Quantum Computing @ CINECA

Integrating a Quantum Accelerator into an HPC Environment

Daniele Ottaviani

CINECA QUANTUM COMPUTING LAB

Cineca Quantum Computing Lab

Teaching, Outreaching and Dissemination

CINECA ACADEMY

European and National projects

HPCQS

EURO

Fondazione ICSC
Centro Nazionale di Ricerca in HPC, Big Data and Quantum Computing

QUANTUM COMPUTING AND SIMULATION CENTER

QUANTUM COMPUTING LAB

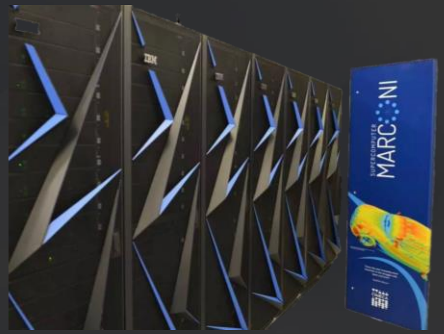
Quantum Computing Resources

Cloud QC

D-Wave
The Quantum Computing Company™

PASQAL

HPC QC Emulation



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⟨HPC|QS⟩

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Quantum Computing Resources

Cloud QC

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?

PASQAL

Hybrid HPC-QC System

Available emulators on Leonardo

Already available

- Cirq (Google) – GPU, cuQuantum
- Ocean (D-wave)
- Qiskit (IBM) – MPI, GPU, cuQuantum
- Pulser (Pasqal)
- Qibo – GPU, cuQuantum
- Pennylane – MPI, GPU, cuQuantum
- Quantum Matcha Tea – MPI, GPU

Work in progress:

- QuEST – MPI, GPU
- Cuda Quantum – MPI, GPU, cuQuantum

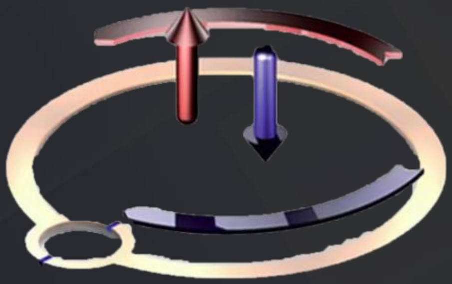
EuroHPC
Joint Undertaking

The EuroHPC JU has selected six sites across the European Union to host and operate the first EuroHPC quantum computers in:

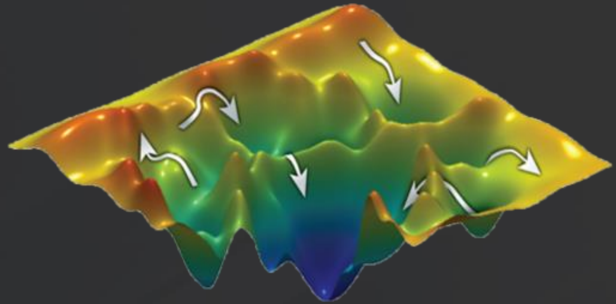
- Czechia
- France
- Germany
- Italy
- Poland
- Spain

EuroQHPC-I

EuroQCS Italy

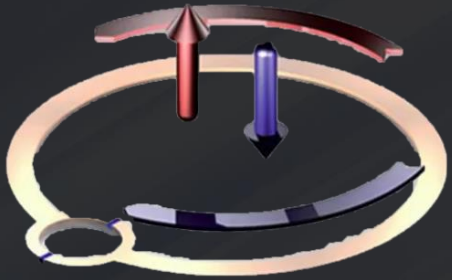


LUMI-Q

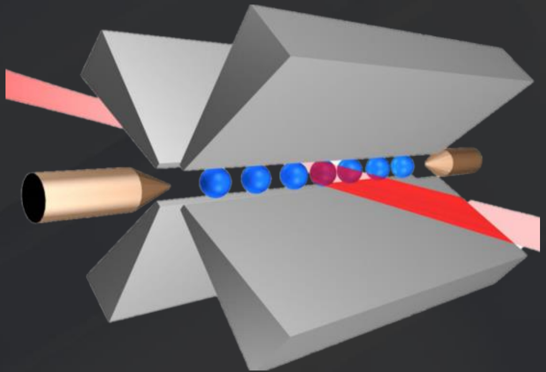


EuroQCS Spain

EuroQCS France



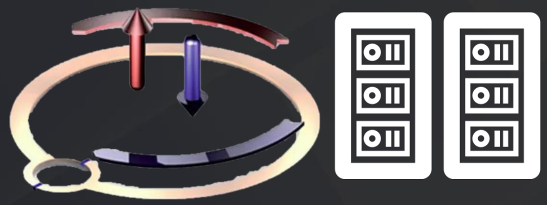
Euro-Q-Exa



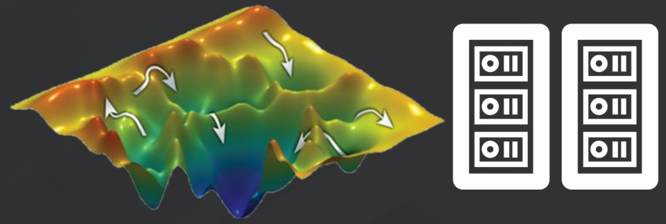
EuroQCS Poland

EuroQHPC-I

EuroQCS Italy

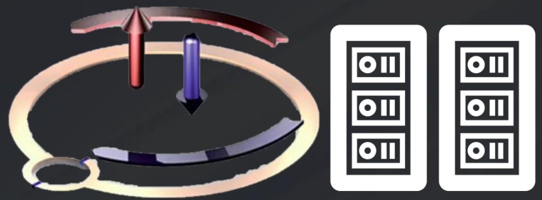


LUMI-Q

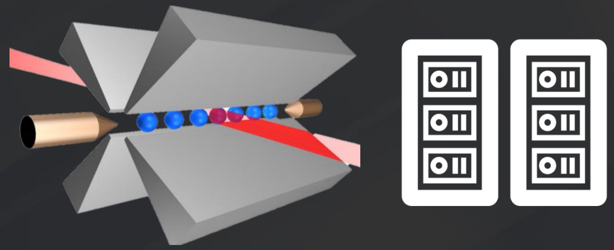


EuroQCS Spain

EuroQCS France

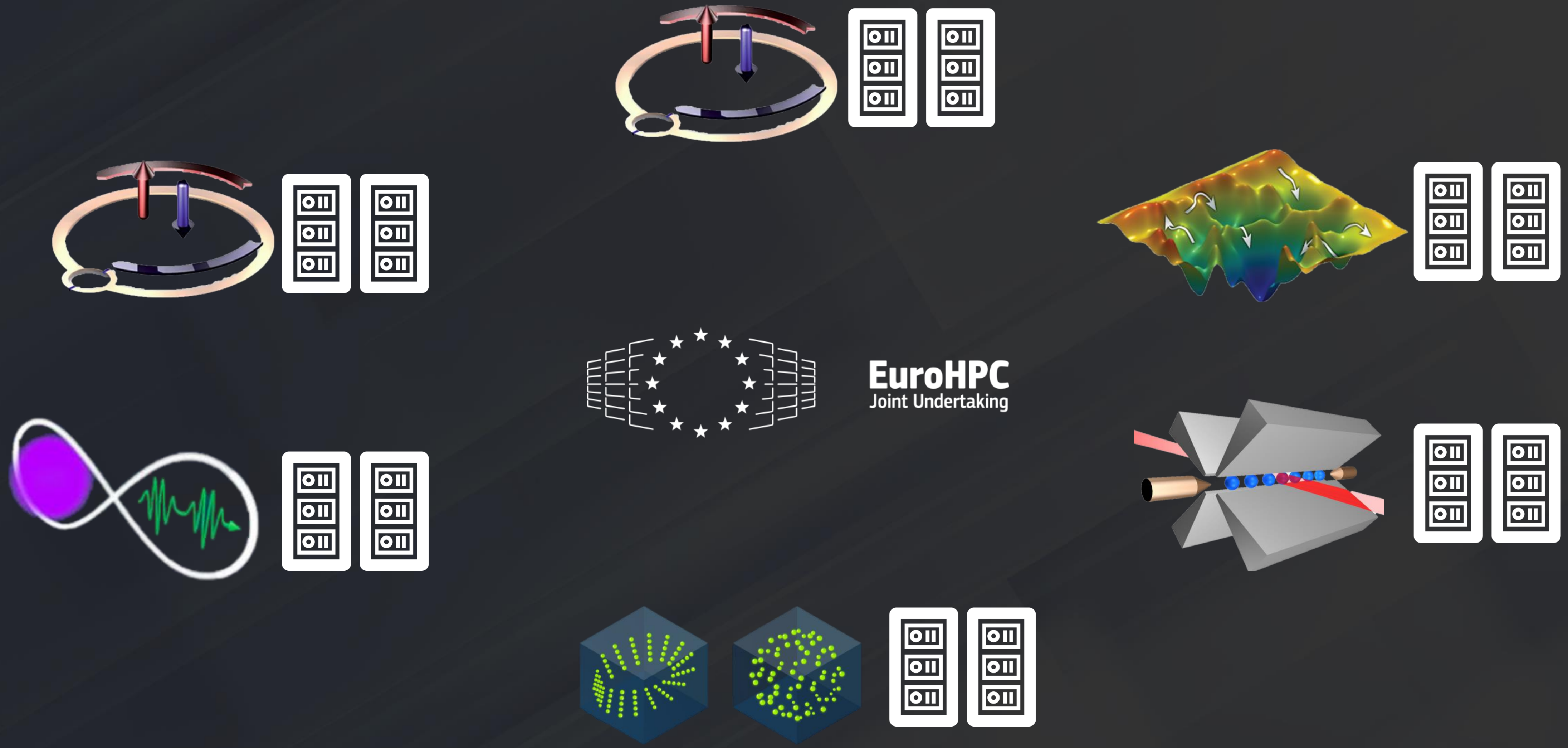


Euro-Q-Exa



EuroQCS Poland

EuroQHPC-I



EuroQCS-Italy

Leonardo - BullSequana XH2000, Xeon Platinum 8358 32C 2.6GHz, NVIDIA A100 SXM4 64 GB, Quad-rail NVIDIA HDR100 Infiniband

Rpeak 306.31 PFlop/s, Top500 Rank: 7

EuroHPC Joint Undertaking

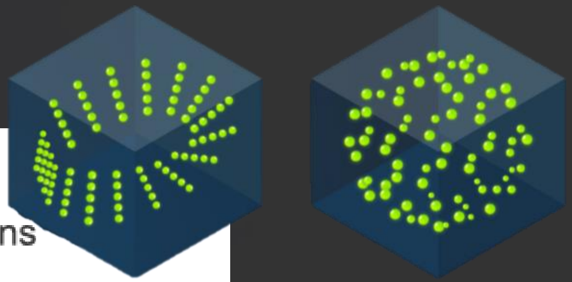
Neutral Atoms Analog Quantum Simulator
140 qubits – Q2 2025
Upgrade path: enabling partial addressability (Q3 2026)

Superconducting Digital Quantum Computer
54 qubits – Q1 2025

Fondazione ICSC
Centro Nazionale di Ricerca in HPC, Big Data and Quantum Computing

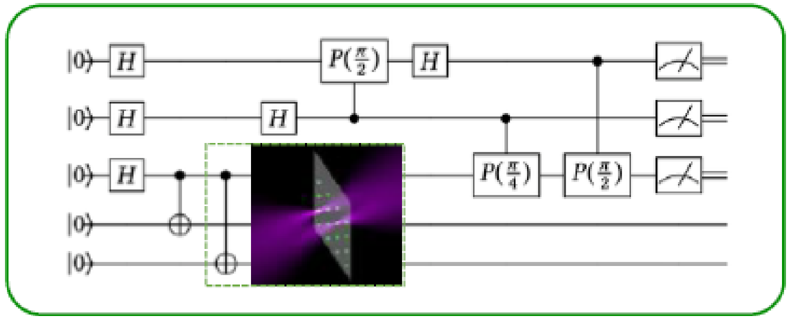
CINECA QUANTUM COMPUTING LAB

Neutral Atoms Quantum Simulators

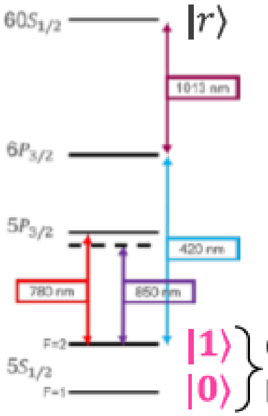


Digital mode

Programming a logic circuit = **quantum gates**



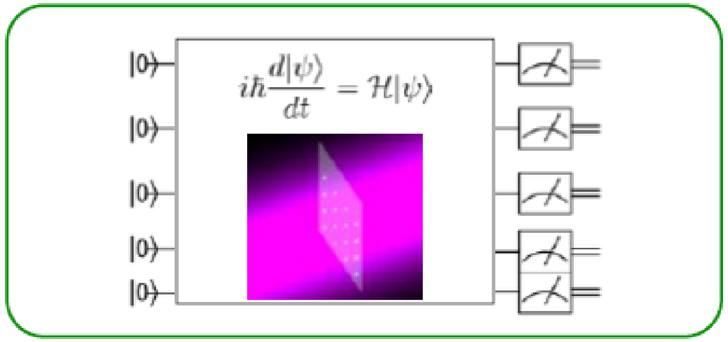
Elementary operations on individual qubits, or on several qubits at the same time → **universal** but very **sensitive to noise**



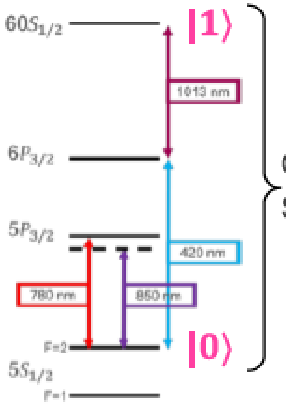
Qubits are encoded in the hyperfine ground levels.
No interaction, but long-lived memory qubits.

Analog mode

Programming a **sequence of Hamiltonian** evolutions



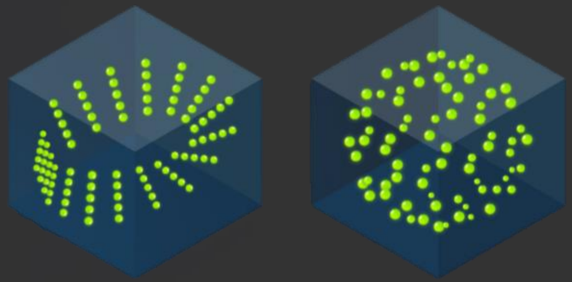
The Hamiltonian faithfully describes the dynamics of the physical system
→ **not universal** but offers **better performances with NISQ processors**.

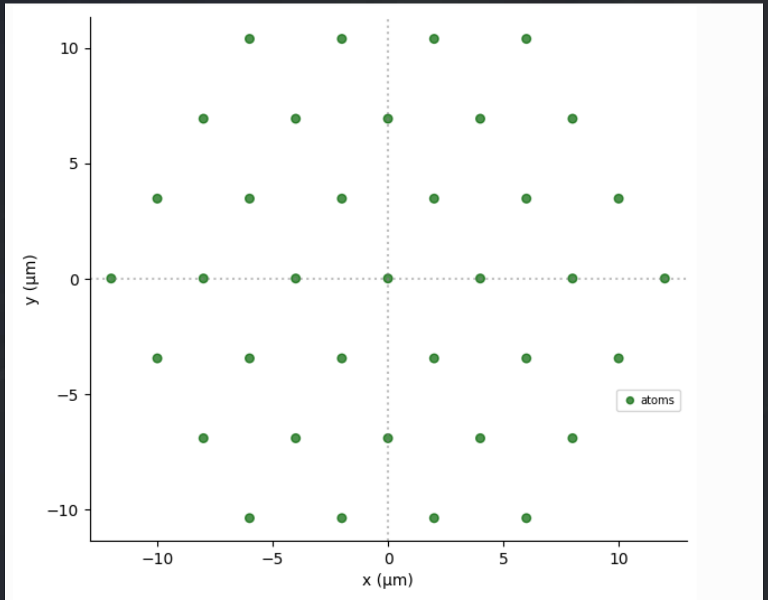


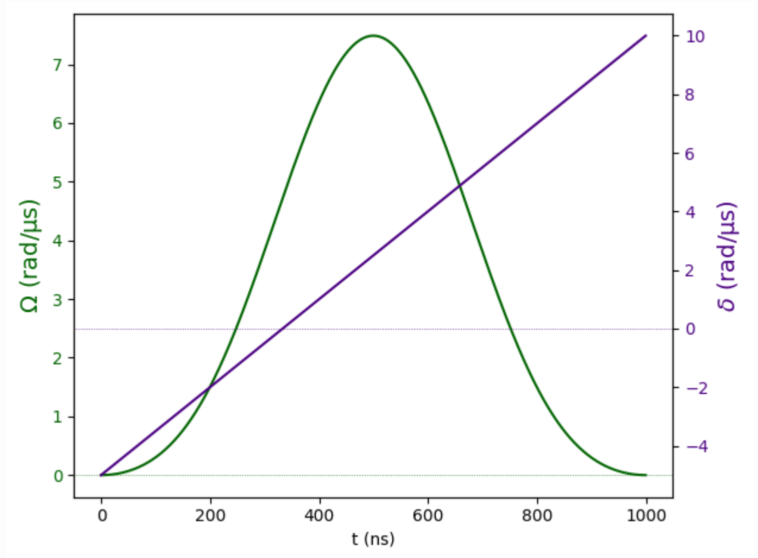
Qubits are encoded in the ground-Rydberg levels.
Strong interaction, entanglement, but short lifetime.

Figure 454: a clear explanation of the difference between a digital gate-based mode and an analog, quantum simulation mode. Source: Pasqal. 2023.

Neutral Atoms Quantum Simulators







$$\frac{\hbar}{2}\sum_i \Omega(t)\sigma_i^x - \frac{\hbar}{2}\sum_i \delta(t)\sigma_i^z + \sum_{i<j} U_{ij} n_i n_j$$

$$\mathrm{n} = (1+\sigma^z)/2, \qquad U_{ij} \propto R_{ij}^{-6}$$

https://pulser.readthedocs.io/en/stable/review.html

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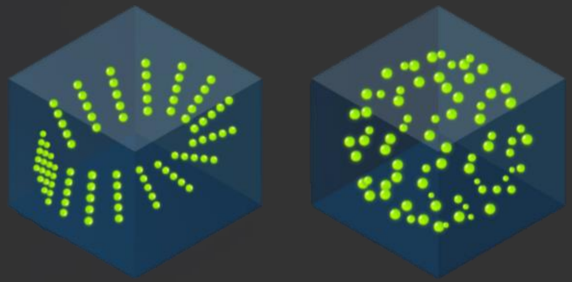
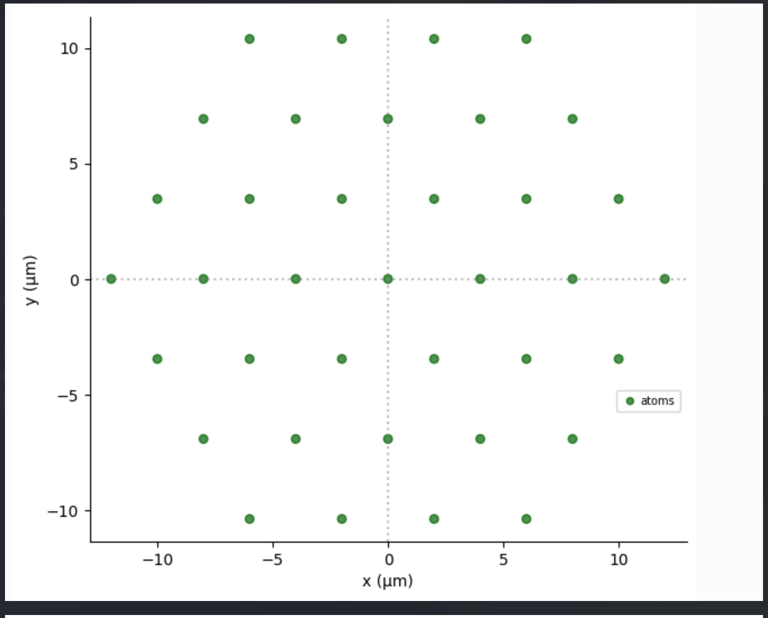
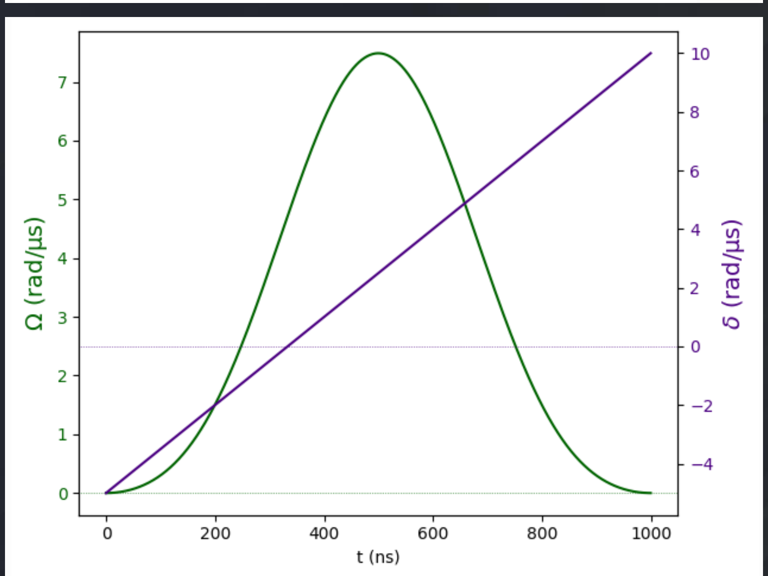
Neutral Atoms Quantum Simulators







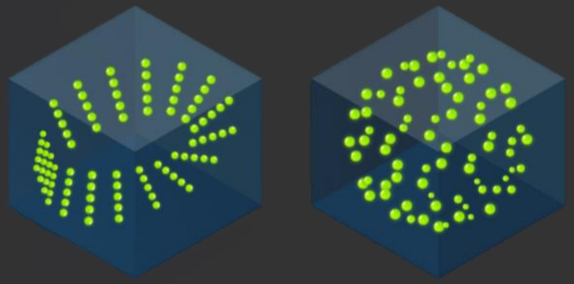
$$\frac{\hbar}{2}\sum_i \Omega_i(t)\sigma_i^x - \frac{\hbar}{2}\sum_i \delta(t)\sigma_i^z + \sum_{i<j} U_{ij} n_i n_j$$

$$\mathrm{n} = (1+\sigma^z)/2, \qquad U_{ij} \propto R_{ij}^{-6}$$

Partial Addressability

Understanding Quantum Technologies

Neutral Atoms Quantum Simulators



neutral atoms qubits key takeaways

highlights

- **operational systems** with 100-300 atoms in simulation mode and not far from a provable quantum advantage.
- **long qubit coherence time and fast gates.**
- **identical atoms,** that are controlled with the same laser and micro-wave frequencies.
- **first logical qubits** thanks to movable atoms.
- works in both **simulation** and **gate-based** paradigms.
- no need for specific **integrated circuits.**
- uses **standard apparatus**: lasers, optics, controls, cryogenics.
- low **energy consumption.**

challenges

- **crosstalk between qubits**: can be mitigated with two-elements atom architectures.
- **slow operations:** 1 Hz simulation cycle.
- **harder to implement with gate-based model**: need a stable universal gate set with support for error correction.
- **need to move atoms around:** to enable many-to-many two-qubit gates and reducing QEC overhead, enabling qLDPC, but with risk of losing the atoms on the way.
- **implement full QND measurement:** needed for error correction.
- **losing atoms during computing while disconnecting the tweezers.**

variations

- **dual species qubits**: to improve QND measurement.
- **nucleus spin qubits**: with longer coherence times, in seconds.
- **circular Rydberg atoms**: more stable.
- **fermionic computing**: better for chemical simulations.
- **bosonic codes (cat-codes, GKP) with atom qubits**: better QEC.
- **hybrid gate-based and analog**: for specific case studies.
- **atoms trapped on nanophotonic circuits**: enabling interactions.
- **hybrid neutral atoms and ions**: getting the best of both worlds.
- **atom ensembles**: studied particularly in China.

path to scalability

- **powerful lasers**: needed to control >300 atoms, with stabilized power, fiber lasers.
- **atoms positioning**: large scale SLM+AOD to trap up to 10K atoms.
- **QND measurement**: using dual species and/or atoms shuttling.
- **faster operations and duty cycle**: better and more powerful lasers, fast classical controls (FPGA, ASIC).
- **implement full universal gate set**: T gate & magic state distillation.
- **QPU interconnect**: photon based, including for memories, can also use nanophotonic circuit traps.

Figure 441: pros and cons of cold atoms quantum computers and simulators. (cc) Olivier Ezratty, 2022-2024.

Neutral Atoms Quantum Simulators

		2022 - 2023	2024 - 2025	2026 - 2027	2028+
Technology PASQAL & affiliated ecosystem	**HARDWARE PLATFORM**				
	Max qubits	200	1,000	10,000	
	Addressability	Z add	Z+X add Addressable 1Q and 2Q gates		
	Base repetition rate	1 Hz	3 Hz	10 Hz	100 Hz
	FTQC Program		Atom shuttling Ultra High-Fidelity Gates	Scalable logical qubits architecture	
	HARDWARE ACCELERATED LIBRARIES				
	Quantum Matter & Quantum AI	Algorithm Blueprint	Algorithm Development	Production	
Products	**QUANTUM PROCESSORS**				
	Generation	**Orion Alpha** ~3M gates	**Orion Beta** ~5M gates On premise delivery **Orion Gamma** ~10M gates On premise delivery	**Vela** ~40M gates **Pegasus** ~200M gates	**Centaurus FTQC QPU** 128+ Logical qubits 200M+ gates
	Total hours of QPU for users	500	5-10,000 20-30,000	60-70,000 200-250,000	500-550,000
	Factories	France	Canada Factory 3		
	COMMUNITY				
	Platform		Learn Interact	Collaborate	
	Open-source Software Stack	Pulser	Qadence Solvers & Emulators		

Pasqal

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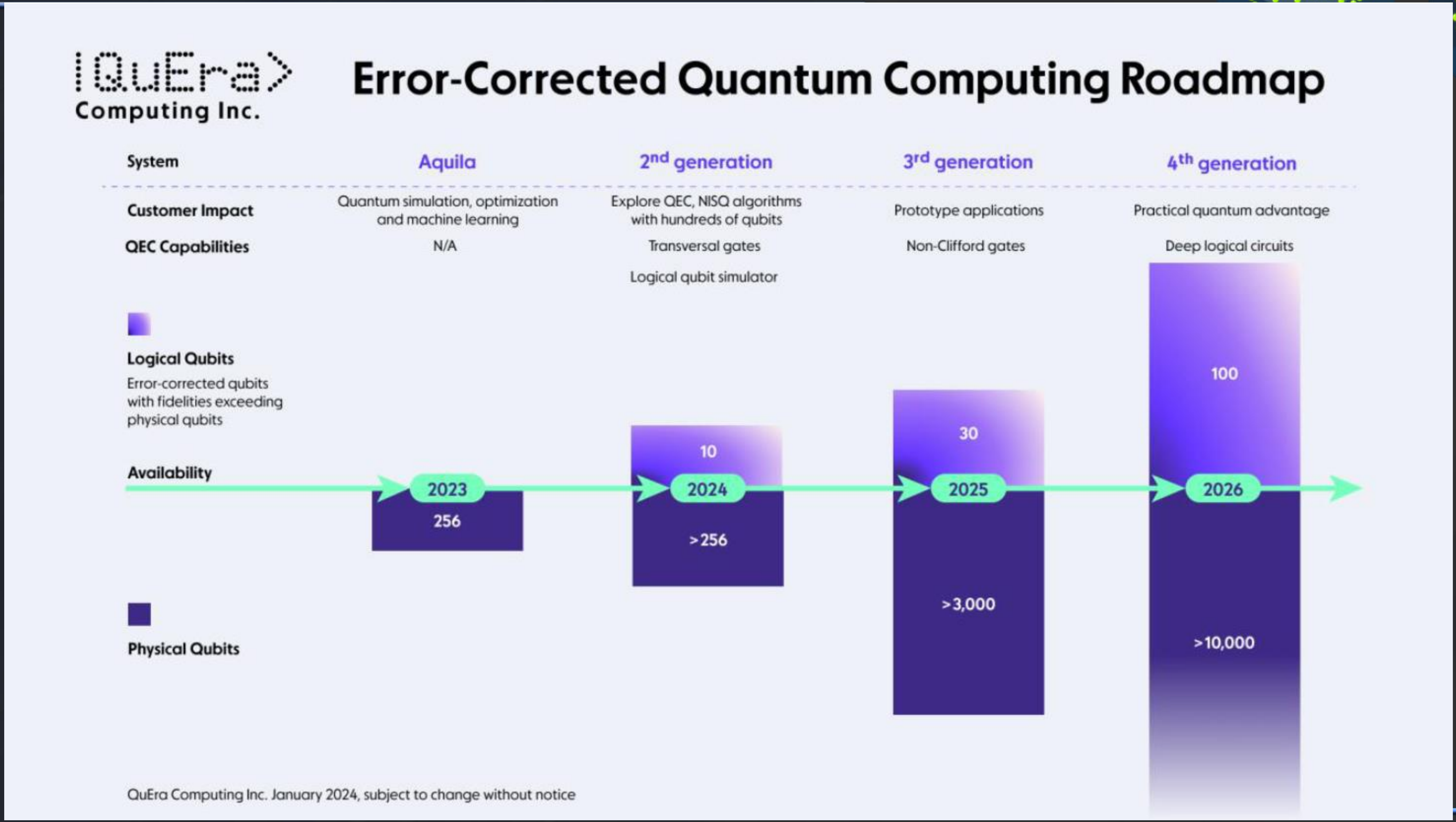
Neutral Atoms Quantum Simulators



Superconducting Qubits

superconducting qubits key takeaways

highlights

- **key technology** in the academic world and with the largest and well funded commercial vendors community including large players like IBM, Google, IQM and Rigetti.
- **record of 156 programmable qubits** with 99.7% two qubit gates fidelities (IBM Heron r2, 2024).
- **noise reduction** constant progress in regular transmons with tunable couplers and with bosonic qubits which could enable a record low ratio of physical/logical qubits.
- **first break-even logical qubits**: Google in August 2023.
- **enabling technologies** are abundant with cryostats, cabling, analog electronics, amplifiers, and sensors.
- **quantum error mitigation** and **quantum error correction** known techniques to enable NISQ applications and future FTQC designs.

challenges

- **qubits variability**: requires calibration and complex micro-wave frequency maps and need to contain crosstalk.
- **qubit connectivity**: limited to neighbor qubits in 2D structures.
- **qubit coherence time**: usually < 300 µs with some lab records >1ms.
- **cryogeny**: constrained technology at <15 mK, but not a scientific obstacle per se, more an engineering one. Yield can be improved.
- **logical qubits**: are not yet under break even. They are currently worse than physical qubits in most experiments.
- **cabling clutter**: complexity and many passive and active electronic components to control qubits with micro-waves and other signals.
- **qubits size**: uneasy miniaturization limits qubit # per chips and requires QPU interconnect solutions.
- **qubit fidelities**: have a hard time reaching 99.9%, needed for QEC.

variations

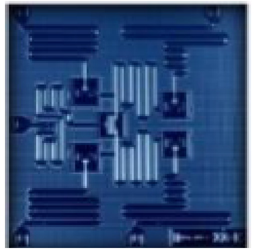
- **bosonic qubits**: cat-qubits, GKP, dual rail with self-correction and lower QEC overhead. They are less mature but promising.
- **fluxonium qubits**: with better fidelities but a more complicated designs and few involved vendors.
- **qutrits**: with larger Hilbert space, which are exotic in the commercial world.
- **Andreev spin qubits**: localized excitation of the BCS condensate that natively has only two levels, using a nanowire.
- **hybrid quantum analog-digital** architectures: to solve specific problems, not generic.

path to scalability

- **materials**: improve elements purity, identify other promising ones.
- **EDA**: full stack electronic design automation tools.
- **manufacturing**: industrialization, 300 mm wafers epixaxial deposition.
- **qubit mid-range coupling**: to enable lower overhead qLDPC QEC.
- **interconnect**: using transduction and photonic gate teleportation.
- **signals multiplexing or SFQ control electronics**: to reduce cabling overhead and cryogenic requirements.
- **QEC syndrome detection** speed improvements using ASICs.
- **cryostats**: larger and more efficient.

Figure 301: superconducting qubits highlights, challenges, variations and path to scalability. (cc) Olivier Ezratty, 2021-2024.

Superconducting Qubits



IBM Q may 2016
5 qubits

IBM Q may 2017
17 qubits

IBM Q oct 2017
50 qubits
(labo)

IBM oct 2017
HPC 56 qubits simulator

IBM Q System One jan 2019
20 qubits

Rochester sept 2019
53 qubits

IBM Q System One jan 2020
28 qubits

Hummingbird 2020
65 qubits

Eagle nov 2021
127 qubits

Nature paper on quantum utility with QEM june 2023

System Two 2023

Osprey may 2023
433 qubits
(retired in 2023)

Condor 2023
1,121 qubits (retired)

Heron r1 2023
133 qubits

Heron r2 2024
156 qubits

2017 2018 2019 2020 2021 2022 2023 2024

IBM

EuroQCS-France

JOLIOT-CURIE ROME - Bull Sequana XH2000 , AMD Rome 7H12 64C 2.6GHz, Mellanox HDR100

Rpeak 12.04 PFlop/s, Top500 Rank: 132

Neutral Atoms Analog Quantum Simulator
100 qubits – Q1 2025

Photonic Quantum Computer
12 qubits – Q3 2025
Upgrade path: 24+ qubits Q3 2026

HPCQS

EuroHPC Joint Undertaking

QUANDELA

Photonic Quantum Computers

photon qubits key takeaways

highlights

- **stable qubits with absence of decoherence.**
- **ambient temperature for processing.**
- **emerging nano-photonic** manufacturing techniques enabling scalability.
- **easier to scale-out** with inter-qubits communications and quantum telecommunications.
- **MBQC/FBQC** circumventing the fixed gates depth computing capacity and difficulty to create multiple qubit gates.
- **boson sampling-based quantum advantage**: starts to being programmable but a practical quantum advantage remains to be proven.

challenges

- **need to cool photon sources and detectors**: but at relatively reasonable temperatures between 2K and 10K, requiring lighweight cryogenic systems (unless also cooling the whole photonic circuit).
- **not yet scalable in number of operations**: due to probabilistic character of quantum gates and the efficiency of photon sources in most paradigms.
- **non-deterministic** cluster states and two-photon interactions.
- needs **delay lines** and **optical switches.**
- **heat generated by phasers**: increasing cooling budget.
- **photon detectors efficiency** is too low, at 89% with PsiQuantum.
- **photon losses** must be contained in nanophotonic circuits.

variations

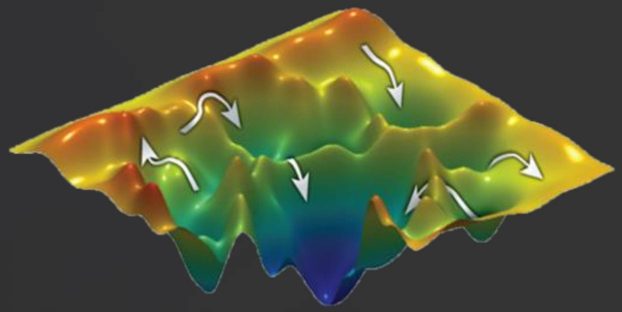
- **encoding**: direct variables qubits (DV), continous variables (CV) qubits, multimode photon encoding.
- **MBQC** (measurement based quantum computing) and **FBQC** (fusion-based quantum computing).
- **BS/GBS**: programmable Boson sampling and Gaussian boson sampling.
- **hybrid approaches**: spin-optical quantum computing (SPOQC) with quantum dots spin qubits (Quandela), hybrid atom-photon qubits.
- **classical photonic models**: coherent Ising models, photonic waveguide arrays and interferometric systems.

path to scalability

- **efficiency**: improve photon sources efficiency, determinism and indistinguishability, improve photon detectors efficiency (SNSPD and PNRD).
- **cluster states**: generate large cluster states, with or without heralding.
- **interactions**: improve fusion efficiency in FBQC.
- **losses**: large-scale and low-losses optical switches and wave guides, reduce photon losses in nanophotonic circuits thanks to higher precision manufacturing and new materials.
- **energy**: create low-heating phasers to minimize power consumption.
- **nanophotonics**: heterogeneous nanophotonic circuits (III-V + silicon).
- **classical control speed**: particularly with FBQC models.

Figure 465: highlights, challenges, variations and path to scalability of photon qubits. (cc) Olivier Ezratty, 2022-2024.

EuroQCS-Spain



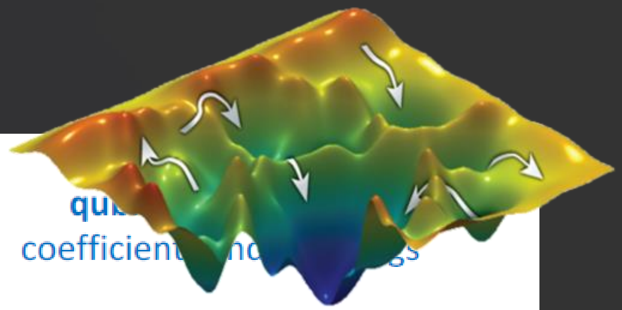
MareNostrum 5 ACC - BullSequana XH3000, Xeon Platinum 8460Y+ 32C 2.3GHz, NVIDIA H100 64GB, Infiniband NDR

Rpeak 249.44 PFlop/s, Top500 Rank: 8

Superconducting qubits Coherent Quantum Annealer
10 qubits – Q3 2025
Upgrade path: two different upgrades
First one Q3 2026
Second one Q3 2027

EuroHPC Joint Undertaking

Quantum Annealing



2-local Ising Hamiltonian initialization

defines h_i and J_{ij} and set all σ_i^z at +1

quantum annealing process

increases $B(s)$ and decreases $A(s)$ gradually

qu

coefficient

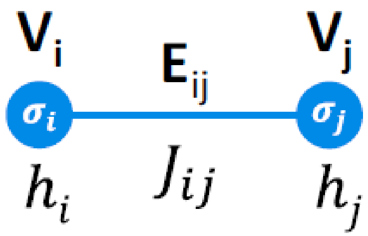
net qubits energy: *longitudinal interactions*

qubits connections energy: *longitudinal field*

$$\mathcal{H}_P = \sum_{i=0}^{N} h_i \, \sigma_i^z + \sum_{i<j}^{N} J_{ij} \, \sigma_i^z \sigma_j^z$$

$$\mathcal{H}_S(t) = \mathcal{H}_P \frac{B(s)}{2} + \mathcal{H}_n(t) - \frac{A(s)}{2} \sum_{i=0}^{N} \sigma_i^x$$

- $\mathcal{H}_P$: *Ising model Hamiltonian*
- $\mathcal{H}_n(t)$: *unknown effect of noise*
- $A(s)$: *effect from the variation of a transverse field*
- $\sum_{i=0}^{N} \sigma_i^x$: *trivial initial state all qubits at +1 in x direction*
- $\mathcal{H}_P \frac{B(s)}{2} + \mathcal{H}_n(t)$: final Hamiltonian
- $\frac{A(s)}{2} \sum_{i=0}^{N} \sigma_i^x$: initial Hamiltonian



problem variables

h_i linear coefficient (bias) on qubit
usually discretized

J_{ij} coupling between vertices V_i and V_j
discretized and implemented with couplers
non zero values limited by coupling topology

problem unknowns

σ_i^z qubits values : +1 or -1 (« spin orientation »)

σ_i^z and σ_i^x are Pauli operators

annealing time operators

t	time
t_f	total annealing time, about 5µs
s	fraction of annealing time=t/t_f
A(s)	tunneling energy at anneal fraction s reduced over time as a $\Gamma(t)$ transverse magnetic field applied to all qubits is reduced
B(s)	problem Hamiltonian energy at anneal fraction s increases over time during annealing

qubits topology

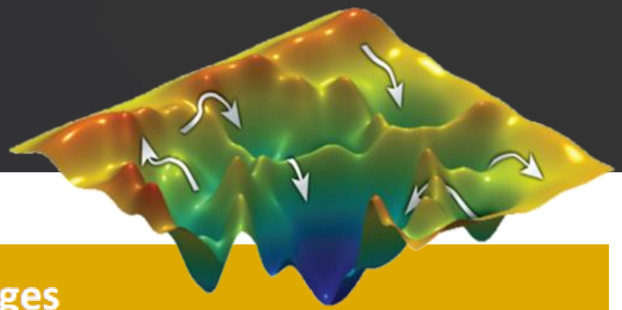
V_i vertices containing qubit i

E_{ij} edge connecting qubits i and j

system energy

$\mathcal{H}_P$	initial system Hamiltonian
$\mathcal{H}_n(t)$	system noise Hamiltonian
$\mathcal{H}_S(t)$	total Hamiltonian

Quantum Annealing



quantum annealing key takeaways

highlights

- **mature development tools offering**: D-Wave hybrid solver.
- **large number of software startups**: particularly in Japan and Canada.
- **cloud availability**: quantum annealers are available in the cloud by D-Wave and Amazon Web Services.
- **case studies**: greatest number of well documented case studies in many industries although still at the proof-of-concept stage.
- **near quantum advantage**: in some situations.
- **highly integrated DC qubit control** integrated in the chip (SFQ).

challenges

- **only one operational commercial vendor, D-Wave.**
- **computing high error rate.**
- **most commercial applications are still at the pilot stage and not production-grade scale, but they are closer than gate-based use cases.**
- **no generic operational proof of quantum advantage.**
- **need to improve qubit connectivity to improve embeddings.**

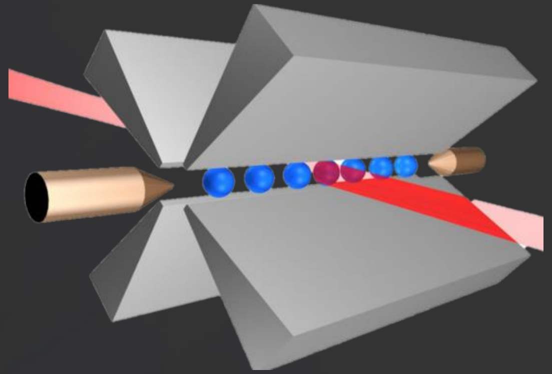
variations

- **hybrid quantum analog-digital** architectures: to solve specific problems, not generic.
- **digital annealing** ala Fujitsu.
- **photonic coherent Ising machines**.

path to scalability

- **better qubit connectivity**.
- **noise reduction**.
- **error mitigation**.

EuroQCS-Poland



Altair - CH121L V5 Liquid-Cooled, Xeon Platinum 8268
24C 2.9GHz, Infiniband EDR

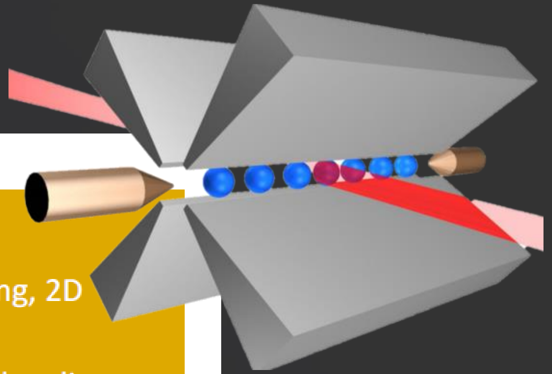
Rpeak 5.88 PFlop/s, Top500 Rank: 250

Trapped Ions digital quantum computer
20 qubits Q3 2025

EuroHPC
Joint Undertaking

AQT

Trapped Ions Quantum Computers



trapped ions qubits key takeaways

highlights

- **first two-qubit gate fidelities reaching 99.9%** (Quantinuum, Oxford Ionics).
- **first logical qubits** above break-even.
- **high ratio between coherence time and gate time**: supports deep algorithms in number of gate cycles.
- **low qubits variability** given the ions are all the same.
- **entanglement** possible between all qubits on 1D architecture which speeds up computing, avoiding SWAP gates.
- requires some cryogeny at **4K to 10K**.
- **QPU interconnect** can directly use photon entangled resources.

challenges

- **unproven scalability options beyond 60 qubits** (ions shuttling, 2D architectures, photon interconnect, micro-Penning traps).
- **slow computing**: due to long quantum gate times and ions shuttling which may be problematic for deep algorithms in a FTQC regime despite better qubit many-to-many connectivity at small scale.
- **two-qubit gate times** increase with ion distance in some laser-driven 1D and 2D settings.
- **many-to-many connectivity** works only at small scale.
- **control signals variability**: microwave, lasers, etc.
- **ions heating phenomenon**: it is not yet explained yet and really contained.

variations

- **microwave/DC drive** instead of laser drive.
- **connectivity**: many-to-many within zones and ions shuttling between zones.
- **dual species** like ytterbium + barium for computing and cooling.
- **Rydberg ion** qubits for avoiding phonon and heating effect.
- **hybrid** neutral atoms-ions platforms.

path to scalability

- **2D QCCD** and ions shuttling.
- **QCCD tiling** (Universal Quantum).
- **multi modules** ion traps with intermodules ions shuttling.
- **multi-layer ion traps** to enable long-range microwave based entanglement.
- **photonic interconnect** to entangle qubits from different QPUs.

Figure 408: highlights, challenges, variations, and path to scalability of trapped ions qubits. (cc) Olivier Ezratty, 2022-2024.

Euro-Q-EXA

SuperMUC-NG - ThinkSystem SD650, Xeon Platinum 8174 24C 3.1GHz, Intel Omni-Path

Rpeak 26.87 PFlop/s, Top500 Rank: 50

Superconducting Digital Quantum Computer
54 qubits – Q3 2025
Upgrade path: 150 qubits Q4 2026

Selected IQM Radiance Machine
https://www.meetiqm.com/products/iqm-radiance

EuroHPC Joint Undertaking

IQM

LUMI-Q

Karolina, GPU partition - Apollo 6500, AMD EPYC 7763 64C 2.45GHz, NVIDIA A100 SXM4 40 GB, Infiniband HDR200

Rpeak 9.08 PFlop/s, Top500 Rank: 135

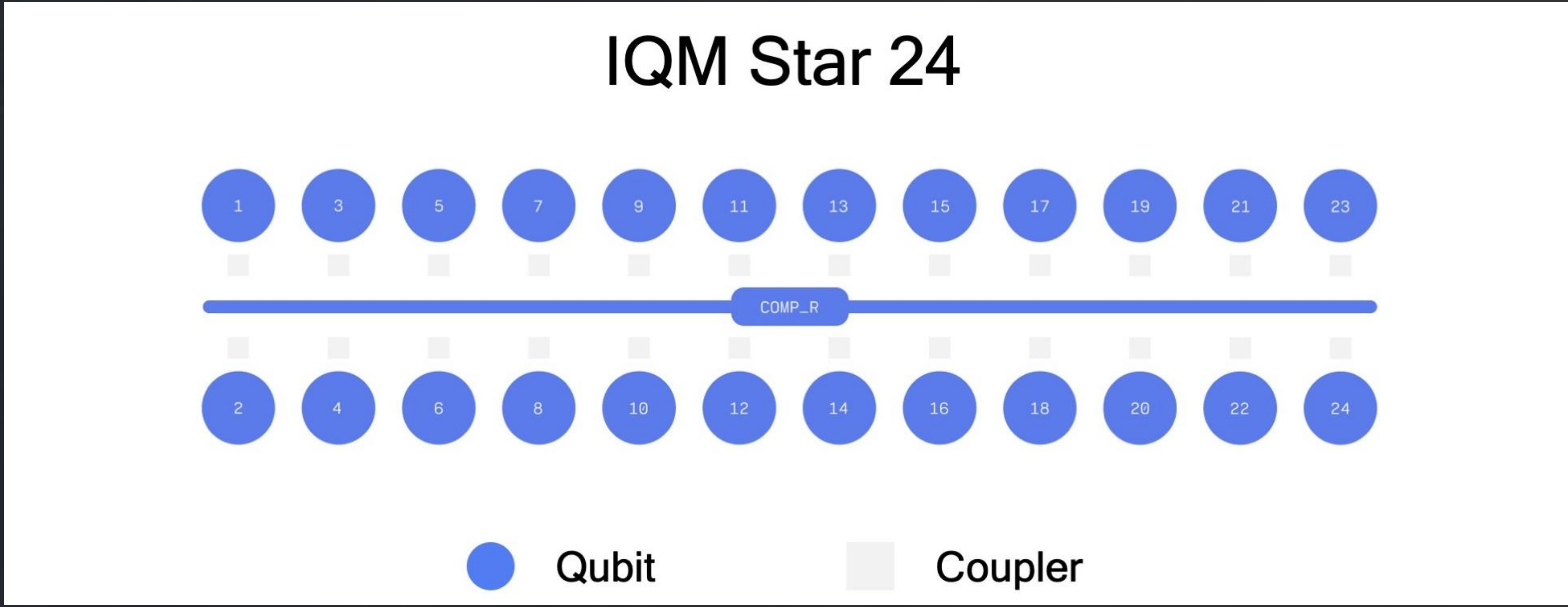
Superconducting Digital Quantum Computer with unique star topology
24 qubits – Q3 2025

Selected IQM Custom («Radiance Star») Machine

EuroHPC Joint Undertaking

IQM

Radiance Star Topology



Integrating HPC and QC

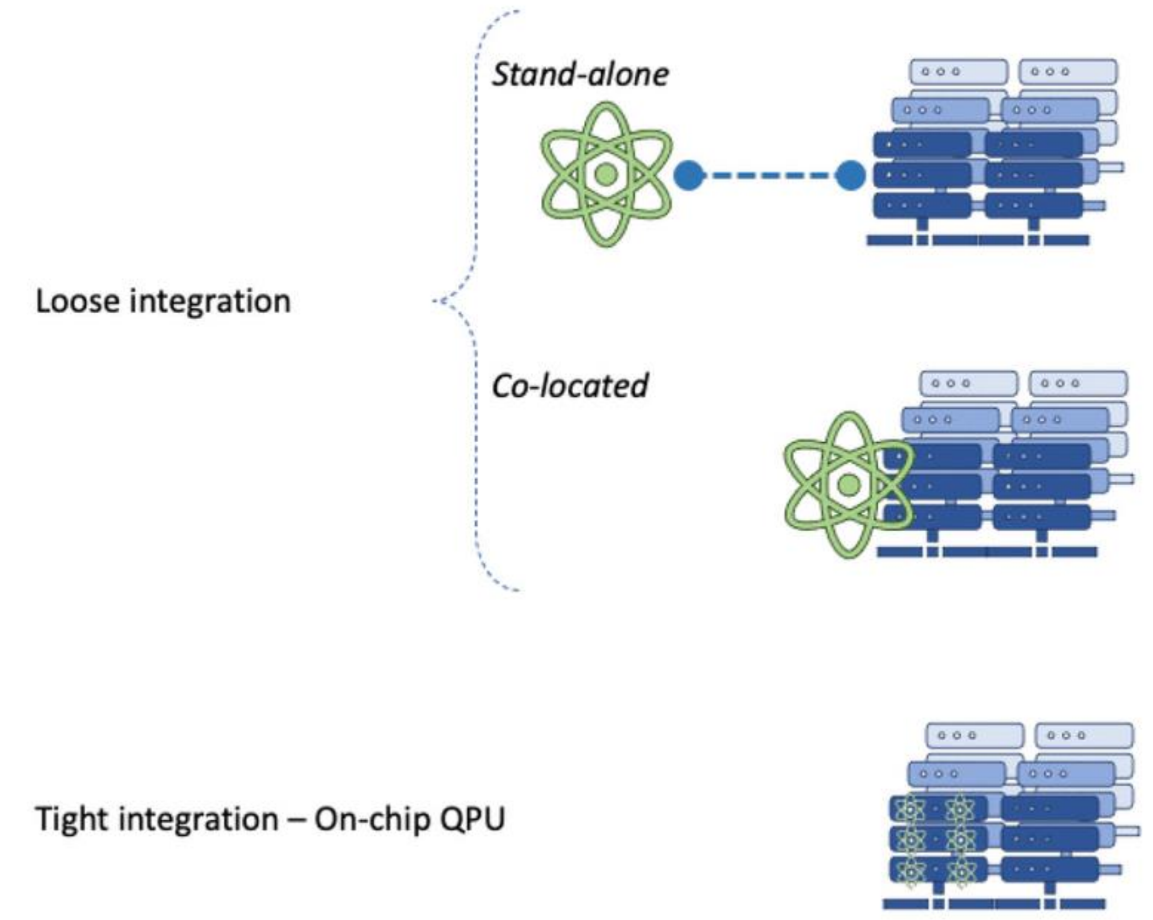
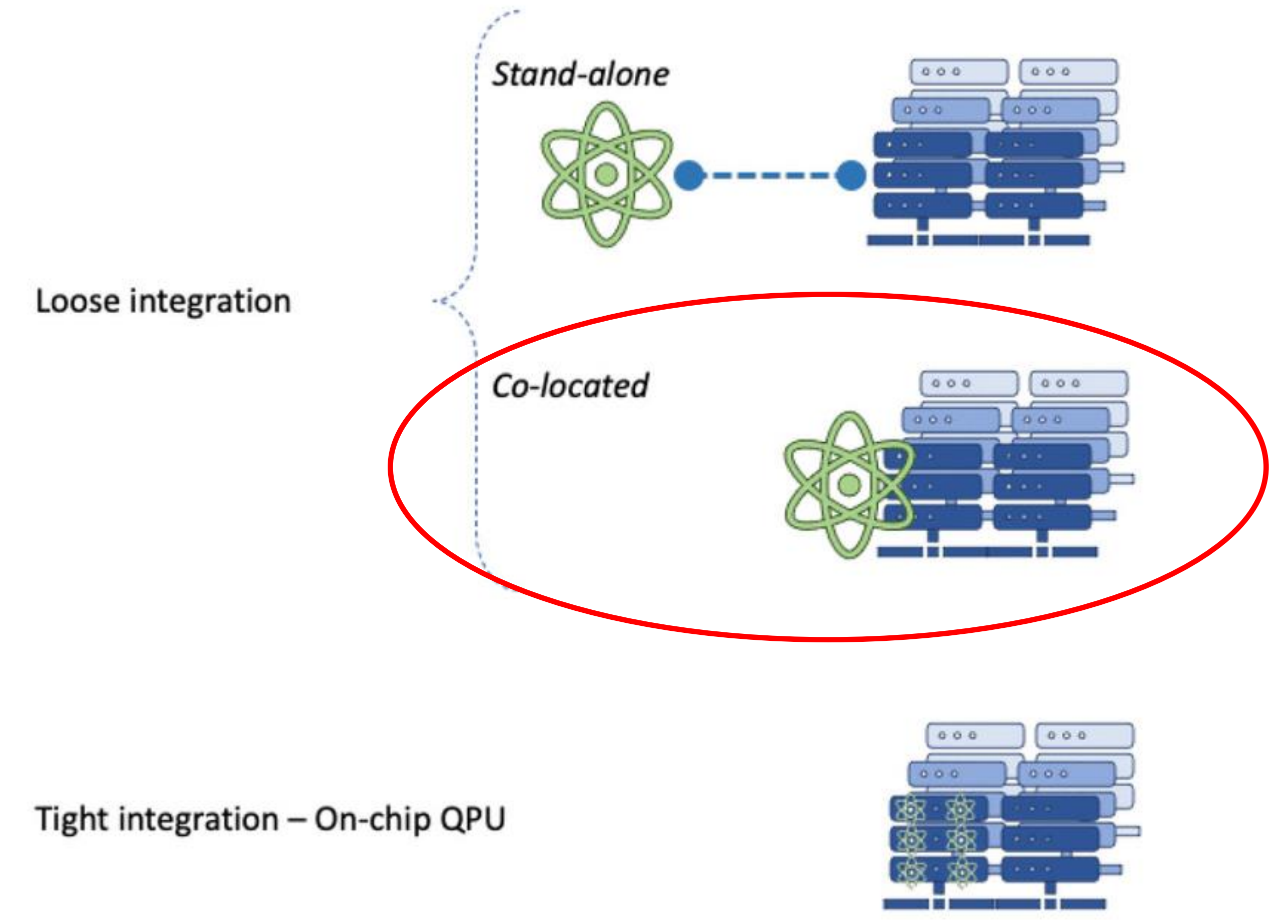


Figure 2.Representation of different levels of integration of QC systems with classical systems (tight or loosely coupled)

ETP4HPC White Paper: < QC | HPC > Quantum for HPC → https://www.etp4hpc.eu/white-papers.html#quantum

Integrating HPC and QC



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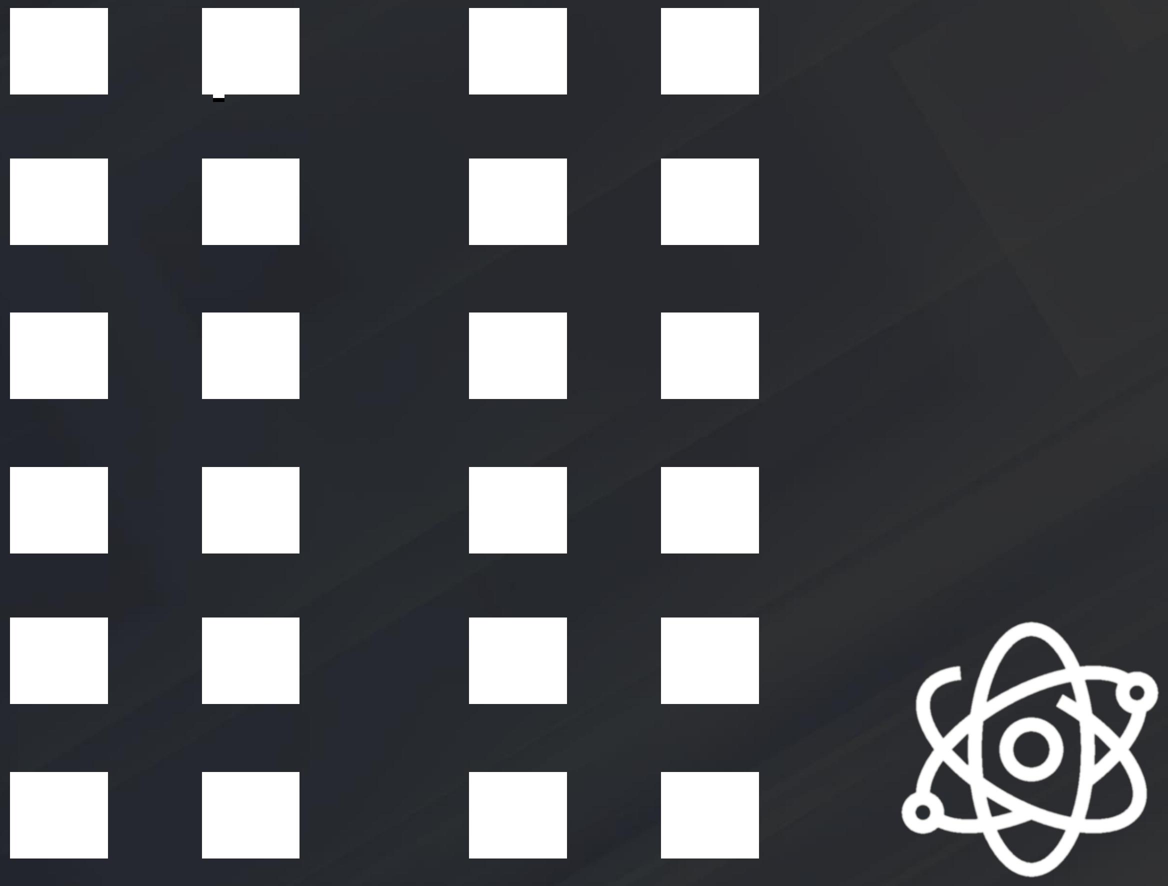
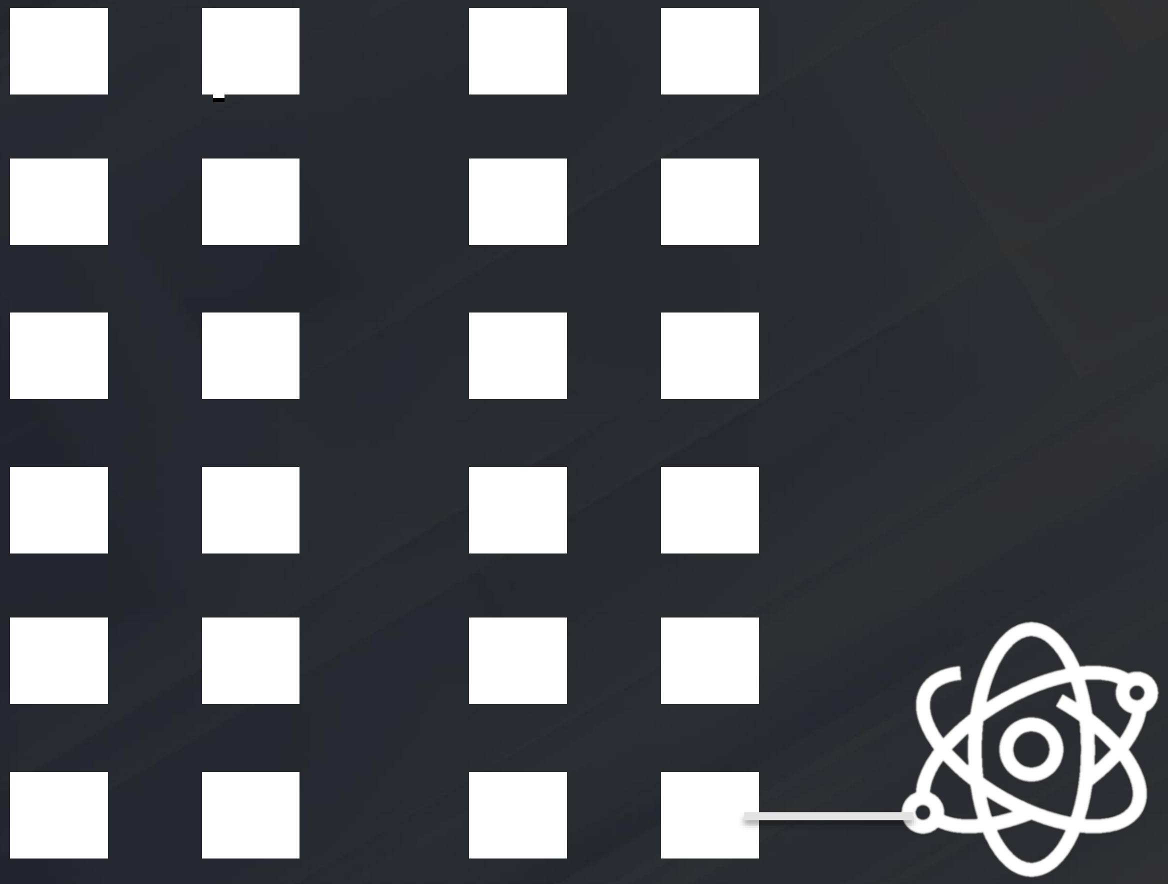
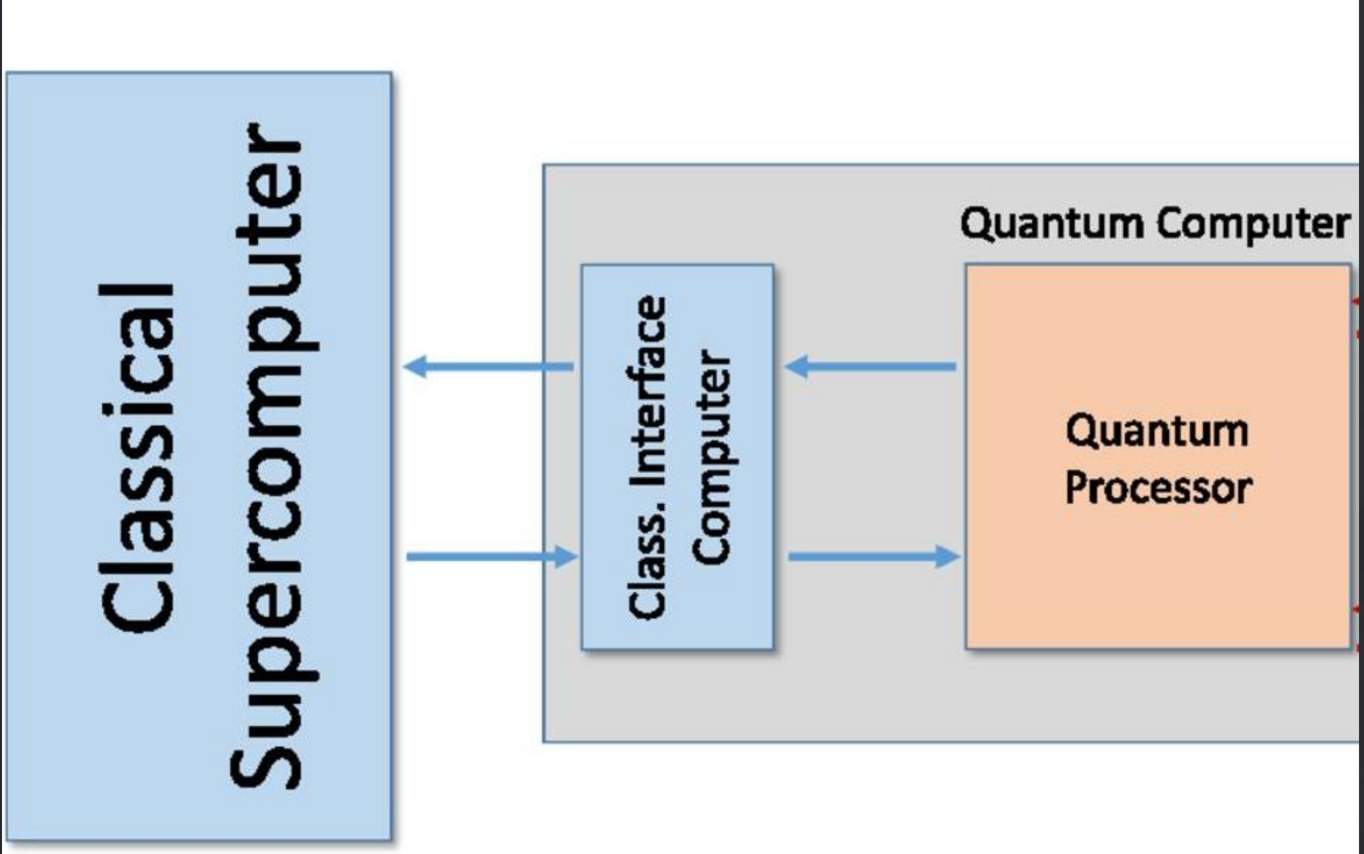


The Hardware part



- Beginners: Connecting the qc to a node
  - A commercial qc usually is set up to be connected to a classic computer via an Ethernet cable – easy part!

The Hardware part



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- Advanced: Hijack the connection
  - To achieve a tighter connection and eliminate unnecessary latencies, one could also consider connecting the HPC node directly to the QPU (without going through the control computer present in the QC)

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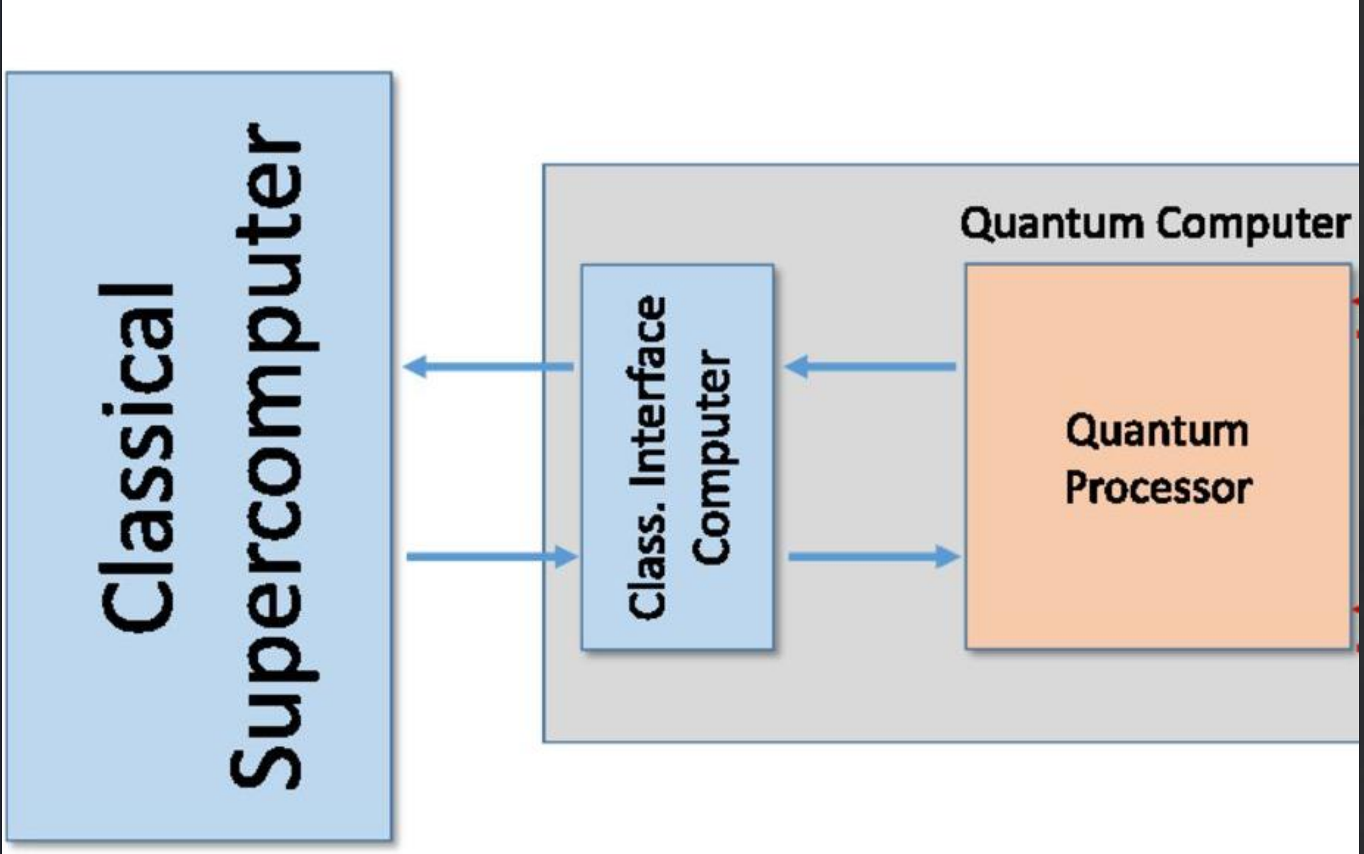

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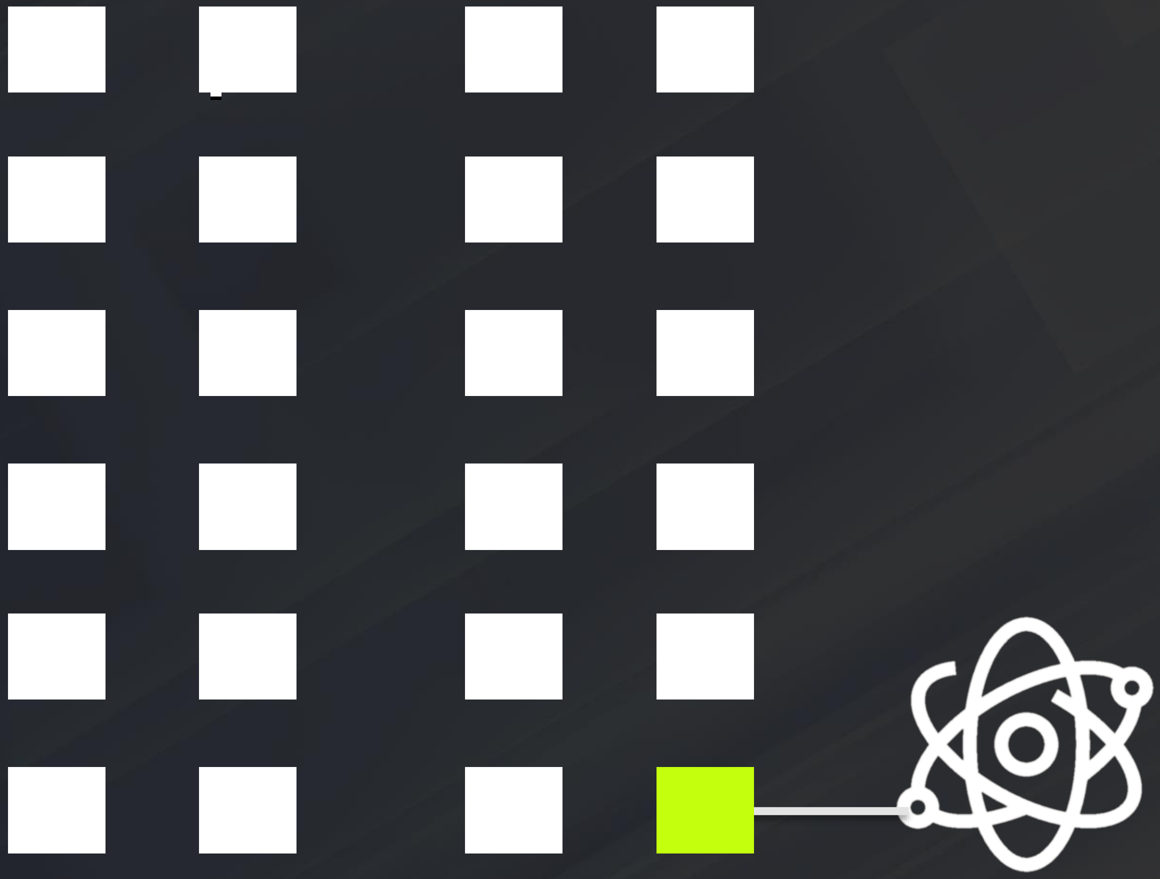
  - To achieve a tighter connection and eliminate unnecessary latencies, one could also consider connecting the HPC node directly to the QPU (without going through the control computer present in the QC)
  - This means installing firmware and operating systems for the QC on the HPC node, making it a de facto control system for the QPU

The Software part



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  - Usually the vendors that produce QC also develop SDKs that can talk to the control computer and consequently to the QPU
  - Installing and using such software is step 0 for integration

The Software part

- Beginners: Use the QC without HPC
  - Usually the vendors that produce QC also develop SDKs that can talk to the control computer and consequently to the QPU
  - Installing and using such software is step 0 for integration
- Advanced: Use the QC as a part of an HPC job
  - SDKs provided by vendors often do not include the use of MPI and/or CUDA to take advantage of HPC
  - One solution might be to explore existing software (Nvidia CUDA Quantum, Eviden Qaptiva)
  - Or work with the vendor to write a custom SDK

The Middleware part

```
#!/bin/bash
#SBATCH -A <account_name>
#SBATCH -p quantum_module
#SBATCH --time 00:10:00
#SBATCH -N 1
#SBATCH --gres=qpu
#SBATCH --job-name=my_batch_job

srun ./my_quantum_executable.x
```

- Beginners: Exclusive allocation
  - Exclusive usage of the QPU – other jobs have to wait
  - Control over the whole computation, not single shots (good for VQA, not for Error Mitigation)

The Middleware part

```
#!/bin/bash
#SBATCH -A <account_name>
#SBATCH -p quantum_module
#SBATCH --time 24:00:00
#SBATCH -N 10
#SBATCH --gres=qpu
#SBATCH --gres=gpu:4
#SBATCH --job-name=my_batch_job

mpirun -np 10 ./my_hybrid_executable.x
```

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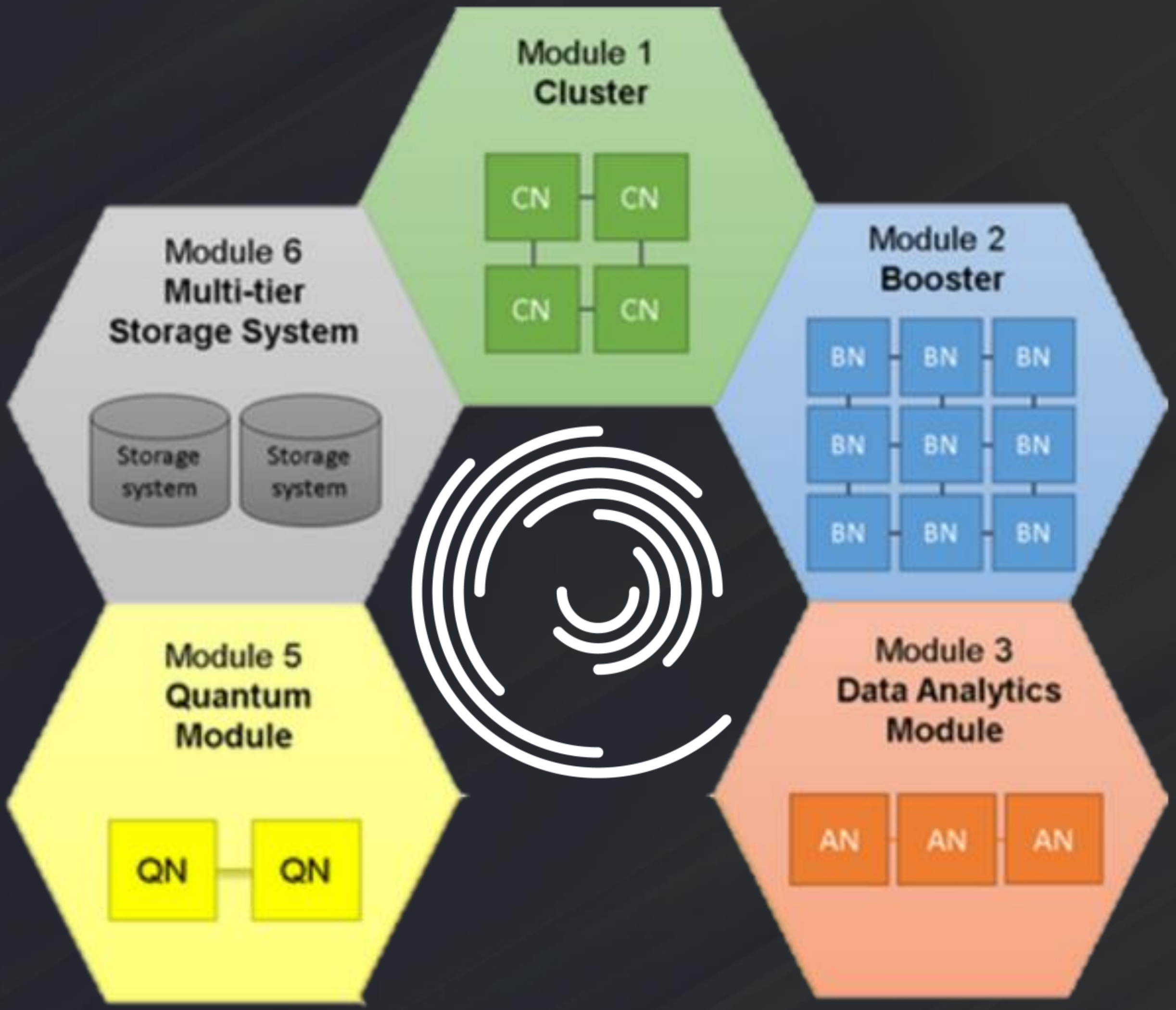
The Middleware part



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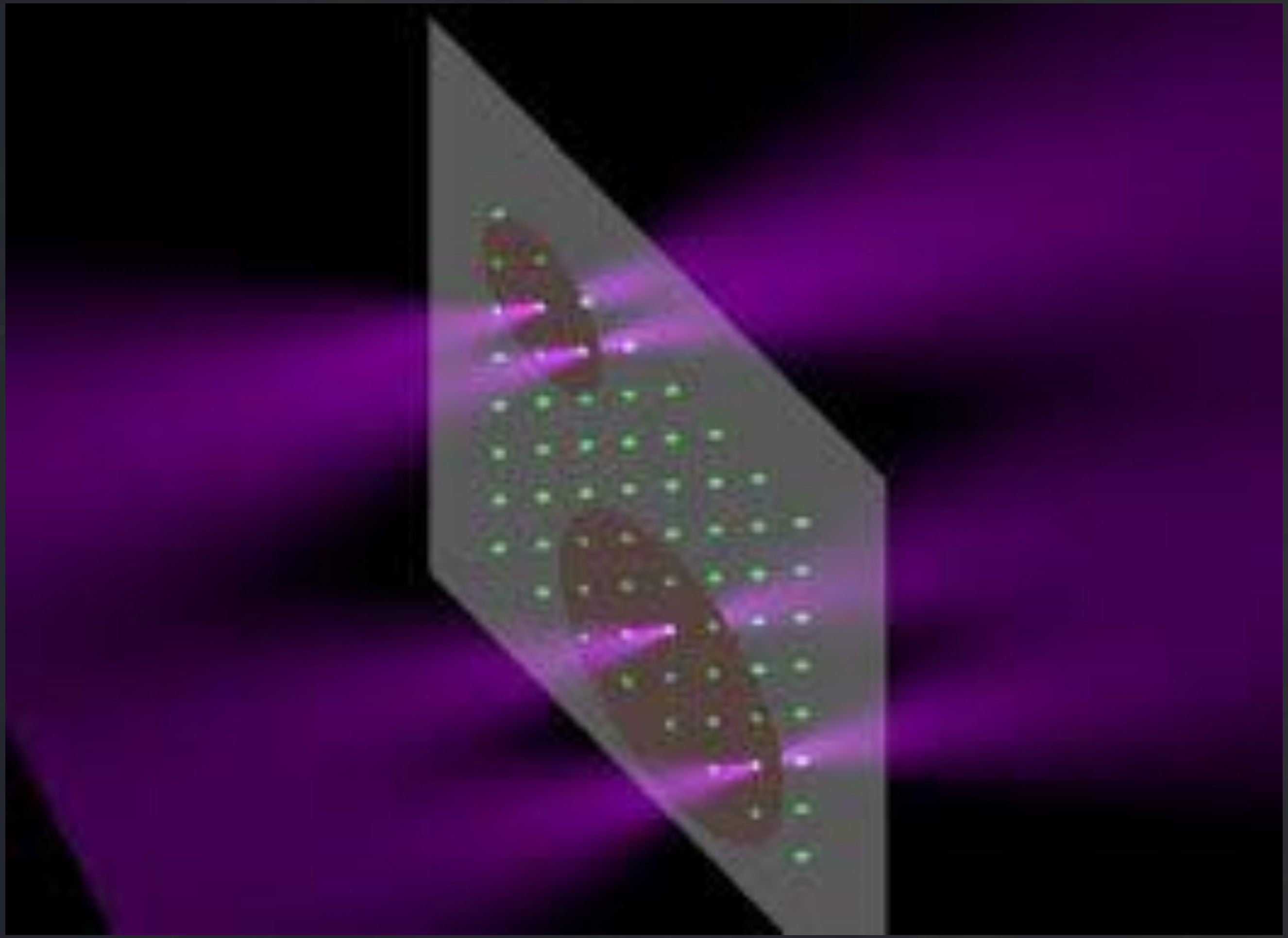

QUANTUM COMPUTING WITH NEUTRAL ATOMS
Loïc Henriet, Lucas Beguin, Adrien Signoles, Thierry Lahaye, Antoine Browaeys, Georges-Olivier Reymond and Christophe Jurczak

- Beginners: Exclusive allocation
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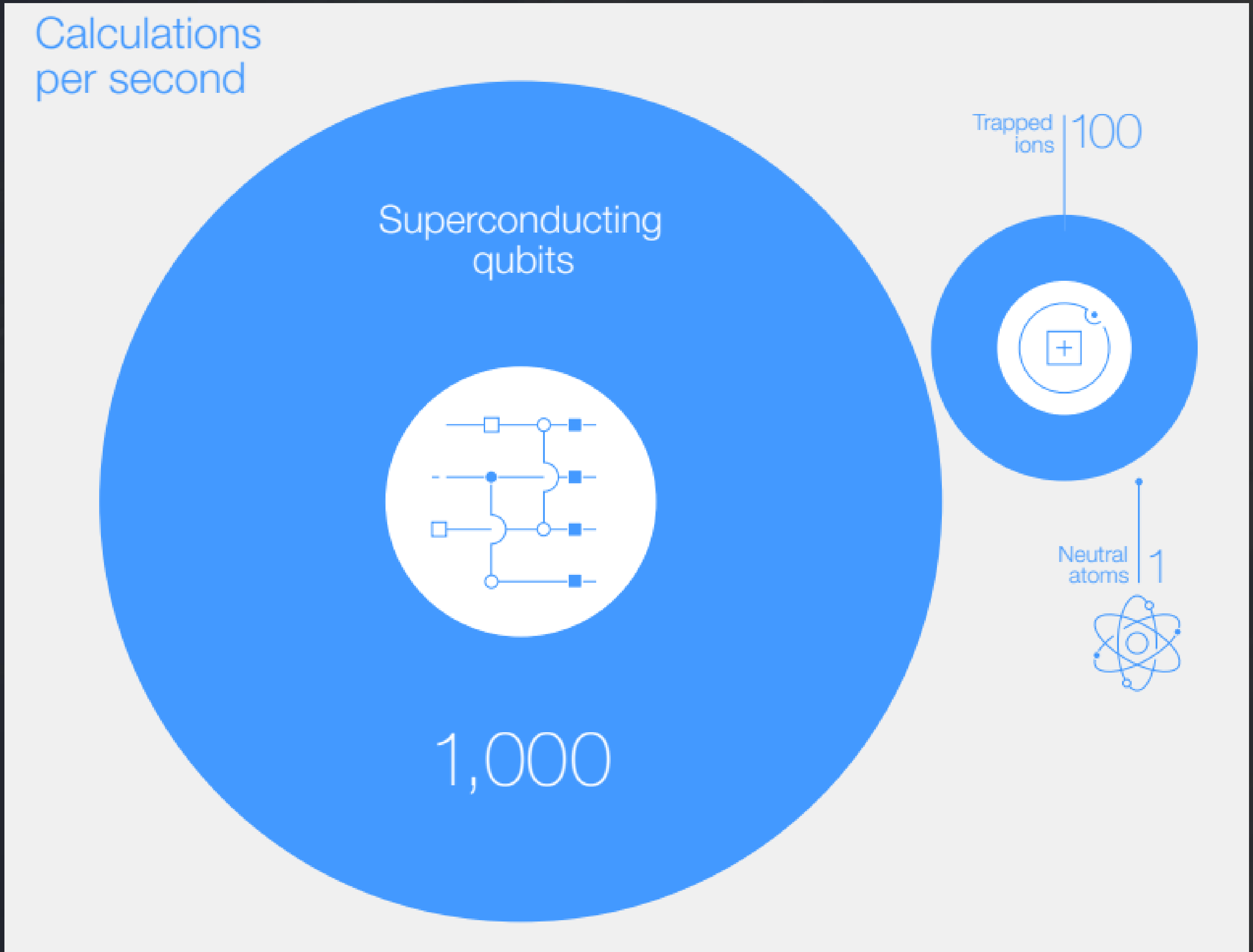
- Advanced: Efficient allocation
  - Non-exclusive usage – merging jobs

CINECA QUANTUM COMPUTING LAB

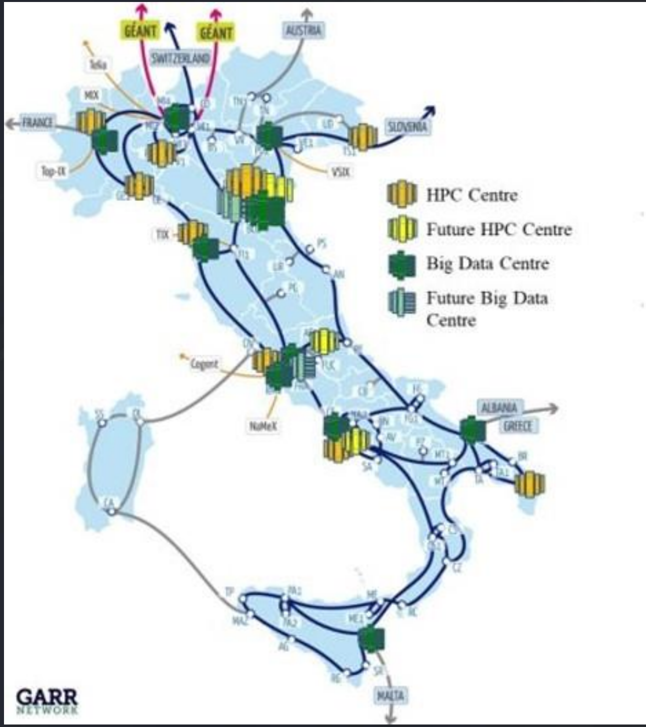
The Middleware part



https://www3.weforum.org/docs/WEF_State_of_Quantum_Computing_2022.pdf

- Beginners: Exclusive allocation
  - Exclusive usage of the QPU – other jobs have to wait
  - Control over the whole computation, not single shots (good for VQA, not for Error Mitigation)
- Advanced: Efficient allocation
  - Non-exclusive usage – merging jobs
  - Control over the single shots
  - Shots frequency very low (neutral atoms, trapped ions) – Free the HPC resources during the QPU computation
  - Shots frequency very high (superconducting QC) – Be sure that your scheduler is able to catch the shots!

Italian and European QC Environment



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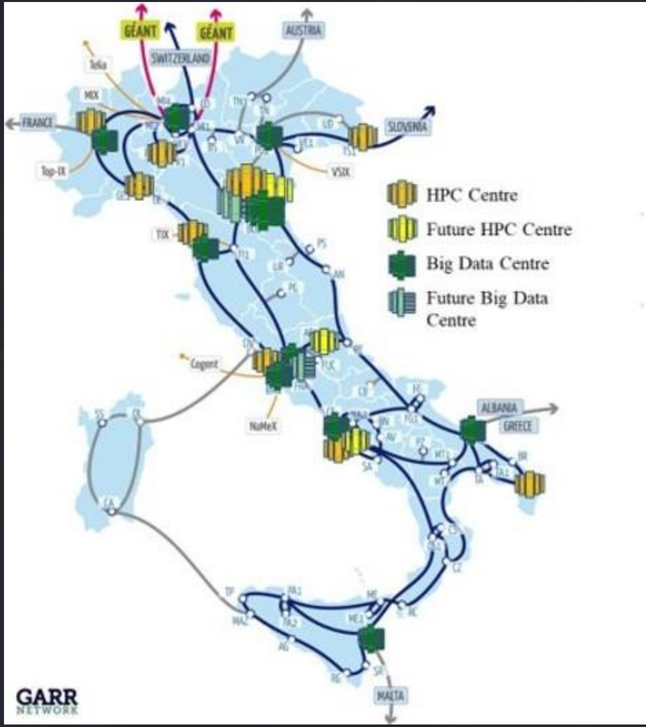
Italian and European QC Environment



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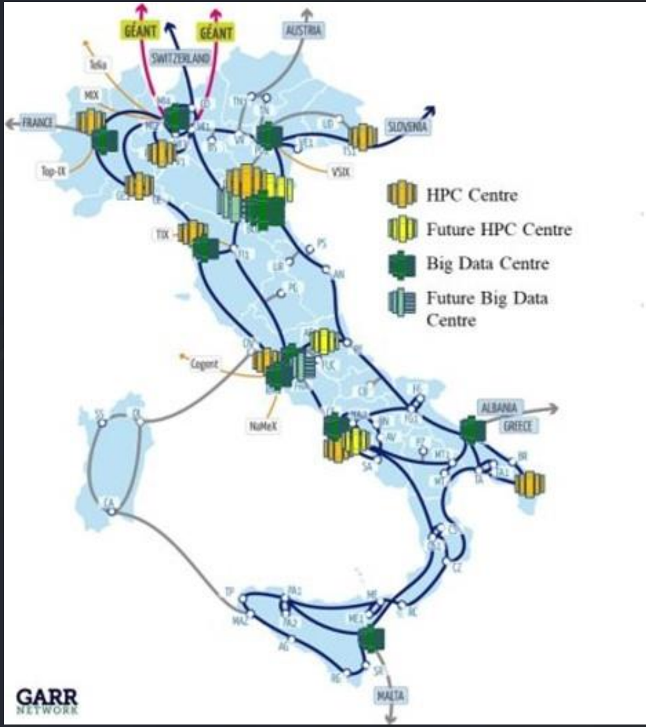

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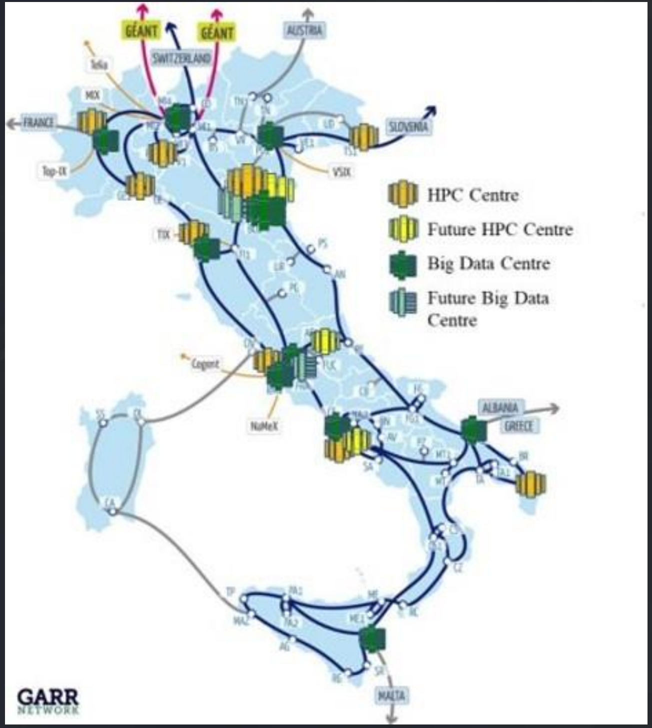

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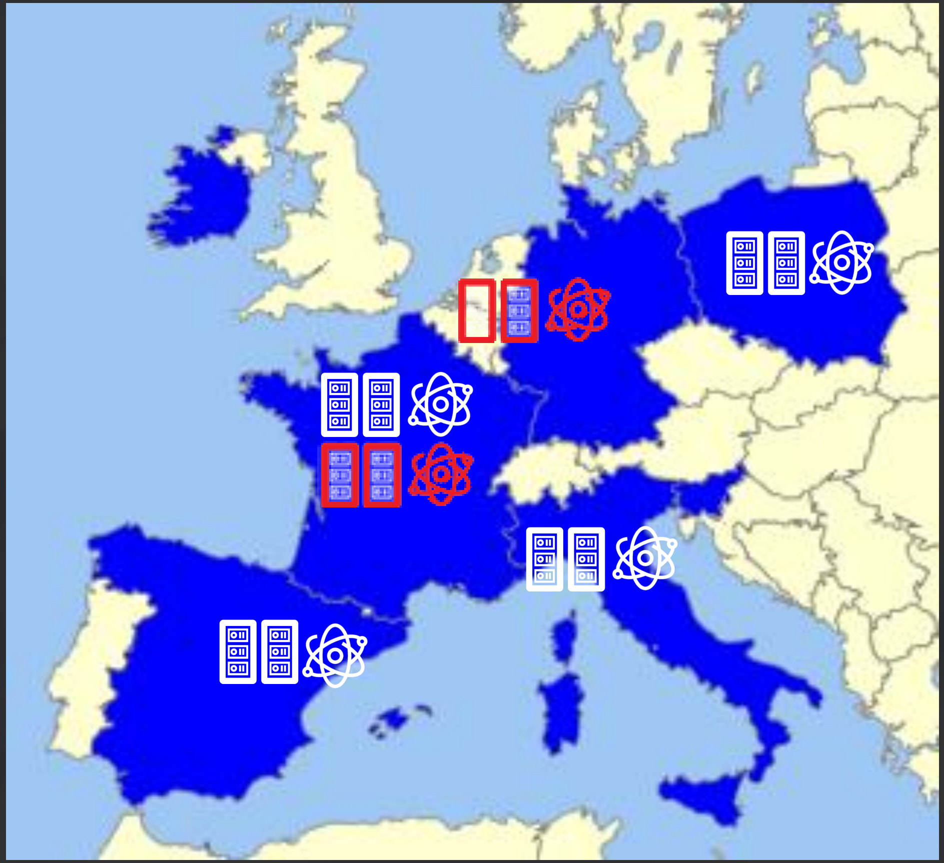
⟨HPC|QS⟩ EuroQCS



Enjoy the Workshop!

Thank You!

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