Modeling noisy quantum circuits for neutra-atom devices

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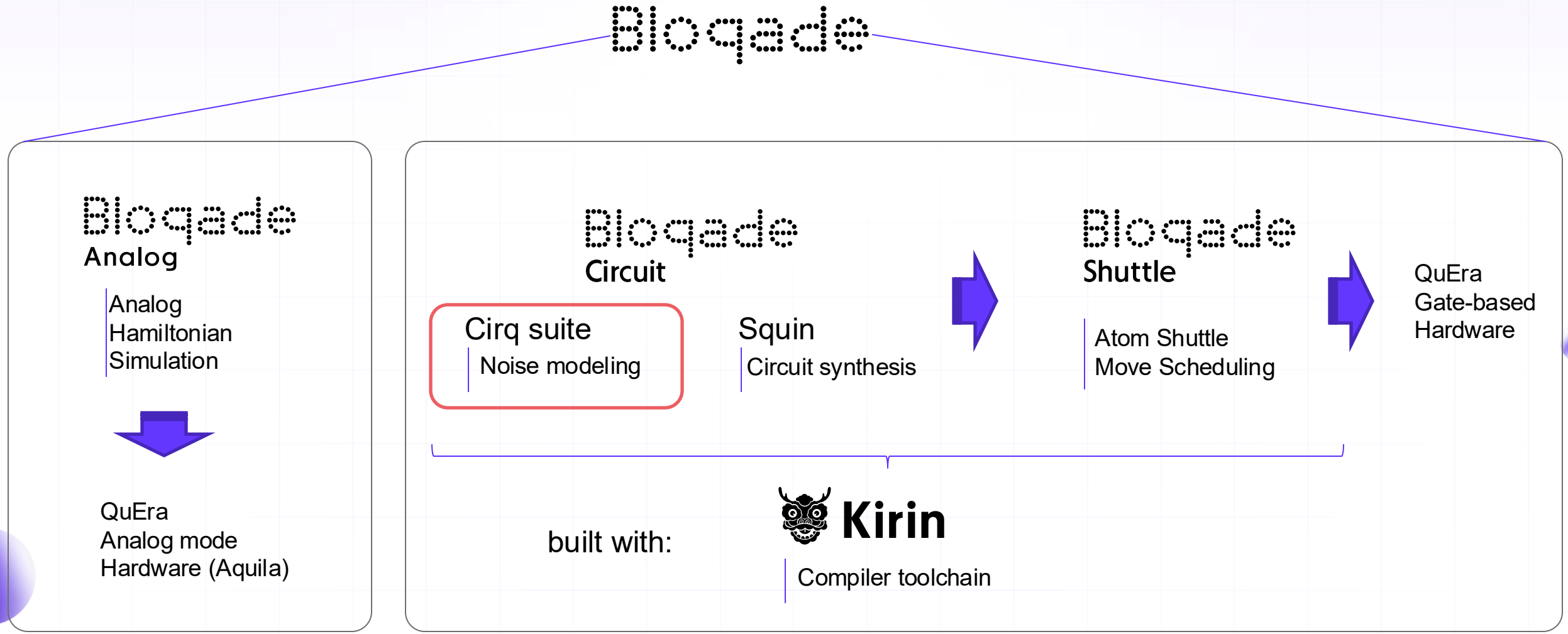
Programming tools hierarchy



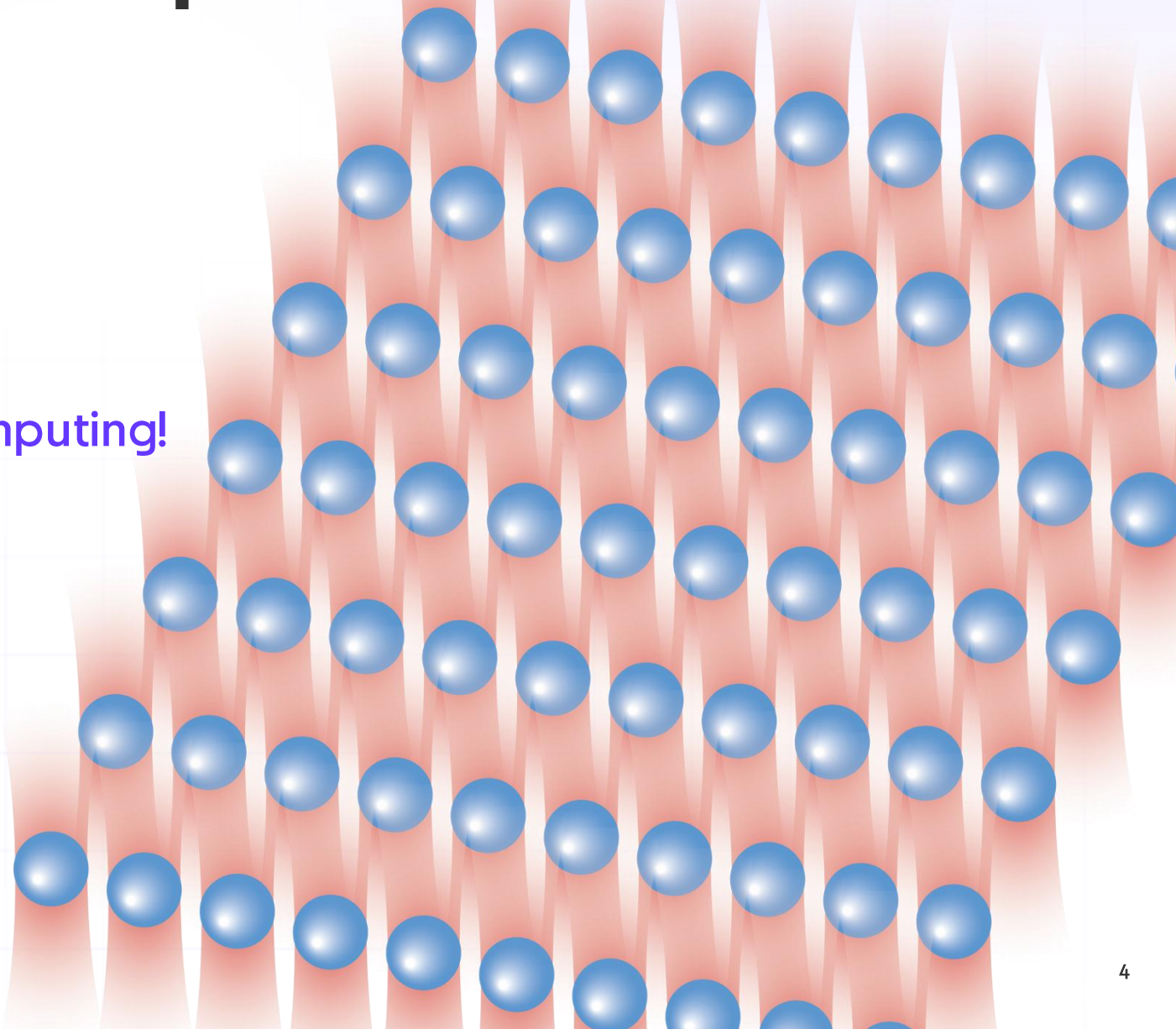
Learning objectives

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

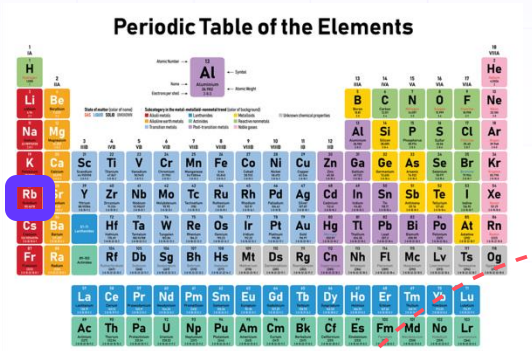
- **Describe** the baseline **functionality** of a digital neutral-atom quantum computer architecture based on zoned architectures
- **State constraints for atom shuttling operations**, register sizes, and geometrical and temporal scales
- **Write down** a phenomenological **hierarchy of the errors** for different operations during a circuit execution
- **Exemplify design rules** for hardware-aware implementation of quantum circuits
- **Validate** strategies of hardware-aware **heuristic noisy** circuit simulation

Neutral-atom quantum processor

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



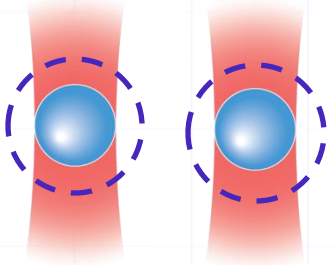
Entanglement mediated by puffing atoms up

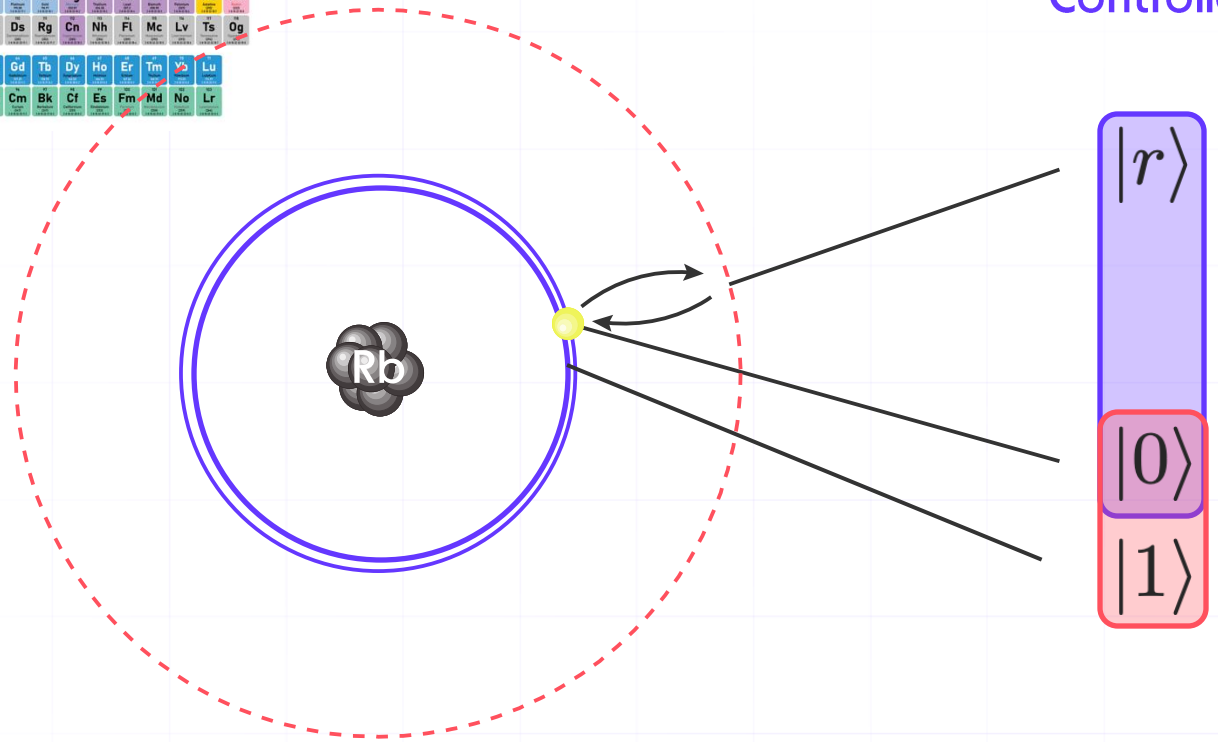


Entanglement via high-energy levels

Strong interactions
Controlled interactions

$V \sim d^{-6}$





Rydberg state

Hyperfine states

Long coherence times
High stability, flexibility

Quantum information in low-energy levels

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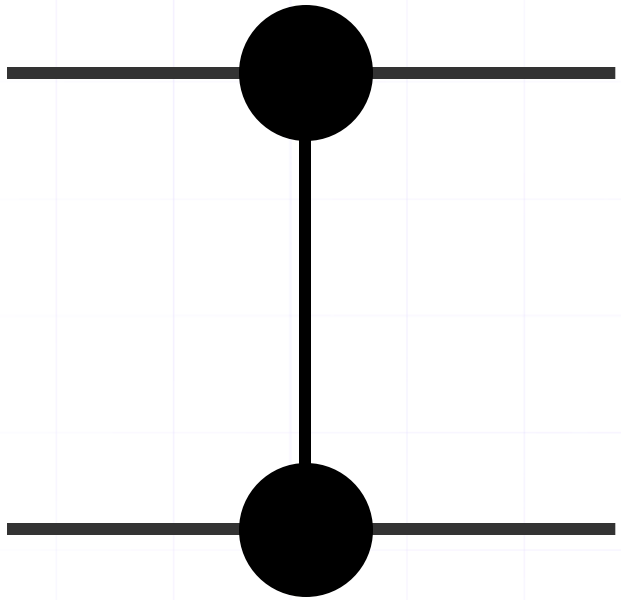
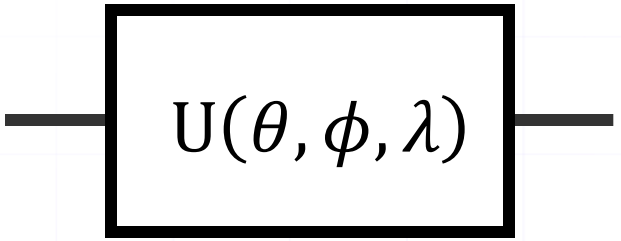
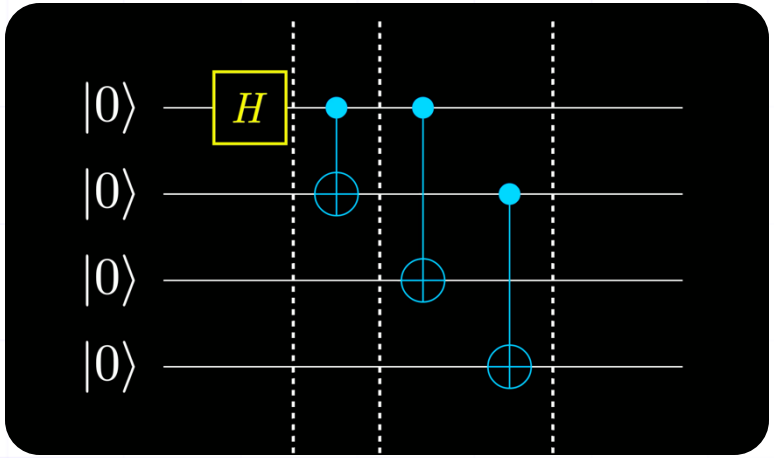
Programming constraints – native gate set

Controlled Z gates



Arbitrary 1-qubit rotations (favoring Z separate from XY-plane rotations





Gemini-class: digital-mode computing

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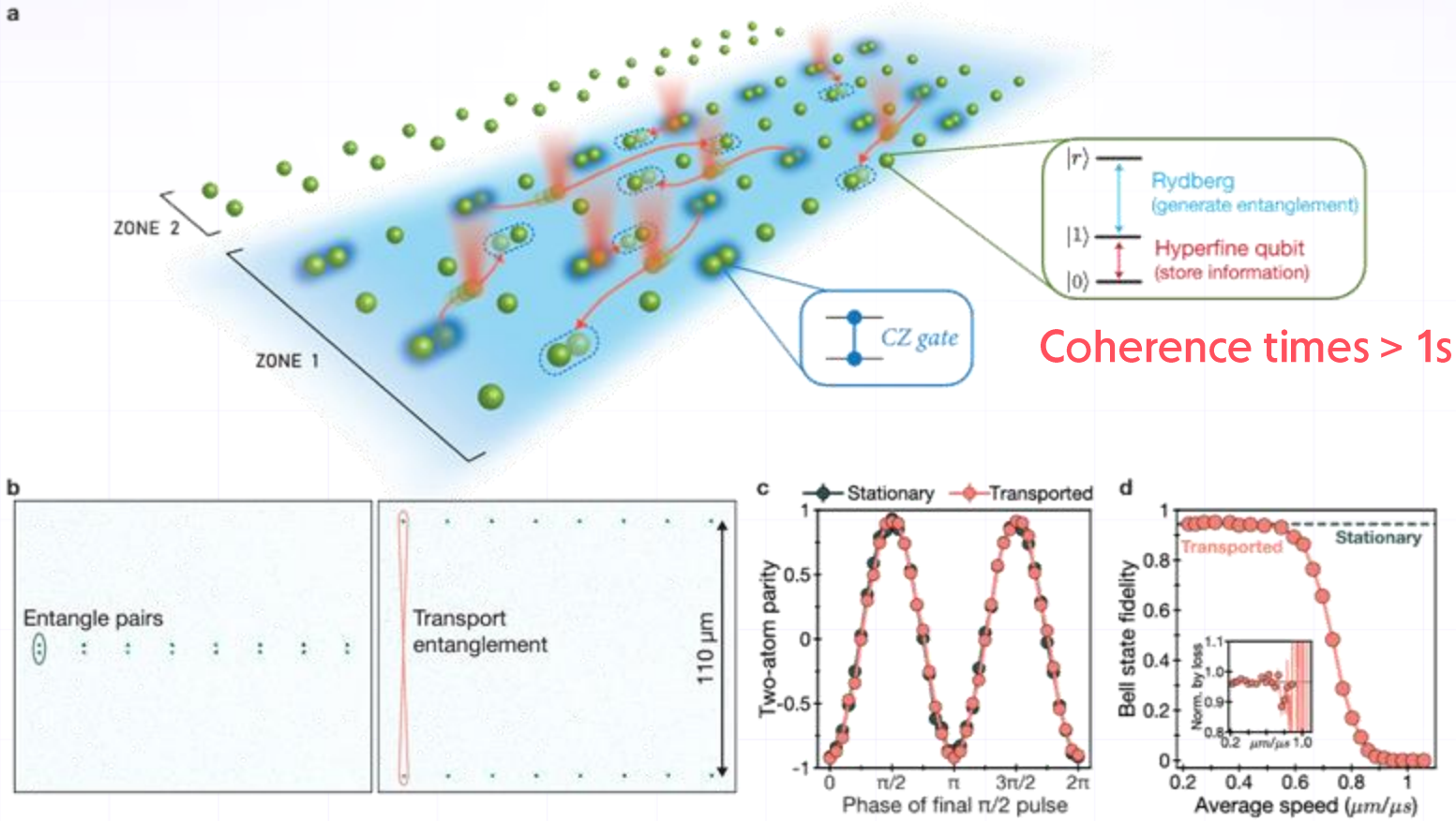
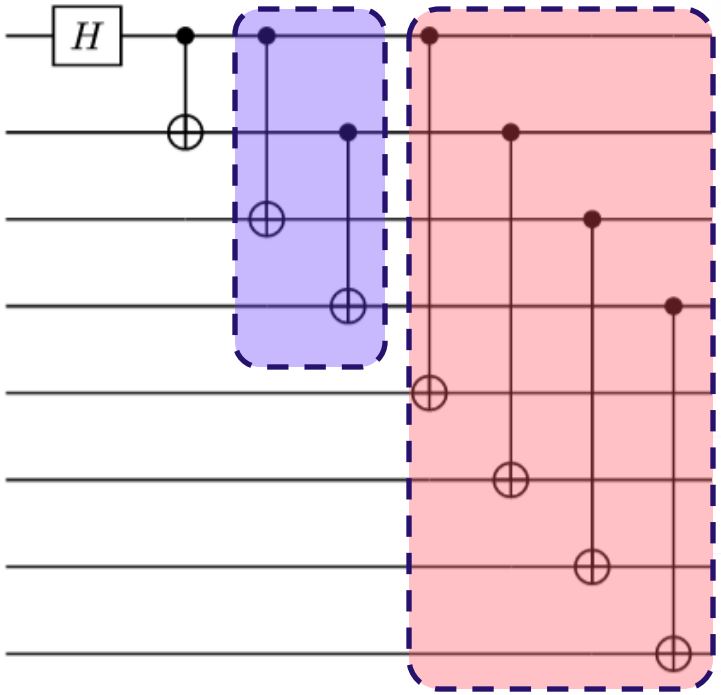
Basic architecture: mid-circuit reconfigurability

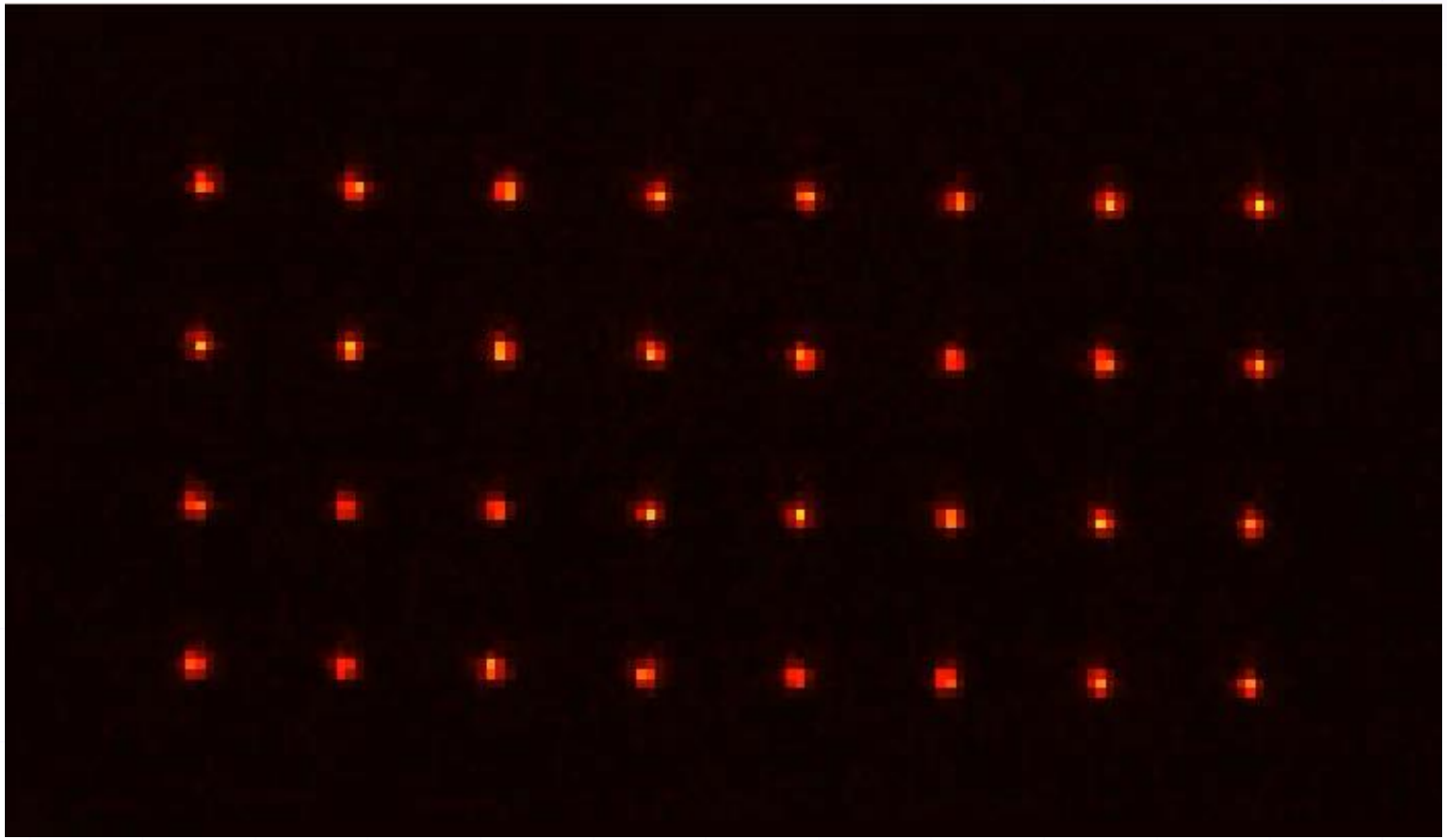


Coherence times > 1s

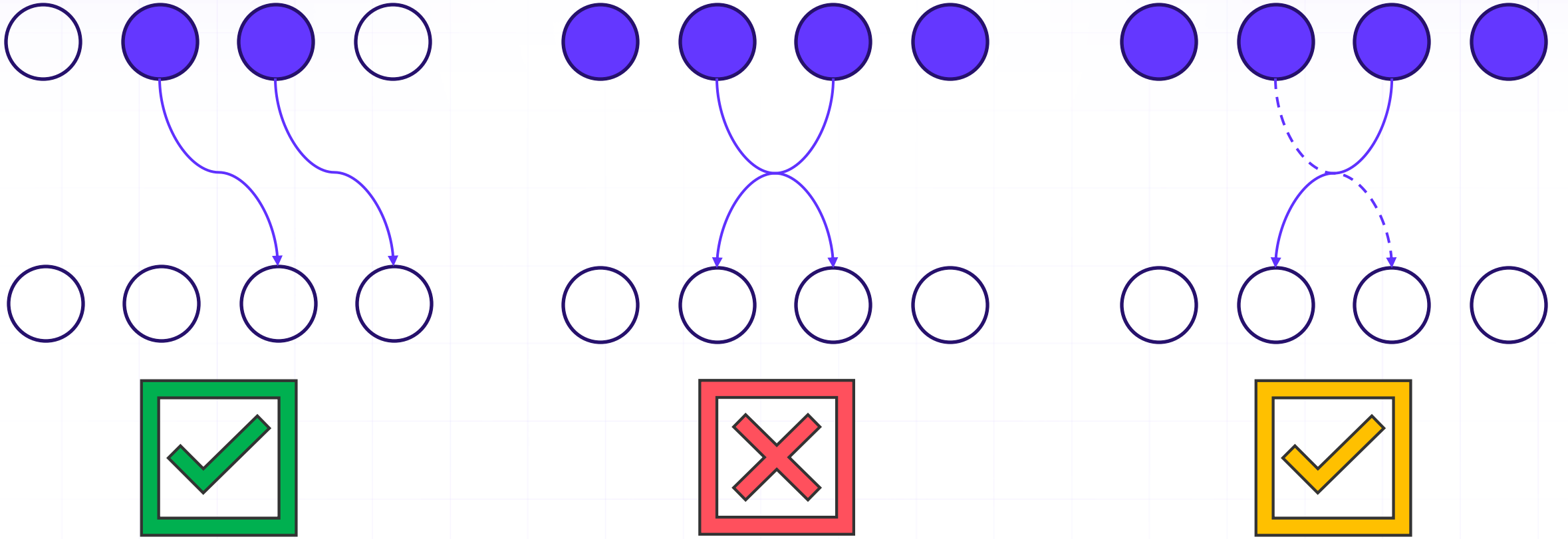
Bluvstein et al., Nature (2022)

Entangling and logic through reconfiguration

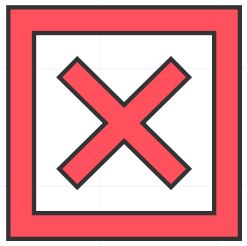




Atom shuttling rules #1 – crossing conflict



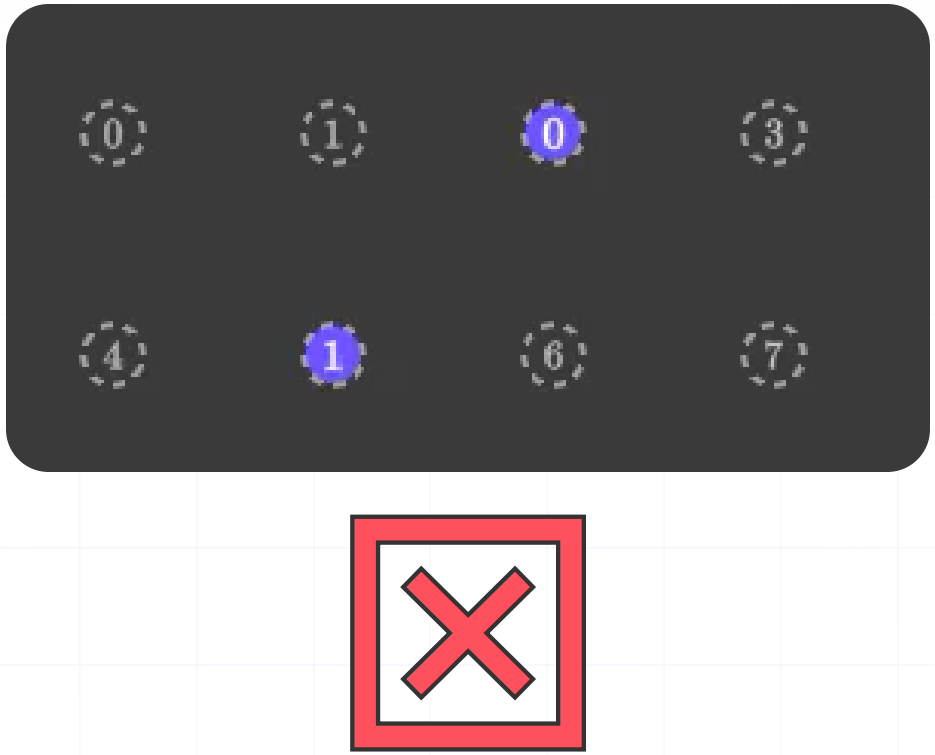
Atom shuttling rules #1 – crossing conflict



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

Activity: why these rules?

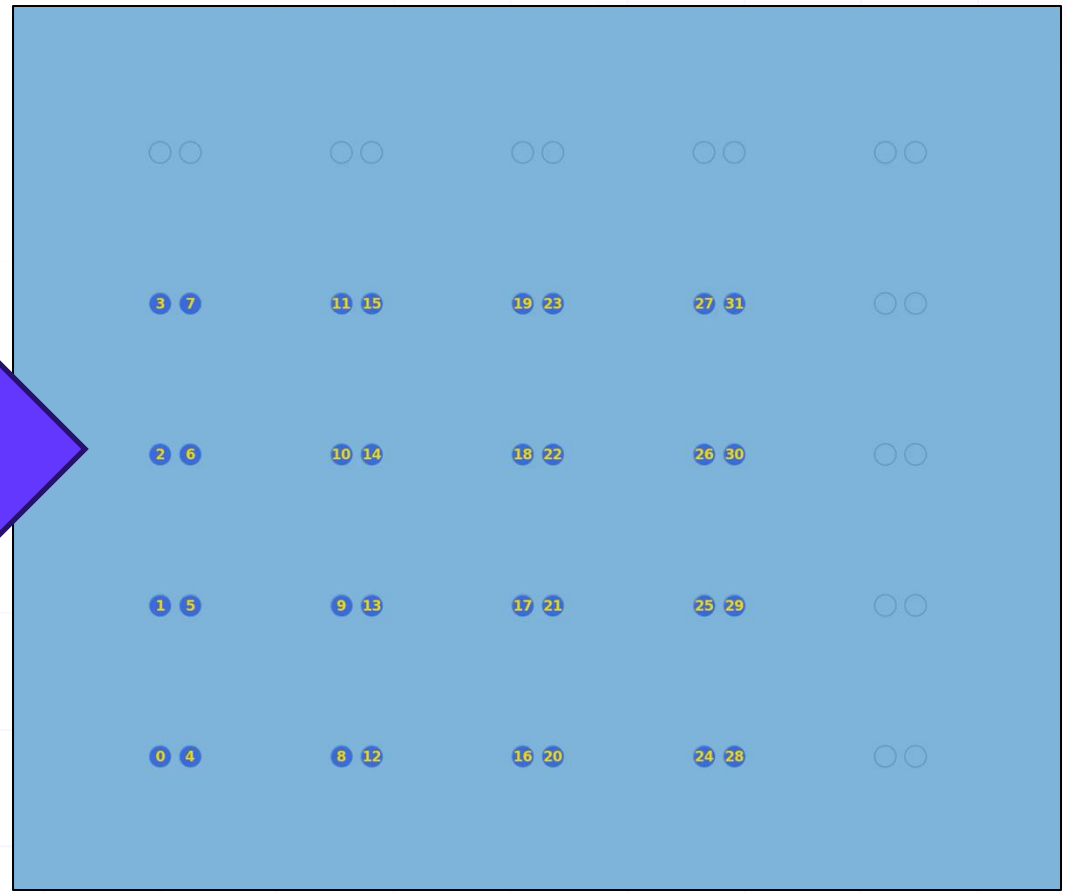
Atom shuttling rules #2 – “many-to-one” conflict (bonus)



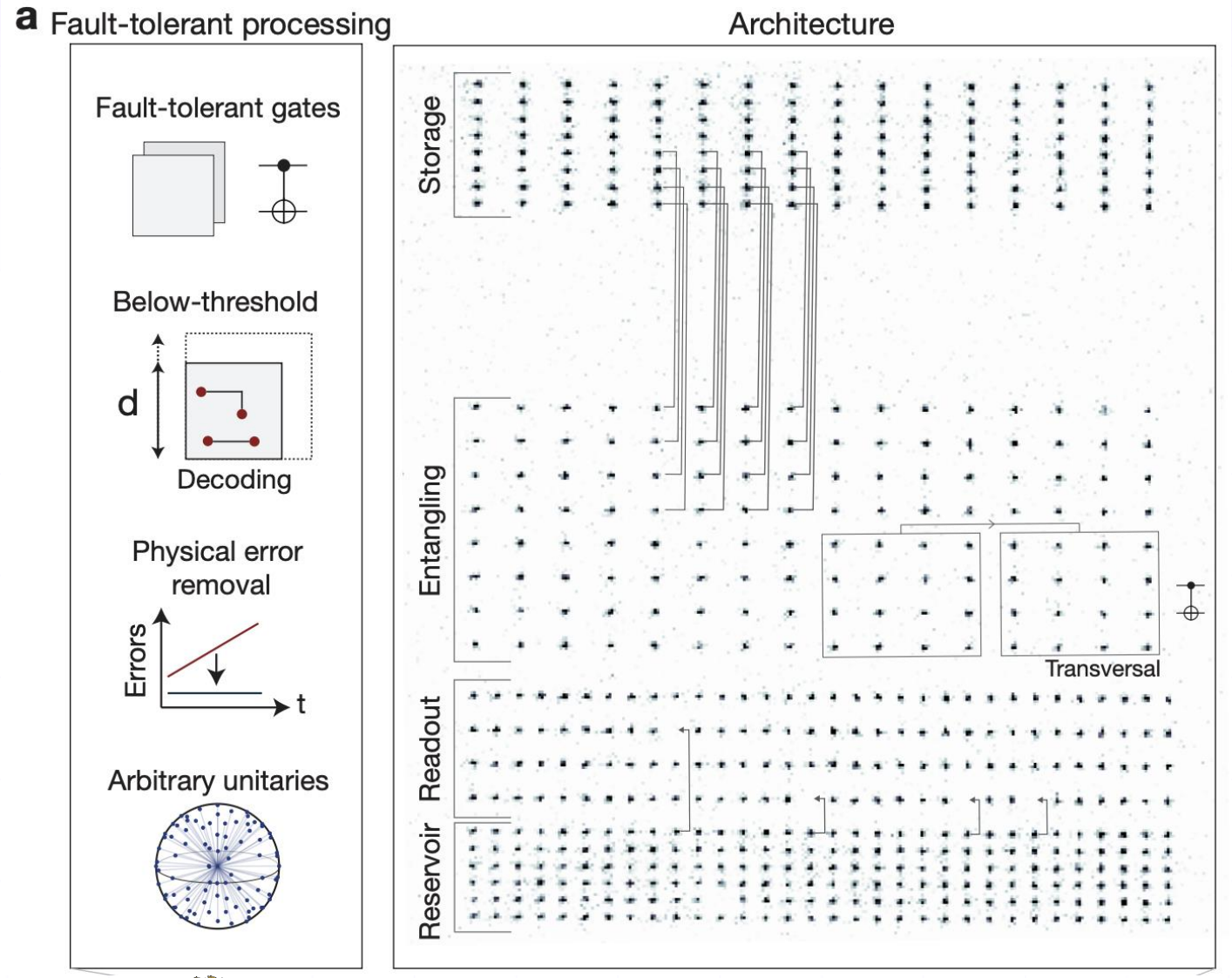
Preview: Programming moves with Bloqade

Executing the QCrank algorithm arxiv:2507.10699

```python
@move
def main():
    traps = spec.get_static_trap(zone_id="traps")
    sub_view = grid.sub_grid(traps, [0, 1, 2, 3, 4, 5, 6, 7], [0, 1, 2, 3])
    init.fill([sub_view])

    mover_ids = ilist.IList([0, 2, 4, 6])
    stationary_ids = ilist.IList([1, 3, 5, 7])
    rows = ilist.IList([0, 1, 2, 3])

    def single_qubit_gates():
        gate.global_r(0.1, 1.0)
        gate.local_rz(0.5, grid.sub_grid(traps, stationary_ids, rows))
        gate.local_rz(-0.5, grid.sub_grid(traps, stationary_ids, rows))
        gate.global_r(0.1, -1.0)

    single_qubit_gates()
    for _ in range(len(mover_ids)):
        for _ in range(len(rows)):
            gate.top_hat_cz(traps)
            row_aux = ilist.IList([rows[-1] + 1])
            rearrange(mover_ids, rows[0:1], mover_ids, row_aux)
            rearrange(mover_ids, rows[1:] + row_aux, mover_ids, rows)

        col_aux = ilist.IList([mover_ids[-1] + 2])
        rearrange(mover_ids[0:1], rows, col_aux, rows)
        rearrange(mover_ids[1:] + col_aux, rows, mover_ids, rows)
        single_qubit_gates()
```

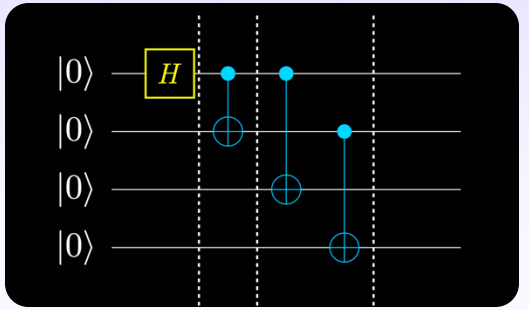


Zoned architectures for fault tolerant computing

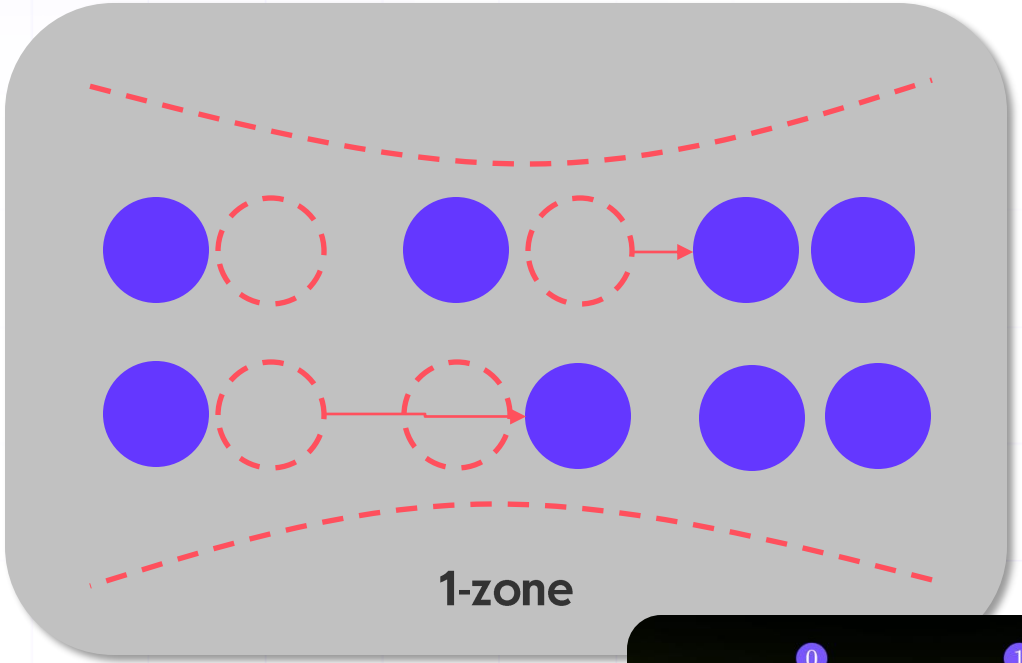


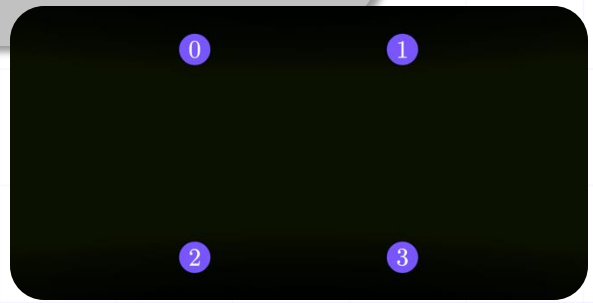
Bluvstein et al., arxiv:2506.20661

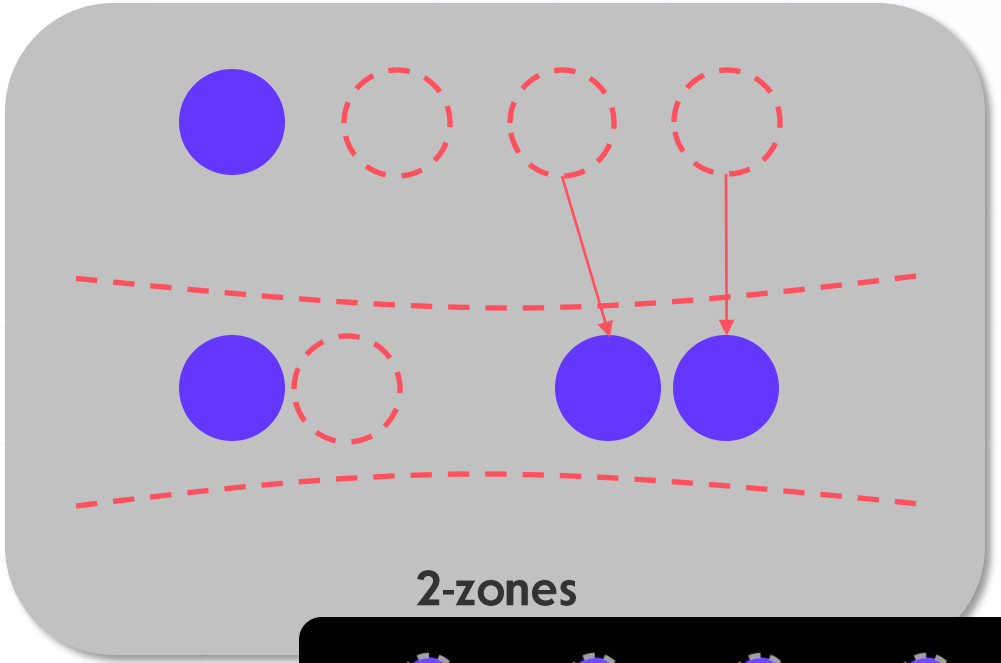
Zoned architectures

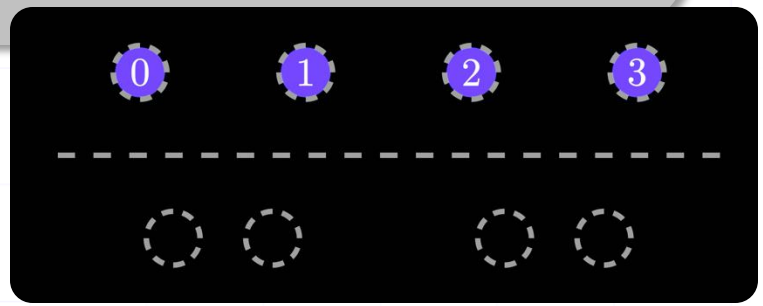


Qubit count ~ 256









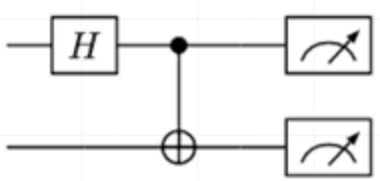
Programming pipeline

Squin: Bloqade's circuit composition dialect

```
from bloqade import squin

@squin.kernel
def main():
    q = squin.qubit.new(2)
    H = squin.op.h()
    CX = squin.op.cx()
    squin.qubit.apply(H, q[0])
    squin.qubit.apply(CX, q)
    squin.qubit.measure(q)
```

Full interoperability with Cirq

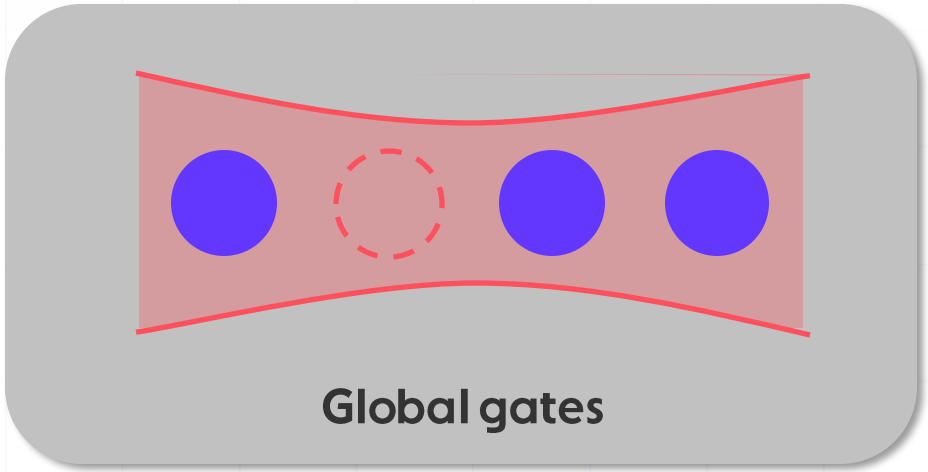
```
import cirq

qubits = cirq.LineQubit.range(2)
circuit = cirq.Circuit(
    cirq.H(qubits[0]),
    cirq.CX(qubits[0], qubits[1]),
    cirq.measure(qubits)
)

main_loaded = squin.cirq.load_circuit(circuit, kernel_name="main_loaded")
```

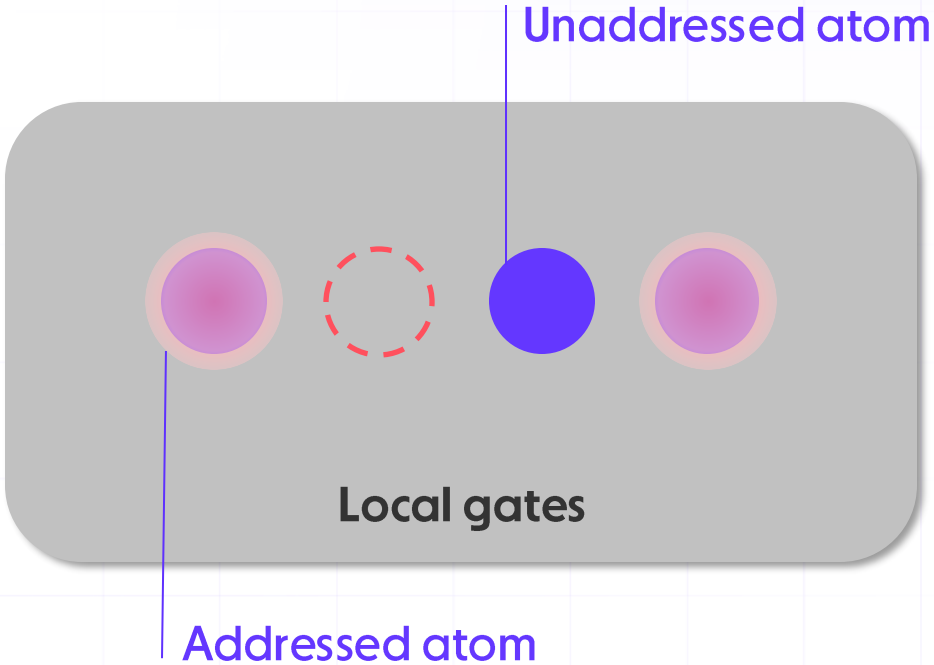


Atom moving composition (bloqade-shuttle)
Simulation (pyqrack)

Noisy circuit analysis (more in what follows!)

Error channels – single qubit operations



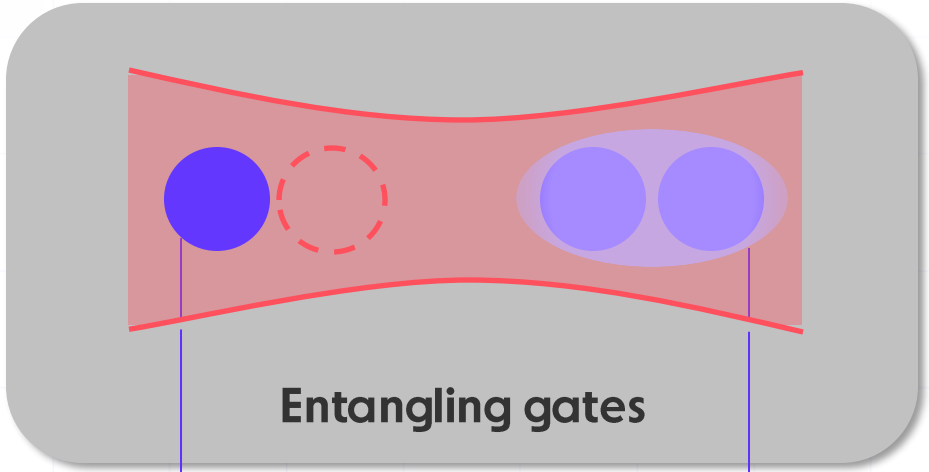


Error budget ~ 10^{-5}

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

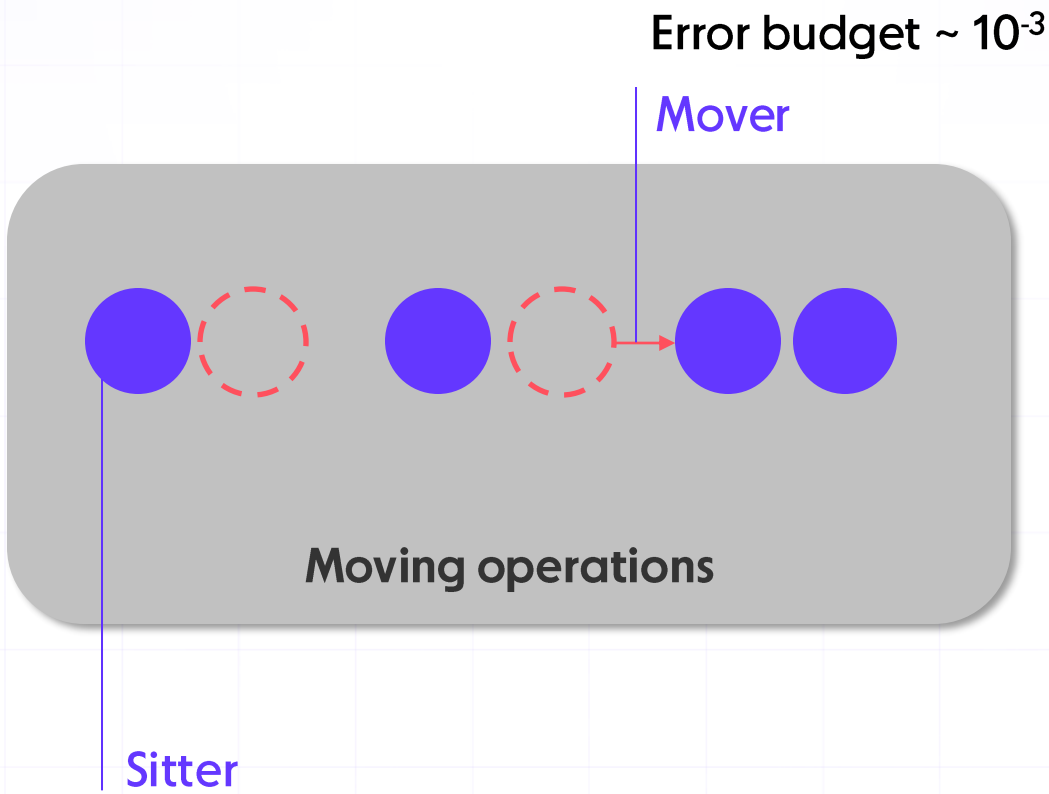
Error budget ~ 10^{-3} (z-biased)

Unpaired/spectator atom

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

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

Error channels – shuttling



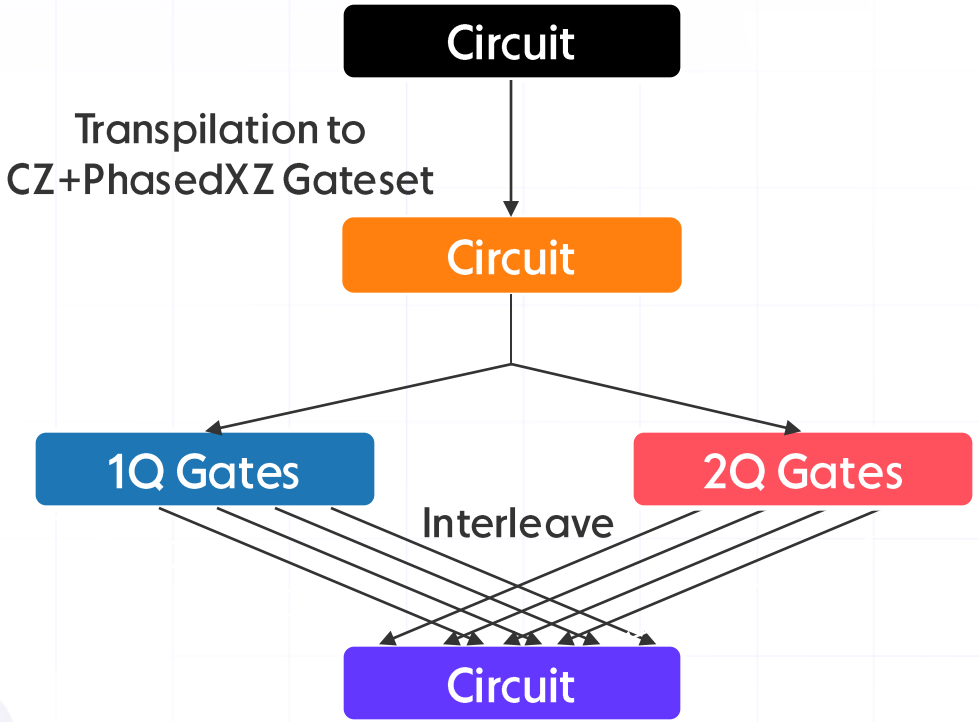
Bluvstein et al., Nature '23, '24, '25
Evered et al., Nature '23
Rodriguez et al. Nature '25

Noise hierarchy

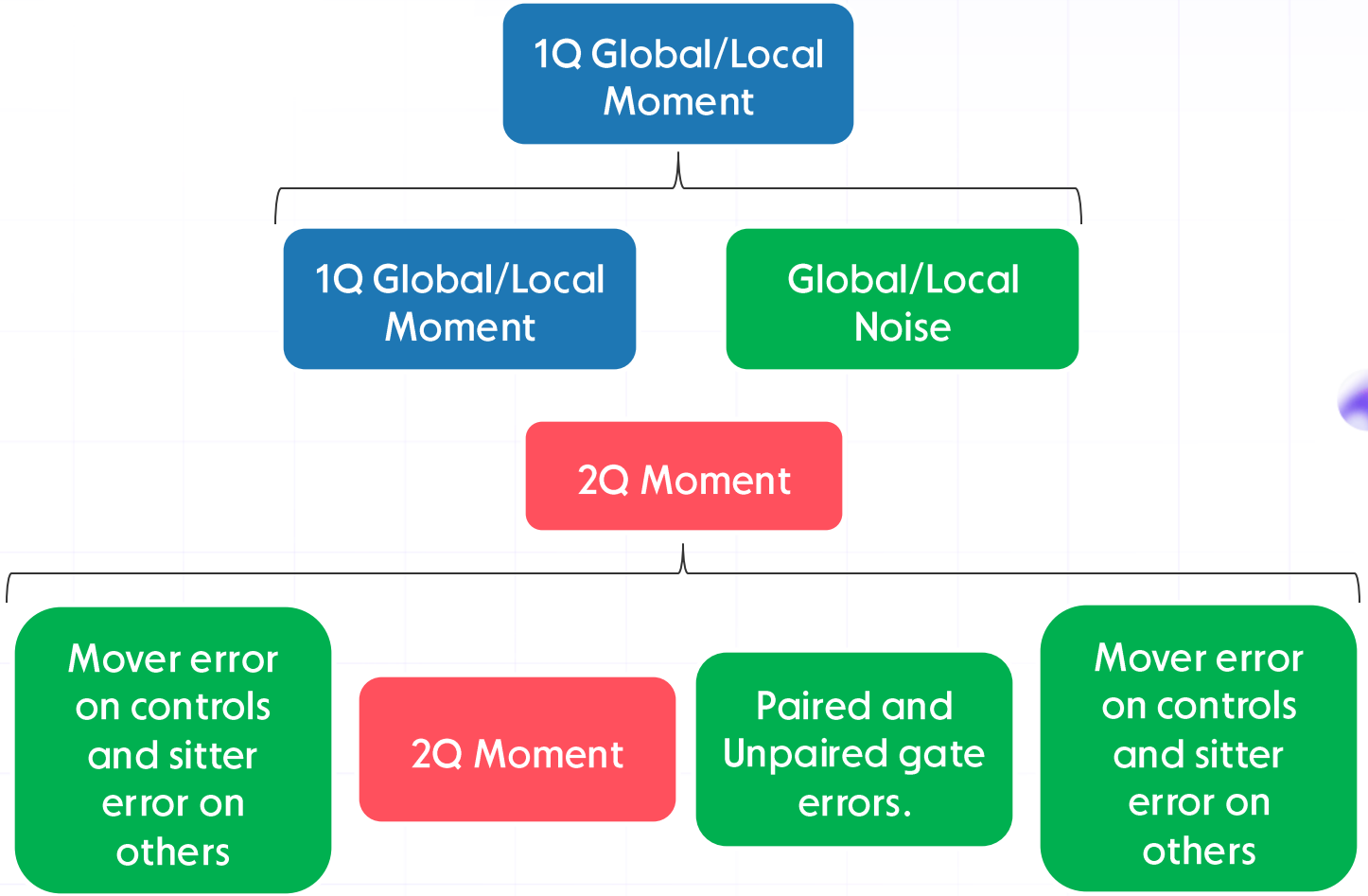
$$\underbrace{E_{CZ} \gtrsim E_{mover} \sim E_{unpaired}}_{\text{Z-biased}} > E_{sitter} \sim E_{1-qubit,local} > E_{1-qubit,global}$$

Heuristic noise model - one-zone logic

Step 1
cirq_utils.transform_to_noisy_one_zone_circuit

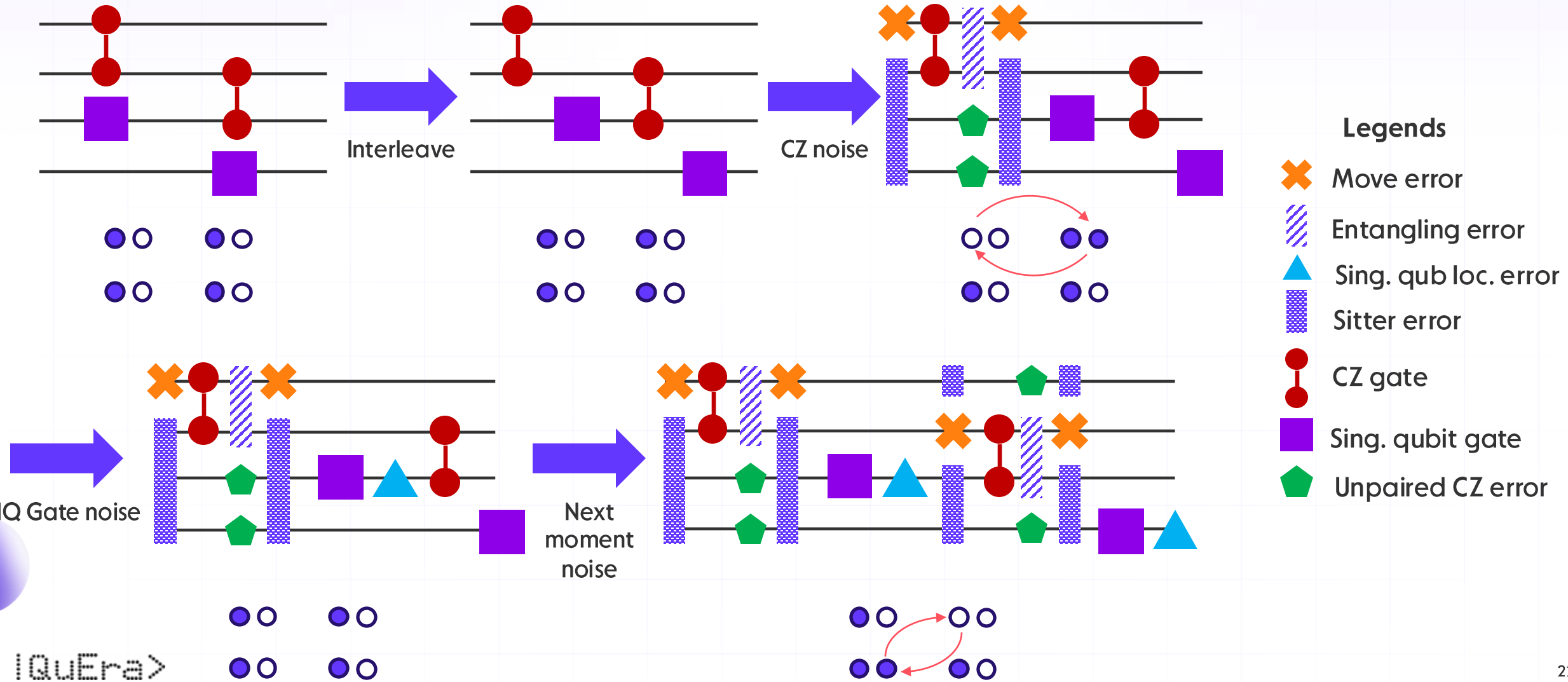


Step 2
circuit.with_noise(GeminiOneZoneNoiseModel())



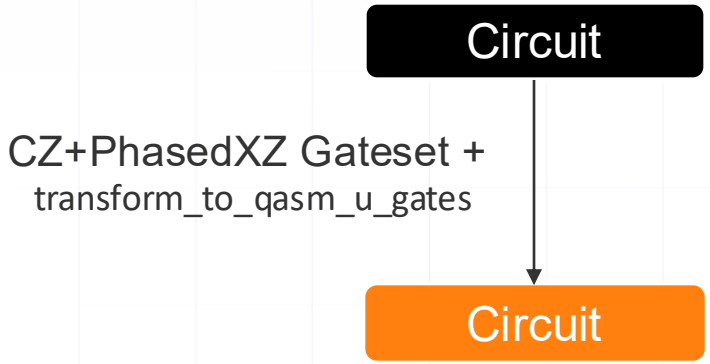
Heuristic noise model - one-zone logic

Example

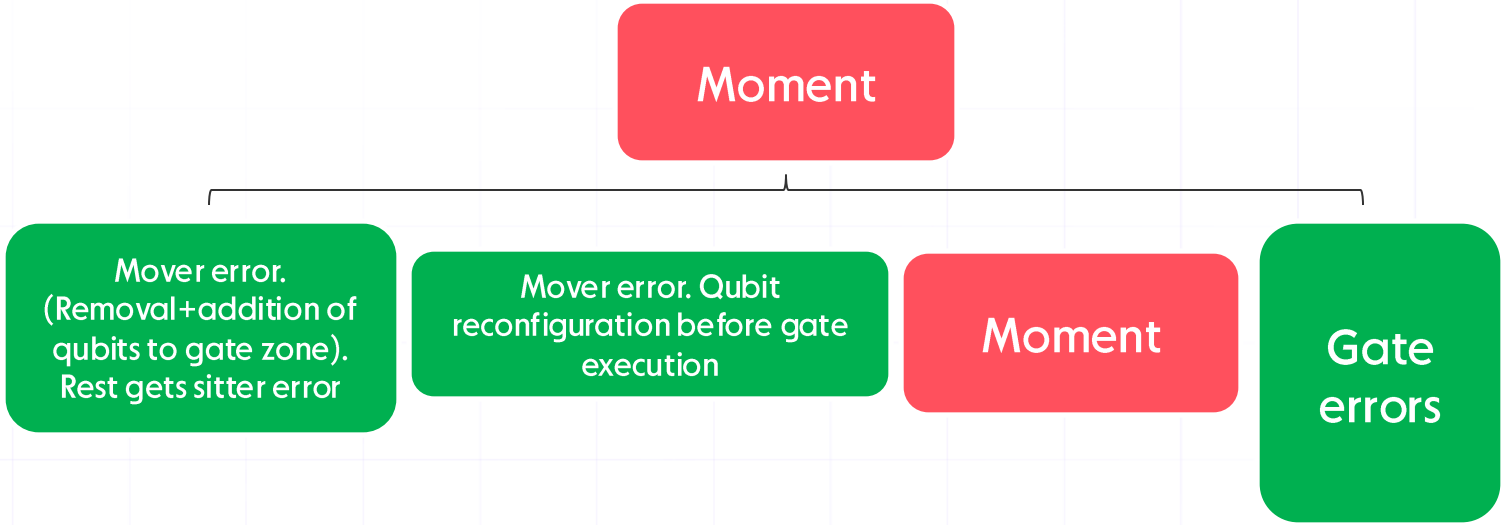


Heuristic noise model – two-zone logic

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



Step 2.
noisy_circuit = get_two_zoned_noisy_circ(circuit)
Main assumption: all gates in a moment are executed in the gate zone

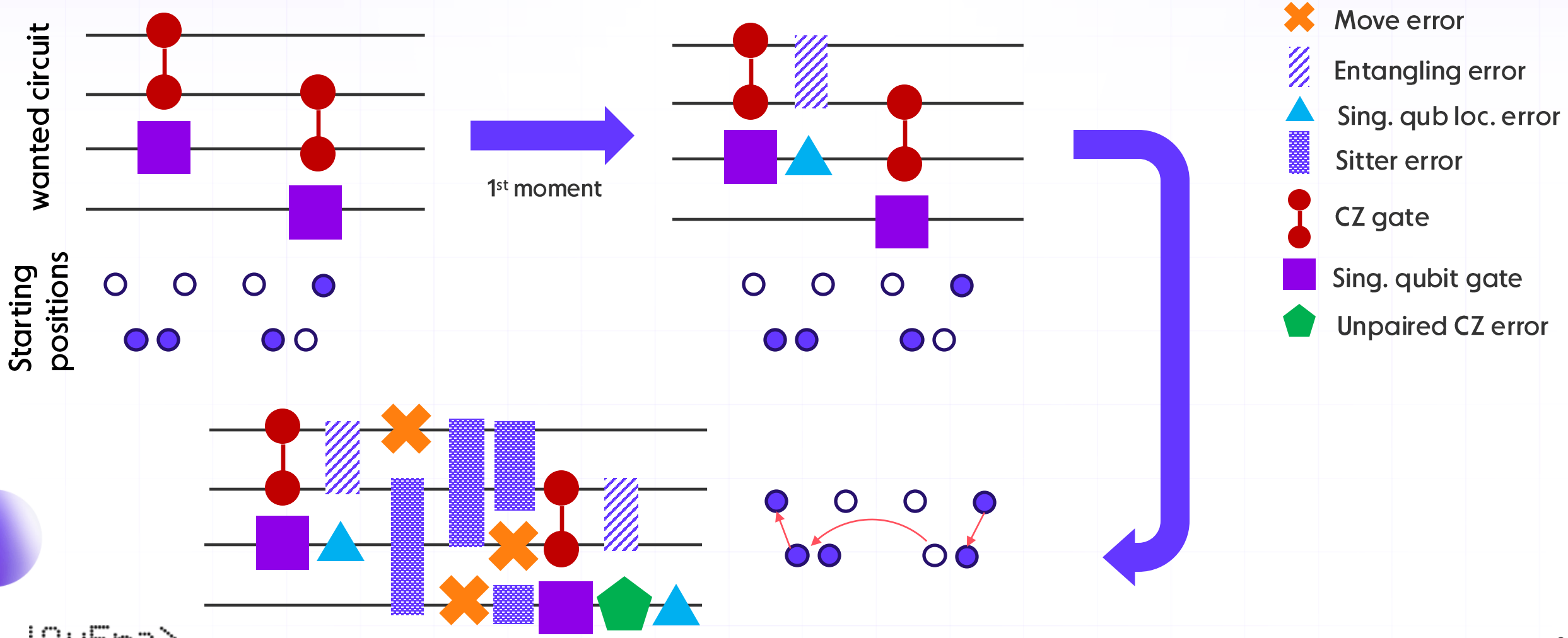


Caveats:

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

Heuristic noise model - two-zone logic

Example/Exercise



Example calls

Define your circuit (say in Cirq)

```python
import cirq
from bloqade.cirq_utils import noise

def ghz_circuit(n: int) -> cirq.Circuit:
    qubits = cirq.LineQubit.range(n)

    # Step 1: Hadamard on the first qubit
    circuit = cirq.Circuit(cirq.H(qubits[0]))

    # Step 2: CNOT chain from qubit i to i+1
    for i in range(n - 1):
        circuit.append(cirq.CNOT(qubits[i], qubits[i + 1]))

    return circuit
```

```python
ghz_circuit_3 = ghz_circuit(3)
print(ghz_circuit_3)
```

✓ 0.0s

```
0: ──H──@──────
        │
1: ─────X──@───
           │
2: ────────X───
```

Pick up your noise model of interest

```python
noise_model = noise.G
```

- GeminiTwoZoneNoiseModel
- GeminiOneZoneNoiseModel
- GeminiOneZoneNoiseModelABC
- GeminiOneZoneNoiseModelConflictGraphMoves
- GeminiOneZoneNoiseModelCorrelated
- { } conflict_graph
- OneZoneConflictGraph

Generate your noisy circuit! (and simulate, etc...)

```python
noise_model = noise.GeminiOneZoneNoiseModel()
noisy_ghz_circuit_3 = noise.transform_circuit(ghz_circuit_3, model=noise_model)
print(noisy_ghz_circuit_3)
```

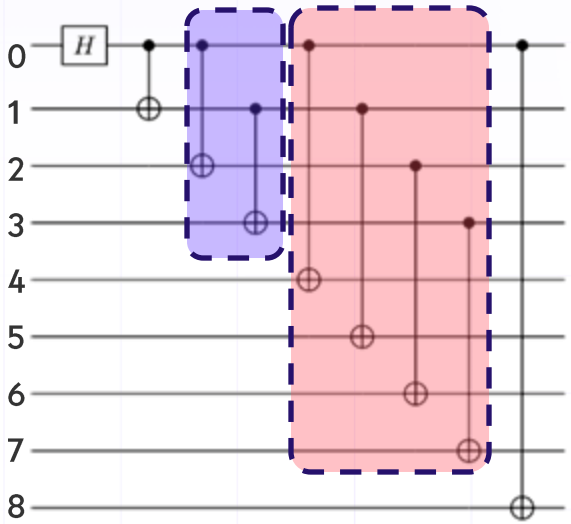
✓ 0.0s

```
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
```

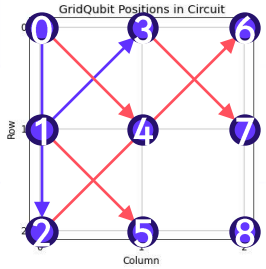
IQuEra

Circuit design practices

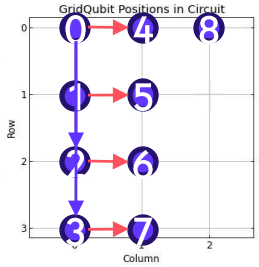
Evaluating move error



1-zone routing examples



Atom-moving conflicts



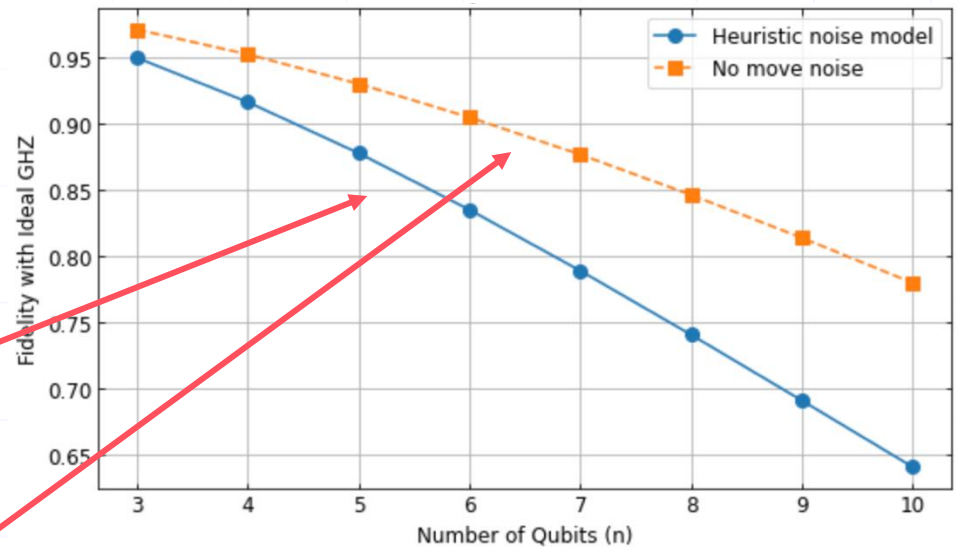
No atom-moving conflicts

```
# standard one zone noise model
one_zone_std = noise.GeminiOneZoneNoiseModel()
# define your own adjusted model
onezone_no_move_noise = noise.GeminiOneZoneNoiseModel(
                        mover_px=0, mover_py=0, mover_pz=0,
                        sitter_px=0, sitter_py=0, sitter_pz=0
                        )

full_noise_ghz = noise.transform_circuit(ghz_circuit(n_qubits), model=noise_model)
noiseless_move_ghz = noise.transform_circuit(ghz_circuit(n_qubits), model=onezone_no_move_noise)
```

simulate

Lesson:

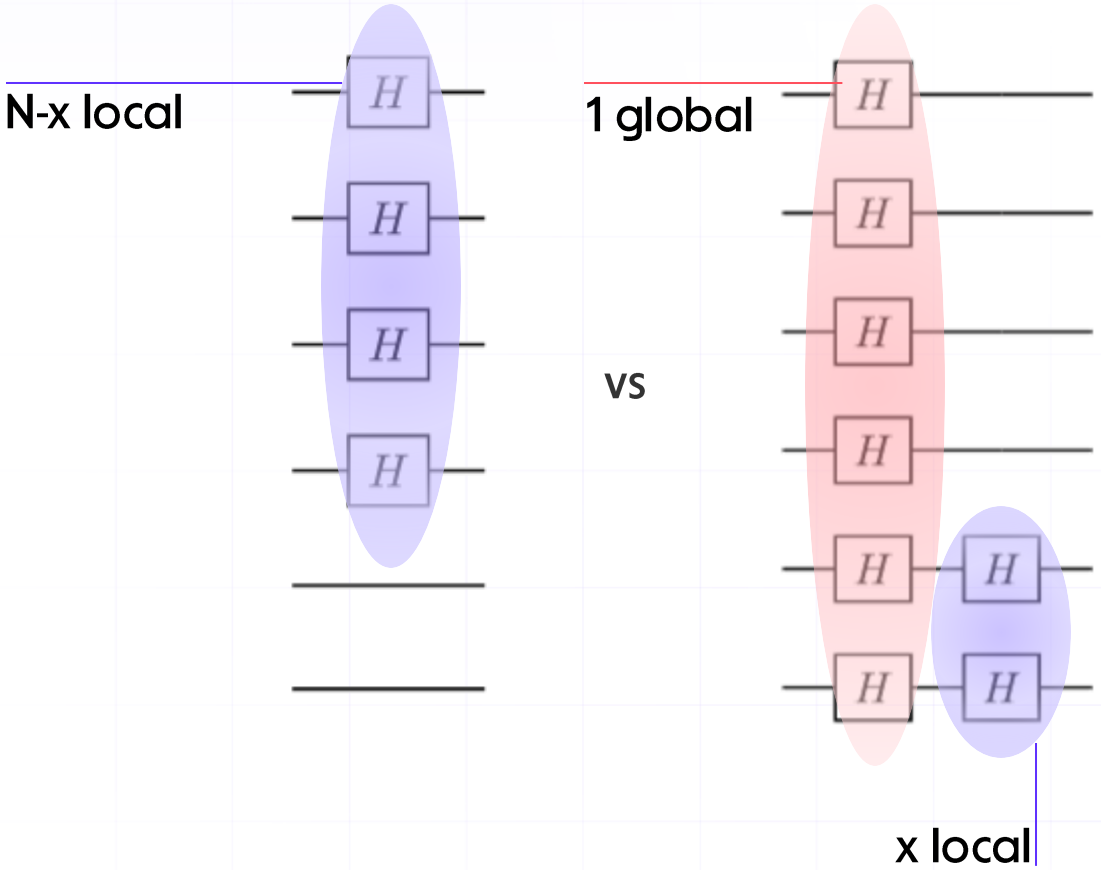
The heuristic noise model overestimates moves and different routing compilations will lead to different performance predictions. Bound realistic performance by running simulations with suppressed move errors!

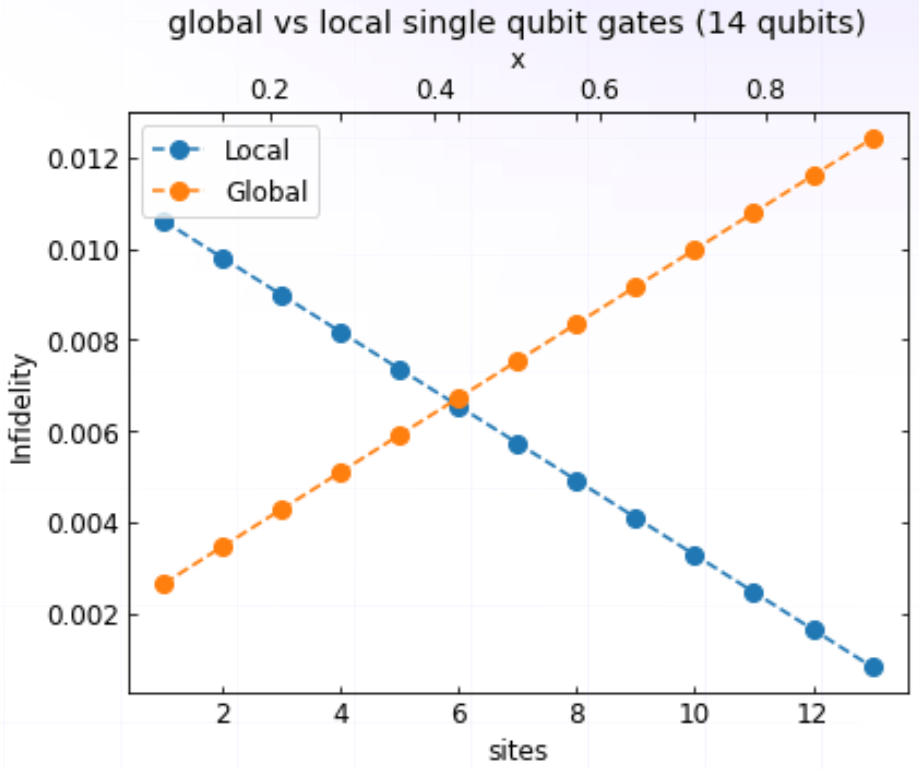


IQuEra

Circuit design practices

Global-local balance





$$F = (1-\epsilon_L)^{N-x}$$

$$F = (1-\epsilon_G)^{N}(1-\epsilon_L)^{x}$$

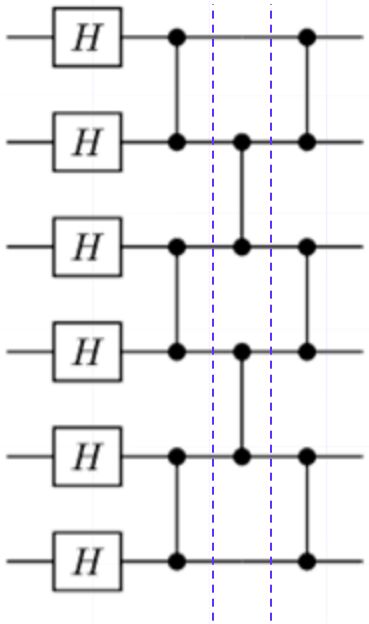
$$x_c \approx 0.421N$$

Lesson:
If circuit has a moment with more than 60% equal 1-qubit gates, it is better to exchange for a global and undo the undesired gates

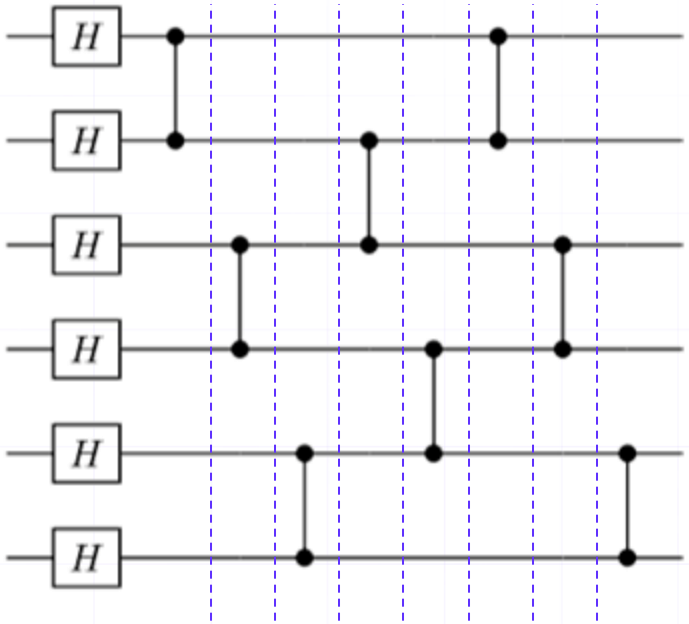
Circuit design practices

Parallelism and zones

Parallel brick wall



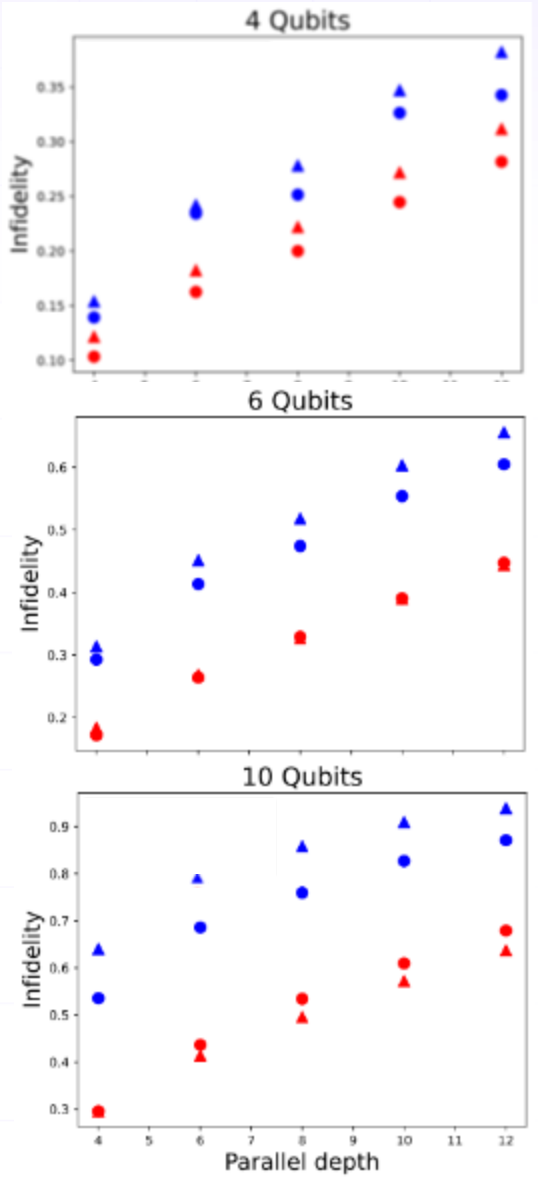
Series brick wall



Brick wall circuit Loschmidt echo

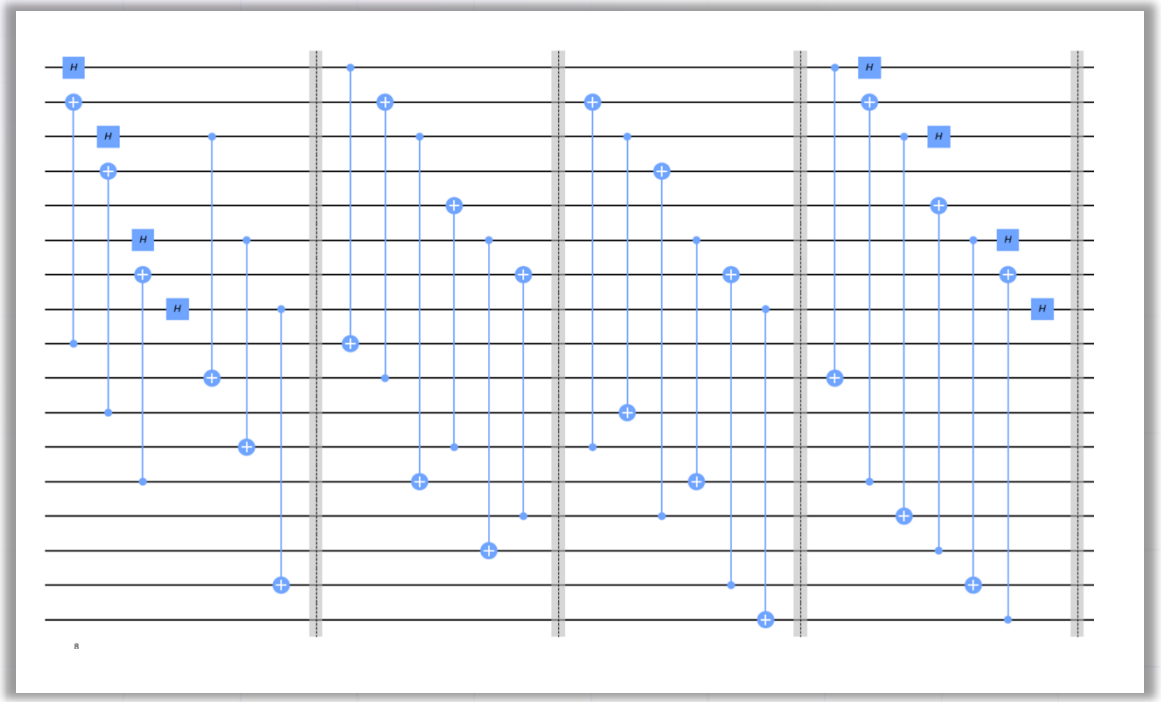
Lessons:

- Parallelization is always better!
- Zones ⇒ performance crossover
- Similar performance in zones due to high gate density and similar move dynamics

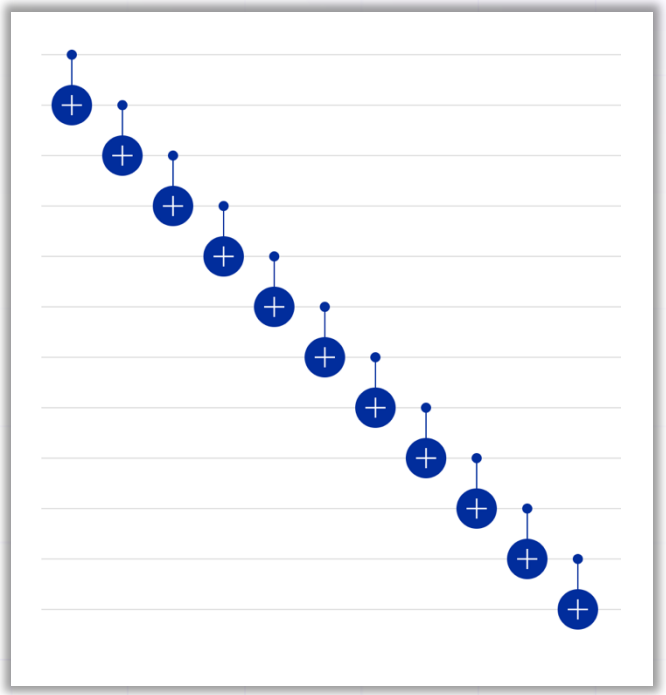


Summary: what makes a good neutral-atoms program?

Parallelism is key



A round of syndrome extraction for the surface code

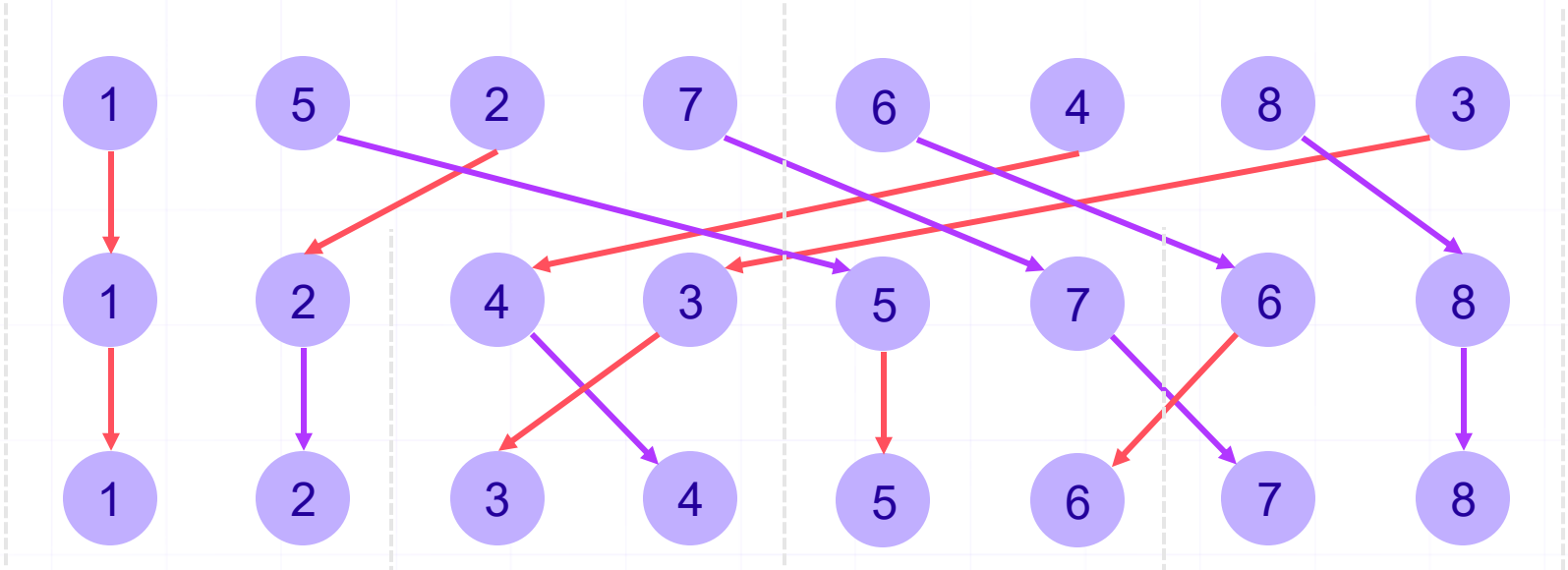


A staircase circuit

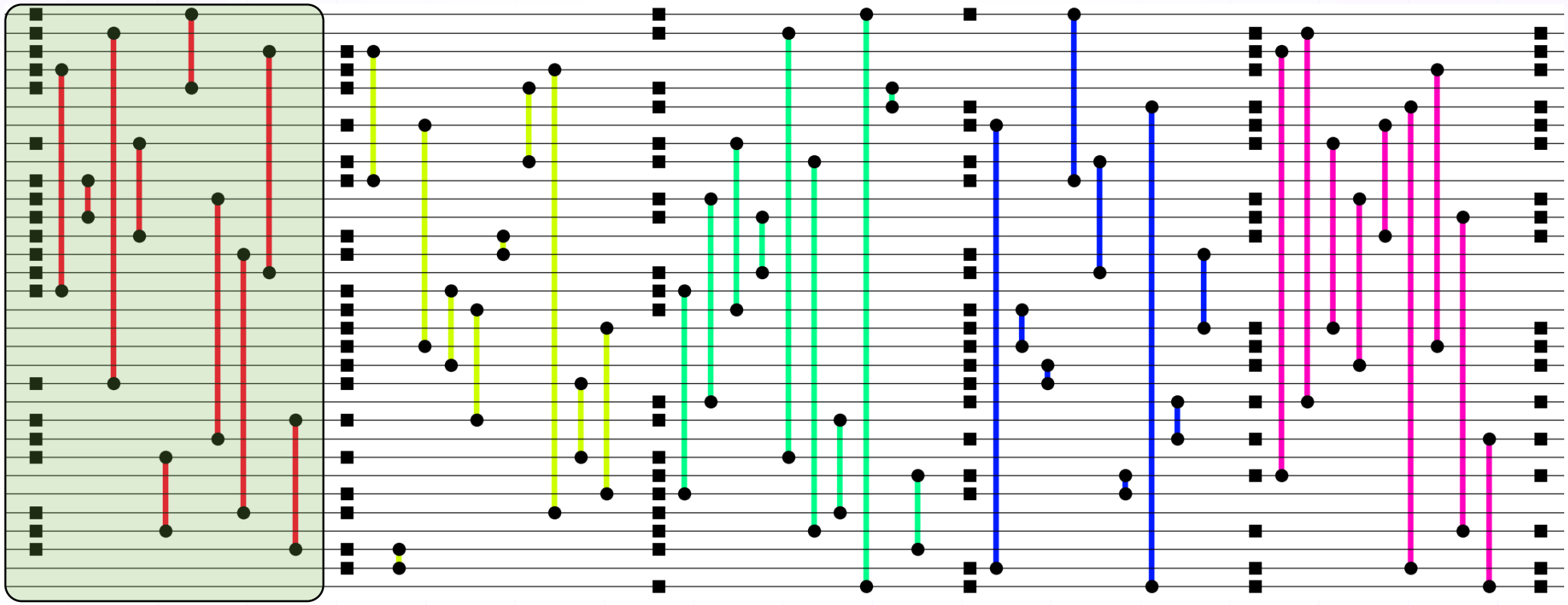
Careful choice of atom layout

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

Atoms can be efficiently sorted in $\sim log_2(N)$ parallel moves.



A healthy circuit: an overview



Learning objectives

Now you are be able to:

- **Describe** the baseline **functionality** of a digital neutral-atom quantum computer architecture based on zoned architectures
- **State** **constraints for atom shuttling operations**, register sizes, and geometrical and temporal scales
- **Write down** a phenomenological **hierarchy of the errors** for different operations during a circuit execution
- **Exemplify** **design rules** for hardware-aware implementation of quantum circuits

Meeting QuEra at IEEE QCE 2025

Talks

- Neutral-atom programming and modeling tutorial – **TUT04 (Sun)**
- Quantum Software 2.1: Open Problems - **WKS08 (Tue)**
  - Also, parallel session with Unitary Foundation, ask Kai about it!
- Bridging the gap between compilers and scientists – **BoF02 (Wed)**
- Control Systems for Quantum Computing - **WKS25 (Wed)**
- Quantum algos for life-sciences workshop – **WKS31 (Thu)**
- Enabling programming abstractions workshop - **WKS41 (Fri)**

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- **Poster sessions!**
- **Booth!**

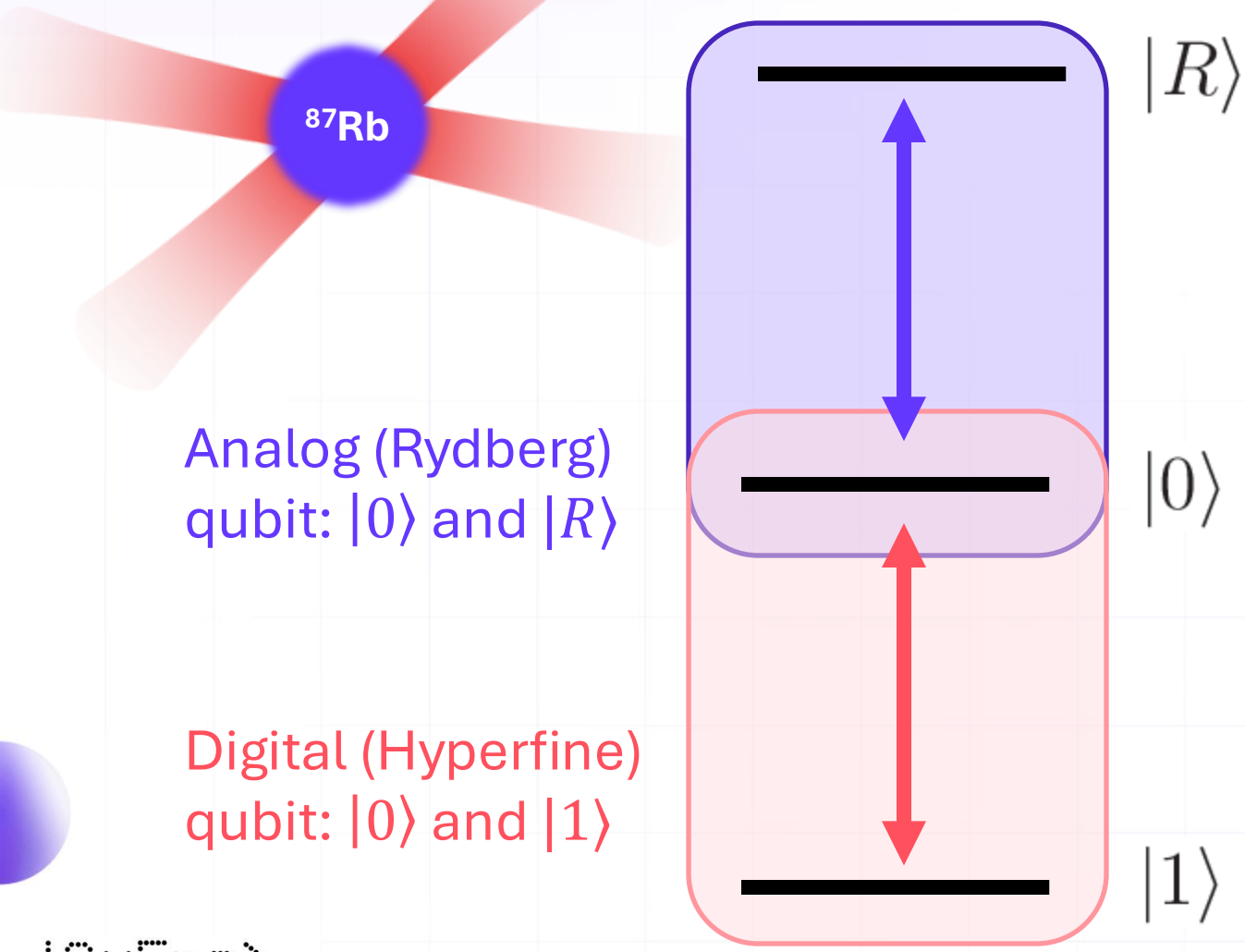
An example and more activities:

https://github.com/QuEraComputing/quera-education/tree/main/IEEE_2025

*If not ready to run notebooks locally, look for the **Launch on qBraid** button for the IEEE 2025 activities in the repo's root folder!*

Appendix

Digital mode qubits



Analog (Rydberg) qubit: $|0\rangle$ and $|R\rangle$

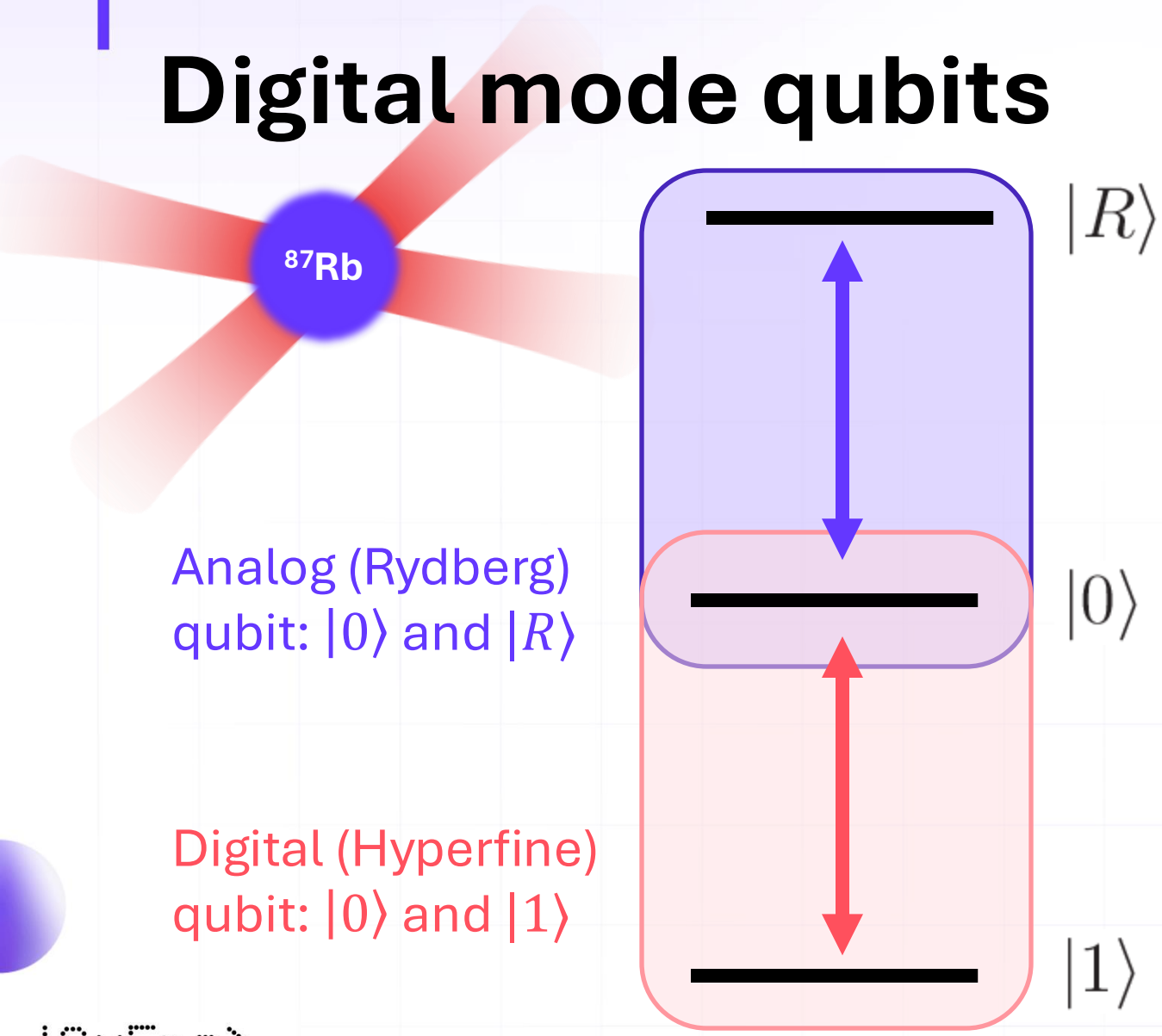
Digital (Hyperfine) qubit: $|0\rangle$ and $|1\rangle$

Interactions and entanglement:
Coherently drive dynamics with the Rydberg state using a 2-photon transition

Single-qubit gates:
Coherently drive dynamics with the hyperfine states using a Raman transition

Hyperfine states
Insensitive to the environment with a very long coherence time

Digital mode qubits



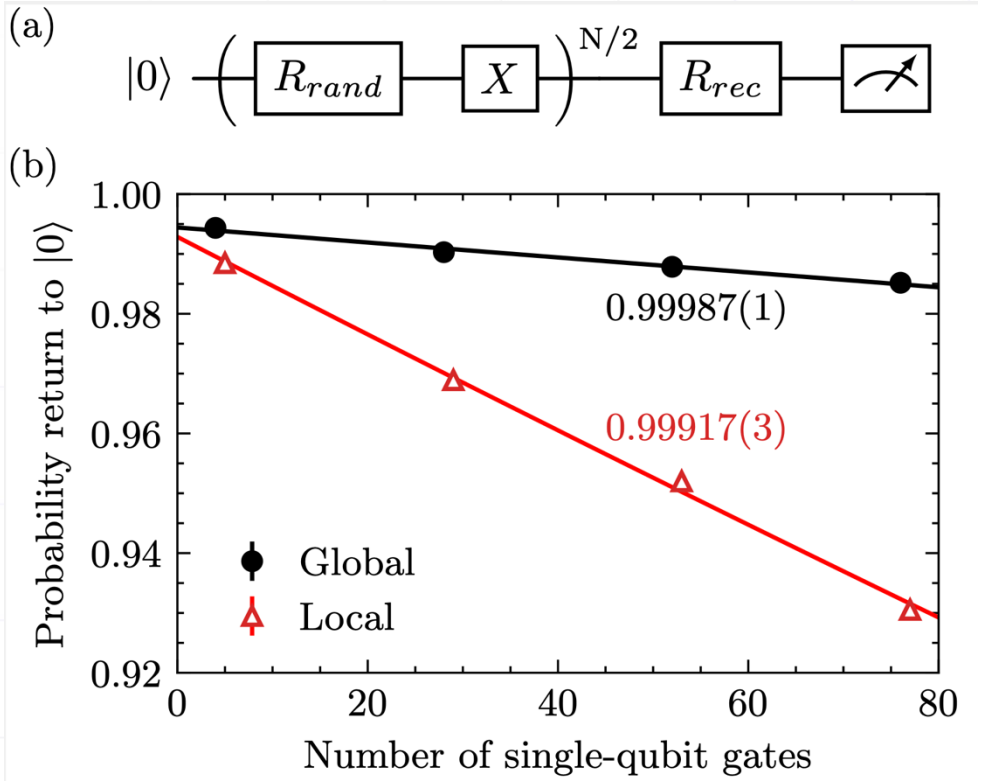
Analog (Rydberg) qubit: $|0\rangle$ and $|R\rangle$

Digital (Hyperfine) qubit: $|0\rangle$ and $|1\rangle$

Single-qubit gates:

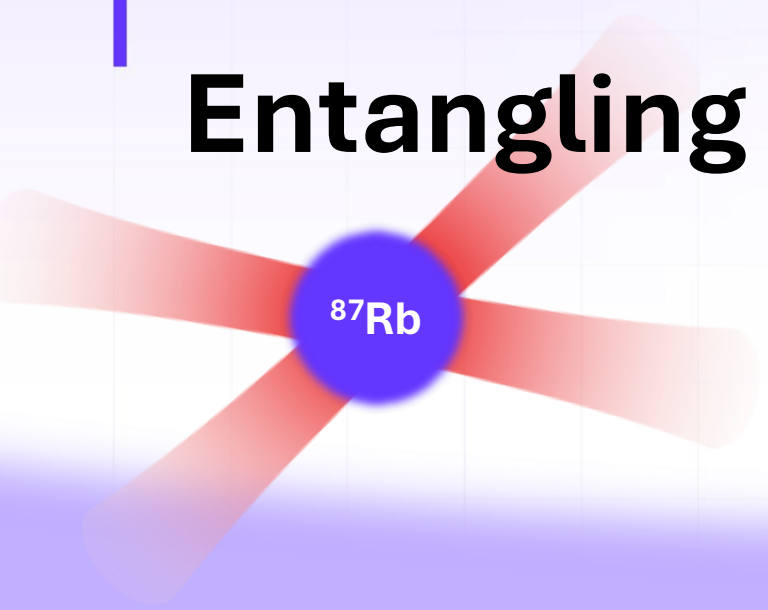
99.917% fidelity local gate

99.987% fidelity global gate



From Gemini-class hardware in QuEra Boston HQ

Entangling gates by moving atoms

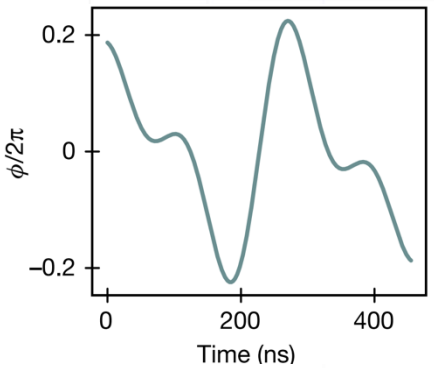


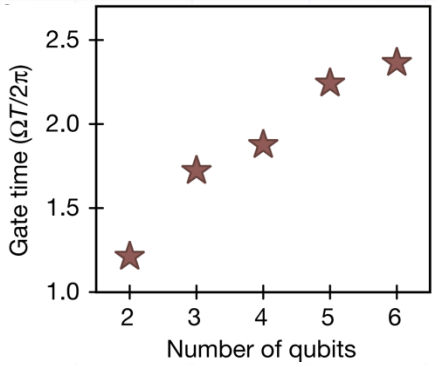
Entangling gates with the Rydberg blockade

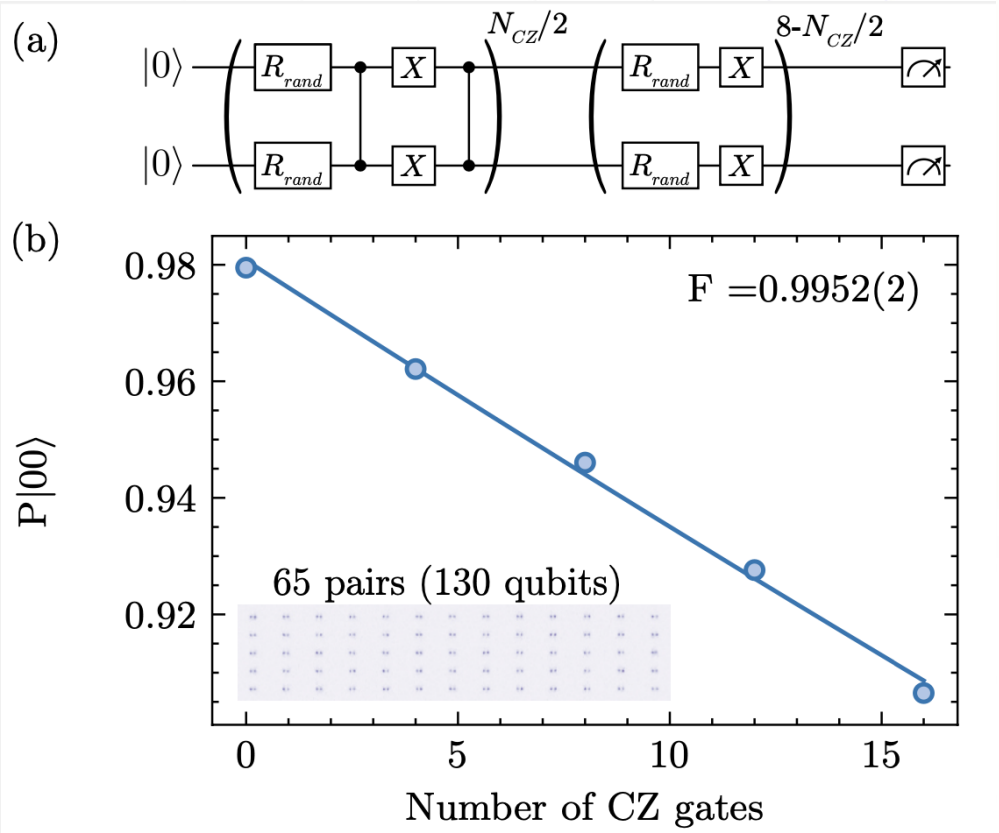
Robust entangling gates enabled by the Rydberg blockade

Rydberg blockade: only 1 atom can be in the Rydberg state. Multi-Rydberg states can be energetically excluded from dynamics. Move atoms together to do a gate

Blockade naturally extends to **multi-qubit gates**







Evered (Harvard) et al. *Nature* **volume 622**, pages268–272 (2023)

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