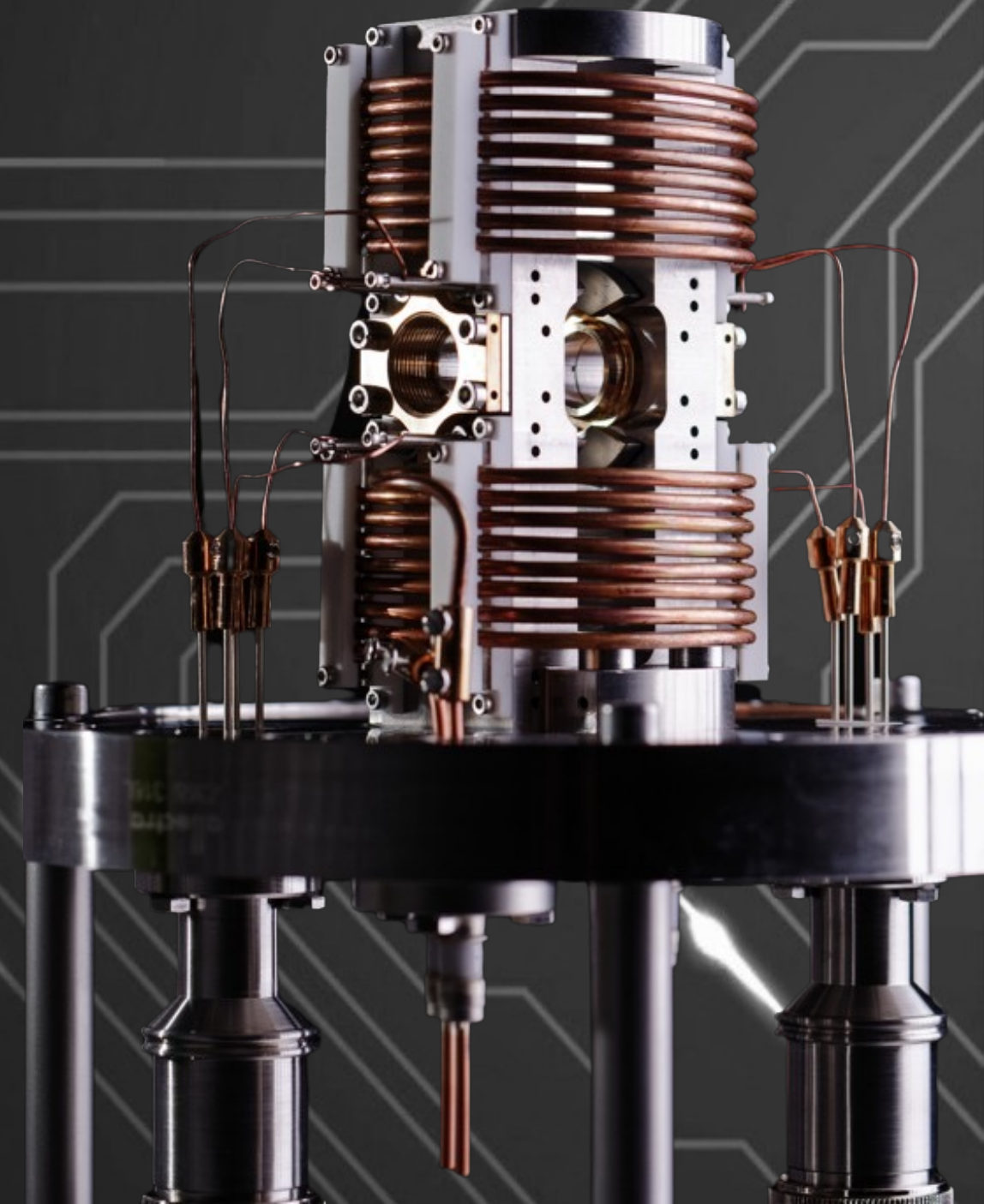


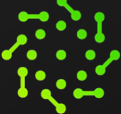

PASQAL

QUANTUM PROCESSING UNITS WITH NEUTRAL-ATOMS: APPLICATIONS AND EMULATION

Emulation Team
Engineering Department



AGENDA

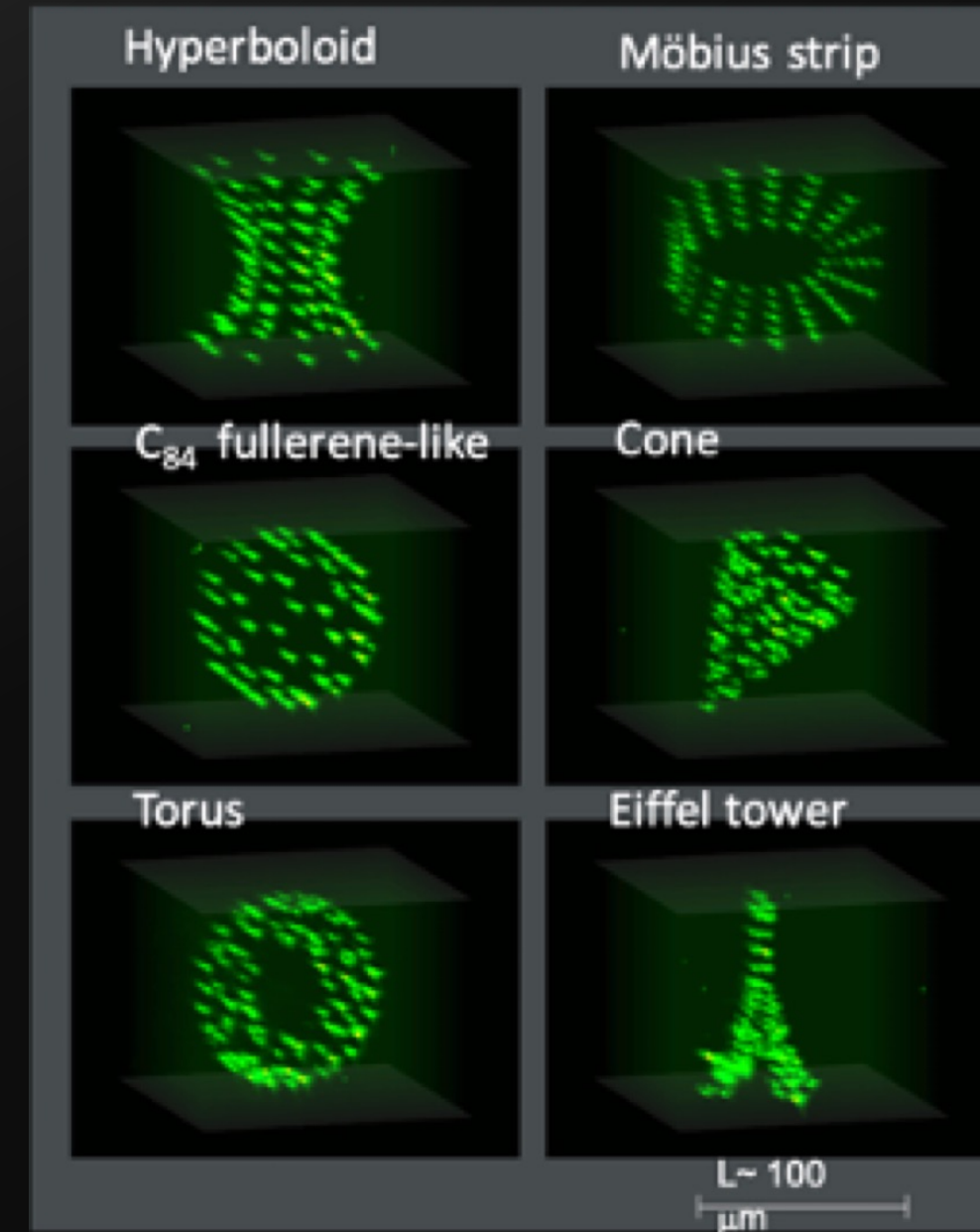
- 09h30 – 10h20: Introduction to  **PASQAL** Neutral Atoms QPU Technology
- 10h30 – 11h40: Simulating Quantum Systems with  **julia**
- 11h50 – 13h00: Introduction to Tensor Networks for Quantum Systems
- 14h30 – 15h30: Hands-on Session I: State Vector Evolution
- 15h40 – 16h40: Hands-on Session II: Tensor Network Representations

OUTLINE

- NEUTRAL ATOMS
- THE QUANTUM PROCESSOR
- EMULATION OF THE QPU
- OVERVIEW

NEUTRAL ATOMS

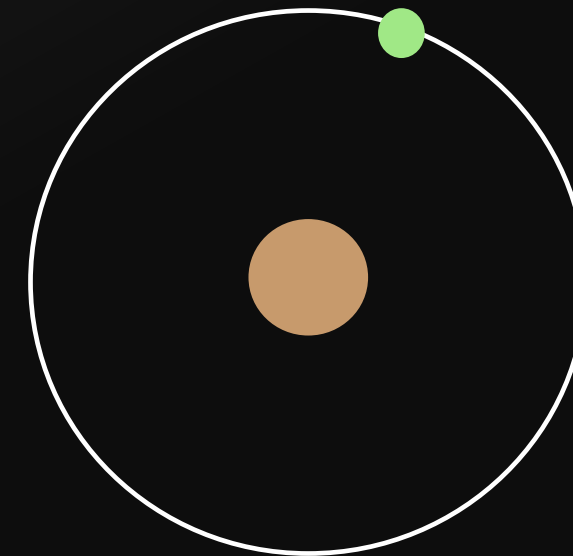
- Our qubits are **Neutral Atoms** trapped in very stable arrays of optical tweezers.
- Long-range interactions appear between **Rydberg atoms**, with inherent high connectivity.
- Quantum information is stored in the electronic state of the atoms.
- Scalable technology: Up to **hundreds** of qubits, in arbitrary geometries



NEUTRAL ATOMS

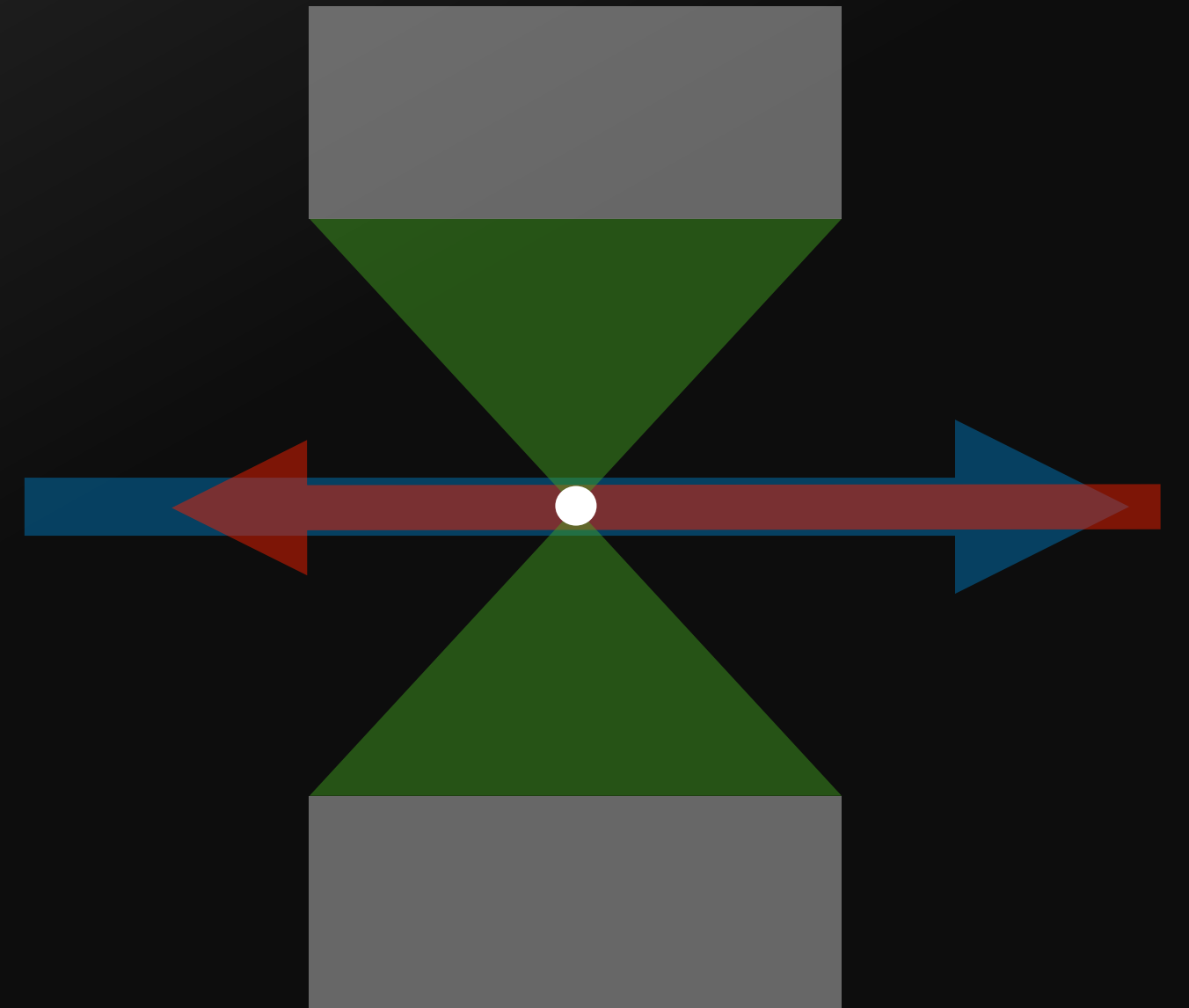
When a neutral atom e.g. Rubidium is excited to a very high **principal quantum number level** :

- Very reactive to electric and magnetic fields, long decay periods
- Outermost electron, very far from the nucleus, feels an almost hydrogenic potential.
- Called **Rydberg Atom**.



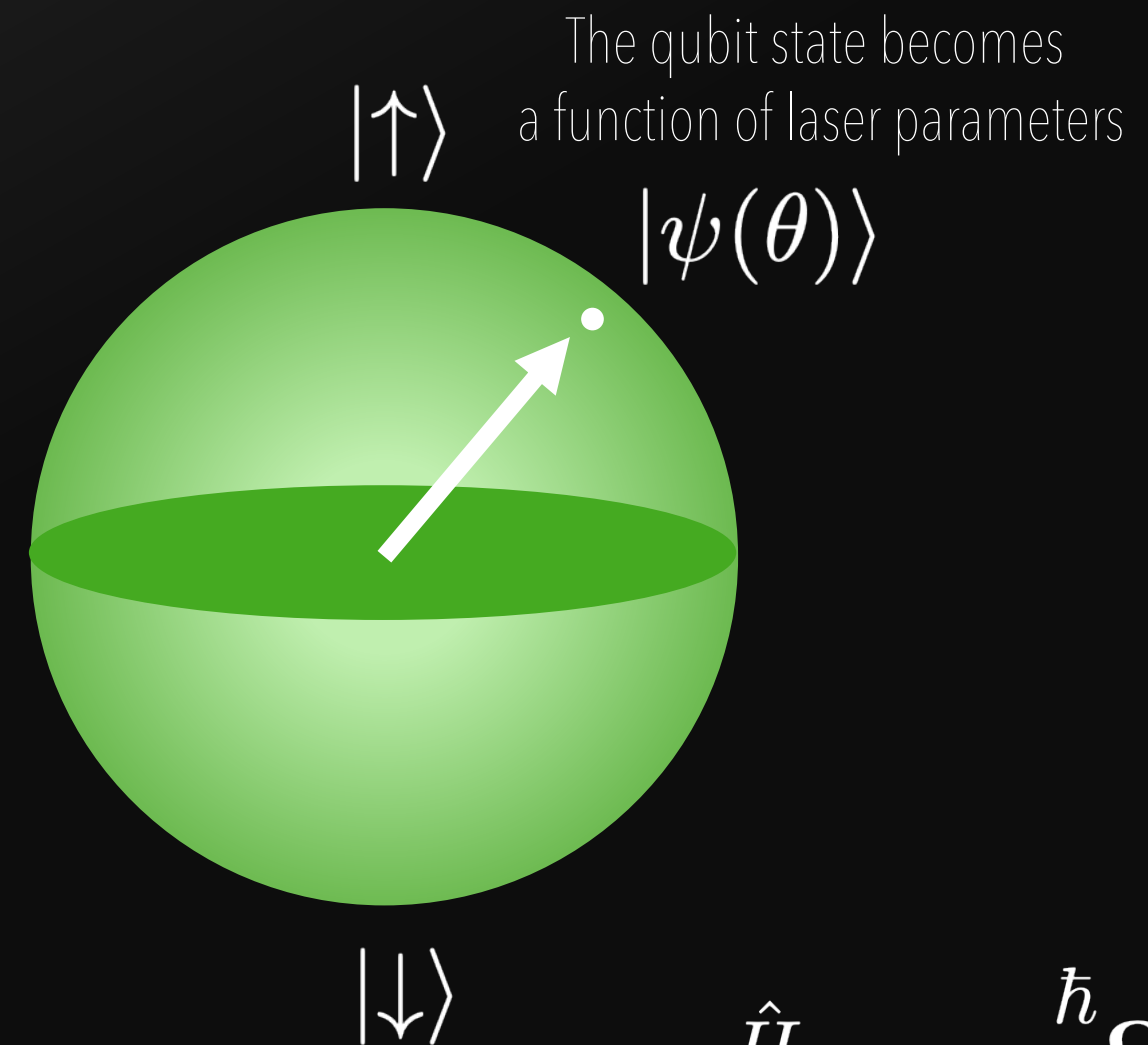
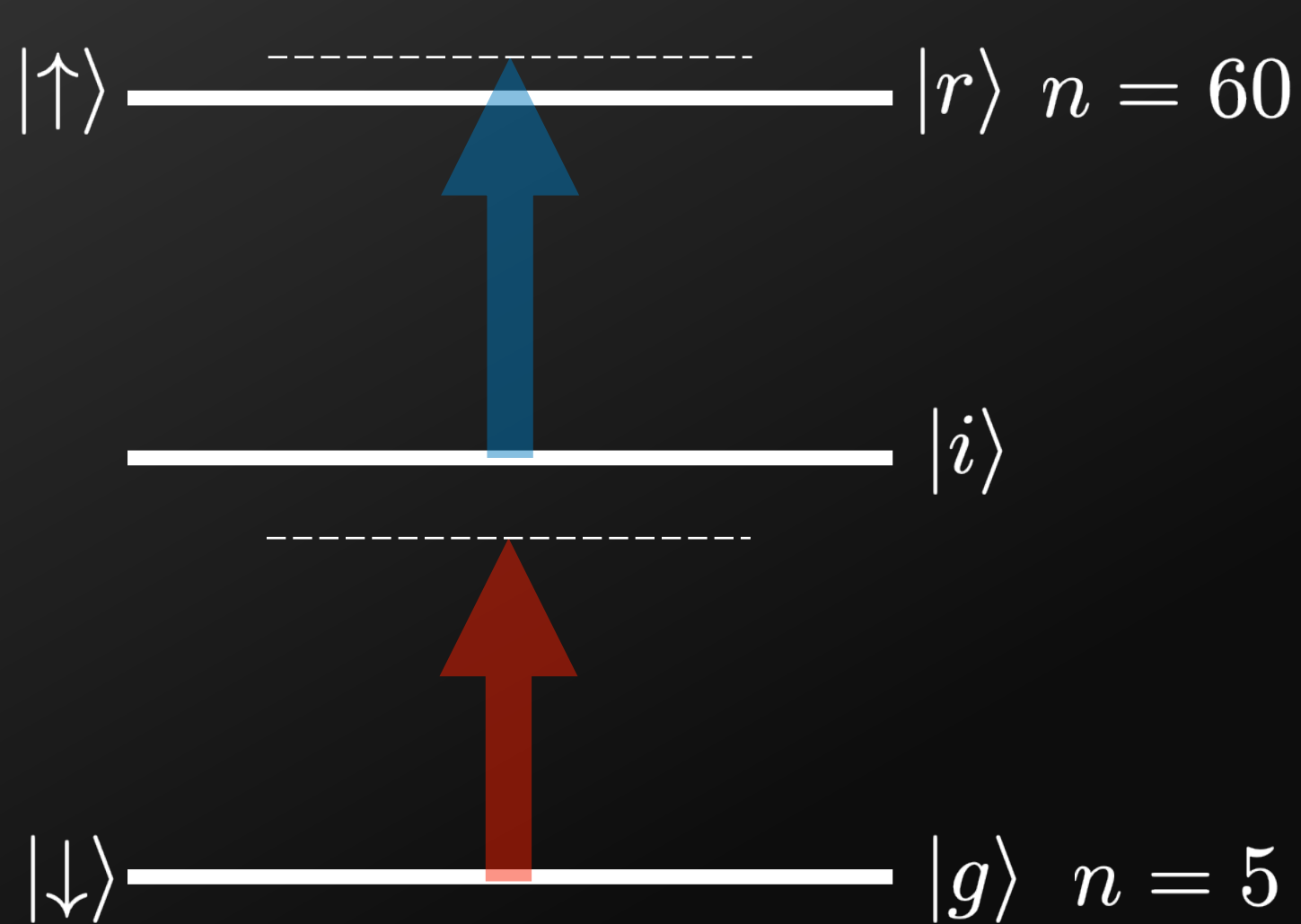
NEUTRAL ATOMS

- Rydberg atoms can be trapped using an **optical tweezer**.
- For example, one can prepare several Rubidium atoms in the same targeted "ground state" (e.g. 5p)
- Then one can act with additional lasers that drive transitions from the ground state to an excited Rydberg state.



NEUTRAL ATOMS

- By driving transitions between selected levels, a **qubit** can be defined, whose state is determined by the laser parameters.



$$\hat{H}_{\text{drive}} = \frac{\hbar}{2} \boldsymbol{\Omega}(t) \cdot \boldsymbol{\sigma}$$

$$\boldsymbol{\Omega}(t) = (\Omega(t) \cos(\varphi), -\Omega(t) \sin(\varphi), -\delta(t))$$

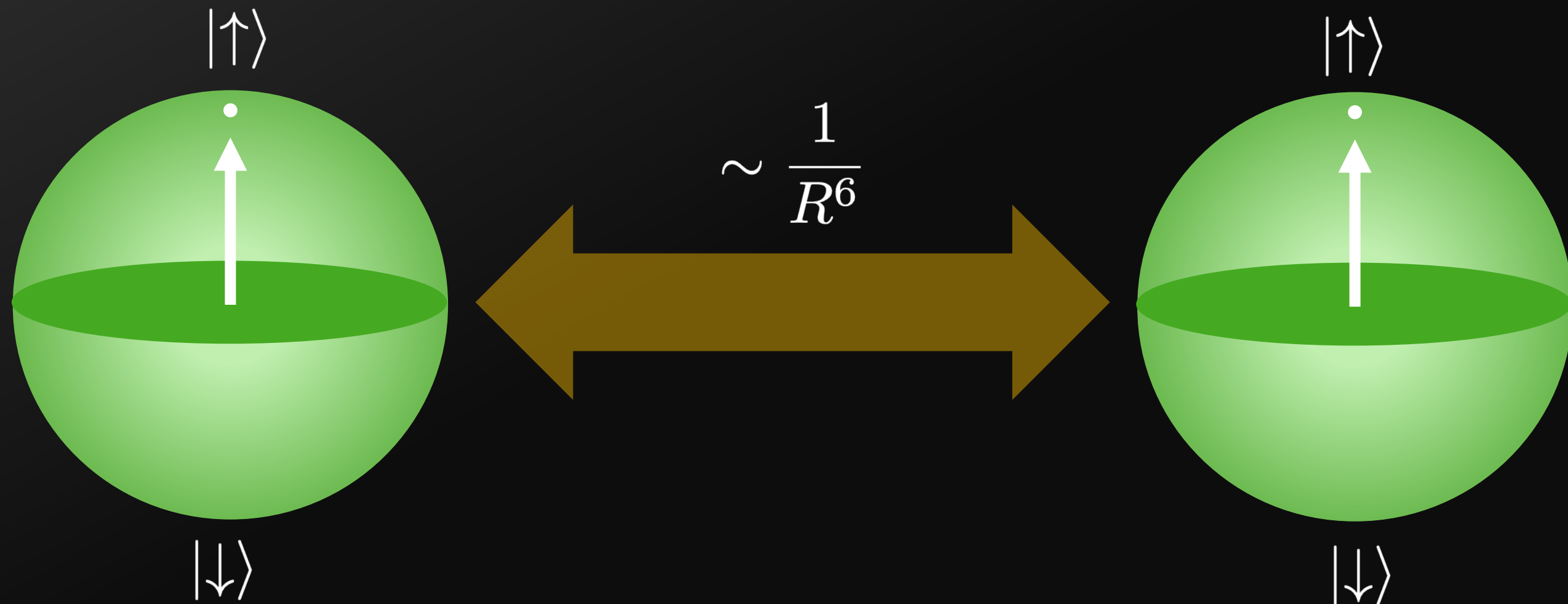
$$\boldsymbol{\sigma} = (\sigma^x, \sigma^y, \sigma^z)$$

- With precise laser control, one can build arbitrary **one-qubit gates**.

$$U(\boldsymbol{\Omega}, t) = \mathcal{T} \exp \left(-\frac{i}{2} \int_0^t d\tau \boldsymbol{\Omega}(\tau) \cdot \boldsymbol{\sigma} \right)$$

NEUTRAL ATOMS

- Two excited atoms interact with a Van der Waals term that decays quickly with the interatomic distance.



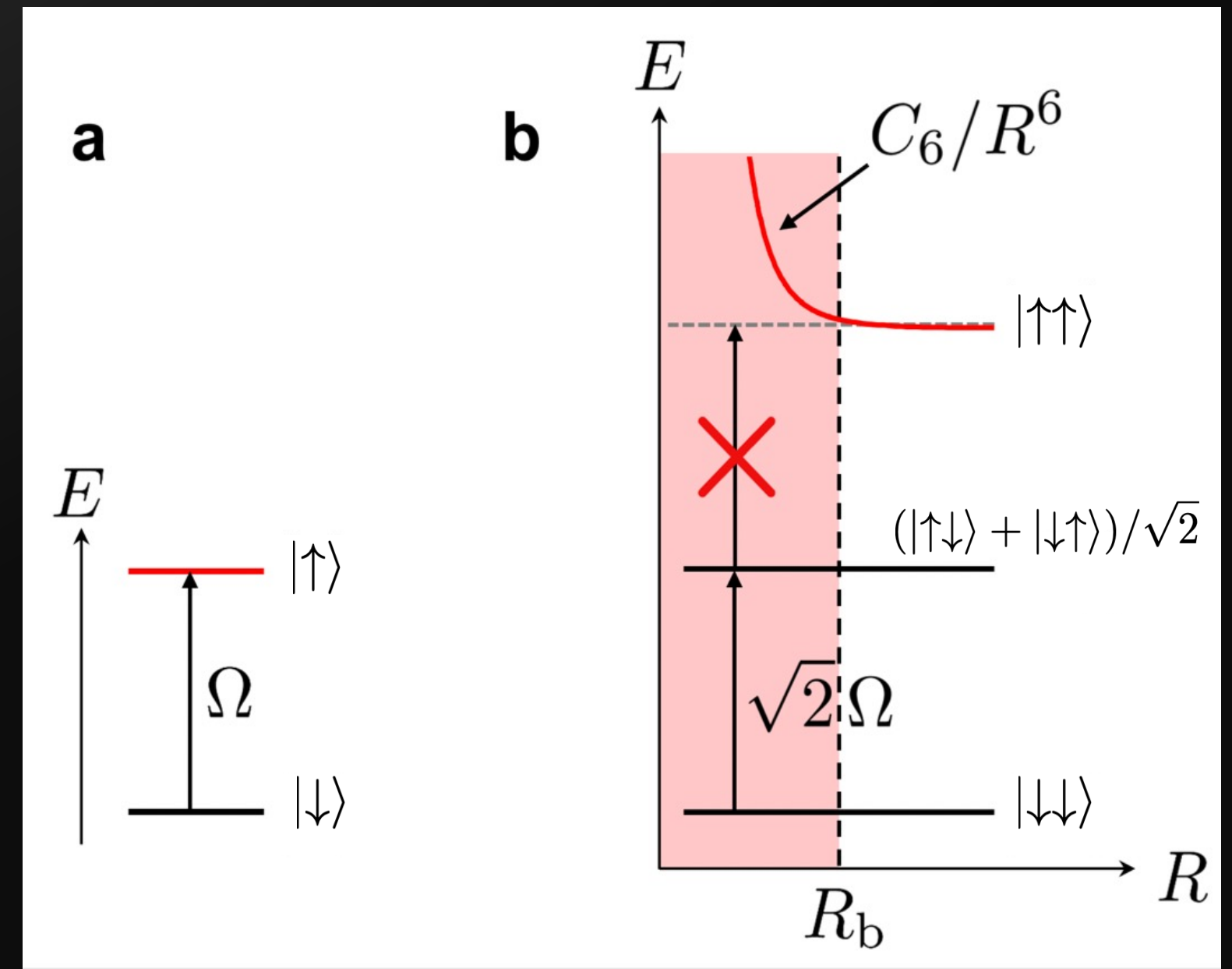
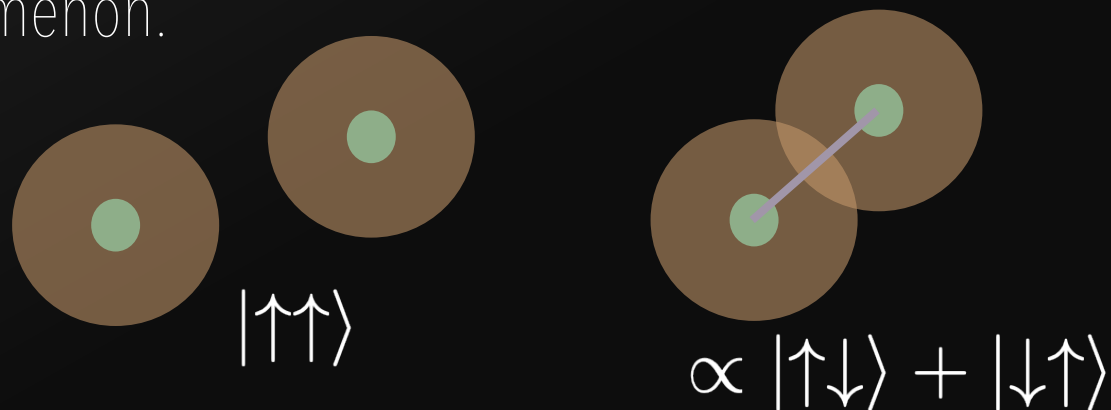
NEUTRAL ATOMS

- When two atoms are close enough, a strong interaction appears. As a two-body operator, using $\hat{n} = |\uparrow\rangle\langle\uparrow|$:

$$\frac{C_6}{R^6} \hat{n}_1 \hat{n}_2$$

- A doubly excited state $|\uparrow\uparrow\rangle$ is suppressed by the interaction energy cost. This is called the “**Blockade Effect**”. Instead, an entangled state $\propto |\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle$ is observed.

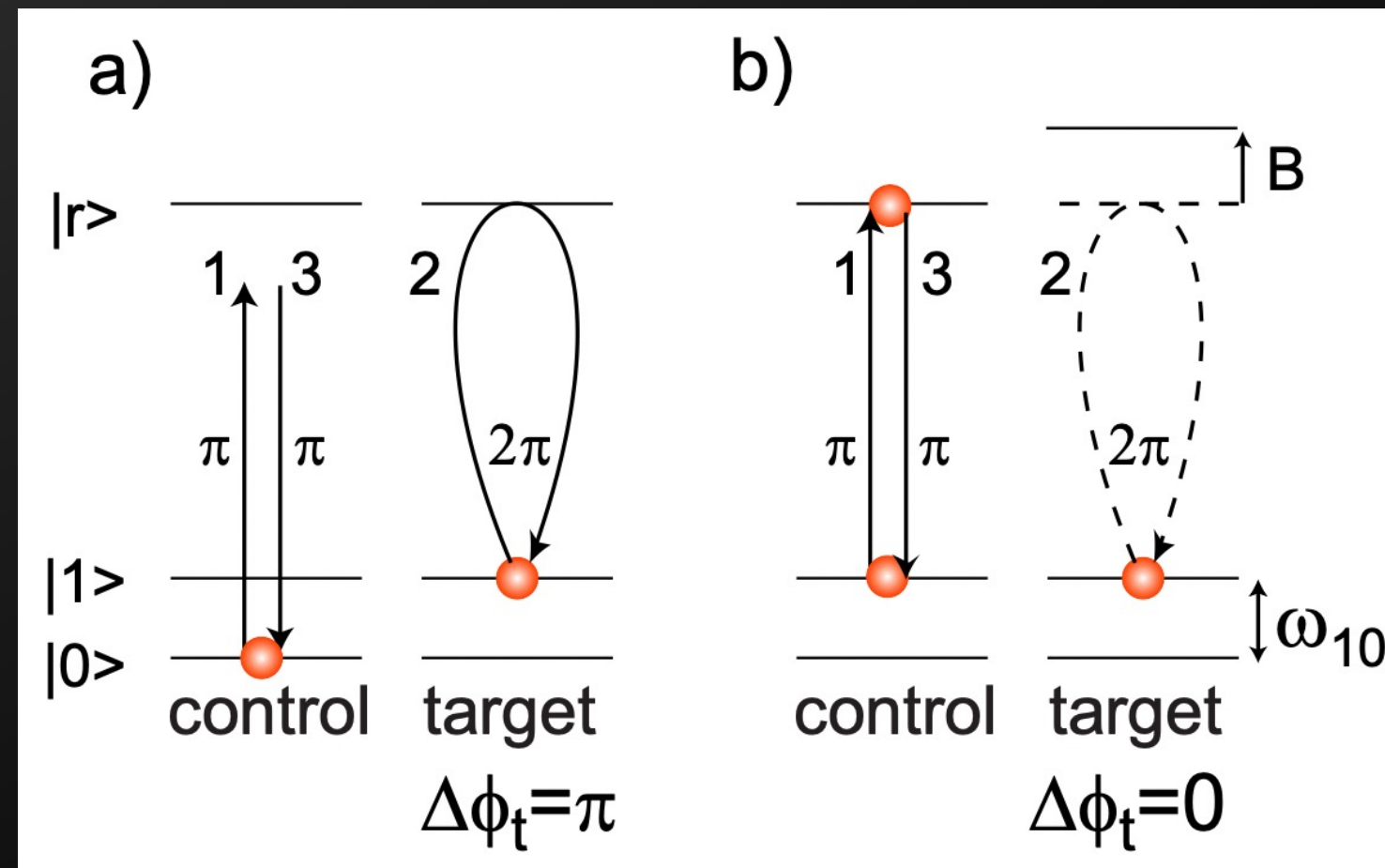
- An effective “**Blockade Radius**” R_b can be defined from this phenomenon.



Browaeys, A., & Lahaye, T. (2020). Many-body physics with individually controlled Rydberg atoms. *Nature Physics*, 16(2), 132-142.

NEUTRAL ATOMS

- The blockade effect is the basis to construct multi-qubit gates. In a common setup, two hyperfine ground states are chosen as logical states $|0\rangle$ and $|1\rangle$ while a rydberg level is used as an **auxiliary state**.



Saffman, M., Walker, T. G., & Mølmer, K. (2010). Quantum information with Rydberg atoms. *Reviews of modern physics*, 82(3), 2313.

- By including Hadarmard gate on the target qubit before and after this sequence, one obtains a **CNOT gate**.
- Together with one-qubit gates, this constitutes a universal set of gates for quantum computing

NEUTRAL ATOMS

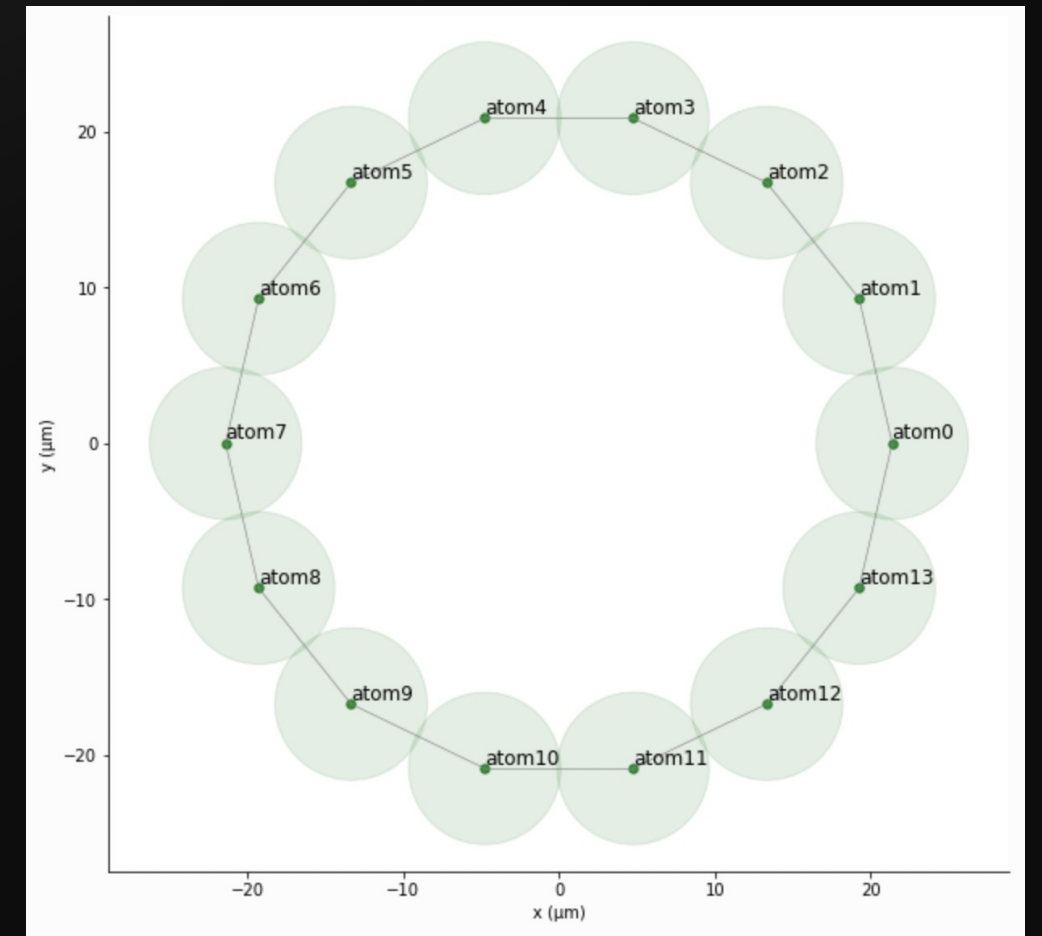
- In the analog mode. The system evolves under an effective Ising-like Hamiltonian with for example a **single** control in the Rabi Frequency of the Laser:

$$\hat{H}_{\text{Ising}} = \sum_i \hat{H}_{\text{drive}}^{(i)} + \sum_{i>j} \frac{C_6}{R_{ij}^6} \hat{n}_i \hat{n}_j$$

$$\hat{H}_{\text{Ising}} = \frac{\hbar}{2} \sum_i \Omega^{(i)}(t) \sigma_i^x + \sum_{i>j} \frac{C_6}{R_{ij}^6} \hat{n}_i \hat{n}_j$$

$$\hat{H}_{\text{Ising}} = \frac{\hbar}{2} \Omega(t) \sum_i \sigma_i^x + \sum_{i>j} \frac{C_6}{R_{ij}^6} \hat{n}_i \hat{n}_j$$

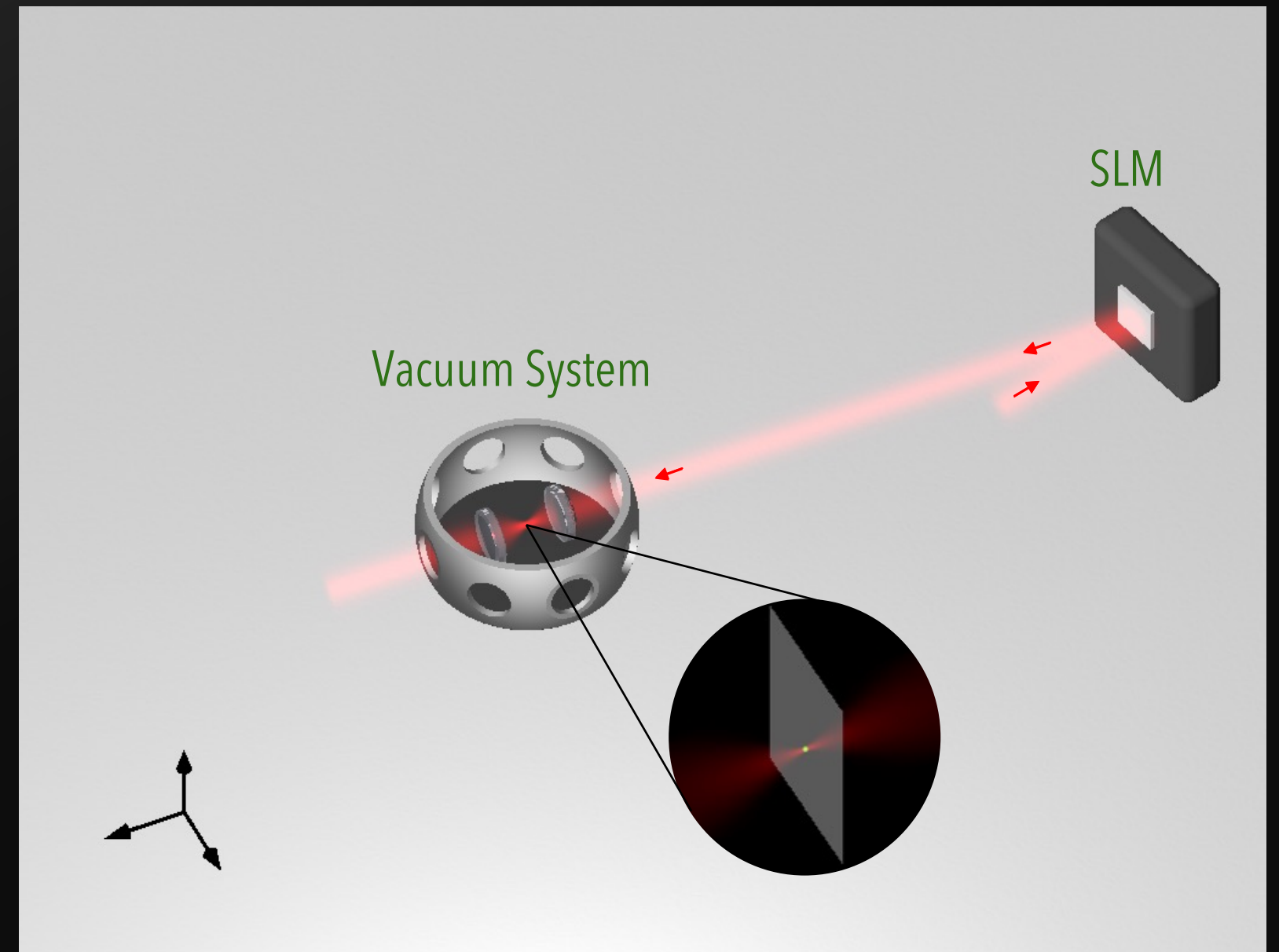
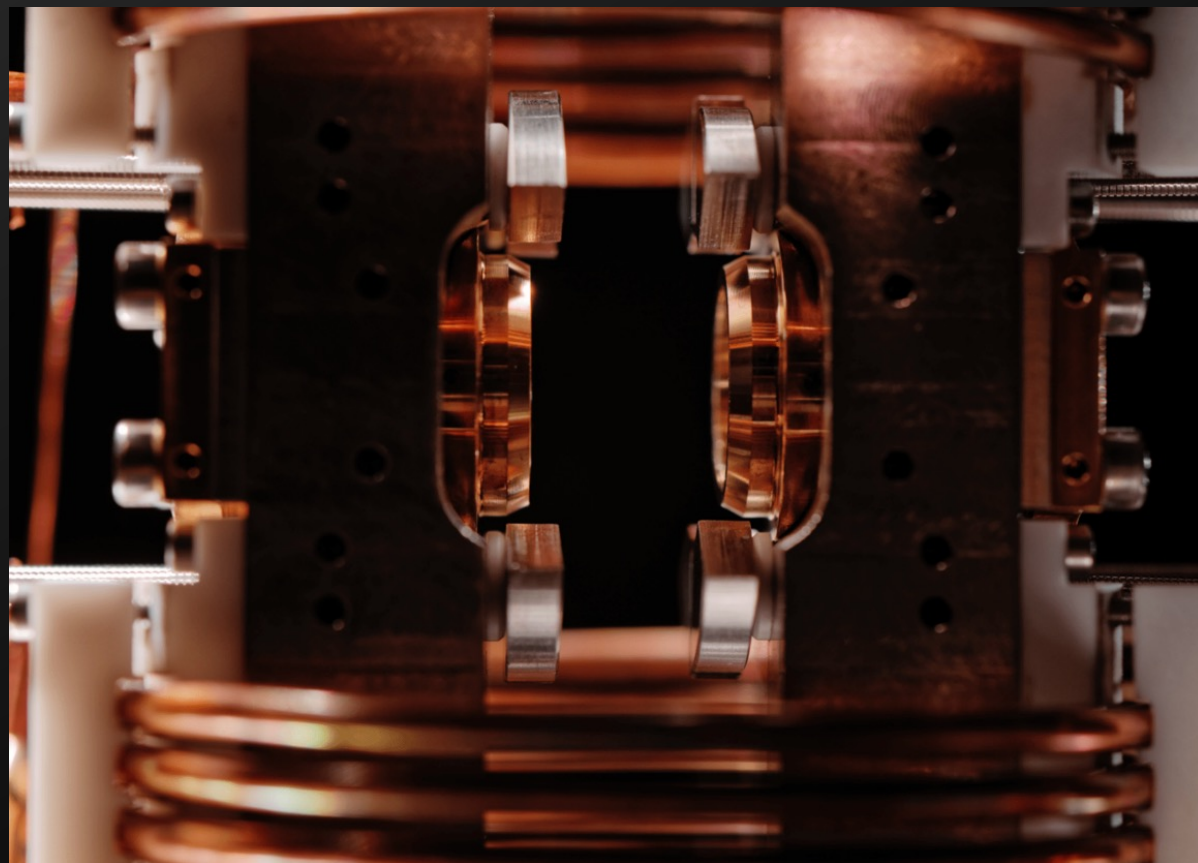
$$\hat{n}_i = |\uparrow\rangle_i \langle\uparrow| = (\mathbb{I}_i + \sigma_i^z)/2$$



- Notice the **Graph** defined by the (rydberg-blocked) atoms in the register is highly customizable, therefore allowing for a **custom connectivity!**
- This type of platform serves as a basis for **Quantum Simulation**, using the Ising Hamiltonian as a **Resource**.

THE NEUTRAL ATOMS QUANTUM PROCESSOR

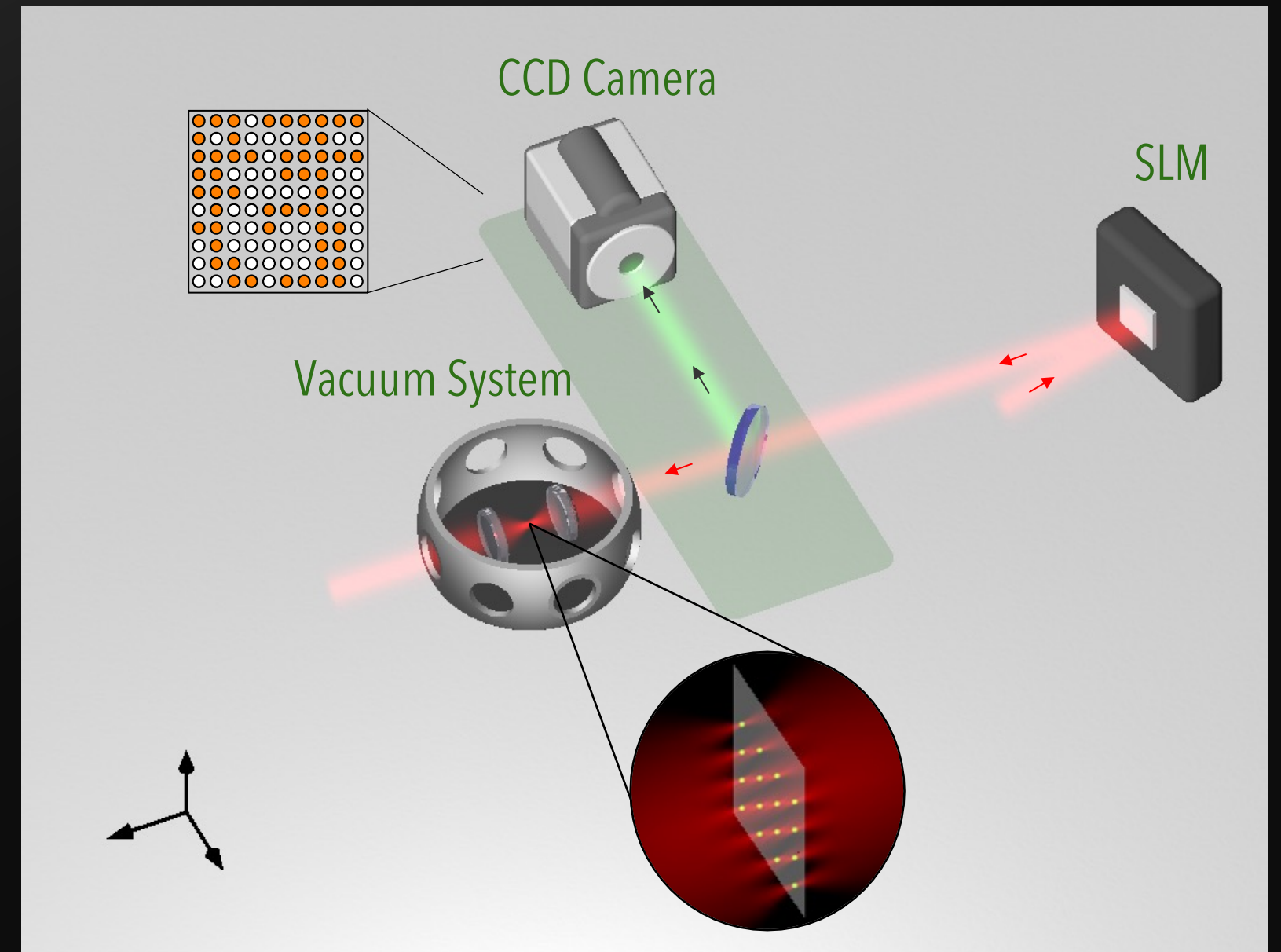
- SLM (Spatial Light Modulator) modulates the intensity/phase of the beam.
- The interplay of the optical tweezer system and the SLM allows for the loading (up to several hundred!) atoms.



Henriet, L., Beguin, L., Signoles, A., Lahaye, T., Browaeys, A., Reymond, G. O., & Jurczak, C. (2020). Quantum computing with neutral atoms. *Quantum*, 4, 327.

THE NEUTRAL ATOMS QUANTUM PROCESSOR

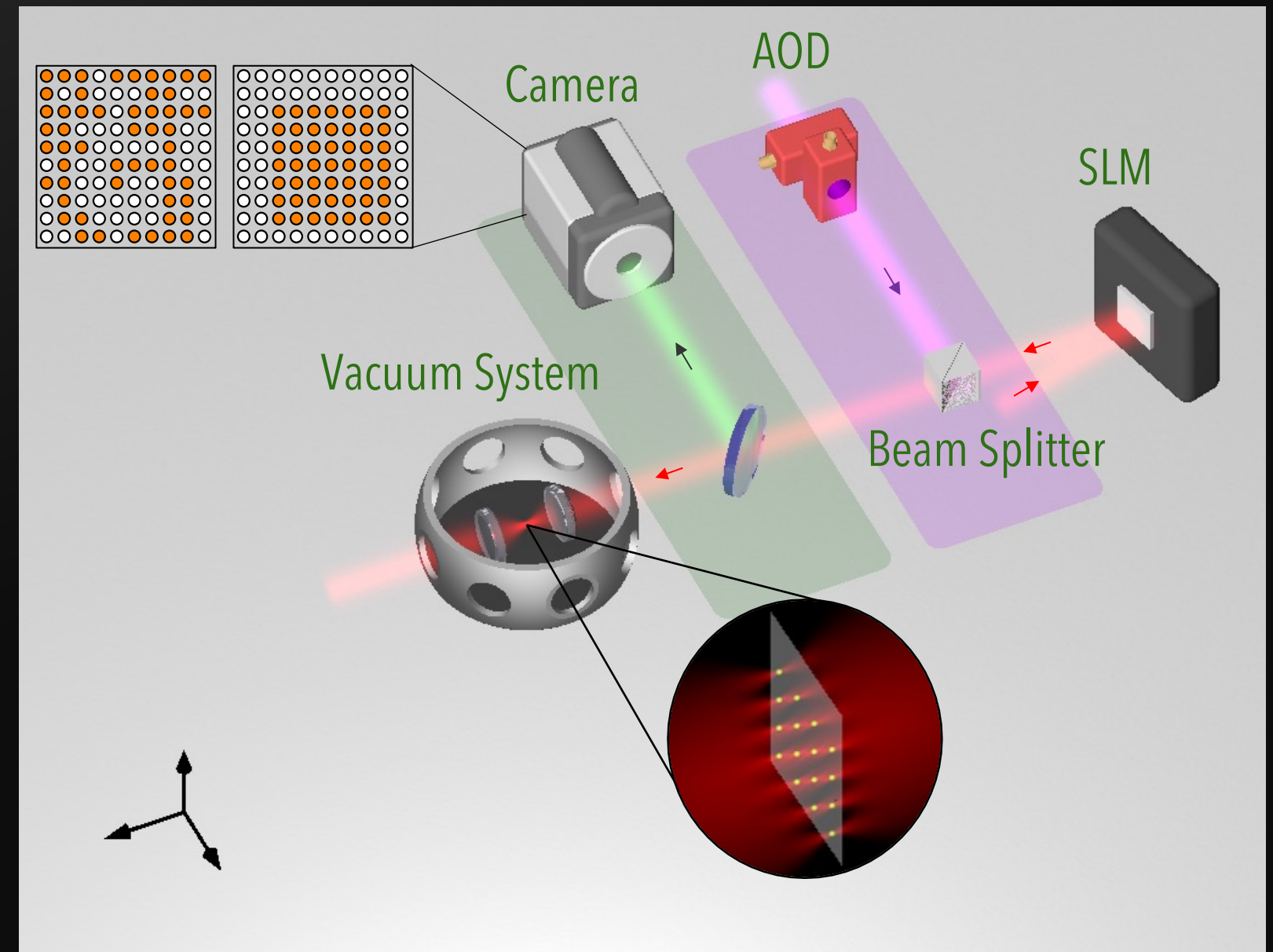
- A CCD camera captures photons emitted from trapped atoms (via fluorescence)
- The observed pixels define "zeros" of a projective measurement of the state



Henriet, L., Beguin, L., Signoles, A., Lahaye, T., Browaeys, A., Reymond, G. O., & Jurczak, C. (2020). Quantum computing with neutral atoms. *Quantum*, 4, 327.

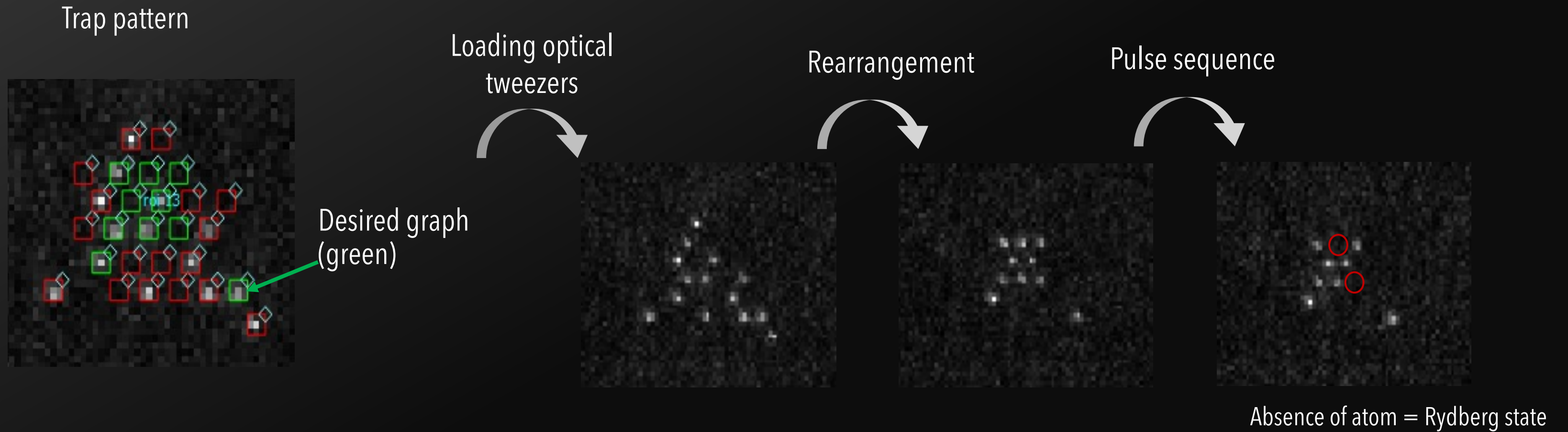
THE NEUTRAL ATOMS QUANTUM PROCESSOR

- An AOD (acousto-optic deflector) modifies the laser beam to **move** individual atoms and obtain the desired array.
- Several rearrangement steps are produced, with fluorescence captures between the operations to ensure the atom array is correct.



Henriet, L., Beguin, L., Signoles, A., Lahaye, T., Browaeys, A., Reymond, G. O., & Jurczak, C. (2020). Quantum computing with neutral atoms. *Quantum*, 4, 327.

THE NEUTRAL ATOMS QUANTUM PROCESSOR



THE NEUTRAL ATOMS QUANTUM PROCESSOR

- PASQAL is a spin-out of Institut d'Optique Graduate School (Pailaseau, France), from the Laboratory of Antoine Browaeys and Thierry Lahaye.
- Built upon several generations of experience in fundamental research.
- We build quantum processors made of **neutral atoms**.

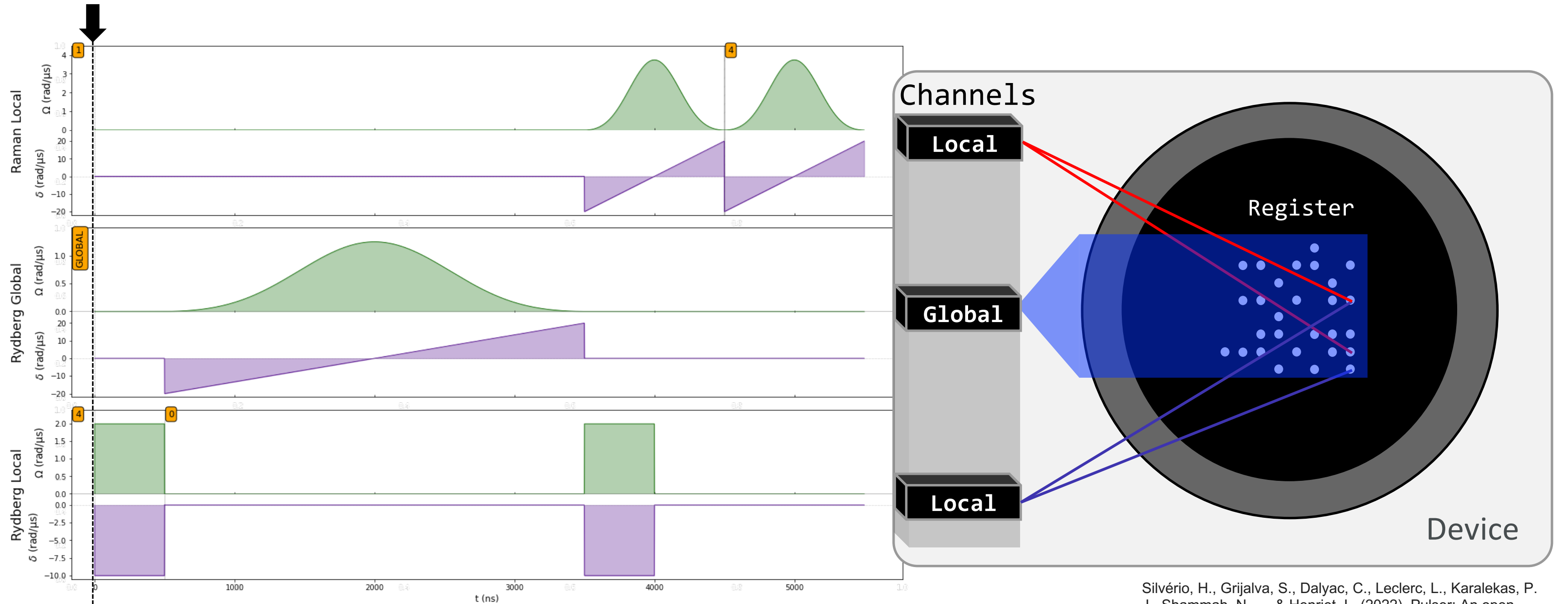


EMULATION OF THE QPU

Emulation (not just Simulation) happens at different stages:

- Compilation of a Circuit **into Pulse Sequences** : Hardware-Efficient translation
- Compilation of a Program into Machine Operations (simulate all the steps from register creation to readout and a higher level algorithm) : Reproduce Specific Device Characteristics > **Device Noise Model**
- **Emulation**: Compilation + Noise Model + Classical Simulation of the Quantum System

EMULATION USING Pu1ser



Silvério, H., Grijalva, S., Dalyac, C., Leclerc, L., Karalekas, P. J., Shammah, N., ... & Henriët, L. (2022). Pulser: An open-source package for the design of pulse sequences in programmable neutral-atom arrays. *Quantum*, 6, 629.

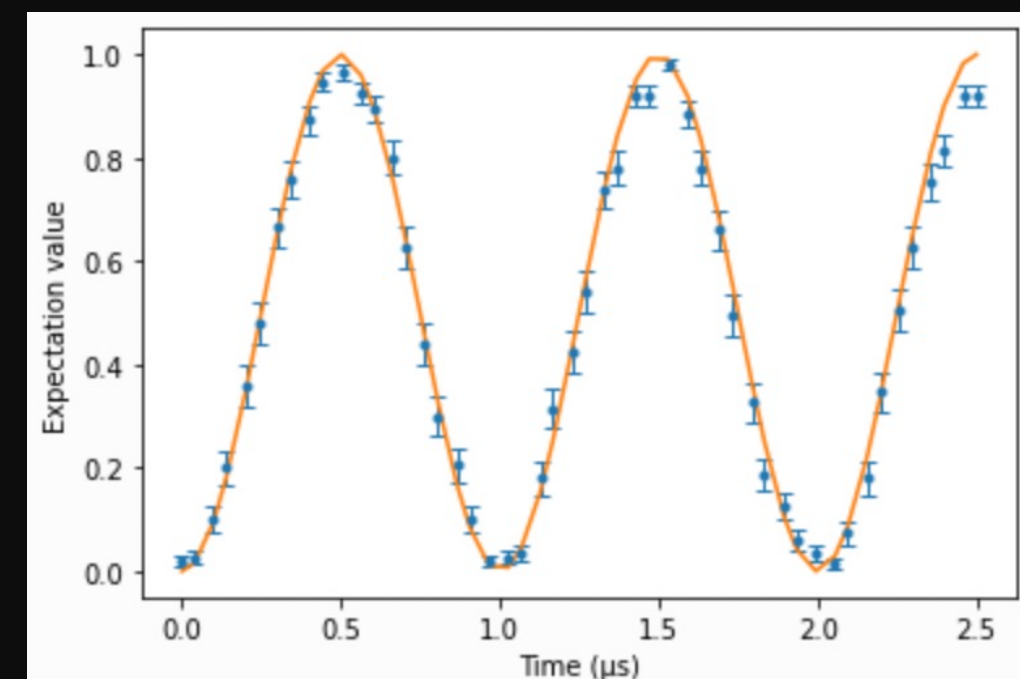
EMULATION: USING `Pu1ser`

- Goal: straightforward time-evolution simulation for all the instructions in the sequence.

```
sim = Simulation(my_sequence)
results = sim.run() #Schroedinger equation solver for clean systems
bitstrings = results.sample_final_state(300)
```

- Based on the `qutip` package: includes python-optimized algorithms and data-structures. Direct access to numerical configuration parameters (tolerances, evaluation times, solver methods).
- Includes a customizable noise model based on neutral-atom controls: laser amplitude fluctuations, SPAM errors, doppler effect, and effective noise channels (solved with a Quantum Master Equation).

```
cfg = SimConfig(noise=('SPAM'),
                eta=0.01,
                epsilon=0.05,
                epsilon_prime=0.02)
my_sim.set_config(cfg)
noisy_results = sim.run()
noisy_results.plot(my_observable)
```



EMULATION: USING **Pu1ser**

Full Installation: **pip install pulser**

Pre-requisites:

- ✓ Python 3.7 or higher
- ✓ Recommended: Jupyter Notebook installed

GitHub Repository: <https://github.com/pasqal-io/Pulser>

Documentation: <https://pulser.readthedocs.io/>

EMULATION OF THE QPU

- What limits the simulation of quantum computers?
- State Vector Evolution (Schrodinger Equation)
- Density Matrix (Quantum Master Equation)
- Tensor Network Simulations.

hard to simulate. Indeed, in recent years many techniques have been developed to simulate quantum computers, and they all have an exponential cost in some parameter. A brute force approach where one holds the full quantum state in memory as a large vector of size 2^N (N is the number of qubits) requires a computing time and memory that scales exponentially with N but linearly with the depth D of the circuit. Other approaches require a computing time that scales exponentially with the number of 2-qubit gates [6–9], with the number of non-Clifford gates [10], and/or with the number of gates that are nondiagonal in a chosen basis [11,12]. All these techniques can simulate *perfect* quantum computers. In all cases, the required computing resources are exponential so that getting beyond $N = 50$ and a depth $D = 20$ for an arbitrary circuit is extremely difficult.

In this article, we show that *real* quantum computers can be simulated at a tiny fraction of the cost that would be needed for a perfect quantum computer. To do so, we take

Zhou, Y., Stoudenmire, E. M., & Waintal, X. (2020). What limits the simulation of quantum computers?. *Physical Review X*, 10(4), 041038.

HIGH PERFORMANCE EMULATORS

- We have two main projects in emulation, written in **Julia**:

EMU-TN	EMU-SV
<ul style="list-style-type: none">- Based on Tensor Networks (<code>iTensors.jl</code>)- Simulates dynamics with TDVP algorithm.- Can handle several tasks in 1D and 2D atom geometry, based on MPS.<ul style="list-style-type: none">- (In Development) PEPS dynamics.	<ul style="list-style-type: none">- Based on State Vector evolution- Uses Krylov methods and exploits Julia's speed<ul style="list-style-type: none">- Includes Noise model from Pulser- Includes Parallelization algorithms for stochastic Schrödinger equation jobs.

- Examples of simulation tasks:

- $2\mu\text{s}$ dynamics for a 10×10 square array of atoms interacting with Ising coupling and using the resulting MPS to calculate entanglement entropy (using **EMU-TN**).
- Multi-threaded simulation of a set of parametrized noisy pulse sequences for a 20-qubit system to determine an optimal shape (using **EMU-SV**)

PASQAL DGX GPU CLUSTER



HARDWARE SPECIFICATIONS:

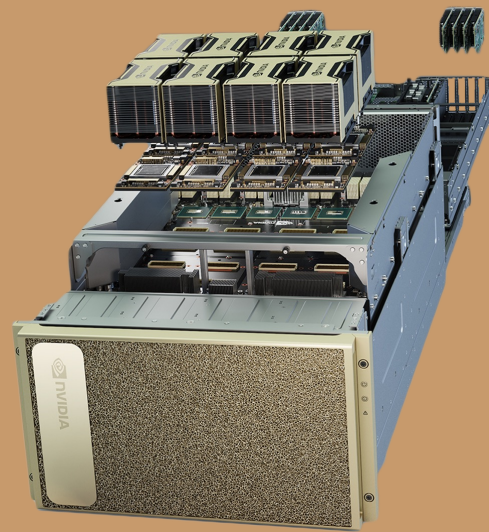
Cluster of 10 nodes with DGX A100 320 GB, 2x AMD Rome 7742 (64 cores/ 2,25 GHz) processors, and 1 TB RAM
Mellanox® Quantum(TM) HDR InfiniBand Switch

OVERVIEW

Applications SDK (QUBO, UD-MIS, QEK, DQC)
Quantum Computing Framework (Pulser, PasQasm)

Quantum Circuit Emulators (pulser-simulation, EMU-T, EMU-R)

PASQAL GPU Cluster



HPC Centers



PASQAL QPU

