

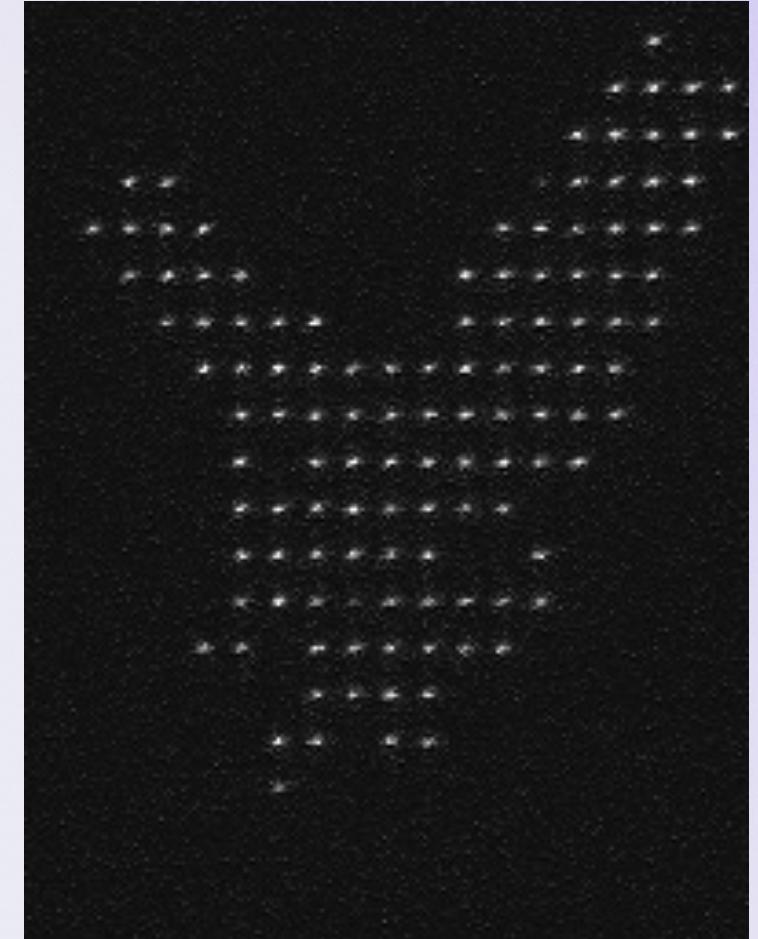
IQuEra®

Quantum computing with neutral atoms on the cloud

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QuEra Computing Inc.

IEEE Quantum Week 2023: TUT23

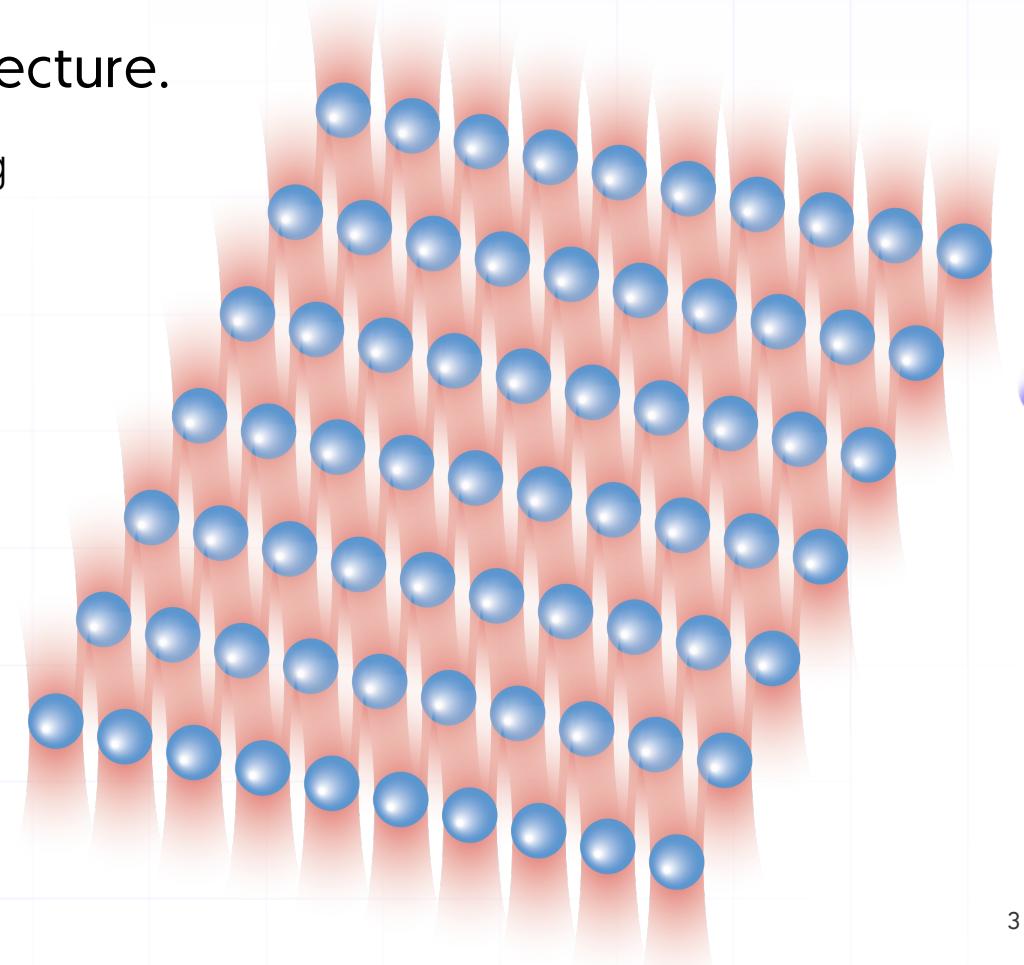


IQuEra>

Session I: Basics

Why you should care about neutral atoms.

1. Scalable to ~100,000 physical qubits with **all-to-all connectivity**, using current technology and physical architecture.
 - Scalable ‘wiring’: optical addressing + atom shuttling
 - Fidelities that don’t degrade with processor size:
2-qubit 99.5%, 1-qubit 99.95%
 - Fast gates (1-100 us) and long memory times (>1 s)



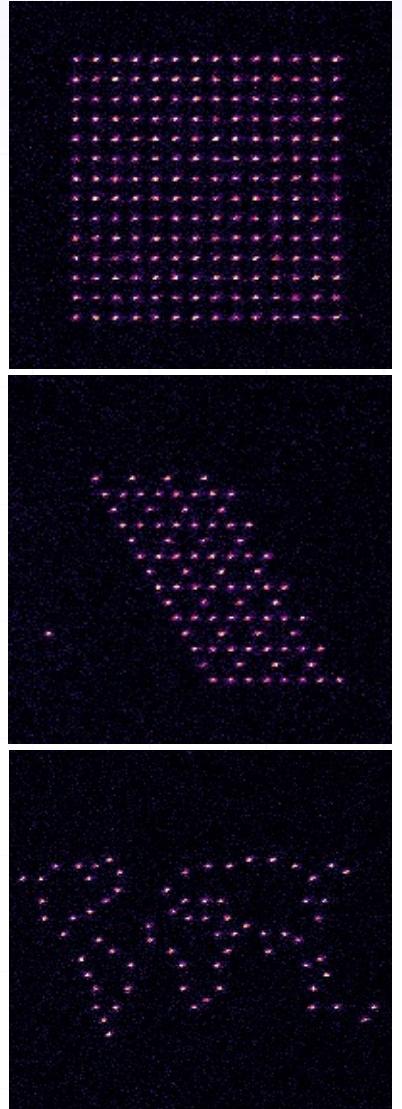
Bluvstein et al (2022), *Nature*, 604(7906), 451-456

Evered et al (2023), arXiv:2304.05420

Why you should care about neutral atoms.

2. Analog-mode machines are already driving scientific discovery and application development

- Quantum simulations: antiferromagnets, many-body scars, spin liquids
- Commercial applications: optimization, machine learning
- QuEra's Aquila, with 256 qubits, is accessible on the cloud through AWS
 - FPQA™: 'Field-Programmable Qubit Array' enables problem encoding directly into atom positions
 - Defining Hamiltonian parameters as arbitrary waveforms enables a variety of quantum algorithms



Ebadi et al (2021), *Nature*, 595(7866), 227–232

Bluvstein, (2021), *Science*, 371(6536), 1355–1359

Semeghini (2021), *Science*, 374(6572), 1242–1247

Ebadi et al (2022), *Science*, 376(6598), 1209–1215

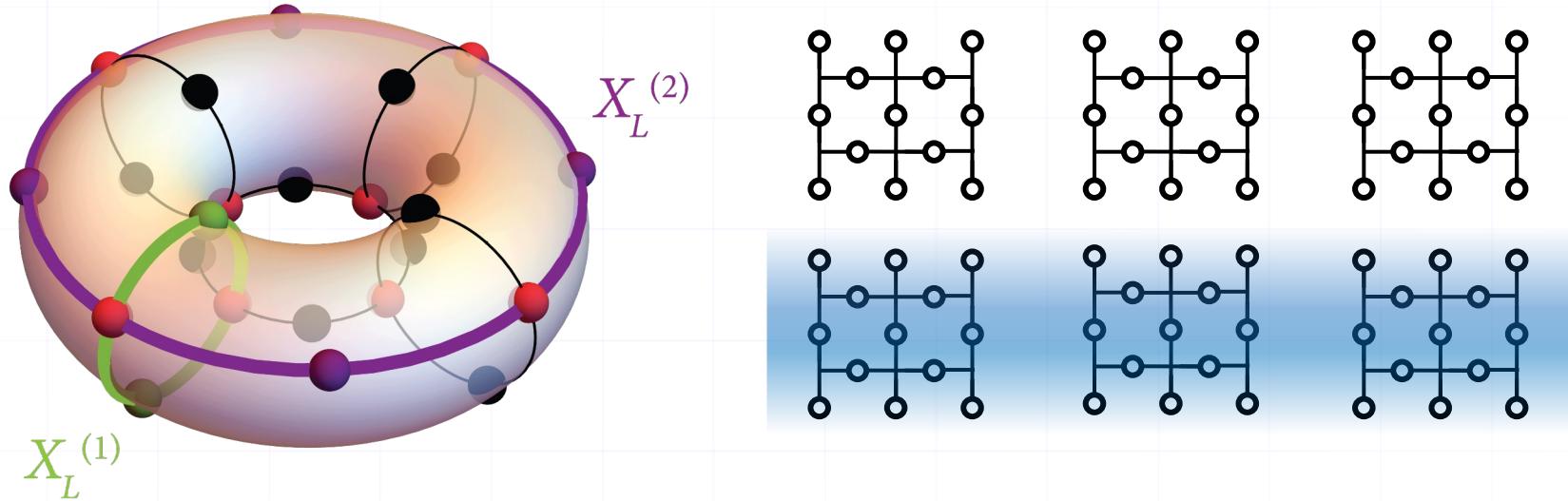
Wurtz et al (2022), arXiv:2205.08500

Wurtz et al (2023), arXiv:2306.11727

Why you should care about neutral atoms.

3. Digital-mode machines are a powerful testbed for fault-tolerant architectures:

- FPQA™ approach enables programmable qubit layout
- All-to-all connectivity enables novel error-correcting codes and efficient logical qubit operations
- Mid-circuit readout and 100s of qubits coming soon



Bluvstein et al (2022), *Nature*, 604(7906), 451-456

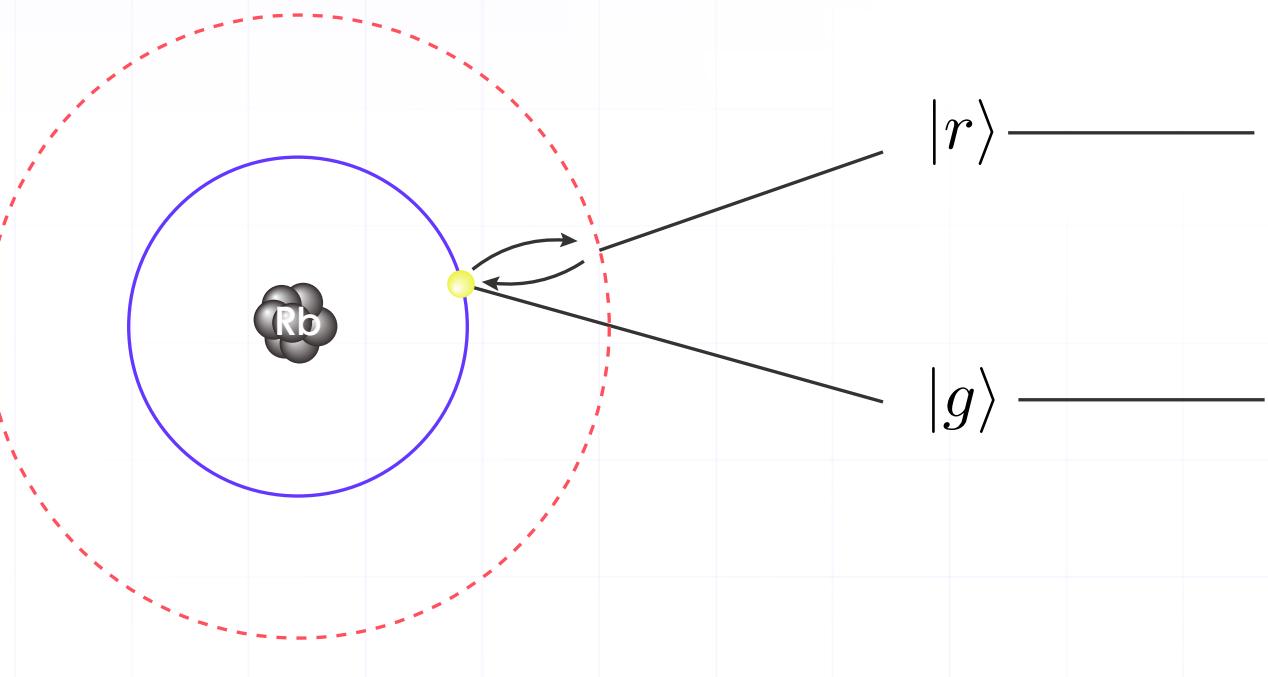
Evered et al (2023), arXiv:2304.05420

Learning objectives

By the end of the session, you will be able to:

- **Explain** how **neutral atoms** can be used as a **platform** for quantum computing
- **Distinguish** **analog** and **digital** (gate-based) quantum computing
- **Describe** Aquila's **programming** range
 - its Hamiltonian and controllable parameters, limitations of service
- **Remember** the physics of **Rabi oscillations** and **describe** how to **emulate** it with QuEra's software

Qubits by puffing atoms



Periodic Table of the Elements

Periodic Table of the Elements

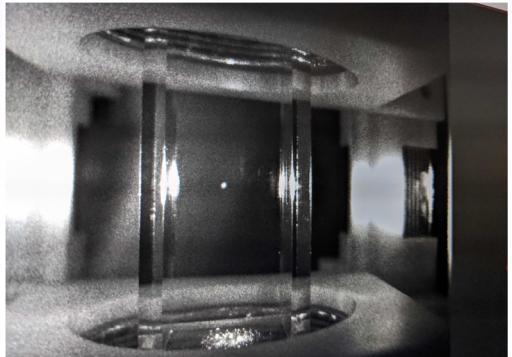
The table includes the following information for each element:

- Atomic Number**: The element's position in the periodic table.
- Symbol**: The standard two-letter symbol for the element.
- Name**: The element's name.
- Atomic Weight**: The element's mass number.
- Electrons per shell**: The electron configuration of the element.
- State of matter [color of name]**: The element's state at room temperature (Solid, Liquid, Gas) and its color.
- Subcategory in the metal-metalloid-nonmetal trend (color of background)**: Categories include Alkali metals (red), Alkaline earth metals (blue), Lanthanides (light blue), Actinides (green), Transition metals (yellow), Post-transition metals (orange), Metalloids (purple), Nonmetals (pink), and Noble gases (light pink).
- Unknown chemical properties**: Indicated by a grey question mark icon.

Atomic Number	Symbol	Name	Atomic Weight	Electrons per shell	State of matter [color of name]	Subcategory in the metal-metalloid-nonmetal trend (color of background)	Unknown chemical properties
1	H	Hydrogen	1.008	1	GAS	Alkali metals	
2	He	Helium	4.003	2	LIQUID	Alkaline earth metals	
3	Li	Lithium	6.941	2, 1	SOLID	Lanthanides	
4	Be	Beryllium	9.012	2, 2	SOLID	Actinides	
5	B	Boron	10.81	2, 3	SOLID	Transition metals	
6	C	Carbon	12.011	2, 4	SOLID	Post-transition metals	
7	N	Nitrogen	14.007	2, 5	SOLID	Metalloids	
8	O	Oxygen	15.999	2, 6	SOLID	Nonmetals	
9	F	Fluorine	18.998	2, 7	SOLID	Noble gases	
10	Ne	Neon	20.180	2, 8	SOLID		
11	Na	Sodium	22.989	2, 8, 1	SOLID	Alkali metals	
12	Mg	Magnesium	24.32	2, 8, 2	SOLID	Alkaline earth metals	
13	Al	Aluminum	26.981	2, 8, 3	SOLID	Lanthanides	
14	Si	Silicon	28.085	2, 8, 4	SOLID	Actinides	
15	P	Phosphorus	30.973	2, 8, 5	SOLID	Transition metals	
16	S	Sulfur	32.065	2, 8, 6	SOLID	Post-transition metals	
17	Cl	Chlorine	35.45	2, 8, 7	SOLID	Metalloids	
18	Ar	Argon	39.948	2, 8, 8	SOLID	Nonmetals	
19	K	Potassium	39.092	2, 8, 1, 1	SOLID	Noble gases	
20	Ca	Calcium	40.078	2, 8, 2, 1	SOLID		
21	Sc	Scandium	44.955	2, 8, 3, 1	SOLID		
22	Ti	Titanium	47.867	2, 8, 4, 1	SOLID		
23	V	Vanadium	50.941	2, 8, 5, 1	SOLID		
24	Cr	Chromium	51.996	2, 8, 6, 1	SOLID		
25	Mn	Manganese	54.938	2, 8, 7, 1	SOLID		
26	Fe	Iron	55.845	2, 8, 8, 1	SOLID		
27	Co	Cobalt	58.933	2, 8, 8, 2	SOLID		
28	Ni	Nickel	58.693	2, 8, 8, 2	SOLID		
29	Cu	Copper	63.546	2, 8, 9, 1	SOLID		
30	Zn	Zinc	65.401	2, 8, 9, 2	SOLID		
31	Ga	Gallium	69.723	2, 8, 9, 3	SOLID		
32	Ge	Germanium	72.610	2, 8, 9, 4	SOLID		
33	As	Arsenic	74.924	2, 8, 9, 5	SOLID		
34	Se	Selenium	78.911	2, 8, 9, 6	SOLID		
35	Br	Bromine	80.912	2, 8, 9, 7	SOLID		
36	Kr	Krypton	83.813	2, 8, 9, 8	SOLID		
37	Rb	Rubidium	85.461	2, 8, 9, 8, 1	SOLID	Alkali metals	
38	Sr	Samarium	87.612	2, 8, 9, 8, 2	SOLID	Alkaline earth metals	
39	Y	Yttrium	88.905	2, 8, 9, 8, 2	SOLID	Lanthanides	
40	Zr	Zirconium	91.224	2, 8, 9, 8, 2	SOLID	Actinides	
41	Nb	Nobium	92.903	2, 8, 9, 8, 2	SOLID	Transition metals	
42	Mo	Molybdenum	95.941	2, 8, 9, 8, 2	SOLID	Post-transition metals	
43	Tc	Technetium	97.905	2, 8, 9, 8, 2	SOLID	Metalloids	
44	Ru	Ruthenium	101.074	2, 8, 9, 8, 2	SOLID	Nonmetals	
45	Rh	Rhenium	102.905	2, 8, 9, 8, 2	SOLID	Noble gases	
46	Pd	Palladium	106.443	2, 8, 9, 8, 2	SOLID		
47	Ag	Silver	107.87	2, 8, 9, 8, 2	SOLID		
48	Cd	Cadmium	112.40	2, 8, 9, 8, 2	SOLID		
49	In	Inertium	114.82	2, 8, 9, 8, 2	SOLID		
50	Sb	Sulfur	118.71	2, 8, 9, 8, 2	SOLID		
51	Te	Technetium	121.74	2, 8, 9, 8, 2	SOLID		
52	I	Iodine	127.60	2, 8, 9, 8, 2	SOLID		
53	Xe	Xenon	131.29	2, 8, 9, 8, 2	SOLID		
54	Rn	Radon	222.07	2, 8, 9, 8, 2	SOLID		
55	Cs	Cesium	132.911	2, 8, 9, 8, 2, 1	SOLID	Alkali metals	
56	Ba	Barium	137.32	2, 8, 9, 8, 2, 1	SOLID	Alkaline earth metals	
57	La	Lanthanum	138.912	2, 8, 9, 8, 2, 1	SOLID	Lanthanides	
58	Ce	Cerium	140.913	2, 8, 9, 8, 2, 1	SOLID	Actinides	
59	Pr	Praseodymium	141.914	2, 8, 9, 8, 2, 1	SOLID	Transition metals	
60	Nd	Neodymium	144.242	2, 8, 9, 8, 2, 1	SOLID	Post-transition metals	
61	Pm	Promethium	147.000	2, 8, 9, 8, 2, 1	SOLID	Metalloids	
62	Sm	Samarium	150.918	2, 8, 9, 8, 2, 1	SOLID	Nonmetals	
63	Eu	Europium	151.960	2, 8, 9, 8, 2, 1	SOLID	Noble gases	
64	Gd	Gadolinium	157.250	2, 8, 9, 8, 2, 1	SOLID		
65	Dy	Dysprosium	160.937	2, 8, 9, 8, 2, 1	SOLID		
66	Tb	Terbium	161.935	2, 8, 9, 8, 2, 1	SOLID		
67	Ho	Holmium	164.935	2, 8, 9, 8, 2, 1	SOLID		
68	Er	Erbium	167.260	2, 8, 9, 8, 2, 1	SOLID		
69	Tm	Thulium	168.935	2, 8, 9, 8, 2, 1	SOLID		
70	Yb	Ytterbium	173.040	2, 8, 9, 8, 2, 1	SOLID		
71	Lu	Lutetium	174.940	2, 8, 9, 8, 2, 1	SOLID		
72	Ac	Actinium	227.037	2, 8, 9, 8, 2, 1	SOLID		
73	Th	Thorium	232.041	2, 8, 9, 8, 2, 1	SOLID		
74	Pa	Protactinium	231.034	2, 8, 9, 8, 2, 1	SOLID		
75	U	Uranium	238.03	2, 8, 9, 8, 2, 1	SOLID		
76	Np	Neptunium	237.027	2, 8, 9, 8, 2, 1	SOLID		
77	Pu	Plutonium	239.027	2, 8, 9, 8, 2, 1	SOLID		
78	Am	Americium	243.027	2, 8, 9, 8, 2, 1	SOLID		
79	Cm	Curium	247.027	2, 8, 9, 8, 2, 1	SOLID		
80	Bk	Berkelium	247.027	2, 8, 9, 8, 2, 1	SOLID		
81	Cf	Californium	250.027	2, 8, 9, 8, 2, 1	SOLID		
82	Es	Einsteinium	257.027	2, 8, 9, 8, 2, 1	SOLID		
83	Fm	Mendelevium	259.027	2, 8, 9, 8, 2, 1	SOLID		
84	Md	Magnesium	261.027	2, 8, 9, 8, 2, 1	SOLID		
85	Rs	Rutherfordium	264.027	2, 8, 9, 8, 2, 1	SOLID		
86	At	Astatine	227.027	2, 8, 9, 8, 2, 1	SOLID		
87	Rn	Radon	222.027	2, 8, 9, 8, 2, 1	SOLID		
88	Og	Oganesson	269.027	2, 8, 9, 8, 2, 1	SOLID		

The routine

Load MOT in 20-40ms



Load 60% of traps

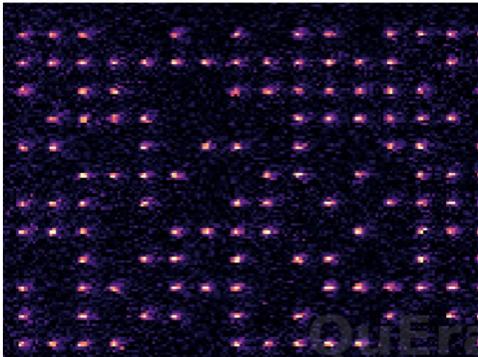
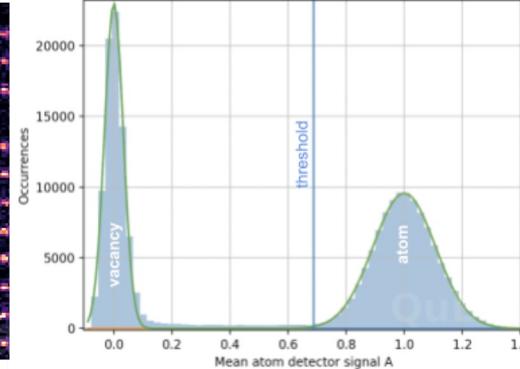
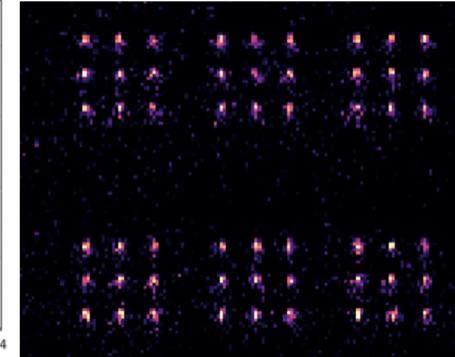


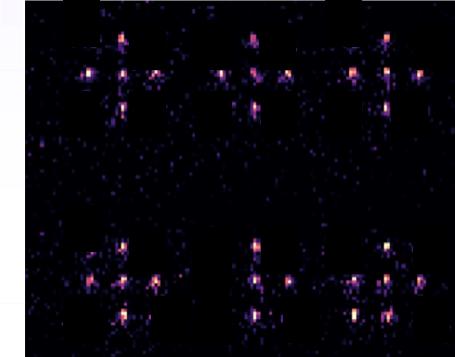
Image in 5ms



Sorting in ~30 ms



Results



QPU

load MOT

load tweezers

img a

sort

img e

init

QC

img h

Data to devices

CPU

build seq

b proc

c

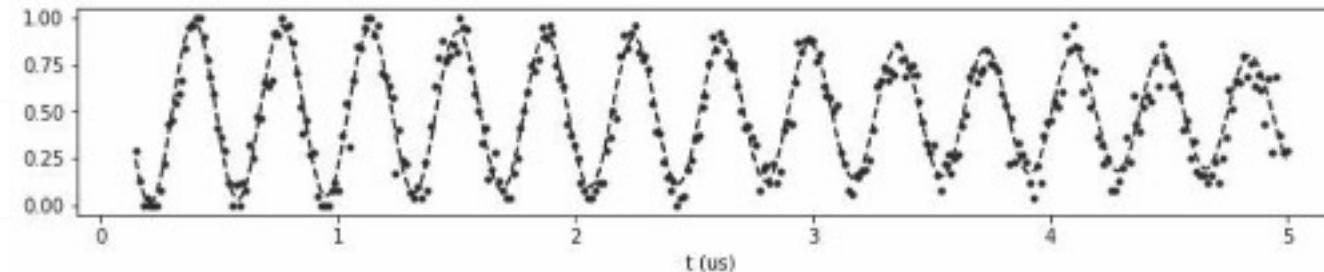
Tweezer waveforms

Camera image

f proc

g

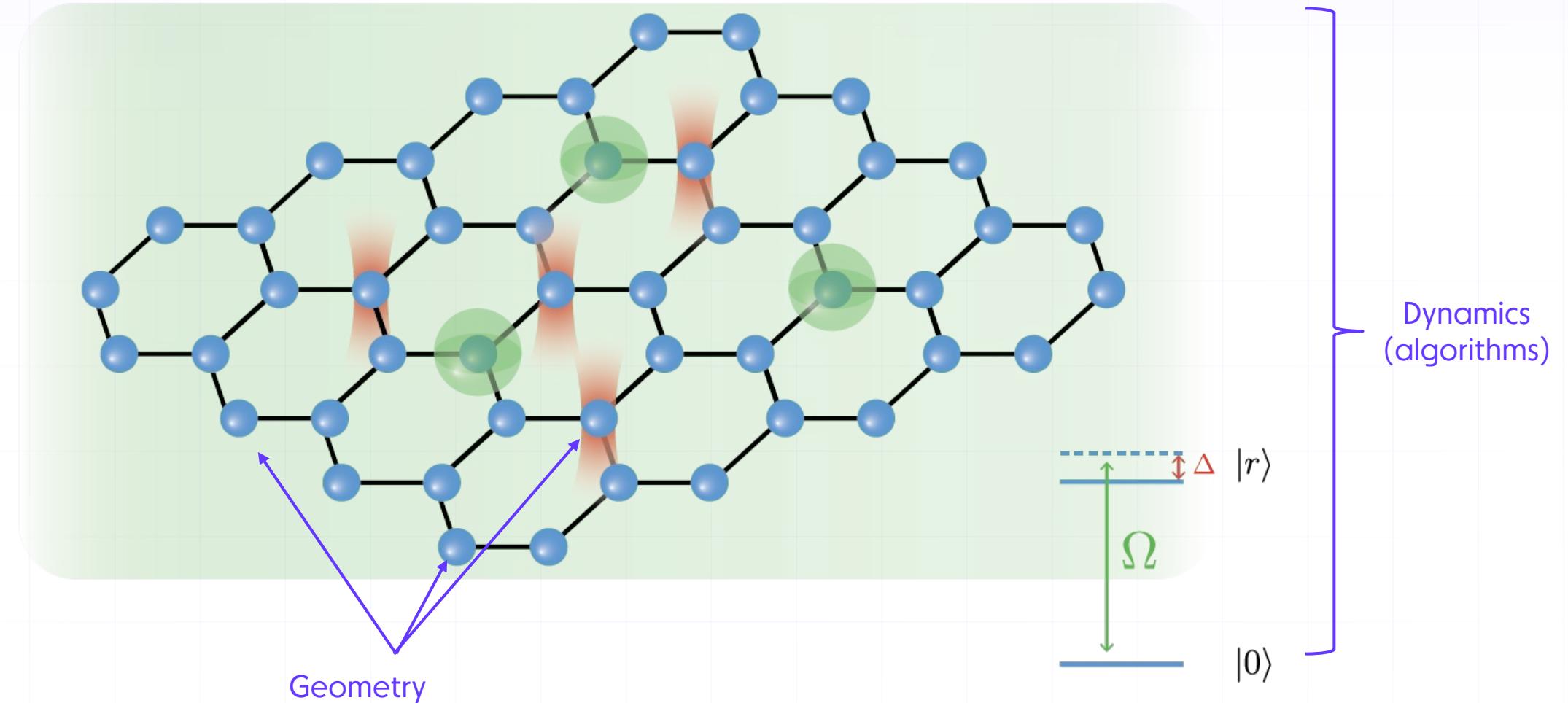
i proc



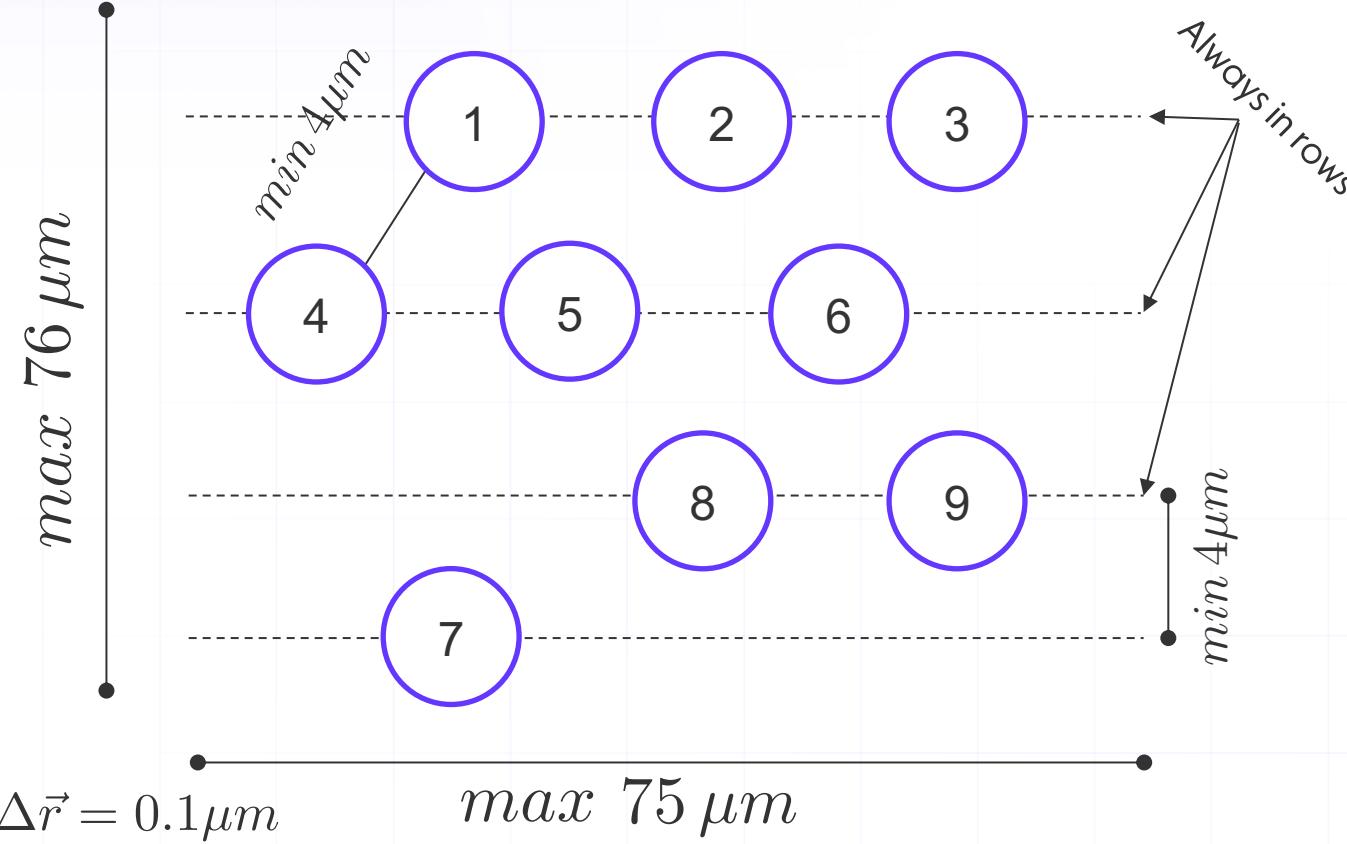
Sneak peak under the hood

[Q View Demo](#)

A neutral-atom quantum processor

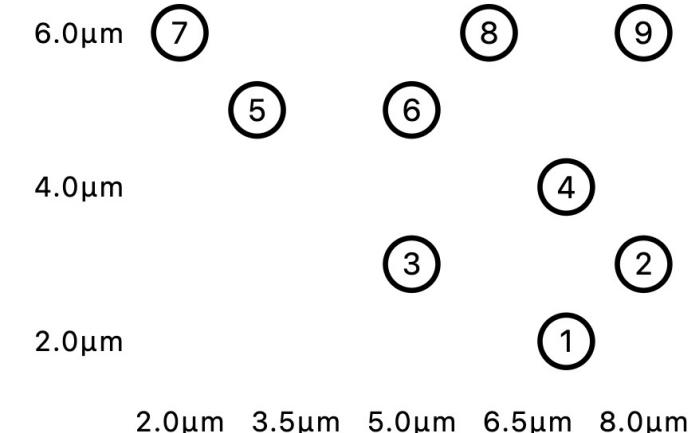


Hardware constraints: Geometry



BLOQADE

```
AtomList([(7.0, 2.0), (8.0, 3.0), (5.0, 3.0), (7.0, 4.0),  
         (3.0, 5.0), (5.0, 5.0), (2.0, 6.0), (6.0, 6.0), (8.0, 6.0)])
```

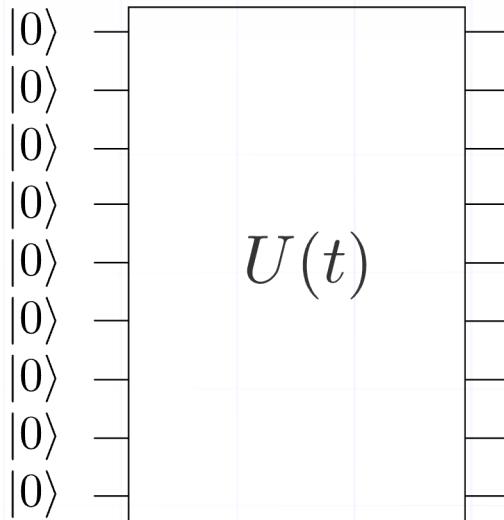


More details @

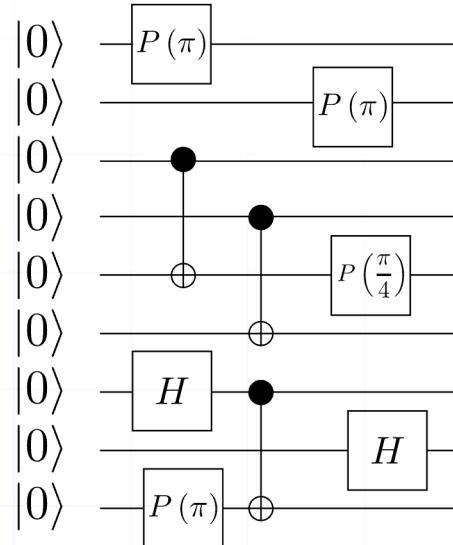
<https://queracomputing.github.io/Bloqade.jl/dev/capabilities/>

Information processing: Analog computing

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

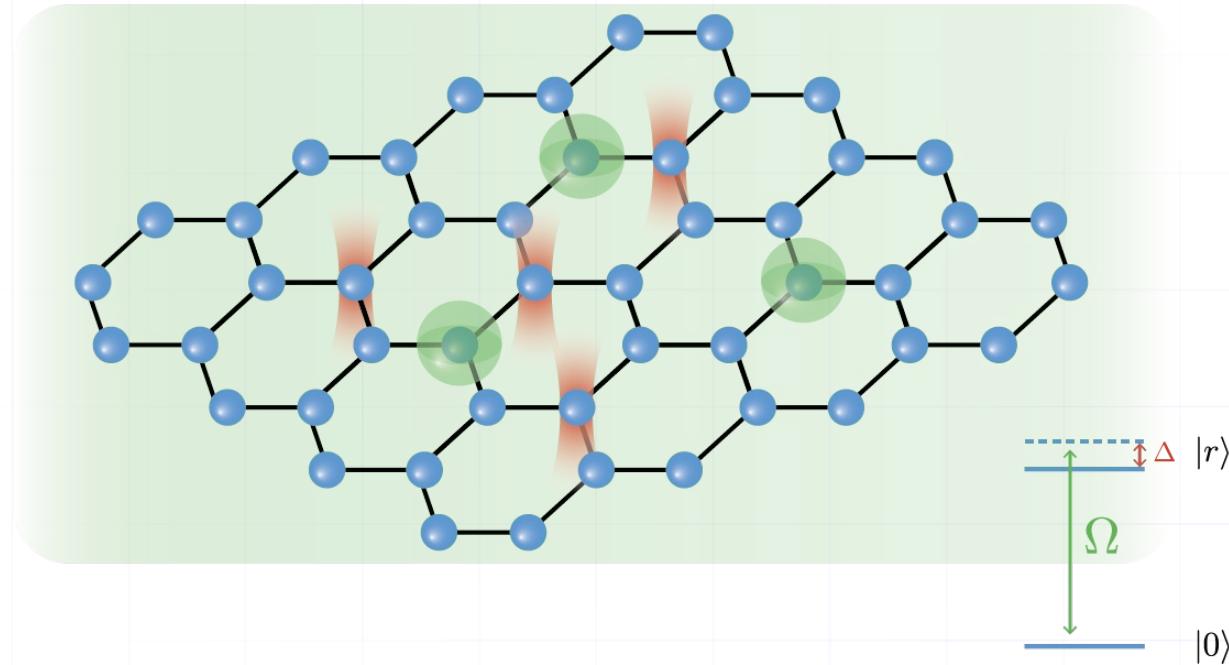
More on analog processors:
[Nature volume 607](#), p. 667–676 (2022)

Algorithm = time evolution

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

Analog quantum dynamics control

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

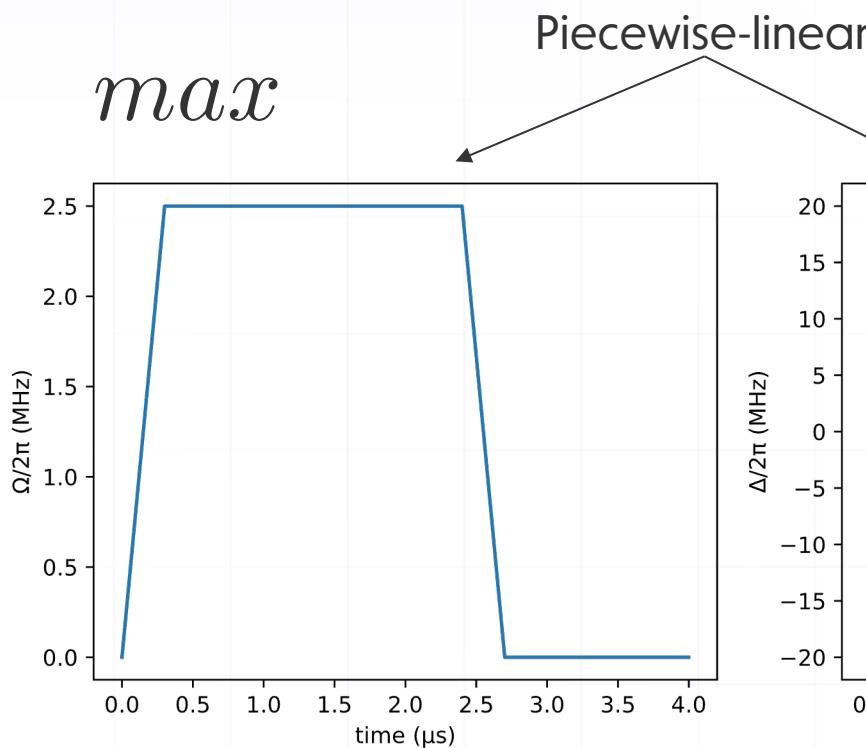


$$n_i = 1 * |r_i\rangle\langle r_i| + 0 * |g_i\rangle\langle g_i|$$

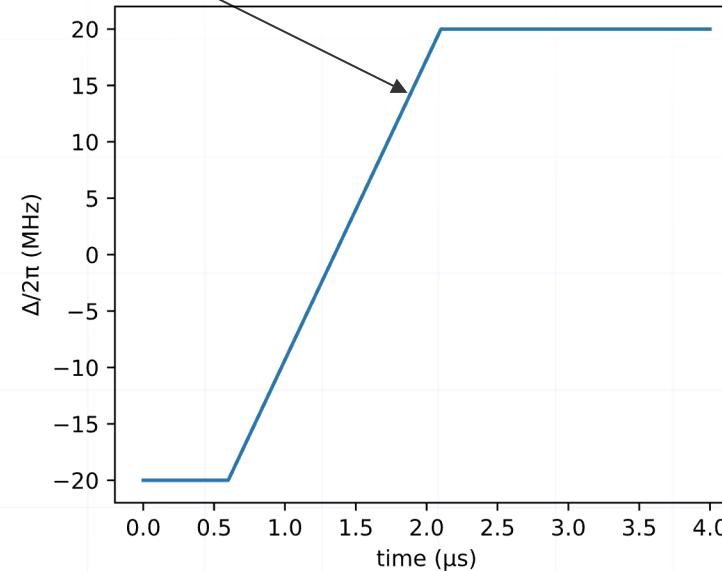
$$V_{ij} \sim d_{ij}^{-6}$$

Hardware constraints: dynamics

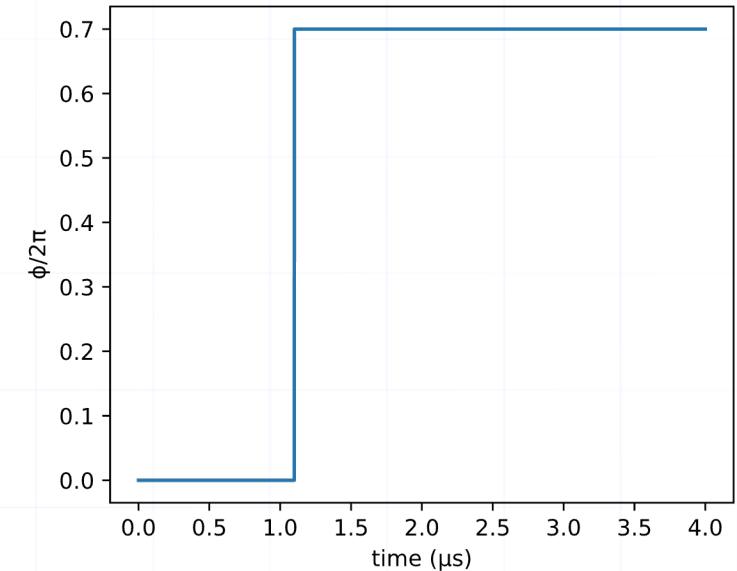
```
 $\Delta = \text{piecewise\_linear}(\text{clocks} = [0.0, 0.1, 0.5, T_{\max}], \text{values} = [\Delta_{\text{start}}, \Delta_{\text{start}}, \Delta_{\text{end}}, \Delta_{\text{end}}])$   
 $\phi = \text{piecewise\_constant}(\text{clocks}=[0.0, T_{\max}], \text{values}= [0.0]);$ 
```



max



BLOQADE



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

Piecewise-constant

Full swing: Bloqade emulation example

- *Rabi oscillations*

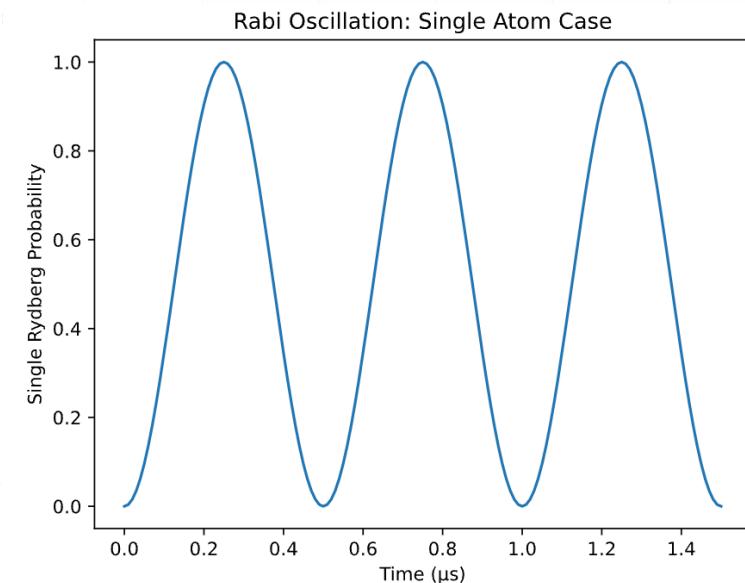
$$H = \frac{\Omega}{2} \sigma_x$$

$$|\psi(0)\rangle = |g\rangle$$



$$|\psi(t)\rangle = \cos \frac{\Omega}{2}t |g\rangle - i \sin \frac{\Omega}{2}t |r\rangle$$

$$n(t) = \langle \psi(t) | \hat{n} | \psi(t) \rangle = \sin^2 \frac{\Omega}{2} t$$

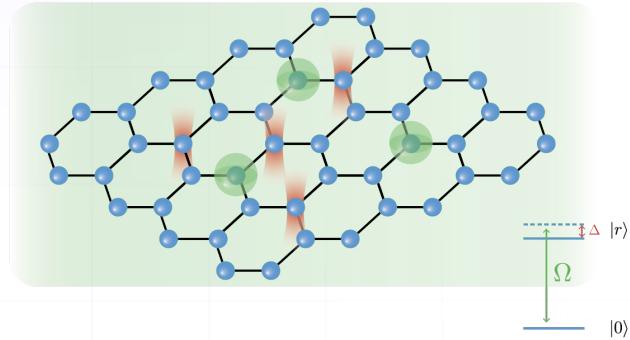
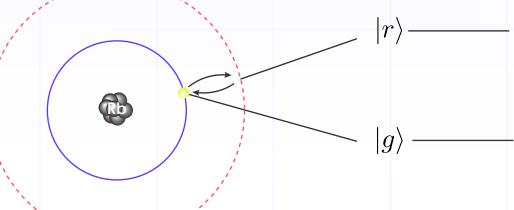


```
atom1 = AtomList([(0.0, 0.0)])
clocks = 0.0:1e-2:1.5
prob1 = KrylovEvolution(zero_state(1), clocks, rydberg_h(atom1; Δ = 0, Ω = 2π * 2))
[ ]
```

Hamiltonian call
Evolution method
Initial register
geometry
waveforms

Summary

Architecture

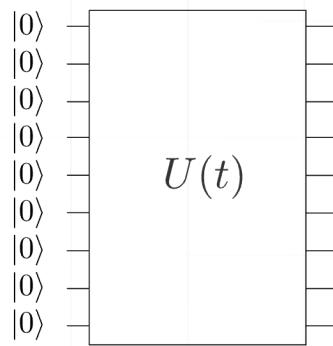


BLOQADE

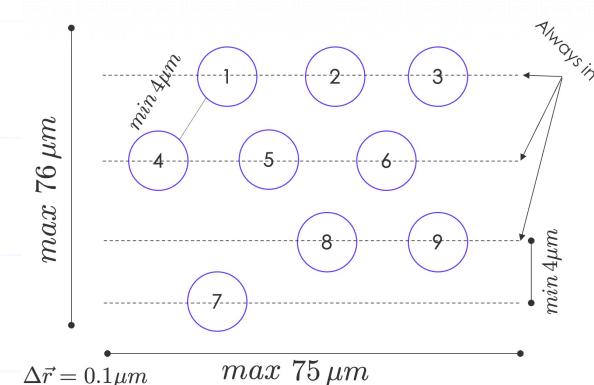
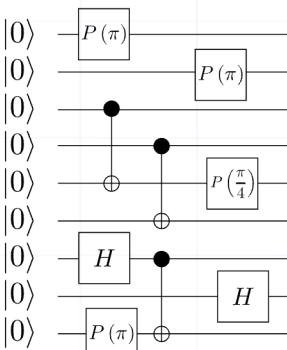
```
▷ AtomList([(7.0, 2.0), (8.0, 3.0), (5.0, 3.0), (7.0, 4.0),  
           (3.0, 5.0), (5.0, 5.0), (2.0, 6.0), (6.0, 6.0), (8.0, 6.0)])
```

```
Δ = piecewise_linear(clocks = [0.0, 0.1, 0.5, T_max], values = [Δ_start, Δ_start, Δ_end, Δ_end])  
φ = piecewise_constant(clocks=[0.0, T_max], values= [0.0]);
```

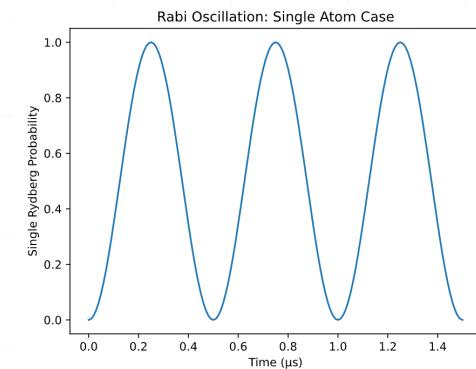
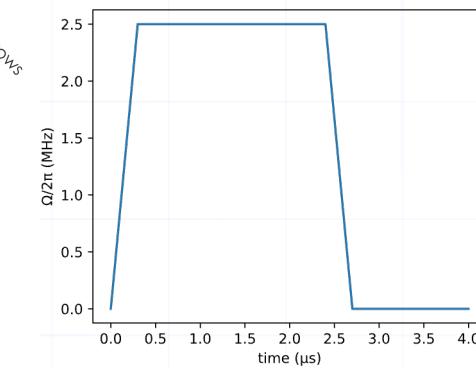
Analog operation



Digital operation



Hardware constraints



Emulation

Learning objectives

Now you are able to:

- **Explain** how **neutral atoms** can be used as a **platform** for quantum computing
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