ANNEALING QUANTUM COMPUTING AND OPTIMIZATION

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Chief Development Officer
June 17th, 2024

D:WAVE

PRIMARY APPROACHES TO QUANTUM COMPUTING

ANNEALING

AN EASIER ON-RAMP
TO QUANTUM COMPUTING

Natively optimization

Commercial today

ANNEALING OR GATE

GATE-MODEL

HIGHER INVESTMENT
COST & LEARNING CURVE

Suited to differential equations

7+ years to commercialization

COMBINATORIAL OPTIMIZATION

Employee Scheduling
Autonomous Vehicle Routing
Peptide Design
Fraud Detection
Patient Trial Optimization

LINEAR ALGEBRA & FACTORIZATION

Machine Learning
Cryptography
Drug Toxicity
Global Weather Modeling

DIFFERENTIAL EQUATIONS

Designer Drugs
New Materials
Longer-Life Batteries

QC industry, except D-Wave, almost exclusively focused on gate-model QC

LONG TERM ADVANTAGE IN OPTIMIZATION

OPTIMIZATION IS A KEY APPLICATION AREA FOR ANNEALING QC

- More resilient to errors
- Does not require significant preprocessing or tuning
- Does not require high bandwidth qubit control
- Technology is scaling to thousands of qubits
- Near-term large-scale quantum computing technology

LONG TERM ADVANTAGE IN OPTIMIZATION

OPTIMIZATION IS A KEY APPLICATION AREA FOR ANNEALING QC

Research points to QA outperforming in scale, quality, and speed

Optimization Applications as Quantum Performance Benchmarks

Thomas Lubinski,[1,2] Carleton Coffrin,[3] Catherine McGeoch,[4]
Pratik Sathe,[5,6,7] Joshua Apanavicius,[8,9] and David E. Bernal Neira[6,10,11]
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(Dated: February 5, 2024)

LONG TERM ADVANTAGE IN OPTIMIZATION

OPTIMIZATION IS A KEY APPLICATION AREA FOR ANNEALING QC

NISQ-era systems are not competitive in optimization

Article | Open access | Published: 12 March 2024

Short-depth QAOA circuits and quantum annealing on higher-order ising models

Elijah Pelofske, Andreas Bärtschi & Stephan Eidenbenz

npj Quantum Information **10**, Article number: 30 (2024) | Cite this article

2127 Accesses | **3** Altmetric | Metrics

LONG TERM ADVANTAGE IN OPTIMIZATION

OPTIMIZATION IS A KEY APPLICATION AREA FOR ANNEALING QC

Fault tolerant gate-model systems have high overhead

Focus beyond Quadratic Speedups for Error-Corrected Quantum Advantage

Ryan Babbush, Jarrod R. McClean, Michael Newman, Craig Gidney, Sergio Boixo, and Hartmut Neven
PRX Quantum **2**, 010103 – Published 29 March 2021

APPLICATION-ORIENTED BENCHMARKING

- End users assessing QC technology care about performance on specific applications
- End users assessing QC technology also care about cost of computation
  - Total execution time
  - Energy required
- Application focus makes it possible to compare different quantum computing technologies and modalities
- Application focus makes it possible to understand emerging advantages to using quantum computing technologies over classical approaches
- As new hardware becomes available, and as new application classes are identified, there is a strong framework for assessment

APPLICATION-ORIENTED BENCHMARKING

Quantum Computing

IEEE Transactions on Quantum Engineering

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Application-Oriented Performance Benchmarks for Quantum Computing

THOMAS LUBINSKI[1,2], SONIKA JOHRI[3], PAUL VAROSY[4], JEREMIAH COLEMAN[5], LUNING ZHAO[3], JASON NECAISE[6], CHARLES H. BALDWIN[7], KARL MAYER[7], AND TIMOTHY PROCTOR[8]

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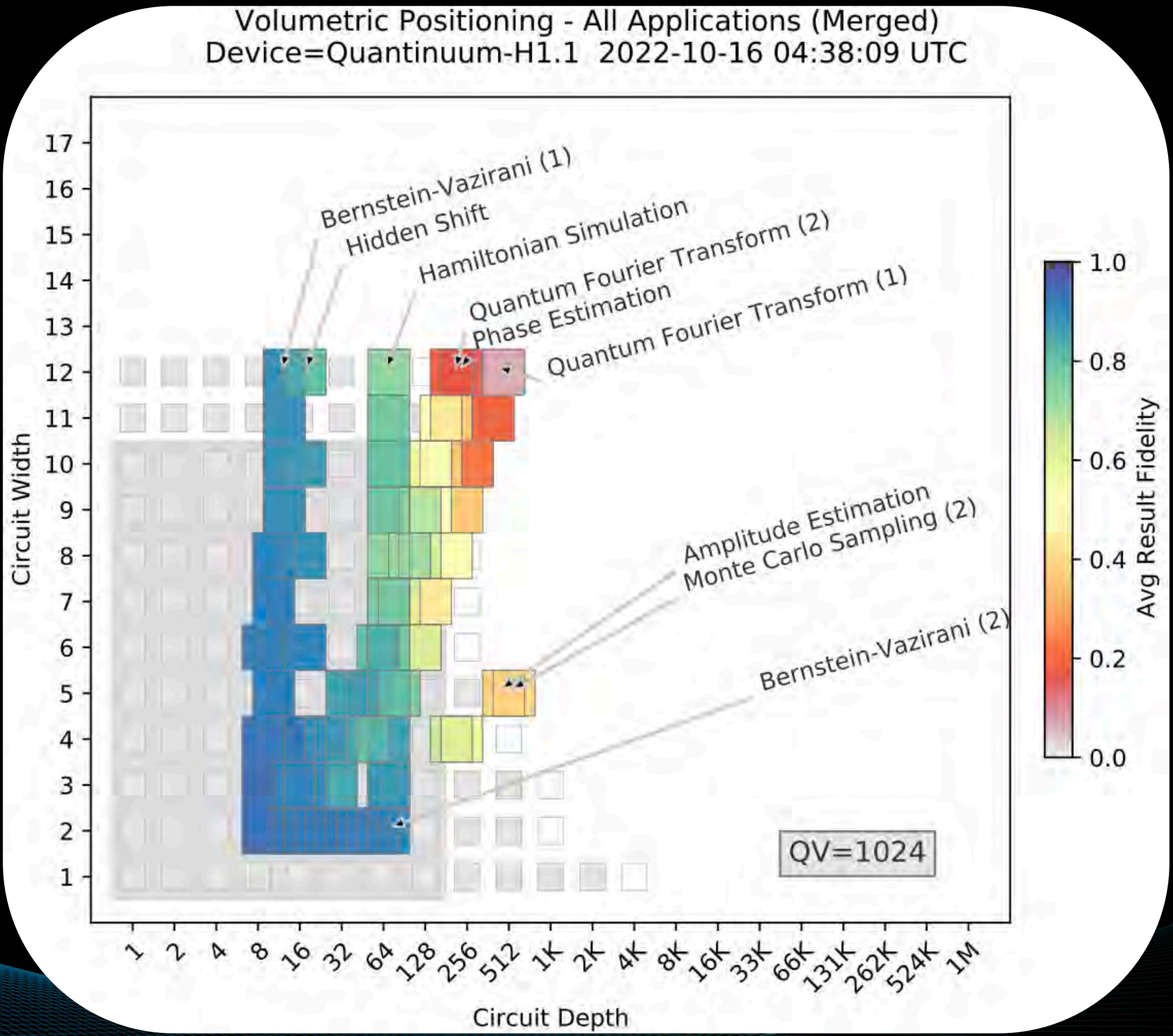
- This is the framework IonQ has adopted

APPLICATION-ORIENTED BENCHMARKING

- Adapting 'volumetric' metrics to actual applications
- Gate-model focused
- Mix of algorithmic complexity
  - Tutorial
  - Subroutine
  - Functional/Complete
- Advantages: stepping toward application performance
- Disadvantage:
  - Execution time ignored
  - Transpilation/compilation resources ignored
  - Hard to interpret problem scaling



Lubinski et al 2021

ADDING A KEY APPLICATION AREA: OPTIMIZATION

ASSESS MULTIPLE QUANTUM COMPUTING PLATFORMS FOR OPTIMIZATION

Optimization Applications as Quantum Performance Benchmarks

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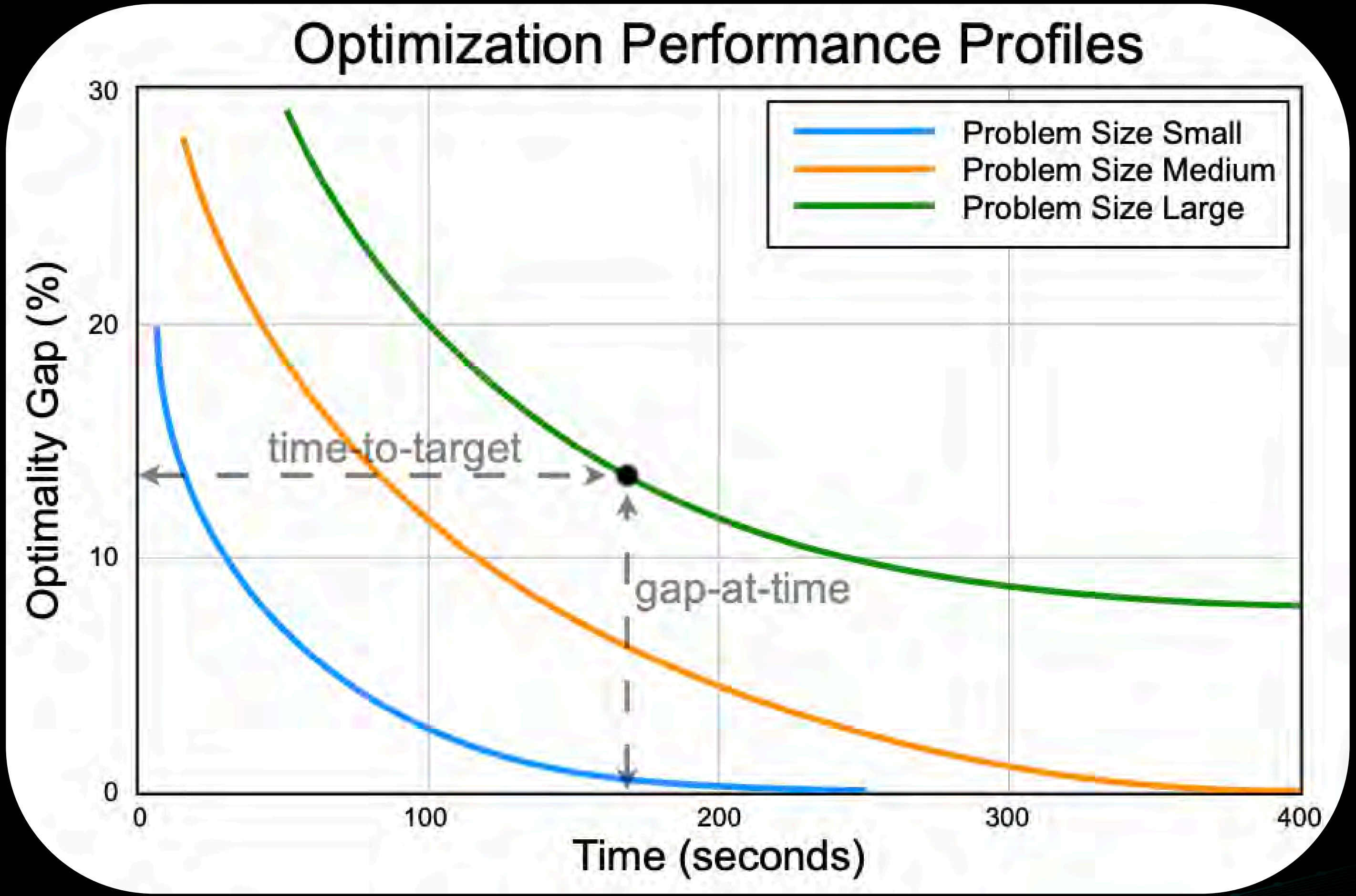
(Dated: February 5, 2024)

ADDING A KEY APPLICATION AREA: OPTIMIZATION

- Several performance criteria involved with assessing optimization performance
- Problem scale
- Time to a quality target
- Time to optimal
- Quality after a particular time
- ‘Quantum execution time’ and ‘cumulative execution time’ are important: variational approaches need tuning
- Operations Research field primarily focused on ‘gap-at-time’



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ADDING A KEY APPLICATION AREA: OPTIMIZATION

- Use MAX-CUT problem class
- Challenging combinatorial optimization class
- Unconstrained discrete optimization problem
- Well suited to QA
- Well suited to QAOA
- Useful for comparing many quantum computing technology platforms

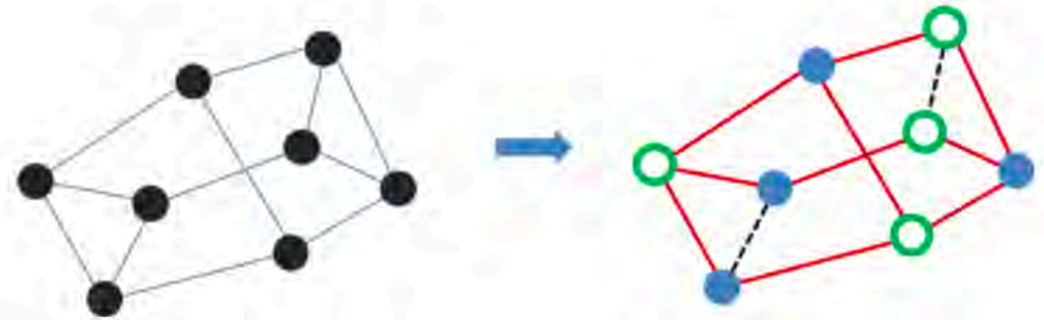

FIG. 3: **The MaxCut Problem.** For an undirected graph consisting of nodes, or vertices, (V) and edges (E), partition the vertices into complementary sets such that the number of edges between the sets is the greatest. This graph shows one solution to one instance of the MaxCut problem for a graph with eight nodes, using colored nodes and edges. Nodes with different colors belong to the two sets of the solution cut. The number of solid red edges that connect nodes from different sets is the MaxCut of that graph.

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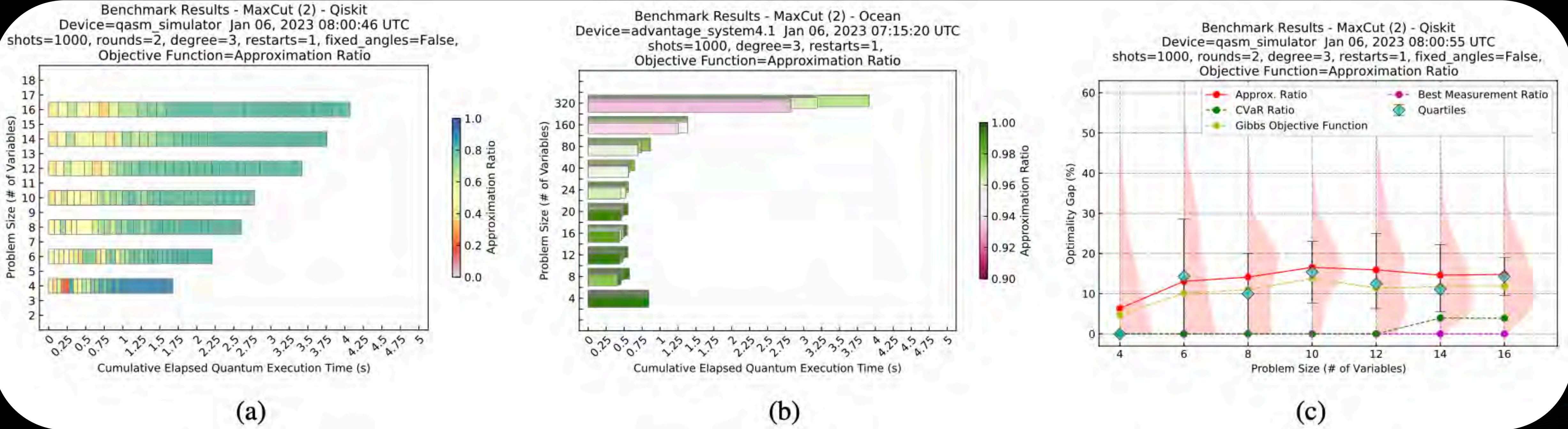
APPLICATION-ORIENTED BENCHMARKING: OPTIMIZATION

- Characterizes Performance of QAOA and Quantum Annealing
- Quantum execution time and application problem scale: central to benchmarking
- Ideal QAOA (gate) simulator struggling to return answers at a small scale



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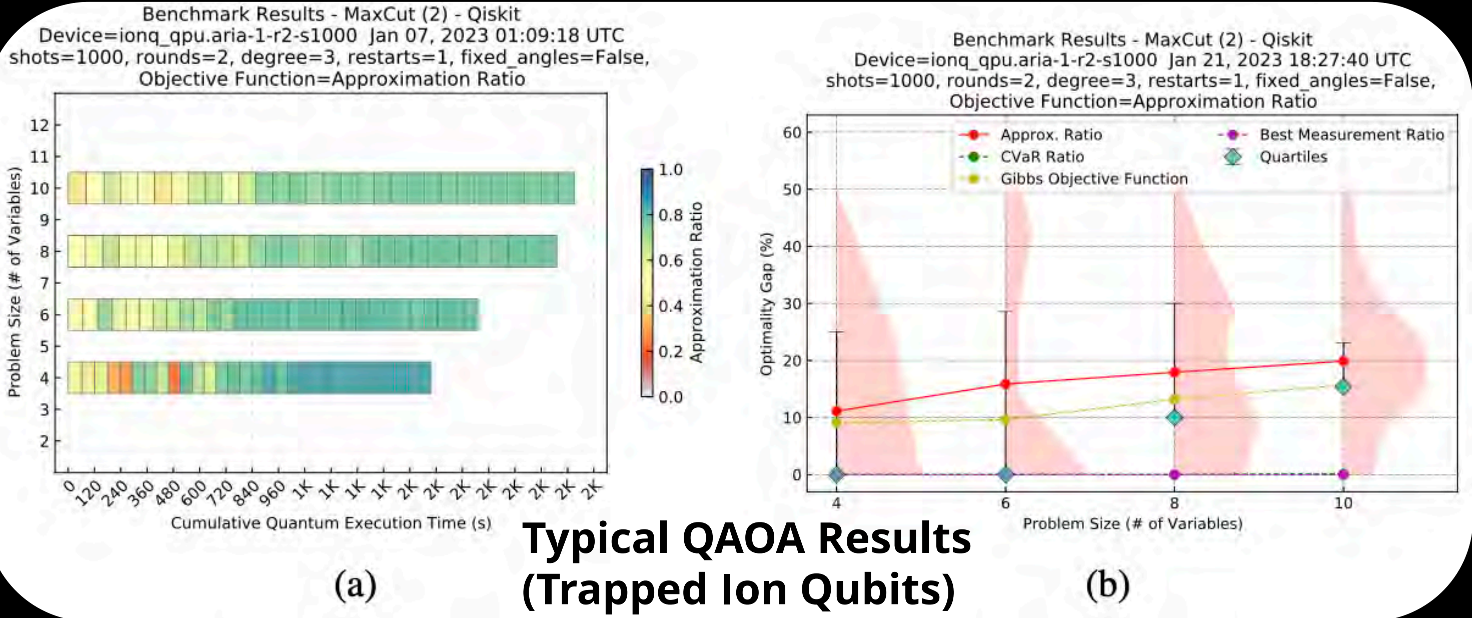
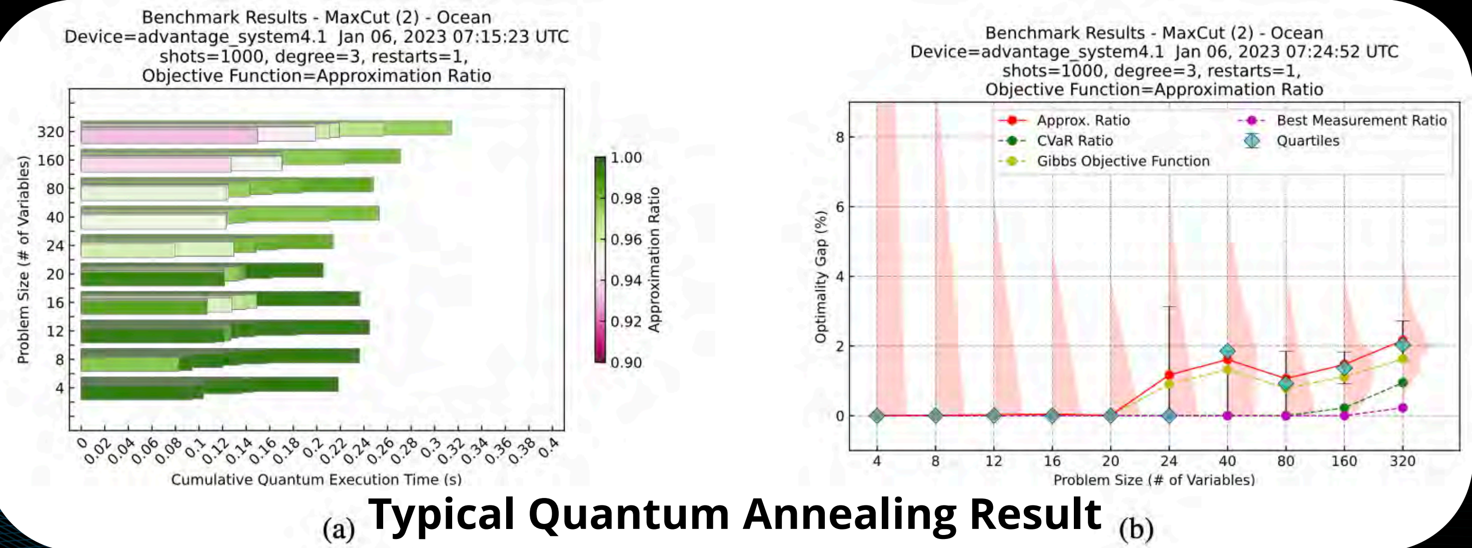
COMPARING APPROACHES: QUANTUM ANNEALING WINS

- QA: solves larger instances
- QA: provides higher quality solutions
- QA: significantly lower run times



Typical QAOA Results (Trapped Ion Qubits)



Typical Quantum Annealing Result

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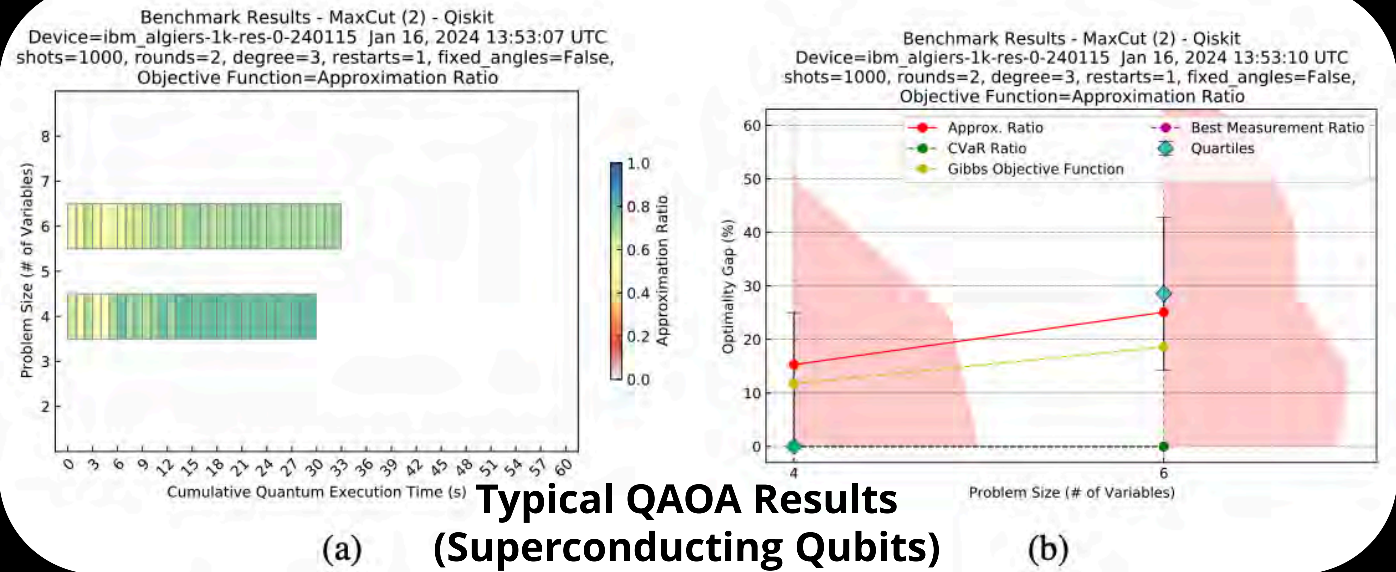
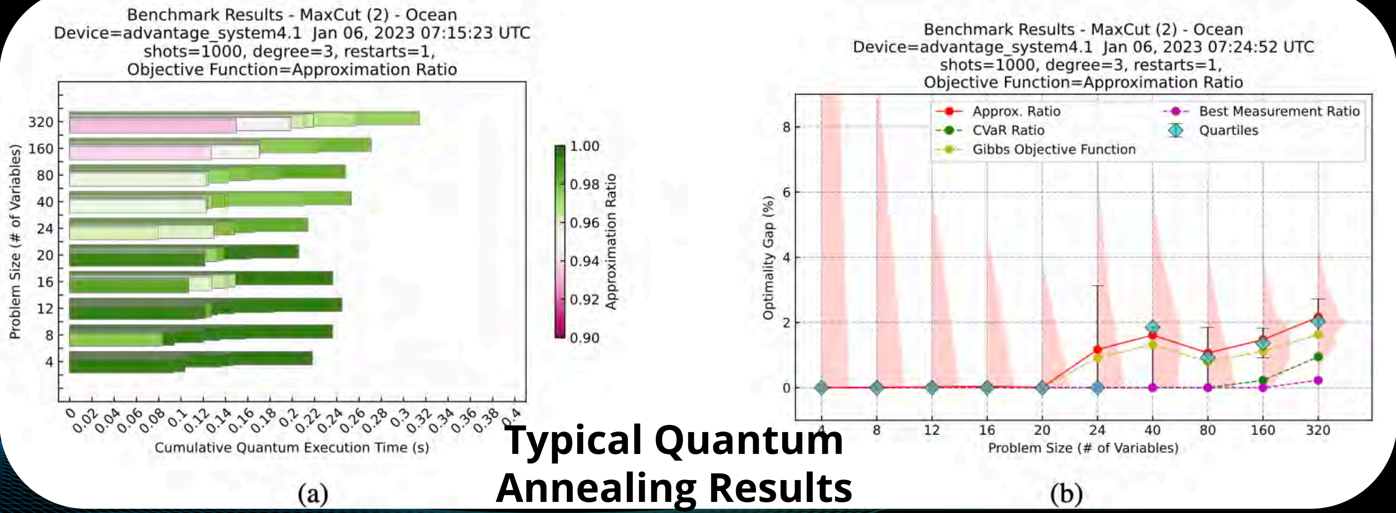
COMPARING APPROACHES: QUANTUM ANNEALING WINS

- QA: solves larger instances
- QA: provides higher quality solutions
- QA: significantly lower run times



Typical QAOA Results (Superconducting Qubits)



Typical Quantum Annealing Results

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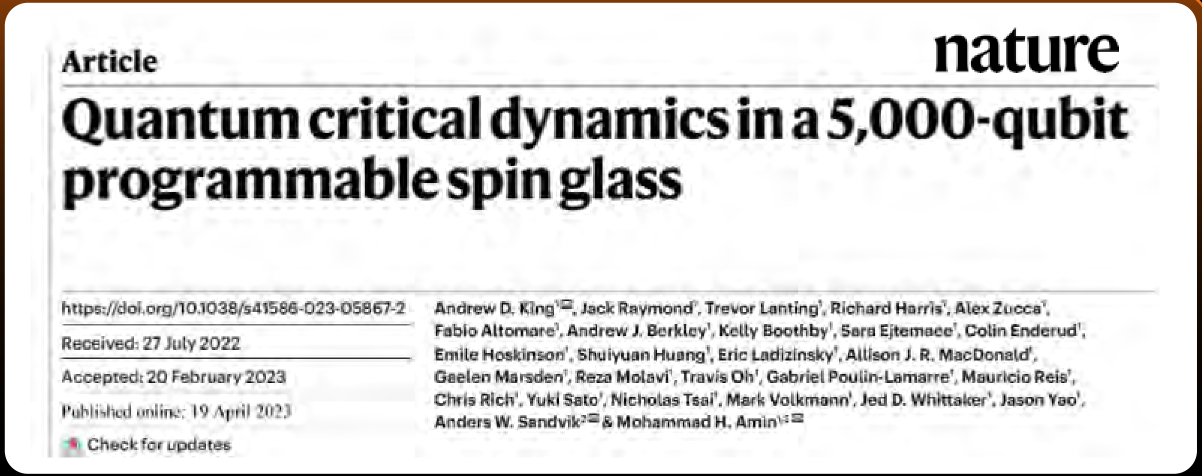
ADDING A KEY APPLICATION AREA: ISING SPIN GLASSES



Article

nature

Quantum critical dynamics in a 5,000-qubit programmable spin glass

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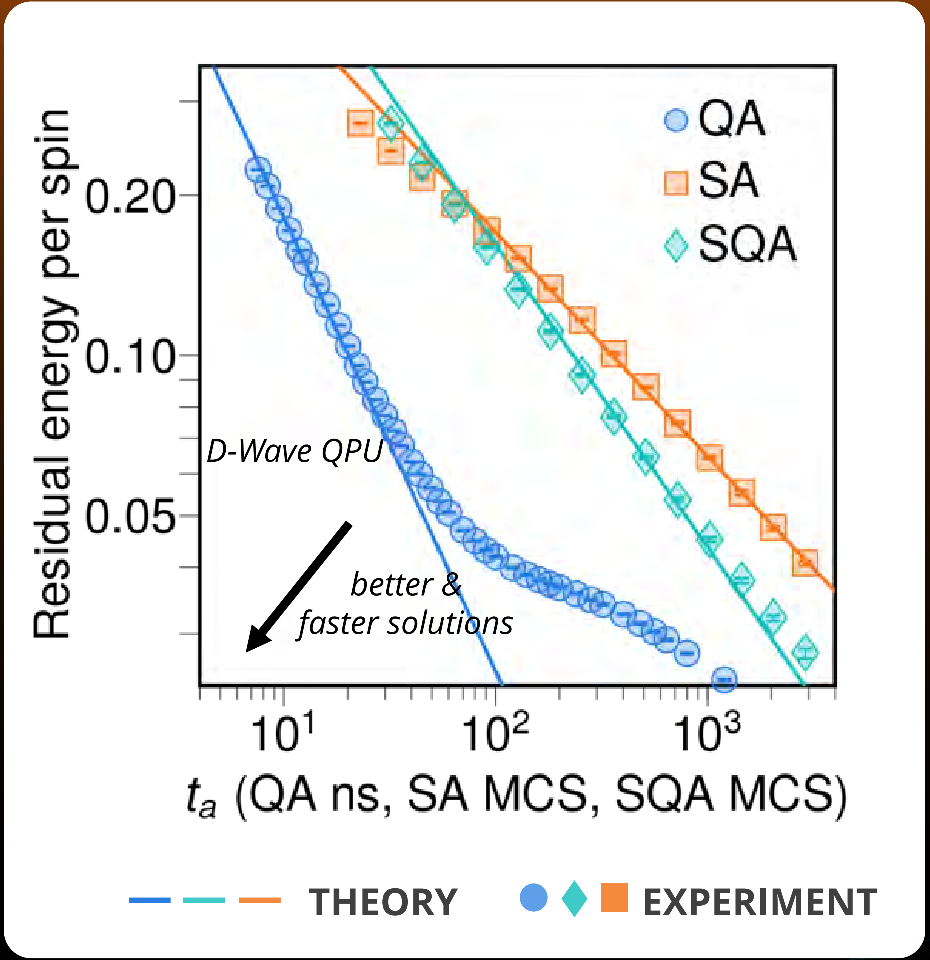
- Another well studied and challenging combinatorial optimization task
- Growing evidence that harnessing coherent quantum dynamics gives a scaling advantage
- Basis for computational supremacy investigation

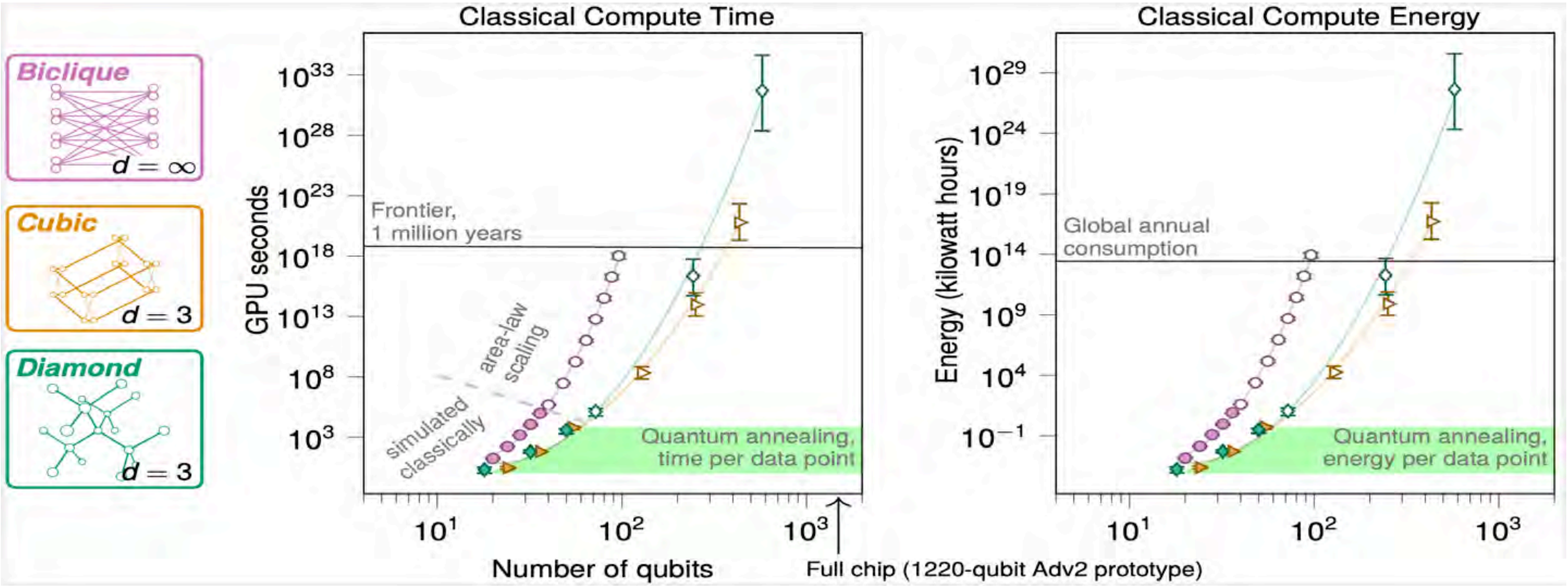


QA: Quantum Annealing
SA: Simulated Annealing
SQA: Simulated Quantum Annealing

D:WAVE

COMPUTATIONAL SUPREMACY IN QUANTUM SIMULATION USING ADVANTAGE2™ PROTOTYPE

We believe D-Wave is the first in the world to demonstrate quantum supremacy on real-world problems; These problems cannot be solved by classical computers. https://arxiv.org/abs/2403.00910



- Classical computations performed on **FRONTIER AND SUMMIT SUPERCOMPUTERS AT OAK RIDGE NATIONAL LAB**
- **EXPONENTIAL ADVANTAGE** over state-of-the-art classical techniques (tensor networks, neural networks, heuristics)
- **CLASSICAL COMPUTERS TOO SLOW** and power hungry for all but the smallest instances

CAN GATE-MODEL QC SYSTEMS EMULATE ANNEALING QC SYSTEMS? NO.

- In principle, gate-model systems can simulate annealing systems
- In practice, the overhead is prohibitive -- even for very simple systems!
- This analysis does not even account for the overhead involved with error correction

The Cost of Emulating a Small Quantum Annealing Problem in the Circuit-Model

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(Dated: February 28, 2024)

Demonstrations of quantum advantage for certain sampling problems has generated considerable excitement for quantum computing and has further spurred the development of circuit-model quantum computers, which represent quantum programs as a sequence of quantum gates acting on a finite number of qubits. Amongst this excitement, analog quantum computation has become less prominent, with the expectation that circuit-model quantum computers will eventually be sufficient for emulating analog quantum computation and thus rendering analog quantum computation obsolete. In this work we explore the basic requirements for emulating a specific analog quantum computation in the circuit model: the preparation of a biased superposition of degenerate ground states of an Ising Hamiltonian using an adiabatic evolution. We show that the overhead of emulation is substantial even for this simple problem. This supports using analog quantum computation for solving time-dependent Hamiltonian dynamics in the short and mid-term, assuming analog errors can be made low enough and coherence times long enough to solve problems of practical interest.