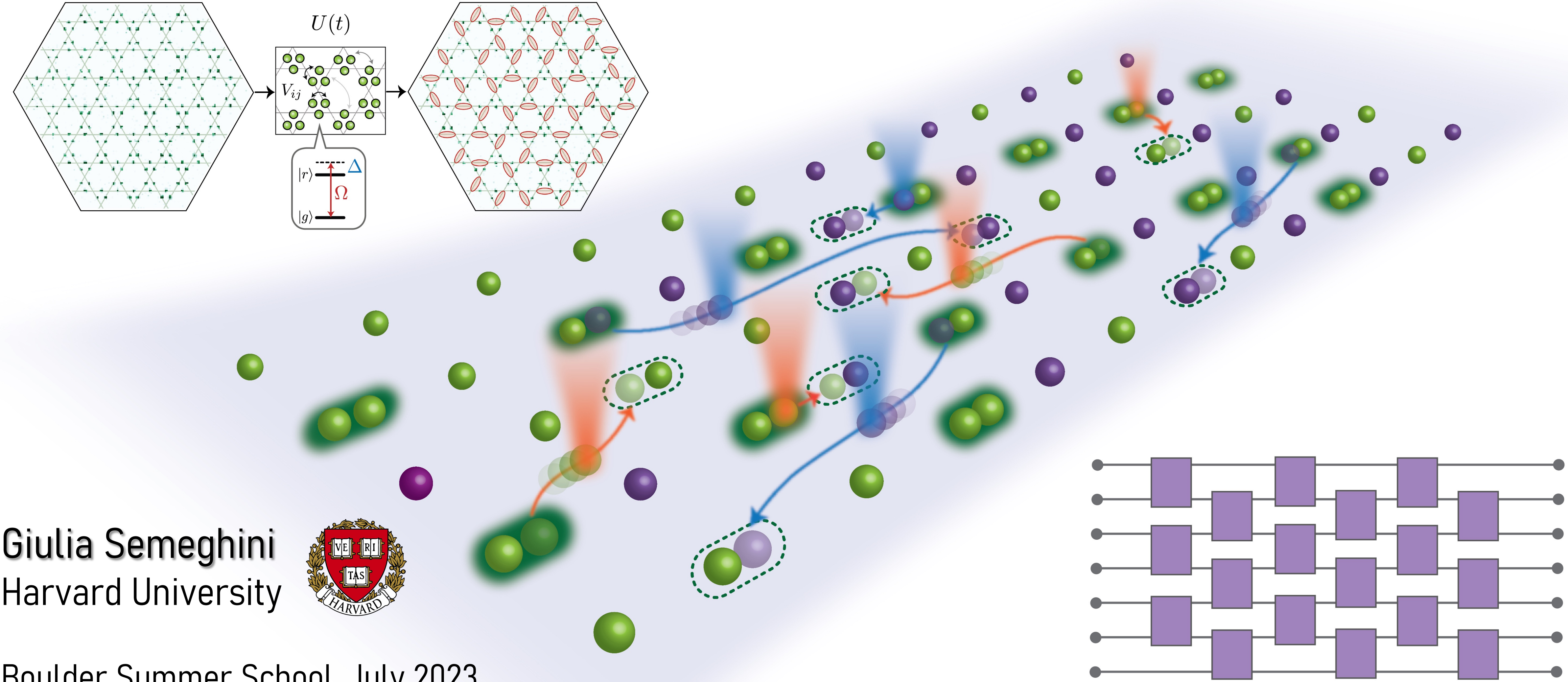
Quantum simulation (and information processing) with Rydberg atoms



Giulia Semeghini
Harvard University

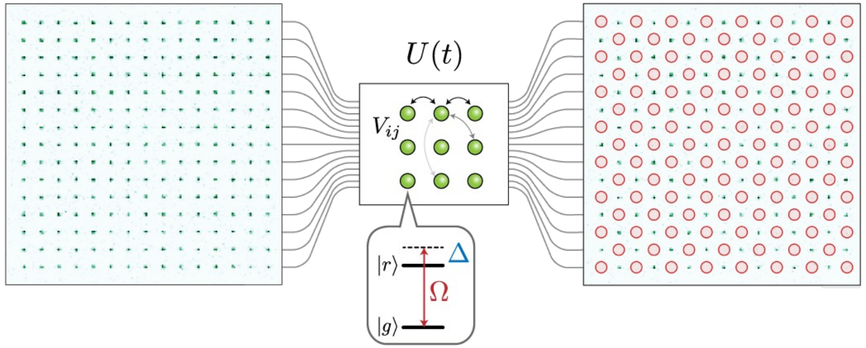
Boulder Summer School, July 2023

Outline

- Lecture 1: Programmable Rydberg arrays – introduction to the platform
- Lecture 2: Quantum simulation experiments with programmable Rydberg arrays
- Lecture 3: Quantum information processing with programmable Rydberg arrays

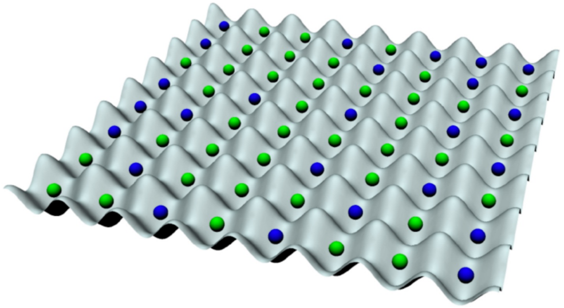
  + conclusion/discussion about opportunities and challenges for quantum science with Rydberg arrays

Programmable quantum platform: modes of operation



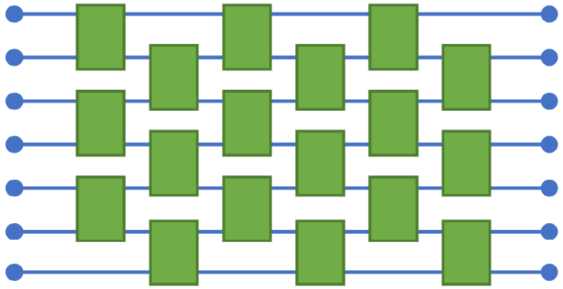
Analog

Engineer the system Hamiltonian such that the desired phase is the ground state in accessible range of parameters



Digital

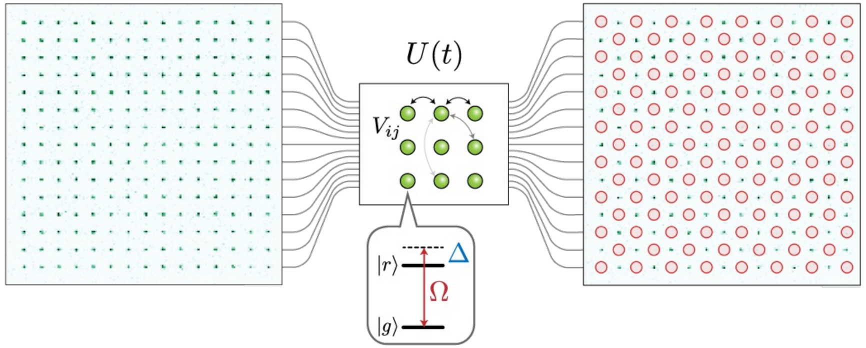
Implement quantum circuit to generate the desired entangled state



Hybrid

analog + digital

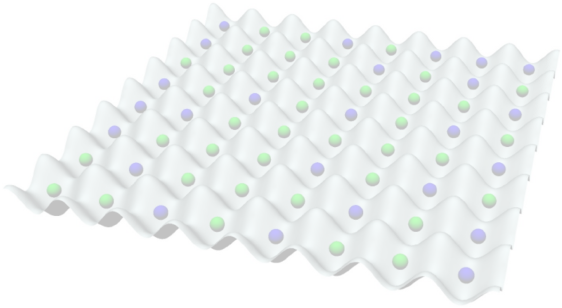
Programmable quantum platform: modes of operation



Quantum information processing

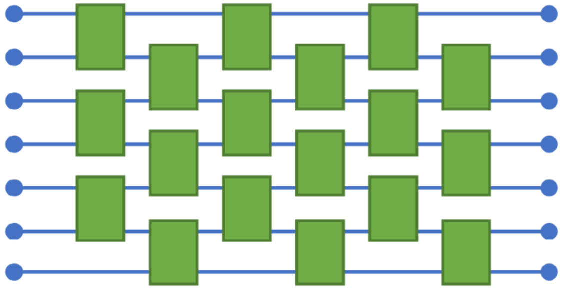
Analog

Engineer the system Hamiltonian such that the desired phase is the ground state in accessible range of parameters



Digital

Implement **quantum circuit** to generate the desired entangled state



Hybrid

analog + digital

Digital quantum dynamics

Experimental toolbox

Qubit encoding

Single-qubit operations

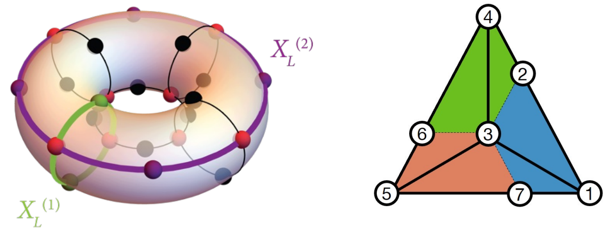
Two-qubit gates (extension to multi(>2)-qubit gates)

Reconfigurable any-to-any connectivity

Mid-circuit operations

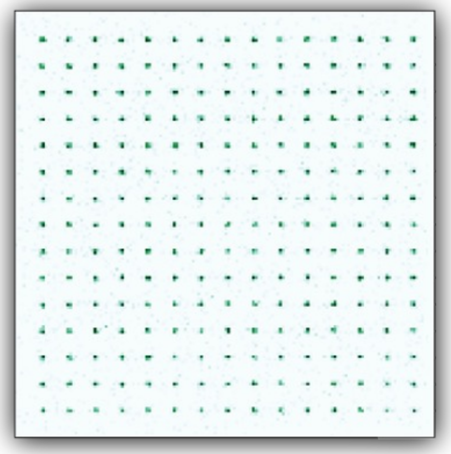
Applications

Initial steps toward quantum error correction applications

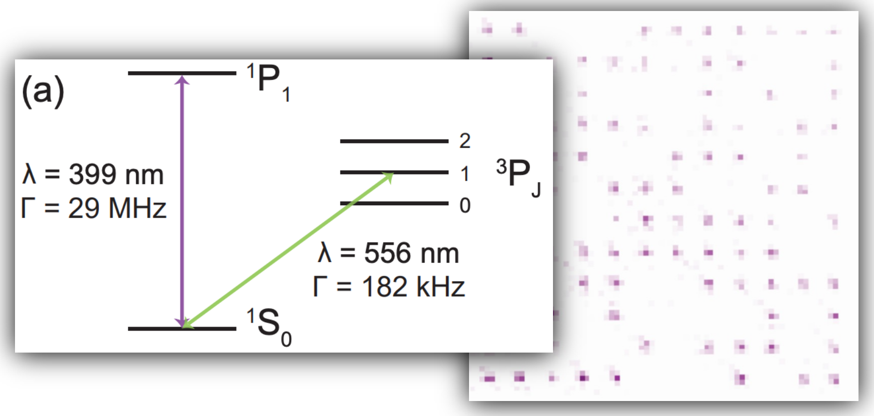


Different versions of Rydberg atom arrays

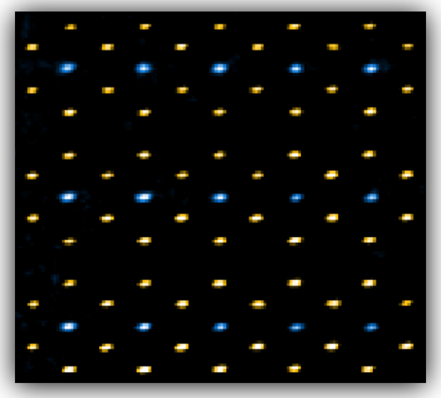
Alkali atoms



Alkaline-earth atoms



Atomic mixtures



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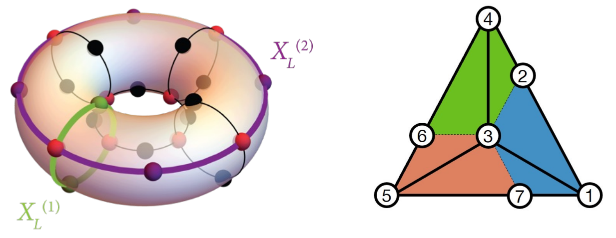

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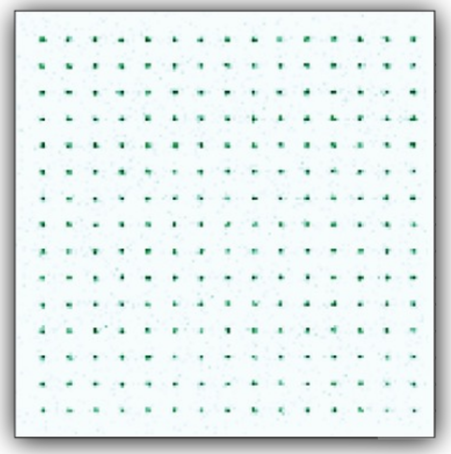

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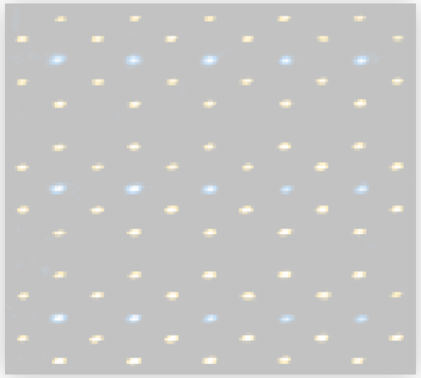

Digital quantum dynamics

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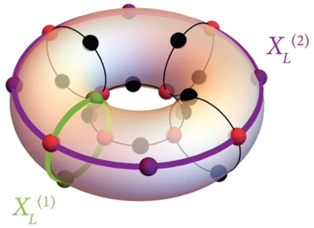

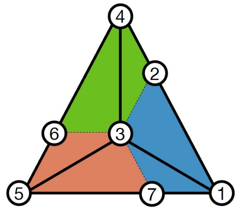

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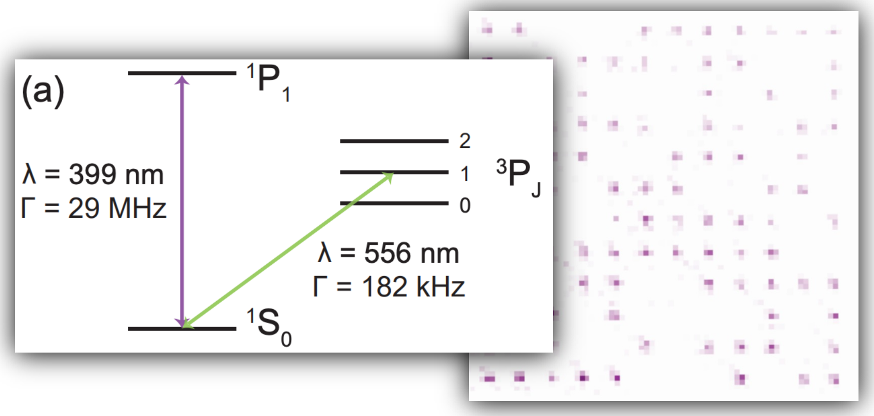

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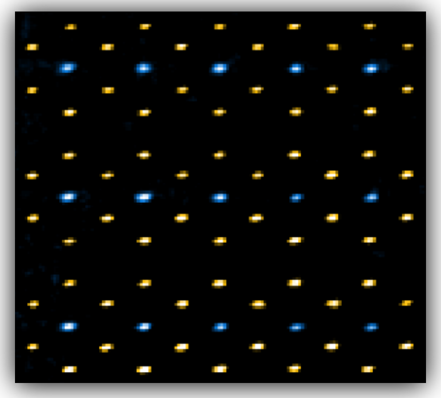

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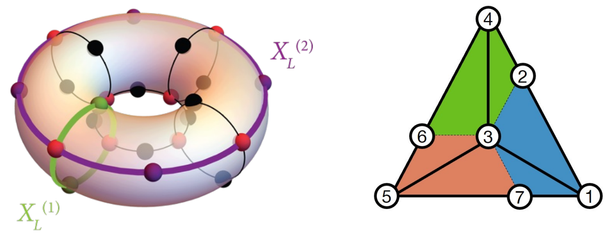

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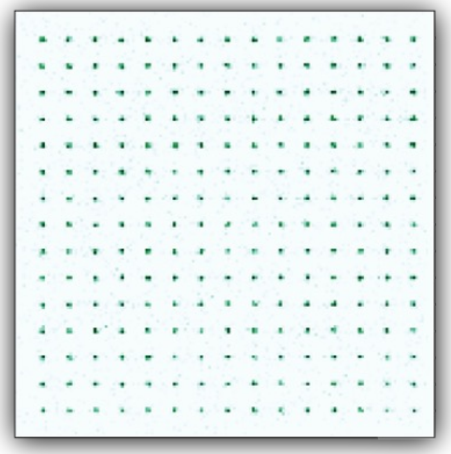

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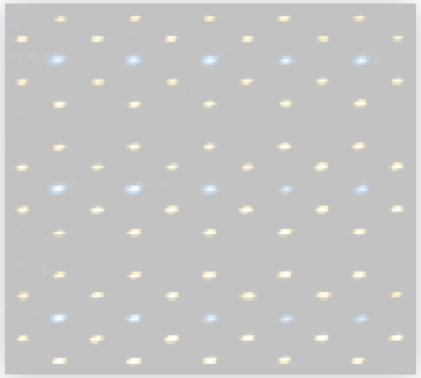
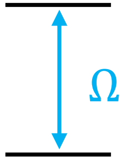


Toolbox: Qubit encoding (alkali)

Rydberg qubit:

Rydberg state: $|r\rangle = |1\rangle$

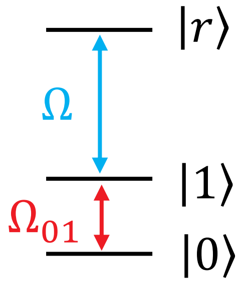
Ground state: $|g\rangle = |0\rangle$



mainly used in quantum simulation applications

^{87}Rb

Hyperfine qubit:



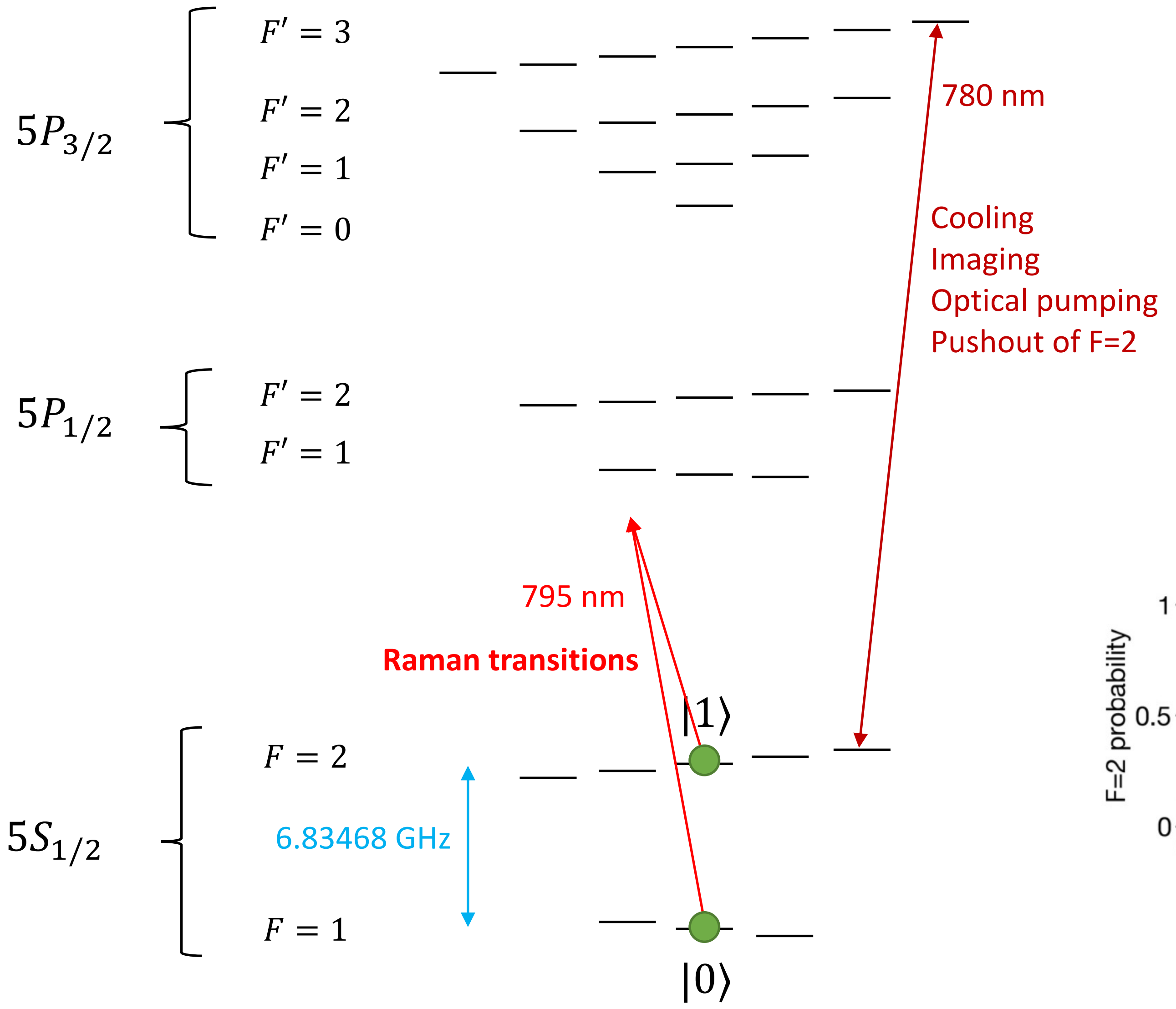
Ground states:
$F = 2, m_F = 0$
$F = 1\ m_F = 0$

- Long lived coherence in tweezers $\longrightarrow$ $T_2^* \sim$ 4-10 ms [1-4] up to 200 ms [5]; $T_2 > 1$ s (up to 12.6 s in [3])
- High-fidelity manipulation + readout
- Suitable for universal quantum gates (non-interacting)

[1] Kuhr … Meschede, PRA 2005, [2] Xia … Saffman, PRL 2015,
[3] Wang … Weiss, PRL 2015, [4] Levine … Lukin, PRA 2022,
[5] Sheng … Zhan, PRL 2018

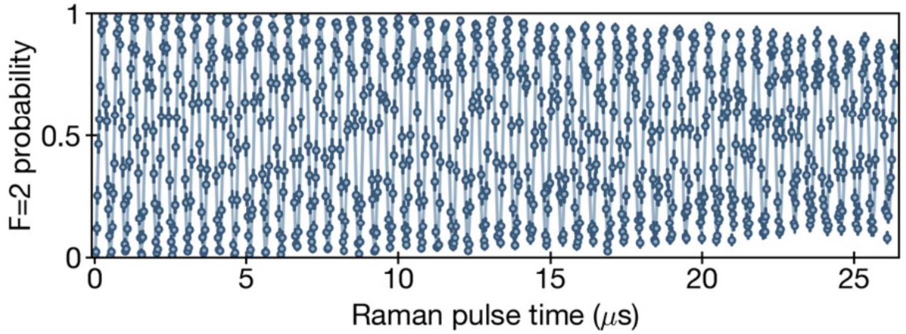
Toolbox: Single-qubit operations (alkali)

Hyperfine qubit in ^{87}Rb



Hyperfine rotations:

- Global microwave (slow, robust)
- Raman transitions



π-pulse fidelity (Raman): $0.999873(1)$ [1]

[1] H. Levine et al, PRA 2022; [2] Sheng et al, PRL 2018

state of the art for global single-qubit gates (mw): $0.99995(1)$ [2]

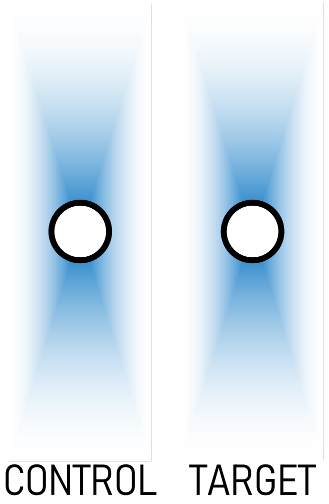
Toolbox: Two-qubit gate

Native 2-qubit gate: CZ (controlled-phase) gate

Unitary map:

$$|00\rangle \rightarrow |00\rangle$$
$$|01\rangle \rightarrow -|01\rangle$$
$$|10\rangle \rightarrow -|10\rangle$$
$$|11\rangle \rightarrow -|11\rangle$$

standard protocol using Rydberg blockade originally proposed by Jaksch et al., PRL **85**, 2208 (2000)



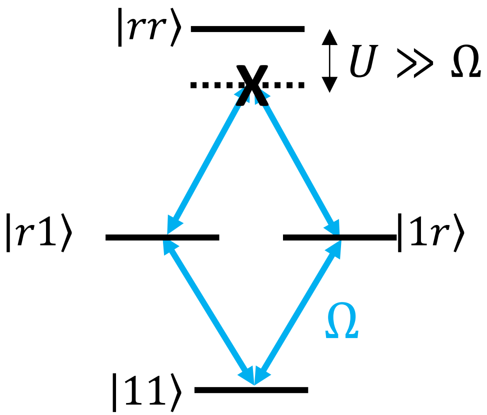
local Rydberg coupling

technically challenging

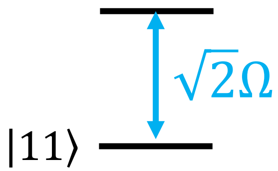
can we build a CZ gate using global Rydberg coupling?

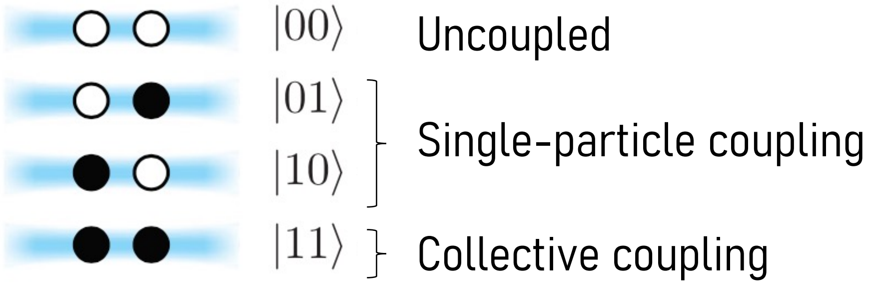
challenge: designing a symmetric protocol for states with one or two atoms coupled to the Rydberg state

Rydberg blockade:

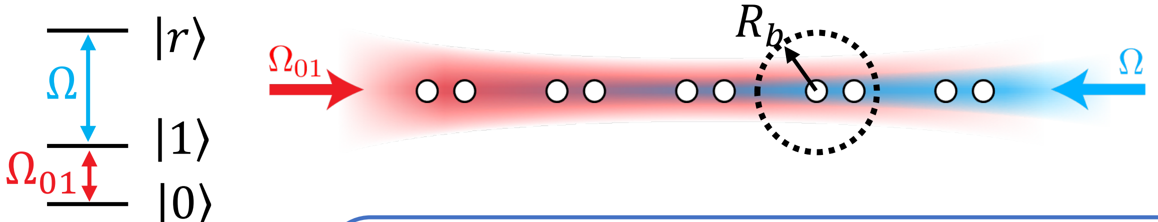


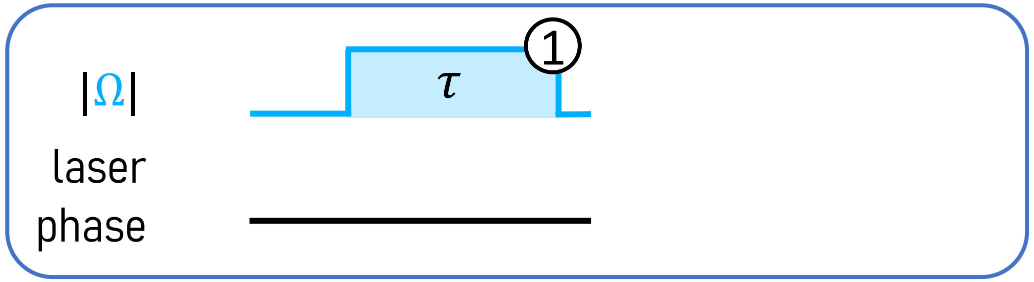
$$|W\rangle = \frac{1}{\sqrt{2}}(|r1\rangle + |1r\rangle)$$





Toolbox: Two-qubit gate
Levine-Pichler gate



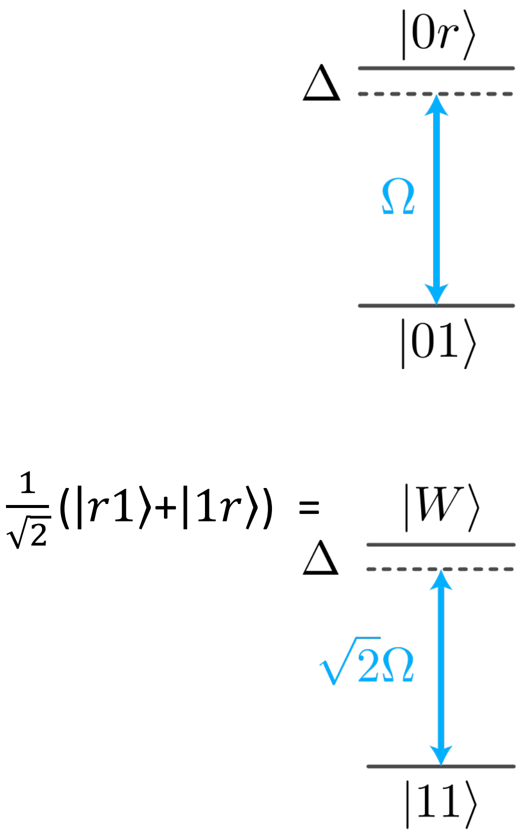


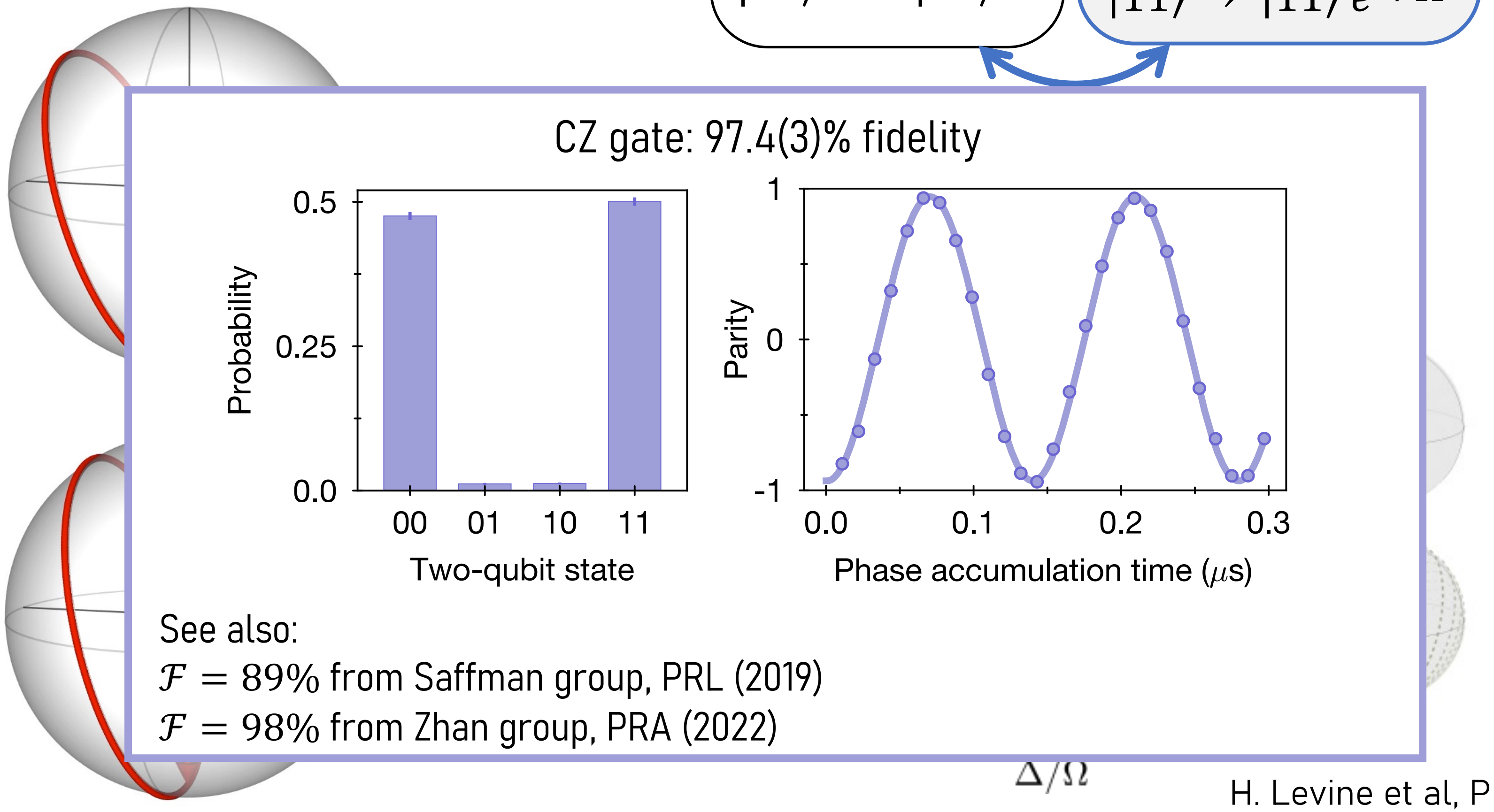
Target map:

$|00\rangle \rightarrow |00\rangle$
$|01\rangle \rightarrow -|01\rangle$
$|10\rangle \rightarrow -|10\rangle$
$|11\rangle \rightarrow -|11\rangle$

We implement:

$|00\rangle \rightarrow |00\rangle$
$|01\rangle \rightarrow |01\rangle\, e^{i\phi_{01}}$
$|10\rangle \rightarrow |10\rangle\, e^{i\phi_{10}}$
$|11\rangle \rightarrow |11\rangle\, e^{i\phi_{11}}$





See also:
$\mathcal{F}$ = 89% from Saffman group, PRL (2019)
$\mathcal{F}$ = 98% from Zhan group, PRA (2022)

H. Levine et al, PRL 2019

Toolbox: Two-qubit gate

But… 2-qubit gate fidelities still limited!

Google, Satzinger et al arXiv: 2207.06431

Component	Error probability
SQ gates	1.09×10^{-3}
CZ gates	6.05×10^{-3}
Data qubit idle	2.46×10^{-2}
Reset	1.86×10^{-3}
Readout	1.96×10^{-2}
CZ leakage	2.0×10^{-4}
Leakage from heating	6.4×10^{-4}
CZ crosstalk	9.5×10^{-4}

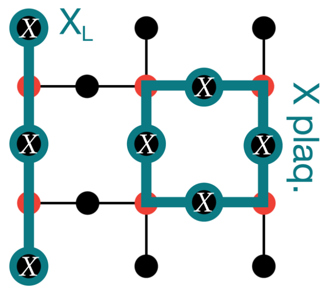
Google SC qubit state-of-the-art (when doing on ~10s of qubits in parallel): F_{CZ} = 99.4%

Levine-Pichler CZ gate (2019): 97.4(3)% fidelity

Quantum error correction has a threshold

As we grow the lattice (increase distance d), do we increase or decrease the logical qubit error rate?

$$P_L \sim \left(\frac{p}{p_{th}}\right)^{\frac{d+1}{2}}$$



$p_{th} \approx$ 1% CZ gate error (surface code)

Improving two-qubit gate fidelity to 99-99.9% is critical to building a large-scale quantum computer

Recent significant improvements:

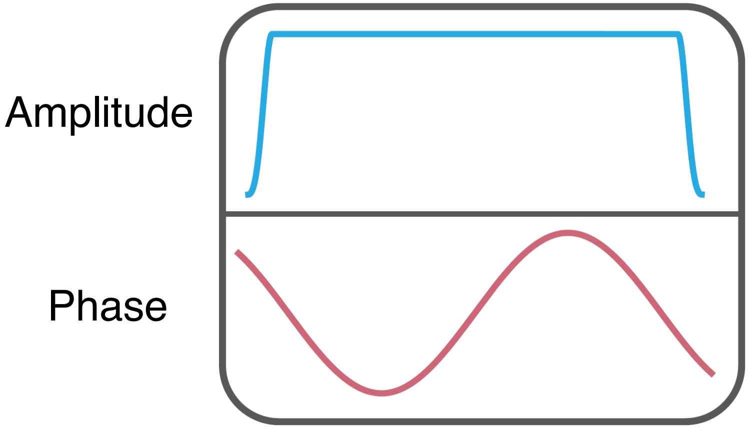
- new gate ideas
- technical improvements to reduce intermediate-state scattering and Doppler dephasing

slide credit: Dolev Bluvstein

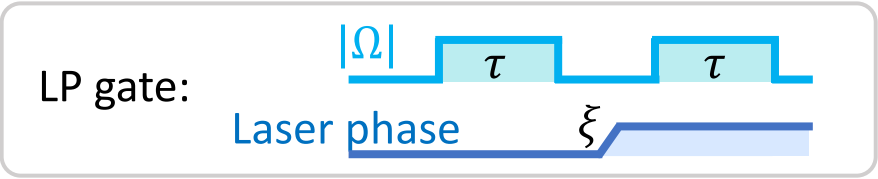
Toolbox: Two-qubit gate

Robust, continuous family of gates

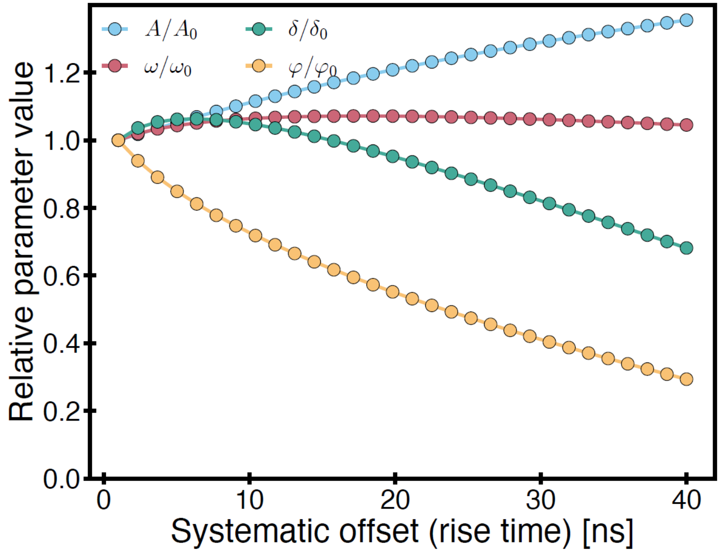
Single-pulse, continuous-phase gates (based on S. Jandura, G. Pupillo, arXiv:arXiv:2202.00903 (2022))

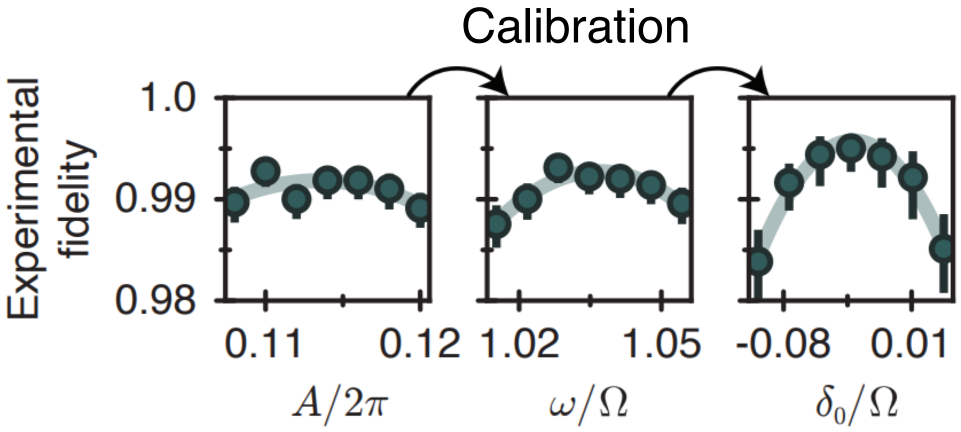


$$A\cos(\omega t + \varphi) + \delta t$$



Key observation: experimental robustness and tunability



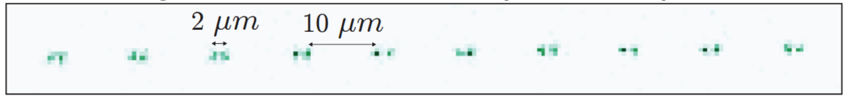


S. Evered*, D. Bluvstein*, M. Kalinowski*, et al arXiv: 2304.05420 (2023)

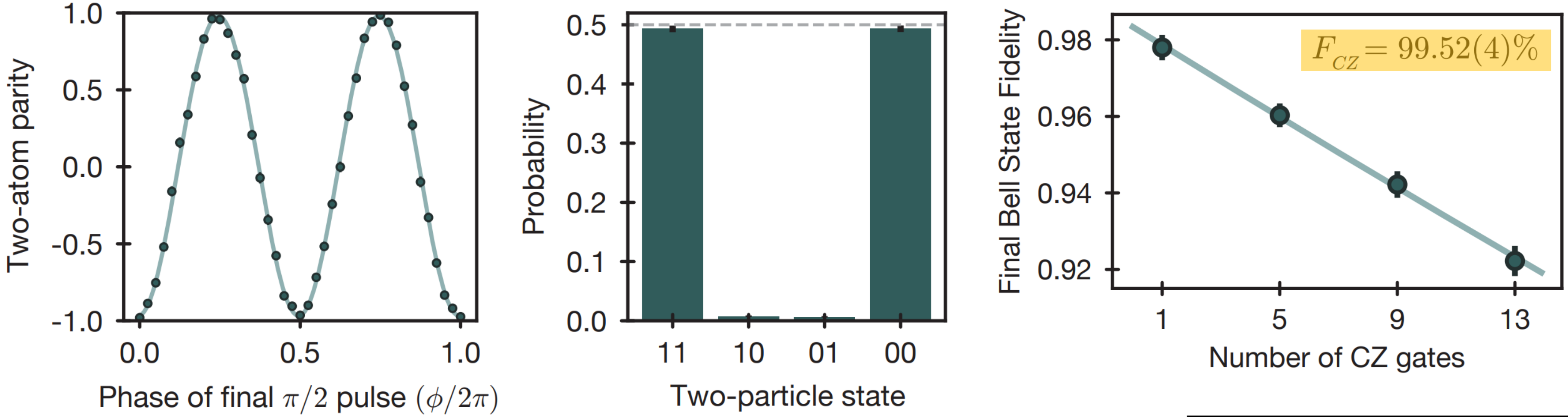
Toolbox: Two-qubit gate

Robust, continuous family of gates: Experimental implementation and benchmarking of new CZ gate fidelities

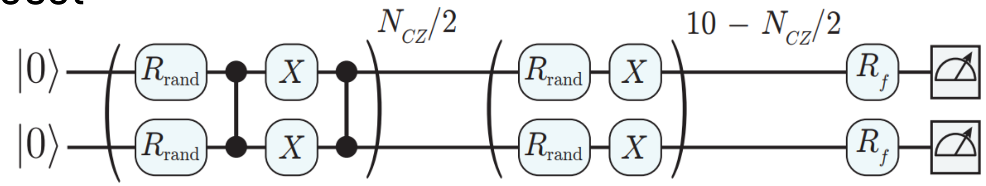
averaged across 20-60 qubits in parallel



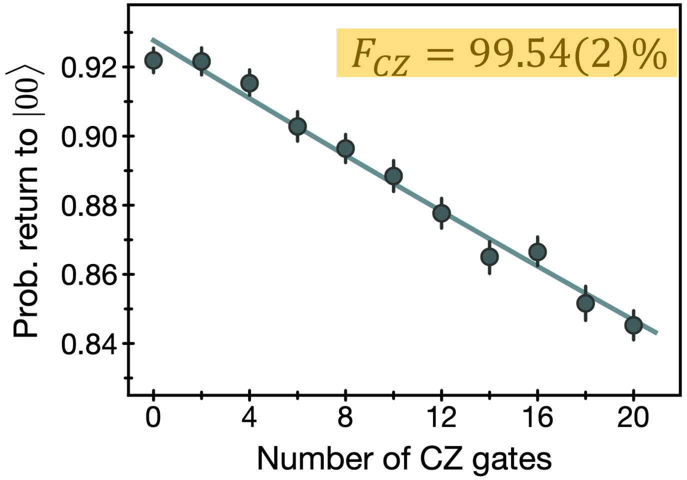
1. Bell state measurement



2. Benchmarking protocol



Apply sequence of random rotations interspersed with entangling gate – carefully calculated final rotation brings back to initial state if no errors occur



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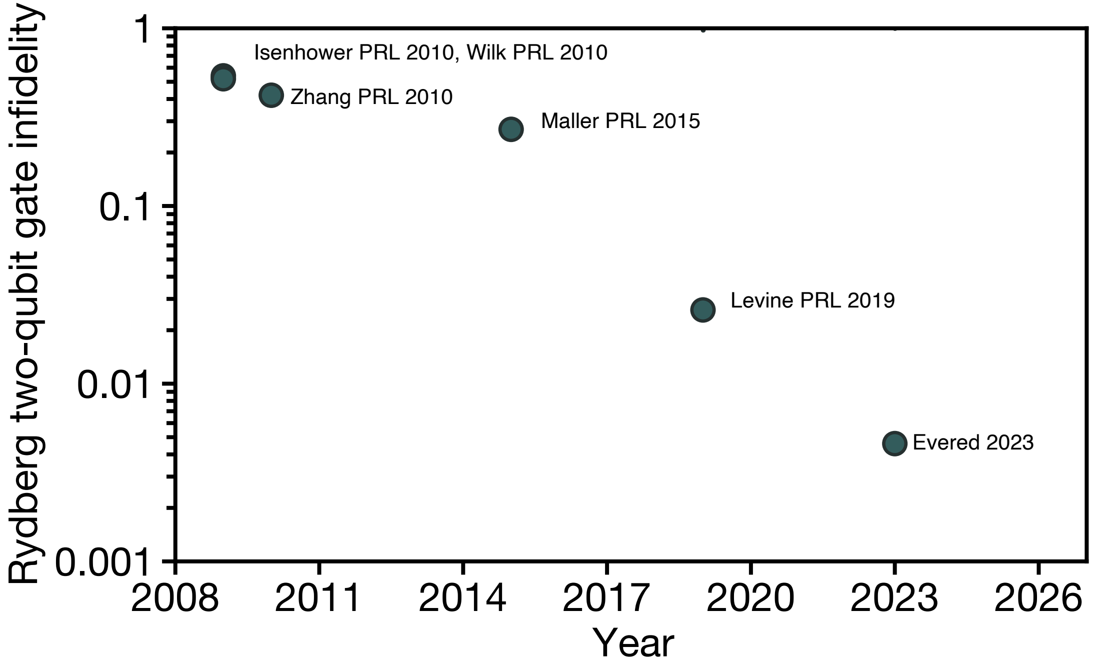
See also related work (including erasure) from Endres (Scholl 2305.03406) and Thompson (Ma 2305.05493) slide credit: Dolev Bluvstein

Toolbox: Two-qubit gate

Robust, continuous family of gates: Remaining error sources → Can we go higher?

Saffman review article (2016)



Simulated error sources

Error source	Time optimal
Scattering* $\lvert 1\rangle$	0.038%
Scattering $\lvert 0\rangle$	0.017%
Rydberg decay	0.133%
$T_2^* = 3\,\mu s$	0.134%
Position fluct.	0.012%
Power fluct.	0.001%
Rydberg $m_{J=-\frac{1}{2}}$	0.06 - 0.15%
Total fidelity	**99.51 - 99.60%**

Next frontier: 99.9% fidelity

- Good understanding of atomic physics error model
- 99.9% can be done with e.g. 3x Rabi frequency and 2x detuning, which requires technical optimizations

S. Evered*, D. Bluvstein*, M. Kalinowski*, et al arXiv: 2304.05420 (2023)

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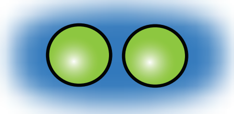
Toolbox: Dynamically reconfigurable connectivity

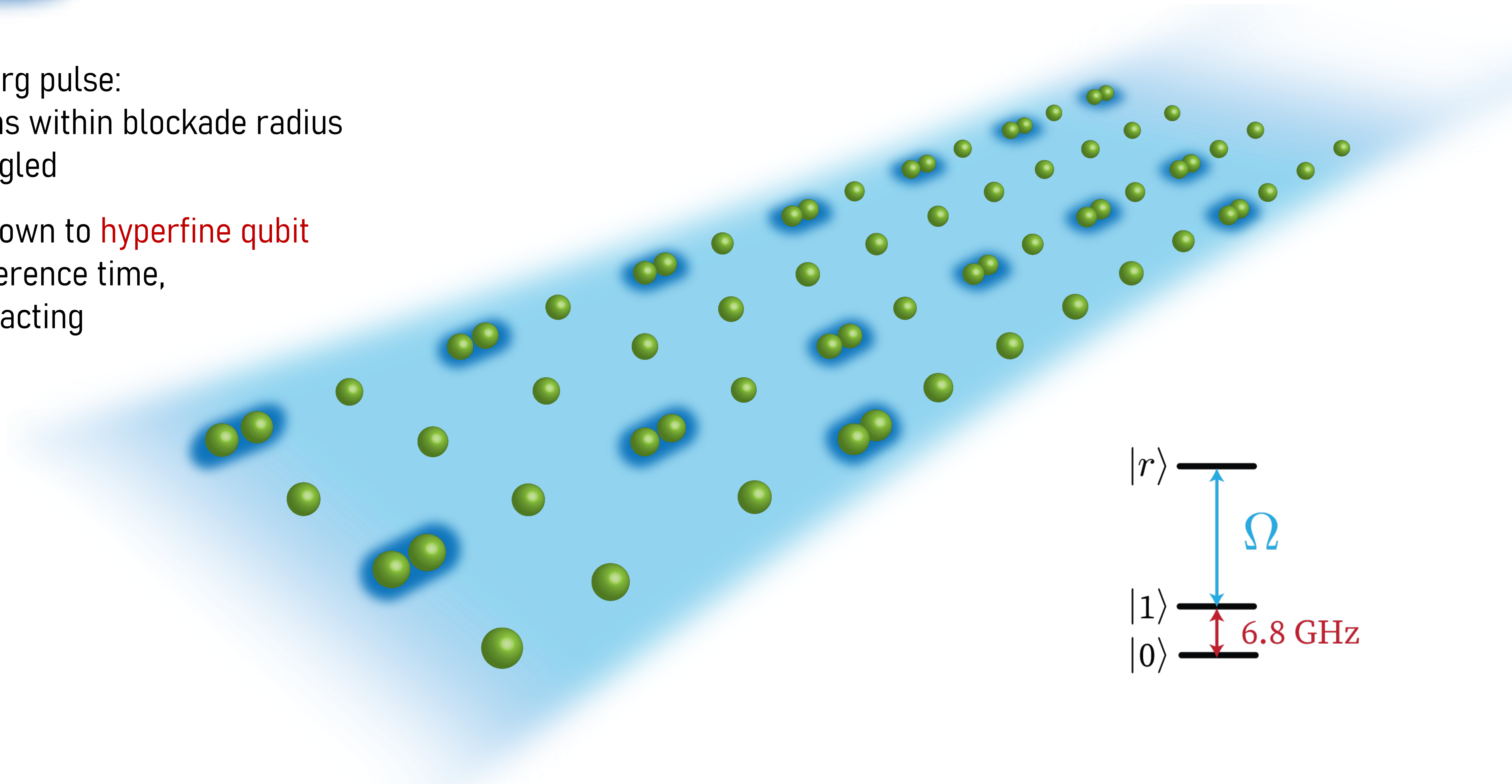
how can we generate long-range entanglement (efficiently)?



pair of atoms: can be entangled using Rydberg blockade ⟶ LOCAL

- Rydberg pulse:
only atoms within blockade radius get entangled

- Map down to hyperfine qubit
Long coherence time, non-interacting



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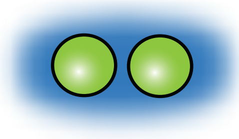

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- Tweezers:
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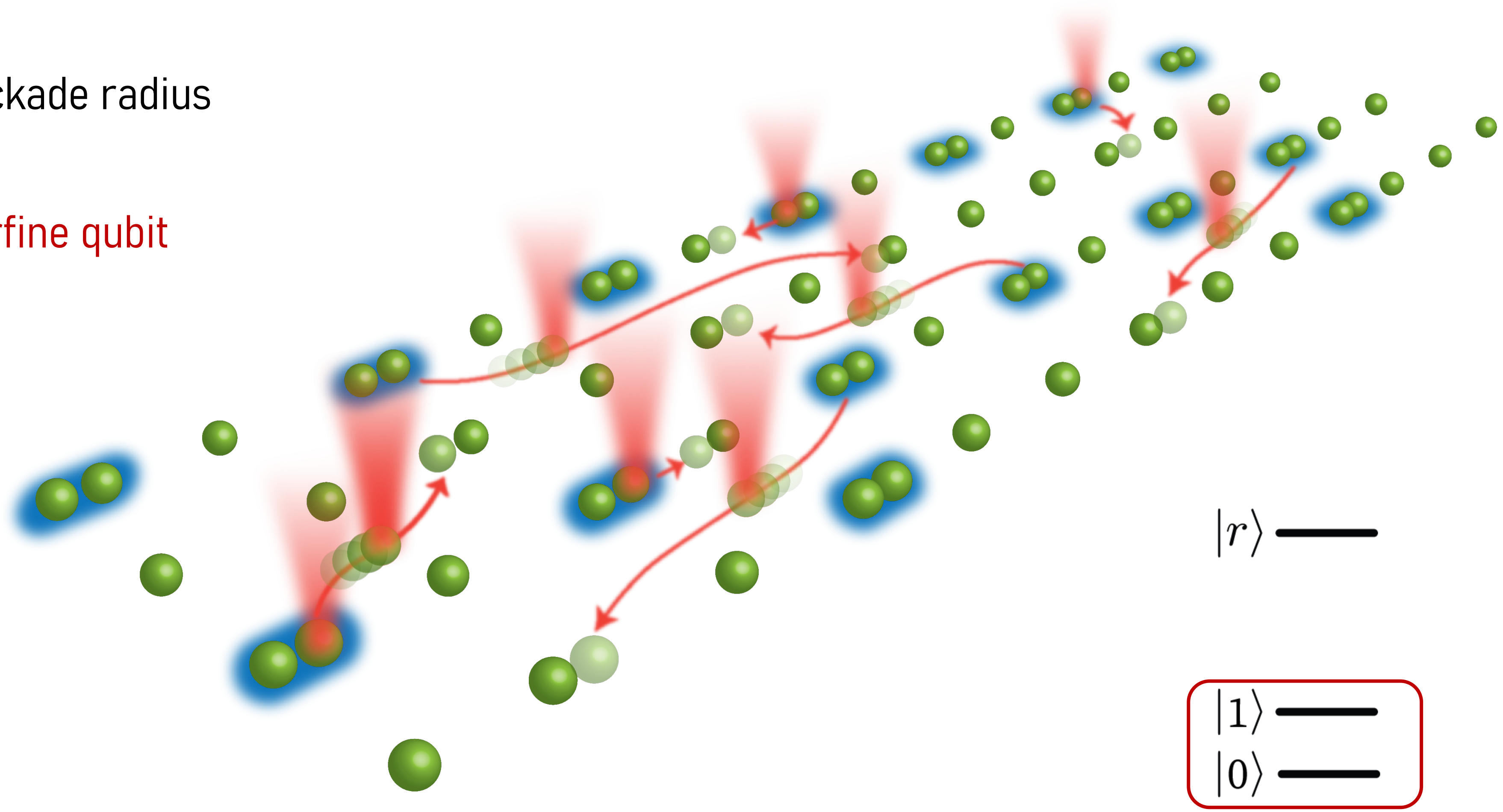

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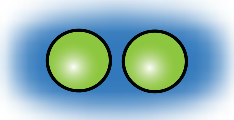

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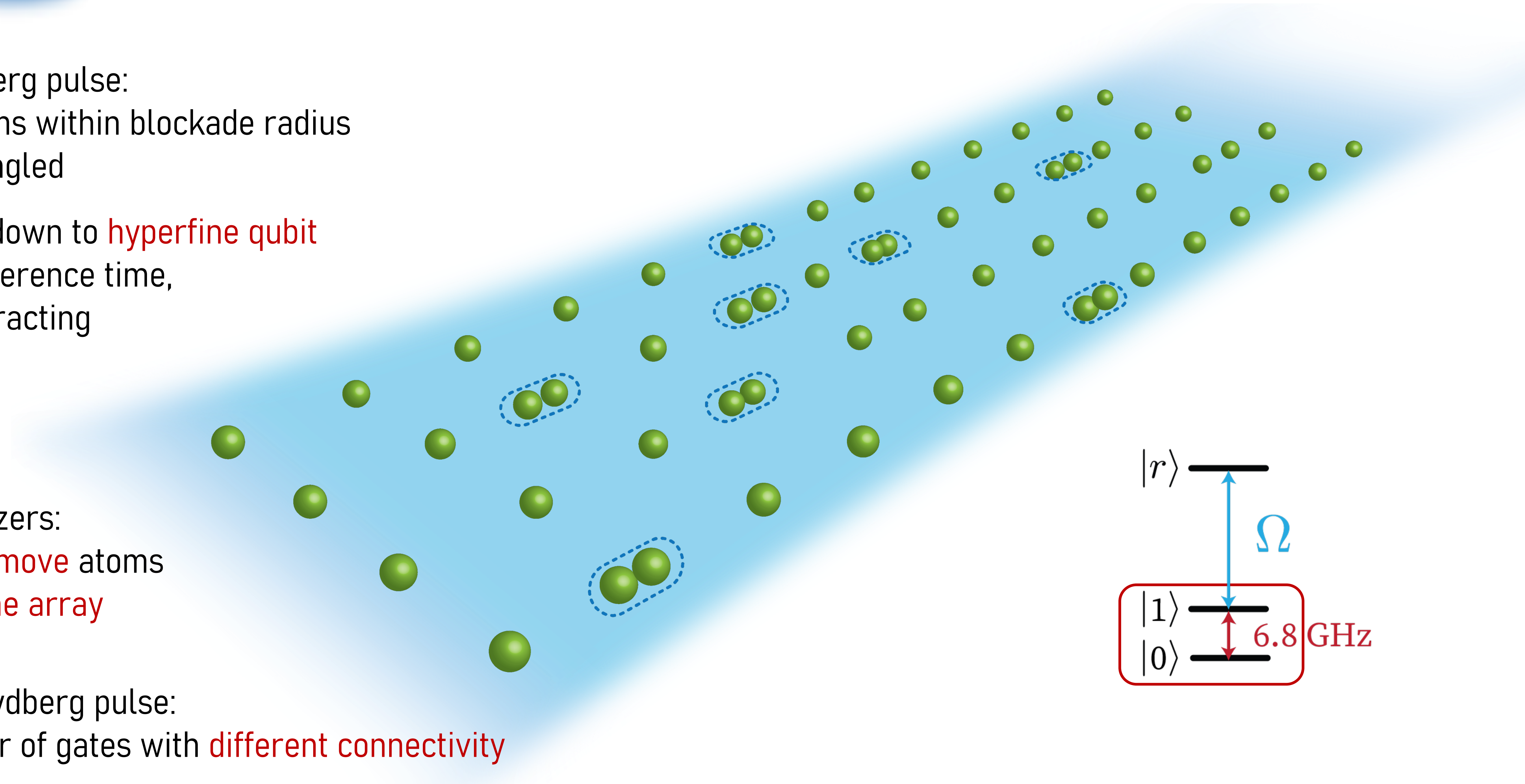

- Tweezers:
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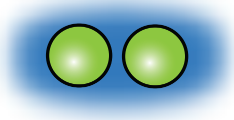
- 2nd Rydberg pulse:
new layer of gates with different connectivity

Toolbox: Dynamically reconfigurable connectivity

how can we generate long-range entanglement (efficiently)?



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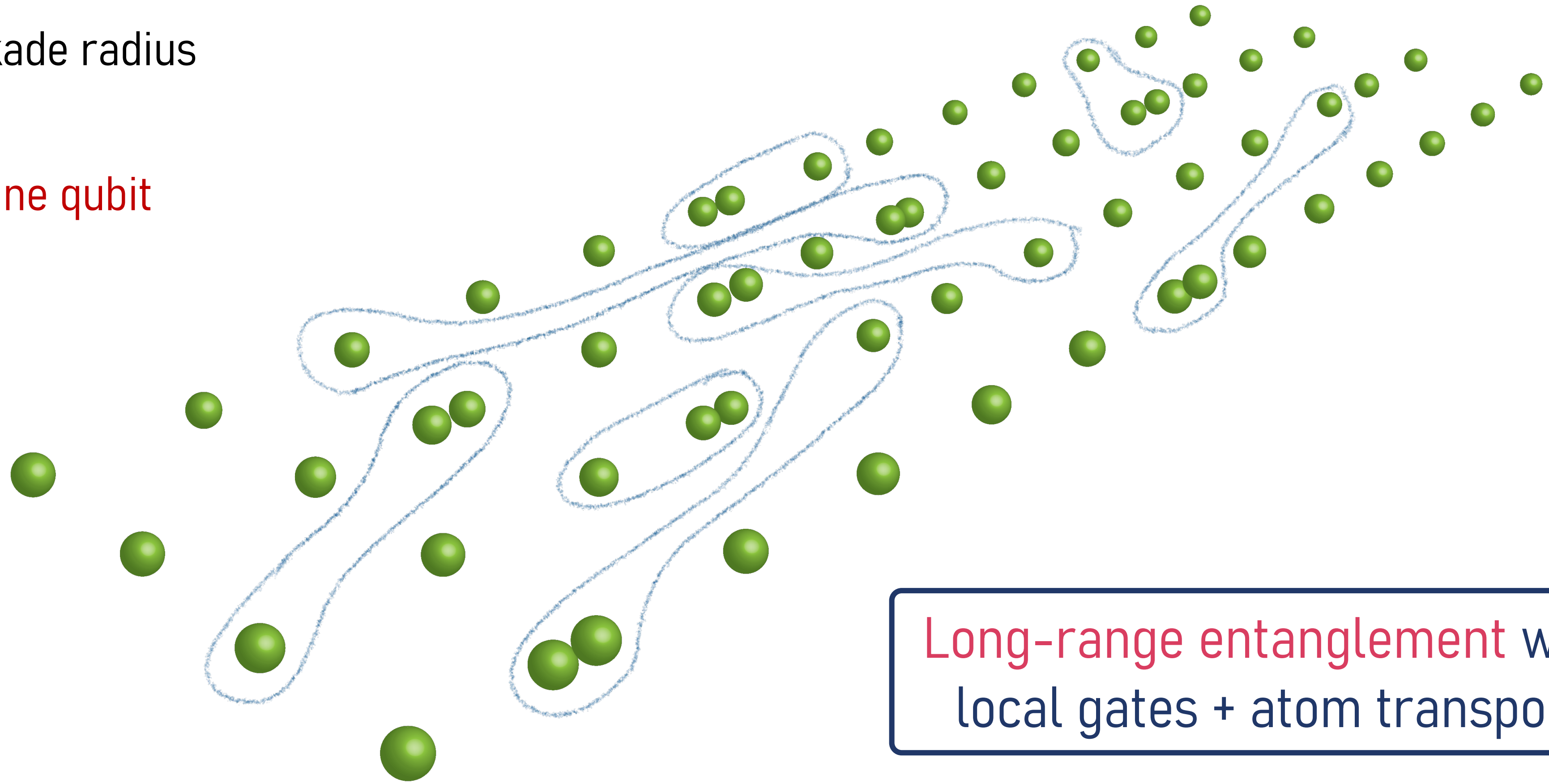

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allow to move atoms across the array

- 2^{nd} Rydberg pulse:
new layer of gates with different connectivity

Long-range entanglement with local gates + atom transport

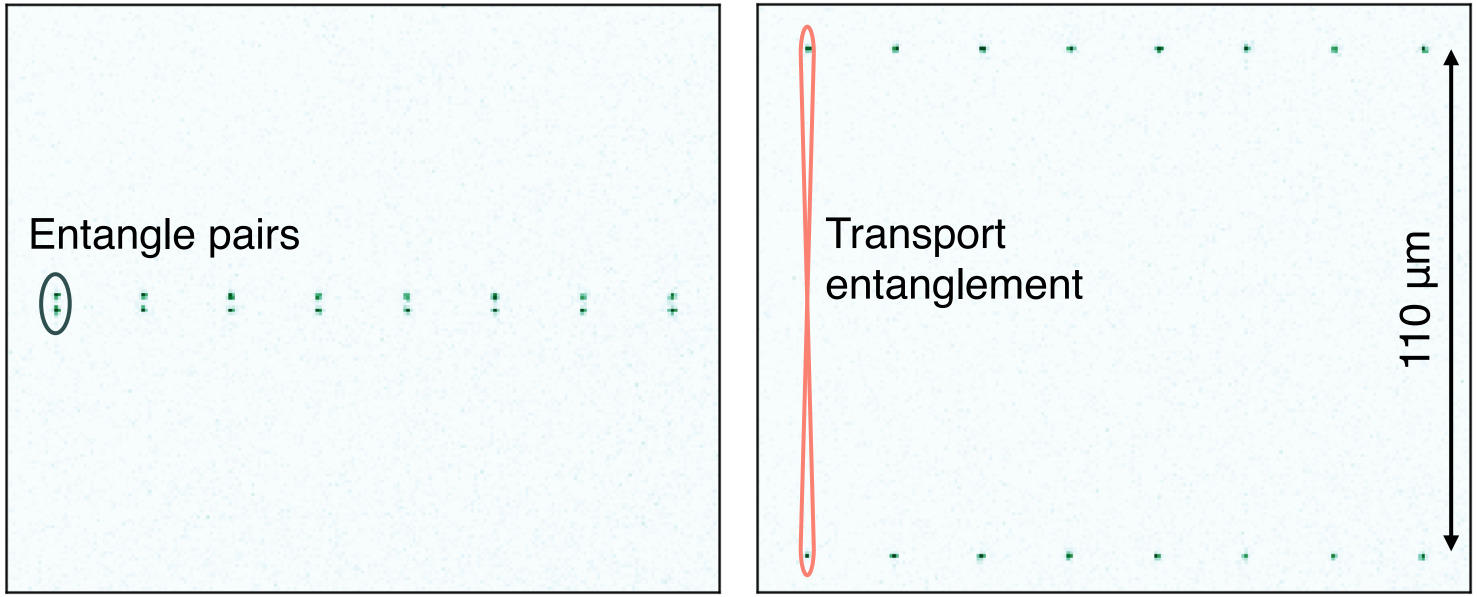
D. Bluvstein, et al, Nature 604, 451-456 (2022)

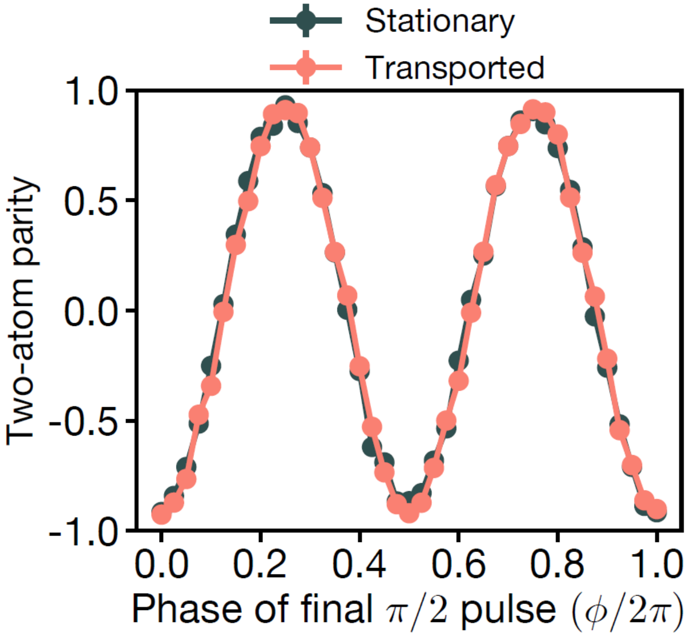
related work on coherent transport:
Beugnon et al, Nat Phys 2007; Dordevic et al, Science 2021

D. Bluvstein, et al, Nature 604, 451-456 (2022)

Toolbox: Dynamically reconfigurable connectivity

Transporting entanglement across the array: Bell pairs





Many potential applications:
complex quantum computing architectures
& new probes for many-body phases

⟵

Coherence is preserved when transporting the atoms over a hundred µm in a few hundred µs (~10^{-4} T_2)

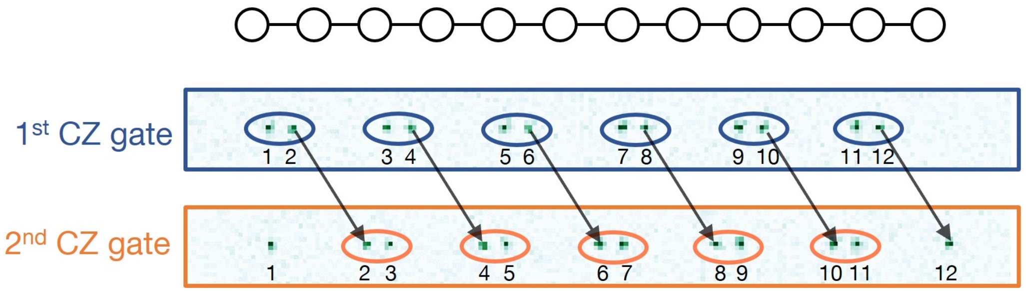
related work on coherent transport:
Beugnon et al, Nat Phys 2007; Dordevic et al, Science 2021

Toolbox: Dynamically reconfigurable connectivity

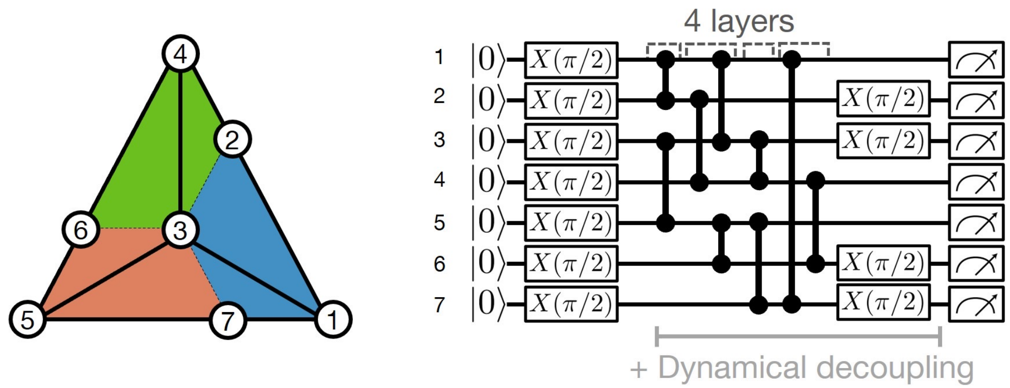
D. Bluvstein, et al, Nature 604, 451-456 (2022)

Many different applications

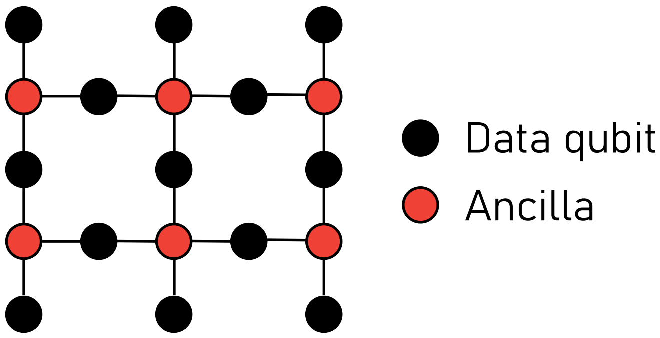
1D cluster states



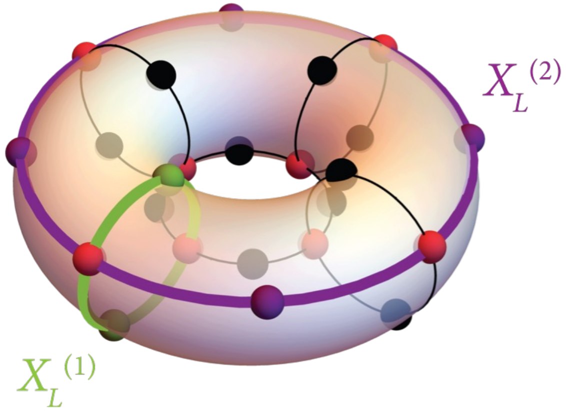
Steane Code



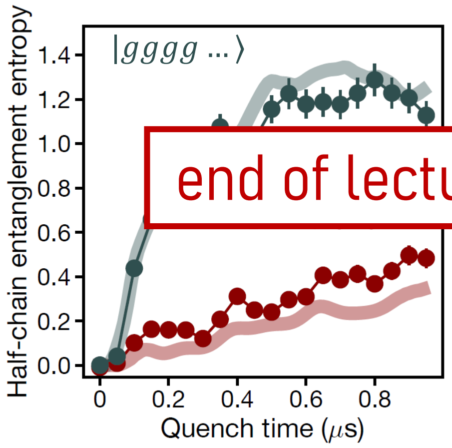
Surface Code (2D)



Toric Code (3D)



Measurement of entanglement entropy



end of lecture 2

Toolbox: Dynamically reconfigurable connectivity

D. Bluvstein, et al, Nature 604, 451-456 (2022)

Many different applications

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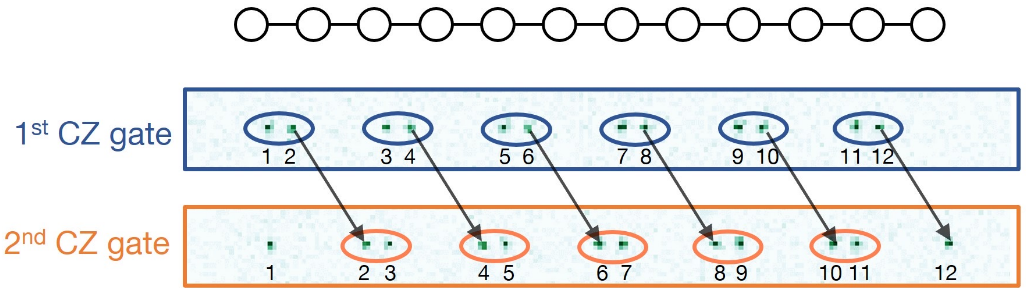

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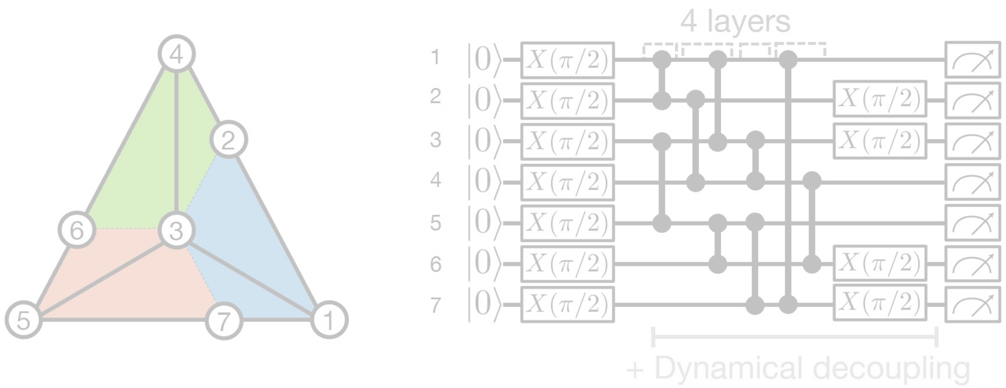

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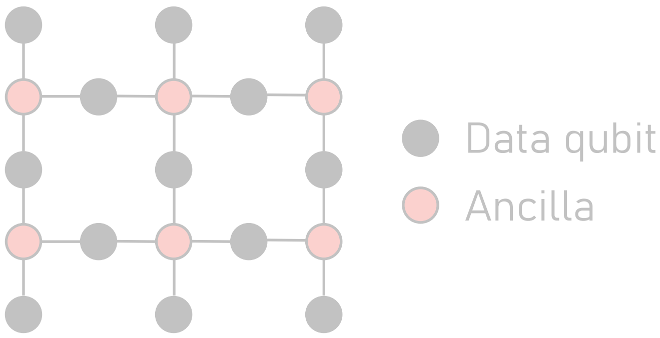
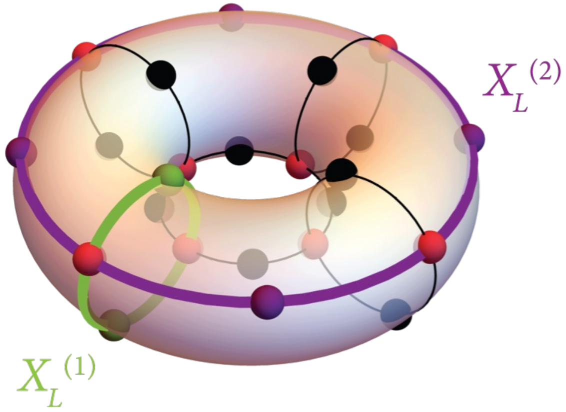


Toric Code (3D)



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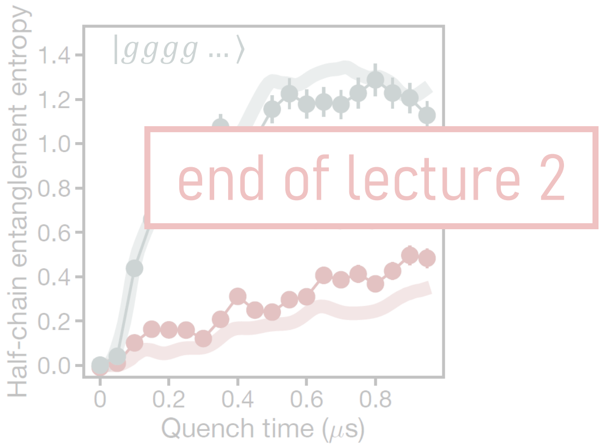


end of lecture 2

Digital quantum dynamics

Experimental toolbox

Qubit encoding

Single-qubit operations

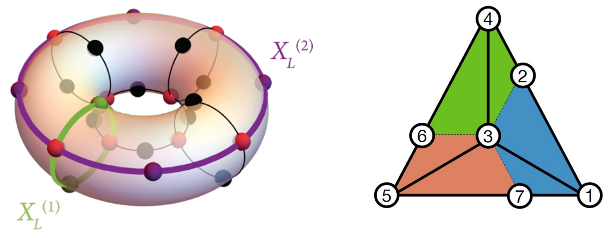
Two-qubit gates (extension to multi(>2)-qubit gates)

Reconfigurable any-to-any connectivity

Mid-circuit operations

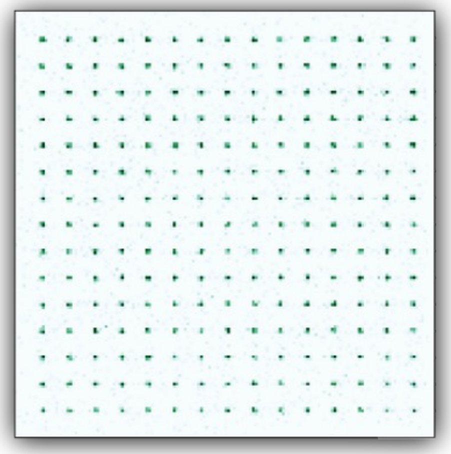
Applications

Initial steps toward quantum error correction applications



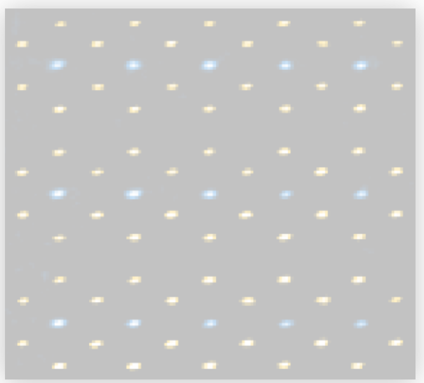
Different versions of Rydberg atom arrays

Alkali atoms



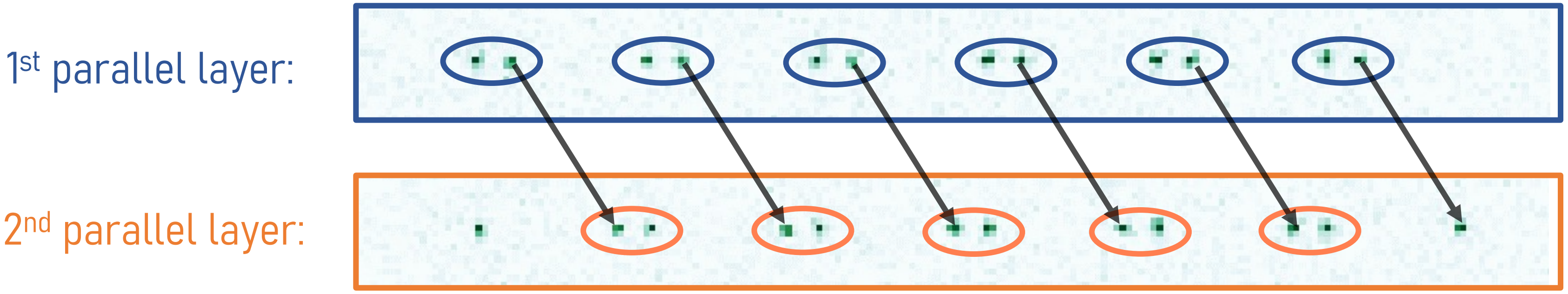
Alkaline-earth atoms

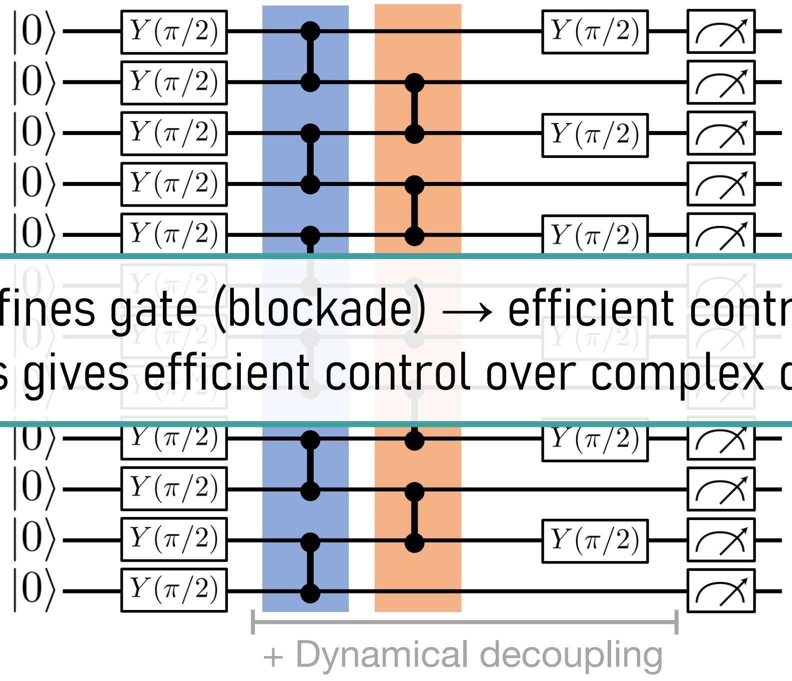
Atomic mixtures

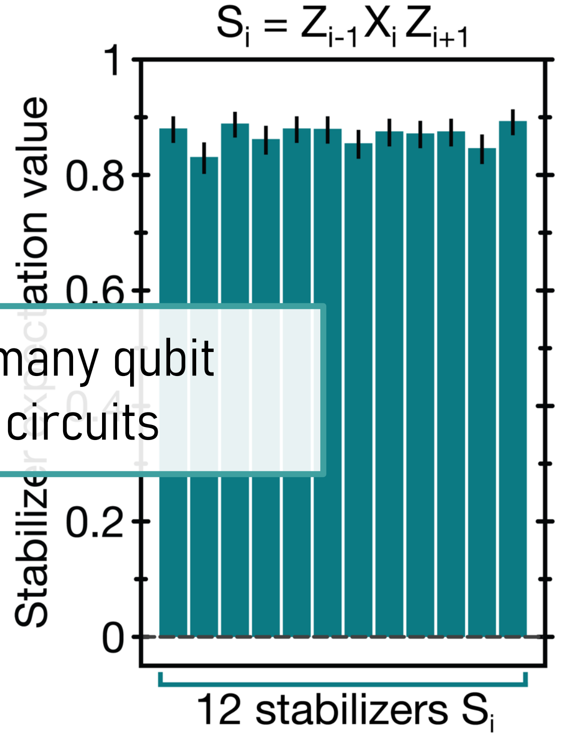


Application: 12-atom cluster state

D. Bluvstein, et al, Nature 604, 451-456 (2022)



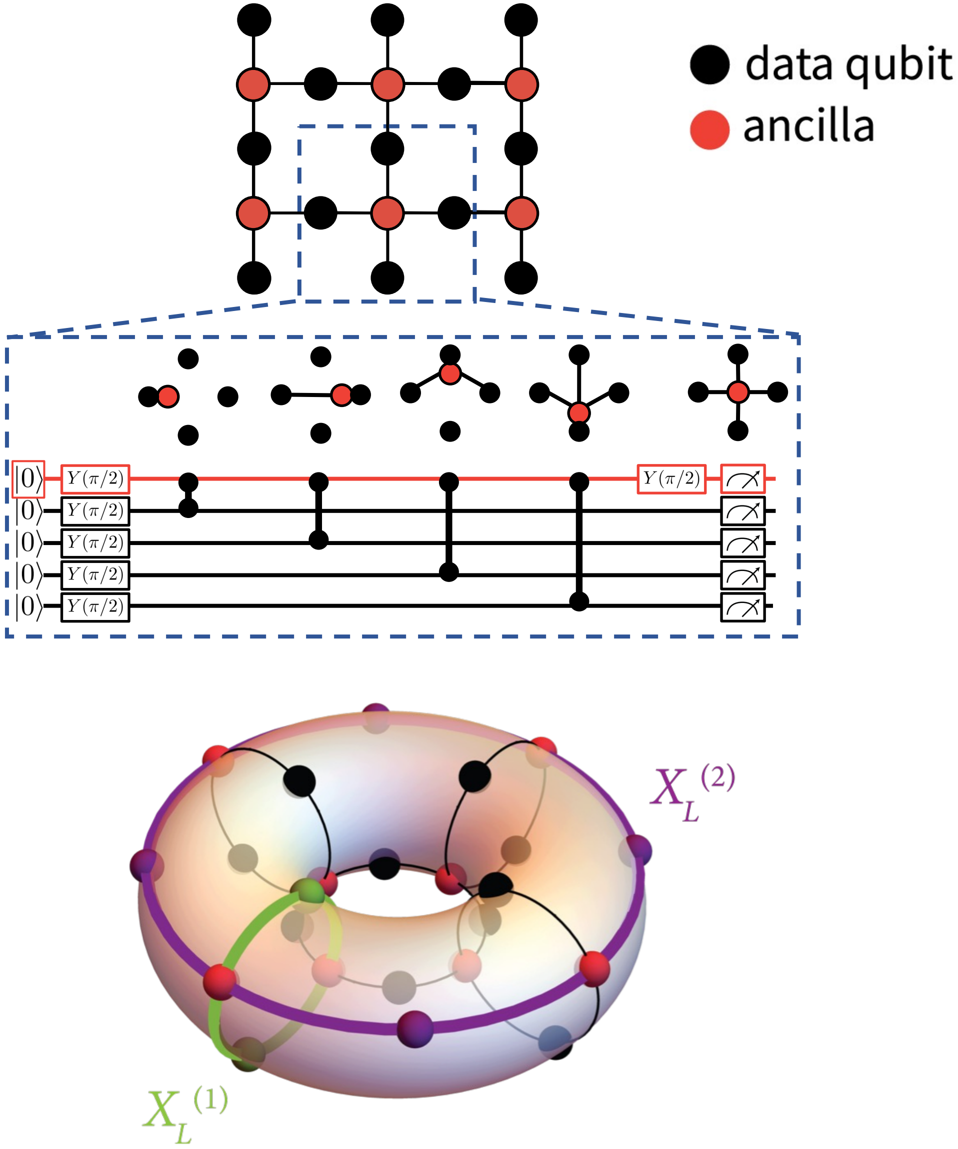


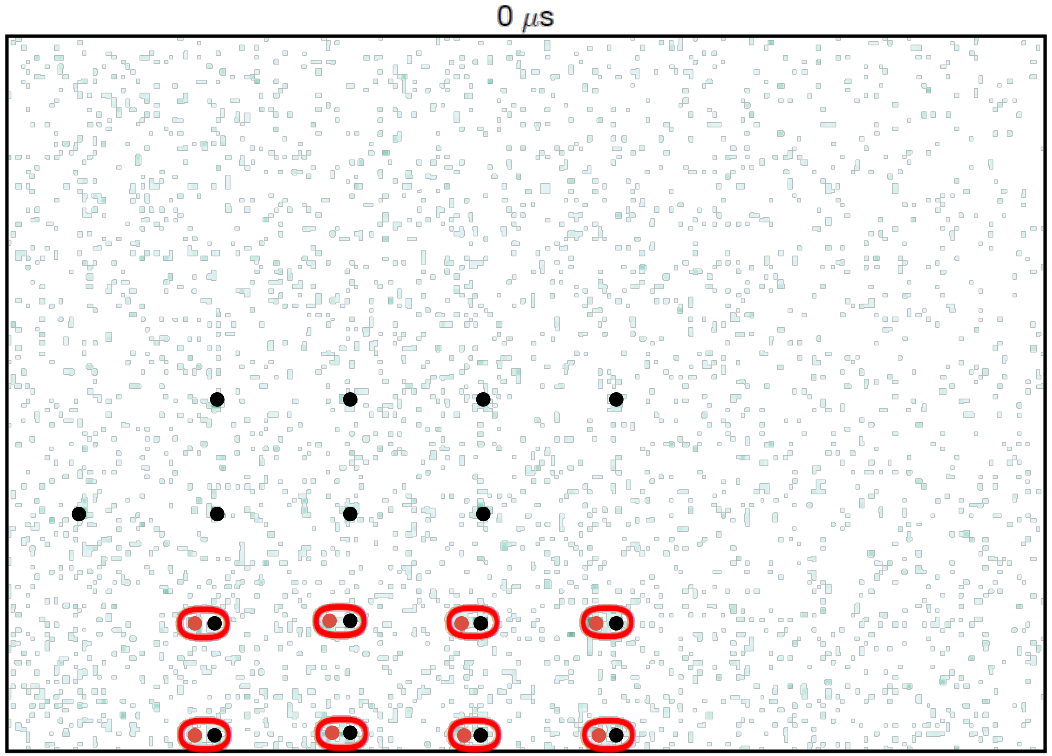


Position defines gate (blockade) → efficient control over many qubit positions gives efficient control over complex quantum circuits

Shows successful creation of the state

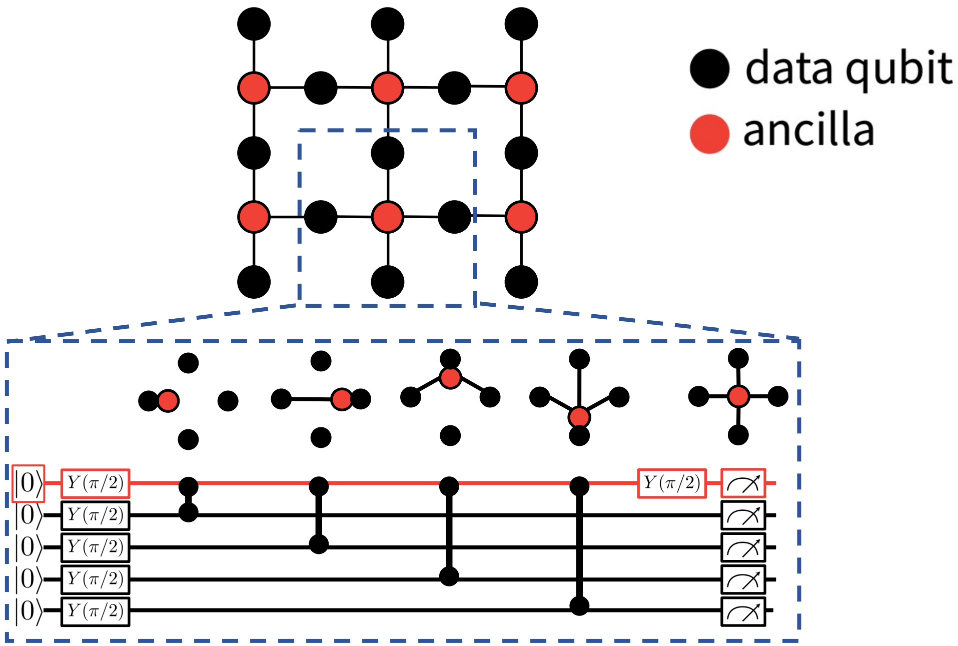
Application: Toric code on a 3D torus

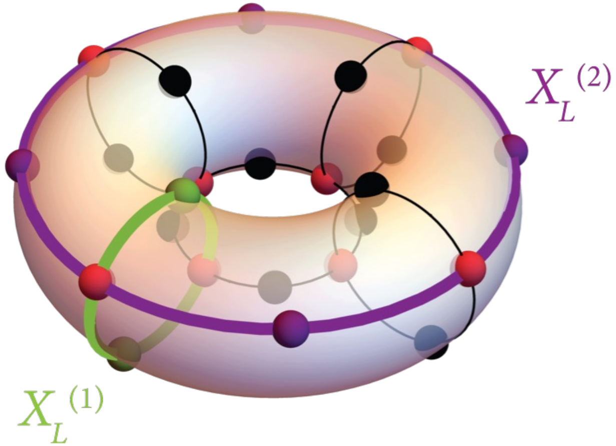


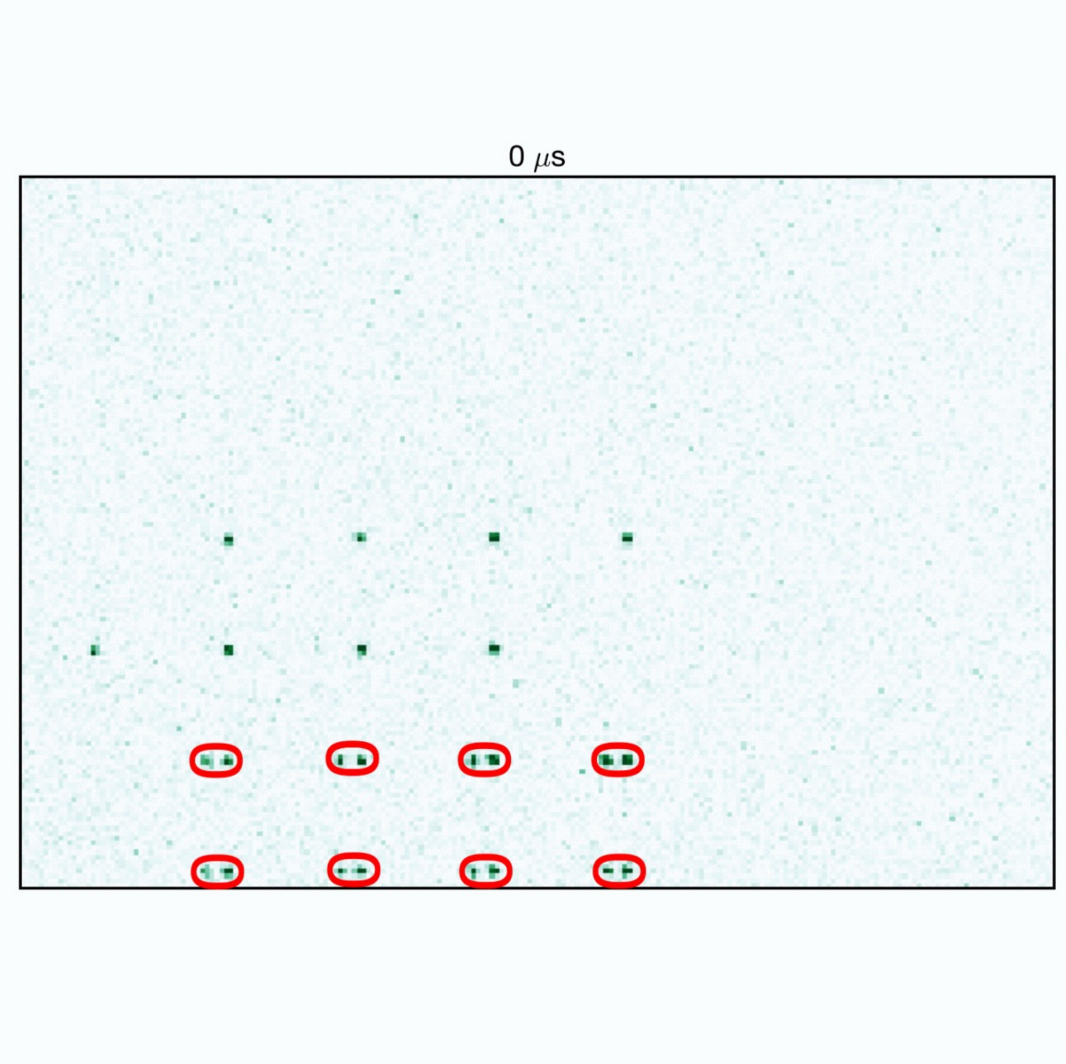


D. Bluvstein, et al, Nature 604, 451-456 (2022)

Application: Toric code on a 3D torus







D. Bluvstein, et al, Nature 604, 451-456 (2022)

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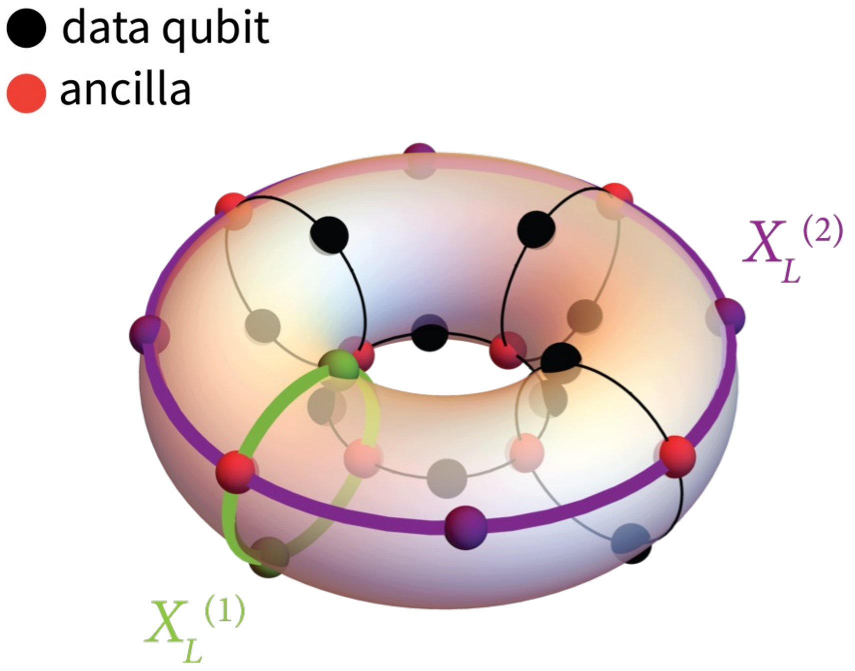
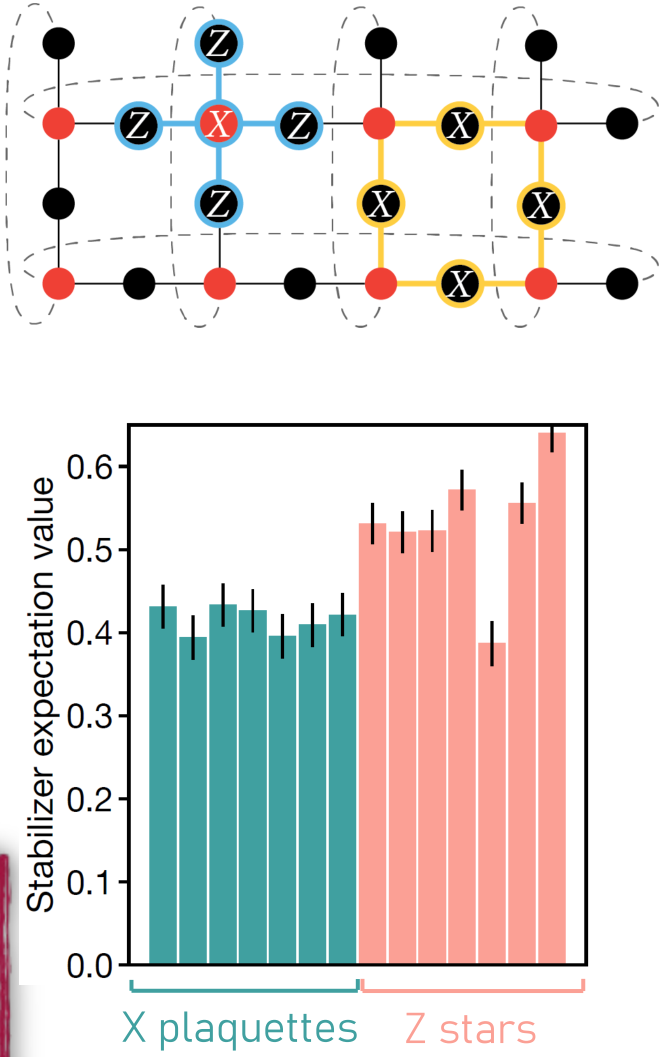
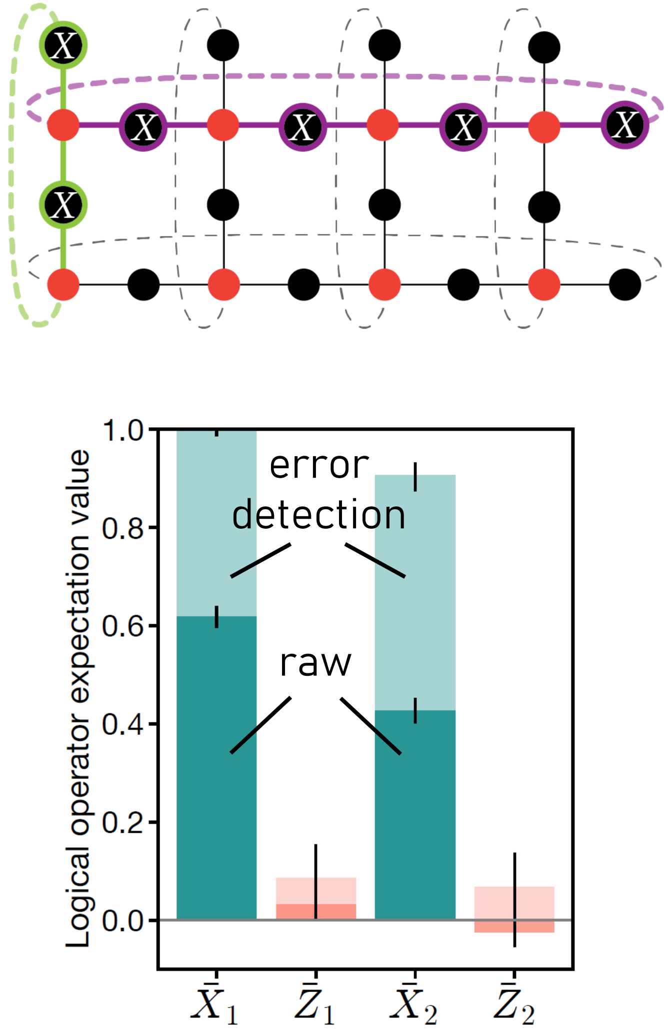


Stabilizers



Two logical qubits!



Efficient realization of QEC thanks to highly-parallel optical control

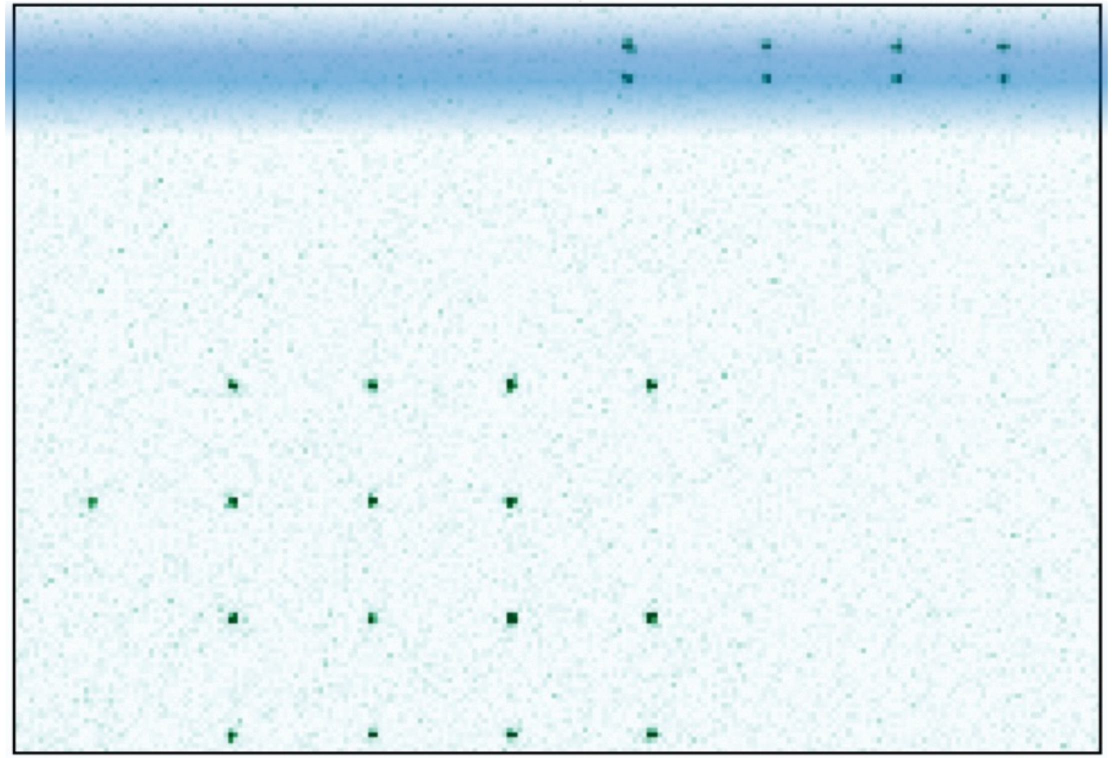
D. Bluvstein, et al, Nature 604, 451-456 (2022)

Toolbox: Mid-circuit readout

Fundamental tool for QEC

With single species alkali atoms:

Move ancilla qubits in separate zone



Imaging with localized resonant beam

Coming soon from Lukin group, Harvard

see also different approach from Graham … Saffman, arXiv (2023)

Digital quantum dynamics

Experimental toolbox

- Qubit encoding
- Single-qubit operations
- Two-qubit gates (extension to multi(>2)-qubit gates)
- Reconfigurable any-to-any connectivity
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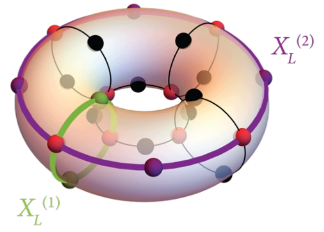
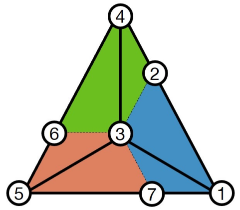
Applications

Initial steps toward quantum error correction applications

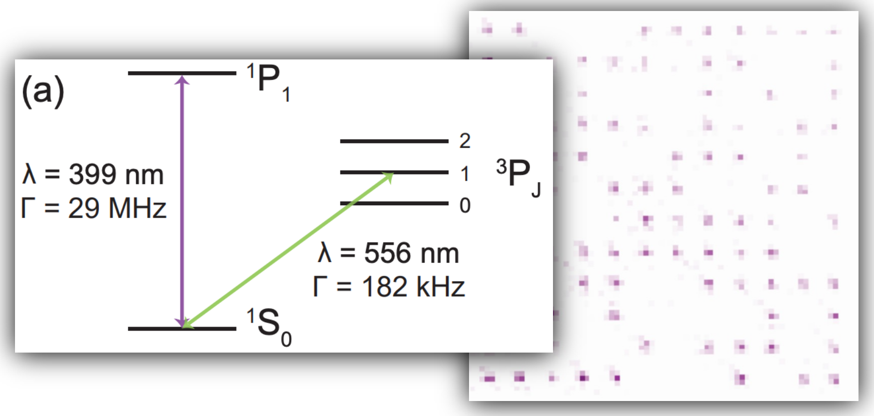




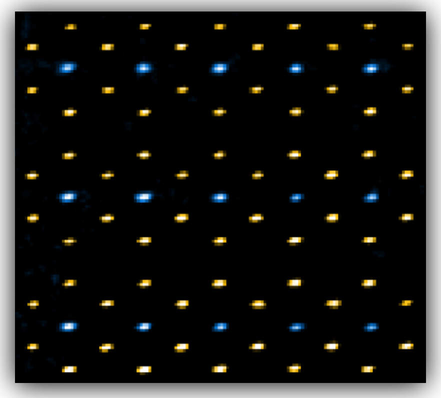
Different versions of Rydberg atom arrays

Alkali atoms

Alkaline-earth atoms



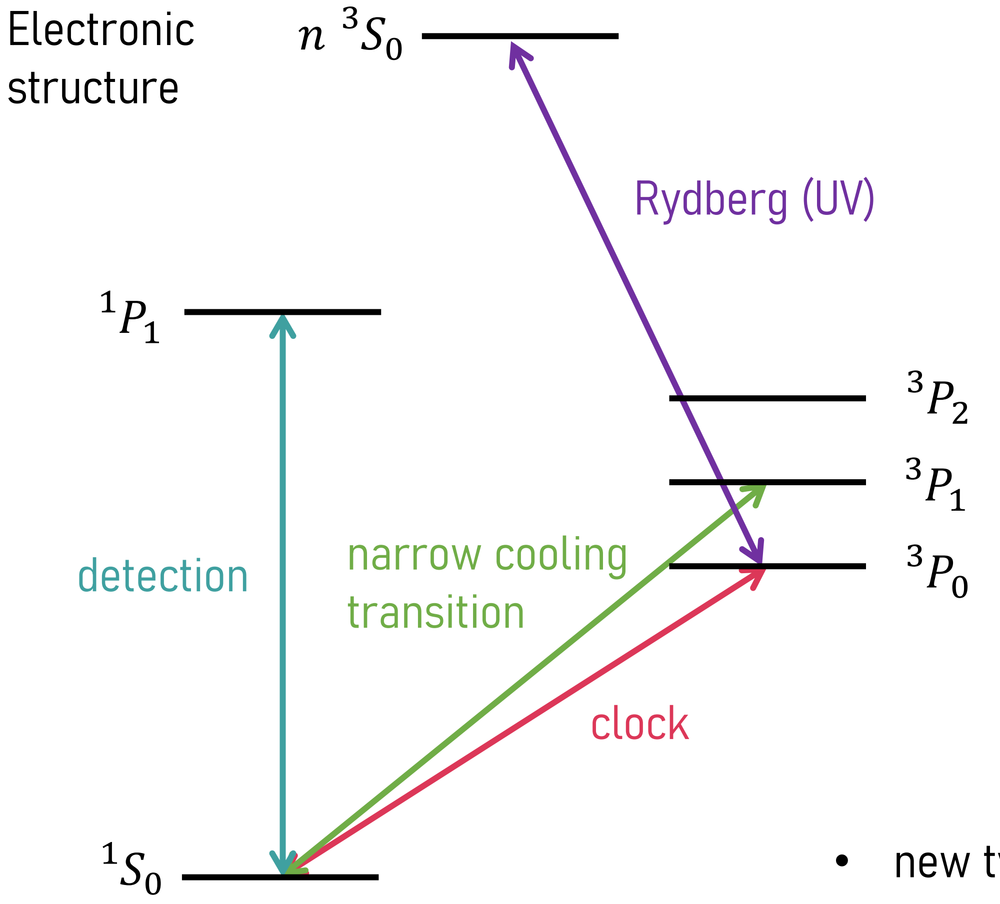
Atomic mixtures

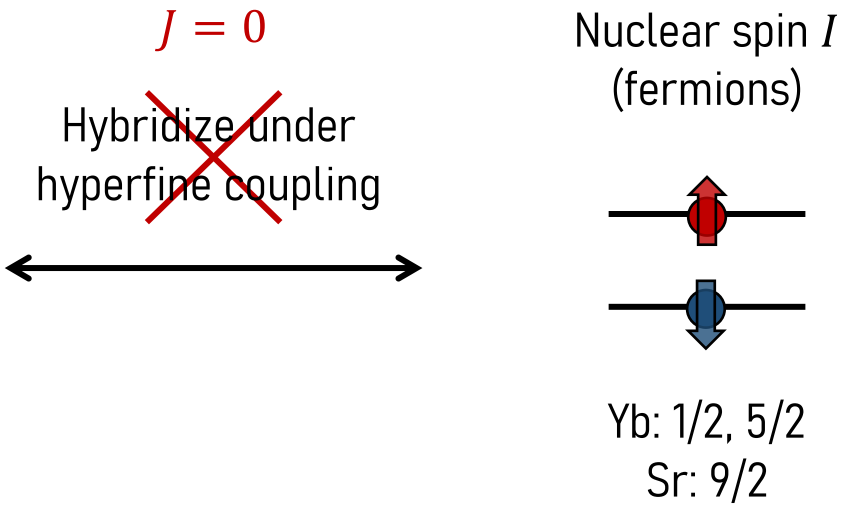


Alkaline-earth(-like) atoms

Research direction started by Manuel Endres (Caltech), Jeff Thompson (Princeton) and Adam Kaufman (JILA) - 2017

2 valence electrons → interesting spectral structure





- new type of qubit encoding with advantageous features
- new tools for qubit manipulation

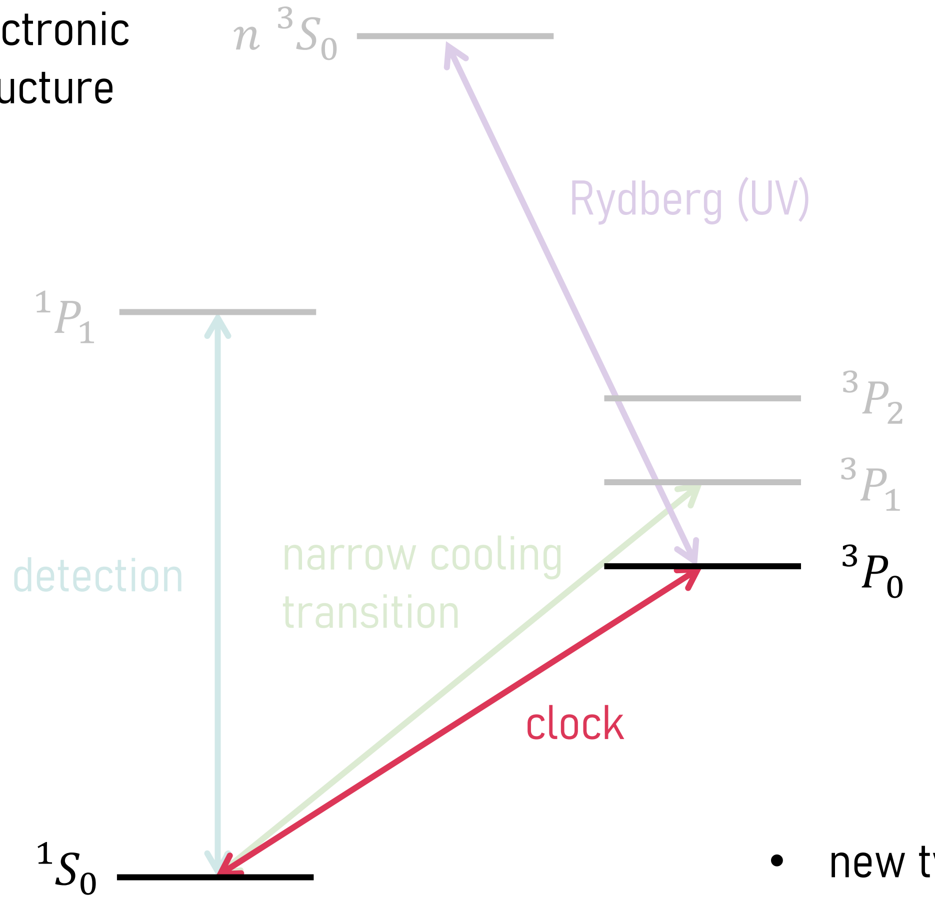
credit slide: Adam Kaufman

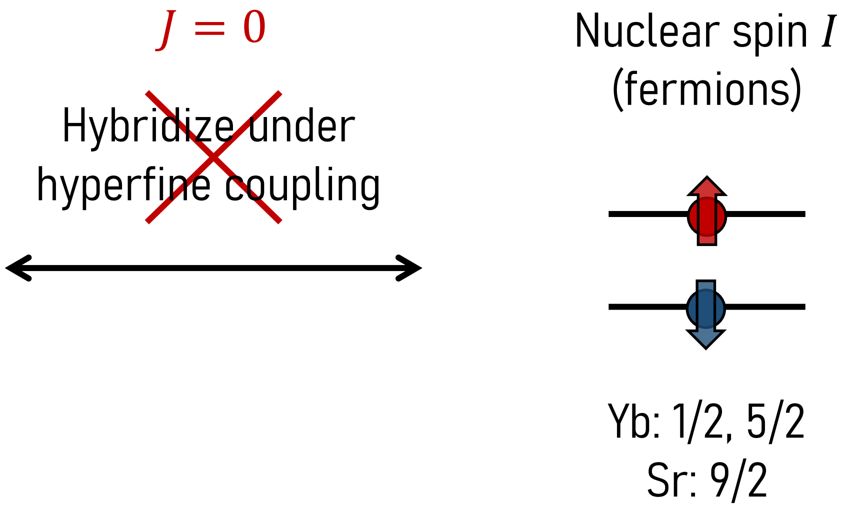
Alkaline-earth(-like) atoms

Research direction started by Manuel Endres (Caltech), Jeff Thompson (Princeton) and Adam Kaufman (JILA) - 2017

2 valence electrons → interesting spectral structure

Electronic structure



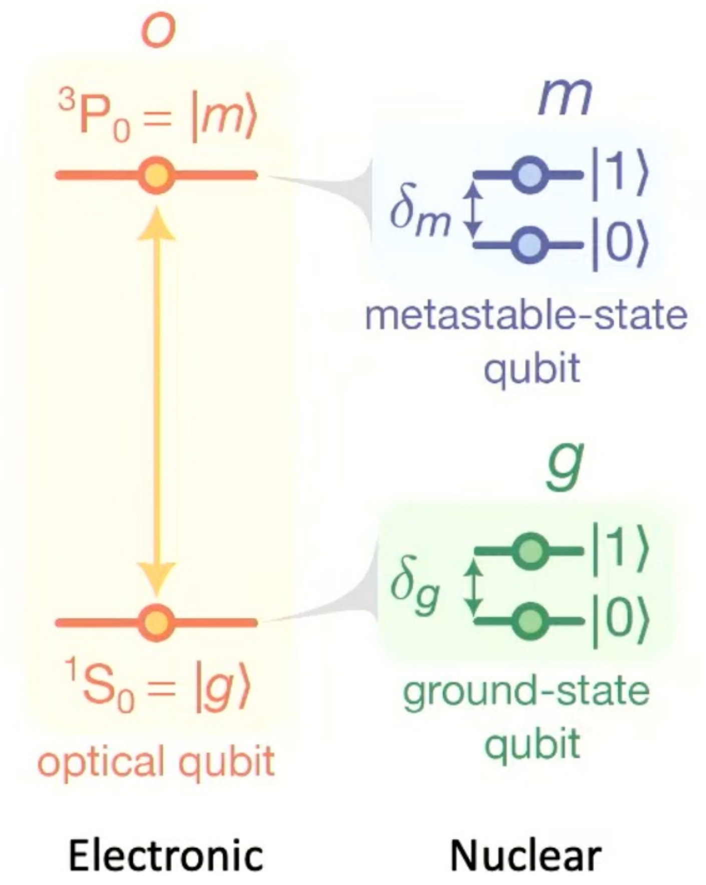


- new type of qubit encoding with advantageous features
- new tools for qubit manipulation

credit slide: Adam Kaufman

Alkaline-earth(-like) atoms

omg architecture:



from Lis et al, arXiv:2305.19266 (2023)

Enables:
- mid-circuit operations
- erasure conversion

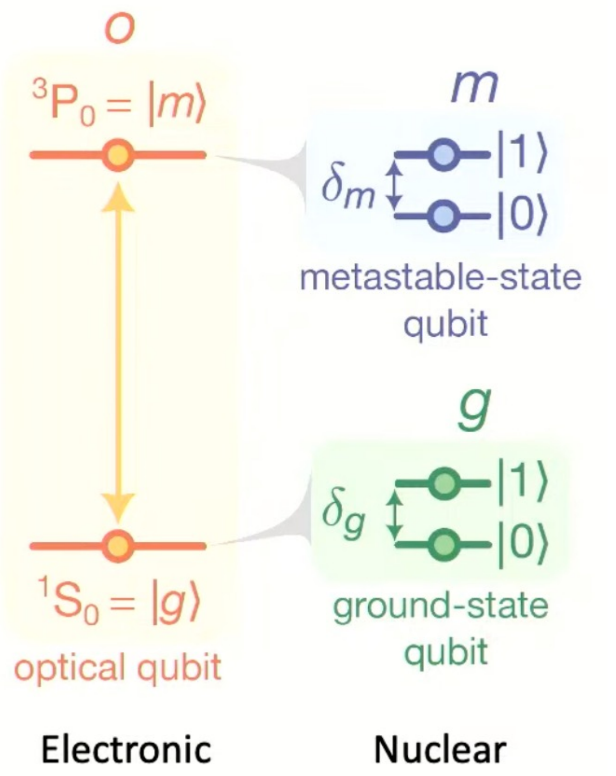
Nuclear qubits:
- robust to light shifts
- long T1 time

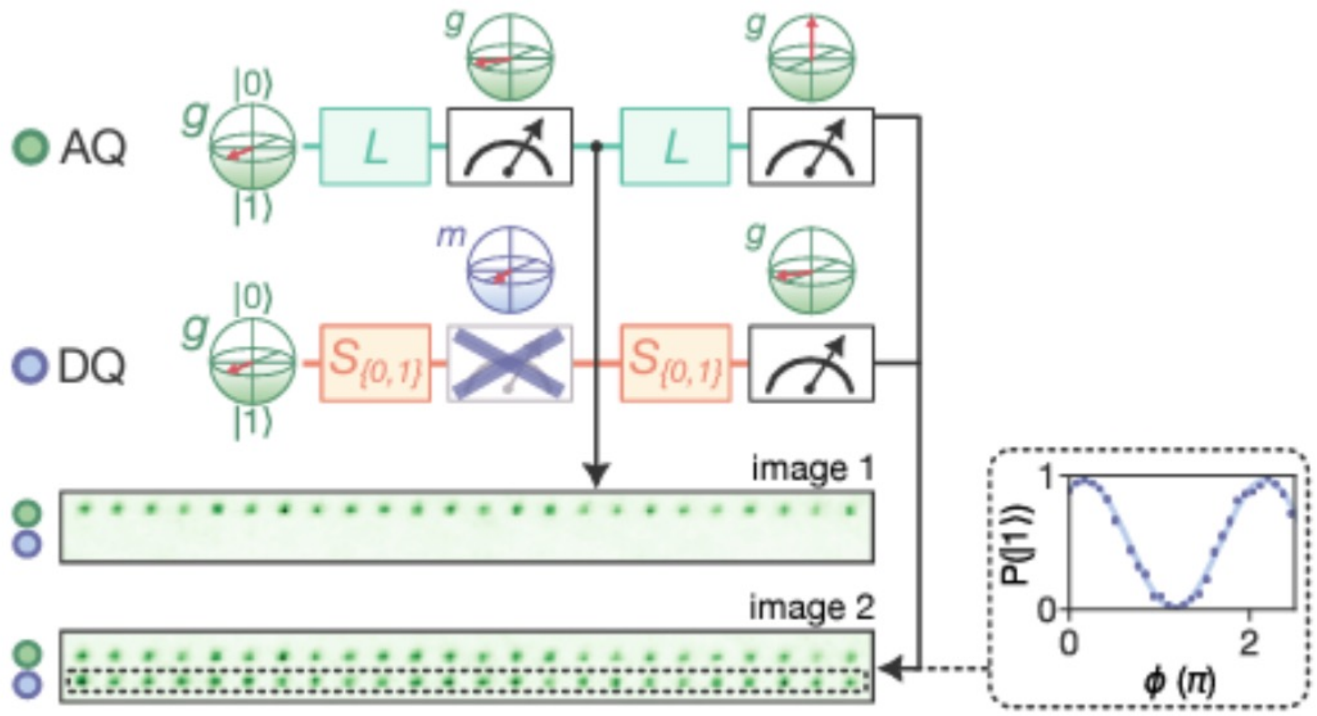
omg: Allcock et al, APL 2021, Chen et al, PRA 2022
related idea: Wu et al, Nat Comm 2022

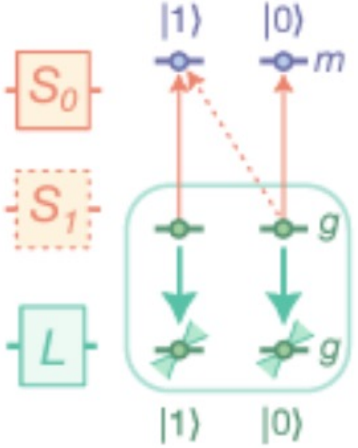
experimental realization with Yb atoms: Lis et al, arXiv:2305.19266 (2023)

Alkaline-earth(-like) atoms

Mid-circuit readout with omg architecture





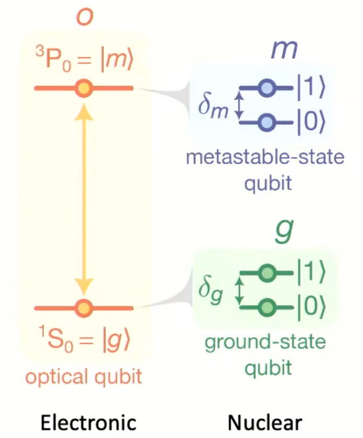


- qubit encoded in *g*
- data qubits (DQ) that we do not want to image are transferred to *m*, ancilla qubits (AQ) stay in *g* (local light shifts prevent excitation)
- imaging of atoms in *g* leaves atoms in *m* unperturbed

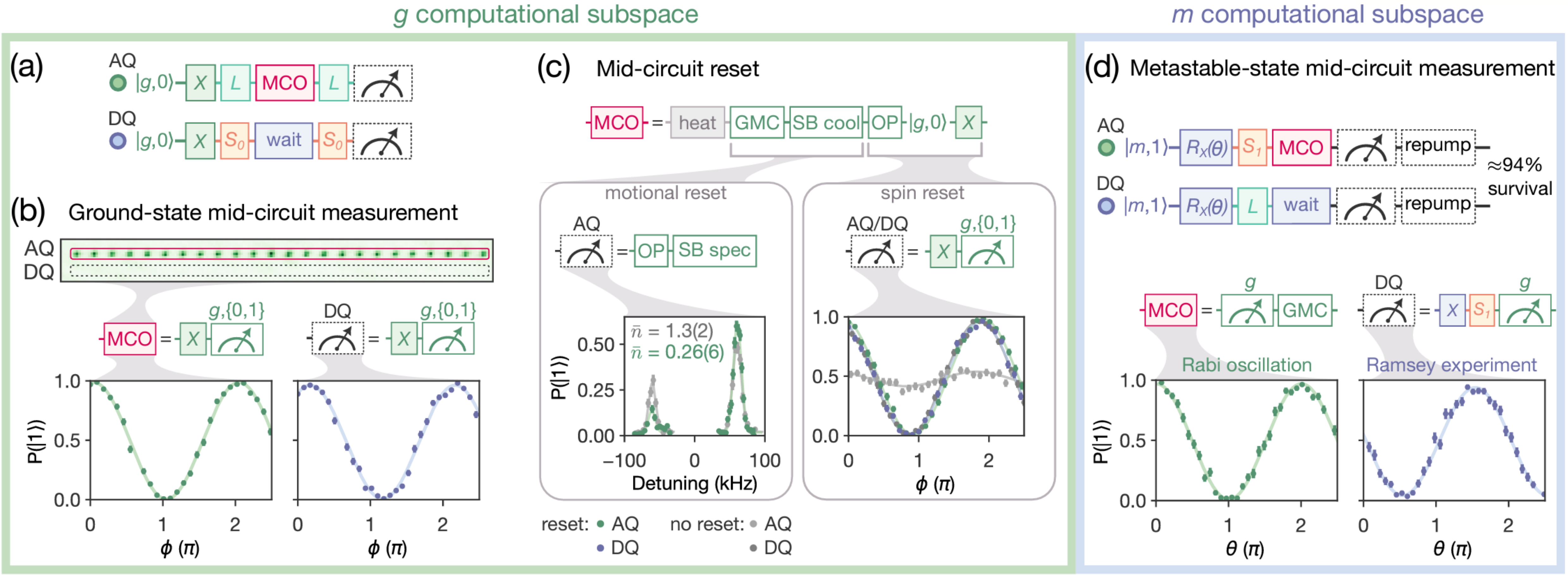
Lis et al, arXiv:2305.19266 (2023)

Alkaline-earth(-like) atoms

More mid-circuit operations with omg architecture



ancilla qubits can be measured and also reset (cooling and re-initialization)
while data qubits are left unperturbed



see also alternative approach in: Norcia et al, arXiv (2023)

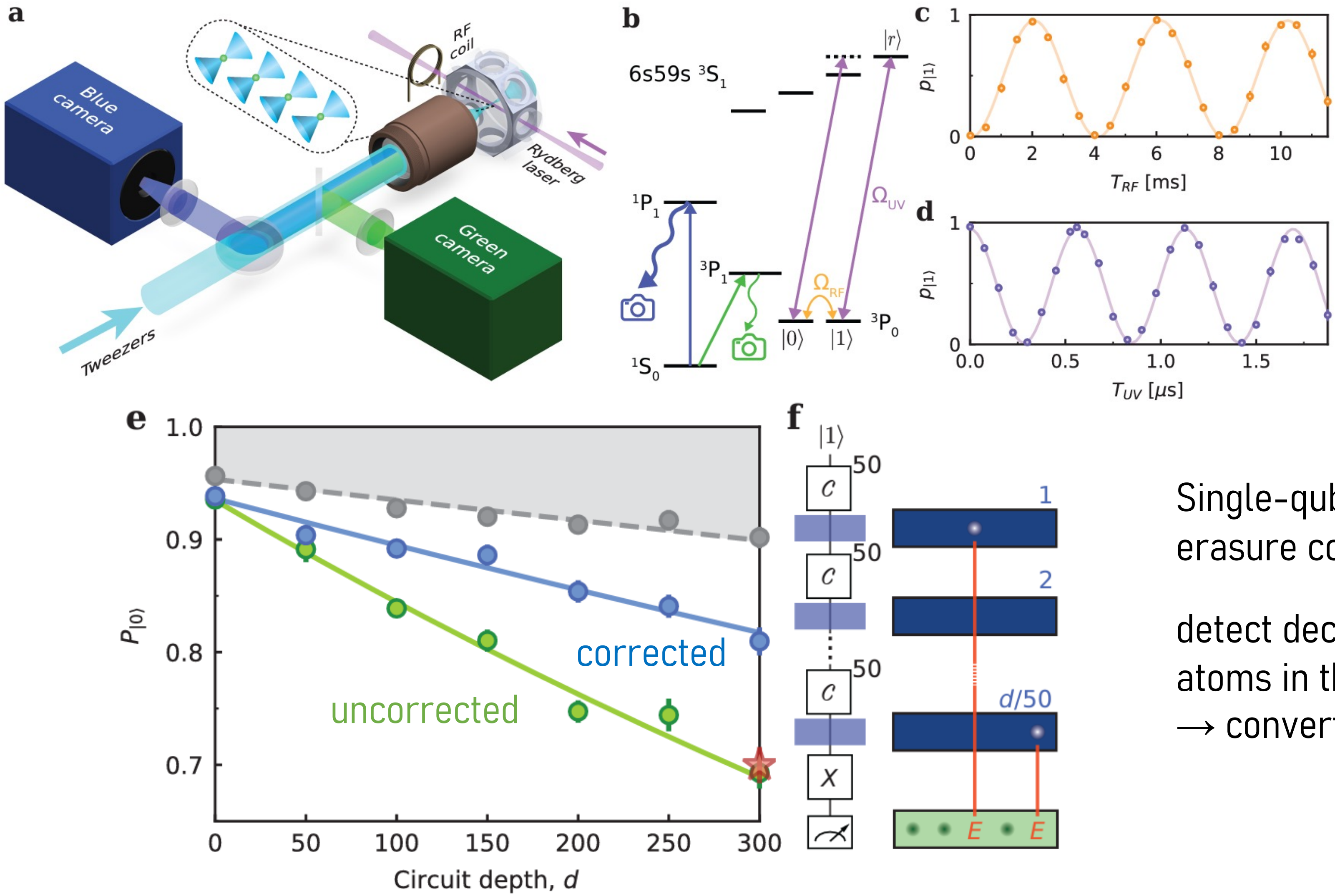
Lis et al, arXiv:2305.19266 (2023)

Alkaline-earth(-like) atoms

Mid-circuit erasure conversion

idea: convert dominant physical errors into erasures (= errors in known locations) → lower requirements for QEC

see original proposal: Y. Wu … J. Thompson, Nat Comm 13 (2022)



- fast destructive imaging @ 399nm
- slow (quasi-)non-destructive imaging @556nm

Single-qubit gates with mid-circuit erasure conversion

detect decay out of the qubit states, by imaging atoms in the ground state manifold
→ converts into erasure errors

→ easier to handle for QEC

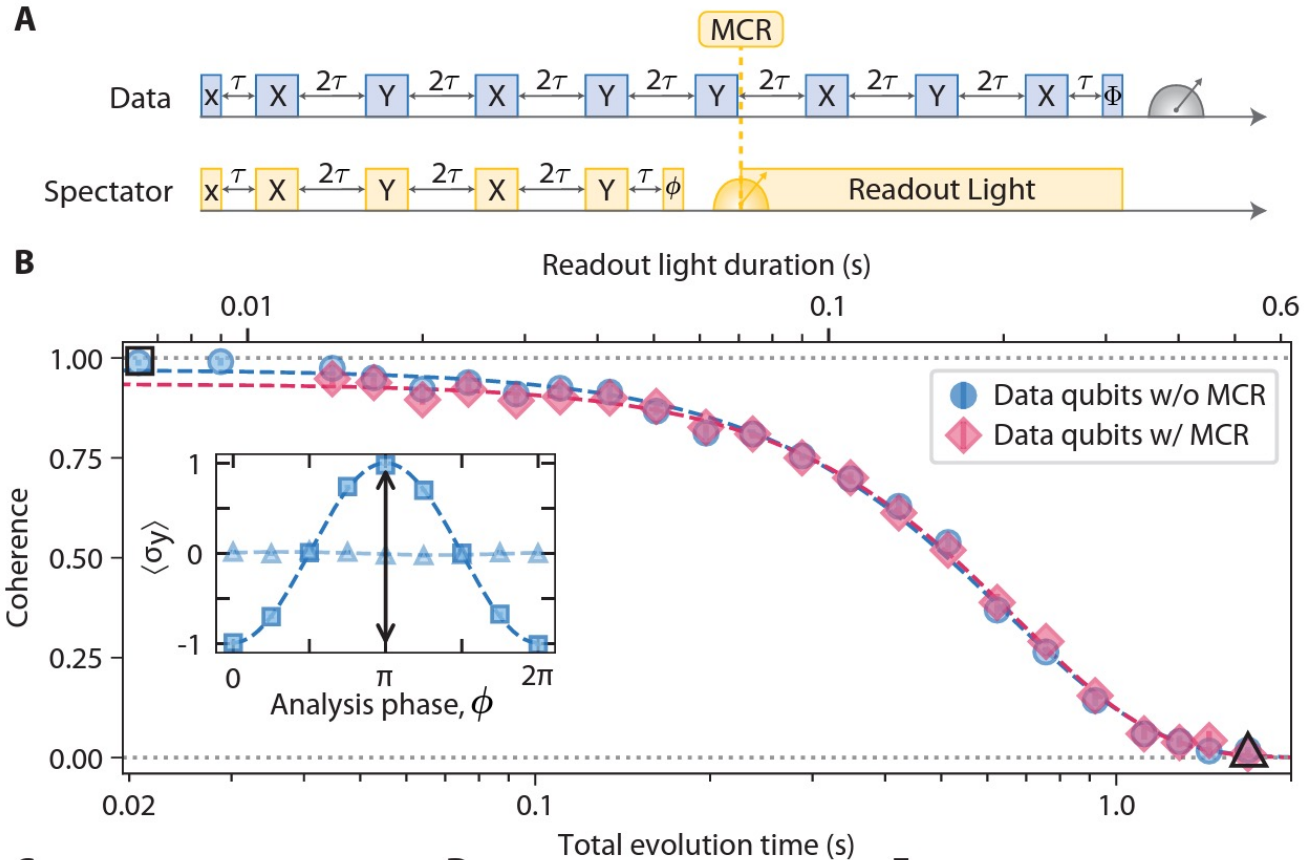
see also related work: Huie et al, arXiv (2023), Scholl et al, arXiv (2023)

Ma … Thompson, arXiv:2305.05493 (2023)

Dual-species atom arrays

Selective control of the two atomic species (separate wavelengths of control lasers)

Mid-circuit readout of “spectator qubits”

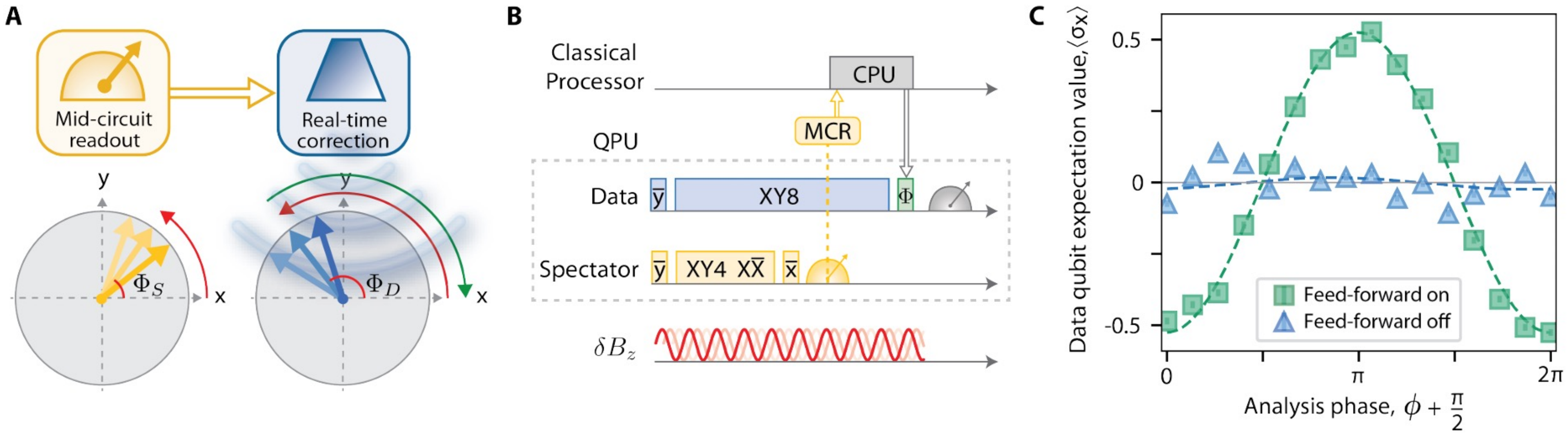


Singh et al, arXiv:2208.11716 (2023)

Dual-species atom arrays

Selective control of the two atomic species (separate wavelengths of control lasers)

Mid-circuit correction of correlated phase errors

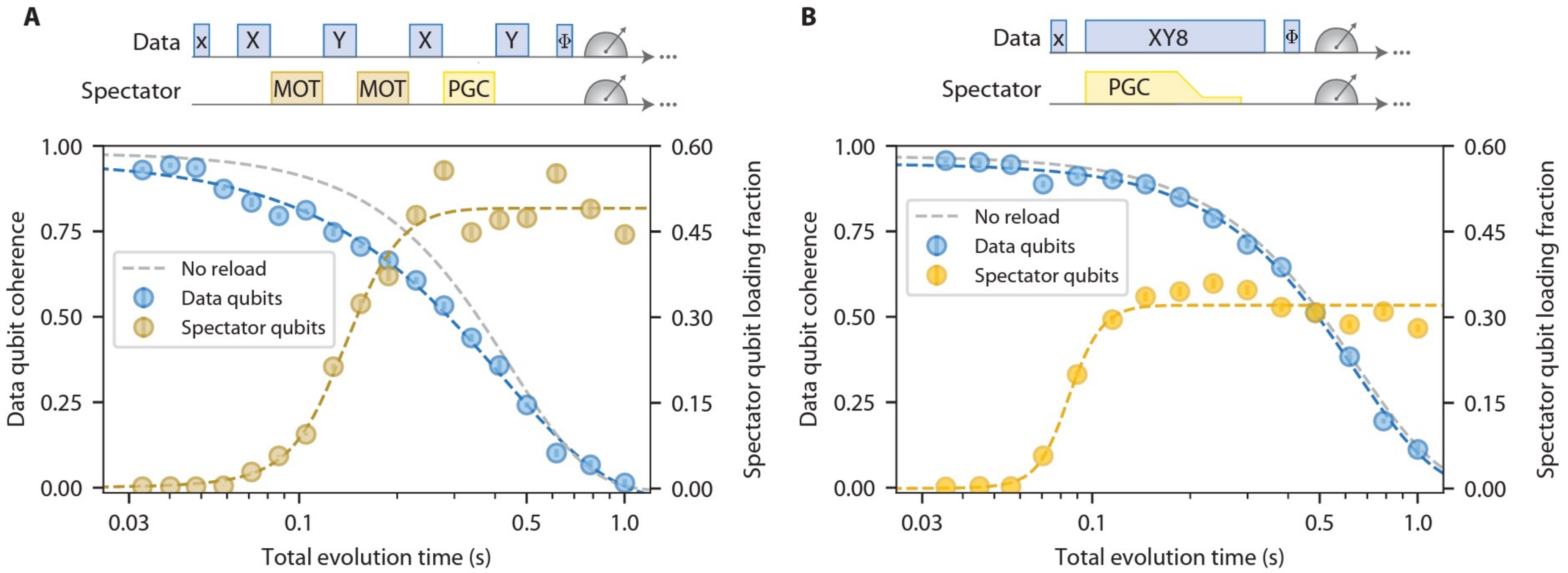


Singh et al, arXiv:2208.11716 (2023)

Dual-species atom arrays

Selective control of the two atomic species (separate wavelengths of control lasers)

Reloading of spectator qubits while maintaining coherence in data qubits



Singh et al, arXiv:2208.11716 (2023)

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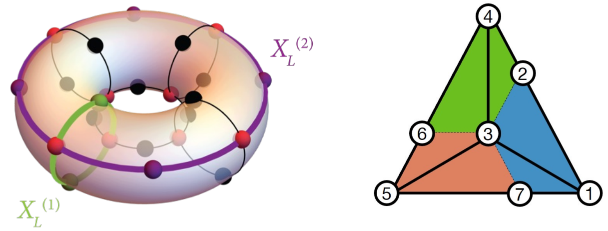

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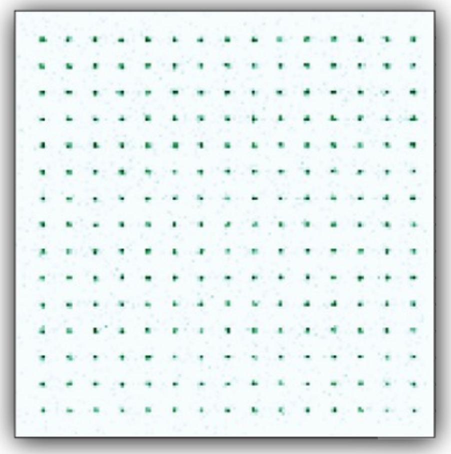
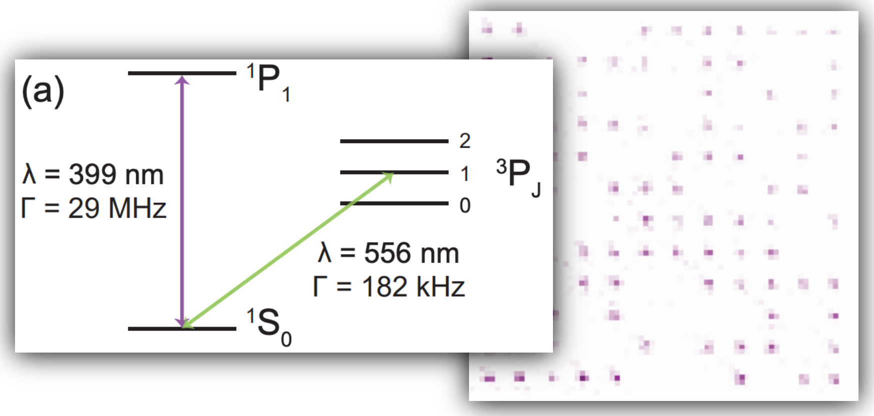


Alkaline-earth atoms



Atomic mixtures