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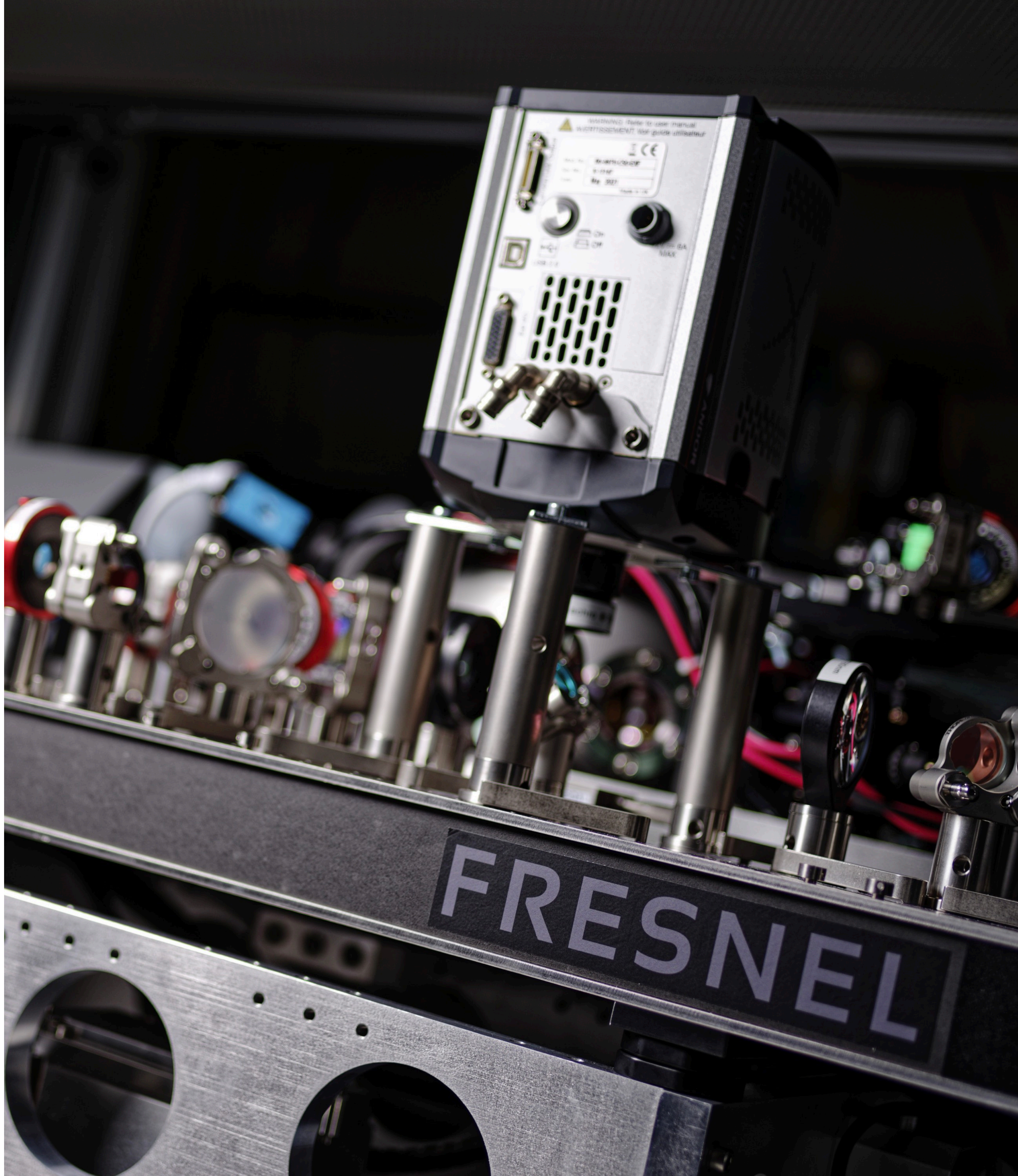
PASQAL neutral atom arrays processors and their applications

QT4HEP

Louis Vignoli

- Neutral atom arrays physics and technology
- Applications
- Quantum simulations

- Based on the expertise of Antoine BROWAEYS and Thierry LAHAYE lab, PASQAL constructs neutral atom quantum processing units (QPU)
- Neutral atoms (^{87}Ru) are trapped with optical tweezers, their states are driven by lasers and they interact together using atomic physics phenomena
- Multi-purpose, flexible, thousands qubits QPUs for analog and digital QC, operating at room temperature with low energy consumption
- A full surrounding software stack for QPUs ready to be exploited on-premise or from the Cloud



- Created in 2019
- 115+ employees between 3 main sites (France – Netherlands – Canada) and full remote
- ≥ 100 qubits in Fresnel industrial series (Q1 2023), more in R&D prototypes
- 1 QPU in operation, 3 in construction, more to come
- Electrical consumption of 4 hair dryers

Physics and technology of neutral atoms arrays

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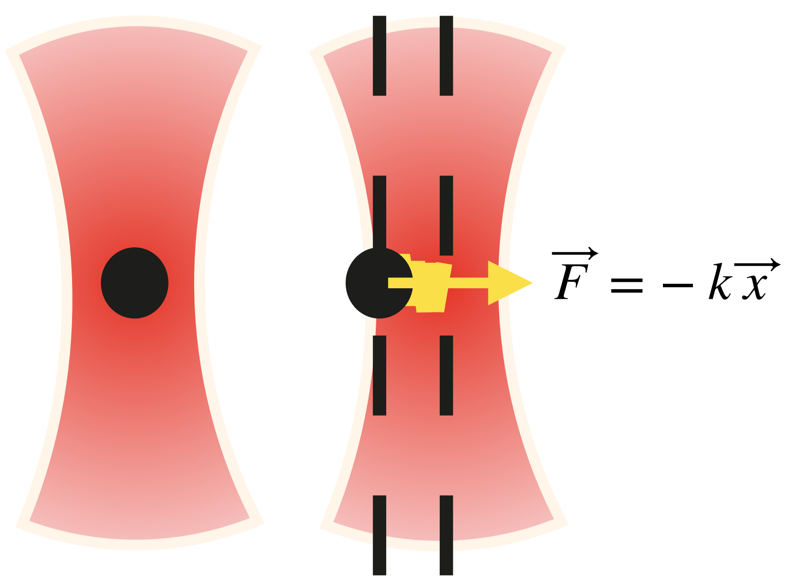
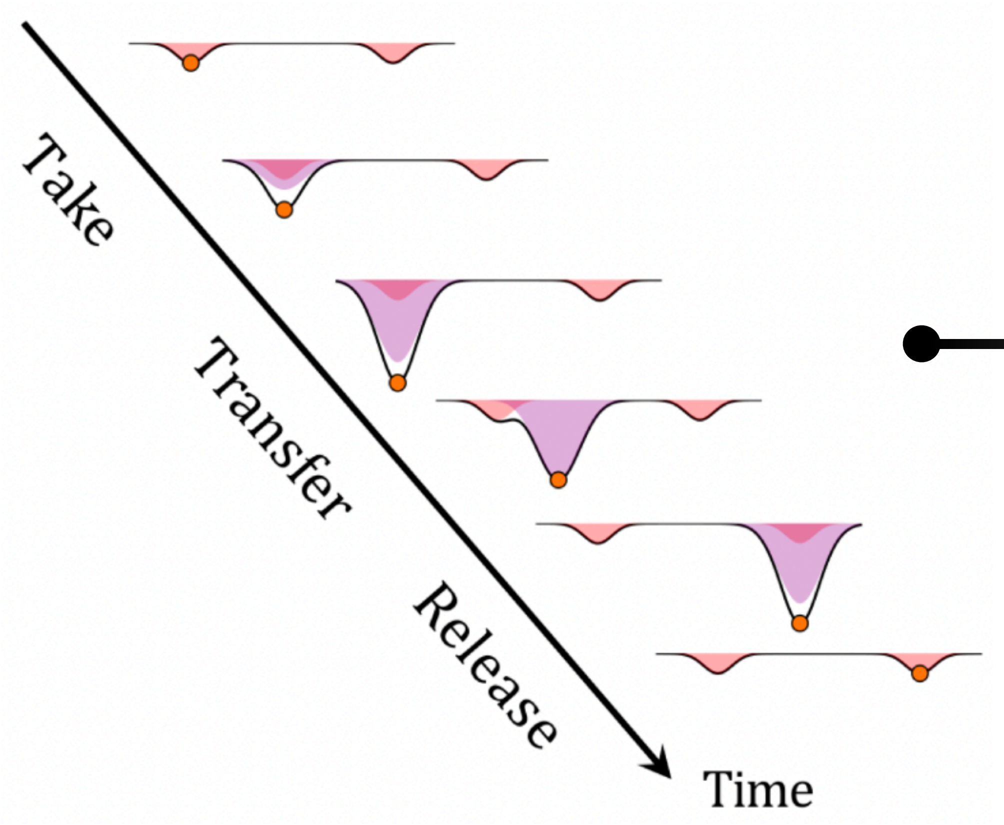
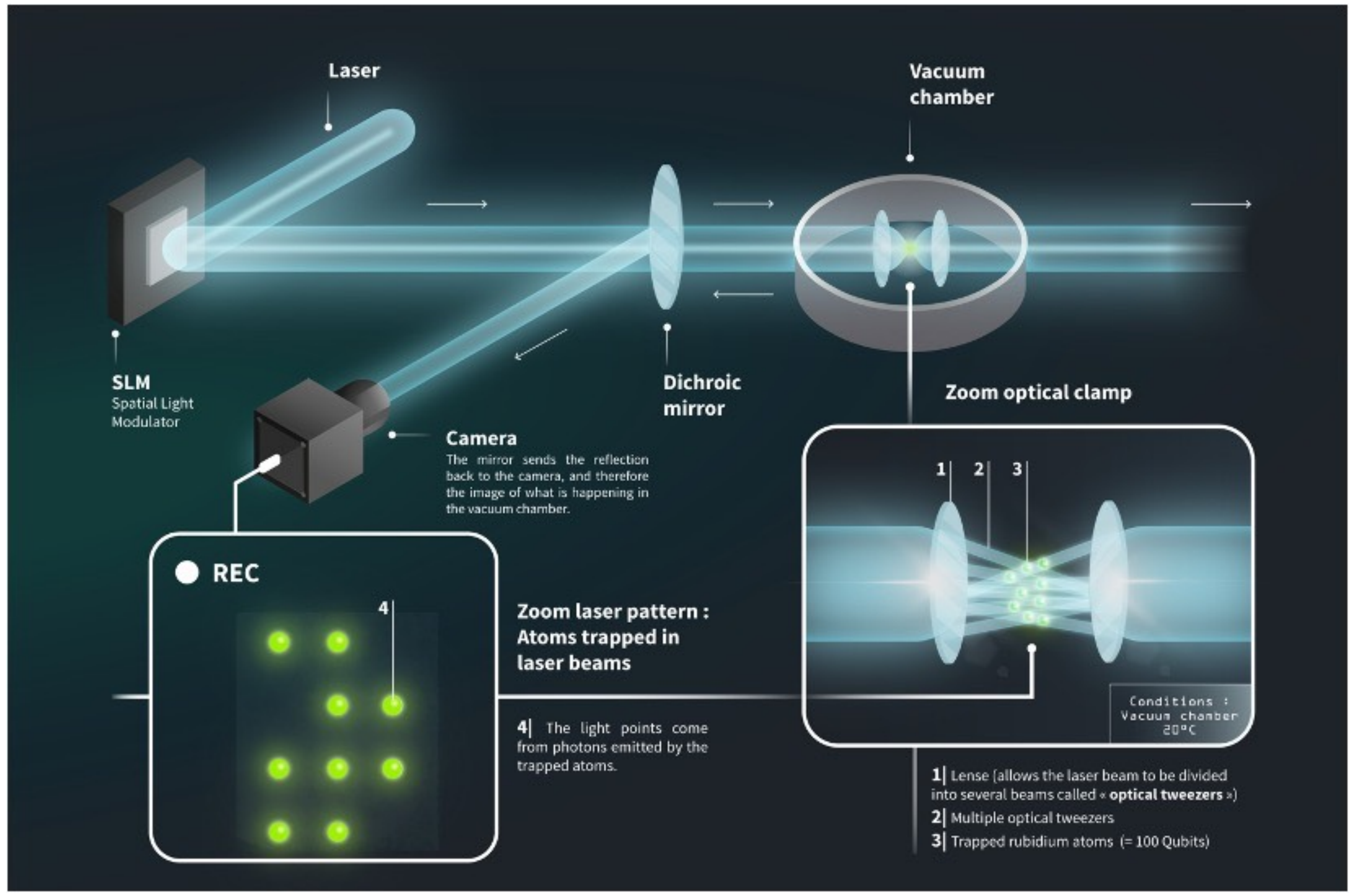
Optical tweezers
trap Rubidium atoms in place

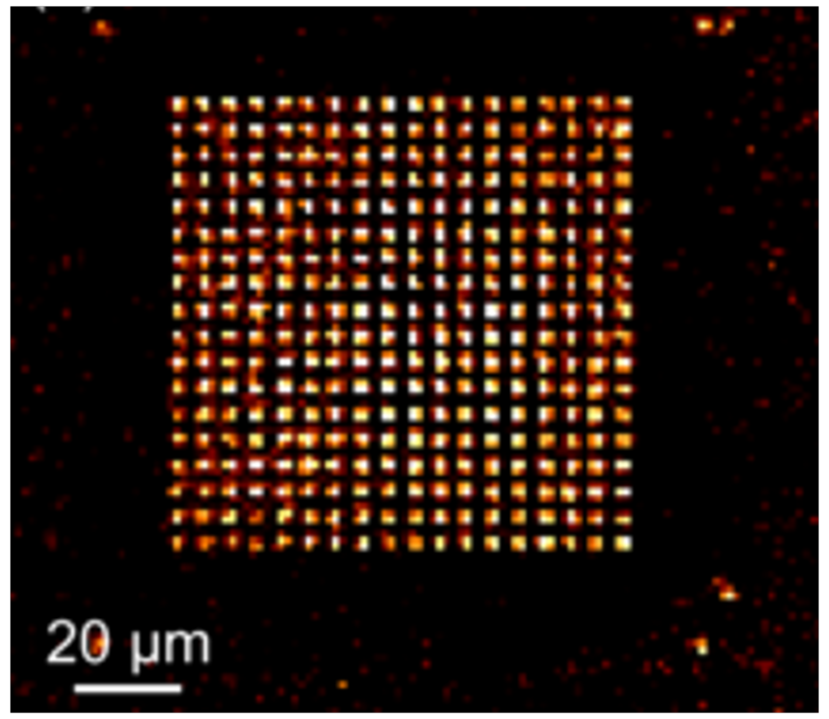


Atoms are rearranged to the target geometry
by moving them from traps to traps

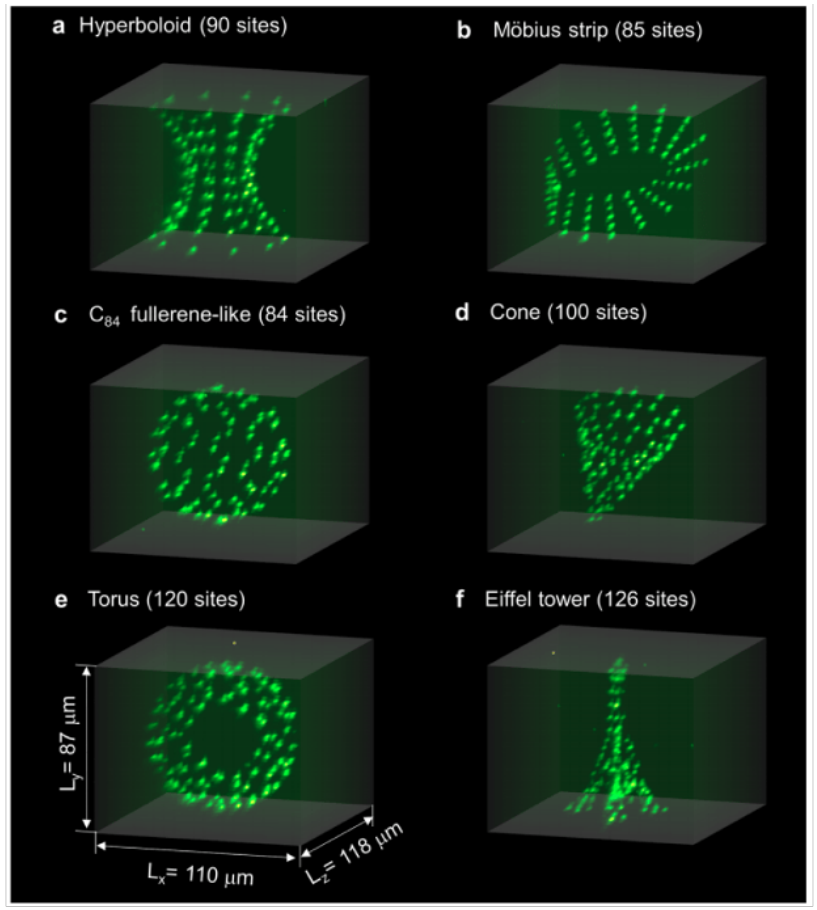


Schematics of the optical apparatus





Fluorescence image of a defect-free 324-atom array, in Phys. Rev. A 106, 022611 (2022)



Single-atom fluorescence in 3D arrays, in Nature 561, 79 (2018) 6

Geometry is flexible
with hundreds of atoms in 2D and 3D setups

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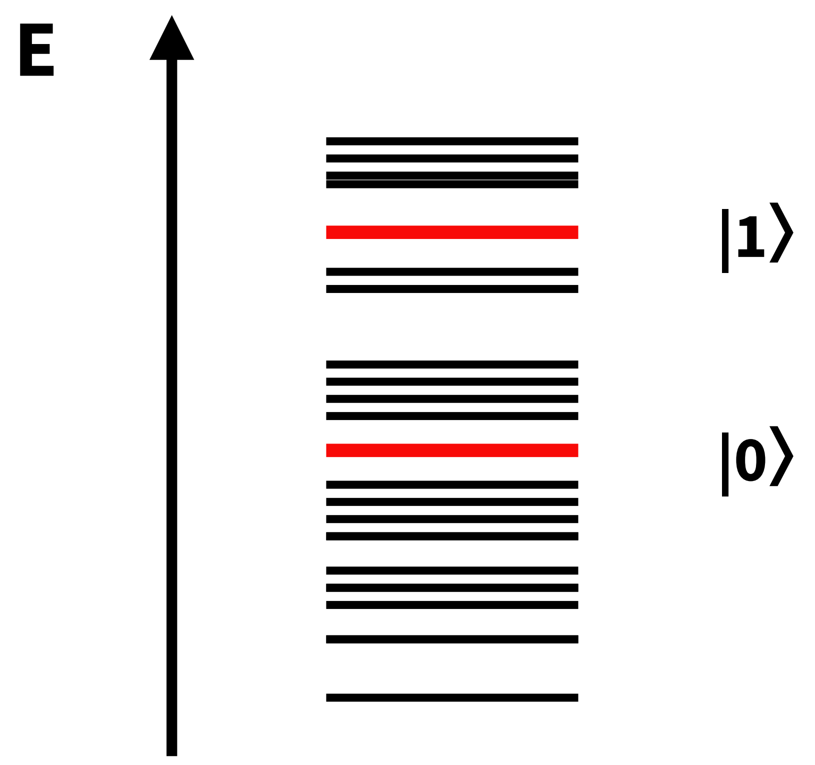
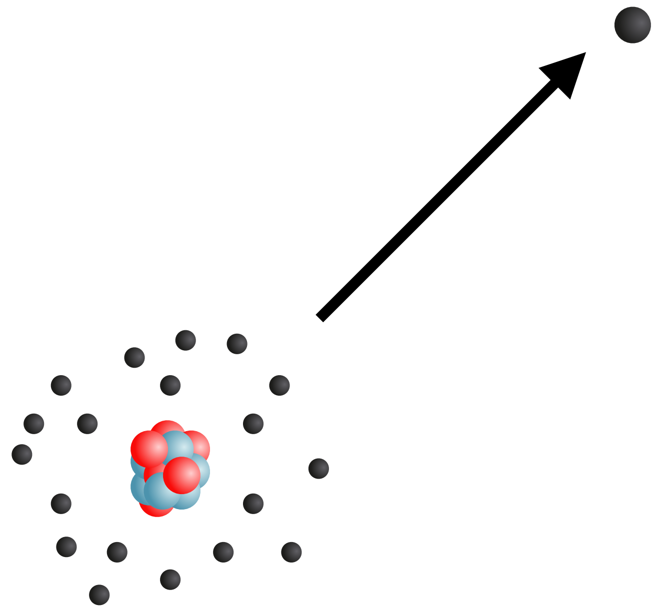
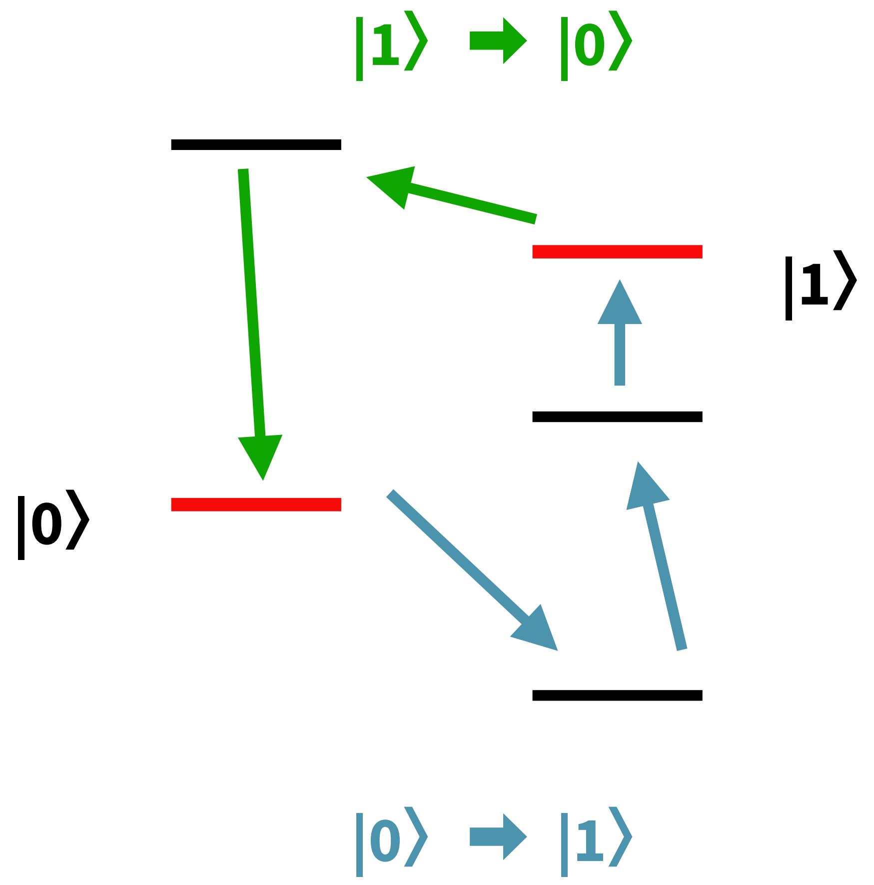


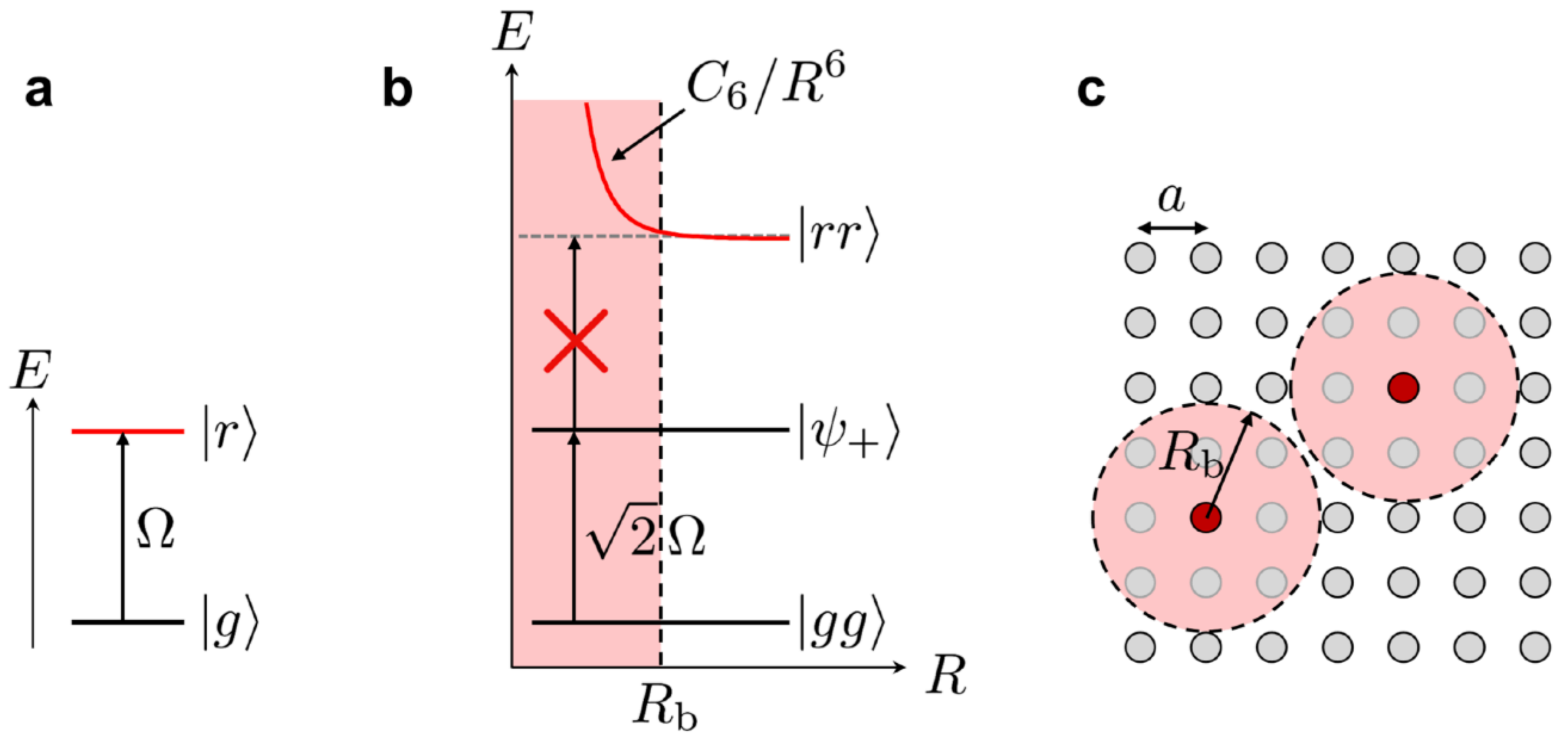
Two electronic states are chosen
to form a qubit

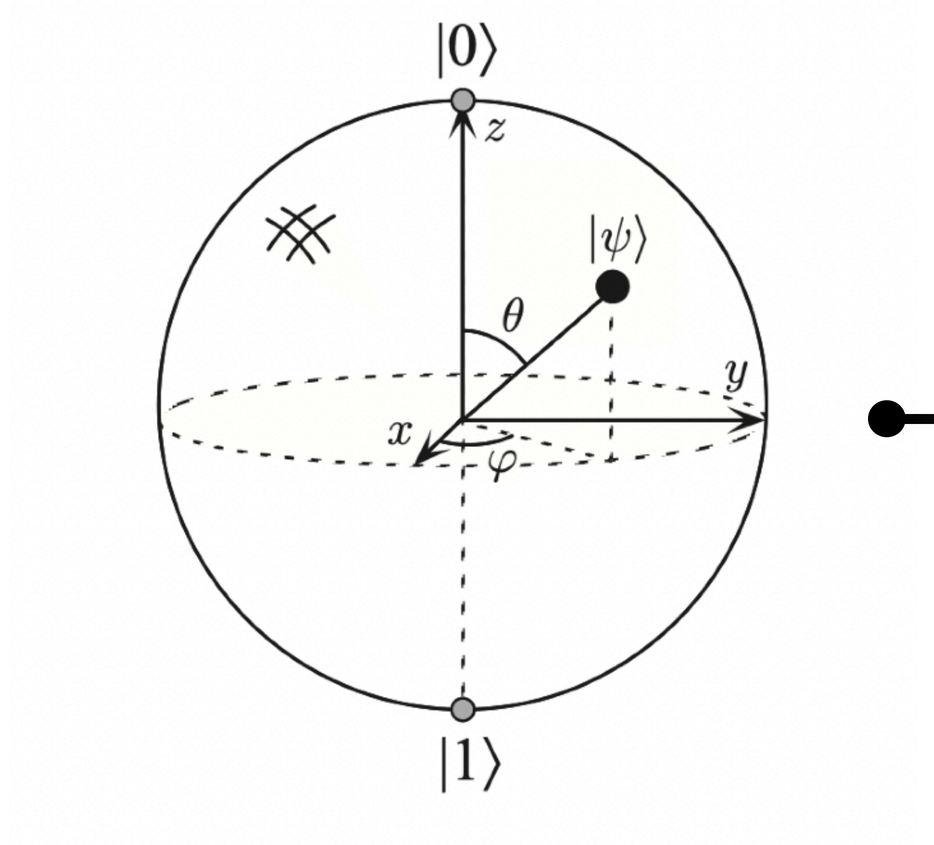


Atoms can be excited to a Rydberg state
where they behave as huge electric dipoles

Transition is operated by lasers
through intermediate states if needed







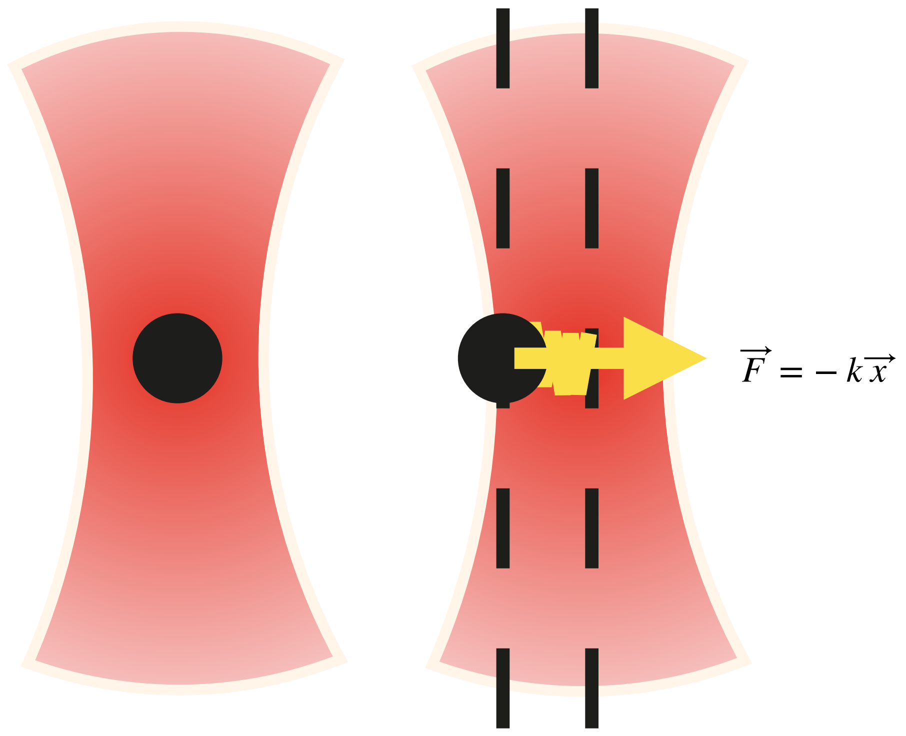
Giving full control to the qubit state

$$\frac{\hbar\Omega(t)}{2}\sigma^x - \frac{\hbar}{2}\delta(t)\sigma^z$$

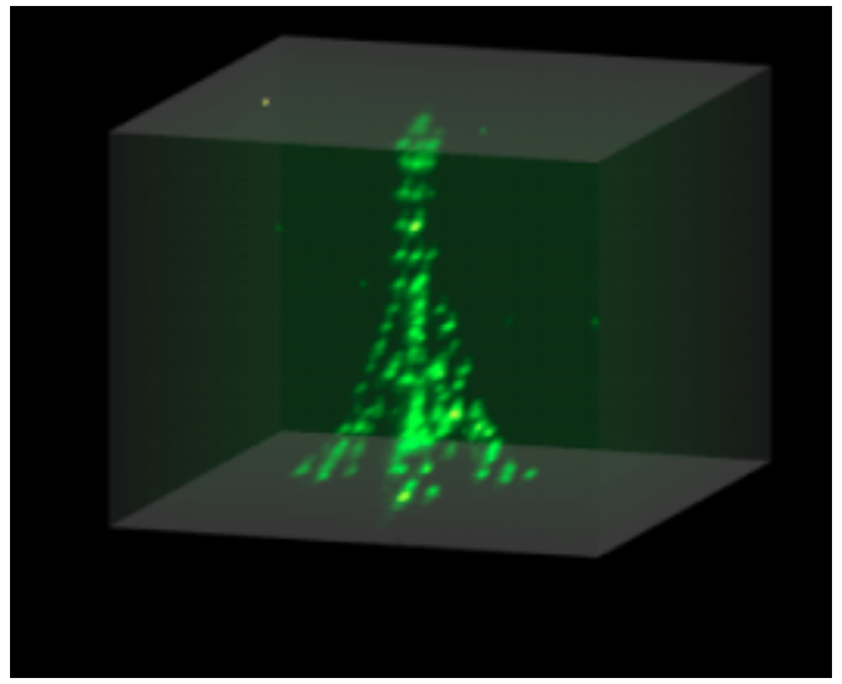
Rydberg atoms interact
through Van der Waals interactions
leading to Rydberg blockade

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

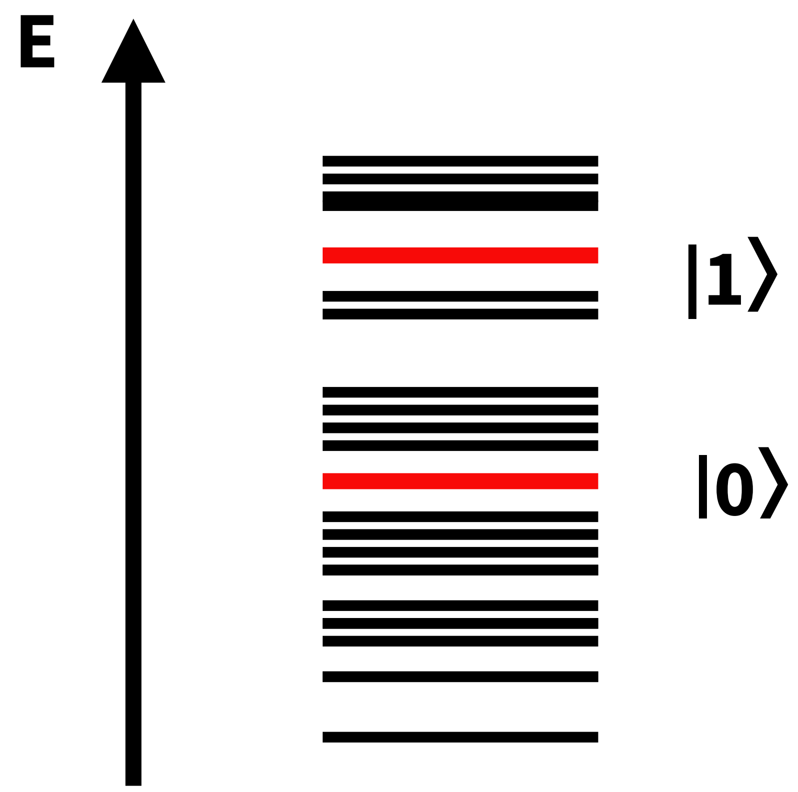
Trapping atoms with lasers...



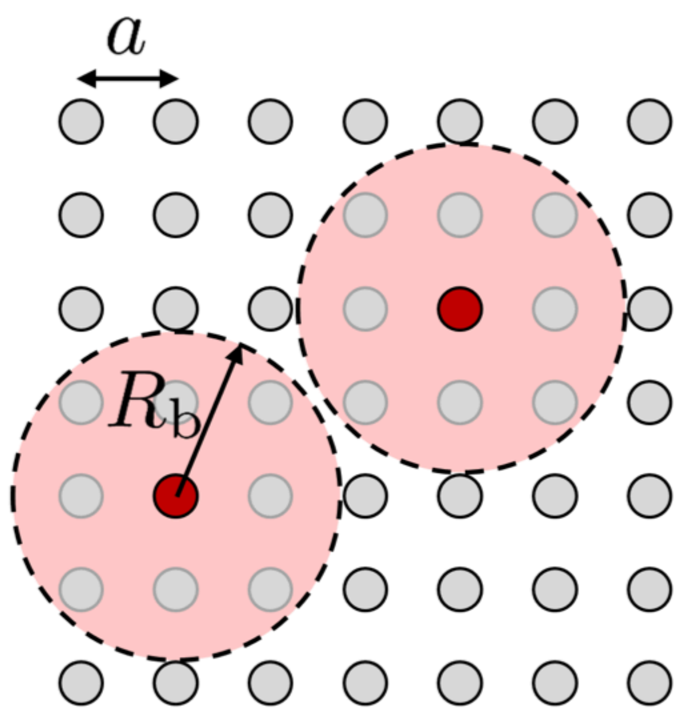
in a custom geometry;



to create qubits...



that interact together.



We create controllable quantum systems to:

- solve computational problems
- probe physical phenomena

Applications and Industrial use cases

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Energy

- Example applications:
  - Reservoir simulation
  - Electric grid management
  - ...

Mobility

- Example applications:
  - Battery & fuel-cell design
  - Materials deformation
  - ...

Healthcare

- Example Applications:
  - De-novo design
  - Toxicity screening
  - ...

Finance

- Example applications:
  - Derivatives pricing
  - Time-series data generation
  - ...

Hightech

- Example applications:
  - Materials modelling
  - Multiphysics simulation
  - ...

Public

- Example applications:
  - Aerodynamics modelling
  - Mission planning
  - ...

Industry relevance

Numerical simulation from data has enabled more and more accurate weather forecasts.

It requires huge computational power, while

Computational challenge

Weather models require solving complex nonlinear sets of PDE and boundary conditions

5% of global high performance computing ressources are used for weather modeling[1].

Quantum solution

PASQAL has developed Differentiable Quantum Circuits[2] (DQC) which are quantum neural network, that are trainable to satisfy differential equations and specified boundary conditions.

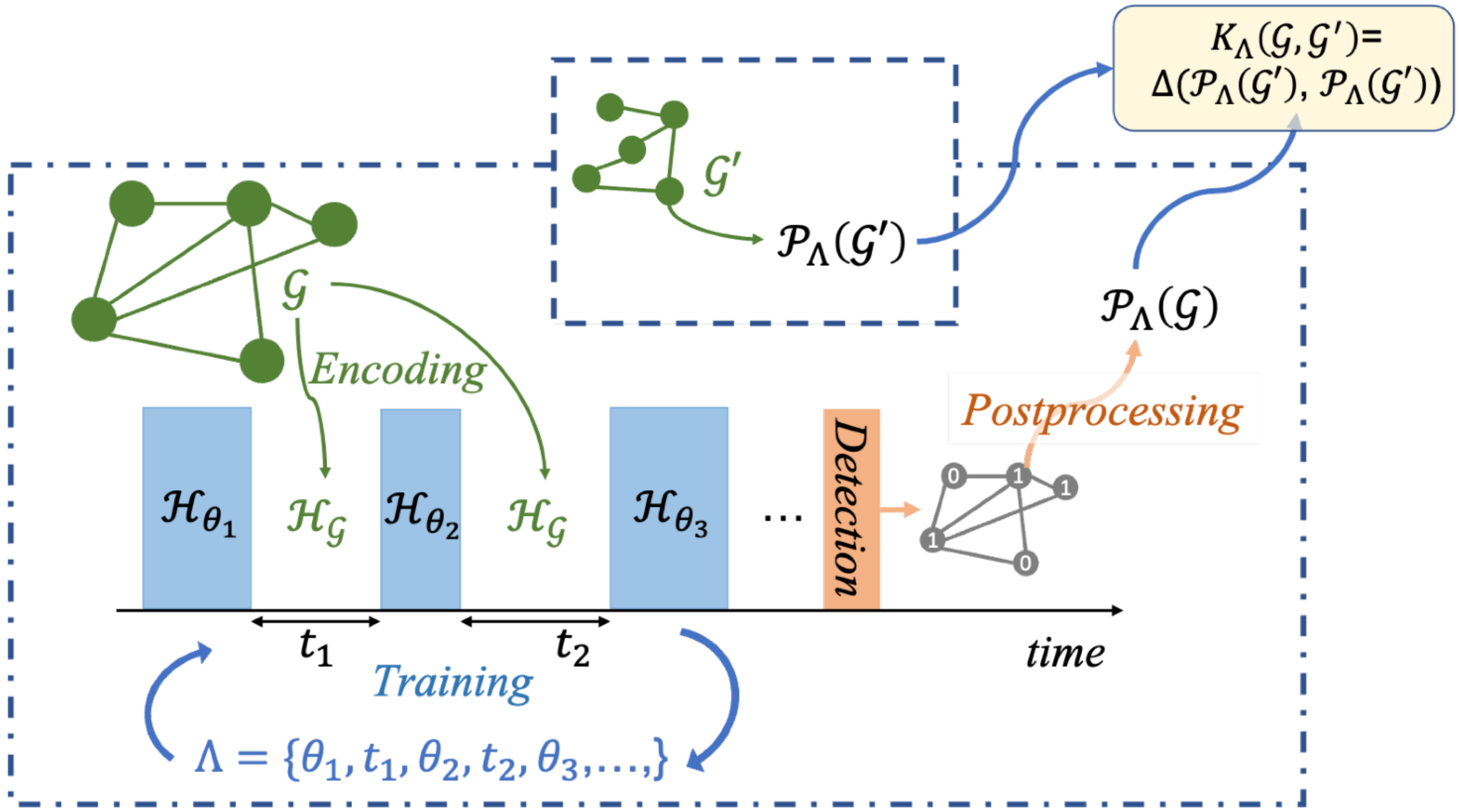
PASQAL and BASF are testing it on BASF specific challenges related to weather forecast.

[1] https://hyperionresearch.com/wp-content/uploads/2021/11/Hyperion-Research-SC21-Market-Update-Briefing_Team.pdf
[2] doi.org/10.1103/PhysRevA.103.052416

Industry relevance

Supply is less predictable with renewable sources of energy while demand increases
Grid management becomes more complex

A way to deal with this complexity is by identifying parts of a grid that have similar operating modes



Computational challenge

Graph theory is a convenient approach to model electricity grids[1]. Similar operating modes can be identified by studying graph similarity

Graph kernels are proper tools to compare graphs[2]

Quantum solution

PASQAL developed a quantum graph kernel[3] method designed to be natively implemented in analog mode on neutral atom processor

Collaboration with French grid regulator RTE to test it on their specific challenges

[1] doi.org/10.17775/CSEEJPES.2021.00430
[2] doi.org/10.1007/s41109-019-0195-3
[3] doi.org/10.1103/PhysRevA.104.032416

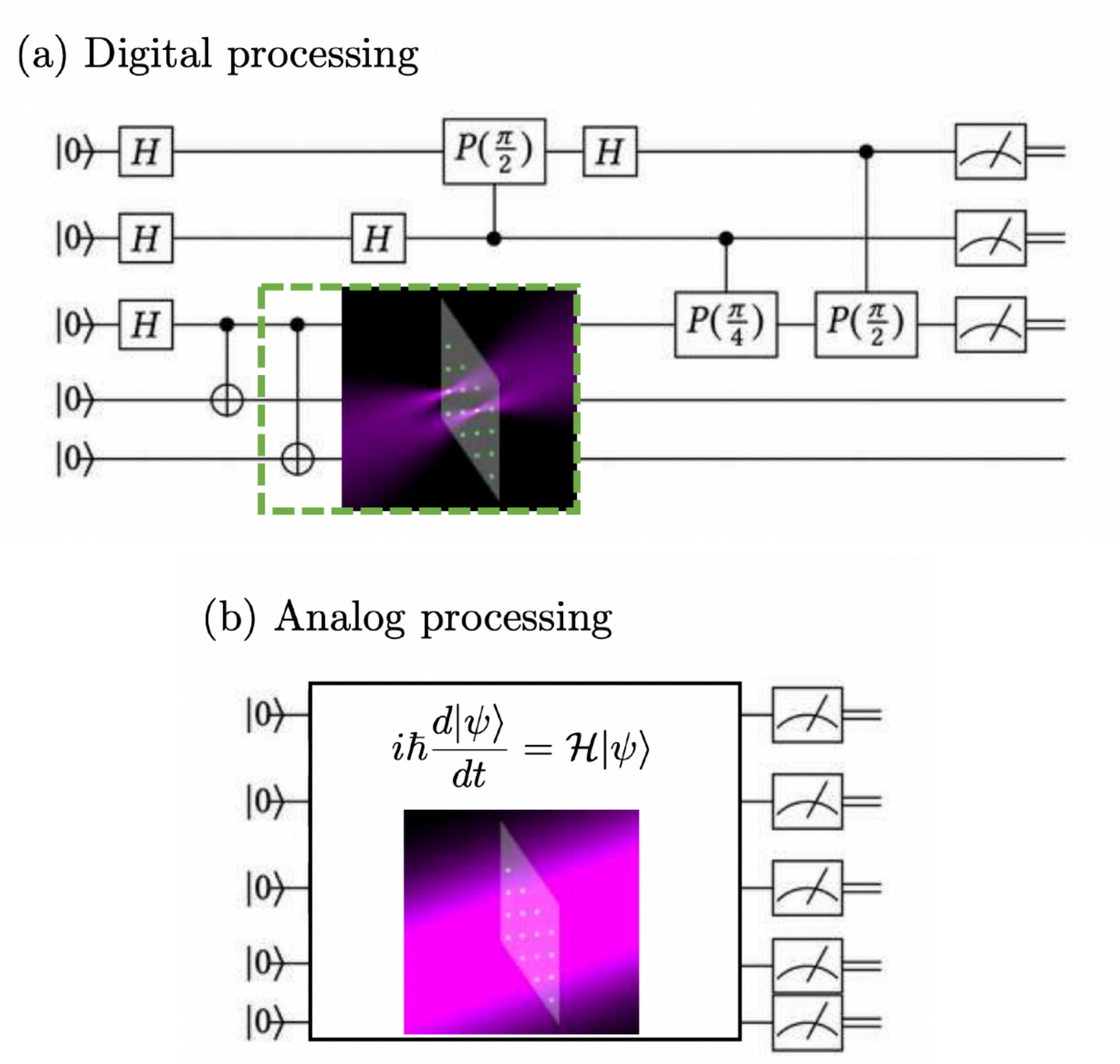
The QPU at Noisy Intermediate Scale (NISQ) is a specialized tool dedicated to several high performance computing tasks

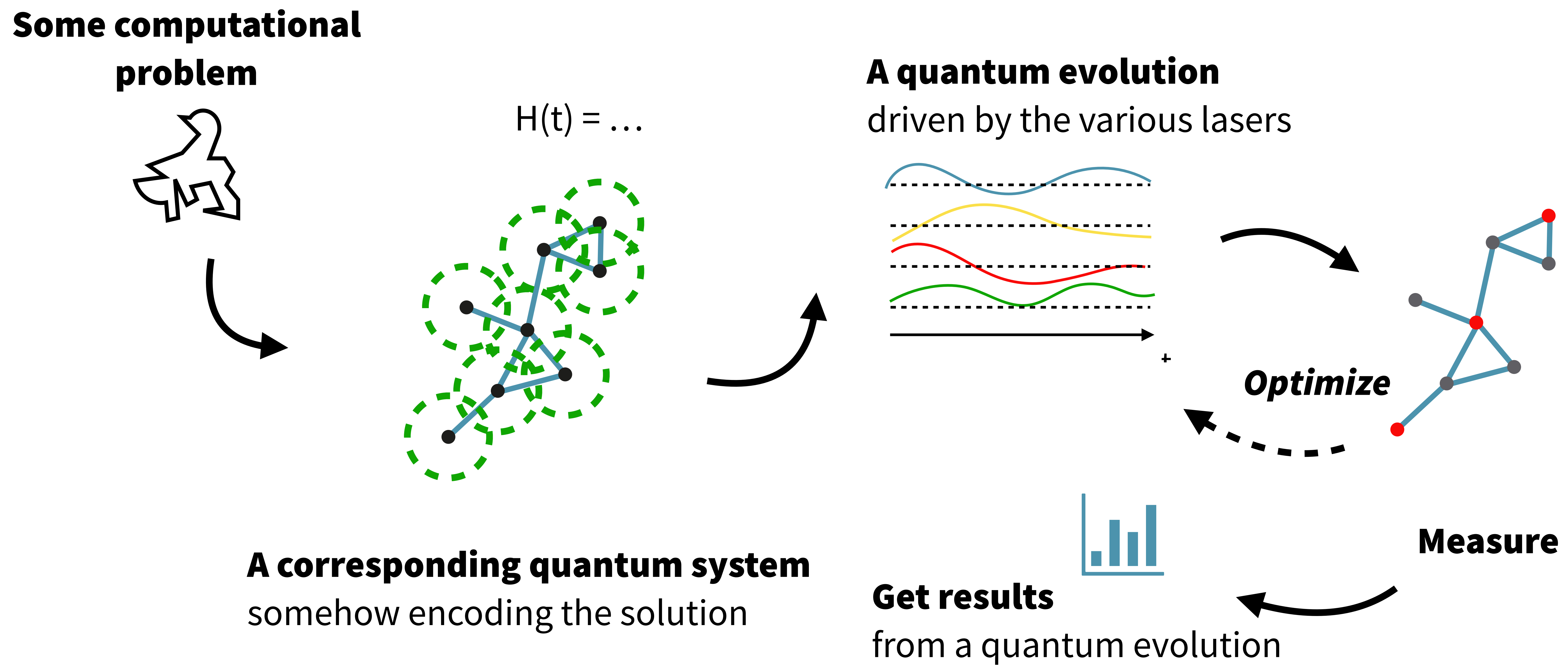
Now: Proof-of-concepts and demonstration of scalable advantages in R&D settings

Soon: Performance on-par with classical approaches for a handful of well-identified problems

Towards: Tailored solutions to production challenges

Eventually: Universal quantum computer with unprecedented applications





Scientific opportunities from quantum simulation

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nature

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Article | Published: 07 July 2021

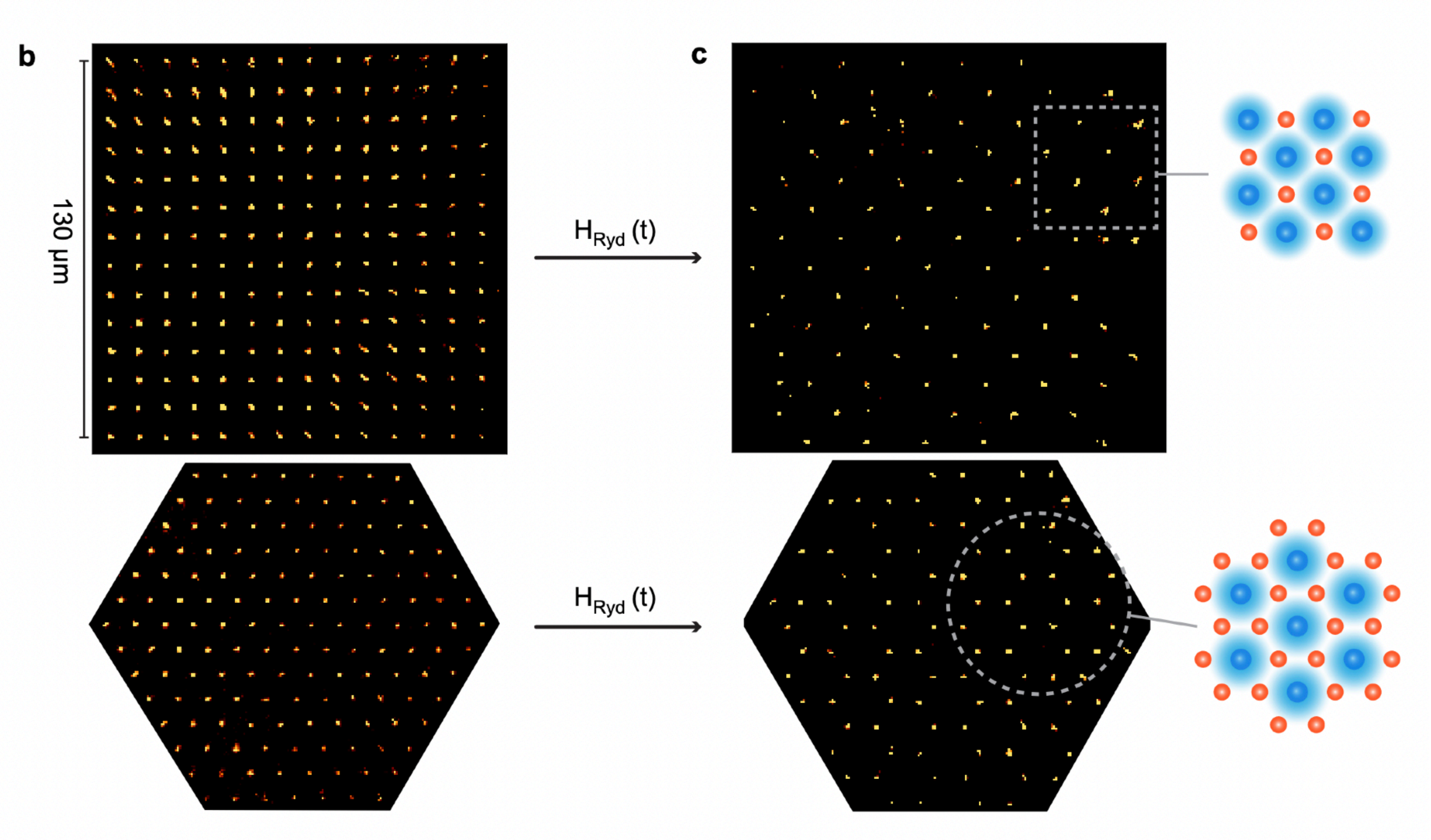
Quantum simulation of 2D antiferromagnets with hundreds of Rydberg atoms

Pascal Scholl, Michael Schuler, Hannah J. Williams, Alexander A. Eberharter, Daniel Barredo, Kai-Niklas Schymik, Vincent Lienhard, Louis-Paul Henry, Thomas C. Lang, Thierry Lahaye, Andreas M. Läuchli & Antoine Browaeys

Nature **595**, 233–238 (2021) | Cite this article

Quantum simulation of antiferromagnetic 2D transverse Ising model of various system sizes and different geometries, up to 196 atoms.

- “We have shown a **high degree of coherence and control, over a large number of atoms**”
- “Combined, this demonstrates that our platform is now able to study quantum spin models in regimes **beyond those accessible via numerical investigations**”



Lattice Gauge Theories and String Dynamics in Rydberg Atom Quantum Simulators

Federica M. Surace, Paolo P. Mazza, Giuliano Giudici, Alessio Lerose, Andrea Gambassi, and Marcello Dalmonte
Phys. Rev. X **10**, 021041 – Published 21 May 2020

- 1D
- Schwinger model U(1) (1+1 quantum electrodynamics)
- String dynamics

Gauge theories describe the fundamental forces of nature […]

Despite the conceptual elegance of these theories, probing their predictions is a formidable task: Experiments require gigantic facilities such as the Large Hadron Collider at **CERN** […]

Promising candidates for such experiments include quantum simulators […]

Emerging Two-Dimensional Gauge Theories in Rydberg Configurable Arrays

Alessio Celi, Benoît Vermersch, Oscar Viyuela, Hannes Pichler, Mikhail D. Lukin, and Peter Zoller
Phys. Rev. X **10**, 021057 – Published 16 June 2020

- 2D
- Rokhsar-Kivelson 2D U(1) (quantum dimer and spin ice dynamics)
- Phases and quench dynamics

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Thank You for Attention