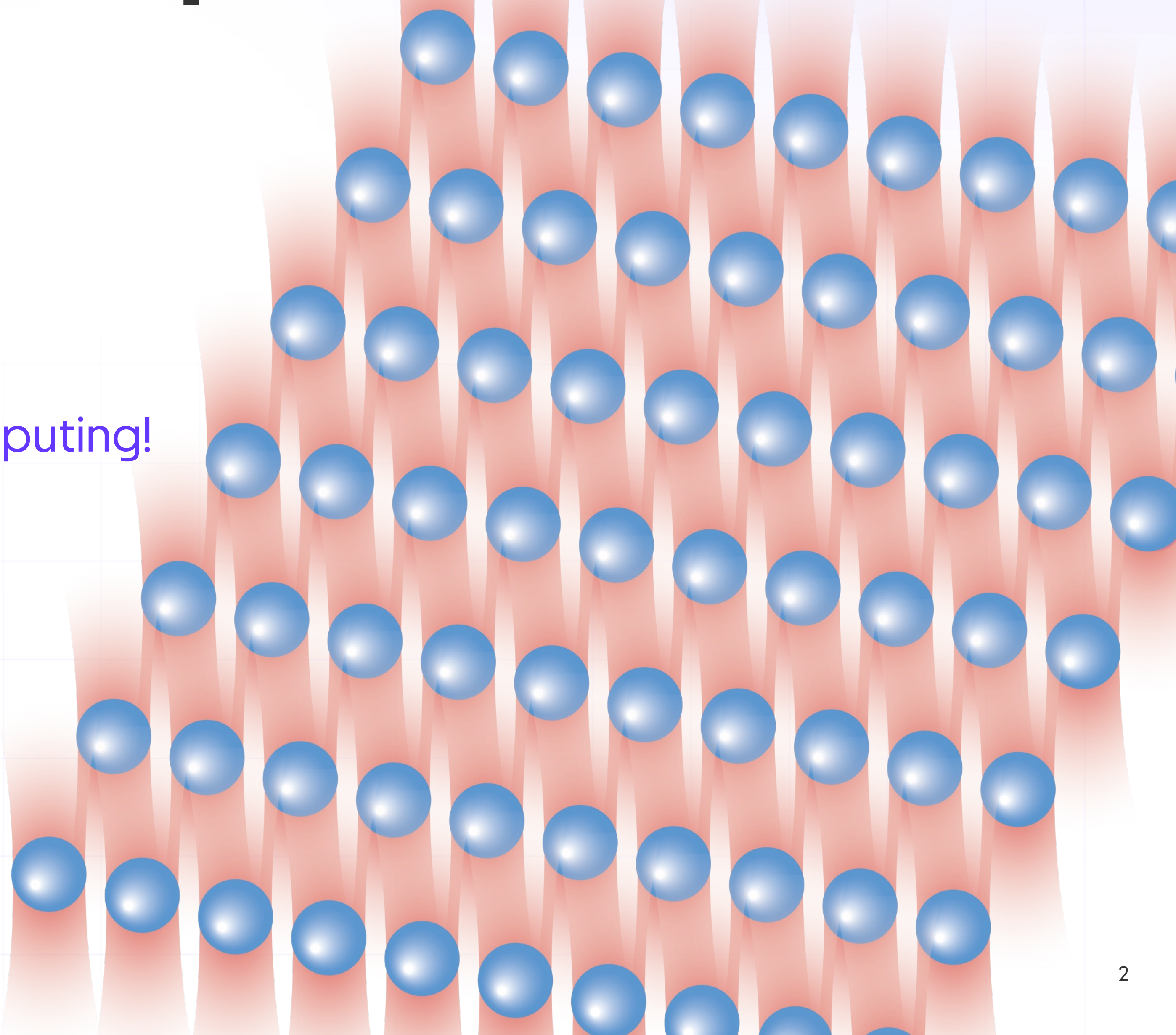
QRISE 2024
Intro workshop

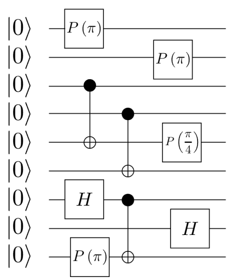
Pedro Lopes, Phd
Quantum Advocate

Neutral-atom quantum processor

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

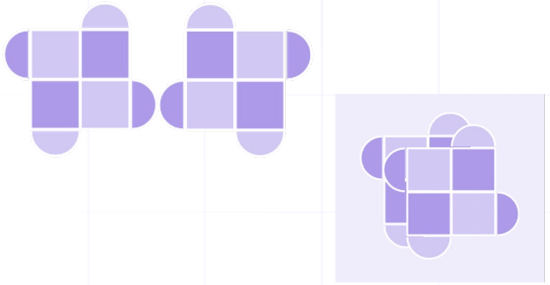


Main theme



Algorithmic pipeline

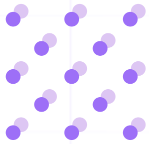
Error-correcting code choice
Compilation
Gate design
Protocol layout + spacetime optimization

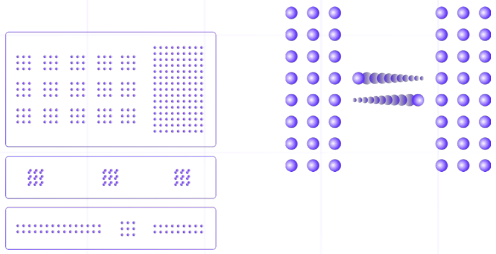


Co-Design

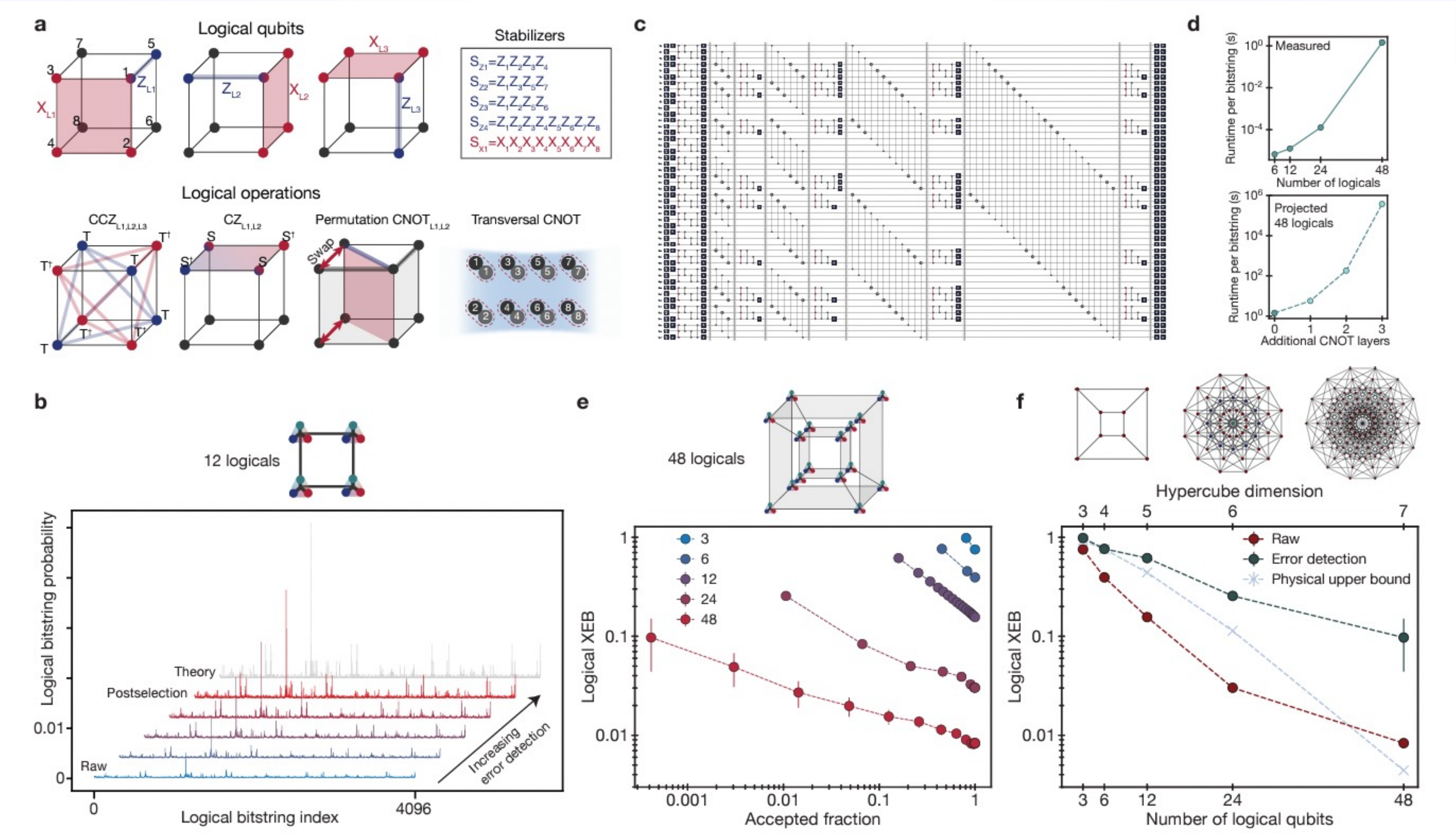
Native hardware capabilities

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



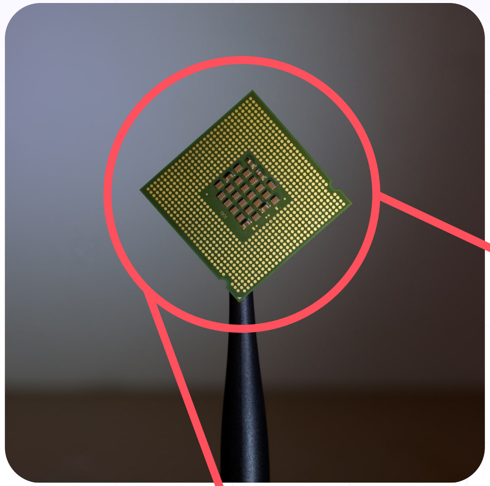


Example:

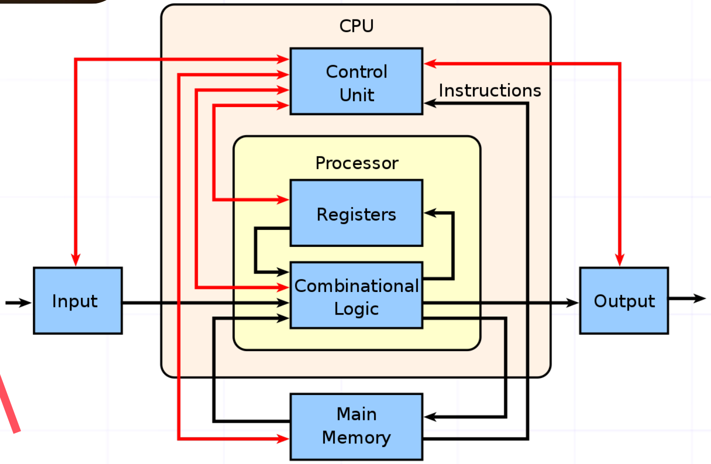


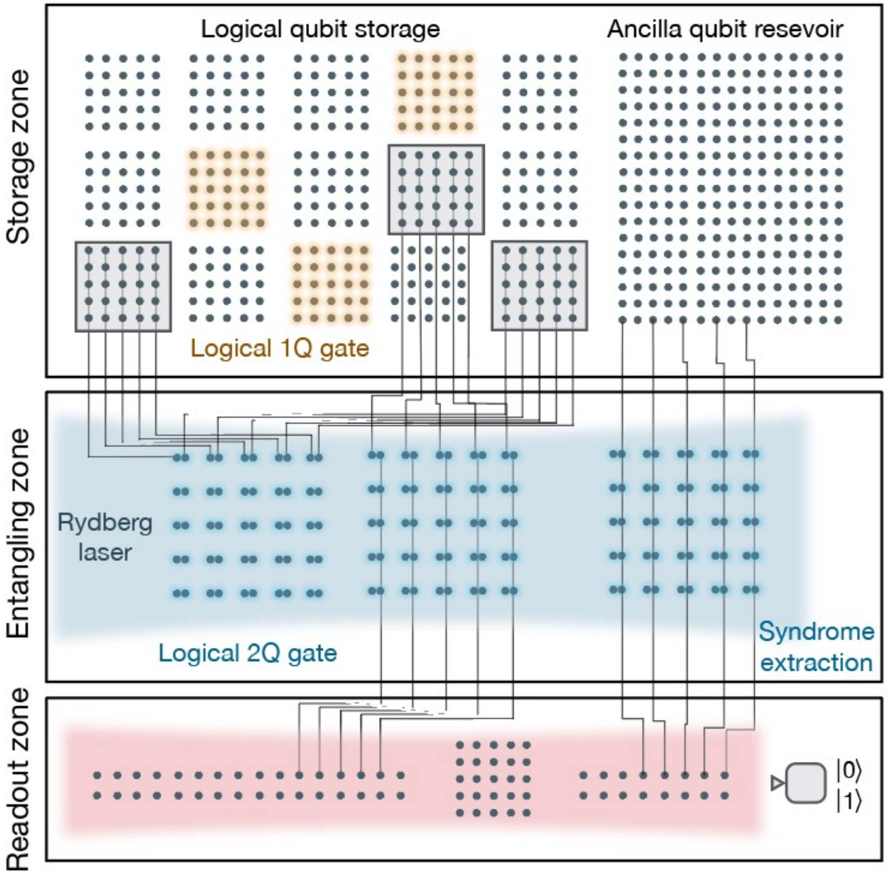
Bluvstein et al., Nature (2024)

(Quantum) Computer architectures



Not homogenous
Not monolithic

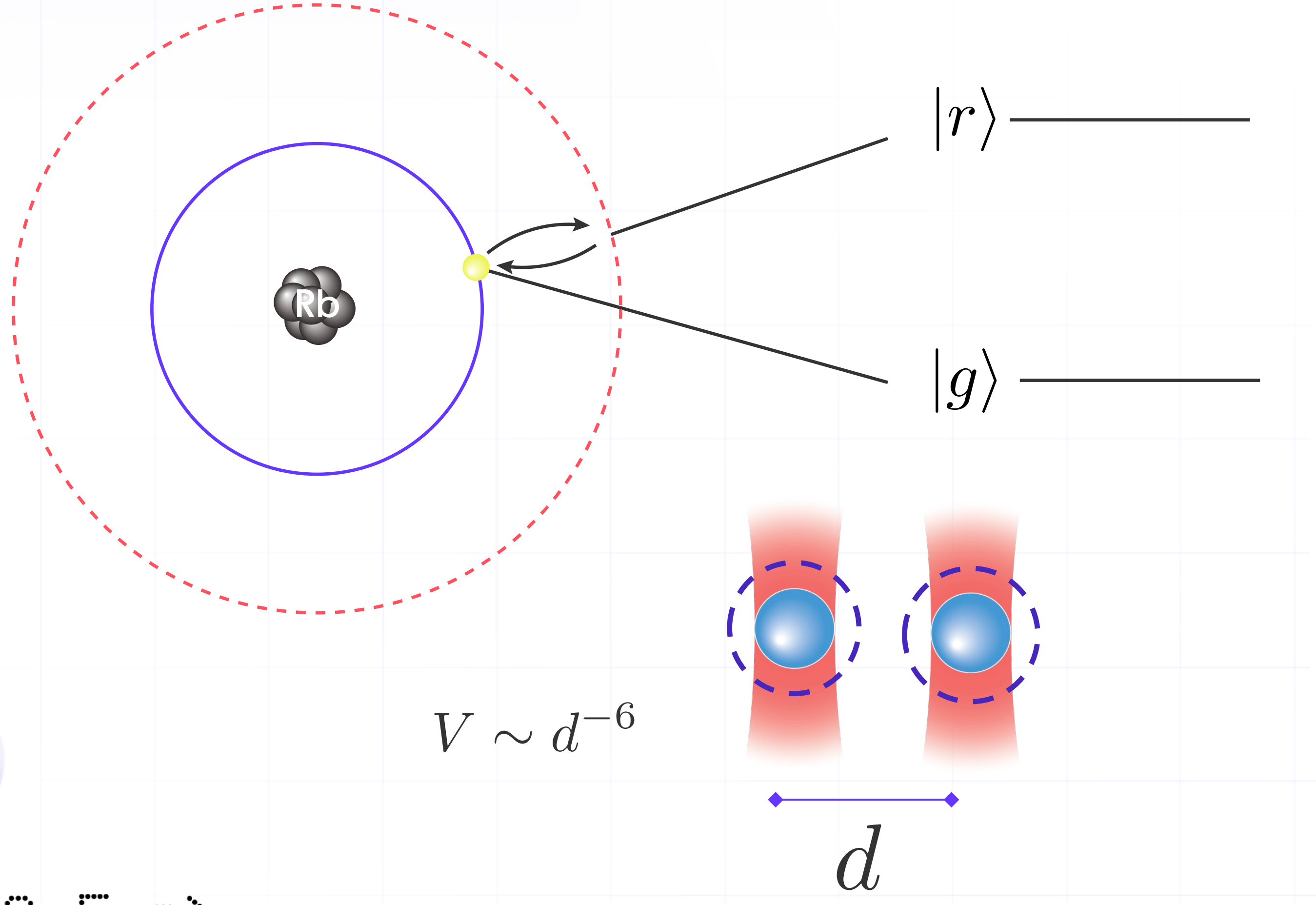


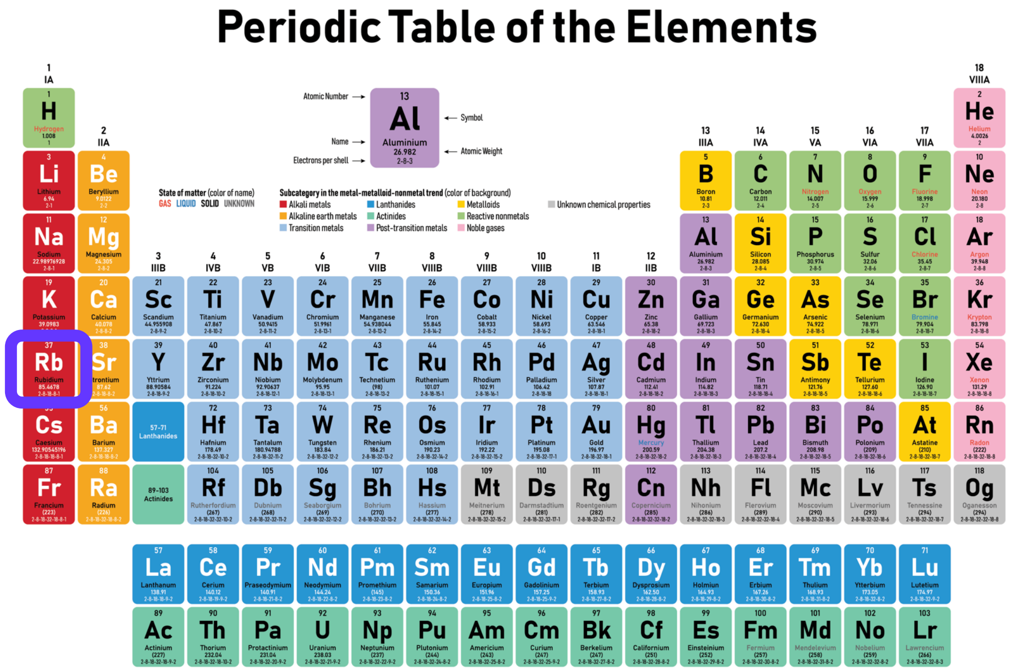


Neutral-atoms "zoned" QPUs: heterogeneous

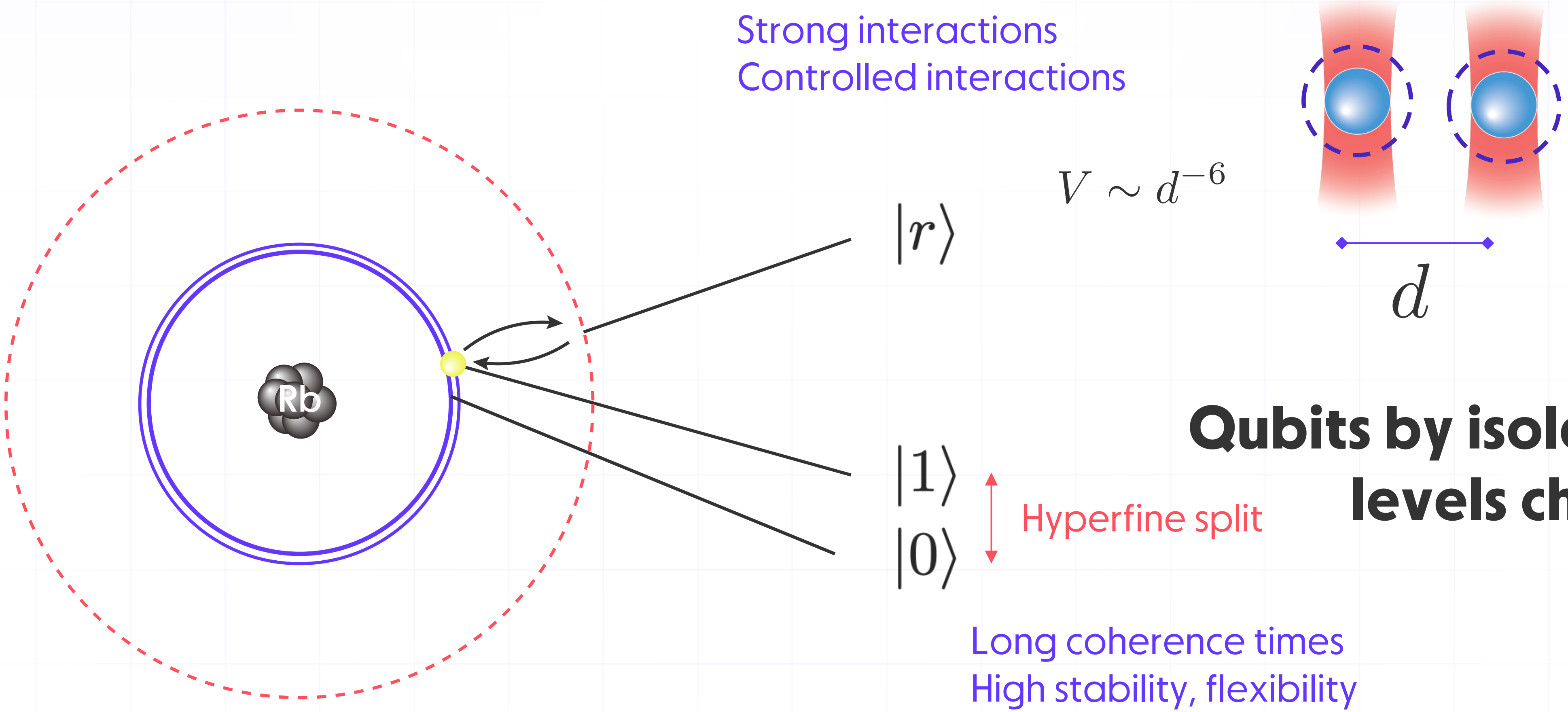
Bluvstein et al., Nature 2024
Bluvstein et al., Nature 2022;
Evered et al., Nature 2023

Analog: Qubits by puffing-up atoms



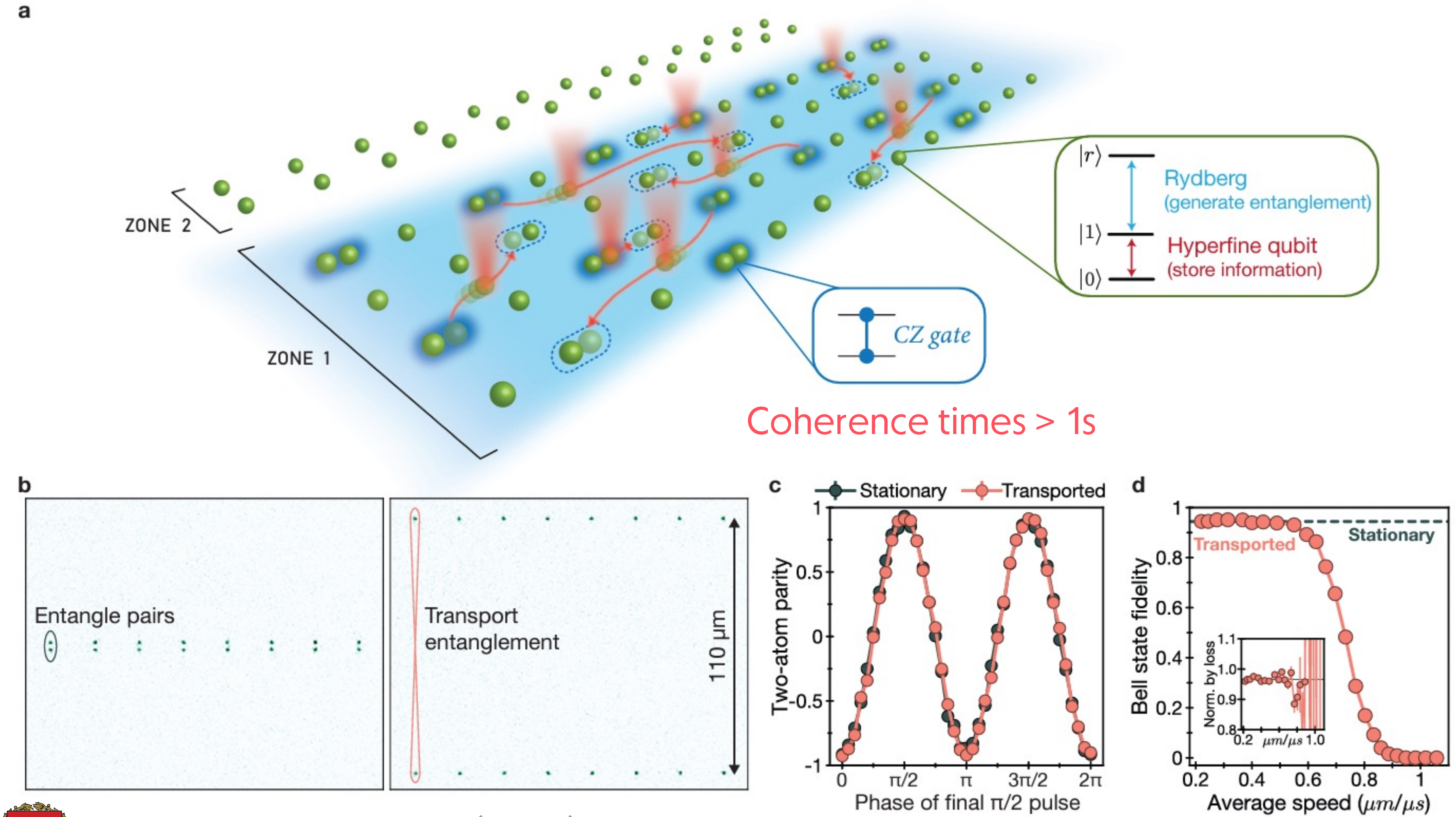


Digital: ~~Qubits~~ Entanglement by puffing-up atoms



Qubits by isolated levels choice

Basic architecture



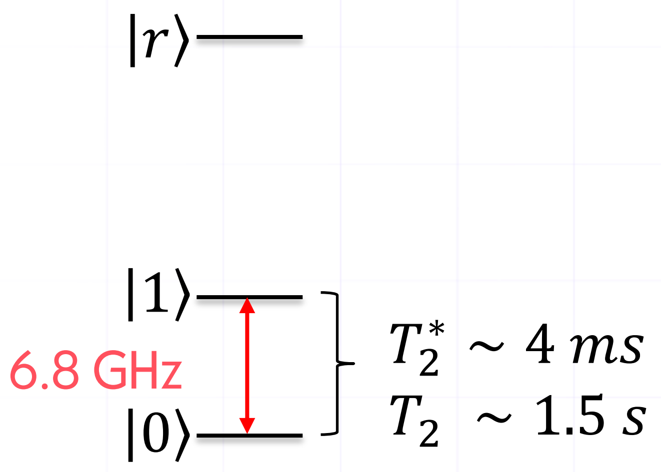
Coherence times > 1s

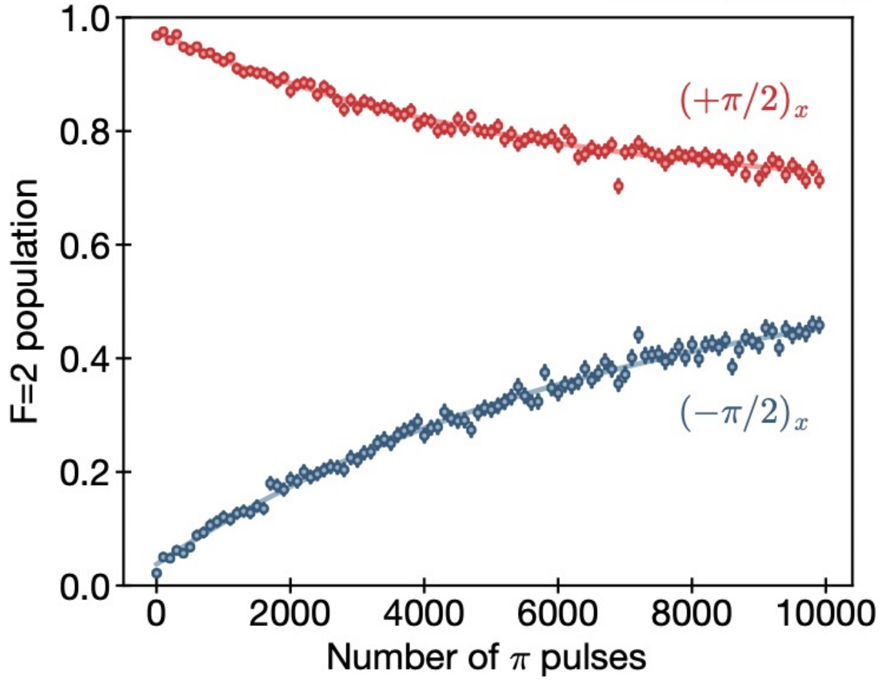
Bluvstein et al., Nature (2022)

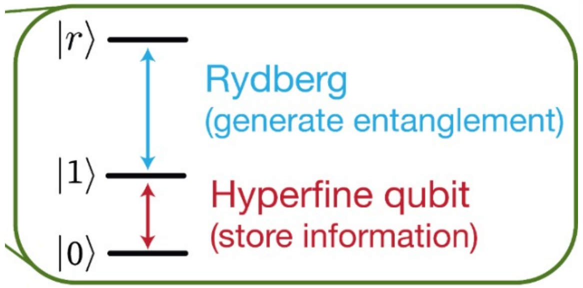
Single-qubit gates

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)

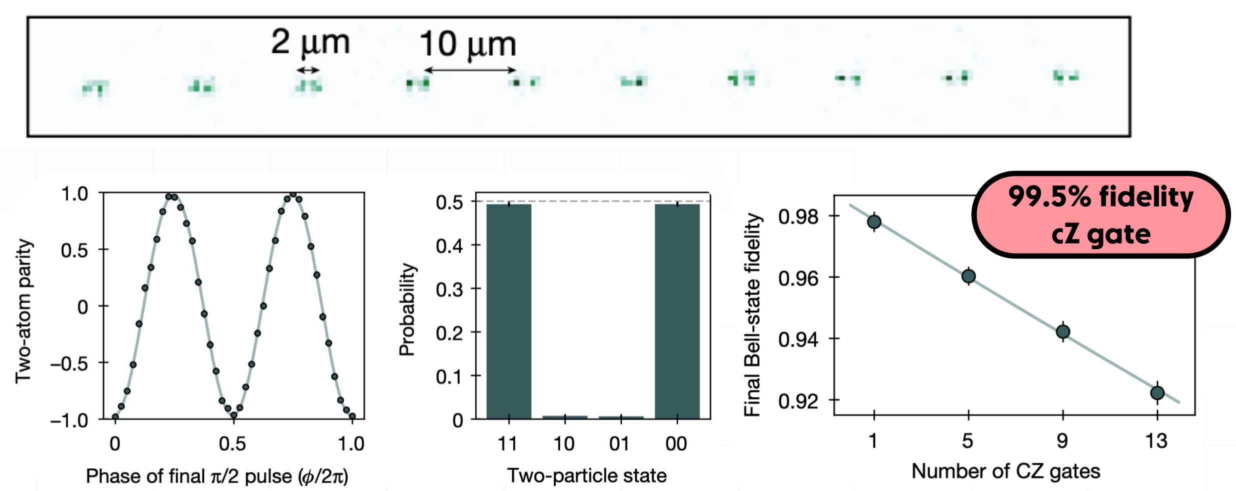


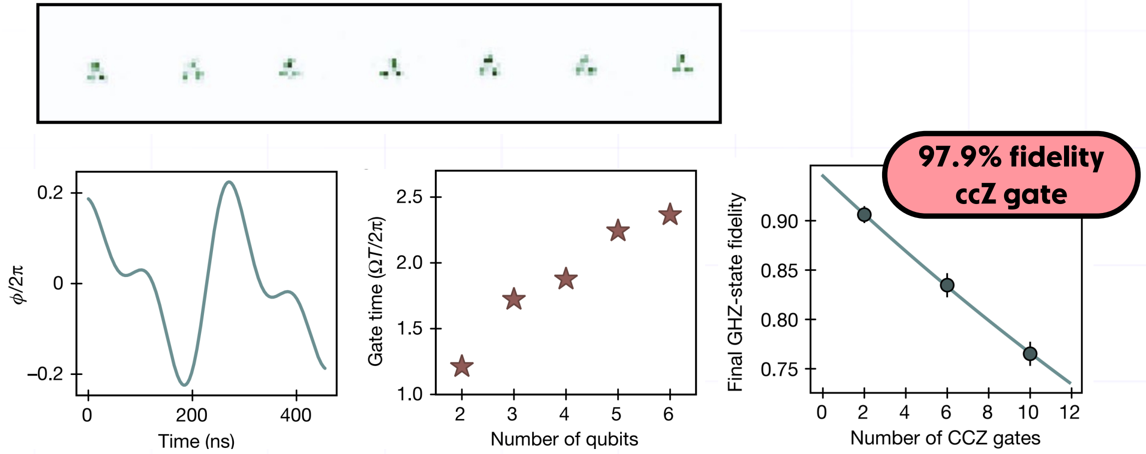




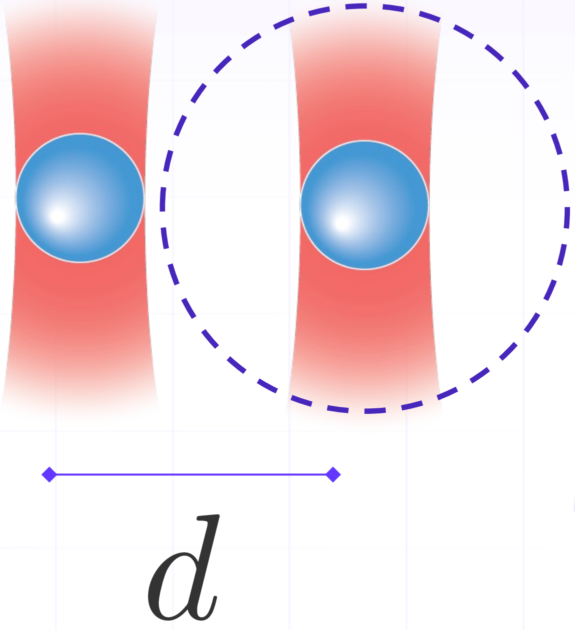
99.99% single-qubit gate fidelity

Two-(or more-)qubit gates





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



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

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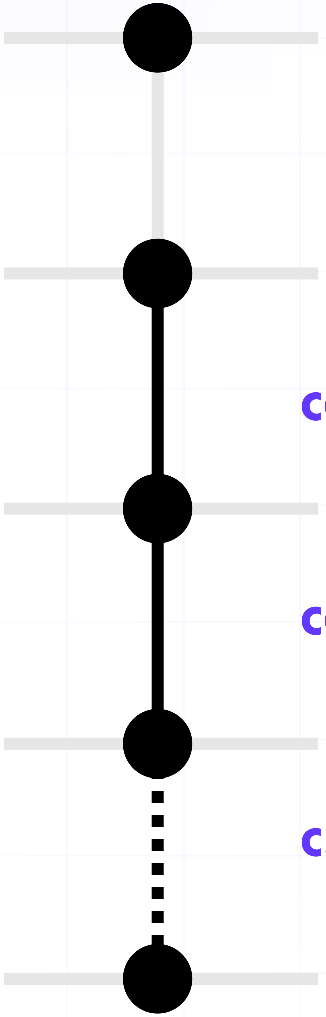
Evered et al., Nature (2023)

Native gate set

Controlled Z gates

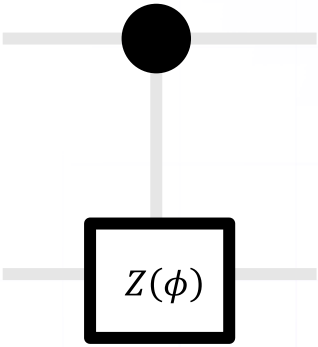


ccZ gates

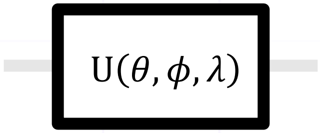
cccZ gates

c..cZ gates

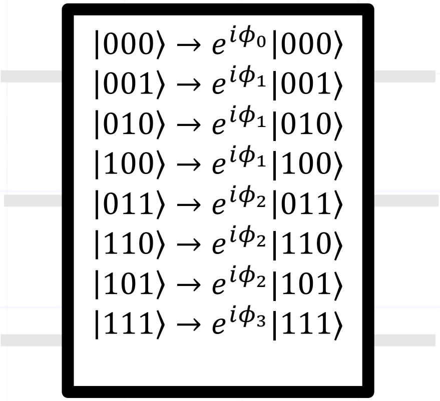
Controlled Z-phase gates



Arbitrary 1 qubit rotations



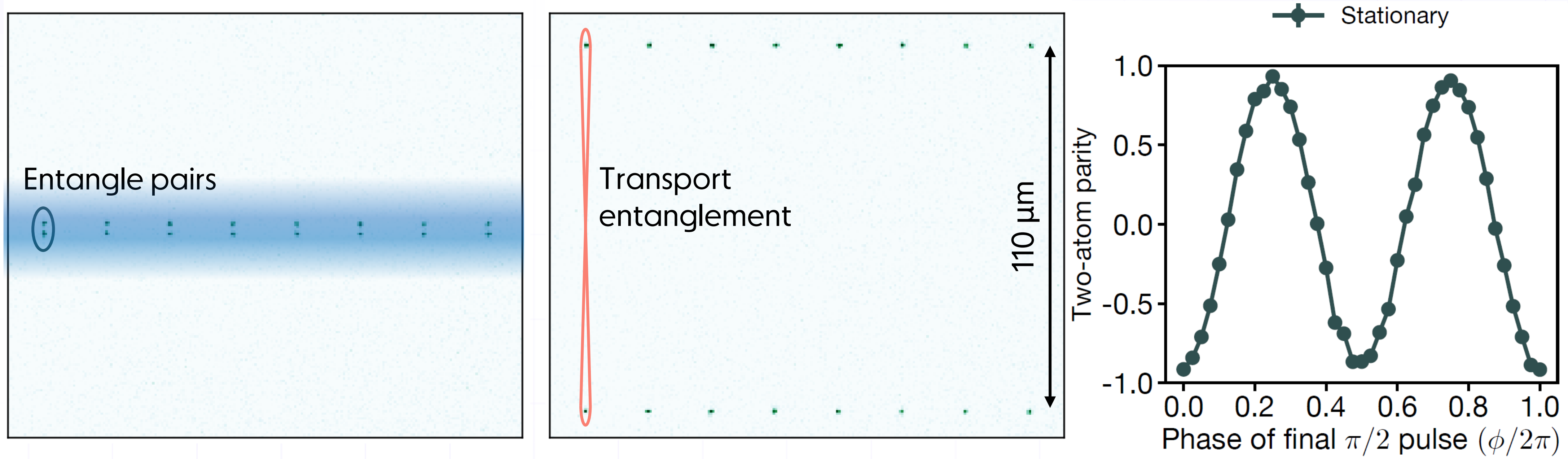
Permutation-symmetric Z-phase gates

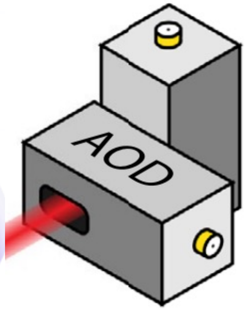


$$
\begin{aligned}
|000\rangle &\rightarrow e^{i\phi_0}|000\rangle\\
|001\rangle &\rightarrow e^{i\phi_1}|001\rangle\\
|010\rangle &\rightarrow e^{i\phi_1}|010\rangle\\
|100\rangle &\rightarrow e^{i\phi_1}|100\rangle\\
|011\rangle &\rightarrow e^{i\phi_2}|011\rangle\\
|110\rangle &\rightarrow e^{i\phi_2}|110\rangle\\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

Entanglement transport

<300 μs to move across entire array (T_2 ~ 1.5 s)





Atom-atom spacing of ~3 μm
→ transport across array of ~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

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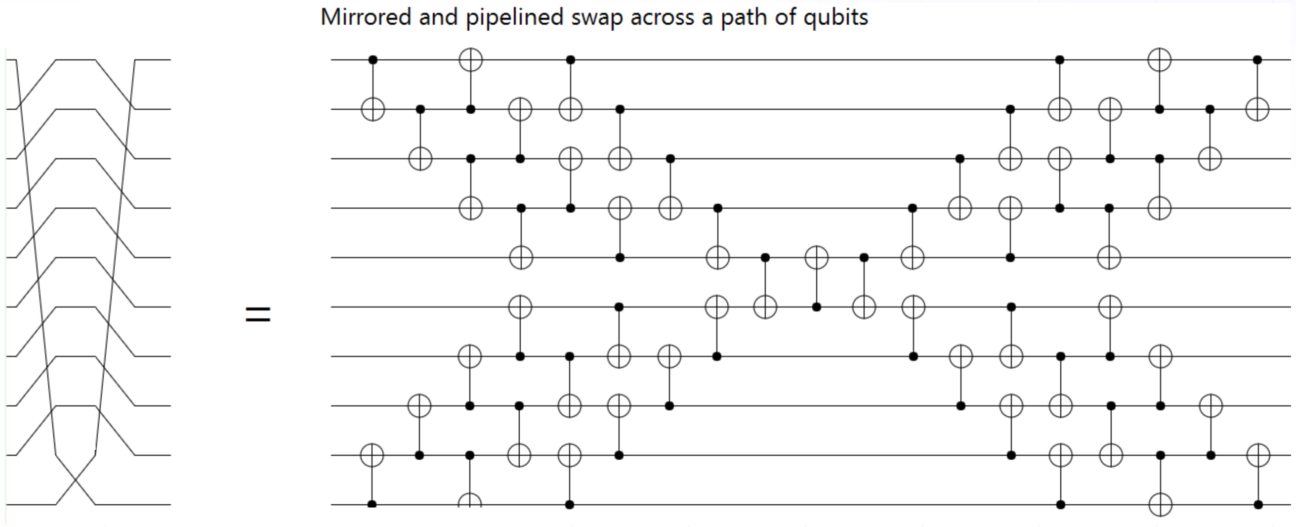
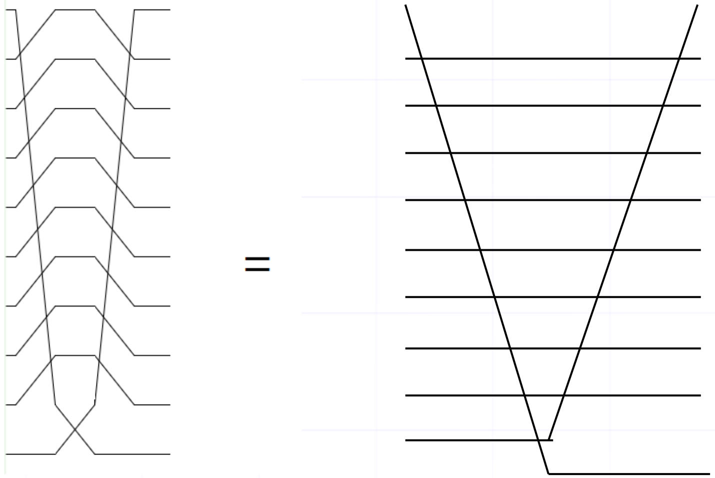
Entanglement transport why #1:
Long-range/arbitrary connectivity

Source: Craig Gidney's blog

Nearest-neighbor connectivity

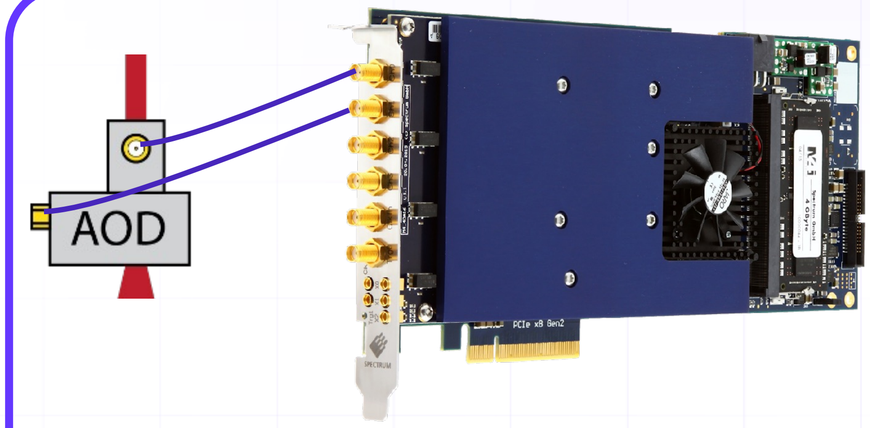


Reconfigurable connectivity

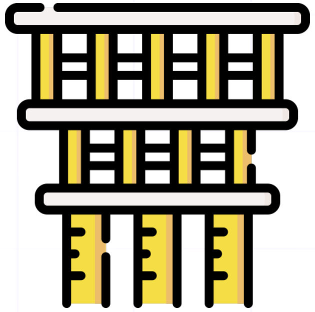


Entanglement transport why #2:
controls budget

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



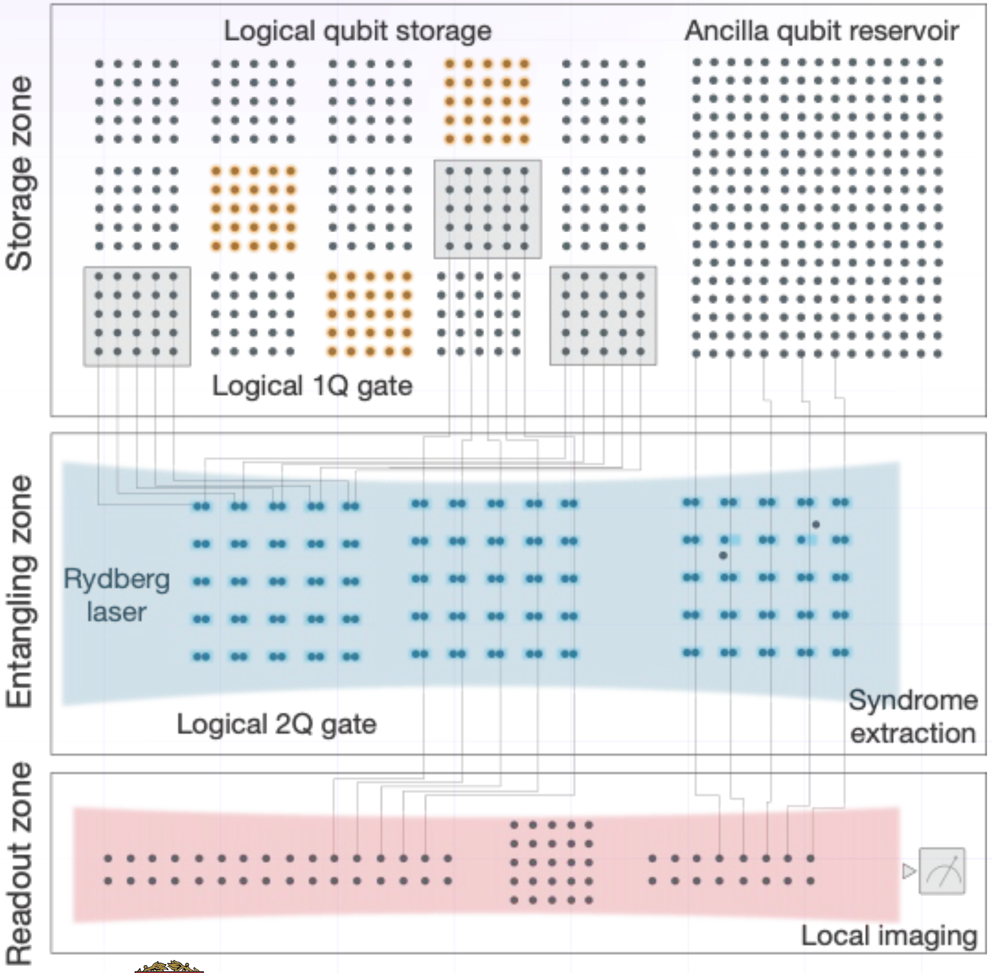
1 wire => 1 AOD
Two AODs => entire grid of qubits!
++ gate beams => **~5 controls** for a **50-qubit** experiment



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

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

Sandbox Model for Current Gen. Quantum Computer

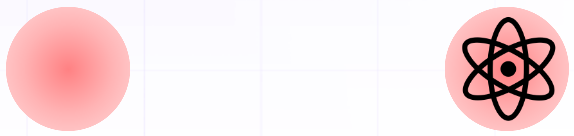


Bluvstein et al., Nature 2024

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

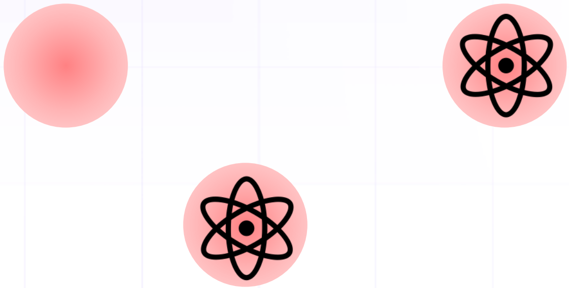
- Hundreds to a thousand qubits
- High-fidelity parallel gate operation, with long coherence times
- Parallel movement of qubits on a grid
- Mid-circuit measurement and feedforward
- Some analogies to classical RAMs

Rules of the Game: Sites and Qubits



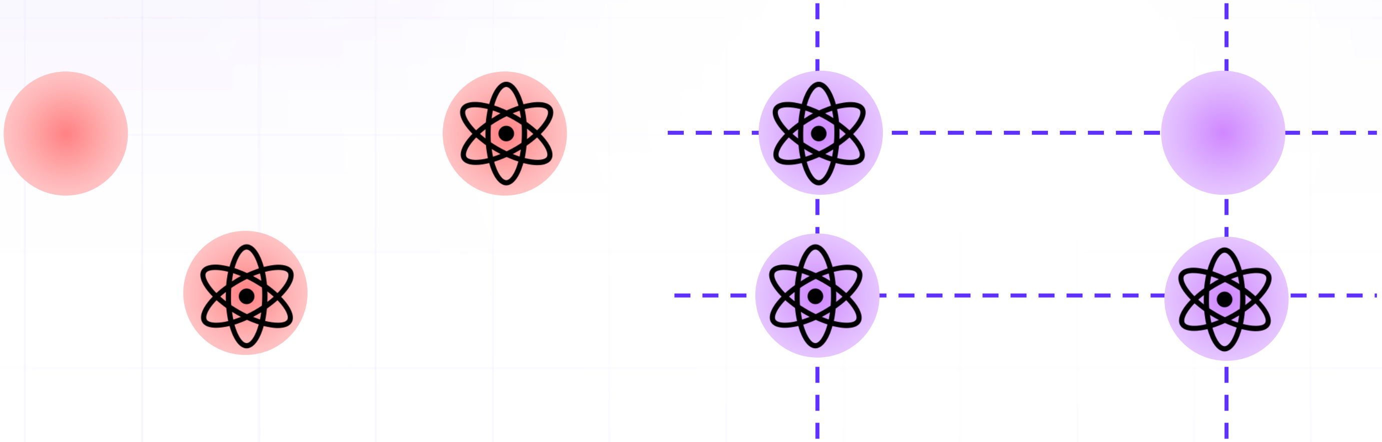
- “Sites” can contain 0 or 1 qubits

Rules of the Game: Sites and Qubits



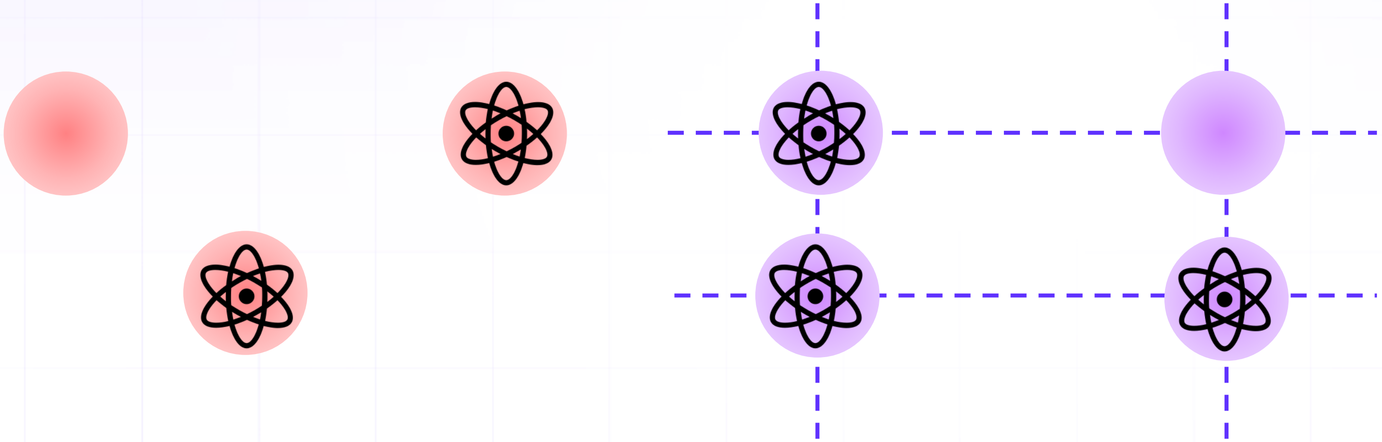
- “Sites” can contain 0 or 1 qubits
- Fixed sites: arbitrary, but fixed locations

Rules of the Game: Sites and Qubits



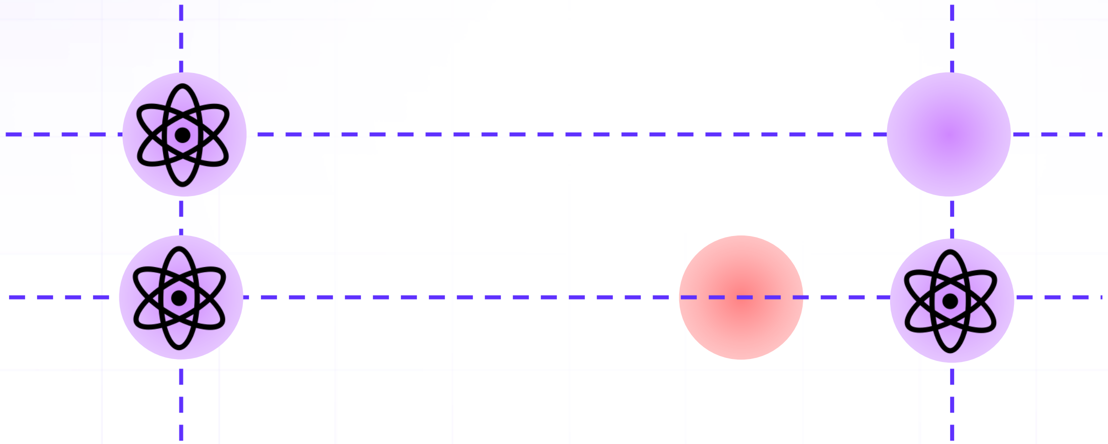
- “Sites” can contain 0 or 1 qubits
- Fixed sites: arbitrary, but fixed locations
- Movable sites: rectangular arrays of sites

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

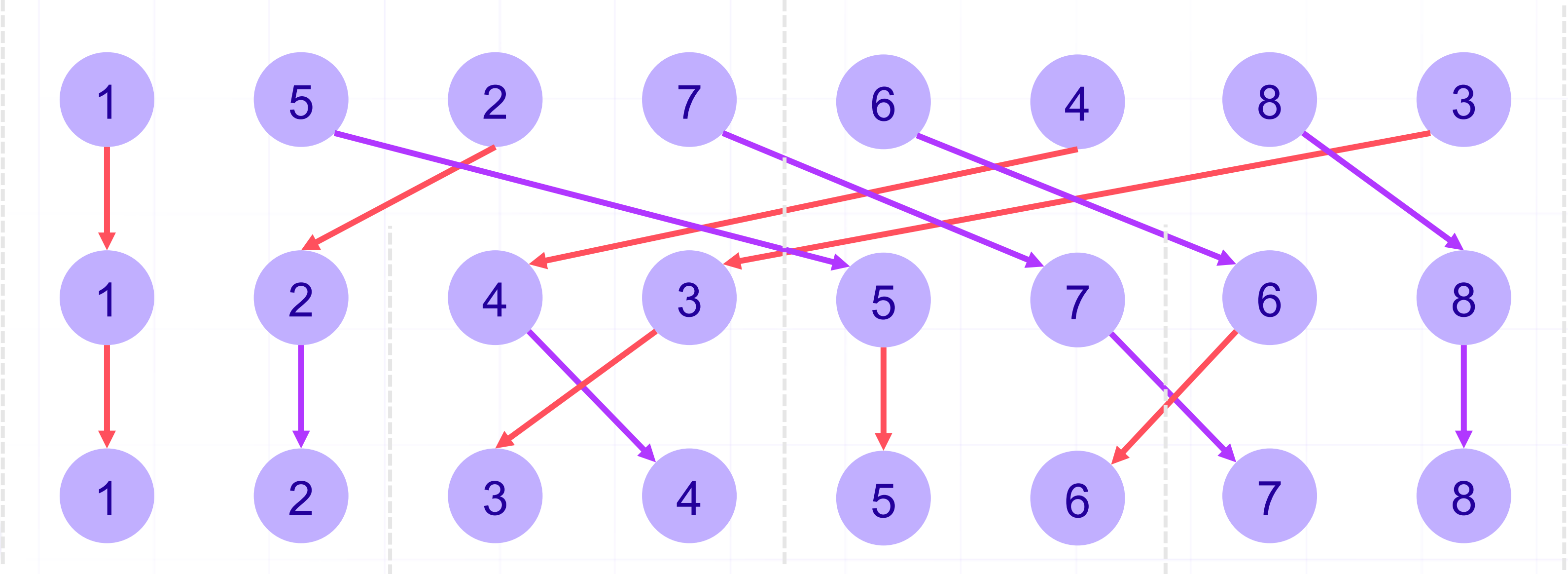


- In the movable array, row/columns of traps move together
- A row cannot move over another row, same for columns
- Atoms can be picked up and dropped off between fixed and movable traps

A Compilation Mindset

~~"All to All"~~ ⇒ **Efficient parallel swap**

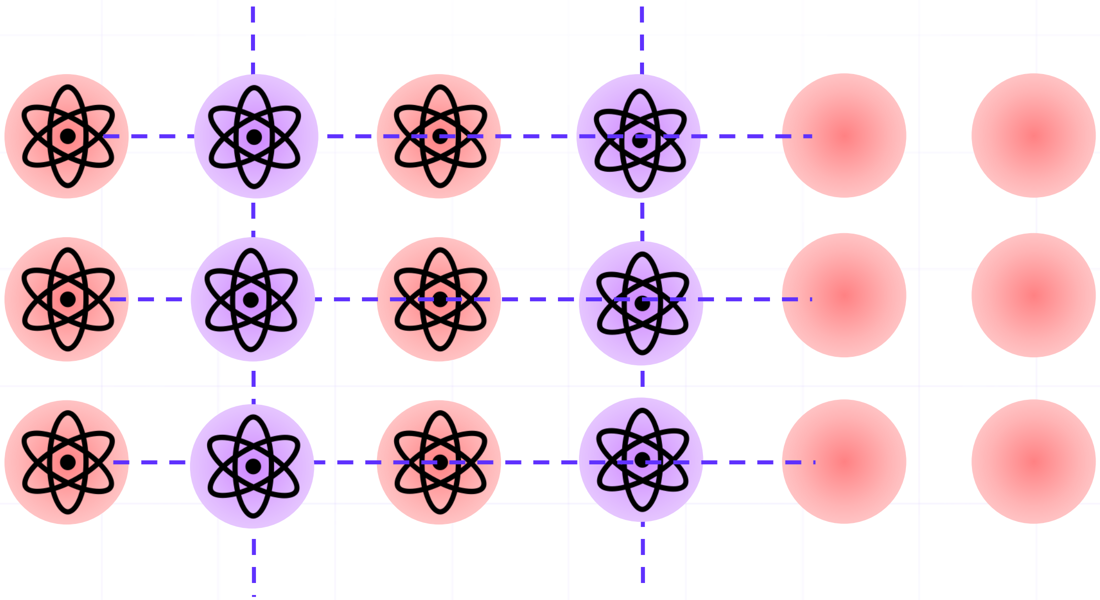
Atoms can **be efficiently sorted in $log(N)$** parallel moves.



Xu et al., arXiv:2308.08648

Simple Model for Neutral Atom Operations

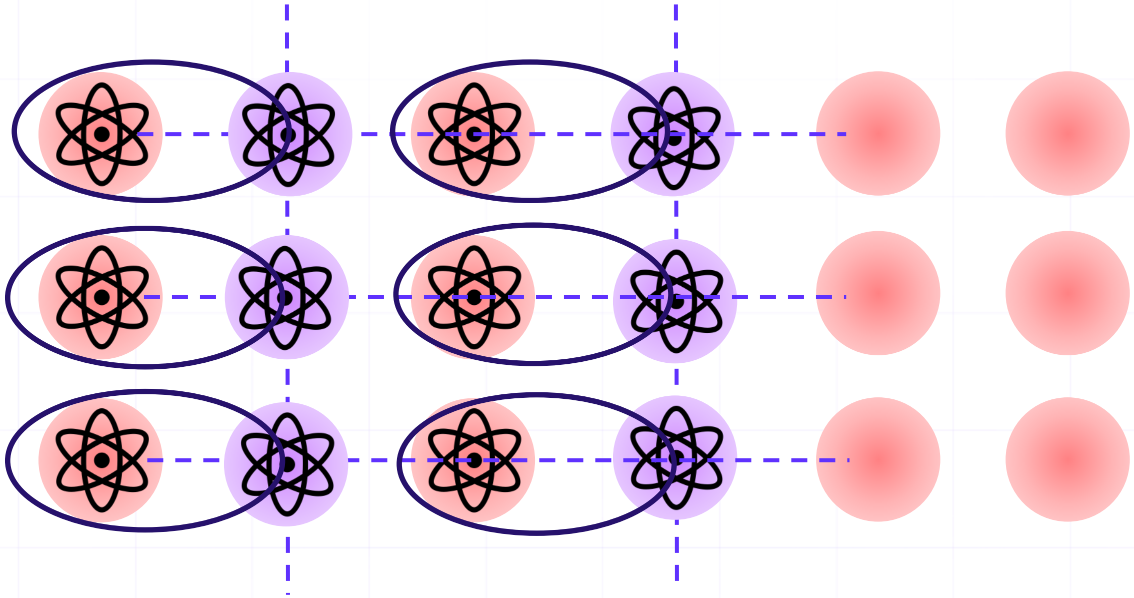
- 2D rectangular array of sites and qubits
- We can take a rectangular subarray of qubits and move them to another empty subarray



- 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



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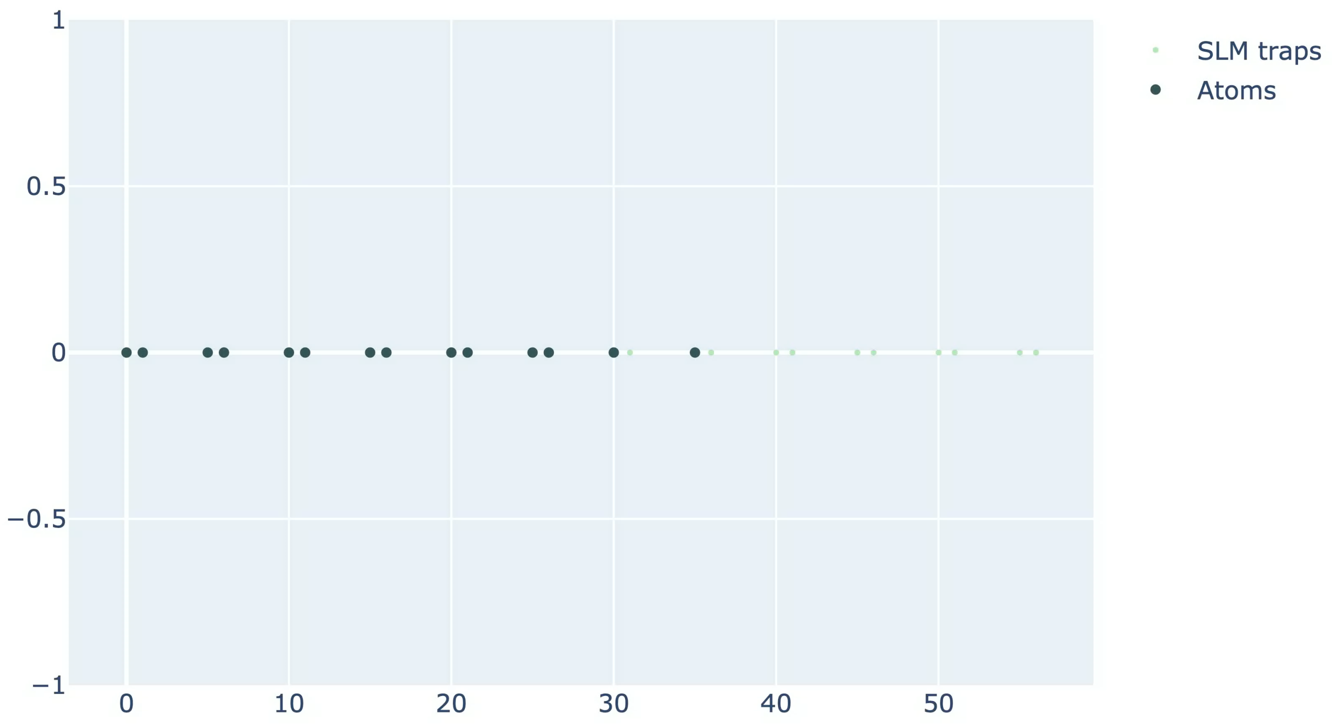
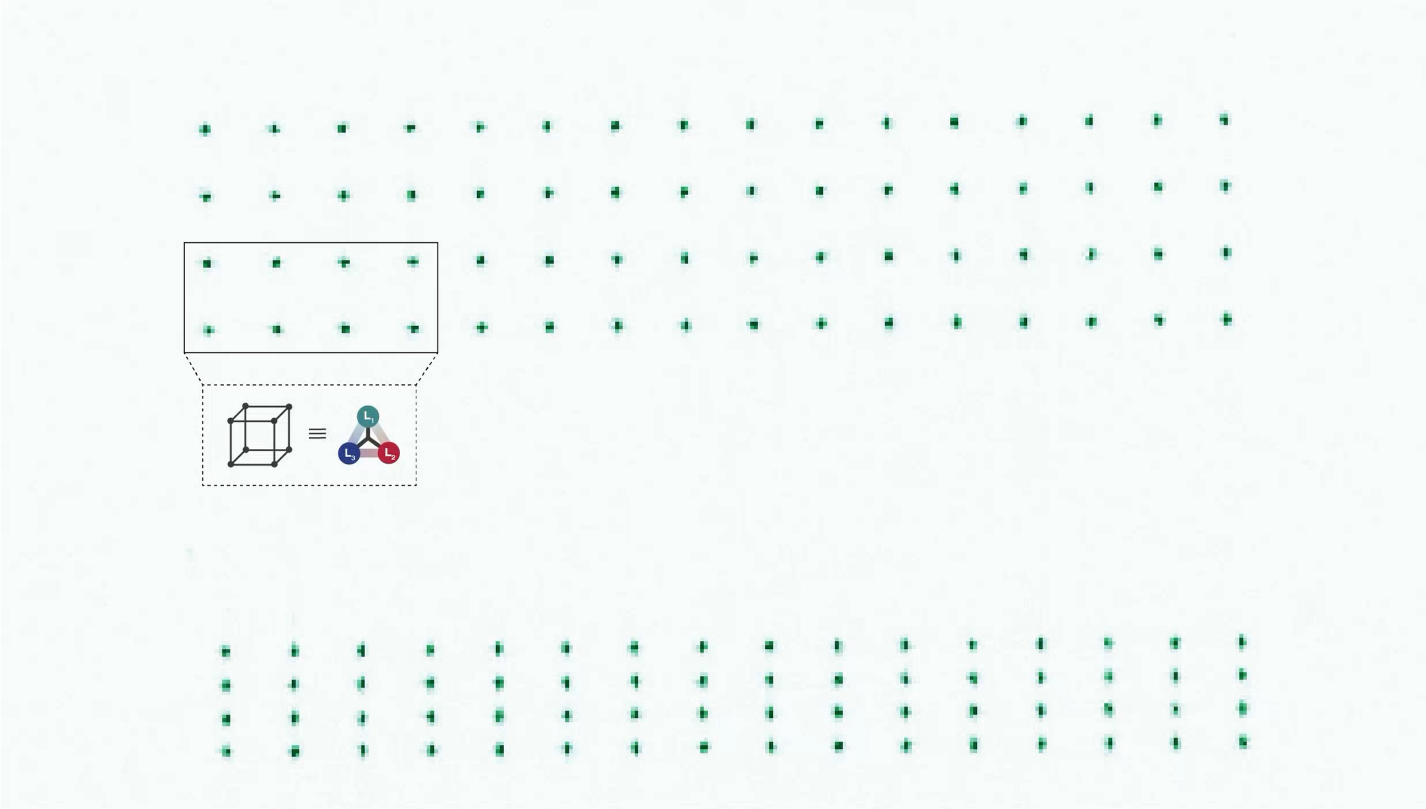
Dynamics Example #1



Dynamics Example #2



Bluvstein et al., Nature (2022)

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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	**99.53 - 99.62%**	**99.70%**	**2%, 2%, 41%, 17%, 38%**

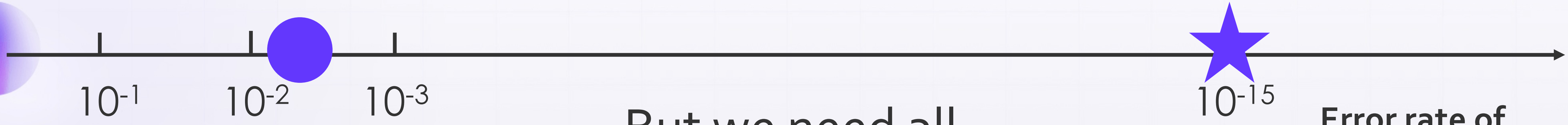
- *Evered*, Bluvstein*, Kalinowski* et al., Nature 2023; See also Ma et al., Scholl et al., Nature 2023. Cong et al., PRX 2022, Wu et al., Nature Comm. 2022, Sahay et al., PRX 2023*

Outlook

Quantum error correction will bridge this gap!

Physical error rates today

What large-scale quantum algorithms require



Error rate of encoded qubit

But we need all breakthroughs possible…

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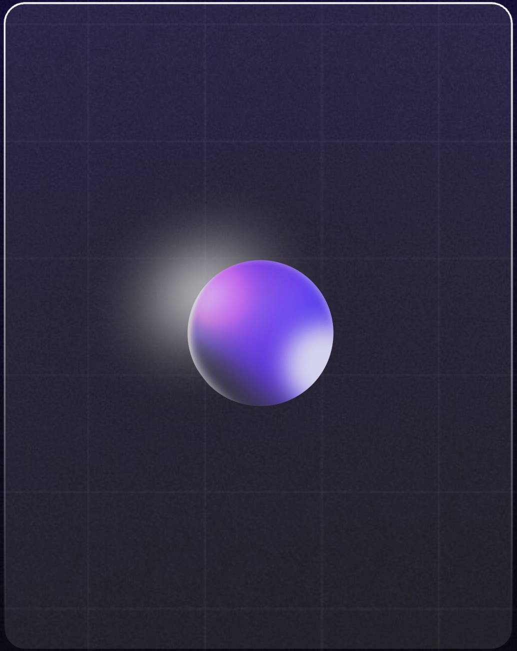
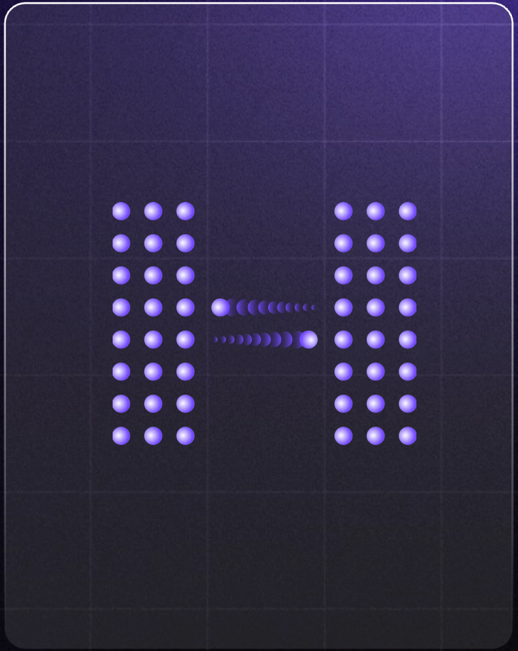
Image generated with DALL E

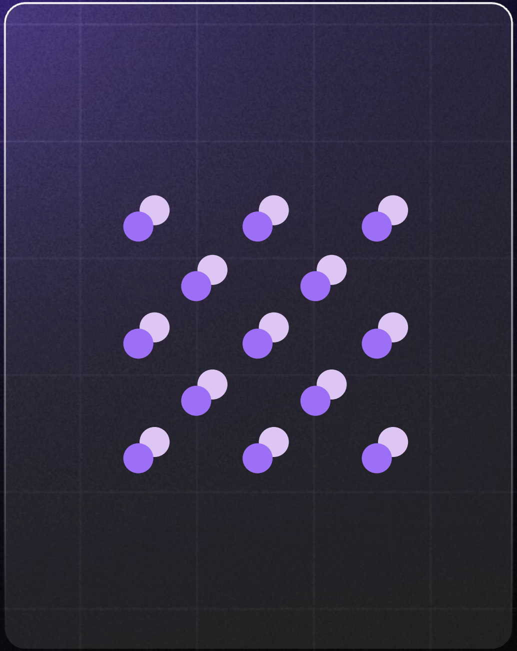
Neutral-atoms contributions



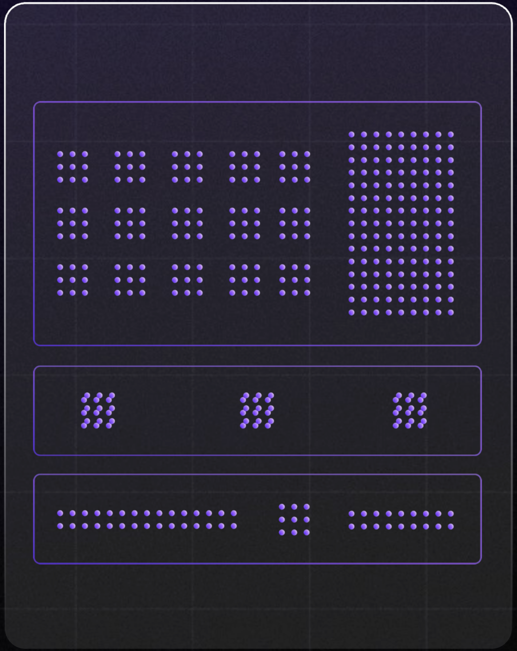
Neutral Atoms



Qubit Shuttling

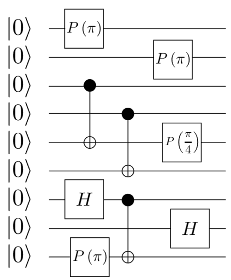


Parallel Operations



Zoned Architecture

Final words



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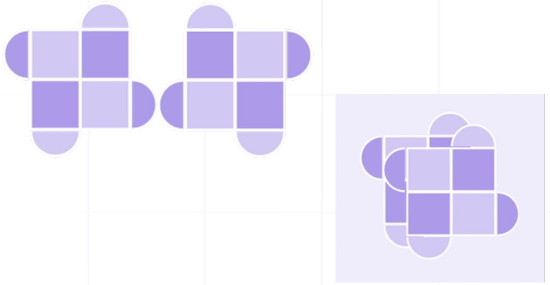

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