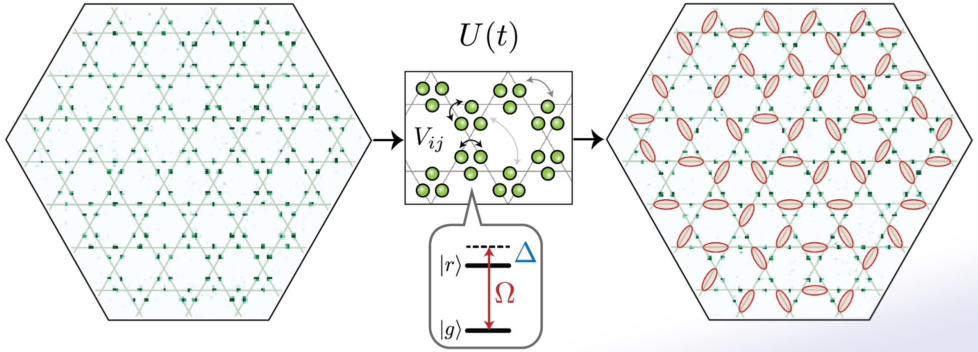
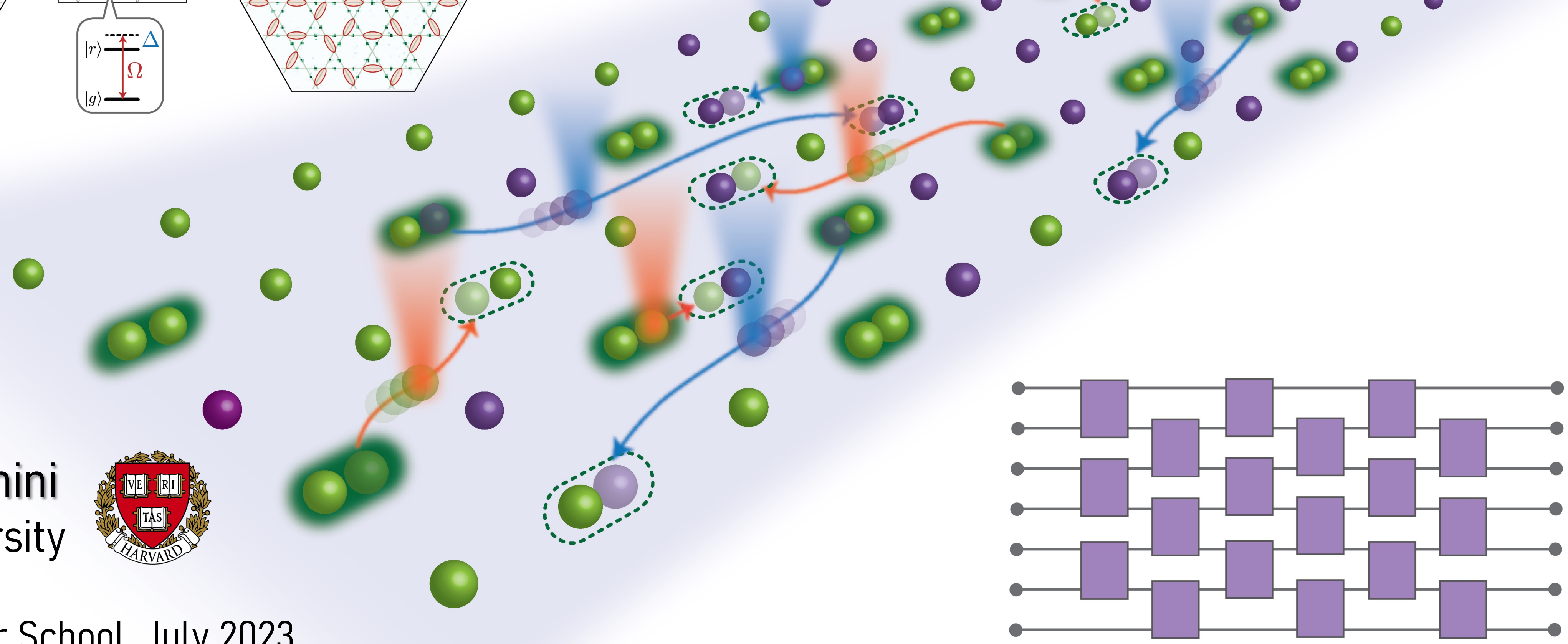
Quantum simulation (and information processing) with Rydberg atoms





Giulia Semeghini
Harvard University

Boulder Summer School, July 2023

In these weeks you have learned about:

Quantum many-body dynamics

Quantum phase transitions

Quantum circuits

Quantum spin chains

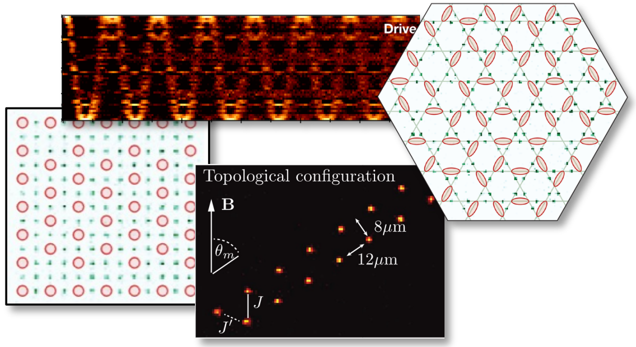
Quantum error correction

...

In these three lectures: <u>Experimental platform where we can implement some of these ideas</u>

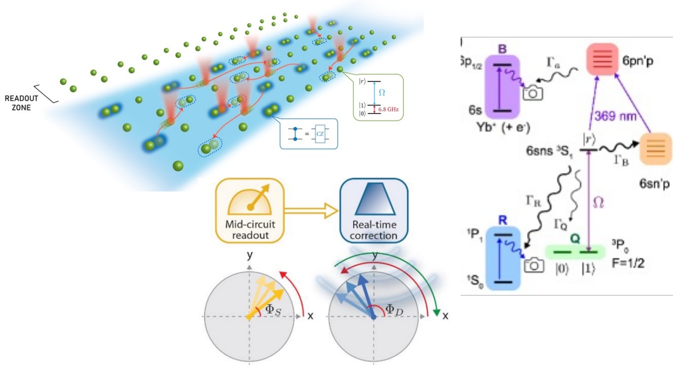
In particular, three broadly defined goals:

Quantum simulation of many-body phases and dynamics



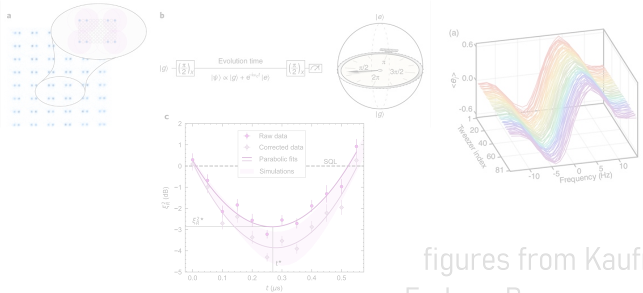
figures from Lukin, Browaeys groups

Quantum information processing



figures from Lukin, Thompson, Bernien groups

Quantum metrology



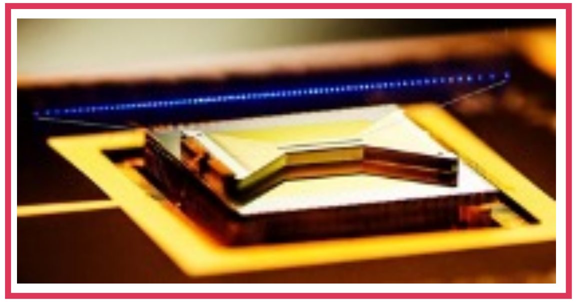
figures from Kaufman, Endres, Browaeys groups

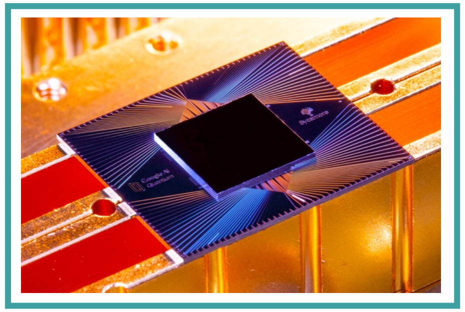
What are the requirements for a quantum platform that wants to achieve those goals?

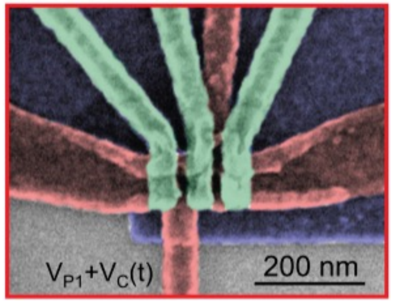
How do we choose the building blocks of our quantum machine?

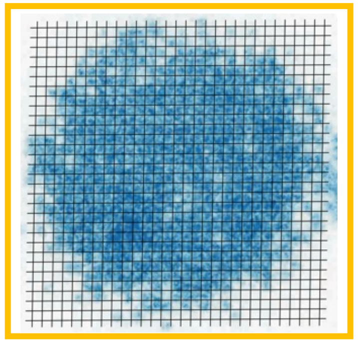
Quantum platforms explored so far

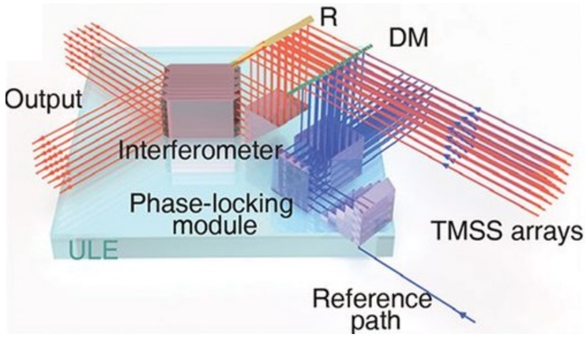
Superconducting qubits, trapped ions, neutral atoms, photons, defects in solids…











Images from: C. Monroe, Google, M. Greiner, J. Petta, I. Bloch, J-W. Pan, M. Loncar groups

These lectures:

Individual neutral atoms

- Excellent isolation from the environment
- Well-developed toolbox:
  - High-fidelity initialization, manipulation and readout
  - Strong, switchable Rydberg interactions
- Highly scalable defect-free arrays
- Tunable system parameters

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

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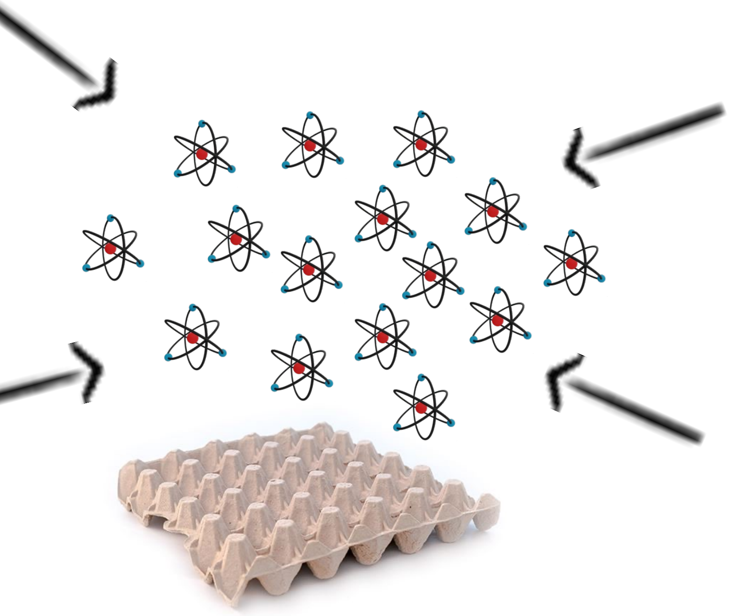
Programmable Rydberg arrays – a bit of history

One of the most recent quantum platforms: ~ 7 years old

New approach to the creation of large ordered arrays of atoms:

Top-down:
optical lattices



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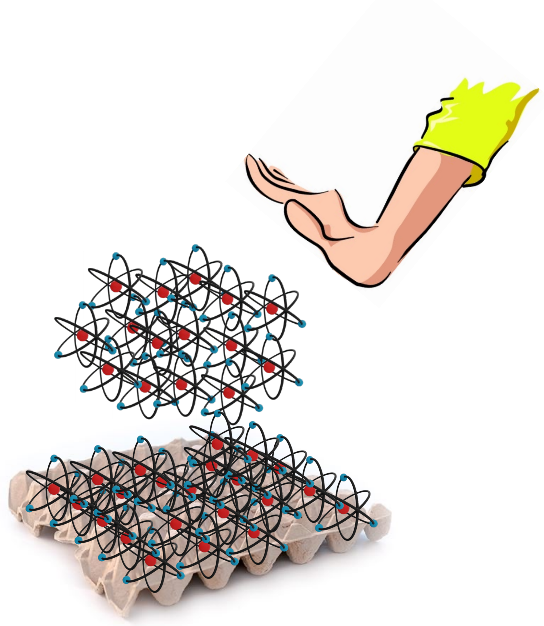
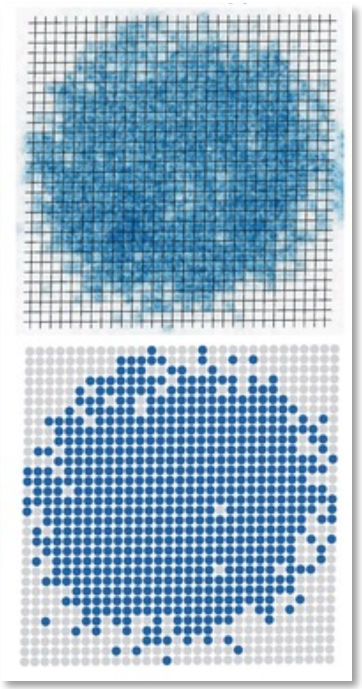
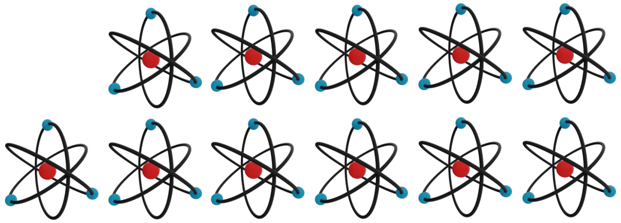


I. Bloch's lectures next week:



D. Greif et al Science 2016

Bottom-up:
tweezer arrays



Lukin, Browaeys, Ahn groups (2016)

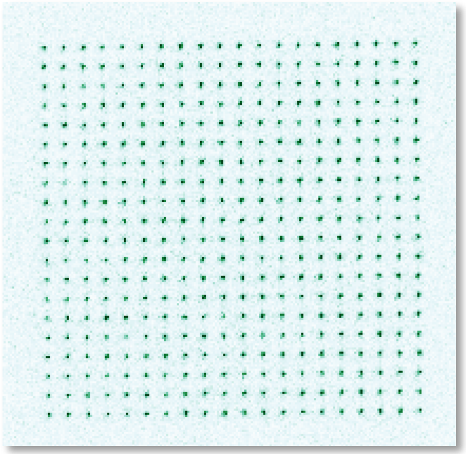
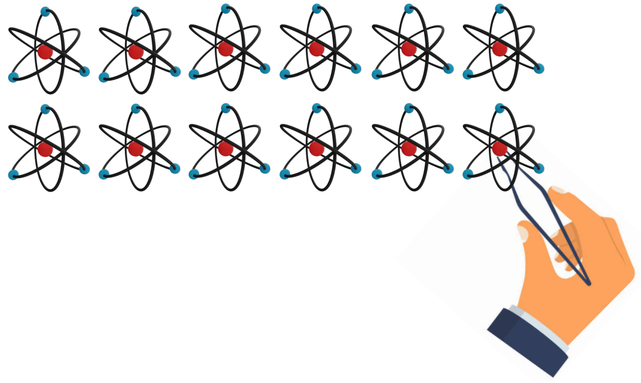


image from Lukin group

Programmable Rydberg arrays



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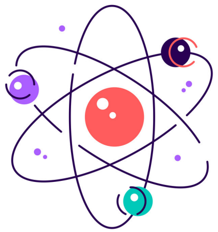
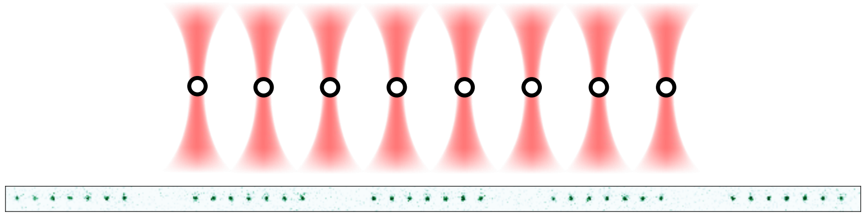
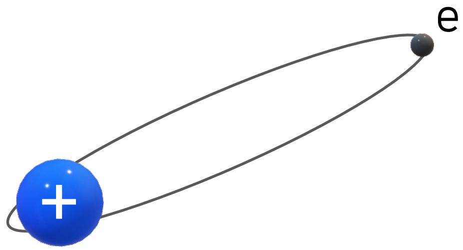
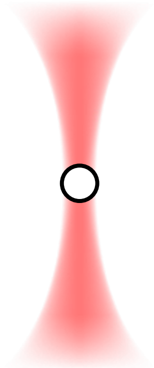




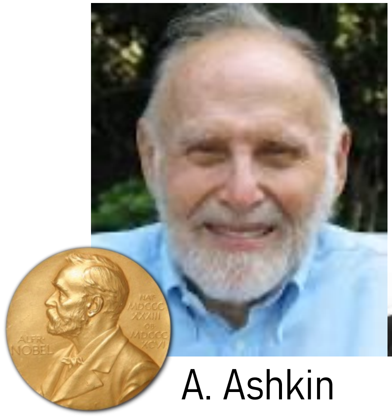


- optical tweezer



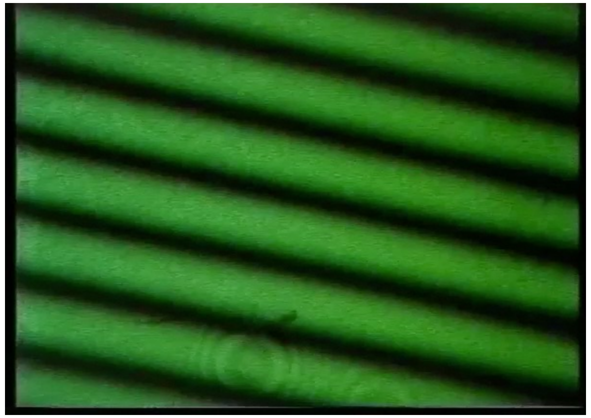
- **optical tweezer** = tightly focused laser beam
  → traps single atoms

Original idea:



A. Ashkin

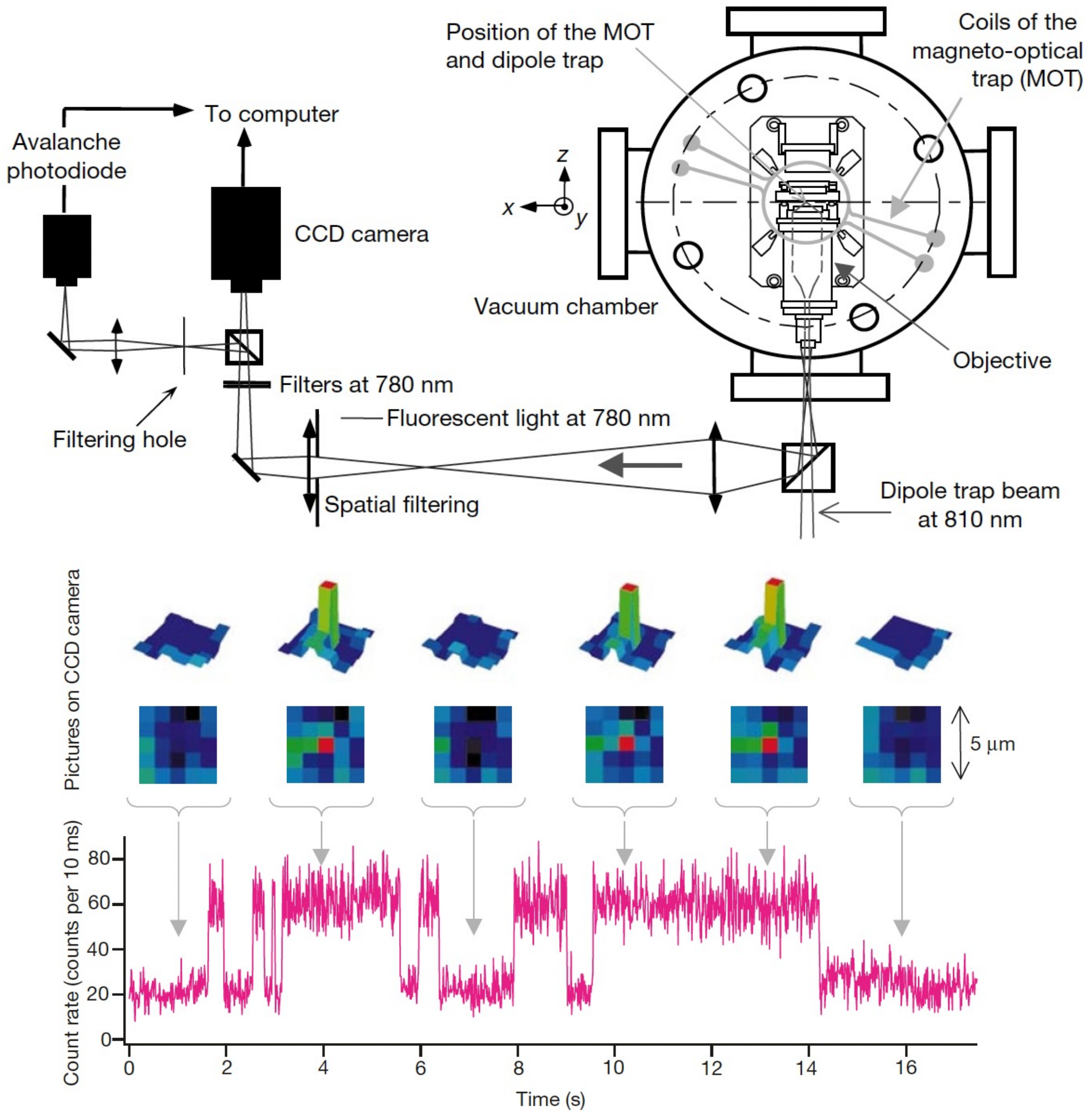
T.W. Hansch



Light pressure from laser beams used to suspend dielectric objects

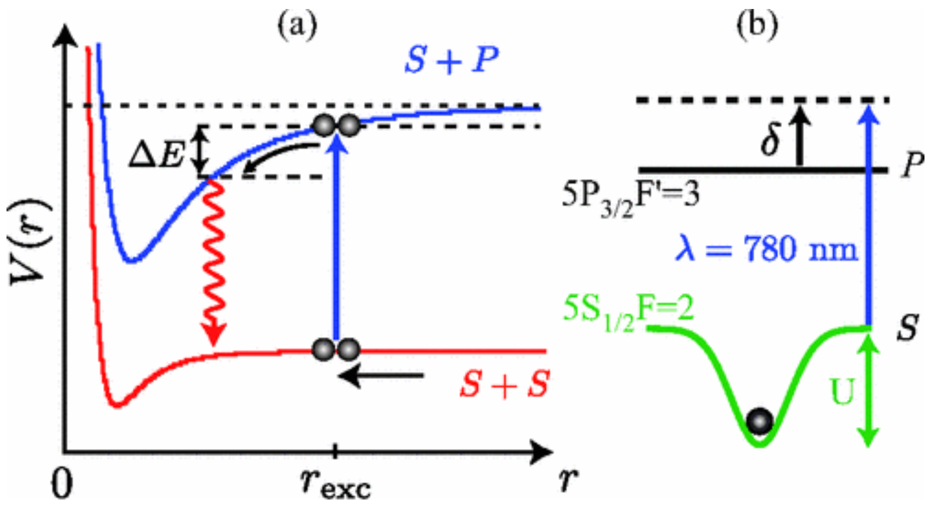
N. Schlosser et al. Nature 411, 1024–1027 (2001)

Trapping of individual atoms in tweezers: First experiments by P. Grangier (Institut d'Optique, Palaiseau):

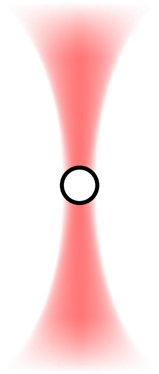


N. Schlosser et al. Nature 411, 1024–1027 (2001)

Loading of single atoms ensured by light-assisted collisions:



related work:
M. Weber et al, PRA 73 (2006)
K. D. Nelson et al, Nat Phys 3 (2007)
A. Kaufman et al, Science 345 (2014)



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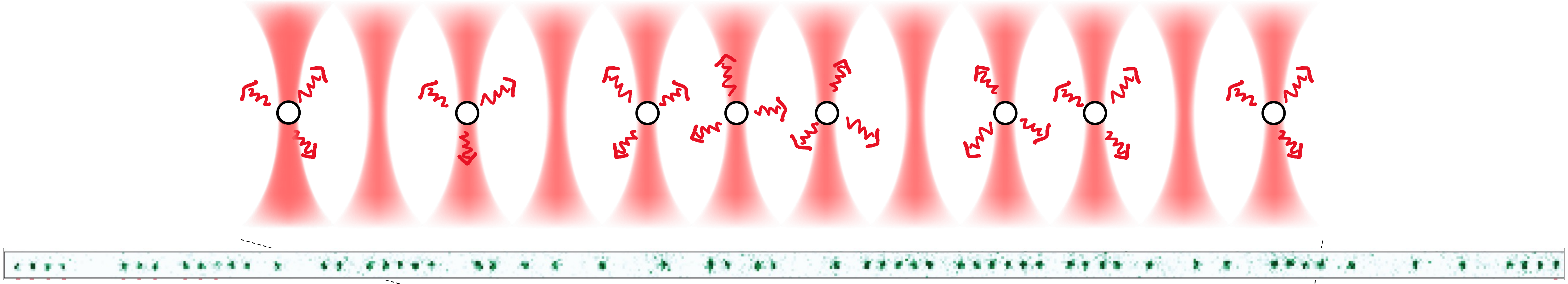

- **optical tweezer** = tightly focused laser beam
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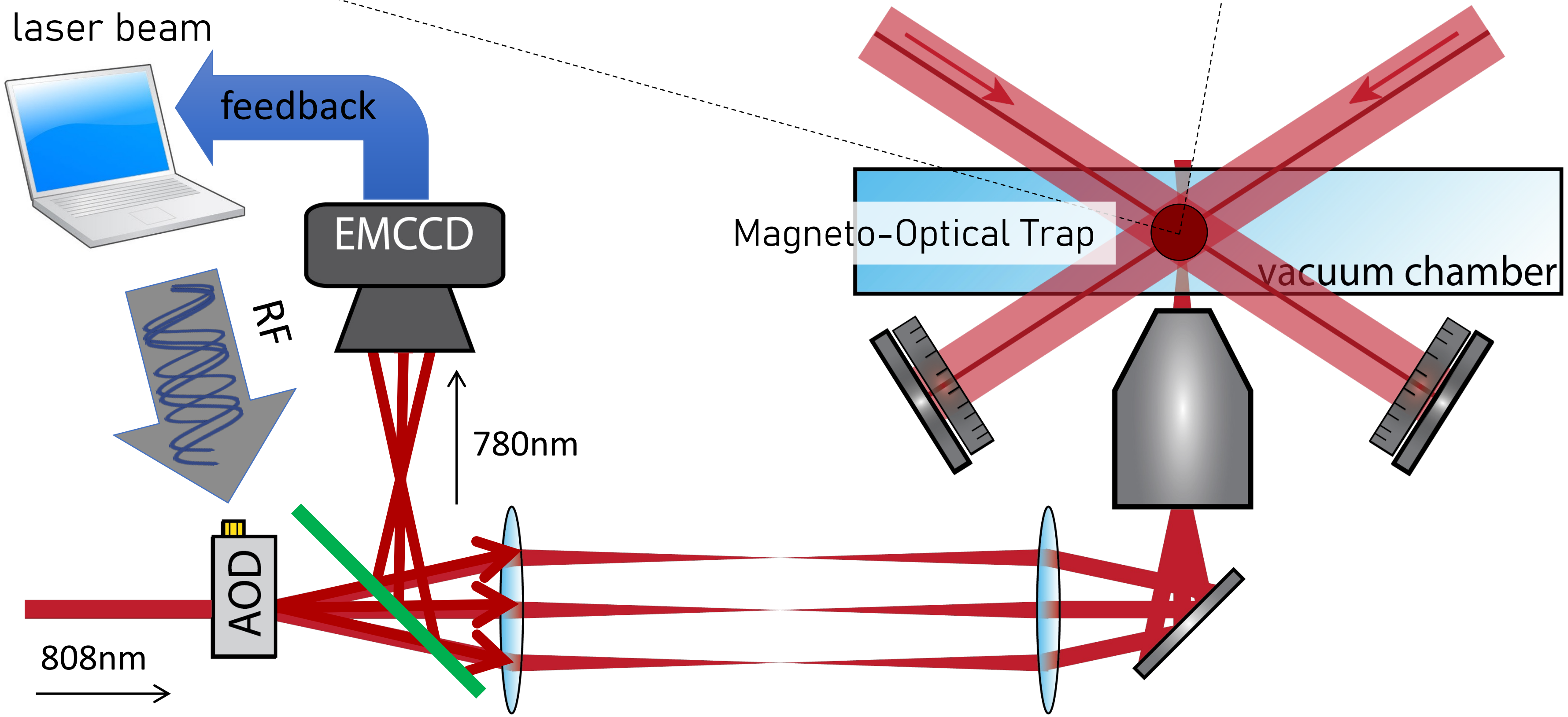
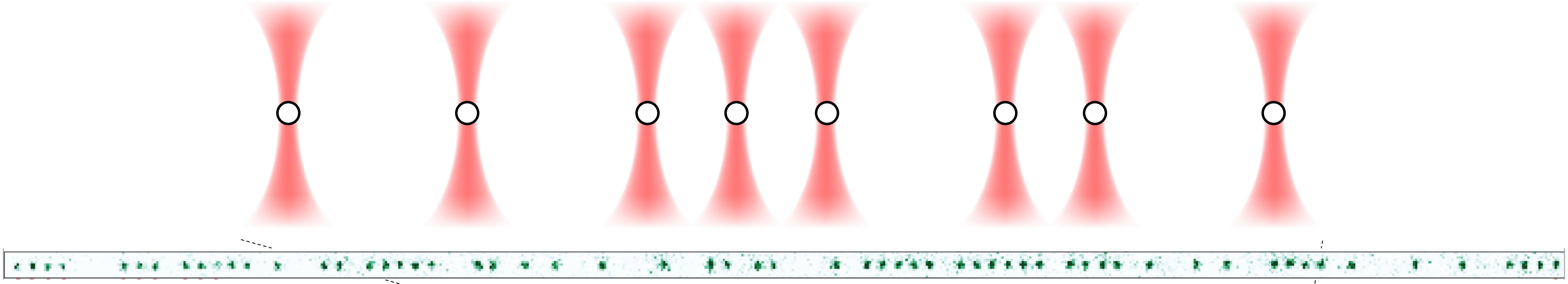
- 1D tweezer array generated by an AOD
  → stochastic loading from MOT
- Image atoms





- **optical tweezer** = tightly focused laser beam
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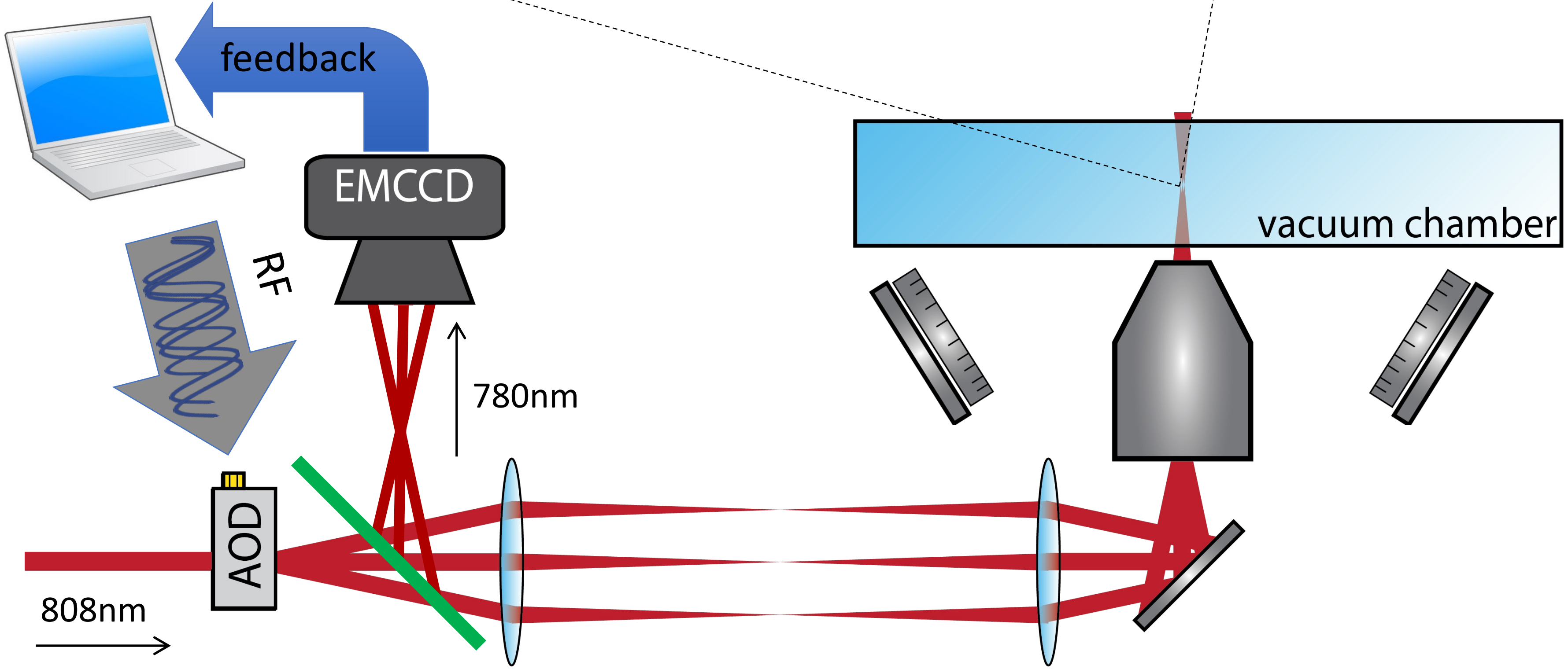
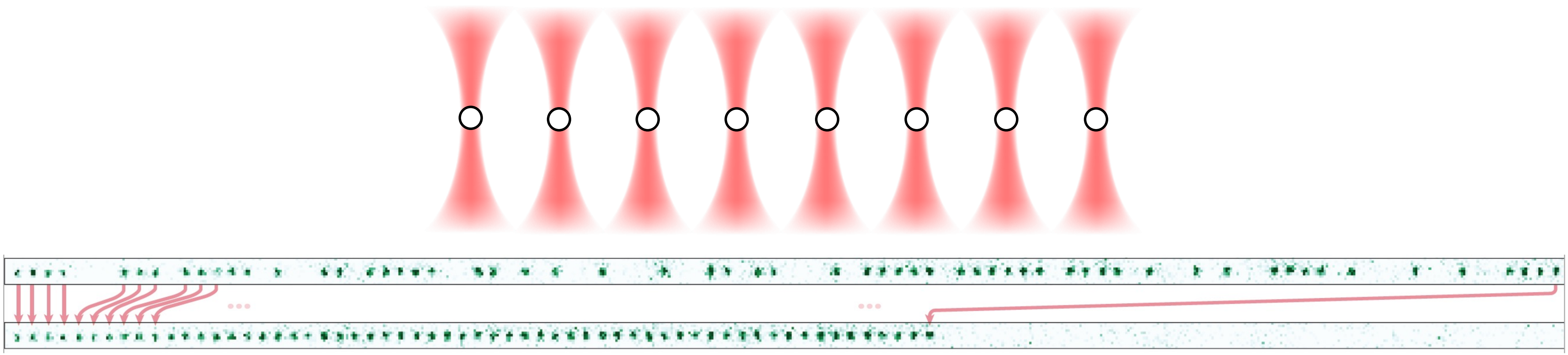
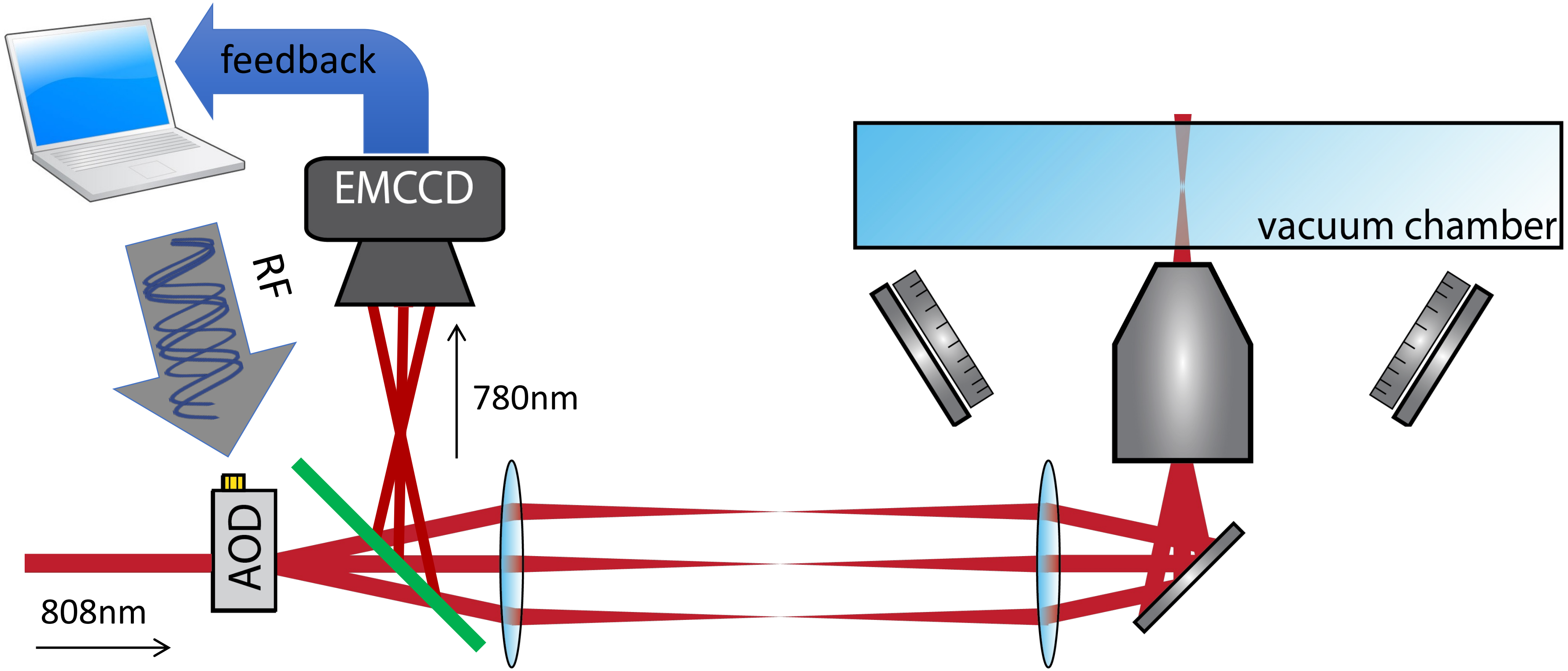
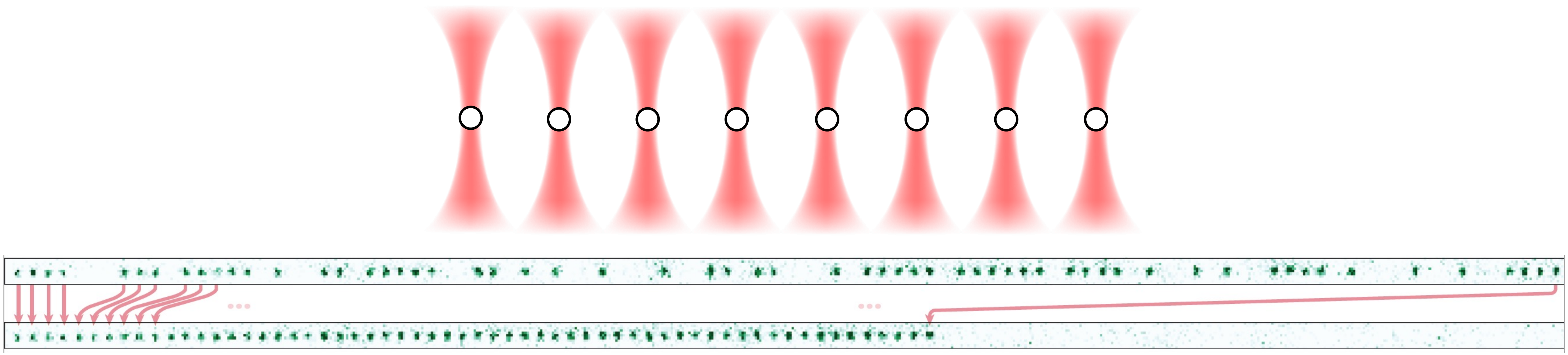
- Remove empty traps

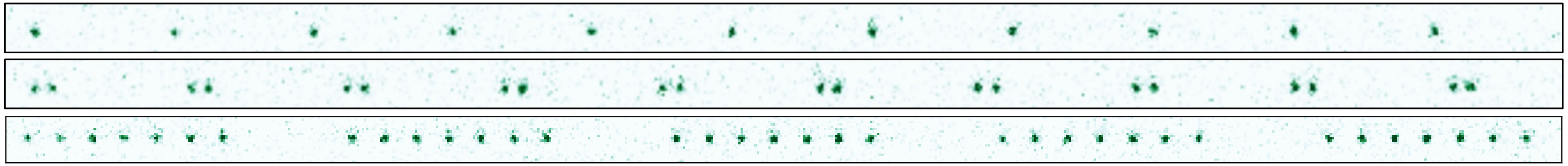




- **optical tweezer** = tightly focused laser beam
  → traps single atoms
- 1D tweezer array generated by an AOD
  → stochastic loading from MOT
- Image atoms
- Remove empty traps
- Rearrange remaining traps into regular atom array







Early ideas on atom rearrangement and entropy removal:

D. S. Weiss … K. B. Whaley, PRA 70 (2004)

J. Vala … K. B. Whaley, PRA 71 (2005)

Y. Miroshnychenko … A. Rauschenbeutel, Nature 442 (2006)

J. Beugnon … P. Grangier, Nat Phys 3 (2007)

M. Schlosser … G. Birkl, New J Phys 14 (2012)

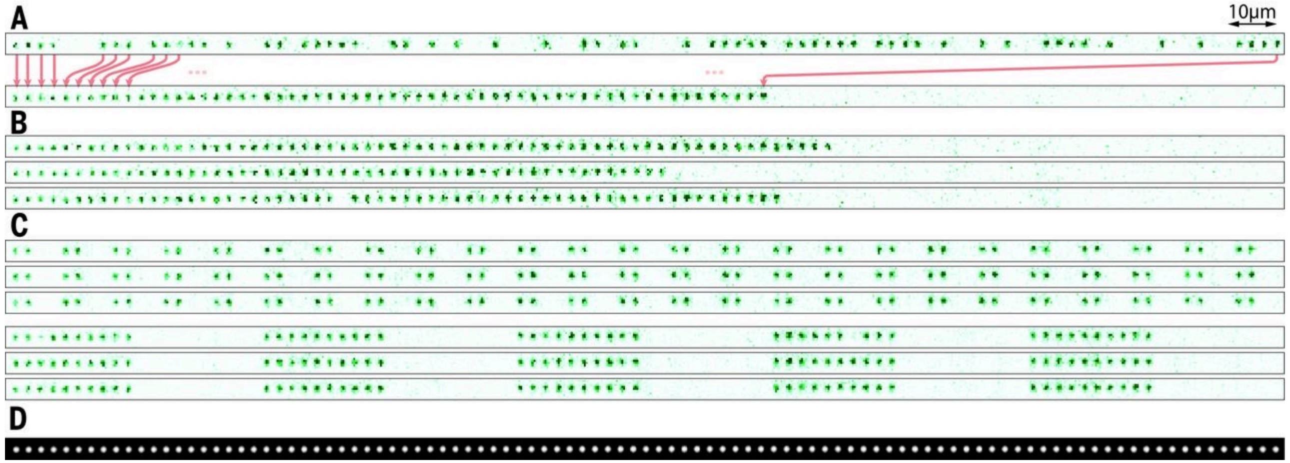
First atom array experiments:

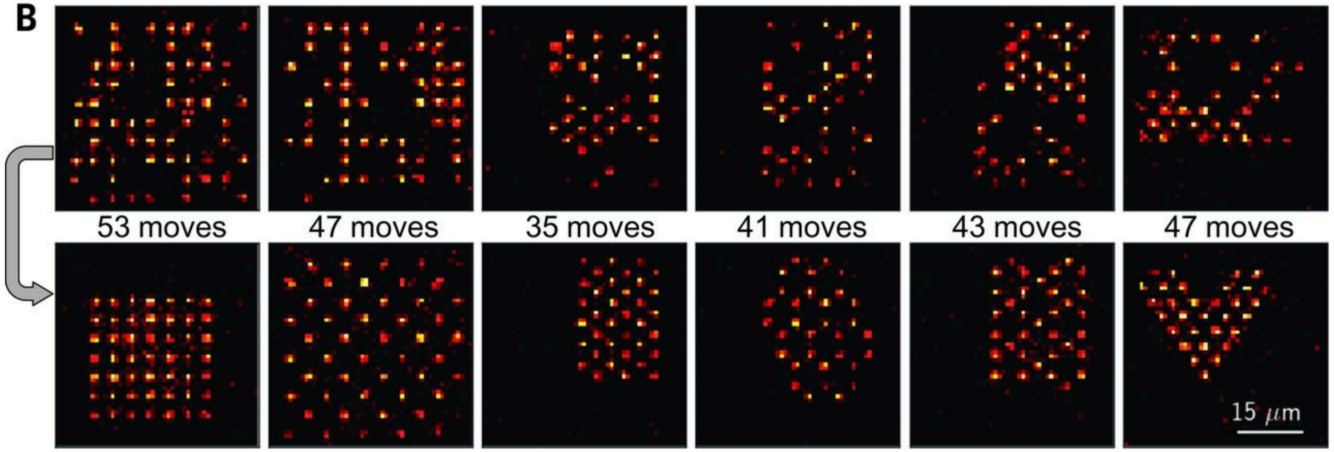
M. Endres … M. Lukin, Science 354 (2016)

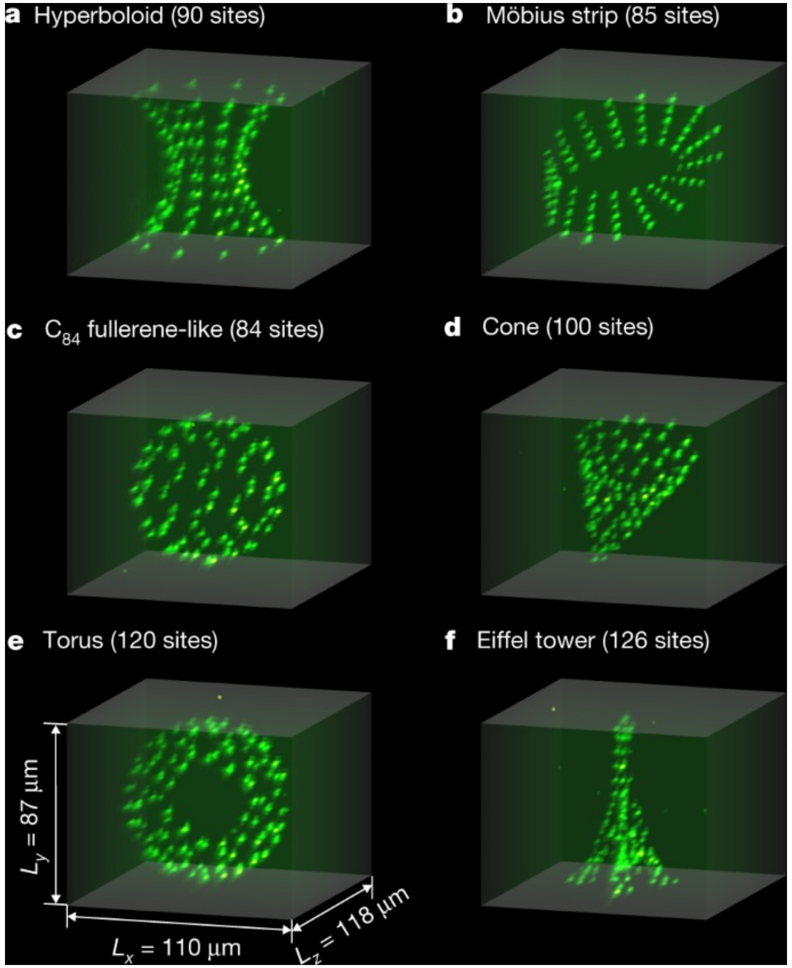
D. Barredo … A. Browaeys, Science 354 (2016)

H. Kim … J. Ahn, Nat Comm 7 (2016)

Optical tweezer array – 1D, 2D and 3D



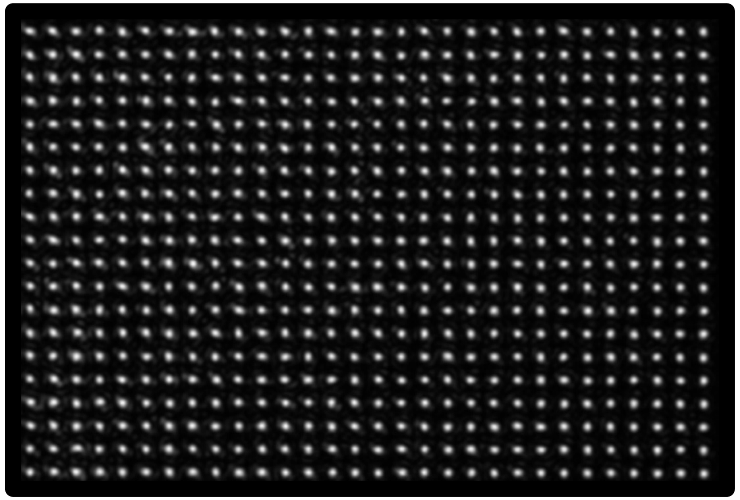




Lukin, Browaeys, Ahn, Regal, Endres, Kaufman, Saffman, Thompson, Ni, Bakr, Bloch, Bernien, …

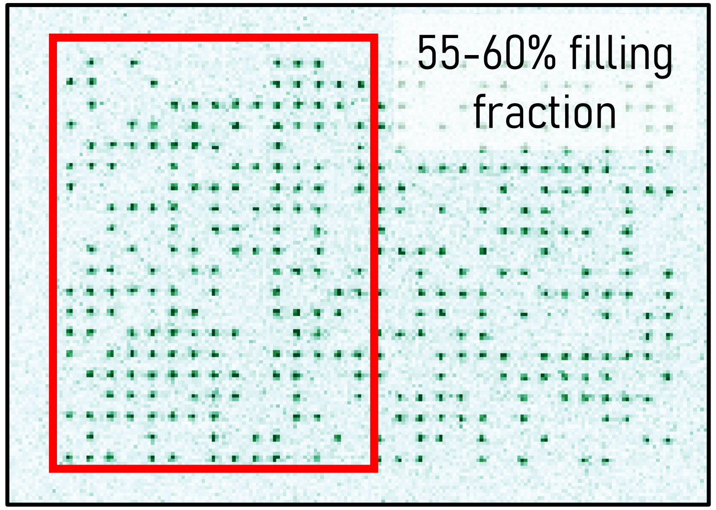
2D tweezer arrays

2D array of optical tweezers

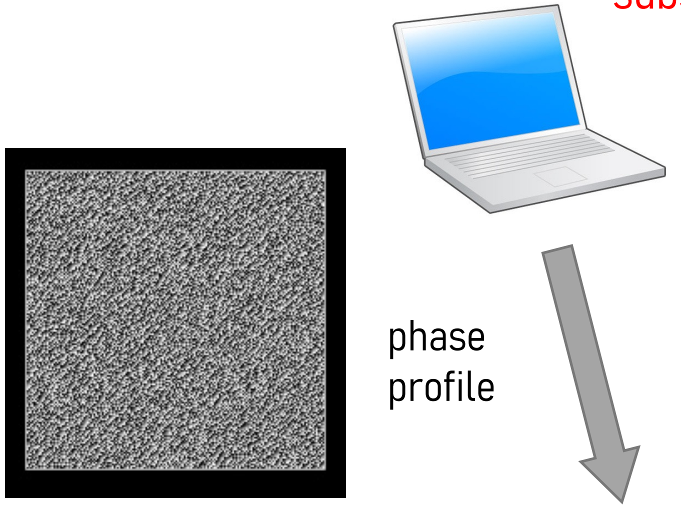


D. Kim, et al, Opt. Lett. 44, 3178 (2019)

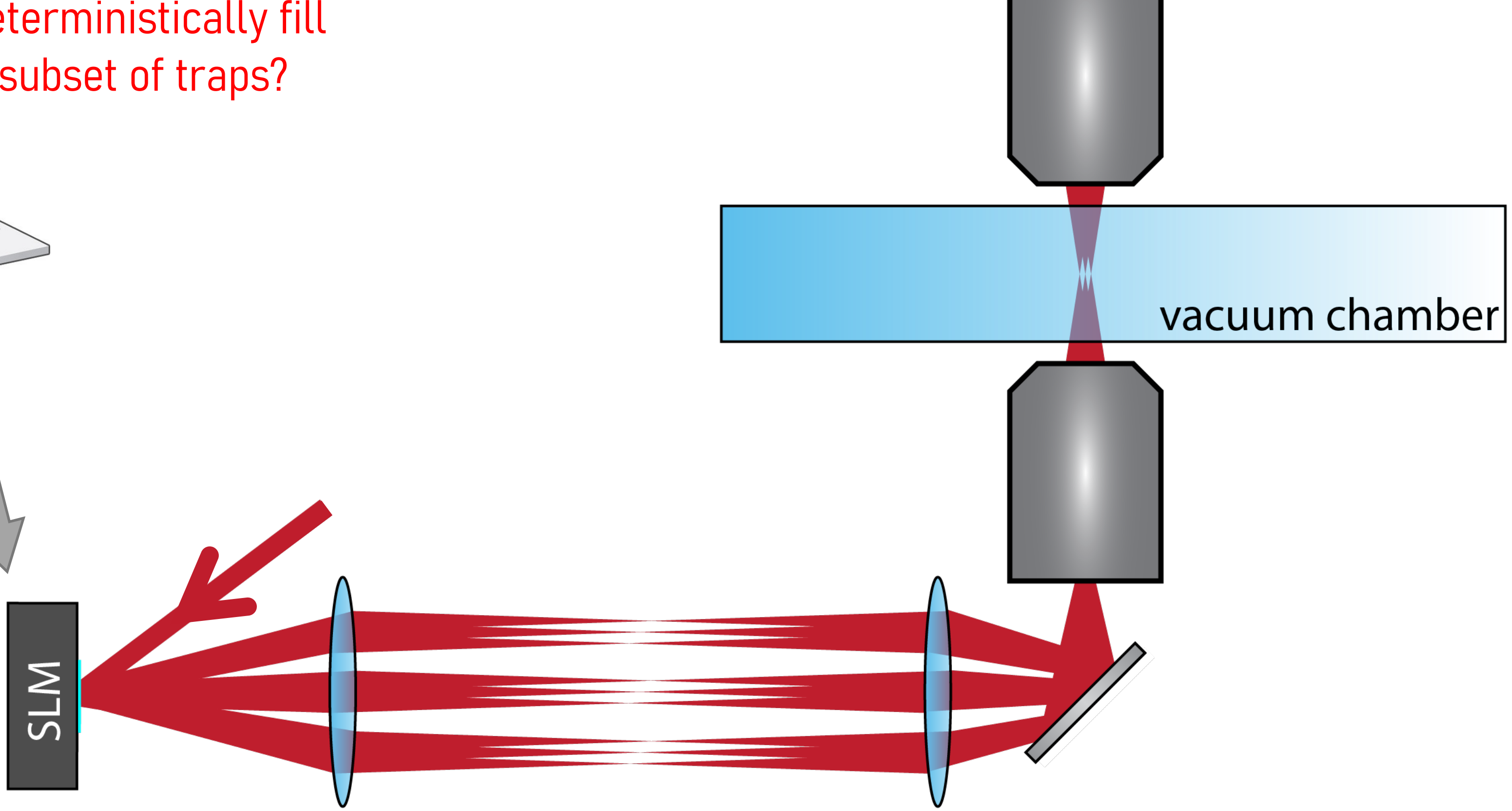
Atoms:



Deterministically fill subset of traps?

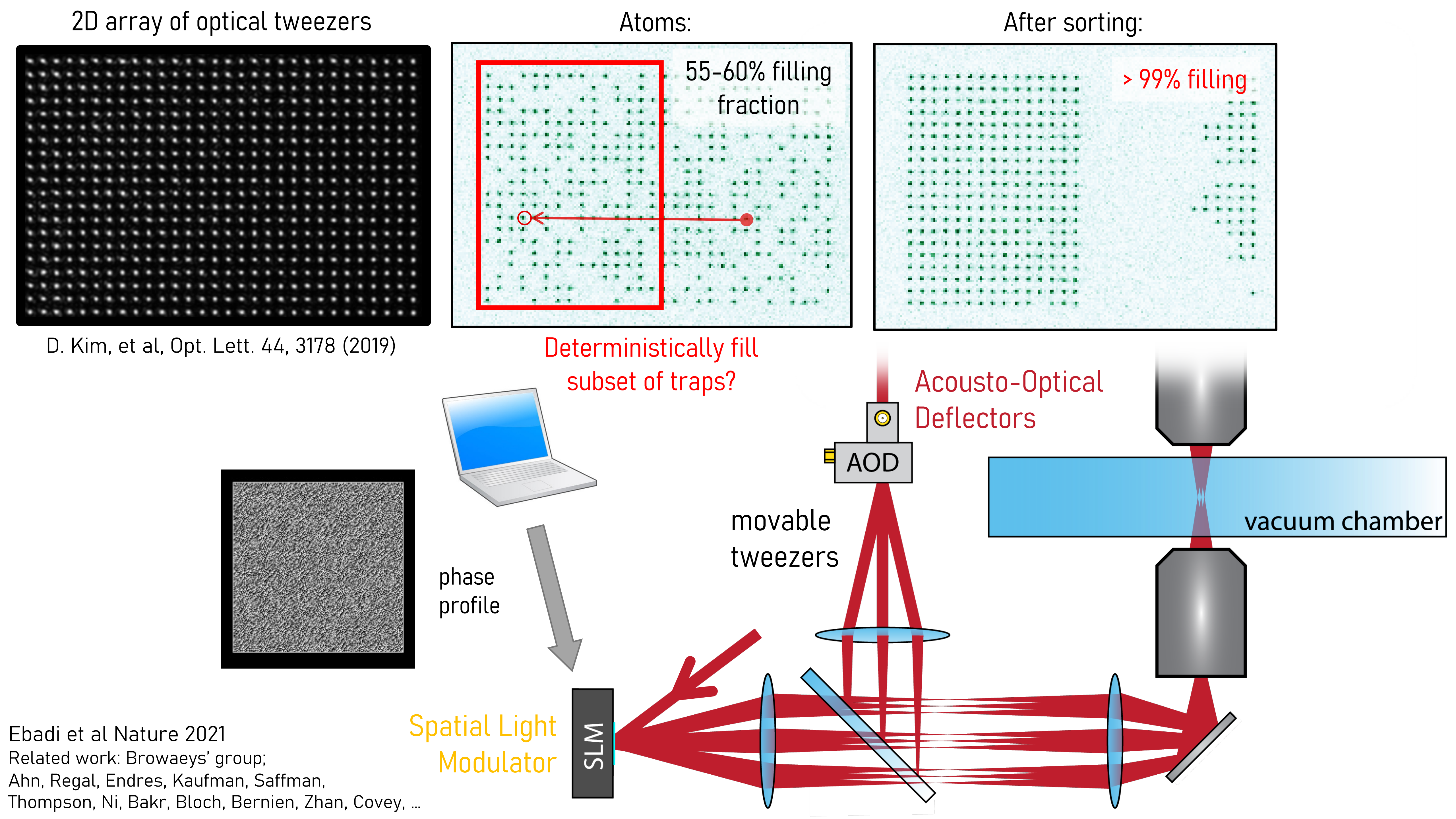


Spatial Light Modulator



Ebadi et al Nature 2021

Related work: Browaeys' group;
Ahn, Regal, Endres, Kaufman, Saffman,
Thompson, Ni, Bakr, Bloch, Bernien, Zhan, Covey, …



2D array of optical tweezers
D. Kim, et al, Opt. Lett. 44, 3178 (2019)
Atoms:
55-60% filling
fraction
Deterministically fill
subset of traps?
After sorting:
> 99% filling
Acousto-Optical
Deflectors
AOD
vacuum chamber
movable
tweezers
phase
profile
Spatial Light
Modulator
SLM
Ebadi et al Nature 2021
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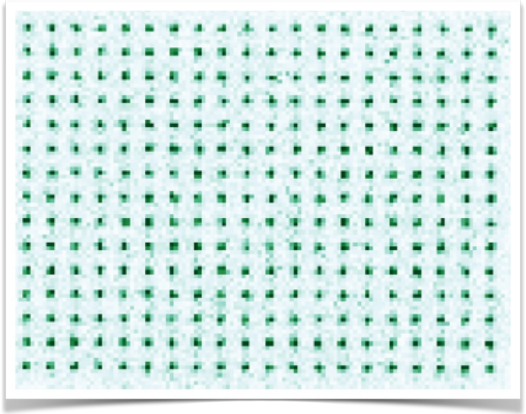
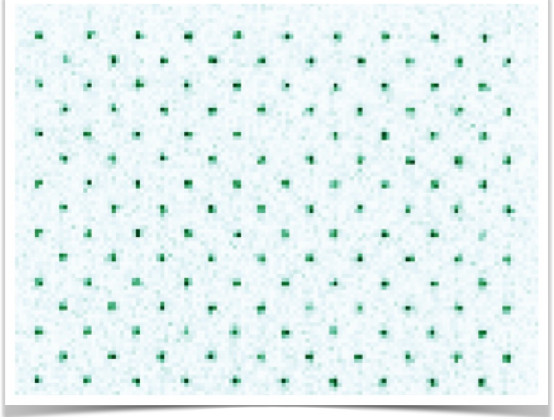
Programmable geometry

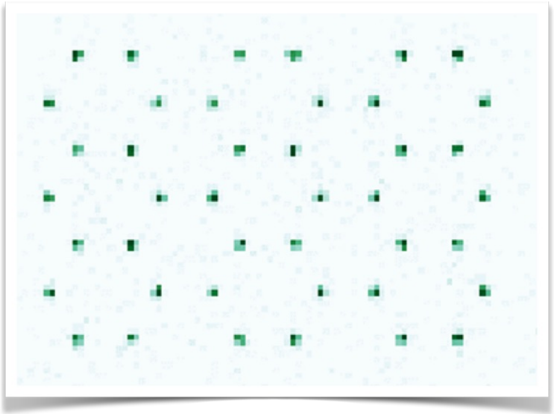
Square



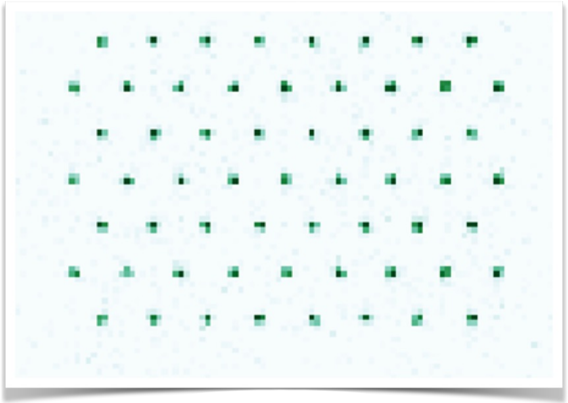
Tilted Square



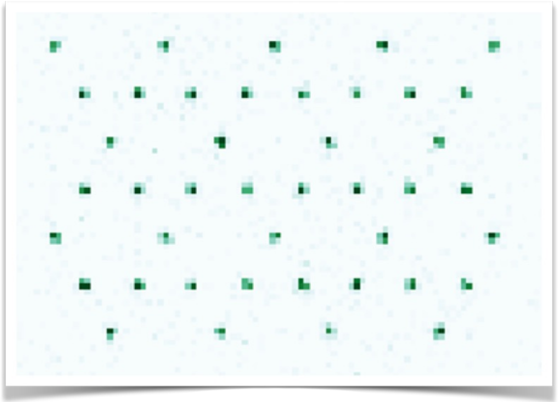
Honeycomb



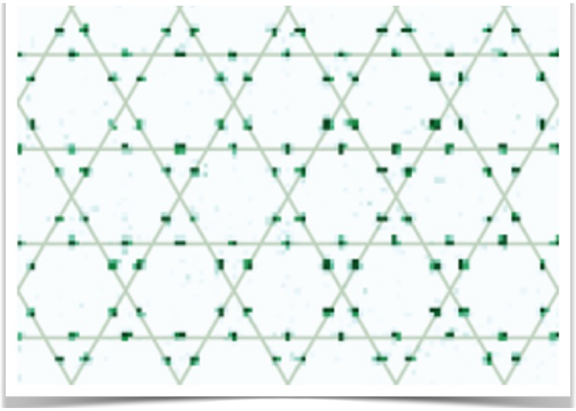
Triangular



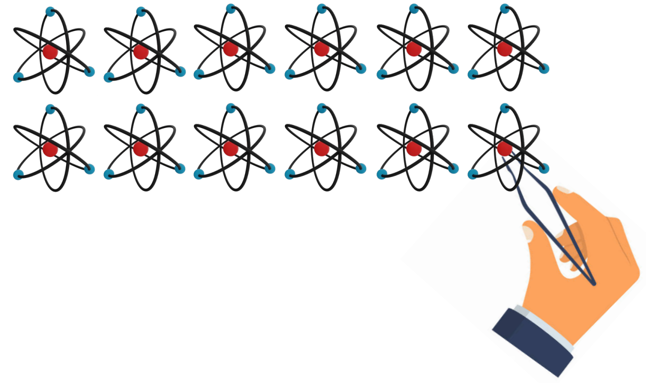
Kagome



Link-kagome (ruby)

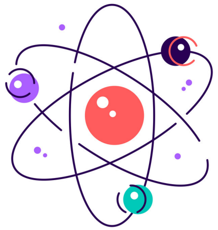


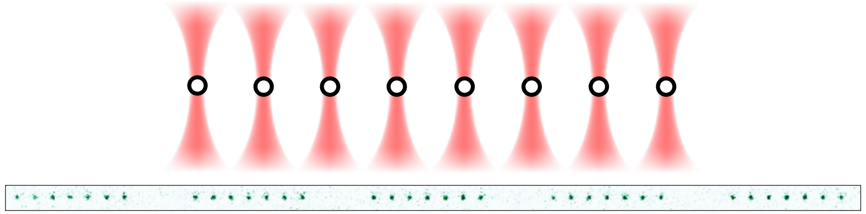
Programmable Rydberg arrays

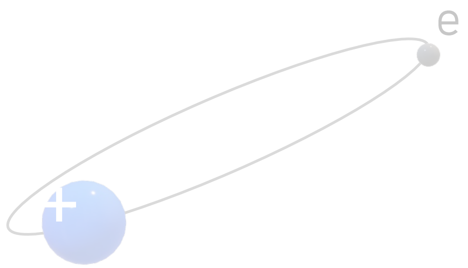


Core ingredients:

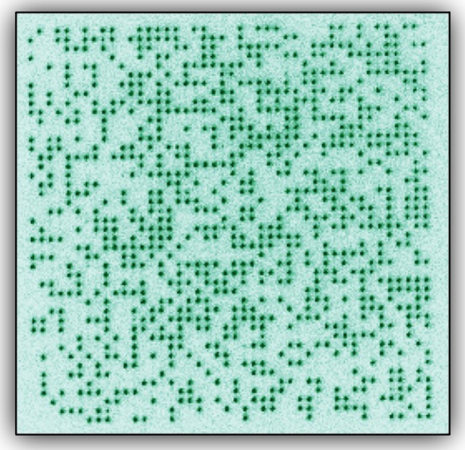
neutral atoms + individual control and site-resolved readout + strong interactions via Rydberg excitations



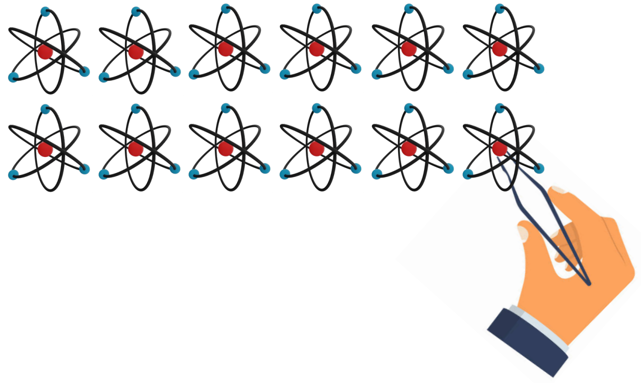




arrays with 100s (up to 1000!) neutral atoms with programmable geometries



Programmable Rydberg arrays



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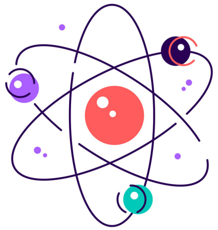
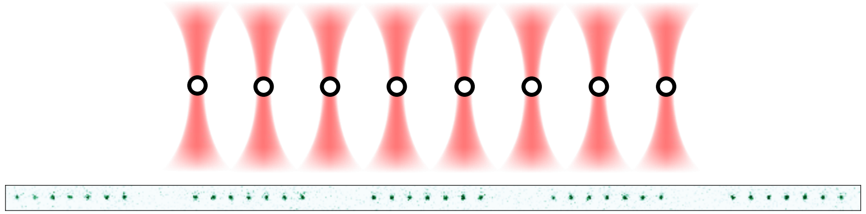
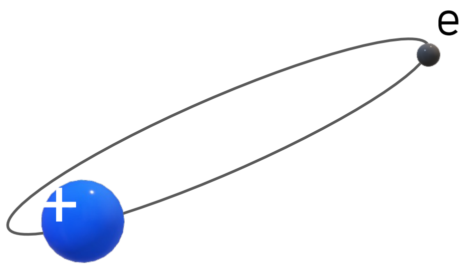
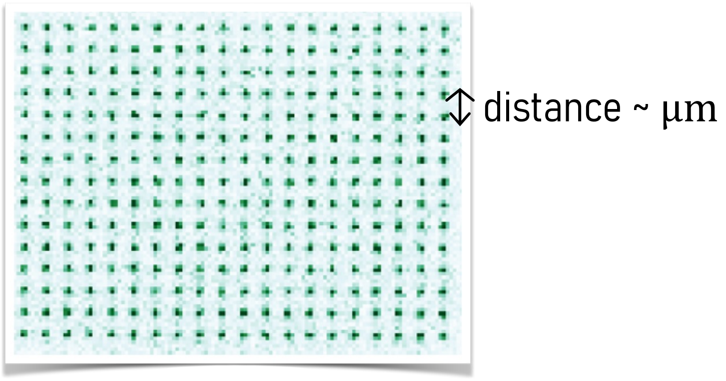






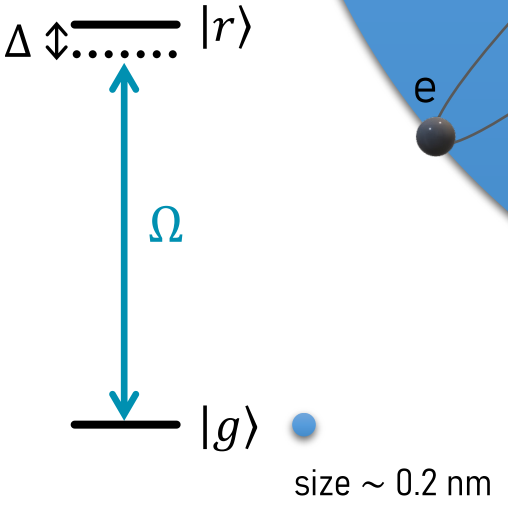
arrays with 100s (up to 1000!) neutral atoms with programmable geometries

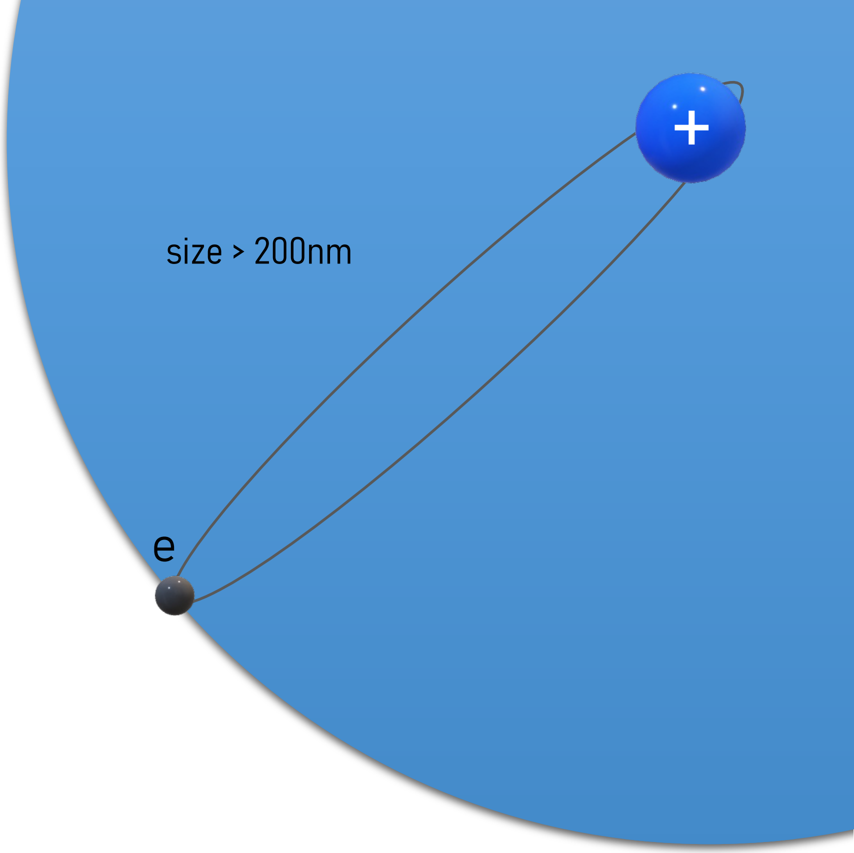
Rydberg states and long-range interactions

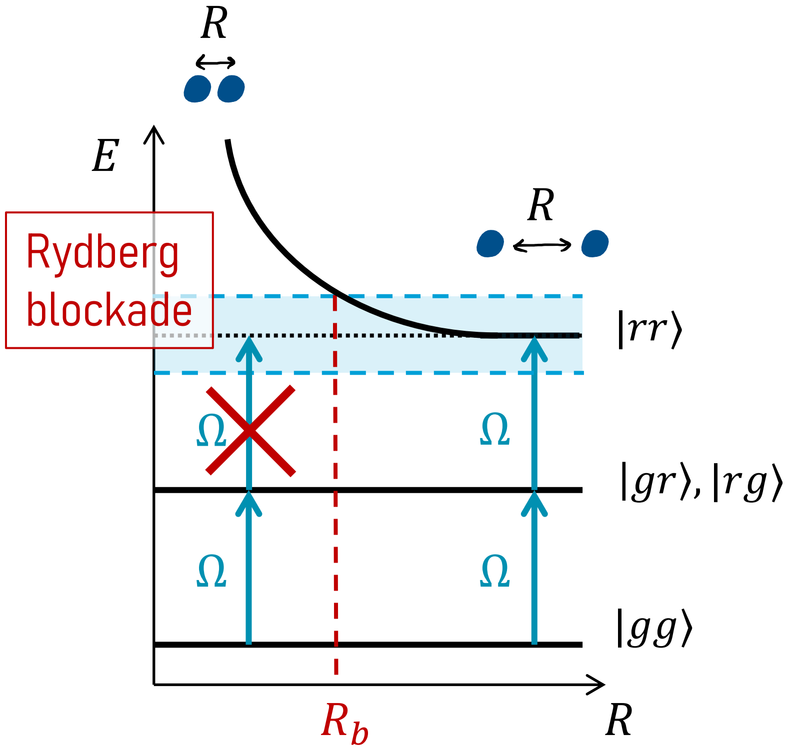


excitation to Rydberg state ($n \sim 40 - 100$):

- lifetime $> 100\ \mu s$
- strong dipole $d \sim n^2 e a_0$







van der Waals interactions $\propto n^{11}/R^6$

$$R \sim 2-5\ \mu m \longrightarrow \frac{V_{int}}{h} \sim 10s\ \text{MHz} - \text{GHz}$$

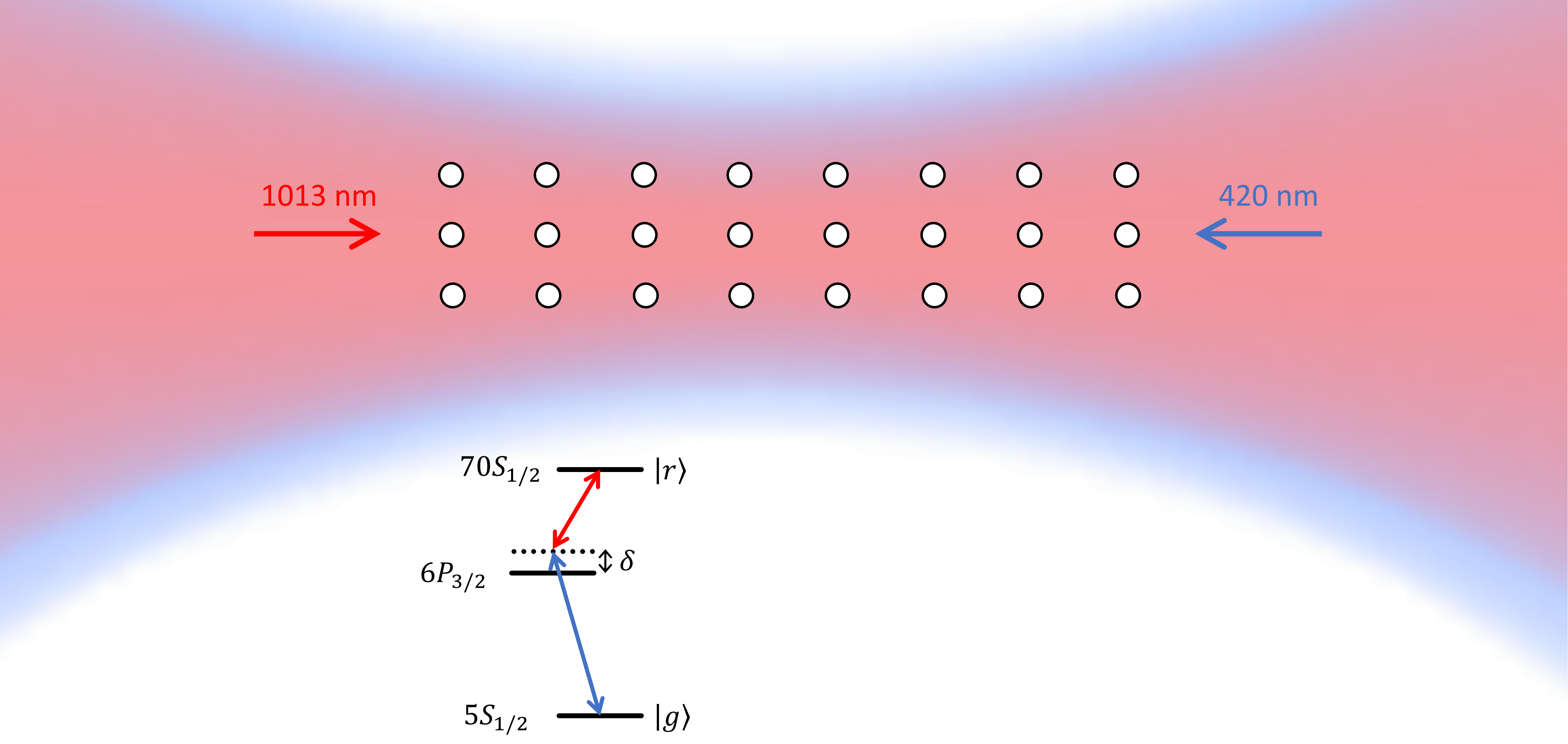
blockade radius R_b :

$$V(R_b) = \Omega$$

Lukin, Zoller 2000
Saffman, RMP 2020
Browaeys, Nat Phys 2020

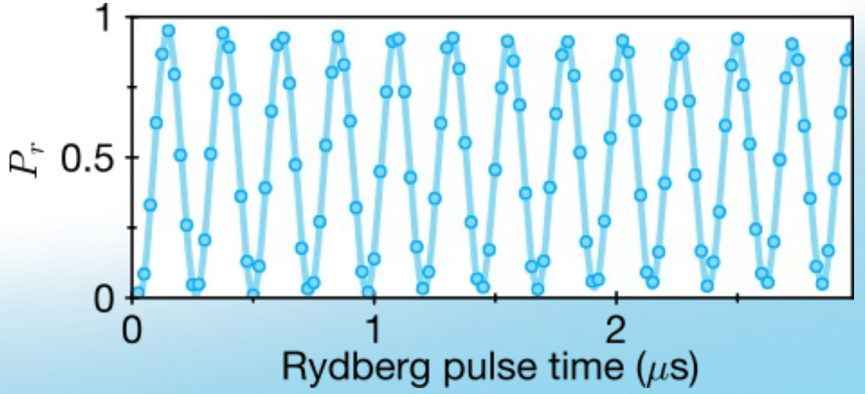
Coherent coupling to Rydberg states

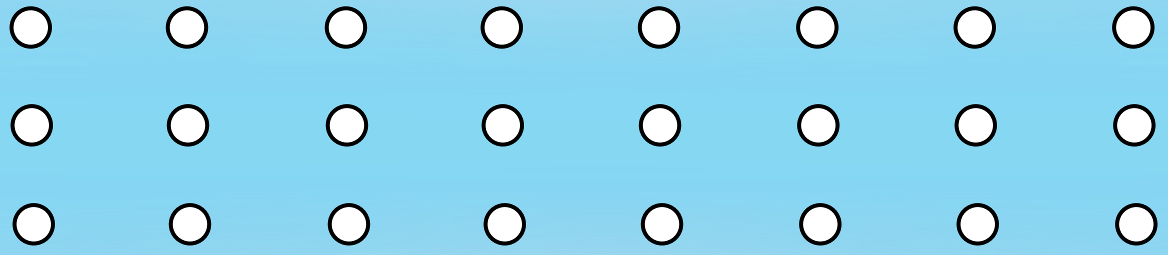
e.g. for ^{87}Rb

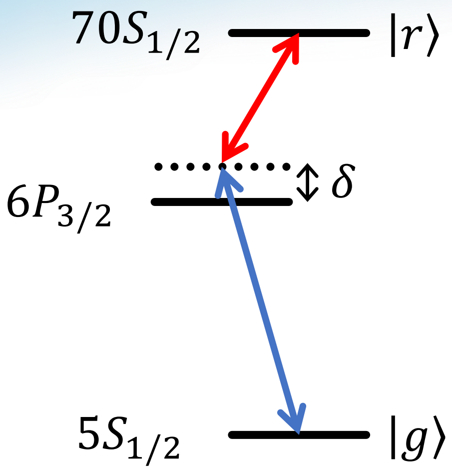


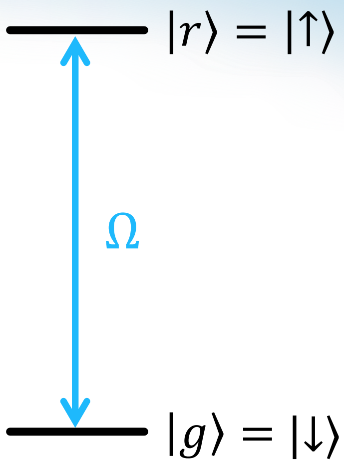
Coherent coupling to Rydberg states

e.g. for ^{87}Rb

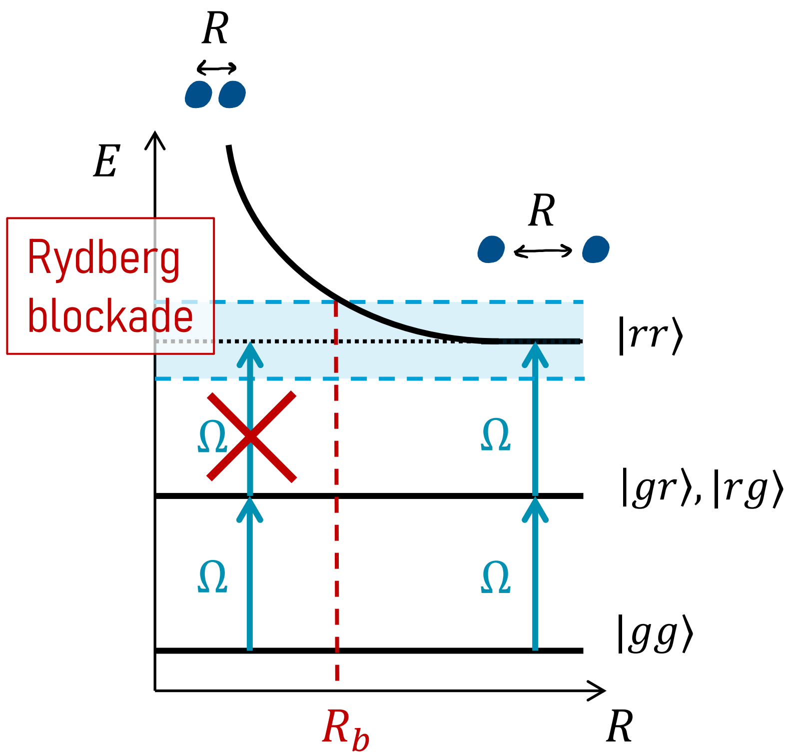


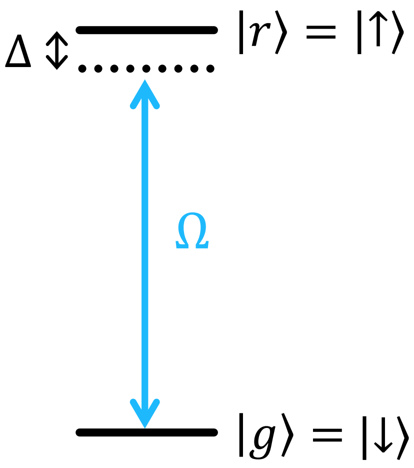


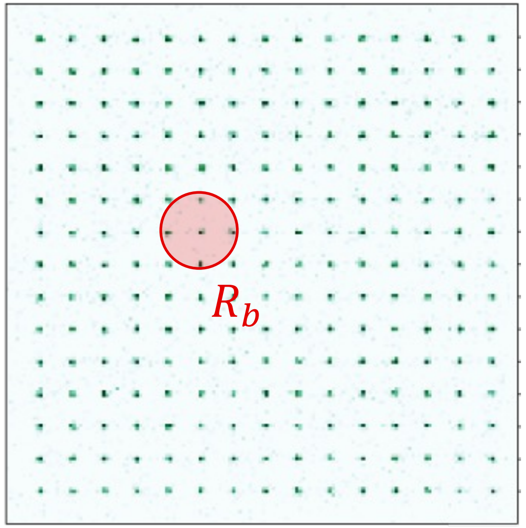




Rydberg blockade and Ising Hamiltonian







$$\mathcal{H} = \frac{1}{2}\Omega(t)\sum_i \sigma_x^{(i)} - \sum_i \Delta(t)\, n_i + \sum_{i<j} V_{ij} n_i n_j$$

$$n_i = |r_i\rangle\langle r_i|$$
$$n_i = (\sigma_z^i + 1)/2$$

drive term — detuning — interaction

Most used type of interaction in Rydberg atom arrays

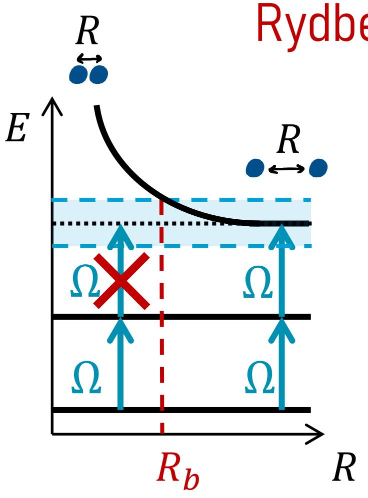
extremely robust!

Quantum Ising model with transverse field $B_\perp \propto \Omega$ and longitudinal field $B_\parallel \propto -\Delta$

But can we access different types of Hamiltonians (types of interaction)?

Interactions between Rydberg atoms (and spin models)

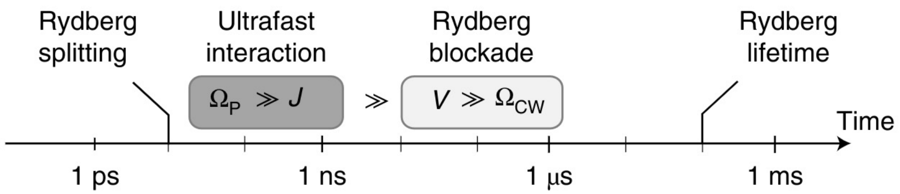
Rydberg blockade



$V_{vdW} \sim \frac{C_6}{R^6}$

⟶ Ising Hamiltonian (ZZ coupling)

Ultrafast interactions



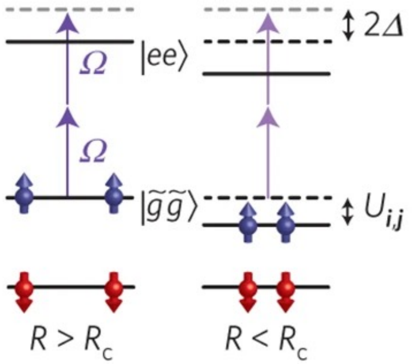
short pulses (~10ps) ⟶ faster than blockade

⟶ coherent energy exchange via Forster oscillations

(see Ohmori group)

Rydberg dressing

nearly-resonant coupling to Rydberg state



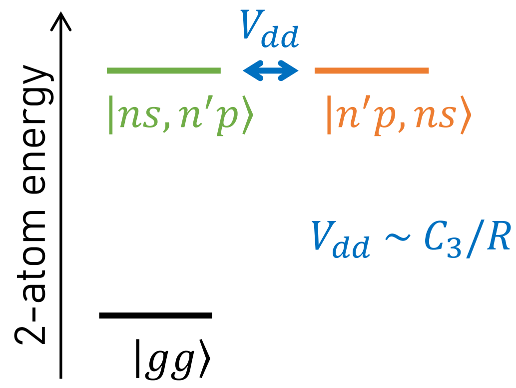
soft-core potential

⟶ Ising, XYZ Hamiltonian

(see e.g.: Bloch, Gross groups)

Dipole-dipole interactions

atoms in two different Rydberg states $|ns\rangle, |n'p\rangle$



$V_{dd} \sim C_3/R^3$

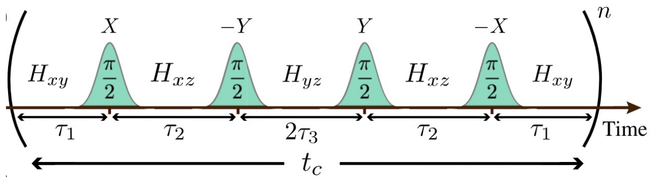
⟶ XY Hamiltonian

(see e.g.: Browaeys group)

Floquet engineering

periodic drive

⟶ effective static Hamiltonian



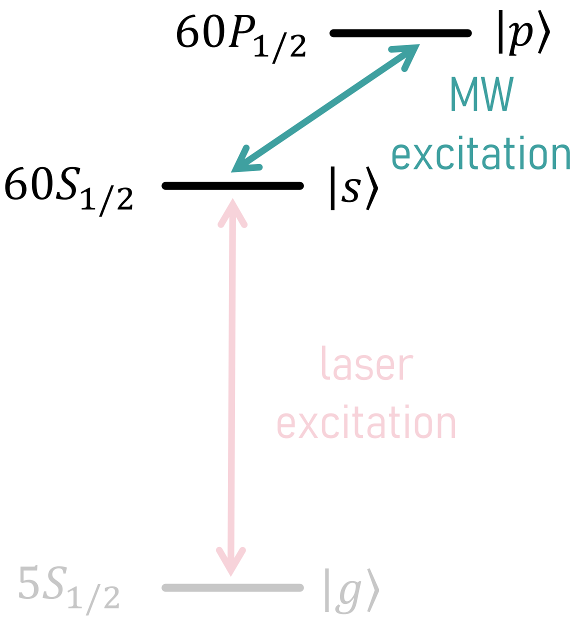
⟶ broad range of Hamiltonians

(see e.g.: Scholl et al, PRX Quantum (2022), Kalinowski et al, arXiv:2211.00017 (2023))

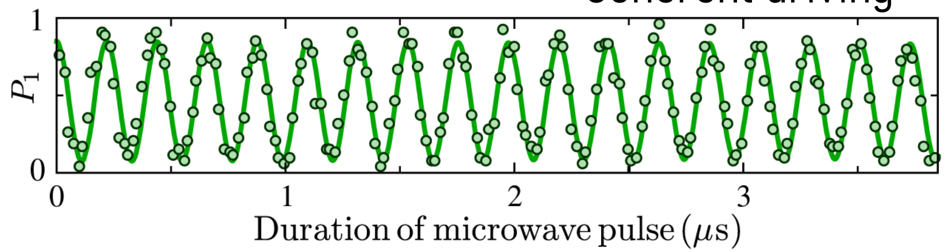
Resonant dipole-dipole interactions

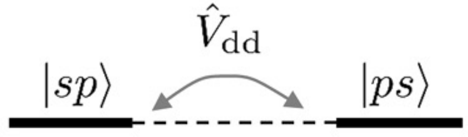
Barredo et al, PRL (2015)
de Leseleuc et al, PRL (2017)

Two distinct Rydberg states



Coherent driving

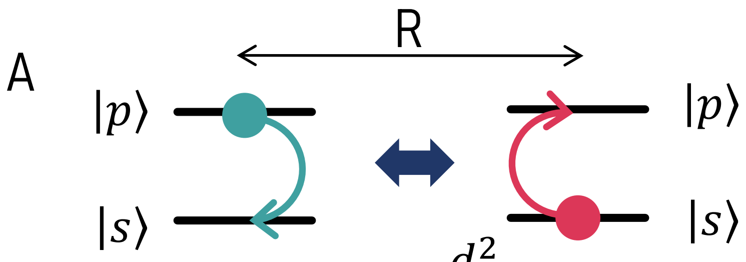




degenerate pair states

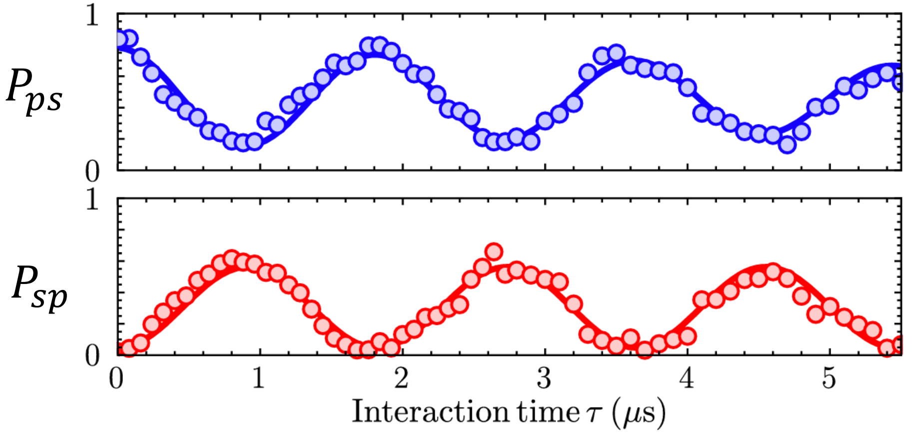
→ resonant dipole-dipole interactions

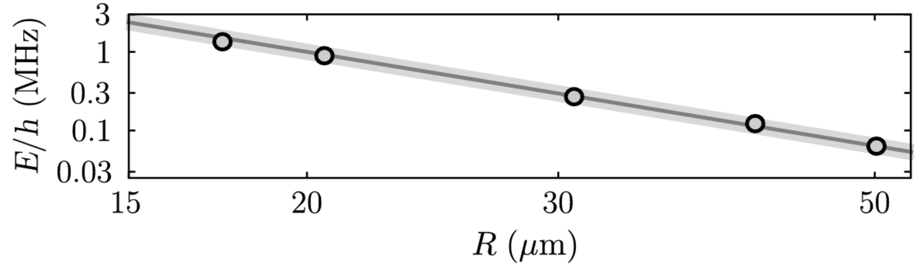
flip-flop interactions

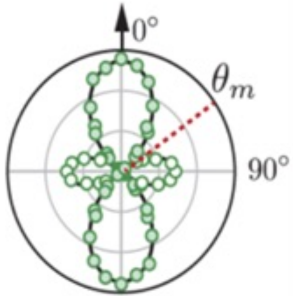


$$V_{dd} \sim \frac{d^2}{R^3}$$

$R = 30\mu m$







anisotropic:

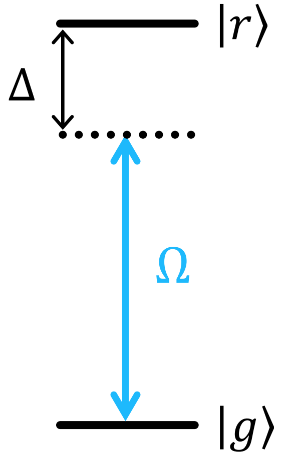
$$\frac{d^2}{R_{ij}^3}(3\cos^2\theta_{ij} - 1)$$

XY Hamiltonian: $$H = \frac{\hbar\Omega_{\mu w}}{2}\sum_i \sigma_x^i - \frac{\hbar\delta_{\mu w}}{2}\sum_i \sigma_z^i + \sum_{i\neq j}\frac{C_3}{R_{ij}^3}\left(\sigma_+^i\sigma_-^j + \sigma_-^i\sigma_+^j\right)$$

for detailed explanation of dipole-dipole interactions, see Antoine Browaeys' lectures at Boulder Summer School 2021

Rydberg dressing

Coupling off-resonantly to the Rydberg state → ground-state weakly admixed with the Rydberg state



weak dressing regime: $\Omega \ll \Delta$

small admixture of the Rydberg state

dressed ground state: $|\tilde{g}\rangle = |g\rangle + \beta|r\rangle$, $\beta = \Omega/2\Delta$

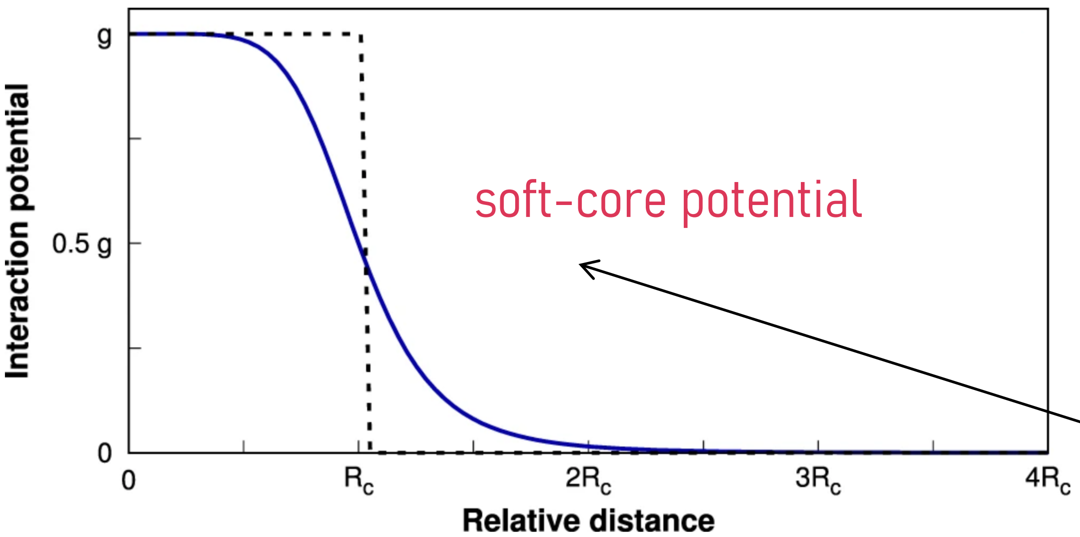
lifetime of $|\tilde{g}\rangle$: $\tau_r/\beta^2 \gg \tau_r$ (bare Rydberg state)

Effective interactions between atoms in $|\tilde{g}\rangle$:

at large R ($R > R_c$): $U(R) \approx \beta^4 V(R)$

reduced by probability of exciting both atoms at once

Ryd-Ryd interaction potential



at small $R < R_c$: blockade!

saturation of the potential to $U_0 = \hbar\Omega^4/(8|\Delta|^3)$

I. Bouchoule et al, PRA 6 (2002); G. Pupillo et al, PRL 104 (2010); J.E. Johnson et al, PRA 82 (2010); J.B. Balewski et al, New J. Phys. 16 (2014)

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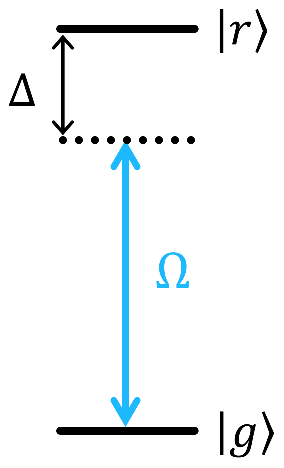

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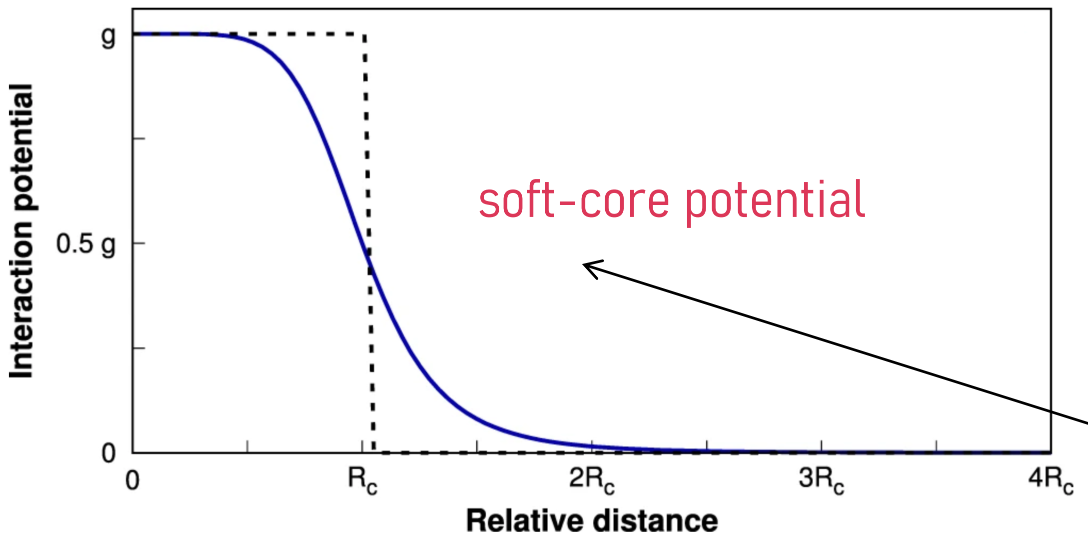


Rydberg dressing used so far mostly to realize Ising model (e.g. Y. Jau et al, Nature Phys.12 (2016))

Recently used to achieve spin squeezing: W. Eckner … A. Kaufman, arXiv (2023); J. Hines … M. Schleier-Smith, arXiv (2023)

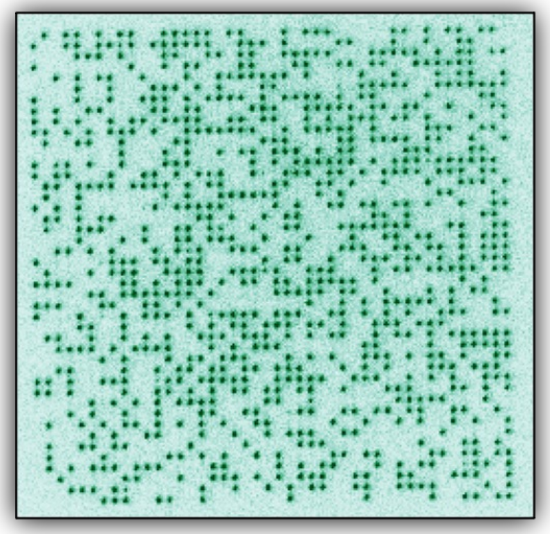
Interesting potential application explored in C. Gross's group: realize universally programmable analog qubit couplings

In L. Steinert … C. Gross, arXiv:2206.12385 (2022):
2-color Rydberg dressing to engineer XYZ-type interactions
(no coherent interactions yet due to experimental limitations)

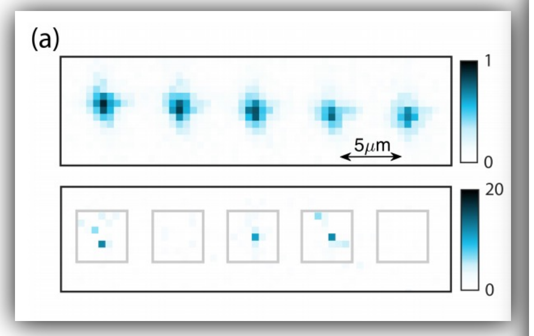
I. Bouchoule et al, PRA 6 (2002); G. Pupillo et al, PRL 104 (2010); J.E. Johnson et al, PRA 82 (2010); J.B. Balewski et al, New J. Phys. 16 (2014)

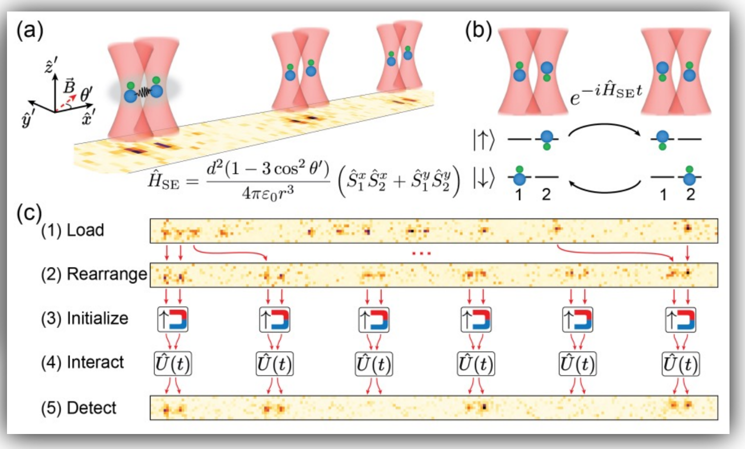
Different types of tweezer arrays

Alkali atoms

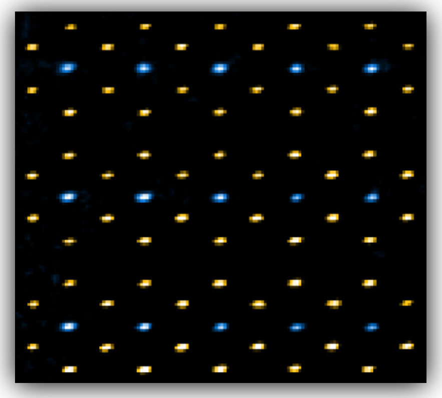


Molecules

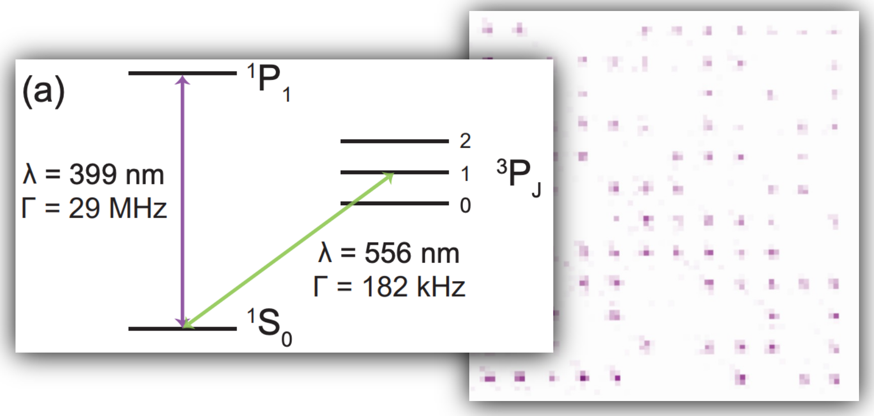




Atomic mixtures



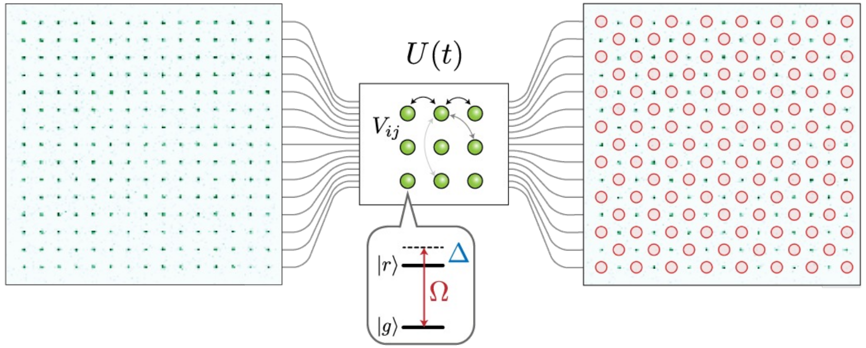
Alkaline-earth atoms



QuEra: programmable quantum simulator available on the cloud

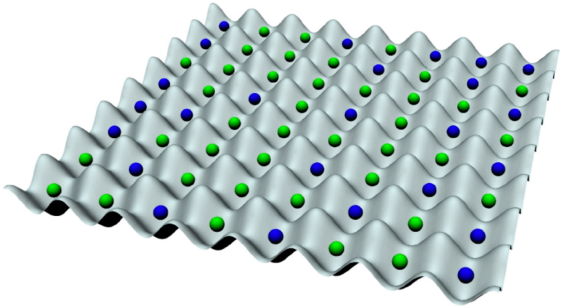
Endres, Thompson, Kaufman, Bloch, Doyle, Ni, Bernien, Cheuck, Covey… + startup companies: QuEra, Atom Computing, Pasqal, Cold Quanta…

Programmable quantum platform: modes of operation



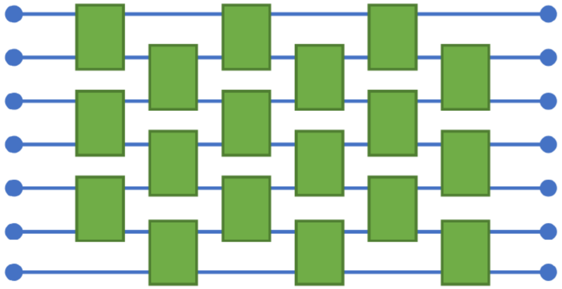
Analog

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