A Hybrid Computing Ecosystem for Practical Quantum Advantage

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NSF post-quantum AI
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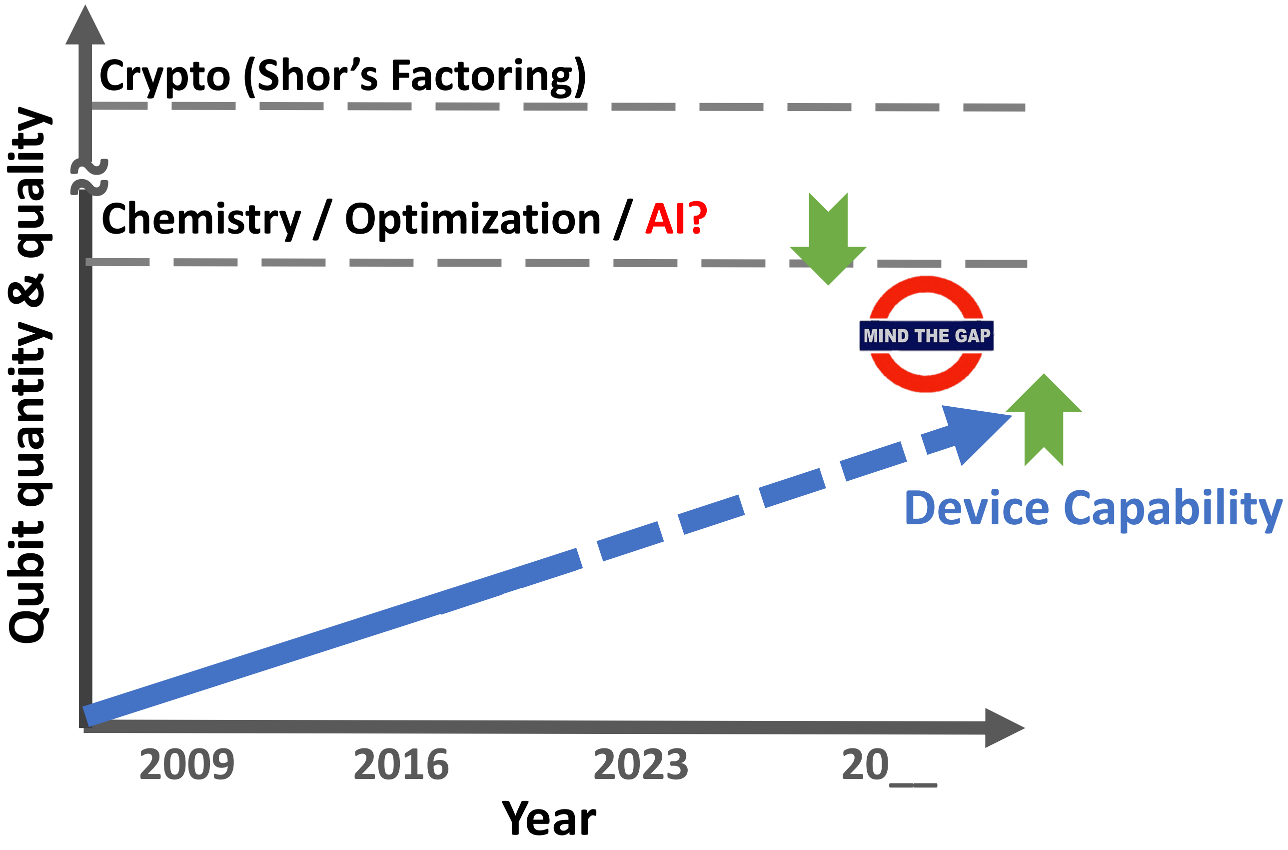
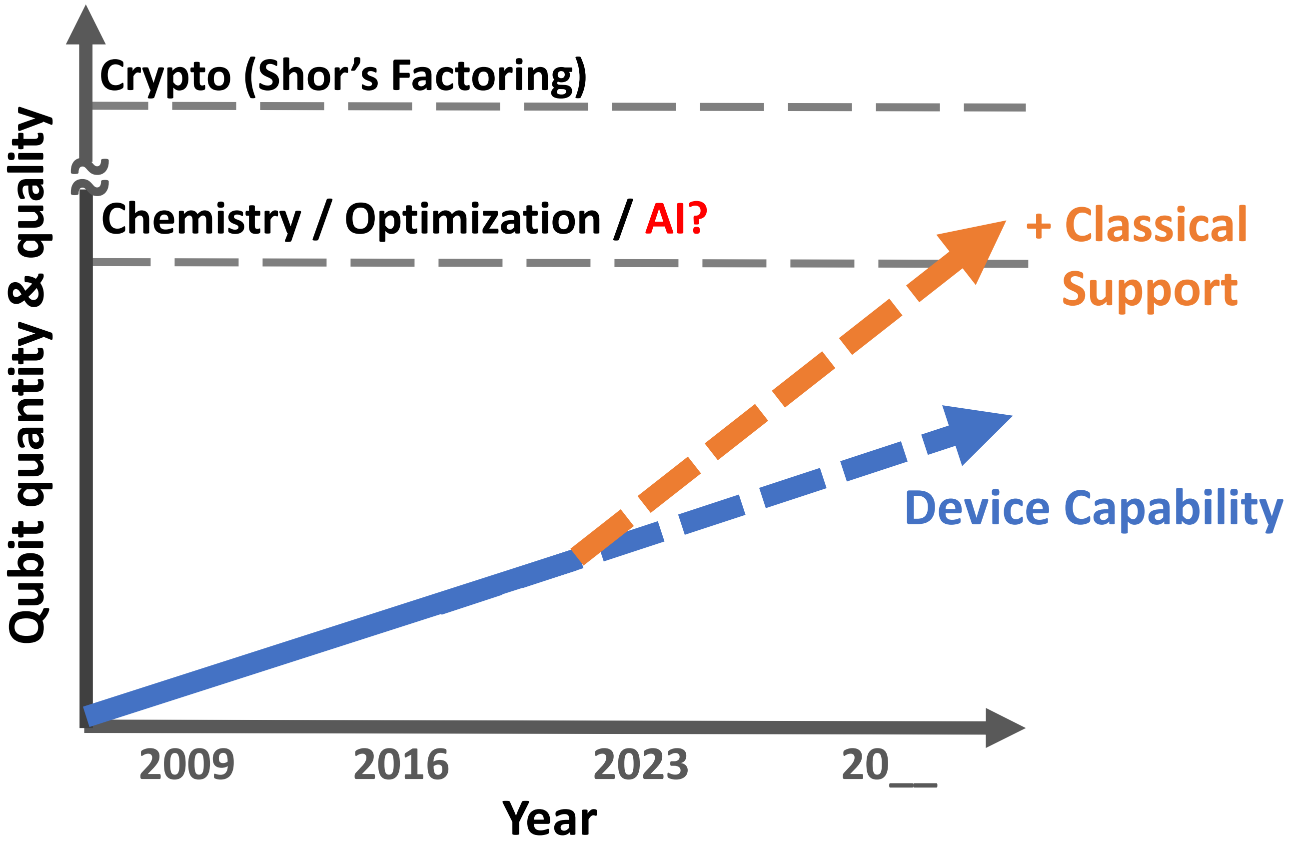
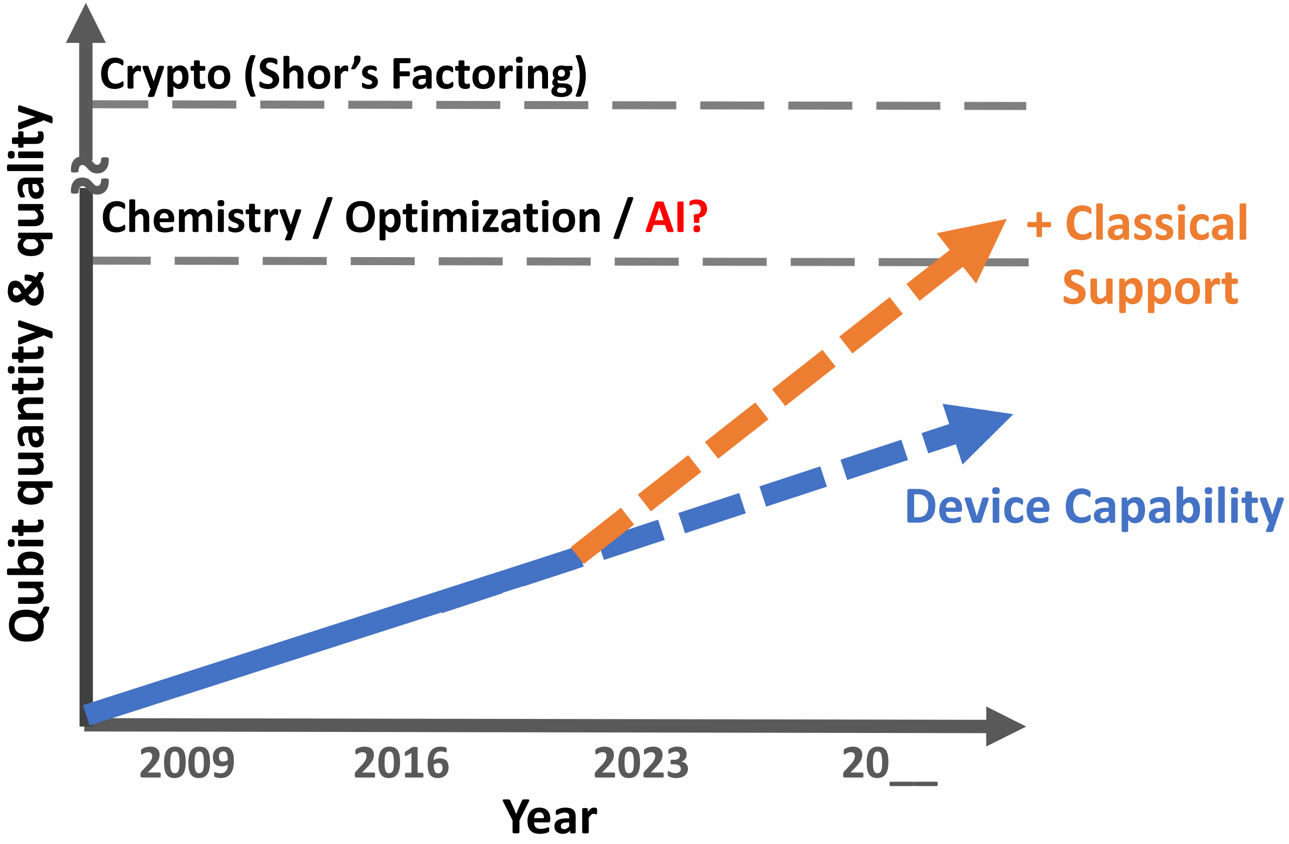
Wide gap between application requirements and technology capability



Bridging the gap: Hybrid quantum-classical computing approaches



Bridging the gap: Hybrid quantum-classical computing approaches



1. **PL, compilation, computer architecture**
2. **High performance computing**
3. **Classical (e.g. cryogenic) hardware design**
4. **Scalable classical simulation**
5. **Multi-chip / distributed computing**
6. **Resource management**
7. **ML-driven noise mitigation / optimization**
8. **Secure quantum systems**

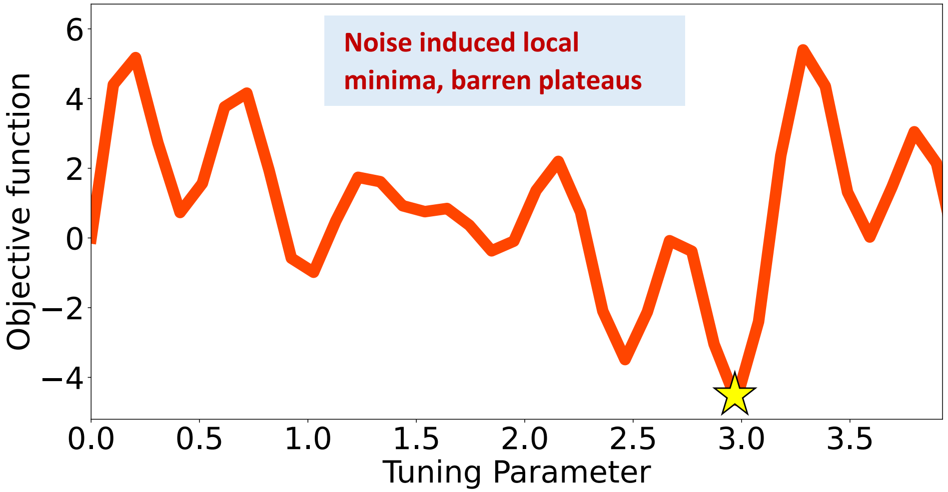
Any novel pre-processing, post-processing, co-processing, especially those with potential scalability challenges.

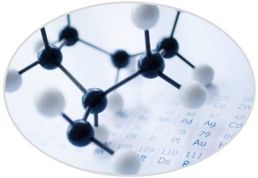
CAFQA: A Classical Simulation Bootstrap for Variational Quantum Algorithms

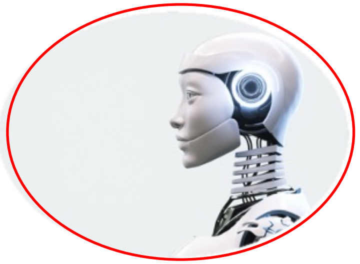
Gokul Ravi, Pranav Gokhale, Yi Ding, William Kirby, Kaitlin Smith, Jonathan Baker, Peter Love, Hank Hoffmann, Kenneth Brown, Frederic Chong. ASPLOS 2023 + ICCAD Drug Discovery Innovation Award 2023

arXiv:2202.12924

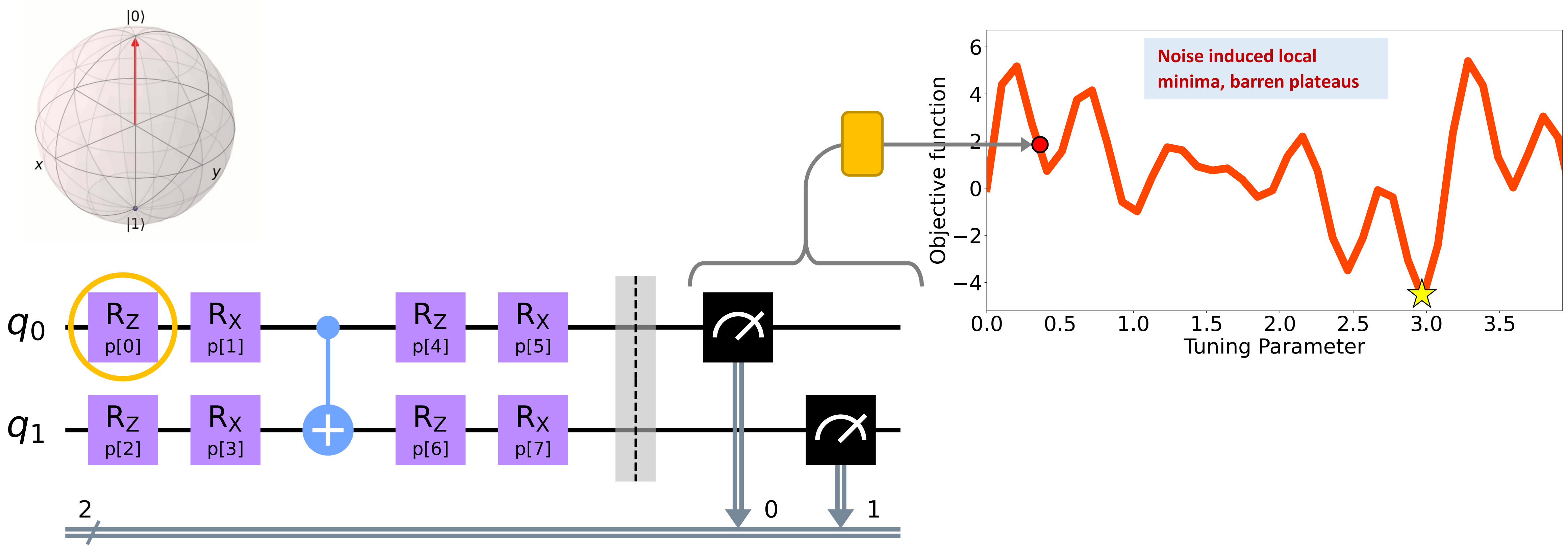
How VQA works





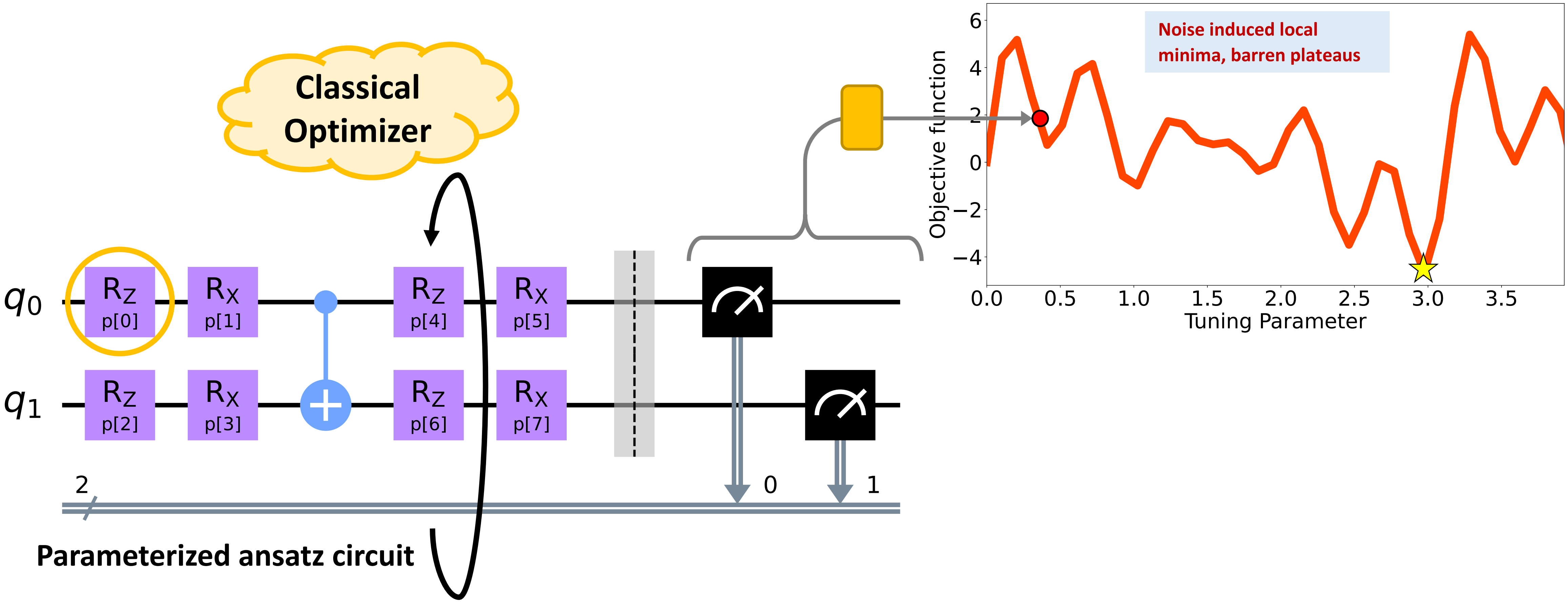


How VQA works

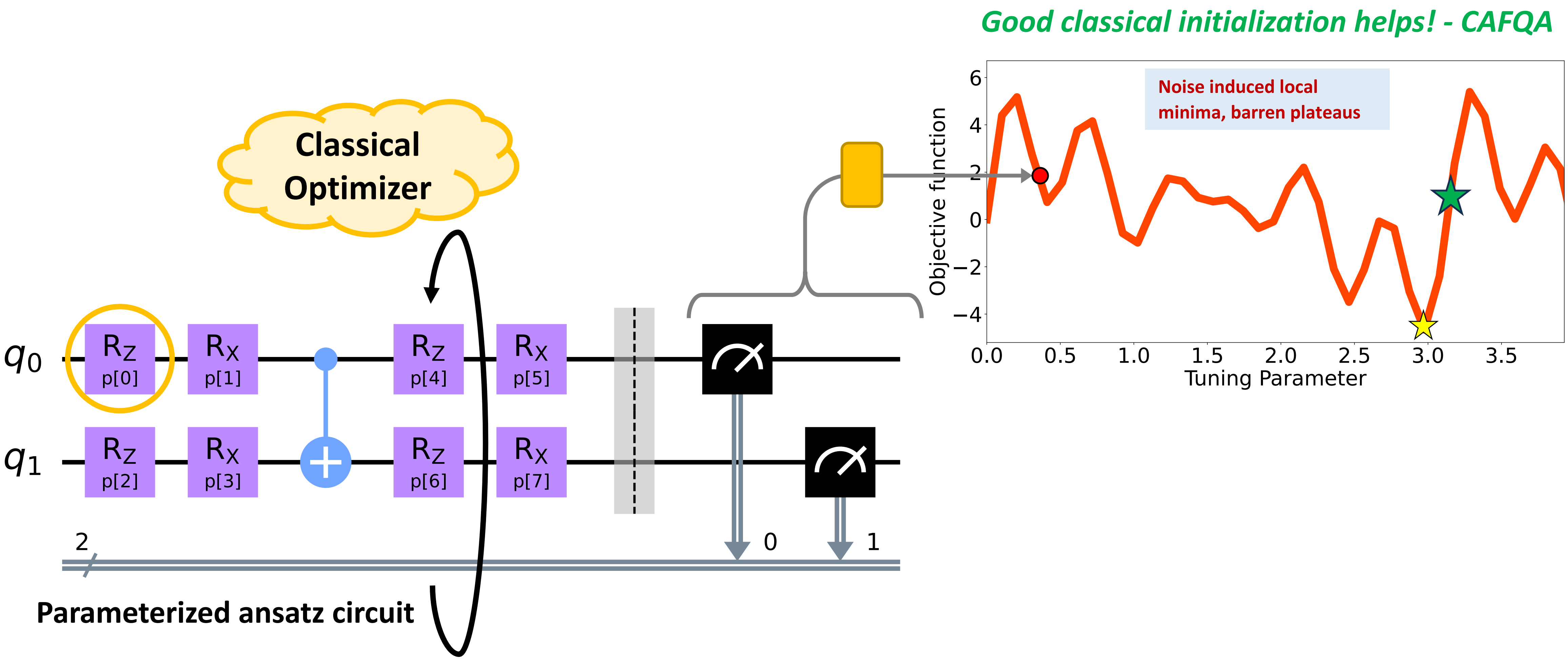


Parameterized ansatz circuit

How VQA works

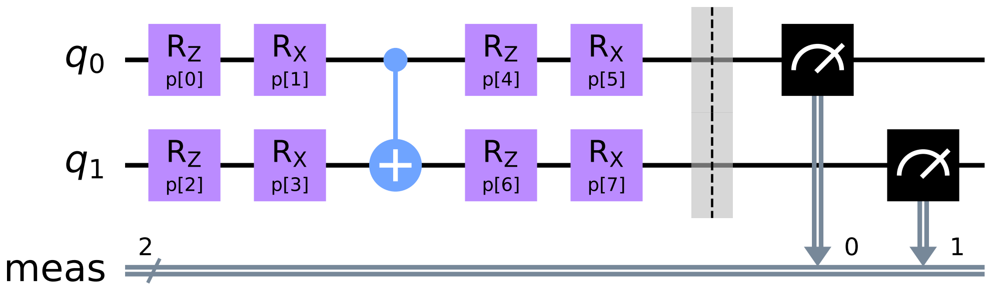


How VQA works



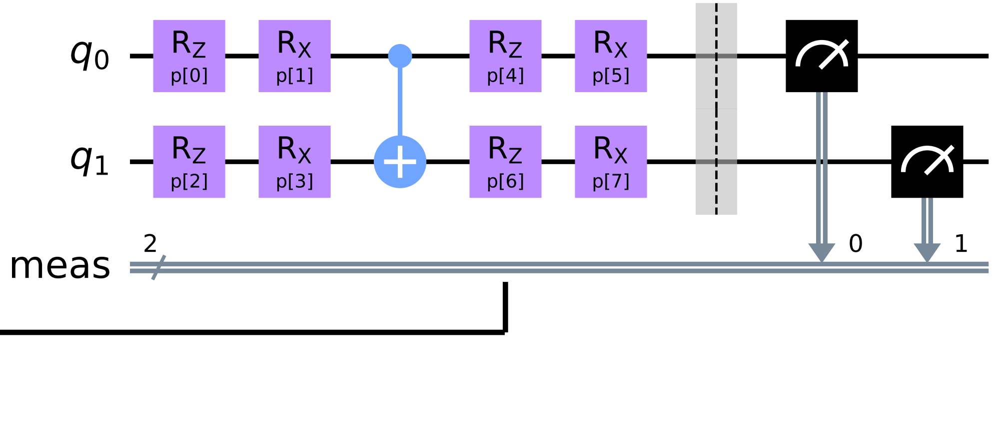
Classical simulability of Clifford quantum circuits

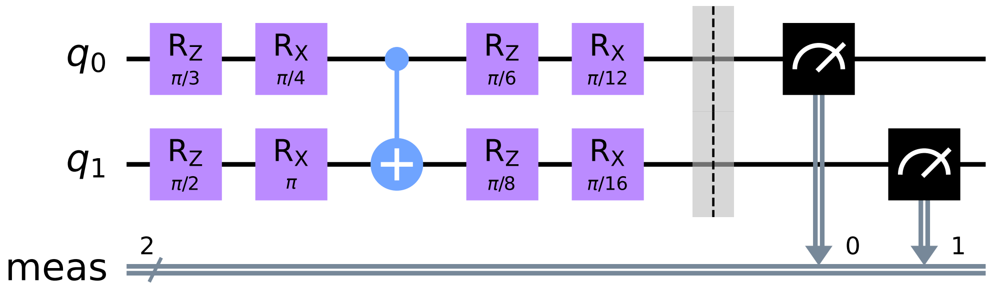
Parameterized ansatz circuit



Classical simulability of Clifford quantum circuits

Parameterized ansatz circuit





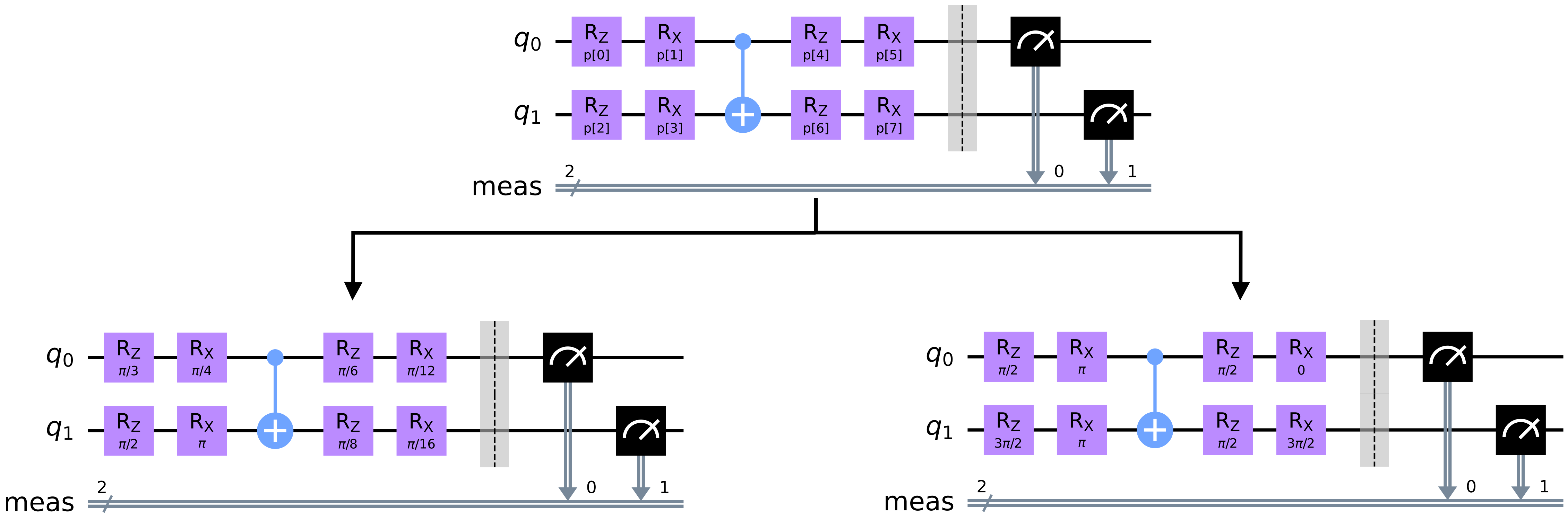
A classically <u>intractable general</u> circuit

Continuous angles = [0, 2*pi]

Classical simulability of Clifford quantum circuits

Gottesman–Knill theorem ['98] - A QC circuit can be classically simulated efficiently if: (a) it has only Clifford gates, (b) classical qubit prep and measurement.

Parameterized ansatz circuit



A classically <u>intractable general</u> circuit

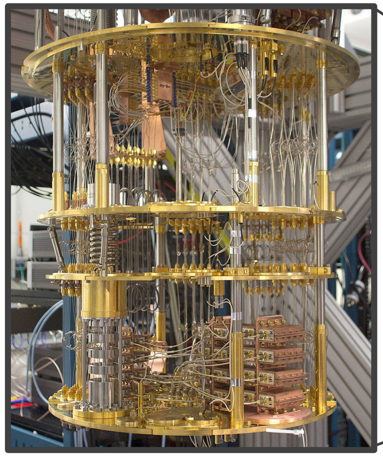
Continuous angles = [0, 2*pi]

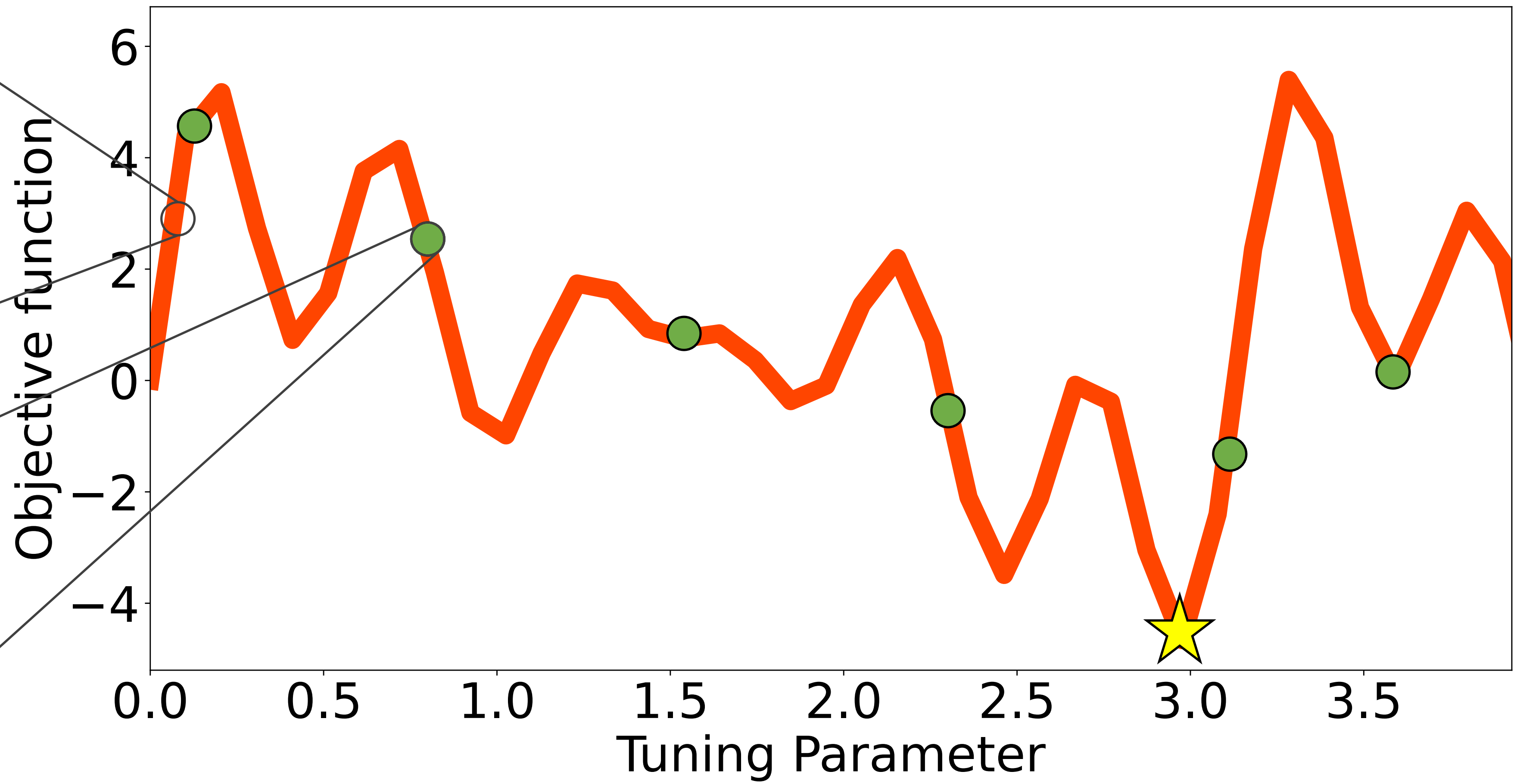
A classically <u>simulable Clifford</u> circuit

Discrete angles = {0, pi/2, pi, 3*pi/2}

CAFQA classical initialization

CAFQA Insight #1: Portion of the quantum space is classically simulable (Clifford space).

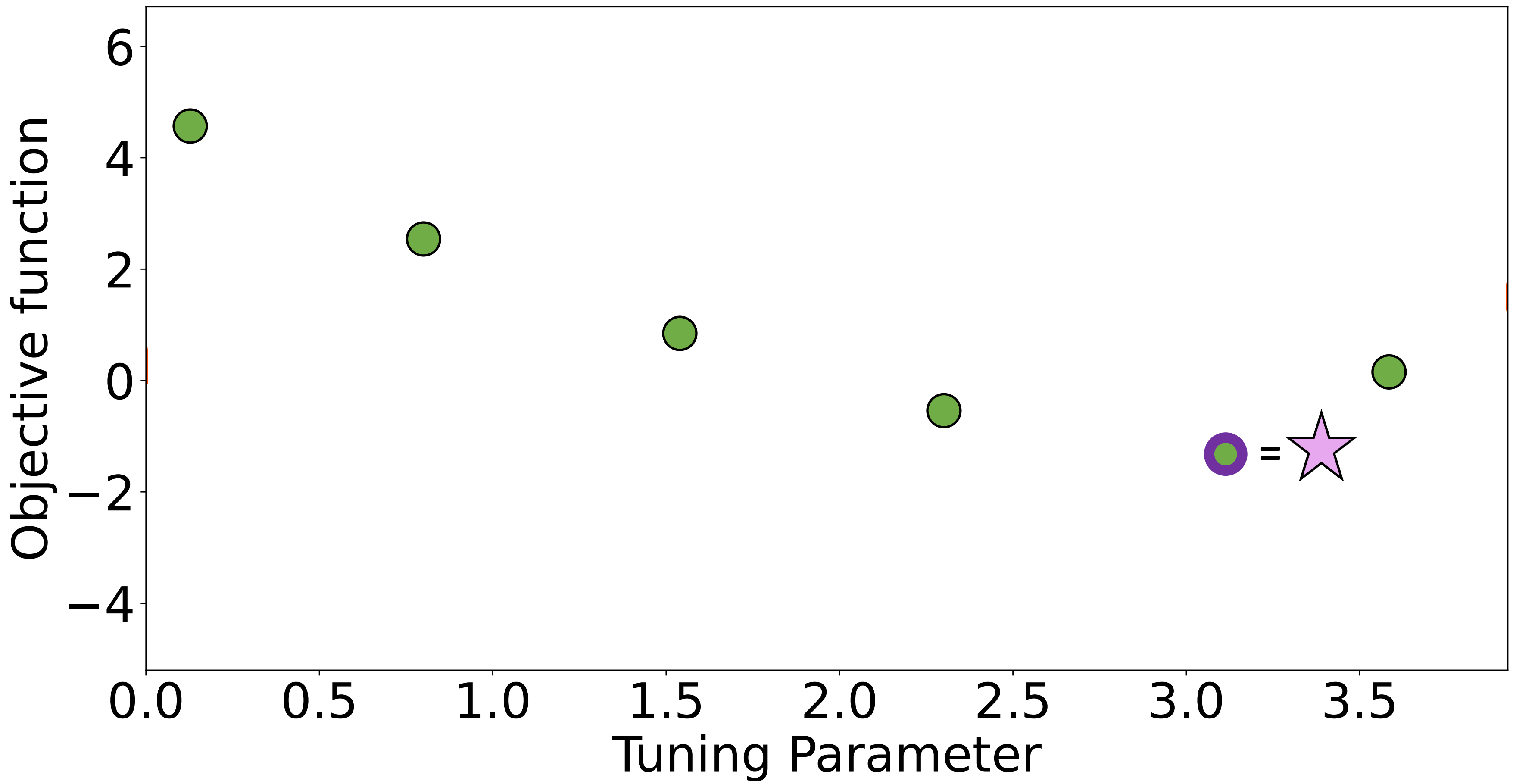




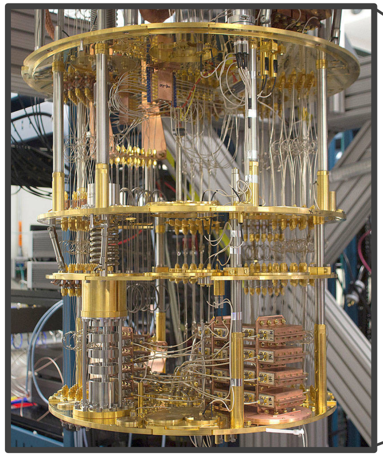
CAFQA classical initialization

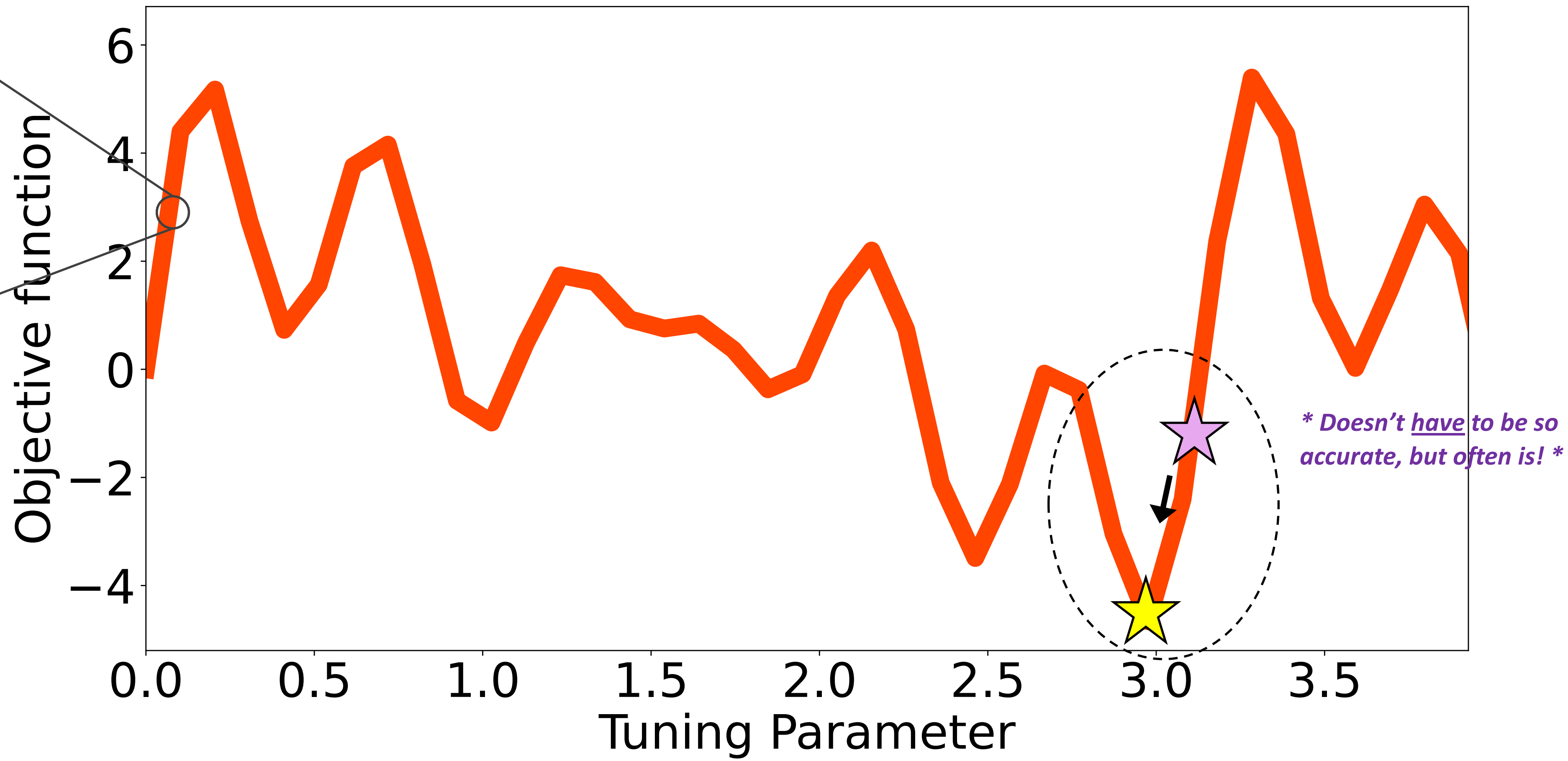
CAFQA Insight #2: Efficiently search the discrete space classically to find the lowest objective.

Bayesian Optimization



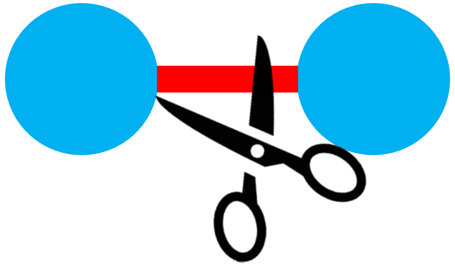
CAFQA classical initialization



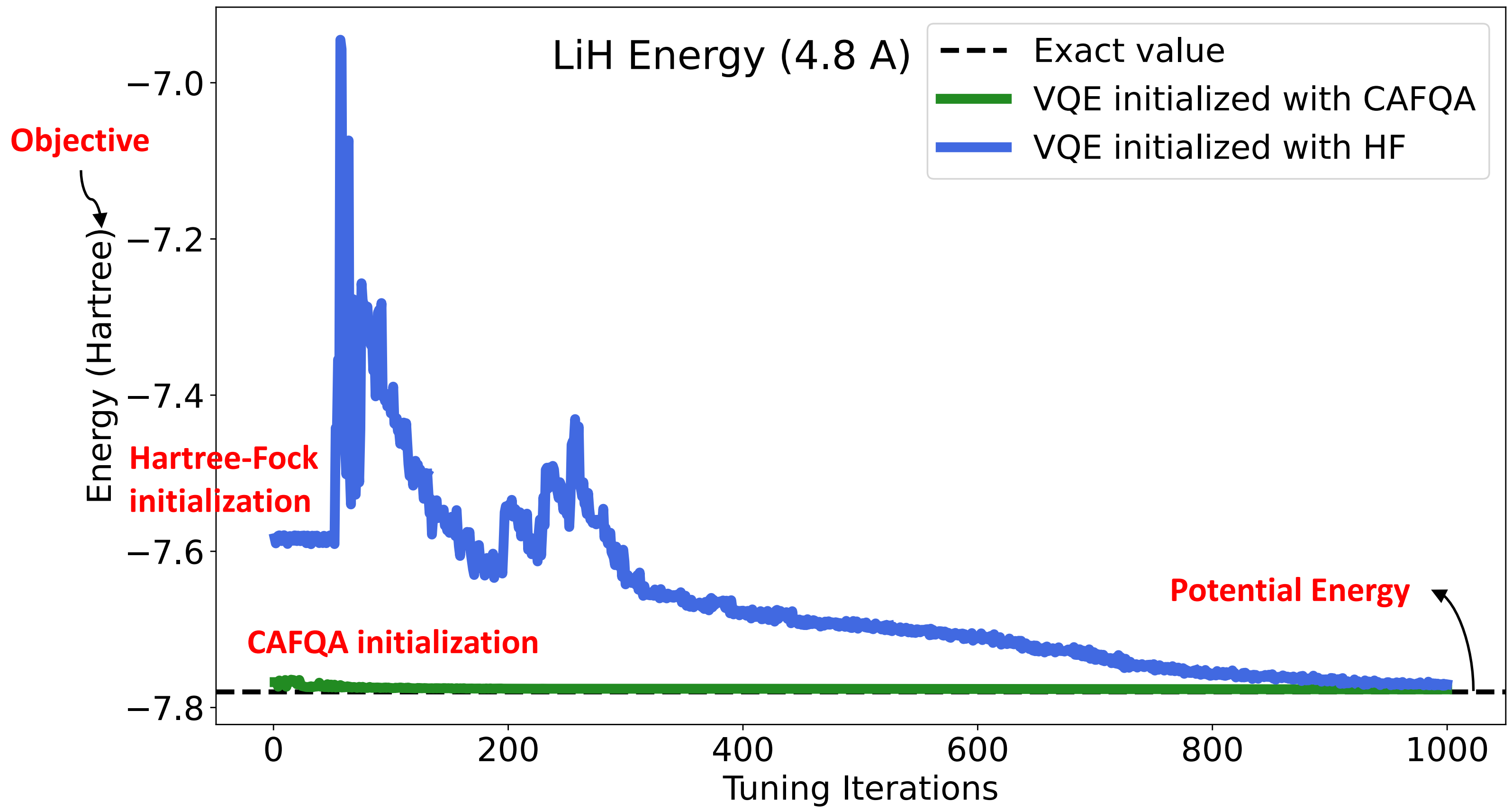


Quantitative benefits for chemistry applications

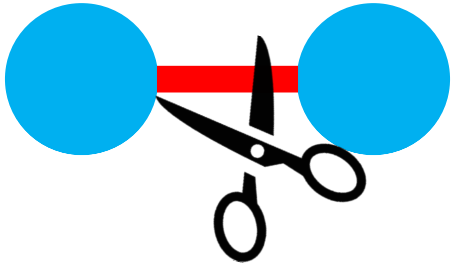
Potential Energy



Quantitative benefits for chemistry applications

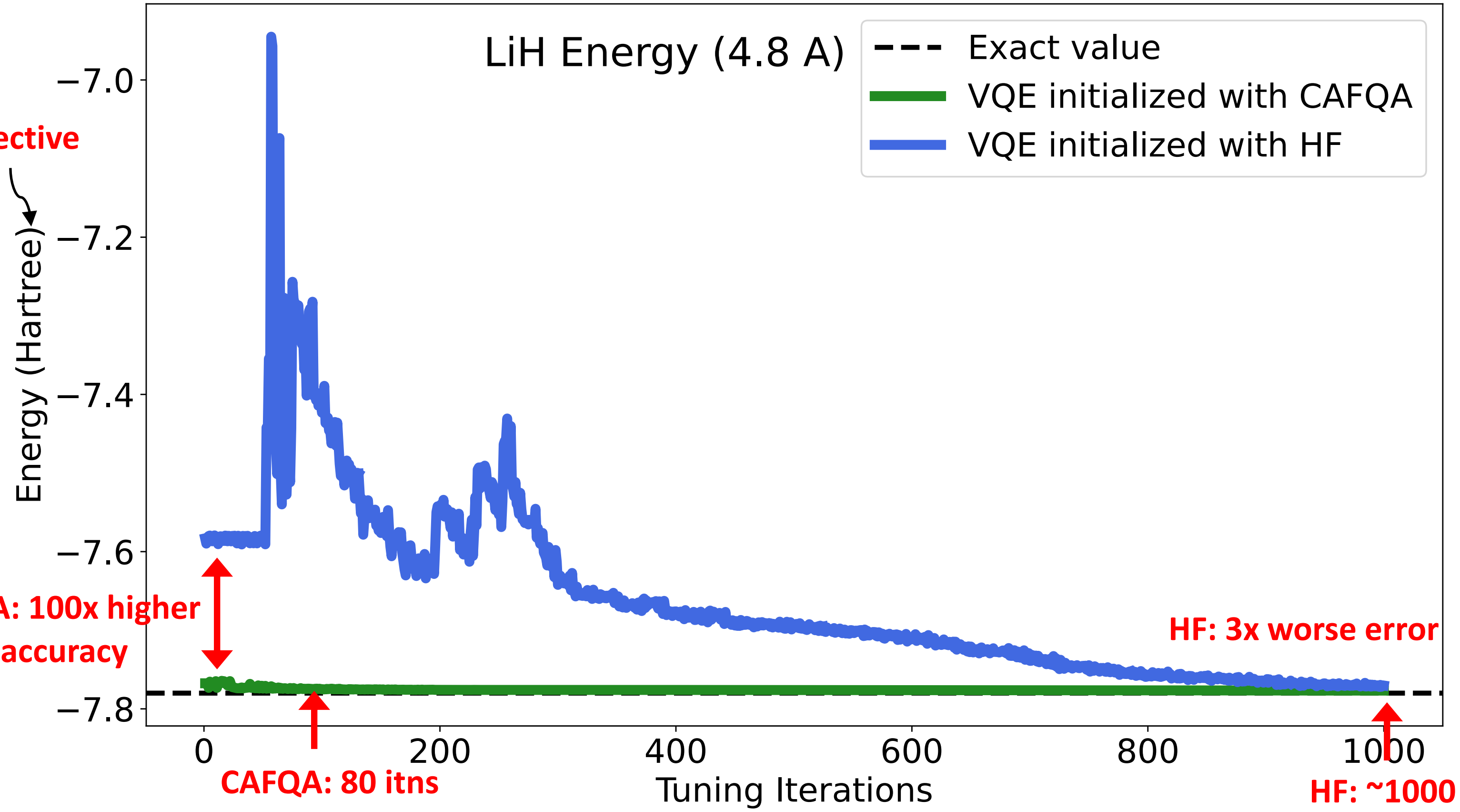


Potential Energy



Quantitative benefits for chemistry applications

Objective



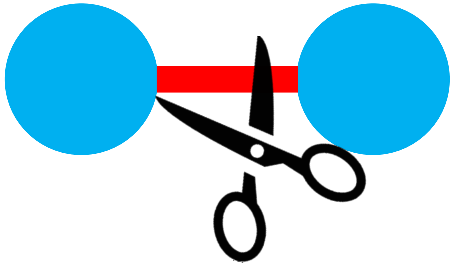
CAFQA: 100x higher initial accuracy

HF: 3x worse error

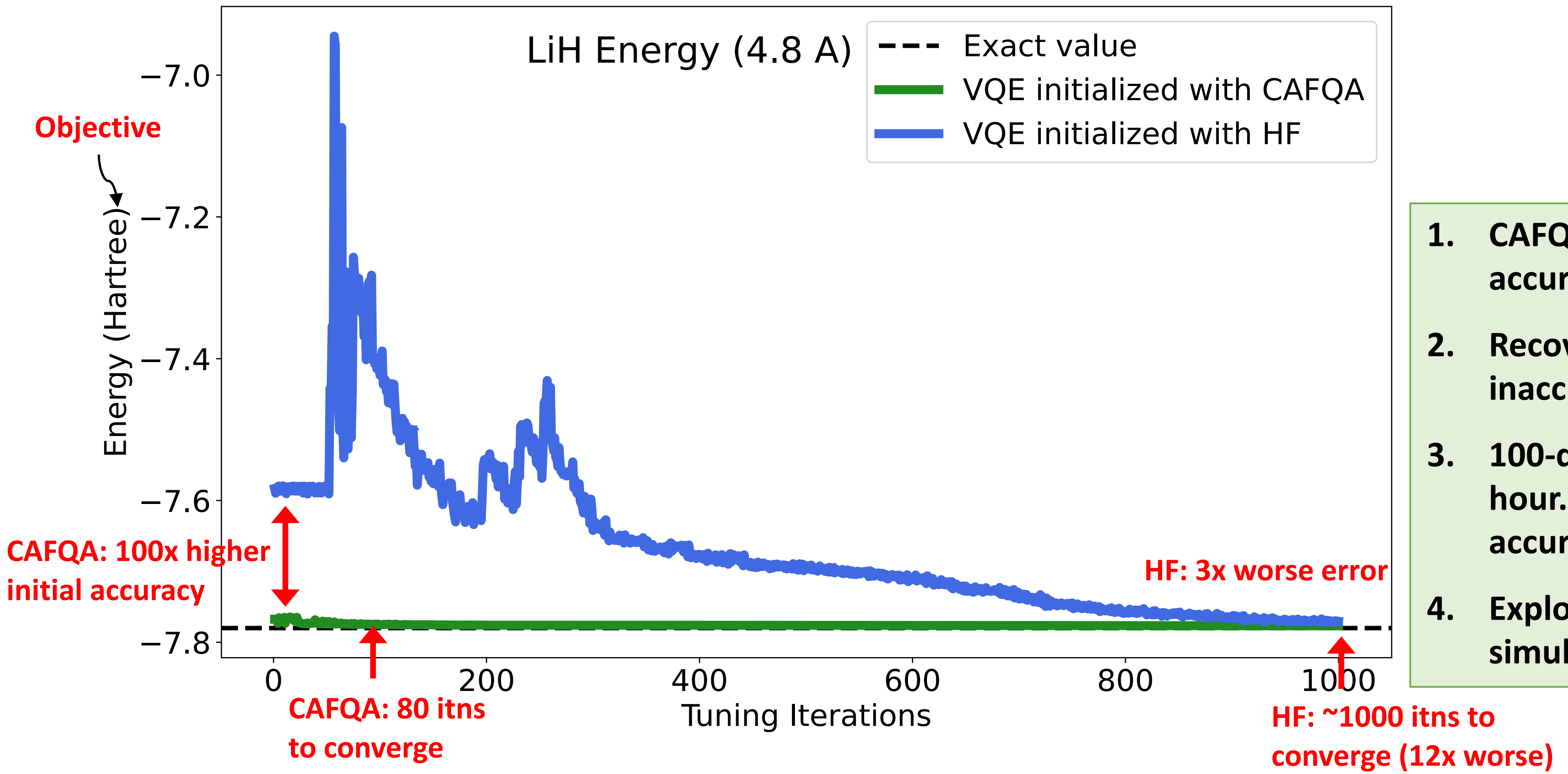
CAFQA: 80 itns to converge

HF: ~1000 itns to converge (12x worse)

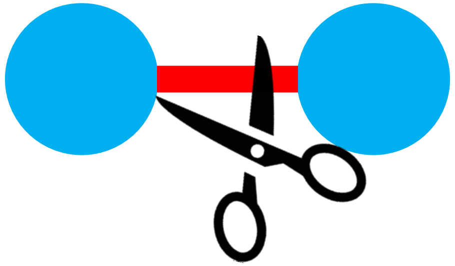
Potential Energy



Quantitative benefits for chemistry applications



Potential Energy



1. **CAFQA achieves 99% mean initialization accuracy (molecule systems <34 qubits).**
2. **Recovers up to 99.99% of Hartree-Fock inaccuracy (57x mean).**
3. **100-qubit spin models – 99% accuracy in 1 hour. Cr2 molecule (34q, 30k terms) – 99% accuracy in <10 hours.**
4. **Exploring near-cliffords and other classical simulation methods.**

Optimal Clifford Initialization for Ising Hamiltonians (w/ Bikrant Bhattacharyya, ICRC 2023)

Minimizing VQE cost function over Clifford States

- Finds optimal circuit parameters
- Bayesian Optimizer
- SLOW!!

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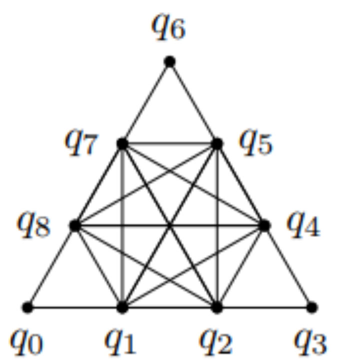
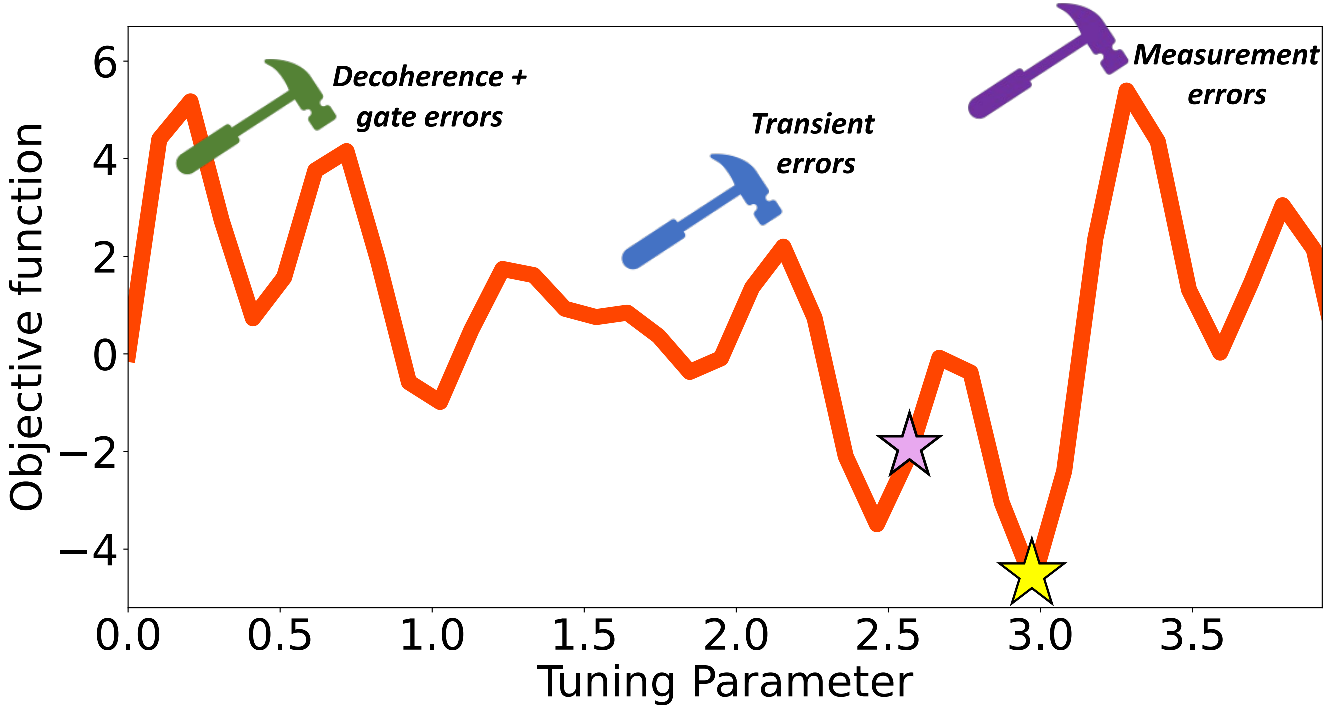
Graph Theoretic Optimization Problem

- Find Optimal Subgraph
- Submodular Optimization
- Time Bounds



Chakrabarty, Jain, Kothari [‘14] – Psuedopolynomial bound on runtime of Fujishige-Wolfe algorithm, [‘00]

Other VQA work: noise mitigation on superconducting quantum devices



VAQEM: A Variational Approach to Quantum Error Mitigation. Ravi et al., HPCA '22

QISMET: Navigating the Dynamic Noise Landscape of Variational Quantum Algorithms. Ravi et al., ASPLOS '23

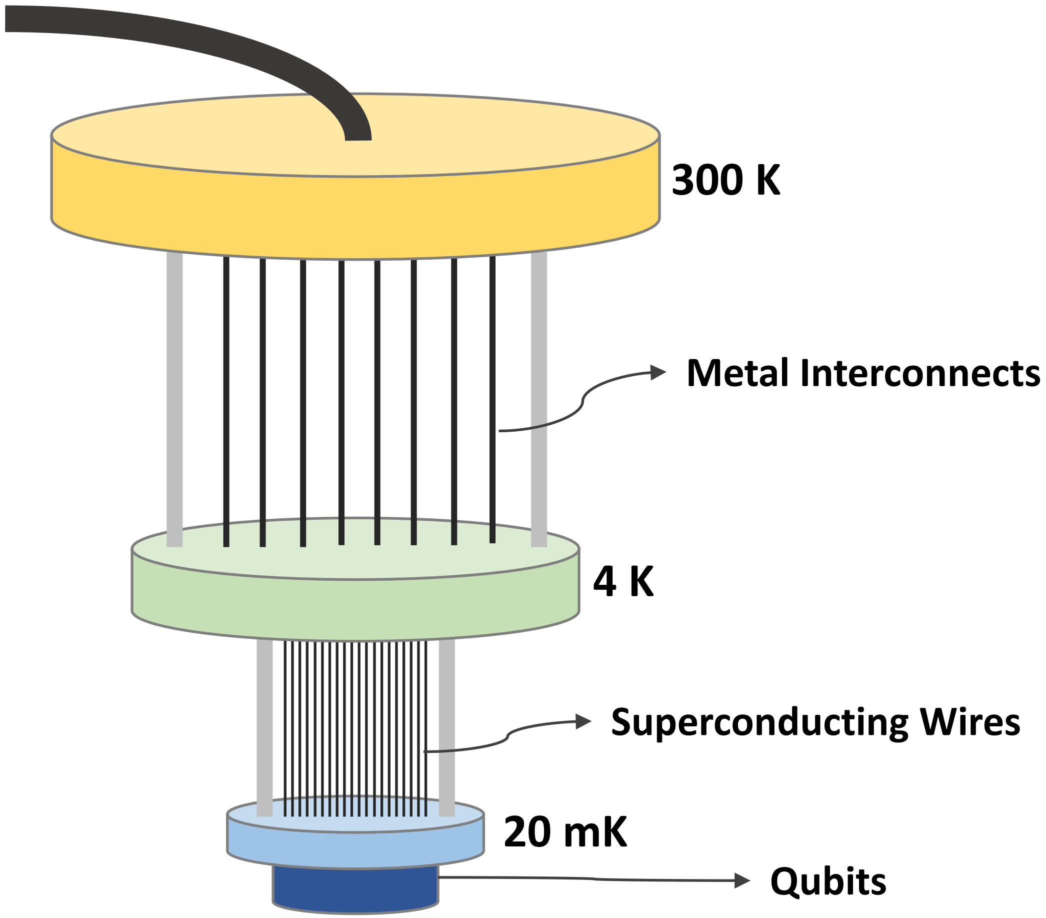
VarSaw: Application-tailored Measurement Error Mitigation for Variational Quantum Algorithms. Dangwal*, Ravi* et al., ASPLOS '24

Clique: Better Than Worst-Case Decoding for Quantum Error Correction

Gokul Ravi, Jonathan Baker, Arash Fayyazi, Sophia Lin, Ali Javadi-Abhari, Massoud Pedram, Frederic Chong. ASPLOS 2023

arXiv:2208.08547

Scope: Cryogenic quantum systems

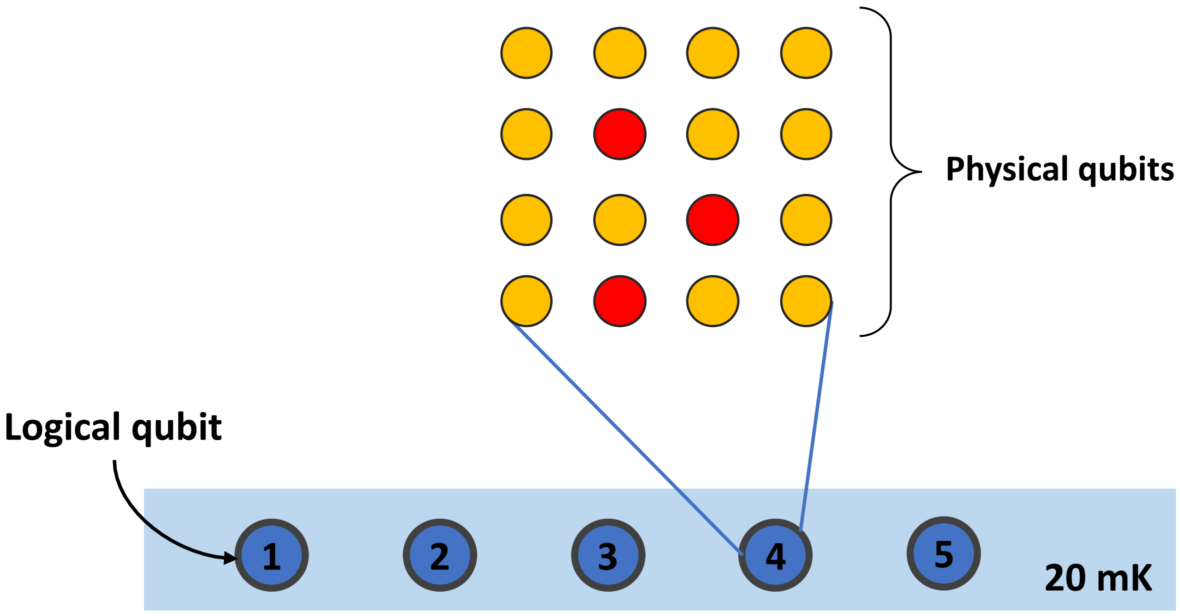


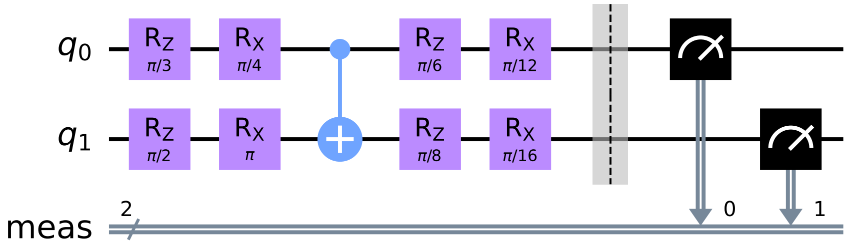
IBM scientists cool down the world's largest quantum-ready cryogenic concept system

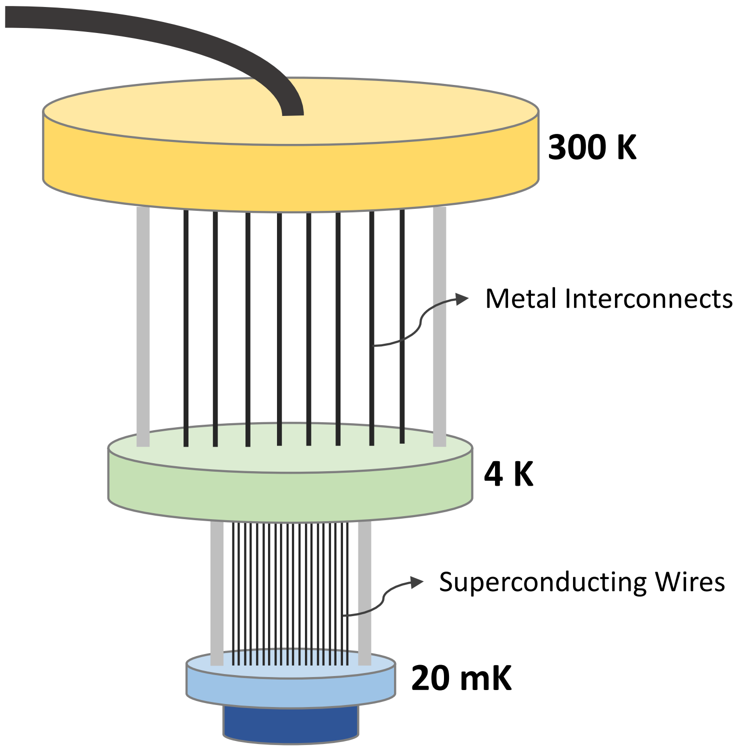
Project Goldeneye pushes the limits of low-temperature refrigeration while laying the groundwork for the quantum industry's ability to scale to larger experiments.

https://research.ibm.com/blog/goldeneye-cryogenic-concept-system

Scope: Cryogenic quantum systems





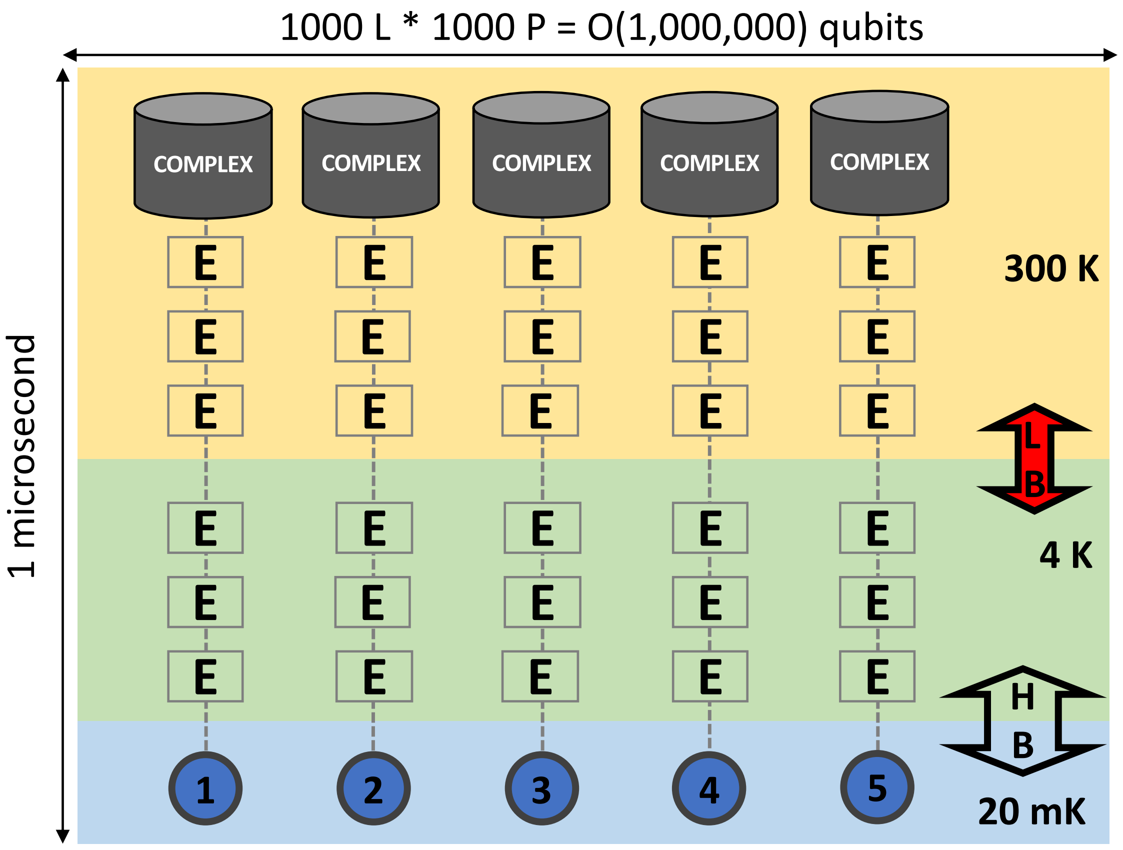


System-level view: Traditional outside-fridge QEC decoding

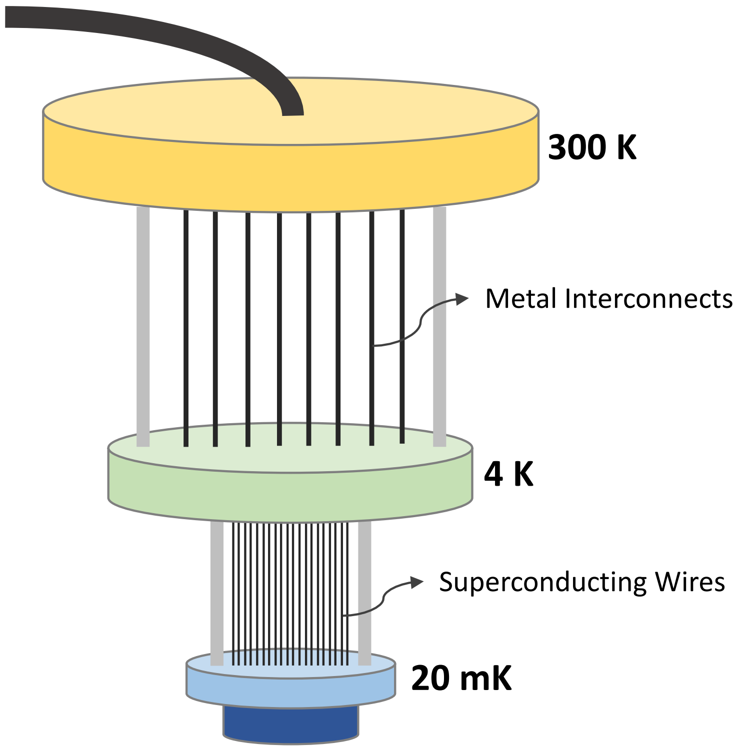
Tbps I/O bandwidth → <u>bandwidth bottleneck!</u>

[Fowler, PR-A ’12]
..
..
[Das, HPCA ’22]
[Das, ASPLOS ’22]

Low latency needed for functional correctness!!



E: Error Signatures



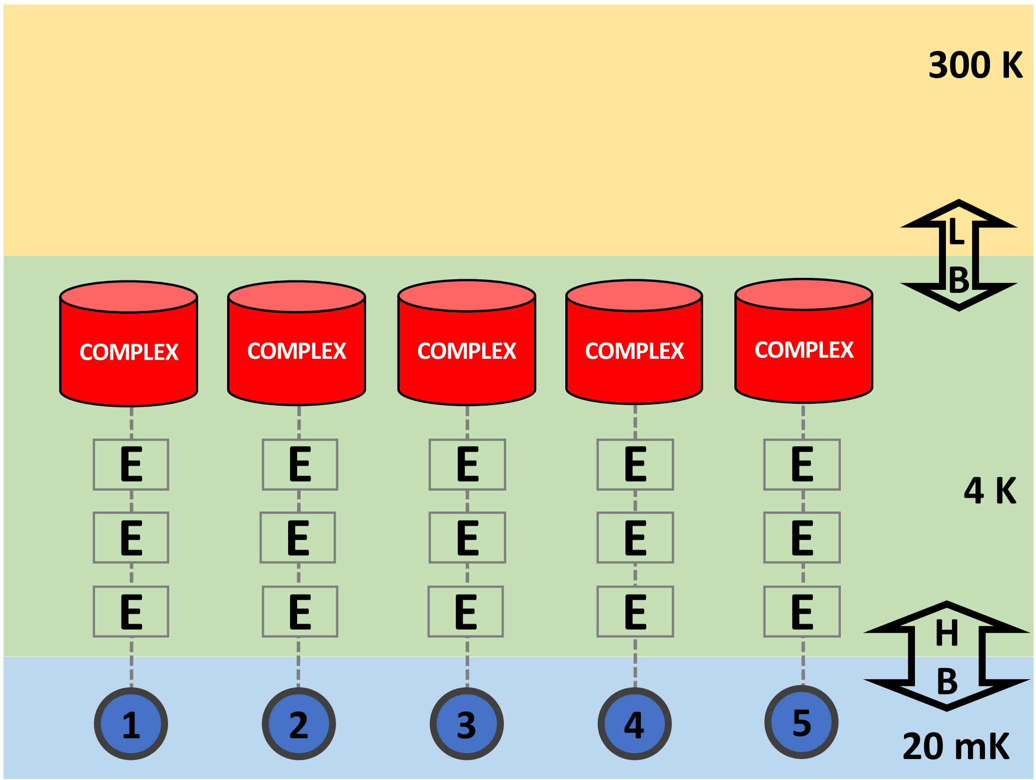
System-level view: Cryogenic inside-fridge QEC decoding

Limited cryogenic power budget (~1W) cryo-resource <u>bottleneck</u>!

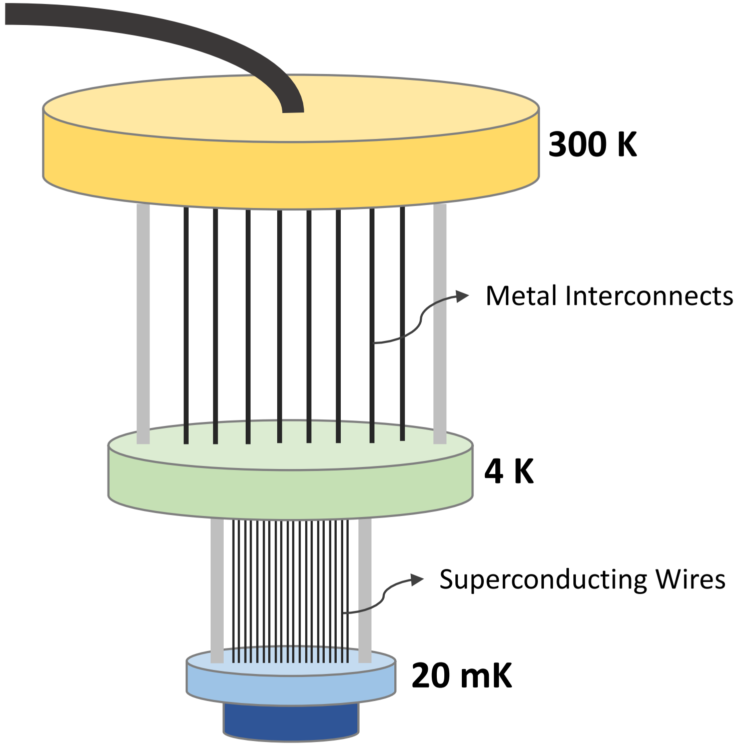
[Holmes, ISCA ’20]
[Byun, ISCA ’22]
[Ueno, HPCA ’22]

1000 L * 1000 P = O(1,000,000) qubits

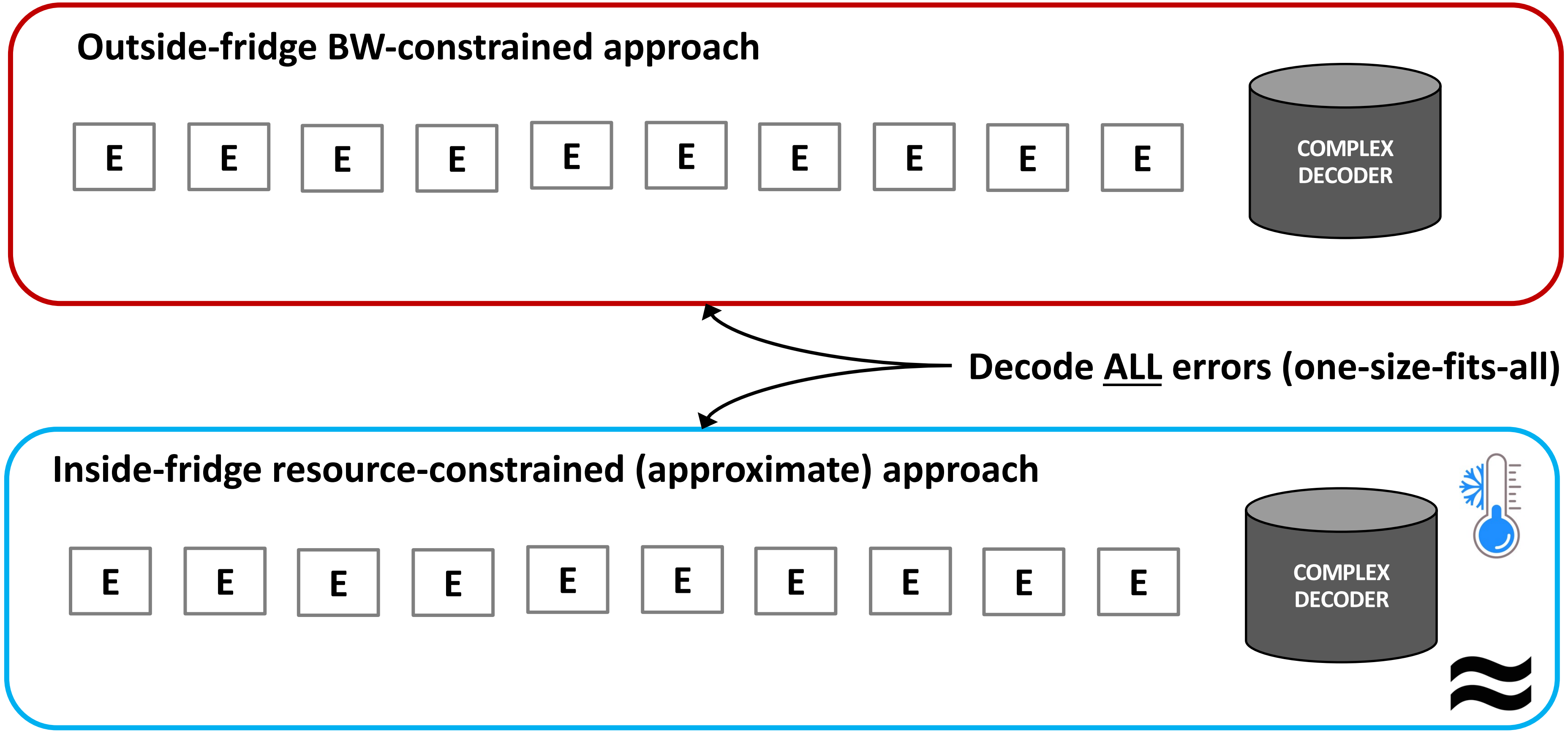
P = ~1W



E: Error Signatures

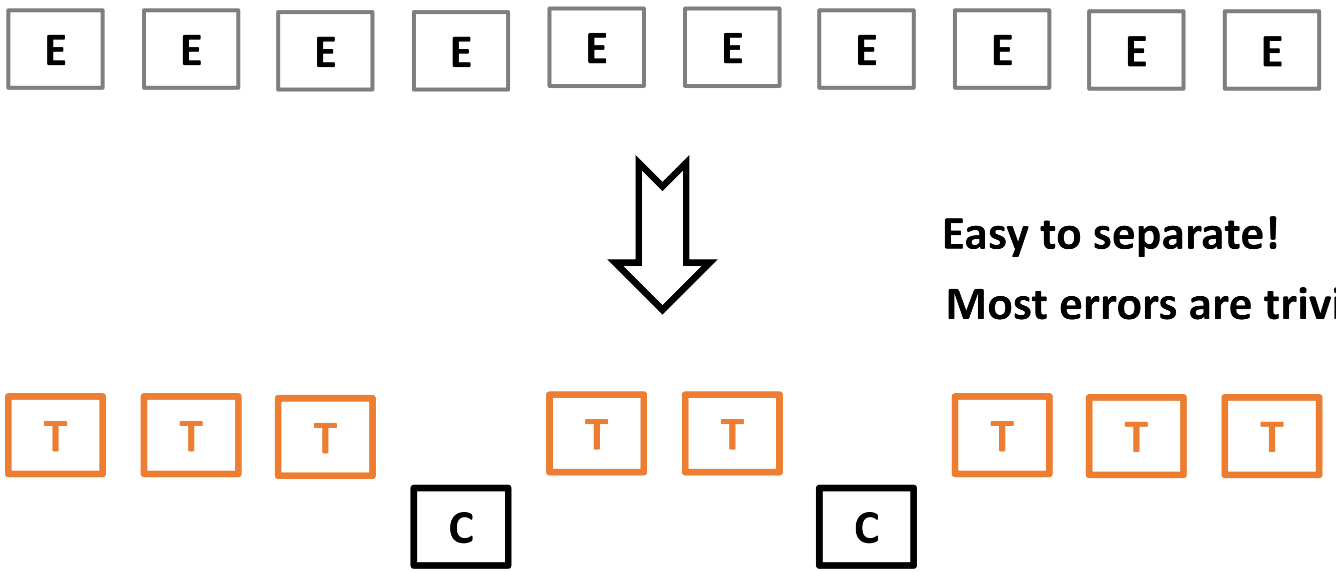


Most prior methods to decoding: treat all errors similarly



Better than worst case approach to decoding

Key Insight: Not all errors hard to decode → Separate common trivial errors from rare complex errors.



Easy to separate!

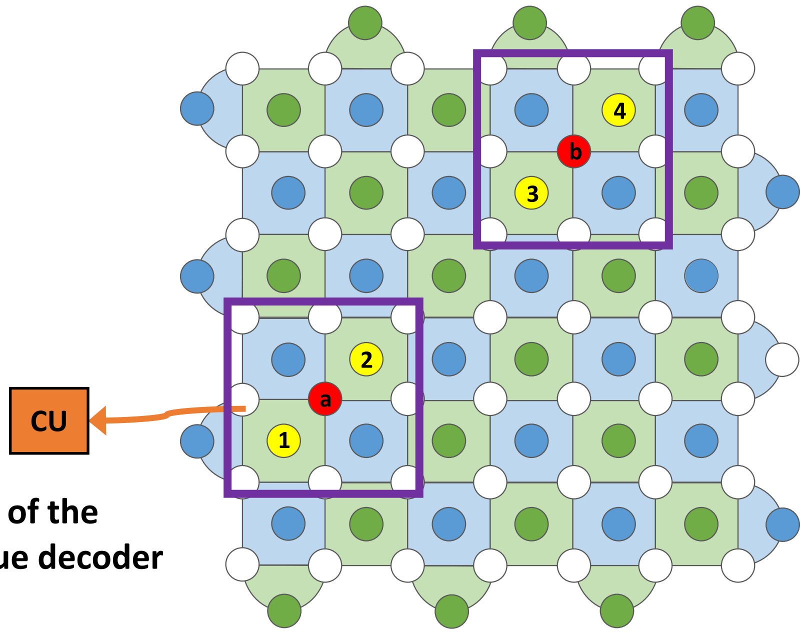
Most errors are trivial!

T: Trivial-to-decode
C: Complex-to-decode

Better than worst case approach to decoding

<u>Key Insight:</u> Not all errors hard to decode → Separate common trivial errors from rare complex errors.

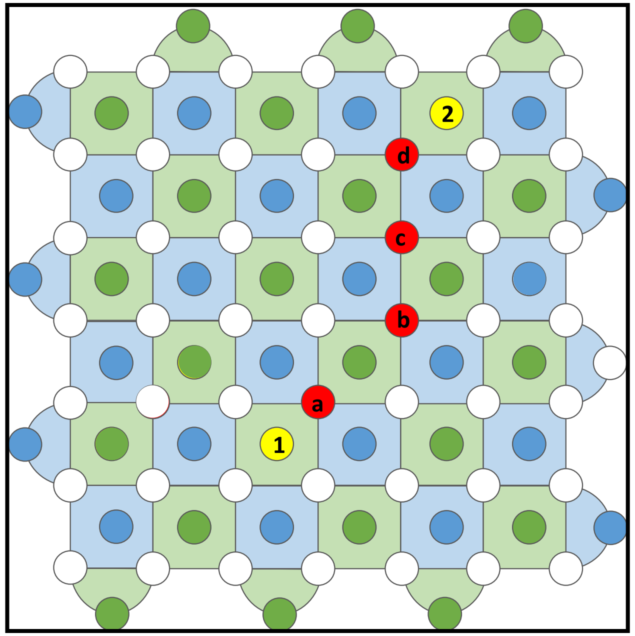
T (90-99+ %)



Unit of the Clique decoder

Isolated errors: Trivial to decode + common

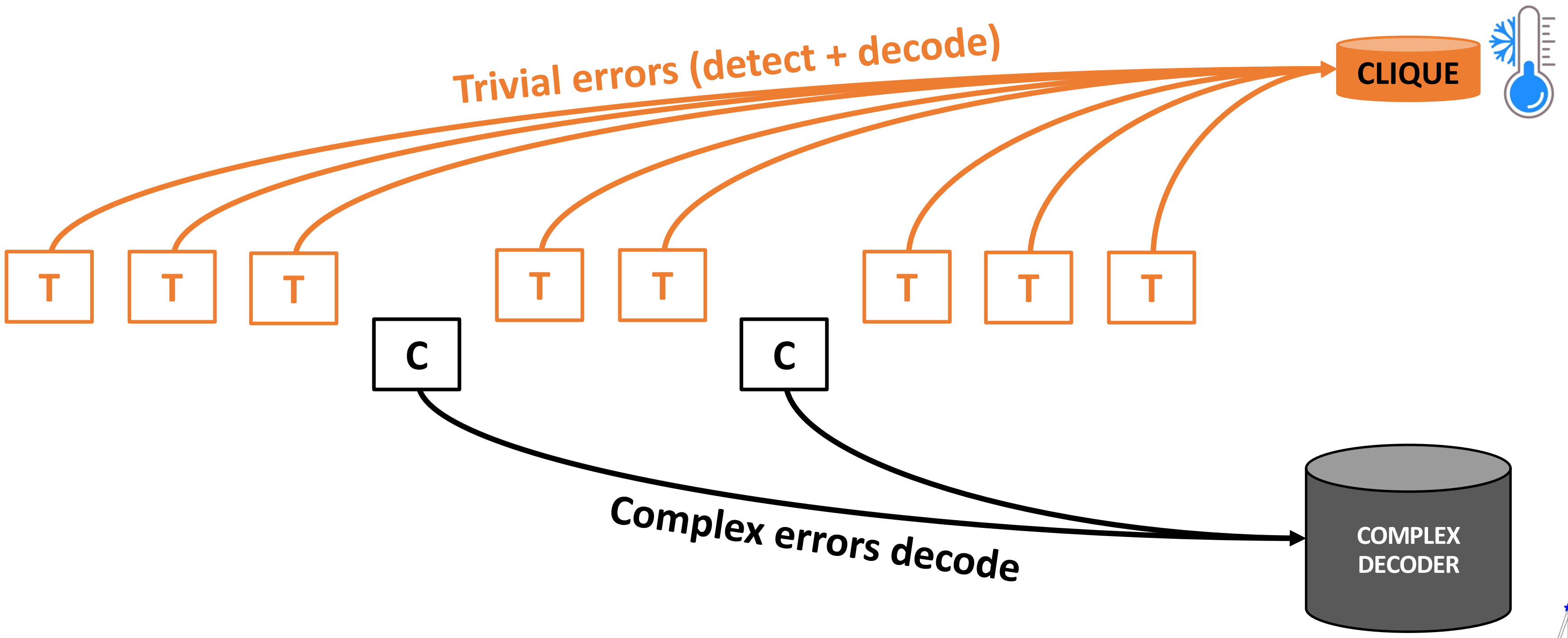
C (<1-10 %)

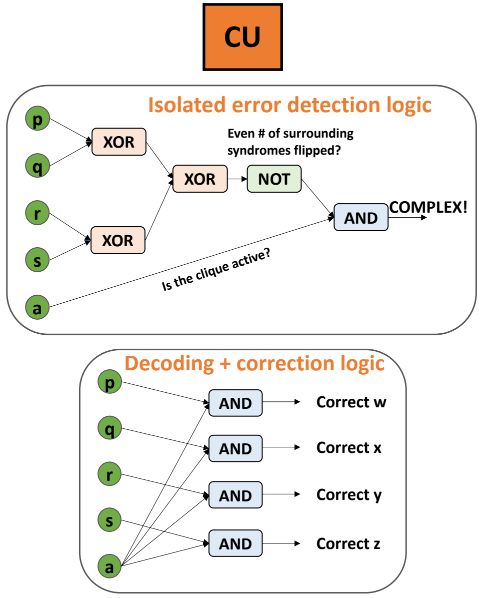


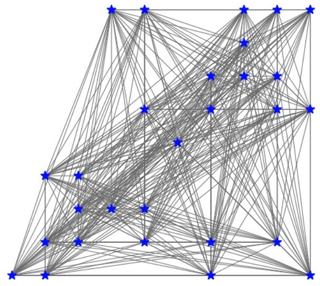
Error chains: Hard to decode + very rare

Better than worst case approach to decoding

Common trivial errors → simple cryogenic 'Clique' decoder.
Rare complex errors → outside-fridge SOTA complex decoder.





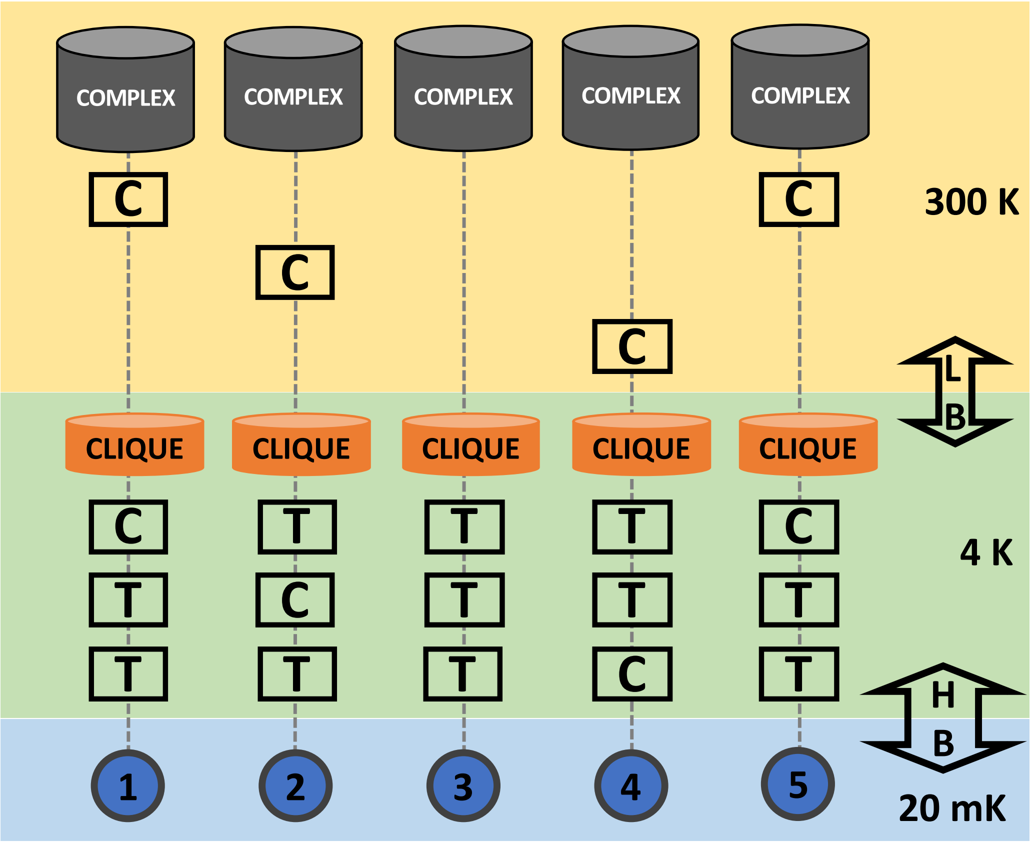


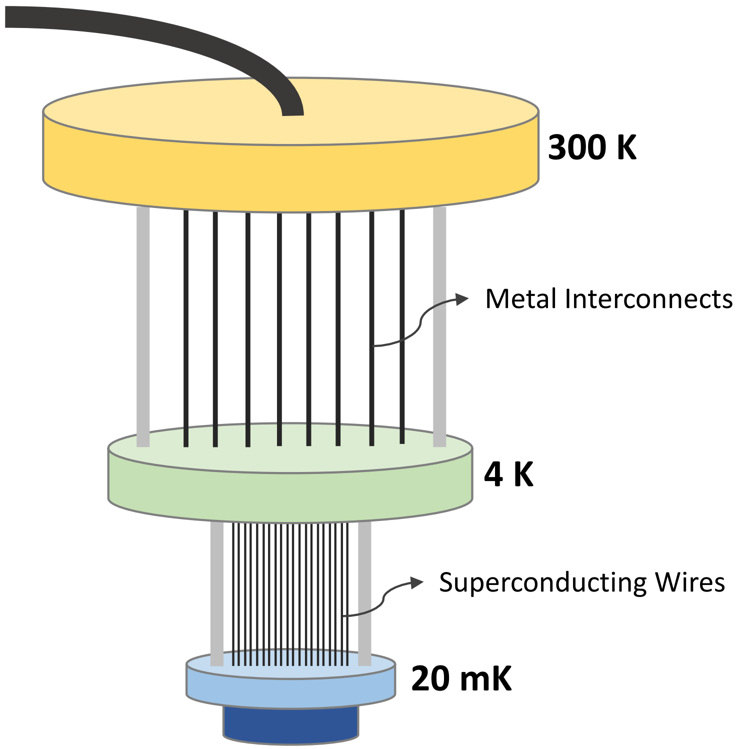
Minimum Weight Perfect Matching

T: Trivial-to-decode
C: Complex-to-decode

System-level view: Better than worse-case decoding

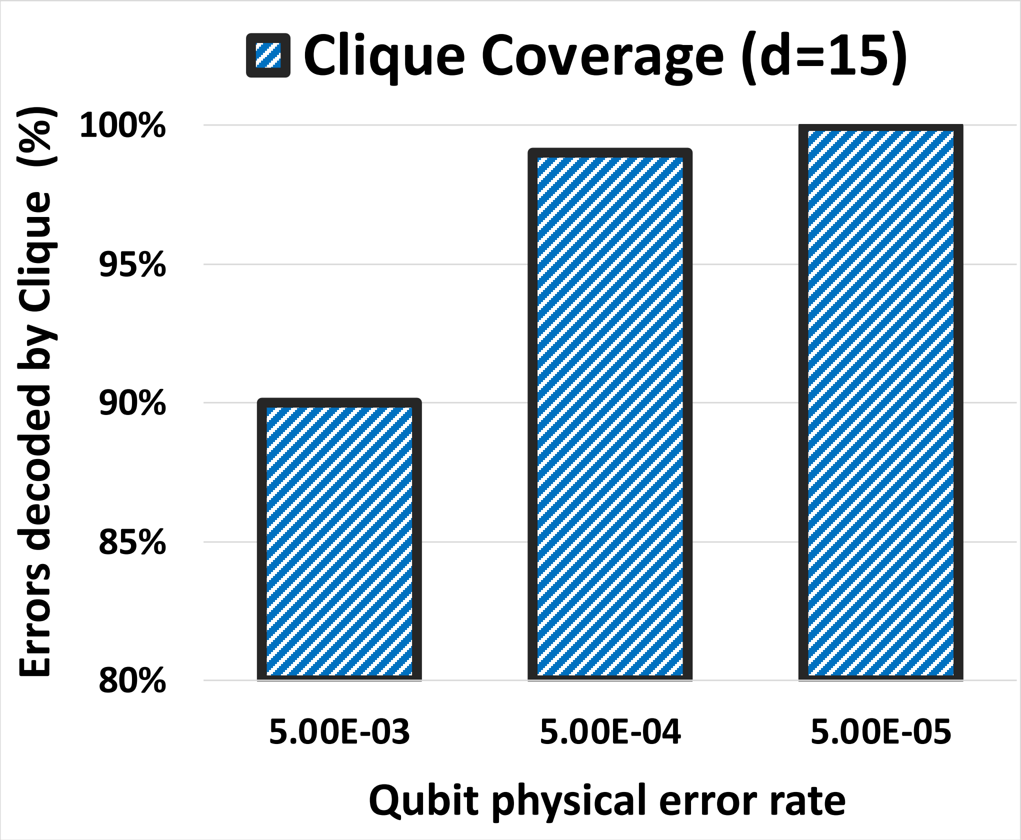
Reduced outside-fridge decoding → No bandwidth bottleneck!
Reduced inside-fridge decoding HW → No cryo-resource bottleneck!

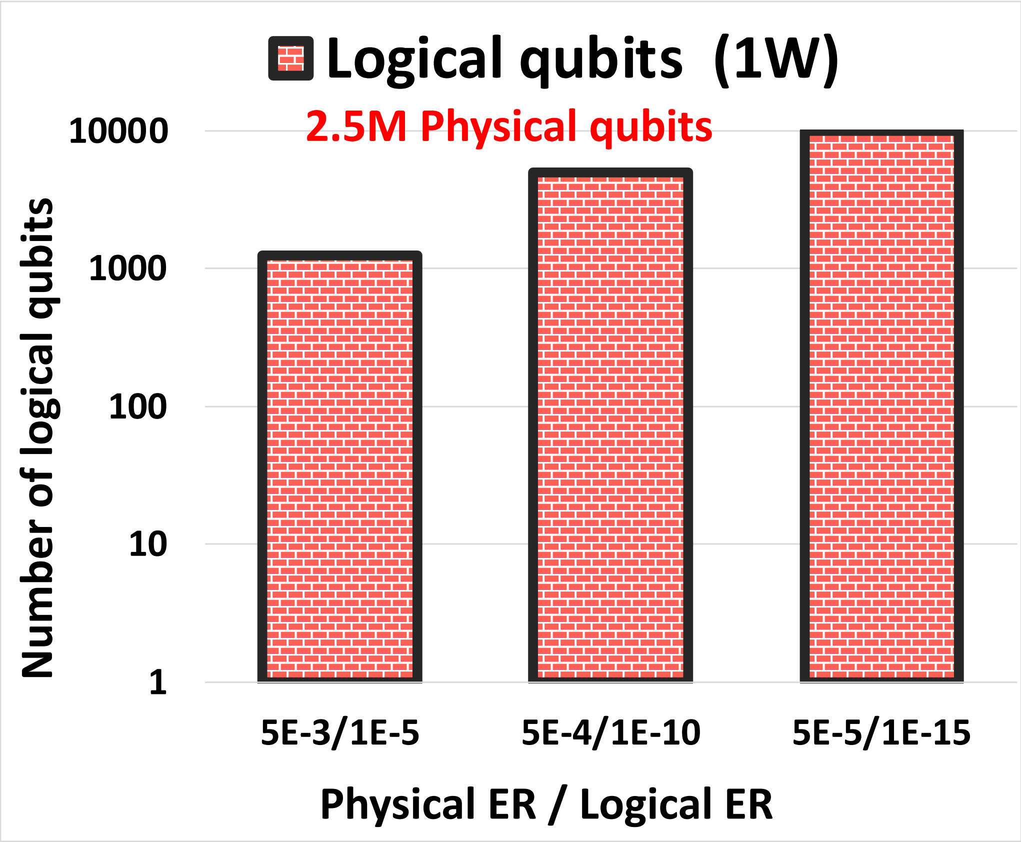




Quantitative benefits

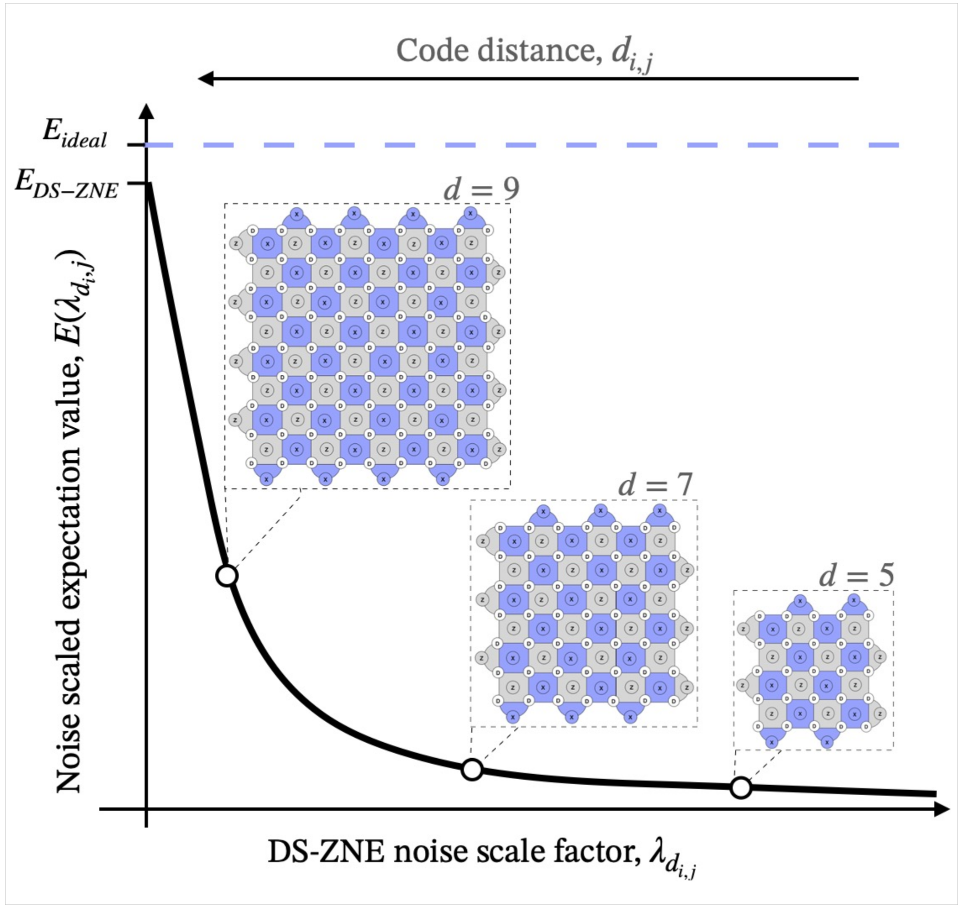
90 - 100% of decodes handled trivially by Clique. Supports 2.5M physical qubits with 1W power.

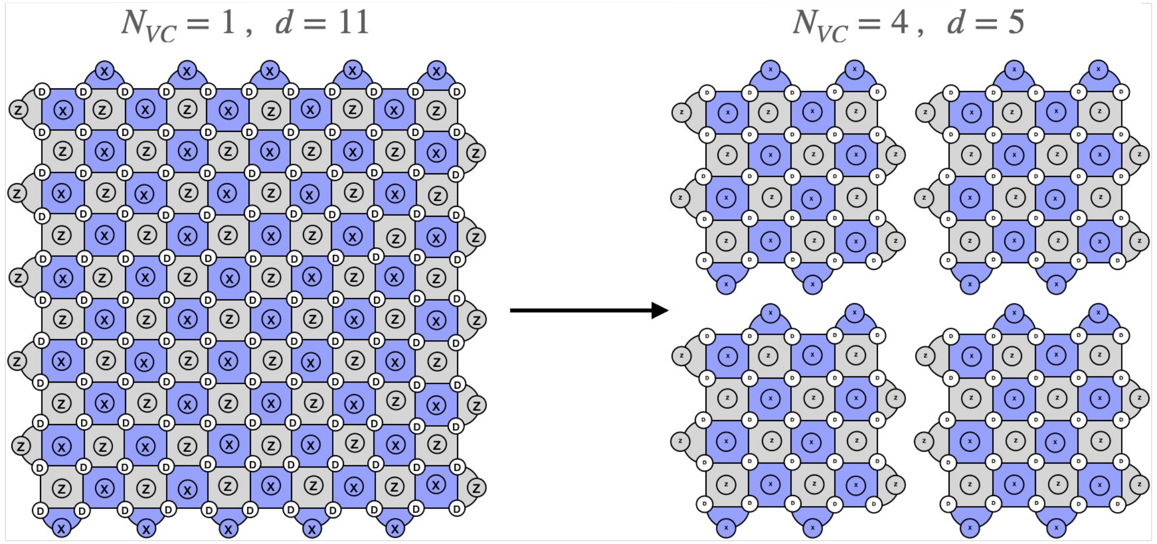




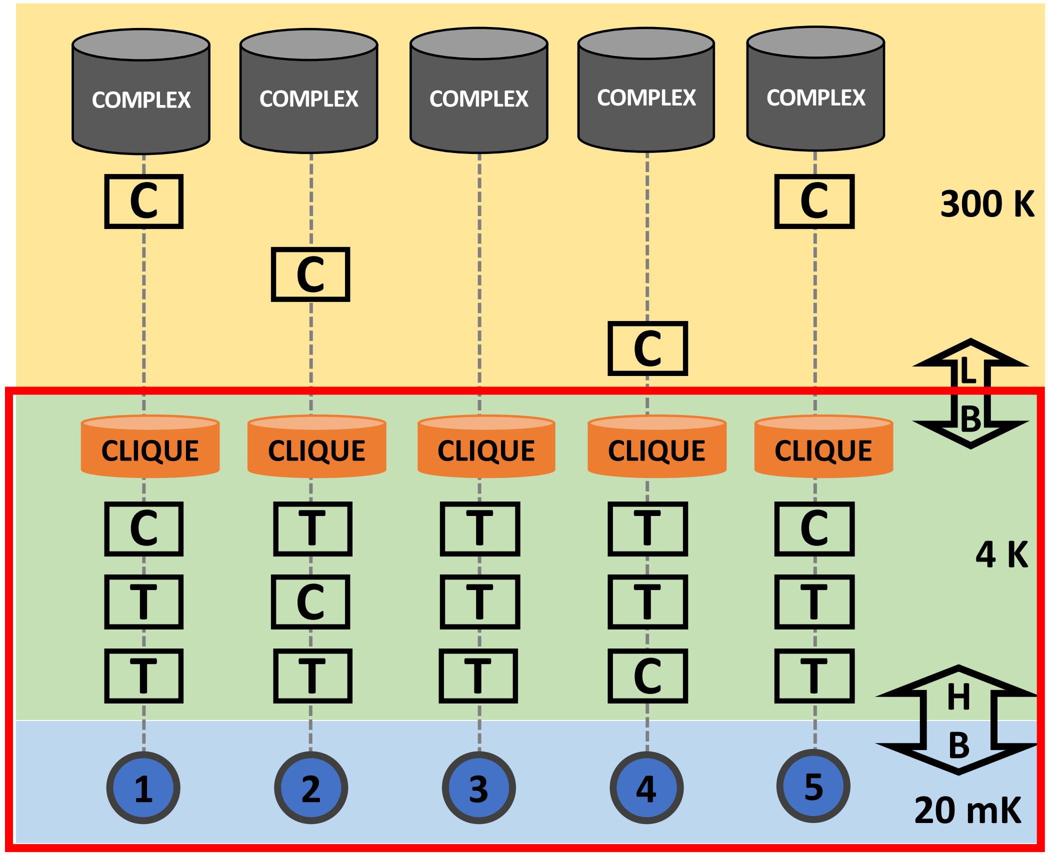
DS-ZNE: Zero noise extrapolation on logical qubits by scaling the error correction code distance

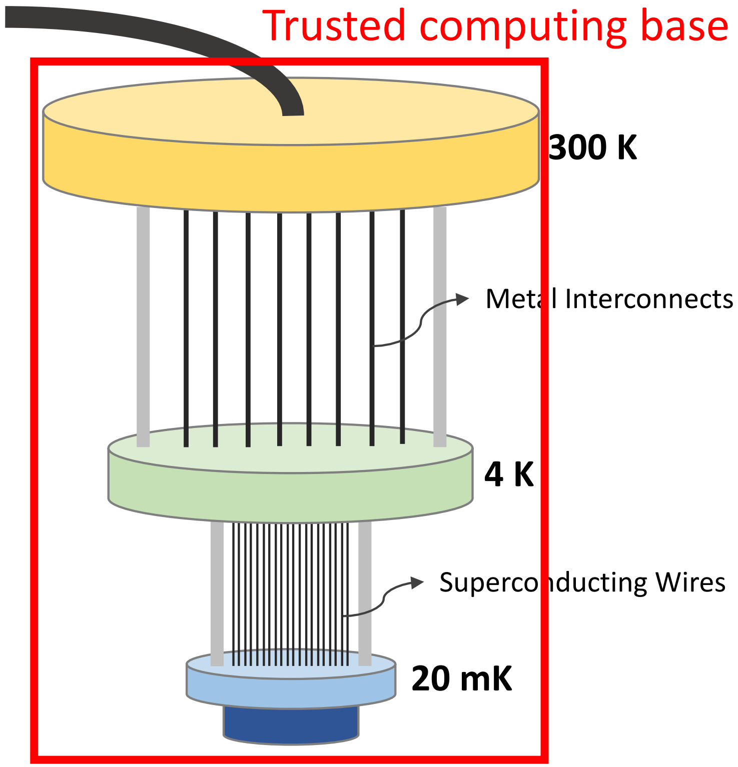
Misty Wahl, Andrea Mari, Nathan Shammah, William Zeng, Gokul Ravi. QCE 2023. arXiv:2304.14985



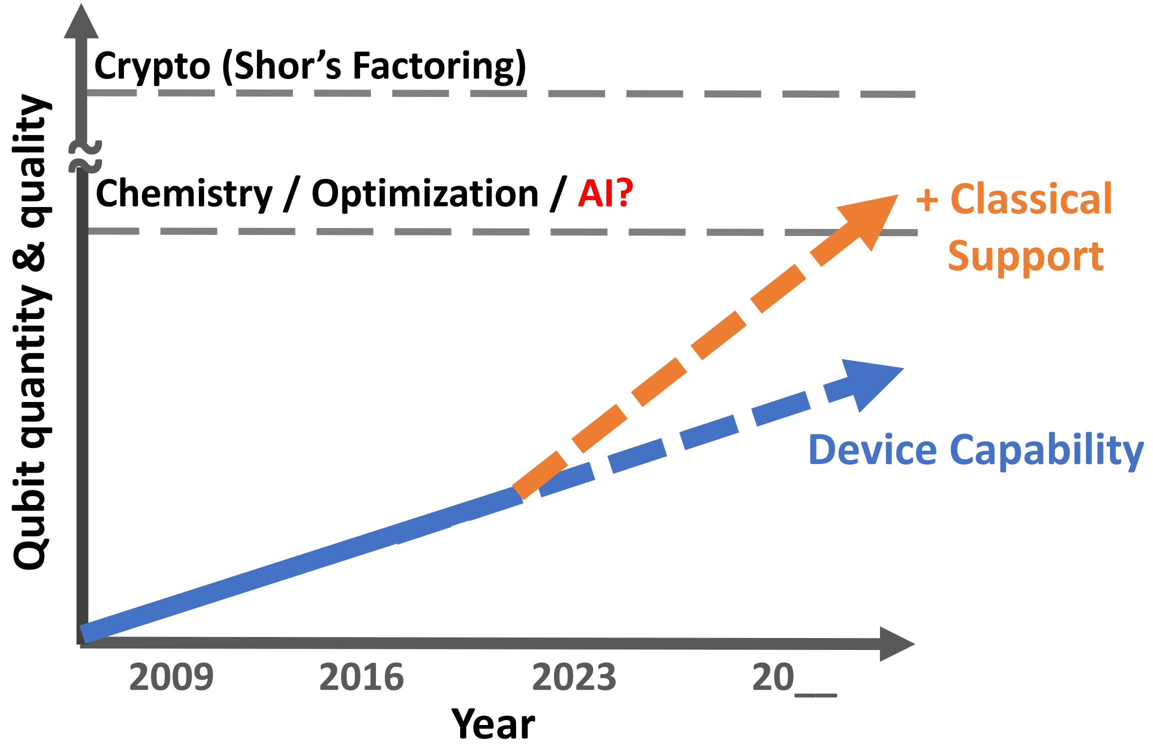


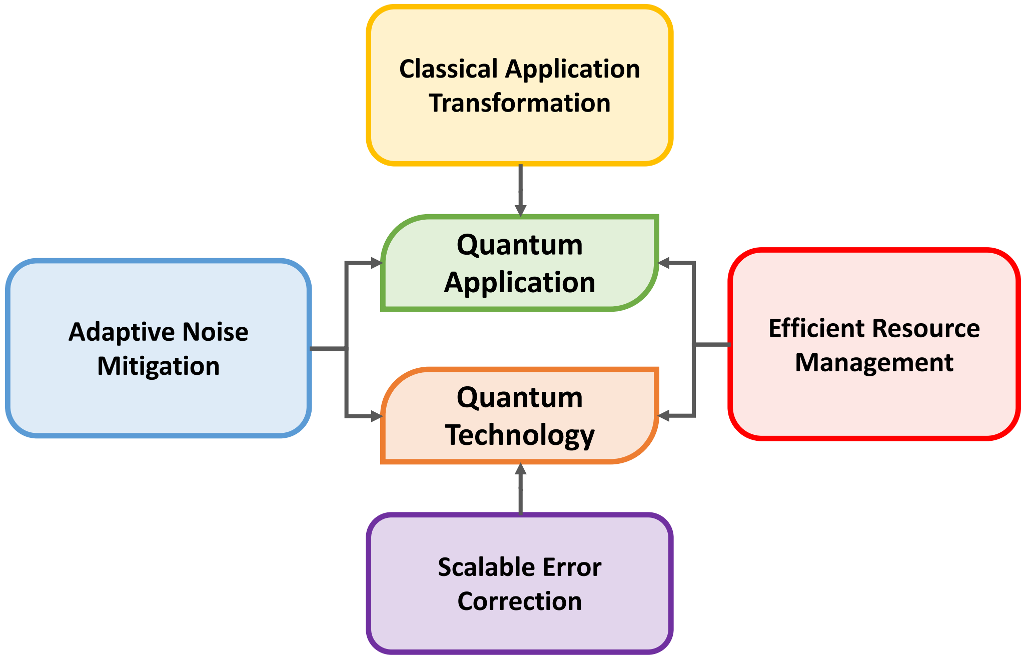
Secure quantum system architectures





Summary: A Hybrid Computing Ecosystem for Practical Quantum Advantage





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