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Basics on Rydberg tweezer experiments

Introductory Course on Ultracold Quantum Gases 2023

Manfred J. Mark,

Institute for Experimental Physics, University Innsbruck

Institute for Quantum Optics and Quantum Information, Austrian Academy of Sciences, Innsbruck

ÖAW AUSTRIAN ACADEMY OF SCIENCES
INSTITUTE FOR QUANTUM OPTICS AND QUANTUM INFORMATION

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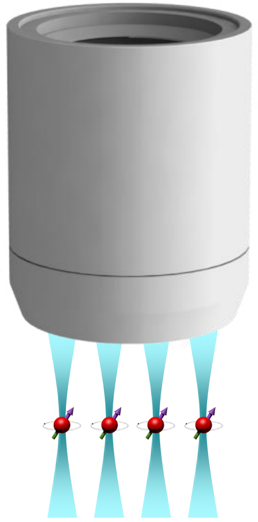
Preamble



OUTLINE

Basics on Tweezers

Tweezer arrays

Experiments with neutral atoms

Experiments with Rydberg atoms

Basic knowledge

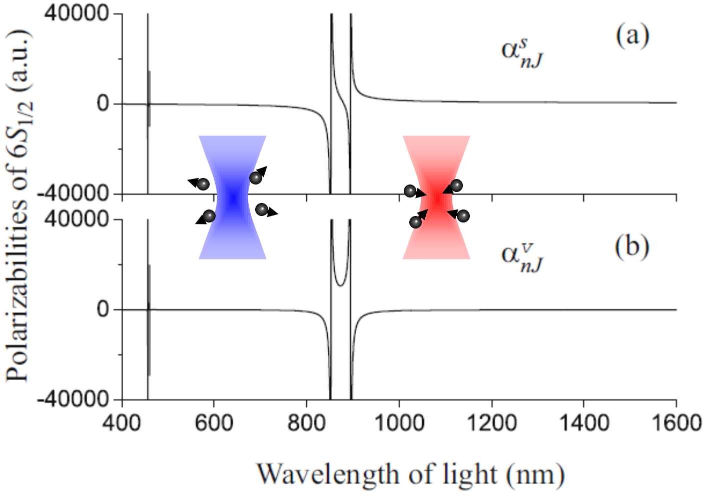
Atomic polarizability

Light fields create attractive or repulsive forces depending on the frequency detuning to atomic transitions due to the AC Stark shift

$$U_{\mathrm{dip}} = -\frac{1}{2}\langle \mathbf{pE} \rangle = -\frac{1}{2\epsilon_0 c}\,\mathrm{Re}(\alpha)\, I$$

Example cesium

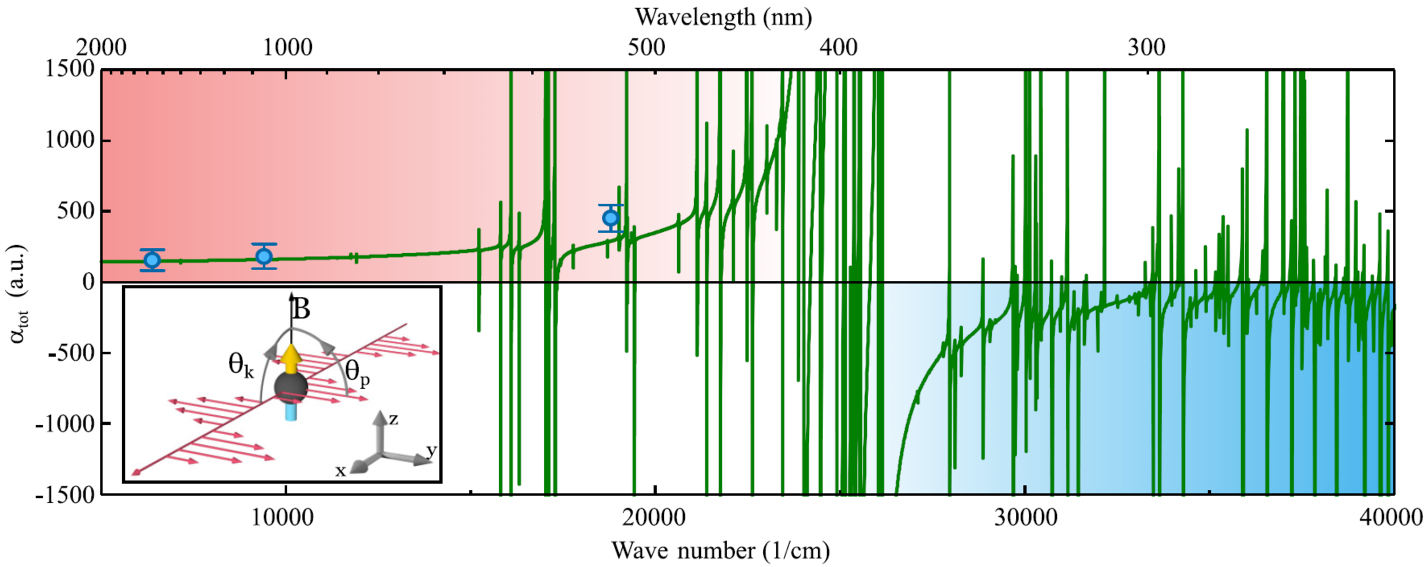
Groundstate cesium atoms have two main optical transitions



Eur. Phys. J. D 67, 92 (2013)

Example erbium

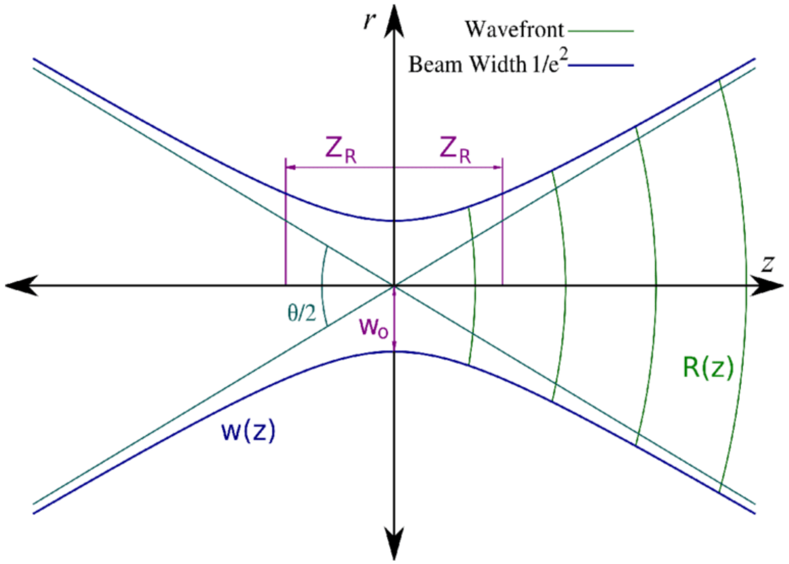
Groundstate erbium atoms have many optical transitions with varying strength



PHYSICAL REVIEW A 97, 012509 (2018)

Basic knowledge

Gaussian beams



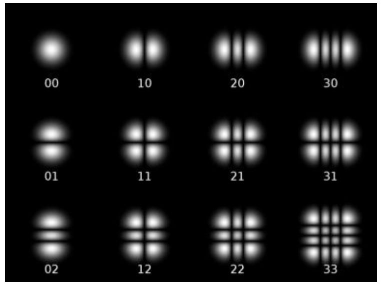
$$I(r,z) = I_0(z)\exp\left(-2\frac{r^2}{w^2(z)}\right)$$

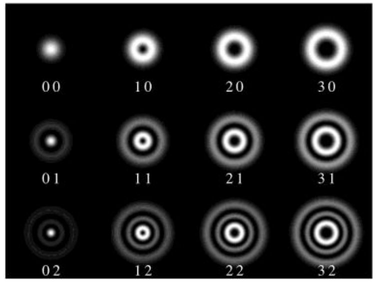
$$I_0(z) = \frac{2P}{\pi w^2(z)}$$

$$w(z) = \sqrt{w_0^2 + \frac{\lambda^2 z^2}{\pi^2 w_0^2}}$$

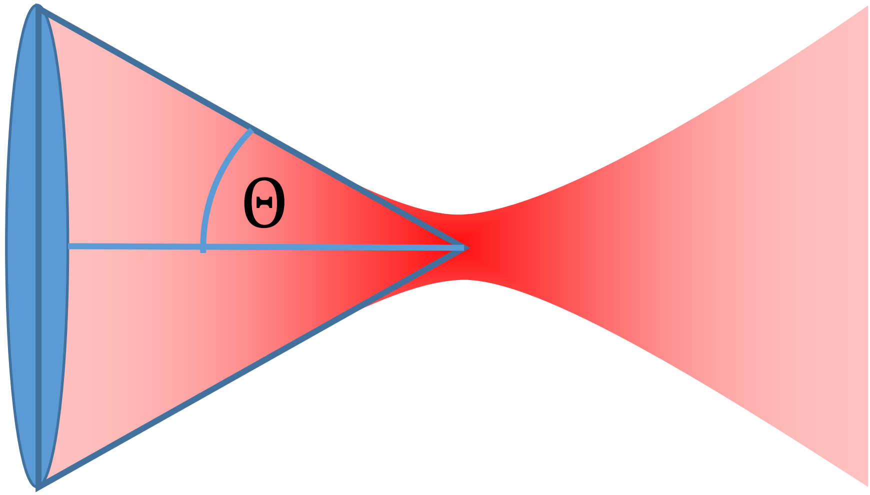
$$z_R = \frac{\pi w_0^2}{\lambda}$$

In principle also other modes possible e.g.
Laguerre-Gauss, Hermite-Gauss, …





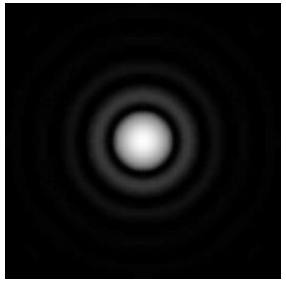
Creating single beam traps



Numerical aperture: $NA = n \sin\Theta$

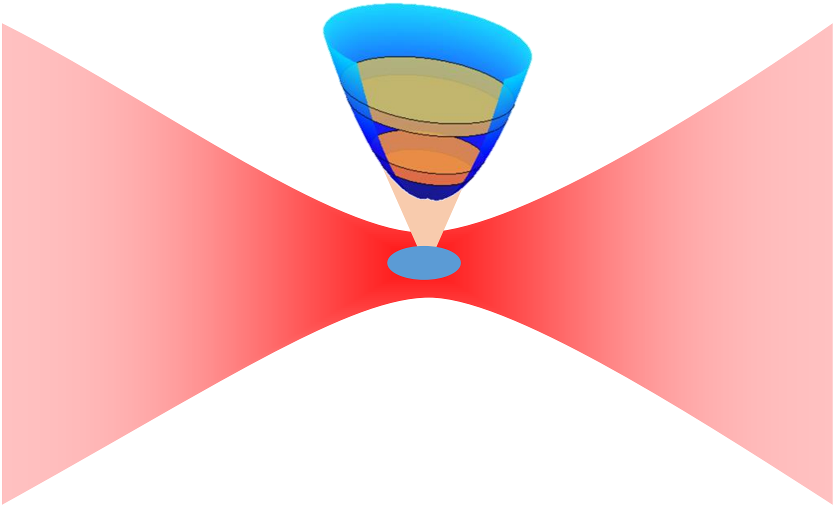
Any circular aperture leads to diffraction
$\Rightarrow$ Airy pattern instead of pure Gaussian shape
In reality: something in between

Airy disk: $r = \dfrac{0.61\lambda}{\mathrm{NA}}$



Basic knowledge

Tweezer trap parameters



- Size: $d = \frac{1.22\lambda}{\mathrm{NA}} \approx 2w_0$
- Radial trap frequency: $\omega_R \sim \frac{\sqrt{P}}{w_0^2}$
- Longitudinal trap frequency: $\omega_z \sim \omega_R \frac{\lambda}{\sqrt{2}\pi w_0}$
- Trap depth: $U_0 \sim \frac{P}{w_0^2}$

Examples

Browaeys Group:

- NA = 0.5
- λ = 850nm
- d ~ 2um
- U_0 ~ 1mK
- w_R ~ 100kHz
- w_z ~ 20kHz

Barredo, D. et al.
Science 354, 1021-1023 (2016)

Endres Group:

- NA = 0.5
- λ = 515nm
- d ~ 1um
- U_0 ~ 1.4mK
- w_R ~ 210kHz
- w_z ~ 32kHz

Cooper, A. et al.
Phys. Rev. X 8, 041055 (2018)

Outline

Basics on Tweezers

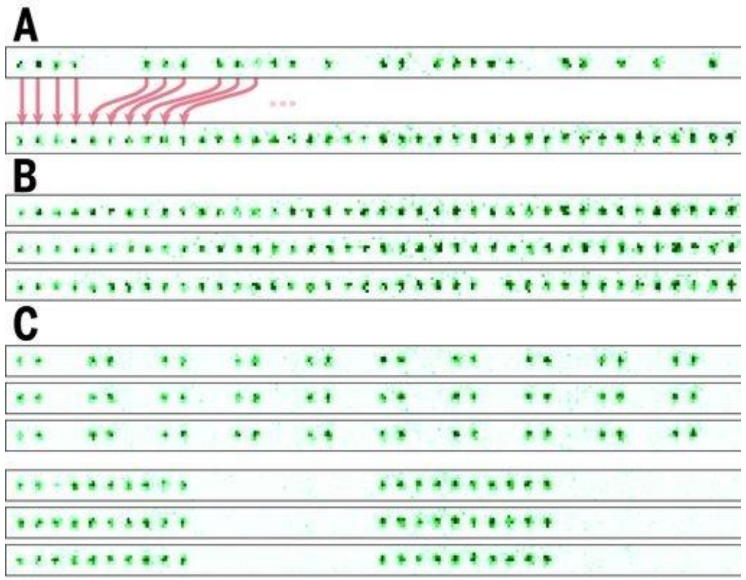
Tweezer arrays

Experiments with neutral atoms

Experiments with Rydberg atoms

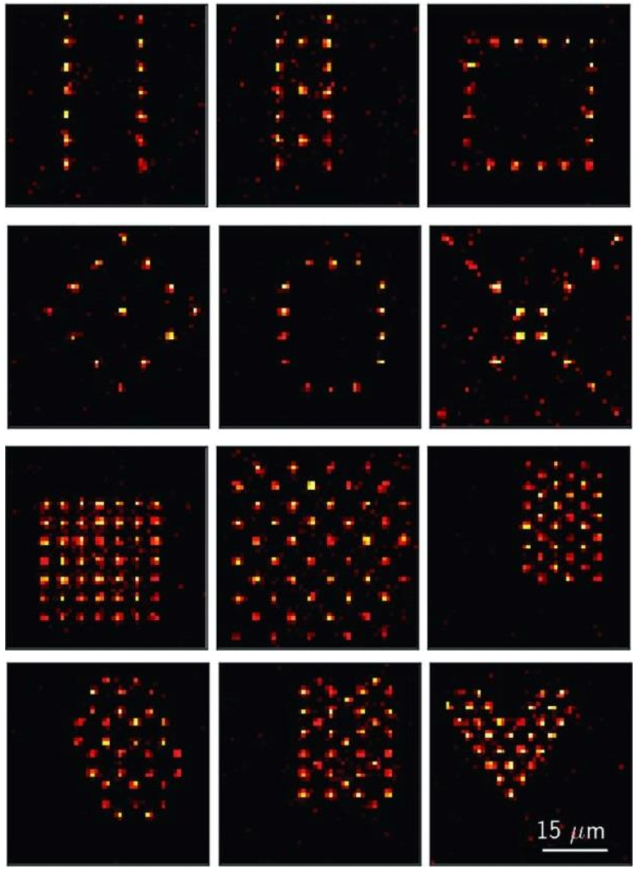
Tweezer arrays

1D



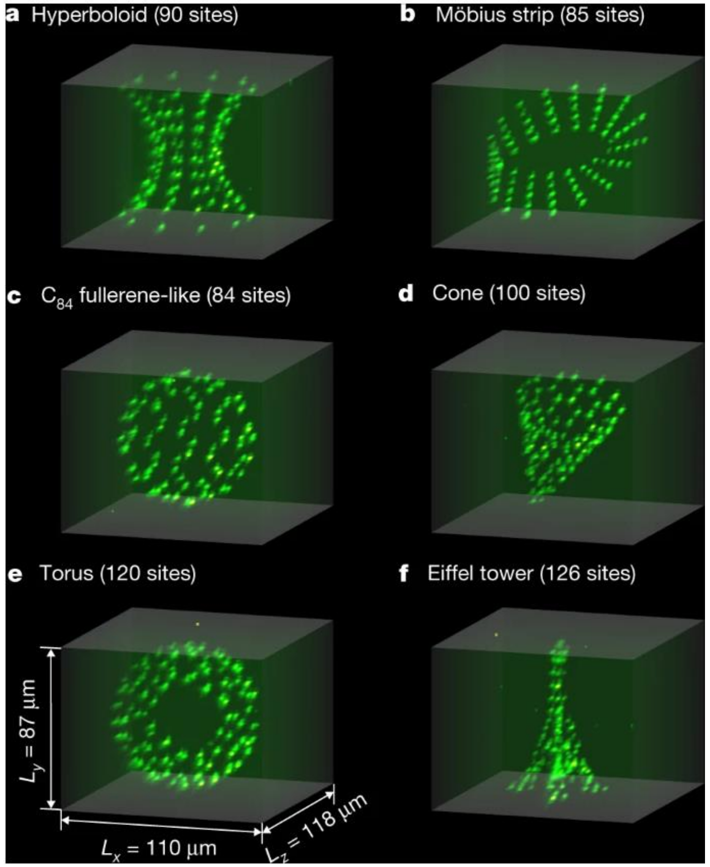
Endres, M. et al.
Science 354, 1024-1027 (2016)

2D



Barredo, D. et al.
Science 354, 1021-1023 (2016)

3D



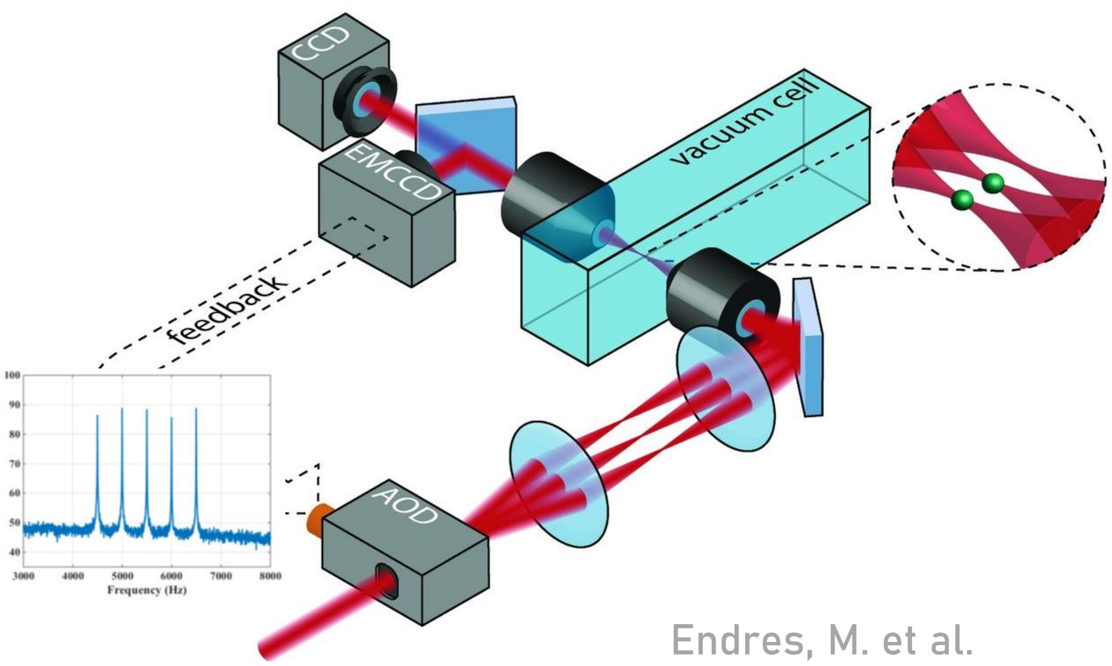
Barredo, D. et al.
Nature 561, 79–82 (2018)

Creating a 1D Tweezer array

Optical setup

Ingredients:

- High-NA Objective
- Large-Bandwidth AOD to create multiple spots



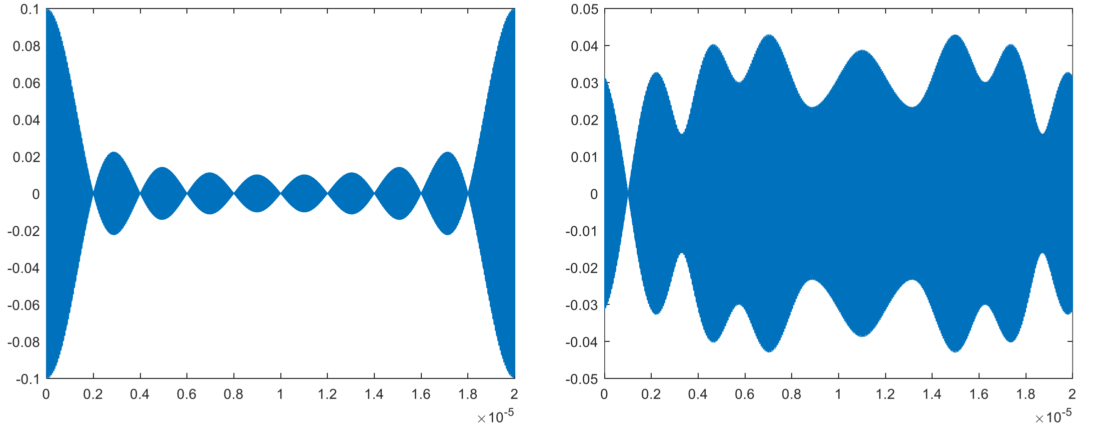
Endres, M. et al.
Science 354, 1024-1027 (2016)

Driving Signal

Create Multitone RF-Signal with 1 frequency for each Tweezer position

Challenges:

- CREST-Factor / PAPR (Peak-to-Average Power Ratio)
- IMD (Inter-Modulation Distortion) from nonlinearities



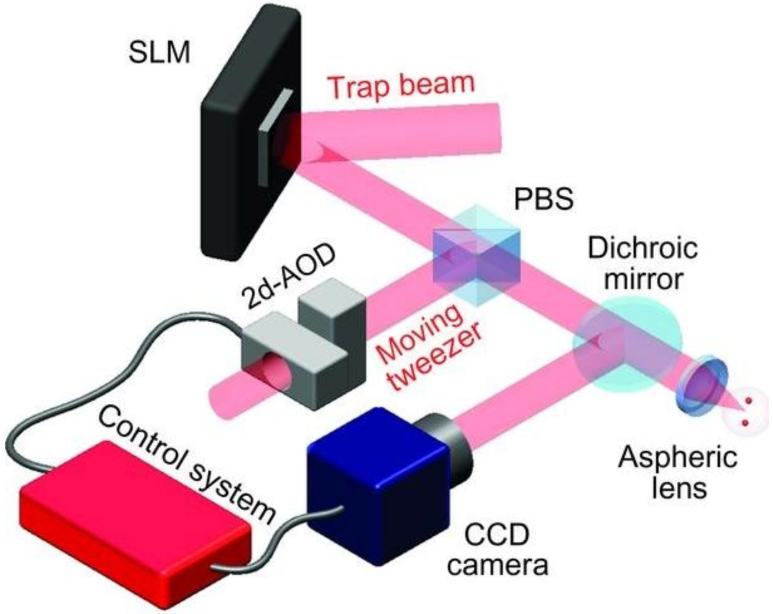
Waveform of a multitone signal with 10 frequencies with 0 relative phases (left) and Neumann phases (right)

TWEEZER ARRAYS

Creating a 2D Tweezer array

Ingredients:

- High-NA Objective
- Large-Bandwidth 2D-AOD and/or SLM to create multiple spots
- 2D-AOD for manipulation

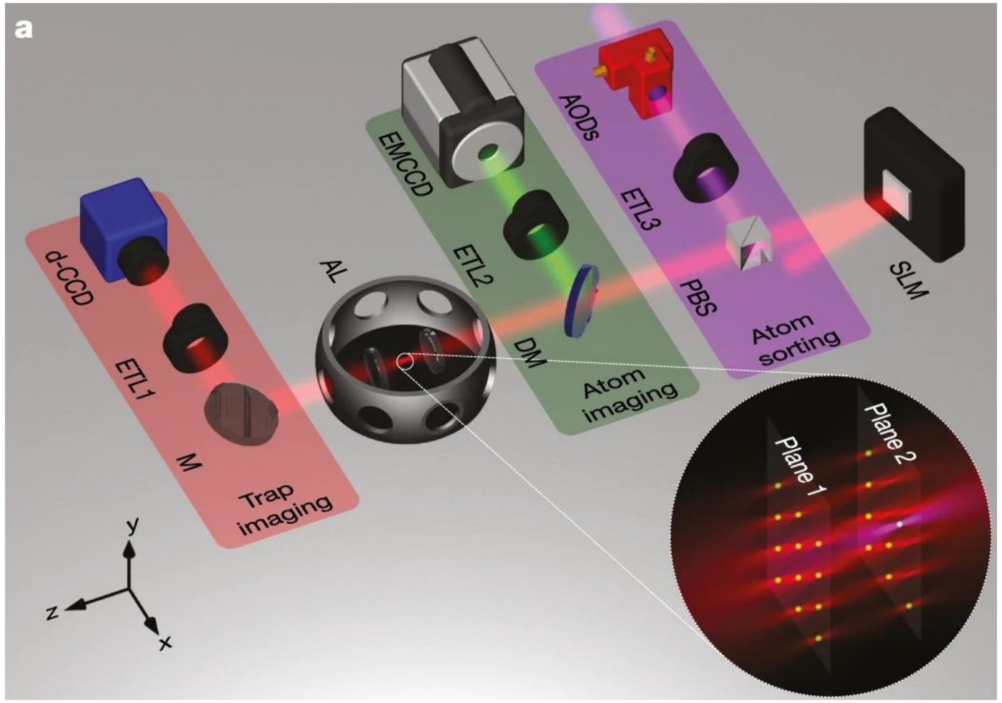


Barredo, D. et al.
Science 354, 1021-1023 (2016)

Creating a 3D Tweezer array

Ingredients:

- High-NA Objective
- Large-Bandwidth 2D-AOD and SLM to create multiple spots
- Electro-tunable lenses for 3D manipulation and imaging

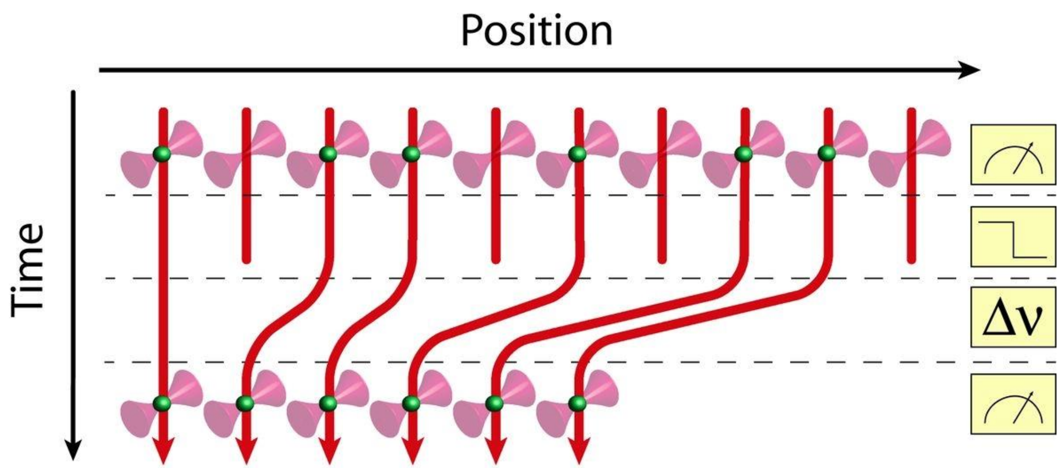


Barredo, D. et al.
Nature 561, 79–82 (2018)

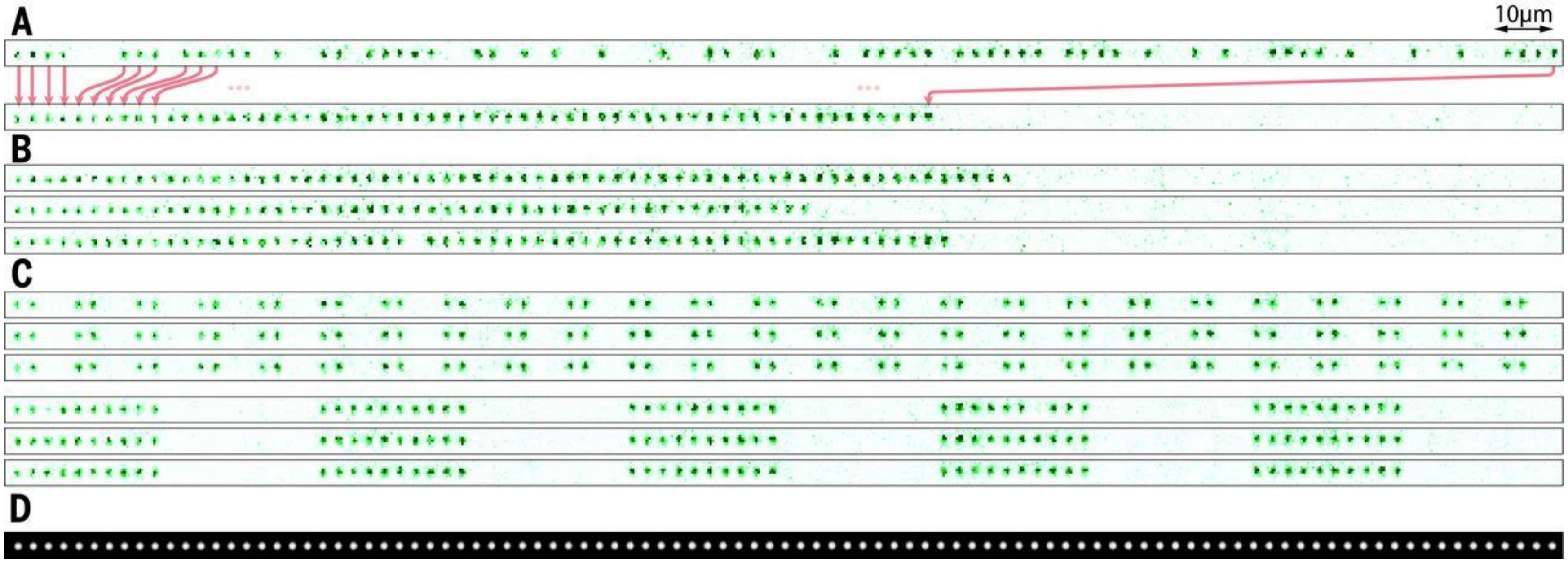
Controlling a 1D Tweezer array

Sorting / Ordering

1) Check initial occupations via imaging
2) Switch off empty traps
3) Move occupied traps to final positions
4) Check success with imaging



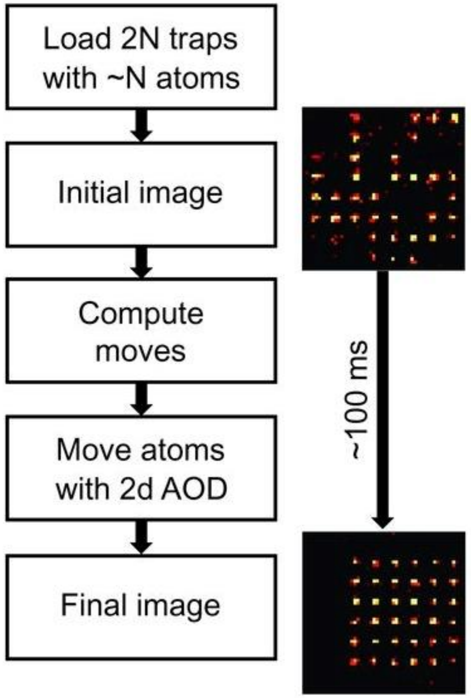
Example images

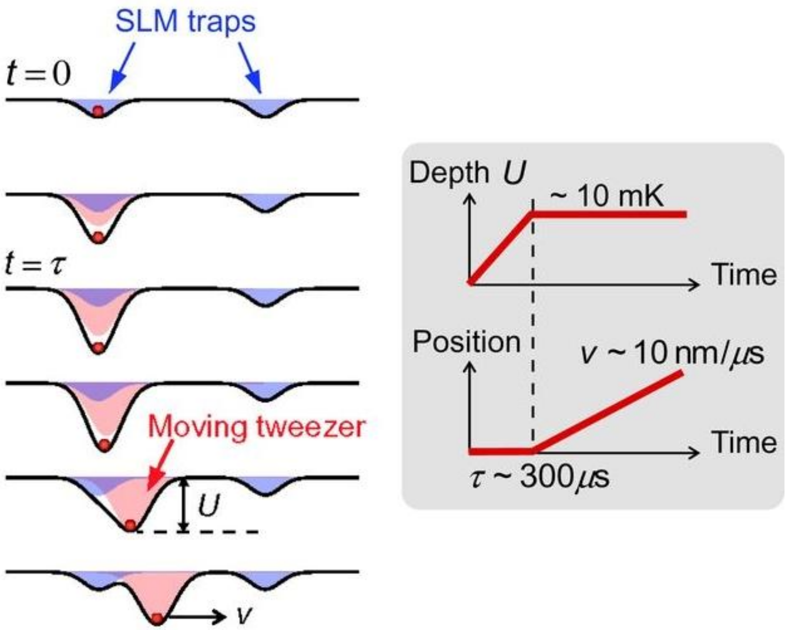


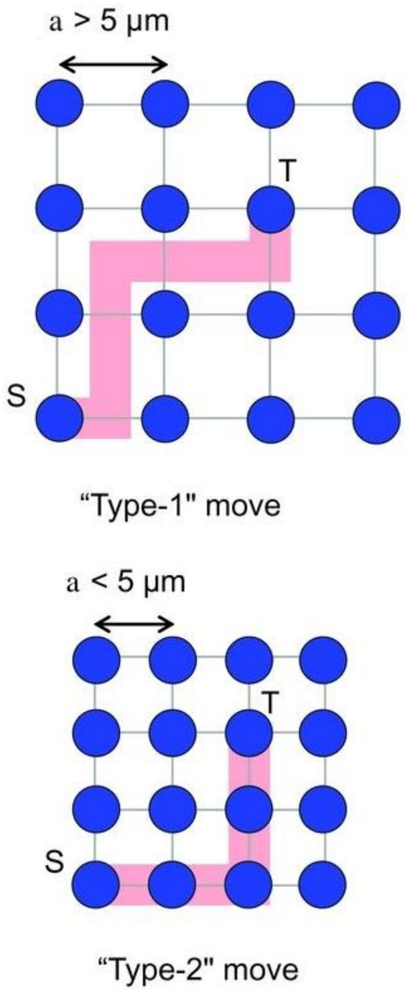
Endres, M. et al.
Science 354, 1024-1027 (2016)

Controlling a 2D Tweezer array (SLM+AOD)

Sorting / Ordering







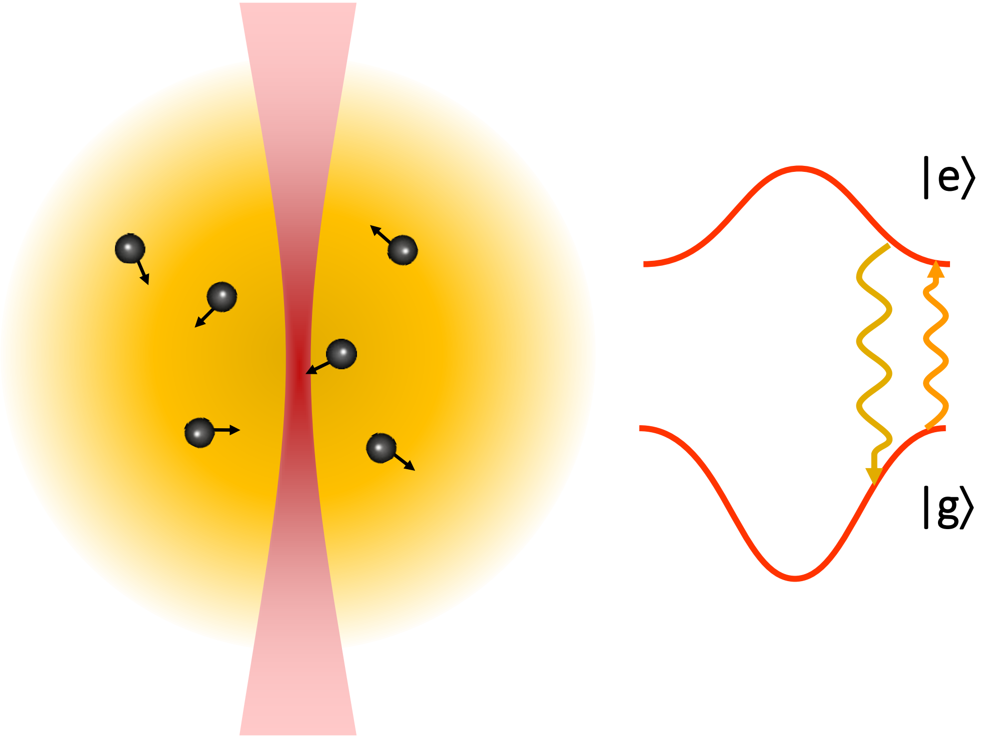
Endres, M. et al.
Science 354, 1024-1027 (2016)

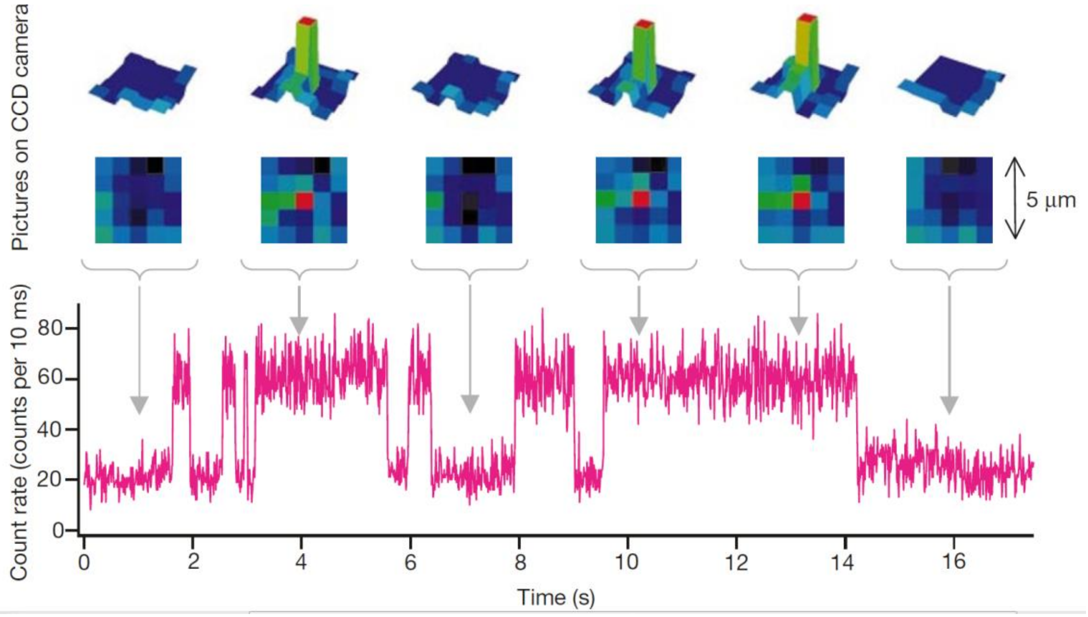
Outline

- Basics on Tweezers
- Tweezer arrays
- **Experiments with neutral atoms**
- Experiments with Rydberg atoms

Loading atoms into tweezers

Superimpose Magneto-optical trap with tweezers

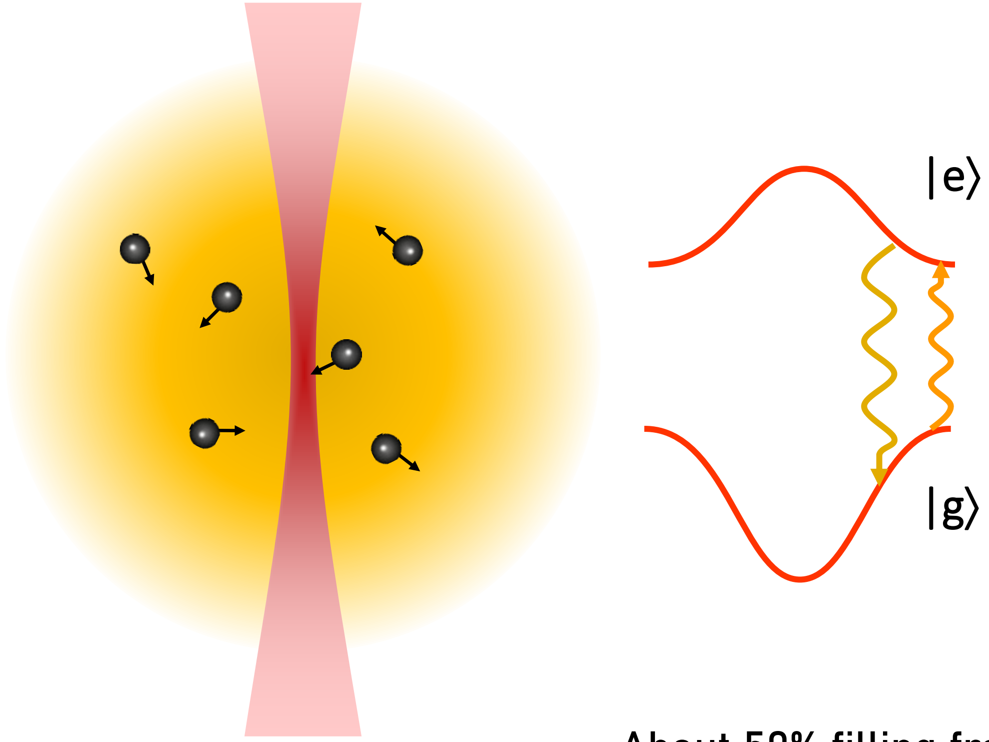




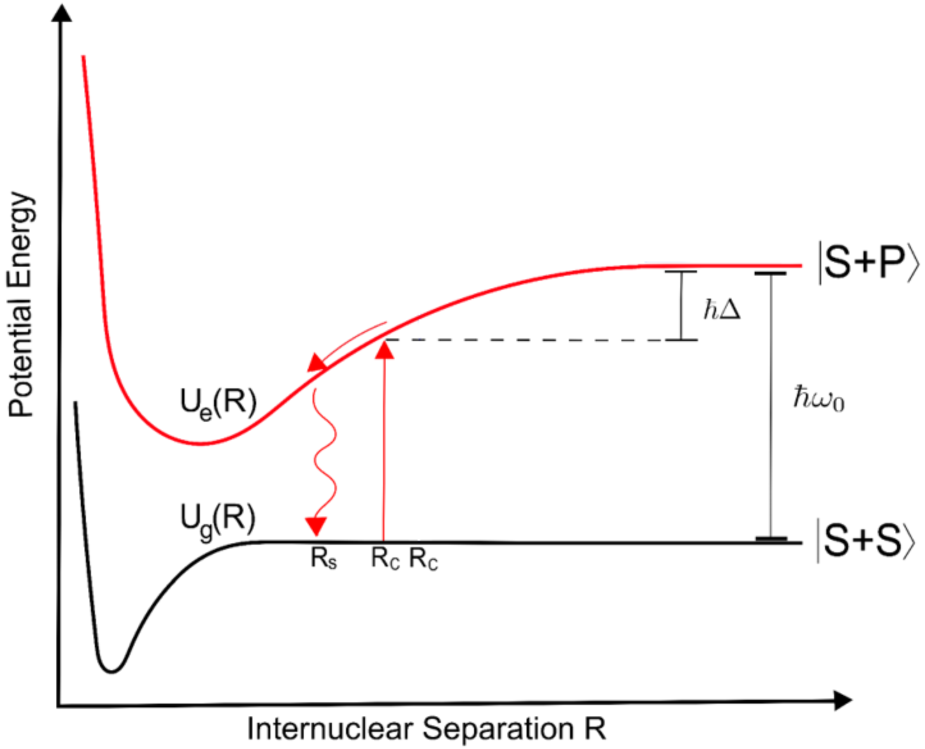
Schlosser, N. et al.
Nature 411, 1024-1027 (2001)

Loading atoms into tweezers

Superimpose Magneto-optical trap with tweezers

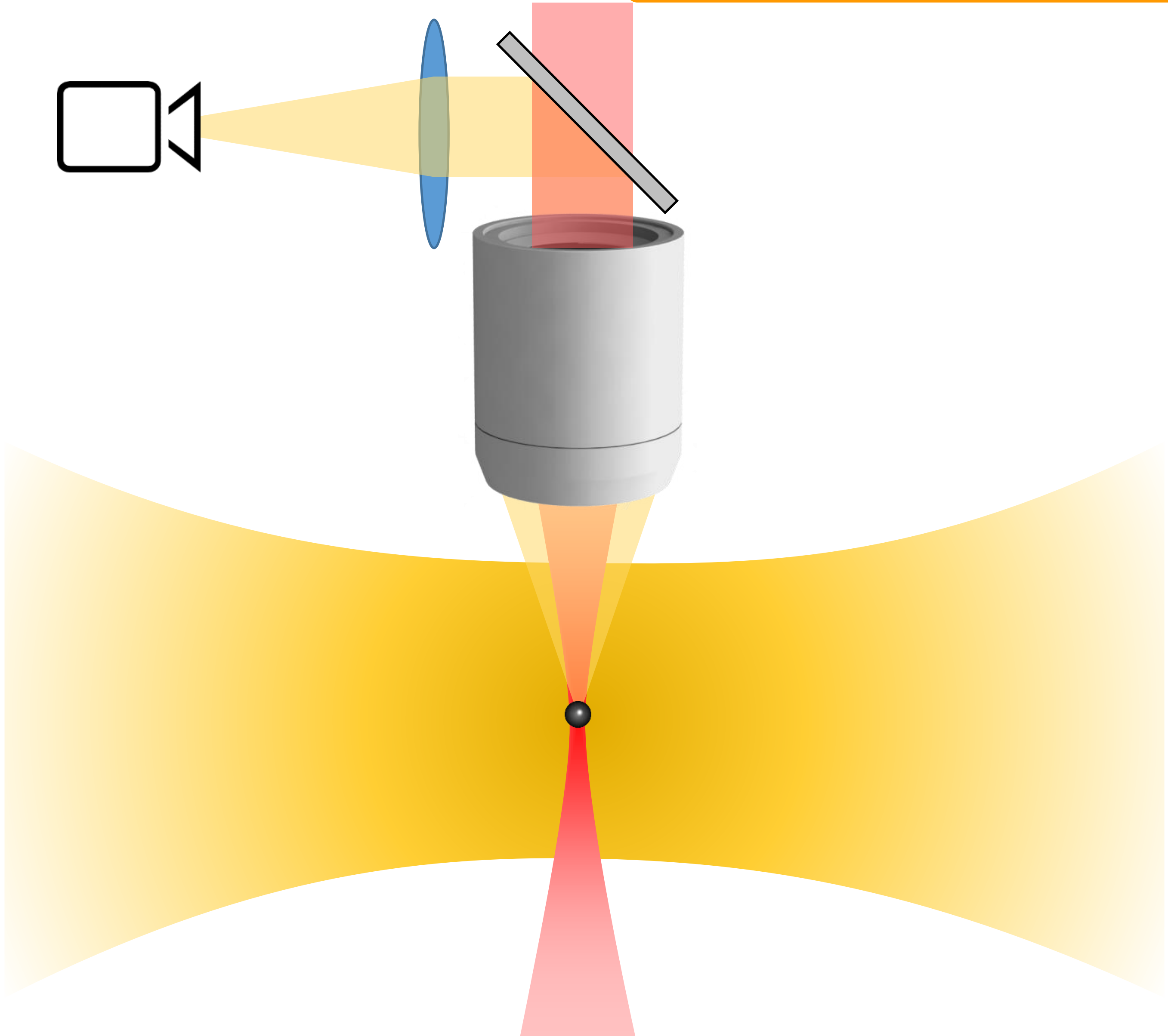


Light-assisted collisions remove atom pairs

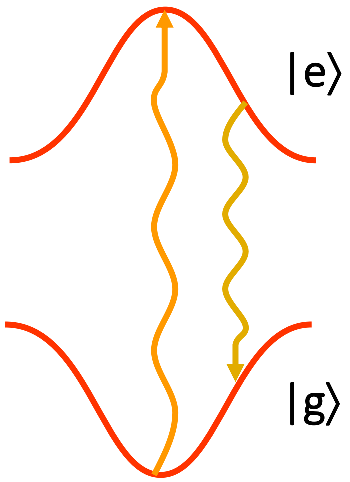


About 50% filling fraction of Tweezers with 0 and 1 atoms
(Can be enhanced up to 90% with blue detuned light)

Imaging atoms in tweezers



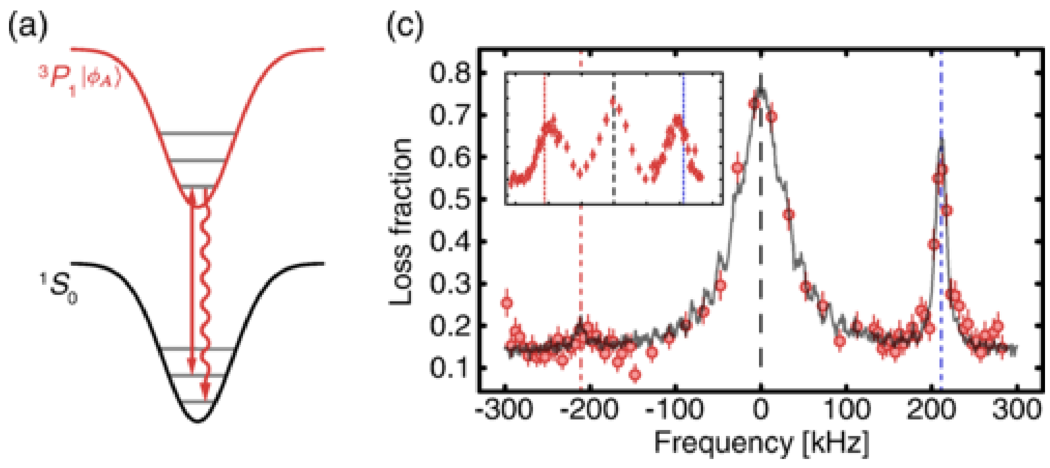
Fluorescence imaging leads to heating and loss
=> at least Molasses cooling needed



Cooling atoms in tweezers

Resolved Sideband cooling

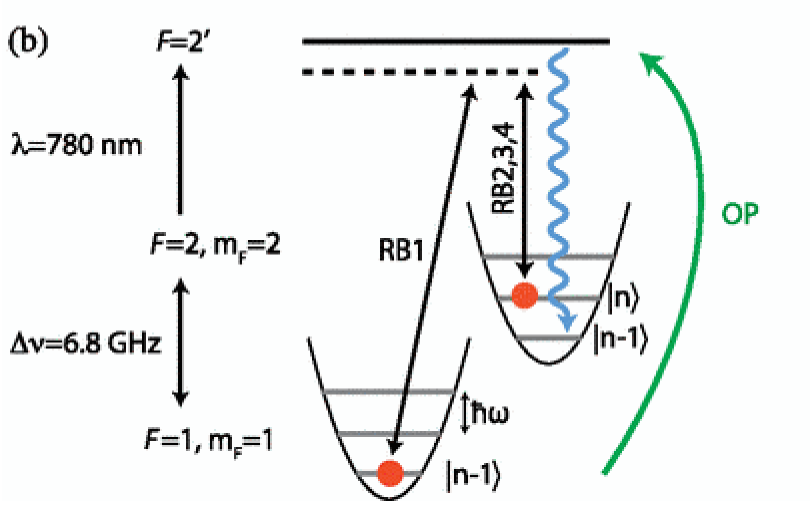
Only possible if the linewidth of the cooling light is smaller then the trap state spacing & „magic“ trap conditions



Cooper, A. et al.
Phys. Rev. X 8, 041055 (2018)

Raman Sideband cooling

Works also in the case where trap states cannot be resolved with the cooling light



Kaufman, A. M. et al.
Phys. Rev. X 2, 041014 (2012)

ATOMS IN TWEEZERS

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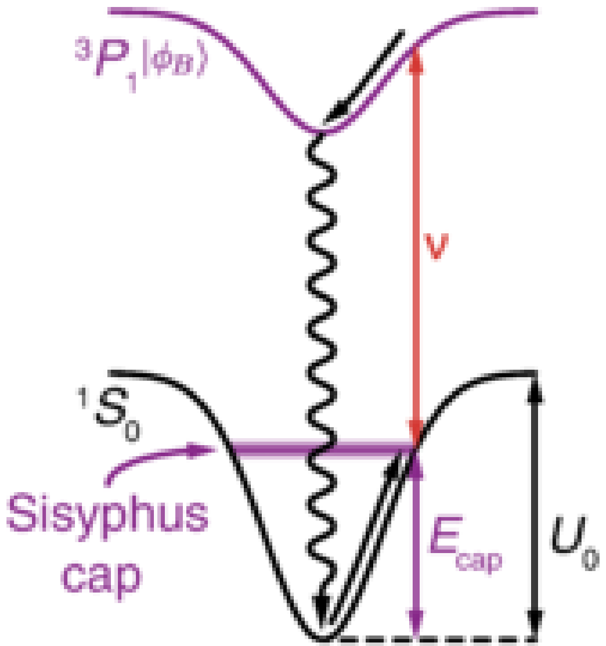
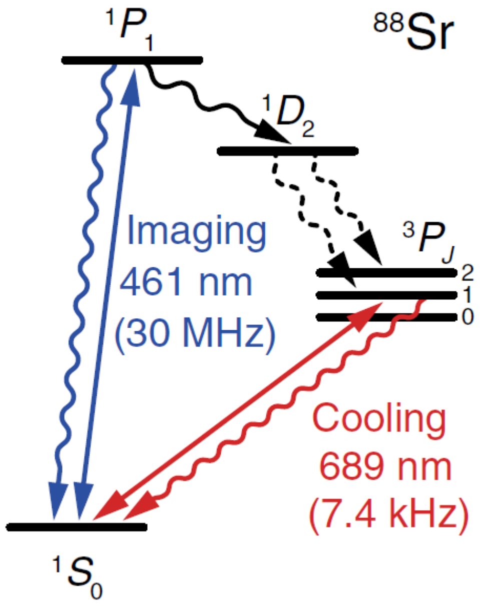
Sisyphus cooling

repulsive

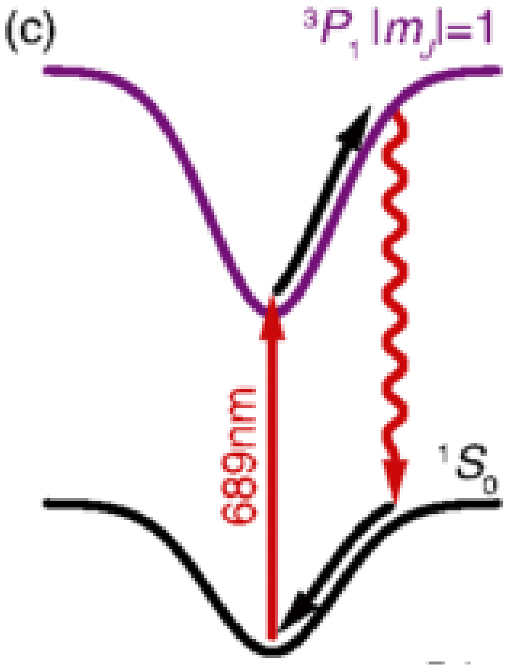
Trap light: 515.2nm





attractive

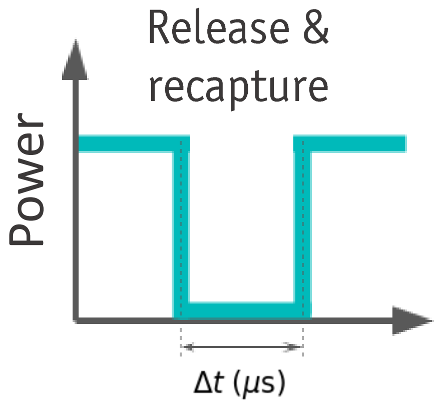
Trap light: 813.4nm



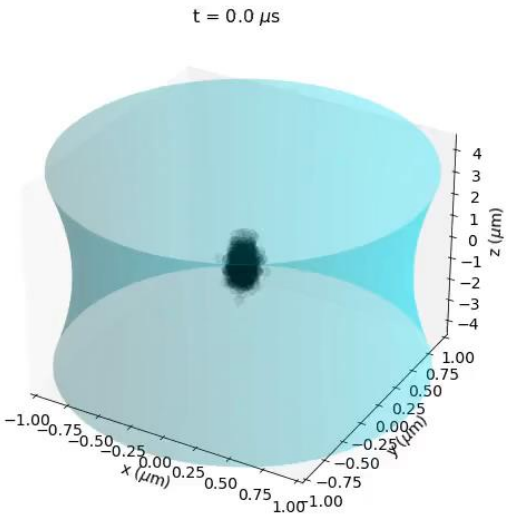
Cooper, A. et al.
Phys. Rev. X 8, 041055 (2018)

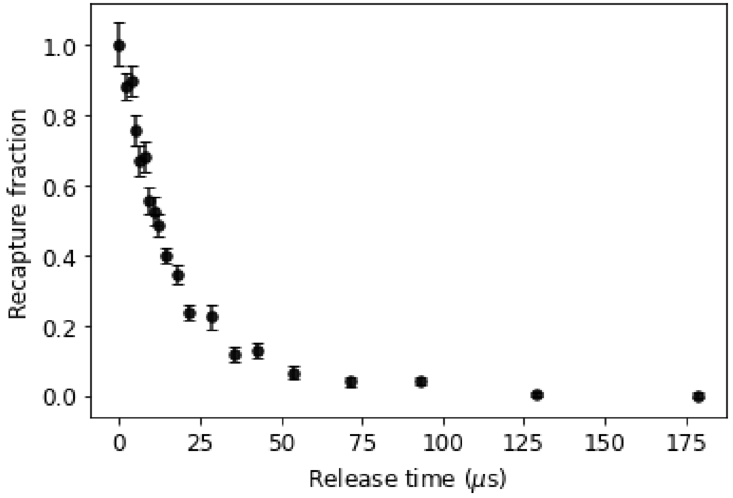
Covey, J. et al.
Phys. Rev. Lett 122, 173201 (2019)

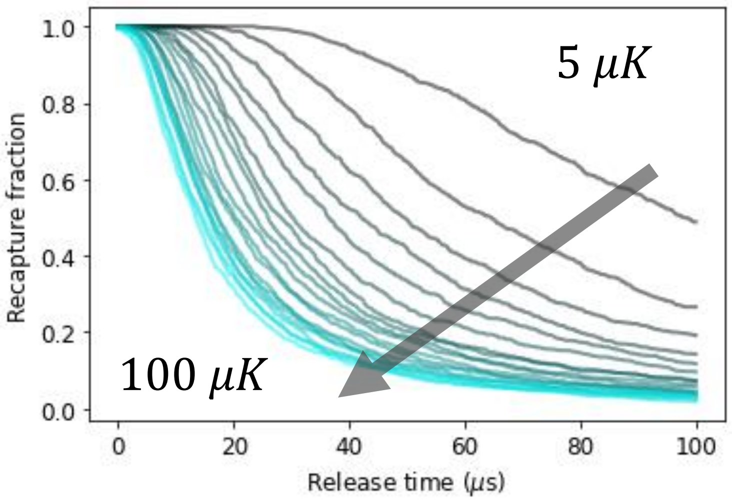
Measuring temperature

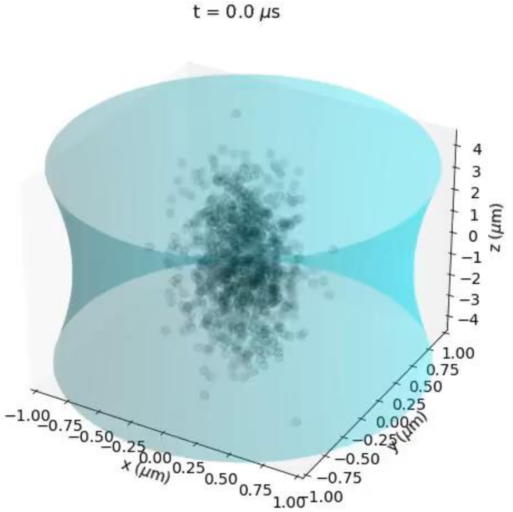


Monte Carlo Trajectories







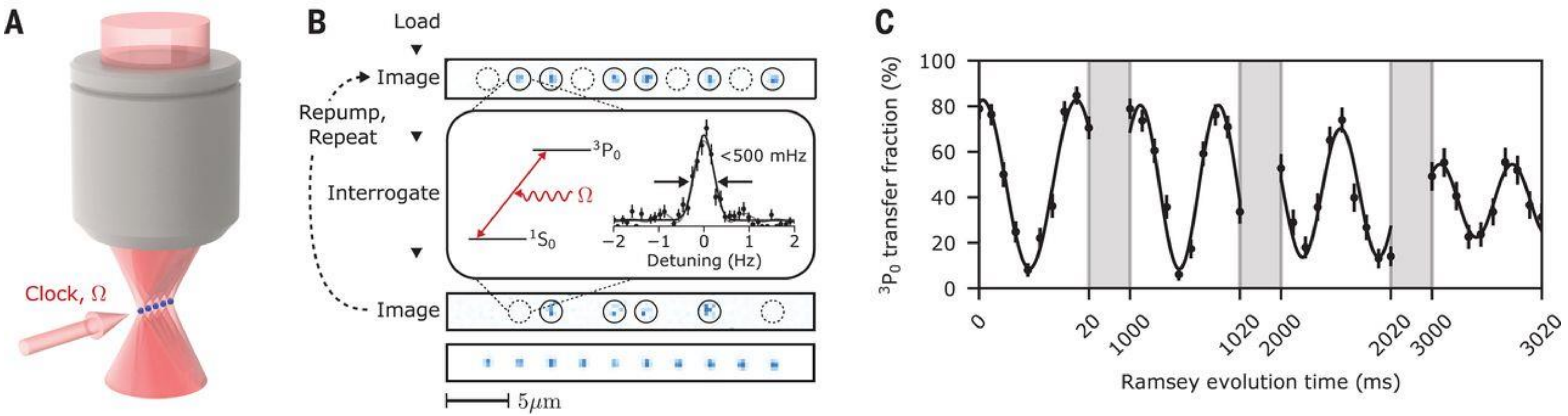


C. Tuchendler et al., Phys. Rev. A 78, 033425 (2008)

Simulation by D. Grün

Application example atomic clock

- Bosonic ^{88}Sr offers clock transition with arbitrarily narrow linewidth (698nm)
- „Magic“ wavelength trapping between groundstate and clock state possible (813.4nm)
- Repeated clock interrogation of the same isolated atoms with fast duty cycle



Fractional frequency instability: $4.7 \times 10^{-16}\,(\tau/s)^{-1/2}$

Norcia, A. et al.
Science 366, 93-97 (2019)

Outline

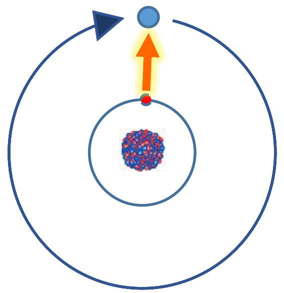
- Basics on Tweezers
- Tweezer arrays
- Experiments with neutral atoms
- **Experiments with Rydberg atoms**

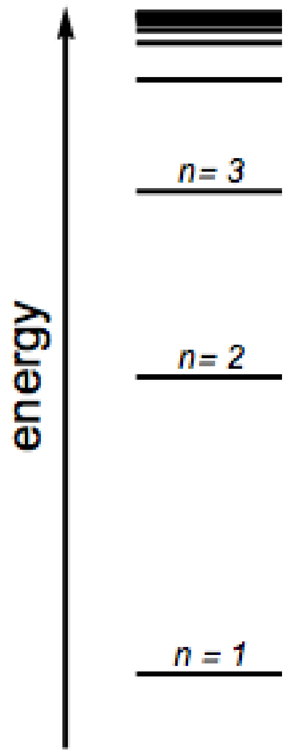
Rydberg atoms in tweezers

Quick reminder Rydberg atoms

- An excited atom with an electron at high principal quantum number $n > 10$

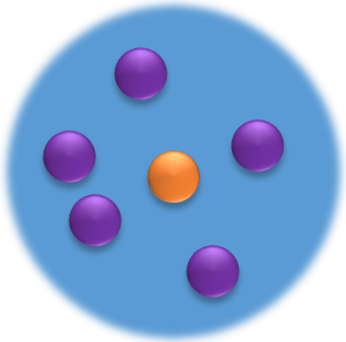
$$E = E_{IP} - \frac{R_y}{(n-\mu_{n,l})^2}$$





- Exaggerated properties:
  - High polarizability $\propto n^7$
  - Long range interaction $C_6 \propto n^{11}, C_3 \propto n^4$
  - Long radiative life time $\propto n^3$
  - Large radius $\propto n^2$

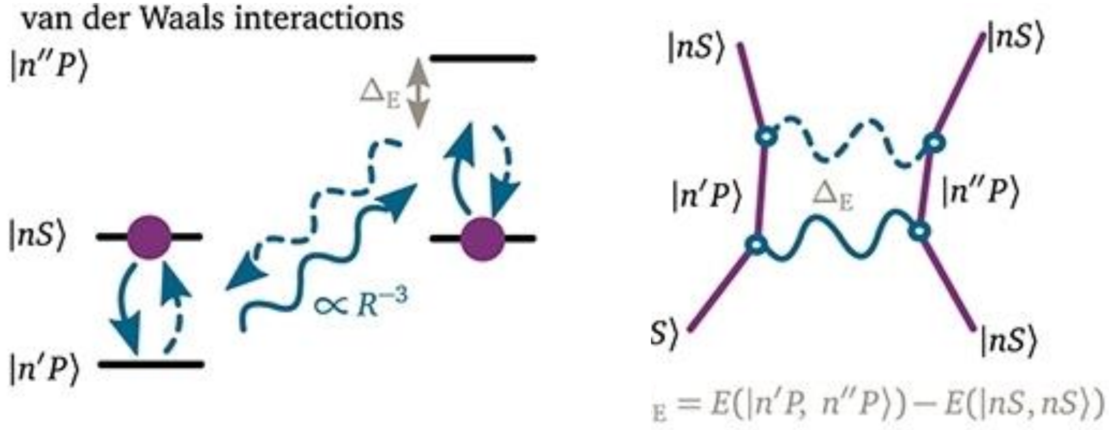
- Rydberg blockade



Rydberg atoms in tweezers

Interactions between Rydberg atoms

Van der Waals

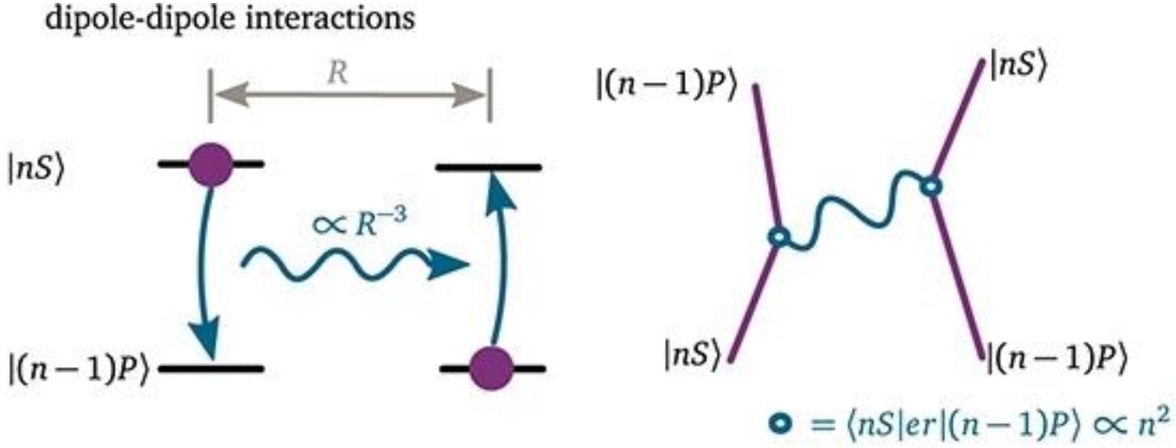


With the mapping |↓⟩=|g⟩ and |↑⟩=|r⟩

Quantum Ising model with transverse field

$$H = \frac{\hbar\Omega}{2}\sum_i \sigma_x^i - \hbar\delta\sum_i n_i + \sum_{i<j} V_{ij} n_i n_j, \text{ with } V_{ij} = \frac{C_6}{R_{ij}^6}$$

Dipole-dipole



With the mapping |↓⟩=|ns⟩ and |↑⟩=|np⟩

Spin ½ XZ model with transverse field

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

Šibalić and Adams
Rydberg Physics (2018)

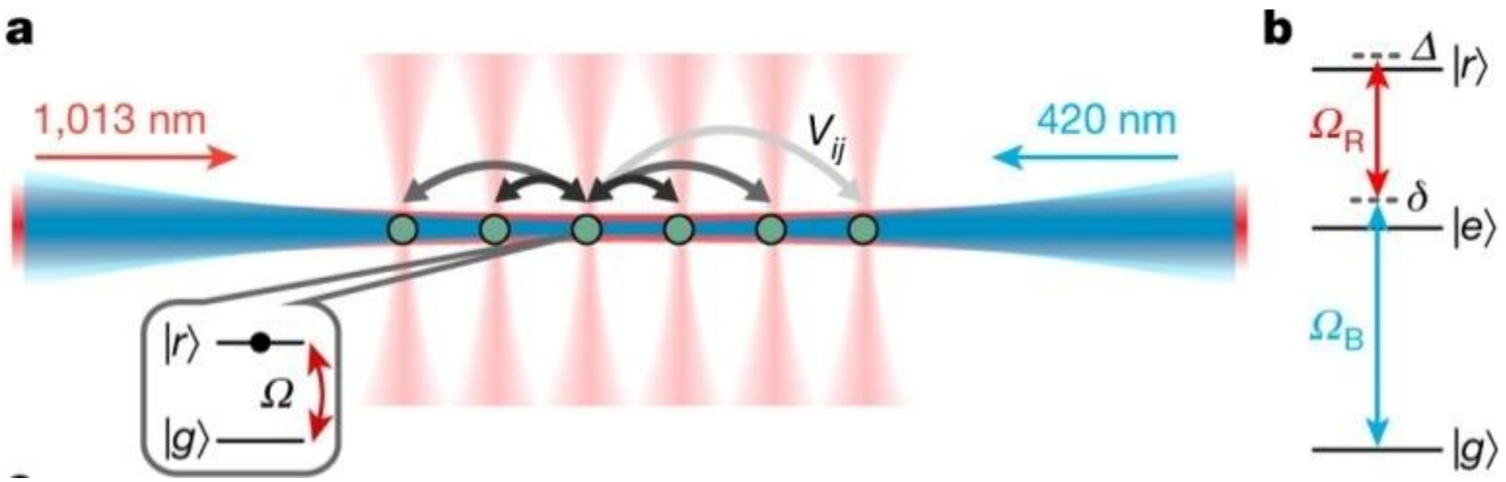
Simulating a quantum Ising model

ARTICLE

doi:10.1038/nature24622

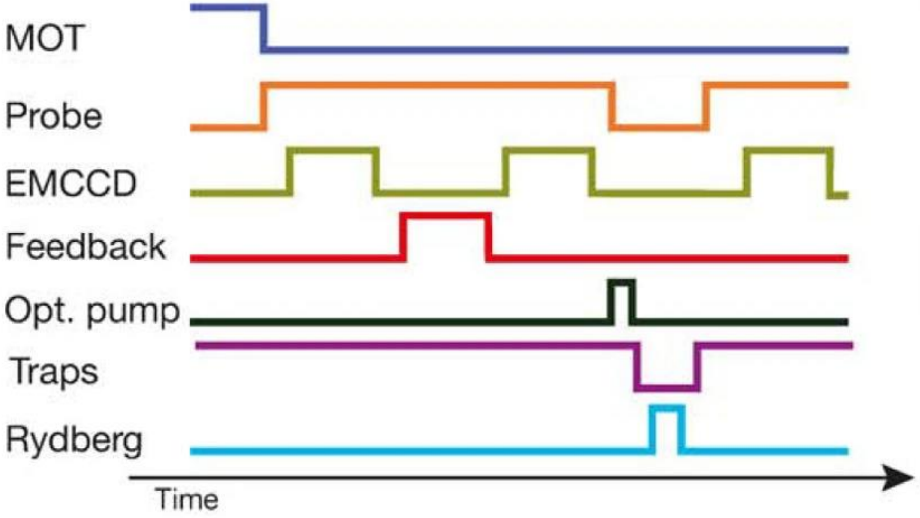
Probing many-body dynamics on a 51-atom quantum simulator

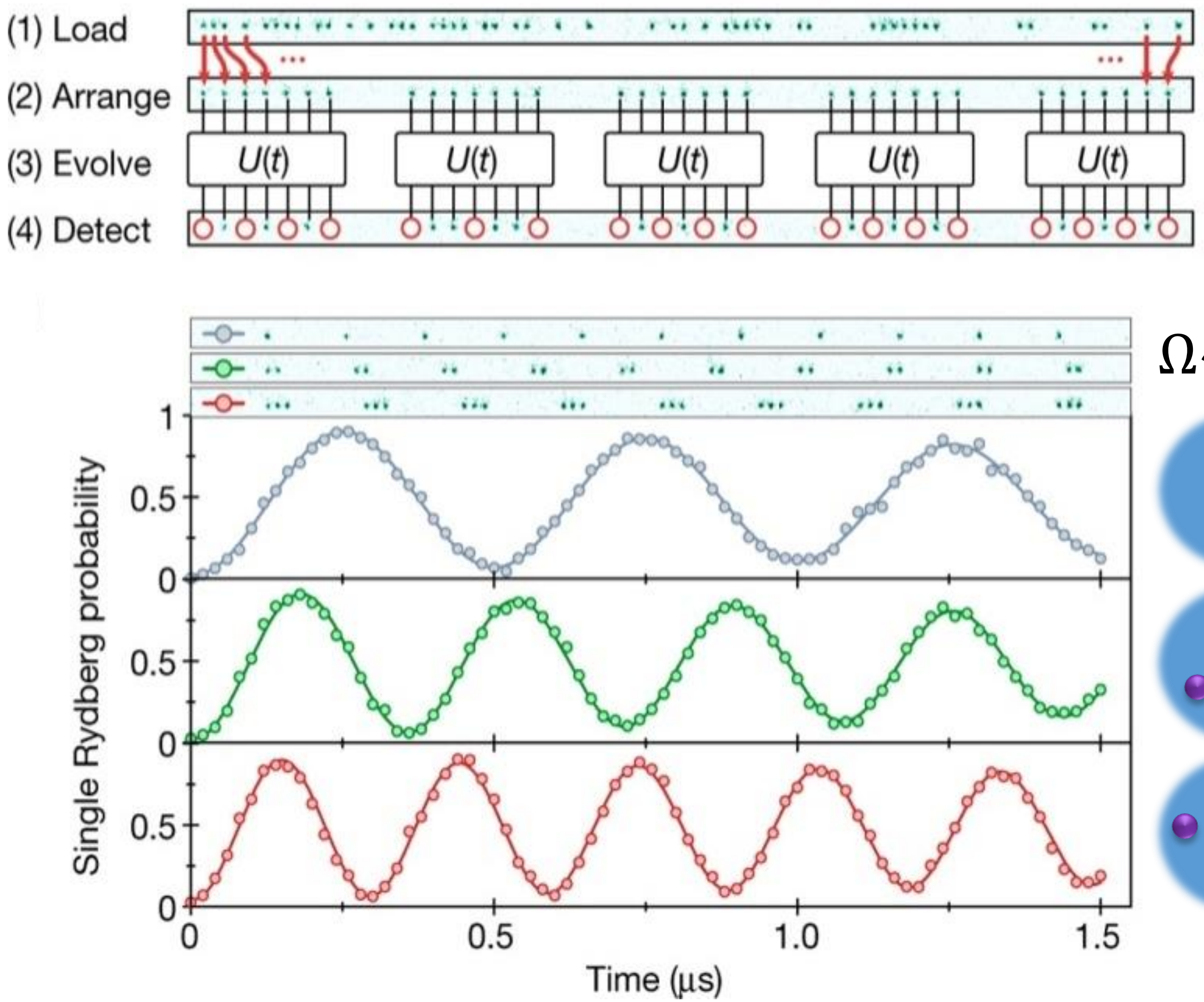
Hannes Bernien[1], Sylvain Schwartz[1,2], Alexander Keesling[1], Harry Levine[1], Ahmed Omran[1], Hannes Pichler[1,3], Soonwon Choi[1], Alexander S. Zibrov[1], Manuel Endres[4], Markus Greiner[1], Vladan Vuletić[2] & Mikhail D. Lukin[1]



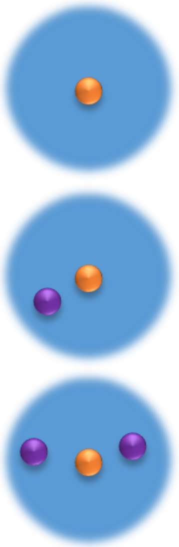
RYDBERG ATOMS IN TWEEZERS

Simulating a quantum Ising model





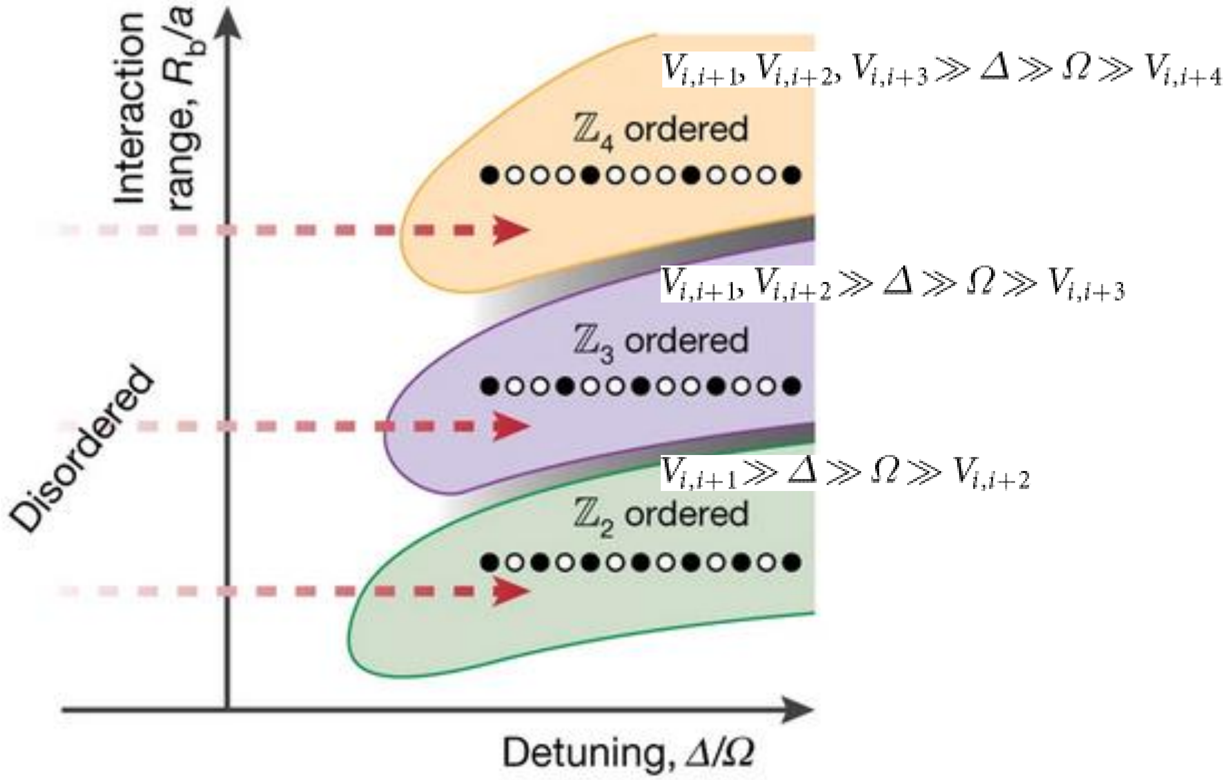
$\Omega \sim \sqrt{N}$



Simulating a quantum Ising model

$|\downarrow\rangle = |g\rangle$ and $|\uparrow\rangle = |r\rangle$

$$\frac{\mathcal{H}}{\hbar} = \sum_i \frac{\Omega_i}{2}\sigma_x^i - \sum_i \Delta_i n_i + \sum_{i<j} V_{ij} n_i n_j \qquad \sigma_x^i = |g_i\rangle\langle r_i| + |r_i\rangle\langle g_i|$$



Simulating a quantum Ising model

|↓⟩=|g⟩ and |↑⟩=|r⟩

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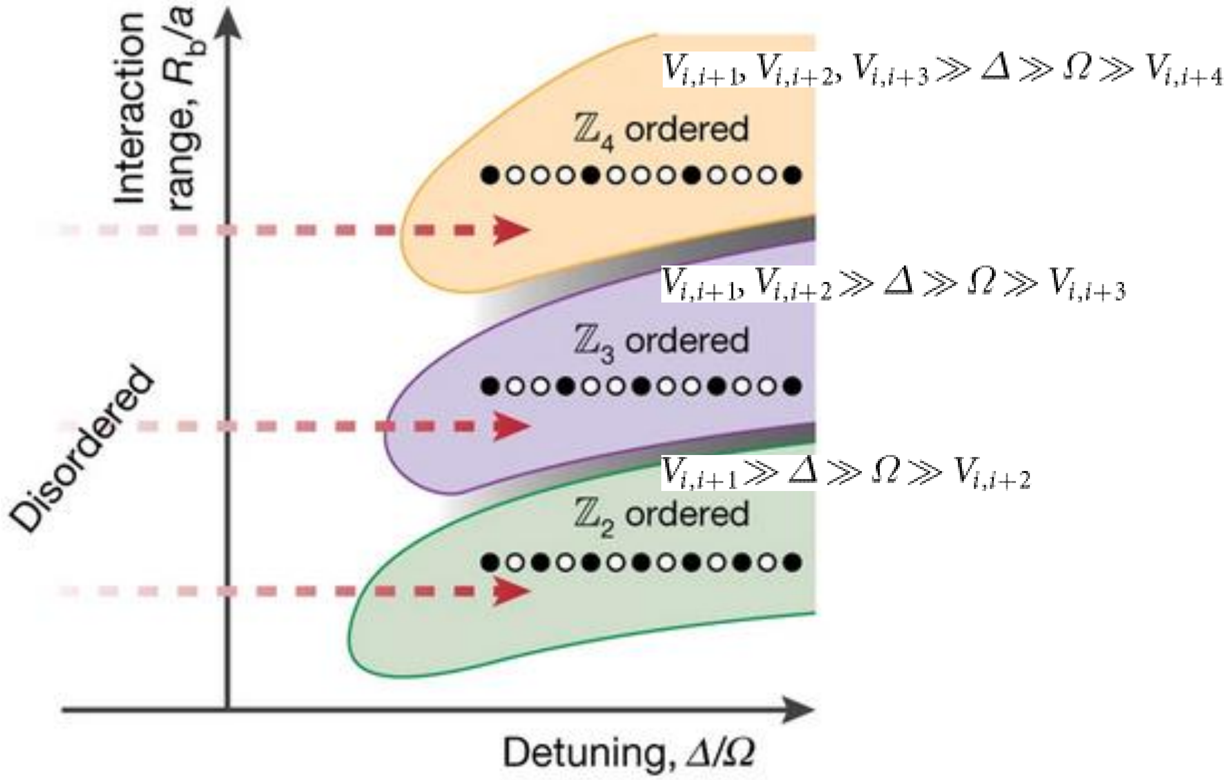
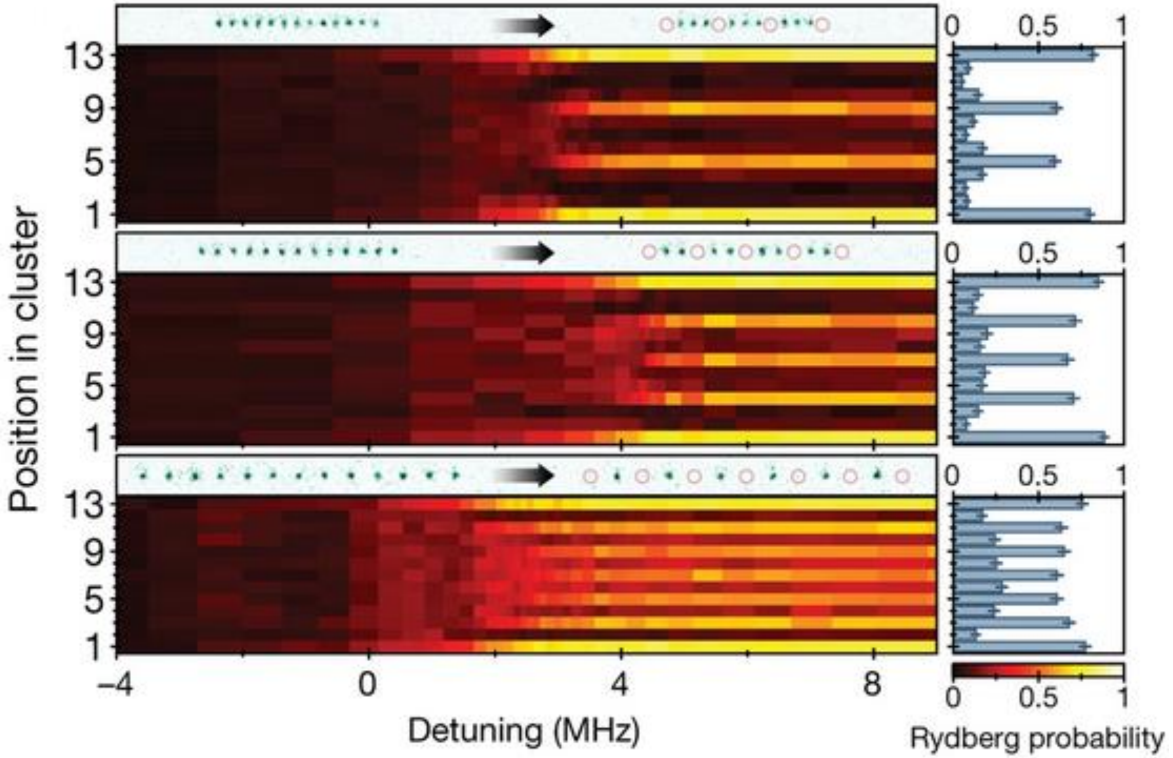
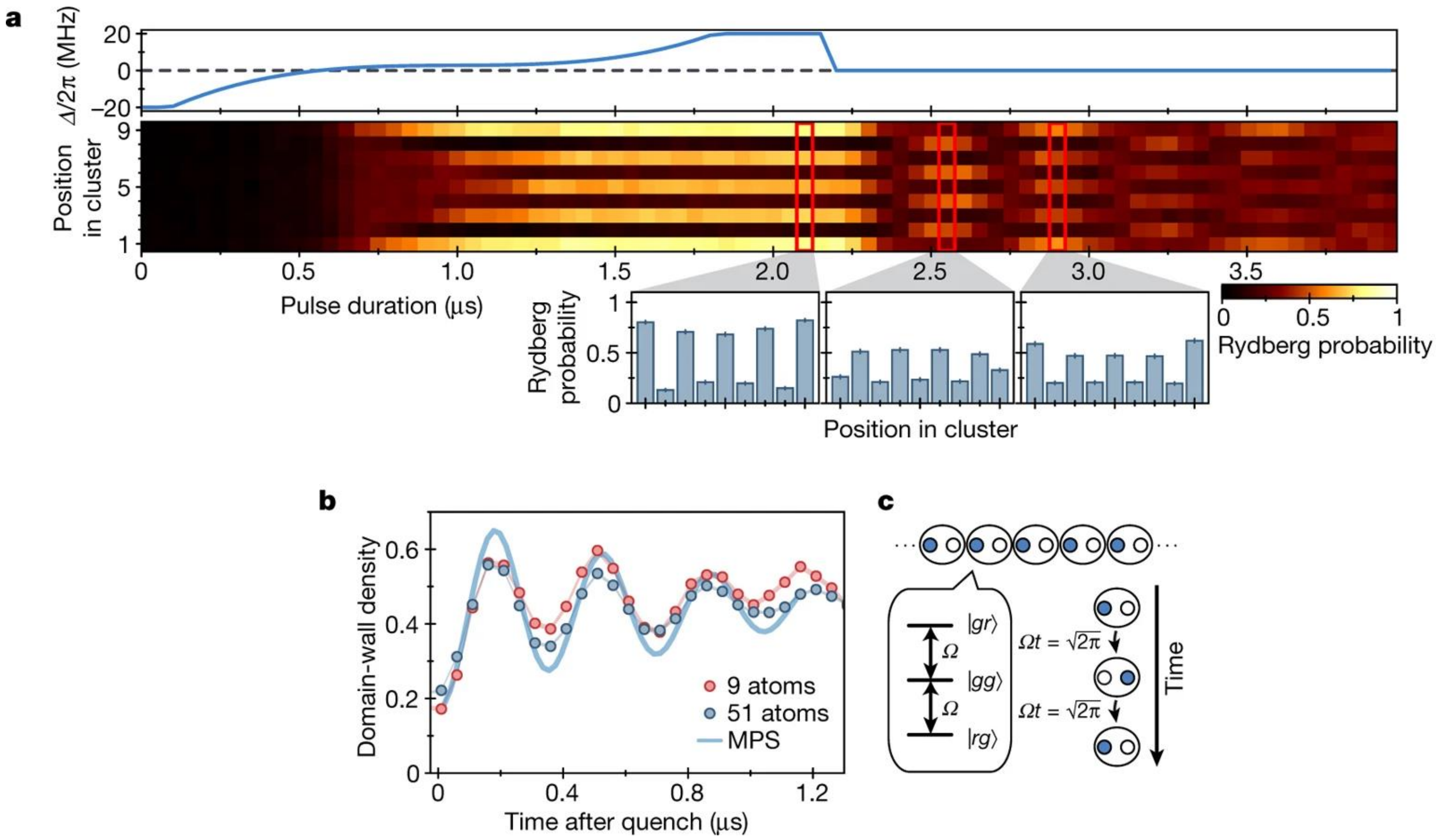




Simulating a quantum Ising model



Simulating a spin ½ XZ model

PRL **114,** 113002 (2015) PHYSICAL REVIEW LETTERS week ending 20 MARCH 2015

Coherent Excitation Transfer in a Spin Chain of Three Rydberg Atoms

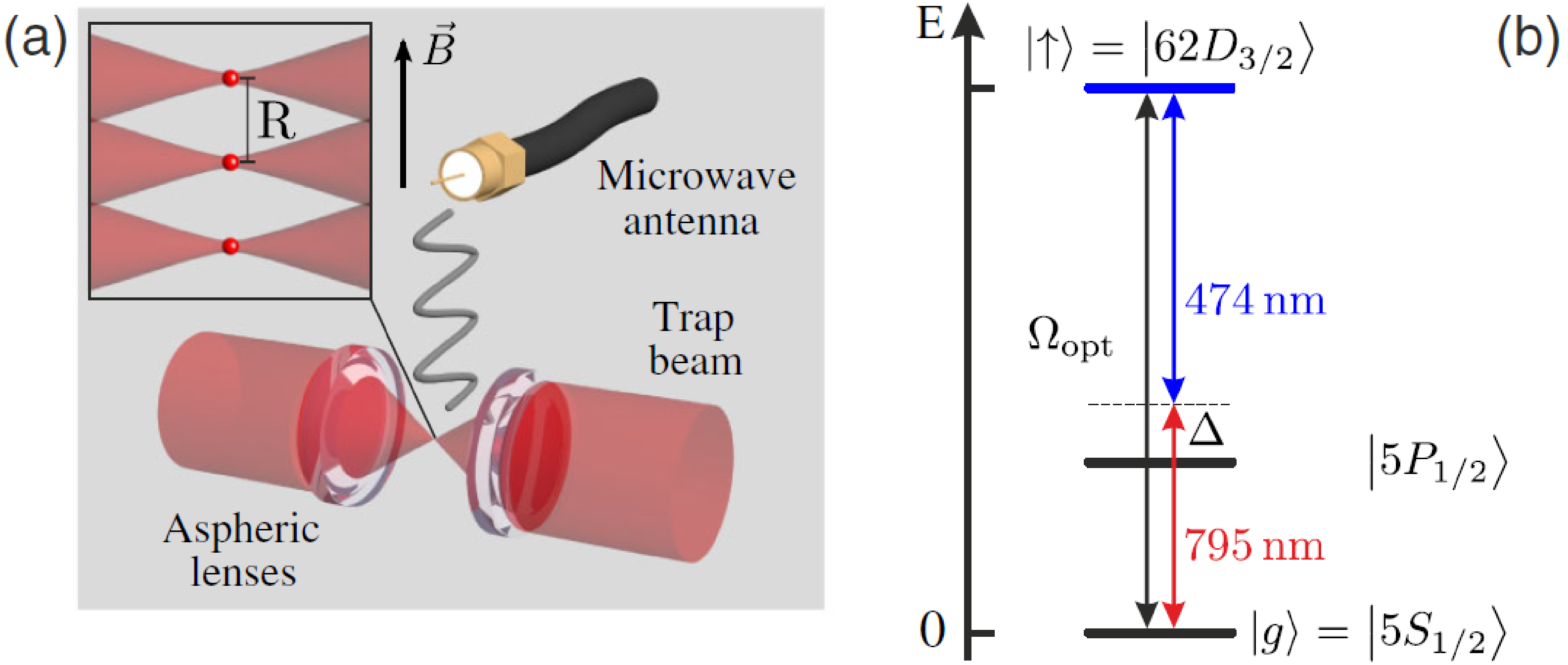
Daniel Barredo, Henning Labuhn, Sylvain Ravets, Thierry Lahaye, and Antoine Browaeys
Laboratoire Charles Fabry, UMR 8501, Institut d'Optique, CNRS, Université Paris Sud 11,
2 avenue Augustin Fresnel, 91127 Palaiseau cedex, France

Charles S. Adams
Joint Quantum Centre (JQC) Durham-Newcastle, Department of Physics, Durham University,
Durham DH1 3LE, United Kingdom

(Received 23 September 2014; revised manuscript received 21 November 2014; published 19 March 2015)

Simulating a spin ½ XZ model

$$H = \frac{1}{2}\sum_{i\neq j}\frac{C_3}{R_{ij}^3}(\sigma_i^+\sigma_j^- + \sigma_i^-\sigma_j^+)$$



Simulating a spin ½ XZ model

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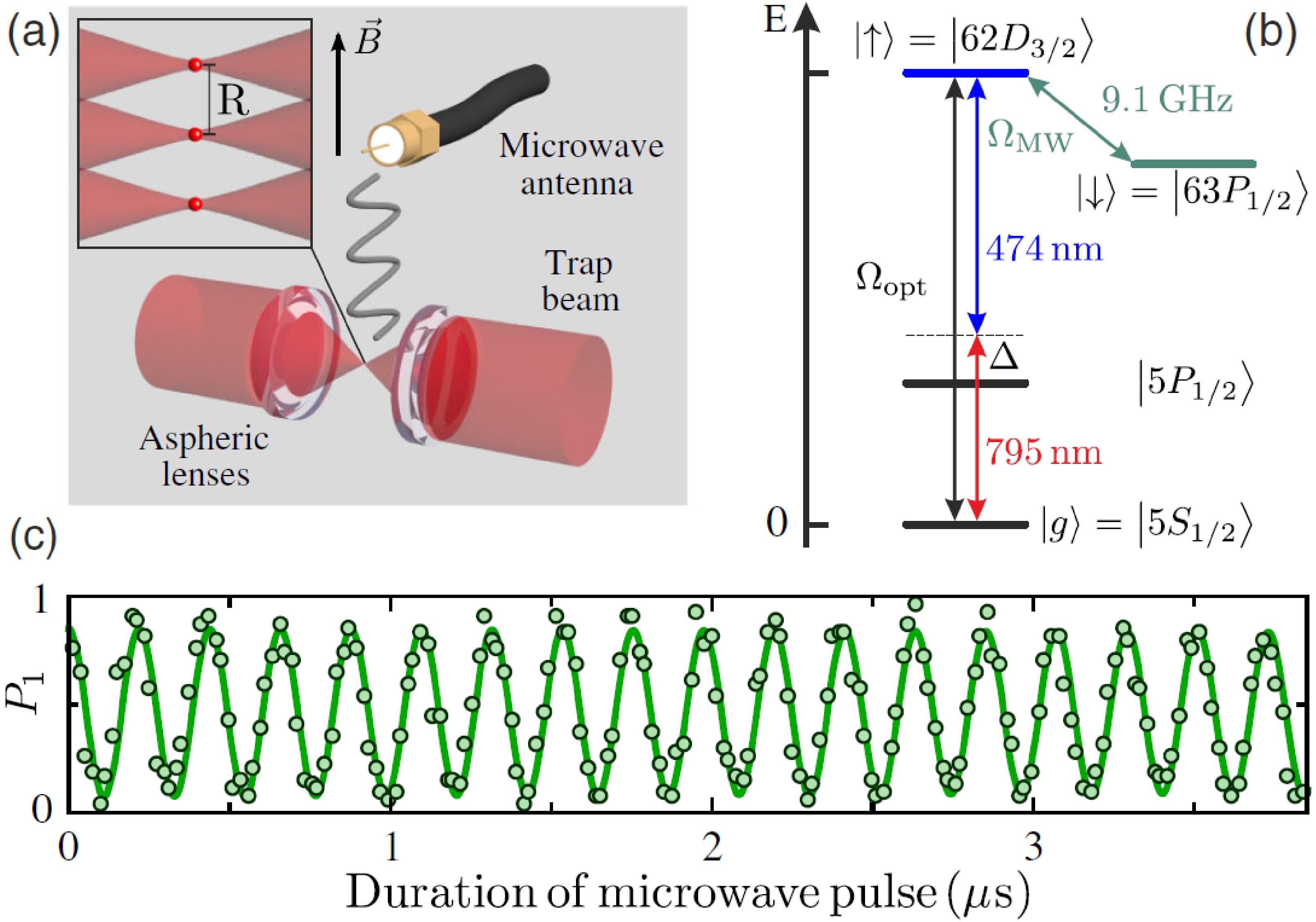
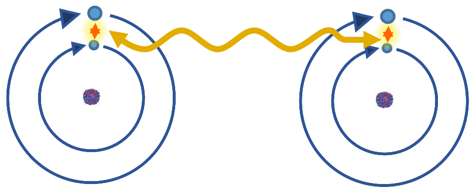
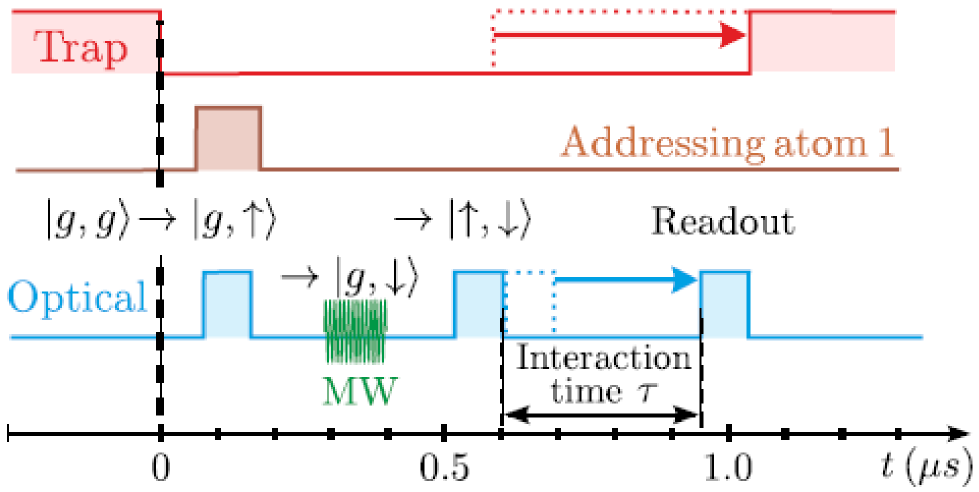
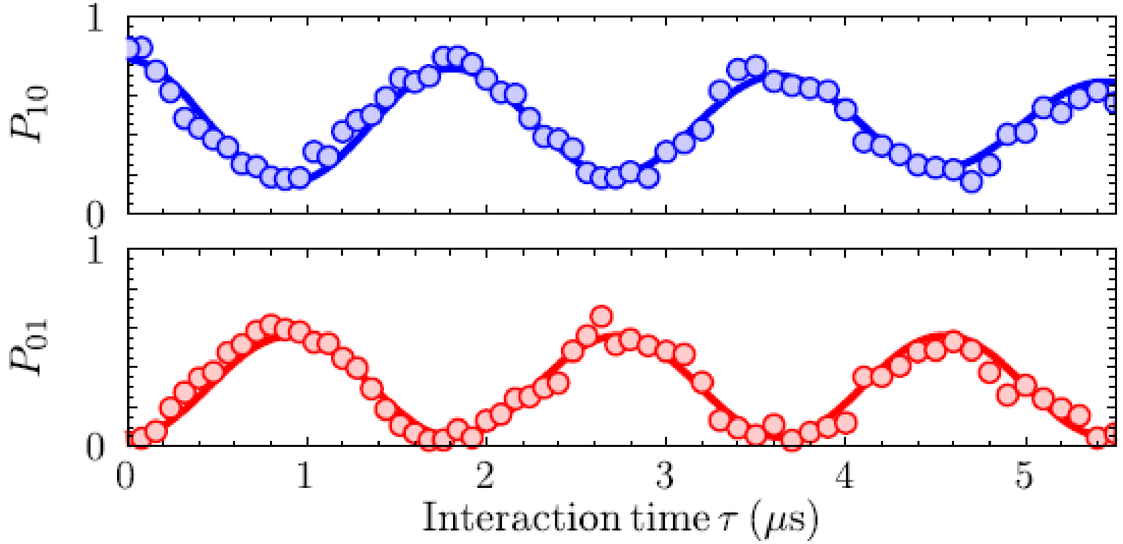


Simulating a spin ½ XZ model

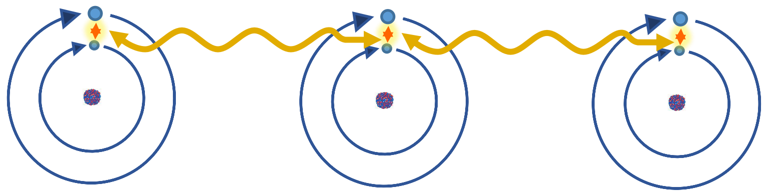




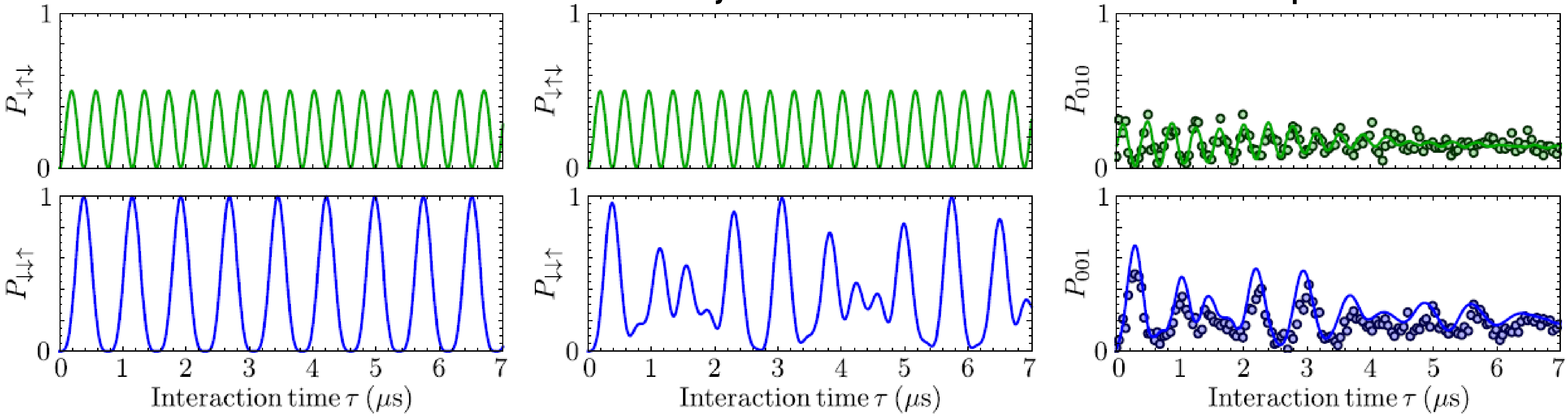


$$H = \frac{1}{2}\sum_{i\neq j}\frac{C_3}{R_{ij}^3}\left(\sigma_i^+\sigma_j^- + \sigma_i^-\sigma_j^+\right)$$

Simulating a spin ½ XZ model



Theory only NNI | **Theory all interactions** | **Experiment**



$$H = \frac{1}{2}\sum_{i\neq j}\frac{C_3}{R_{ij}^3}\left(\sigma_i^+\sigma_j^- + \sigma_i^-\sigma_j^+\right)$$

Outline

Basics on Tweezers

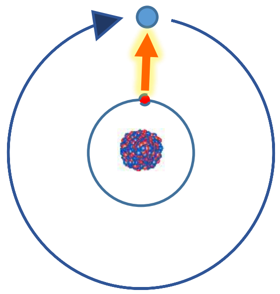
Tweezer arrays

Experiments with neutral atoms

Experiments with Multi-electron Rydberg atoms

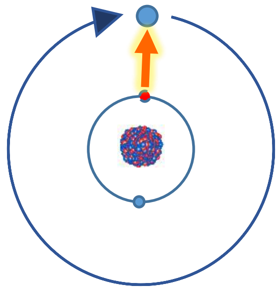
RYDBERG ATOMS IN TWEEZER ARRAYS

More electrons – more possibilities



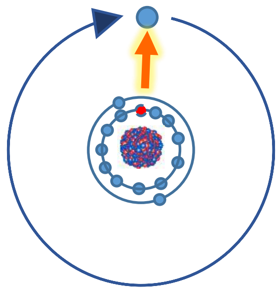
Alkali Rydberg atoms

Single valence electron



Alkaline-earth like Rydberg atoms

Two valence electrons

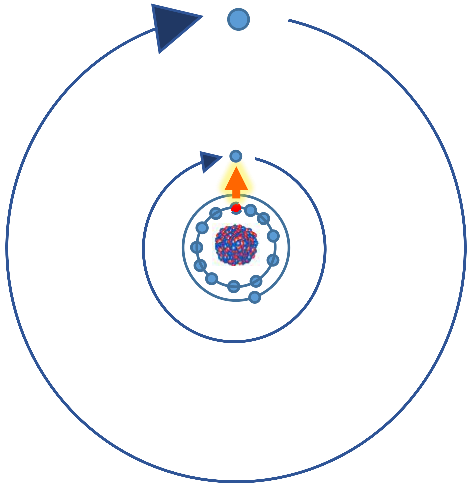


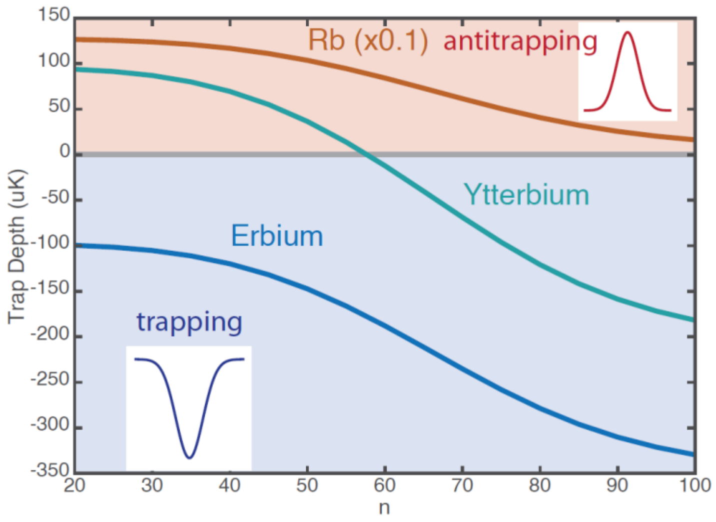
Lanthanide Rydberg atoms

Many valence electrons

Remaining optically active electron(s) maybe allow for:

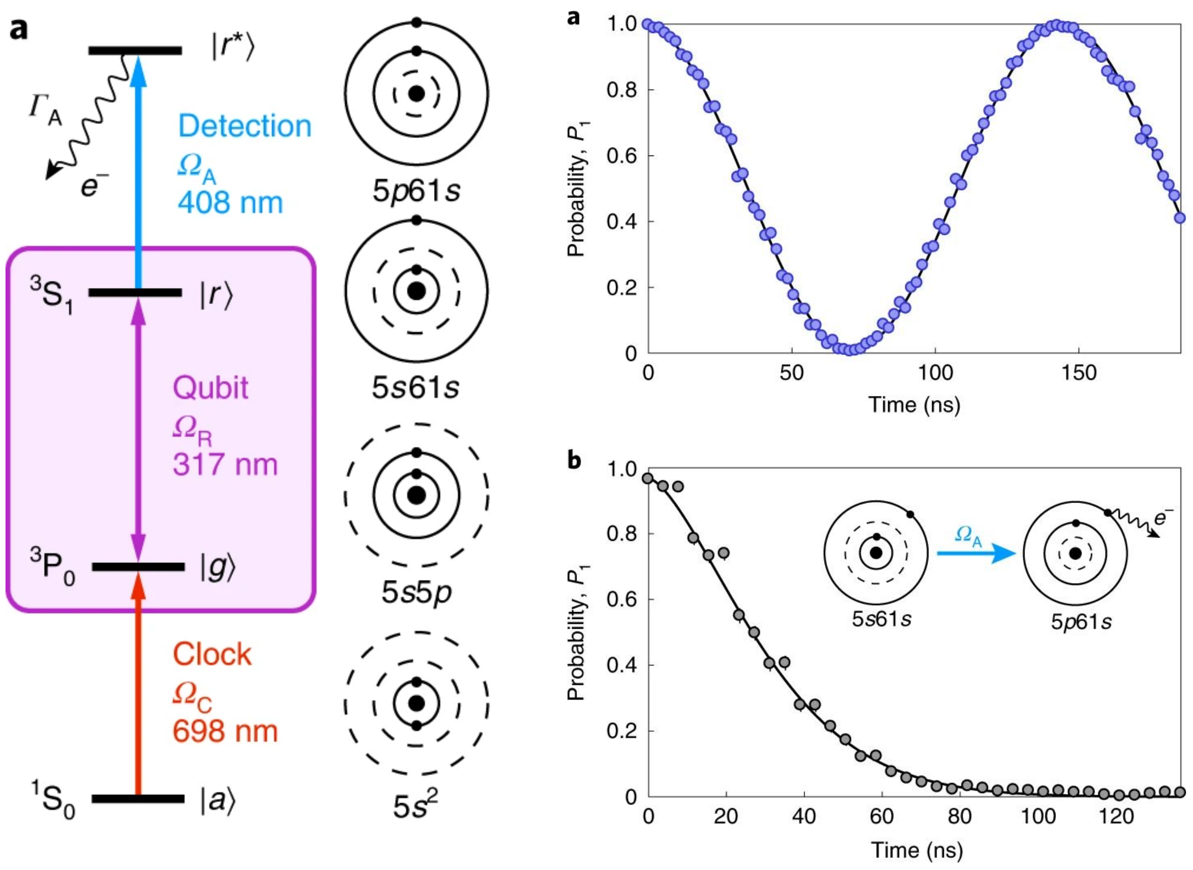
- Direct trapping (large remaining core polarizability)
- Controlled autoionization
- Direct Imaging
- New excitation schemes (into large angular momentum states)

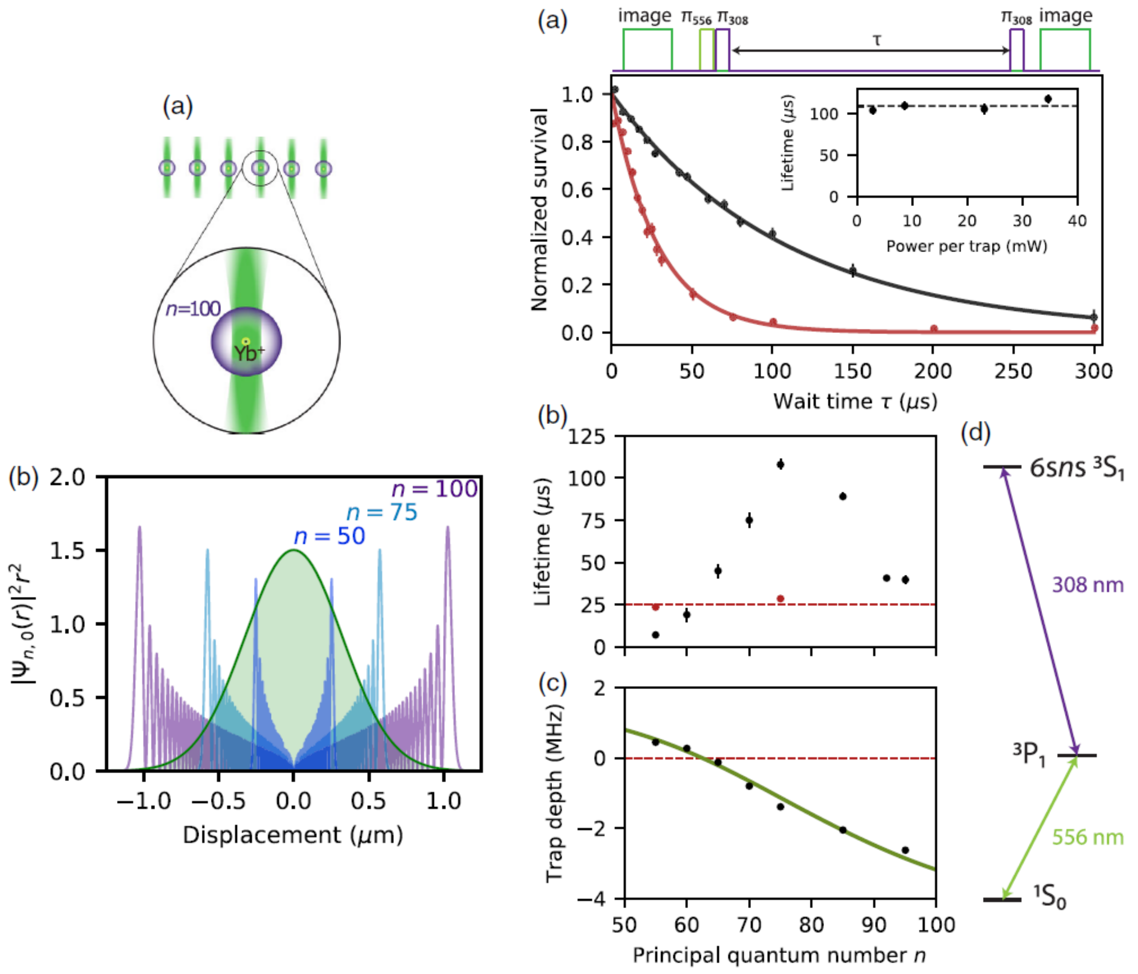




Rydberg atoms in tweezers

Recent first demonstrations



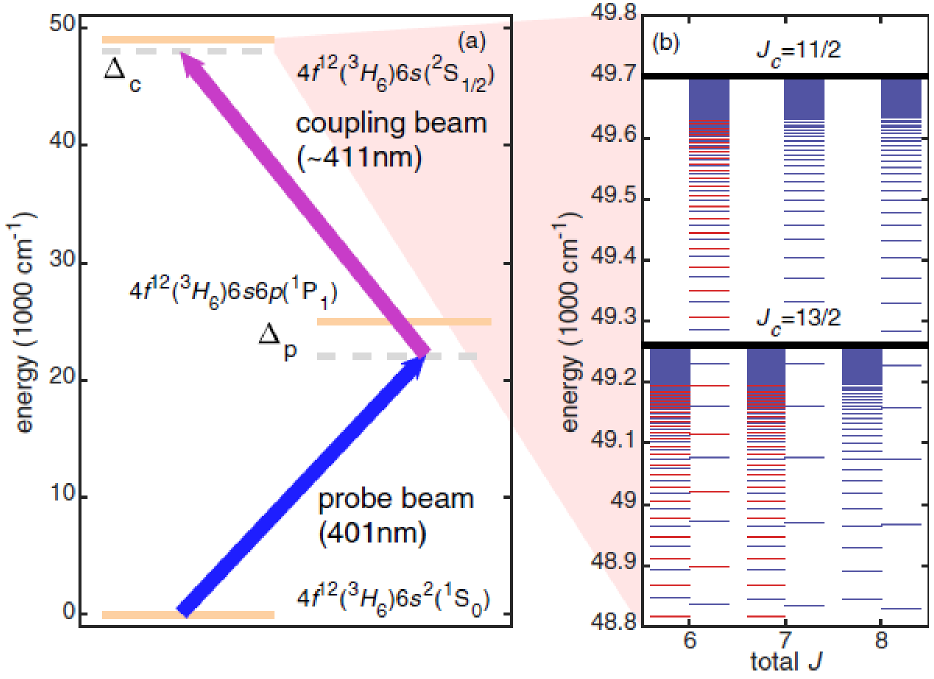


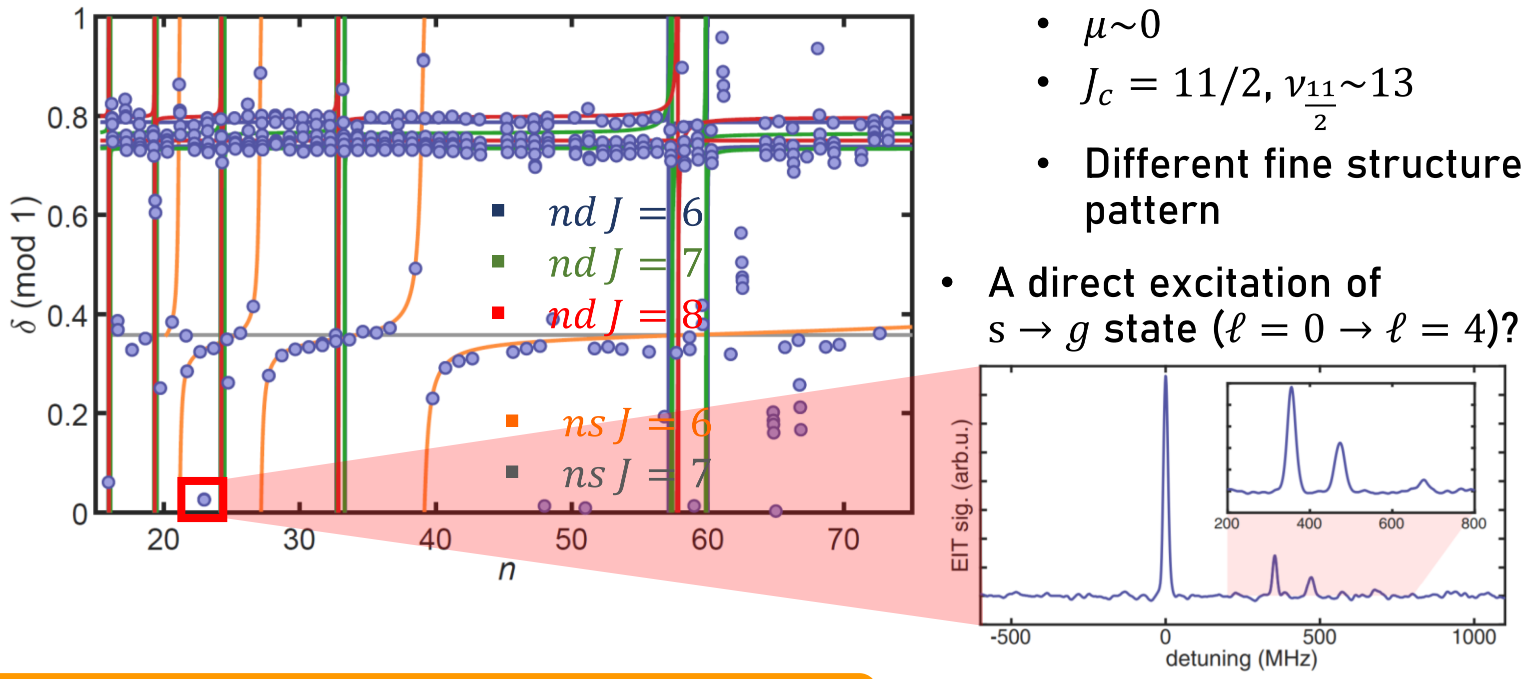
Madjarov et al.,
Nature Physics 16, 857-861 (2020)

Wilson et al.,
Phys. Rev. Lett. 128, 033201 (2021)

Rydberg atoms in tweezers

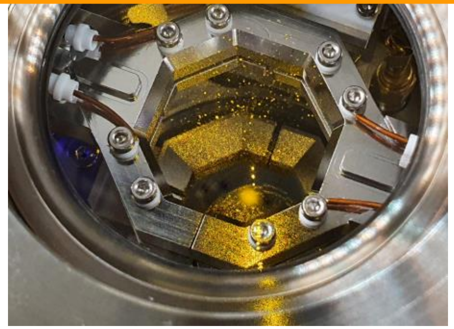
Recent first demonstrations

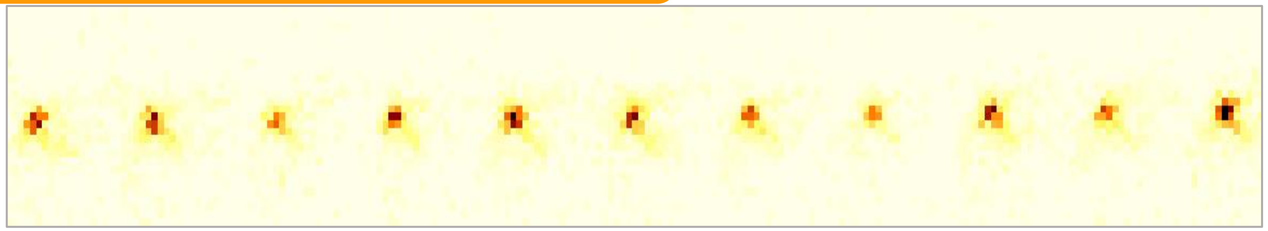




- An interesting state with:
  - $\mu \sim 0$
  - $J_c = 11/2$, $\nu_{\frac{11}{2}} \sim 13$
  - Different fine structure pattern
- A direct excitation of $s \to g$ state ($\ell = 0 \to \ell = 4$)?

First lanthanide tweezer experiment running!





A. Trautmann, et al., Phys. Rev. Research 3, 033165 (2021)

Thanks for your attention!

Some references to very good reviews on this topic:

Many-body physics with individually controlled Rydberg atoms, Antoine Browaeys & Thierry Lahaye, Nature Physics 16, 132–142 (2020)

Quantum science with optical tweezer arrays of ultracold atoms and molecules, Adam M. Kaufman & Kang-Kuen Ni, Nature Physics 17, 1324–1333 (2021)

A concise review of Rydberg atom based quantum computation and quantum simulation, Wu et al., Chinese Phys. B 30, 020305 (2021)

Rydberg Physics, Nikola Šibalić and Charles S Adams, Book (IOP Publishing), https://doi.org/10.1088/978-0-7503-1635-4ch1

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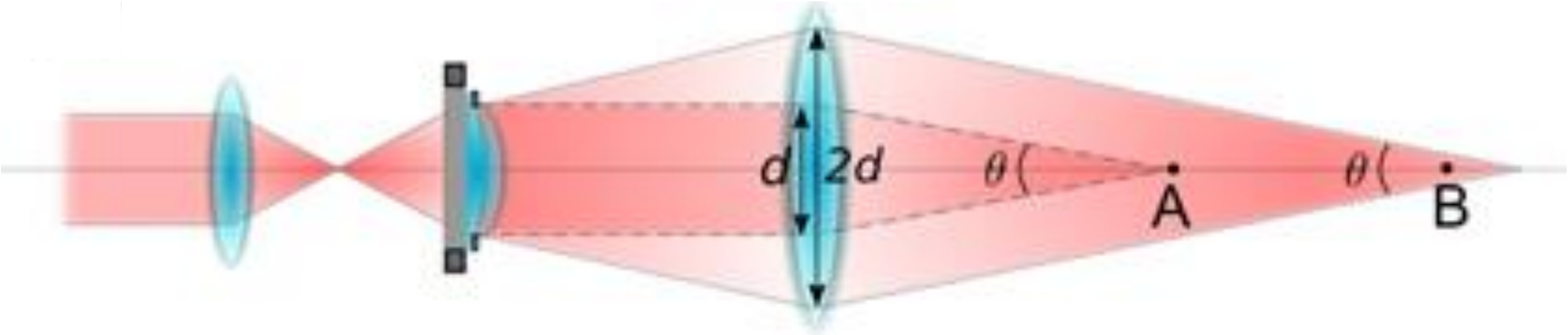
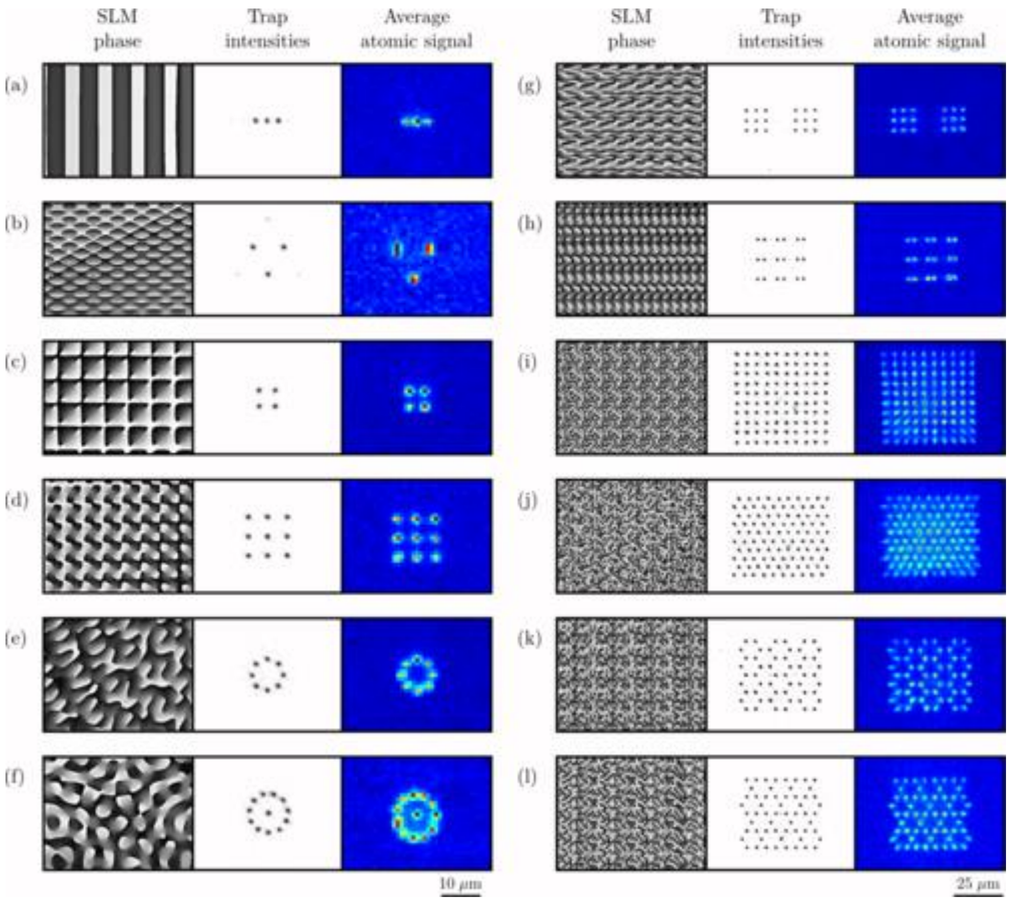


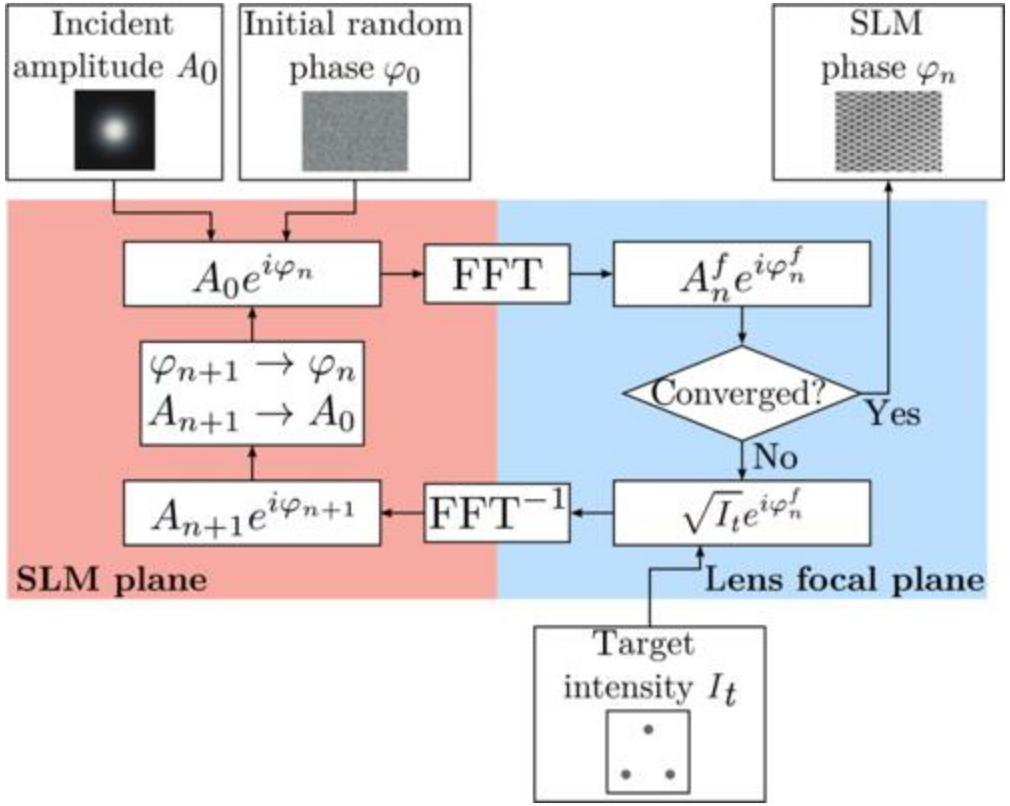
Julian Léonard et al 2014 New J. Phys. 16 093028

BACKUP SLIDES

Creating 2D intensity pattern:

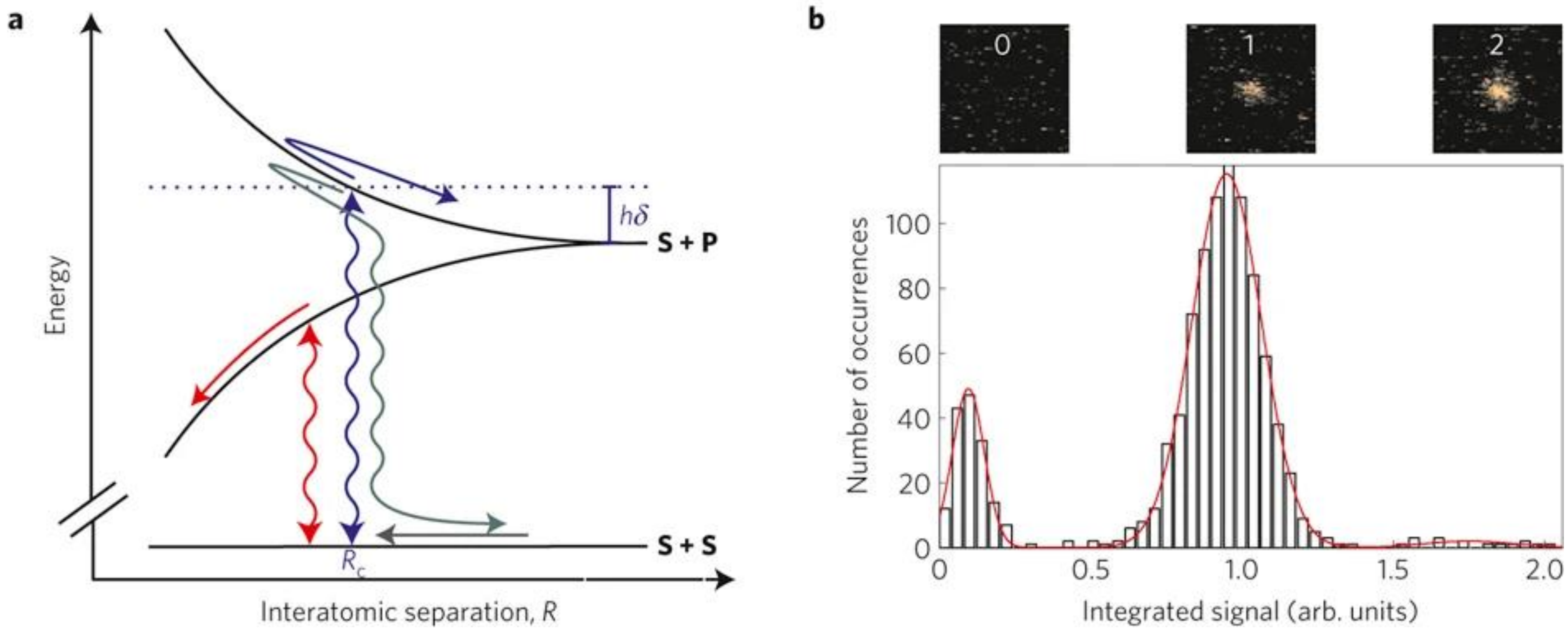


Gerchberg-Saxton (GS) algorithm



Nogrette et al.
Phys. Rev. X 4, 021034 (2014)

Increasing loading of tweezers:



Grünzweig, A.
Nature Physics 6, 951–954 (2010)