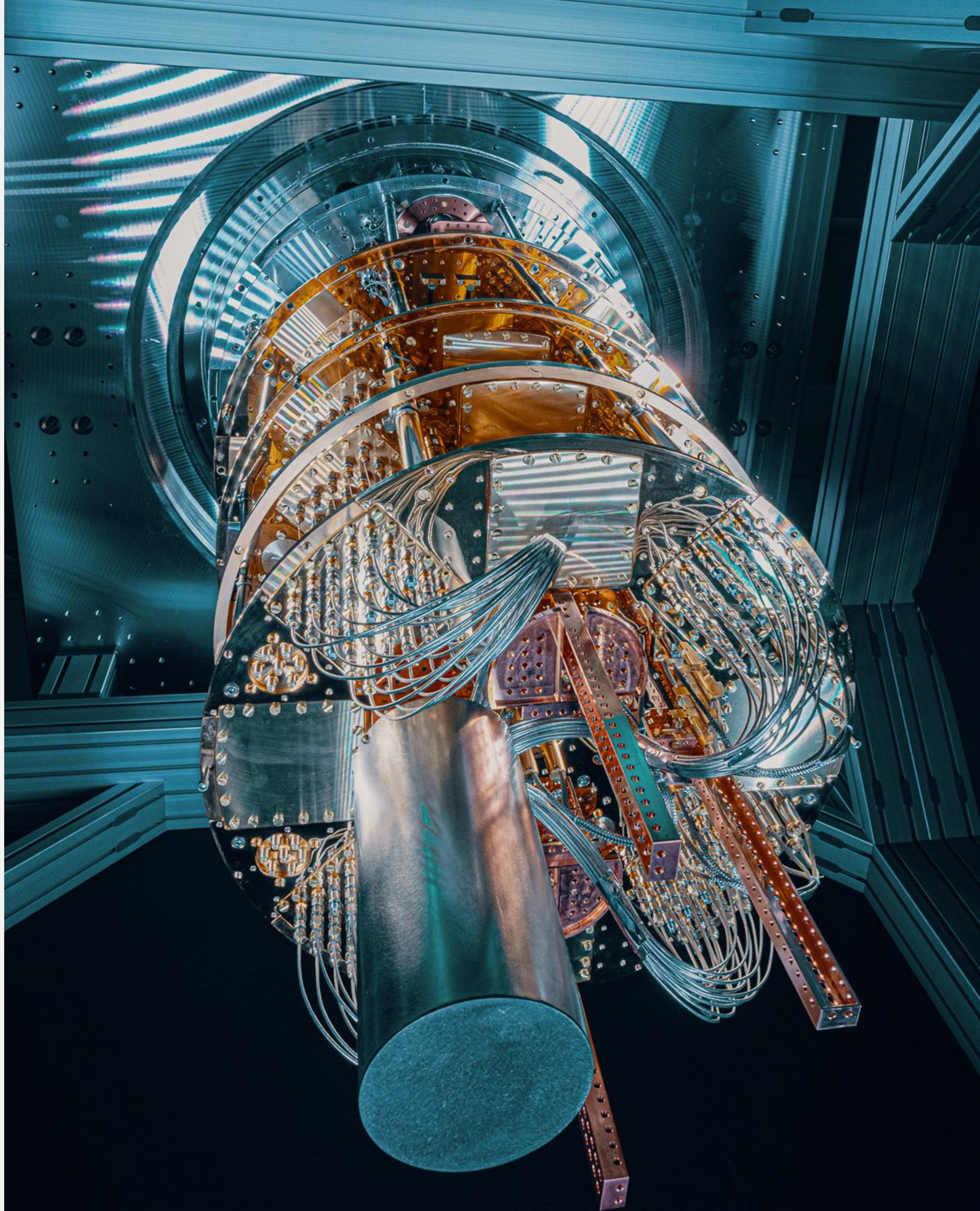
Industrialization and deployment of quantum computing technologies:

Scaling up superconducting qubit quantum computers at IQM

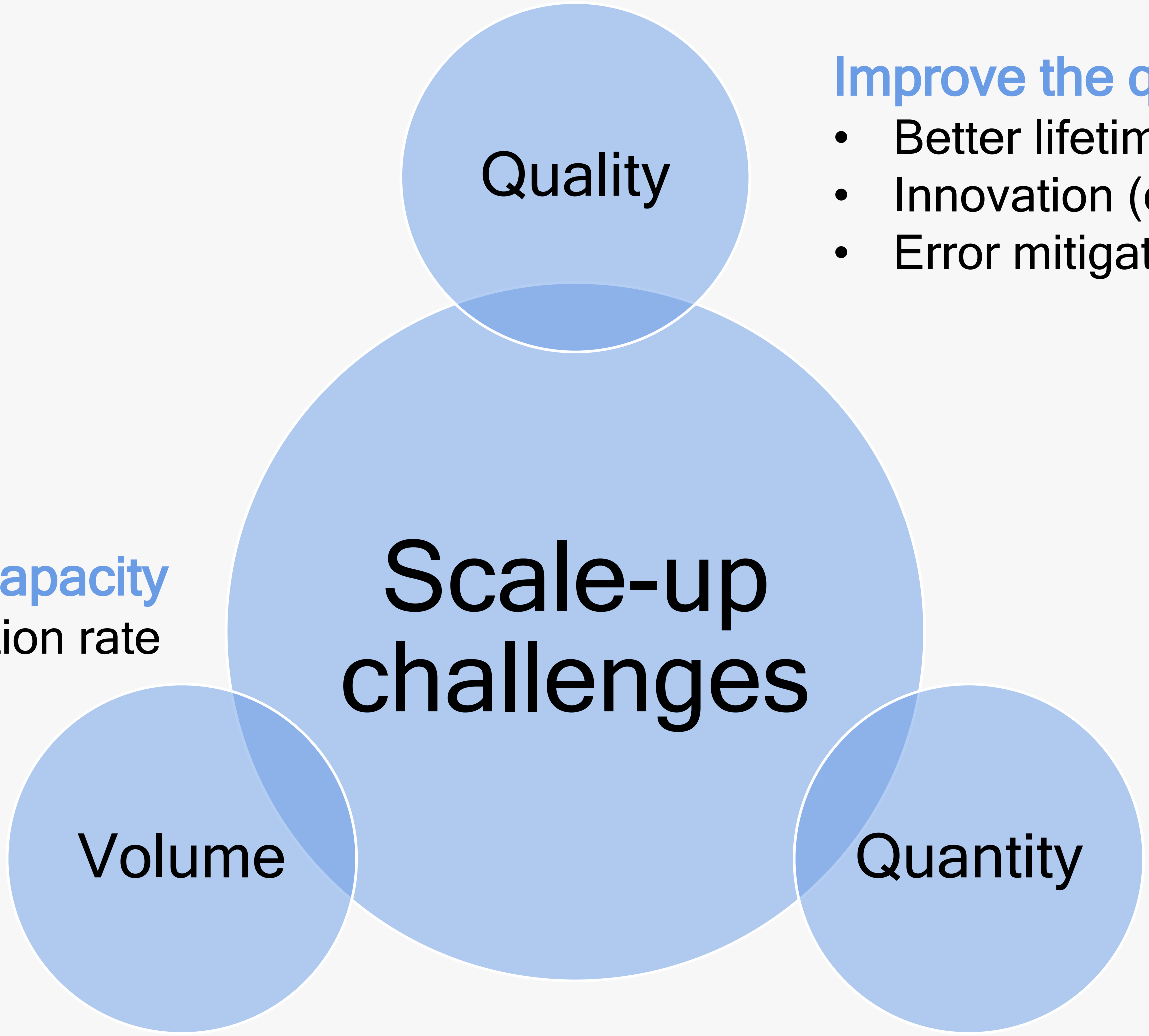
Xavier Geoffret - 05 Sept 2024



IQM

Teratec Quantum Computing Initiative

Superconducting qubit scale-up challenges

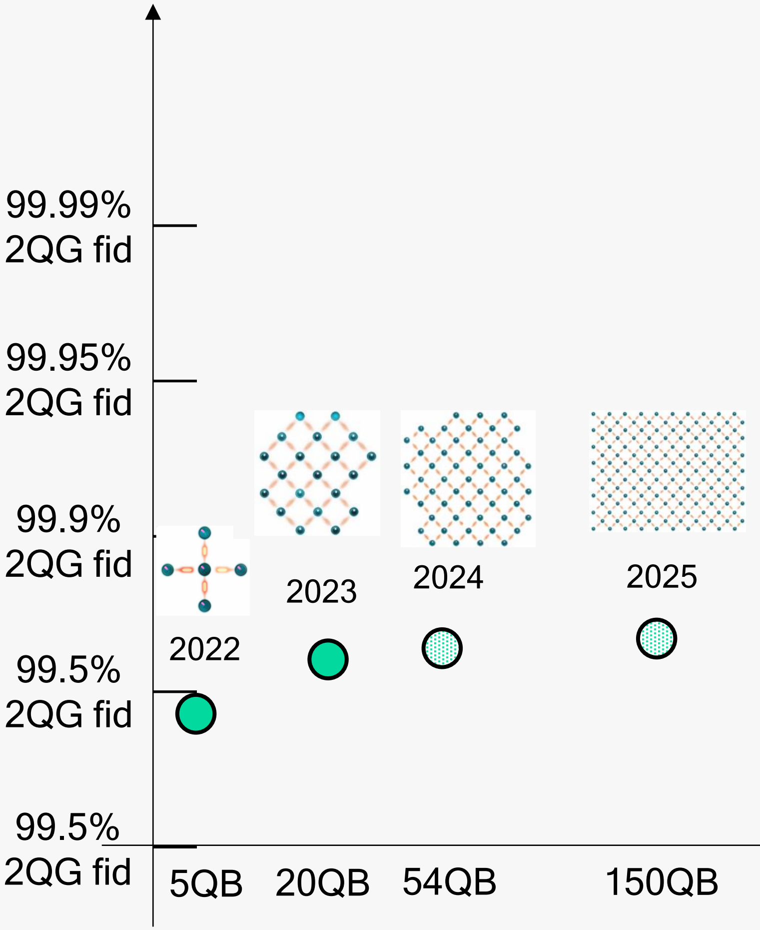


Improve the quality
- Better lifetimes and fidelities
- Innovation (couplers, topology)
- Error mitigation, error correction

Expand the production capacity
- High-throughput production rate
- Reproducibility
- Testing capacities

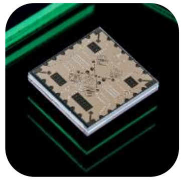
Increase the number of qubits
- Cooling power
- Wiring
- Denser integration

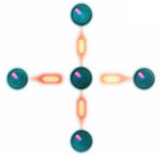
Scaling in the Noise-Intermediate Scale Quantum (NISQ) era



5 qubits

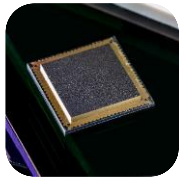
Largest GHZ genuinely entangled state	5
Quantum volume (Classical simulation complexity)	8
Q-score (Max-cut task size)	6
1Q fidelity	median 99.92 % best 99.94 ± 0.003 %
2Q fidelity	median 99.45 % best 99.72 ± 0.5 %

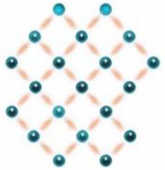




20 qubits

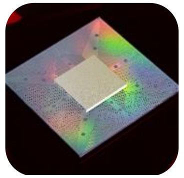
Largest GHZ genuinely entangled state	20
Quantum volume (Classical simulation complexity)	32
CLOPS (Computation rate)	2600
Q-score (Size of combinatorial optimization solved)	11
1Q fidelity	median 99.91 % best 99.944 ± 0.003 %
2Q fidelity	median 99.51 % best 99.8 ± 0.5 %





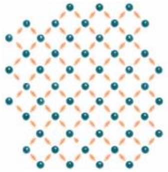
54 qubits

90 coupler qubits
144 qubits in total



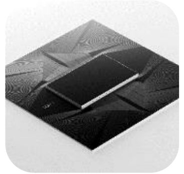
Expected in Q4-2024 (*)

- Prototype testing ongoing
- Ongoing first delivery (VTT), passed preliminary test report



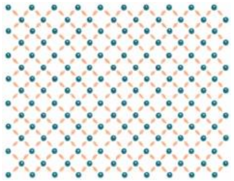
150 qubits

266 coupler qubits
416 qubits in total



Expected in 2025 (*)

- System and chip ready for cooldown



IQM

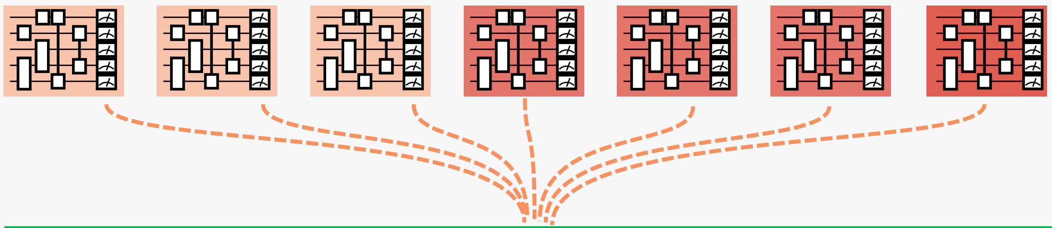
QC: Quantum Computer, QPU: Quantum Processing Unit,
(*) Subject to change with average system lead times of 1 year

Path to fault tolerance

Challenge: Quantum information is very fragile!

- Qubit lifetime is short and limited
- Quantum gates are faulty

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

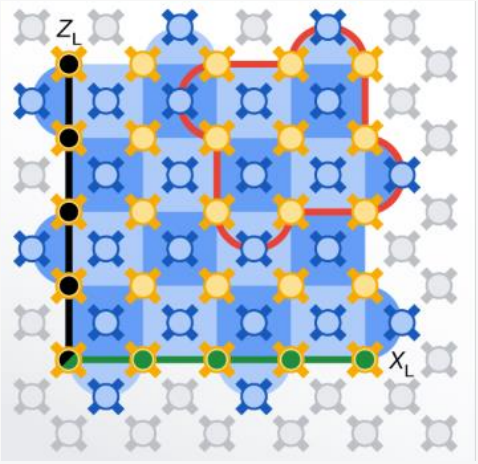


Post processing → Better estimator for $\langle O \rangle$

- Applicable now

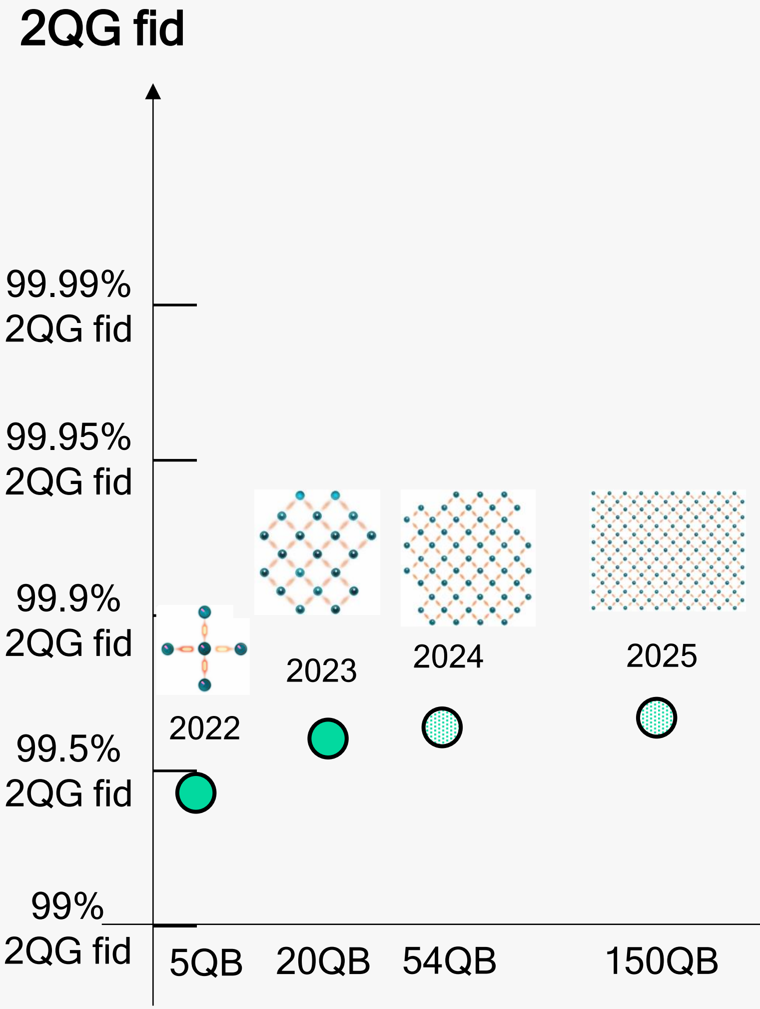
QEC: Using long-range correlations of entangled quantum many-body states.

- Reduces *error rate* at logical level
- Needs many physical qubits (>10K)
- At large scale applicable in the future



Nature **614**, 676 (2023)

Utility in the NISQ era: how many qubits can be used?



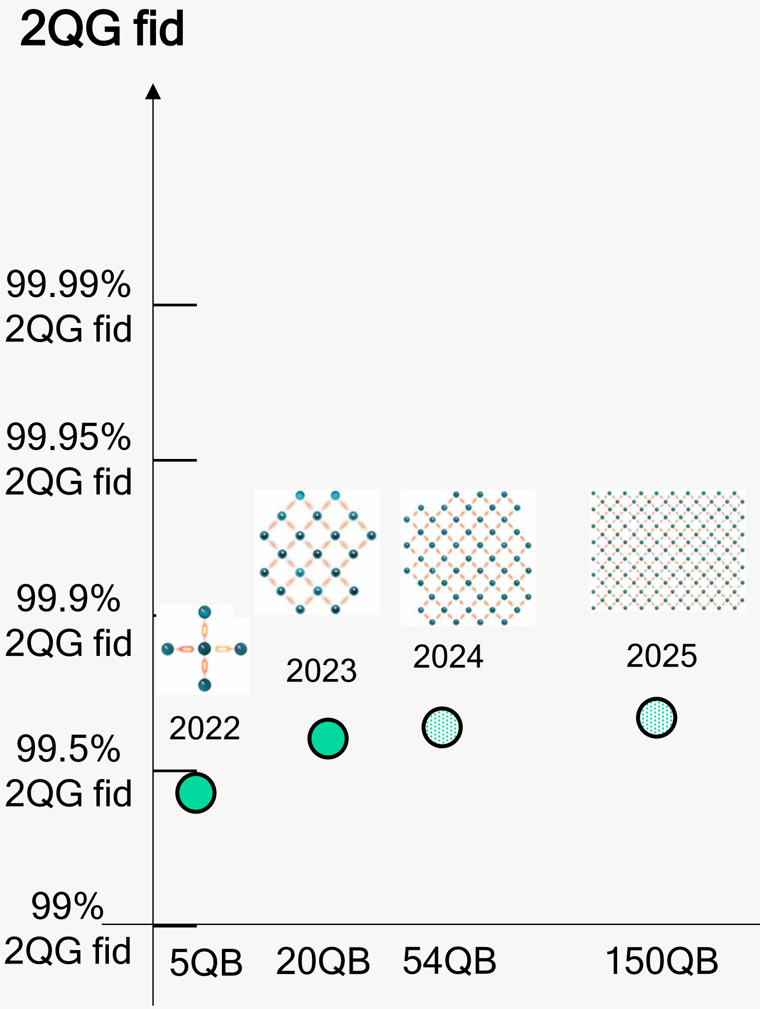
✓ Number of utility qubits obtained with error mitigation (EM)*:

EM technique	**N** (2 nines)	**N** (3 nines)	**N** (4 nines)
Probabilistic error cancellation, virtual distillation	19	60	190
ZNE, Clifford data regression	27	85	270
Ideal post selection	38	120	380

IQM will achieve 100x100 challenge between 3 and 4 nines

Calculations done by assuming NxN circuits and error mitigation overhead that takes an experiment from minutes to max one day

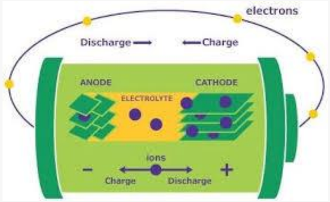
Utility in the NISQ era: how to bring earlier the applications?

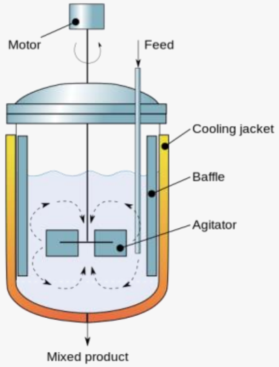


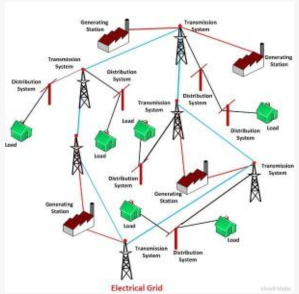
Quantum applications

Quantum simulation	**Battery optimization (automotive company)**, molecular simulation.
Quantum ML	**Time series prediction of polymer production (Siemens), optimal control of polymer reactor (Siemens)**, fraud detection (Insurance company), novel image generation for self-driving (Airbus, BMW)
Optimization	**Power plant maintenance scheduling (EDF)**, product portfolio optimization (DATEV), waste disposal optimization (Infineon), supply chain optimization (Airbus, BMW)

Physical qubits







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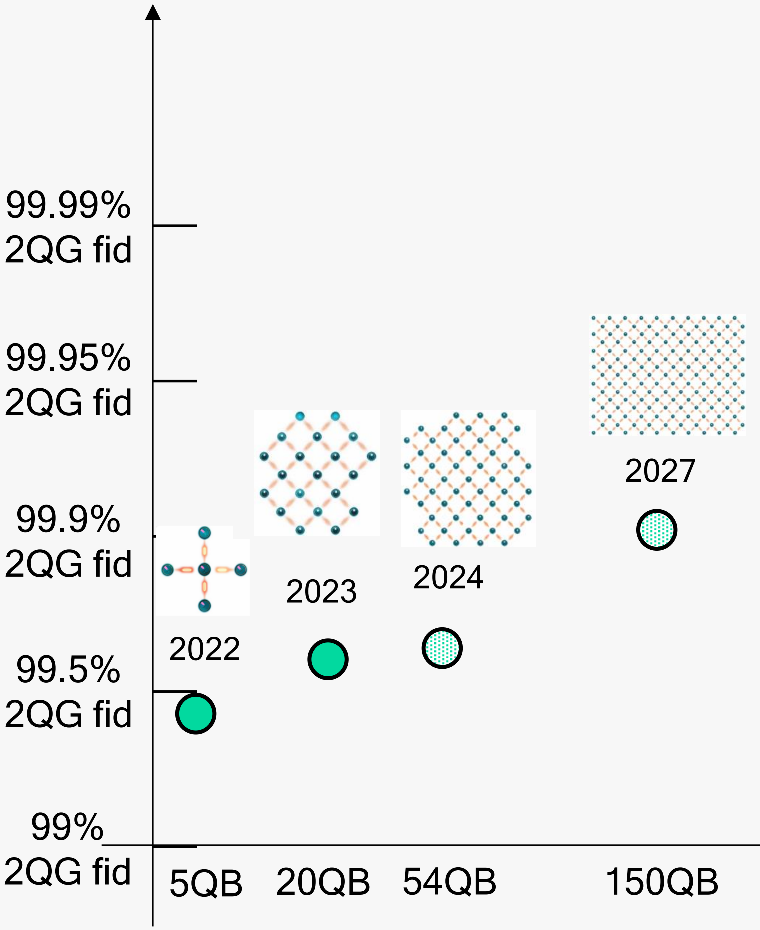
Utility in the NISQ era: how to bring earlier the applications?



Physical qubits

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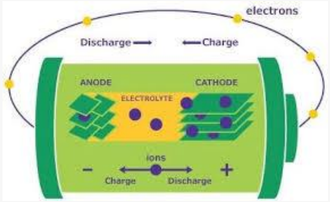
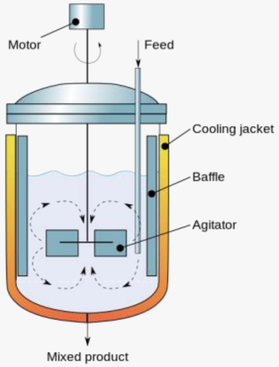
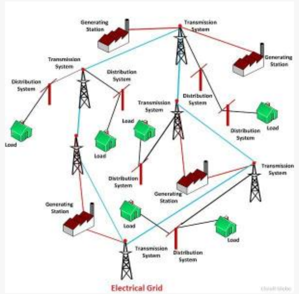
- ✓ Error mitigation aiming at R&D advantage
- ✓ Hybrid approaches to increase system size and early error correction (*) to increase precision towards industry advantage







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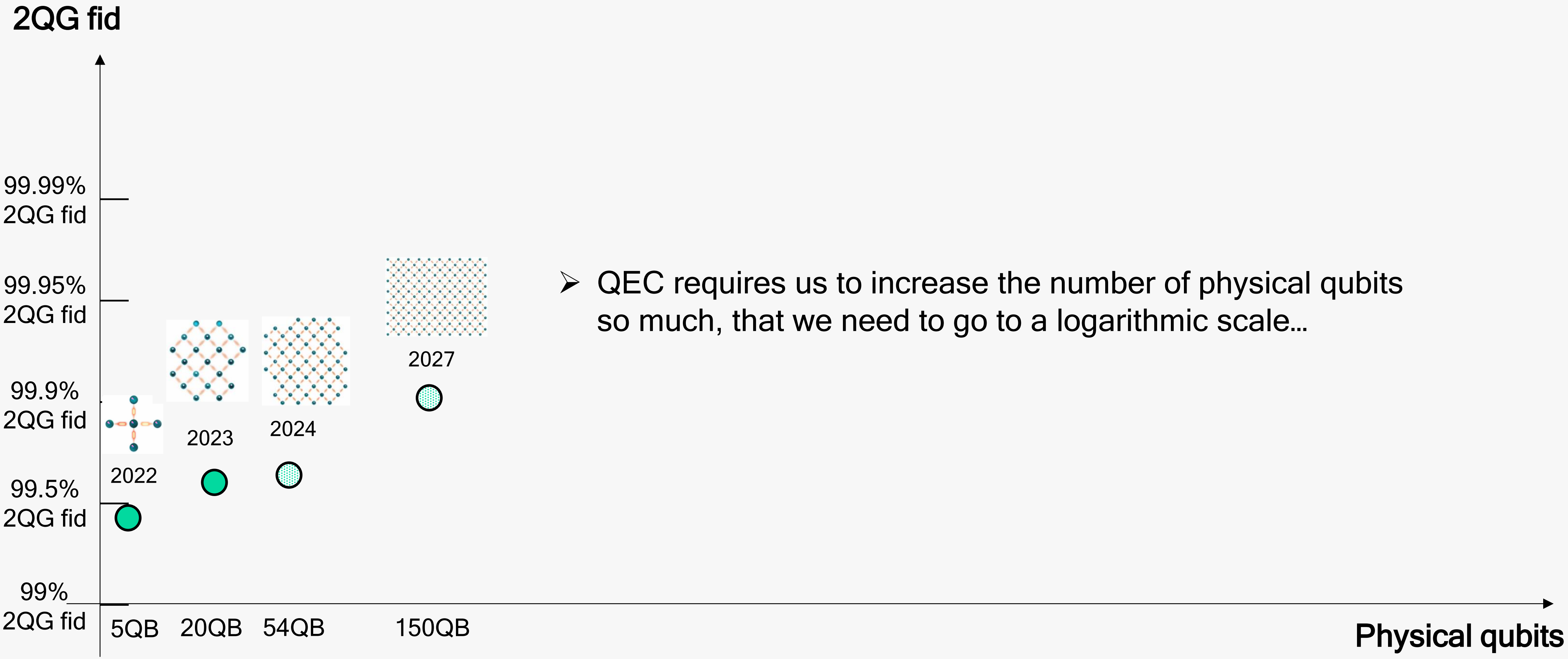
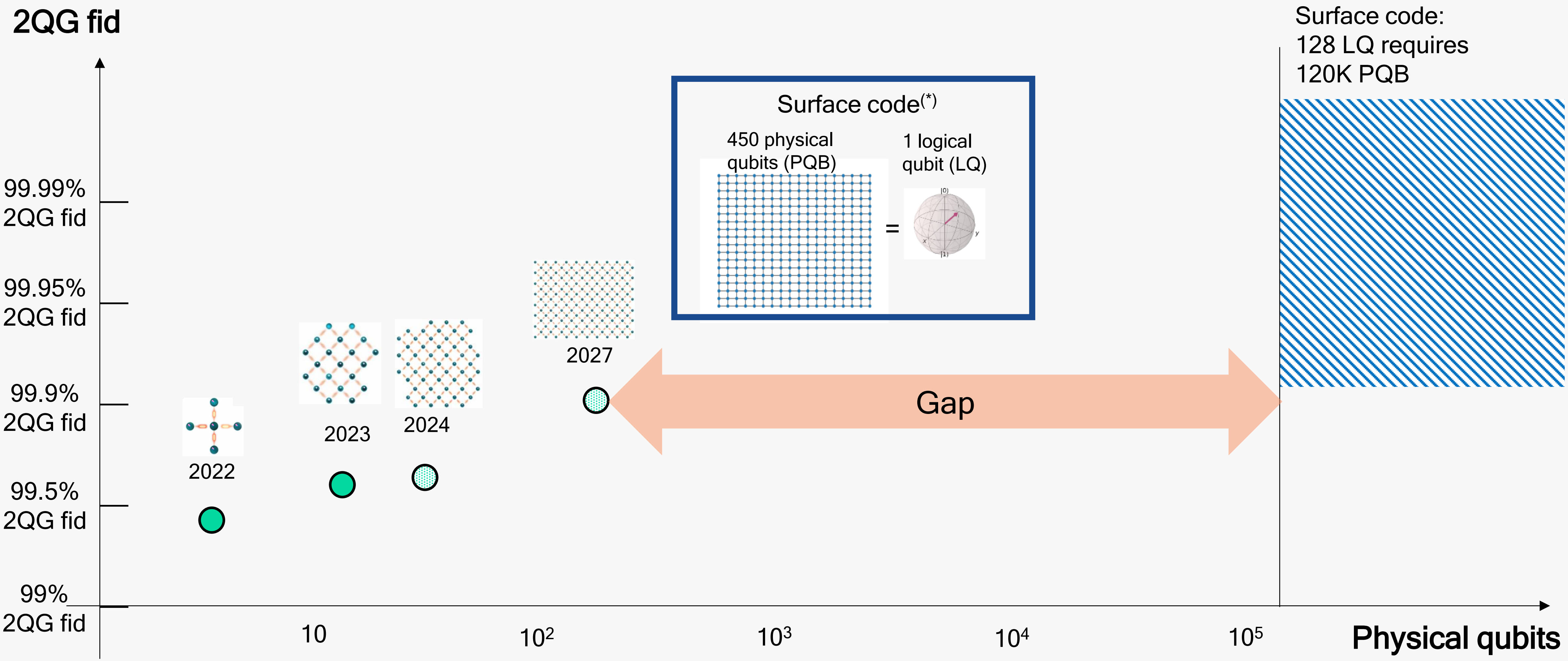
(*) Low-weight high-distance error correcting fermionic encodings arXiv:2402.15386

Path to fault tolerance



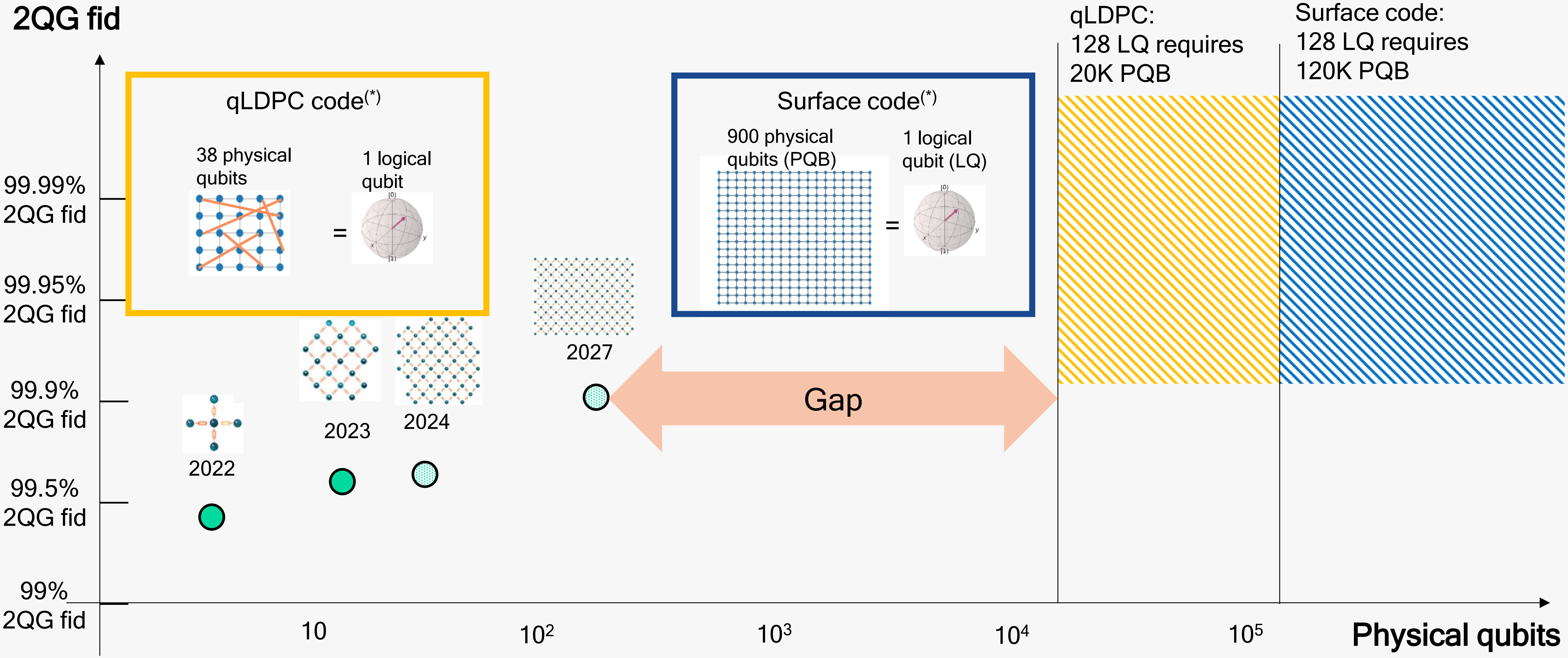
➢ QEC requires us to increase the number of physical qubits so much, that we need to go to a logarithmic scale…

Path to fault tolerance



(*) Memory logical qubits (LQ) with 7-9 nines of logical fidelity and 99.8-99.95% physical TQG fidelity.

Fast track to fault tolerance



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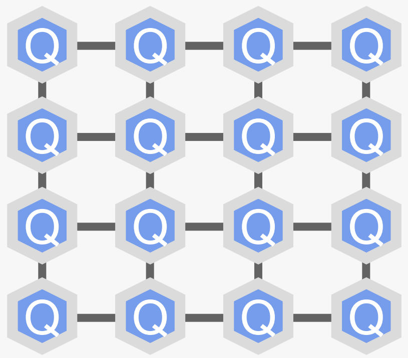
IQM

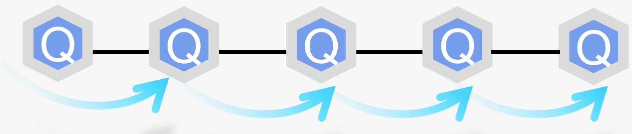
Fast track to fault tolerance

✓ We extend the theory on qLDPC: We have built a scalable method to create qLDPC codes that are topologically scalable (arXiv:2401.07583): We can aim to have a basic building block!

✓ We develop an optimal HW to implement qLDPC with low overhead



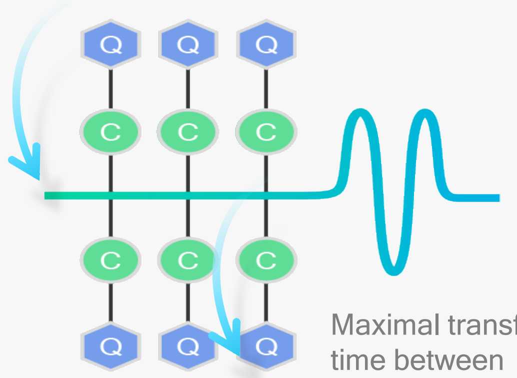
- Algorithm depth to ensure completion below the coherence (T1) time
- Reduced overhead in additional two qubit gates (SWAP) to connect distant qubits



If longer than T1, computation fails!

gate time 2 x gate time 3 x gate time 4 x gate time

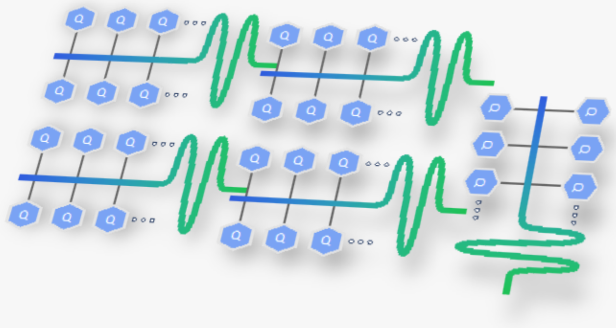
Cloud system IQM Deneb



Maximal transfer time between qubits reduced to 2 x gate time

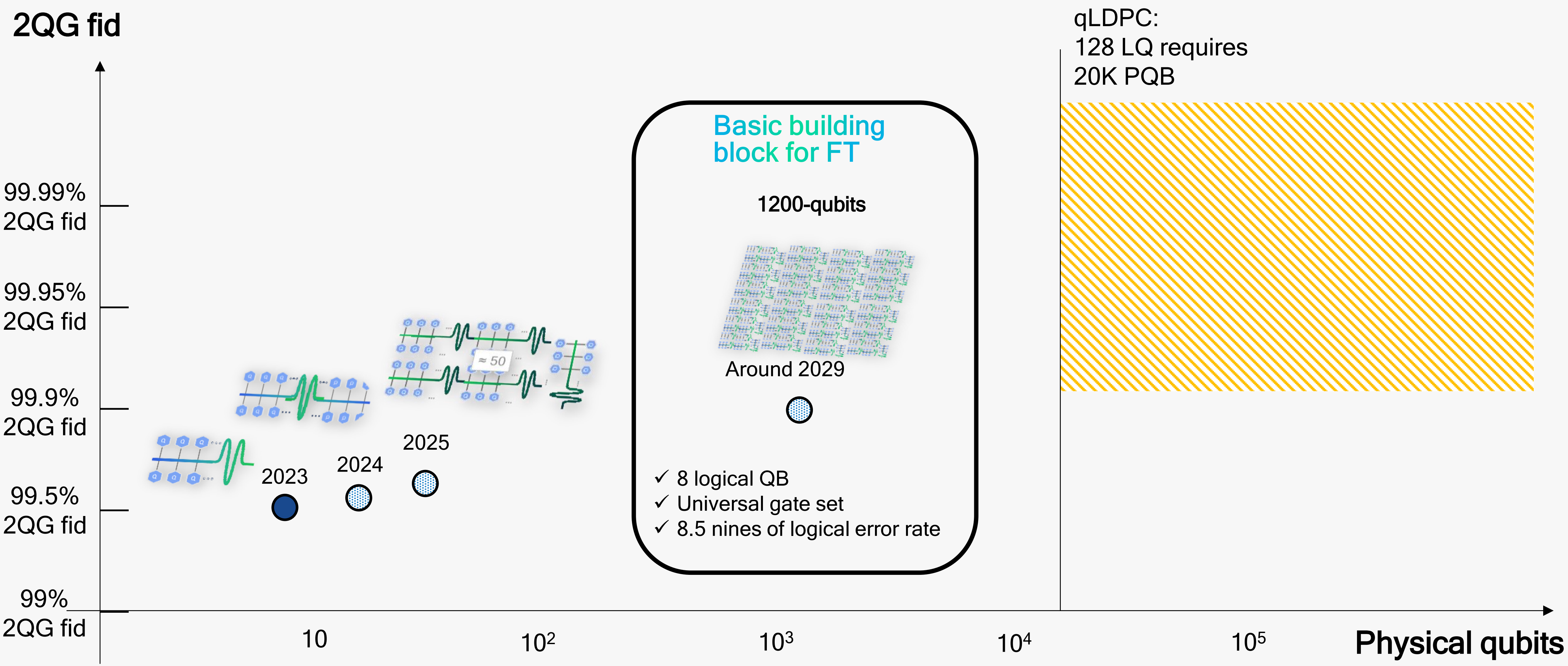
✓ Minimizes the number of SWAP gates to connect qubits

Scaled up architecture native to some qLDPC families



➢ Stay tuned!!

We target to build a basic building block to scale up



IQM

IQM Tech Roadmap

2022 | 2024 | 2026 | 2028 | 2030 | 2032

IQM RESEARCH — 5 Qbits

IQM FOUNDATION — 20-150 Qbits

IQM ADVANTAGE — 1k+ Qbits

IQM DISRUPTION — 1M+ Qbits

Full-stack Technical Showcase
(Q-Hardware, Q-OS)

Utility Algorithms (Error Mitigated)

Quantum Memory

NISQ Research Advantage

NISQ Commercial Advantage

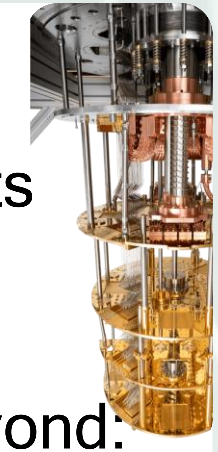
Logical Qubit

Error-correction at QPU

General-purpose quantum computer

Superconducting qubit scale-up challenges

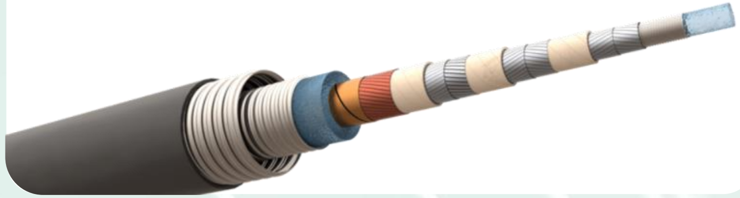
Increase cooling power



- Current cryostats are ± OK to ~1000 qubits
- Several approaches beyond:
  → Larger models
  → Several cryostats tightly connected (with a single vacuum chamber)
  → Several cryostats loosely connected (with long-range couplers)

Reduce wiring

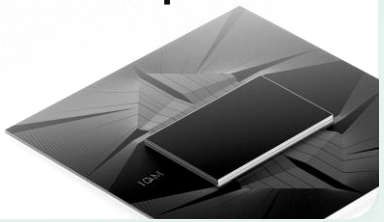
- To reduce the heat
- Possible approaches:
  → Same wires to control different qubits (less heat load but less parallel operations)
  → Cryo-electronics (futuristic)



Increase QPU density

- 3D integration:

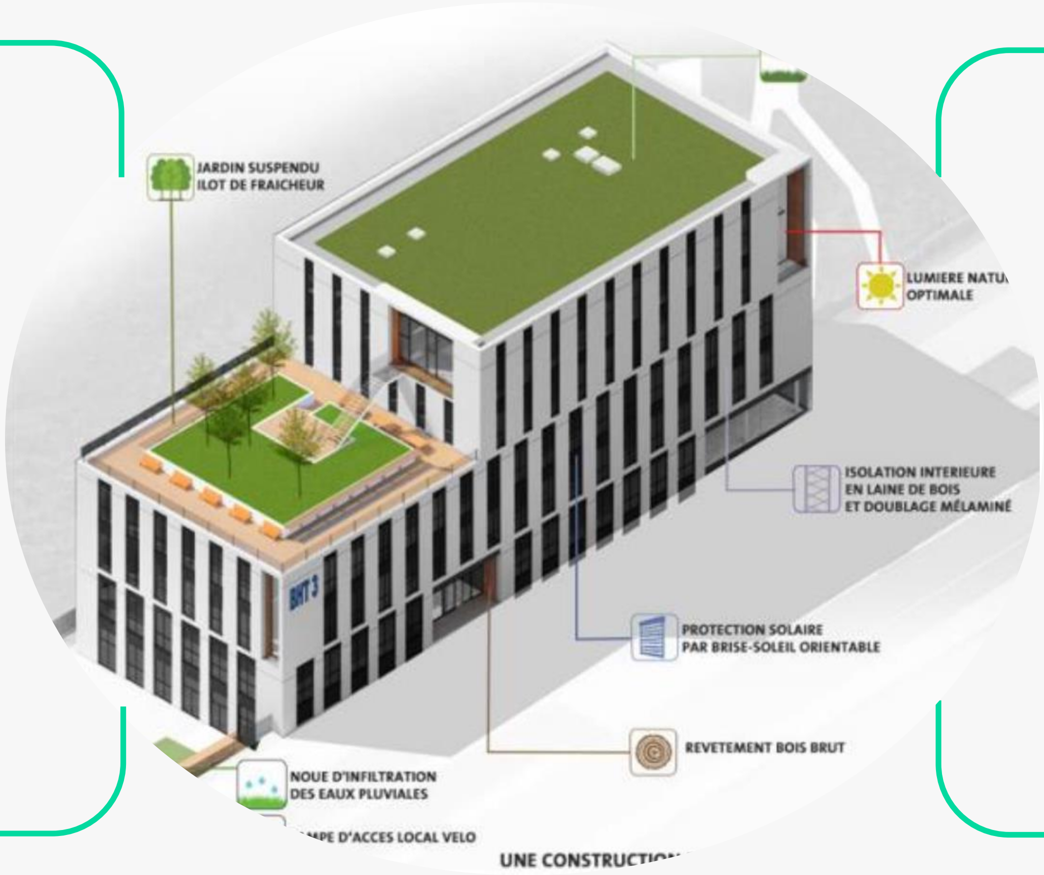
1. Two layers for qubits and control
2. Enhance the layer interconnections with superconducting Through-silicon vias (TSVs)
3. Increase the number of layers with qubits



First-of-a-kind Quantum Factory in Europe

Tech roadmap

Sovereignty



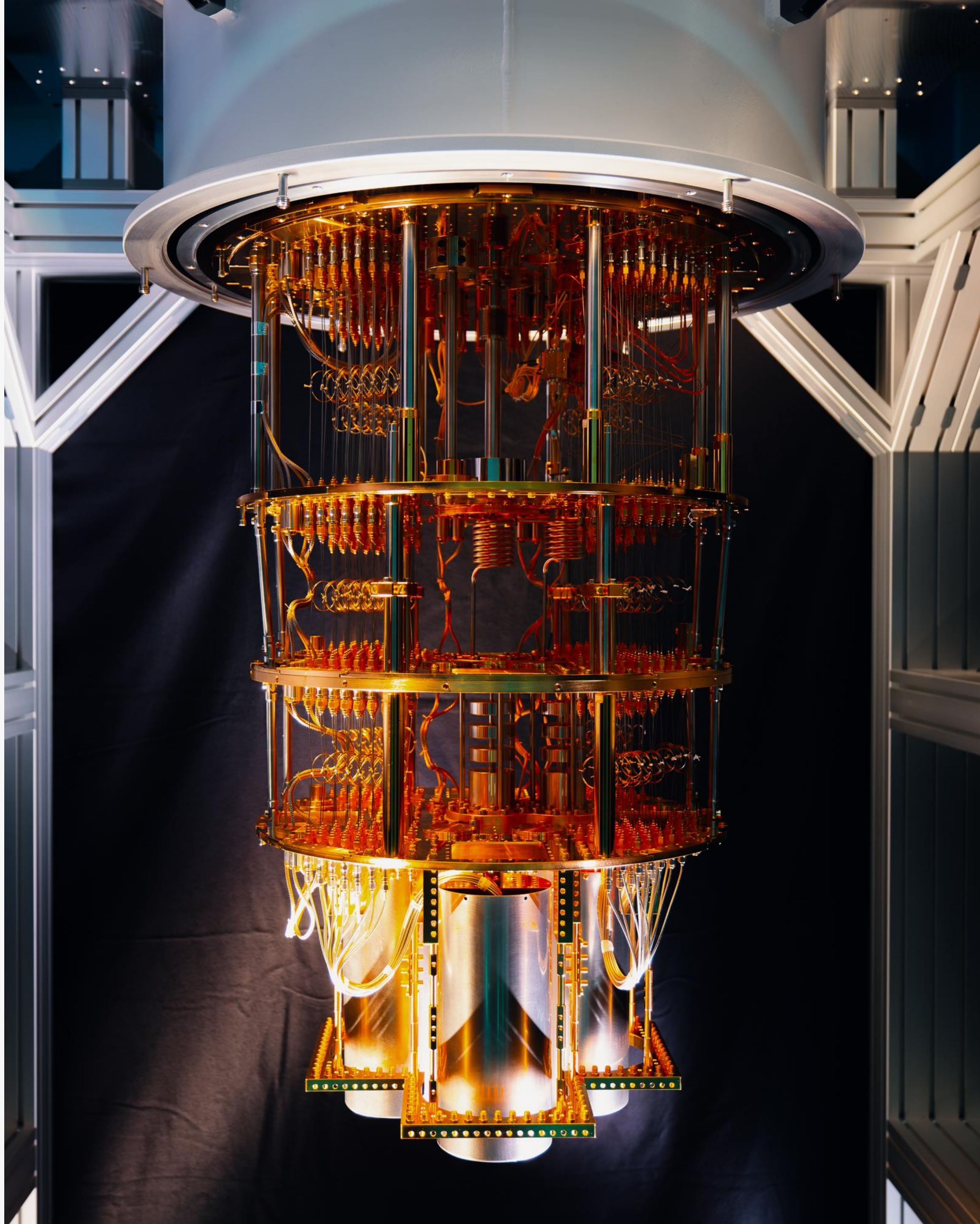
Volume scaleup

Industrialization

Building design (Reprinted from Minatec Entreprises)

Key take-aways

- Scaling up superconducting qubit quantum computers involves overcoming numerous technical and engineering challenges.
- Collaboration between quantum physicists, engineers, and computer scientists is essential to address these issues.
- In that context, the future Quantum Factory in Grenoble will play a key role in implementing capabilities to produce high-volume, high-quality, large-scale superconducting processor.



Thanks!

Xavier Geoffret
Technical Sales Manager
xavier.geoffret@meetiqm.com

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