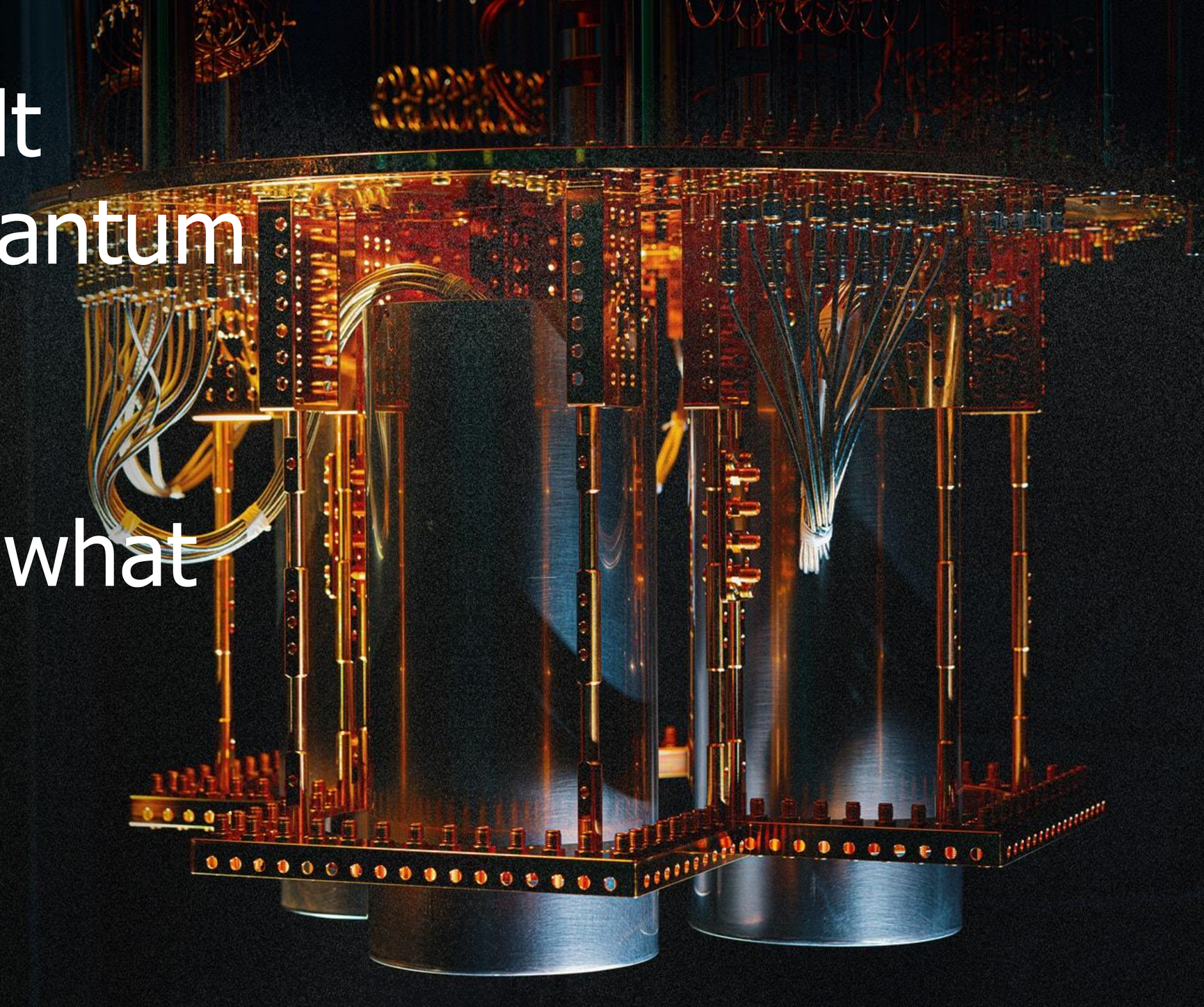
Toward Fault Tolerant Quantum Computing: milestones, impact and what to expect.



Inés de Vega- VP Solutions

IQM

IQM builds and delivers quantum computers

Our Mission:

We build world leading quantum computers for the well-being of humankind, now and for the future.

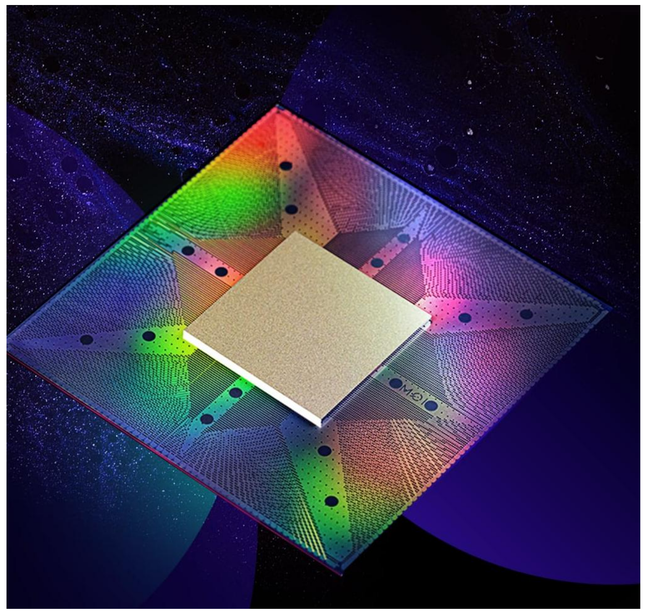
- → **ca 300** experts
- → **125+** PhDs
- → **50+** nationalities
- → Own **fab** and **assembly line**
- → **200M€** investment (best funded in Europe)
- → On-premises & cloud access
- → **30** full systems built
- → **150** qubit chip in development

IQM

Content

1. From NISQ to Fault Tolerance

2. Strategy and challenges towards quantum error correction (QEC)



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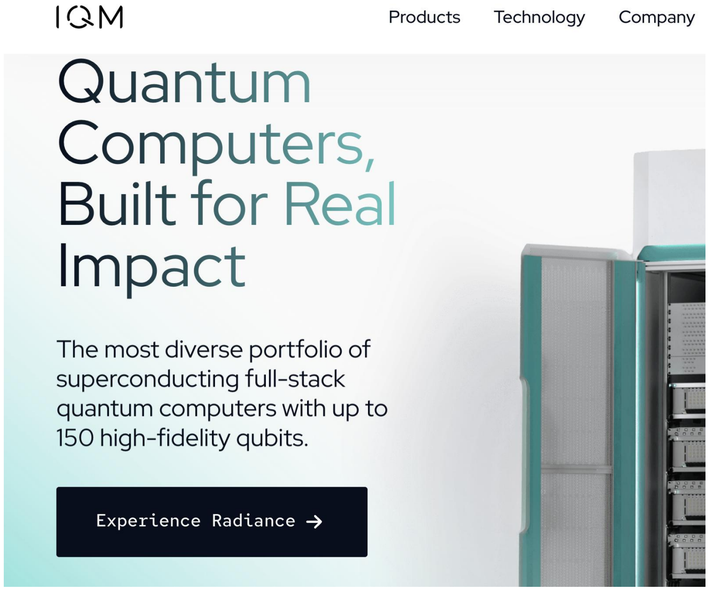
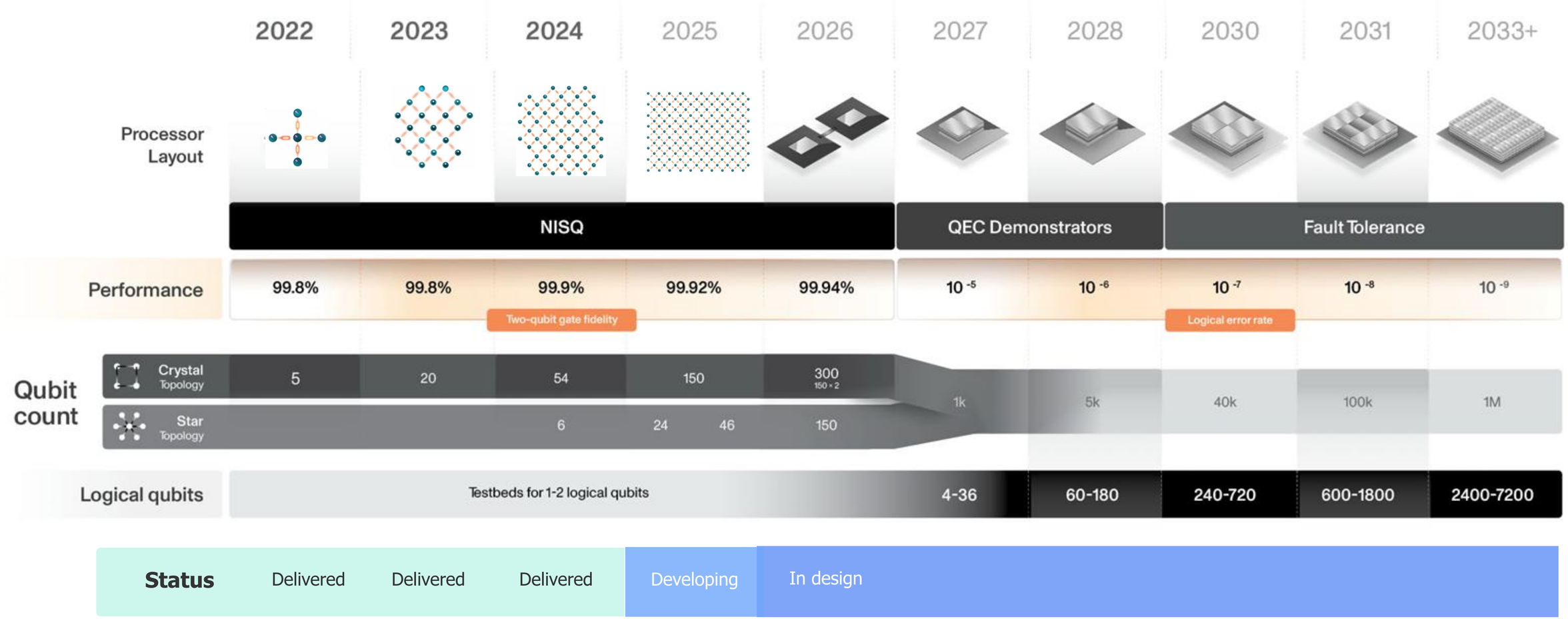


1.From NISQ to Fault Tolerance

Challenge: We need to reduce the errors beyond what is possible with HW means



(*) NISQ = Noise Intermediate Scale Quantum

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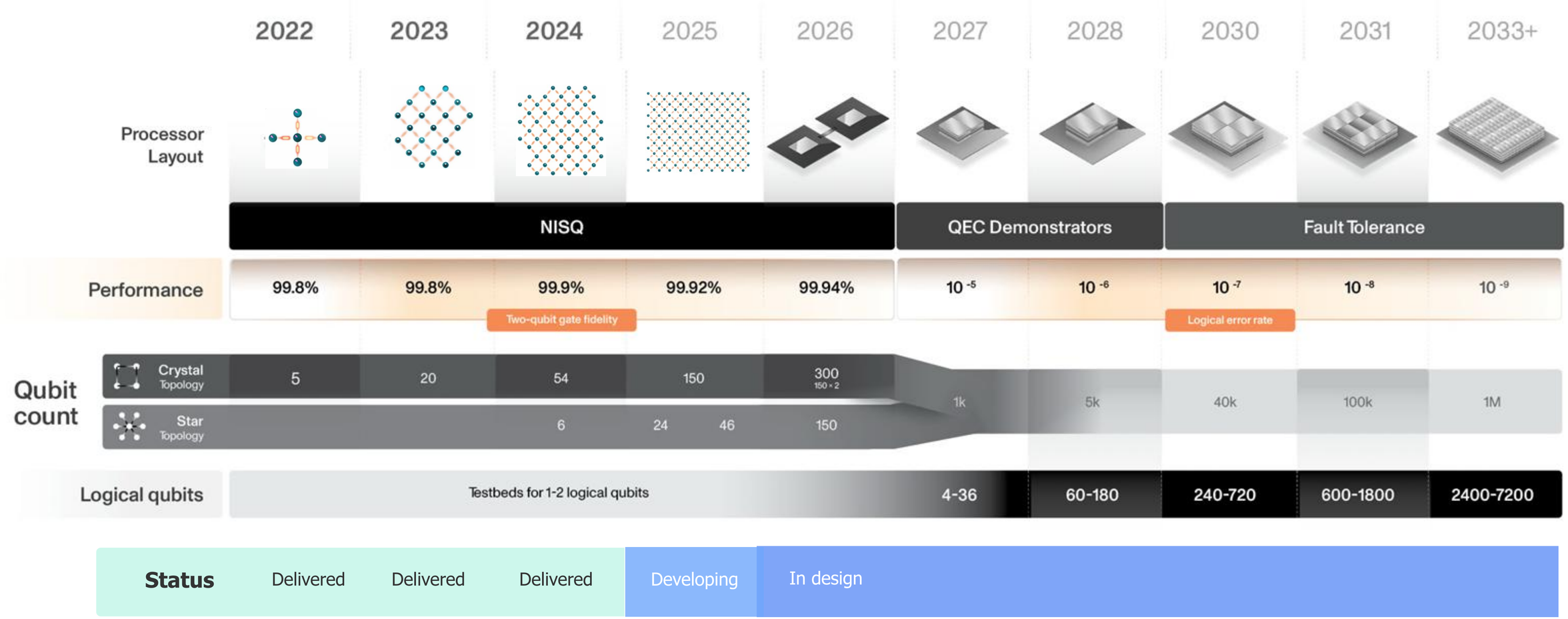

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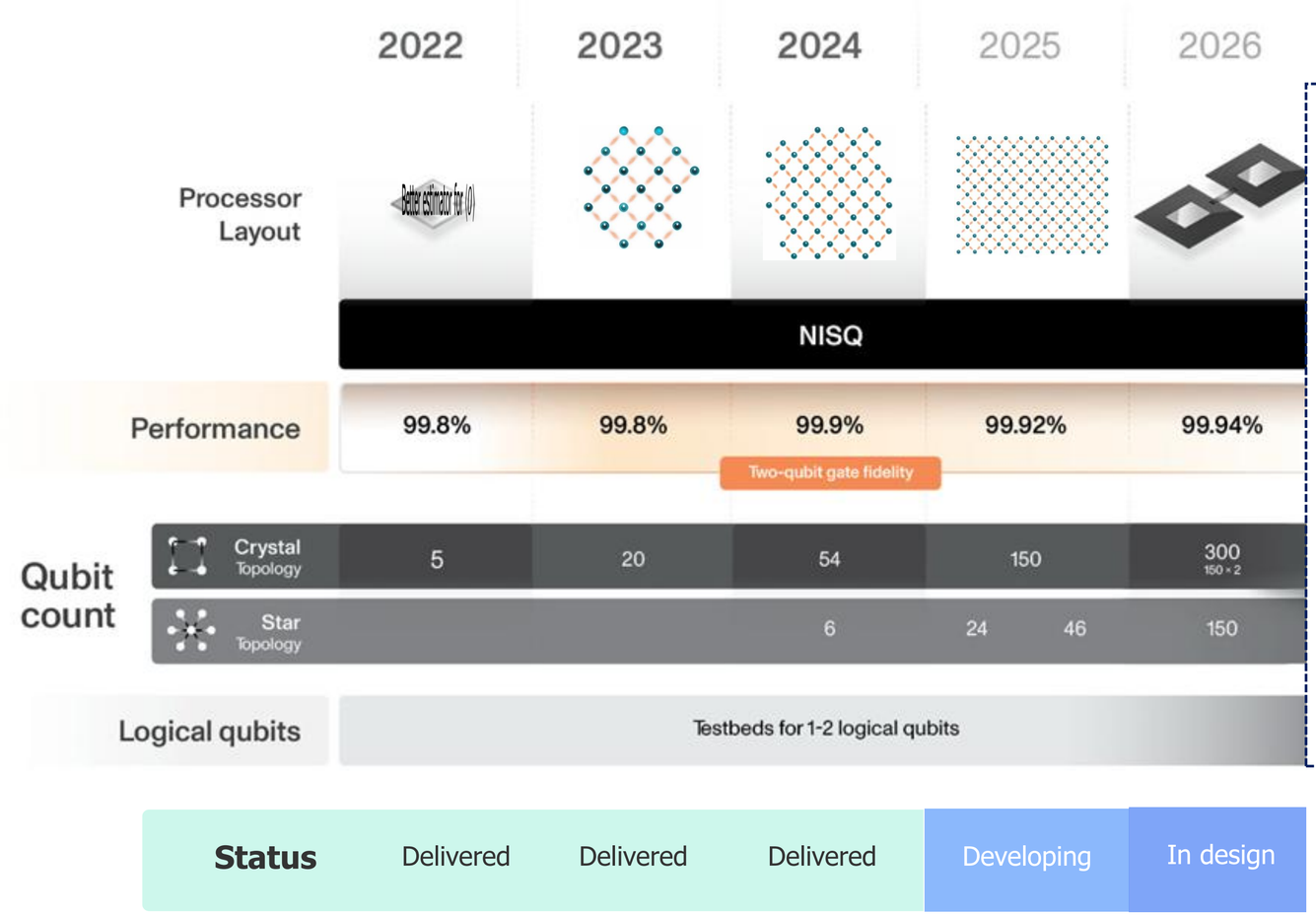
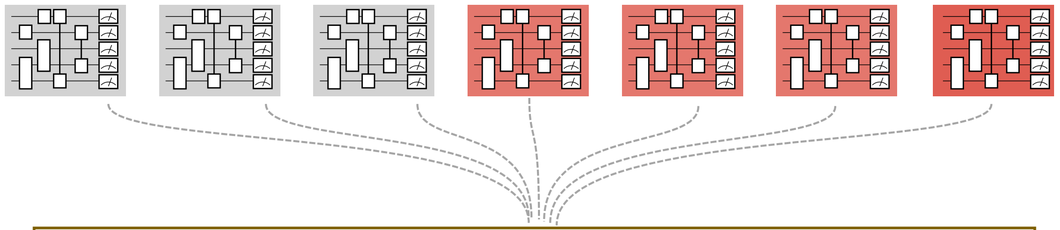


QEM: Algorithmic scheme that *effectively reduces the effect of errors* in estimating the observable [exploiting a *whole ensemble* of runs on several circuits]



Post processing ⟶ Better estimator for $\langle O \rangle$

- Applicable now

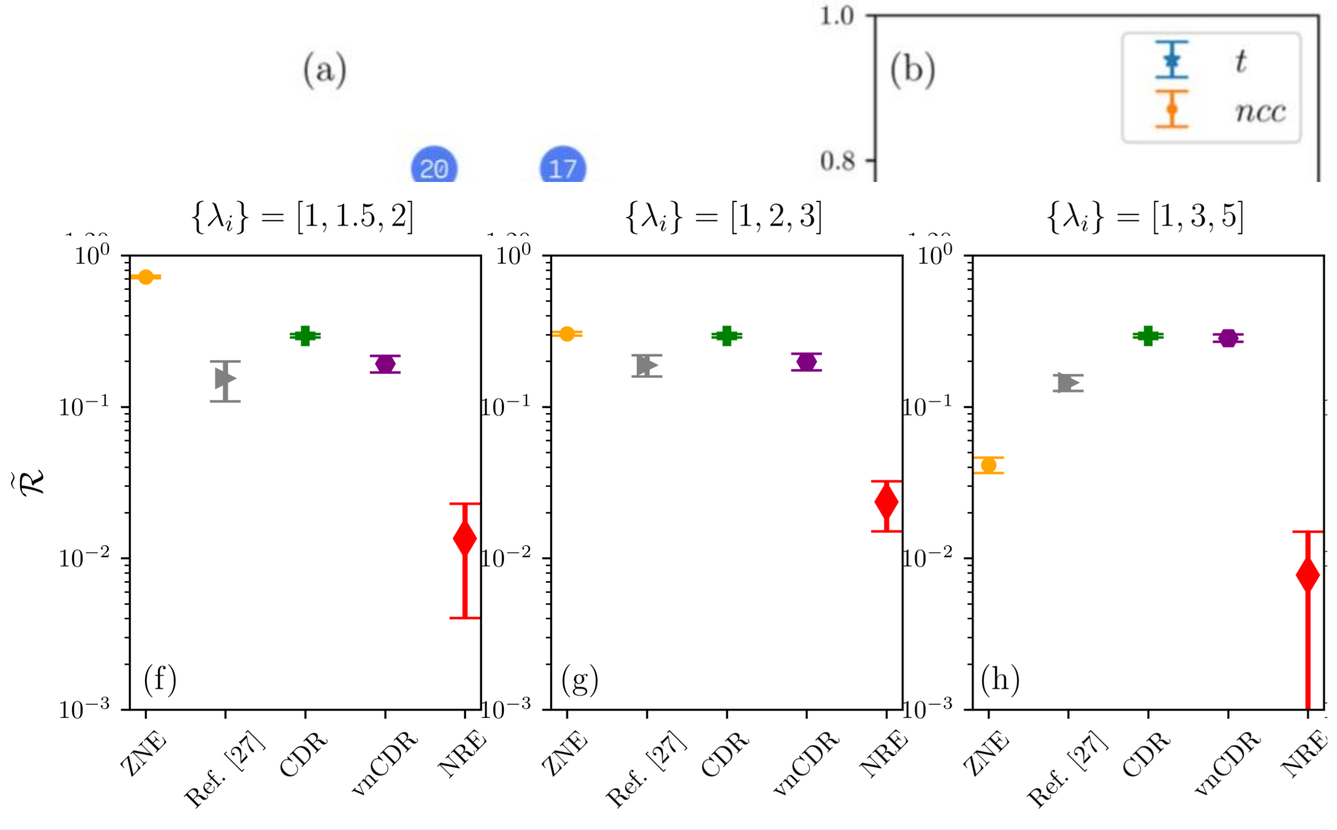
(*) NISQ = Noise Intermediate Scale Quantum

Noise Robust Estimation (NRE)

Ground-state energy (QAOA ansatz, 4 layers)

$$H_{\mathrm{TFIM}} = -2\sum_j \sigma_X^j - \sum_{(i,j)} \sigma_Z^i \sigma_Z^j$$

QPU	IQM Garnet
Qubit count	20
CZ count	240
Depth	77
Weight of observables	1 and 2
Noise amplification	Global unitary folding



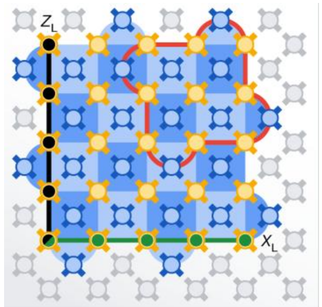
A. Hosseinkhani *et al.*, arXiv:2503.06695

1.From NISQ to Fault Tolerance

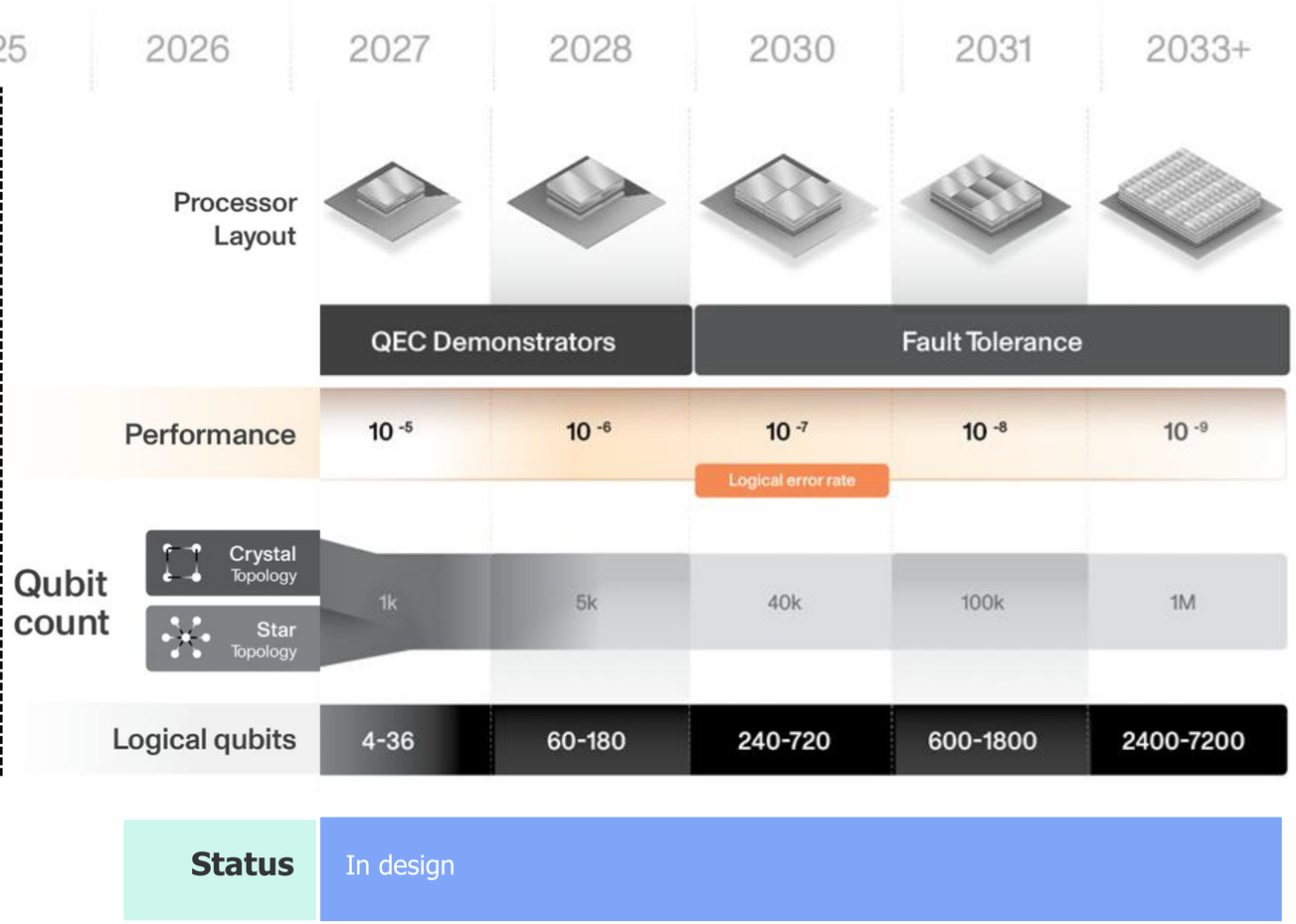
Challenge: We need to reduce the errors beyond what is possible with HW means

QEC(*): Uses long-range correlations of entangled quantum many-body states.

- Needs many physical qubits (>10K). Depends on:
  - Code parameters (distance, stabilizer weight, threshold)
  - HW quality (physical error rate)
  - Target logical error rate (depends on the application needs, e.g. ~10^{-8} to 10^{-12})
- Large applicability still in progress



Nature **614**, 676 (2023)



(*) QEC = Quantum Error Correction

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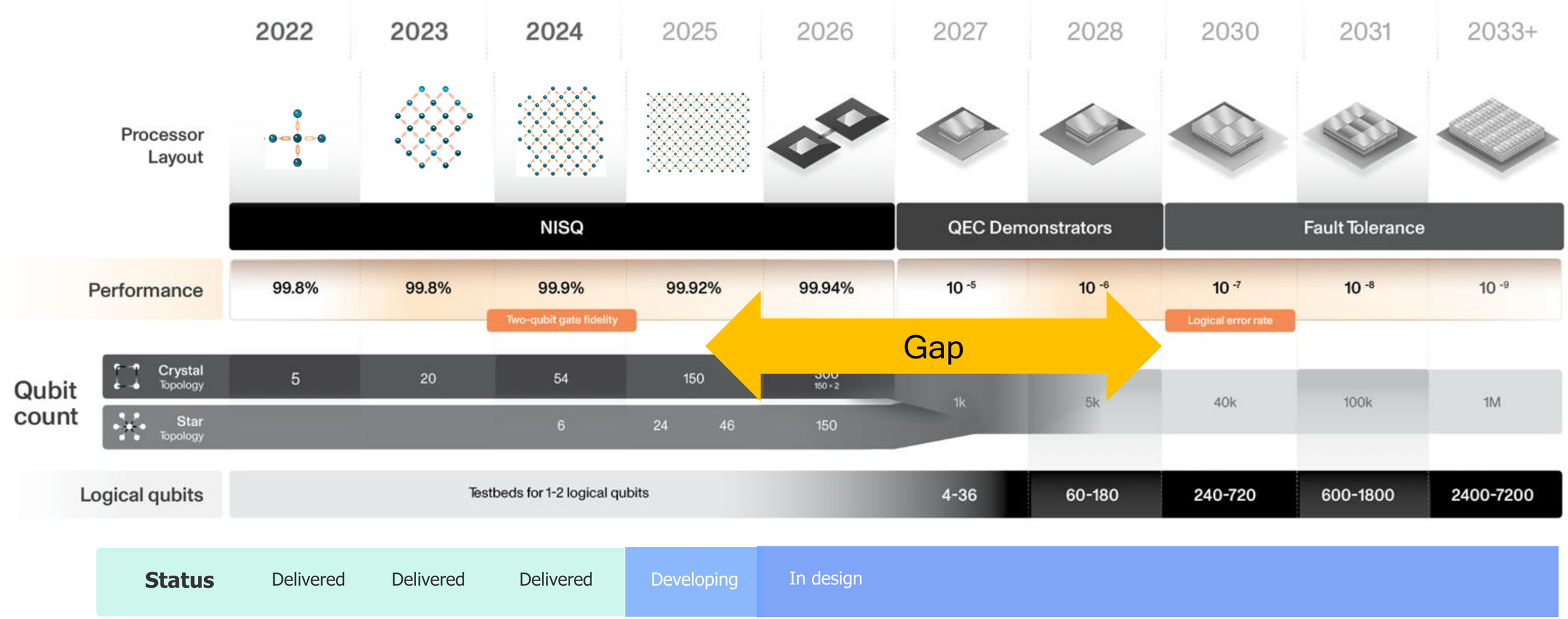

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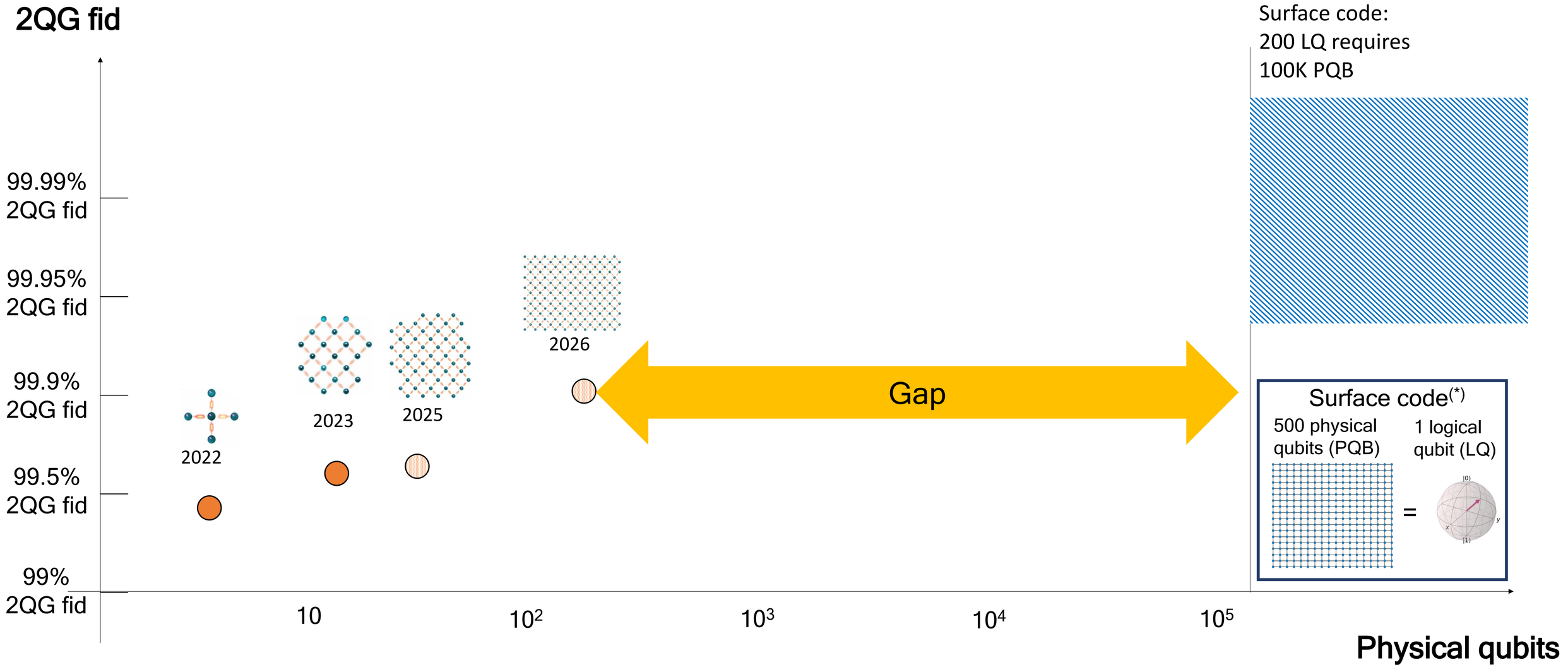

(*) Memory logical qubits (LQ) with 10^{-8} logical error rate with 99.95% physical TQG fidelity.

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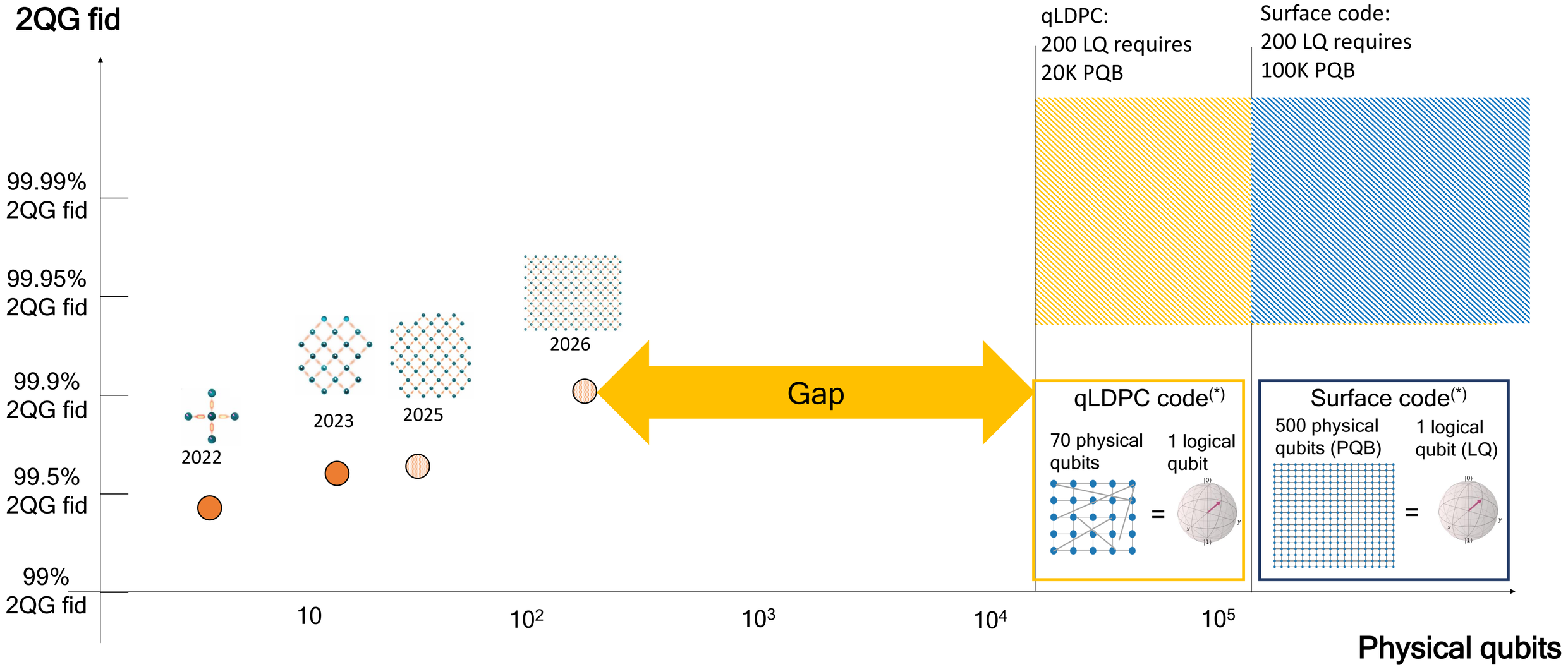

(*) Memory logical qubits (LQ) with 8 nines of logical fidelity for 99.9% physical TQG fidelity.

Content

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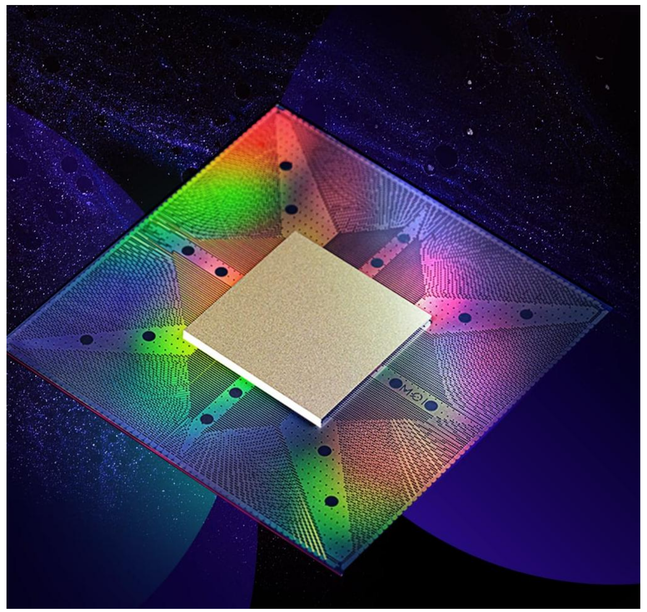
2. Strategy and challenges towards QEC



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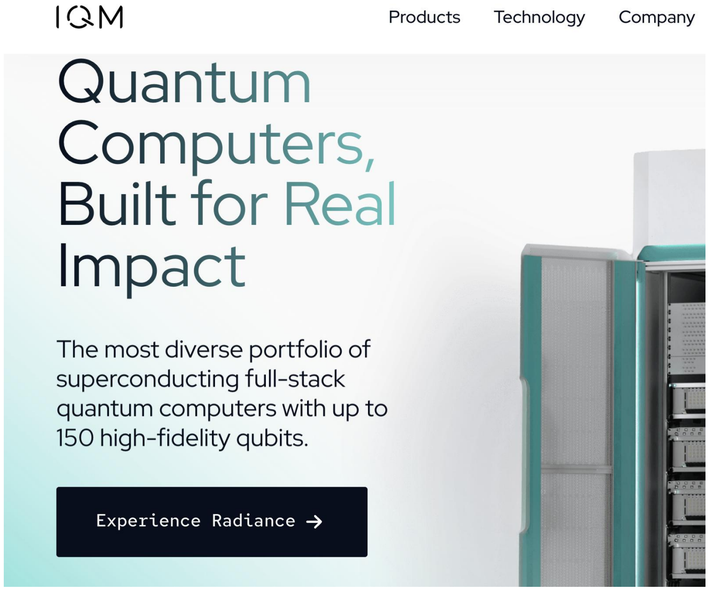
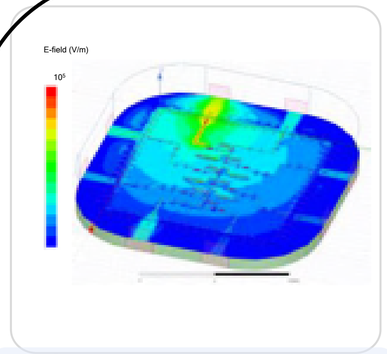


2.Strategy and challenges towards QEC

What are the key challenges across the stack?

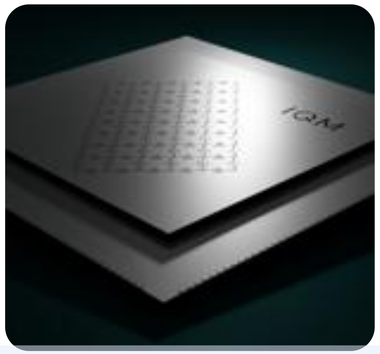


QPU design & production

- **Design** process for all elements of advantage QCs.
- **Fidelity** to meet QEC requirements (99.95% CZ-fidelities, 99.99% SQG and 99.9 readout).

Fabrication & packaging

- **1K QB systems:** vertical connectivity to enhance signal routing efficiency
- **5K+ QB systems**, including tiling, tile qualification, long range connectivity, superconducting vertical wiring

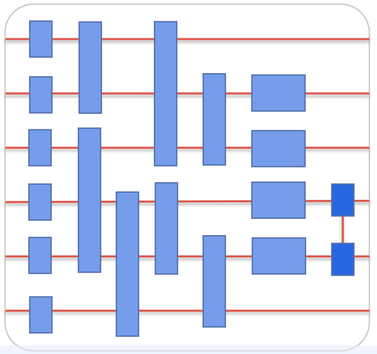


Full system integration

- **Cryogenics and wiring** to reduce heat leak
- **Electronics** to address physical qubits and for QEC implementation

SW stack HPC, Cloud & QEC

- **Autocalibration** ready.
- **FT SW stack i**ncluding real-time decoding and feedback



Algorithm & Error Correction Theory

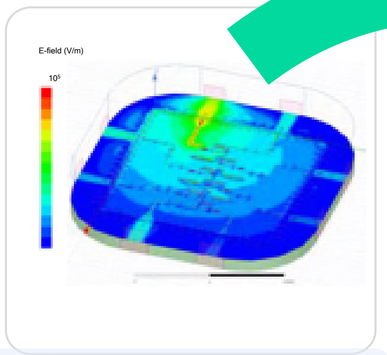
- **Identify implementable QEC codes** with high encoding rates, minimal long-range connectivity requirements, efficient decoding algorithms and magic states

➢ **IQM's unique accelerated path towards FT requires specific innovations:**

- ❖ QEC theory advances for qLDPC
- ❖ IQM Star lattice: high-performant CRC-CZ gates required

2.Strategy and challenges towards QEC

Co-designing the QEC code with the QPU topology



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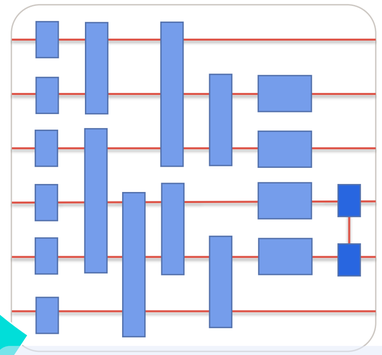
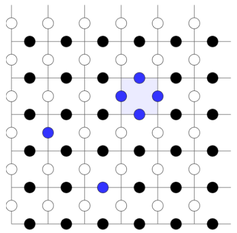
Fabrication & packaging

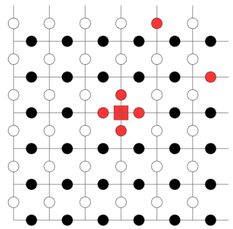


Error Correction Theory

1. QEC code engineering

Goal: 10x better performance-per-physical-qubit than standard surface code.





Systematically search QLDPC code space with stabilizers weight ≥ 6

We engineer novel high-performance QLDPC codes

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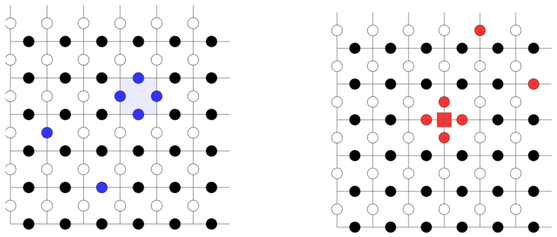

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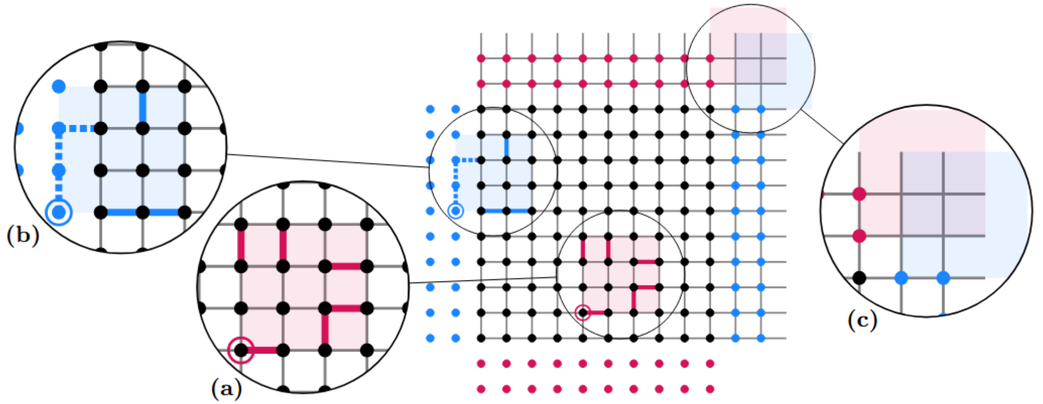
Recent example: Tile codes

- **Open boundary conditions**
- From ~ 5-10x **higher efficiency** compared to the surface code
- **Dynamic**: patches can be moved, shrunk & stretched, similar to surface code
- **Nice scaling**: Code distance or number of logical qubits increased by growing the lattice locally, preserving connectivity



V. Steffan et al., arxiv:2504.0917

Disclaimer: this efficient improvement is for memory only. Adding gates would decrease the savings ~1.7–3×, because factory regions and routing currently dominate footprint → active research

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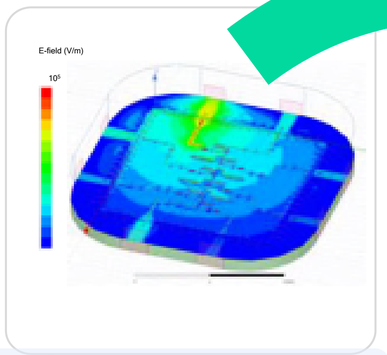

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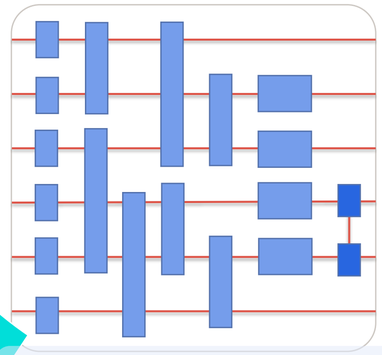

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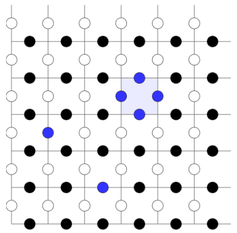
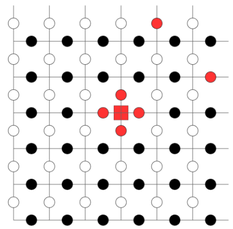


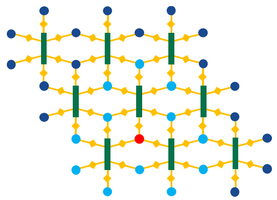


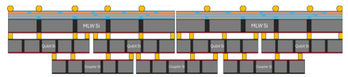
Systematically search QLDPC code space with stabilizers weight ≥ 6

We engineer novel high-performance QLDPC codes

2. QPU topology

Goal: Develop QPU topology for larger code search space and limited fabrication complexity





Star-lattice with optimal trade-off between parallelism and in-plane connectivity

Reduce fab stack requirements

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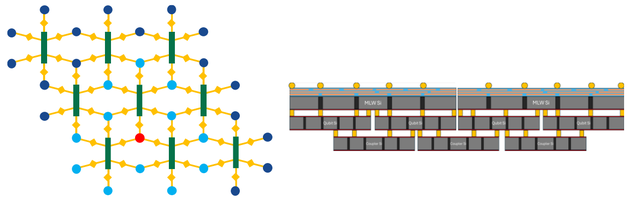
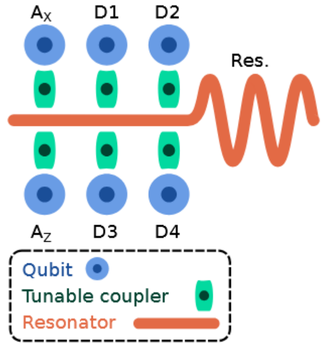


Star-lattice with optimal trade-off between parallelism and in-plane connectivity

Reduce fab stack requirements

Topologies co-designed for qLDPC codes

- Error detection with logical fidelity of 96.6% - 99.9% (4 physical qubits, 2 logical qubits) similar to prior results with same code on neutral atom and superconducting qubits.



- IQM's tunable couplers also achieve high Q-R operation fidelity.

- Explore novel compute elements

  Juha Leppäkangas et al., arXiv:2503.11507

F. Vigneau et al., arxiv:2503.12869

Quantum error detection in qubit-resonator star architecture

Florian Vigneau,[1] Sourav Majumder,[1] Aniket Rath,[1] Pedro Parrado-Rodríguez,[2] Francisco Revson Fernandes Pereira,[1] Stefan Pogorzalek,[1] Tyler Jones,[1] Nicola Wurz,[1] Michael Renger,[1] Jeroen Verjauw,[1] Ping Yang,[1] Hsiang-Sheng Ku,[1] William Kindel,[1] Frank Deppe,[1] and Johannes Heinsoo[3]

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[2] *IQM Quantum Computers, P. de la Castellana 200, Madrid 28046, Spain*
[3] *IQM Quantum Computers, Keilaranta 19, 02150 Espoo, Finland*

(Dated: April 11, 2025)

M. Regner et al., arXiv:2503.10903

A Superconducting Qubit-Resonator Quantum Processor with Effective All-to-All Connectivity

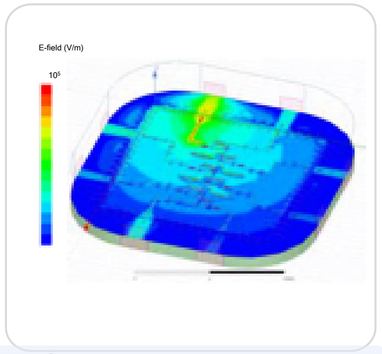
Michael Renger,[1,*] Jeroen Verjauw,[1,*] Nicola Wurz,[1,*] Amin Hosseinkhani,[1] Caspar Ockeloen-Korppi,[2] Wei Liu,[2] Aniket Rath,[1] Manish J. Thapa,[1] Florian Vigneau,[1] Elisabeth Wybo,[1] Ville Bergholm,[2] Chun Fai Chan,[2] Bálint Csatári,[2] Saga Dahl,[2] Rakhim Davletkaliyev,[2] Rakshyakar Giri,[1] Daria Gusenkova,[1] Hermanni Heimonen,[2] Tuukka Hiltunen,[2] Hao Hsu,[1] Eric Hyyppä,[2] Joni Ikonen,[2] Tyler Jones,[1] Shabeeb Khalid,[2] Seung-Goo Kim,[2] Miikka Koistinen,[2] Anton Komlev,[2] Janne Kotilahti,[2] Vladimir Kukushkin,[2] Julia Lamprich,[1] Alessandro Landra,[2] Lan-Hsuan Lee,[2] Tianyi Li,[2] Per Liebermann,[2] Sourav Majumder,[1] Janne Mäntylä,[2] Fabian Marxer,[2] Arianne Meijer - van de Griend,[2] Vladimir Milchakov,[2] Jakub Mrożek,[2] Jayshankar Nath,[1] Tuure Orell,[2] Miha Papič,[1,3] Matti Partanen,[2] Alexander Plyushch,[2] Stefan Pogorzalek,[1] Jussi Ritvas,[2] Pedro Figueroa Romero,[1] Ville Sampo,[2] Marko Seppälä,[2] Ville Selinmaa,[2] Linus Sundström,[2] Ivan Takmakov,[2] Brian Tarasinski,[2] Jani Tuorila,[2] Olli Tyrkkö,[2] Alpo Välimaa,[2] Jaap Wesdorp,[2] Ping Yang,[1] Liuqi Yu,[2] Johannes Heinsoo,[2] Antti Vepsäläinen,[2] William Kindel,[1] Hsiang-Sheng Ku,[1] and Frank Deppe[1,†]

[1] *IQM Quantum Computers, Georg-Brauchle-Ring 23-25, 80992 Munich, Germany*
[2] *IQM Quantum Computers, Keilaranta 19, 02150 Espoo, Finland*
[3] *Department of Physics and Arnold Sommerfeld Center for Theoretical Physics, Ludwig-Maximilians-Universität München, Theresienstr. 37, 80333 Munich, Germany*

(Dated: April 23, 2025)

2.Strategy and challenges towards QEC

Implementing the QEC stack



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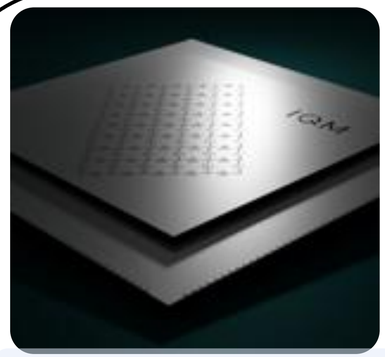

Full system integration

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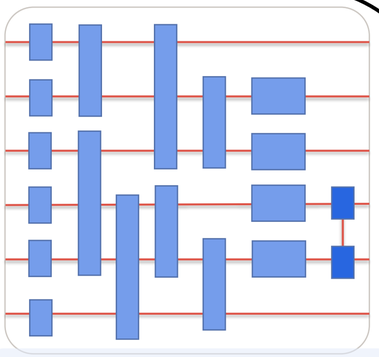
SW stack HPC, Cloud & QEC

- **Autocalibration** ready.
- **Fault tolerant SW stack** with real-time decoding and feedback



Algorithm & Error Correction Theory

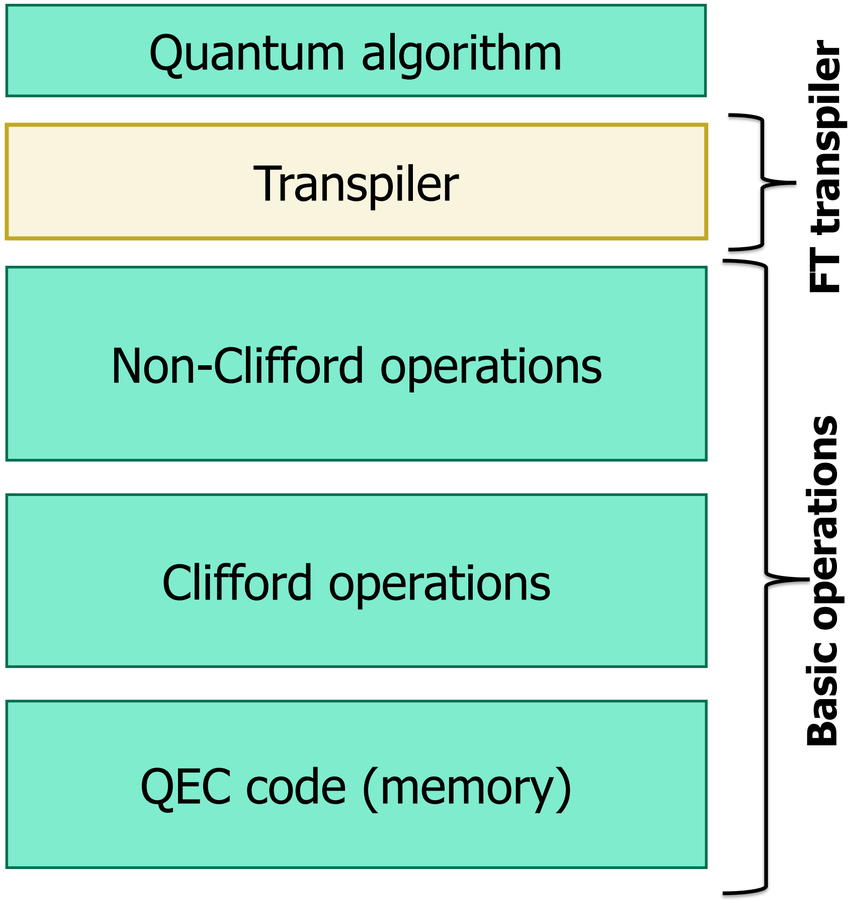
- **Identify implementable QEC codes** with high encoding rates and minimal fabrication requirements

➢ QEC stack enabling surface code for square lattices and qLDPC codes for co-designed lattices

2.Strategy and challenges towards QEC

Theoretical QEC Stack – From Codes to Algorithms

All elements in the QEC stack are already solved for surface codes….



Quantum Compiler/Transpiler
- Adds QEC scaffold (syndrome qubits, QEC cycles, measurements) and adapt to native gates
- First implementations done

Non-Clifford Operations
- Based on magic state distillation within T-gate factories
- First implementations done

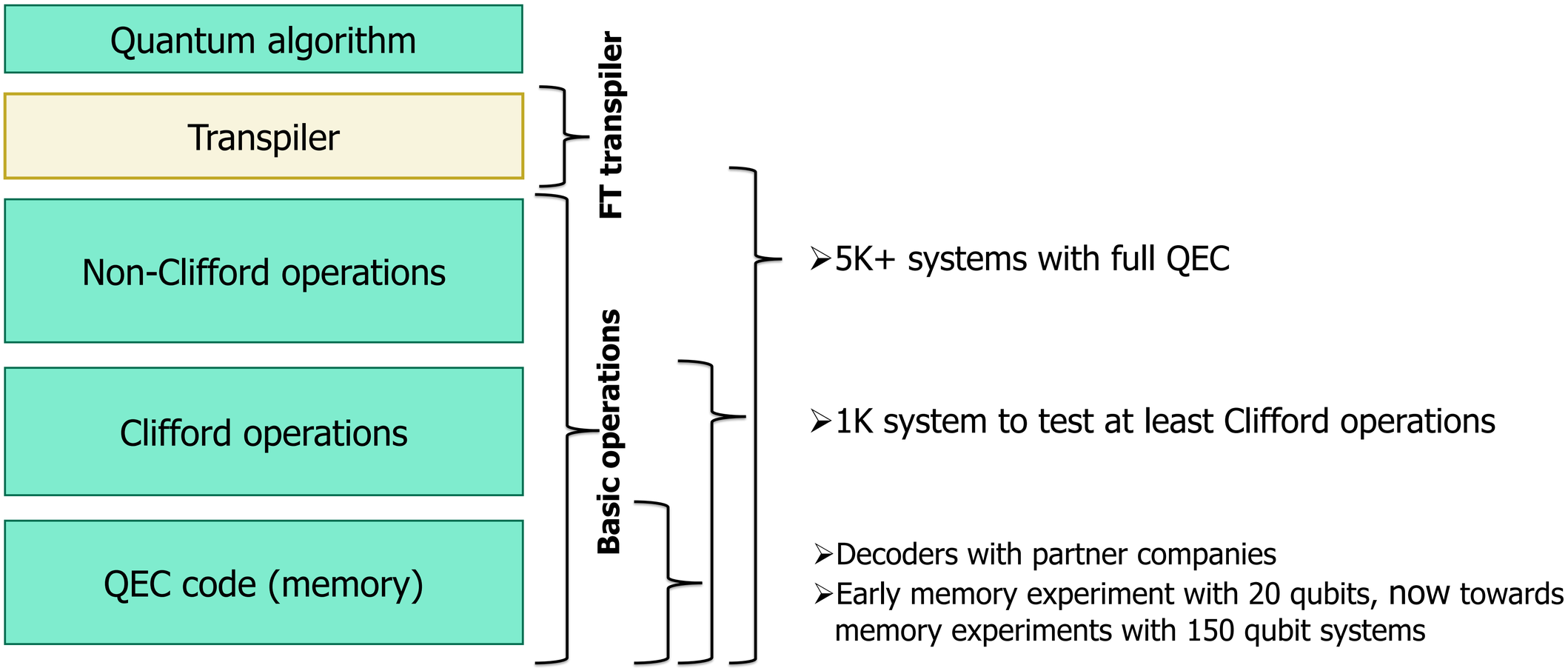
Clifford Operations
- Based on lattice surgery
- First implementations done

Quantum Error Correcting Code
- Well established with minor evolution

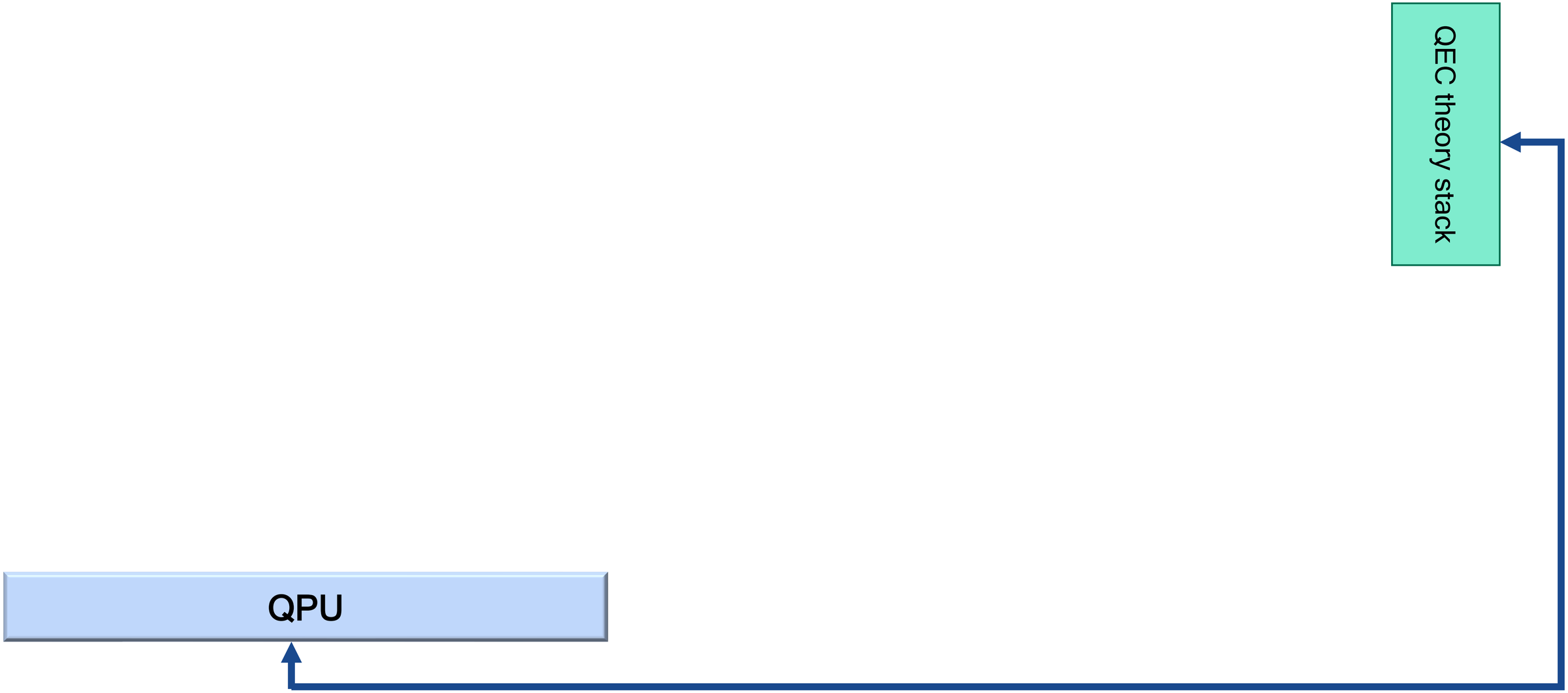
2.Strategy and challenges towards QEC

Theoretical QEC Stack – From Codes to Algorithms

All elements in the QEC stack are already solved for surface codes…. but not for qLDPC codes



2.Strategy and challenges towards QEC: Control concept(*)



(*) innocent version ☺

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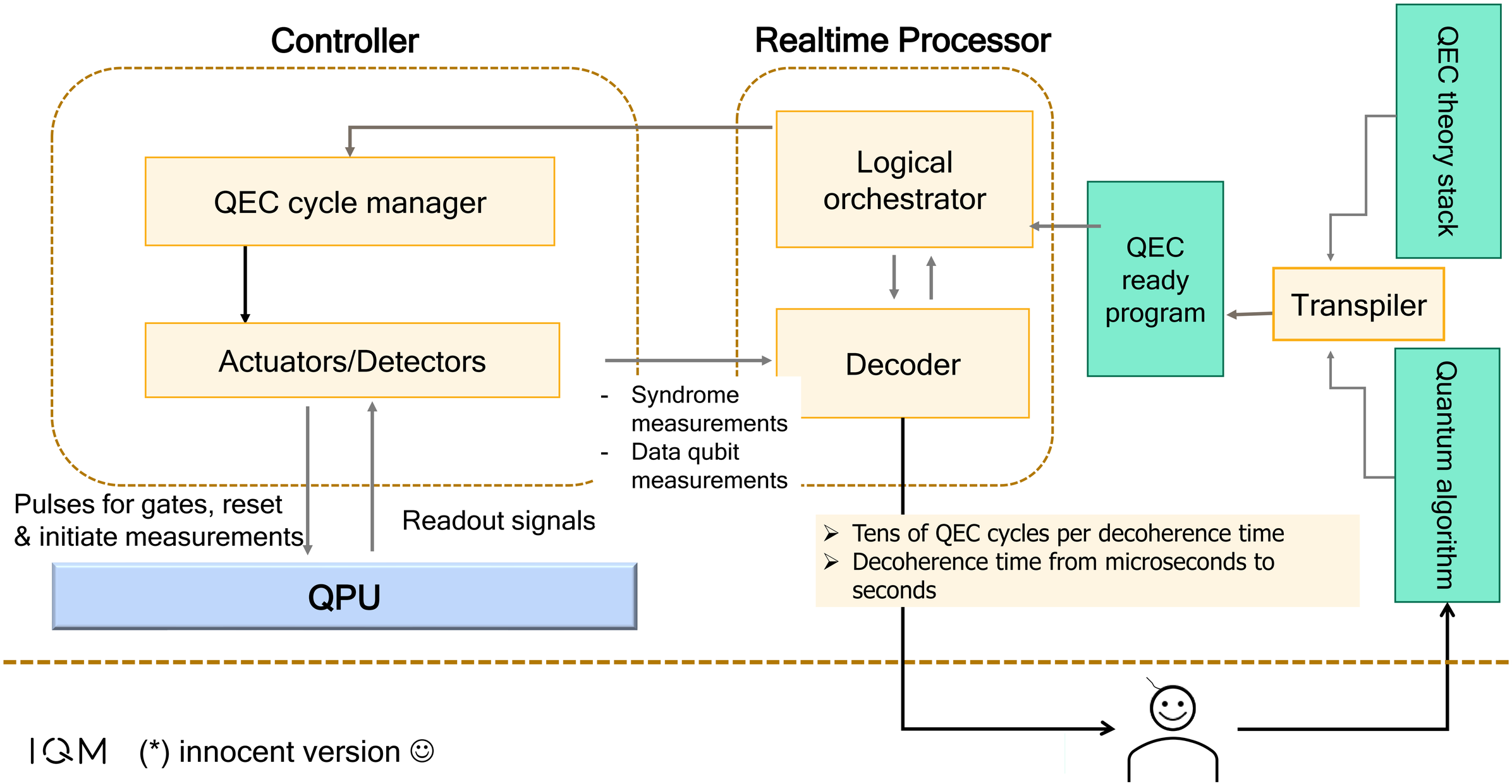
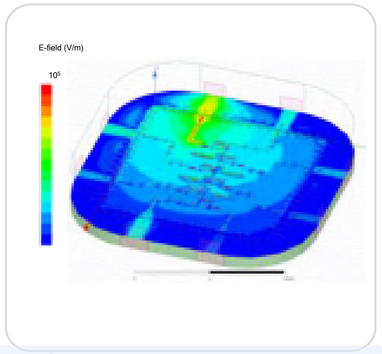


(*) innocent version ☺

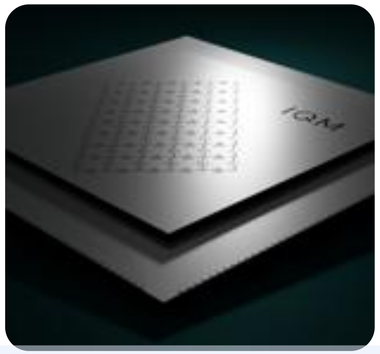
2.Strategy and challenges towards QEC

Global challenges to achieve advantage



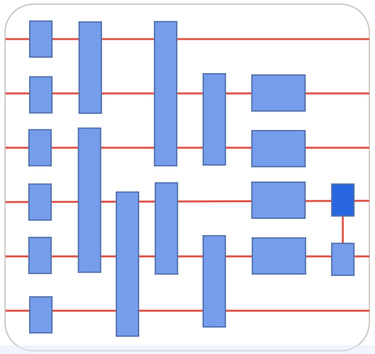
01 QPU design & production

02 Fabrication & packaging



03 Full system integration

04 SW stack HPC, Cloud & QEC



05 Algorithm & Error Correction

➢ **Accelerating innovation cycle**

- Fast speed in testing different solutions in parallel

➢ **Reduce cost-per-Qubit**

- Currently: Tens of thousands USD (incl. electronics, cryogenics, wiring)
- Target: ~$1,000 (requires 10–100× reduction for scalability)
- Reduction Strategies: Large-scale production, efficient QEC, and innovations in material use and cooling.

➢ **Increase system production**

- Current estimations ~5–10 systems per year
- Target: depending on the use scenarios
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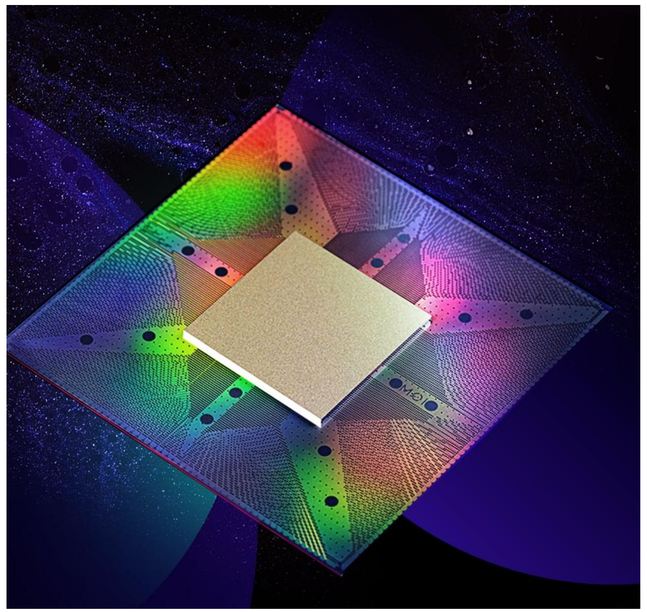
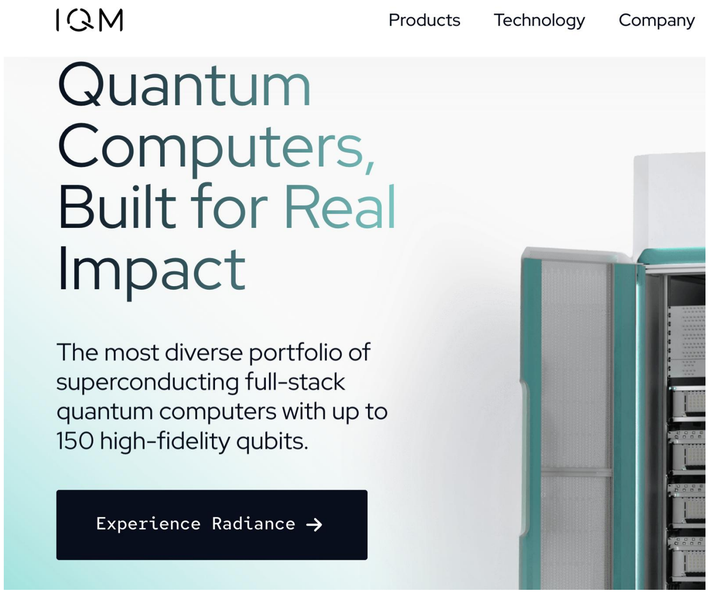
Content

1. From NISQ to Fault Tolerance

2. Strategy and challenges towards QEC



3. The impact of quantum advantage



IQM

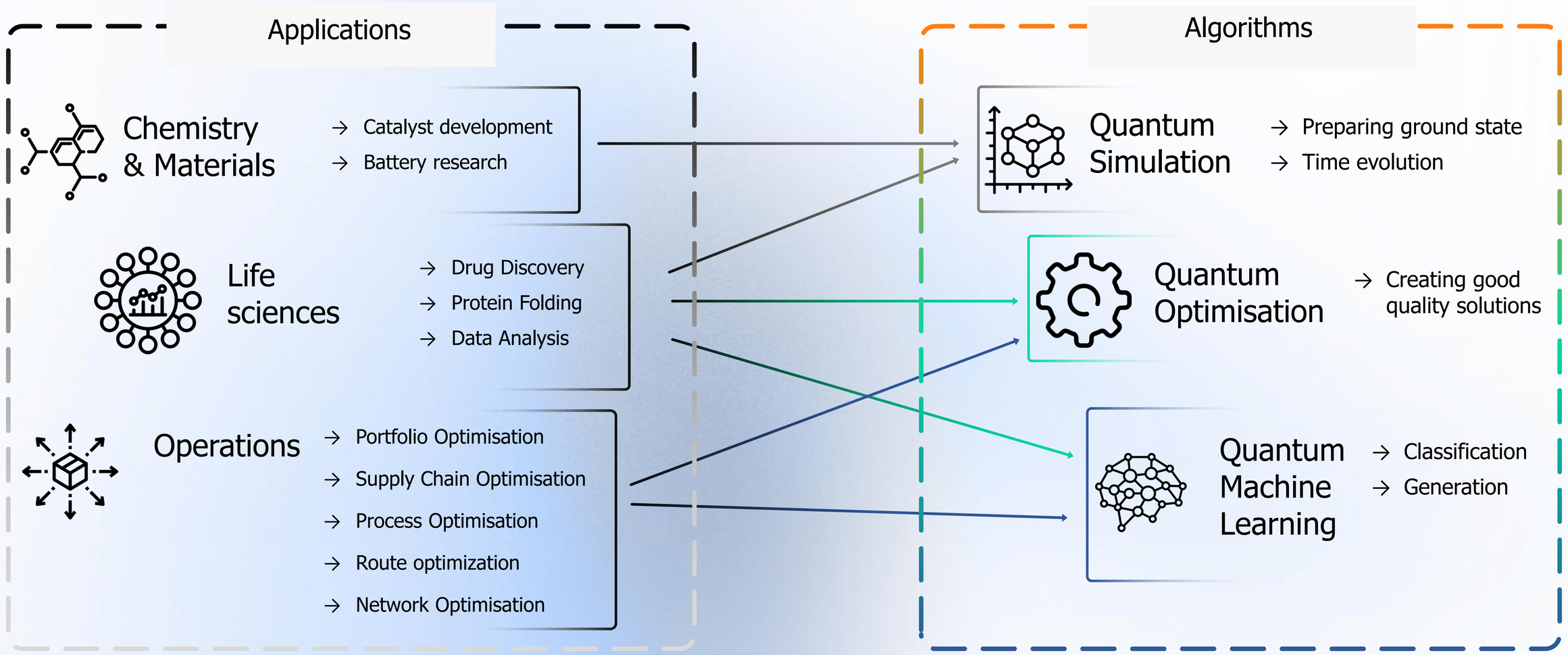
3.The impact of quantum advantage

INTRACTABLE PROBLEMS

There is a class of commercial problems that can never be solved with conventional computers.

THE ENERGY CHALLENGE

There is now way we will be able to grow computing power as needed.



3.The impact of quantum advantage

INTRACTABLE PROBLEMS

There is a class of commercial problems that can never be solved with conventional computers.

Solving problems that reduce carbon footprint

TRANSPORT

THE ENERGY CHALLENGE

There is now way we will be able to grow computing power as needed.

Providing higher/alternative computation with potentially less consumption

DRUG DESIGN

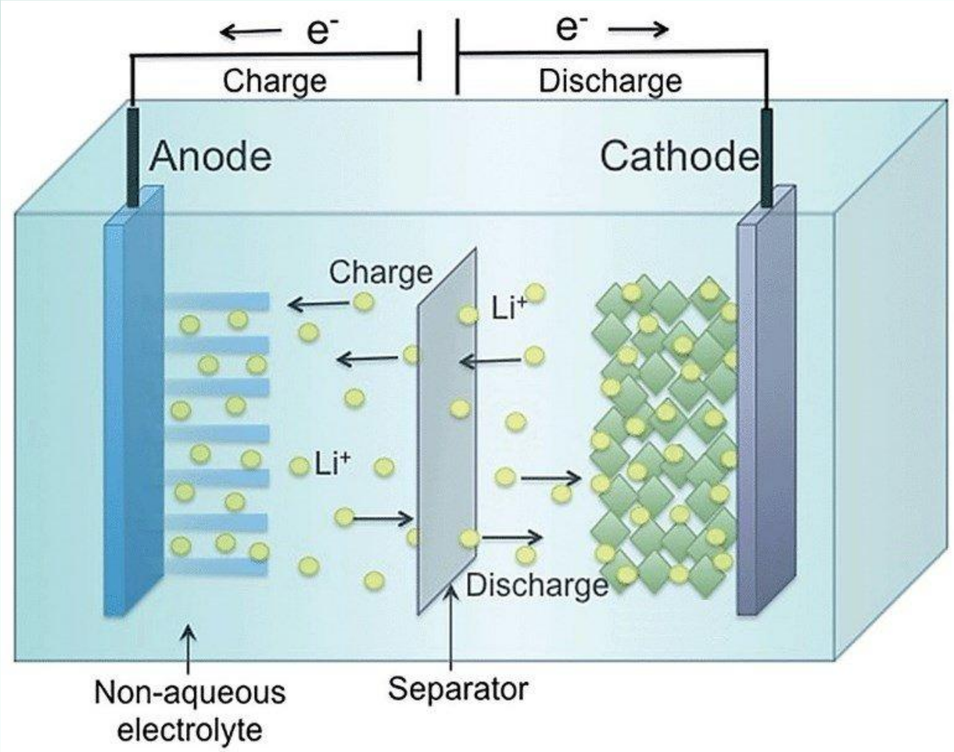
https://www.sciencedirect.com/science/article/pii/S2590098621000282

3. The impact of quantum advantage

Solving problems that reduce carbon footprint: Battery optimization

→ Understanding the chemical reactions of the electrolyte region is key to increase battery performance and longevity.

→ This region contains electrons that are strongly correlated (heavily entangled): very hard to compute classically.



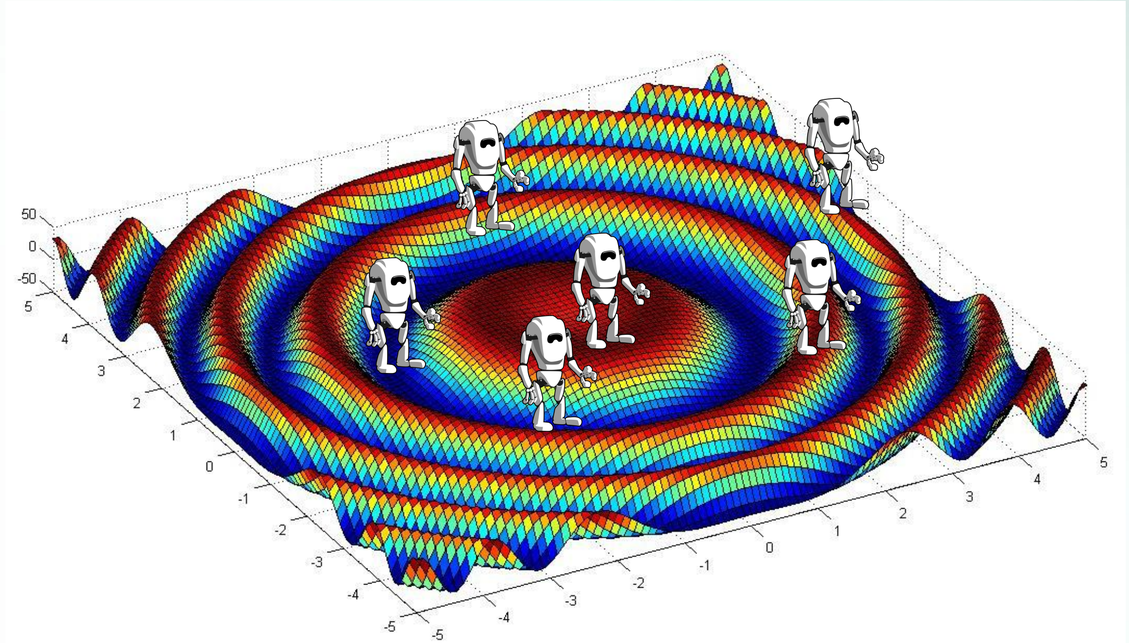
IQM

Source: A Review of Lithium-Ion Battery Fire Suppression - Published in 2020

3.The impact of quantum advantage

Solving problems that reduce carbon footprint: Battery optimization

Hybrid flow: The computational task is divided so that the classical and quantum components are utilized to their respective advantages.

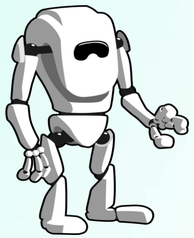


Contextual Subspace Auxiliary-Field Quantum Monte Carlo: Improved bias with reduced quantum resources. Matthew Kiser, Matthias Beuerle, Fedor Simkovic IV arXiv:2408.06160

Quantum computer

- Noisy information of the entire wavefunction
- Gives hints to classical part of the computation to be more efficient.

Classical Walker



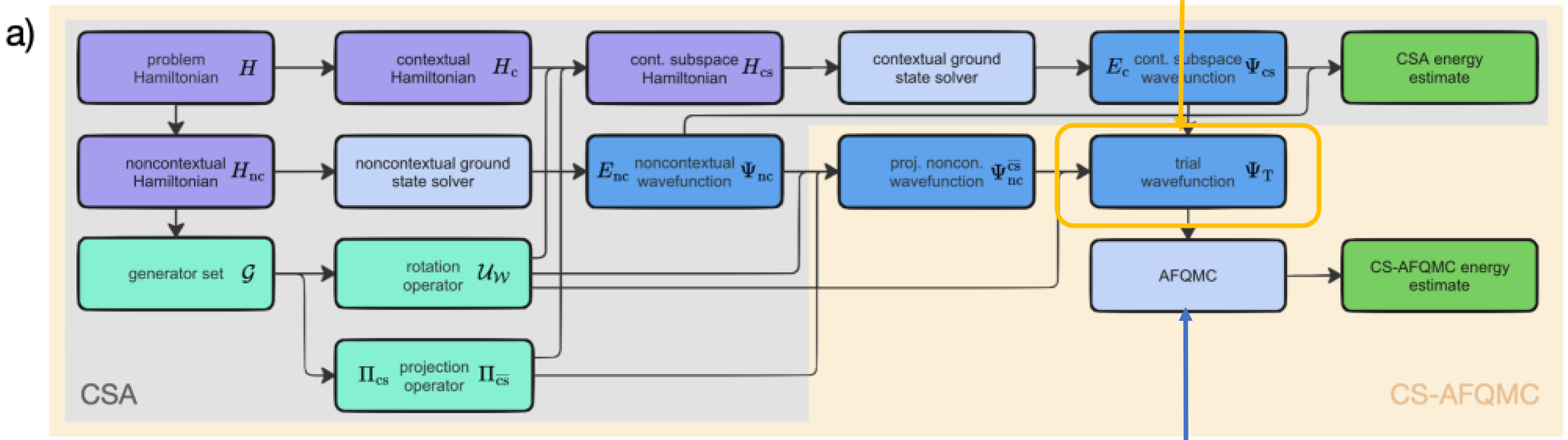
- Gathers high precision info on wavefunction
- Classical walkers avoid crossing borders between blue and red areas (thanks to knowing the wavefunction)

Provides Speedup → **Provides Noise Resilience**

3.The impact of quantum advantage

Solving problems that reduce carbon footprint: Battery optimization

Quantum Computation



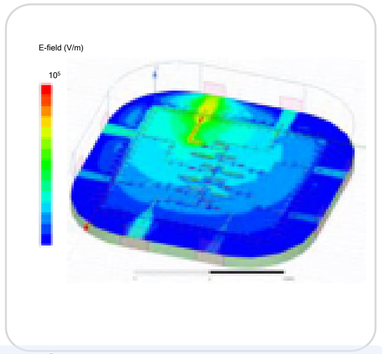
Intensive classical computation

Classical Post-Processing

Kiser, M, Beuerle M, Simkovic, F: "Contextual Subspace Auxiliary-Field Quantum Monte Carlo: Improved bias with reduced quantum resources" Journal of Chemical Theory and Computation Feb 2025. https://arxiv.org/pdf/2408.06160

3.The impact of quantum advantage

How will it depend on the cost and the system production?



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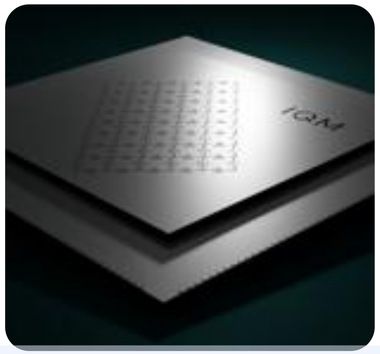

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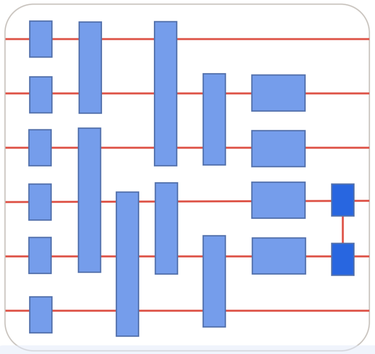
04 SW stack HPC, Cloud & QEC



05 Algorithm & Error Correction

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➢ **Increase system production**

- Current estimations ~5–10 systems per year
- Target: depending on the use scenarios
- Increase strategies: Identifying and solving bottlenecks in coordination with technology (e.g. increasing tile qualification capability in fab)

3.The impact of quantum advantage: future ahead

How will quantum computers impact the society?

➢ **Reduce cost-per-Qubit**

- Currently: Tens of thousands USD (incl. electronics, cryogenics, wiring)
- Target: ~$1,000 (requires 10–100× reduction for scalability)

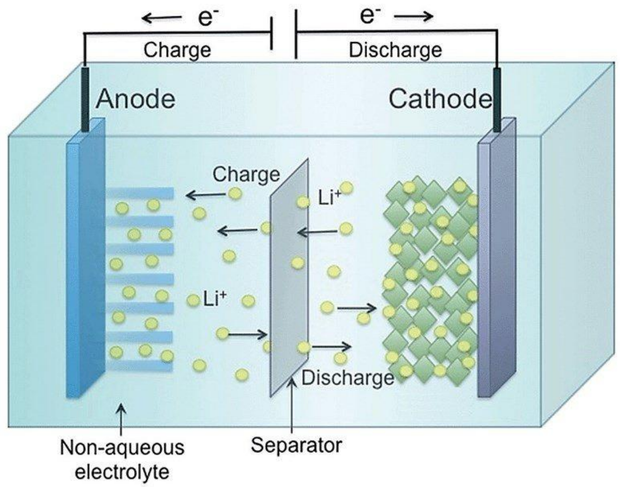
➢ **Increase system production**

- Current estimations few systems per year
- Target: depending on the use scenarios

Few-shot use

Example: Battery material optimization, synthesize fertilizers

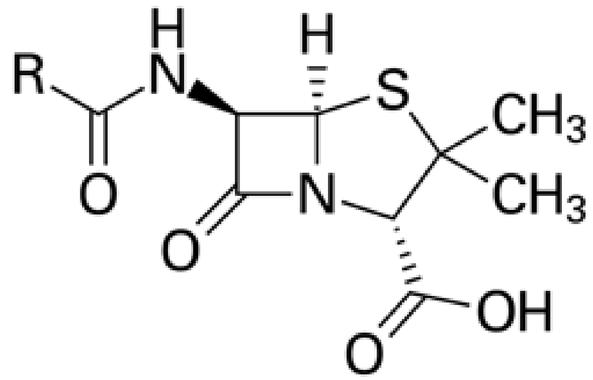
✓ High-value low-frequency quantum jobs
✓ Business case: rare use with high value
✓ Target Production: ~few systems/year



Iterative use

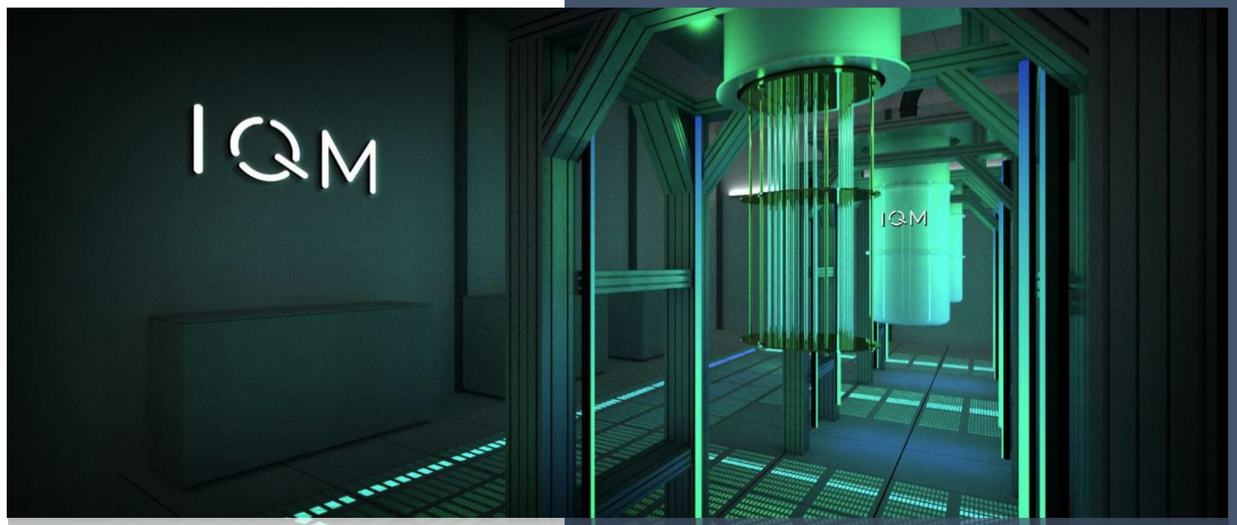
Example: kernel solutions for molecular and material design, portfolio optimization, decision support

✓ High-frequency quantum jobs
✓ Business case: many customers; cost amortized over many jobs.
✓ Target Production: ~10–200 systems/year



Thank you!

- IQM focuses its QEC roadmap in co-designing high-performant qLDPC codes and chip architecture
- Ahead of quantum advantage, we have to overcome three main challenges: accelerate innovation cycle, reduce price per qubit, and increase system production
- We foresee that quantum advantage may have impact in two different kinds of applications: few-shot and iterative use applications



IQM