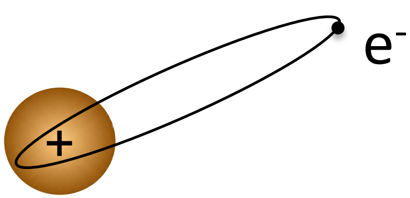
Faire de la physique quantique

avec quelques atomes



Antoine Browaeys

Laboratoire Charles Fabry,
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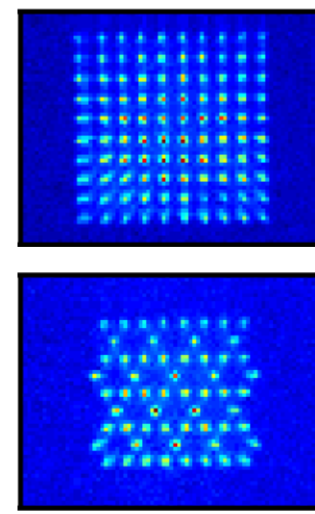


Manipulation of individual quantum systems: the point of view of a founding father…

In the first place it is fair to state that we are not *experimenting* with single particles, anymore than we can raise Ichtyosauria in the zoo.

…., this is the obvious way of registering the fact, that we **never** experiment with just **one** electron or atom or (small) molecule. In thought-experiments we sometimes assume that we do; this envariably entails **ridiculous** consequences.

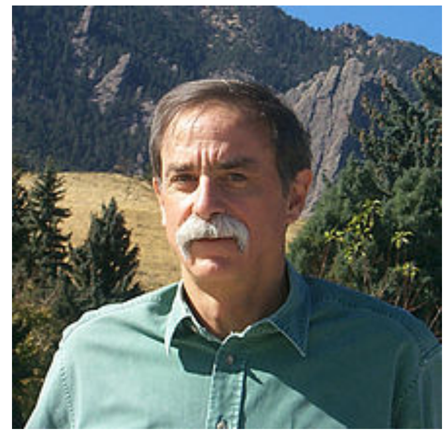
E. Schrödinger

British Journal of the Philosophy of Science III (10), (1952)

60 years later…

2012

S. Haroche



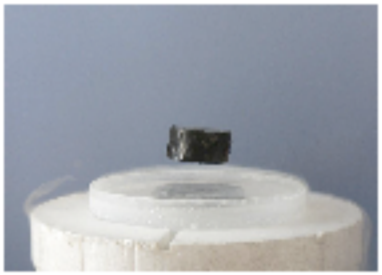
D. Wineland

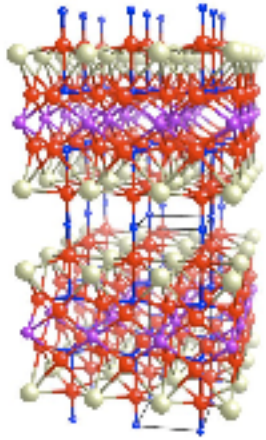
"for ground-breaking experimental methods that enable measuring and manipulation of individual quantum systems"

Quantum state engineering

Applications of quantum state engineering

Many-body physics

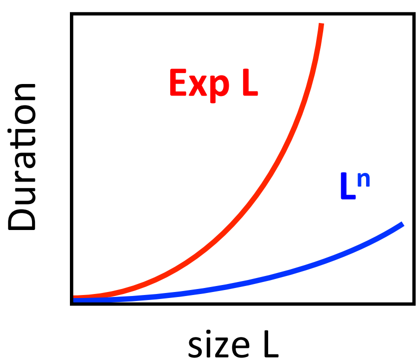




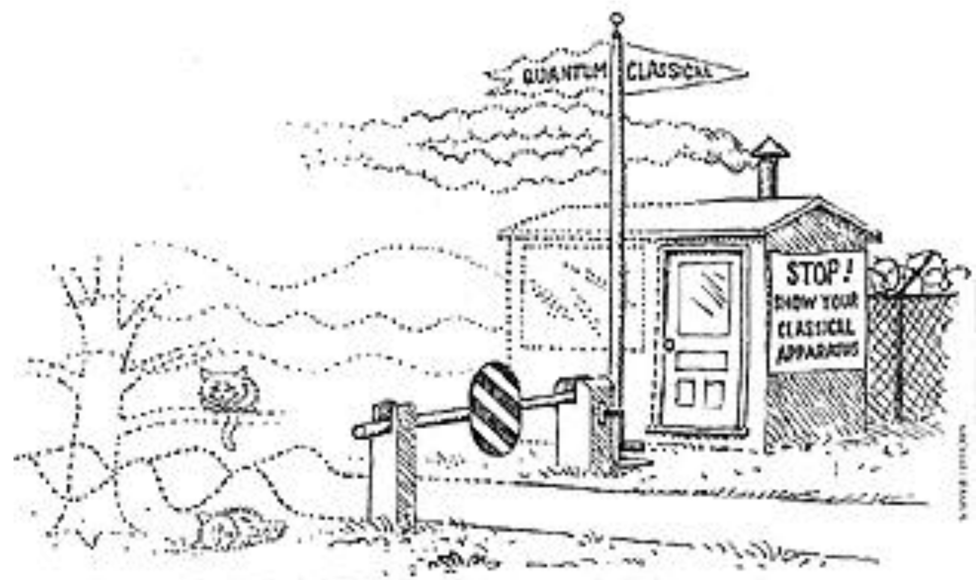
Quantum metrology

Quantum information

Message

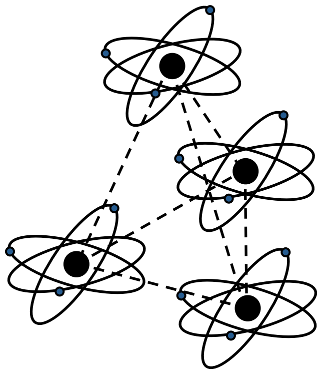


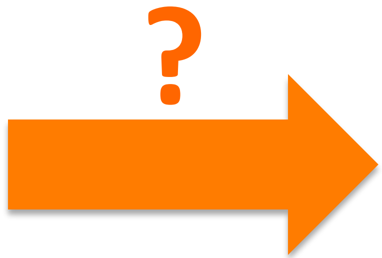
Transition quantum / classical



From microscopic to macroscopic world…

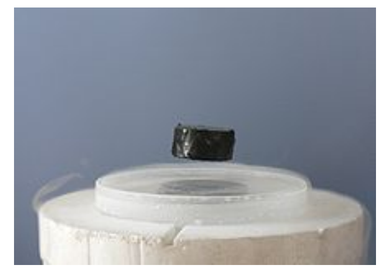
Microscopic





Macroscopic

Quantum laws…



quantum or classical laws

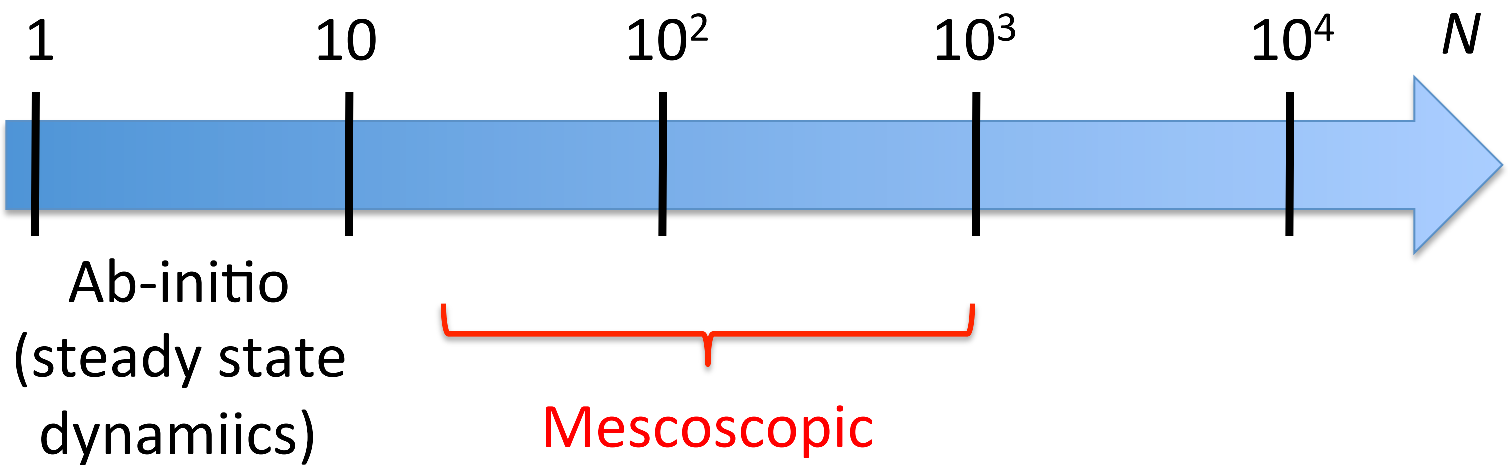
Schrödinger's equation: $i\hbar \frac{\partial \Psi}{\partial t} = H_{\mathrm{tot}} \Psi$

$$H_{\mathrm{tot}} = \sum_{i=1}^{N} -\frac{\hbar^2}{2m}\nabla_i^2 - \sum_{i=1}^{N}\sum_{j\neq i} \frac{e^2}{r_{ij}} - \frac{\mu_{\mathrm{B}}^2}{r_{ij}^3}\mathbf{s}_i \cdot \mathbf{s}_j$$

Many - body systems and complexity

Complexity: for N > 30 – 40, ab-initio calculations impossible!!

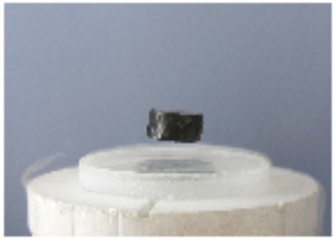
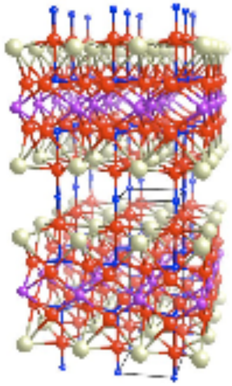
Ex: spin 1/2 $\Rightarrow$ size of Hilbert space $\sim 2^N$ too large



Approximate methods ($10^2 < N < 10^5$): DMRG, Monte Carlo, density functionnal, mean field…

One idea (Feynman 1982): engineer quantum systems in the lab. Measure to find properties you can't calculate!

Quantum simulation: an example

Ex: high-T_c superconductivity

simplify

Experience on the real system

Model Hamiltonian

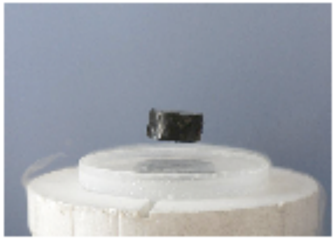
$$H_{\mathrm{model}} = -\sum_{i,j} J_{ij} a_i^\dagger a_j + \sum_i g (a_i^\dagger)^2 (a_i)^2$$

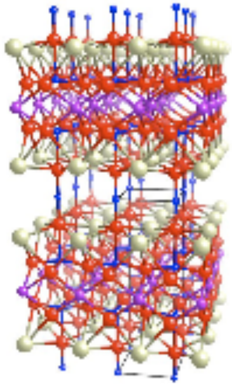
Calcul… H_{model}

$\Rightarrow$ super…uctivty ?

Calculation too hard…

Quantum simulation: an example





Ex: high-T_c superconductivity

Experience on the real system

simplify →

Model Hamiltonian

$$H_{\text{model}} = -\sum_{i,j} J_{ij} a_i^\dagger a_j + \sum_i g (a_i^\dagger)^2 (a_i)^2$$

Lab... ↓

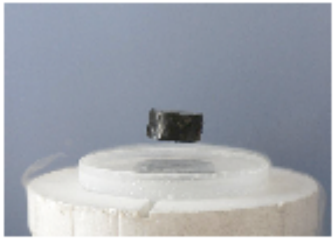
Quantum simulator = engineer ensemble of atoms ruled by H_{model}

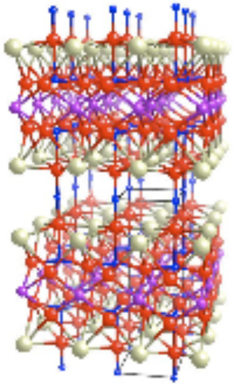
←

Mesure outcome of simulator:
ground state = supercond.?

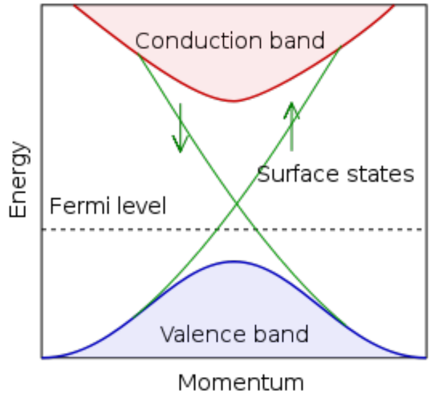
What can you simulate = N-body problem?

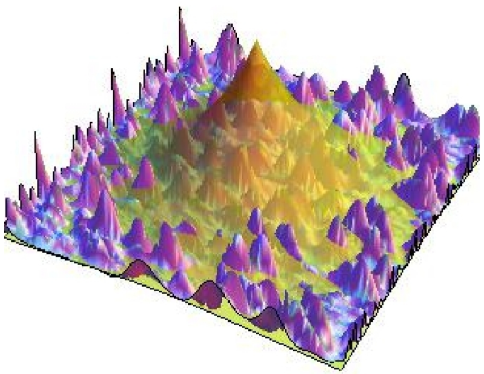
High-Tc superconductivity





Conduction properties of metal:
Influence of disorder and interactions

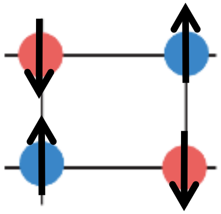


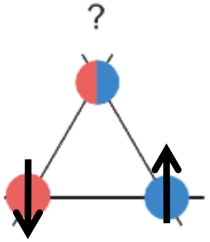


Anderson localization

Quantum magnetism: ferro & anti-ferromagnetic order

Néel order



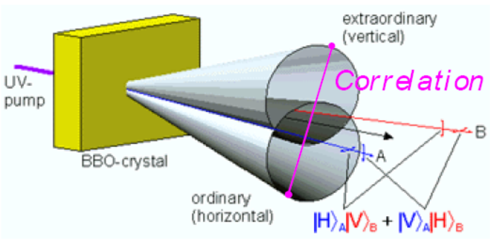


frustration

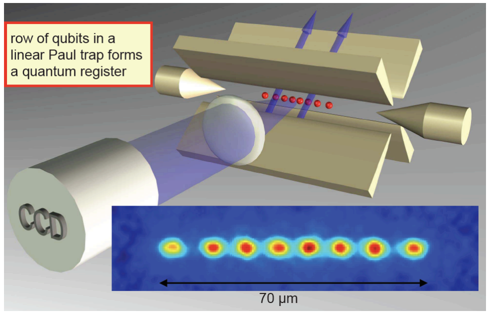
Phase diagram, dynamics…

Example of individual quantum systems (AMO)

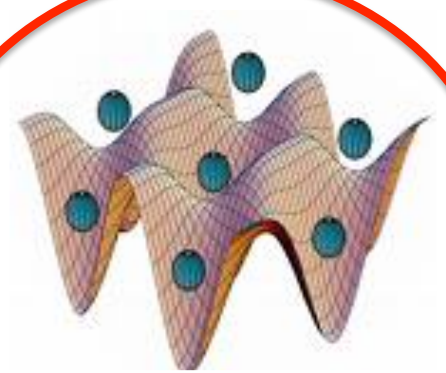
Photons



Trapped, laser-cooled ions

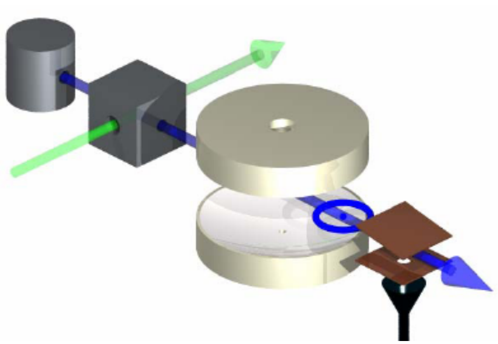


Trapped, ultracold atoms



Cold **Rydberg** atoms

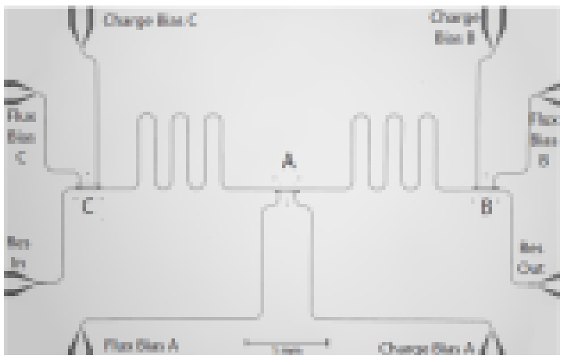
Atoms or ions in cavities



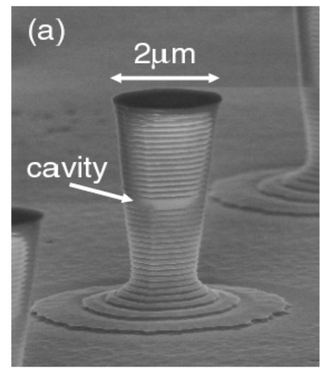
Example of individual quantum systems (condensed matter)

“Artificial” atoms

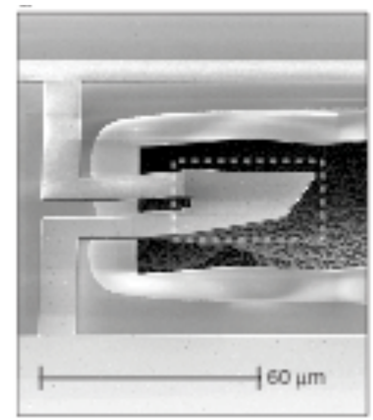
Superconducting circuits



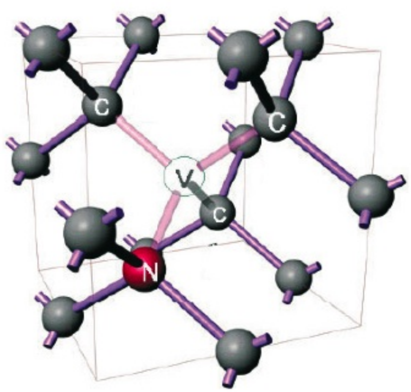
Quantum dots



Nanoresonators



NV center in diamond

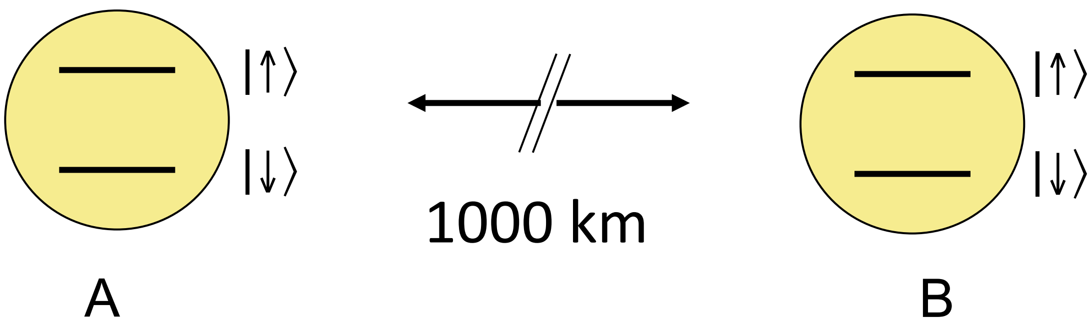


Quantum state engineering

Requirements:

1. Individual quantum systems
2. Control of their interactions

A key concept: entanglement = non-local quantum correlations

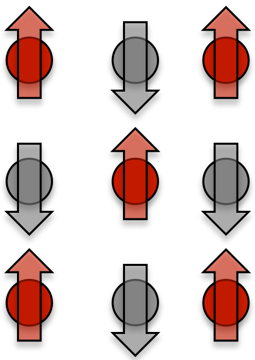


$$\frac{1}{\sqrt{2}}(|\downarrow_{\mathrm{A}},\uparrow_{\mathrm{B}}\rangle + |\uparrow_{\mathrm{A}},\downarrow_{\mathrm{B}}\rangle)$$

$$|\Psi_{\mathrm{A,B}}\rangle \neq |\Psi_{\mathrm{A}}\rangle \otimes |\Psi_{\mathrm{B}}\rangle$$

Ground-state of an interacting many-body system = entangled

Prototypical Hamiltonian: assembly of spins



Ising $$H_z = \sum_{i \neq j} J_{ij} \, S_i^z S_j^z$$

XY model $$H_{XY} = \sum_{i \neq j} J_{ij} \, \left(S_i^+ S_j^- + S_i^- S_j^+ \right)$$

Many problems can be mapped onto these Hamiltonian

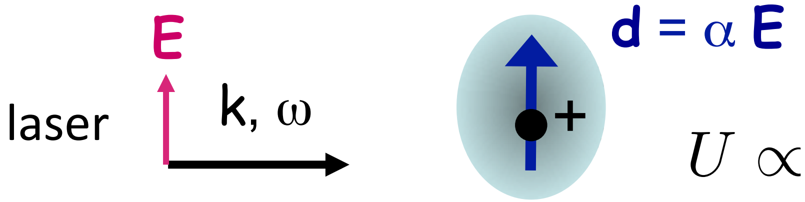
Goal: implement them in the lab

Outline

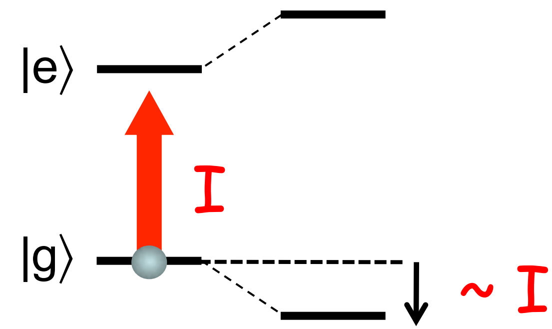
1. Trapping individual atoms in optical tweezers
2. Rydberg atoms and collective excitation of 2 interacting atoms
3. Measurement of the van der Waals interaction between 2 atoms & Rydberg blockade
4. Resonant interaction at a Förster resonance: controlling interactions with a DC E-field

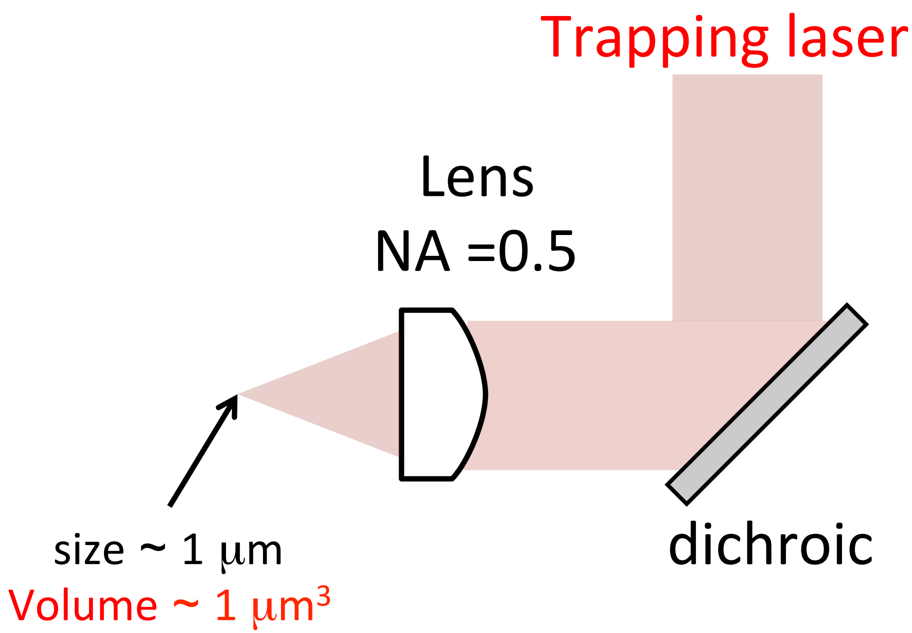
Microscopic dipole trap = "optical tweezers"

Non resonant atom-laser interaction



$$U \propto -\alpha E^2 \propto I$$



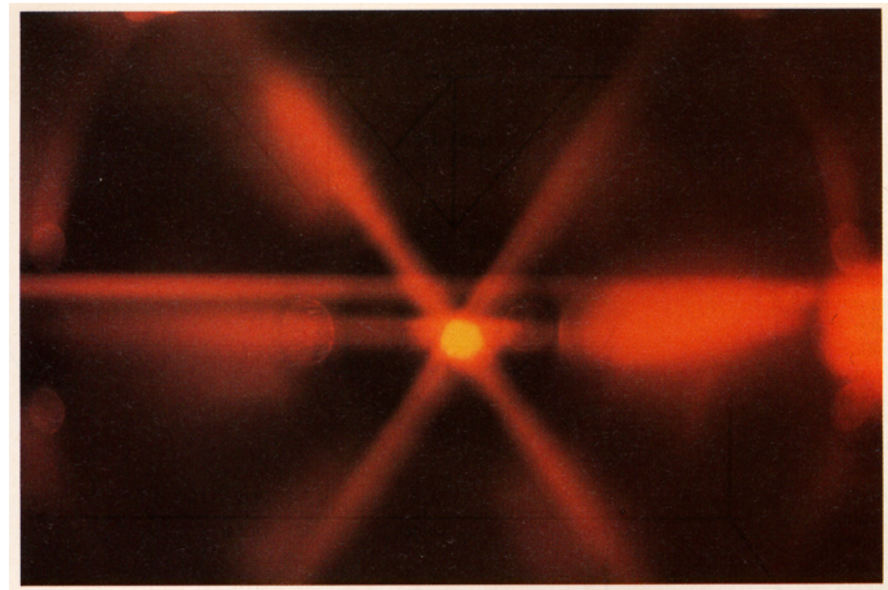


Trap depth ≈ 1 mK ⇒ **laser cooled atoms**

Laser cooling of atoms (1980 - 1990)

Use lasers to cool dilute atomic vapor down to T ~ 10 μK

Sodium T ~ 100 μK
S. Chu (1985)



Nobel Prize in Physics 1997

S. Chu, C. Cohen-Tannoudji, W. D. Phillips

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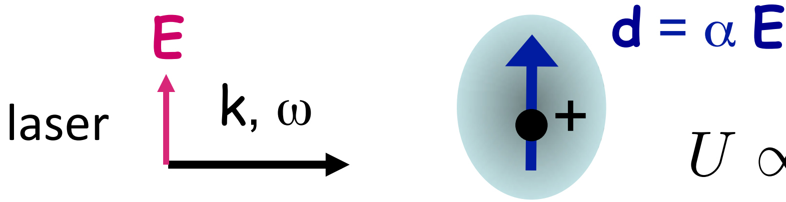
Non resonant atom-laser interaction



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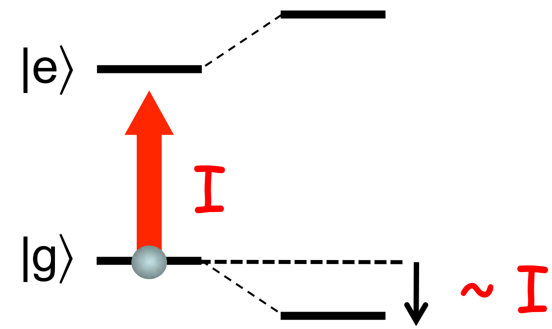
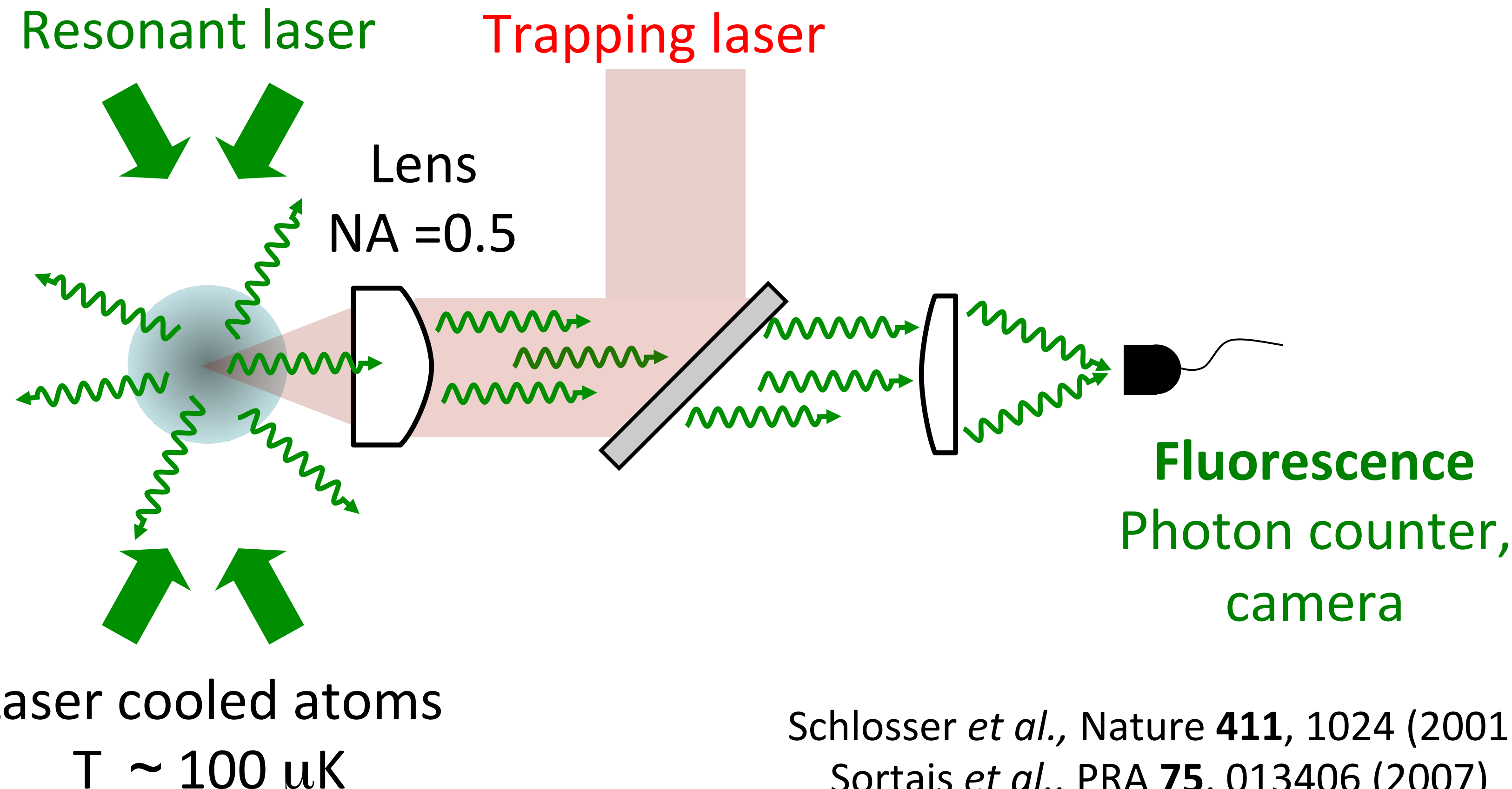
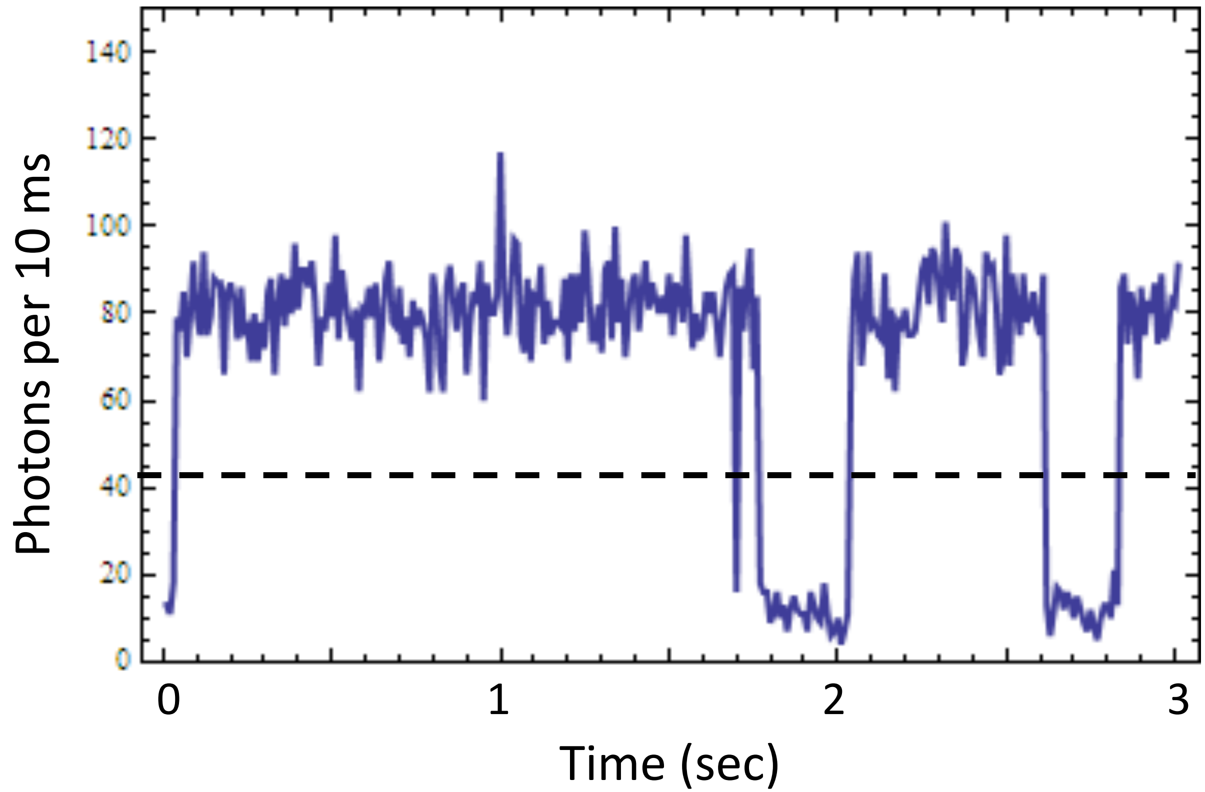


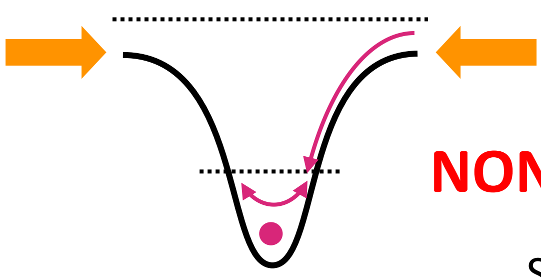


Schlosser *et al.*, Nature **411**, 1024 (2001)
Sortais *et al.*, PRA **75**, 013406 (2007)

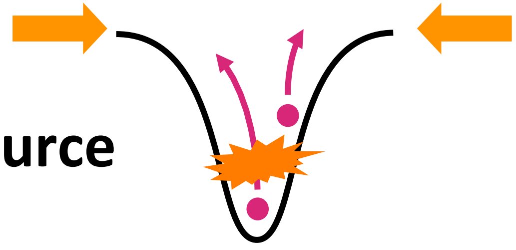
Fast light-assisted collision prevents two atoms at the same time…

Fluorescence @ 780 nm induced by the cooling lasers



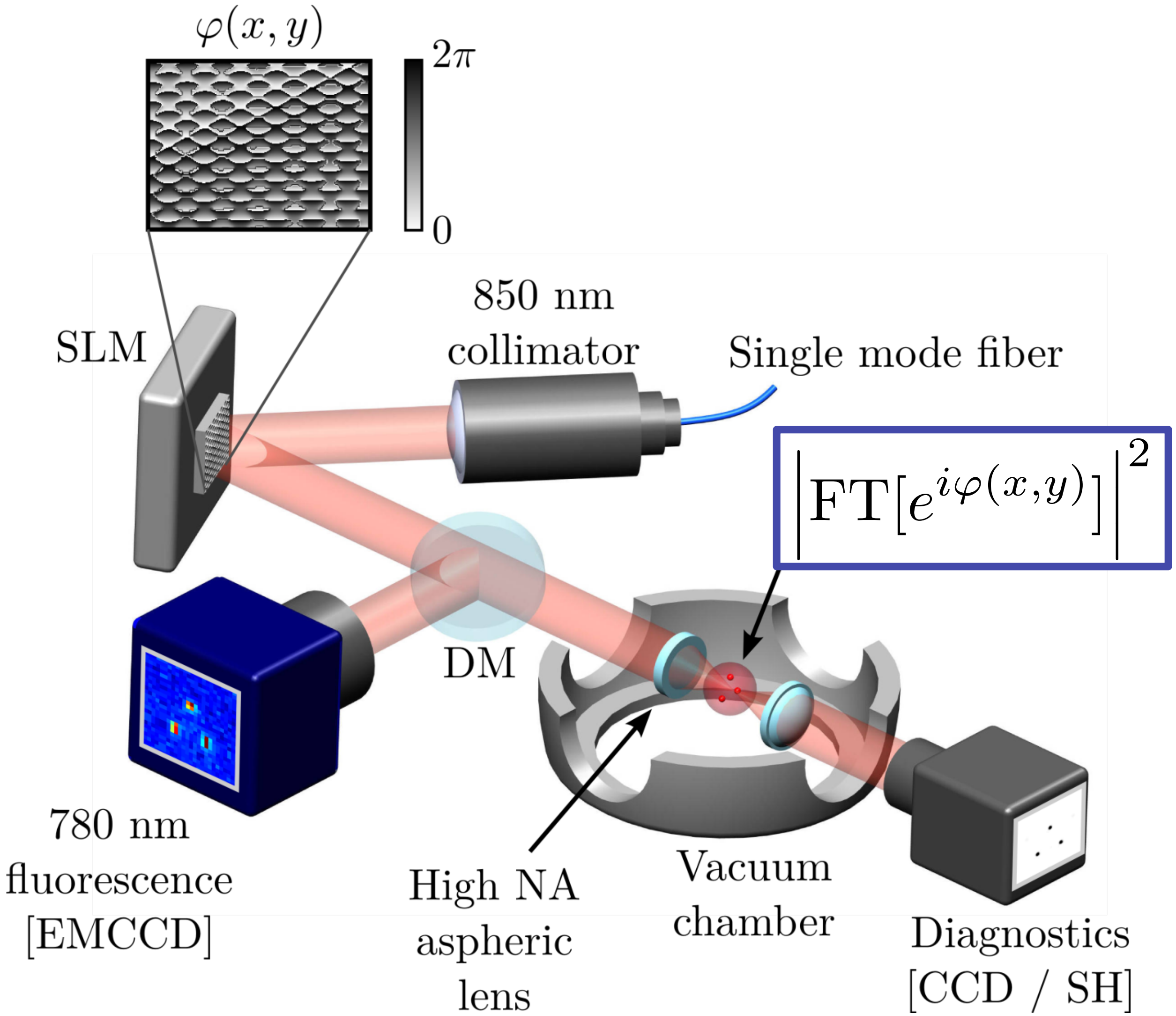


NON deterministic single-atom source

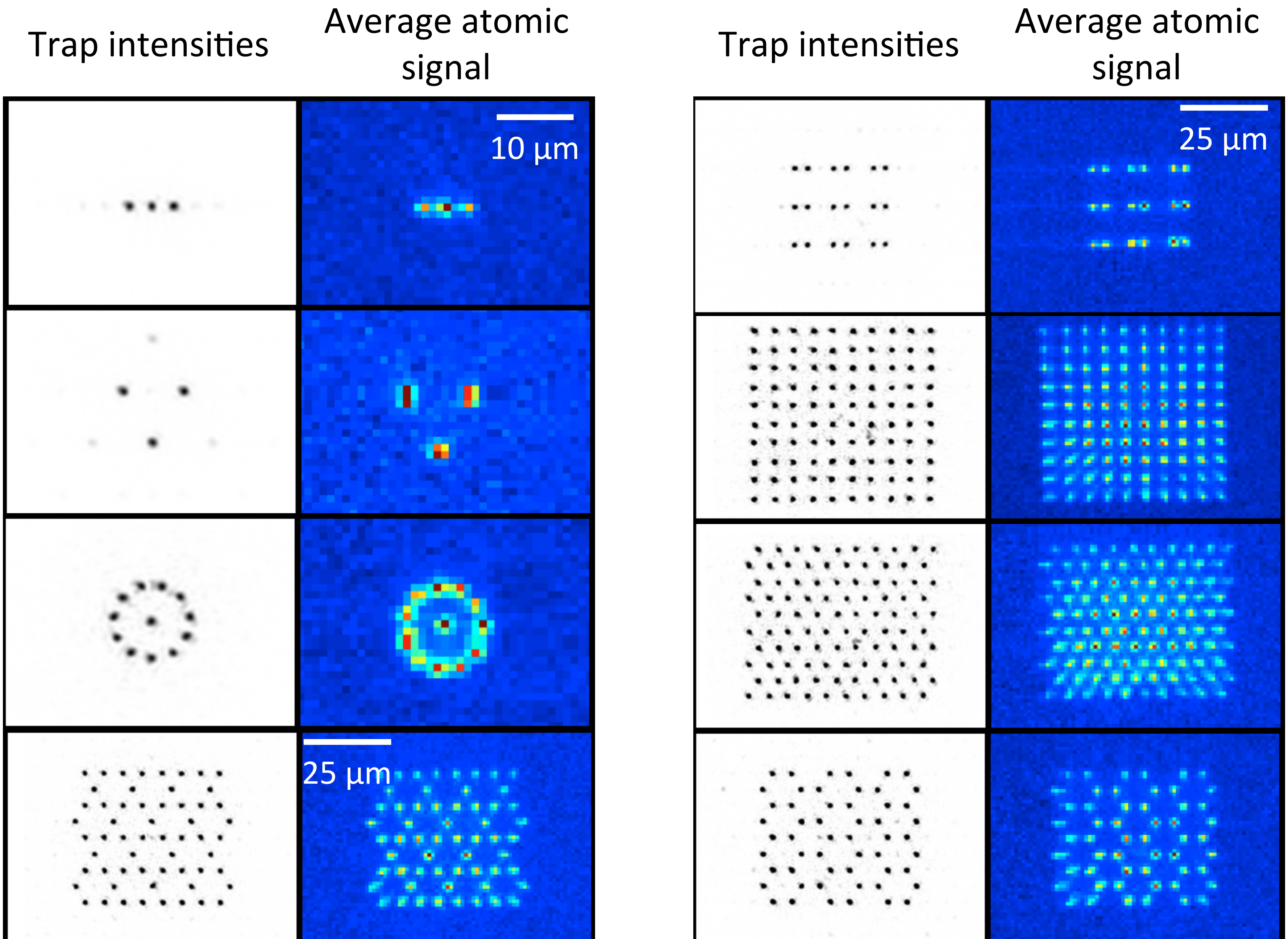


Schlosser *et al.*, Nature **411**, 1024 (2001)
Sortais *et al.*, PRA **75**, 013406 (2007)

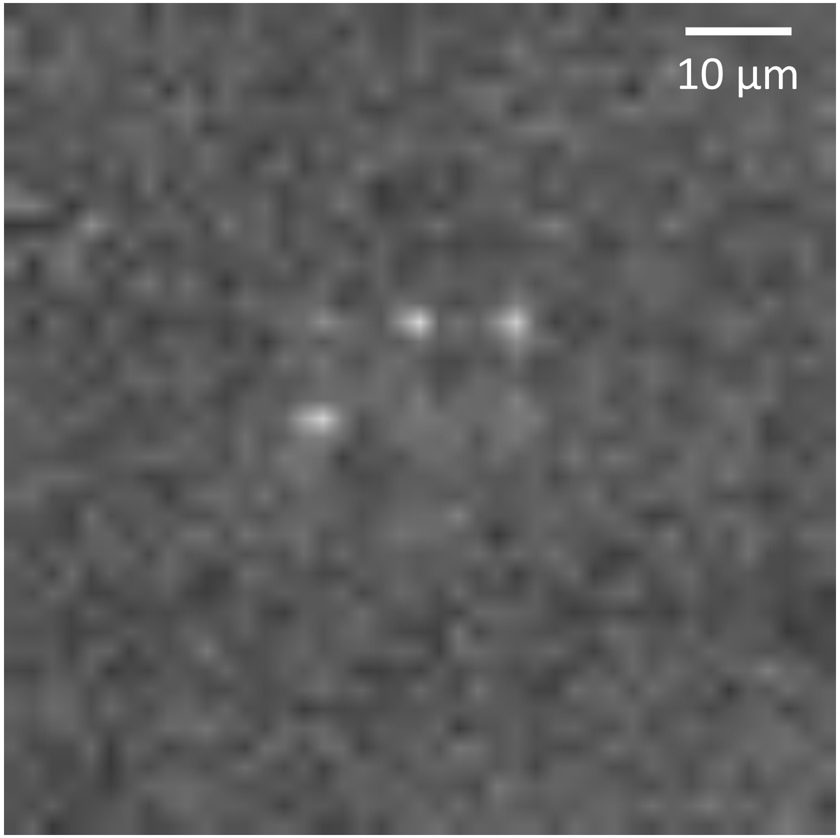
Arrays of optical tweezers: Spatial Light Modulator



Gallery of 2D arrays of tweezers



Arrays of optical tweezers with individual atoms



Nogrette *et al.*, PRX **4**, 021034 (2014)

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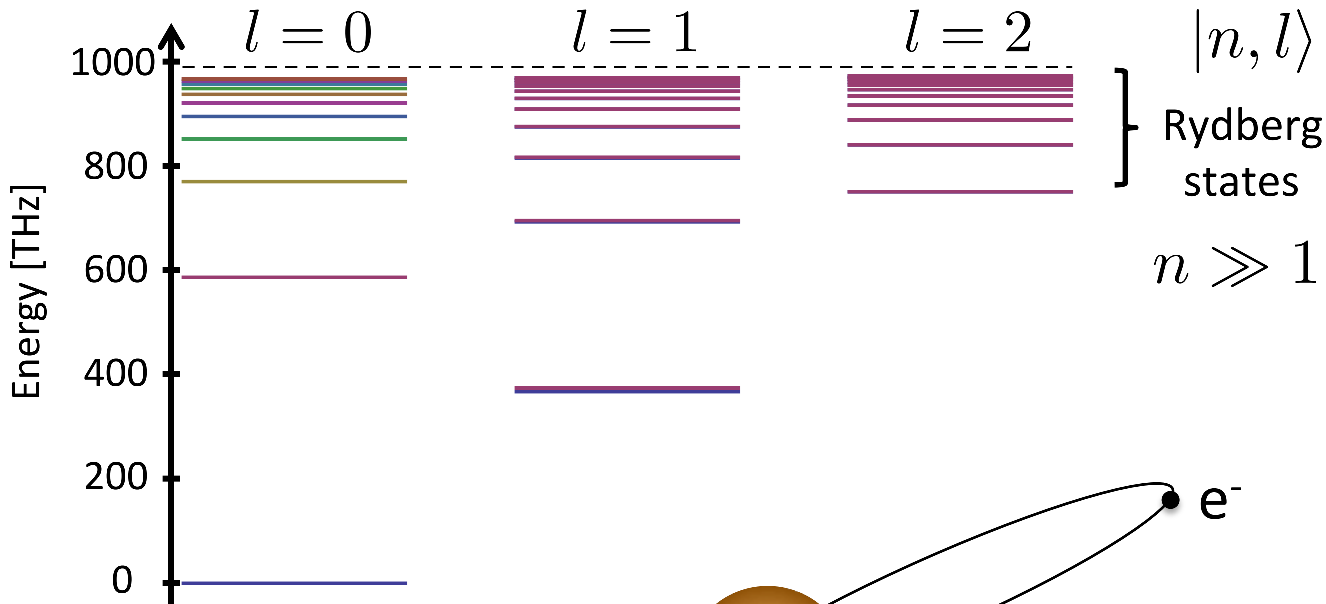
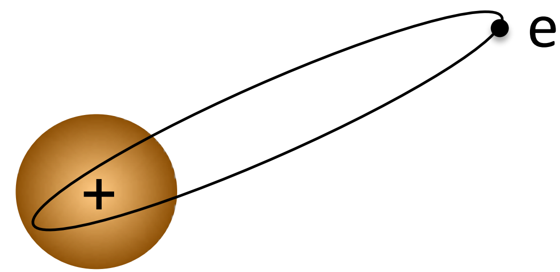
Rydberg atoms (alcalies)

Johannes Rydberg
1854-1919

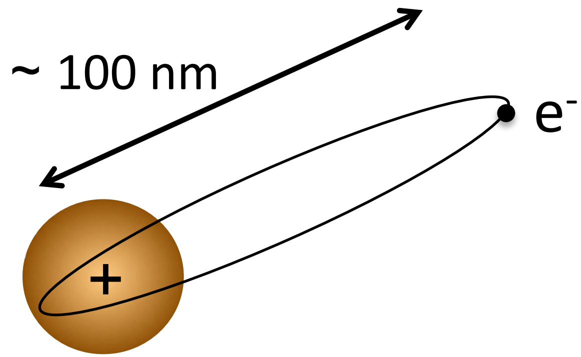




Atomes alcalins (Rb, Cs) $\Rightarrow$ hydrogénoïde $|n, l, j, m\rangle$

$$E_{n,l} \approx -\frac{13.6}{n^2}\ \mathrm{e}V$$

Properties of Rydberg atoms



Size $\sim n^2 a_0$

1. Long lifetime ~ n^3 (> 100 µs)

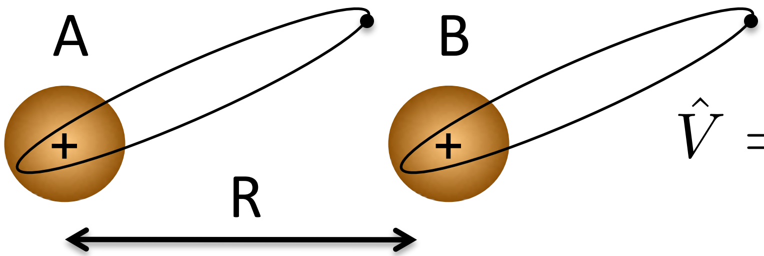
2. Large dipole moments of transition $nL \rightarrow n(L \pm 1)$

$$d \propto n^2 e a_0$$

Ex : $n \approx 50 \Rightarrow$ 3000 × d(H_2O) !

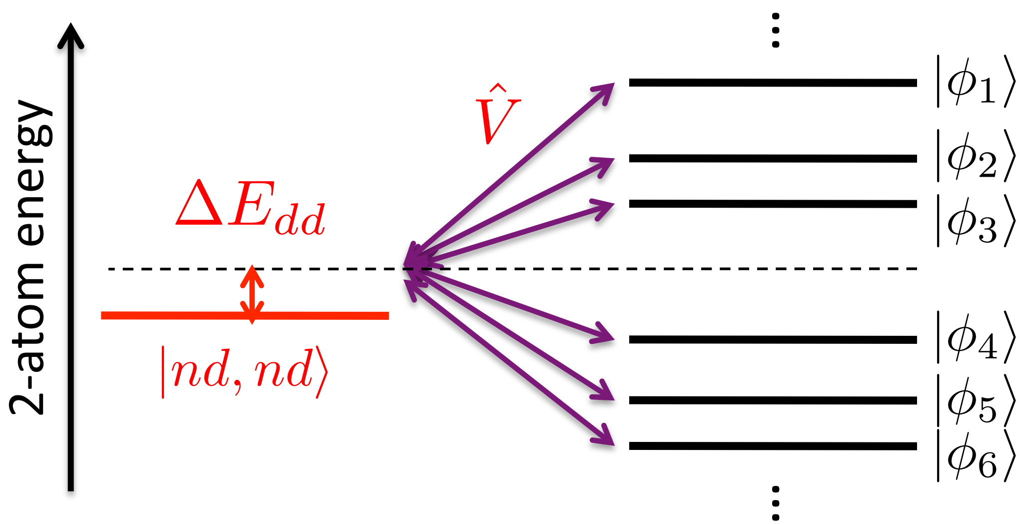
3. Large polarizability ~ $n^7 \Rightarrow$ large AC & DC Stark shift

Van der Waals interaction



$$\hat{V} = \frac{1}{4\pi\epsilon_0 R^3}\left(\hat{\mathbf{d}}_A \cdot \hat{\mathbf{d}}_B - 3(\hat{\mathbf{d}}_A \cdot \hat{\mathbf{r}})(\hat{\mathbf{d}}_B \cdot \hat{\mathbf{r}})\right)$$

2-atom basis: $\{|\phi_{nn'}\rangle = |n,l\rangle \otimes |n',l'\rangle\}$



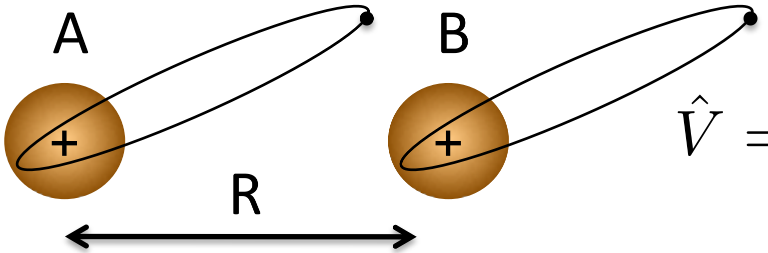
Van der Waals regime:

$$\Delta E_{dd} = \sum_{|\phi\rangle} \frac{|\langle\phi|\hat{V}|dd\rangle|^2}{E_\phi - E_{dd}} = \frac{C_6}{R^6}$$

Scaling law: $C_6 \propto n^{11}$

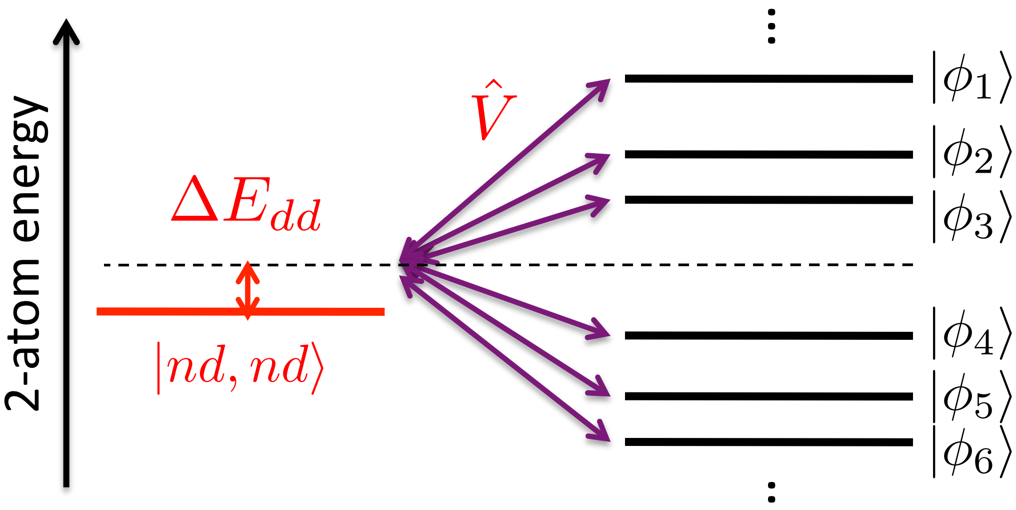
Interaction in Rydberg state = **10^{11}** x ground state interaction!!

Van der Waals interaction



$$\hat{V} = \frac{1}{4\pi\epsilon_0 R^3}\left(\hat{\mathbf{d}}_A \cdot \hat{\mathbf{d}}_B - 3(\hat{\mathbf{d}}_A \cdot \hat{\mathbf{r}})(\hat{\mathbf{d}}_B \cdot \hat{\mathbf{r}})\right)$$

2-atom basis: $\{|\phi_{nn'}\rangle = |n,l\rangle \otimes |n',l'\rangle\}$



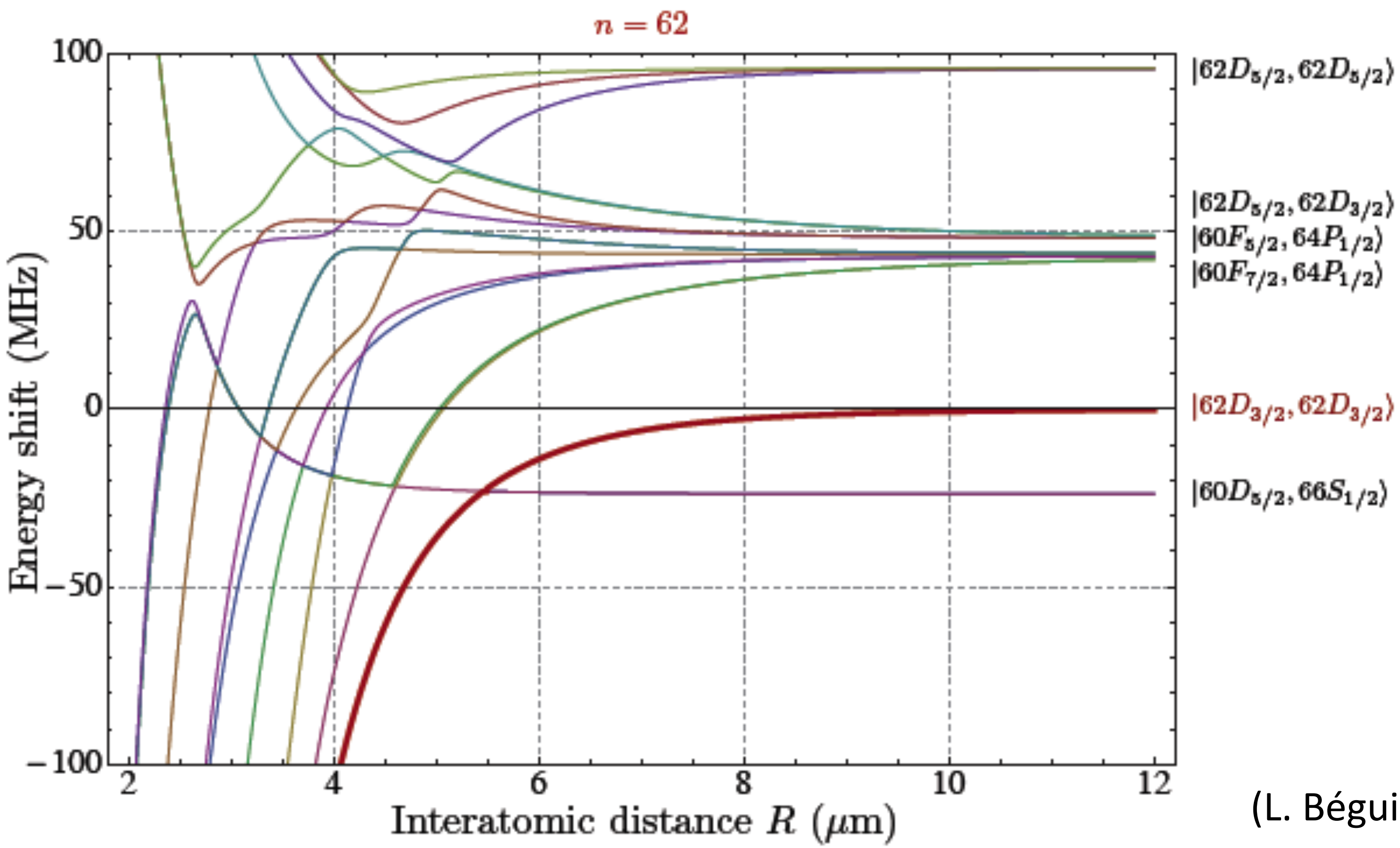
Van der Waals regime:

$$\Delta E_{dd} = \sum_{|\phi\rangle} \frac{|\langle\phi|\hat{V}|dd\rangle|^2}{E_\phi - E_{dd}} = \frac{C_6}{R^6}$$

Implement: $\hat{H} = \sum_{i,j} \frac{C_6}{R_{i,j}^6}\,\hat{S}_i^z \hat{S}_j^z$

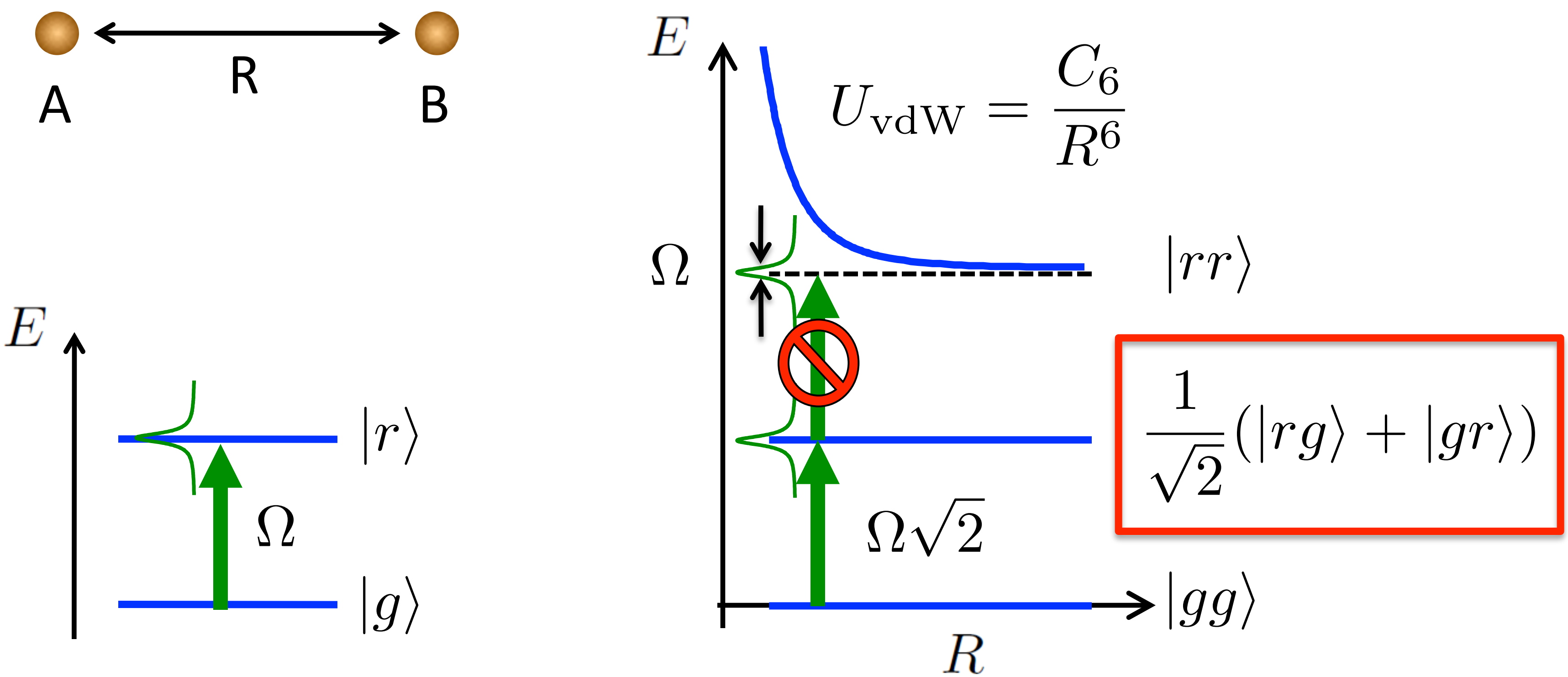
Interaction between two "real" Rydberg atoms

Ex: ^{87}Rb in $62d_{3/2}$



(L. Béguin)

Collective excitation of two interacting Rydberg atoms



Collective oscillation between $|gg\rangle$ and $\frac{1}{\sqrt{2}}(|rg\rangle + |gr\rangle)$

with coupling $\Omega\sqrt{2}$ (N atoms $\Rightarrow$ $\Omega\sqrt{N}$)

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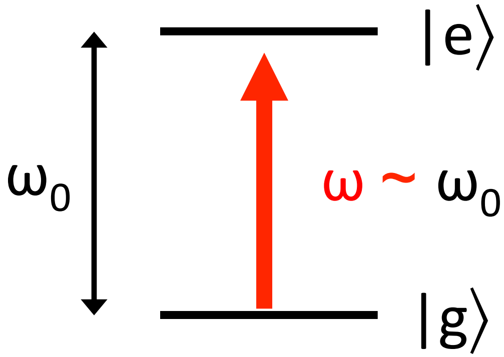
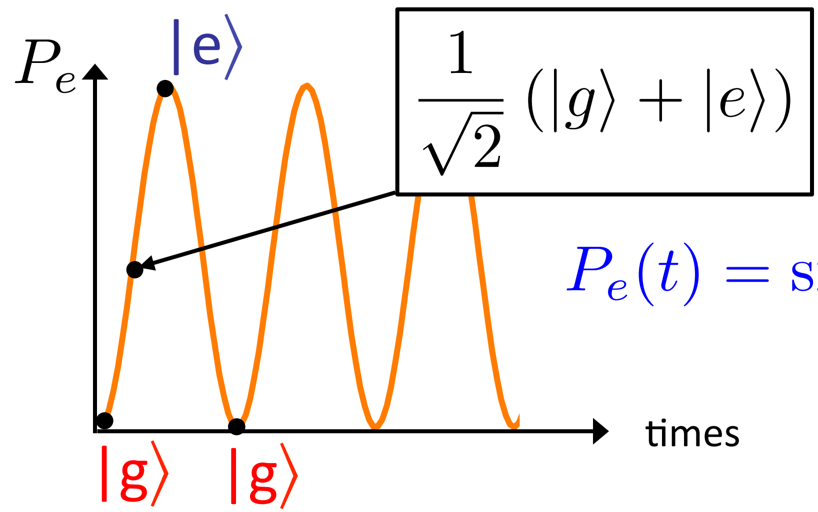
Old ideas... on individual quantum systems

Rabi oscillations (1930s!): stimulated emission



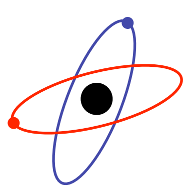
Ω = Rabi frequency

$\propto \sqrt{\text{Intensity}}$

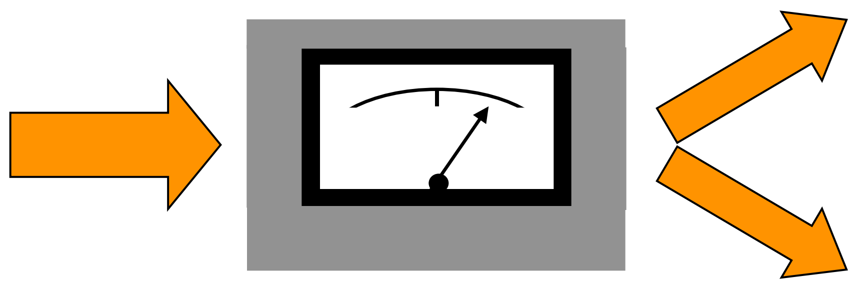


$$P_e(t) = \sin^2 \frac{\Omega t}{2}$$

Measurement on individual system



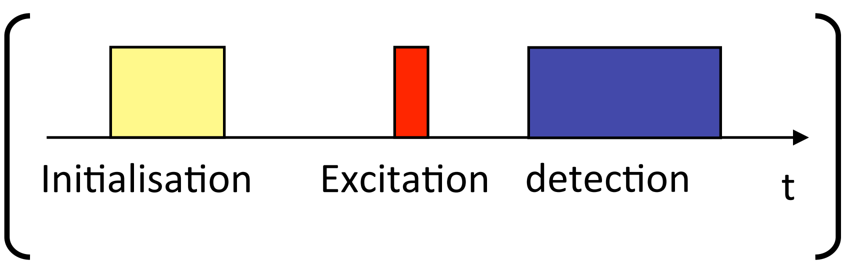
$\alpha|g\rangle + \beta\,|e\rangle$



$|g\rangle, |\alpha|^2$

OR

$|e\rangle, |\beta|^2$

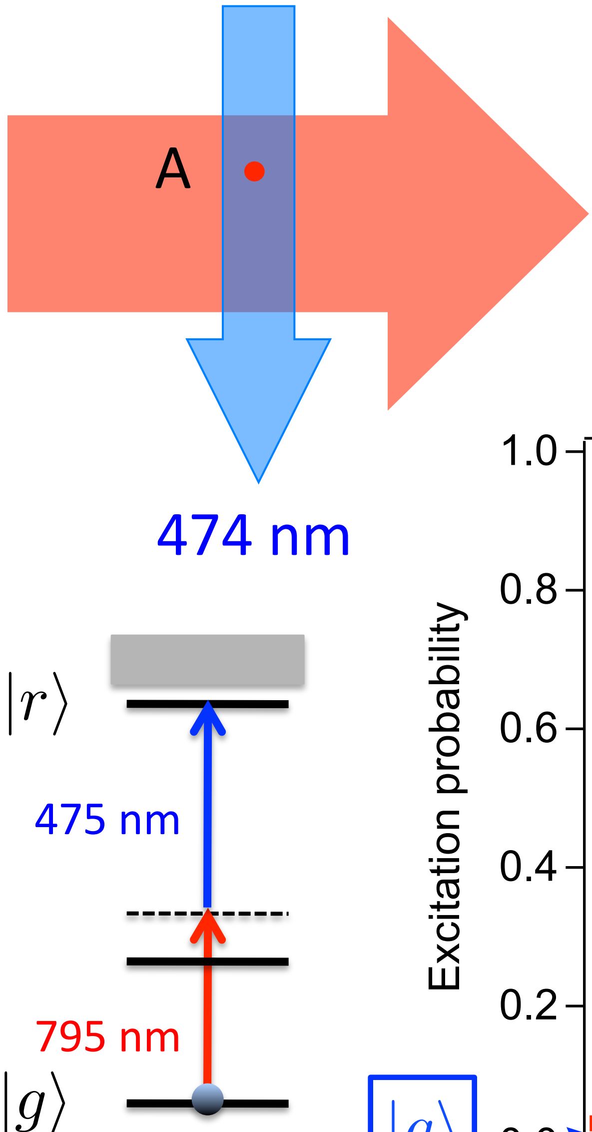


× 100

$|g\rangle, |e\rangle, |e\rangle, |g\rangle, \ldots, |e\rangle, |g\rangle$

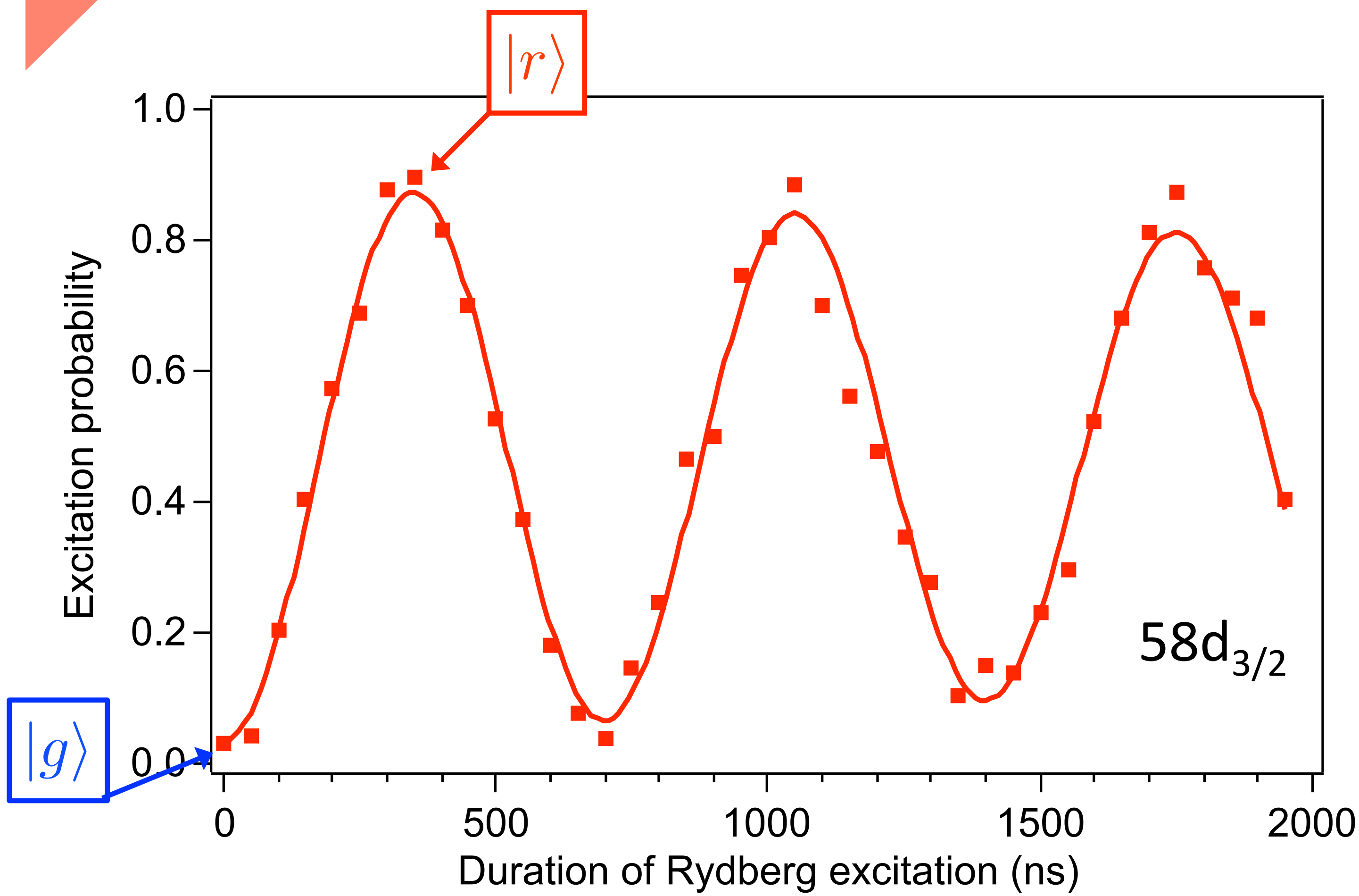
$\Rightarrow$ Probability P(g)

Rydberg blockade and collective excitation

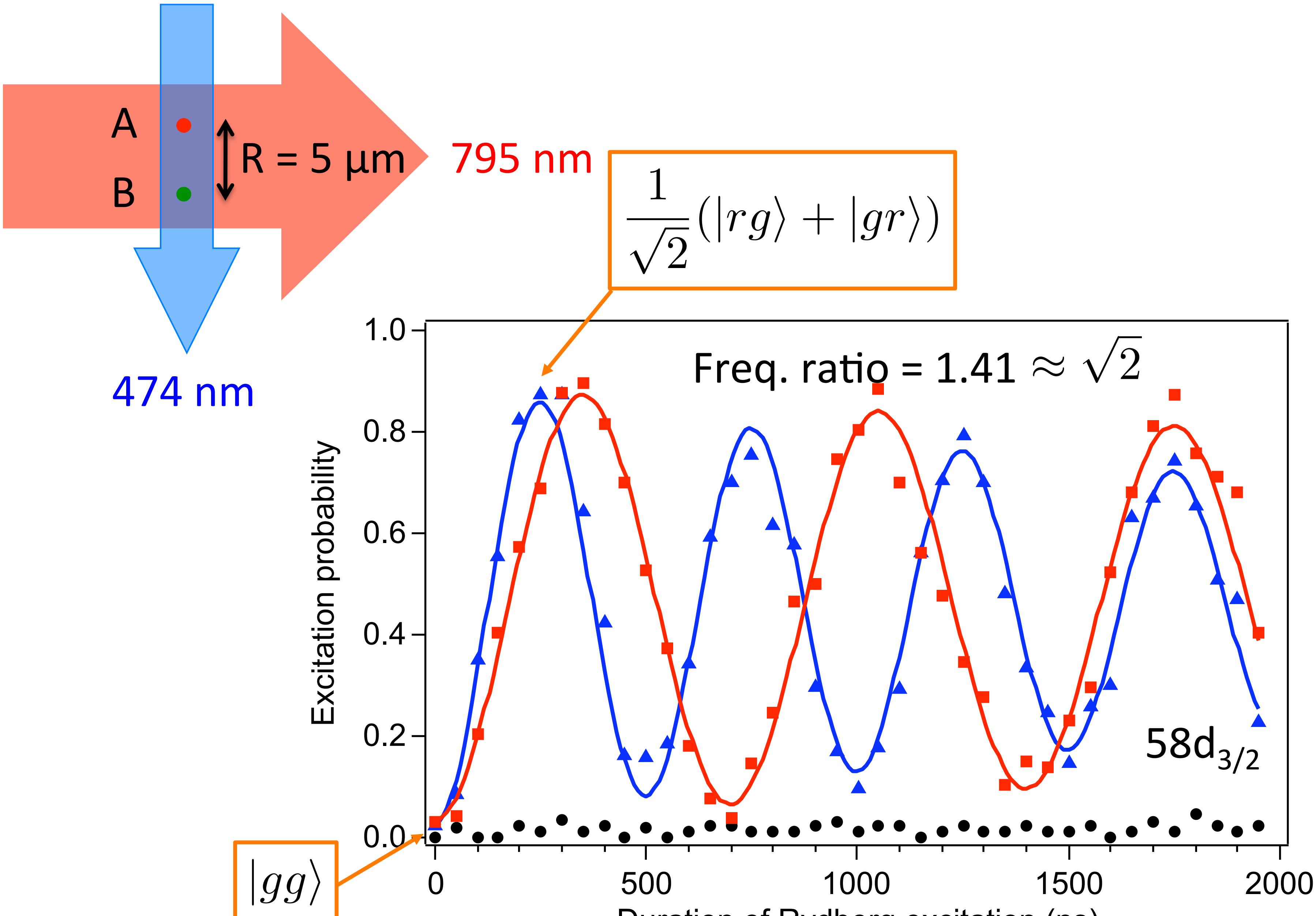


Exc. proba atom A only

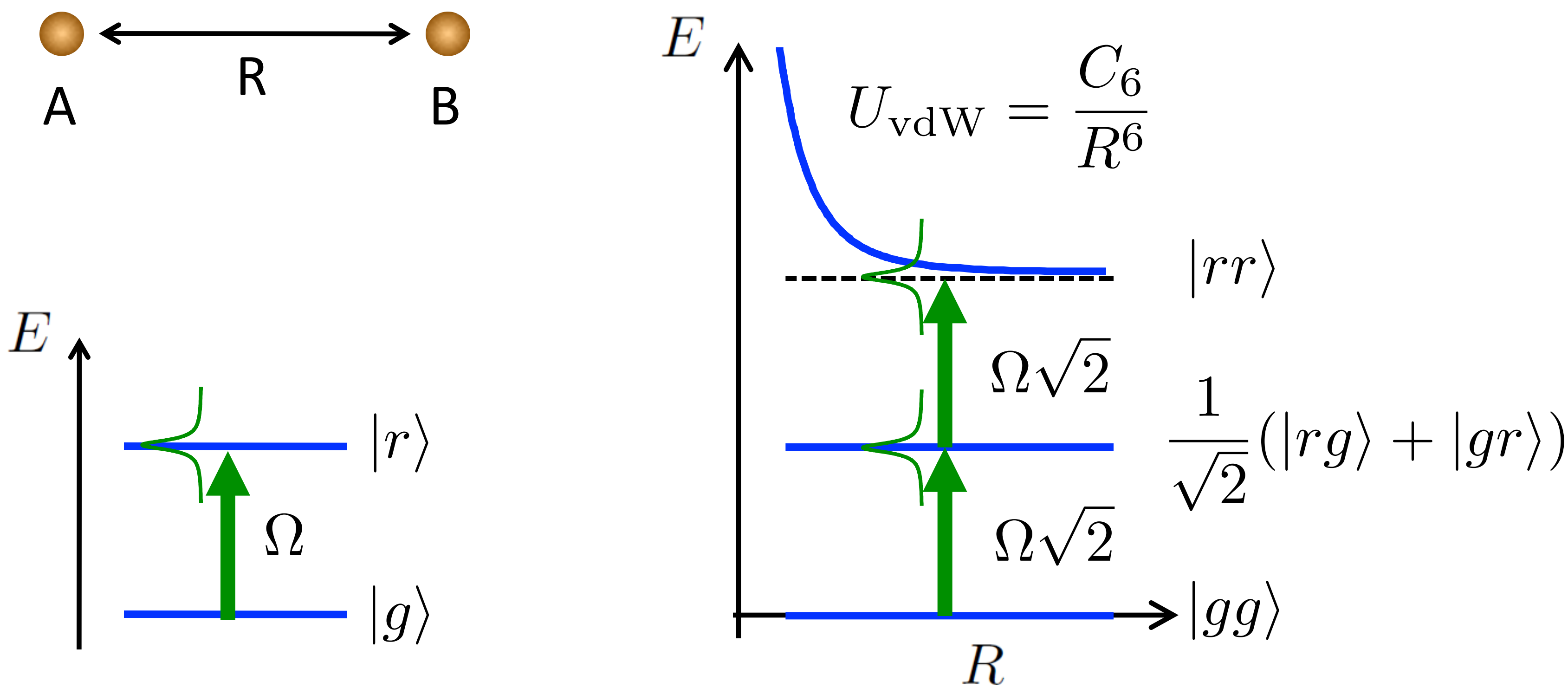
Repeat 100 times on 1 atom



Rydberg blockade and collective excitation



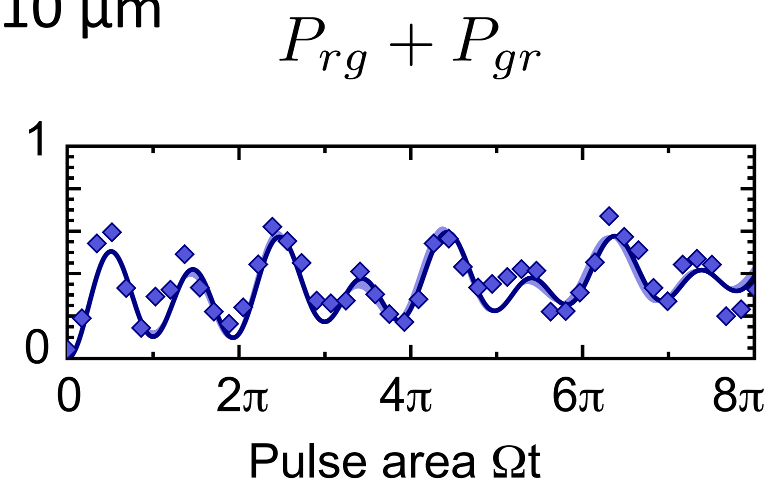
Collective excitation of two interacting Rydberg atoms

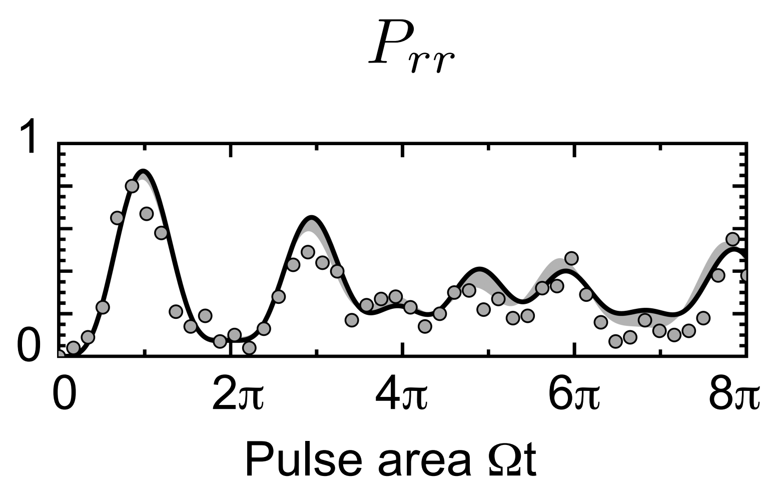


If $\hbar\Omega \approx U_{\rm vdW}$: dynamics involves Ω **and** U_{vdW} ⇒ **partial blockade**

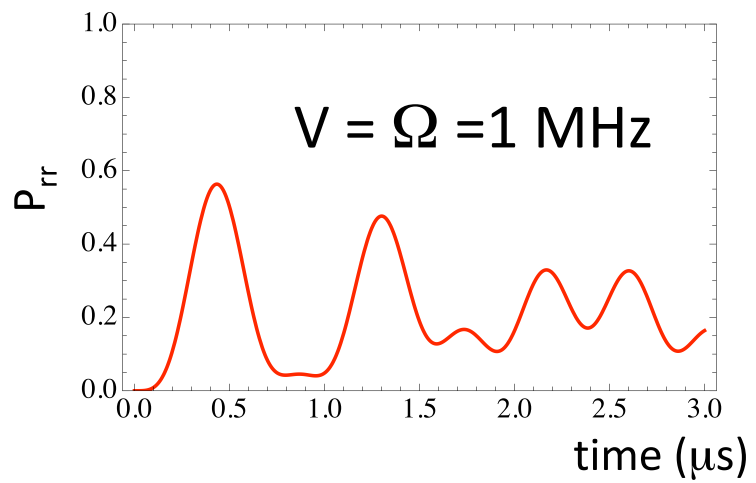
Collective excitation in the "partial blockade" ($62d_{3/2}$)

R = 10 µm



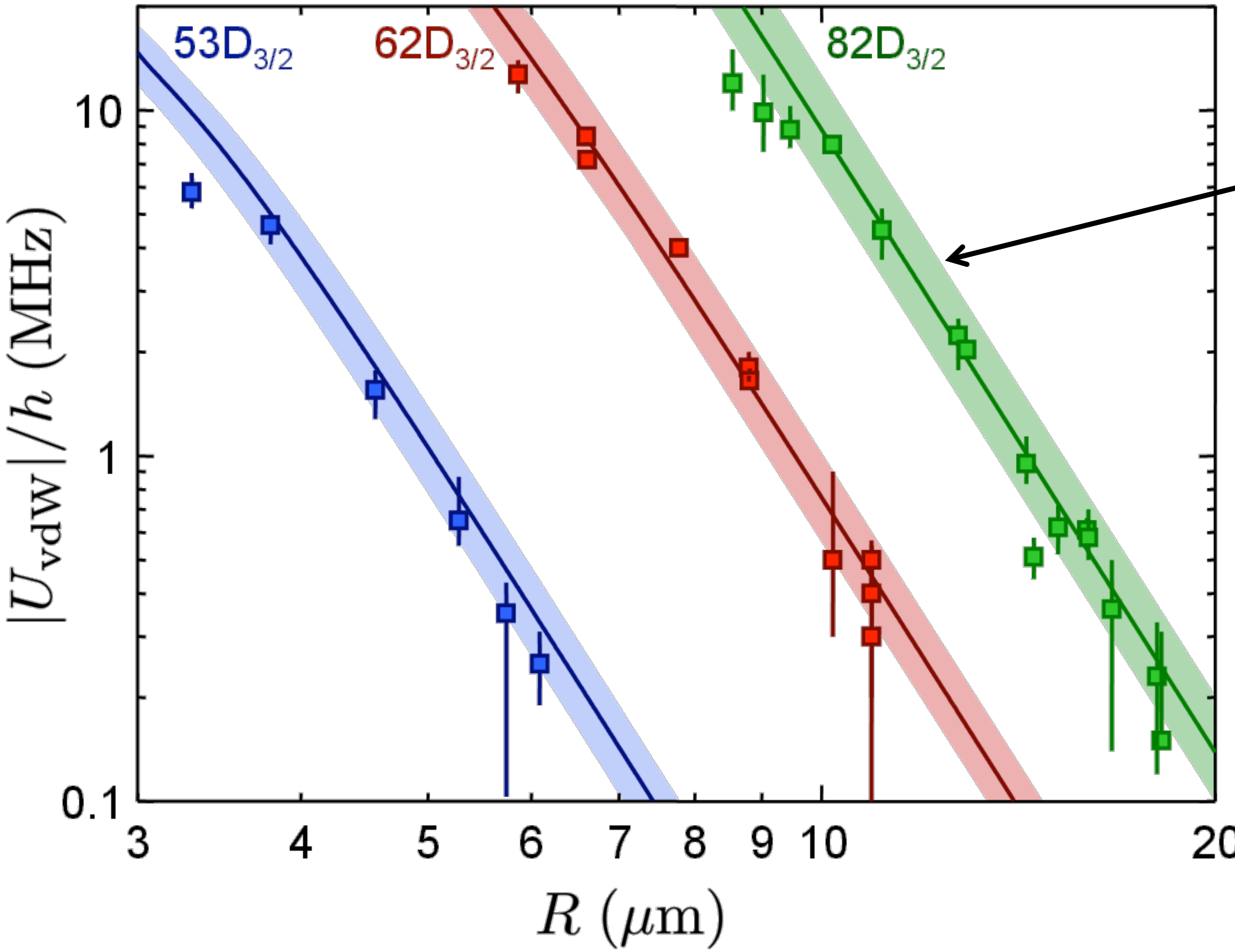


Schrödinger's equation:



Fit ⇒ extract U_{vdW}

Measuring U_{vdW} vs distance



Calibration R (5%)

Theory curves: direct diagonalization (dipole-dipole interaction)

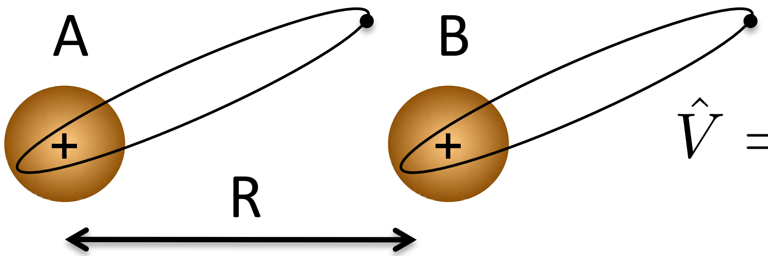
No adjustable parameter!

Béguin *et al.*, PRL **110,** 263201 (2013).

Outline

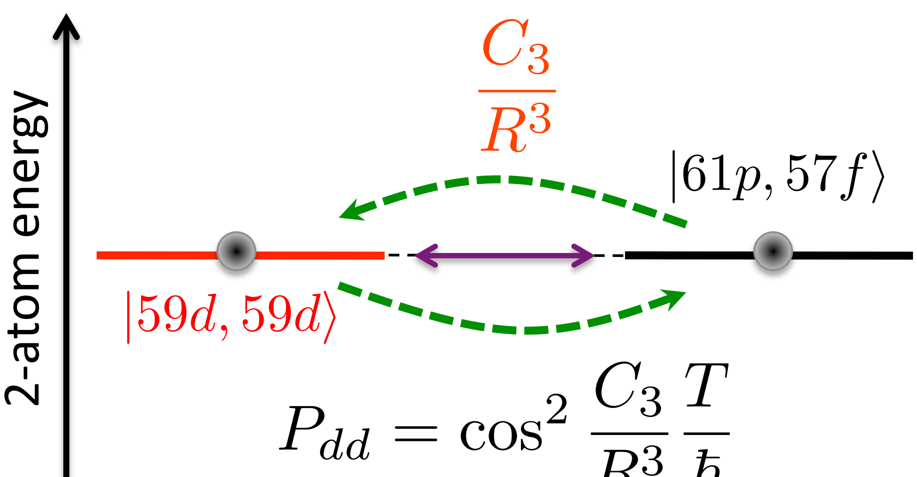
1. Trapping individual atoms in optical tweezers
2. Rydberg atoms and collective excitation of 2 interacting atoms
3. Measurement of the van der Waals interaction between 2 atoms & Rydberg blockade
4. Resonant interaction at a Förster resonance: controlling interactions with a DC E-field

From van der Waals to resonant interaction

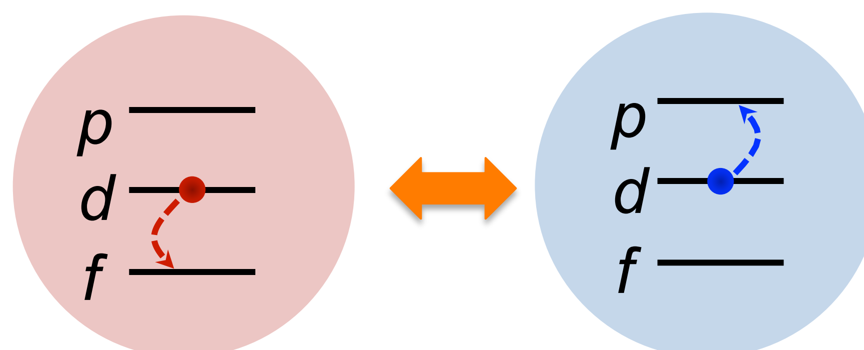


$$\hat{V} = \frac{1}{4\pi\epsilon_0 R^3}\left(\hat{\mathbf{d}}_A \cdot \hat{\mathbf{d}}_B - 3(\hat{\mathbf{d}}_A \cdot \hat{\mathbf{r}})(\hat{\mathbf{d}}_B \cdot \hat{\mathbf{r}})\right)$$

2-atom basis: $\{|\phi_{nn'}\rangle = |n, l\rangle \otimes |n', l'\rangle\}$



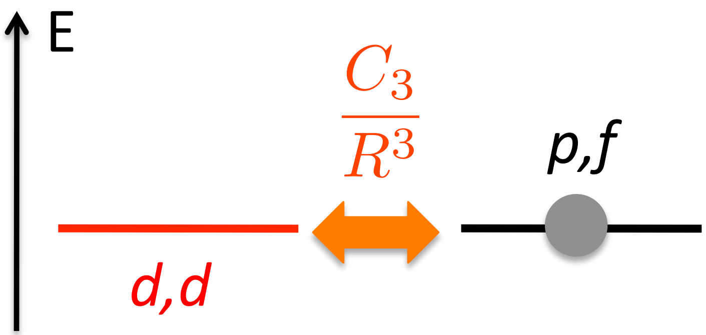
$$P_{dd} = \cos^2 \frac{C_3}{R^3}\frac{T}{\hbar}$$



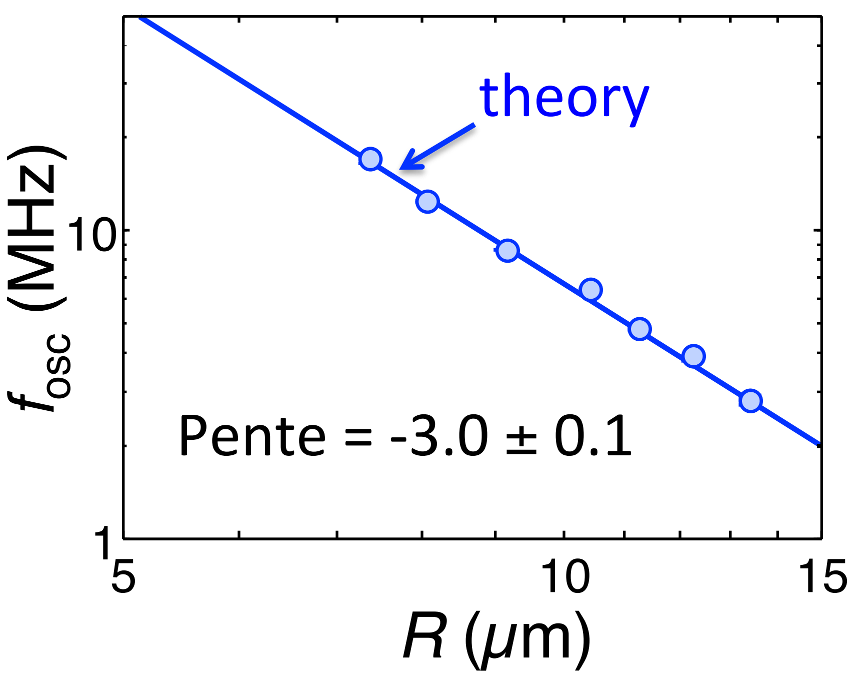
Implement: $\hat{H} = \sum_{i,j} \frac{C_3}{R^3_{i,j}}\left(\hat{S}_i^+ \hat{S}_j^- + \hat{S}_i^- \hat{S}_j^+\right)$

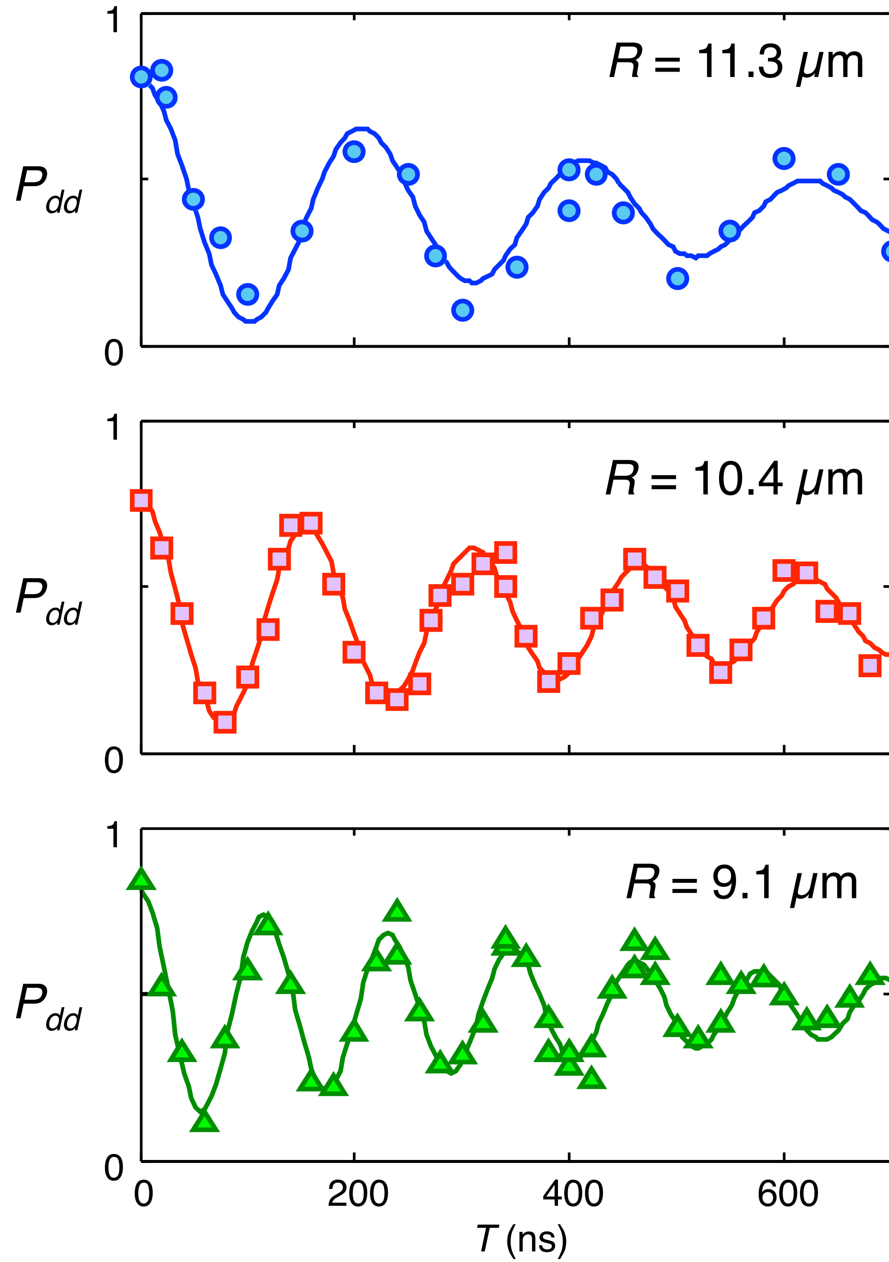
Observation of interaction-induced oscillations between two atoms

n = 59



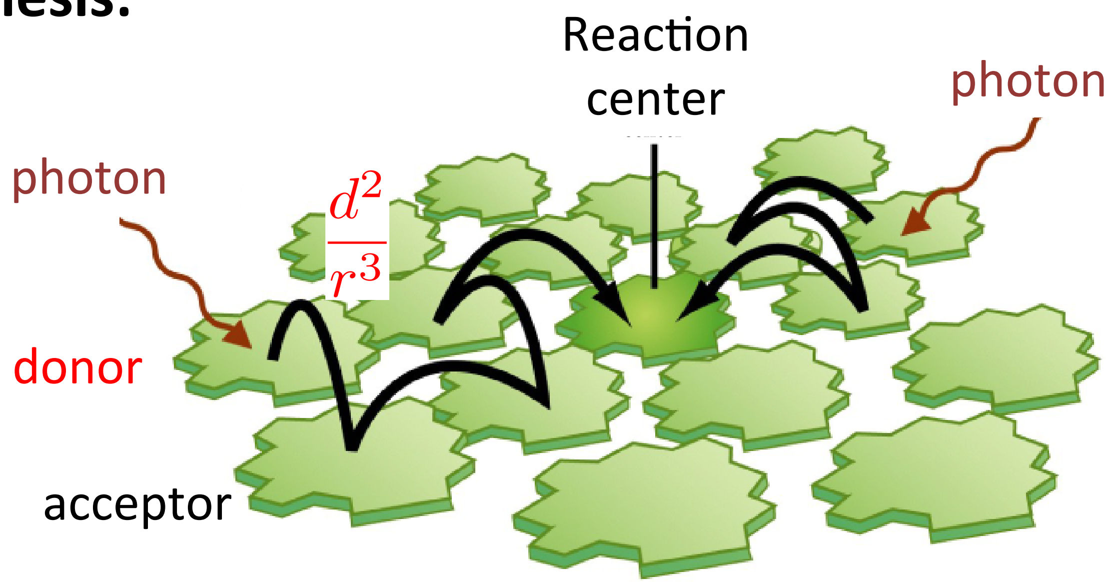
S. Ravets et al., Nat. Phys. (2014)

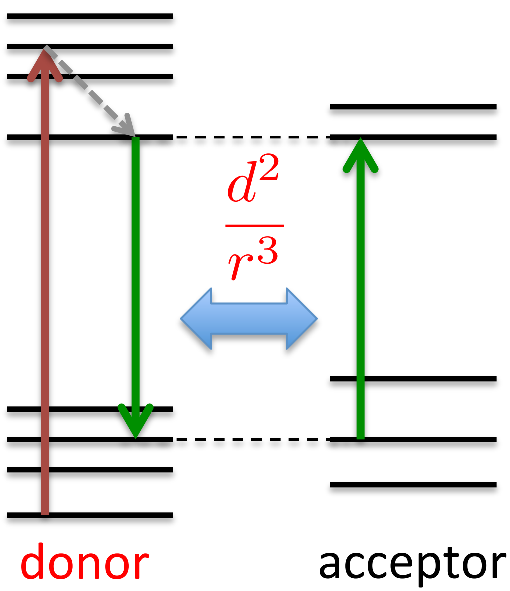




Resonant energy exchange in biological systems

Photosynthesis:





$$k_{tr} = \frac{1}{\tau}\left(\frac{R_0}{r}\right)^6 \propto \left(\frac{d^2}{r^3}\right)^2$$

F. Perrin (1933), Oppenheimer (1941)
Th. Förster (1946)

Clegg, *The History of FRET* (2006)

Role of coherence, entanglement?

Conclusion

Manipulation of Rydberg interactions with 2-3 atoms

1. Van der Waals
2. Control interaction by E-field
3. Resonant interaction

$\Rightarrow$ **Engineer Hamiltonians**

$$\hat{H} = \sum_{i,j} \frac{C_6}{R_{i,j}^6} \hat{S}_i^z \hat{S}_j^z$$

van der Waals

$$\hat{H} = \sum_{i,j} \frac{C_3}{R_{i,j}^3} \left(\hat{S}_i^+ \hat{S}_j^- + \hat{S}_i^- \hat{S}_j^+ \right)$$

X-Y exchange

Future directions: arrays of ~ 10 – 20 atoms

1. Study of elementary interacting systems with long range interaction: spectroscopy, phase diagrams, dynamics…
2. Transport in ordered or disordered arrays

« Taking the attitude that the pursuit of

as basic an ideal as a single atomic particle at rest

in space is a thoroughly worthwhile intellectual endeavor

we are undertaking experiments along these lines »

Neuhauser *et al.*,
Phys. Rev. Lett., vol. 41, p. 233 (1978)

The “Quantum Optics – Atom” group at Institut d’Optique

Stephan Jennewein | Sylvain Ravets | A B | Yvan Sortais | Thierry Lahaye

Henning Labuhn | Daniel Barredo | Joseph Pellegrino | Ronan Bourgain | Lucas Béguin | Florence Nogrette

DGA

TRIANGLE DE LA PHYSIQUE

IFRAF

COHERENCE

erc