

# AWS re:Invent

NOV. 28 – DEC. 2, 2022 | LAS VEGAS, NV

QTC201

# How AWS is making quantum technologies a practical reality

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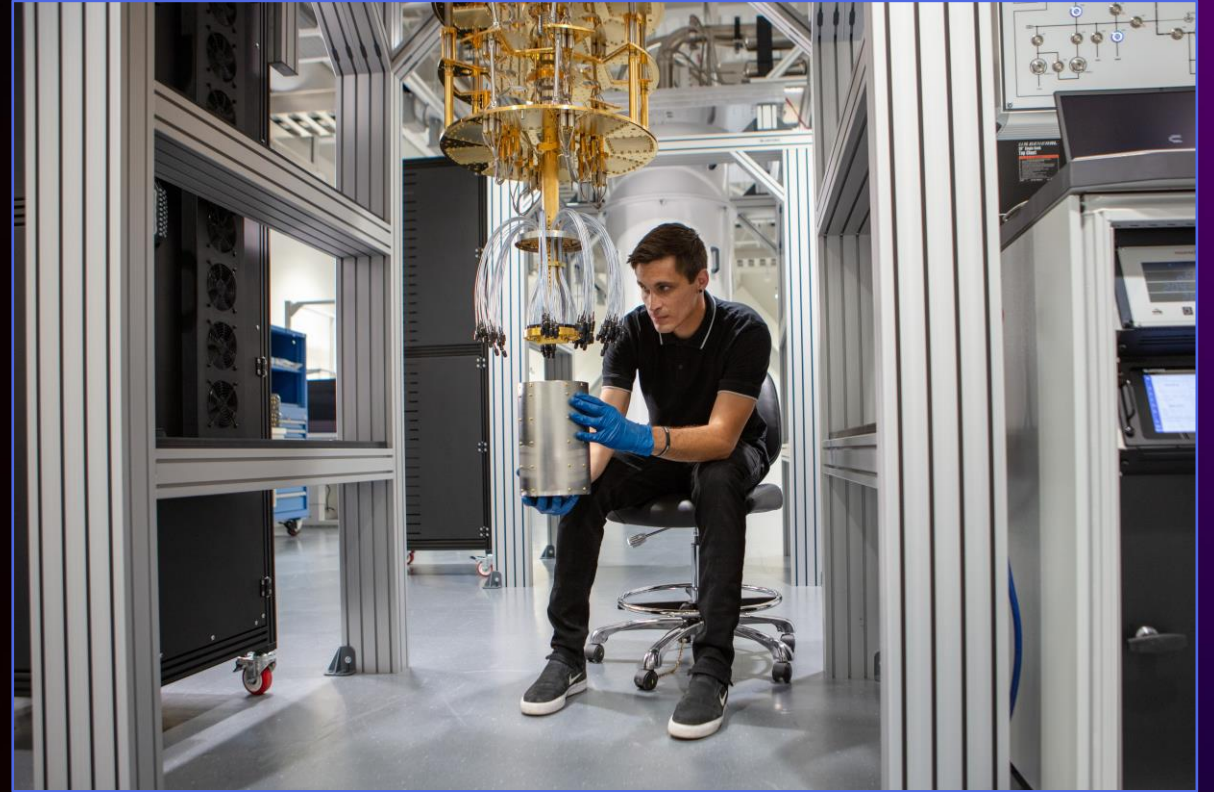
GM, Quantum Technologies  
AWS



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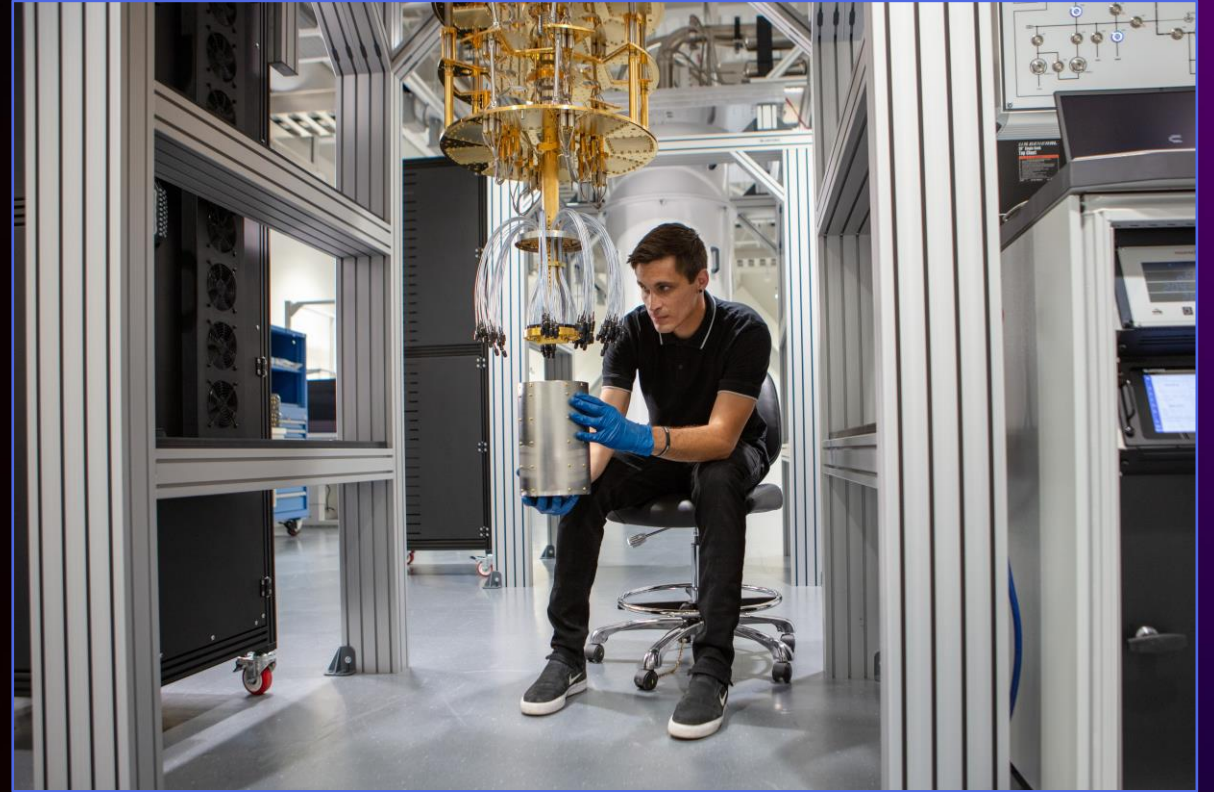
# What is quantum computing?

- A **new paradigm** for computation that leverages the laws of quantum physics
- Will potentially solve certain problems **much more efficiently**
- Building hardware at scale is a **difficult challenge** because quantum computers are prone to errors



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- Will potentially solve certain problems **much more efficiently**
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# Where is quantum computing today?



- The quest for **practical quantum advantage** is ongoing
- The **elephant in the room**: today there is no advantage in business
- “If a company doesn't do anything about the market right now [...], when quantum advantage becomes real, it might be **too late**”

*Marco Pistoia, JPMorgan*

# Where is quantum computing today?



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**Customer problem (2019)**

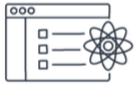
**Customers need a one-stop shop  
for exploring quantum computing**

# Amazon Braket

## Service dashboard

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### Welcome to Amazon Braket



#### [Example Jupyter notebooks](#)

Explore real world examples of all features offered by Amazon Braket.



#### [Braket Python SDK](#)

A feature rich open source library to ease your experience.



#### [Developer guide](#)

Learn the fundamentals to get the most out of Amazon Braket.

### Recent jobs [Info](#)



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Amazon Braket Hybrid Jobs combines classical compute resources with quantum computing devices to optimize the performance of today's quantum systems.

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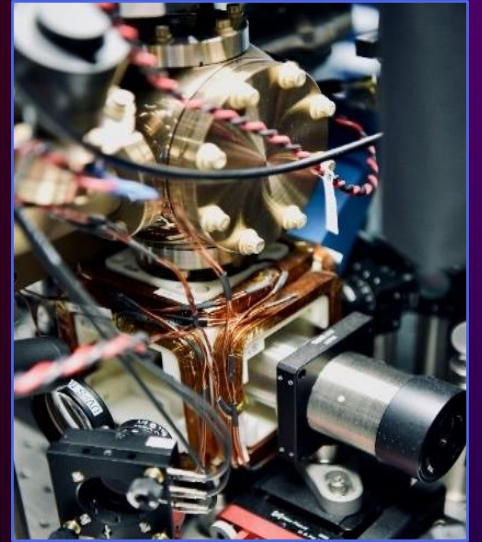
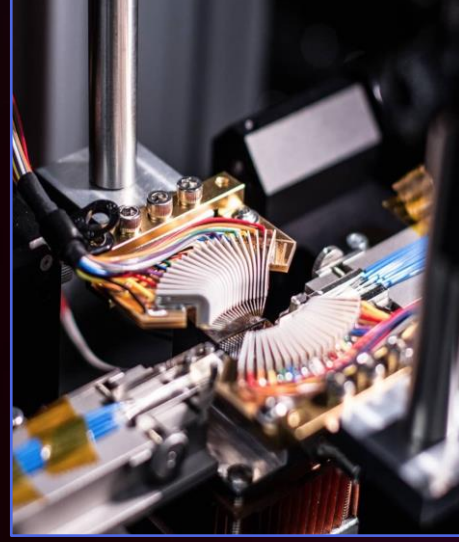
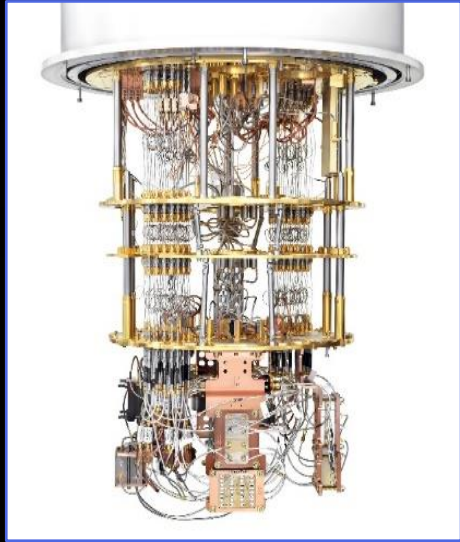
AWS re:Post enables you to ask questions about anything related to designing, building, deploying, and operating workloads on AWS, and get answers from community experts, including AWS customers, Partners, and employees.

#### [AWS Quantum Computing Blog](#)

Follow the latest news and announcements.

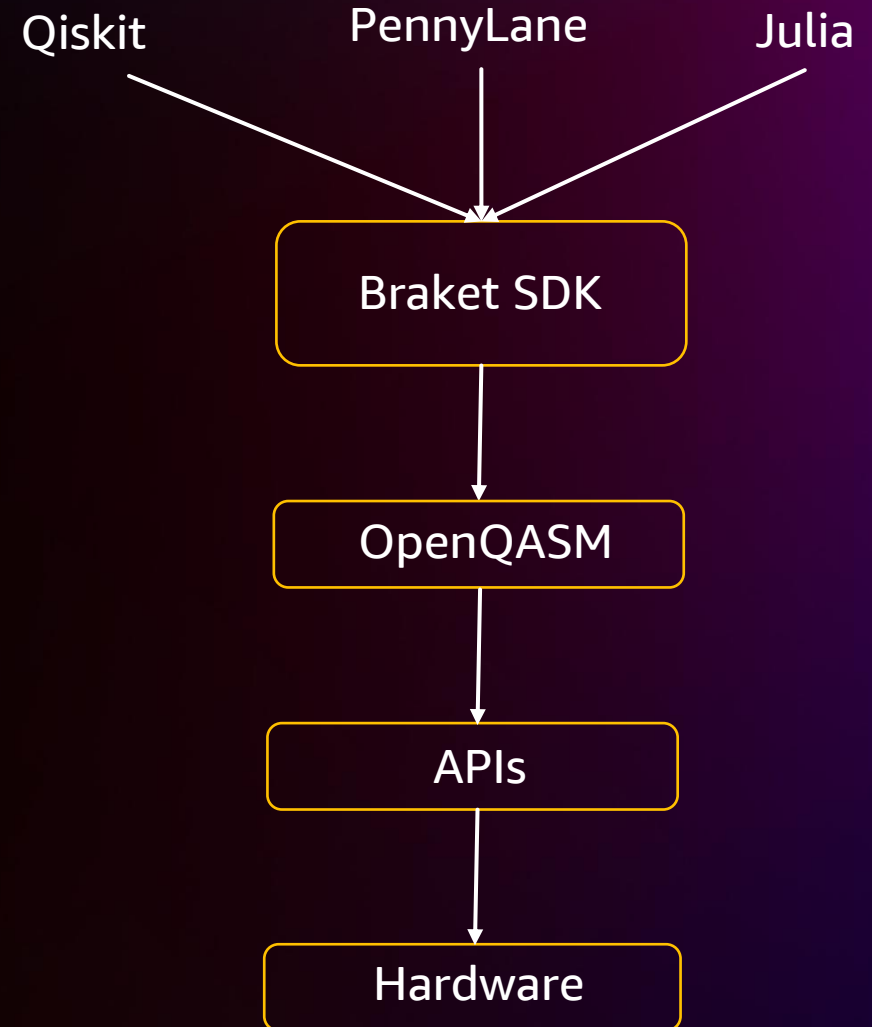


# Quantum hardware available on Amazon Braket



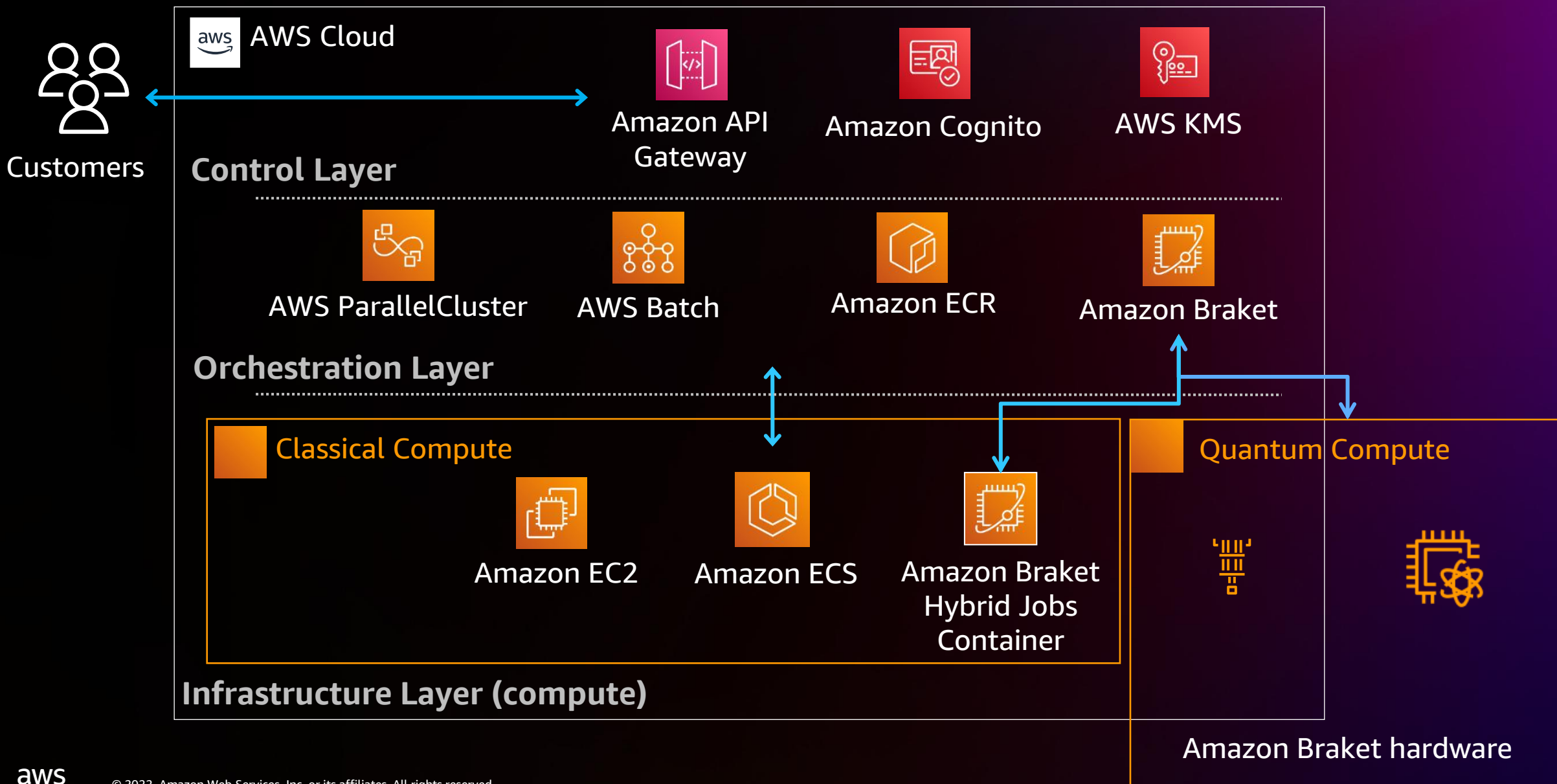
# Amazon Braket software stack

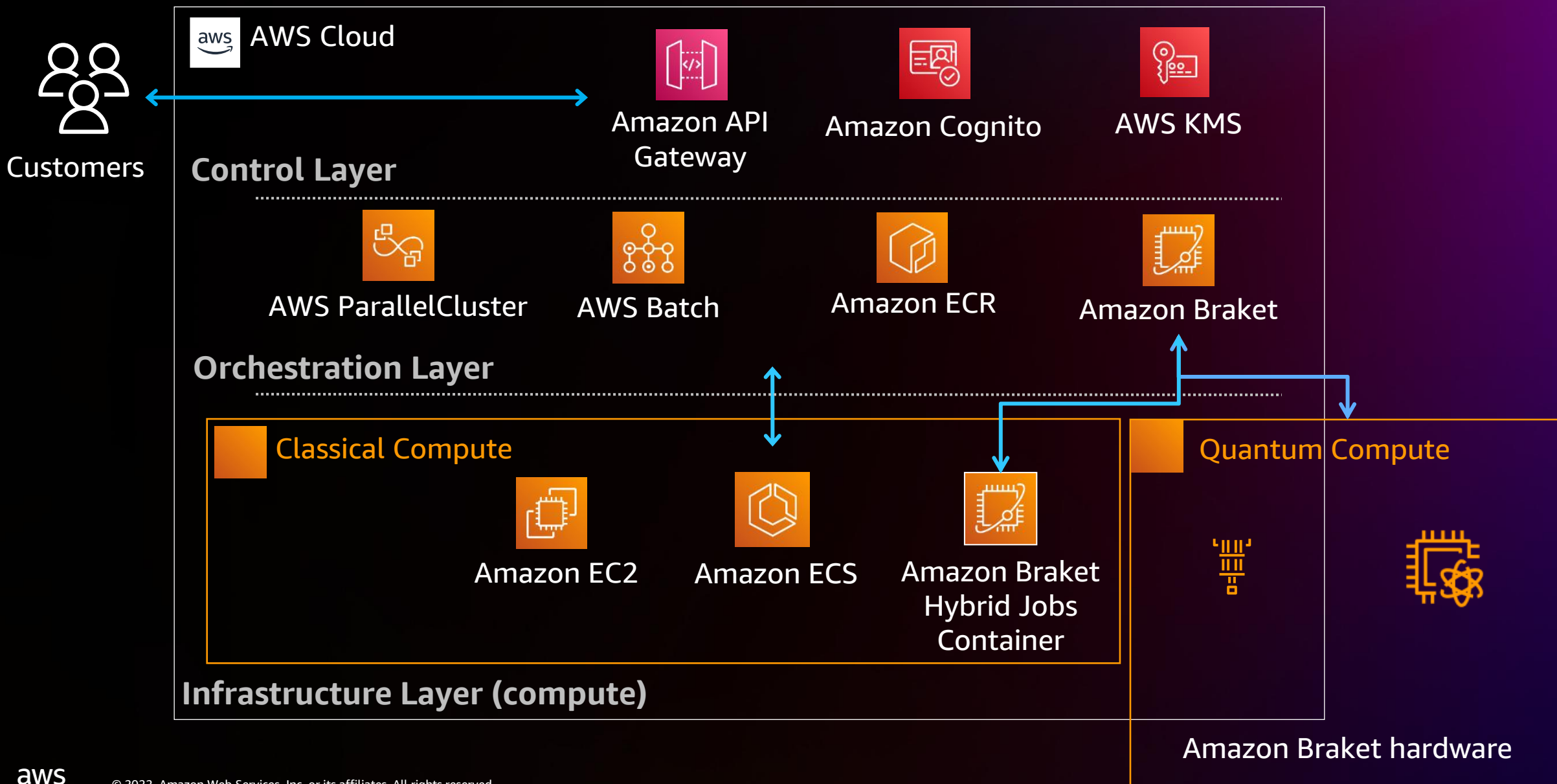
- **One-stop shop interface** for accessing different quantum computers and state-of-the-art simulators
- **Compatible** with popular tooling such as PennyLane, TensorFlow, Qiskit, Julia
- **Choice** of interfaces to enable builders operate at different levels depending on their application



**Customer problem (2019)**

**Customers need quantum hardware  
integrated with cloud resources**







**Preparing for your  
quantum future:**

**Start your journey today!**

**Deloitte.**



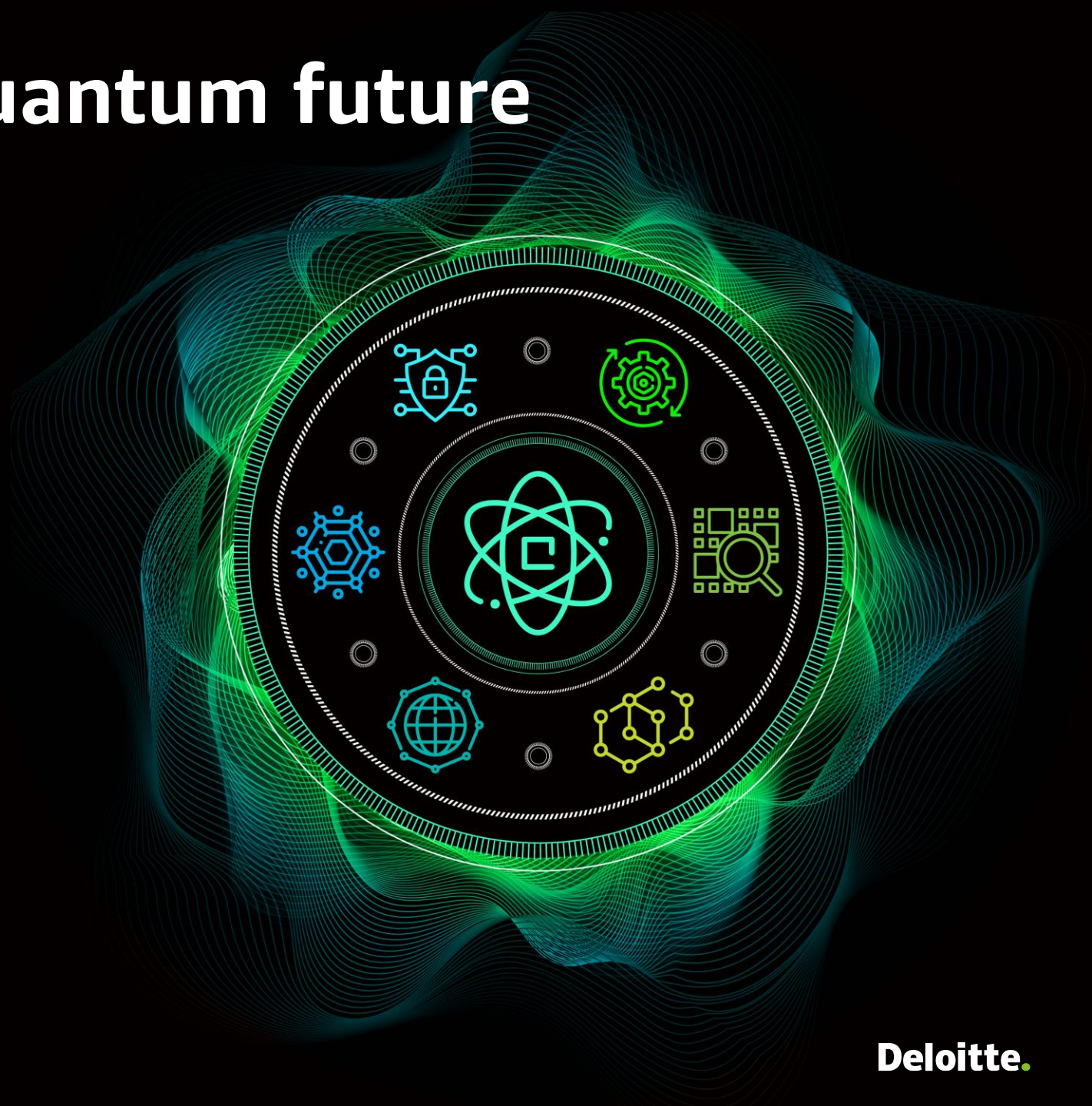
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# Preparing for your quantum future

At Deloitte, we help you ...

- Explore and understand
- Connect and discover
- Amplify and accelerate

... your quantum journey



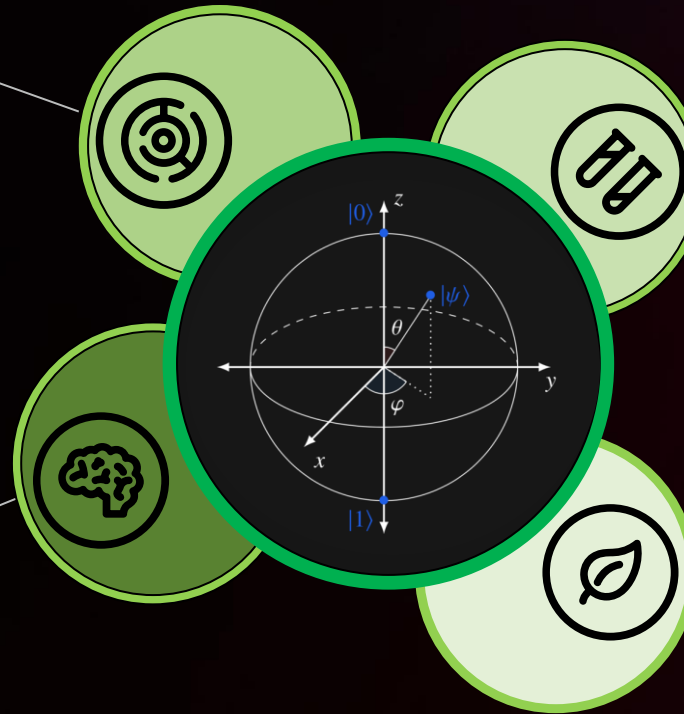
# Why quantum computing?

## Problem complexity

Quantum computers should be able to solve problems that are unsolvable by classical and high performance computers.

## Model training effort

AI applications require significant training efforts. Hybrid algorithms using quantum computers should provide dramatic improvements.



## Giant state spaces

Quantum computers leverage the power of quantum mechanics to simulate the laws of nature such as the bonding of different atoms.

## Energy consumption

Quantum computers should produce more results per unit of energy used compared to conventional high performance and classical computing.

**Sometimes, physics beats math**

# Quantum will be a game changer



Quantum computing and related technologies are steadily advancing, showing promising results

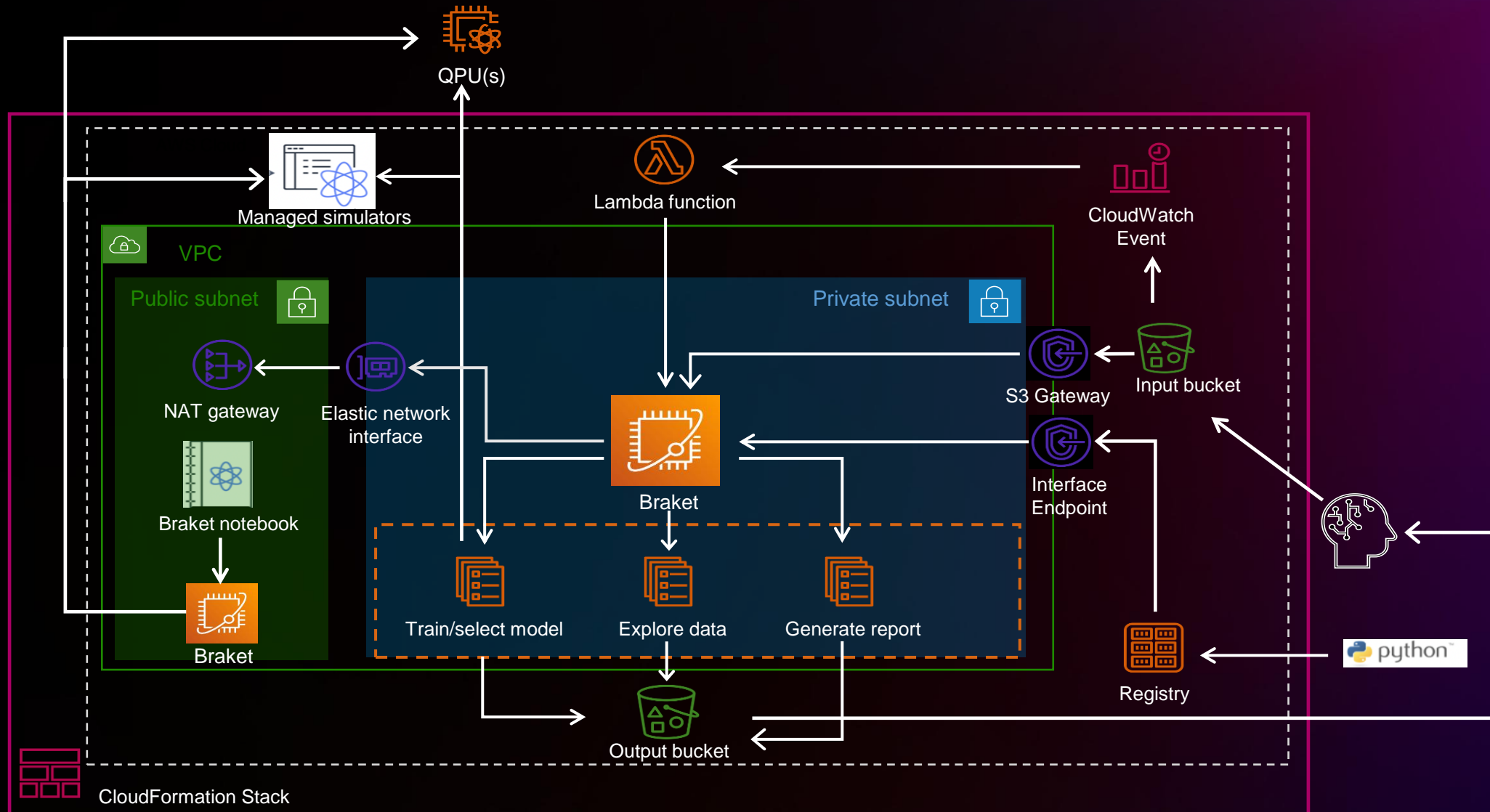


Global investments are surging across the Fortune 500, startups, governments, and academia



New skills are required across different disciplines from the sciences to math to IT and beyond

# A representative “as built” architecture





# Join Us

**To learn more, join us for a  
joint AWS/Deloitte Event in  
February 2023 to accelerate  
your Quantum Computing  
journey!**



QTC201

# Anatomy of a (practical) Quantum Computer

Oskar Painter

Director, Quantum Hardware,  
AWS



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# Criteria for a “practical” quantum computer

Quantum computers, capable of commercially-relevant computations at significant quantum advantage, will require:

- 1) Quantum processors supporting  $\gtrsim 100$  (logical) qubits
- 2) A universal set of gate operations between qubits
- 3) Error-free circuit operation at a circuit depth (number of gate steps)  $\sim 1\text{B}$
- 4) Clock rate (limited by quantum gate times) exceeding tens of kHz

The most demanding criteria is the required gate error rate, which for a circuit of depth 1B operating over 1000 qubits, requires gate error rates  $< 1\text{e-}12$  (0.000001%).

**This is 9 orders of magnitude beyond the current state-of-the-art.**

# Lowering error rates

1. **Noise filtering:** Reduce the amplitude of the noise
  - Cooling and shielding systems
  - Design and packaging of processor
2. **Hardware-level error protection:** Reduce errors at the physical level
  - Materials and processing improvements
3. **Quantum Error Correction:** Detect and correct errors
  - Redundant encoding of information

# Quantum error correction (QEC)

Q: Is it possible, even in principle?

Two types of errors on a qubit  $(\alpha|0\rangle + \beta|1\rangle)$

bit flip:

$$\alpha|0\rangle + \beta|1\rangle \rightarrow \alpha|1\rangle + \beta|0\rangle$$

phase flip:

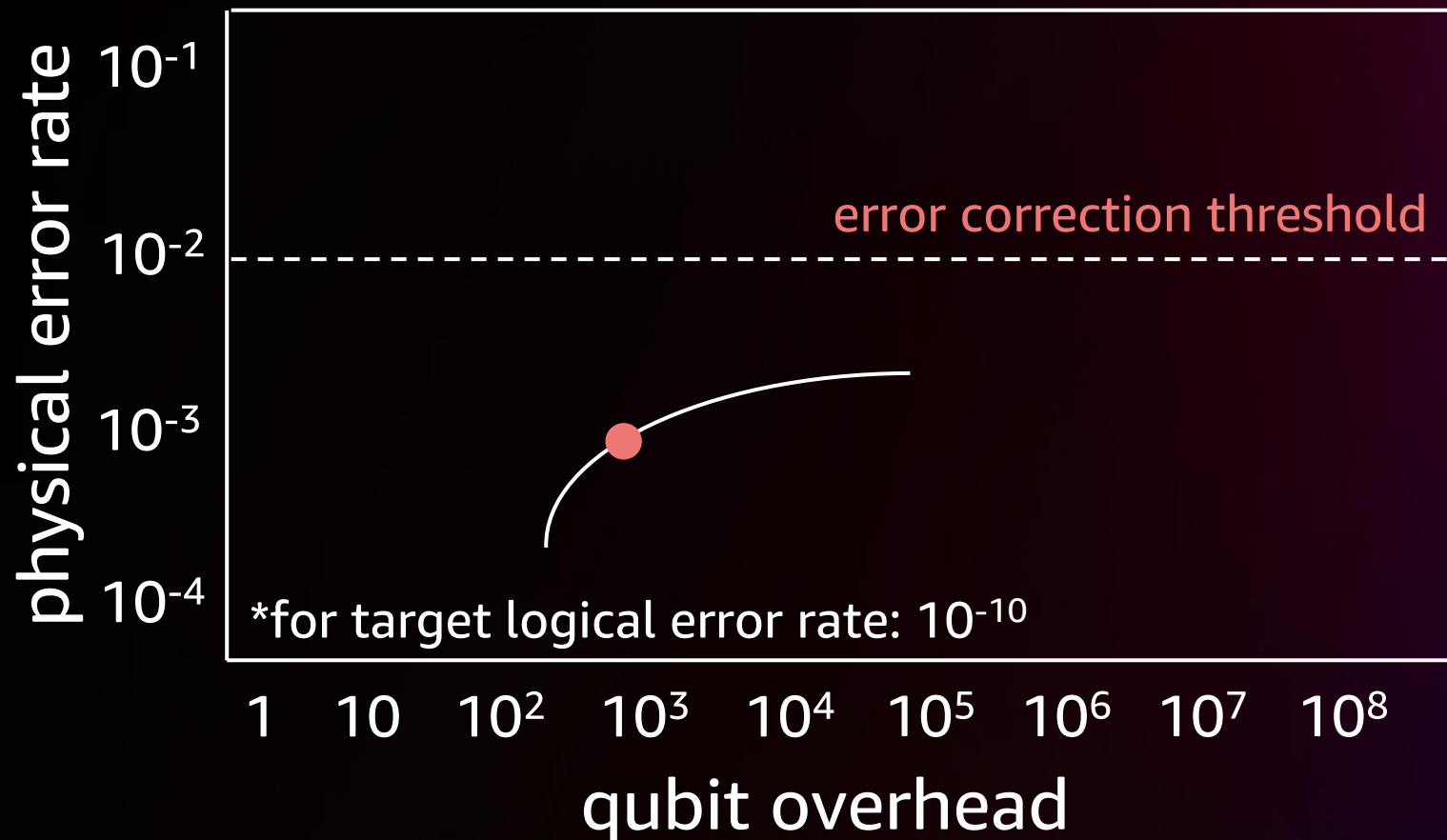
$$\alpha|0\rangle + \beta|1\rangle \rightarrow \alpha|0\rangle - \beta|1\rangle$$

Can't measure qubit state in a single-shot ('quantum collapse')

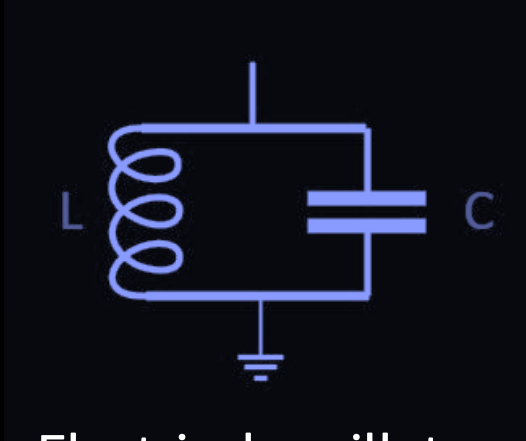


# Quantum error correction overhead

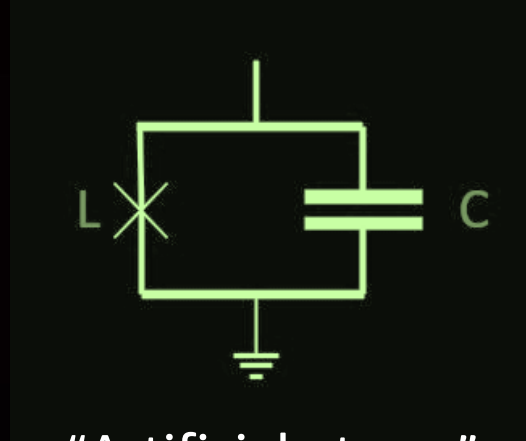
A: Yes, but only with special encoding into 'logical' qubits



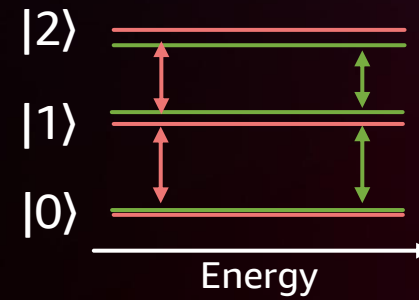
# Superconducting qubit



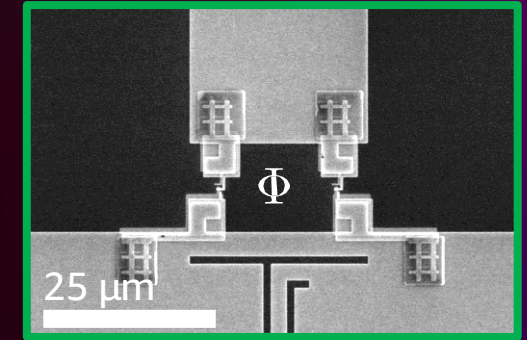
Electrical oscillator



"Artificial atoms"



Anharmonicity



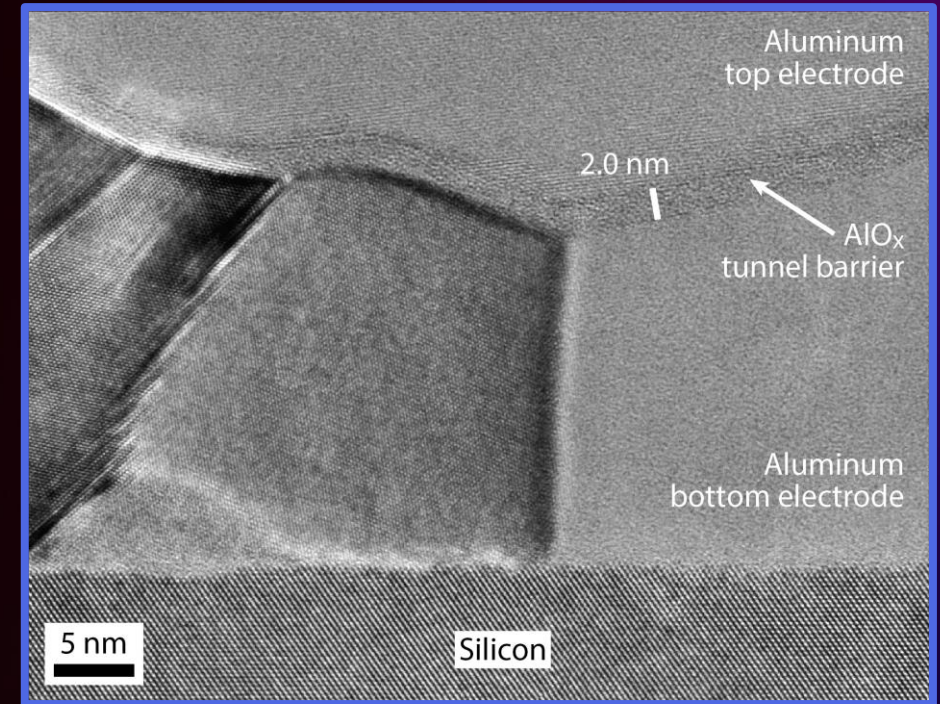
Josephson junction

- Wafer-scale microfabrication
- Flexible architecture
- Fast quantum gates
- Single-shot, high-fidelity qubit read-out



# Physical qubit development

- **10-100X** reduction in physical qubit gate and read-out error rates is required in order to efficiently use QEC
- **How are we going to get there?**
- Investment in physical qubit development from top to bottom:
  - New physical qubits
  - Materials development
  - Josephson junction manufacturability

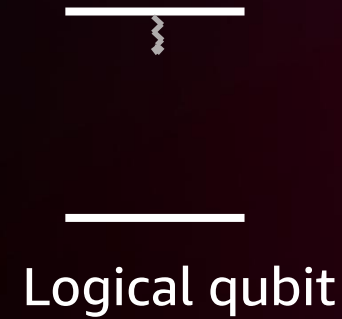


# Logical qubits

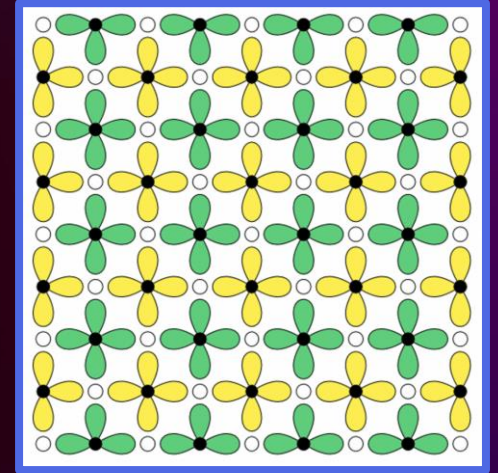
## Multi-qubit QEC



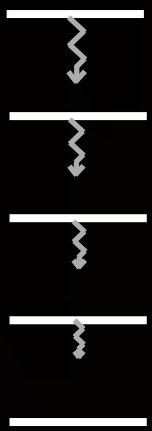
QEC



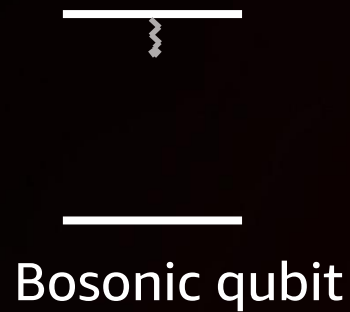
## surface code



## Bosonic QEC

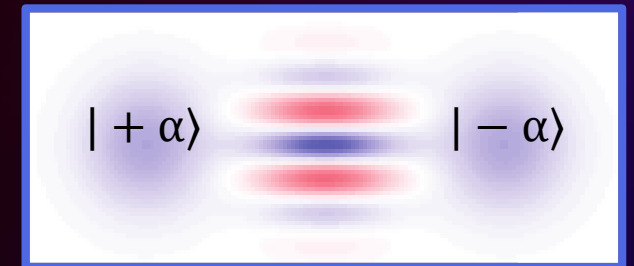


QEC



Physical oscillator

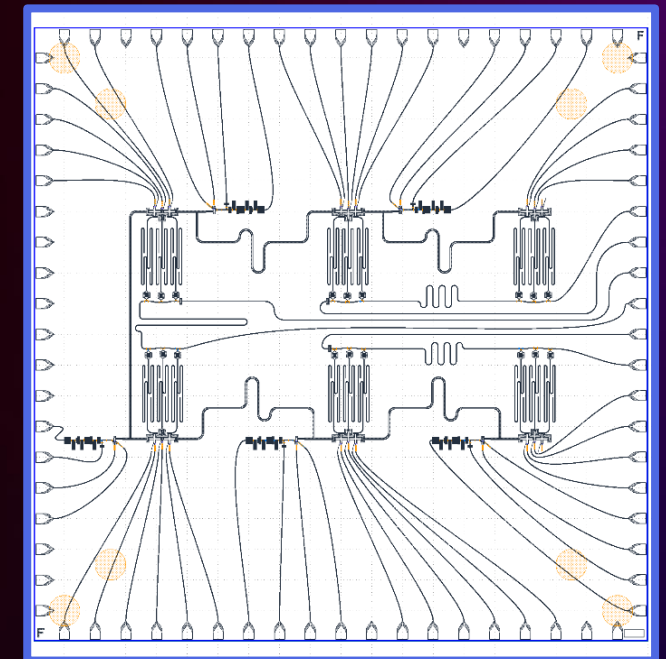
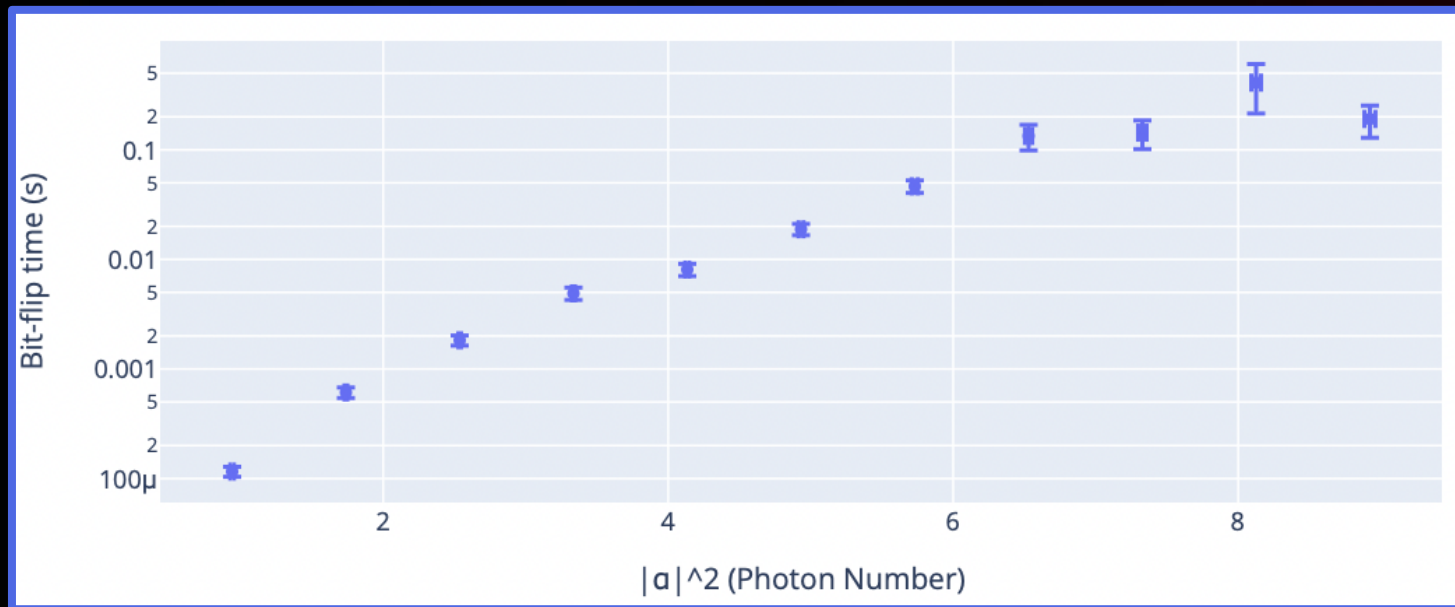
## cat states



# Repetition cat code: hardware-efficient QEC

Bit flips are exponentially suppressed through special dissipation engineering of cat qubits, while phase flips are corrected by a repetition code

Bit flip times extended by 5-orders of magnitude

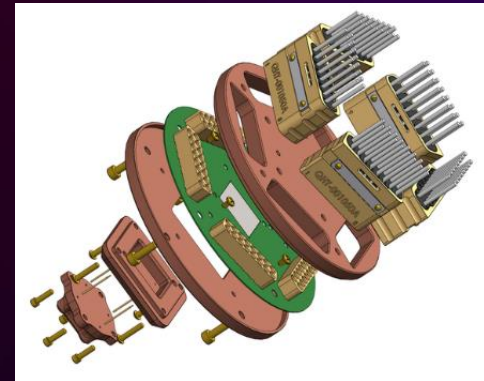
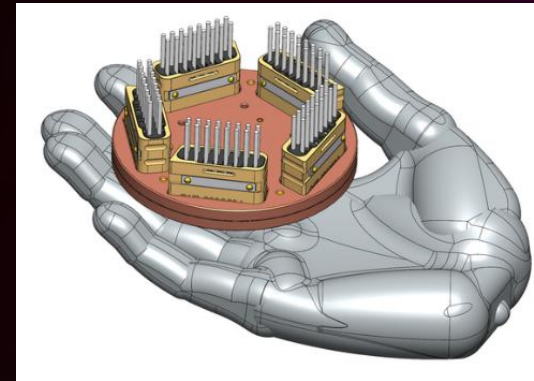
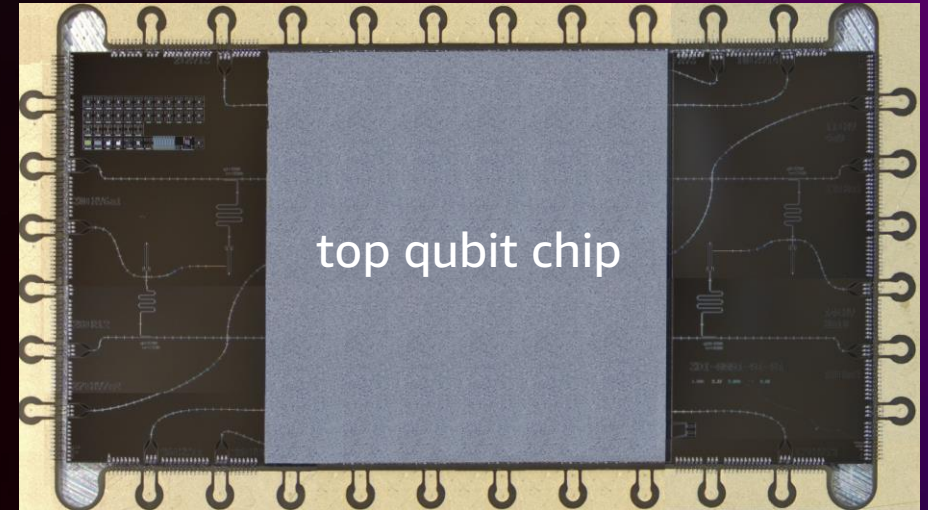


Chip layout of 2x2 cm<sup>2</sup>, d=5 rep code



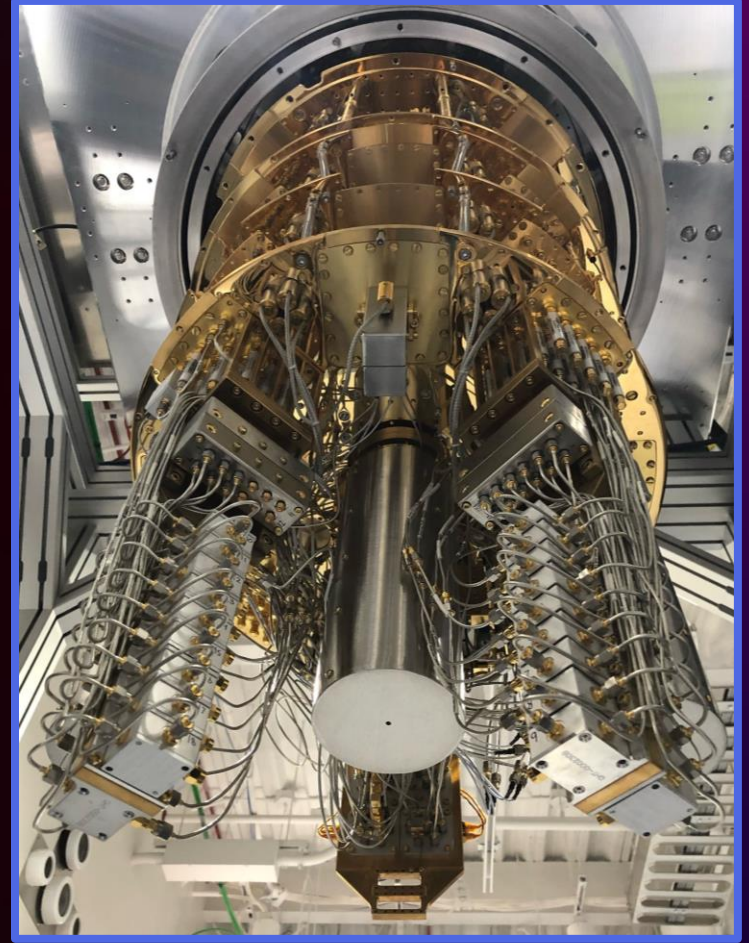
# Processor scaling and packaging

- **3D chip integration:** scalable, low x-talk signal routing
- **Package design:** large format chips (>2x2cm)
- **Connectors:** RF/microwave, high pitch-density
- **Scale-out:** inter-processor connectivity



# Fridge and wiring infrastructure

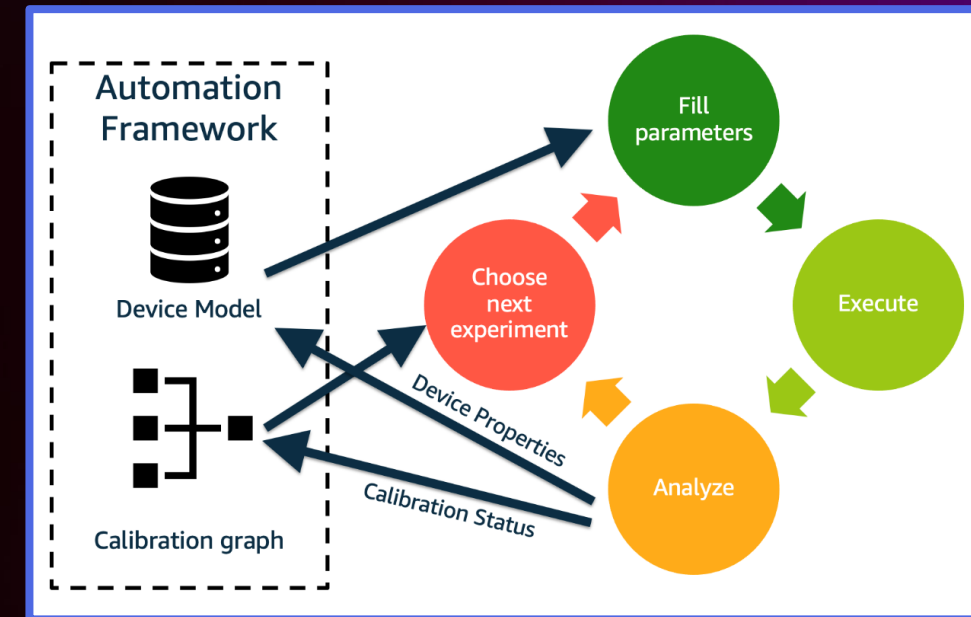
- Scalable fridge technologies that can support **100,000+ physical qubits**
- Scalable cryogenic wiring:
  - Microwave, DC, and thermal performance
  - High density form-factor
  - Drop-in components (filters, attenuators, etc.)



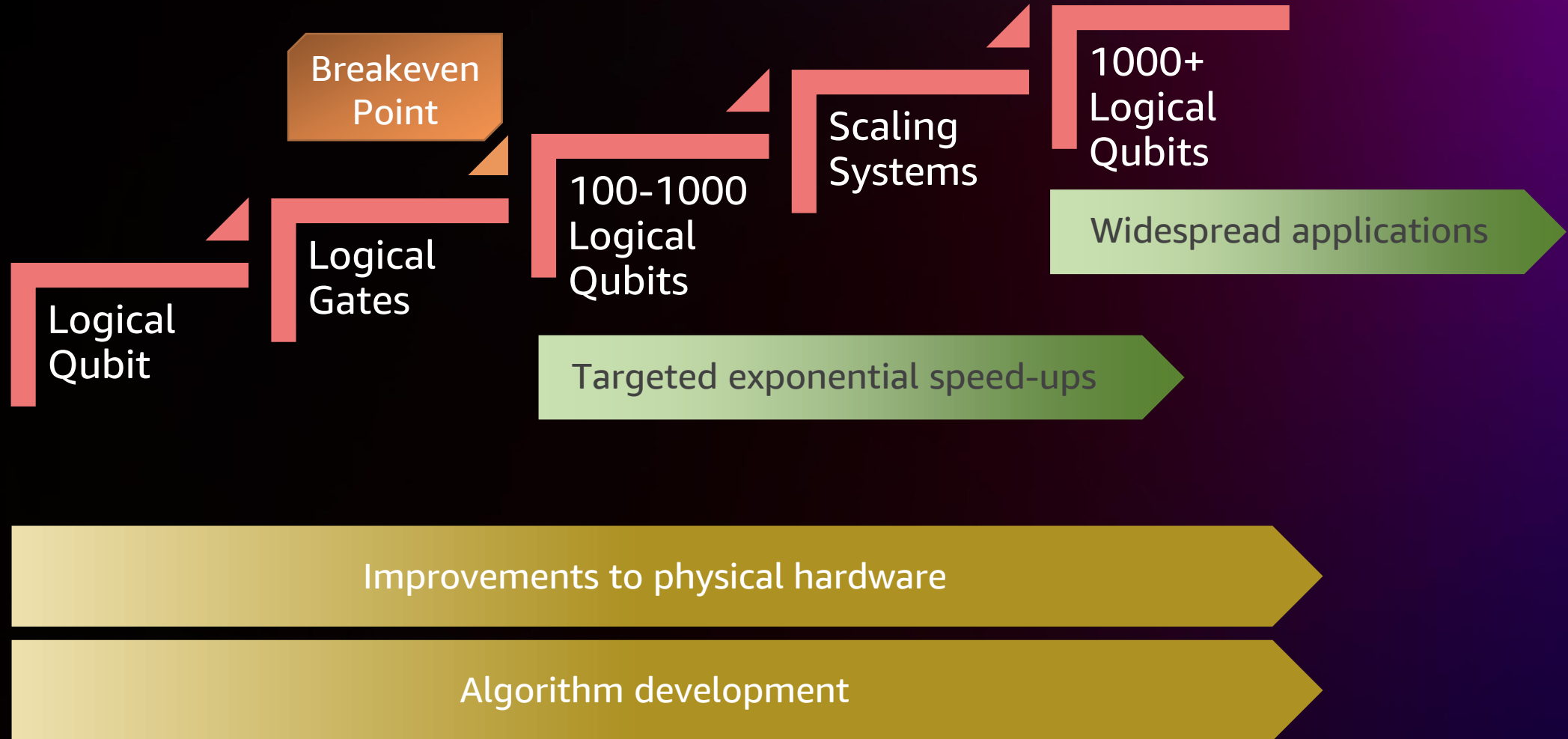
# Software stack

Quantum error correction requires **tight integration between software and (classical) control hardware:**

- Distributed computation and real-time feedback with ultra-low latency ( $< 10$  microseconds)
- Error correction operating system for coordinating the classical hardware
- Customers/developers will program at the quantum layer, shielded from underlying details of the control hardware

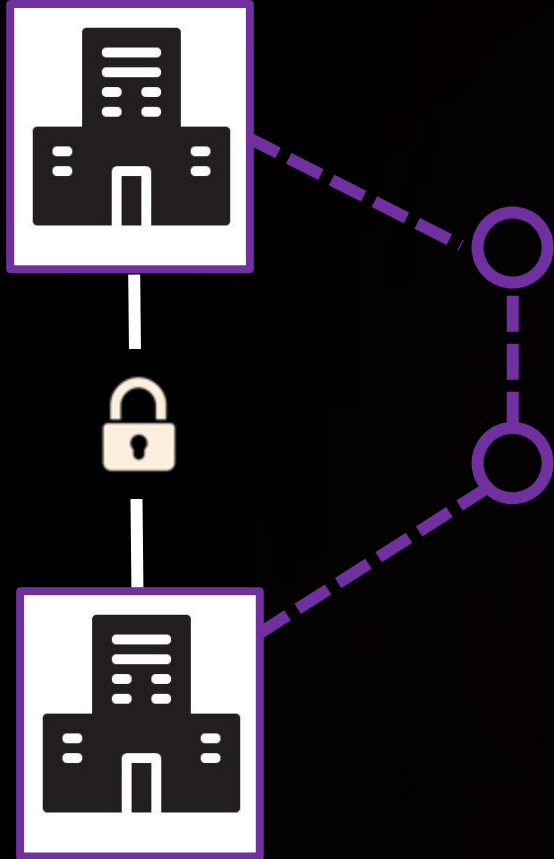


# Development path

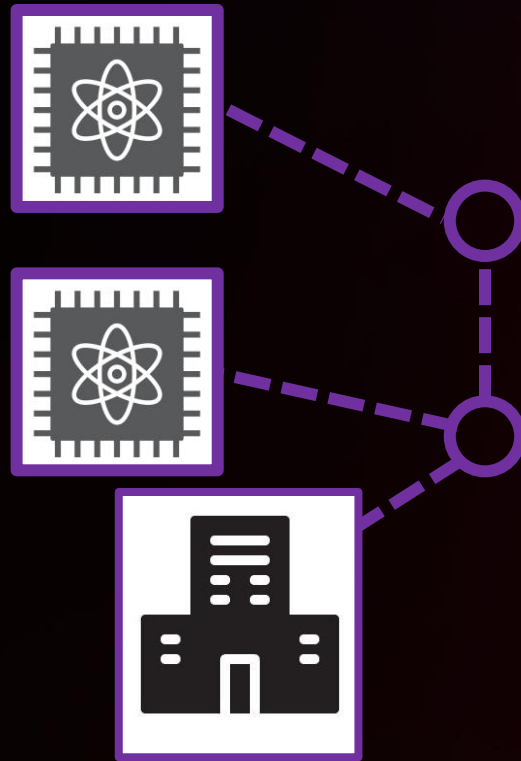


# Quantum networks

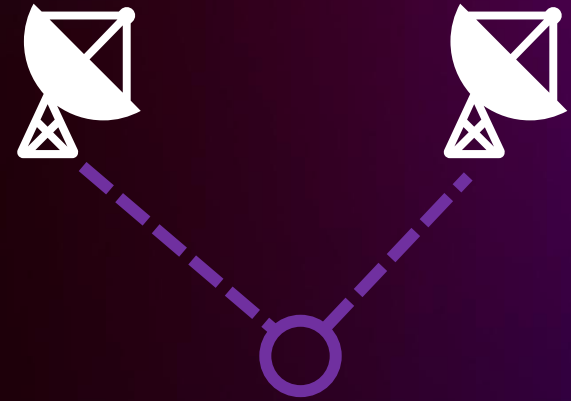
## Secure communication



## Private quantum computation



## Enhanced sensing



- Entanglement distribution
- Quantum network nodes



# AWS Center for Quantum Networking

## AWS Quantum Computing Blog




### Announcing the AWS Center for Quantum Networking

by Denis Sukachev and Mihir Bhaskar | on 21 JUN 2022 | in [Amazon Quantum Solutions Lab](#), [Announcements](#), [AWS Center For Quantum Computing](#), [Quantum Technologies](#) | [Permalink](#) | [Share](#)

Over the last decade, governments and technology companies have invested heavily in research and development of quantum computers that have the potential to revolutionize science and technology. While there is still a long way ahead, these investments have already transformed quantum computers: They have evolved from delicate laboratory systems accessible to only a few research [...]



Adam Selipsky ✓  
@aselipsky

Introducing the [#AWS](#)  Center for Quantum Networking, our new home for [#quantum](#) networking R&D. We're on a mission to build the underlying technologies that will enable the distribution of quantum information anywhere on Earth.



# Who are the customers for quantum computing today?

## Pioneers



Academic researchers  
Quantum solution  
providers  
Enterprise quantum  
centers of excellence

## Enablers



Global system  
integrators  
Quantum solution  
providers

## Pragmatists



Enterprises

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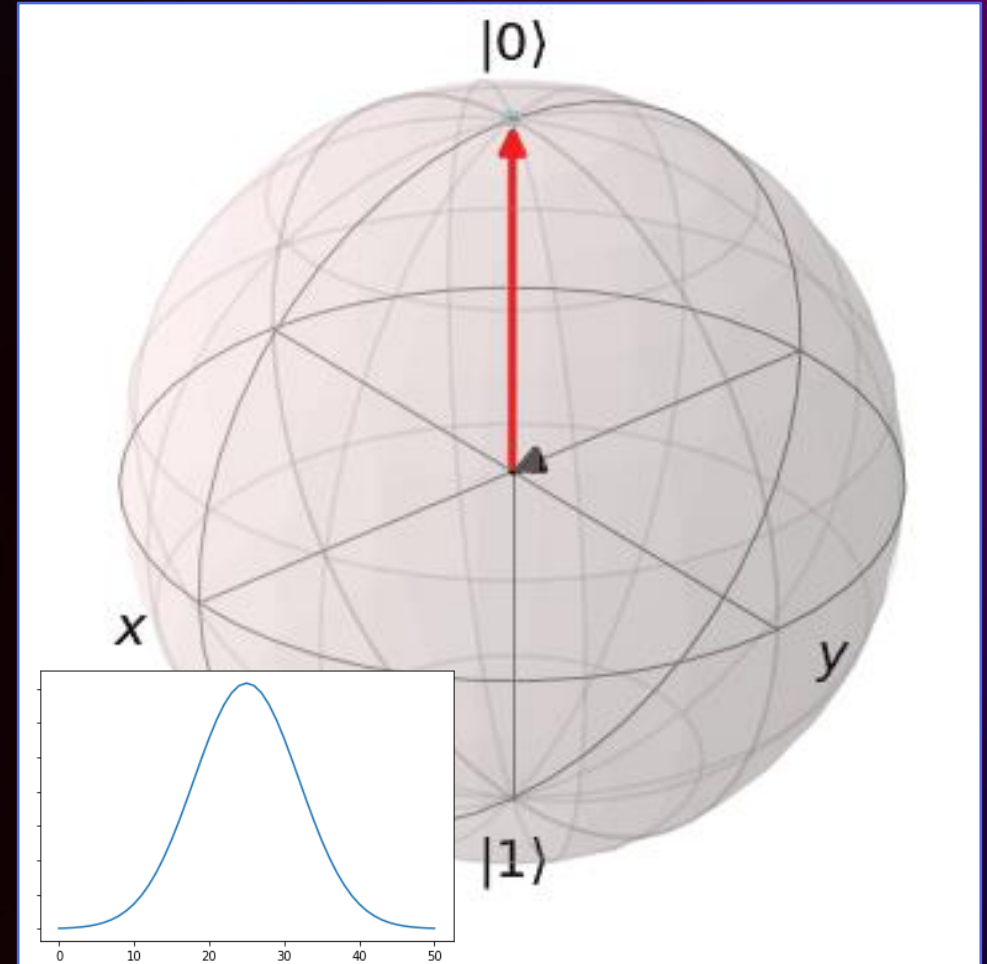
Enterprises

**Customer problem (2022)**

**Pioneers need tools to  
get the most out of quantum computers**

# Amazon Bracket Pulse

- Program quantum computers with **bare-metal access** down to the analog signals that control qubits
- Improve performance of quantum devices by **understanding noise and mitigating errors**



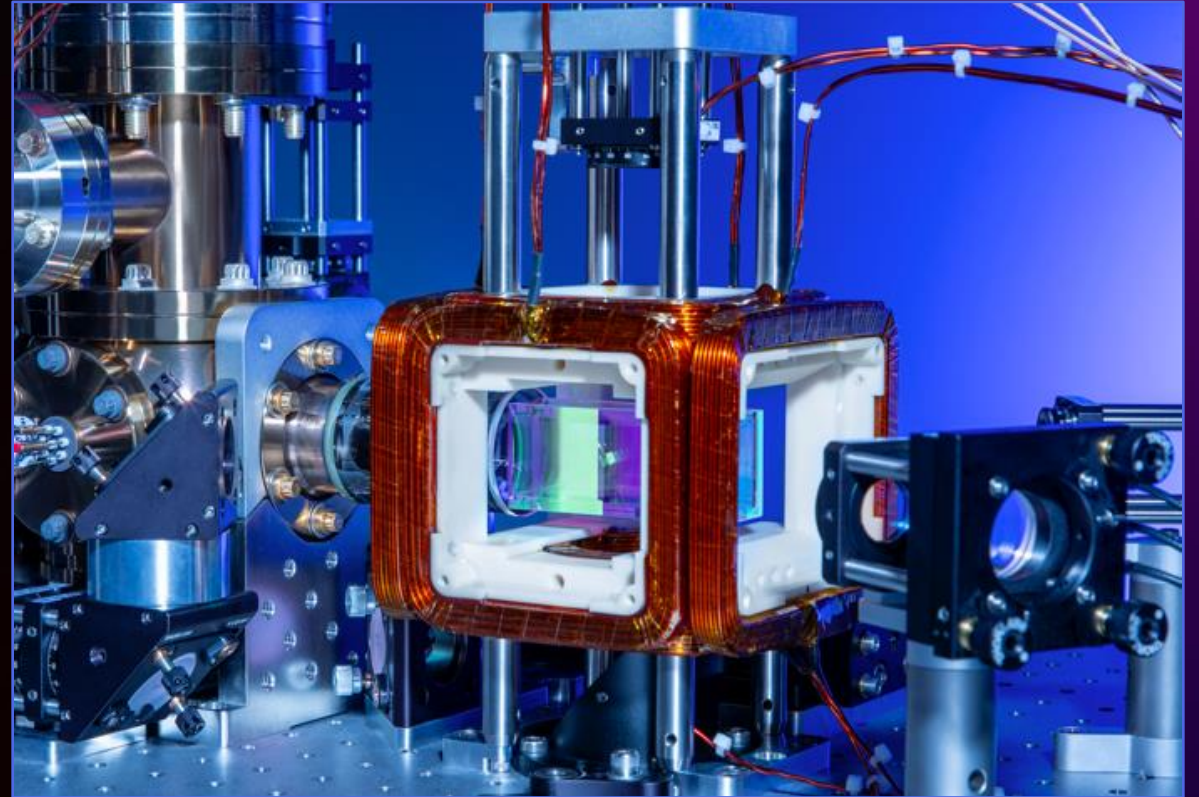


**Customer problem (2022)**

**Pioneers want to explore novel use cases**

# Analog Hamiltonian Simulation

- First publicly accessible Analog Hamiltonian Simulation machine with up to **256 qubits**
- Map problems in **fundamental physics, materials science, and optimization** to Hamiltonians
- Simulates system sizes that are **difficult to solve with conventional hardware**

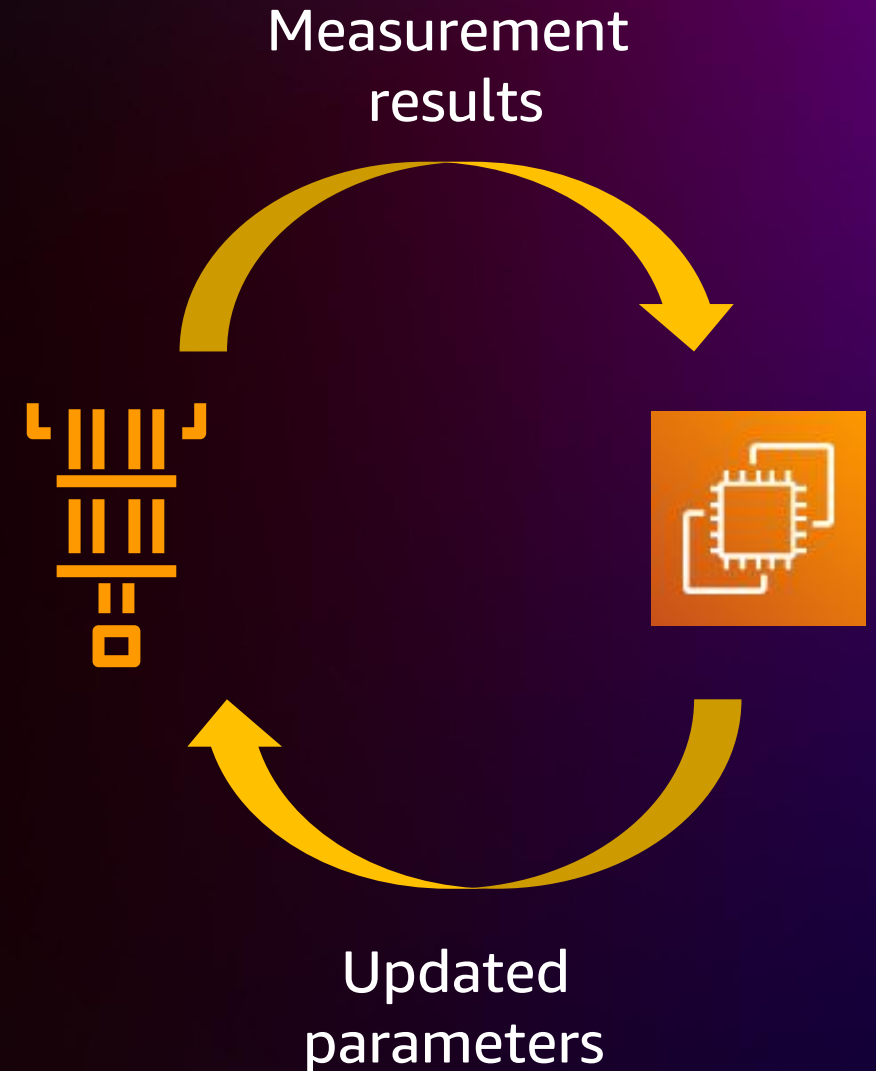


**Customer problem (2022)**

**Enablers need programming interfaces to develop quantum applications**

# Amazon Braket Hybrid Jobs

- Quantum computers will increasingly rely on **conventional co-processing**
- Application developers don't care about detailed workings of quantum computers or **orchestrating conventional resources**



**Customer problem (2022)**

**Pragmatists need **support** to understand how quantum computing will impact their business**





ENTROPICA LABS



# So how can I get started?

## Research quantum algorithms and test quantum computers

Experiment on a variety of quantum computers and use AWS Credits to speed up academic research.

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Quantum computing is an interdisciplinary area of research combining quantum physics and computer science. Research in quantum computing studies the physical limits of information processing and is breaking new ground in fundamental physics. This research leads to advances in many fields of science and industry, such as chemistry, optimization, and molecular simulation.

The Amazon Braket quantum computing service enables researchers at universities and national labs to perform experimentation with different quantum hardware technologies in one place, including trapped ions, superconducting qubits, quantum annealing, and others – as they emerge. With Amazon Braket, scientists can test and compare different quantum computers, explore hybrid quantum-classical, quantum machine learning and variational algorithms, and develop error correction strategies for Noisy Intermediate-Scale Quantum (NISQ) hardware.

**1 free hour of simulation time**

per month for a year with the [AWS Free Tier](#)

### [AWS Quantum Technologies Blog](#)

## Winners announced in the BMW Group Quantum Computing Challenge

by James Goeders and Martin Schuetz | on 09 DEC 2021 | in [Amazon Braket](#), [Amazon Quantum Solutions Lab](#), [Announcements](#), [Quantum Technologies](#) | [Permalink](#) | [Share](#)

The four winning teams of the [BMW Quantum Computing Challenge](#) were announced this morning at the annual Q2B conference in Santa Clara, California. The challenge, focused on discovering potential quantum computing solutions for real-world use cases, was a collaboration between the [BMW Group](#) and the [Amazon Quantum Solutions Lab](#) Professional Services team.

"We at the BMW Group are convinced that future technologies such as quantum computing have the potential to make our products more desirable and sustainable," said Dr. Peter Lehnert, Vice President BMW Group Research and New Technologies Digital Car. "We have succeeded in reaching the global quantum computing community with our crowd-innovation approach and enthusing them about automotive use cases. We look forward to continuing to work with the winners."

- **Apply for AWS Cloud Credits for Research** to get research credits to explore new quantum workloads
- **Engage our partners or the Amazon Quantum Solutions Lab** to explore use cases
- **Sponsor hackathons and challengers** to develop use cases in your industry



# Thank you!

Scott Buchholz



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Simone Severini



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