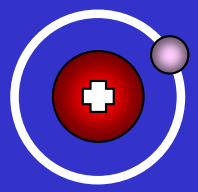
Rydberg atoms and their applications

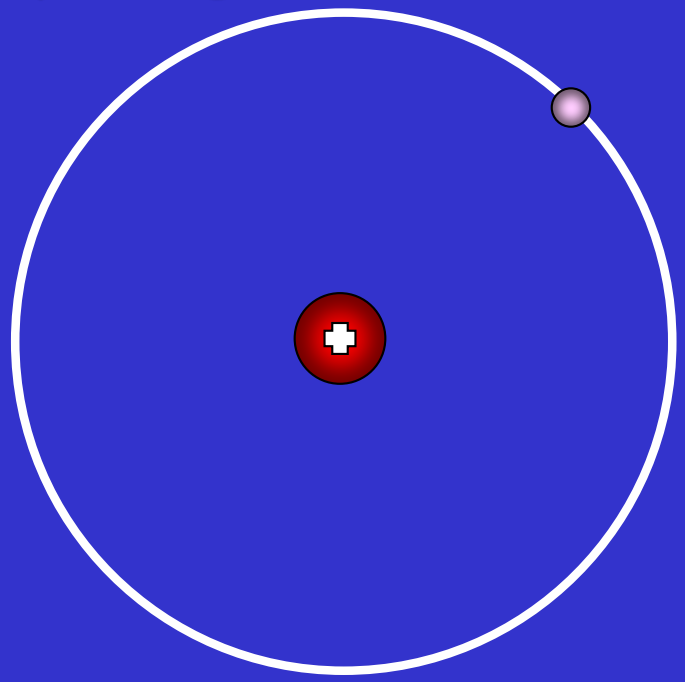
I.I.Ryabtsev[1,2], I.I.Beterov[1,2,3], E.A.Yakshina[1,2,3], D.B.Tretyakov[1,2], V.M.Entin[1], I.N.Ashkarin[1,2], A.M.Faruk[2], N.V.Alyanova[1,3], P.I.Betleni[1,2], N.O.Zhuravlev[2]

[1] Rzhanov Institute of Semiconductor Physics SB RAS, Novosibirsk, Russia
[2] Novosibirsk State University, 630090 Novosibirsk, Russia
[3] Institute of Laser Physics SB RAS, Novosibirsk, Russia

Atom in a ground state with n~1



Rydberg atom with n >> 1



Quantum numbers: *n* , *L*

n - principal quantum number

L - orbital moment

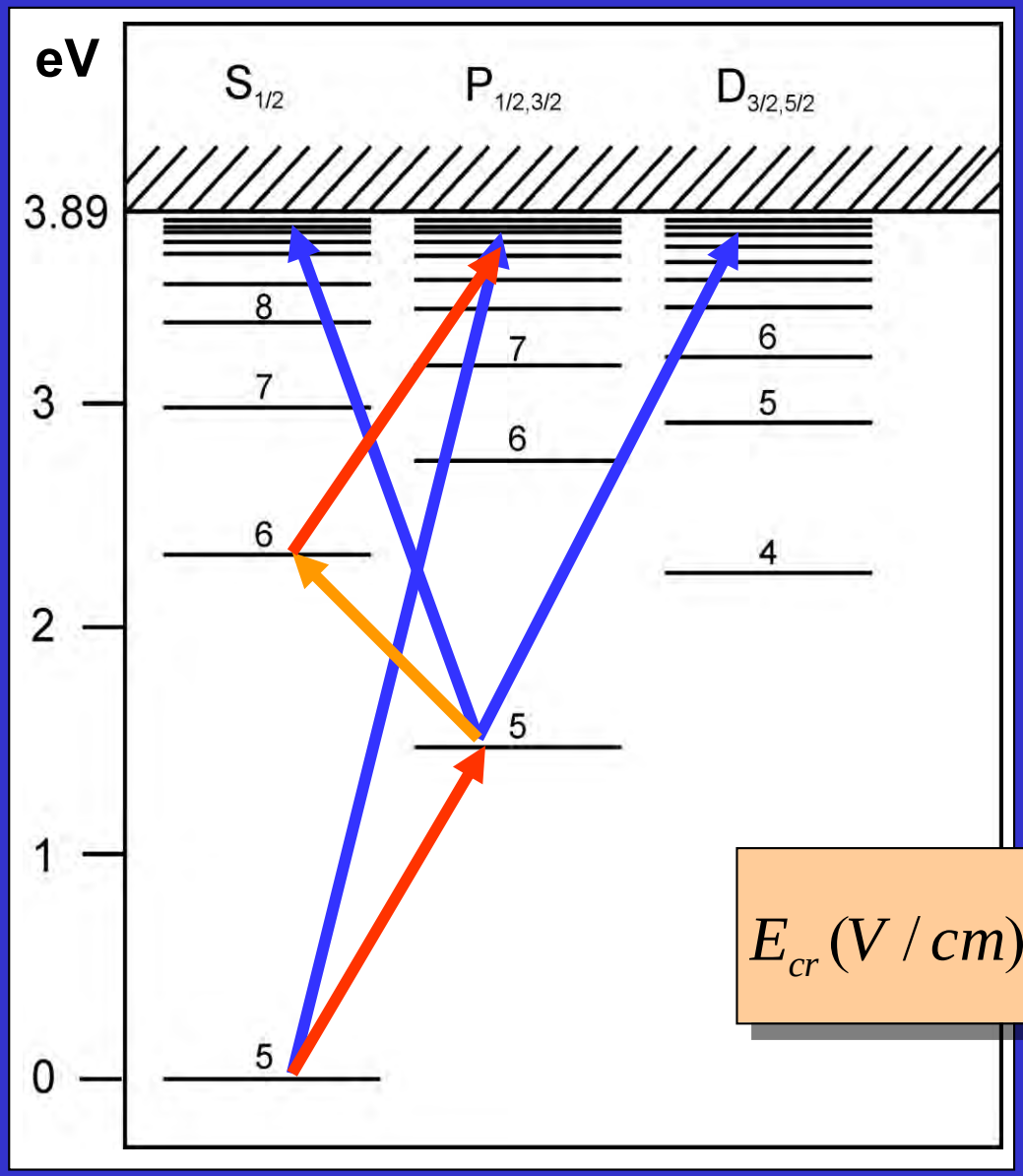
$$E_n = -\frac{Ry}{n^2}$$

$$E_n = -\frac{Ry}{(n-\delta_L)^2}$$

$$r_n \sim n^2$$

Rydberg atoms

Energy levels in Rb atoms

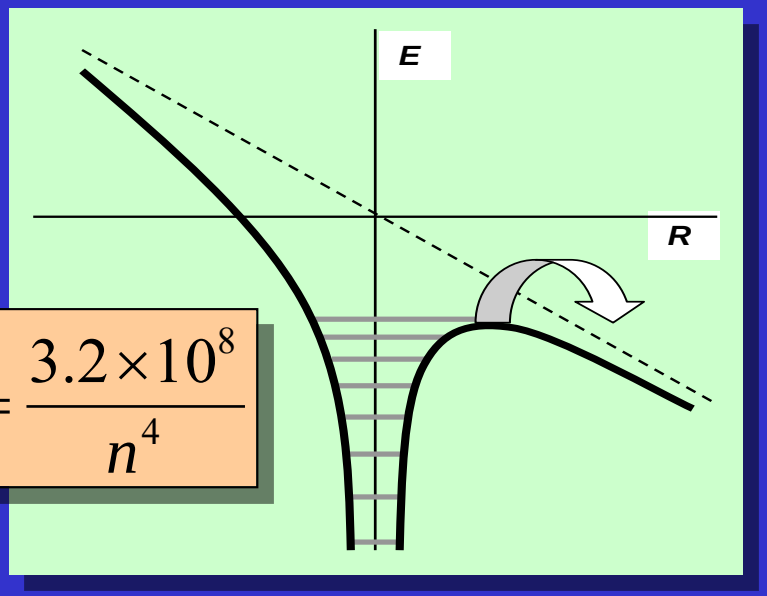


$$E_n = -\frac{Ry}{(n-\delta_L)^2}$$

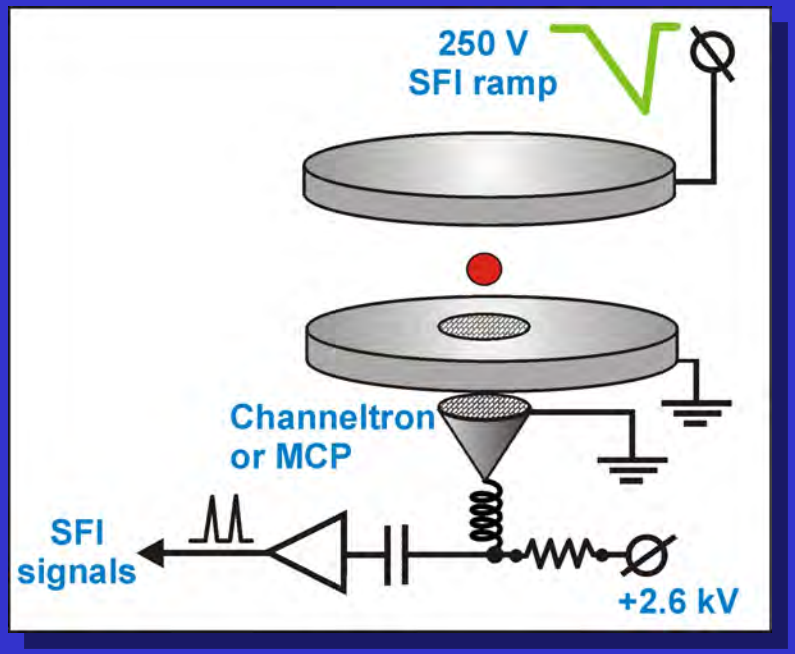
$$r_n \sim n^2 \qquad \tau_n \sim n^3 - n^5$$

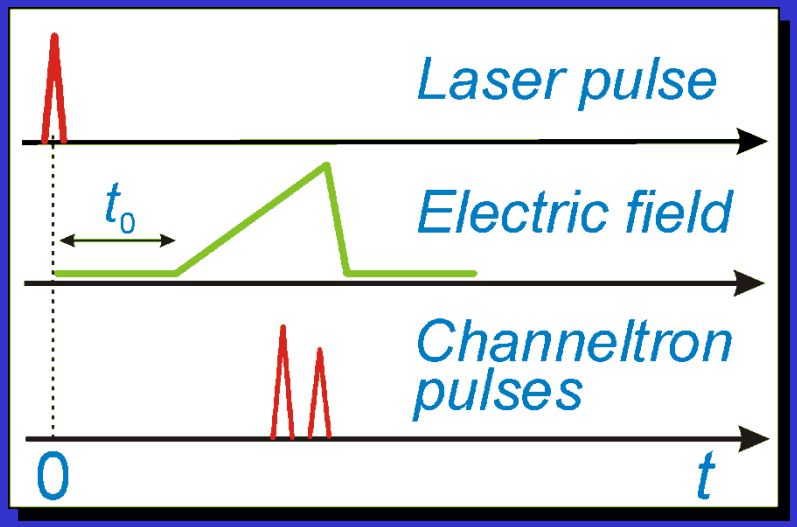
$$\alpha_n \sim n^7$$

$$E_{cr}(V/cm) = \frac{3.2\times10^8}{n^4}$$



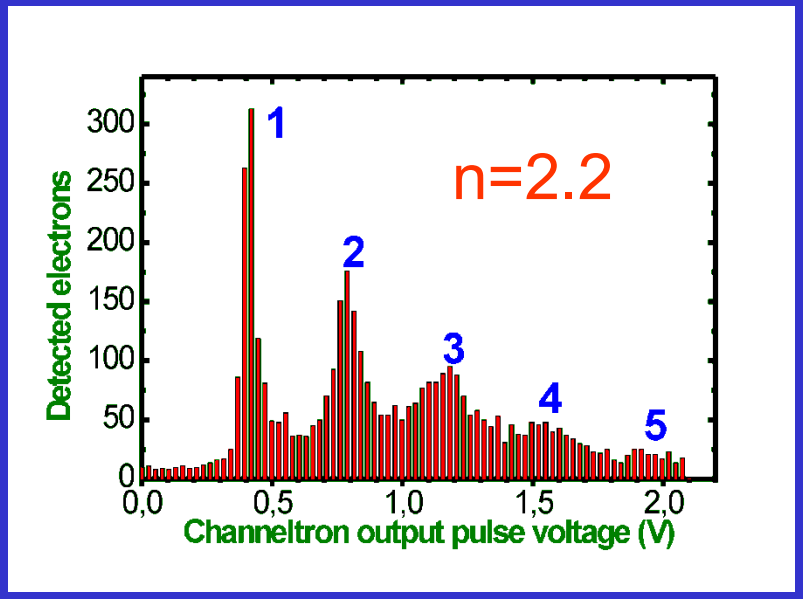
Selective Field Ionization detector

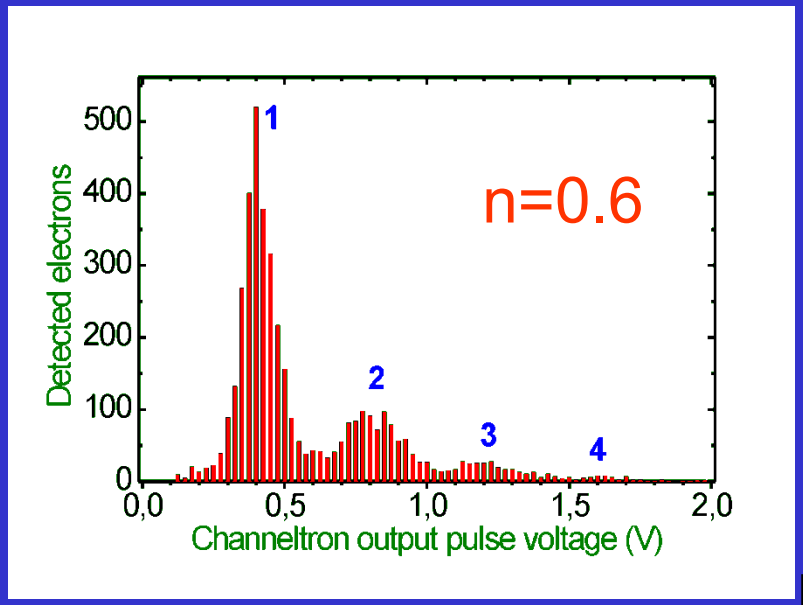




Atom counting with CEM

Ryabtsev et al., PRA 76 (2007) 012722

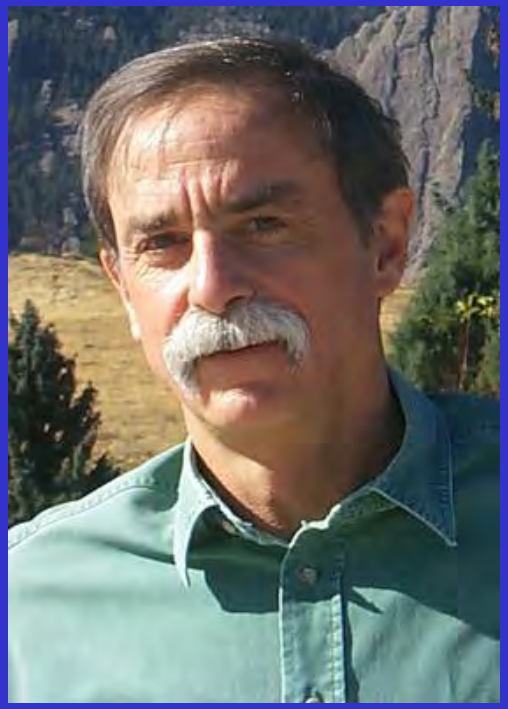




MOTIVATION

- Laser and microwave spectroscopy
- Collisions and chemionization
- Photoionization
- Ultracold plasmas
- Many-body phenomena
- Neutral atom quantum computing
- Single-photon sources
- Electric-field sensors

Nobel Prize laureates for physics in 2012



Serge Haroche

Born: 1944, Casablanca, Morocco

Affiliation at the time of the award: Collège de France, Paris, France, École Normale Supérieure, Paris, France

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

David J. Wineland

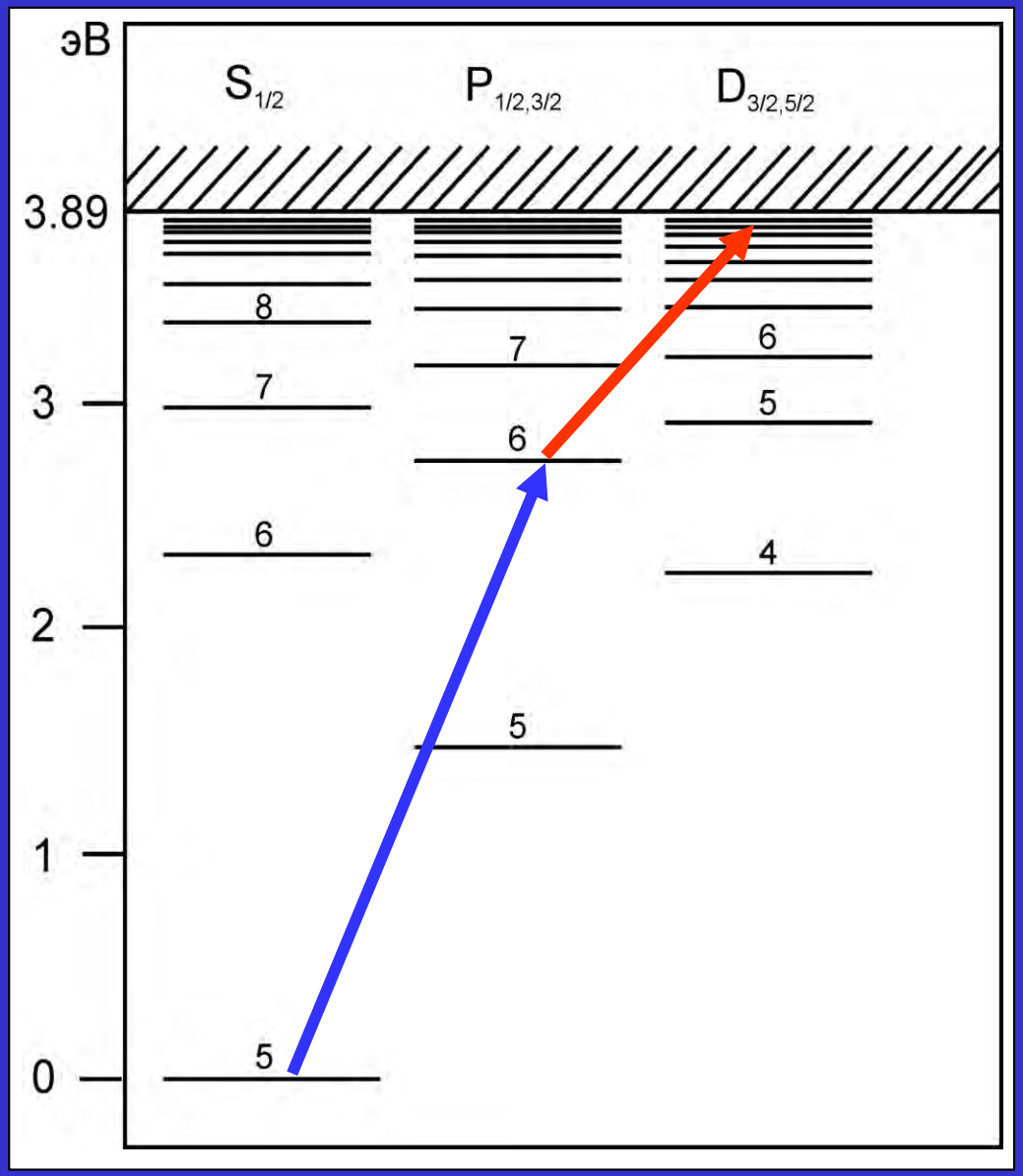
Born: 1944, Milwaukee, WI, USA

Affiliation at the time of the award: National Institute of Standards and Technology, Boulder, CO, USA, University of Colorado, Boulder, CO, USA

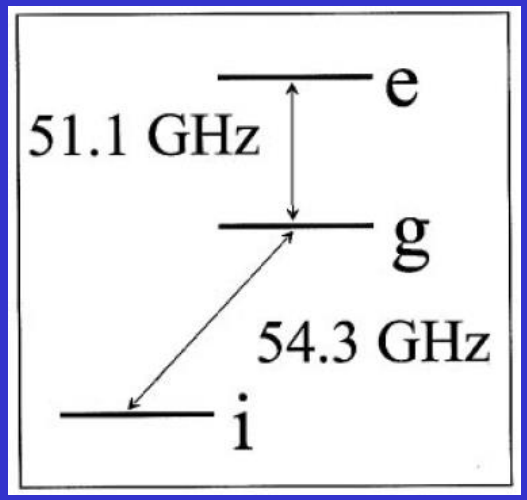
Prize motivation: "for ground-breaking experimental methods that enable measuring and manipulation of individual quantum systems"

Experiments of S.Haroche

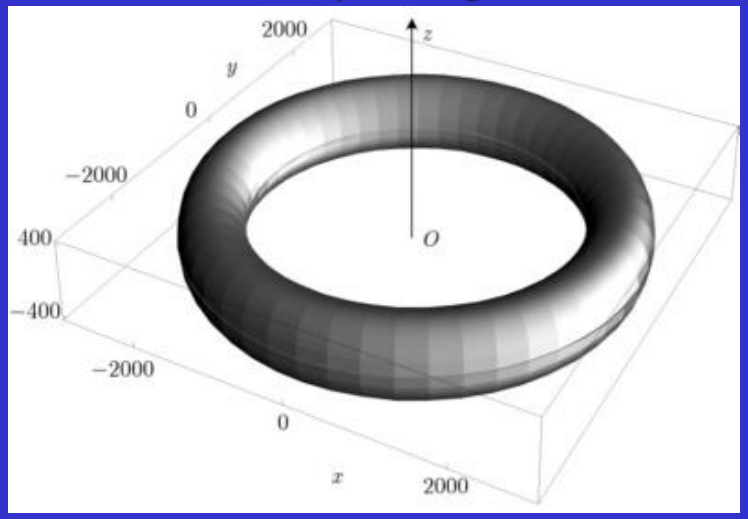
Energy levels in Rb atoms



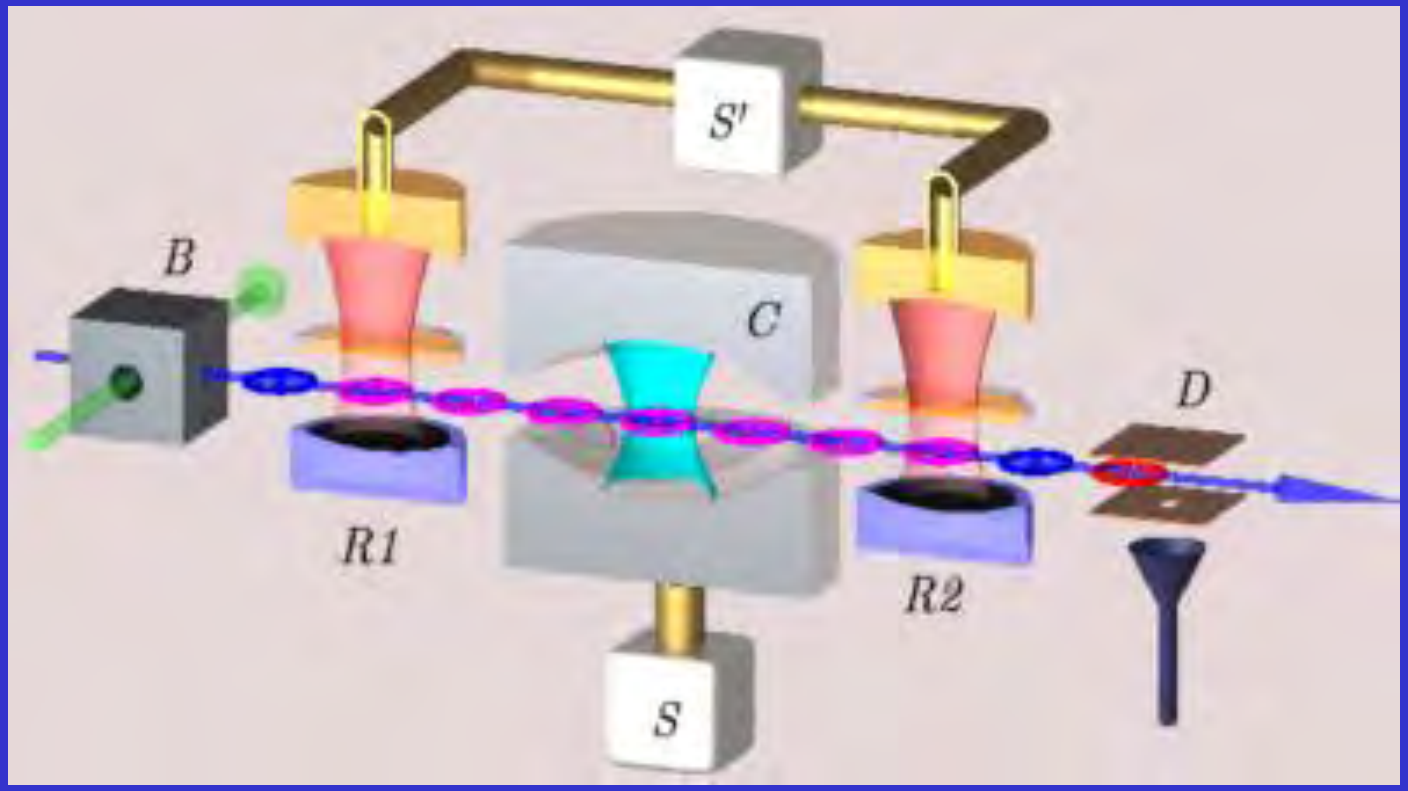
Microwave transition



Circular Rydberg state

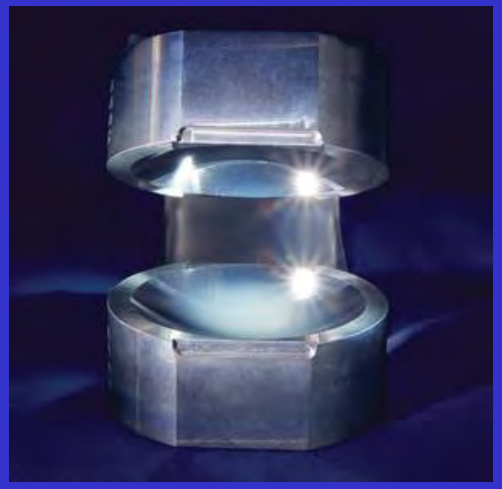


Experiments of S.Haroche



$$E_n = (n + 1/2)\hbar\omega$$

$$P_n = e^{-\mu}\ \mu^n / n!$$



Experiments of S.Haroche

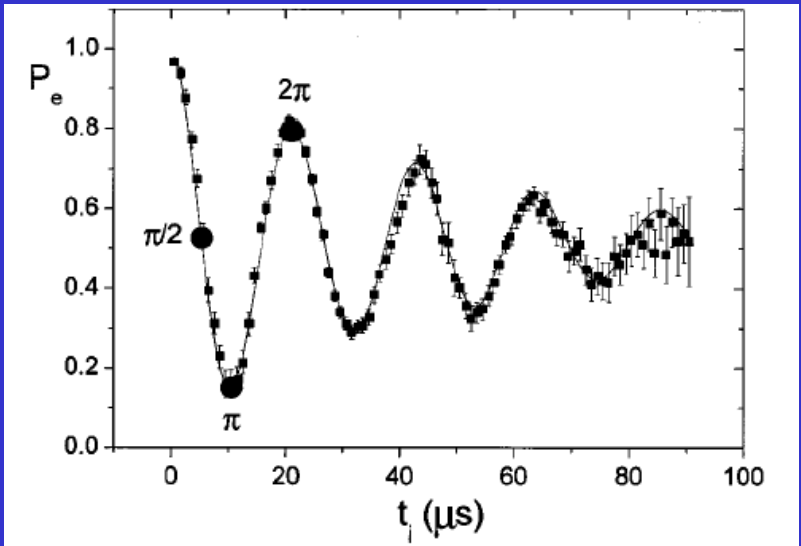


FIG. 3. Vacuum Rabi oscillations. The atom in state *e* enters

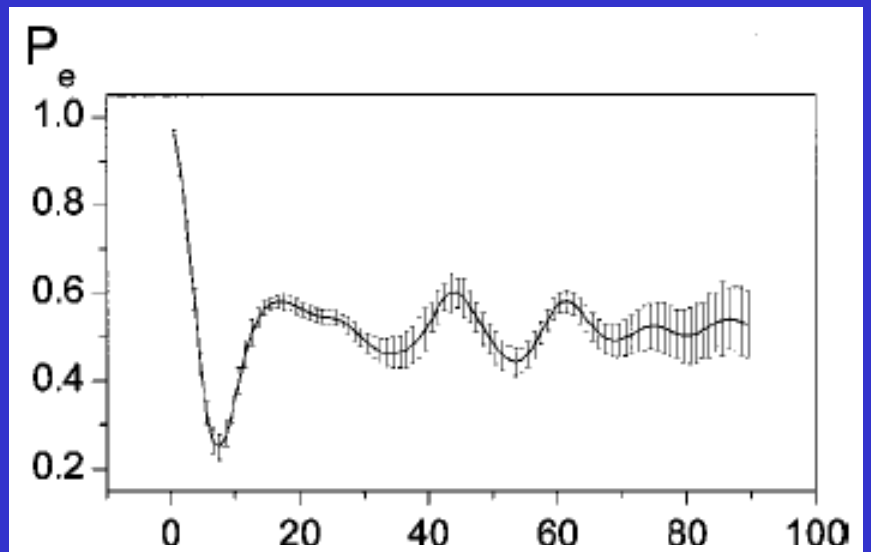
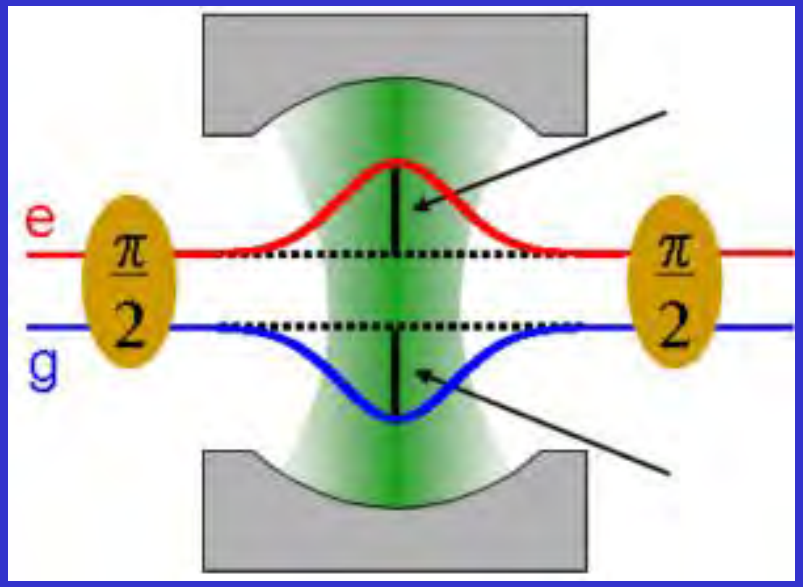
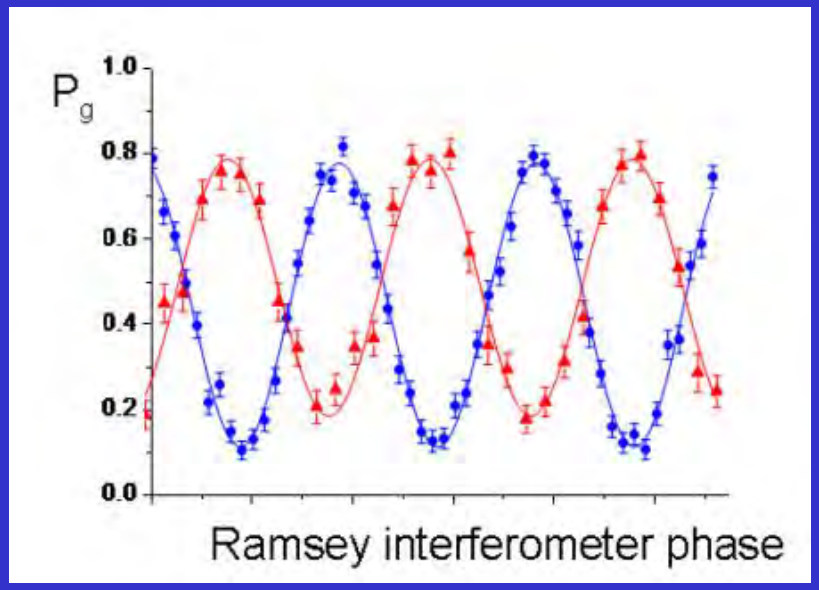


FIG. 5. Quantum Rabi oscillation in a coherent field.

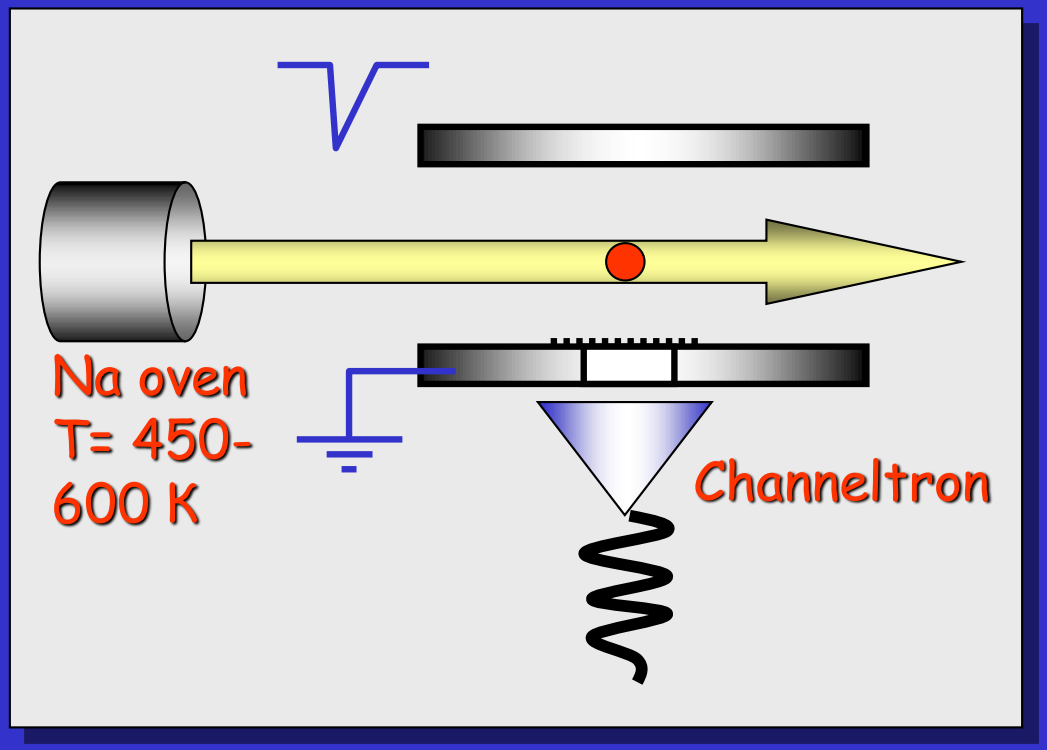


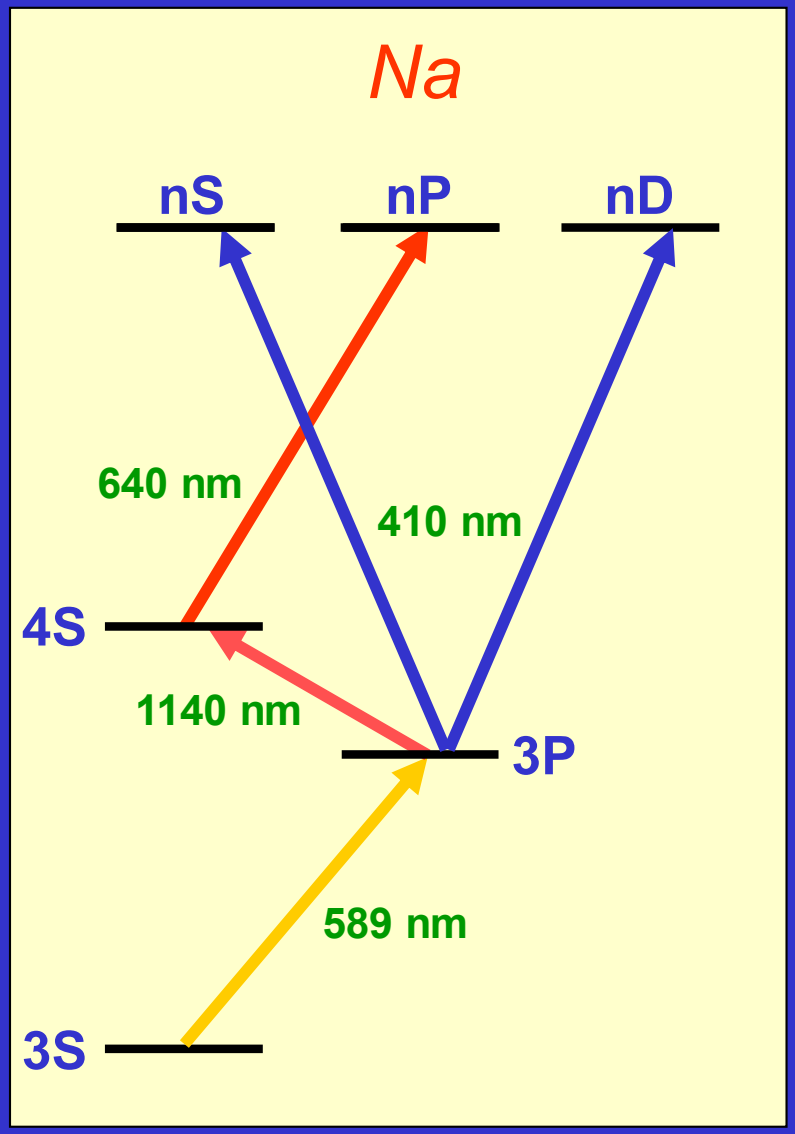


Veniamin Chebotaev
(1938-1992)

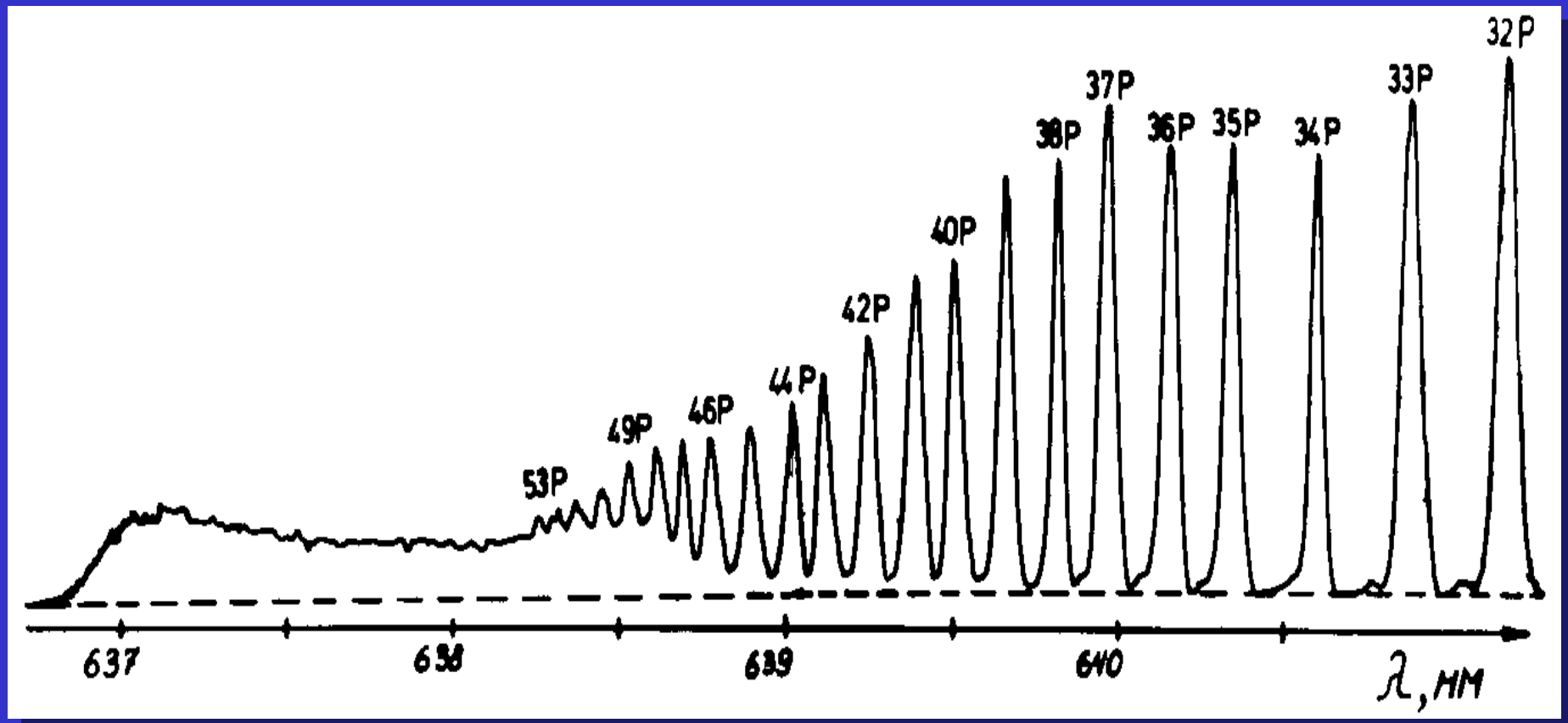
Igor Beterov
(1942-1999)

Experiments with Na atomic beam

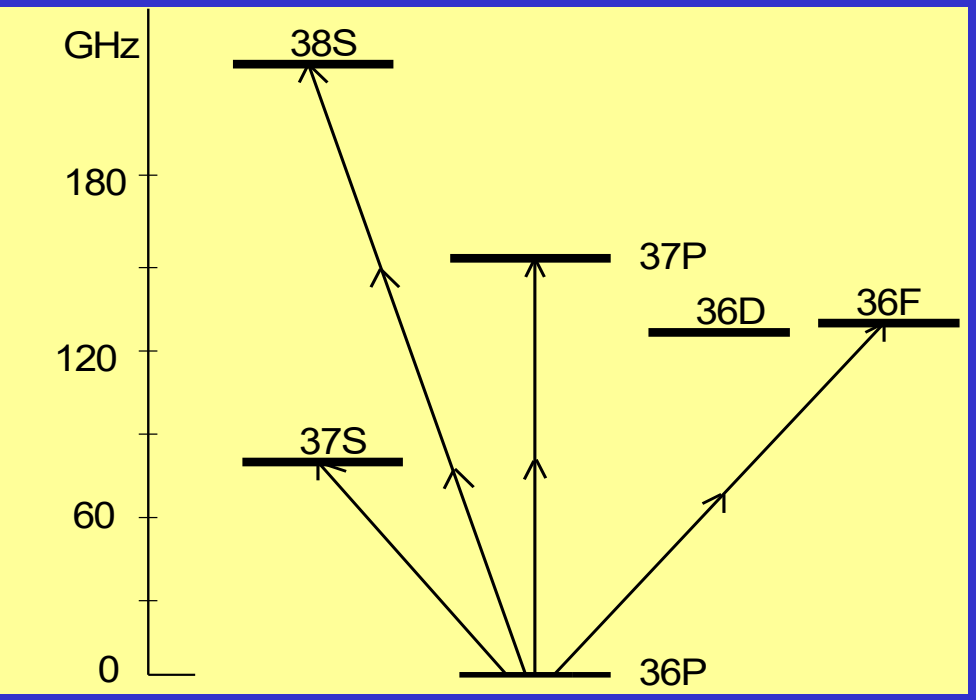


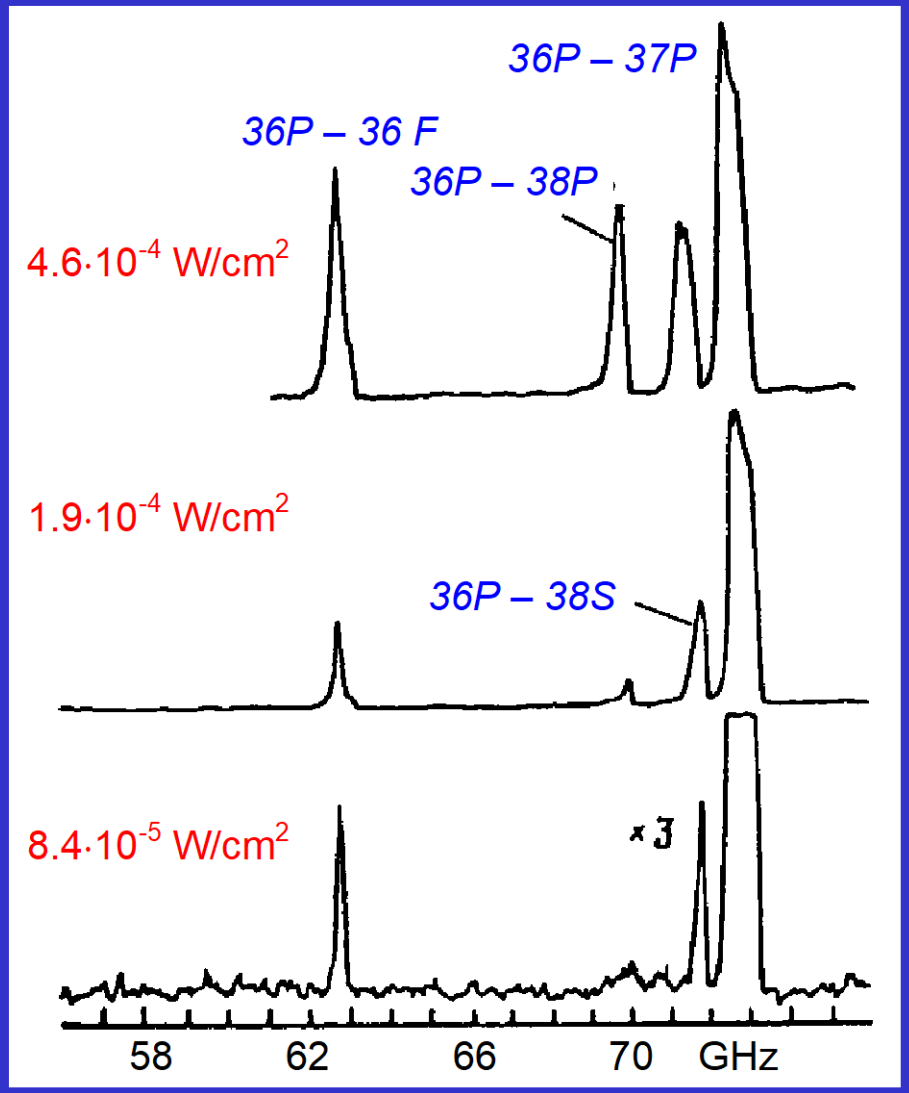


Three-photon laser excitation spectrum of nP Rydberg states in Na atoms

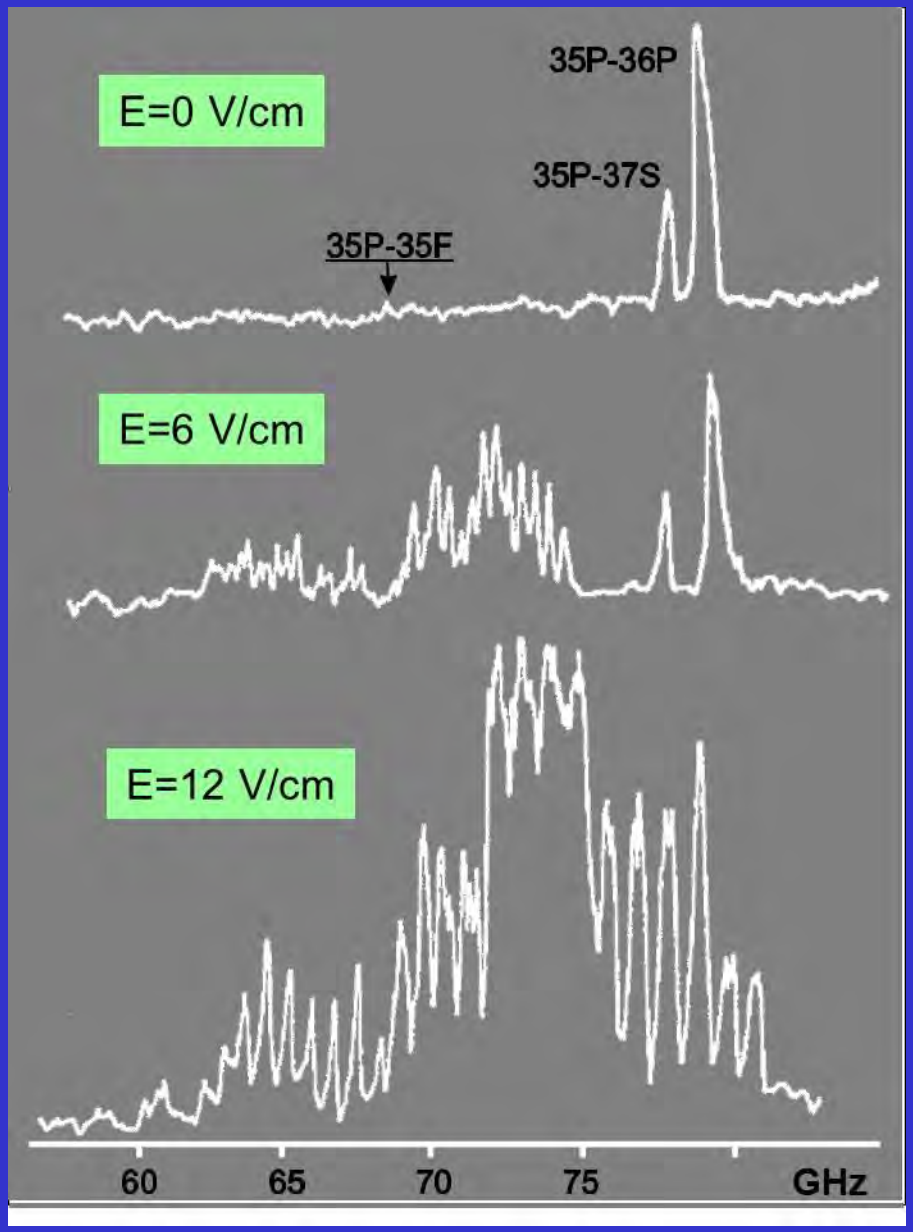


Multiphoton microwave transitions from the 36P state

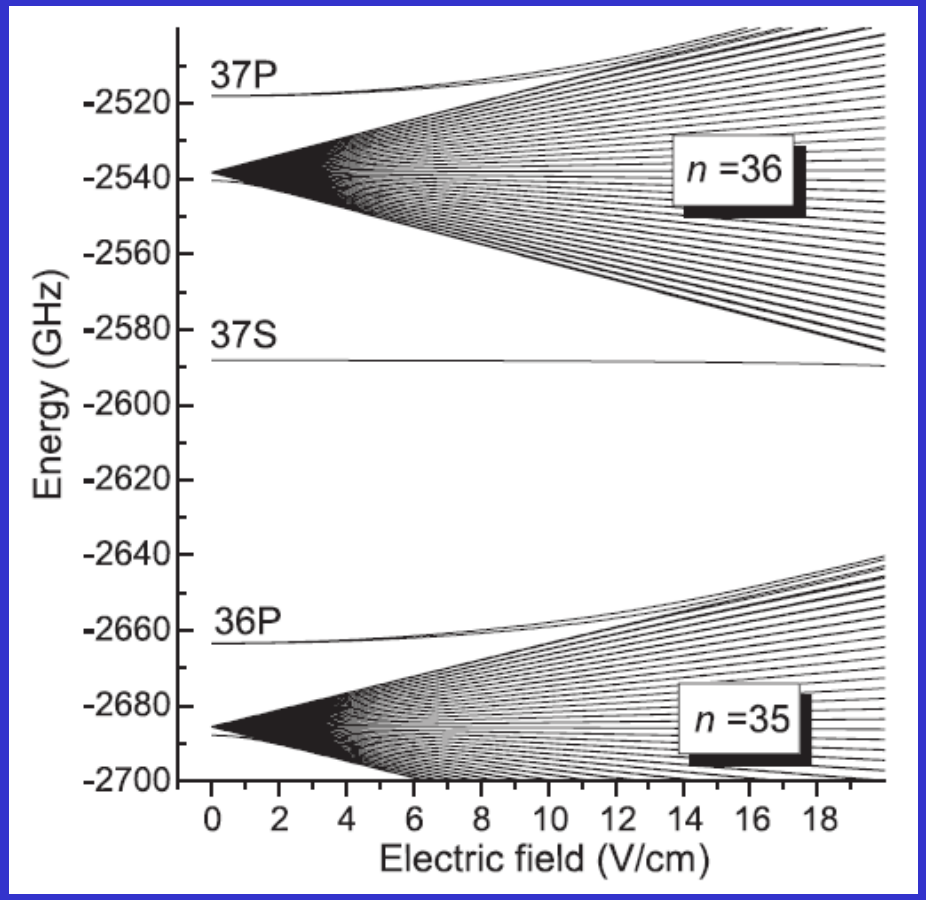




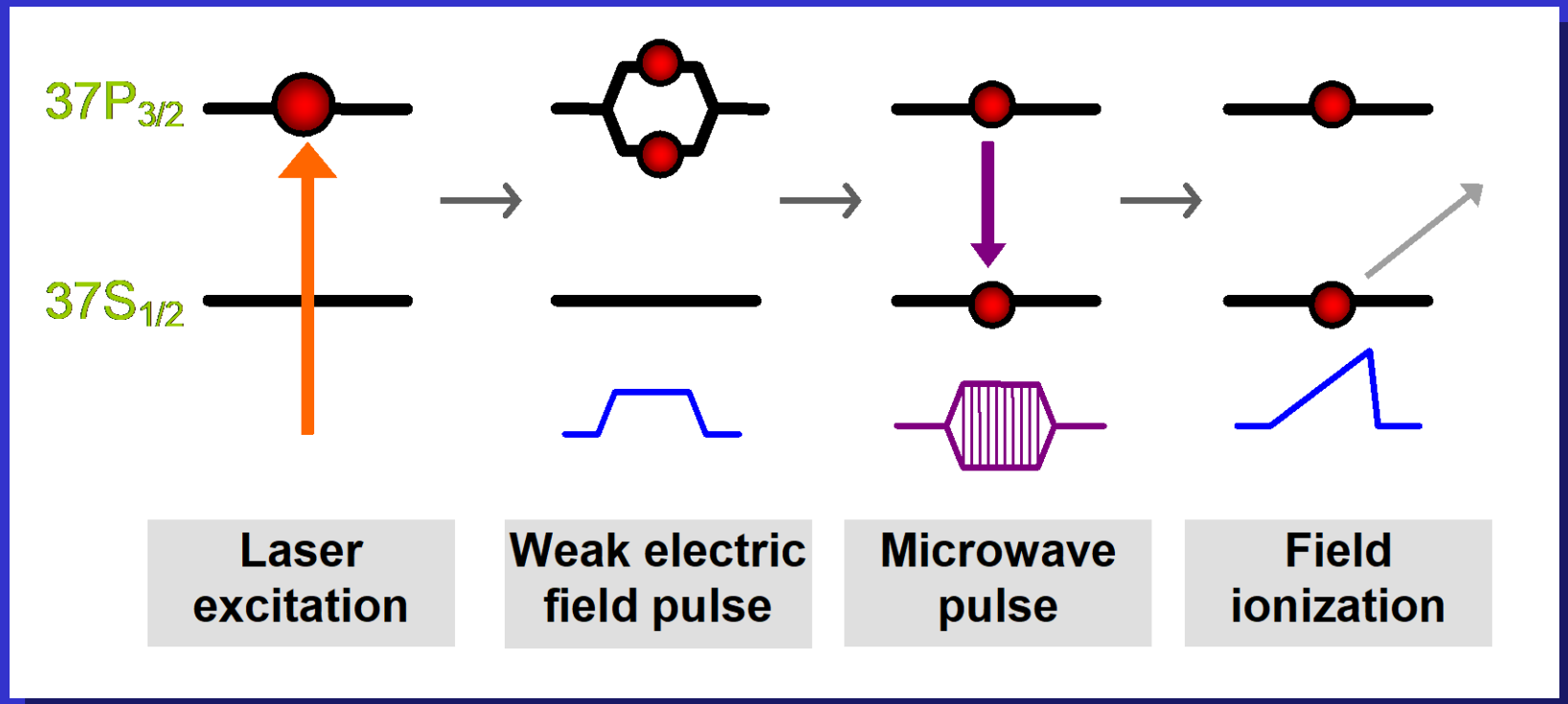
dc Stark effect on microwave transitions from 35P state



Stark map of Na Rydberg states



Quantum interferometry of degenerate Rydberg states



Phase shift from the electric-field pulse

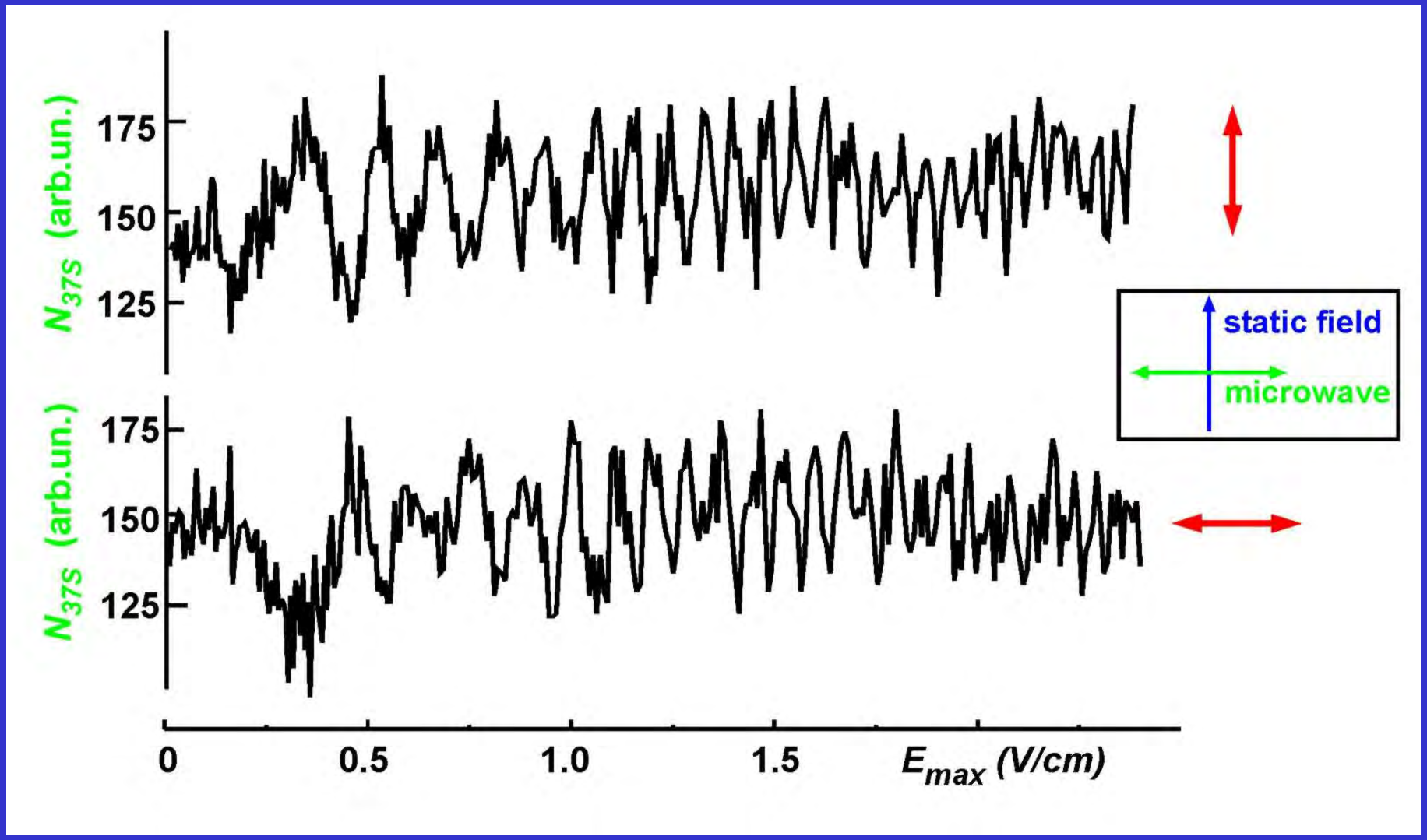
$$\varphi = 2\pi\alpha_2 \int_0^\infty E^2(t)\,dt$$

Population of the final state

$$N(37\mathrm{S}) \sim 5 + 3\cos\varphi$$

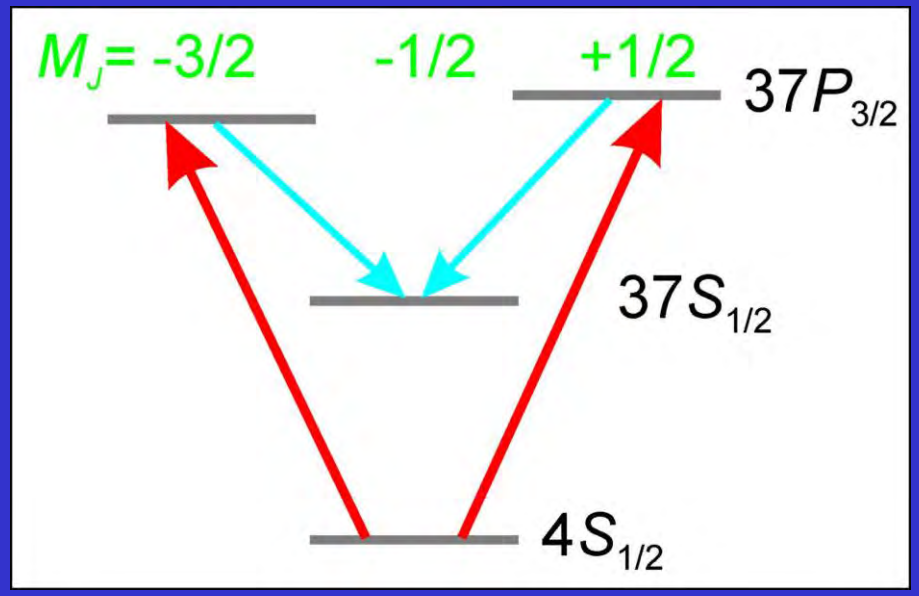
*I.I.Ryabtsev and I.M.Beterov, Phys. Rev. A **61**, 063414 (2000)*

Quantum interferometry of degenerate Rydberg states

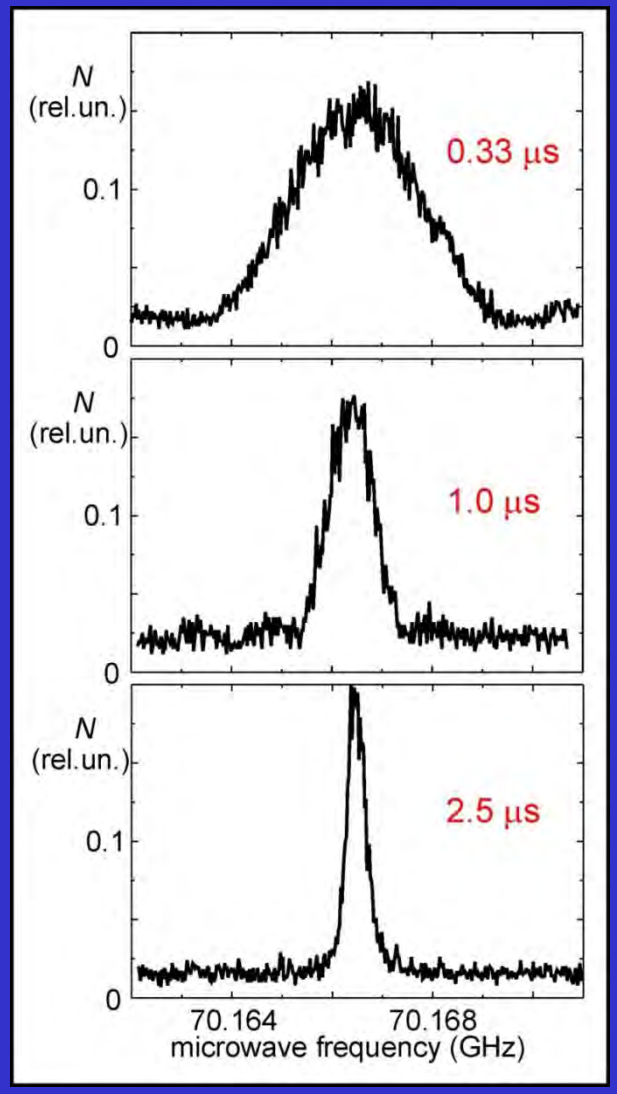


*I.I.Ryabtsev and I.M.Beterov, Phys. Rev. A **61**, 063414 (2000)*

Microwave Hanle effect for degenerate Rydberg states



Spectra without magnetic field

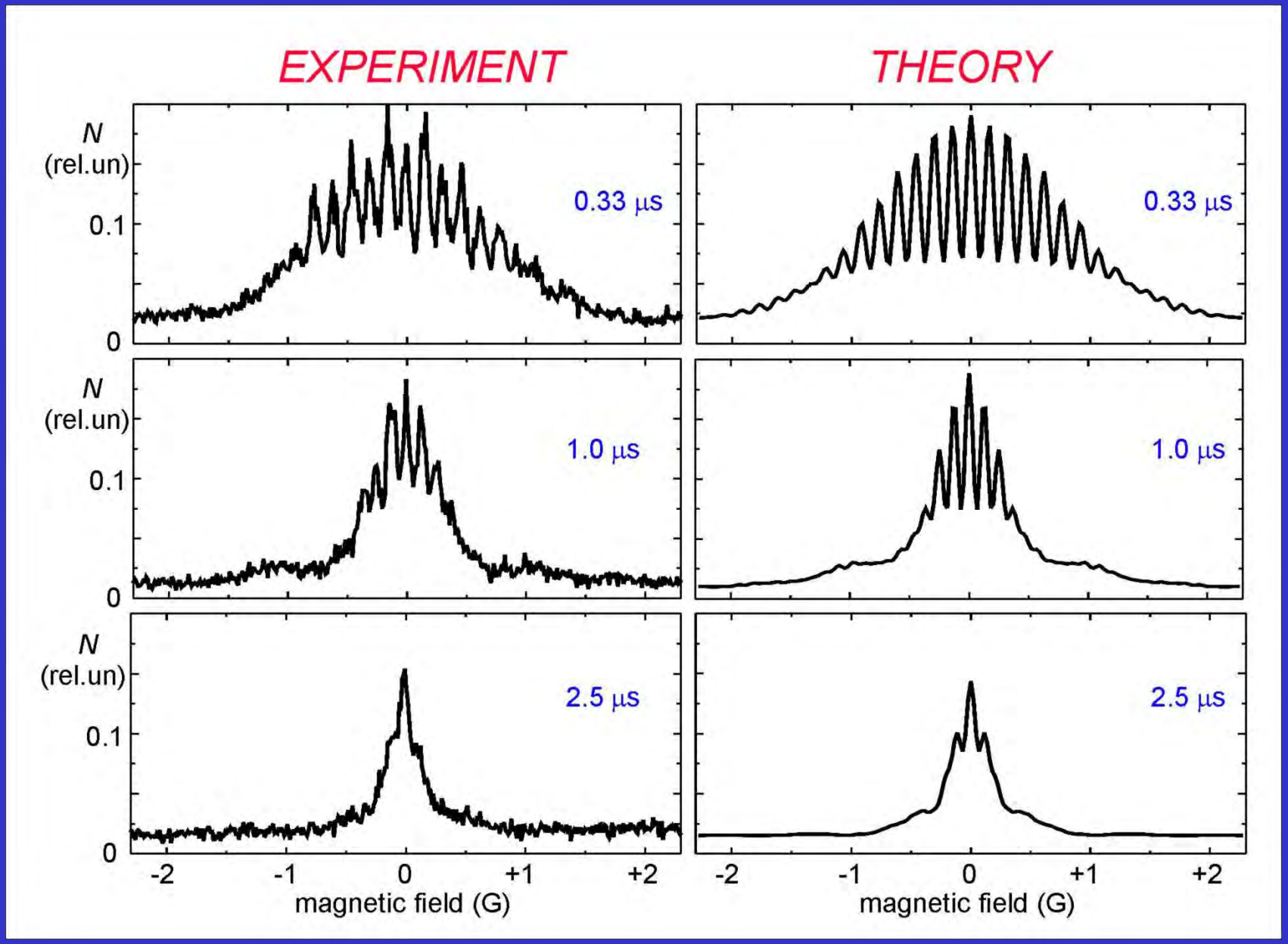


Population of the final state

$$N(37S) \sim 5 + 3\cos\left(\frac{8}{3}\frac{\mu_B B}{\hbar}t_0\right)$$

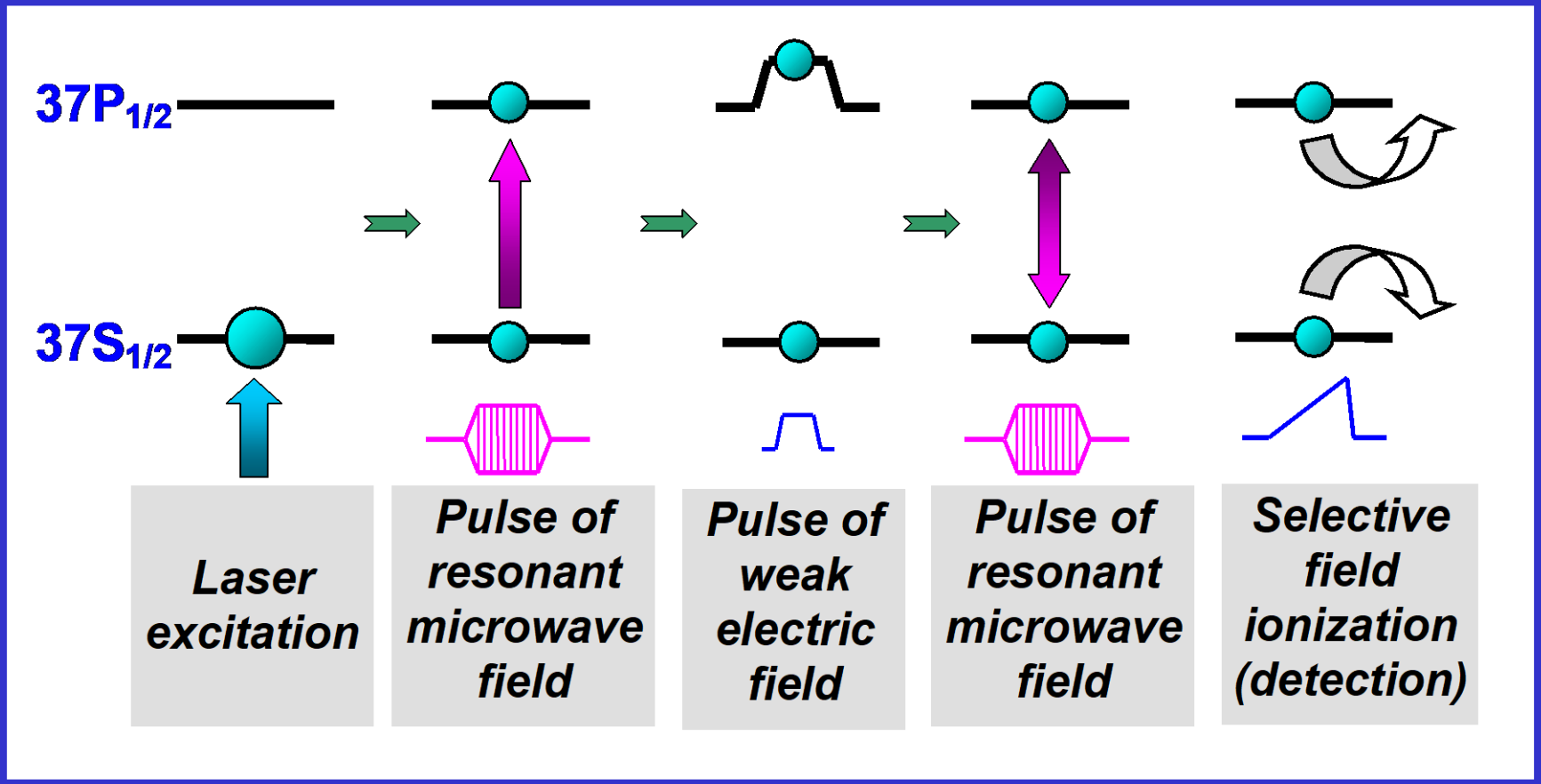
*I.I.Ryabtsev and D.B.Tretyakov, Phys. Rev. A **64**, 033413 (2001)*

Microwave Hanle effect



*I.I.Ryabtsev and D.B.Tretyakov, Phys. Rev. A **64**, 033413 (2001)*

Stark-switched interferometer for non-degenerate states

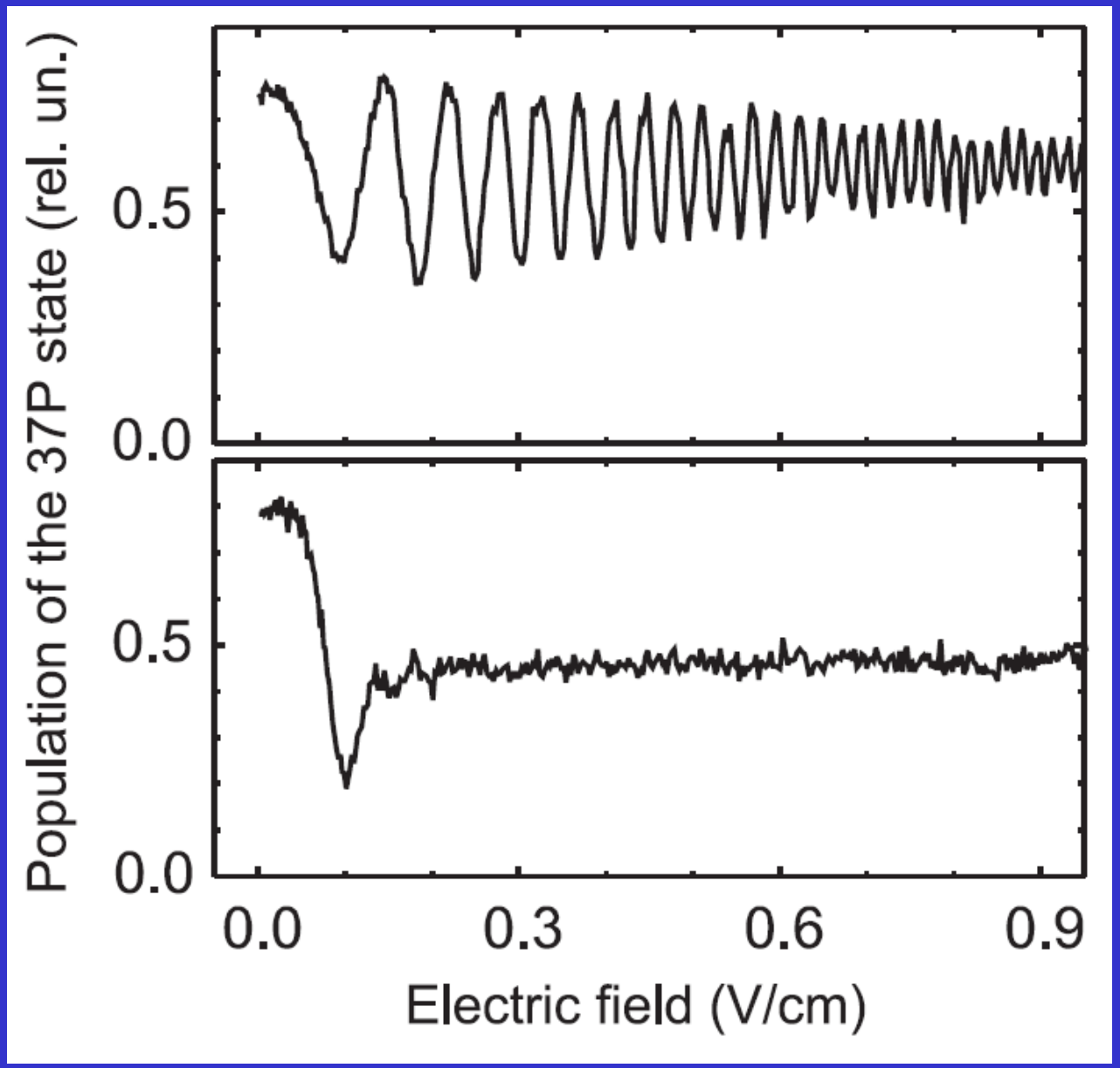


Phase shift from the electric-field pulse

$$\varphi = \pi \int_{-\infty}^{+\infty} (\alpha_P - \alpha_S) E(t)^2 \, dt = \pi (\alpha_P - \alpha_S) E_{\max}^2 \tau_{eff}$$

I.I.Ryabtsev, D.B.Tretyakov, and I.I.Beterov, J. Phys. B ***36****, 297 (2003)*

Stark-switched Ramsey interferometer



Two interactions

One interaction

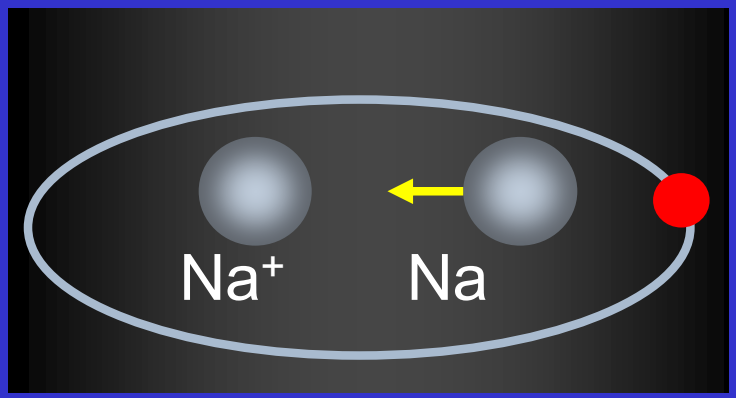
I.I.Ryabtsev, D.B.Tretyakov, and I.I.Beterov, J. Phys. B ***36****, 297 (2003)*

Decoherence of Rydberg states

Photoionization

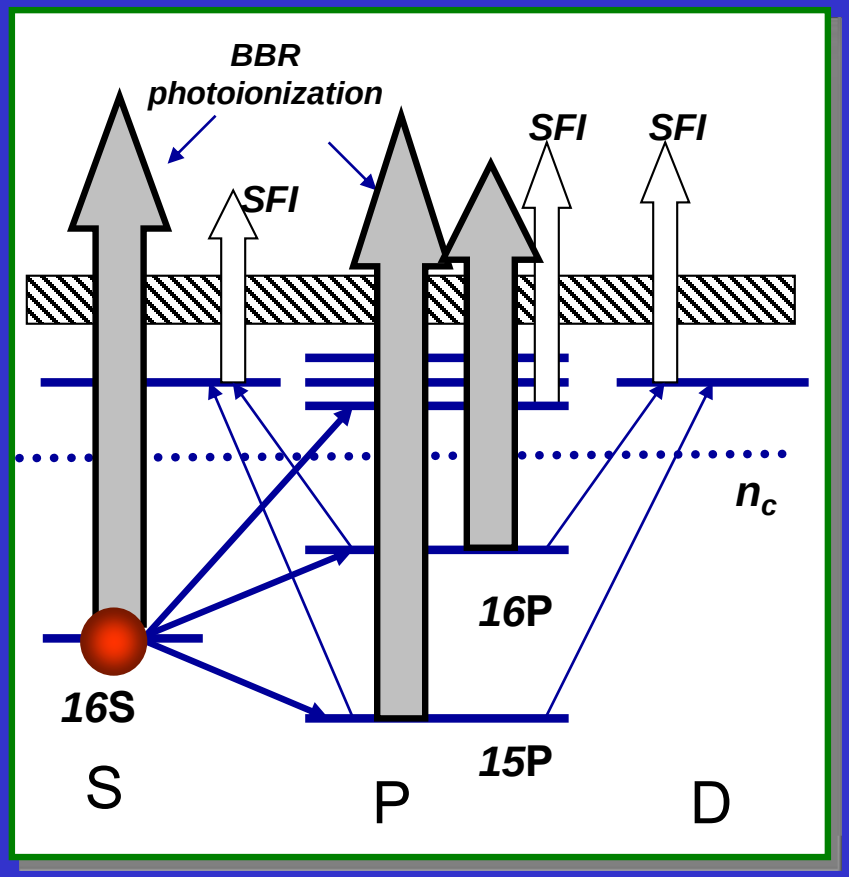
Opt. Sectr. 1989, v.66, p.36
JETP Lett. 1992, v.55, p.431
Opt. Spectr. 1993, v.75, p.531
Opt Spectr. 1996, v.81, p.383

Collisional ionization



J. Phys. B 2005, v.38, p.S17
J. Phys. B 2005, v.38, p.1811
J. Phys. B 2005, v.38, p.4349

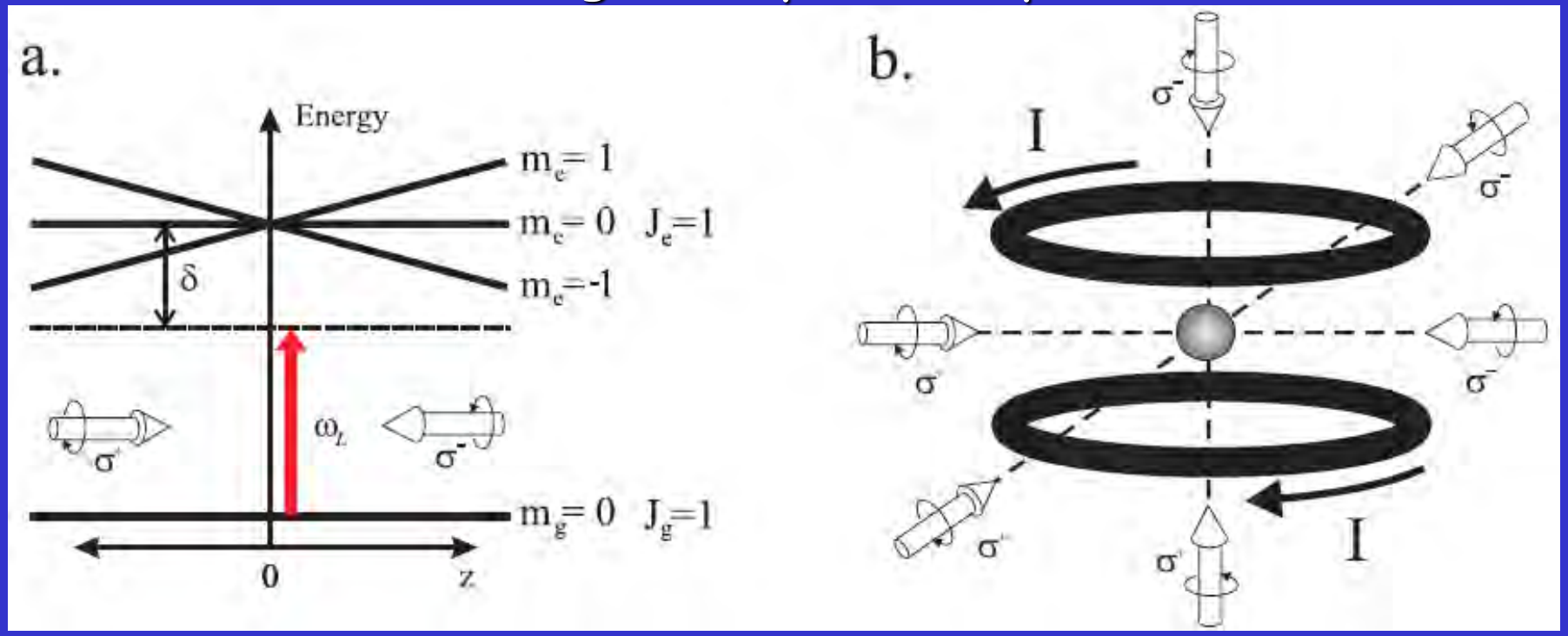
Interaction with blackbody radiation

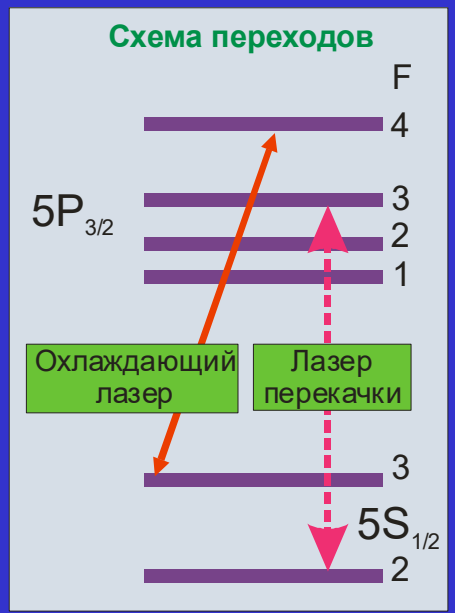


Phys. Rev. A 2007, v.75, p.052720
JETP 2008, v.107, p.20
New J. Phys. 2009, v.11, p.013052

Phys. Rev. A 2009, v.79, p.052504

Magneto-optical trap





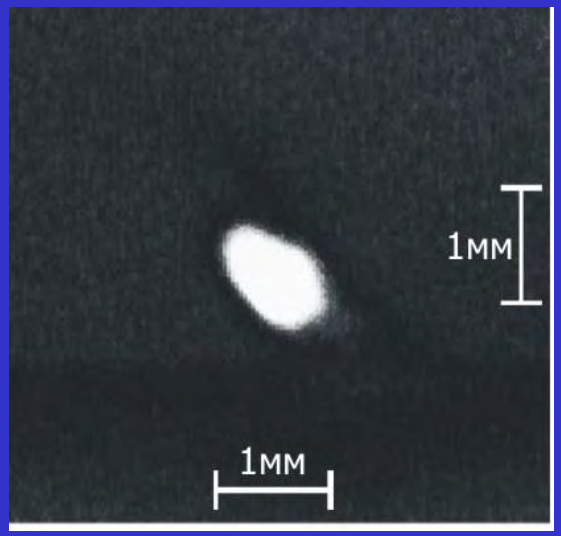
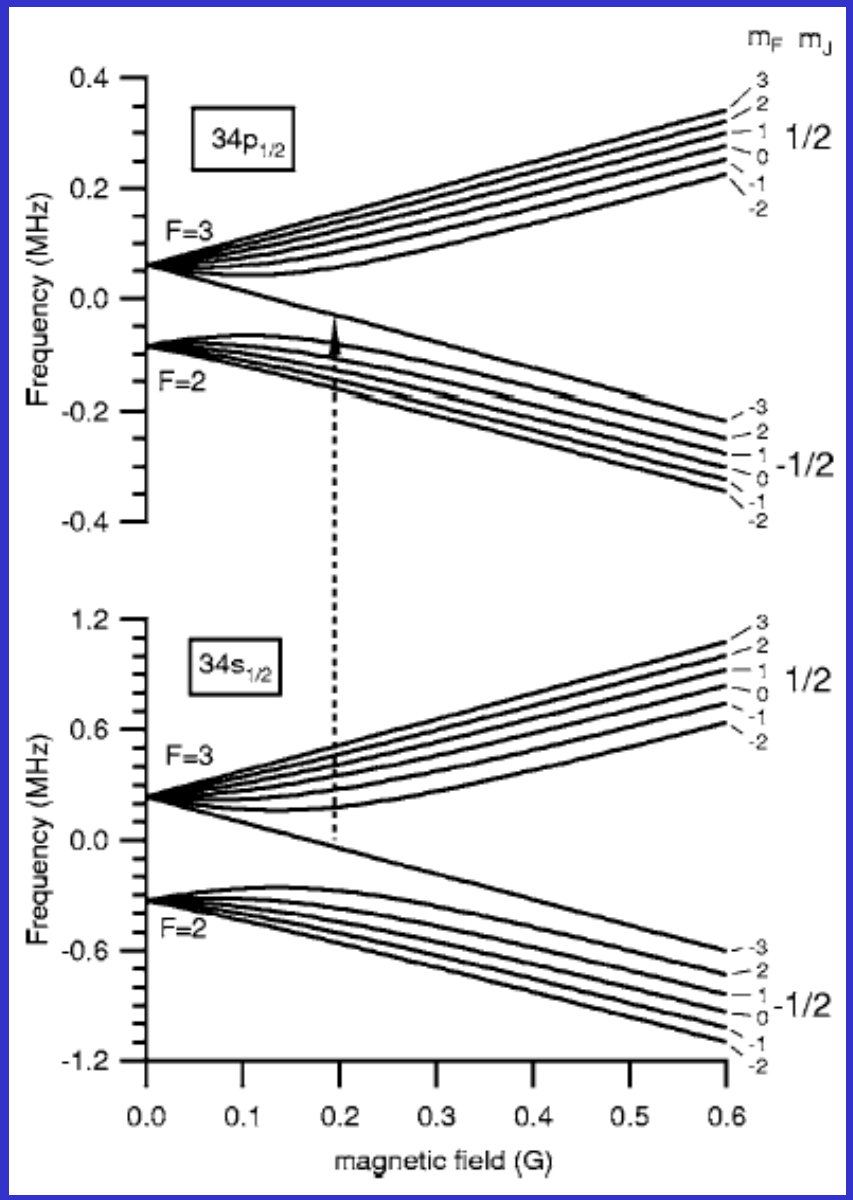
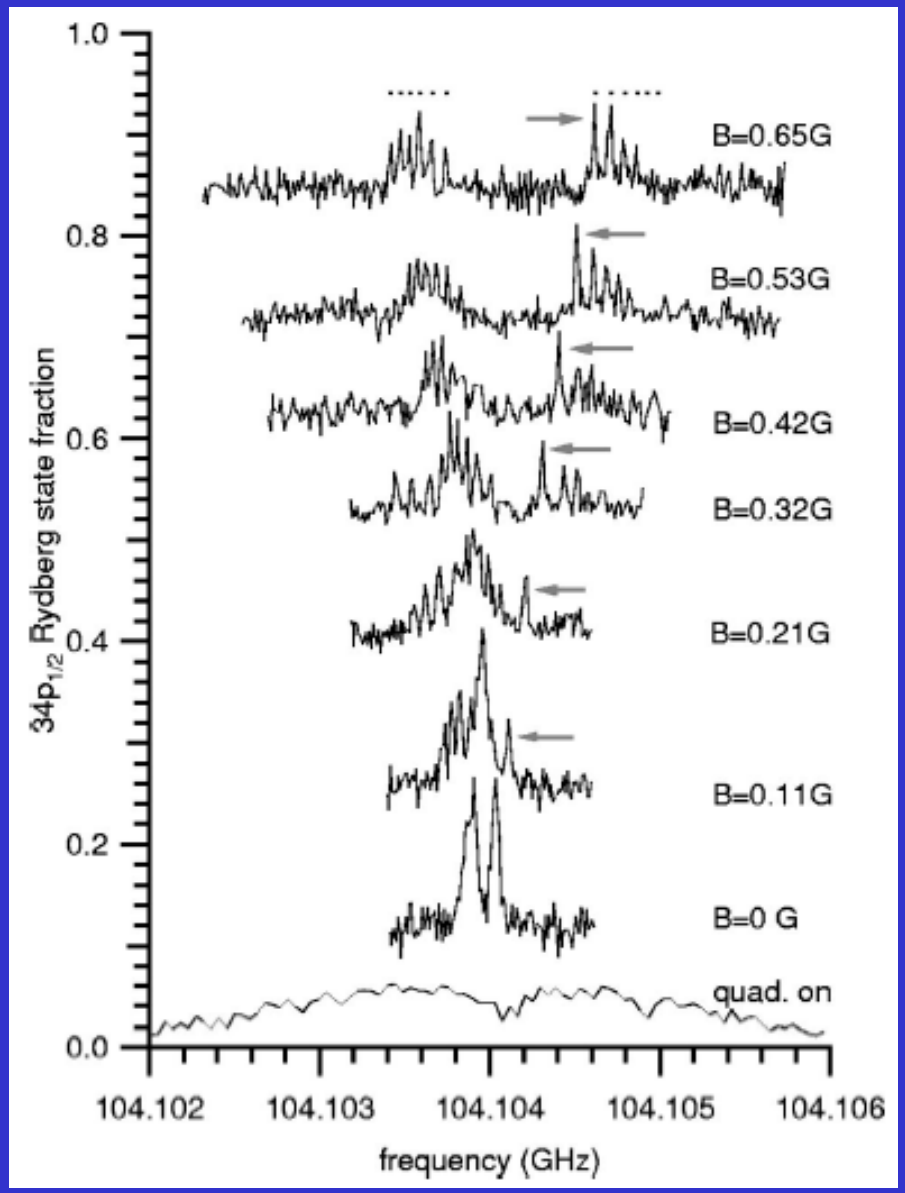


Image of a cloud of cold Rb atoms obtained with a CCD camera

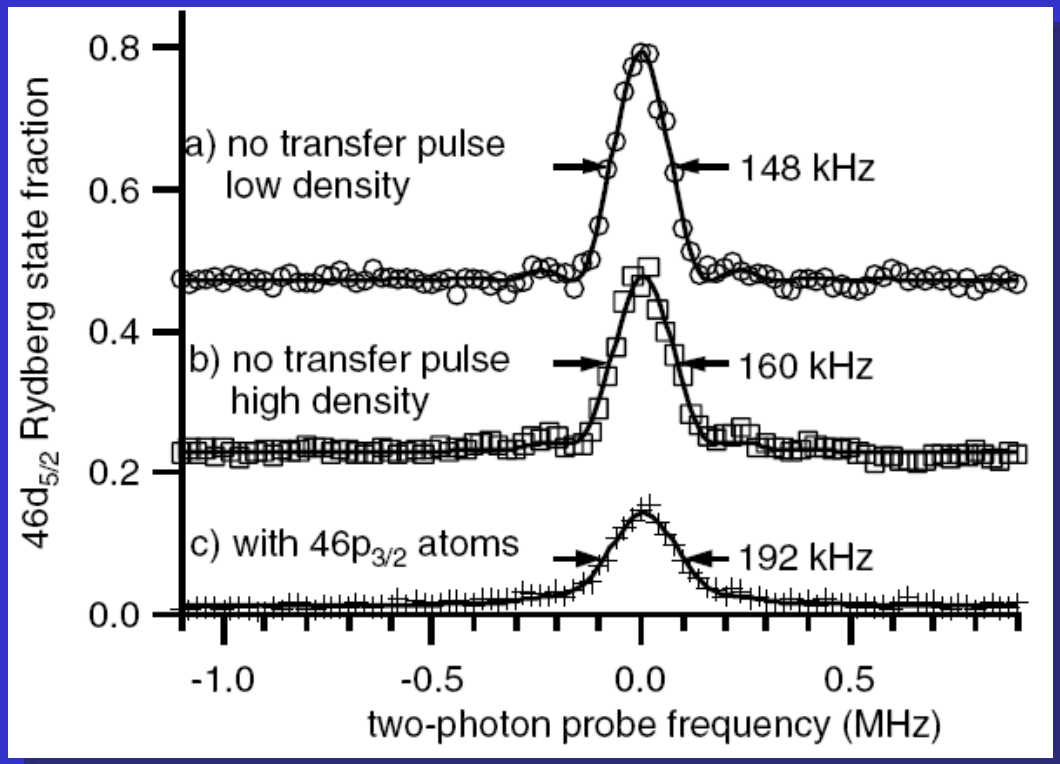
Spectroscopy of microwave transitions



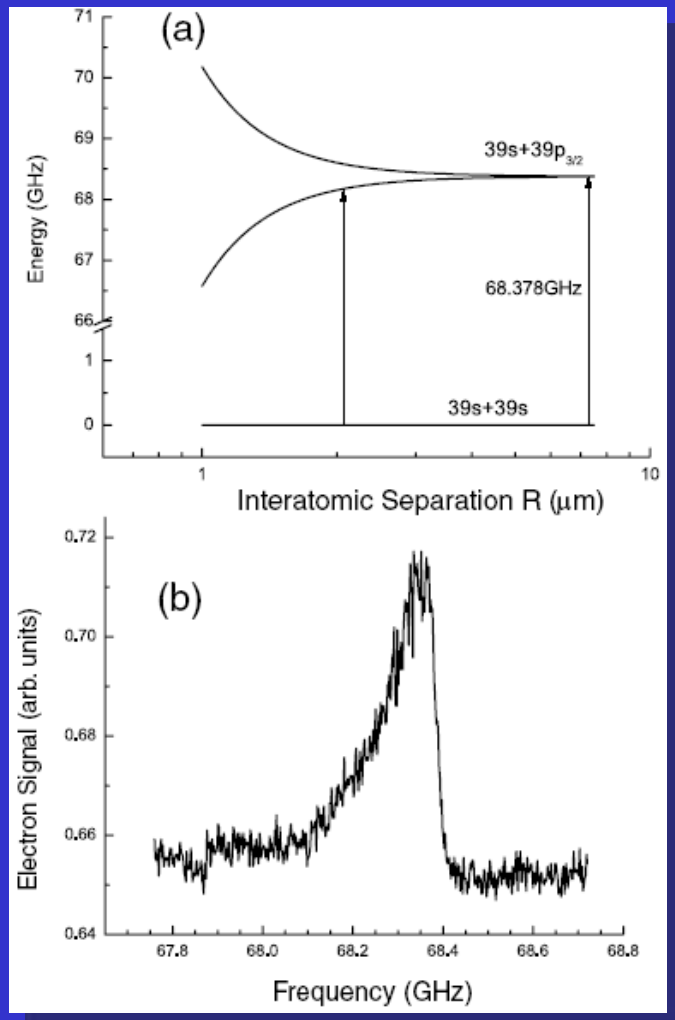


K. Afrousheh et al. PRA 73 (2006) 063403

Microwave spectroscopy of long-range interactions

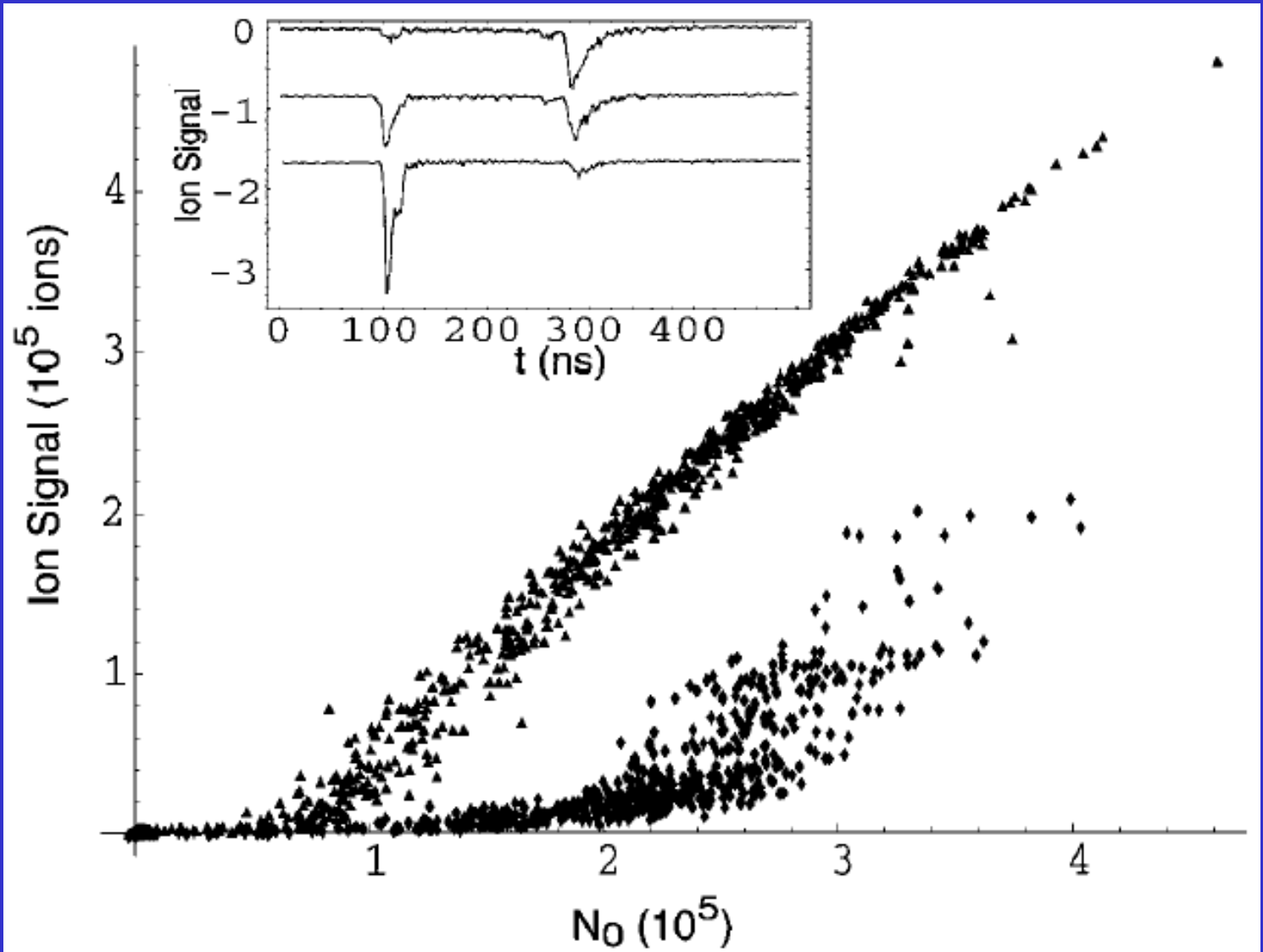


K. Afrousheh et al.
PRL 93 (2004) 233001

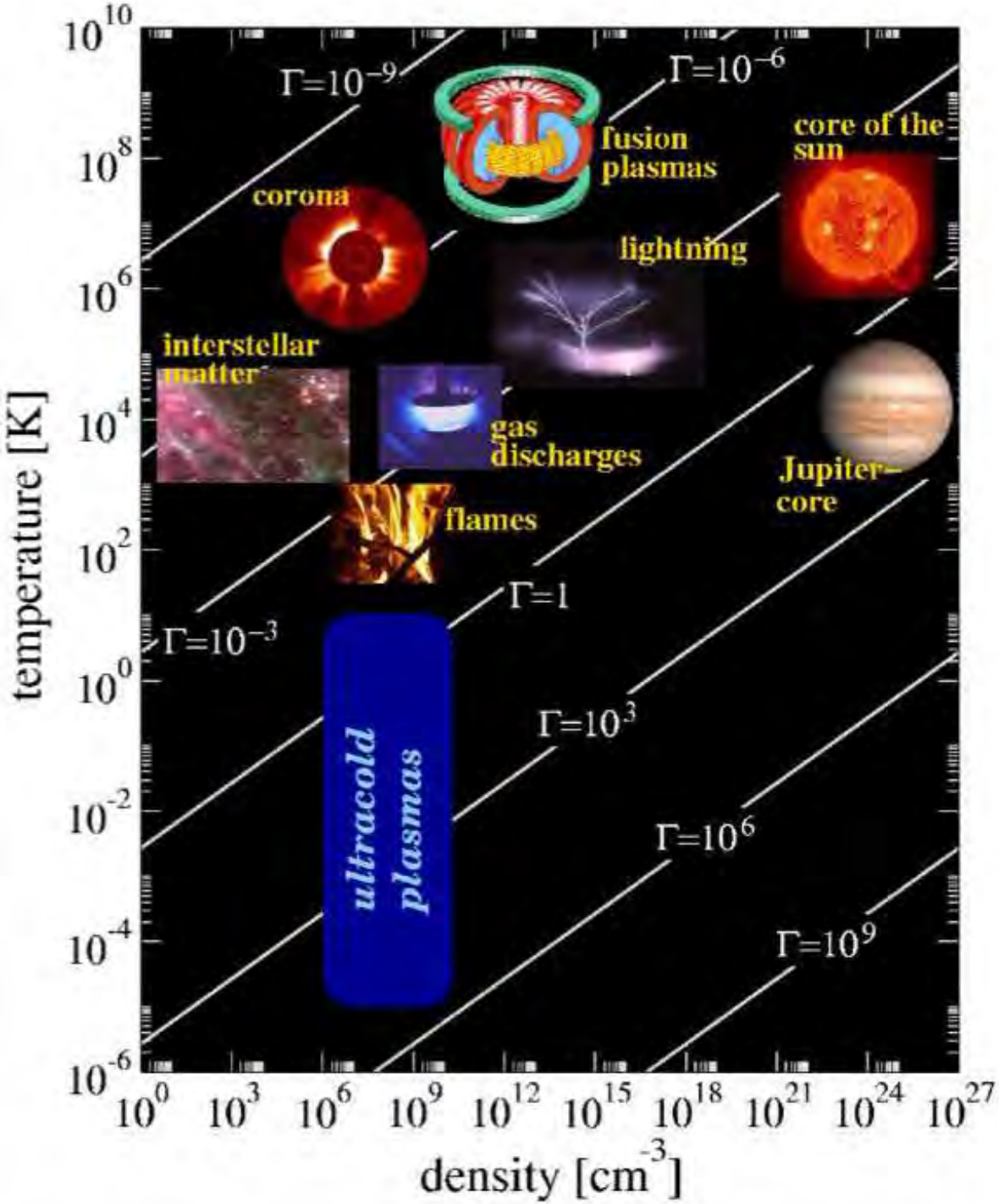


W. Li et al. PRL 94 (2005) 173001

Ultracold plasma formation



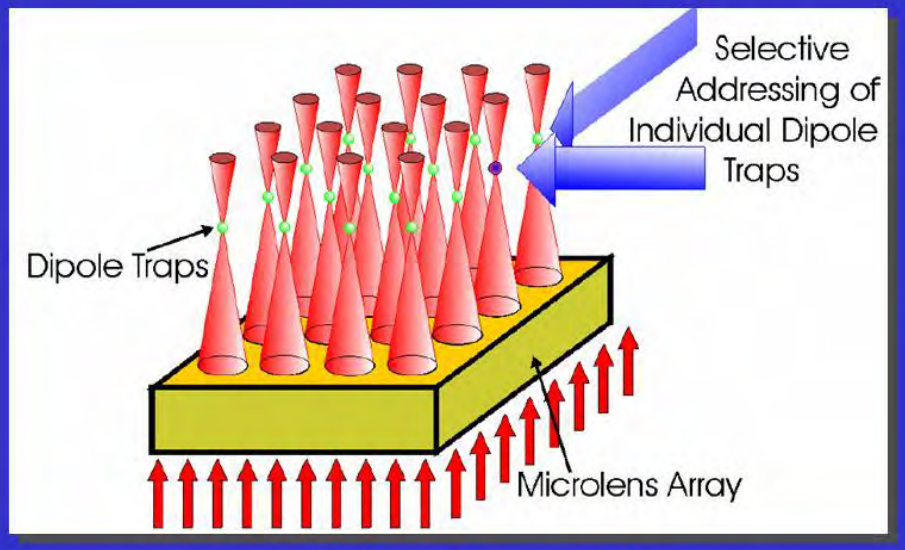
M. Robinson et al. PRL 85 (2000) 4466



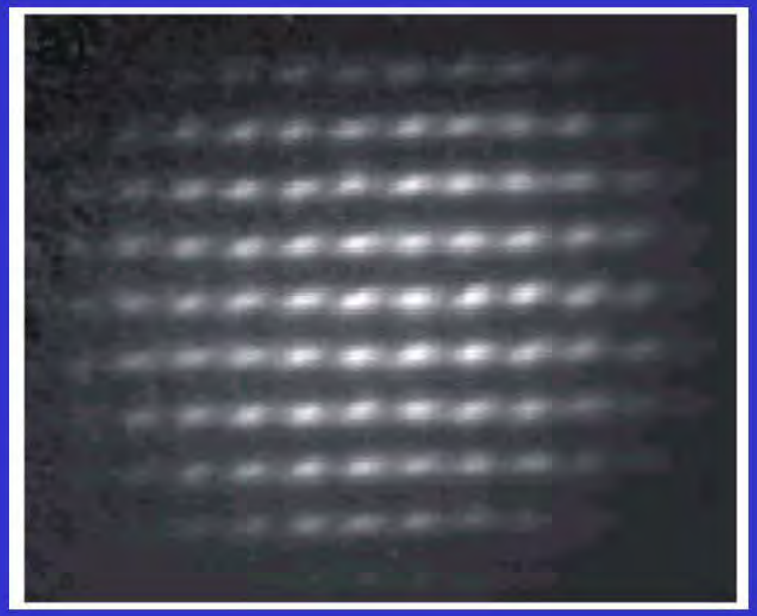
$$\Gamma = e^2/[4\pi\varepsilon_0 a k_B T]$$

$\Gamma > 1$
strongly coupled plasma

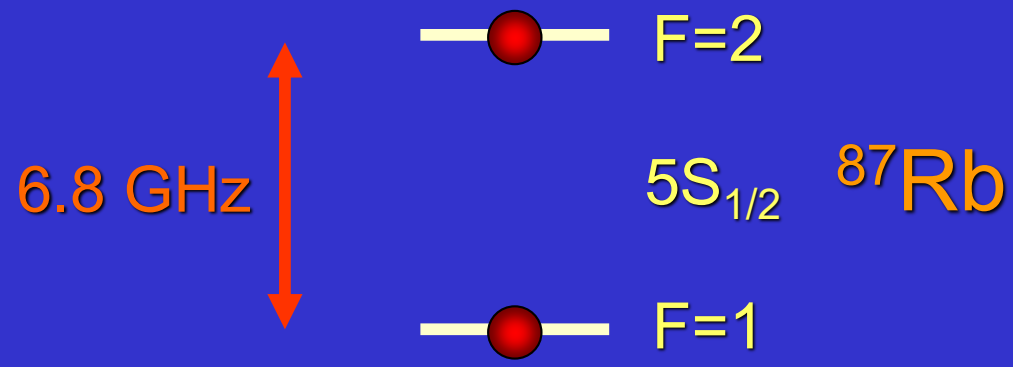
Qubits of a quantum computer – single trapped neutral atoms in optical trap arrays



R. Dumke et al.
PRL 89 (2002) 097903

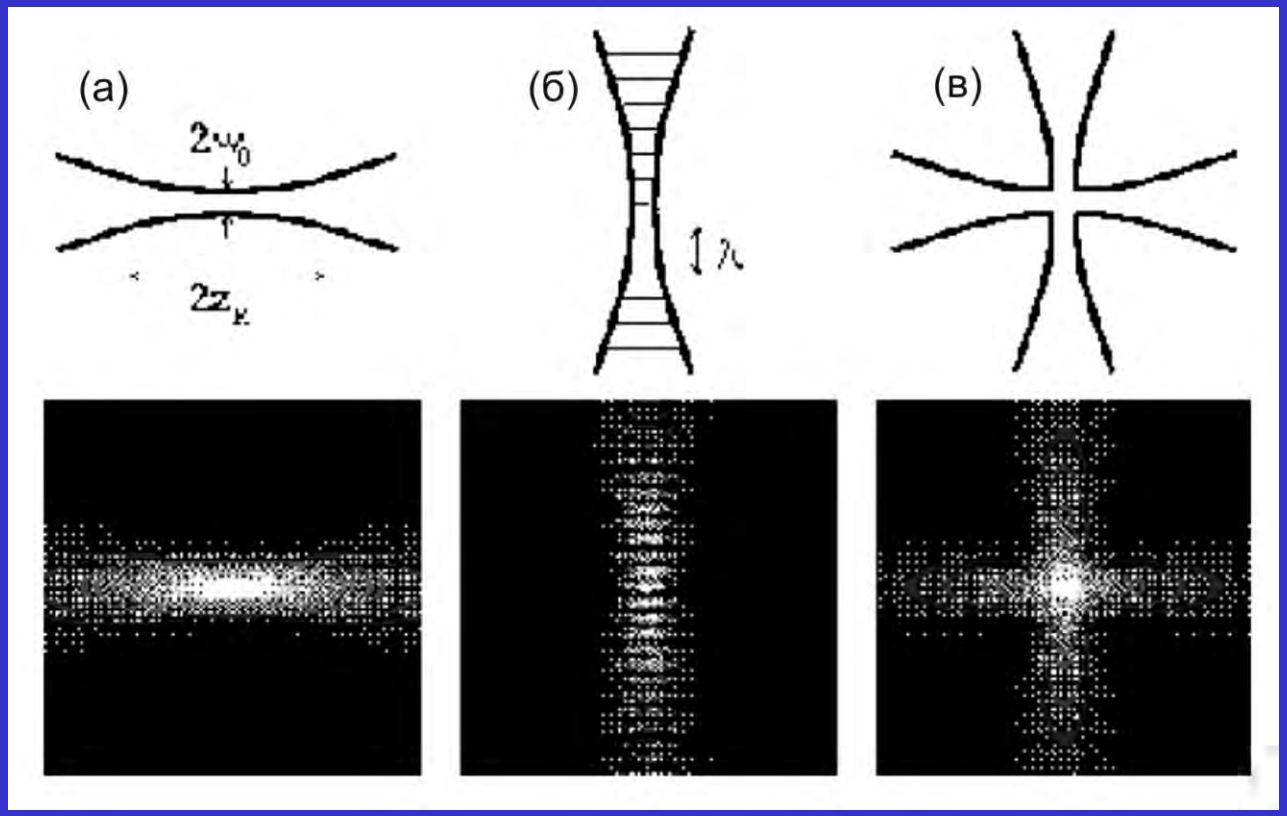


Qubit levels – two hyperfine sublevels of the ground state



Satisfy the DiVincenzo's criteria for qubits of a quantum computer

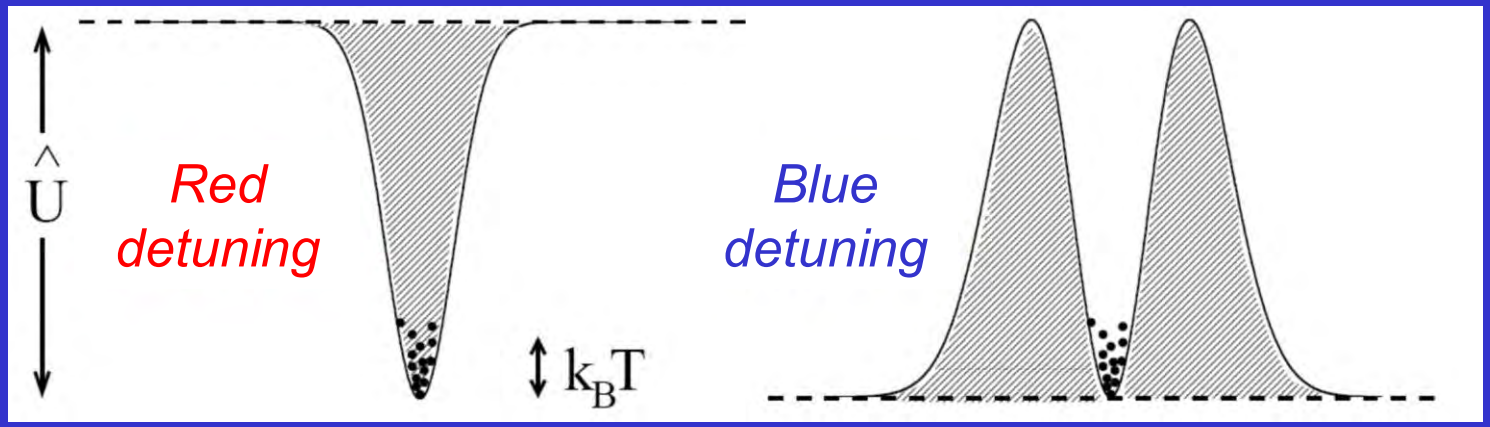
Optical dipole traps and lattices



Atom potential in the laser field:

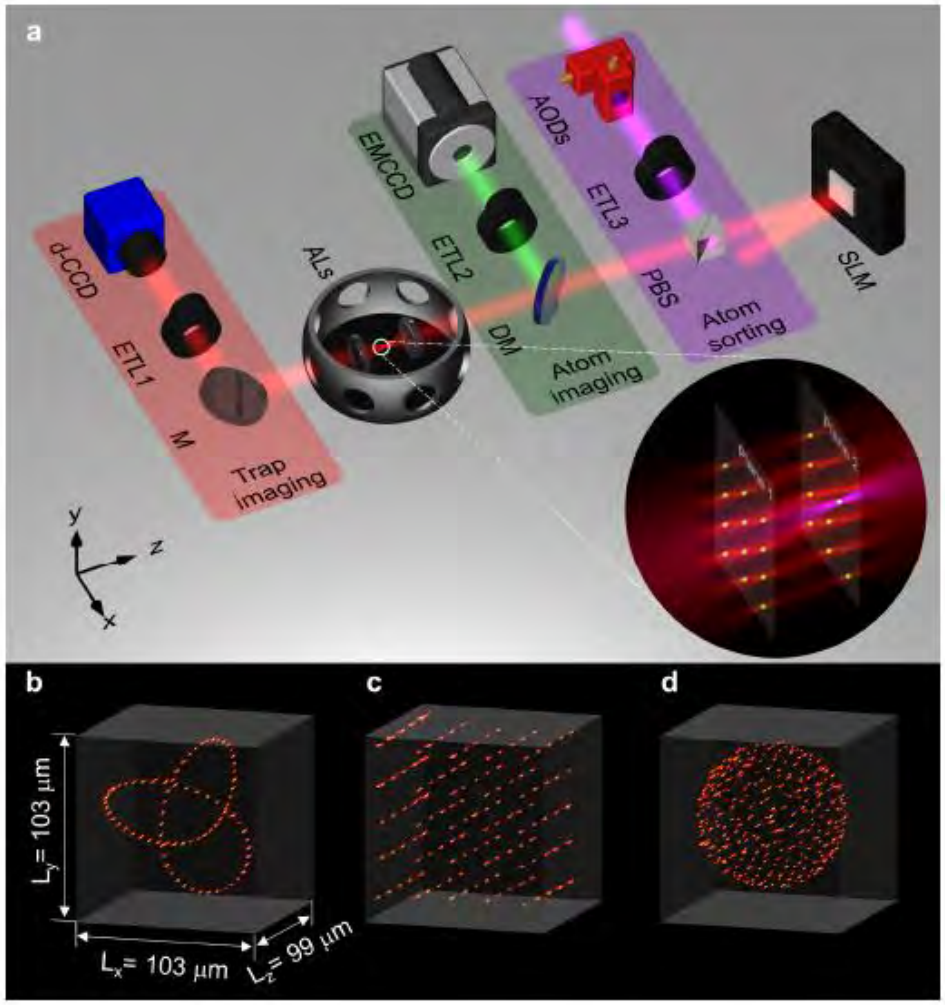
$$U_{dip}(\mathbf{r}) = \pm \frac{3\pi c^2}{2\omega_0^3}\left(\frac{\Gamma}{\Delta}\right) I(\mathbf{r})$$

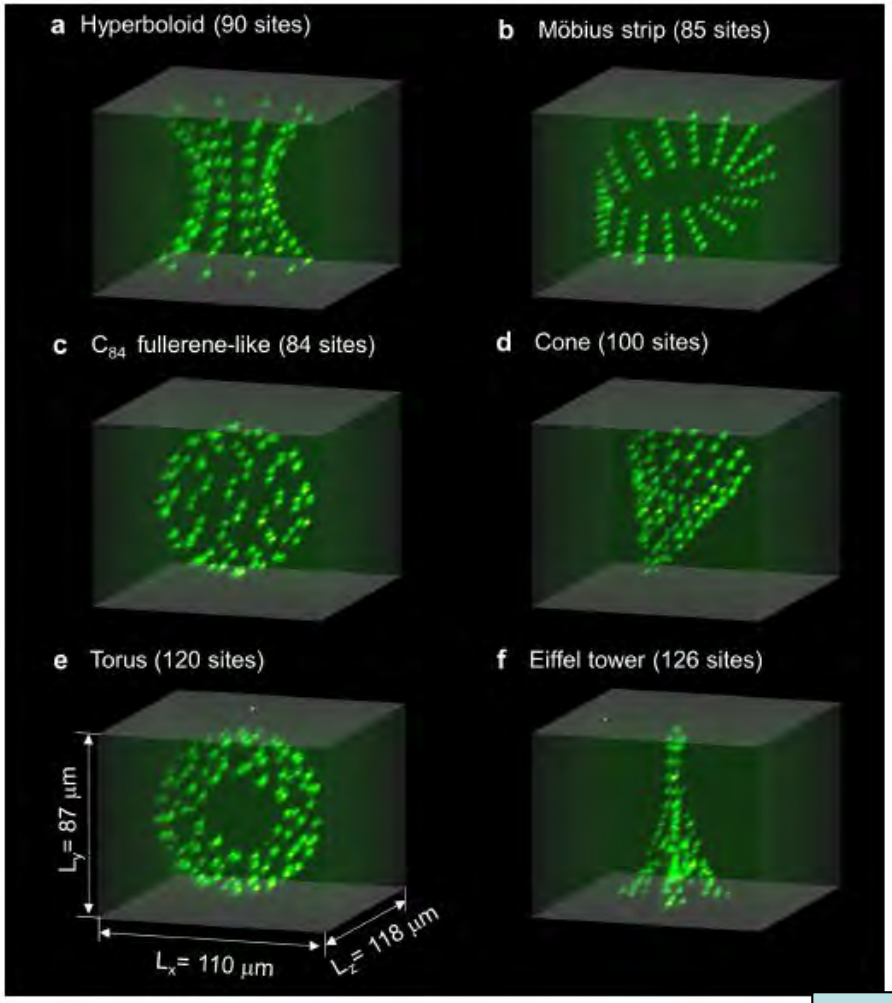
Atoms are trapped in the maxima or minima of tightly focused laser field or standing light wave, and can be readily scaled to large arrays.



Synthetic three-dimensional atomic structures assembled atom by atom

Daniel Barredo*, Vincent Lienhard*, Sylvain de Léséleuc*, Thierry Lahaye, and Antoine Browaeys
Laboratoire Charles Fabry, Institut d'Optique Graduate School, CNRS,
Université Paris-Saclay, F-91127 Palaiseau Cedex, France
(Dated: December 8, 2017)

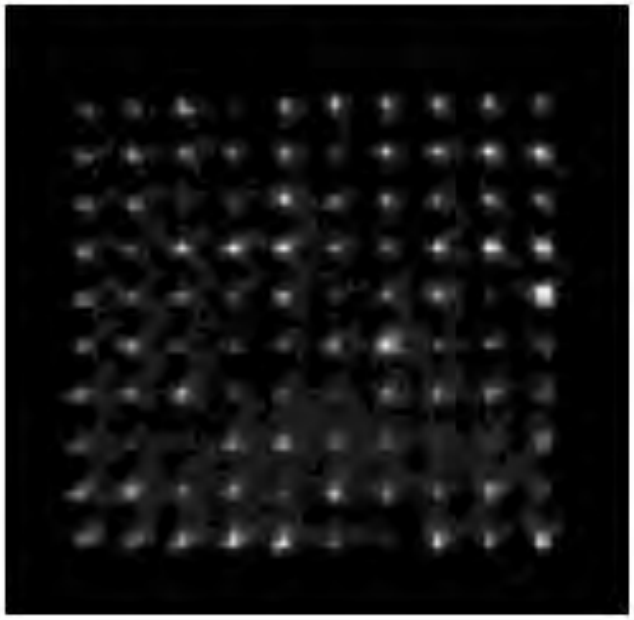




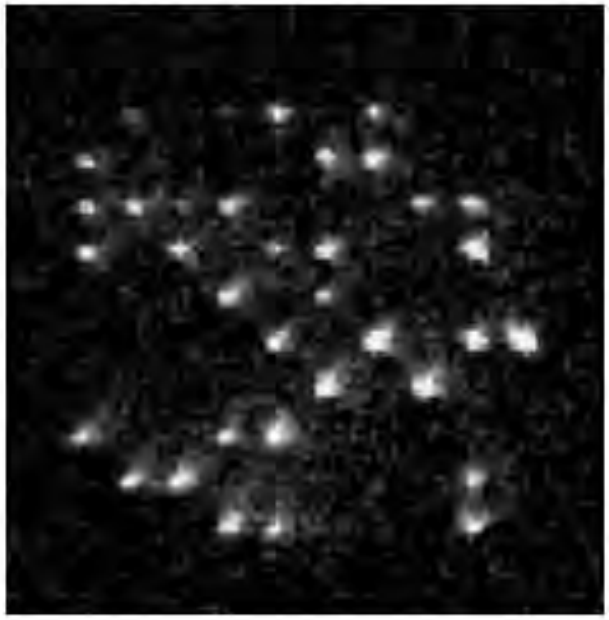
Experiments of Moscow State University on trapping Rb Atoms in large trap arrays

Fluorescence image of single Rb atoms
in a 10x10 trap array

Averaging over 100 shots



Single-shot image



Universal quantum gates

$$\begin{pmatrix} \cos\theta & i\sin\theta \\ i\sin\theta & \cos\theta \end{pmatrix}$$

One-qubit rotation

$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & \cos\theta & i\sin\theta \\ 0 & 0 & i\sin\theta & \cos\theta \end{pmatrix}$$

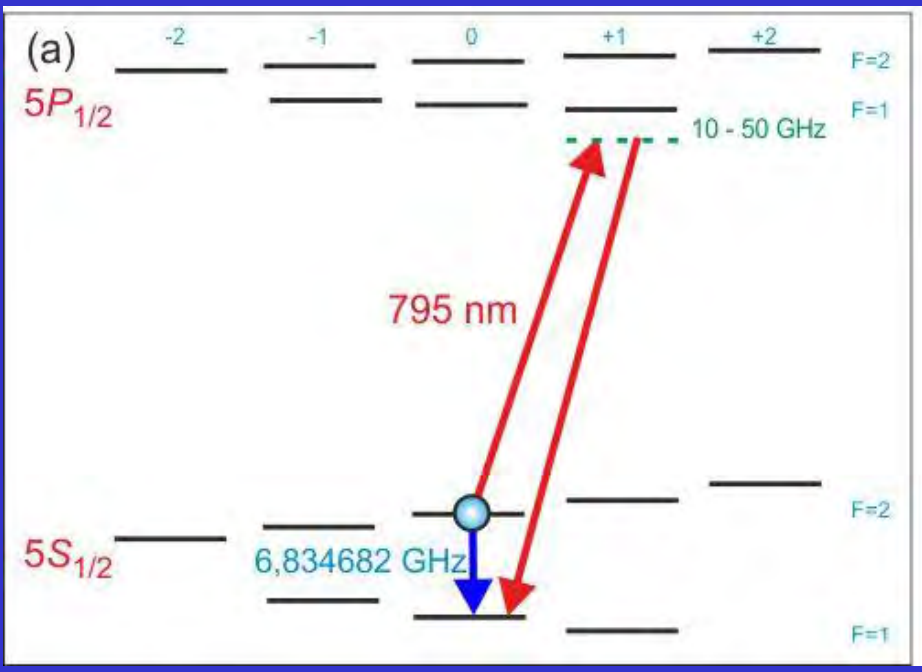
Two-qubit quantum phase gate

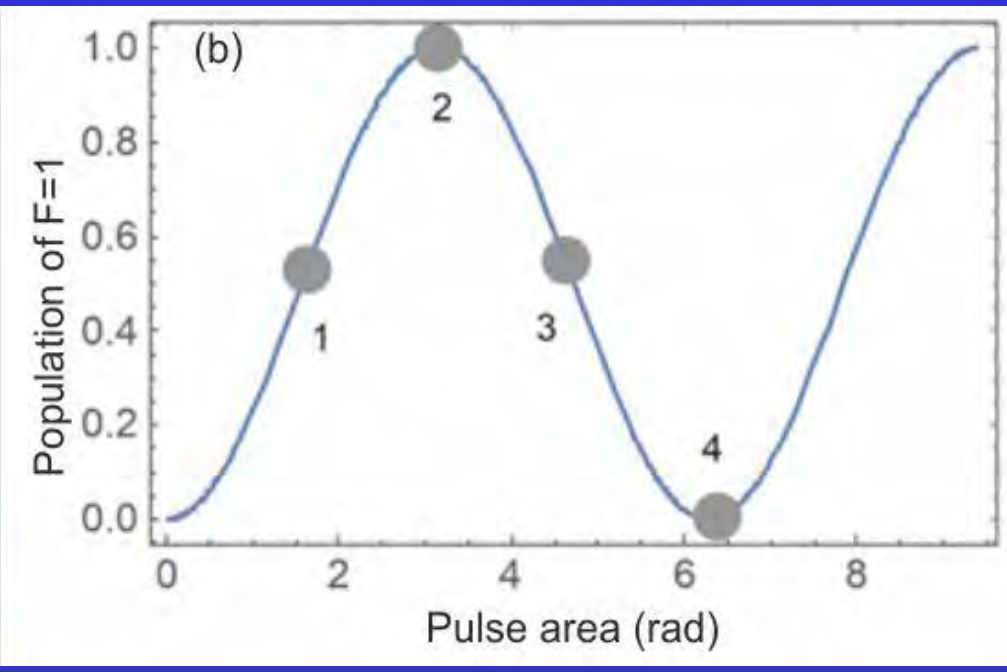
Conditional quantum phase gate $|a\ b\rangle \rightarrow \exp(i\ \theta\ \delta_{a1}\ \delta_{b1}\ )\ |a\ b\rangle$

One-qubit gate: a rotation by arbitrary angle

↑ ↑ ↑ ↑ ↑ ↓ ↑ ↑ ↑ ↑ ↑ NOT

Raman or microwave transition between qubit levels



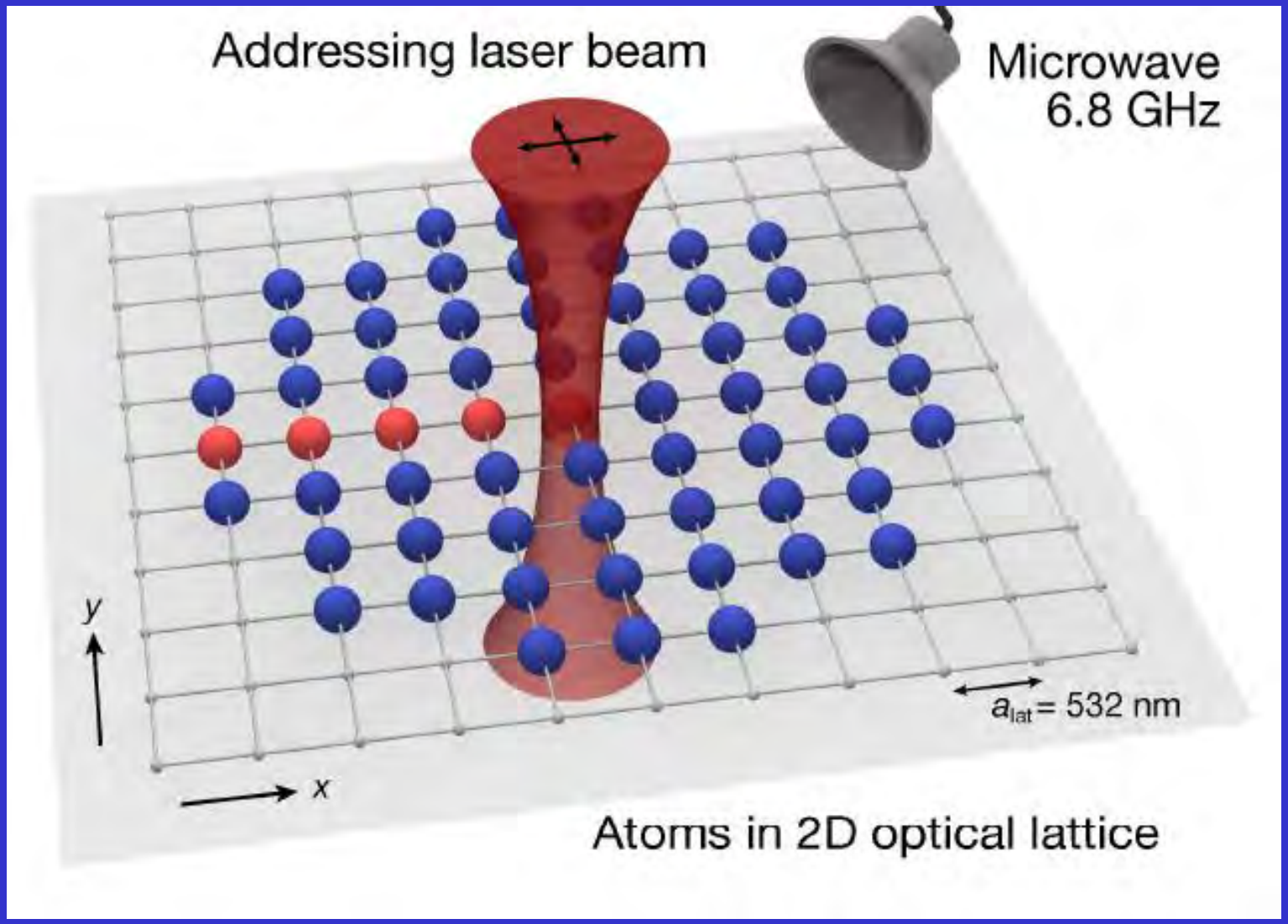


Rabi population oscillations at various phases correspond to various one-qubit gates.

Single-spin addressing in an atomic Mott insulator

17 MARCH 2011 | VOL 471 | NATURE | 319

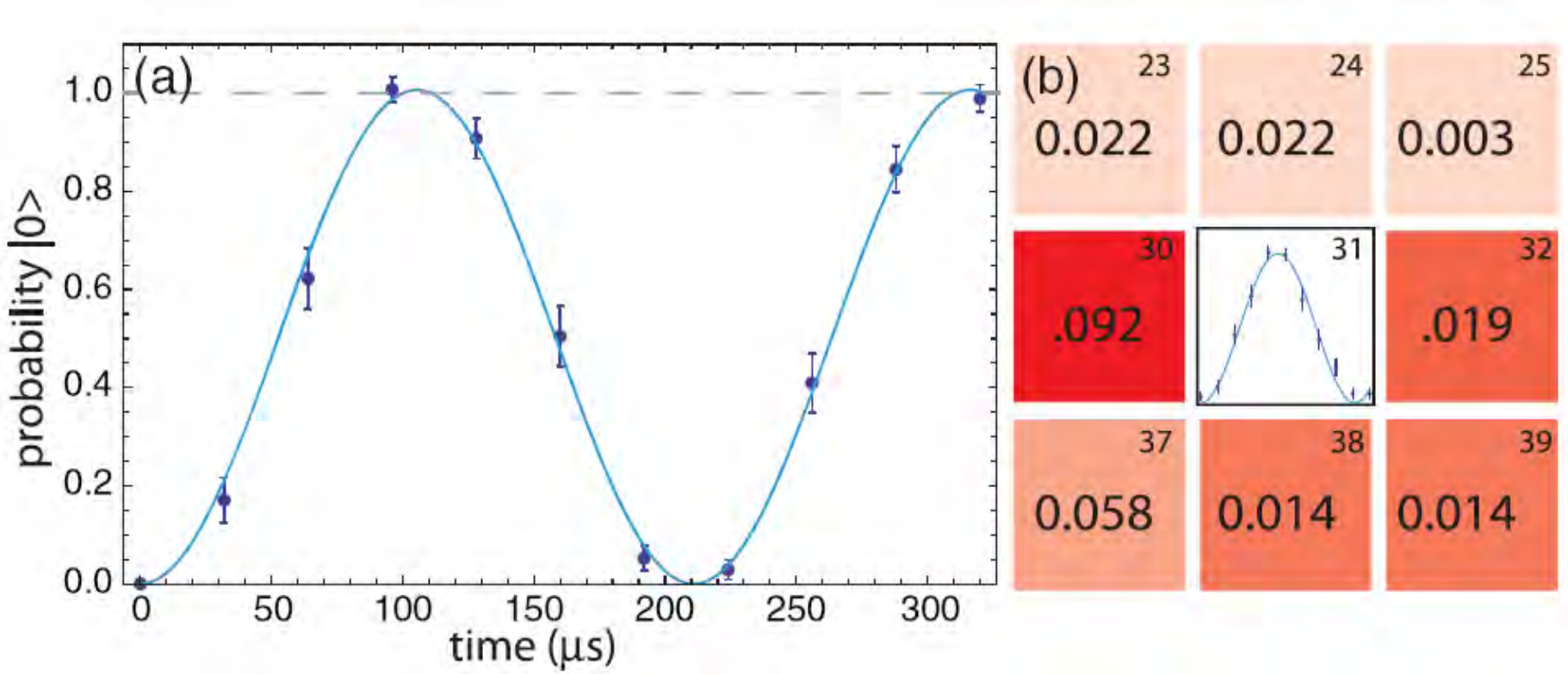
Christof Weitenberg[1], Manuel Endres[1], Jacob F. Sherson[1]†, Marc Cheneau[1], Peter Schauß[1], Takeshi Fukuhara[1], Immanuel Bloch[1,2] & Stefan Kuhr[1]



PRL 114, 100503 (2015) PHYSICAL REVIEW LETTERS week ending 13 MARCH 2015

Randomized Benchmarking of Single-Qubit Gates in a 2D Array of Neutral-Atom Qubits

T. Xia, M. Lichtman, K. Maller, A. W. Carr, M. J. Piotrowicz, L. Isenhower, and M. Saffman

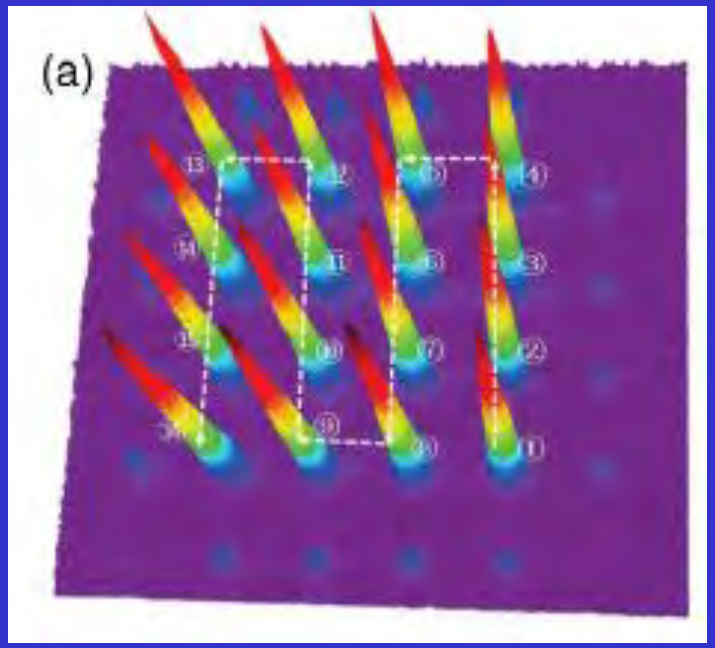


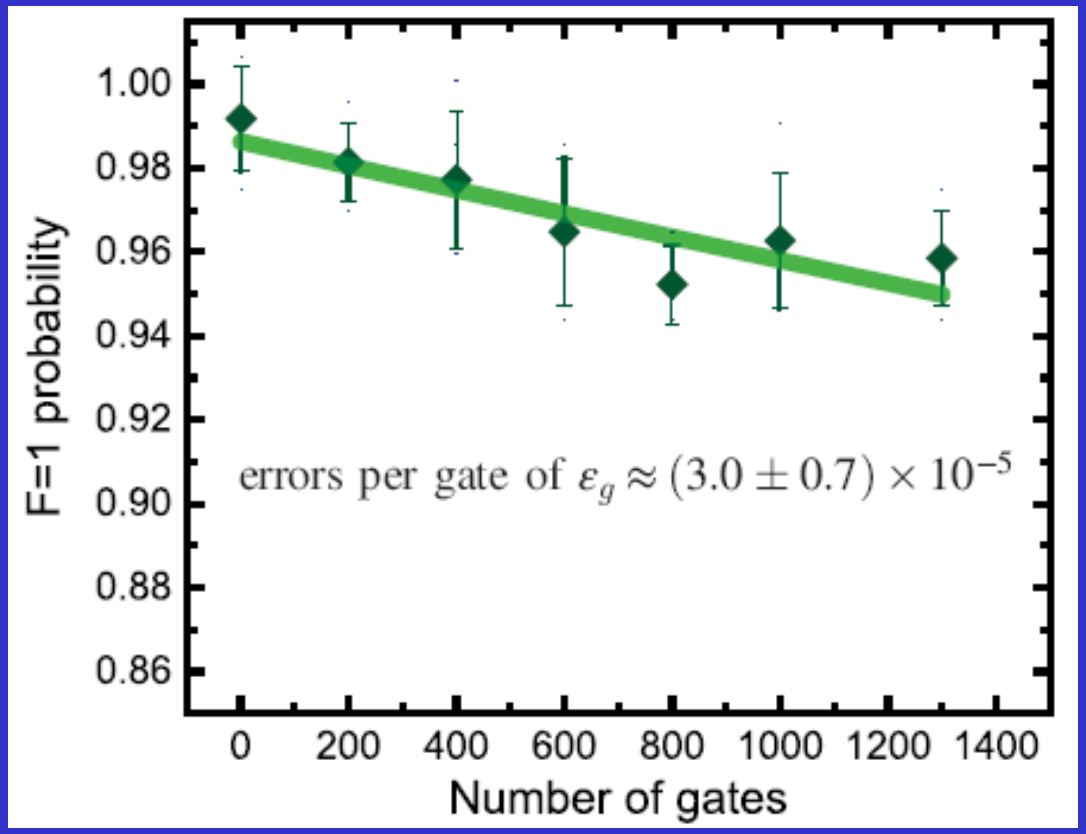
Addressing single Cs atoms by focused beam at 459 nm, producing the light shift of 33 kHz. For one trap the average one-qubit fidelity is F = 0.9923, and the crosstalk is 1-5%. The main error sources are finite atom temperature (5-10 μK), magnetic field noise and repumping at blowing-away.

PHYSICAL REVIEW LETTERS **121,** 240501 (2018)

High-Fidelity Single-Qubit Gates on Neutral Atoms in a Two-Dimensional Magic-Intensity Optical Dipole Trap Array

Cheng Sheng,[1,2,3] Xiaodong He,[1,3,*] Peng Xu,[1,3] Ruijun Guo,[1,2,3] Kunpeng Wang,[1,2,3] Zongyuan Xiong,[1,3] Min Liu,[1,3] Jin Wang,[1,3] and Mingsheng Zhan[1,3,†]

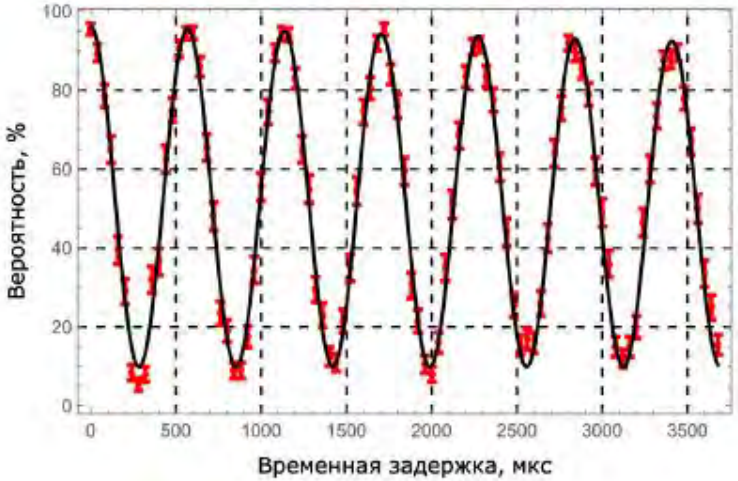


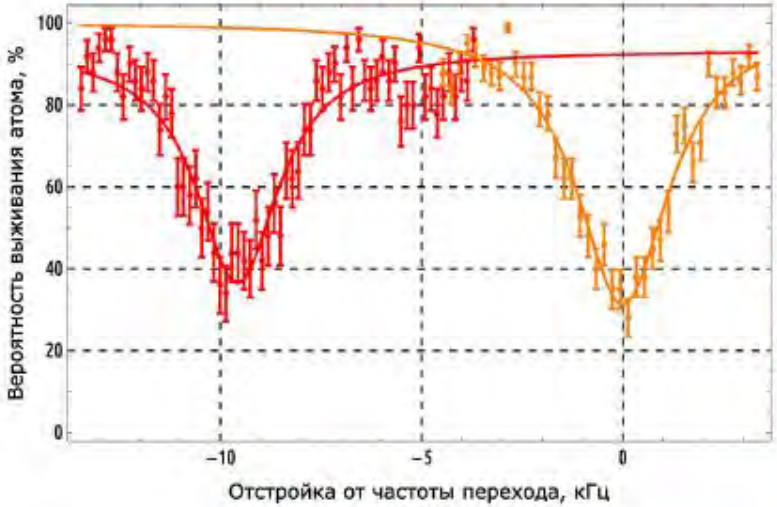


An array 4×4 of optical dipole traps for Rb atoms. The average error per gate for Clifford gate sequence is 3×10^{-5} due to compensation of DLS at circular laser polarization and active magnetic field stabilization below 1 mG.

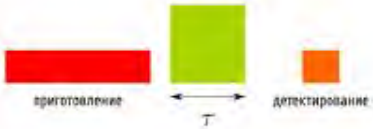
Индивидуальная адресация

Центр Квантовых Технологий

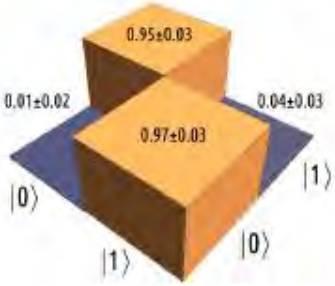




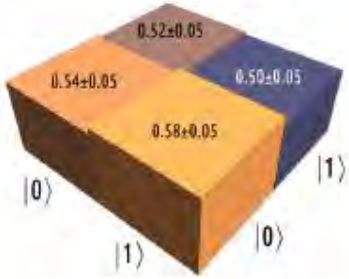
кросс-корреляции при π-импульсе в центральном узле



$$V \simeq 90\%$$
$$\tilde{V} = 96.0 \pm 1.6\%$$



операция NOT

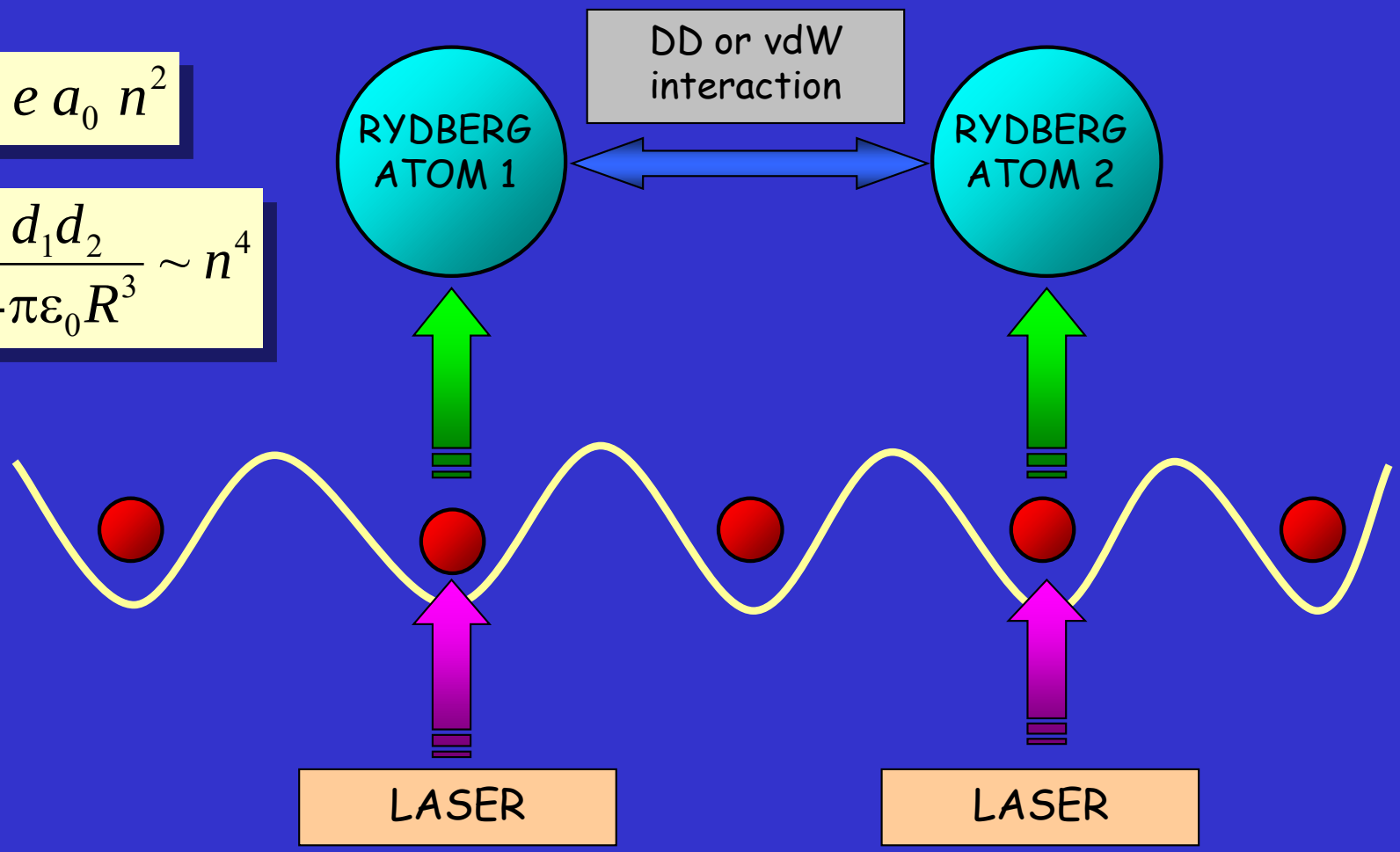


преобразование Адамара

Two-qubit gates based on laser excitation of neutral atoms to Rydberg states and their interaction

$$d \sim e\, a_0\, n^2$$

$$V_{DD} \sim \frac{d_1 d_2}{4\pi\varepsilon_0 R^3} \sim n^4$$

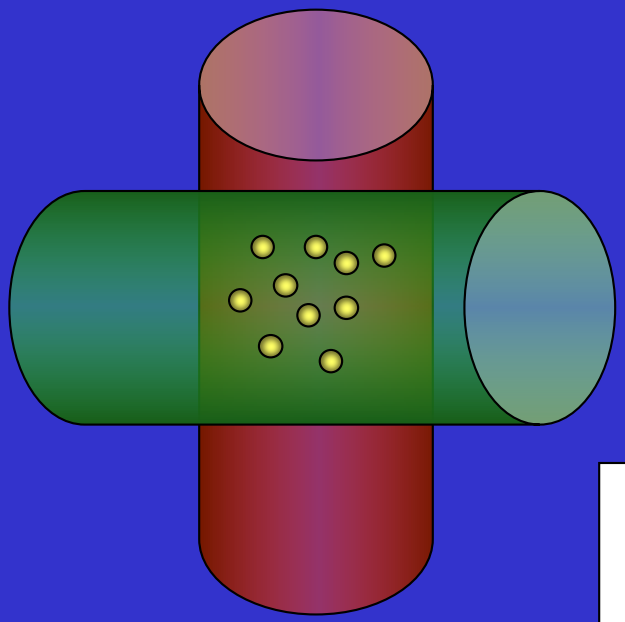


D. Jaksch et al. PRL 85 (2000) 2208; M.Lukin et al. PRL 87 (2001) 037901

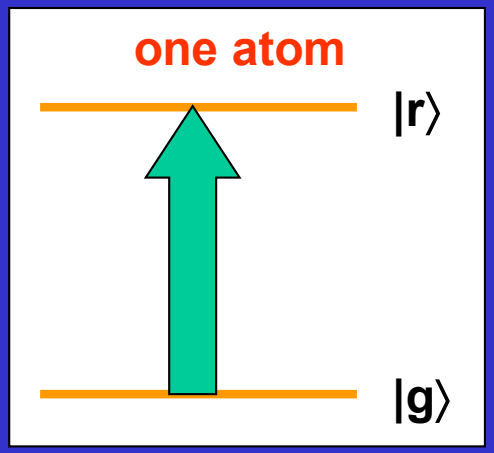
$V \sim 100$ MHz at $n = 100$, $R \approx 5$ μm

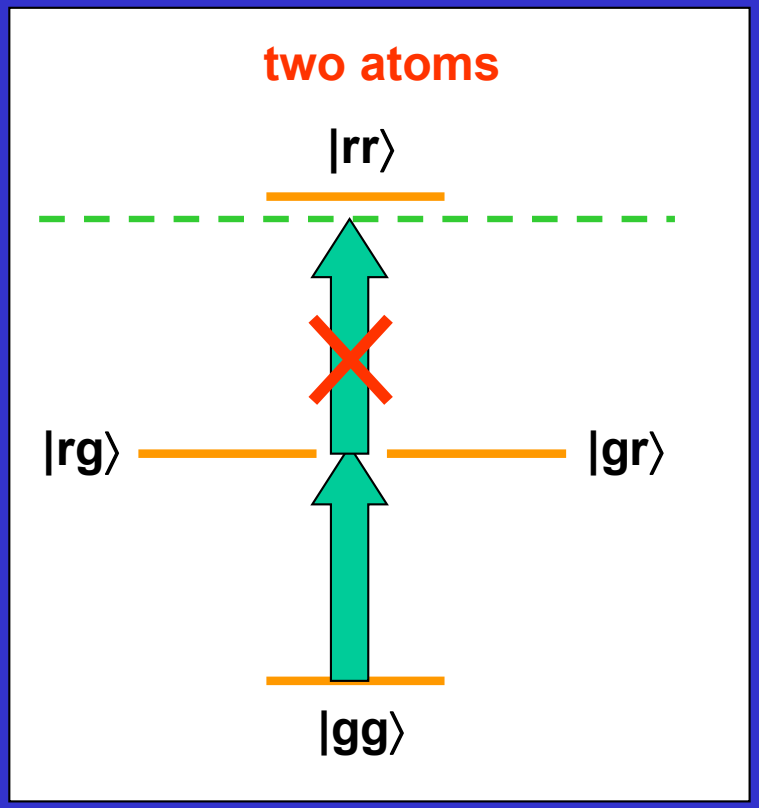
Dipole blockade in mesoscopic ensembles

M. Lukin et al. PRL 87 (2001) 037901



$\Psi = |rg\rangle + |gr\rangle$

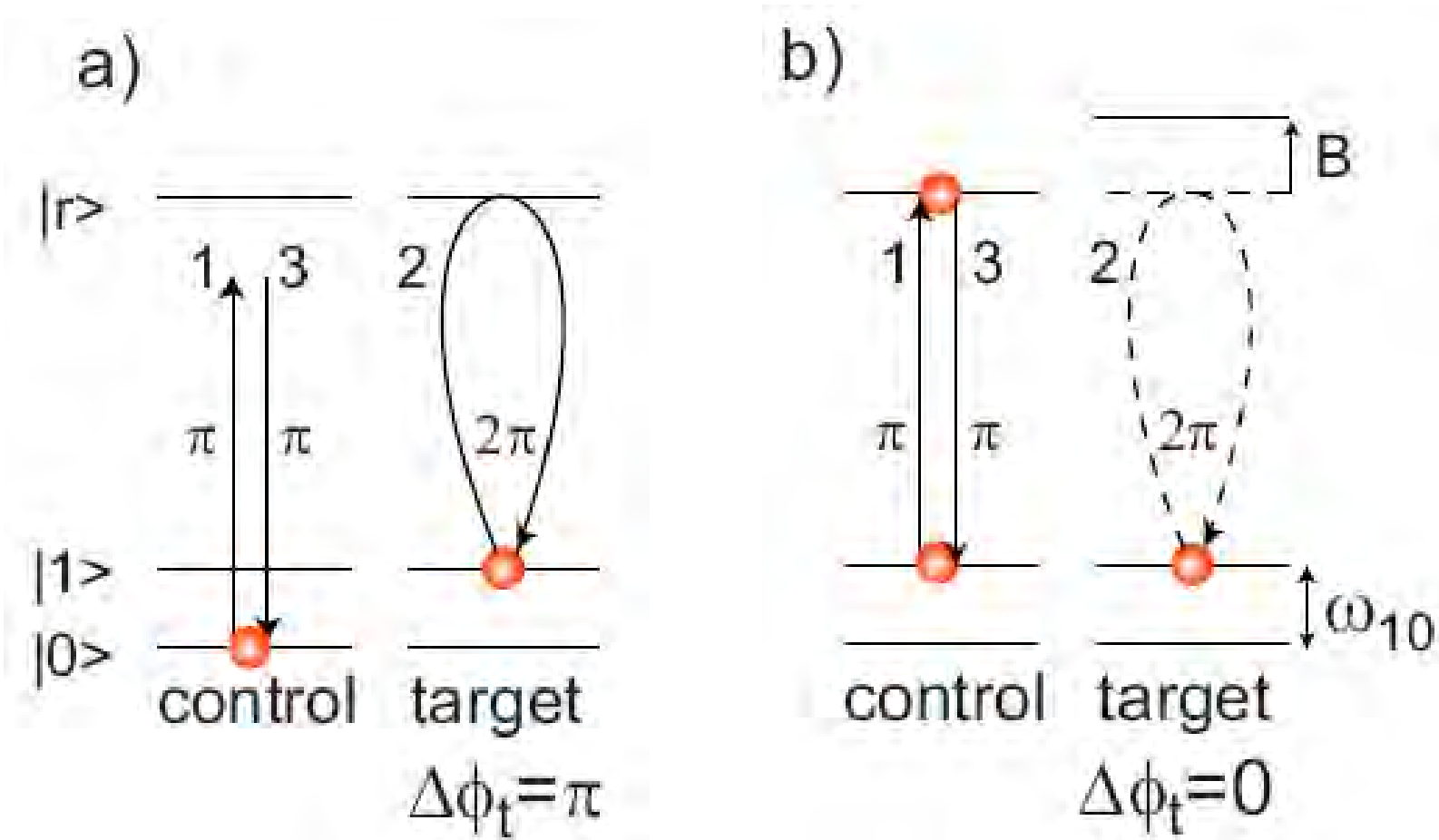




M.Saffman et al., Rev. Mod. Phys. ***82****, 2313 (2010)*

D.Comparat et al., J. Opt. Soc. Am. B ***27****, A208 (2010)*

CZ quantum gate with dipole blockade

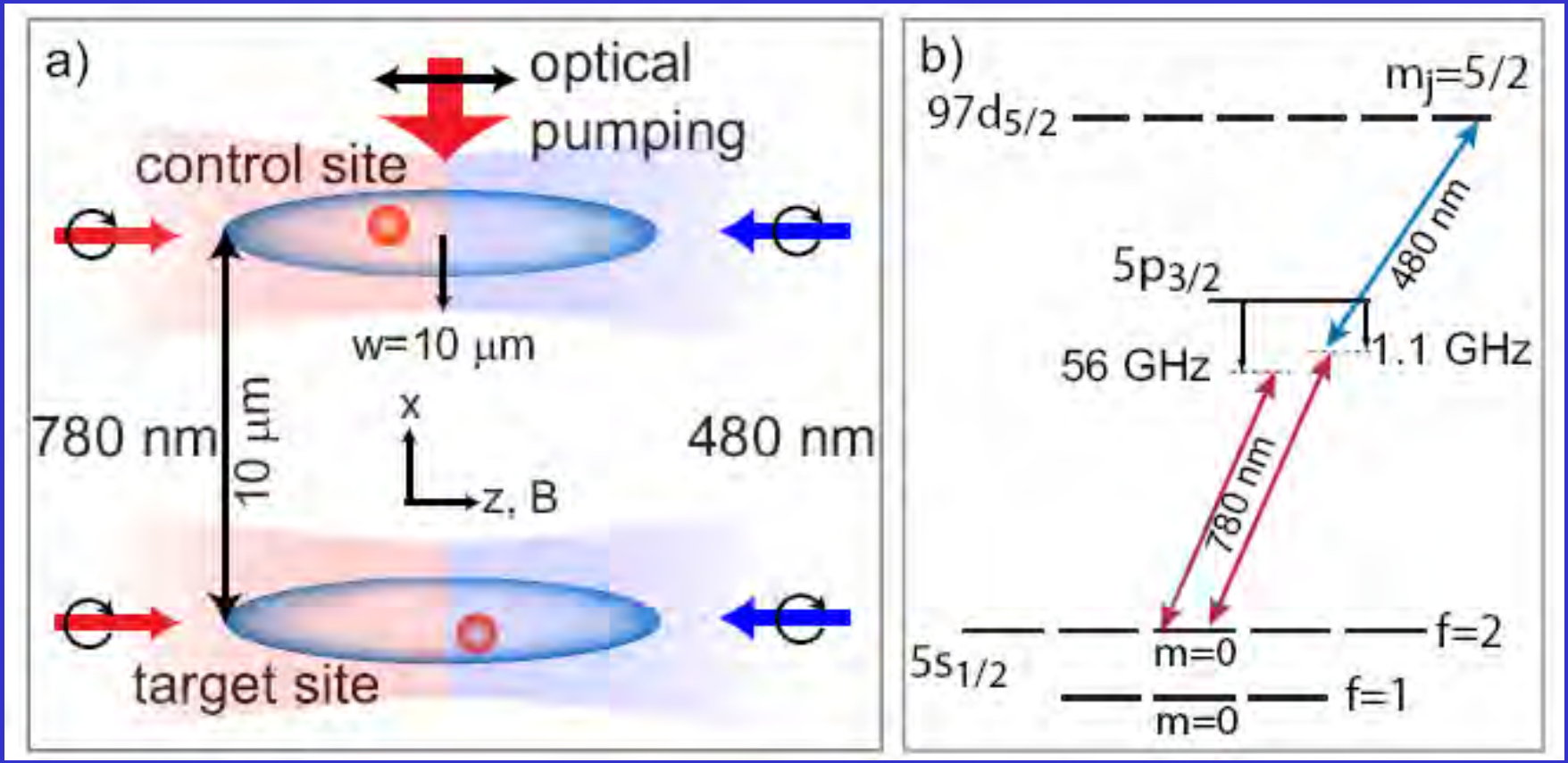


M.D.Lukin et al., Phys. Rev. Lett., 2001, v.87, p.037901

PRL 104, 010503 (2010) PHYSICAL REVIEW LETTERS week ending 8 JANUARY 2010

Demonstration of a Neutral Atom Controlled-NOT Quantum Gate

L. Isenhower, E. Urban, X. L. Zhang, A. T. Gill, T. Henage, T. A. Johnson,* T. G. Walker, and M. Saffman
Department of Physics, University of Wisconsin, 1150 University Avenue, Madison, Wisconsin 53706 USA
(Received 5 August 2009; published 8 January 2010)

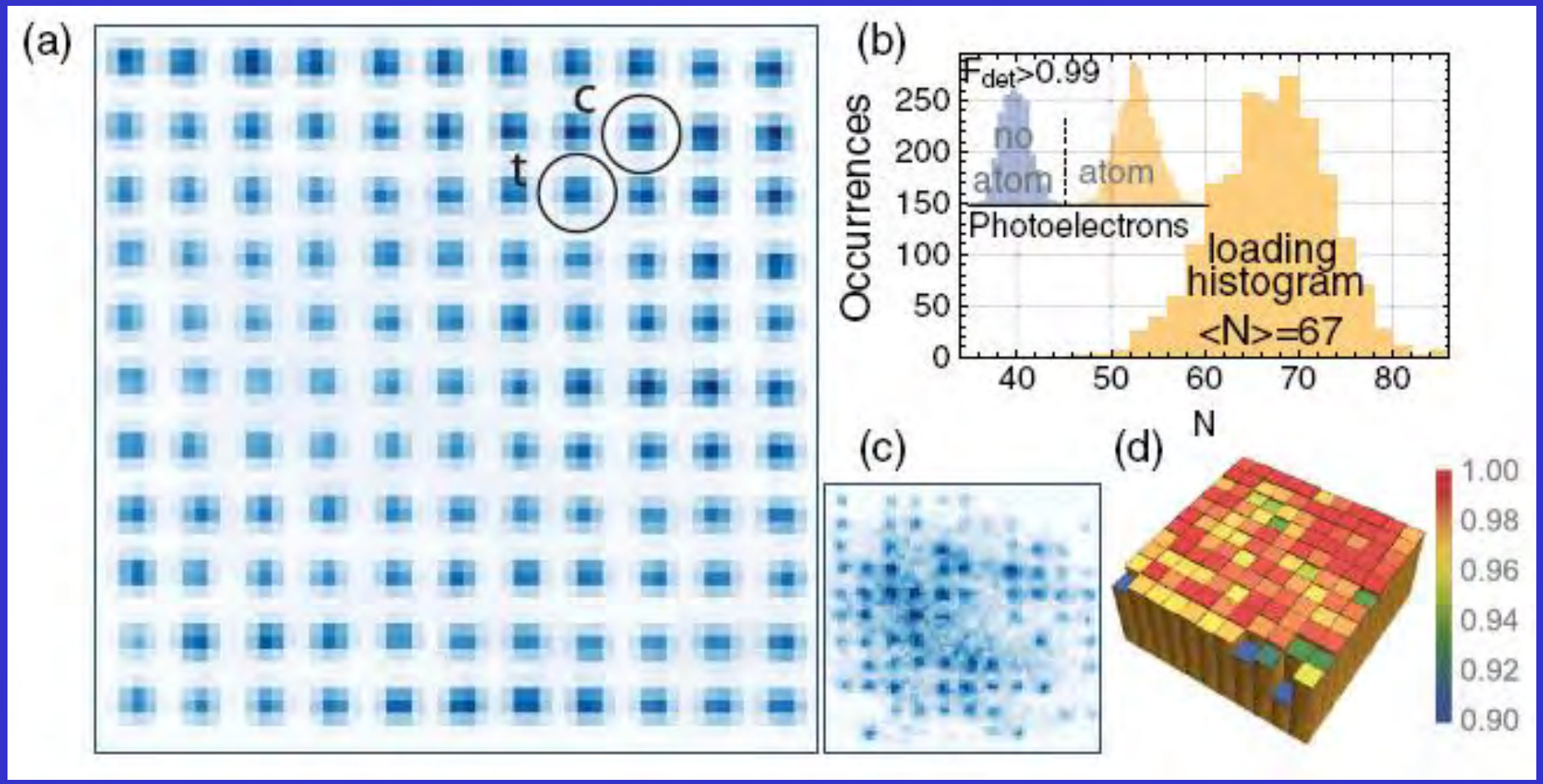


Fidelity of two-qubit gates F~80%.

PHYSICAL REVIEW LETTERS **123,** 230501 (2019)

Rydberg-Mediated Entanglement in a Two-Dimensional Neutral Atom Qubit Array

T. M. Graham, M. Kwon, B. Grinkemeyer, Z. Marra, X. Jiang, M. T. Lichtman,*
Y. Sun,† M. Ebert,‡ and M. Saffman‡
Department of Physics, University of Wisconsin-Madison, 1150 University Avenue, Madison, Wisconsin 53706, USA



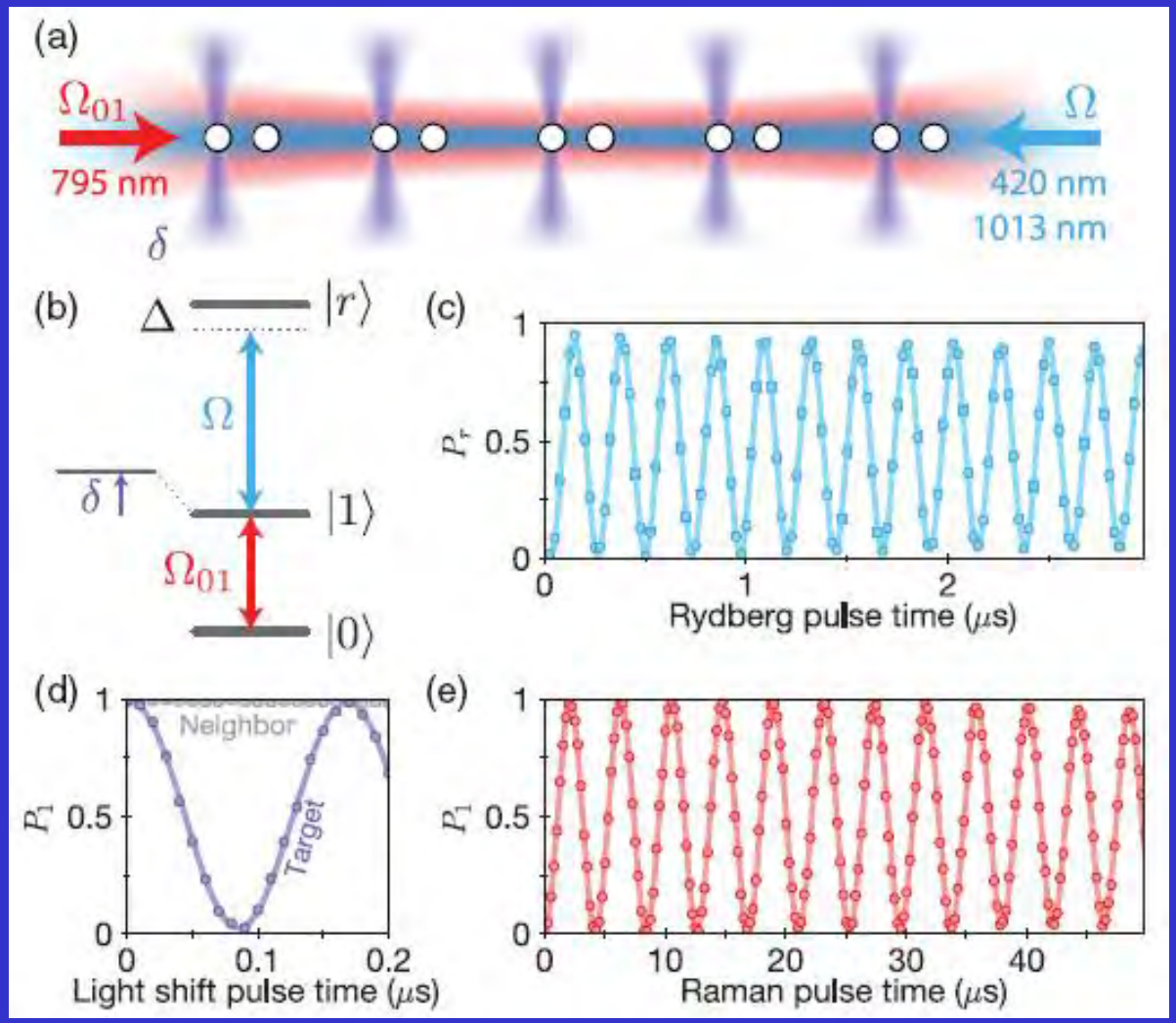
Fidelity of two-qubit gates for neighboring qubits F~90%.

PHYSICAL REVIEW LETTERS **123,** 170503 (2019)

Editors' Suggestion | Featured in Physics

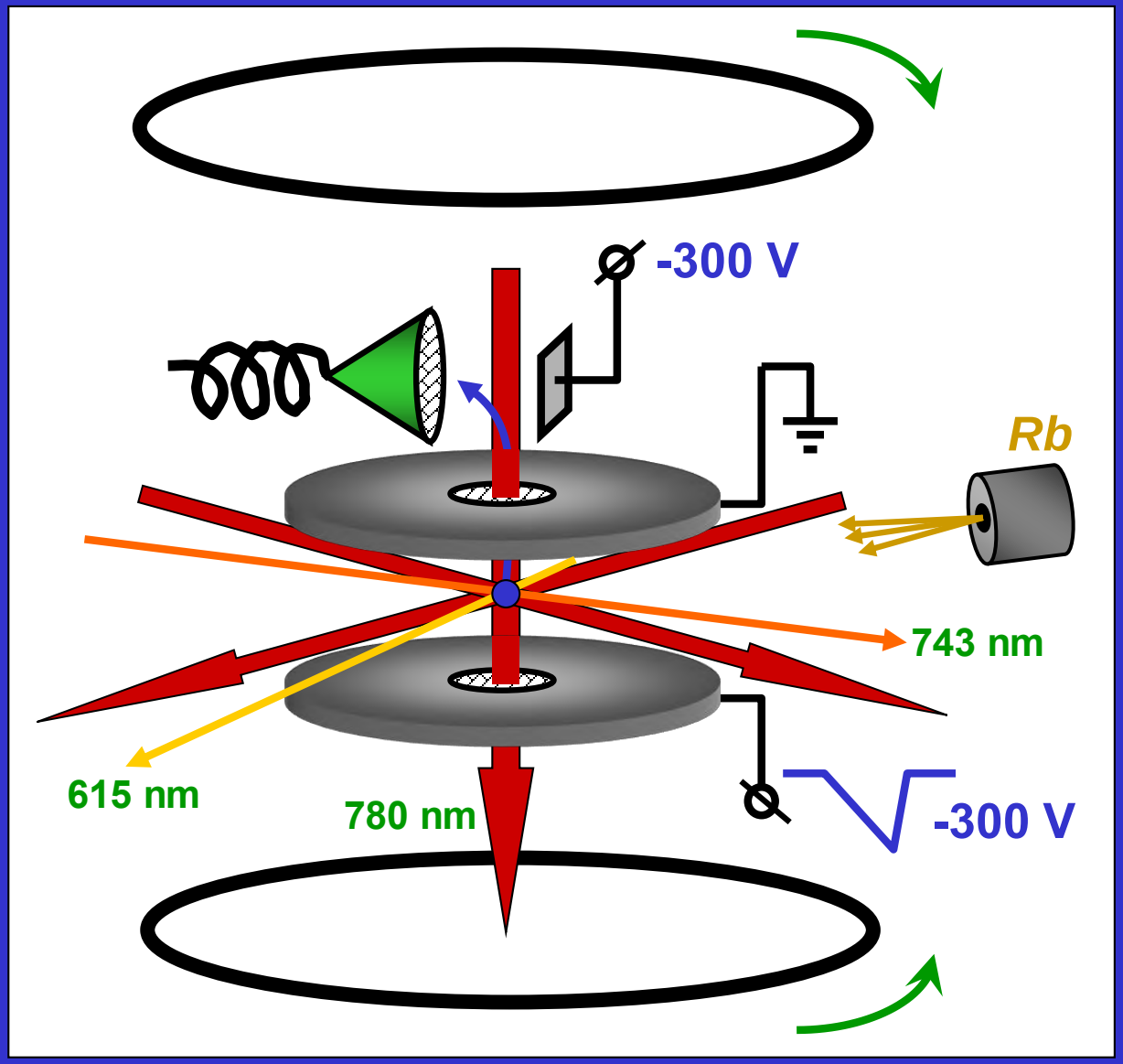
Parallel Implementation of High-Fidelity Multiqubit Gates with Neutral Atoms

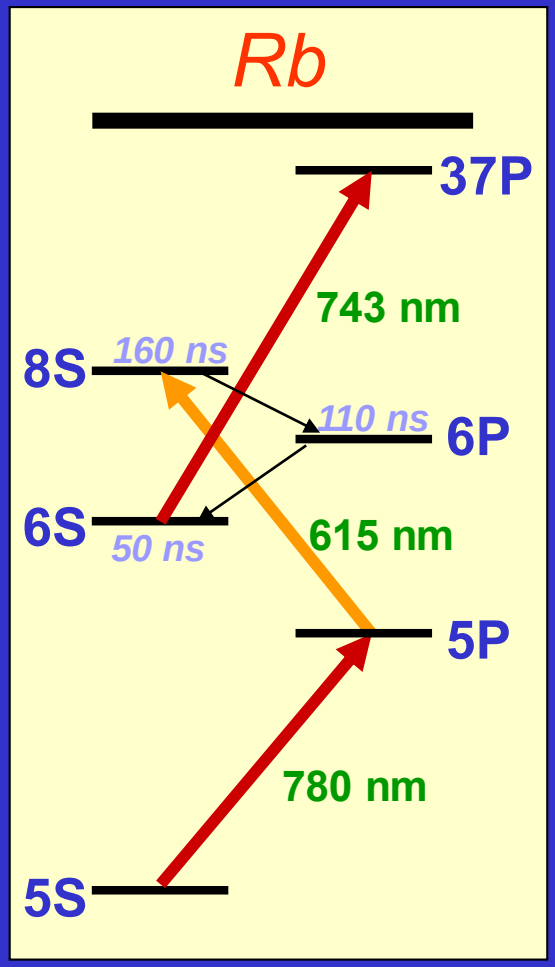
Harry Levine,[1,*] Alexander Keesling,[1] Giulia Semeghini,[1] Ahmed Omran,[1] Tout T. Wang,[1,2] Sepehr Ebadi,[1] Hannes Bernien,[3] Markus Greiner,[1] Vladan Vuletić,[4] Hannes Pichler,[1,5] and Mikhail D. Lukin[1]



Fidelity of two-qubit gates for neighboring qubits F~97% due to laser phase noise suppression.

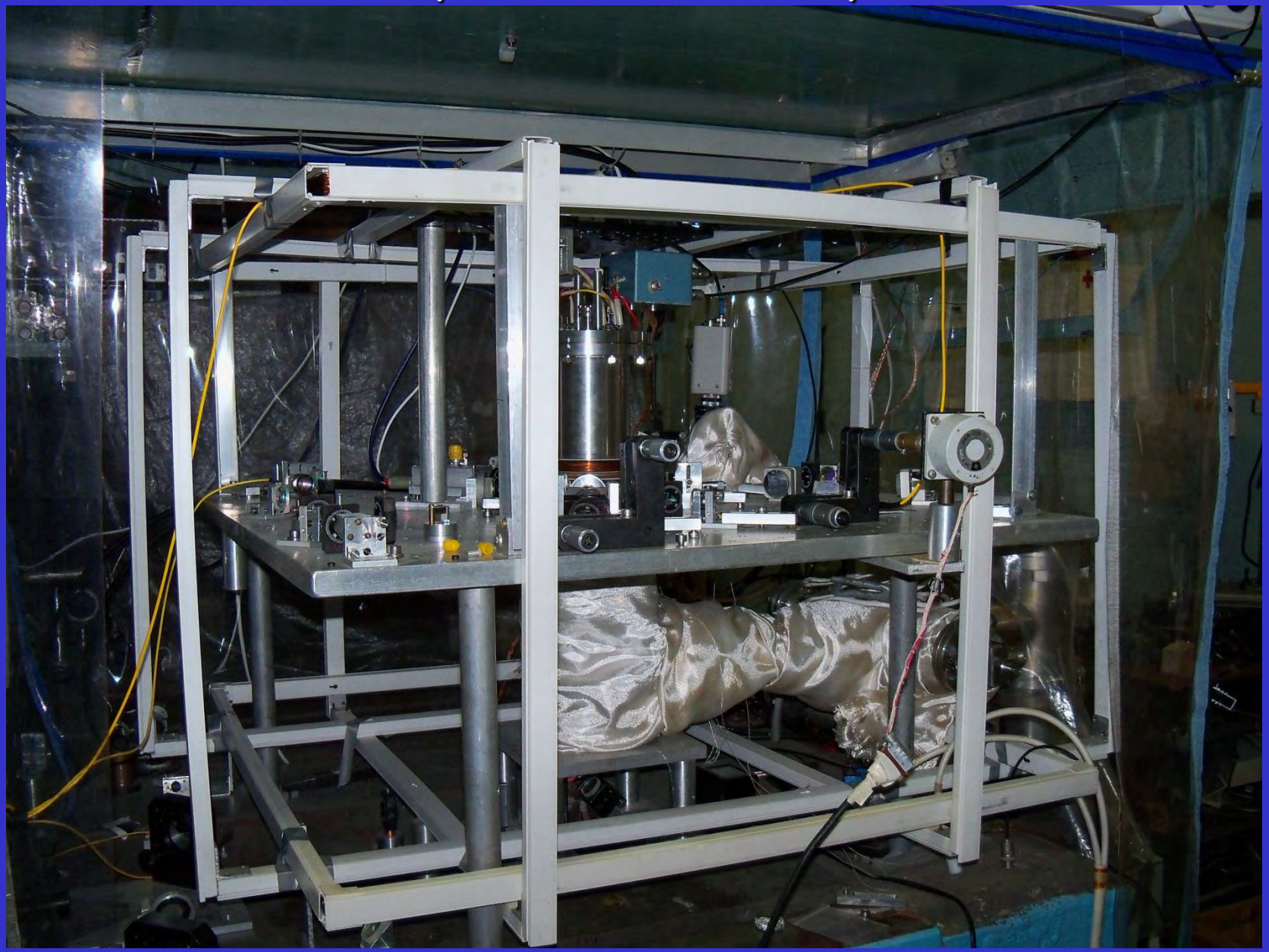
Our Rb magneto-optical trap with detection system for Rydberg atoms



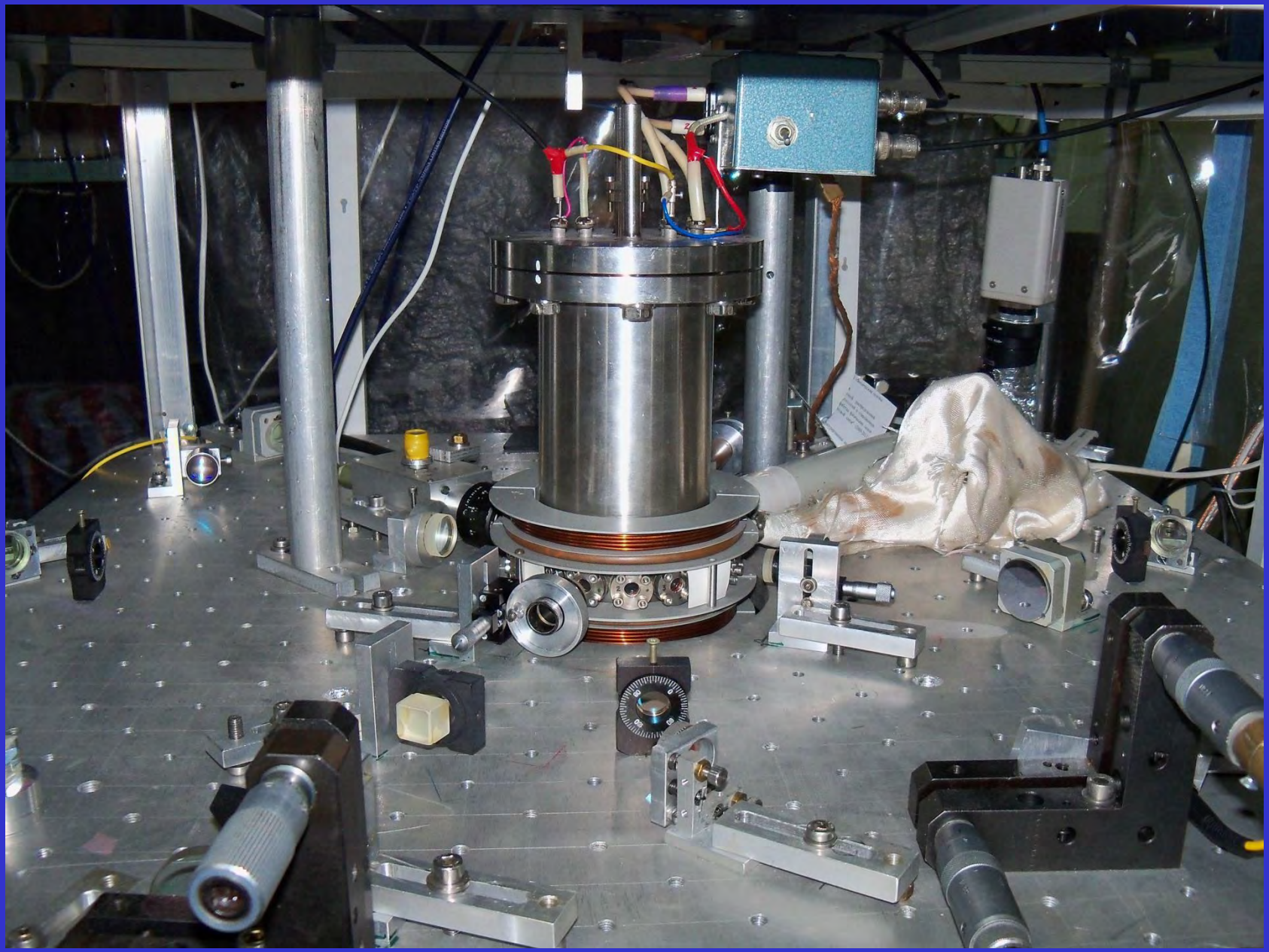


*Tretyakov et al., JETP **108**, 374 (2009)*

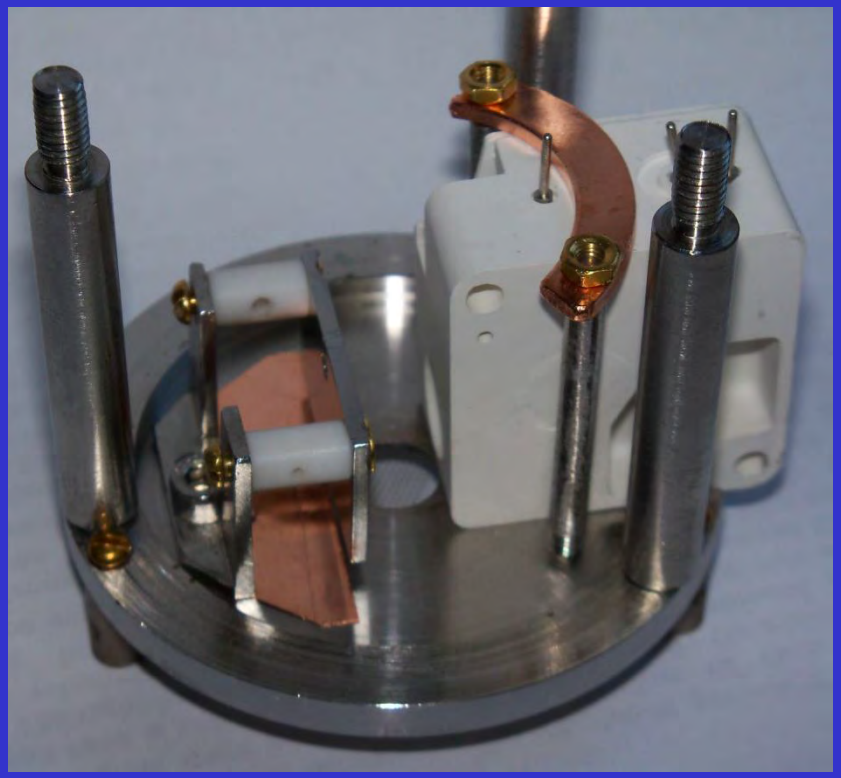
Experimental setup



Experimental setup

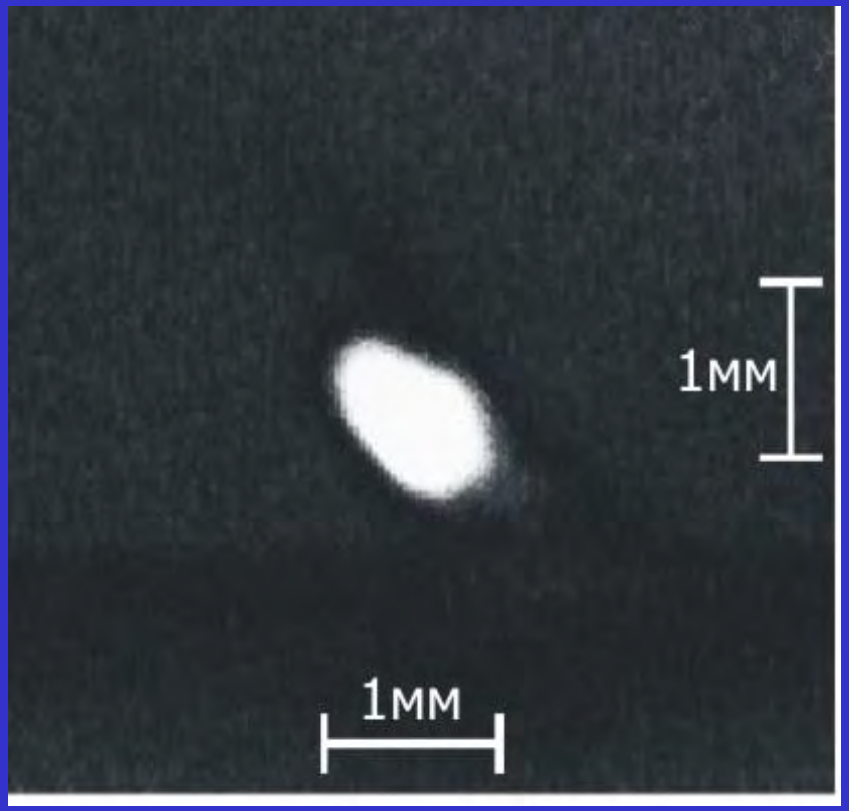


Field ionization detector

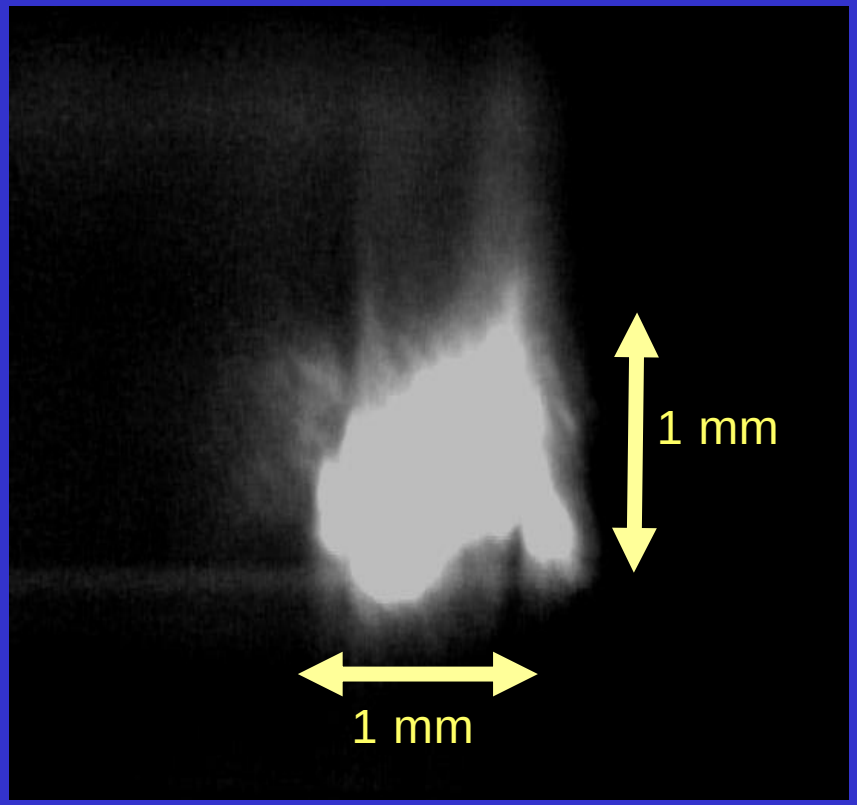


Cold Rb atom cloud

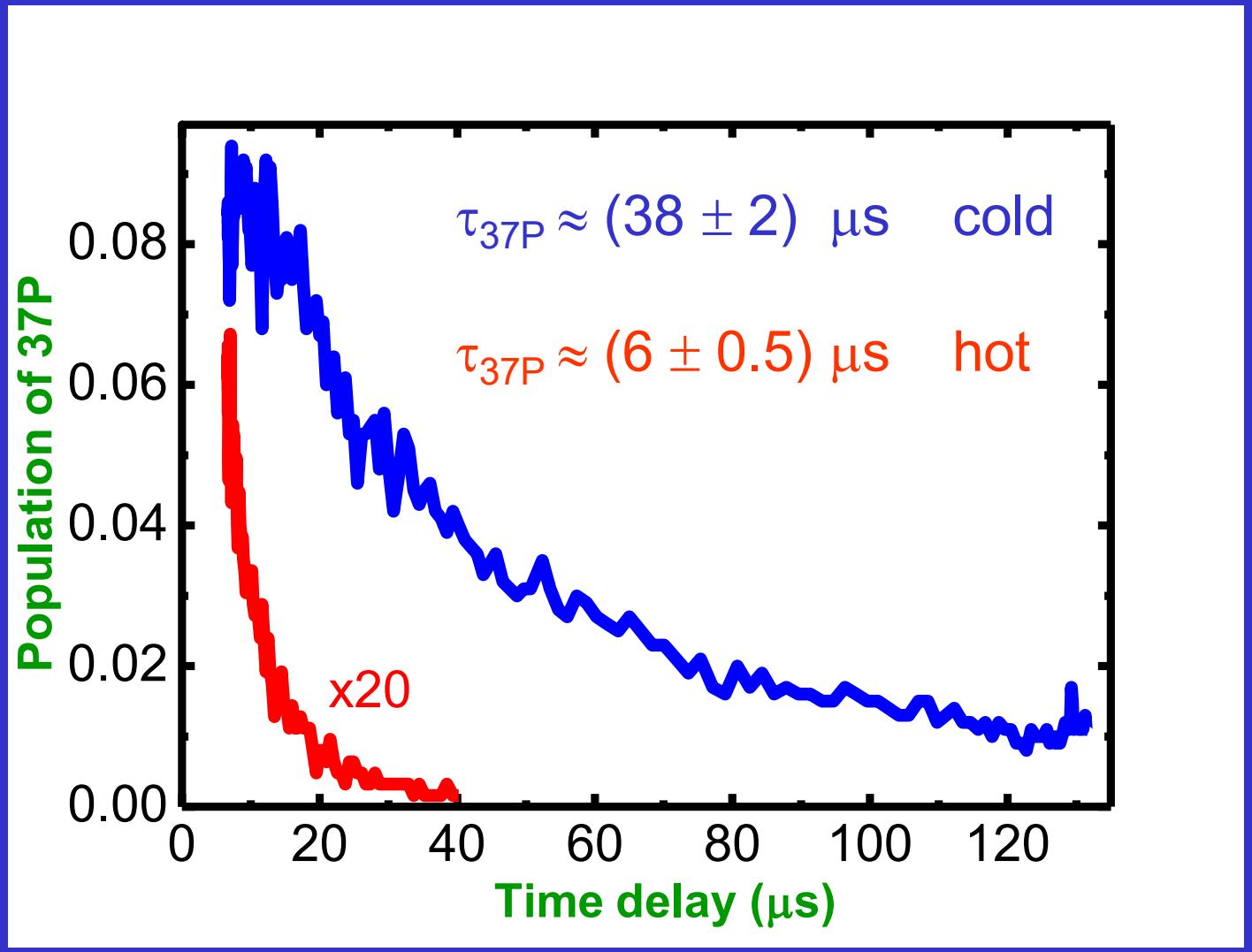
No meshes



With meshes



Lifetime of Rb(37P)

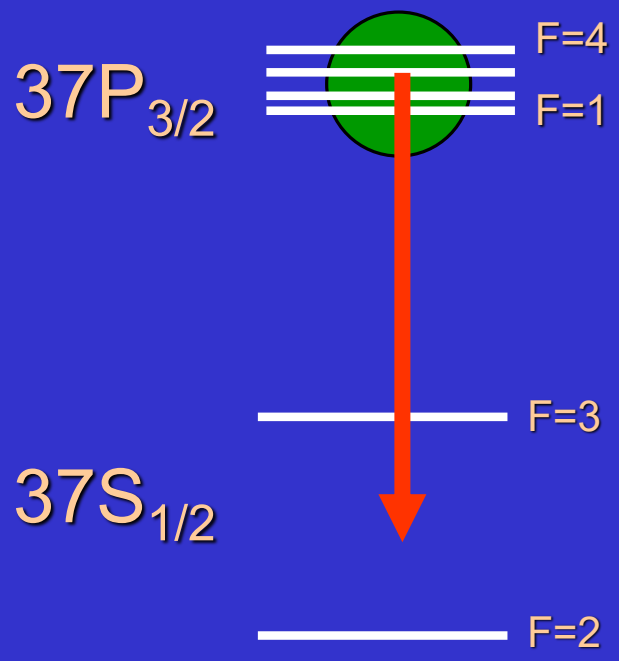


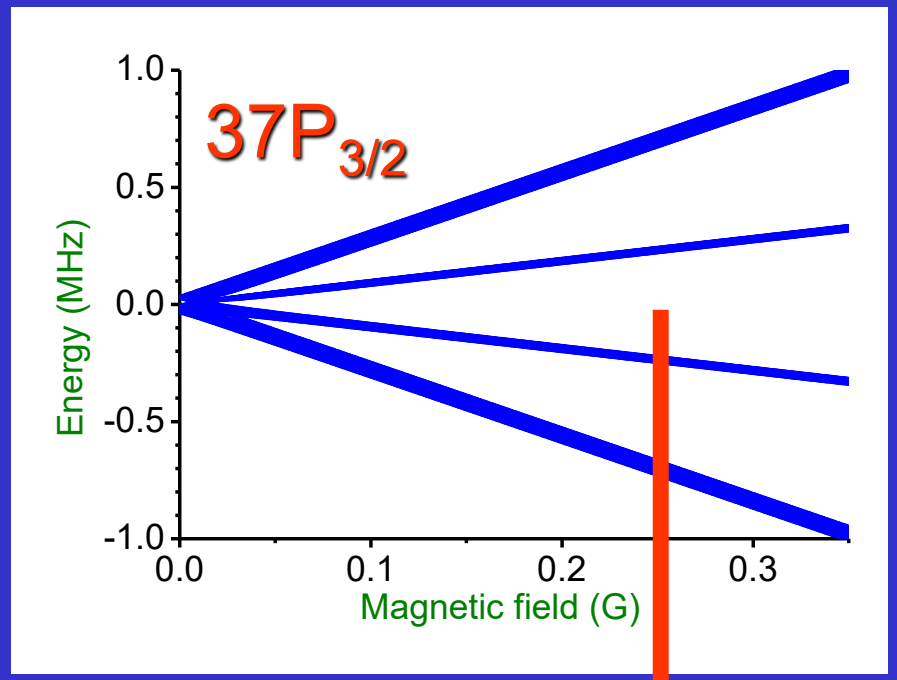
Experiment : *Tretyakov et al., JETP **108**, 374 (2009)*

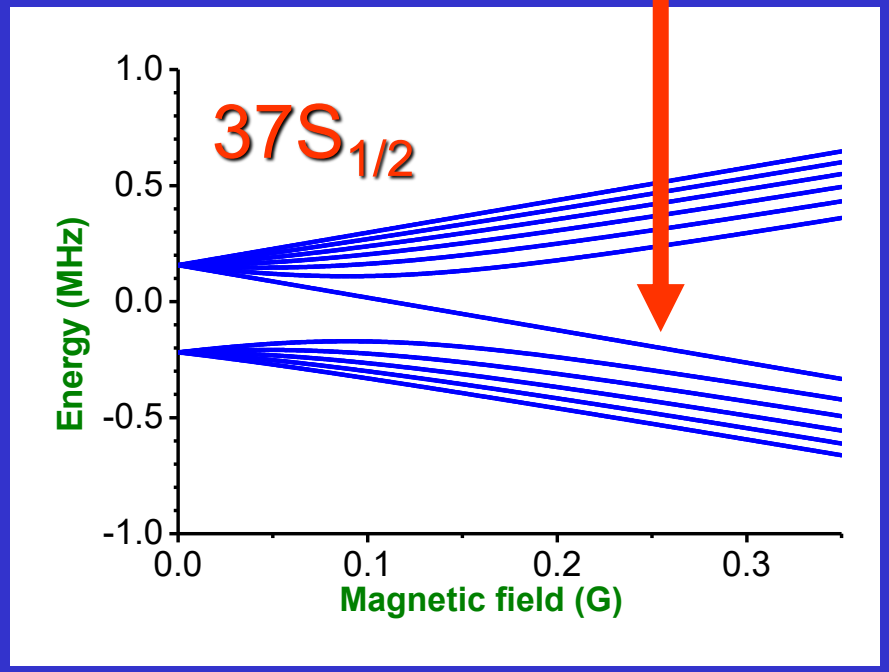
Theory at 300 K : $\tau_{37P} \approx 43$ μs *Beterov et al., PRA **79**, 052504 (2009)*

$37P_{3/2} \rightarrow 37S_{1/2}$ microwave transition

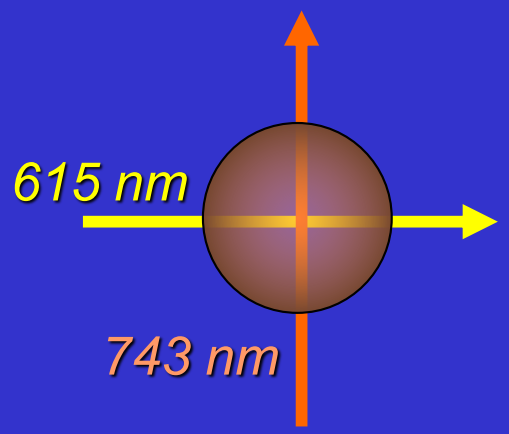
*Tretyakov et al., JETP **108**, 374 (2009)*

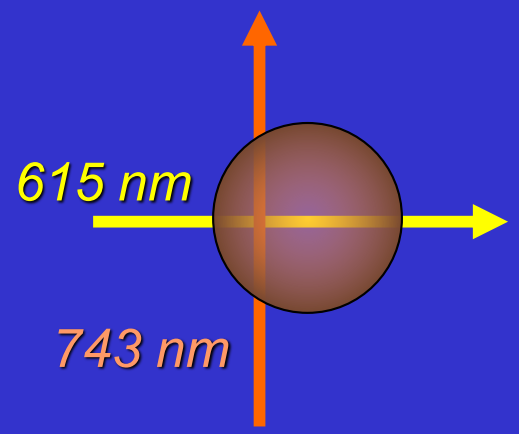




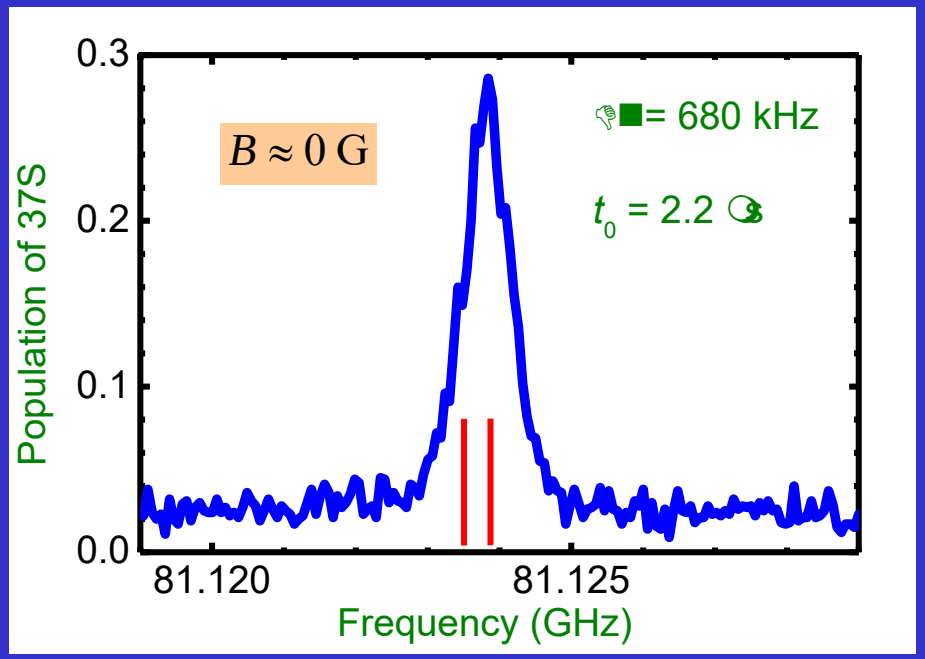


$37P_{3/2} \rightarrow 37S_{1/2}$ microwave transition in a quadrupole magnetic field 15 G/cm

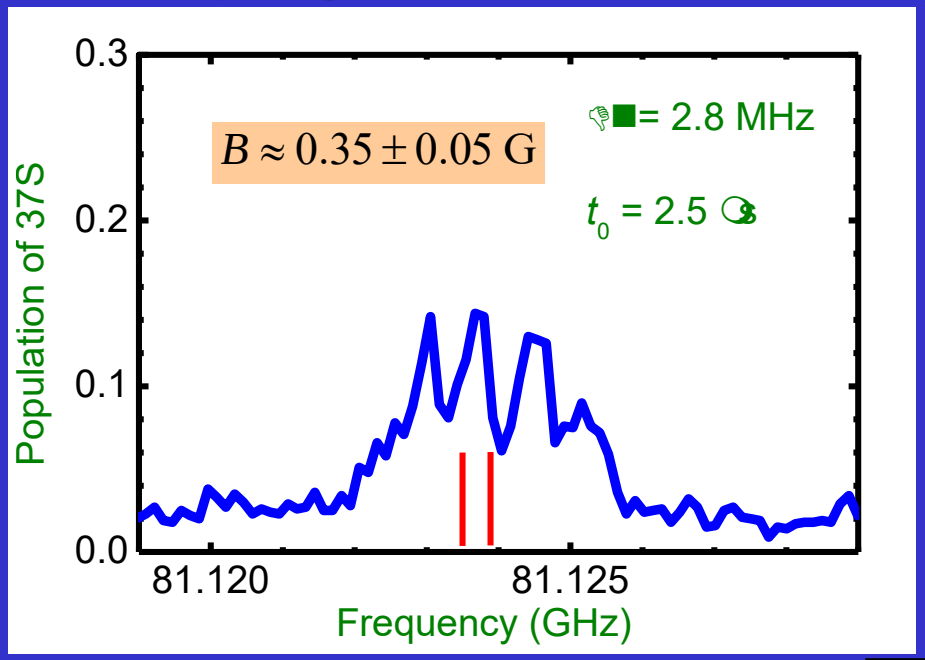




Center of cold atom cloud

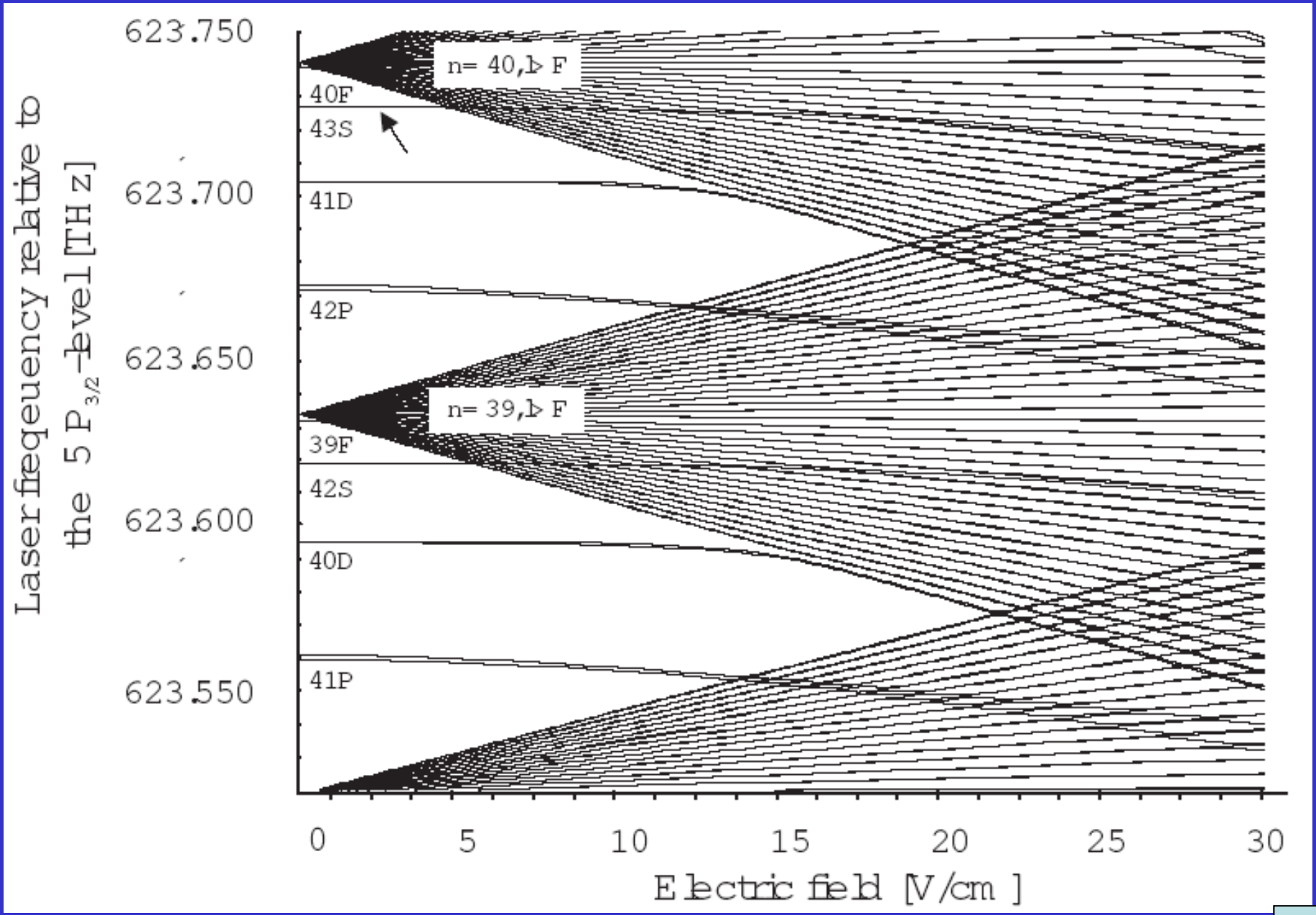


Periphery of cold atom cloud



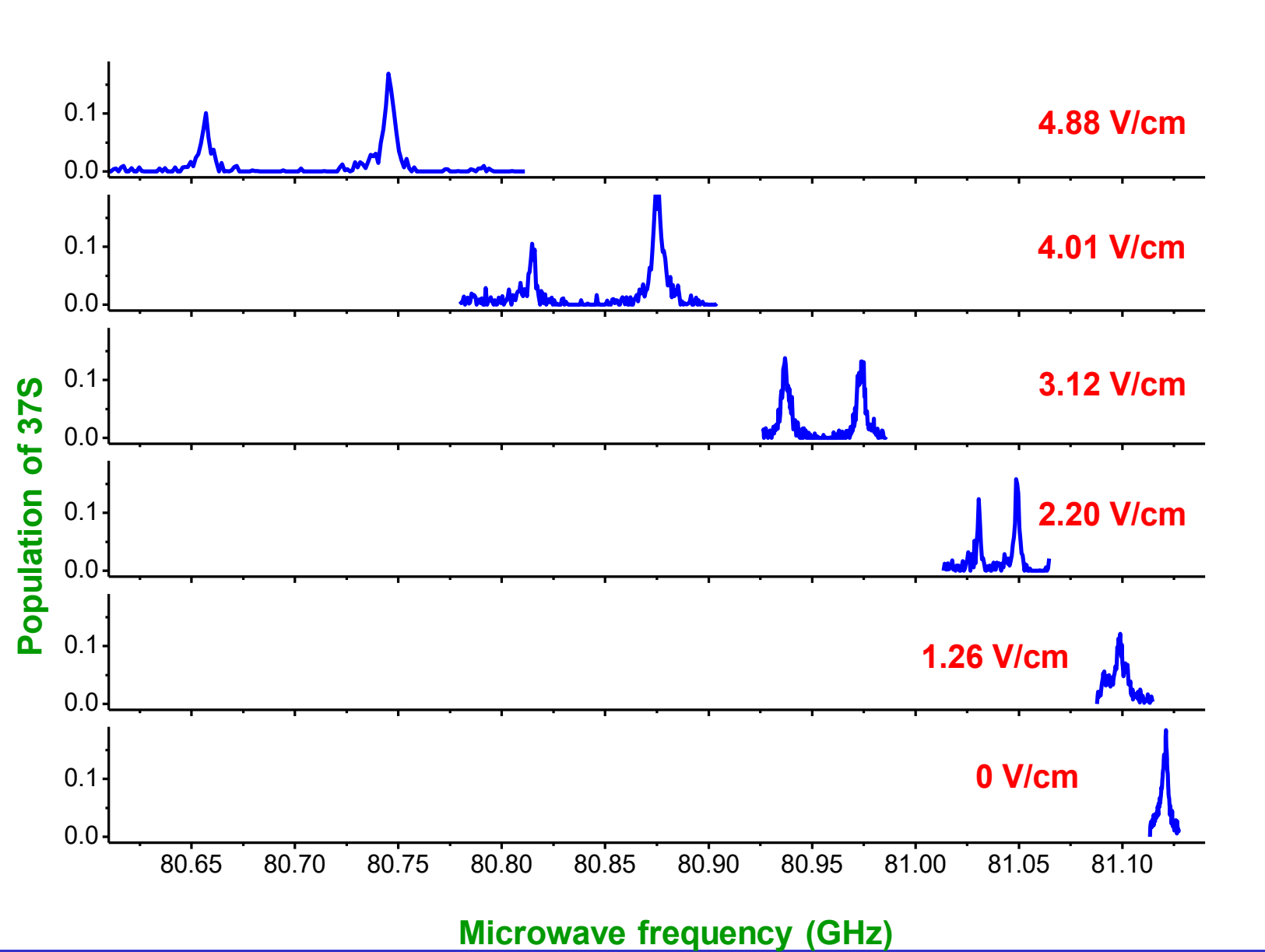
*Tretyakov et al., JETP **108**, 374 (2009)*

Rydberg states of Rb atoms in the electric field



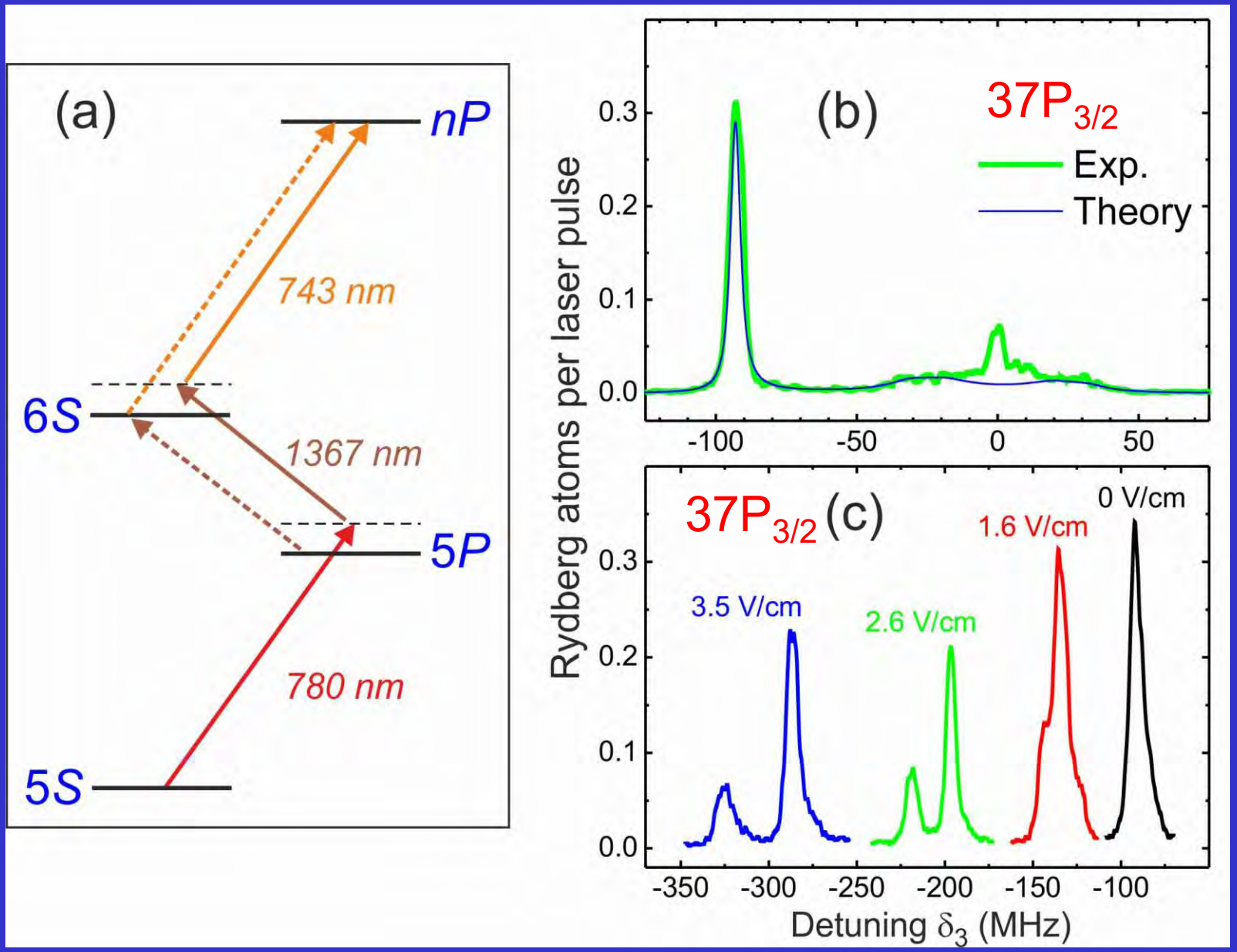
R.Low et al., http://arxiv.org/abs/0706.2639v1

Stark effect on the microwave transition $37P_{3/2} \rightarrow 37S_{1/2}$



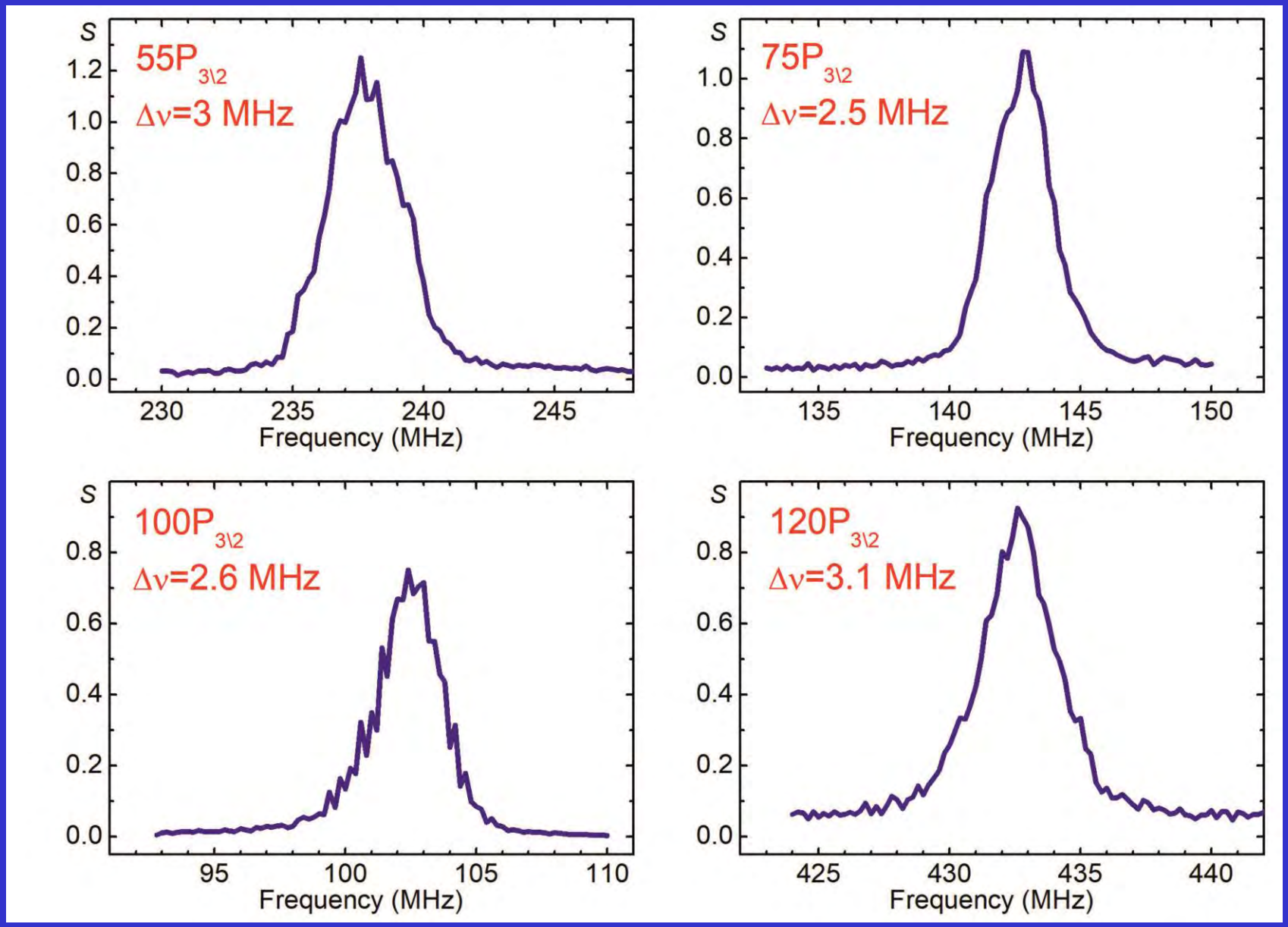
*Tretyakov et al., JETP **108**, 374 (2009)*

Three-photon laser excitation with cw lasers

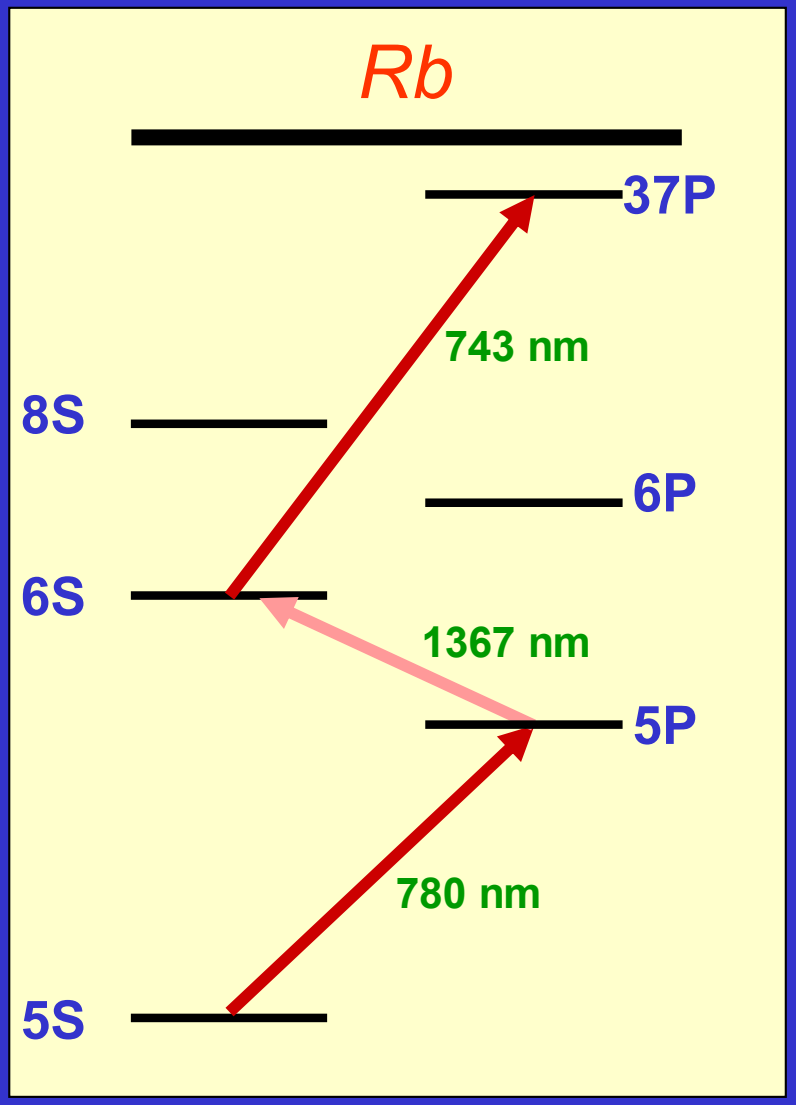


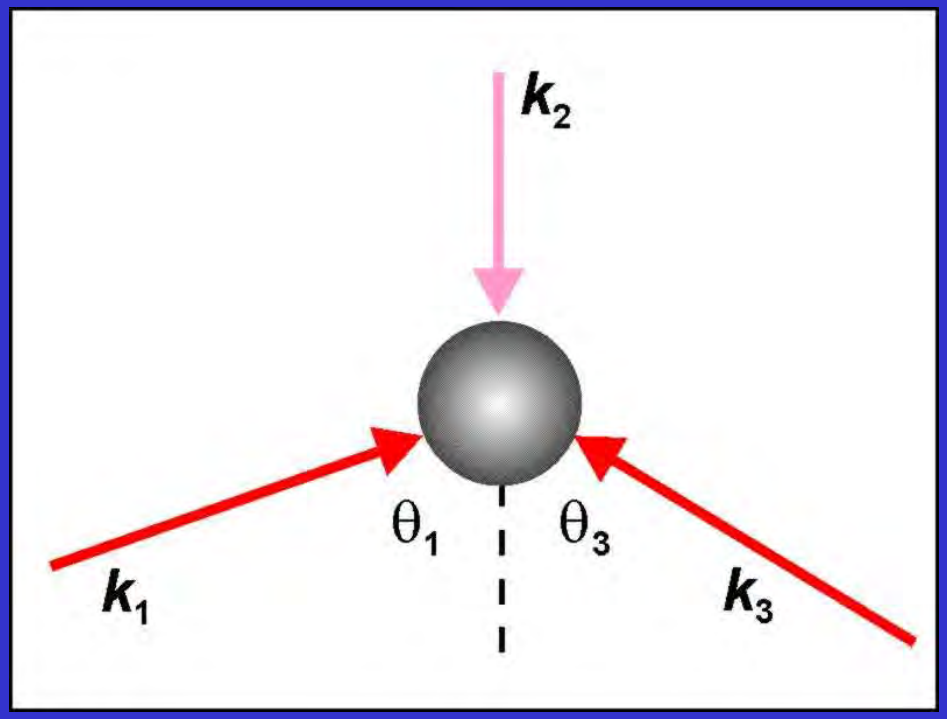
*I.I.Ryabtsev et al., Physics − Uspekhi **59**, 196 (2016)*

Spectra of three-photon laser excitation of high Rydberg *nP* states in Rb atoms



Doppler- and recoil-free laser excitation of Rydberg states via three-photon transitions

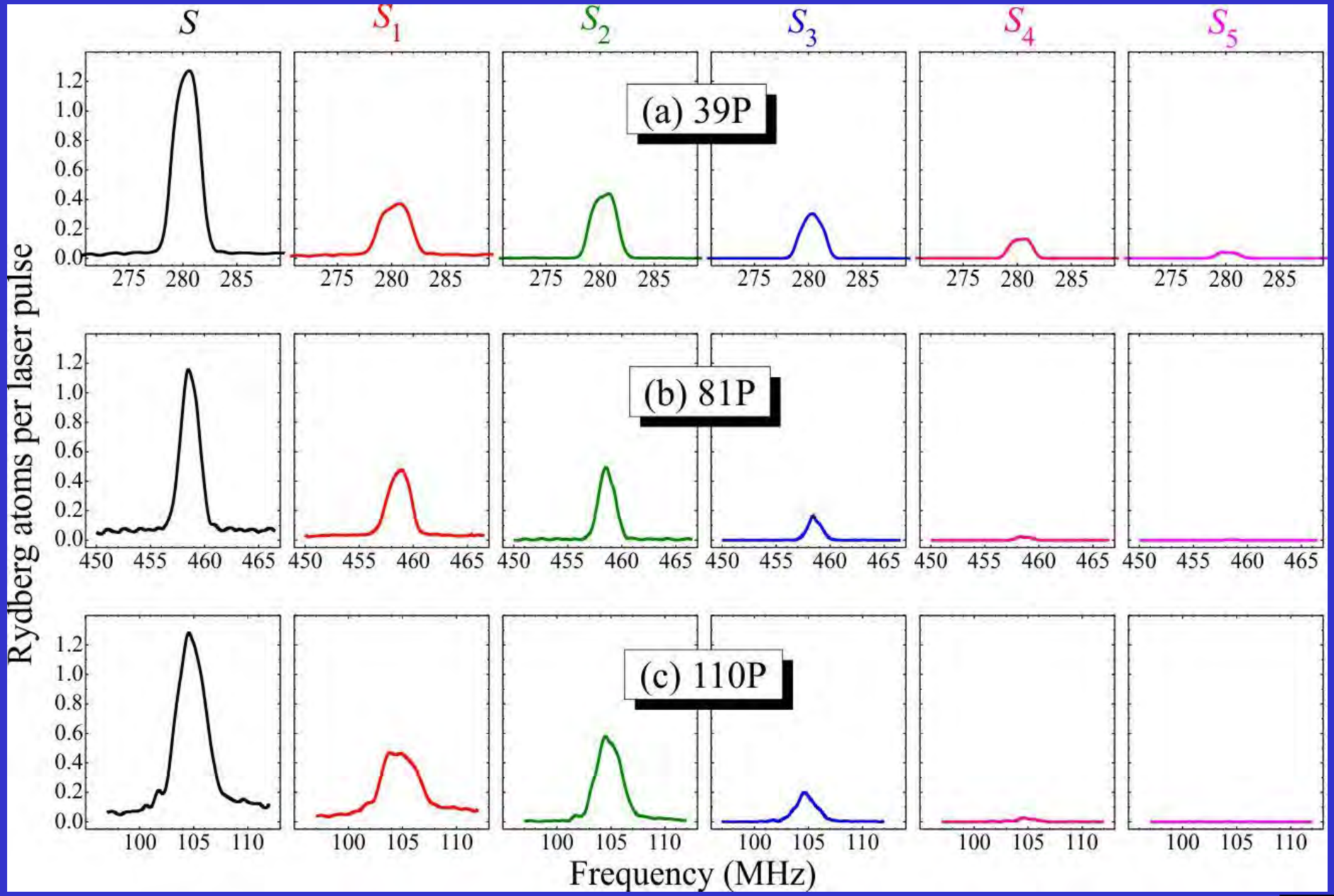




$$\vec{k}_1 + \vec{k}_2 + \vec{k}_3 \equiv 0$$

I.I.Ryabtsev et al., Phys. Rev. A, 2011, v.84, p.053409

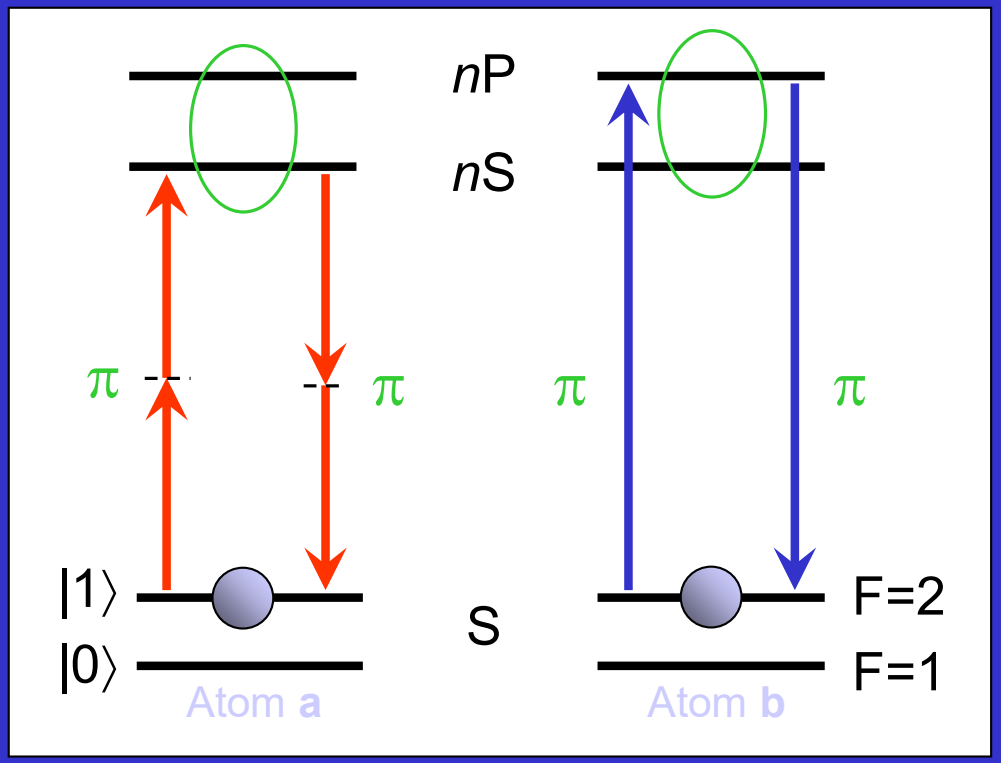
Observation of partial dipole blockade for $81P_{3/2}$ and $110P_{3/2}$ states



E.A.Yakshina et al., JETP **130**(2), 170 (2020)

Conditional Quantum Phase Gate

$$|ab\rangle \rightarrow \exp(i\Phi\delta_{a1}\delta_{b1})\,|ab\rangle$$



$$V_{DD} \sim \frac{d_1 d_2}{4\pi\varepsilon_0 R^3}$$

$$\Psi(t) = |SP\rangle \cos(V_{dd} t/\hbar) - i\,|PS\rangle \sin(V_{dd} t/\hbar)$$

$\Phi = \pi$ at $T = \pi\hbar / V_{dd}$

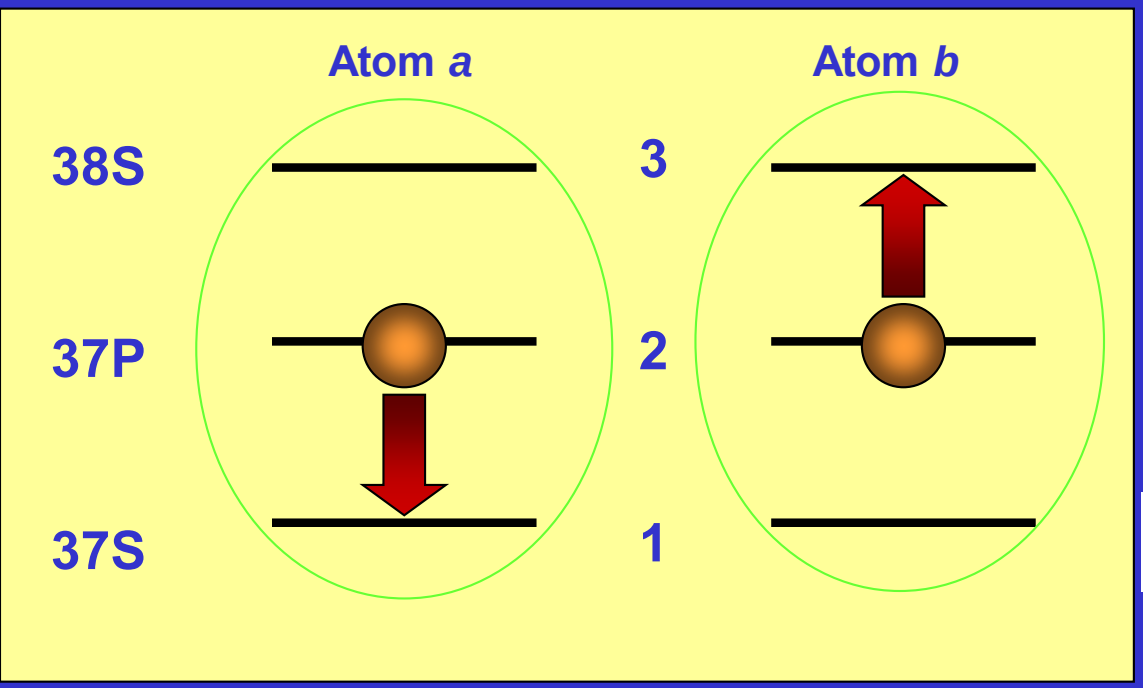
$\langle r \rangle \sim 2500$ at $n = 50$

$R \approx 5\ \mu m$

$V_{dd}/h \sim 10$ MHz $T \sim 50$ ns

*I.I.Ryabtsev, D.B.Tretyakov, and I.I.Beterov, J. Phys. B **38**, S421 (2005)*

Förster resonance in Rydberg atoms Rb($37P_{3/2}$)



$$\hat{V}_{ab} \sim \frac{\hat{d}_a \, \hat{d}_b}{R^3}$$

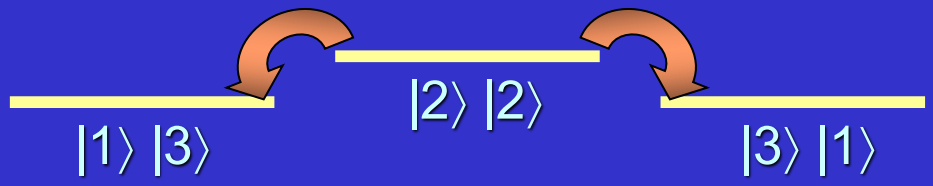
$n = 37$, $R \approx 10\ \mu m$

$V_{dd} / h \sim 400$ kHz

Collective states:

$$\Psi = A\,|2\,2\rangle + a_{13}\,|1\,3\rangle + a_{31}\,|3\,1\rangle$$

Example of two atoms:

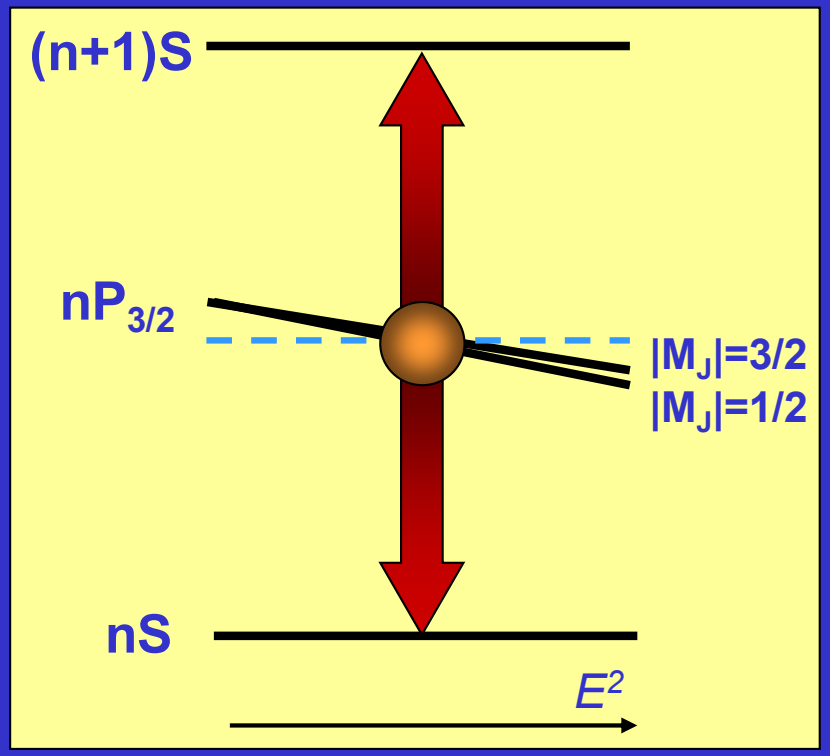


Evolution of populations:

$$\rho_2(t) = \frac{\Omega_{ab}^2}{2\,\Omega_{ab}^2 + \Delta^2/4} \sin^2\left(t\,\sqrt{2\,\Omega_{ab}^2 + \Delta^2/4}\right)$$

Förster resonance for Rb($nP_{3/2}$) atoms

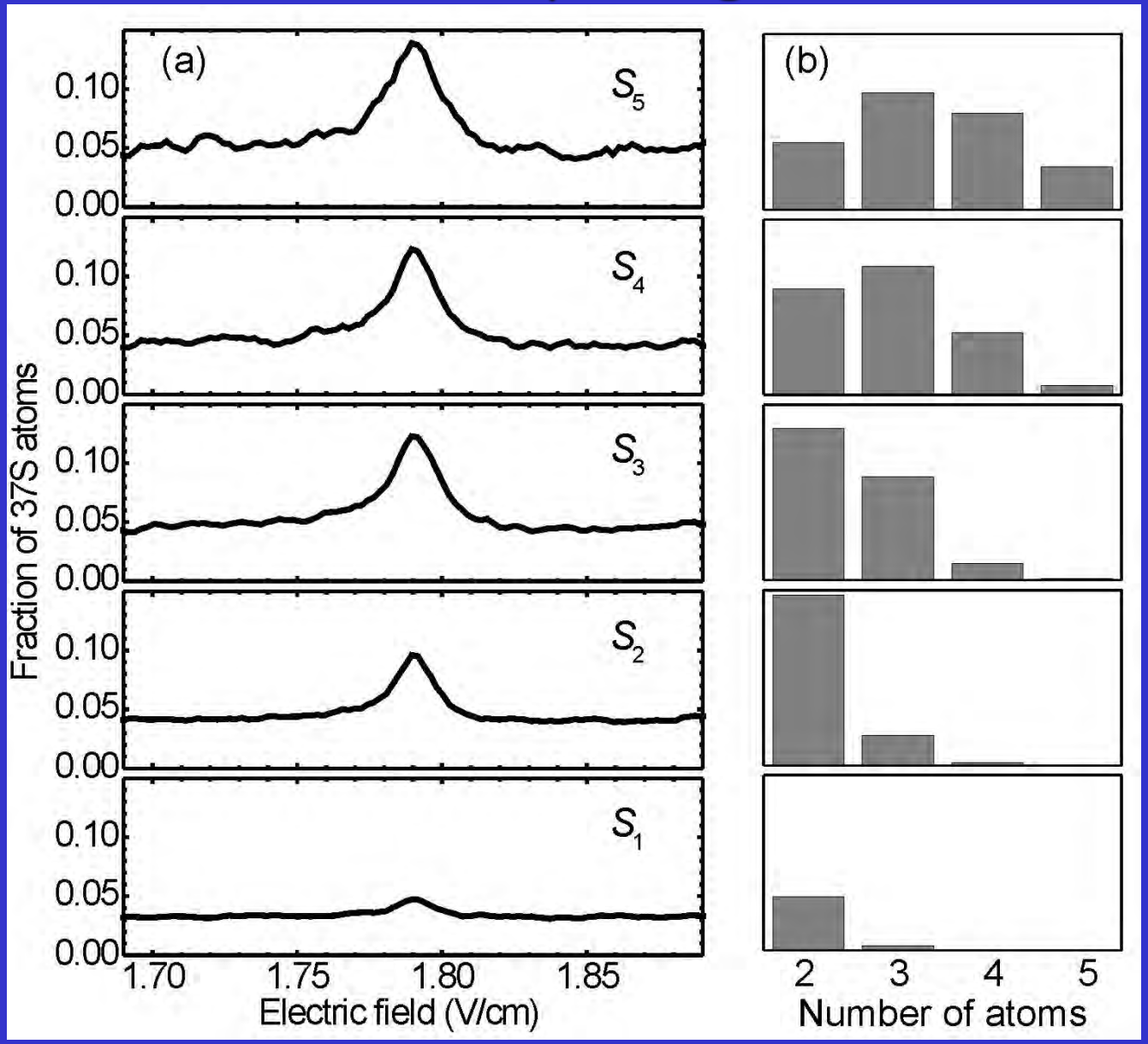
$$Rb(nP_{3/2}) + Rb(nP_{3/2}) \leftrightarrow Rb(nS_{1/2}) + Rb([n+1]S_{1/2})$$



n	Δ_0 (MHz)	E_{cr} (V/cm)
35	382	4.5
36	228	3.1
37	105	1.9
38	5.6	0.4
39	-73	
40	-136	

$$S_N = \frac{n_N(37S)}{n_N(37P) + n_N(37S) + n_N(38S)}$$

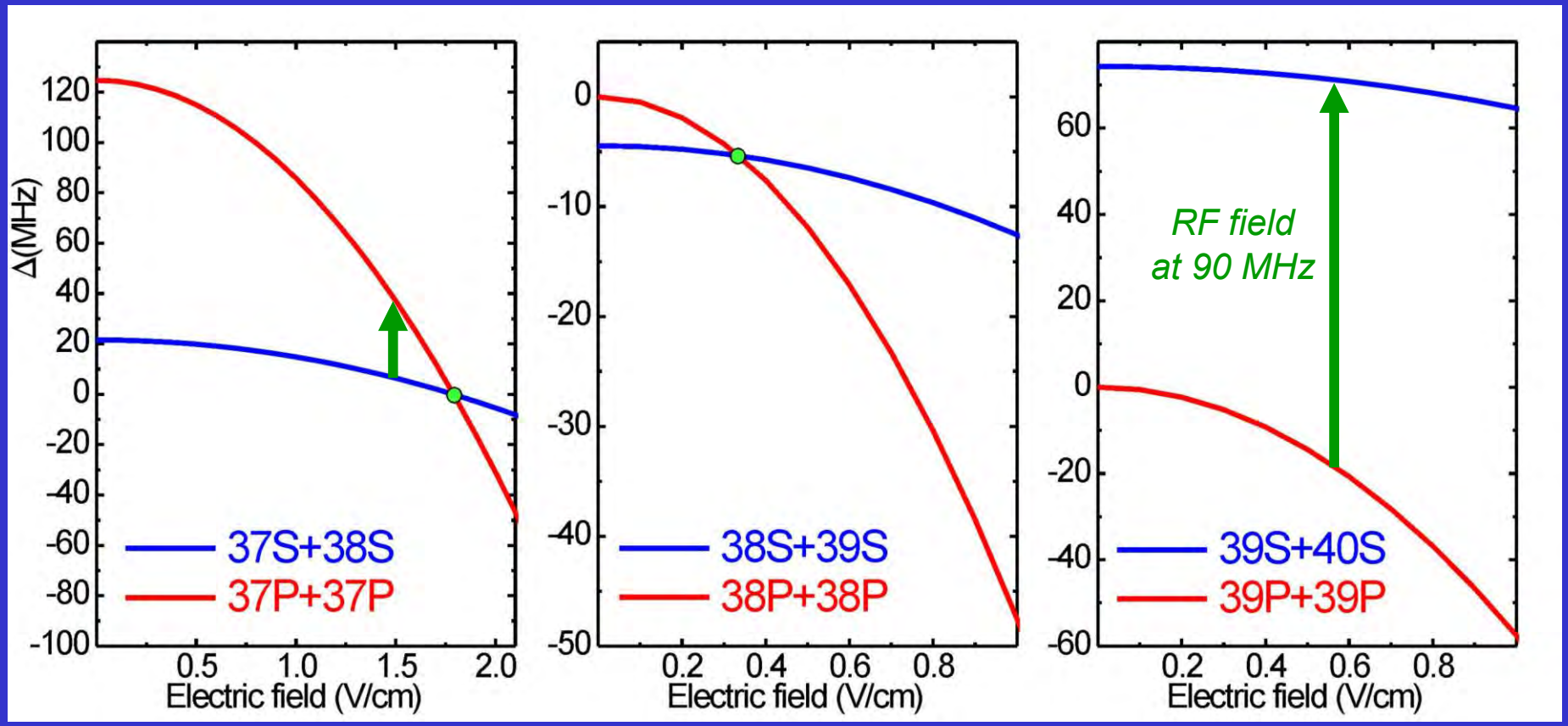
Förster resonance in Rydberg atoms Rb($37P_{3/2}$)



I.I.Ryabtsev, D.B.Tretyakov, I.I.Beterov, V.M.Entin, PRL 104 (2010) 073003

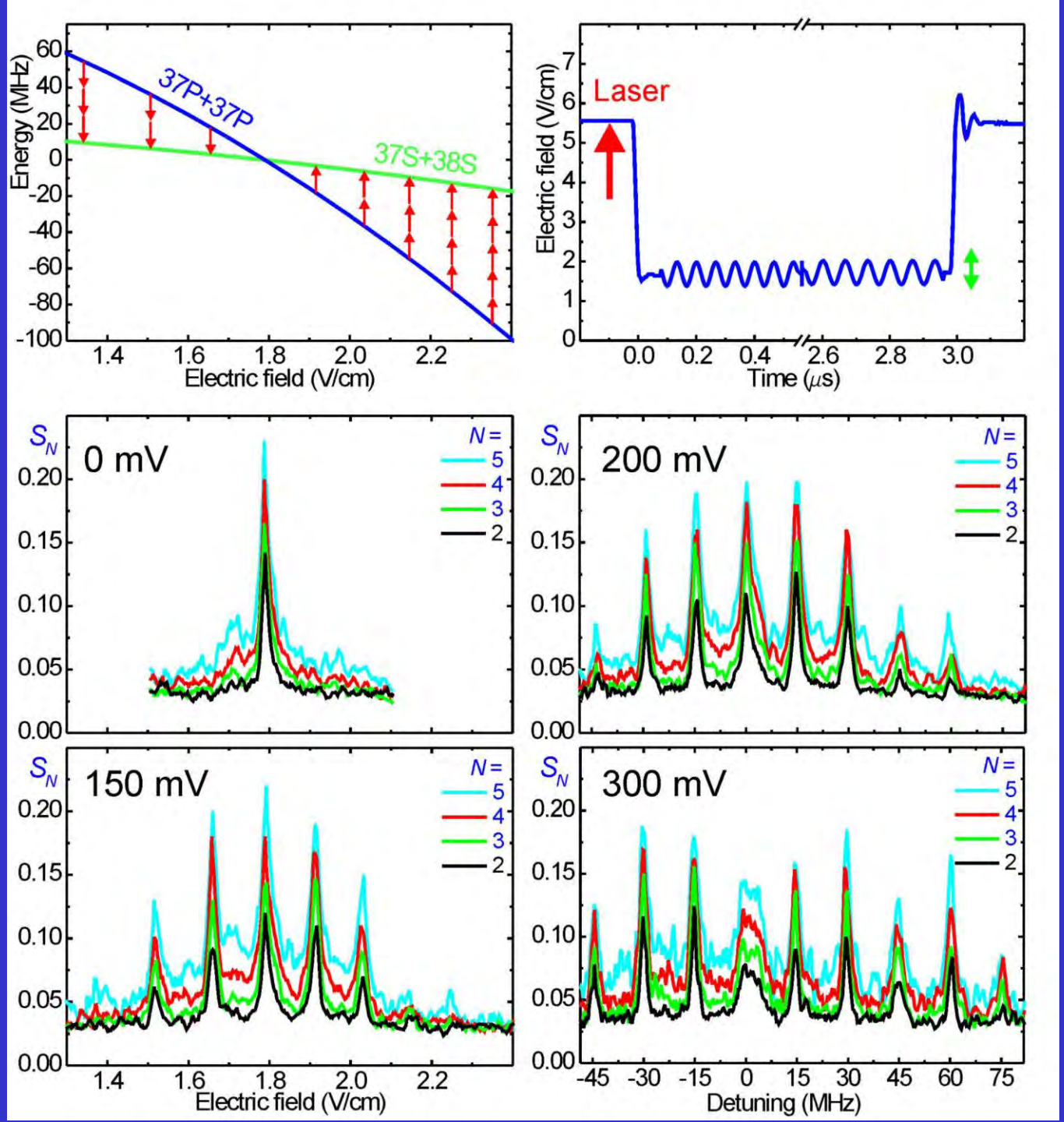
Förster resonances

$Rb(nP_{3/2}) + Rb(nP_{3/2}) \rightarrow Rb(nS_{1/2}) + Rb([n+1]S_{1/2})$



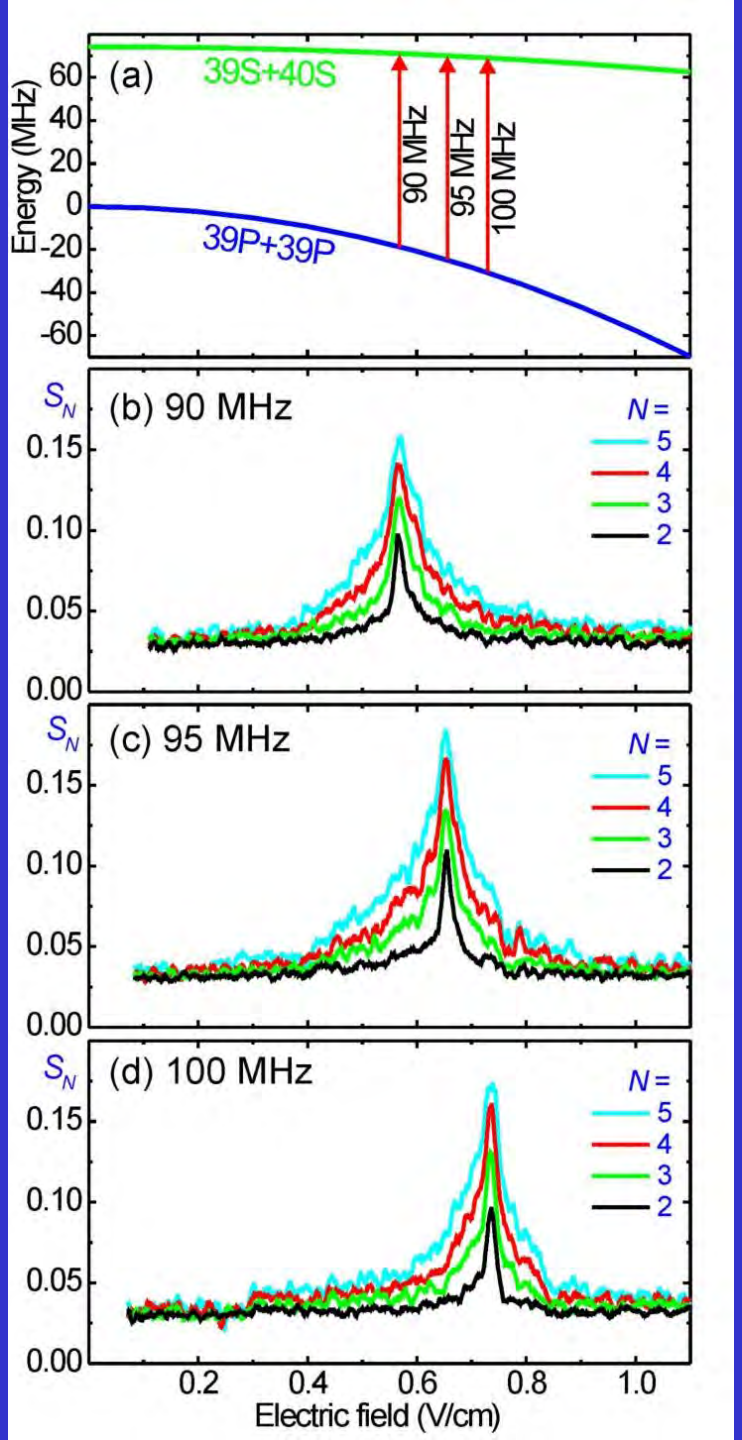
*D.B.Tretyakov et al., Phys. Rev. A **90**, 041403(R) (2014)*
*E.A.Yakshina et al., Phys. Rev. A **94**, 043417 (2016)*

RF-assisted Förster resonances for 37P state at 15 MHz



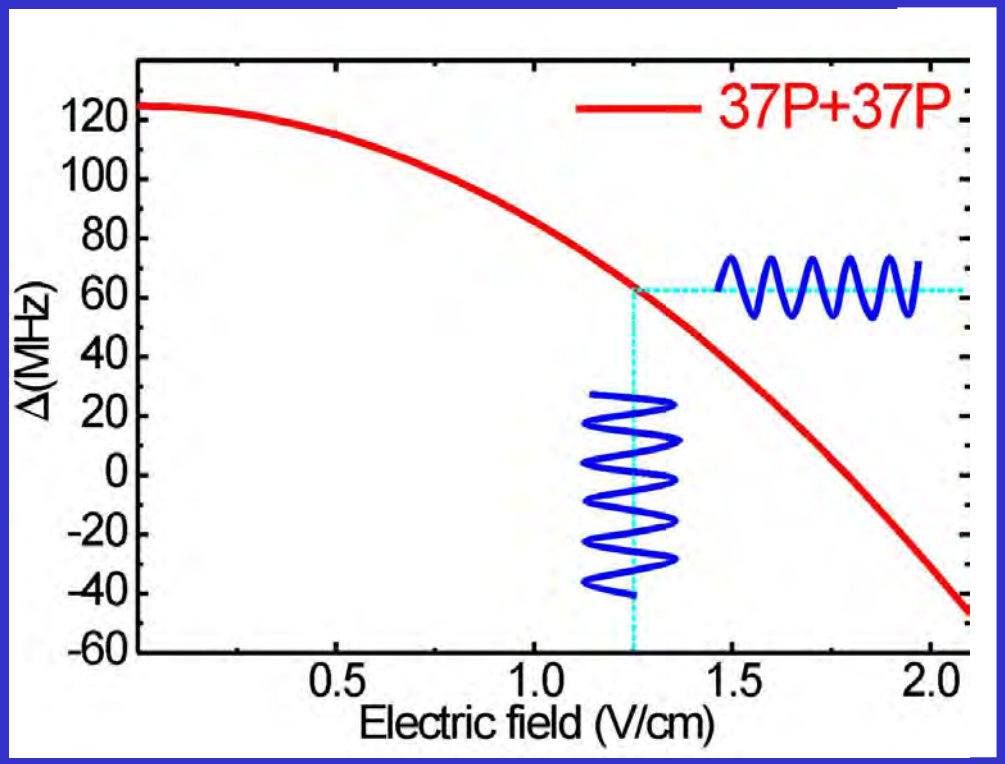
*D.B.Tretyakov et al., Phys. Rev. A **90**, 041403(R) (2014)*

RF-assisted Förster resonances for 39P state



*D.B.Tretyakov et al., Phys. Rev. A **90**, 041403(R) (2014)*

Floquet sidebands at rf-modulation of Rydberg states



Electric field

$$F = F_{dc} + F_{rf} \cos(\omega t)$$

Energy of nL Rydberg state

$$E_{nL} = -\alpha_{nL} F^2 / 2$$

$$E_{nL} = -\frac{1}{2}\alpha_{nL}[F_{dc}^2 + \frac{1}{2}F_{rf}^2 + 2F_{dc}F_{rf}\cos(\omega t) + \frac{1}{2}F_{rf}^2\cos(2\omega t)]$$

Wave function of Rydberg state

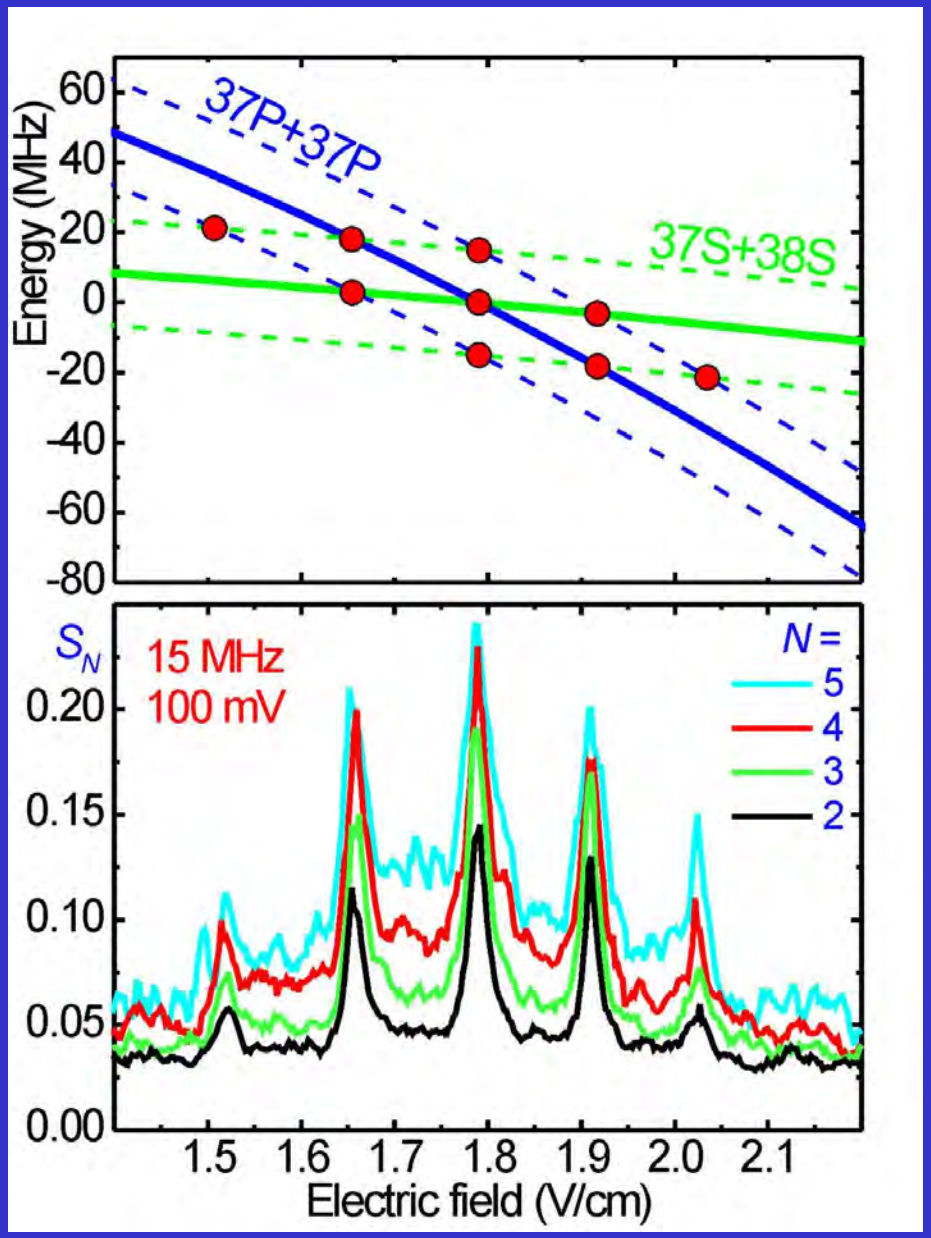
$$\Psi_{nL}(r,t) = \psi_{nL}(r) e^{i\alpha(F_{dc}^2 + F_{rf}^2/2)t/2} \sum_{m=-\infty}^{\infty} a_{nL,m} e^{im\omega t}$$

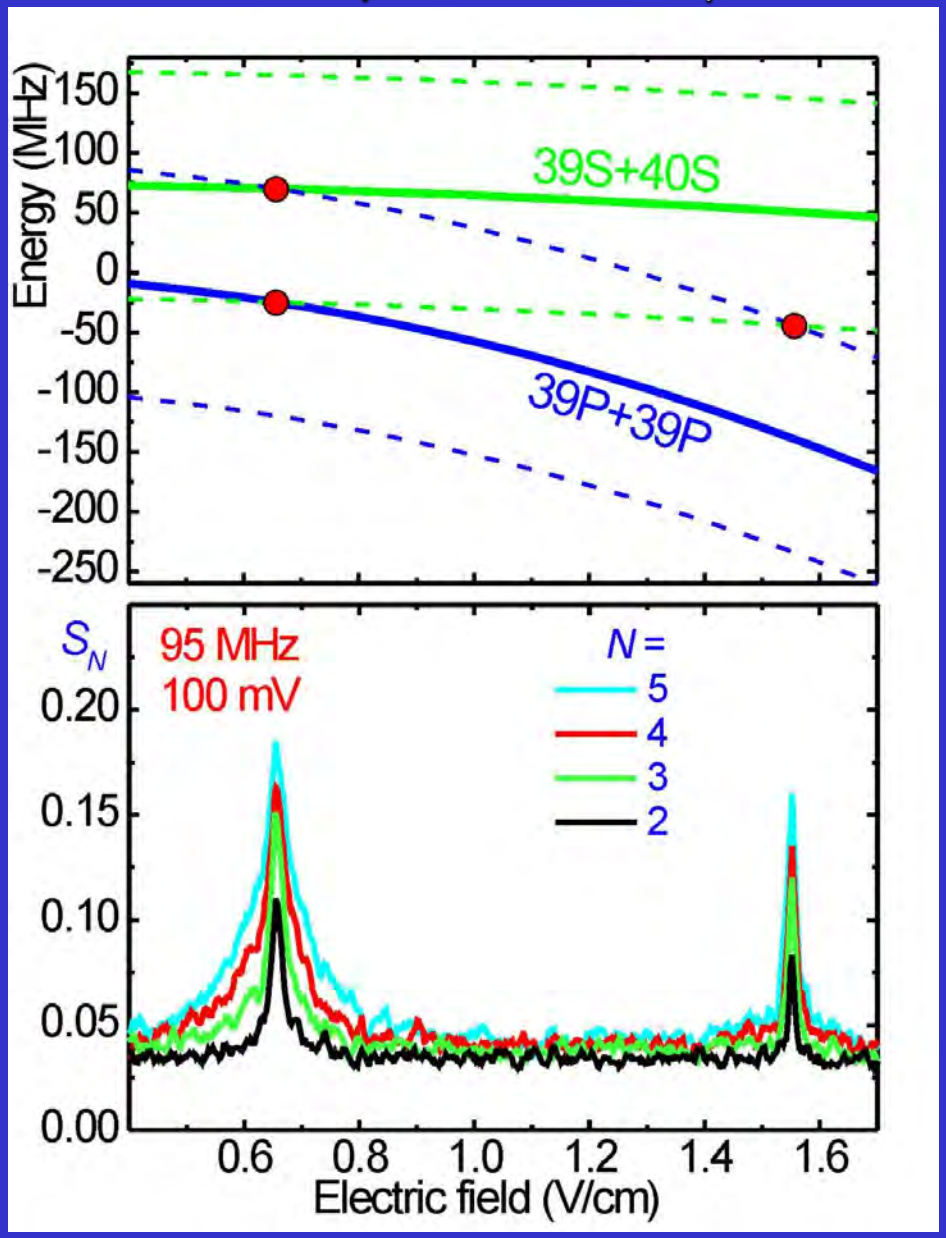
Amplitudes of Floquet states

$$a_{nL,m} = \sum_{k=-\infty}^{\infty} J_{m-2k}\left(\frac{\alpha_{nL}F_{dc}F_{rf}}{\omega}\right) J_k\left(\frac{\alpha_{nL}F_{rf}^2}{8\,\omega}\right)$$

*C.S.E. van Ditzhuijzen et al., Phys. Rev. A **80**, 063407 (2009)*

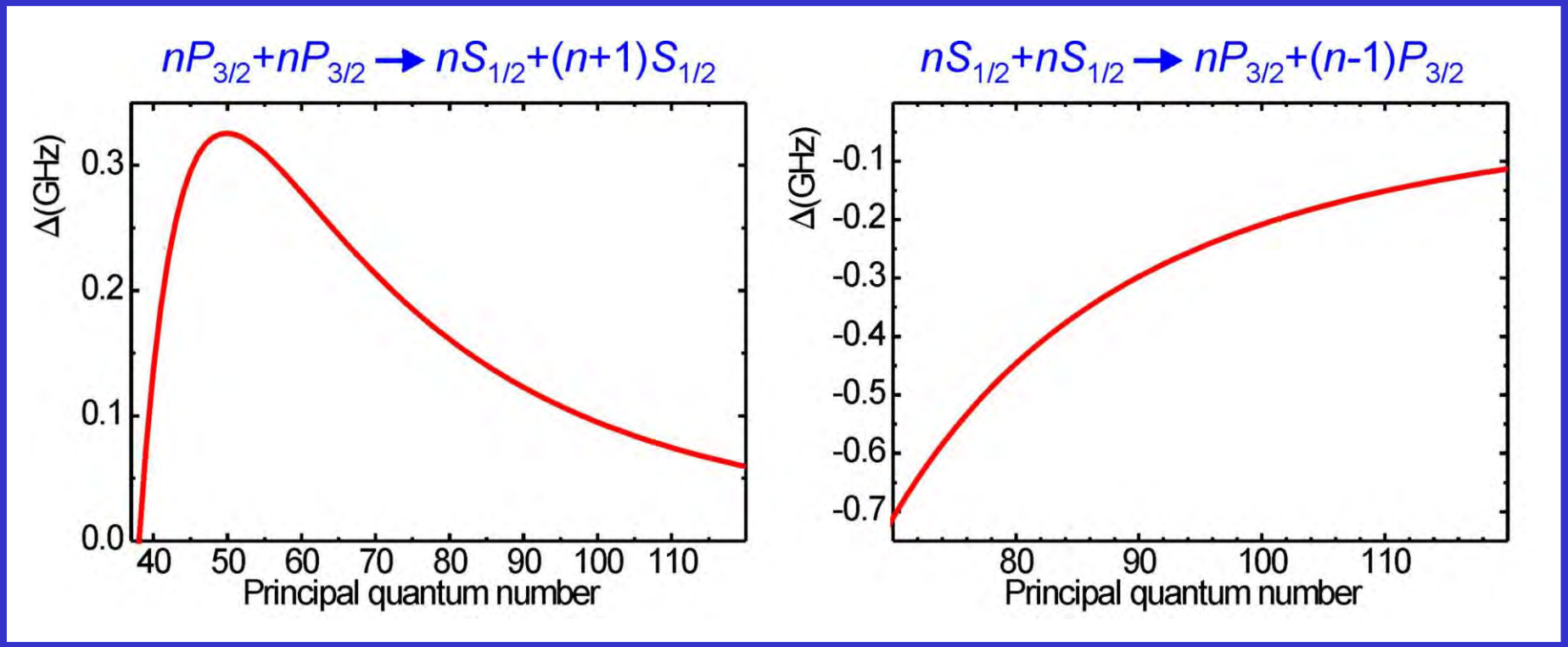
RF-assisted Förster resonances in the Floquet states picture





D.B.Tretyakov et al., Phys. Rev. A ***90****, 041403(R) (2014)*

Energy defects of Förster resonances in Rb atoms



Interaction of any Rydberg atoms with large principal quantum number can be converted from van der Waals to resonant dipole-dipole using radio-frequency assisted Förster resonances with ω < 1 GHz !

nature COMMUNICATIONS

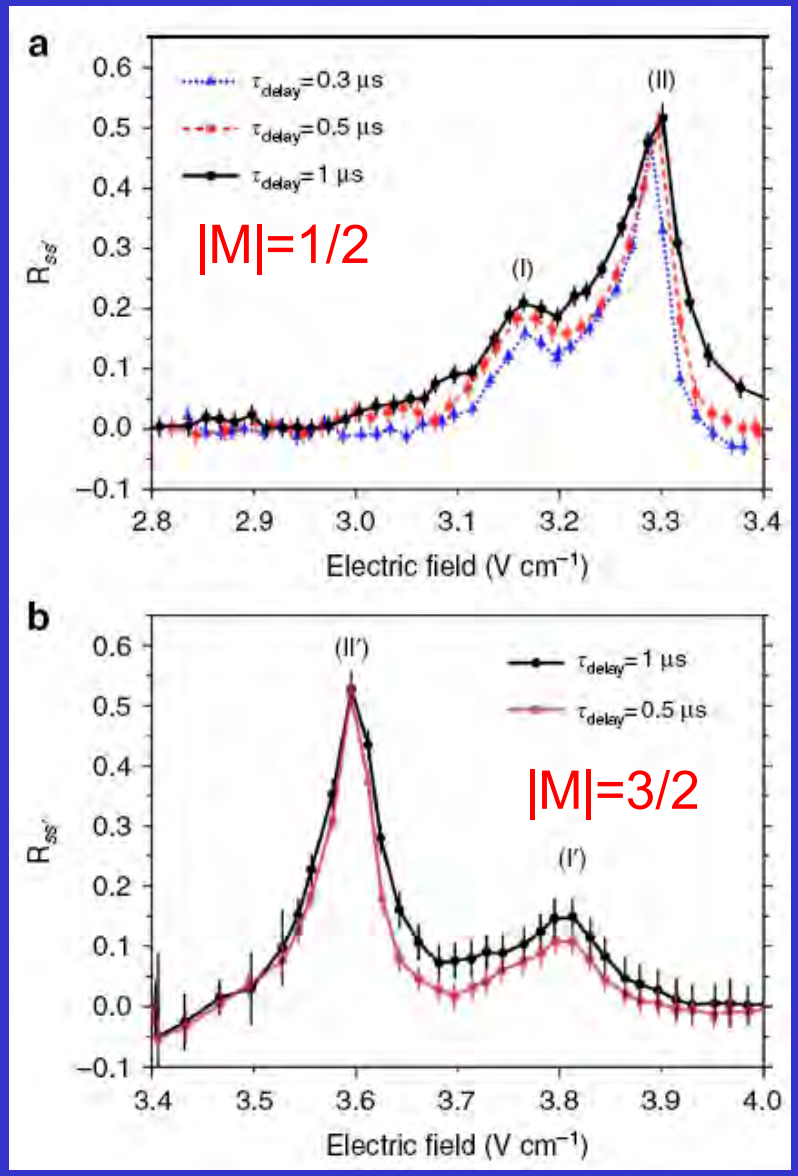
ARTICLE

Received 7 Jan 2015 | Accepted 25 Jul 2015 | Published 8 Sep 2015

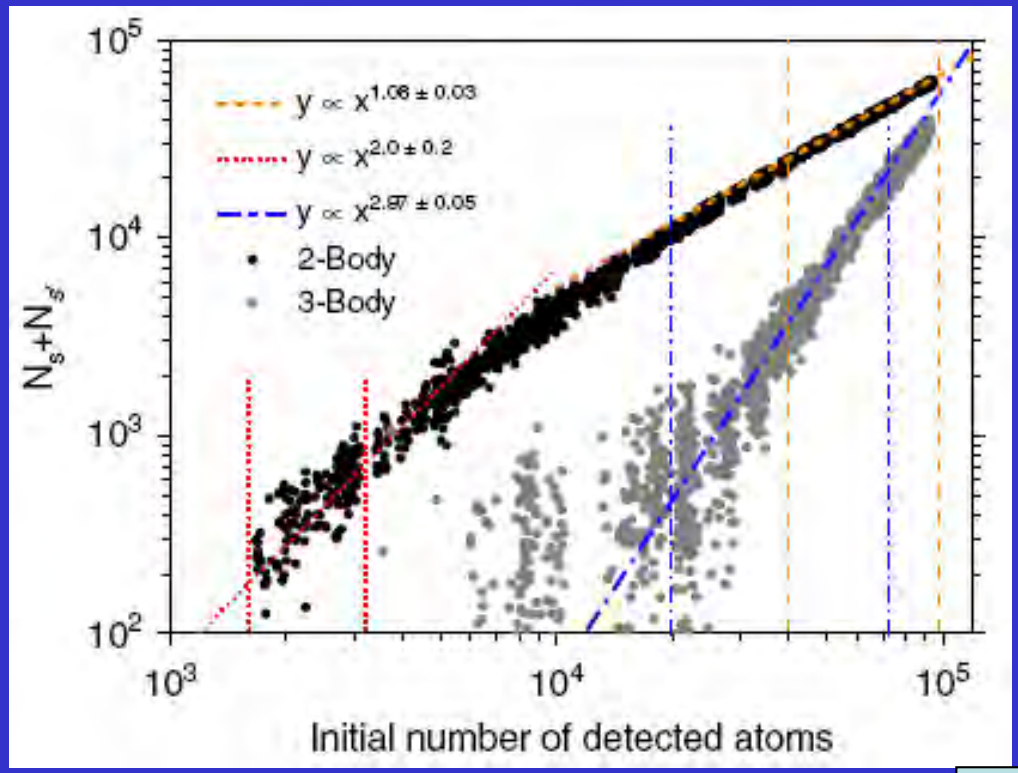
DOI: 10.1038/ncomms9173

Borromean three-body FRET in frozen Rydberg gases

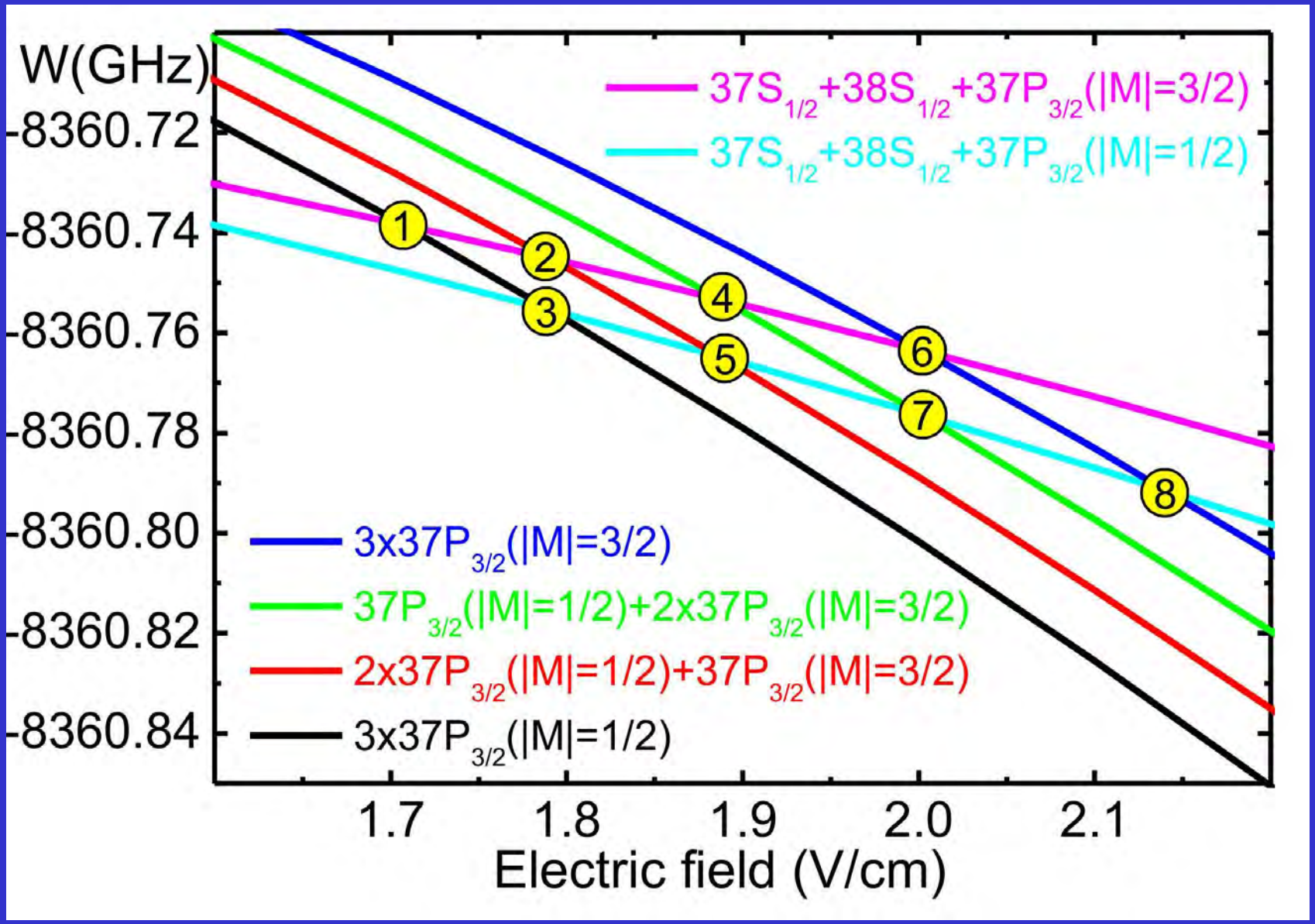
R. Faoro[1,2], B. Pelle[1], A. Zuliani[1], P. Cheinet[1], E. Arimondo[2,3] & P. Pillet[1]



~10^5 Cs($35P_{3/2}$) atoms in the volume of ~200 μm in size



Three-body Förster resonances for Rb($37P_{3/2}$) atoms

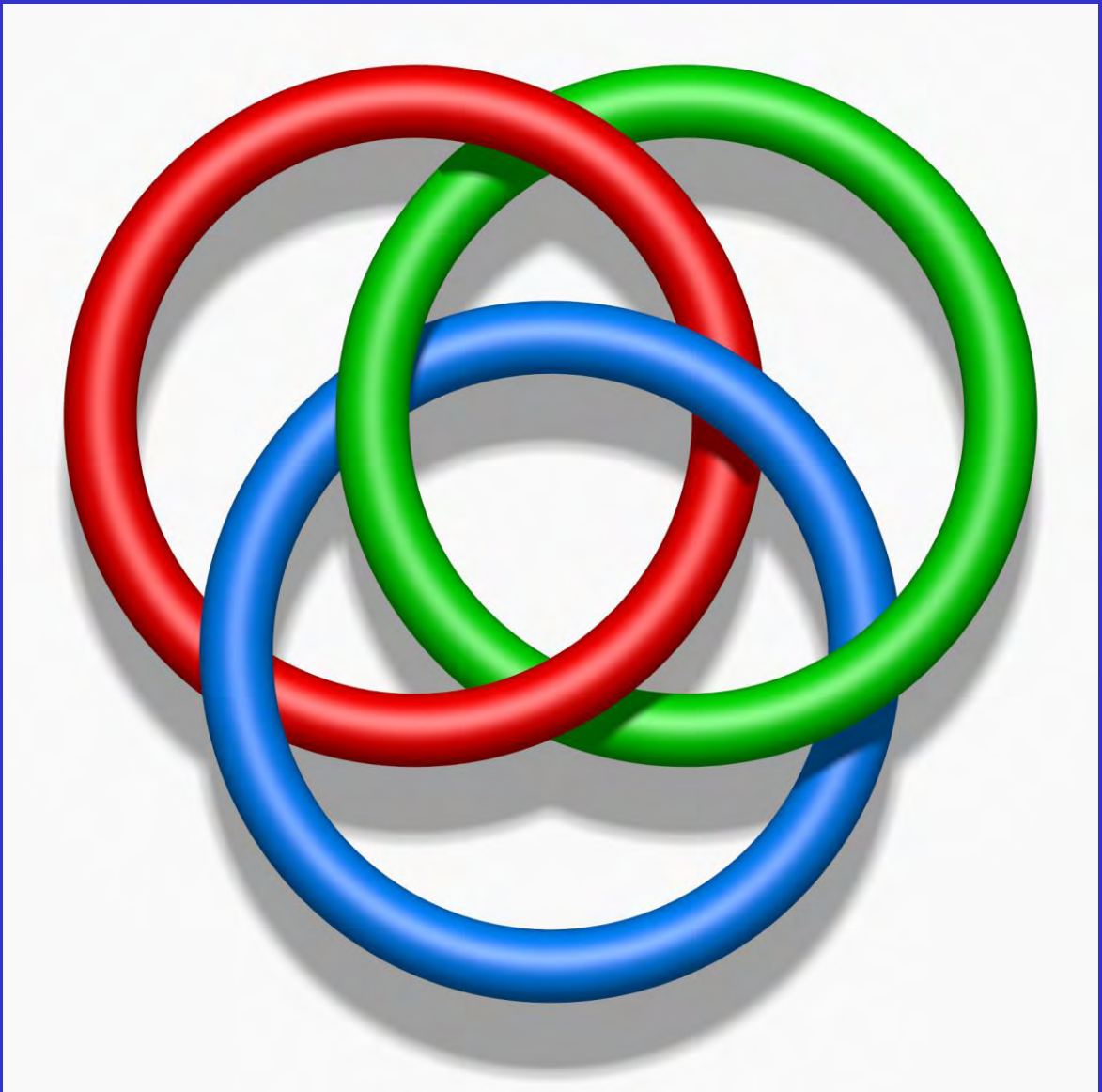


D.B.Tretyakov, I.I.Beterov, E.A.Yakshina, V.M.Entin, I.I.Ryabtsev, P.Cheinet, and P.Pillet, Phys. Rev. Lett. ***119****, 173402 (2017)*

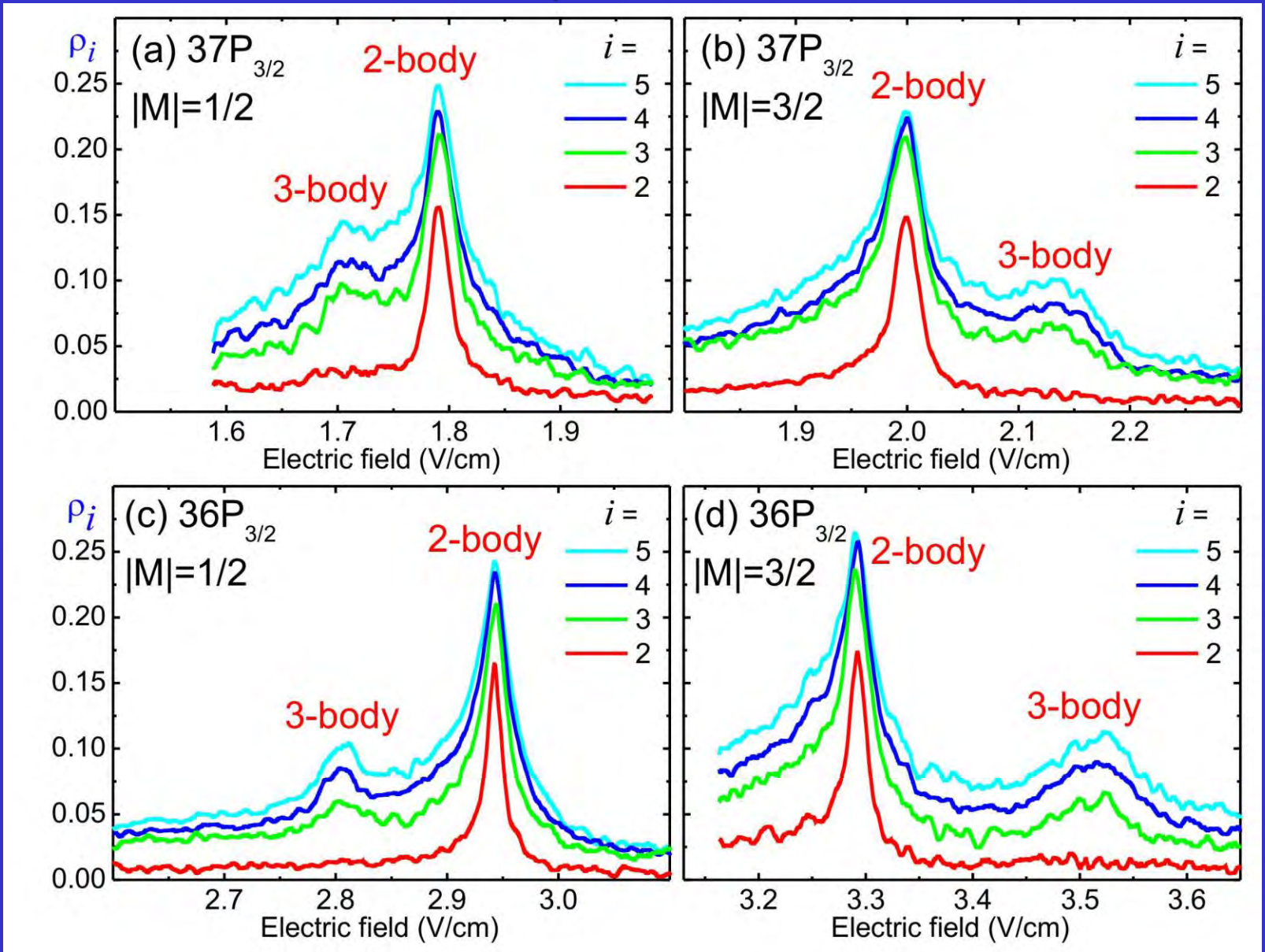
Borromean three-body interactions of Rydberg atoms

Why Borromean? Borromean rings consist of three circles which are linked, but removing any ring results in two unlinked rings.

Borromean FRET is featured by the strong three-body interactions with a negligible contribution of two-body interactions.

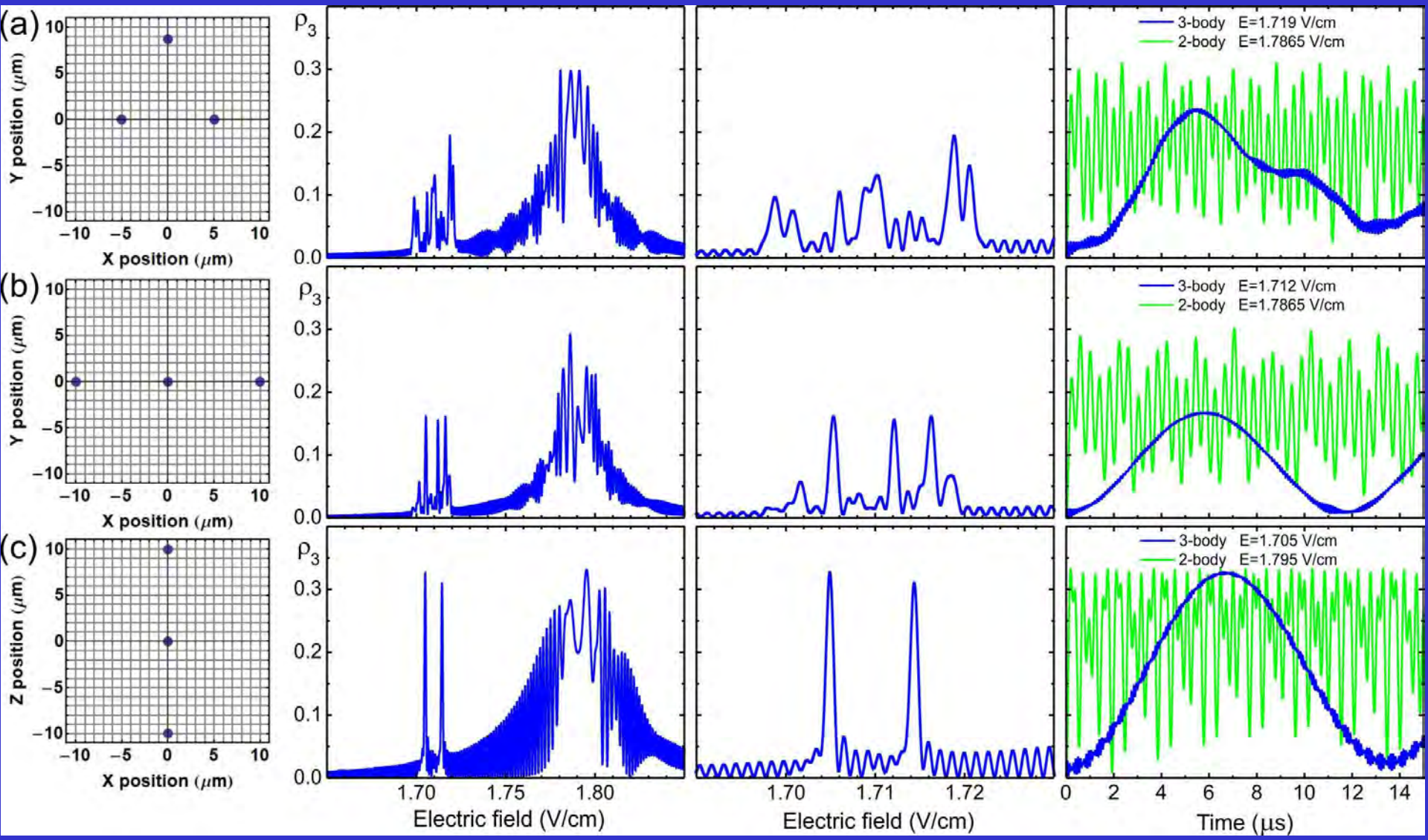


Observation of three-body Förster resonances in Rb atoms



D.B.Tretyakov, I.I.Beterov, E.A.Yakshina, V.M.Entin, I.I.Ryabtsev, P.Cheinet, and P.Pillet, Phys. Rev. Lett. ***119****, 173402 (2017)*

Coherence of three-body Förster resonances (full theory)



I.I.Ryabtsev, I.I.Beterov, D.B.Tretyakov, E.A.Yakshina, V.M.Entin, P.Cheinet, and P.Pillet, Phys. Rev. A 98, 052703 (2018)

Three-qubit quantum gates

Toffoli gate

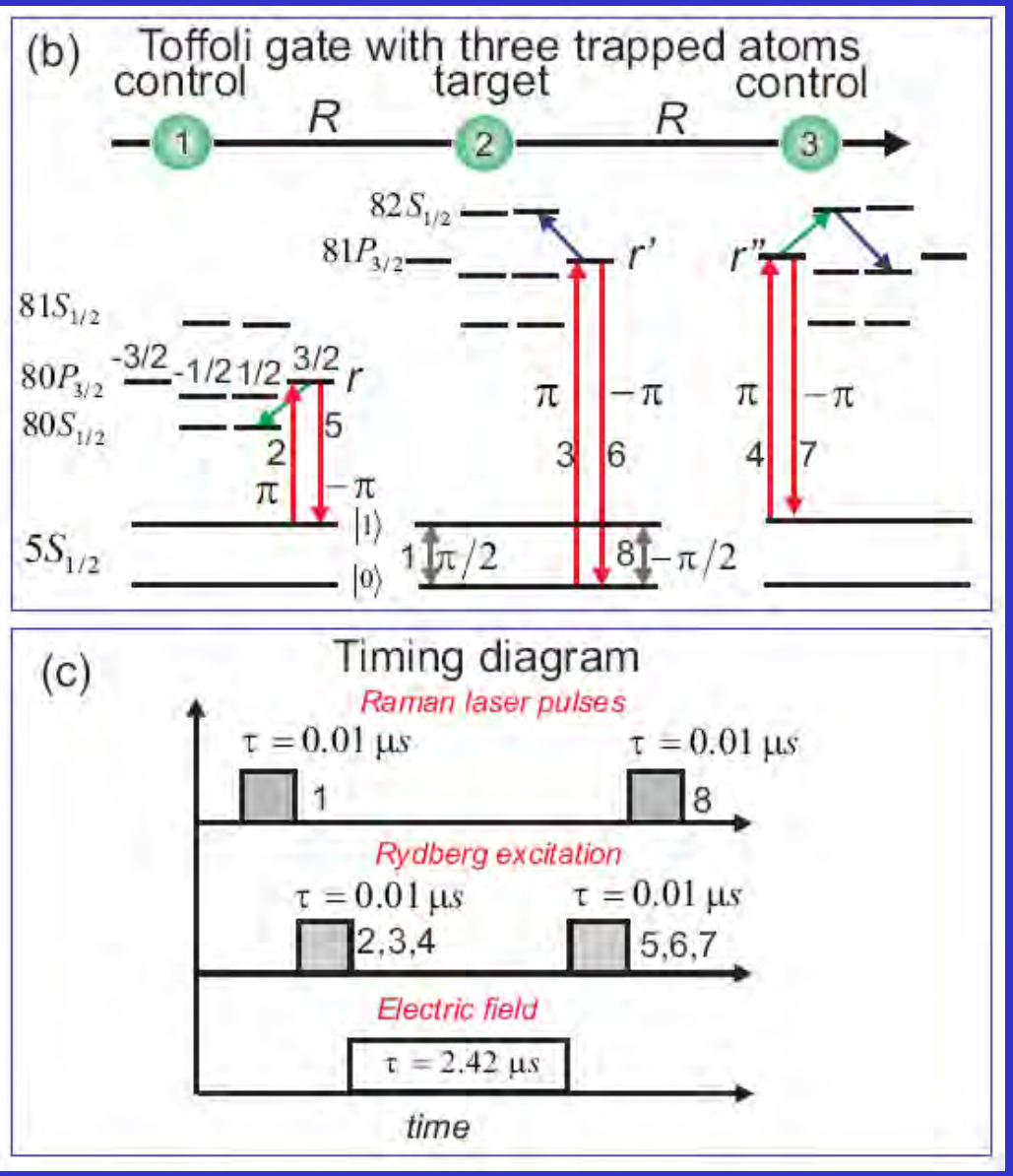
INPUT			OUTPUT		
0	0	0	0	0	0
0	0	1	0	0	1
0	1	0	0	1	0
0	1	1	0	1	1
1	0	0	1	0	0
1	0	1	1	0	1
1	1	0	1	1	1
1	1	1	1	1	0

Fredkin gate

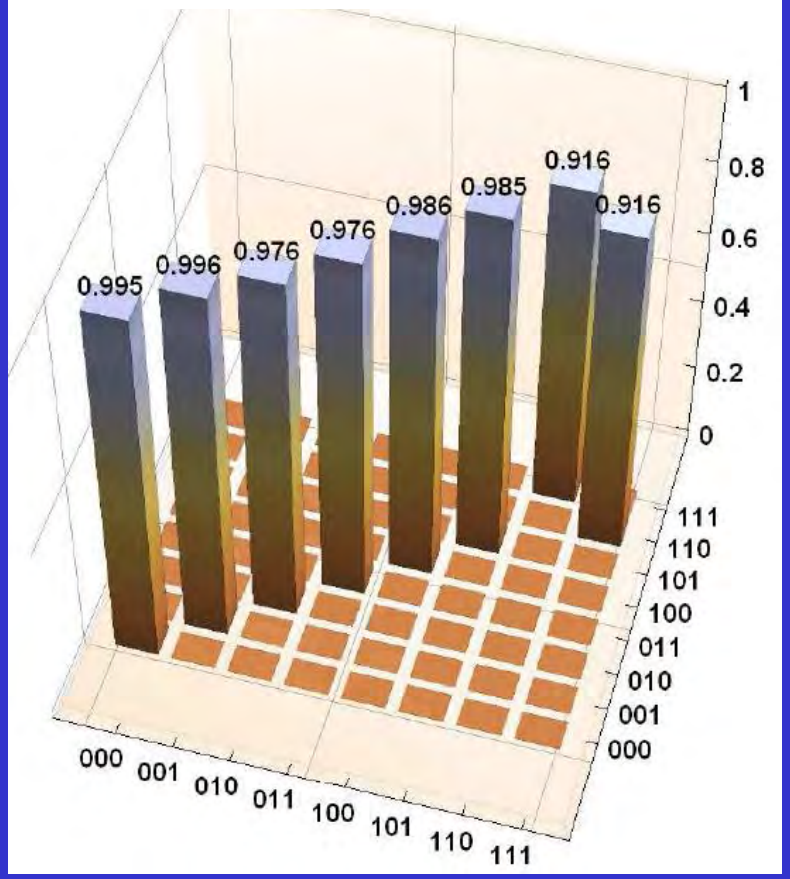
INPUT			OUTPUT		
0	0	0	0	0	0
0	0	1	0	0	1
0	1	0	0	1	0
0	1	1	0	1	1
1	0	0	1	0	0
1	0	1	1	1	0
1	1	0	1	0	1
1	1	1	1	1	1

Useful for error correction and further speedup of quantum computation

Scheme of a 3-qubit Toffoli gate

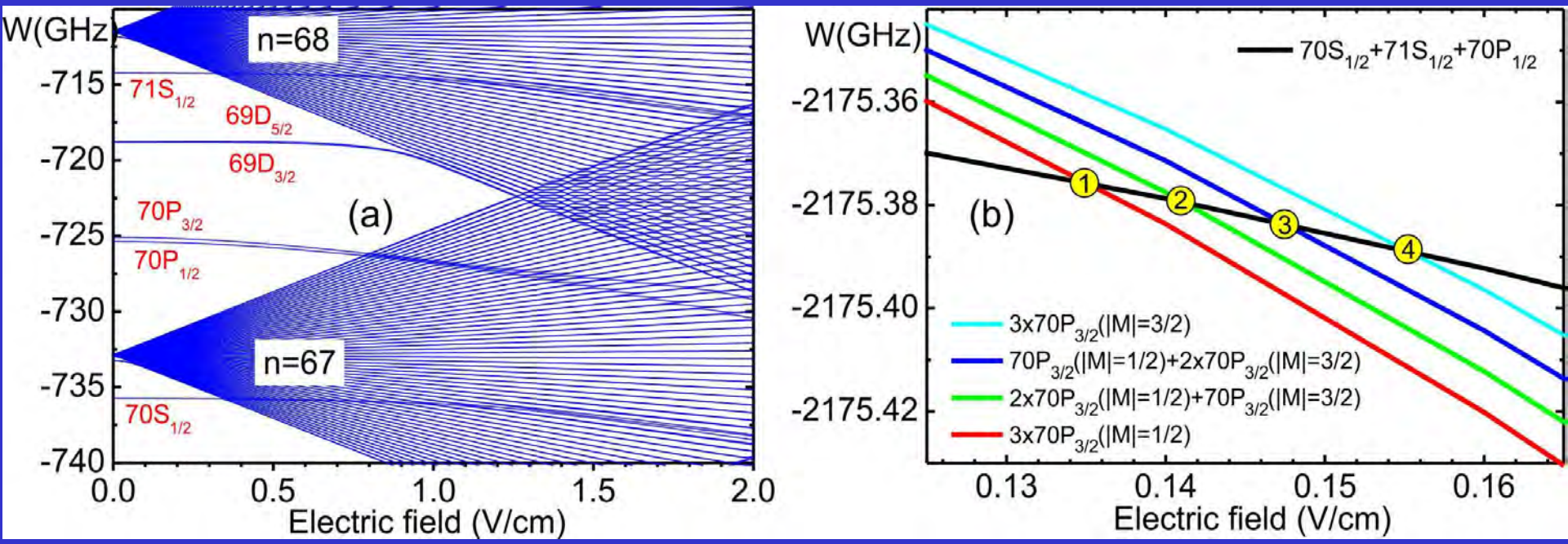


$$F = Tr\sqrt{\sqrt{\rho_{sim}}\ \rho_{et}\ \sqrt{\rho_{sim}}} = 0.983$$



I.I.Beterov, I.N.Ashkarin, E.A.Yakshina, D.B.Tretyakov, V.M.Entin, I.I.Ryabtsev, P.Cheinet, P.Pillet, M.Saffman, Phys. Rev. A ***98****, 042704 (2018)*

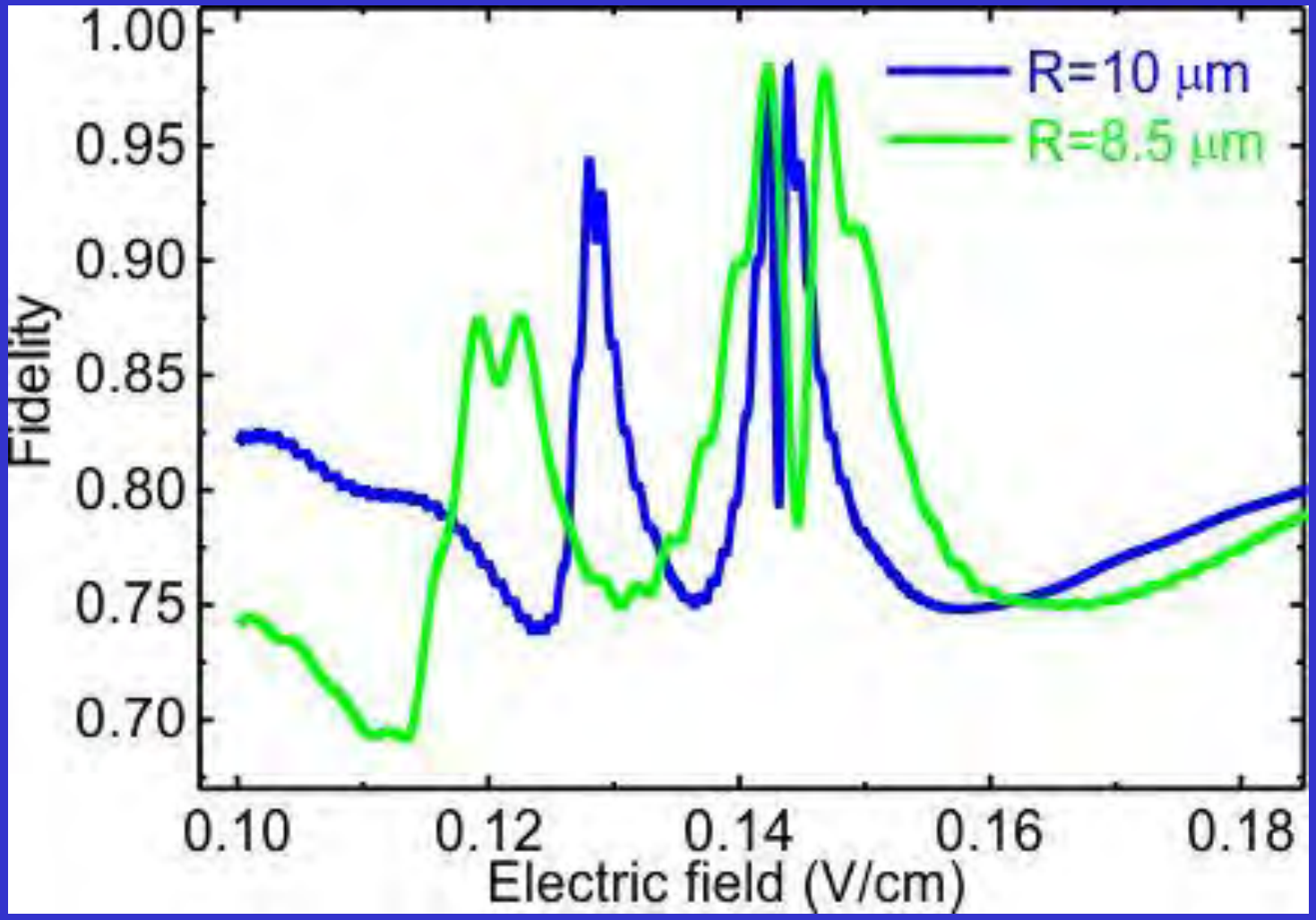
Three-body Förster resonance of a new type $3\times nP_{3/2} \rightarrow nS_{1/2}+(n+1)S_{1/2}+nP_{1/2}$ for Rb atoms



(a) Calculated Stark map of Rydberg states of Rb atoms near the 70*P* state. (b) Calculated Stark structure of a new-type Förster resonance for three Rb Rydberg atoms. Crossings of collective states (indicated by numbers) correspond only to three-body Förster resonances, when all three atoms change their states, while two-body resonances are absent.

P.Cheinet et al., Quantum Electronics ***50****(3), 213 (2020).*

Numerical results for the fidelity of new Toffoli gate



Dependence of the fidelity of the Toffoli gate on the dc electric field for interatomic distances of 10 and 8.5 μm. The maximum achievable fidelity is 98.5%.

I.N.Ashkarin et al., Phys. Rev. A, 2022 , v.106, p.032601

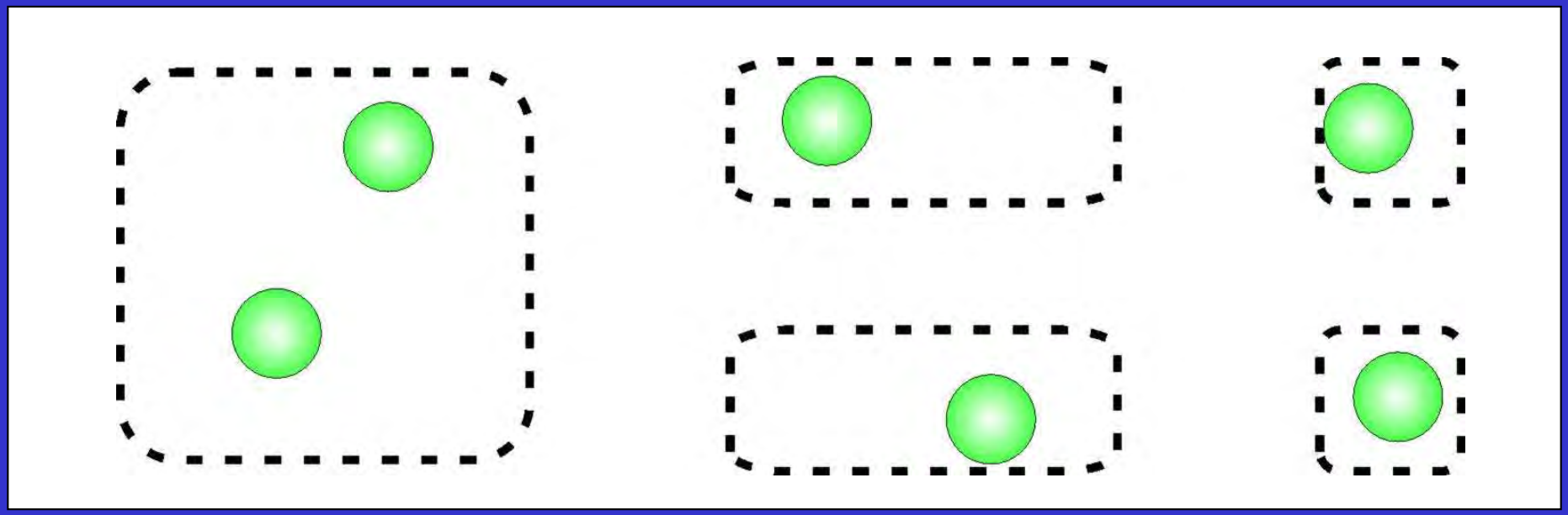
Conditional Quantum Phase Gate $|ab\rangle \rightarrow \exp(i\,\pi\,\delta_{a1}\delta_{b1})\,|ab\rangle$

Evolution of population at Förster resonance in two frozen atoms:

$$\rho_2(t) = \frac{1}{2}\sin^2\left(\sqrt{2}\,\Omega_{ab}t\right)$$

$$\Omega_{ab} \cong \frac{d_1 d_2}{\hbar\, R^3}$$

Spatial configurations for two trapped Rydberg atoms



Numerical modeling for Conditional Quantum Phase Gate

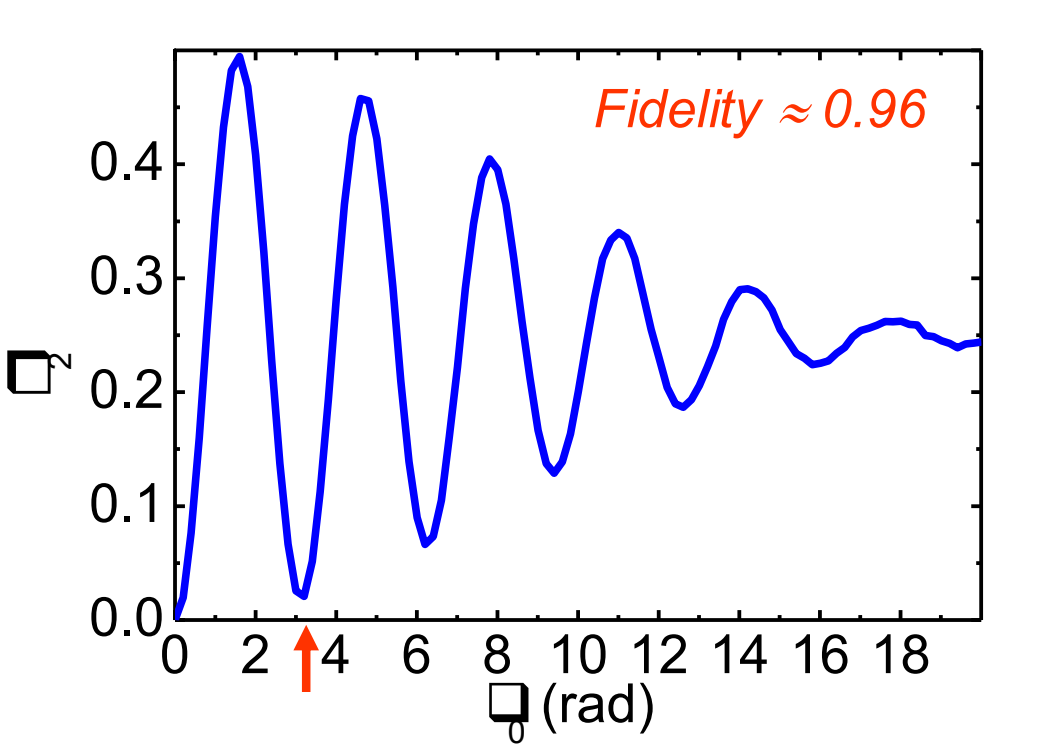
$$|ab\rangle \rightarrow \exp(i\,\pi\,\delta_{a1}\delta_{b1})\,|ab\rangle$$

R_0=10 μm

T~10 μK

$$\rho_2(t) = \frac{1}{2}\sin^2(\theta_0)$$

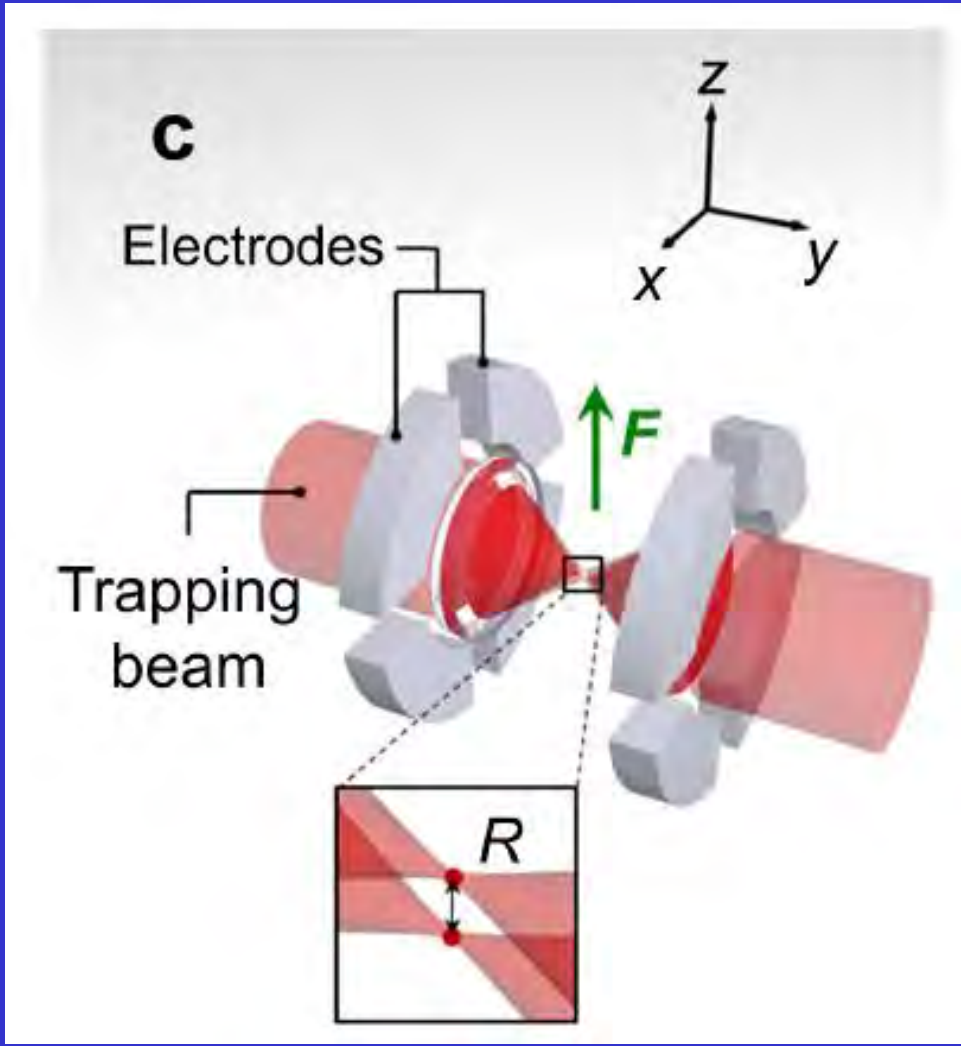
$$\theta_0 = \frac{2\sqrt{2}d_1 d_2 t_0}{4\pi\varepsilon_0 \hbar R_0^3}$$

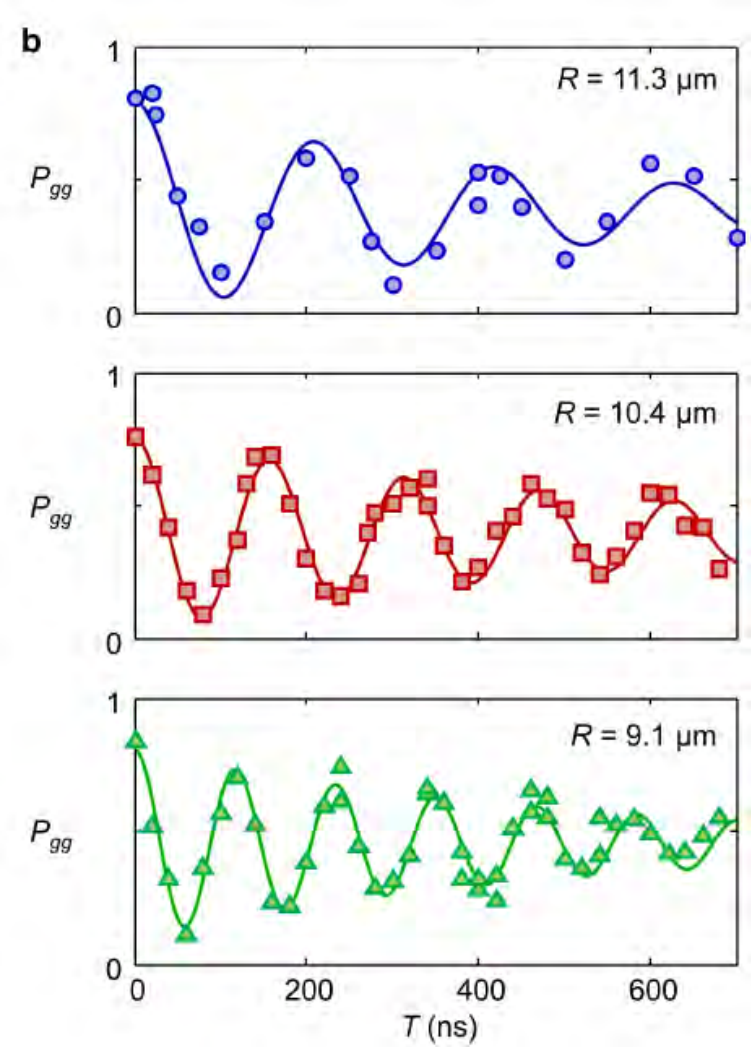


I.I.Ryabtsev et al., Phys. Rev. A ***82****, 053409 (2010)*

Coherent dipole-dipole coupling between two single atoms at a Förster resonance

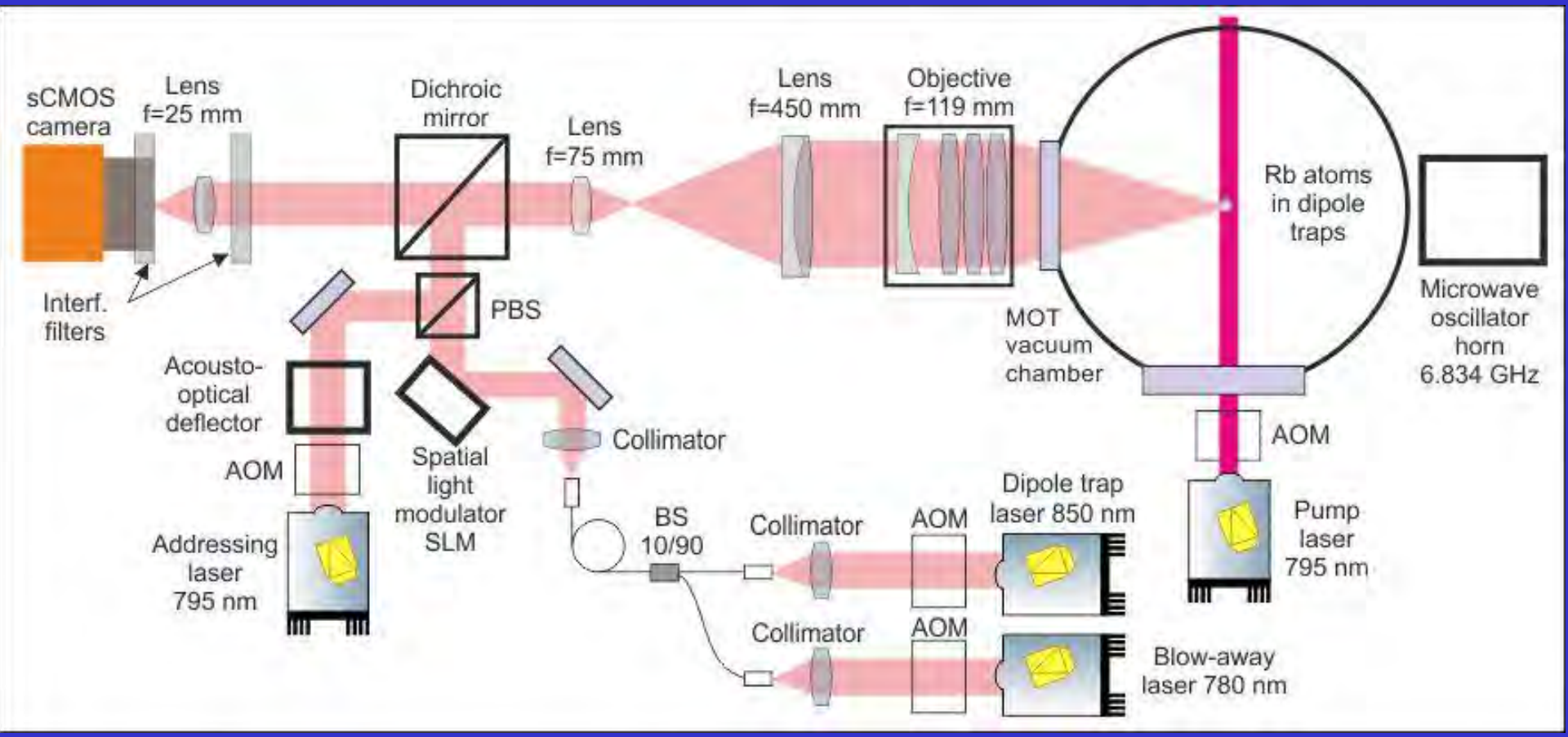
S. Ravets, H. Labuhn, D. Barredo, L. Béguin, T. Lahaye, and A. Browaeys
Laboratoire Charles Fabry, UMR 8501, Institut d'Optique, CNRS, Univ Paris Sud 11,
2 avenue Augustin Fresnel, 91127 Palaiseau Cedex, France





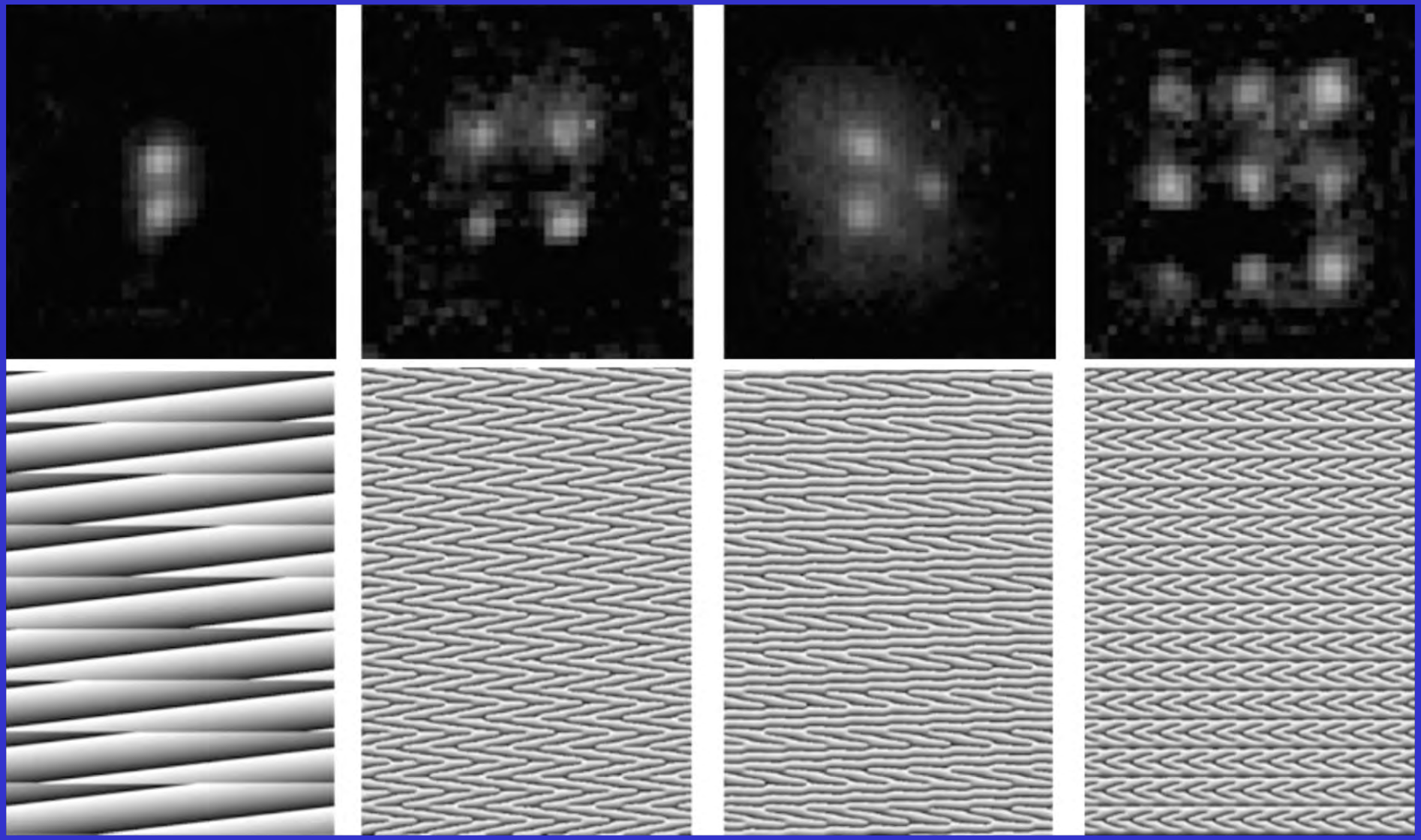
Experimental setup for implementing individually-addressed quantum gates with ^{87}Rb atoms in an array of optical dipole traps

Experimental setup for implementing individually-addressed one-qubit gates with ^{87}Rb atoms in an array of optical dipole traps



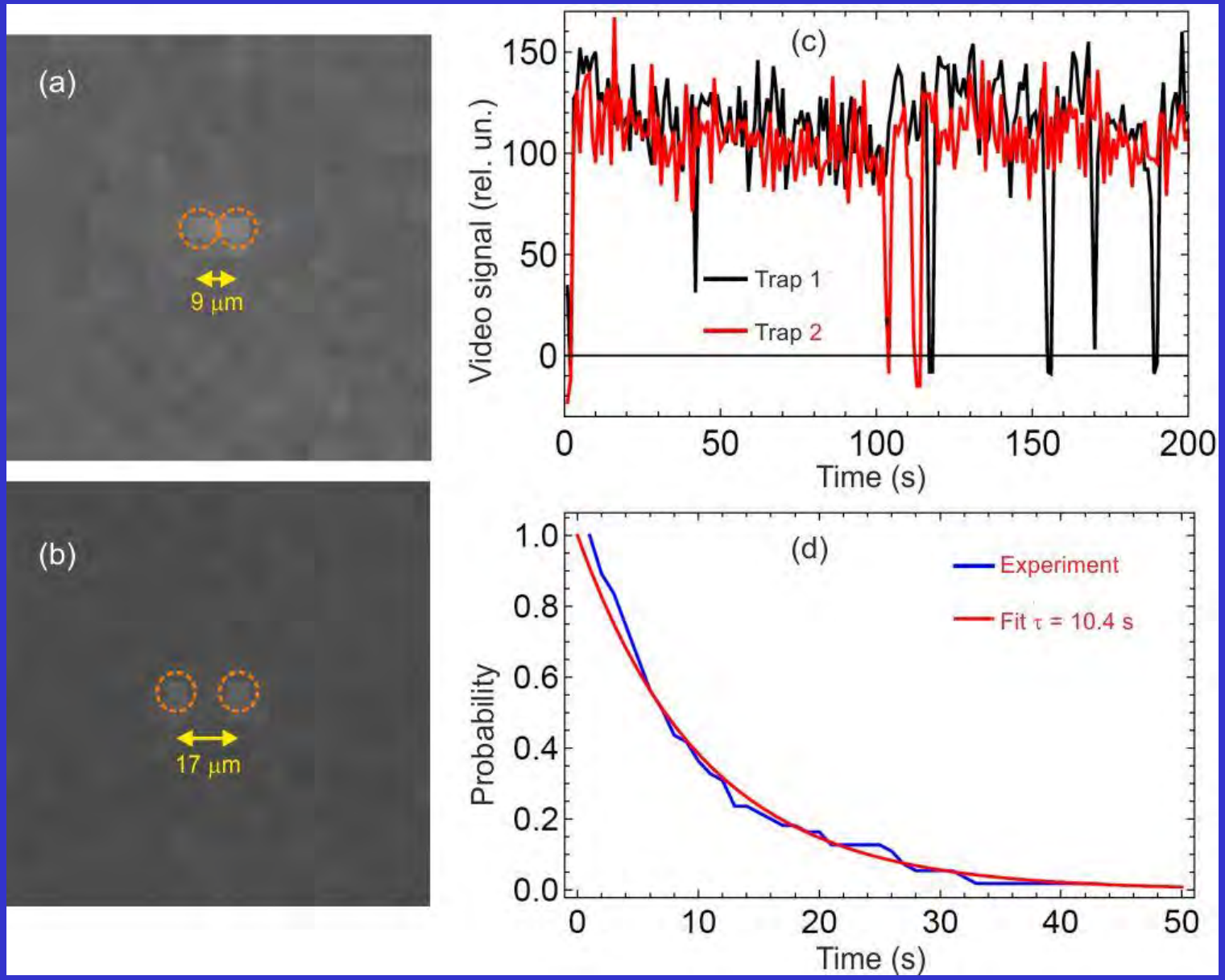
A spatial light modulator SLM forms a trap array, and addressing laser 795 nm with acousto-optical deflector (AOD) is used for individual addressing. SLM is a mirror split to many 20 micron-sized elements controlled independently. It forms a mask for the laser wave front. After focusing, an array of optical dipole traps of arbitrary dimensions can be formed.

Trapping of Rb atoms in arrays of various dimensions with separation of 15 μm, and corresponding phase masks of SLM



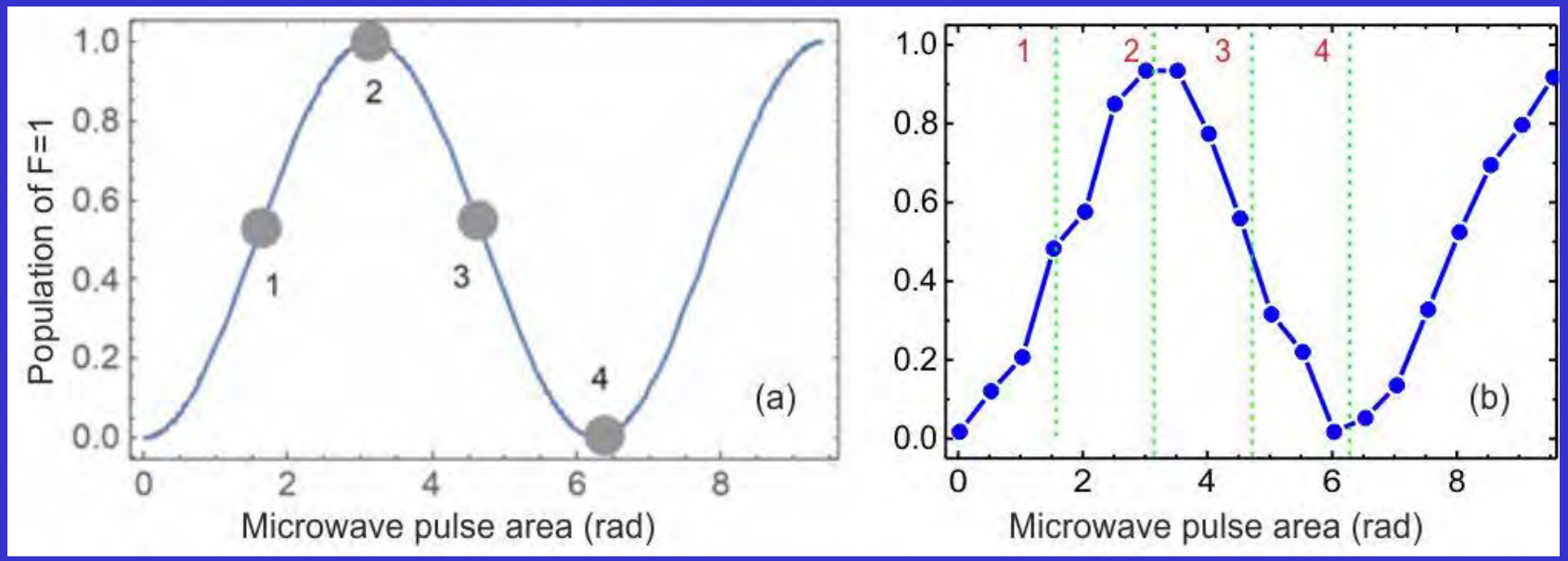
I.I.Ryabtsev et al., Optoelectr., Instrument. and Data Process., ***56****(5), 510 (2020)*

Trapping of two ^{87}Rb atoms into two optical dipole traps separated by 9-17 μm and measurement of simultaneous trapping time



I.I.Beterov et al., Quantum Electronics ***51****(6), 464 (2021)*

Rabi oscillations on a "clock" microwave transition in a single ^{87}Rb atom and the truth table for one-qubit gates



Various points correspond to various one-qubit gates:

1 - Hadamard gate form state "0"; 2 - NOT gate from state "0";

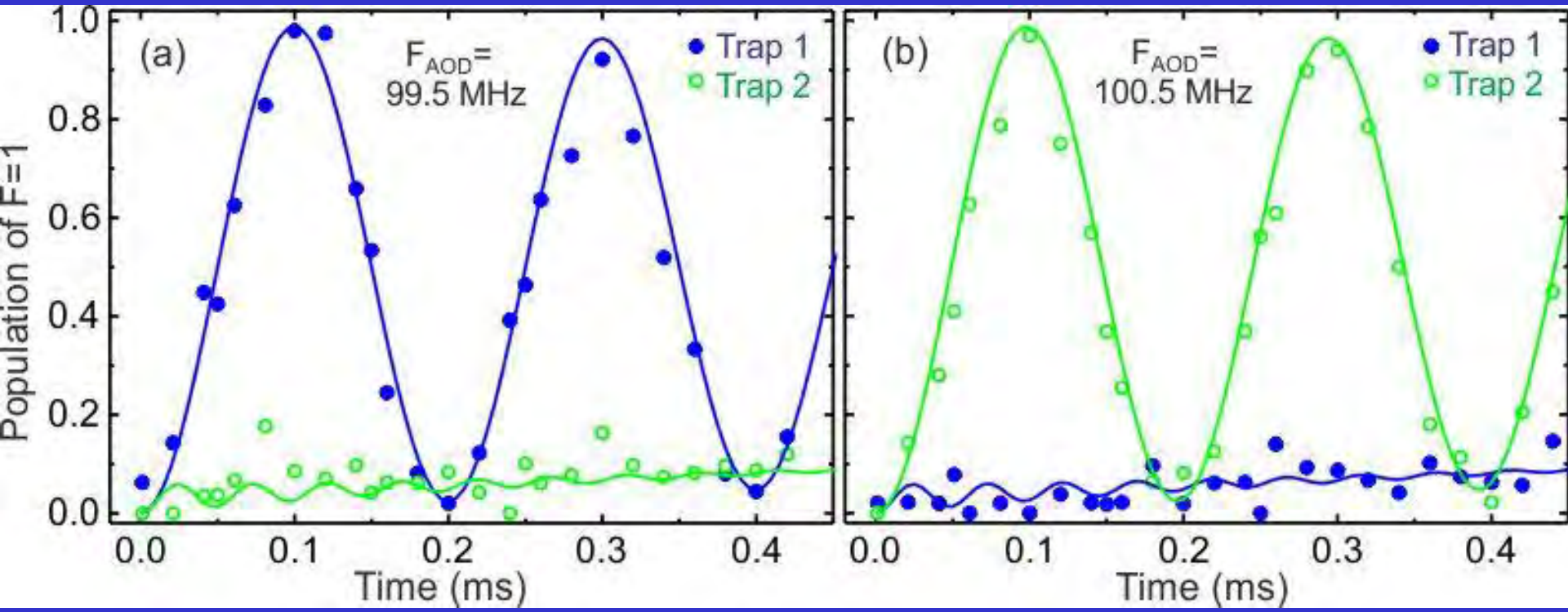
3 - Hadamard gate form state "1"; 4 - NOT gate from state "1".

Initial qubit state	Result of performing the gate H	Fidelity of performing the gate H	Result of performing the gate NOT	Fidelity of performing the gate NOT
0	0.489±0,02	97.8±4%	0.935±0,02	93.5±2%
1	0.465±0,02	93±4%	0.035±0,02	96.5±2%

The average fidelity of one-qubit gates is 95.2 ± 3 %.

*I.I.Beterov et al., JETP **132**(3), 341 (2021)*

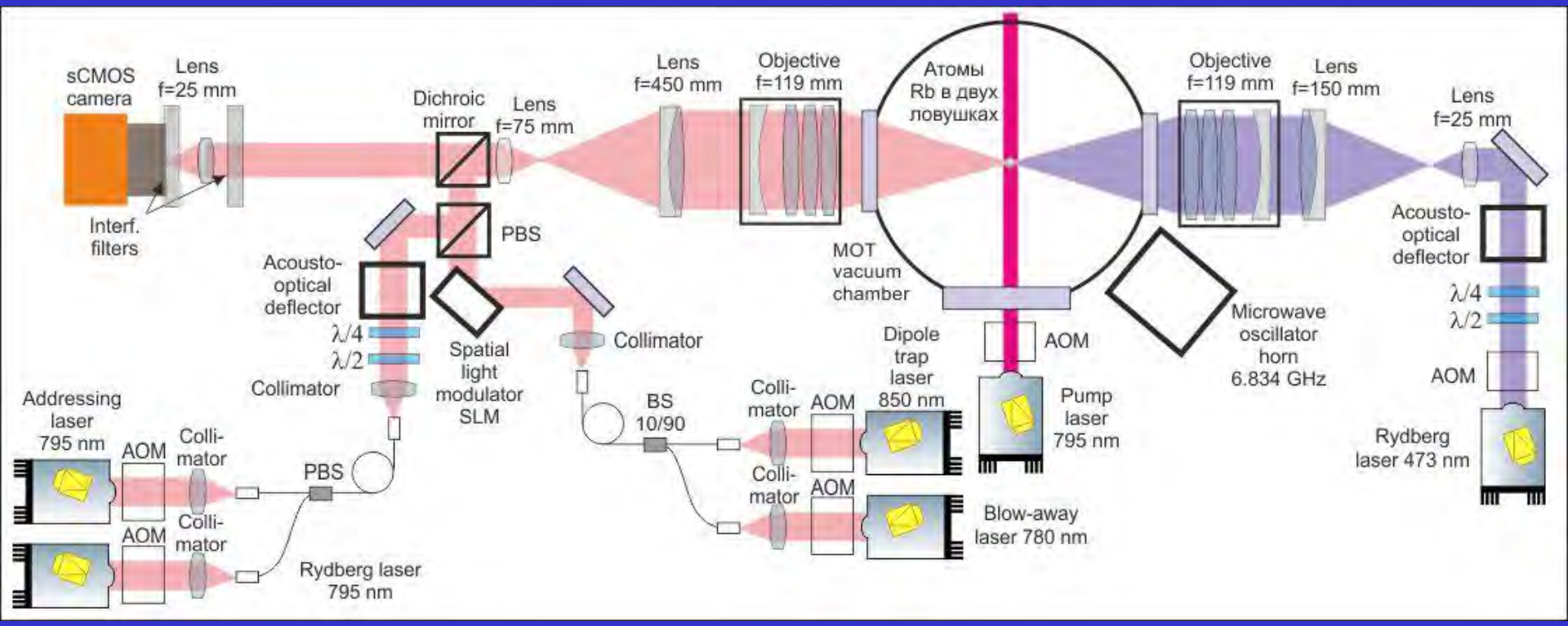
Rabi oscillations on a "clock" microwave transition in two ^{87}Rb atoms with individual addressing



The Rabi frequency is 5 kHz, contrast is 97%, and coherence time is 4 ms. The average fidelity of one-qubit gates is 91.8 ± 3%, crosstalk is 4.7 ± 1 %. For SPAM error taken into account, the fidelity of one-qubit rotations is 97 ± 3 %. To reduce SPAM error, we need to increase the fidelity of optical pumping and reduce the parasitic repumping at blowing-away detection. But it is already possible to start experiments on two-qubit gates.

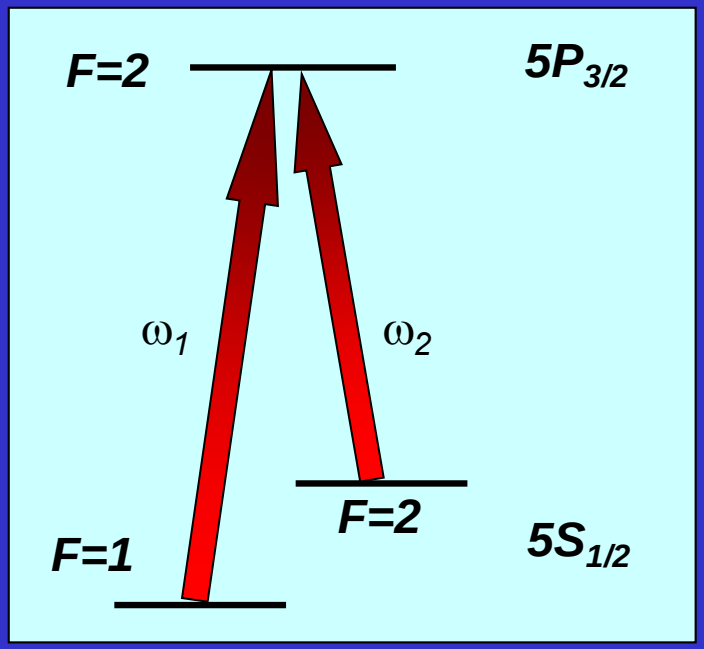
I.I.Beterov et al., Quantum Electronics ***51****(6), 464 (2021)*

Experimental setup for implementing two- and three-qubit quantum gates with ^{87}Rb atoms in an array of optical dipole trap

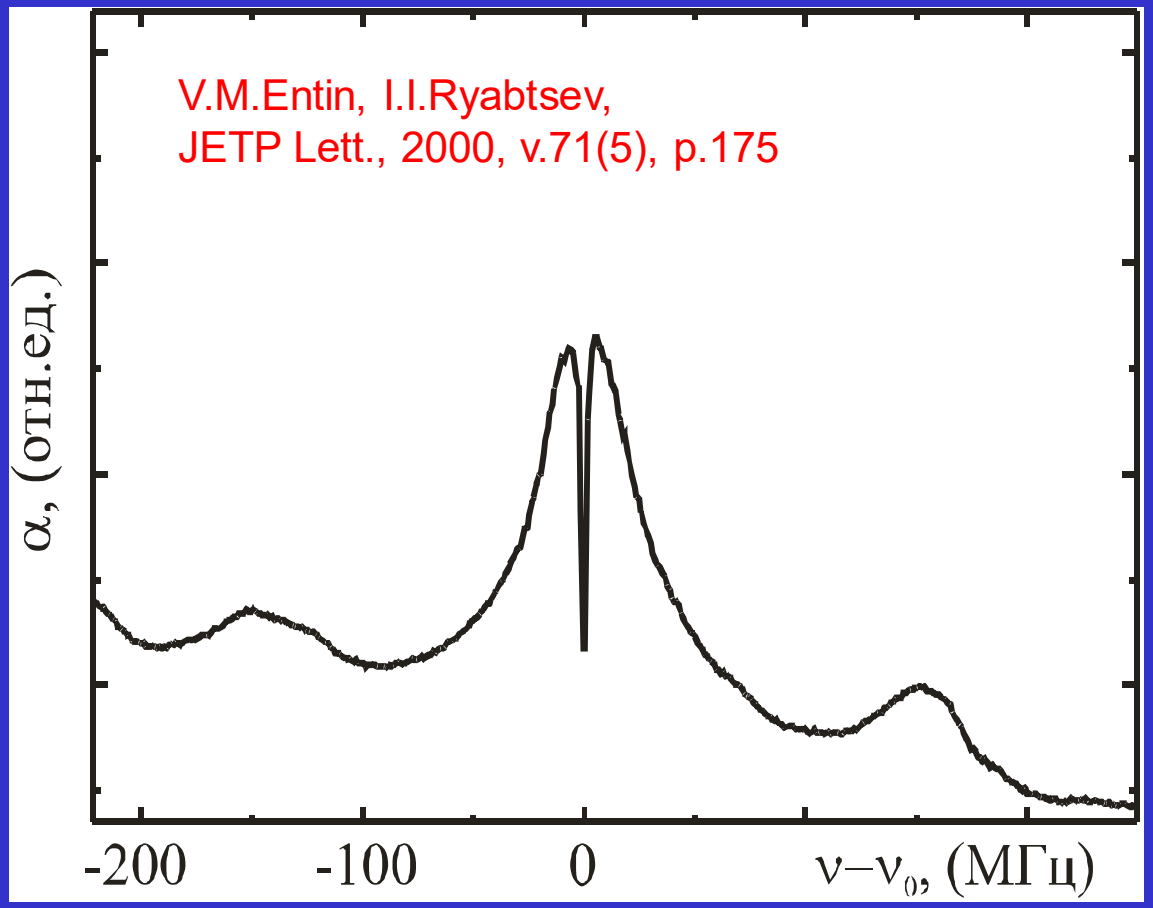


Added are the lasers of the first (795 nm) and second (473 nm) excitation steps of Rydberg states and an optical system to focus the second-step laser radiation. The experiments are in progress.

Electromagnetically induced transparency (EIT)



Two long-lived ground-state levels



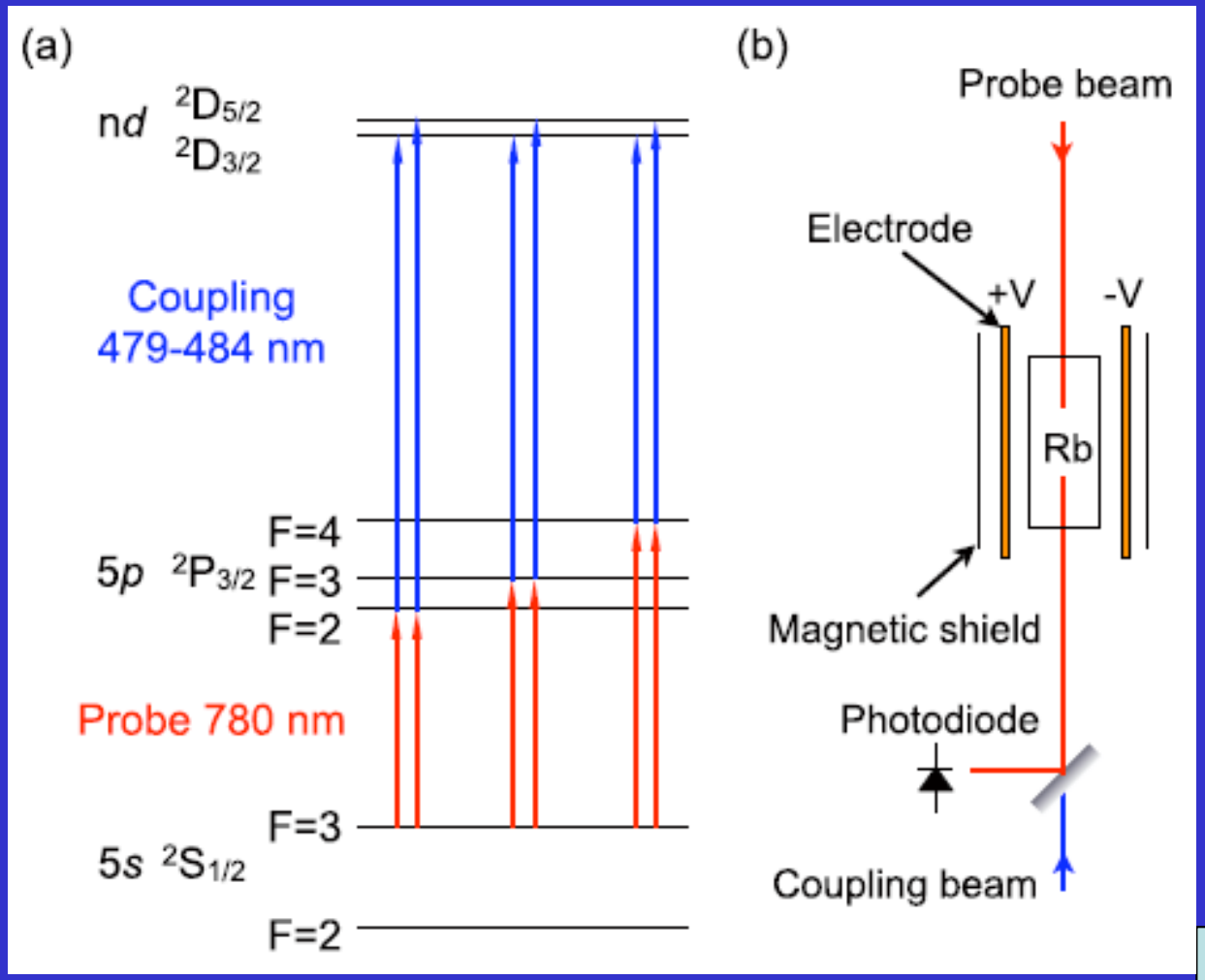
The width of the narrow EIT dip is determined by the lifetimes of ground-state levels or by transit time

PRL 98, 113003 (2007) PHYSICAL REVIEW LETTERS week ending 16 MARCH 2007

Coherent Optical Detection of Highly Excited Rydberg States Using Electromagnetically Induced Transparency

A. K. Mohapatra, T. R. Jackson, and C. S. Adams
Department of Physics, Durham University, Rochester Building, South Road, Durham DH1 3LE, United Kingdom

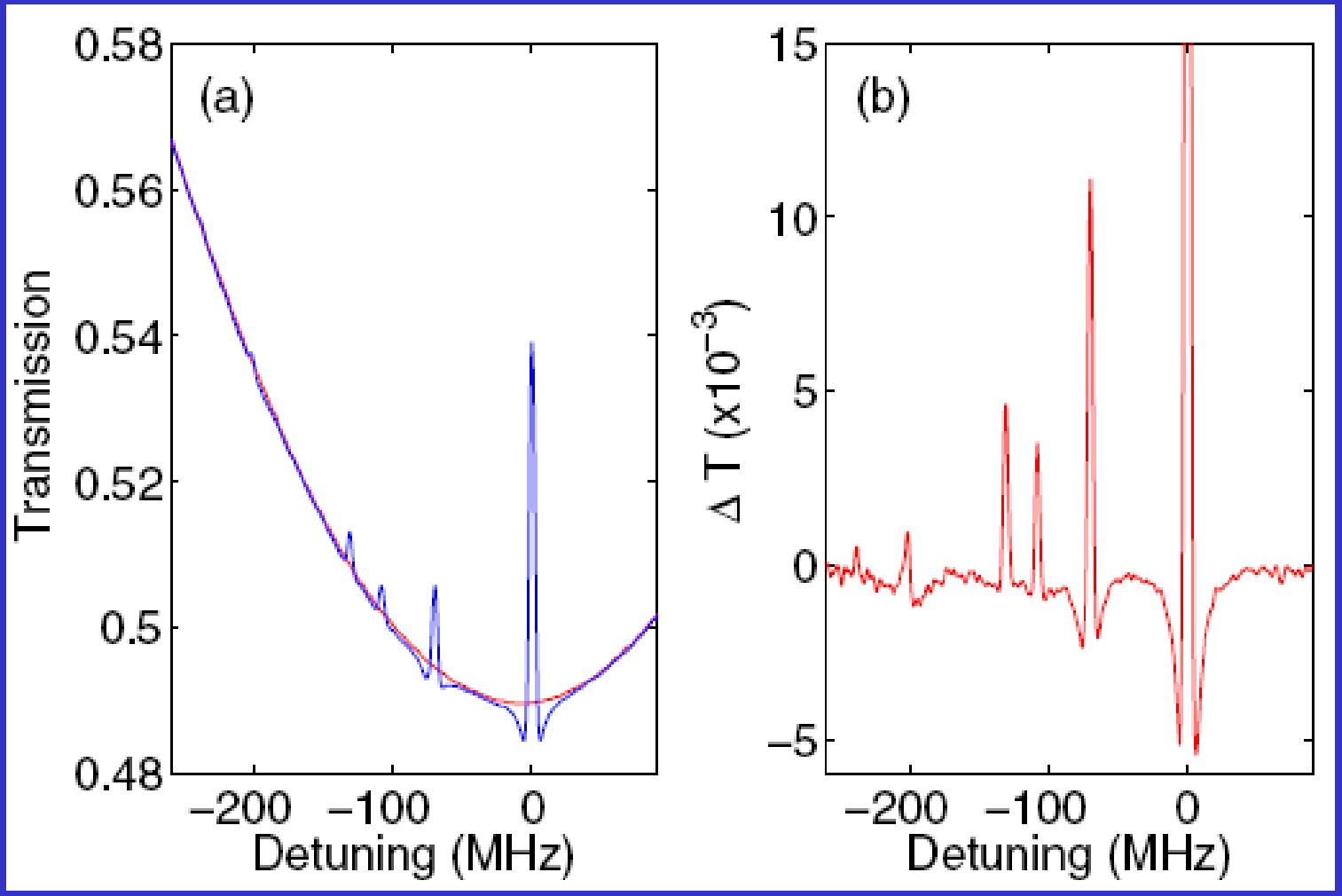
One of the long-lived ground-state level is replaced by a long-lived Rydberg state



PRL **98,** 113003 (2007) PHYSICAL REVIEW LETTERS week ending 16 MARCH 2007

Coherent Optical Detection of Highly Excited Rydberg States Using Electromagnetically Induced Transparency

A. K. Mohapatra, T. R. Jackson, and C. S. Adams
Department of Physics, Durham University, Rochester Building, South Road, Durham DH1 3LE, United Kingdom



A giant electro-optic effect using polarizable dark states

ASHOK K. MOHAPATRA[1]*, MARK G. BASON[1], BJÖRN BUTSCHER[2], KEVIN J. WEATHERILL[1] AND CHARLES S. ADAMS[1]*

Nature Physics **4**, 890 (2008)

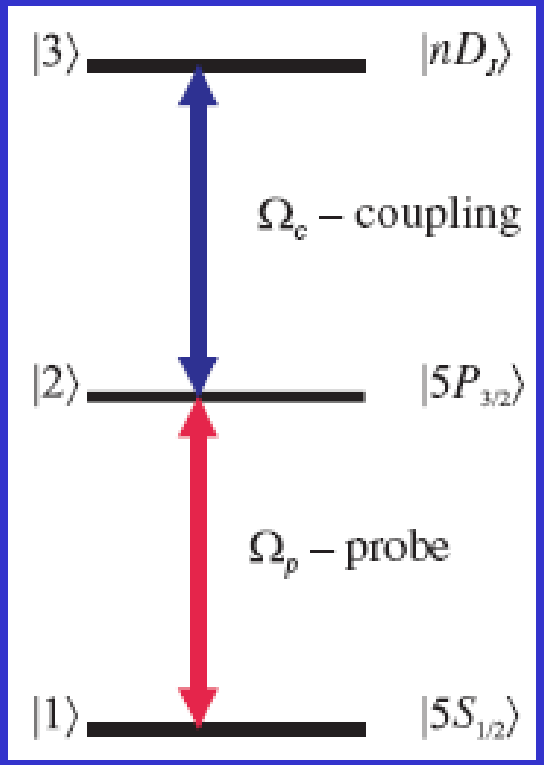
Table 1 The value of the Kerr coefficient, B_0, for various media.

Medium	B_0 ($\times 10^{-18}$ m V^{-2})
Gas (CO_2, 1 atm)[35]	10^0
Water[36]	10^2
Glass[36]	10^4
Nitrobenzene[36]	10^6
Rydberg dark states (this experiment)	$> 10^{12}$

Measurement of the electric dipole moments for transitions to rubidium Rydberg states via Autler–Townes splitting

M J Piotrowicz[1], C MacCormick[1,3], A Kowalczyk[1], S Bergamini[1,3], I I Beterov[2] and E A Yakshina[2]

New Journal of Physics 13 (2011) 093012



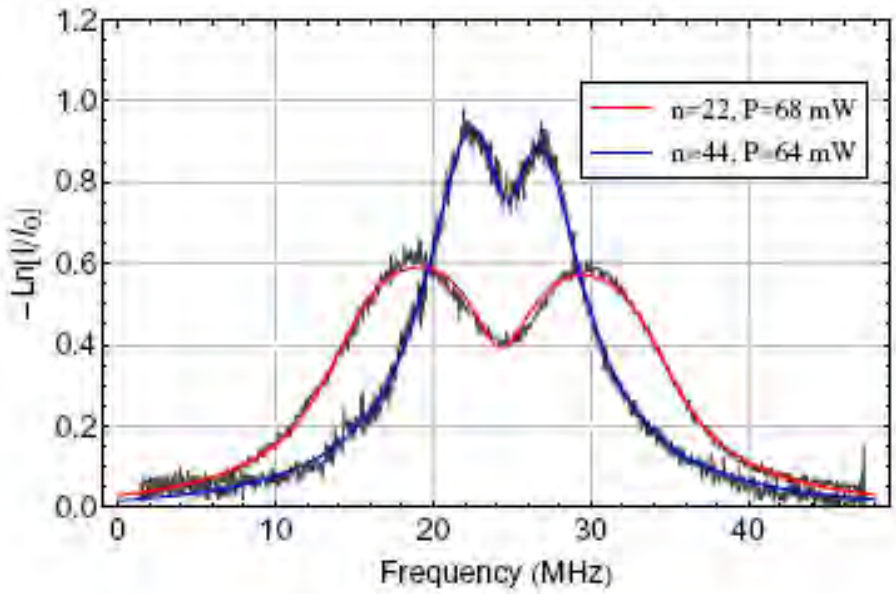
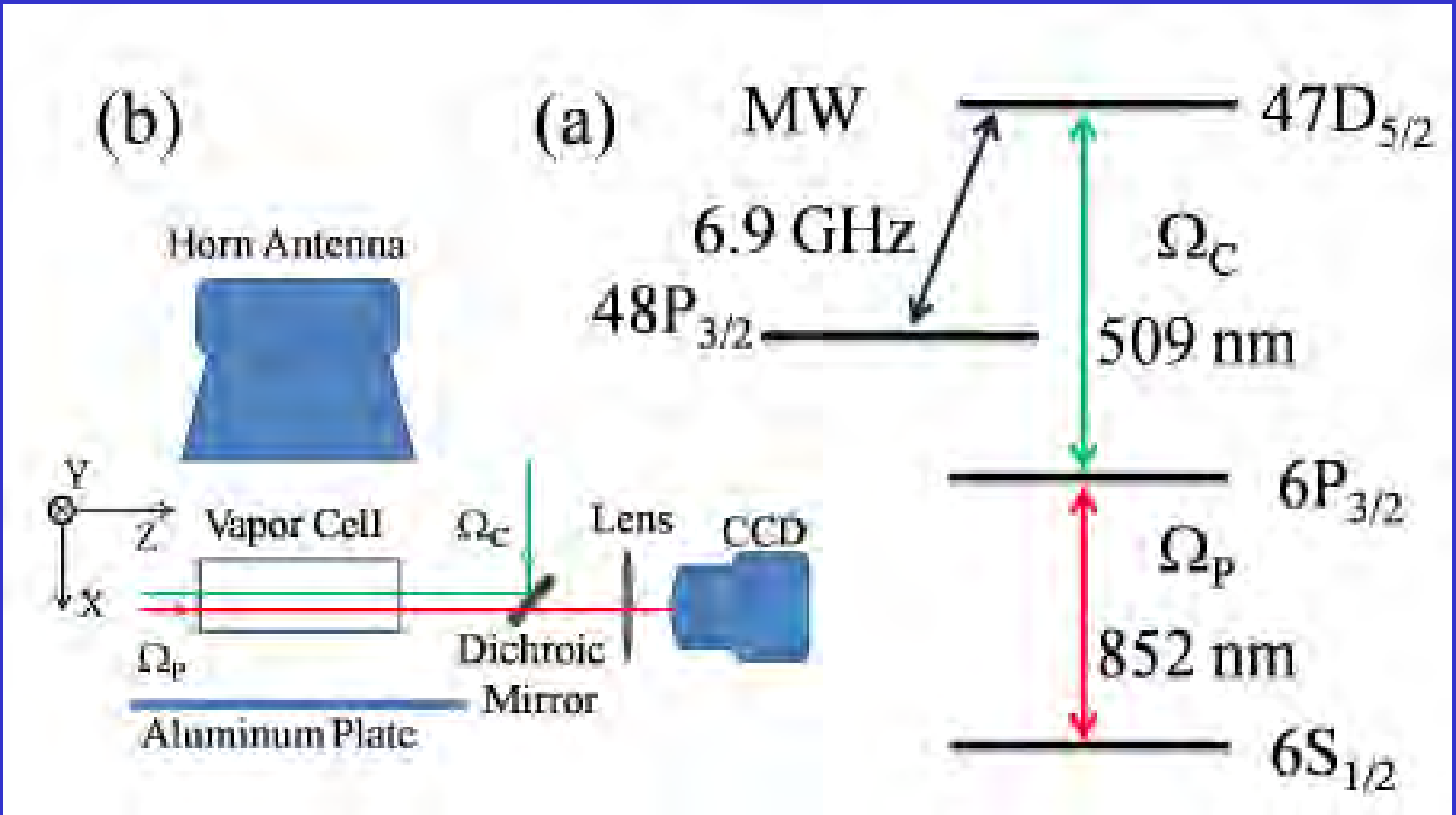


Figure 3. Typical AT spectra recorded for the upper state $44D_{5/2}$ and $22D_{5/2}$. Solid lines show the modeling of the lineshape.

Sub-wavelength microwave electric field imaging using Rydberg atoms inside atomic vapor cells

H.Q. Fan,[1] S. Kumar,[1] R. Daschner,[2] H. Kübler,[1,2] and J. P. Shaffer[1,*]

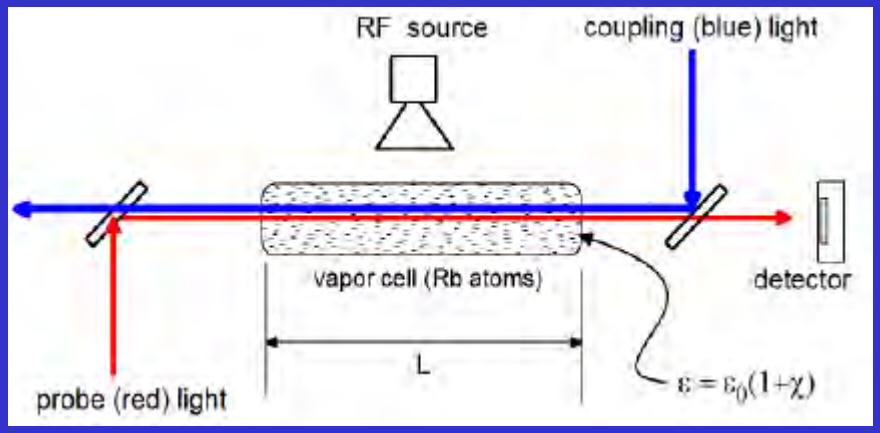
Optics Letters Vol. 39, Issue 10, pp. 3030-3033 (2014)

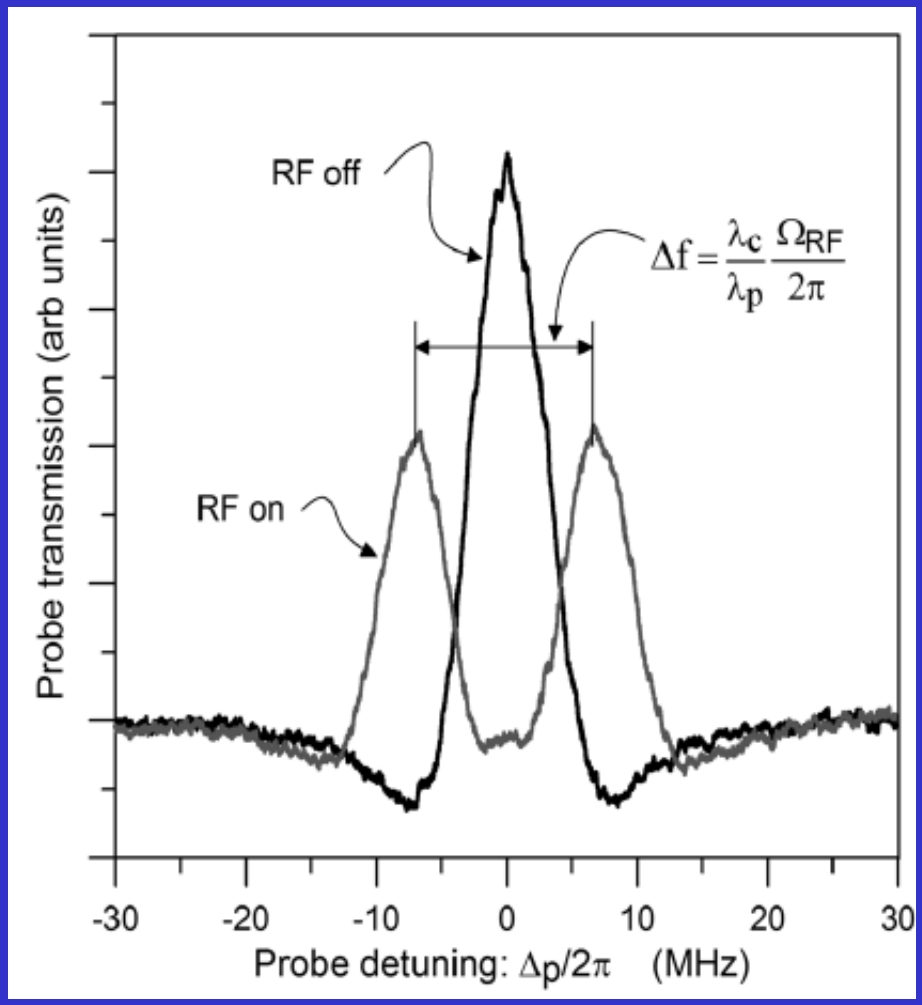


Sub-Wavelength Imaging and Field Mapping via EIT and Autler-Townes Splitting In Rydberg Atoms*

Christopher L. Holloway,[1,†] Joshua A. Gordon,[1] Andrew Schwarzkopf,[2] David A. Anderson,[2] Stephanie A. Miller,[2] Nithiwadee Thaicharoen,[2] and Georg Raithel[2]

Appl. Phys. Lett. 104, 244102 (2014)

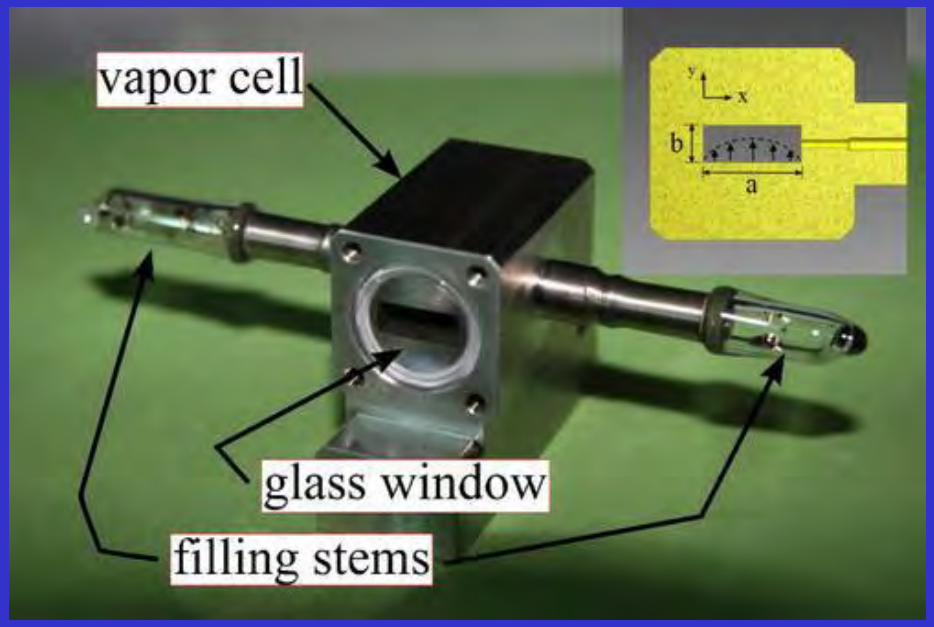


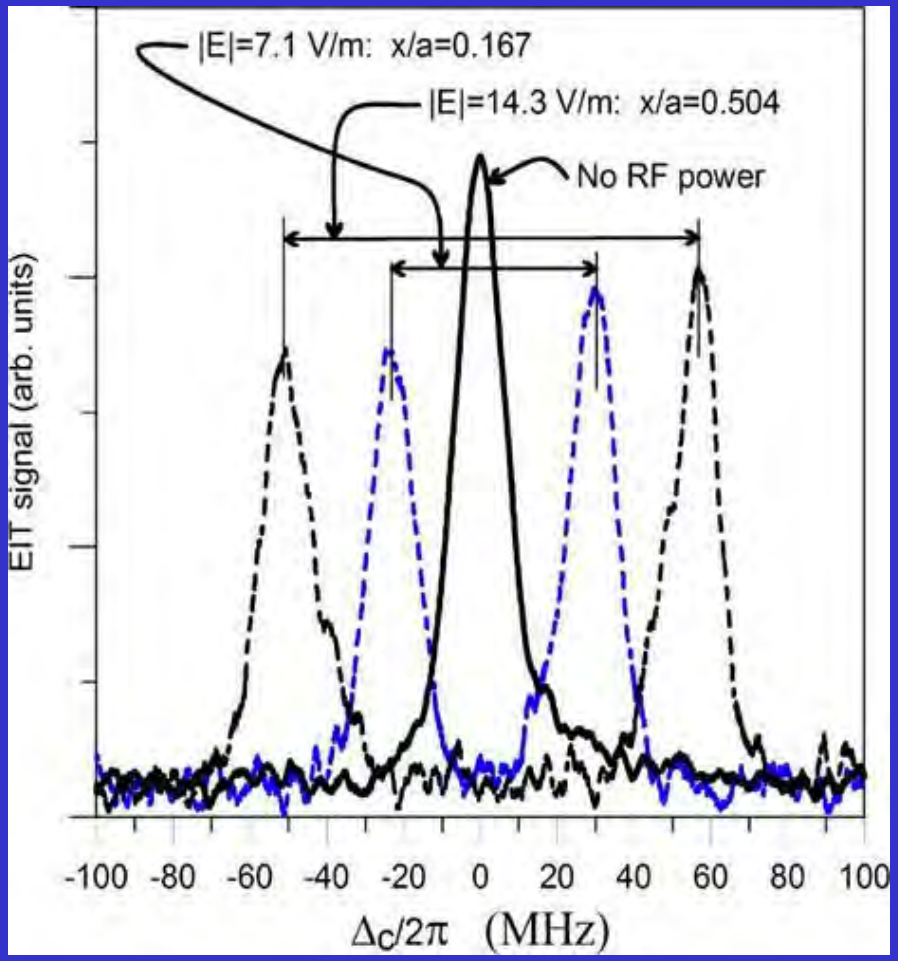


A New Quantum-Based Power Standard: Using Rydberg Atoms for a SI-Traceable Radio-Frequency Power Measurement Technique in Rectangular Waveguides[a)]

Christopher L. Holloway,[1, b)] Matthew T. Simons,[1] Marcus D. Kautz,[1] Abdulaziz H. Haddab,[1] Joshua A. Gordon,[1] and Thomas P. Crowley[2]

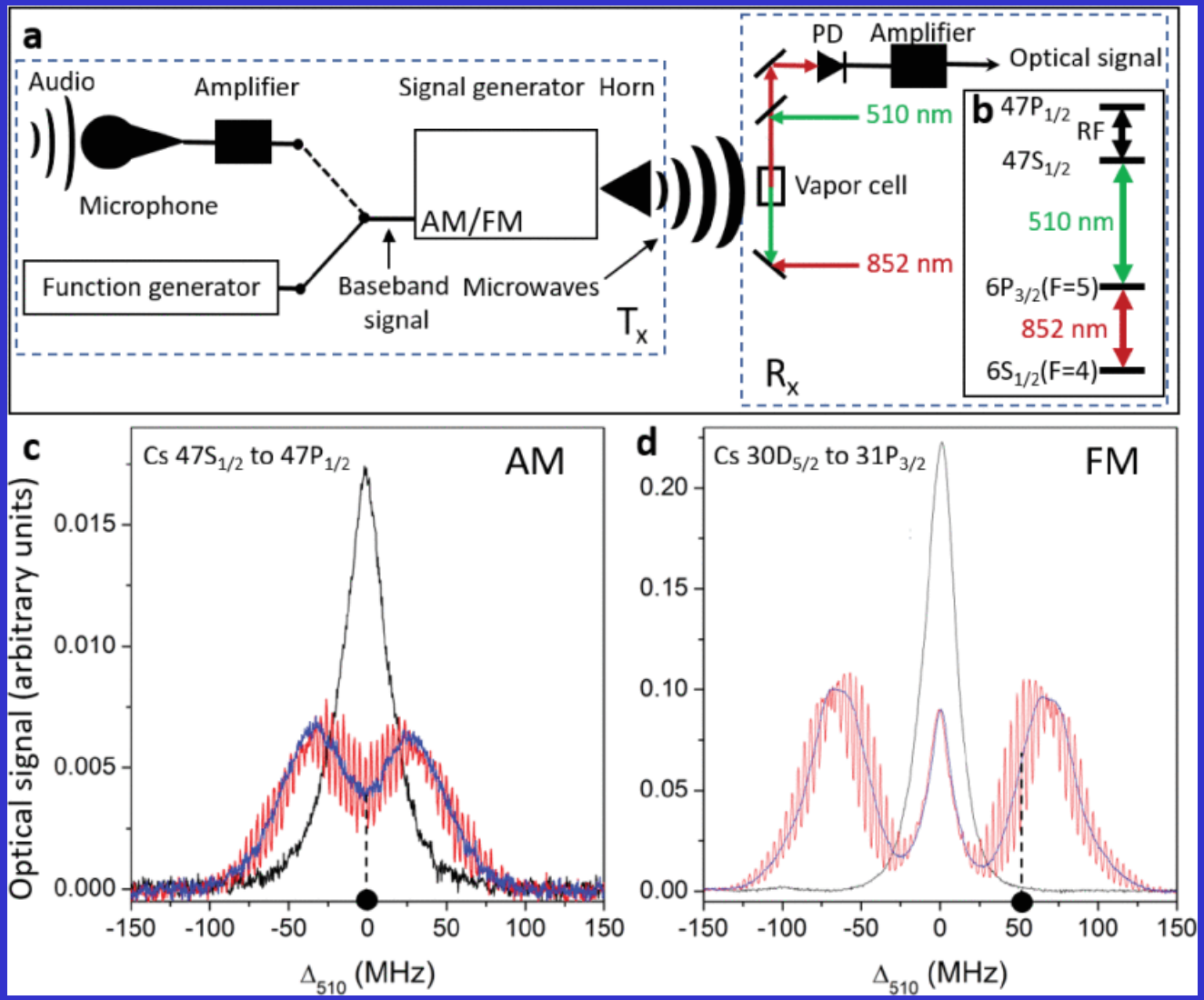
Appl. Phys. Lett. 113, 094101 (2018)





An atomic receiver for AM and FM radio communication

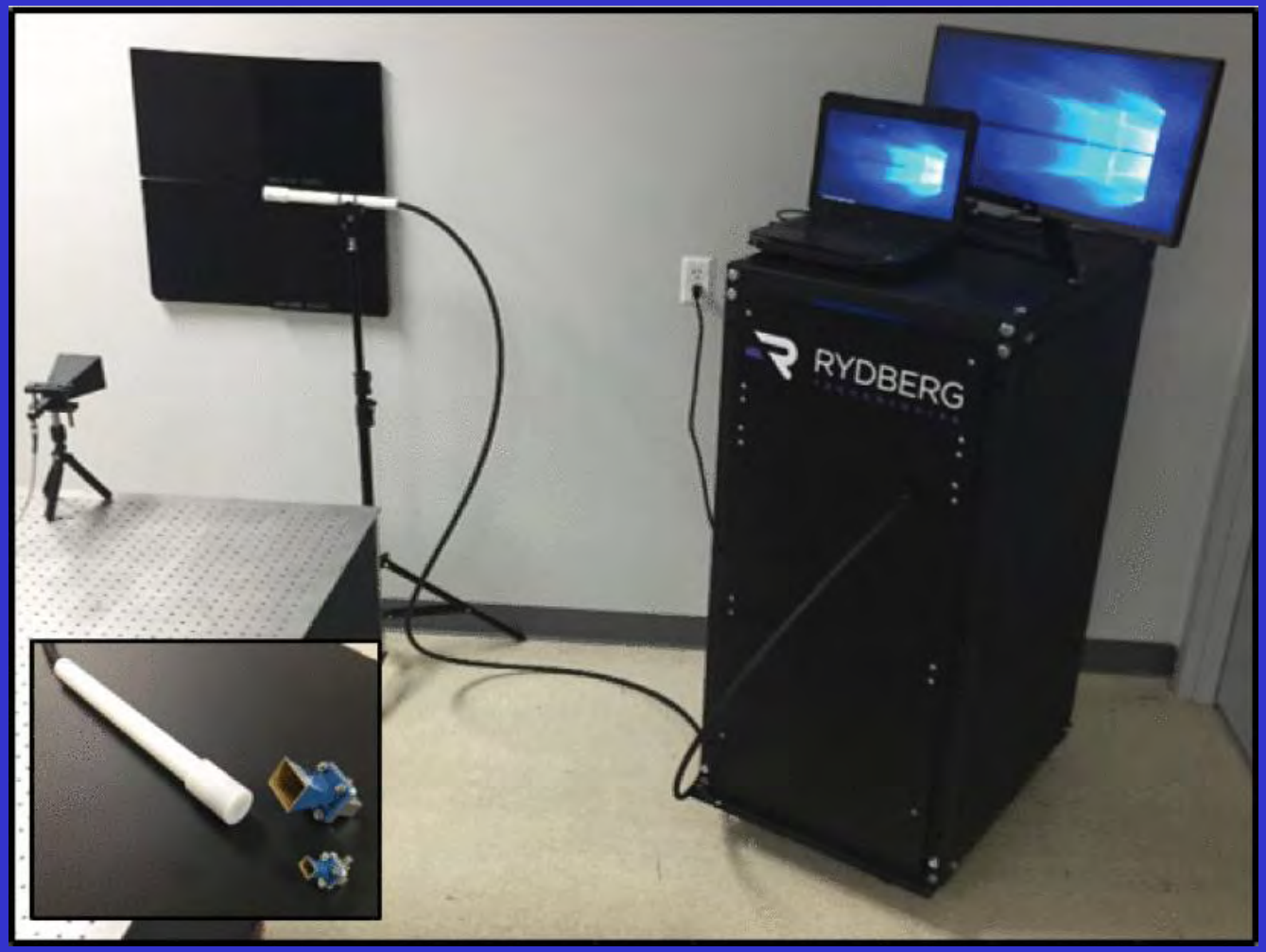
D. A. Anderson[1],* R. E. Sapiro[1], and G. Raithel[1,2]
1. *Rydberg Technologies, Ann Arbor, MI 48104 USA and*
2. *Department of Physics, University of Michigan, Ann Arbor, MI 48109 USA*



IEEE Transactions on Antennas and Propagation, v.69, p.2455 (2021)

A self-calibrating SI-traceable broadband Rydberg atom-based radio-frequency electric field probe and measurement instrument.

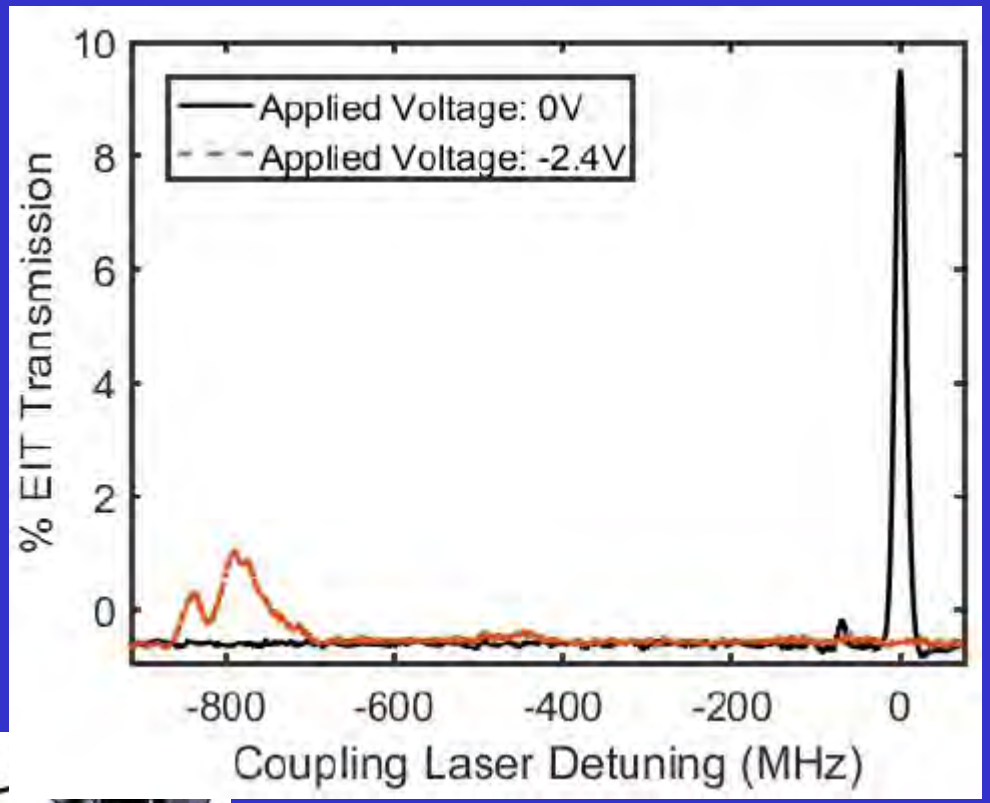
David Alexander Anderson, Rachel Elizabeth Sapiro, and Georg Raithel

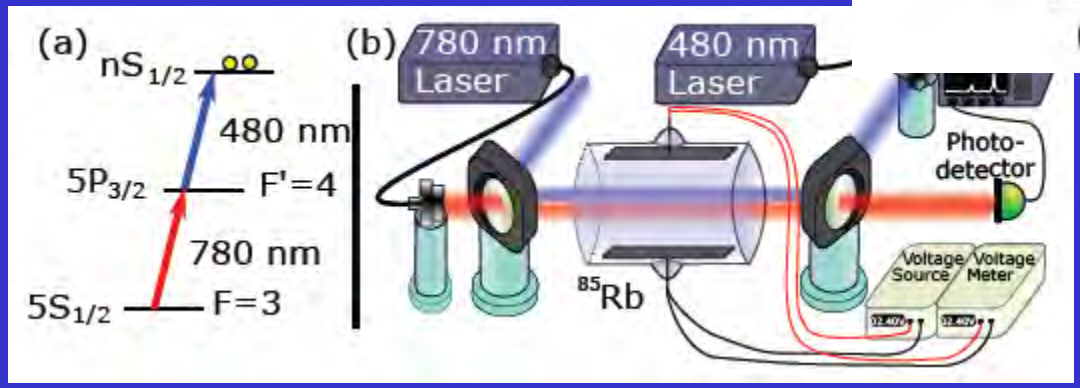


IEEE Transactions on Antennas and Propagation v.69, p.5931 (2021)

Electromagnetically induced transparency based Rydberg-atom sensor for quantum-based voltage measurements[a)]

Christopher L. Holloway,[1] Nikunjkumar Prajapati,[1,2] John Kitching,[1] Jeffery A. Sherman,[1] Carson Teale,[1] Alain Rüfenacht,[1] Alexandra B. Artusio-Glimpse,[1] Matthew T. Simons,[1] Amy K. Robinson,[3] and Eric B. Norrgard[4]

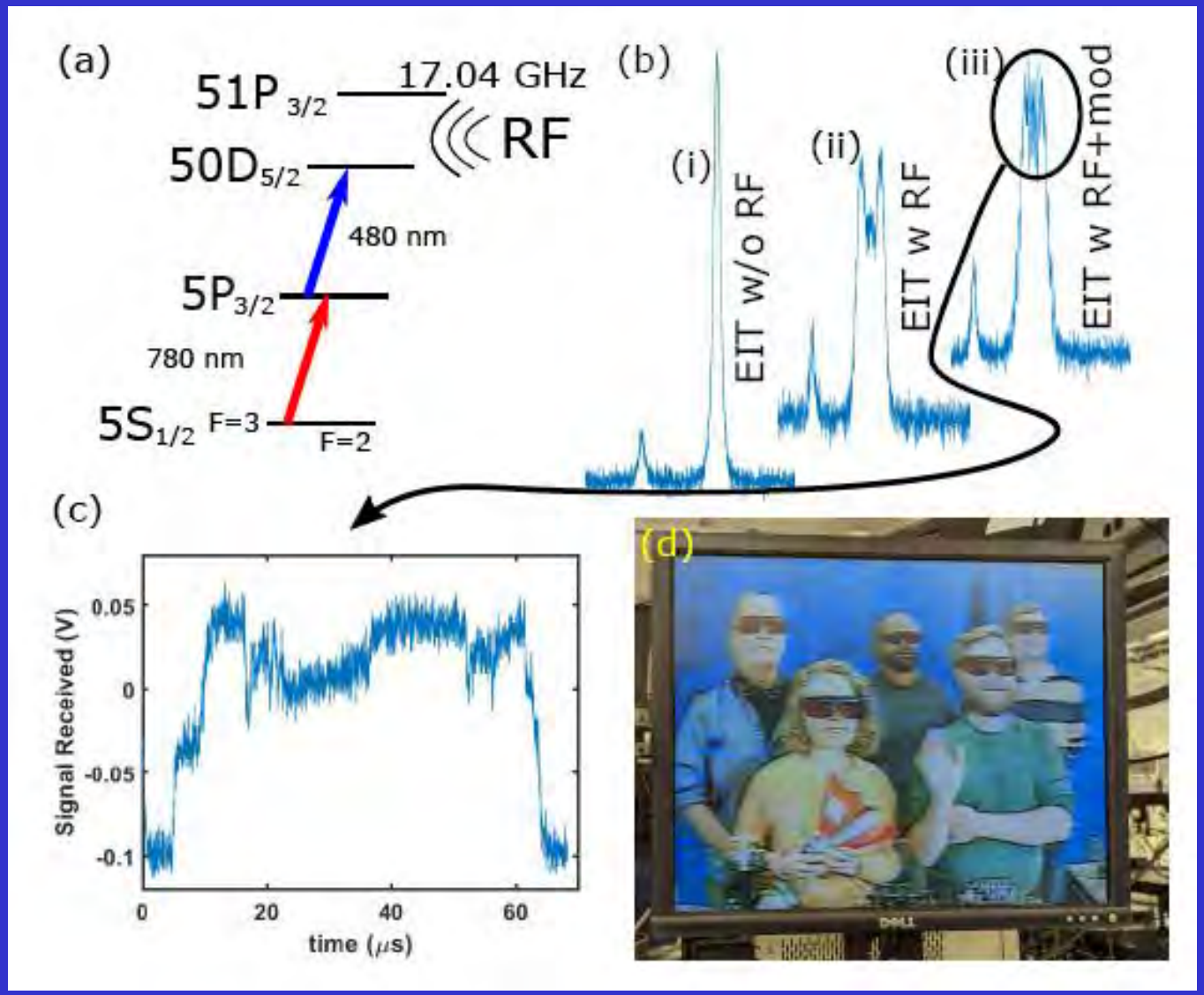




arXiv:2110.02335

TV and Video Game Streaming with a Quantum Receiver: A Study on a Rydberg atom-based receiver's bandwidth and reception clarity[a)]

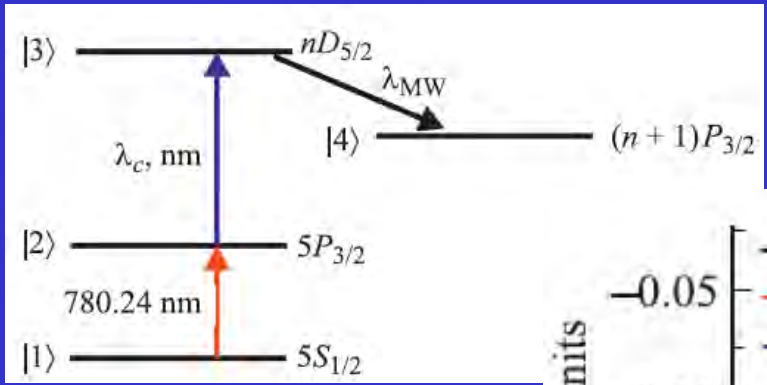
Nikunjkumar Prajapati, Andrew P. Rotunno, Samuel Berweger, Matthew T. Simons, Alexandra B. Artusio-Glimpse, and Christopher L. Holloway



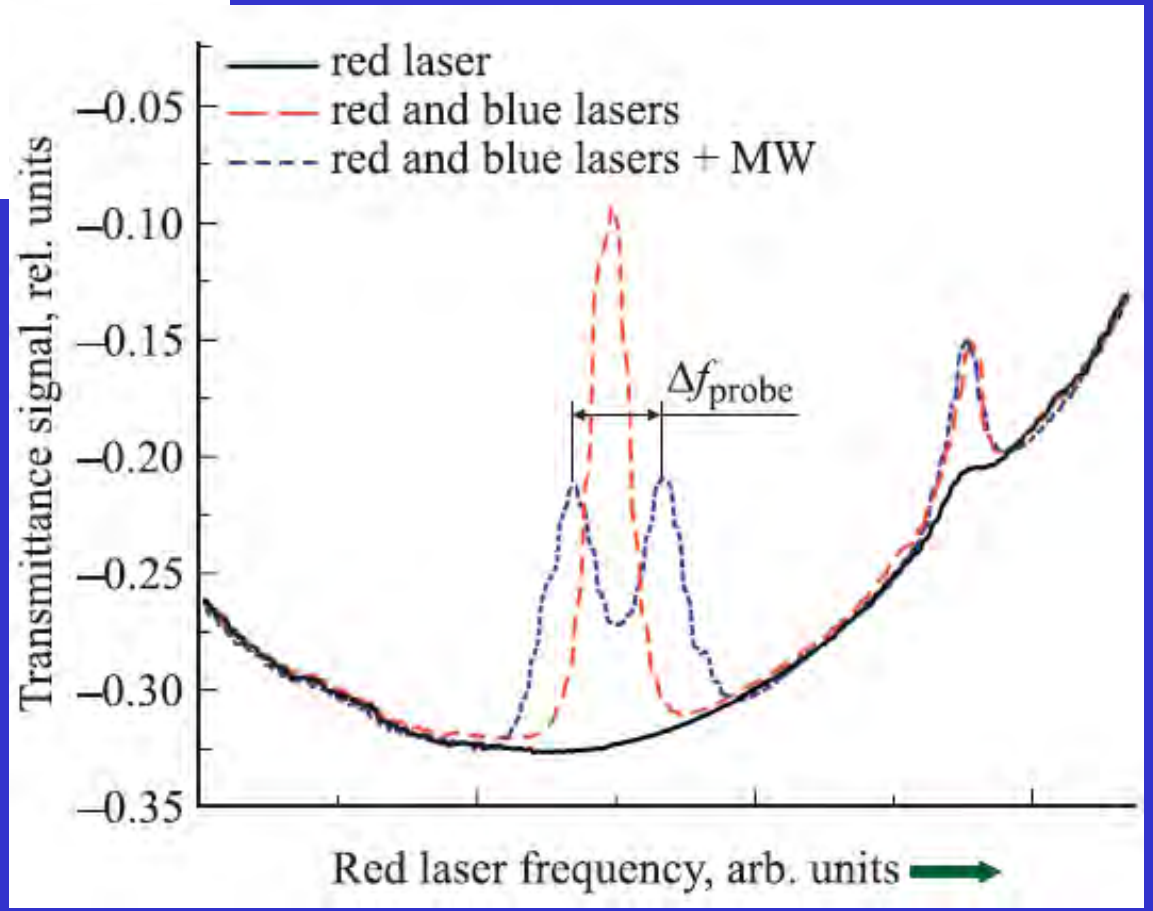
arXiv: 2205.02716

Измерение напряженности электрического поля СВЧ излучения на частоте радиационного перехода между ридберговскими состояниями атомов ^{85}Rb

© Е.Ф. Стельмашенко[1], О.А. Клезович[1], В.Н. Барышев[1], В.А. Тищенко[1], И.Ю. Блинов[1], В.Г. Пальчиков[1,2], В.Д. Овсянников[1,3]



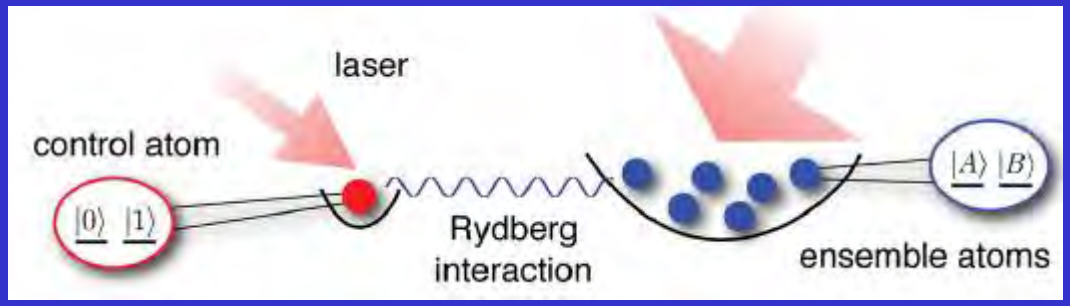
Оптика и спектроскопия, 2020, том 128, вып. 8, 1063

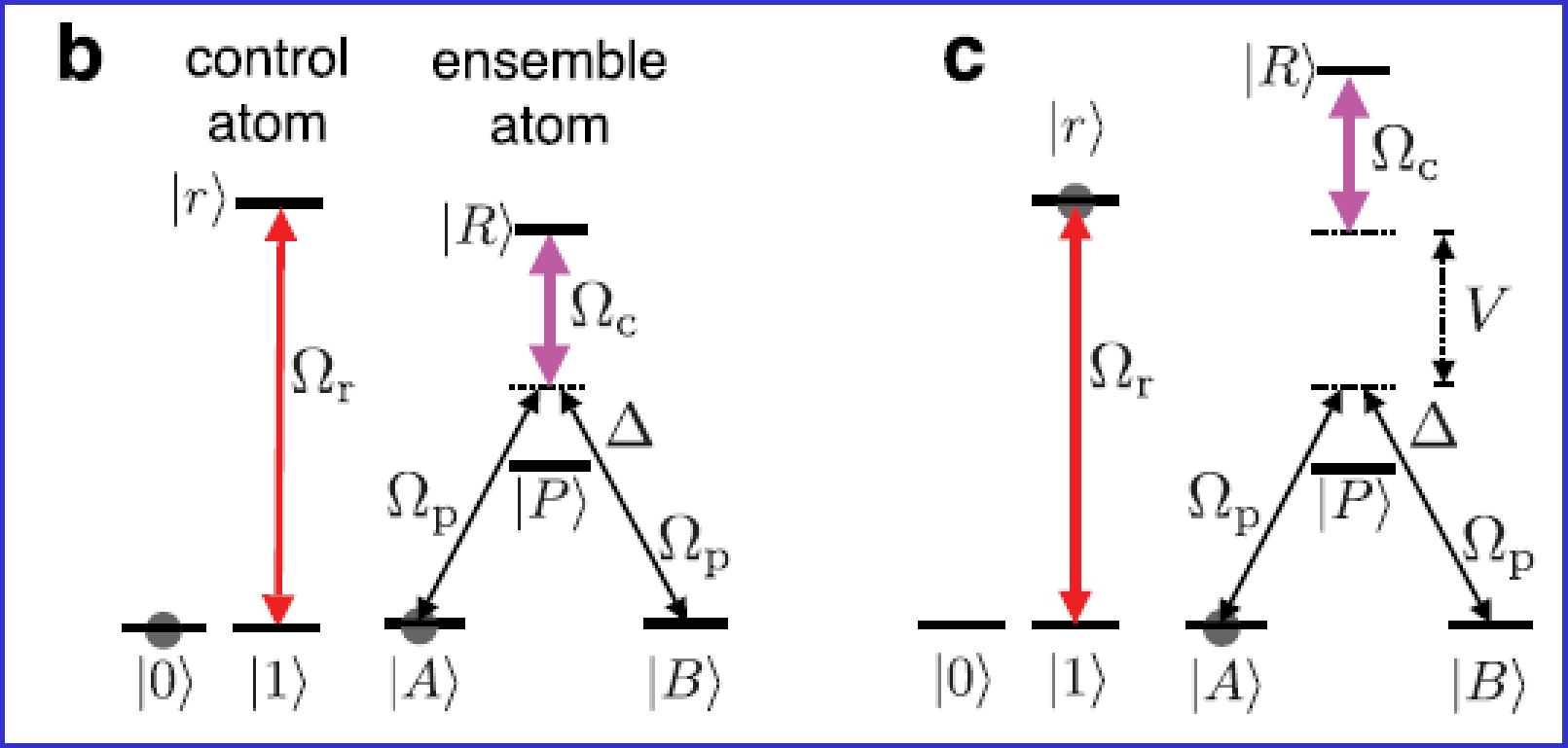


PRL **102,** 170502 (2009) PHYSICAL REVIEW LETTERS week ending 1 MAY 2009

Mesoscopic Rydberg Gate Based on Electromagnetically Induced Transparency

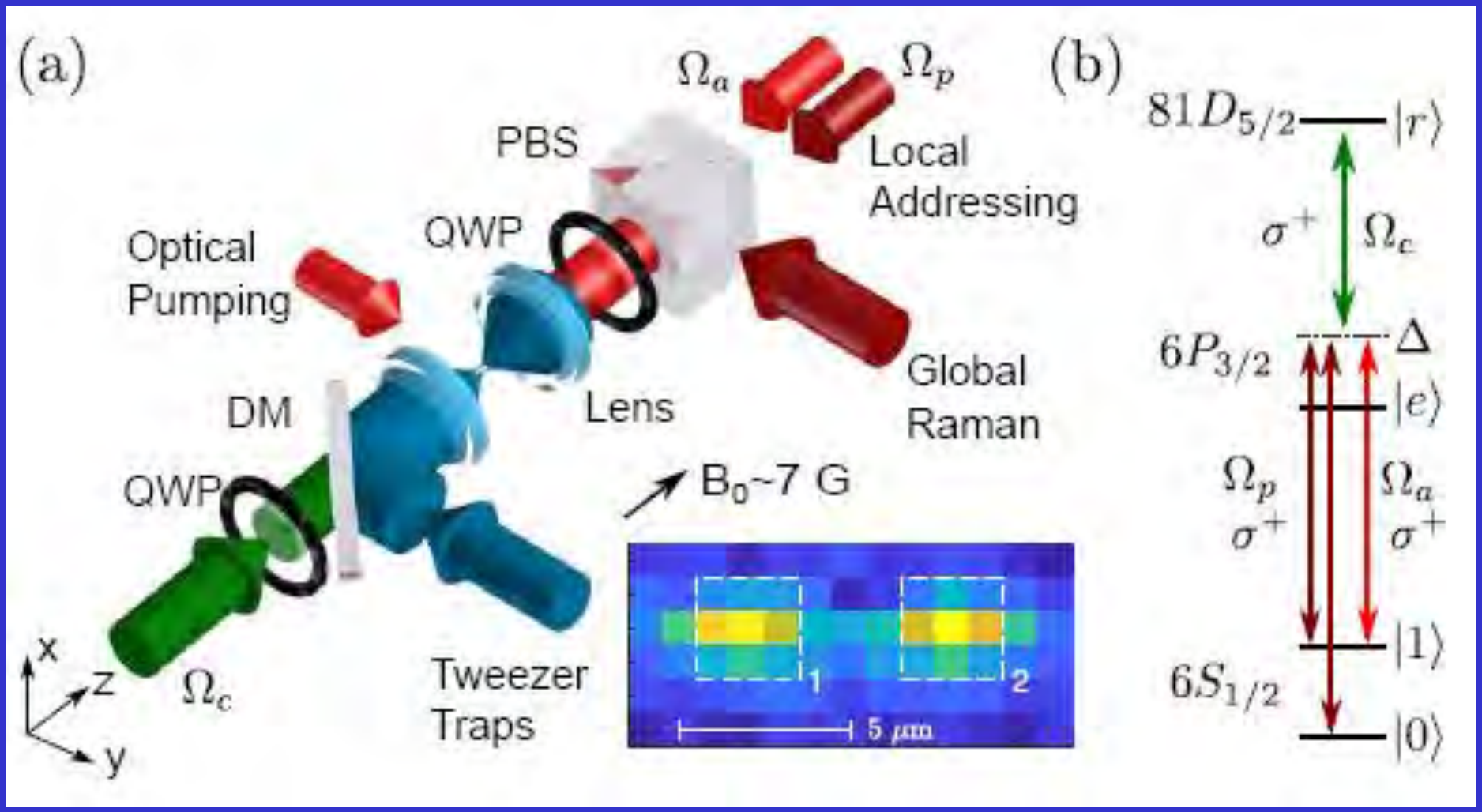
M. Müller,[1] I. Lesanovsky,[1] H. Weimer,[2] H. P. Büchler,[2] and P. Zoller[1]





Demonstration of a Quantum Gate using Electromagnetically Induced Transparency

K. McDonnell, L.F. Keary, and J.D. Pritchard*
EQOP, Department of Physics, University of Strathclyde, SUPA, Glasgow G4 0NG, UK



arXiv: 2204.03733

Demonstration of a Quantum Gate using Electromagnetically Induced Transparency

K. McDonnell, L.F. Keary, and J.D. Pritchard*
EQOP, Department of Physics, University of Strathclyde, SUPA, Glasgow G4 0NG, UK

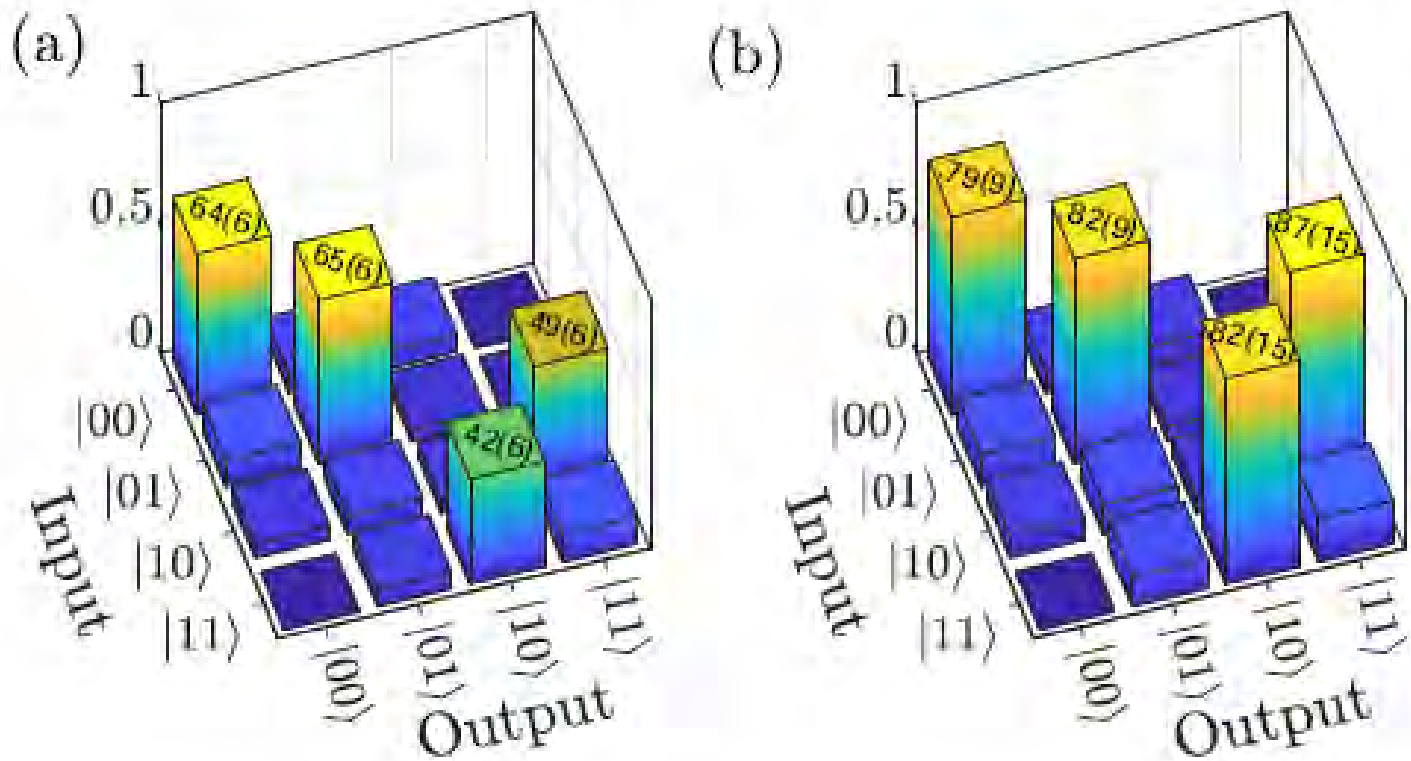


FIG. 4. Gate Measurement. (a) Raw and (b) loss-corrected CNOT gate data with fidelities of $\mathcal{F}_{\mathrm{CNOT}} = 0.55(3)$ and $\mathcal{F}^{\mathrm{cor}}_{\mathrm{CNOT}} = 0.82(6)$.

arXiv: 2204.03733

SUMMARY

- Rydberg atoms have unique properties compared to low-excited atoms and are of great interest for high-resolution laser and microwave spectroscopy.
- Cold Rydberg atoms demonstrate strong long-range interactions which can be used to implement two- and three-qubit gates in quantum information processing with neutral atoms in optical lattices.
- Stark-tuned and rf-assisted Förster resonances provide fine and flexible control of many-body interactions between Rydberg atom.
- Rydberg atoms in optical gas cells demonstrate narrow EIT resonances which can be used as high-precision sensors of dc and ac electric fields.
- Our current aim is to build a medium-scale quantum computer and simulator with qubits based on single Rb atoms. We have demonstrated optical dipole traps, single atom loading and detection, initialization and one-qubit gates with individual addressing.
- Our experiments on two- and three-qubit gates with coherent interactions of Rydberg atoms in optical traps are in progress.

Федеральное государственное бюджетное учреждение науки Институт физики полупроводников им. А.В.Ржанова Сибирского отделения Российской академии наук

ИНСТИТУТСКИЙ СЕМИНАР

Административный корпус
Конф. зал

29 апреля 2013 г.
Понедельник, 9:30

Alain Aspect

Augustin Fresnel Professor,
Institut d'Optique, Palaiseau, France

Coherent Back Scattering and Anderson Localization of Ultra Cold Atoms

16-я Всероссийская научная конференция с международным участием

"Физика ультрахолодных атомов – 2022"

Организаторы: ИЛФ СО РАН, ИФП СО РАН, ИАиЭ СО РАН, НГУ

19-21 декабря 2022 года, Новосибирск, Академгородок, проспект Лаврентьева 15 Б, конференц-зал Института лазерной физики СО РАН

Сайт конференции: ultracoldatoms2022.laser.nsc.ru

The team and assembled setup with Rb trap array