Quantum information processing with neutral atoms

3000 qubits

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Massachusetts Institute of Technology
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Overview

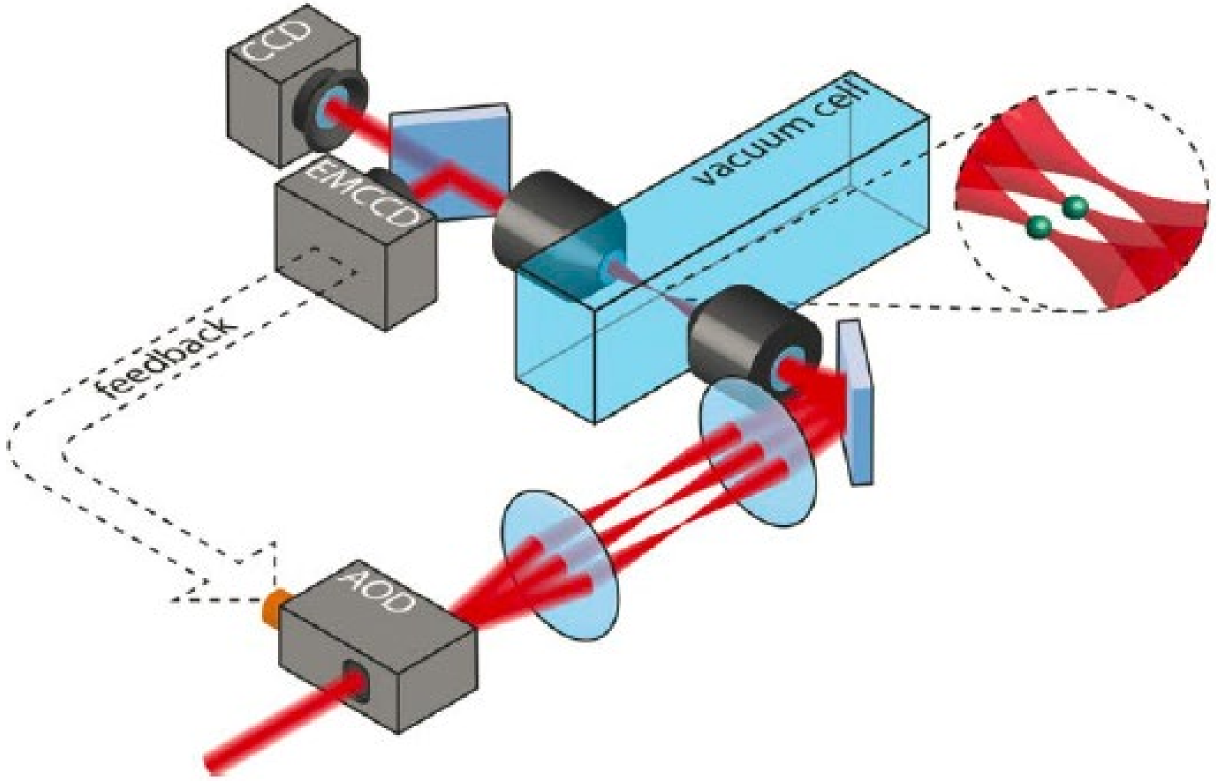
Select work from the community

New tools in atomic physics: combine cavity QED, atomic arrays and Rydberg interactions

- Arrays of optical tweezers
- Cavity QED with arrays of atoms or arrays of cavities

Applications and new physics
- Atom-cavity interactions
- Rydberg quantum computing with neutral atoms
- Arrays, clocks, and entanglement for operation below SQL
- Arrays of molecules

Trapping many single atoms in optical tweezers

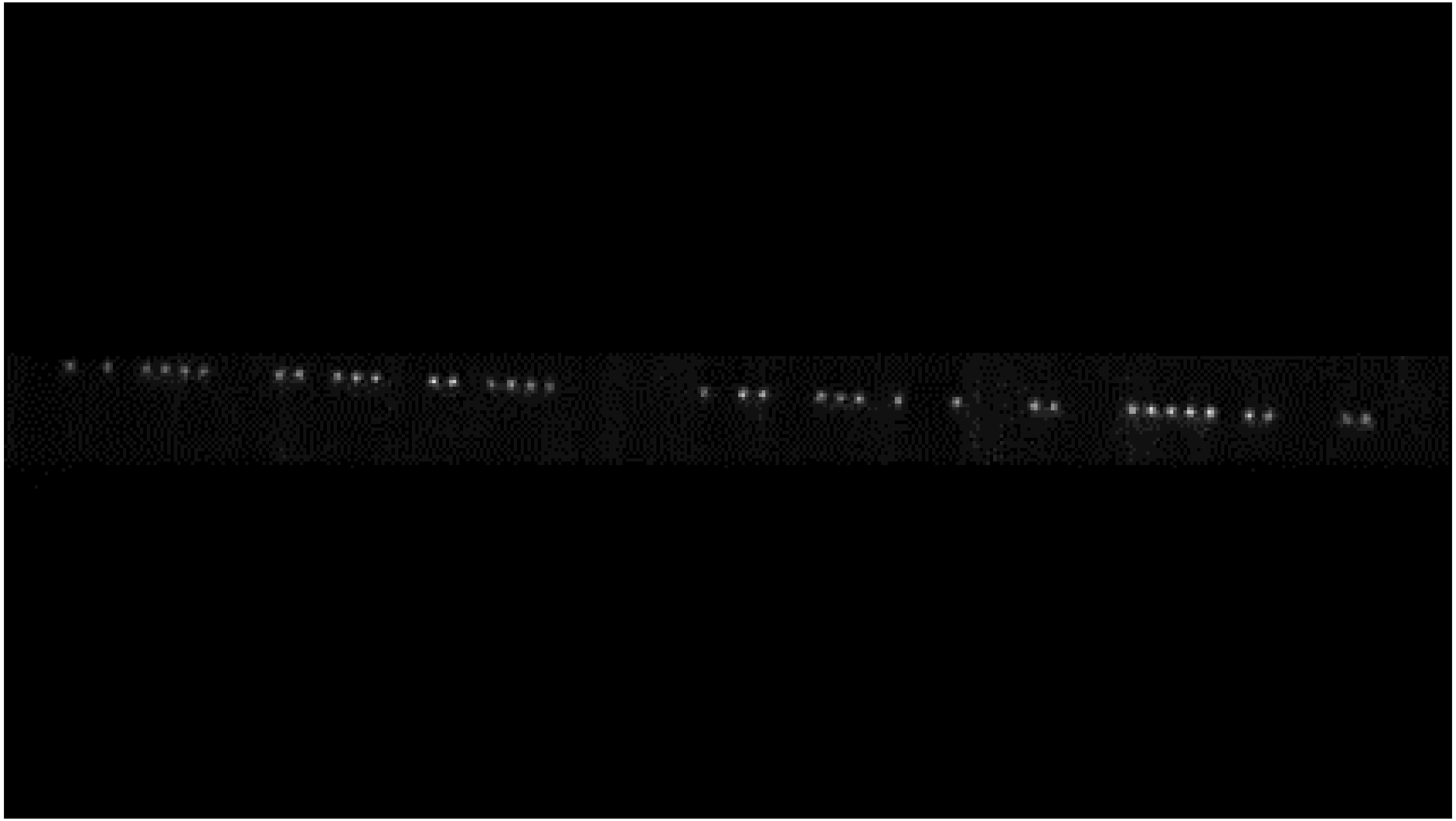


Problem: each trap is only loaded with ~50% probability.
Solution: real-time rearrangement after imaging (feedback)

M. Endres, H. Bernien, A. Keesling, H. Levine, E. Anschuetz, A. Krajenbrink, C. Senko, V. Vuletić, M. Greiner, and M.D. Lukin, Science **354**, 1024-1027 (2016).

Individual atoms in reconfigurable traps

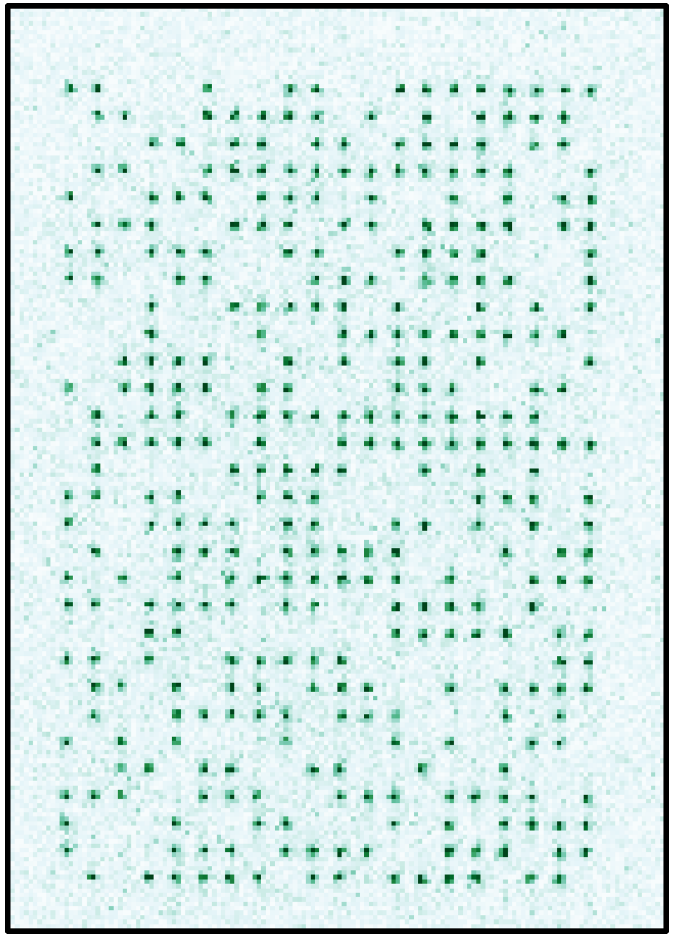
Lukin – Vuletic - Greiner collaboration



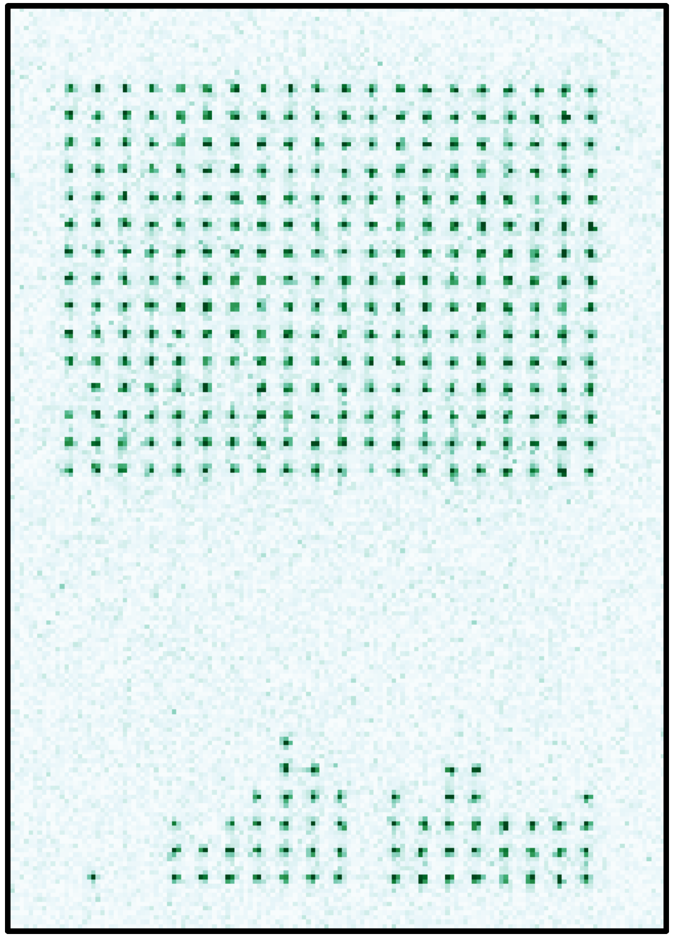
M. Endres, H. Bernien, A. Keesling, H. Levine, E. Anschuetz, A. Krajenbrink, C. Senko, V. Vuletić, M. Greiner, and M.D. Lukin, Science **354**, 1024-1027 (2016).

Sorting 300 atoms in two dimensions

Initial loading:

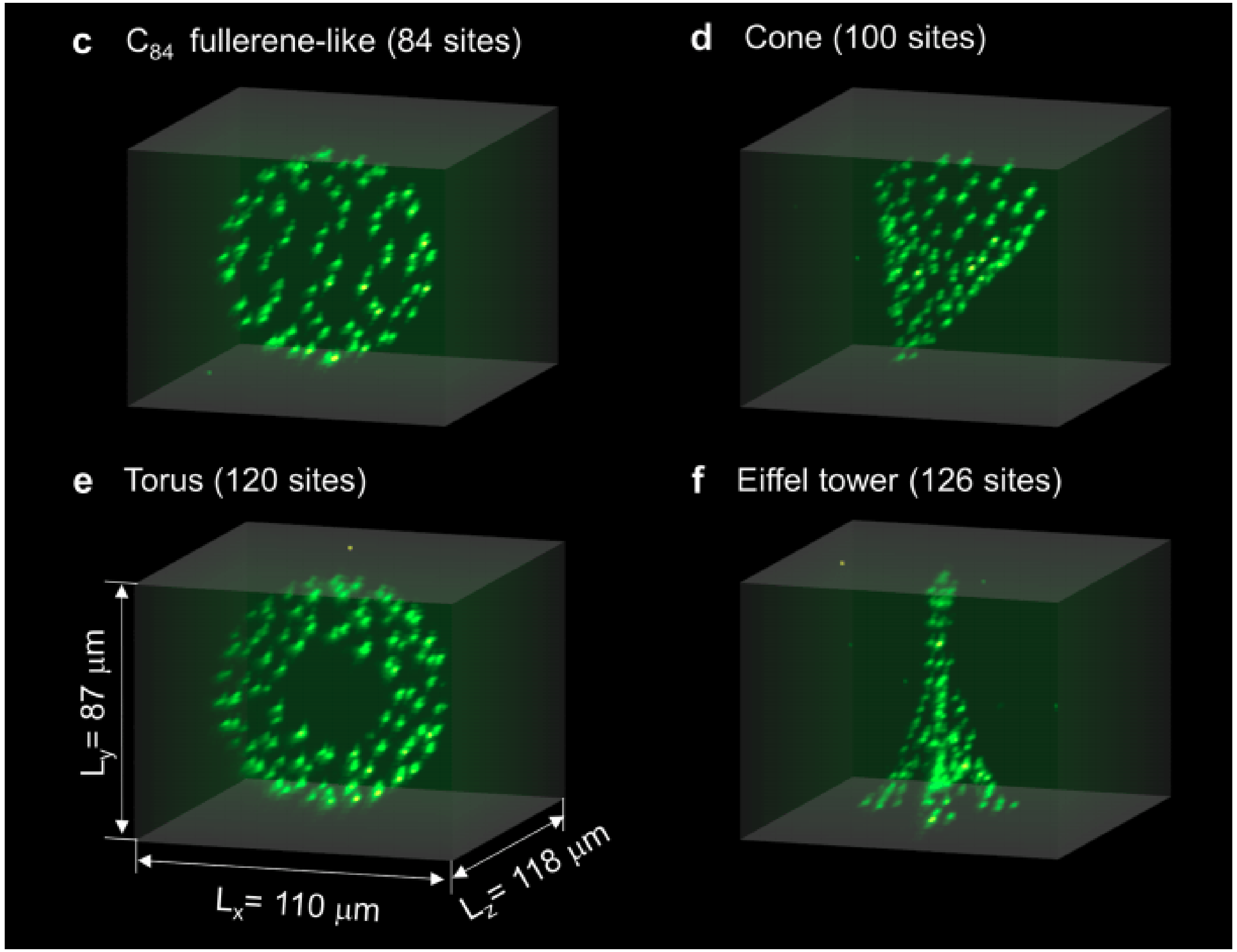


After sorting:



> 98% filling fraction

Three dimensional arrays also possible



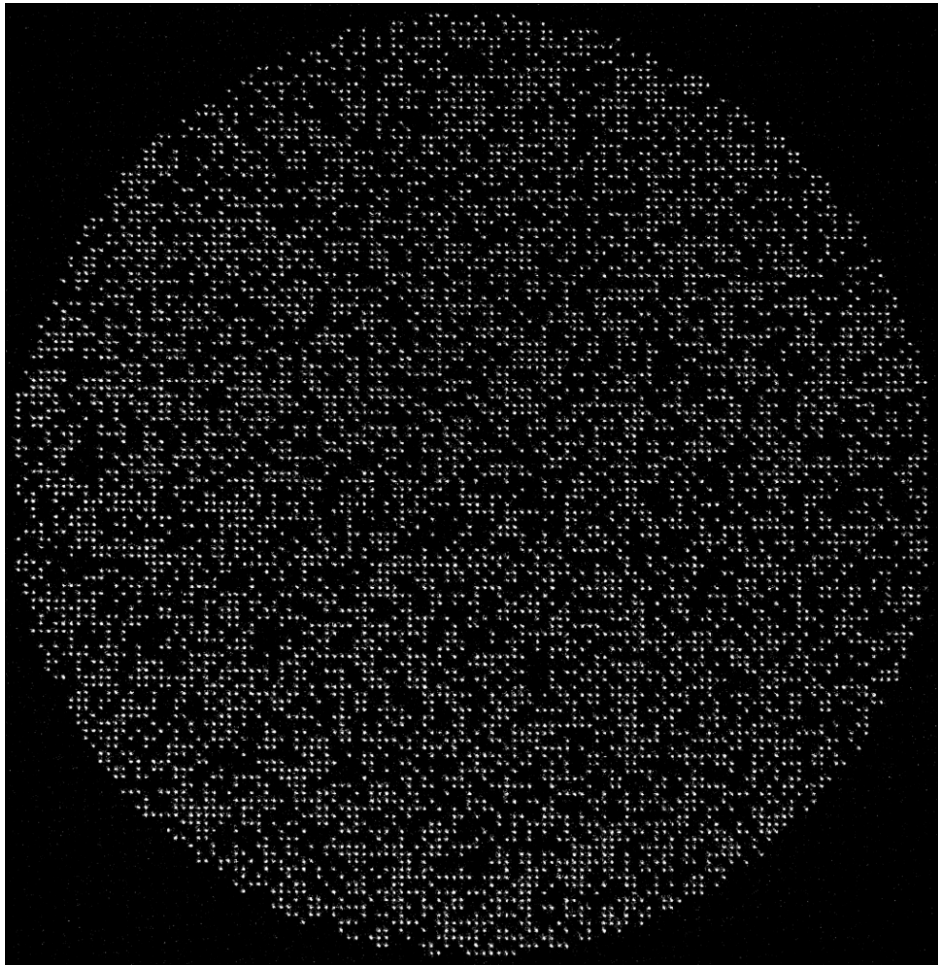
Synthetic three-dimensional atomic structures assembled atom by atom. D. Barredo, V. Lienhard, S. de Léséleuc, T. Lahaye & A. Browaeys, Nature **561**, 79–82 (2018).

Large-scale systems

Record system size of >6,000 qubits

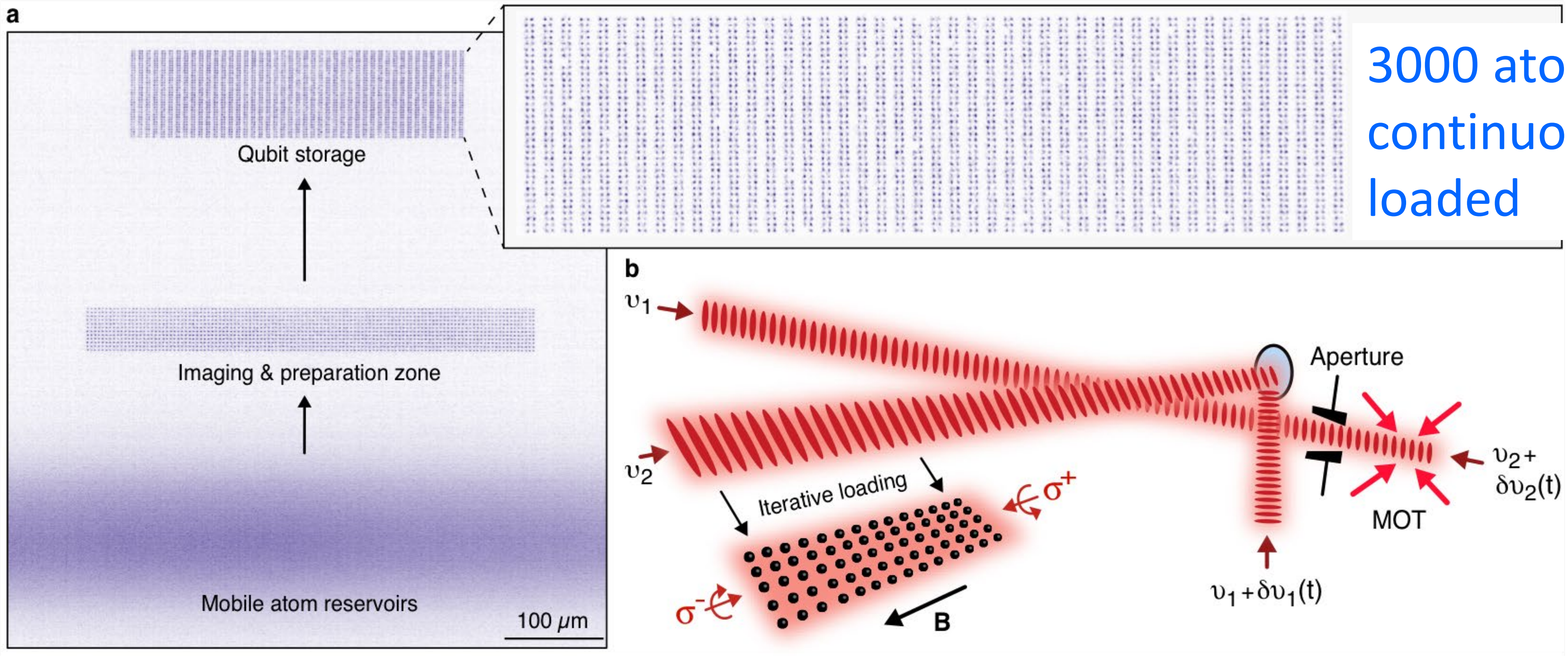
- 1QB global fidelity > 0.9998
- Record hyperfine coherence > 12s
- Record coherent transport distance > 600um

Manetsch, Nomura, Bataille … Endres
A tweezer array with 6100 highly coherent atomic qubits.
Nature (2025), advanced online,
https://doi.org/10.1038/s41586-025-09641-4



Manuel Endres, Caltech

Continuously loaded large-scale system



3000 atoms continuously loaded

Continuous operation of a coherent 3,000-qubit system.
N.-C. Chiu et al., *Nature* (2025).

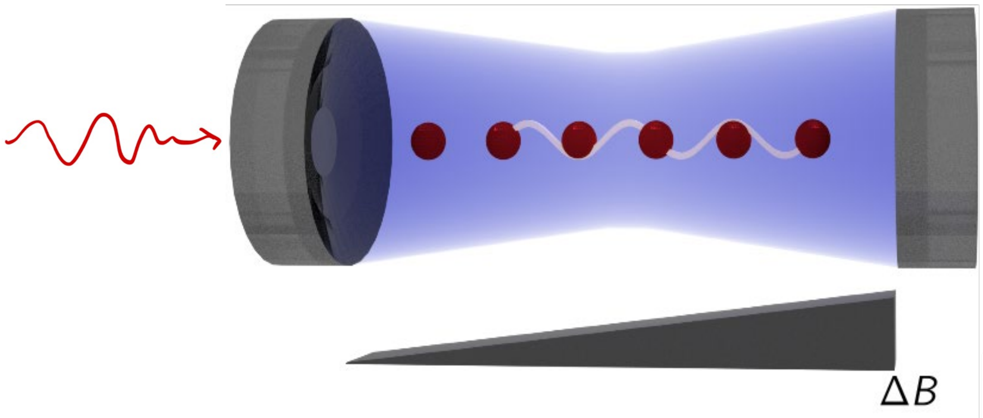
Lukin-Greiner-Vuletic, Harvard-MIT

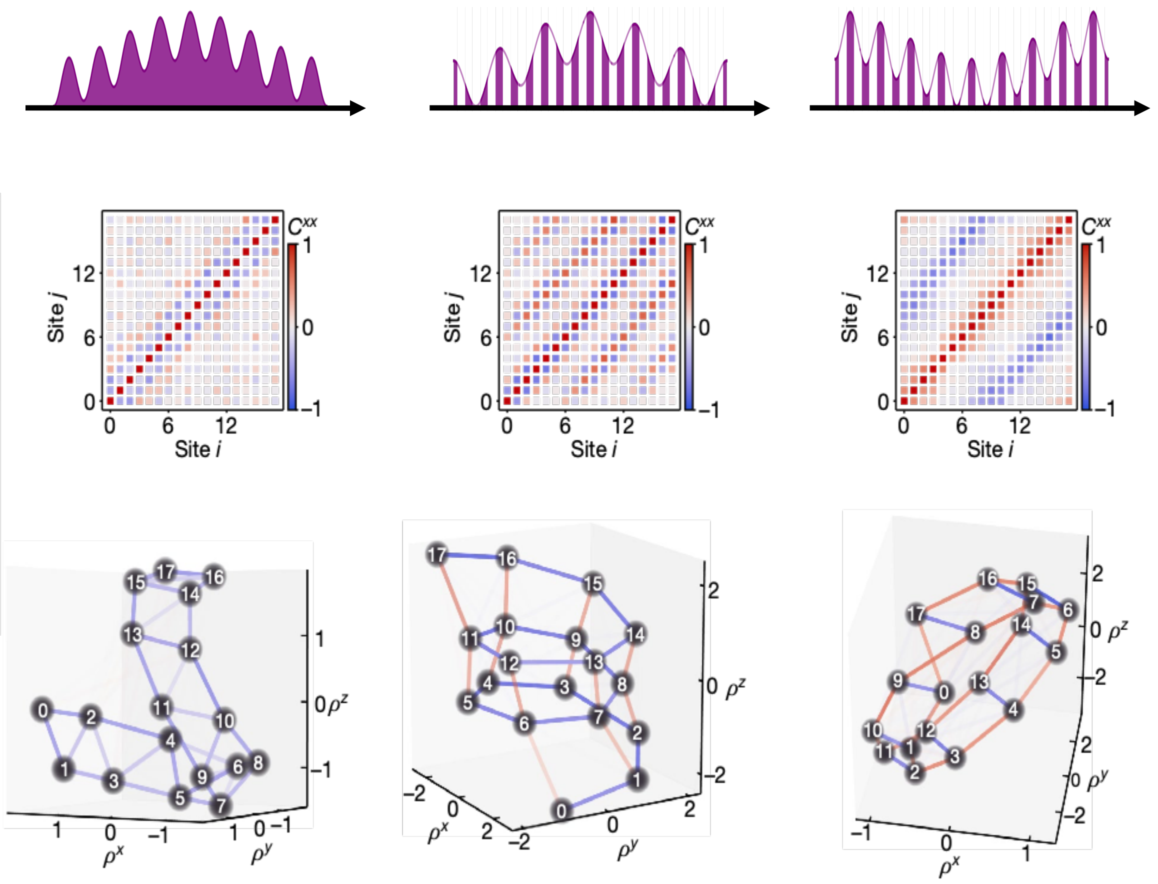
Cavity QED

Atoms Interlinked by Light

Nonlocal photon-mediated interactions in arrays of atomic ensembles

Programmable Interactions

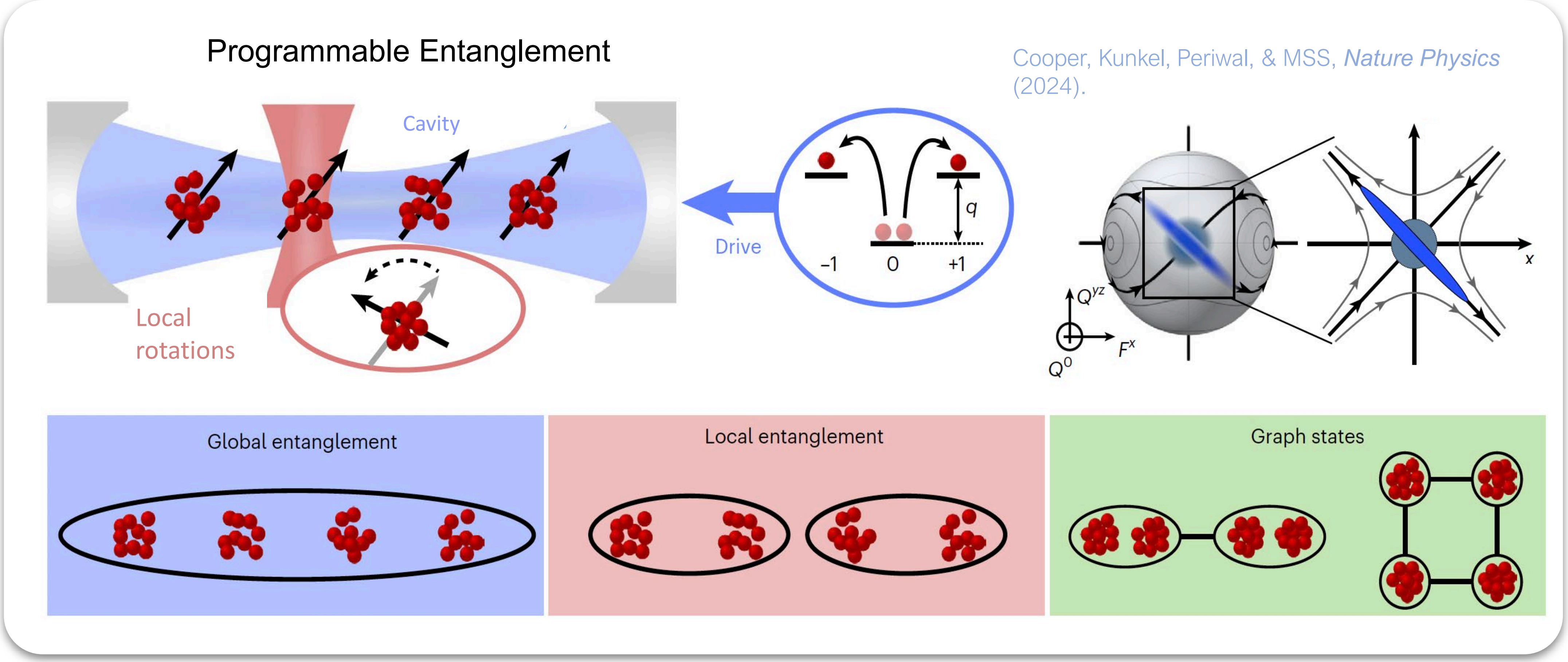




Periwal, Cooper, Kunkel, Wienand, Davis, MSS, *Nature* (2021).

Atoms Interlinked by Light

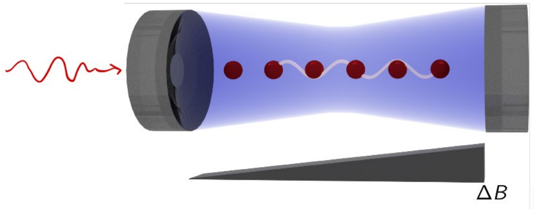
Nonlocal photon-mediated interactions in arrays of atomic ensembles

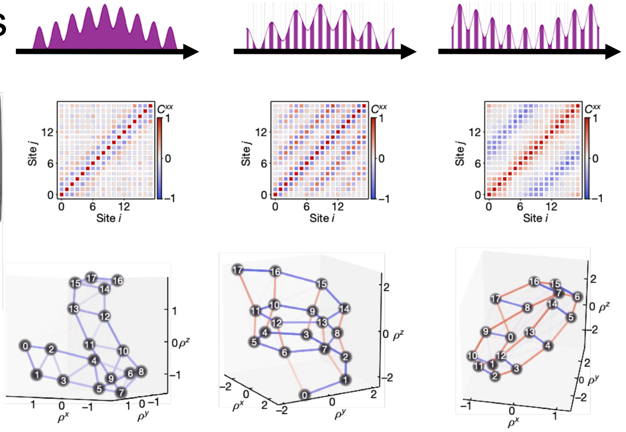


Atoms Interlinked by Light

Nonlocal photon-mediated interactions in arrays of atomic ensembles

Programmable Interactions

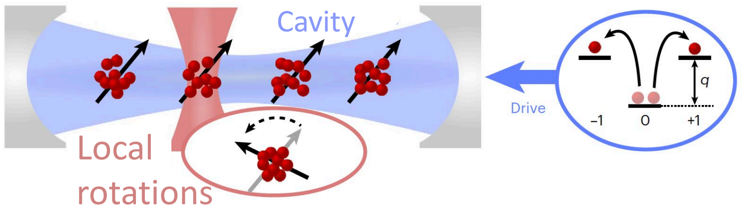


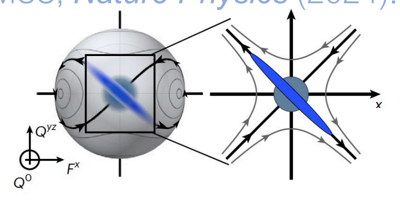


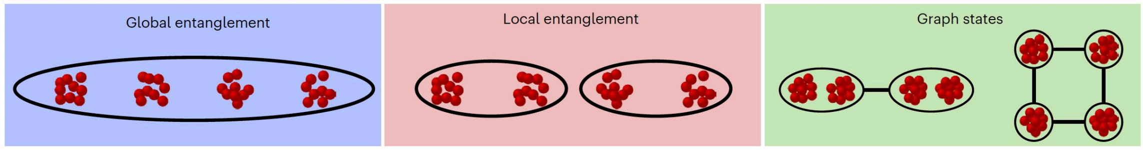
Periwal, Cooper, Kunkel, Wienand, Davis, MSS, *Nature* (2021).

Programmable Entanglement

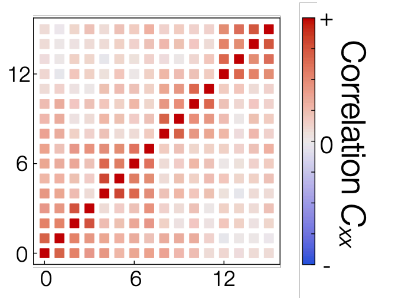
Cooper, Kunkel, Periwal, & MSS, *Nature Physics* (2024).



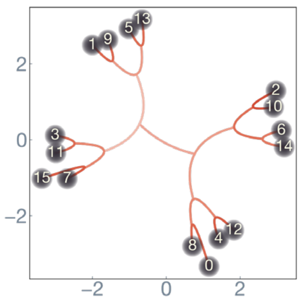




Simulating quantum gravity

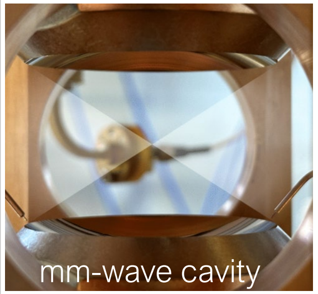


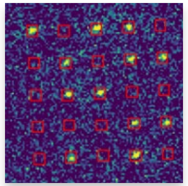
Correlations



Emergent geometry

Stronger atom-photon coupling?

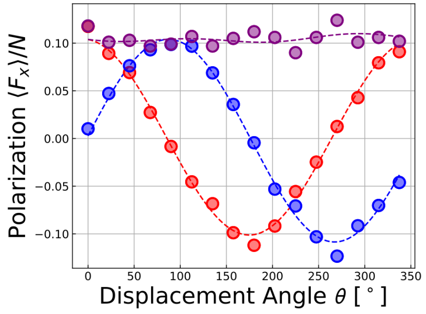


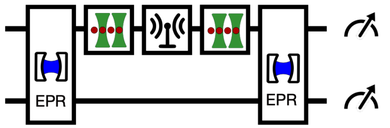


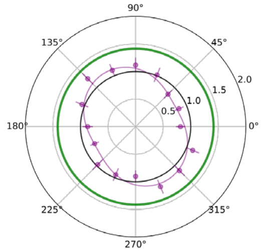
...for arrays of single atoms

Zhang et al., *Phys. Rev. Applied* (2025).

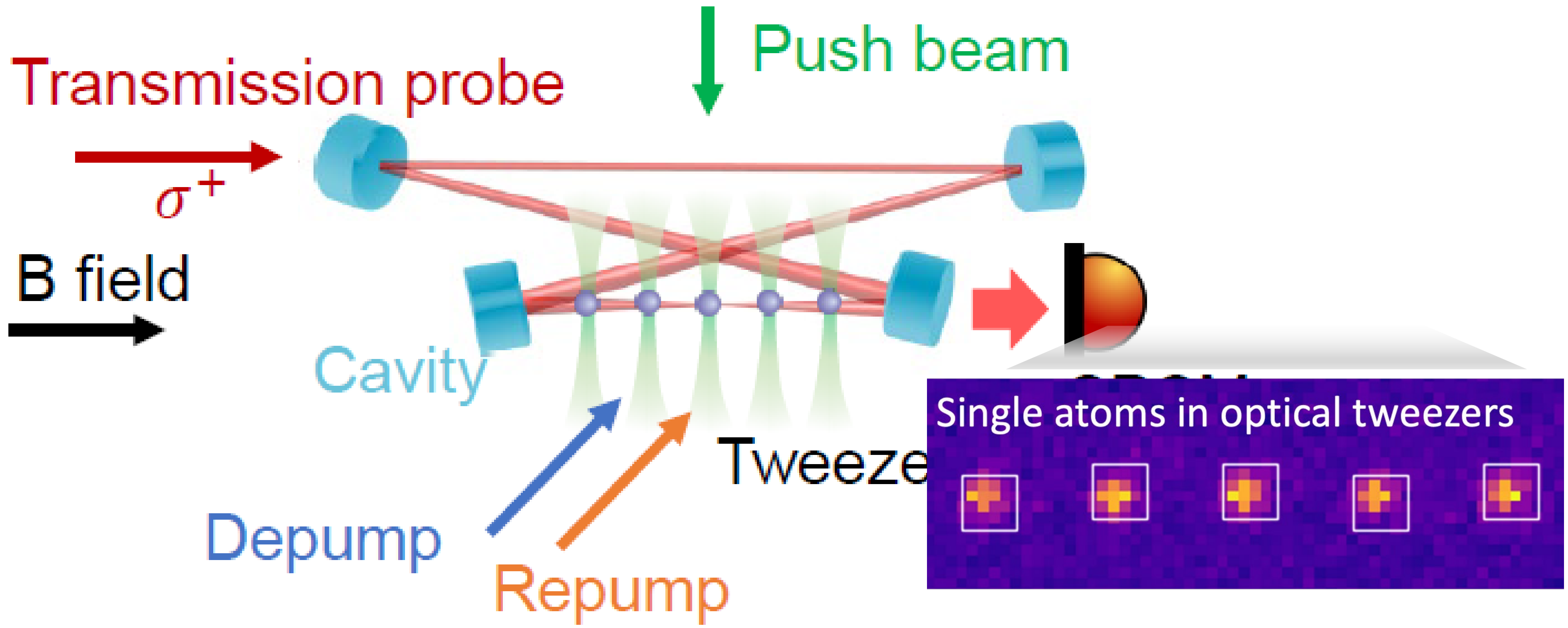
Multiparameter sensing





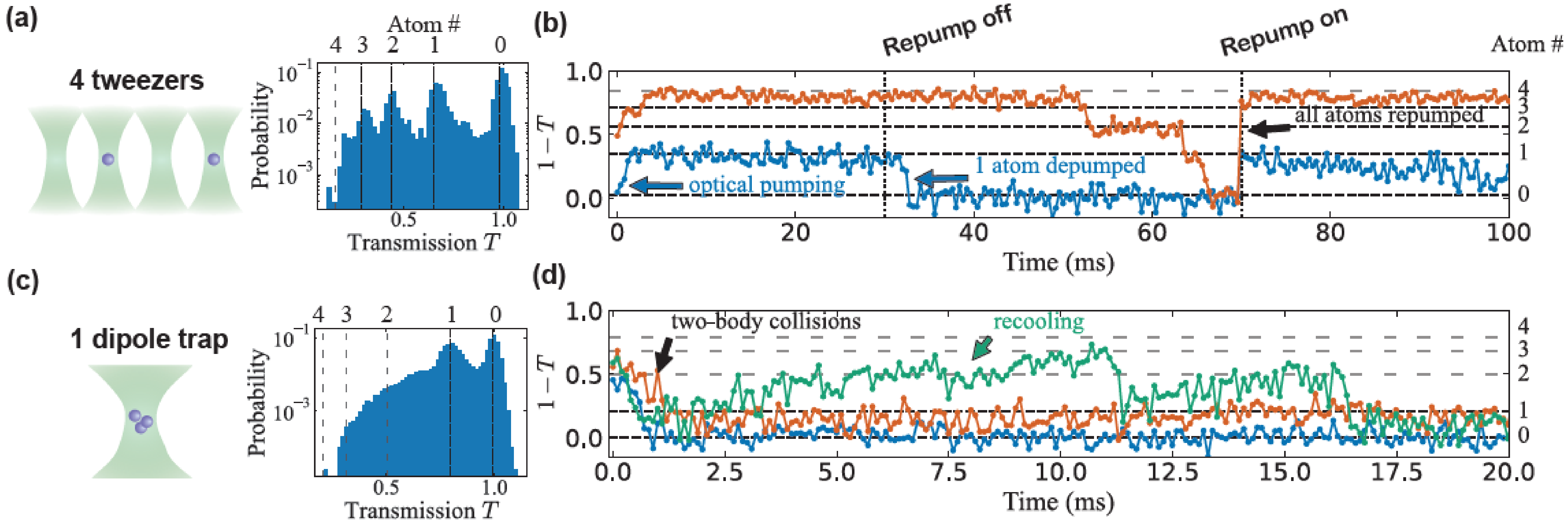


Observing atoms with high-cooperativity ring cavity



Vuletic, MIT

Observing individual atomic collisions with high-cooperativity ring cavity



Vuletic, MIT

Time resolution 100 μs, can observe individual inelastic collisions, recooling

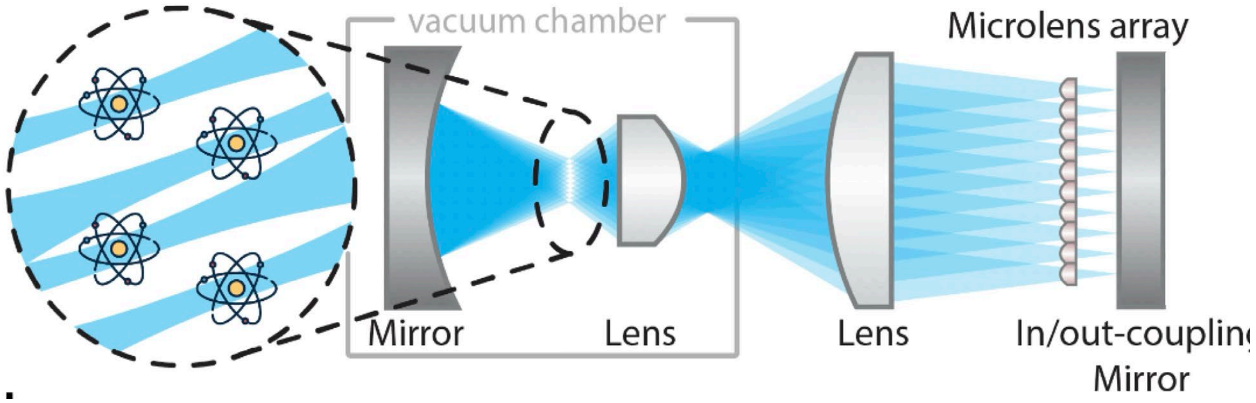
Many cavities: Cavity Array Microscope

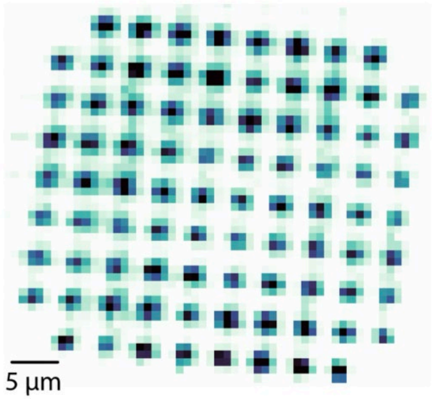
Light Collection efficiency χ is key for scalable quantum computing:

- Determines atom readout speed: $T_{readout} \propto 1/\chi$
- Determines networking bandwidth: $T_{entangle} \propto 1/\chi^2$

Interfacing each atom with *its own cavity* ensures large χ:

- In situ networking+fast readout
- Small waist+low finesse keeps optics away from atoms, limiting stray E-fields
- Scalable to thousands of cavities



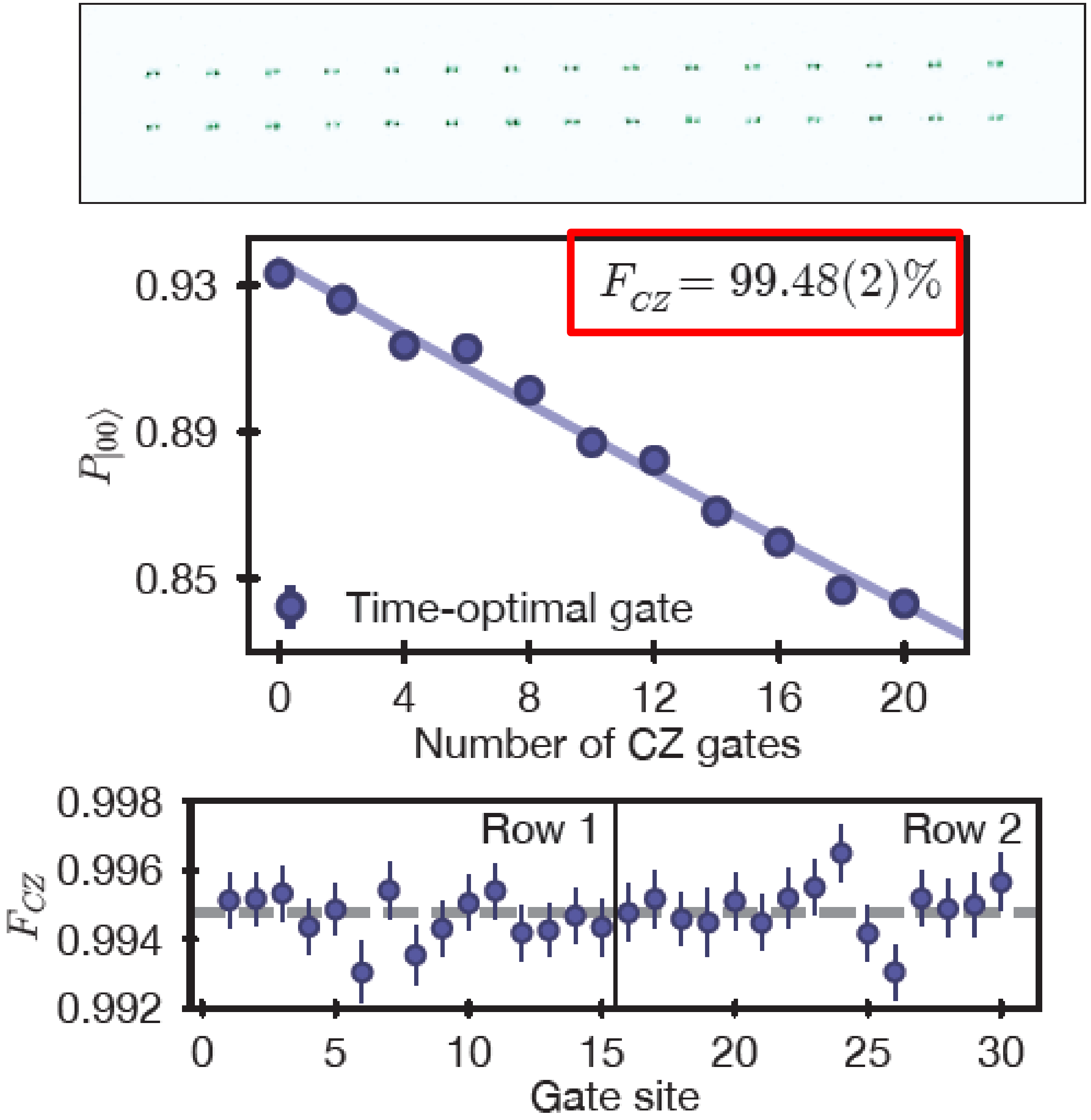


Shaw *et al.* "A cavity array microscope for parallel single-atom interfacing" arXiv 2506.10919, (2025).
Shadmany *et al.* "Cavity QED in a High NA Resonator" Science Advances 11, eads8171, (2025).

Jon Simon, Stanford

Tweezer arrays for neutral-atom quantum computing and simulation

Two-qubit gate fidelity: ^{87}Rb



Parallel two-qubit gates on 30 pairs of atoms.
Randomized benchmarking.
99.5% gate fidelity
Error below 1% threshold of surface code.

High-fidelity parallel entangling gates on a neutral atom quantum computer. S. Evered et al., *Nature* (2025).

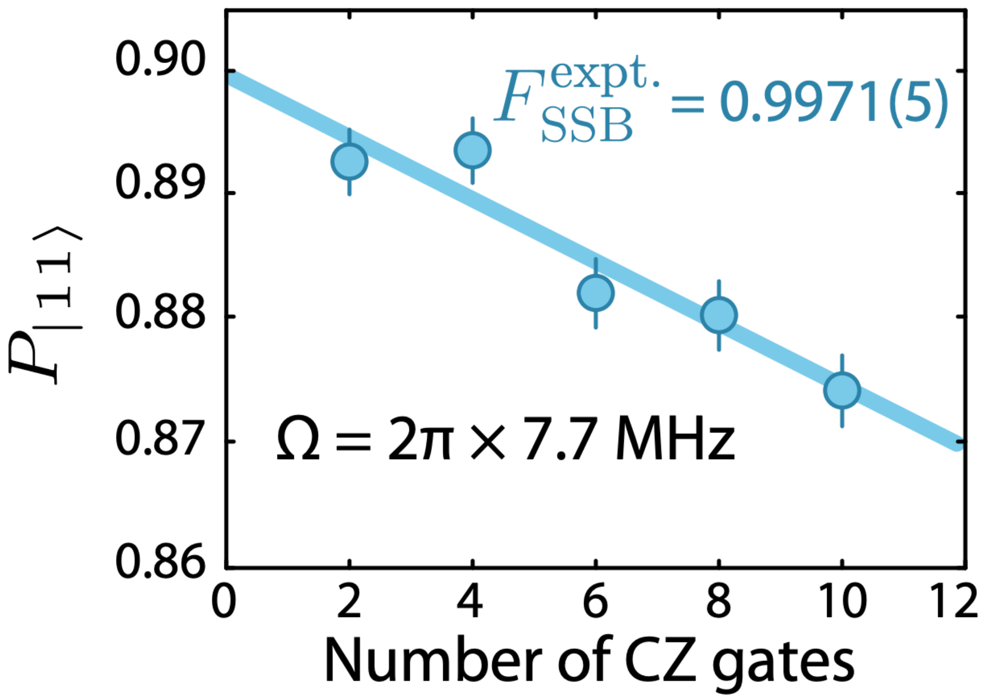
Lukin-Greiner-Vuletic, Harvard-MIT-Quera

High-fidelity 2QB gates: ^{171}Yb

Record 2QB Rydberg gates with F > 0.997

- Detailed understanding of error-model
- Clear path to F~0.999

Tsai*, Sun*, Shaw, Finkelstein, Endres
Benchmarking and fidelity response theory of high-fidelity Rydberg entangling gates
PRX Quantum 6, 010331 (2025)

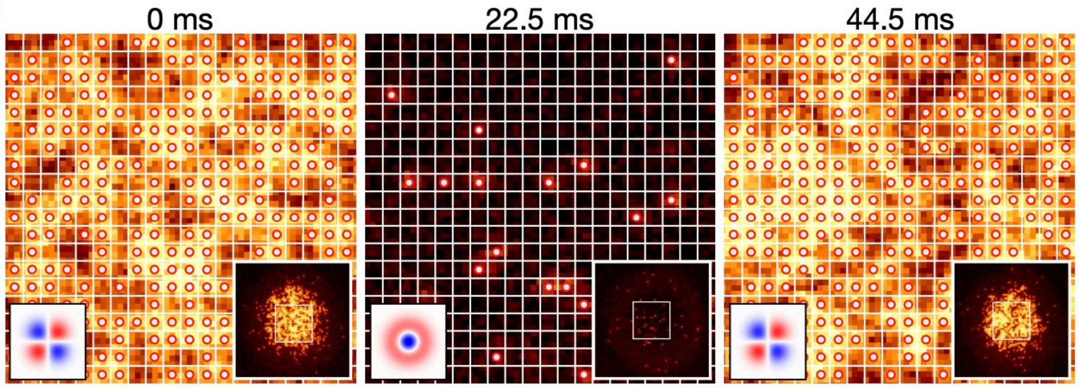


Manuel Endres, Caltech

Towards Quantum Computing with Fermions

- Qubit-based QC of many-fermion problems require large overhead in number of qubits or gates to implement fermion exchange

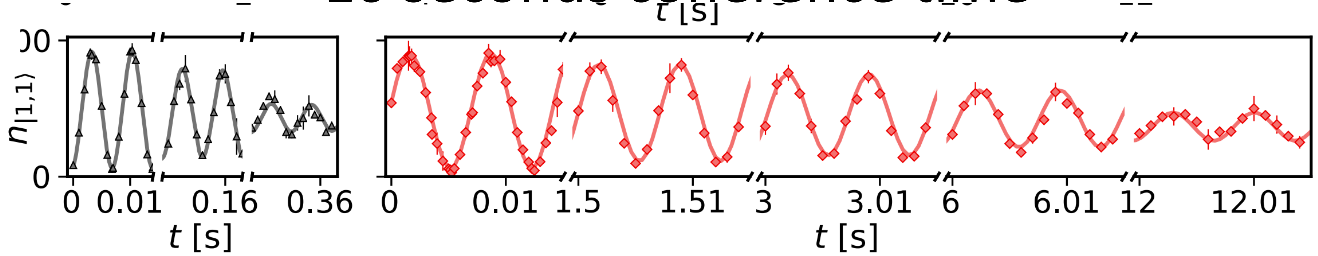
→ Use fermions as building blocks of a quantum computer



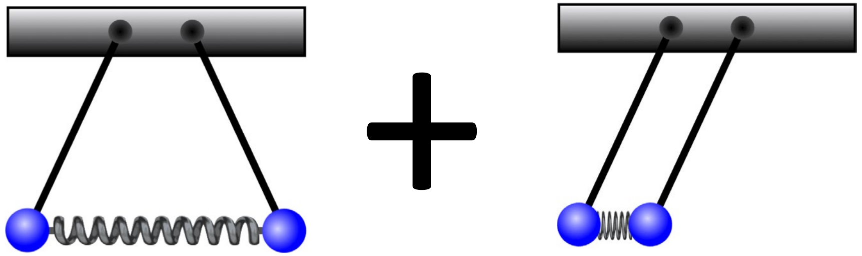
Quantum register based on fermion pairs

- Utilize Pauli principle for robust initialization (2/site)
- > 200 qubits, encoded in pair vibration
- ~ 10 seconds coherence time
- Opens the door towards
  - programmable quantum simulation
  - fermion-based quantum computation

~ 10 seconds coherence time



Zwierlein, MIT



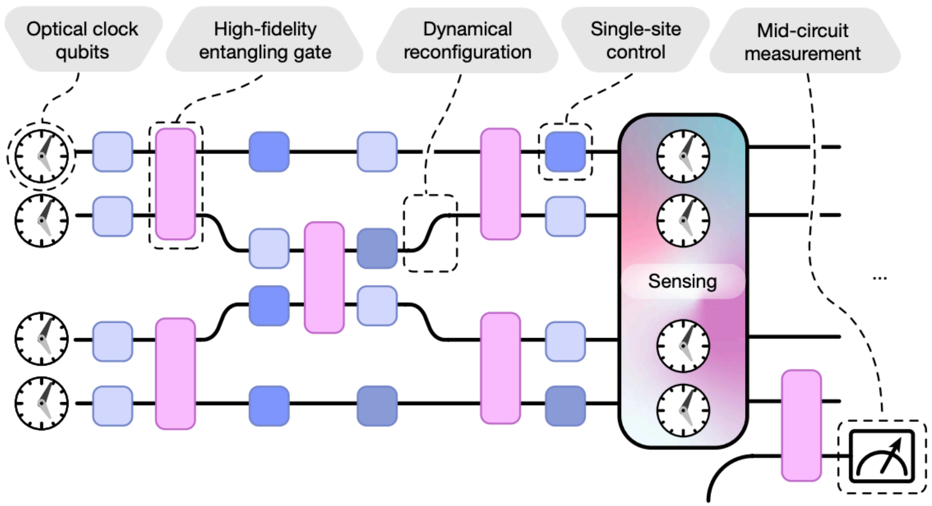
T. Hartke, B. Oreg, N. Jia, M. Zwierlein, Nature **601**, 537 (2022)

Array clocks and entangled clocks

Quantum Computers & Clocks

Effective hybridization of quantum computers and optical clocks

- Preparation of complex entangled states for quantum metrology
- Multi-ensemble metrology



Finkelstein*, Tsai*, Sun*, …. Endres
Universal quantum operations and ancilla-based readout for tweezer clocks
Nature 634, 321–327 (2024)

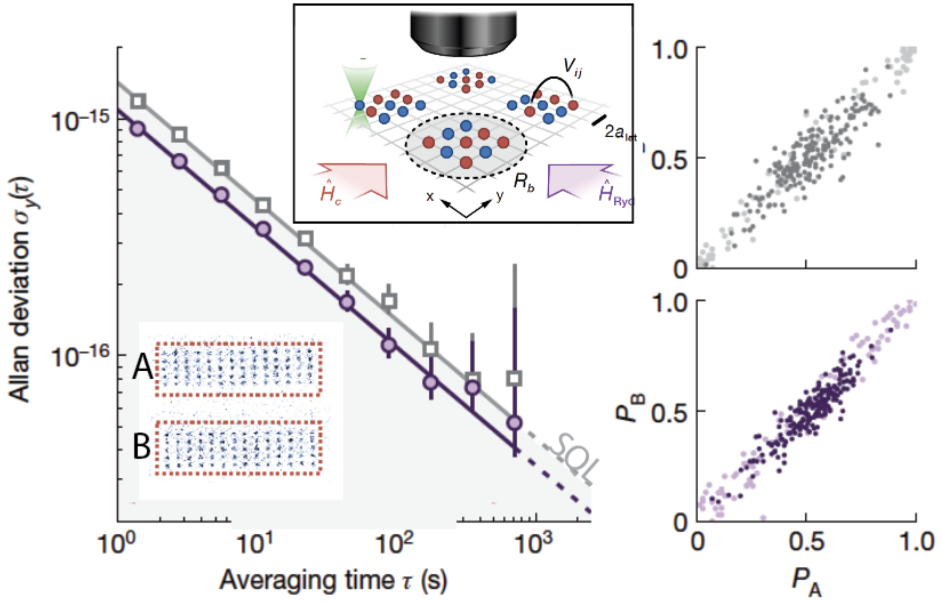
Shaw*, Finkelstein*, Tsai, … Endres
Multi-ensemble metrology by programming local rotations with atom movements
Nature Physics 20, 195–201 (2024)

Manuel Endres, Caltech

Programmable optical clocks

Squeezing via local Rydberg-mediated interactions,
Below SQL performance at 10^{-17} precision

Eckner…Ye, Kaufman, Nature (2023)

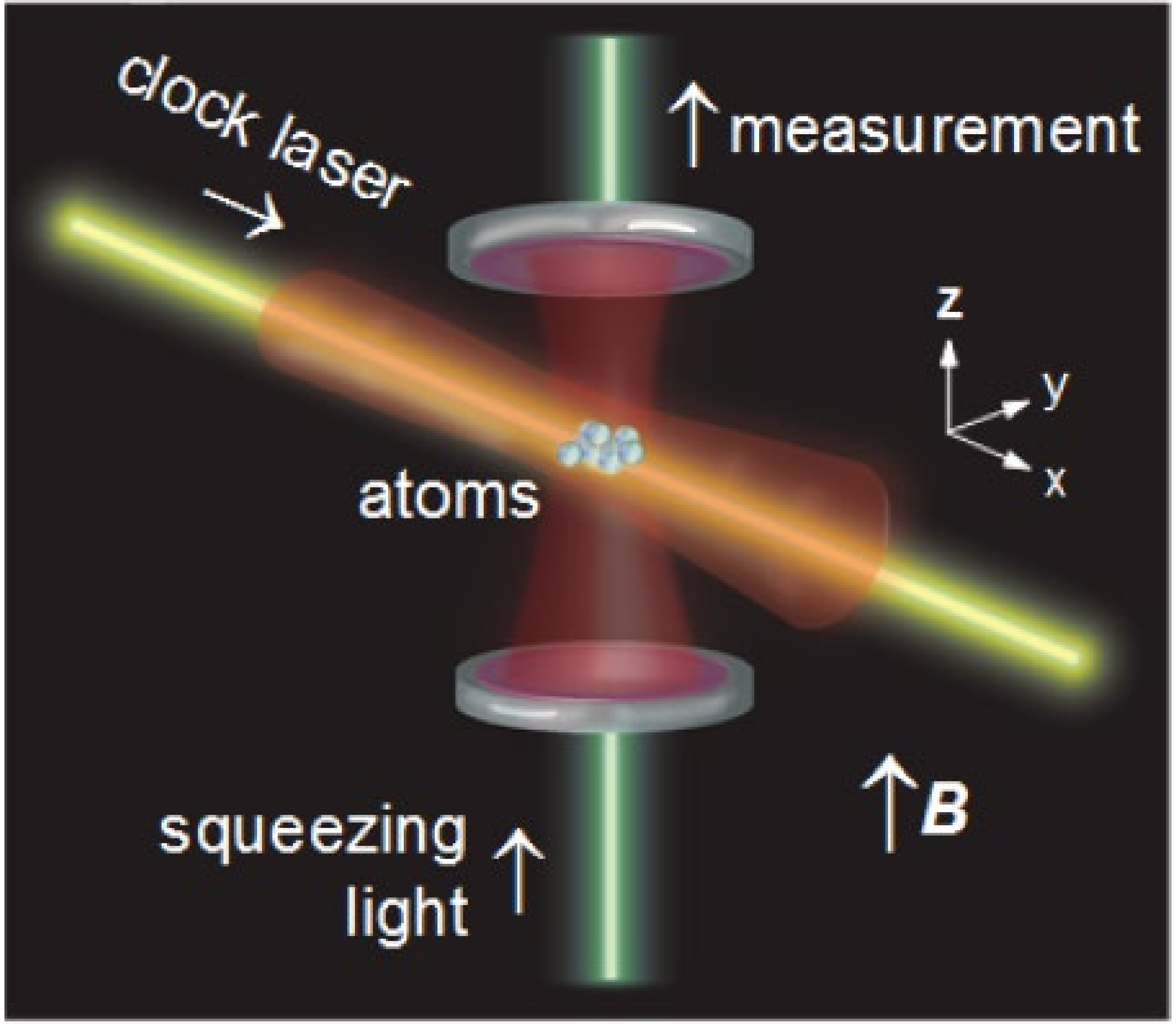


High-fidelity multi-qubit gates
Phase estimation w/ cascaded GHZ states

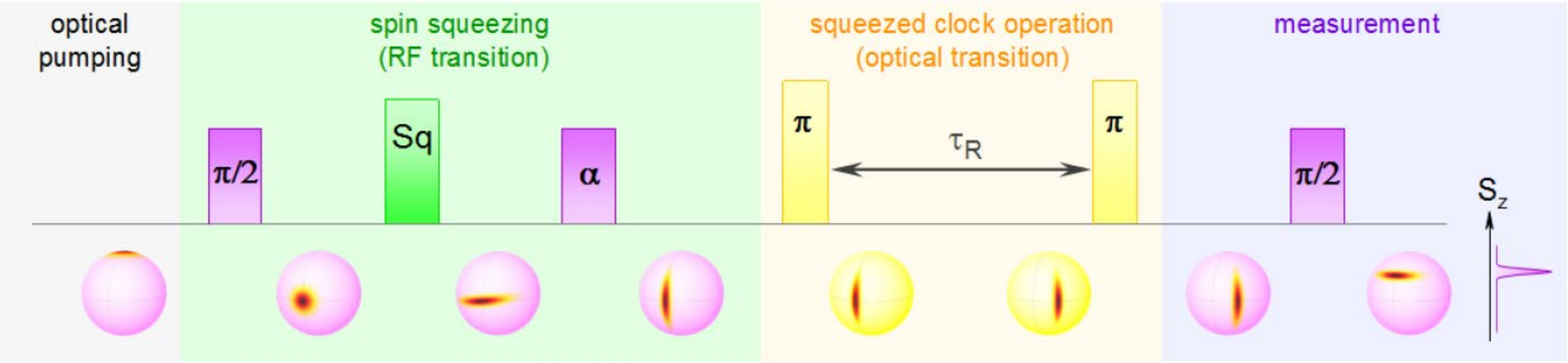
Cao…Darkwah-Oppong, Kaufman, Nature (2023)

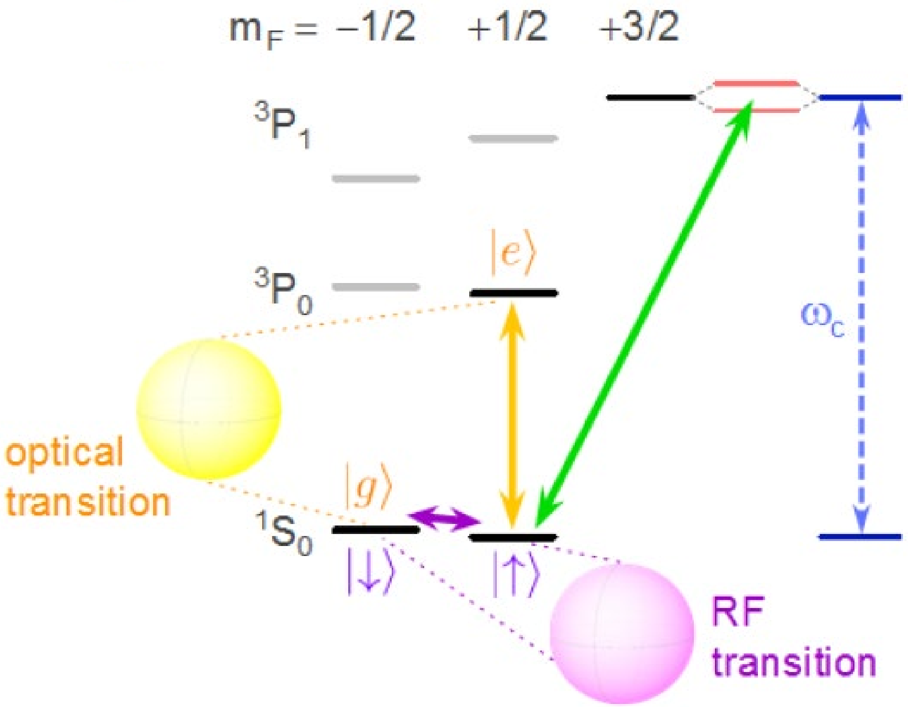
Adam Kaufman, Boulder

Spin squeezing on atomic clock transition in ^{171}Yb



Entanglement on optical transition

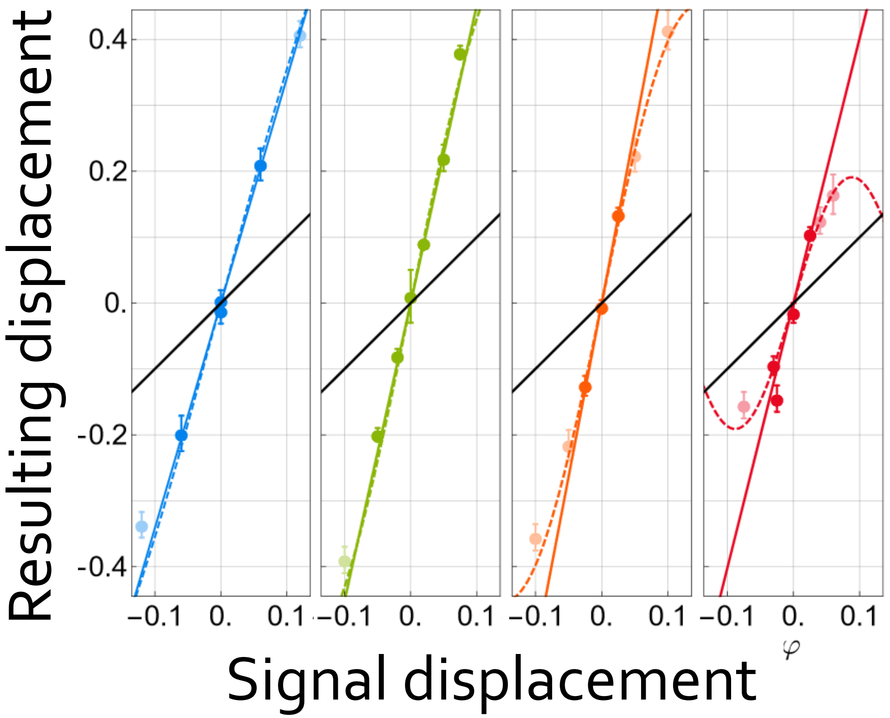


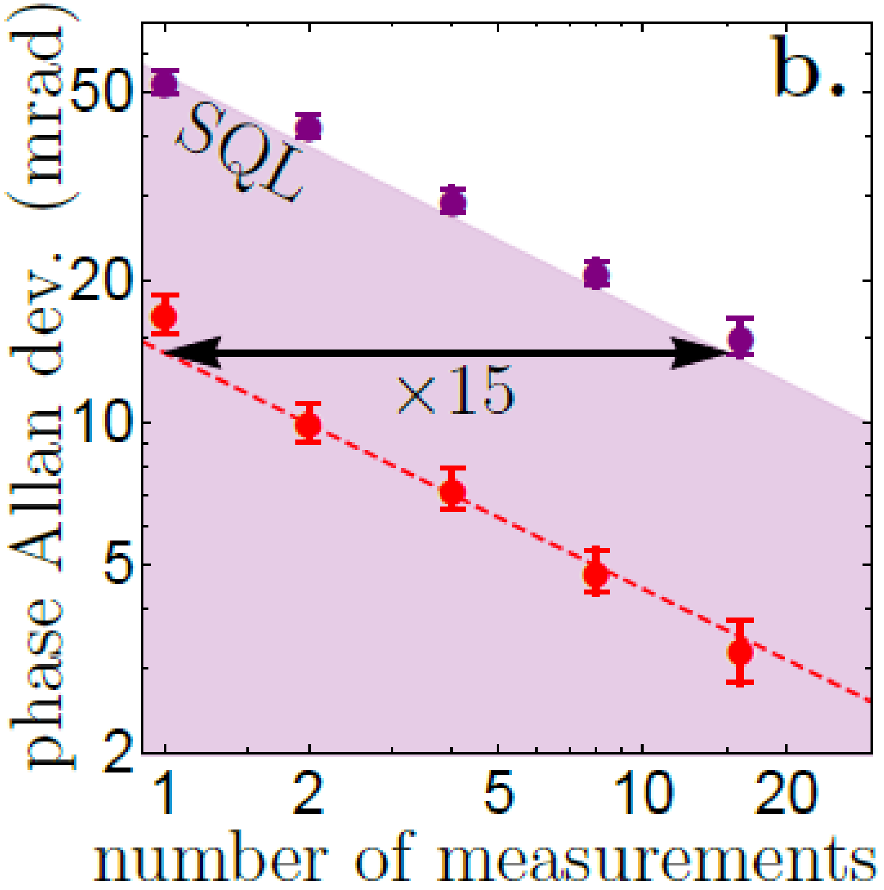


- Squeezing generated between nuclear sublevels in the electronic ground states
- The squeezed state is transferred onto the optical clock transition with a p pulse to perform Ramsey sequence
- Readout after mapping back to ground state

Vuletic, MIT

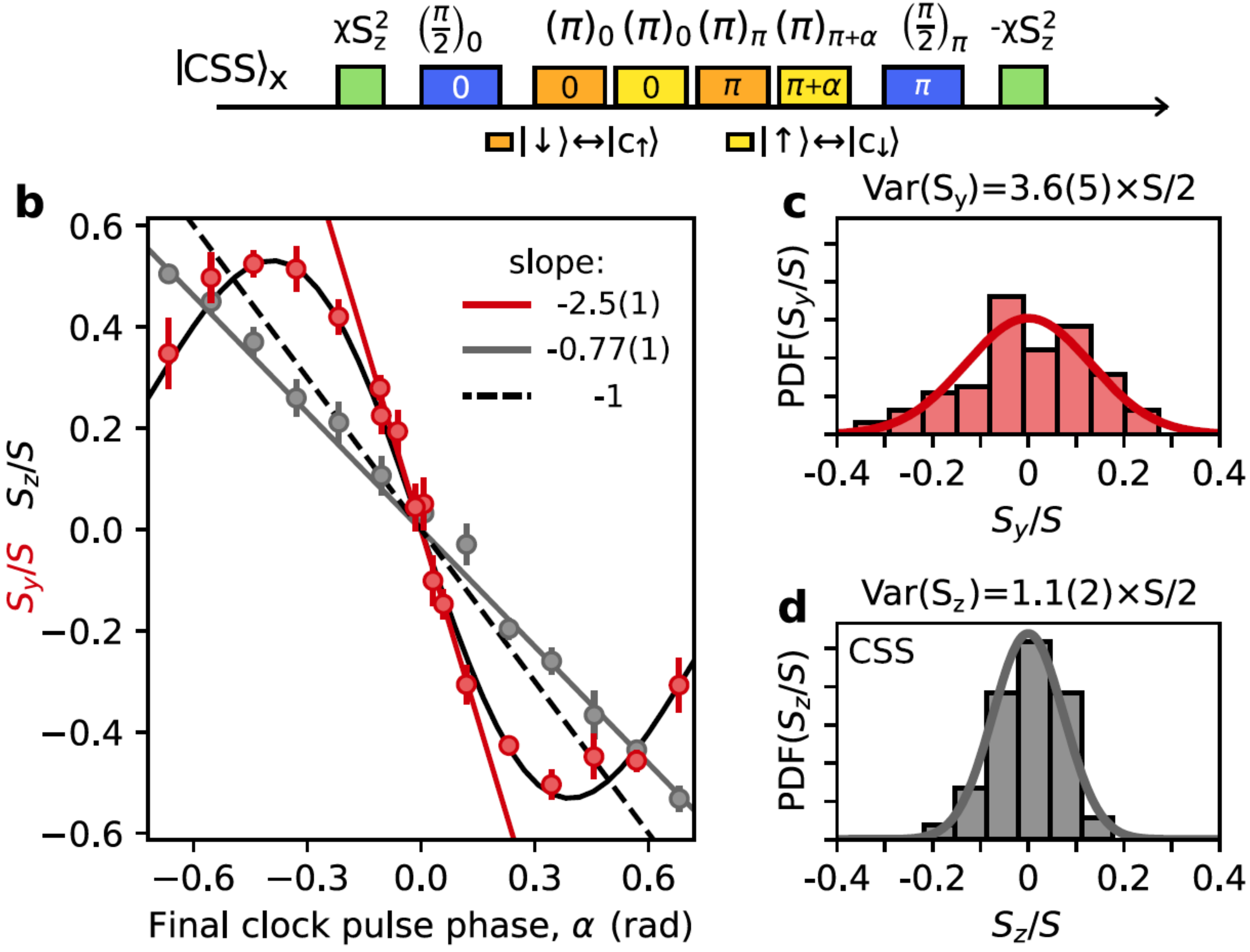
Magnification of phase signal through time-reversed interactions





S. Colombo, E. Pedrozo-Penafiel, A. Adiyatullin, Z. Li, E. Mendez, C. Shu, and V. Vuletić, Nature Physics 18, 925–930 (2022);

Time-reversal sequence with global phase spectroscopy (GPS) with entanglement



L. Zaporski, Q. Liu, G. Velez, M. Radzihovsky, Z. Li, S. Colombo, E. Pedrozo-Penafiel, and V. Vuletić, *Nature* (2025, in print)

Vuletic, MIT

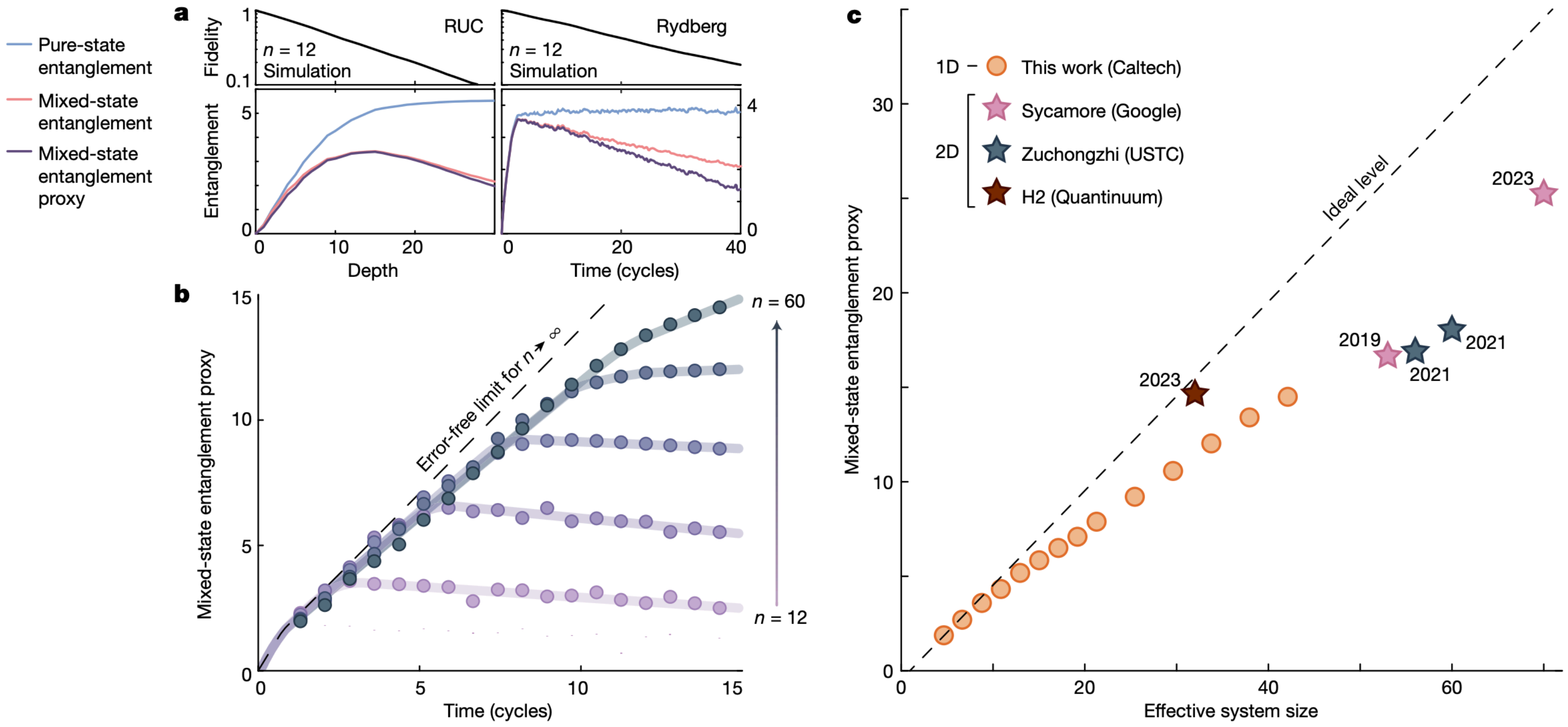
Arrays for quantum simulation

Quantum Simulation

Preparation of record-size entangled states

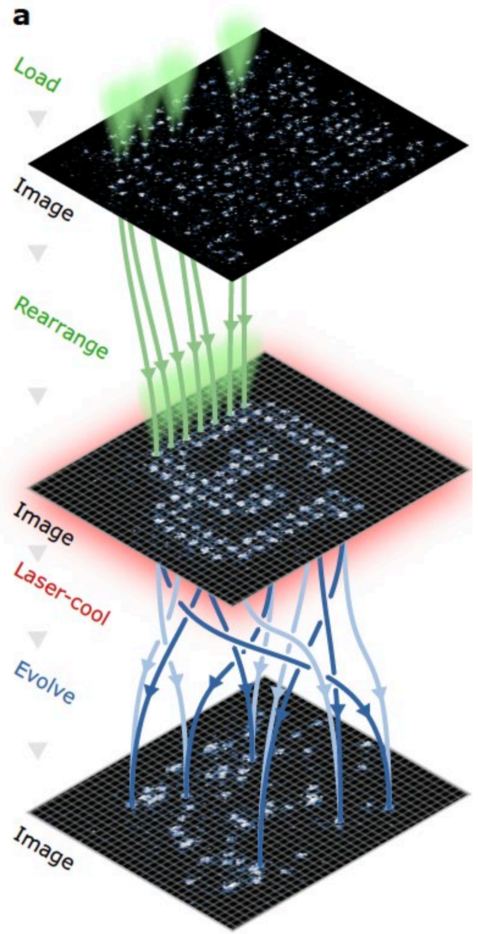
- At the boundary of quantum advantage
- New approaches to benchmarking analog simulators

Shaw*, Chen*, Choi*, Mark*, … S. Choi, Endres
Benchmarking highly entangled states on a 60-atom analog quantum simulator
Nature 628, 71–77 (2024)



Manuel Endres, Caltech

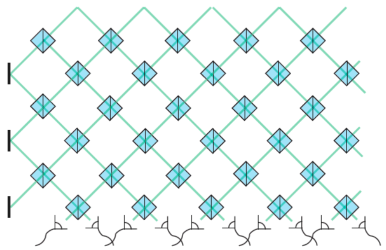
Assembled Hubbard systems



A. Young….A. M. Kaufman,
Science (2022)

Large-scale Fock-state boson sampling

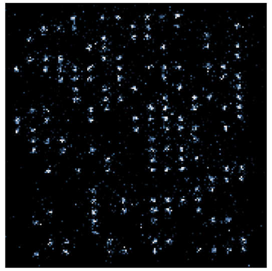
, E. Knill, A. M. Kaufman,
ler, Nature (2024)



Atom-by-atom assembly of superfluids

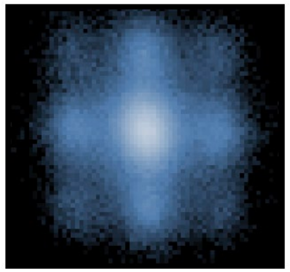
W. Eckner…L. Polet, A. M. Kaufman, *in prep.*

Disordered array



Rearrangement
+ Laser cooling

Many-body coherence

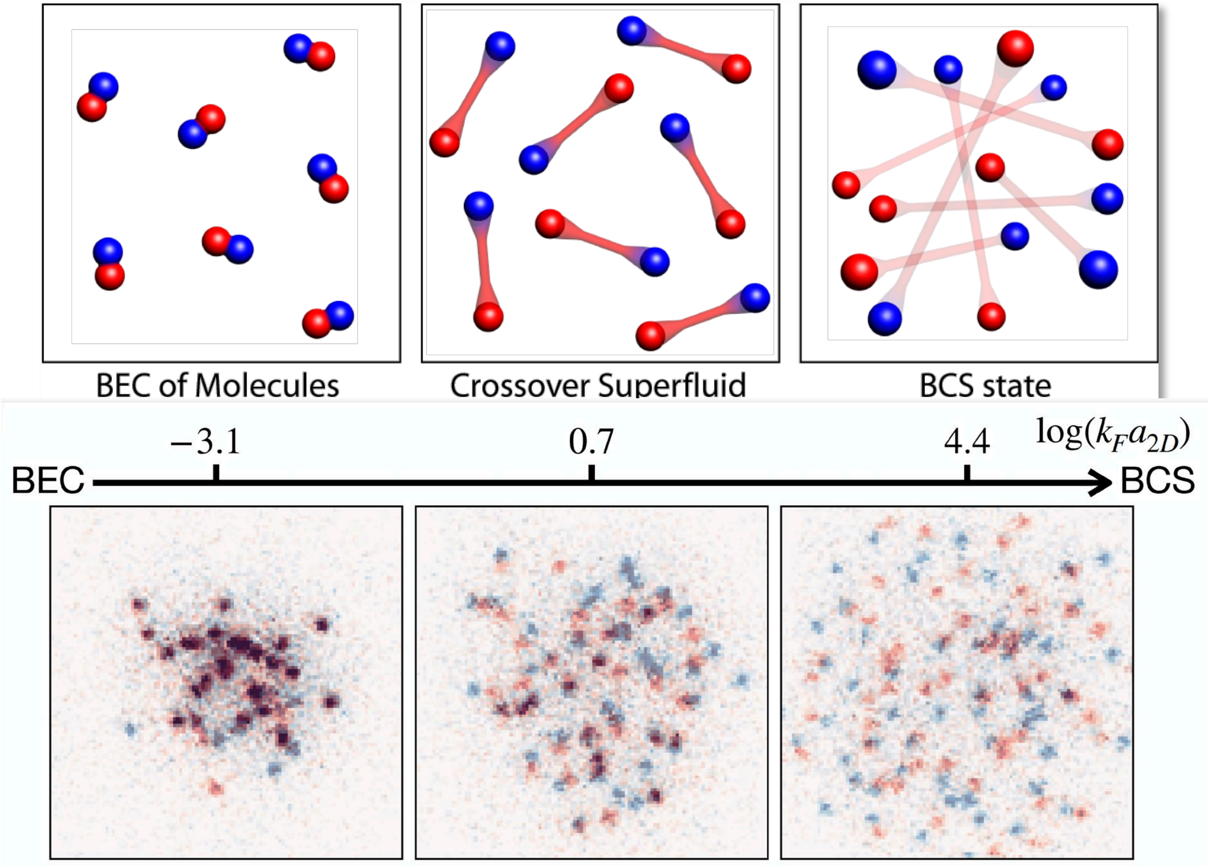


Adam Kaufman, Boulder

Atom-resolved Quantum Many-Body Physics

- Continuum quantum gas microscopes for understanding quantum many-body physics with single particle resolution

e.g. Fermionic Superfluids



R. Yao, S. Chi, K. Wang, R. Fletcher, M. Zwierlein, in preparation

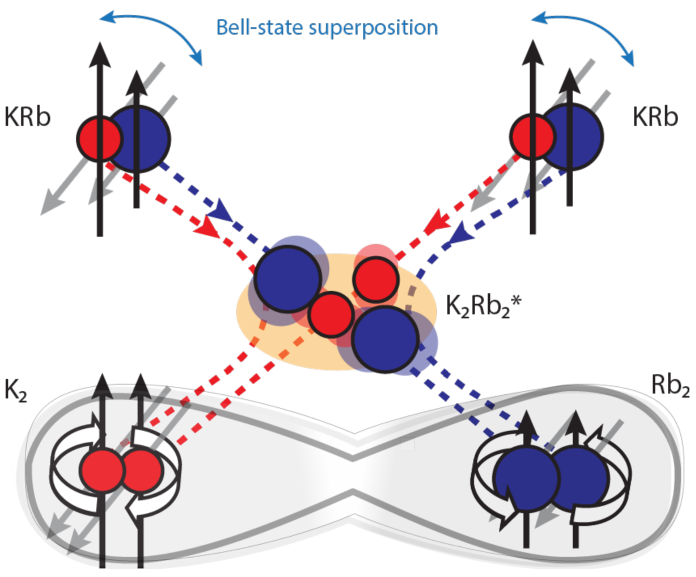
Zwierlein, MIT

Arrays for molecules

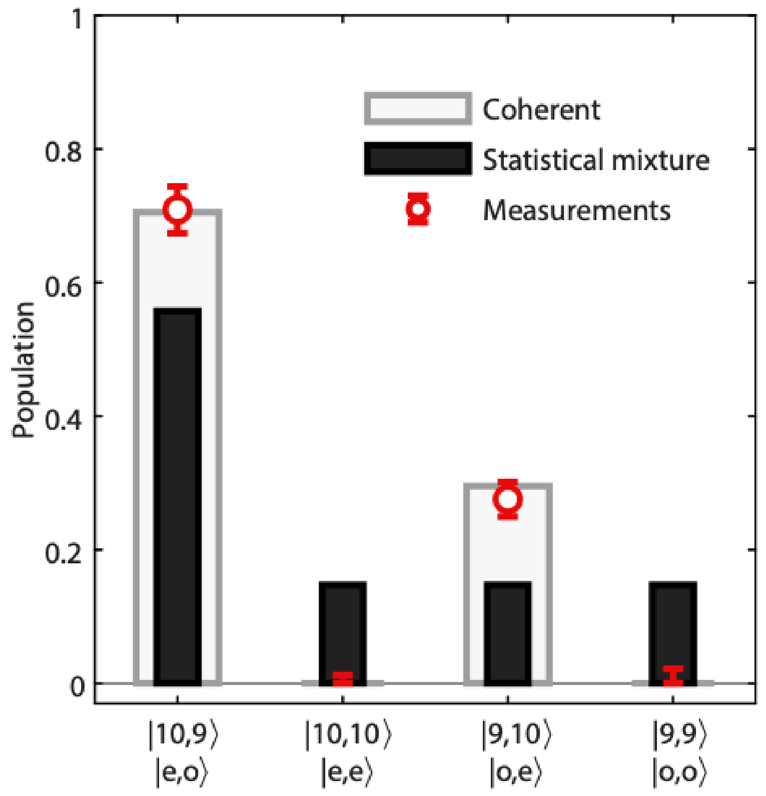
Phase coherence and entanglement in chemical reaction?

Prepare entangled spins within each molecules, then use chemical reaction to rearrange the atoms into separate, entangled molecules

Questions: Can coherence (phase) be maintained throughout a reaction?



Liu and Zhu et al., Science **384**, 1117 (2024)



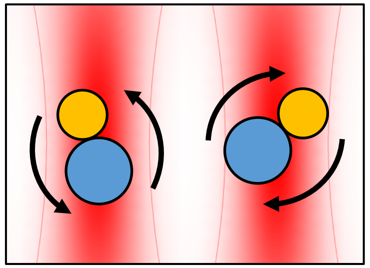
Coherence is [0.9014, 1] (95% confidence level)

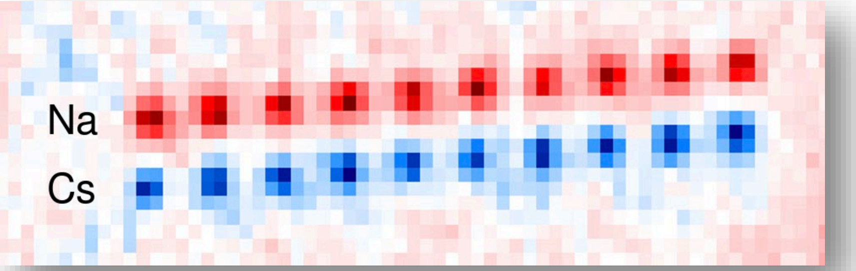
Kang-Kuen Ni, Harvard

CAMOS 2025

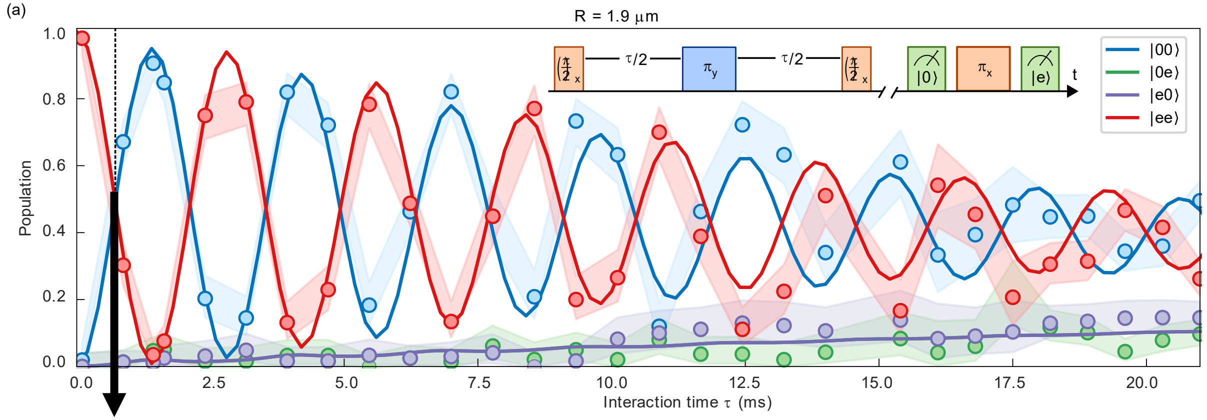
Entanglement and iSWAP gate between molecular qubits

Ultracold molecule assembler: NaCs



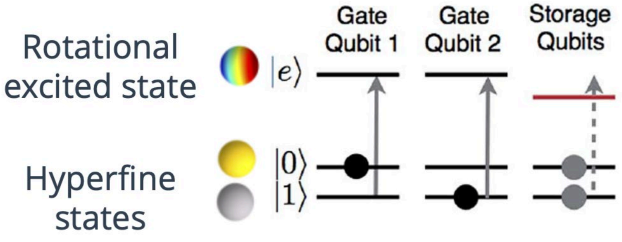


~7 coherent dipole-dipole interactions:



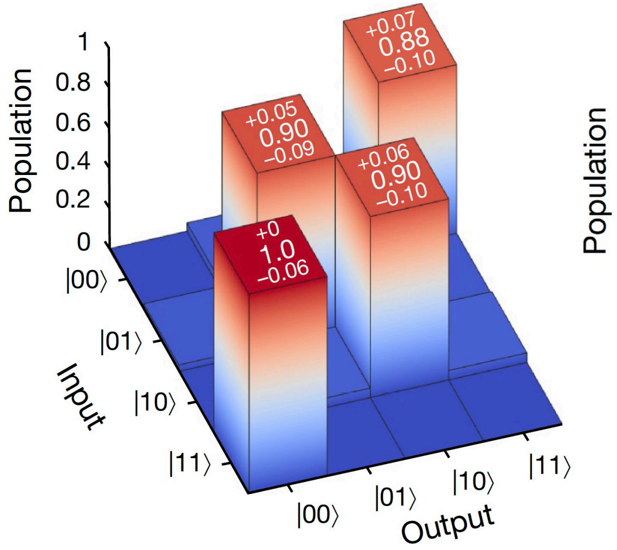
94(3)% Bell state fidelity

Kang-Kuen Ni, Harvard

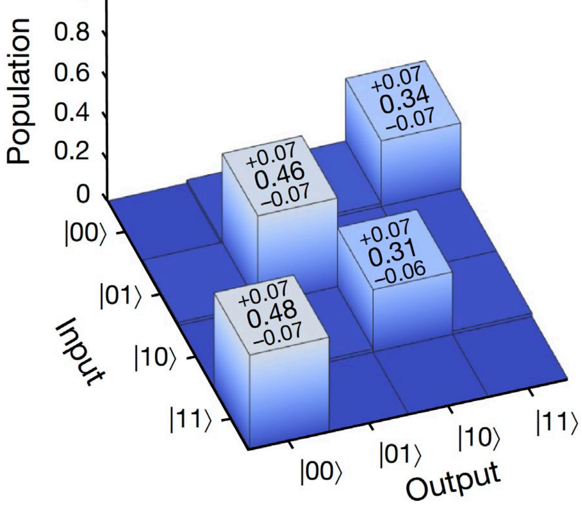


Toggle interaction

K.K. Ni *et al.*
Chemical Science **9**, 6830–6838 (2018)



Limited by state prep (single qubit rotation)



iSWAP gate: $0.92^{+0.05}_{-0.09}$ fidelity

- post-selected on having both molecules in 0,1 basis

$0.39^{+0.1}_{-0.09}$ fidelity

- post-selected on having both molecules

Quantum computing with neutral atoms

Continuous reloading of atoms for large processors and deep circuits

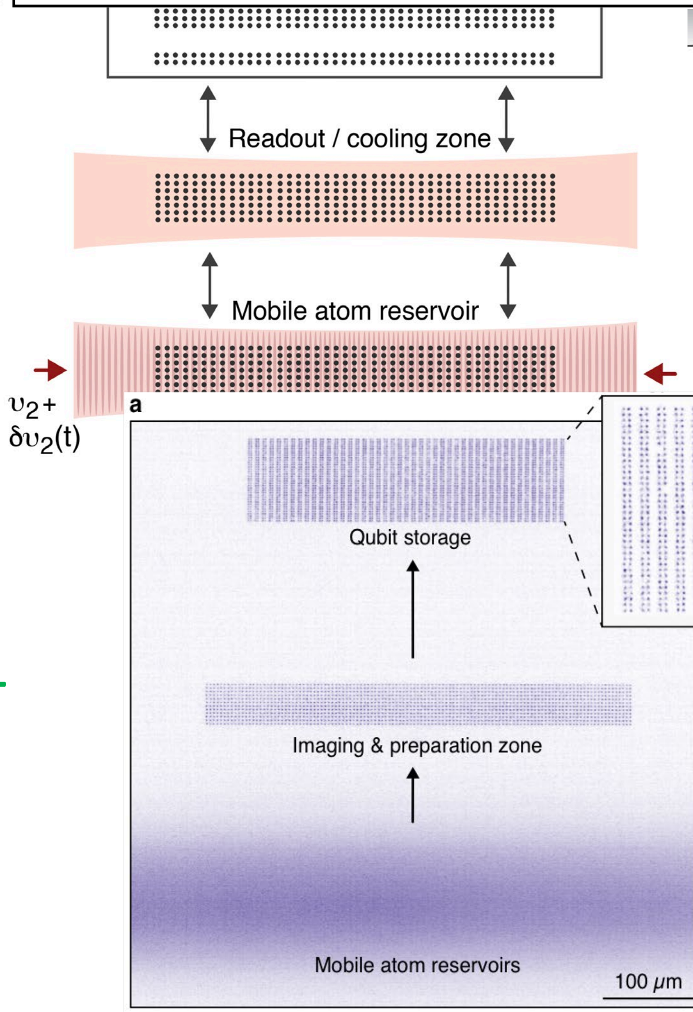
Continuous Reloading Harvard Array 2 experiment

3000 atomic qubits

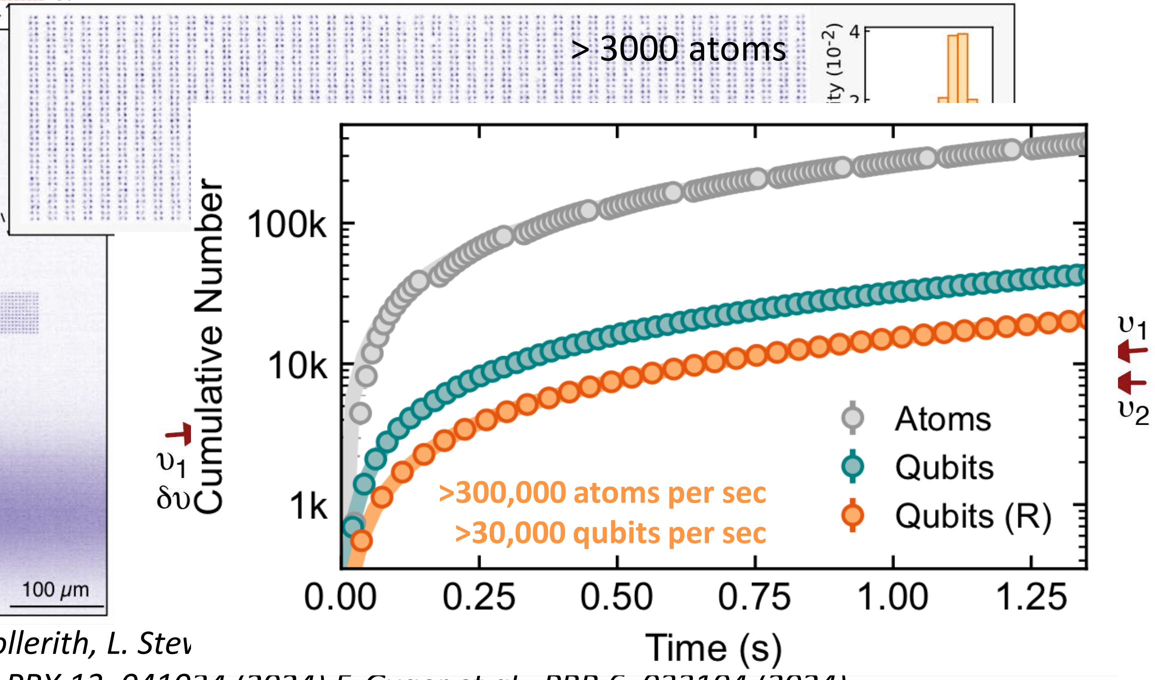
Lukin-Vuletic-Greiner Harvard-MIT-Quera collaboration

A. Chiu, E. Trapp, M. Abobeih, T. Guo, S. Hollerith, L. Stewart, et al arXiv 2506.20660 slowed by 500x (2025)

Continuous Reloading



- Neutral atom quantum computers require high rate atom reloading
- Tweezers loading from optical lattice reservoir (prepared via conveyor belts)
- Continuous operation beyond lifetime of atoms

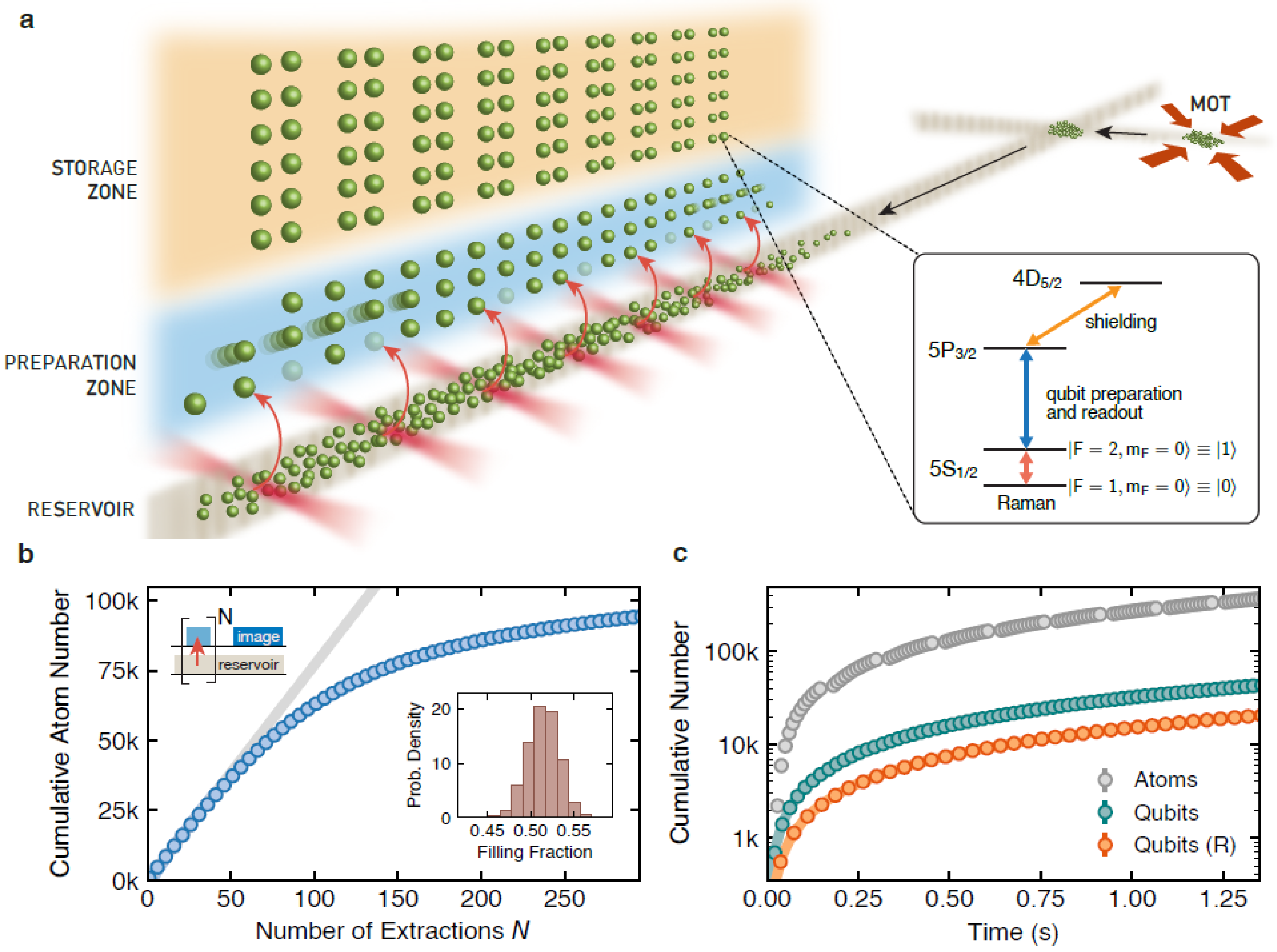


Harvard-MIT-Quera collaboration

A. Chiu, E. Trapp, M. Abobeih, T. Guo, S. Hollerith, L. Stev

See also recent work by M.A. Norcia et al., PRX 13, 041034 (2024) F. Gyger et al., PRR 6, 033104 (2024)

Continuous reloading



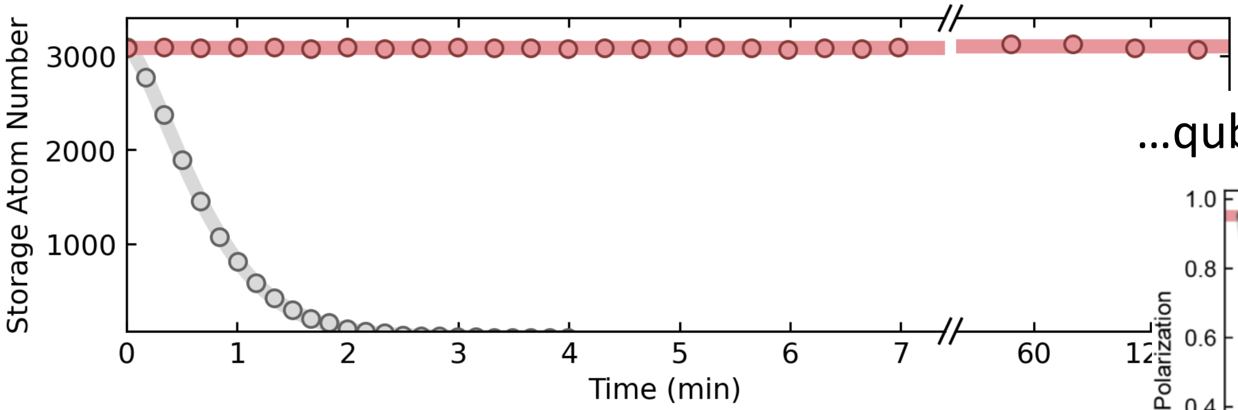
Continuous operation of a coherent 3,000-qubit system

Neng-Chun Chiu et al., to appear in Nature

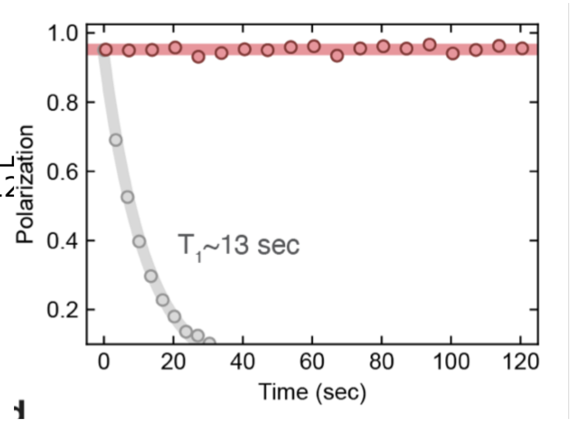
Harvard-MIT-Quera collaboration

Continuous Operation: Reloading + single qubit operations

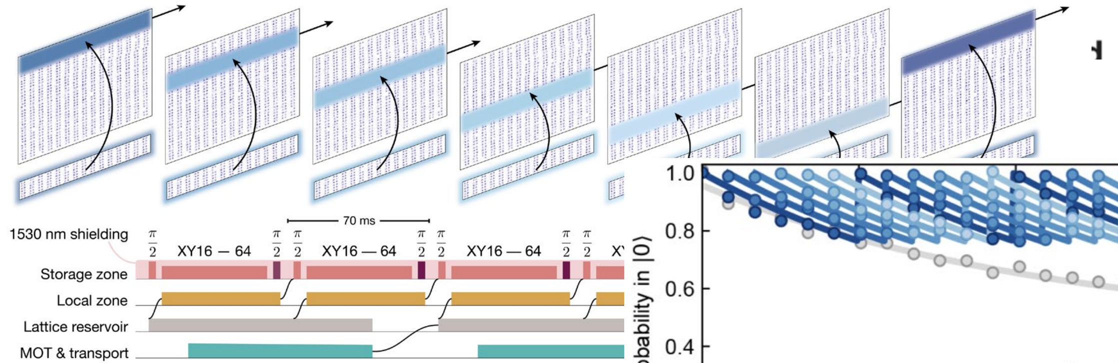
Preserving atom number …

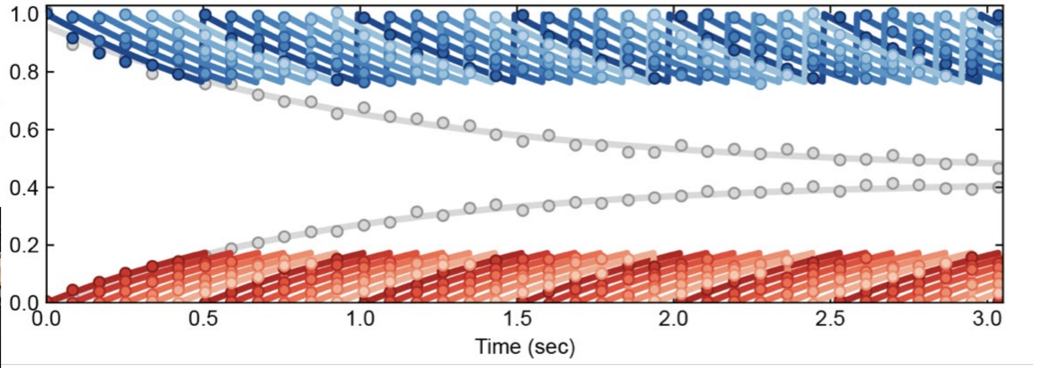


…qubit polarization …



… and coherence





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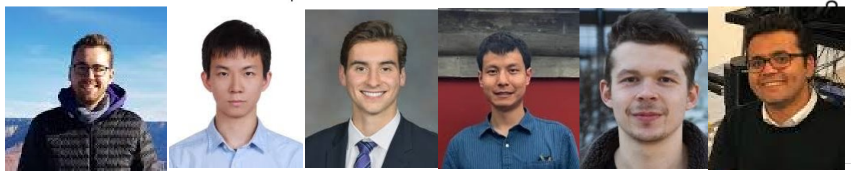
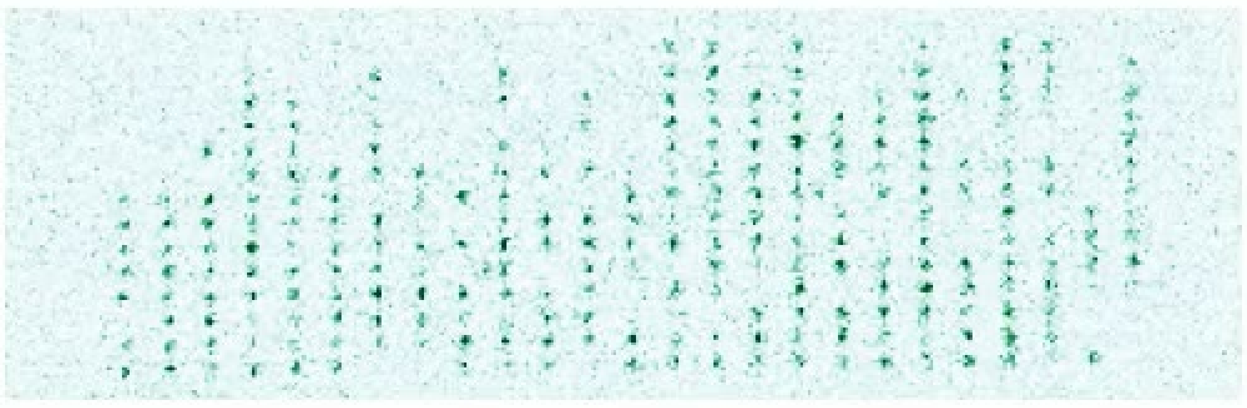
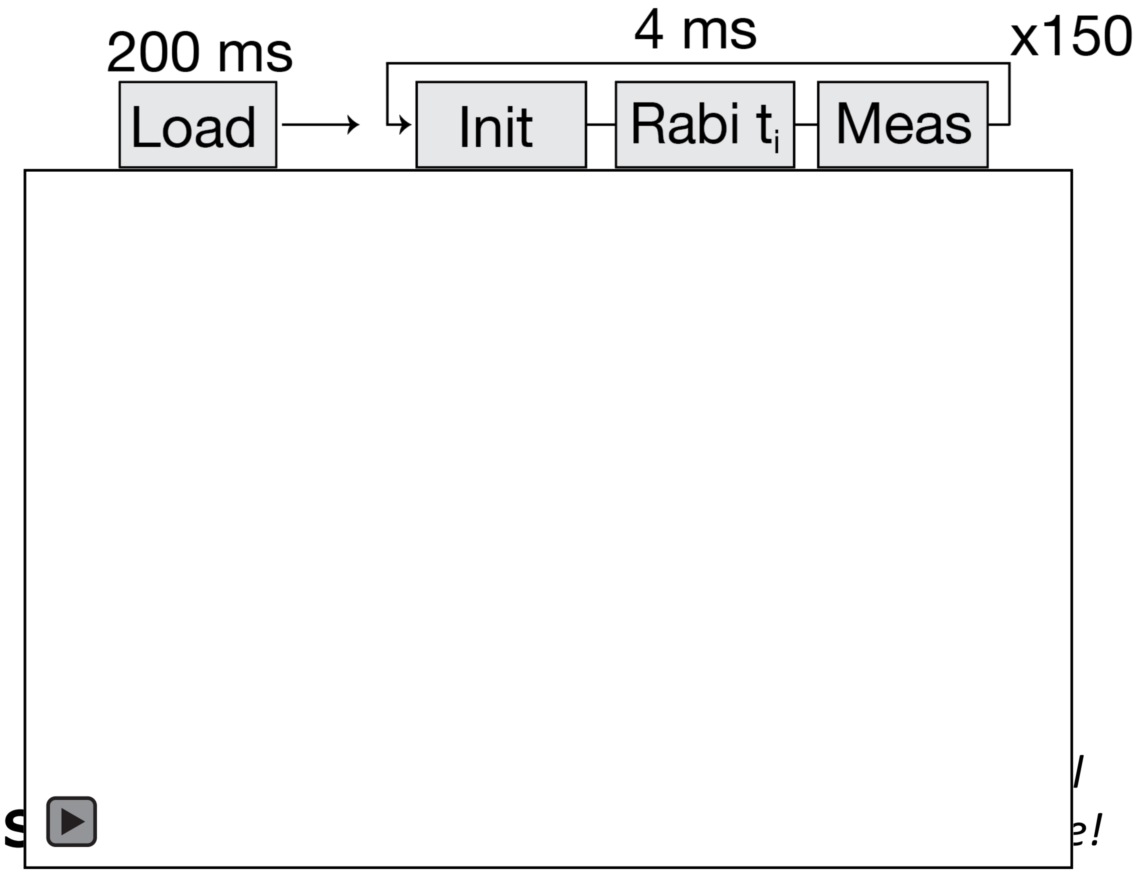


Example: qubit re-use for fast Rabi calibrations





250 Hz cycle rate by re-cooling and re-us atoms

Using parallelism across hundreds of atoms

Harvard-MIT-Quera collaboration

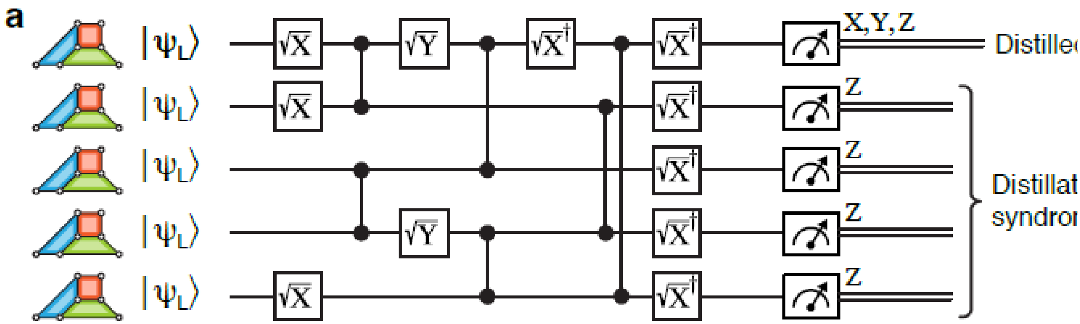
Non-Clifford gates

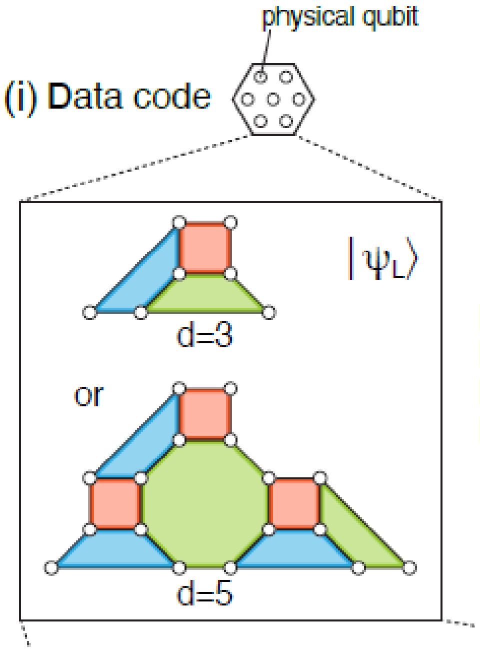
Non-Clifford gates

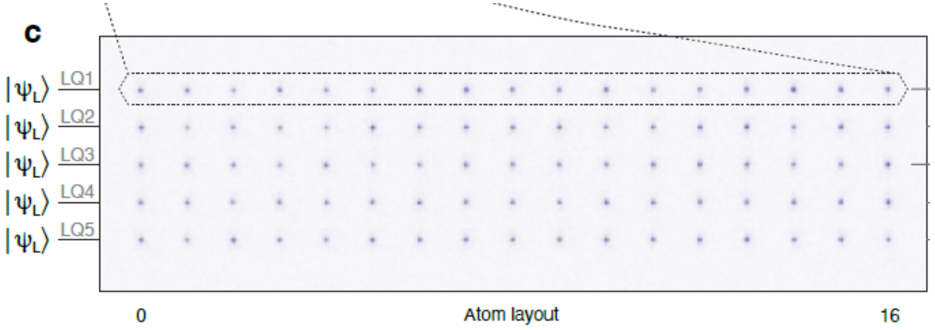
- Universal quantum computation requires two types of gates: Clifford and non-Clifford
- Processes that are hard to simulate on classical computers require both types of gates
- Non-Clifford gates can be small rotations; small rotations are easy on single physical qubits but hard to perform on logical qubits
- “Magic states” are one approach to implementing non-Clifford gates
- Better magic states can be “distilled” from more copies of worse-quality magic states

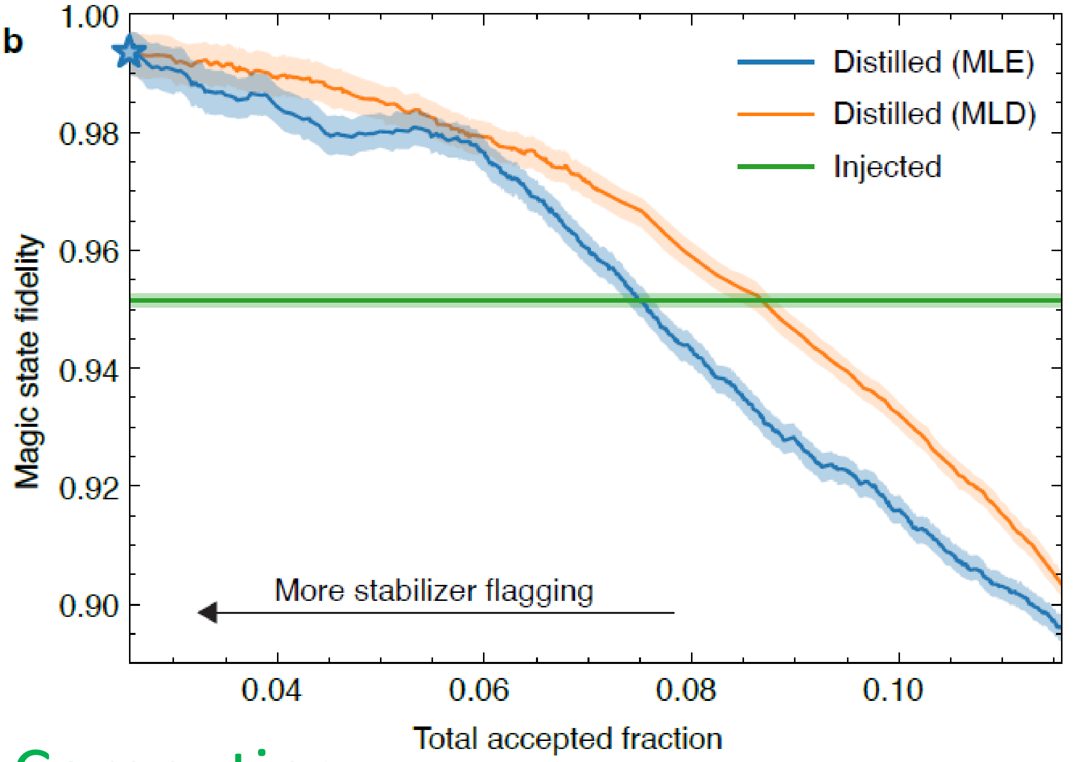
Non-Clifford gates: Magic state distillation (Quera Computing)

- Small-angle rotations are hard on logical qubits
- Magic states can be used to implement those
- Distillation of magic states encoded in d=3 and d=5 color codes









Experimental demonstration of logical magic state distillation, Pedro Sales Rodriguez et al., Nature **645**, 620 (2025).

Quera Computing

Neutral atom logical processor

Zoned architecture with ~450 atomic qubits,
Up to 96 logical qubits

Storage

- Idle logical qubits are stored, safe from errors

Entangling

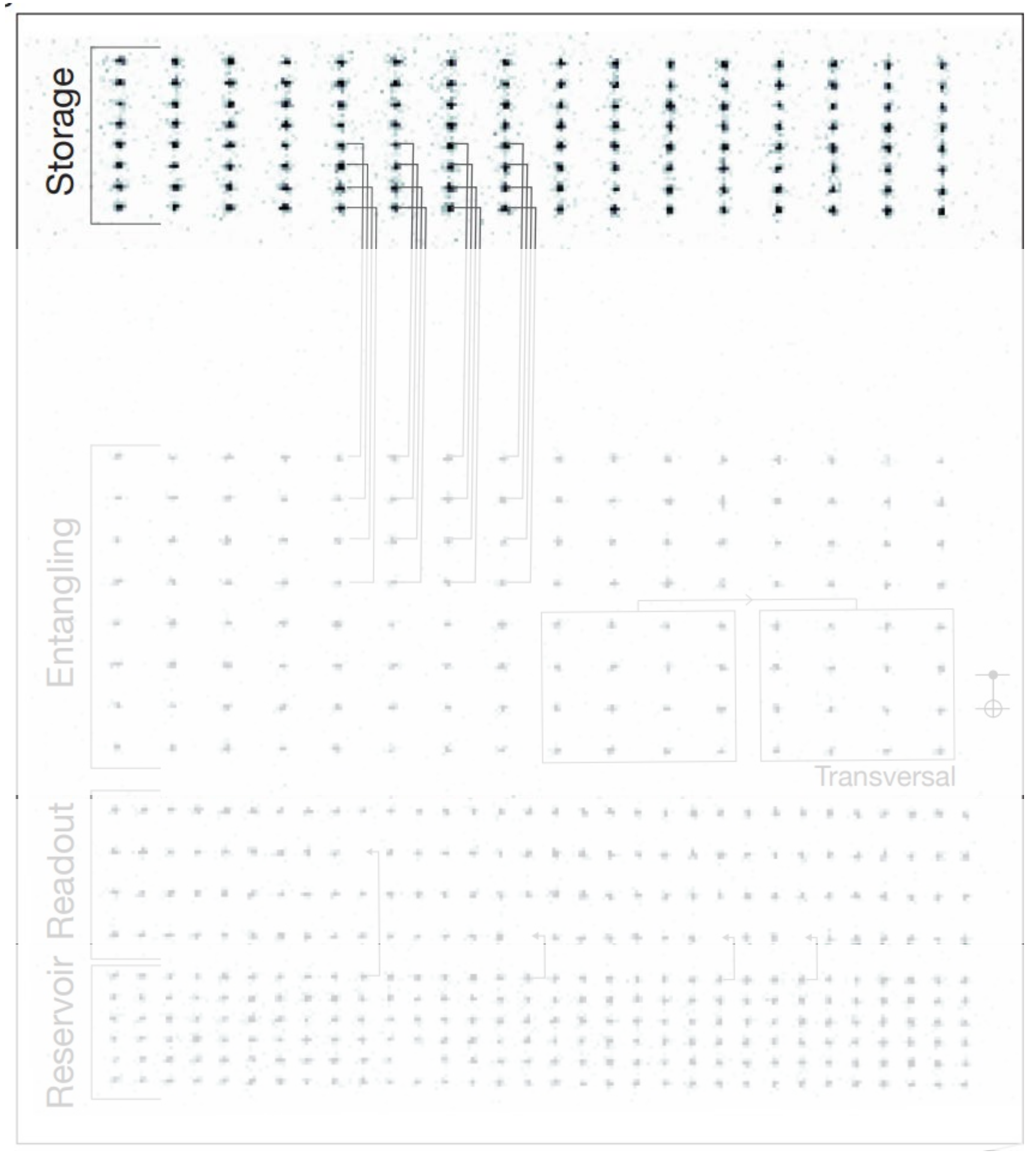
- Long-range connectivity via atom motion
- Parallel 2Q gates
- Fully-programmable SQ gates

Readout

- Mid-circuit measurement and qubit re-use

Reservoir

- Refill lost qubits (towards continuous operation)



Logical (error corrected) qubits

Circuits with high-rate codes: cluster state with logical qubits

[[16,6,4]] hypercube code

Architectures and mechanisms for fault-tolerant quan computation. D. Bluvstein, A.A. Geim, et al., to appear Nature (2025).

Harvard-MIT-Quera collaboration

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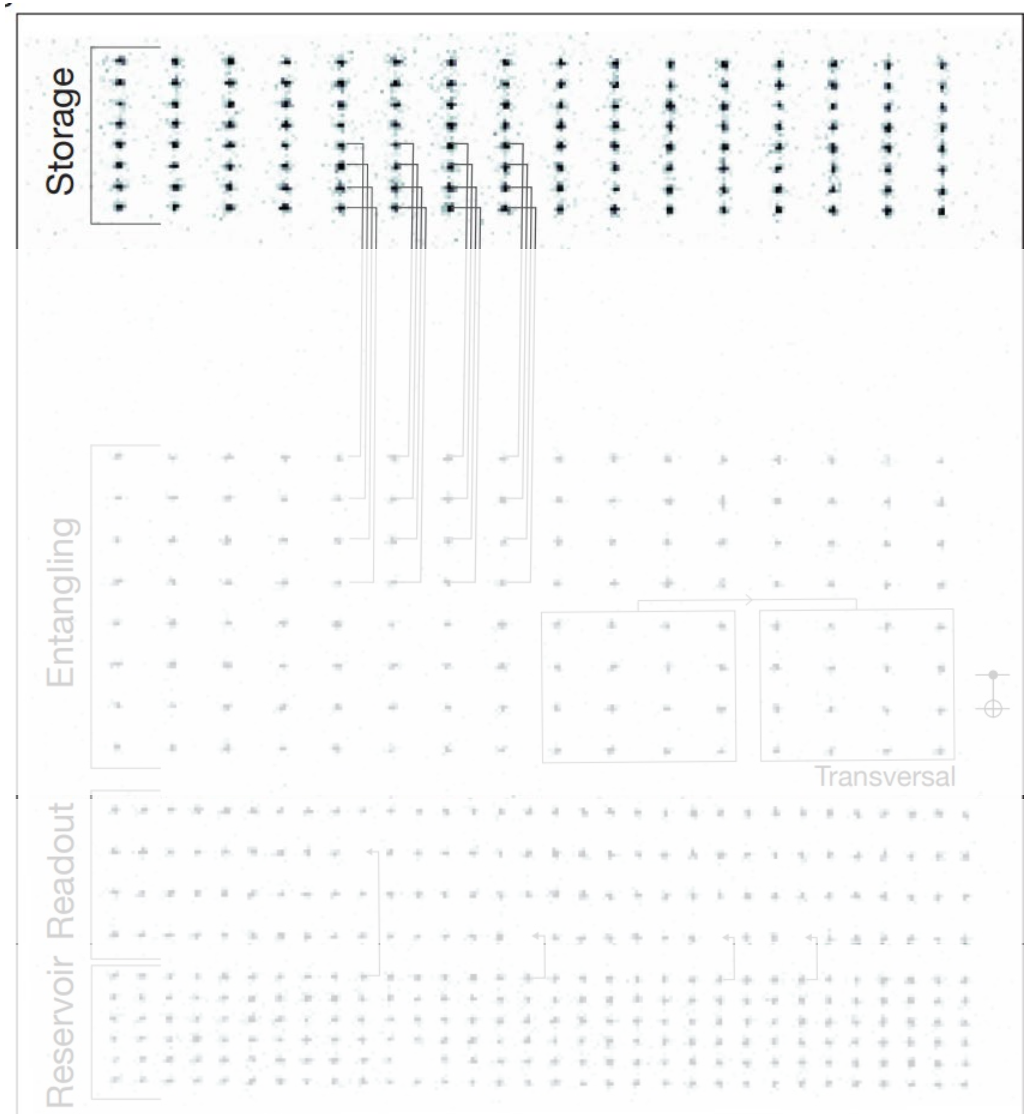
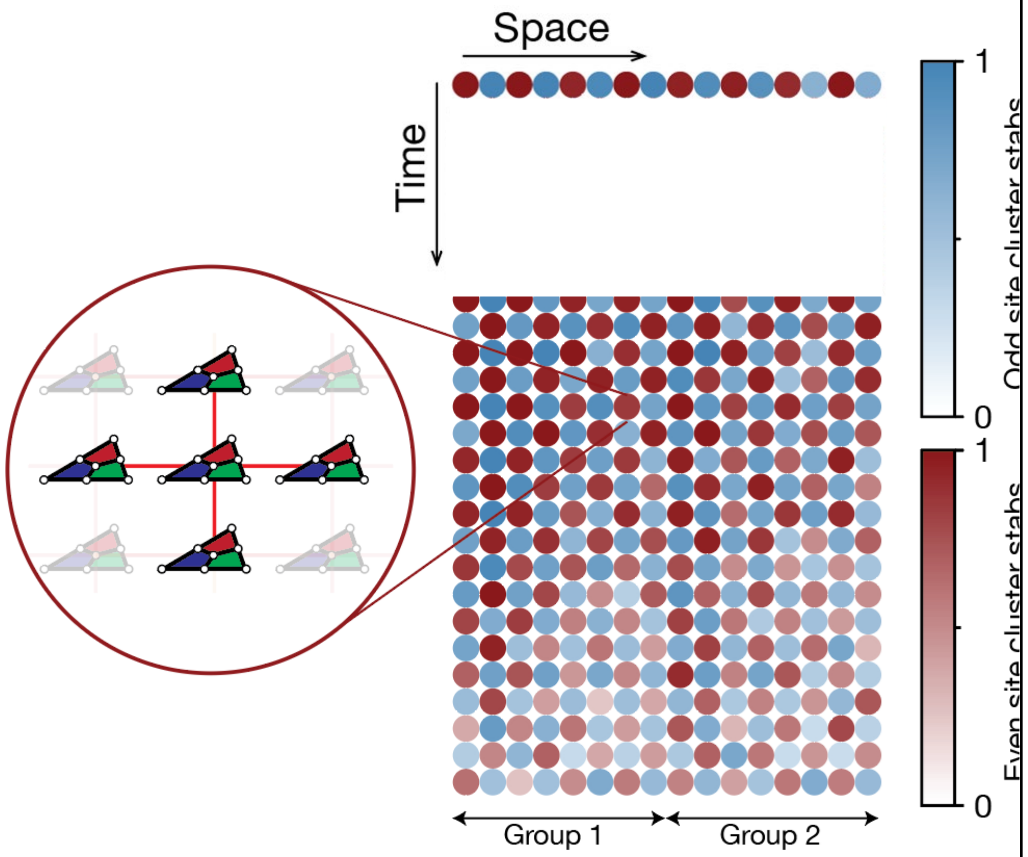


Harvard-MIT-Quera collaboration



Experimental 2D cluster state stabilizers with Steane codes

Outlook

- We are entering the era of first algorithms with logical (i.e. error corrected) qubits
- Path towards larger quantum computers:
  - First experiments with ~100 logical qubits, error correction
  - Non-Clifford logical gates
  - 100,000 physical qubits within reach in next 1-2 years.
  - Quantum computers with be useful for science.
  - Quantum error corrections seems feasible: 100 logical qubits with error 10^{-6} to 10^{-9} within next three years.
  - What useful algorithms exist in this error range?