Pasqal Defining the quantum reality

# Quantum Computing with Neutral Atoms Pulser & MyQLM

20th May 2025

Krisztian BENYO, Ph. D.
Quantum Solutions Expert

Pasqal

# 1

# Introduction

# Unique mix of Excellence in Science and Engineering

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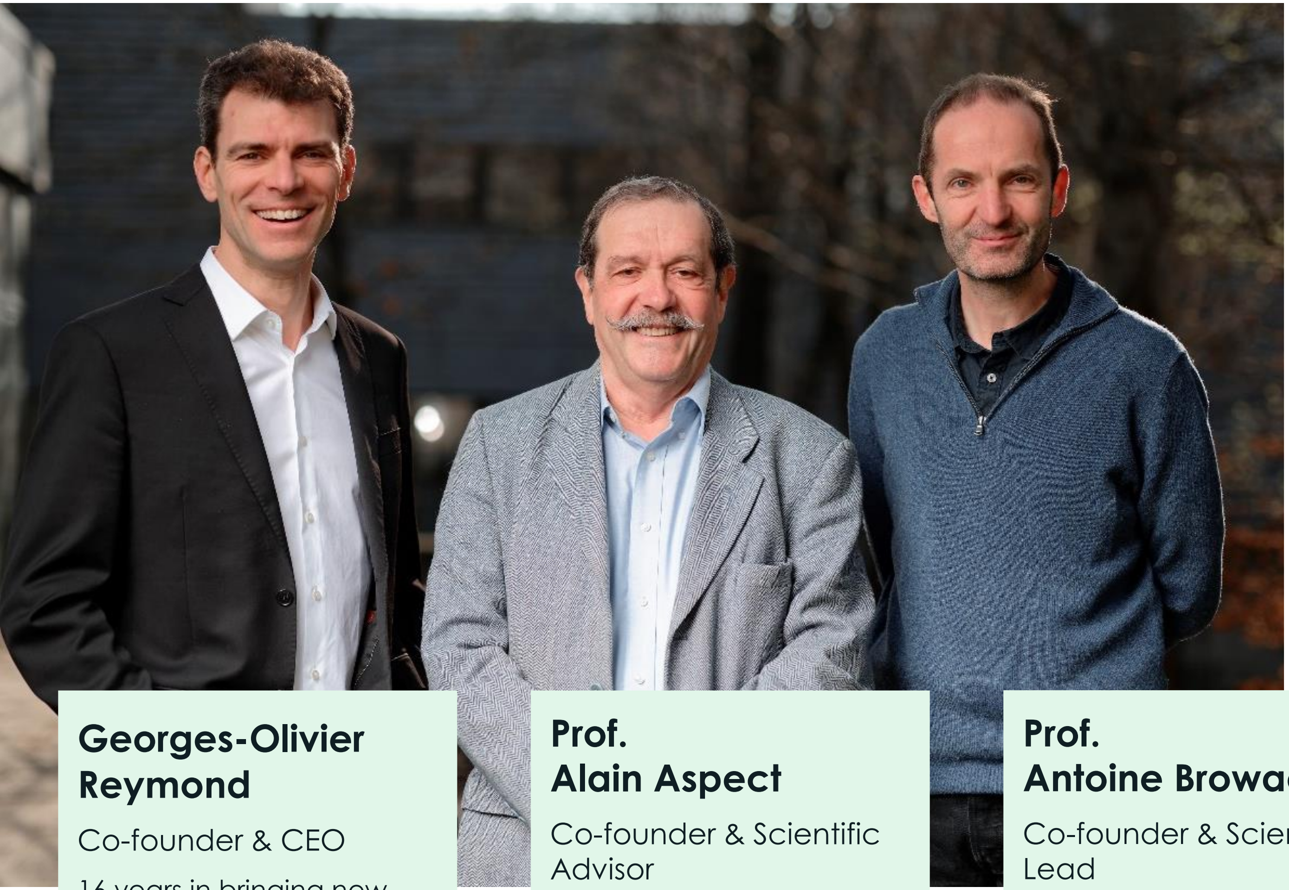

**Georges-Olivier Reymond**

Co-founder & CEO

16 years in bringing new tech to the market

**Prof.**
**Alain Aspect**

Co-founder & Scientific Advisor

2022 Nobel Prize Laureate in Physics

**Prof.**
**Antoine Browaeys**

Co-founder & Scientific Lead

2022 Solvay conference.
Nature 2021 & 2023

2024 Member French Academy of Sciences

OUR MISSION

From single atoms to global impact, our passion for science helps interpret the complexity of the world

OUR VISION

Our ambition is to break through the limits of computing by leading the delivery of state-of-the art quantum computing

"When there are no fundamental limitations, engineers find a path."

*- Prof. Alain Aspect*

# We Co-invented Neutral Atom Quantum Computing

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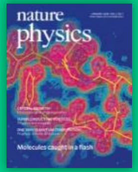
1983

Bell's inequalities violation by A. Aspect


2001

First single atom in an optical tweezer by G. Reymond
Nature 411, 1024–1027




2009

First Rydberg blockade by A. Browaeys
Nature Physics volume 5, 115–118


2016

Simulation with 30 qubits by T. Lahaye & A. Browaeys
Nature volume 534, 667–670


2018

Simulation with 49 qubits, 3D and 72 atoms in tweezers by T. Lahaye & A. Browaeys
Nature volume 561, 79–82
Phys. Rev. X 8, 021070

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2019

Founding of Pasqal by T. Lahaye, A. Browaeys, G. Reymond, C. Jurczak


2021

Simulation with 196 qubits- Quantum Advantage- by T. Lahaye & A. Browaeys
Nature volume 595, 233–238

Pasqal Defining the quantum reality

2019
Pasqal Founded
Headquarters: France

2021
Pasqal raises €25 M
in Series A

2022
Pasqal merges with
Qu & Co.

2022
Prof. Alain Aspect, co-founder, is
awarded the Nobel Prize in Physics

2022
First Neutral Atoms Quantum
Computer available on the cloud

2022
Pasqal acquires
My Cryo Firm

2023
Highlighted by the BCG
company developing enterprise-
grade ready offer

2023
Pasqal raises
€100 M in Series B

2024
Pasqal exceeds 1,000 atoms
in quantum processor

2024
IBM collaboration

2024
First quantum
computers delivered
to GENCI and CEA

2024
CMA CGM Group
and Pasqal join forces

# Pasqal at a Glance

Pasqal

- **7 QPUs** in operations & manufacturing; 5 sold (2 already deployed)
- **400+** Publications & patents by 2024
- **20+** Public Customer Use cases[1]
- **75+** International PhDs
- **HQ in Europe** (France) and presence in Europe, Asia, North America and Middle East
- **2x Quantum Factories** in Paris (France) and Sherbrooke (Canada)

| Partnership | Partners |
|---|---|
| End-User Pool *(Public and Private)* | A*STAR (Agency for Science, Technology and Research), Capgemini, covestro, gesda, KIPU Quantum, MBDA Missile Systems, PINQ², Sumitomo Corporation, TATA, Rte |
| Cloud Access & Remote HPC | aws, Microsoft Azure, TGCC, Google Cloud, OVHcloud |
| Development of Application Portfolio & Software Stack | Capgemini, KIPU, Mila, Multiverse Computing, NVIDIA, Odyssey Therapeutics, parityqc, Qubit Pharmaceuticals, Sumitomo Corporation, tcs, Tech Mahindra, Unitary Fund, University of Notre Dame, universität innsbruck |
| Programming Environment *(QC Framework and Open-Source Library)* | Atos, Google |

# Multiple Paths to build Quantum Computers

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QPUs can be built using different technologies

| Technology | Maturity | Description | Companies |
|---|---|---|---|
| NEUTRAL ATOMS | I I I | Trapping atoms with lasers and encoding qubits in the atoms' energy levels | Pasqal, QuEra Computing Inc. |
| SUPERCONDUCTING | I I I | Cooling down electronic circuits to near absolute zero to create superconducting qubits out of artificial atoms, or quantum dots | IBM, Google AI Quantum |
| PHOTONIC | I I | Using photons in light as qubits themselves | PsiQuantum, Xanadu |
| TRAPPED IONS | I I I | Confining and suspending ions, or charged atomic particles, in free space using electromagnetic fields | Quantinuum, IonQ |
| SPIN QUBITS | I I | Based on controlling the spin of charge carriers (electrons and electron holes) in semiconductor devices | intel, Silicon Quantum Computing |

| | |
|---|---|
| Scalability | No major roadblocks near-term to scale the qubit count to 10,000 qubits and beyond, following our roadmap |
| Dual digital-analog modes | The unique dual analog-digital capability, offers the opportunity of near-term value with analog while developing FTQC |
| Uniformity and Quality | Since we use atoms as qubits, they are naturally identical and free from any imperfections |
| Room temperature operation | No cryogenics required, the system operates at room temperature, significantly reducing power consumption |

# Pasqal is the only company delivering commercially ready QPUs

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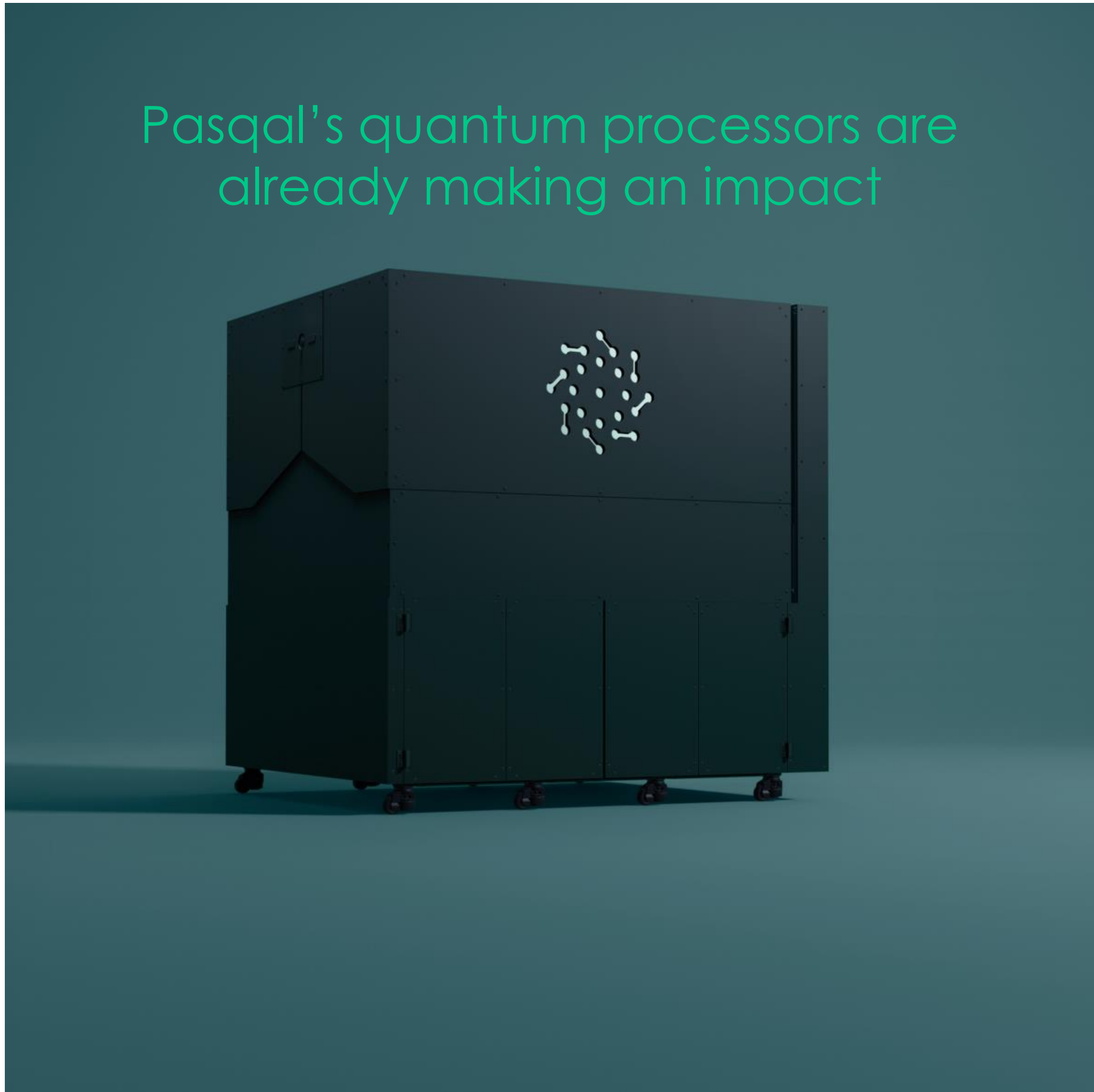
Pasqal is delivering quantum-powered solutions today with QPUs shipped to industry leaders and institutions worldwide.

## Notable Deliveries of Pasqal Hardware:

- June 2024: CEA Genci (France) delivery
- November 2024: Delivered processors to Jülich, Germany
- Planned Deliveries in 2025: Saudi Aramco (KSA)

From finance to energy, businesses are unlocking value with Pasqal's quantum computing solutions right now



# A Roadmap Articulating Our Vision

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| | | 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 IQ 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** 200+ 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 & Emulation | | | |

Note: Webinar to discover PASQAL's roadmap to Quantum Readiness with a Full-Stack Approach & Transformative Use Cases - https://lnkd.in/evejEWUc

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# Neutral Atoms Quantum Computing

# Our Plug and Play Quantum Computers for Customers

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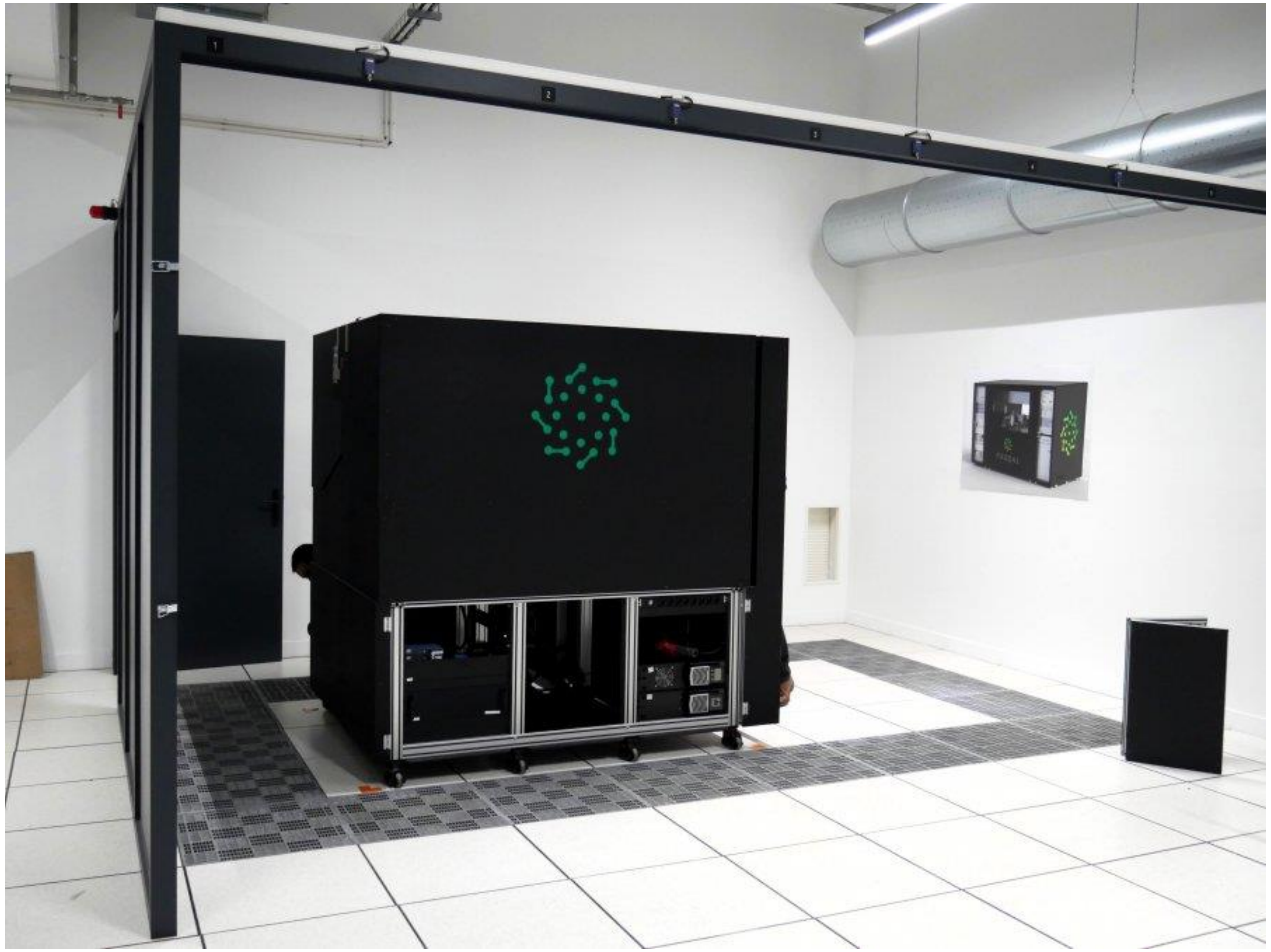

Quantum computers compatible with **standard environment**

Setup at **room temperature**

Industrial **off-the-shelf** components

**Low energy** consumption (equivalent to 4 hair dryers)

# Neutral atom quantum processors

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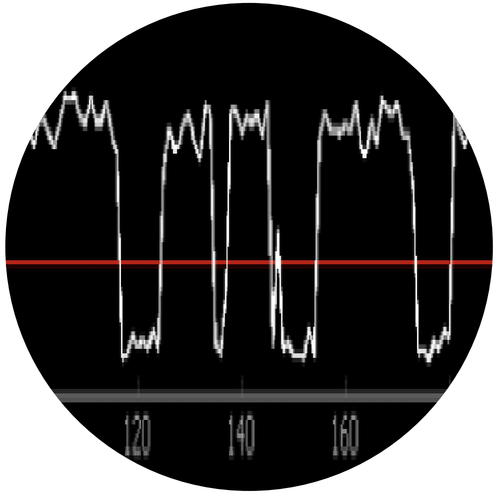
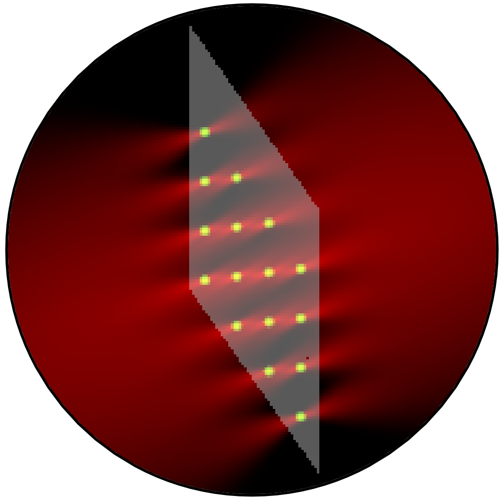
## Single atom trapping/detection

Qubits are encoded into two of the many electronic states of neutral atoms.



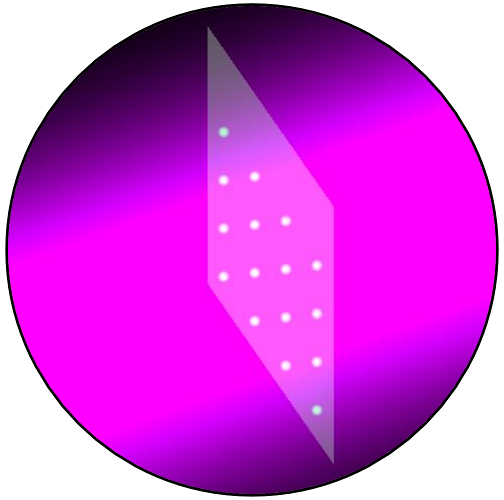

## Register made with tweezers

The register is prepared using laser cooling and trapping techniques



## Processing using laser fields

Lasers are used to manipulate the internal degree of freedom



# Rydberg atomic arrays as quantum processing units

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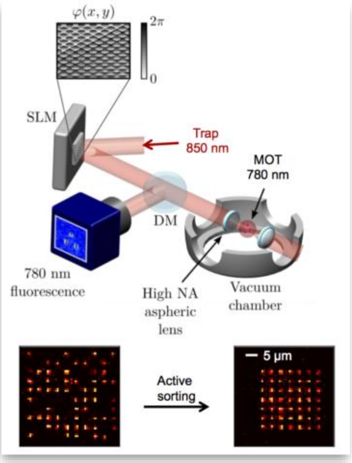
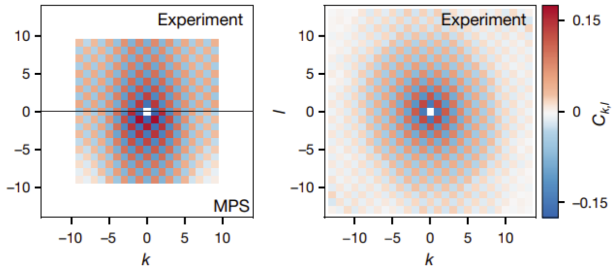
Neutral atoms (typically Rubidium or Strontium), trapped in an optical tweezer array.




*Nat. Phys.* ***16,*** *132 (2020).*

Scalable to hundreds of atoms – *can capture both short-range order and lack of long-range order.*



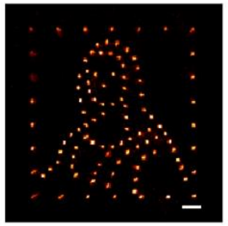

Adapted from *Nature*, **595**, 233–238 (2021)

Can realise both the Ising model and XY model

$$\mathcal{H}(t) = \frac{\hbar}{2}\Omega(t)\sum_j \sigma_j^x - \hbar\delta(t)\sum_j n_j + \sum_{i\neq j}\frac{C_6}{r_{ij}^6} n_i n_j,$$

$$\mathcal{H}(t) = \frac{\hbar}{2}\Omega(t)\sum_j \sigma_j^x - \frac{\hbar}{2}\delta(t)\sum_j \sigma_j^z + 2\sum_{i\neq j}\frac{C_3}{r_{ij}^3}\left(\sigma_i^x\sigma_j^x + \sigma_i^y\sigma_j^y\right).$$

Flexible atomic register



Adapted from *Phys. Rev. A* ***102****, 063107*

# How does one make qubits out of atoms ?

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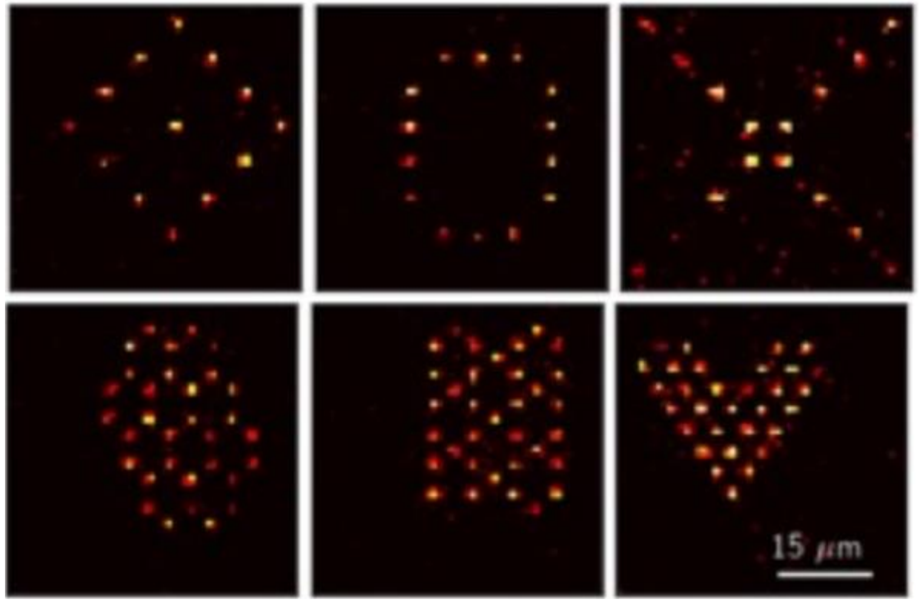
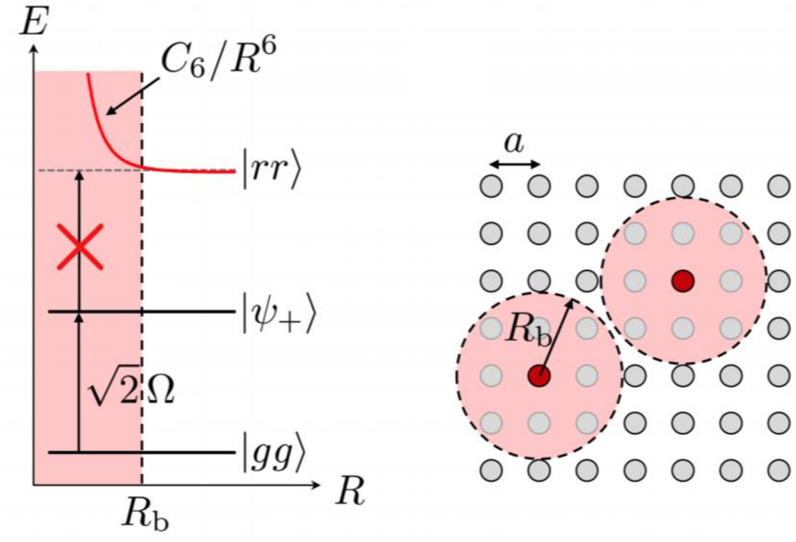
1. We need to identify a $|0\rangle$ and a $|1\rangle$ **state**
   - Ground states and hyper-excited Rydberg states of Rubidium atoms
2. We need to be able to address **transition** between $|0\rangle$ and $|1\rangle$ states
   - Laser beams
3. We need to know where the atoms are
   - Optical tweezers
4. We need to be able to produce **entanglement** between the atoms
   - Rydberg blocade
5. We need to be able to **measure** the system
   - Fluorescence imaging



# Neutral Atoms Drive Our Quantum Technology

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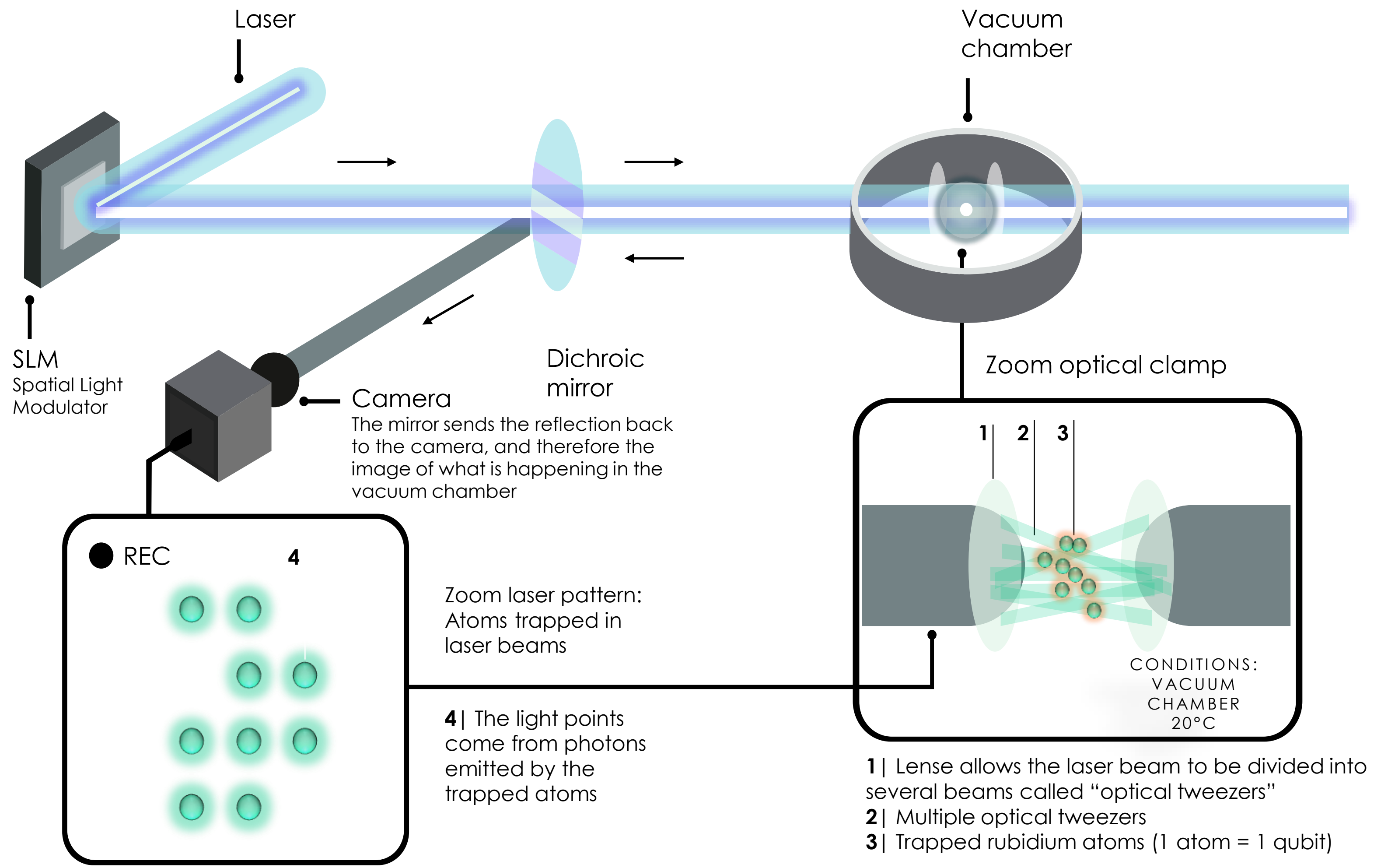
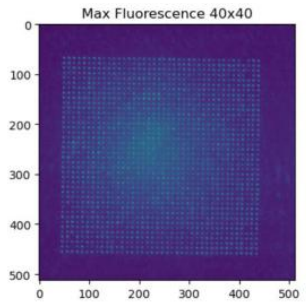
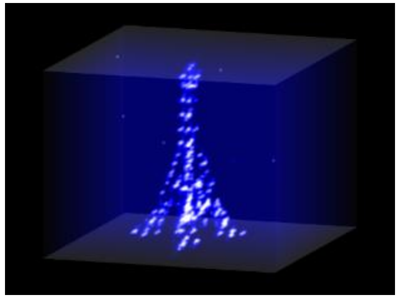



*"After 20 years in the field, I now strongly believe that Neutral Atoms technology has all the assets to embrace Quantum Computing challenges and unlock all its opportunities"*

*- Prof. Antoine Browaeys, CSO and Co-founder of Pasqal; Research Director of CNRS*



Source: Quantum computing with neutral atoms, Quantum 4, 327 (2020)

# Machine cycle

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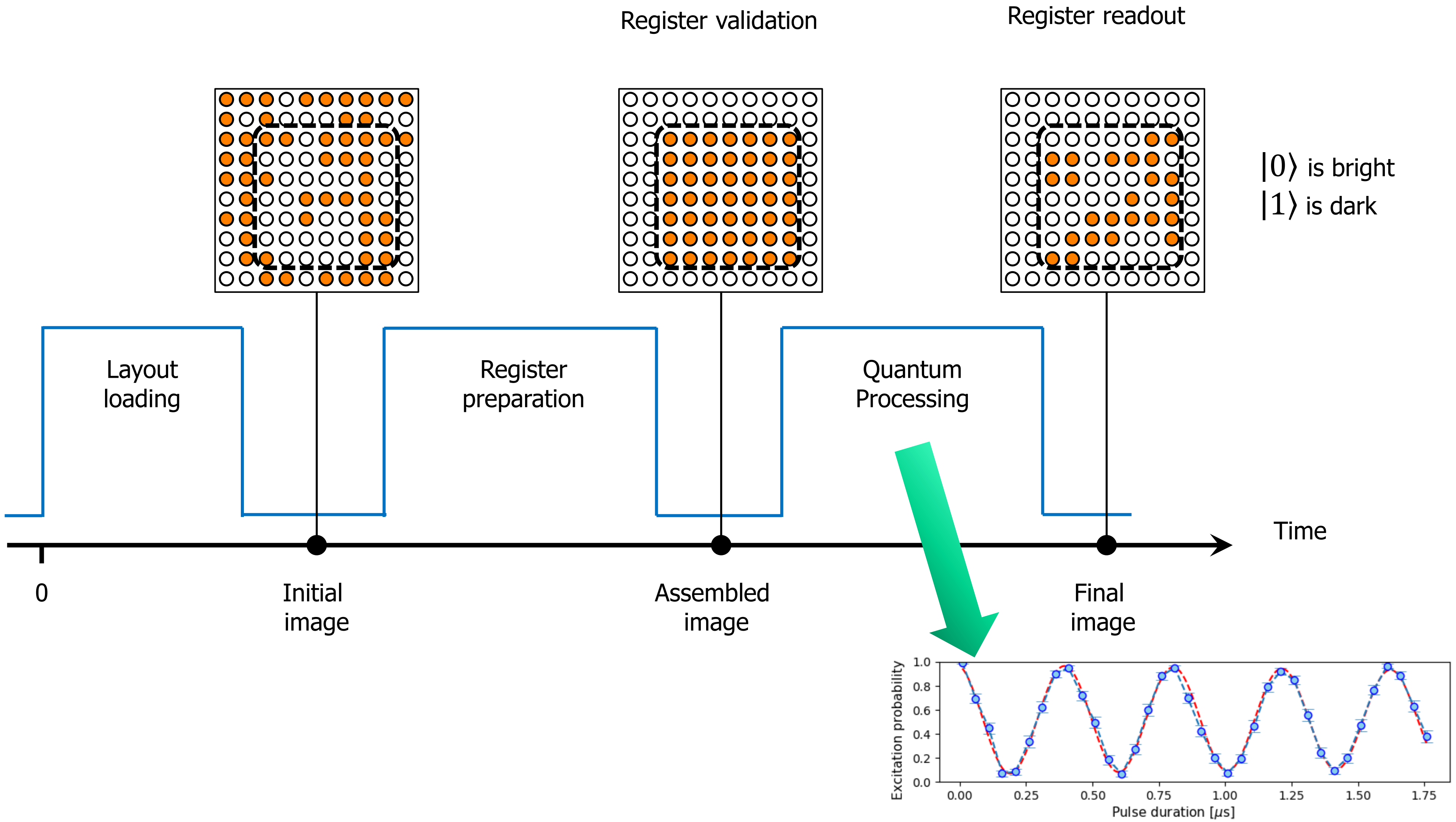

# Antiferromagnetic states / Maximum Independent Set

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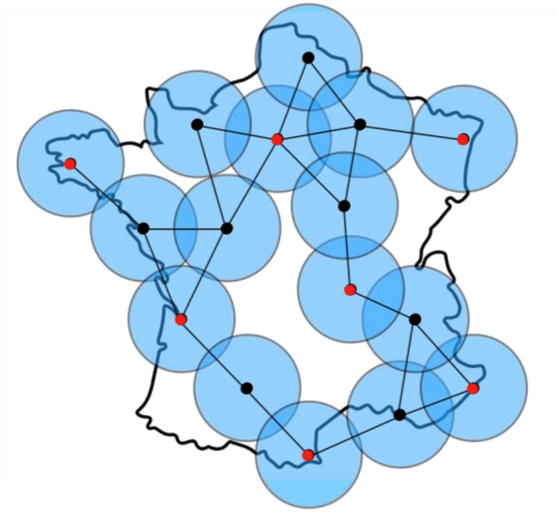
# Algorithmic components

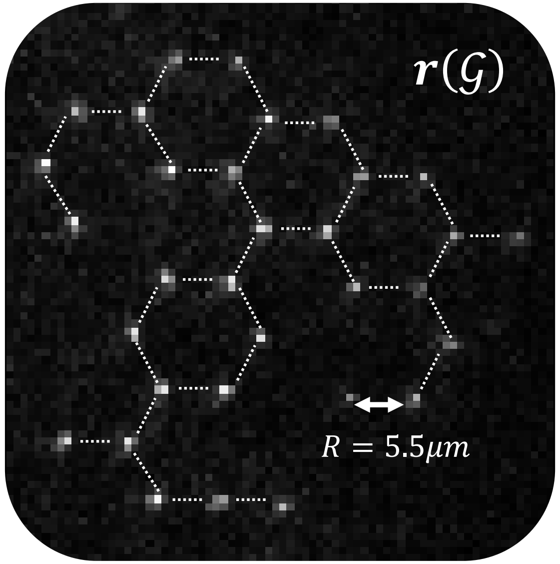
# How to map graph problems onto a neutral atoms QPU?



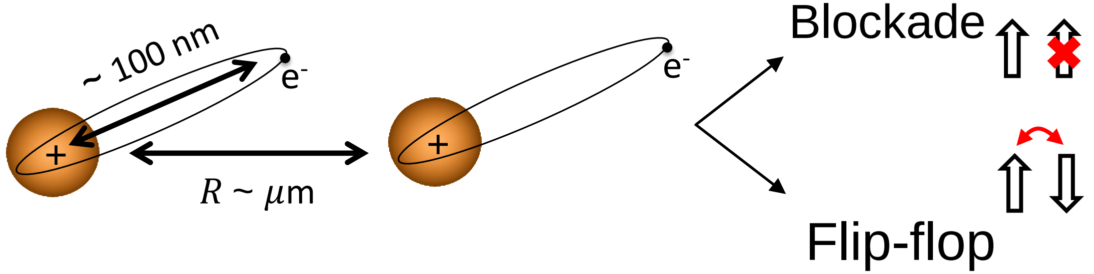
Graph topology

$$H_{\mathcal{G}} = \sum_{(i,j)\in E(\mathcal{G})} n_i n_j$$

Nodes -> atoms
Edges -> interactions




Dipole-dipole interactions



# Entangling atomic qubits

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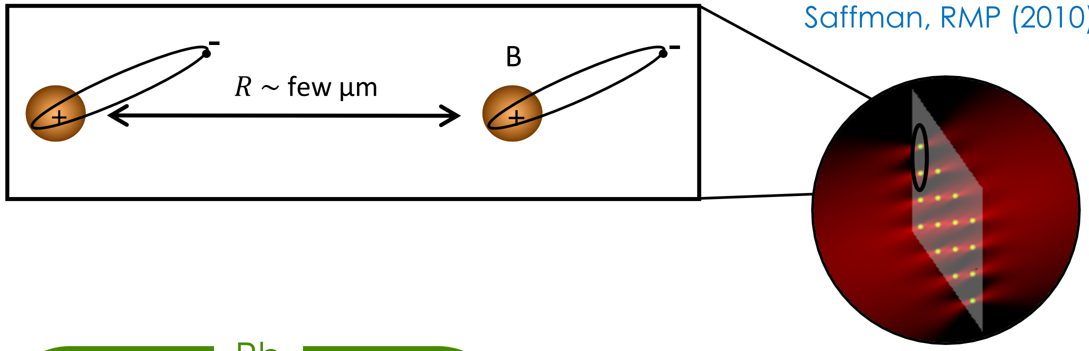
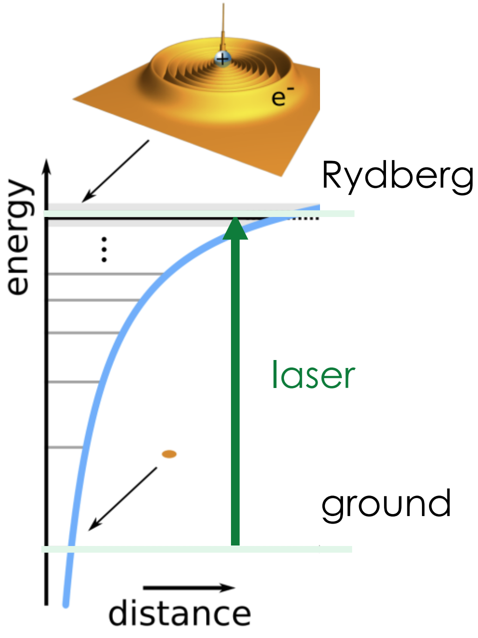
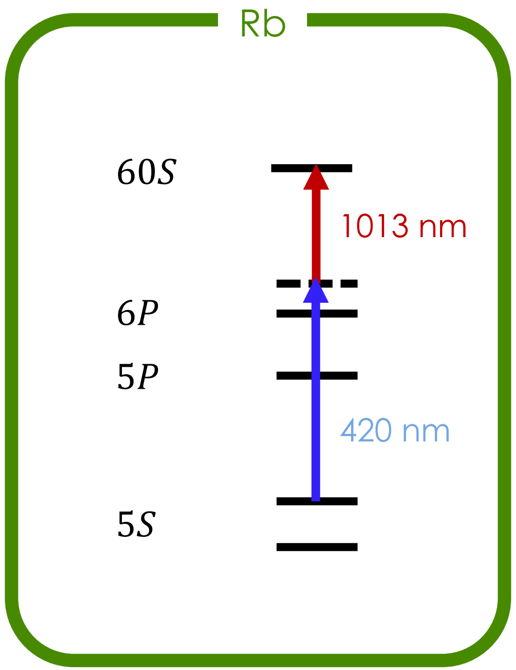
- Rydberg states are highly excited states
- Atoms in those states behave as electric dipoles
- dipole-dipole interactions generate entanglement




Jaksch et al., PRA (2000)
Saffman, RMP (2010)




Morgado, Withlock, AVS Quantum Sci. (2021)



# Tunable Ising Hamiltonian

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Transverse field

Ising couplings: $J_{ij} \propto 1/R_{ij}^6$

$$\mathcal{H}(t) = \sum_i \left( \frac{\hbar\Omega(t)}{2}\sigma_i^x - \hbar\delta(t)\hat{n}_i + \sum_{j<i} \frac{C_6}{(R_{ij})^6}\hat{n}_i\hat{n}_j \right)$$

$$\frac{1+\sigma_i^z}{2}$$

**Quantum Simulation**

Permits the simulation of quantum many-body systems far beyond the limits of classical computers, allowing, for example, the:

- Observation of out-of-equilibrium dynamics
- Adiabatic preparation of ground states

# Quantum for QUBO

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Quantum computers promise a performance improvement for solving quadratic unconstrained binary optimization (QUBO) problems

Quantum optimization through adiabatic evolution can solve QUBO (quadratic unconstrained binary optimization) problems

$$f(x) = \sum_{i<j}^{N} Q_{i,j} x_i x_j + \sum_{i}^{N} Q_{i,i} x_i$$

with f(x) the optimization function, Q an NxN upper triangular matrix with real weights and x a vector of binary variables

This problem can also be formulated through an Ising type Hamiltonian

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

where J represents the spin-spin interaction, h represents an external field, and the σ are the individual spins on each of the lattice sites; or (when implemented in quantum): $\sigma^{(i)}_{x,z}$ are Pauli matrices operating on a qubit $q_i$, and $h_i$ and $J_{i,j}$ are the qubit biases and coupling strengths

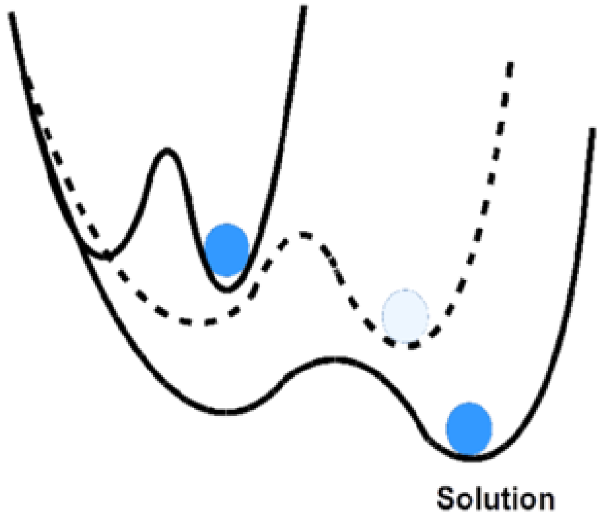
# Quantum for QUBO

Quantum computers promise a performance improvement for solving quadratic unconstrained binary optimization (QUBO) problems

In adiabatic quantum computation (such as D-Wave quantum annealer), we start in the ground state of some well known physical system with a trivial Hamiltonian $H_0$

Then, we evolve *adiabatically* (very slowly to remain in the ground state) the Hamiltonian towards that of the problem Hamiltonian, $H_1$

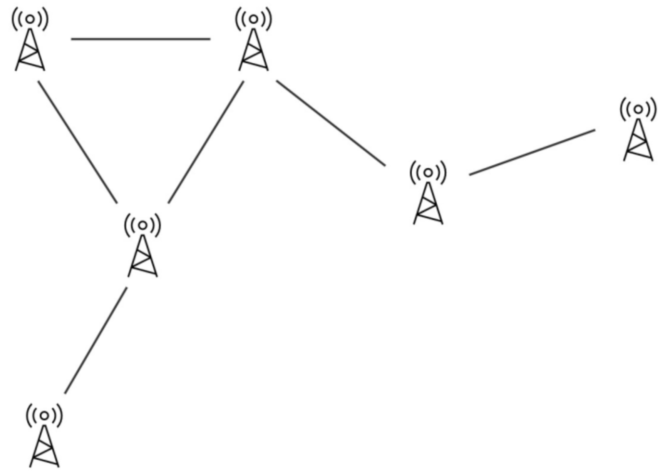
On gate-based (digital) quantum computers a similar process can be implemented using a variational qantum algorithm called QAOA

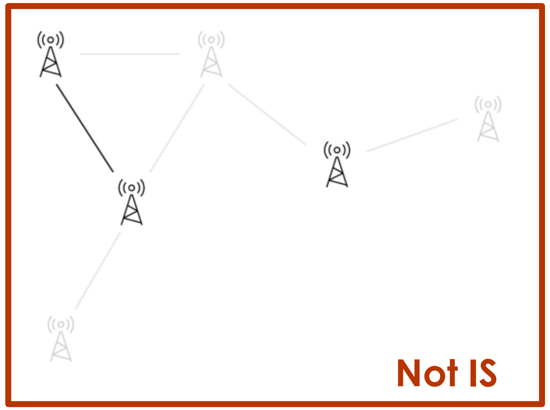


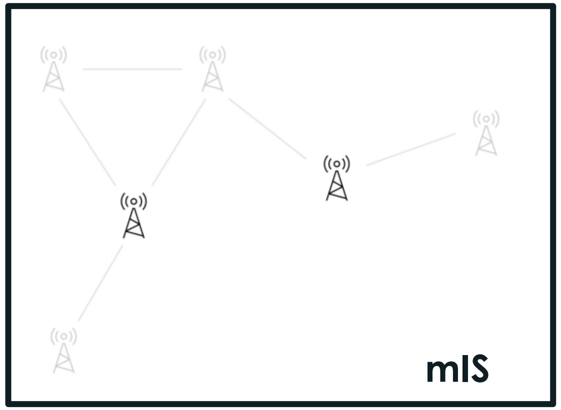
# MIS (Maximum Independent Set)

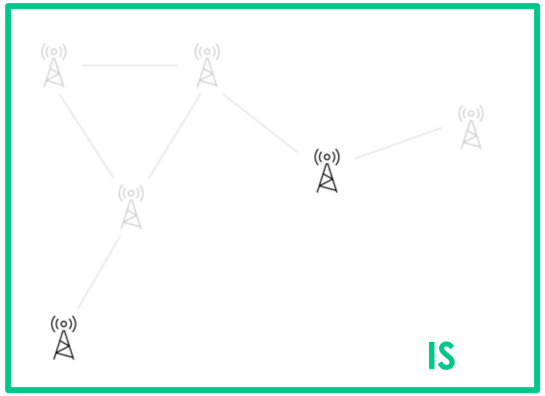
Definition: Independent set (IS) = set of nodes of a graph where no two nodes are adjacent

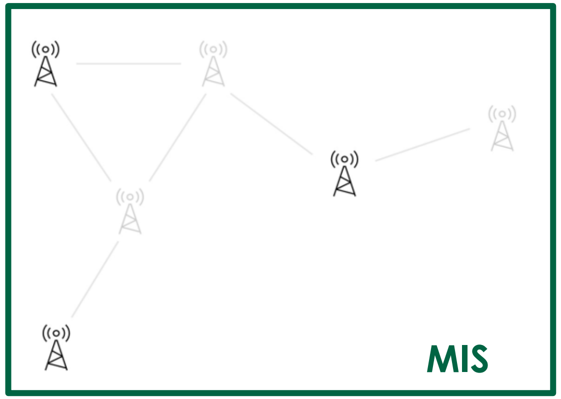
***Maximal independent set (mIS)*** vs **Maximum independent set (MIS)**





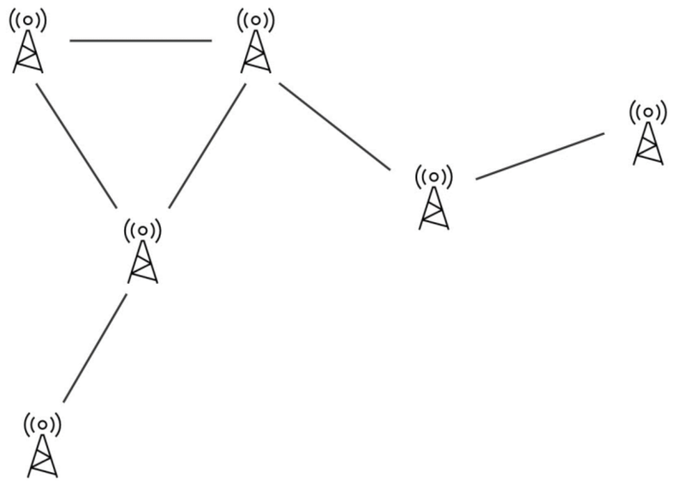



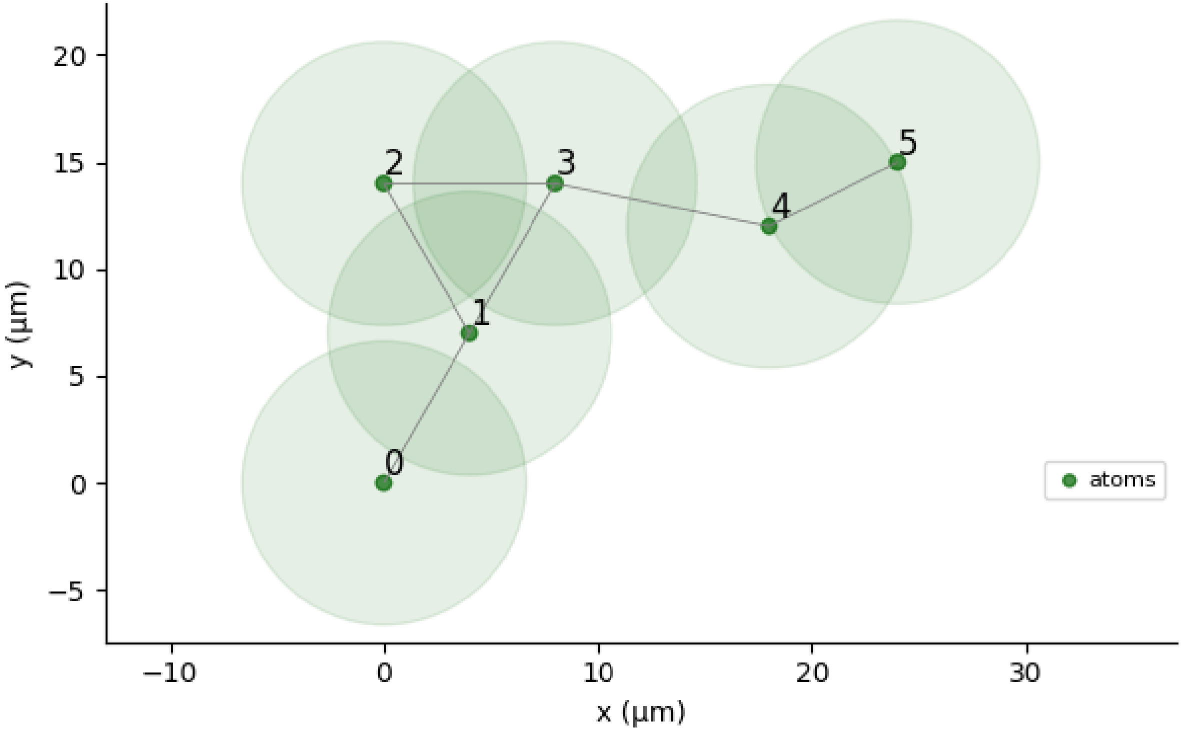



# MIS (Maximum Independent Set) Solver

Neutral-atoms are good are finding MIS by design:

- Flexible atomic positions allow us to allow us to easily tackle graph problems by directly encoding the graph with the positions of the atoms and the distances between them.
- Rydberg dynamics can be leveraged to naturally encode the constraints and solution to the MIS problem for unit-disk graphs.



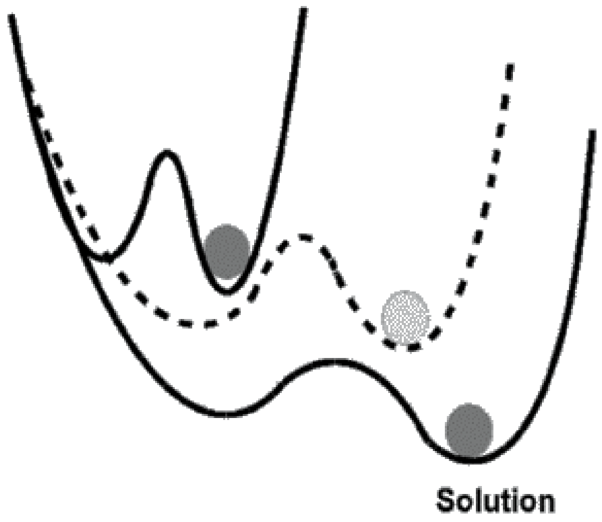


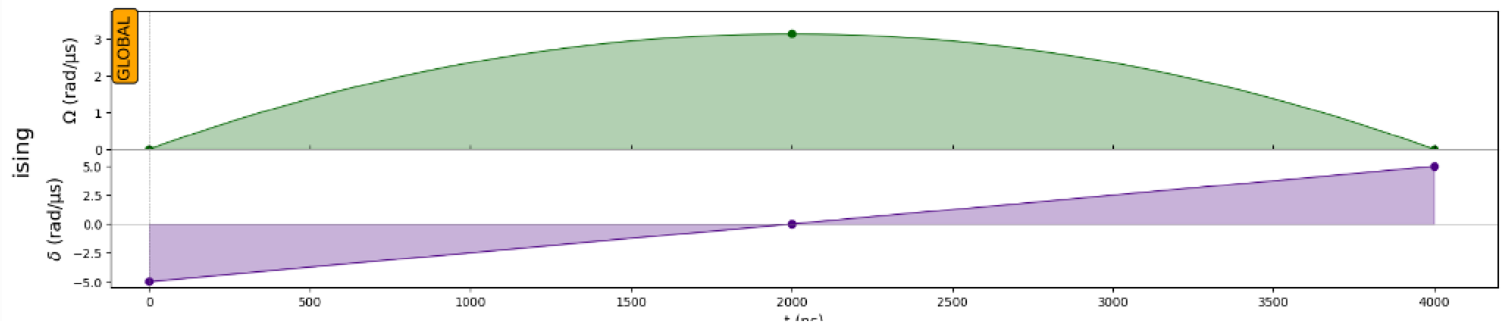
# MIS (Maximum Independent Set) Solver

## Quantum optimization through adiabatic evolution

In adiabatic quantum computation, we start in the ground state of some well-known physical system with a trivial Hamiltonian $H_0$

Then, we evolve *adiabatically* (very slowly to remain in the ground state) the Hamiltonian towards that of the problem Hamiltonian, $H_1$



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# Pulser Studio

# Exercise 1

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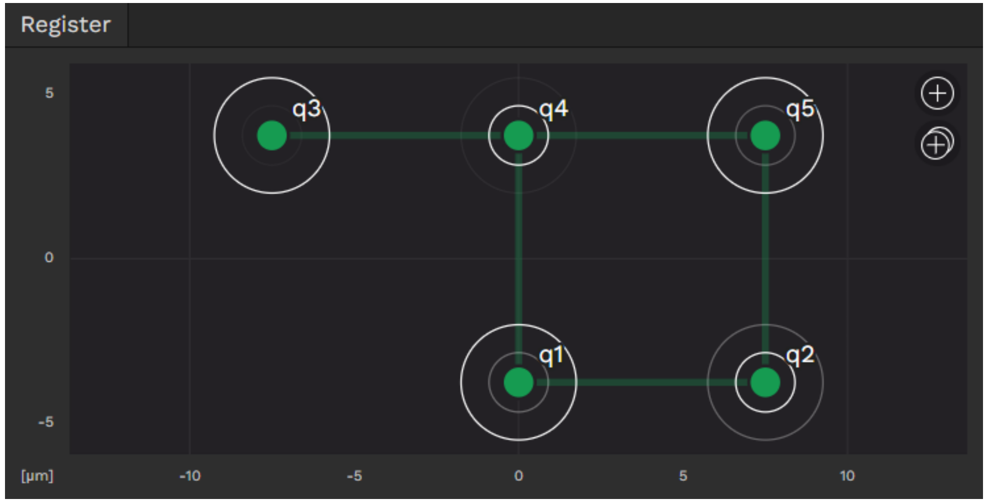
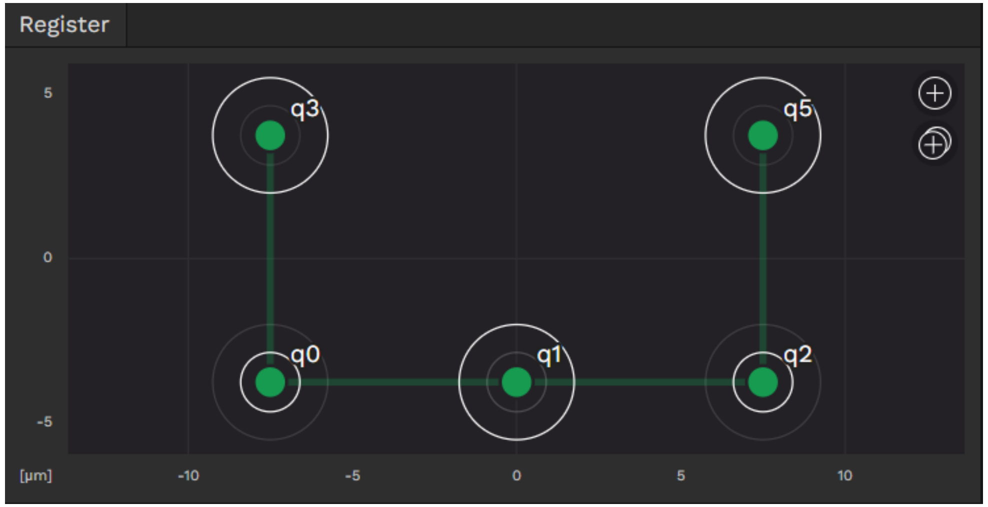
In the antiferromagnetic state example, what happens if we remove a node?




In the antiferromagnetic state example, what happens if we remove two nodes?

# Exercise 2A

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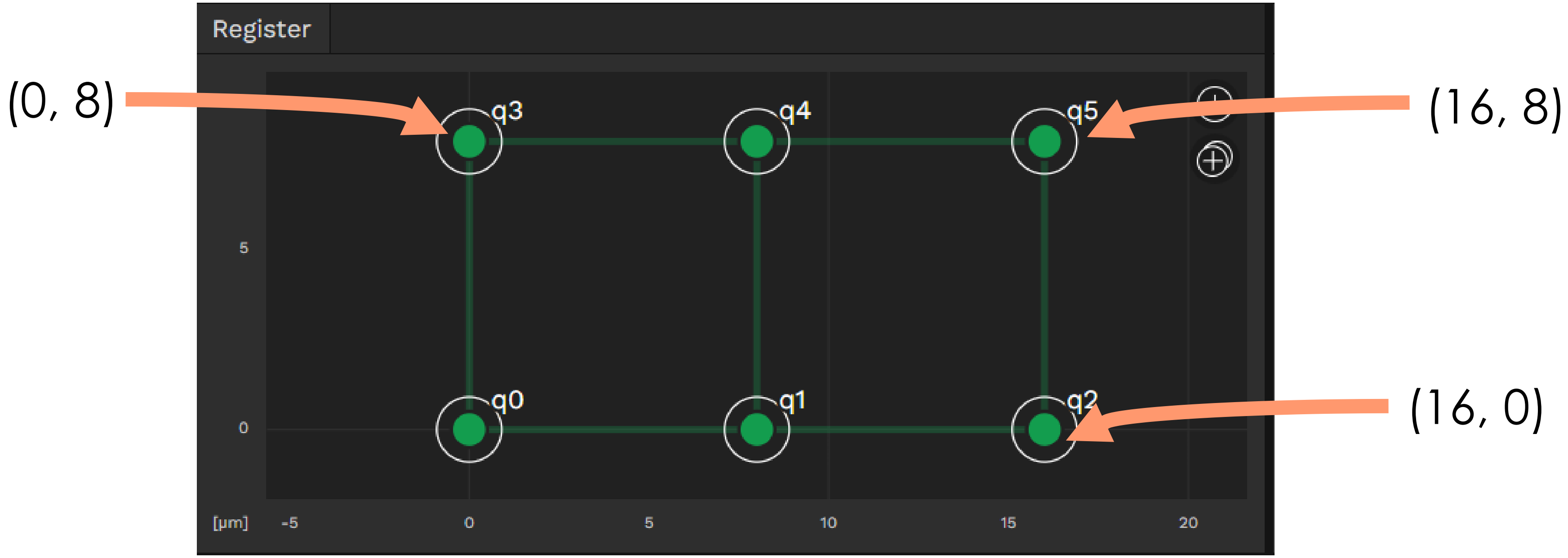
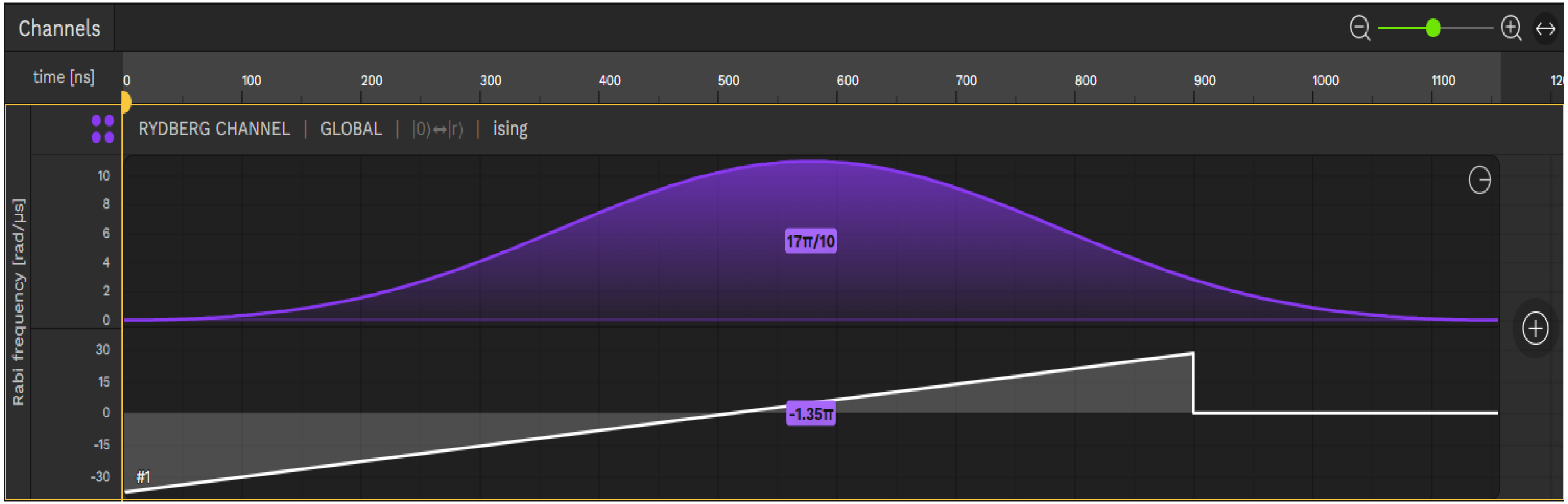
Try to create a new quantum register, while keeping the pulse parameters the same!
Let's define once again the geometry of the antiferromagnetic state example on a structured grid of 8 micrometers per neighbor, starting from(0,0).
What happens with the simulation now?

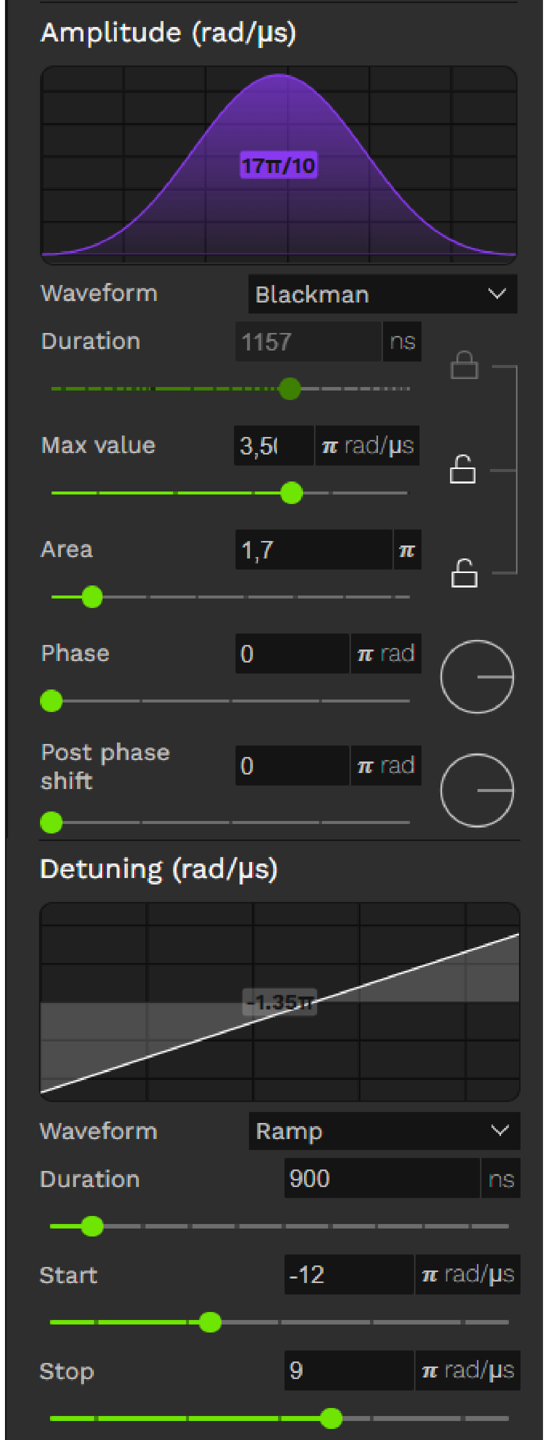



Bonus : What happens if we change the length between neighbours of the grid to larger or smaller, all the while keeping the same pulse?

# Exercise 2B

For this newly created register, let us create a new pulse!
We will define a pulse as a continuous extension of the existing pulse, with a truncated Gaussian and a shifted detuning!
What are the simulation results now?




Bonus : What happens if we shift further the detuning parameter in time?

# Exercise 3

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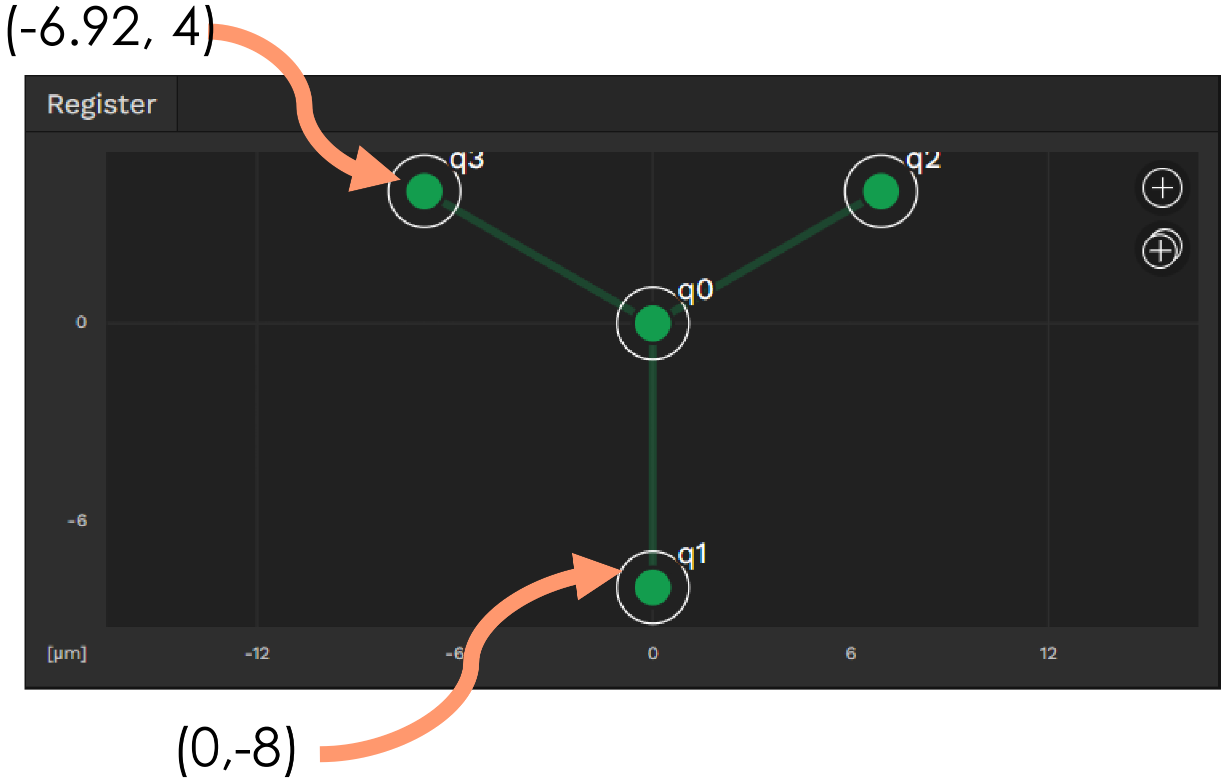
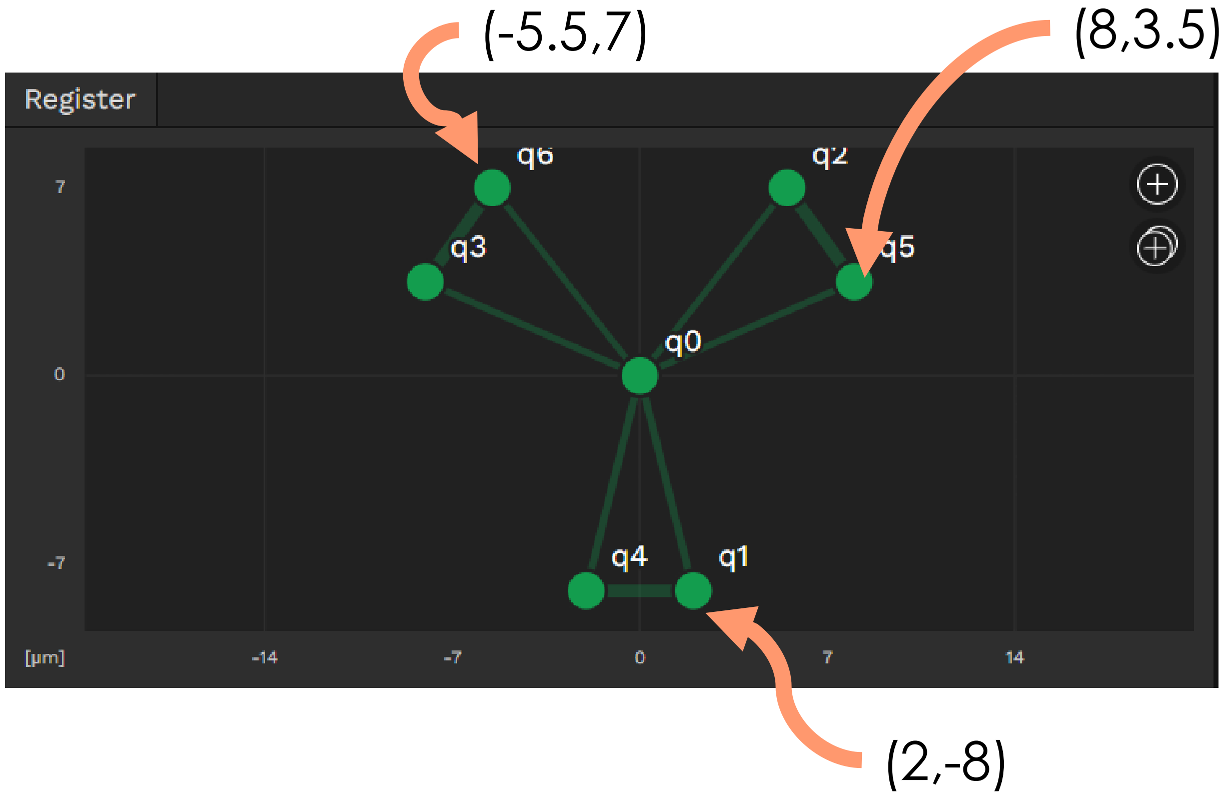
Let us try this new pulse for other geometries!
Construct a star shaped quantum register of 4 points. What happens after the simulation?
How does it compare with the original pulse?




Now construct a star shaped register with 7 points by doubling the existing leaves. What is the result of the simulation?
How does it compare with the original pulse?

# Exercise 4

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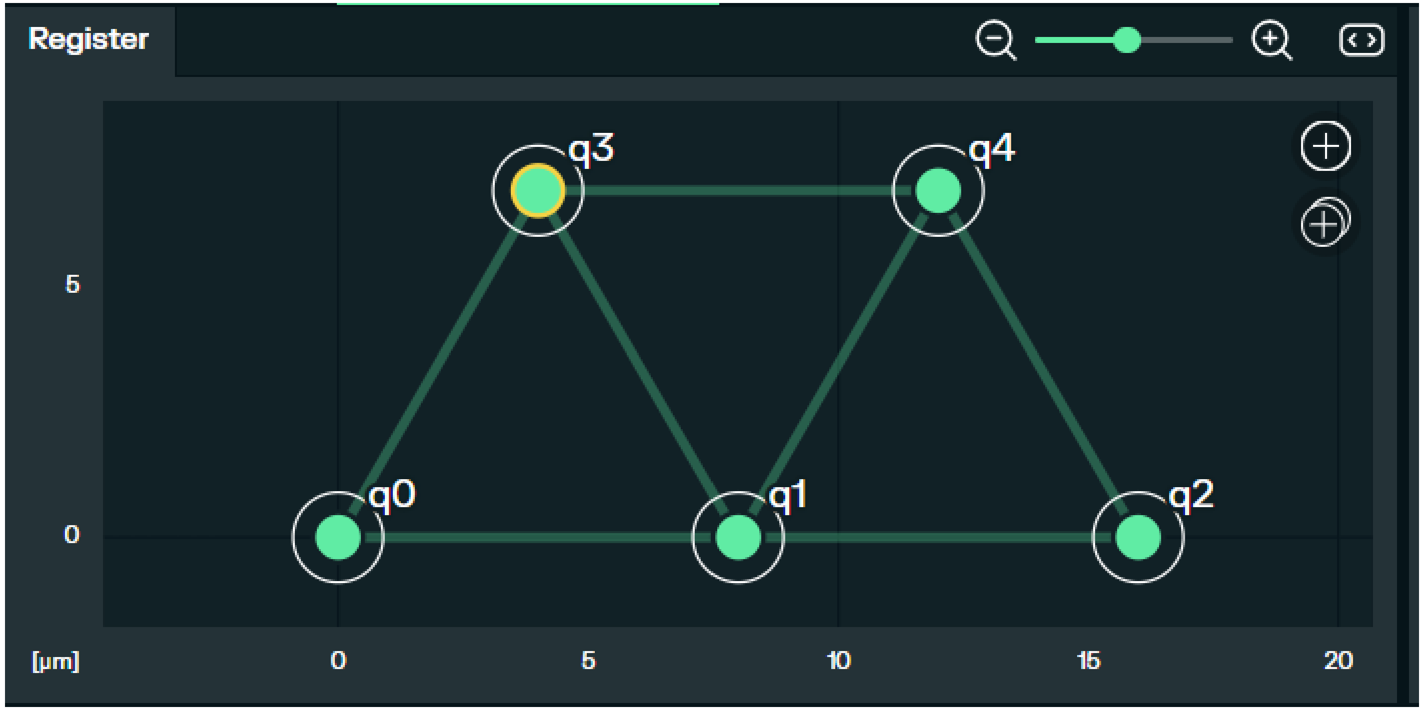
Let us try this new pulse with yet another quantum register!
Construct the following 5 point register. What is the result of the simulation?
How does it compare with the original pulse?



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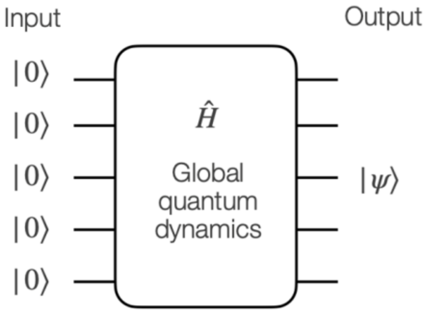
# Programming on a neutral atoms system

# Neutral Atom QPUs can implement Algorithm with High Number of Equivalent Gates

## Analog Control

Programming a Hamiltonian sequence

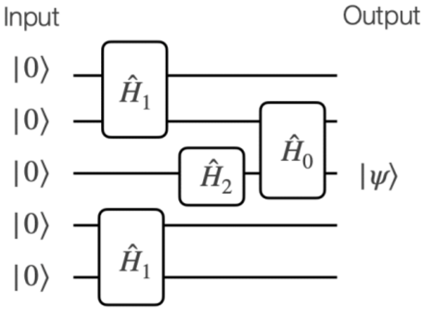
The Hamiltonian faithfully describes the dynamics of a physical quantum system or a reformulation of an operational case. Parameters can be tuned continuously.



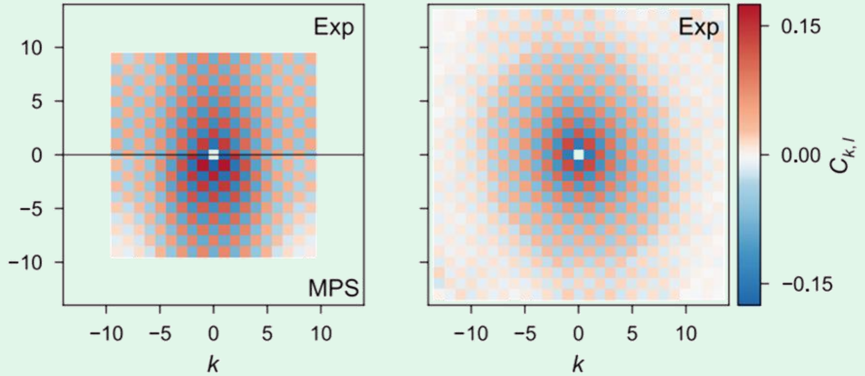

## Digital Control

Programming a quantum circuit with digital quantum gates

Elementary operations are discrete digital quantum gates, that can act either on individual qubits, or on several qubits at the same time.




## Quantum Materials



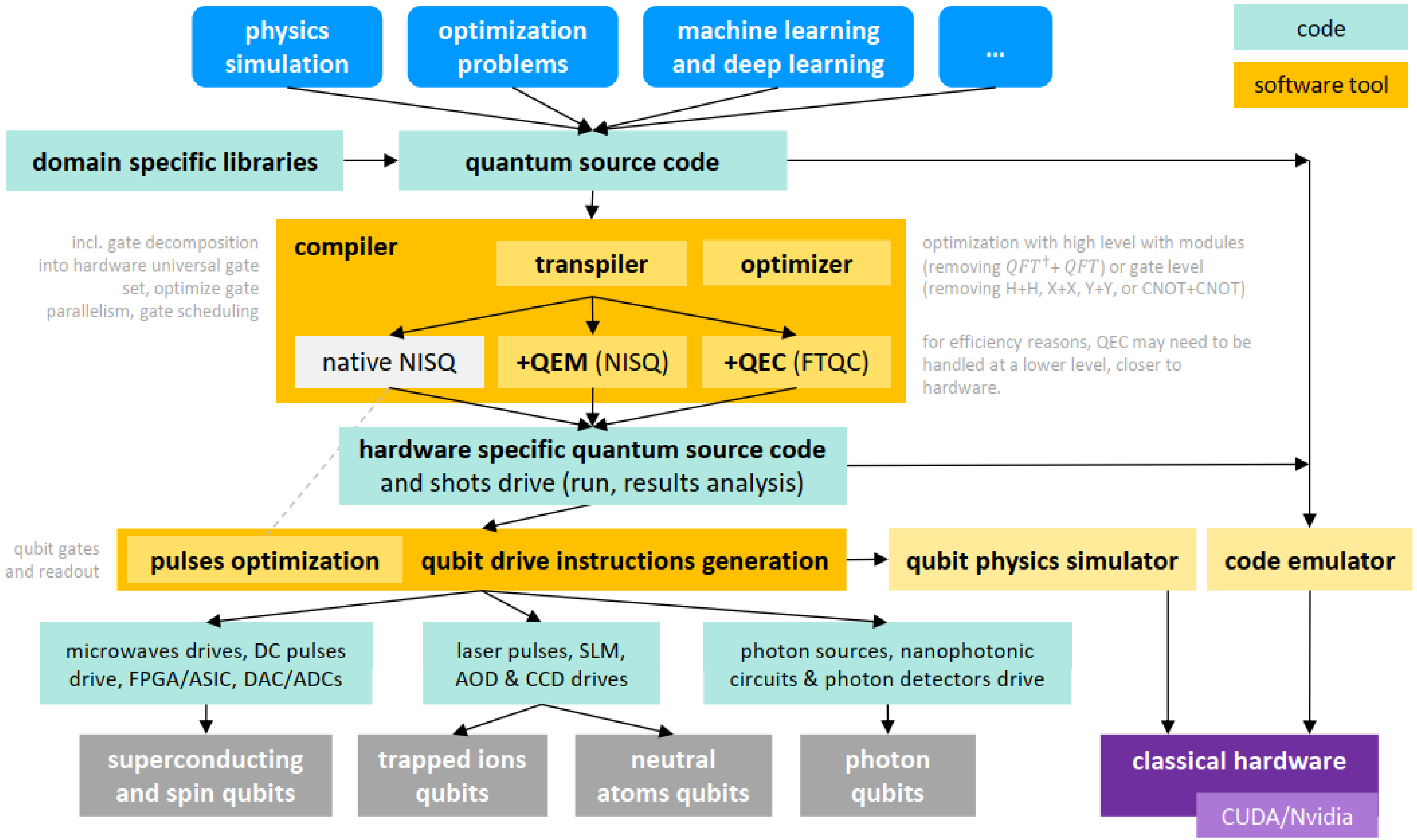

Staggered magnetisation histograms for 10 × 10 and 14 × 14 arrays, with MPS shown on the lower part of the 10 × 10 array (14 days for simulation with TeNPy) [1].

With typical error level of 1% of the analog mode, $10^6$ gates are required with $1\text{-}F < 10^{-6}$ to simulate the same quantum dynamics of a 10x10 2D Ising-like model system[2].


[1] Scholl, et al., Nature 595 (2021)
[2] Flannigan, Pearson, Low, Buyskikh, Kokail, Bloch, Zoller, Troyer, Daley (Nature 2022, Q Sci. Technol. 2022)

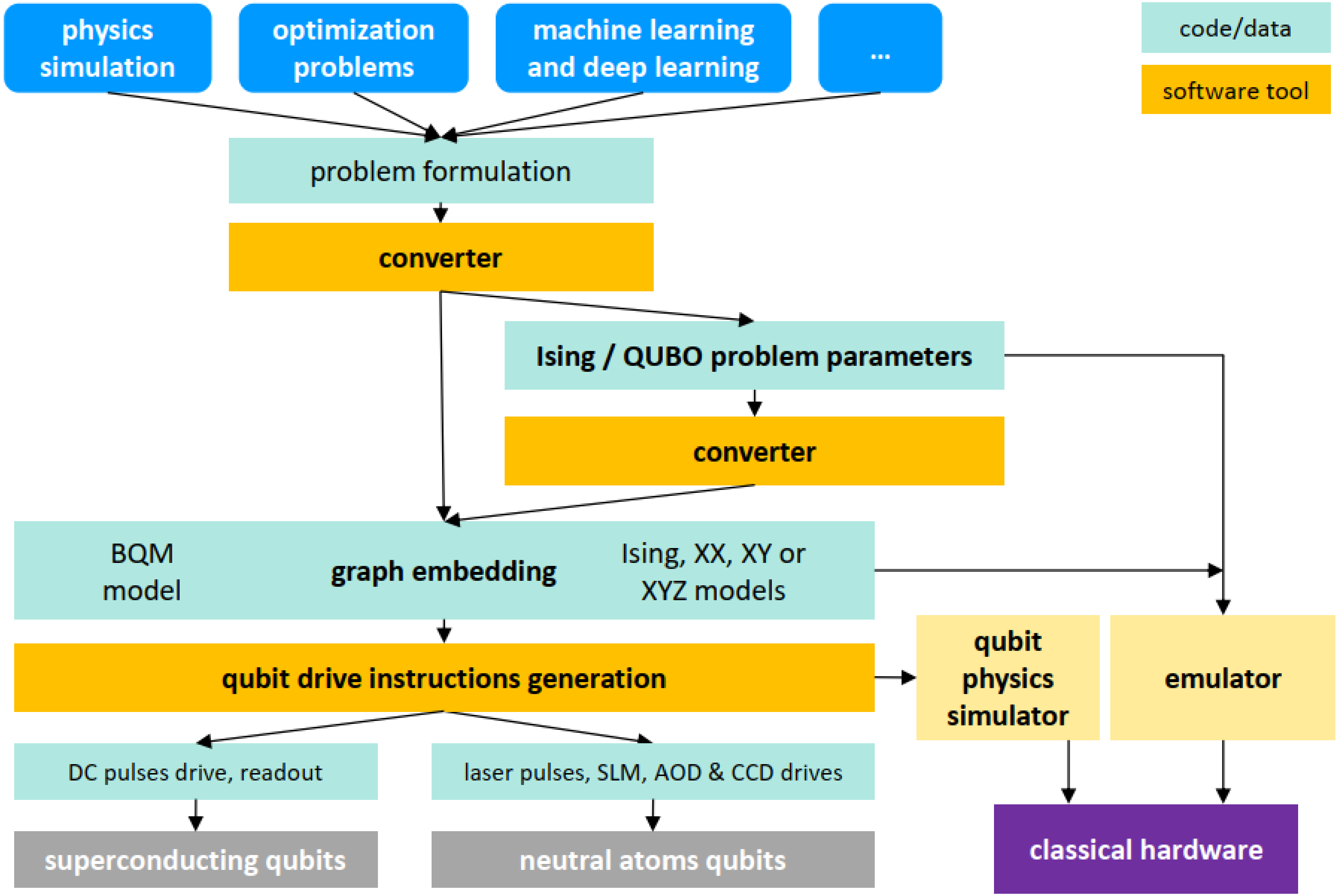
# Quantum Computing software stack - overview

Pasqal

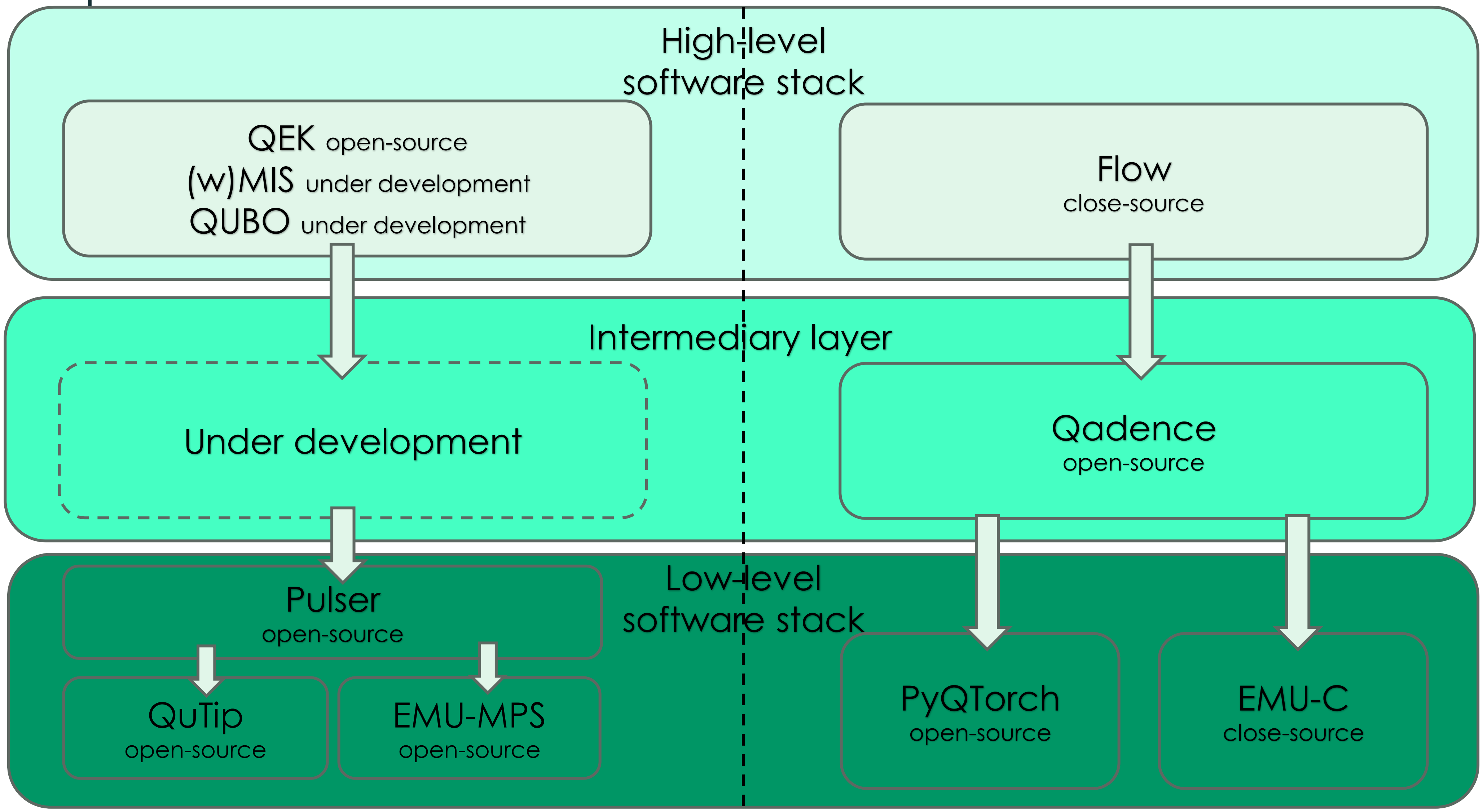


# Quantum Computing software stack - analog

Pasqal



# Pasqal software stack



# Quantum Software solutions: Pulser and Qadence

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Pulser is central in our software stack.

It is an open-source Python library for programming neutral atoms quantum processing units (QPUs) at the pulse level.

The low-level nature of Pulser makes it a versatile framework for quantum control both in digital and analog settings.

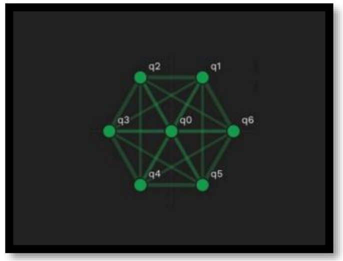
The library also contains simulation routines for studying and exploring the outcome of pulse sequences for small systems.

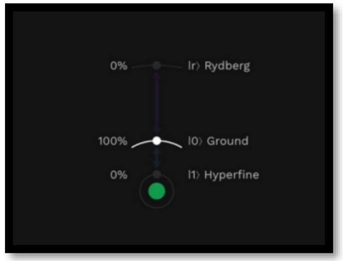
Pulser is also used today as the main interface for writing quantum jobs meant for PASQAL QPUs.

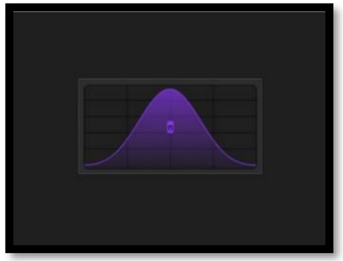
Qadence builds upon Pulser to provide a stable, higher level coding environment.

## To remember

In Pulser Studio, using the Code panel, you can view the Pulser code that is generated from the sequence being created.



# Programming on a neutral atoms device

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## Pulser

The open source Python library Pulser is designed with the flexibility and control of Pasqal's neutral atoms QPU in mind to provide full influence on all relevant physical parameters.

It is fully tailored to be compatible with the physical device, moreover it allows for experimentation on both analog and digital quantum computational paradigms.

## Qadence

The open source Python library Qadence builds upon the fundaments of Pulser to provide a simple, higher level interface for digital-analog quantum computing programs with full compatibility for arbitrary register topologies featured in a neutral atoms device.

```
from qadence import Register, AnalogRX, sample, PI

# Global analog RX block.
block = AnalogRX(PI)

# Almost non-interacting qubits as too far apart.
register = Register.from_coordinates([(0,0), (0,15)])
samples = sample(register, block)

# Interacting qubits are close to each other.
register = Register.from_coordinates([(0,0), (0,5)])
samples = sample(register, AnalogRX(PI))
```

```
from qadence import CNOT, H, chain, sample

# Preparing a Bell state by composing a Hadamard and CNOT gates in sequence.
bell_state = chain(H(0), CNOT(0,1))

# Sample with 100 shots.
samples = sample(bell_state, n_shots=100)
```

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# Integrating Neutral Atoms Systems into HPC

# Future of HPC

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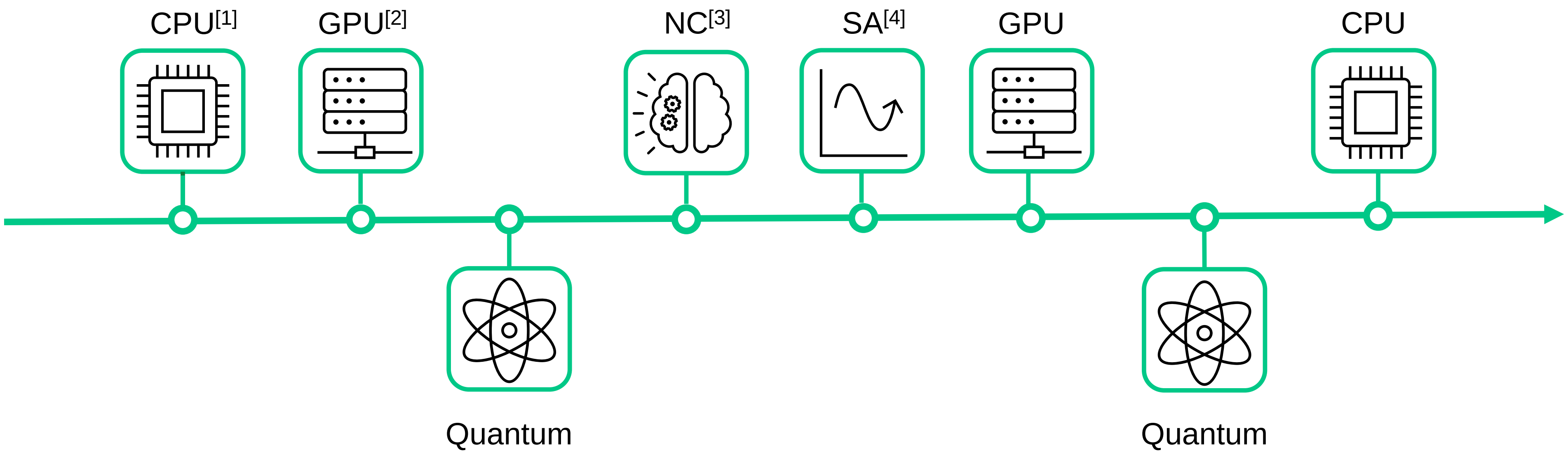
We envision that future HPC workflows will combine multiple type of specialized compute resources; each of them best positioned to solve a specific mathematical challenge

Diversity in computational resources employed in a future HPC workflow




1: CPU = Central Processing Unit (like the processor in most laptops)
2: GPU = Graphics Processing Unit, nowadays mostly used for parrallel computing
3: NC = Neuromorphic Computing, containing electronic analogue circuits aiming o exploit massive parallelism
4: SA = Simulated Annealing a probabilistic technique for approximating the global optimum of a given objective function

# Europe Envisions Hybrid HPC – Quantum Infrastructures

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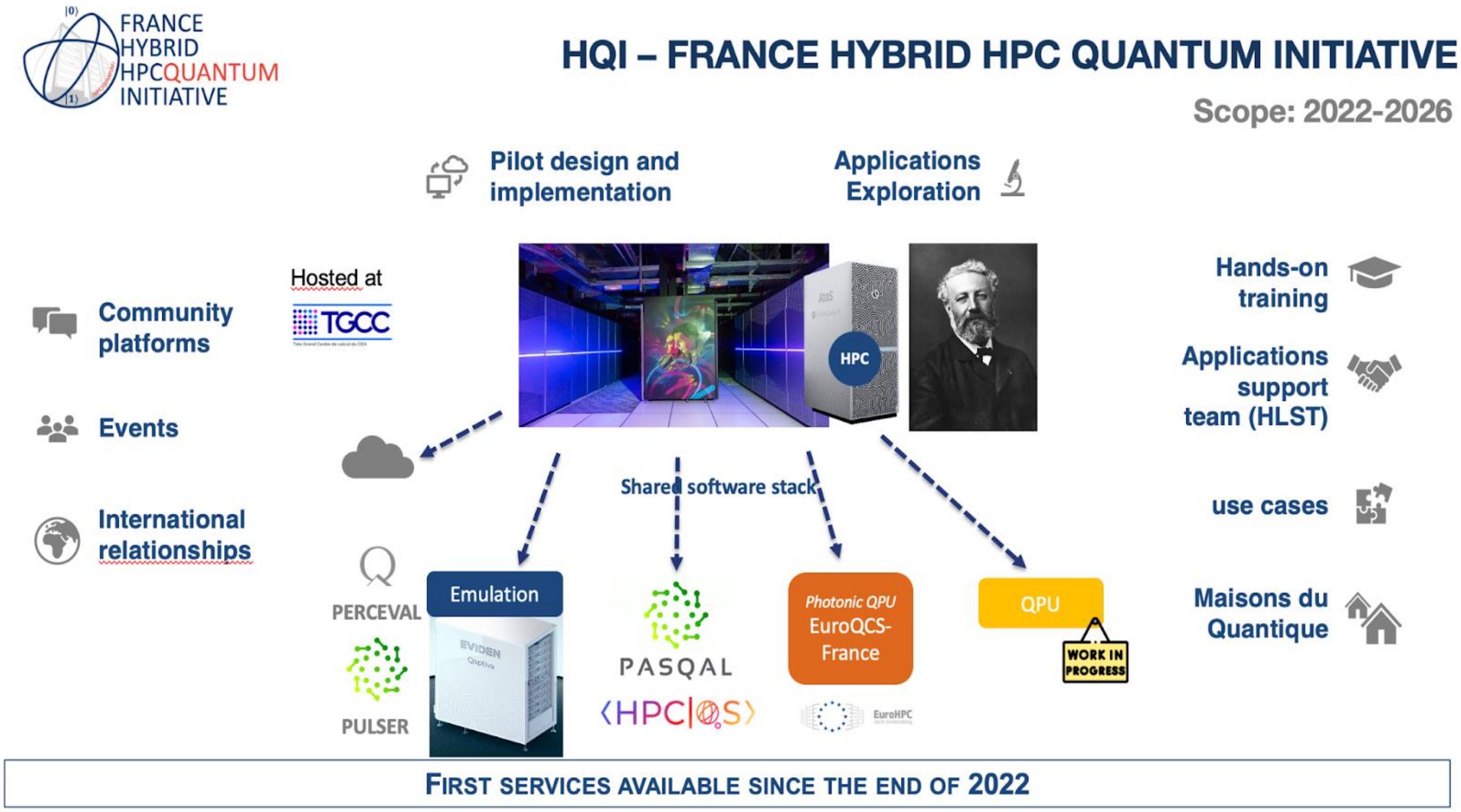
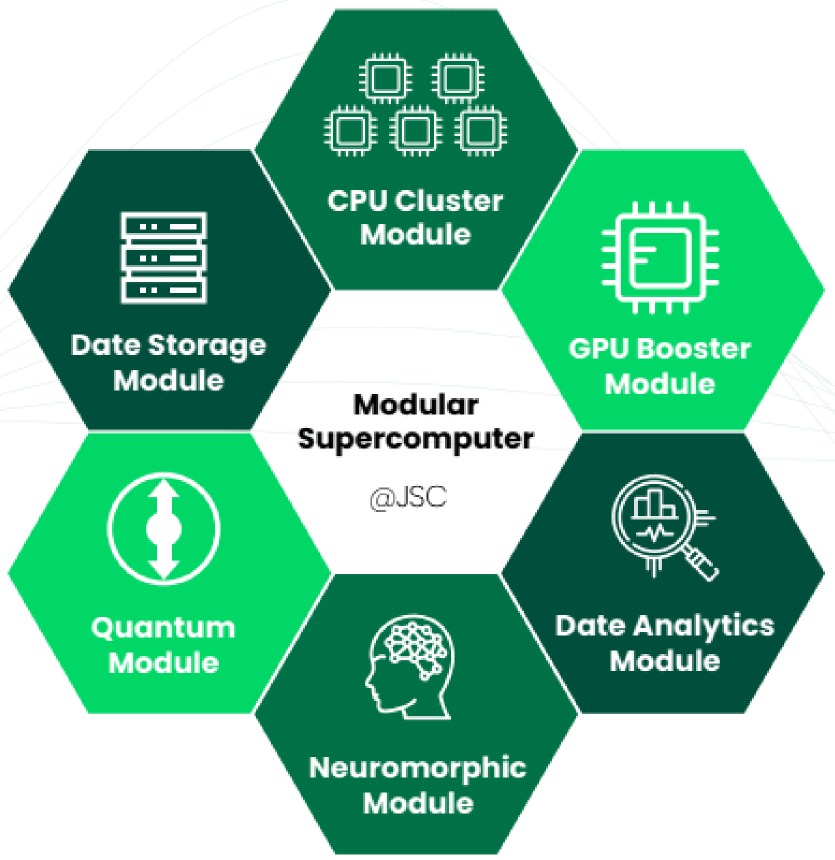
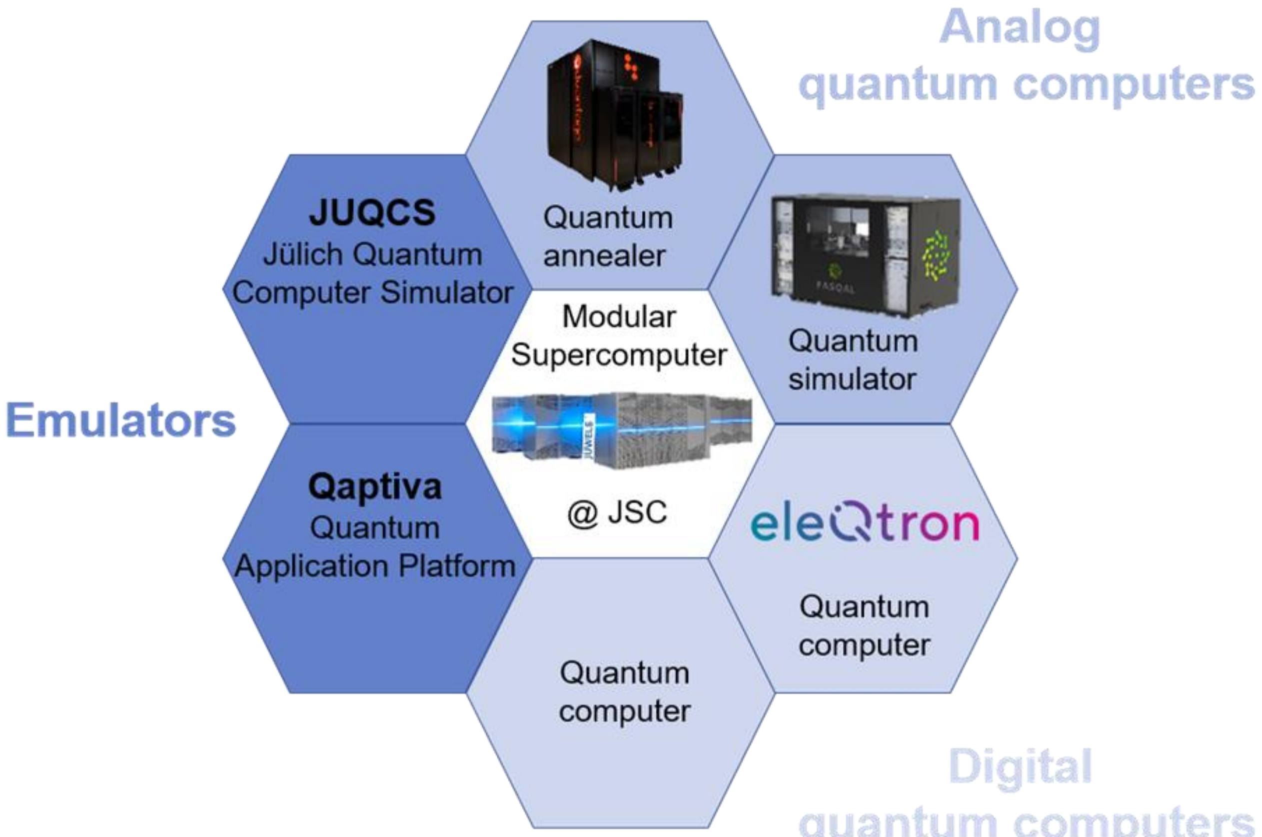


# Europe Envisions Hybrid HPC – Quantum Infrastructures

Pasqal



# Existing approaches & architectures

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Current HPC-QC integration efforts:

- Predominantly loose coupling with individual quantum jobs scheduled via Slurm

myQLM IBM Quantum

- Schedule a Quantum Access Node, tighter logical integration

CINECA

- Tight integration moving the quantum stack onto the HPC node
- Cloud bursting to test integration

# Pasqal's perspectives – physical integration

Temperature

- Room temperature is not data-center temperature
- Fresnel weather report ☺

Accessability

Software environment

# Pasqal’s perspectives – software integration

Pasqal

Which tasks / which applications are good fit for hybrid quantum-HPC?

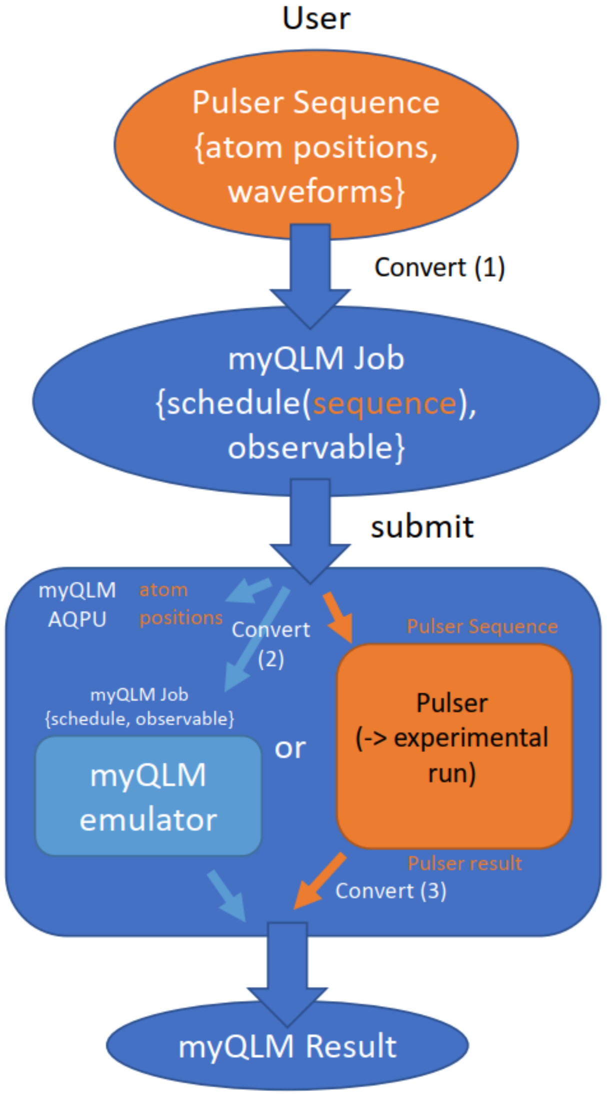
Quantum accelerators or quantum-centric supercomputing?

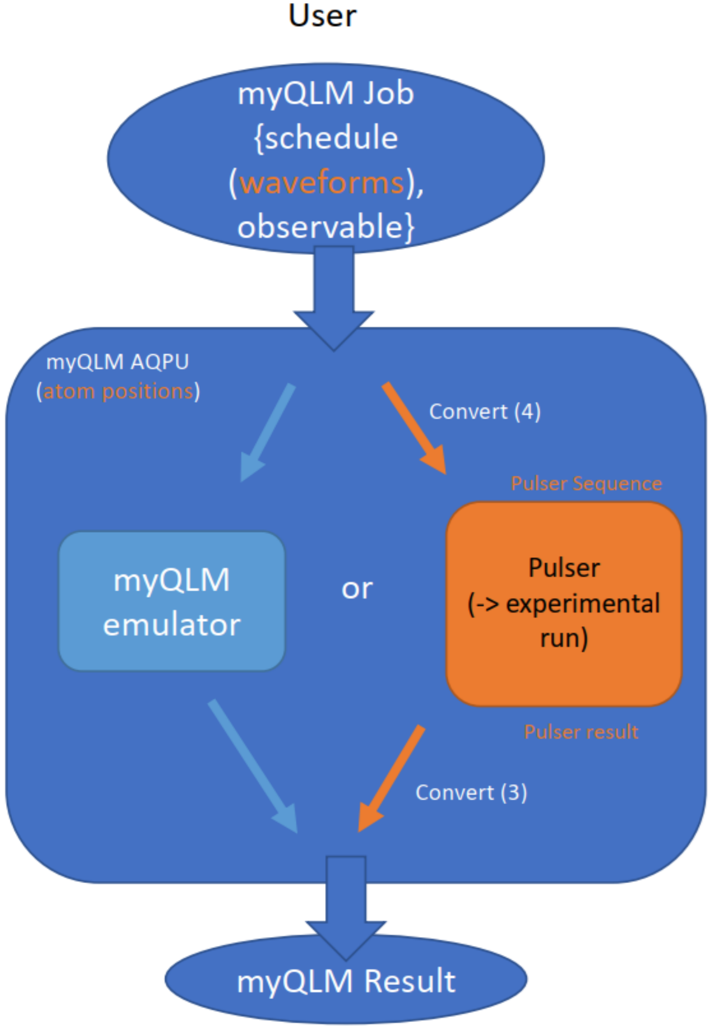
Scheduling for an optimal usage of the devices:

- Reduce idle time
- Parallelism at the input layer
- Exclusive usage mode

# Pasqal's perspectives – the myQLM example

Pasqal




**Convert (1):**
Serialize Sequence

**Convert (2):**
Sequence -> QLM compatible coefficients for schedule (+ atom positions)

**Convert (3):**
From Pulser Result to myQLM Result

**Convert (4):**
From QLM compatible coefficients for schedule (+ atom positions) to Sequence

Pasqal Defining the quantum reality

# Thank you for your attention