Atom-atom interactions for quantum metrology and quantum computing

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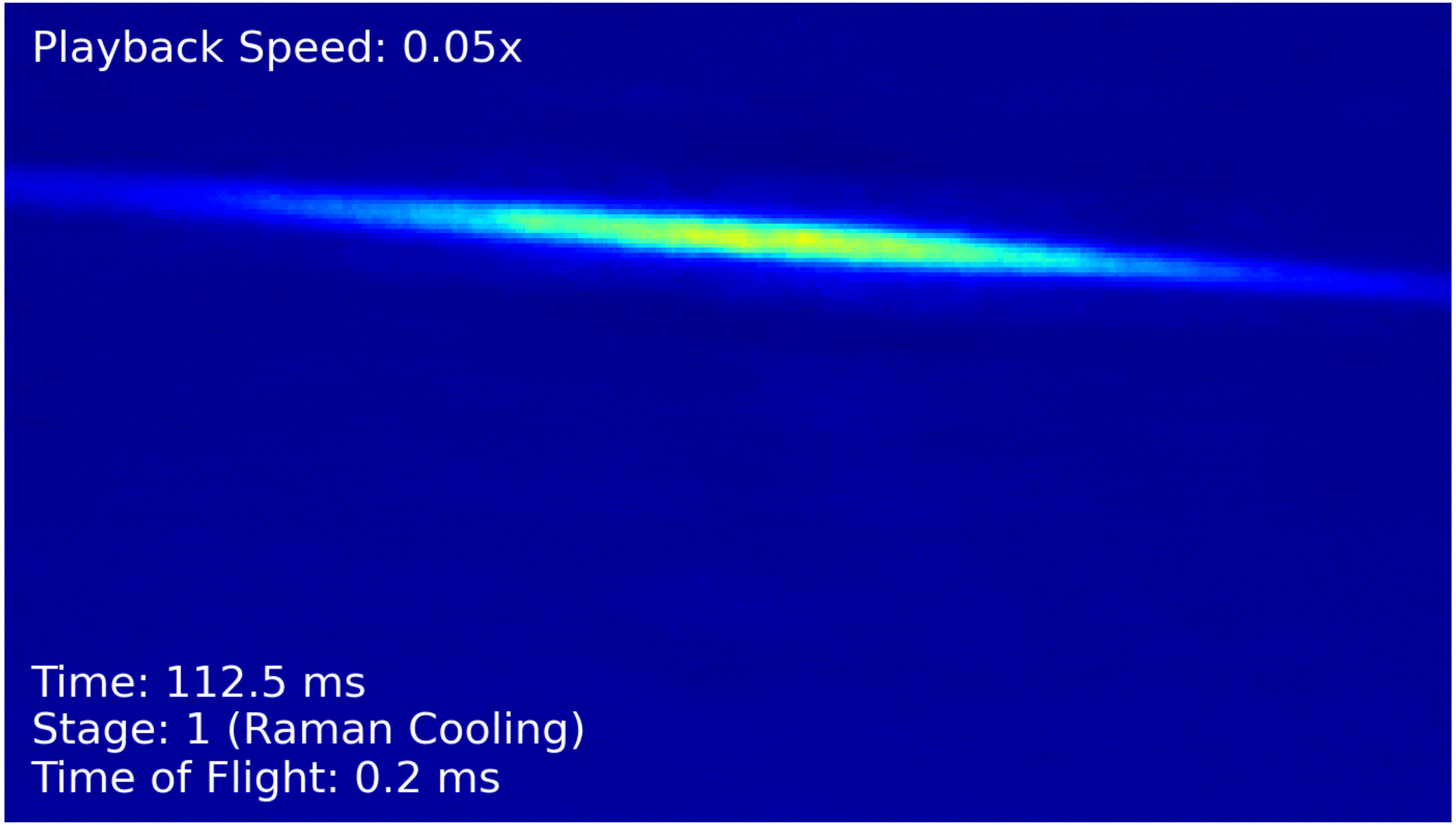
Outline

- A surprise in laser cooling
- Time-reversal quantum metrology with entangled states
- Rydberg-based quantum computing with transported atoms

Machine-learning-accelerated Bose-Einstein condensation by optical cooling

Machine-learning accelerated Raman cooling of Rubidium to BEC in crossed optical dipole trap



- 0.575s, including MOT loading time, found overnight by algorithm
- Manual optimization: 3s, smaller condensate
- γ=16 for Raman cooling (γ=7 manual optimization)

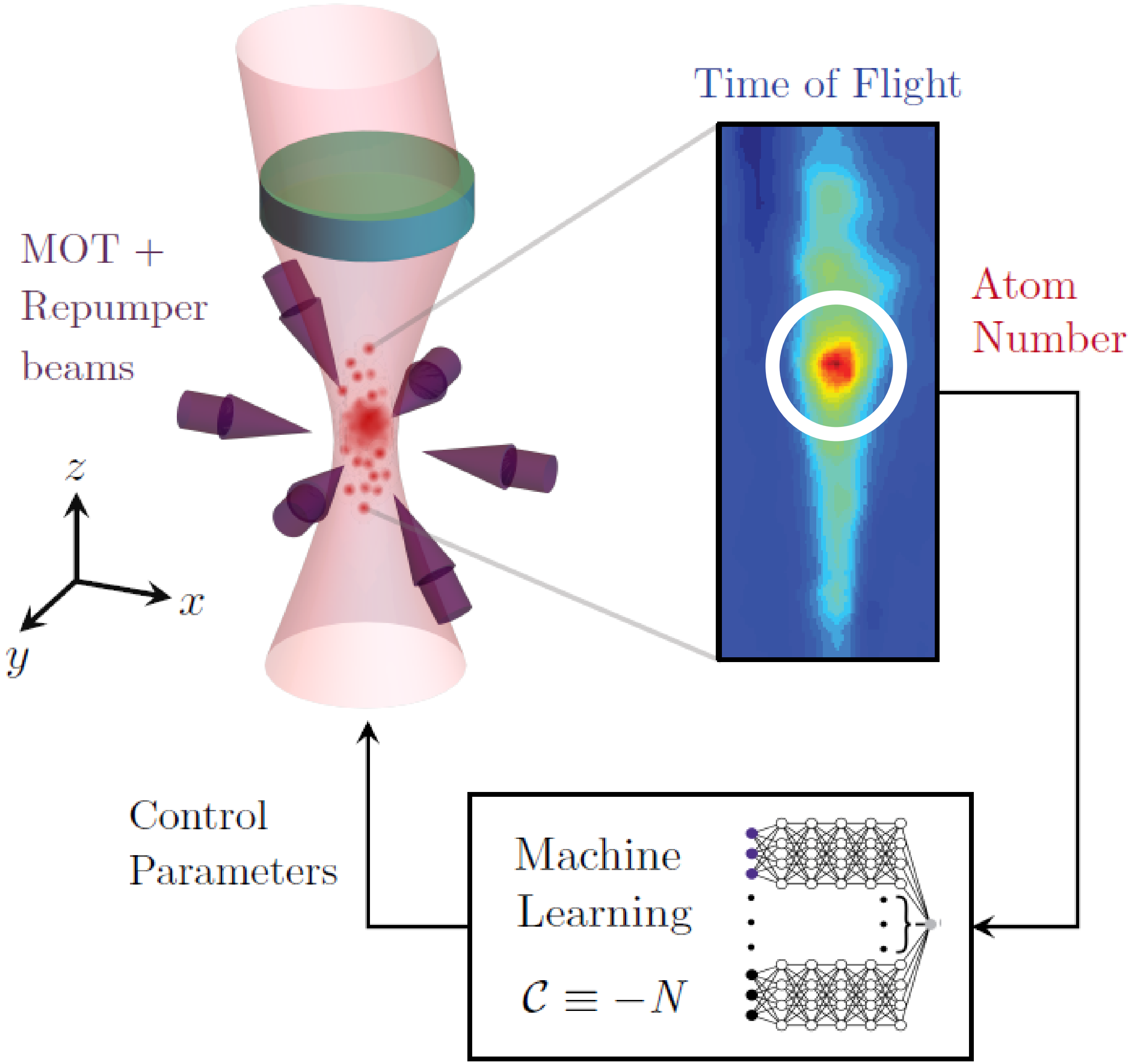
Z. Vendeiro, J. Ramette, A. Rudelis, M. Chong, J. Sinclair, L. Stewart, A. Urvoy, and V. Vuletić, Phys. Rev. Res. 4, 043216 (2022).

Laser cooling to quantum degeneracy

- Cooling to BEC achieved with tuned parameters, in particular very large and carefully chosen detuning of the optical pumping laser in Raman cooling;
- For atom with narrow optical transition (Sr), Florian Schreck and collaborators have used special technique to shield condensate;
- But everybody knows that polarization gradient cooling cannot create condensate due to light-induced heating and severe atom loss.

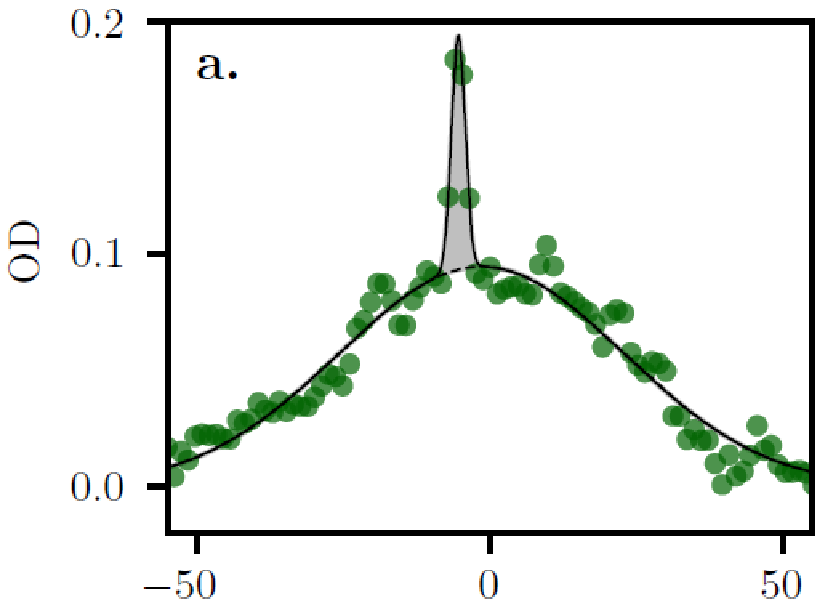
Loading many atoms into an optical tweezer trap for Rydberg experiment: optimize by machine learning

Polarization gradient cooling in misaligned 3μm tweezer

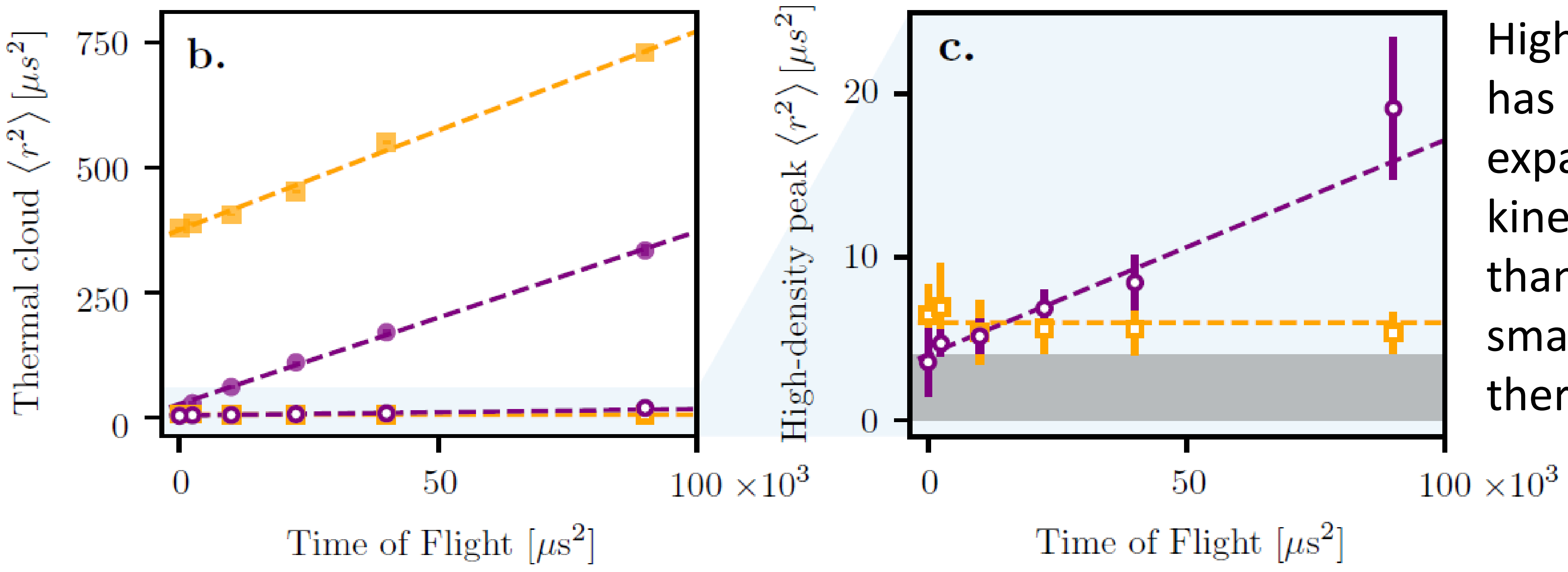


After 40 ms of polarization gradient cooling optimized by machine learning algorithm to load maximum number of atoms into trap …

Bimodal time-of-flight distribution

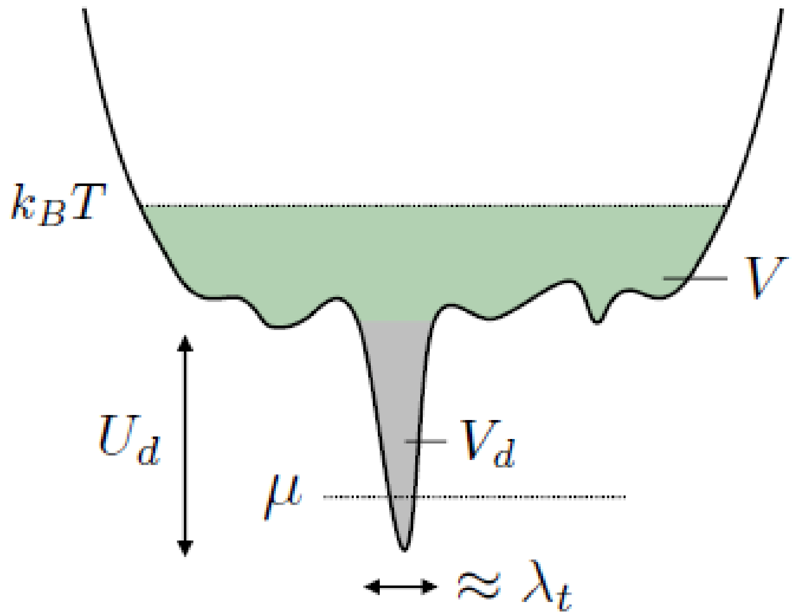


Thermal cloud distribution
35 μK

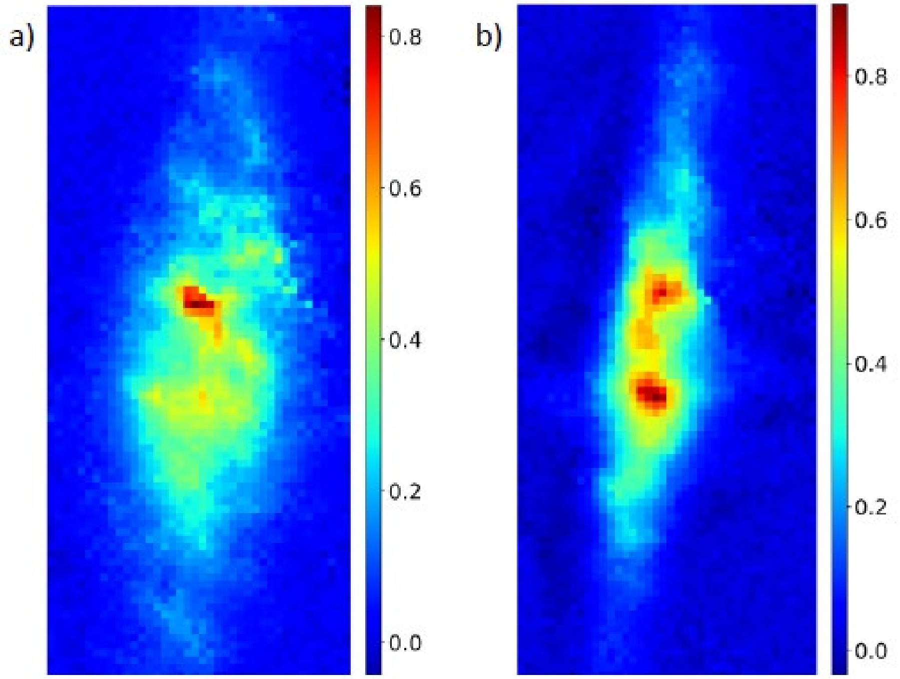


High density peak has anisotropic expansion and kinetic energy more than 40 times smaller than thermal cloud

Corrugation in potential due to misalignment

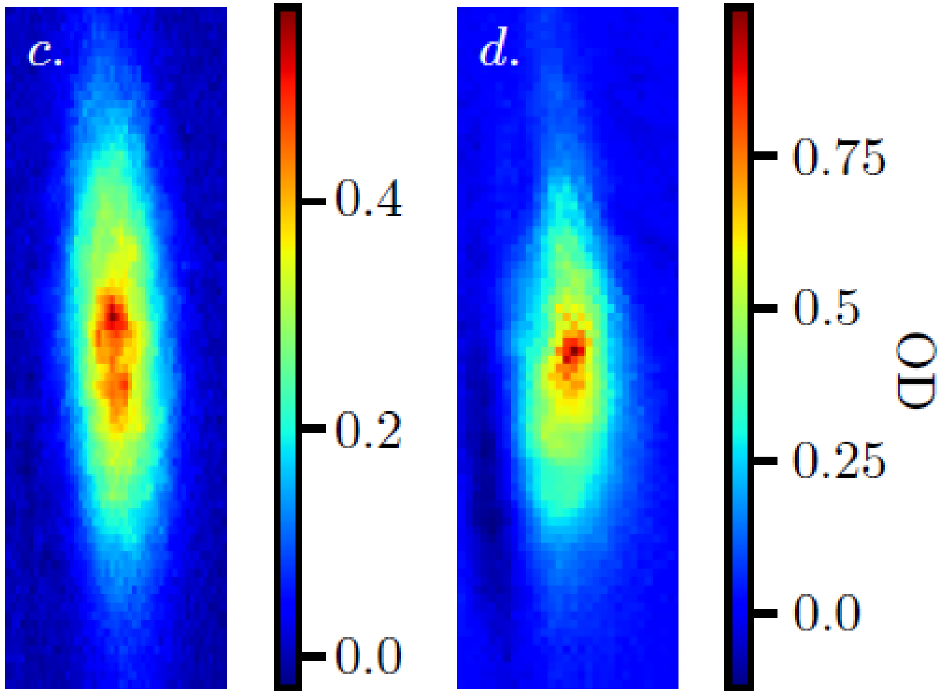


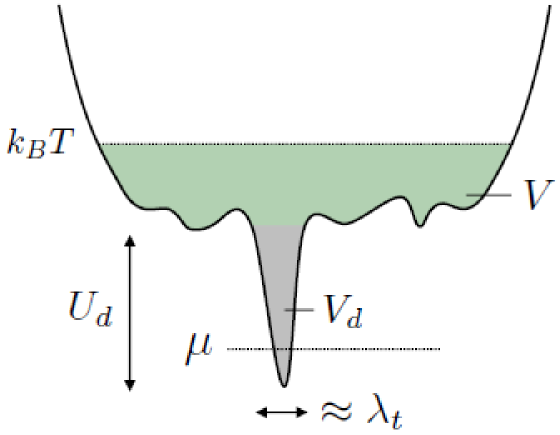
D. Stamper-Kurn, H.-J. Miesner, A. Chikkatur, S. Inouye, J. Stenger, and W. Ketterle, Reversible formation of a Bose-Einstein condensate, Phys. Rev. Lett. 81, 2194 (1998).



- BEC not observed for aligned beam
- Only observed for ~3μm size waists
- N=2500 atoms, only with Machine Learning

BEC in corrugated potential





Fraction of condensate atoms disappears during 100 μs time of flight, but is stable in trap

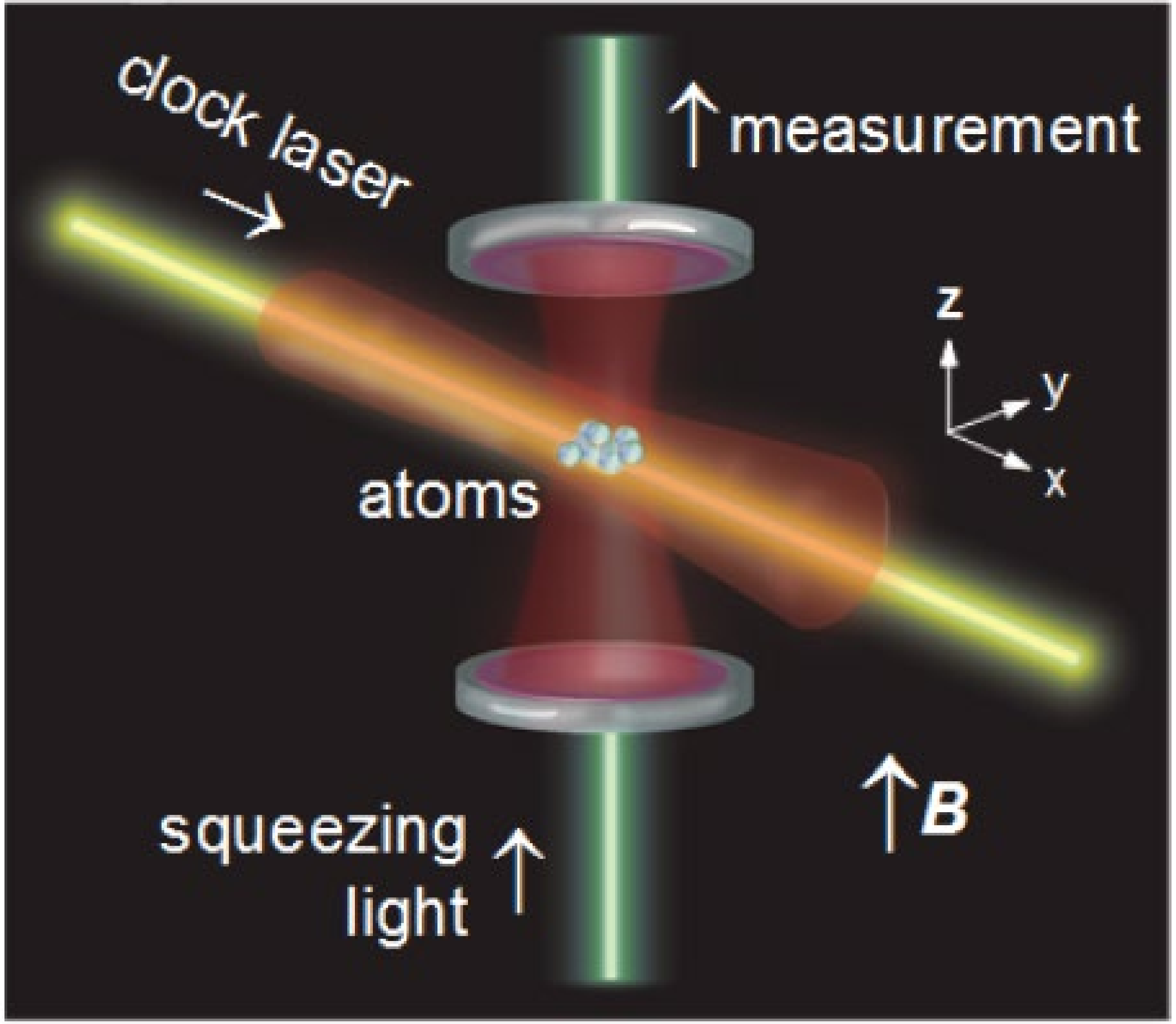
Left: Spatial light modulator creating speckle pattern in trapping light
Right: Two traps with 2 μm waist separated by 3.5 μm
No BEC in single not clipped trap

Machine learning improves quality of life

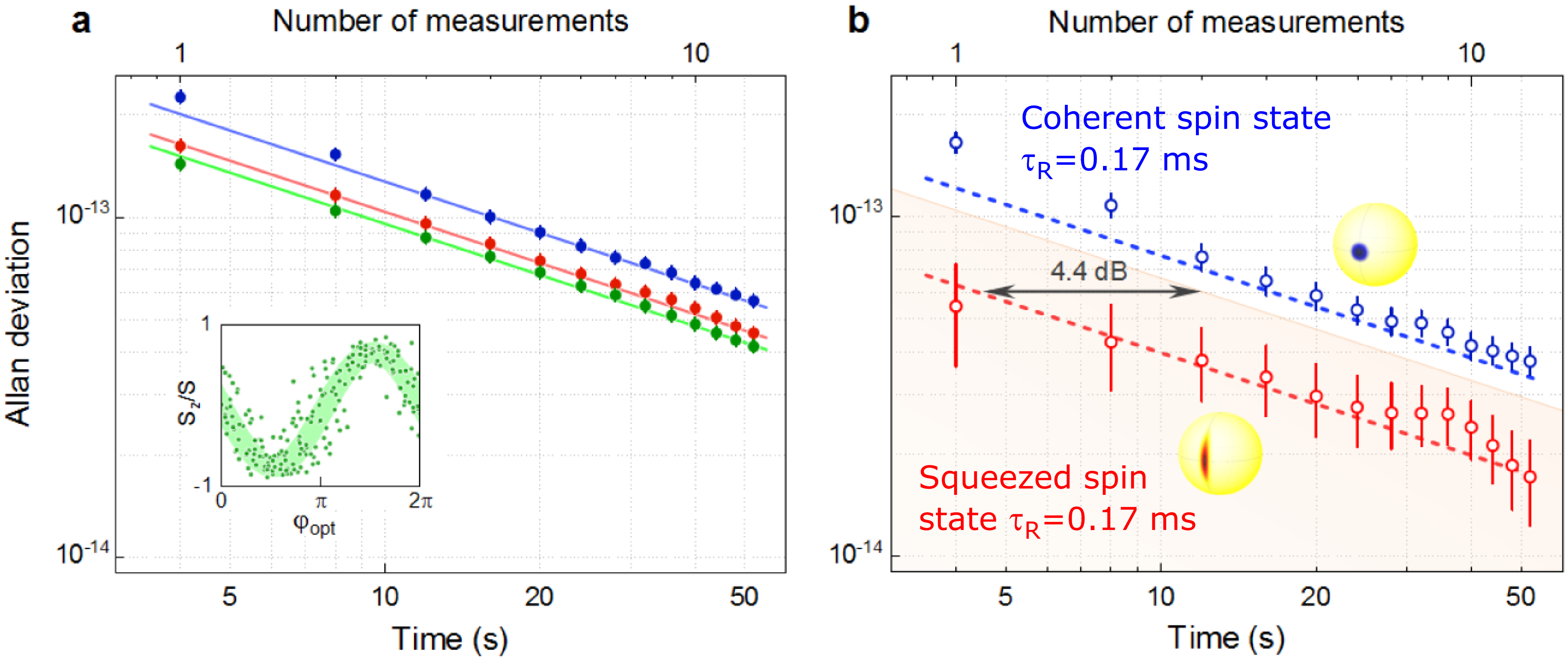
- Machine learning as a powerful technique to optimize complex experimental sequences with nonlinear dynamics
- Process can deal with unknown noise or imperfections
- Challenge and opportunity: physical interpretation of optimized sequences to develop new understanding

Entanglement on optical clock transition and time-reversal quantum metrology

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



Allan deviation of squeezed optical clock



Right: use of squeezed state reduces averaging time by factor 2.8 over the Standard Quantum Limit

Entanglement on an Optical Atomic-Clock Transition. E. Pedrozo-Penafiel, S. Colombo, C. Shu, A. Adiyatullin, Z. Li, E. Mendez, B. Braverman, A. Kawasaki, D. Akamatsu, Y. Xiao, and V. Vuletić, Nature **588**, 414–418 (2020).

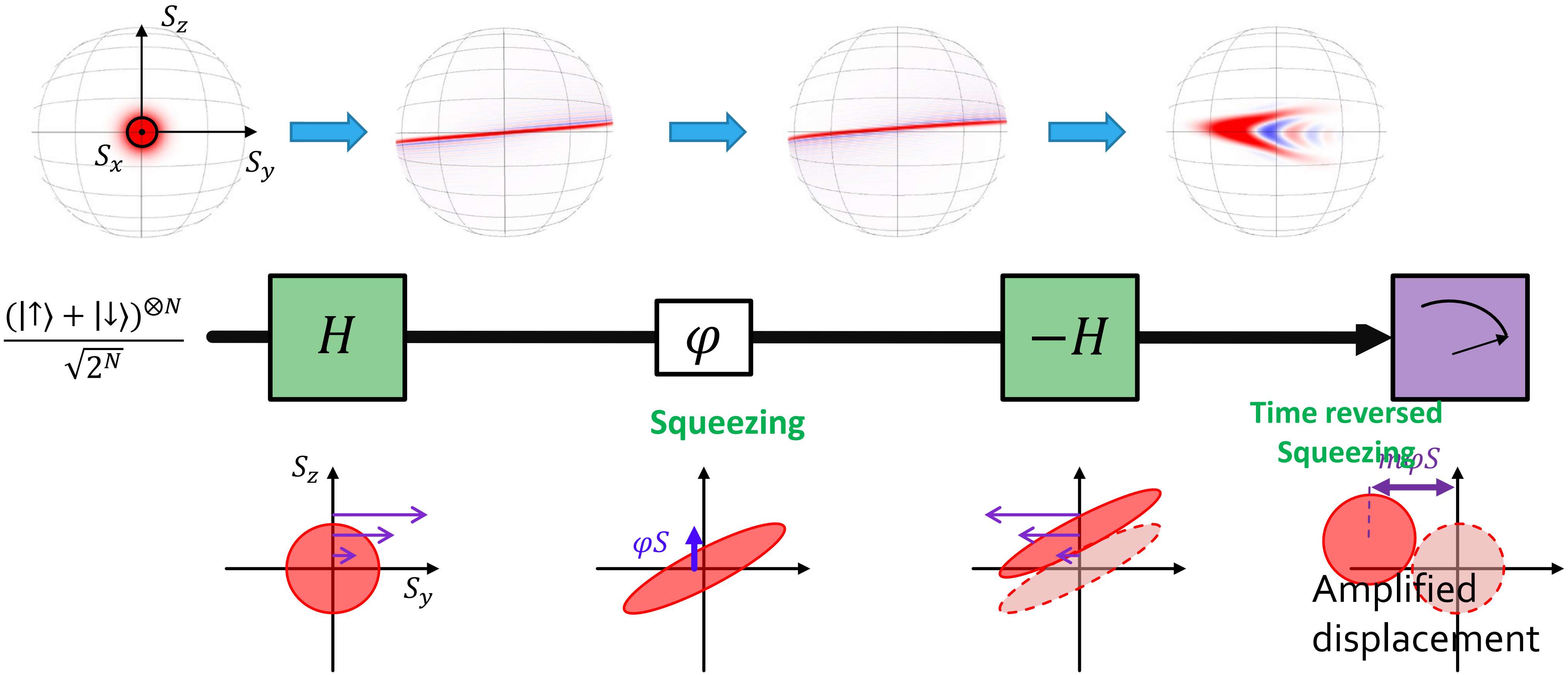
Spin squeezing performance

- Spin squeezing for not very large atom numbers limited by detection rather than by the ability to entangle the atoms via the cavity

Time-reversal based quantum metrology

(Signal amplification by time-reversed interaction, SATIN)

Time-reversal via negative Hamiltonian



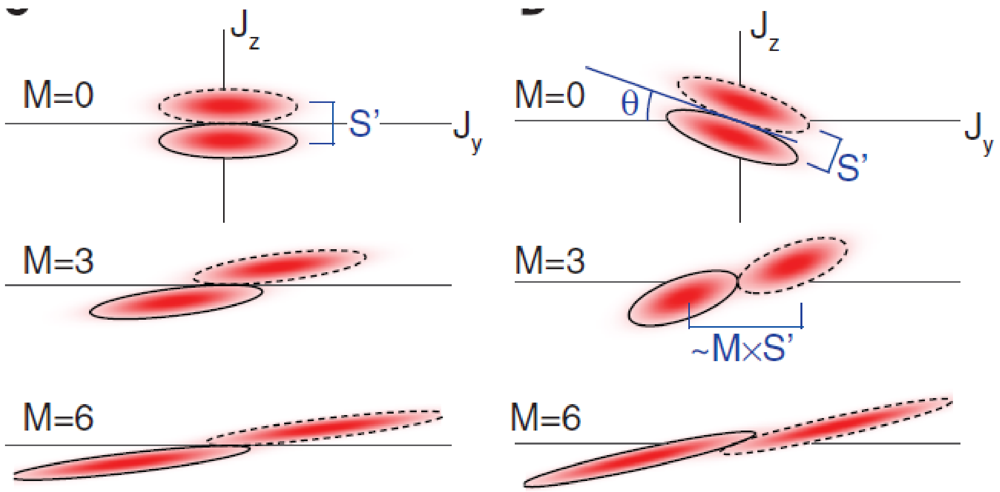
Squeezing

Time reversed Squeezing

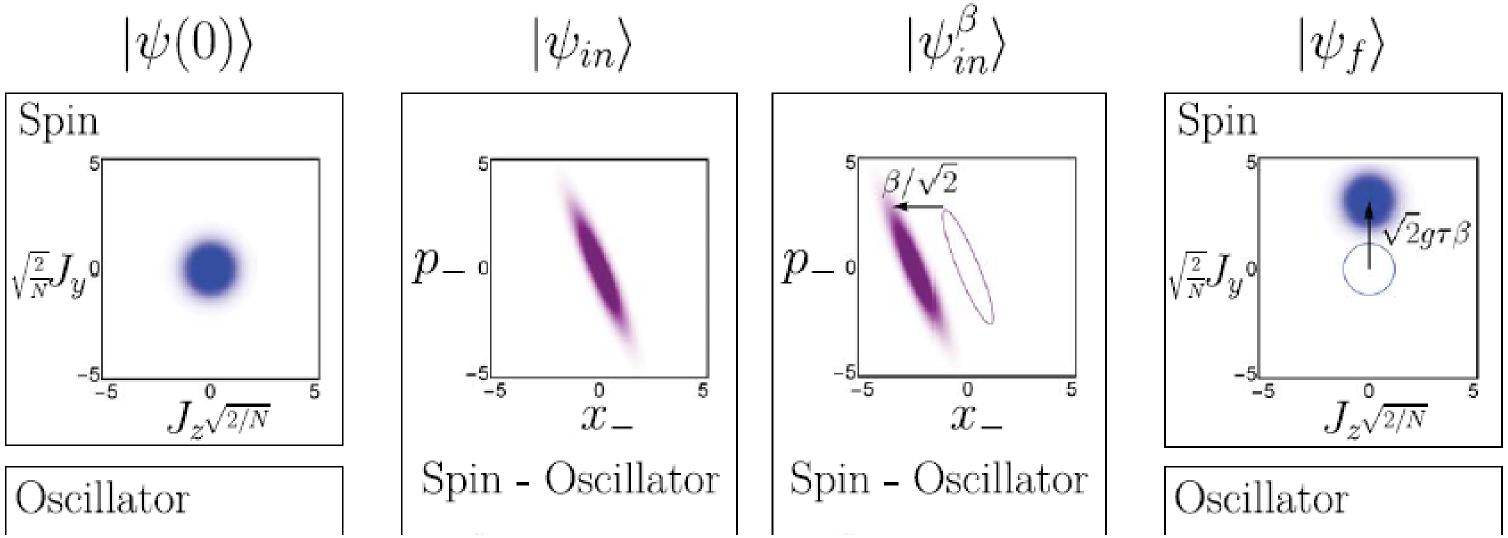
Amplified displacement

E. Davis, G. Bentsen, M. Schleier-Smith, Phys. Rev. Lett. **116**, 053601 (2016).

Related work



Related: O. Hosten, R. Krishnakumar, N. J. Engelsen, and M. A. Kasevich, Science **352**, 1552 (2016); no switching of sign of Hamiltonian, limited to spin squeezed states.



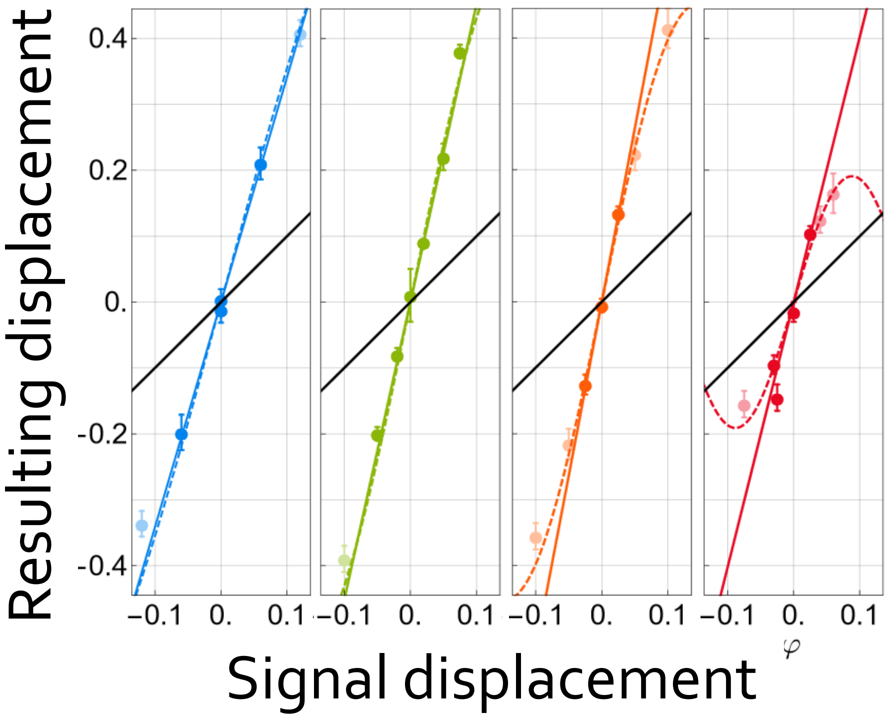
Ion crystal in Penning trap K.A. Gilmore, M. Affolter, R.J. Lewis-Swan, D. Barberena, E. Jordan, A.M. Rey, J.J. Bollinger, Science **373**, 673–678 (2021): Spin squeezing by coupling spin to motional degrees of freedom.

Squeezing around the Bloch sphere

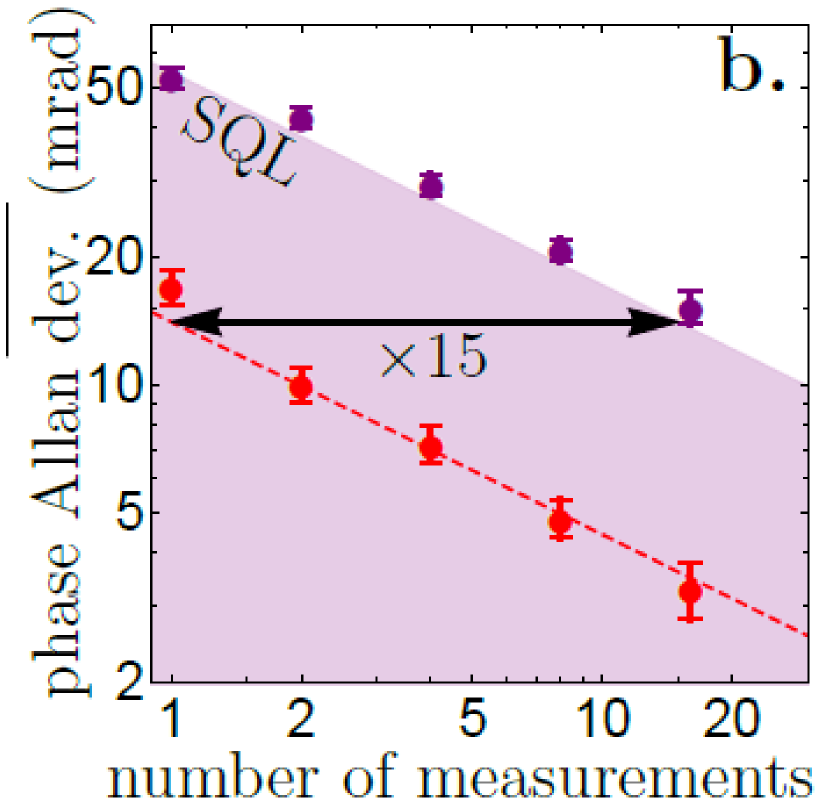
Increasing squeezing time

H

Magnification of phase signal

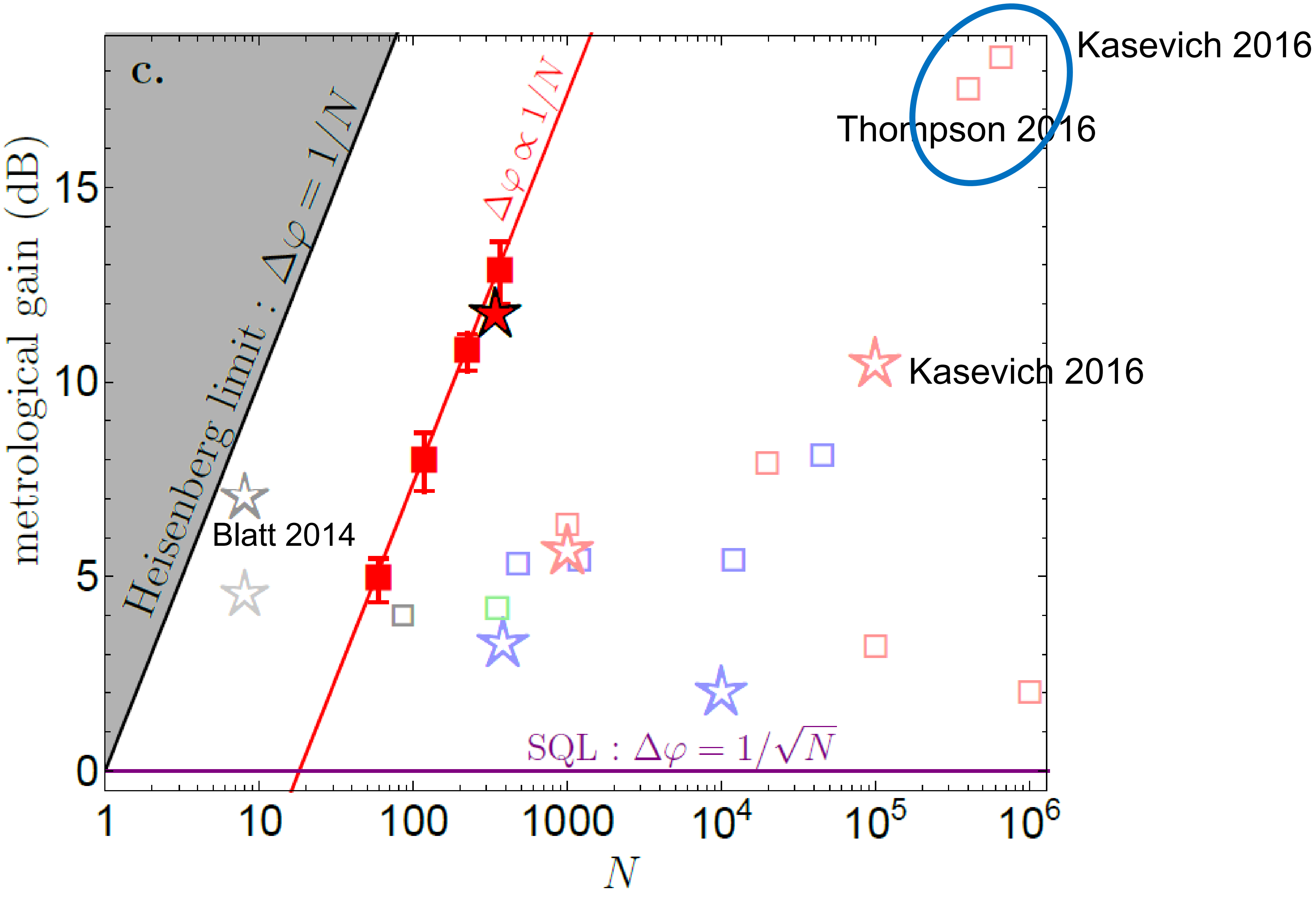


Black line: Standard Quantum Limit



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

Metrological gain and Heisenberg scaling



Stars indicate full interferometer

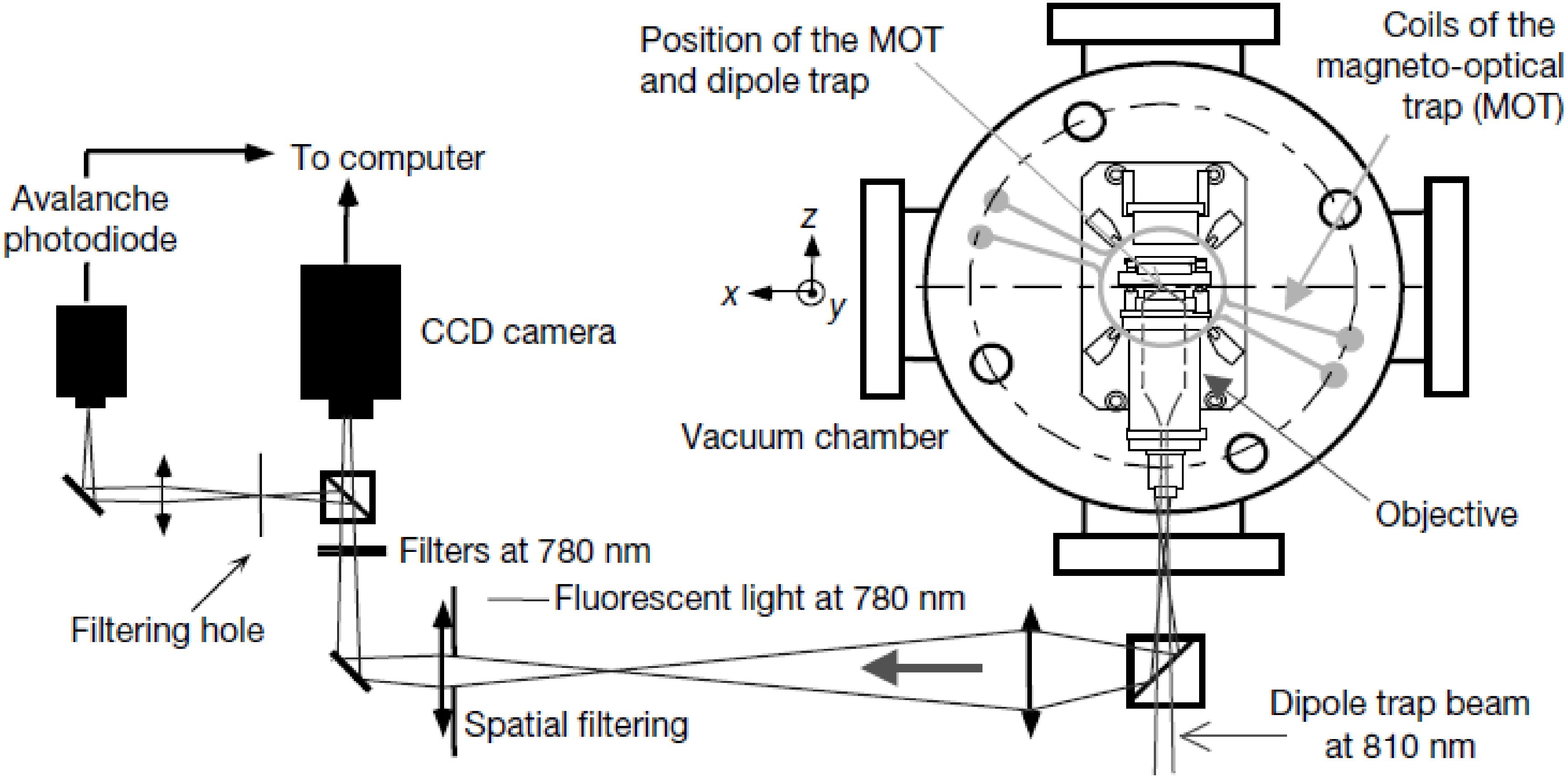
Rydberg quantum gates

H. Levine, A. Keesling, A. Omran, H. Bernien, S. Schwartz, A.S. Zibrov, M. Endres, M. Greiner, V. Vuletić, and M.D. Lukin, Phys. Rev. Lett. **121**, 123603 (2018).

H. Levine, A. Keesling, G. Semeghini, A. Omran, T. T. Wang, S. Ebadi, H. Bernien, M. Greiner, V. Vuletić, H. Pichler, and M. D. Lukin, Phys. Rev. Lett. **123**, 170503 (2019).

S. Evered, D. Bluvstein, M. Kalinowski, S. Ebadi, T. Manowitz, H. Zhou, S.H. Li, A.A. Geim, T. T. Wang, N. Maskara, H. Levine, G. Semeghini, M. Greiner, V. Vuletić, and M.D. Lukin, arXiv:2304.05420

Trapping a single atom in a strongly focused laser beam (optical tweezer)

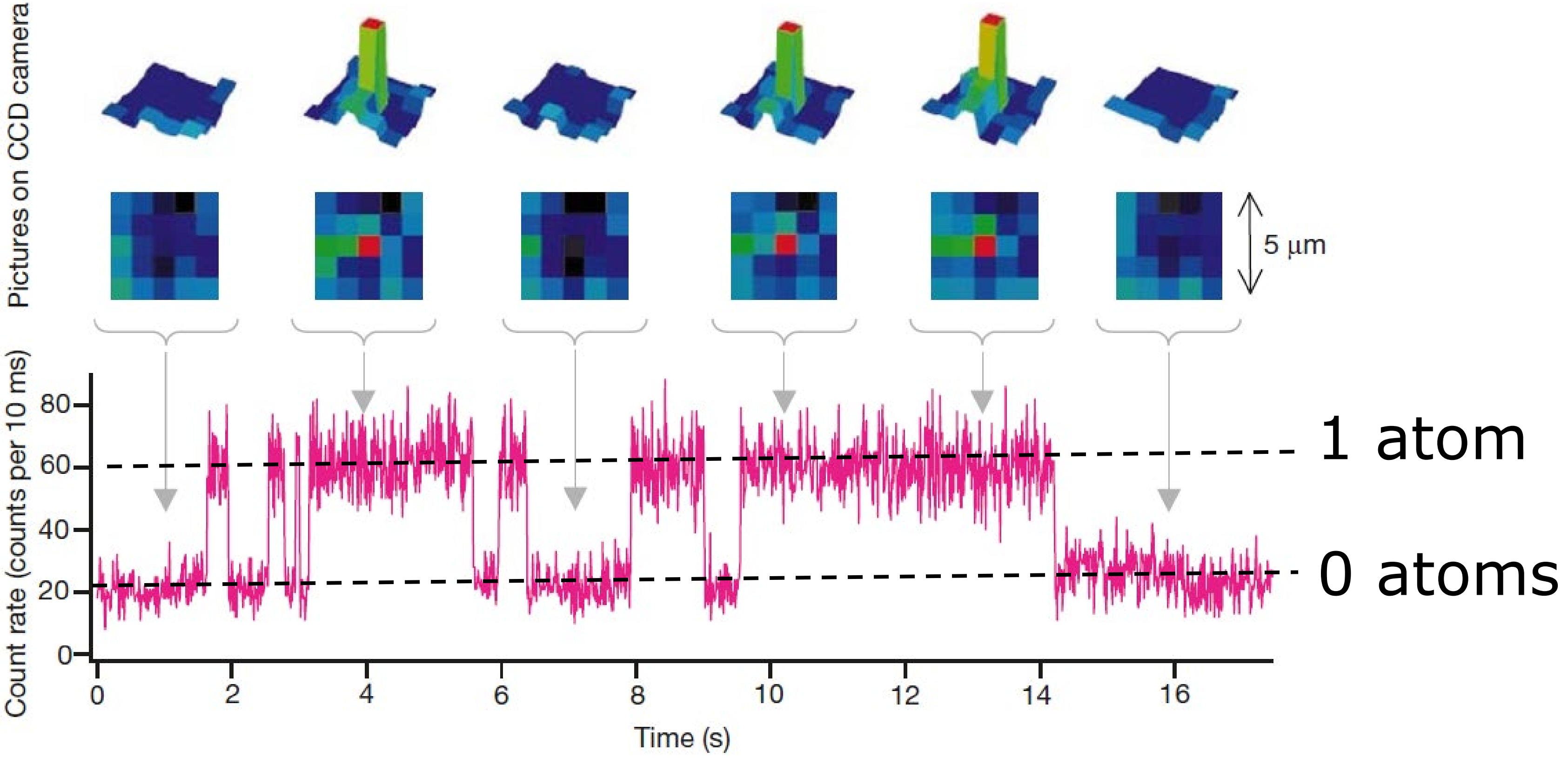


N. Schlosser, G. Reymond, I. Protsenko, P. Grangier, Nature **411**, 1024 (2001)

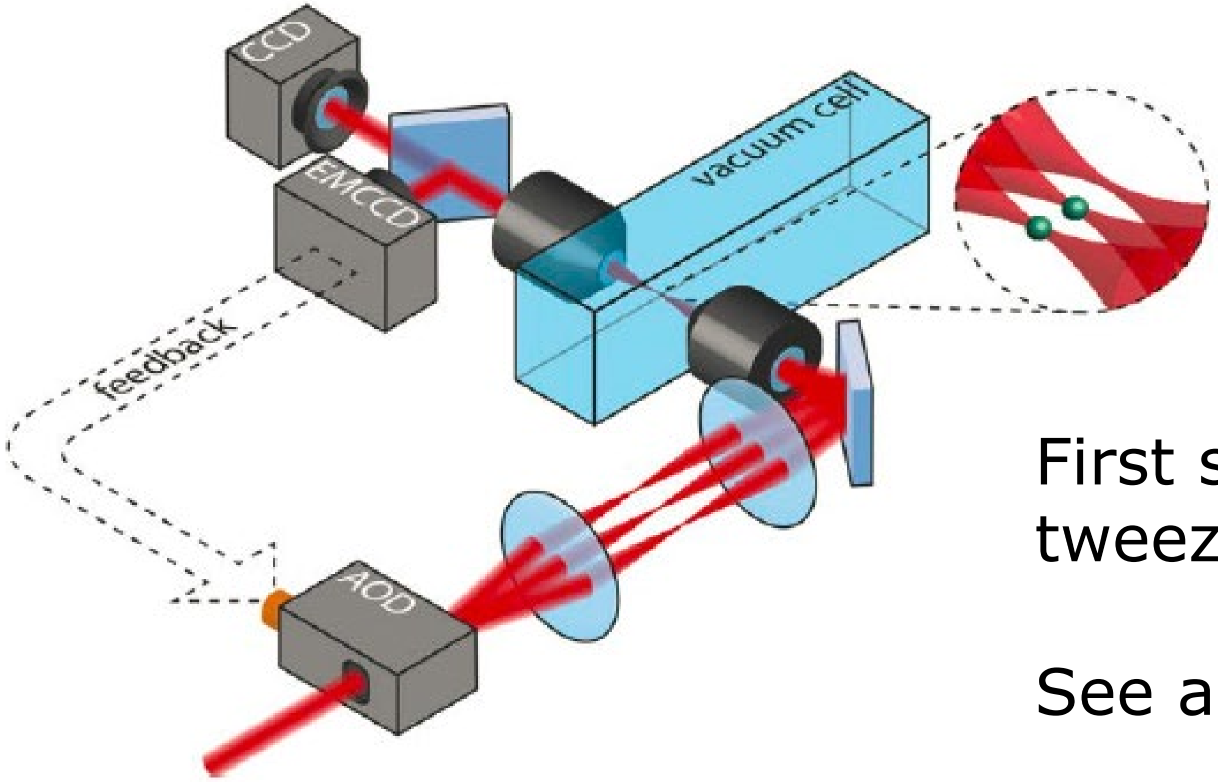
Trapping single atoms

- Single neutral atoms can be trapped and imaged in focused laser beams

N. Schlosser, G. Reymond, I. Protsenko, P. Grangier, Nature **411**, 1024 (2001).



Trapping many single atoms deterministically



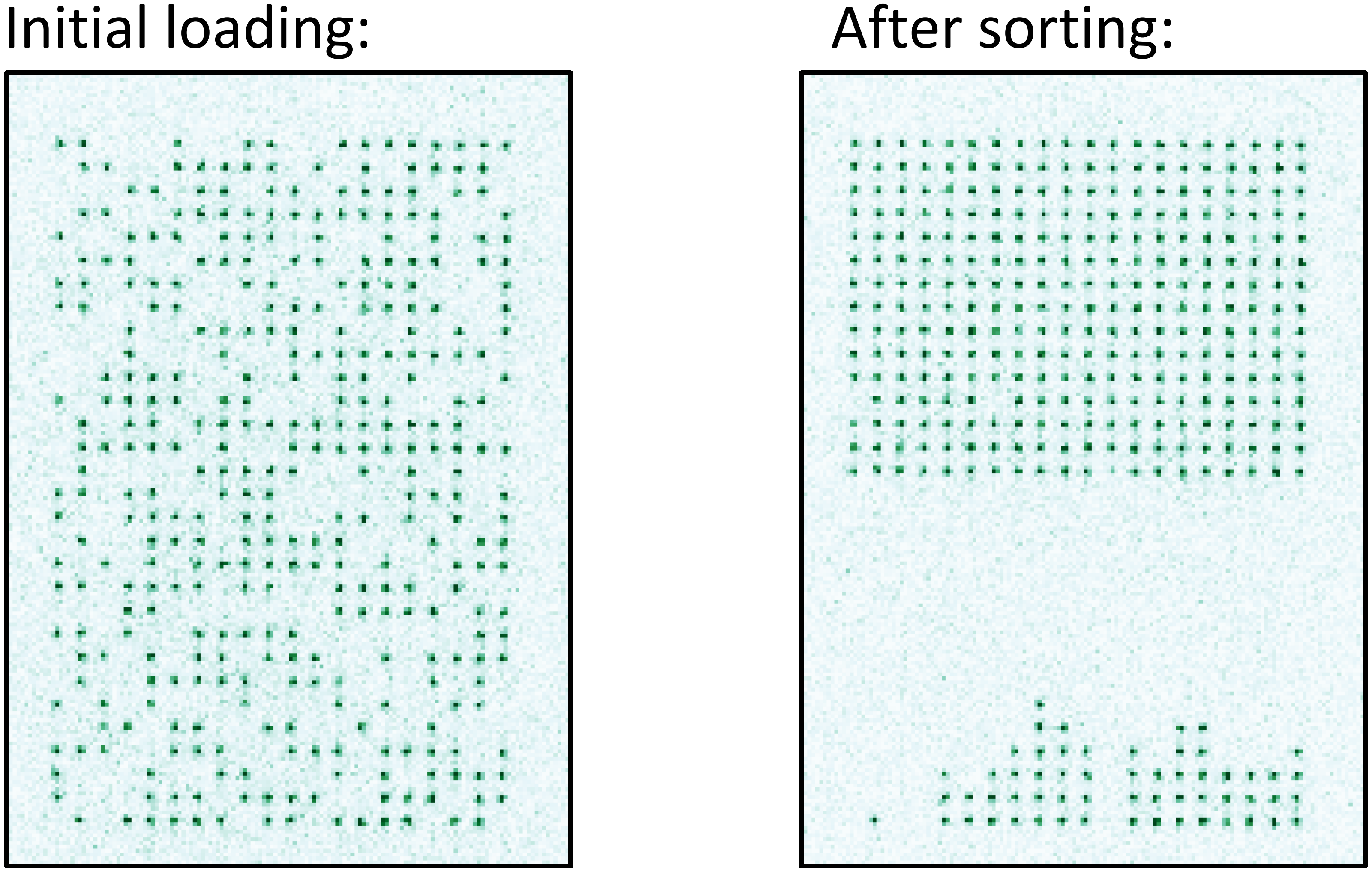
First single-atom optical tweezer: P. Grangier

See also: A. Browaeys work

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).

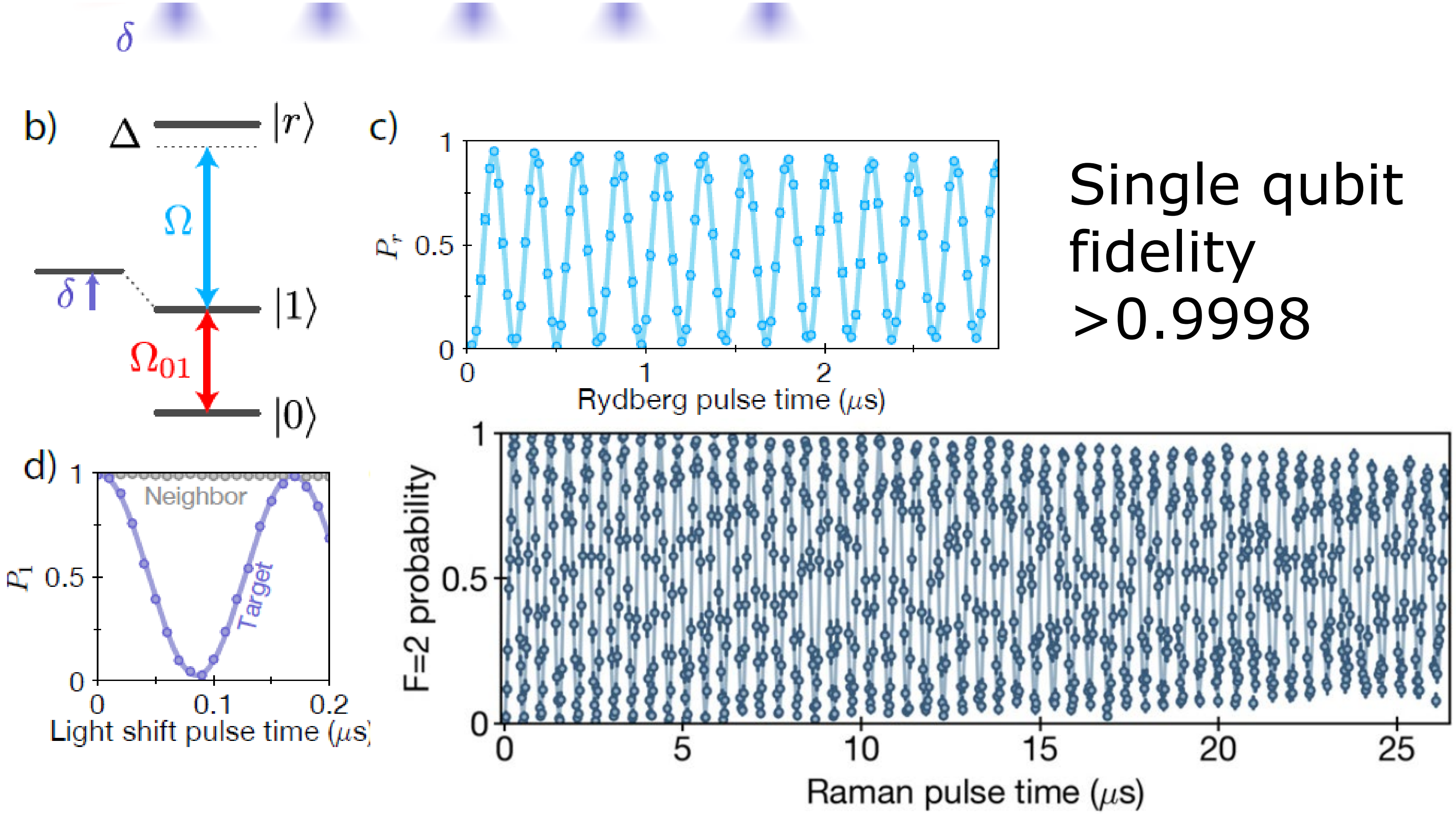
Sorting 300 atoms in two dimensions


Initial loading:
After sorting:

> 98% filling fraction

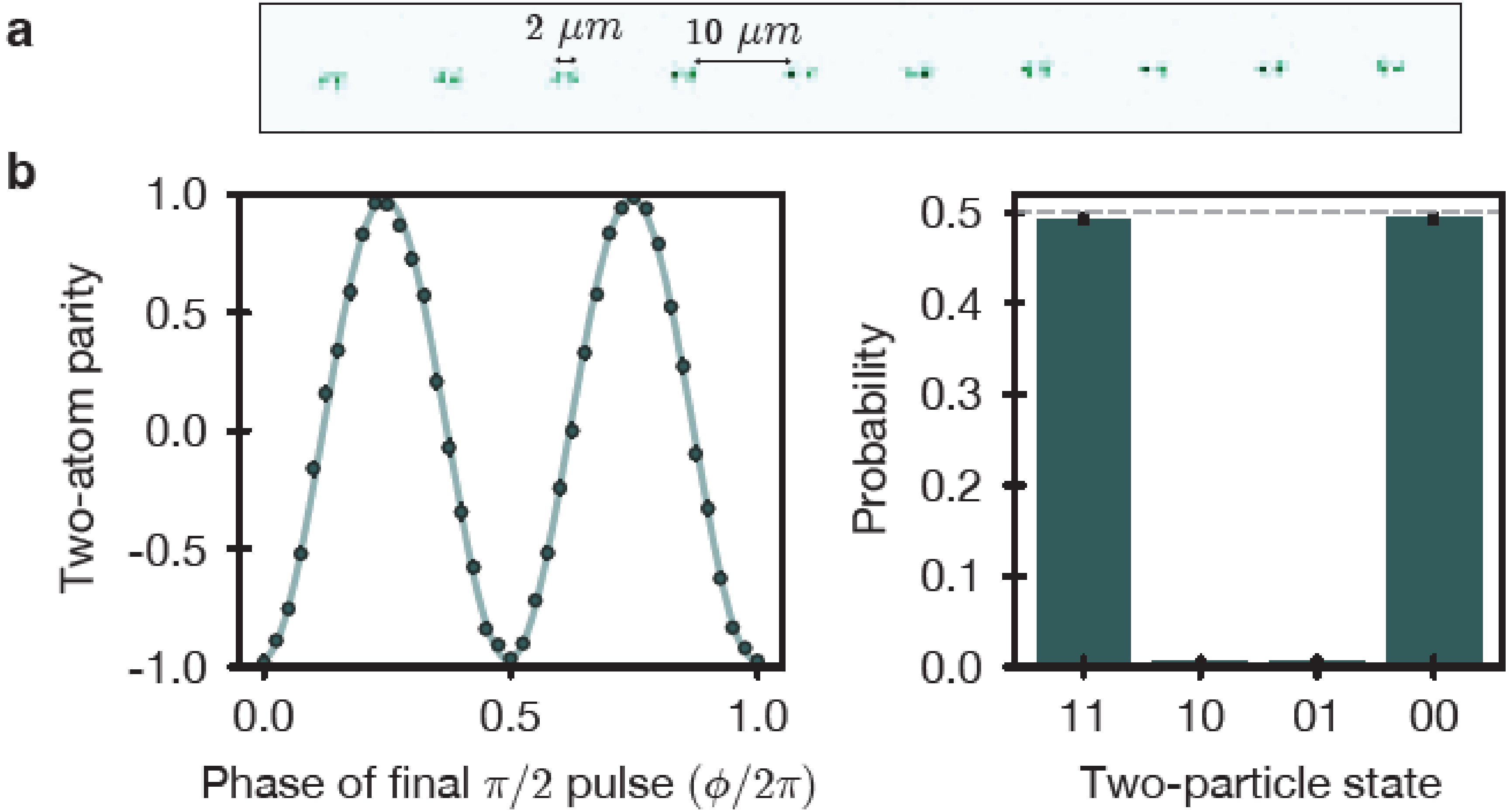
Characterization of single-qubit gate

Dispersive optical systems for scalable Raman driving of hyperfine qubits. H. Levine, D. Bluvstein, A. Keesling, T. T. Wang, S. Ebadi, G. Semeghini, A. Omran, M. Greiner, V. Vuletić, and M.D. Lukin, Phys. Rev. A **105**, 032618 (2022);



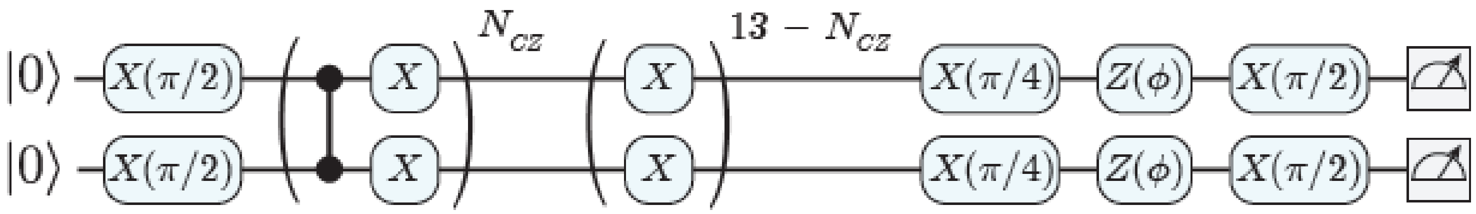
Single qubit fidelity >0.9998

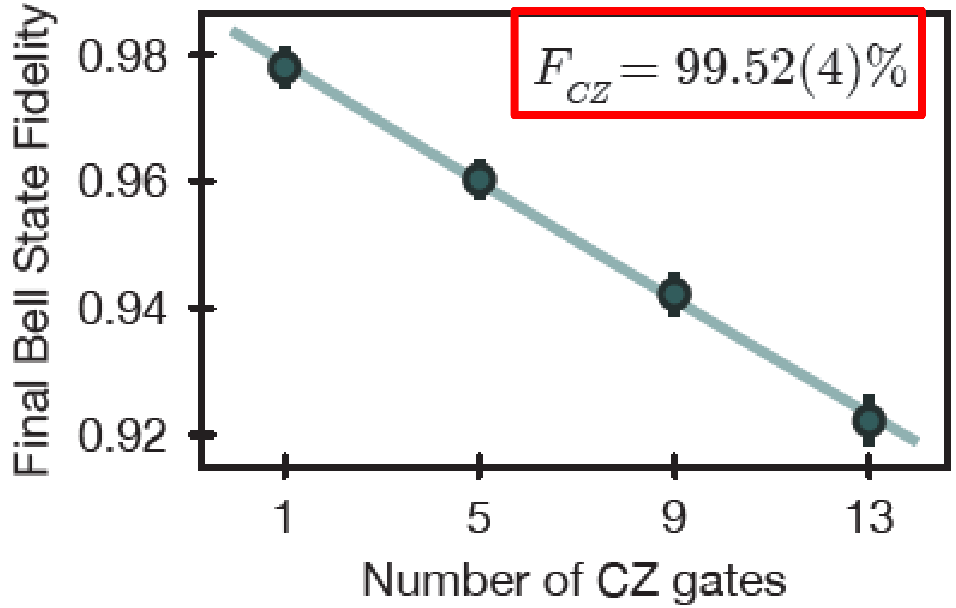
Two-qubit gates



Parallel two-qubit gates on 10 pairs of atoms

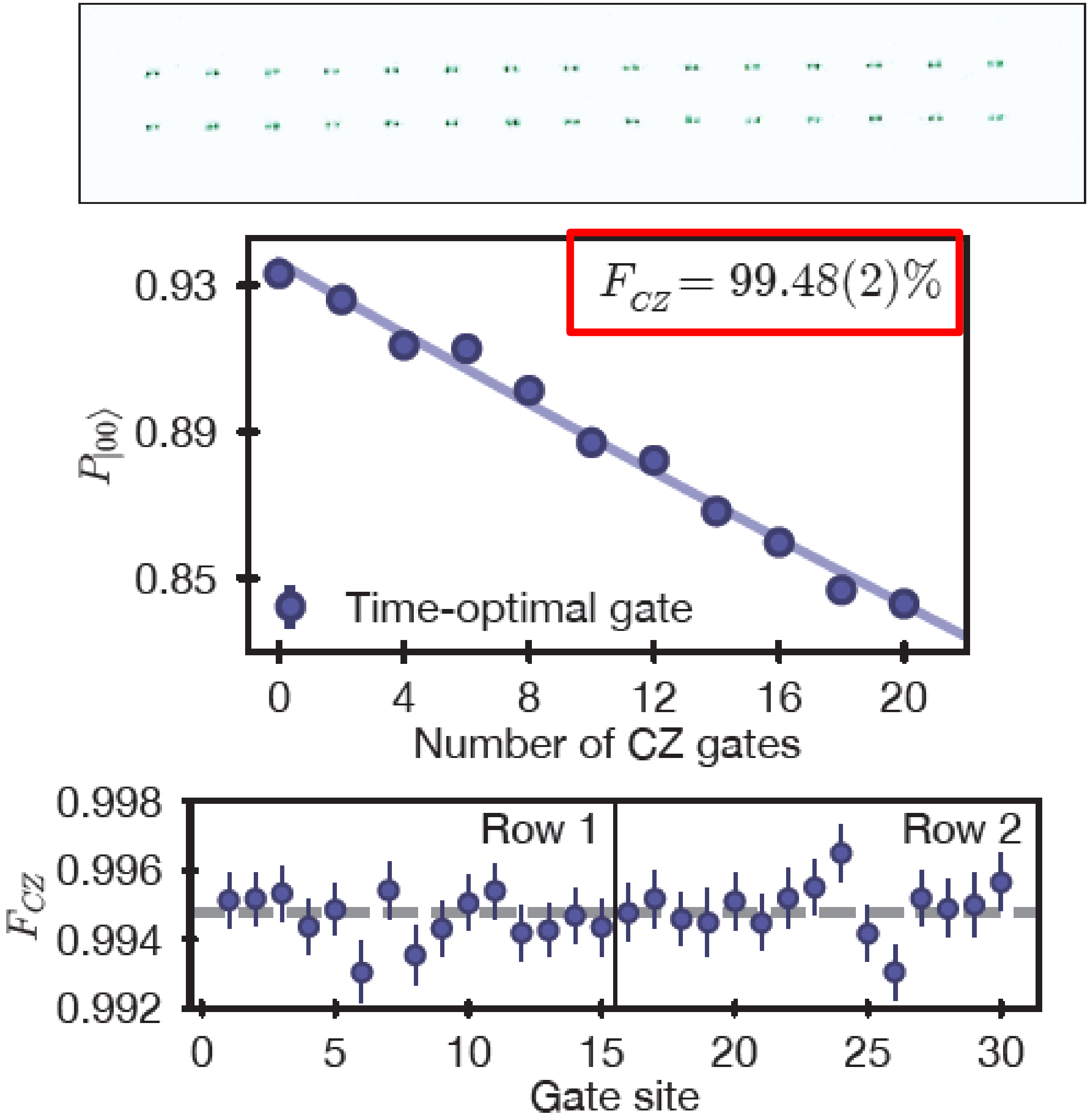
Two-qubit gate fidelity





Parallel two-qubit gates on 10 pairs of atoms.

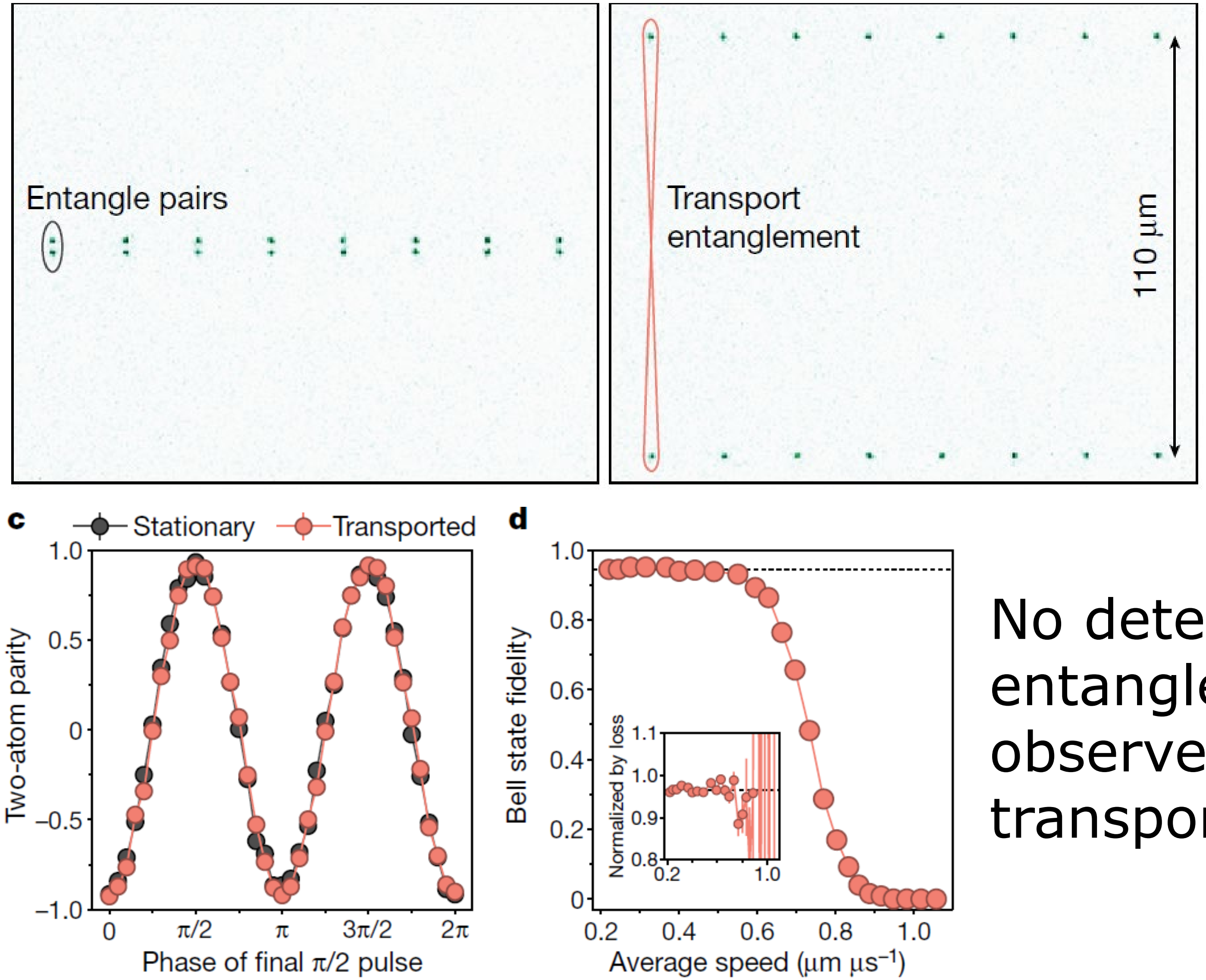
Two-qubit gate fidelity



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

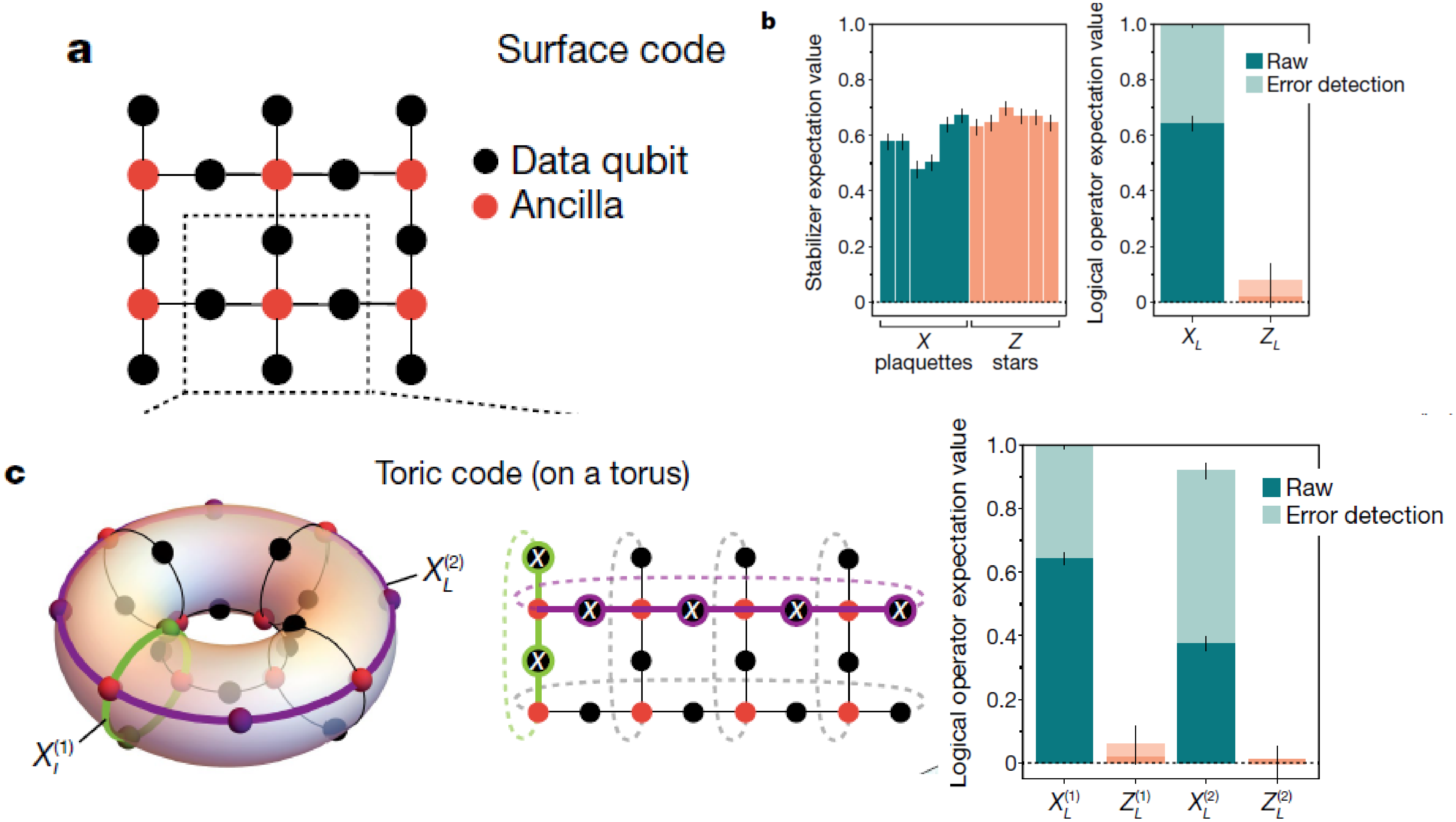
Transporting entangled states
Towards quantum error correction

Transporting entanglement



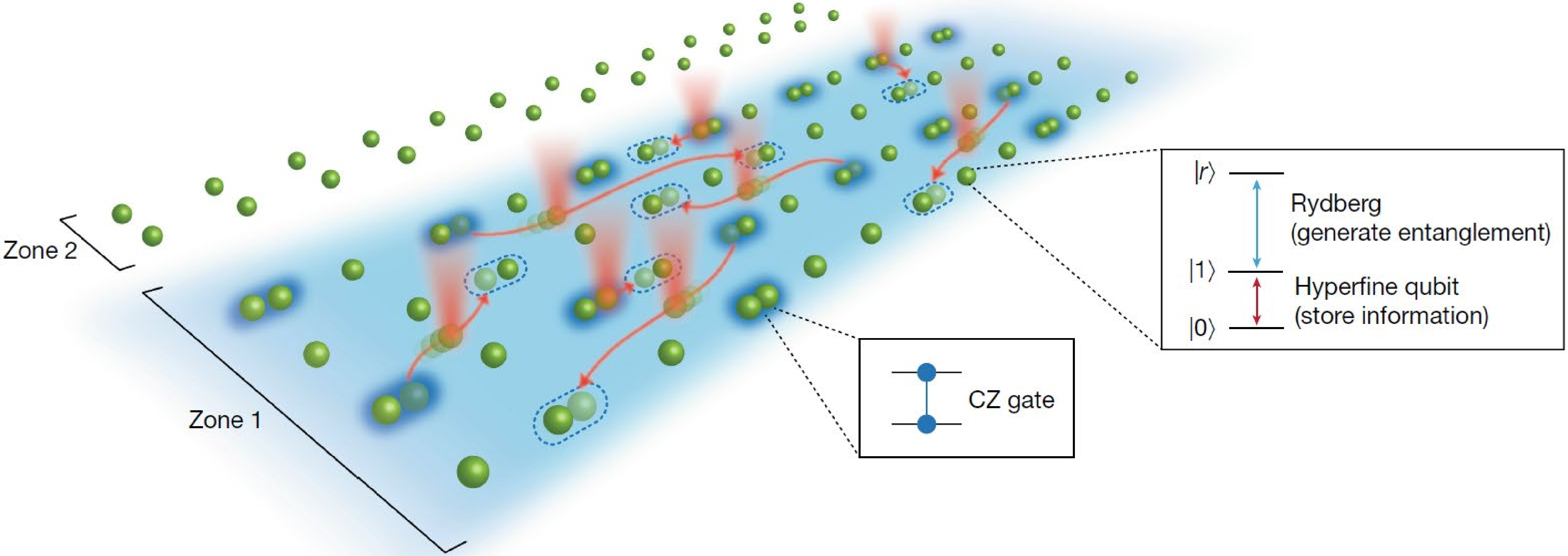
No deterioration in entanglement observed for transported Bell pair

Syndrome measurements for quantum error correction codes



Implementation of Toric code

Quantum processor architecture



A quantum computing device with atoms …

Richard Feynman

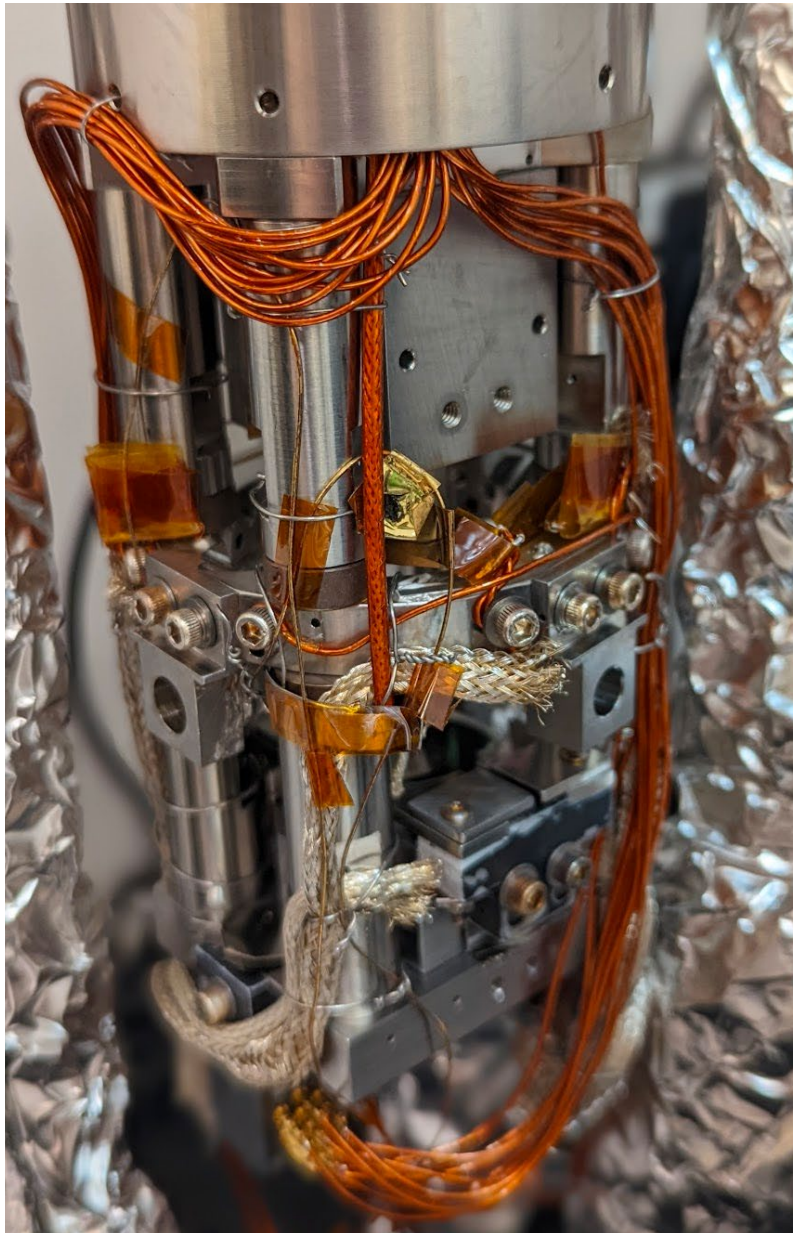
"Now, we can, in principle make a computing device in which the numbers are represented by a row of atoms with each atom in either of the two states. That's our input. [Then the] Hamiltonian starts.. The ones move around, the zeros move around. Finally, .. a particular bunch of atoms.. represents the answer. Nothing could be made smaller.. Nothing could be more elegant."*

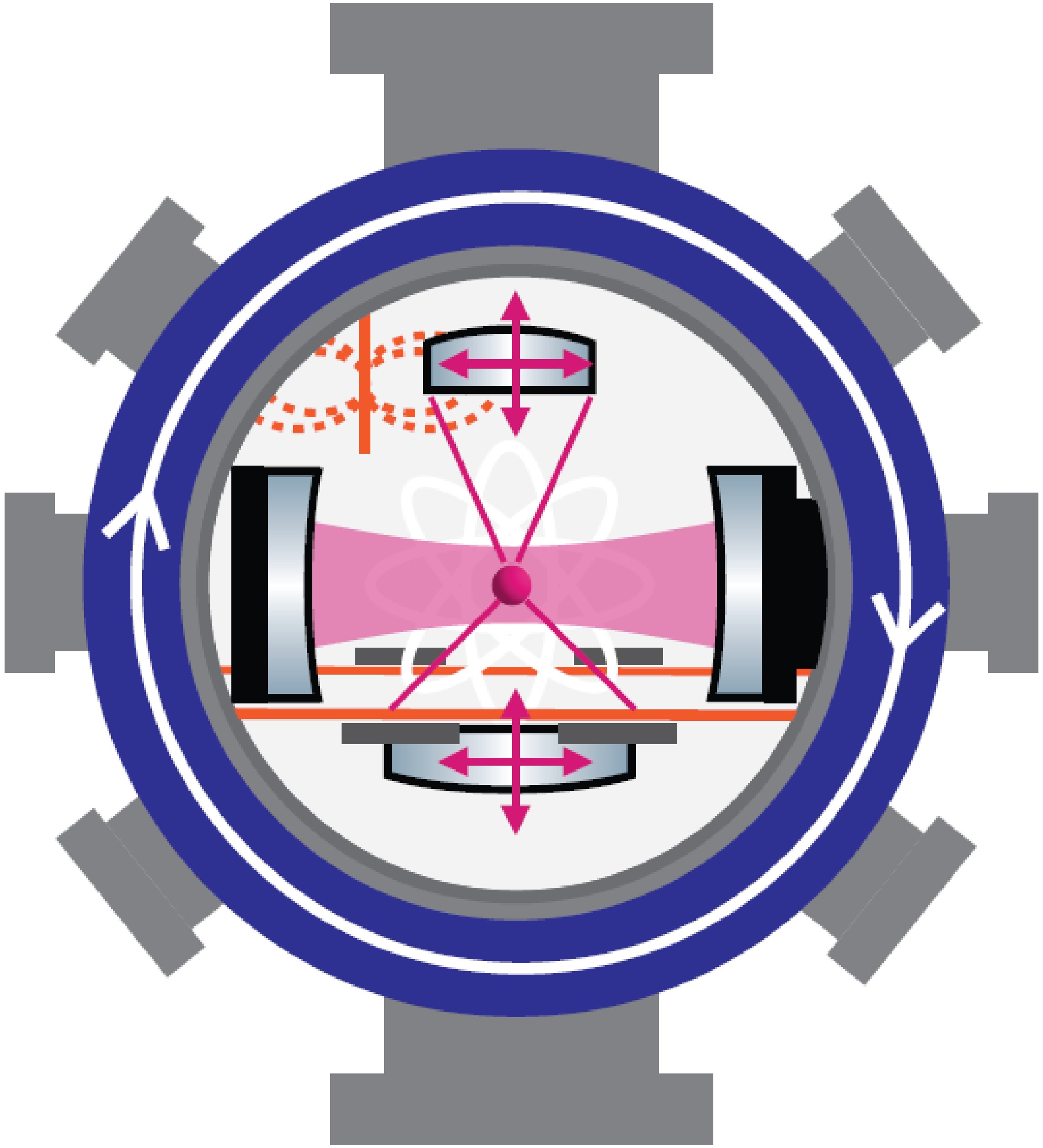
* R. P. Feynman, 1983, Tiny Computers Obeying Quantum Mechanical Laws. Talk delivered at Los Alamos National Laboratory.

Summary and Outlook

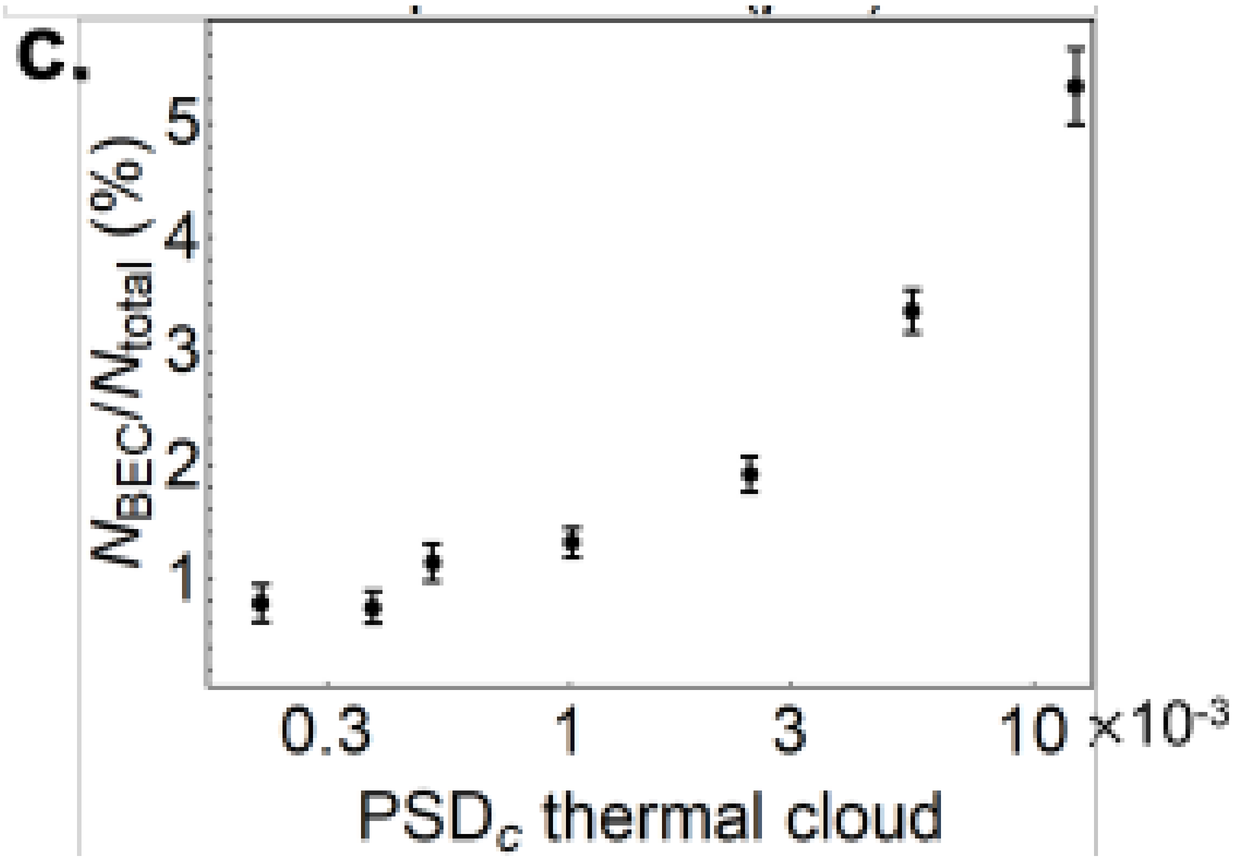
- There are still surprises in laser cooling
- Large-scale entanglement, both for collective spin states, and individually controlled spins, is now experimentally possible;
- Path towards large quantum simulators:
  - 10,000 to 100,000 physical qubits within reach in next 1-2 years
  - Quantum simulators with be useful for science
  - Quantum error corrections seems feasible
  - Are there practical computing problems beyond scientific applications that we can solve?

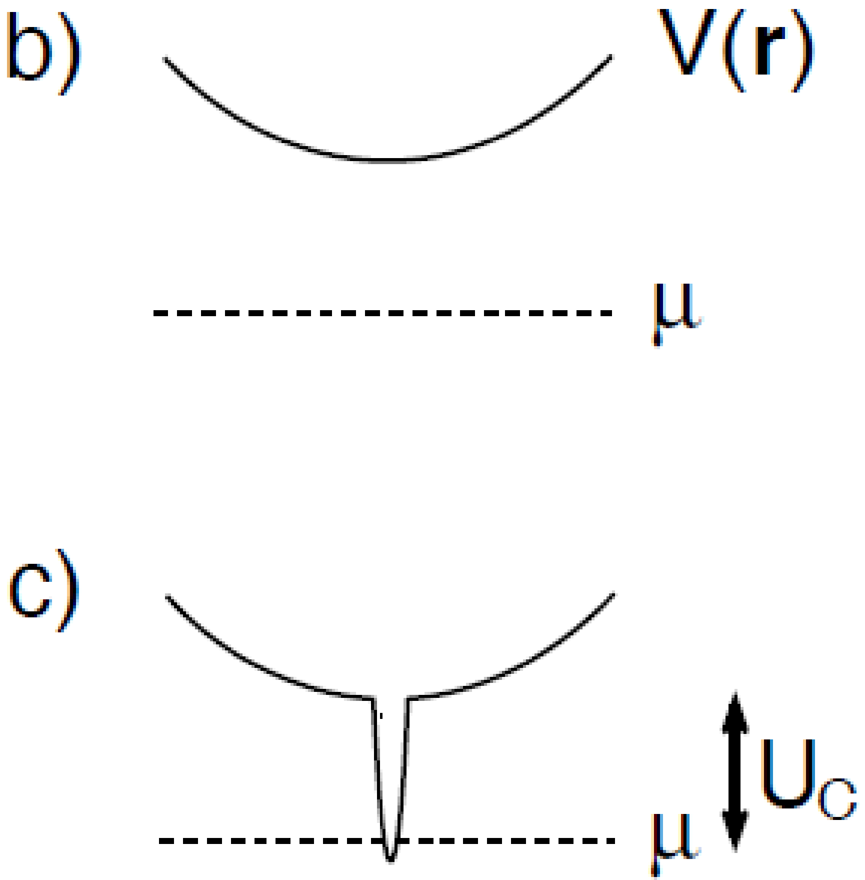
Cavity setup



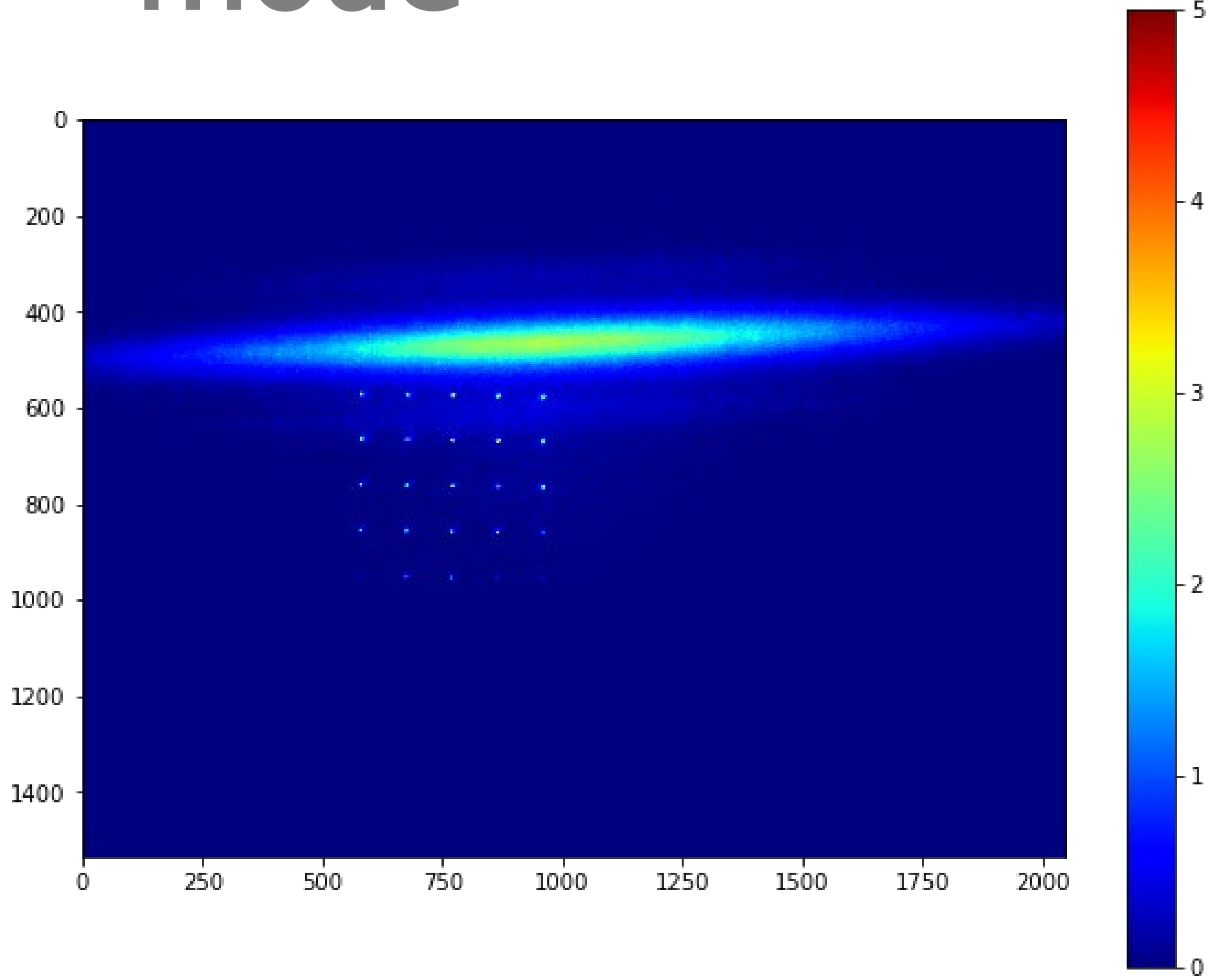


Small BEC fraction

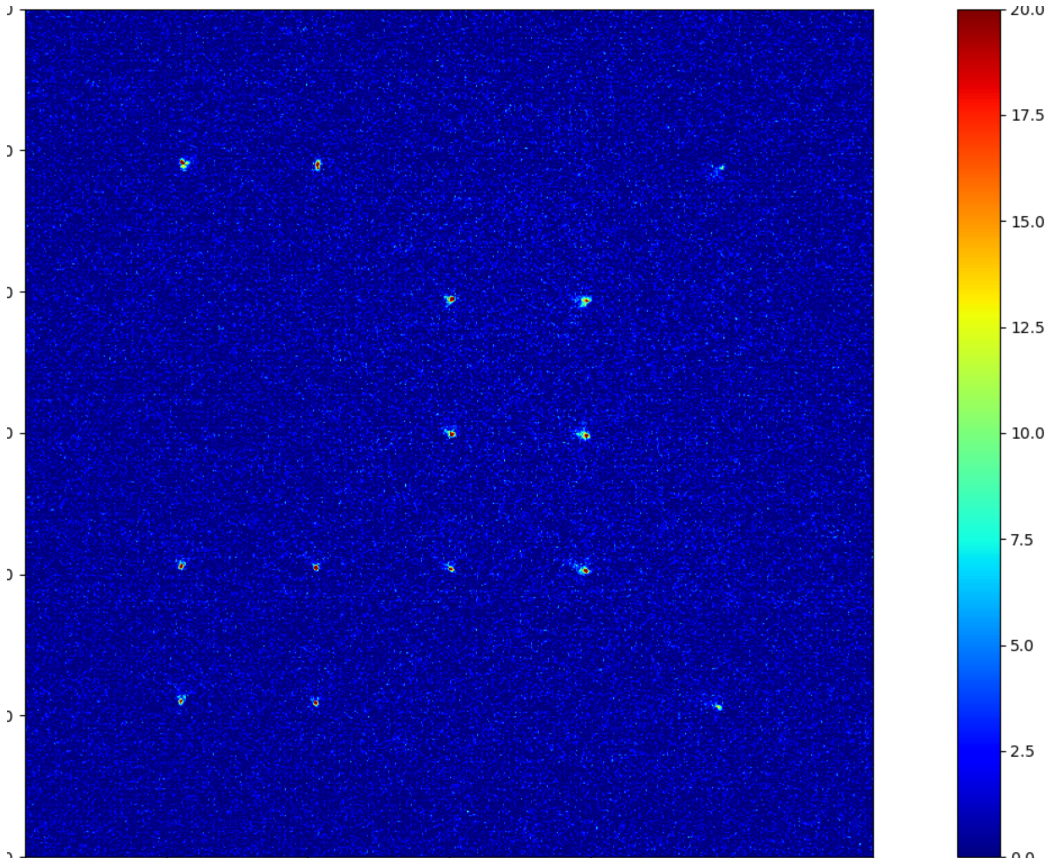




Single trapped atoms and cavity mode



average



Single shot

Summary

- Cavities provide an interesting alternative to free-space imaging on cameras (serial, but logarithmic search possible);
- Continuous reloading will likely be required
- It is time to think ahead how to quantum connect locally error corrected modules