New Technologies area

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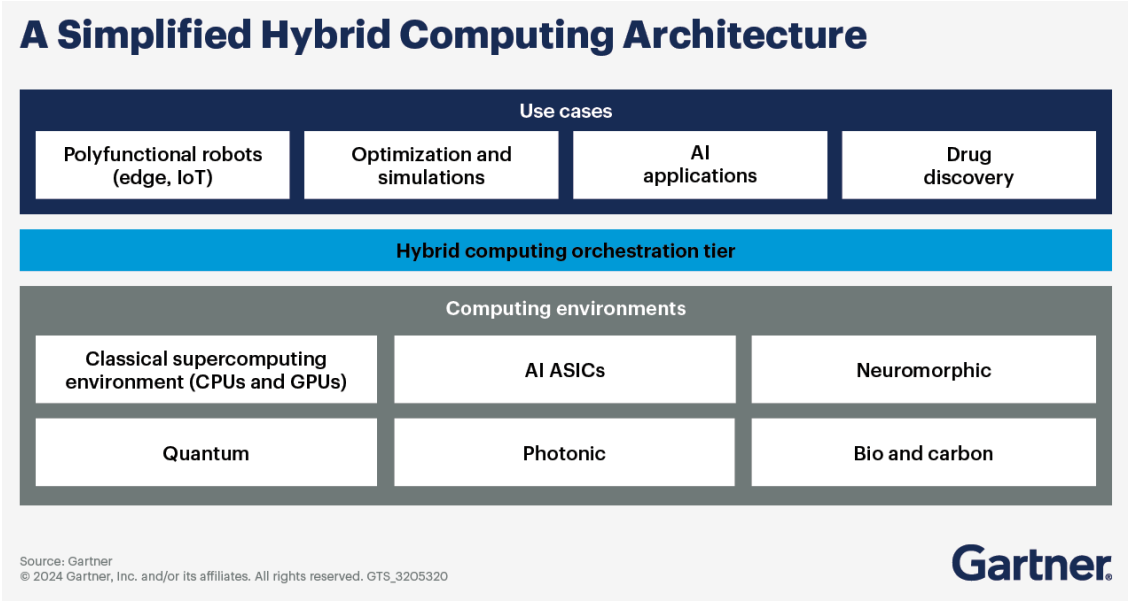
Introduction

"The next era of computing will **combine conventional computing technologies with quantum, neuromorphic and other computing mechanisms** …» *Gartner, October 2024*

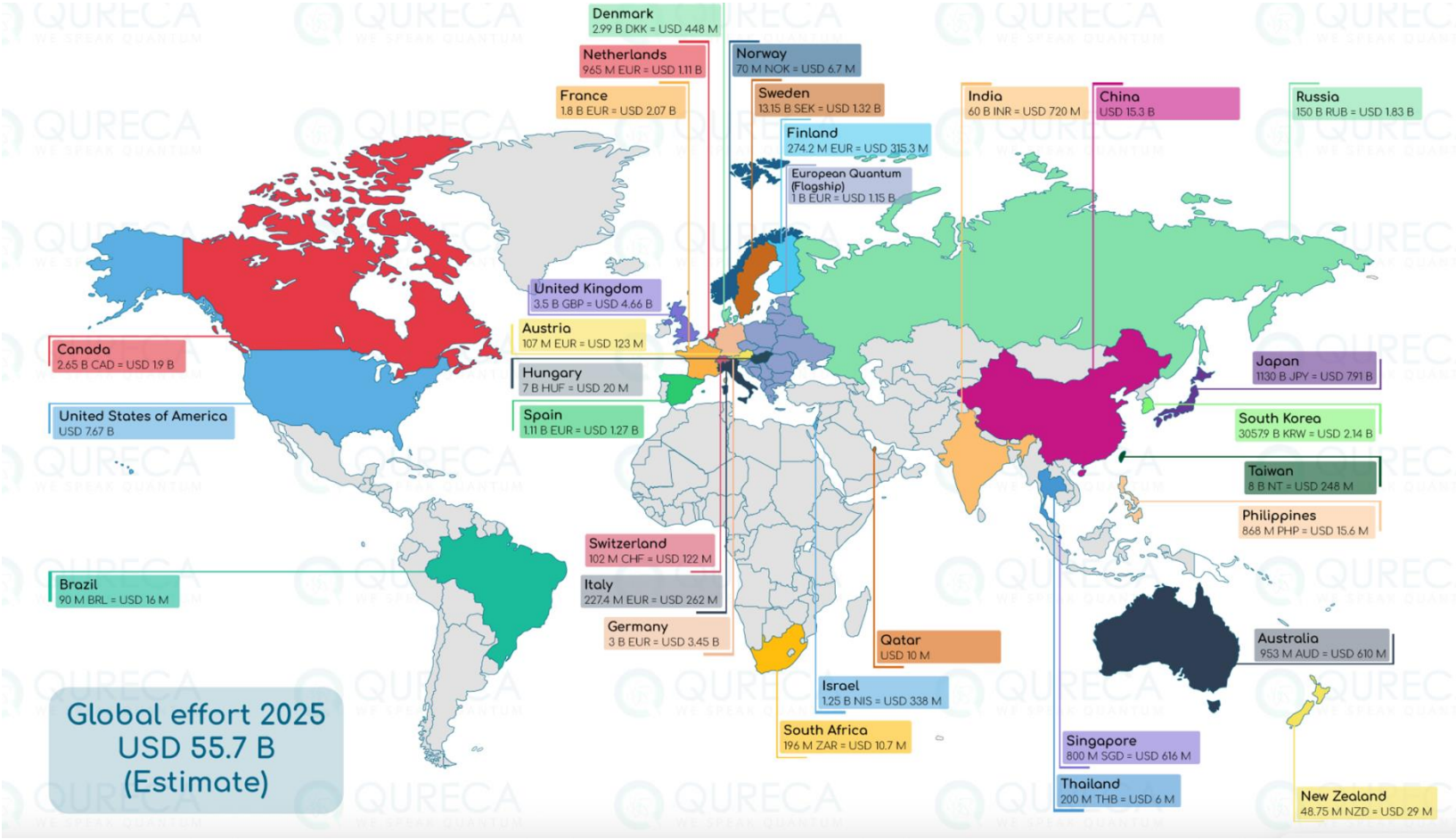


- HEP has a long history of **exploiting cutting edge technologies**
  - Some had a fundamental impact. Recently e.g. full **SW triggers** in LHCb, **GPU based HLT** in CMS, **AI** for data processing/analysis
- Today we study interesting approaches such as e.g. **Quantum Computing, Neuromorphic**
  - Others (FPGA, GPUs, …) are not «new», but their use in HEP is still «relatively» limited.
- Based on the input we received, we focus on **Quantum Computing**
  - Keeping in mind that over HEP experiments time scales different «new technologies» might mature.

Efficiently integrating new technologies requires time!

Worldwide Quantum Technologies ecosystem

- A **strategic sector**
- A large **number of initiatives** on quantum technologies (**computing, sensing and communication**) in **CERN Member States and worldwide**
- **Applications in multiple fields** of fundamental science, industry and society



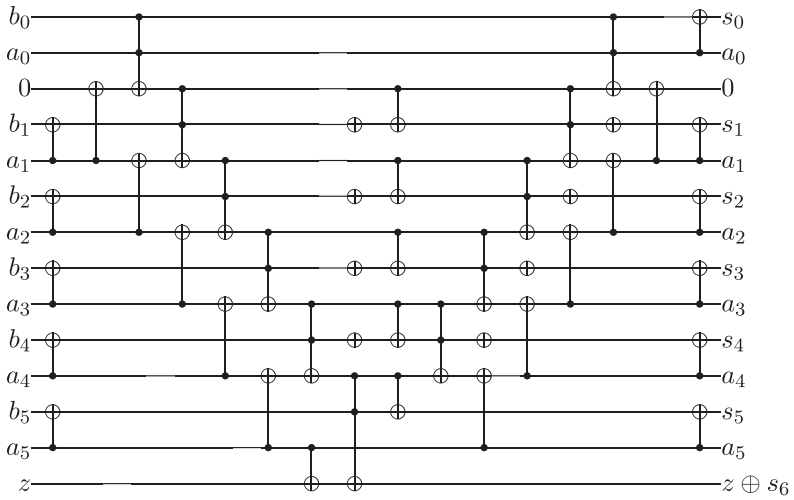
https://www.qureca.com/quantum-initiatives-worldwide

CERN QUANTUM TECHNOLOGY INITIATIVE

CERN has its own Quantum Technology Initiative (https://quantum.cern), complementing those in CERN Member States

Main Quantum Computing Paradigms

Gate-based quantum computers

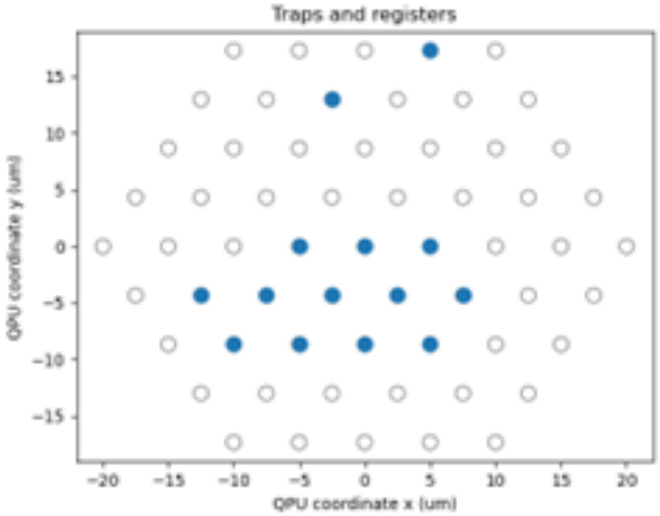


The ripple-carry adder for $n = 6$.

Algorithms are built as series of quantum gates (unitary transformation)

IBM QUANDELA

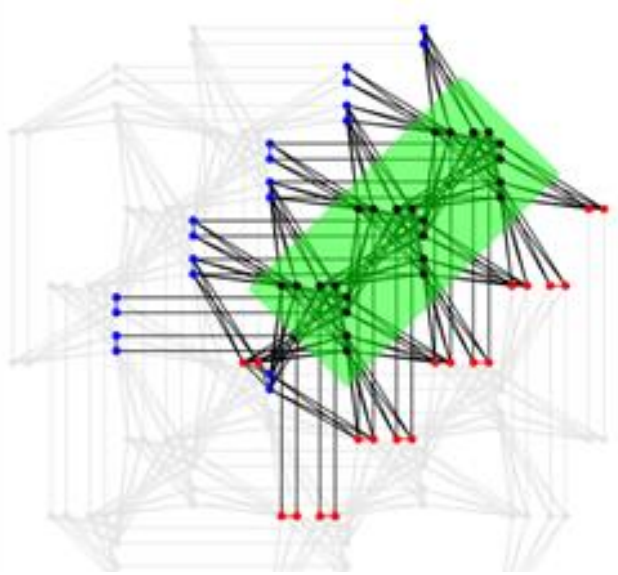
Analog quantum simulators



Problems embedded as graphs, solved as Ising or QUBO, using dynamic qubit positioning but no or poor local qubit control

Pasqal IQUERA

Quantum annealers

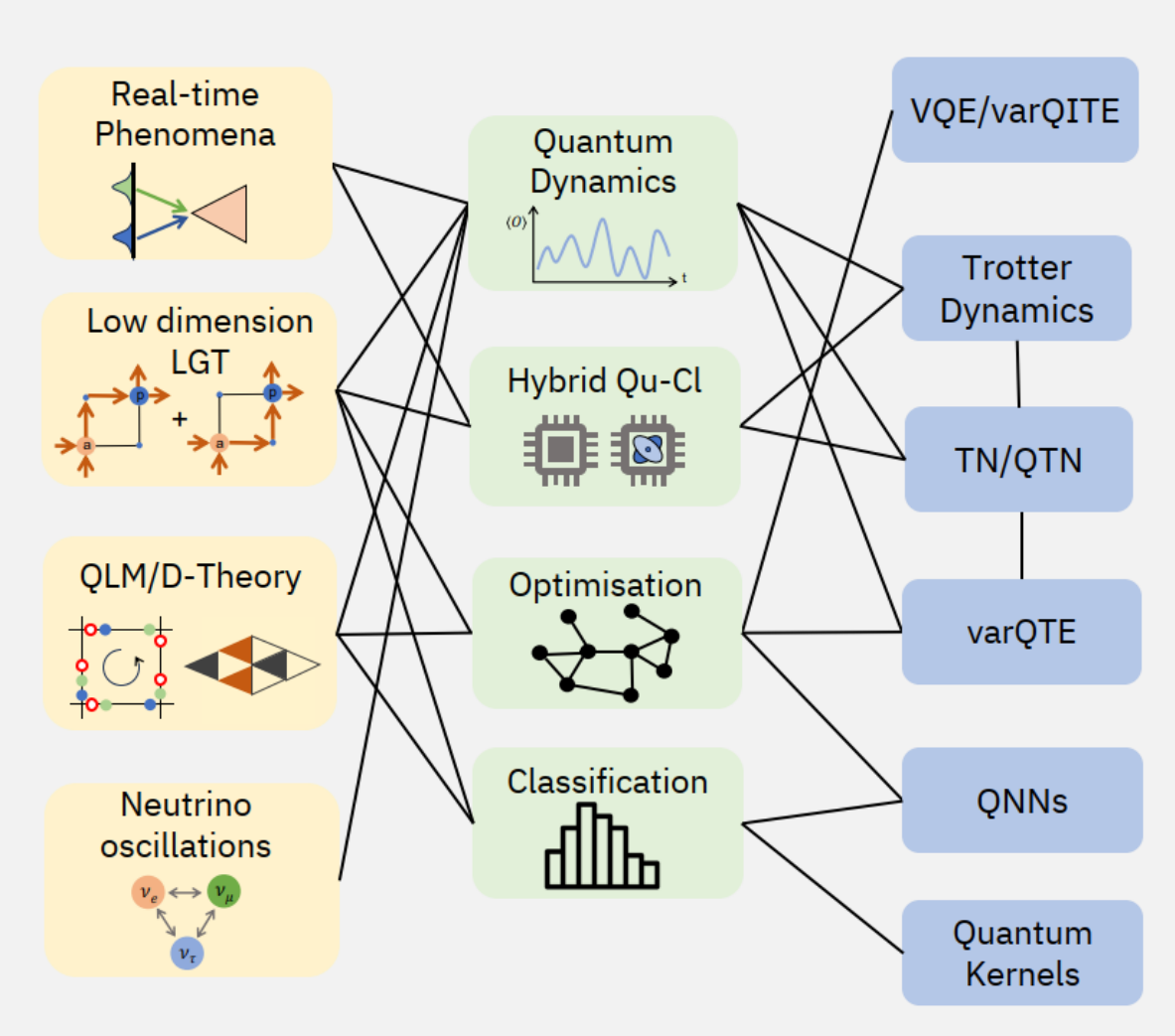


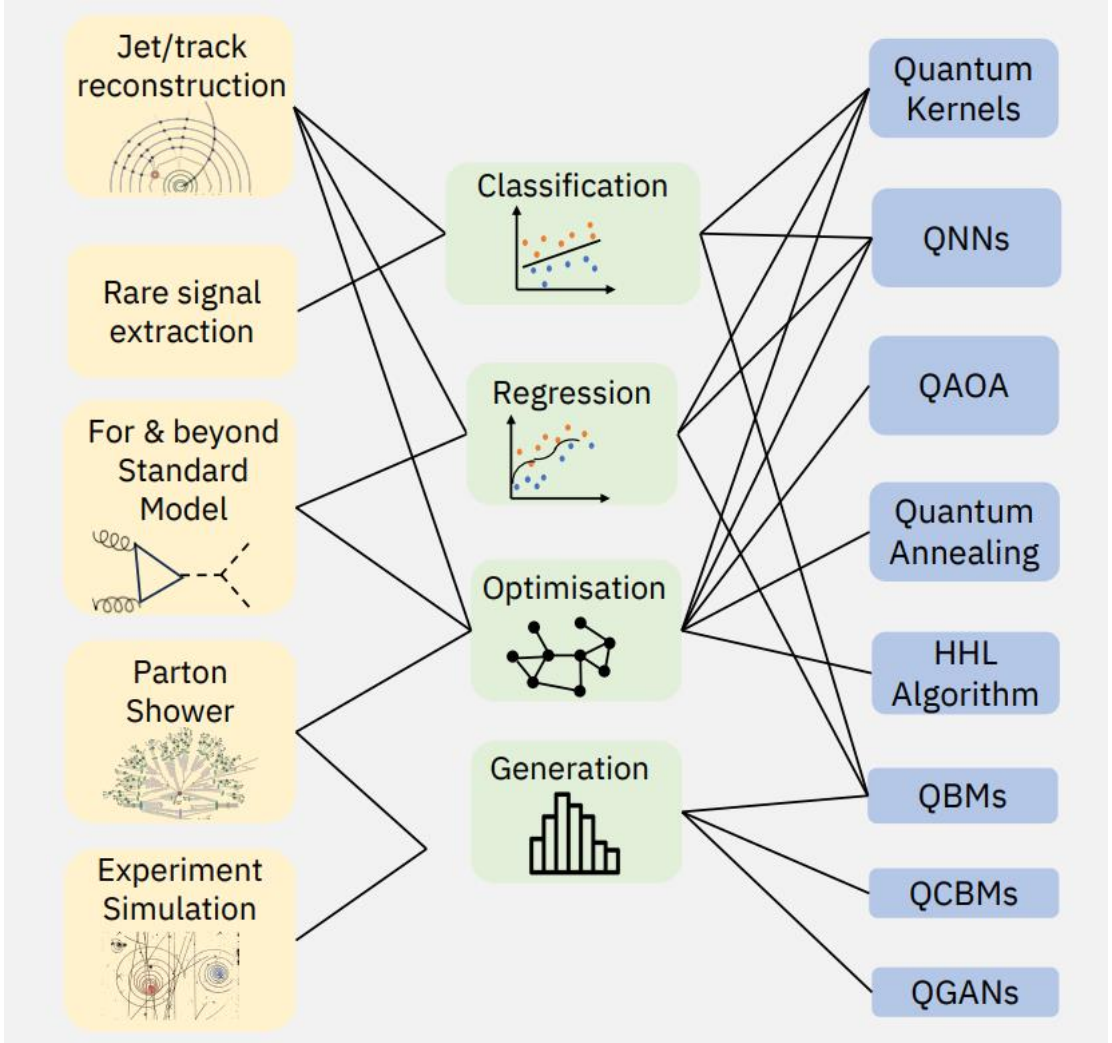
Problem embedded as Binary Quadratic Models, solved as Ising or QUBO, using static qubit connectivity and local control

D-Wave The Quantum Computing Company™

Quantum inspired : classical methodologies inspired by quantum system behavior

A wide range of quantum algorithms useful for HEP

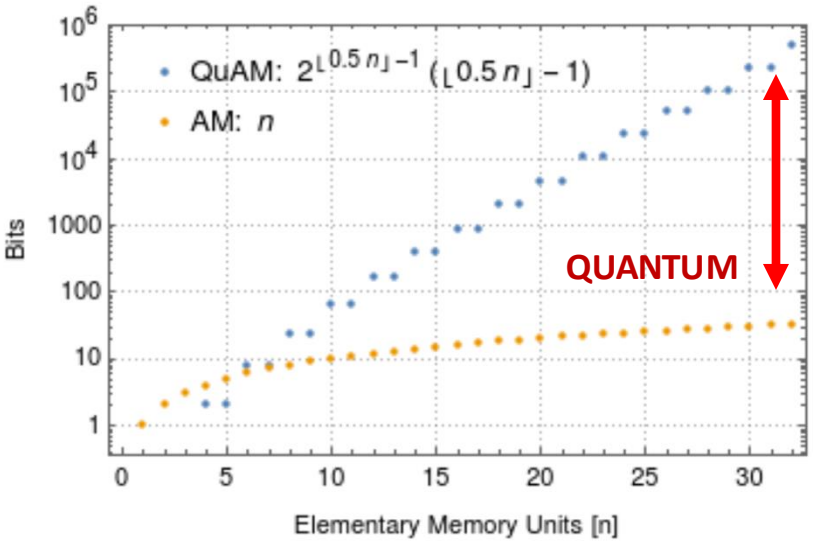




"Quantum computing for high-energy physics: State of the art and challenges." PRX Quantum 5.3 (2024): 037001.

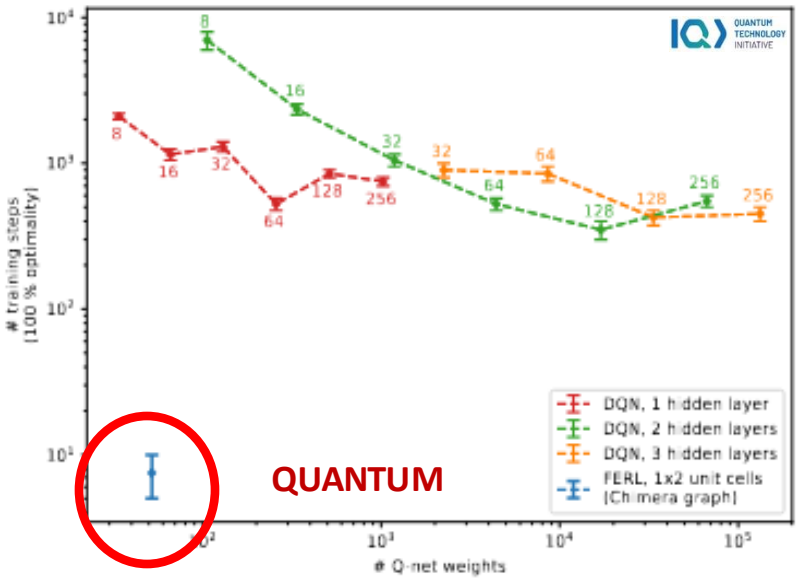
What does «useful» mean in this context?

The **definition of quantum advantage has extended** from «finding problems that cannot be reasonably solved on classical hardware» toward **proving usability for realistic problems.**



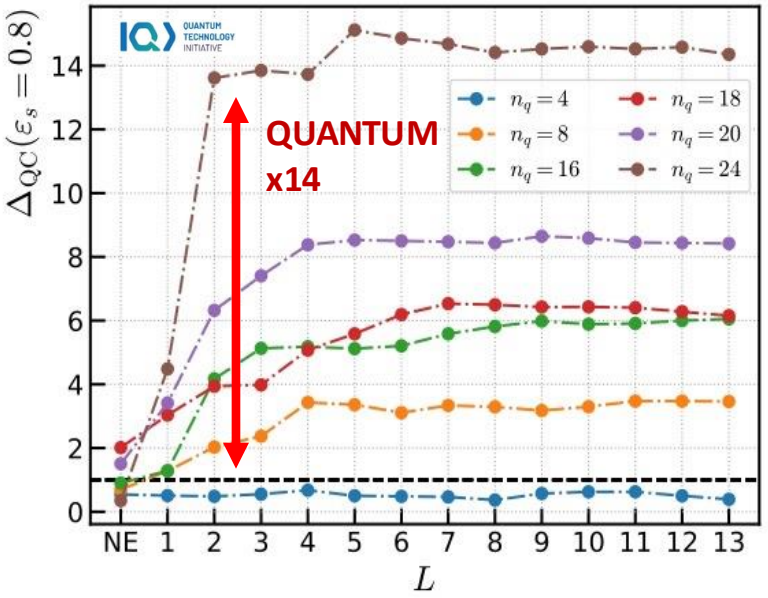
Exponential Memory
(Quantum **associative memory** for tracking)

arXiv:1902.00498 [hep-ex]



Resource efficiency
(Quantum **reinforcement learning** for beam steering in accelerators)

Quantum Science and Technology 9.2 (2024): 025012.



Improved discovery capability
(Quantum **anomaly detection**)

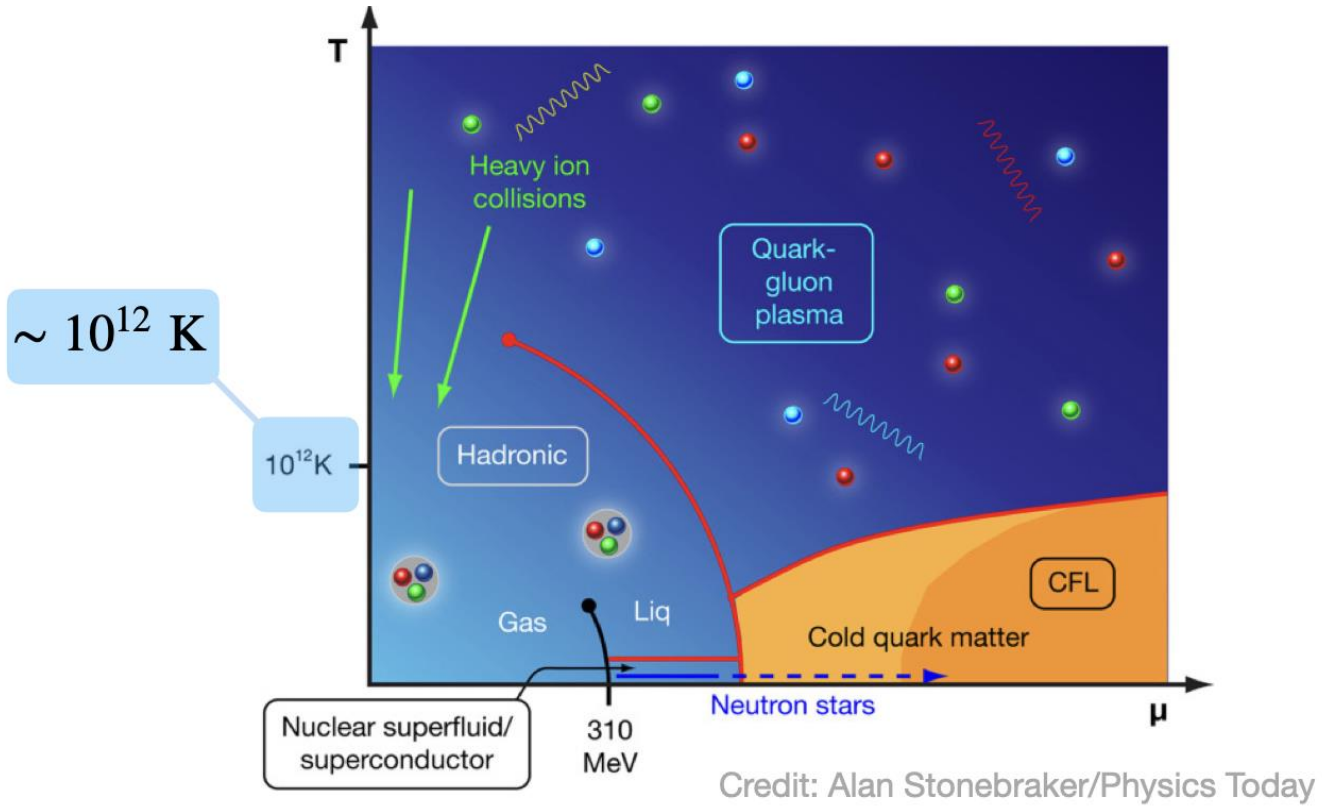
Communications Physics 7.1 (2024): 334.

And we need quantum computers in theoretical physics…

A particularly hard field is the **simulation of quantum systems**

Classical computing limitations have been identified and broadly described:

- First-principles **simulations of nuclei** as **complexity grows factorially** with number of quarks
- Studies of **dense matter, phase diagram of strong interactions not yet fully feasible**
- **Real-time dynamics of matter**, dynamical response functions, transport properties, structure functions, **not fully accessible.**



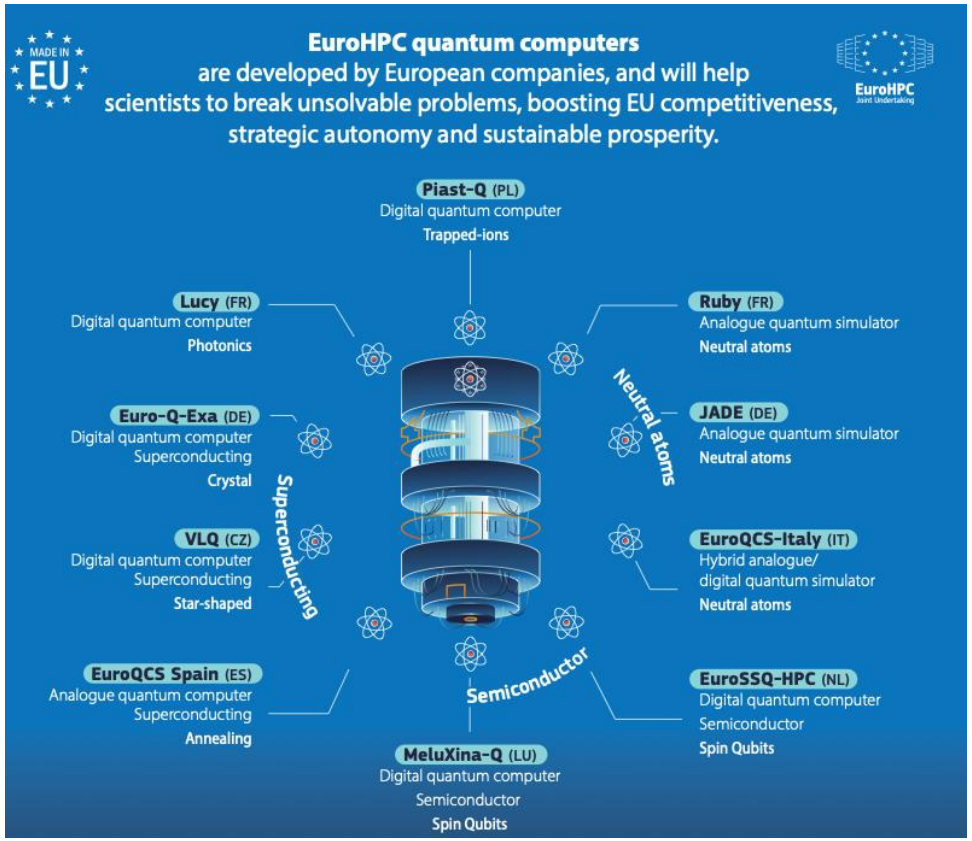
Credit: Alan Stonebraker/Physics Today

A recent review is available here: https://indico.cern.ch/event/1519819/

How do we use quantum computers today?

Today quantum computers are part of a broader computing model (Cloud, HPC, …)

- **Hybrid classical-quantum setup extends the reach** of near-term quantum infrastructure (through pre/post-processing, data compression, error mitigation, …)
- **Develop hybrid algorithms** (e.g. Quantum Machine Learning) for near-term quantum devices (limited in coherence time, number of qubits, connectivity)
- **Study scaling** toward fault-tolerant era (allowing full error correction at a sizeable scale)



https://eurohpc-ju.europa.eu/eurohpc-quantum-computers_en

HEP community and CERN QTI are actively contributing to this field

A summary of the received input

- Mostly from **National Programs, focus on quantum technologies**.
- Strong connection between **Quantum Computing and Quantum Sensing**
- Importance of **integration between QC and classical infrastructure**
- **General goals** (e.g. «contribute to better computing» or «possible solution to sustainability»)
- **Several suggestions on most promising applications**
  - **ML in conjunction with QC** is one of the main areas (potential improvements: speed, complexity, ..)
  - **Quantum Simulation** for theory applications (lattice QCD, Parton Showers, Event Generation,..)
- The **need of coordinated efforts and structured initiatives** (such as CERN QTI) are recognized in several submissions (e.g. UK National input)
  - **Ensuring cooperation with National Initiatives** and research in both **academic and private sector**

Further investigations are recognized as «critical». QT time scale matches HEP's!

Thanks!

Two contributions covering different approaches beyond digital quantum computers:

Quantum Inspired ML on FPGA Marco Zanetti, INFN-Padova

Quantum Reservoir Computing in hybrid settings Ameer Azzam, IFAE