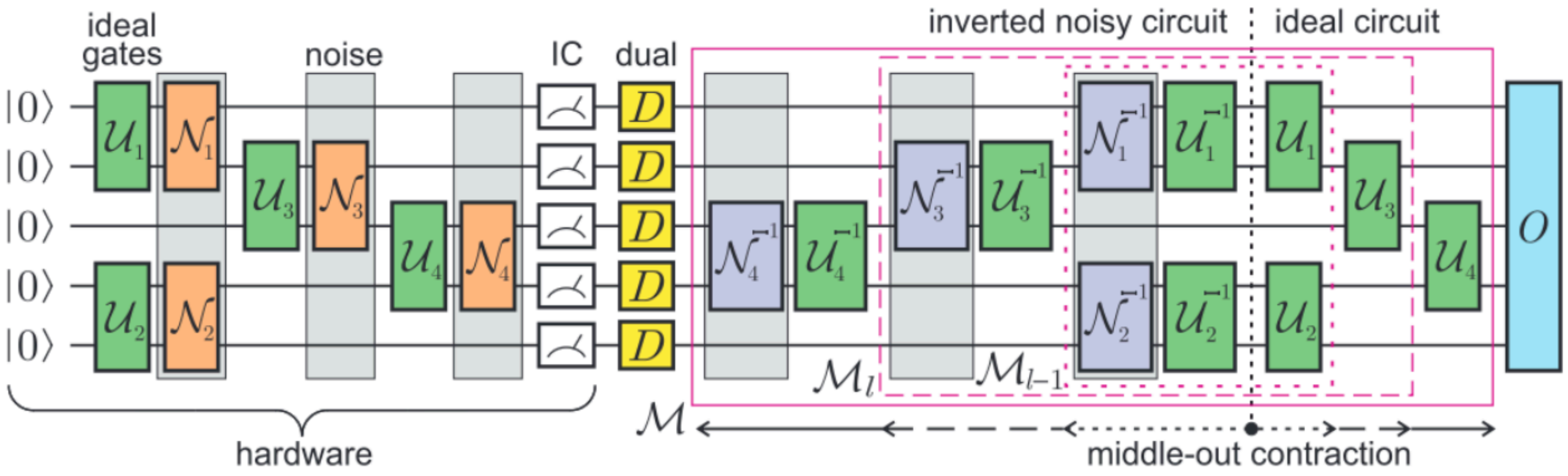
Key idea:
Find an efficient representation of this map and apply it in post-processing

Ideal circuit

Noise mitigation

Characterised noise

algorithmiq

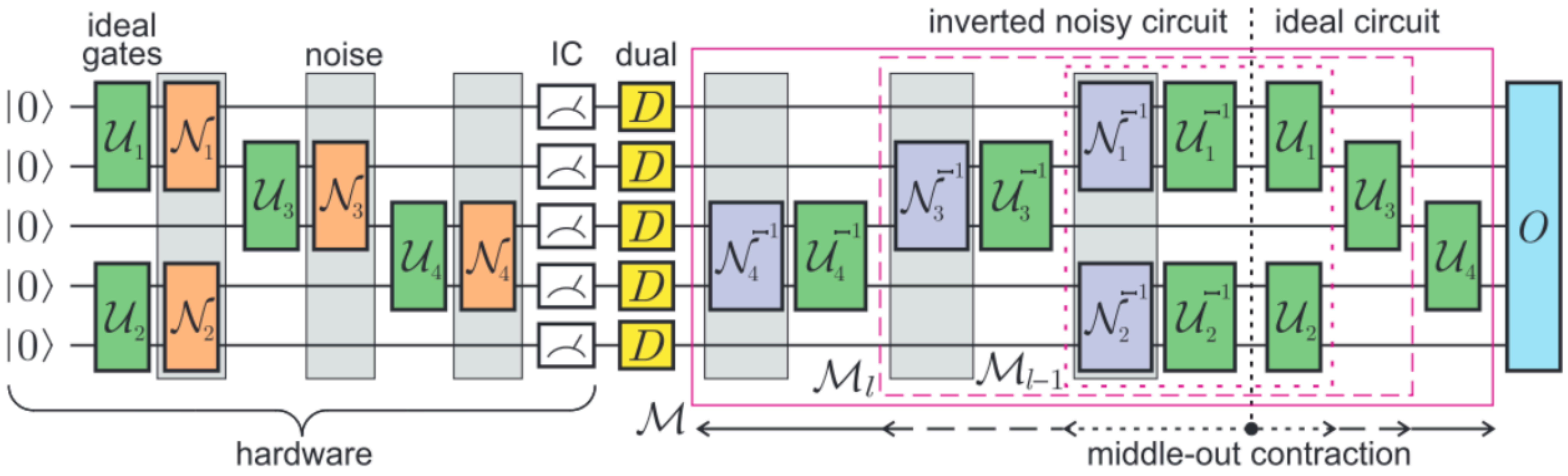


TEM - noise mitigation

Characterised noise

algorithmiq

arXiv:2307.11740



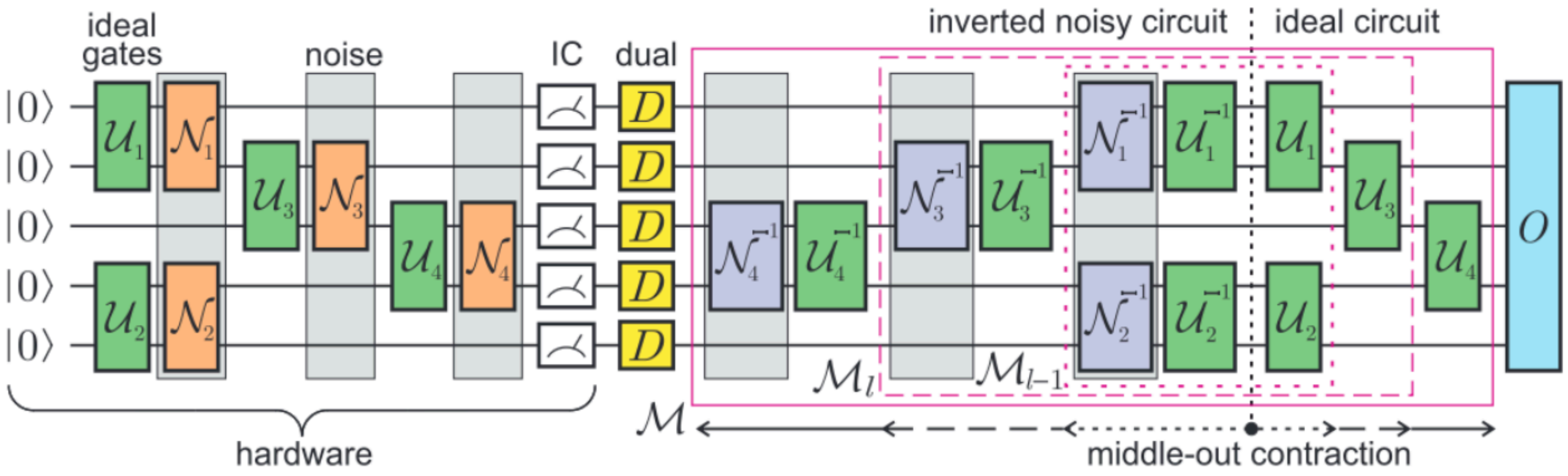
Noise mitigation map in software post-processing
(in contrast to hardware-based PEC)

TEM - noise mitigation

Characterised noise

arXiv:2307.11740

algorithmiq



Noise mitigation map in software post-processing (in contrast to hardware-based PEC)

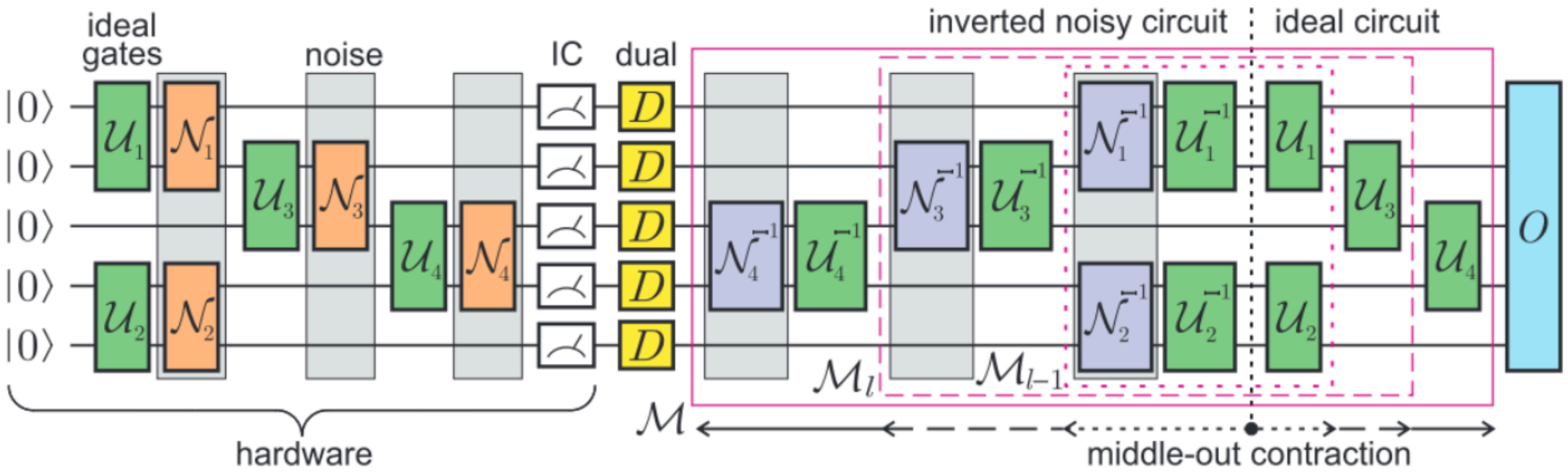
Scalable TN techniques capture cancellation effects for unitaries and their inverses

TEM - noise mitigation

arXiv:2307.11740

Characterised noise

algorithmiq



Noise mitigation map in software post-processing
(in contrast to hardware-based PEC)

Scalable TN techniques capture cancellation effects for unitaries and their inverses

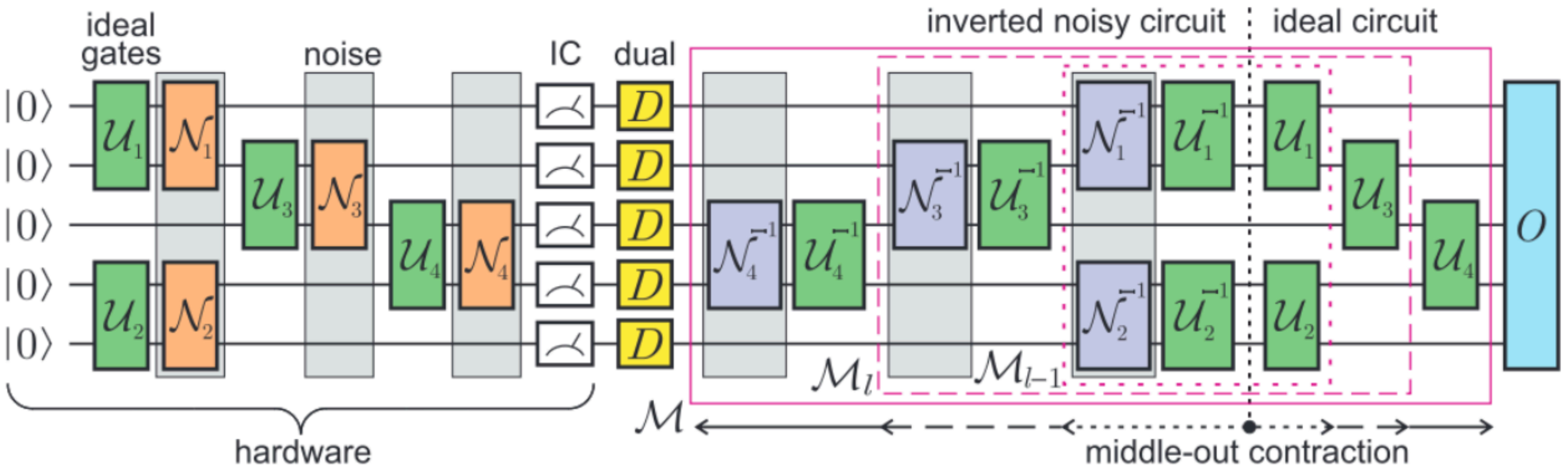
Requires IC data obtained with POVMs

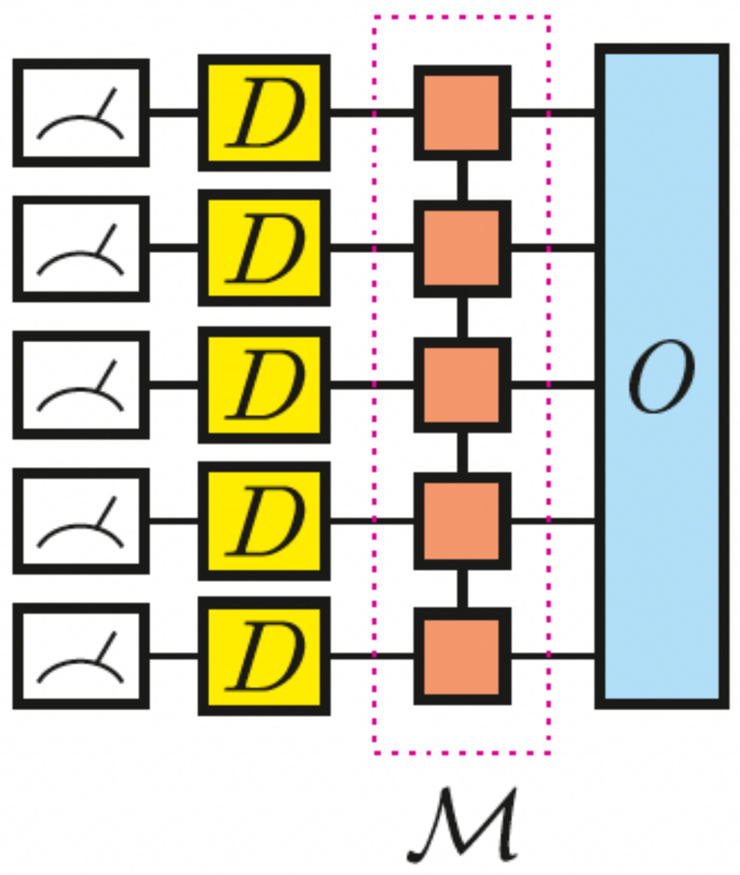
TEM - noise mitigation

Characterised noise

arXiv:2307.11740

algorithmiq

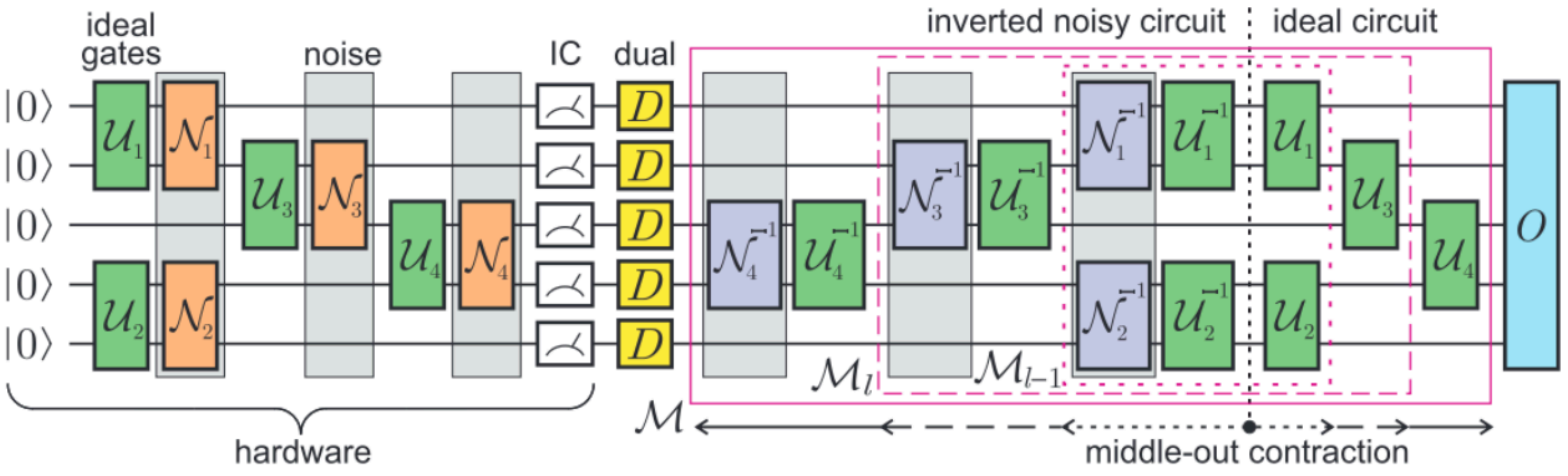


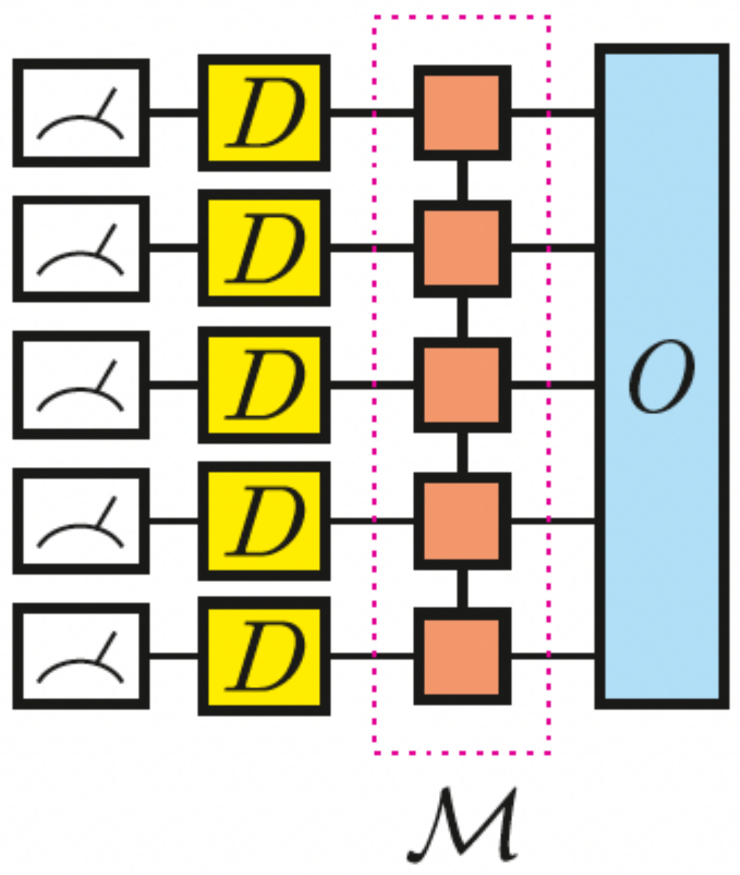


TEM - noise mitigation

arXiv:2307.11740

Characterised noise





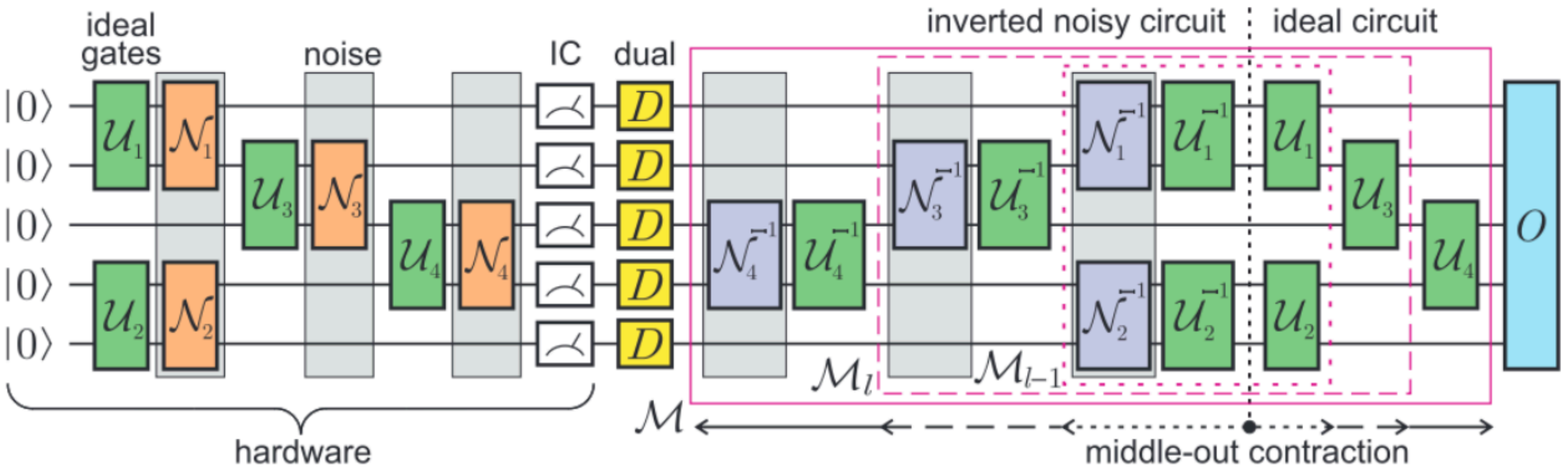
TEM uses a compact description of the noise map given, e.g., in the form of the one-dimensional tensor network with topology of the locally-purified density operator (matrix product channel).

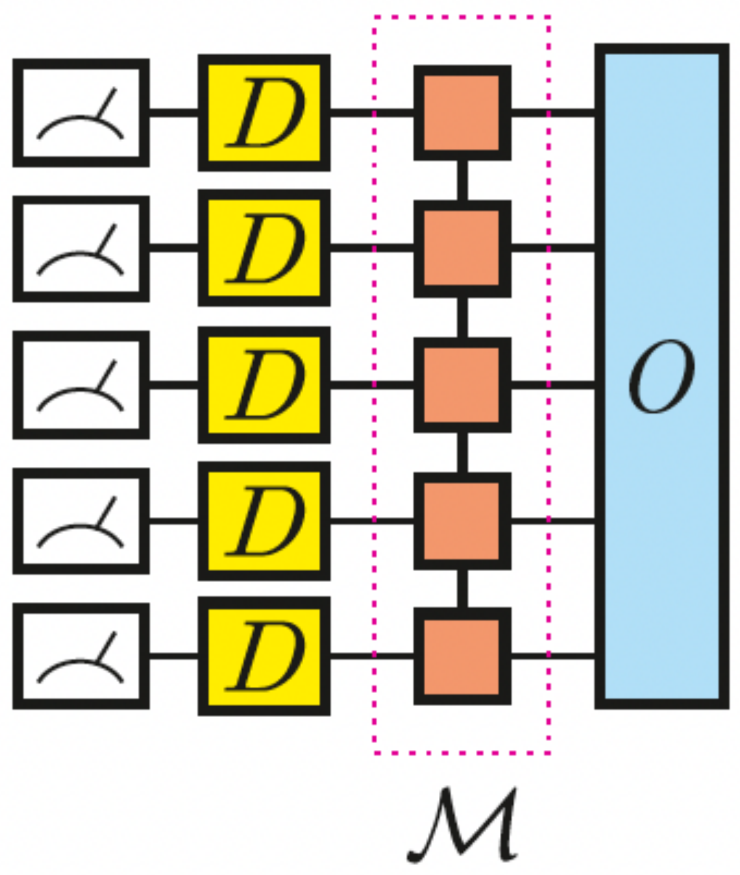
TEM - noise mitigation

Characterised noise

arXiv:2307.11740

algorithmiq





TEM uses a compact description of the noise map given, e.g., in the form of the one-dimensional tensor network with topology of the locally-purified density operator (matrix product channel).

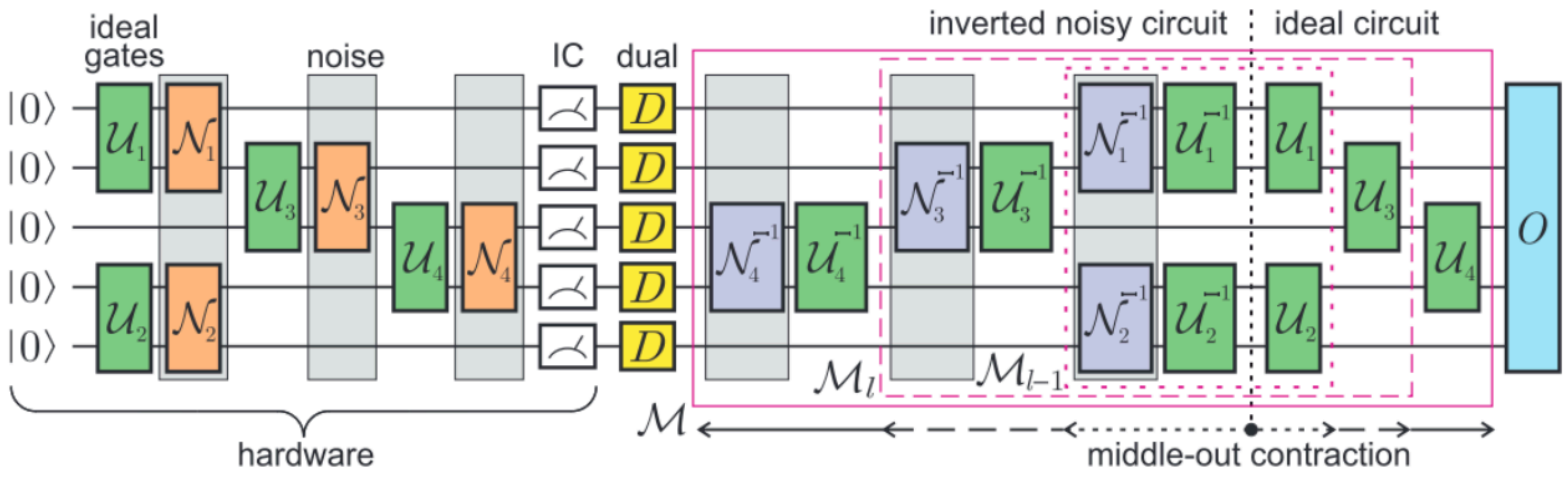
Key requirement is that the inverse map has a compact tensor network representation with a modest bond dimension.

TEM - noise mitigation

arXiv:2307.11740

Characterised noise

algorithmiq



Measurement overhead:

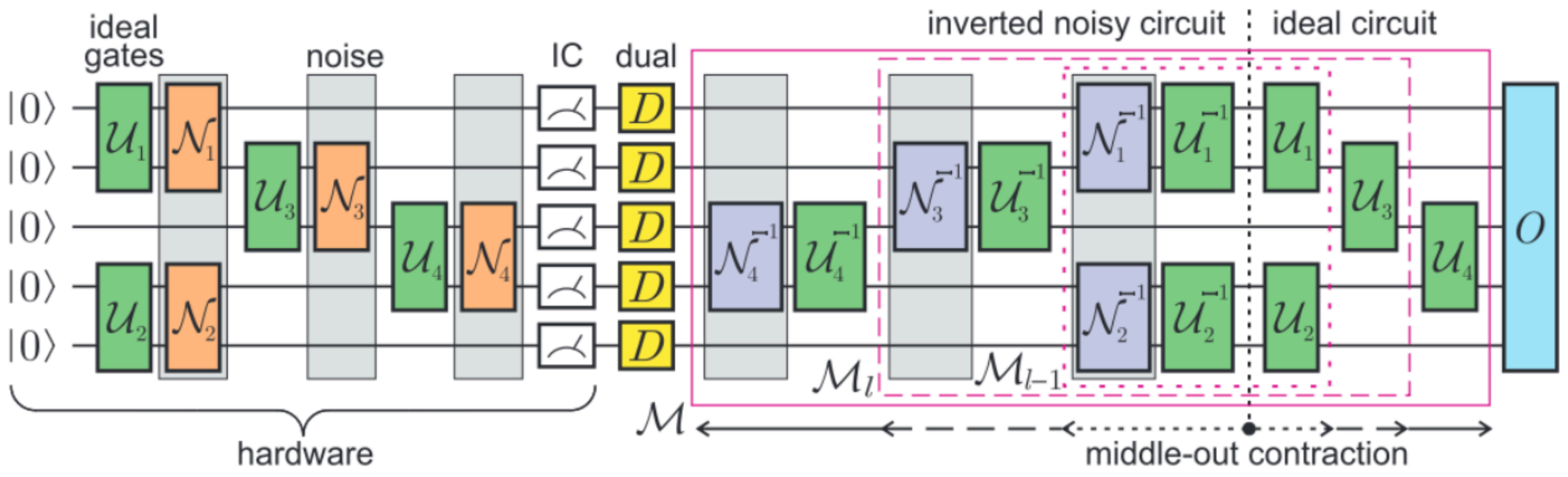
$$\gamma^2 = \frac{N_{\text{moreshots}}}{N_{\text{shots}}} = \frac{(\Delta E)^2_{\text{mitigated}}}{(\Delta E)^2_{\text{noisy}}}$$

TEM - noise mitigation

arXiv:2307.11740

Characterised noise

algorithmiq



Measurement overhead:

$$\gamma^2 = \frac{N_{\text{moreshots}}}{N_{\text{shots}}} = \frac{(\Delta E)^2_{\text{mitigated}}}{(\Delta E)^2_{\text{noisy}}}$$

Quadratic speed-up
in getting the same precision!

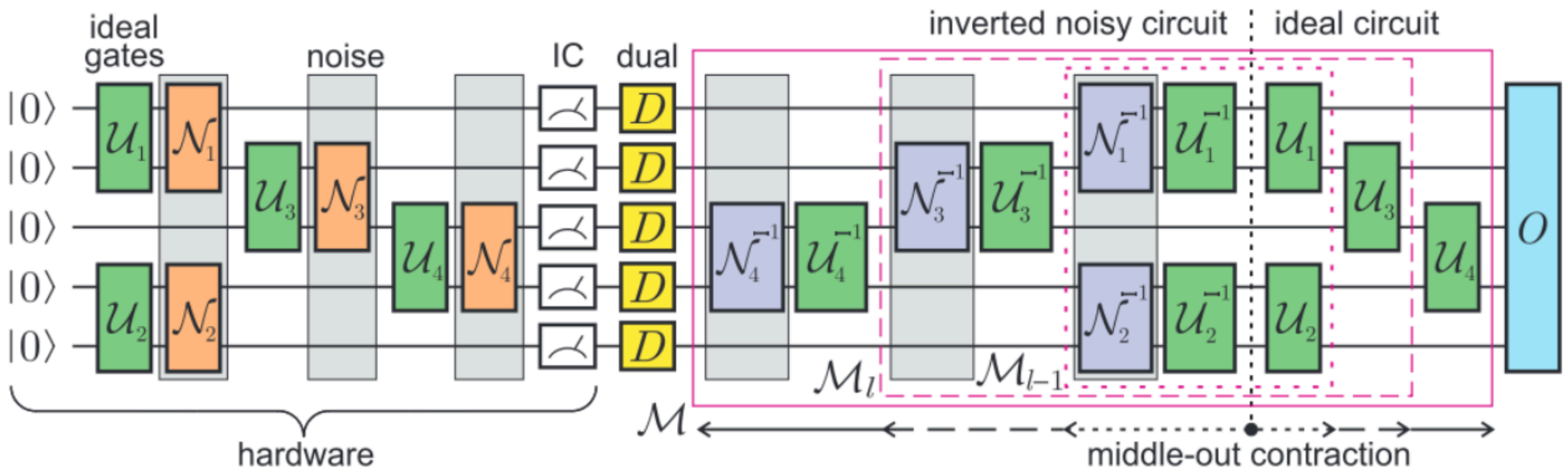
$$\gamma_{\text{TN}} = \sqrt{\gamma_{\text{PEC}}}$$

TEM - noise mitigation

arXiv:2307.11740

Characterised noise

algorithmiq

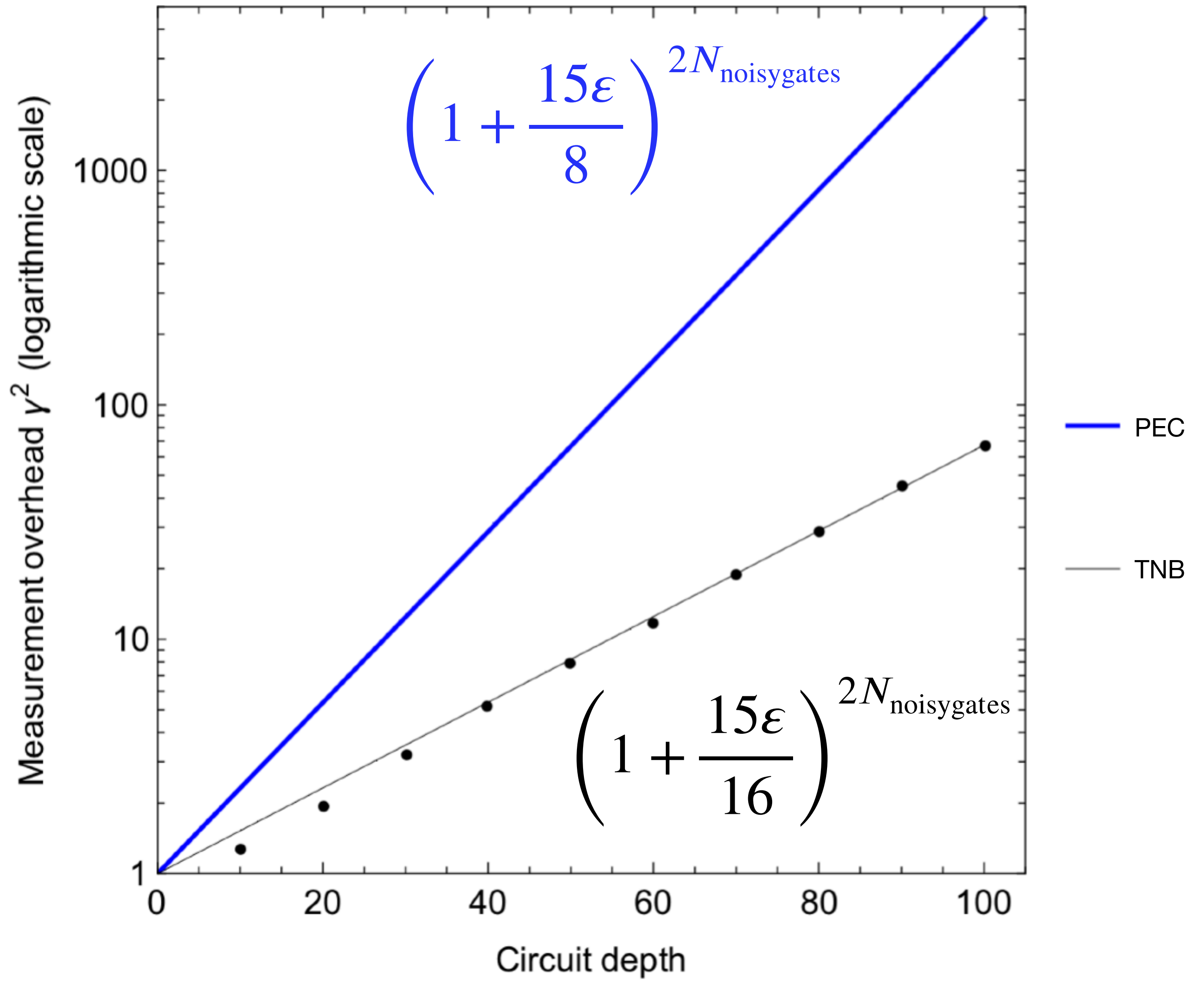


Measurement overhead:

$$\gamma^2 = \frac{N_{\text{moreshots}}}{N_{\text{shots}}} = \frac{(\Delta E)^2_{\text{mitigated}}}{(\Delta E)^2_{\text{noisy}}}$$

Quadratic speed-up
in getting the same precision!

$$\gamma_{\text{TN}} = \sqrt{\gamma_{\text{PEC}}}$$



Example: Theory and numerical experiments
for 2-local depolarising noise with param. ε

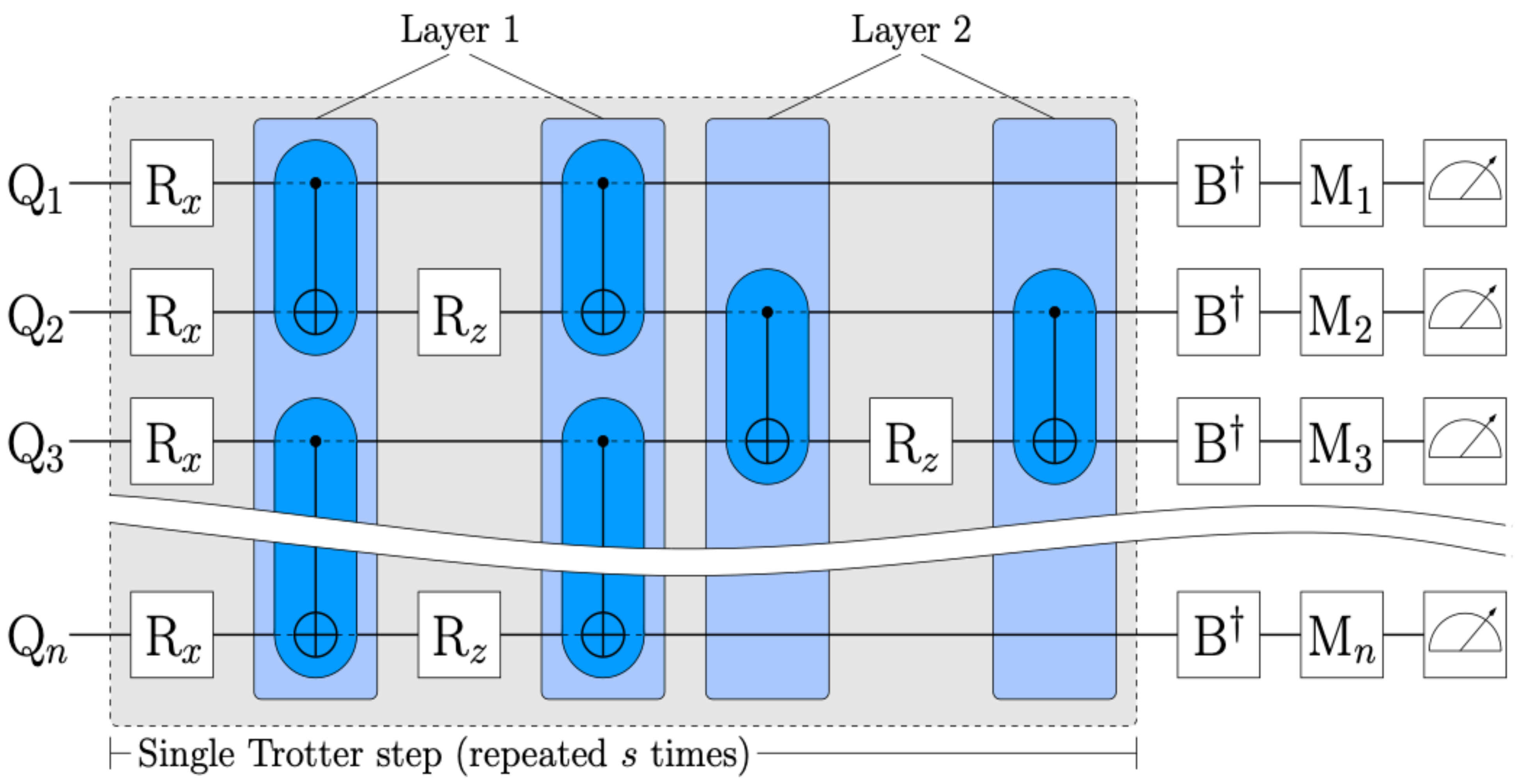
TEM - noise mitigation

arXiv:2307.11740

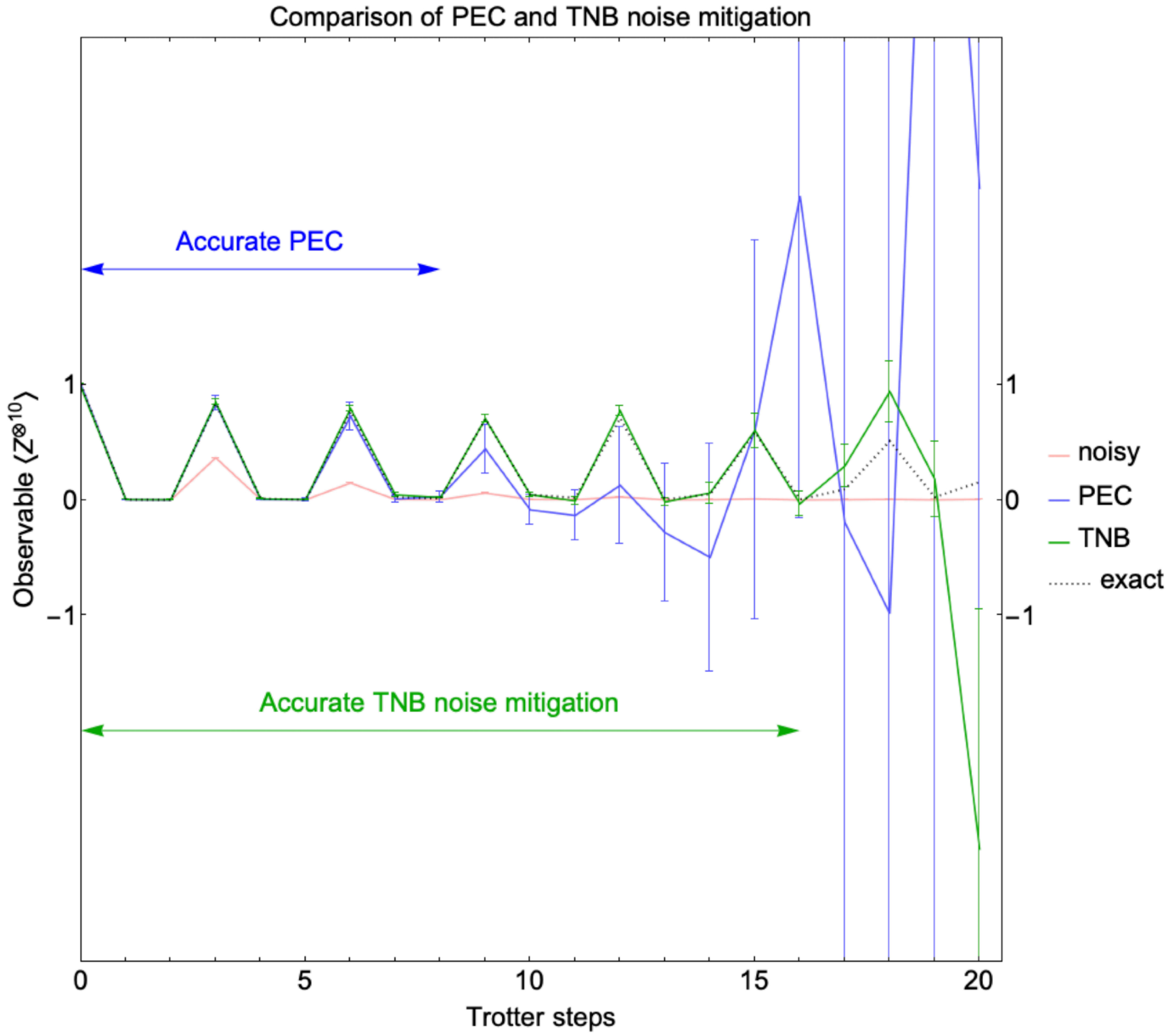
Characterised noise

algorithmiq

Trotter dynamics of a spin chain in TFI model, $O = Z \ldots Z$



E. van den Berg, Z.K. Minev, A. Kandala, K. Temme. *Nat. Phys.* (2023)



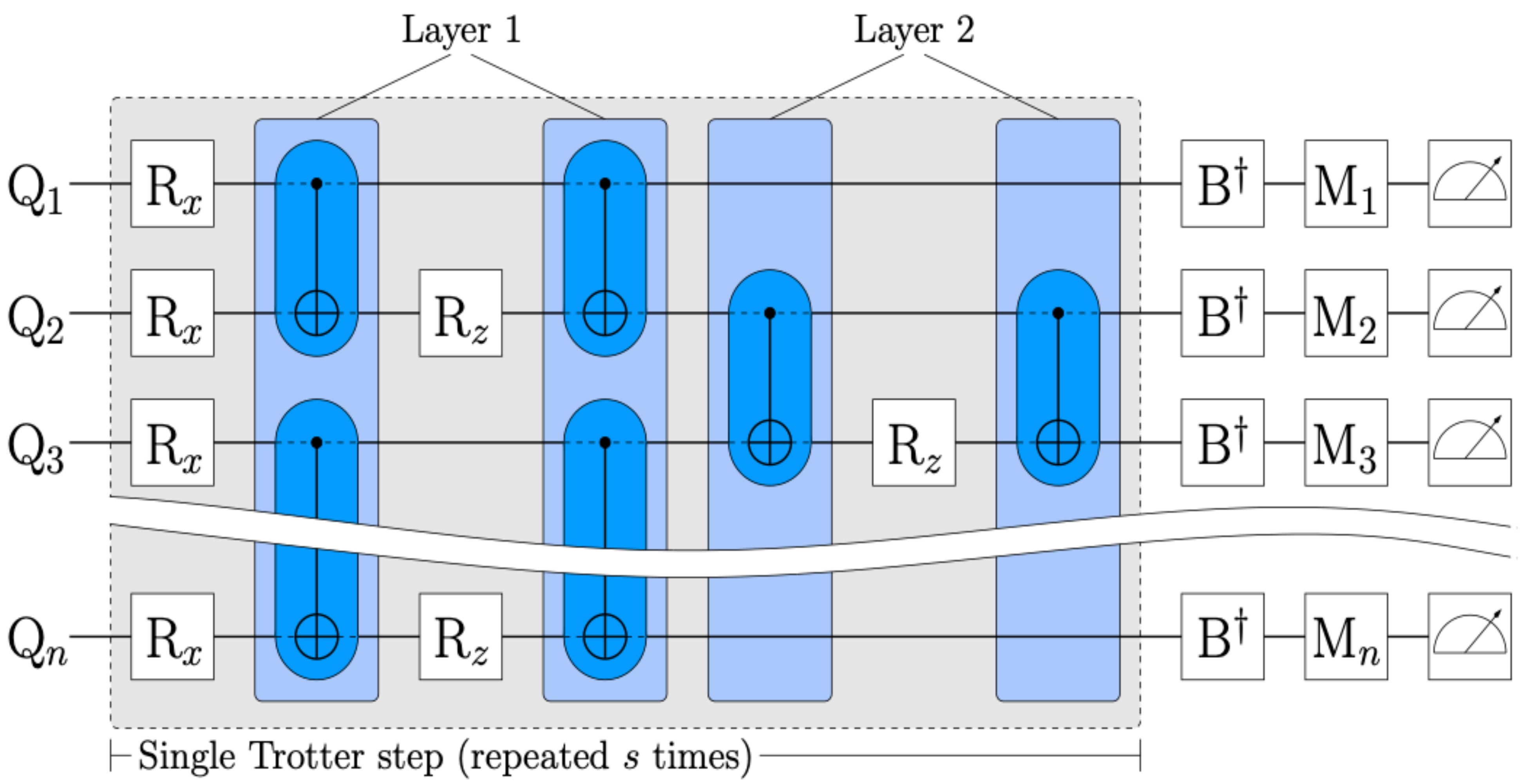
TEM - noise mitigation

Characterised noise

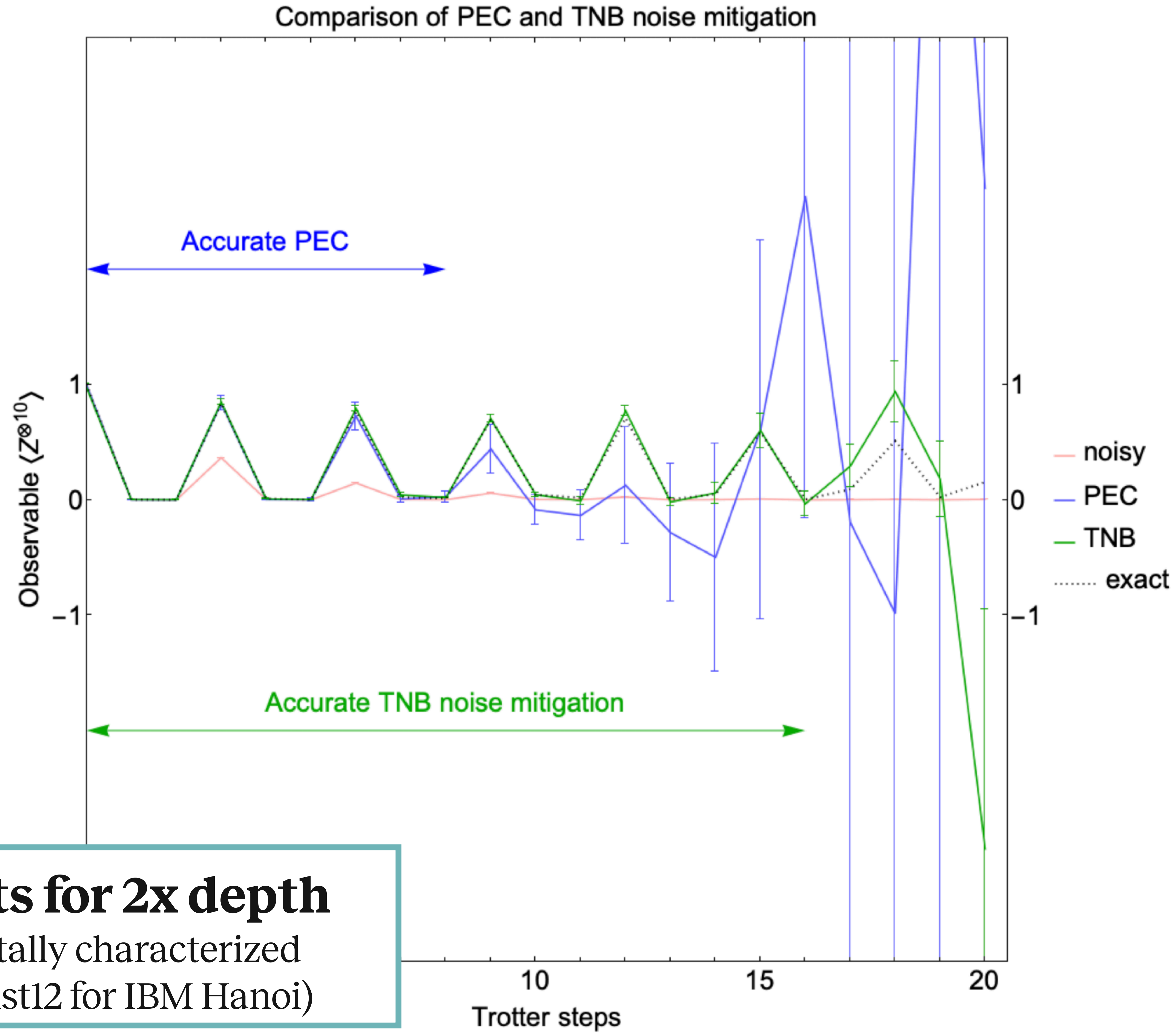
algorithmiq

arXiv:2307.11740

Trotter dynamics of a spin chain in TFI model, $O = Z \ldots Z$



E. van den Berg, Z.K. Minev, A. Kandala, K. Temme. *Nat. Phys.* (2023)



Reliable results for 2x depth
(with the experimentally characterized noise for 10 qubits: inst12 for IBM Hanoi)

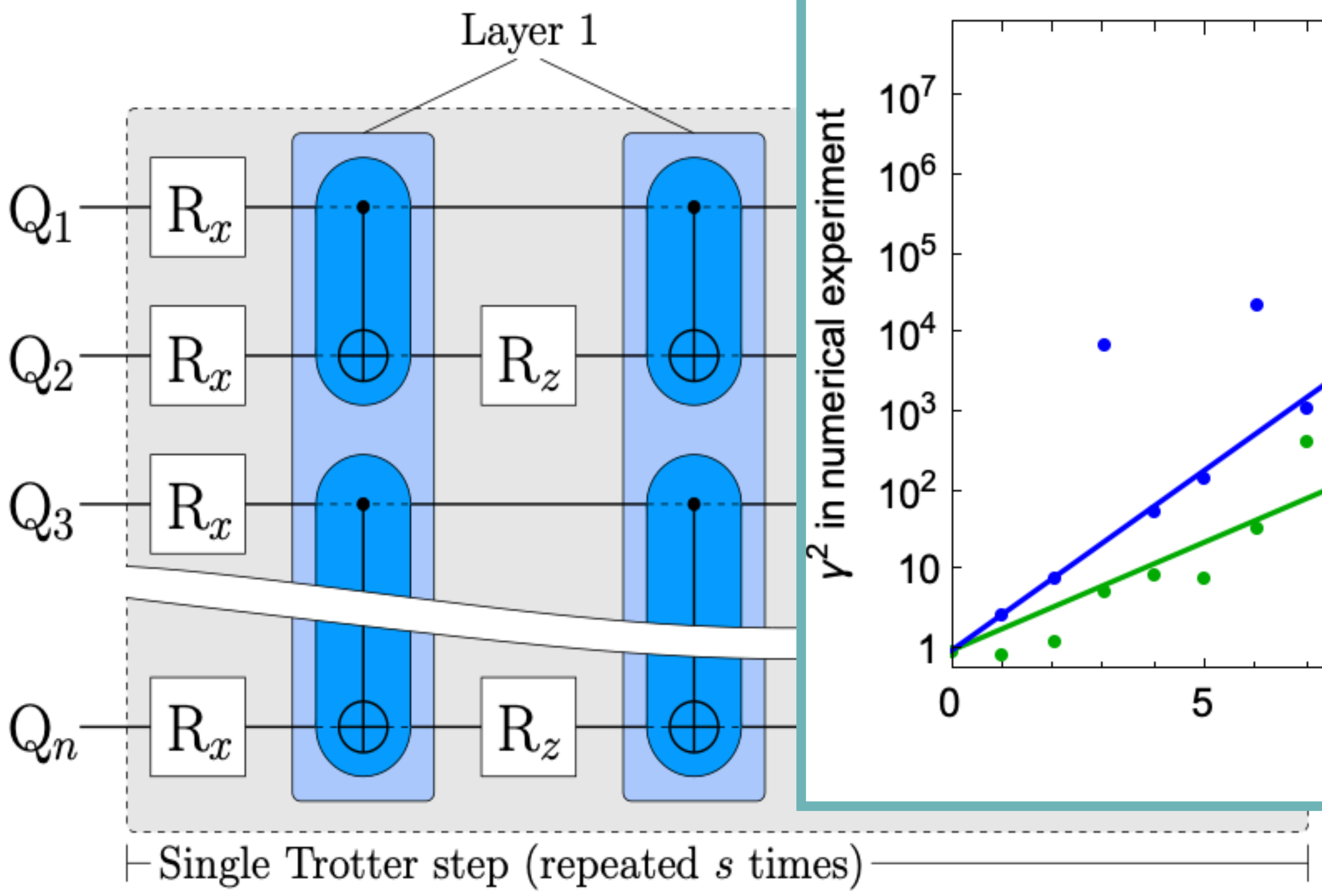
TEM - noise mitigation

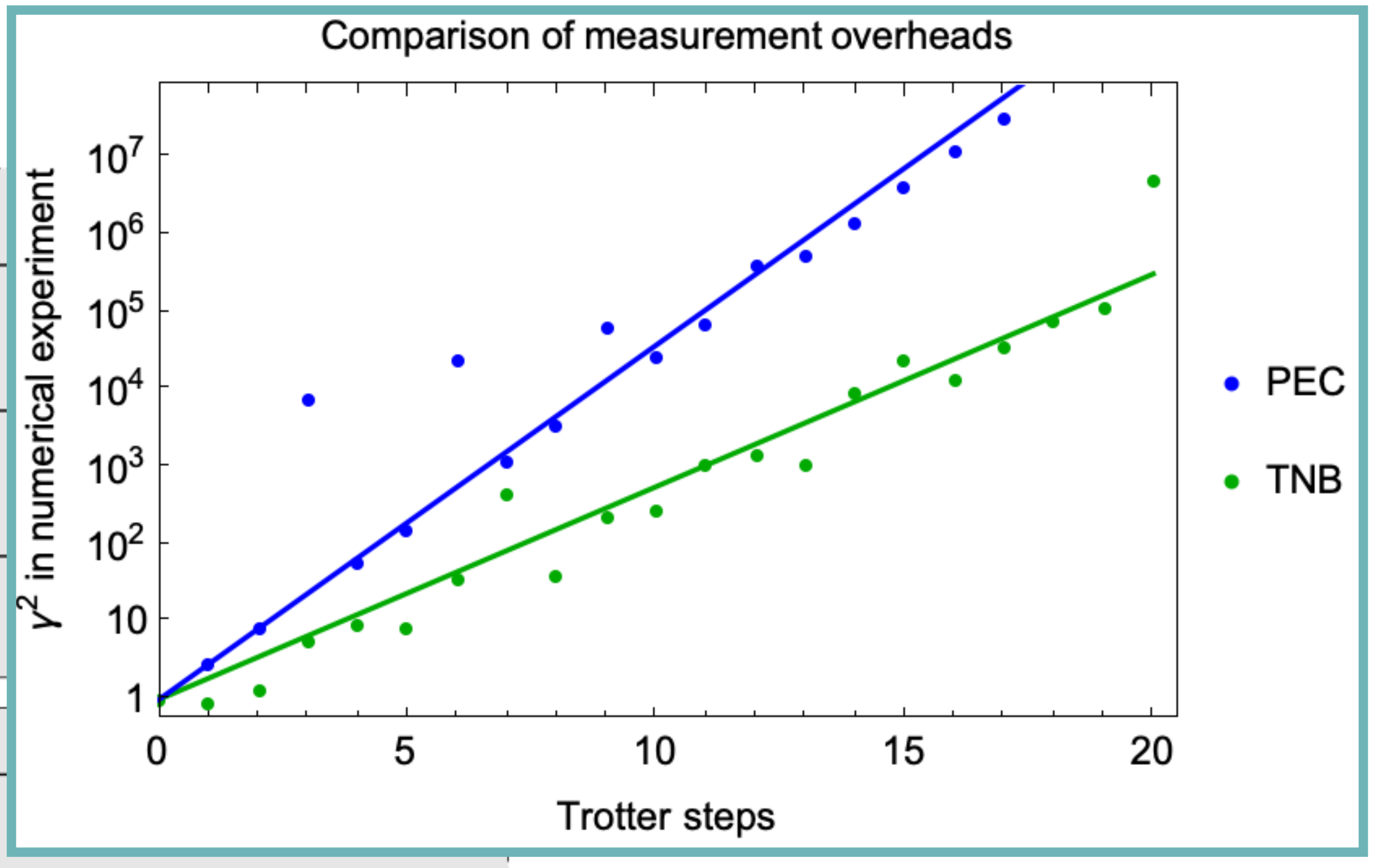
Characterised noise

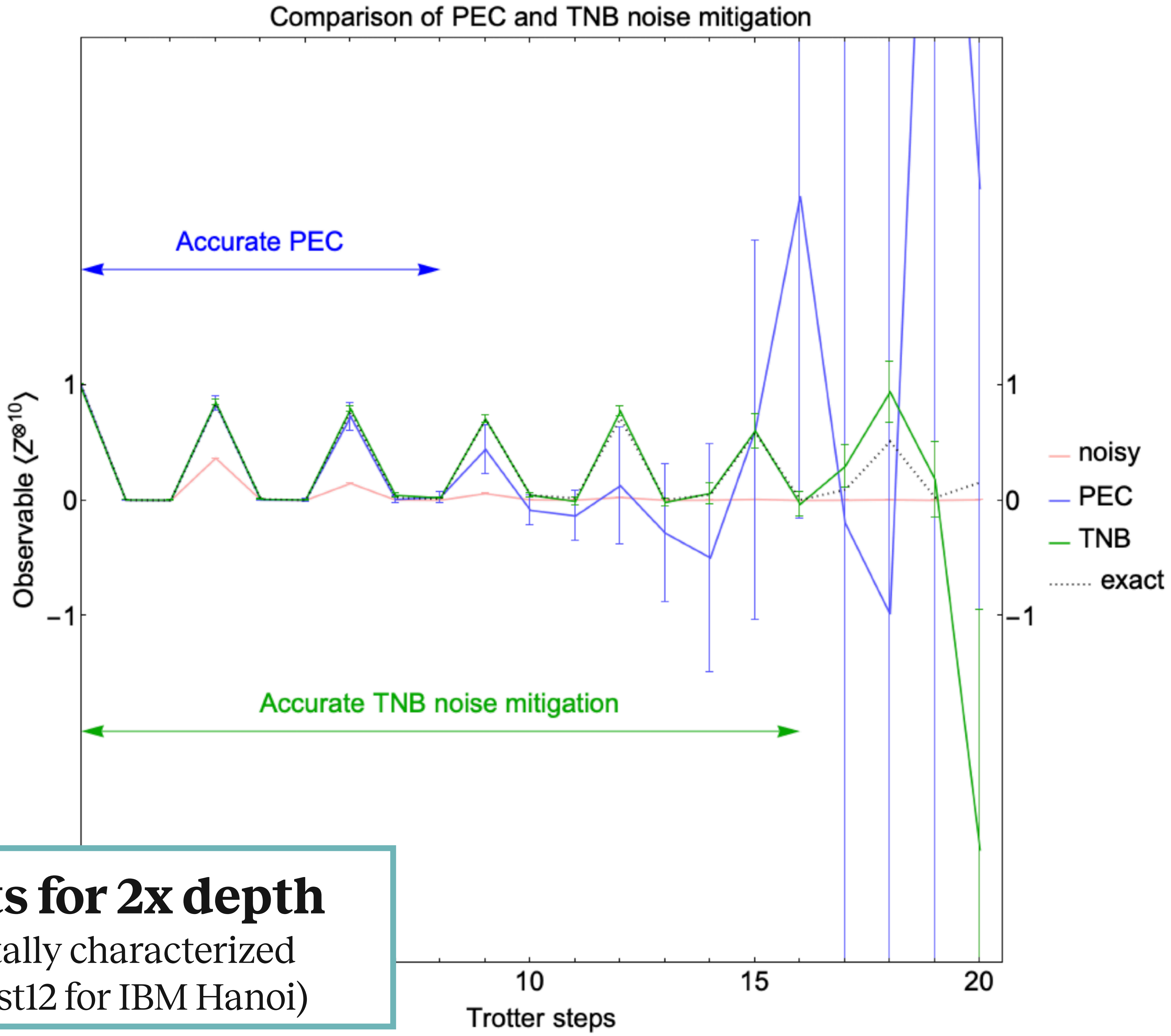
algorithmiq

arXiv:2307.11740

Trotter dynamics of a spin chain in TFI model, $O = Z \ldots Z$







Reliable results for 2x depth
(with the experimentally characterized noise for 10 qubits: inst12 for IBM Hanoi)

E. van den Berg, Z.K. Minev, A. Kandala, K. Temme. *Nat. Phys.* (2023)

TEM - noise mitigation

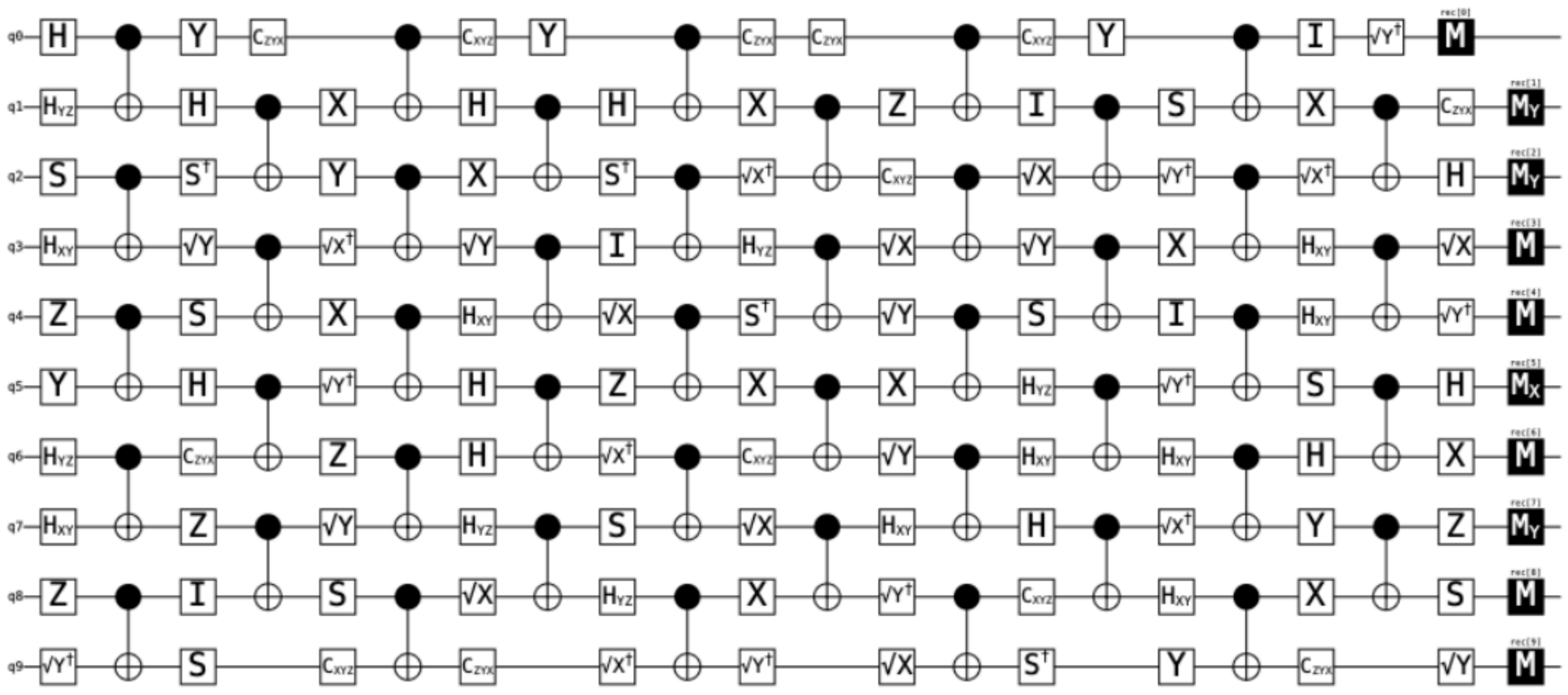
Characterised noise

algorithmiq

arXiv:2307.11740

100×100: IC-TEM outperforms ZNE and PEC

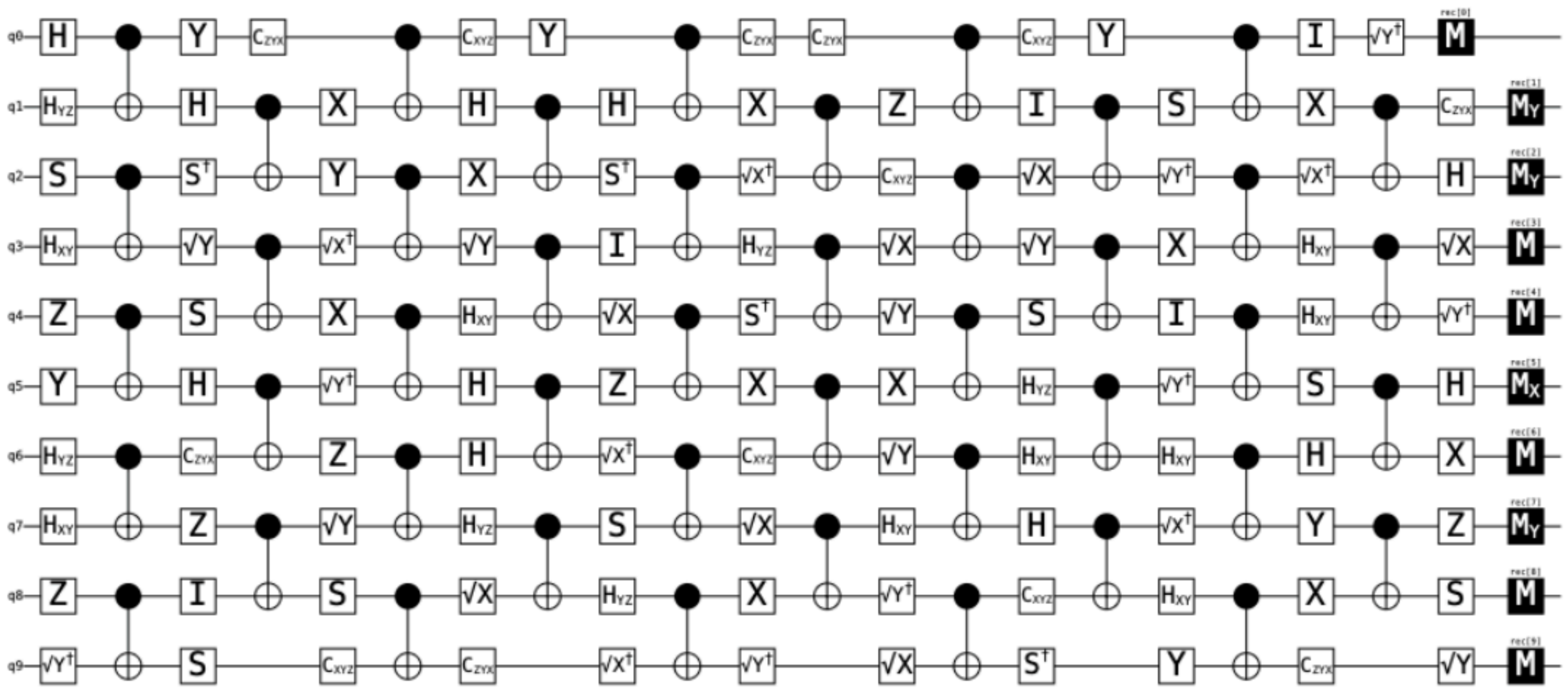
The example:



Circuit is an N-qubit brickwork of random unitary Clifford gates and noisy CNOT gates (with error rate ε)

100×100: IC-TEM outperforms ZNE and PEC

The example:



Circuit is an N-qubit brickwork of random unitary Clifford gates and noisy CNOT gates (with error rate ε)

Sparse Pauli-Lindblad noise with cross-talk, the effective noise per qubit 0.00091

TEM - noise mitigation

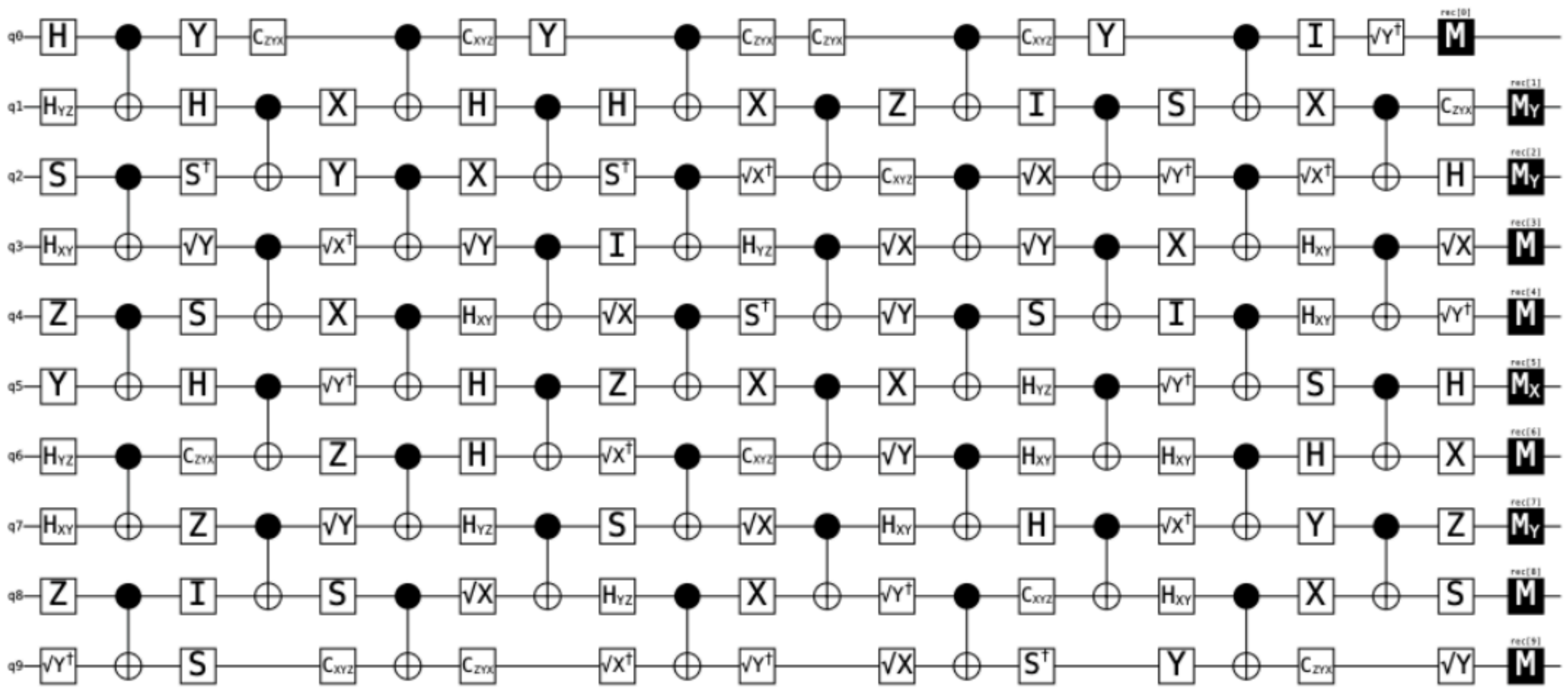
100 x 100 Challenge

algorithmiq

arXiv:2307.11740

100×100: IC-TEM outperforms ZNE and PEC

The example:



Circuit is an N-qubit brickwork of random unitary Clifford gates and noisy CNOT gates (with error rate ε)

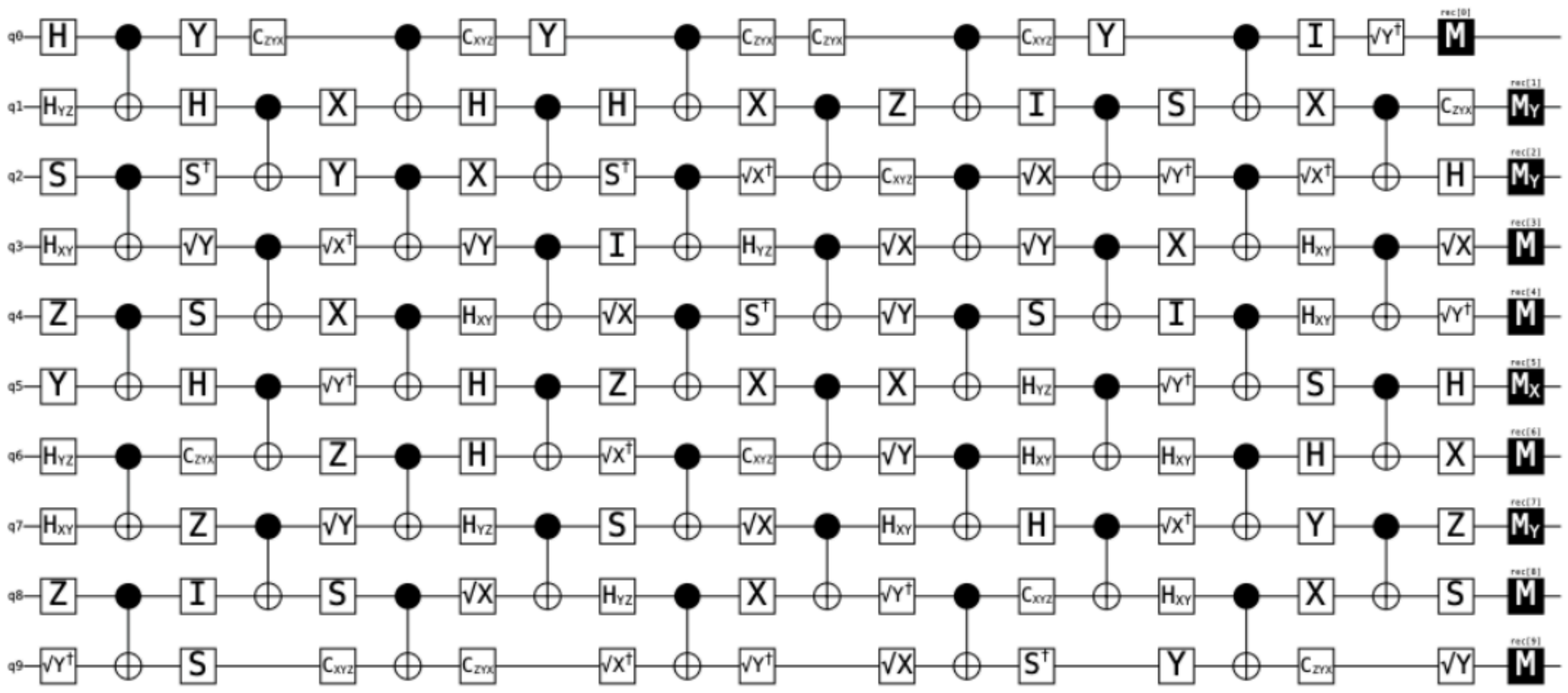
Sparse Pauli-Lindblad noise with cross-talk, the effective noise per qubit 0.00091

N=100 qubits and depth up to L=100.
300,000 shots per data point in TEM and PEC
(in ZNE 300,000 shots per each of three noise gains G=1.0, 1.2, 1.6)

arXiv:2307.11740

100×100: IC-TEM outperforms ZNE and PEC

The example:



Circuit is an N-qubit brickwork of random unitary Clifford gates and noisy CNOT gates (with error rate ε)

Sparse Pauli-Lindblad noise with cross-talk, the effective noise per qubit 0.00091

N=100 qubits and depth up to L=100.
300,000 shots per data point in TEM and PEC
(in ZNE 300,000 shots per each of three noise gains G=1.0, 1.2, 1.6)

Observable $O = UZ^{\otimes 100}U^{\dagger} = IXXYZXYIYYIYIYYYXXIIZZXIIIIIYYXZYZIYXYXZXIYZXXXIZIXZYZYXIYZYXIYXXZXYXYIYXIIYYIYIYIIXYIYZZXYIYZIYZIXZ$

TEM - noise mitigation

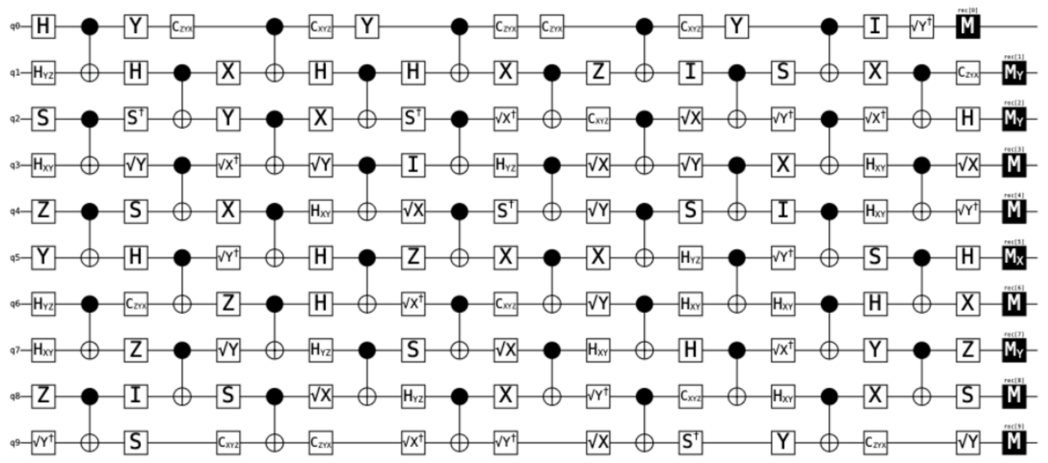
100 x 100 Challenge

algorithmiq

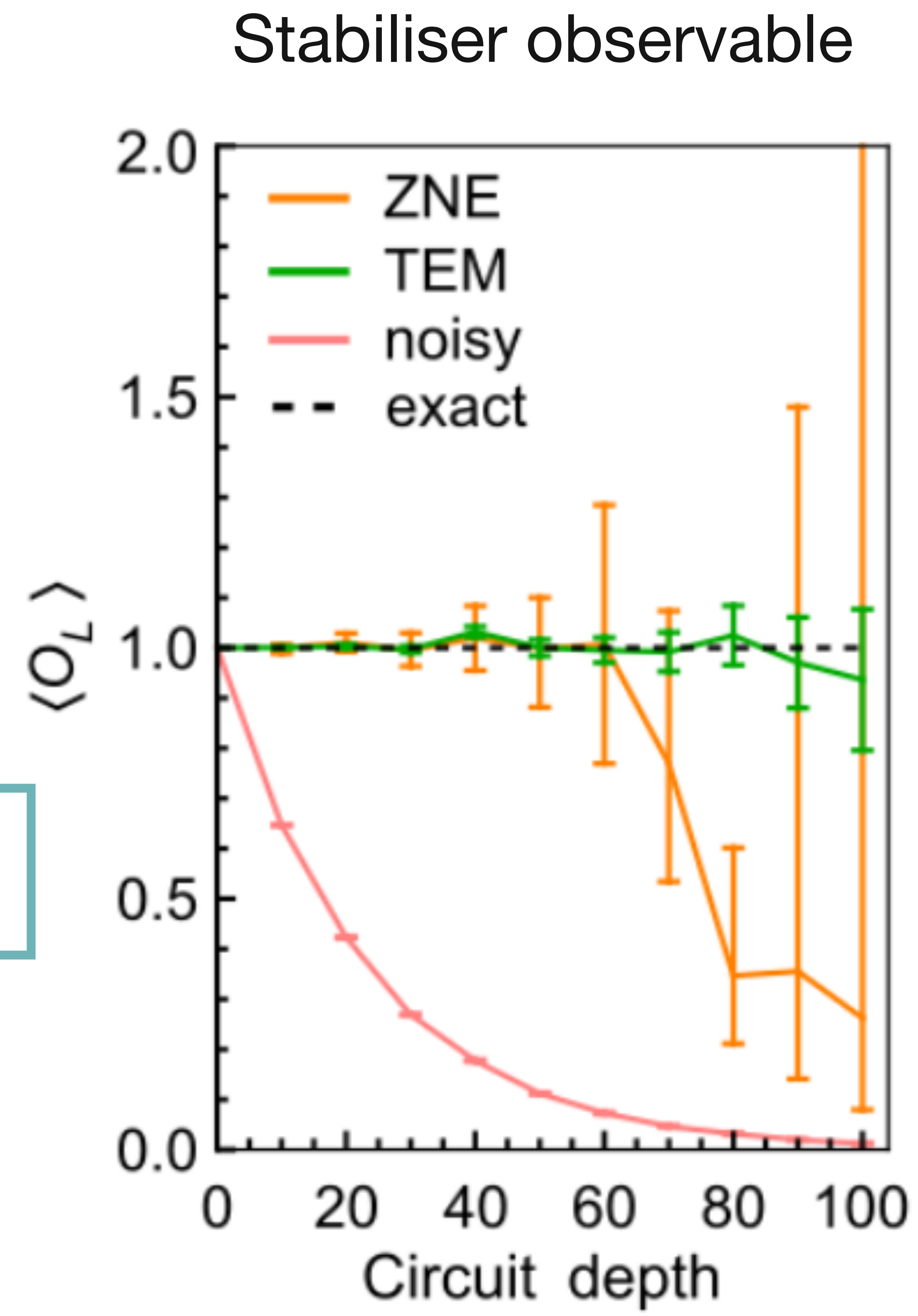
arXiv:2307.11740

100×100: IC-TEM outperforms ZNE and PEC

The example:



ZNE exhibits extrapolation instability due to vanishing noisy estimations:



TEM - noise mitigation

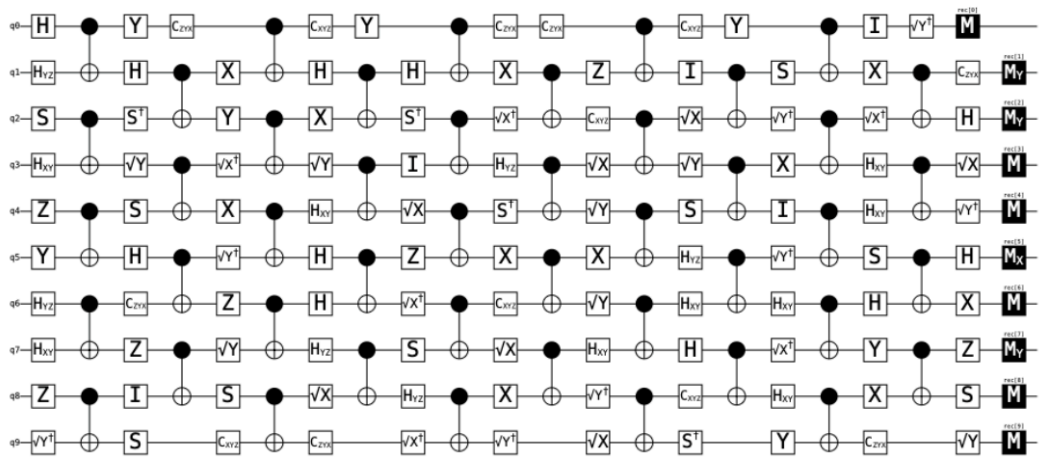
100 x 100 Challenge

algorithmiq

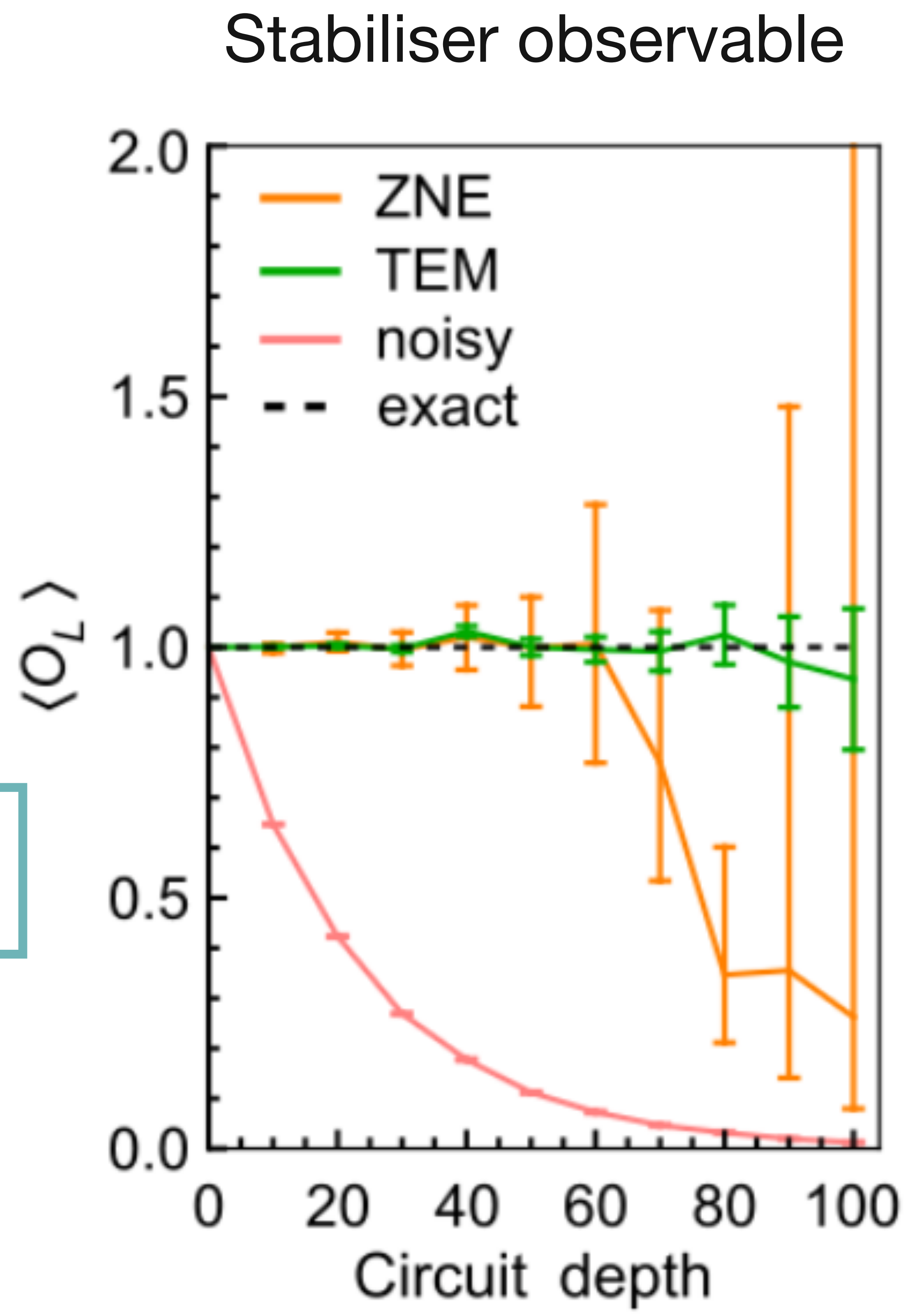
arXiv:2307.11740

100×100: IC-TEM outperforms ZNE and PEC

The example:

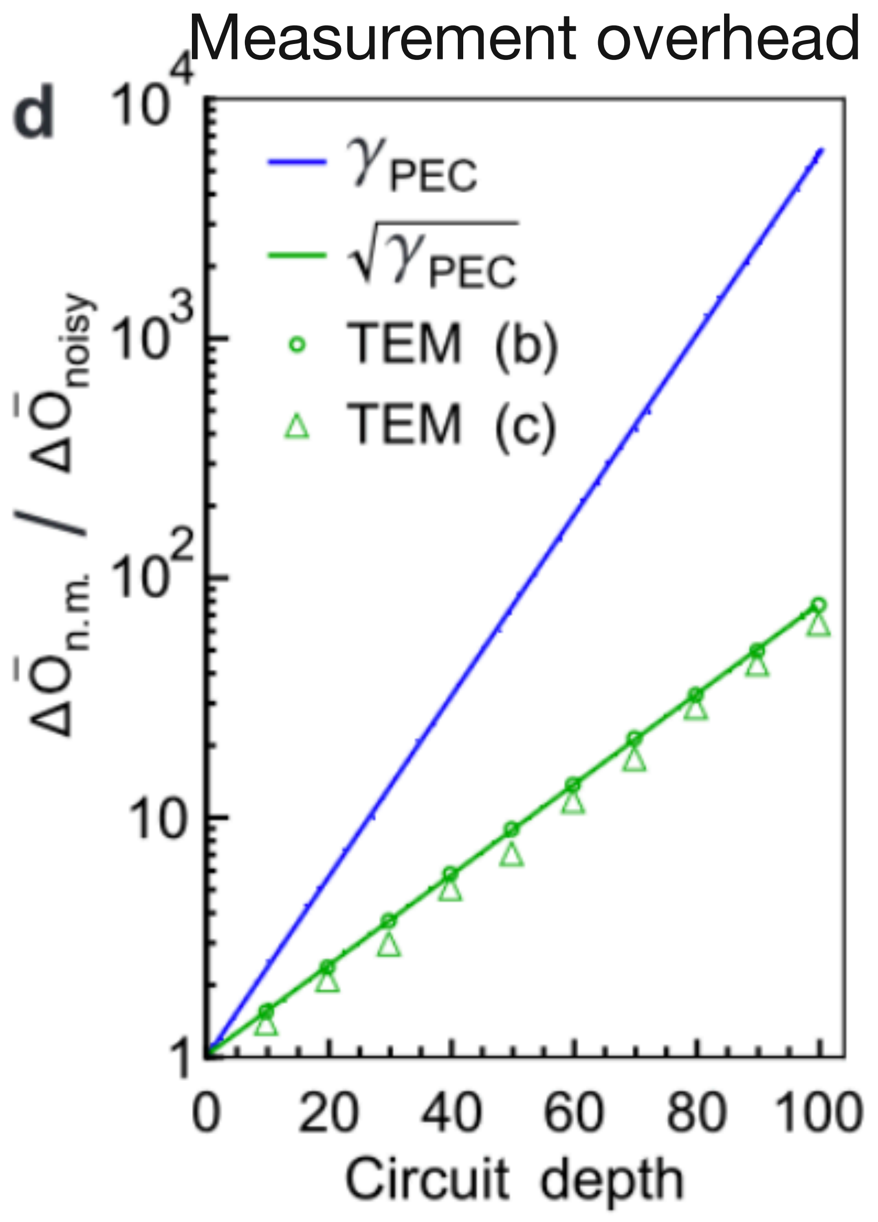


ZNE exhibits extrapolation instability due to vanishing noisy estimations:



Measurement overhead in PEC: $\gamma_{\mathrm{PEC}}^2 \sim 10^8$

Measurement overhead in TNB: $\gamma_{\mathrm{TEM}}^2 \sim 10^4$



Number of shots required by PEC to reach this accuracy: ~10^{11} (2.5 yrs @ 10^8 shots/day)

Postprocessing time with unoptimized code: ~60 h (44 CPUs from 2017, no GPU)

TEM - noise mitigation

100 x 100 Challenge

algorithmiq

arXiv:2307.11740

THANK YOU

algorithmiq