Intro to Neutral-atom Quantum Computing

ETH Quantum Hackathon 2024

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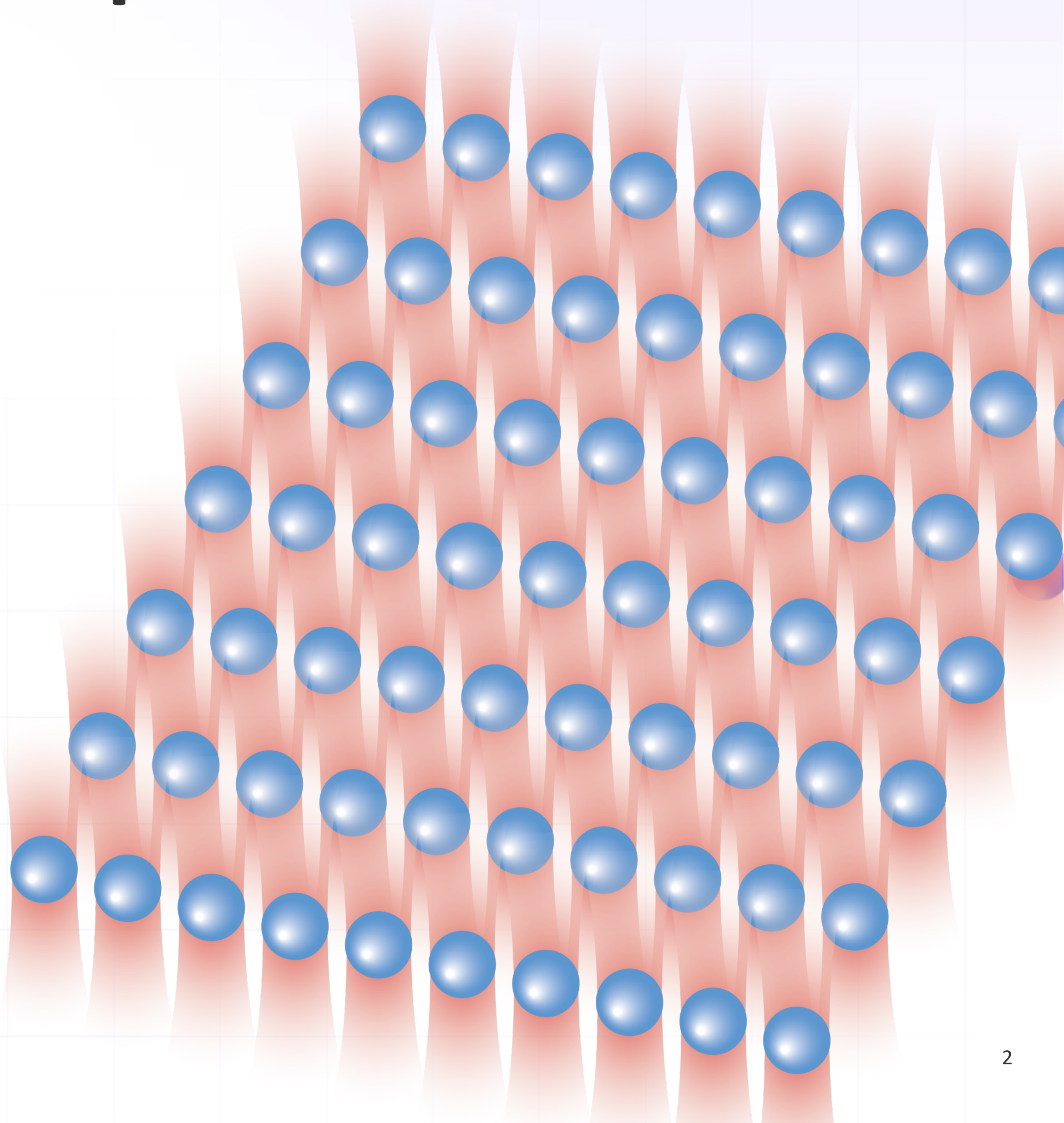
Why neutral-atom quantum processor

- Densely packed qubits (atoms)
- Efficient qubit control
- Flexible problem encoding
- The fastest path to quantum error correction
- New ways to think quantum computing!

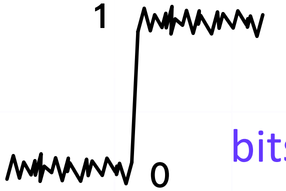


Quantum computing == new rules!

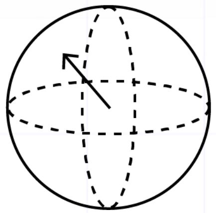
Classical

Quantum

Information input

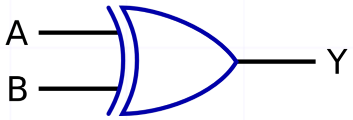


bits

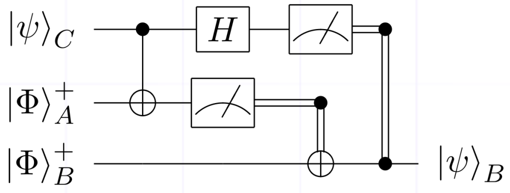


qubits

Information processing



Logic gates



Quantum gates

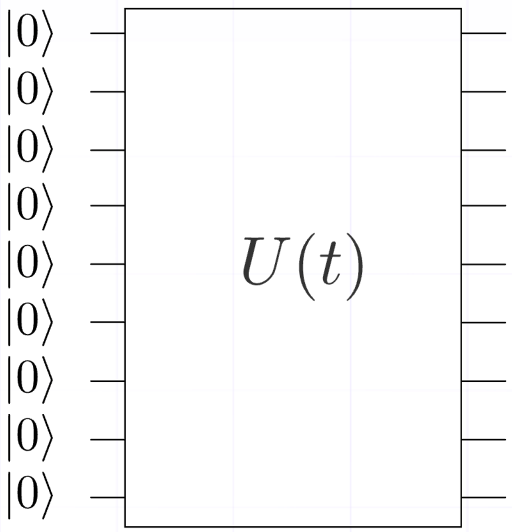
Results & output

Deterministic

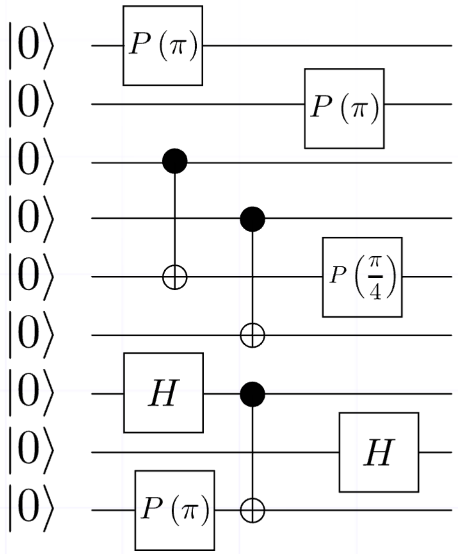
Probabilistic & deterministic

Paradigms of Q. Information processing

Analog operation



Digital operation



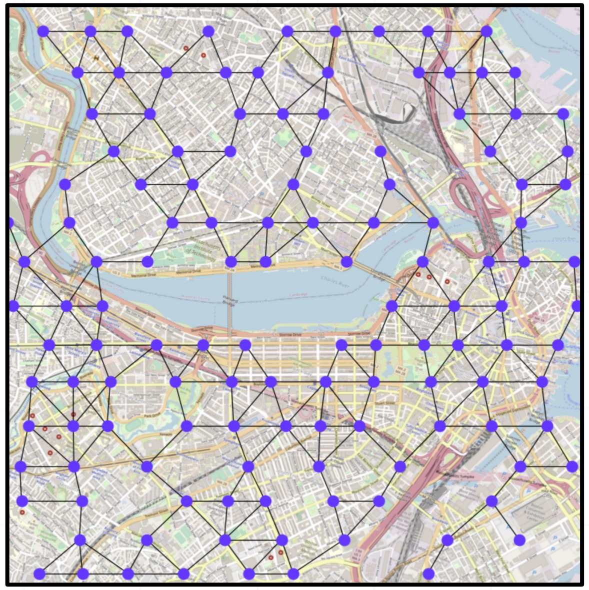
Designed for the early stage of maturity of the quantum computing resources of today…

- ✓ Robustness to errors
- ✓ Efficient control
- ✓ Single-step large entanglement
- ✗ Universal applicability

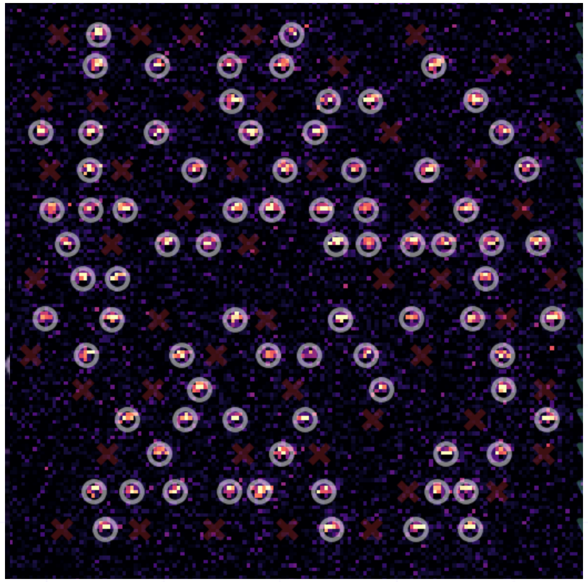
More on analog processors:
Nature **volume 607**, p. 667–676 (2022)

FPQA = Efficient Problem Encoding

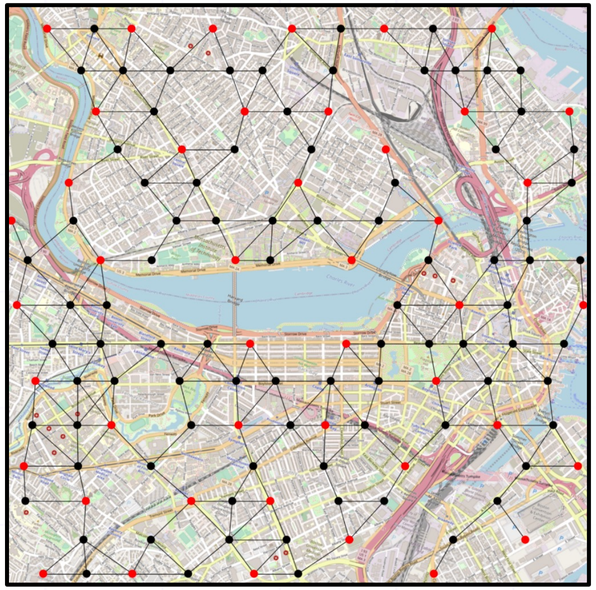
Problem: choosing optimal locations in Boston



Possible locations as atom coordinates

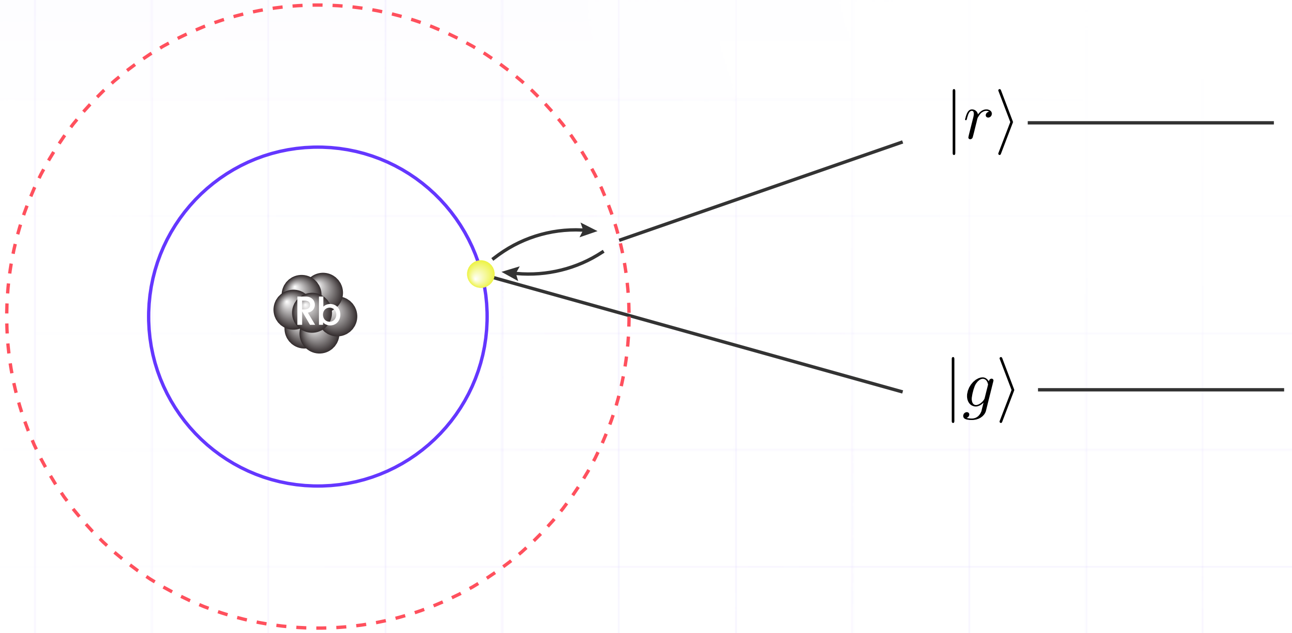


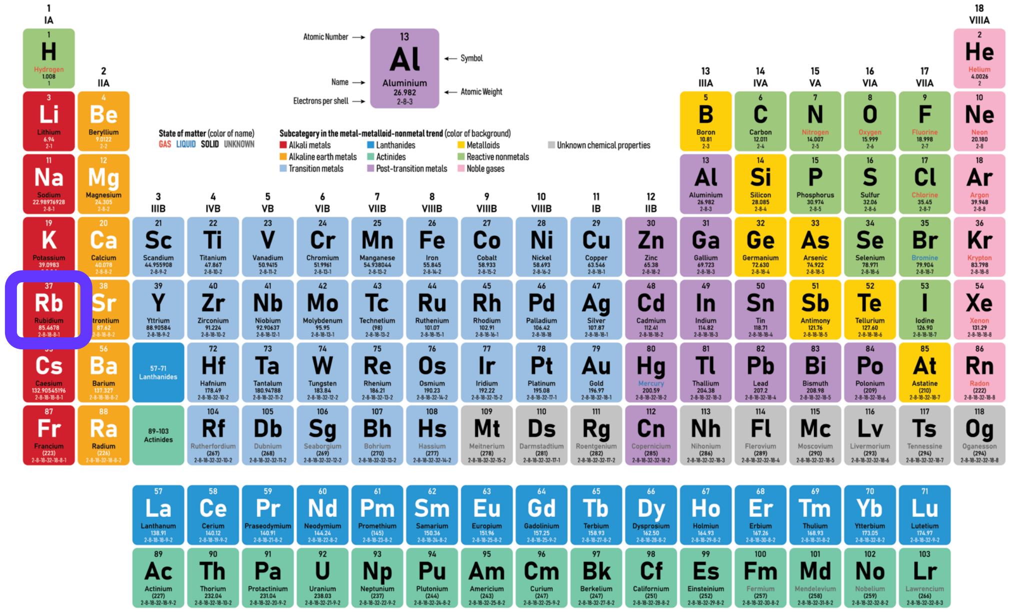
Solution



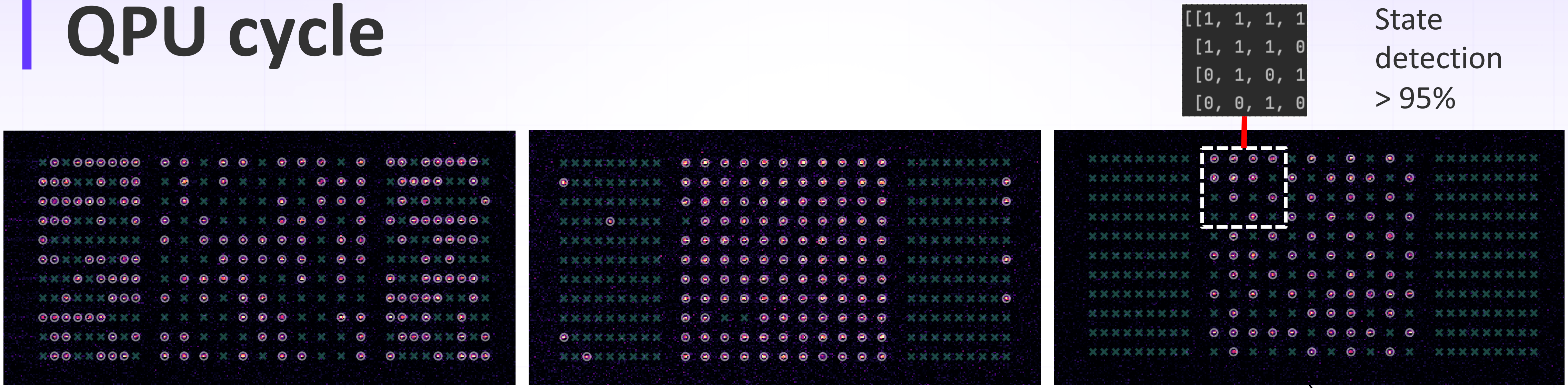
|QuEra>

Architecture: qubits by puffing-up atoms

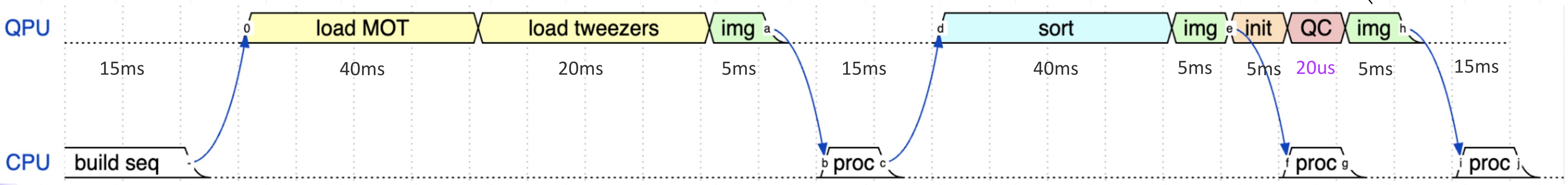




QPU cycle



State detection > 95%



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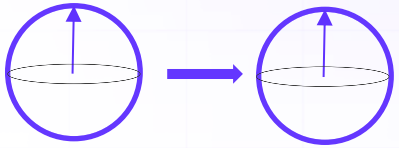
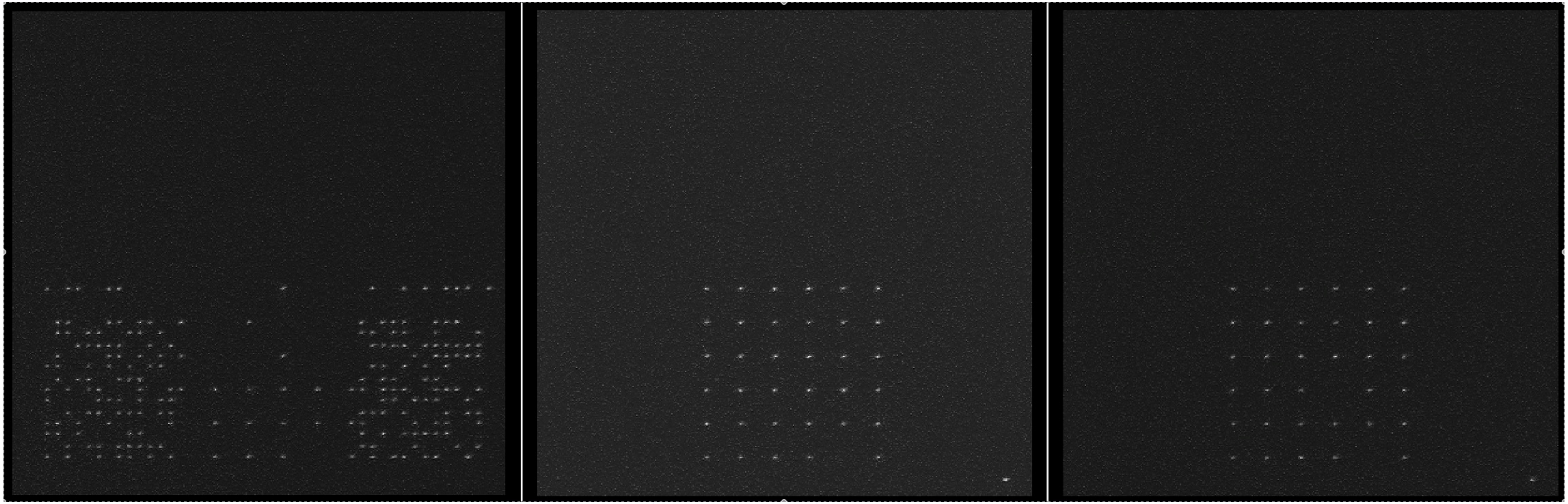
What qubit control really looks like:

2π pulse

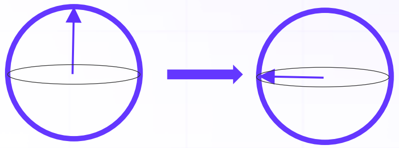


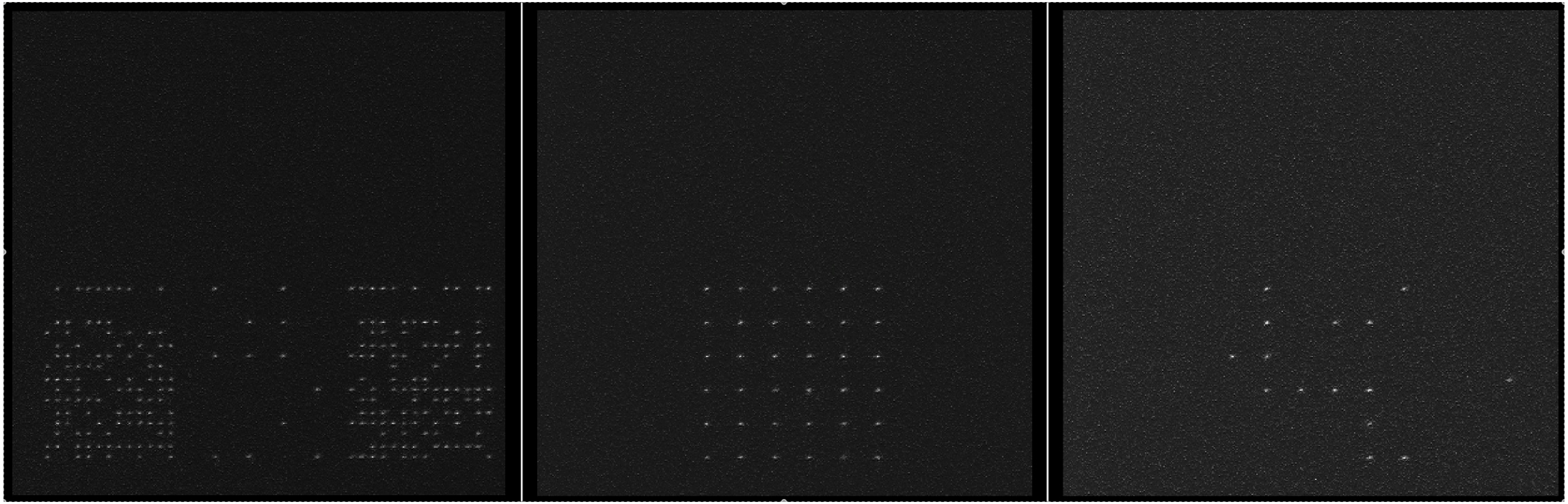


|QuEra>

What qubit control really looks like:

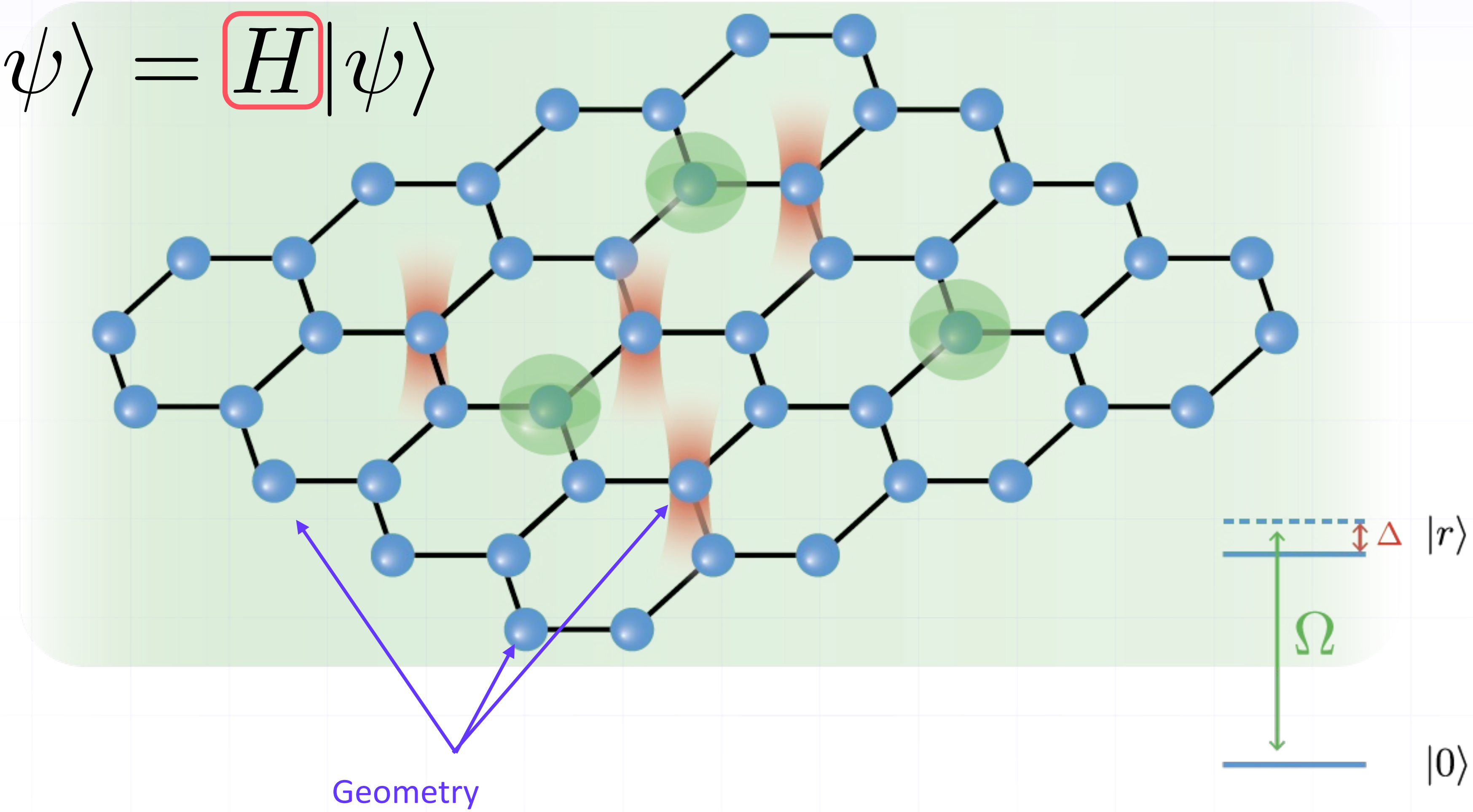
$\pi/2$ *pulse*





A neutral-atom quantum processor

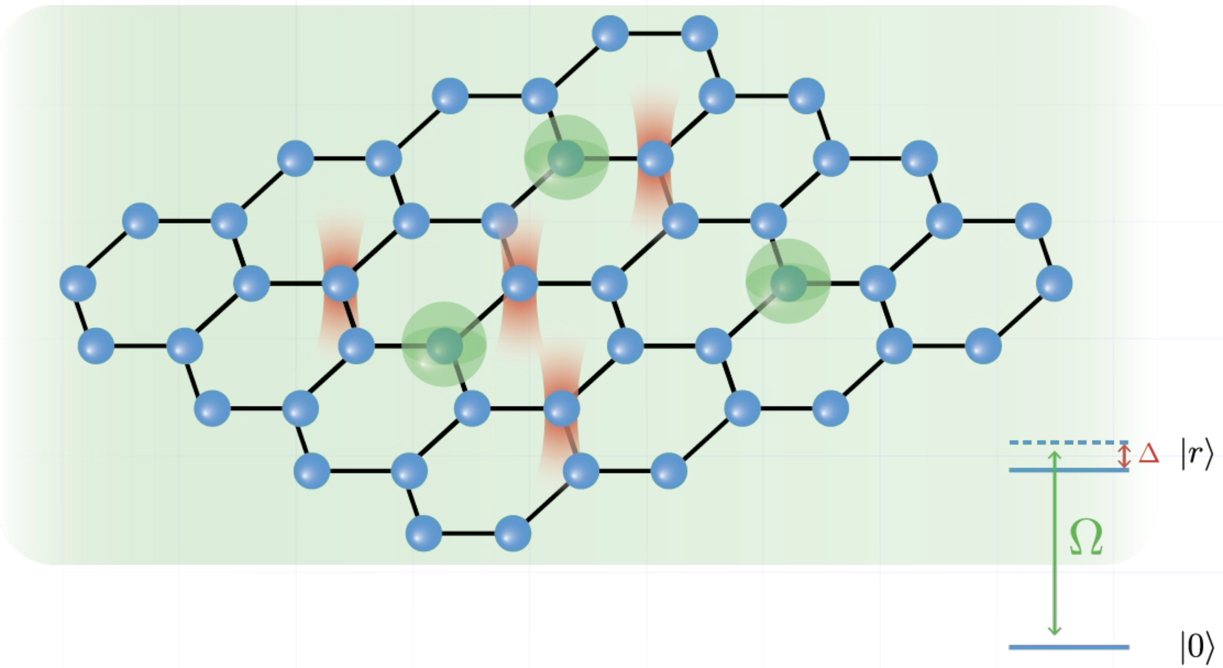
$$i\frac{\partial}{\partial t}|\psi\rangle = \boxed{H}|\psi\rangle$$



Dynamics
(algorithms)

Analog quantum dynamics control

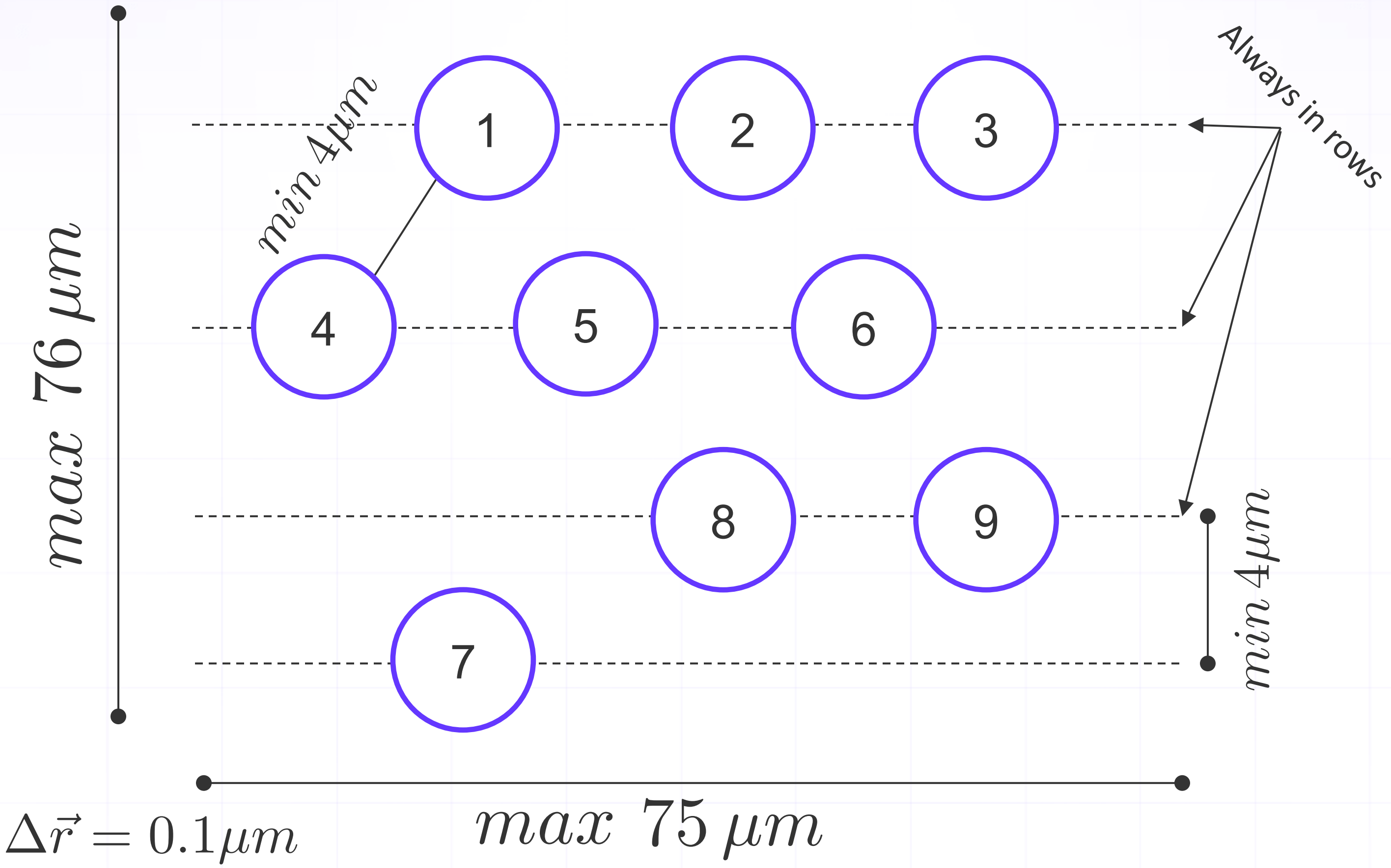
$$H = \sum_i \frac{\Omega(t)}{2}\left(e^{i\phi(t)}|g_i\rangle\langle r_i| + e^{-i\phi(t)}|r_i\rangle\langle g_i|\right) - \sum_i \Delta(t) n_i + \sum_{i<j} V_{ij} n_i n_j$$



$$n_i = 1 * |r_i\rangle\langle r_i| + 0 * |\mathrm{g}_i\rangle\langle \mathrm{g}_i|$$

$$V_{ij} \sim d_{ij}^{-6}$$

Hardware constraints: Geometry

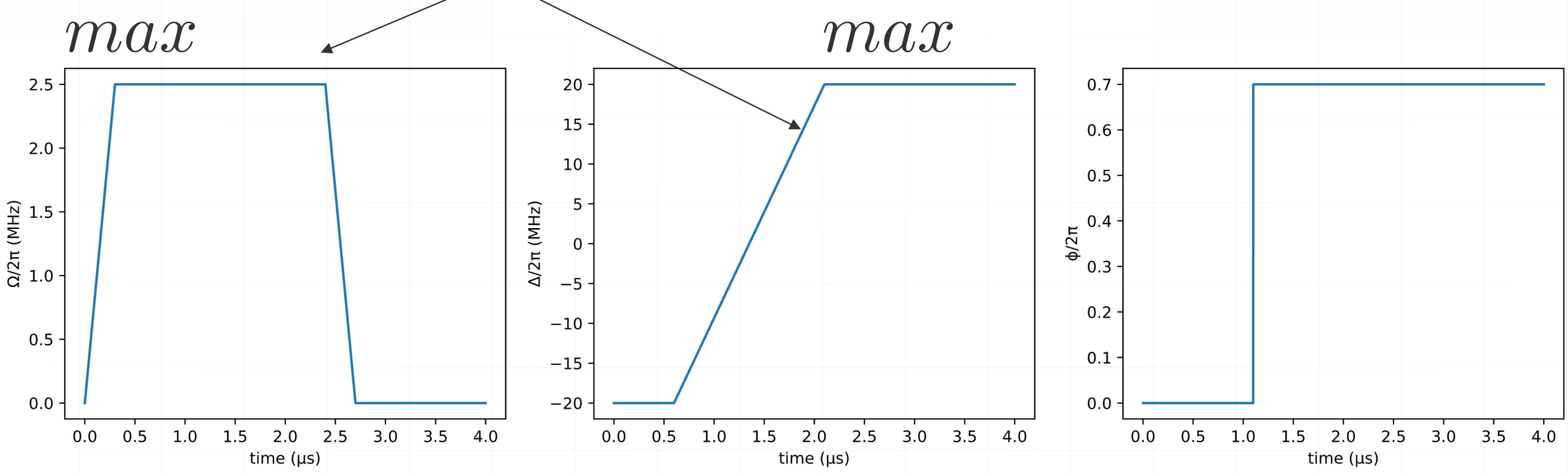


More details @
https://queracomputing.github.io/Bloqade.jl/dev/capabilities/

Hardware constraints: dynamics

Activity: Encoding waveforms on Bloqade

Piecewise-linear



$$t_{max} = 4\mu s$$

Piecewise-constant

Rydberg blockade: phenomenology

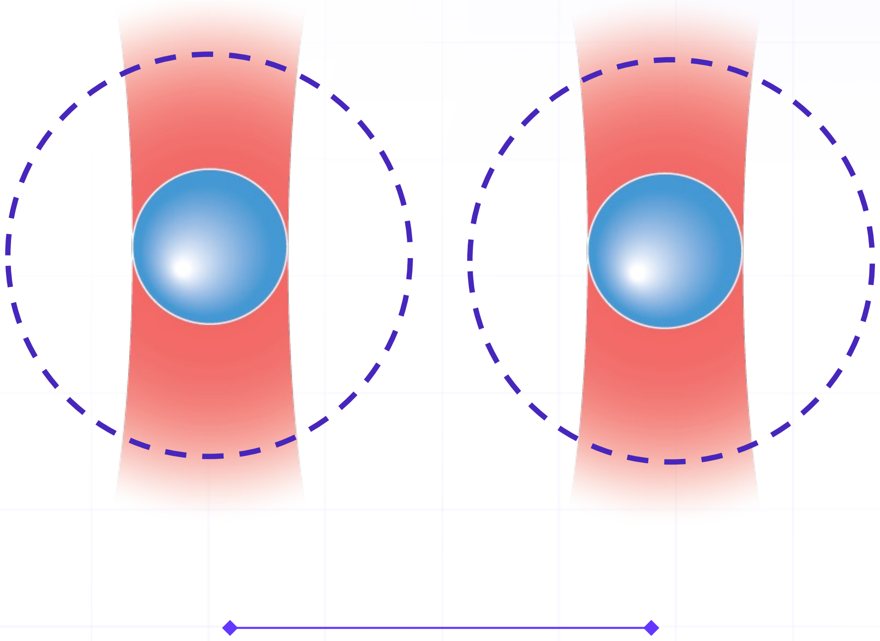
$|rr\rangle$

$V + \Delta$

$|gr\rangle \quad |rg\rangle$

Δ

$|gg\rangle$



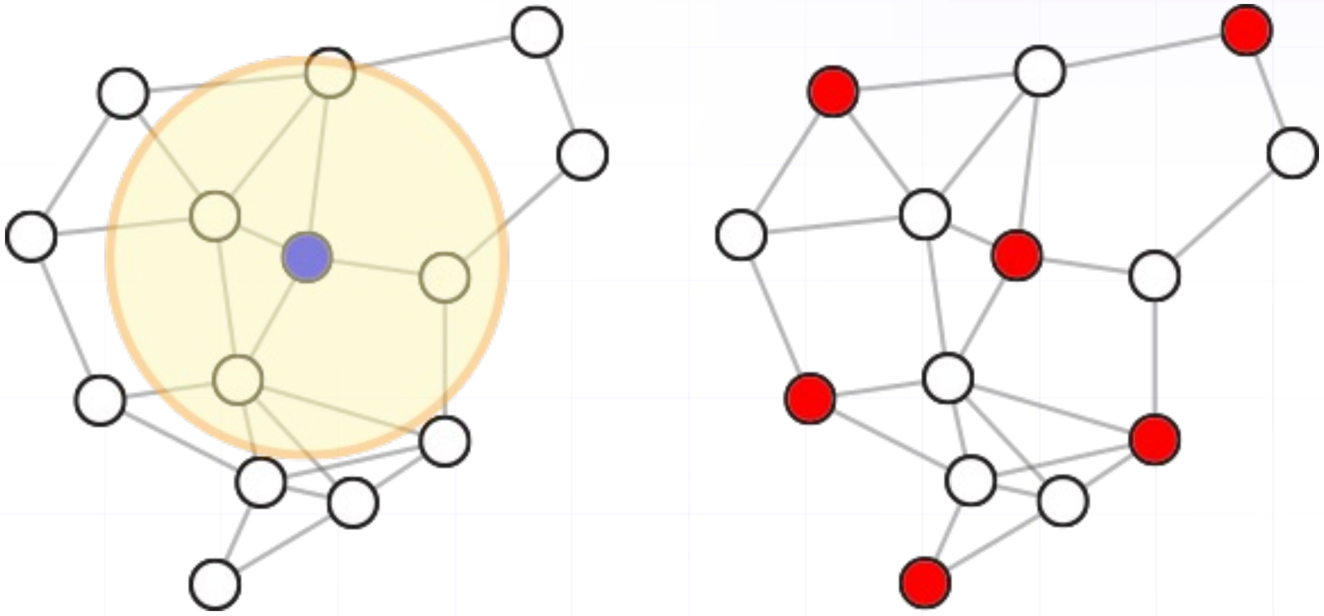
$$V \sim d^{-6}$$

$$R_b = (C_6/\sqrt{\Omega^2 + \Delta^2})^{1/6}$$

Rydberg blockade: utility

Maximum
Independent
Set

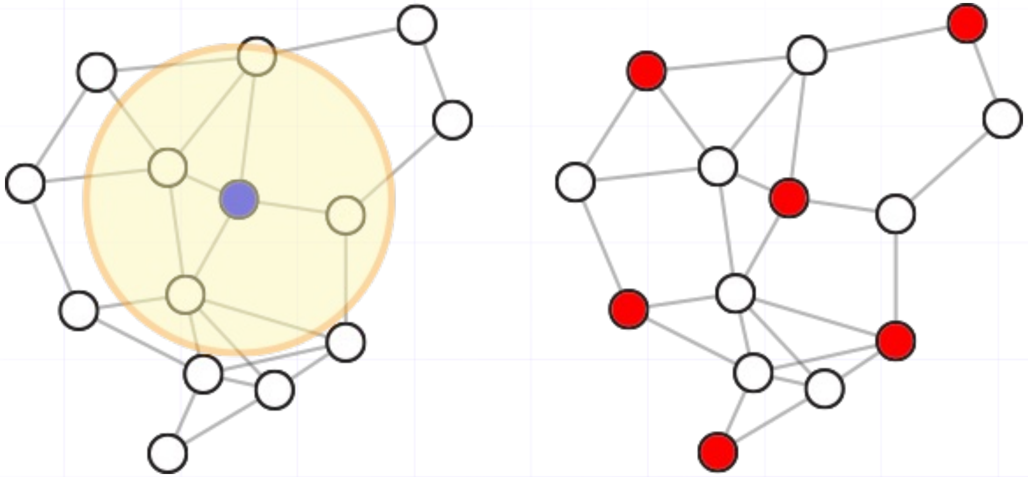
(NP-Complete)

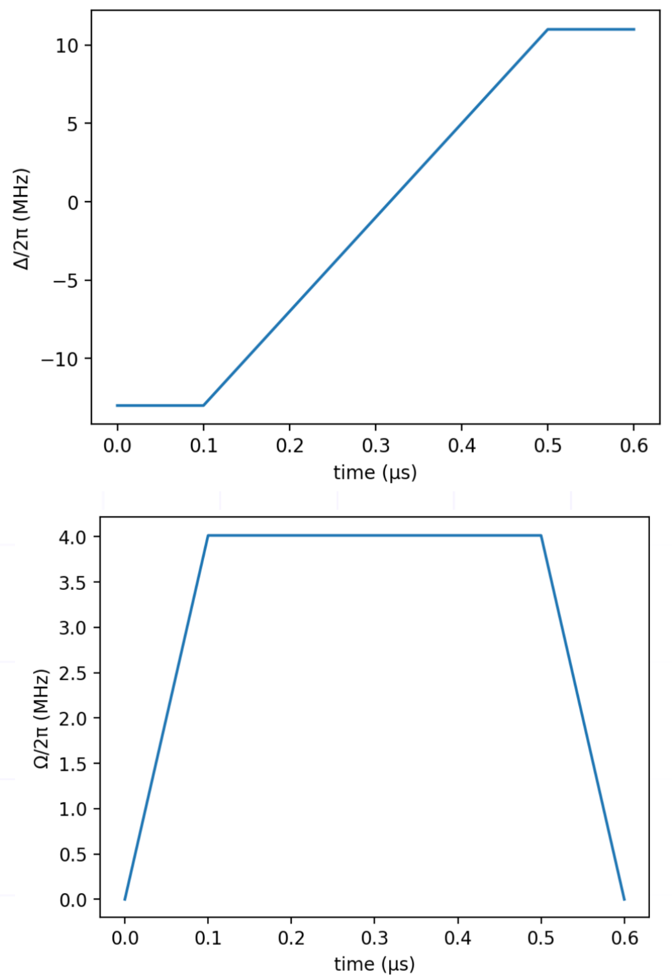


Adapted from Ebadi et. al Science, 376, 6598 (2022)

An algorithm for MIS

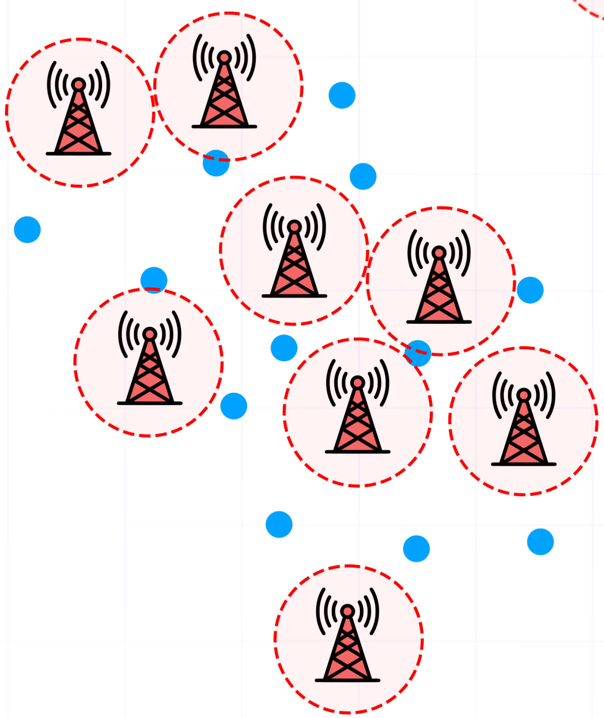
$$H = \Omega(t)\sum_i (|g_i\rangle\langle r_i| + H.c.) - \Delta(t)\sum_i n_i + \sum_{i<j} V_{ij} n_i n_j$$

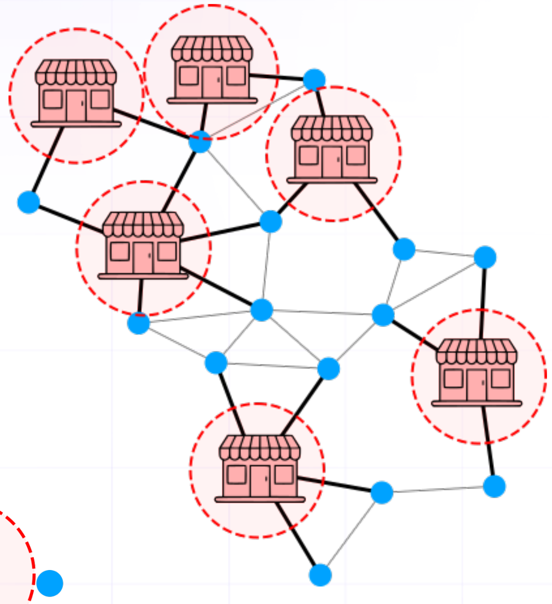


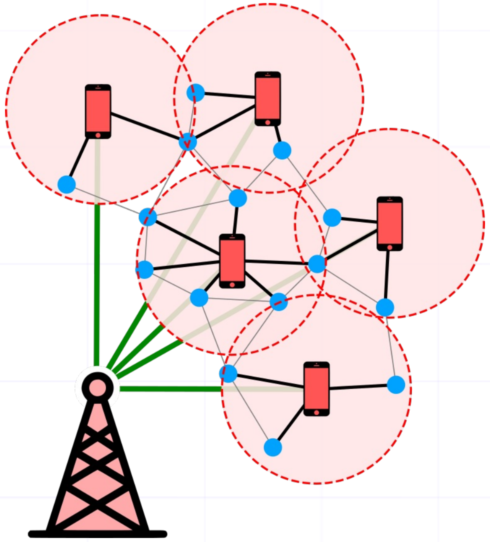


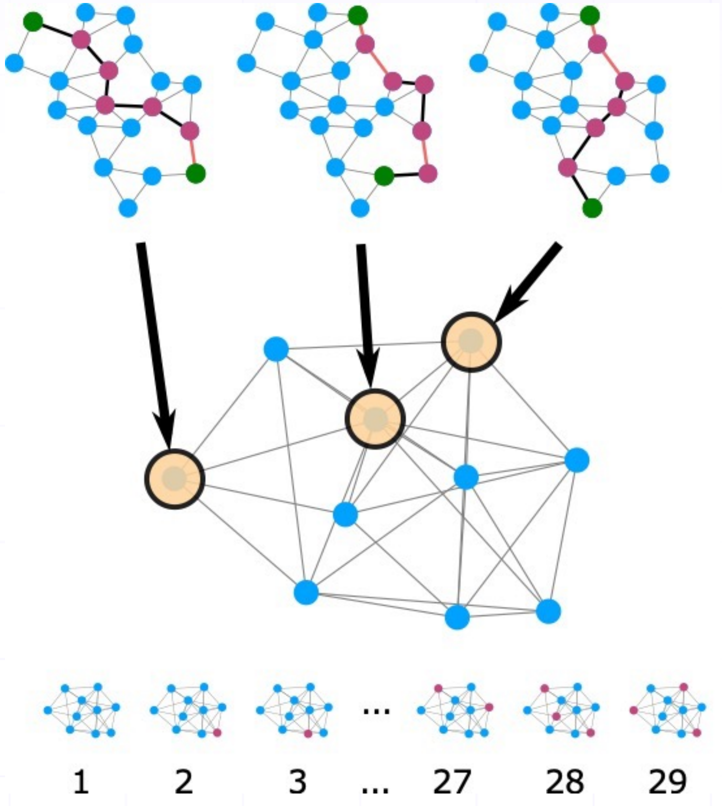
$$R_b = (C_6/\Delta)^{1/6}$$

MIS applications are ubiquitous









Wurtz et al., “Industry applications of neutral-aom quantum computing solving independent set problems” https://arxiv.org/abs/2205.08500

Programming neutral atoms in 5 steps

1. Define atom positions => Rydberg radius
2. Define time traces of Hamiltonian parameters
3. Initialize Hamiltonian
4. Evolve!
5. Measure!