
AWS
re:Invent
NOV. 28 – DEC. 2, 2022 | LAS VEGAS, NV

QTC302

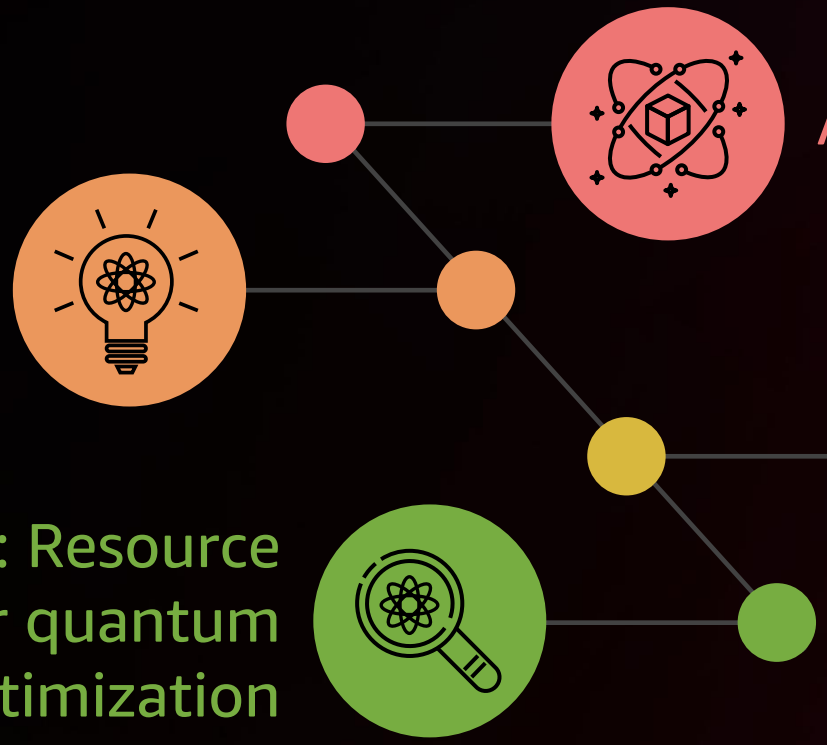
Analyzing use cases and running applications on quantum computers

Grant Salton
Sr. Quantum Research Scientist
AWS Quantum Technologies

Will Zeng
Head of Quantum Research
Goldman Sachs

© 2022, Amazon Web Services, Inc. or its affiliates. All rights reserved.

Agenda



AWS quantum technologies

Goldman Sachs quantum computing

Status of quantum technology in finance

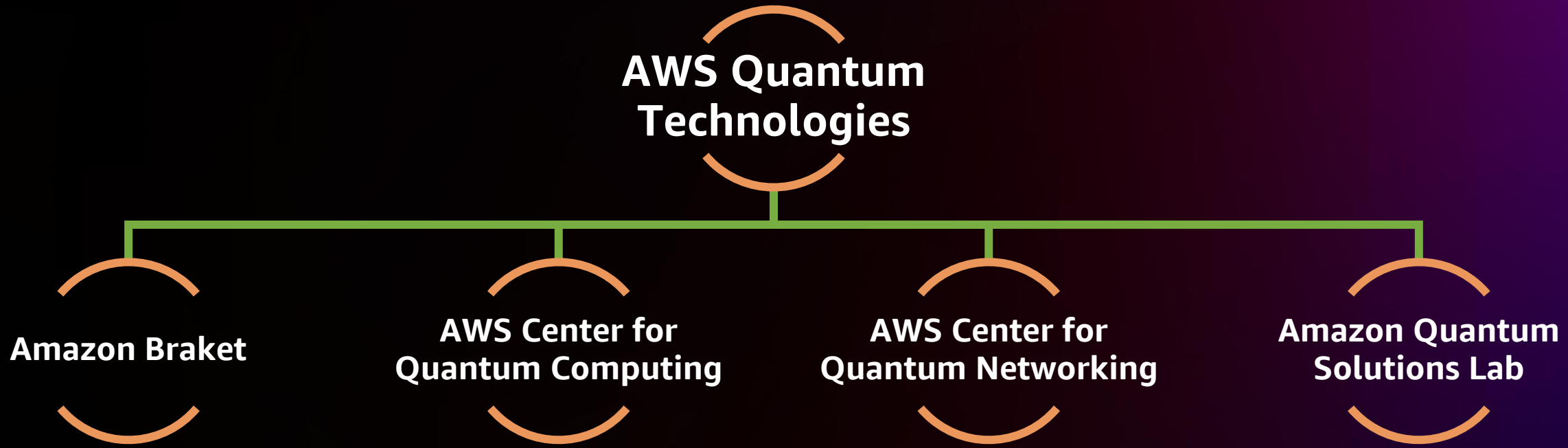
Case study: Resource estimation for quantum portfolio optimization

© 2022, Amazon Web Services, Inc. or its affiliates. All rights reserved.

AWS quantum technology

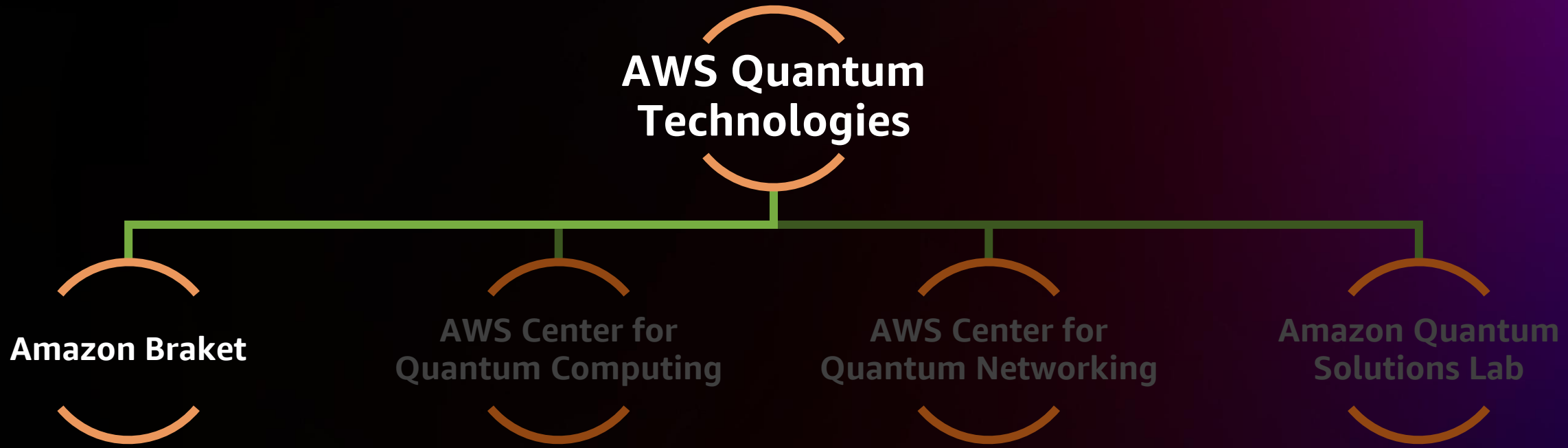
© 2022, Amazon Web Services, Inc. or its affiliates. All rights reserved.

Overview of quantum technologies at AWS



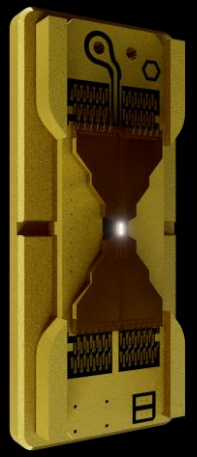
aws
© 2022, Amazon Web Services, Inc. or its affiliates. All rights reserved.

Overview of quantum technologies at AWS

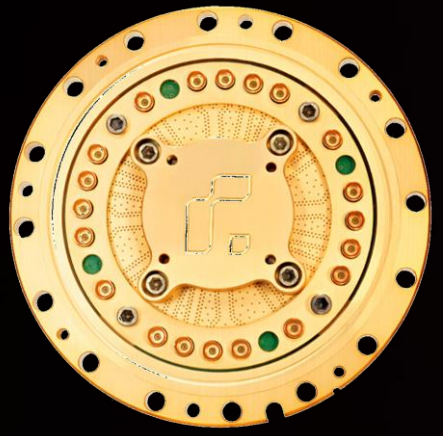


© 2022, Amazon Web Services, Inc. or its affiliates. All rights reserved.

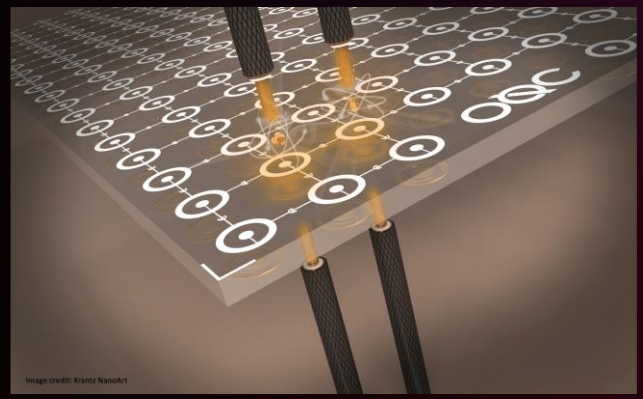
Choice of quantum hardware on Amazon Braket



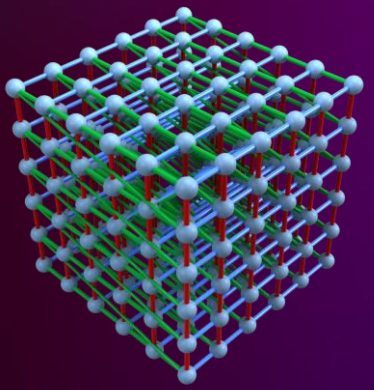
IONQ



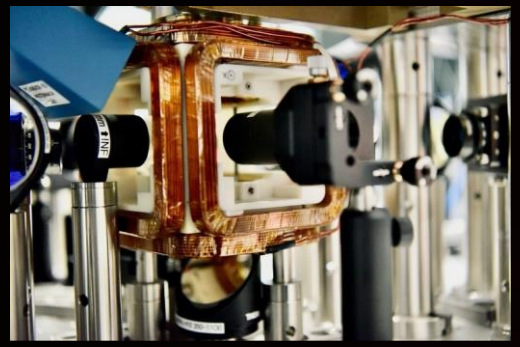
rigetti



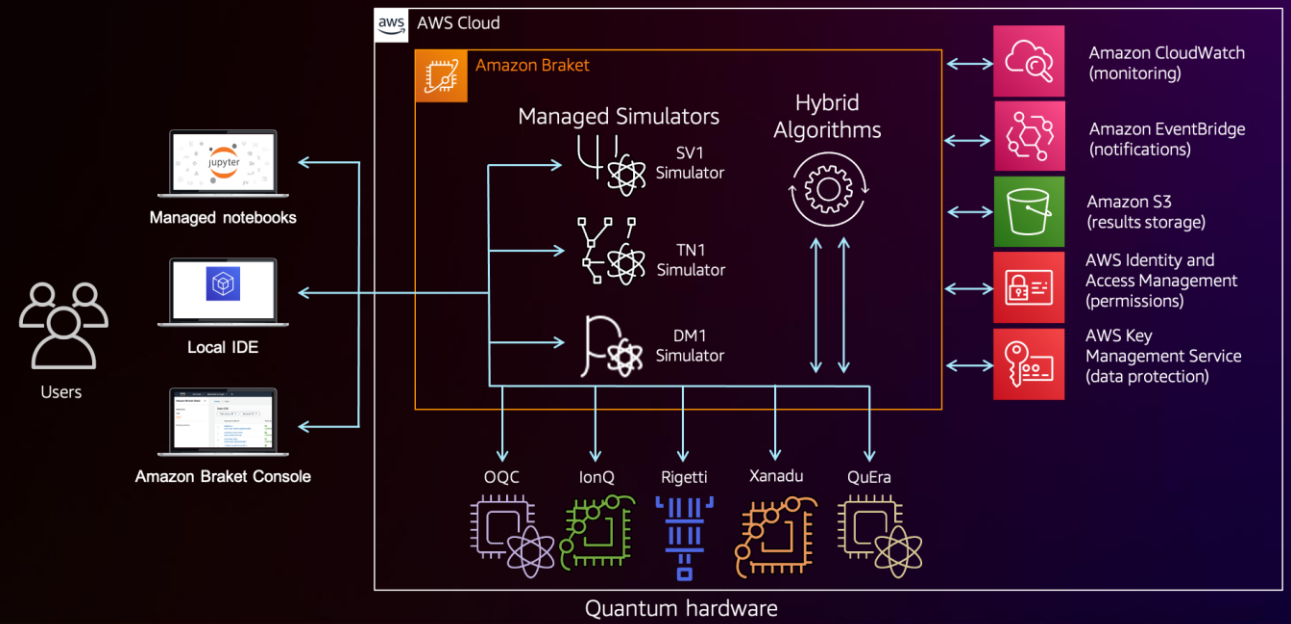
OQC



XANADU

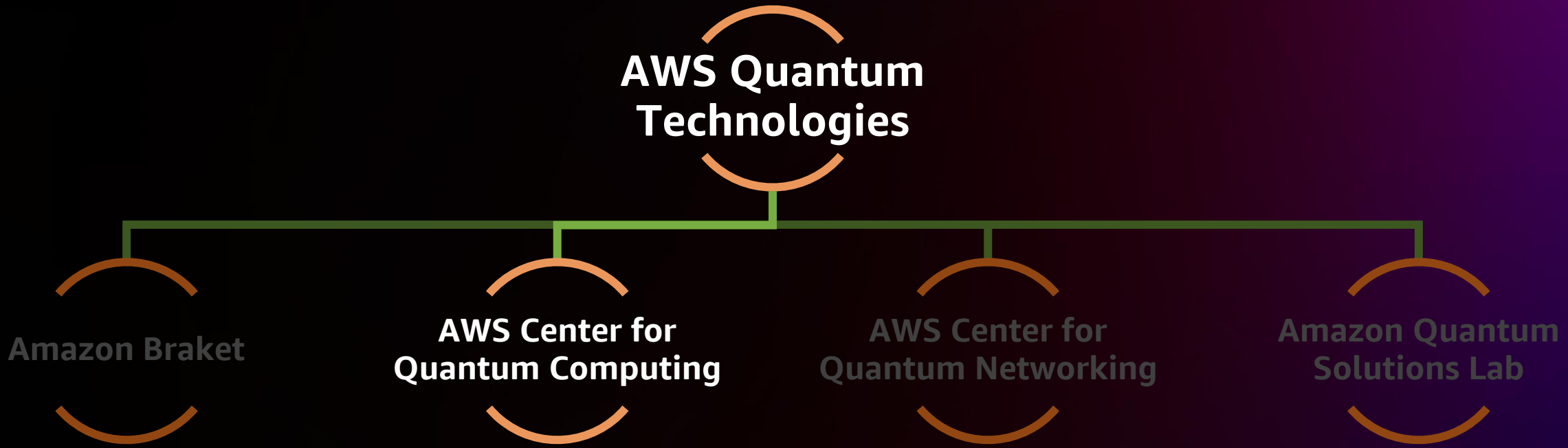


QuEra COMPUTING INC.



© 2022, Amazon Web Services, Inc. or its affiliates. All rights reserved.

Overview of quantum technologies at AWS

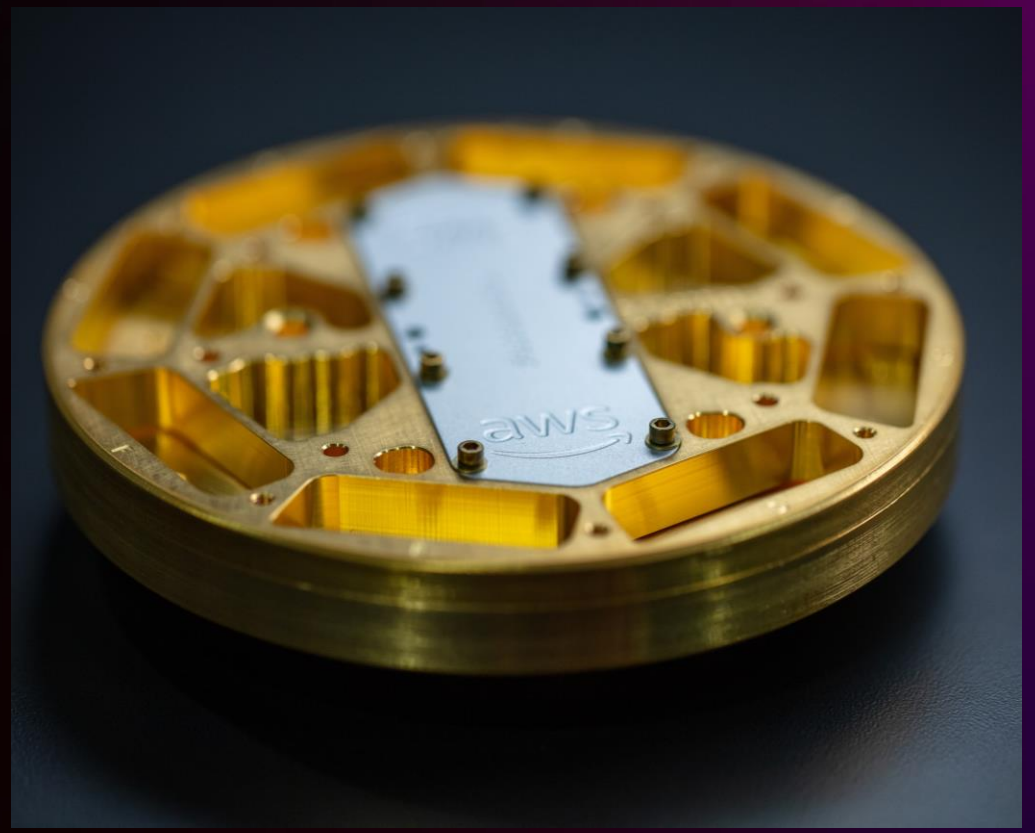


© 2022, Amazon Web Services, Inc. or its affiliates. All rights reserved.

AWS Center for Quantum Computing



On campus at Caltech in Pasadena, CA



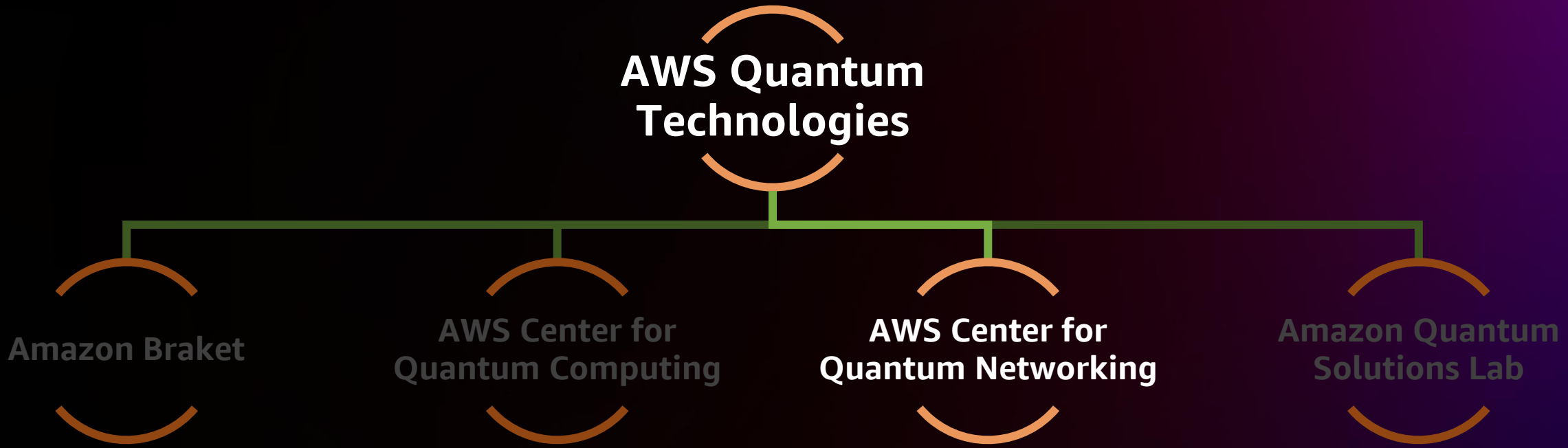
Focus on the fundamental research required to bring fault-tolerant quantum computers to market:

- Hardware development (qubit design, testing and measurement, etc.)
- Theory research (QEC, algorithms, applications, hardware-adjacent theory, etc.)

aws

© 2022, Amazon Web Services, Inc. or its affiliates. All rights reserved.

Overview of quantum technologies at AWS



© 2022, Amazon Web Services, Inc. or its affiliates. All rights reserved.

AWS Center for Quantum Networking



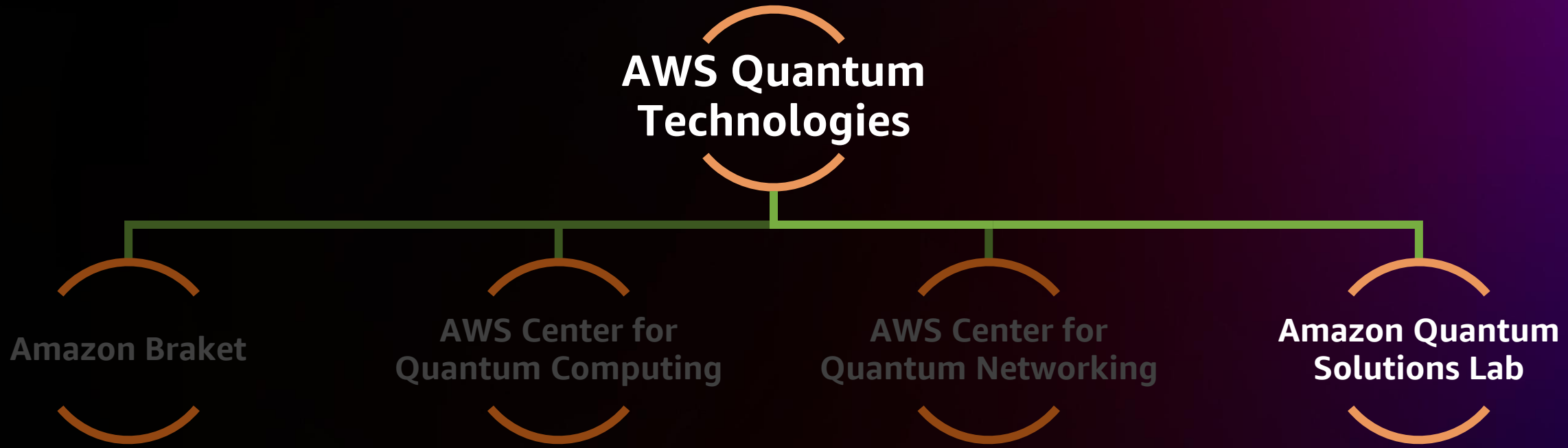


Research lab focusing on quantum networking:

- Quantum key distribution
- Quantum secure, entanglement-based communication channels
- …

© 2022, Amazon Web Services, Inc. or its affiliates. All rights reserved.

Overview of quantum technologies at AWS



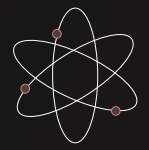
aws
© 2022, Amazon Web Services, Inc. or its affiliates. All rights reserved.

Interdisciplinary science, solution-focused team

THE AMAZON QUANTUM SOLUTIONS LAB COLLABORATES WITH CUSTOMERS TO SOLVE HARD PROBLEMS

Quantum computing

- Be a thought leader
- Build expertise and solutions for the quantum future



Machine learning

- Accelerate business decisions
- Insights and inferences from ML and statistical methods



High-performance computing

- Boost the core of the businesses
- Better products, time to market, discoveries, products and innovation



By combining expertise, AWS Professional Services helps customers find state-of-the-art solutions

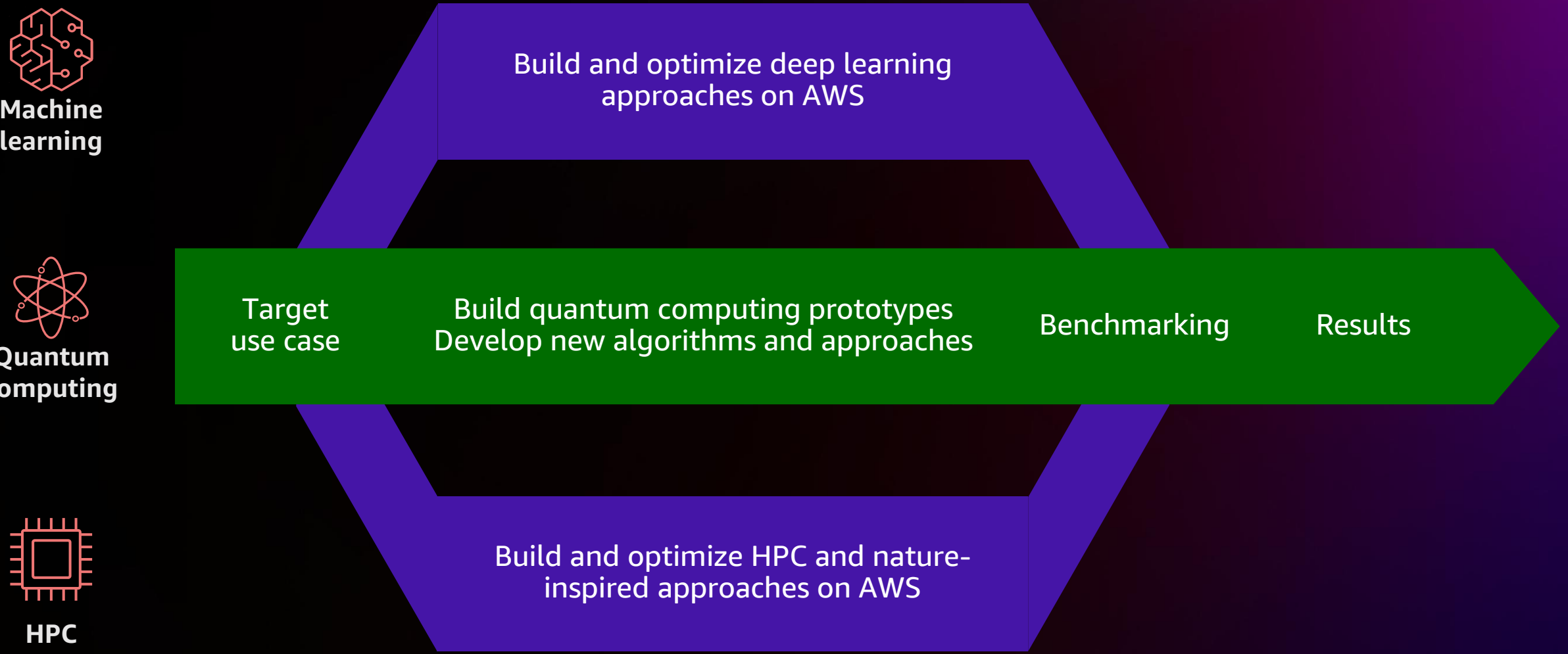


aws

© 2022, Amazon Web Services, Inc. or its affiliates. All rights reserved.

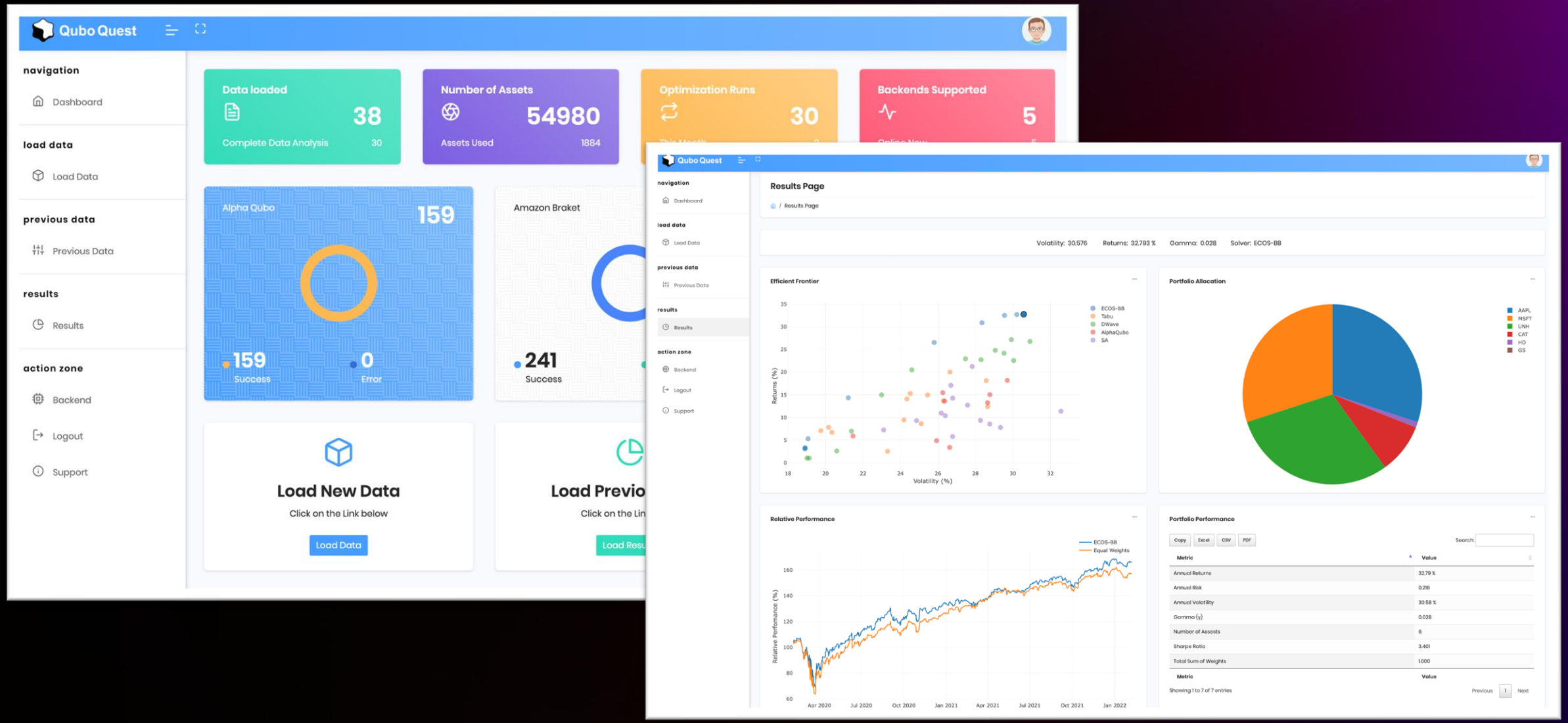
Amazon Quantum Solutions Lab

Goal: Assess future quantum applications for fault-tolerant machines and deliver value to customers today



© 2022, Amazon Web Services, Inc. or its affiliates. All rights reserved.

Quantum solutions for tomorrow, value today



© 2022, Amazon Web Services, Inc. or its affiliates. All rights reserved.

Quantum research at Goldman Sachs

© 2022, Amazon Web Services, Inc. or its affiliates. All rights reserved.

Quantum research at Goldman Sachs

WORKING TOWARD QUANTUM ADVANTAGE

- Work backwards: what quantum resources are needed for valuable advantage?

RESOURCE ESTIMATION
defines what is needed for quantum advantage

ALGORITHM DESIGN
reduces resource requirements

HARDWARE INTEGRATION
including error-correction or specialized hardware

- Collaborators include industry, startups, academics
  - Access to current and developing quantum hardware

aws

© 2022, Amazon Web Services, Inc. or its affiliates. All rights reserved.

Finance has many potential quantum use cases

SIMULATION

- Monte Carlo pricing of derivatives
- Risk calculations, hedging

OPTIMIZATION

- Portfolio optimization
- Allocations under constraints

MACHINE LEARNING

- More speculative as classical ML in finance is still emerging
- Anti-money laundering, credit analysis
- Transaction execution, alpha generation?

OUR APPROACH

Domain specific knowledge matters significantly for resource estimation

EXAMPLE Quantum Chemistry

Theoretically $O(2^N) \rightarrow O(N^p)$ advantage

First estimates > $O(N^{12})$

Successive work $O(N^3)$ or less for specific types of problems

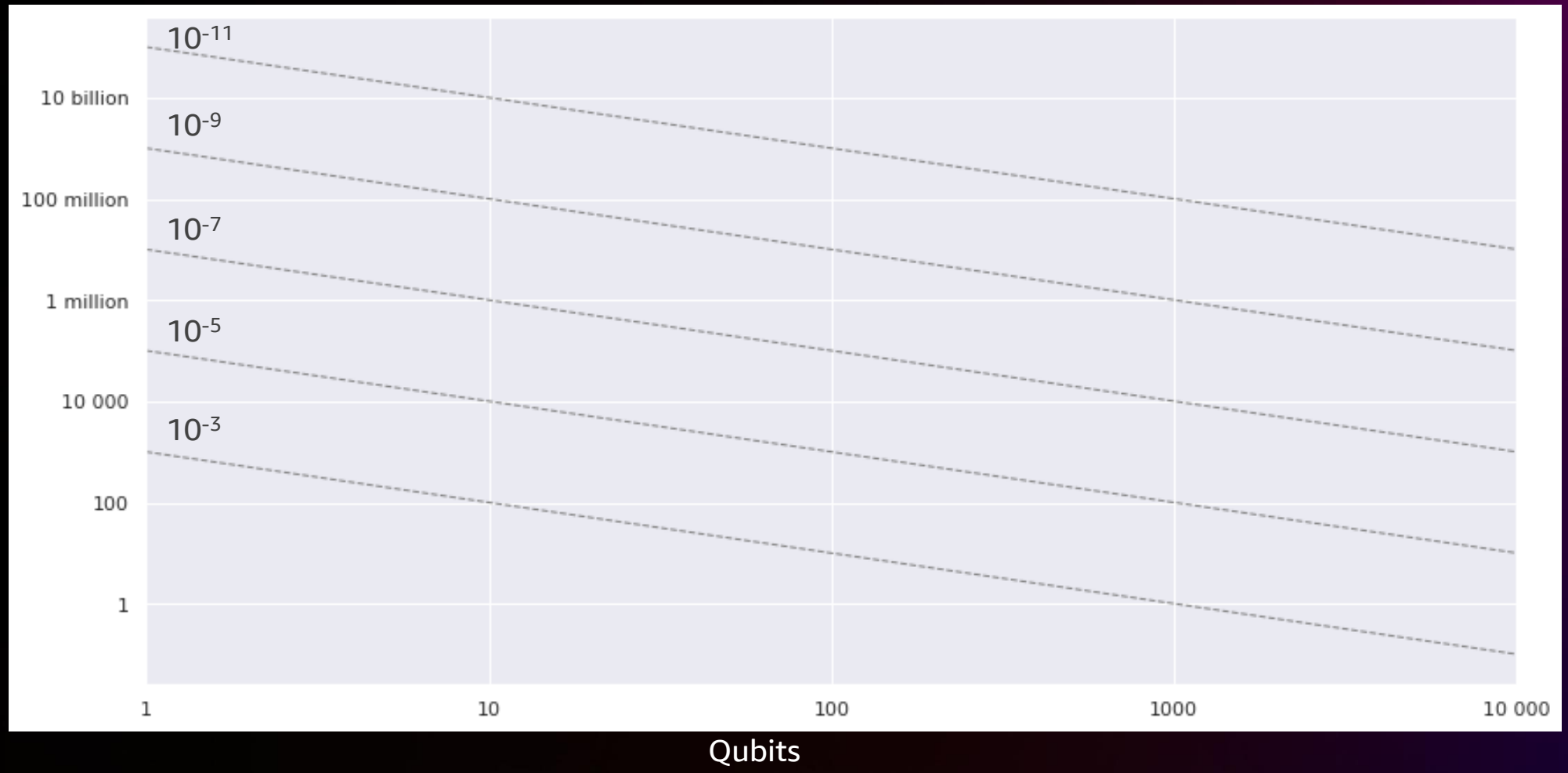
This work can make all the difference for quantum advantage in finance

aws

© 2022, Amazon Web Services, Inc. or its affiliates. All rights reserved.

Landscape of quantum power

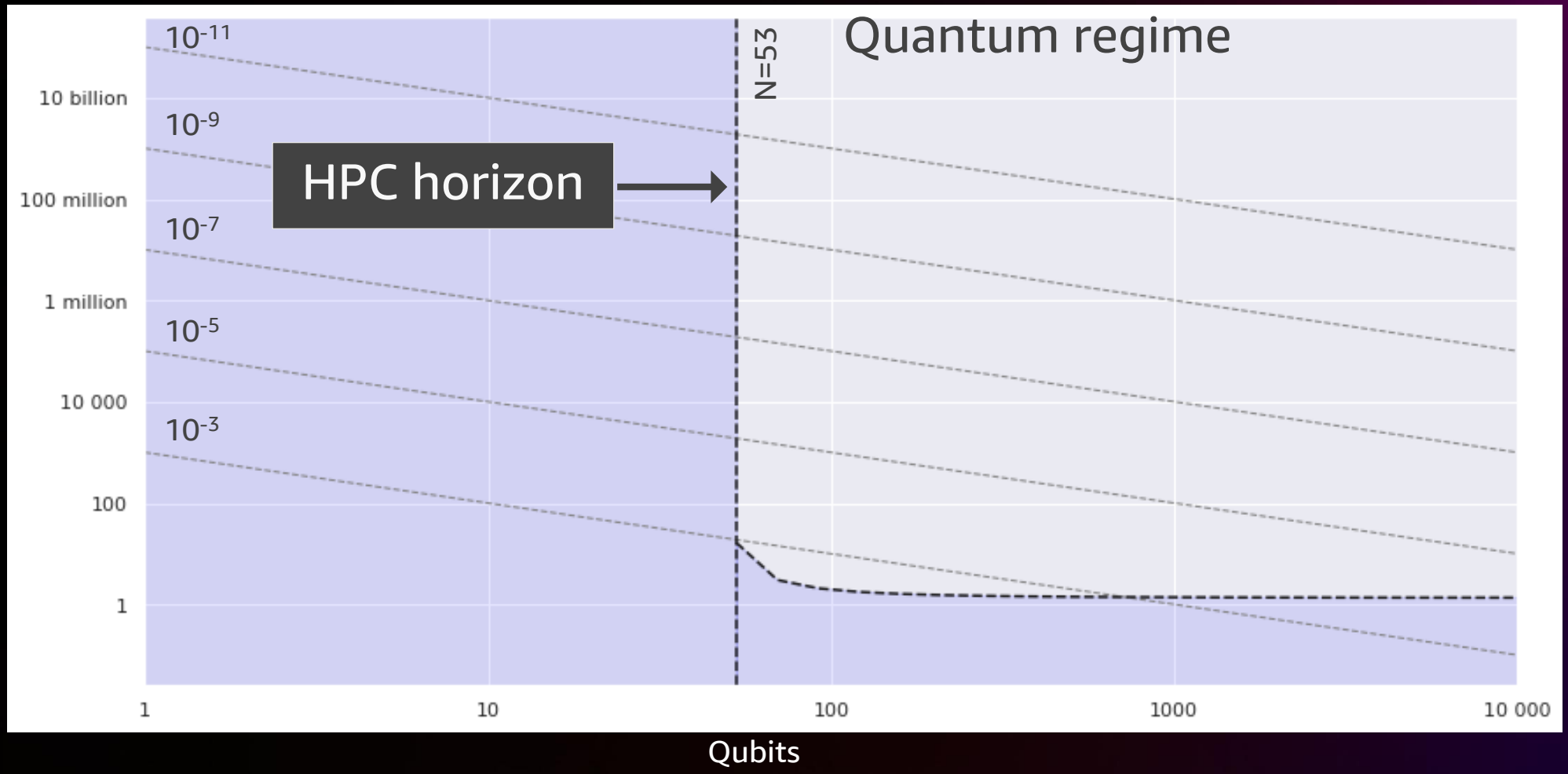
BOTH QUBIT NUMBER AND ERROR RATES MATTER



© 2022, Amazon Web Services, Inc. or its affiliates. All rights reserved.

Landscape of quantum power

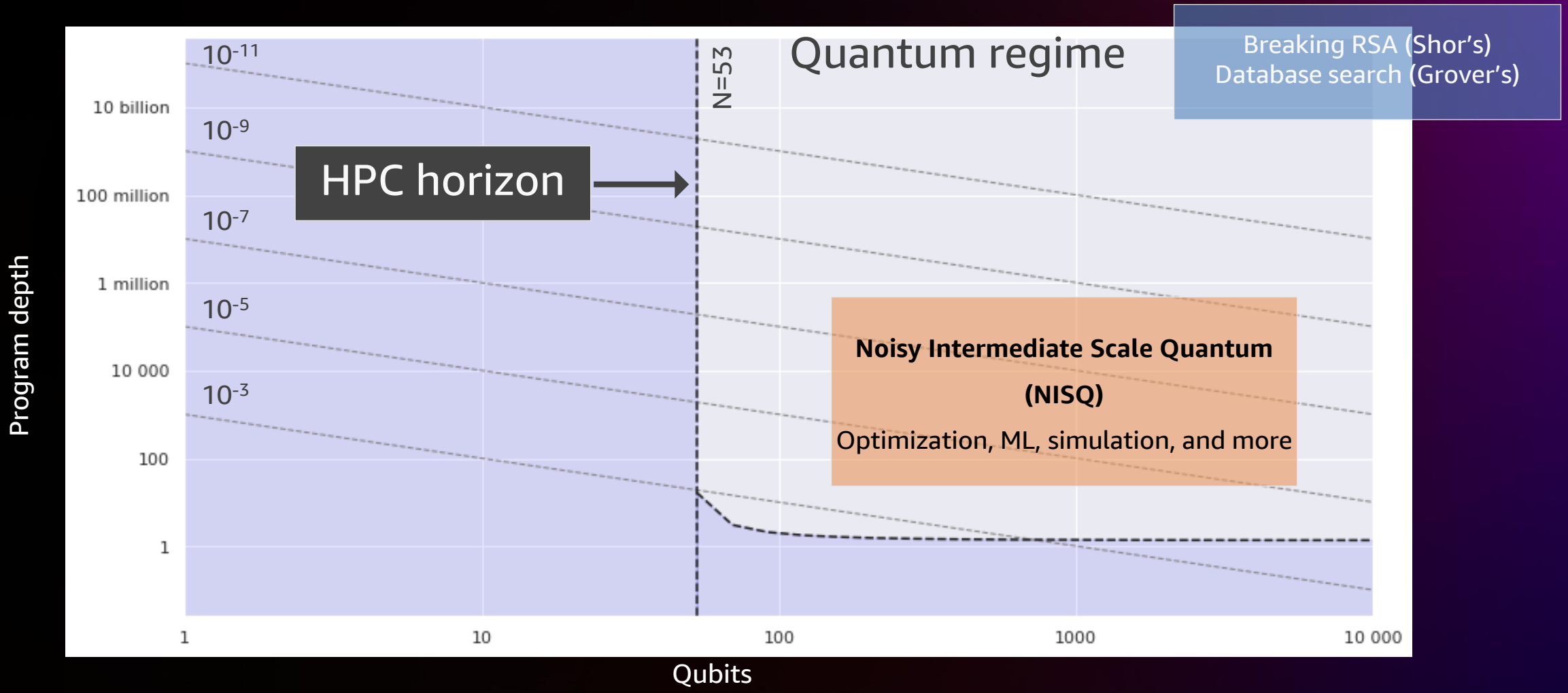
BOTH QUBIT NUMBER AND ERROR RATES MATTER



© 2022, Amazon Web Services, Inc. or its affiliates. All rights reserved.

Landscape of quantum power

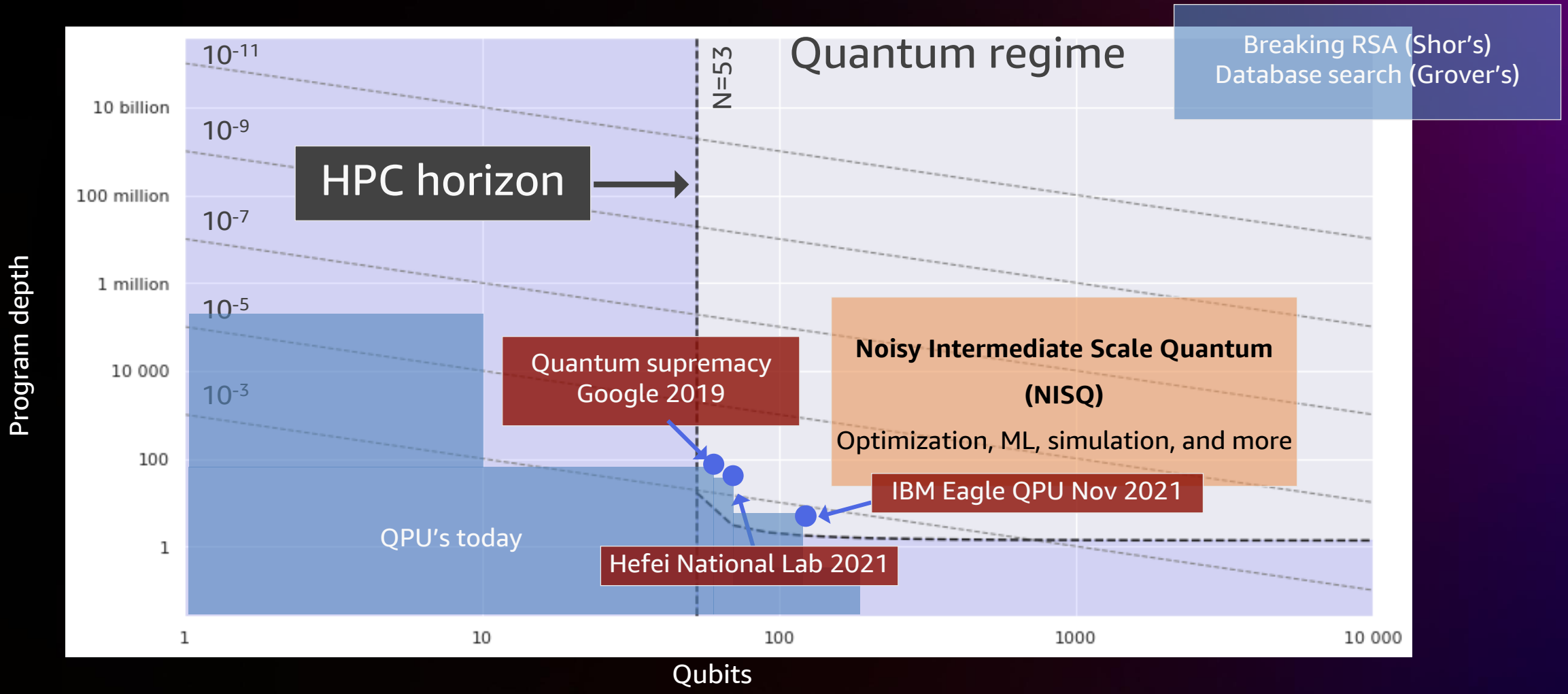
BOTH QUBIT NUMBER AND ERROR RATES MATTER



© 2022, Amazon Web Services, Inc. or its affiliates. All rights reserved.

Landscape of quantum power

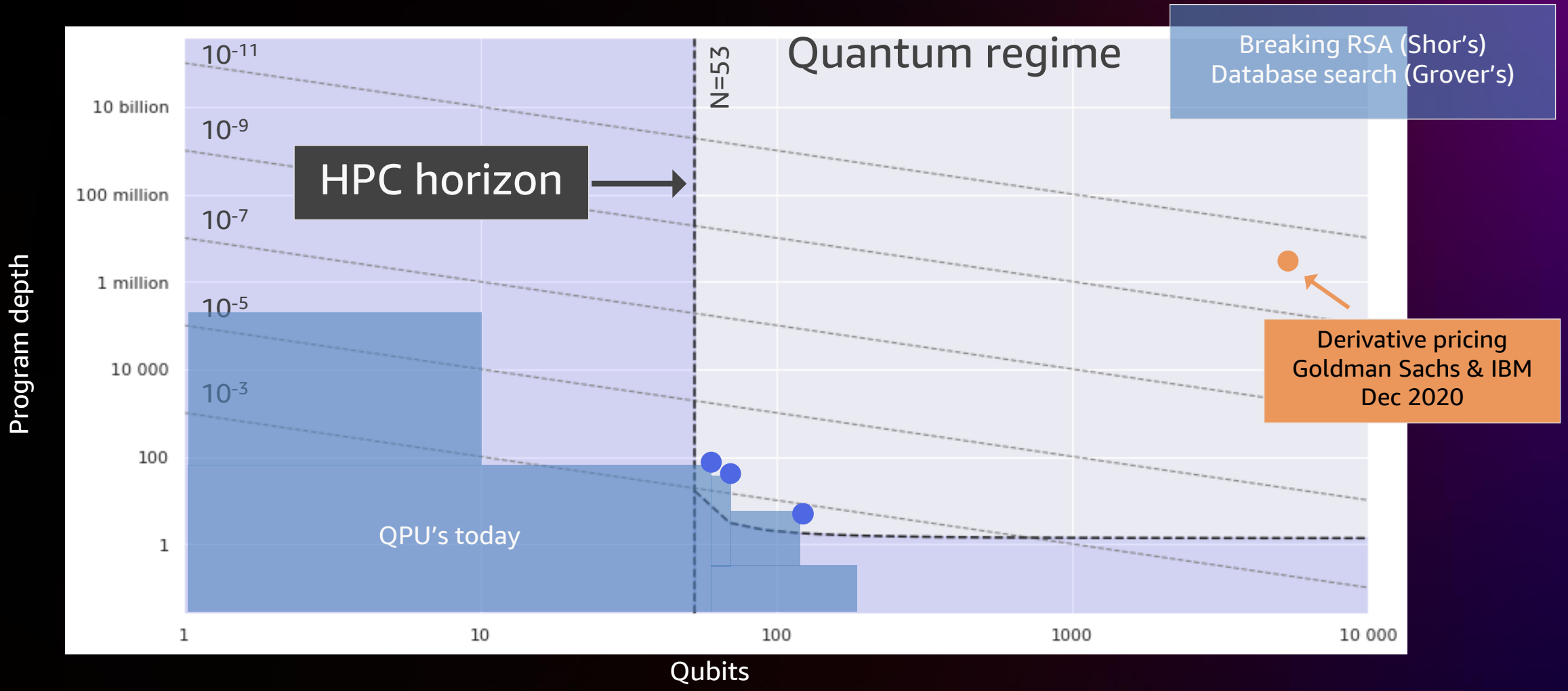
BOTH QUBIT NUMBER AND ERROR RATES MATTER



© 2022, Amazon Web Services, Inc. or its affiliates. All rights reserved.

Landscape of quantum power

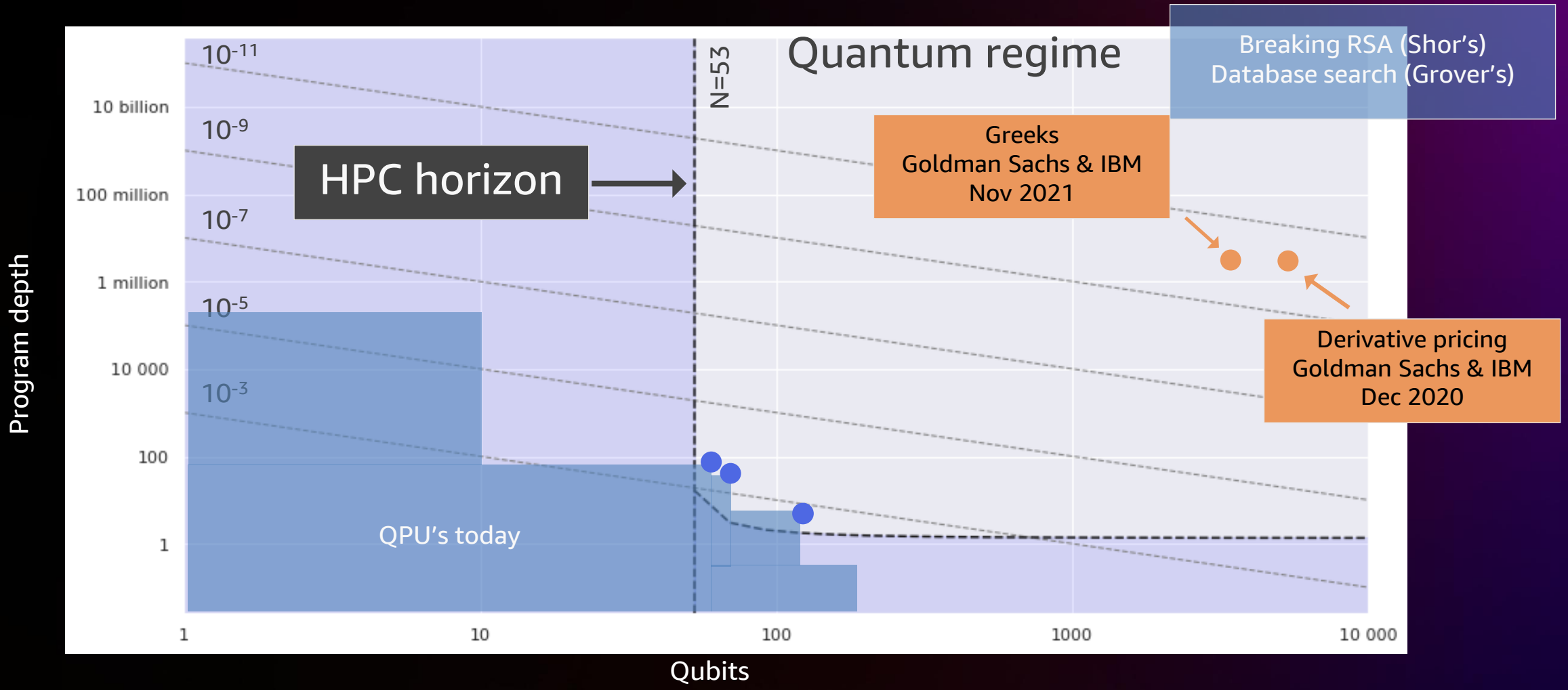
BOTH QUBIT NUMBER AND ERROR RATES MATTER



© 2022, Amazon Web Services, Inc. or its affiliates. All rights reserved.

Landscape of quantum power

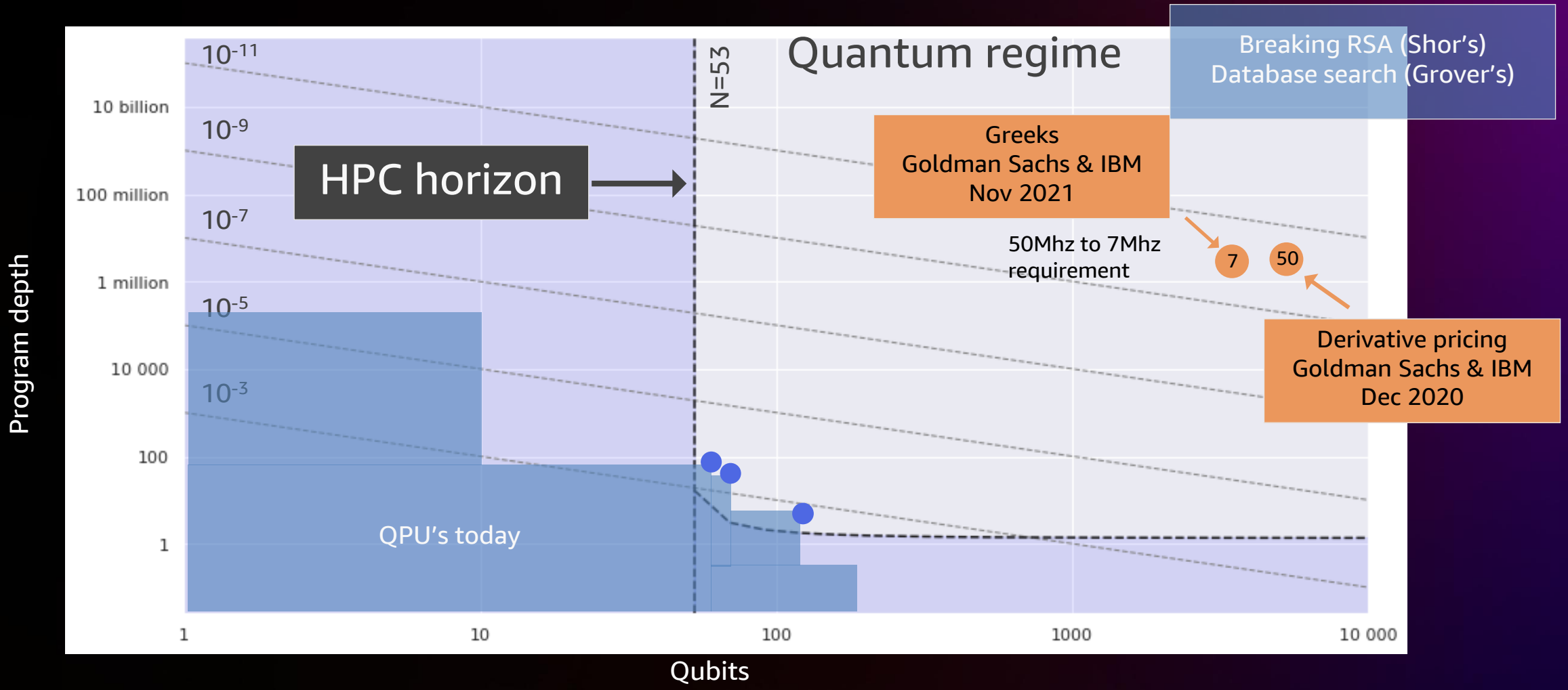
BOTH QUBIT NUMBER AND ERROR RATES MATTER



© 2022, Amazon Web Services, Inc. or its affiliates. All rights reserved.

Landscape of quantum power

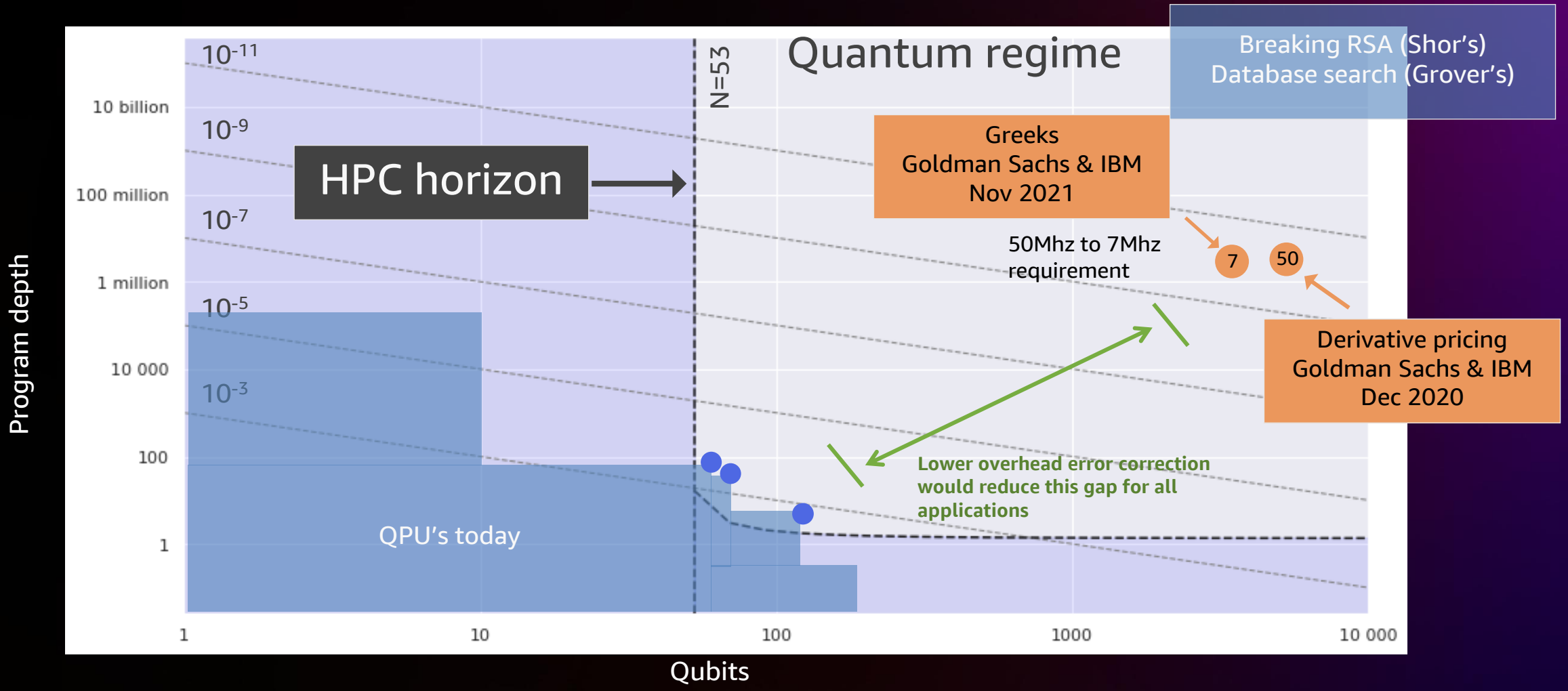
BOTH QUBIT NUMBER AND ERROR RATES AND CLOCK SPEED MATTER



© 2022, Amazon Web Services, Inc. or its affiliates. All rights reserved.

Landscape of quantum power

BOTH QUBIT NUMBER AND ERROR RATES AND CLOCK SPEED MATTER



© 2022, Amazon Web Services, Inc. or its affiliates. All rights reserved.

Case study: Resource estimation for portfolio optimization

arXiv:2206.03505 and arXiv:2211.12489

© 2022, Amazon Web Services, Inc. or its affiliates. All rights reserved.

Case study: AWS/Goldman Sachs collaboration

GOAL

- Use quantum algorithms to solve real-world customer use cases
- Carefully quantify the quantum computational resources required

CHALLENGE

- Identify algorithmic bottlenecks
- Quantify the quantum resources required

QUANTUM APPROACH

- End-to-end algo from input to output
- Portfolio opt. as a guiding example
- Leading quantum algorithm for P.O.
- Full algorithm stack right down to quantum circuits

OUTCOMES

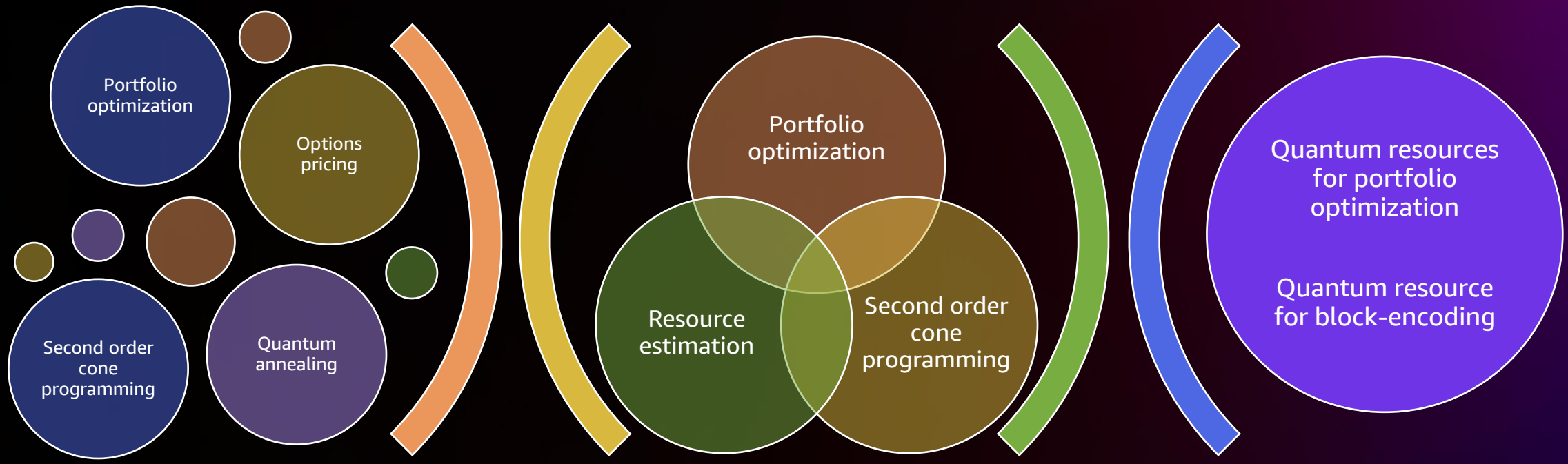
Quantum resource estimation:

- Number of logical qubits
- T-depth
- T-count

aws

© 2022, Amazon Web Services, Inc. or its affiliates. All rights reserved.

Case study: AWS/Goldman Sachs collaboration



Use case and solution discovery

Project formulation and exploration

Read out & write up

© 2022, Amazon Web Services, Inc. or its affiliates. All rights reserved.

Modern portfolio theory: Markowitz model

Given: N investable assets

Find: the optimal allocation of funds into the assets to maximize expected returns and/or minimize risk

Minimize risk

$$\min_{\boldsymbol{w}} \quad \frac{1}{2}\boldsymbol{w}^{\top}\Sigma\boldsymbol{w}$$

Subject to

$$\boldsymbol{w}^{\top}\mathbf{1} = 1$$
$$\boldsymbol{w}^{\top}\boldsymbol{r} = r_0$$

Maximize return

$$\max_{\boldsymbol{w}} \quad \boldsymbol{w}^{\top}\boldsymbol{r}$$

Subject to

$$\boldsymbol{w}^{\top}\mathbf{1} = 1$$
$$\boldsymbol{w}^{\top}\Sigma\mathbf{w} = \sigma_0^2$$

Maximize risk-adjusted return

$$\max_{\boldsymbol{w}} \quad \boldsymbol{w}^{\top}\boldsymbol{r} - \frac{1}{2}\gamma\boldsymbol{w}^{\top}\Sigma\boldsymbol{w}$$

Subject to

$$\boldsymbol{w}^{\top}\mathbf{1} = 1$$



Definitions:

- $\boldsymbol{w}$—vector of weights specifying fraction of total investment allocated to each asset
- $\boldsymbol{r}$ —vector of returns; r_0 is a target expected return
- Σ —covariance matrix for the assets; σ_0^2 is a target variance
- γ —risk-aversion parameter

aws

© 2022, Amazon Web Services, Inc. or its affiliates. All rights reserved.

Modern portfolio theory: Constraints

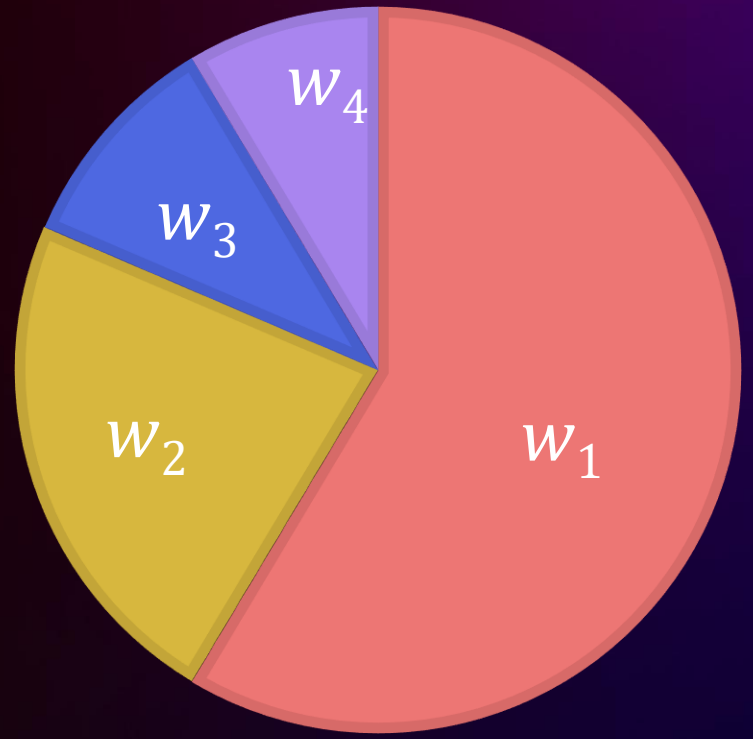
Constraints can make the problem richer and more complex:

$$\max_{\boldsymbol{w}} \boldsymbol{w}^\top \boldsymbol{r} - \frac{1}{2}\gamma \boldsymbol{w}^\top \Sigma \boldsymbol{w}$$

Subject to

$$\boldsymbol{w}^\top \mathbf{1} = 1$$

- $w_j \geq 0, \forall\, j$ — Long only (in other words, no short trades)
- $w_j \in [w_j^{\min}, w_j^{\max}]$ — Investment bands with minimum and maximum holding for asset j
- $|\Delta w_j| \leq U_j$ — Turnover constraints on asset j
- Many other possibilities:
  - sector constraints
  - cardinality constraints
  - transaction costs
  - …



© 2022, Amazon Web Services, Inc. or its affiliates. All rights reserved.

Quantum approaches to portfolio optimization

Fault tolerant algorithms that can be used to optimize portfolios:

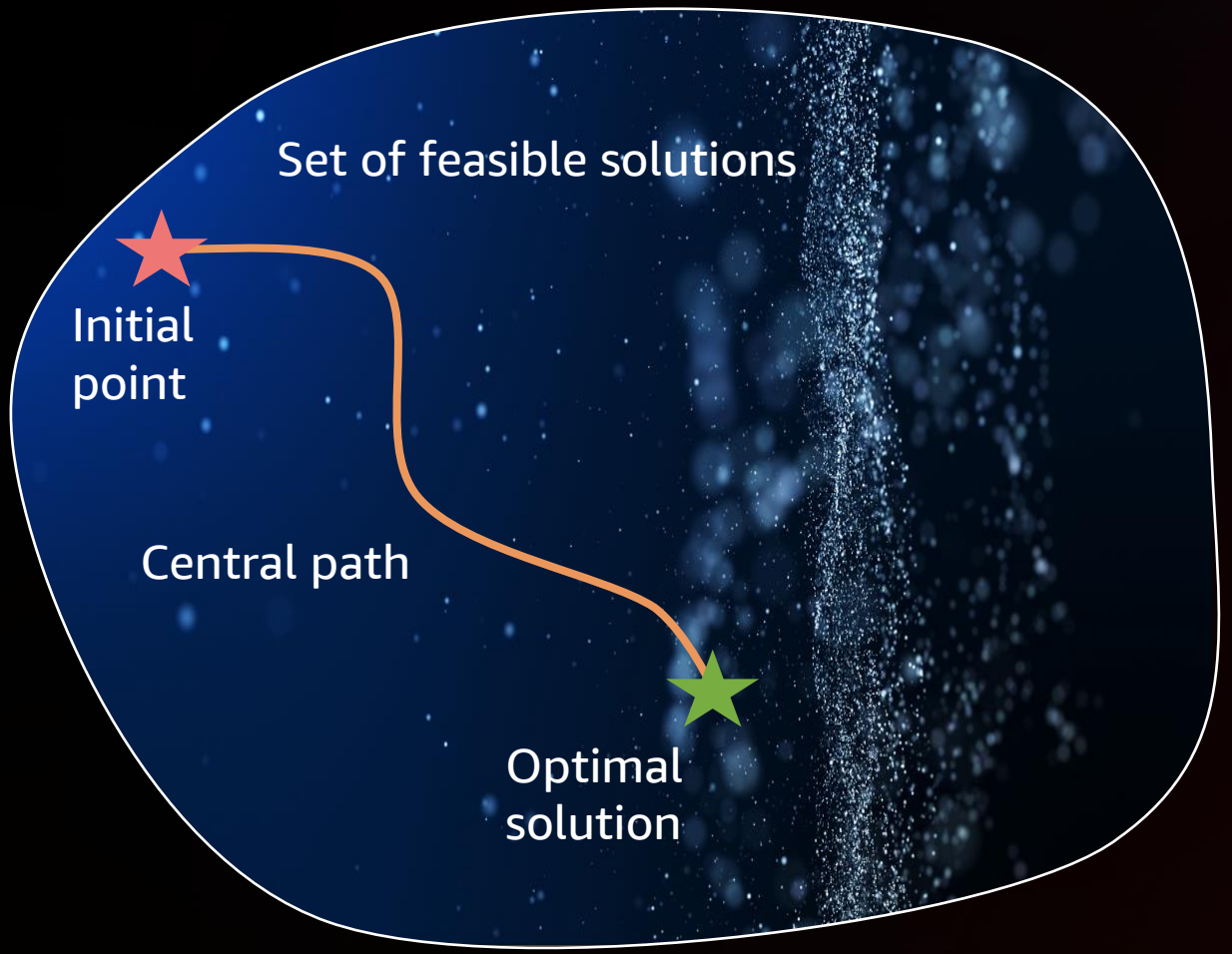
Metric	Second-order cone programming	Semidefinite programming	Branch-and-bound	Short-path
Model formulation	Continuous	Continuous	Discrete	Discrete
Solution quality	Depends on tomographic accuracy	Duality gap (1/poly)	Exact	Exact
Runtimes and speed-up	Potential for O(n)	Polynomial, potentially quartic	Near-quadratic	Super-quadratic speedup over brute force
Potential caveats	QRAM	QRAM	Grover may be better in practice	Brute force isn't the industry benchmark

Not shown: quantum annealing approaches

aws

© 2022, Amazon Web Services, Inc. or its affiliates. All rights reserved.

Quantum Interior Point Methods

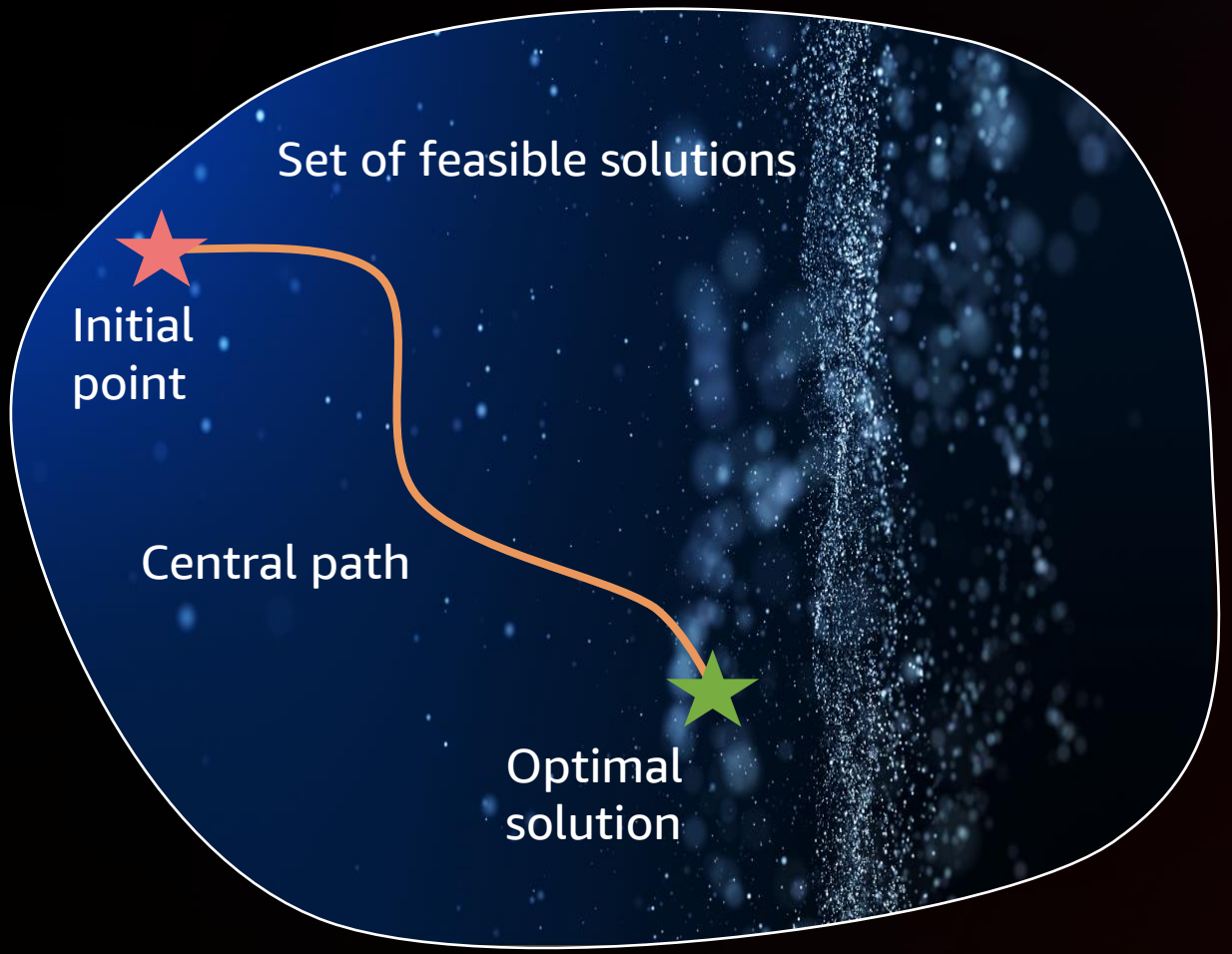


Classical Interior Point Method:

- Map the use case to SOCP
- Start at a reasonable initial point
- Loop until desired accuracy is met:
  - Solve a system of linear equations to determine the optimal direction to search
  - Update the solution in that direction
  - Check solution accuracy
- Read out the optimal portfolio

aws
© 2022, Amazon Web Services, Inc. or its affiliates. All rights reserved.

Quantum Interior Point Methods



Quantum Interior Point Method:

- Map the use case to SOCP
- Start at a reasonable initial point
- Loop until desired accuracy is met:
  - Solve a system of linear equations to determine the optimal direction to search
  - Update the solution in that direction
  - Check solution accuracy
- Read out the optimal portfolio

aws
© 2022, Amazon Web Services, Inc. or its affiliates. All rights reserved.

Quantum Interior Point Methods

Quantum Interior Point Method:

Block-encoding and QRAM

- Encode the classical problem data (e.g., stock history) into quantum states
- Build quantum circuits for encoding

Quantum linear system solver

- Use a quantum algorithm for solving linear systems to prepare a state representing the new search directions
- Upgrade to state-of-the-art linear systems solvers

Tomography

- Need a classical solution to the linear system, not a quantum state
- Repeat the process many times and perform quantum state tomography to read out the results

Optimizations

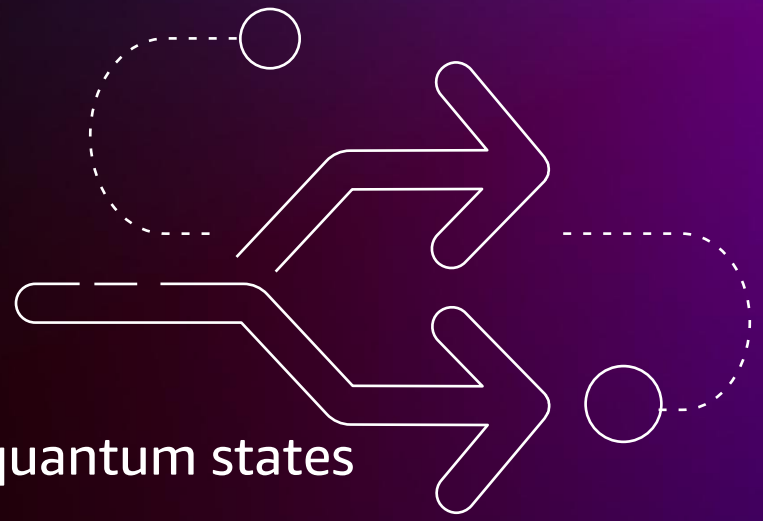
- Fix bugs in previous analyses
- Optimize all subroutines and identify bottlenecks

Solve a system of linear equations

aws

© 2022, Amazon Web Services, Inc. or its affiliates. All rights reserved.

Quantum Interior Point Methods



Quantum Interior Point Method:

Solve a system of linear equations

- Encode the classical problem data (for example, stock history) into quantum states
  - Block encoding:

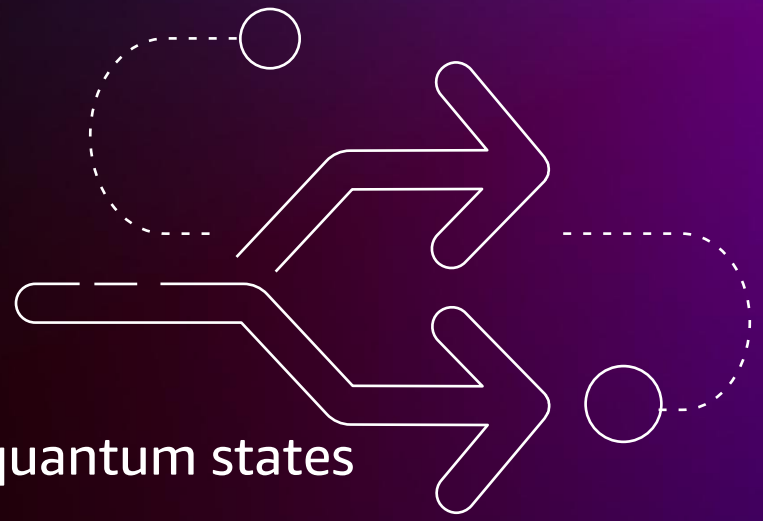
arXiv:2206.03505

Resource	Minimum Depth	Minimum Count
# Qubits	$4N^2$	$N\log(1/\epsilon)$
T-Depth	$\mathbf{10}\log N + \mathbf{24}\log(1/\epsilon)$	$8N + 12\log N(\log(1/\epsilon))^2$
T-Count	$12N^2\log(1/\epsilon)$	$16N\log(1/\epsilon) + 12\log N(\log(1/\epsilon))^2$

aws

© 2022, Amazon Web Services, Inc. or its affiliates. All rights reserved.

Quantum Interior Point Methods



Quantum Interior Point Method:

Solve a system of linear equations

- Encode the classical problem data (for example, stock history) into quantum states
  - Block encoding:

arXiv:2206.03505

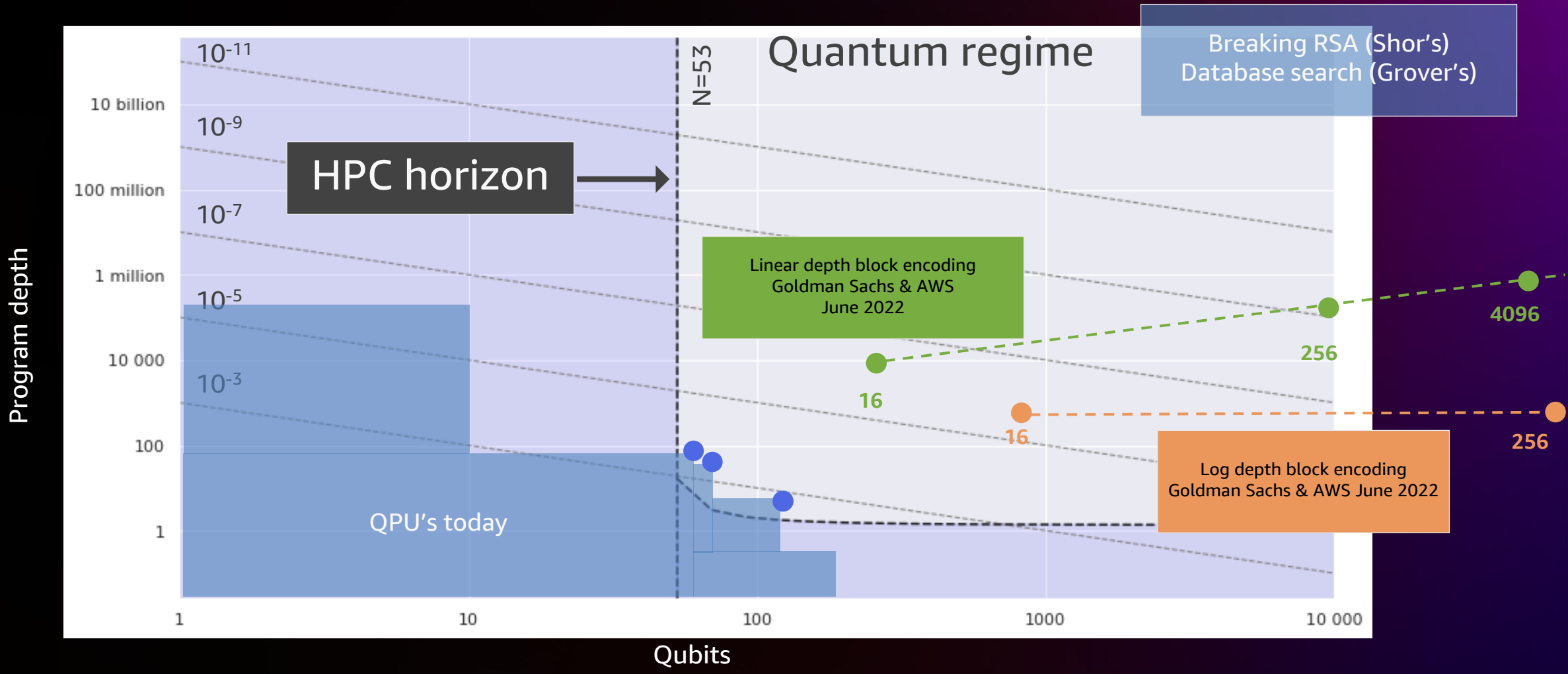
Resource	Minimum Depth	Minimum Count
# Qubits	$[1 \times 10^3, 3 \times 10^5, 7 \times 10^7]$	$[4 \times 10^2, 7 \times 10^3, 1 \times 10^5]$
T-Depth	$[5 \times 10^2, 7 \times 10^2, 8 \times 10^2]$	$[2 \times 10^4, 7 \times 10^4, 2 \times 10^5]$
T-Count	$[7 \times 10^4, 2 \times 10^7, 7 \times 10^9]$	$[3 \times 10^4, 2 \times 10^5, 2 \times 10^6]$
	16×16, 256×256, 4096×4096	16×16, 256×256, 4096×4096

aws

© 2022, Amazon Web Services, Inc. or its affiliates. All rights reserved.

Landscape of quantum power

BOTH QUBIT NUMBER AND ERROR RATES MATTER



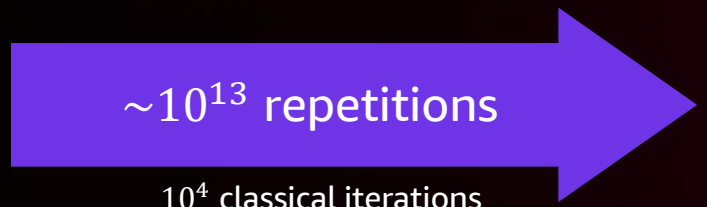
© 2022, Amazon Web Services, Inc. or its affiliates. All rights reserved.

Conclusions

- Final quantum resource estimates:

100 stocks, duality gap 10^{-7}:

Single quantum run	
Resource	Count
Num Qubits	10^7
T-Depth	10^{11}
T-Count	10^{17}



Full end-to-end	
Resource	Count
Num Qubits	10^7
T-Depth	10^{24}
T-Count	10^{30}

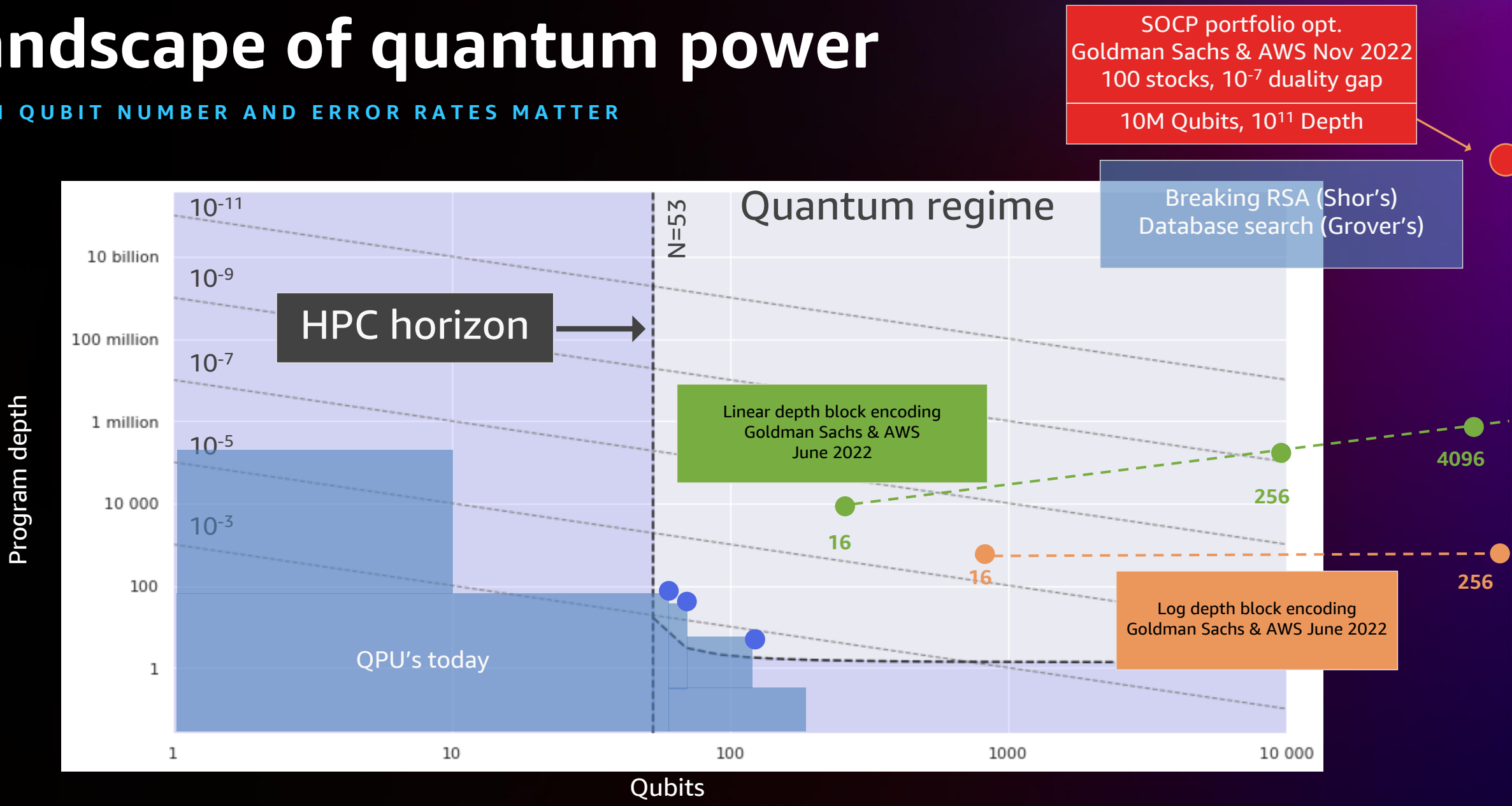
- Suppose: each layer of T-Gates takes one nanosecond (GHz clock speed)
- Then: a T-Depth of 10^{24} takes 10s of millions of years. QRAM alone: $\sim 10^4$ years
- Optimizing a portfolio with 100 stocks is trivial with classical commercial solvers

aws
© 2022, Amazon Web Services, Inc. or its affiliates. All rights reserved.

arXiv:2211.12489

Landscape of quantum power

BOTH QUBIT NUMBER AND ERROR RATES MATTER

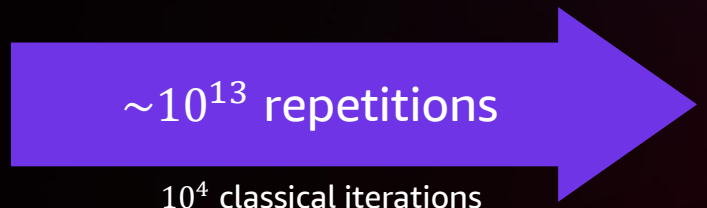


© 2022, Amazon Web Services, Inc. or its affiliates. All rights reserved.

Conclusions

100 stocks, duality gap 10^{-7}:

Single quantum run	
Resource	Count
Num Qubits	10^7
T-Depth	10^{11}
T-Count	10^{17}



Full end-to-end	
Resource	Count
Num Qubits	10^7
T-Depth	10^{24}
T-Count	10^{30}

- We need vast improvements in both algorithms *and* hardware development
- We will necessarily require dedicated hardware for various quantum primitives

- Further work on end-to-end quantum solutions to commercially relevant problems will help inform algorithmic and hardware development

aws
© 2022, Amazon Web Services, Inc. or its affiliates. All rights reserved.

arXiv:2211.12489

Thank you!

Grant Salton
saltg@amazon.com

Will Zeng
william.zeng@gs.com



Please complete the session survey in the **mobile app**

© 2022, Amazon Web Services, Inc. or its affiliates. All rights reserved.