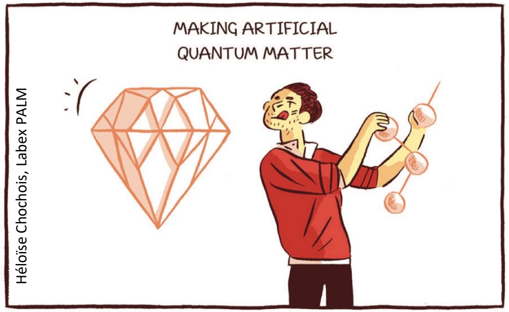
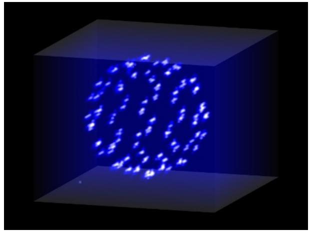
Arrays of atoms for Quantum Simulation and Computation

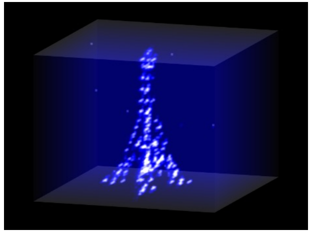


Antoine Browaeys

Laboratoire Charles Fabry,
Institut d'Optique, CNRS, FRANCE

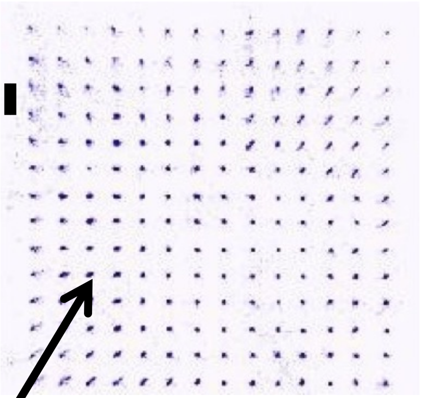
Summer School, ICAP2026, Wuhan, june 11th, 2026



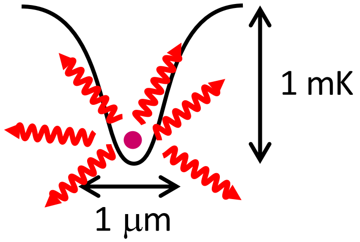


These lectures: combining arrays of atoms and Rydberg interactions

5 µm

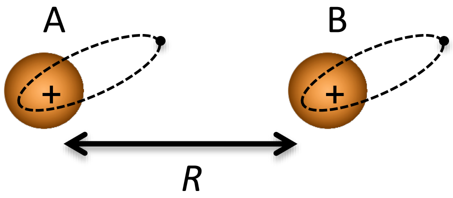


Addressable!!



+

Rydberg interactions



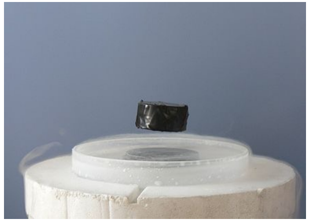
Van der Waals	resonant
$\frac{C_6}{R^6}$	$\frac{C_3}{R^3}$

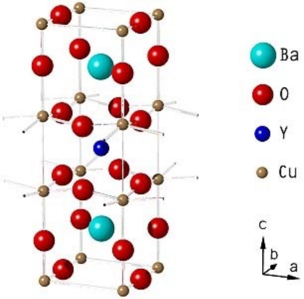
Quantum state engineering:

create controlled quantum systems

Quantum engineering: create controlled quantum systems

Many-body physics

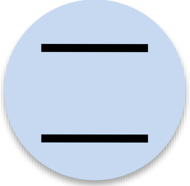




YBaCuO

Quantum metrology

^{133}Cs



1 sec = 9 192 631 770 cycles

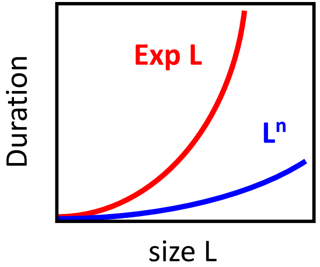
$$\frac{\Delta\nu}{\nu_0} \propto \frac{1}{\sqrt{N}} \xrightarrow{\text{Q states}} \frac{\Delta\nu}{\nu_0} \propto \frac{1}{N}$$

Quantum information processing

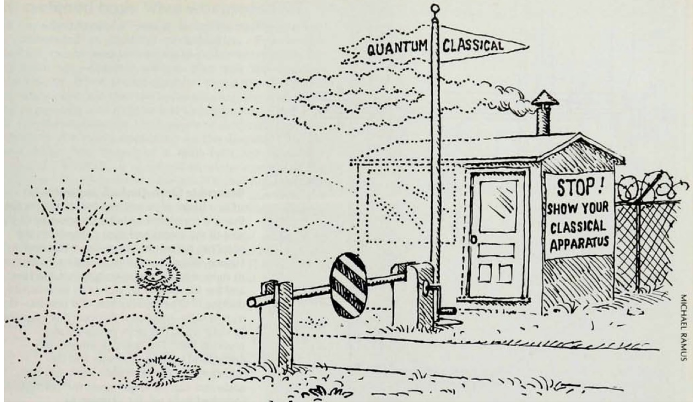
Quantum communication

Message

Quantum computing

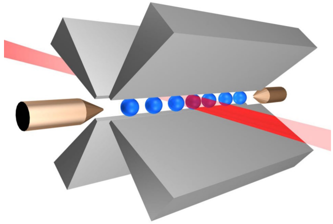


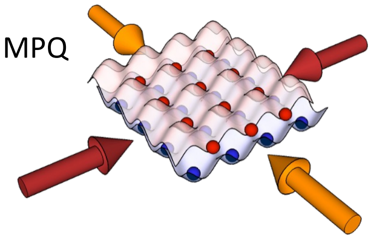
Foundations of quantum physics

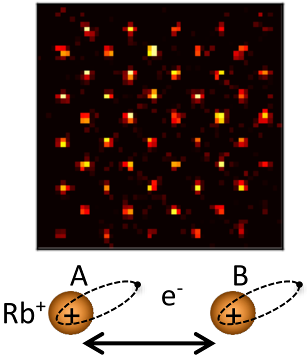


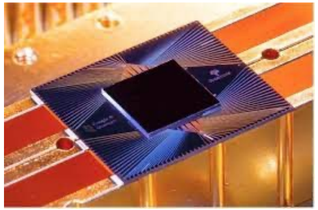
Zurek, Physics Today 1991

Engineering with individual quantum systems (examples)









Trapped ions

Atoms in optical lattices

Atoms in tweezer arrays

Supercond. Circuits

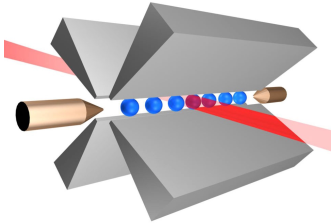
Scalable: beyond 1000 particles

Addressability: local manipulations and measurement

$$\langle \sigma_i^\alpha \rangle, \langle \sigma_i^\alpha \sigma_j^\beta \rangle, \ldots$$

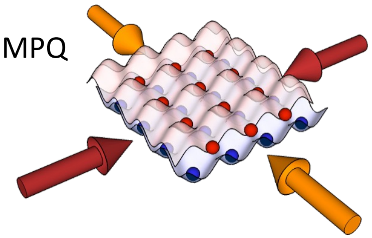
Programmable: controlled geometry, interactions…

Engineering with individual quantum systems (examples)

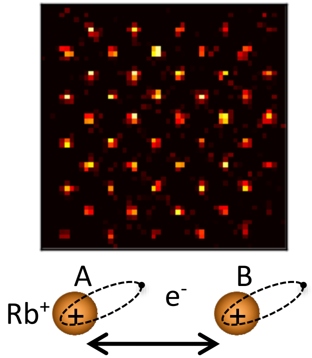


Trapped ions

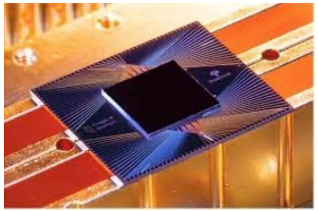
MPQ



Atoms in optical lattices



Atoms in tweezer arrays



Supercond. Circuits

Scalable: beyond 1000 particles

Addressability: local manipulations and measurement

$$\langle \sigma_i^\alpha \rangle, \langle \sigma_i^\alpha \sigma_j^\beta \rangle, \dots$$

Programmable: controlled geometry, interactions…

The program

Lecture 1: Arrays of atoms in optical tweezers
Rydberg atoms

Lecture 2: Interactions between Rydberg atoms
Rydberg blockade
Quantum computing with Rydberg atoms

Lecture 3: Quantum simulation: from Rydberg interactions to spin models… and more

Outline – Lecture 1

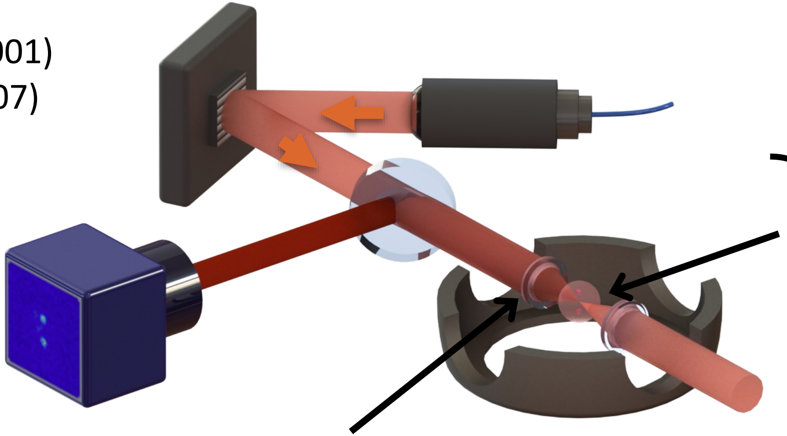
1. Arrays of individual atoms in optical tweezers

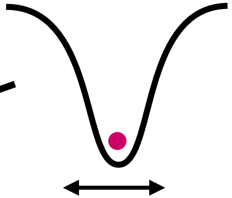
Review: Kaufman & Ni, Nat. Phys. **17**, 1324 (2021)

2. Basics of Rydberg physics

Optical tweezers: trapping in 3D

Grangier (2001)
Sortais (2007)

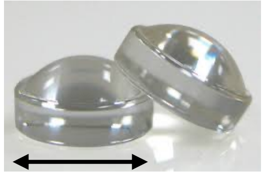




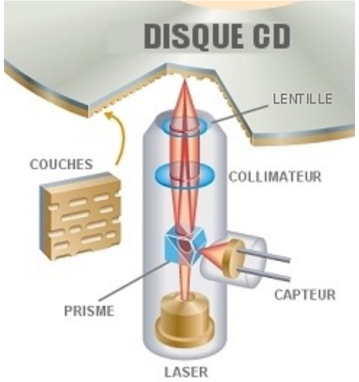
1 μm

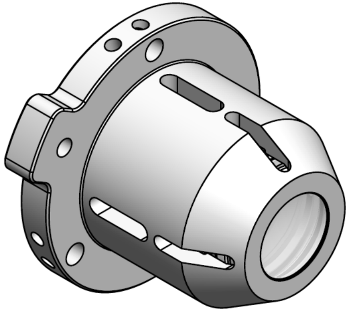
Lens NA $\geq$ 0.5

Aspherical lens



~ 1 cm

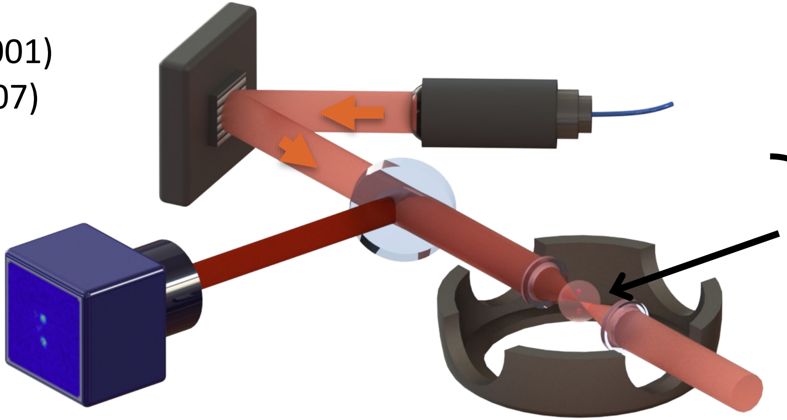


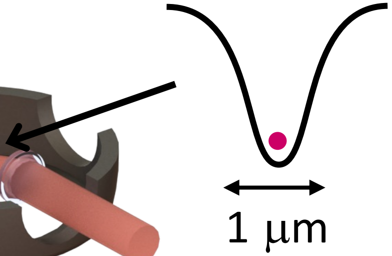


Microscope objective

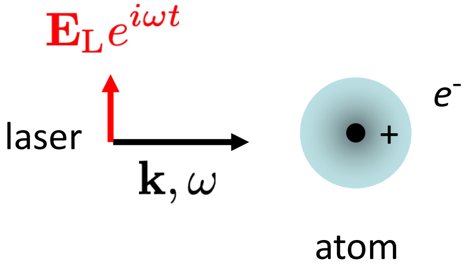
Optical tweezers: trapping in 3D

Grangier (2001)
Sortais (2007)





Dipole force



Optical tweezers: trapping in 3D

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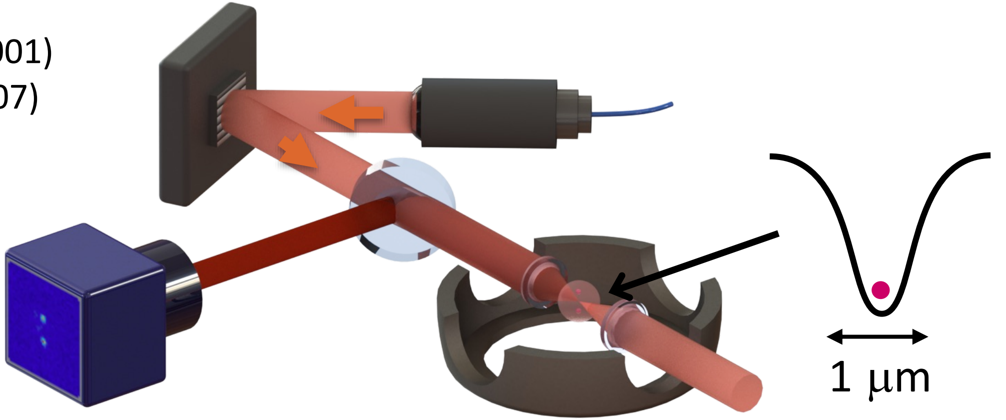

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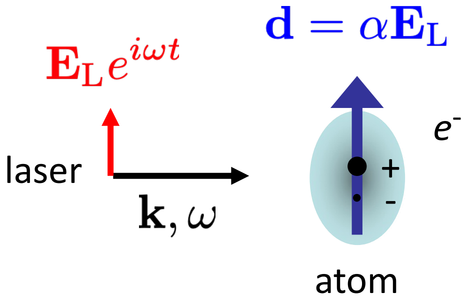

Optical tweezers: trapping in 3D

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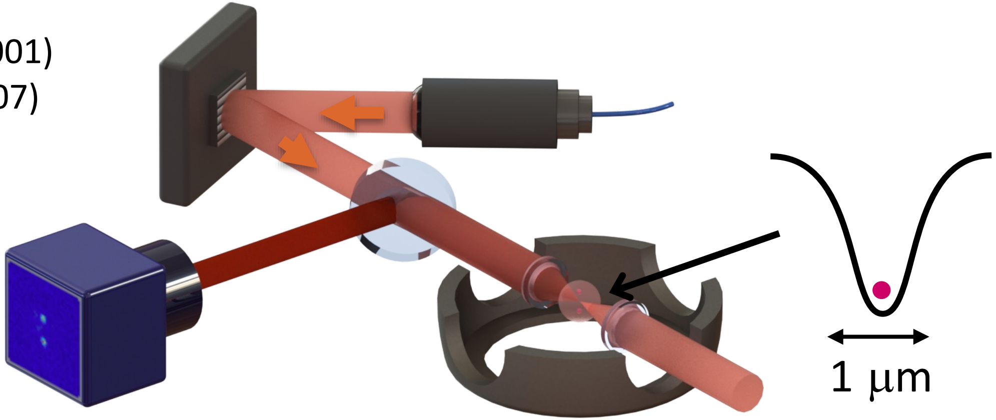
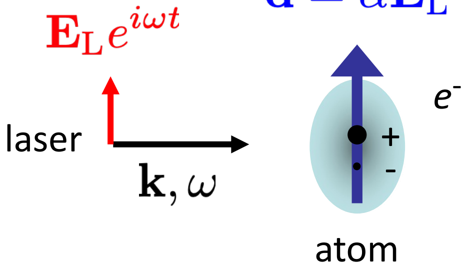
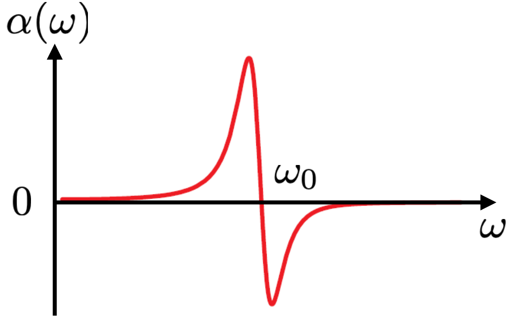


Dipole force

$$\mathbf{d} = \alpha \mathbf{E}_\mathrm{L}$$



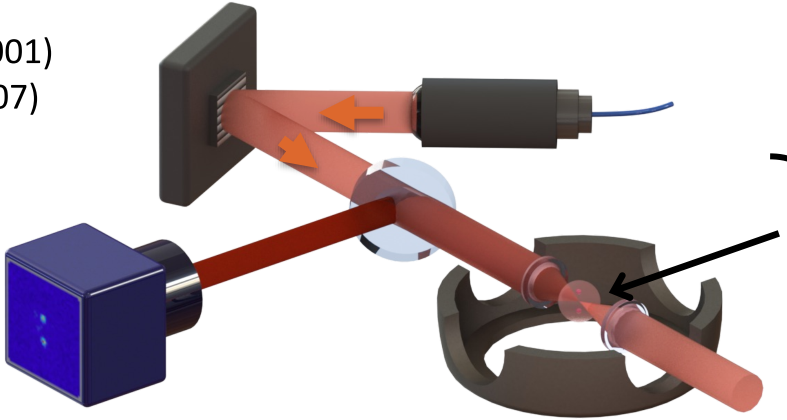
$$U = -\frac{1}{2}\langle \mathbf{d} \cdot \mathbf{E}_\mathrm{L} \rangle$$
$$= -\frac{1}{2}\alpha \langle \mathbf{E}_\mathrm{L}^2 \rangle$$

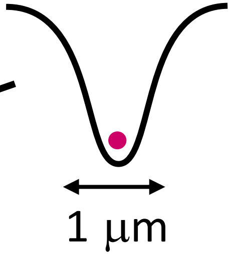


$\omega < \omega_0 \Rightarrow$ high-intensity seeker

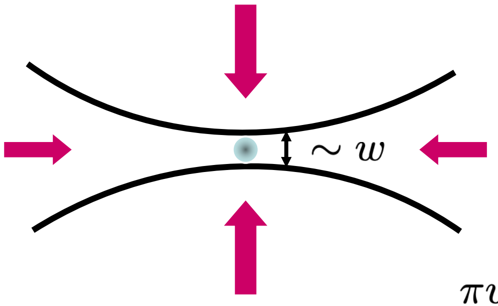
Optical tweezers: trapping in 3D

Grangier (2001)
Sortais (2007)





Gaussian beam



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

$$w \sim \lambda/\mathrm{NA} \Rightarrow V \sim \pi\lambda^3$$

Dipole force

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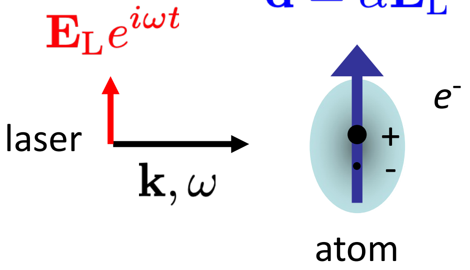

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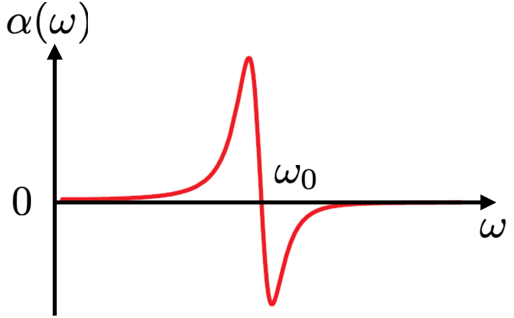

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Optical tweezers: trapping in 3D

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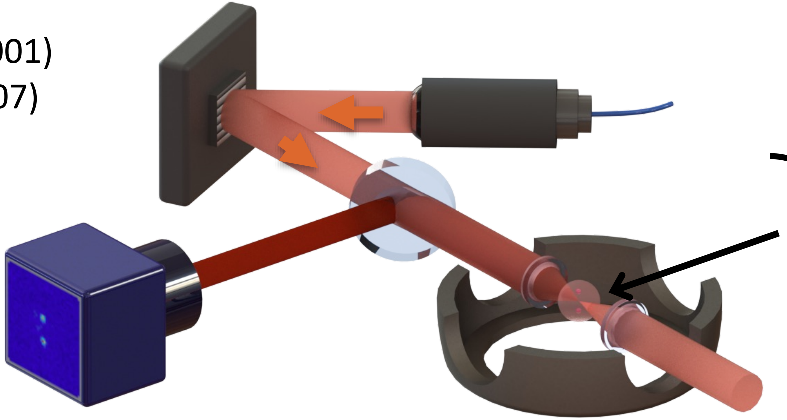

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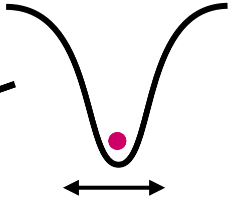

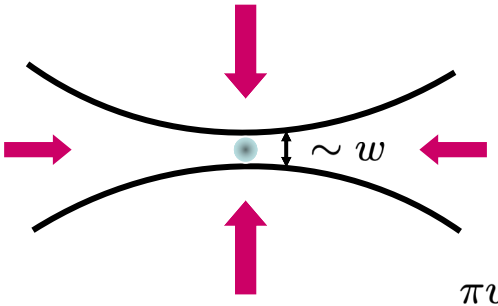

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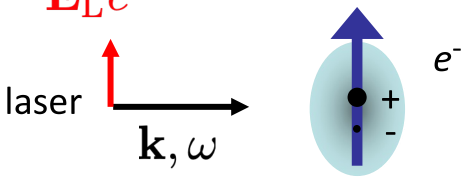

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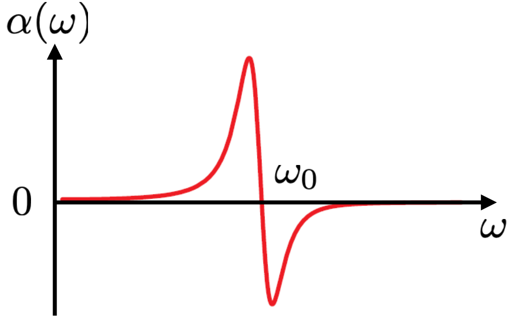
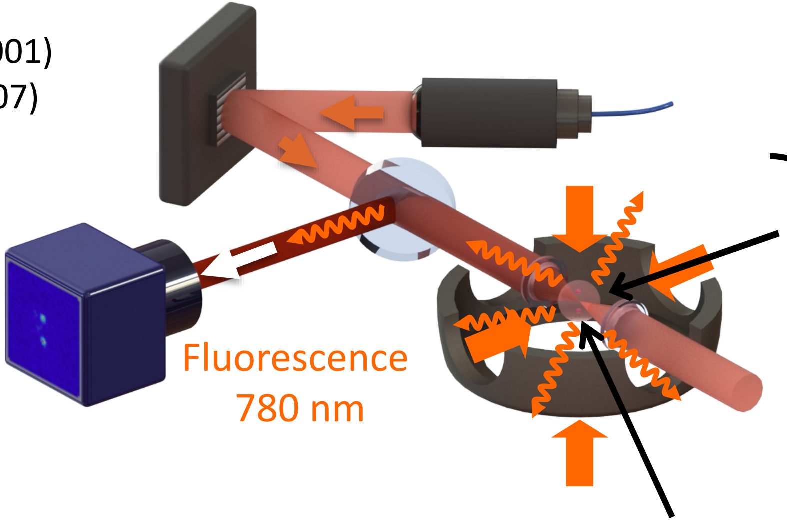


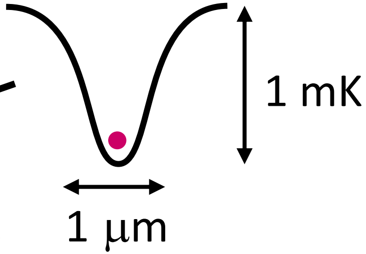
$\omega < \omega_0 \Rightarrow$ high-intensity seeker

Ex: 1 mW on 1 μm $\Rightarrow$ **Trap depth = 1 mK** $\Rightarrow$ Laser cooled atoms…

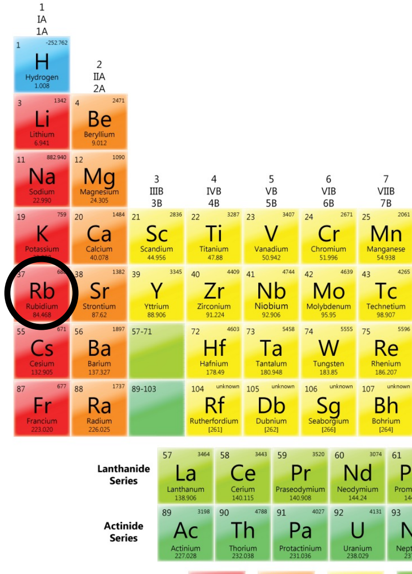
A single Rb atom in an optical tweezer

Grangier (2001)
Sortais (2007)





Rubidium



Reservoir = laser-cooled Rb atoms
T ~ 100 μK

A single Rb atom in an optical tweezer

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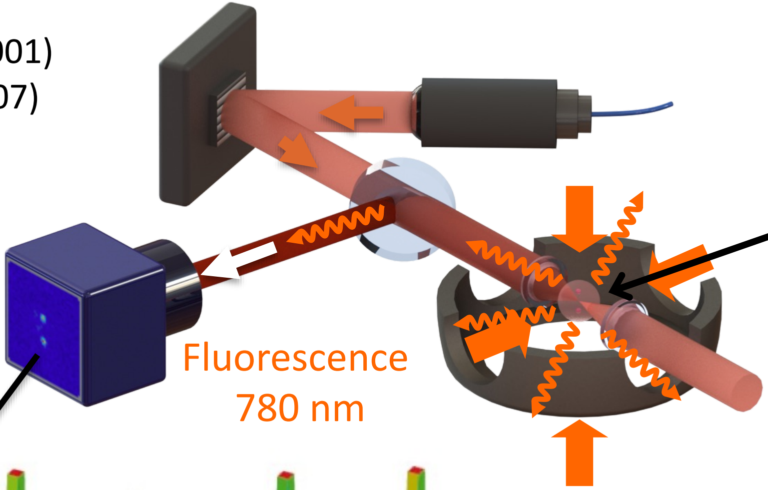
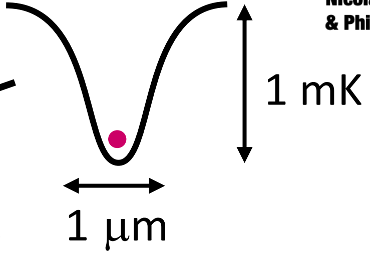
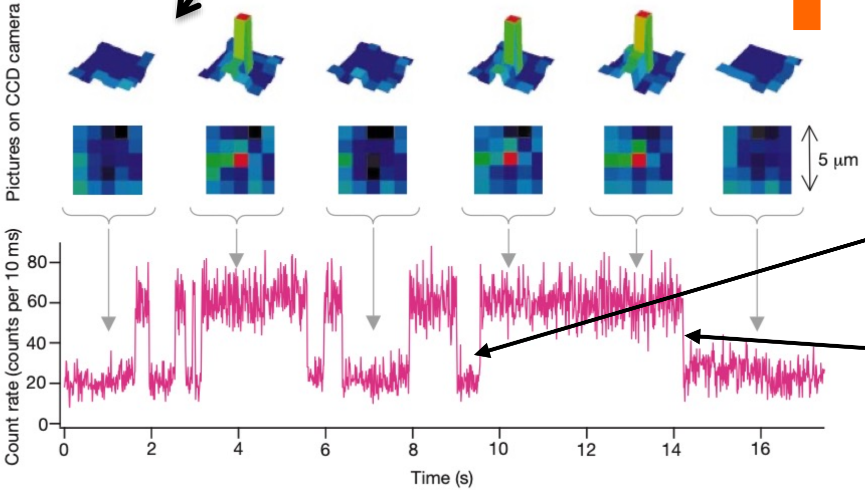


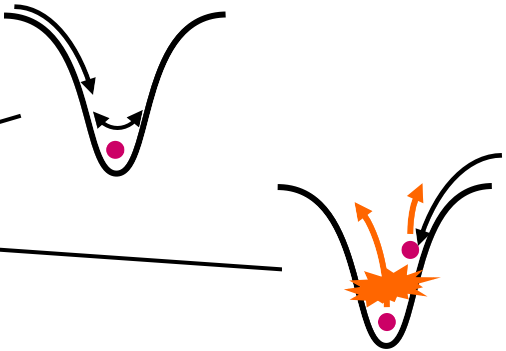


Sub-poissonian loading of single atoms in a microscopic dipole trap

Nicolas Schlosser, Georges Reymond, Igor Protsenko & Philippe Grangier

Nature 2001





A single Rb atom in an optical tweezer

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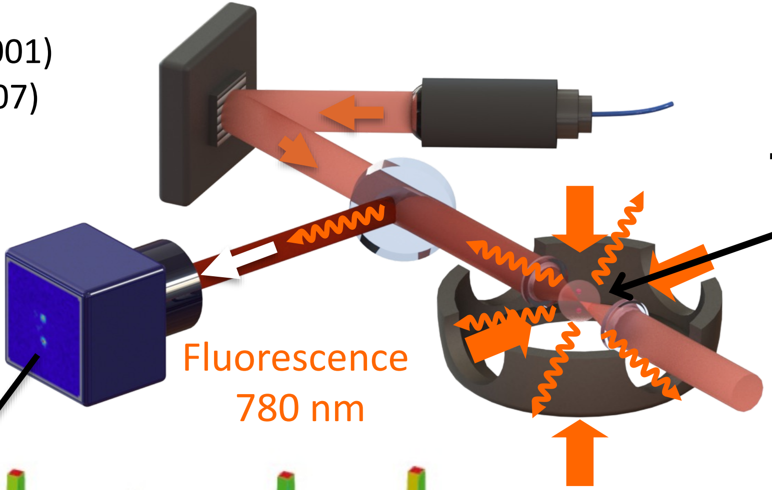

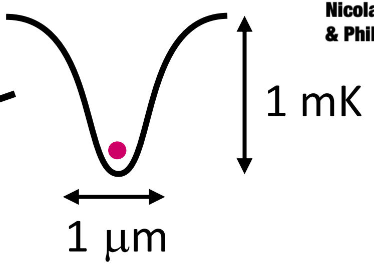

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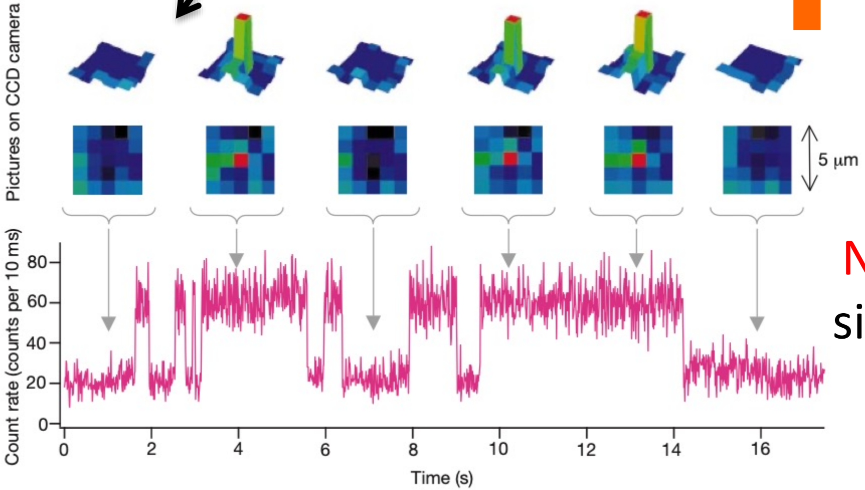
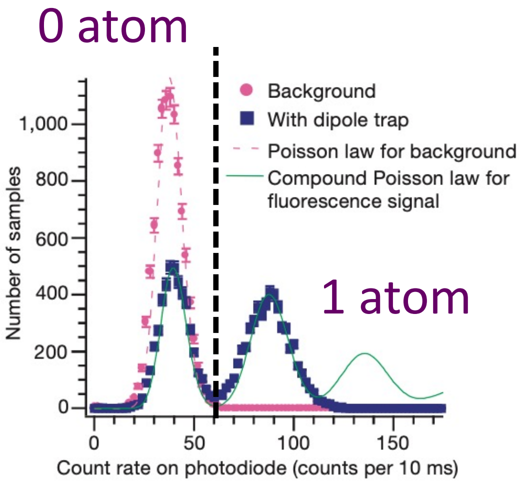
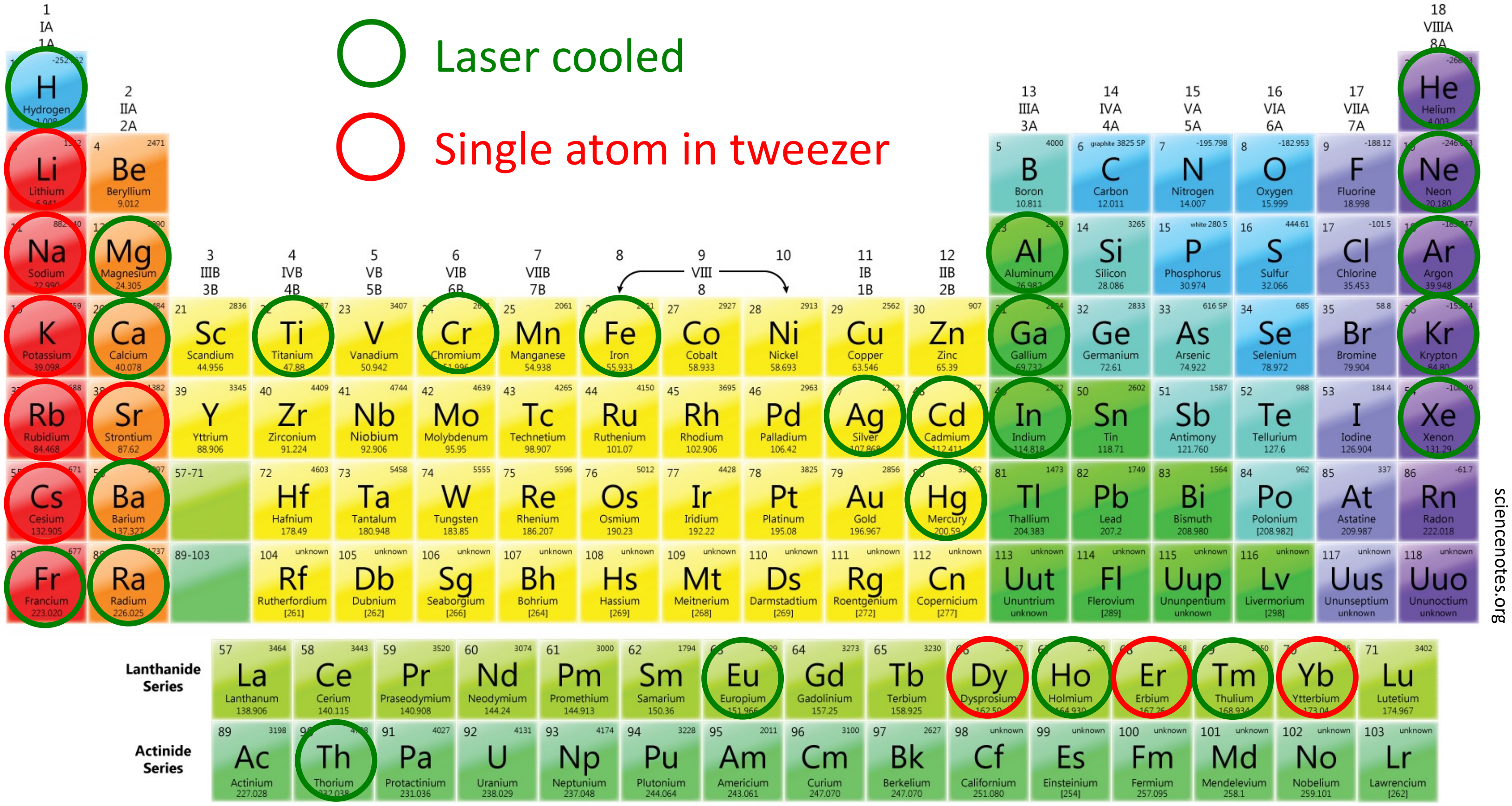


Non-deterministic
single-atom source

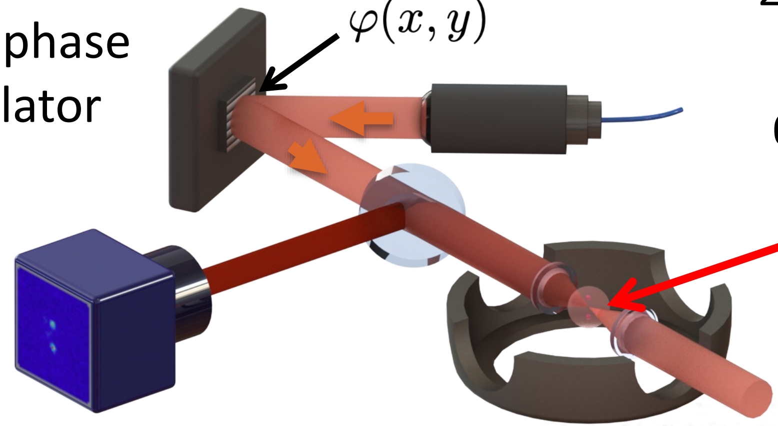


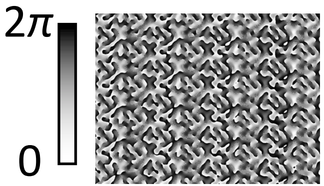
Single-atom trapping zoo (2026)



Atoms in arrays of optical tweezers

Spatial phase modulator



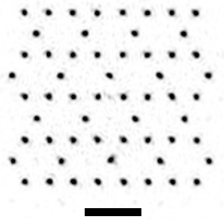


Phase mask

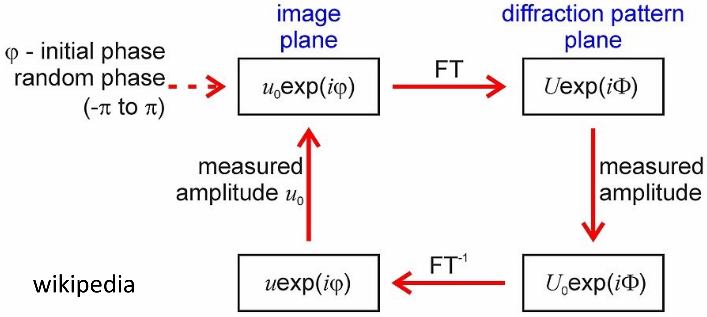
Bergamini JOSA B (2004)
Nogrette, PRX (2014)

$$\left|\mathrm{FT}[e^{i\varphi(x,y)}]\right|^2$$

Phase calculation: iterative algorithm (Gerchberg-Saxton)



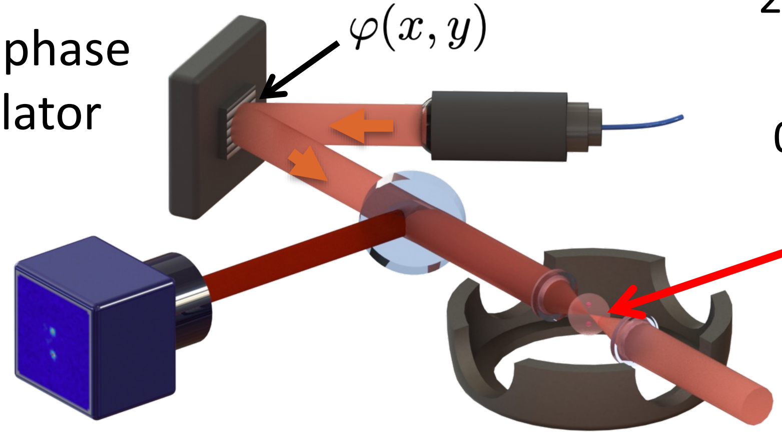
Optik **35**, 237 (1972)

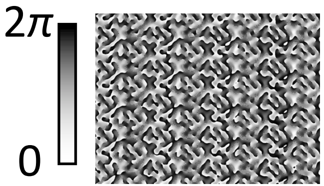


wikipedia

Atoms in arrays of optical tweezers

Spatial phase modulator





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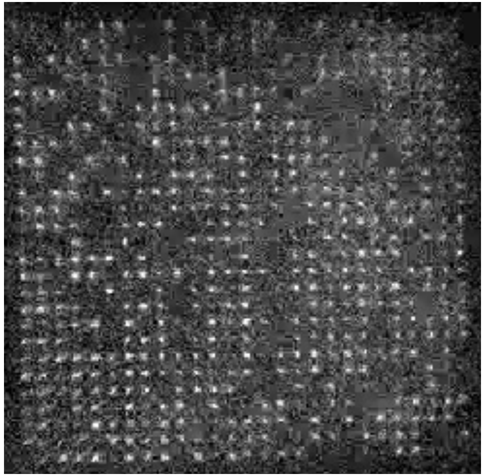
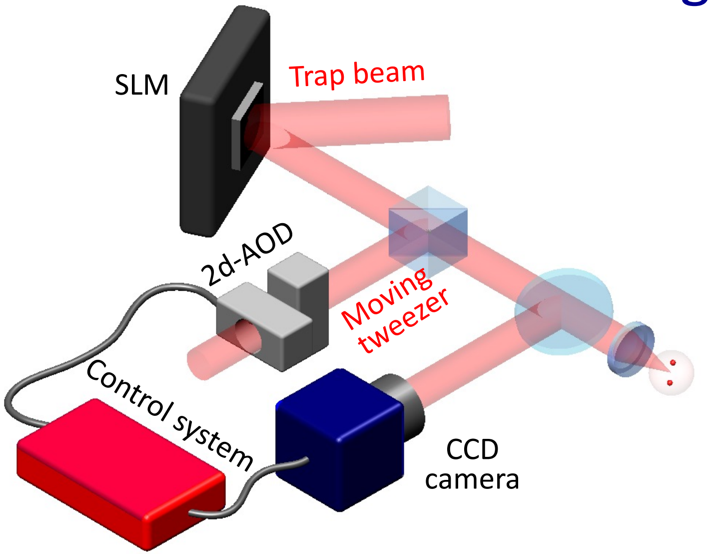
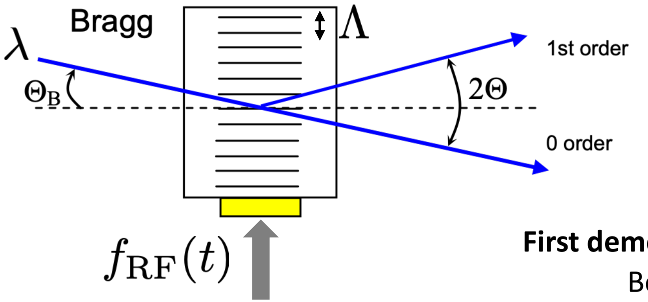


Fluorescence (729 traps)

Assembling atomic arrays atom-by-atom



Moving tweezer with 2D optical deflector

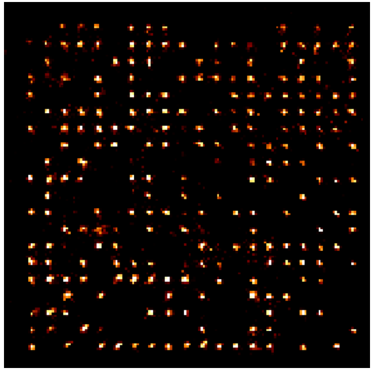


$$\Theta(t) \approx \frac{\lambda}{\Lambda} = \lambda\,\frac{f_{RF}(t)}{v_s}$$

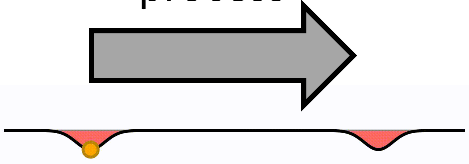
First demo (1D): Meschede, Nature (2006); Beugnon, Nat. Phys. (2007)

Barredo *et al.*, Science **354**,1021 (2016)

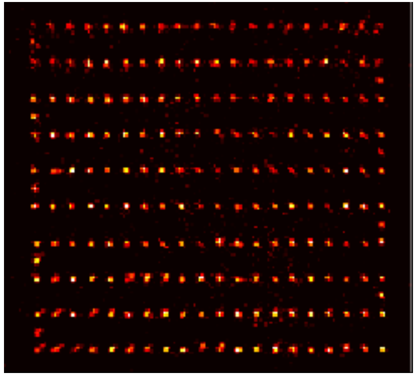
Initial configuration



Assembling process

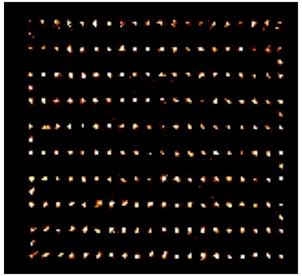


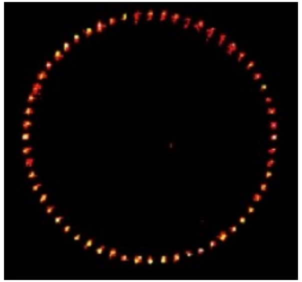
Assembled configuration



Atoms in arrays of optical tweezers (single-shot images)

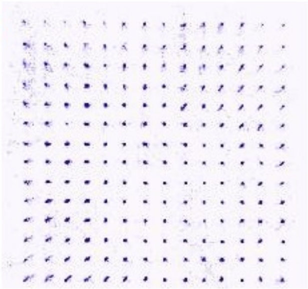
1D

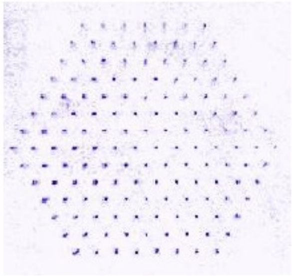


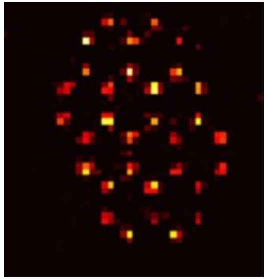


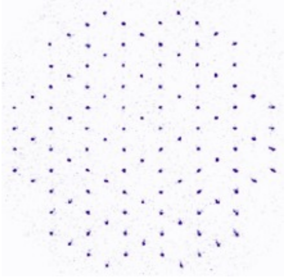
~100 μm

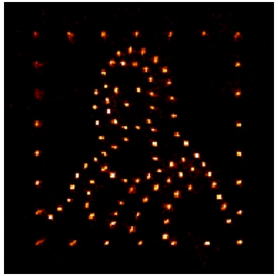
2D









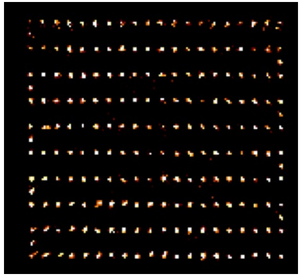


L. da Vinci

Barredo, Science 2016 ; Schymik, PRA 2020, 2022; PRAppl. 2021

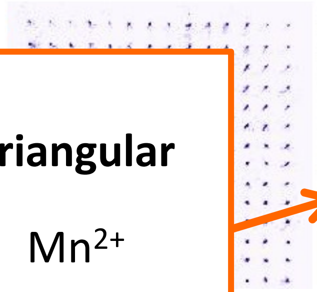
Atoms in arrays of optical tweezers (single-shot images)

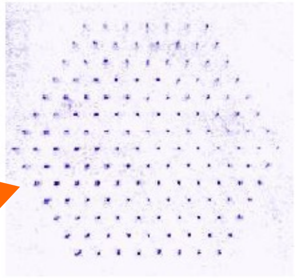
1D

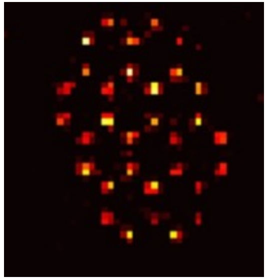


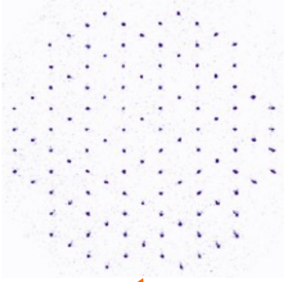
~100 μm

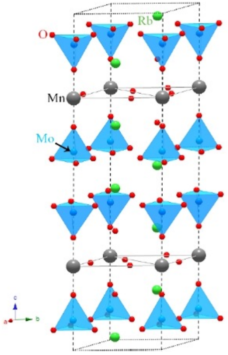
2D







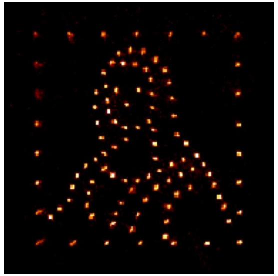




Triangular

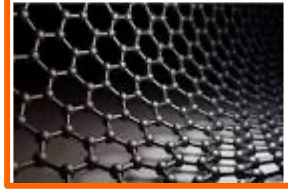
Mn^{2+}

$Rb_4Mn(MoO_4)_3$



L. da Vinci

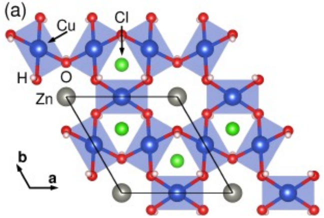
Hexagonal



graphene

Kagome: Herbertsmithite

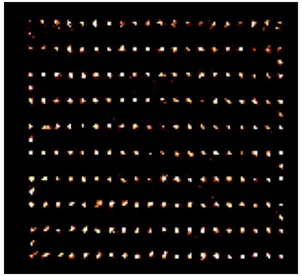
$ZnCu_3(OH)_6Cl_2$

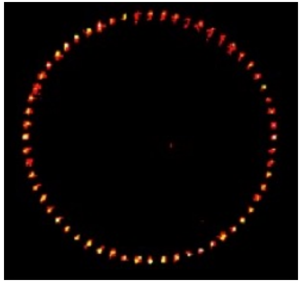


Barredo, Science 2016 ; Schymik, PRA 2020, 2022; PRAppl. 2021

Atoms in arrays of optical tweezers (single-shot images)

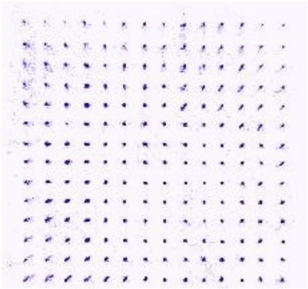
1D

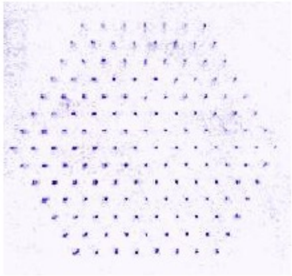




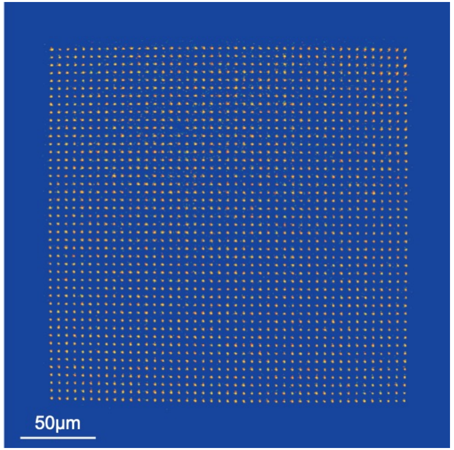
~100 μm

2D



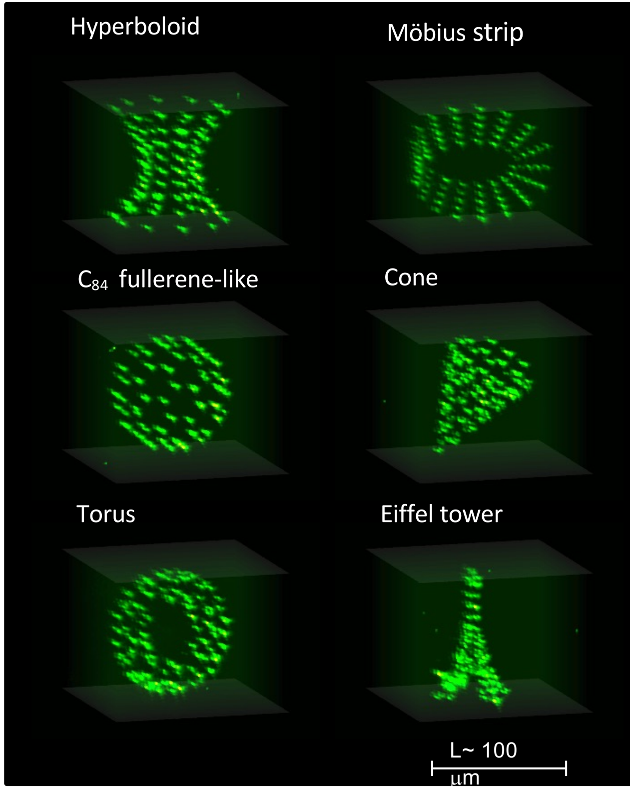


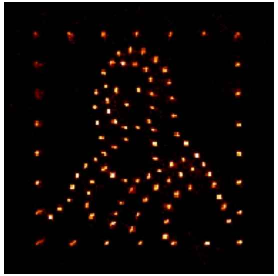
2024 atoms (AI + fast SLM)



3D

Barredo, Nature (2018)





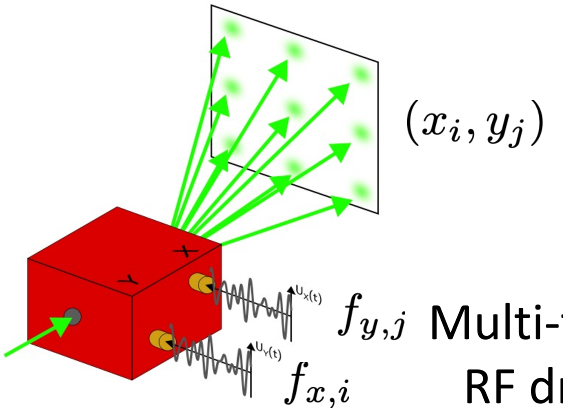
L. da Vinci

Barredo, Science 2016 ; Schymik, PRA 2020, 2022; PRAppl. 2021

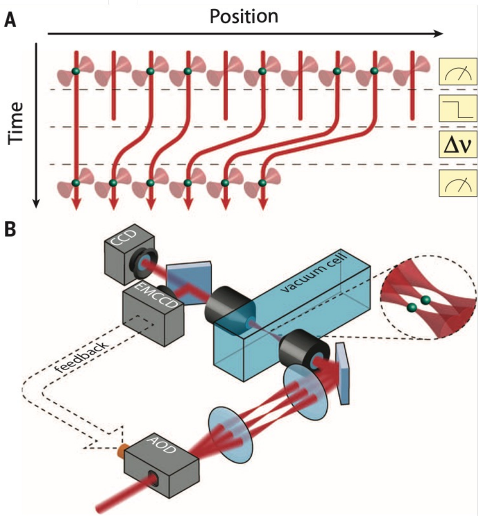
arXiv:2412.14647

Also: Weiss, Nat. Phys (2007); Ahn, Opt. Exp (2016)

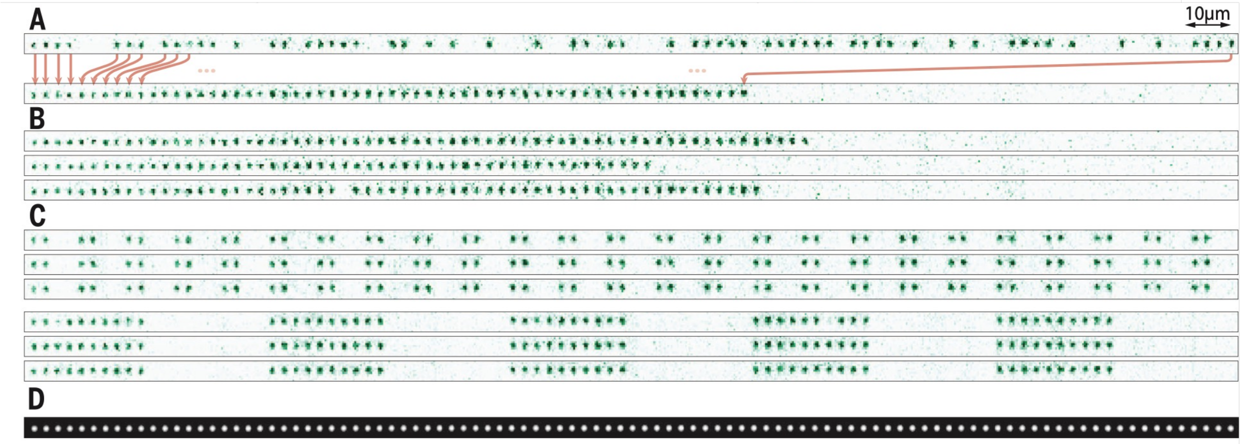
Another method: Arrays of moving tweezers



Multi-tone
RF drive

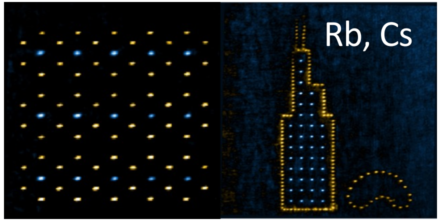


Endres *et al.*,
Science **354**,1024 (2016)

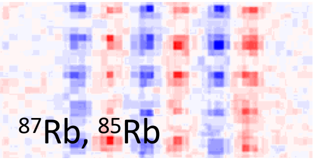


Now a popular platform…with many developments

Dual species arrays



H. Bernien PRX 2022

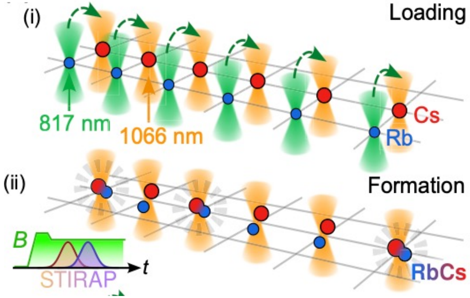


Zhan
PRL 2022

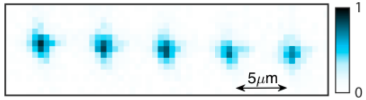
Trapping molecules

NaCs, RbCs

K-K Ni (2018)
Cornish (2023)

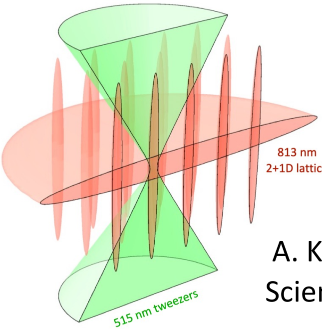


CaF



Ni, Doyle, Cheuck

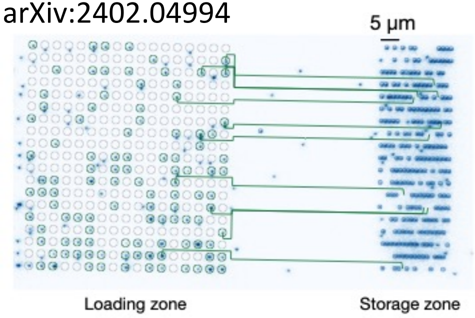
Combining optical lattices + tweezer

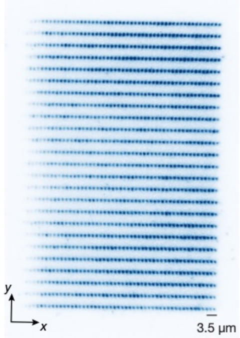


A. Kaufman
Science 2022

Continuous reloading schemes

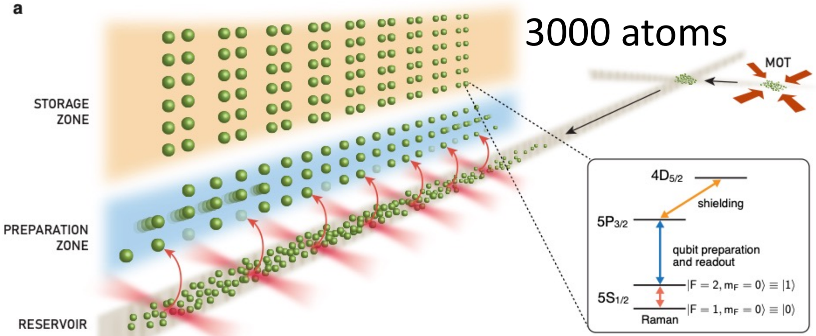
arXiv:2402.04994





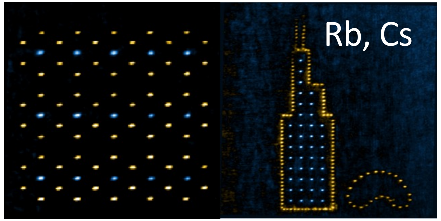
Thompson, arXiv:2506.15633
Lukin, Nature 2025

3000 atoms

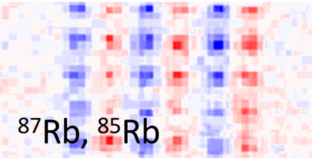


Now a popular platform…with many developments

Dual species arrays



H. Bernien PRX 2022



Zhan
PRL 2022

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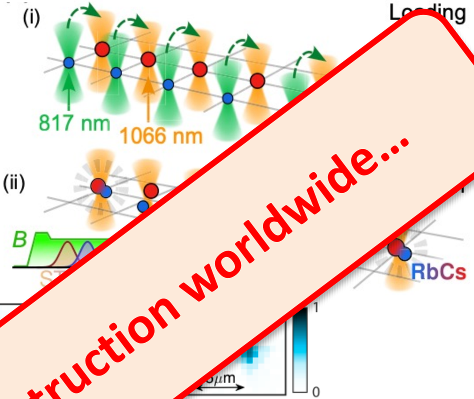
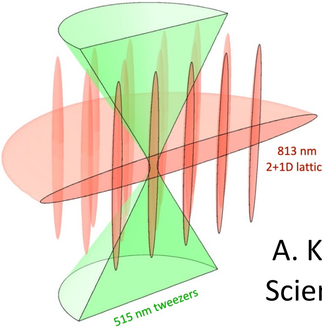


…, Cheuck

Combining optical lattices + tweezer

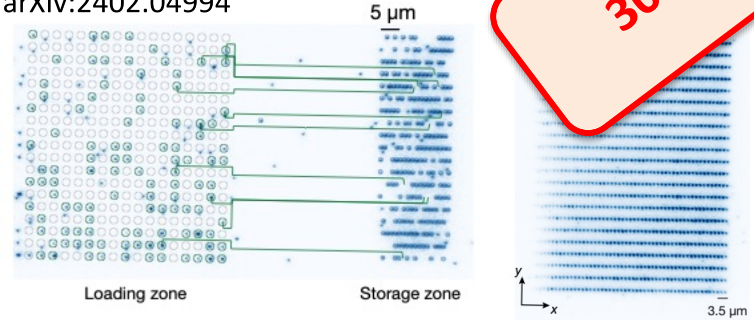


A. Kaufman
Science 2022

300+ in construction worldwide…

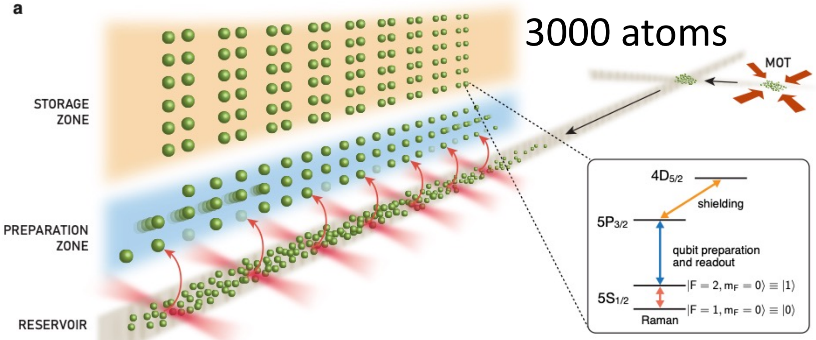
Continuous reloading sche…

arXiv:2402.04994



Thompson, arXiv:2506.15633
Lukin, Nature 2025

3000 atoms

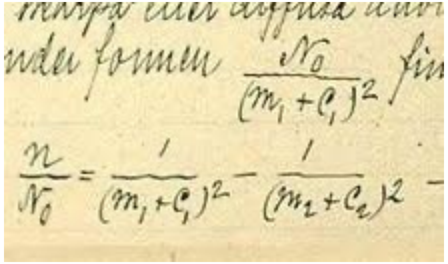


Outline – Lecture 1

1. Arrays of individual atoms in optical tweezers

2. Basics of Rydberg physics

1888

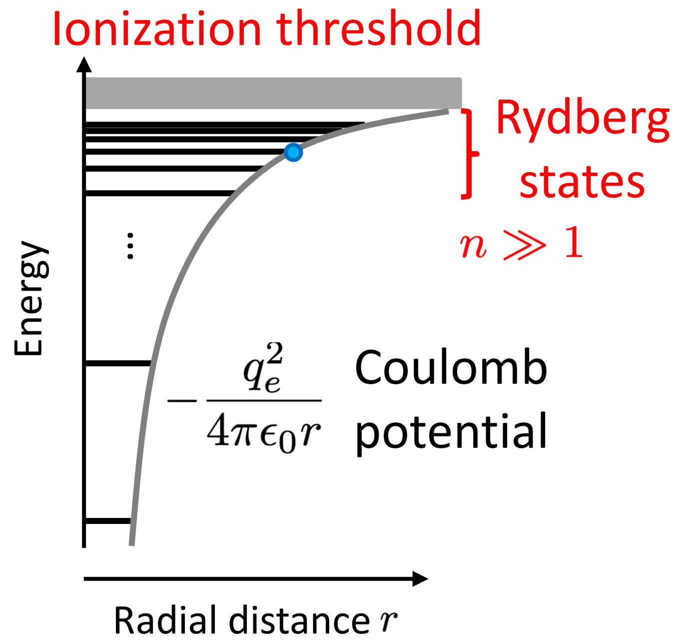


Johannes Rydberg
1854-1919

$$\frac{1}{\lambda_{nm}} = R_{\mathrm{H}}\left(\frac{1}{n^2} - \frac{1}{m^2}\right)$$

Idea of an infinite series
⇒ highly excited states

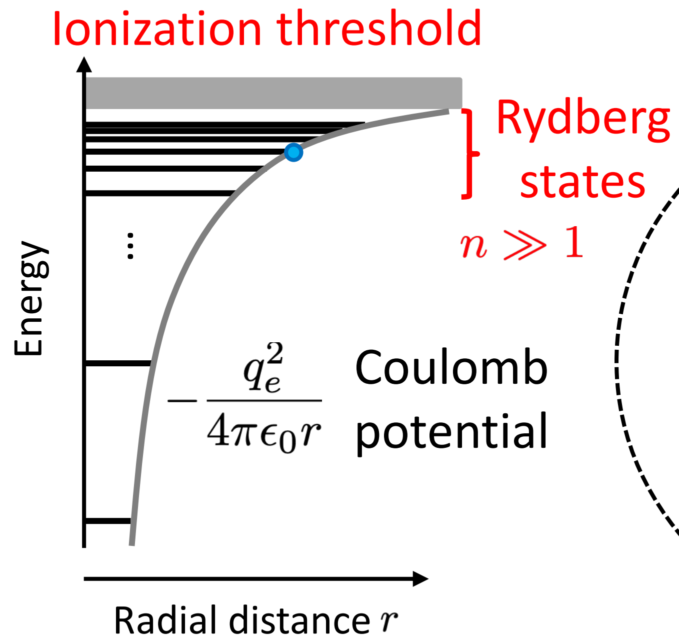
"Rydberg atom" = a highly excited atom



$$E_n = -\frac{R_y}{n^2}$$

$R_y = 13.6\,\mathrm{eV} = 3300\,\mathrm{THz}$

"Rydberg atom" = a highly excited atom



$$E_n = -\frac{R_y}{n^2}$$

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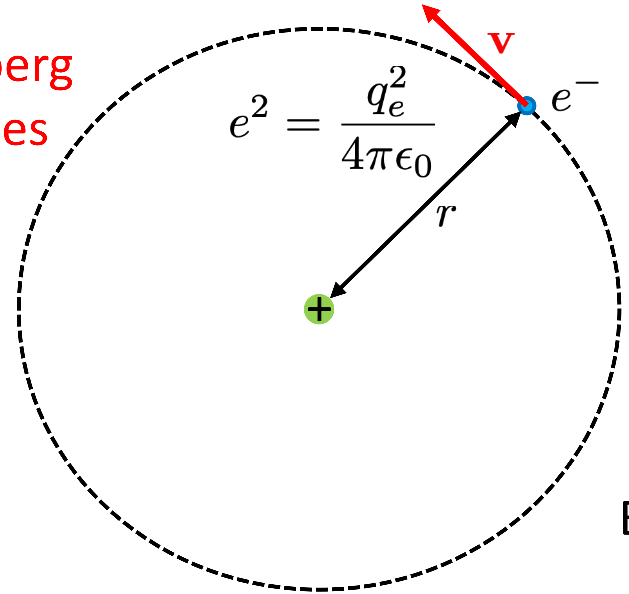
Bohr model



$$m_e \frac{v^2}{r} = \frac{e^2}{4\pi\epsilon_0 r^2}$$

Bohr quantization condition:

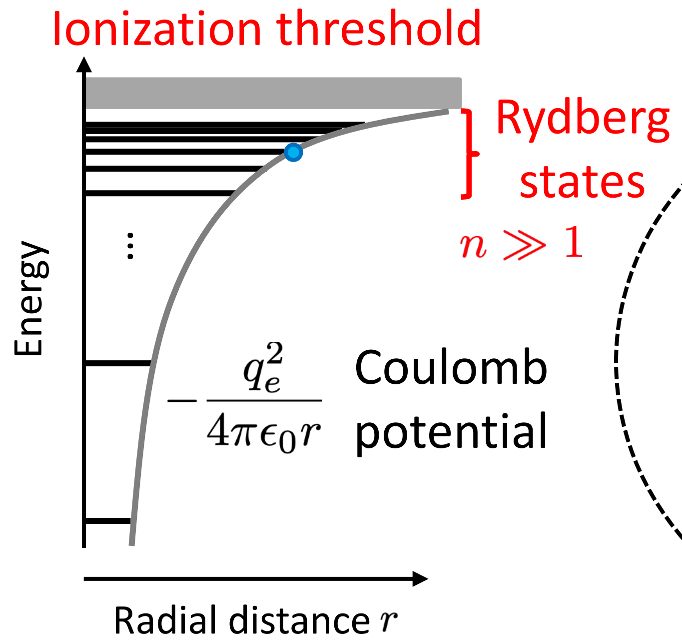
$$L = m_e v r = n\hbar$$

$$\Rightarrow r_n = \frac{\hbar^2}{m_e e^2} n^2$$

Bohr radius: $a_0 \approx 0.05\,\mathrm{nm}$

$$E_n = -\frac{1}{2}\frac{e^2}{r_n} = -\frac{e^2}{2a_0}\frac{1}{n^2}$$

"Rydberg atom" = a highly excited atom



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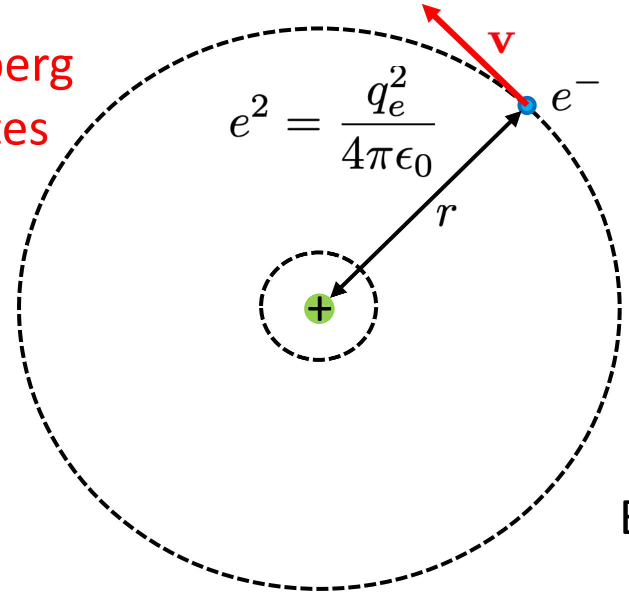
Bohr model



$$n = 10 \to r = 5\,\mathrm{nm}$$

$$n = 100 \to r = 500\,\mathrm{nm}$$

$$m_e \frac{v^2}{r} = \frac{e^2}{4\pi\epsilon_0 r^2}$$

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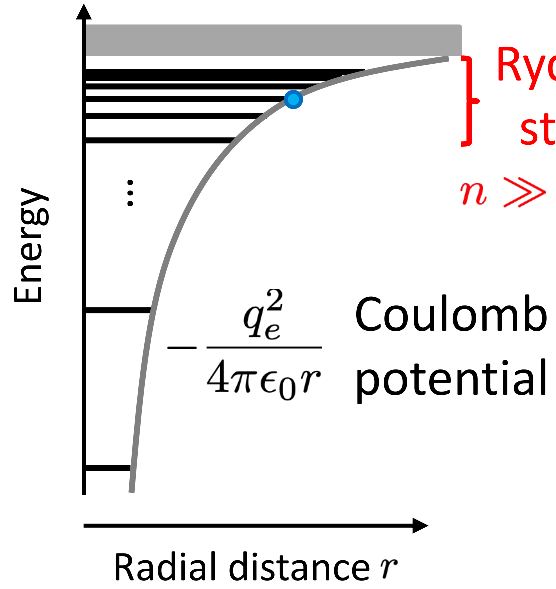
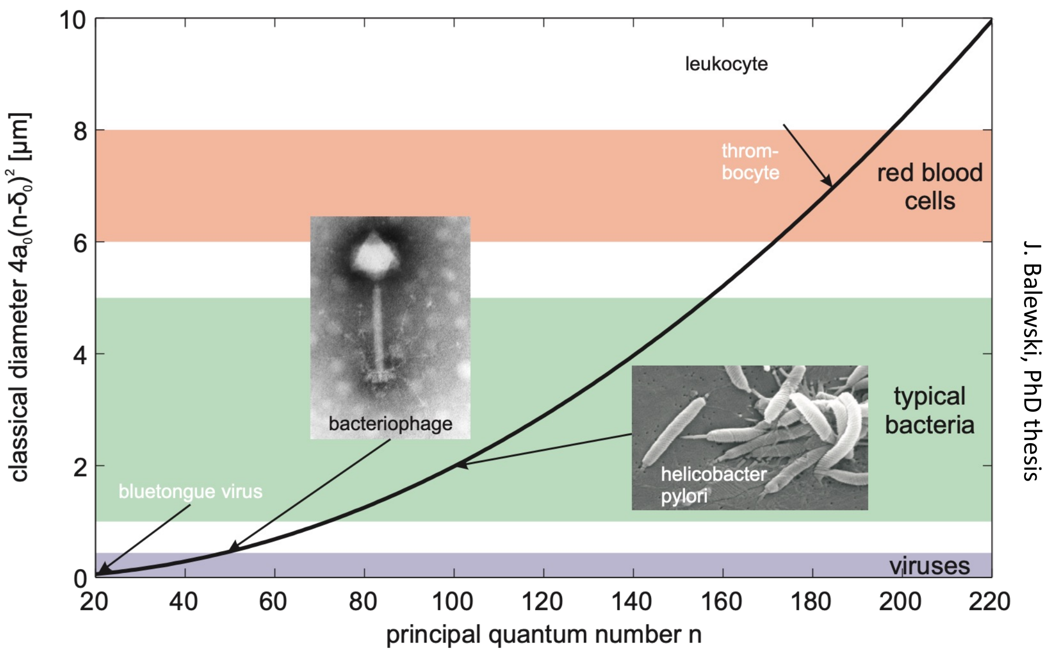


$$E_n = -\frac{R_y}{n^2}$$

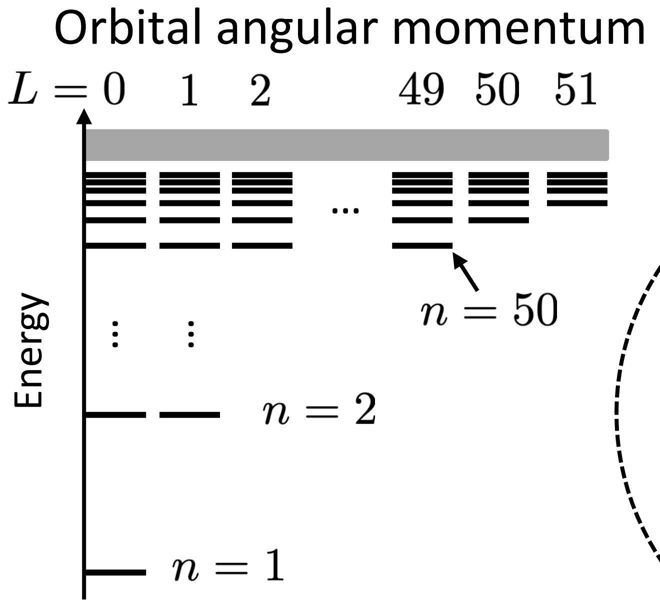
$$R_y = 13.6\,\mathrm{eV} = 3300\,\mathrm{THz}$$



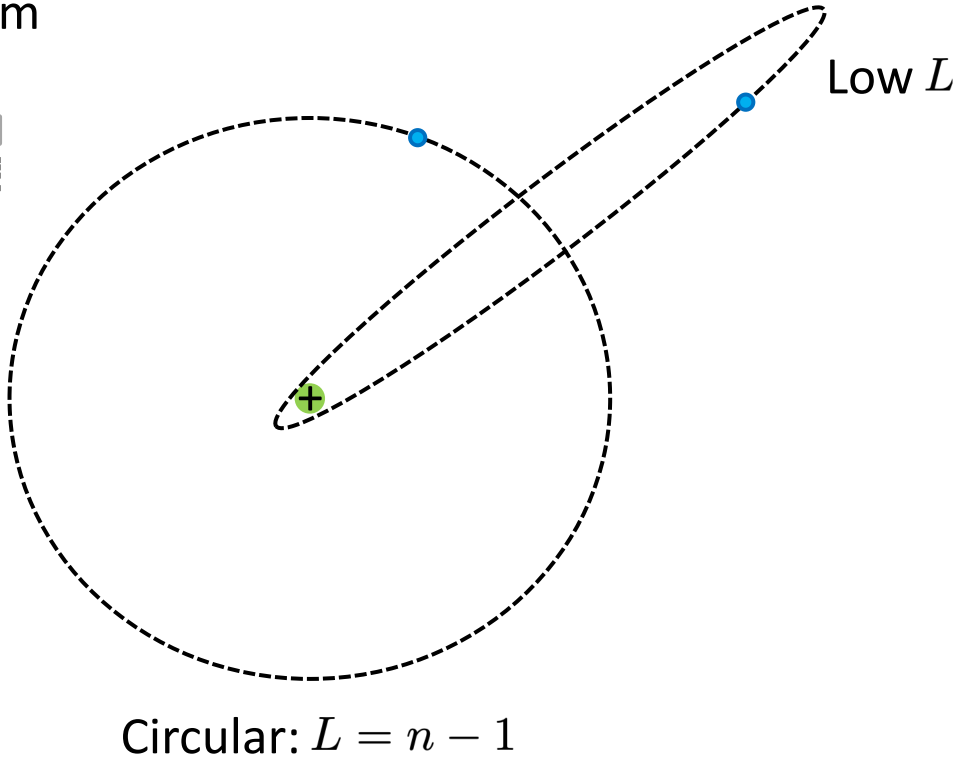
$$n = 10 \rightarrow r = 5\,\mathrm{nm}$$

$$n = 100 \rightarrow r = 500\,\mathrm{nm}$$

Circular and low angular momentum orbits



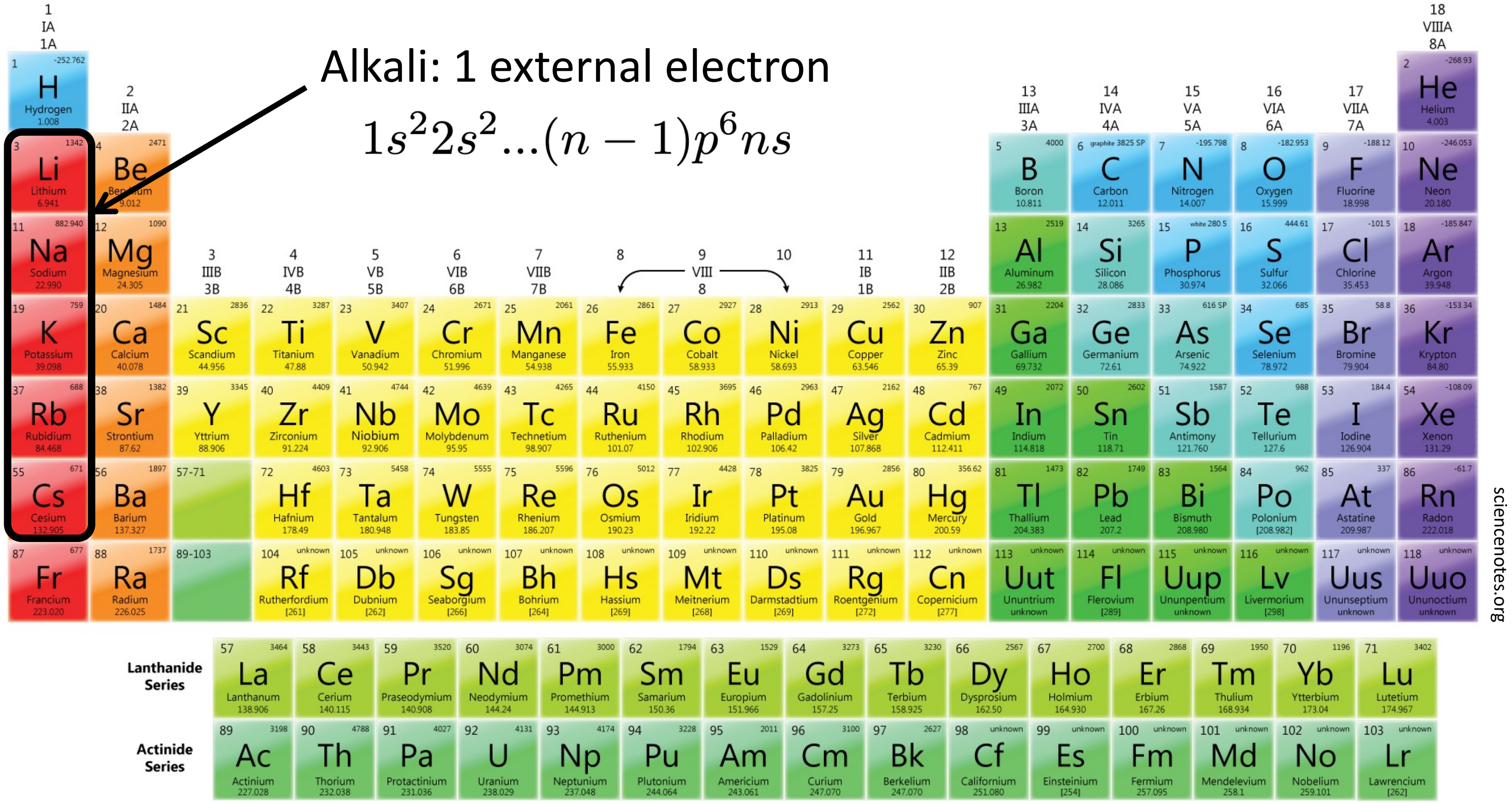
Coulomb potential:
E_n independent of L



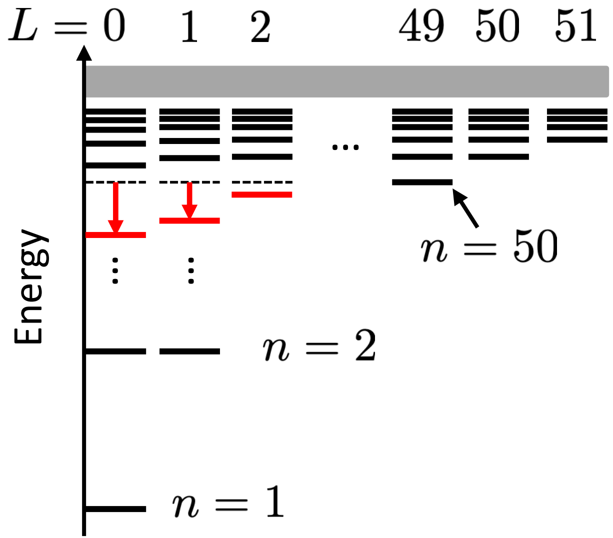
Alkali atoms = hydrogen-like atoms

Alkali: 1 external electron

$$1s^2 2s^2 \ldots (n-1)p^6 ns$$

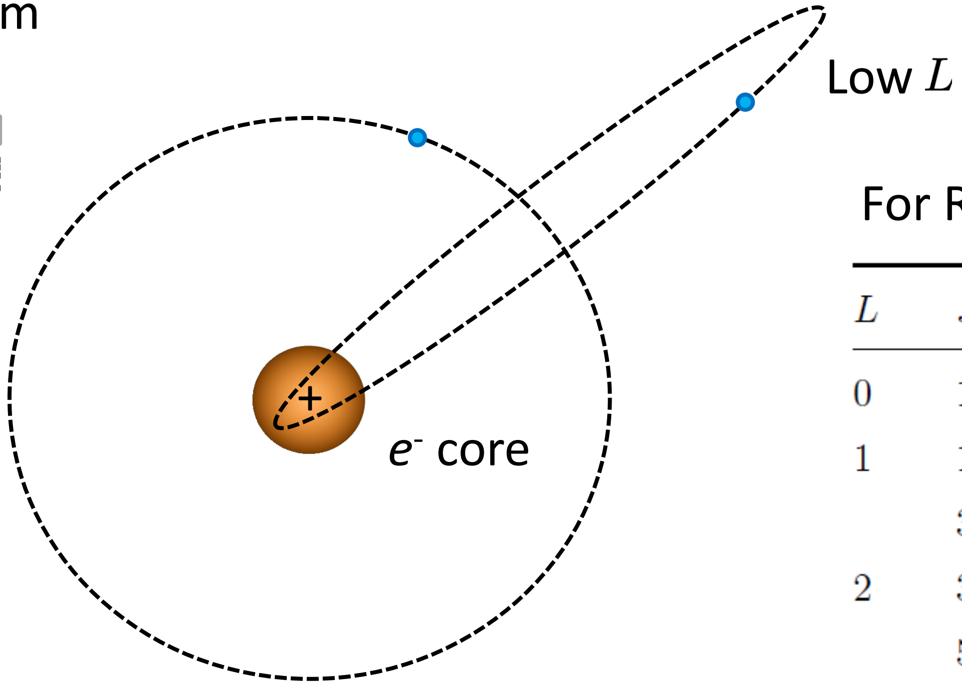


Alkali atoms = hydrogen-like atoms



$$E_n = -\frac{R_y}{(n - \delta_{nlj})^2}$$

Quantum defects (experimental)

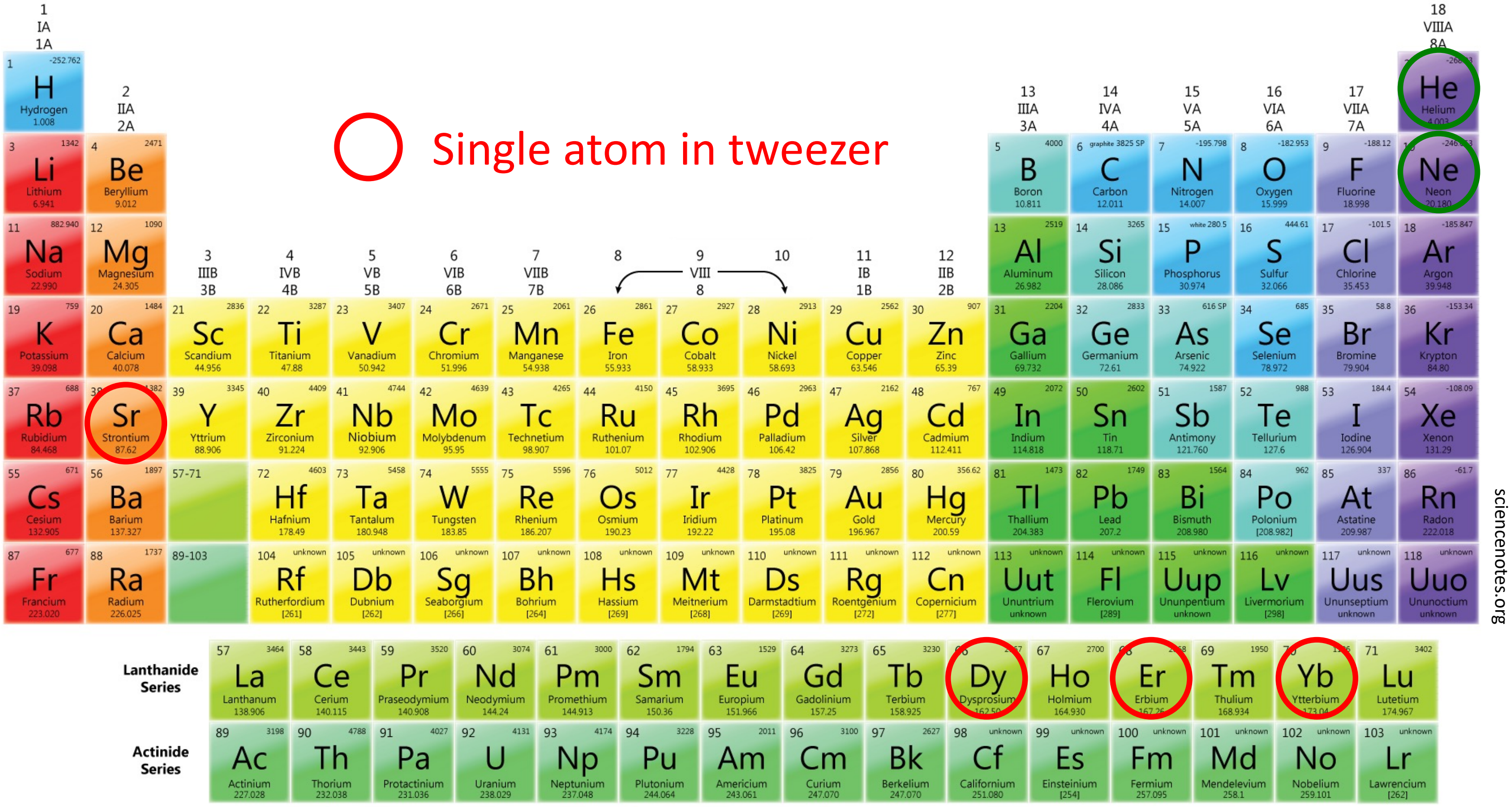


Low-L e^- polarize and penetrate core electronic cloud $\Rightarrow$ more tightly bound

For Rb: $n \geq 30$

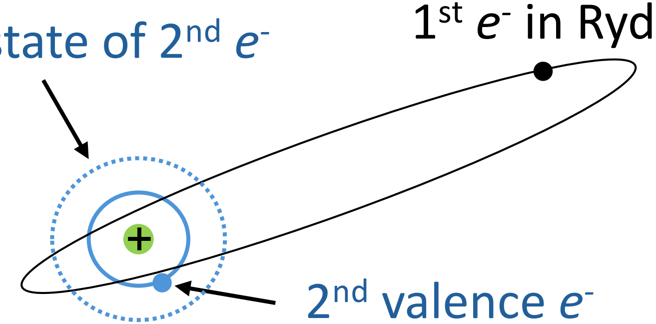
L	J	$\delta_{L,J}$
0	1/2	3.131
1	1/2	2.654
	3/2	2.641
2	3/2	1.348
	5/2	1.346
3	5/2	0.016
	7/2	0.016

Atoms with more than 1 valence electron



Atoms with more than 1 valence electron

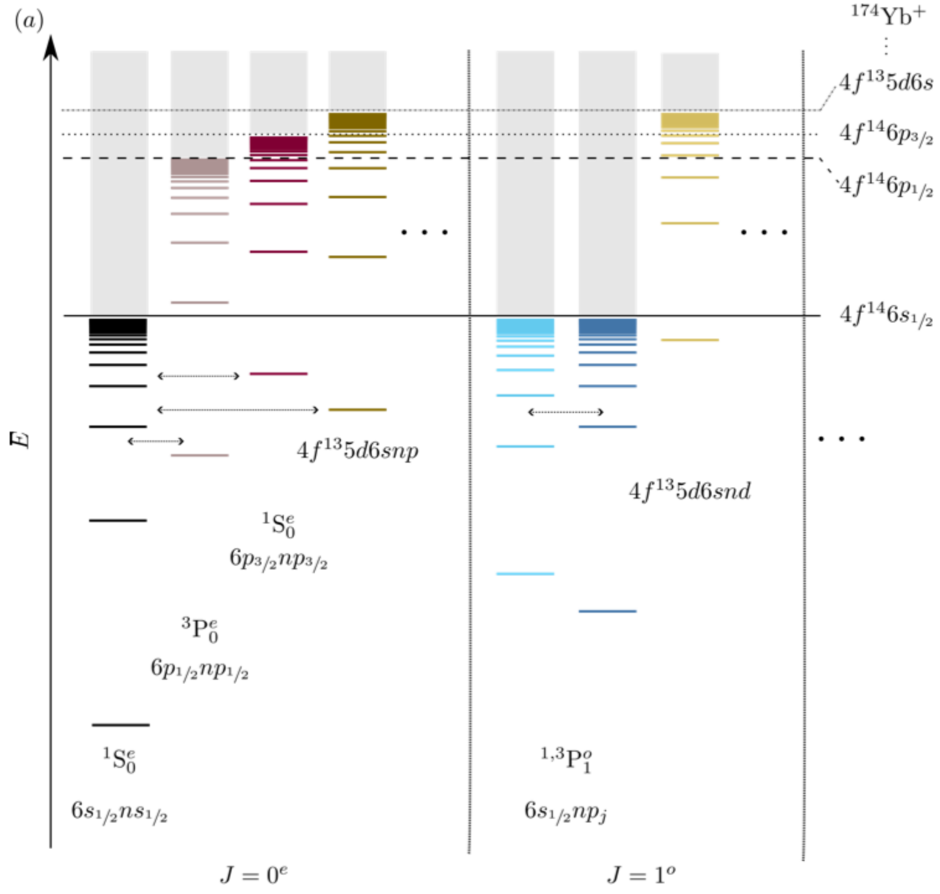
2 *e*⁻ atoms: Sr [$5s^2$], Yb [$6s^2 4f^{14}$]



- Rydberg series perturbed by second *e*⁻
- Rydberg *e*⁻ + excited second *e*⁻
  $\Rightarrow$ auto-ionization

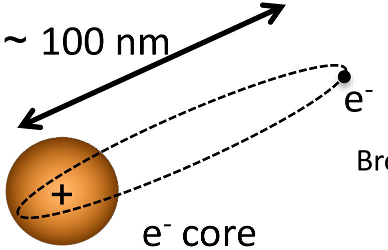
C L Vaillant, *et al.* J. Phys. B **47** 155001 (2014)

Other atoms: Er [$6s^2 4f^{12}$] Ferlaino 2021
Dy [$6s^2 4f^{10}$] Ferioli 2026



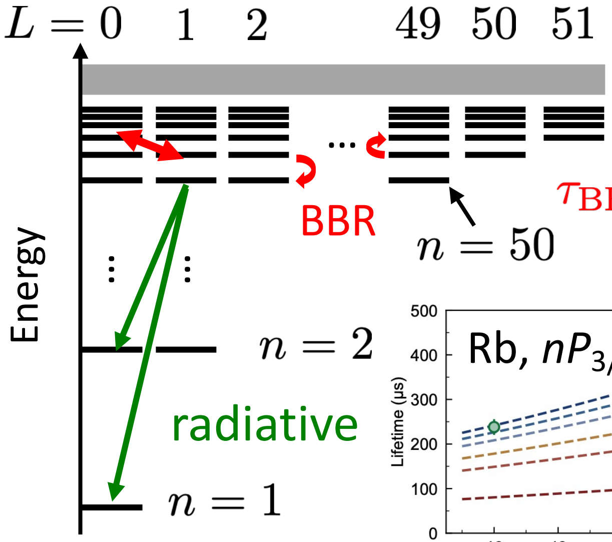
Cheinet, PRX Quantum **3**, 020327 (2022)
Thompson, Phys. Rev. X **15**, 011009 (2025)

Rydberg's have exaggerated properties



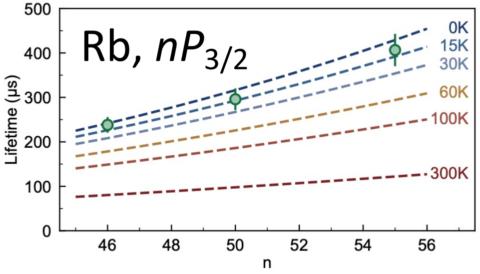
$\langle r \rangle \sim n^2 a_0$

Browaeys, Barredo, Lahaye,
J. Phys. B 2016



$\tau_{\mathrm{BB}} \sim \dfrac{n^2}{k_{\mathrm{B}} T}$

$\tau_{\mathrm{rad}} \sim n^3$



Bakr, arXiv:2602.05959

Transition frequency:

$$\nu_{n,n-1} \approx 1 - 10\,\mathrm{GHz}$$

Long lifetime: $\tau \sim n^3$

$\Rightarrow$ *n* > 60, τ > 100 μs

Large transition dipole:

$$\langle n, l | \hat{D} | n, l \pm 1 \rangle \sim n^2 e a_0$$

Large polarizability: $\alpha \sim n^7$

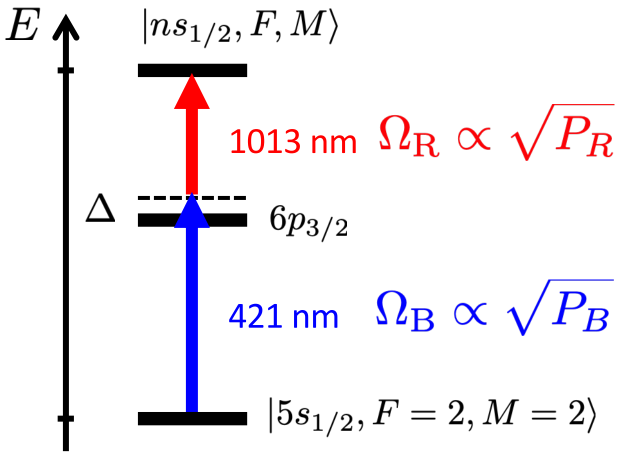
$$\langle \hat{D} \rangle = \alpha E$$

$\Rightarrow$ **Exaggerated properties:**

- strong interaction
- strong coupling to fields (DC, MW)

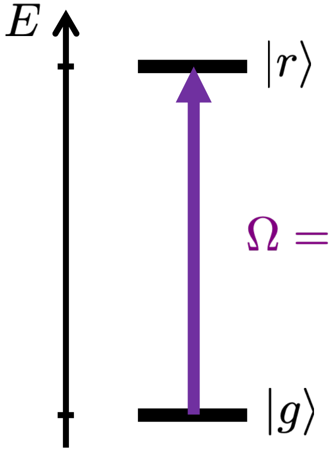
Coherent optical Rydberg excitation (n = 50 – 100)

Alkali: Rb, Cs

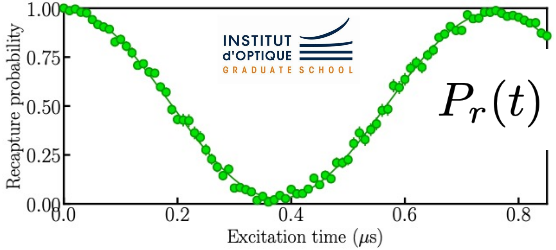


Coherent optical Rydberg excitation (n = 50 – 100)

Alkali: Rb, Cs



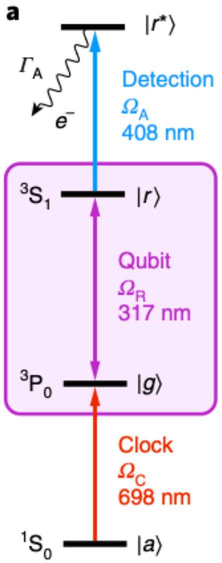
$$\Omega = \frac{\Omega_R \Omega_B}{2\Delta}$$

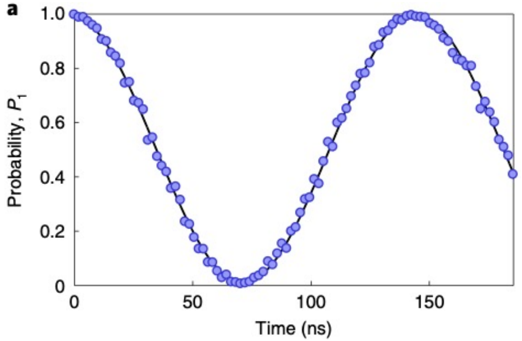


$$P_r(t) = \sin^2 \frac{\Omega t}{2}$$

$F > 98\%$

2-e^- atom: Sr, Yb



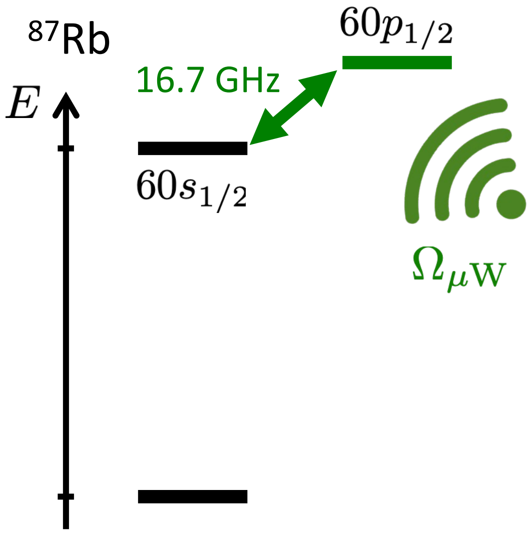


Endres, Nat. Phys. 2020

$F > 99.5\%$

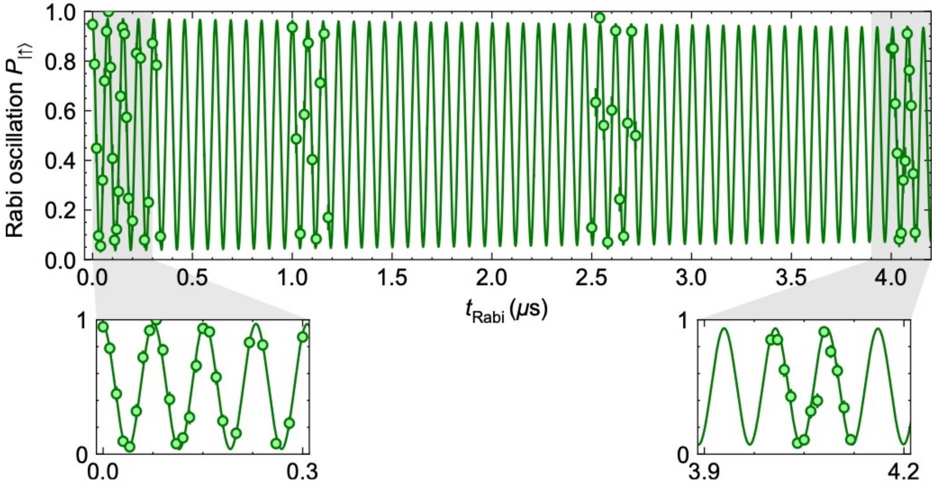
$$|\psi(t)\rangle = \cos\frac{\Omega t}{2}|g\rangle - i\sin\frac{\Omega t}{2}e^{i\varphi}|r\rangle$$

Coherent microwave manipulations (n = 50 – 100)



Single atom ⇒ repeat 100 times

Microwave Rabi oscillations

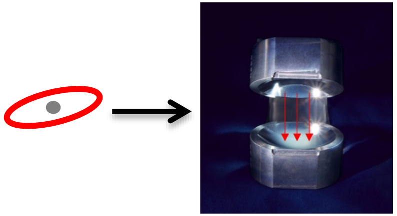


D. Barredo *et al.*,
PRL **114**, 113002 (2015)

Rydberg atoms: a few historical landmarks

1975 Spectroscopy using lasers (Gallagher, Kleppner, Haroche…)

1980 – 2000 Cavity Quantum Electrodynamics using Rydbergs

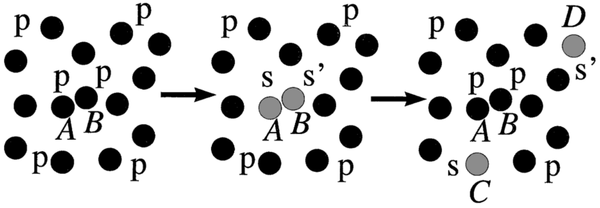


High Q cavity: photon lifetime > 1ms
+ large dipole ⇒
1 Rydberg interacts with 1 photon!

Haroche, Walther…

1998 Rydbergs meet cold atoms P. Pillet and T. Gallagher

Anderson, PRL **80**, 249 (1998)
Mourachko, PRL **80**, 253 (1998)



p + p ↔ s + s'
p + s ↔ s + p

"Frozen" gas

Diffusion of excitation faster than motion ⇒ correlations between all atoms

$k_B T$ << Interaction energy
⇒ $T < 1$ mK

References:

"Rydberg atoms", T. Gallagher, Cambridge (1994)

"An experimental and theoretical guide to strongly interacting Rydberg gases", R. Loew, J. Phys. B **45**, 113001(2012)

"Quantum Information with Rydberg atoms", M. Saffman, T. Walker, K. Moelmer, Rev. Mod. Phys. **82**, 2313 (2010)

Special Issue on Rydberg Atomic Physics, J. Phys. B (2016) contains many reviews

"Many-body physics with individually controlled Rydberg atoms", Browaeys & Lahaye, Nature Physics **16**, 132 (2020)

The program

Lecture 1: Arrays of atoms in optical tweezers
Rydberg atoms

Lecture 2: Interactions between Rydberg atoms
Rydberg blockade
Quantum computing with Rydberg atoms

Lecture 3: Quantum simulation: from Rydberg interactions
to spin models… and more