Atom-by-atom assembly of defect-free cold atom arrays

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KITP, Oct 27, 2016
Synthetic Quantum Matter

This work: Endres et al. arXiv:1607.03044 (accepted in Science)
See also: Browaeys Group: arXiv:1607.03042 (accepted in Science)

Outline

1) ‚Synthetic quantum matter‘: Experimental goals and challenges

2) Neutral atom approaches: top-down and bottom-up

3) New approach: bottom-up + measurement and feedback

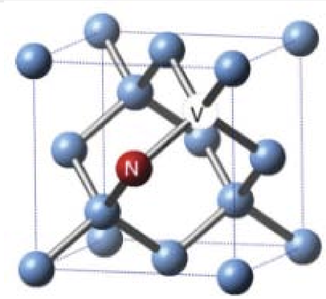
4) Experimental results

5) Current and future work

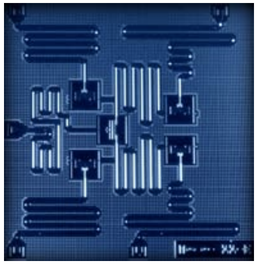
6) Discussion: Did we gain anything?

Systems for studying ‘synthetic quantum matter’

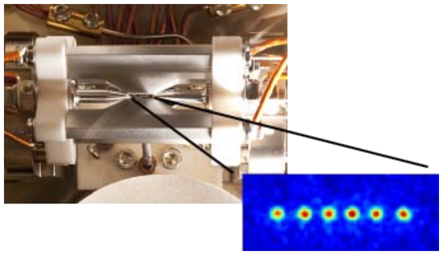
Traditional solid state materials



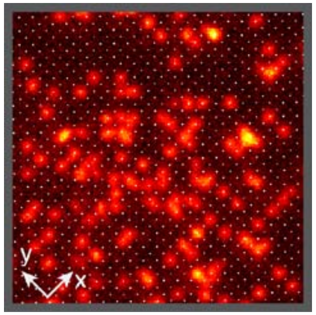
Solid state qubits (SC qubits, NV centers, Majorana wires…)



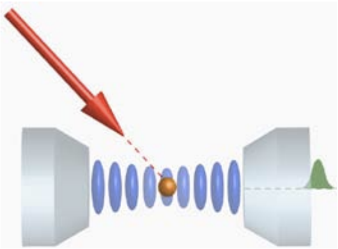
Ion traps



Neutral atoms (optical lattices, Rydberg atoms, …)

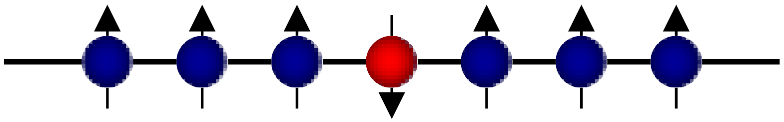


Photonic systems (cavities, nanophotonics,…)

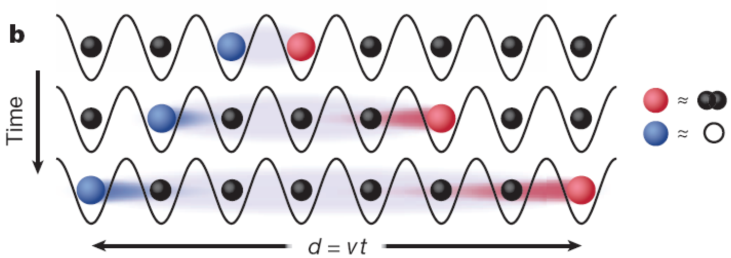


Common protocol

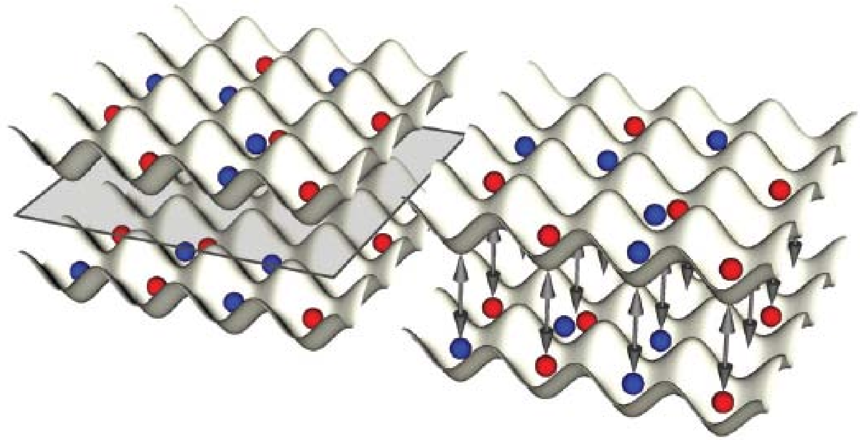
1) Initialization: create a certain quantum state
   - Thermal equilibrium state
   - Pure product state
   - …



2) Evolution: time-evolution under certain H(t) (or L(t))
   - Sequence of gates
   - Adiabatic change of Hamiltonian
   - Quench
   - …

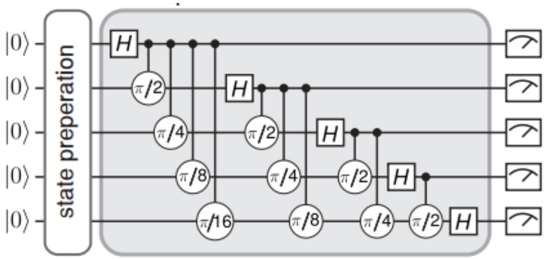


3) Detection: measure some useful quantity
   - Correlation function
   - Entanglement
   - State reconstruction
   - …

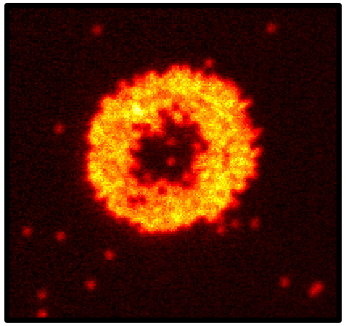


Common goals

1) Build quantum computers + networks



2) Study quantum many-body physics



3) Generate useful quantum states for other tasks, e.g., precision measurement

….

Challenges

1) Scalability: reaching large, homogeneous systems

2) Controllability: control of single particles/spins and interaction terms

3) Engineering of interesting Hamiltonians/Liovillians

4) Low dissipation/dephasing

5) High-fidelity initialization of low entropy states

6) Fast experimental repetition rates

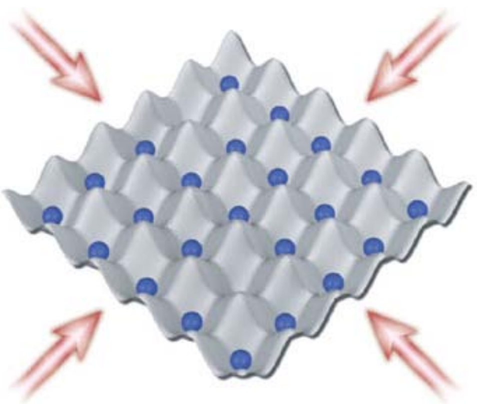
7) Experimental complexity

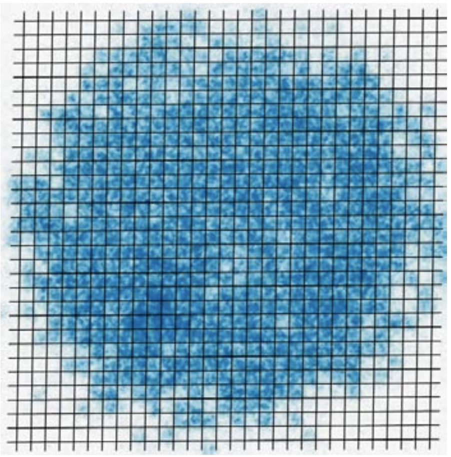
Neutral atom approaches (with single atom control):

1) Top-down: optical lattices
2) Bottom-up: optical tweezers

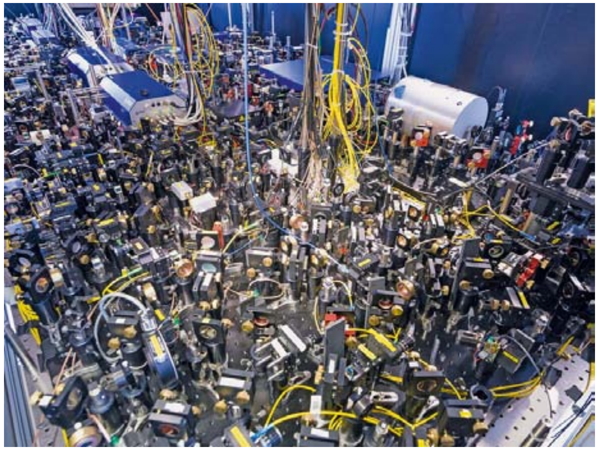
Top-down approach

1. Top-down: Optical lattices





Greiner Group



Bloch Group

Preparation:

1. Start with atoms trapped in a Magneto-Optical Trap (MOT)
2. Evaporative cooling
3. Ramp up lattice
4. Reach Mott insulator state

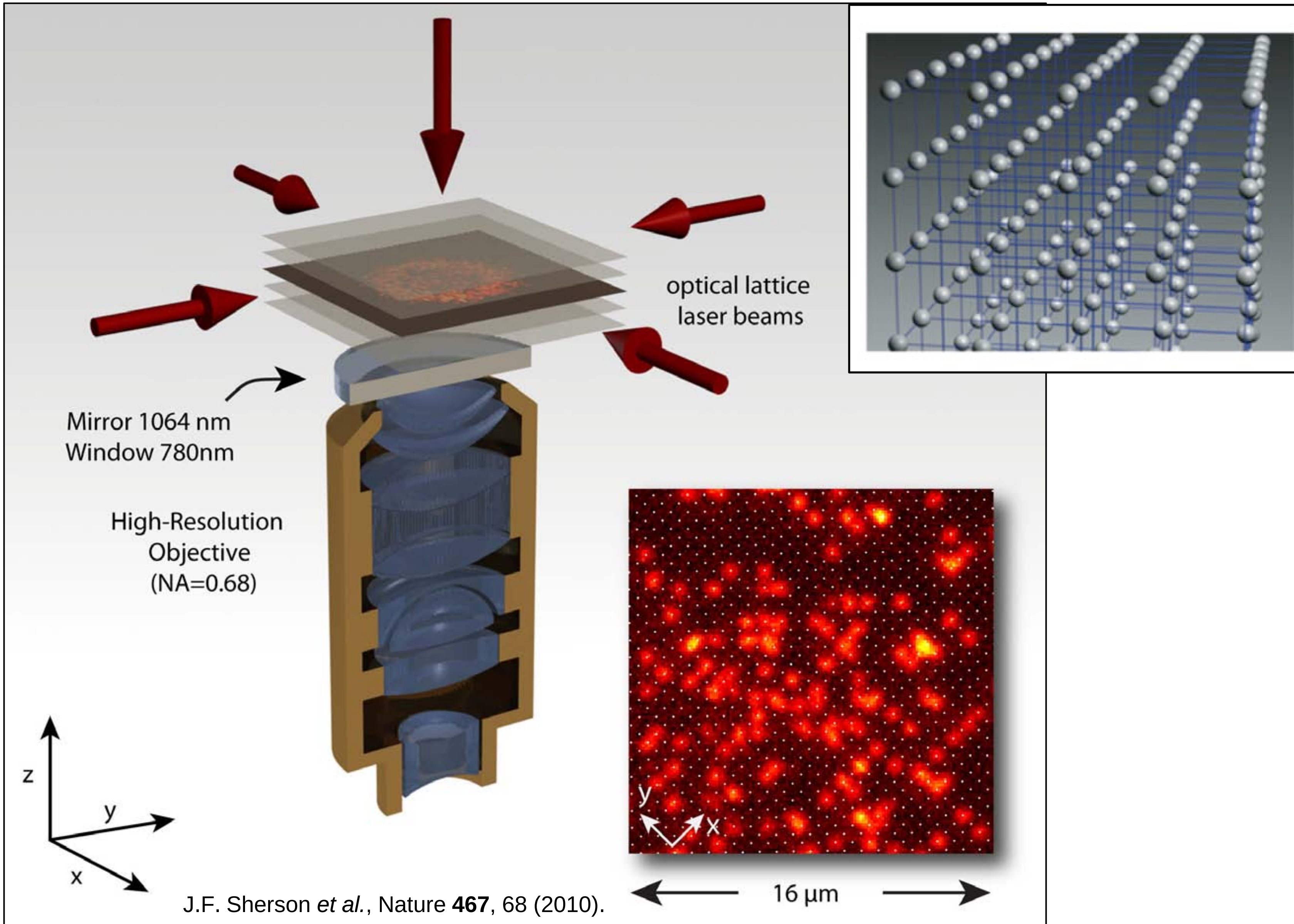
Pros:

- Large numbers of atoms
- Efficient loading

Cons:

- Complex experimental setup
- Long experimental cycle times (~1/2 min)

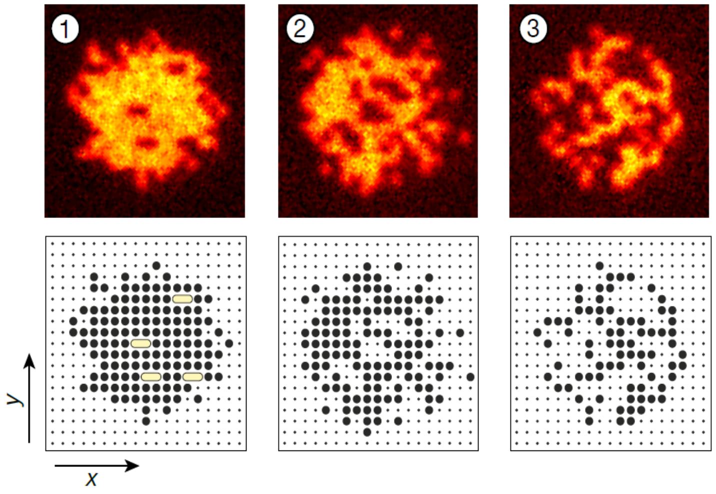
Experimental Setup: quantum microscope

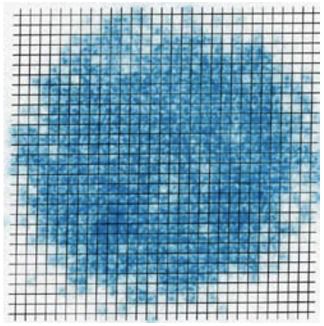


J.F. Sherson *et al.*, Nature **467**, 68 (2010).

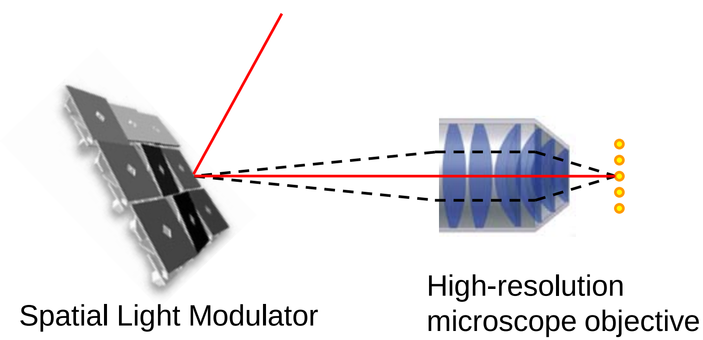
Quantum microscopes

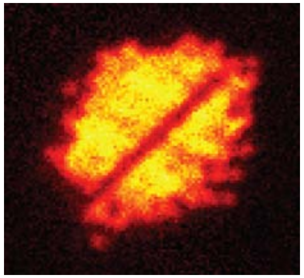
Imaging:

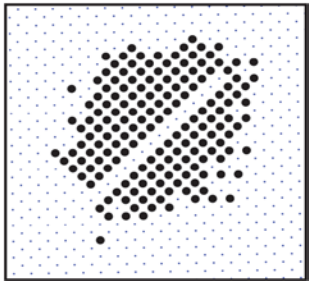




Control:





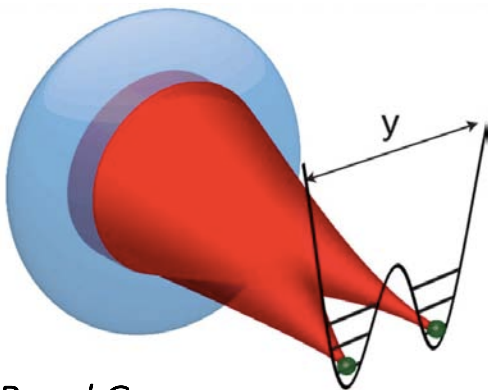


Spin-control is not fully developed

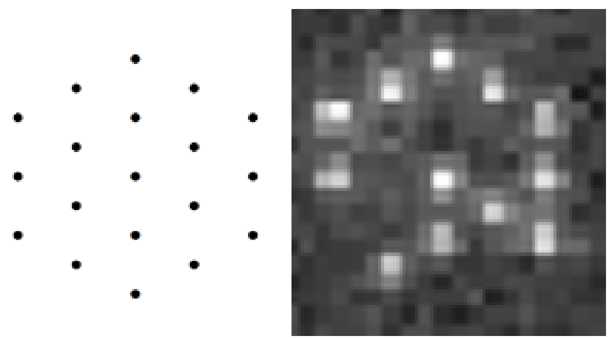
How to generate ordered arrays of atoms?

2. Bottom-up: Optical Tweezers

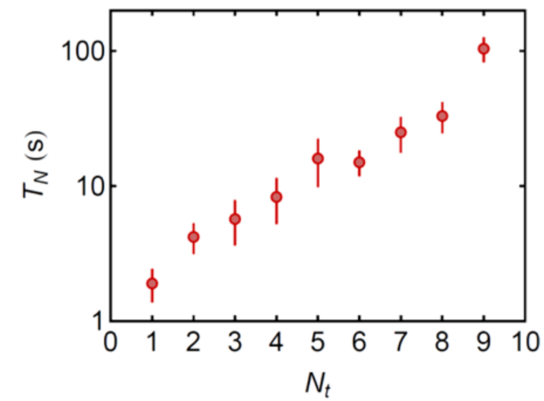
Probability to load N traps:
$p(N) = p_1^N$, (typical $p_1 \sim 0.5$)



Regal Group



Browaeys Group



Labuhn et al. Nature 534, 667 (2016)

Preparation:

1. Start with atoms trapped in a Magneto-Optical Trap (MOT)
2. Focus the tweezer inside the MOT and wait for an atom to be trapped

Pros:

- Short cycle times (<0.5s)
- Comparatively simple setup
- Individual control of each trap

Cons:

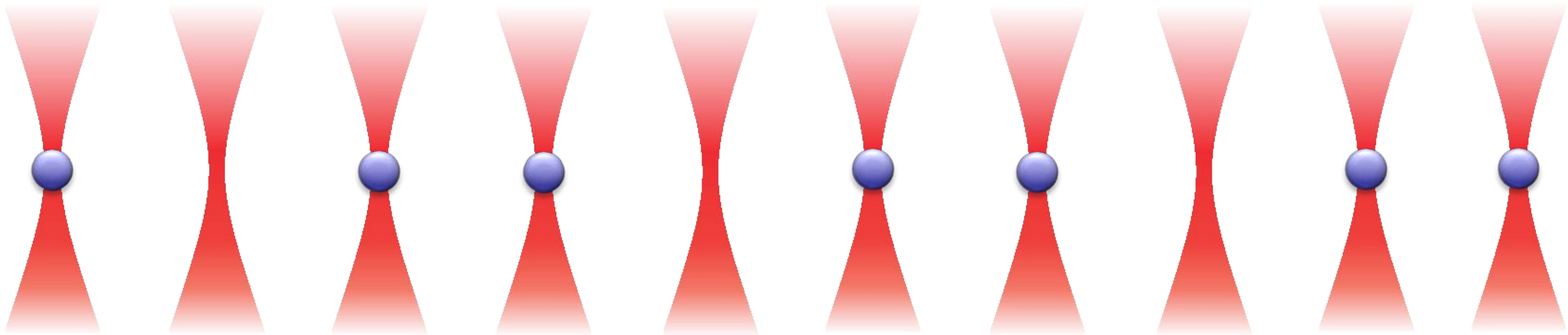
- Stochastic loading makes it hard to scale up to many atoms

See also: Grangier Group, Saffman Group, Ahn Group and many more

Our scheme:
- bottom-up: tweezer-based but with many tweezers
- Entropy removal via measurement and feedback

Scheme

1. Array of tweezers loaded stochastically from Magneto-Optical Trap (Rubidium-87)
2. Image and remove empty traps
3. Rearrange remaining traps to form a defect-free array

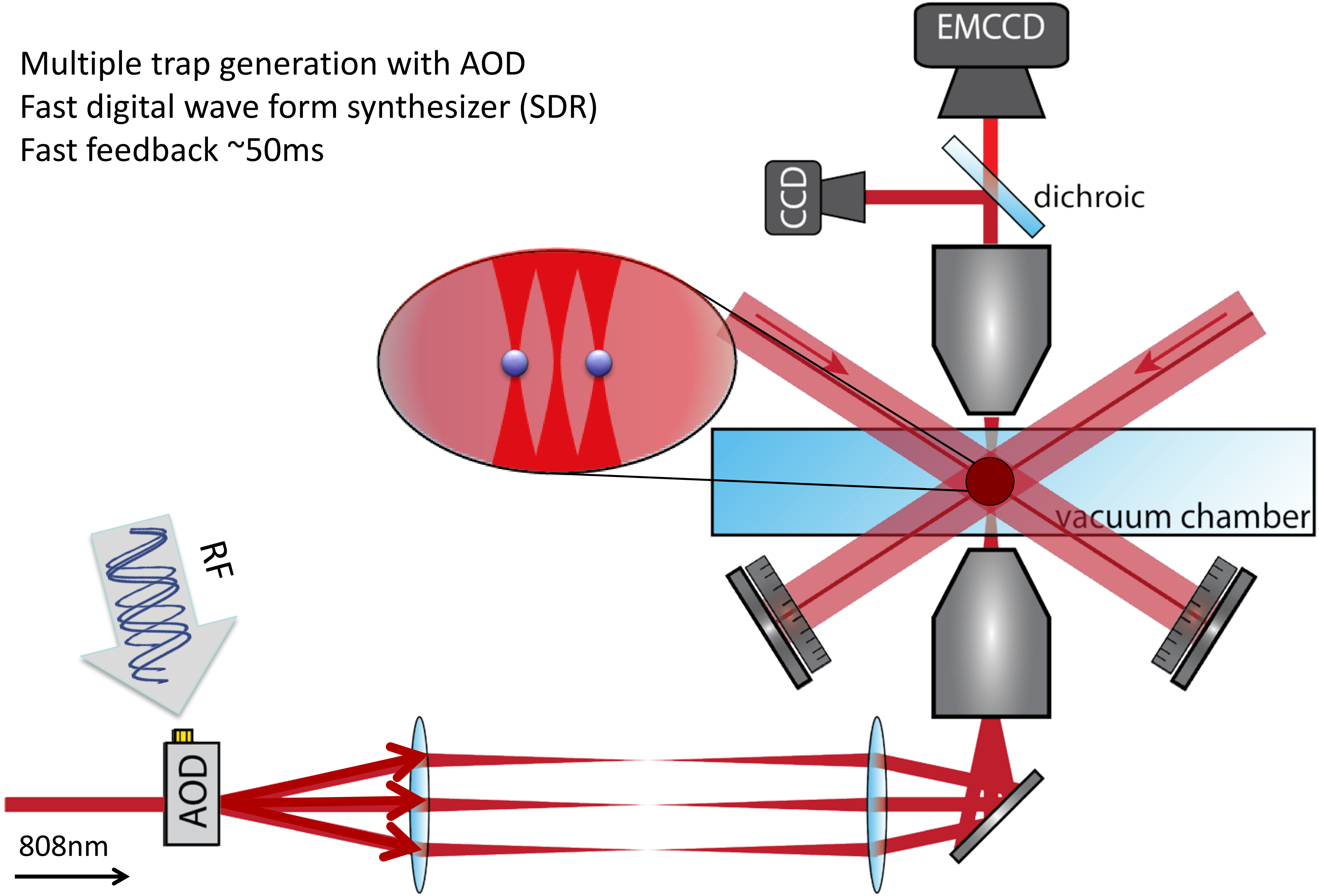


4. Engineer interactions between atoms: $\hat{H} = \ldots$

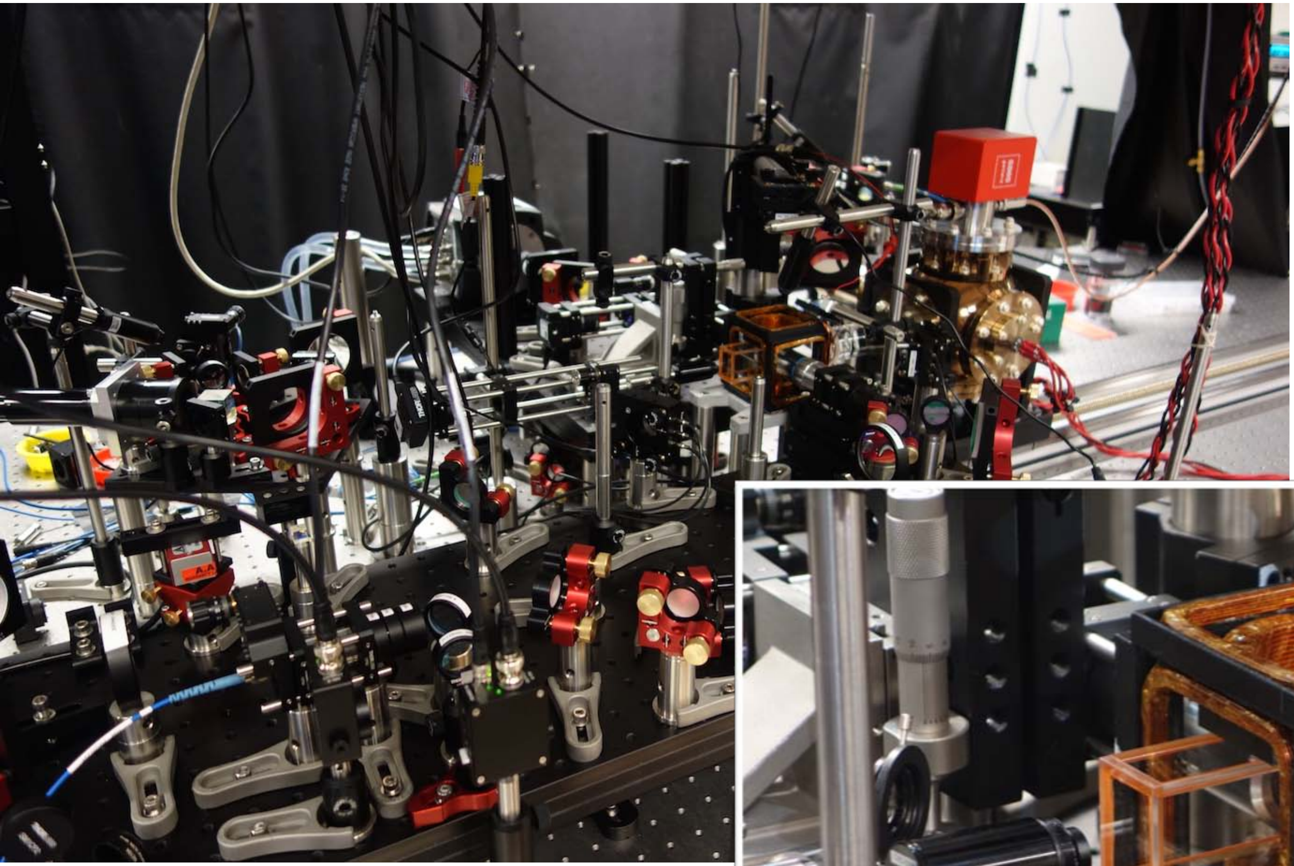
*Related proposals: Weiss et al., Phys. Rev. A **70**, 040302 (2004), Vala et al., Phys. Rev. A **71**, 032324 (2005)*

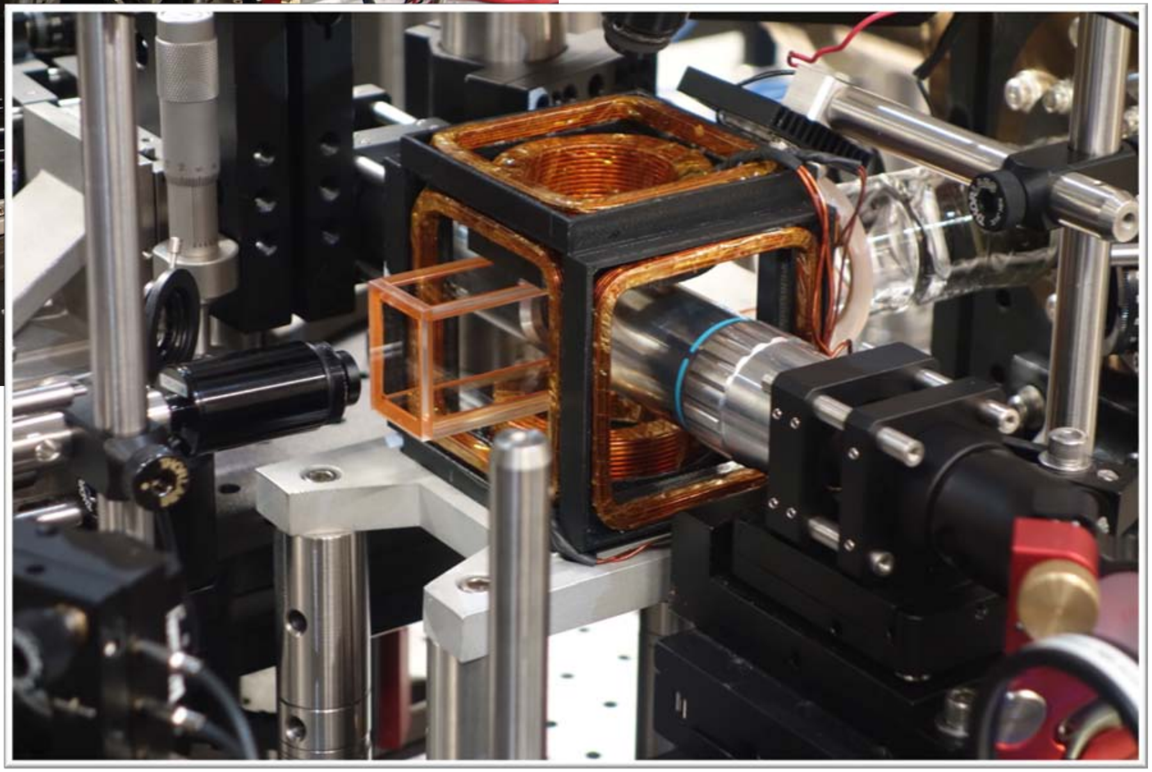
Experimental setup and scheme

- Multiple trap generation with AOD
- Fast digital wave form synthesizer (SDR)
- Fast feedback ~50ms



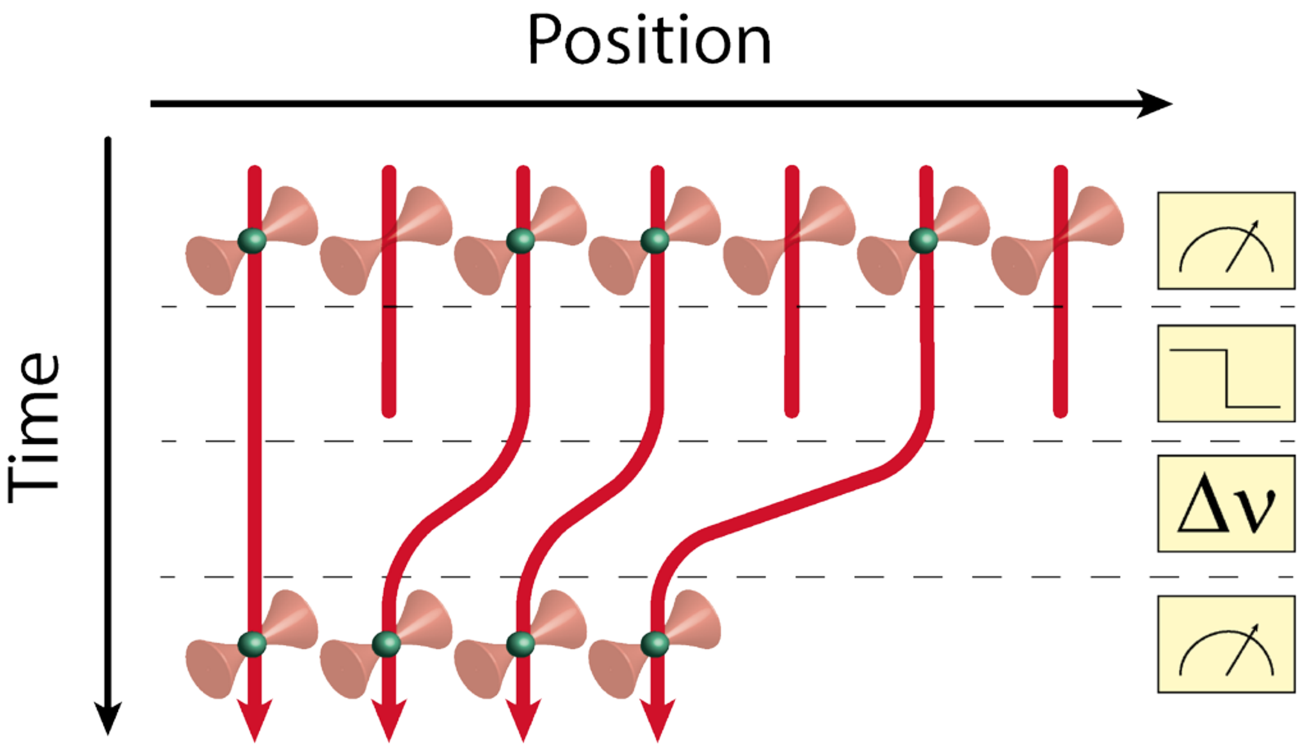
Experimental setup





Experimental Results

Our scheme



Rearranging atoms

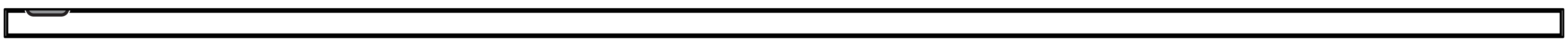
Array of 100 optical tweezers

a = 2.6 μm

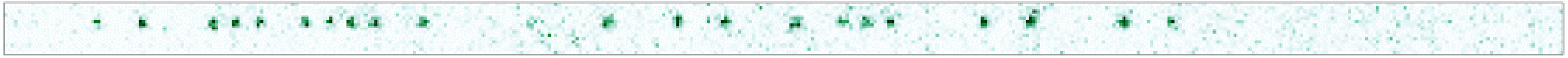
Randomly loaded array

Defect-free array

Video: Before and after images



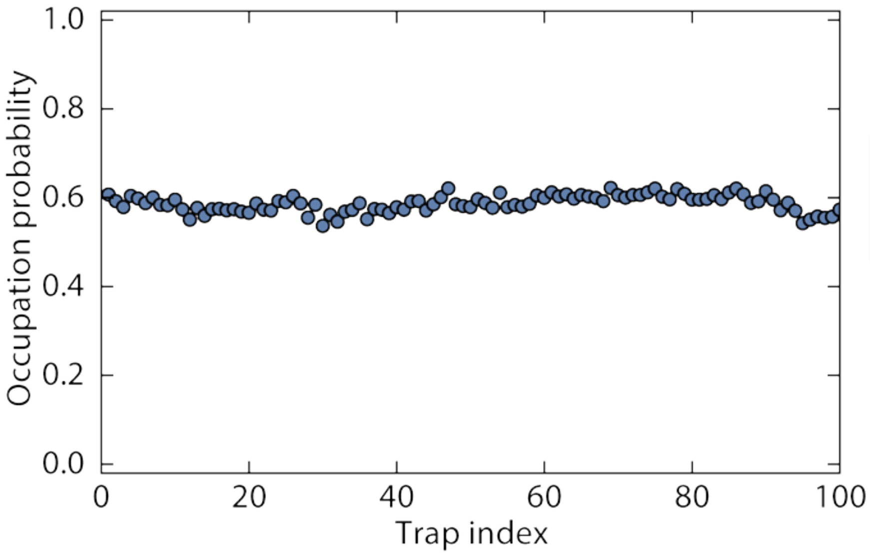
Rearrangement process

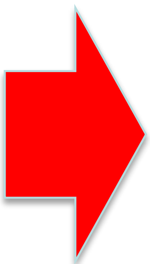


Quantitative results

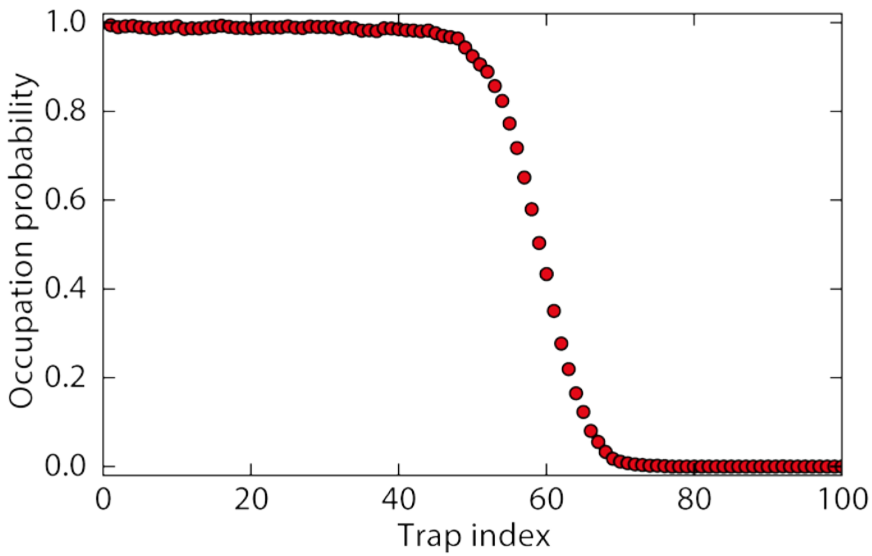
What's the probability for an individual trap to be filled?

1. Image



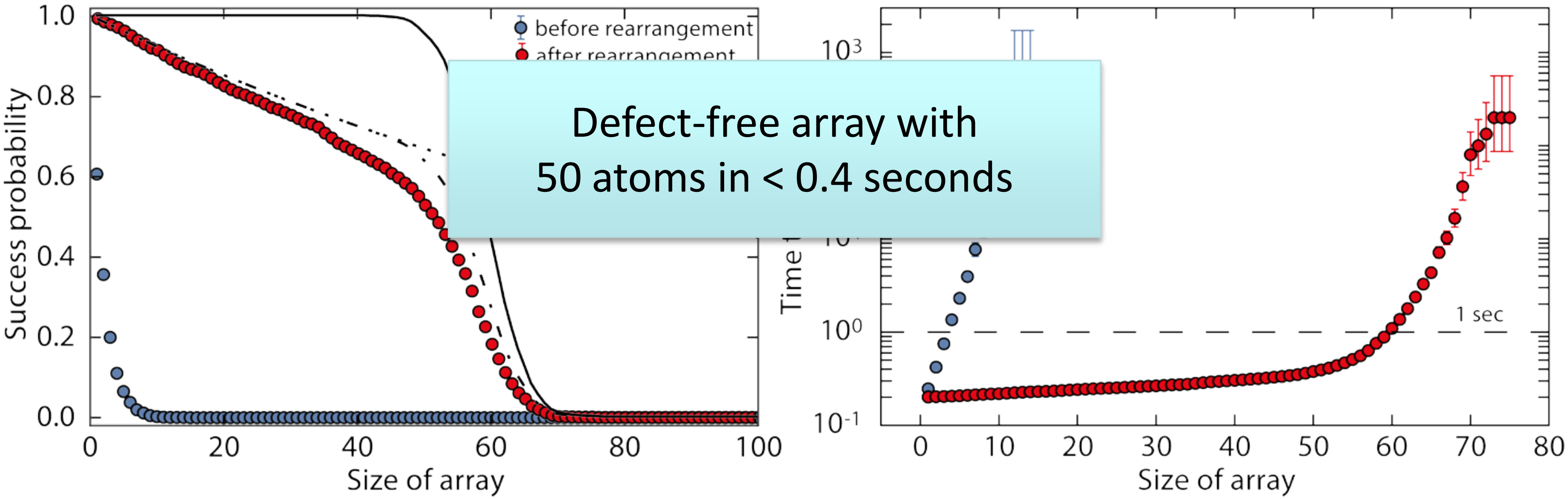


2. Image



Quantitative results:

What's the probability for finding a defect-free array of size N?



Defect-free array with
50 atoms in < 0.4 seconds

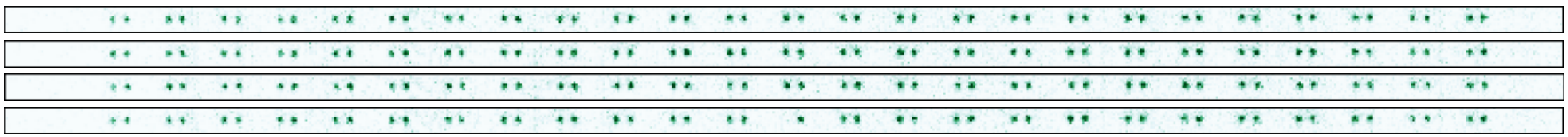
Probability to load N traps:
$p(N) = p_1^N$,
Before rearrangement p_1~0.6
After rearrangement p_1~$\exp(-t_r/\tau)$

This work: Endres et al. arXiv:1607.03044
See also: Browaeys Group: arXiv:1607.03042, Ahn Group: arXiv:1601.03833

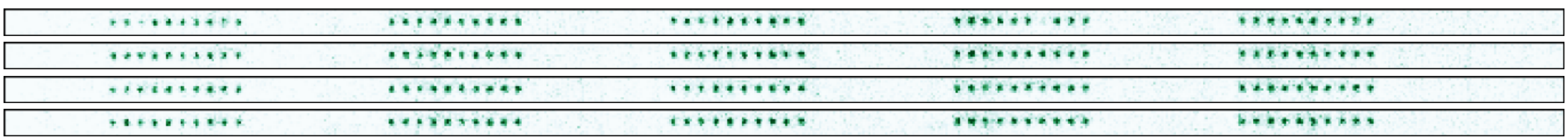
Flexible patterns

Start with a randomly loaded array…

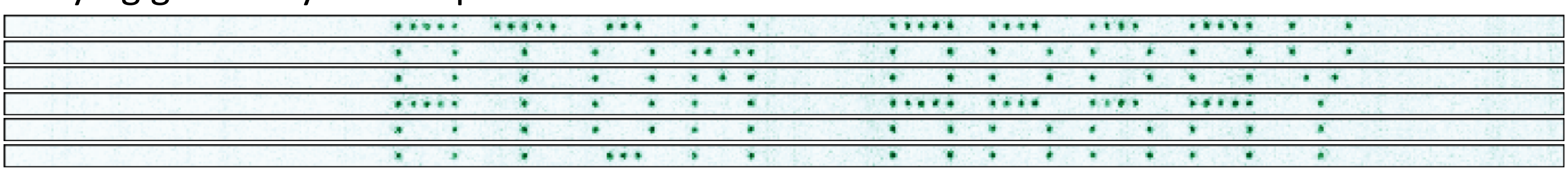
Clusters of 2



Clusters of 10

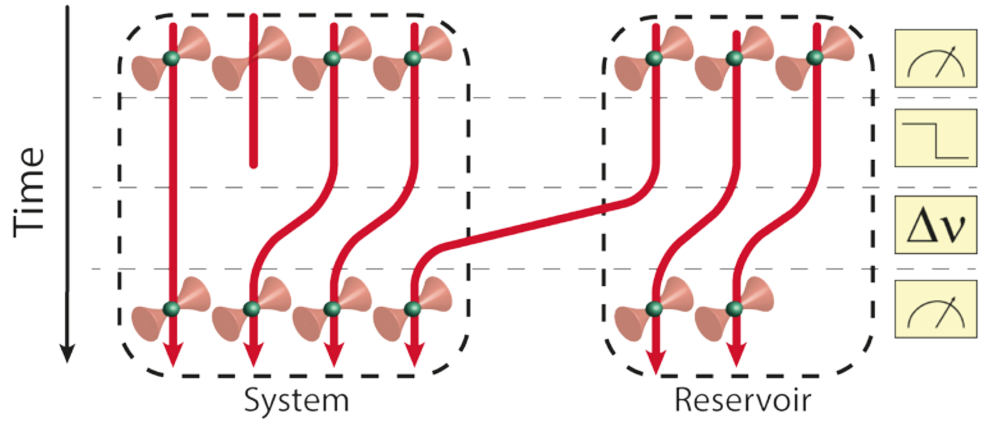


Varying geometry each repetition:

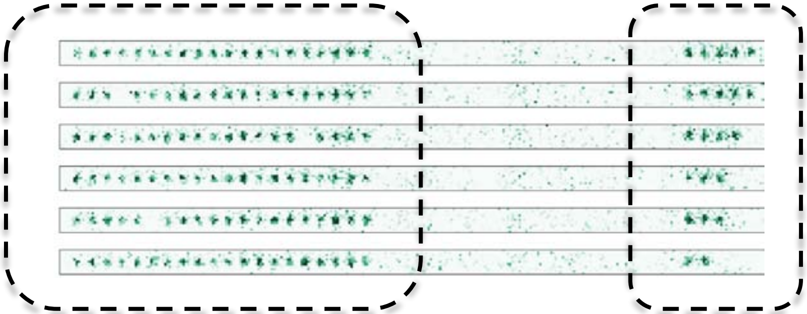


Reloading from a reservoir

Scheme:



Implementation:



20 atom array

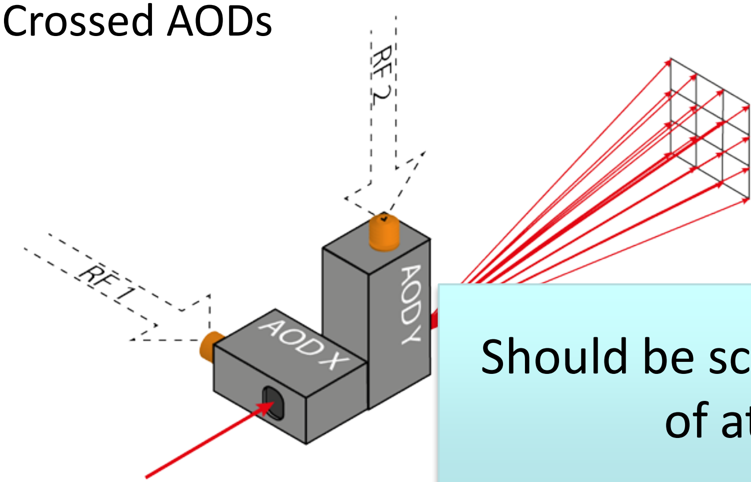
Real-time video:

Current and future work:

- Scaling to 2d
- Spin control
- Engineering of interactions

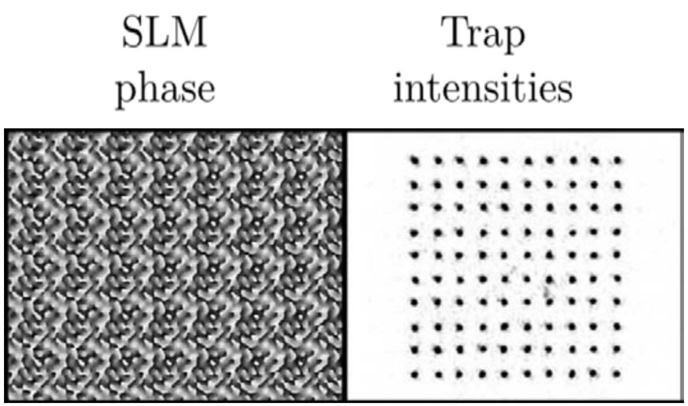
Scaling to 2D

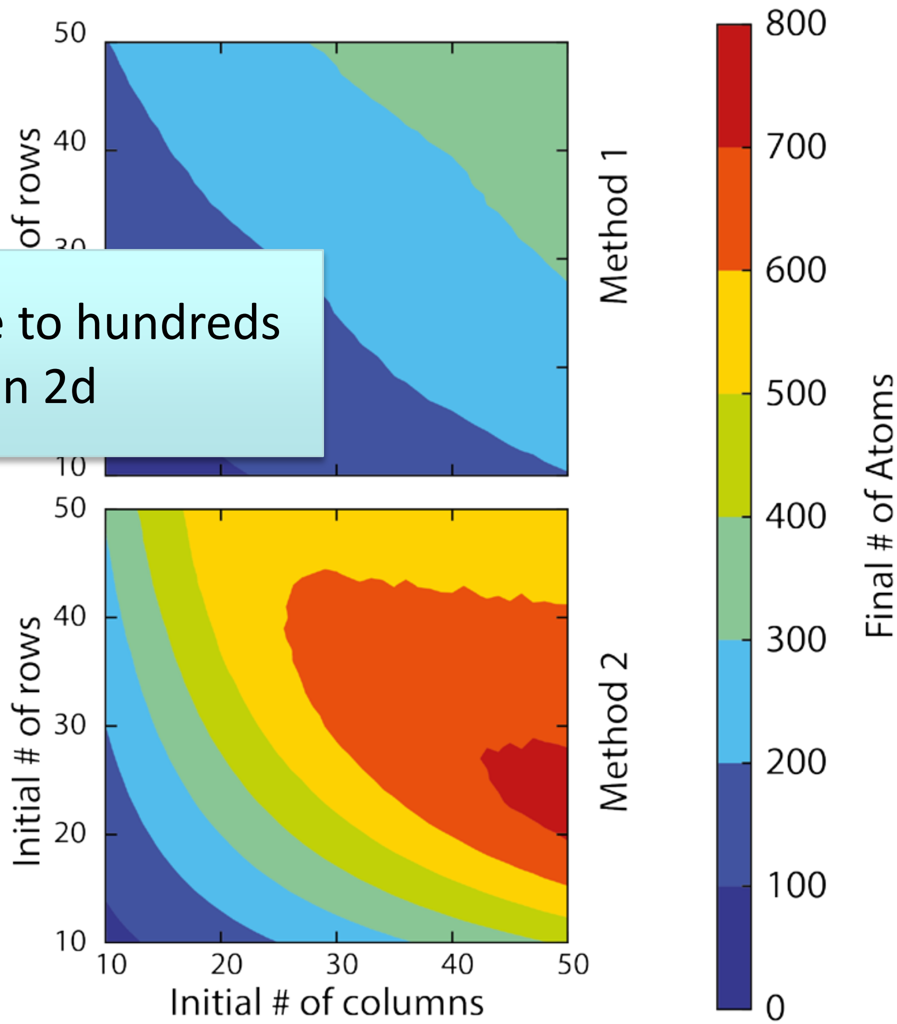
1. Crossed AODs



Should be scalable to hundreds of atoms in 2d

2. Crossed AODs overlapped with static traps

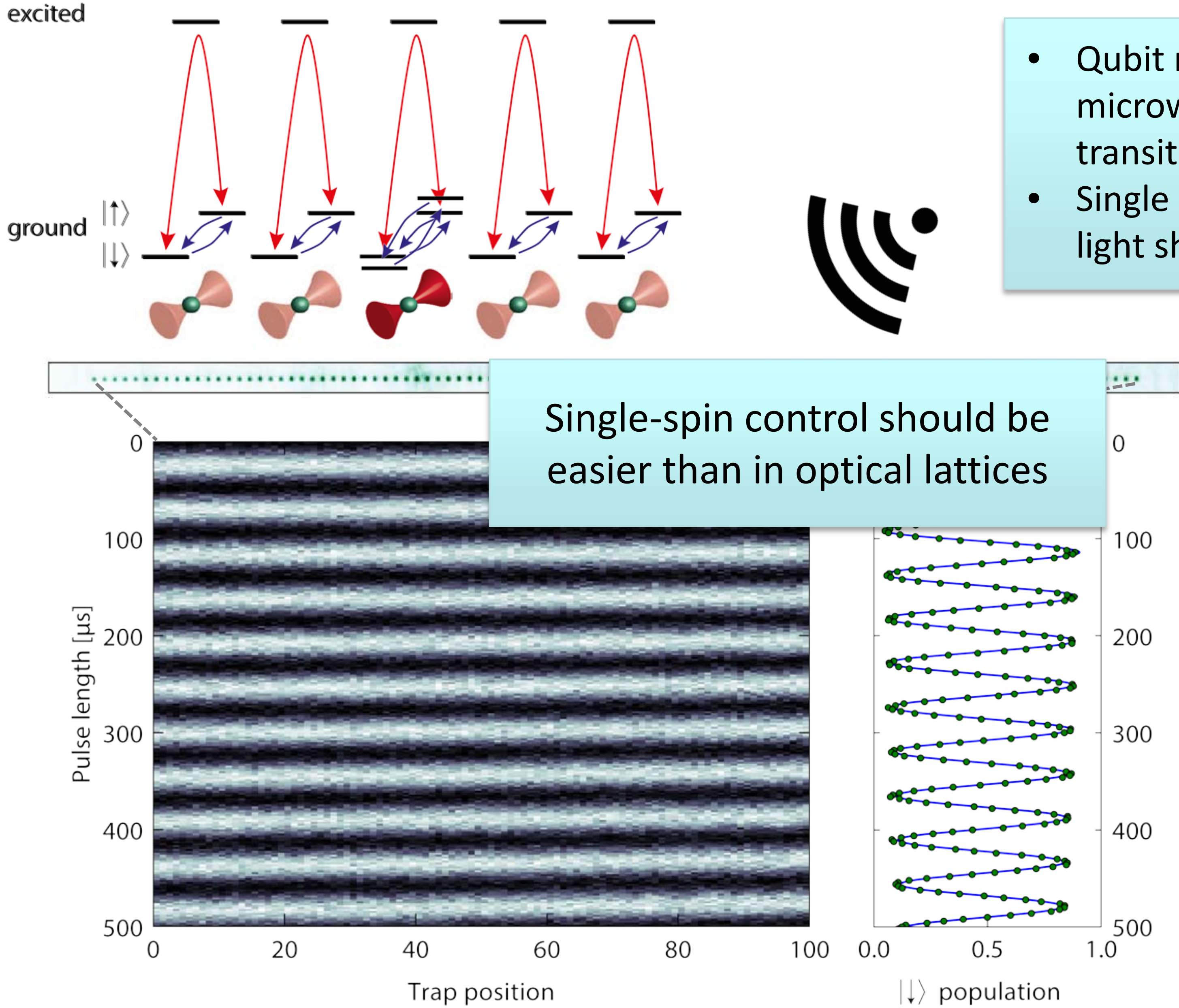




Nogrette et al., PRX 4, 021034 (2014)
Barredo et al., arXiv:1607.03042 (2016)

Current work: Spin control

- Qubit manipulations via microwave or Raman transitions
- Single side addressing with light shifts possible

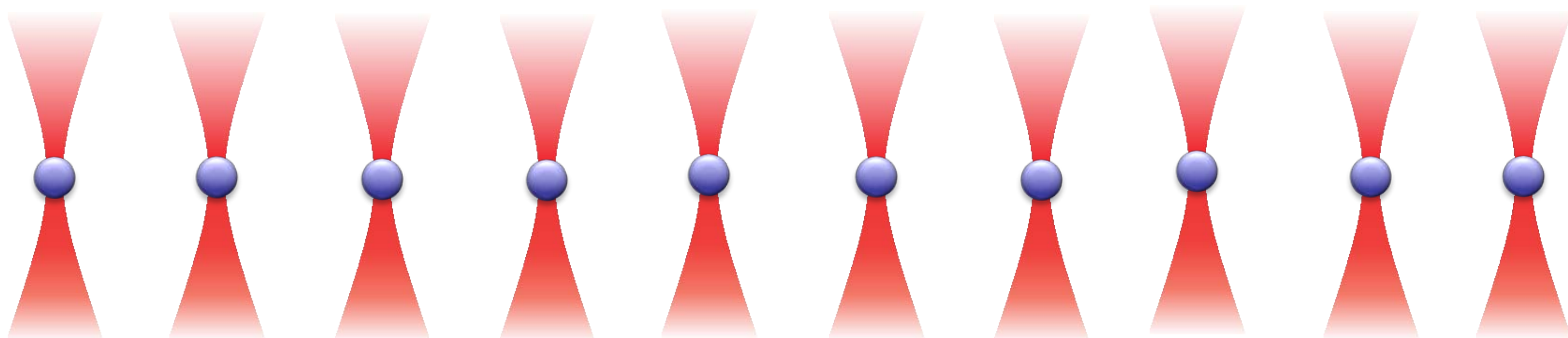


Single-spin control should be easier than in optical lattices

Single spin addressing in optical lattice: C. Weitenberg et al., Nature **471**, 319 (2011)

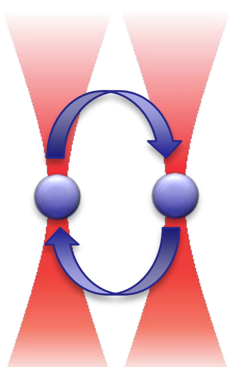
Engineer interactions

1. Tightly focused laser trap loaded from Magneto-Optical Trap
2. Image and remove empty traps
3. Rearrange remaining traps->regular atom array

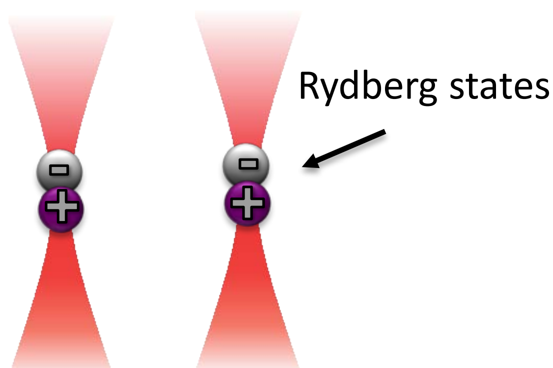


4. Engineer interactions: $\hat{H} = \ldots$

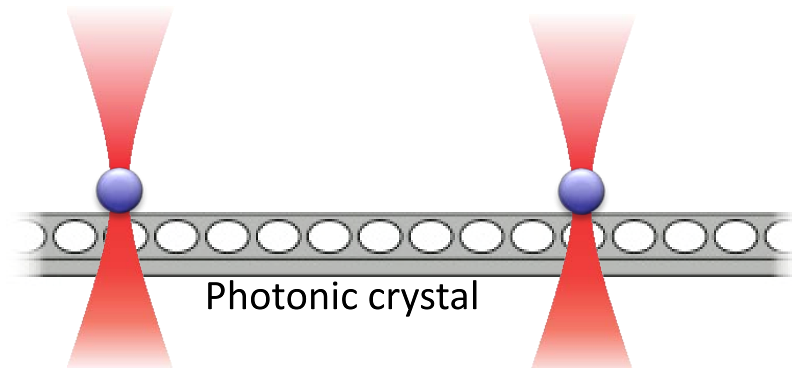
tunneling



Dipole-dipole



Photon-mediated



Rydberg atoms

^{87}Rb $5S_{1/2}$

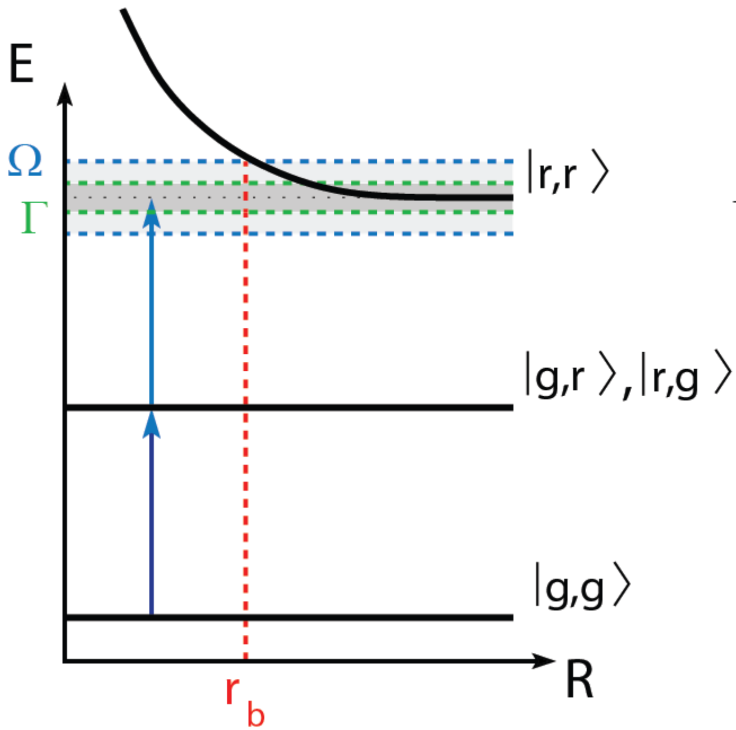
Ø 0.5nm

Go to very high quantum number

^{87}Rb $43S_{1/2}$

Ø 250 nm

Leads to strong induced dipole-dipole interactions



$$H_{\text{Ising}} = \frac{\hbar\Omega}{2}\sum_i \sigma_x^i + \sum_i (\hbar\delta + B_i)\sigma_z^i + \sum_{i<j} \frac{C_6}{R_{ij}^6}\sigma_z^i \sigma_z^j$$

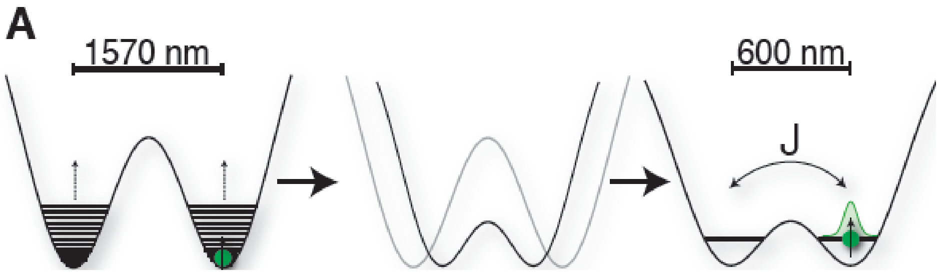
Can be controlled at single-atom level

Can be controlled by atom positioning

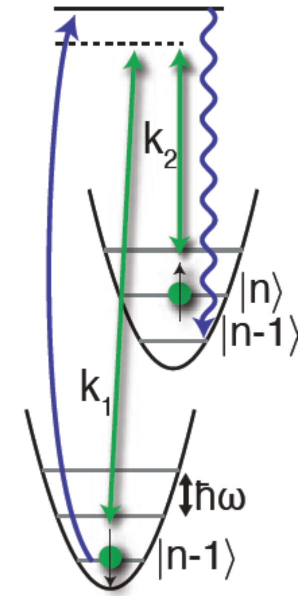
More complex models:
Zoller group: Glaetzle,…PRL 2015
van Bijnen, Pohl, PRL 2015

Saffman, Walker, & Mølmer Rev. Mod. Phys. (2010), Browaeys et al., J. Phys. B 49, 52001 (2016)

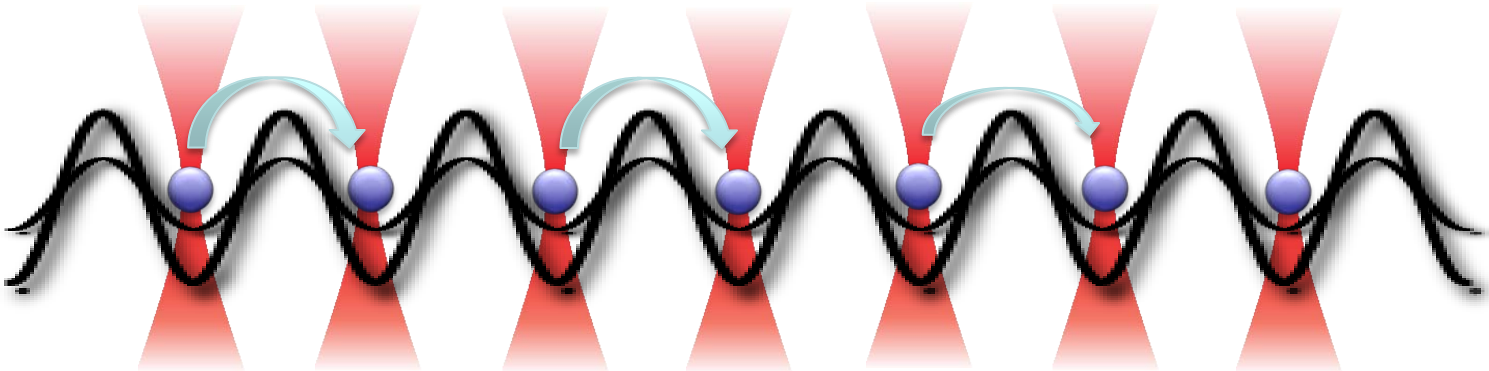
Tunneling



Requirement:
ground state cooling



Question:
Can we assemble a Mott insulator and melt it into a superfluid?



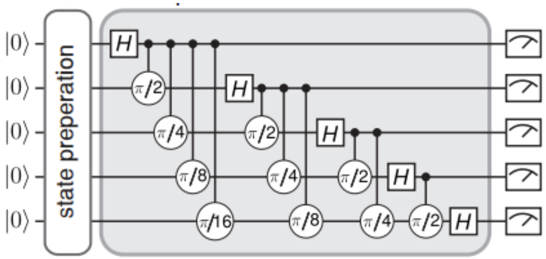
Challenges:
- Quality of side-band cooling
- Length scales are tight
- Strong on-site interactions

Regal Group: Kaufman et al., Science 345, 306 (2014)

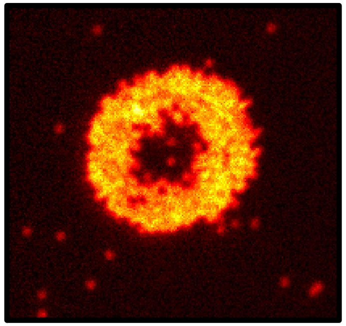
Discussion: Did we gain anything?

Common goals

1) Build quantum computers + networks



2) Study quantum many-body physics



3) Generate useful quantum states for other tasks, e.g., precision measurement

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Challenges

1) Scalability: reaching large, homogeneous systems

2) Controllability: control of single particles/spins and interaction terms

3) Engineering of interesting Hamiltonians/Liovillians

4) Low dissipation/dephasing

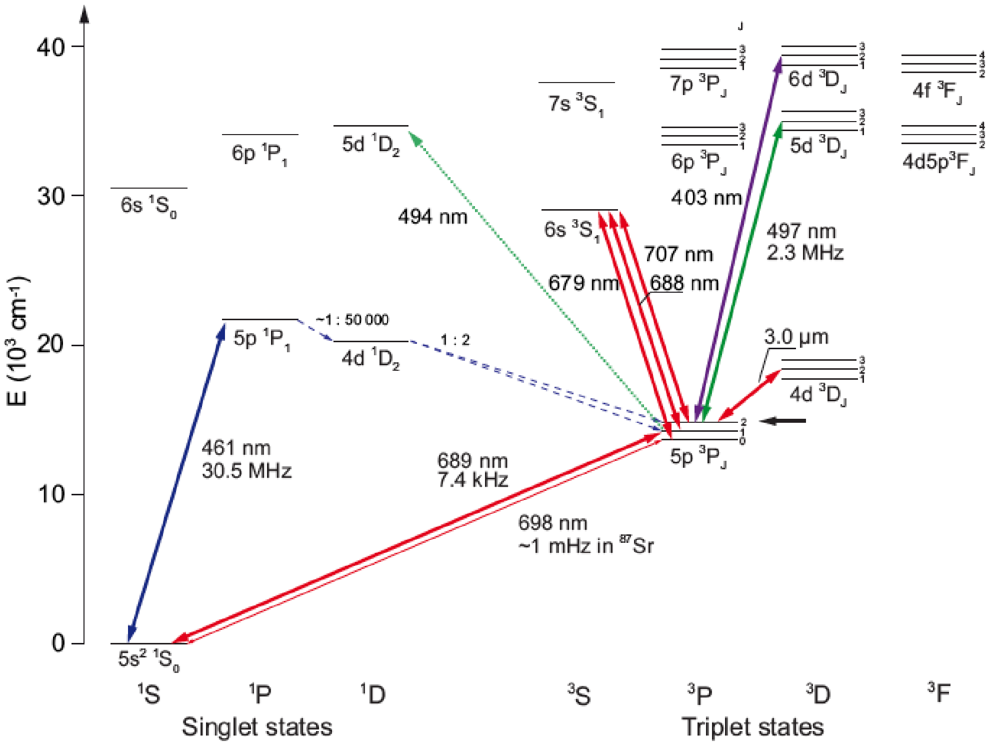
5) High-fidelity initialization of low entropy states

6) Fast experimental repetition rates

7) Experimental complexity

@Caltech: Strontium in tweezers

Improve controllability and scalability further: use two-electron atom



Advantages:

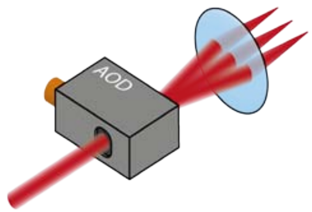
1) Trapping with 532nm possible
->improved resolution
->up to ~5000 tweezers

2) Narrow transitions
-> direct side-band cooling
-> clock transition

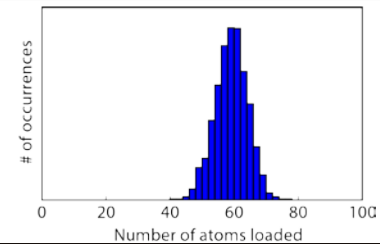
3) Rydberg properties
-> Rydberg states are trapped
-> repulsive and attractive
-> no hyperfine substructure (bosons)

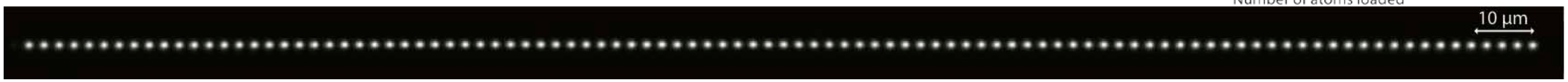
4) Range of nice magic-wavelengths
-> state-dependent trapping
with less heating

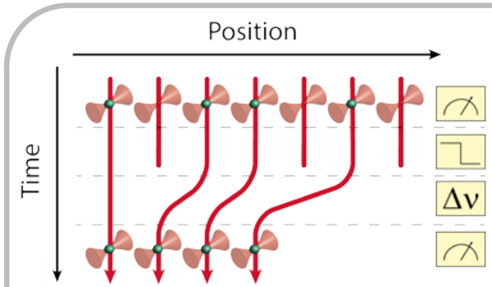
Summary



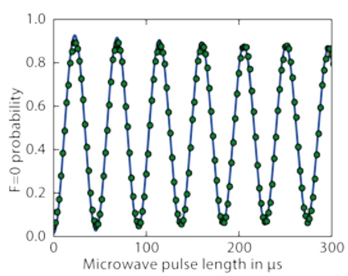
Large arrays of optical tweezers generated by AOD.





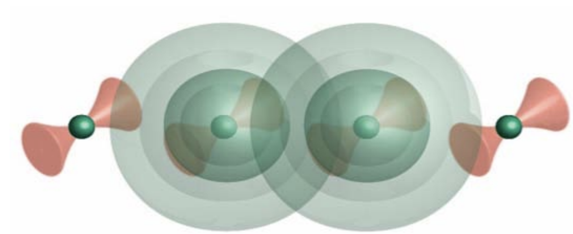


Feedback on trap position overcomes probabilistic loading and generates large well ordered atom arrays.

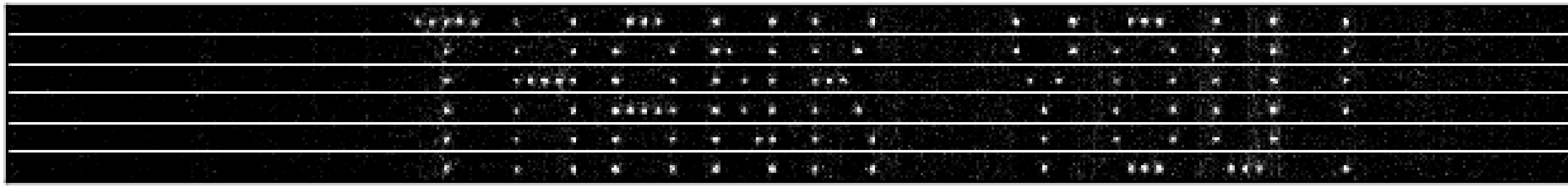


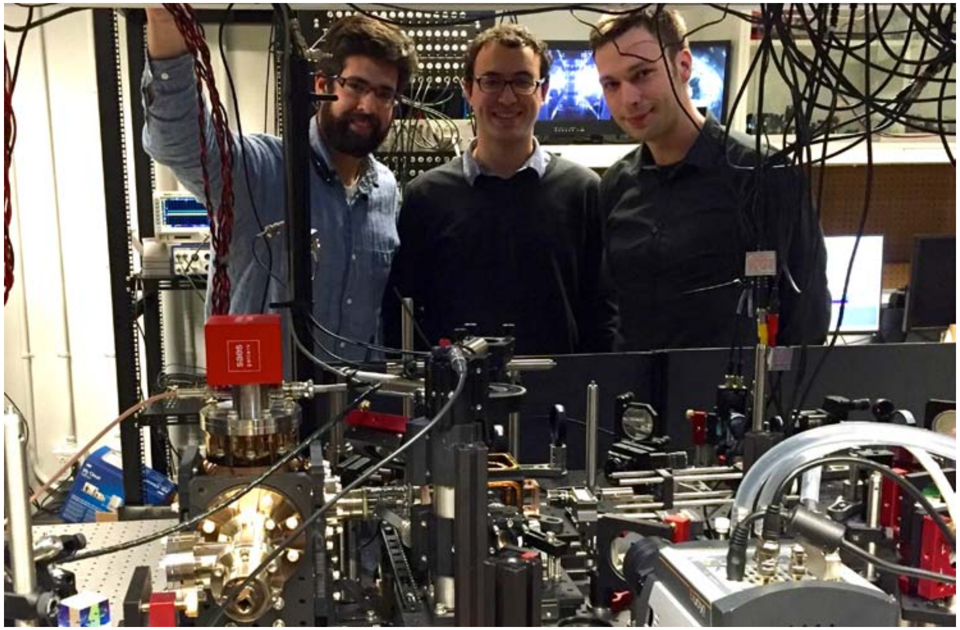
Current and future work:

- Single qubit rotations
- Interactions mediated via Rydberg excitations



Find out more: arXiv:1607.03044(2016)





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