

IQuEra>

# QRISE 2024

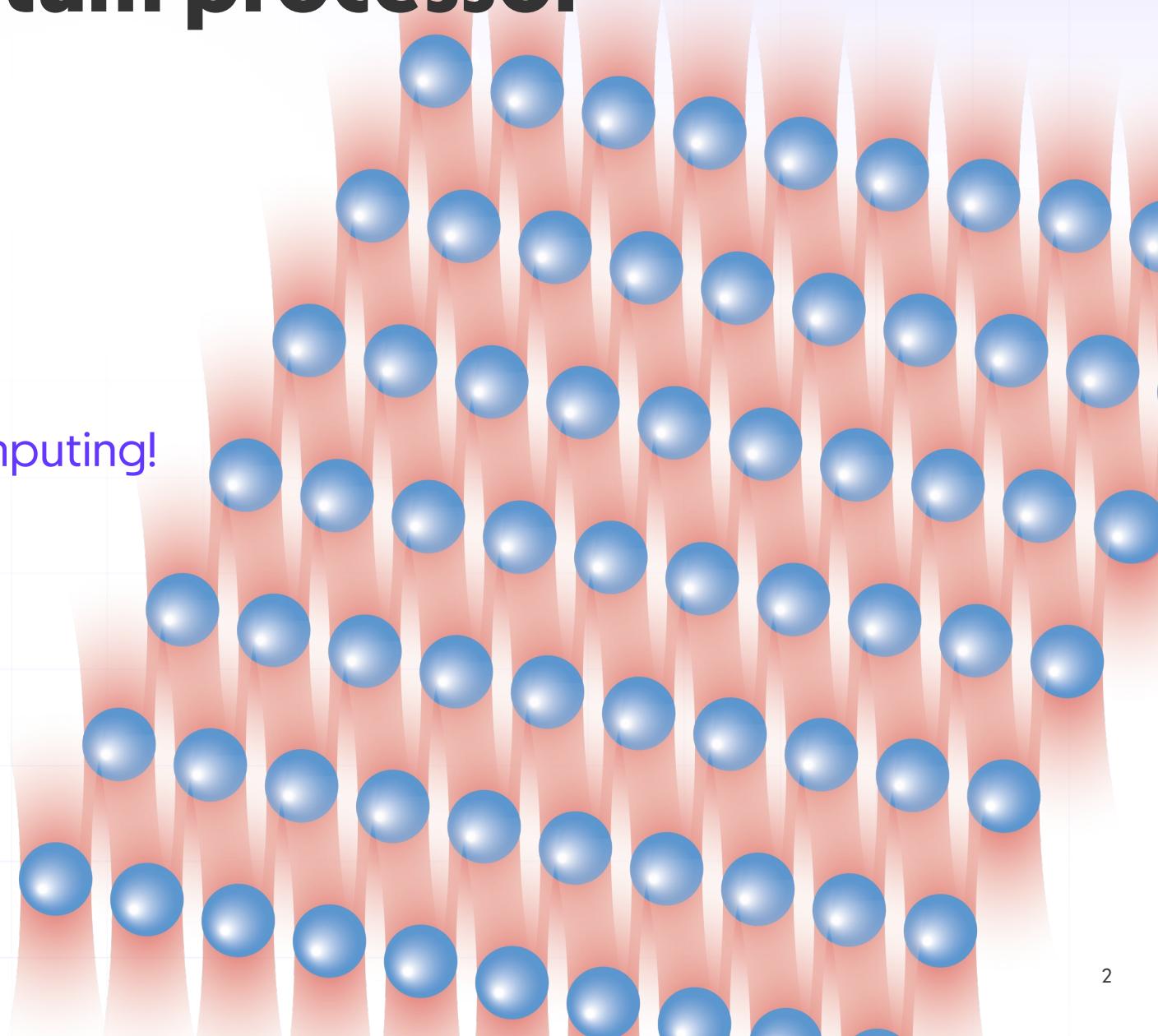
## Intro workshop



**Pedro Lopes, Phd**  
**Quantum Advocate**

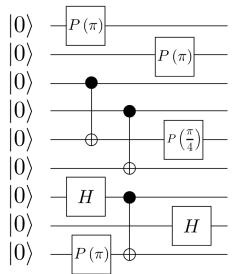
# Neutral-atom quantum processor

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



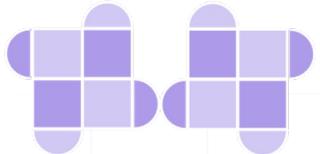
# Main theme

## Co- Design



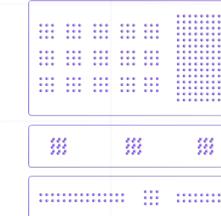
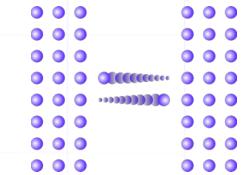
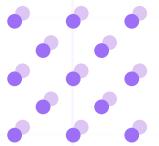
### Algorithmic pipeline

Error-correcting code choice  
Compilation  
Gate design  
Protocol layout + spacetime optimization

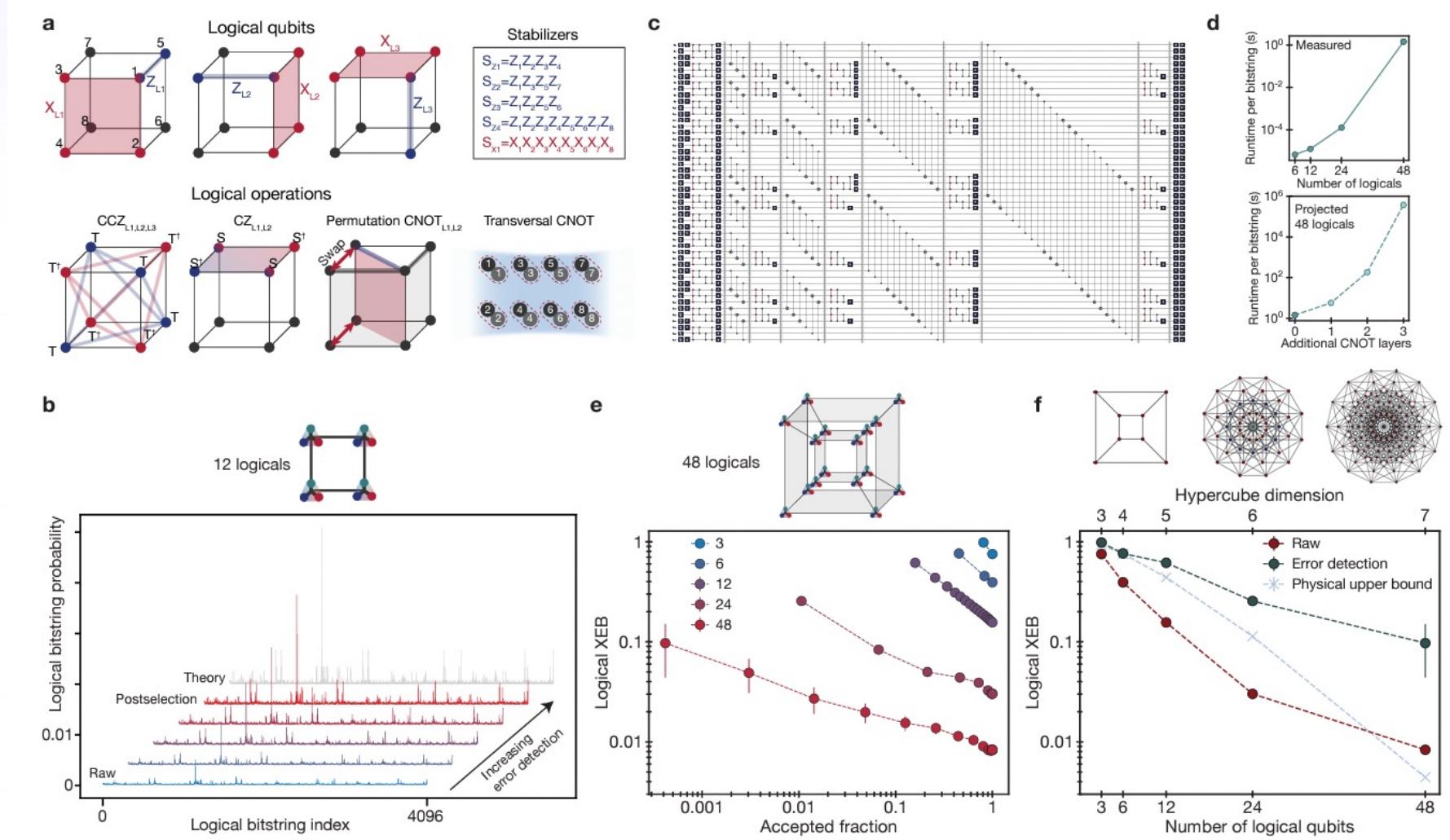


### Native hardware capabilities

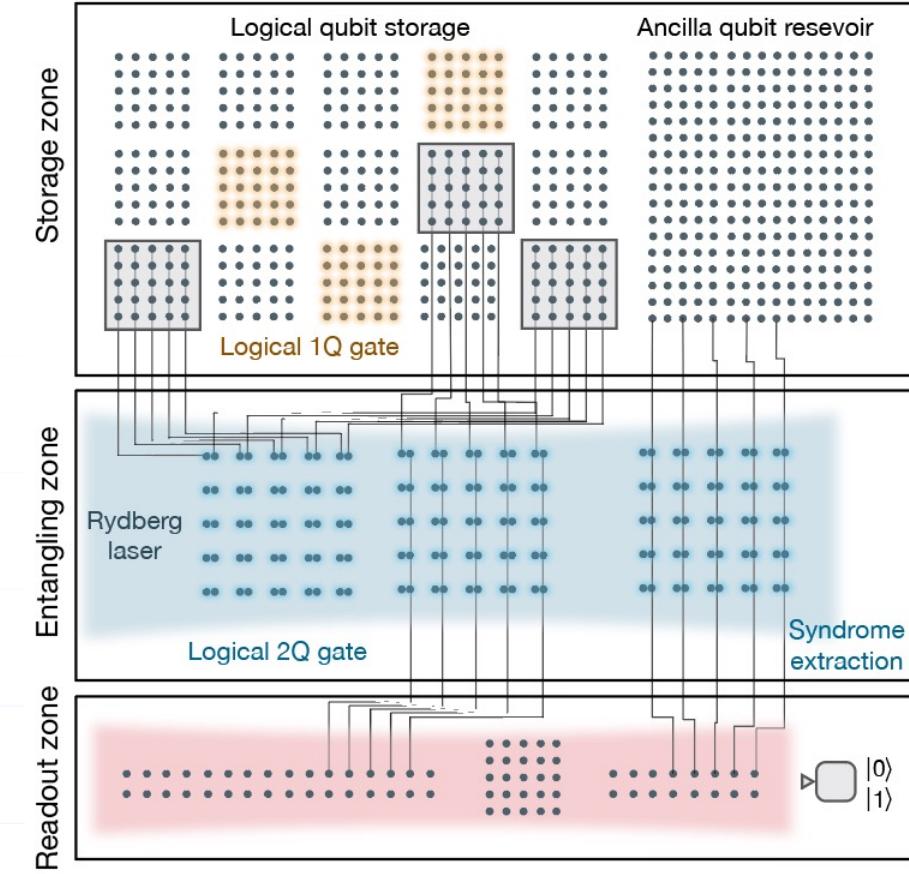
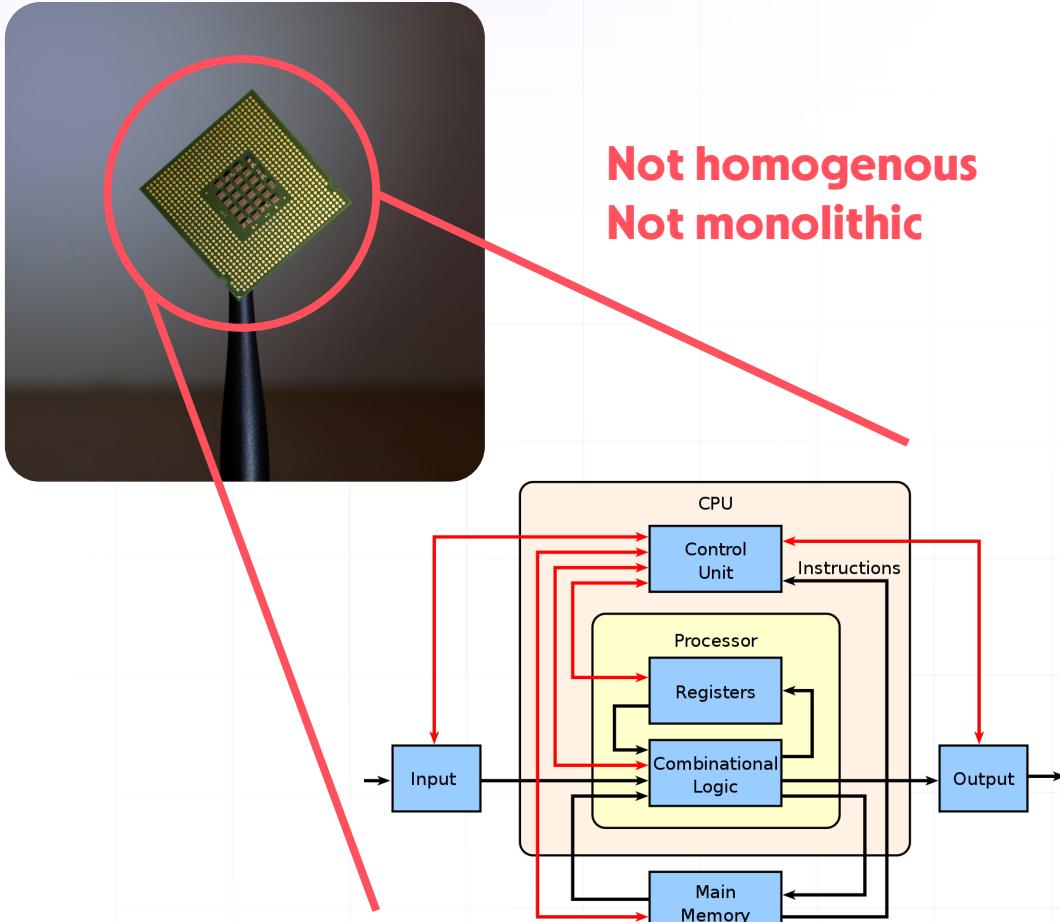
Speed  
Qubit connectivity  
Parallelization  
Universal gate-set  
Biased noise & erasure



# Example:



# (Quantum) Computer architectures



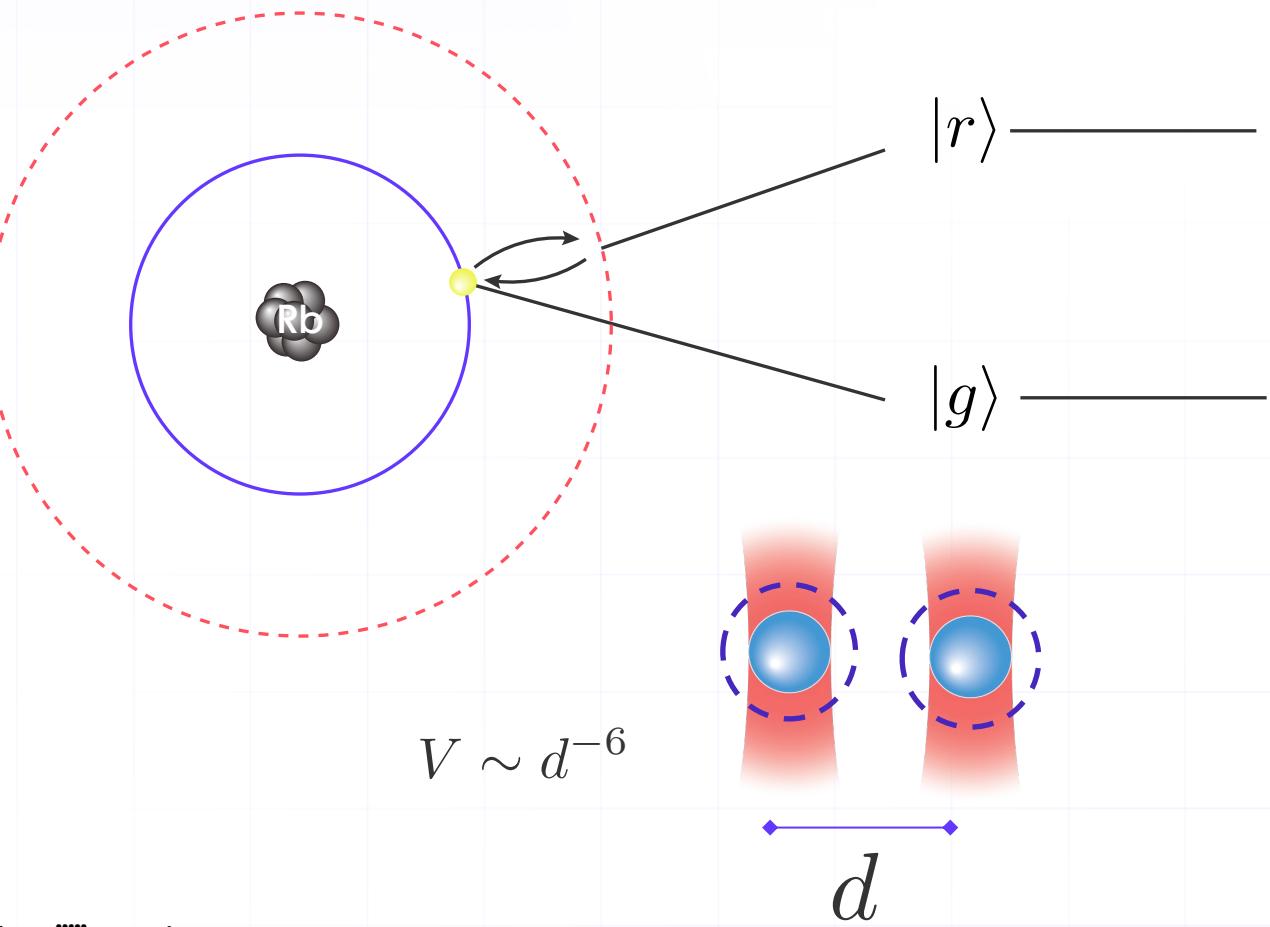
**Neutral-atoms “zoned”  
QPUs: heterogeneous**

Bluvstein et al., Nature 2024

Bluvstein et al., Nature 2022;

Evered et al., Nature 2023

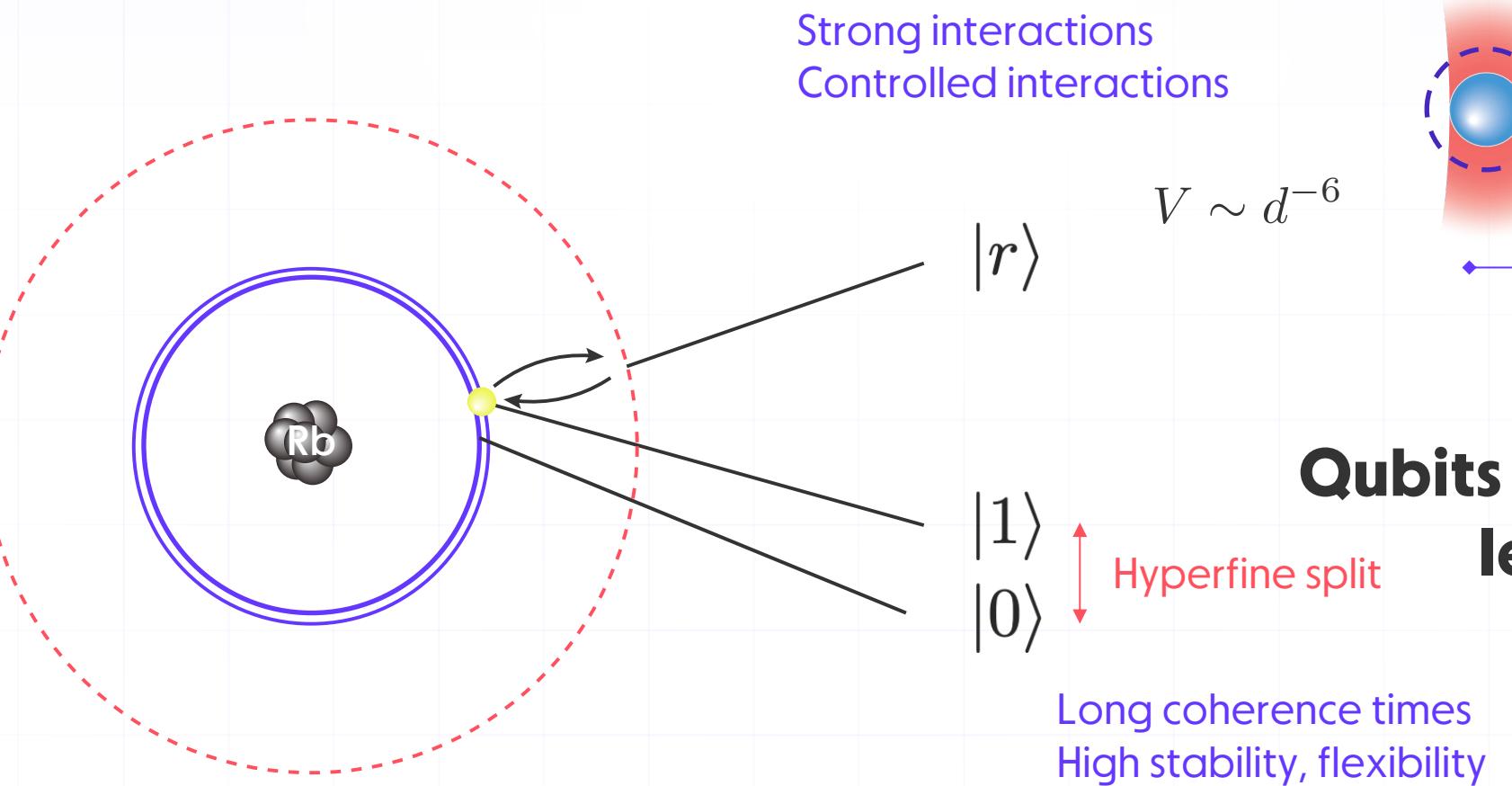
# Analog: Qubits by puffing-up atoms



Periodic Table of the Elements

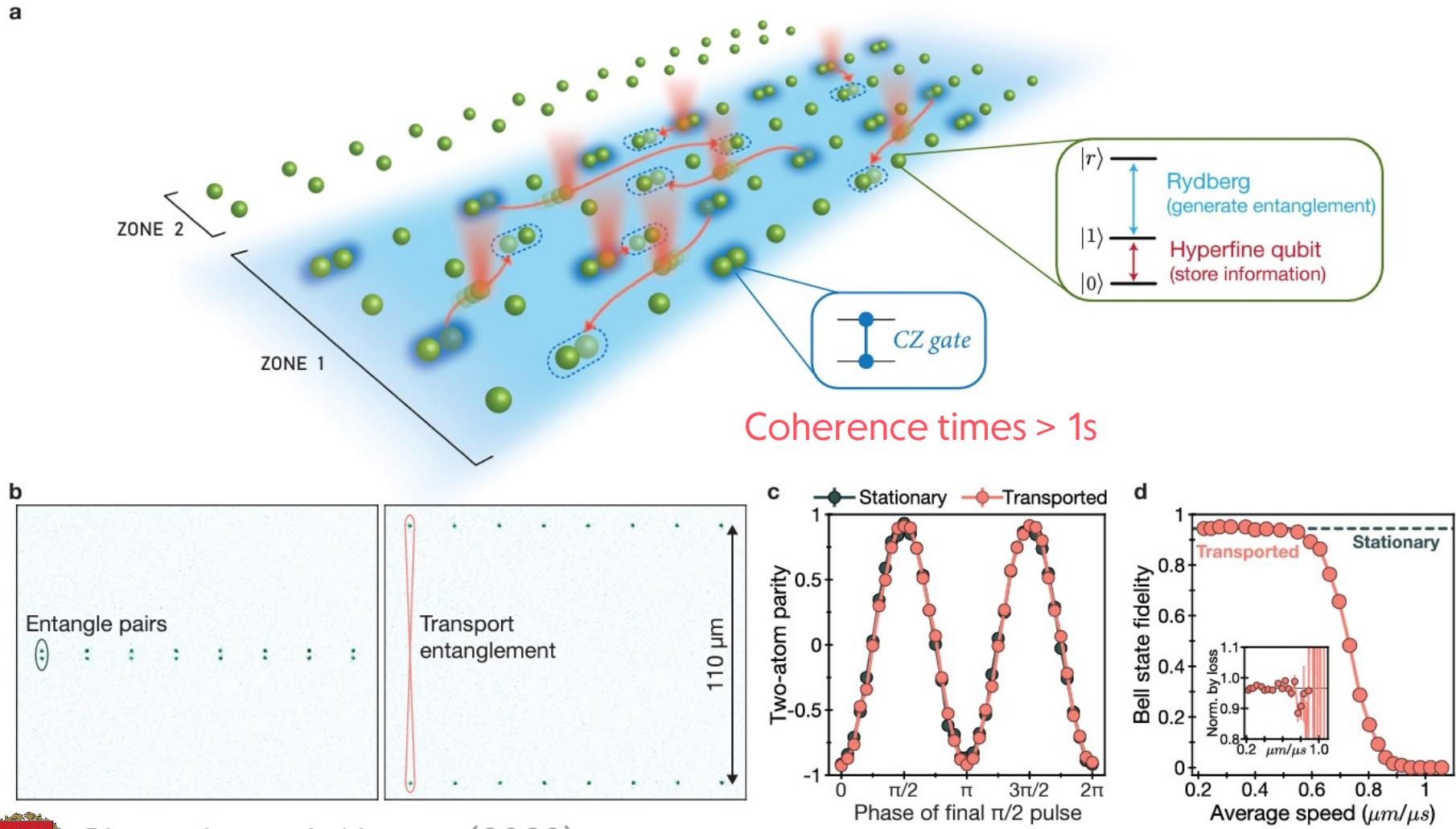
Atomic Number →	Symbol	← Atomic Weight
1	H	1.01
2	He	4.0026
3	Li	6.94
4	Be	9.012
5	B	10.81
6	C	12.011
7	N	14.027
8	O	15.999
9	F	18.998
10	Ne	20.180
11	Na	22.9876
12	Mg	24.32
13	Al	26.982
14	Si	28.09
15	P	30.973
16	S	32.065
17	Cl	35.45
18	Ar	39.948
19	K	39.0923
20	Ca	40.078
21	Sc	44.955
22	Ti	47.867
23	V	50.944
24	Cr	51.996
25	Mn	54.938
26	Fe	55.845
27	Co	58.931
28	Ni	58.693
29	Cu	63.546
30	Zn	65.401
31	Ga	69.723
32	Ge	72.610
33	As	74.924
34	Se	78.917
35	Br	79.904
36	Kr	83.800
37	Rb	84.918
38	Sr	87.62
39	Y	88.90584
40	Zr	91.224
41	Nb	92.906
42	Mo	95.94
43	Tc	96.903
44	Ru	101.07
45	Rh	102.905
46	Pd	106.44
47	Ag	107.87
48	Cd	112.41
49	In	114.82
50	Ga	115.71
51	Sn	118.71
52	Te	121.46
53	I	126.90
54	Xe	131.29
55	Cs	132.91
56	Ba	137.34
57	La	138.906
58	Ce	140.113
59	Pr	140.914
60	Nd	142.914
61	Pm	144.913
62	Sm	149.912
63	Eu	151.912
64	Gd	157.912
65	Dy	162.913
66	Tb	164.913
67	Ho	165.913
68	Er	167.913
69	Tm	168.913
70	Yb	170.913
71	Lu	172.913
72	Hf	178.49
73	Ta	180.95
74	W	183.84
75	Osm	186.917
76	Rh	190.23
77	Ir	192.23
78	Pt	195.07
79	Hg	200.59
80	Pb	204.20
81	Th	227.02
82	Po	210.02
83	Bismuth	208.917
84	At	210.02
85	Rn	222.02
86	Og	226.02
87	Fr	(223)
88	Ra	(226)
89	Ac	(227)
90	Th	(232.0)
91	Pa	(231.0)
92	U	(238.0)
93	Np	(237.0)
94	Pu	(244.0)
95	Am	(243.0)
96	Cm	(247.0)
97	Bk	(249.0)
98	Cf	(250.0)
99	Es	(257.0)
100	Fm	(258.0)
101	Md	(259.0)
102	No	(259.0)
103	Lr	(264.0)

# Digital: Qubits Entanglement by puffing-up atoms



**Qubits by isolated levels choice**

# Basic architecture

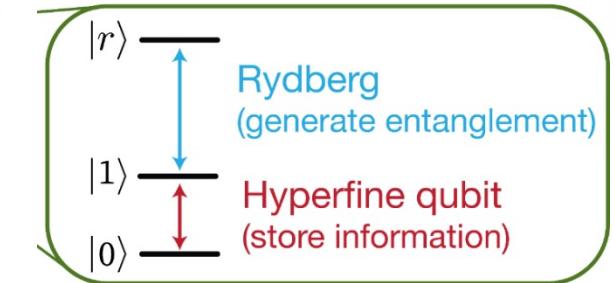
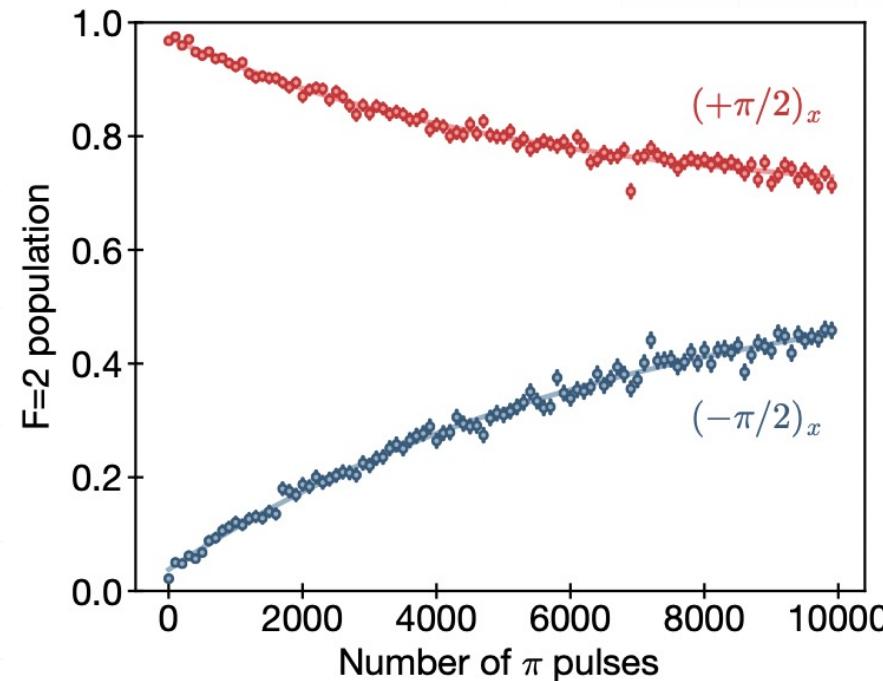
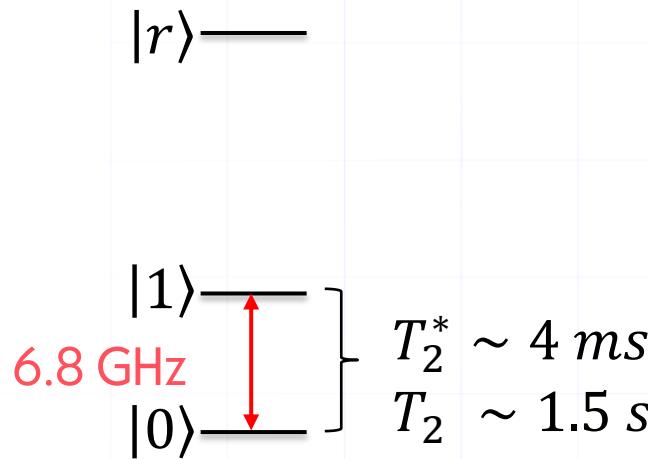


# Single-qubit gates

General principles:

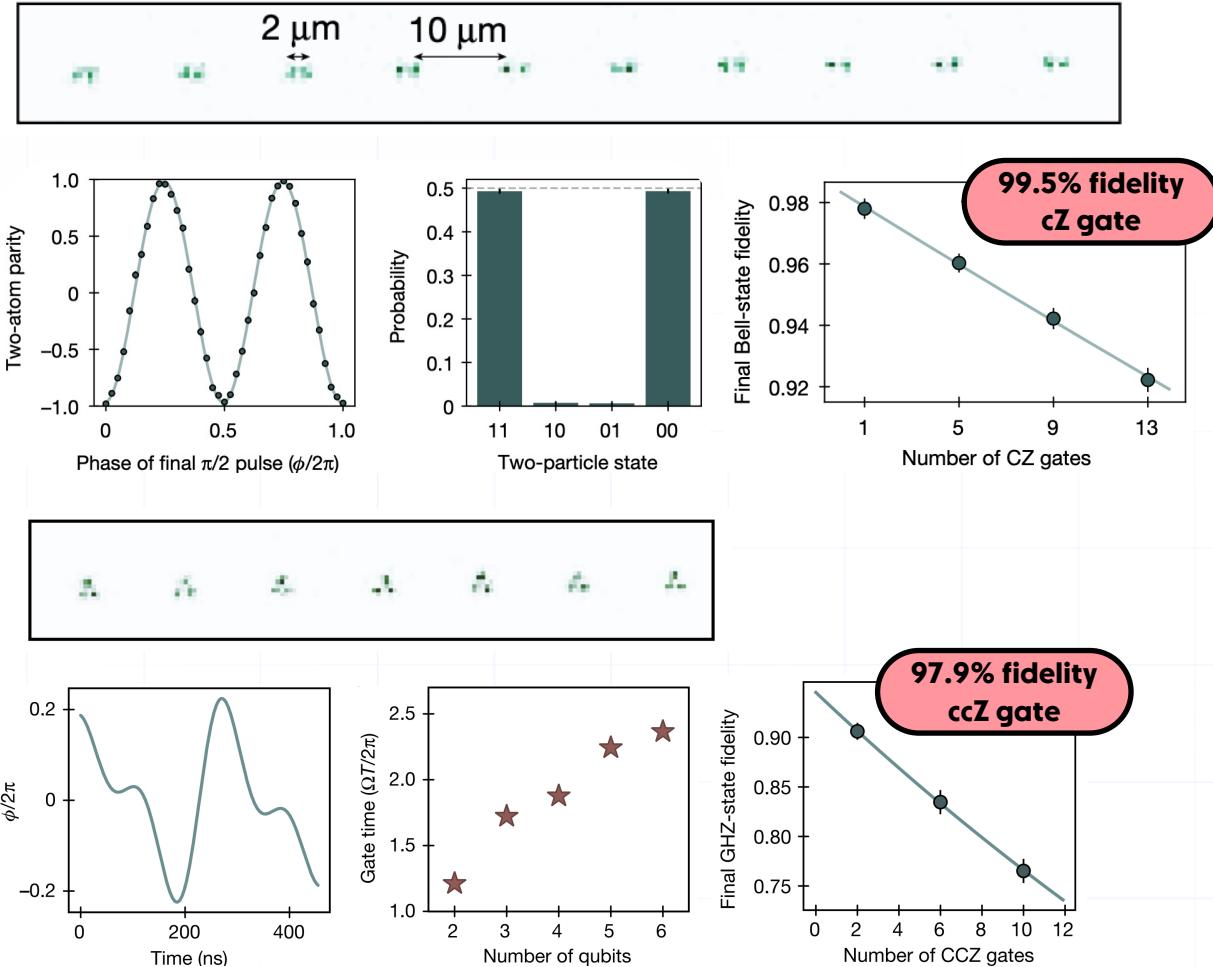
- $m_F = 0$  clock states largely insensitive to tweezer potential
- High-fidelity gate operations available

Levine et al. Phys. Rev. A **105**, 032618 (2022)



**99.99% single-qubit gate fidelity**

# Two-(or more-)qubit gates



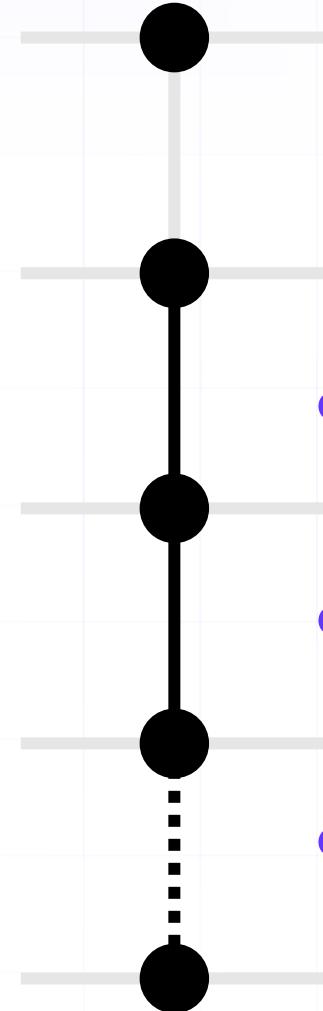
$$V \sim d^{-6}$$

$d$

→ Rydberg blockade: state-selective dynamics  
→ Position => two-qubit gate

# Native gate set

Controlled Z gates

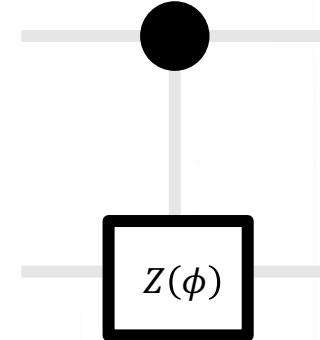


ccZ gates

cccZ gates

c..cZ gates

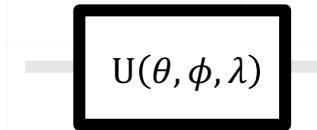
Controlled Z-phase gates



Permutation-symmetric  
Z-phase gates

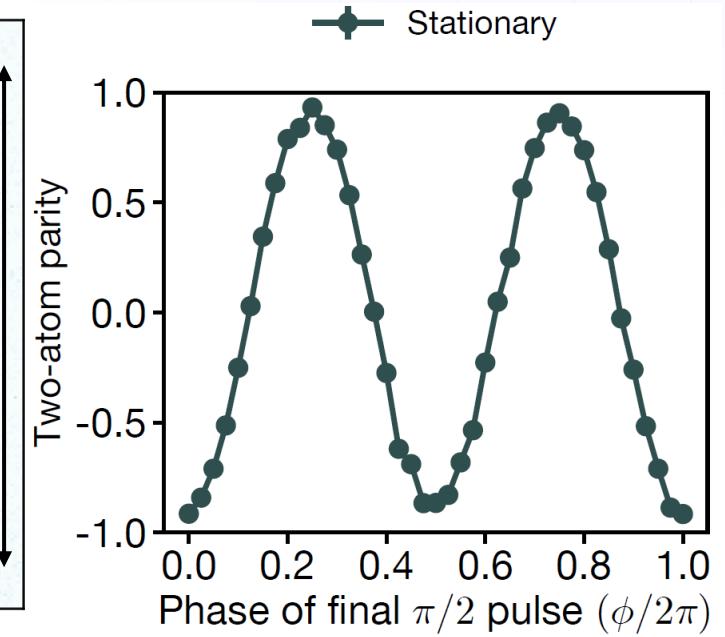
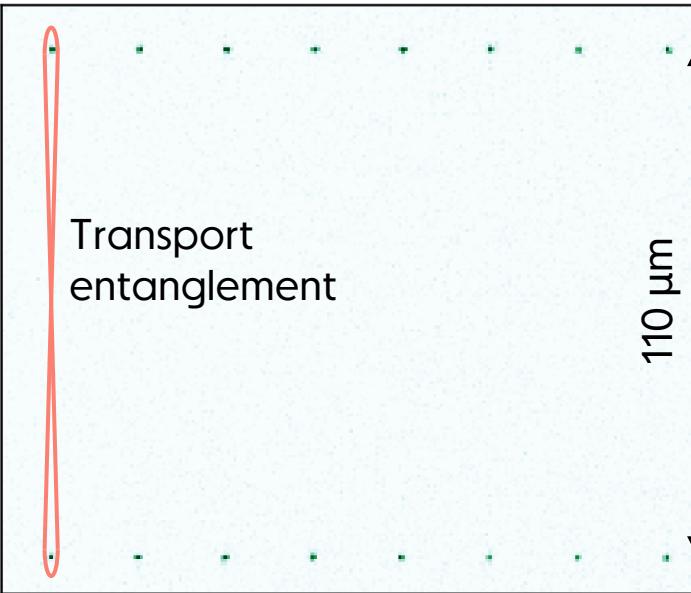
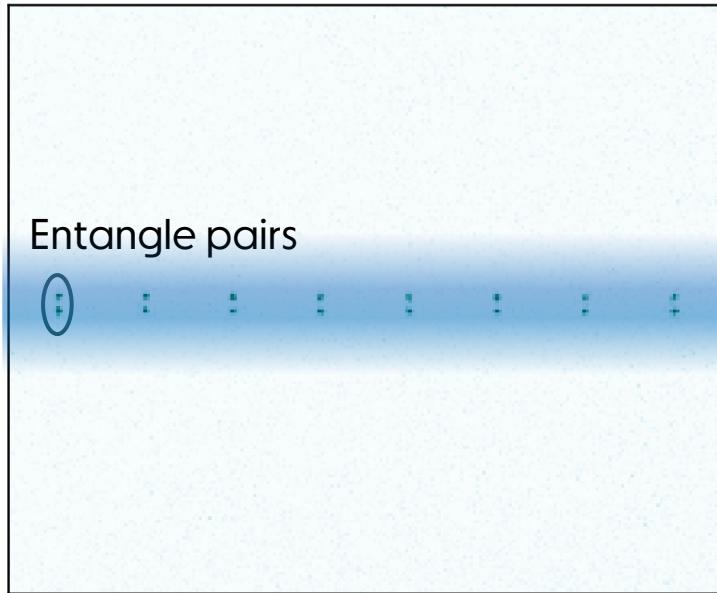
$$\begin{aligned}|000\rangle &\rightarrow e^{i\phi_0}|000\rangle \\|001\rangle &\rightarrow e^{i\phi_1}|001\rangle \\|010\rangle &\rightarrow e^{i\phi_1}|010\rangle \\|100\rangle &\rightarrow e^{i\phi_1}|100\rangle \\|011\rangle &\rightarrow e^{i\phi_2}|011\rangle \\|110\rangle &\rightarrow e^{i\phi_2}|110\rangle \\|101\rangle &\rightarrow e^{i\phi_2}|101\rangle \\|111\rangle &\rightarrow e^{i\phi_3}|111\rangle\end{aligned}$$

Arbitrary 1 qubit rotations

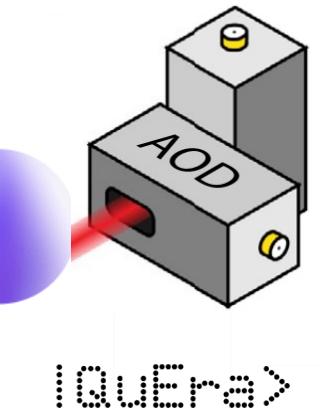


# Entanglement transport

<300  $\mu$ s to move across entire array ( $T_2 \sim 1.5$  s)



Atom-atom spacing of  $\sim 3$   $\mu$ m  
→ transport across array of  $\sim 2000$  qubits in a time of  $< 10^{-3} T_2$



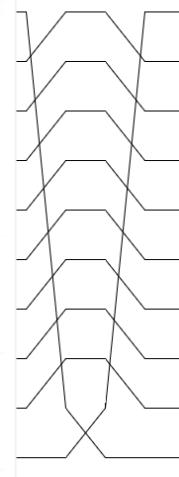
Bluvstein et al., Nature 2022

Beugnon et al Nat Phys 2007; T. Đorđević et al Science 2021

# Entanglement transport why #1: Long-range/arbitrary connectivity

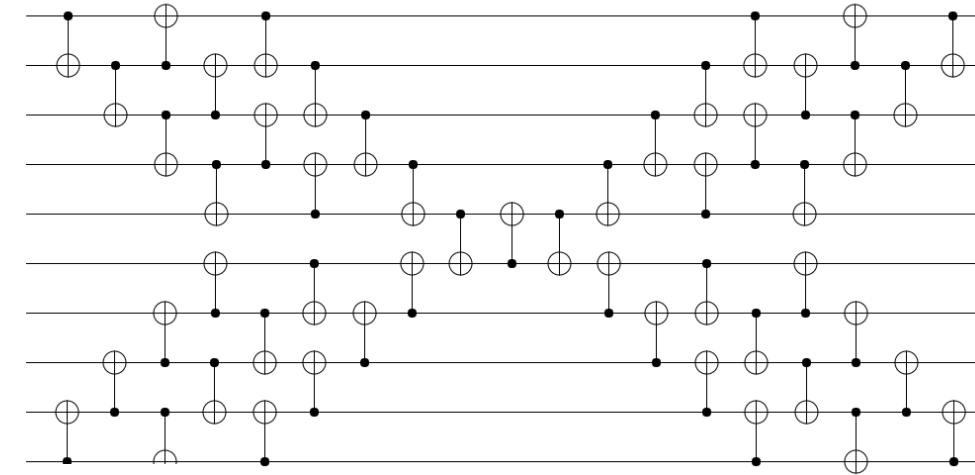
Source: Craig Gidney's blog

Nearest-neighbor  
connectivity

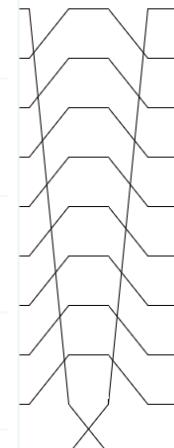


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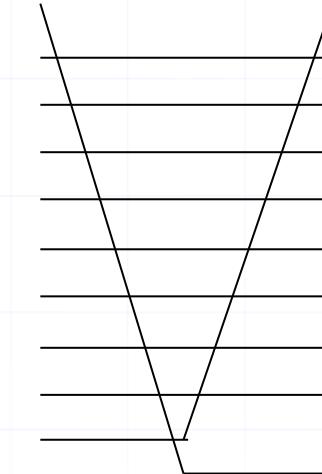
Mirrored and pipelined swap across a path of qubits



Reconfigurable  
connectivity



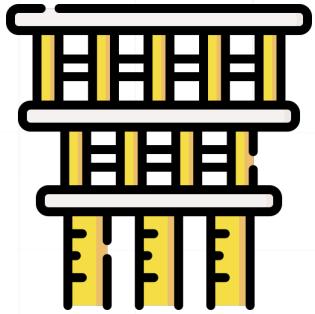
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# Entanglement transport why #2: controls budget

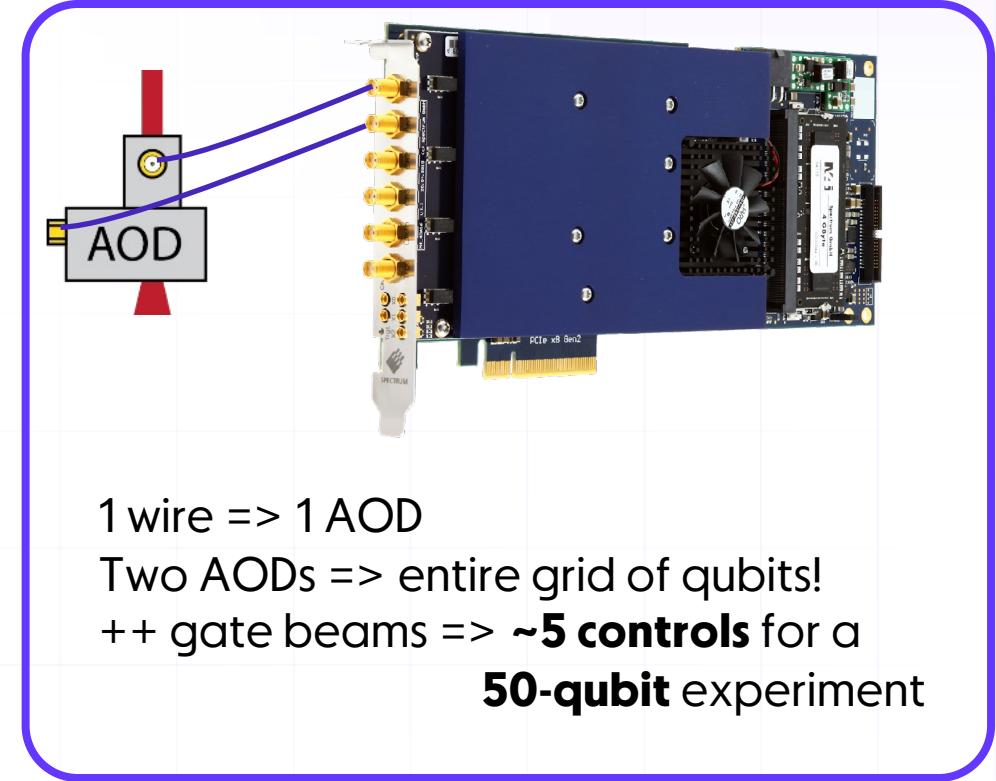


Classical computers:  
**Billions** of transistors  
~**1000** external controls



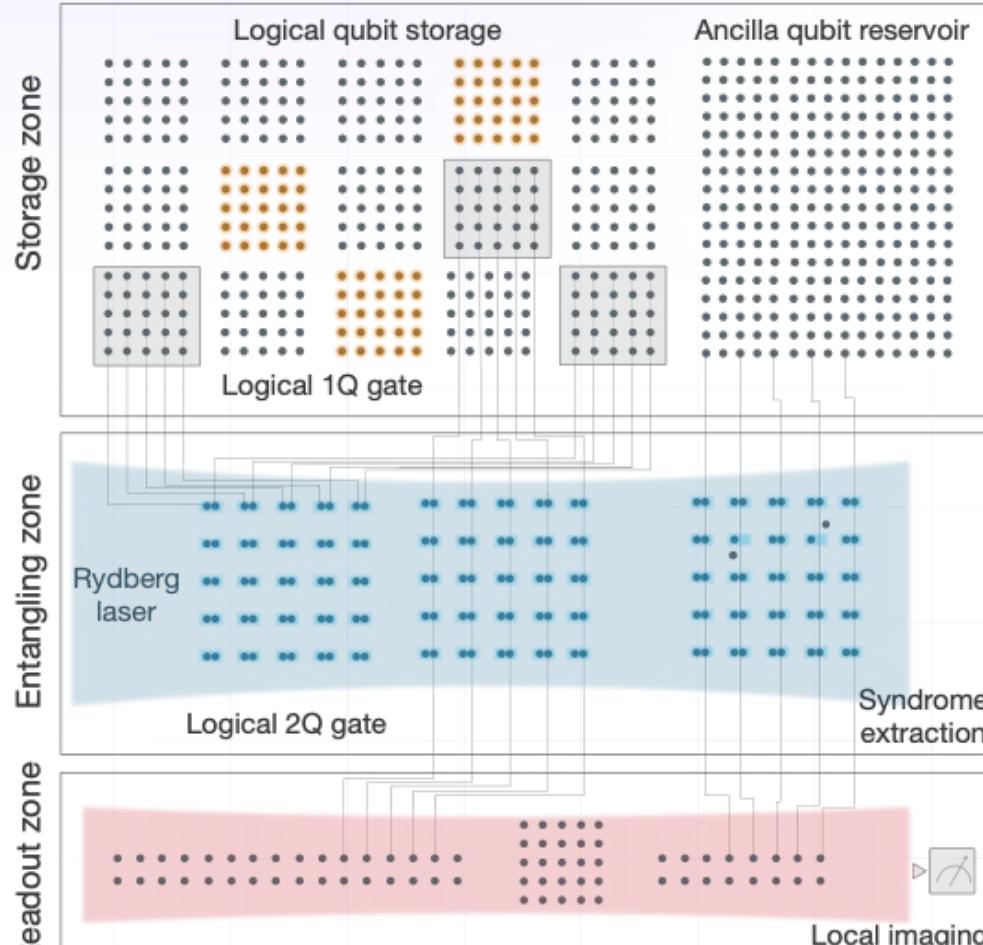
~3 wires/qubit => **100s** of high-performance controls  
for a **50-qubit** experiment

Assume \$1k/wire => 20M qubits ~ **\$20B**  
(estimate for 2048 RSA)



1 wire => 1 AOD  
Two AODs => entire grid of qubits!  
++ gate beams => **~5 controls** for a  
**50-qubit** experiment

# Sandbox Model for Current Gen. Quantum Computer



Keep in mind: the technology is still rapidly developing, and **tomorrow's systems** may look **very different!**

- Hundreds to a thousand qubits
- High-fidelity parallel gate operation, with long coherence times
- Parallel movement of qubits on a grid
- Mid-circuit measurement and feedforward
- Some analogies to classical RAMs



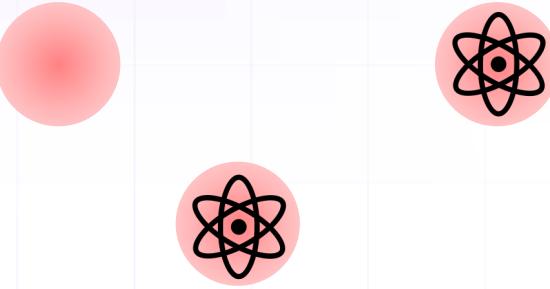
Bluvstein et al., Nature 2024

# Rules of the Game: Sites and Qubits



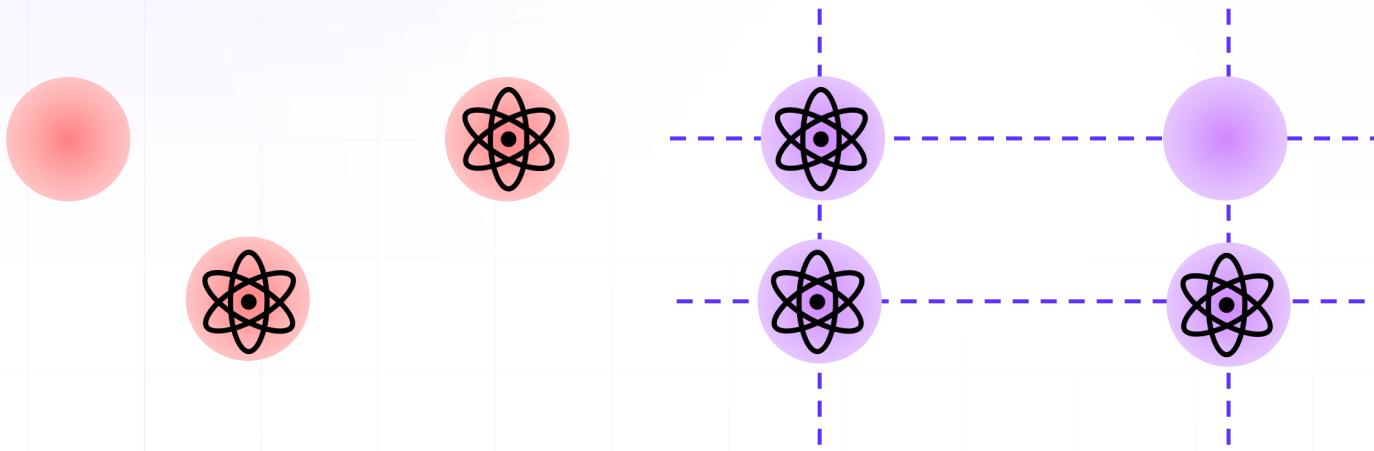
- “Sites” can contain 0 or 1 qubits

# Rules of the Game: Sites and Qubits



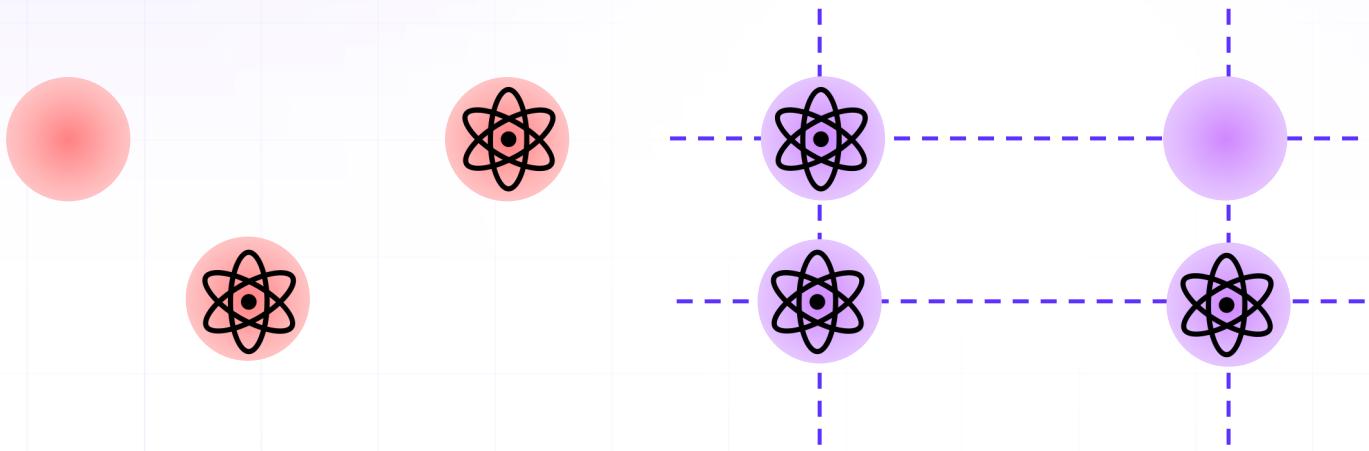
- “Sites” can contain 0 or 1 qubits
- Fixed sites: arbitrary, but fixed locations

# Rules of the Game: Sites and Qubits



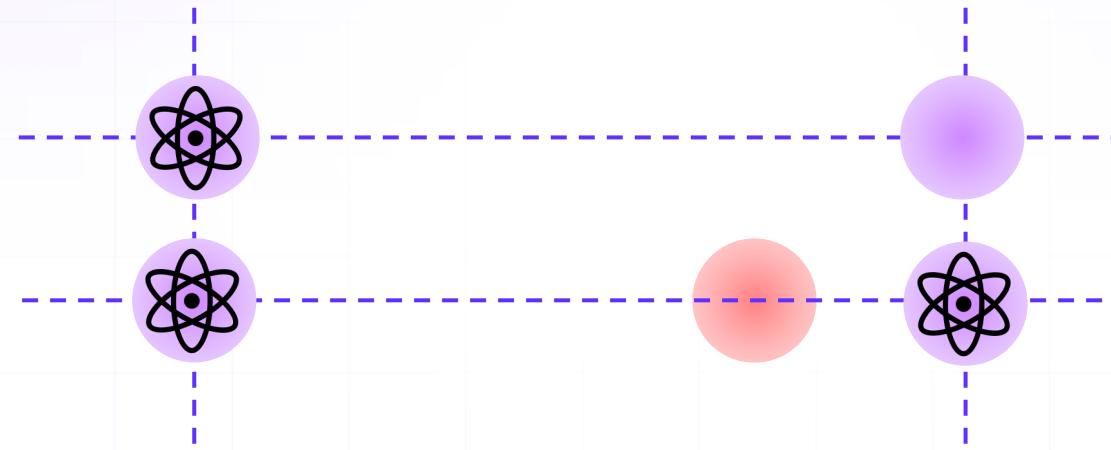
- “Sites” can contain 0 or 1 qubits
- Fixed sites: arbitrary, but fixed locations
- Movable sites: rectangular arrays of sites

# Rules of the Game: Sites and Qubits



- In the movable array, row/columns of sites move together
- A row cannot move past another row, same for columns

# Rules of the Game: Traps and Atoms



- In the movable array, row/columns of traps move together
- A row cannot move over another row, same for columns
- Atoms can be picked up and dropped off between fixed and movable traps

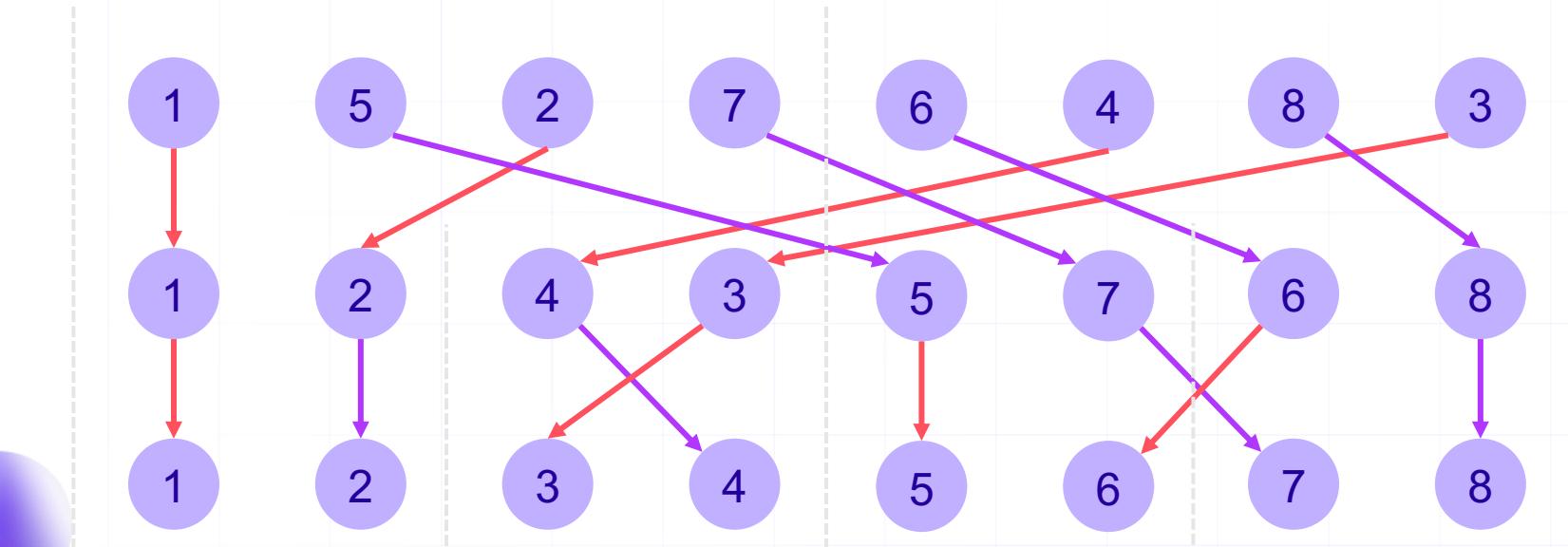
# A Compilation Mindset

~~"All or All"~~



Efficient parallel swap

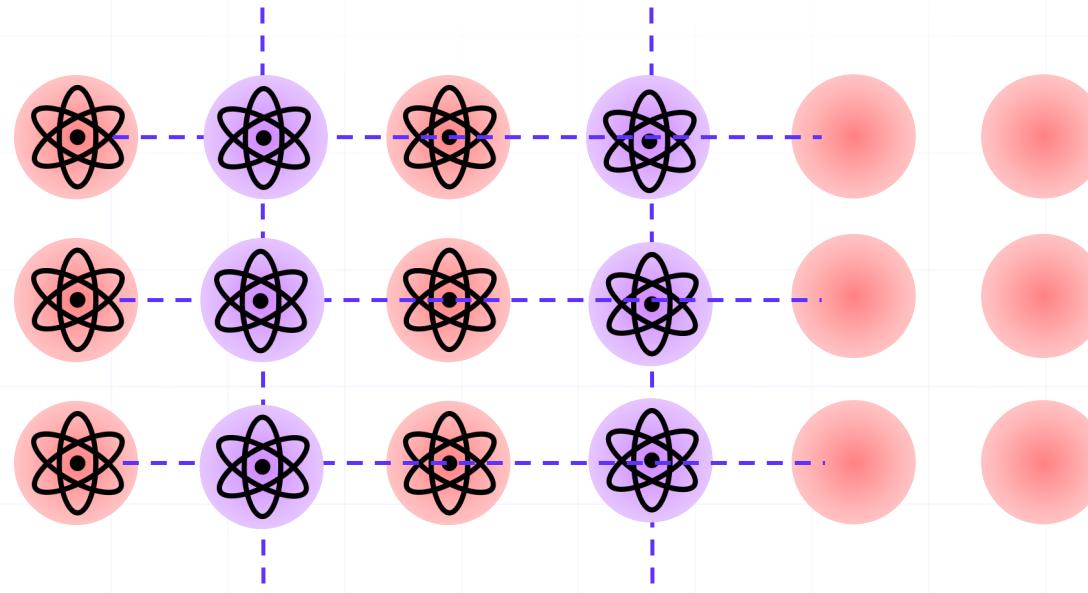
Atoms can **be efficiently sorted in  $\log(N)$  parallel moves.**



Xu et al., [arXiv:2308.08648](https://arxiv.org/abs/2308.08648)

# Simple Model for Neutral Atom Operations

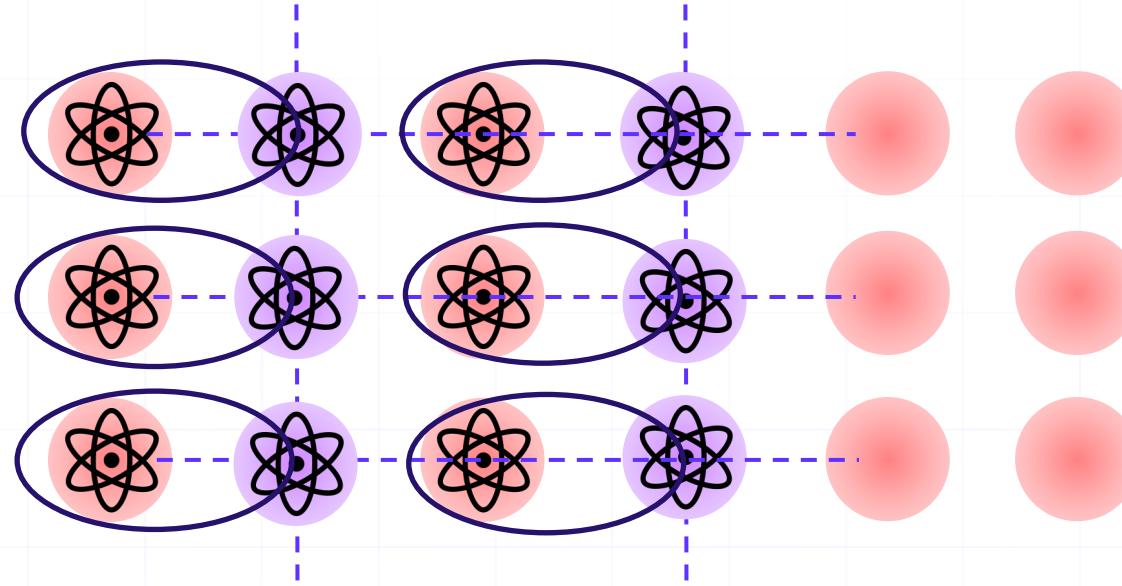
- 2D rectangular array of sites and qubits
- We can take a **rectangular** subarray of qubits and move them to another empty subarray



- More general operations possible; Tan et al., ICCAD 2023

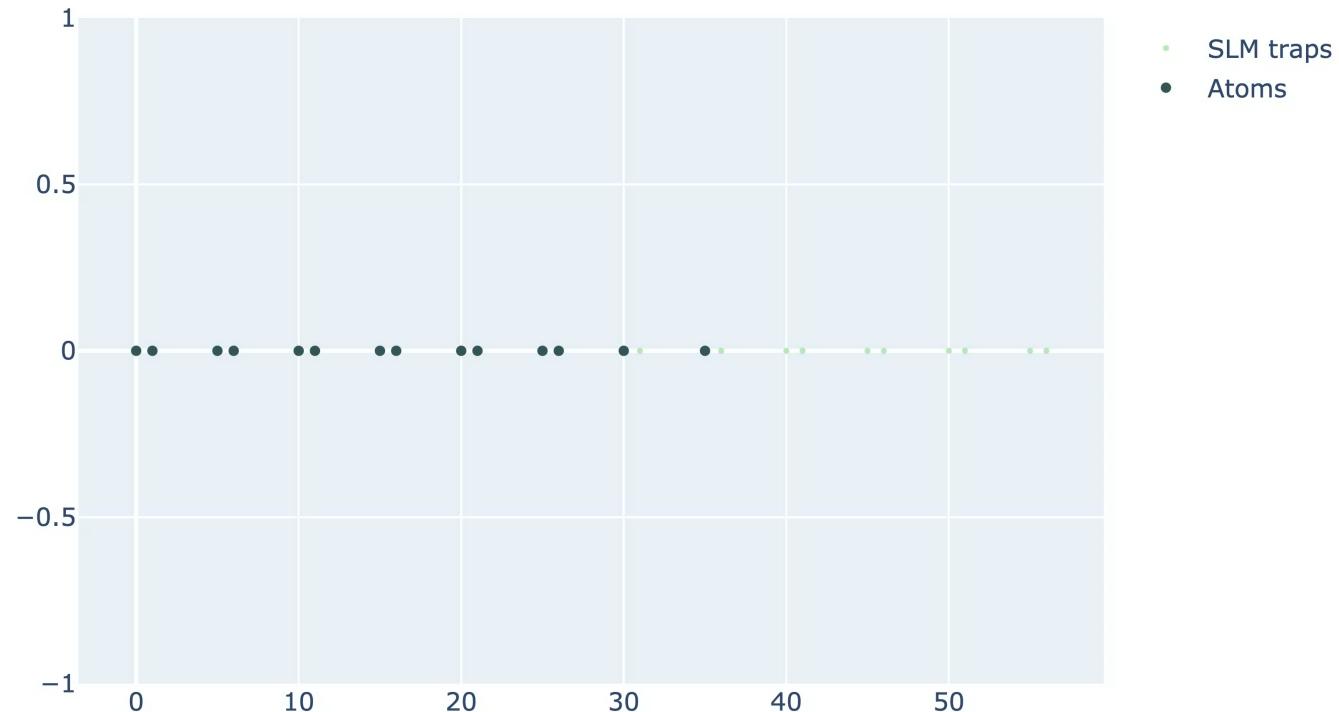
# Simple Model for Neutral Atom Operations

- We can do parallel two-qubit gates on pairs of qubits that are within a certain radius

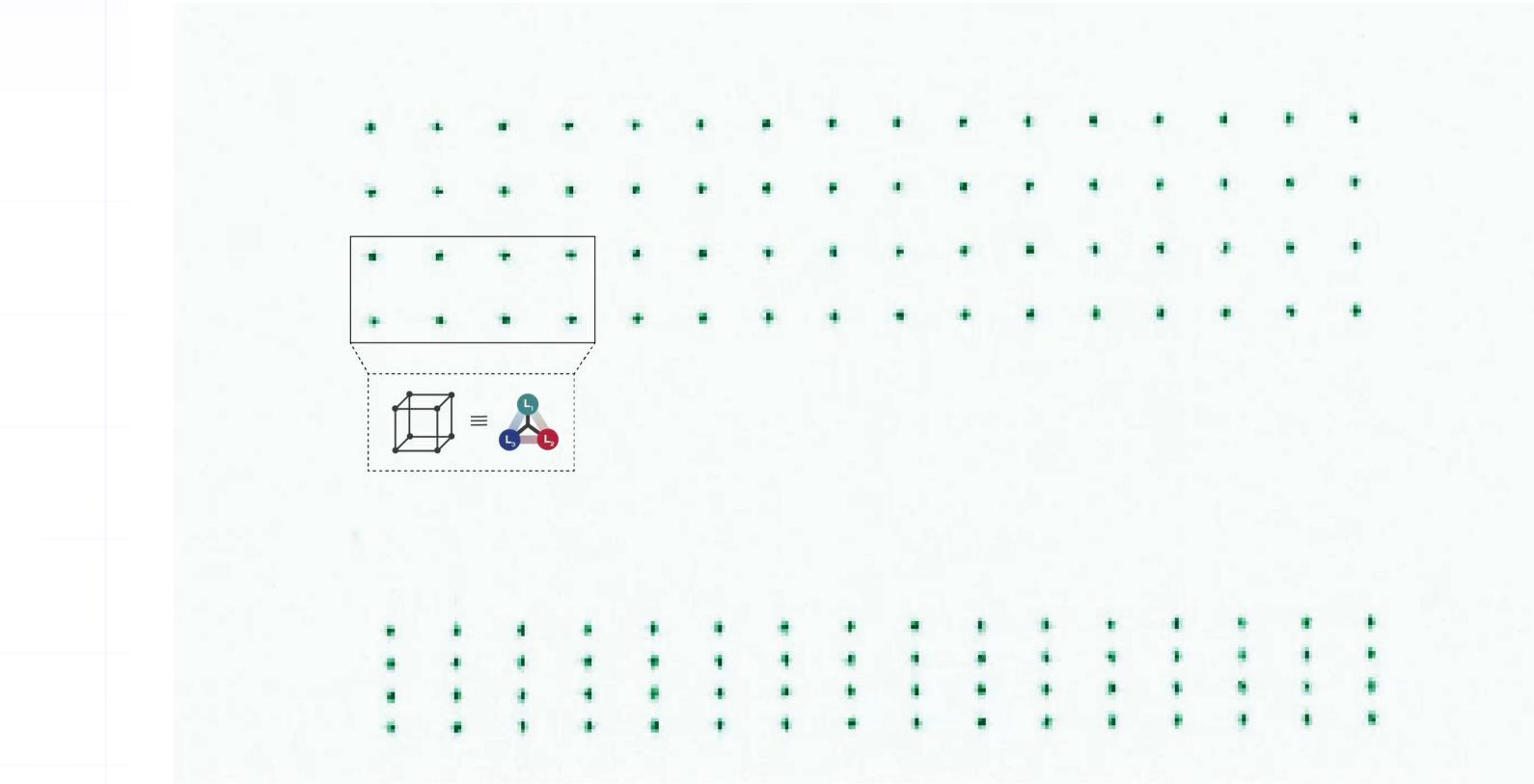


- More general operations possible; Tan et al., ICCAD 2023

# Dynamics Example #1



# Dynamics Example #2



# Summary Neutral Atom Gates

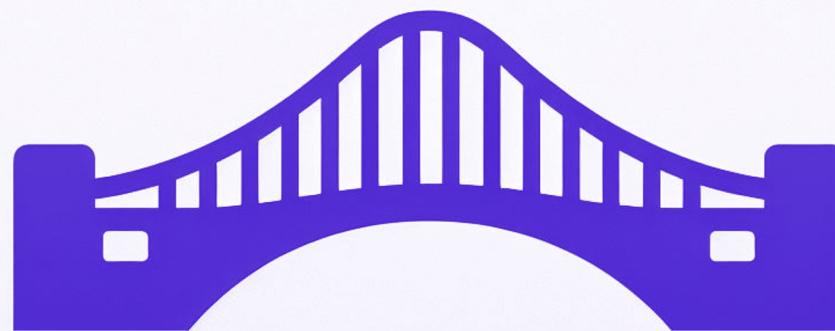
- Single-qubit gate: 99.9% ~ 99.99%, parallelized
- Two-qubit gate: 99.5%, position-programmed connectivity, parallel application on 10s to 100 qubits
- Noise sources fairly well understood
  - Structured: biased towards Z errors and atom loss => tailored QEC, conversion to erasure

Error source	Time optimal	Smooth amplitude	Error type X, Y, Z, LG, AL**
Total fidelity	<b>99.53 - 99.62%</b>	<b>99.70%</b>	<b>2%, 2%, 41%, 17%, 38%</b>

- Evered\*, Bluvstein\*, Kalinowski\* et al., *Nature* 2023; See also Ma et al., Scholl et al., *Nature* 2023. Cong et al., *PRX* 2022, Wu et al., *Nature Comm.* 2022, Sahay et al., *PRX* 2023

# Outlook

Quantum error correction will  
bridge this gap!



Physical error  
rates today

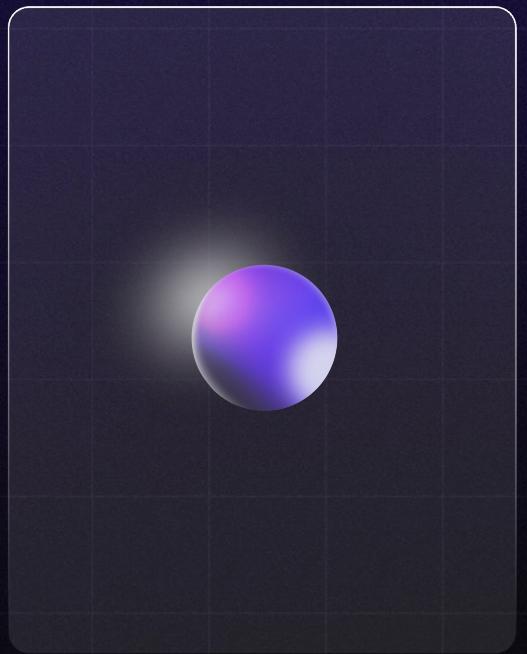


What large-scale quantum  
algorithms require

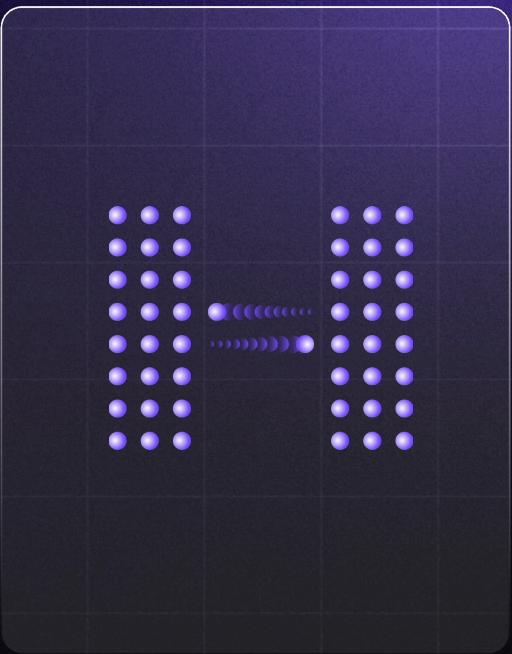


But we need all  
breakthroughs possible...

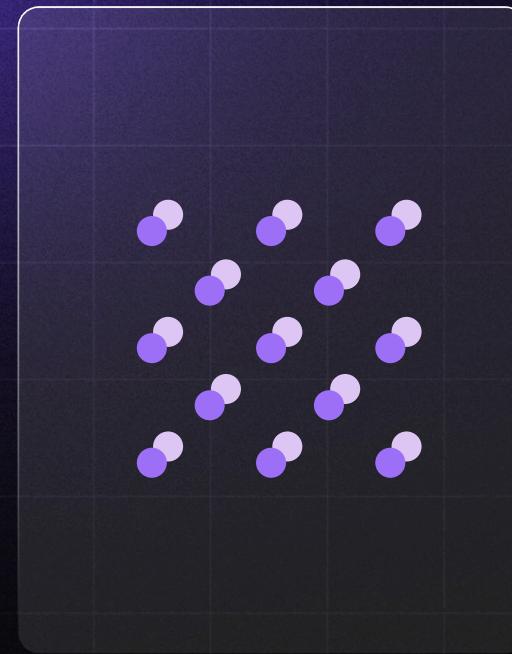
# Neutral-atoms contributions



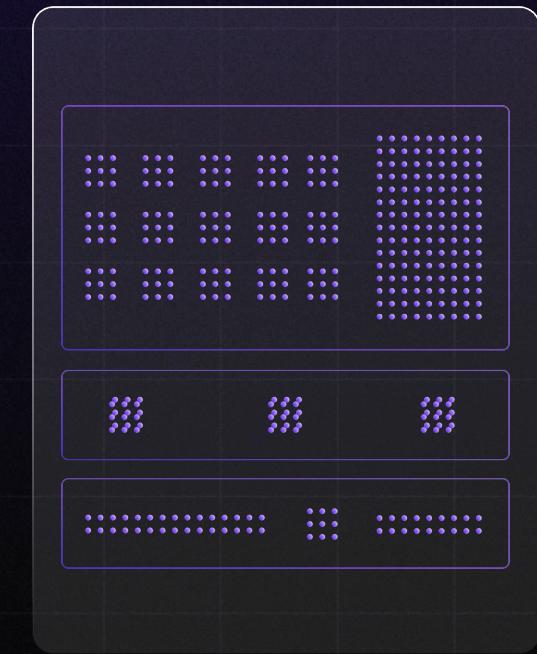
*Neutral Atoms*



*Qubit Shuttling*

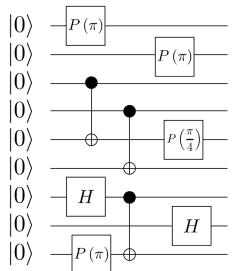


*Parallel Operations*



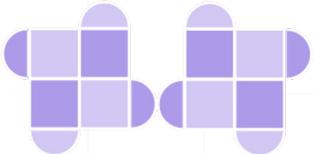
*Zoned Architecture*

# Final words



## Algorithmic pipeline

Error-correcting code choice  
Compilation  
Gate design  
Protocol layout + spacetime optimization



## Co- Design

## Native hardware capabilities

Speed  
Qubit connectivity  
Parallelization  
Universal gate-set  
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