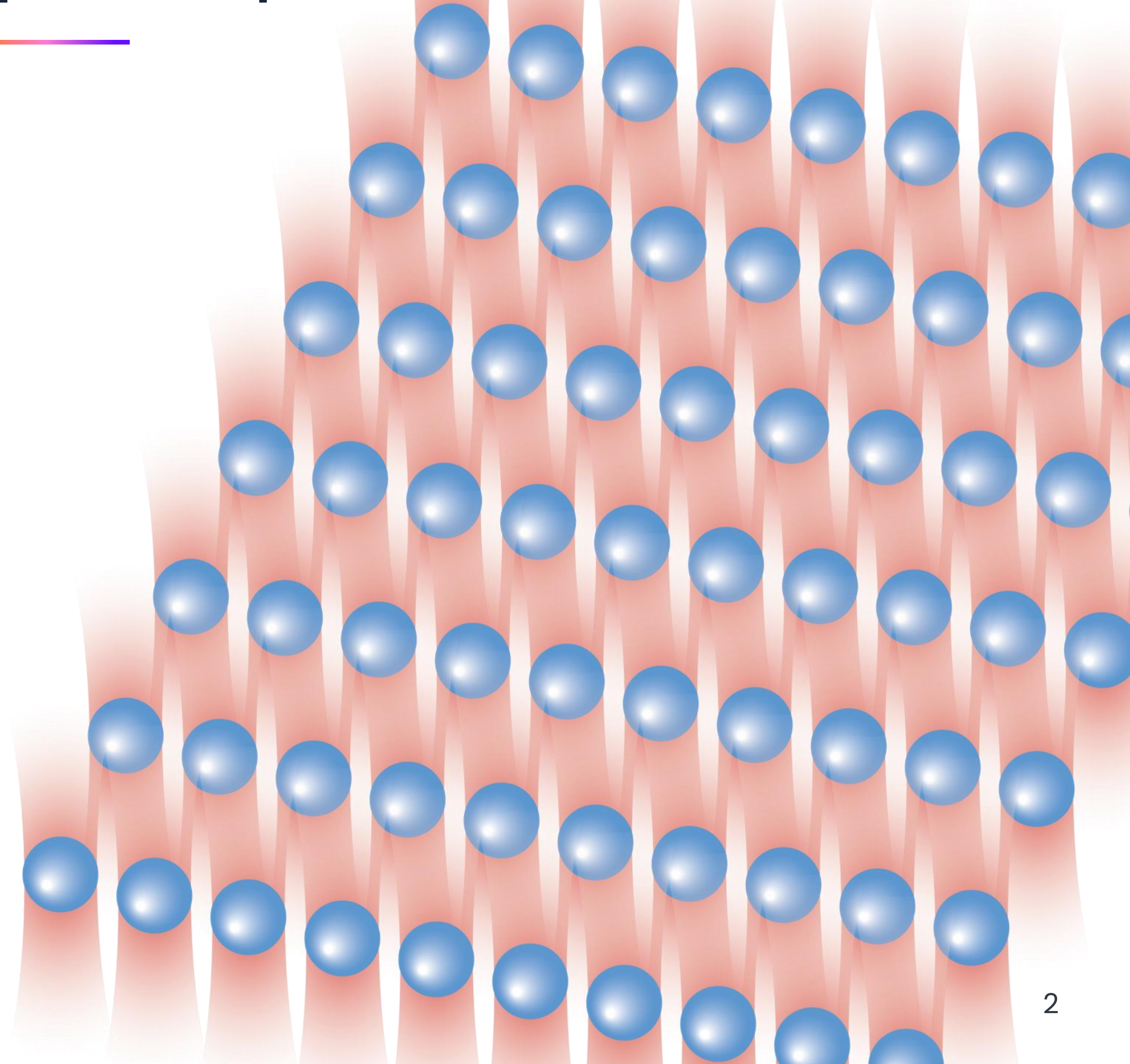
QuEra
Putting Quantum to Work

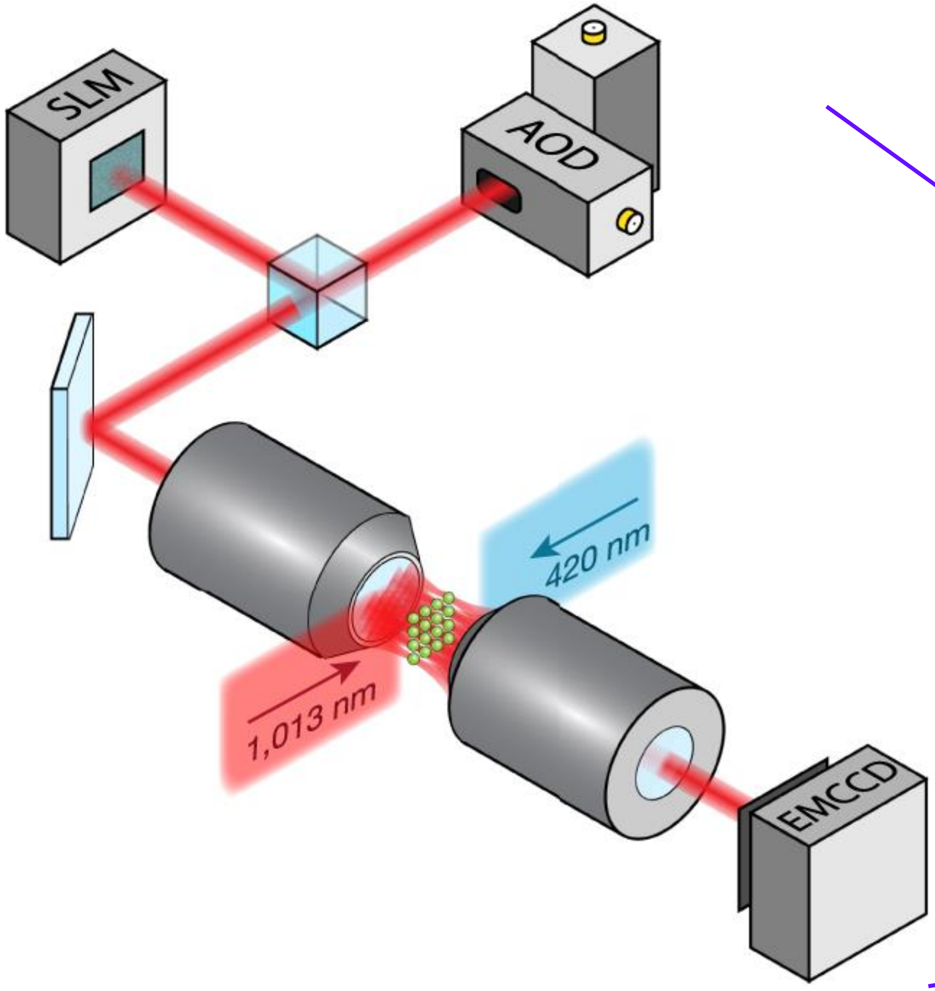
Introduction: Gate-based quantum computing with neutral-atoms

Neutral-atom quantum processor

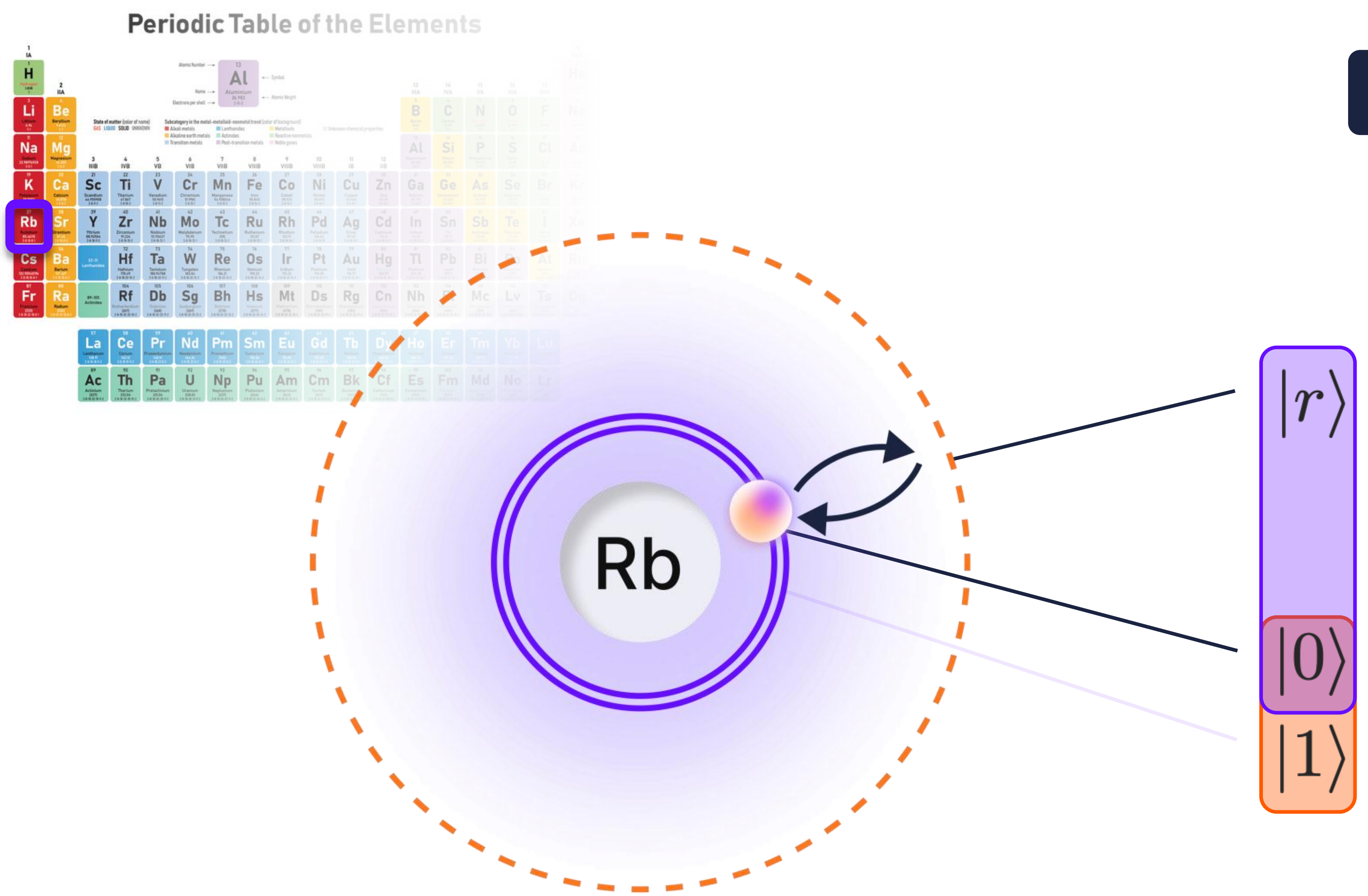
- Atoms (qubits) trapped on laser tweezers
- Densely packed qubits
- Efficient qubit control
- Flexible problem encoding
- New ways to think quantum computing!



Hardware elements overview



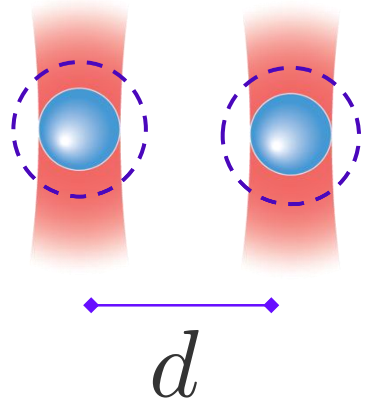
Rubidium qubit inner works



Entanglement through high-energy level

Strong geometrically controlled interactions

$V \sim d^{-6}$



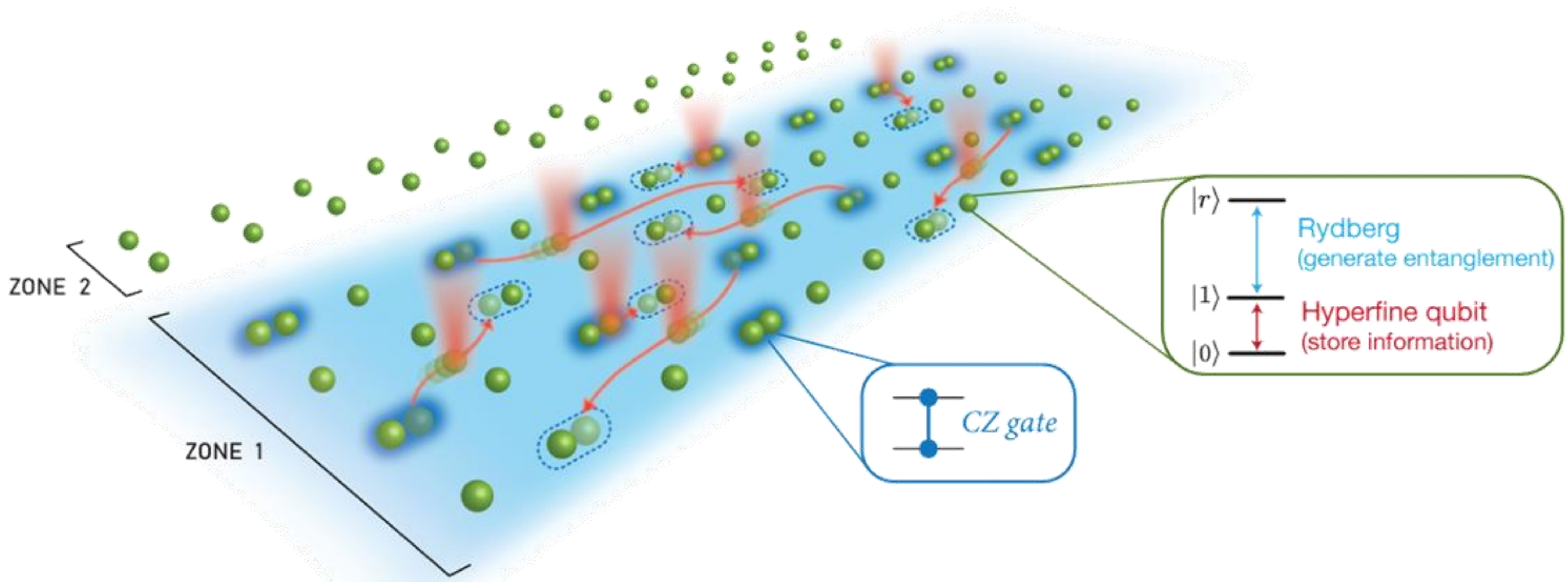
Rydberg state

Hyperfine states

Long coherence times
High stability, flexibility

Information storage in low-energy levels

Basic architecture: mid-circuit reconfigurability



Bluvstein et al., Nature (2022)

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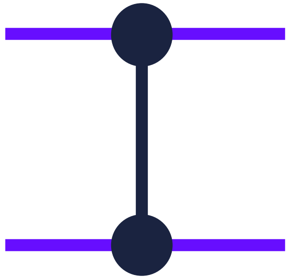
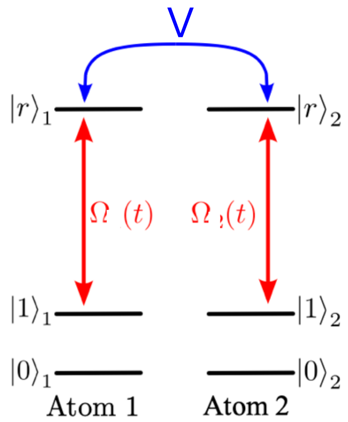
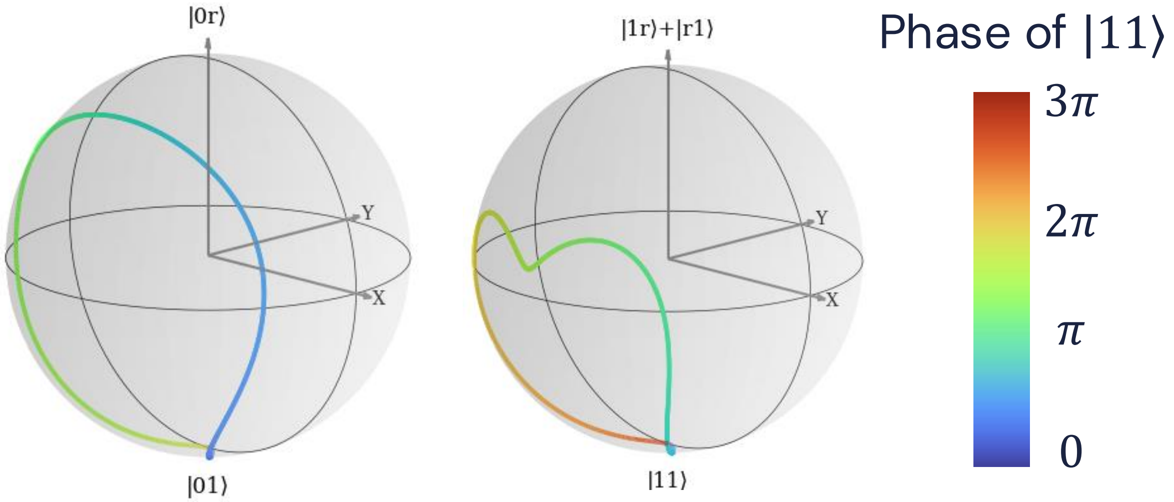
Native gates

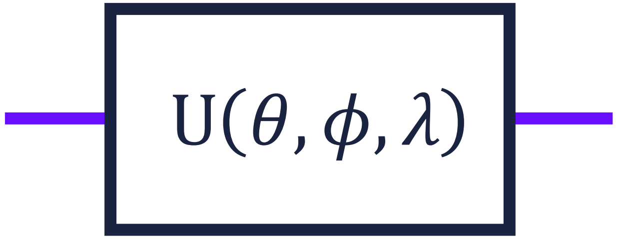
Controlled-Z gates



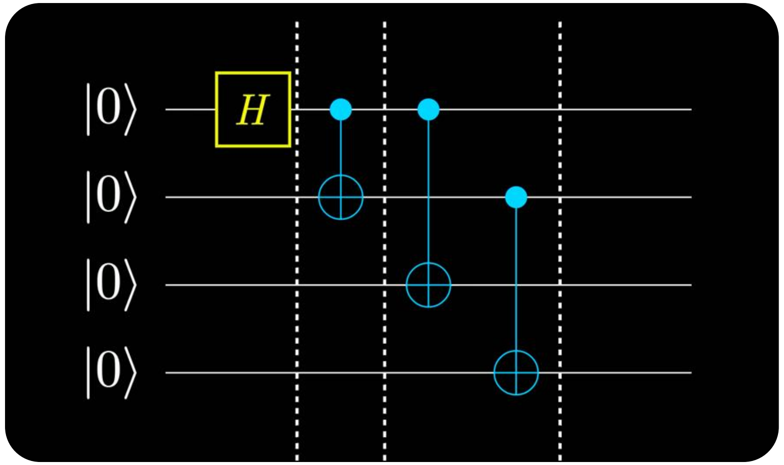




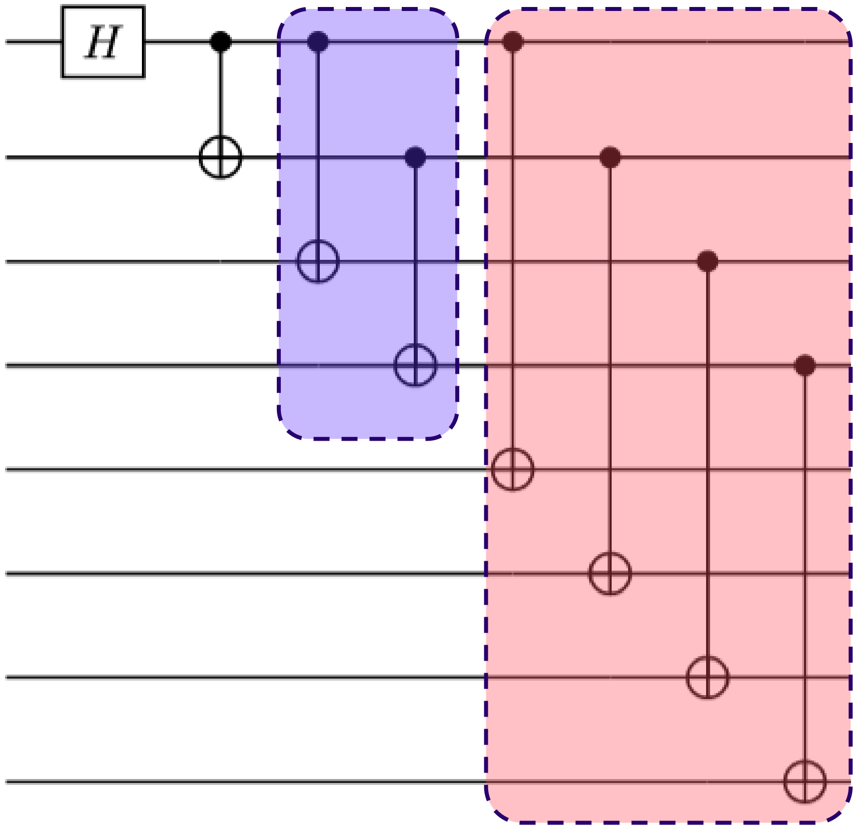
Arbitrary 1-qubit rotations (Z * XY-plane rotations)

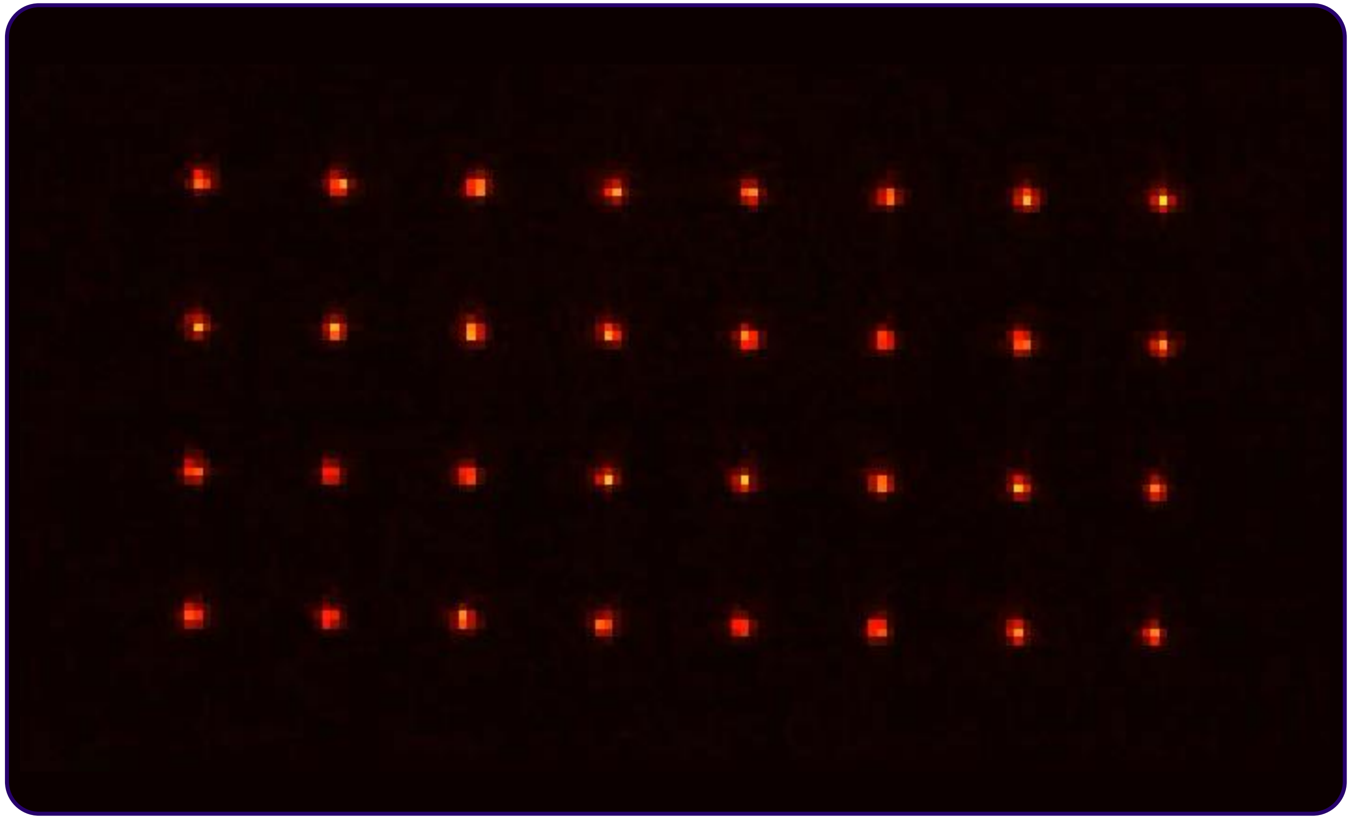


Hardware-native compilation (GHZ prep.)

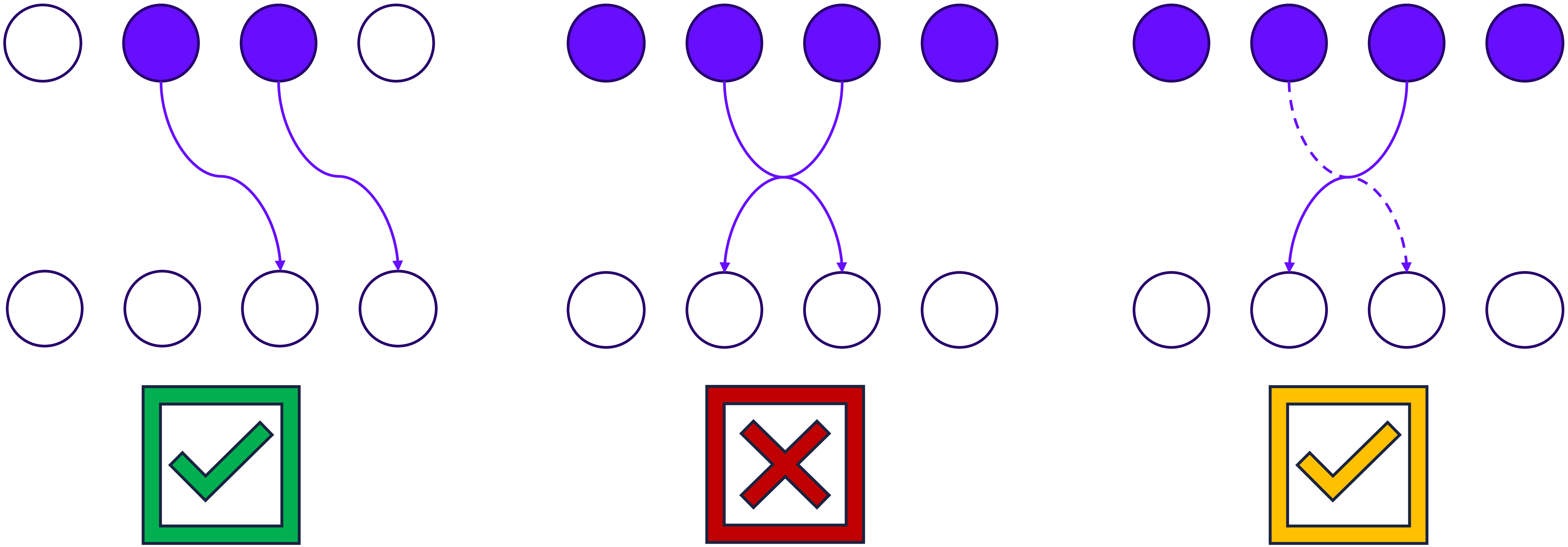


Entangling and logic through reconfiguration



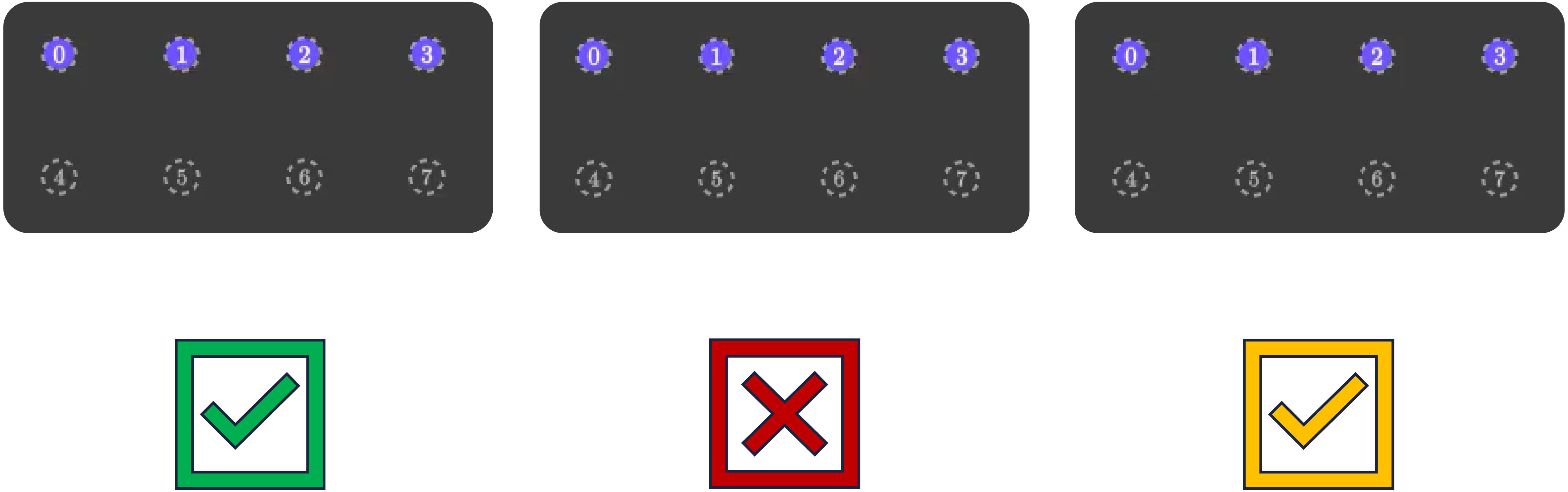


Atom shuttling rules #1 – crossing conflict



Atom shuttling rules #1 – crossing conflict

"atoms cannot collide"
"atoms cannot change order in a single move"



Activity: why these rules?

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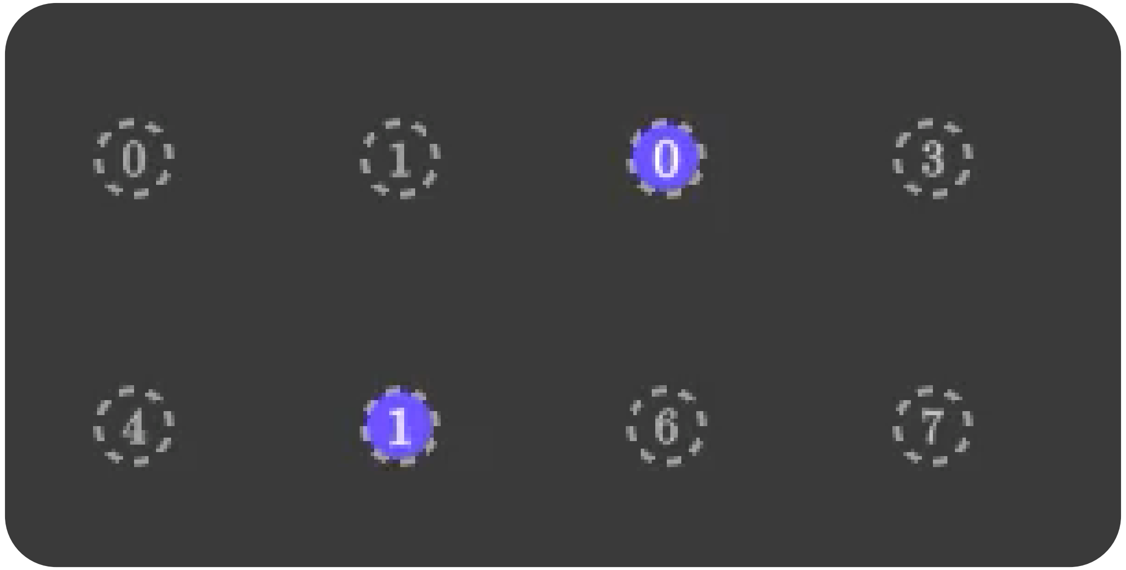
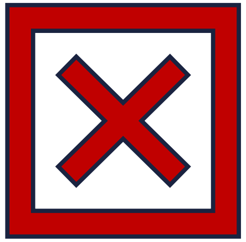
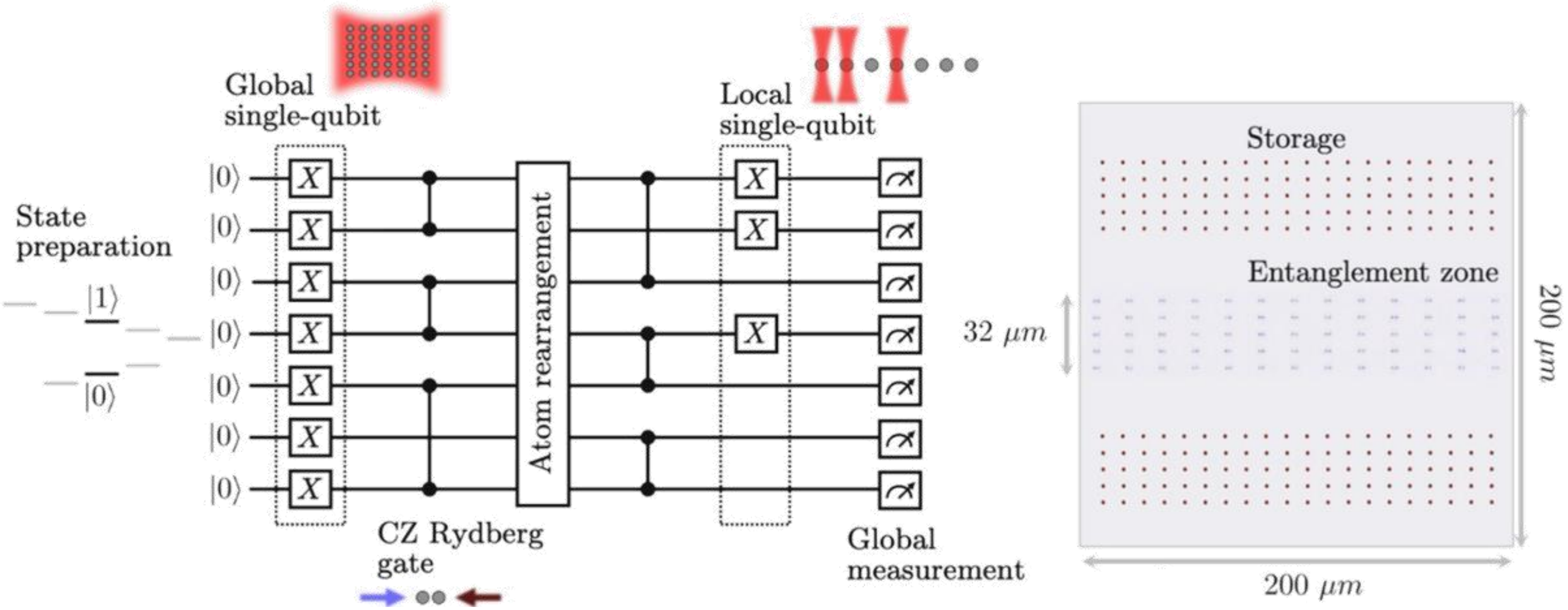
Atom shuttling rules #2 – "many-to-one" conflict (bonus)

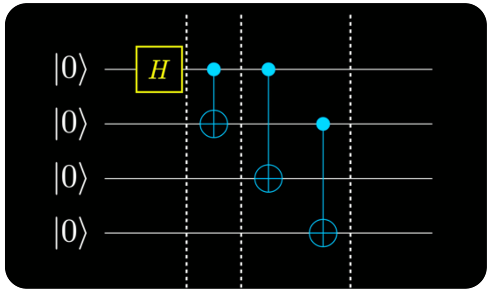


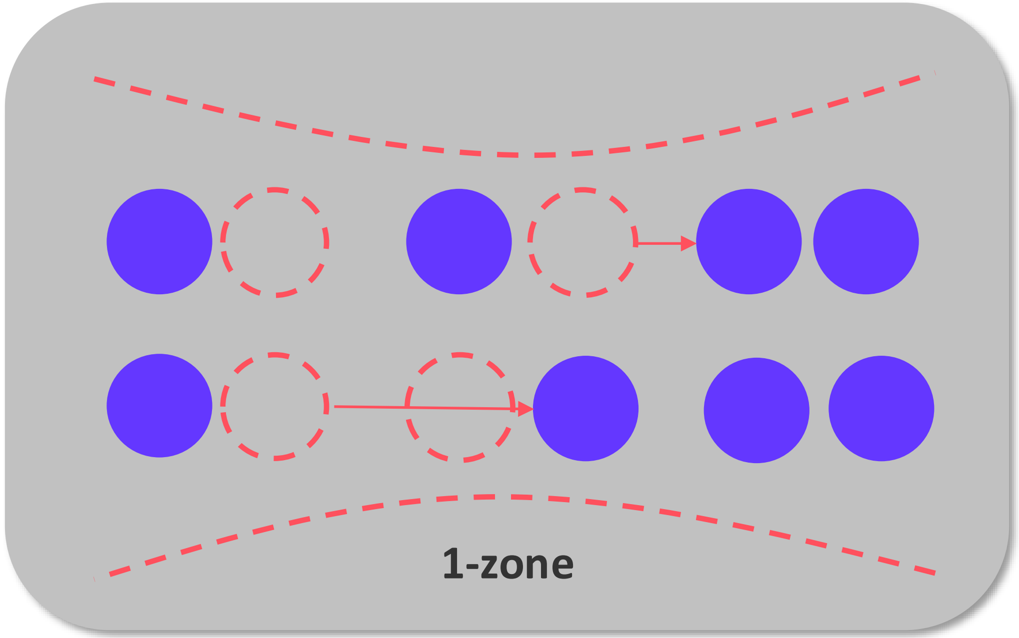


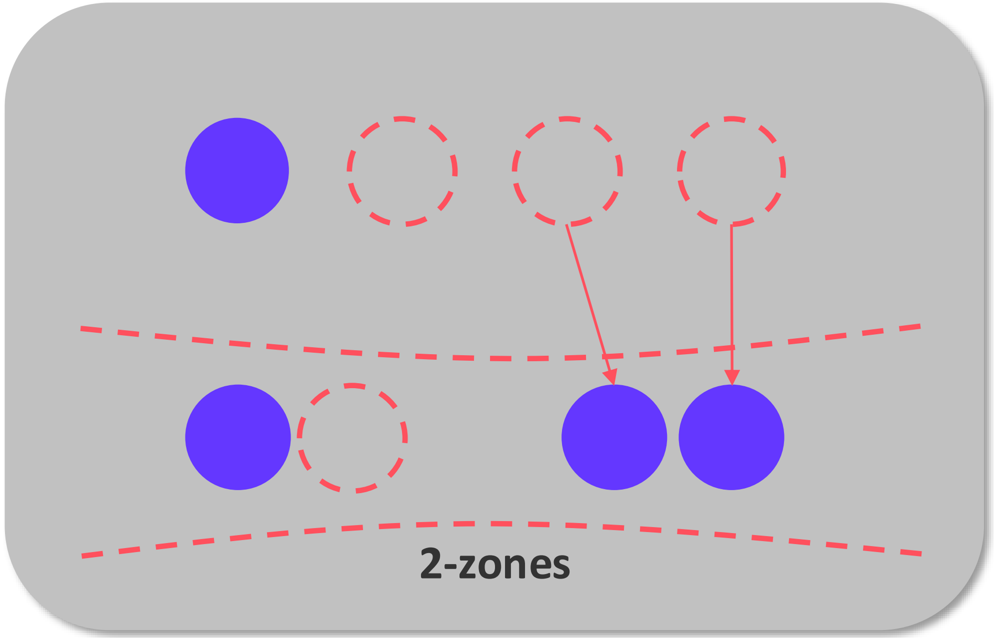
Systems overview

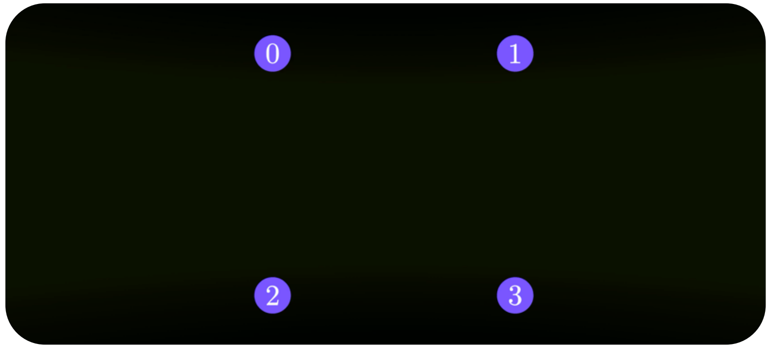


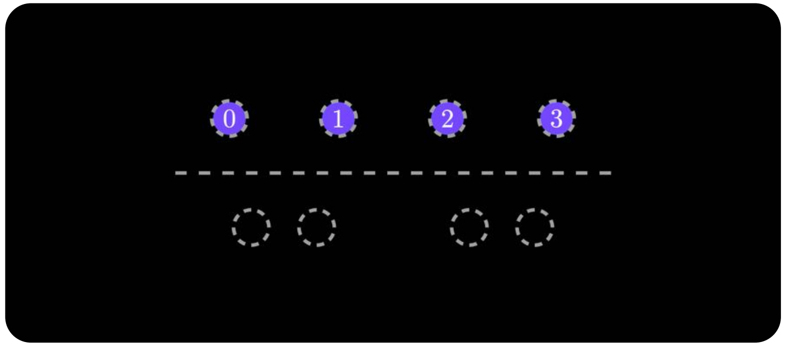
Zoned architectures



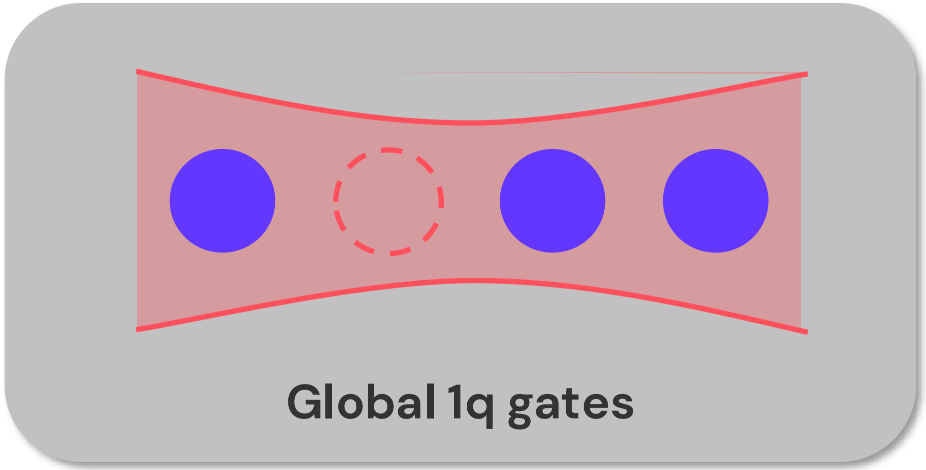


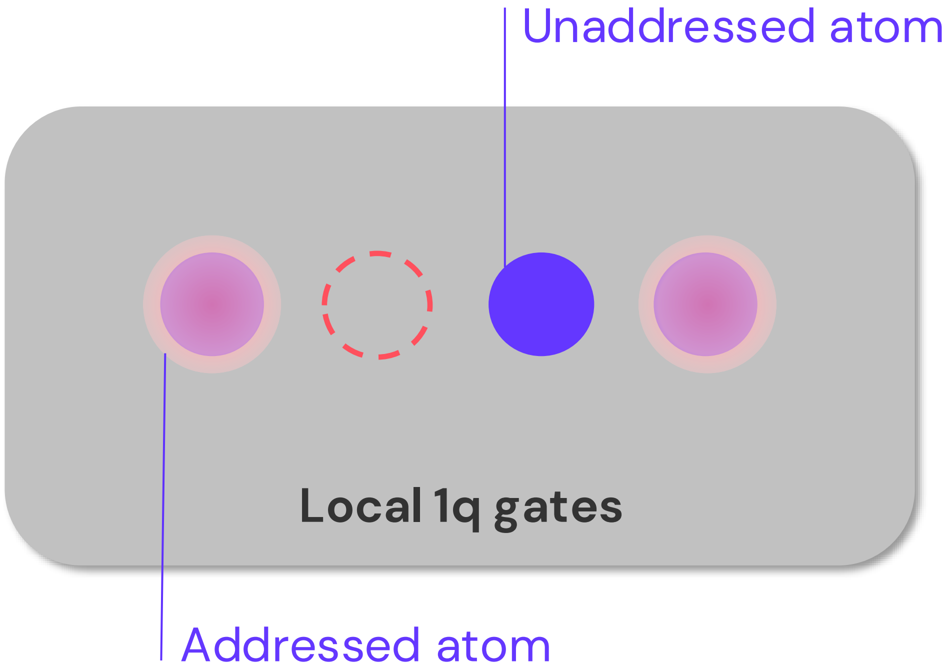






Error channels – single qubit operations



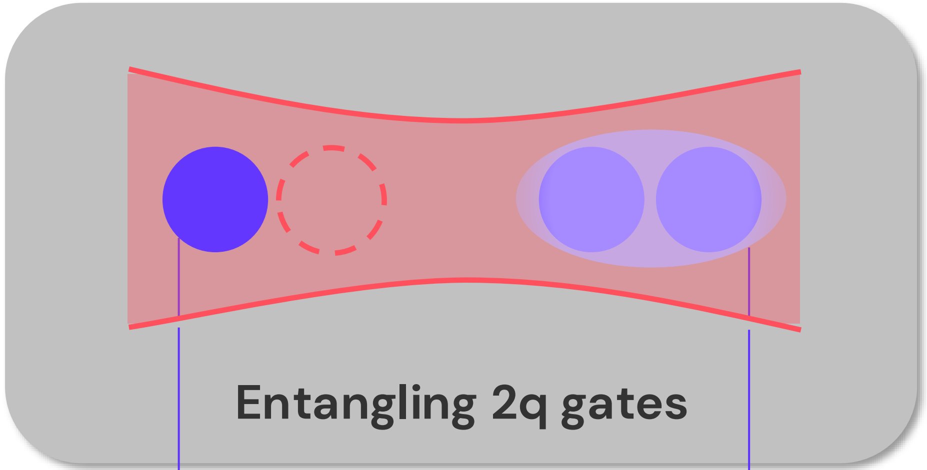


Error budget ~ 10^{-5}

Error budget ~ 10^{-4}

Bluvstein et al., Nature ’23, ’24,’25
Evered et al., Nature ’23
Rodriguez et al. Nature ’25

Error channels – two-qubit operations



Paired/entangled atoms

Error budget ~ 10^{-3} (z-biased)

Unpaired/spectator atom

Error budget ~ 10^{-3} (z-biased)

Bluvstein et al., Nature '23, '24,'25
Evered et al., Nature '23
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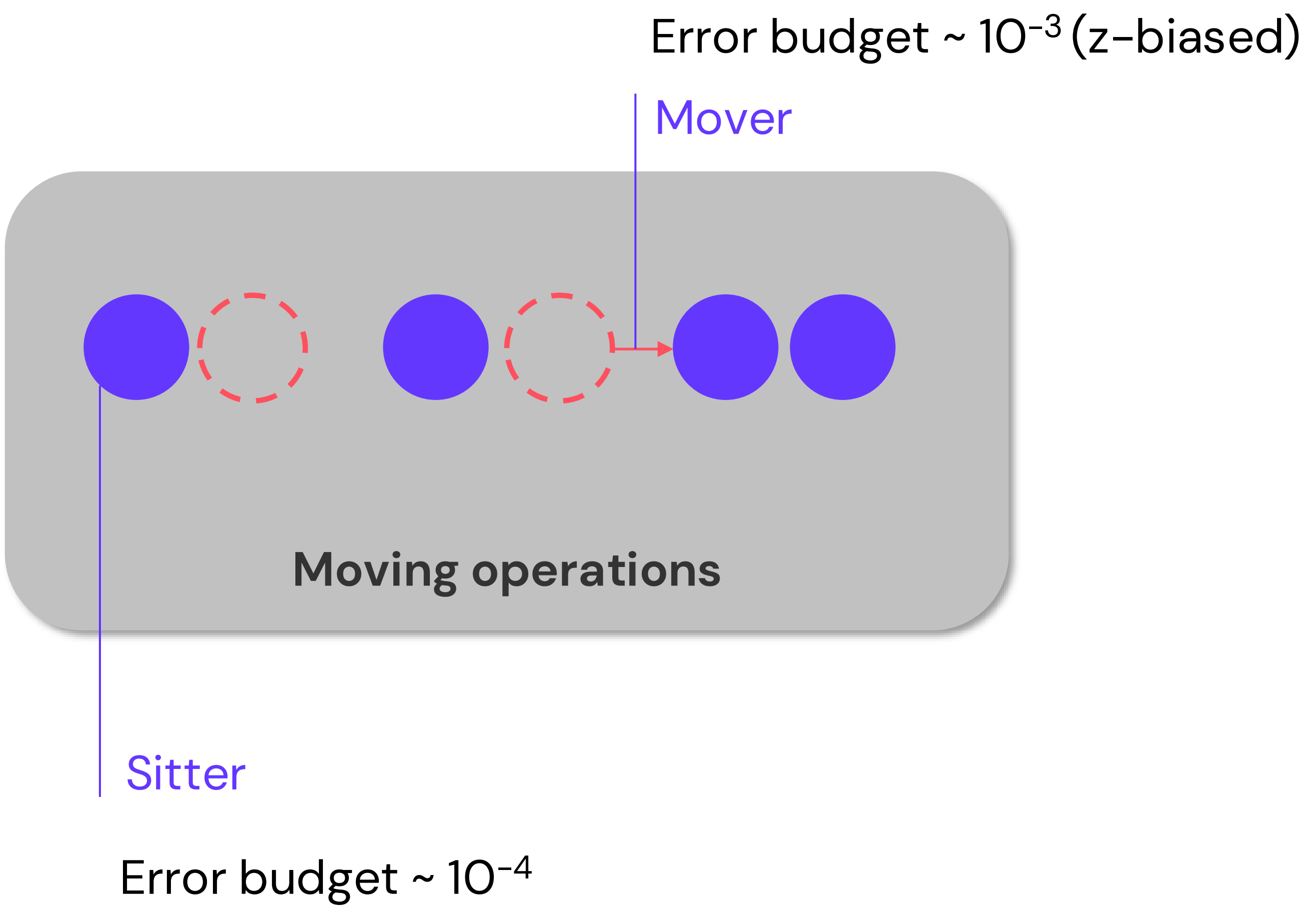
Error channels – shuttling



Bluvstein et al., Nature ’23, ’24,’25
Evered et al., Nature ’23
Rodriguez et al. Nature ’25

Noise hierarchy

$$\underbrace{E_{CZ} \gtrsim E_{mover} \sim E_{unpaired}}_{\text{Z-biased}} > E_{sitter} \sim E_{1-qubit,local} > E_{1-qubit,global}$$

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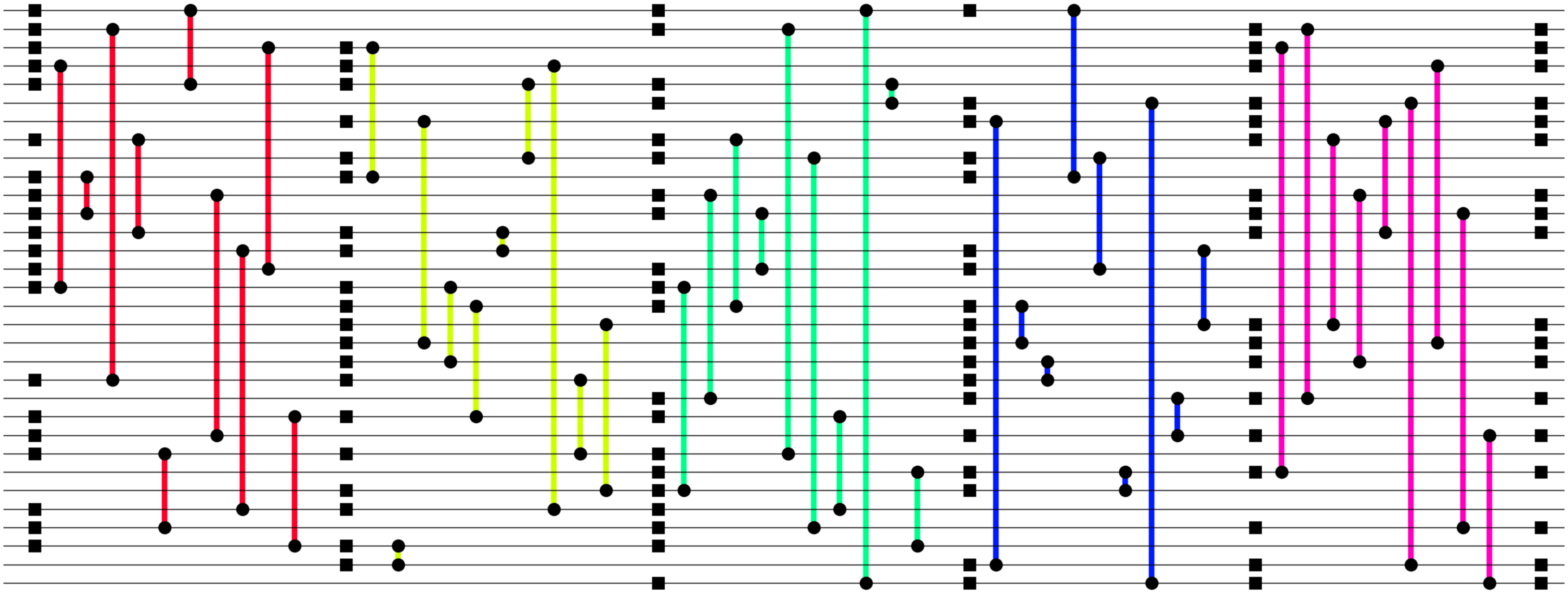
Program design goals



Programming tools hierarchy

Bloqade

Bloqade Analog

Analog Hamiltonian Simulation

QuEra Analog mode Hardware (Aquila)

Bloqade Circuit

Cirq suite

Noise modeling

Squin

Circuit synthesis

Bloqade Shuttle

Atom shuttle move scheduling

built with: **Kirin**

Compiler toolchain

Programming pipeline

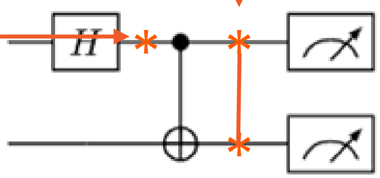
Squin: Bloqade's circuit composition dialect

Kernel for automatic compiler interpretation

```python
@squin.kernel
def noisy_linear_ghz(n: int, p_single: float, p_paired: float):
    q = squin.qalloc(n)

    squin.h(q[0])
    squin.depolarize(p_single, q[0])

    for i in range(1, n):
        squin.cx(q[i - 1], q[i])
        squin.depolarize2(p_paired, q[i - 1], q[i])

    return squin.broadcast.measure(q)
```

parallel ops

Noise insertion



Cirq utils for automatic annotation from heuristic hardware-inspired noise models

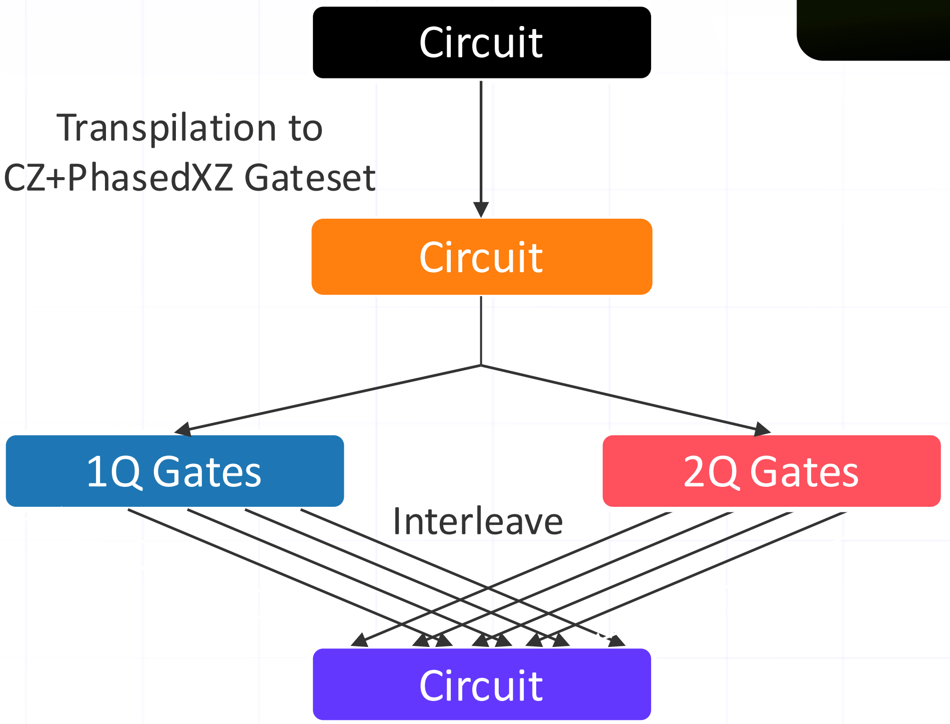
```
noise_model = noise.G
    GeminiTwoZoneNoiseModel
    GeminiOneZoneNoiseModel
    GeminiOneZoneNoiseModelABC
    GeminiOneZoneNoiseModelConflictGraphMoves
    GeminiOneZoneNoiseModelCorrelated
    conflict_graph
    OneZoneConflictGraph
```

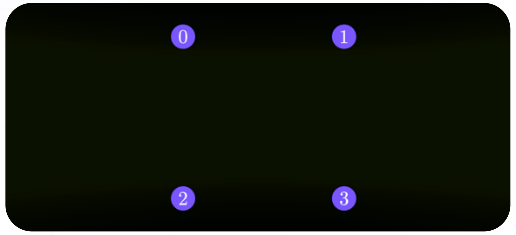
```
noise_model = noise.GeminiOneZoneNoiseModel()
noisy_ghz_circuit_3 = noise.transform_circuit(ghz_circuit_3, model=noise_model)
print(noisy_ghz_circuit_3)
✓ 0.0s

0: ───PhXZ(a=0.5,x=0.5,z=0)───A(0.00041,0.00041,0.000411)───A(0.000806,0.000806,0.002

1: ───PhXZ(a=0.5,x=0.5,z=0)───A(0.00041,0.00041,0.000411)───A(0.000307,0.000307,0.000

2: ──────────────────────────────────────────────────────────A(0.000307,0.000307,0.000
```

- **Atom moving composition**
- **Simulation (Pyqrack, Stim, Tsim)**
- **Noisy circuit analysis**
- Quantum hardware

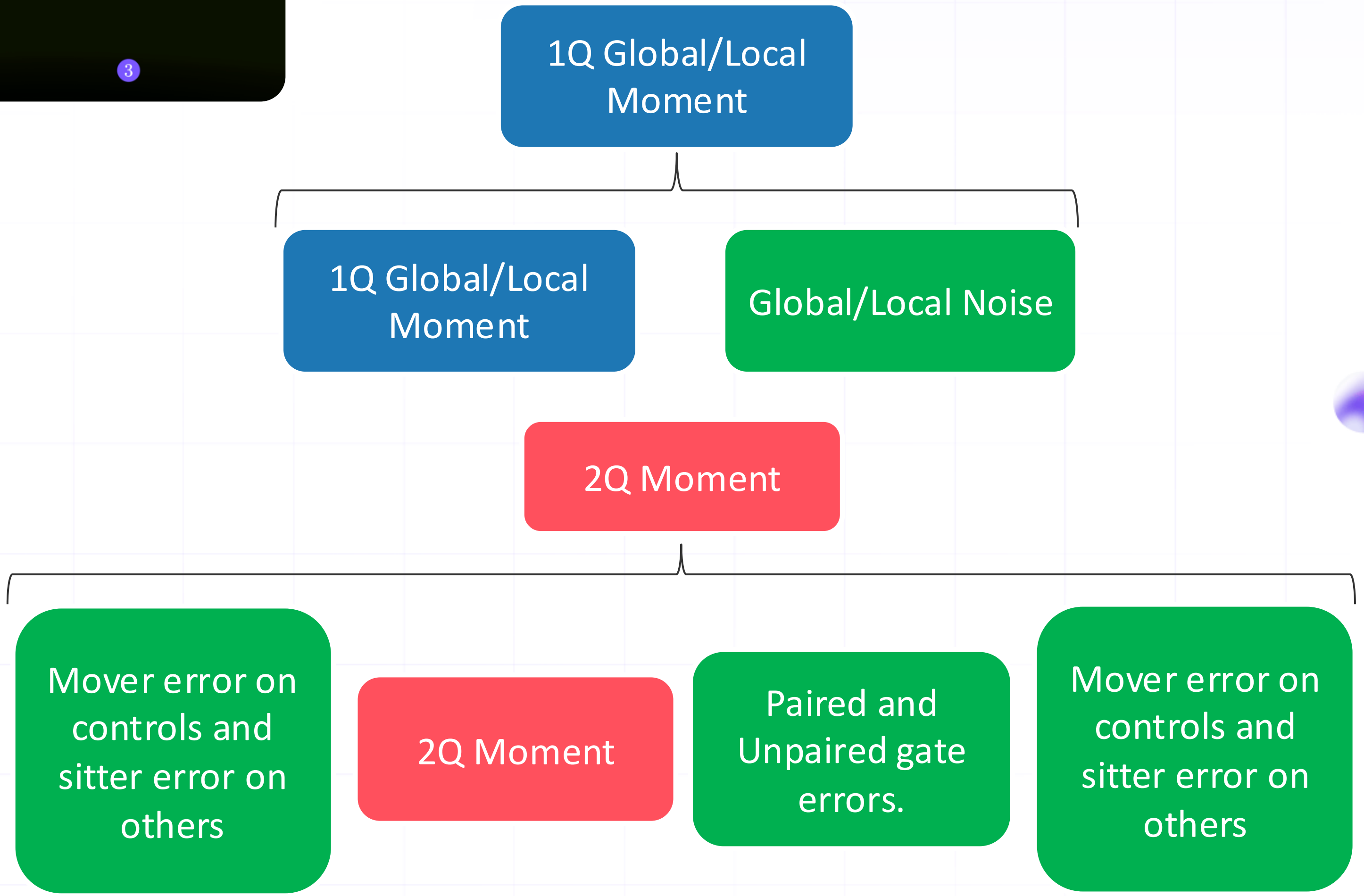
Heuristic noise model - one-zone logic

Step 1





Step 2



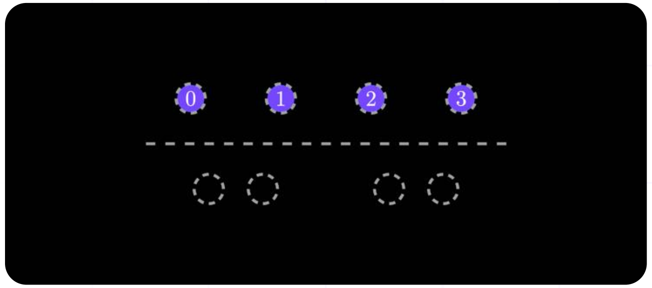
Heuristic noise model – two-zone logic

Step 1.
Transpilation to U3 (or PhasedXZ)+CZ gateset

Circuit

CZ+PhasedXZ Gateset

Circuit



Step 2.
Main assumption: all gates in a moment are executed in the gate zone

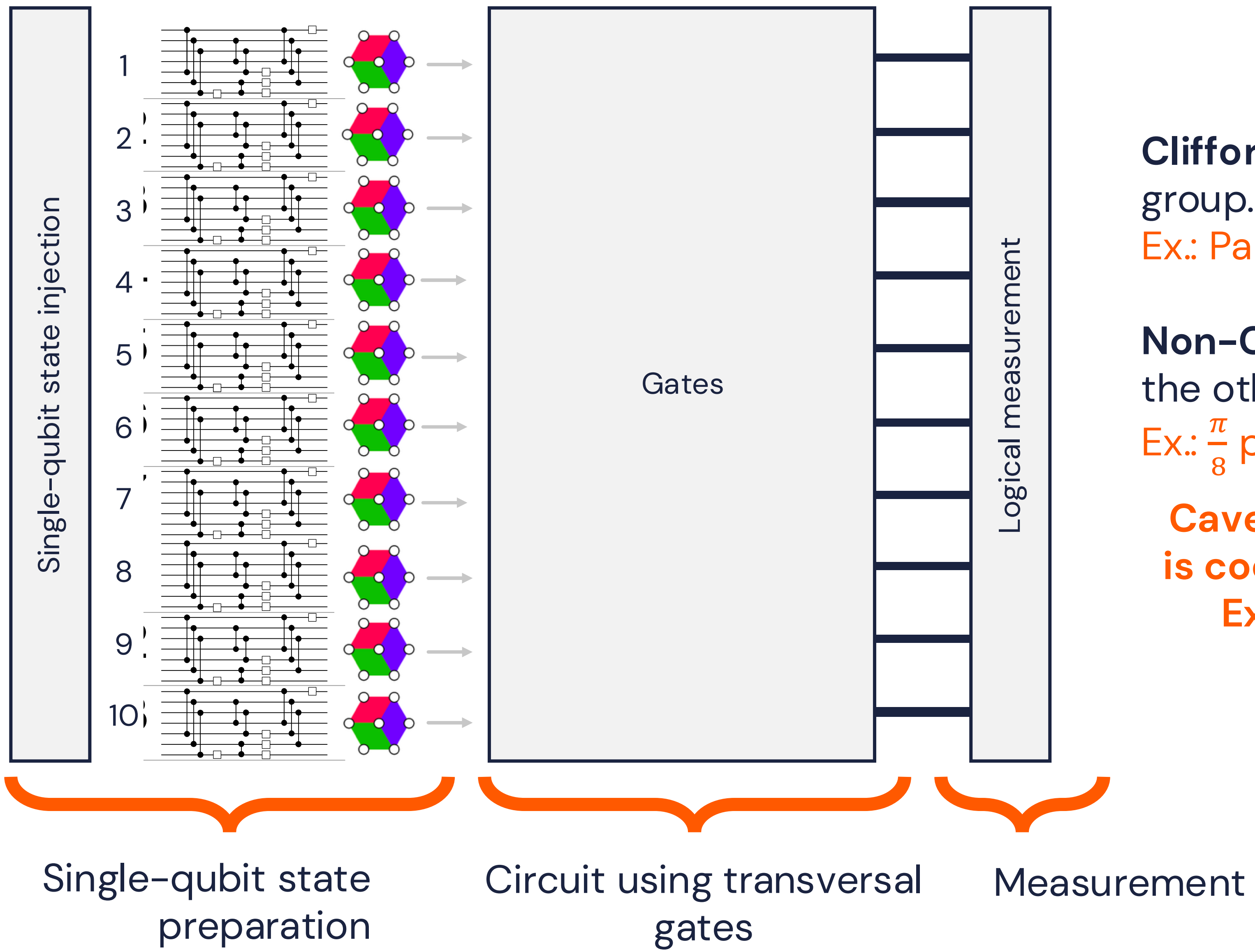
Moment

- Mover error. (Removal+addition of qubits to gate zone). Rest gets sitter error
- Mover error. Qubit reconfiguration before gate execution
- Moment
- Gate errors

Caveats:

- Assumes qubits **must** be in entangling zone to be operated on
- Gates in a moment are performed **together**

Quantum Error Correction 101



Universal gate set

Clifford gates – preserve Pauli group. (“Cheap”)
Ex.: Paulis, Hadamard, CNOT

Non-Clifford gates (magic) – all the others. (“Expensive”)
Ex.: $\frac{\pi}{8}$ phase (T gate), Toffoli

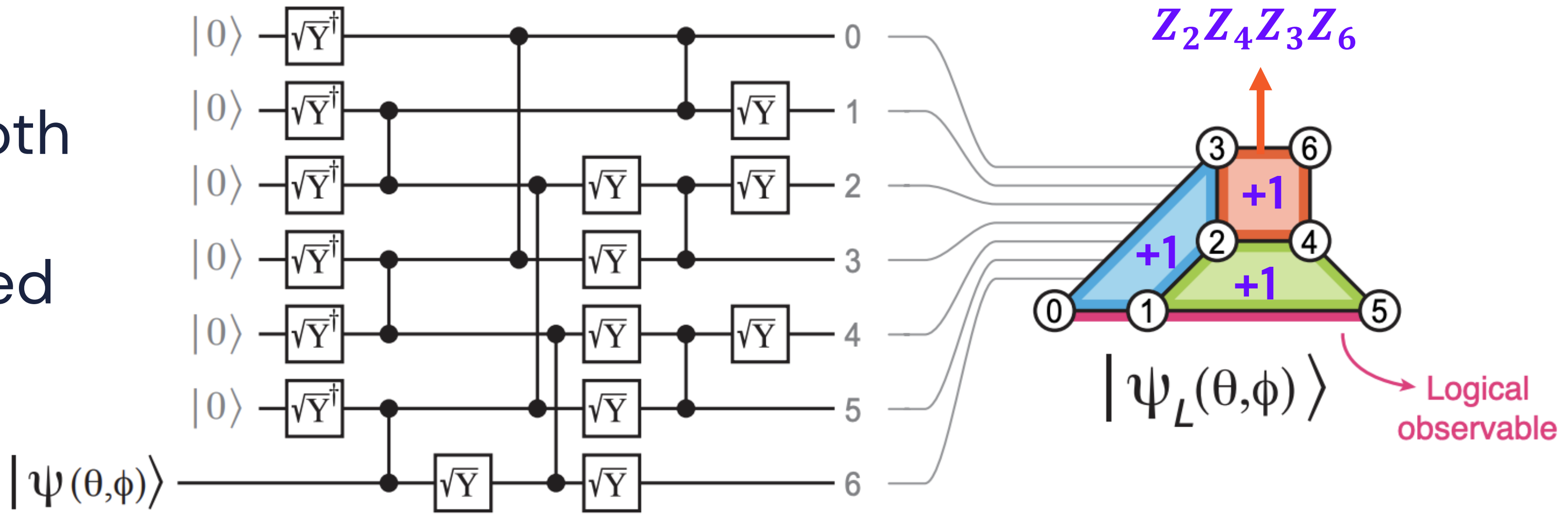
Caveat: cheap/expensive is code/basis-dependent! Examples above are stereotypical

The d=3 color (Steane) code

Error correction: extract errors from **syndrome parity** measurements

Color code: syndromes are 4-bit parity measurements. 7 bits can correct 1 error.

Quantum error correction: correct both X and Z errors without destroying the encoded qubit.



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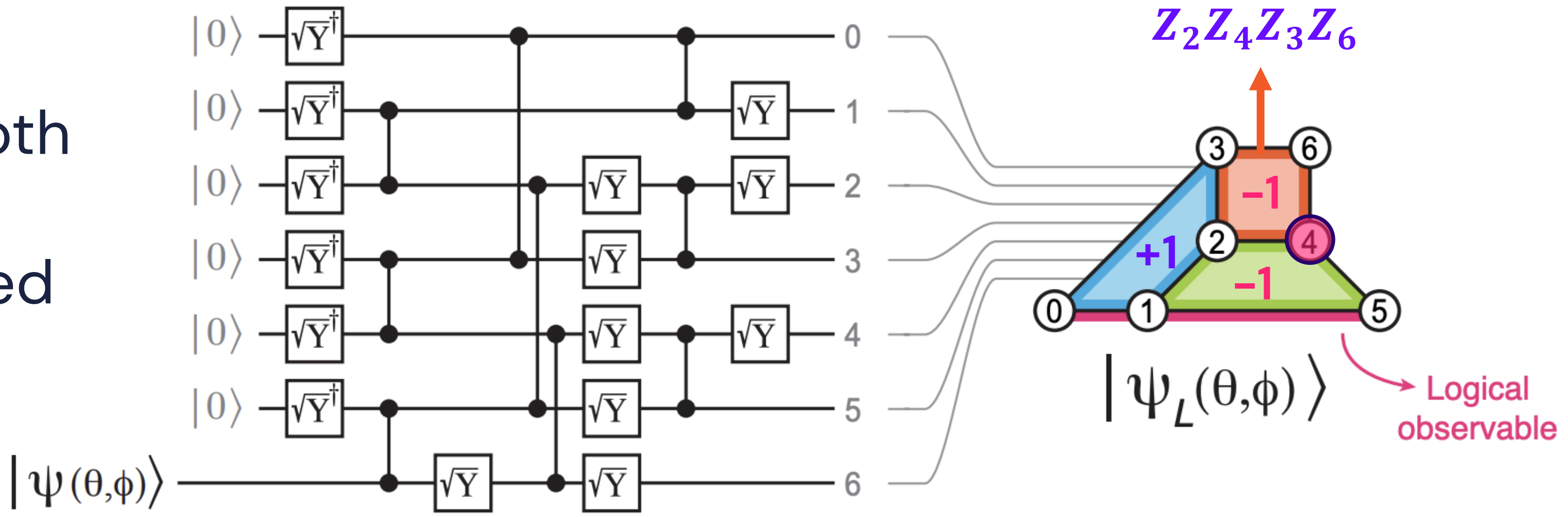
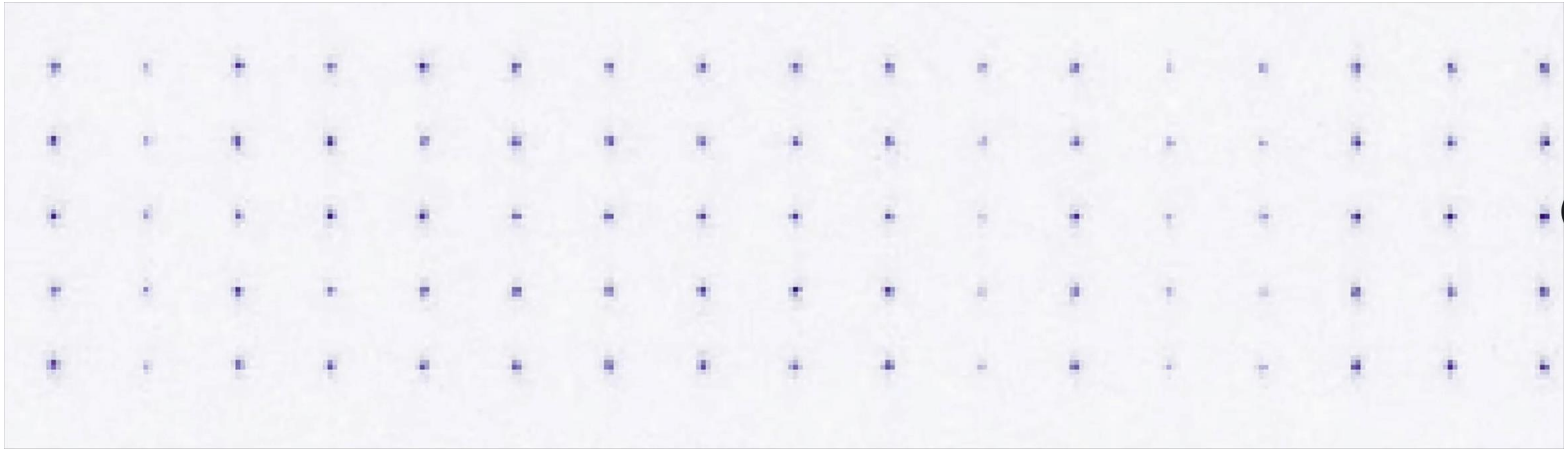
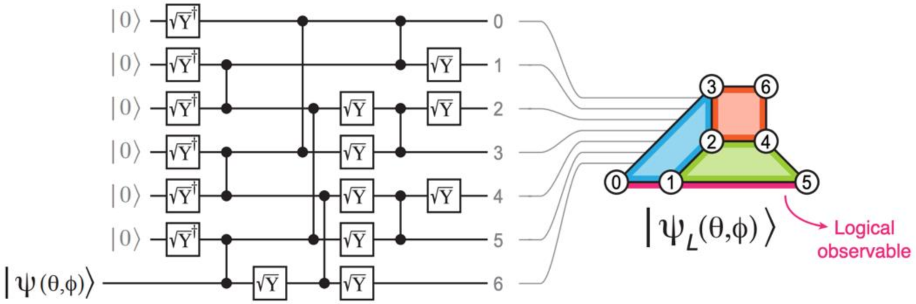


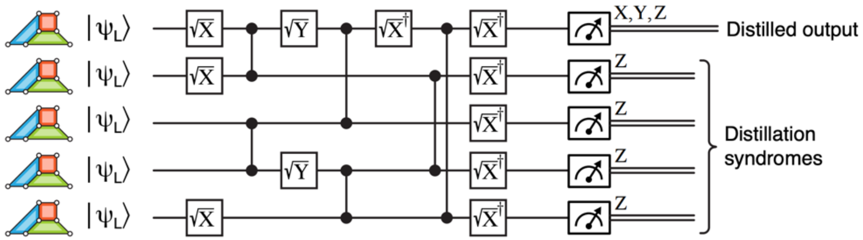
Logical operations example



State prep: magic state injection



Algorithmic primitive: magic state distillation



Get ready!

A new foe has appeared!

QuEra Technical Challenge – Noise, Geometry, and Fault Tolerance
Explore how real-world hardware constraints, noise, and geometry shape the performance of quantum circuits, and discover how clever design choices can dramatically change outcomes on neutral-atom platforms.

QuEra Creators' Challenge – Visualizing Quantum Motion
Turn quantum computation into motion, geometry, and story by crafting compelling visual narratives that reveal how algorithms and hardware interact inside a neutral-atom quantum computer.