Overview of different QC hardware approaches and QC types of computing

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Information is physical!!

It takes energy to flip a bit from 0 to 1!

→ A computer chip processes and stores energy and dissipates heat!!

Information is physical

Rolf Landauer, IBM, Physics Today 1991

To throw away information costs ENERGY !

Erasing a computer memory destroys infomation!

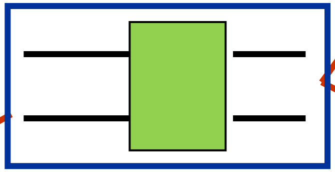
Maxwell’s demon gets hot!!

Reversible - irreversible computing

Gate operations, algorithms

Coherent

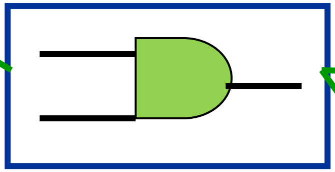
One big memory.
→ All information kept all the time.
Logically reversible
”No dissipation”



Logically reversible

µP
Micro processors

Logically irreversible



Incoherent

Information destroyed all the time.
Logically irreversible.
Dissipation

Quantum computer, COHERENT,
-> Superposition, Entanglement
Atom traps, nuclear spins
Josephson Junction circuits
Semicond QDs, impurities

Reversible classical computer
QUANTUM INCOHERENT
Ballistic
Brownian
Wave computer:
Classically coherent

Scaled down µP, INCOH.

Quantum device µP,
INCOHERENT
RTD, RTT, QD, SET
SFQ, Josephson flux circuits
Spin valves, Molecular Electronics

Moore's Law is not dead!!

Moore's Law originally described **exponential** scaling of computer **hardware** - # of transistors

Moore's Law now describes **exponential** scaling of computer **performance** via parallelization.
Currently leading HPCs employ ≥ 10 000 000 cores

→ Implies exponential scaling of electrical power!

HPC needs lots of electrical power

The **FRONTIER exascale HPC** at Oak Ridge needs **21 MW electrical power.**

→ Needs a powerstation of its own!

→ Supercomputer upscaling may run out of electrical power!!

→ Internet, Social media, Internet of things, AI, ……

→ This is becoming a real problem!

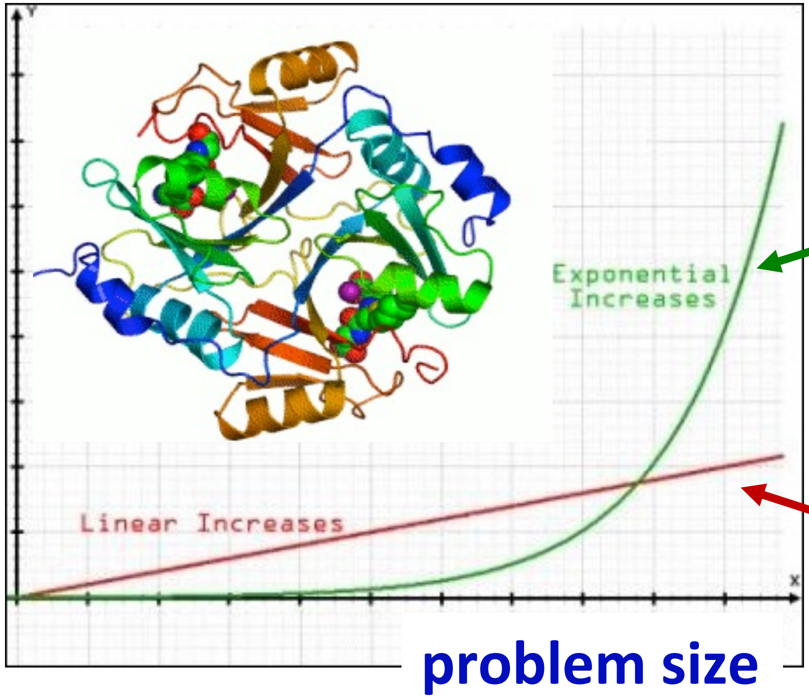
Why do we need quantum computers ?

Quantum Computers (QC) can (probably) provide **exponential speed-up** for approximately(!) **solving (some) hard problems** with **finite resources** (time, memory, **energy**).

Quantum Advantage (QA)

Quantum computers offer, in principle, Quantum Advantage for certain classes of hard problems

Time-to-solution TTS



TTS for a HPC:
Grows exponentially

TTS for a quantum computer:
Grows linearly/polynomially

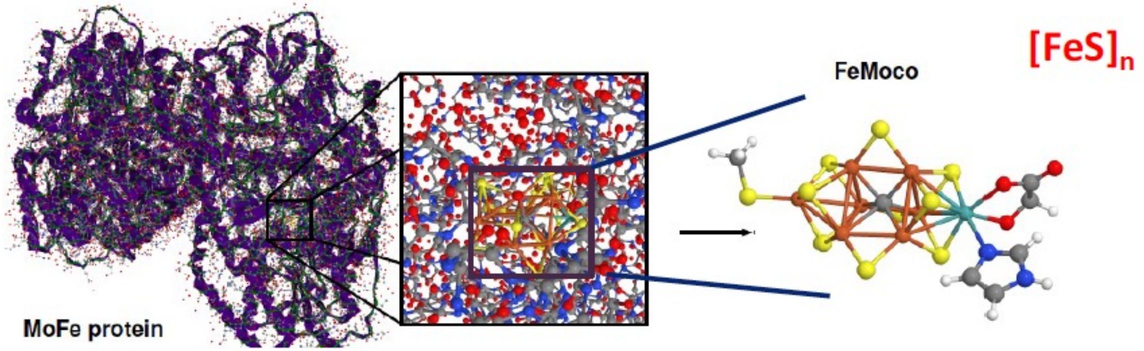
No Quantum Advantage

Killer applications - use cases

The original "killer application": Shor's algorithm for factorisation (1995)

Today, the typical killer applications are "use cases":

- **Quantum Chemistry** – designing enzymes and catalysers; pharma
- **Materials science** – describing strong electron correlations; new materials
- **Optimization** - logistics, scheduling, big data, machine learning, ….



Complexity classes

HPC efficient

Hard for HPC
QC efficient

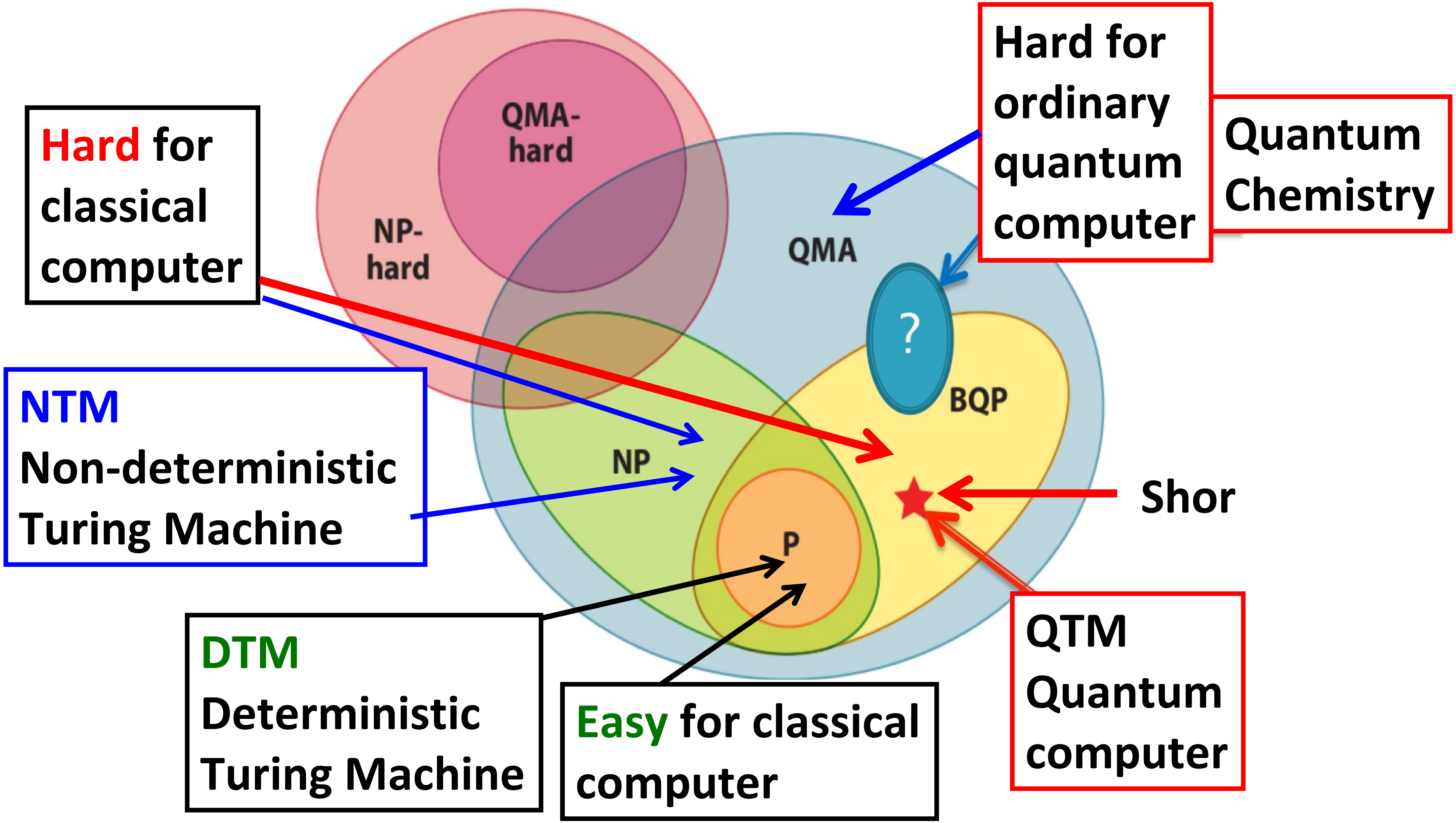
Hard for QC

Complexity classes

P — Polynomial time

BQP — Bounded error, Quantum Polynomial time

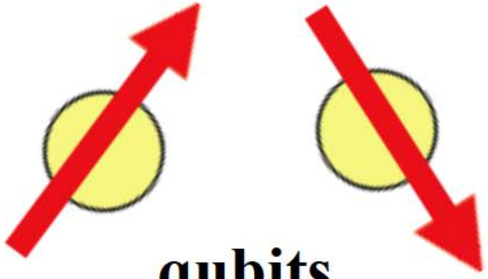
QMA — Quantum Merlin Arthur


QMA-
hard
NP-
hard
QMA
?
BQP
NP
P
Hard for classical computer
NTM
Non-deterministic Turing Machine
DTM
Deterministic Turing Machine
Easy for classical computer
Hard for ordinary quantum computer
Quantum Chemistry
Shor
QTM
Quantum computer

The physical workings of a quantum computer

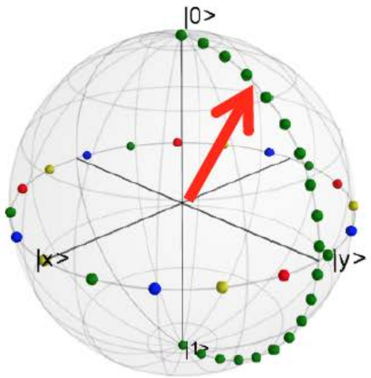
QC makes use of some fundamental properties of matter at "atomic & molecular" levels (like NMR):

- -Quantum physics
- -Coherence
- -Superposition
- -Parallelism
- -Entanglement



qubits

Bloch sphere



qubit = 2-level system

|1>

|0>

$|\psi(t)\rangle$ a|0> + b|1>

State vector on the unit sphere

QC solves problems by generating and interpreting **dynamics of quantum wave patterns** in registers of quantum bits (qubits) – "quantum matter"

$$i\hbar\frac{\partial}{\partial t}\Psi(\mathbf{r},t) = \left[\frac{-\hbar^2}{2\mu}\nabla^2 + V(\mathbf{r},t)\right]\Psi(\mathbf{r},t)$$

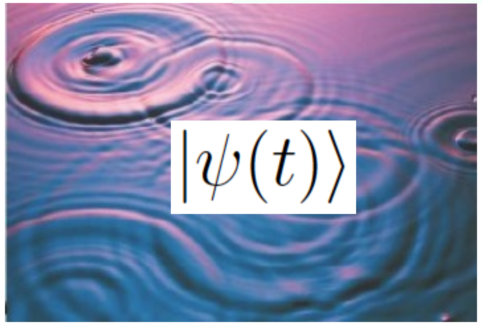
Schrödinger wave equation

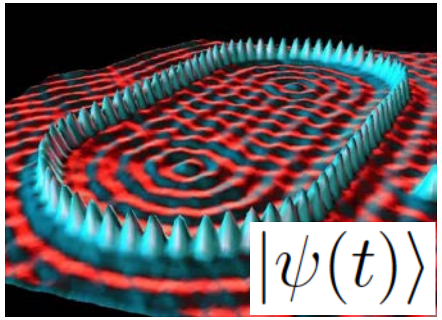
Superposition & entanglement !!!

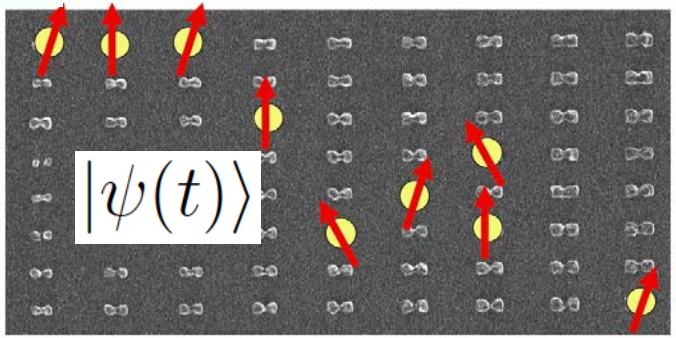
a_1 l00..000> +
a_2 l00..001> +
a_3 l00..010> +
a_4 l00..011> +
.... +
a_{n-1} l11..110> +
a_n l11..111>

$\boxed{|\psi(t)\rangle}$

$n=2^N$



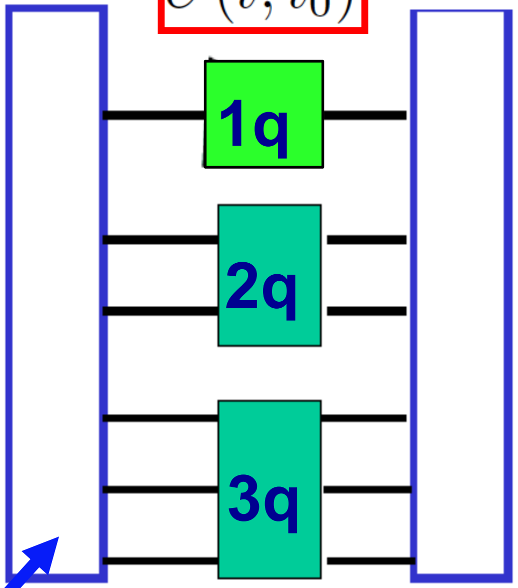




Quantum gates and states: superposition and entanglement

N qubits, n = 2^N states

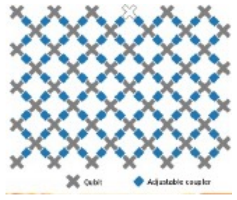
$|\psi(t_0)\rangle > \boxed{\hat{U}(t,t_0)} |\psi(t)\rangle$



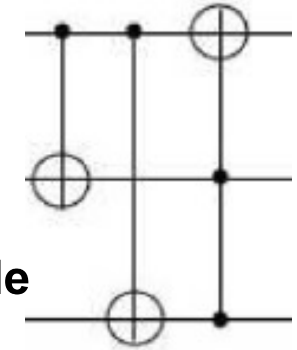
|00..000> +
|00..001> +
|00..010> +
|00..011> +
.... +
|11..110> +
|11..111> =
|0+1>|0+1>...|0+1>

Product state
Not entangled

Qubit register ("memory")



Reversible gates



U

Rotation

NOT, Hadamard

CNOT
CPHASE

C-Rotation

c-c-NOT
c-swop

$|\psi(t)\rangle >$ = $f_1(t)$ I0...00>
+ $f_2(t)$ I0...01>
+ $f_3(t)$ I0...10>
+ ....
+ $f_n(t)$ I1...11>

Super-position of 2^N states; Not possible classically

Superposition of 2^N state configurations - entanglement

$$|\psi(t)\rangle = U(t,t_0)|\psi(t_0)\rangle$$

$$\boxed{U(t,t_0) = e^{-\frac{i}{\hbar}\hat{H}(t-t_0)}}$$

Generic quantum gate

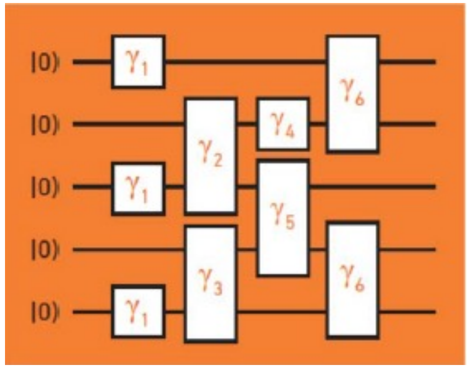
The terms in the **Hamiltonian $\hat{H}$** defines the **problem** and the **control operations**.

Machine Learning used to design multi-qubit gates and quantum circuits.

HPC + QC hybrid computing

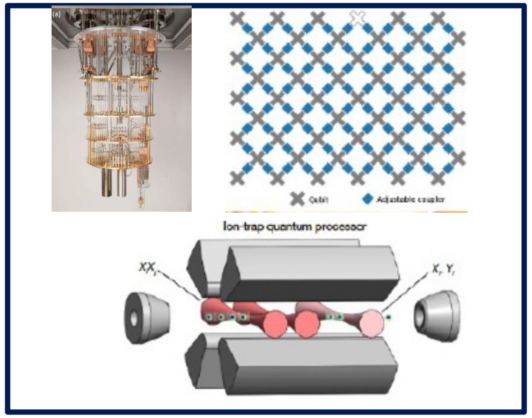
Cloud access

HPC: Classical gates



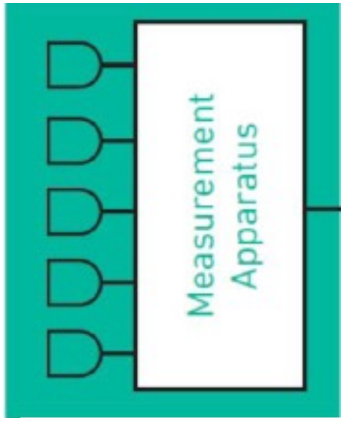
Classical pre/post-processing of quantum state

QC: quantum gates



a_1 |00000> +
a_2 |00001> +
a_3 |00010> +
a_4 |00011> +
.... +
a_n |11111>

$n = 2^5 = 32$



Execution of quantum gates

Readout of state -> classical info

HPC + QC hybrid computing

HPC: Cloud access with high-speed classical processing

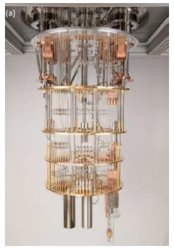
QC computer with internal ***super-high-speed*** classical (CC) processing

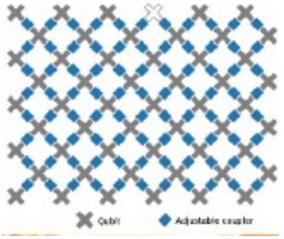
Cloud access

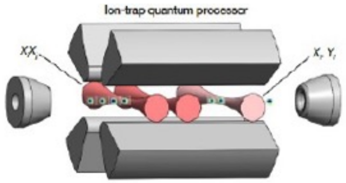
High speed optical link

Floating HPC/QC division

- **FPGA**
- **Classical control**
- **Super-fast CC-QC hybrid processing**
- **Quantum error mitigation (QEM); Quantum error correction (QEC)**
- **Very low latency**



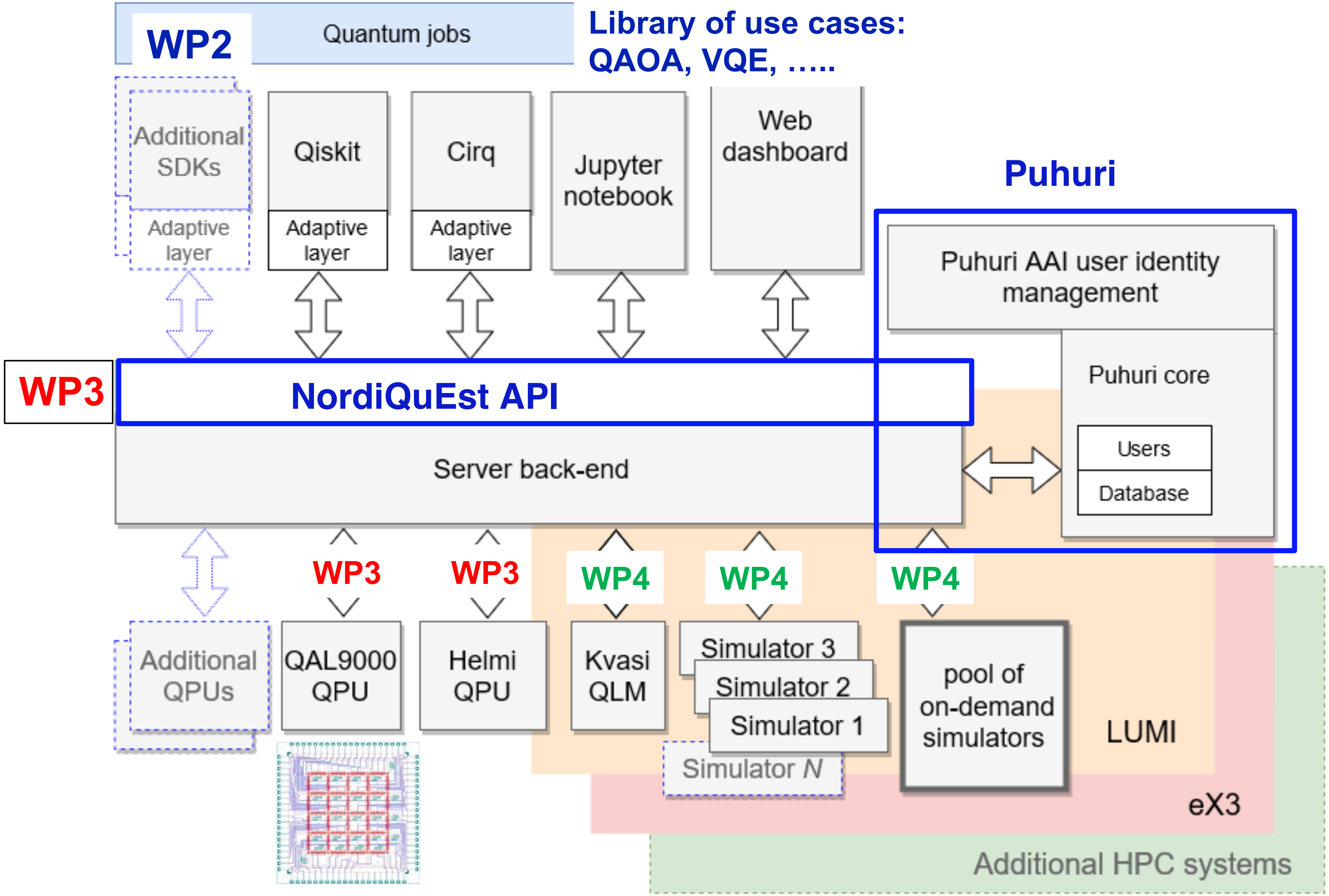




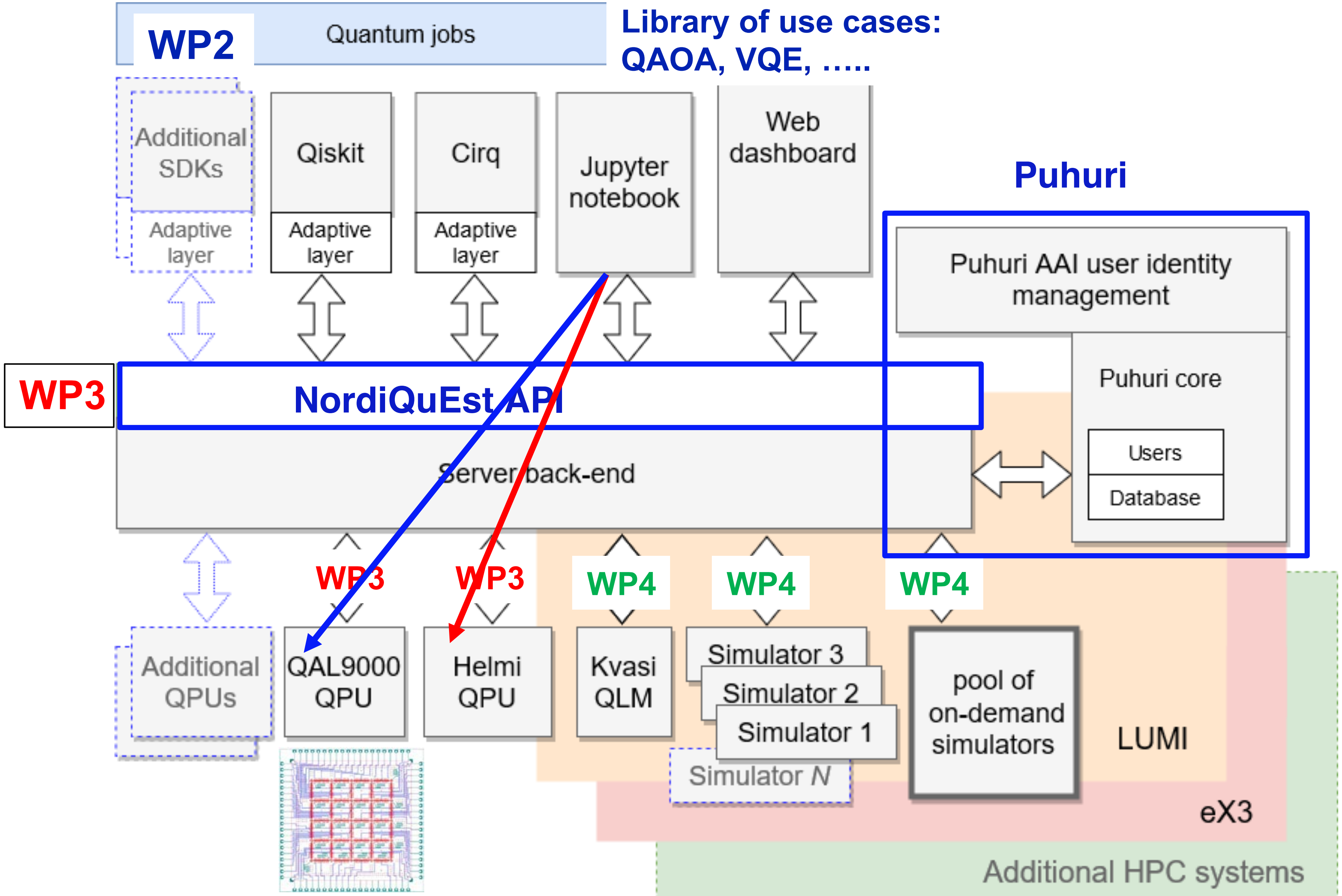
Classical pre/post-processing
Fast CC-QC hybrid processing
Quantum error mitigation

Note: execution of quantum gates in the QC is done by classical code controlling classical electronics.

NordIQuEst in a (hard) nutshell

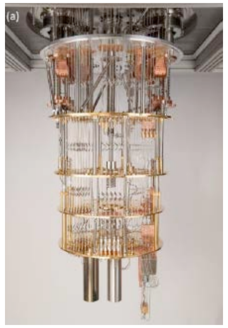


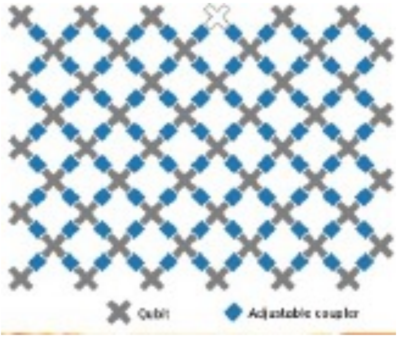
NordIQuEst in a (hard) nutshell



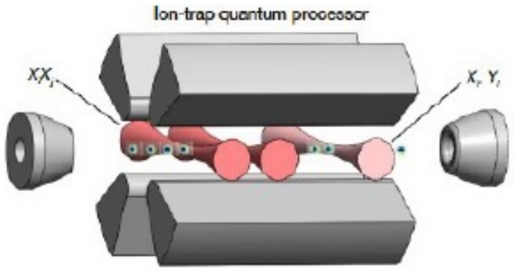
Qubits/architectures for quantum computing

Superconducting architectures

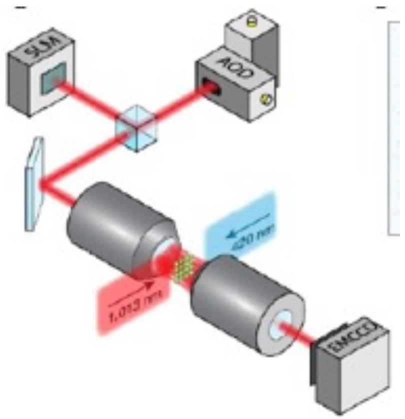




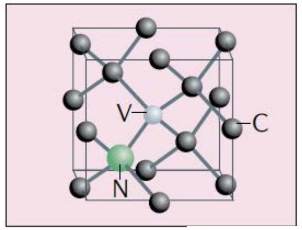
Ion trap architectures

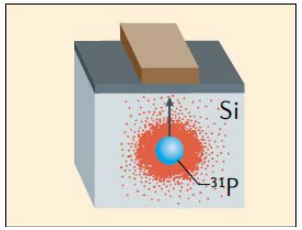


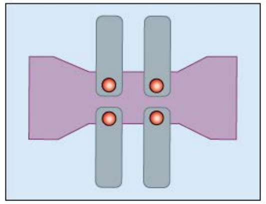
Neutral atom architectures

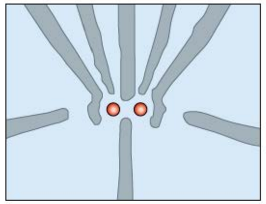


Semiconductor architectures

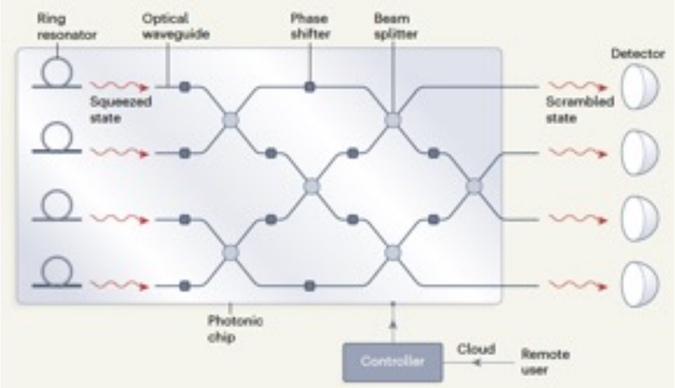








Photonic architectures



The Future of competitive Quantum Computing ….

WHAT IS NEEDED:

1000+ perfect qubits with “infinite” coherence time to compute during seconds, minutes, hours, days, weeks, months, …, executing millions-to-billions of CNOT gates

WHAT IS POSSIBLE TODAY:

NISQ (Noisy Intermediate-Scale Quantum) devices:

→ Often described by the Quantum Volume (QV) metric (IBM)

→ QV = 2^N, where N=# of qubits entangled with 67% probability

→ IBM can currently ”only” entangle 9 qubits (QV = 512 = 2^9).

→ Quantinuum (ion trap) can currently entangle 19 qubits (QV = 524288 = 2^{19}).

WE MAY NEED TO ENTANGLE 100 QUBITS FOR DECISIVE BREAKTHROUGHS!!

And **QV=2^{100}** involves a huge number of almost PERFECT (!!) CNOT gates ……

The Future of competitive Quantum Computing ….

For **competitive digital QC**, prepare for a marathon ….

Quantum Error Correction (QEC) → 10 years ….. mid 2030ies ….. ?? ☹

But on the way, there will be great discoveries …. ☺

However, analog-digital simulators may provide near-future non-universal shortcuts to Quantum Advantage.

Recommended reading:
Andrew J. Daley, Immanuel Bloch, Christian Kokail, Stuart Flannigan, Natalie Pearson, Matthias Troyer, and Peter Zoller,
Practical quantum advantage in quantum simulation,
Nature **607**, 667–676 (2022).

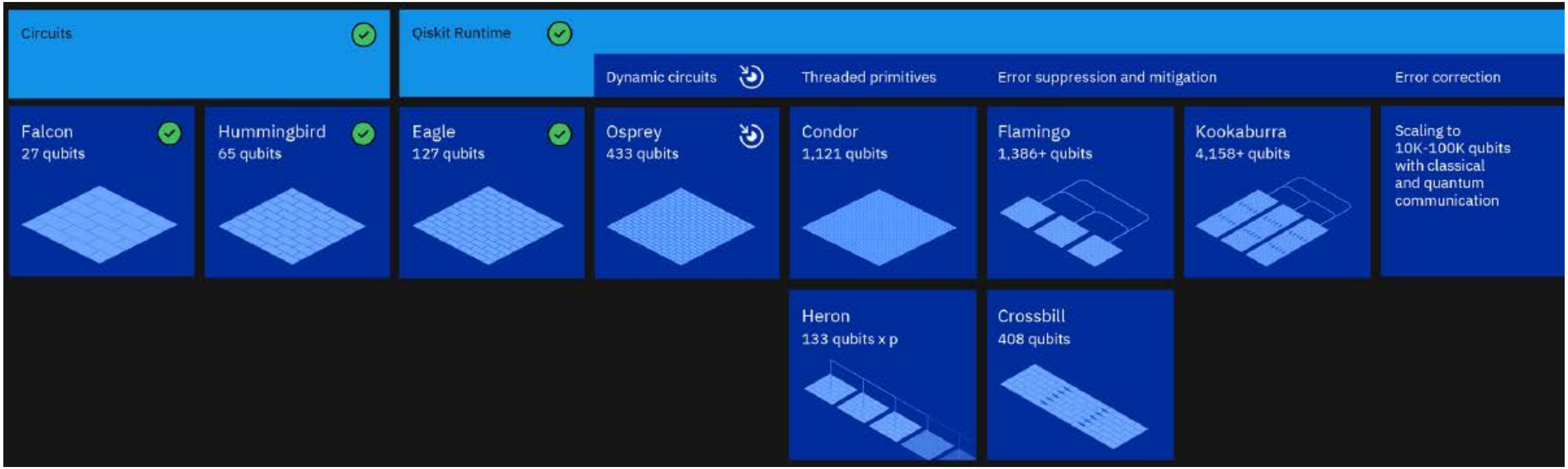
Also, the following review:
Quantum information processing with superconducting circuits: a perspective
G. Wendin; https://arxiv.org/abs/2302.04558

discusses "Simulating physical systems on engineered superconducting quantum platforms".

The IBM HPC + QC agenda

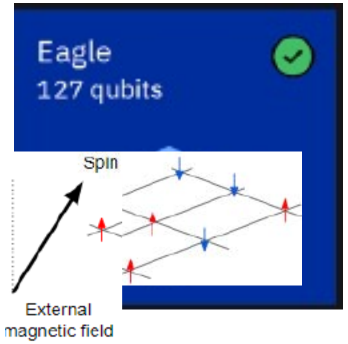
IBM is currently scaling up their superconducting NISQ QPUs:
127q (2022), 433q (2023), 1121q (2024?); > 4000q (2025?)

Part of IBM Q Experience: Education, Training, preparing for future Quantum Advantage (QA).



The Future of competitive Quantum Computing ….

Recently IBM published a paper on digital-analog simulation of average magnetization of a **2-dimensional transverse-field Ising model (TFIM) with 127-spins** programmed on a **127 qubit Eagle processor**:



Evidence for the utility of quantum computing before fault tolerance
Kim et al. *Nature* **618**, 500–506 (2023)
implying that scalable **error mitigation** (noise extrapolation) for noisy quantum circuits produces competitive expectation values for measurable quantities.

This experiment is **impossible** by brute-force HPC simulation for memory reason and indicates emerging **Quantum Advantage of scale (but not time).**

However, soon after appeared the following paper classically reproducing the 127q IBM result.
Efficient tensor network simulation of IBM's Eagle kicked Ising experiment,
Joseph Tindall, Matthew Fishman, E. Miles Stoudenmire, and Dries Sels, arXiv: 2306.14887

So we are now waiting for the 433 Osprey to show what it can do ….. ☺ with lots of error mitigation

→ In the near term, **Quantum Advantage** may take the form of NISQ devices emulating interesting physical systems intractable by HPC supercomputers – "Quantum wind tunnel experiments".

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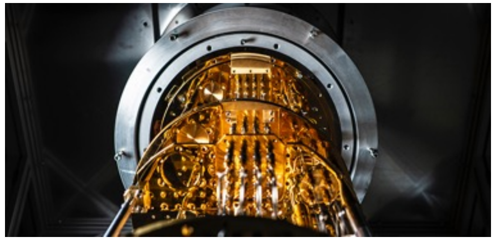
NordIQuEst

LUMI-Q



Thanks for listening

Questions?
Comments?

OpenSuperQPlus
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