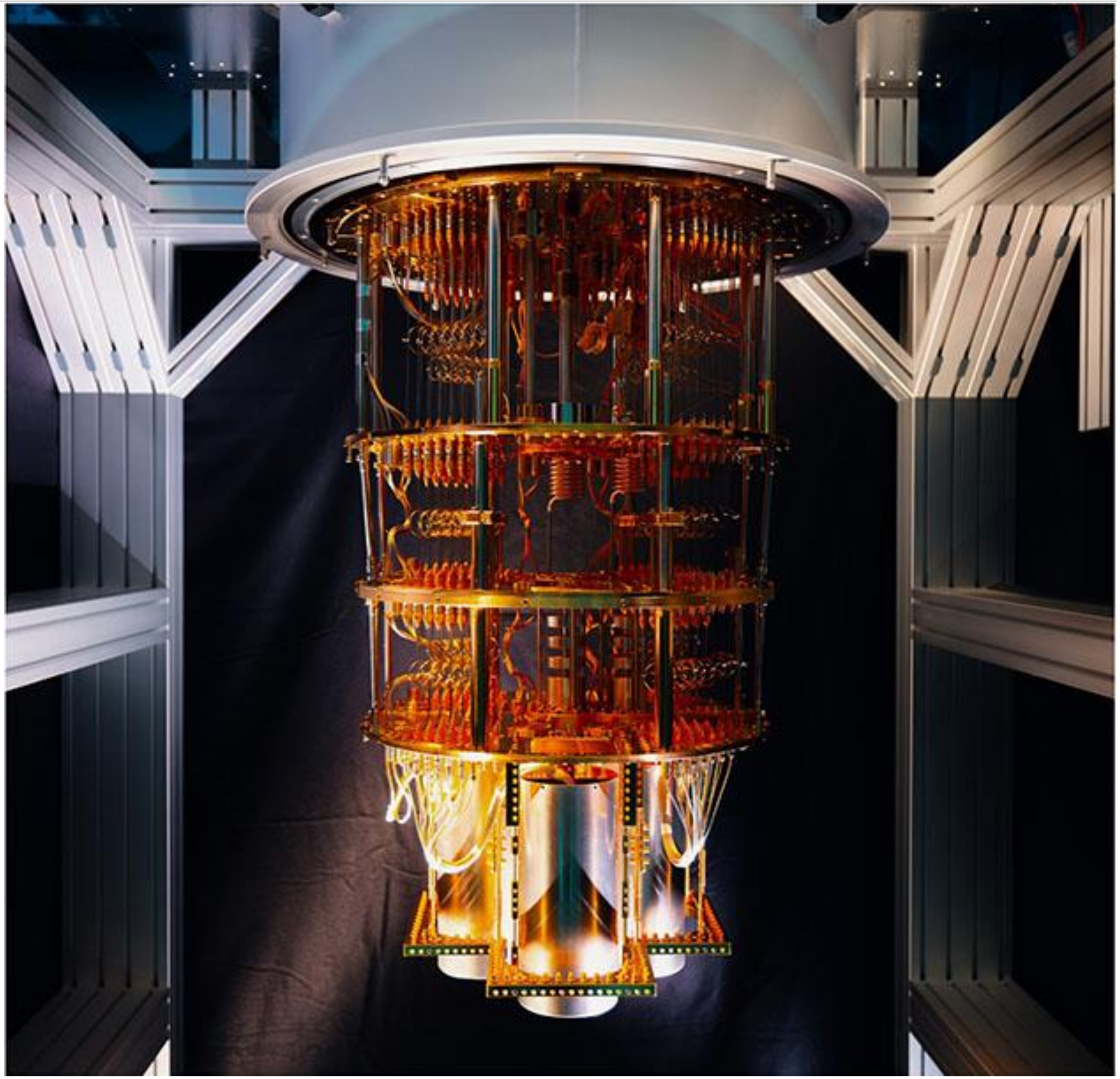
WE BUILD QUANTUM COMPUTERS

Quantum Computing Platforms



Jiri Guth Jarkovsky, Jay Nath, Markus Weber

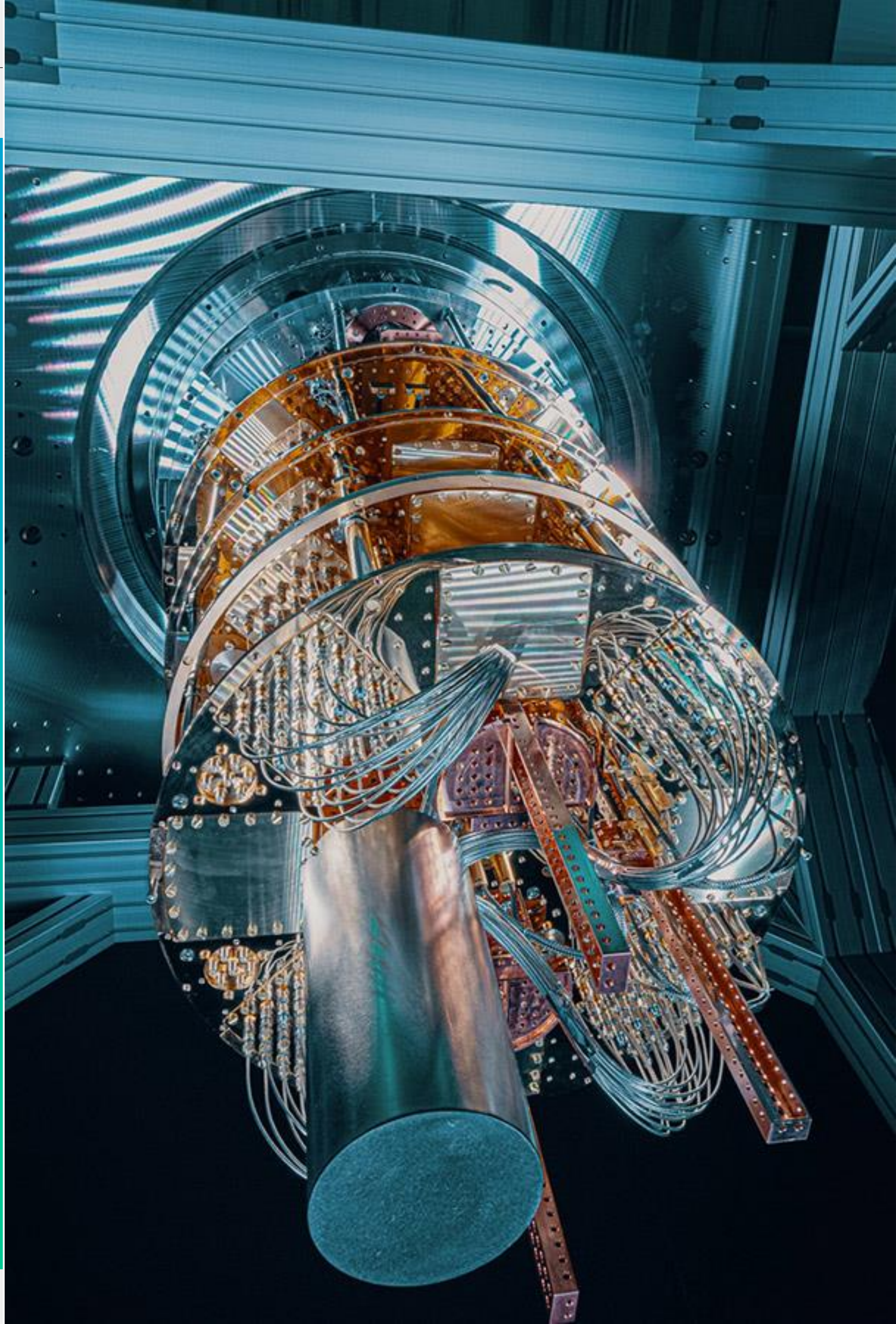
Martin Leib, Frank Deppe, Bjorn Potter

IQM Team

www.meetiqm.com

Outline

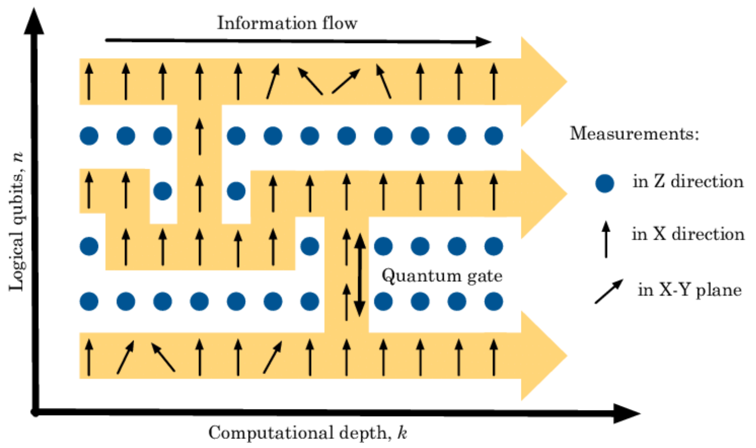
- Quantum Computer
- QC Platforms
  - Superconducting Qubits
    - Superconducting Quantum Annealers
  - Trapped Ions
  - Cold Atoms
  - Photonics
    - Photonic Boson Sampling
  - Spin Qubits
  - Topological Qubits
- QC Metrics
  - Quantum Technology Readiness Level
- Bonus
  - Some QC Roadmaps



Quantum Computer

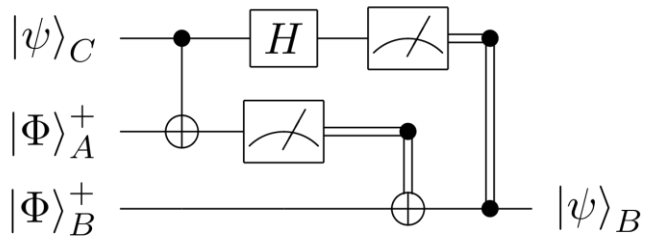
DiVincenzo Criteria for **quantum computation**:

1. A scalable physical system with well-characterized **qubit**
2. The ability to **initialize** the state of the qubits to a simple fiducial state
3. Long relevant decoherence times (**stability**)
4. A "universal" set of quantum **gates**
5. A qubit-specific **measurement** capability

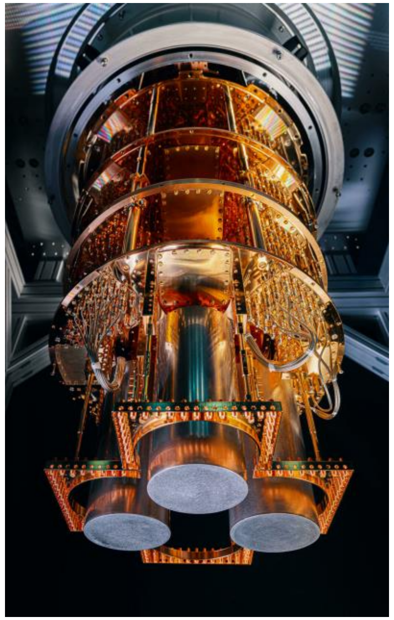


DiVincenzo Criteria for **quantum communication**:

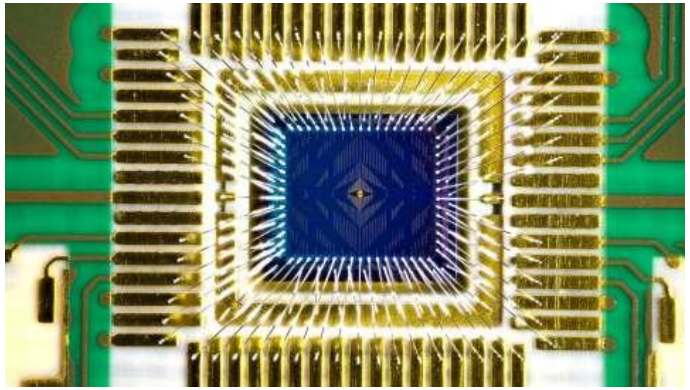
1. The ability to interconvert stationary and flying qubits
2. The ability to faithfully transmit flying qubits between specified locations



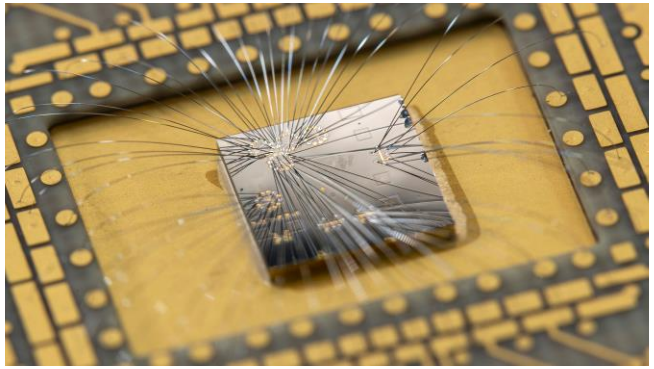
Superconducting



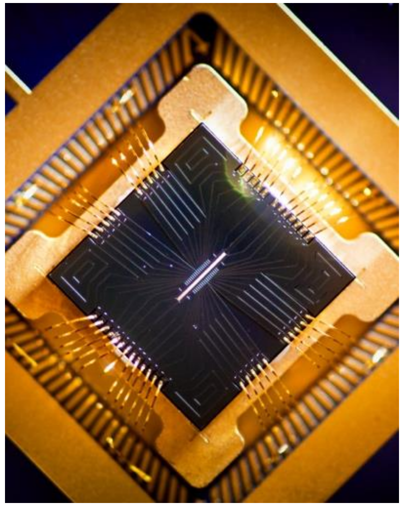
Spins



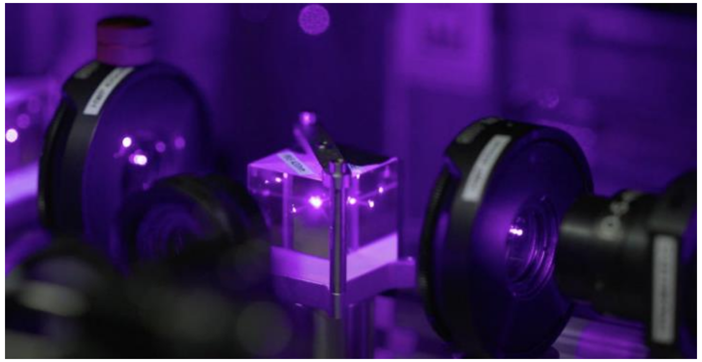
Topological



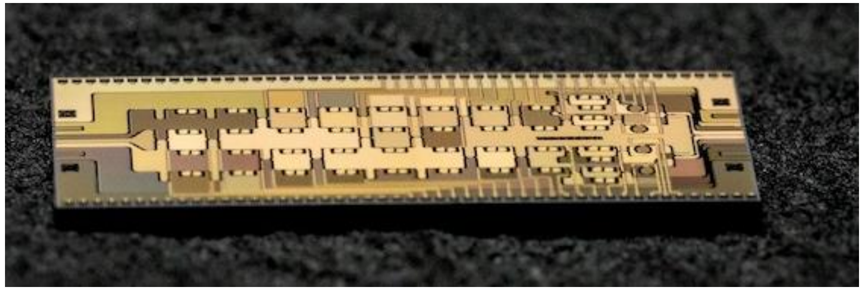
Trapped Ions



Cold Atoms

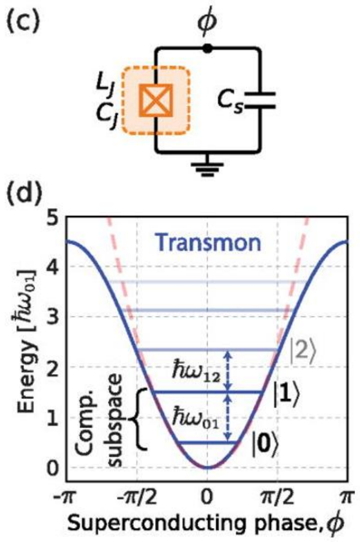


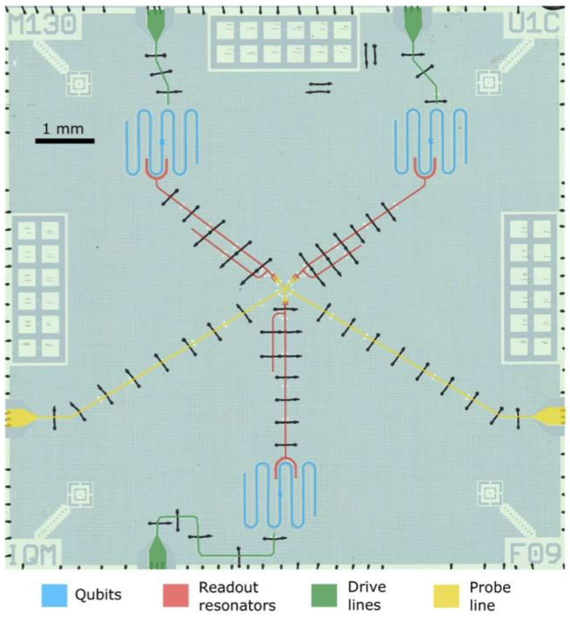
Photonics



Superconducting Qubits

- Qubits are states of a small (LC) electric circuit
  - States |0⟩ and |1⟩ are the lowest two energy states
- Gates via microwave/flux pulses



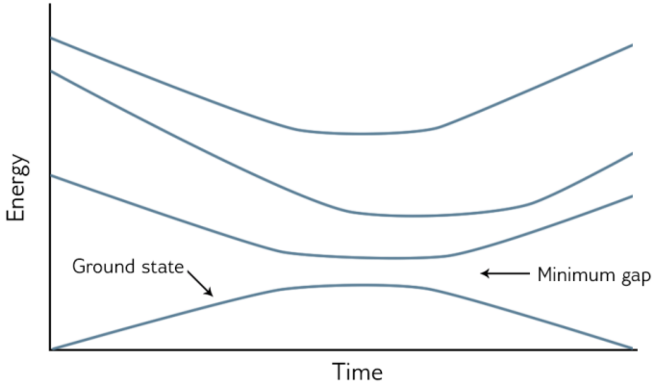


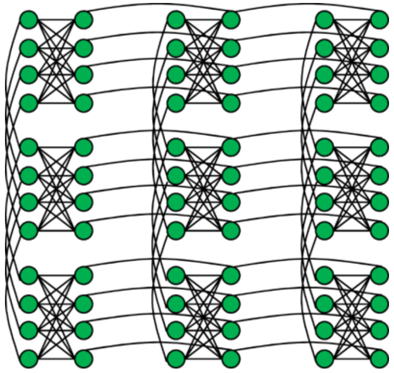
Advantages	Disadvantages
• Fast gate and cycle times • Good device metrics (fidelity etc.) • Large arrays demonstrated (100+ Qbs) • Demonstrated supremacy	• Wiring and packaging • Limited connectivity

IQM
Google Quantum AI
IBM
OQC
RIKEN QUANTUM COMPUTING
rigetti
ALICE & BOB

Superconducting Quantum Annealers

- Adiabatic QC:
  1. Start with a trivial Hamiltonian, prepare the ground state
  2. Slowly change the Hamiltonian, state remains the ground state
  3. End up with the problem Hamiltonian, state is the ground state = solution





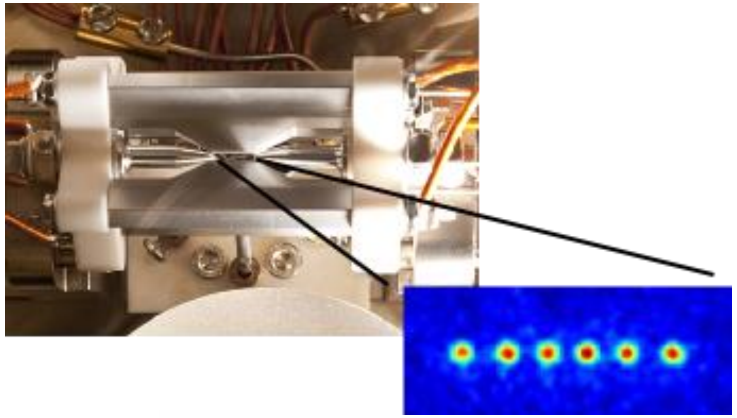
$$H(\sigma) = \sum_{i,j}^{N} J_{i,j}\sigma_i\sigma_j + \sum_{i}^{N} h_i\sigma_i$$

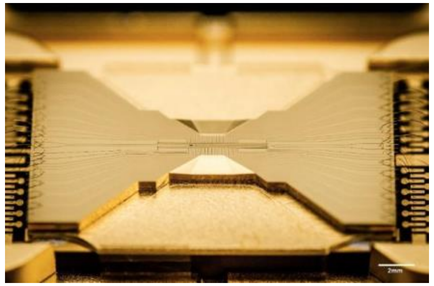
Advantages	Disadvantages
• Very large qubit numbers (5000+ Qbs)	• Speed ↔ quality tradeoff • Limited connectivity • Not universal

D:Wave
The Quantum Computing Company™

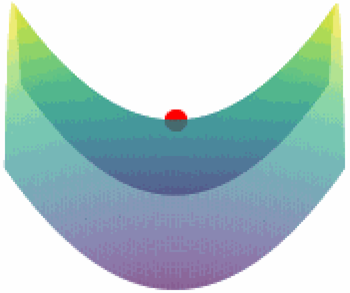
Trapped Ions

- Array of ions (Yb, Ba) trapped in EM field
- Laser qubit control, cooling and detection
- Entangling gate via phononic excitations





Advantages	Disadvantages
• Excellent gate fidelities • Easier optical network connection • All-to-all connectivity	• Slow gate times (=longer cycle times) • Limited number of ions in a single trap • Difficulty in on-chip scaling



QUANTINUUM

eleQtron

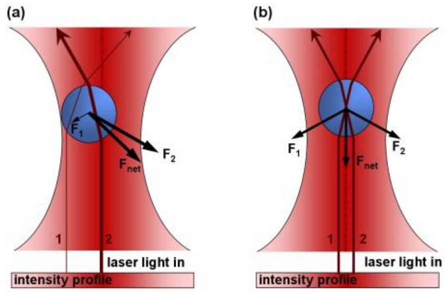
AQT

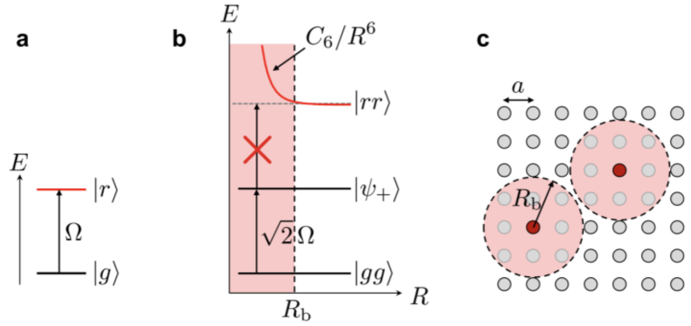
IONQ

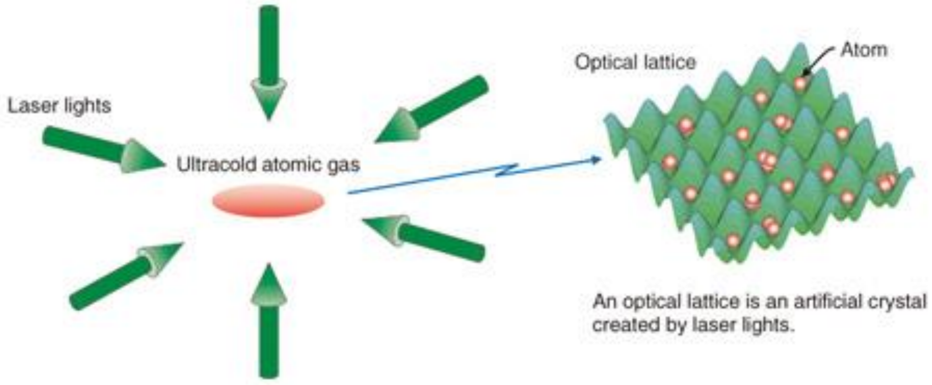
Cold Atoms

- 2D array of neutral atoms (Rb, Sr, Cs) in optical lattice / optical tweezers
- Gate based and quantum simulator
- CNOT gates via Rydberg blockade

Advantages	Disadvantages
• Large qubit arrays (100+ Qbs) demonstrated • Good connectivity and fidelities	• Tweezer arrays not scalable • Significant initialization error for lattices (60%)







atom computing

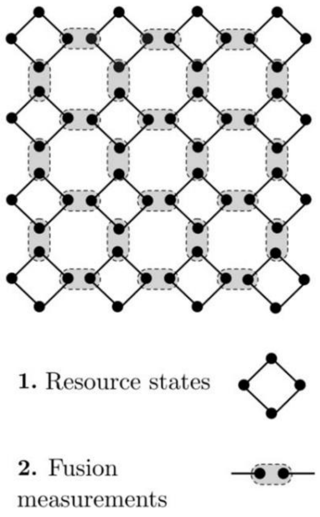
planqc

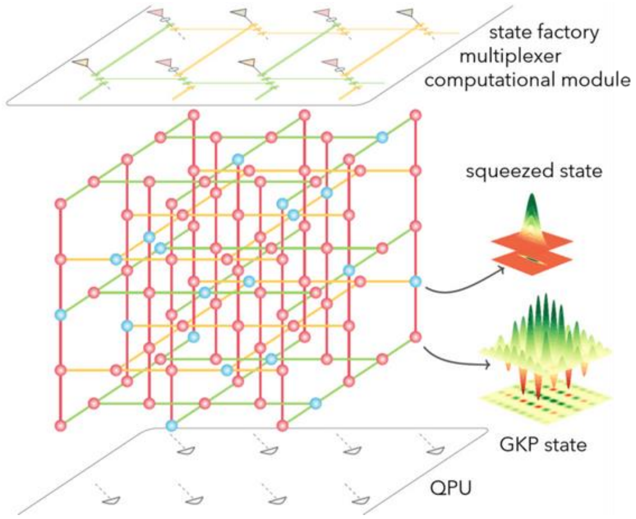
PASQAL

QuEra Computing Inc.

Photonics

- Qubits are the photons (polarization / count) or Gaussian states of photons
- Integrated optics (PsiQuantum) or optical table based (Xanadu)
- Measurement-based QC (Xanadu)
- Fusion-based QC (PsiQuantum)

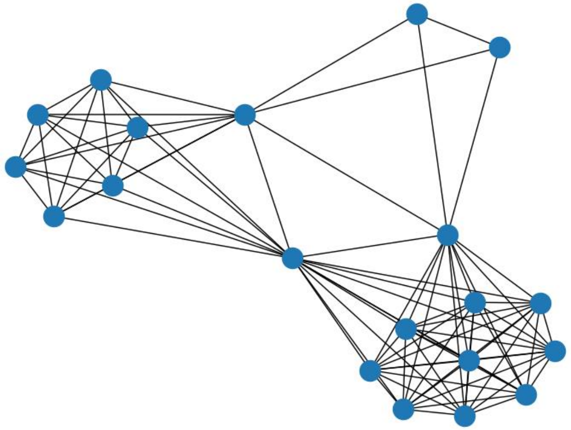




Advantages	Disadvantages
• Easier optical network connectivity • Modular architecture • Minimal cooling needed	• Significant photon loss (66%: gate) • Source, gate heralding needing post-selection

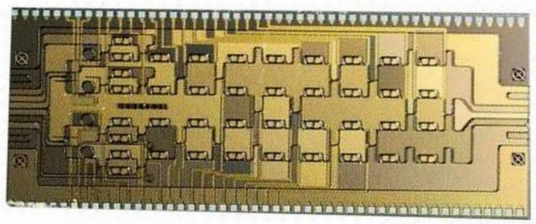
XANADU PsiQuantum QUIX QUANTUM

Photonic Boson Sampling

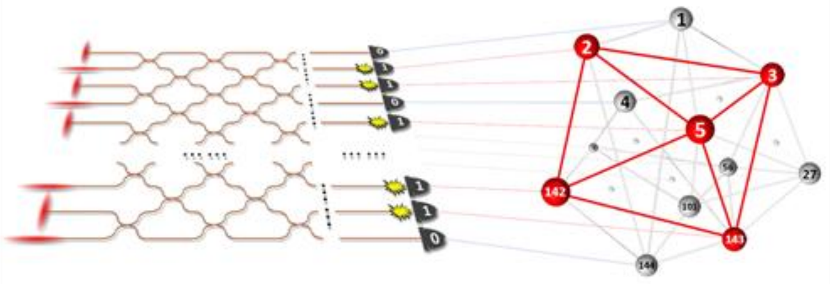


- A matrix is encoded in the interferometer
- Measurements correspond to samples proportional to sub-matrix Hafnian
- Adjacency matrix of graph:
    - Large Hafnian ↔ large density

$$\mathrm{haf}(A) = \frac{1}{n!2^n} \sum_{\sigma \in S_{2n}} \prod_{j=1}^{n} A_{\sigma(2j-1),\sigma(2j)},$$

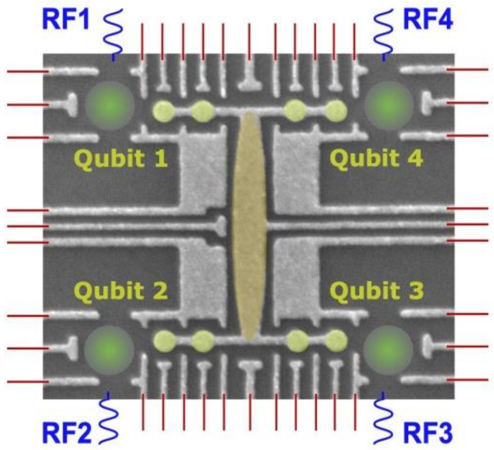


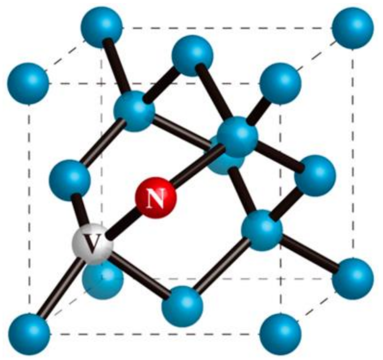
Advantages	Disadvantages
• Demonstrated supremacy	• Requires hybrid algorithm to be useful • Not universal



Spin Qubits

- Qubits are spins (semiconductor-based quantum dots or NV centers in diamond)
- Exchange based gates, spin-charge readout



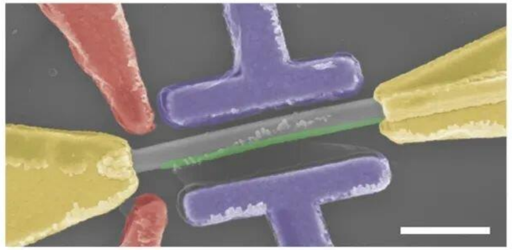


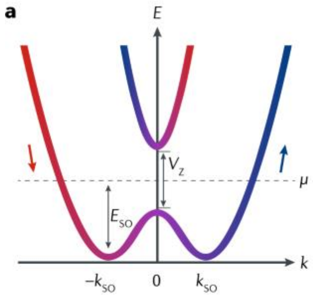
Advantages	Disadvantages
• Scalable architecture with integrated control electronics • Compatible with CMOS	• Short-range connectivity • Underdeveloped (low fidelities & qubit numbers)

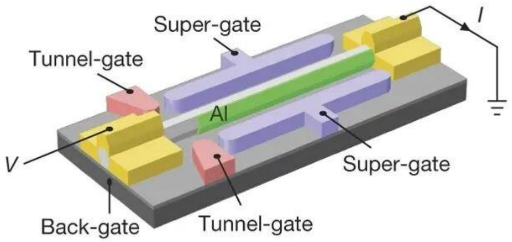
Topological Qubits

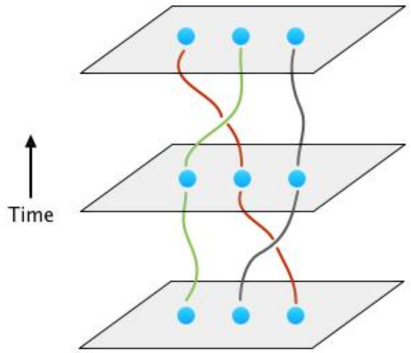
- Qubits are Majorana zero modes localized on topological superconductor
- Gates are made by “braiding” the qubits’ wordlines

Advantages	Disadvantages
• Theoretically highly stable and protected from errors	• No acceptable demonstrations yet









QC Metrics

Hardware-oriented

- **Number of qubits**: The possible width of a quantum algorithm
- **Cycle / Gate Time**: Time to run 1 shot of an algorithm / 1 gate
- **Single- and two-qubit gate fidelity**: The accuracy of implementing gates on the hardware
- **Connectivity**: How well are qubits connected with each other for performing multi-qubit gates
- **Scalability:** How well can the qubit number be scaled up
- **T1, T2 times**: The time that qubits remain in their quantum state
- **Native gate set:** Which quantum gates can be implemented natively on the hardware

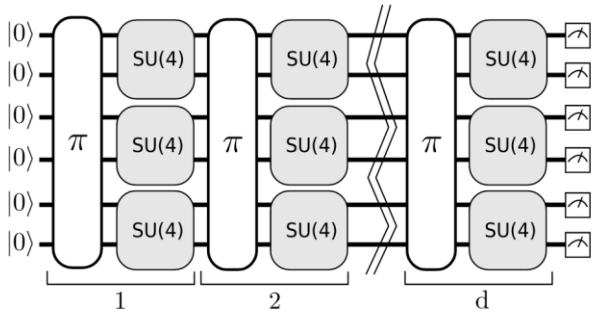
	Qb Type	Basis Gates	Highest Qb count	1 Qb Gate Time	1 Q Fid
Superconducting					
IQM	Tunable transmon qbs and tunable couplers	CZ, 1Q	20		
IBM	Osprey - Fixed frequency transmon qbs and fixed couplers	ECR, ID, RZ, SX, X	433	10-50 ns	99.
IBM	Sherbrooke - Fixed frequency transmon qbs and fixed couplers	ECR, ID, RZ, SX, X	127		99.
IBM	Prague - Tunable frequency transmon qbs and tunable couplers	CZ, ID, RZ, SX, X	33		99.
Google	Tunable transmon qbs and tunable couplers	CZ, fSim, 1Q	72	25 ns	99.
Rigetti	Tunable transmon qbs and fixed couplers	CZ, XY, 1Q	Aspen - 80		99.
Rigetti	Tunable transmon qbs and tunable couplers	CZ, SWAP	Ankaa - 1 (square lattice): 84 -> 184 (2024)		

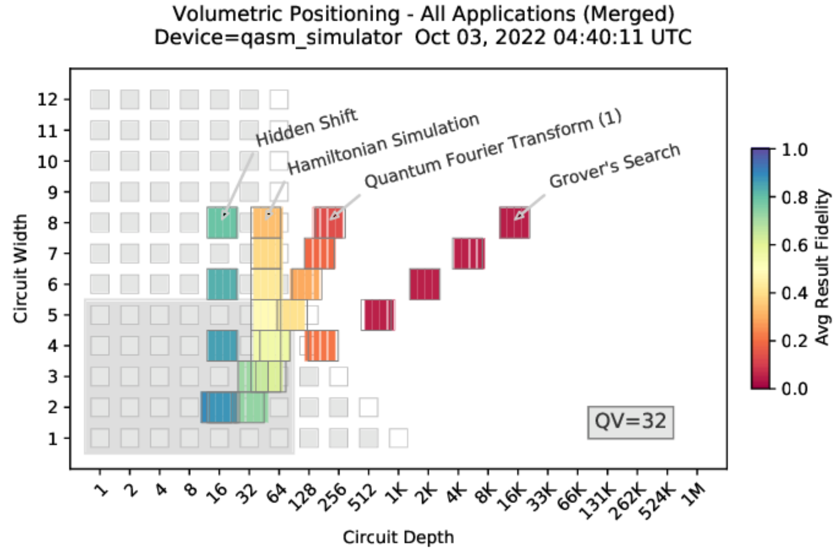
Snap-shot of QC metrics compiled in QC4EO report

QC Metrics

Algorithm-oriented

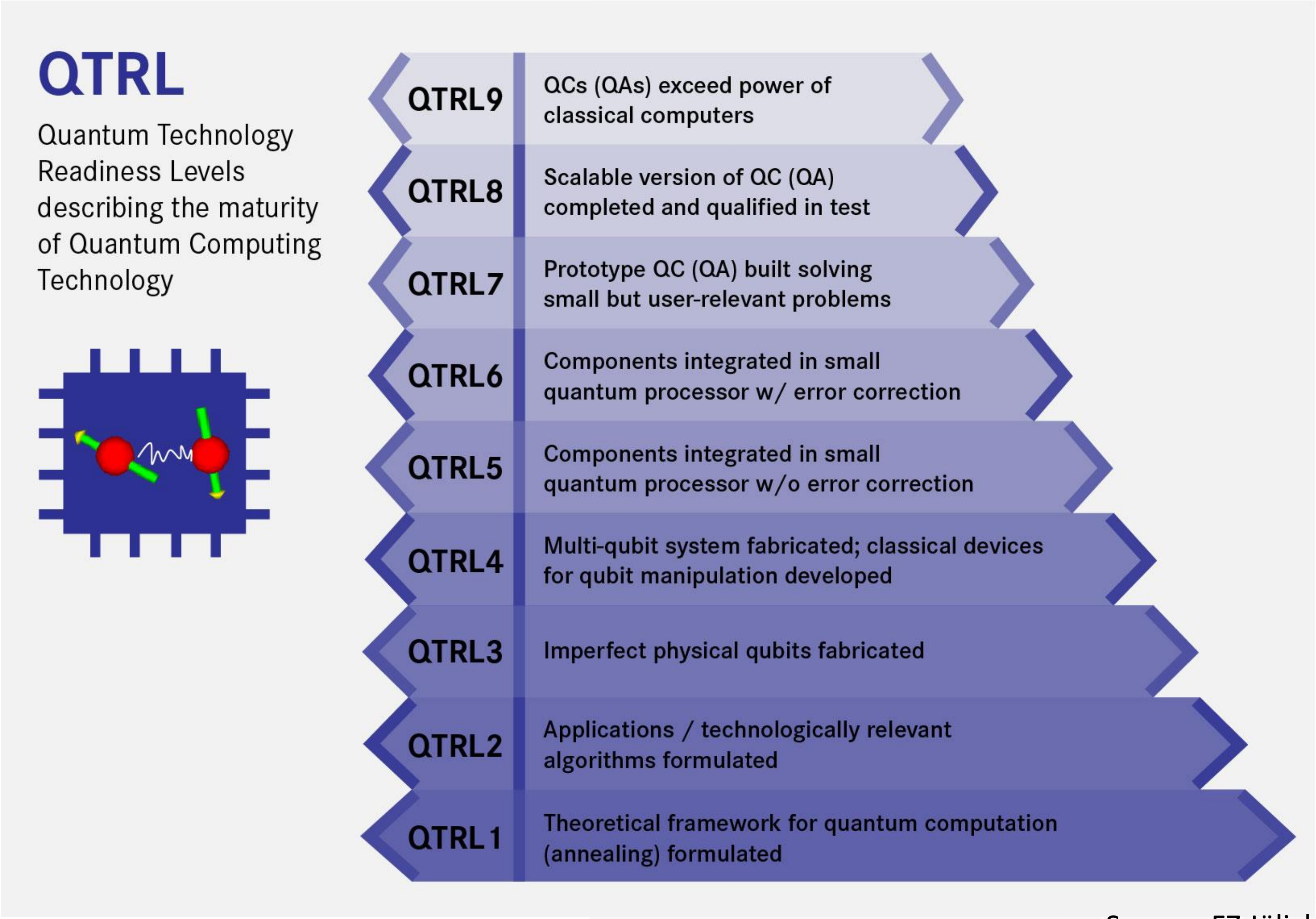
- **Logical number of qubits**: The number of error-corrected qubits
- **Logical gate fidelities**: The error rates of gates performed on logical qubits
- **Quantum volume**: The depth to which a certain random quantum circuit can be faithfully executed
- **CLOPS**: The number of quantum volume circuit layers executed per second
- **Q-score:** Largest max-cut problem that can be solved better than random guessing
- **Algorithmic qubits**: Largest number of qubits that can faithfully run a certain set of algorithm
- **QTRL:** TRL-inspired rating for quantum technologies



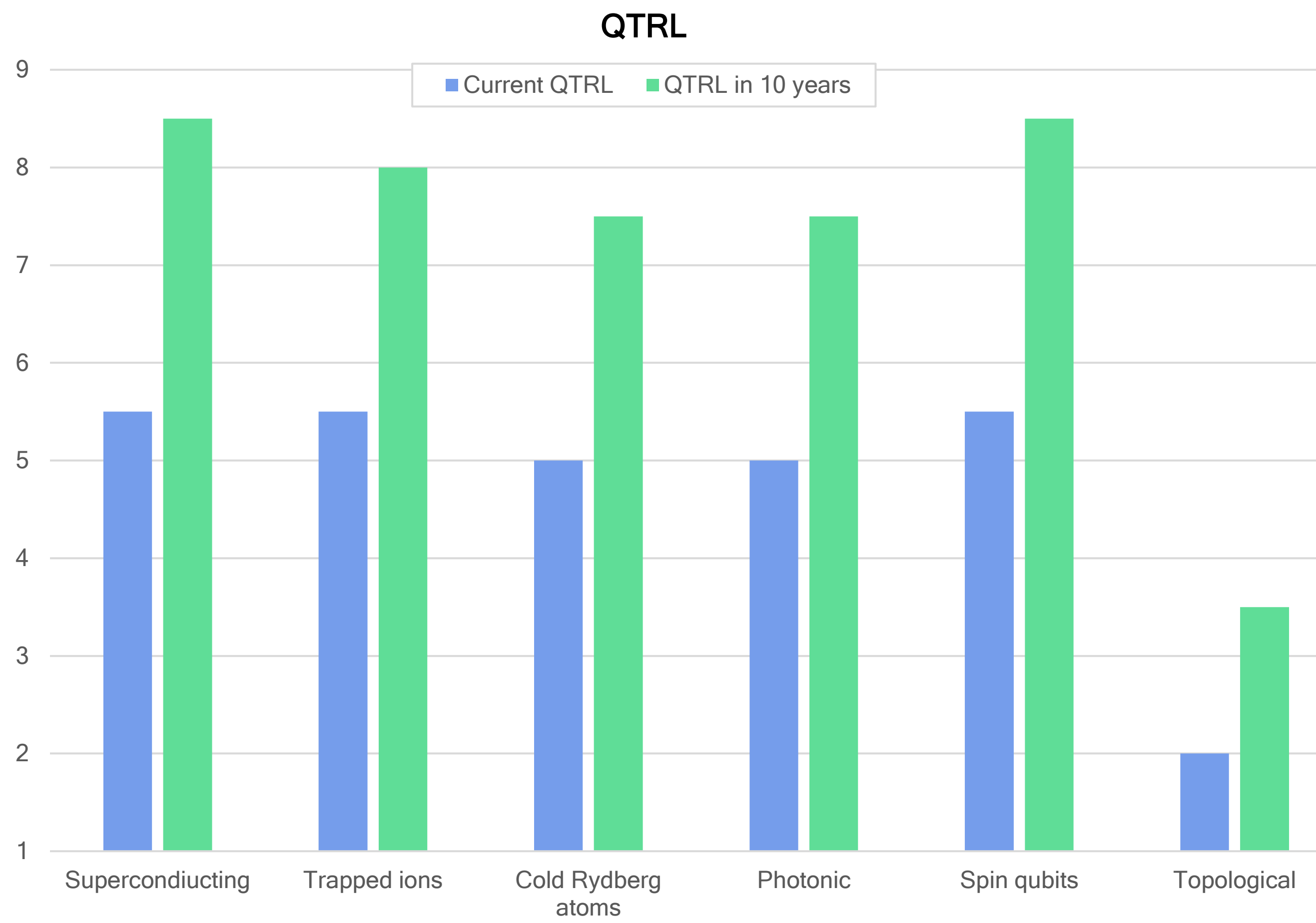


Quantum Technology Readiness Level

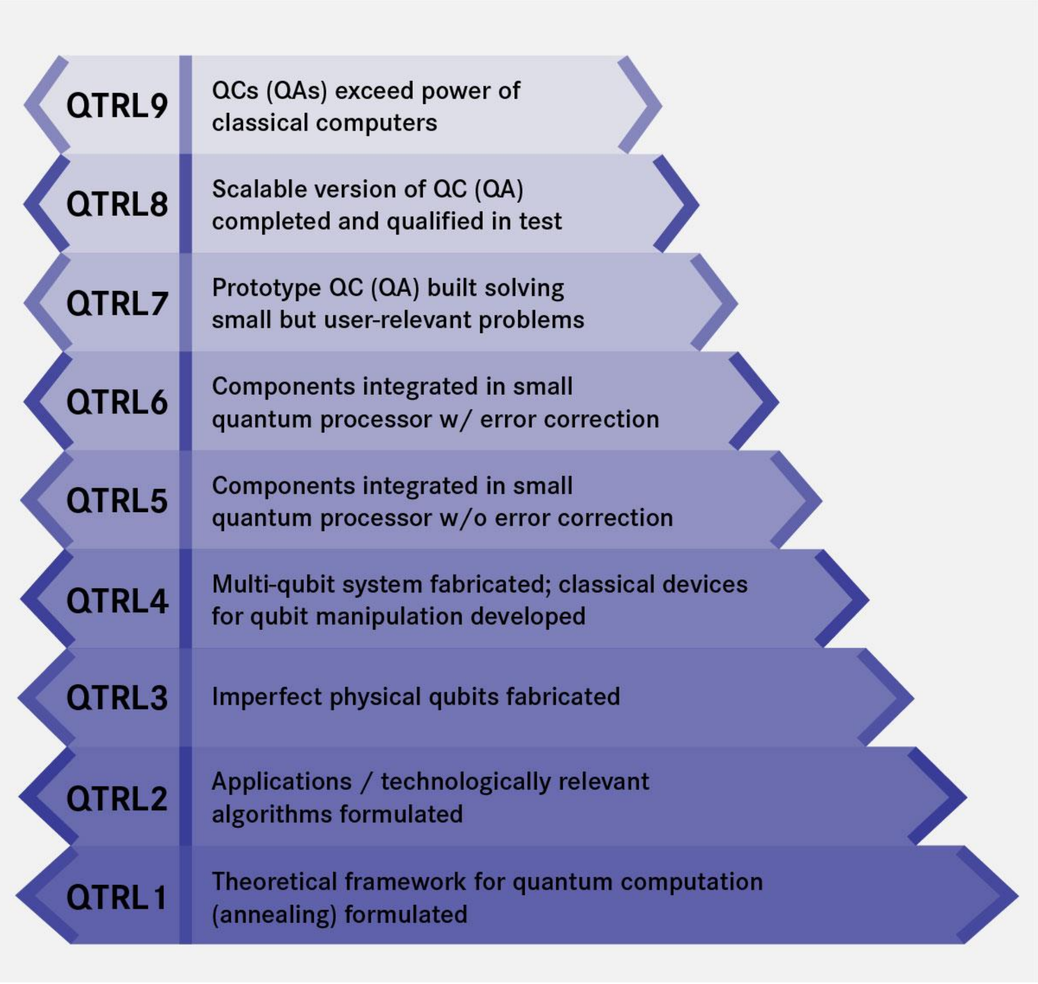
- 7-9: Engineering & Development (Products)
- 4-6: Industrial research (Demonstrators)
- 1-3: University research (Laboratory tests)



Source: FZ Jülich

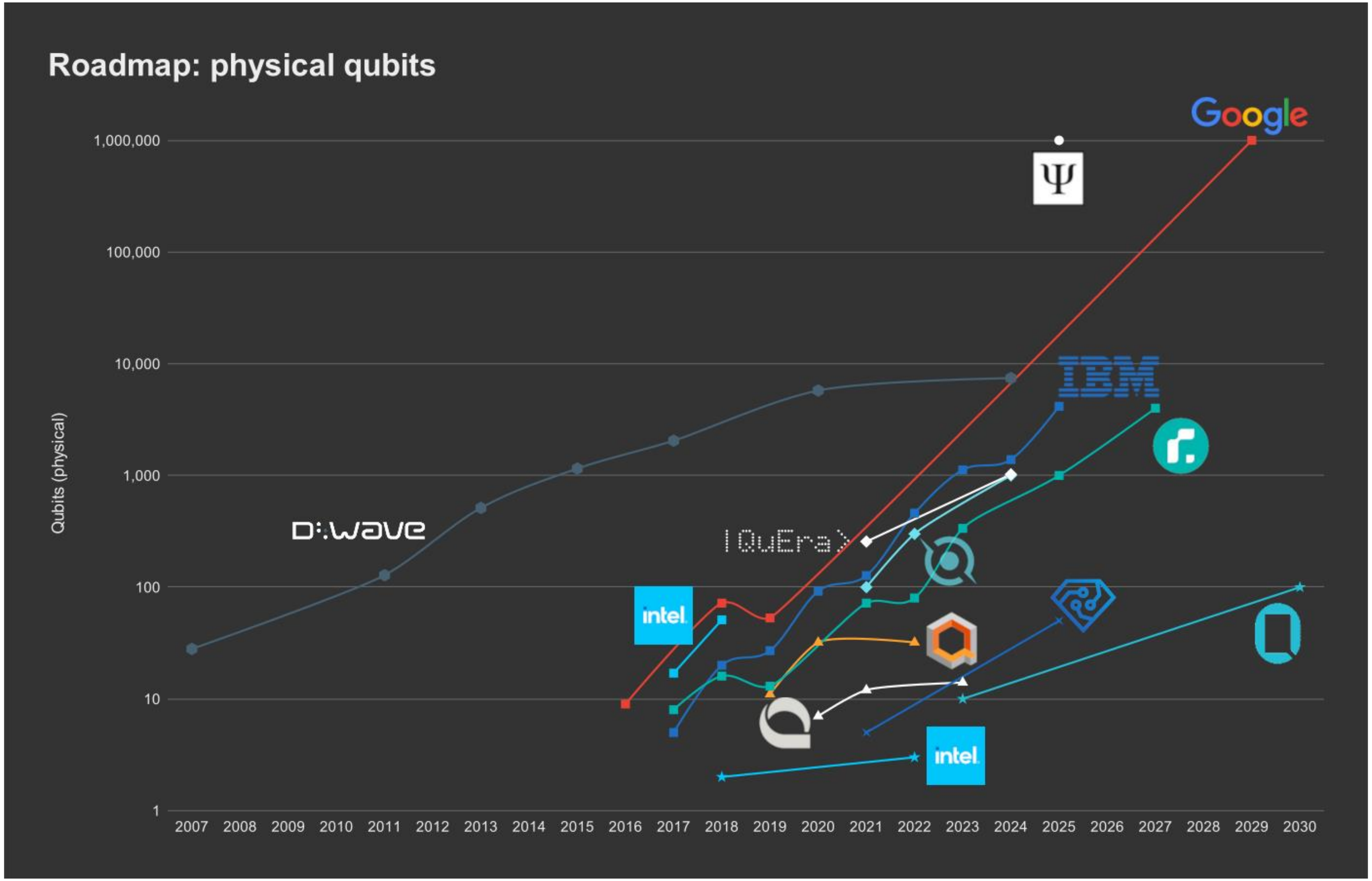


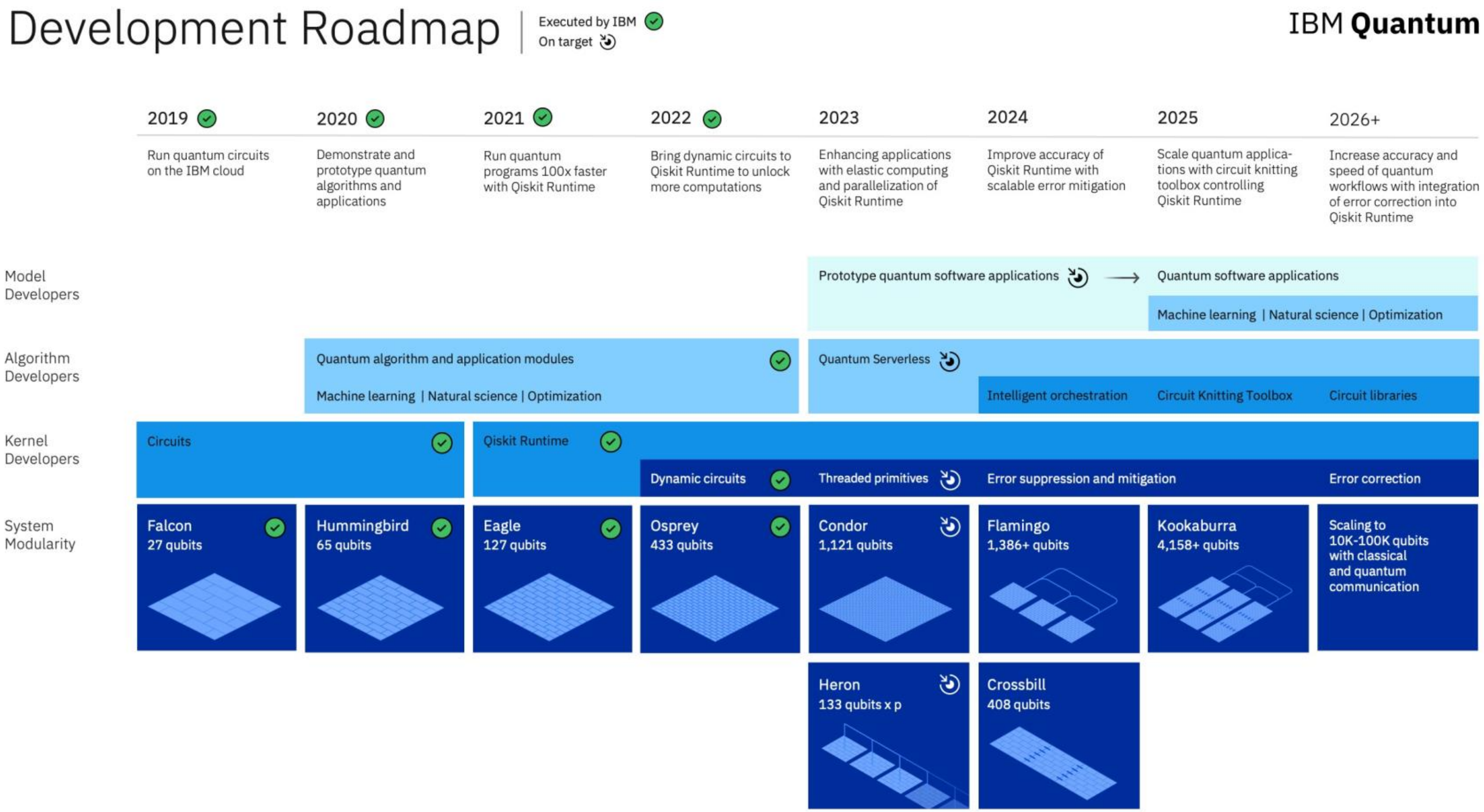
Supercondiucting	Trapped ions	Cold Rydberg atoms	Photonic	Spin qubits	Topological
IQM	IonQ	PasQal	PsiQuantum	Intel	Microsoft
IBM	Quantinuum	QuEra	Xanadu	Quobly	
Google	AQT	Cold Quanta		Diraq	
Amazon	ElecQtron	Planqc		Semiqon	
Rigetti				Quantum-Motion	
OQC					
Alice and Bob					

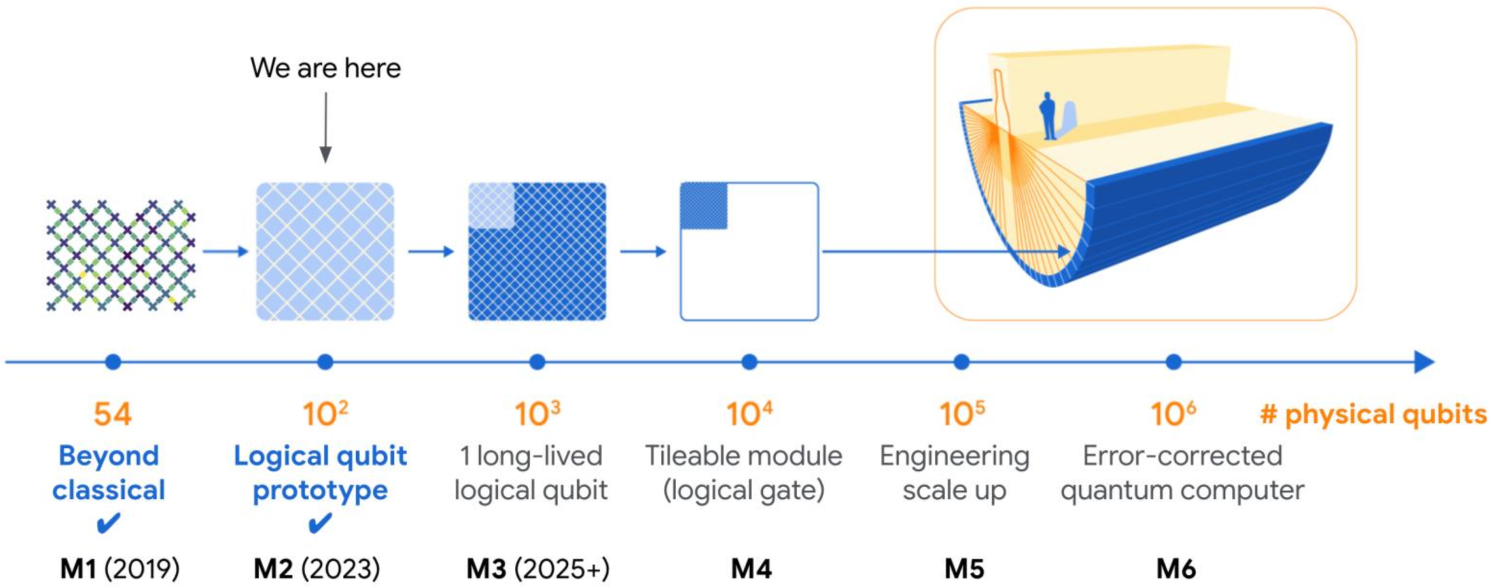


Thank you for tuning in!

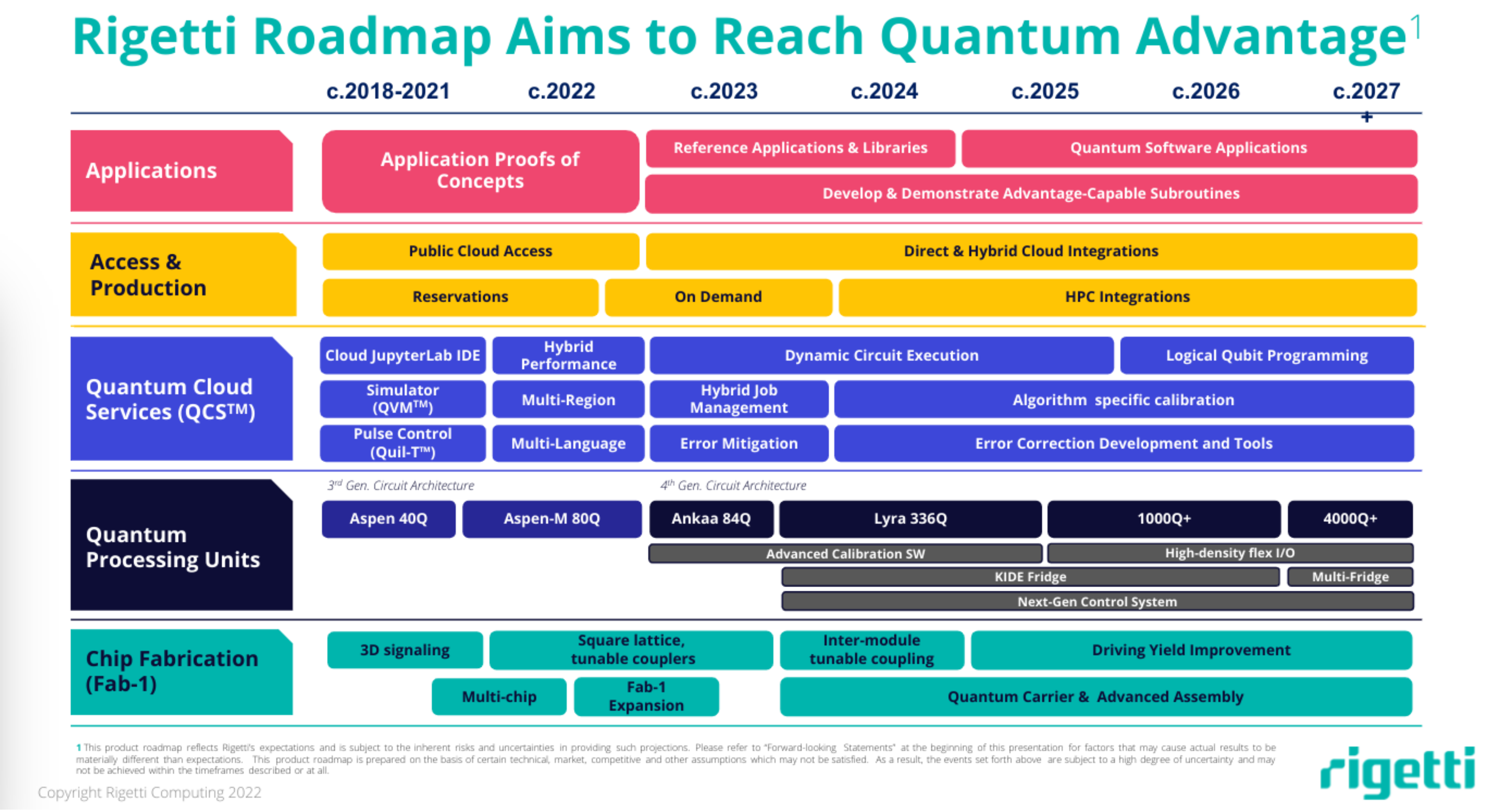
Backup slides


Roadmap: physical qubits
Qubits (physical)
1,000,000
100,000
10,000
1,000
100
10
1
2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030
Google
IBM
D:wave
|QuEra〉
intel
intel


Development Roadmap
Executed by IBM
On target
IBM Quantum
2019
Run quantum circuits on the IBM cloud
2020
Demonstrate and prototype quantum algorithms and applications
2021
Run quantum programs 100x faster with Qiskit Runtime
2022
Bring dynamic circuits to Qiskit Runtime to unlock more computations
2023
Enhancing applications with elastic computing and parallelization of Qiskit Runtime
2024
Improve accuracy of Qiskit Runtime with scalable error mitigation
2025
Scale quantum applications with circuit knitting toolbox controlling Qiskit Runtime
2026+
Increase accuracy and speed of quantum workflows with integration of error correction into Qiskit Runtime
Model Developers
Prototype quantum software applications
Quantum software applications
Machine learning | Natural science | Optimization
Algorithm Developers
Quantum algorithm and application modules
Machine learning | Natural science | Optimization
Quantum Serverless
Intelligent orchestration
Circuit Knitting Toolbox
Circuit libraries
Kernel Developers
Circuits
Qiskit Runtime
Dynamic circuits
Threaded primitives
Error suppression and mitigation
Error correction
System Modularity
Falcon 27 qubits
Hummingbird 65 qubits
Eagle 127 qubits
Osprey 433 qubits
Condor 1,121 qubits
Flamingo 1,386+ qubits
Kookaburra 4,158+ qubits
Scaling to 10K-100K qubits with classical and quantum communication
Heron 133 qubits x p
Crossbill 408 qubits



We are here
54
Beyond classical
✔
M1 (2019)
10²
Logical qubit prototype
✔
M2 (2023)
10³
1 long-lived logical qubit
M3 (2025+)
10⁴
Tileable module (logical gate)
M4
10⁵
Engineering scale up
M5
10⁶
Error-corrected quantum computer
M6
physical qubits



Rigetti Roadmap Aims to Reach Quantum Advantage1
c.2018-2021
c.2022
c.2023
c.2024
c.2025
c.2026
c.2027 +
Applications
Application Proofs of Concepts
Reference Applications & Libraries
Quantum Software Applications
Develop & Demonstrate Advantage-Capable Subroutines
Access & Production
Public Cloud Access
Direct & Hybrid Cloud Integrations
Reservations
On Demand
HPC Integrations
Quantum Cloud Services (QCS™)
Cloud JupyterLab IDE
Hybrid Performance
Dynamic Circuit Execution
Logical Qubit Programming
Simulator (QVM™)
Multi-Region
Hybrid Job Management
Algorithm specific calibration
Pulse Control (Quil-T™)
Multi-Language
Error Mitigation
Error Correction Development and Tools
Quantum Processing Units
3rd Gen. Circuit Architecture
4th Gen. Circuit Architecture
Aspen 40Q
Aspen-M 80Q
Ankaa 84Q
Lyra 336Q
1000Q+
4000Q+
Advanced Calibration SW
High-density flex I/O
KIDE Fridge
Multi-Fridge
Next-Gen Control System
Chip Fabrication (Fab-1)
3D signaling
Square lattice, tunable couplers
Inter-module tunable coupling
Driving Yield Improvement
Multi-chip
Fab-1 Expansion
Quantum Carrier & Advanced Assembly
1 This product roadmap reflects Rigetti's expectations and is subject to the inherent risks and uncertainties in providing such projections. Please refer to "Forward-looking Statements" at the beginning of this presentation for factors that may cause actual results to be materially different than expectations. This product roadmap is prepared on the basis of certain technical, market, competitive and other assumptions which may not be satisfied. As a result, the events set forth above are subject to a high degree of uncertainty and may not be achieved within the timeframes described or at all.
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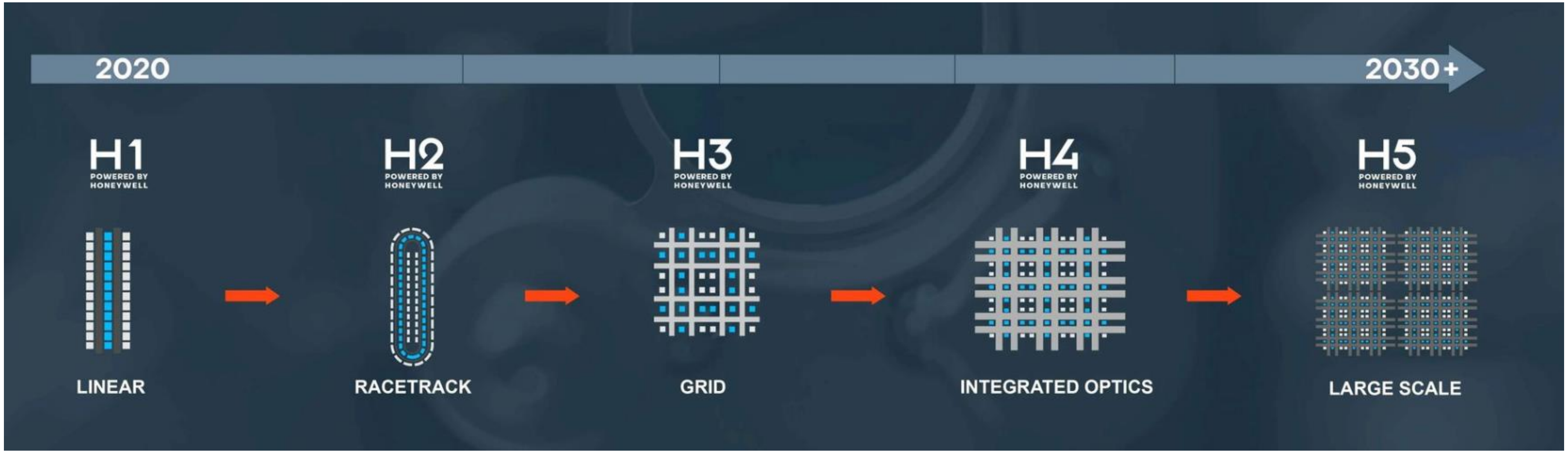
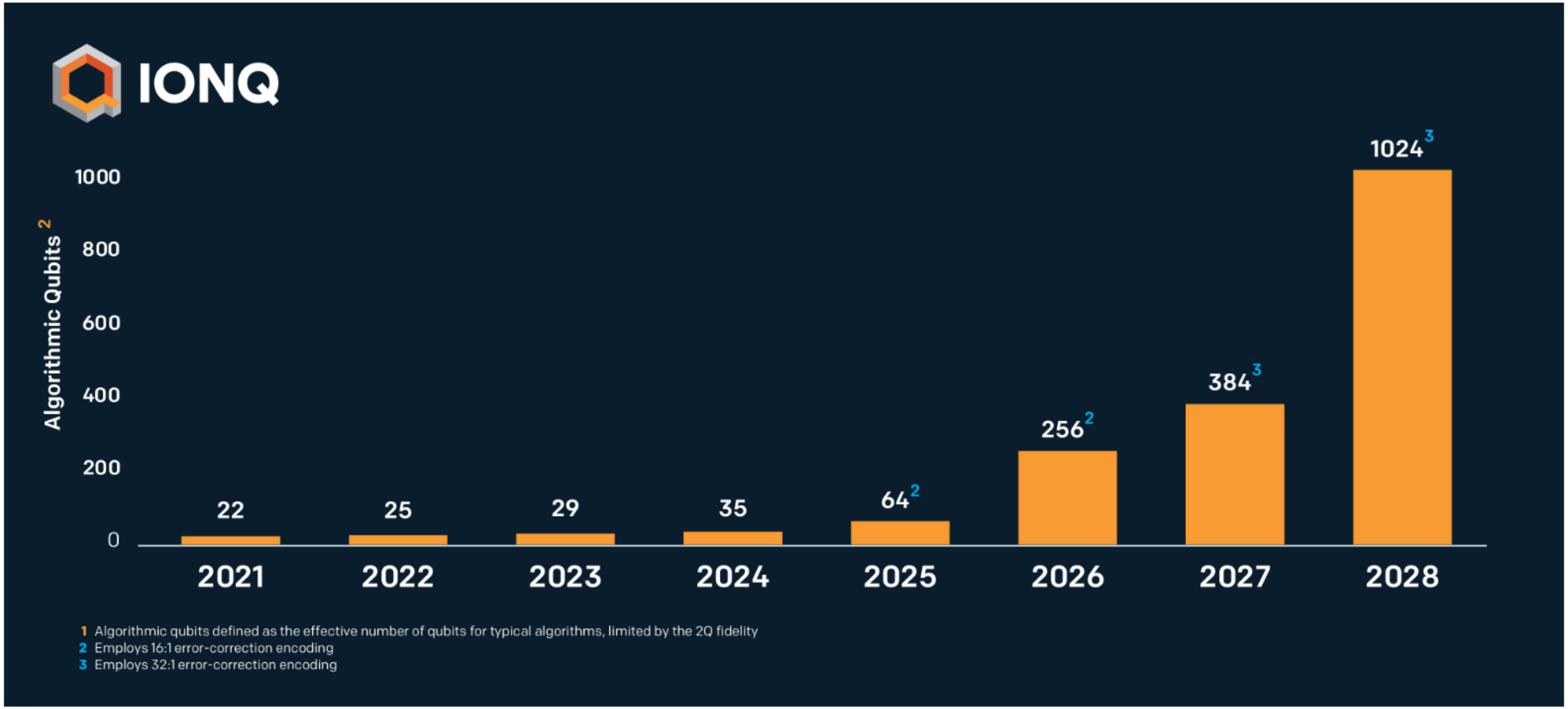

2020
2030+
H1
POWERED BY HONEYWELL
H2
POWERED BY HONEYWELL
H3
POWERED BY HONEYWELL
H4
POWERED BY HONEYWELL
H5
POWERED BY HONEYWELL
LINEAR
RACETRACK
GRID
INTEGRATED OPTICS
LARGE SCALE


IONQ
Algorithmic Qubits 2
1000
800
600
400
200
0
22
25
29
35
64 2
256 2
384 3
1024 3
2021
2022
2023
2024
2025
2026
2027
2028
1 Algorithmic qubits defined as the effective number of qubits for typical algorithms, limited by the 2Q fidelity
2 Employs 16:1 error-correction encoding
3 Employs 32:1 error-correction encoding