DeiC Q-Access Roadshow Part I – Introduction & Motivation

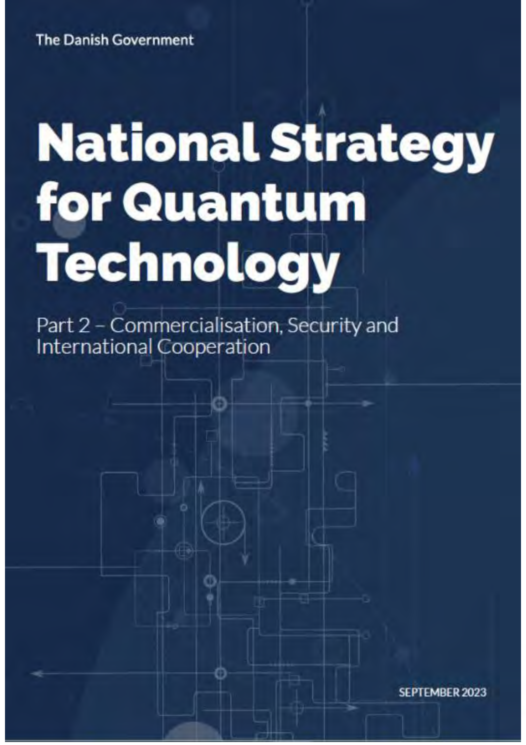
Henrik Navntoft Sønderskov, Head of Quantum Infrastructure, DeiC

- **Introduction**
- **Vision and goal for Danish quantum infrastructure and access?**
- **Where are we going?**

Quantum Ambition

In this video you can hear a Danish presentation of the importance of all of DeiCs quantum initiatives, and how industry can benefit from activities originating from the research environment from Jørgen Ellegaard, SDU.

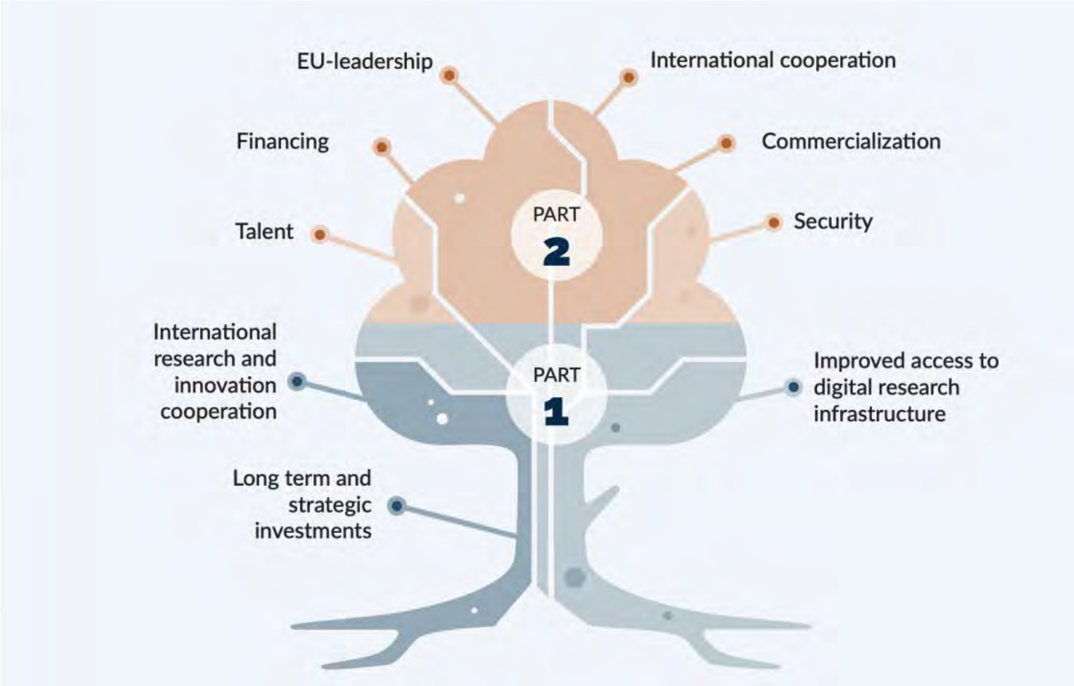
In this video you can hear a Danish presentation of DeiCs work enabling access to Quantum Computers from Dean Marianne Holmer, The University of Southern Denmark, DeiC board member and chairperson of the Q-Access Working Group.



The Objective of the Strategy for Quantum Technology - Part 1

"Denmark aims to have one of the world's leading quantum research environments and to have the ability to effectively translate research into new, usable technology.

Link between Part 1 and Part 2



National Quantum infrastructure:
https://www.deic.dk/en/quantum-infrastructure

Grants and Funding:
https://www.deic.dk/en/grants

Strategy - part 1:

https://ufm.dk/en/publications/2023/strategy-for-quantum-technology-part-1-2013-world-class-research-and-innovation

Strategy - part 2:

https://eng.em.dk/publications/2023/national-strategy-for-quantum-technology

DEIC QUANTUM DEPARTMENT: GOVERNANCE STRUCTURE & STRATEGIC ROADMAP FOR 2026

PURPOSE: TO VISUALIZE HOW DEIC BUILDS QUANTUM INFRASTRUCTURE

AVAILABLE ON DEIC'S WEBSITE FOR TRANSPARENCY AND KNOWLEDGE SHARING

LIVING WORKING DOCUMENT, UPDATED EVERY QUARTER

DeiC
DANISH eINFRASTRUCTURE CONSORTIUM

Strategic benchmark

Actively follow the development within quantum computing and algorithms and support the national development and future application in the field

Core initiatives	Core purpose	Regular internal meetings incl. i.a. the following governance bodies
DANISH QUANTUM ALGORITHM ACADEMY	Quantum algorithm and software development initiatives for academia and industry	Academy Council Evaluation committee
Q-COMPETENCE	Quantum competence-building educational activities for industry, public administration and research	Working group Evaluation committee
Q-ACCESS	Access to testing on quantum computing facilities at quantum computing and HPC facilities for universities, public administration and industry	Working group Evaluation committee POC @HPC department
NIELS BOHR QUANTUM SUMMER SCHOOL	Attract quantum talent to Denmark and foster a robust and innovative quantum sector	Steering committee Planning committee
LUMI-Q	Participate in the LUMI-Q consortium under EuroHPC JU, to establish a quantum computer	Steering committee
QUEX (QUANTUM EXCELLENCE CENTRE)	One-stop-shop for end-users of quantum technology, to take full advantage of emerging EuroHPC quantum computing infrastructure	Management committee
NORDIQUEST2	Nordic quantum corporation project on Q-oveview and quantum schools, through NeIC / NORFORSK	Procejctmanagement meetings

Cross-cutting:

University/DeiC Front Offices

Regular external meetings
incl. i.a. the following stakeholders
min. biannually

Cross-cutting:

Public organisations:

Ministry of Foreign Affairs (+ICDK's)

Danish Agency for Higher Education and Science

Danish Business Authority

Danish Defence (FE, FMI, FAK)
National Defence Technology Centre

PET (national security and intelligence service)

Innovation Fund Denmark

Independent Research Fund Denmark

LUMI-Q

QUEX

Danish Chips Competence Centre (DKCCC)

Private organisations:
Novo Nordisk Foundation

Confederation of Danish Industry

Quantum Denmark /DFM

Danish Quantum Community (DQC)

BII - DeepTech Lab/DIANA

Quantum computing companies

Current planned events and activities
some examples

Cross-cutting:

National events:
Digital Lead: Business casen for kvanteteknologi i 2025 - Del I

Social dinner for quantum community

Business Vejle paneldebat

Q-Access university roadshow visits

Sparrow Quantum networking event

Niels Bohr Quantum School incl. industry side event

Defence industy event at Precision Technic Defence

Cyber industry panel

Industryevent at the Confederation of Danish Industry (DI)

DeiC annual conference

International events:

QUEX internal kickoff (CPH)

QUEX external kickoff (Netherlands)

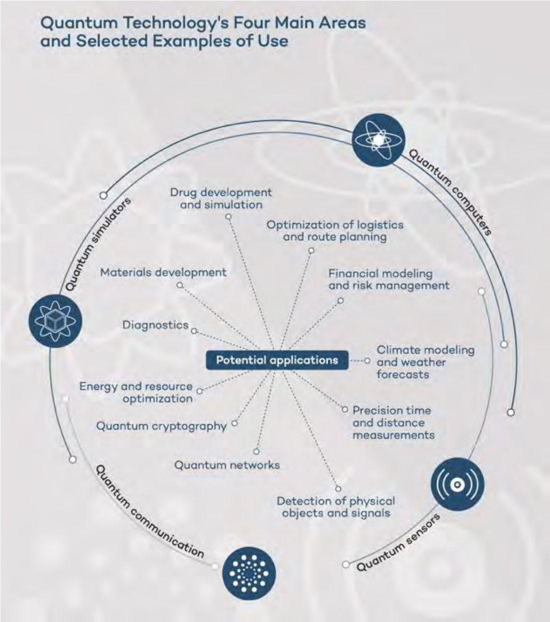
Ostrava / LUMIQ delegation trip

The European Quantum Technologies Conference 2025 (CPH)

The Danish quantum ecosystem now

DANISH MINISTRY OF DEFENCE

MINISTRY OF INDUSTRY, BUSINESS AND FINANCIAL AFFAIRS



Ministry of Higher Education and Science Denmark

NATO OTAN

MINISTRY OF FOREIGN AFFAIRS OF DENMARK

Quantum branches:

1) **Science:** E.g. physics, biologi, Social science, philosophy

2) **Commercial (every sektor i society):** Fx cyber, logistics, banking, climate

3) **Political:** E.g. National strategies, NATO, EU.

Vast Amount of Perspectives = Vast Amounts of Stakeholders (P = k \cdot S)

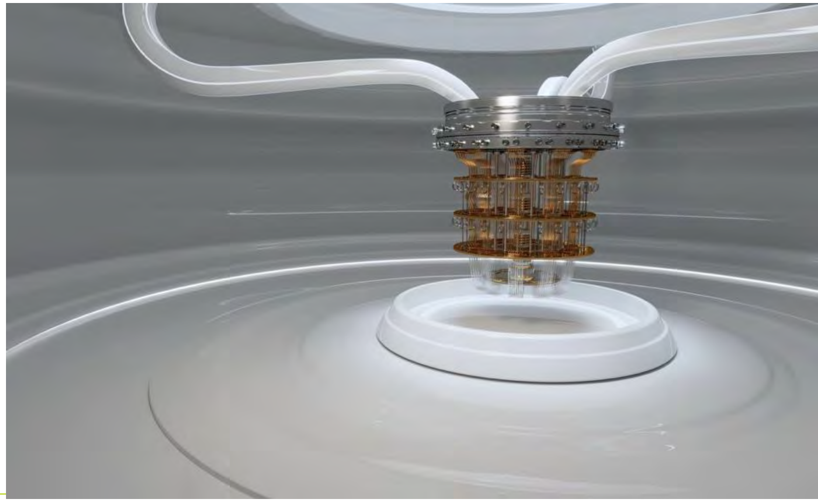
Niels Bohr “If anybody says he can think about **quantum** theory without getting giddy it merely shows that he hasn't understood the first thing about it!”

“If anybody says they can think about the Danish Quantum Ecosystem today without getting giddy it merely shows that they haven´t understood the first thing about it!”

Does anyone have an idea of - which different types of actors are working within the quantum field? and how many there are in Denmark as of October 2025?

Overview of the Stakeholder Landscape in the Danish Quantum Ecosystem:

https://www.deic.dk/sites/default/files/2025-11/Quantum_Overview_of_the_stakeholder_landscape_in_the_Danish_Quantum_Ecosystem.pdf



Other Stakeholder Perspectives and Other Kind of Public Communication about Quantum Infrastructure

Illustration: Rasmus Meisler

- **Børsen,** (udkommer snart): Hvad Danmarks nye muligheder er med kvanteteknologi, og slags verden mulighederne har åbnet.
- **Jyllandsposten**, 05.07.25.Om hvordan kvanteteknologien kan ryste vores grundvold: https://jyllands-posten.dk/debat/kronik/ECE18328191/kvanteteknologien-kan-ryste-vores-grundvold/
- **Weekendavisen,** 25.04.2025. Om hvordan teknologiudviklingen er gået langt hurtigere end udviklingen af ligestilling: https://www.weekendavisen.dk/2025-17/opinion/kvanter-og-koen?gaa_at=eafs&gaa_n=AerBZYMk2lbag1YW1WRRFLCMdGjSH2yUp_mGr9EeadXKHill-WkFDFa1SrAD-VVxr-E%3D&gaa_ts=681882c5&gaa_sig=udx7phWCrNcpbo5M16GcTEkdSekW0caNBFKpfpVkwxb5beN5YVMooqaLpiuz3CjdTWJzZpsWdRx87SE-0ziX2g%3D%3D
- **Børsen,** 18.01.25. Om eksplosionen i kvanteinteressen og årsagerne til det: https://borsen.dk/nyheder/opinion/kvante-kaldes-en-guldrandet-investering-men-hvad-driver-det
- **Weekendavisen,** 18.10.24. Om kvanteteknologiens betydning og ultratætte sammenhæng mellem forskning, industri og samfund: https://www.weekendavisen.dk/opinion/alle-lever-vi-i-en-kvanteverden
- **Kristeligt Dagblad,** 13.08.2024. Om hvorfor kvanteteknologi er uløseligt forbundet med geopolitik og Forsvaret: https://www.kristeligt-dagblad.dk/debat/sociolog-de-nye-teknologier-aendrer-verdens-sikkerhed-grundlaeggende
- **Børsen,** 13.08.2024. Om hvordan kvanteteknologien fæstner sig i samfund og sind: https://borsen.dk/nyheder/opinion/kvanterevolution
- **Podcast 2025:** Kampkraft: Kvanteteknologi som kampkraft: https://open.spotify.com/episode/4O04gMD9ZXDUk5BFwmFWZl

A (very) small fraction and example of the Danish Quantum landscape. Which is in a form of "superposition"

(AI)

abzu

(Defence oriented)

TERMA
ALLIES IN INNOVATION

WEIBEL
DOPPLER RADARS

(Life Science)

MQS Molecular Quantum Solutions

kvantify

novo nordisk

novozymes

(Cyber)

DENCRYPT

ZYBERSAFE

Alea Quantum Technologies

CRYPTOMATHIC

DeiC

(Research / innovation)

DFM

DTU

ALEXANDRA INSTITUTTET

AARHUS UNIVERSITY

SDU Syddansk Universitet

AALBORG UNIVERSITET

IT UNIVERSITY OF CPH

(Transport)

MAERSK

FROGNE
– Part of the KFA Group

NKT Photonics

Sparrow Quantum

SiPhotonIC TECHNOLOGIES

QDevil

FOSS

IndesmaTech

TDC

(Hardware & infrastructure)

STENSBORG

FOM TECHNOLOGIES

Ørsted

ENERGINET

Danish Industry

Danish Quantum Community

DANSK ERHVERV

(Branch organisations)

novo nordisk foundation

NATO OTAN

KPMG

IBM

NATO OTAN
Defence Innovation Accelerator for the North Atlantic

Ministry of Higher Education and Science Denmark

ERHVERVSMINISTERIET

CARLSBERG FOUNDATION

VILLUM FONDEN

Innovationsfonden

Microsoft

DANISH MINISTRY OF DEFENCE

Qpurpose

Danske Bank

DigitalLead

BII BioInnovation Institute

EIFO

INNOVATION CENTRE DENMARK

NVIDIA

MINISTRY OF FOREIGN AFFAIRS OF DENMARK

TRIFORK.

(Investors and accelerators)

Danmarks Grundforskningsfond
Danish National Research Foundation

DANISH eINFRASTRUCTURE

(International)

(Authorities)

(Counselling)

(Banking)

History show we can´t predict the future - yet

"There is not the slightest indication that nuclear energy will ever be attainable. It would mean the atom would have to be shattered at will".*Albert Einstein, 1932.*

"Remote shopping, while entirely feasible, will certainly flop. It has no chance of success." *Time Magazine, 1966.*

"No-one will ever need more than 637KB of memory in a computer. 640KB ought to be enough for anybody." *Bill Gates, CEO of Microsoft, 1981.*

"The idea of a personal communicator in every pocket is nothing more than a pipe-dream fuelled by greed." *Andy Grove, CEO of Intel, 1992.*

"I predict that the internet will go spectacularly supernova, and in 1996 it will catastrophically implode". *Robert Metcalf, inventor of Ethernet, 1995.*

"The internet will fade away because most people have nothing to say to each other. By 2005 it will be clear that the internet's impact on the global economy has been no greater than the fax machine." *Paul Krugman, renowned Economist, 1998.*

"There is practically no chance satellites will ever improve telephone, television or radio reception within the United States." *T. Craven, FCC Commissioner, 1961.*

"There is no reason an individual would ever want a computer in their home". *Ken Olsen, founder of Digital Equipment Corp, 1977.*

"Mobile phones will absolutely never replace the wired telephone". *Marty Cooper, inventor of the mobile phone, 1981.*

"I don't know… there just aren't that many videos I want to watch." *Steve Chen, founder of YouTube, expressing doubts about YouTube's viability as a company. 2005.*

"There is no chance of the iPhone ever gaining significant market share".*Steve Ballmer, CEO of Microsoft, 2007.*

"Subscription models for music are bankrupt. I think you could make the Second Coming of Jesus himself available on subscription and it wouldn't be successful." *Steve Jobs, CEO of Apple, 2003.*

A few perspectives

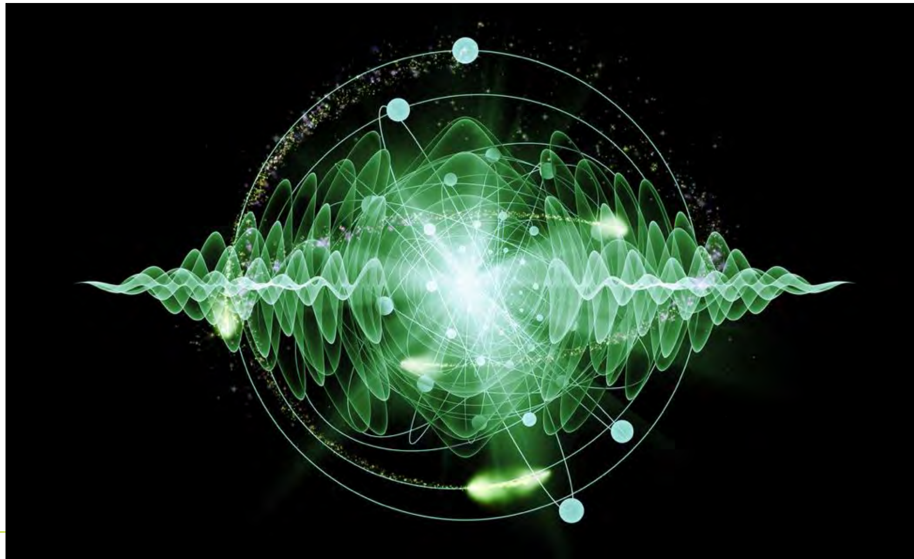
"Those who are not shocked when they first come across quantum theory cannot possibly have understood it"
Niels Bohr, theoretical physicist. 1927

"The paradox is only a conflict between reality and your feeling of what reality 'ought to be'"
Richard Feynman, theoretical physicist. 1963

The main ingredient of the first quantum revolution, wave-particle duality, has led to inventions such as the transistor and the laser that are at the root of the information society"
Alan Aspect, physicist. 2014-

"Quantum mechanics makes absolutely no sense"
Roger Penrose, mathematical physicist. 1980´s

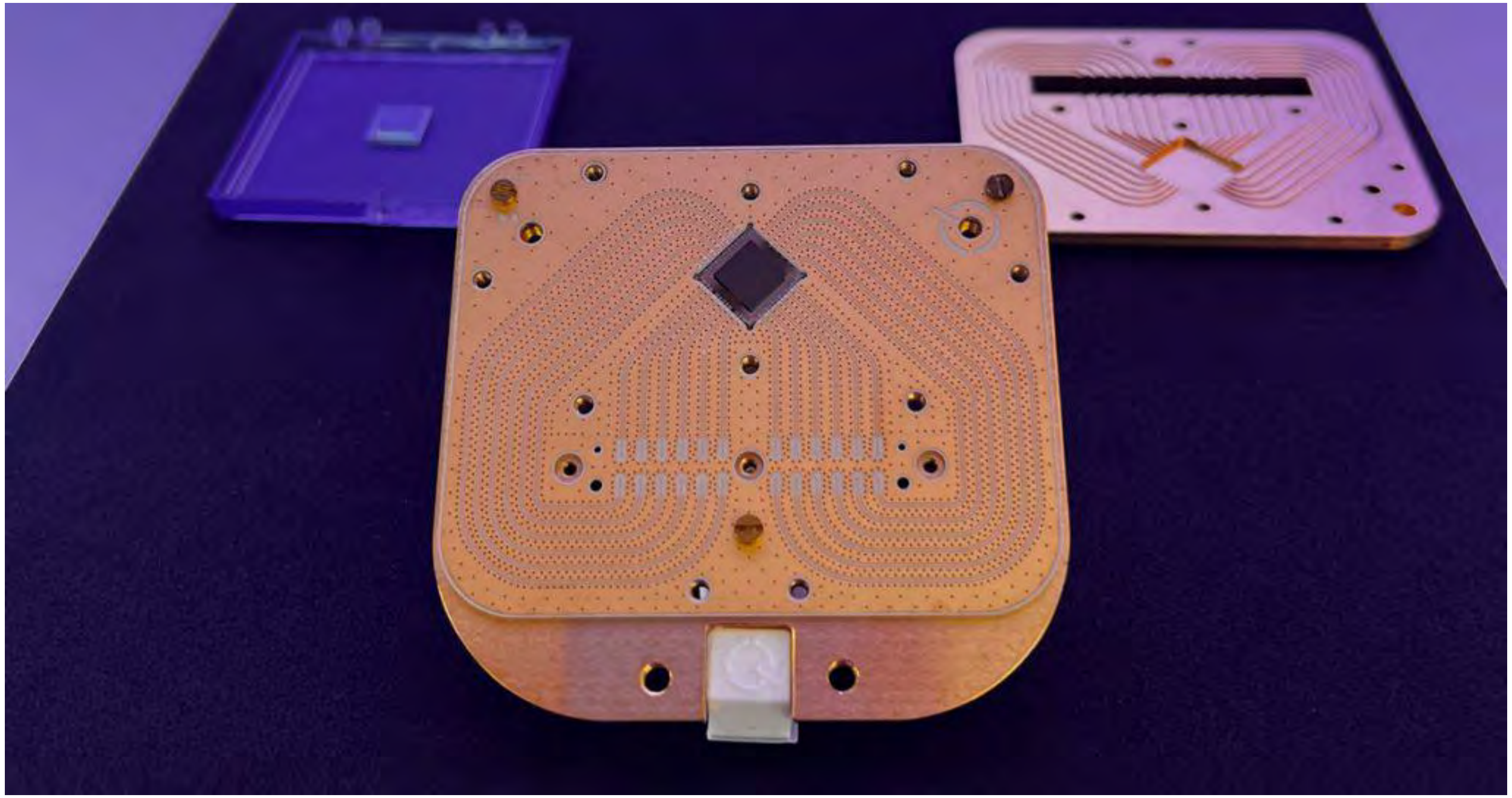
"The fast-advancing quantum computing (r)evolution, will challenge the pre-quantum way of conducting scientific and industrial development by making digital transformation of societies, organizations, and financial markets fundamentally different" A quote on the Goodreads platform.



DeiC Q-Access Roadshow Part II – Concrete Initiatives

Muyang Liu & Greyson Potter

Quantum Computing Infrastructure Developer, DeiC



The new VLQ quantum computer contains 24 superconducting qubits in a star-shaped topology and will be available to users in Denmark!

DeiC Q-Access Roadshow

Outline

1. **Introduction to DeiC's Quantum Department**

2. **DeiC's New Quantum Guide**
   a. Background of quantum computing
   b. Landscape of quantum computing hardware and software providers
   c. Algorithms & Near-term applications

3. **LUMI-Q Consortium and VLQ Quantum Computer**
   a. EuroHPC Joint Undertaking
   b. IQM Quantum Computers
   c. DeiC's Participation in the LUMI-Q Consortium

4. **Proof-of-concept Use Cases**
   a. Optimization
   b. Simulation
   c. Machine Learning

5. **Q-Access**
   a. Consulting and Office Hours
   b. Sandbox Access
   c. Calls for specialized Access
   d. LUMI-Q VLQ Access

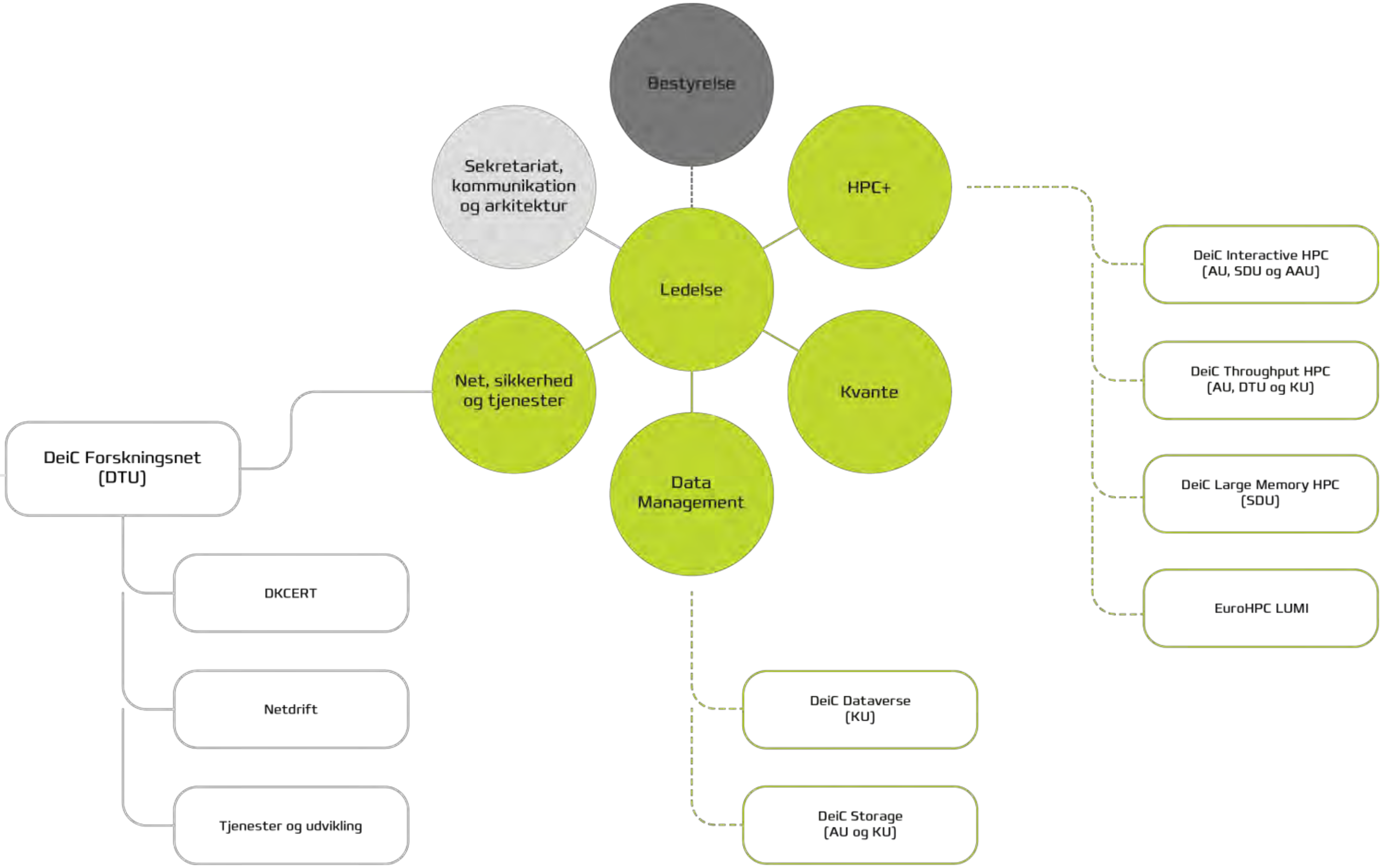
6. **Q & A with Q-Access Team**

1. Introduction to DeiC's Quantum Department

Overview of DeiC

The **Danish e-Infrastructure Consortium (DeiC)** develops and coordinates access to digital research infrastructure for Danish universities, enabling research and education at a high international level.

The research network is a high-speed network that connects Danish universities and research institutions.



DeiC's Quantum Department

- The newest department in DeiC - established as part of the implementation of the Denmark's national quantum strategy.

Initiatives

Q-Competence

- Disseminate skills and increase understanding of the potential and risks of quantum technology.
- Financial support for developing quantum computing material and events.

Q-Algorithm

- DQA Academy to boost work in developing and testing quantum algorithms and the associated software stack.
- Scholarships for Ph.D. students and Postdocs.

Q-Access

- Calls for specialized access to quantum computers.
- Sandbox access via Microsoft Azure for testing.
- Consulting service with quantum experts.
- Access to the new LUMI-Q VLQ quantum computer.
- Overviews, guides, and step-by-step tutorials.

Niels Bohr Quantum Summer School

Two-week summer school, for the next 4 years, for both Danish and international Ph.D. students to learn about quantum computing and attract talent to the quantum community in Denmark.

LUMI-Q

The LUMI-Q consortium set up a quantum computer called "VLQ," which has 24 superconducting qubits in a star-shaped topology. IQM in Finland is the hardware provider, and it is deployed in the Czech Republic at the IT4Innovations Centre at the Technical University of Ostrava.

2.DeiC's New Quantum Guide

A New Published Quantum Computing Guide

Outline

1. **Motivation – a clarified guide for everyone**
2. **Background on Quantum Computing**
   a. Basic unit of quantum computing
   b. Quantum circuit – A diagrammatic format to display the executed algorithms
   c. Two developing stages – NISQ vs FTQC
3. **Another Benefit – Lowering Footprint**
   a. Energy Consumption: Classical HPC vs QC
   b. A case study comparison
4. **Magne – A Danish owned quantum computer**
4. **Benchmarking Quantum Devices**
   a. A simple and quick evaluation using three key metrics
   b. A truly comprehensive assessment
5. **Types of Quantum Computers and their applications**
   a. How to make qubits
   b. Major quantum hardware providers and their industrial end users
   c. A summary of general quantum computing applications across industry sector
6. **Interface with AI**

Motivation – a clarified guide for everyone

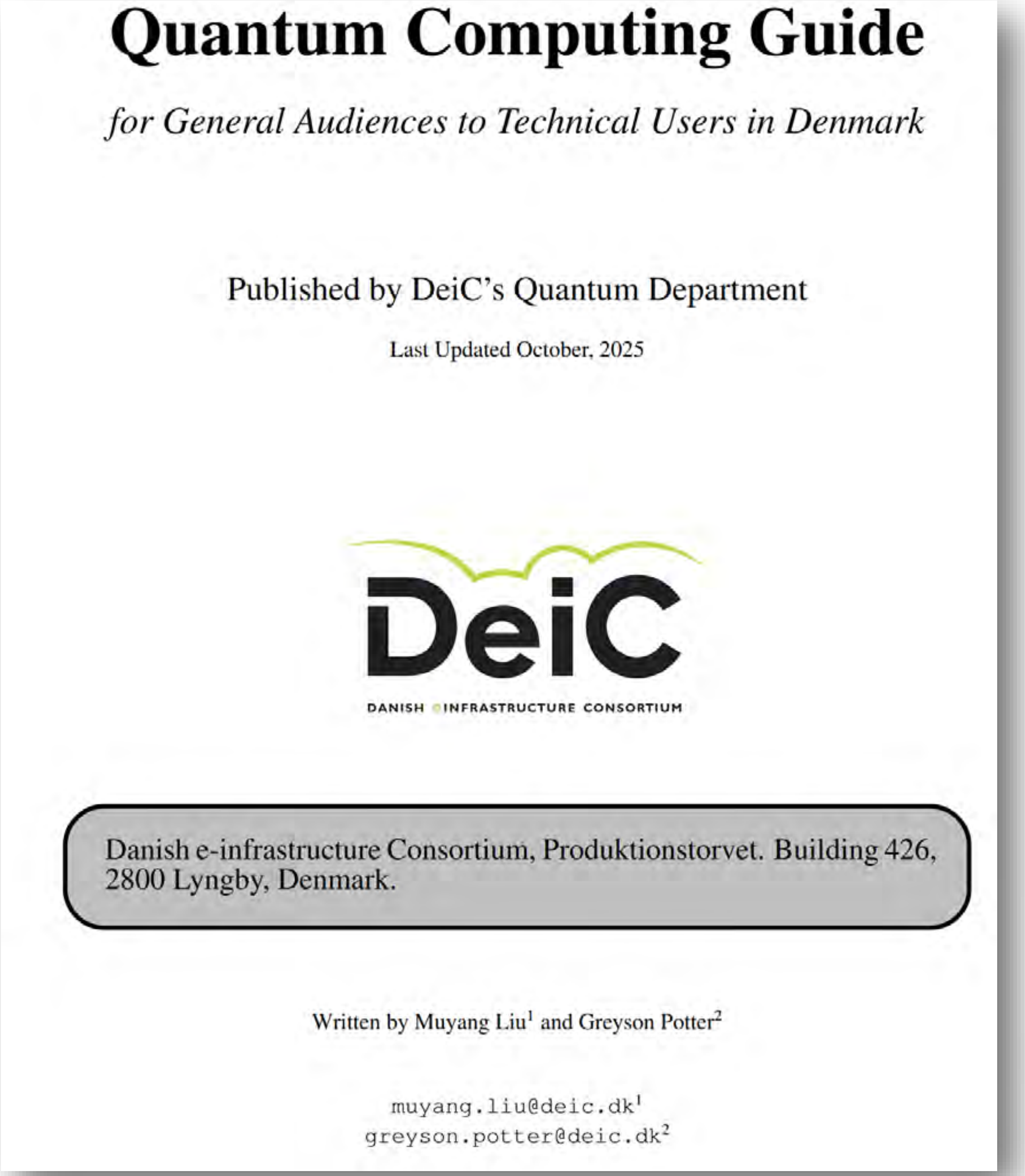
Motivation

A clear, unified overview of quantum computing published by **DeiC's Q-Access team** to show

- *What resources exist (types, major providers, etc)*
- *How to get access*
- *How to benchmark quantum devices*
- *Interdisciplinary Interface, e.g., AI & QC*

Target **multiple audience groups**

- General audiences (policy makers, journalists, industrial newcomers)
- Researchers and technical users
- Decision makers (funding, infrastructure)



Quantum Computing Guide

for General Audiences to Technical Users in Denmark

Published by DeiC's Quantum Department

Last Updated October, 2025

DANISH eINFRASTRUCTURE CONSORTIUM

Danish e-infrastructure Consortium, Produktionstorvet. Building 426, 2800 Lyngby, Denmark.

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Some Warm Feedbacks

- More cross-sectorial dialogues between research and industry
- Establish a common language and perspective on the possibilities

Andreas Greve • 2nd 4d •••
Innovation Manager @ DigitalLead | Innovation Processes & Ecosy...

Henrik Navntoft Sønderskov What an important product to create insight and strengthen understanding of the possibilities of quantum technology for Danish companies 💡⚛️🎯 **Bille Madsen** **Anja Hoffmann** **Jonas Sølberg** **Kasper Nielsen** and others perhaps interesting? ...more

Show translation

Like · 2 | Reply · 3 replies

Anja Hoffmann • 2nd 4d •••
NewTech | Digital Transformation | Innovation | R&D | Trust...

We need to investigate and understand more about which solutions industry can commercialize in the quantum field. This requires more cross-sectoral dialogues between research and industry to identify learnings that can help us solve the complex problems we face. A good starting point is to establish a common language and perspective on the possibilities. Good initiative **Henrik Navntoft Sønderskov** . A deeper understanding of technology maturity in relation to commercial maturity also contains some interesting discussions. Thanks, **Andreas Greve** , for the ping.

9 Sections, 80+ pages, how to read?

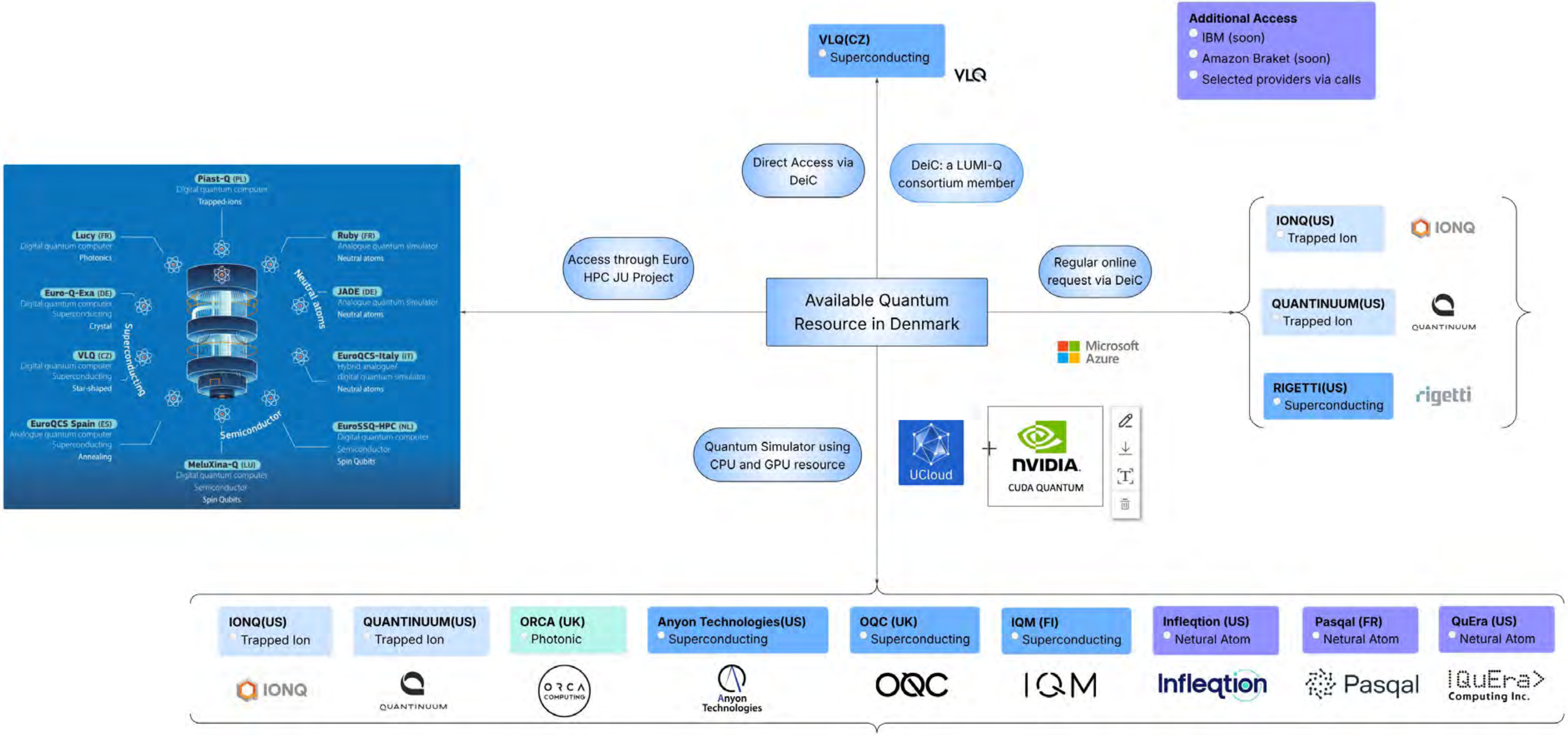
Contents

A Flexible Navigation System

Jump directly to what you need!

- Sec 1: Historical background and motivation
  - *John Preskill: Quantum computing 40 years later*
  - *IBM: What is quantum computing?*
- Sec 2: Quantum algorithms and their applications
  - *Quantum Algorithm Zoo*
- Sec 3-5: Practical access mode
  - *DeiC Q-Access: Access to Quantum Computers*
  - *VLQ: the quantum computer of the LUMI-Q consortium*
  - *UCloud User Guide*
  - *Google Quantum AI: Choosing hardware for your qsim simulation*
- Sec 6-7: Benchmarks, modalities and pricing
  - *Deep Lall et al: A Review and Collection of Metrics and Benchmarks for Quantum Computers: definitions, methodologies and software*
- Sec 8: EuroQHPC - an integration project
  - *The European High Performance Computing Joint Undertaking: Quantum Computers*
- Sec 9: Quantum Interface with AI
  - *Jacob Biamonte et al: Quantum Machine Learning*
  - *Maria Schuld & Francesco Petruccione: Machine Learning with Quantum Computers*
  - *LUMI: From binary computing to quantum AI*
- Appendix: Additional services and initiatives

Quantum computing resources accessible for users in Denmark (see Greyson's talks for details)



Background of Quantum Computing

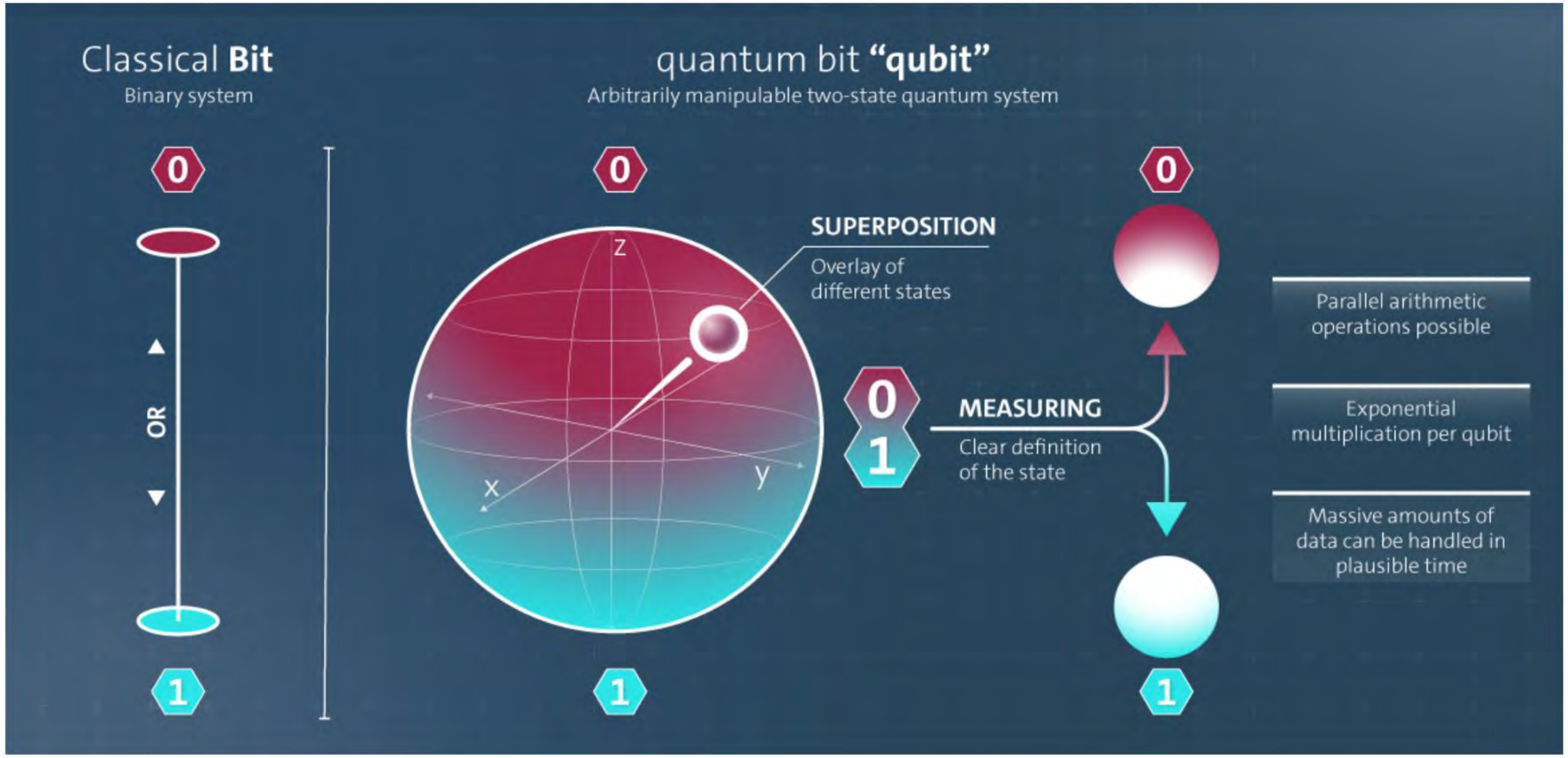
Quantum Computing in a Nutshell

Computational units: Qubit

- Superconducting circuit, trapped ions, neutral atoms...

Manuplational units: Quantum gates

- **Hardware-level processes** that change the qubit's *quantum state,* e.g., Laser beams on ions induce couplings:
    1. between the qubit states (for single qubit gate)
    2. between the internal qubit space and the shared motional spaces (for entanglement)



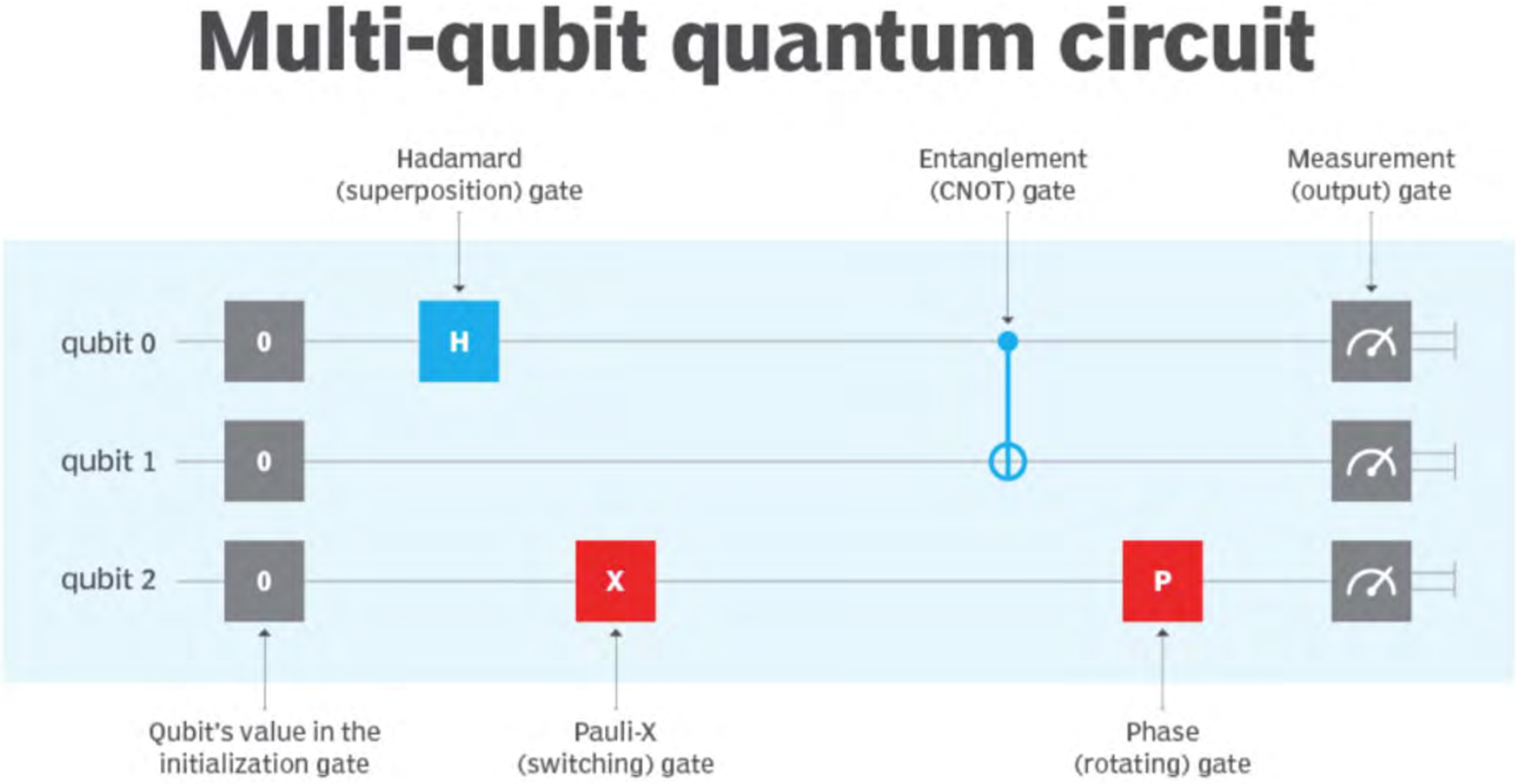
Quantum Computing in a Nutshell

Quantum Circuit - a diagram to display quantum algorithm

- Composed by sequence of quantum gates

Native-gates: every quantum hardware platform has a limited set of physical operations that it can directly implement

- **Compiler** decomposes high entangled gates, Toffoli, T gate, Hadamard, into optimal sequences of *native gates*
- **Benchmarking & Pricing***:* cost and performance are measured at the native-gate level



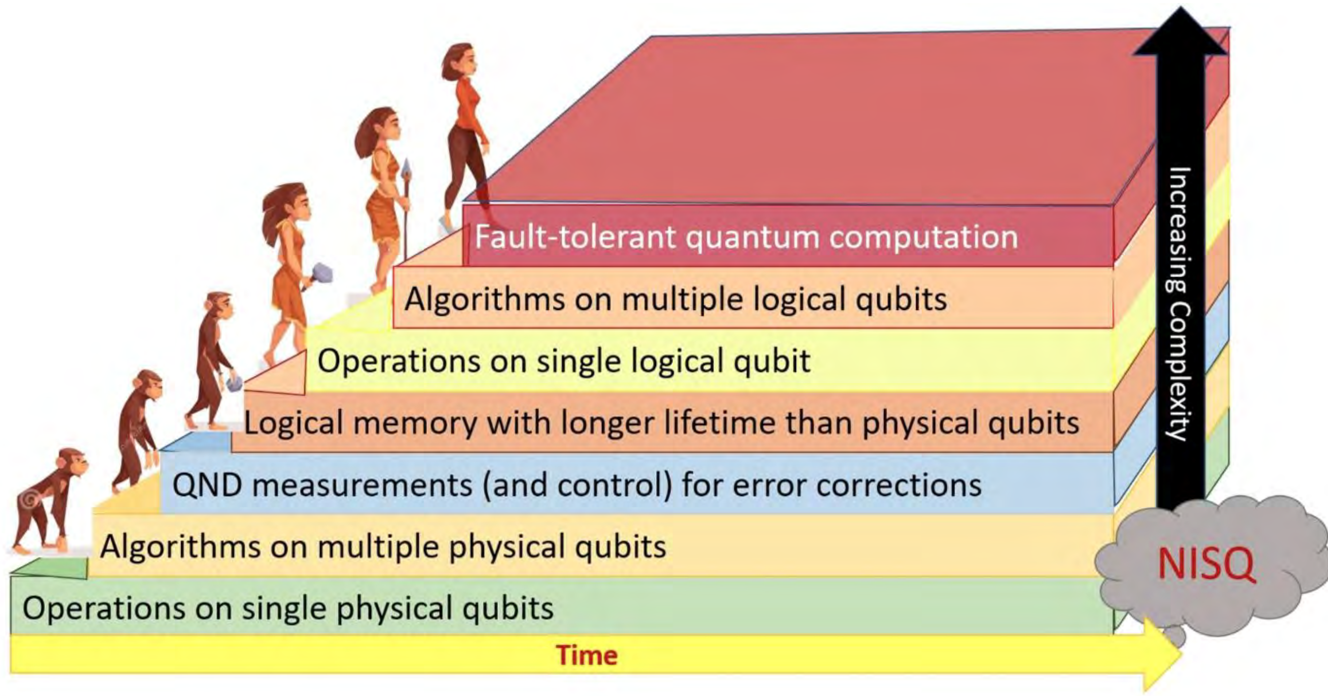
Two Development Stages – NISQ & FTQC

NISQ (Noisy Intermediate-Scale Quantum)

- Current frontier of quantum computing technology
- A scale of tens to a few hundred physical qubits
- Absence of full error correction

FTQC (Fault-Tolerant Quantum Computing)

- Robust error correction – logical qubits
- Execute complex algorithms at large scale
    - For example, HHL, Shor's algorithm....



Another Benefit – Lowering the footprint

Energy footprint – quantum efficiency[1]

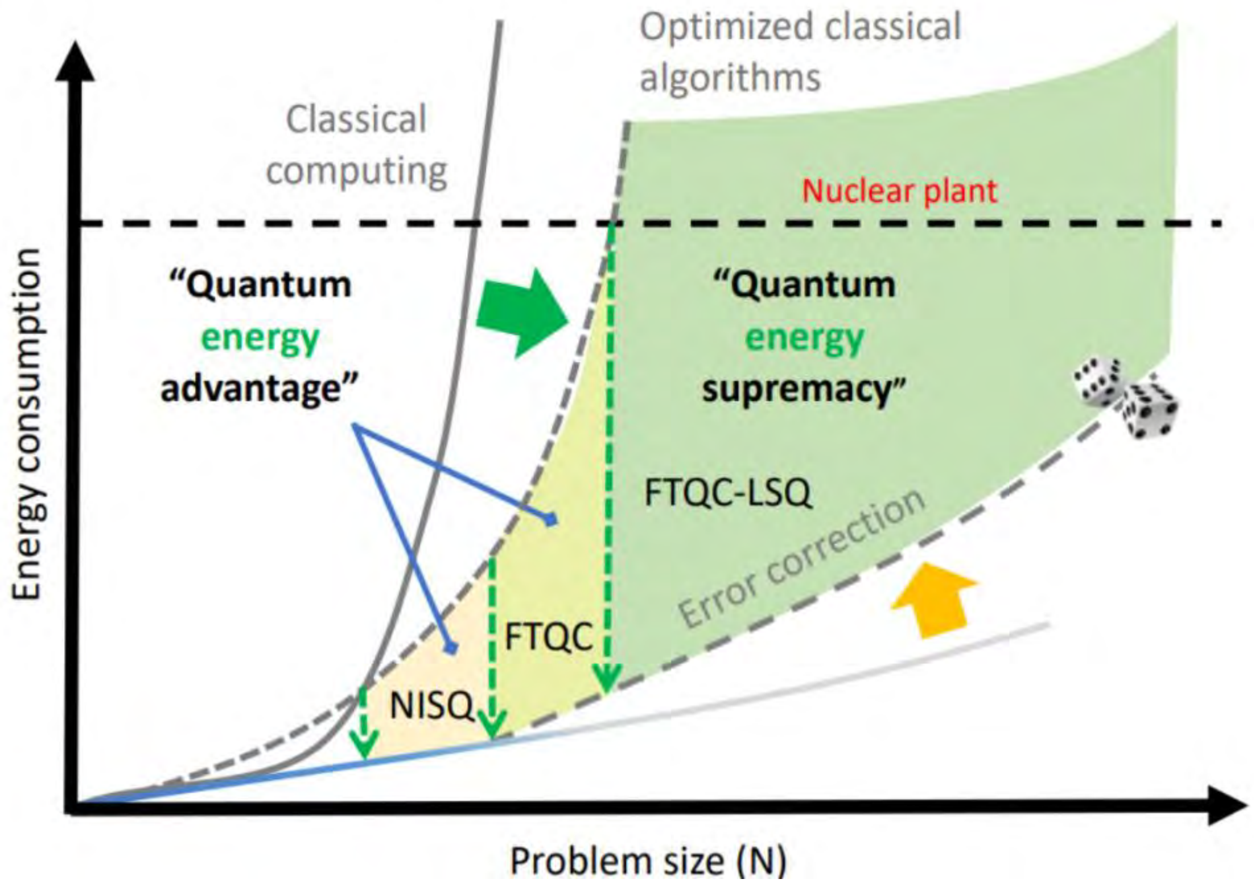
High demanding **supercomputers draw substantial power**

- e.g., Frontier supercomputer ≈ **504 MWh** per day
  - summing up the energy consumed by around 17 thousand average homes in the U.S.

Quantum processors - orders of magnitude
- far below flagship HPC systems

System	Power(kW)	Cooling consumption
Frontier supercomputer	24,600	33% – 40%
Superconducting	25 - 140	64%
Trapped Ions	2	15%
Neutral atom	7-20	~ 50%
Photons	4	75%

Table 2: Illustrative electricity use. Source: Olivier Ezratty CC, 2023.



1. *Summarized from Pasqal, Quantum Computing to Greener Calculations (Oct. 5, 2023).*

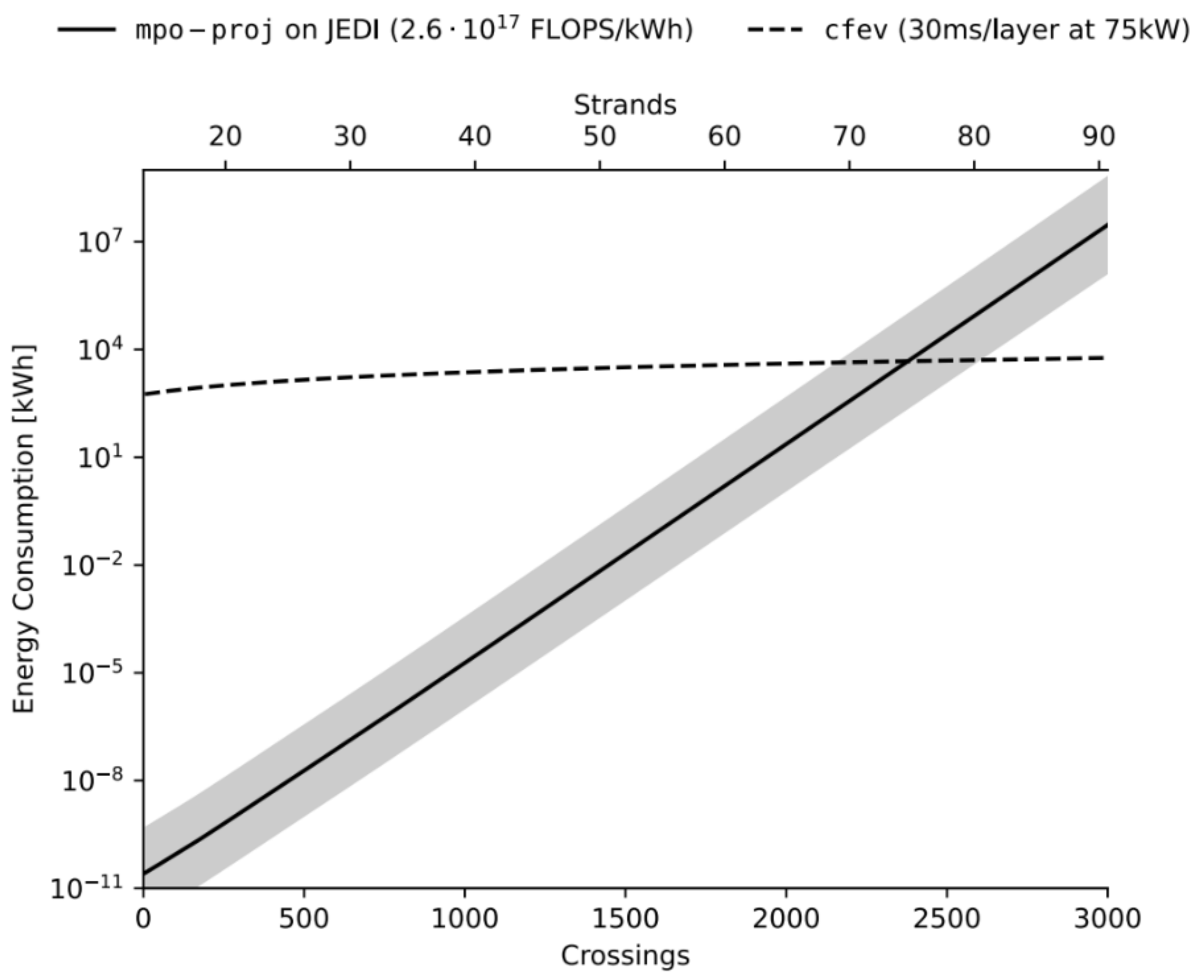
A case study - Quantinuum vs HPC[1]

Task: Evaluating the Jones polynomial for given knots

- A **classical algorithm** (MPO-PROJ) is assumed to run on the ***most energy efficient supercomputer: Jülich-JEDI***
  - peak efficiency of 2.6 × 1017 FLOPS/kWh
- **Quantum circuit implementation** (cefv) on the ***Quantinuum H2*** trapped-ion system

Result:

- cfev (around hundreds of kWh level) used by Quantinuum becomes more energy efficient than mpo-proj at large scales (crossings ≥ 2400).

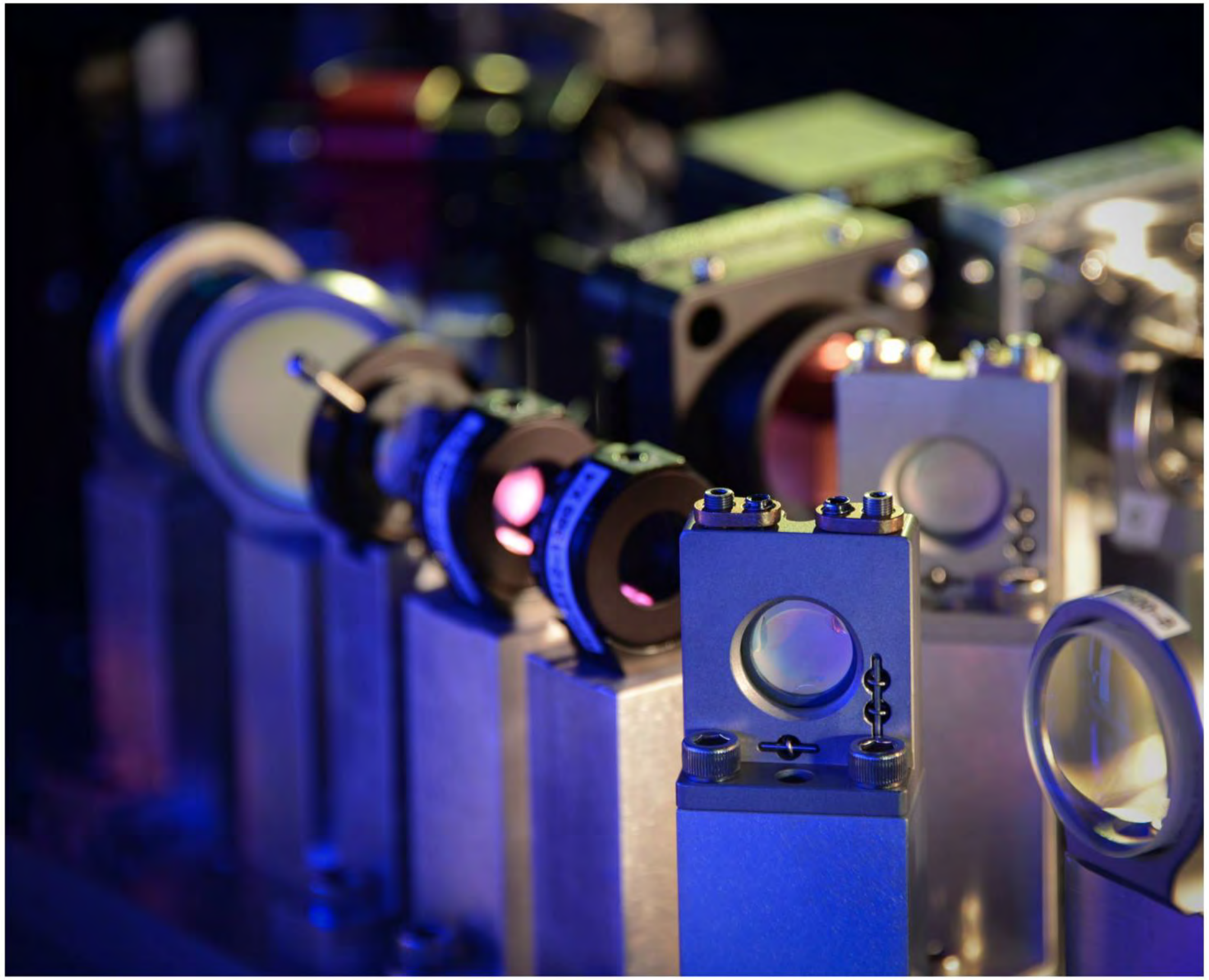


1. *Laakkonen et al, "Less Quantum, More Advantage: An End-to-End Quantum Algorithm for the Jones Polynomial,"* arXiv:2503.05625

Magne – A Danish owned quantum computer

Magne – EIFO and the Novo Nordisk Foundation

- **EIFO** (Export & Investment Fund of Denmark) and the **Novo Nordisk Fonden** - are investing €80 million to build a new quantum computer - Magne.
- In **partnership** with **Microsoft and Atom Computing**, combining Atom's **neutral-atom** hardware and Microsoft's quantum software stack.
- **50 logical qubits** backed by over 1200 physical qubits, full-stack hardware + software, and scheduled for its first tasks in **2026/27.**
- **100% Danish-owned**, based in Copenhagen, bolster Denmark and the Nordic region's positioning in the global quantum race
- Plan to build a small organization of around **10 employees**, whose primary task will be to ensure **optimal utilization** of Magne across **commercial and academic users**



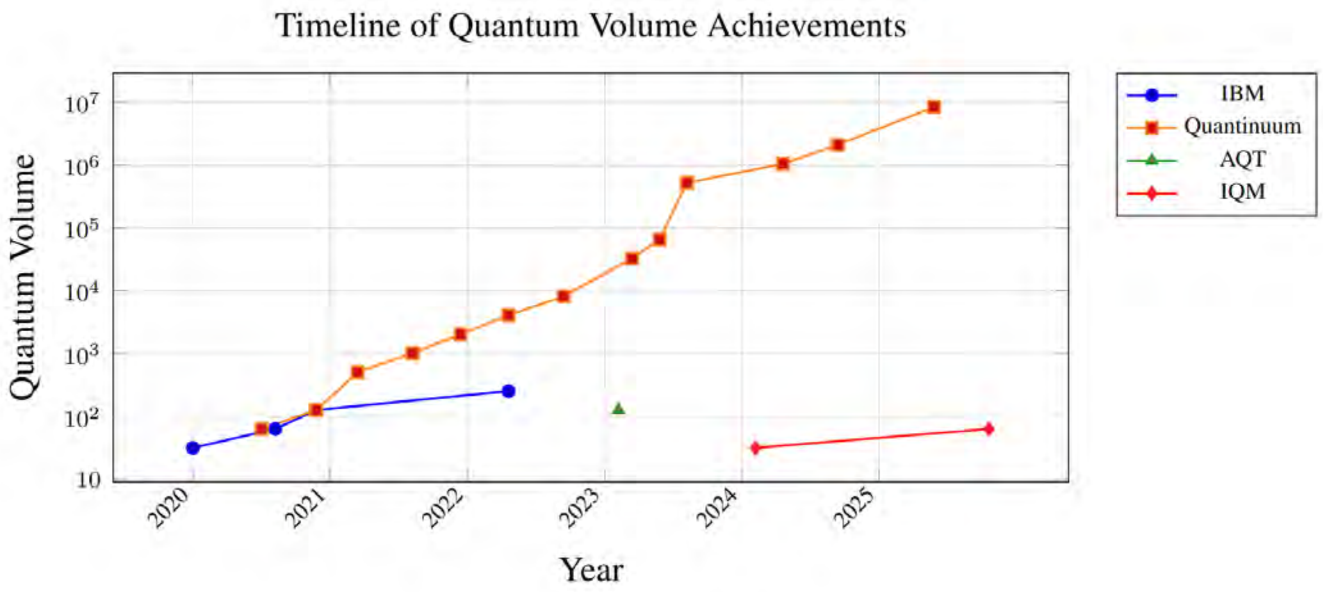
Hardware provider: Atom Computing(US)

Benchmarking Quantum Devices

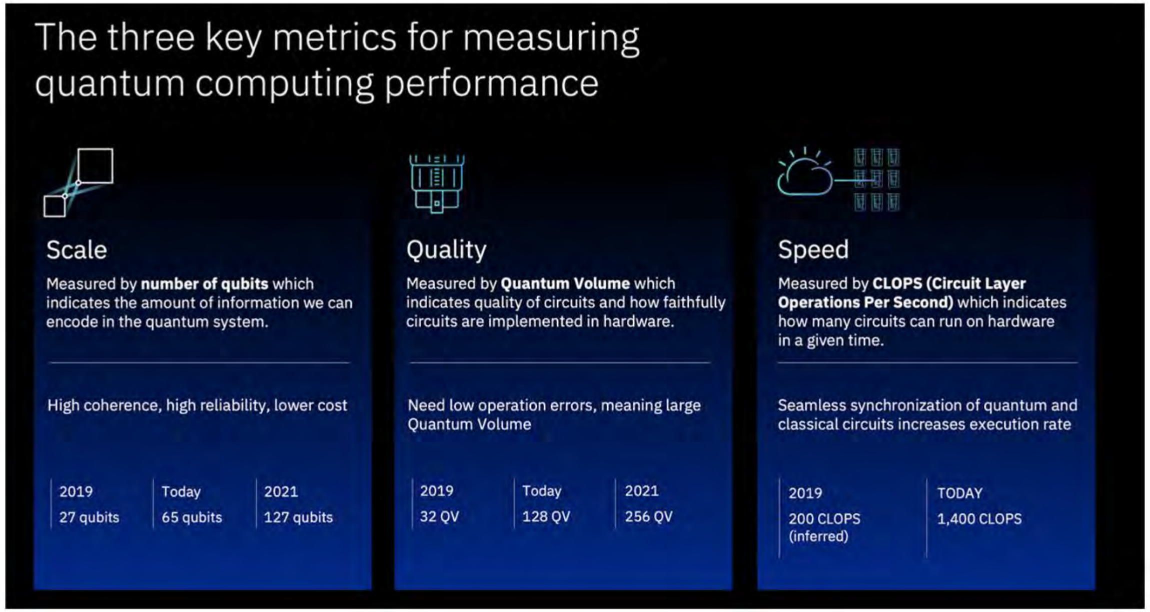
A simple and quick evaluation

IBM's benchmarking framework through **three key metrics**:

- **Scale:** number of qubits (see next slides for comparison) – amount of encoded information
- **Quality:** fidelity and coherence time – often quantified through the **Quantum Volume (QV)** benchmark



- **Speed** – execution throughput and runtime efficiency



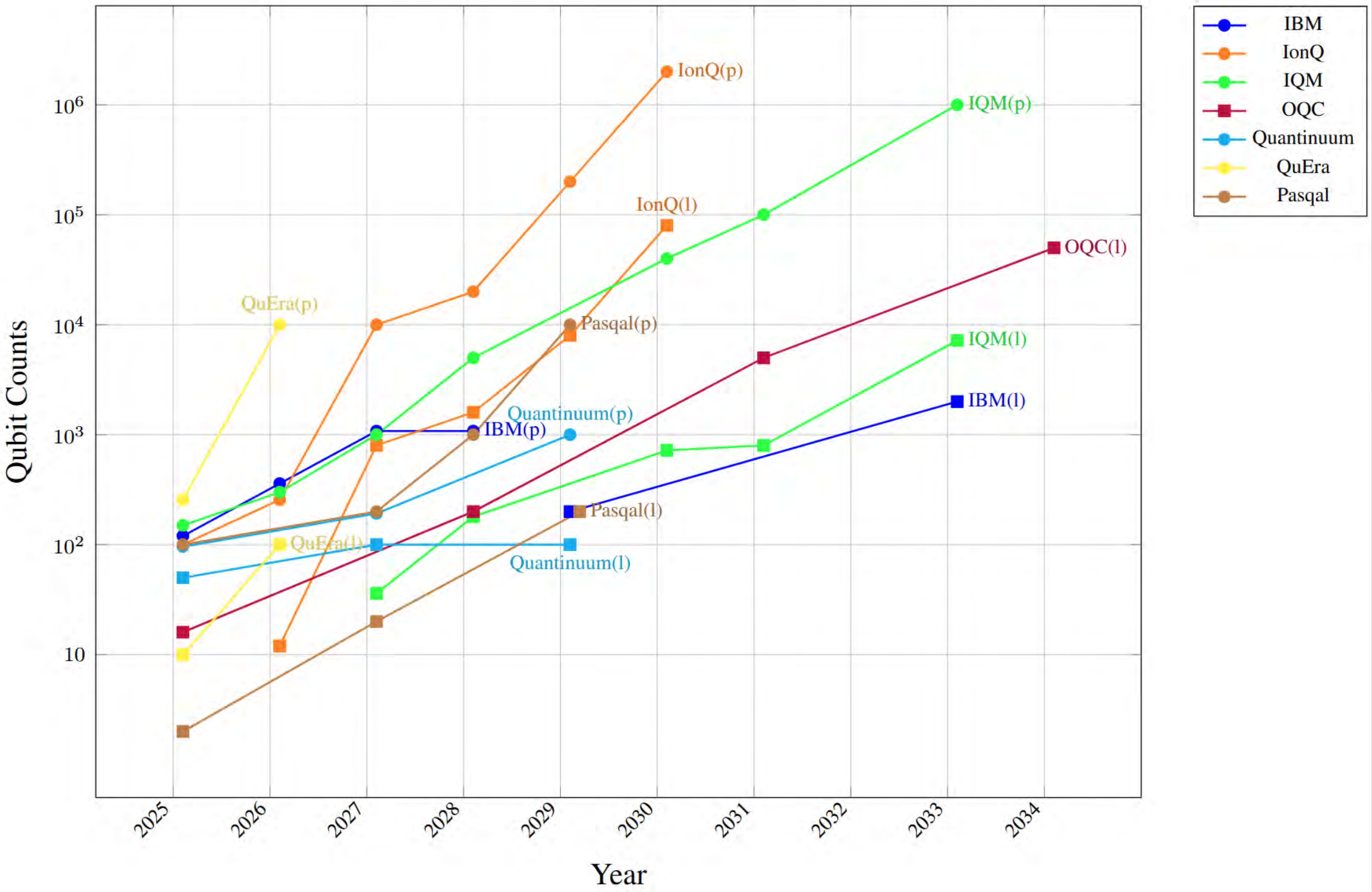
Quantum Volume: measures how large a *random quantum circuit* a processor can successfully execute

$$\mathrm{QV} = 2^m$$

- *m* is the width of the largest random square circuit the device can accurately run.
- A **higher QV** means better ***balance*** between qubit number, quality, and control - Reflects *real, system-level performance* rather than just qubit count.

Development roadmap comparison

Qubit counts development across major providers: Circles = physical; Squares = logical.

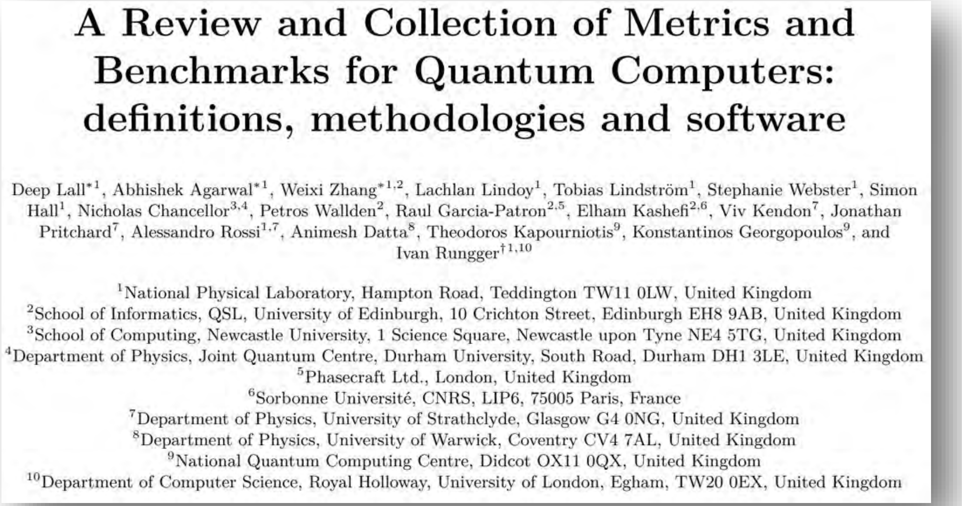


Logical qubit threshold

- No current universal definition a logical qubit across hardware providers
- Typically, hardware provider talks about logical qubit at error rate 10^{-5} - 10^{-9}
- Treat reported logical qubit counts in the diagram as indicative rather than directly comparable values across platforms

Toward Comprehensive Benchmarking

While IBM's framework provides a valuable starting point, a **truly comprehensive benchmark** must include *broader criteria* - span from hardware components to full application performance



A Review and Collection of Metrics and Benchmarks for Quantum Computers: definitions, methodologies and software

Deep Lall[*1], Abhishek Agarwal[*1], Weixi Zhang[*1,2], Lachlan Lindoy[1], Tobias Lindström[1], Stephanie Webster[1], Simon Hall[1], Nicholas Chancellor[3,4], Petros Wallden[2], Raul Garcia-Patron[2,5], Elham Kashefi[2,6], Viv Kendon[7], Jonathan Pritchard[7], Alessandro Rossi[1,7], Animesh Datta[8], Theodoros Kapourniotis[9], Konstantinos Georgopoulos[9], and Ivan Rungger[†1,10]

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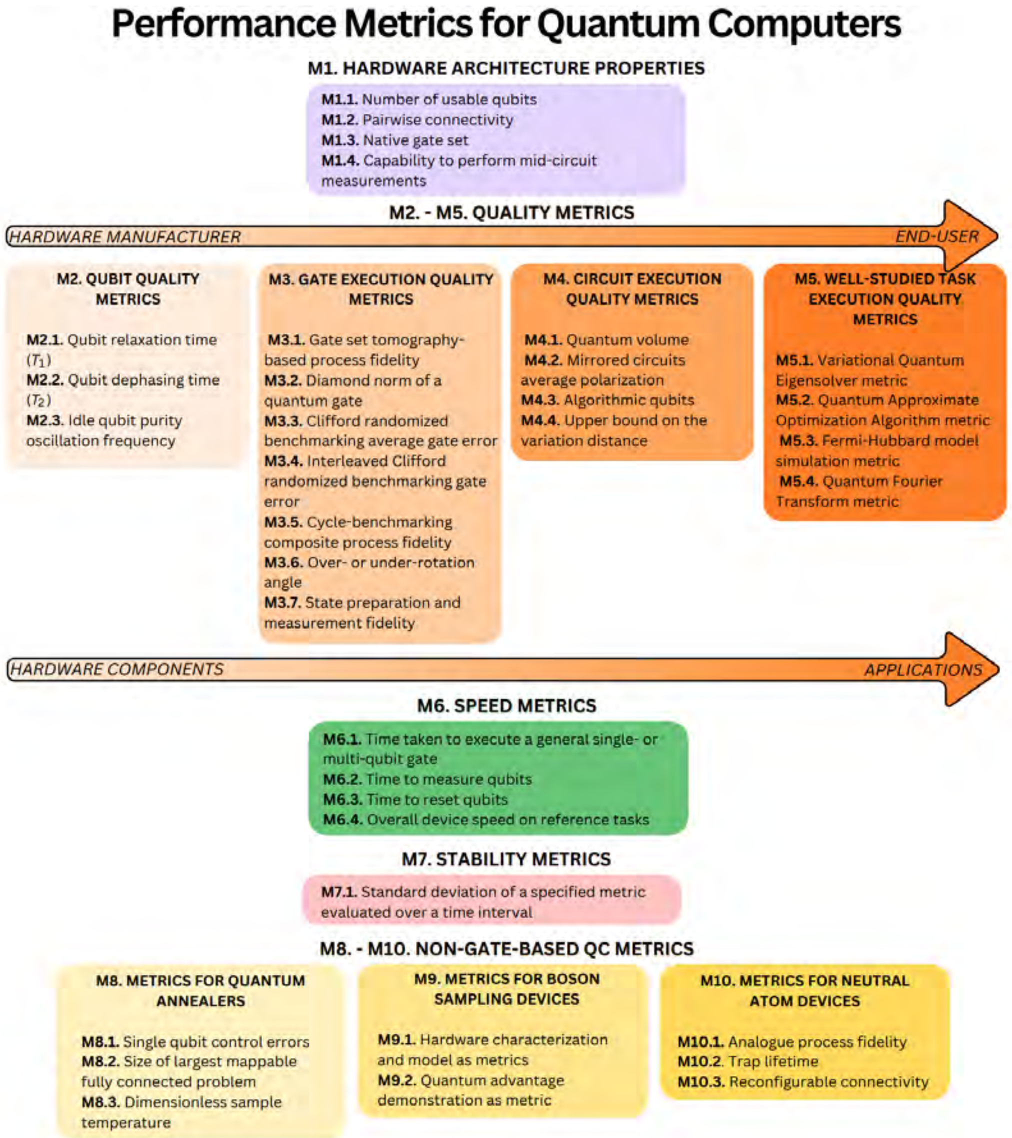
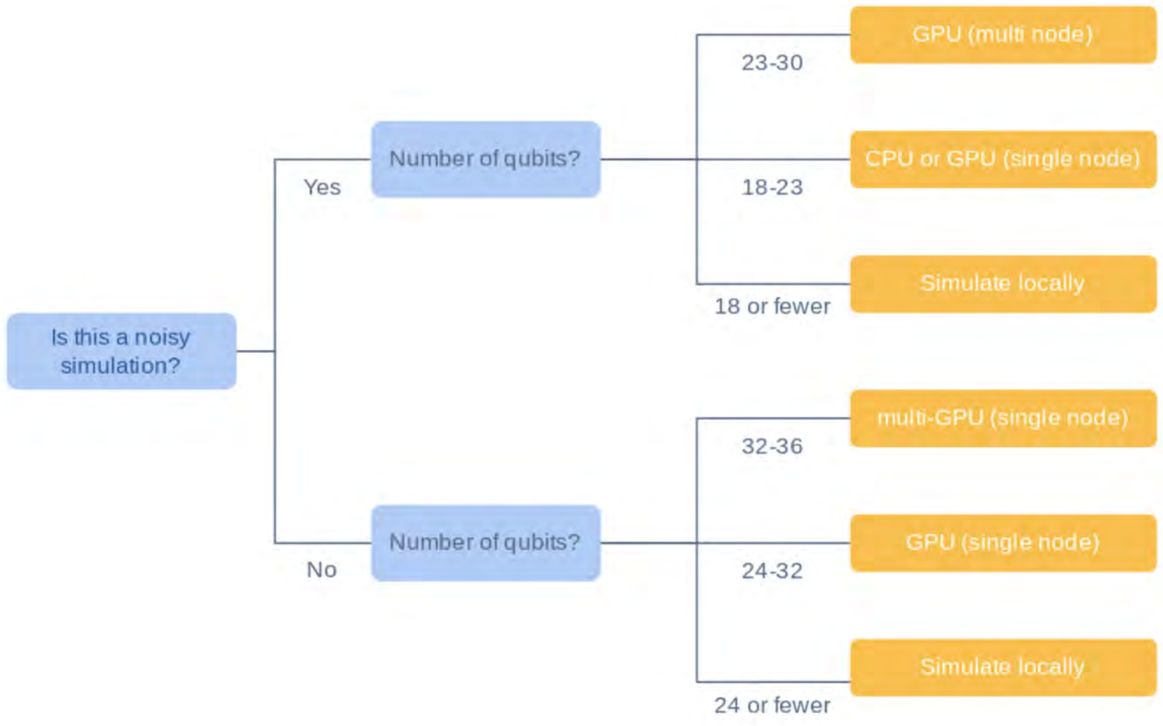
[3]School of Computing, Newcastle University, 1 Science Square, Newcastle upon Tyne NE4 5TG, United Kingdom
[4]Department of Physics, Joint Quantum Centre, Durham University, South Road, Durham DH1 3LE, United Kingdom
[5]Phasecraft Ltd., London, United Kingdom
[6]Sorbonne Université, CNRS, LIP6, 75005 Paris, France
[7]Department of Physics, University of Strathclyde, Glasgow G4 0NG, United Kingdom
[8]Department of Physics, University of Warwick, Coventry CV4 7AL, United Kingdom
[9]National Quantum Computing Centre, Didcot OX11 0QX, United Kingdom
[10]Department of Computer Science, Royal Holloway, University of London, Egham, TW20 0EX, United Kingdom



- **Architectural properties** - Qubit connectivity topology, Native gate set and compilation overhead
- **Gate quality** - Relaxation (T_1) and dephasing (T_2) times, gate set tomography-based process fidelity
- **Stability** - standard deviation of metrics evaluated over a time interval

+ Distinguish metrics for Non-Gate-Based Quantum Computers!

Quantum simulation



Source: quantum simulation guide published by Google

Deciding among CPUs, single GPUs, or multiple GPUs - Key Factors Influencing demanding resource from HPC:

- Noise level - Noisy simulations are much more computationally expensive than ideal noiseless ones
- Number of qubits - Memory and computational resources scale exponentially with qubit count
  - Simulating 40+ qubits already exceeds the limits of most classical HPC systems.
- Circuit depth – proportional to number of sequential operations or time steps in the quantum circuit.
  - Deeper circuits require proportionally more processing and memory to track evolving states.

Types of Quantum Computers and their applications

Models of quantum computing

Focus of the guide

Gate-Based Quantum Computing

- The most **widely adopted** model of quantum computation.
- Perform by a **discrete sequence** of unitary operations (quantum gates)
- Qubits are realized by physical systems that exhibit quantum behavior: superconducting circuits, trapped ions, neutral atoms

Non-Gate-Based Quantum Computing

Exploit **continuous quantum setups** or **intrinsic physical dynamics** of a system to perform computation

- Quantum annealing – energy-based optimization
  - networks of superconducting flux qubits; system evolves adiabatically from an initial Hamiltonian to a problem Hamiltonian
- Boson sampling – photonic interference for sampling tasks
  - Photonic systems through beam splitters and phase shifters
- Analog quantum simulation – direct evolution of quantum systems
  - trapped ions, Rydberg atoms, or cold atoms in optical lattices.

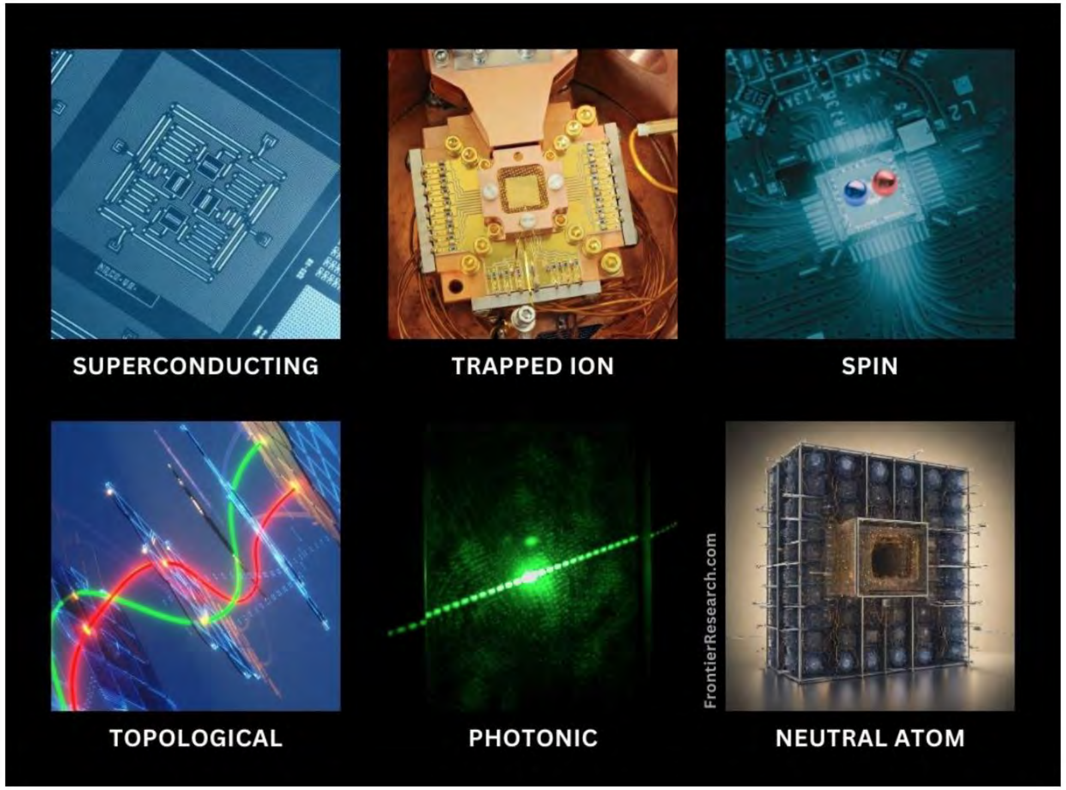


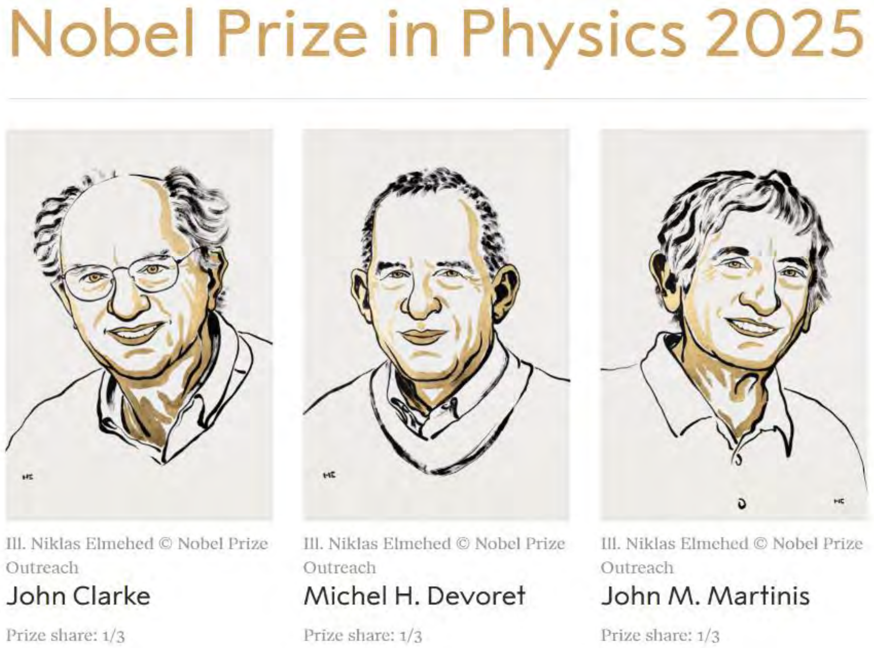
Image source: exoswan, 2025

How to make qubit – e.g., from superconducting circuit

Technology foundation

- 2025 Nobel Prize in Physics - demonstrates quantum tunnelling and quantized energy levels in superconducting circuit, at a scale large enough to be held in the hand
- **Foundation** for many quantum hardware technologies such as **quantum computers** and **quantum sensors**

Background - Cooper pairs behave as a single quantum mechanical unit – this collective state uses a shared wave functions



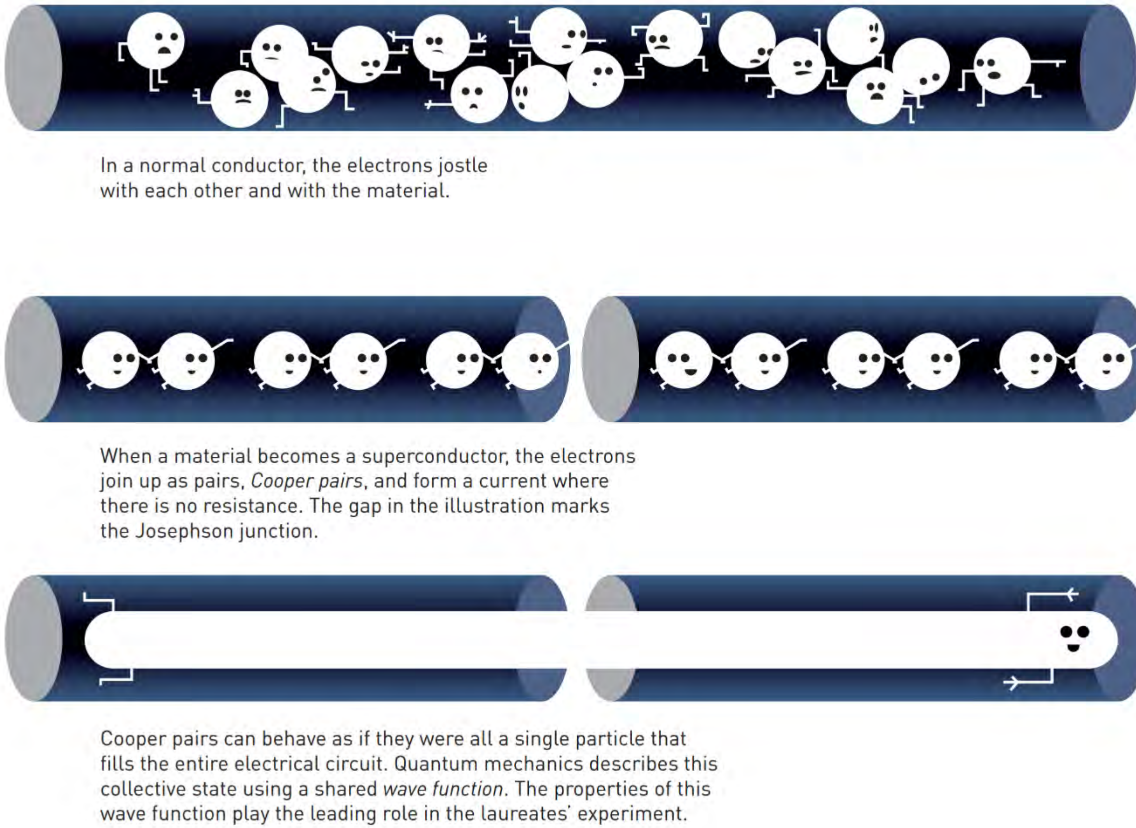


Image source: Johan Jarnestad

Formation of a superconducting qubit

- A **superconducting circuit exhibiting quantized states:** a basic unit of quantum information: **qubit**
- The **lowest energy state and the first excited state** represent the qubit states **|0⟩ and |1⟩,** respectively.
- By **applying microwave photons** to these qubits, their state can be **precisely manipulated**, enabling operations such as initialization, control, and readout of individual qubits.

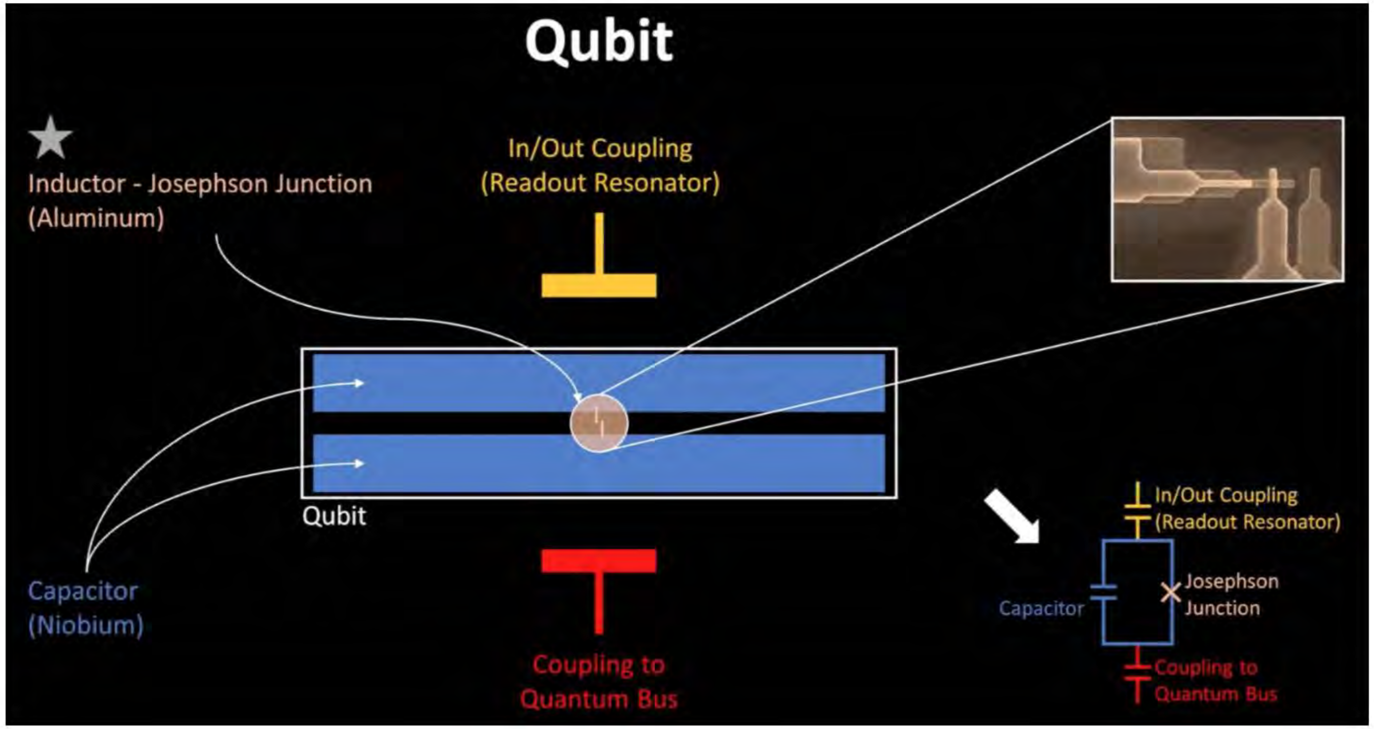


Figure 37: Formation of a qubit within a superconducting circuit. Source: IBM.

IBM Quantum

- **Maintains** the world's largest quantum programming and user ecosystem through its open-source software framework, *Qiskit*.
- **Cost:** per-minute plan tiers ($48–$96/min) + monthly subscription option.
- **Aim** to deliver a system that accurately runs 100 million gates on 200 logical qubits — unlocking the first viable path to realizing the full power of quantum computing in 2029.
- **Global end users** - spanning pharmacy, aerospace, chemistry, energy, routing, etc.

Sector	End Users	Description
Pharmacy	Moderna	Apply variational quantum algorithms (VQAs) and Conditional Value at Risk (CVaR) to the mRNA secondary structure prediction. (Source)
Aerospace	Boeing	Quantum optimization on engineering strong, lightweight materials (ply composite). (Source)
Chemistry	Mitsubishi Chemical	Create and study accurate molecular simulations of complex electrochemical reaction for lithium superoxide rearrangement in lithium-oxygen batteries. (Source)
Electrical Car	Mercedes-Benz	Next generation of batteries technologies – quite possibly the lithium-sulfur (Li-S) battery towards a carbon-neutral new passenger car fleet. (Source)
Semiconductor	JSR	Aid computer chemical simulations of photo-acid generators (PAGs) to develop new photoresists more quickly and at lower cost. (Source)
Energy	E.ON	Energy price decision under weather-related risk modeling. (Source)
Routing	ExxonMobil	Model maritime inventory routing, analyze the strengths and trade-offs of different strategies to efficiently transport Liquefied Natural Gas (LNG). (Source)
Denmark	DTU, KU & SDU	Develop quantum solutions to study molecular properties—such as metalloenzymes and light-harvesting chromophores in proteins. (Granted DKK 40 million by Novo Nordisk Foundation) (Source)

Table 7: IBM Quantum End Users by Industry

IQM

- **Quantum ecosystem** with scalable hardware, advanced software integrations for HPCs, and application development.
- **Cost**: starting at $0.30 per second
- **Optional** for a premier plan with additional pulse-level control (available upon request for customized pricing).
- Achieved the **milestone** of **delivering** more quantum computers than any other company over the past twelve months .

Sector	**End Users**	**Description**
Trading	DATEV	Quantum solution to handle the complexity and scale of portfolio optimization on the selection of assets, in order to maximizing returns and minimizing risk (Source) .
R& D	VTT	A joint project with VTT (a limited liability company owned by the Finnish state) to develop quantum infrastructure. The access to the device is opens for use by companies and researchers through VTT quantum computing service (Source) .
Chemistry	Volkswagen	Apply trial wavefunctions on quantum devices to reduce the bias of auxiliary-field quantum Monte Carlo (QC-AFQMC). This hybrid approach to the simulation of strongly correlated many body systems in battery chemistry reduces the required number of qubits while preserves accuracy (Source) .
HPC Integration	IQM–LUMI-Q	LUMI-Q is a consortium consisting of European quantum stakeholders formed as an initiative to establish and strengthen collaborative ties within the quantum technology sector. The quantum computer is integrated with HPC (LUMI), see LUMI-Q subsection for details (Source) .

Table 9: IQM Quantum End Users by Industry

Pasqal

- Founded in **2019 as a spinoff** from Institut d'Optique in Paris,
- Based on **groundbreaking research** in **neutral atom** quantum computing led by Nobel prized quantum physics pioneer Alain Aspect.
- **Partnering** with industry leaders **across** finance, energy, and manufacturing to solve complex computational challenges previously thought impossible with classical computing systems.

*See the published Quantum Computing Guide for a comprehensive collection of information on **principles of extra 3 modalities of quantum computers** and **8 additional quantum hardware providers**, presented in a similar format.*

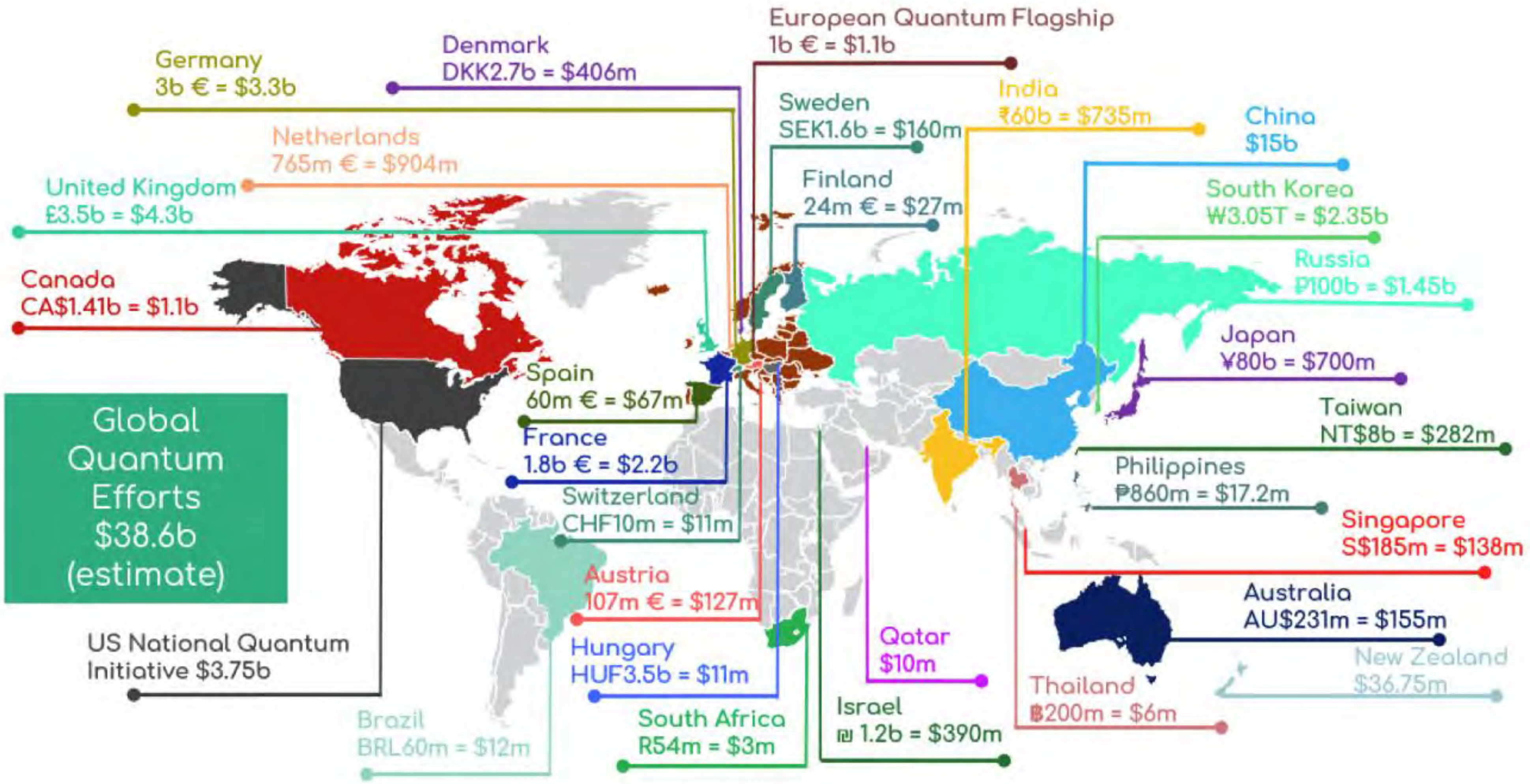
Sector	End User / Project	Description
Aerospace & Defense	Thales	Model the satellite scheduling problem as a Maximum Independent Set (MIS) problem to seek quantum-centric approach to the optimization of satellite positioning and resource allocation under complex constraints, aiming to improve scheduling flexibility and reaction times (Source) .
Material	BMV group	Develop a quantum solution to improve simulation of metal forming, predicting material behavior and optimizing manufacturing settings, with future use in structural and crash simulations. This will later support structural analysis and crash simulations (Source) .
Energy	Electricite de France (EDF)	Quantum optimization for energy distribution and the environmental variables affecting wind farms and photovoltaic plants. Another project involves simulating the ageing of materials within nuclear power plants to ensure safety and operational integrity (Source) .
Bank	Credit Agricole CIB	Quantum computing's potential, e.g., a quantum-enhanced machine learning, in predicting credit rating downgrades 6 to 15 months in advance for financial risk management (Source) .
Weather & Farm	BASF	Solve complex nonlinear differential equations in physics-based weather models via quantum neural networks. It is aligned with BASF's digital farm-

A new record – IonQ, October 21st, 2025

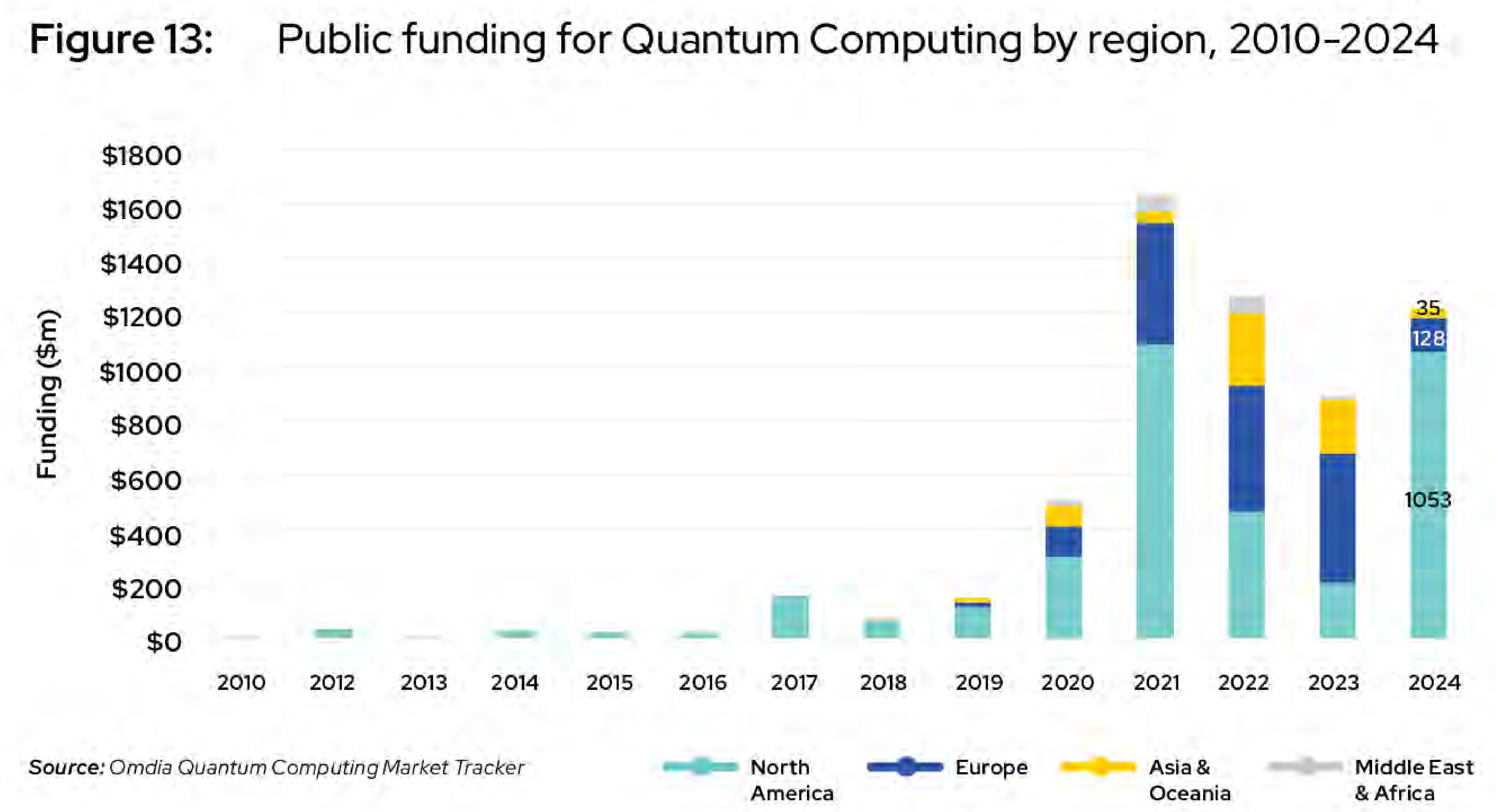
- The first reported instance of a quantum computing company crossing the **“four-nines” (0.9999) benchmark**
- Using IonQ’s proprietary “Electronic Qubit Control” (EQC) technology, which uses **precision electronics rather than just lasers**
- Enabling integration into **massive semiconductor** fabrication processes
- Achieved using **prototypes** in its R&D labs - form the basis for its **256-qubit** systems that will be demonstrated in **2026**
- Already delivering quantum advantage for industries
  - With AstraZeneca, AWS, and NVIDIA - a 20x speed-up in quantum-accelerated drug development announced in June.

Open Question: When and Who will be the first to break five, six...... nines benchmark?

Global Landscape of Quantum Computing

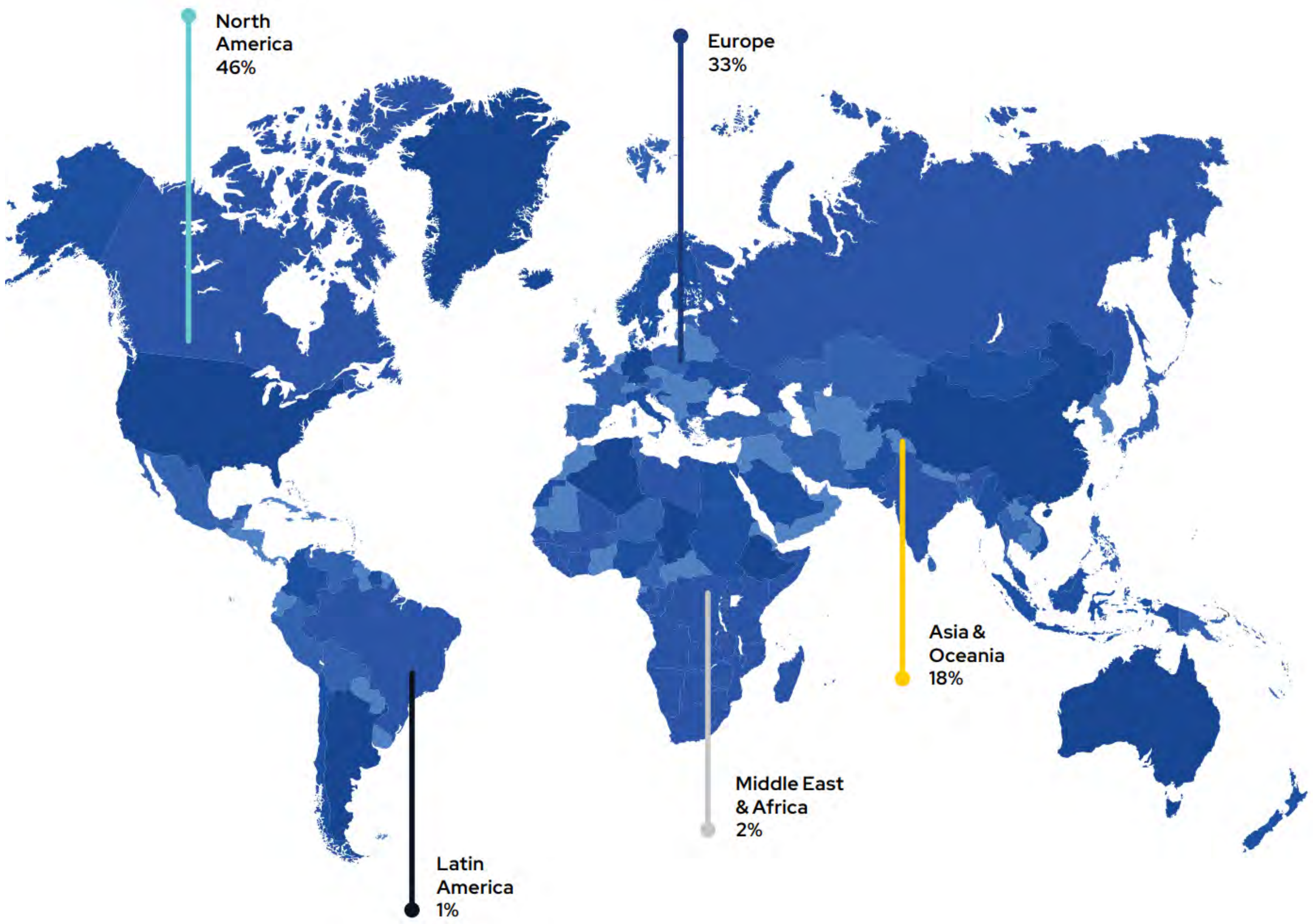


Global Landscape of Quantum Computing



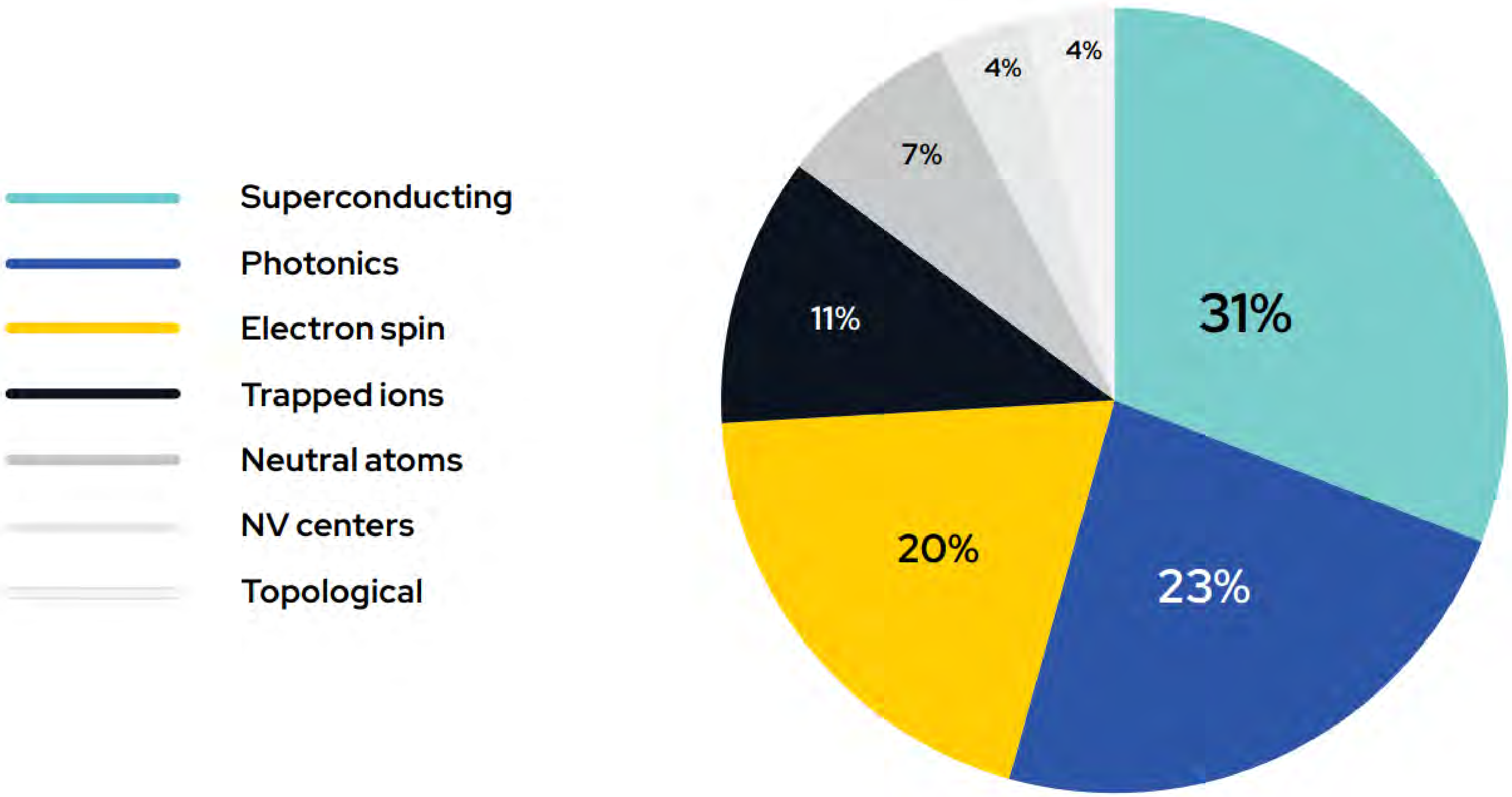
Deployed Quantum Computers by Regions

Regional distribution of quantum computing adopters (number of adopters, %)



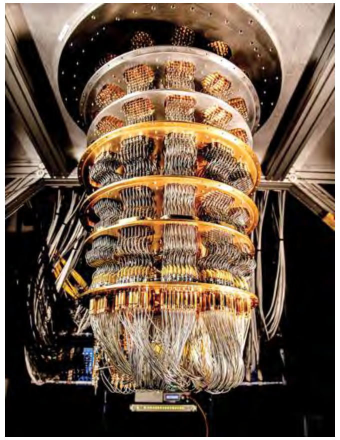
Source: IQM state of quantum report 2025

Qubit technologies used by QPU vendors (% of vendors)



Source: IQM state of quantum report 2025

Implementing a Quantum Computer



Leaders in Superconducting QC

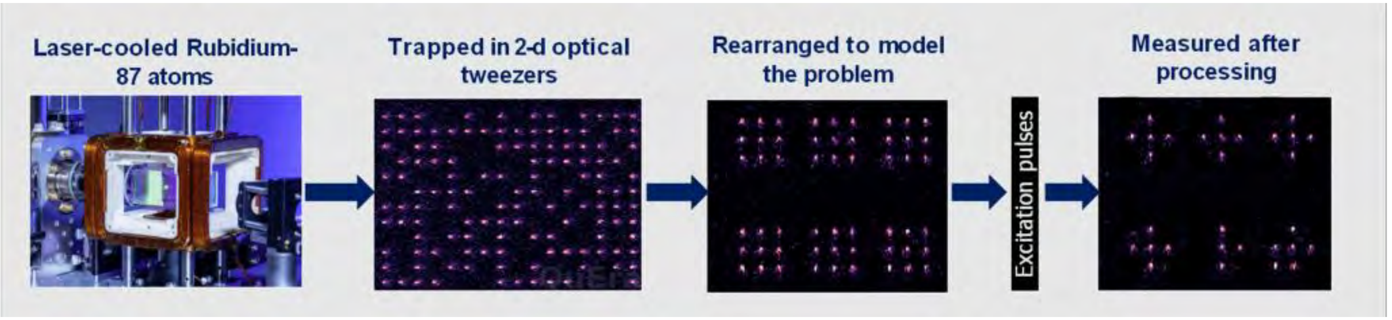
IBM (US)
Google (US)
Amazon (US)
Rigetti (US)
SEEQC (US)
Qolab (US)
Bleximo (US)

D-Wave (CA)
Anyon (CA)
Nord Quantique (CA)
Oxford Quantum Circuits (GB)
QuantWare (NL)
Alice & Bob (FR)
IQM (FI)

Fujitsu (JP)
NEC (JP)
Origin Quantum (CN)
Huawei (CN)
Tencent (CN)

Leaders in Neutral Atom QC

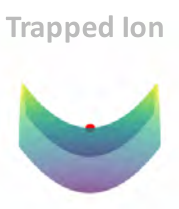
QuEra (US)
Pasqal (FR)
Infleqtion (US)
Atom Computing (US)
planqc (DE)
NanoQT (JP)

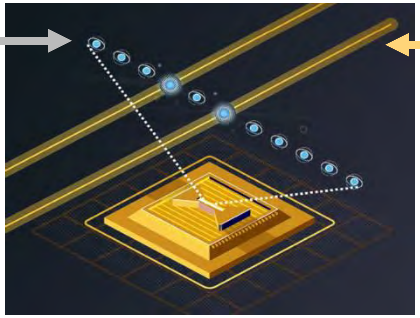


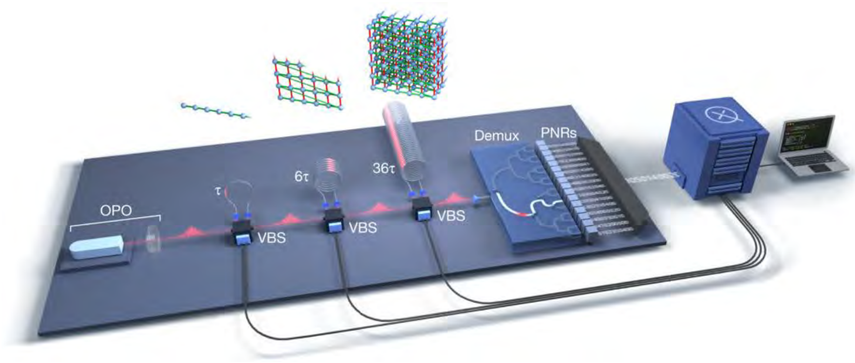
Implementing a Quantum Computer

Leaders in Trapped Ion QC

Quantinuum (US)
IonQ (US)
Universal Quantum (GB)
Oxford Ionics (GB)
AQT (AT)
Qubitcore (JP)







Leaders in Photonic QC

Xanadu (CA)
PsiQuantum (US)
ORCA Computing (GB)
QuiX Quantum (NL)
Quantum Computing Inc. (US)

Quandela (FR)
OptQC (JP)
TuringQ (CN)
eleQtron (DE)
NQCG (NO)

Quantum algorithms and industry applications

	Molecular simulation	Quantum optimization	Quantum Monte Carlo	Machine learning	HHL	Decryption [1]
Life sciences	Calculating a drug's binding affinity	Optimizing the location of clinical trial sites	Predicting the spread of disease in epidemics	Improving image classification in diagnostics	Modelling forces for protein - folding simulations	Protecting patient data privacy
Chemicals	Simulating the reaction pathway in synthesis	Optimizing the production process of chemicals	Simulating meso - scale reactor processes	Predicting the properties of new chemicals	Solving fluid dynamics in reaction vessels	Protecting data related to IP and trade secrets
Energy	Designing new materials for carbon capture	Optimizing power dispatching in an electric grid	Forecasting energy prices in the market	Predicting energy production from weather patterns	Solving DC power flow calculations in electrical grids	Protecting access to data on grid infrastructure
Telecom	Designing new semiconductor materials	Optimizing antenna placement	Stress - testing network resilience	Improving customer segmentation	Solving EM - field calculations in antenna design	Protecting the data exchanged over a network
Advanced manufacturing industries	Designing new batteries for electric vehicles	Optimizing the step sequence in car production	Improving the resilience of the supply chain	Improving fault detection in chip manufacturing	Solving aerodynamics simulations	Protecting communication connections
Logistics	N/A	Optimizing the route of a delivery service	Stress - testing logistic schedules for disruptions	Predicting maintenance needs in a fleet	Improving inventory management	Protecting personalized customer data
Finance	N/A	Optimizing the value of an asset portfolio	Modelling credit value at risk in capital allocation	Improving the detection of fraud in transactions	Estimating risk for the future value of an asset	Protecting customer transaction data

Figure 16: Overview of major quantum use cases, by industry sector and type of quantum algorithm. Source: ALICE & BOB.

Interface with AI

Interface with AI – How can AI help QC?

AI acts as a **connecting bridge** from the classical to the quantum computing world

- **Generate** quantum computing circuits from classical ML algorithms
- **Involves in Auto-Calibration**
- **Optimize quantum error correction**

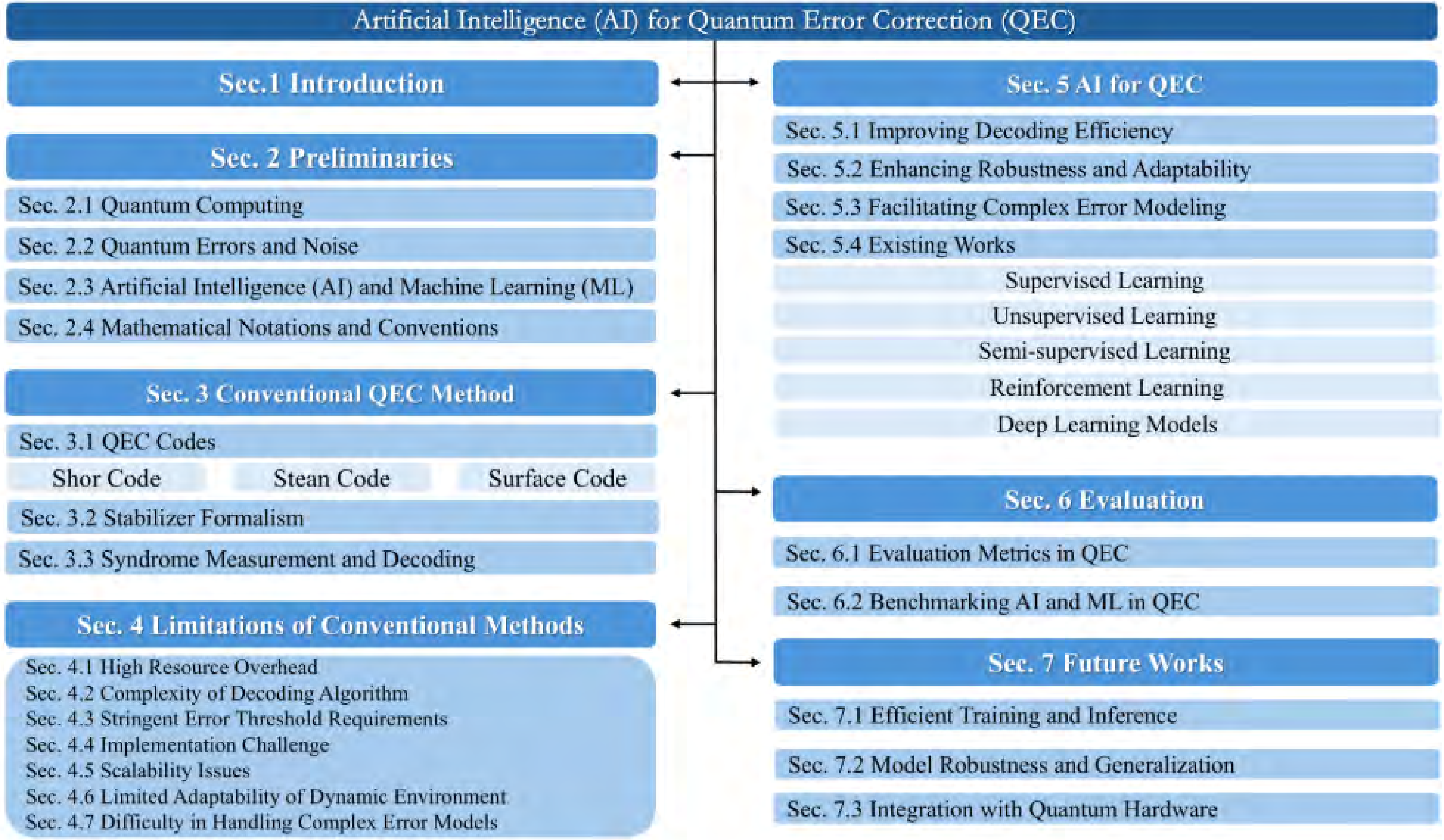


Image source: Zihao Wang, Hao Tang, Artificial Intelligence for Quantum Error Correction: A Comprehensive Review

Interface with AI – How Quantum can assist AI

Section 9: Quantum Interface with AI - covering topics such as

- Introduction to AI and Benchmark index
- Motivation to QML
- Quantum Neural Networks (QNNs)
- Quantum Kernel Methods
- HHL Algorithm as QML subroutines

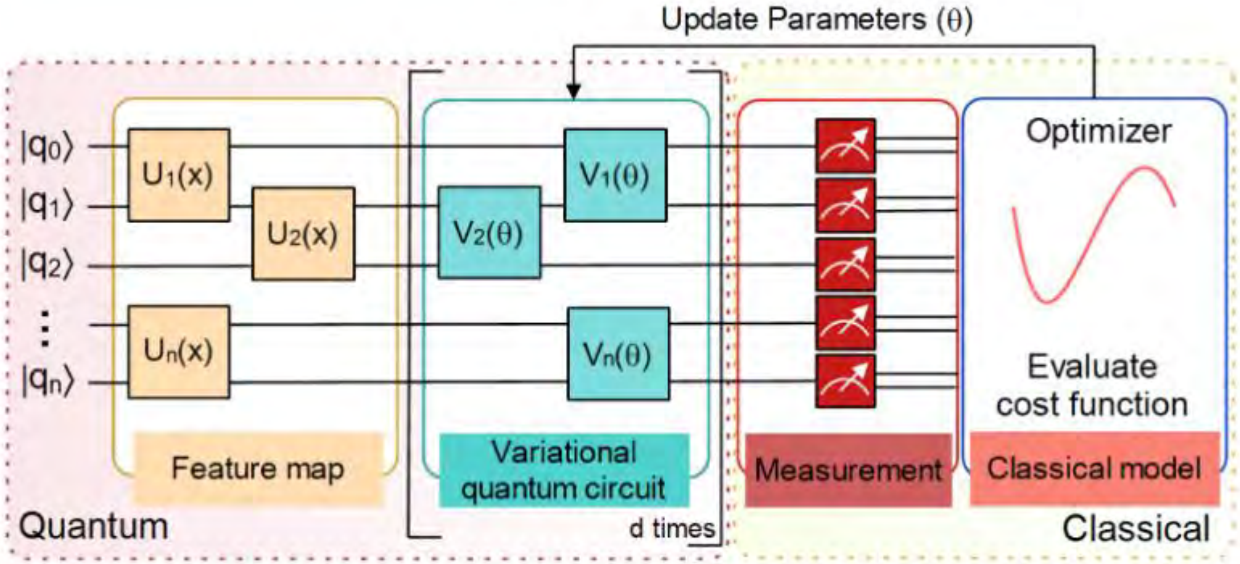


Figure 59: Schematic representation of a variational quantum circuit (VQC). These quantum components are coupled with a classical optimization routine, forming an iterative hybrid quantum–classical learning loop [131]

The guide provides both conceptual overviews and practical examples for researchers exploring AI + Quantum synergies.

Supplement Materials

From Quantum Devices to Quantum Advantage

- We've seen what quantum computers are made of - superconducting qubits, trapped ions, neutral atoms, etc

- The real power of quantum computing lies not in qubits alone, but in the algorithms that make them useful.

- To begin, we'll look at a simple illustrative toy model to o*ptimize store locations, which* adapted from QuEra
    - so that everyone can follow without requiring any advanced mathematics background

A Toy Model: Store Selection in Manhattan Market[1]

Problem and goal:

- **A market decision maker wants to open several coffee shops** in Manhattan.
- However, shops placed too close together would overlap in customer coverage.
- This creates a **constraint optimization problem**:
  - Choose the largest set of shop locations where no two are too close(adjacent)

Graph Theory Background

- Each node = a candidate shop location
- Each edge = two locations that are "too close"
- The goal is to find the maximum independent set - a group of nodes with no edges connecting them

An example set of store locations. Each vertex is a potential location; each edge is an independent set restriction that no adjacent locations can both have stores simultaneously.

1. *Optimizing Store Locations using QuEra's Quantum Computer*

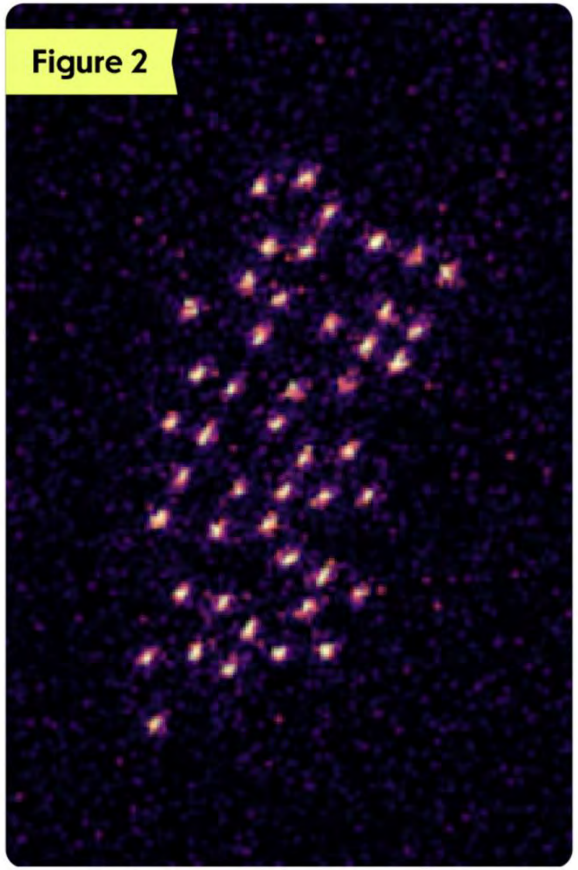
A Toy Model: Store Selection in Market in Manhattan Market[1]

Encoding the Problem

- Each node (shop location) is encoded as a **neutral atom qubit** (e.g., Rydberg atom).
- Atoms are arranged in a 2D array that mirrors the **graph structure** of the problem

Quantum Evolution

- By tuning laser amplitude and phase, the system's ground state evolves toward the **optimal configuration**.
- The **final solution** is read out by measuring the presence or absence of atoms — corresponding to which shop locations are selected.



A photograph of individual atoms positioned in Aquila's atomic array encoding the store placement problem. In this example, each atom corresponds to a

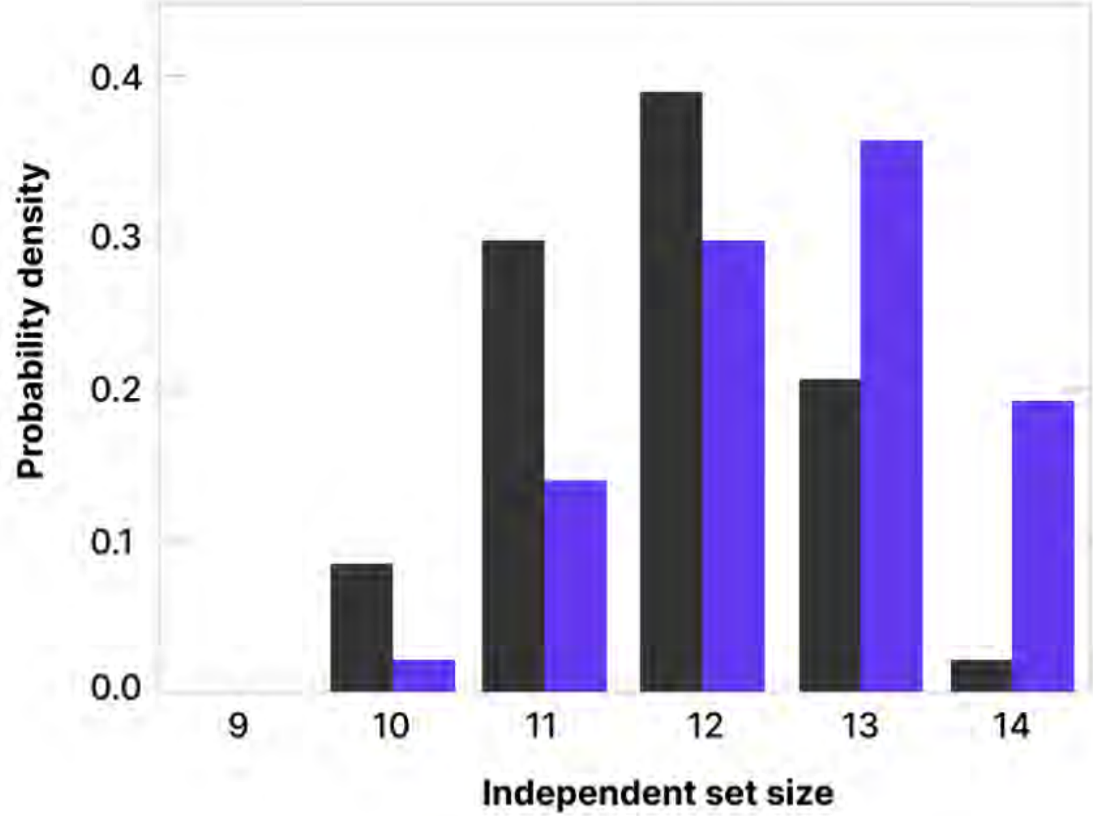
An example maximum independent set solution shown in red vertices.

1. *Optimizing Store Locations using QuEra's Quantum Computer*

A Toy Model: Store Selection in Manhattan Market[1]

Results and Insights

- Quantum optimizer (results in blue) outperforms simple classical algorithm (in black) for small problem sizes
- More advanced classical algorithms still perform better today — but the **quantum approach scales differently** as hardware improves
- The same method can be applied to **logistics**, **network layout**, or **molecular modeling** (e.g., for **drug discovery**).
- **Neutral-atom quantum computers can naturally encode and solve combinatorial optimization problems**, providing a glimpse of how real-world decision-making tasks could benefit from quantum advantage.



1. *Optimizing Store Locations using QuEra's Quantum Computer*

3. LUMI-Q Consortium and the New Quantum Computer “VLQ”

Overview of LUMI Consortium

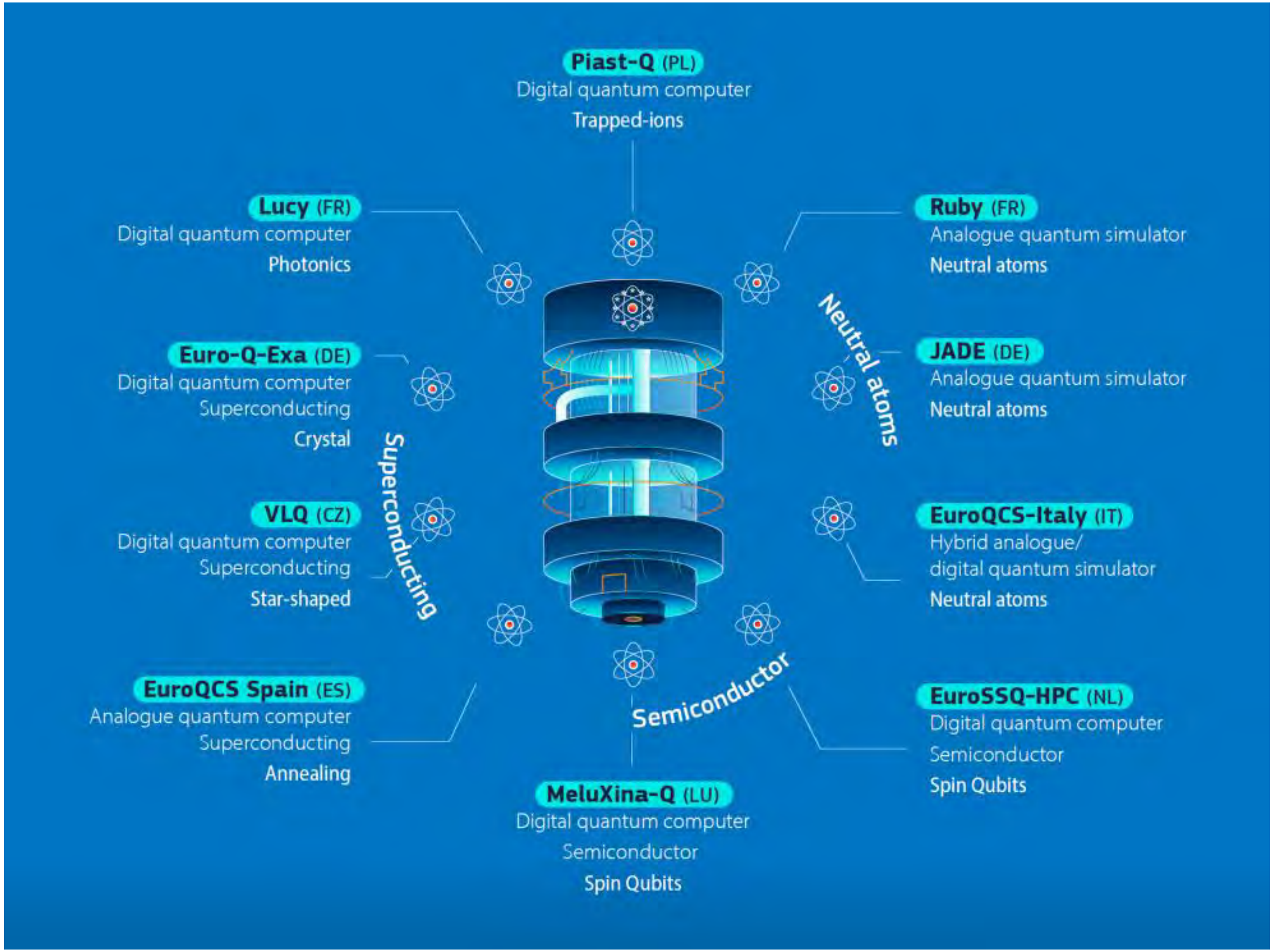
- The **European High-Performance Computing Joint Undertaking (EuroHPC JU)** has been pooling European resources to develop a variety of supercomputers for processing big data, based on competitive European technology.

- **LUMI**, which is in CSC's data center in Kajaani, Finland, is one such supercomputer and is hosted by the **LUMI consortium**.

- The **LUMI (Large Unified Modern Infrastructure) consortium** countries are Finland, Belgium, the Czech Republic, Denmark, Estonia, Iceland, the Netherlands, Norway, Poland, Sweden, and Switzerland.

Overview of LUMI Architecture

EuroHPC JU Quantum Computers



Overview of LUMI-Q

VLQ, the quantum computer of the LUMI-Q consortium, will provide a European-wide quantum computing environment **integrated with the EuroHPC infrastructure**. VLQ will allow the integration of the targeted EuroHPC quantum computer into EuroHPC supercomputer **KAROLINA** in Czechia, **LUMI** in Finland, and **EHPCPL** in Poland.

LUMI-Q CONSORTIUM MEMBERS

- Coordinator: VSB – Technical University of Ostrava, IT4Innovations National Supercomputing Center, Czechia
- CSC – IT Center for Science, Finland
- VTT Technical Research Centre of Finland Ltd, Finland
- Chalmers University of Technology, Sweden
- Danish e-Infrastructure Consortium (DeiC), Denmark
- Akademickie Centrum Komputerowe Cyfronet AGH, Poland
- Nicolaus Copernicus Astronomical Center, Poland
- Sigma2 AS, Norway
- Simula Research Lab, Norway
- SINTEF AS, Norway
- University of Hasselt, Belgium
- TNO Netherlands Organisation for Applied Scientific Research, the Netherlands
- SURF BV, the Netherlands

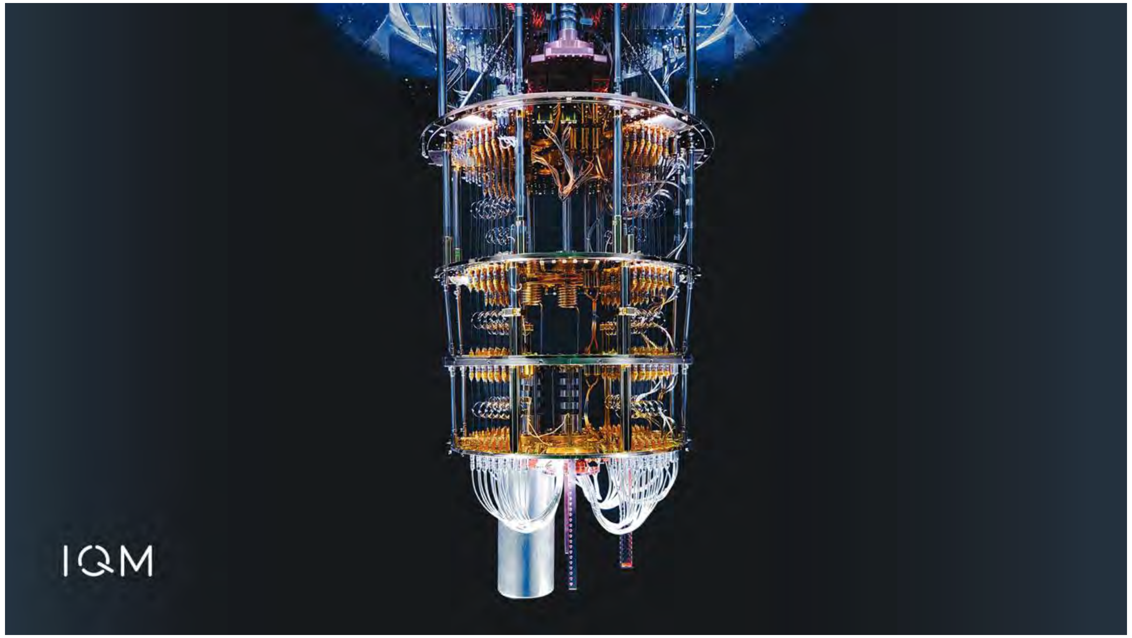
VLQ

ARCHITECTURE

- at least 24 physical qubits,
- the star-shape topology,
- the total cost of the system is EUR 5.0 million,
- integrated into the EuroHPC supercomputer KAROLINA,
- IQM Quantum Computers, supplier of systems,
- installation and commissioning will take place in 2025.

Overview of IQM

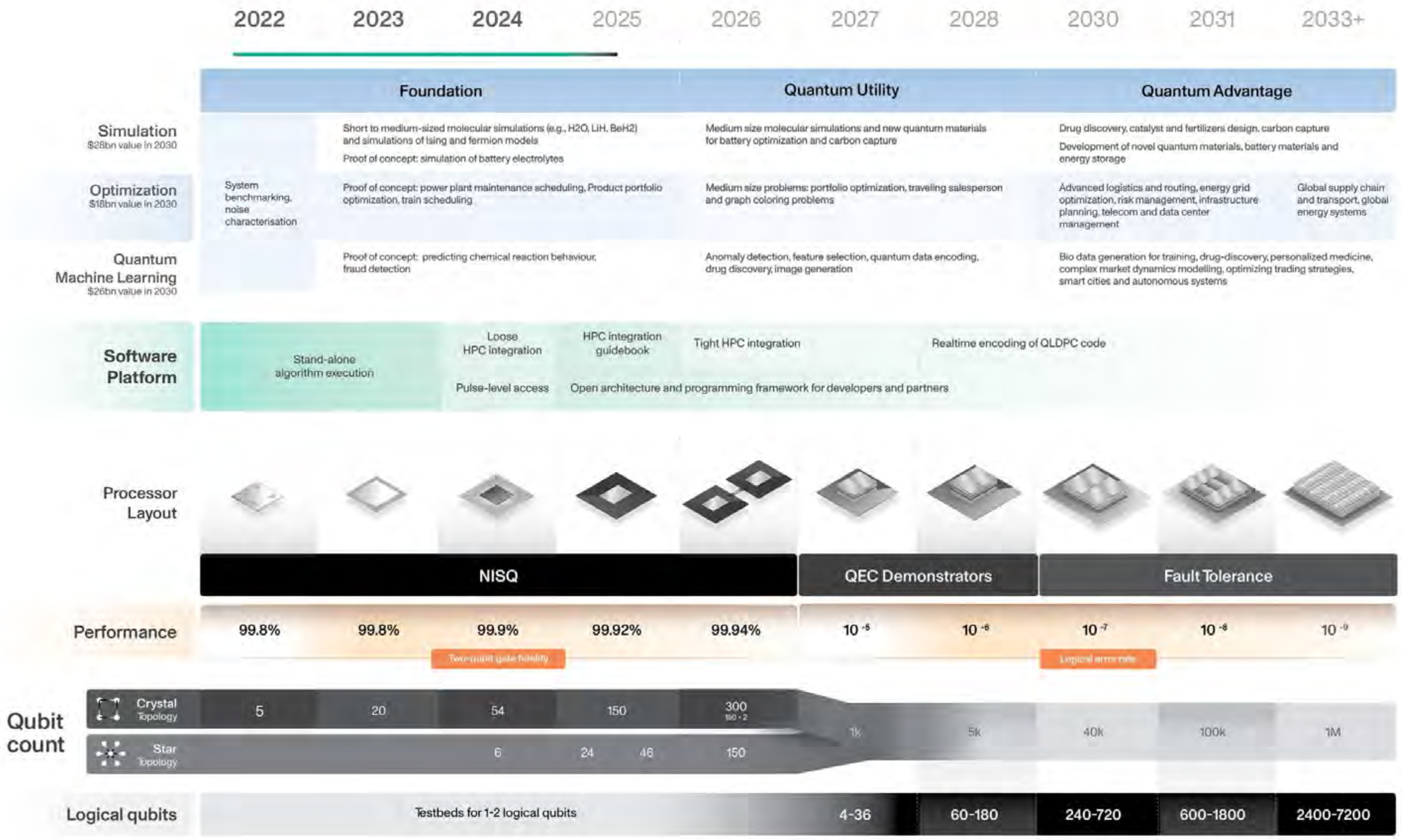
- IQM is the **leading European quantum hardware company in superconducting circuits**, headquartered in **Espoo, Finland**.
- IQM builds **superconducting full-stack quantum computers** with up to 150 high-fidelity qubits.
- Currently, IQM has **some*** QPU access available through AWS (Amazon Braket).



Industrial and Academic Customers

CINECA
lrz
Oak Ridge National Laboratory
VTT
aws
Hewlett Packard Enterprise
JÜLICH Forschungszentrum
EVIDEN an atos business
links PASSION FOR INNOVATION
VSB TECHNICAL UNIVERSITY OF OSTRAVA | IT4INNOVATIONS NATIONAL SUPERCOMPUTING CENTER
TSRI
충북대학교

Overview of IQM



Overview of IT4I

- In the **Czech Republic**, **IT4I** is the leading research, development, and innovation centre active in the fields of HPC, QC, AI, and their application to other scientific fields, industry, and society.

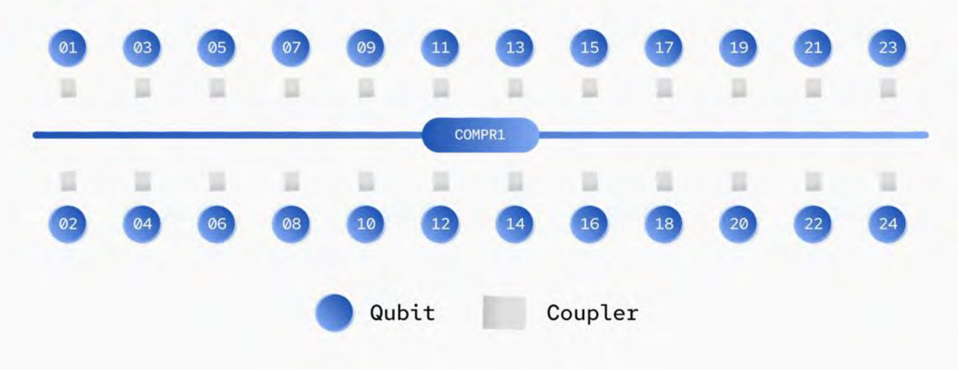
- IT4I operates the most powerful supercomputing systems in the Czech Republic, including **KAROLINA,** which are provided to Czech and foreign research teams from both academia and industry.

VSB TECHNICAL UNIVERSITY OF OSTRAVA | IT4INNOVATIONS NATIONAL SUPERCOMPUTING CENTER

PUT INTO OPERATION	summer 2021
THEORETICAL PEAK PERFORMANCE	15,690 Tflop/s
OPERATING SYSTEM	Rocky Linux 8.9
COMPUTE NODES	831
CPU	720x 2x AMD 7H12, 64 cores, 2,6 GHz, 92,160 cores in total 72x 2x AMD 7763, 64 cores, 2,45 GHz, 9,216 cores in total 72x 8x NVIDIA A100 GPU, 576 GPU in total 32x Intel Xeon-SC 8628, 24 cores, 2,9 GHz, 768 cores in total 36x 2x AMD 7H12, 64 cores, 2,6 GHz, 4,608 cores in total 2x 2x AMD 7452, 32 cores, 2,35 GHz, 128 cores in total
RAM PER COMPUTE NODE	256 GB / 1 TB (GPU) / 24 TB fat node 320 GB HBM2 (8 x 40 GB) GPU
ACCELERATORS	576x NVIDIA A100
STORAGE	30.6 TB / home (1.93 GB/s sequential write performance, 3.10 GB/s sequential read performance), 1,361 TB / scratch (NVMe, 730.9 GB/s sequential write performance, 1, 198.3 GB/s sequential read performance)

Hardware Details of VLQ

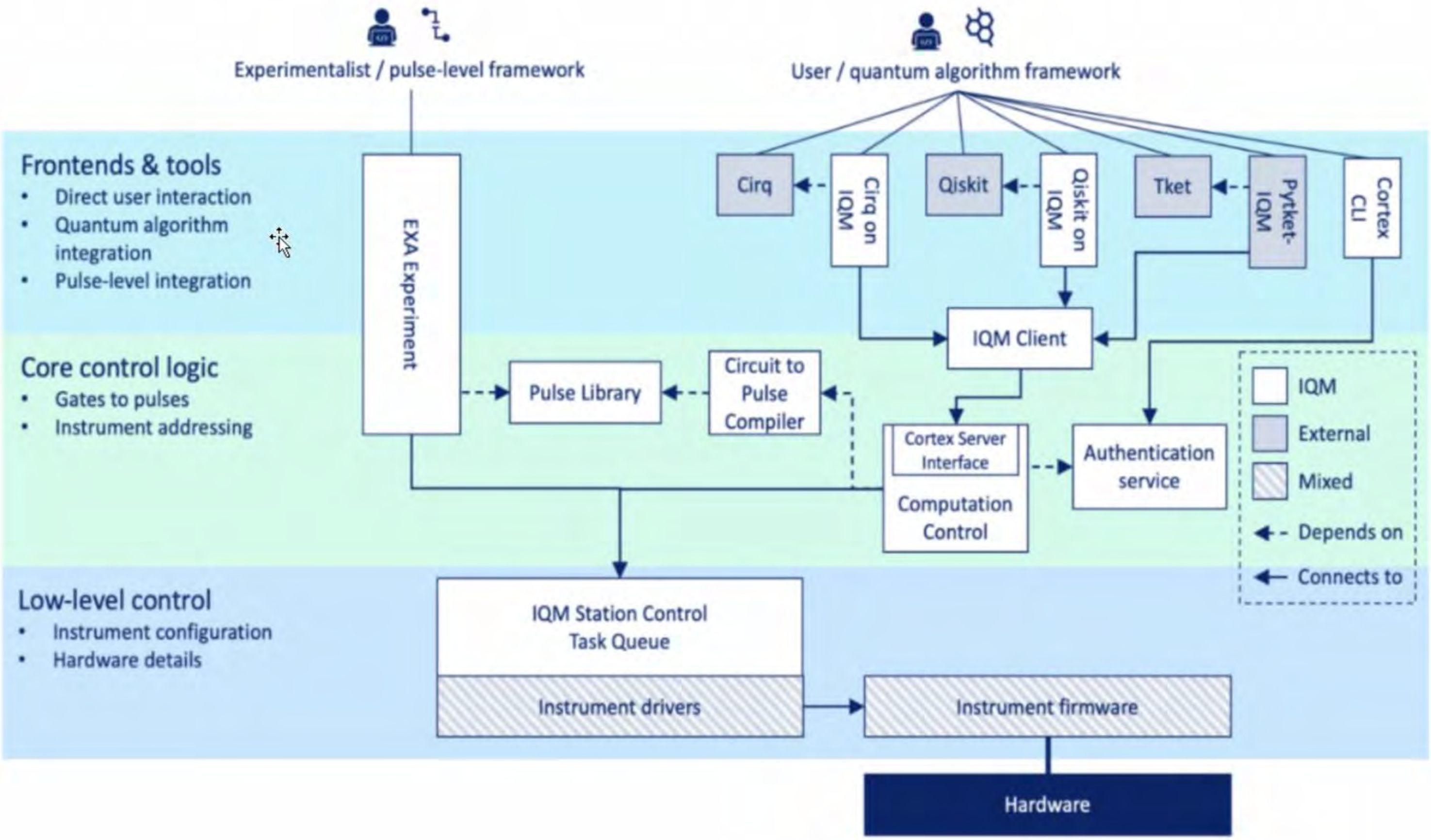
- VLQ's contains a 24-qubit QPU based on superconducting transmon qubits designed for cutting-edge quantum research that requires high connectivity.
- A central resonator hub connects a large number of qubits, optimizing connectivity for highly interactive quantum processes and dramatically reducing the number of SWAP operations needed.



Hardware Details of VLQ

Software Details of VLQ

LUMI-Q MACHINE IMPLEMENTATION



4. Proof-of-concept Use Cases

Developing Proof-of-concept Use Cases

- We are currently in the **noisy intermediate-scale quantum (NISQ)** era, with QPUs not yet capable of **fault tolerance** or **quantum advantage**, but there are many algorithms with the great potential use cases.
- The most common class of NISQ algorithms are “variational algorithms” which leverage classical optimization of tunable parameters.
- DeiC is developing some simple **proof-of-concept use cases** (for both **academia and industry**) with **step-by-step explanations** of the thought process and implementation to help, especially Danish, users best utilize quantum computing resources.
- The three main areas for which DeiC is developing proof-of-concept use cases, and which seem the most promising, are **optimization, simulation, and machine learning.**

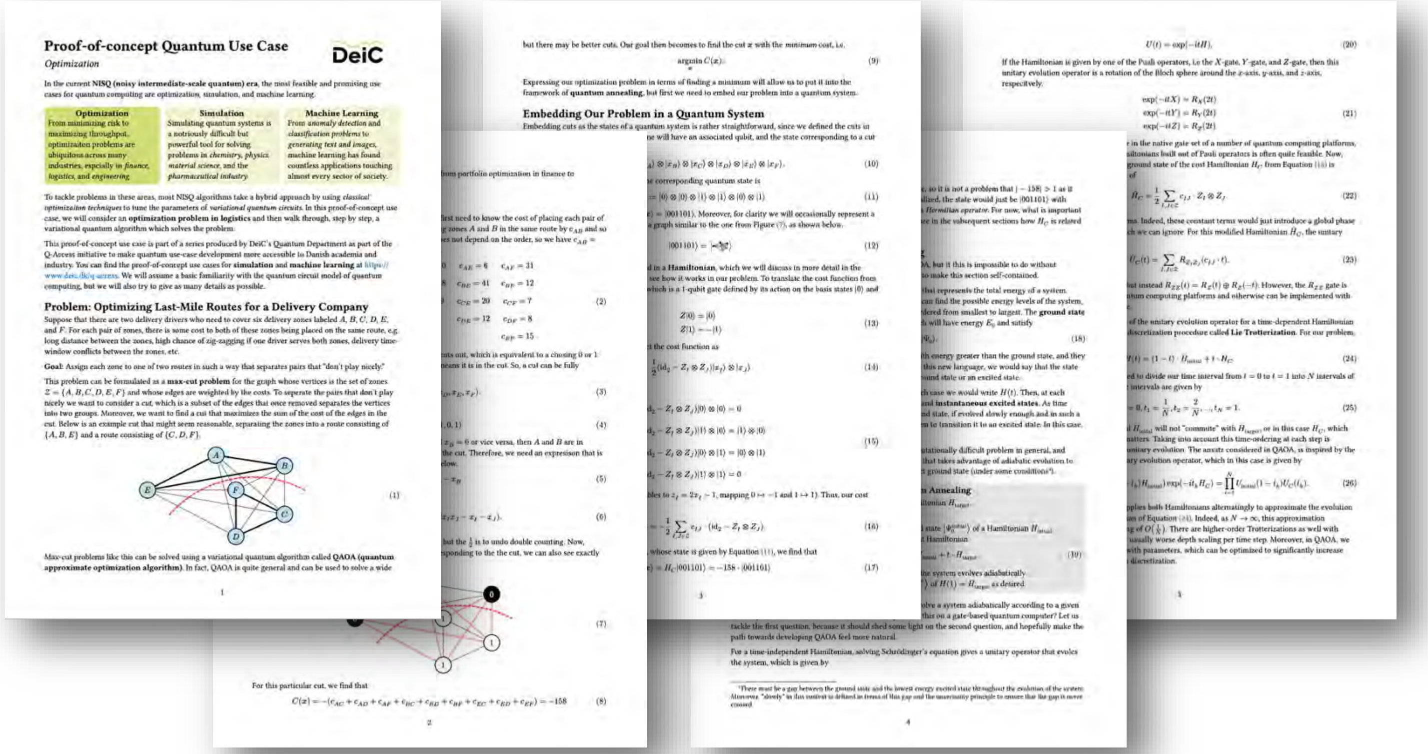
Optimization
From minimizing risk to maximizing throughput, optimizaiton problems are ubiquitous across many industries, espcially in *finance*, *logistics*, and *engineering*.

Simulation
Simulating quantum systems is a notriously difficult but powerful tool for solving problems in *chemistry*, *physics*, *material science*, and the *pharmaceutical industry*.

Machine Learning
From *anomaly detection* and *classification problems* to *generating text and images*, machine learning has found countless applications touching almost every sector of society.

Proof-of-concept Use Case: Optimization

- Practically speaking, these proof-of-concept quantum use cases include a **step-by-step guide** starting from the problem description, then **formalizing and embedding the problem into a quantum system** and finally **describing and implementing a quantum algorithm to solve it**.
- The first proof-of-concept use case that DeiC has developed is in optimization.



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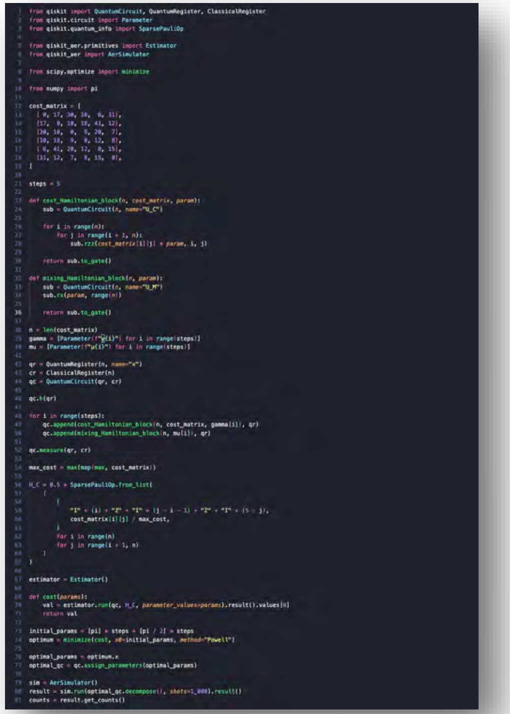


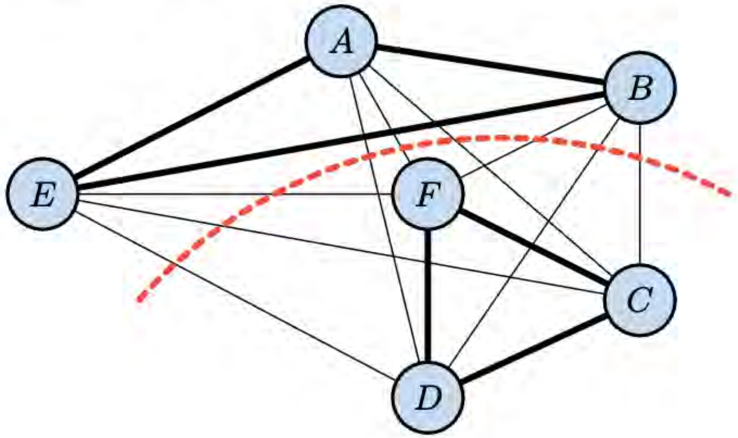
Proof-of-concept Use Case: Optimization

Problem: Optimizing Last-Mile Routes for a Delivery Company

Suppose that there are two delivery drivers who need to cover six delivery zones labeled A, B, C, D, E, and F. For each pair of zones, there is some cost to both of these zones being placed on the same route, e.g. long distance between the zones, high chance of zig-zagging if one driver serves both zones, delivery time-window conflicts between the zones, etc.

Goal: Assign each zone to one of two routes in such a way that separates pairs that "don't play nicely."

This problem can be formulated as a **max-cut problem** for the graph whose vertices is the set of zones $\mathcal{Z} = \{A, B, C, D, E, F\}$ and whose edges are weighted by the costs. To seperate the pairs that don't play nicely we want to consider a *cut*, which is a subset of the edges that once removed separates the vertices into two groups. Moreover, we want to find a cut that maximizes the sum of the cost of the edges in the cut. Below is an example cut that might seem reasonable, separating the zones into a route consisting of $\{A, B, E\}$ and a route consisting of $\{C, D, F\}$.

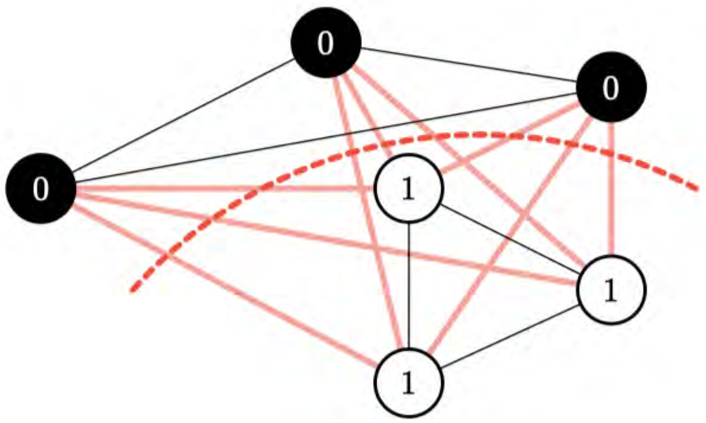


Precise Formulation of Our Problem

- The costs of including both zones in the same route are given below.

$$c_{AB} = 17 \quad c_{AC} = 30 \quad c_{AD} = 10 \quad c_{AE} = 6 \quad c_{AF} = 31$$
$$c_{BC} = 10 \quad c_{BD} = 18 \quad c_{BE} = 41 \quad c_{BF} = 12$$
$$c_{CD} = 9 \quad c_{CE} = 20 \quad c_{CF} = 7$$
$$c_{DE} = 12 \quad c_{DF} = 8$$
$$c_{EF} = 15$$

This problem can be phrased as a **binary optimization** problem where 0 corresponds to one route and 1 to the other.



$$\boldsymbol{x} = (x_A, x_B, x_C, x_D, x_E, x_F)$$
$$= (0, 0, 1, 1, 0, 1)$$

- Then, the cost function is given as follows:

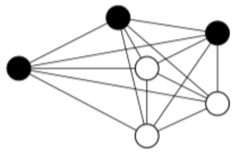
$$C(\boldsymbol{x}) = -\frac{1}{2} \sum_{I,J \in Z} c_{IJ} \cdot (2x_I x_J - x_I - x_J)$$

$$C(\boldsymbol{x}) = -(c_{AC} + c_{AD} + c_{AF} + c_{BC} + c_{BD} + c_{BF} + c_{EC} + c_{ED} + c_{EF}) = -158$$

- Finally, the problem becomes to find the assignment which minimizes the cost: $\underset{\boldsymbol{x}}{\operatorname{argmin}}\, C(\boldsymbol{x})$

Embedding in a Quantum System

- Binary optimization problems are easy to embed in quantum systems: $|\boldsymbol{x}\rangle := |x_A\rangle \otimes |x_B\rangle \otimes |x_C\rangle \otimes |x_D\rangle \otimes |x_E\rangle \otimes |x_F\rangle$

$$|001101\rangle = \Big|$$  $$\Big\rangle$$

- Then, we can express our optimization problem as finding the ground state of a "cost Hamiltonian."

$$\frac{1}{2}(\mathrm{id}_2 - Z_I \otimes Z_J)|0\rangle \otimes |0\rangle = 0$$

$$\frac{1}{2}(\mathrm{id}_2 - Z_I \otimes Z_J)|1\rangle \otimes |0\rangle = |1\rangle \otimes |0\rangle$$

$$\frac{1}{2}(\mathrm{id}_2 - Z_I \otimes Z_J)|0\rangle \otimes |1\rangle = |0\rangle \otimes |1\rangle$$

$$\frac{1}{2}(\mathrm{id}_2 - Z_I \otimes Z_J)|1\rangle \otimes |1\rangle = 0$$

$$H_C = -\frac{1}{2}\sum_{I,J\in Z} c_{IJ} \cdot (\mathrm{id}_2 - Z_I \otimes Z_J).$$

$$H_C|\boldsymbol{x}\rangle = H_C|001101\rangle = -158 \cdot |001101\rangle$$

Motivation from Quantum Annealing

- We can find the ground state of our cost Hamiltonian using quantum annealing.

Outline of Quantum Annealing

Goal: Prepare the ground state $\left|\Psi_0^{\text{target}}\right\rangle$ of a given Hamiltonian H_{target}.

Strategy

1. Intialize the system in an easy-to-construct ground state $\left|\Psi_0^{\text{initial}}\right\rangle$ of a Hamiltonian H_{initial}.
2. Evolve the system according to the time-dependent Hamiltonian

$$H(t) = (1-t) \cdot H_{\text{initial}} + t \cdot H_{\text{target}}$$

   from time $t = 0$ to time $t = 1$ slowly enough that the system evolves adiabatically.
3. The system will now be in the ground state $\left|\Psi_0^{\text{target}}\right\rangle$ of $H(1) = H_{\text{target}}$ as desired.

- While, this algorithm is not directly implementable on a gate-based system, but we can approximate it by the "first-order Trotterization."

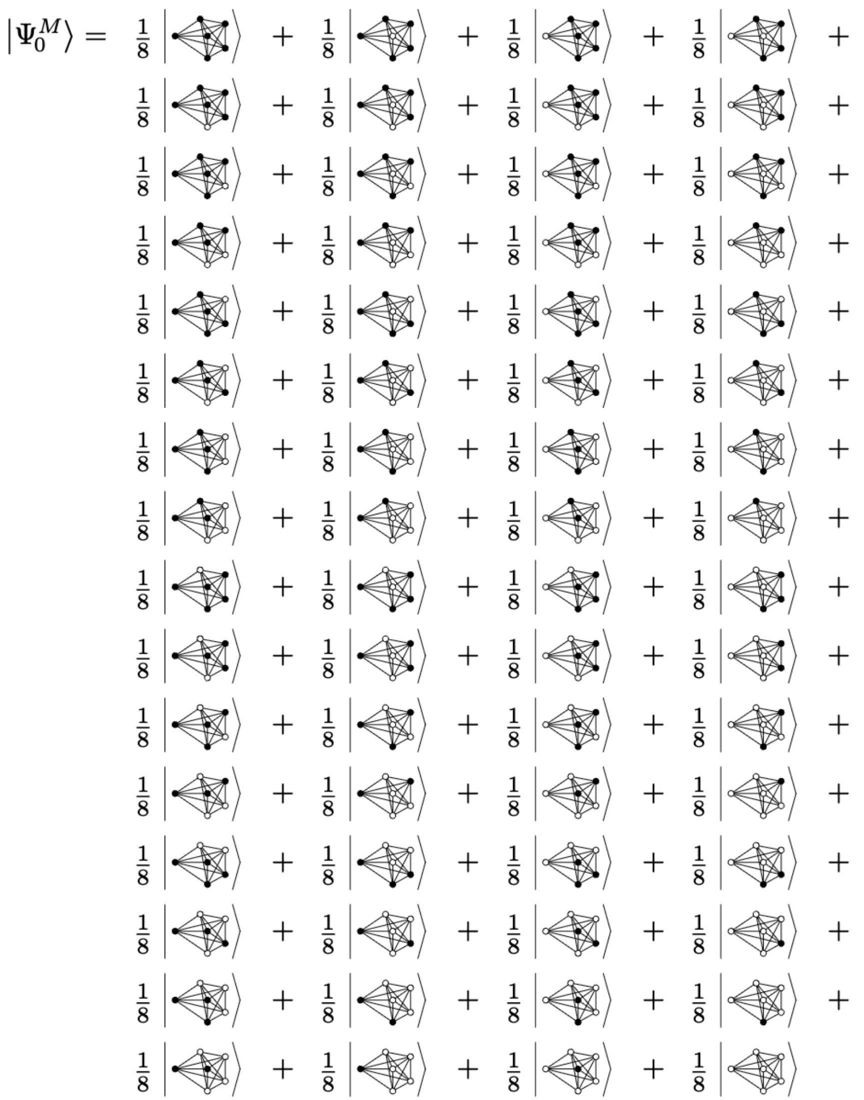
$$U(1) \approx \prod_{i=1}^{N} \exp(-i(1-t_k)H_{\text{initial}}) \exp(-it_k H_C) = \prod_{i=1}^{N} U_{\text{initial}}(1-t_k) U_C(t_k)$$

Quantum Approximate Optimization Algorithm

- We start with the “easy-to-construct” superposition of all possible cuts.

$$H|0\rangle = |+\rangle = \frac{1}{\sqrt{2}}|0\rangle + \frac{1}{\sqrt{2}}|1\rangle$$

$$\left|\Psi_0^M\right\rangle = H \otimes H \otimes H \otimes H \otimes H \otimes H|000000\rangle = |{+}{+}{+}{+}{+}{+}\rangle$$



- The Hamiltonian for which this is the ground state is called the “mixer Hamiltonian,” and its unitarian evolution operator are given as follows.

$$H_M = -\sum_{I \in Z} X_I = -(X_A + X_B + X_C + X_D + X_E + X_F)$$

$$U_M(-t) = \bigotimes_{I \in Z} R_{X_I}(2t) = R_{X_A}(2t) \otimes R_{X_B}(2t) \otimes R_{X_C}(2t) \otimes R_{X_D}(2t) \otimes R_{X_E}(2t) \otimes R_{X_F}(2t)$$

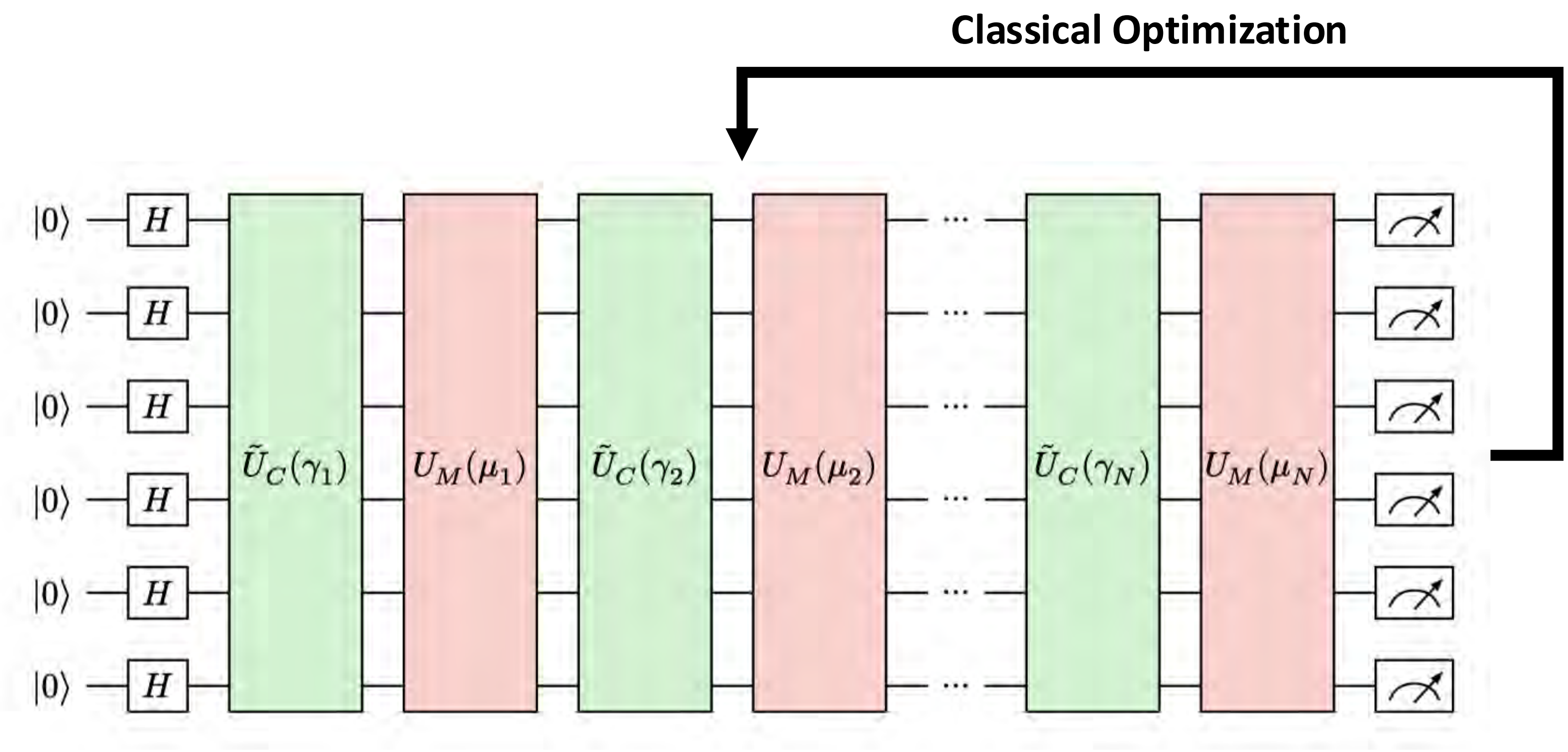
- We can use a simplified version of the cost Hamiltonian as follows.

$$\tilde{H}_C = \frac{1}{2} \sum_{I,J \in Z} c_{IJ} \cdot Z_I \otimes Z_J.$$

$$\tilde{U}_C(t) = \sum_{I,J \in Z} R_{Z_I Z_J}(c_{IJ} \cdot t)$$

Quantum Approximate Optimization Algorithm

- The **QAOA algorithm** treats the time-steps from the first-order Trotterization as **tunable parameters**.
- The parametrized circuit is then **optimized using classical optimization techniques**.
- After optimization, the circuit should **output approximate solutions with higher probability**.



Qiskit Implementation of QAOA

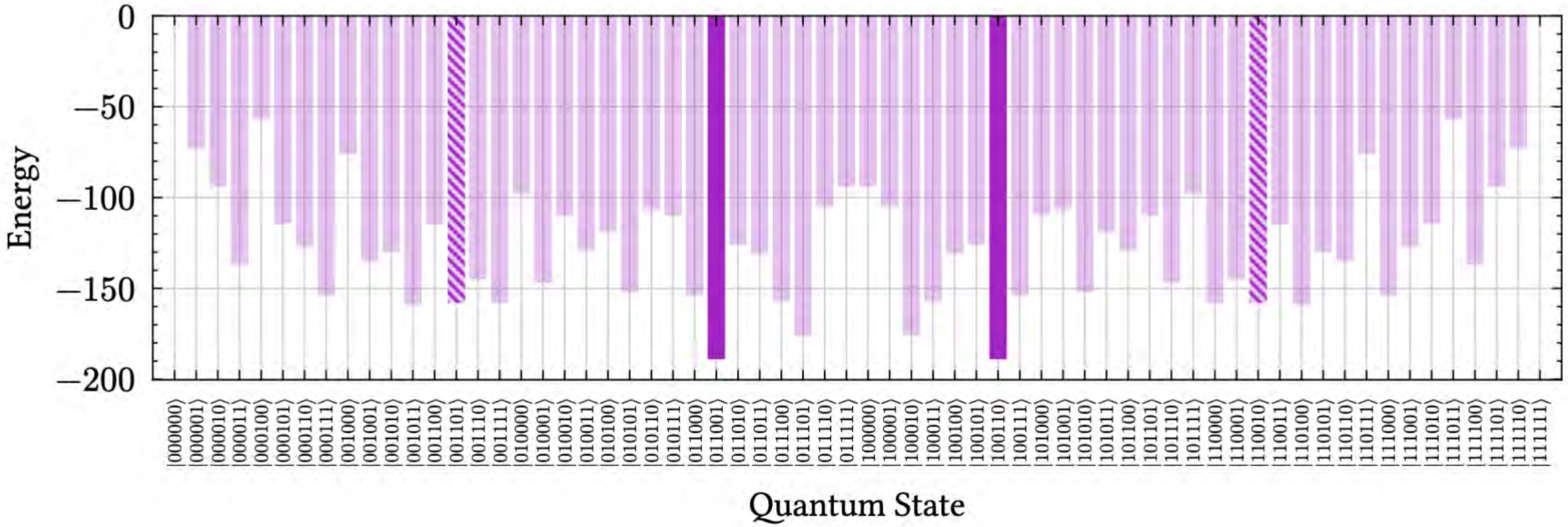
- We can implement this parametrized circuit using Qiskit and optimize it with SciPy.

```python
from qiskit import QuantumCircuit, QuantumRegister, ClassicalRegister
from qiskit.circuit import Parameter
from qiskit.quantum_info import SparsePauliOp

from qiskit_aer.primitives import Estimator
from qiskit_aer import AerSimulator

from scipy.optimize import minimize

from numpy import pi

cost_matrix = [
  [ 0, 17, 30, 10,  6, 31],
  [17,  0, 10, 18, 41, 12],
  [30, 10,  0,  9, 20,  7],
  [10, 18,  9,  0, 12,  8],
  [ 6, 41, 20, 12,  0, 15],
  [31, 12,  7,  8, 15,  0],
]

steps = 5

def cost_Hamiltonian_block(n, cost_matrix, param):
    sub = QuantumCircuit(n, name="U_C")

    for i in range(n):
        for j in range(i + 1, n):
            sub.rzz(cost_matrix[i][j] * param, i, j)

    return sub.to_gate()

def mixing_Hamiltonian_block(n, param):
    sub = QuantumCircuit(n, name="U_M")
    sub.rx(param, range(n))

    return sub.to_gate()

n = len(cost_matrix)
gamma = [Parameter(f"γ{i}") for i in range(steps)]
mu = [Parameter(f"μ{i}") for i in range(steps)]

qr = QuantumRegister(n, name="x")
cr = ClassicalRegister(n)
qc = QuantumCircuit(qr, cr)

qc.h(qr)

for i in range(steps):
    qc.append(cost_Hamiltonian_block(n, cost_matrix, gamma[i]), qr)
    qc.append(mixing_Hamiltonian_block(n, mu[i]), qr)

qc.measure(qr, cr)

max_cost = max(map(max, cost_matrix))

H_C = 0.5 * SparsePauliOp.from_list(
    [
        (
            "I" * (i) + "Z" + "I" * (j - i - 1) + "Z" + "I" * (5 - j),
            cost_matrix[i][j] / max_cost,
        )
        for i in range(n)
        for j in range(i + 1, n)
    ]
)

estimator = Estimator()

def cost(params):
    val = estimator.run(qc, H_C, parameter_values=params).result().values[0]
    return val

initial_params = [pi] * steps + [pi / 2] * steps
optimum = minimize(cost, x0=initial_params, method="Powell")

optimal_params = optimum.x
optimal_qc = qc.assign_parameters(optimal_params)

sim = AerSimulator()
result = sim.run(optimal_qc.decompose(), shots=1_000).result()
counts = result.get_counts()
```

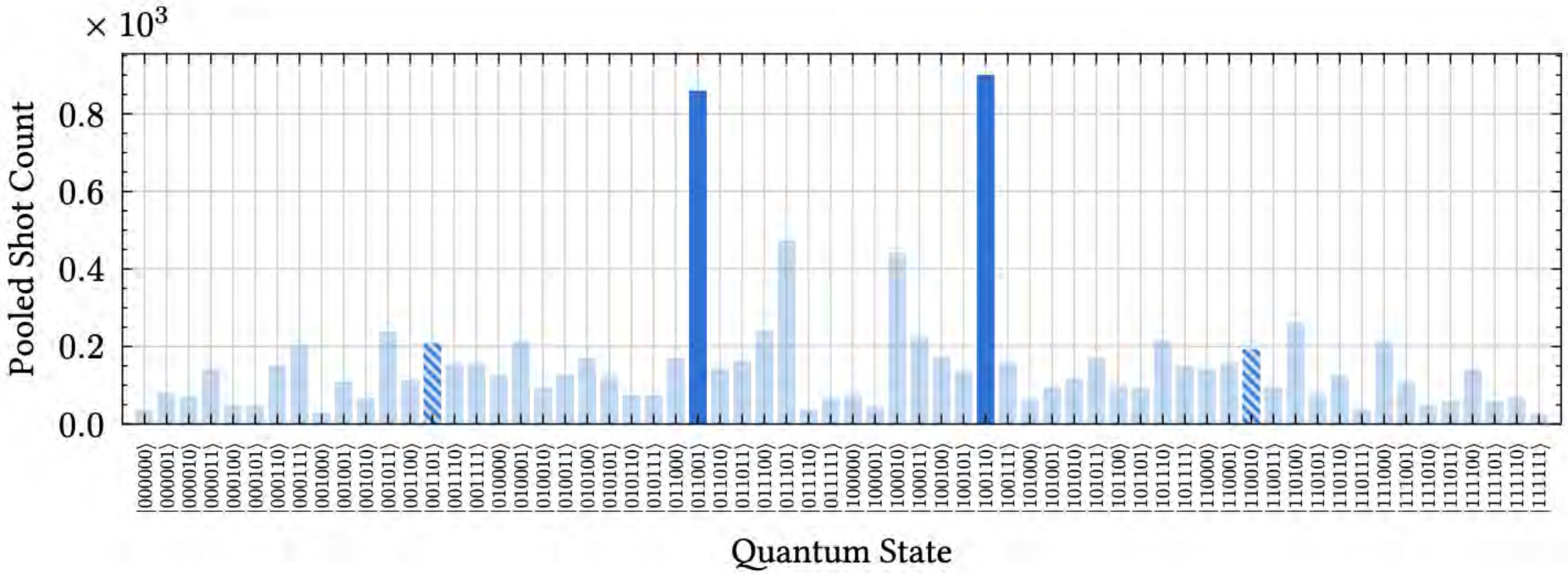
- **Follow-up:** Demonstration of implementation on VLQ (with LEXIS, QProvider, etc.)!

Results

- Just looking at the energy landscape, we can see that there are **several states with energy near the ground state energy** (i.e. approximate solutions).

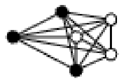
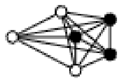


- After optimizing and sampling the circuit (several times and pooling the results), we can see that **the ground state becomes the most probable measurement**.

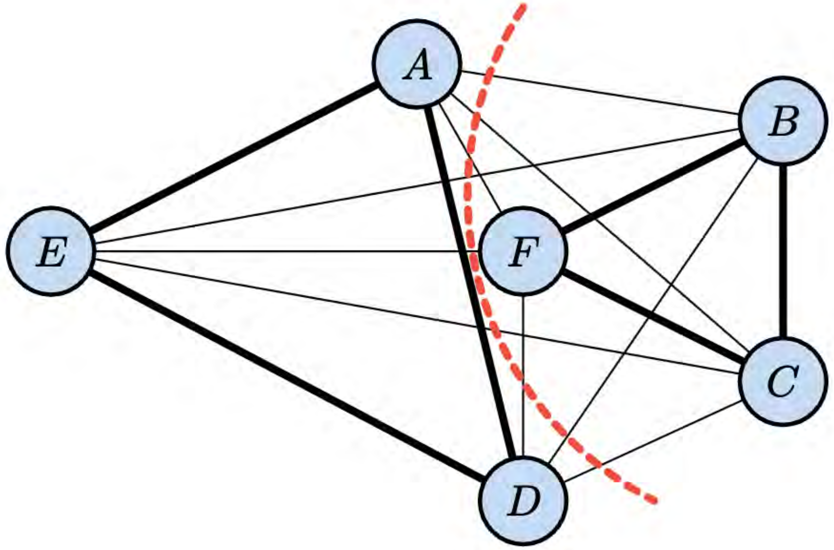


Results

- Because of the symmetry built into our problem, there are **two ground states** that correspond to the same cut.

$\mathcal{G}(H_C) = \Big\{ \big|$  $\big\rangle = |011001\rangle,\ \big|$  $\big\rangle = |100110\rangle \Big\}$

- **The ground state has energy -189** which is about **20% lower than our original guess** (which had an energy of -158), and the corresponding cut which is the **solution to our problem** is given below.

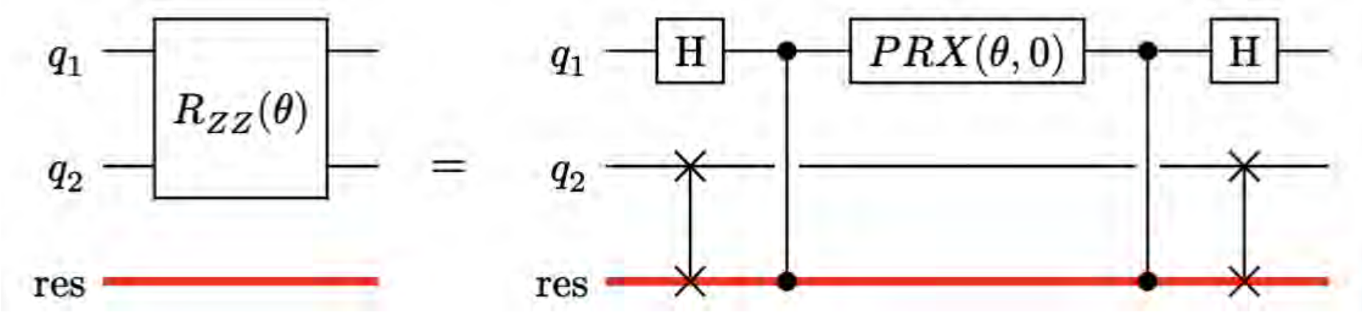


Implementation on VLQ (IQM Star 24)

- The native one-qubit gate for the IQM Star 24 QPU is the phased X-rotation gate.

$$PRX(\theta,\varphi) = R_Z(\varphi)R_X(\theta)R_Z(-\varphi) \longrightarrow \begin{array}{c} PRX(\theta,0) = R_X(\theta) \\ PRX(\theta,\pi/2) = R_Y(\theta) \\ PRX(-\pi,0)PRX(\pi,-\theta/2) = R_Z(\theta) \end{array}$$

- The native two-qubit gate is the controlled Z-gate (after a “move” to the resonator).
- So, the only gate we need to convert is the RZZ-gate, which can be done as follows.

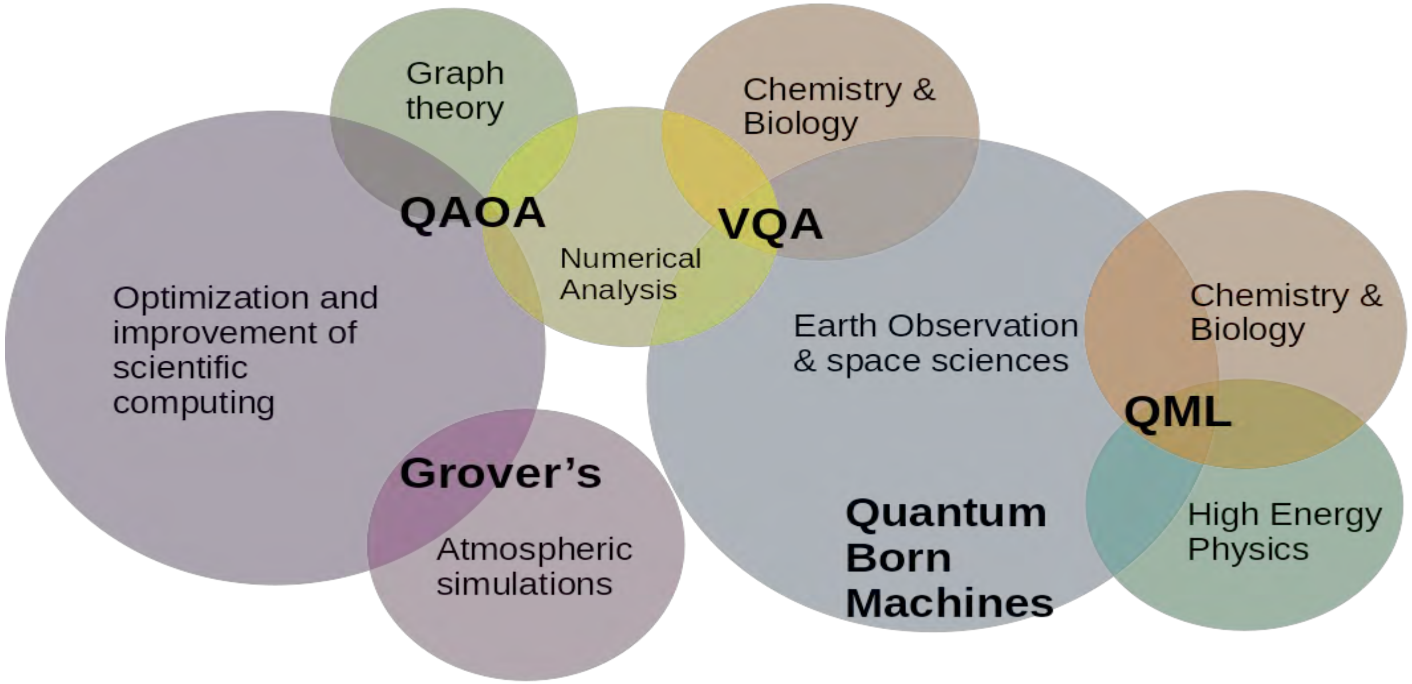


Note: Almost all Hadamard gates will be cancelled or absorbed, and the remaining contribute two PRX-gates each.

- **IQM Pulla** allows users to generate and execute pulse-level instructions on their quantum computers, which could potentially help eke out even more performance.

Further Proof-of-concept Use Cases

- Besides the proof-of-concept use cases in simulation and machine learning that DeiC is developing, there are a wide variety of applications that LUMI-Q partners are working on.



Goal: Help both Danish academia and industry* find practical ways to use LUMI-Q VLQ as well as all the other resources that are available!

5. Q-Access

Consulting with Quantum Experts

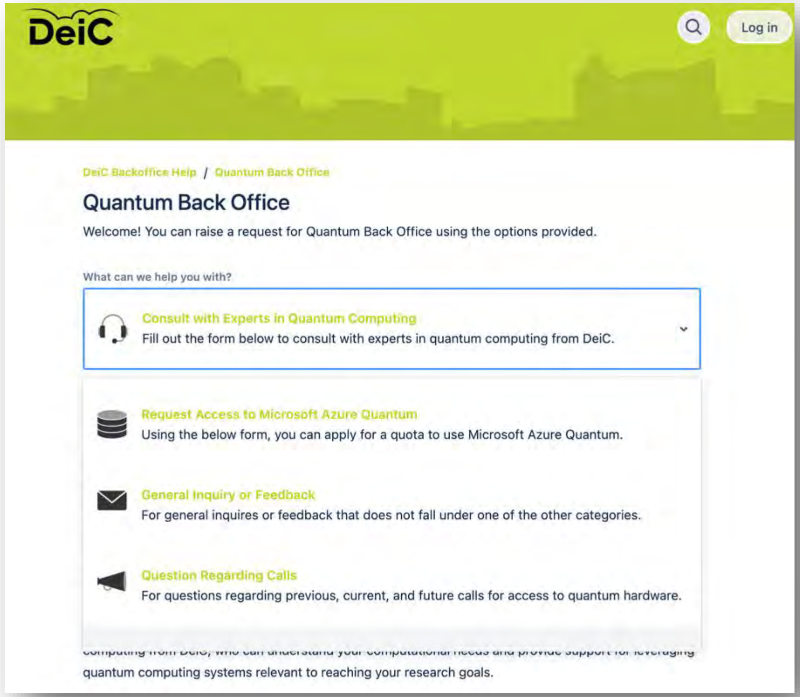
- DeiC provides **consulting with experts in quantum computing**, who can understand your computational needs and provide support for leveraging quantum computing systems relevant to reaching your research goals.

- These services can be utilized by both universities, industry, and the public sector.

- These experts can provide advice and share technical expertise on porting and optimizing applications for quantum computing environments and offer guidance on software development as needed.

- DeiC is now offering **weekly Office Hours** as well to make it easier to drop in and ask questions.

- There are also **Jira Forms** for questions regarding calls, for general inquiry or feedback, and for requesting sandbox access to hardware!



Sandbox Access to Quantum Hardware

DeiC

- Currently, sandbox access to Microsoft Azure for testing worth up to **25.000 DKK** can be applied for by filling out a simple form at: https://deic-backoffice.atlassian.net/servicedesk/customer/portal/3/group/4/create/35
- DeiC will evaluate and respond to your application within a week.
- Users can reapply after they use their allocated resources for a total of **100.000 DKK.**

Microsoft Azure

IONQ QUANTINUUM rigetti

- IBM and Amazon Braket sandbox access are currently under development. More details coming soon!
- This sandbox access can also be used in conjunction with Ucloud resources for testing hybrid algorithms.

Calls for Specialized Access

- For access to specific quantum hardware and corresponding hardware-specific simulators via one of the calls for quantum access, there is a pool of **11.000.000 DKK**.

- See https://www.deic.dk/da/quantum-technology/grants-and-funding for active and previous calls!

Active calls:

Access to quantum computing resources for researchers at Danish universities

Call opens: September 12, 2025

Call closes: October 31, 2025

- **Full Call Description**
- **Application Template**

Access to LUMI-Q VLQ and EuroHPC JU

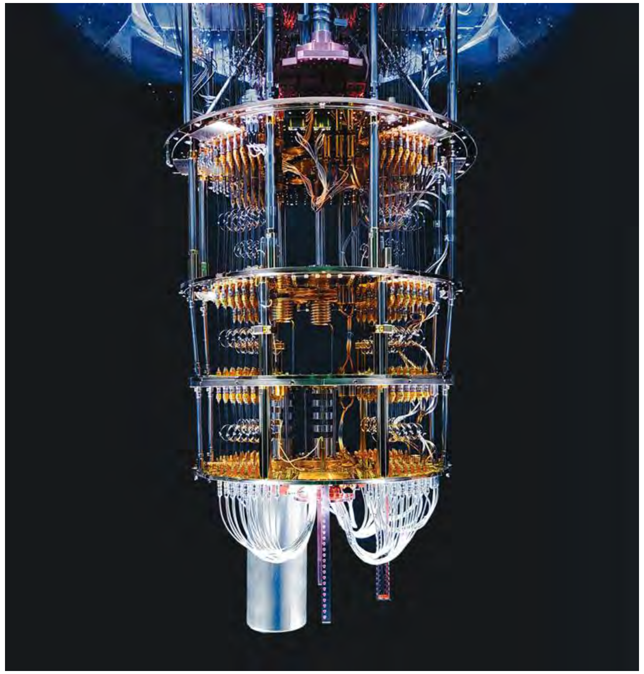
- LUMI-Q VLQ will be an **additional access option provided by Q-Access** to Danish academia.

- DeiC will provide **onboarding sessions and consulting** to help Danish academia take full advantage of VLQ.

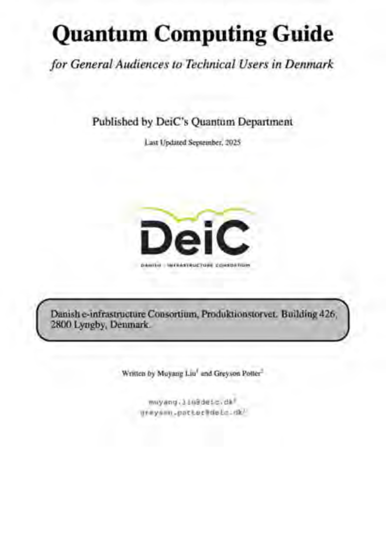
- The **close HPC integration and pulse-level access** will open new possibilities for applications and diversify DeiC's Q-Access offering.

- Direct access to the LUMI-Q VLQ quantum computer, through DeiC's participation in the LUMI-Q Consortium, will be available through a **call for applications in early 2026**.

- 50% of VLQ access will also be available through EuroHPC, along with the the other quantum computers partially financed by the EuroHPC Joint Undertaking.



Guides and Tutorials


Quantum Computing Guide

for General Audiences to Technical Users in Denmark

Published by DeiC's Quantum Department

Last Updated September, 2025

DeiC

Danish e-infrastructure Consortium, Produktionstorvet, Building 426, 2800 Lyngby, Denmark.

Written by Muyang Liu[1] and Greyson Potter[2]

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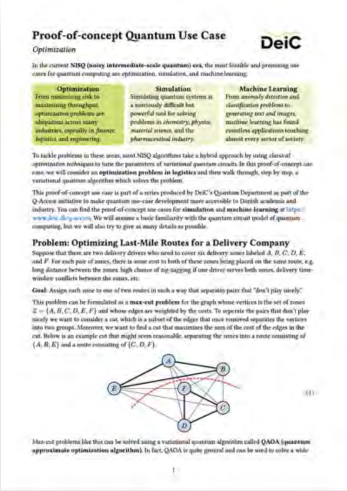
- Overview published by DeiC's Q-Access team to provide a clear and understandable description of the quantum computing resource available to users in Denmark as well as tutorials and guides of how to use them.
- Designed to be useful to both non-technical audiences (policymakers, journalists, and industry leaders) and professional quantum computing users both inside and outside Denmark.
- Begins with an introduction to quantum computing principles, followed by descriptions of different quantum devices, real-world applications, and tutorials for accessing and using resources.

- DeiC is developing some simple **proof-of-concept use cases** (for both **academia and industry**) with **step-by-step explanations** of the thought process and implementation to help, especially Danish, users best utilize quantum computing resources.
- **Proof-of-concept use case for optimization is available**, with proof-of-concept use cases in simulation and machine learning coming by the end of 2025!


Proof-of-concept Quantum Use Case

Optimization

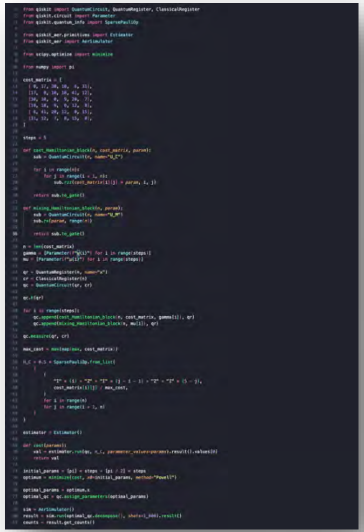
DeiC

Optimization

Simulation

Machine Learning

Problem: Optimizing Last-Mile Routes for a Delivery Company



DeiC Q-Access Roadshow

Resources

- Q-Access Website: https://deic.dk/da/q-access
    - Quantum Computing Guide and Proof-of-concept Use Cases
    - Consulting Service, Office Hours, Inquiry Forms, Calls
- LUMI-Q VLQ: https://www.it4i.cz/en/infrastructure/vlq-quantum-computer
- IBM Quantum Learn: https://learning.quantum.ibm.com/
- Qiskit Documentation: https://docs.quantum.ibm.com/
- Microsoft Azure Documentation: https://learn.microsoft.com/en-us/azure/quantum/
- Xanadu’s Strawberry Fields: https://strawberryfields.ai/
- Tensorflow Quantum Machine Learning: https://www.tensorflow.org/quantum

DeiC Q-Access Roadshow

Thank you all for listening!

Stick around for a Q&A session.