Direct Measurement of the van der Waals interaction between two Rydberg atoms

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DAMOP 2013, Québec
June 7th, 2013

The Rydberg team at Institut d'Optique

Antoine Browaeys   Aline Vernier   Lucas Béguin   TL

Florence Fuchs

Sylvain Ravets

Henning Labuhn

Daniel Barredo

Funding

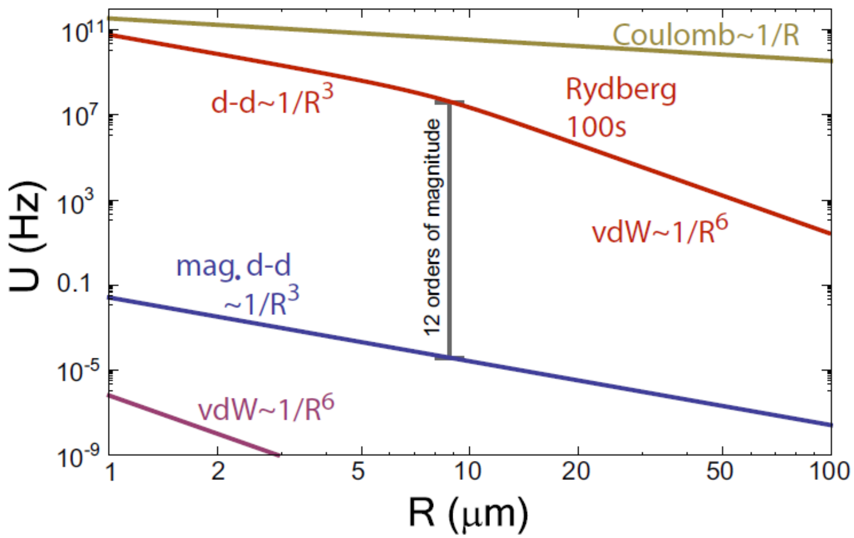
DGA   TRIANGLE DE LA PHYSIQUE   aqute   IFRAF   erc

QIP with neutral atoms

Neutral atoms for Quantum Information Processing

- **Like ions:** very well controlled, low decoherence.
- **Unlike ions:** weak interactions in ground state.
- **Idea:** switch **large** interactions on and off using **Rydberg levels**

Jaksch *et al.*, PRL **85** 2208 (2000)
Lukin *et al.*, PRL **87** 037901 (2001)

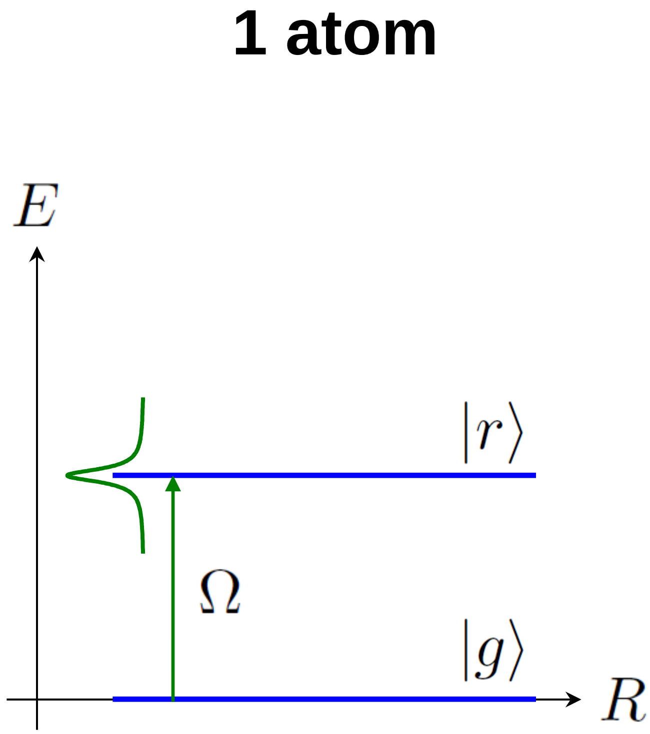


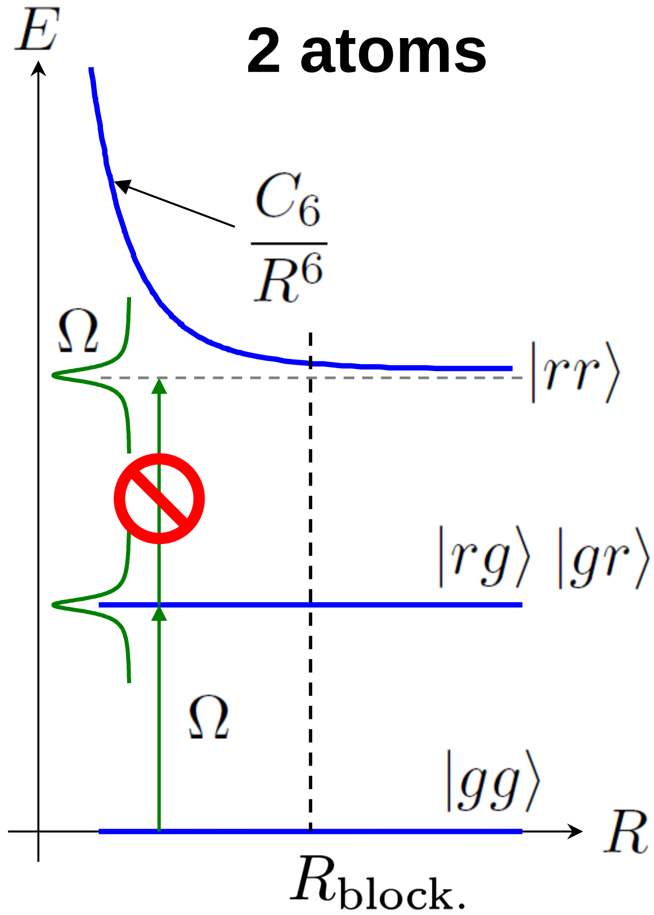
Saffman *et al.*, RMP **82**, 2313 (2010)

Entangle large numbers of atoms in a single step!

Rydberg Blockade

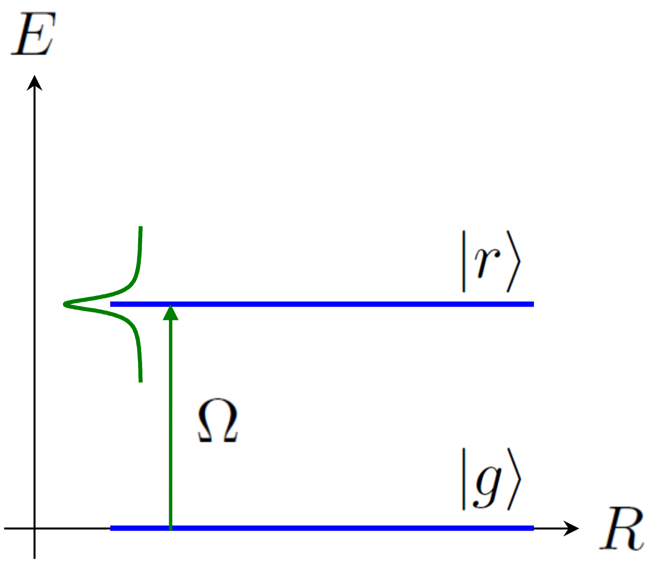
Rydberg blockade



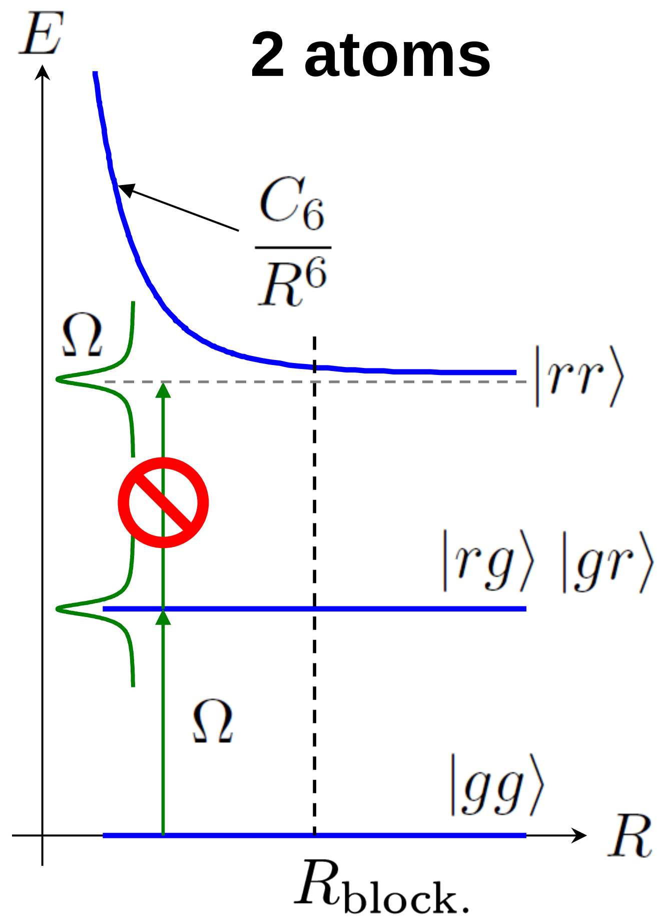


Rydberg blockade

1 atom



2 atoms



If $\hbar\Omega \ll \frac{C_6}{R^6}$ the excitation of $|rr\rangle$ is off-resonant: **BLOCKADE!**

One excites only $|\psi\rangle = \frac{1}{\sqrt{2}}(|rg\rangle + |gr\rangle)$. Coupling $\sqrt{2}\Omega$ to $|gg\rangle$

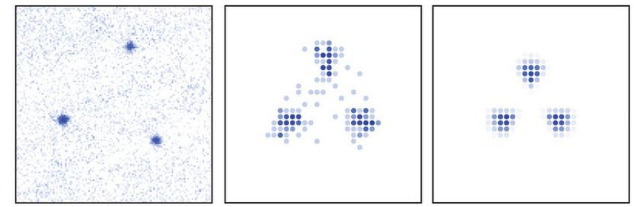
ENTANGLED STATE **COLLECTIVE EXCITATION**

Experimental demonstration of Rydberg blockade

In atomic ensembles (MOTs, BECs, optical lattices…)

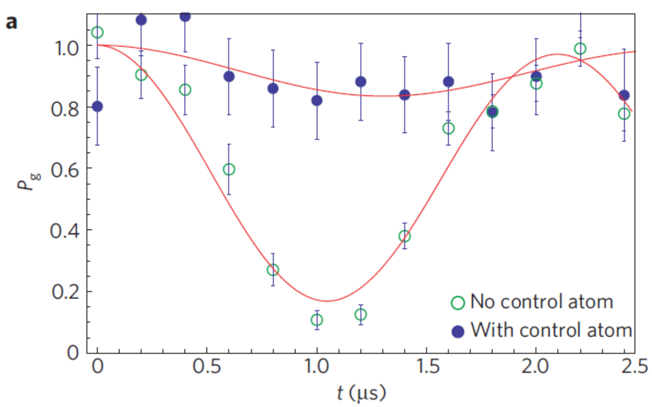
Connecticut (Gould), Freiburg (Weidemüller), Stuttgart (Pfau), Orsay (Pillet-Comparat) Michigan (Raithel), Pisa (Arimondo-Morsch), Munich (Bloch-Kuhr)…

Review: Comparat and Pillet, JOSA B **27**, A208 (2010)

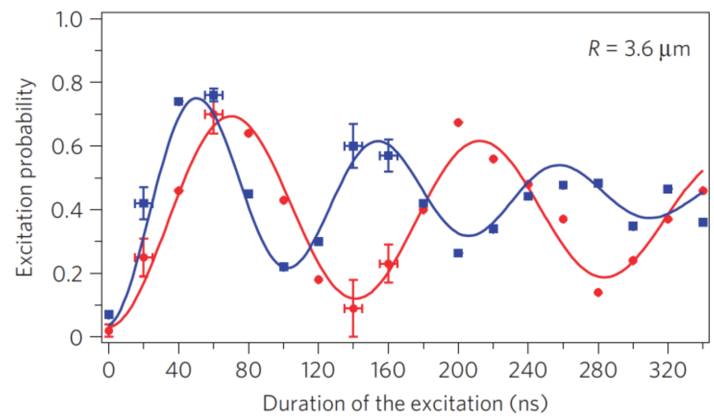


For a pair of single atoms

Wisconsin (Saffman), Palaiseau



Urban *et al.*, Nat. Phys. **5**, 110 (2009)



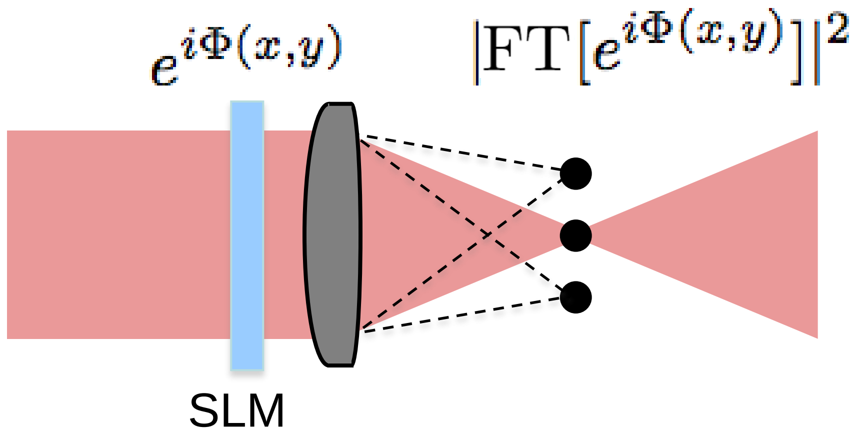
Gaétan *et al.*, Nat. Phys. **5**, 115 (2009)

Creation of entangled states of two neutral atoms

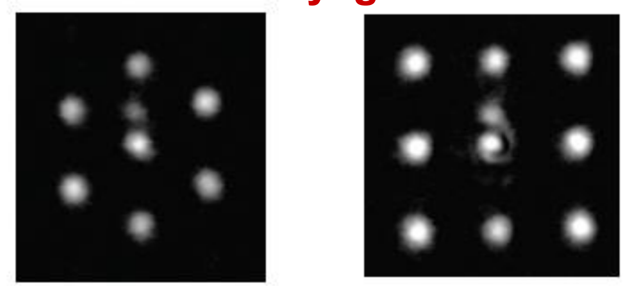
Isenhower *et al.*, PRL **104**, 010503 (2010), Wilk et al., PRL **104**, 010502 (2010).

Next step: arrays of entangled atoms

erc ARENA: Arrays of ENtangled Atoms



Arrays of tweezers with 'arbitrary' geometries



Blockade $\Rightarrow$ **various entangled states**

$$|\mathrm{W}\rangle = \frac{1}{\sqrt{N}}(|r\uparrow\uparrow ...\rangle + |\uparrow r \uparrow ...\rangle + ... + |...\uparrow\uparrow r\rangle)$$

$$|\mathrm{GHZ}\rangle = \frac{1}{\sqrt{2}}(|\uparrow\uparrow\uparrow ...\rangle + |rrr...\rangle)$$

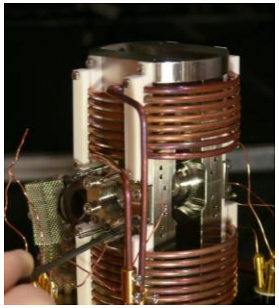
Müller *et al.*, RPL **102**, 170502 (2009)
Moller *et al.*, PRL **100,** 170504 (2008)

Also: quantum simulation of long-range interacting spin systems

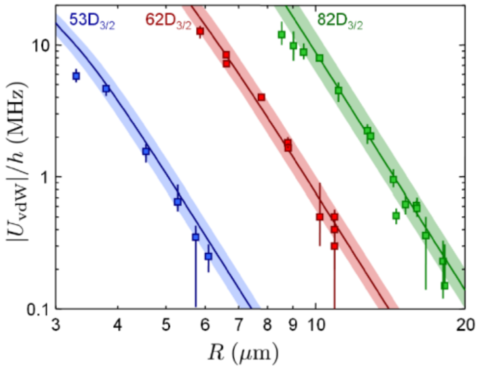
See e.g. Weimar *et al.*, Nat. Phys. **6**, 382 (2010)

Outline

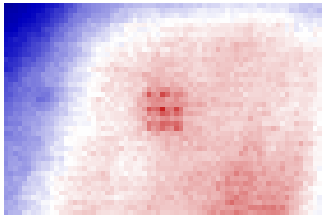
1. The new setup in Palaiseau



2. Measurement of the van der Waals interaction between two Rydberg atoms

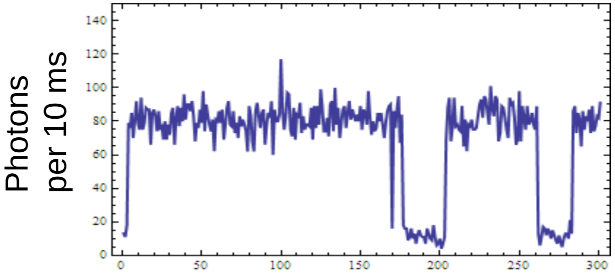


3. Outlook: toward arrays of single atoms

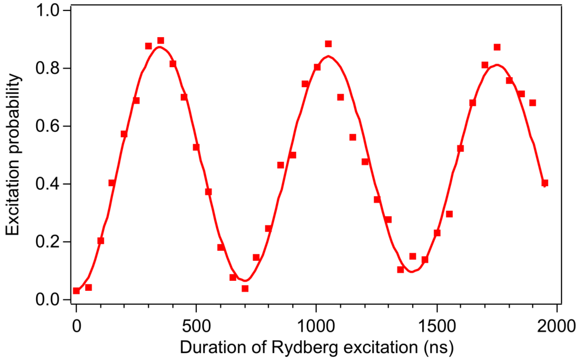


The tools we need to combine:

Single atom trapping and imaging

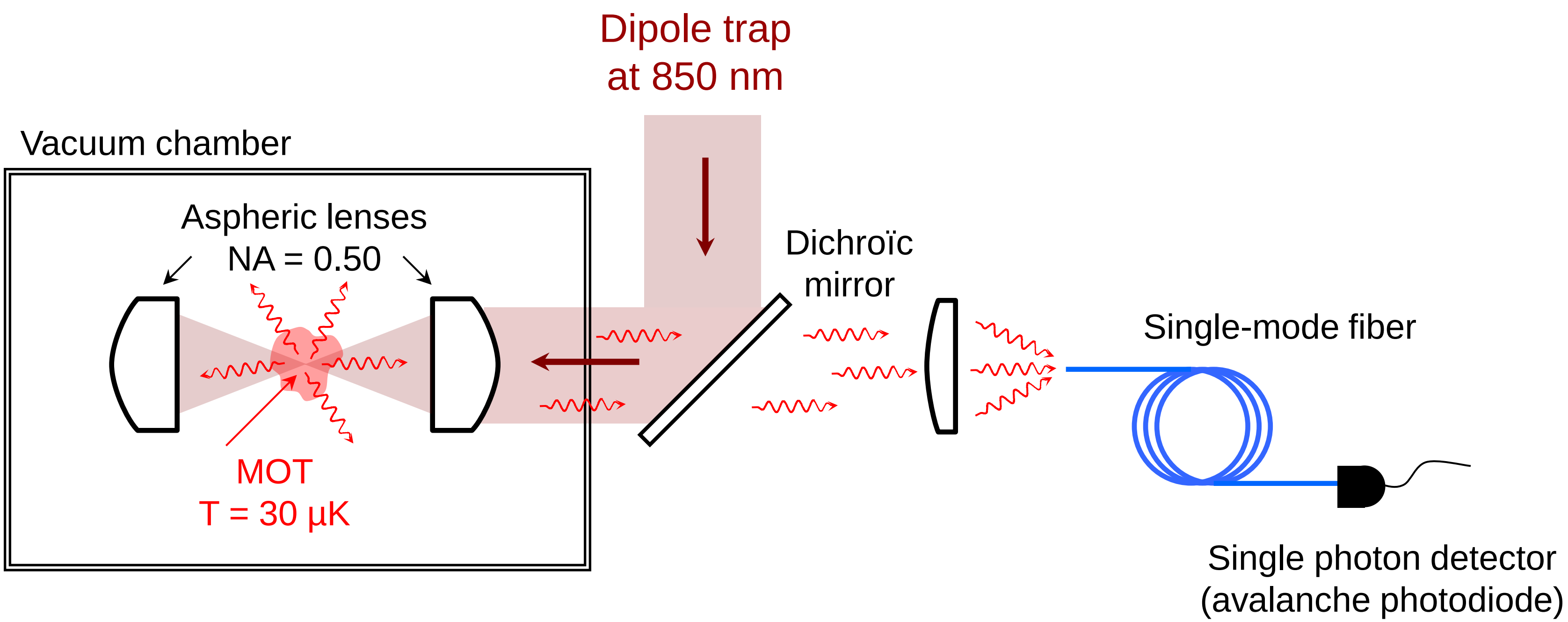


Coherent excitation of Rydberg states



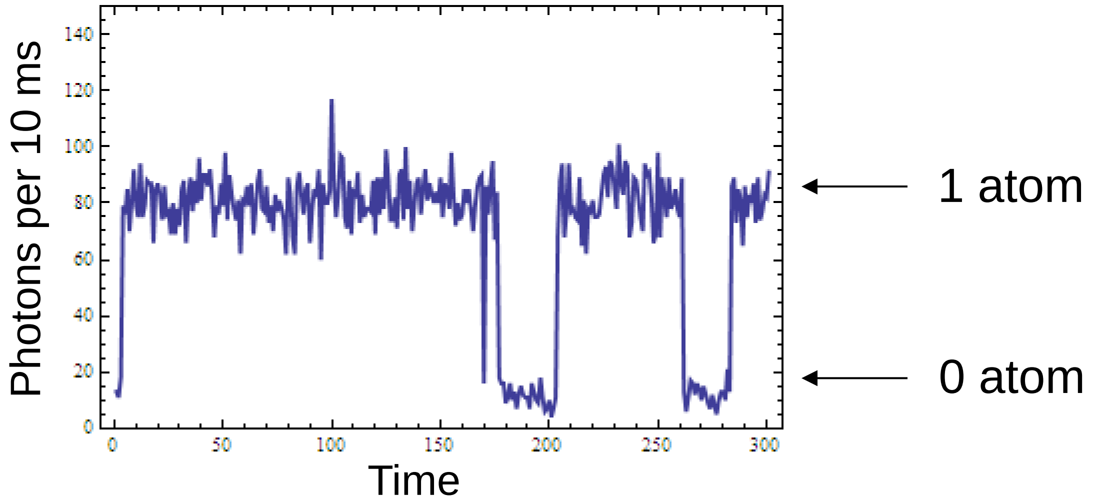
Single atoms in optical tweezers

- Tightly focused (w = 1 µm) optical dipole traps in low-density MOT
- Only one atom trapped due to **light-assisted collisions**
- Detection: collect **fluorescence** (780 nm) on avalanche photodiode

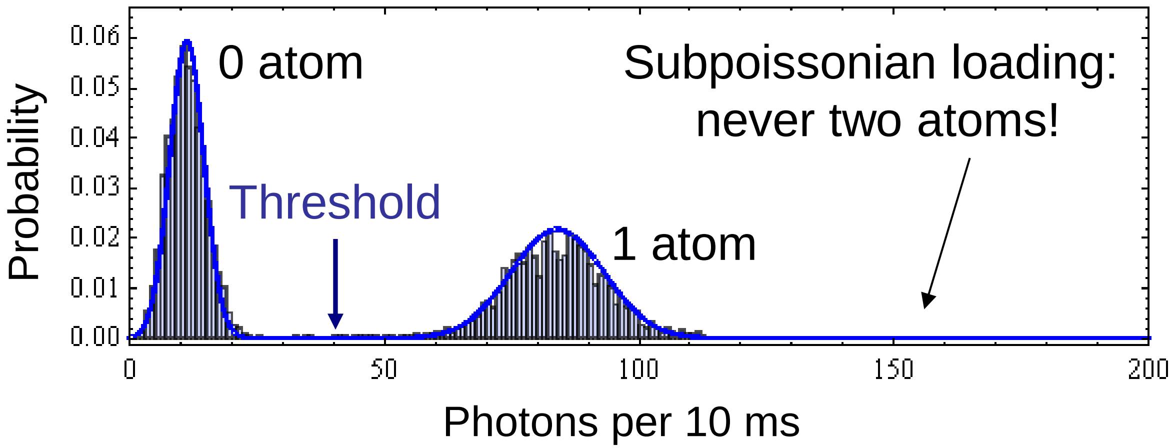


Fast light-assisted collisions yield single atoms

Fluorescence signal (number of photons per 10 ms bins)



Histogram of 40 s of data:

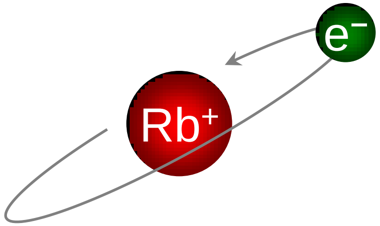


Light-assisted collisions prevent *N*-atom trapping (*N* > 1)

Properties of Rydberg atoms

Johannes Rydberg
1854-1919

Rydberg atoms: atoms in a state with very large principal quantum number n: Hydrogen-like properties.



Energy levels: $E(n,l,j) = \dfrac{-13.6\ \mathrm{eV}}{n^{\star 2}}$

Quantum defect: $n^\star = n - \delta(l,j)$

(e.g. $\delta_S \simeq 3.13$ in Rb)

Exaggerated properties due to large radius (and thus electric dipole moment)

Property	$n^\star$ scaling	Example for $58D_{3/2}$
Binding energy	$1/n^{\star 2}$	~ 1 THz
Level spacing	$1/n^{\star 3}$	~ 40 GHz
Radius	$n^{\star 2}$	~ 180 nm
Lifetime	$n^{\star 3}$	$\sim 90\ \mu$s
Polarizability	$n^{\star 7}$	$\sim 300\ \mathrm{MHz}/(\mathrm{V/cm})^2$

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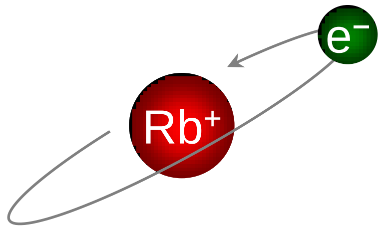

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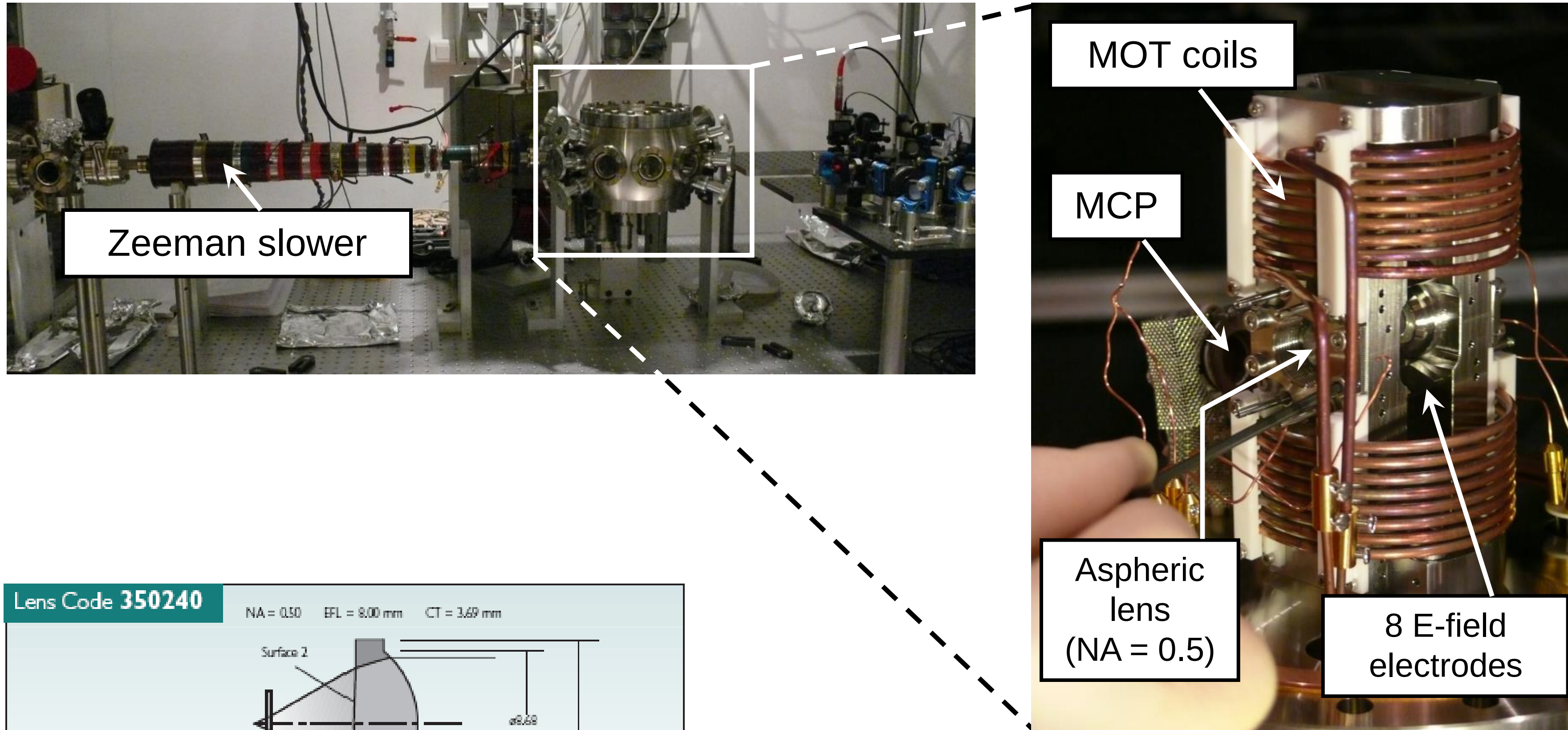
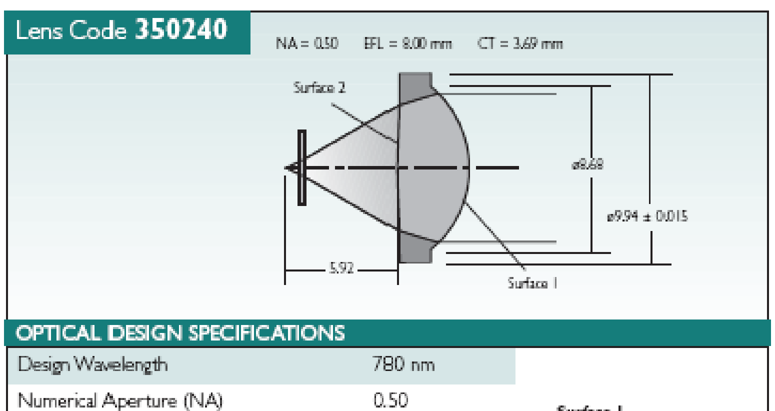
Huge sensitivity to stray electric fields!

The new setup in Palaiseau





OPTICAL DESIGN SPECIFICATIONS	
Design Wavelength	780 nm
Numerical Aperture (NA)	0.50

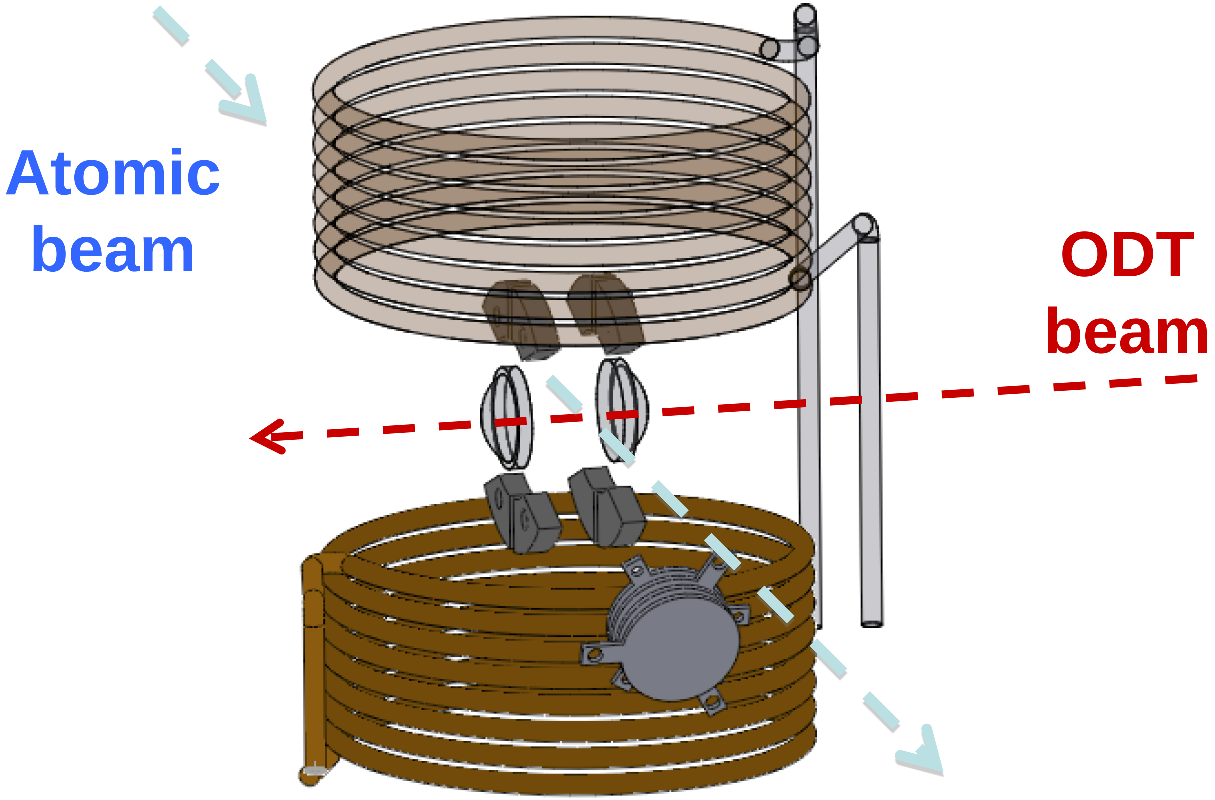
Surface 1

Y. Sortais *et al.* PRA **75**, 013406 (2007)

Design details

Huge sensitivity to static fields !

Polarizability $\alpha_{n=58}$ = 300 MHz / (V/cm)^2 and $\alpha \sim n^7$



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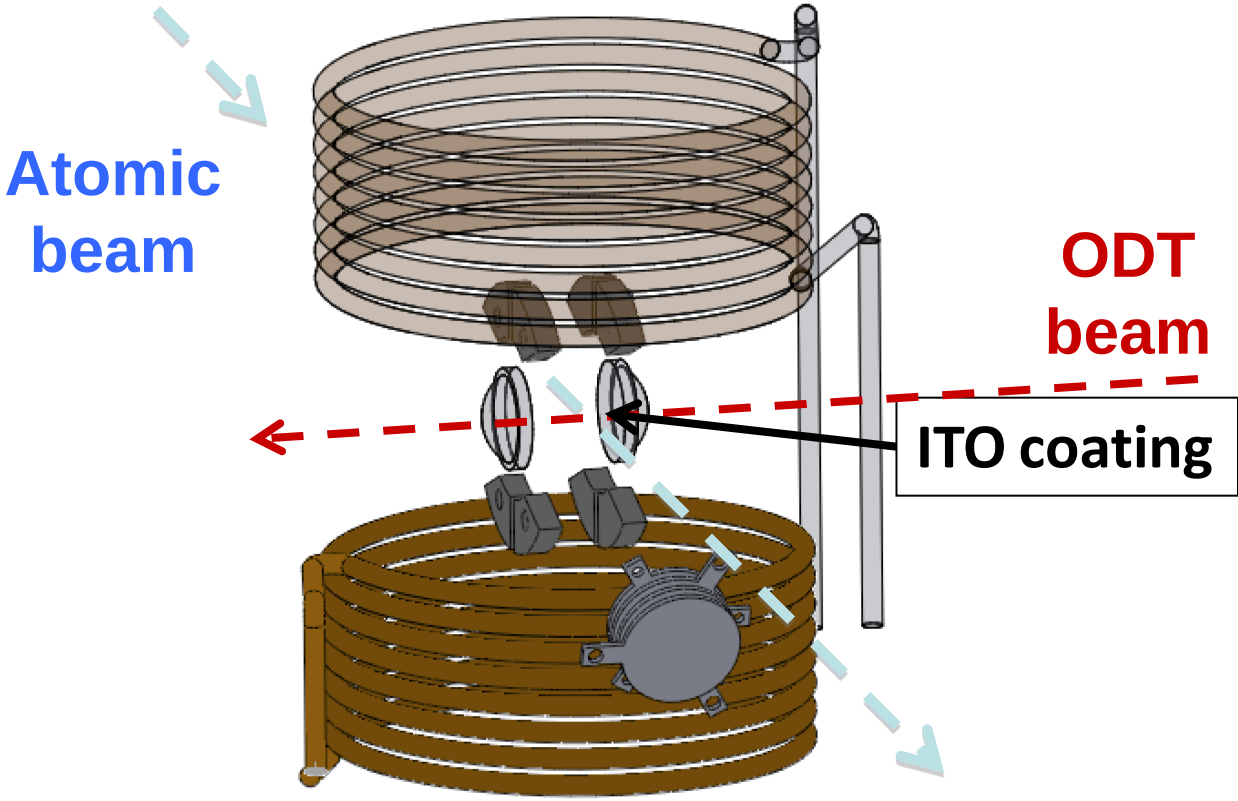
Avoid patch charges
➔ ITO conductive coating



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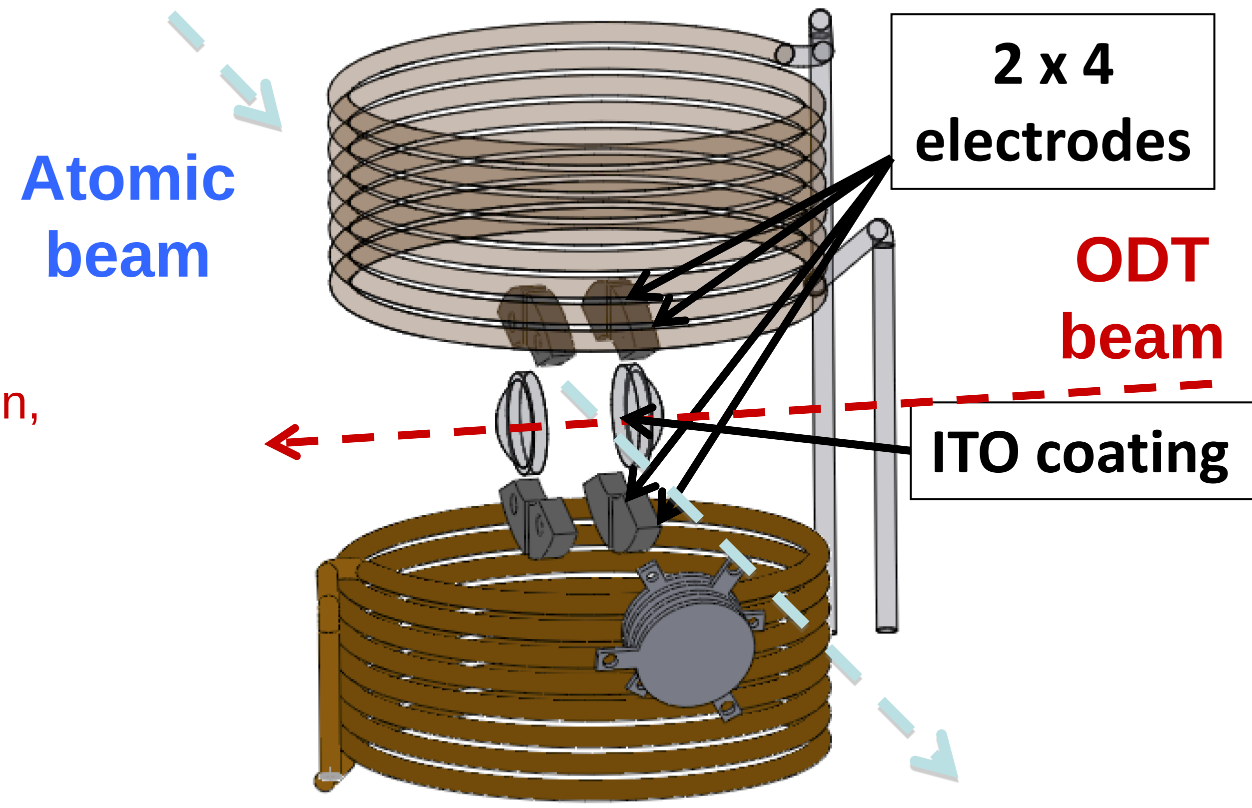
Control of *E*-field
➔ 8 electrodes (compensation, ionization)



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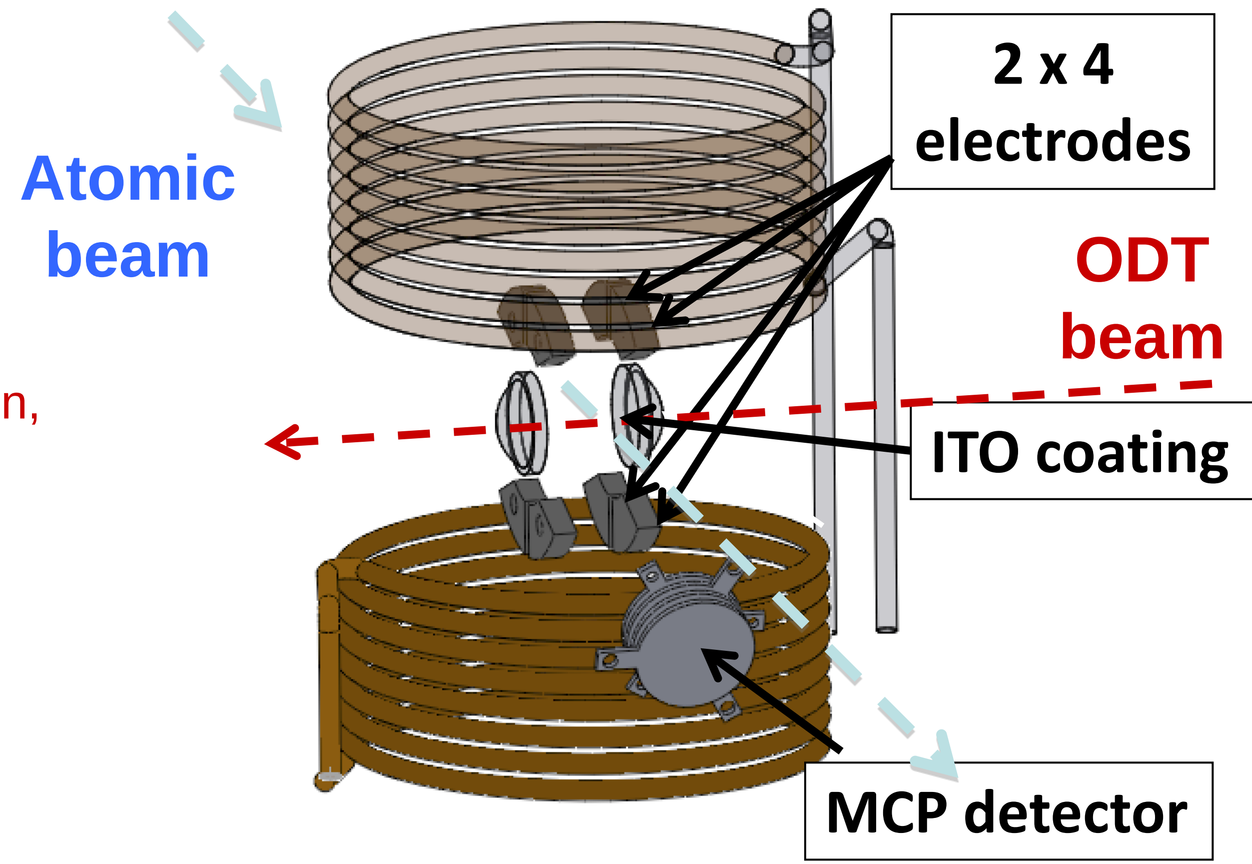
➔ MCP detector



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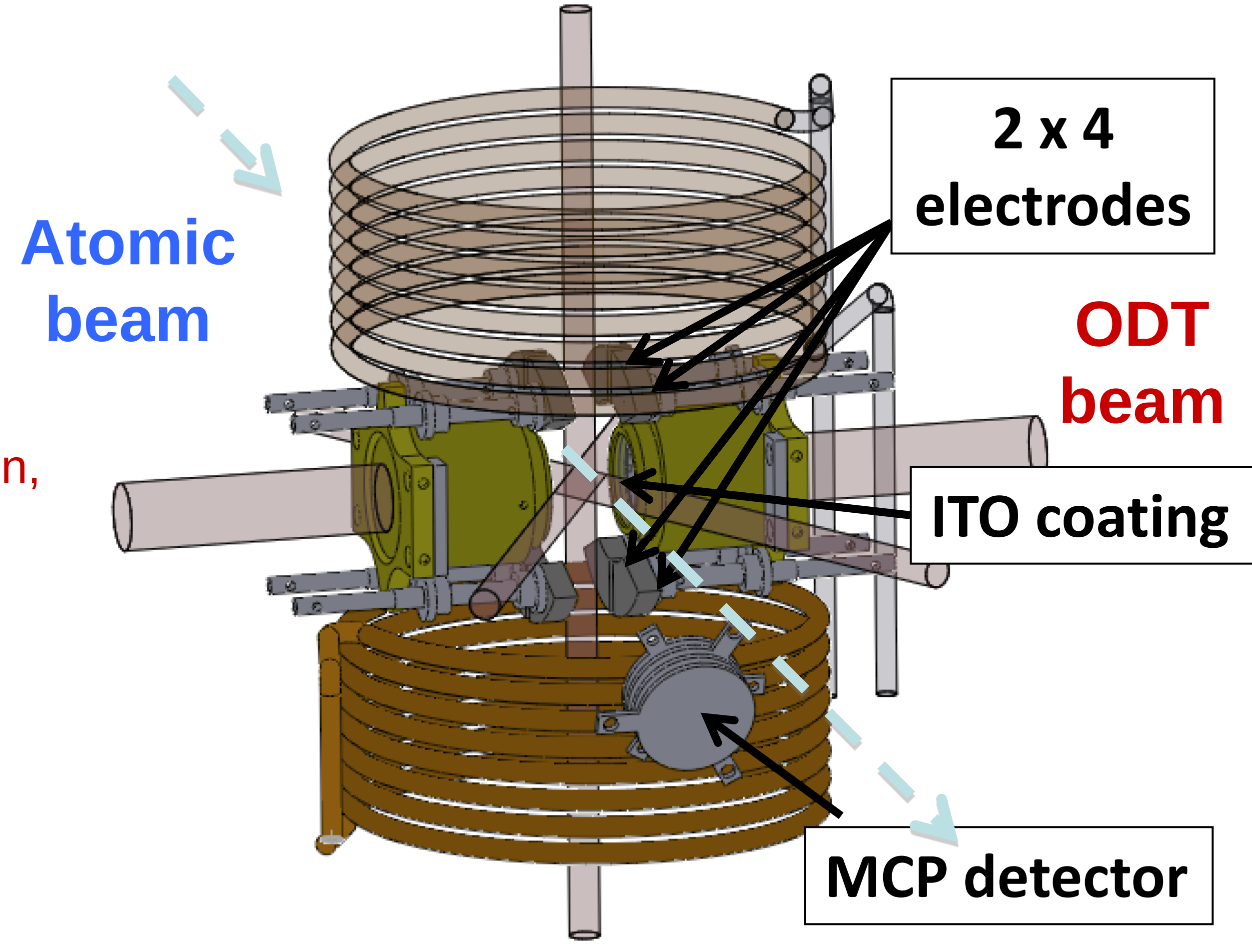

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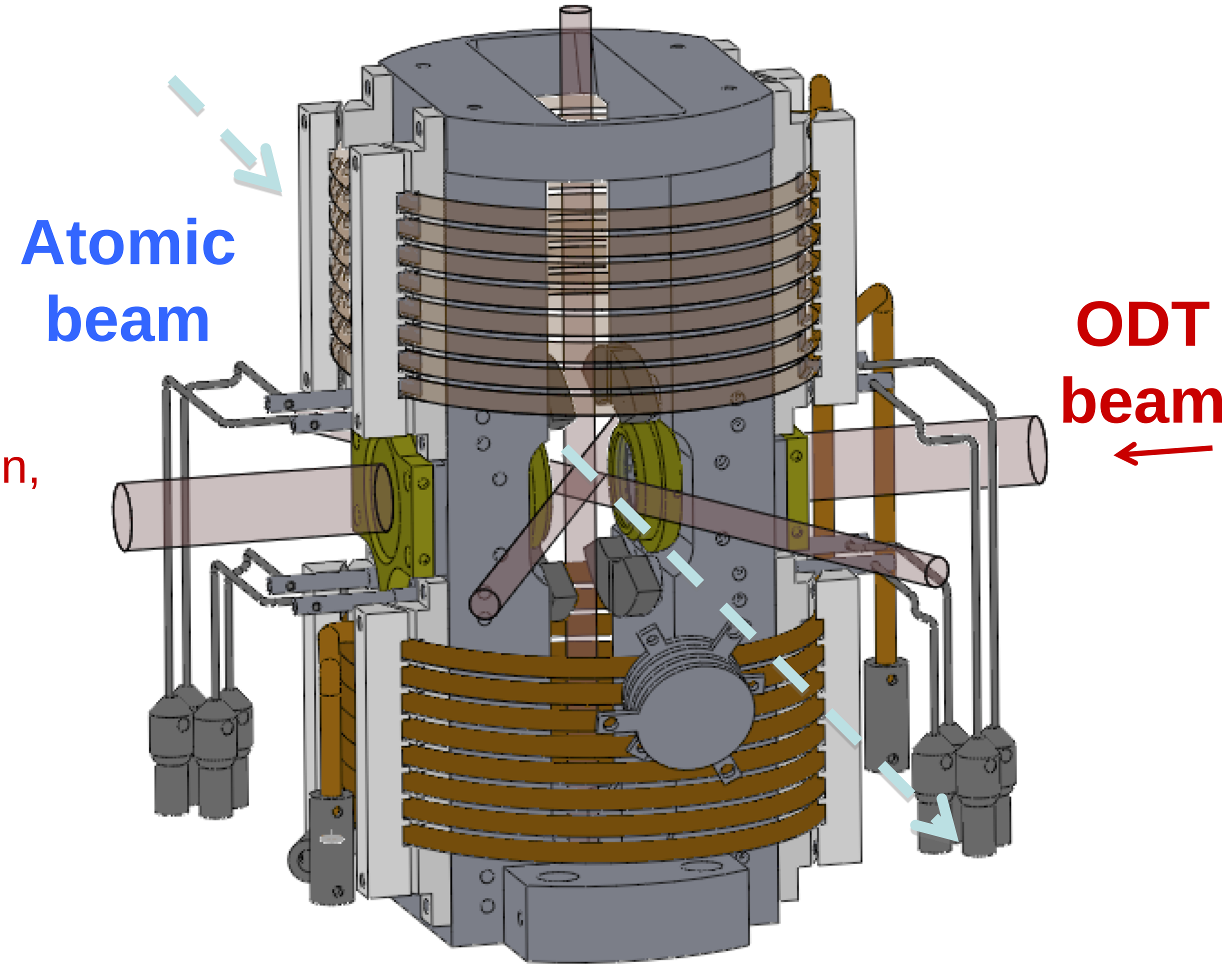
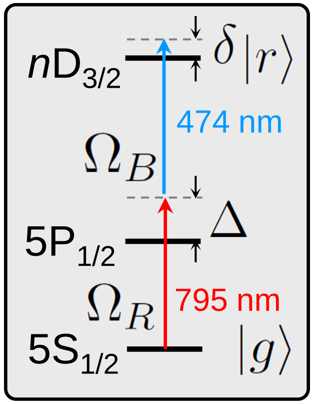


Single atom Rydberg excitation

Two-photon excitation

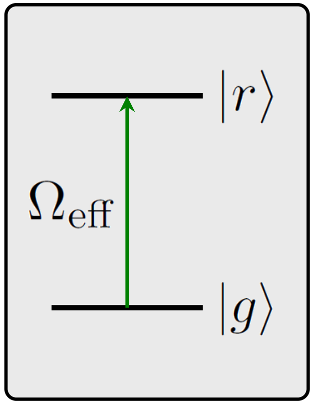


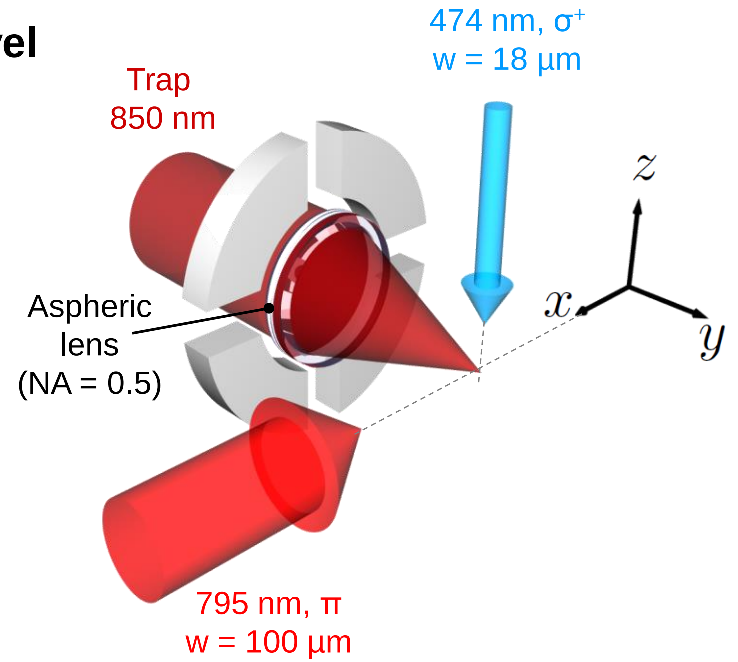
$$\frac{\Delta}{2\pi} \sim 740\ \text{MHz}$$

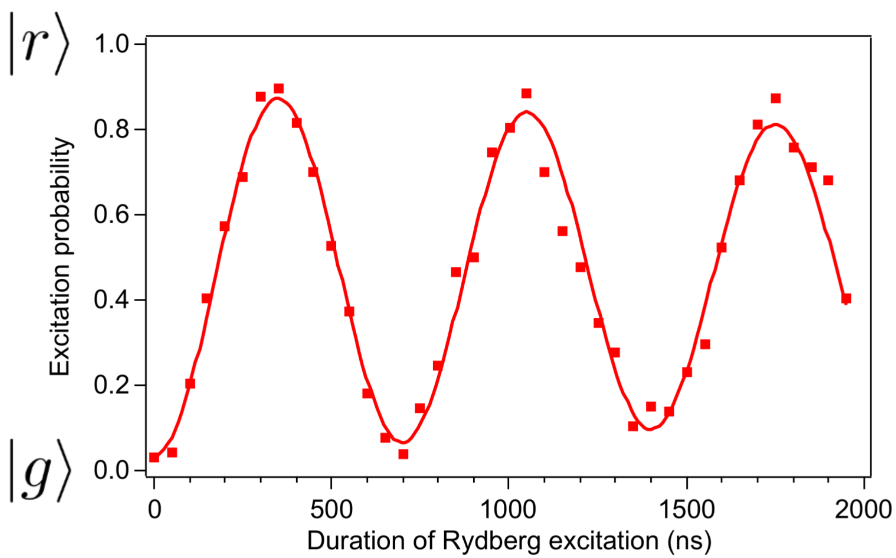
$$\Delta \gg \Omega_R,\ \Omega_B$$

$$\Omega_{\text{eff}} = \frac{\Omega_R \Omega_B}{2\Delta}$$

Effective two-level system



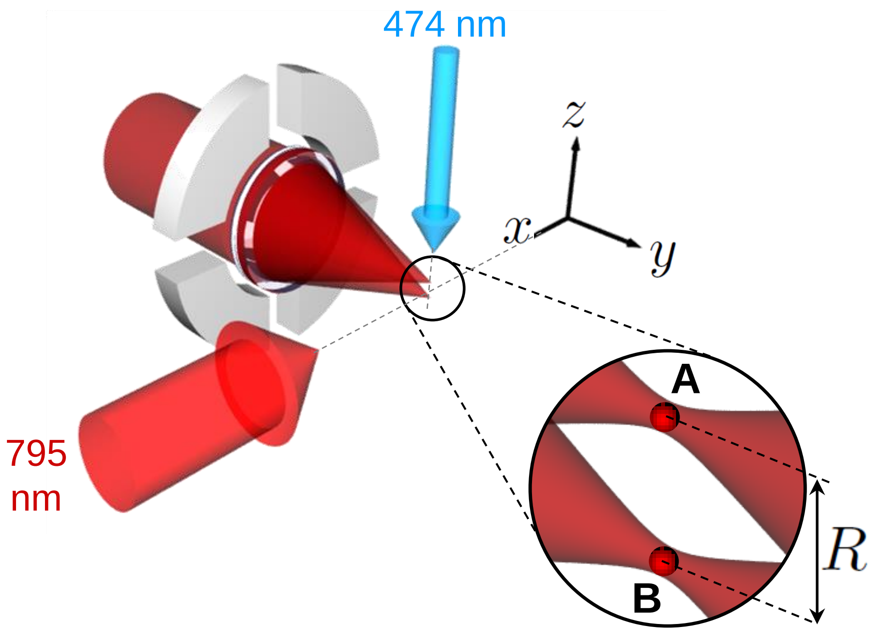




Range of Rabi frequencies:
~ 0.5 to 5 MHz

Two-atom experiments

- Two trapping beams with small angle
- Two avalanche photodiodes
- Two counters
- Trigger experiment on the presence of **one atom in each trap**



4 µm < R < 20 µm

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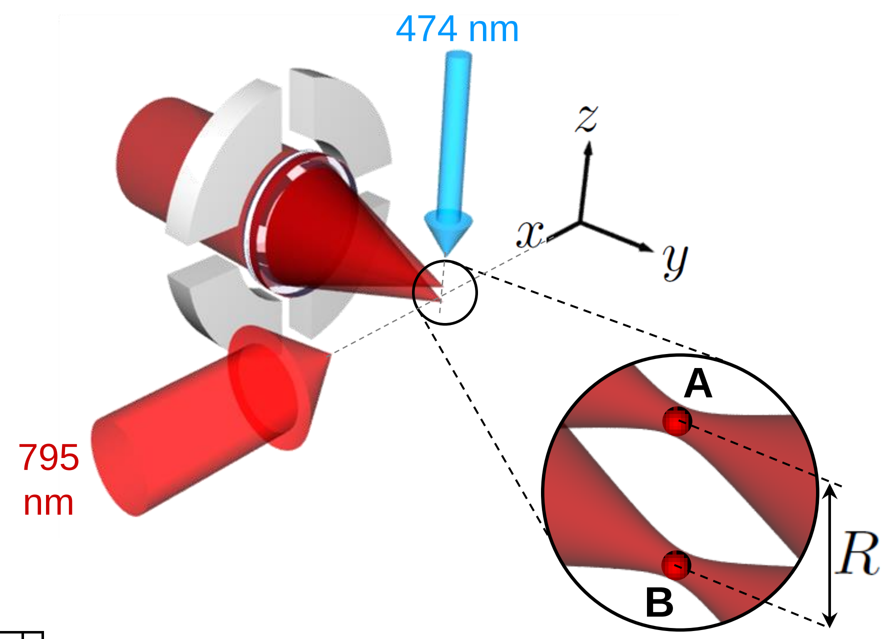
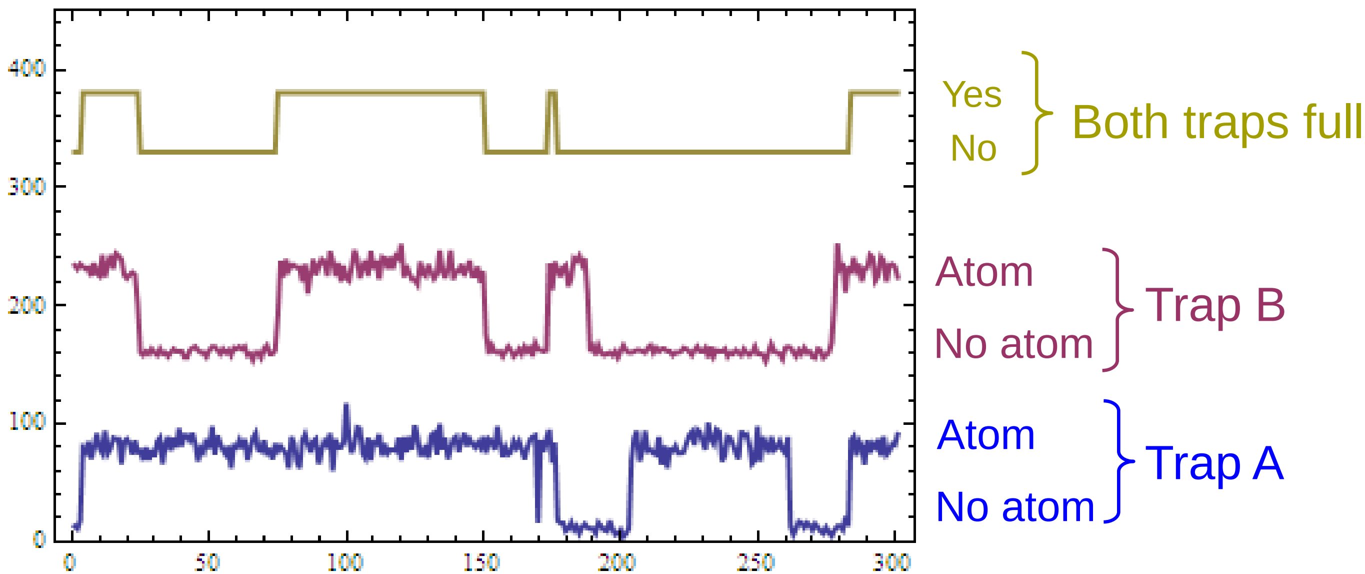
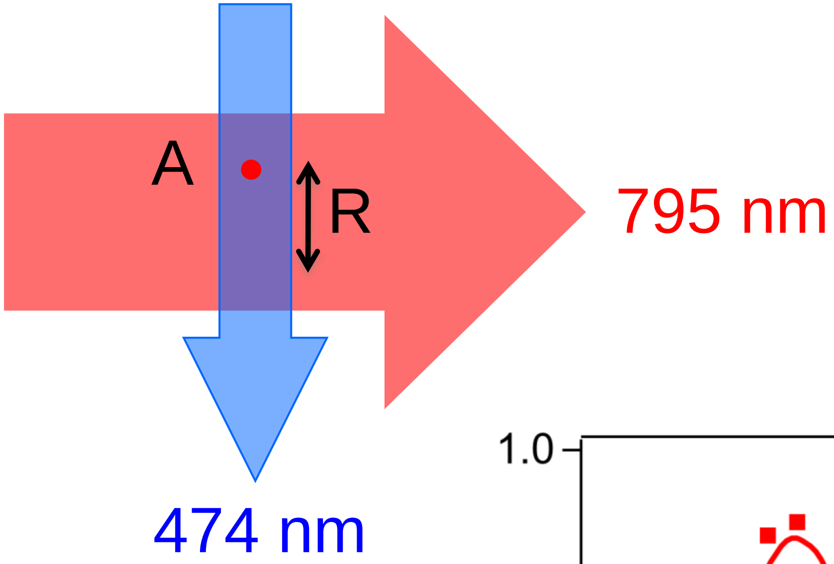


4 µm < R < 20 µm

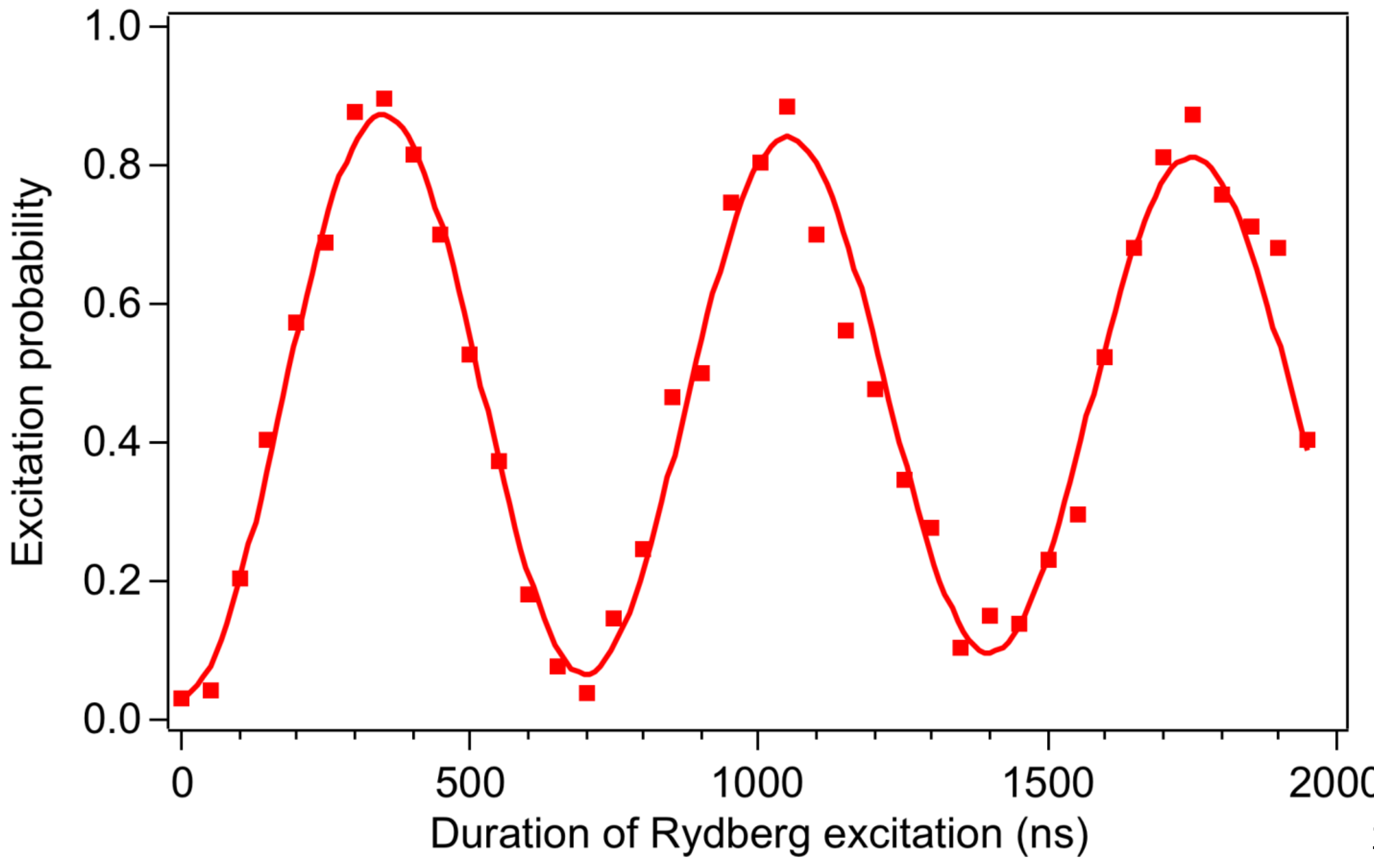


Single atom Rabi oscillation

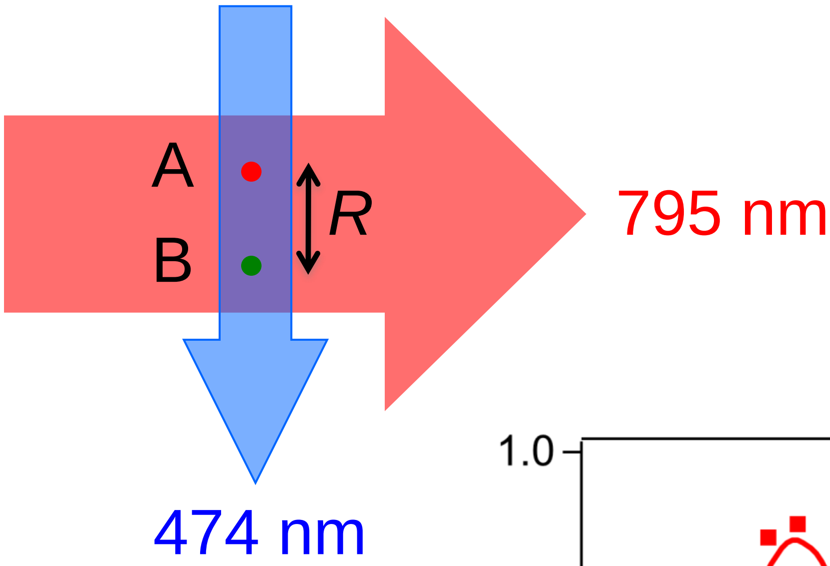
P_1 Exc. prob. atom A only



$58D_{3/2}$



Observation of Rydberg blockade



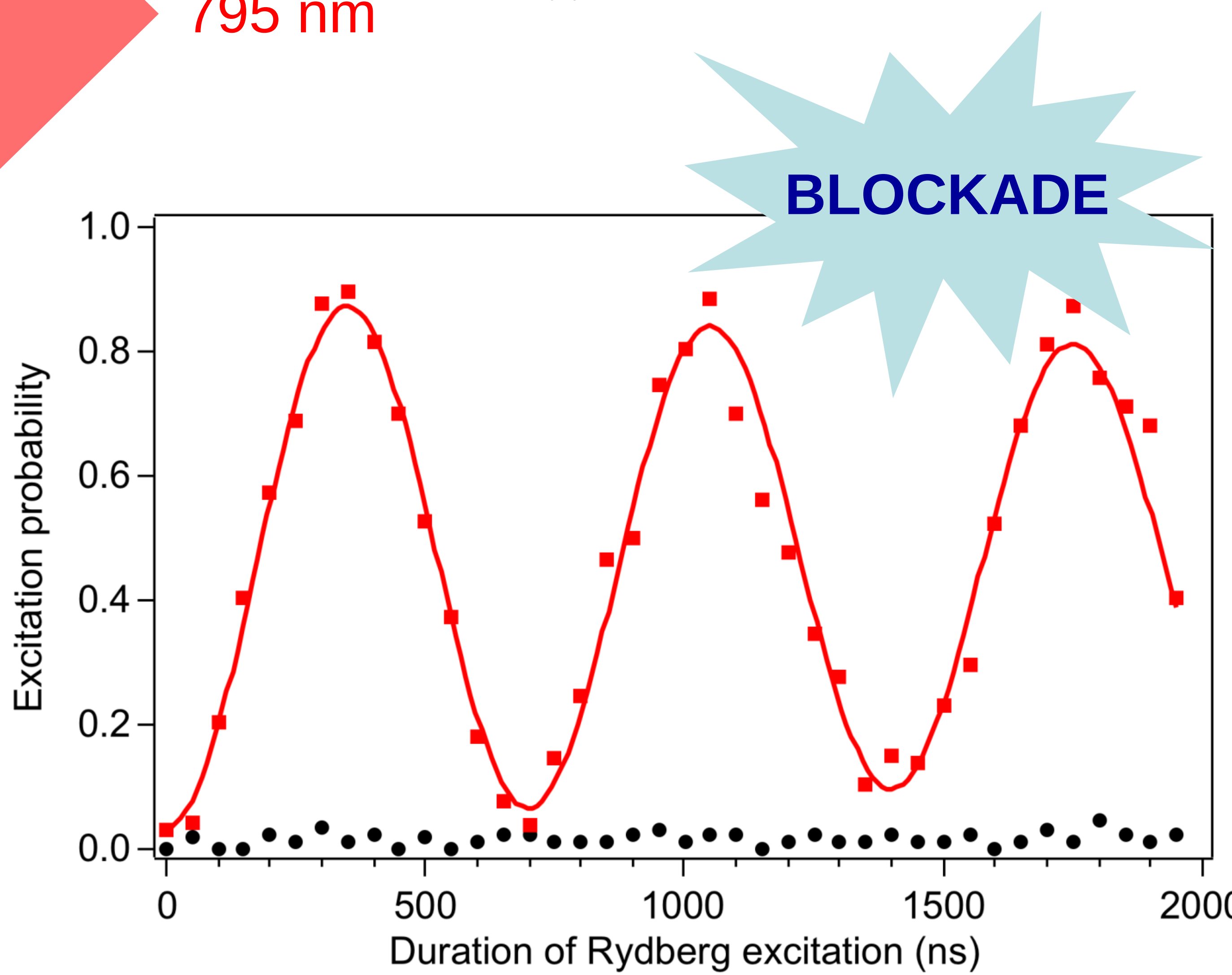
$58D_{3/2}$

R = 5 μm

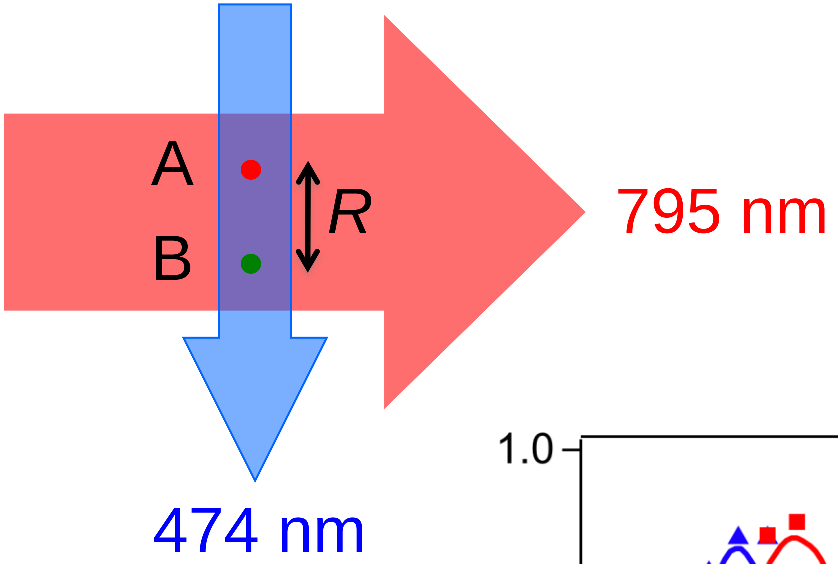
U_{vdW} / h = 25 MHz

P_1 Exc. prob. atom A only

P_{rr} Exc. prob. atom A & B



Collective excitation



P_1 Exc. prob. atom A only

P_{rr} Exc. prob. atom A & B

$P_{rg} + P_{gr}$ Exc. prob. atom A **OR** B

$58D_{3/2}$

R = 5 μm

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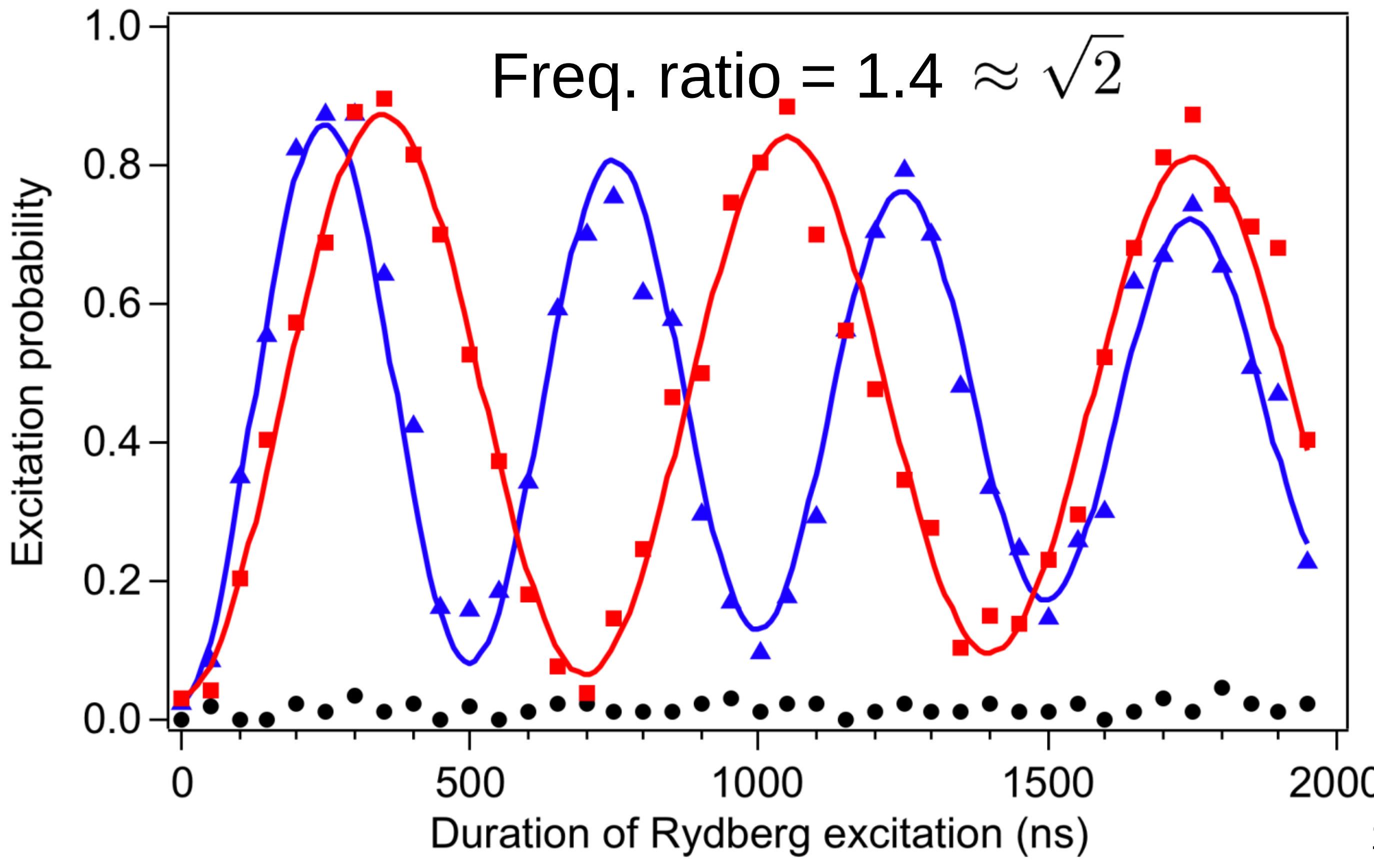
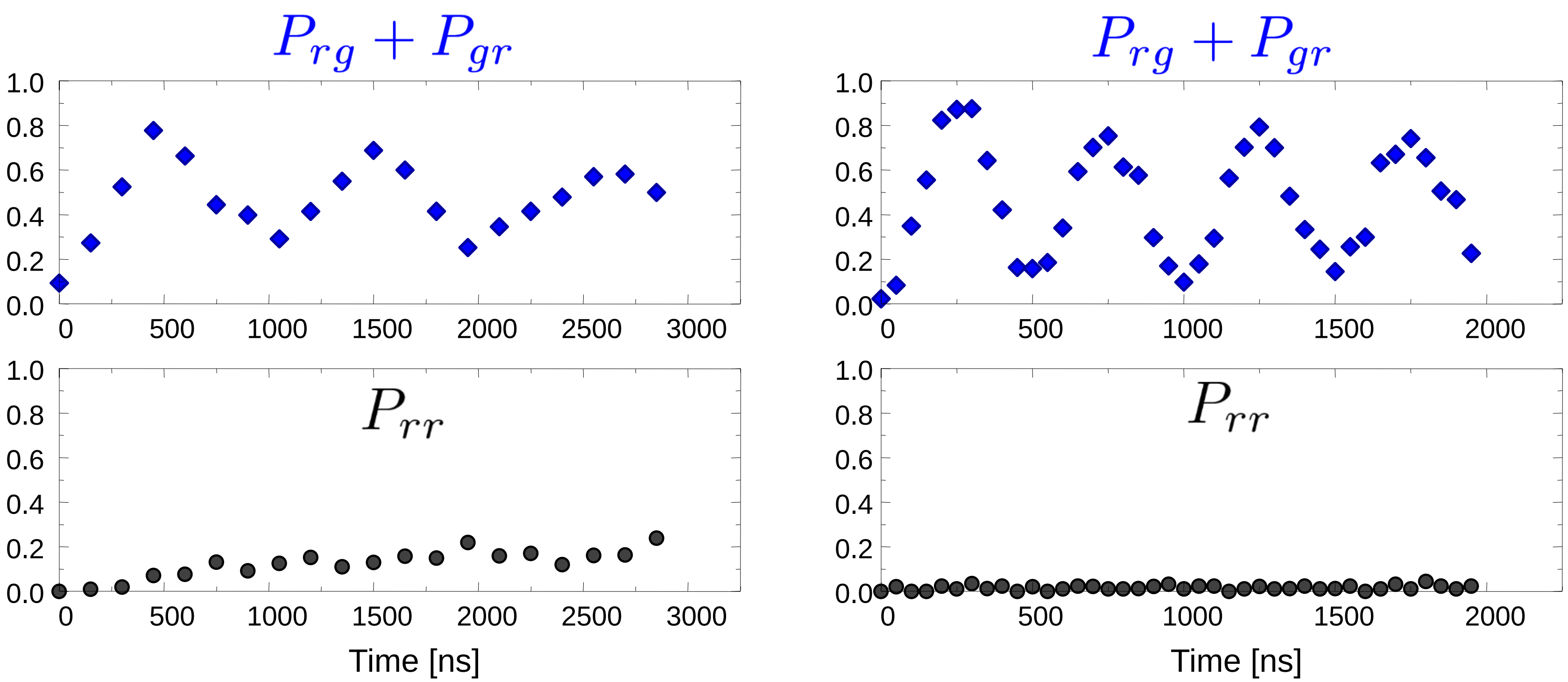


On the importance of stray field cancellation

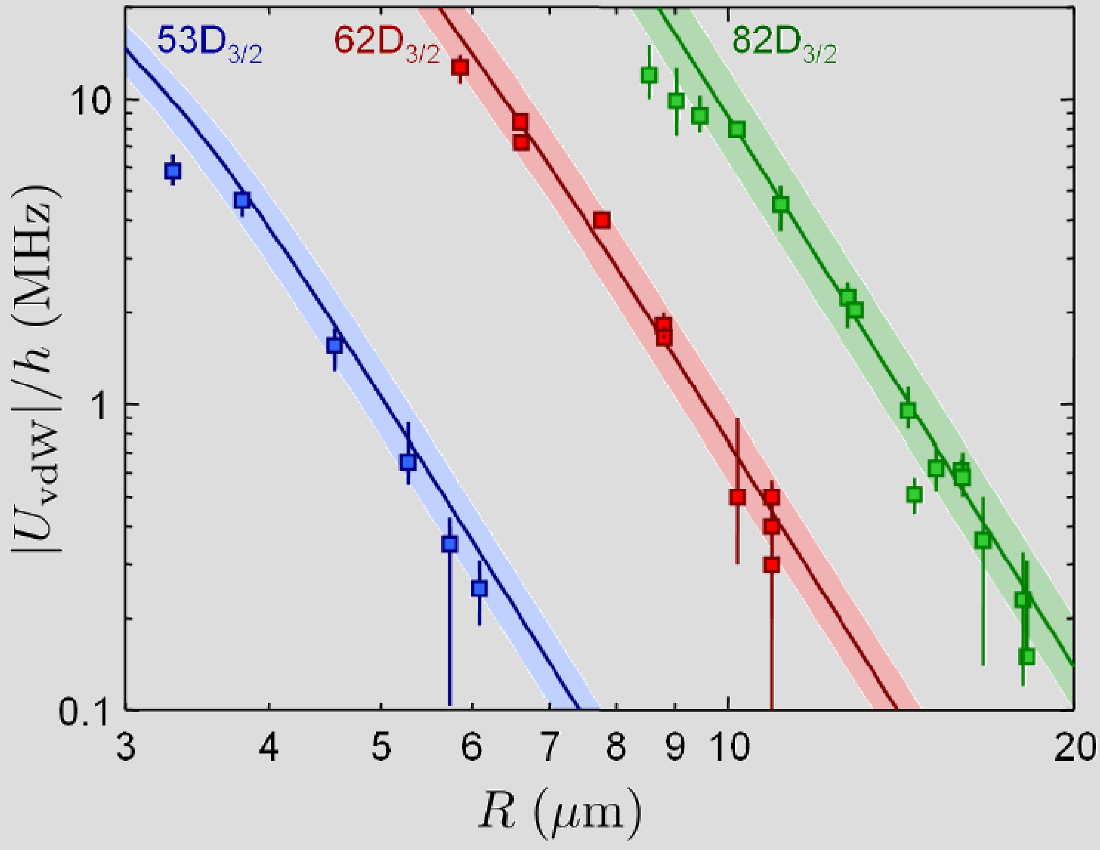
Field compensation by Stark spectroscopy

‘Before’
|E| ~ 150 mV/cm

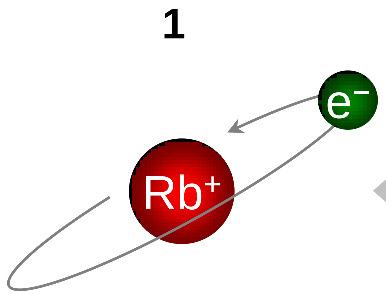
‘After’
|E| ~ 1 mV/cm



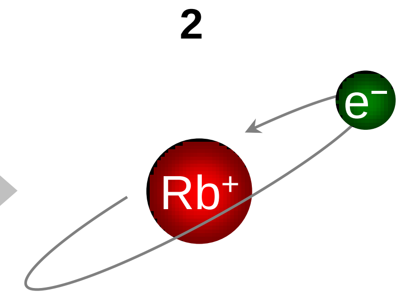
2. Direct measurement of the van der Waals interaction between two Rydberg atoms



Interactions between Rydberg atoms



$$\frac{\hat{\boldsymbol{d}}_1 \cdot \hat{\boldsymbol{d}}_2}{4\pi\varepsilon_0 R^3} - \frac{3(\hat{\boldsymbol{d}}_1 \cdot \boldsymbol{R})(\hat{\boldsymbol{d}}_2 \cdot \boldsymbol{R})}{4\pi\varepsilon_0 R^5}$$



Averge dipole moment vanishes in quantum state $|n,l,j,m_j>$
Second-order perturbation theory: **van der Waals-London**

$$U_{\text{int}} \sim d^4/R^6$$

If two two-atom states have the same energy (e.g. by Stark tuning)
Effect already at first order: **Förster resonance**

$$U_{\text{int}} \sim d^2/R^3$$

Early measurements of the vdW interaction (atom-wall)

Interaction Rydberg atoms - surface

Lennard-Jones potential

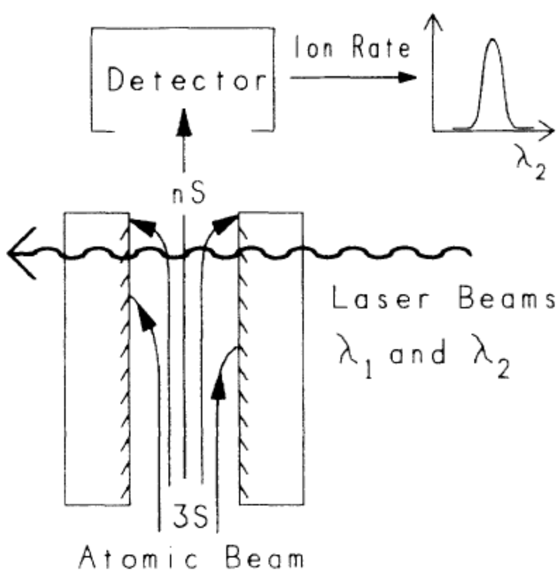
$$U_{\mathrm{LJ}} \propto -\frac{d^2}{z^3}$$

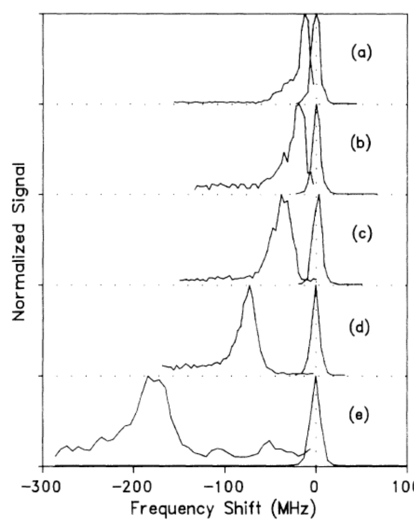
VOLUME 68, NUMBER 23 PHYSICAL REVIEW LETTERS 8 JUNE 1992

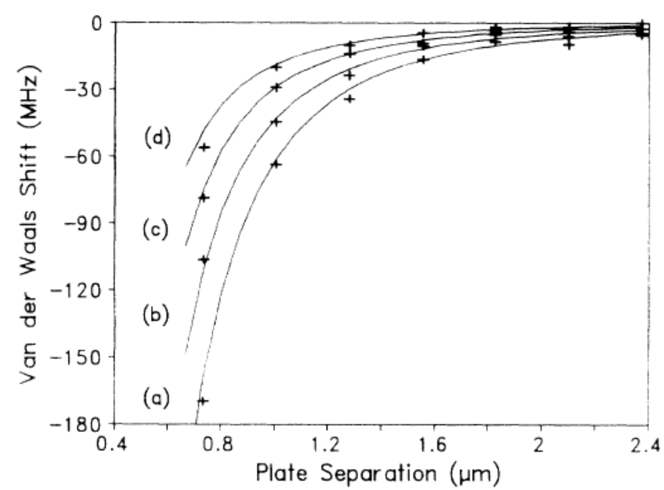
Direct Measurement of the van der Waals Interaction between an Atom and Its Images in a Micron-Sized Cavity

V. Sandoghdar, C. I. Sukenik, and E. A. Hinds
Physics Department, Yale University, New Haven, Connecticut 06520

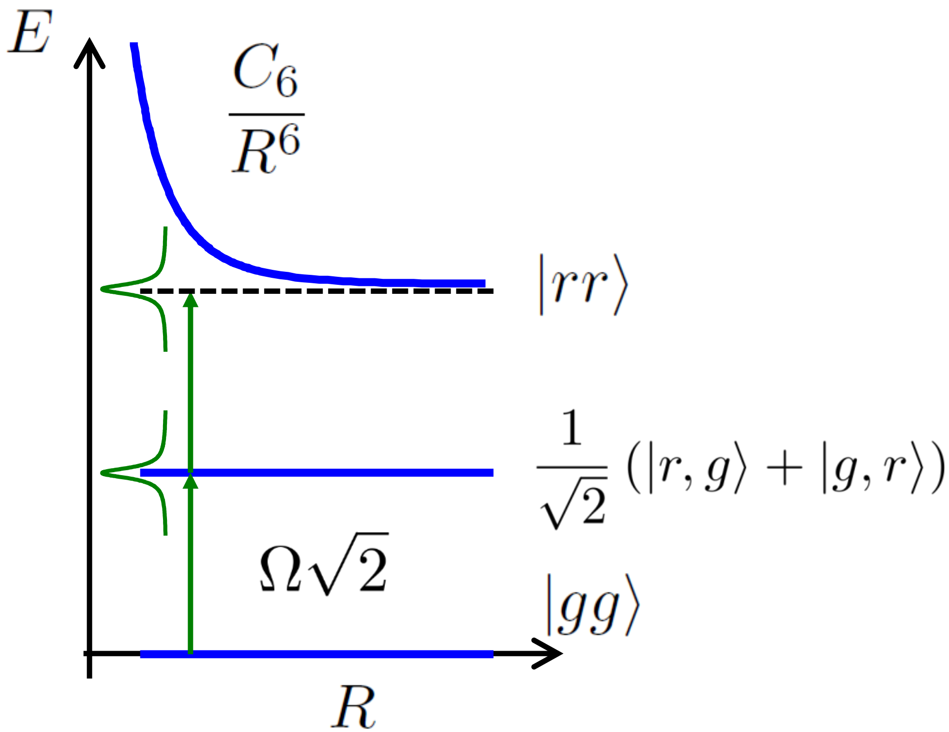
Serge Haroche
Ecole Normale Supérieure, Paris, France and Physics Department, Yale University, New Haven, Connecticut 06520
(Received 27 March 1992)



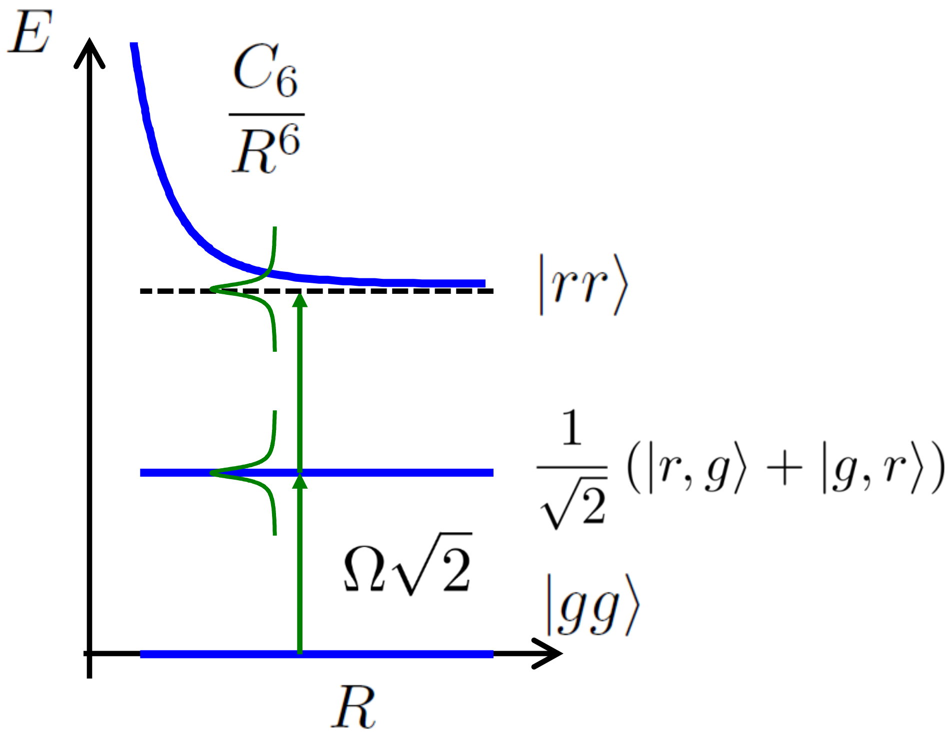




From full blockade…

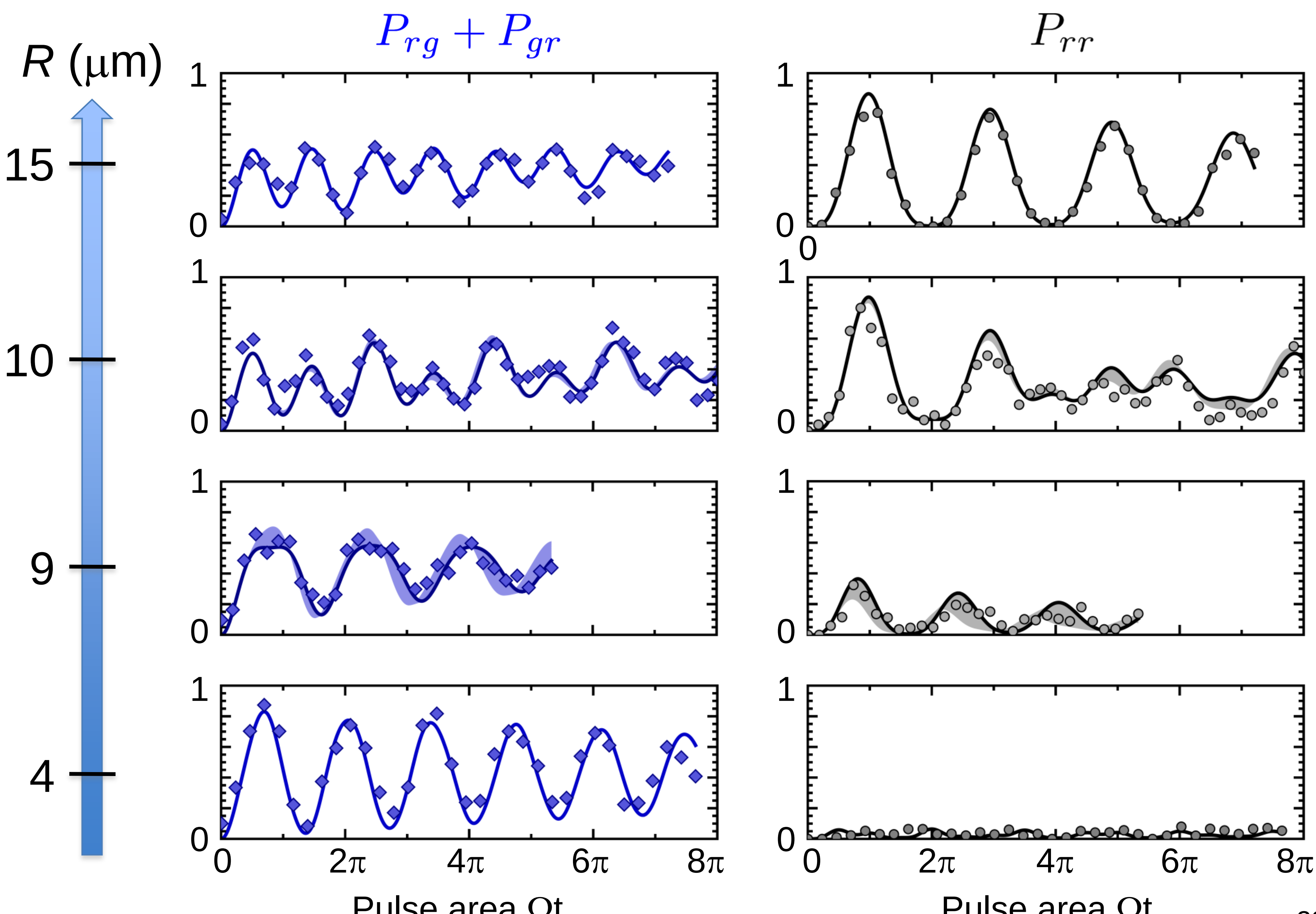


… to *partial* blockade

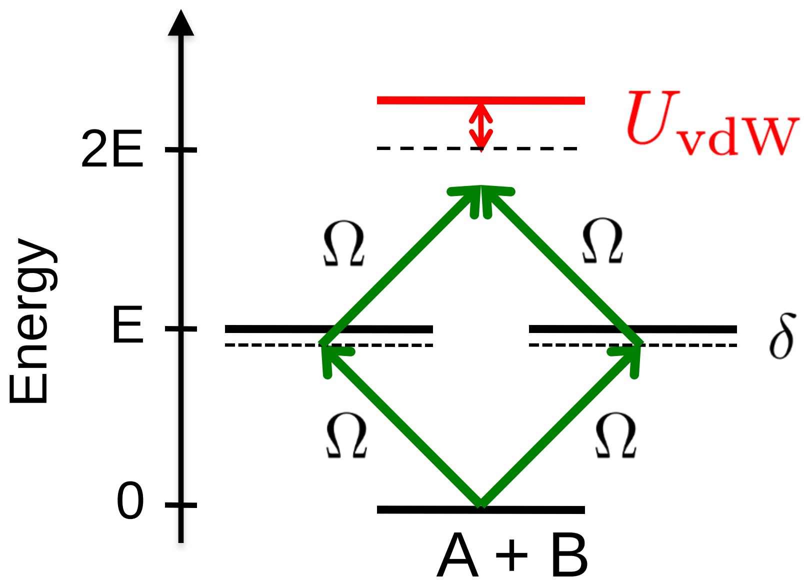


Partial blockade: $\hbar\Omega \approx C_6/R^6$

From independent to blockaded atoms



Measurement of the interaction energy versus distance



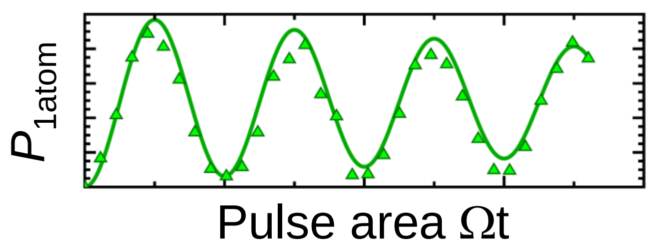
2-atom, 4-level Optical Bloch Equations

$$\dot{\rho} = \frac{1}{i\hbar}[H, \rho] + \mathcal{L}$$

$$\mathcal{L} = \mathcal{L}_A \otimes \rho_B + \rho_A \otimes \mathcal{L}_B$$

$$\mathcal{L}_i = \gamma \begin{pmatrix} \rho_{rr} & -\rho_{gr}/2 \\ -\rho_{rg}/2 & -\rho_{rr} \end{pmatrix}_i$$

Single atom Rabi frequency

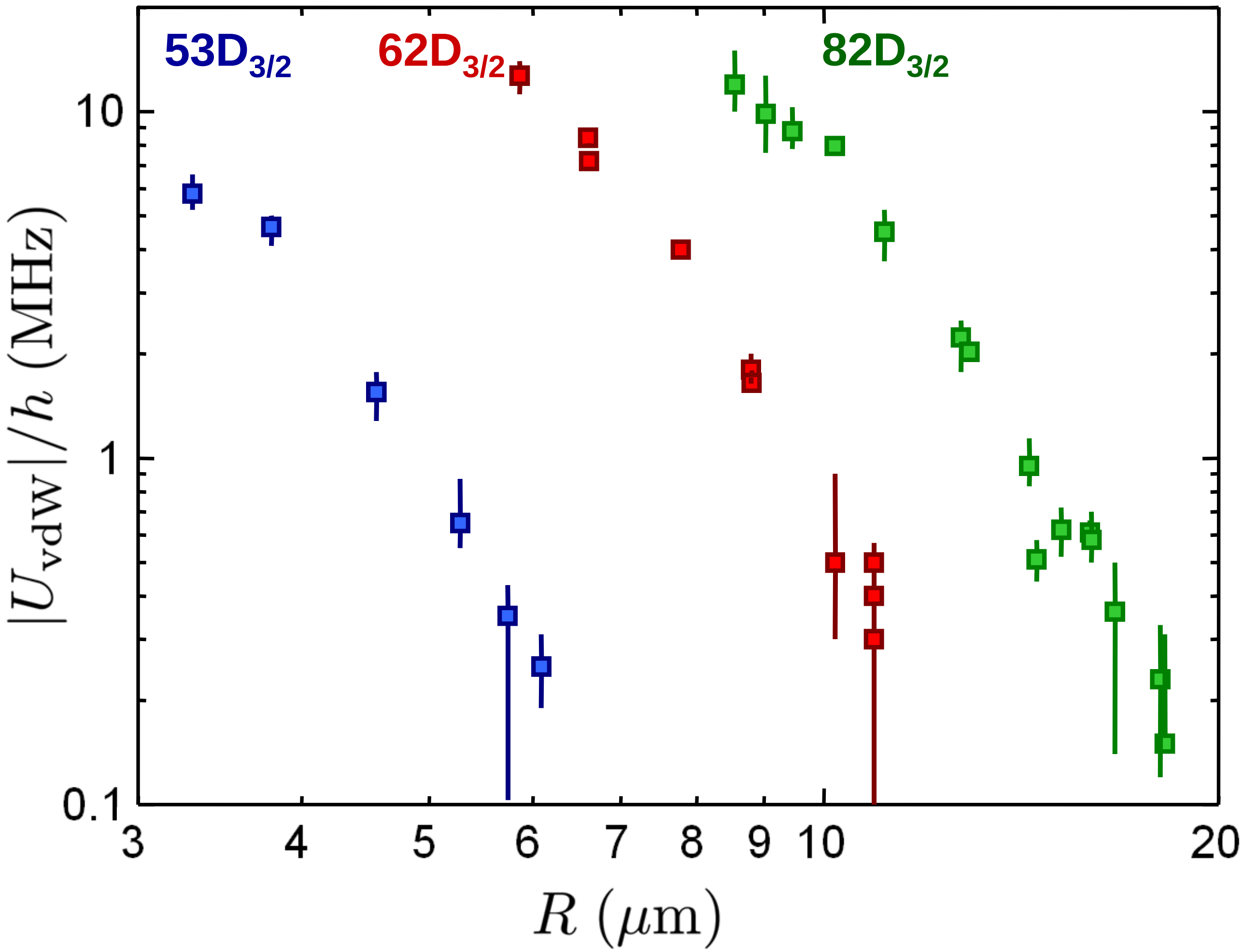


$\Rightarrow$ Ω and γ **(phenomenological)**

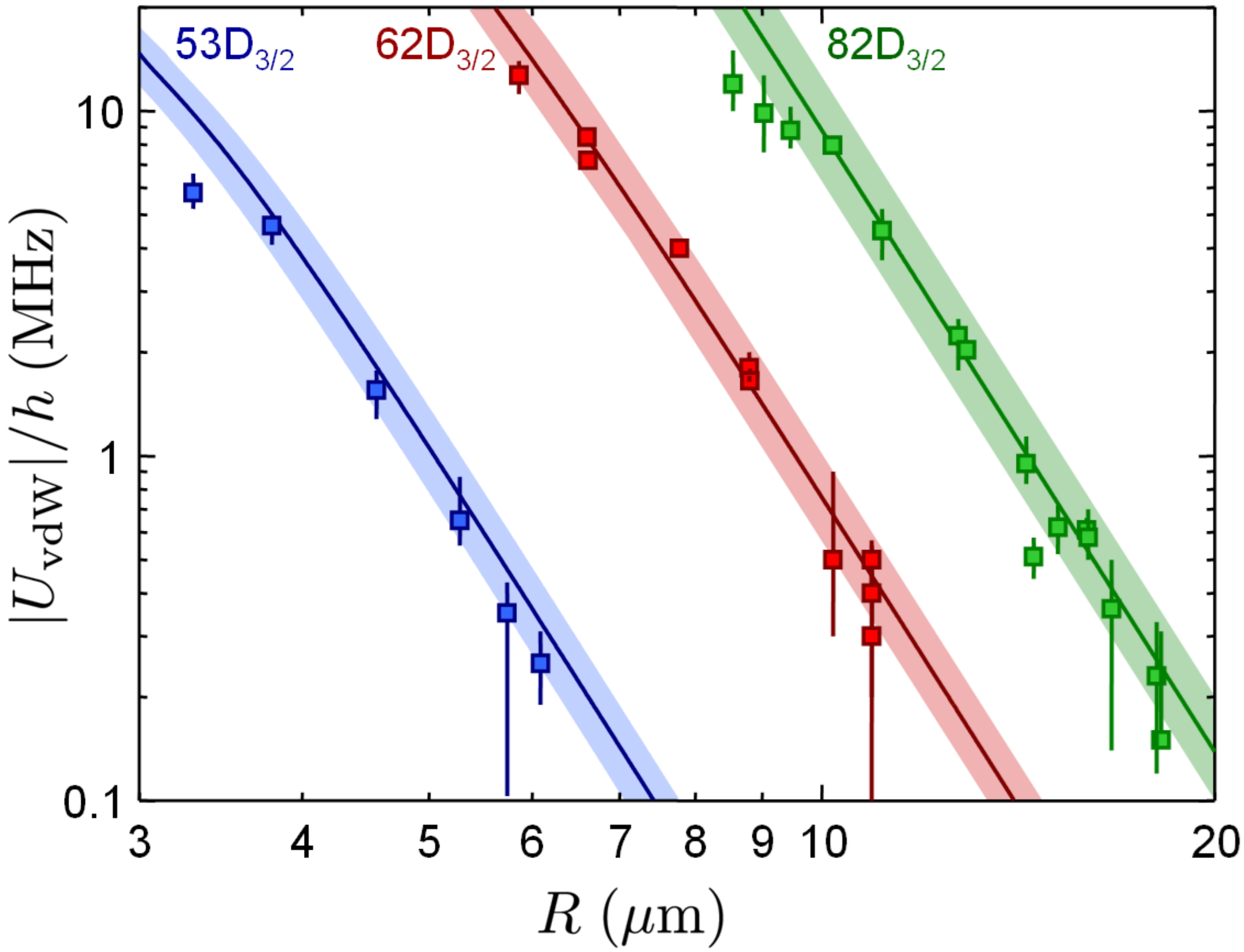
Two atom: χ^2 minimization

Free parameters: U_{vdW} and δ (laser drift, <300 kHz typ.)

Measuring U_{vdW} vs distance



Measuring U_{vdW} vs distance



Theory curves: direct diagonalization (dipole-dipole interaction)

No adjustable parameter!

Béguin *et al.*, to appear in PRL.

Comparison to theory

Assume $\frac{C_p}{R^p}$ $\Rightarrow$ exponent *p*

n	p
53	6.1 ± 0.5
62	5.1 ± 0.2
82	5.8 ± 0.2

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Assume $\frac{C_6}{R^6}$ $\Rightarrow$ $|C_6|_{\text{exp.}}$

n	$\lvert C_6\rvert_{\text{exp.}}$ (GHz $\cdot\ \mu$m^6)	$\lvert C_6\rvert_{\text{th.}}$ (GHz $\cdot\ \mu$m^6)
53	13.7 ± 1.2	16.9 ± 1.7
62	730 ± 20	766 ± 15
82	8500 ± 300	8870 ± 150

What about the 'famous' scaling $C_6 \propto n^{11}$?

Van der Waals shift: dipole-dipole interaction in **second-order perturbation theory**

$$C_6(n) \sim \sum_{p,q} \frac{d_{np}^2 d_{nq}^2}{E_p + E_q - 2E_n} \sim \sum \frac{n^4\, n^4}{n^{-3}} \sim n^{11}$$

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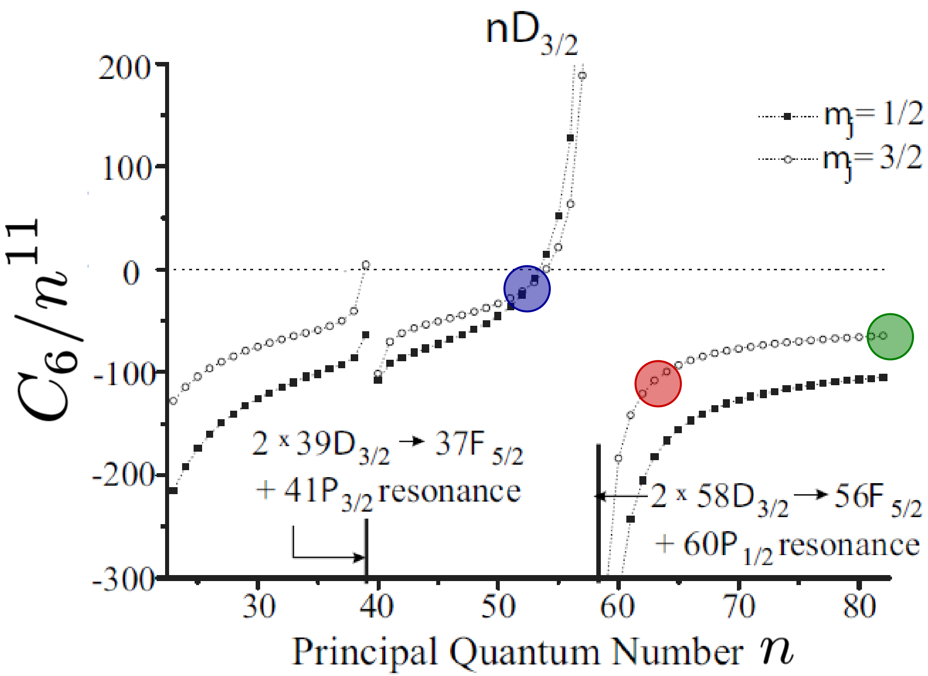
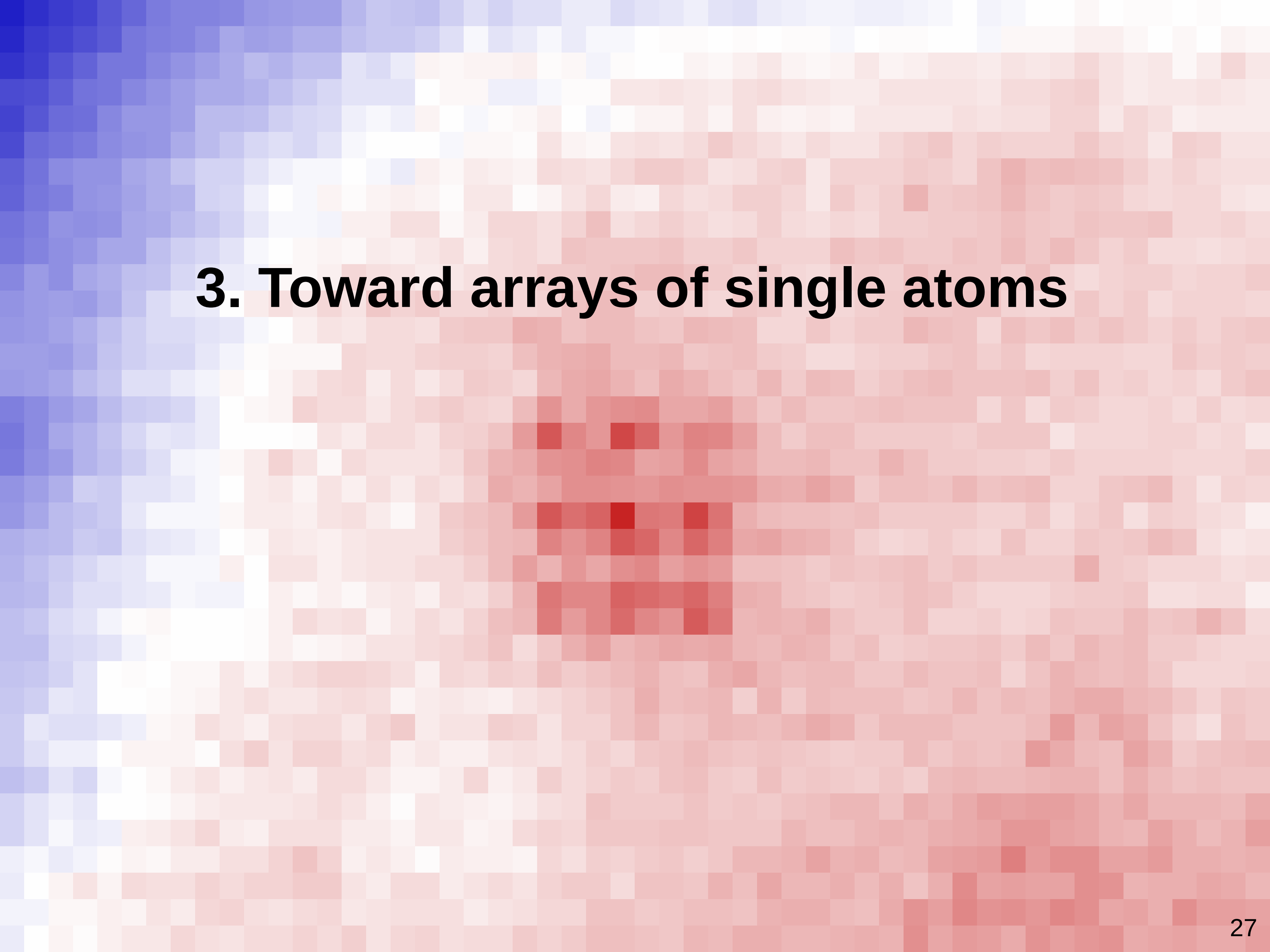
In fact, not so simple for D states (quasi Förster resonances)

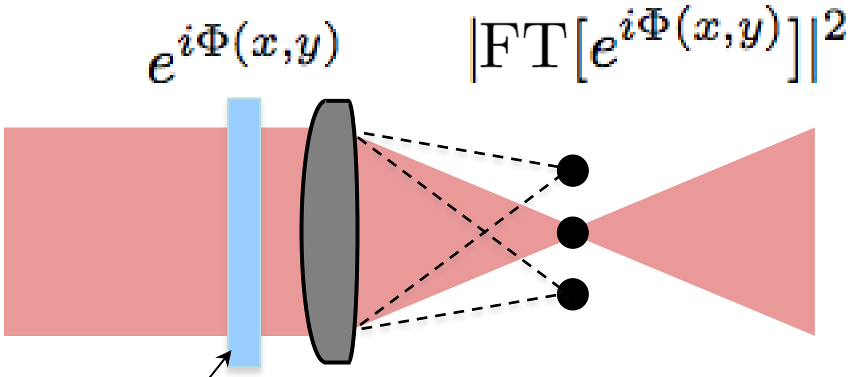


Reinhard *et al.*, PRA **75**, 032712 (2007).

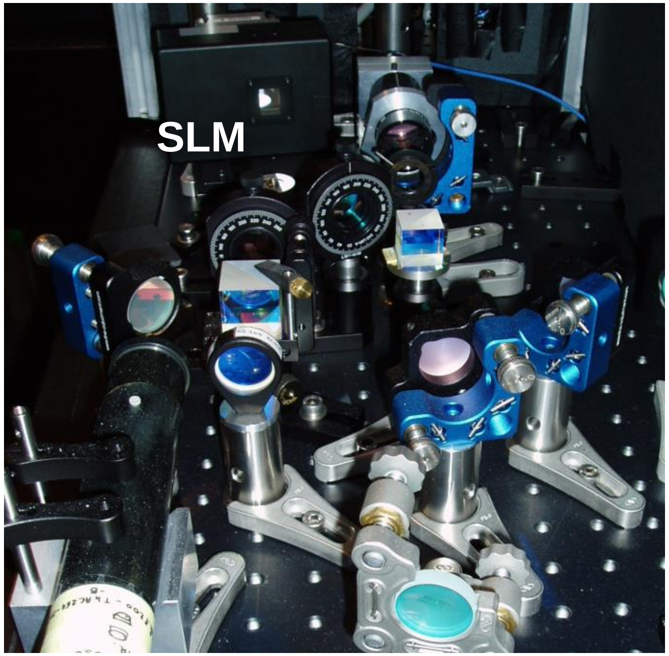


3. Toward arrays of single atoms

Implementing the Spatial Light Modulator

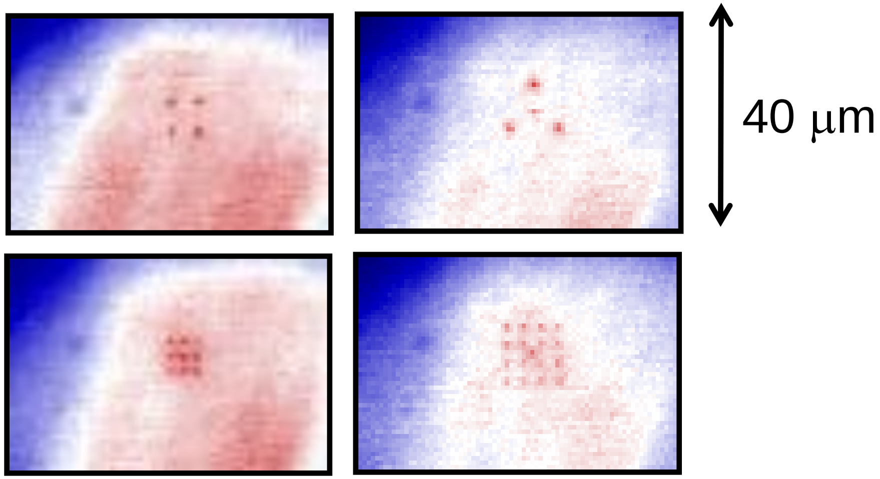


Spatial Light Modulator (liquid crystals)
Reconfigurable phase hologram
Iterative algorithms to obtain the desired intensity pattern



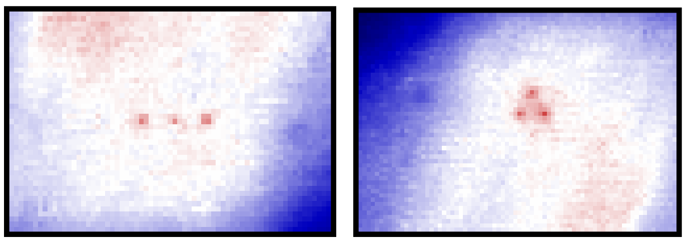
Multi-atom regime:
Fluorescence on CCD

A few tens of atoms per trap



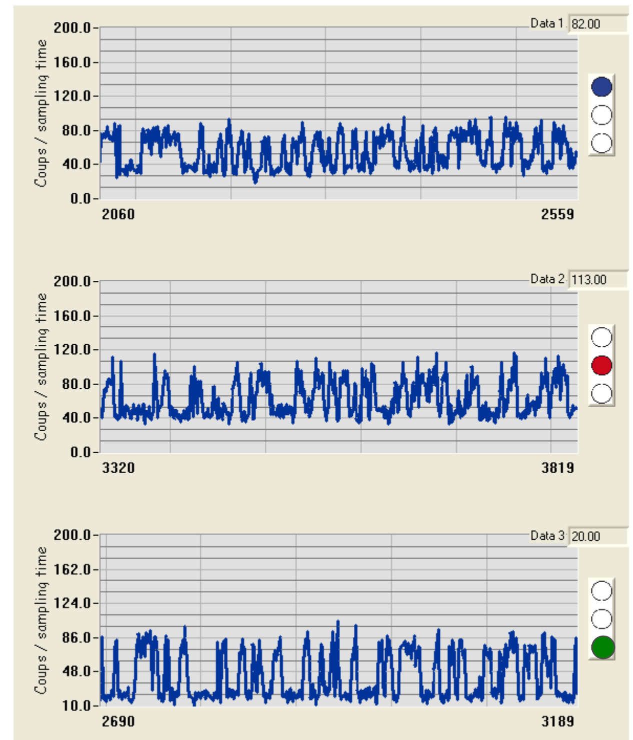
Single atoms: preliminary results with three APDs

Multi-atom regime:
Fluorescence on CCD

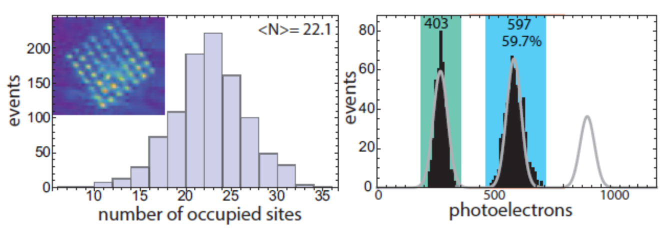


Reduce
MOT density

Single atom regime:
Photon counts per 10ms on APDs



Related work: Wisconsin, Sandia,…



Piotrowicz *et al.*, arXiv:1305.6102

Outlook

Challenges to be addressed

- Scalable detection (EMCCD instead of avalanche photodiodes)
- Improve fidelities
- Deterministic loading of traps

Repulsive blue-detuned light-assisted collisions [Grünzweig *et al*., Nat. Phys. **6,** 951 (2010)]
Rydberg blockade [Saffman group, see poster K1.16]

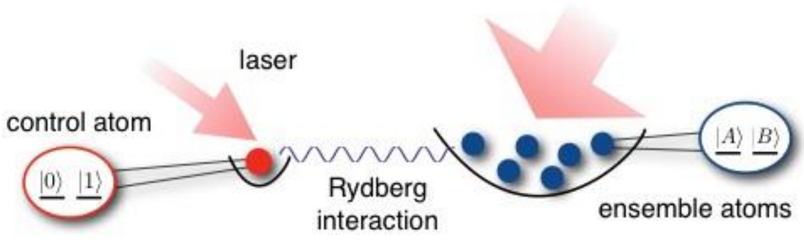
Experiments with arrays of a few atoms

- Geometry of array / anisotropy of DDI
- Electric field control of interactions (Förster resonances)
- Many-atom entanglement (W states, GHZ states…)

Merci !

Preparing GHZ states (Schrödinger 'kittens')

Generalized Control-Not gate



$$
\begin{aligned}
|0\rangle|A^N\rangle &\rightarrow |0\rangle|A^N\rangle, \quad & |0\rangle|B^N\rangle &\rightarrow |0\rangle|B^N\rangle \\
|1\rangle|A^N\rangle &\rightarrow |1\rangle|B^N\rangle, \quad & |1\rangle|B^N\rangle &\rightarrow |1\rangle|A^N\rangle
\end{aligned}
$$

$$|\mathrm{GHZ}\rangle = \frac{1}{\sqrt{2}}\Big(|0000\cdots 0\rangle + |1111\cdots 1\rangle\Big)$$

Prepare *N*-atom GHZ state in a single step!

Implements N-spin interaction $H = |0\rangle\langle 0| \otimes \hat{1} + |1\rangle\langle 1| \otimes J\hat{\sigma}_x^{(1)}\hat{\sigma}_x^{(2)}\hat{\sigma}_x^{(3)}\ldots$

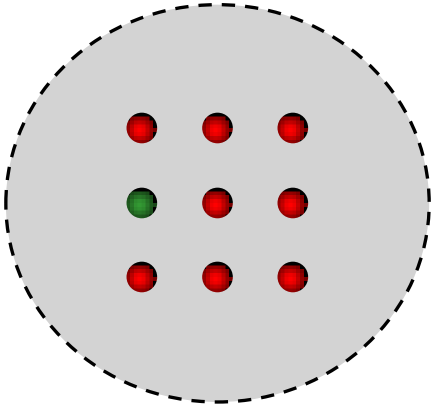
Müller *et al.*, RPL **102**, 170502 (2009)
Also Moller *et al.*, PRL **100,** 170504 (2008)

Quantum simulation with long-range interaction

Dipolar physics (Pohl, Zoller, Lesanowsky, Pupillo, Büchler…)

Preparing *N*-atom W states

Full blockade over an *N*-atom array



One excites only one atom out of *N*: one prepares

$$|\mathrm{W}\rangle = \frac{1}{\sqrt{N}}\Big(|rggg\cdots gg\rangle + |grgg\cdots gg\rangle + \cdots + |ggg\cdots gr\rangle\Big)$$

(Symmetric Dicke state or W state)

Collective coupling $\sqrt{N}\Omega$ with the ground state $|gggg\cdots g\rangle$