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A Brief Overview of Quantum Computing Hardware

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Apologies in Advance

to hardware vendors and experimentalists in the room

Types of Quantum Computers

Models of Quantum Computation

2 Abstraction Layers (qec => gates)	**Fault Tolerant Quantum Computer**
1 Abstraction Layer (gates)	**NISQ* Quantum Computer**
Bare Metal System	**Analog Quantum Computer**

* NISQ = Noisy Intermediate Scale Quantum
arXiv:1801.00862

Analog Quantum Computation

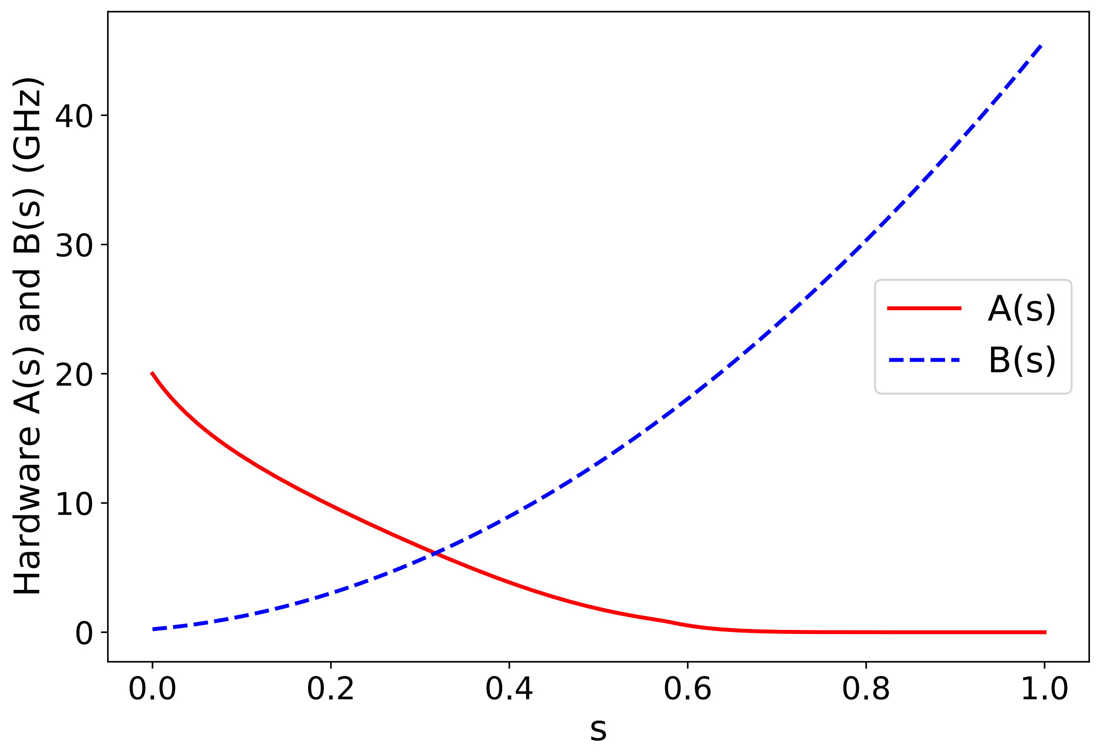
- **What does it do?**
  - Apply control parameters to evolve a real-world quantum system in time
- **Natural use cases**
  - Quantum Simulation (open and closed), Optimization
- **Arguments For**
  - Very efficient use of quantum hardware resources
  - Very fast (no abstraction layers)
- **Arguments Against**
  - Highly specialized to specific applications (i.e. limited Hamiltonian options)
  - Hardware noise can be limiting

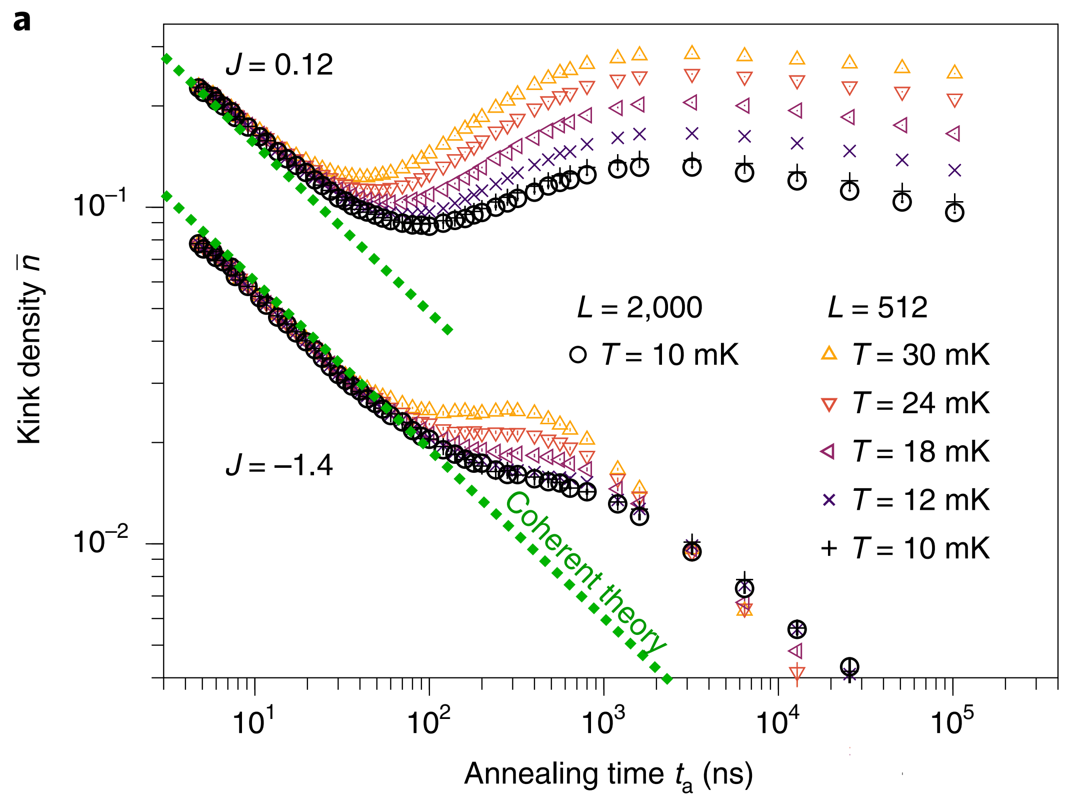
Solve this ODE

$$t \in [0,T], \ |\Psi_0\rangle$$

Evolution Time **Initial State**

$$i\frac{d}{dt}|\Psi(t)\rangle = H(t)|\Psi(t)\rangle$$





$$H_{dwave}(t) = A(t)\left(\sum_i \hat{\sigma}_i^x\right) + B(t)\left(\sum_i h_i\hat{\sigma}_i^z + \sum_{i,j} J_{ij}\hat{\sigma}_i^z\hat{\sigma}_j^z\right)$$

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"Coherent quantum annealing in a programmable 2000-qubit Ising chain"
arXiv:2202.05847

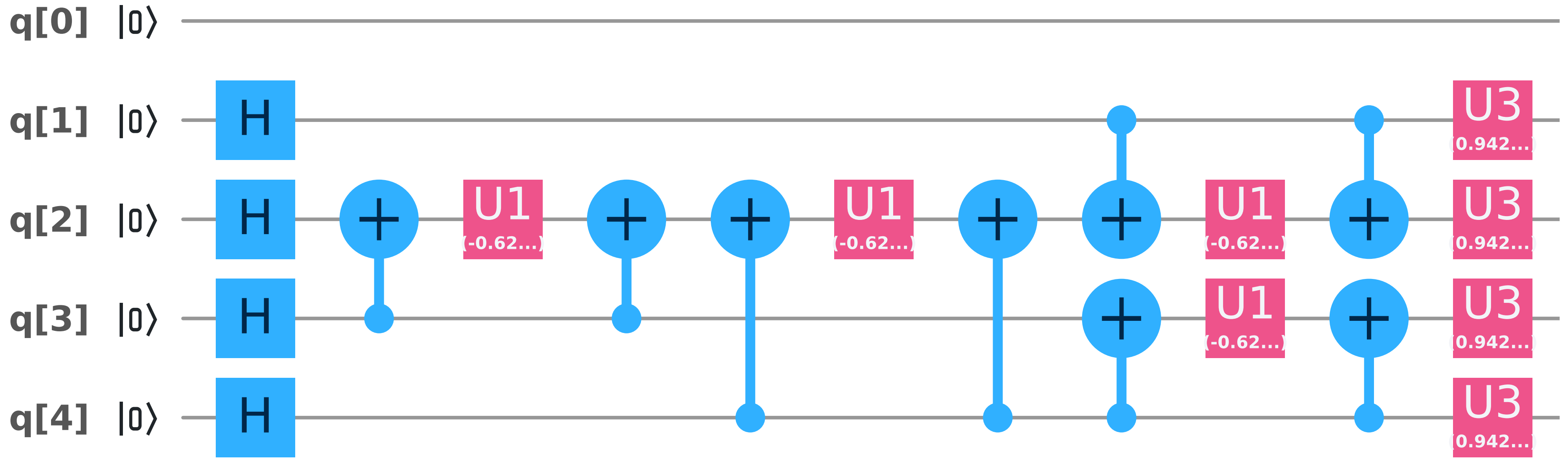
NISQ Gate-Based Computation

- **What does it do?**
  - Apply quantum *imperfect gates* to implement a noisy *universal* quantum computation
  - Note: these usually include arbitrary rotation gates
- **Natural use cases**
  - Quantum Simulation (closed), Variational Quantum Algorithms, Quantum Machine Learning (?)
- **Arguments For**
  - Flexible (all types of quantum computations are in scope)
  - Fast (just 1 abstraction layer)
- **Arguments Against**
  - Hardware noise can be limiting
  - Unclear how to extend beyond qubit coherence time

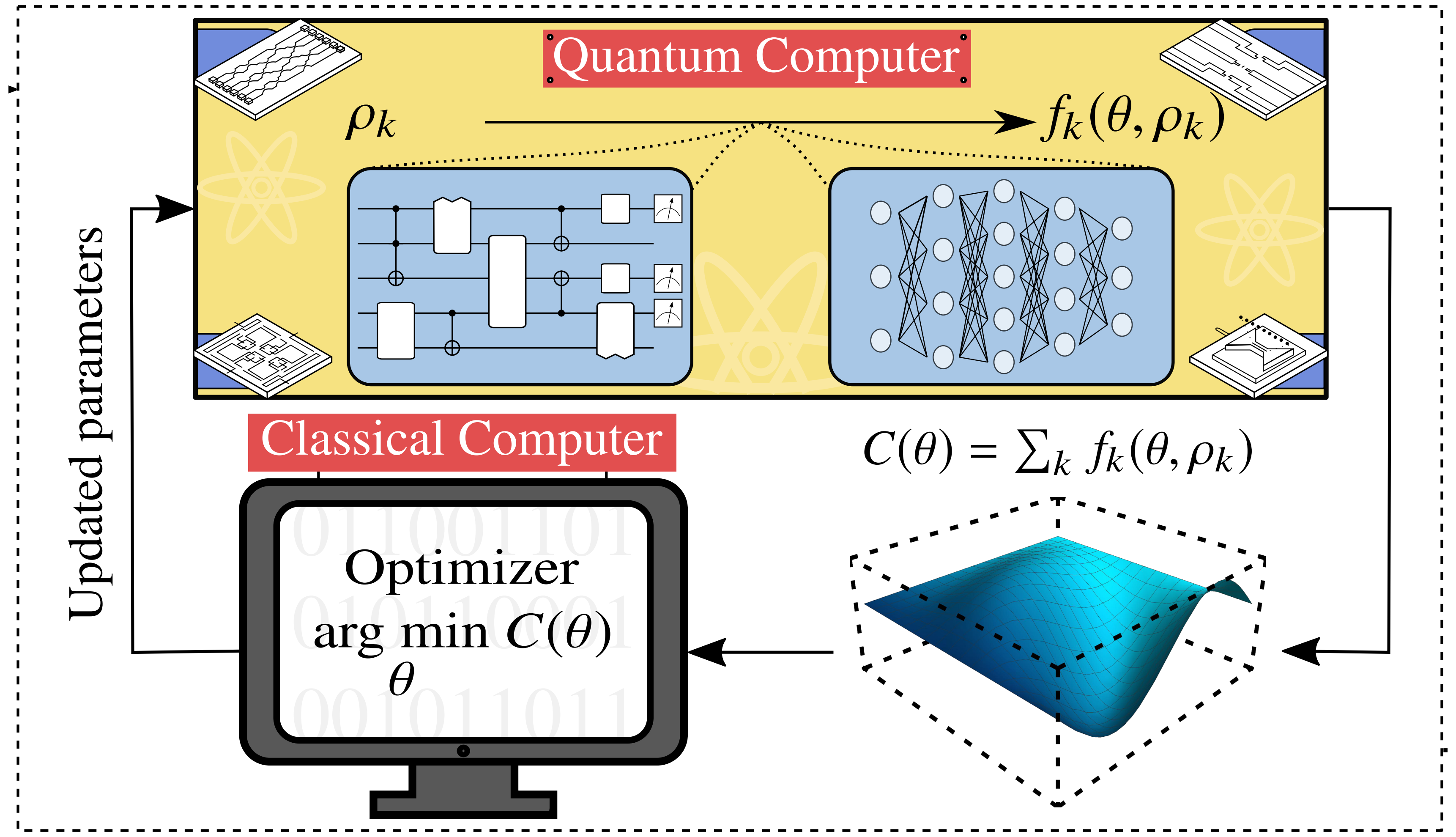
Apply Unitary Matrices (U) to a quantum state (ψ)

$$U_n | \dots | U_3 | U_2 | U_1 | \psi\rangle$$

NISQ Score (Qiskit)



Variational Quantum Algorithm Structure



"Variational quantum algorithms" Cerezo et. al. arXiv:2012.09265

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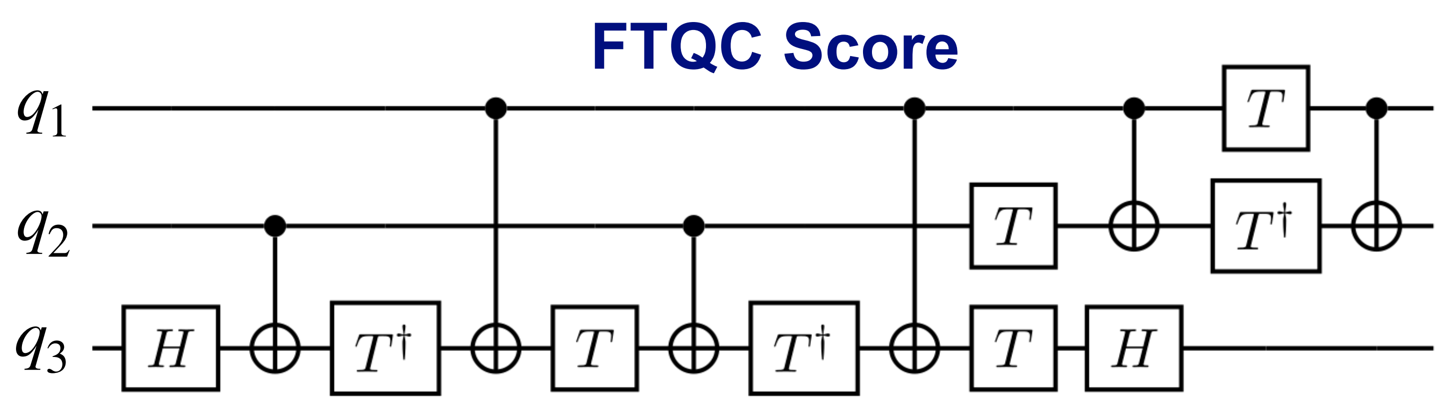
Fault-Tolerant Gate-Based Computation

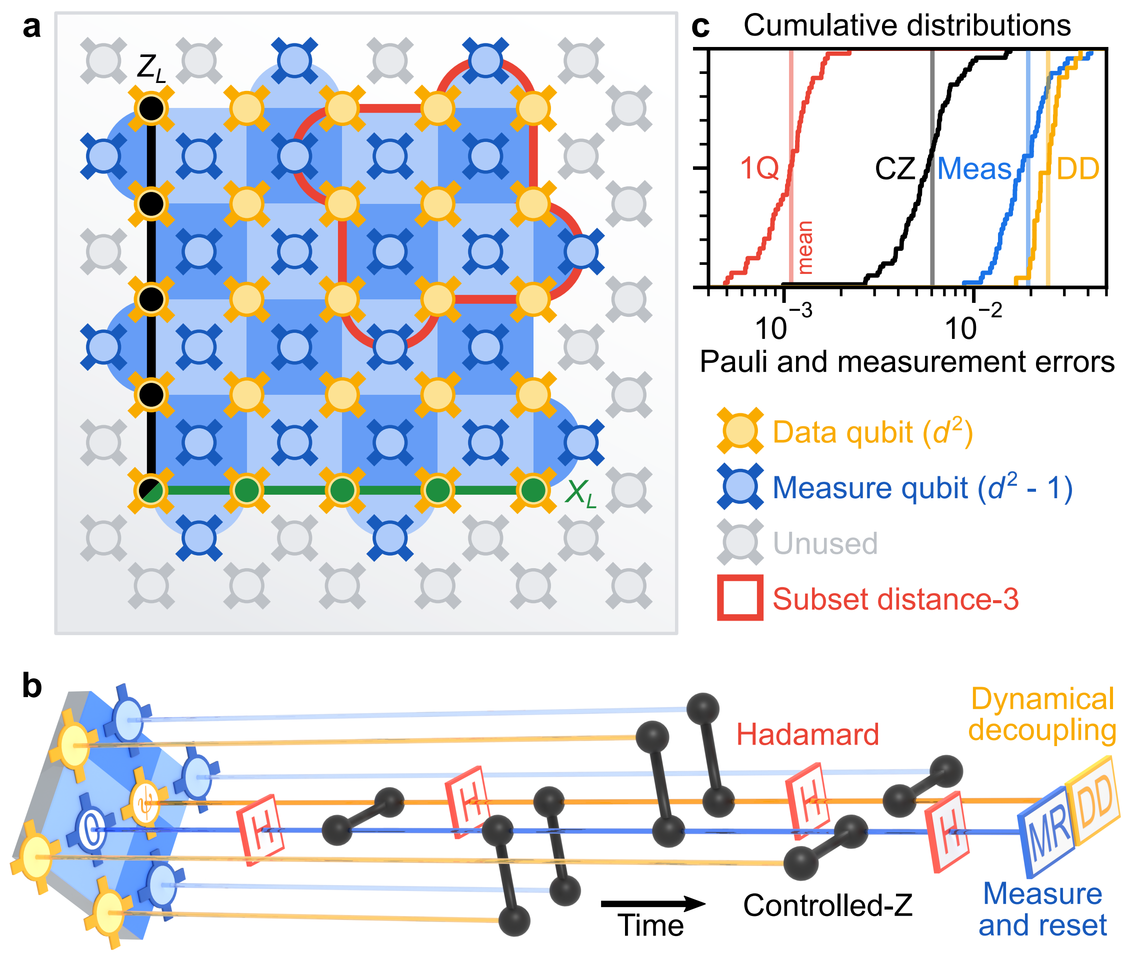


- **What does it do?**
  - Apply quantum *error corrected gates* to implement *perfect universal* quantum computation
  - Note: a restrictive gate set (e.g., Clifford+T)
- **Natural use cases**
  - Quantum Simulation (high-accuracy), Factoring, Linear Systems, Nonlinear Systems (?)
- **Arguments For**
  - Reliable, Algorithms with Proofs
  - Quantum Error Correction (QEC) enables going beyond the limit of qubit coherence time
- **Arguments Against**
  - Requires a LOT of physical qubits
  - Algorithms require a LOT of gates (e.g., $>10^6$)
  - Slow, QEC overheads take time (2 abstraction layers)

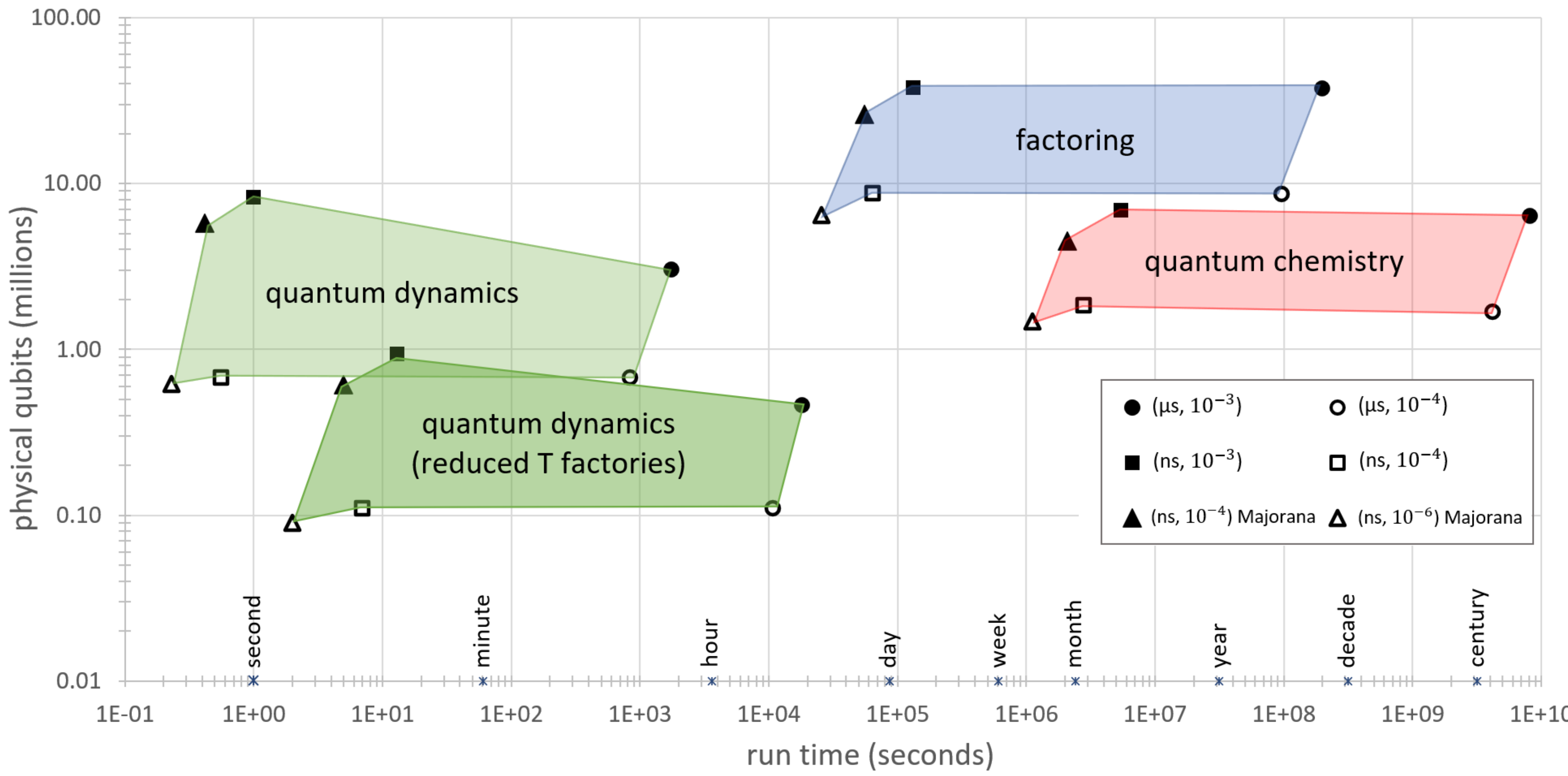
T $\begin{bmatrix} 1 & 0 \\ 0 & e^{i\pi/4} \end{bmatrix}$

H $\frac{1}{\sqrt{2}}\begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}$

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix}$$



"Suppressing quantum errors by scaling a surface code logical qubit"
arXiv:2207.06431



"Assessing requirements to scale to practical quantum advantage"
arXiv:2211.07629

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Who is doing what?

Three Types of Commercial Quantum Computers

	Available Today		Available Soon?
	Noisy Analog	**Noisy Gate-Based**	**Fault-Tolerant Gate-Based**
Who?	D:WAVE |QuEra> PASQAL	IBM Q™ Quantum AI IONQ rigetti XANADU QUANTINUUM qci	Ψ PsiQuantum atom computing D:WAVE Quantum AI qci ALICE & BOB **Public Roadmaps** IBM Q™ PASQAL Infleqtion |QuEra>

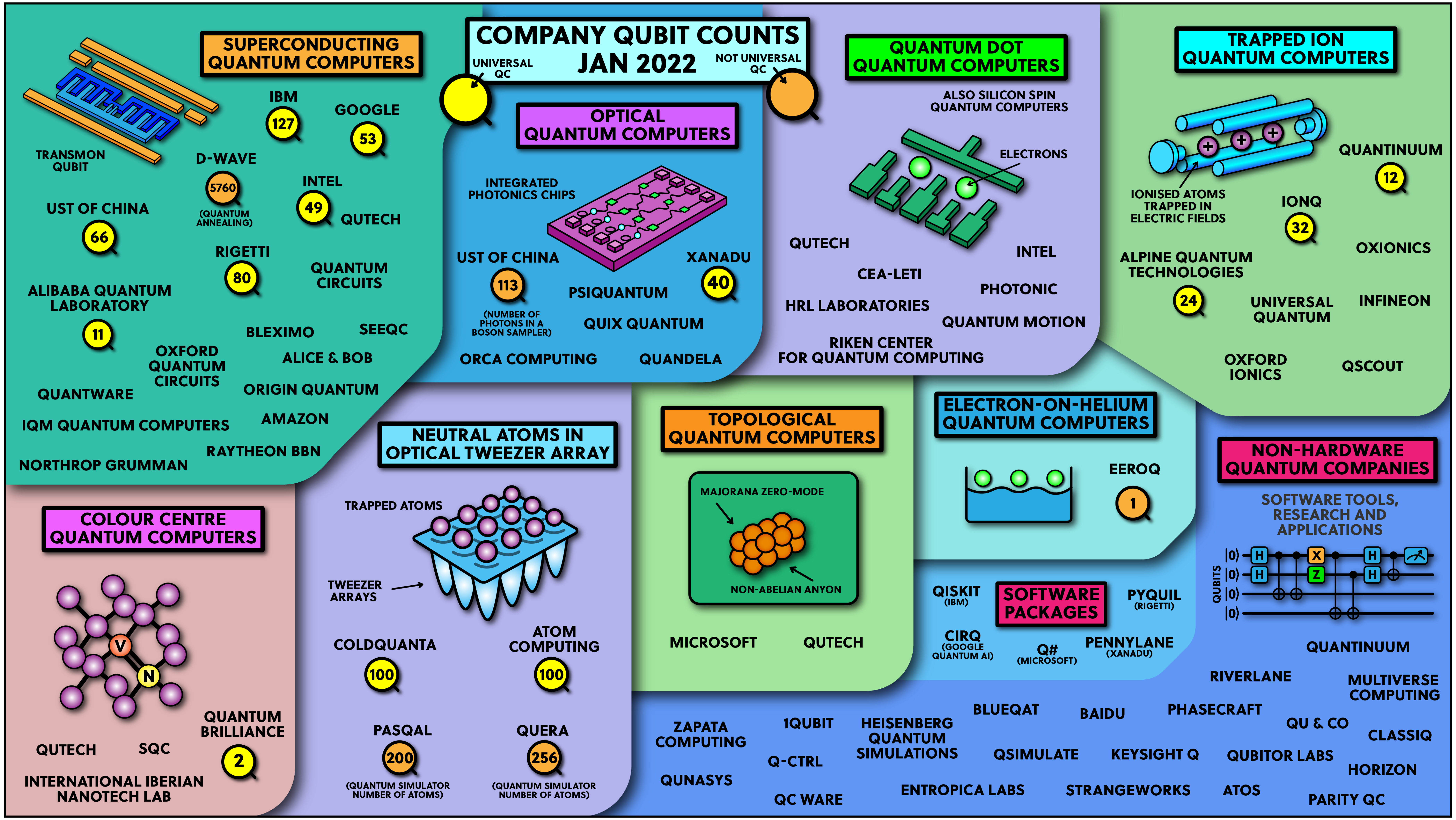
And many others…

FTQC proposed by 2026-2030

Why so many?

There is no "transistor" for quantum computing… yet

Qubit Technologies



Domain of Science - Dominic Walliman

Pros and Cons of *NISQ Hardware* Platforms

Just the vendors I know the best…

Feature	Superconducting Circuits	Trapped Ions	Neutral Atoms	Photonic	Topological / Quantum Dot / Silicon Spin
Speed	Fast	Slow	Slow	?	??
Noise	Medium	Low	Low	?	??
Scale (qubits demonstrated)	High 500-5000	Low 10-50	Medium 100-1000	?	??
Connectivity	Sparse	High	Sparse	?	??

No clear winner,

co-design of hardware and application maximizes performance

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Implemenation Tradeoffs

Quantum computing enhanced computational catalysis

Vera von Burg[1], Guang Hao Low,[2] Thomas Häner[3], Damian S. Steiger[3], Markus Reiher[1,*]
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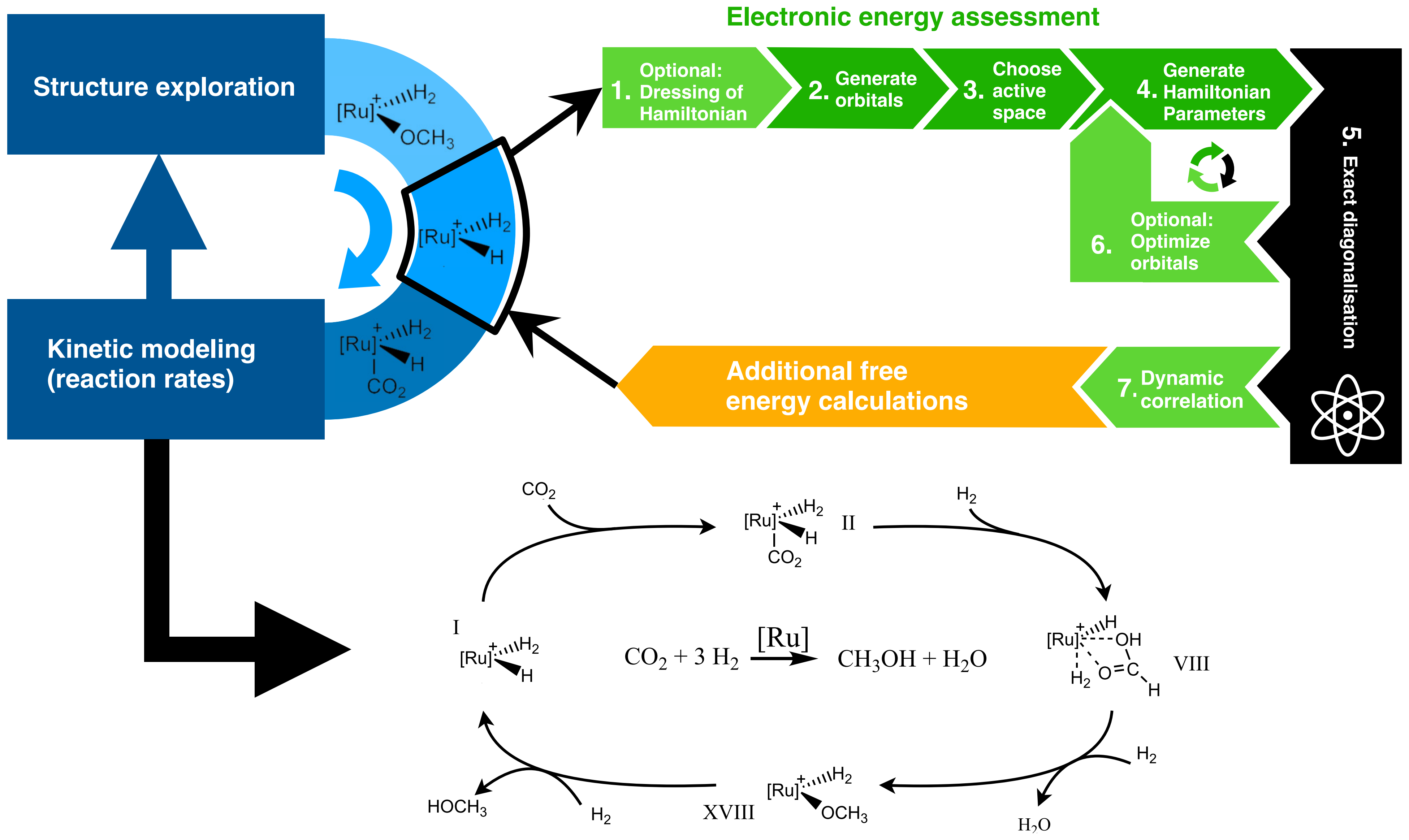
[3] *Microsoft Quantum, 8038 Zürich, Switzerland*



Structure	Approach	α / Hartree	Terms	Qubits	Toffoli gates	Comments
FeMoco	Qubitization H_{DF}	300.5	1.3×10^6	3600	2.3×10^{10}	$\epsilon_{in} = 1$ mHartree
	Qubitization H_{DF}	296.9	2.8×10^5	3600	1.22×10^{10}	Optimistic $\epsilon_{in} = 73$ mHartree
	Trotterization H [11]	–	–	142	1.5×10^{14}	Optimistic Trotter number
	Qubitization H [22]	9.9×10^3	4.4×10^5	5100	2.3×10^{11}	Truncation evaluated by CCSD
	Qubitization H_{CD} [22]	3.6×10^4	4.0×10^5	3000	1.2×10^{12}	Truncation evaluated by CCSD
VIII	Qubitization H_{DF}	425.7	2.5×10^6	4600	4.6×10^{10}	$\epsilon_{in} = 1$ mHartree
	Qubitization H	1.1×10^4	2.2×10^6	11000	9.3×10^{11}	$\epsilon_{in} = 1$ mHartree
	Qubitization H_{CD}	4.2×10^4	1.3×10^6	5800	2.1×10^{12}	$\epsilon_{in} = 1$ mHartree

“Quantum computing enhanced computational catalysis”
arXiv:2007.14460

Common Misconceptions about QC Hardware

- **More qubits = better quantum computer**
  - The “length” of the computation you can run is equally important
  - Also, operation error rate needs to reduce as the system size increase, otherwise marginal value decreases as you add more qubits

- **Longer coherence time = better quantum computer**
  - Energy scale is essential to compute the “effective” computation time
  - Coherence time / operation time ≈ length of computation

- **As long as the quantum computer is “universal” it will be useful for something!**
  - There are many paths to a useless Quantum Computer

- **All computations that are intractable with classical computers are high-value**
  - Many have very little to no-value

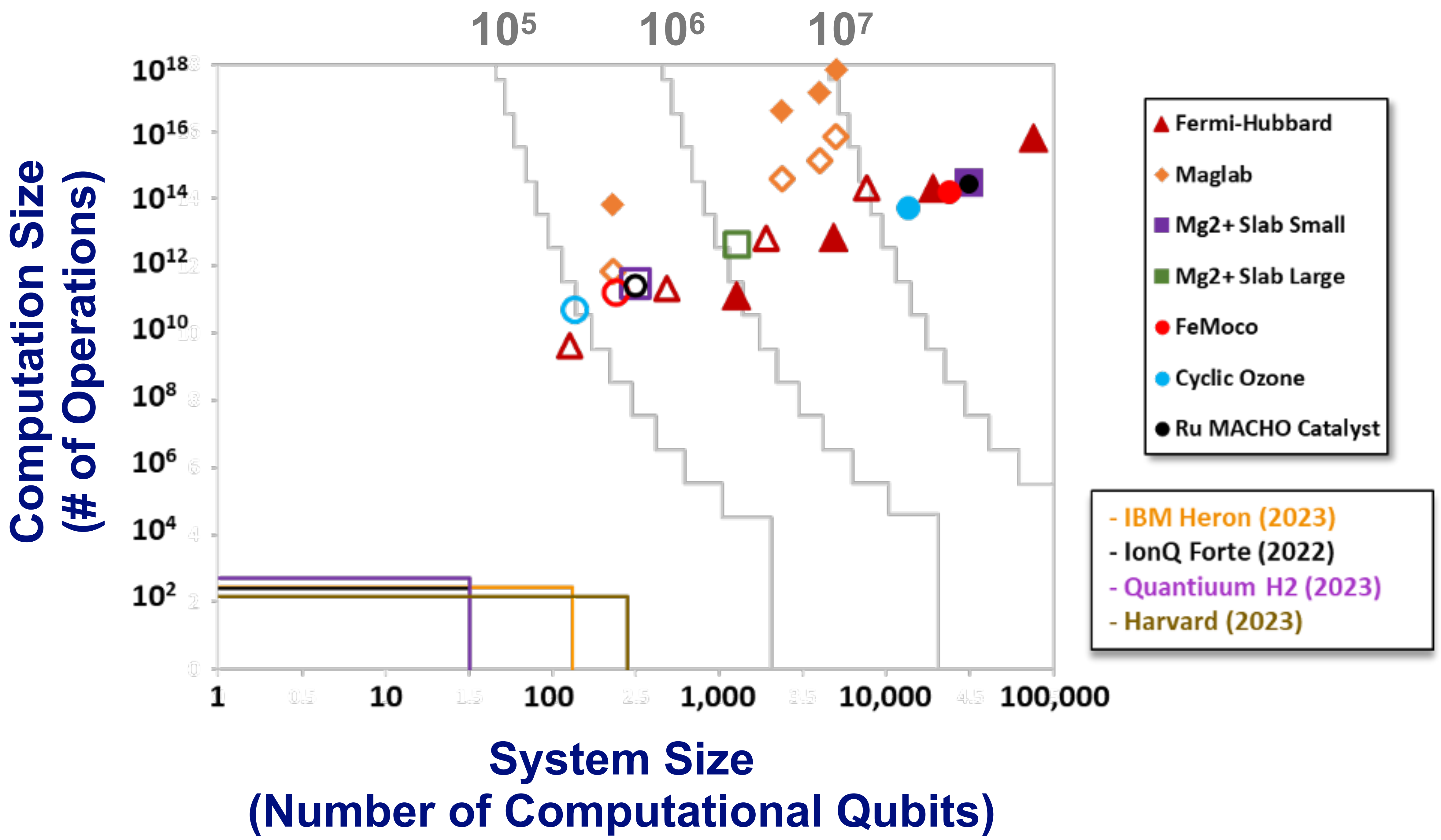
Application Readiness

Current Gap Between Hardware and Applications

- What will it take to achieve *high-impact* quantum computing applications?
- Very limited understanding…
- DARPA's Quantum Benchmarking program is at the bleeding edge
- Preliminary 2023 Findings (right)

Joe Altepeter

Quantum Benchmarking



This research was developed with funding from the Defense Advanced Research Projects Agency (DARPA)

Who will win the Quantum Computing race?

I have no idea!

Everyone has a plausible pitch for why their approach is best

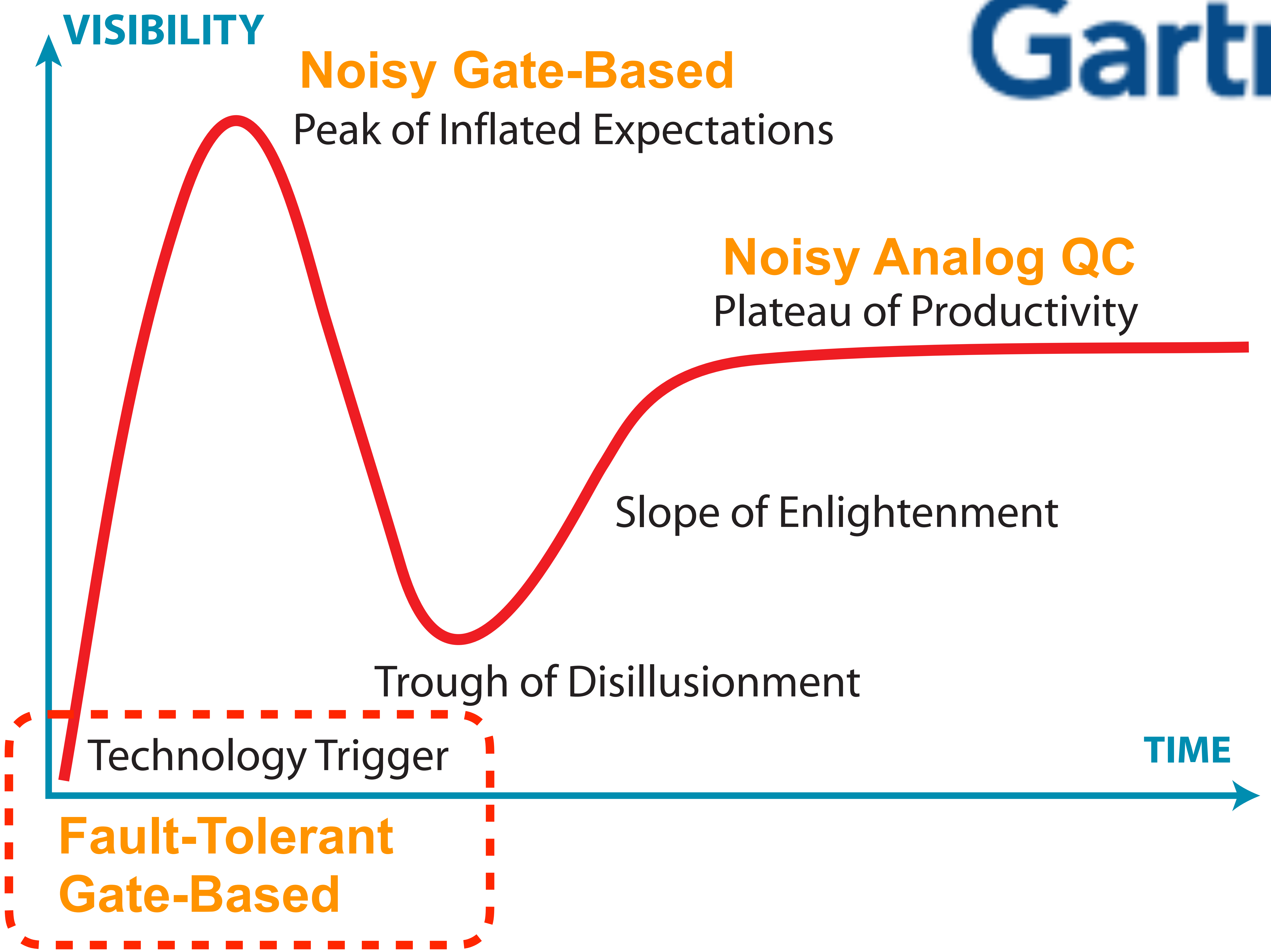
Technology Stage of Quantum Computing Models

Gartner's Technology Hype Cycle

How long before we have a very large and useful Fault-Tolerant quantum computer?

12 months ago most folks would say "10-15 years"

Today it seems much sooner (2026-2030)



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Thanks!

Some Public FTQC Roadmaps

- **IBM**
  - 200 logical qubits by 2029
  - 100M Gates
- **Infleqtion**
  - 100 logical qubits by 2028
  - 1-100M Gates
- **QuEra**
  - 100 logical qubits by ***2026***
  - Gates?