Rydberg-Rydberg interactions in ultracold atomic gases

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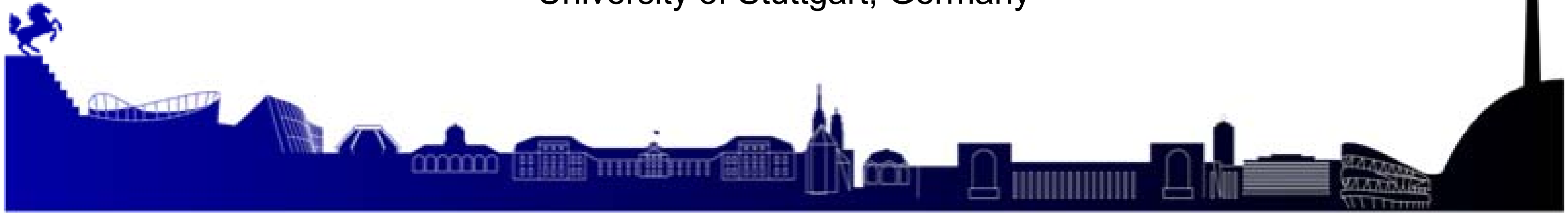
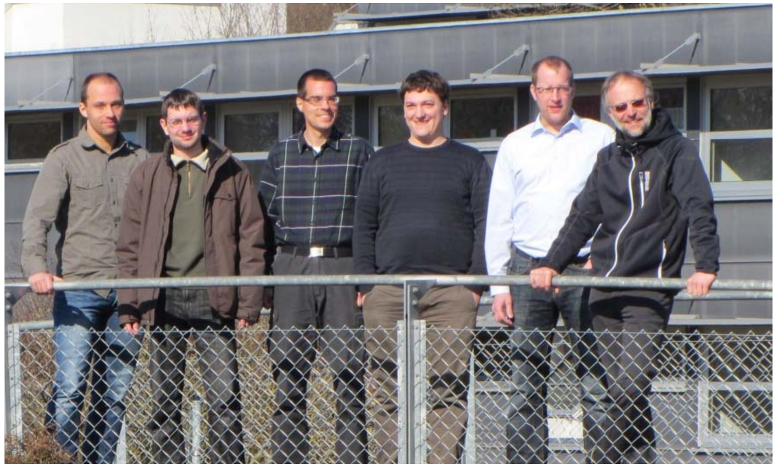


Cold Rydberg Team in Stuttgart

Rydberg BEC I

Johannes Nipper
Alexander Krupp
Jonathan Balewski



Sebastian Robert Tilman
Hofferberth Löw Pfau

Rydberg BEC II

Stephan
Jennewein

Huan
Nguyen

Michael
Schlagmüller

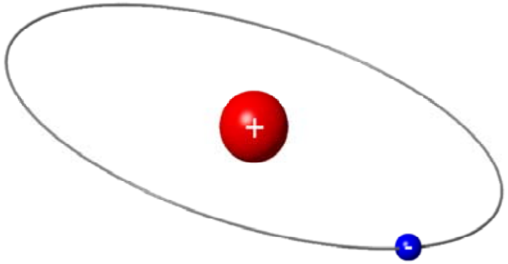
Rydberg Quantum Optics

Hannes
Gorniaczyk

Christoph
Tresp

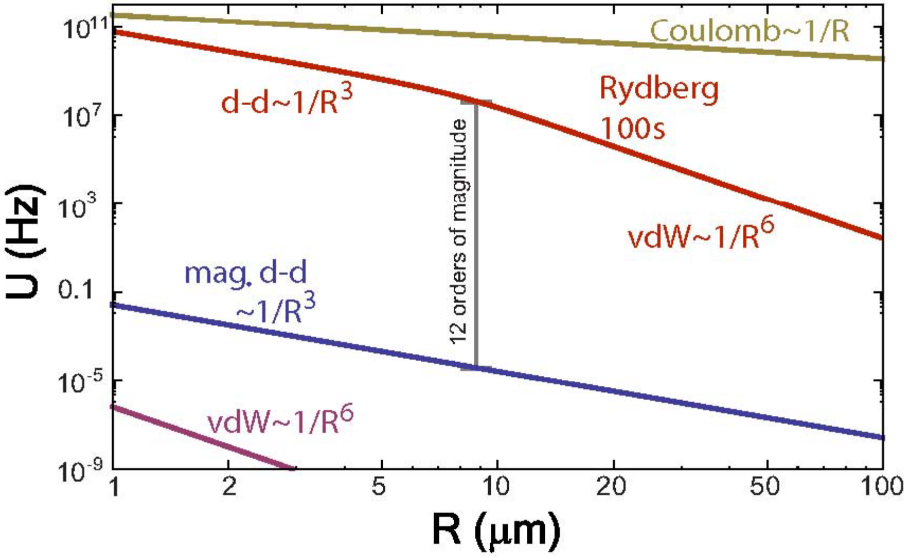
Rydberg atoms

quantity	scaling	43S-state of ^{87}Rb
radius	$\propto n^2$	2384 a_0
lifetime	$\propto n^3$	50µs
Polarizability	$\propto n^7$	8 MHz $(V/cm)^{-2}$
Van der Waals C_6	$\propto n^{11}$	-1.7×10^{19} a.u.



Rydberg-Rydberg interactions are:

- … strong
- … long-range
- … tunable
- … switchable
- … anisotropic



M. Saffman et al., Rev. Mod. Phys. 82, 2313 (2010)

van der Waals & Förster interaction

interaction operator (for $R>n^2a_0$):

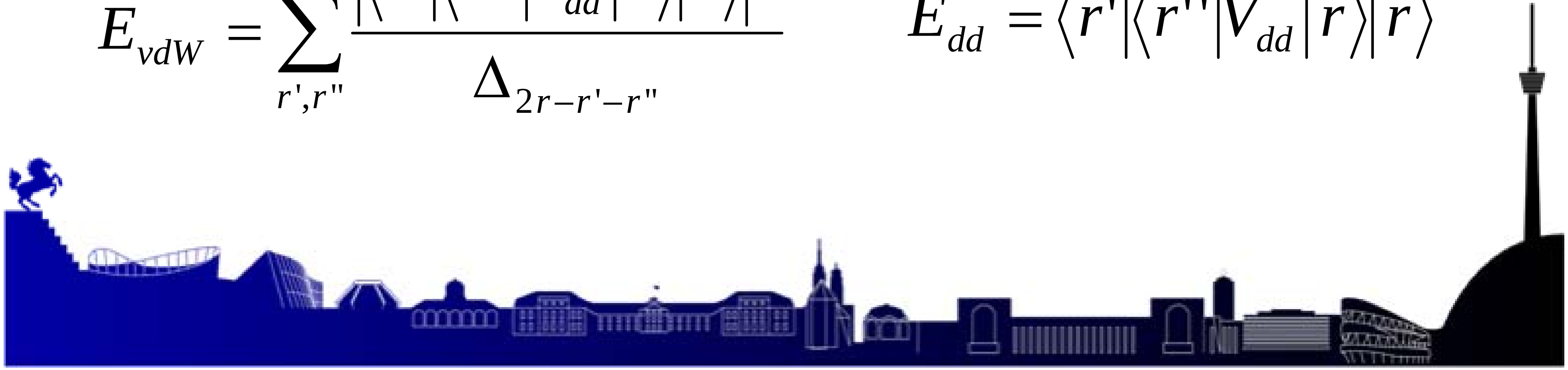
$$V_{dd} = \frac{\mathbf{p}_1 \cdot \mathbf{p}_2 - 3(\mathbf{n} \cdot \mathbf{p}_1)(\mathbf{n} \cdot \mathbf{p}_2)}{R^3}$$

finite Förster defects Δ:
van-der-Waals interaction (~ $1/R^6$)

$$E_{vdW} = \sum_{r',r''} \frac{\left| \langle r' | \langle r'' | V_{dd} | r \rangle | r \rangle \right|^2}{\Delta_{2r-r'-r''}}$$

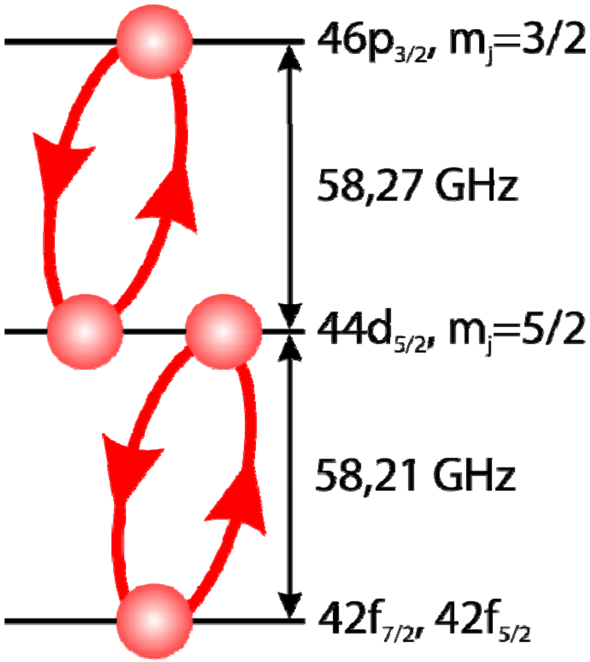
no Förster defect $\Delta = 0$:
resonant dipole-dipole
interaction (~ $1/R^3$)

$$E_{dd} = \langle r' | \langle r'' | V_{dd} | r \rangle | r \rangle$$

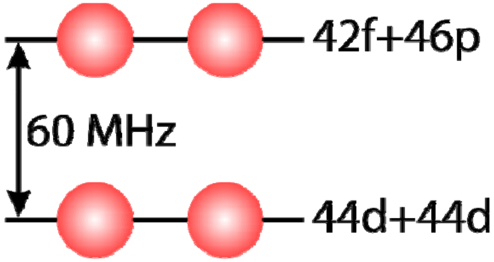


Dipolar interactions: Förster resonances

Bare states



Pair states



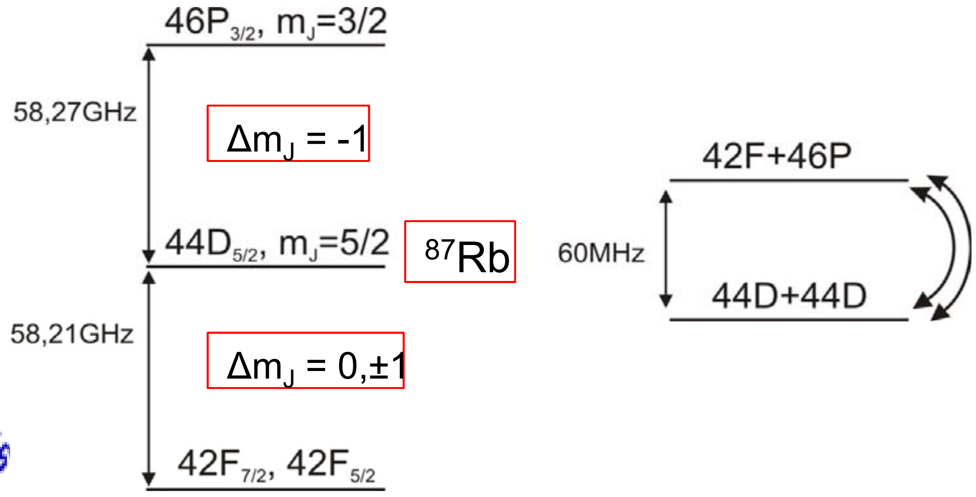
see also: Raithel, Pillet, Martin, van Linden,
Ryabtsev, Gallagher, Weidemüller, Noel, …

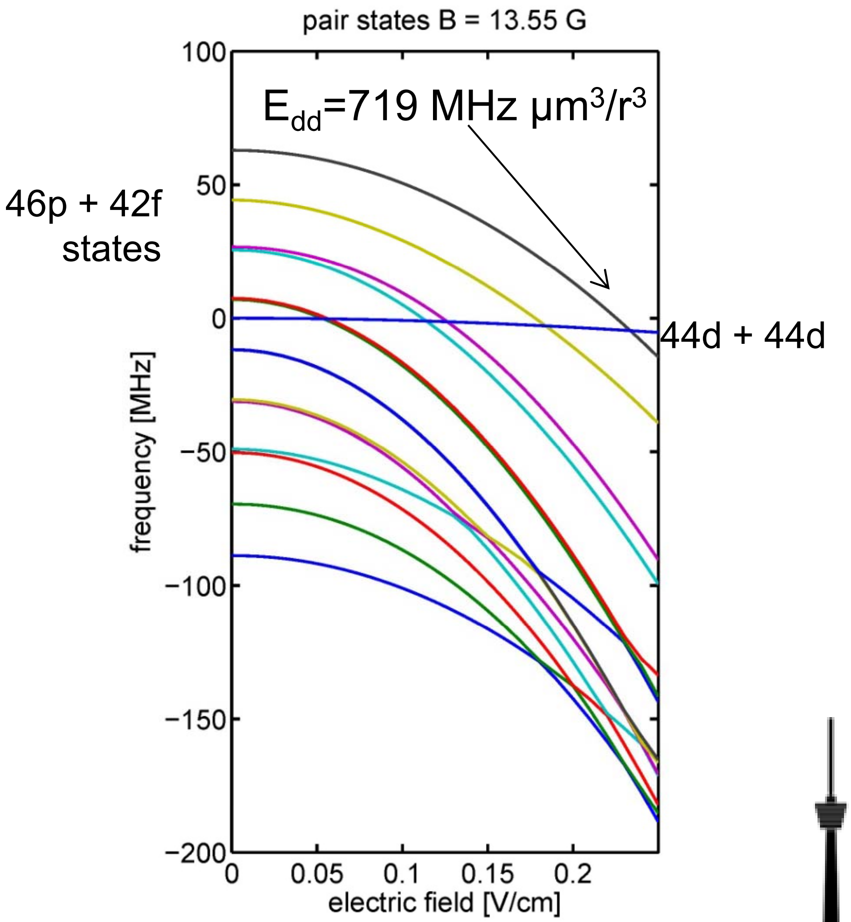
Stark tuning of Förster resonances

different Stark effects for involved states

Förster defect between pair states can be tuned by small electric fields

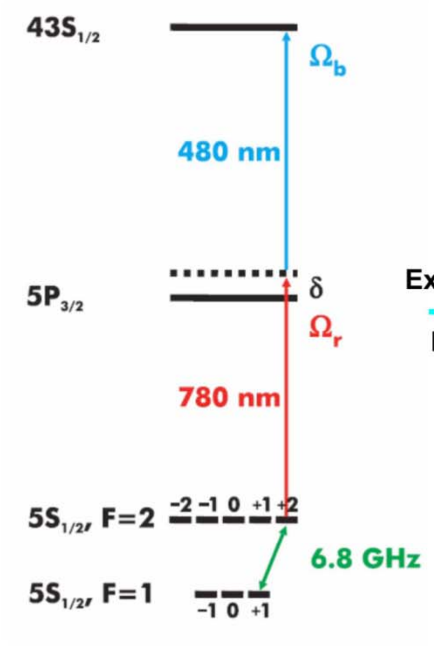
multiple resonances for different magnetic subleves



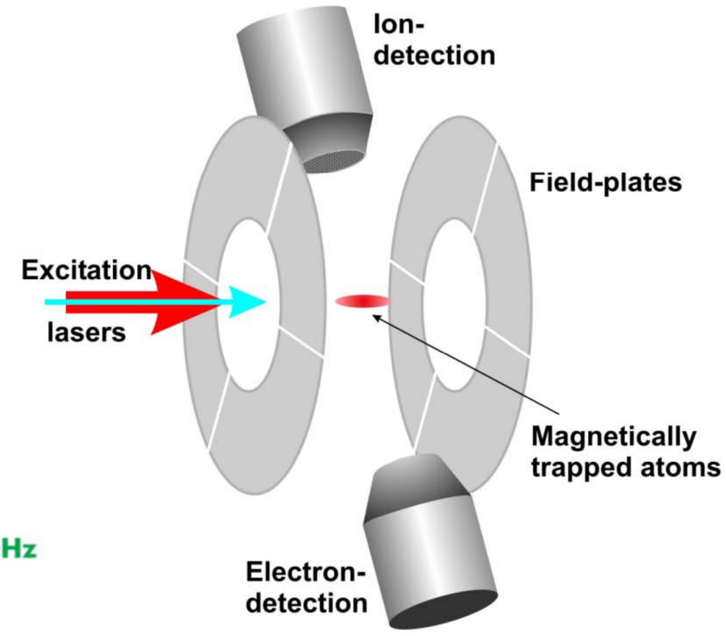


see also: Noel, Martin, Pillet, Raithel

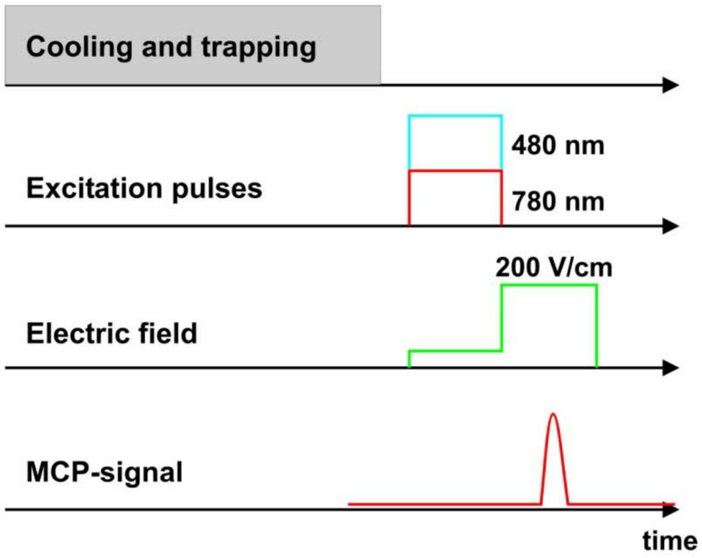
Rydberg excitation & detection



Excitation scheme



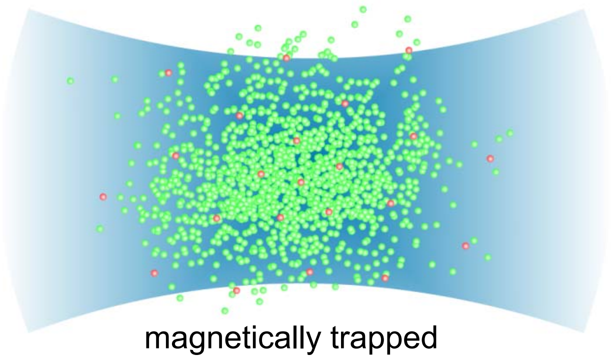
Experimental setup



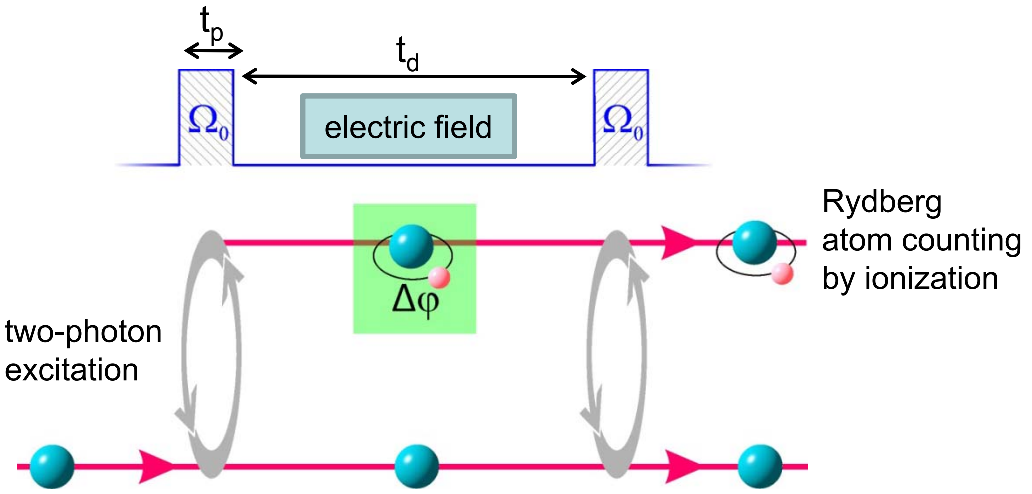
Experimental sequence

Rydberg atom interferometer

Goal: investigate coherence of Förster interaction
Method: Ramsey spectroscopy



magnetically trapped
Rb atoms

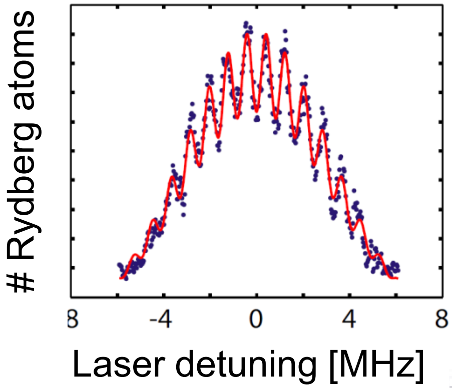


Some experimental details:

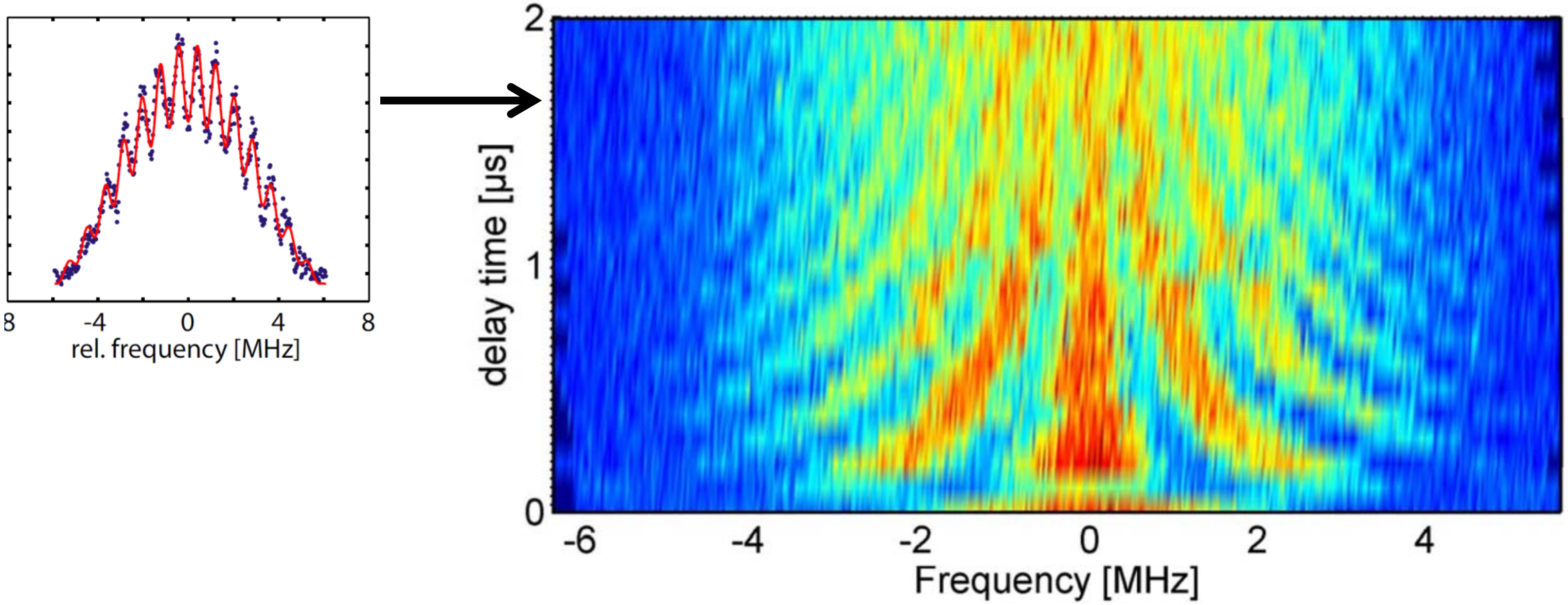
temperature: 0.7 µK
density: 10^{12} cm^{-3}
total laser linewidth: 60 kHz

single cycle gives
Ramsey spectrum

extract visibility & phase

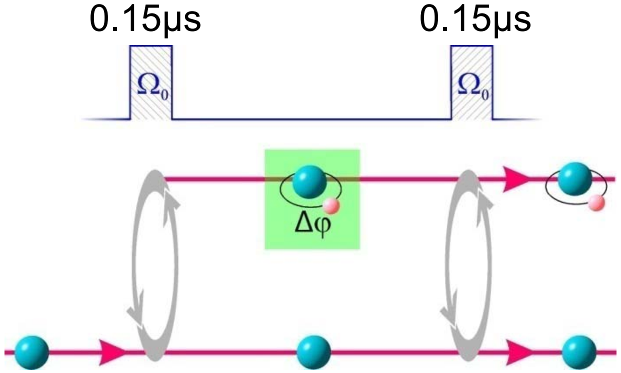


Ramsey spectroscopy

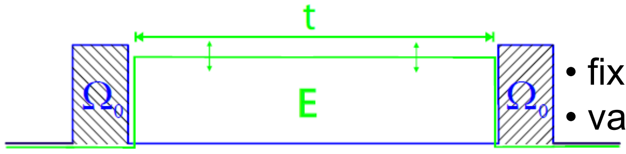


variation of delay time

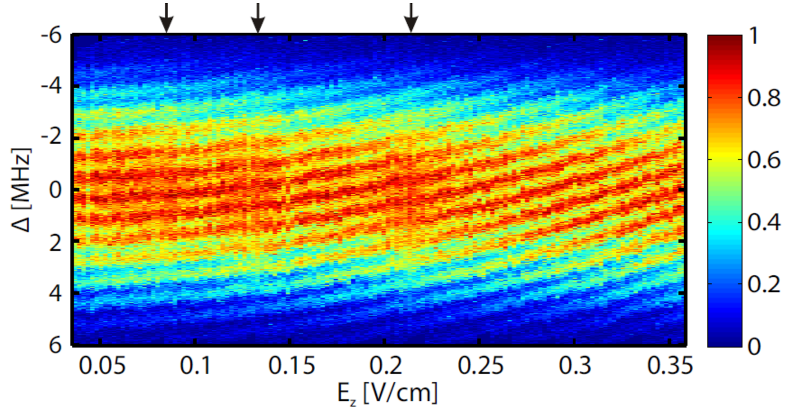
→ proof of coherent excitation

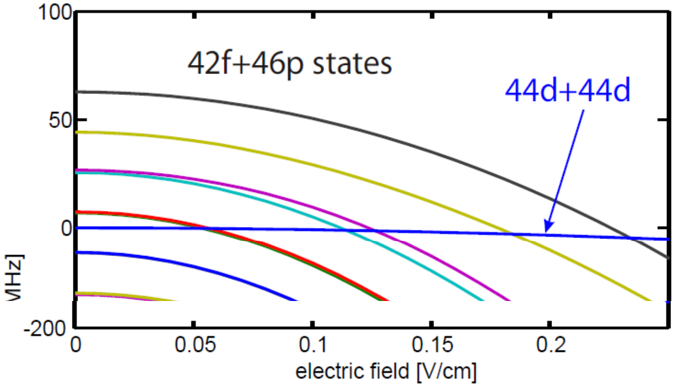


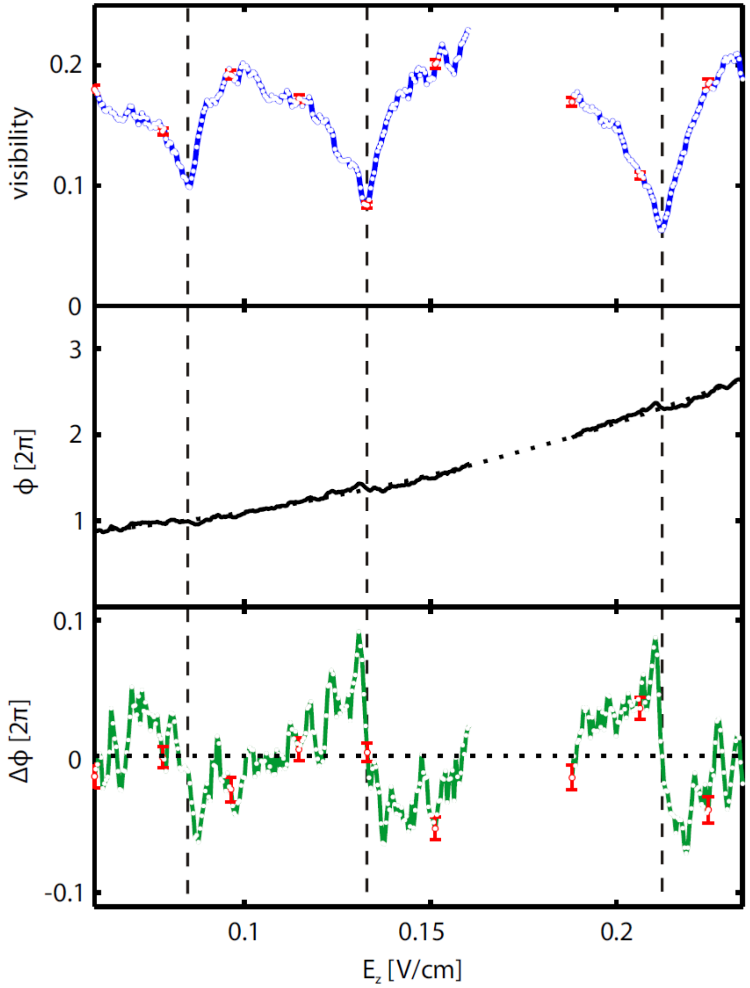
$44d_{5/2}$ Förster resonances



- fixed delay time
- vary E-field amplitude



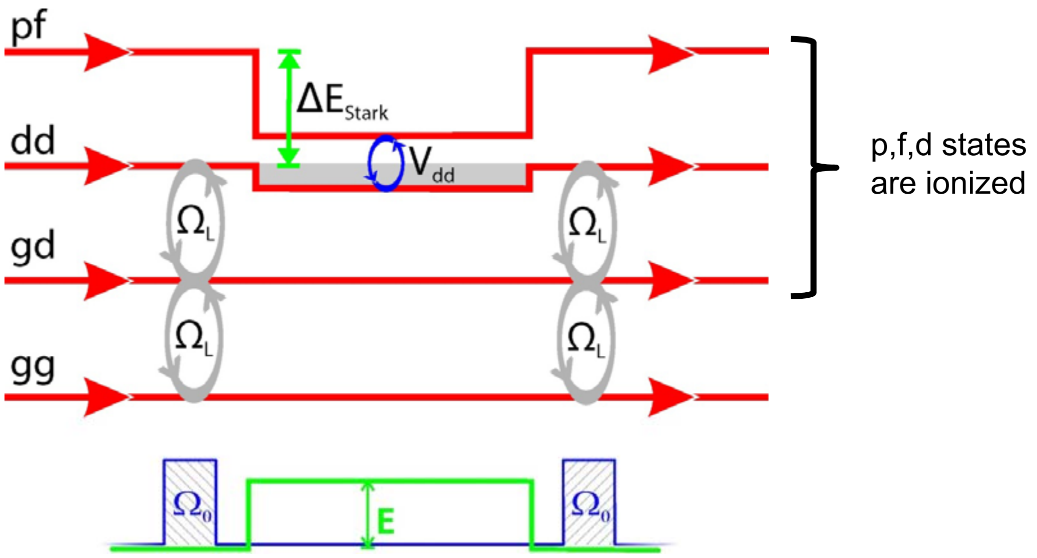




J. Nipper et al. PRL 108 113001 (2012)

Pair state interferometer

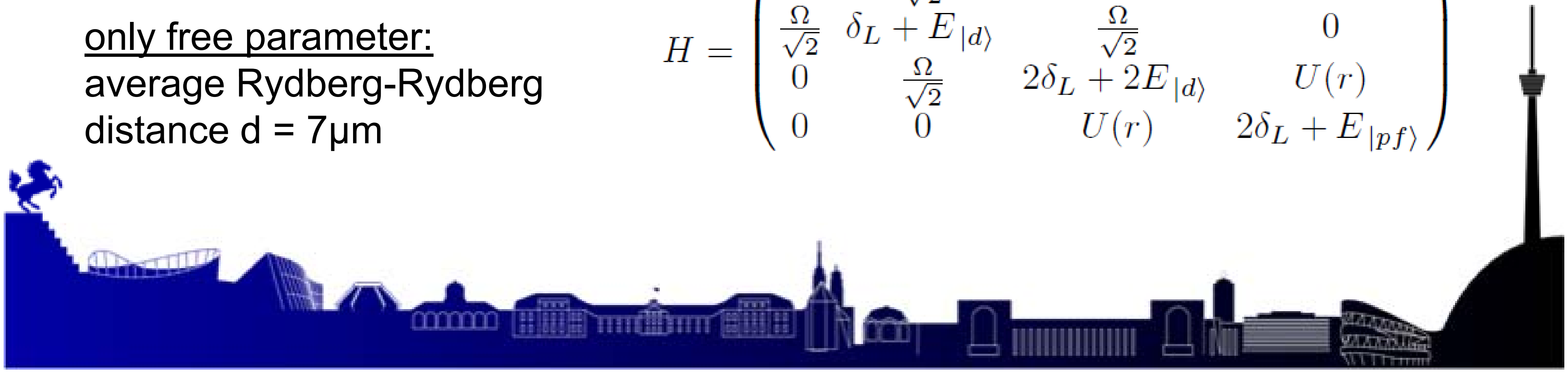
describe full Ramsey sequence by completely coherent 4-level model



numerical solution of Ramsey sequence reproduces dips in visibility and dispersive phase signal

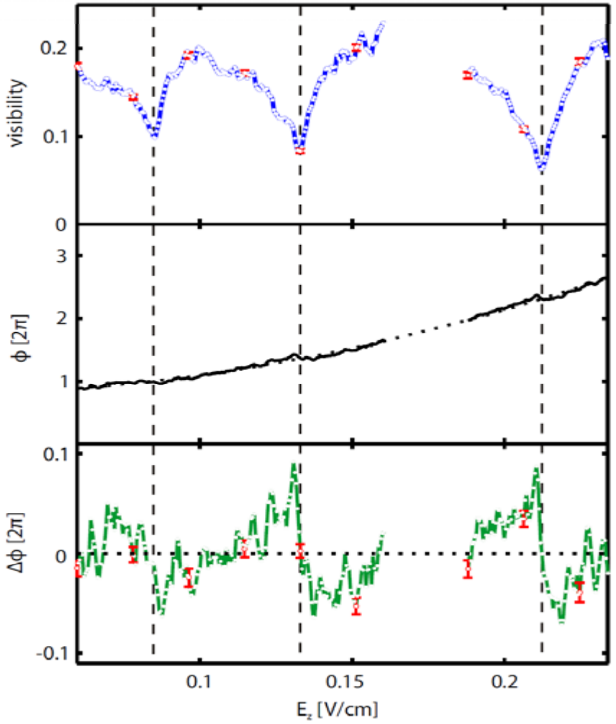
$$H = \begin{pmatrix} 0 & \frac{\Omega}{\sqrt{2}} & 0 & 0 \\ \frac{\Omega}{\sqrt{2}} & \delta_L + E_{|d\rangle} & \frac{\Omega}{\sqrt{2}} & 0 \\ 0 & \frac{\Omega}{\sqrt{2}} & 2\delta_L + 2E_{|d\rangle} & U(r) \\ 0 & 0 & U(r) & 2\delta_L + E_{|pf\rangle} \end{pmatrix}$$

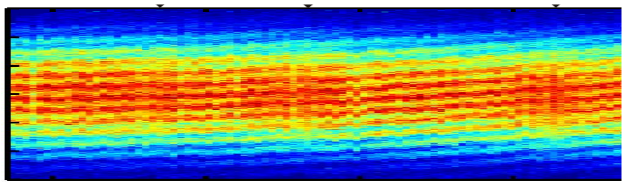
only free parameter:
average Rydberg-Rydberg distance d = 7µm



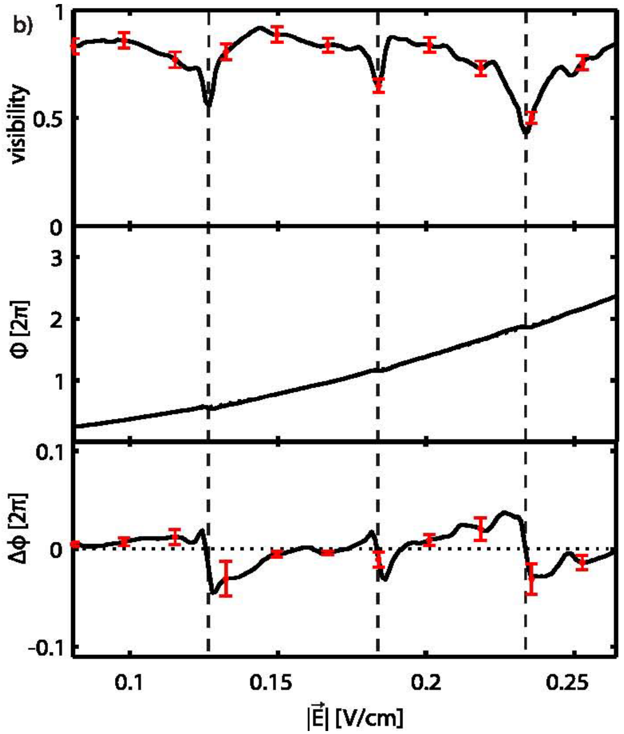
Pair state interferometer

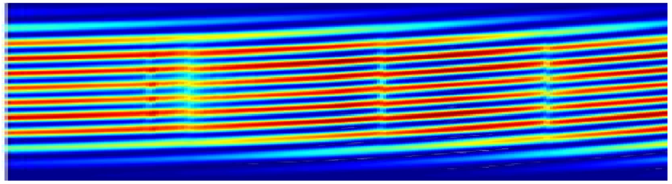
Experiment





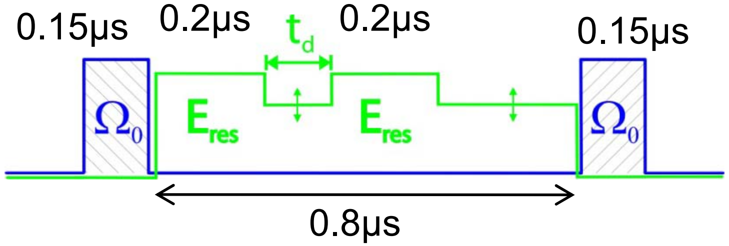
Theory

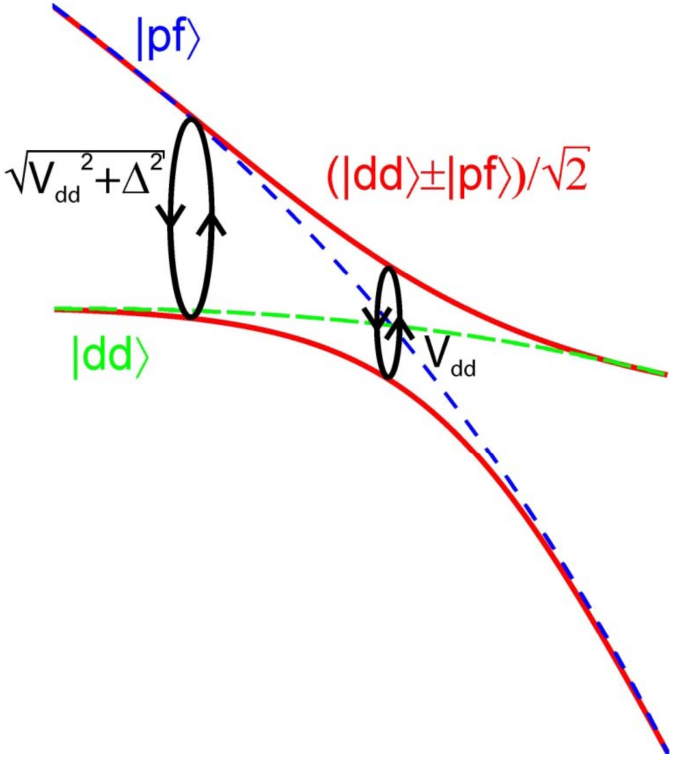




Coherent control at Förster resonance

Double Ramsey sequence: Ramsey-like electric field pulses





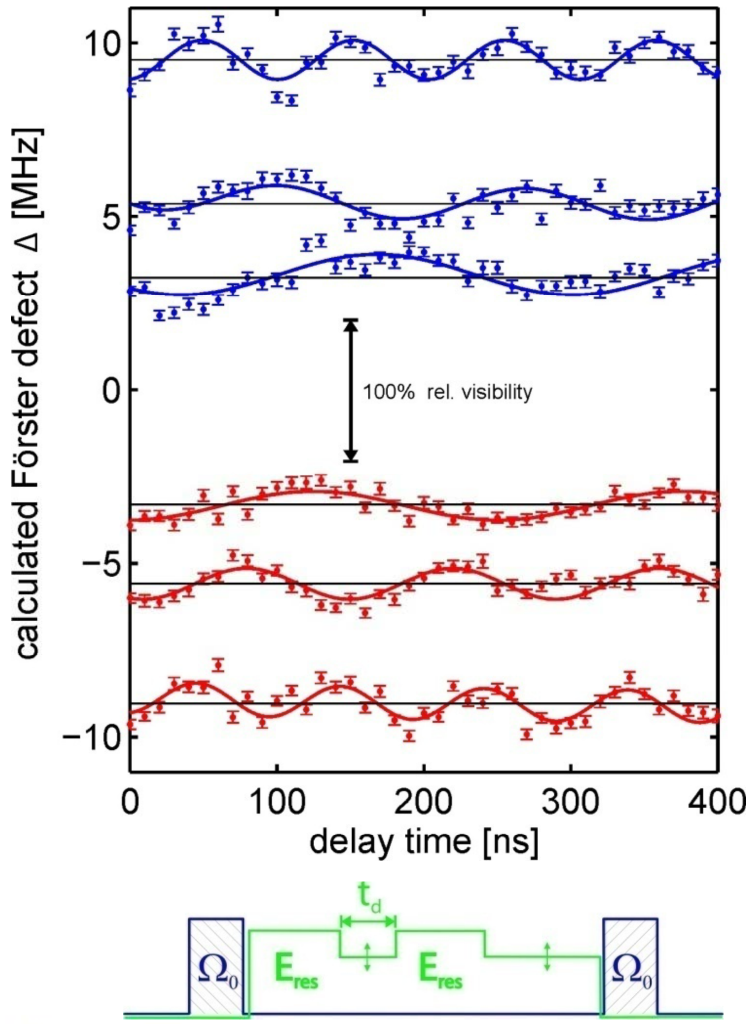
resonant electric field pulses interfere |dd> and |pf>

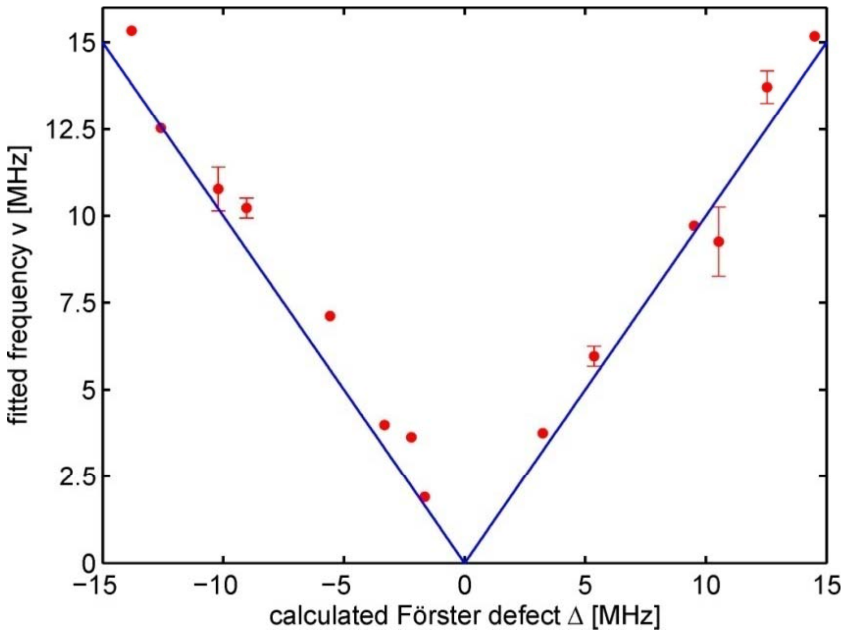
→ oscillation with $\sqrt{\Omega^2+\Delta^2}$ during delay time (off-resonant)

state selective optical Ramsey detection
→ oscillation in visibility

see also: Anderson et al., PRA 63, 063404 (2002)

Double Ramsey interferometer





<u>oscillation with Δ:</u>

proof of coherent coupling between pair states

<u>small E_{dd}:</u>

average interatomic distance = 7µm

J. Nipper et al., accepted in PRX (2012)

Application: Rydberg dressing

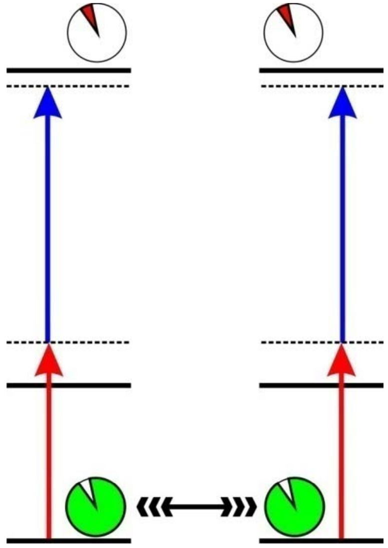
1µs ← Time scale → 100 ms

Frozen Rydberg gas

Internal coherence
between Rydberg atoms

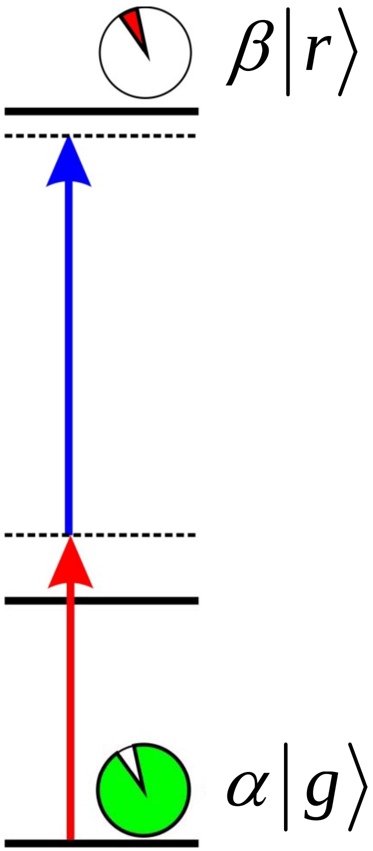
see also
Pohl, Lesanovsky,
Pupillo,…

Rydberg dressing



Modified interaction
between ground state atoms

Rydberg dressing



Weakly dressed ground state

$$|\psi\rangle = \alpha|g\rangle + \beta|r\rangle$$

Long lifetime

$$\tau = \tau_r / \beta^2$$

Interaction energy

$$E = \langle\psi|U_{dd}|\psi\rangle = \beta^2 \langle r|U_{dd}|r\rangle = \beta^2 U(r)$$

Collective Rydberg dressing

Pair state basis:

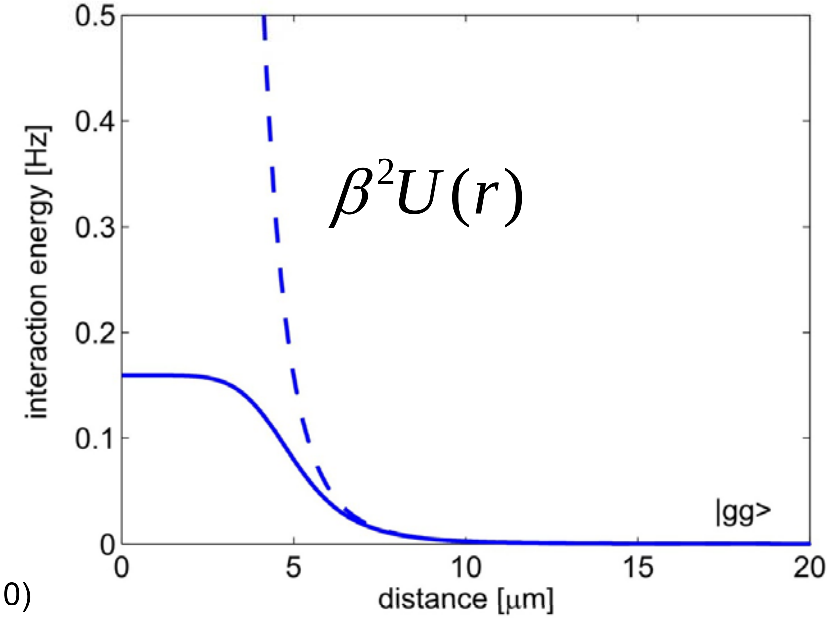
$$|gg\rangle, \frac{|gr\rangle + |rg\rangle}{\sqrt{2}}, |rr\rangle$$

$$H = \hbar \begin{pmatrix} 0 & \Omega/\sqrt{2} & 0 \\ \Omega/\sqrt{2} & \Delta & \Omega/\sqrt{2} \\ 0 & \Omega/\sqrt{2} & 2\Delta + U(r) \end{pmatrix}$$

Energy difference per atom:
collective vs single atom light shift

$$\approx \frac{1}{16}\frac{\Omega^4}{\Delta^3}(N-1)$$

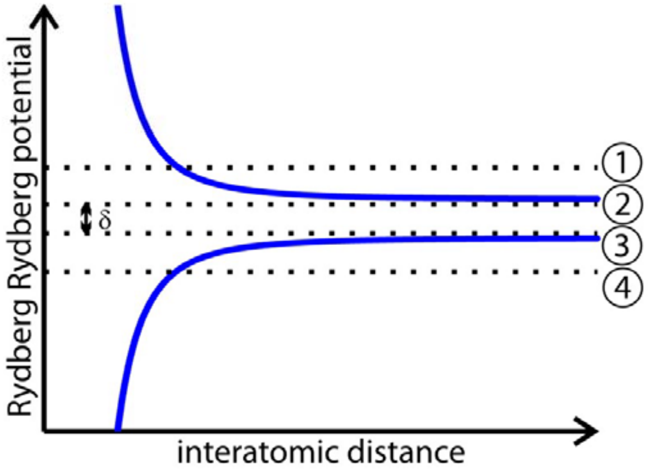
collective suppression $$\frac{\Omega^4}{\Delta^3} \text{ vs. } \frac{\Omega^2}{\Delta^2}$$



J. Honer et al., PRL 105, 160404 (2010)

Rydberg dressing on Förster resonance

bare states

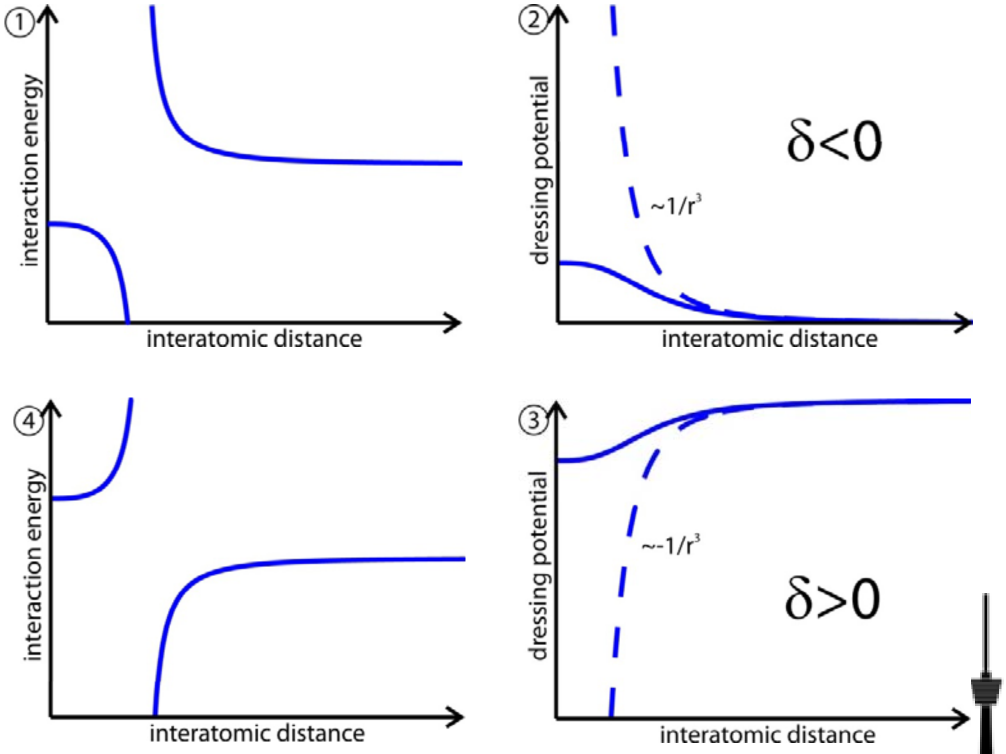


2 pair state branches:

attractive & repulsive interaction

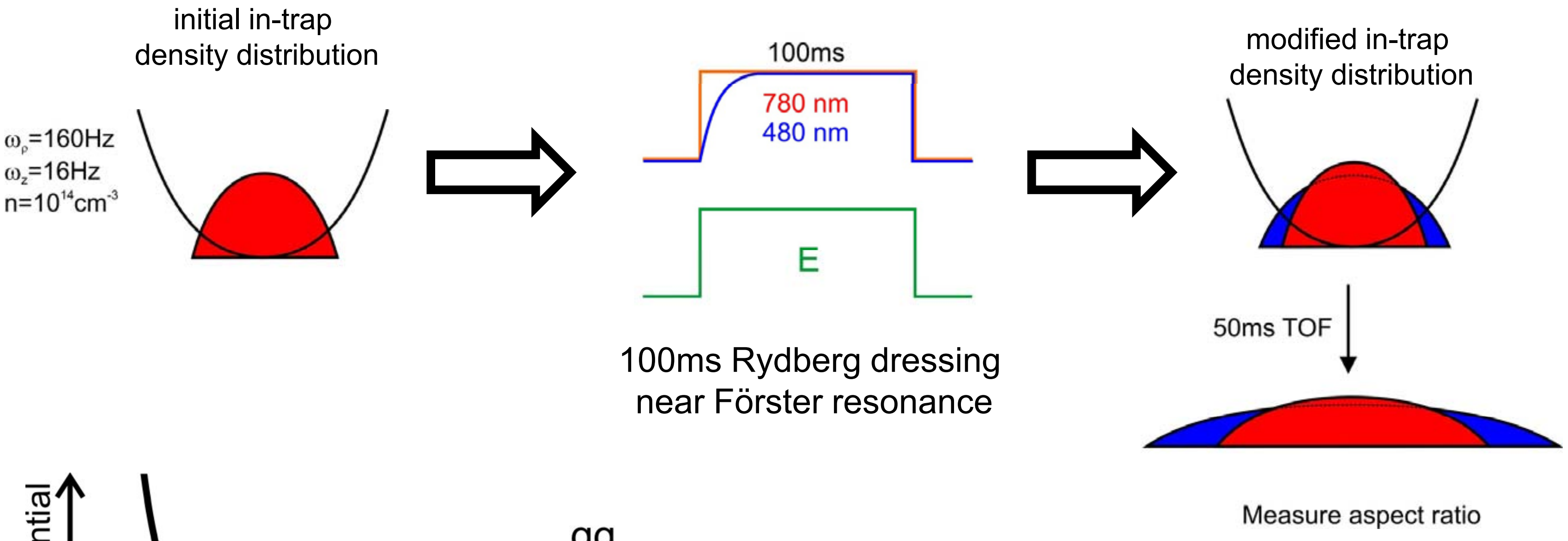
dressed states

resonant „dressing“ | off-resonant dressing

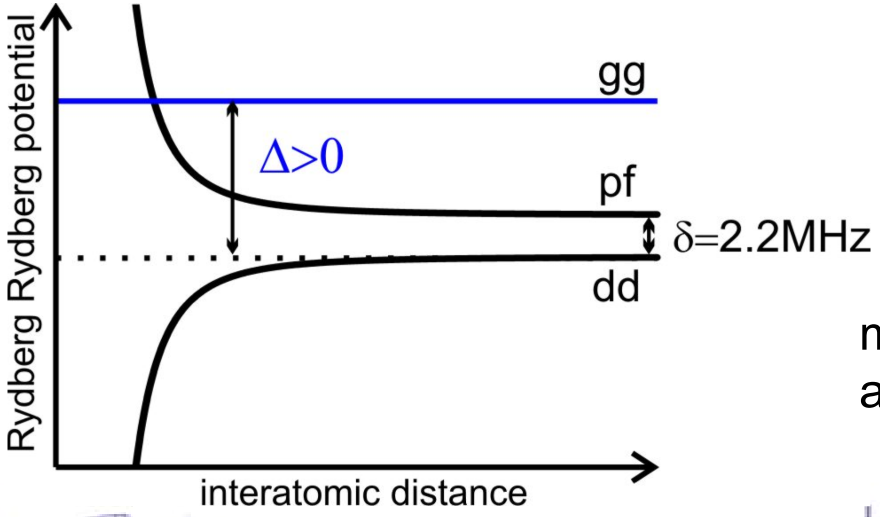


see also G. Pupillo et al., PRL 104, 223002 (2010)

Experimental observation of Rydberg dressing

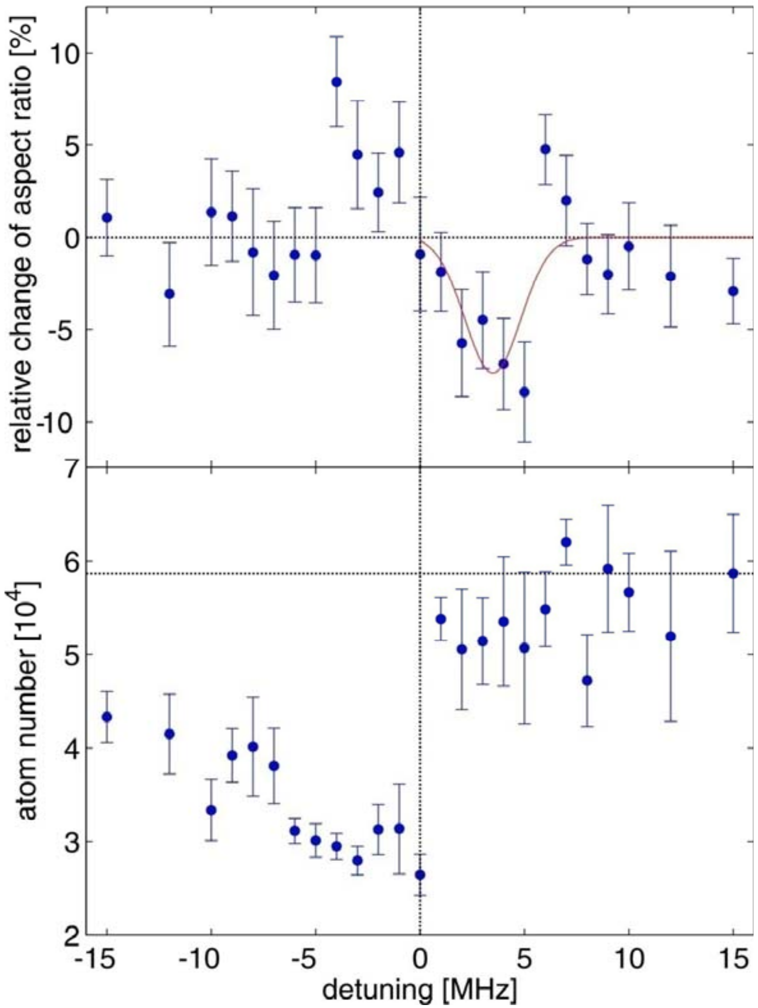


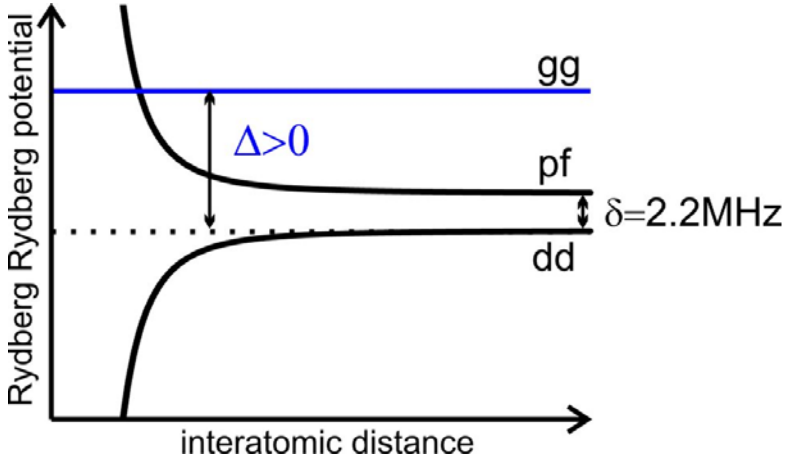
100ms Rydberg dressing
near Förster resonance



measure (expanded) BEC shape
as function of dressing laser detuning

First dressing results





Explanation:

- off-resonant dressing: small BEC size: most atoms sit inside the blockade
  thermal background contributes to blockade but not to dressing
- resonant case: no working theory when most atoms are inside the blockade

Observations:

- (small) effect for resonant excitation
- strong atom loss for resonant excitation of attractive branch

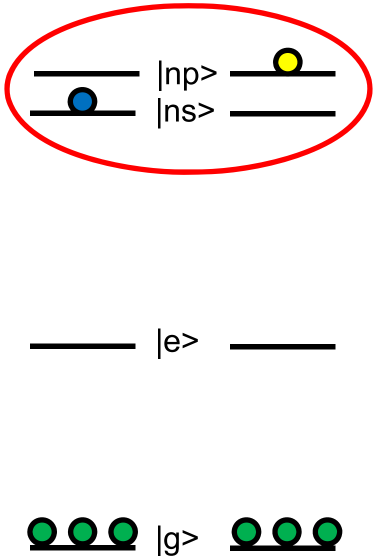
Rydberg excitation hopping

idea: move dynamics completely to Rydberg states

1µs ← Time scale → 10 ns

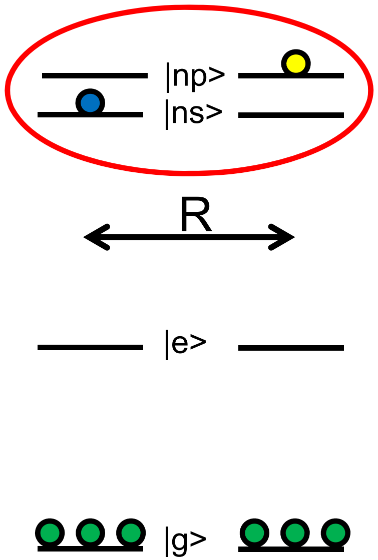
Ground state/Rydberg coupling

2 dipole-coupled Rydberg states



see also: Weidemüller, Coté, Rost

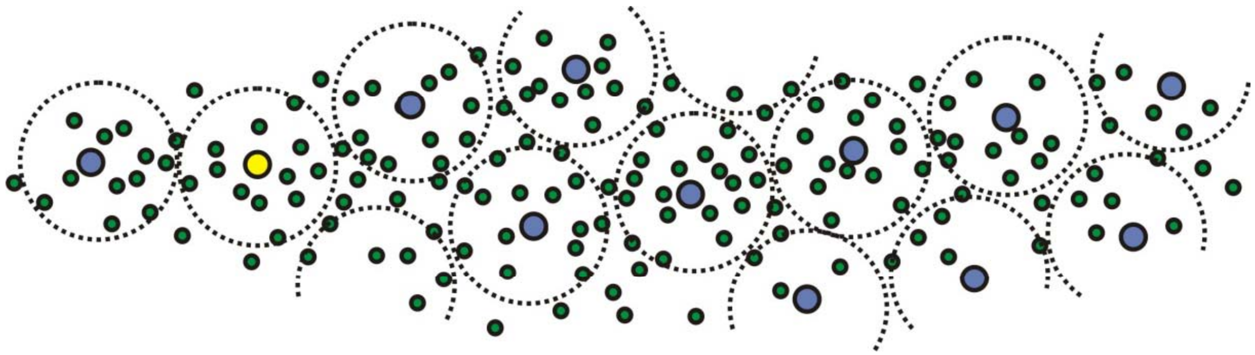
Rydberg networks



non-radiative coupling of dipoles

$$V_{dip} = \frac{C(E)\,\mu_{sp}^{2}}{R^{3}} \sim \frac{n^{4}}{R^{3}}$$

for realistic parameters:
t_{hop} = 1…100ns

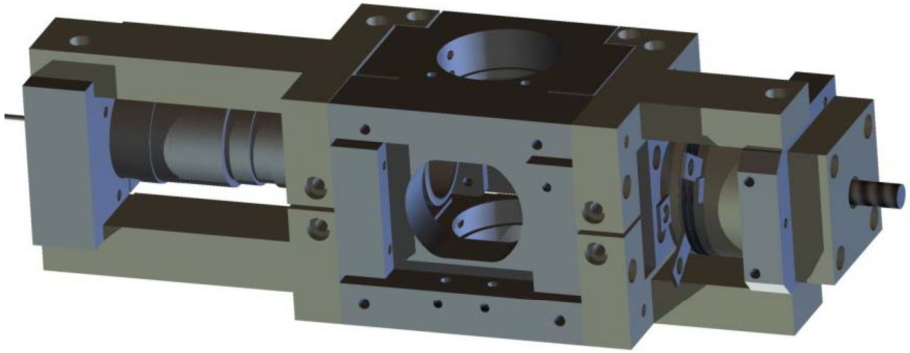


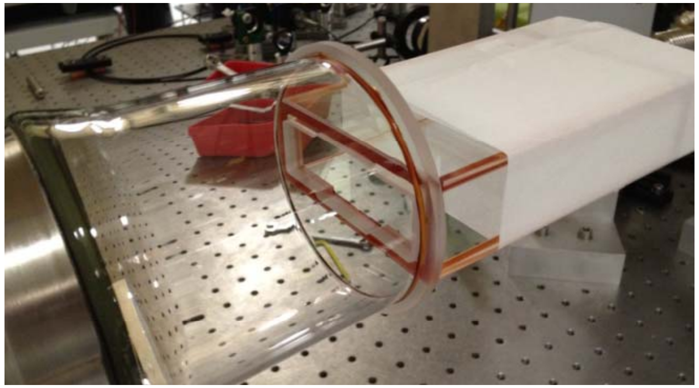
- s-state Rydberg atoms: nodes in arbitrary (2d) grid (optical lattice)
- p-state Rydberg atoms: moving excitations (tunnelling atoms)
- ground state atoms: reservior for many repetitions …

Experimental implementation

Requirements:

- excitation of 2 Rydberg species → combination of lasers & microwave
- deterministic preparation of Rydberg grid
  - → GHz Rabi flopping (demonstrated)
  - → resolution smaller than blockade volume
- single excitation detection → spatially resolved, state selective ionization
  - → single ion detection





new setup with all these features under construction

Single-photon nonlinear optics enabled by Rydberg interactions

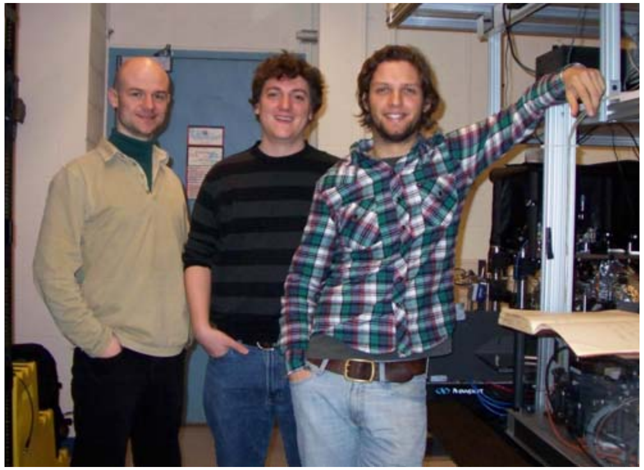
Harvard/MIT Center for Ultracold Atoms

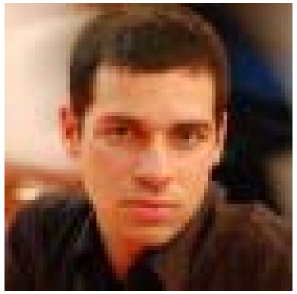
People on the CUA experiment

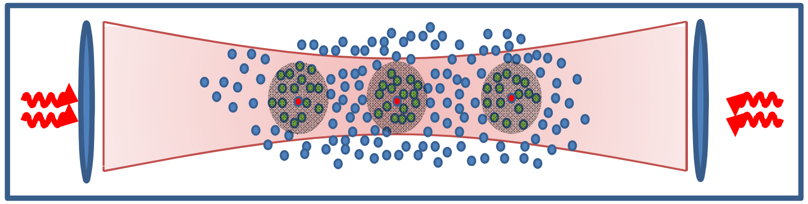
<u>Rydberg Experiment:</u>

- Thibault Peyronel
- Qiyu Liang
- Ofer Firstenberg
- Sebastian Hofferberth

Vladan Vuletic
Mikhail Lukin



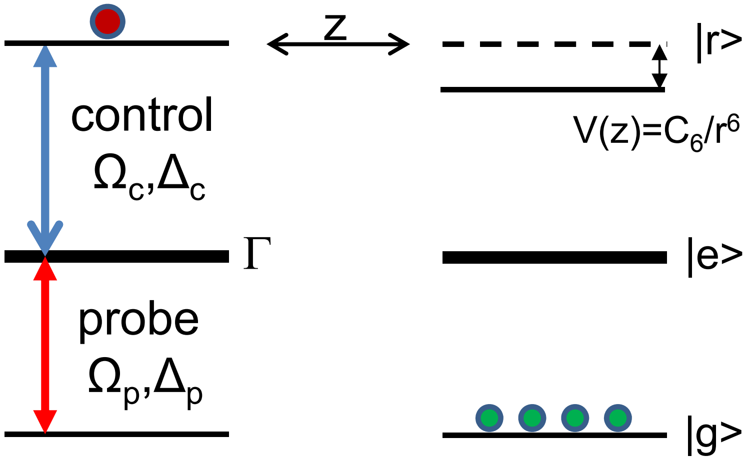




Theory: Thomas Pohl, Alexey Gorshkov

collective Rydberg nonlinearities

Rydberg Blockade:



Blockade radius:

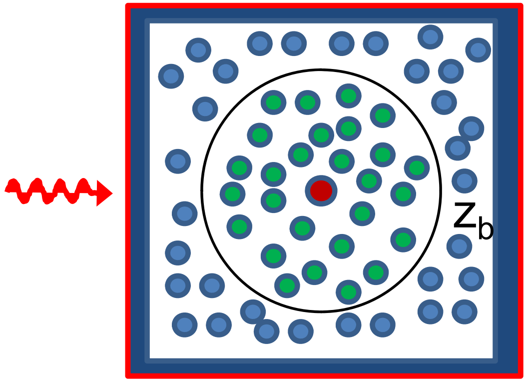
$$V(z_b) = \frac{\Omega_c^2}{\Gamma}$$

EIT linewidth for OD~1

$$\boxed{z_B = \left(\frac{\Gamma C_6}{\Omega_c^2}\right)^{1/6}}$$

	$\Gamma - 2\pi \cdot 7MHz$ $\Omega = 2\pi \cdot 7MHz$	$\Gamma - 2\pi \cdot 7MHz$ $\Omega = 2\pi \cdot 1MHz$
34S-34S	1.6 µm	3.1 µm
40S-40S	2.3 µm	4.4 µm
60S-60S	3.8 µm	7.3 µm
60D-60D	4.1 µm	7.8 µm

collective nonlinearity:



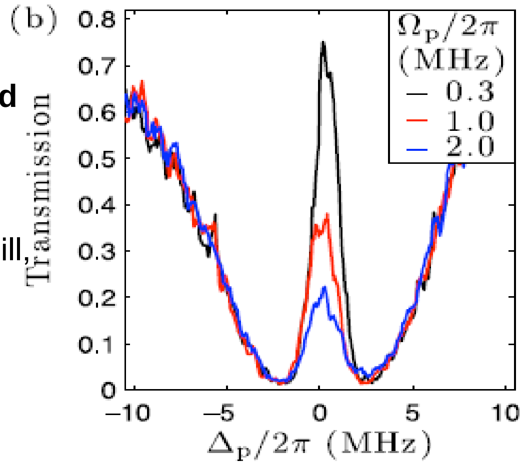
single (stored) photon changes
optical properties of 10…1000 atoms

groundbreaking work:

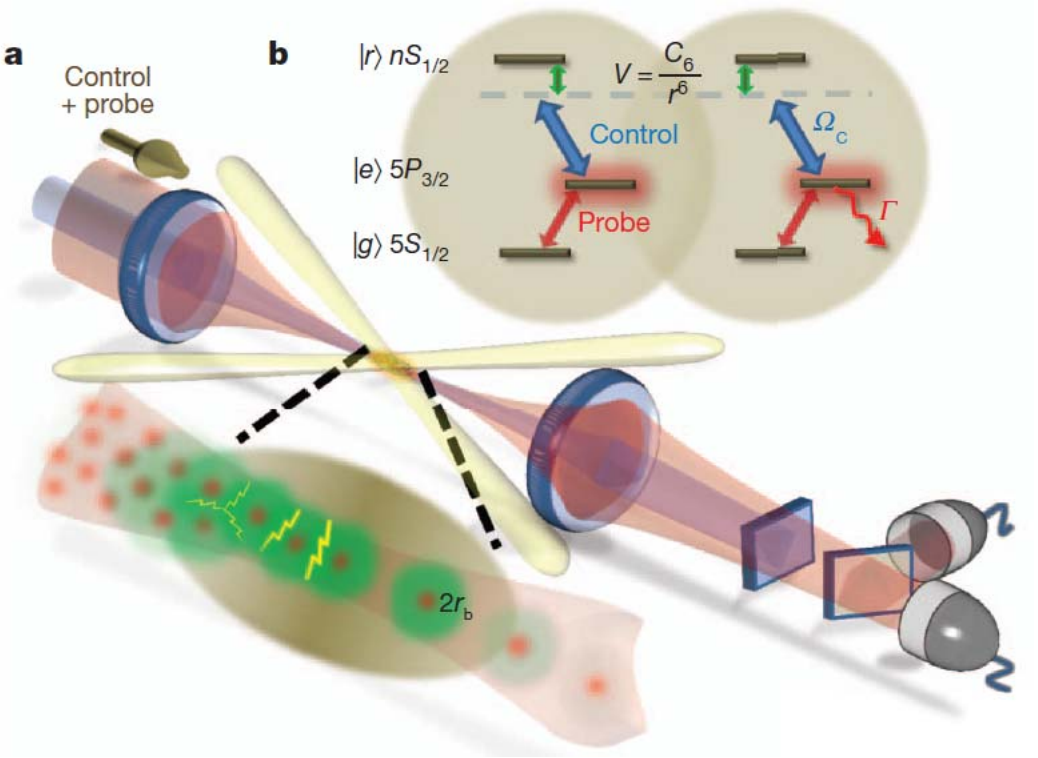
Cooperative Atom-Light Interaction in a Blockaded Rydberg Ensemble

J.D. Pritchard, D. Maxwell,
A. Gauguet, K.J. Weatherhill,
A. Gauguet, K.J. Weatherhill,
M.P.A. Jones, C.S. Adams

PRL 105, 193603 (2010)

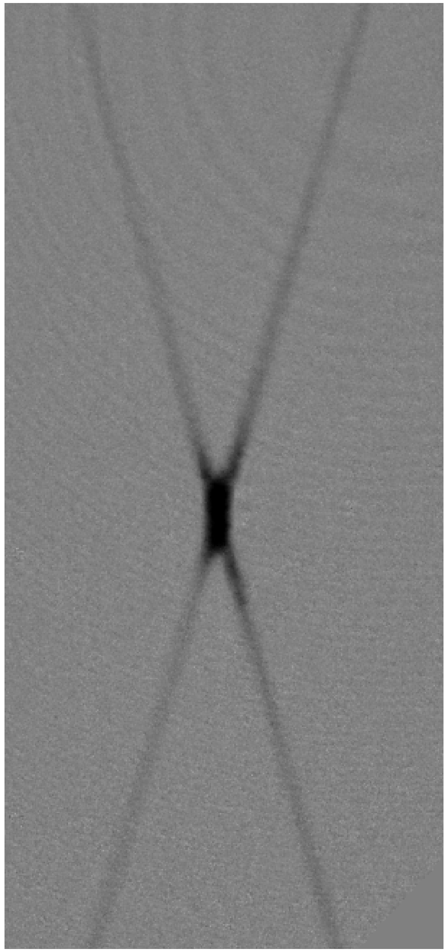


Experimental realization



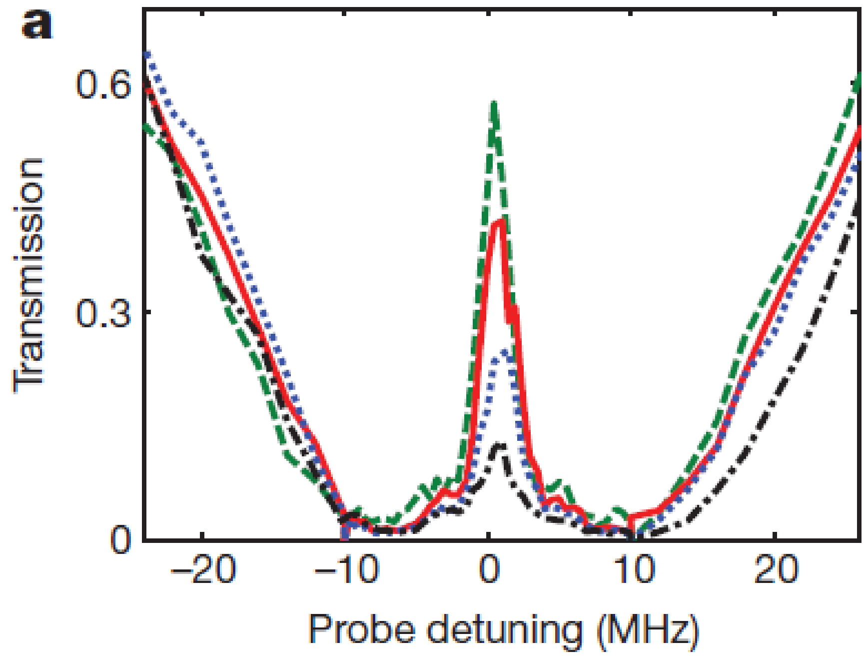
some parameters:

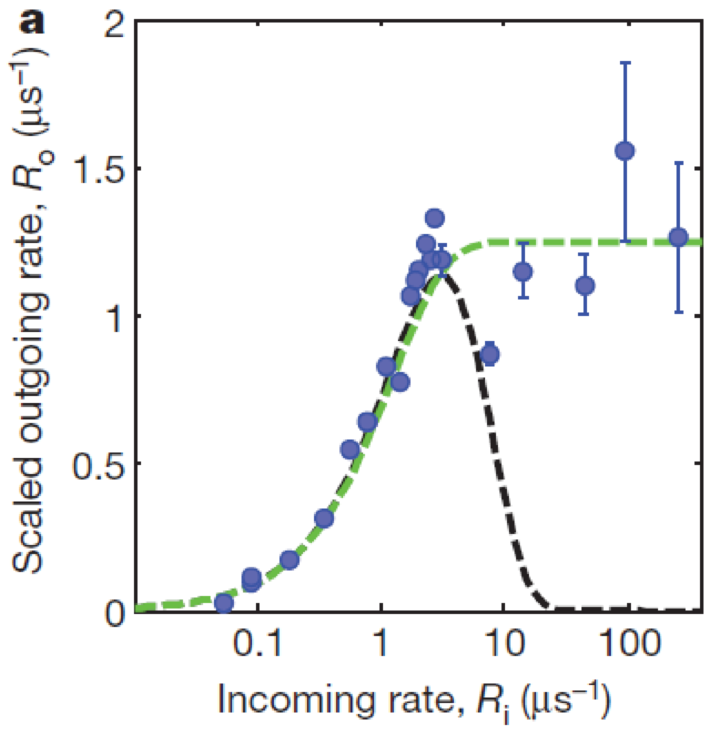
Number of atoms: ~10^5
Waist:16 µm (transverse)/50 µm(long.)
Peak density > $3\text{x}10^{11}$ / cm^3
T=45 µK
Transverse OD > 4
Longitudinal OD > 40 (with optical pumping)
Lifetime: 1s (with 500kHz modulation)



atoms loaded into dipole trap

Single photon nonlinearity





cw EIT transmission for
1, 2, 4, 6 incoming probe
photons per μs

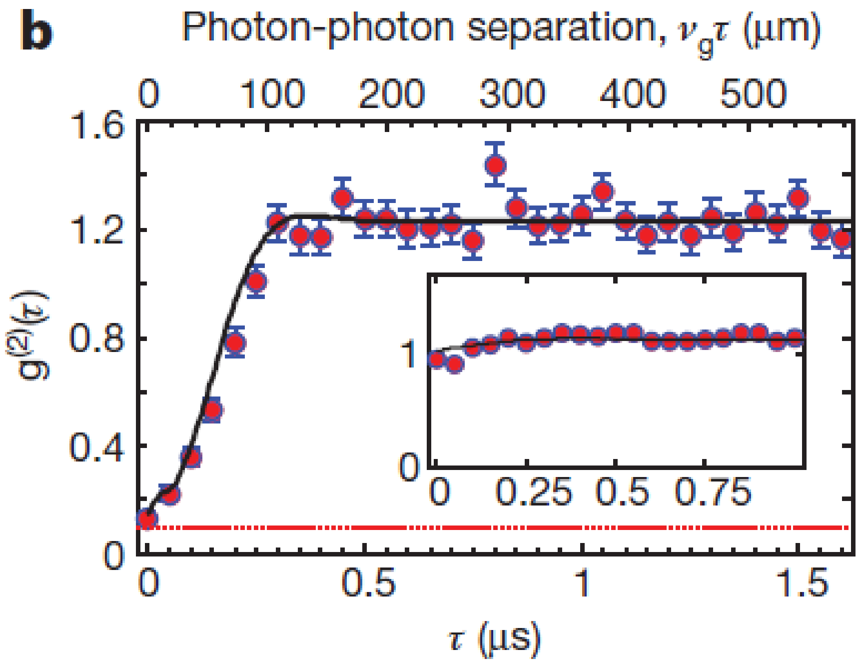
Rydberg blockade suppresses
EIT transmission if more than 1 photon
Is inside the medium

Outgoing vs incoming photon flux

Output saturates at single photon
level

T. Peyronel et al., accepted in Nature (2012)

Photon-photon correlation



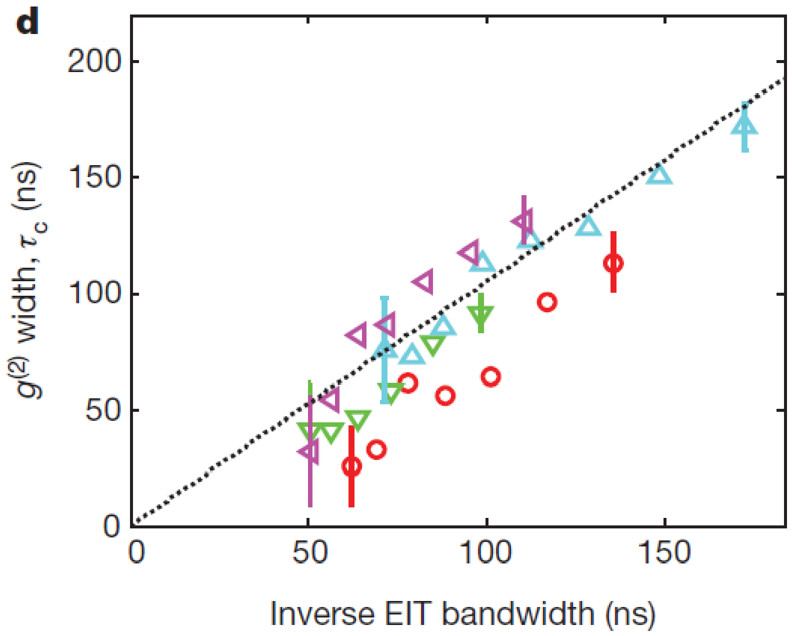
main plot: |100$S_{1/2}$>
inset: |46$S_{1/2}$>

OD = 40
EIT linewidth = 20 MHz

lowest g2(0) = 0.13

g(2) width given by EIT bandwidth!!
(not by blockade diameter)

polariton propagation has to be taken into account.
Full theory: T. Pohl/A. Gorshkov



T. Peyronel et al., accepted in Nature (2012)

Conclusion

Rydberg-Rydberg interaction in BEC

- Observation of coherent Rydberg-Rydberg interaction near stark tuned Förster resonances
- Förster interaction mapped to ground state → interaction-based gates
- First observation of Rydberg dressing
- Rydberg excitation hopping as new approach to tailored strongly interacting
- -

Rydberg mediated nonlinearity

- Rydberg-Rydberg interaction creates nonlinear medium on the single photon level
- width of correlation function given by EIT bandwidth, not blockade diameter
  Full theory: Pohl & Gorshkov
- next steps:

  two-photon phase gate
  single photon switch/transistor

  strongly nteracting photonic many-body systems