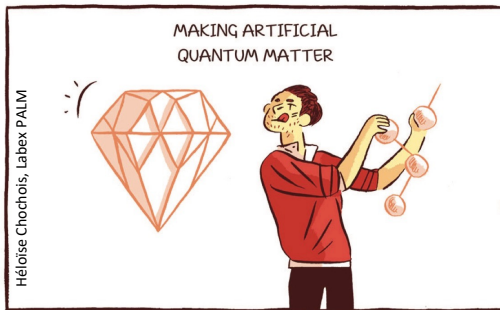


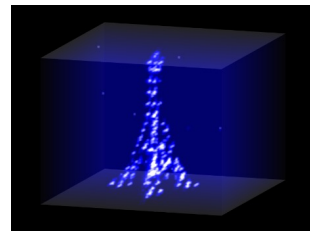
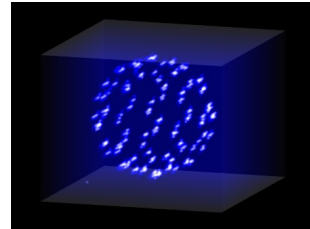
Arrays of atoms for Quantum Simulation and Computation



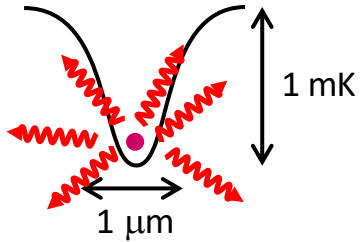
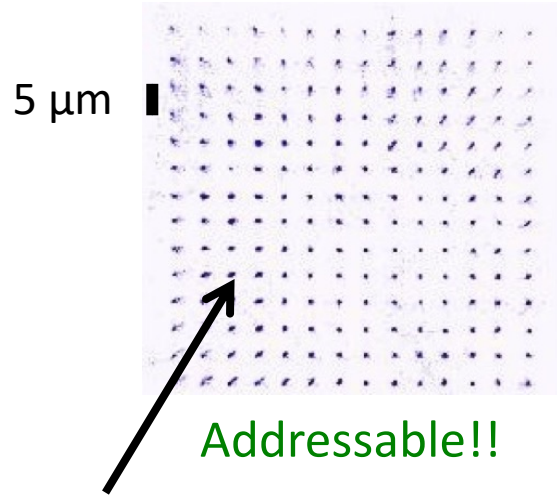
Antoine Browaeys

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

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

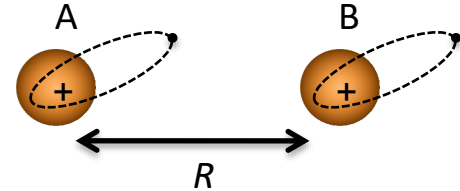


These lectures: combining arrays of atoms and Rydberg interactions



+

Rydberg interactions



Van der Waals

resonant

$$\frac{C_6}{R^6}$$

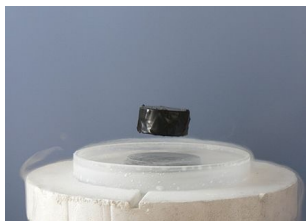
$$\frac{C_3}{R^3}$$

Quantum state engineering:

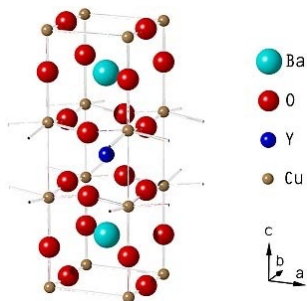
create controlled quantum systems

Quantum engineering: create controlled quantum systems

Many-body physics



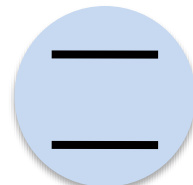
YBaCuO



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

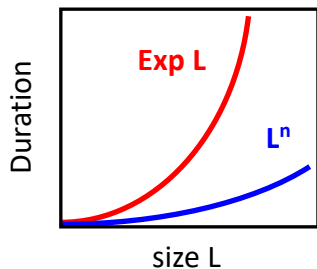
Quantum communication



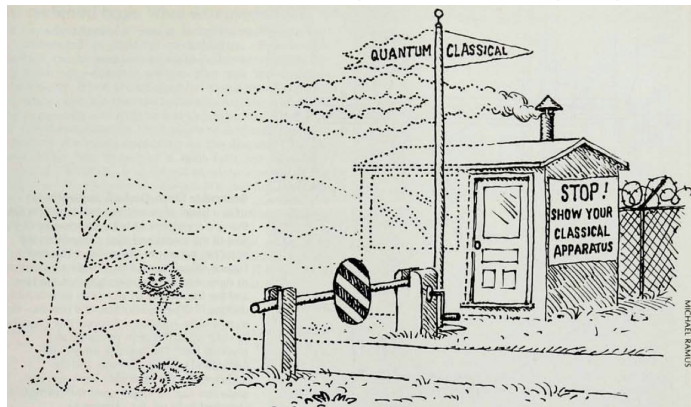
Message



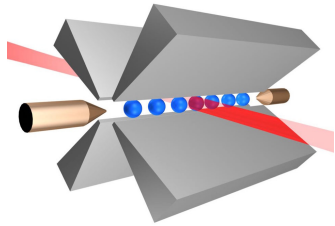
Quantum computing



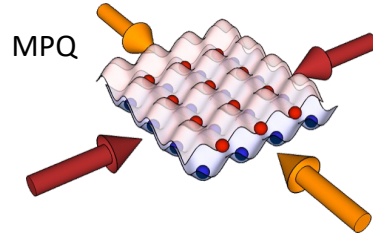
Foundations of quantum physics



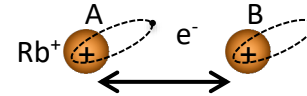
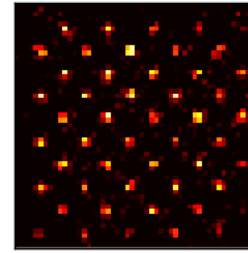
Engineering with individual quantum systems (examples)



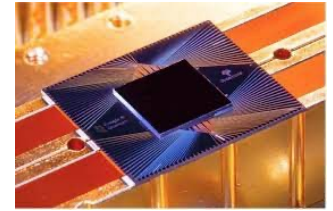
Trapped ions



Atoms in
optical lattices



Atoms in
tweezer arrays



Supercond.
Circuits

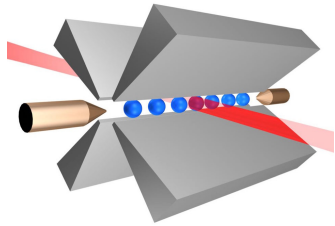
Scalable: beyond 1000 particles

Addressability: local manipulations and measurement

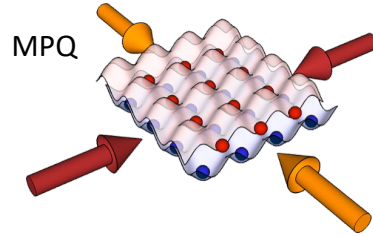
$$\langle \sigma_i^\alpha \rangle, \langle \sigma_i^\alpha \sigma_j^\beta \rangle, \dots$$

Programmable: controlled geometry, interactions...

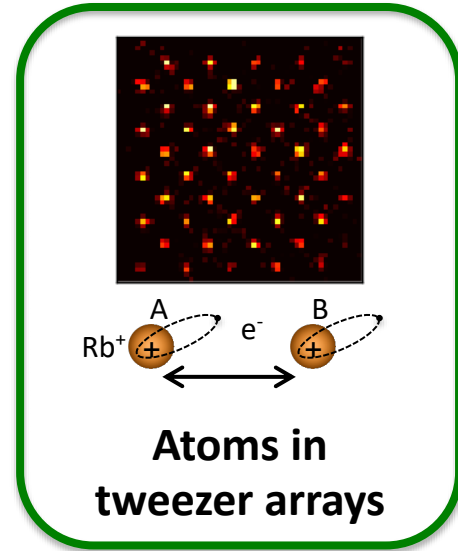
Engineering with individual quantum systems (examples)



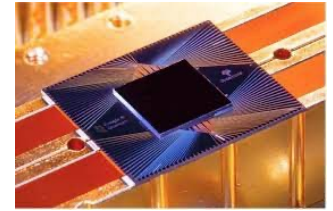
Trapped ions



Atoms in
optical lattices



Atoms in
tweezer arrays



Supercond.
Circuits

Scalable: beyond 1000 particles

Addressability: local manipulations and measurement

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

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

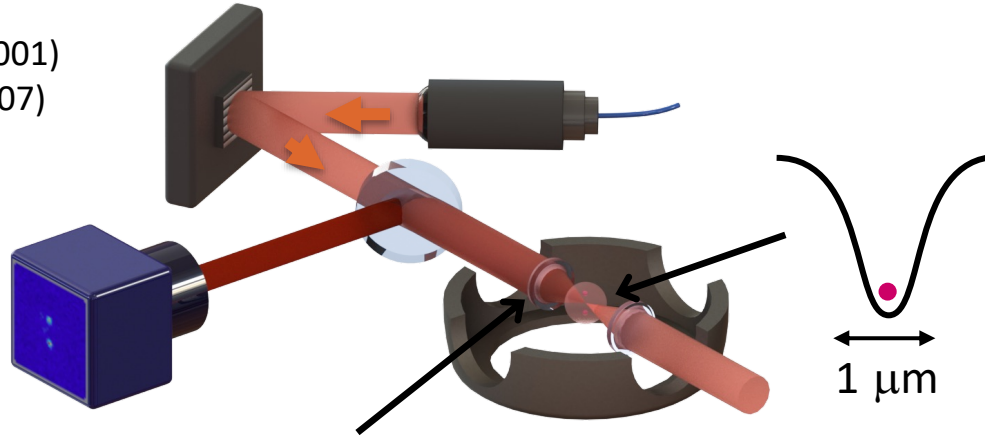
1. Arrays of individual atoms in optical tweezers

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

2. Basics of Rydberg physics

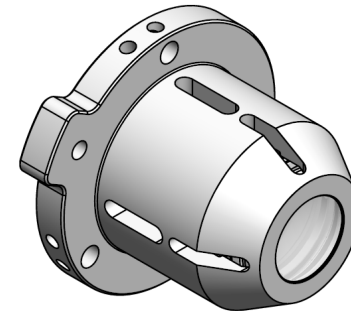
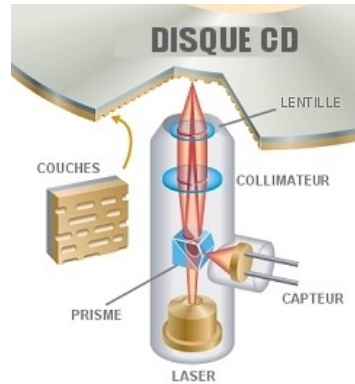
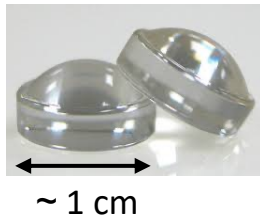
Optical tweezers: trapping in 3D

Grangier (2001)
Sortais (2007)



Lens $NA \geq 0.5$

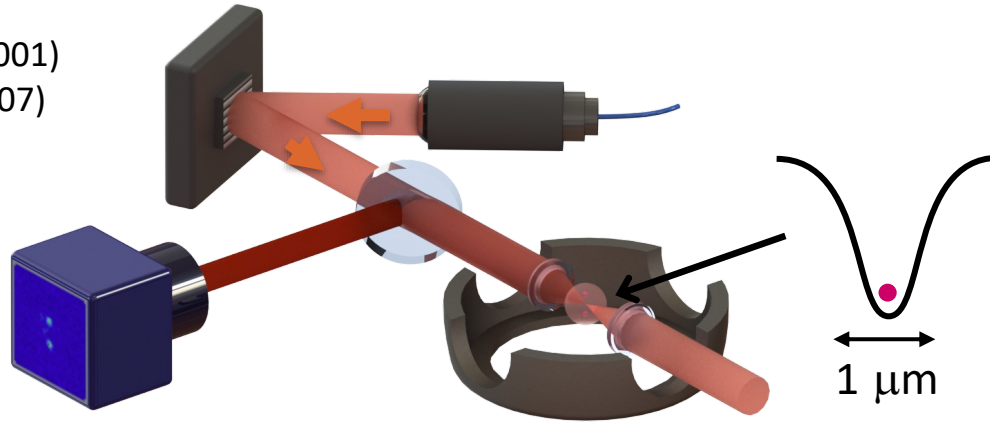
Aspherical lens



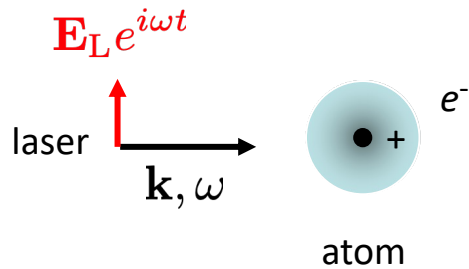
Microscope objective

Optical tweezers: trapping in 3D

Grangier (2001)
Sortais (2007)

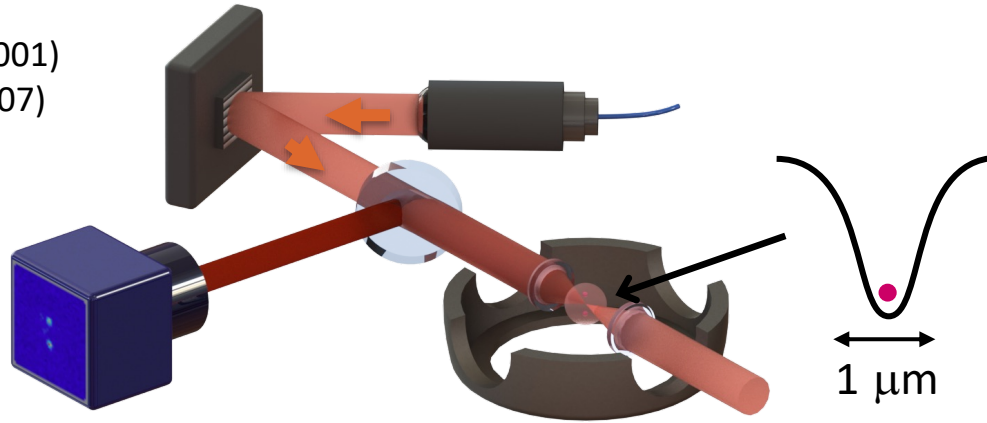


Dipole force

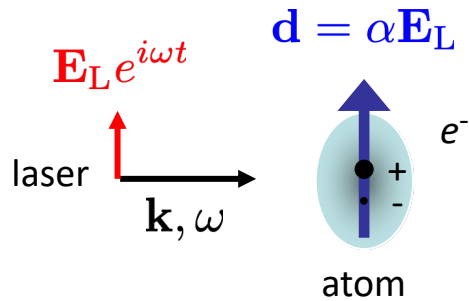


Optical tweezers: trapping in 3D

Grangier (2001)
Sortais (2007)

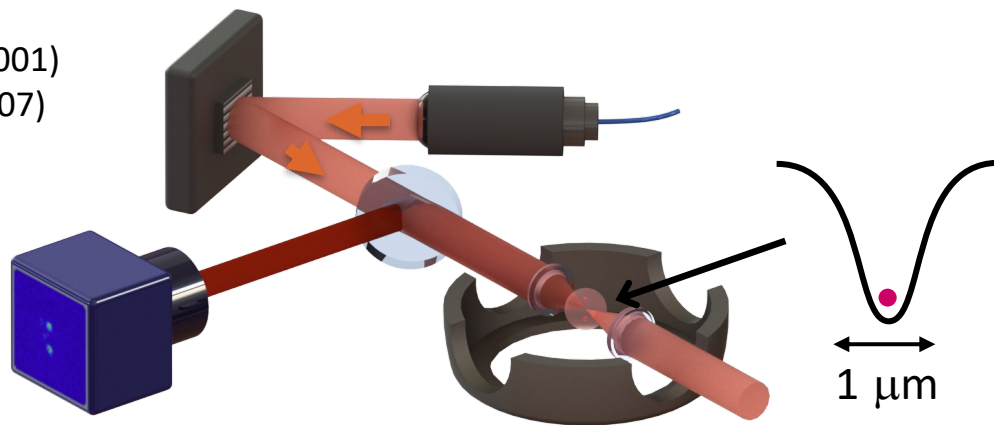


Dipole force

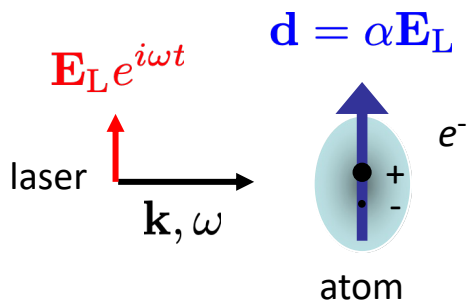


Optical tweezers: trapping in 3D

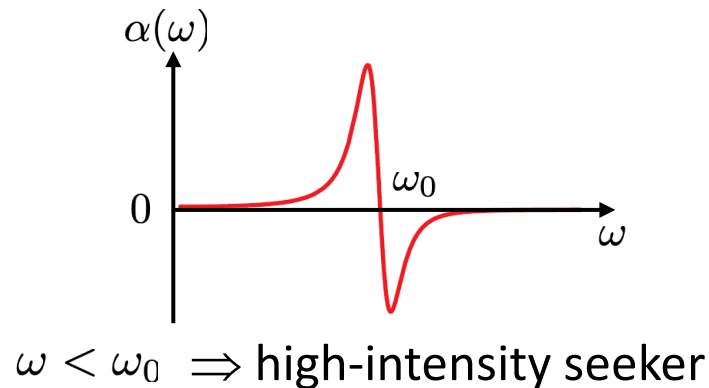
Grangier (2001)
Sortais (2007)



Dipole force

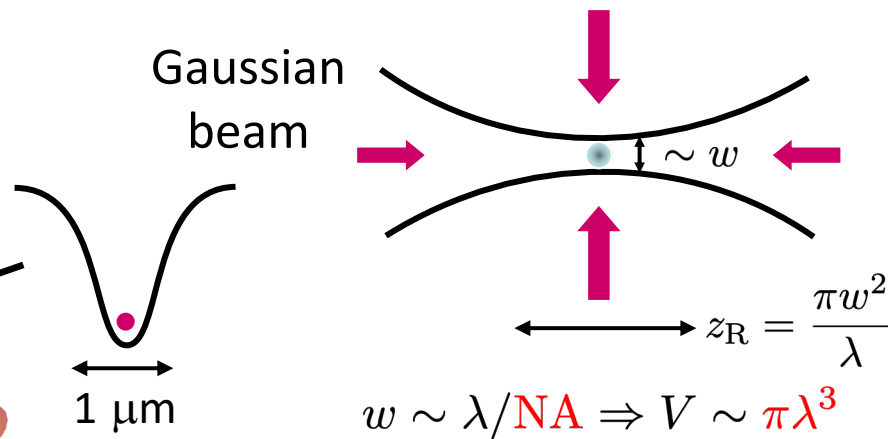
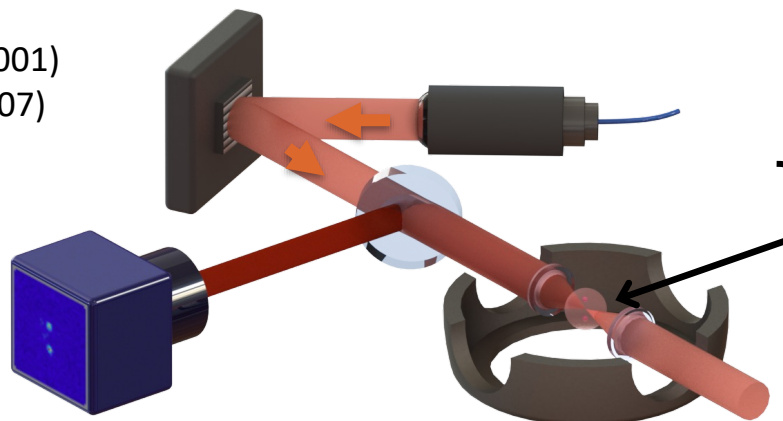


$$U = -\frac{1}{2} \langle \mathbf{d} \cdot \mathbf{E}_L \rangle$$
$$= -\frac{1}{2} \alpha \langle \mathbf{E}_L^2 \rangle$$

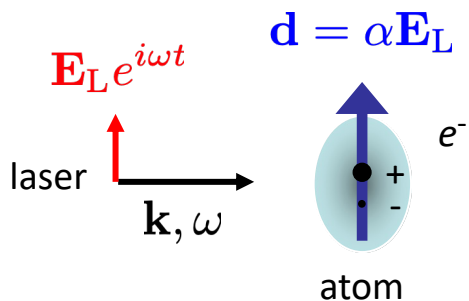


Optical tweezers: trapping in 3D

Grangier (2001)
Sortais (2007)

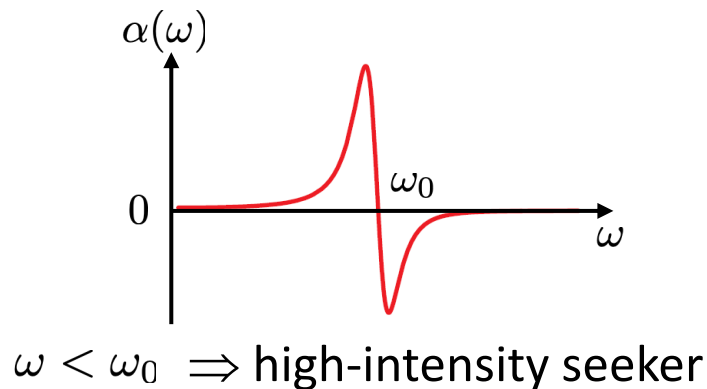


Dipole force



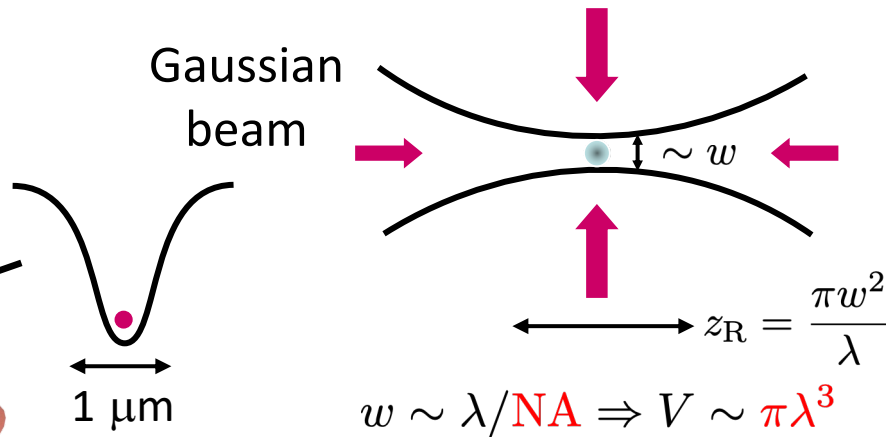
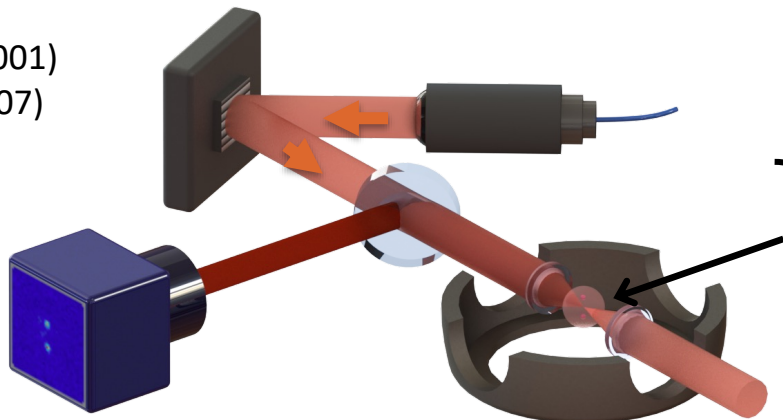
$$U = -\frac{1}{2} \langle \mathbf{d} \cdot \mathbf{E}_L \rangle$$

$$= -\frac{1}{2} \alpha \langle \mathbf{E}_L^2 \rangle$$

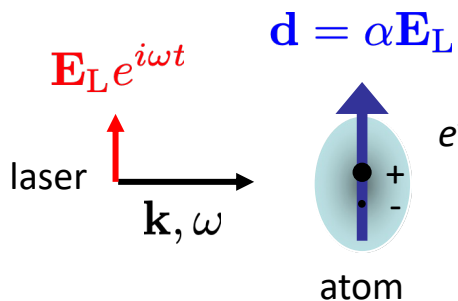


Optical tweezers: trapping in 3D

Grangier (2001)
Sortais (2007)

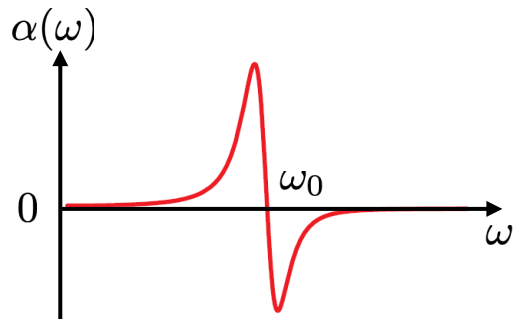


Dipole force



$$U = -\frac{1}{2} \langle \mathbf{d} \cdot \mathbf{E}_L \rangle$$

$$= -\frac{1}{2} \alpha \langle \mathbf{E}_L^2 \rangle$$



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

Ex: 1 mW on 1 $\mu\text{m} \Rightarrow$ **Trap depth = 1 mK** \Rightarrow Laser cooled atoms...

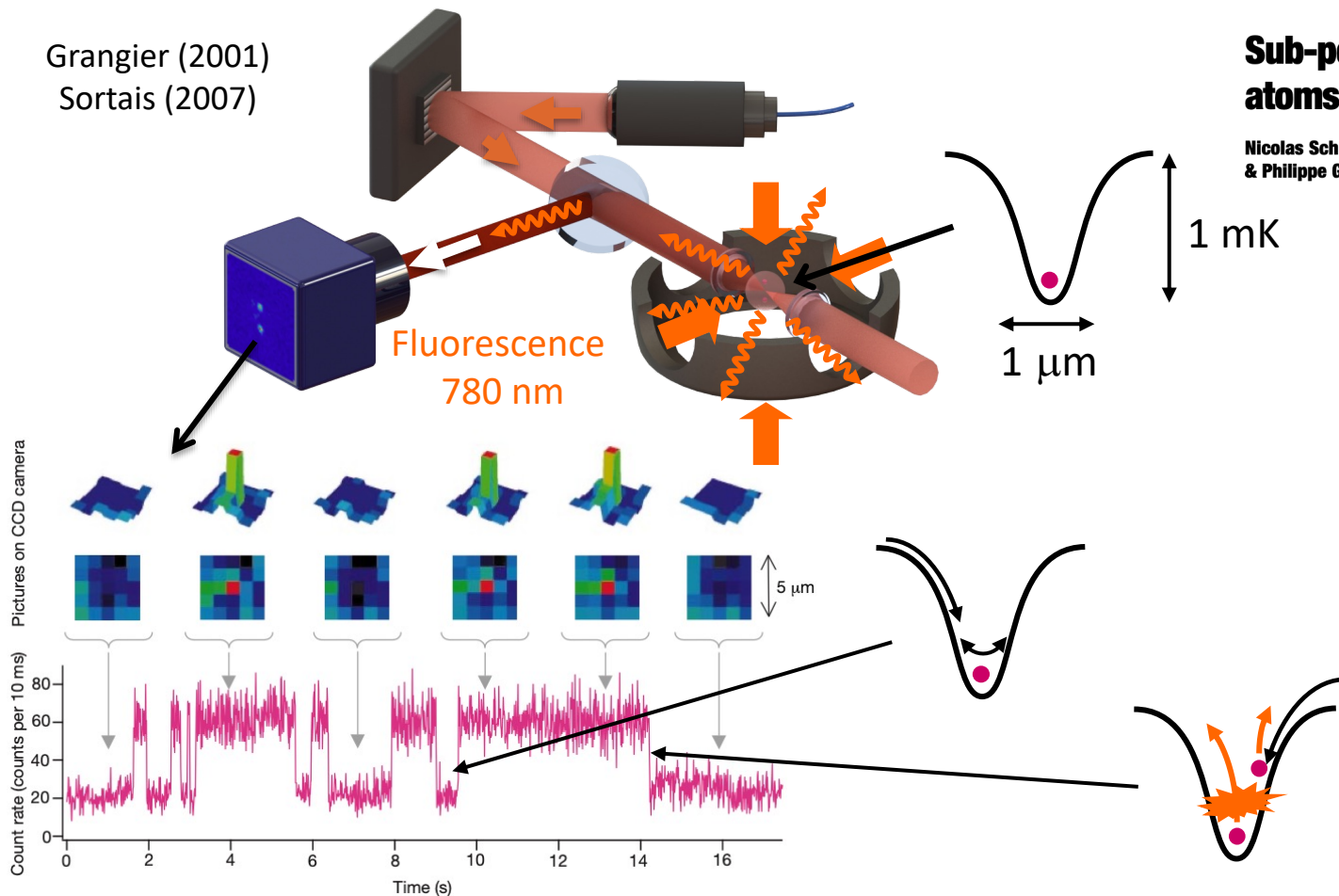
A single Rb atom in an optical tweezer

Grangier (2001)
Sortais (2007)

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

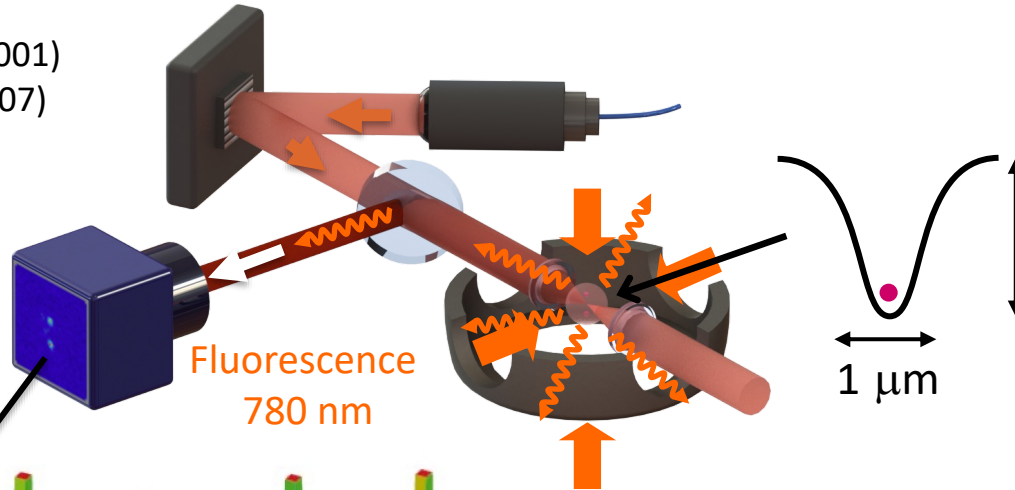
Nicolas Schlosser, Georges Reymond, Igor Protsenko
& Philippe Grangier

Nature 2001



A single Rb atom in an optical tweezer

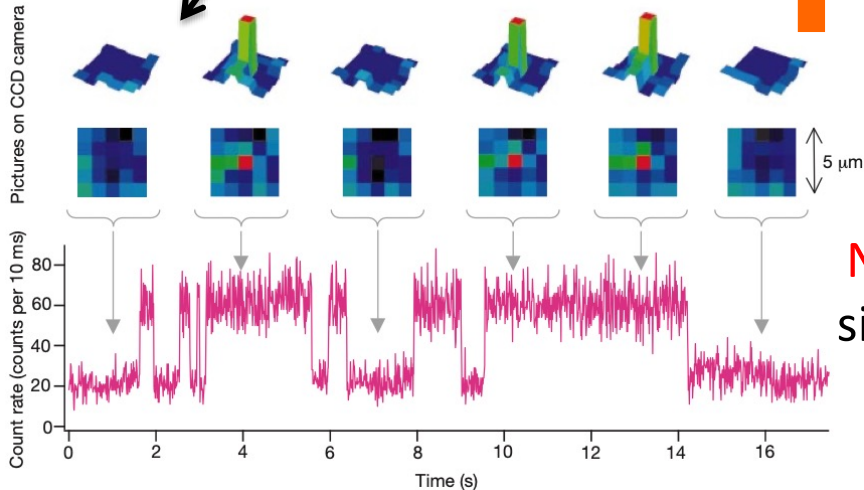
Grangier (2001)
Sortais (2007)



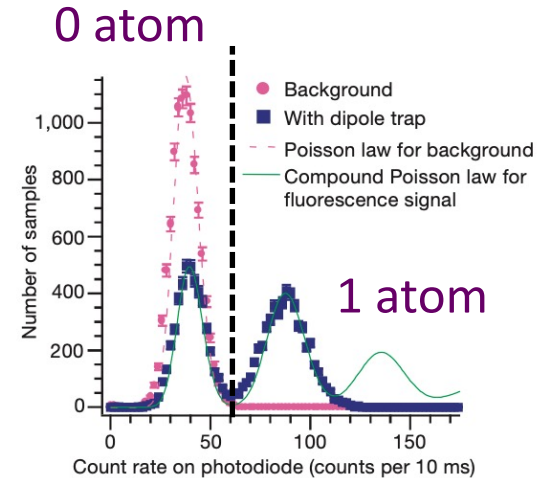
Sub-poissonian loading of single atoms in a microscopic dipole trap

Nicolas Schlosser, Georges Reymond, Igor Protsenko & Philippe Grangier

Nature 2001



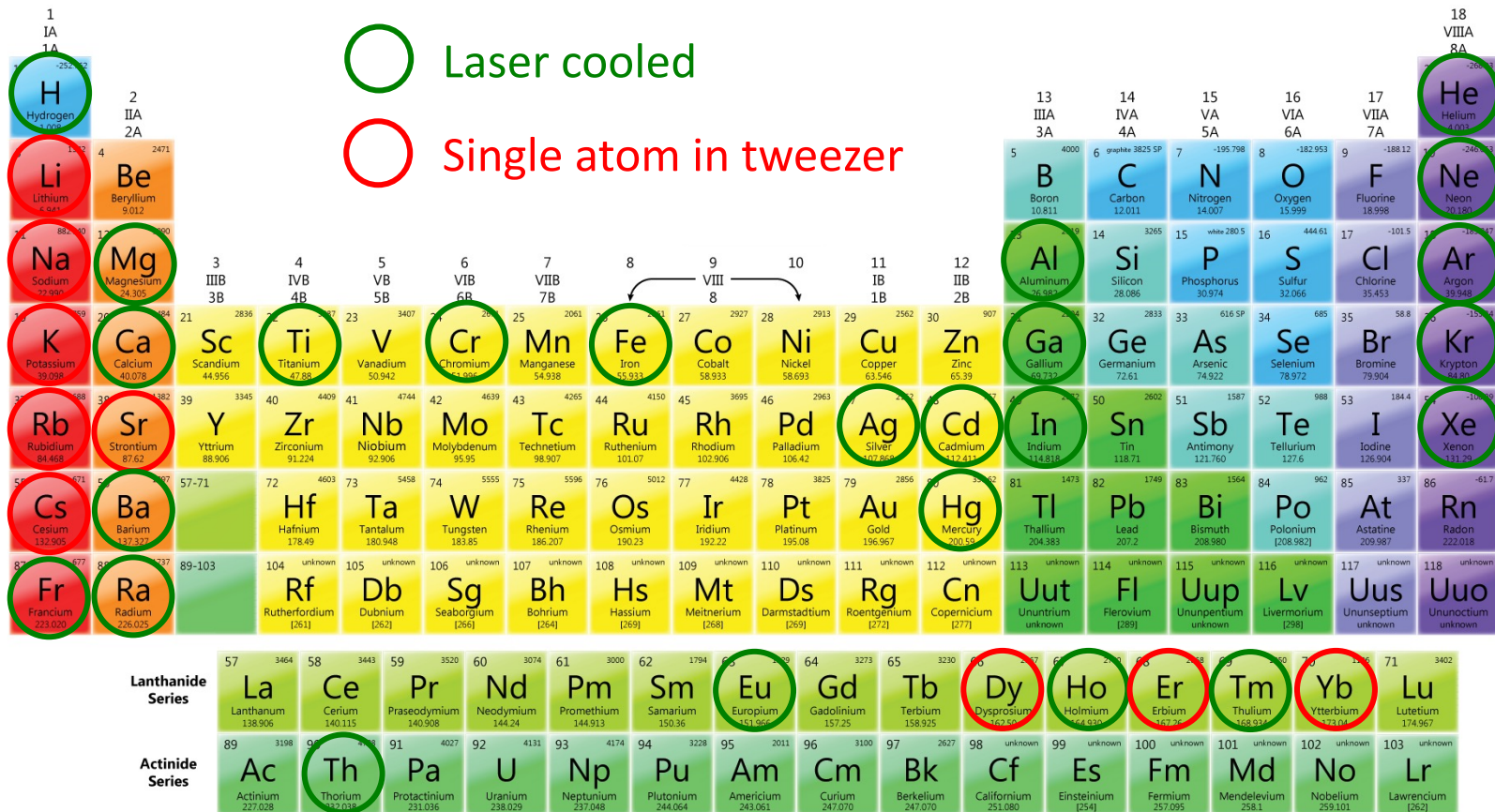
Non-deterministic
single-atom source



Single-atom trapping zoo (2026)

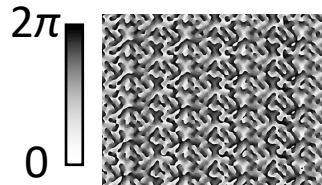
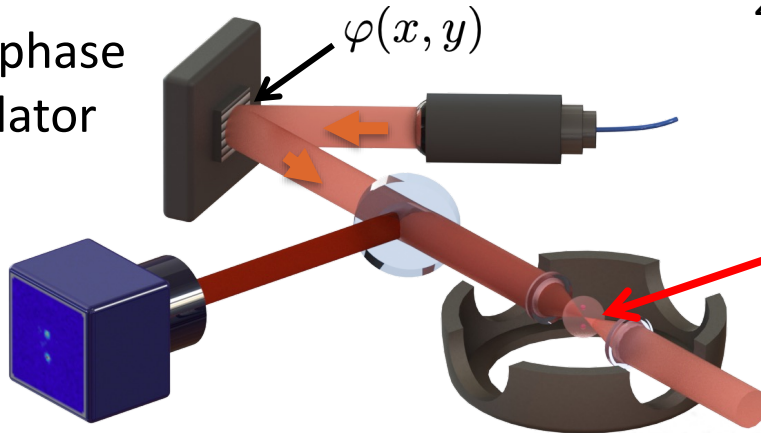
 Laser cooled

 Single atom in tweezer



Atoms in arrays of optical tweezers

Spatial phase modulator

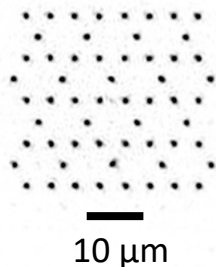


Phase mask

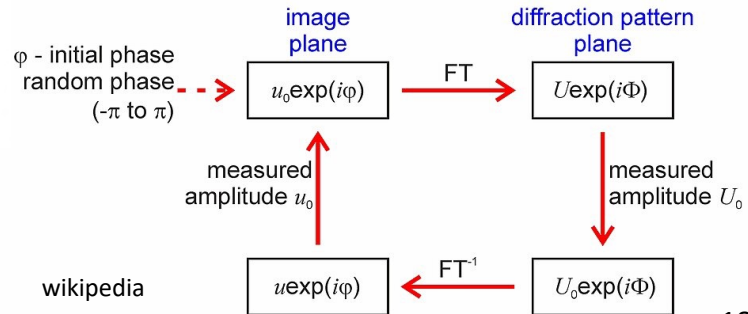
Bergamini JOSA B (2004)
Nogrette, PRX (2014)

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

Phase calculation: iterative algorithm
(Gerchberg-Saxton)

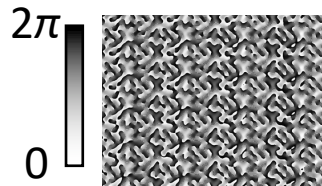
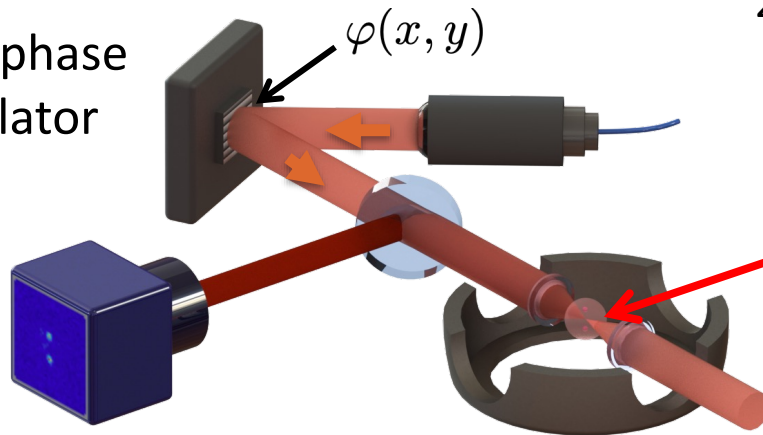


Optik 35, 237 (1972)



Atoms in arrays of optical tweezers

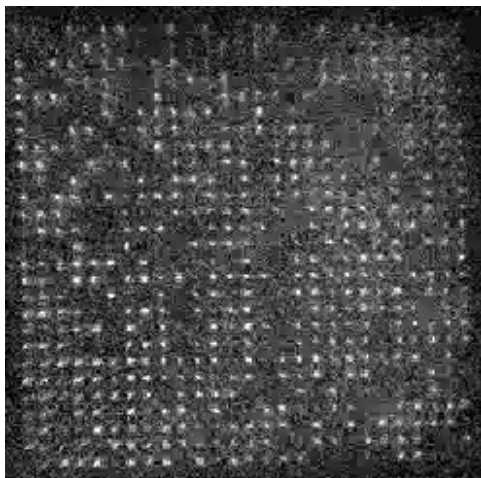
Spatial phase
modulator



Phase mask

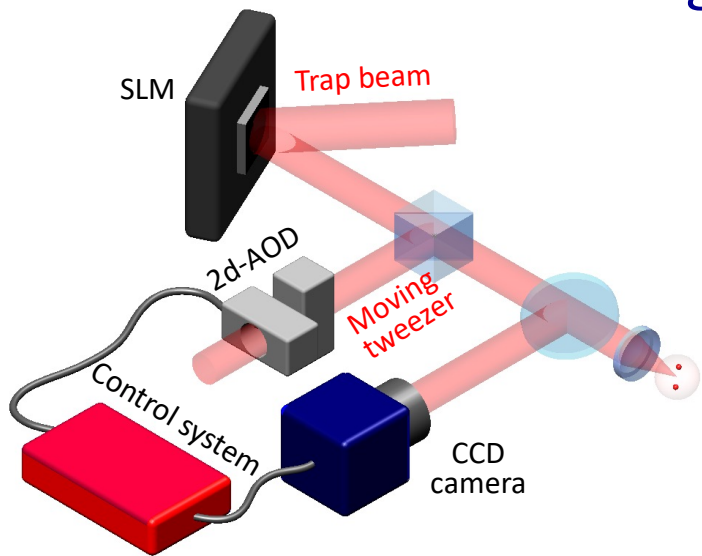
$$\left| \text{FT}[e^{i\varphi(x,y)}] \right|^2$$

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

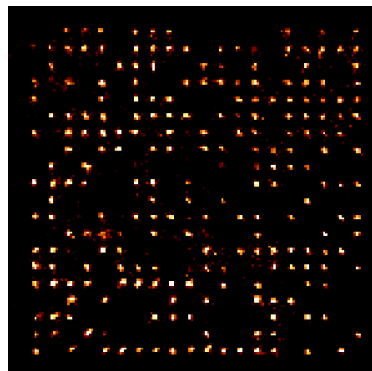


Fluorescence (729 traps)

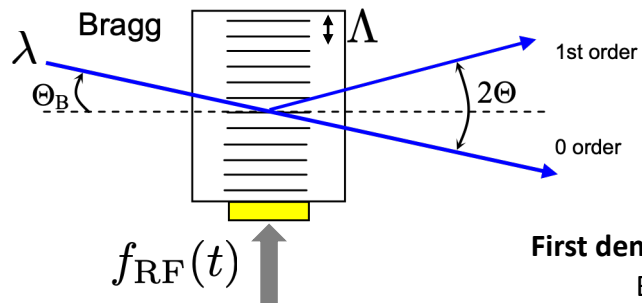
Assembling atomic arrays atom-by-atom



Initial configuration



Moving tweezer with 2D optical deflector

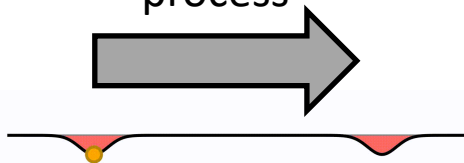


$$\Theta(t) \approx \frac{\lambda}{\Lambda} = \lambda \frac{f_{\text{RF}}(t)}{v_s}$$

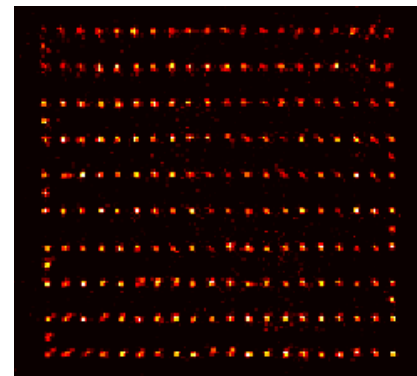
First demo (1D): Meschede, Nature (2006);
Beugnon, Nat. Phys. (2007)

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

Assembling
process



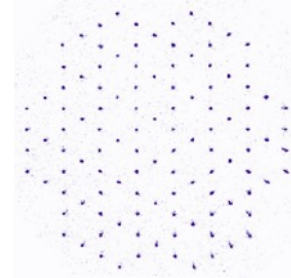
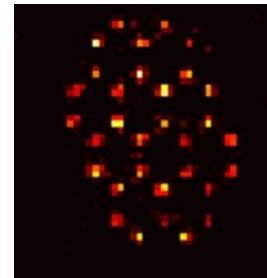
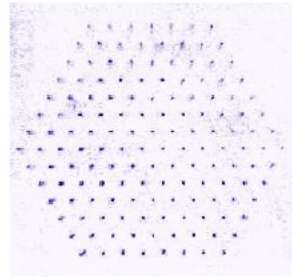
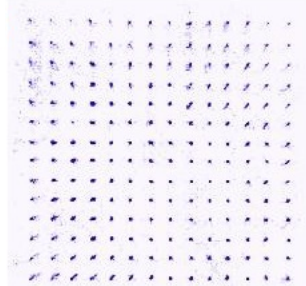
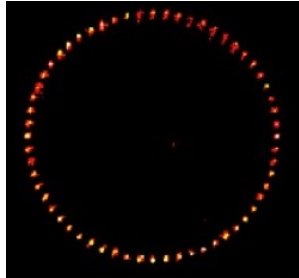
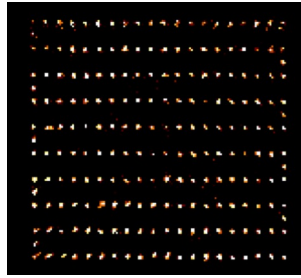
Assembled configuration



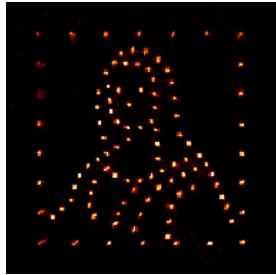
Atoms in arrays of optical tweezers (single-shot images)

1D

2D



~100 μm

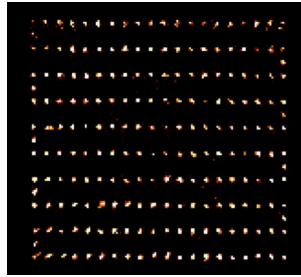


L. da Vinci

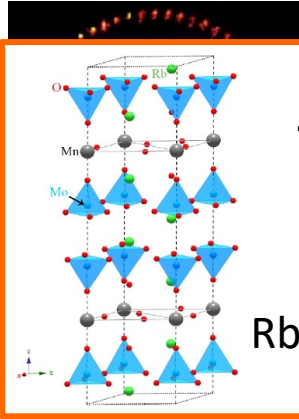
Atoms in arrays of optical tweezers (single-shot images)

1D

2D



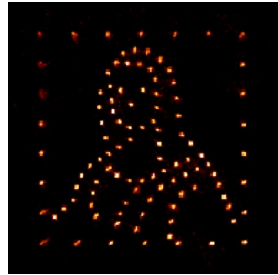
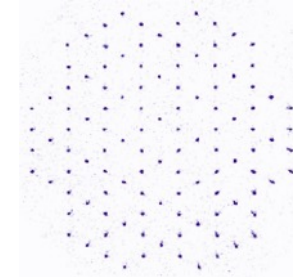
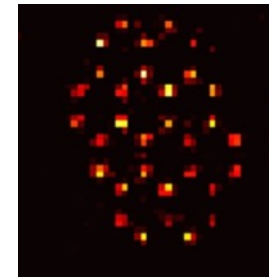
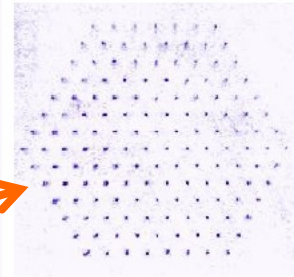
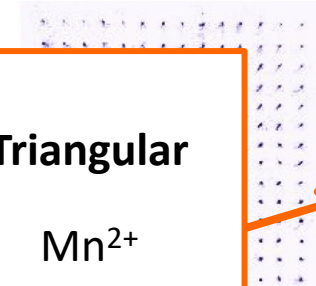
~100 μm



Triangular

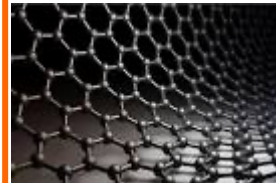
Mn^{2+}

$\text{Rb}_4\text{Mn}(\text{MoO}_4)_3$



L. da Vinci

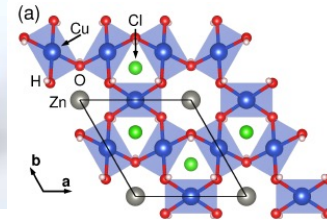
Hexagonal



graphene

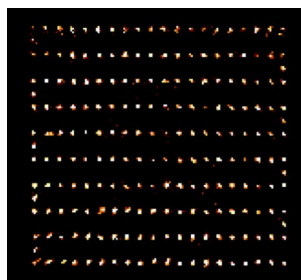
Kagome: Herbertsmithite

$\text{ZnCu}_3(\text{OH})_6\text{Cl}_2$



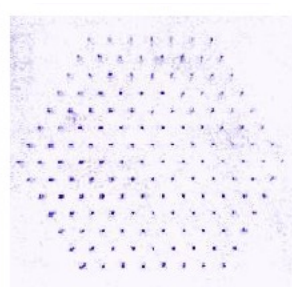
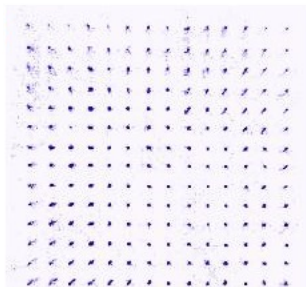
Atoms in arrays of optical tweezers (single-shot images)

1D

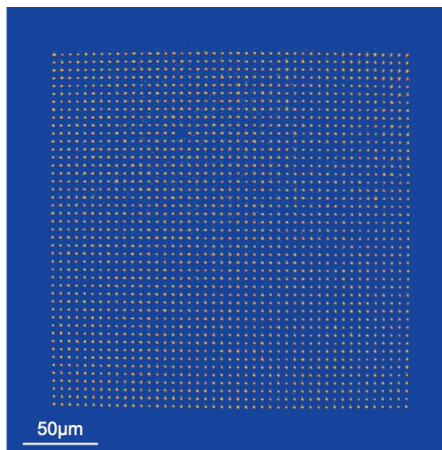


~100 μm

2D

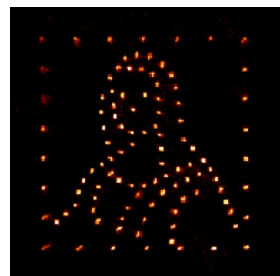
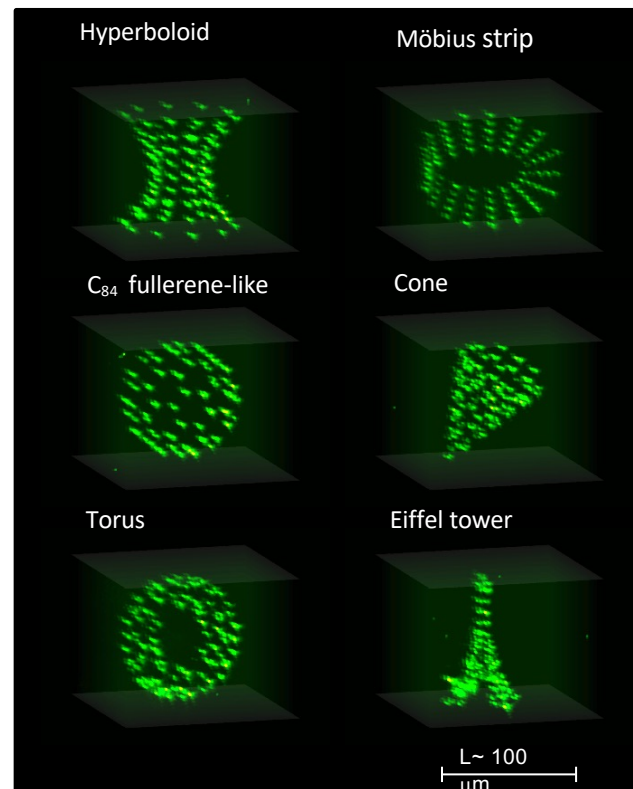


2024 atoms (AI + fast SLM)



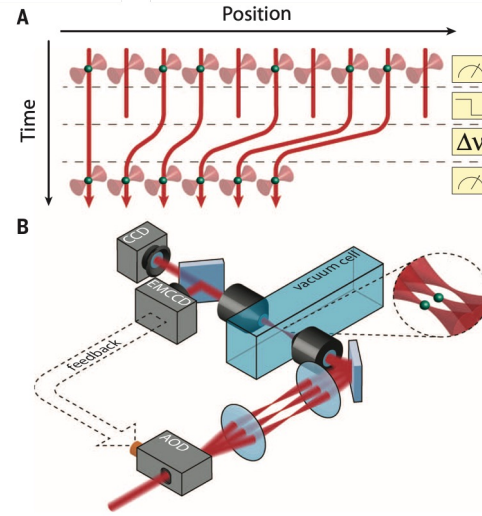
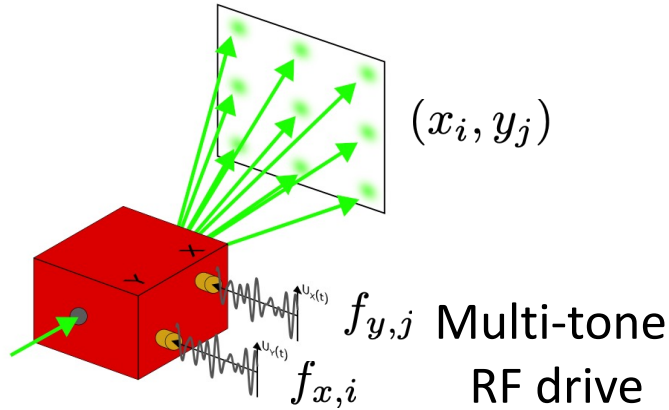
3D

Barredo, Nature (2018)

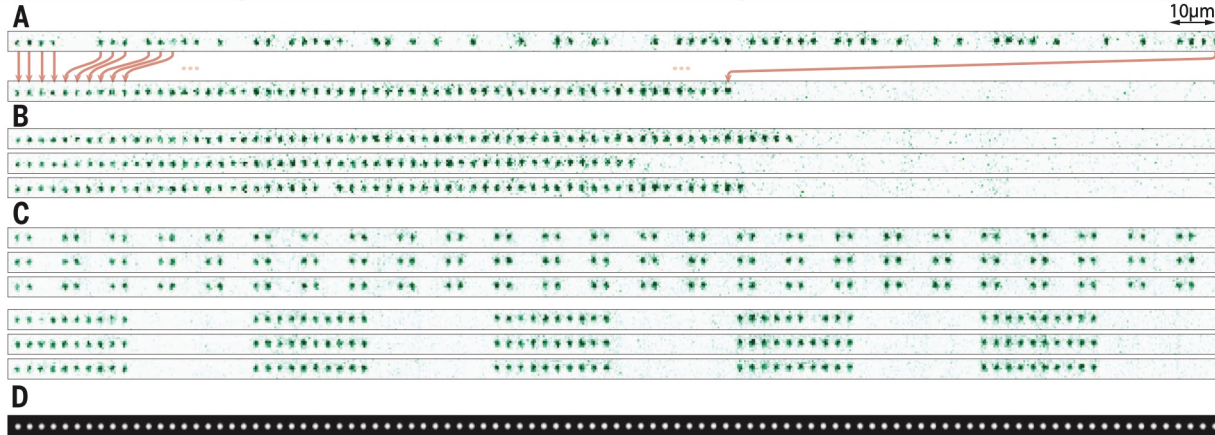


L. da Vinci

Another method: Arrays of moving tweezers

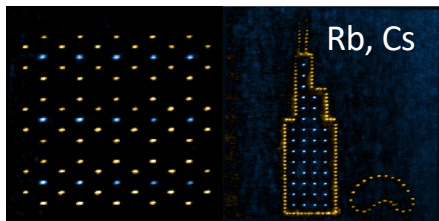


Endres *et al.*,
 Science **354**,1024 (2016)

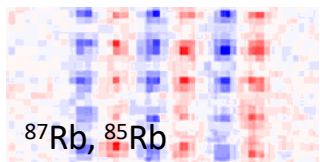


Now a popular platform...with many developments

Dual species arrays



H. Bernien PRX 2022



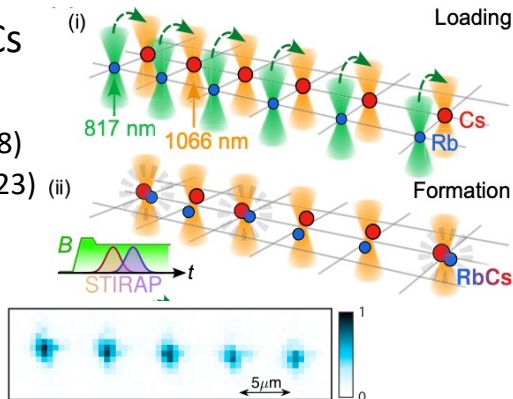
Zhan PRL 2022

Trapping molecules

NaCs, RbCs

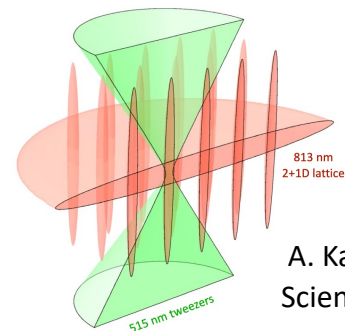
K-K Ni (2018)

Cornish (2023)



Ni, Doyle, Chuck

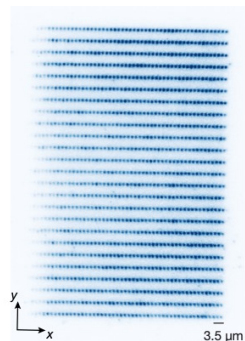
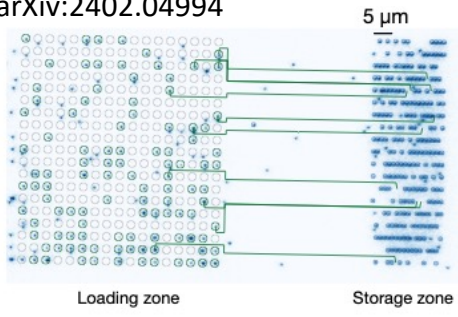
Combining optical lattices + tweezers



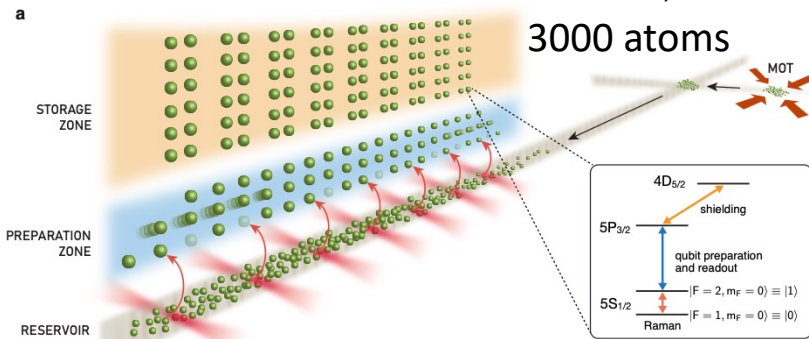
A. Kaufman Science 2022

Continuous reloading schemes

arXiv:2402.04994

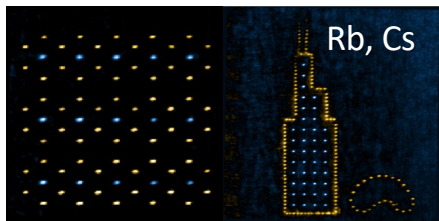


Thompson, arXiv:2506.15633
Lukin, Nature 2025

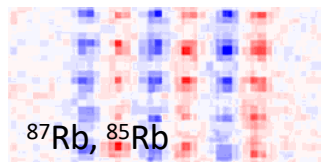


Now a popular platform...with many developments

Dual species arrays



H. Bernien PRX 2022



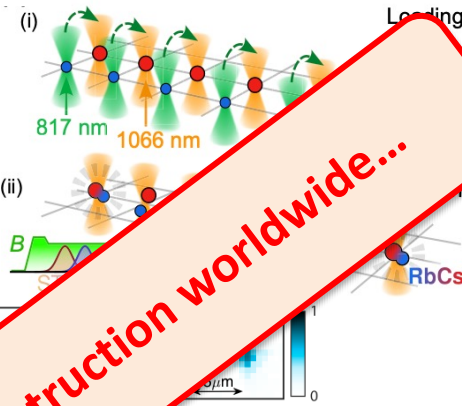
Zhan
PRL 2022

Trapping molecules

NaCs, RbCs

K-K Ni (2018)

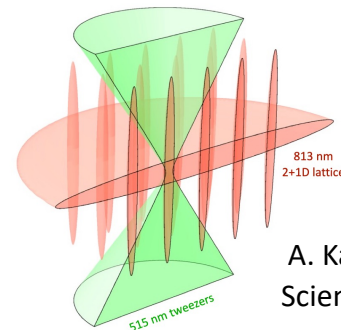
Cornish (2023)



CaF

300+ in construction worldwide...

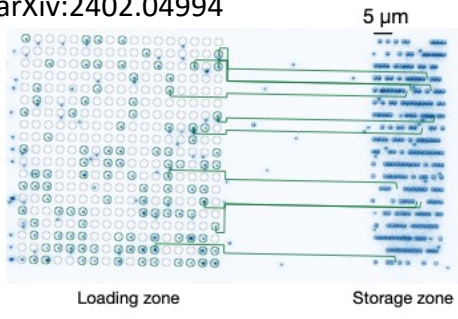
Combining optical lattices + tweezers



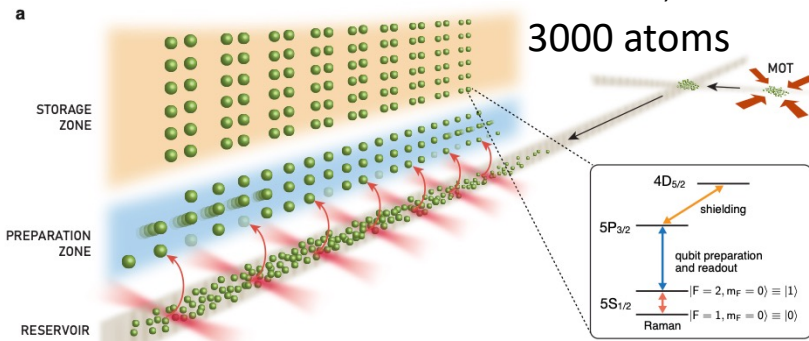
A. Kaufman
Science 2022

Continuous reloading scheme

arXiv:2402.04994



Thompson, arXiv:2506.15633
Lukin, Nature 2025

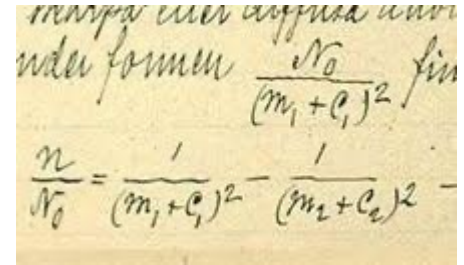


Outline – Lecture 1

1. Arrays of individual atoms in optical tweezers

2. Basics of Rydberg physics

1888



Handwritten manuscript snippet showing the Rydberg formula: $\frac{n}{N_0} = \frac{1}{(m_1 + c_1)^2} - \frac{1}{(m_2 + c_2)^2}$

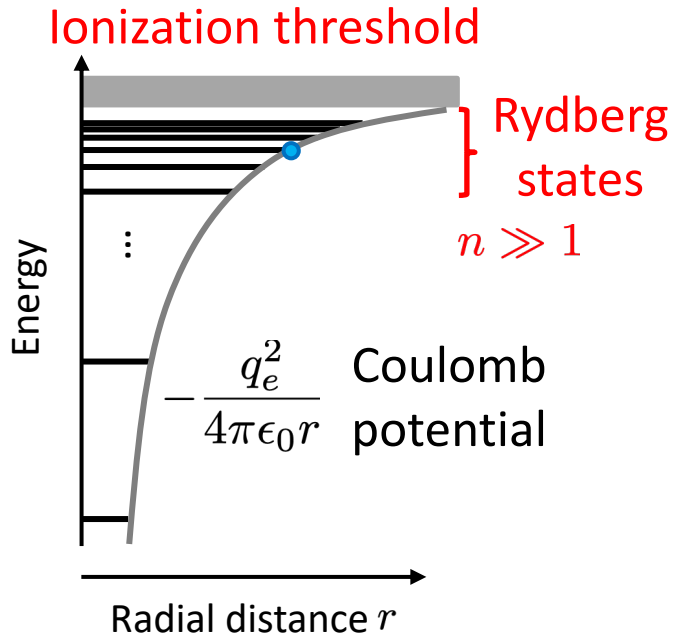


Johannes Rydberg
1854-1919

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

Idea of an infinite series
 \Rightarrow **highly excited** states

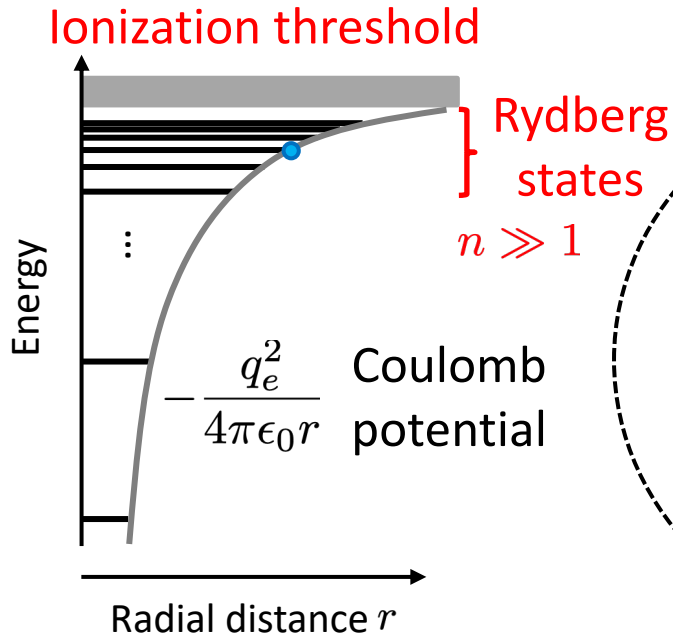
“Rydberg atom” = a highly excited atom



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

$$R_y = 13.6 \text{ eV} = 3300 \text{ THz}$$

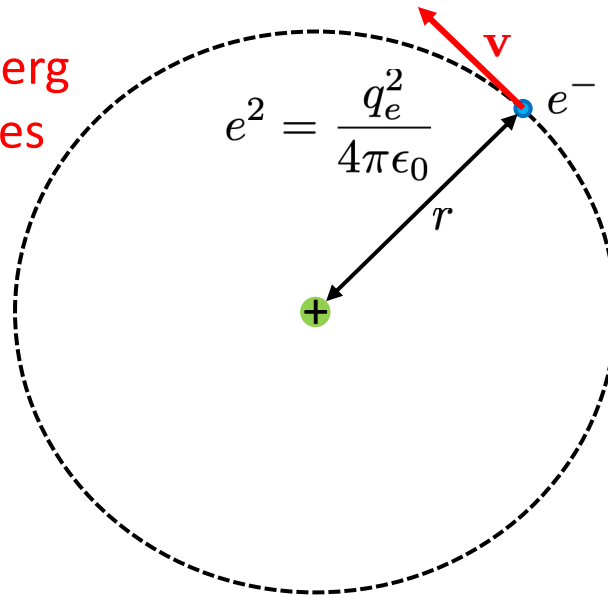
“Rydberg atom” = a highly excited atom



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

$$R_y = 13.6 \text{ eV} = 3300 \text{ THz}$$

Bohr model



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

Bohr quantization condition:

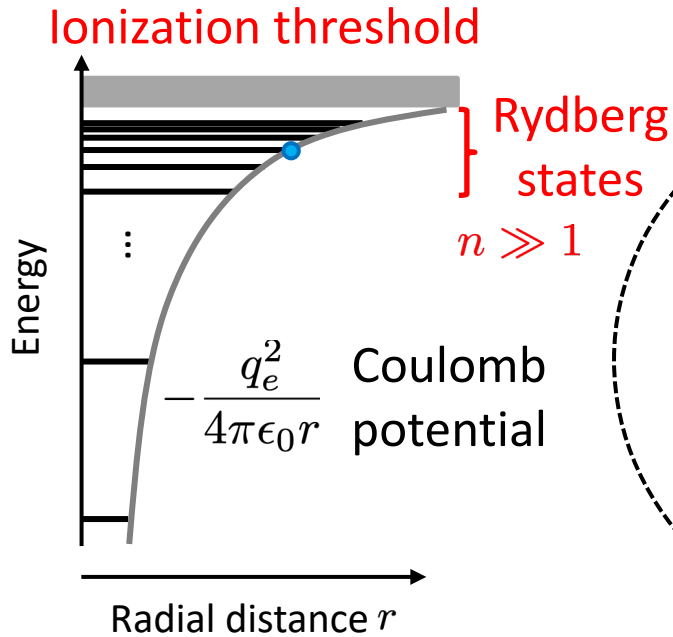
$$L = m_e v r = n \hbar$$

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

Bohr radius: $a_0 \approx 0.05 \text{ nm}$

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

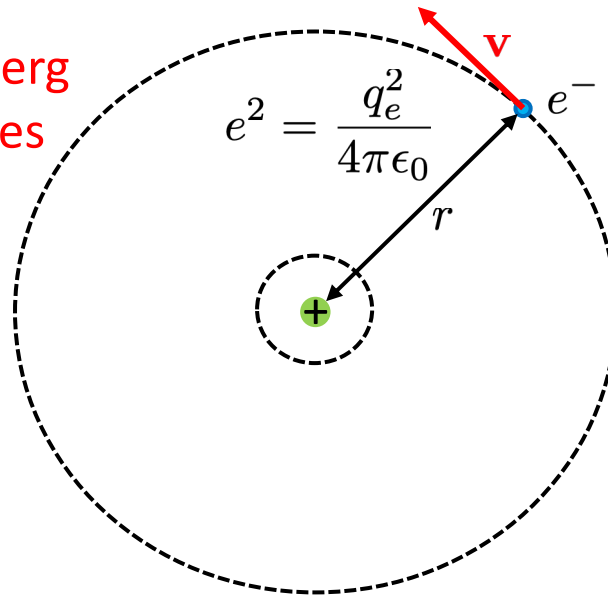
“Rydberg atom” = a highly excited atom



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

$$R_y = 13.6 \text{ eV} = 3300 \text{ THz}$$

Bohr model



$$n = 10 \rightarrow r = 5 \text{ nm}$$

$$n = 100 \rightarrow r = 500 \text{ nm}$$

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

Bohr quantization condition:

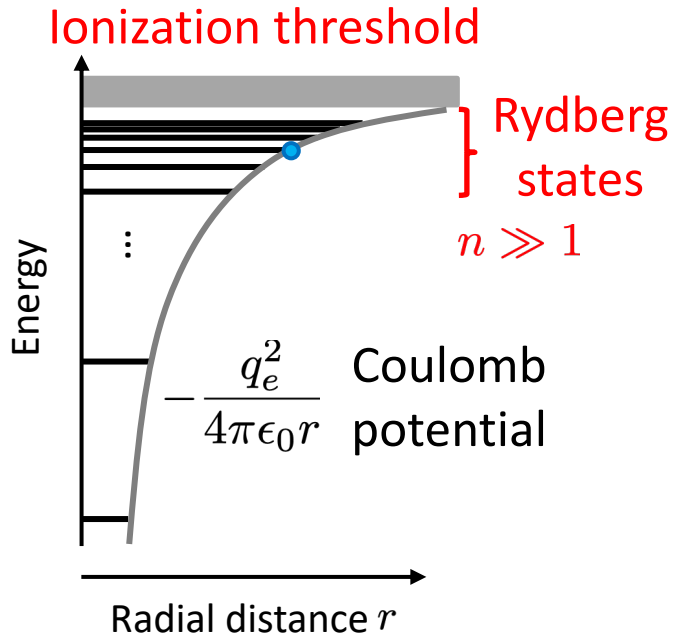
$$L = m_e v r = n \hbar$$

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

Bohr radius: $a_0 \approx 0.05 \text{ nm}$

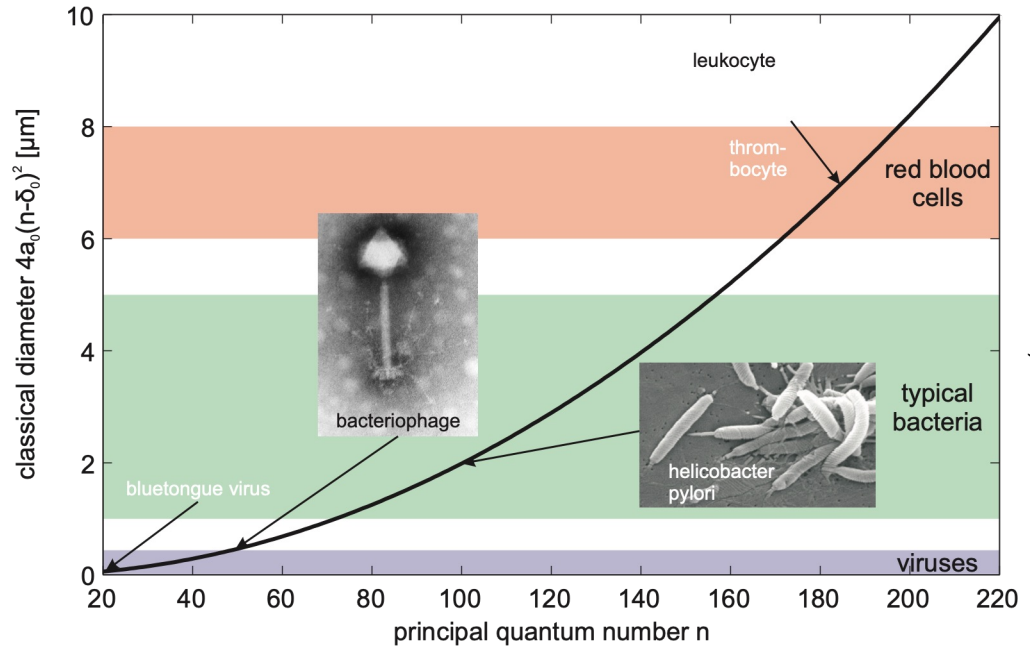
$$E_n = -\frac{1}{2} \frac{e^2}{r_n} = -\frac{e^2}{2a_0} \frac{1}{n^2}$$

“Rydberg atom” = a highly excited atom



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

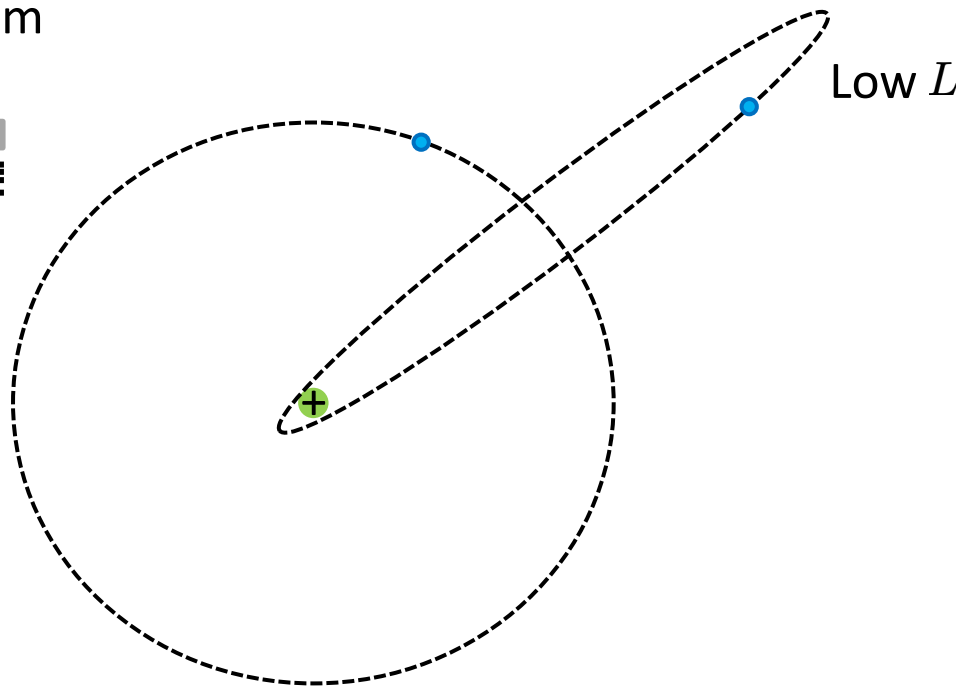
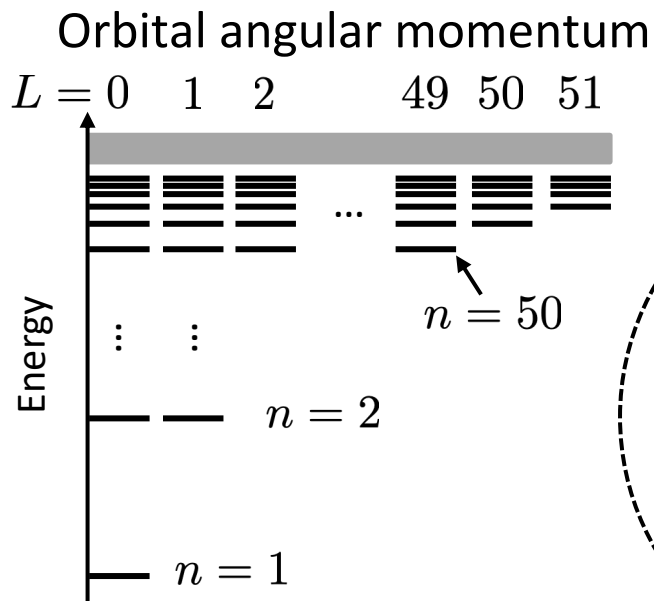
$$R_y = 13.6 \text{ eV} = 3300 \text{ THz}$$



$$n = 10 \rightarrow r = 5 \text{ nm}$$

$$n = 100 \rightarrow r = 500 \text{ nm}$$

Circular and low angular momentum orbits

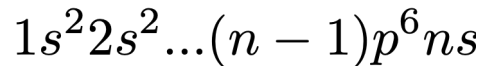


Circular: $L = n - 1$

Coulomb potential:
 E_n independent of L

Alkali atoms = hydrogen-like atoms

Alkali: 1 external electron

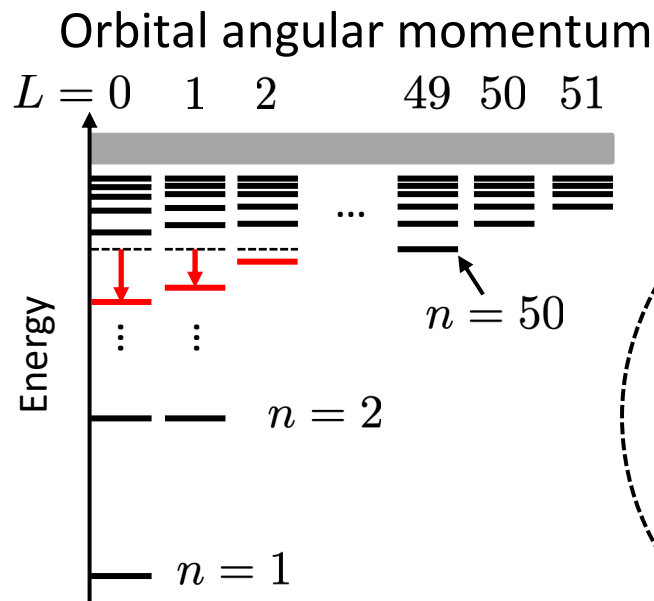


1 IA 1A 1 H Hydrogen 1.008	2 IIA 2A 3 Li Lithium 6.941	4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 VIII 8A He Helium 4.003															
11 Na Sodium 22.990	12 Mg Magnesium 24.305	13 Al Aluminum 26.982	14 Si Silicon 28.086	15 P Phosphorus 30.974	16 S Sulfur 32.066	17 Cl Chlorine 35.453	18 Ar Argon 39.948										
19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.956	22 Ti Titanium 47.88	23 V Vanadium 50.942	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.933	27 Co Cobalt 58.933	28 Ni Nickel 58.693	29 Cu Copper 63.546	30 Zn Zinc 65.39	31 Ga Gallium 69.723	32 Ge Germanium 72.61	33 As Arsenic 74.922	34 Se Selenium 78.972	35 Br Bromine 79.904	36 Kr Krypton 84.80
37 Rb Rubidium 84.468	38 Sr Strontium 87.62	39 Y Yttrium 88.906	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.95	43 Tc Technetium 98.907	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.906	46 Pd Palladium 106.42	47 Ag Silver 107.868	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.71	51 Sb Antimony 121.760	52 Te Tellurium 127.6	53 I Iodine 126.904	54 Xe Xenon 131.29
55 Cs Cesium 132.905	56 Ba Barium 137.327	57-71 Lanthanide Series	72 Hf Hafnium 178.49	73 Ta Tantalum 180.948	74 W Tungsten 183.85	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.22	78 Pt Platinum 195.08	79 Au Gold 196.967	80 Hg Mercury 200.59	81 Tl Thallium 204.383	82 Pb Lead 207.2	83 Bi Bismuth 208.980	84 Po Polonium [209]	85 At Astatine 209.987	86 Rn Radon 222.018
87 Fr Francium 223.020	88 Ra Radium 226.025	89-103 Actinide Series	104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [266]	107 Bh Bohrium [264]	108 Hs Hassium [269]	109 Mt Meitnerium [268]	110 Ds Darmstadtium [269]	111 Rg Roentgenium [272]	112 Cn Copernicium [277]	113 Uut Ununtrium unknown	114 Fl Flerovium [289]	115 Uup Ununpentium unknown	116 Lv Livermorium [293]	117 Uus Ununseptium unknown	118 Uuo Ununoctium unknown

sciencenotes.org

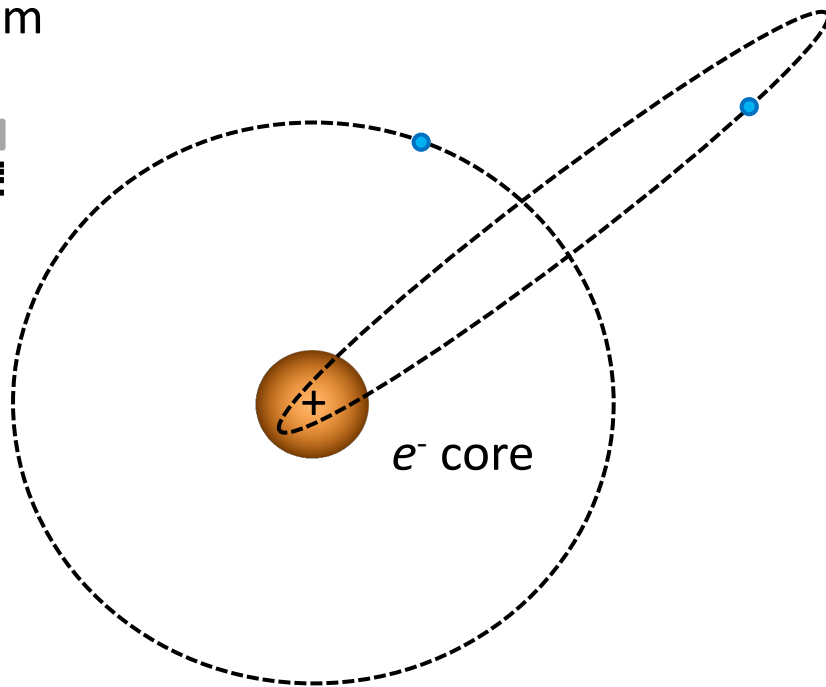
57 La Lanthanum 138.905	58 Ce Cerium 140.115	59 Pr Praseodymium 140.908	60 Nd Neodymium 144.24	61 Pm Promethium 144.913	62 Sm Samarium 150.36	63 Eu Europium 151.966	64 Gd Gadolinium 157.25	65 Tb Terbium 158.925	66 Dy Dysprosium 162.50	67 Ho Holmium 164.930	68 Er Erbium 167.26	69 Tm Thulium 168.934	70 Yb Ytterbium 173.04	71 Lu Lutetium 174.967
89 Ac Actinium 227.028	90 Th Thorium 232.038	91 Pa Protactinium 231.036	92 U Uranium 238.029	93 Np Neptunium 237.048	94 Pu Plutonium 244.064	95 Am Americium 243.061	96 Cm Curium 247.070	97 Bk Berkelium 247.070	98 Cf Californium 251.080	99 Es Einsteinium [254]	100 Fm Fermium 257.095	101 Md Mendelevium 258.1	102 No Nobelium 259.101	103 Lr Lawrencium [262]

Alkali atoms = hydrogen-like atoms



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

Quantum defects
(experimental)



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

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

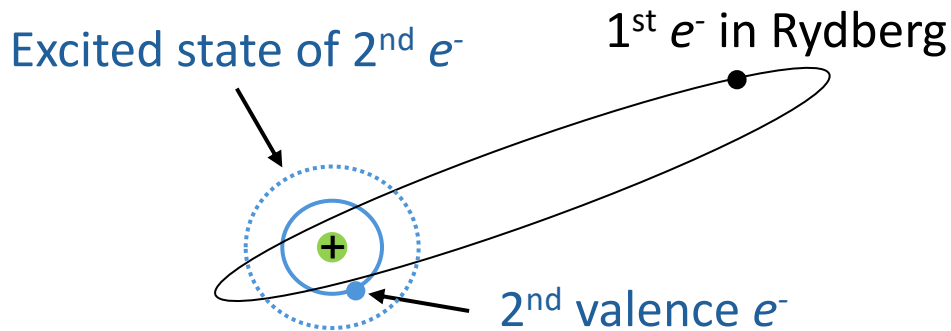
Atoms with more than 1 valence electron

Single atom in tweezer

1 IA 1A	2 IIA 2A											13 IIIA 3A	14 IVA 4A	15 VA 5A	16 VIA 6A	17 VIIA 7A	18 VIIIA 8A	
1 H Hydrogen 1.008																		He Helium 4.003
3 Li Lithium 6.941	4 Be Beryllium 9.012											5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.007	8 O Oxygen 15.999	9 F Fluorine 18.998	10 Ne Neon 20.180	
11 Na Sodium 22.990	12 Mg Magnesium 24.305	3 IIIB 3B	4 IVB 4B	5 VB 5B	6 VIB 6B	7 VIIB 7B	8 VIII 8	9 VIII 8	10 VIII 8	11 IB 1B	12 IIB 2B	13 Al Aluminum 26.982	14 Si Silicon 28.086	15 P Phosphorus 30.974	16 S Sulfur 32.066	17 Cl Chlorine 35.453	18 Ar Argon 39.948	
19 K Potassium 39.098	20 Ca Calcium 40.078	21 Sc Scandium 44.956	22 Ti Titanium 47.88	23 V Vanadium 50.942	24 Cr Chromium 51.996	25 Mn Manganese 54.938	26 Fe Iron 55.933	27 Co Cobalt 58.933	28 Ni Nickel 58.693	29 Cu Copper 63.546	30 Zn Zinc 65.39	31 Ga Gallium 69.723	32 Ge Germanium 72.61	33 As Arsenic 74.922	34 Se Selenium 78.972	35 Br Bromine 79.904	36 Kr Krypton 84.80	
37 Rb Rubidium 84.468	38 Sr Strontium 87.62	39 Y Yttrium 88.906	40 Zr Zirconium 91.224	41 Nb Niobium 92.906	42 Mo Molybdenum 95.95	43 Tc Technetium 98.907	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.906	46 Pd Palladium 106.42	47 Ag Silver 107.868	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.710	51 Sb Antimony 121.760	52 Te Tellurium 127.6	53 I Iodine 126.904	54 Xe Xenon 131.29	
55 Cs Cesium 132.905	56 Ba Barium 137.327	57-71 Lanthanide Series	72 Hf Hafnium 178.49	73 Ta Tantalum 180.948	74 W Tungsten 183.85	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.22	78 Pt Platinum 195.08	79 Au Gold 196.967	80 Hg Mercury 200.59	81 Tl Thallium 204.383	82 Pb Lead 207.2	83 Bi Bismuth 208.980	84 Po Polonium [208.982]	85 At Astatine 209.987	86 Rn Radon 222.018	
87 Fr Francium 223.020	88 Ra Radium 226.025	89-103 Actinide Series	104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [266]	107 Bh Bohrium [264]	108 Hs Hassium [269]	109 Mt Meitnerium [268]	110 Ds Darmstadtium [269]	111 Rg Roentgenium [272]	112 Cn Copernicium [277]	113 Uut Ununtrium unknown	114 Fl Flerovium [289]	115 Uup Ununpentium unknown	116 Lv Livermorium [298]	117 Uus Ununseptium unknown	118 Uuo Ununoctium unknown	
57 La Lanthanum 138.906	58 Ce Cerium 140.115	59 Pr Praseodymium 140.908	60 Nd Neodymium 144.24	61 Pm Promethium 144.913	62 Sm Samarium 150.36	63 Eu Europium 151.966	64 Gd Gadolinium 157.25	65 Tb Terbium 158.925	66 Dy Dysprosium 162.50	67 Ho Holmium 164.930	68 Er Erbium 167.26	69 Tm Thulium 168.934	70 Yb Ytterbium 173.04	71 Lu Lutetium 174.967				
89 Ac Actinium 227.028	90 Th Thorium 232.038	91 Pa Protactinium 231.036	92 U Uranium 238.029	93 Np Neptunium 237.048	94 Pu Plutonium 244.064	95 Am Americium 243.061	96 Cm Curium 247.070	97 Bk Berkelium 247.070	98 Cf Californium 251.080	99 Es Einsteinium [254]	100 Fm Fermium 257.095	101 Md Mendelevium 258.1	102 No Nobelium 259.101	103 Lr Lawrencium [262]				

Atoms with more than 1 valence electron

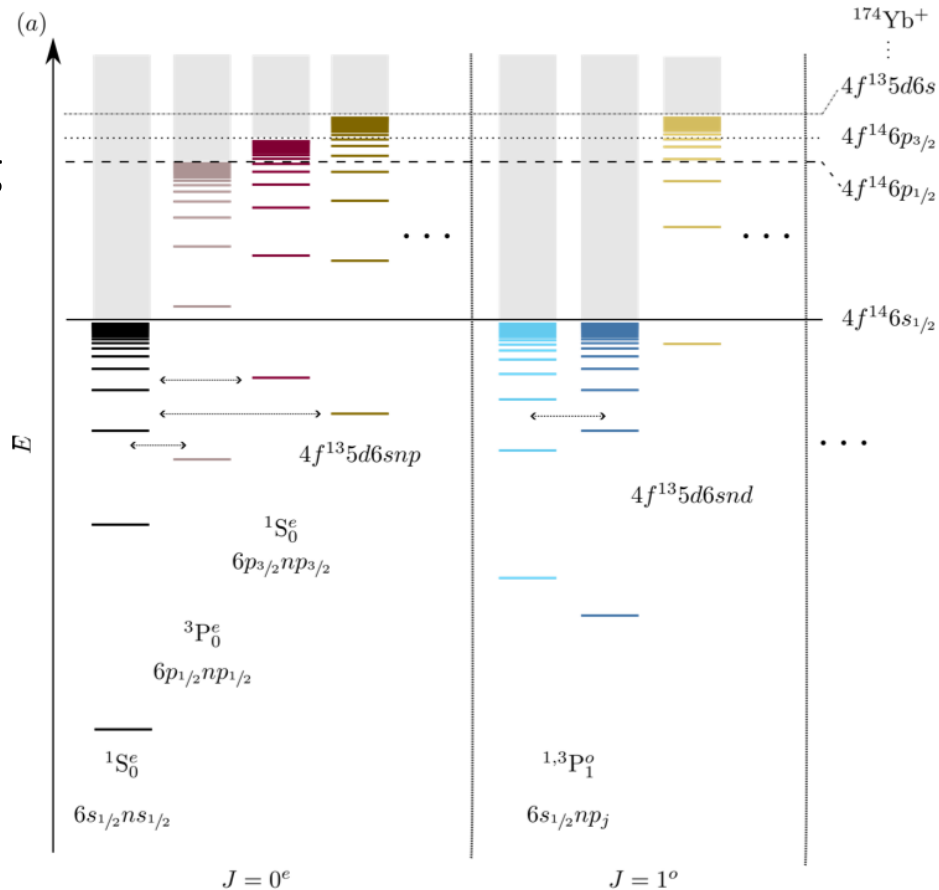
2 e^- atoms: Sr [$5s^2$], Yb [$6s^2 4f^{14}$]



- Rydberg series perturbed by second e^-
- Rydberg e^- + excited second e^-
 \Rightarrow auto-ionization

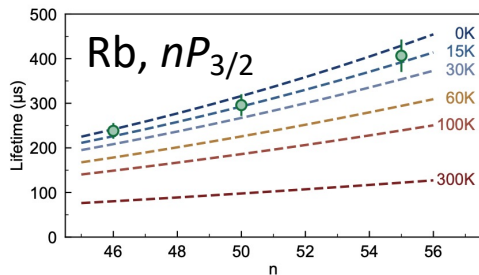
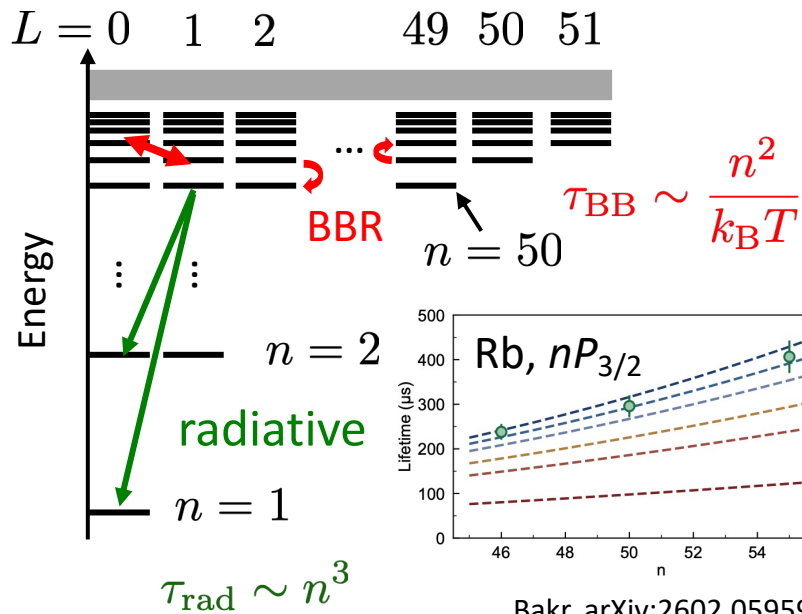
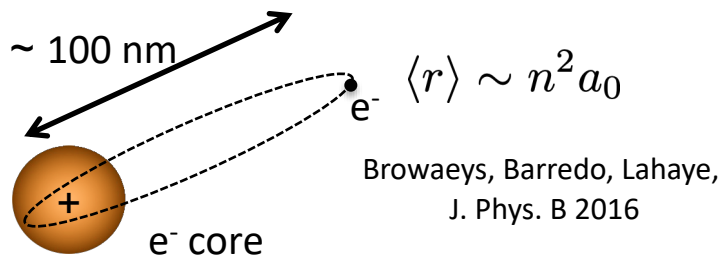
C L Vaillant, *et al.* J. Phys. B **47** 155001 (2014)

Other atoms: Er [$6s^2 4f^{12}$] Ferlino 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



Bakr, arXiv:2602.05959

Transition frequency:

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

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

$$\Rightarrow n > 60, \tau > 100 \mu\text{s}$$

Large transition dipole:

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

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

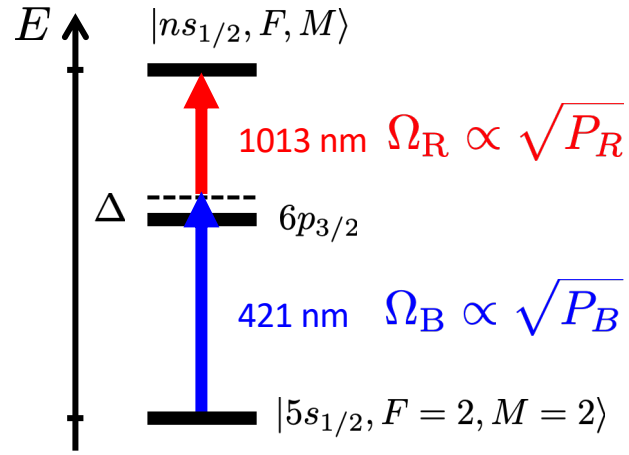
$$\langle \hat{D} \rangle = \alpha E$$

⇒ Exaggerated properties:

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

Coherent optical Rydberg excitation ($n = 50 - 100$)

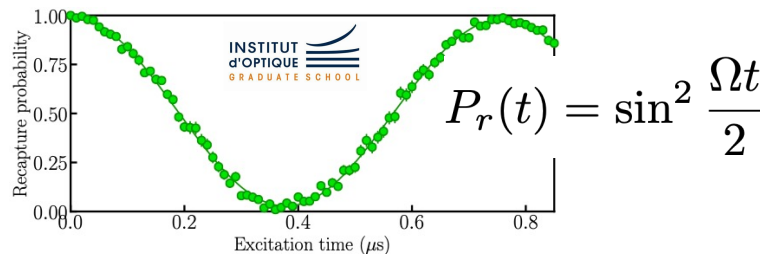
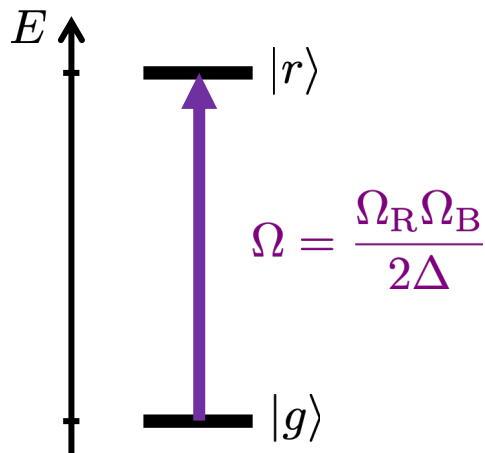
Alkali: Rb, Cs



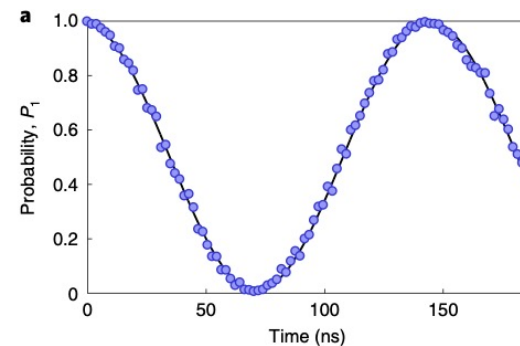
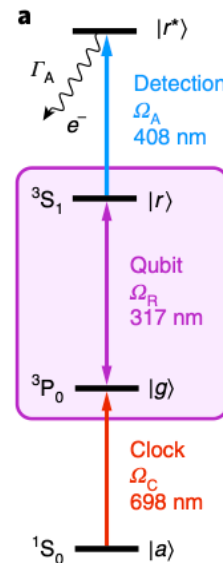
Coherent Rydberg excitation ($n = 50 - 100$)

Alkali: Rb, Cs

2- e^- atom: Sr, Yb



$F > 98\%$

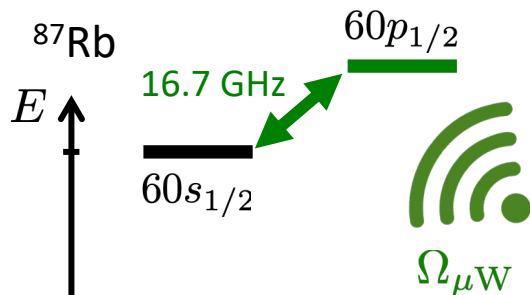


Endres, Nat. Phys. 2020

$F > 99.5\%$

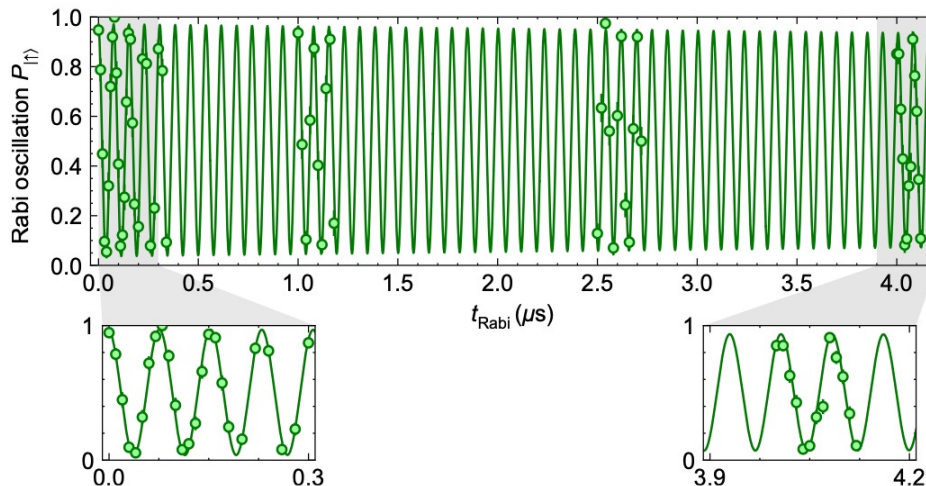
$$|\psi(t)\rangle = \cos \frac{\Omega t}{2} |g\rangle - i \sin \frac{\Omega t}{2} e^{i\varphi} |r\rangle$$

Coherent microwave manipulations ($n = 50 - 100$)



Single atom \Rightarrow repeat 100 times

Microwave Rabi oscillations

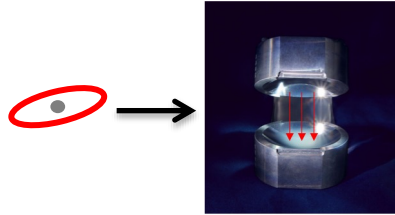


D. Barredo *et al.*,
PRL **114**, 113002 (2015)

Rydberg atoms: a few historical landmarks

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

1980 – 2000 Cavity Quantum Electrodynamics using Rydbergs



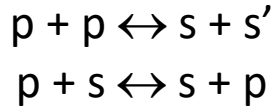
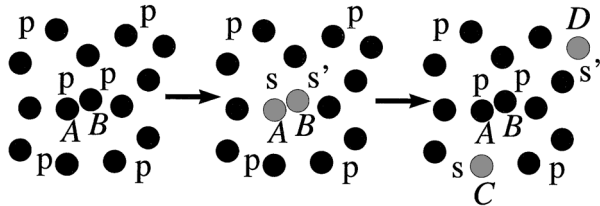
High Q cavity: photon lifetime > 1ms
 + large dipole \Rightarrow
1 Rydberg interacts with 1 photon!

Haroche, Walther...



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

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



“Frozen” gas

Diffusion of excitation faster than motion \Rightarrow correlations between all atoms

$k_B T \ll$ Interaction energy
 $\Rightarrow T < 1$ 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