# EARLY FAULT-TOLERANT QUANTUM COMPUTING IN PRACTICE

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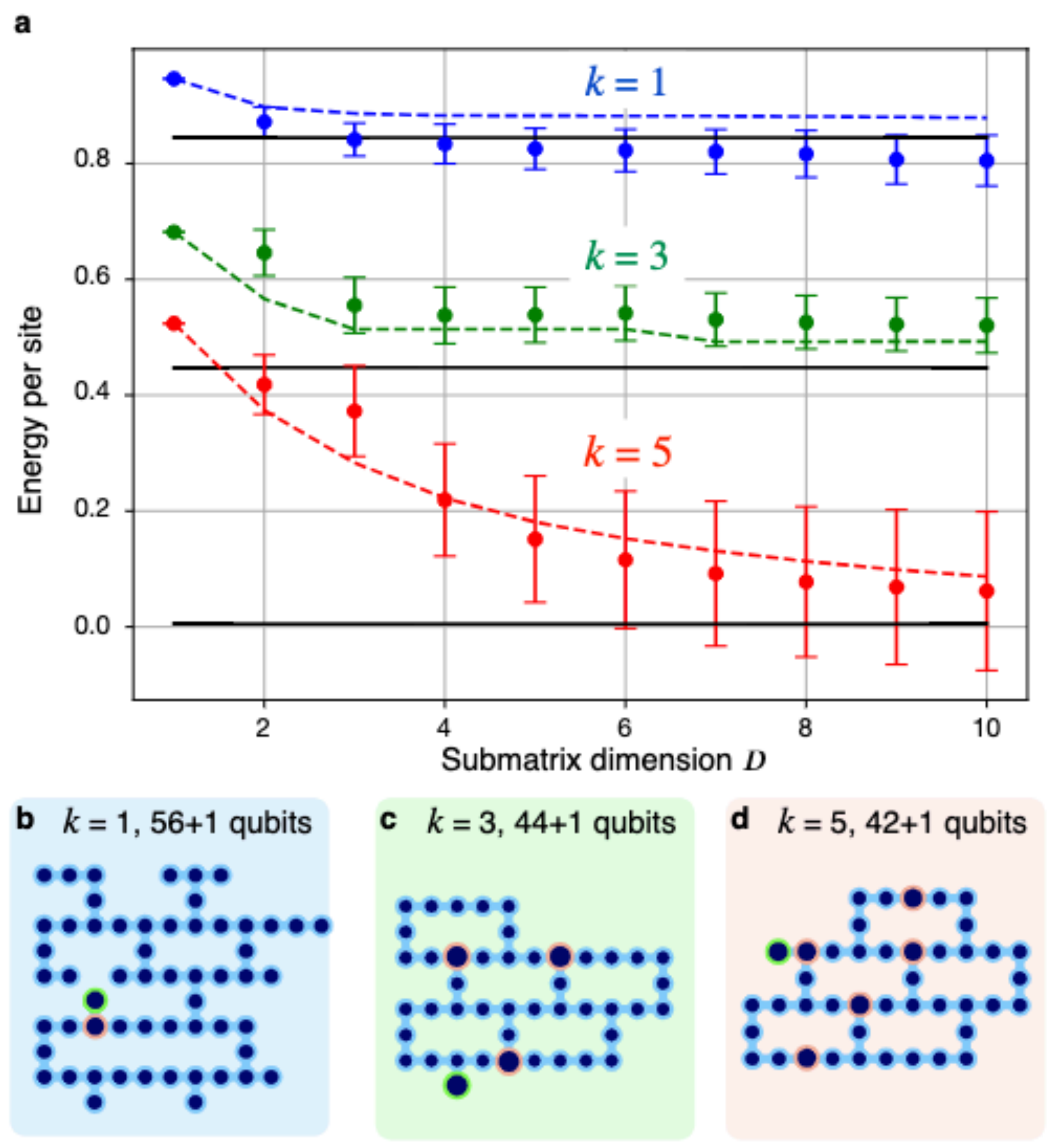
# Quantum computing x many-body problems

Our motivation: How can we advance many-body physics?

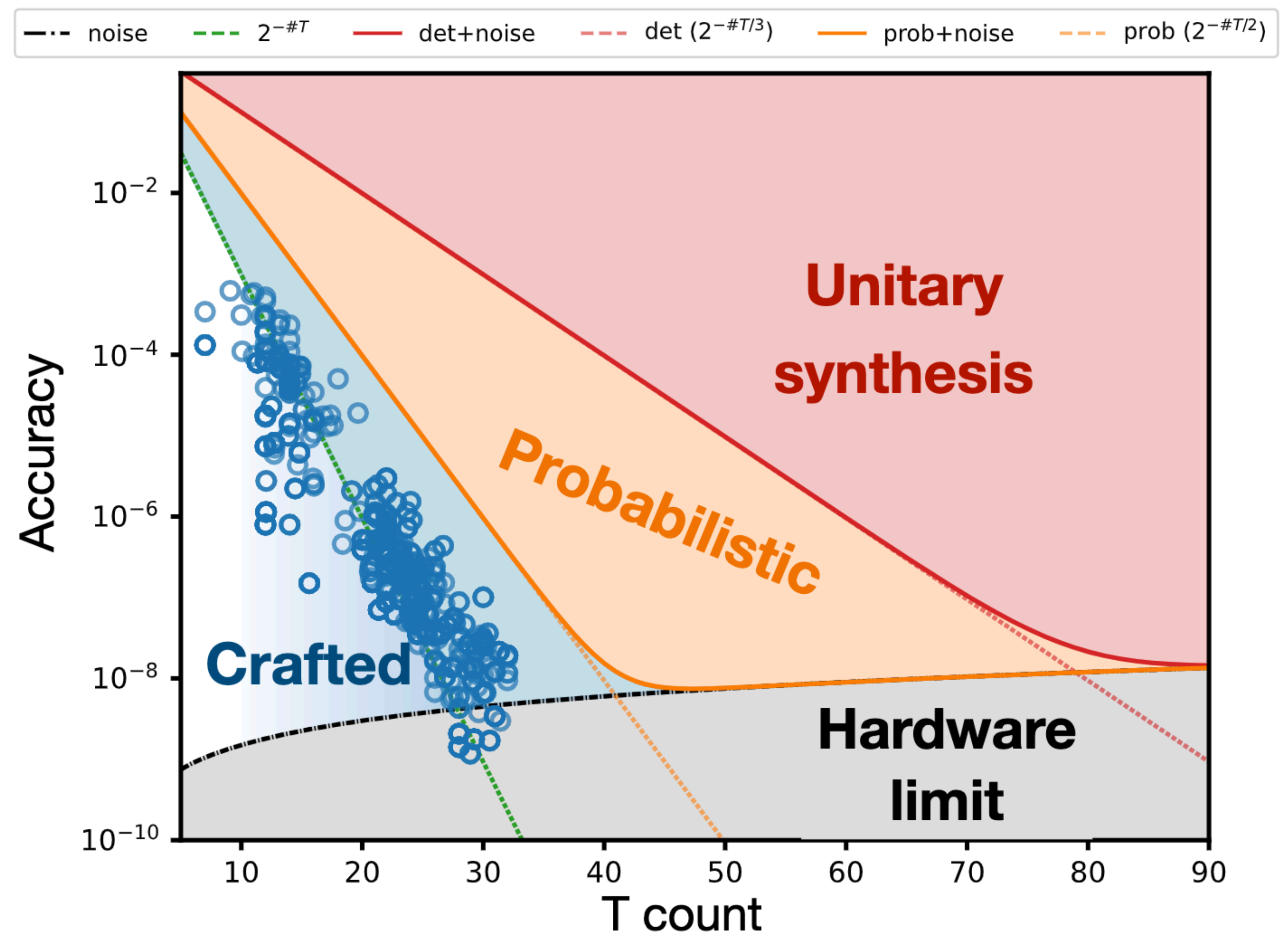
What is the necessary tools?

**Current** — **NISQ - Early FTQC** — **FTQC**

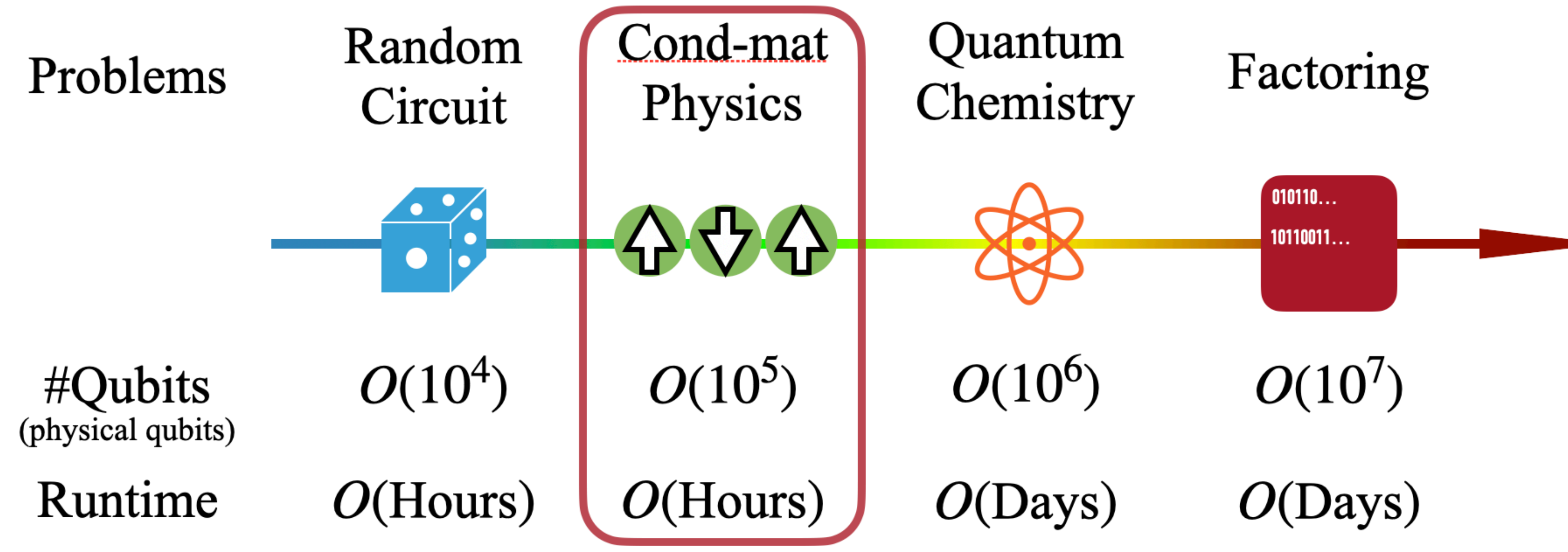
Pushing frontier in many-body QC (w/ IBM)




- Understanding limits of QEM, QEC
- Unification of error countermeasures

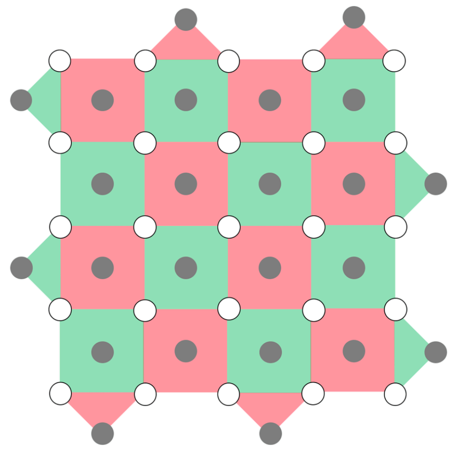



- Methodology of FTQC
- Resource estimation for FTQC

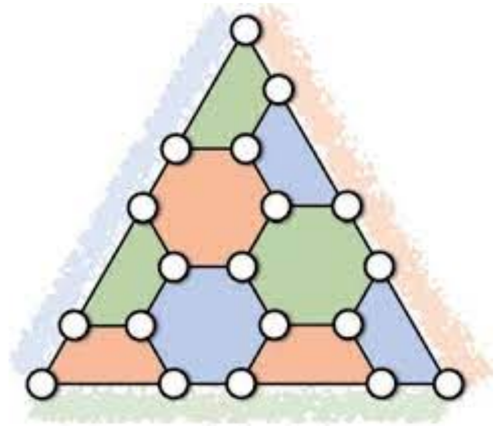


# Counteracting noise

Surface code



Color code



Depends on whether you can

(1) Encode information into logical qubits using ancillary d.o.f.

(2) Perform feedback based on mid-circuit meas.

| Both (1) and (2) | Only (1) | Neither |
|---|---|---|
| **Quantum error correction**<br>protection of quantum info by encoding | **Quantum error detection**<br>encode, but no active entropy reduction | **Quantum error mitigation**<br>Counteract by postprocessing |
| Scalable quantum computation | | Cost $= O(\exp((\#\text{qubit}) \cdot (\#\text{depth})))$ |

Tsubouchi*, Sagawa, **NY***, PRL ('23)

# Fundamental limitation of noisy quantum computation

We have a zoo of QEM methods

- Zero-noise extrapolation
- Probabilistic Error Cancellation
- Purification-based mitigation
- (Generalized) Subspace Expansion
- Symmetry expansion/verification
- Learning-based error mitigation

Question 1: Does QEM replace QEC?

**A. No!** Scalable quantum computation requires error correction.

This can be understood from estimation-theoretic view or state discriminability.

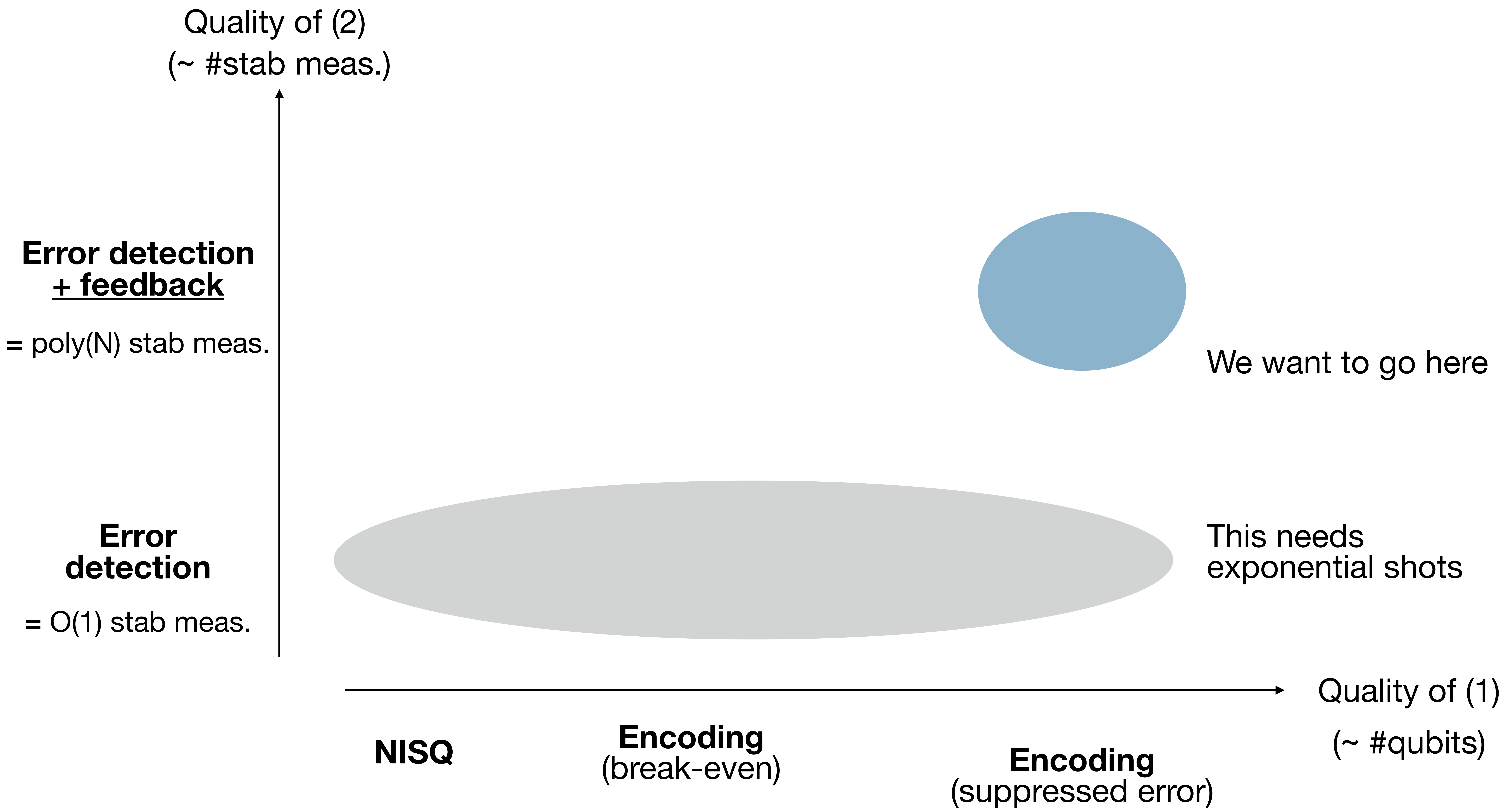
Tsubouchi*, Sagawa, **NY***, PRL ('23) Takagi, Tajima, Gu, PRL ('23) Quek et al.

Question 2: QEM would be necessary in early FTQC anyway. Is there any provably optimal way of QEM?

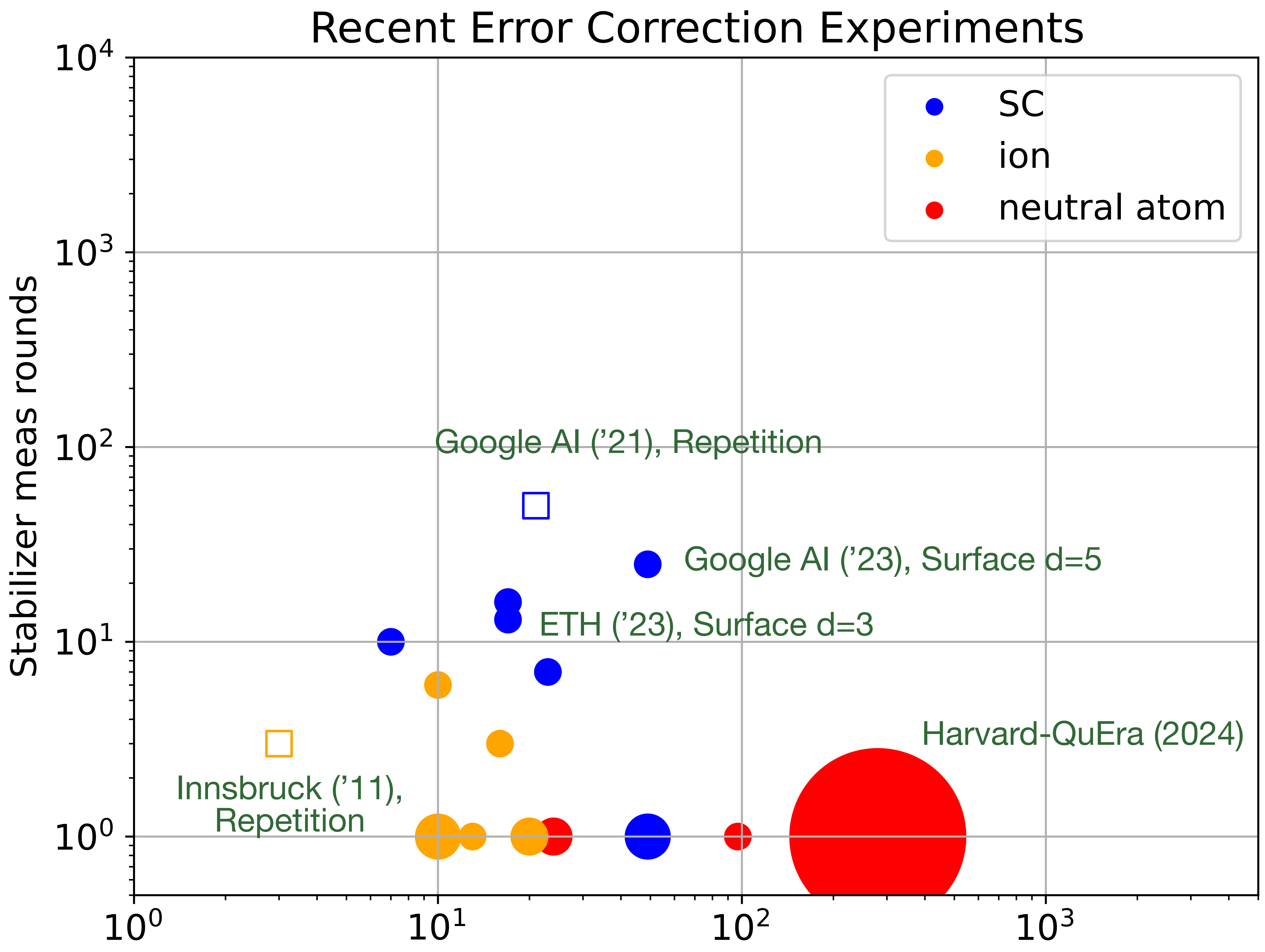
**A. Yes!** We can saturate the bound when white-noise approximation is valid.

Tsubouchi*, Sagawa, **NY***, PRL ('23)

# Moving on to (early) fault-tolerance…



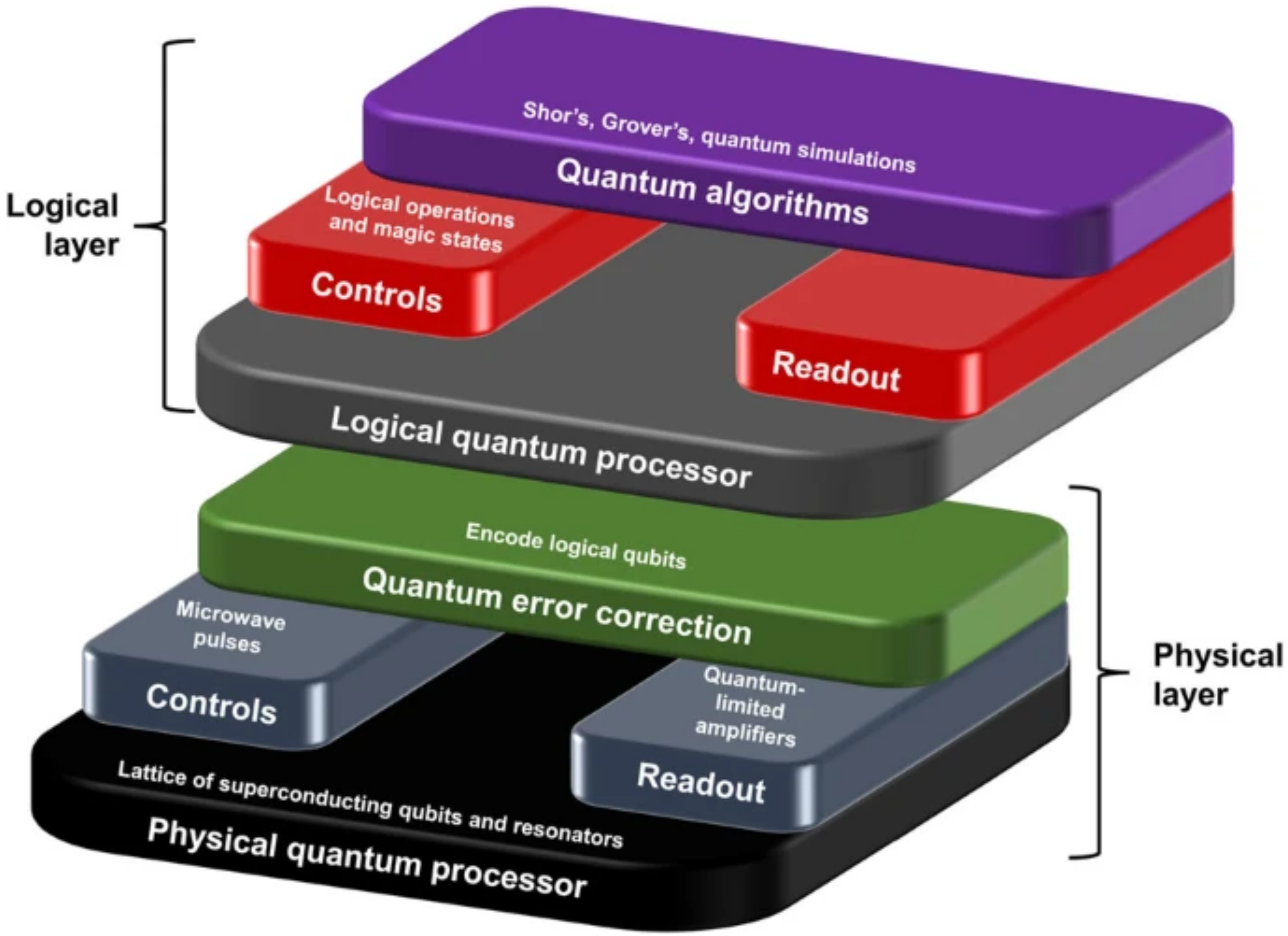
# Current status in early fault-tolerance




(Point size indicate logical qubit counts)

# Next in FTQC

**What do we need in the theory side?**




Gambetta, Chow, Steffen, npj QI ('17)

Seek for utility

When do we start outperforming classical computers, in problems we actually solve right now?

Algorithm Design

Develop useful FTQC-oriented algorithm

Understanding & developing error countermeasures

We don't have error correction right away.

How do we combine error *correction* and *mitigation?*

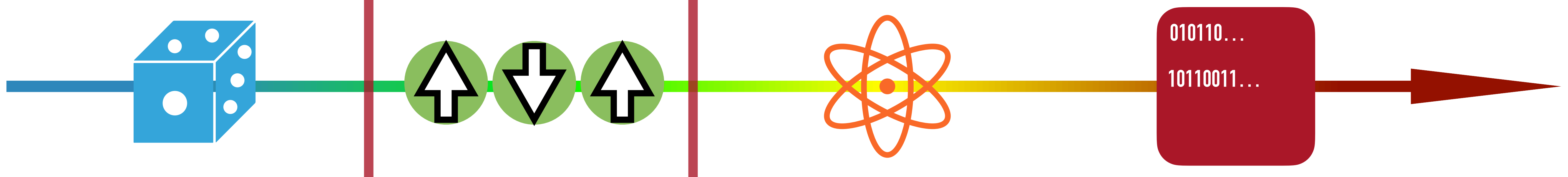
Possible collab. with Jiang group, Fefferman group

# Advancements in fault-tolerant quantum computers

Utility: Estimate what is needed to outperform classical computers

**NY** et al., npj Quantum Information 10, 45 (2024)

| Problems | Random Circuit | Cond-mat Physics | Quantum Chemistry | Factoring |
|---|---|---|---|---|
| #Qubits (physical qubits) | $O(10^4)$ | $O(10^5)$ | $O(10^6)$ | $O(10^7)$ |
| Runtime | $O(\text{Hours})$ | $O(\text{Hours})$ | $O(\text{Days})$ | $O(\text{Days})$ |
| | | | Lee et al. ('21) | Gidney and Ekera ('19) |




- Ground state problem in "cond-mat" and "quantum chemistry":
  - cond-mat : e.g. 2d J1-J2 Heisenberg, 2d Fermi-Hubbard on square lattice
  - QChem : e.g. FeMoco
- All assumes FTQC with surface code, SC qubit on 2d, error rate $p = 10^{-3}$

# Advancements in fault-tolerant quantum computers

Algorithm   Wada, Yamamoto, **NY**, arXiv:2406.03306, **see talk at AQIS 2024**

Useful FTQC-oriented algorithms : extracting physical quantity with minimal query to state prep

| | Eigenphase | $M$ non-commuting observables |
|---|---|---|
| Standard quantum limit $O(1/\epsilon^2)$ | Textbook phase estimation | Projective measurement $\tilde{O}(M/\epsilon^2)$ |
| Heisenberg limit $O(1/\epsilon)$ | Adaptive/Iterative phase estimation | **Our work** (if $M = \Omega(N)$) $O(\sqrt{M}/\epsilon)$ |

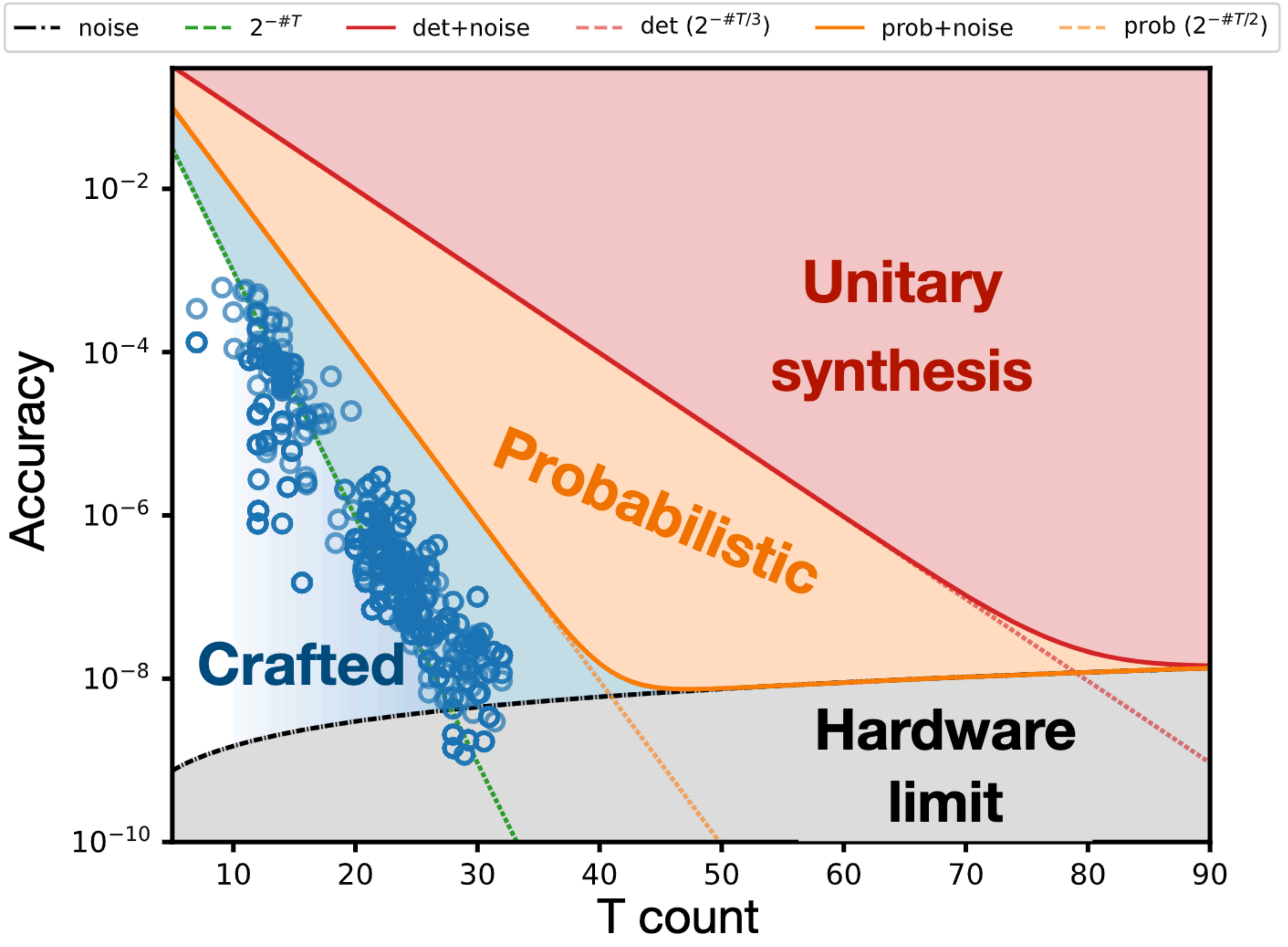
Error countermeasures   Tsubouchi, Mitsuhashi, Sharma, **NY**, arXiv:2405.07720, **see poster today**

**NY,** et al., arXiv:2405.15565

Early FTQC = QEC + error mitigation (constant factor savings of qubits)

Our approach: Charaterizable error → do error correction at logical level

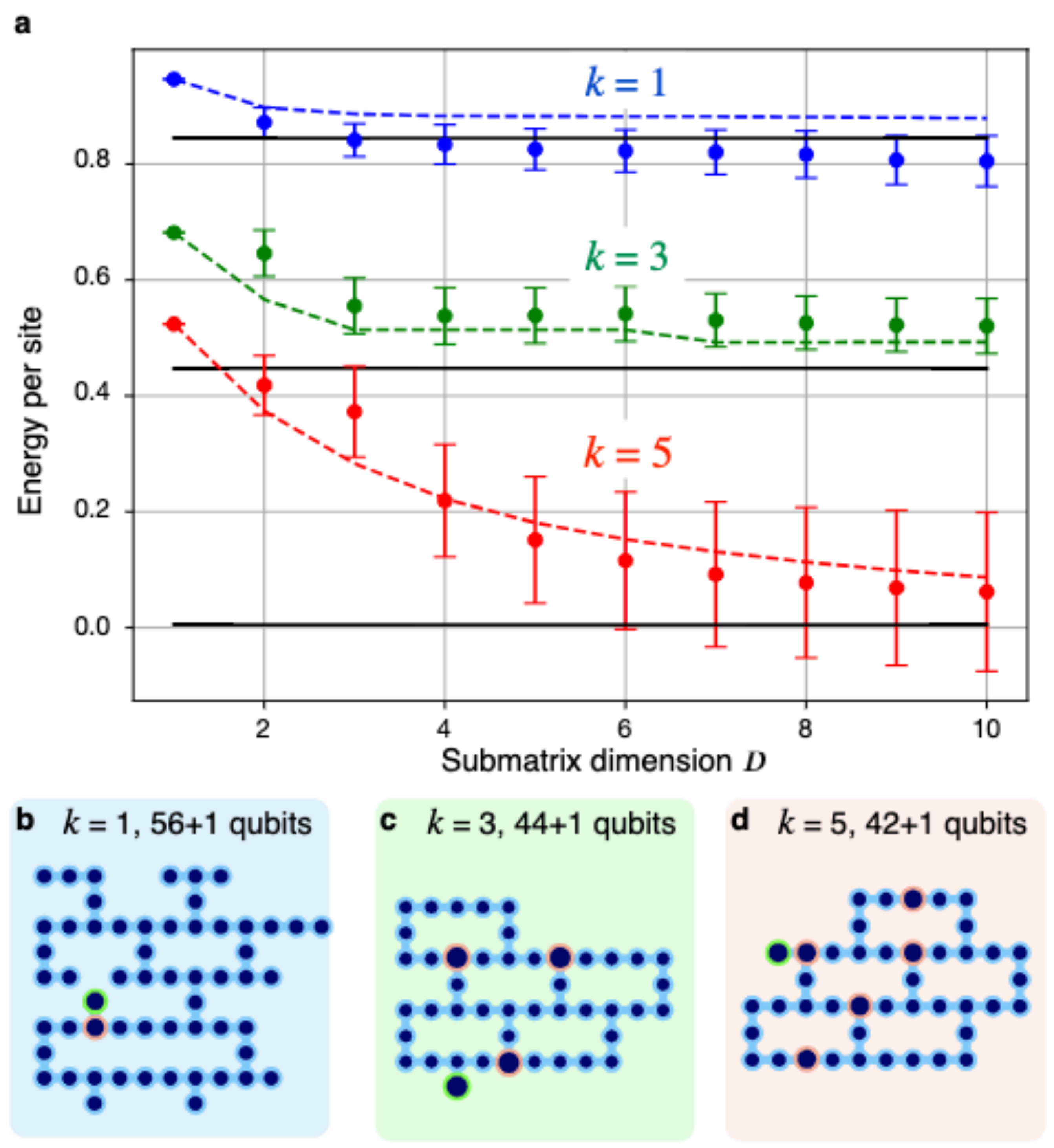
non-charaterizable error → agnostic, optimal approach



# Summary

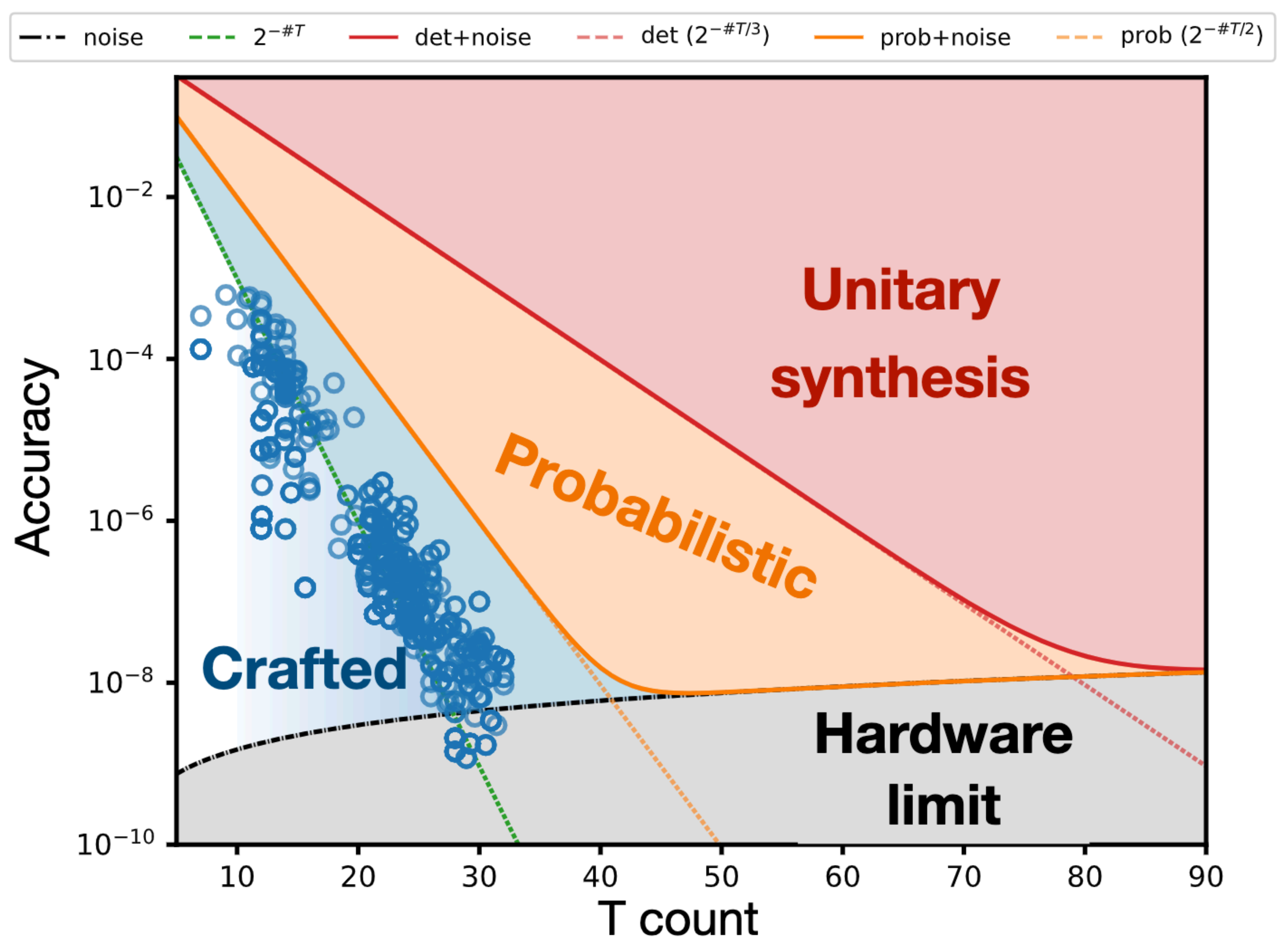
**NISQ**

Pushing frontier in many-body QC (w/ IBM)




**NISQ - Early FTQC**

- Unification of QEM
- Understanding limits of QEM
- Unification of error countermeasures




**FTQC**

- Resource estimation for FTQC
- (Near-) Clifford simulator