Controlling many-body Förster resonances between cold Rydberg atoms by a time-varying electric field

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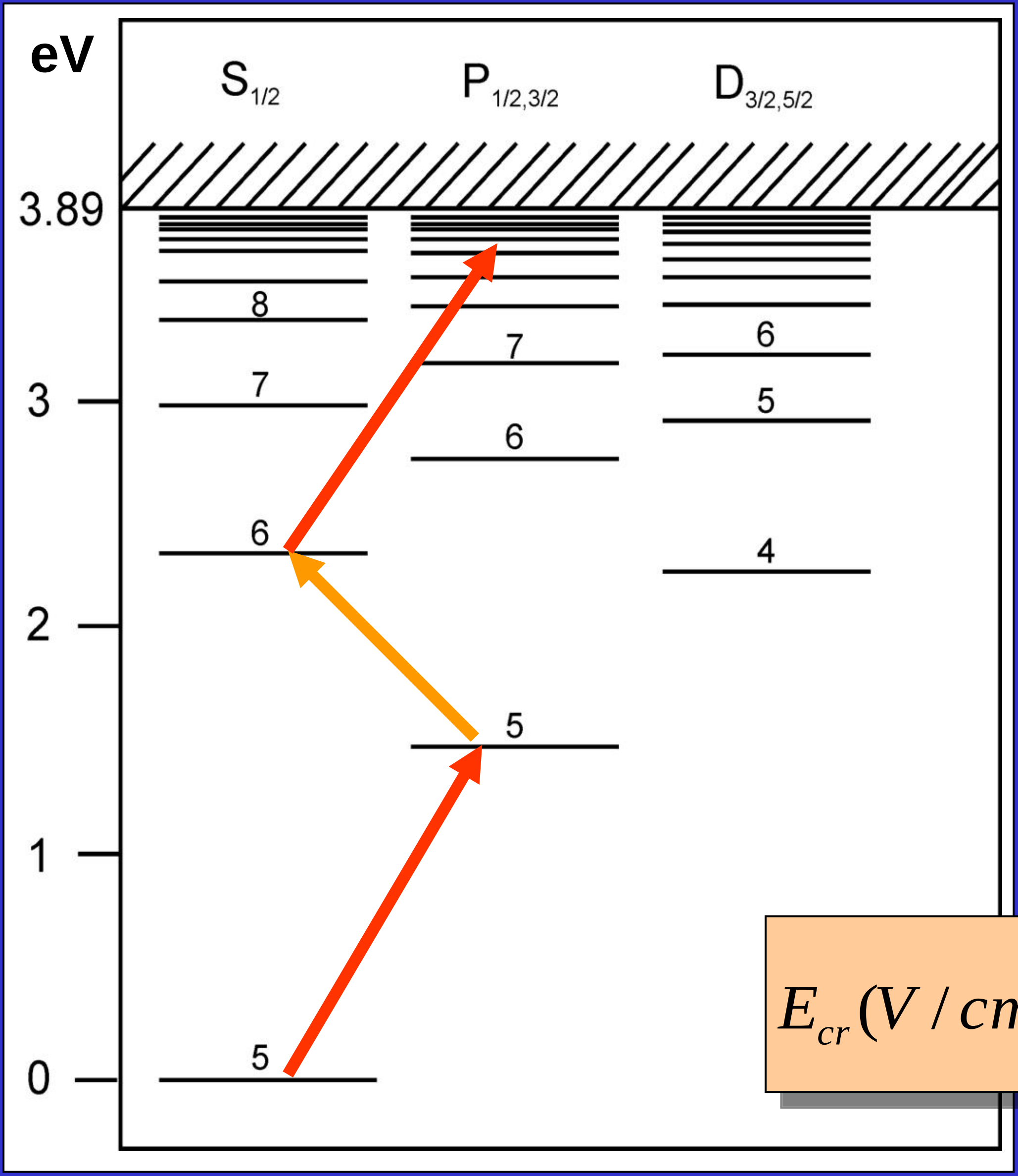
Rydberg atoms

Energy levels in Rb atoms

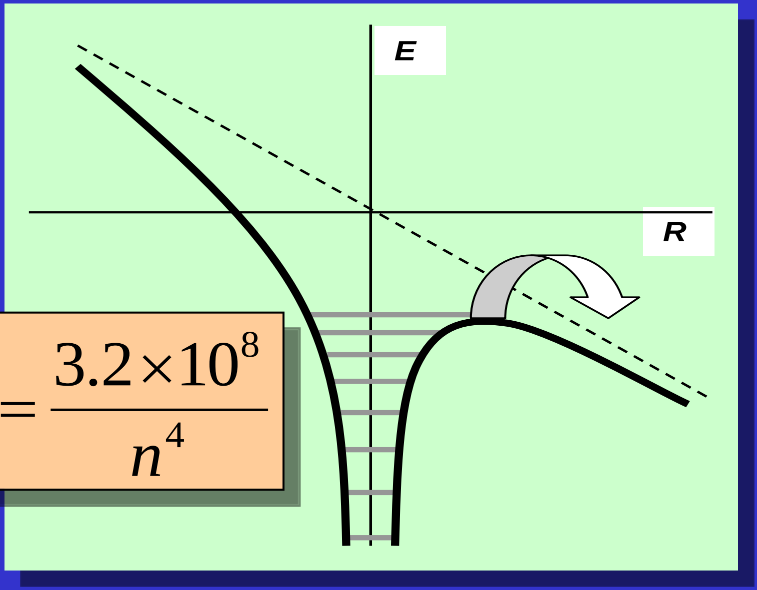


$$E_n = -\frac{Ry}{(n-\delta_L)^2}$$

$$r_n \sim n^2$$

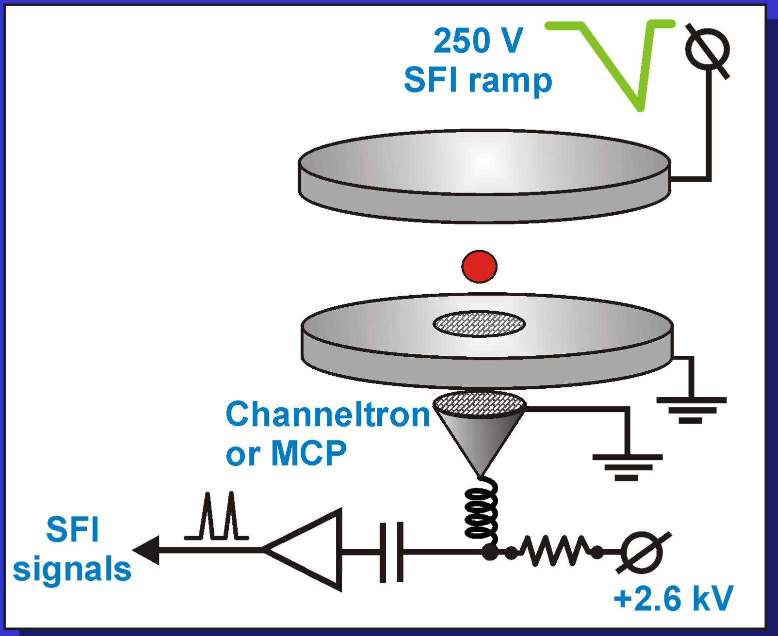
$$\tau_n \sim n^3 - n^5$$

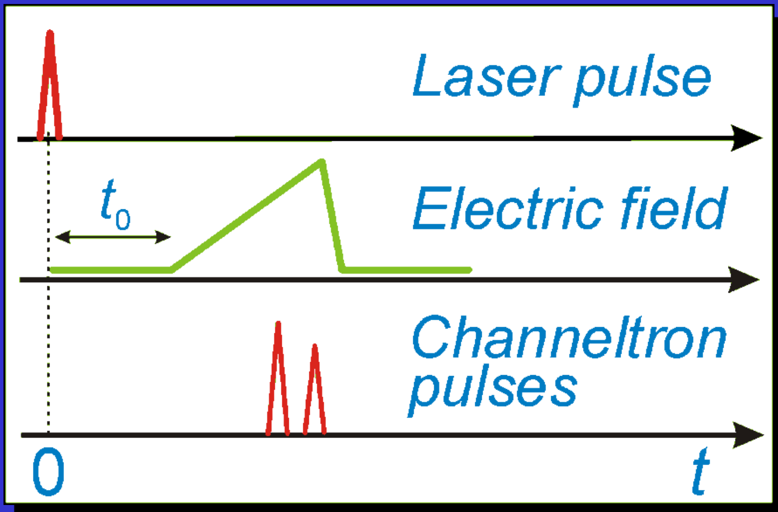
$$\alpha_n \sim n^7$$



$$E_{cr}(V/cm) = \frac{3.2\times 10^8}{n^4}$$

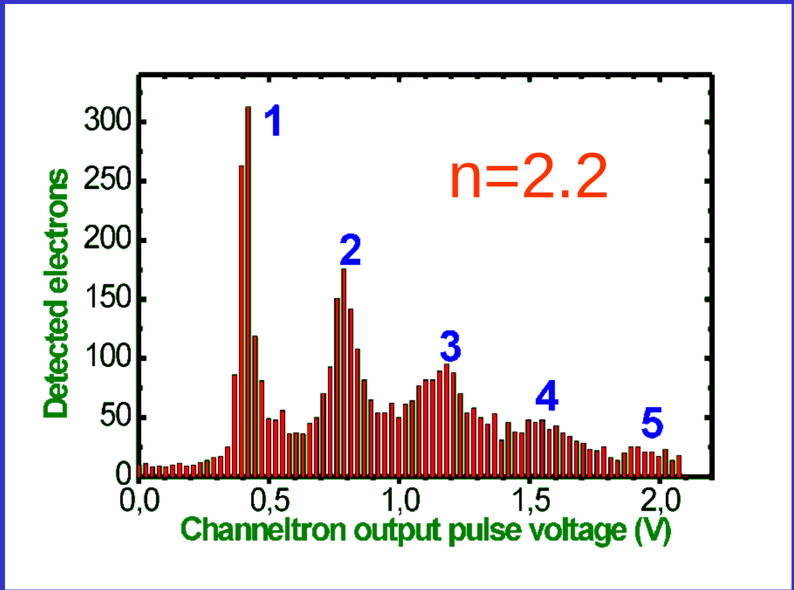
Selective Field Ionization detector

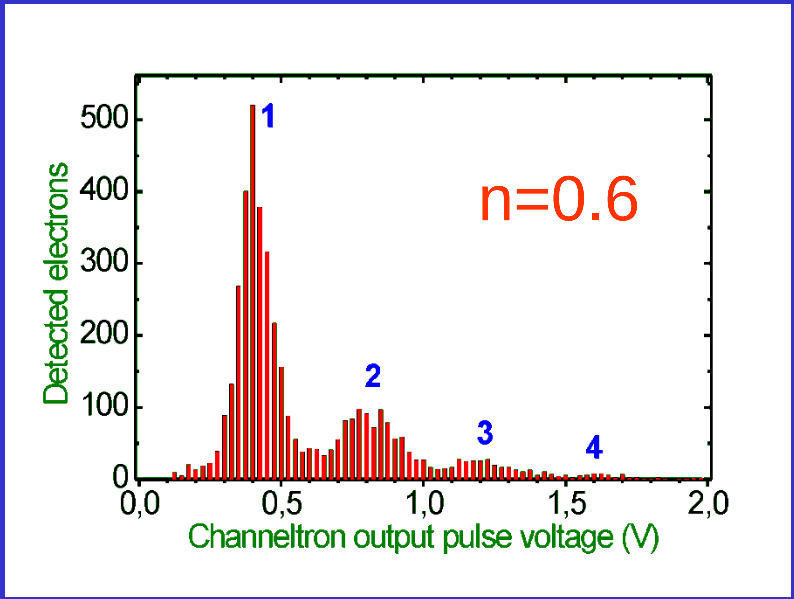




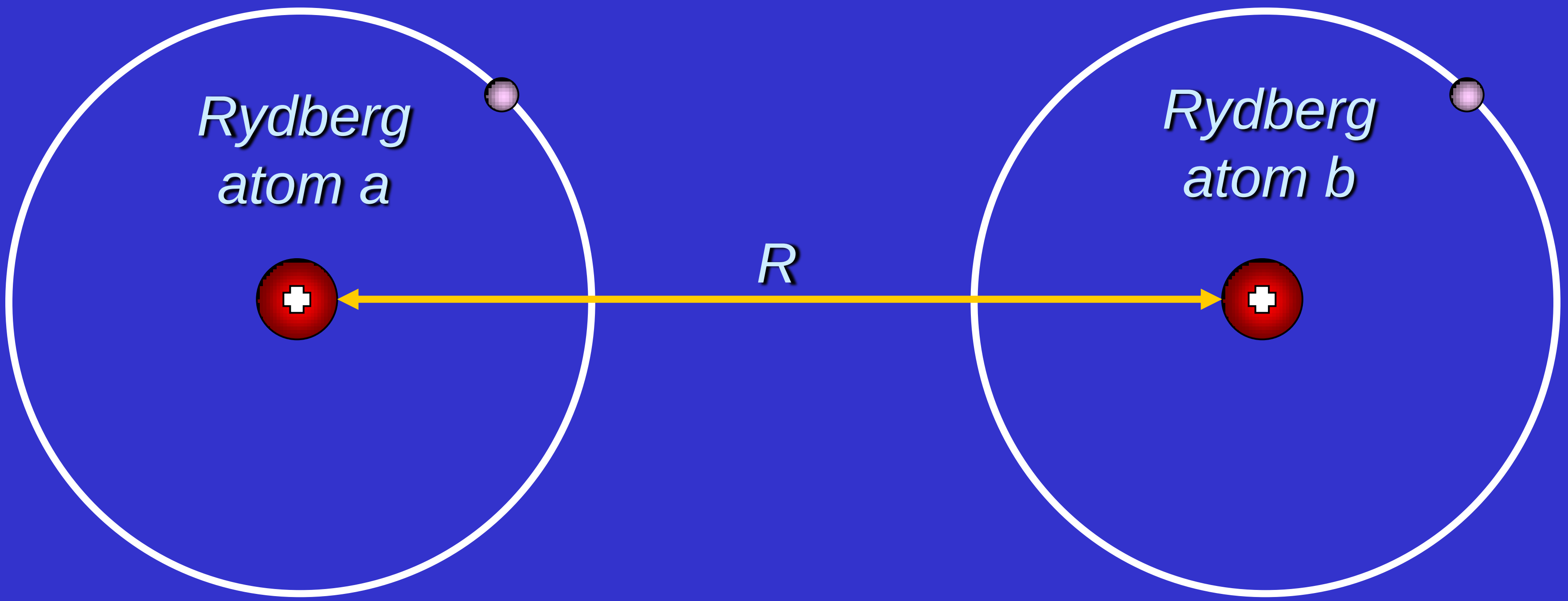
Atom counting with CEM

Ryabtsev et al., PRA 76 (2007) 012722





Long-range interactions of Rydberg atoms



Dipole moments

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

Energy of dipole-dipole interaction

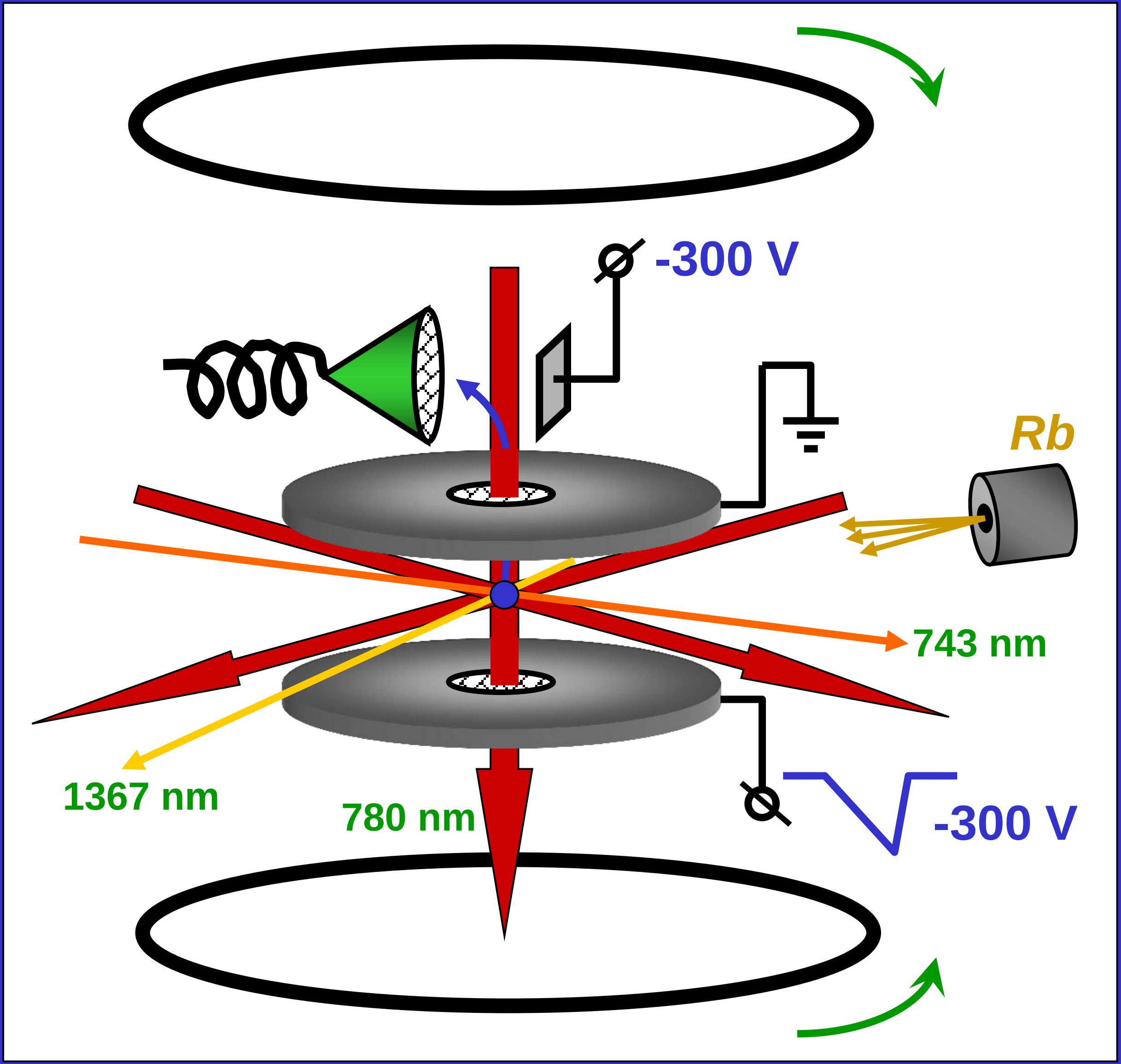
$$V_{ab} \sim \frac{d_a d_b}{R_{ab}^3} \sim n^4$$

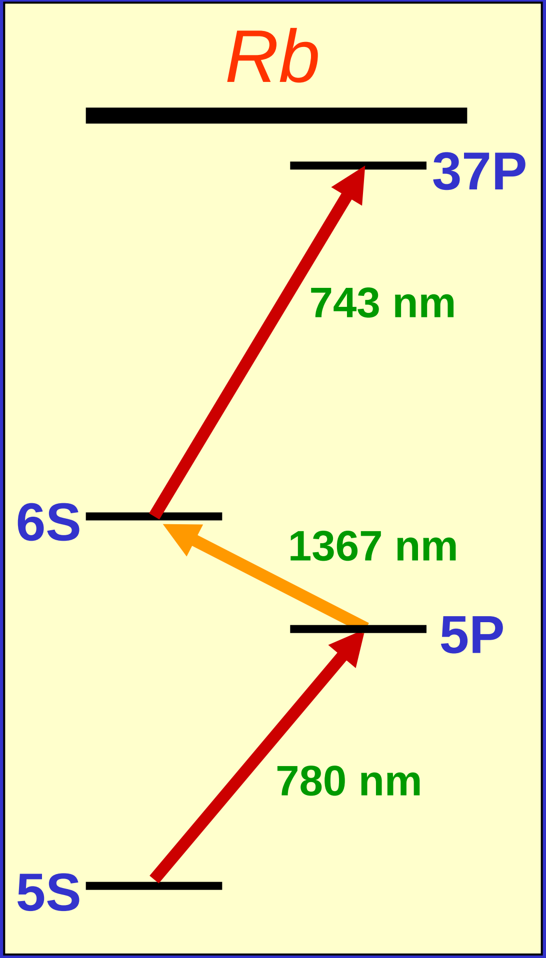
$V \sim 10$ MHz at $n = 50$, $R \approx 5\ \mu$m

MOTIVATION

- Many-body phenomena
- Phase transitions in a cold gas
- Dipole blockade at laser excitation
- Neutral atom quantum computing
- Single-photon gates

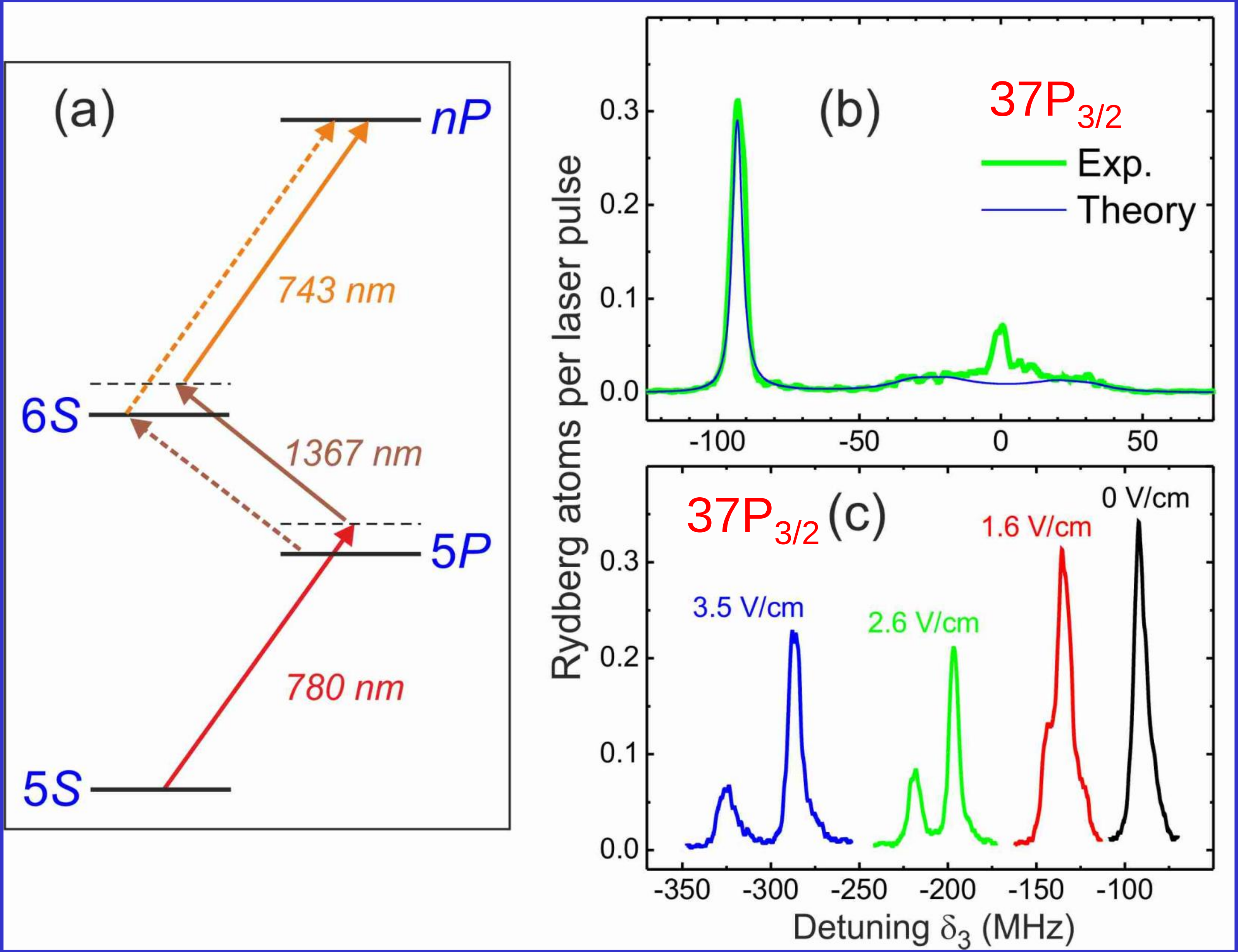
Rb magneto-optical trap with detection system for Rydberg atoms





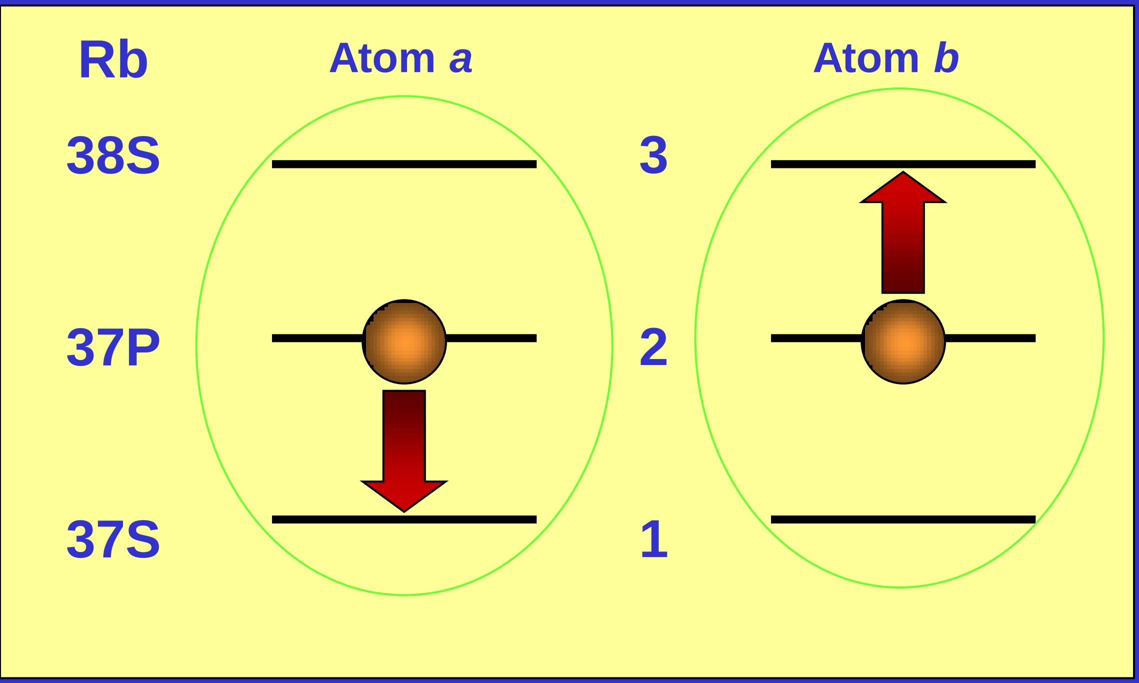
V.M.Entin et al., JETP ***116****, 721 (2013)*

Three-photon laser excitation with cw lasers



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

Two-body Förster resonance in Rb Rydberg atoms



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

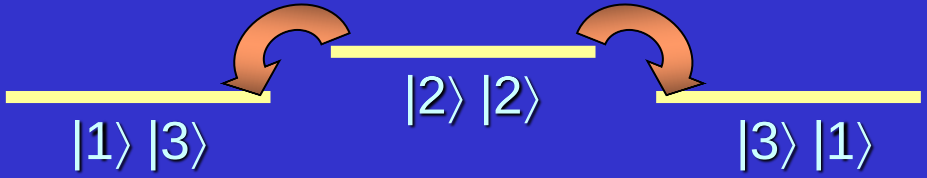
$n = 37$, $R \approx 10$ µm

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

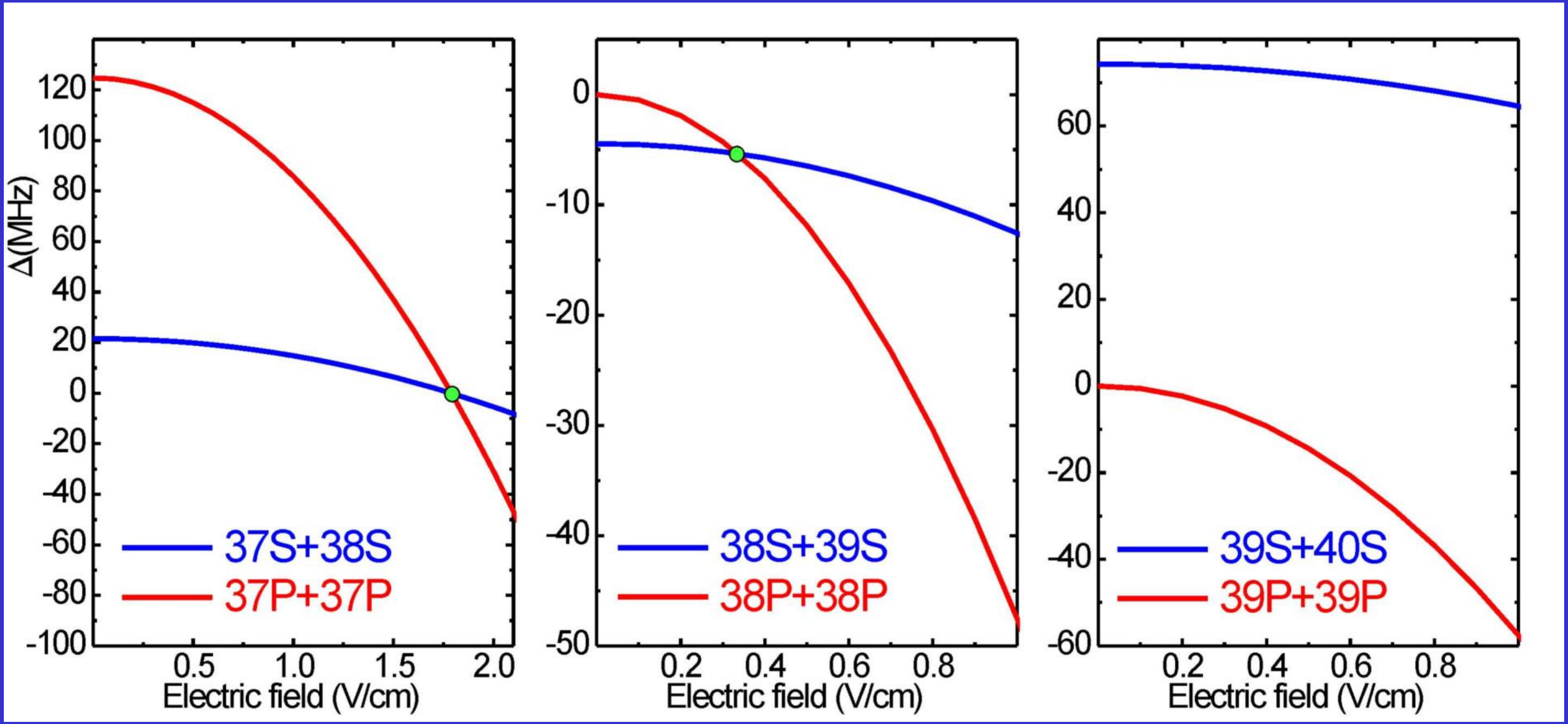
Collective states:

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

Example of two atoms:

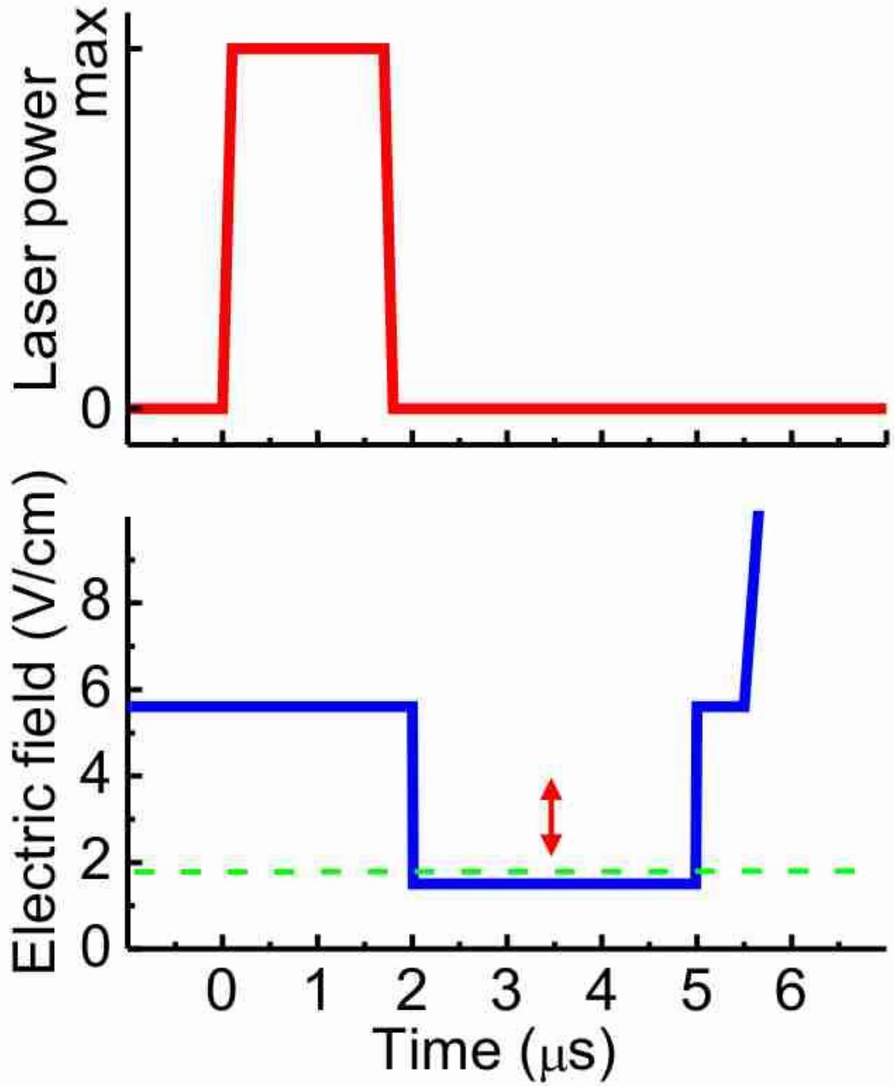


Two-body Förster resonances
$Rb(nP_{3/2}) + Rb(nP_{3/2}) \rightarrow Rb(nS_{1/2}) + Rb([n+1]S_{1/2})$



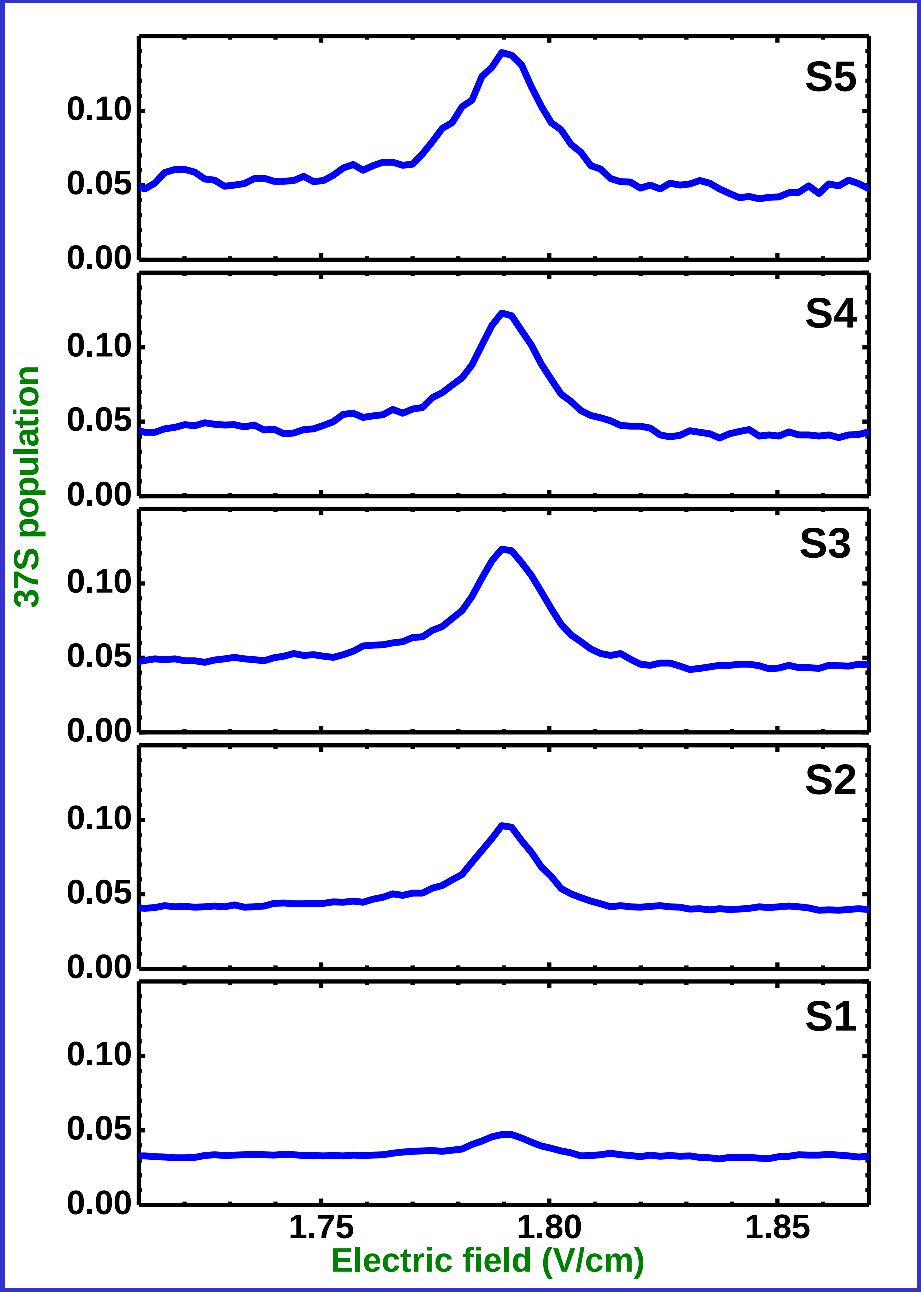
*D.B.Tretyakov et al., Phys. Rev. A **90**, 041403(R) (2014)*

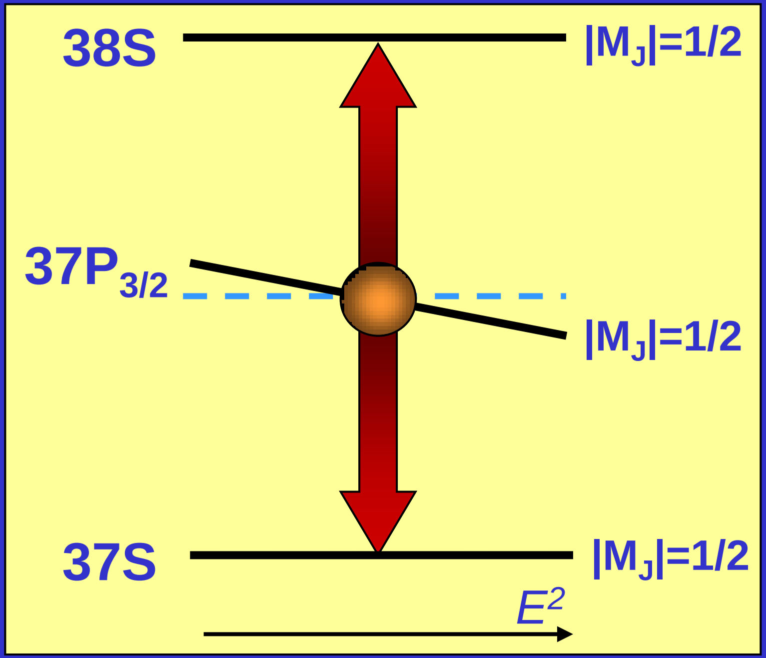
Stark-switching technique to control Rydberg excitation and interactions



E.A.Yakshina et al., Phys. Rev. A ***94****, 043417 (2016)*

Two-body Förster resonance in a 18 μm excitation volume



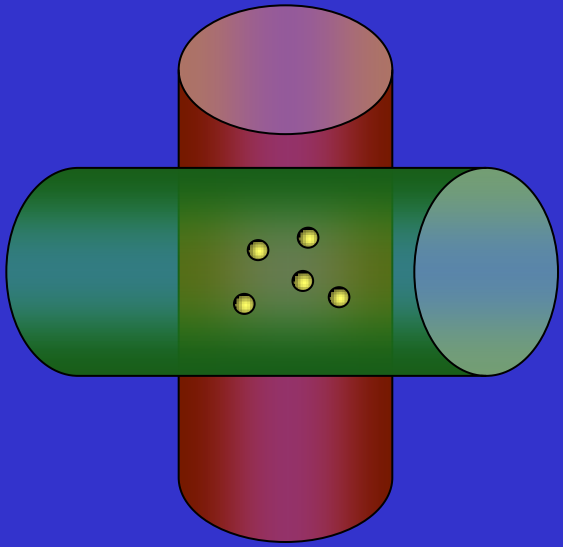


$$S_N = \frac{n_N(37S)}{n_N(37P) + n_N(37S) + n_N(38S)}$$

I.I.Ryabtsev et al., Phys. Rev. Lett. ***104****, 073003 (2010)*

Monte-Carlo simulations for randomly positioned atoms

I.I.Ryabtsev et al., Phys. Rev. A, 2010, v.82, p.053409



Hamiltonian

$$\hat{H} = \sum_{k=1}^{N_0} \hat{H}_k + \sum_{n \neq m} \hat{V}_{nm}$$

Dipole-dipole interaction

$$\hat{V}_{nm} = \frac{1}{4\pi\varepsilon_0}\left[\frac{\hat{\mathbf{d}}_n \hat{\mathbf{d}}_m}{R_{nm}^3} - \frac{3\left(\hat{\mathbf{d}}_n \mathbf{R}_{nm}\right)\left(\hat{\mathbf{d}}_m \mathbf{R}_{nm}\right)}{R_{nm}^5}\right]$$

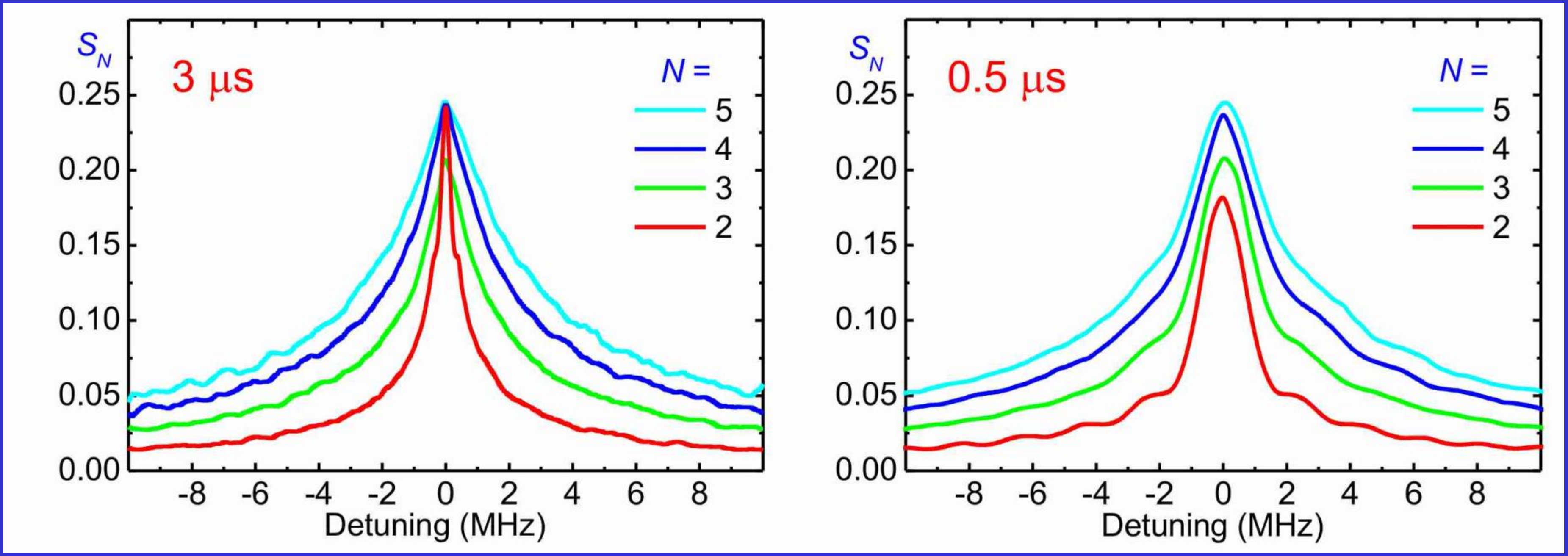
$$\Delta = \left(2\mathrm{E}_{37P} - \mathrm{E}_{37S} - \mathrm{E}_{38S}\right)/\hbar$$ *Detuning*

$$V_{nm}: \quad 37P + 37P \leftrightarrow 37S + 38S$$ *Resonant interaction*

$$V'_{nj}: \quad 37P + 37S \leftrightarrow 37S + 37P$$ *Always resonant interaction 1*

$$V''_{jm}: \quad 37P + 38S \leftrightarrow 38S + 37P$$ *Always resonant interaction 2*

Theoretical spectra of the Förster resonance calculated with the Schrödinger's equation



$V = 18\times18\times18\ \mu m^3$

$t_0 = 3\ \mu s$

S_2: $\Delta\nu \approx 0.9$ MHz

$\Delta\nu_{Exp} \approx 1.95$ MHz

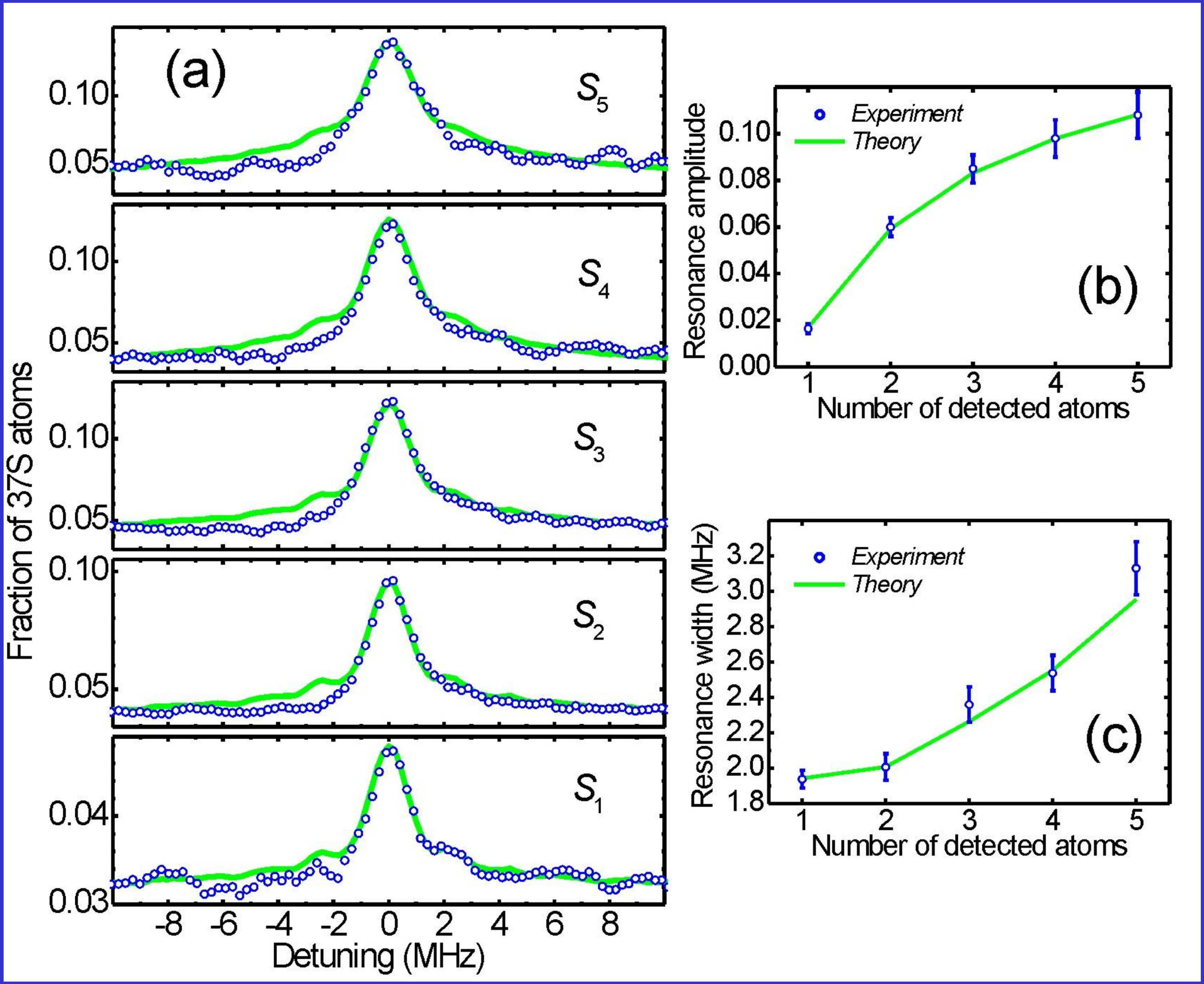
$V = 18\times18\times18\ \mu m^3$

$t_0 = 0.515\ \mu s$

S_2: $\Delta\nu \approx 1.95$ MHz

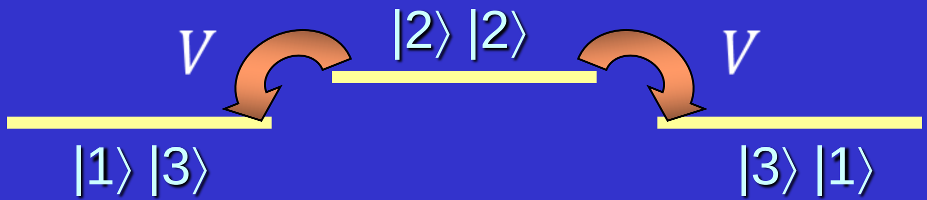
$\Delta\nu_{Exp} \approx 1.95$ MHz

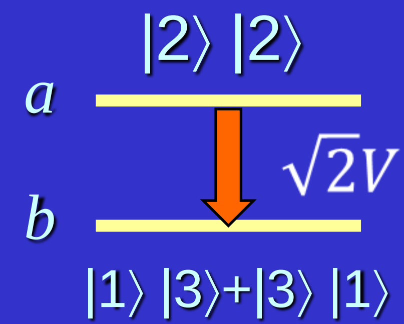
Comparison between theory and experiment



I.I.Ryabtsev, D.B.Tretyakov, I.I.Beterov, V.M.Entin, Phys. Rev. Lett. ***104****, 073003 (2010)*

Modeling the Förster resonance with density matrix equations





Density matrix equations

$$\dot{\rho}_{aa} = i\sqrt{2}V\left(\rho_{ab} - \rho_{ba}\right)$$
$$\dot{\rho}_{bb} = i\sqrt{2}V\left(\rho_{ba} - \rho_{ab}\right)$$
$$\dot{\rho}_{ab} = -i\Delta\rho_{ab} + i\sqrt{2}V\left(\rho_{aa} - \rho_{bb}\right)$$
$$\dot{\rho}_{ba} = i\Delta\rho_{ba} + i\sqrt{2}V\left(\rho_{bb} - \rho_{aa}\right)$$

Phase diffusion model to account for the parasitic broadenings Γ

$$\dot{\rho}_{aa} = i\sqrt{2}V\left(\rho_{ab} - \rho_{ba}\right)$$
$$\dot{\rho}_{bb} = i\sqrt{2}V\left(\rho_{ba} - \rho_{ab}\right)$$
$$\dot{\rho}_{ab} = -\left(i\Delta + \Gamma/2\right)\rho_{ab} + i\sqrt{2}V\left(\rho_{aa} - \rho_{bb}\right)$$
$$\dot{\rho}_{ba} = \left(i\Delta - \Gamma/2\right)\rho_{ba} + i\sqrt{2}V\left(\rho_{bb} - \rho_{aa}\right)$$

E.A.Yakshina et al., Phys. Rev. A ***94****, 043417 (2016)*
I.I.Ryabtsev et al., J. Phys.: Conf. Series, 793, 012024 (2017)

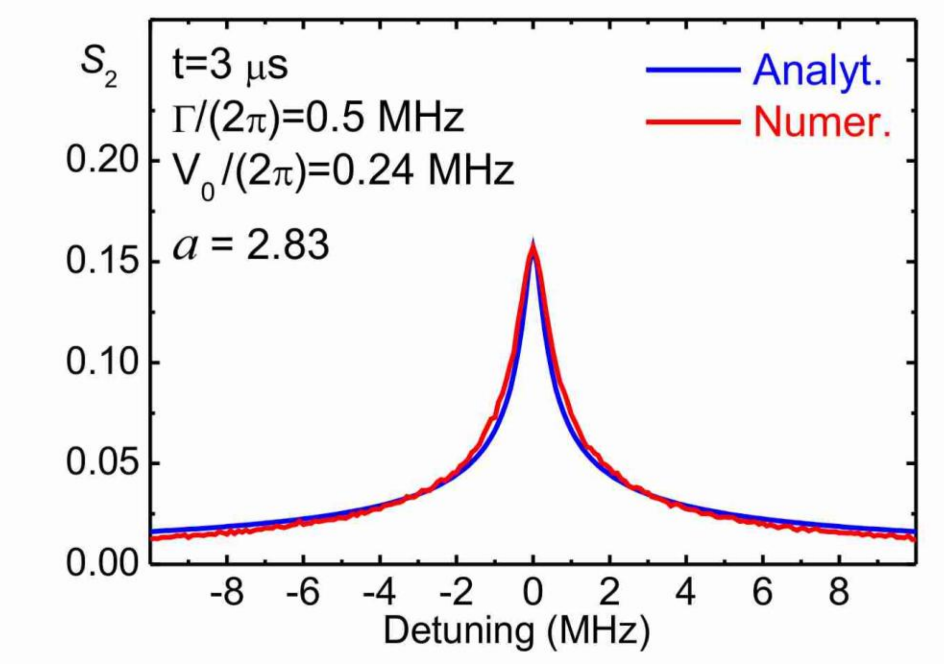
Analytical calculations with density matrix

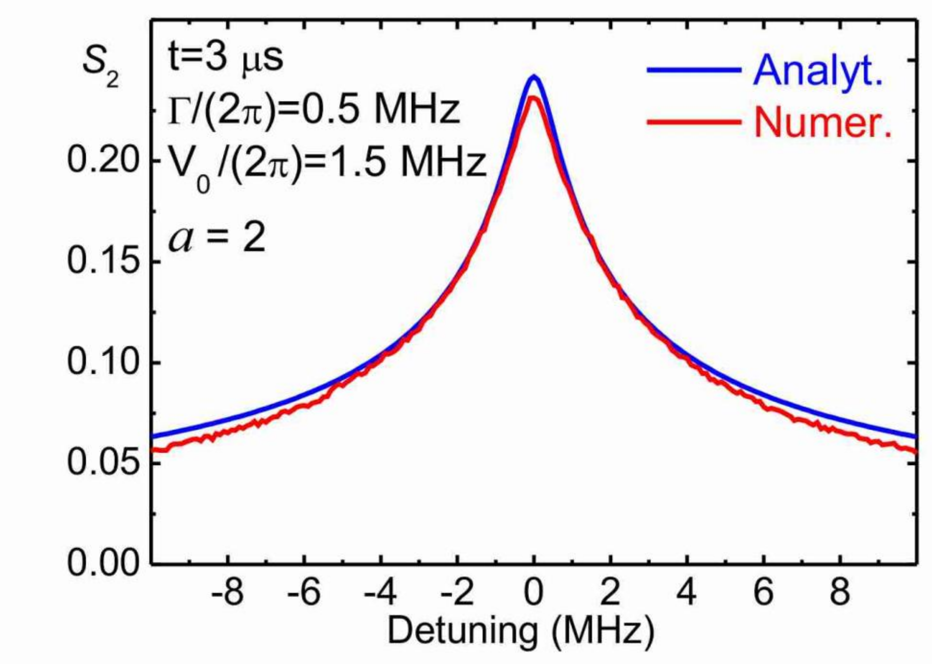
Förster resonance line shape for two disordered Rydberg atoms

$$\left\langle S_2^{strong} \right\rangle \approx \frac{1}{4}\left[1-\exp\left(-\left\{\frac{0.44\,V_0^2\Gamma t}{a^2\Delta^2+\Gamma^2}\right\}^{1/3}\right)\right]$$

$$FWHM^{weak} \approx 5.3\Gamma / a$$

$$FWHM^{strong} \approx V_0\sqrt{5.3\Gamma t} / a$$

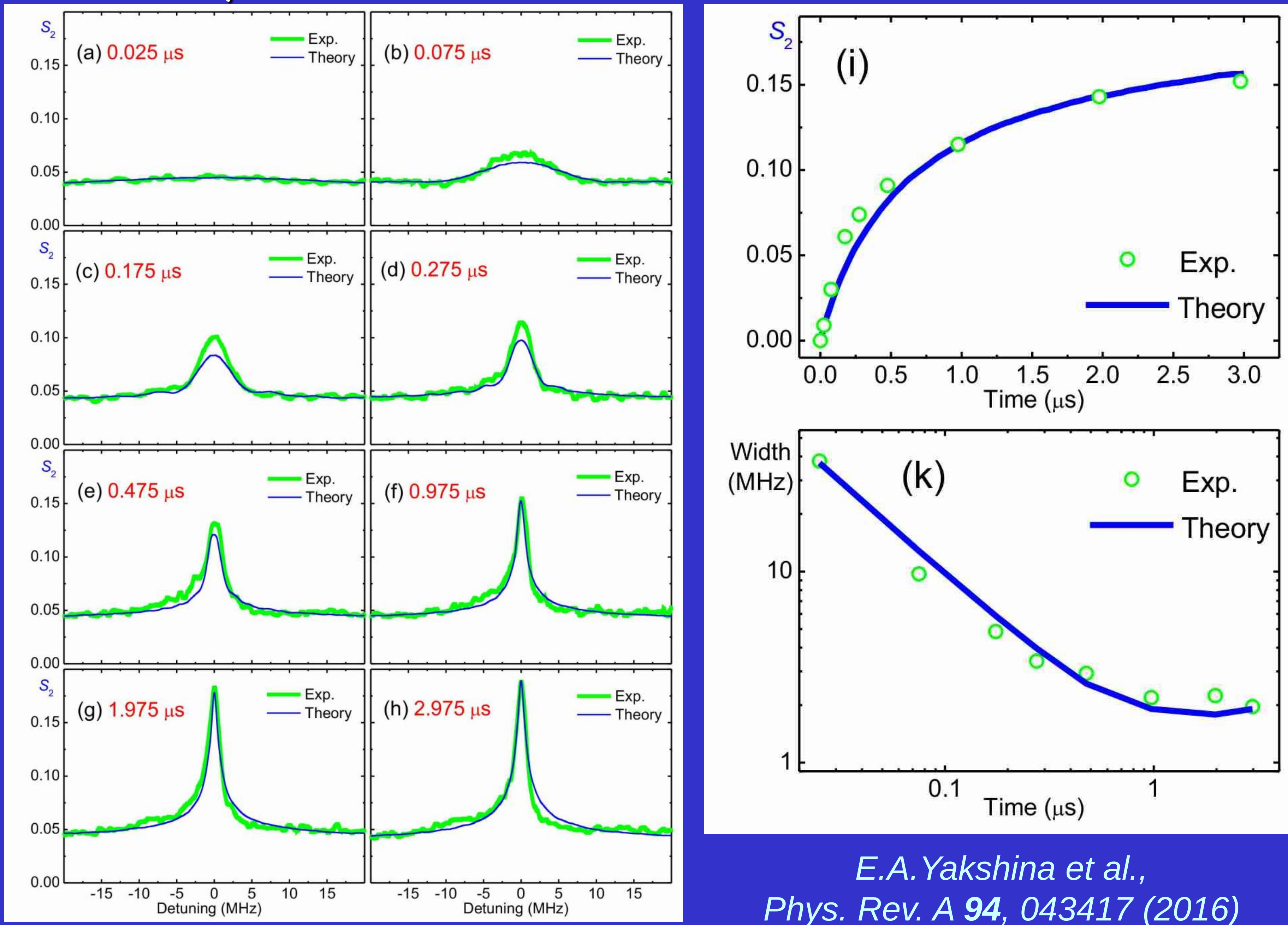




*E.A.Yakshina et al., Phys. Rev. A **94**, 043417 (2016)*

I.I.Ryabtsev et al., J. Phys.: Conf. Series, 793, 012024 (2017)

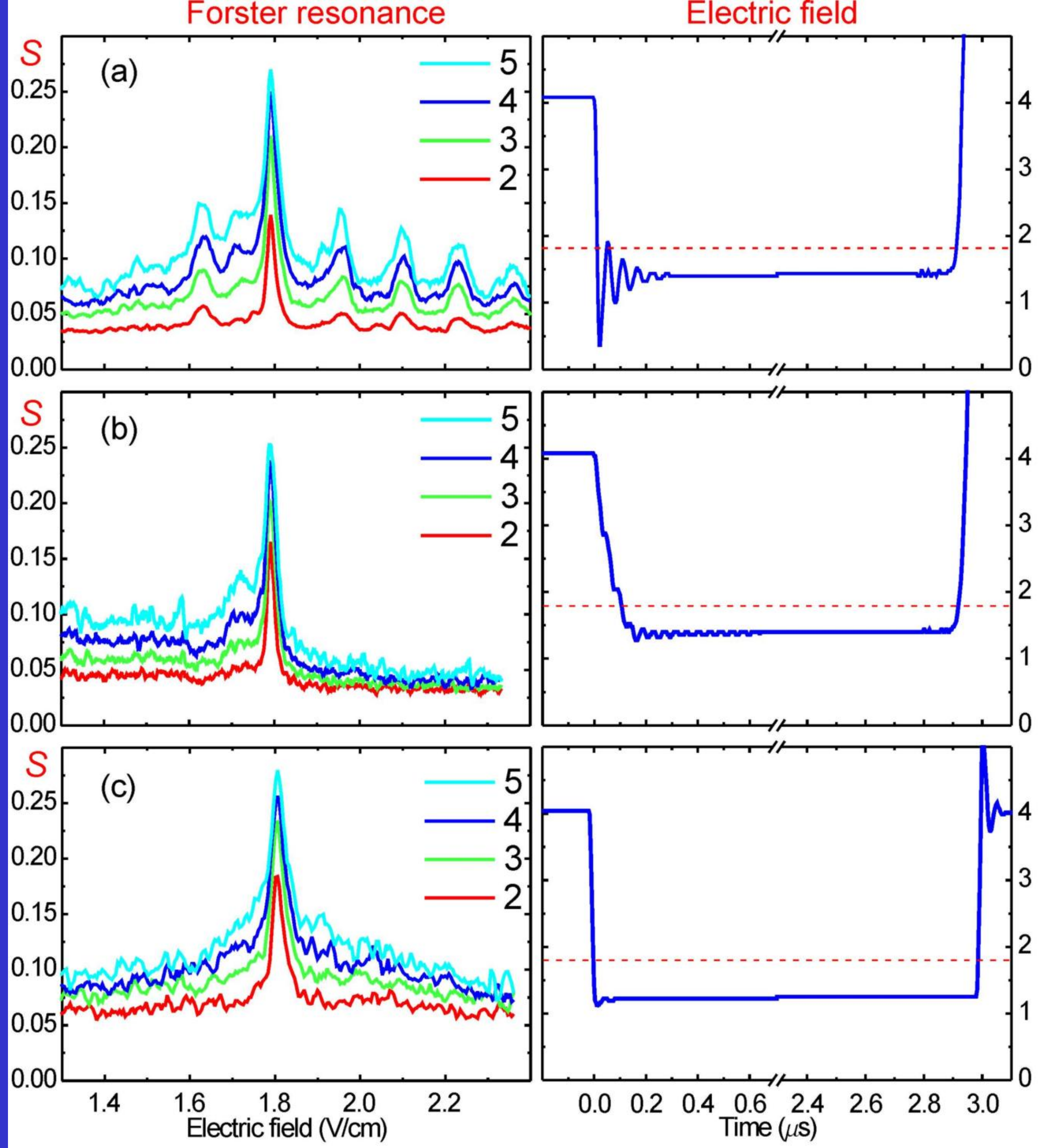
Two-body Förster resonance at various interaction times



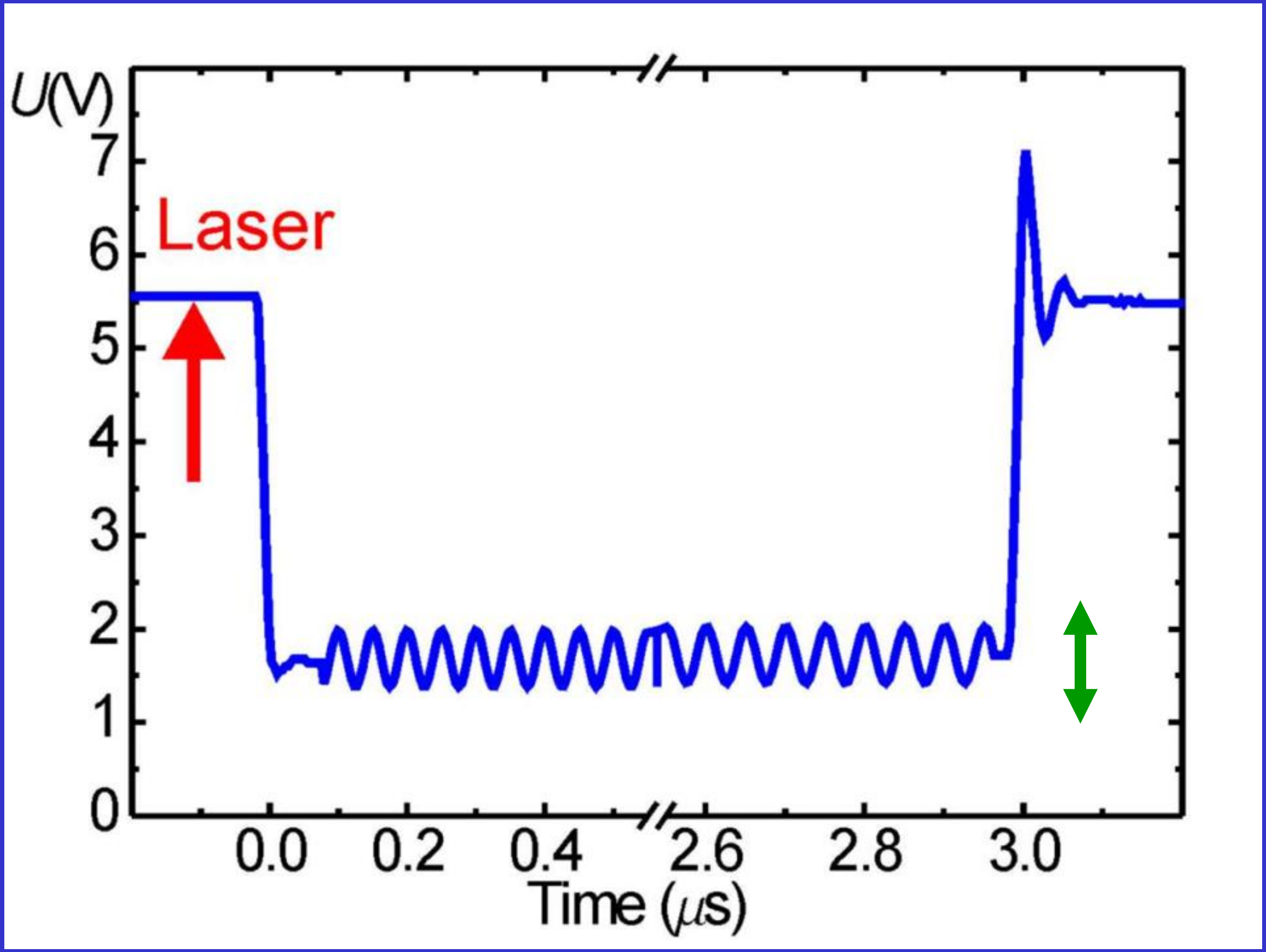
E.A.Yakshina et al.,
*Phys. Rev. A **94**, 043417 (2016)*

Two-body Förster resonance for various edges of the Stark switching

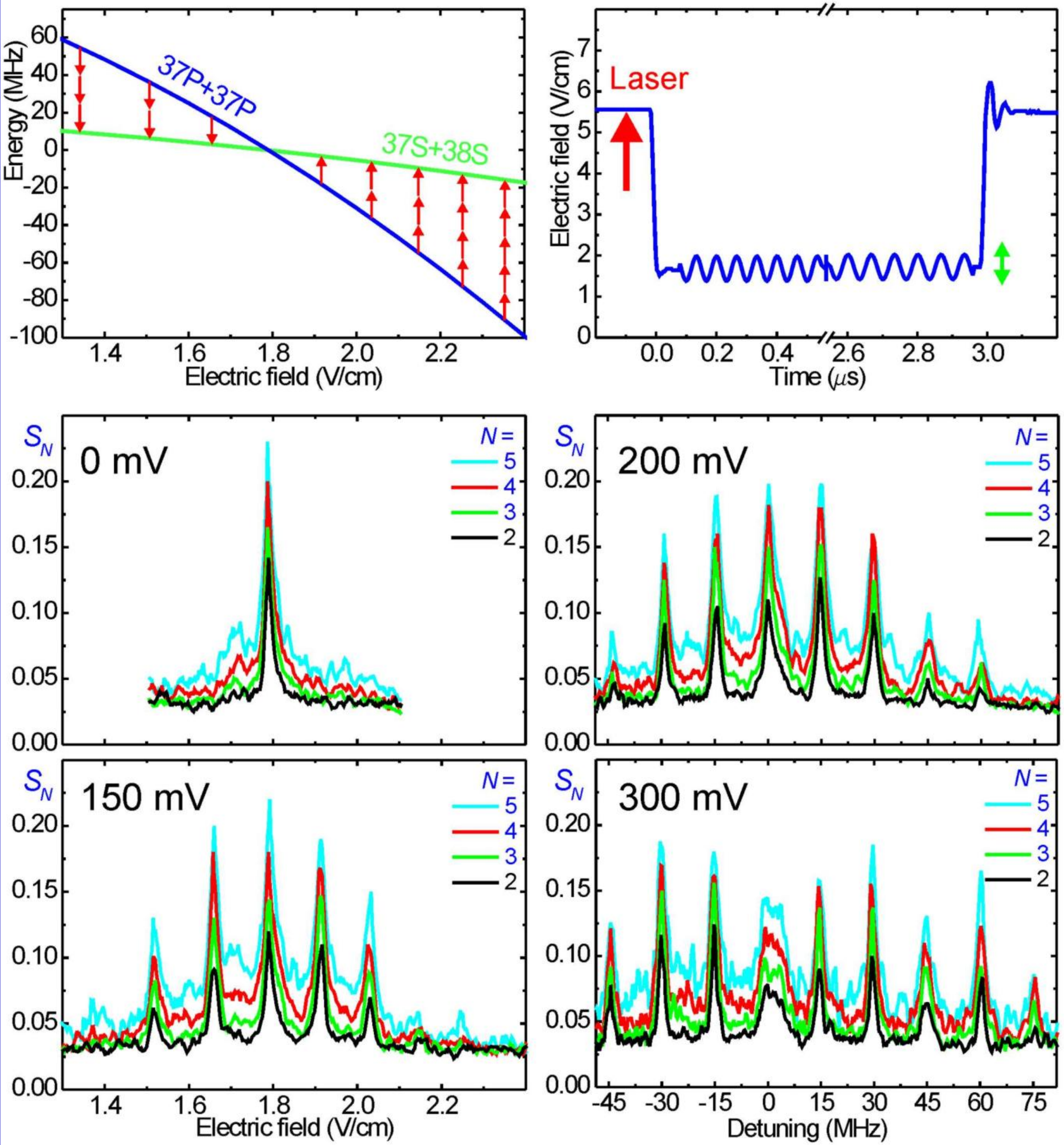
*E.A.Yakshina et al., Phys. Rev. A **94**, 043417 (2016)*



Electric pulse for rf-assisted Förster resonances



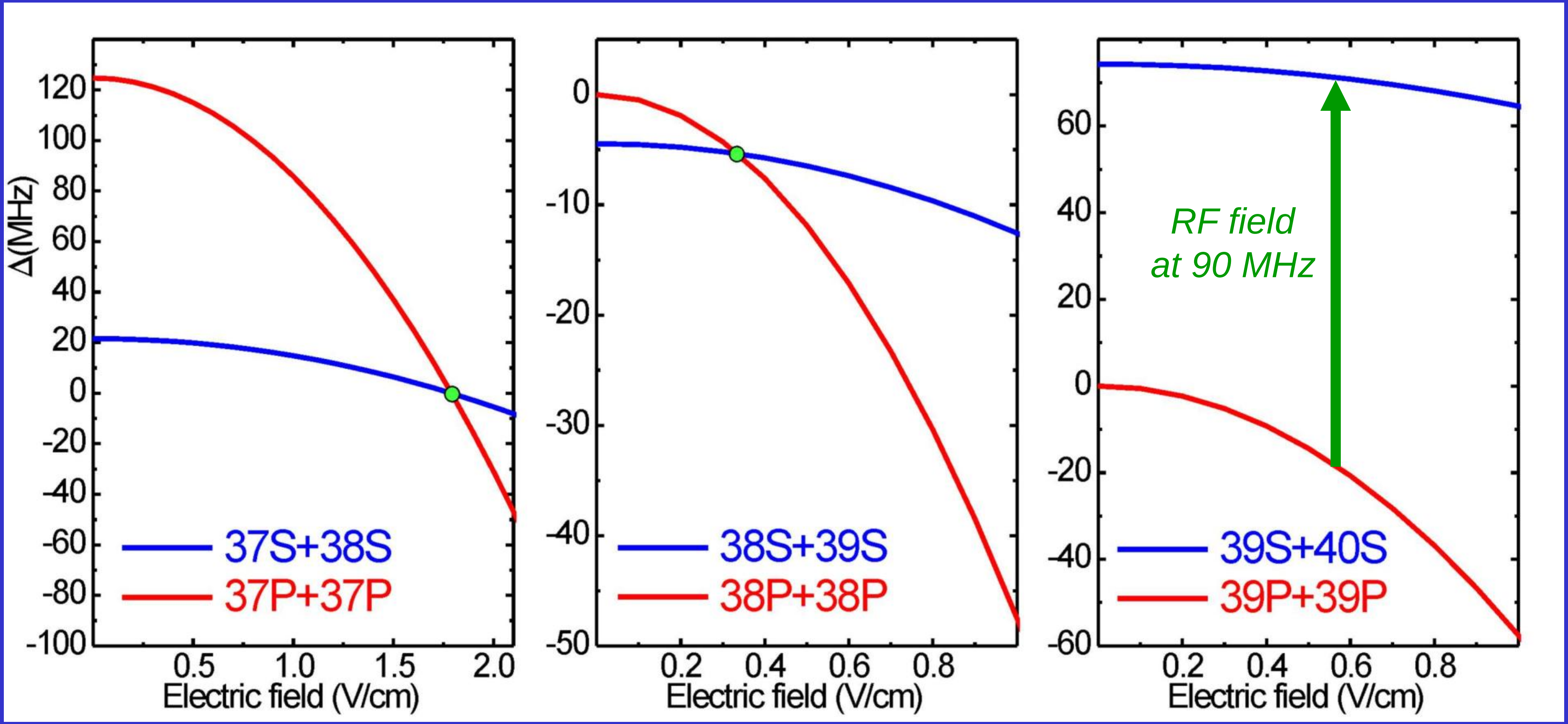
RF-assisted Förster resonances for 37P atoms at 15 MHz



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

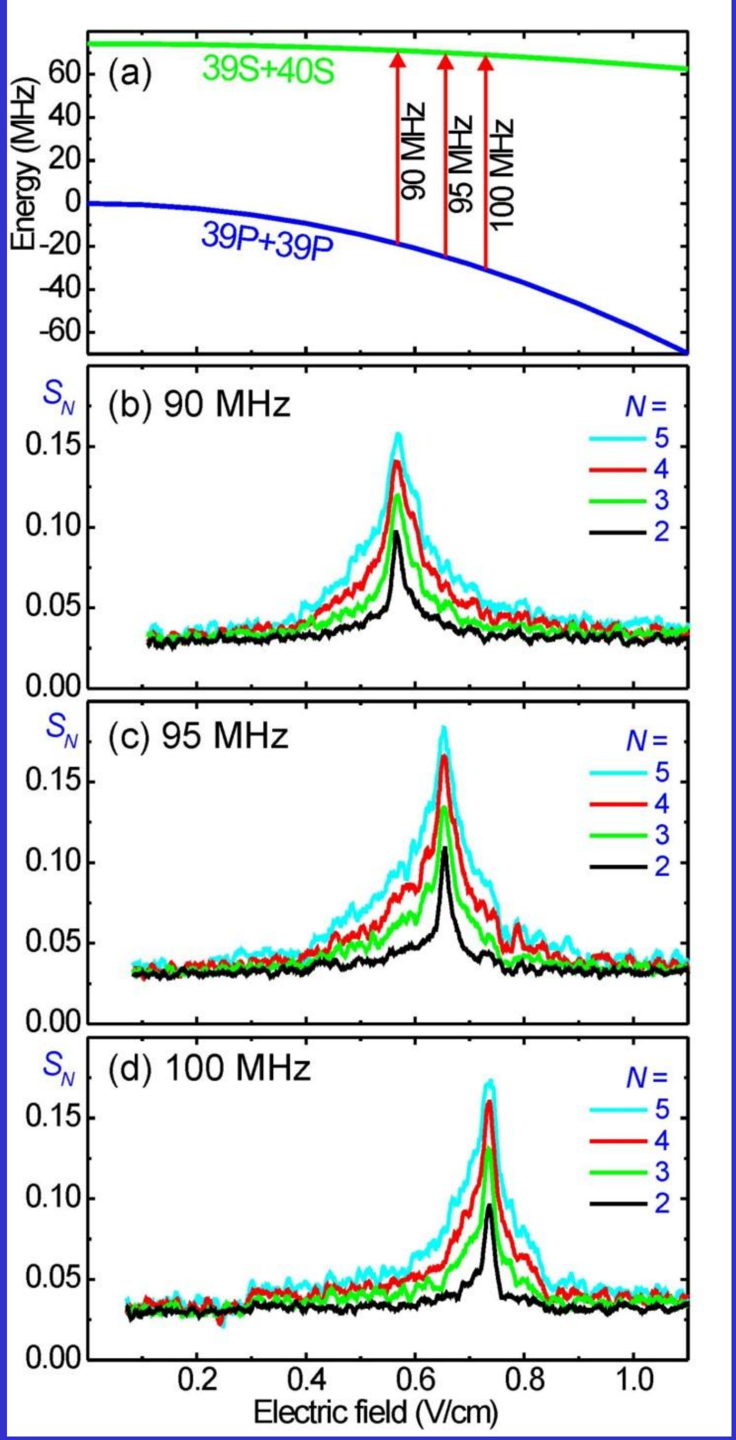
Two-body Förster resonances

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



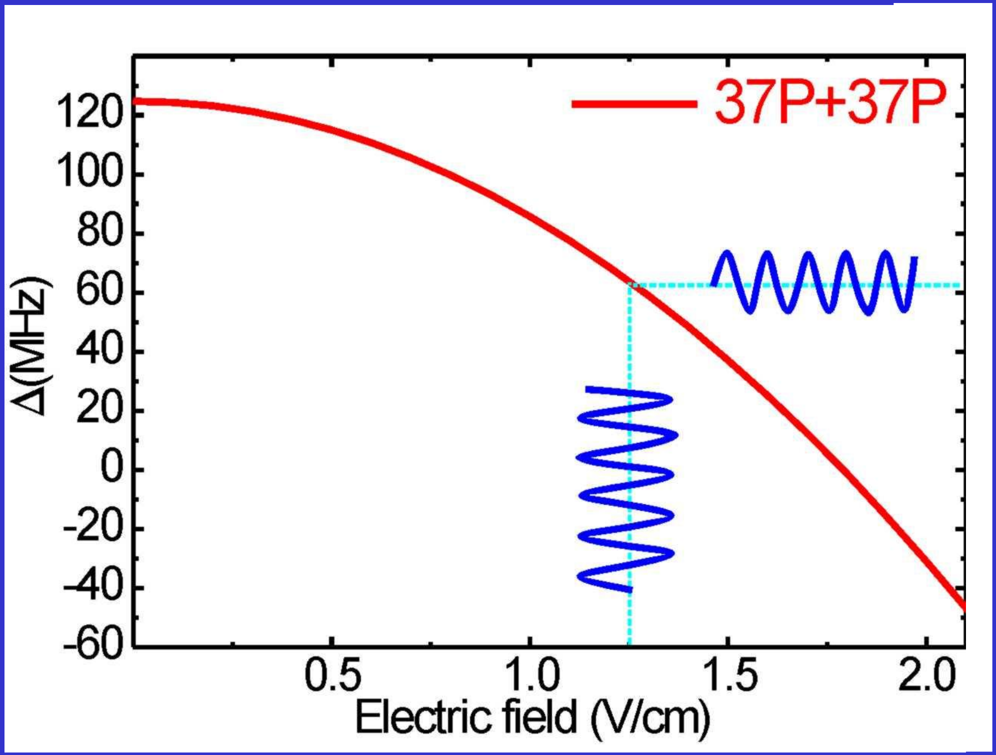
*D.B.Tretyakov et al., Phys. Rev. A **90**, 041403(R) (2014)*

RF-assisted Förster resonances for 39P atoms



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

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

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

Wave function of Rydberg state

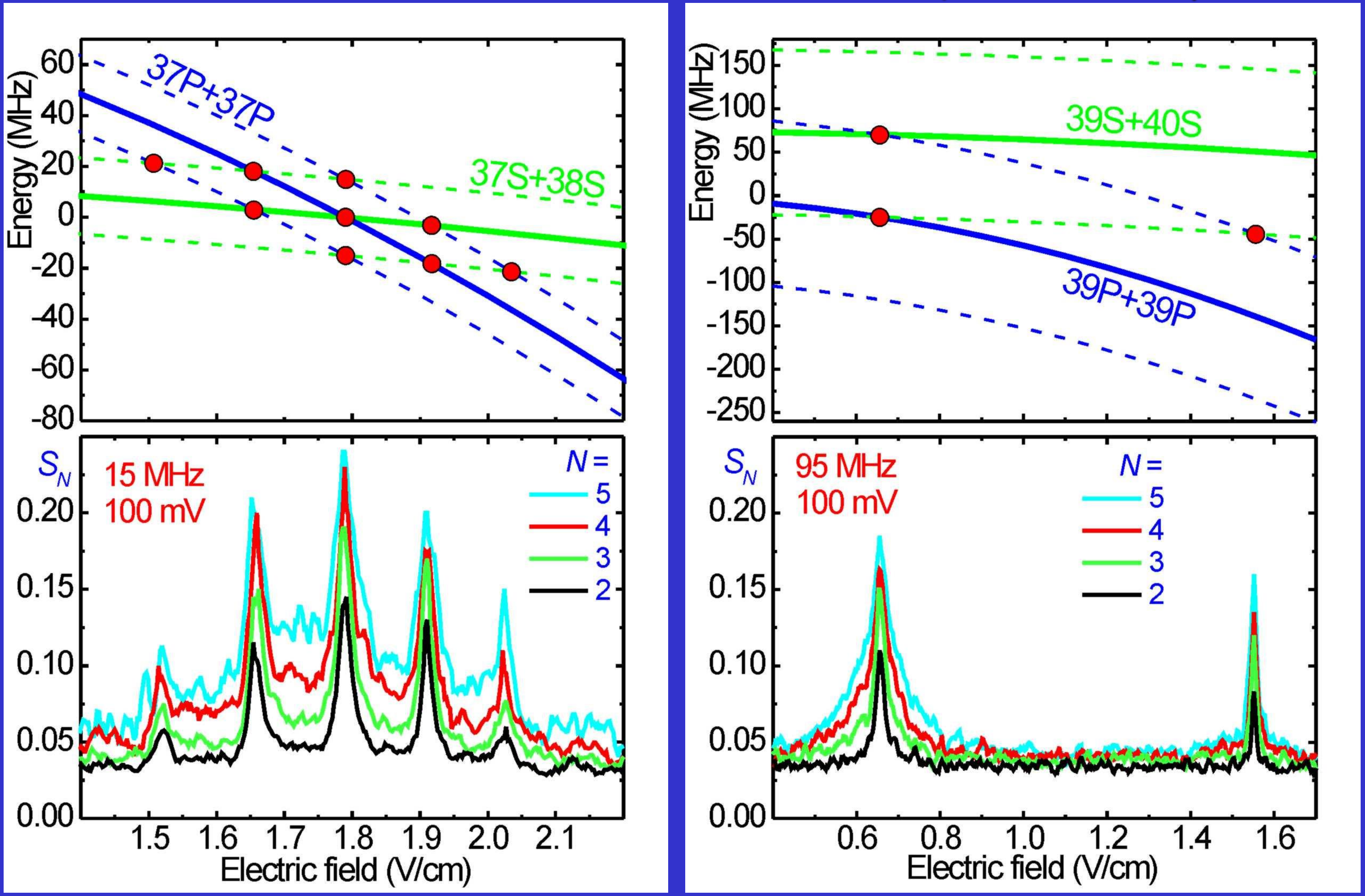
$$\Psi_{nL}(r,t) = \psi_{nL}(r)e^{i\alpha(F_{dc}^2 + F_{rf}^2/2)t/2}\sum_{m=-\infty}^{\infty} a_{nL,m}e^{im\omega t}$$

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)

Experiment and theory for two Rb(37P) atoms at 15 MHz

$$\Delta(t) = \Delta_0 + (\alpha_{nP} - \frac{1}{2}\alpha_{nS} - \frac{1}{2}\alpha_{[n+1]S}) \times \left[F_{dc} + F_{rf}\cos(\omega t)\right]^2$$

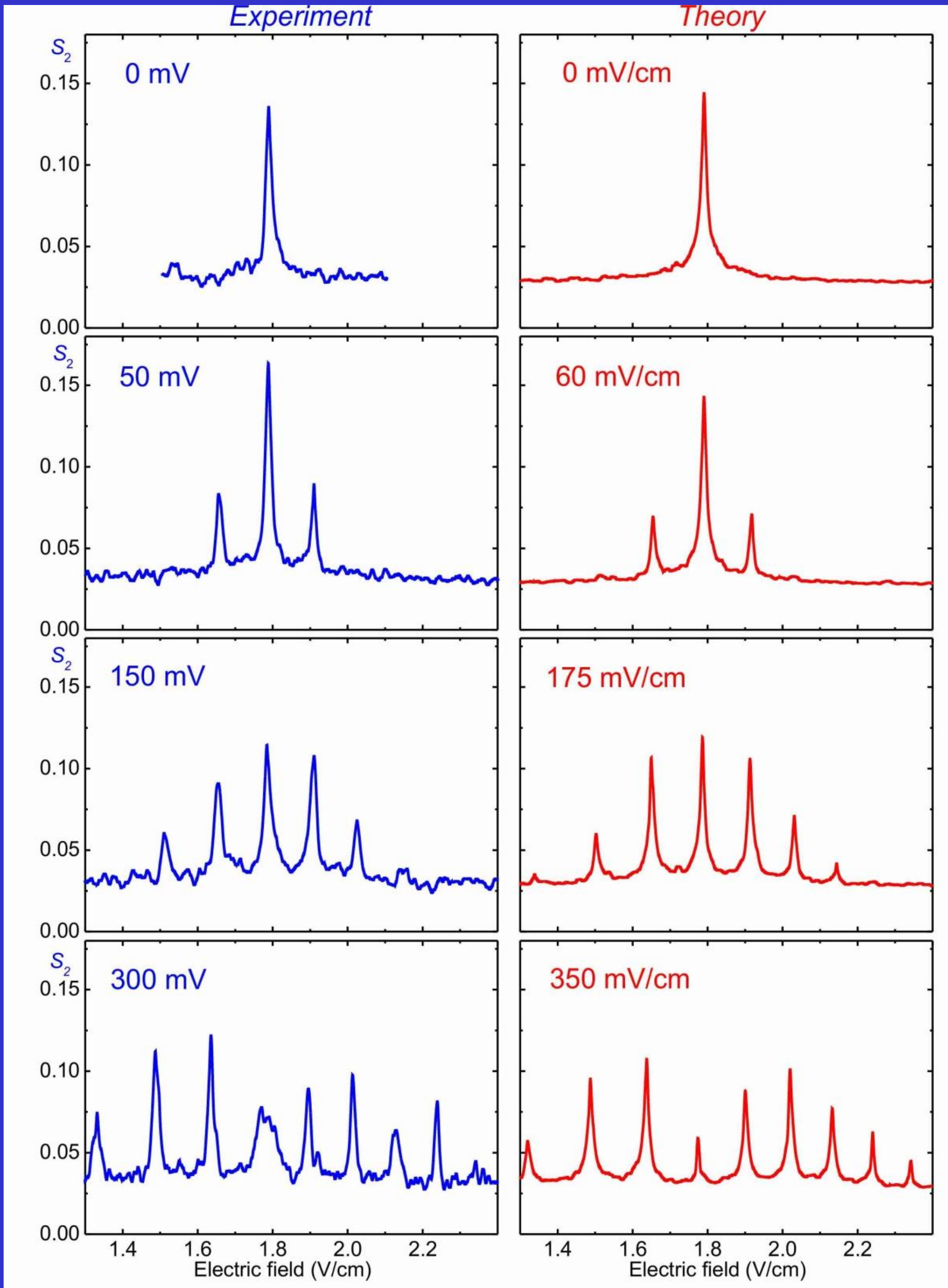
<u>*Theory*</u>

$\Gamma/(2\pi) = 0.5$ MHz

Cubic volume

$30\times30\times30\ \mu m^3$

E.A.Yakshina et al., Phys. Rev. A ***94****, 043417 (2016)*



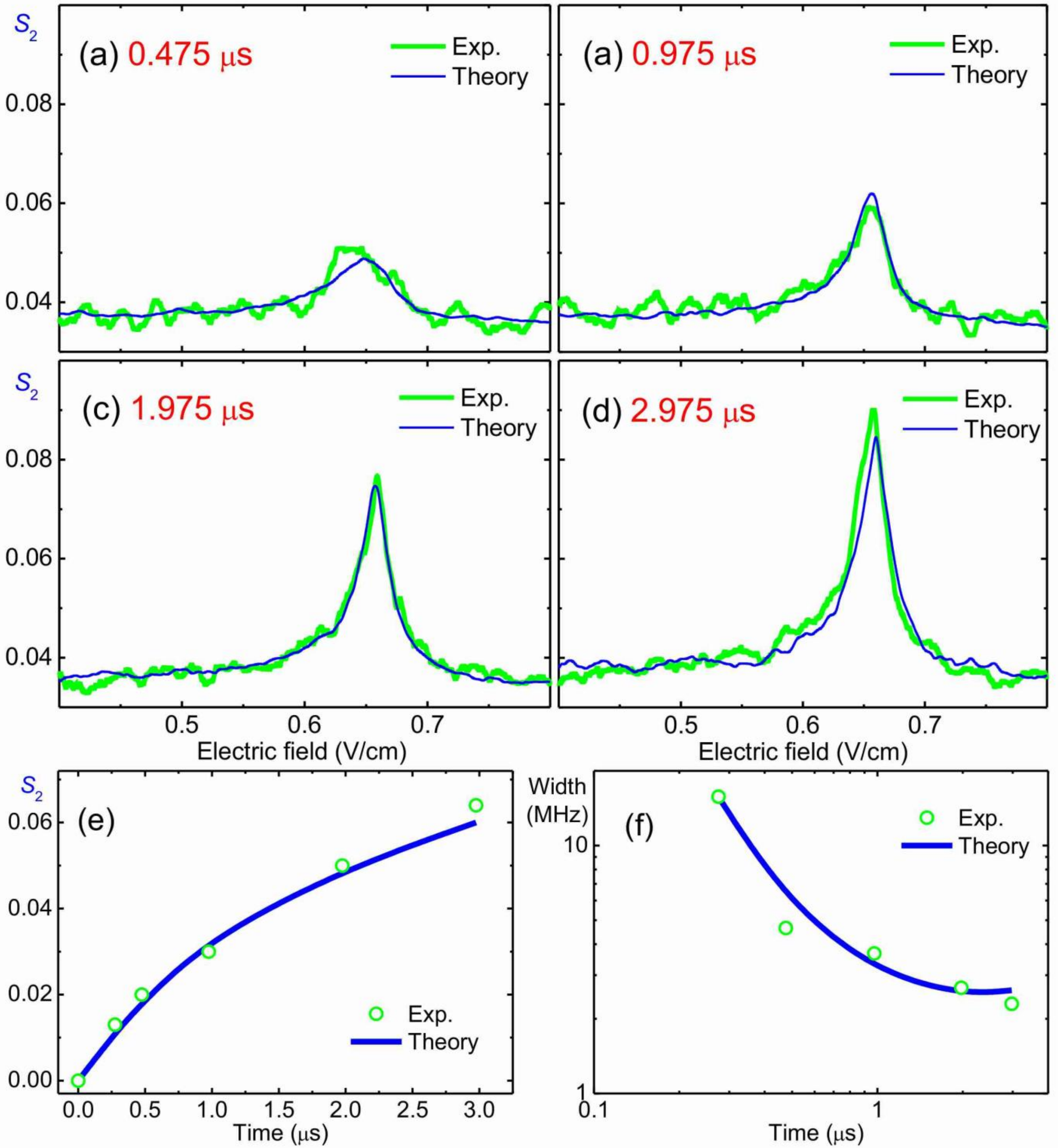
Experiment and theory for two Rb(39P) atoms at 95 MHz

<u>*Theory*</u>

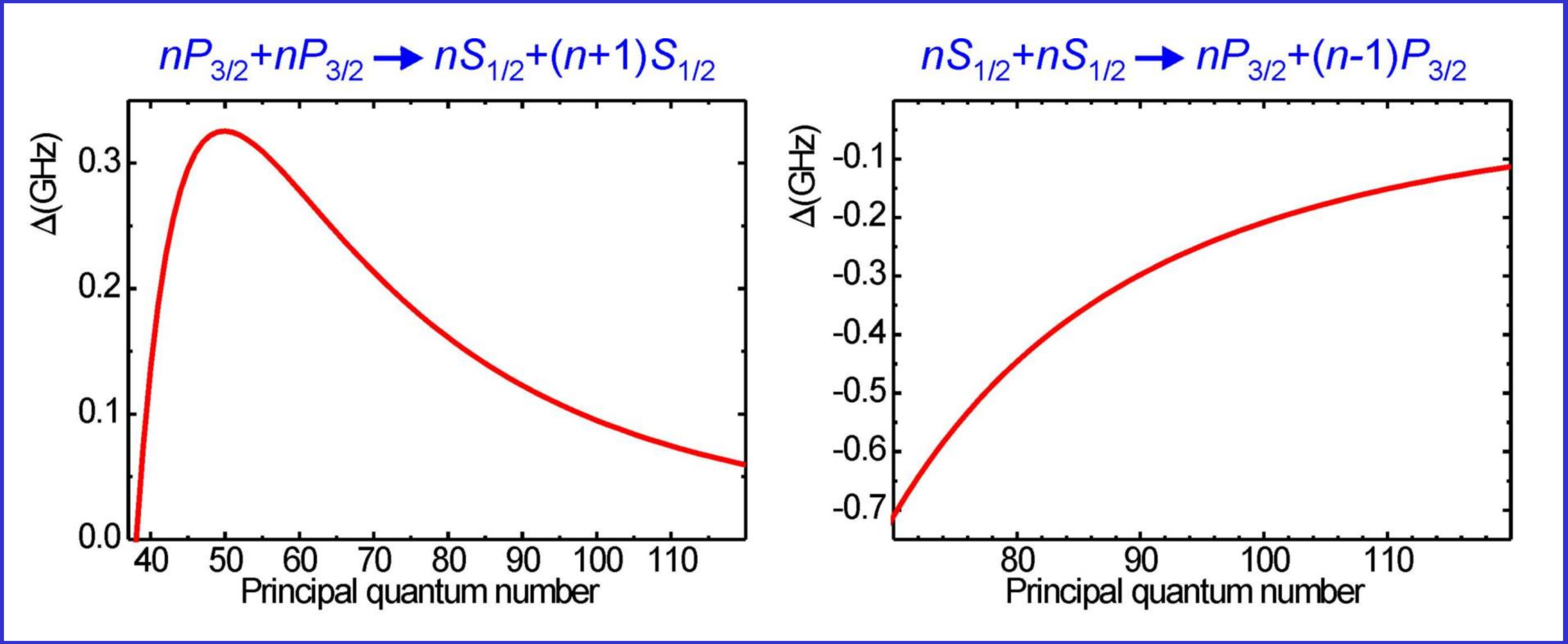
$\Gamma/(2\pi) = 1$ MHz

Cubic volume
$16\times16\times16\ \mu m^3$

*E.A.Yakshina et al., Phys. Rev. A **94**, 043417 (2016)*

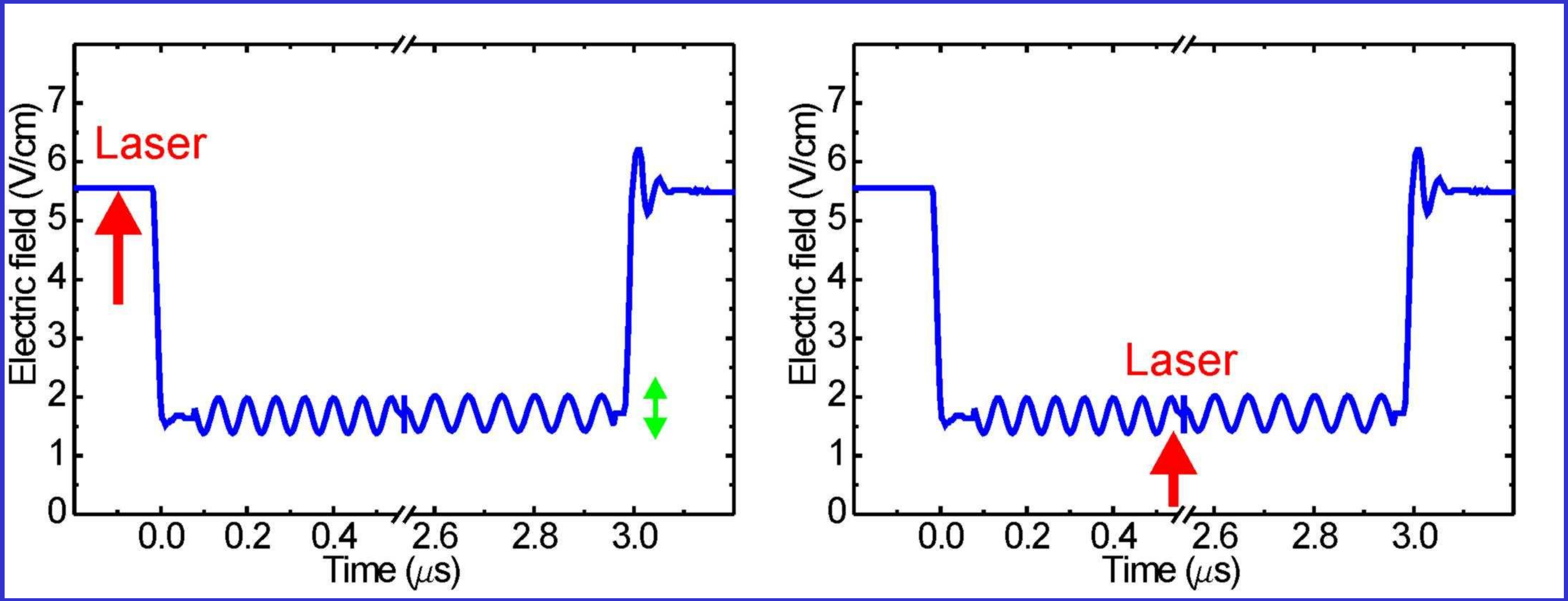


Energy defects of Förster resonances in Rb atoms

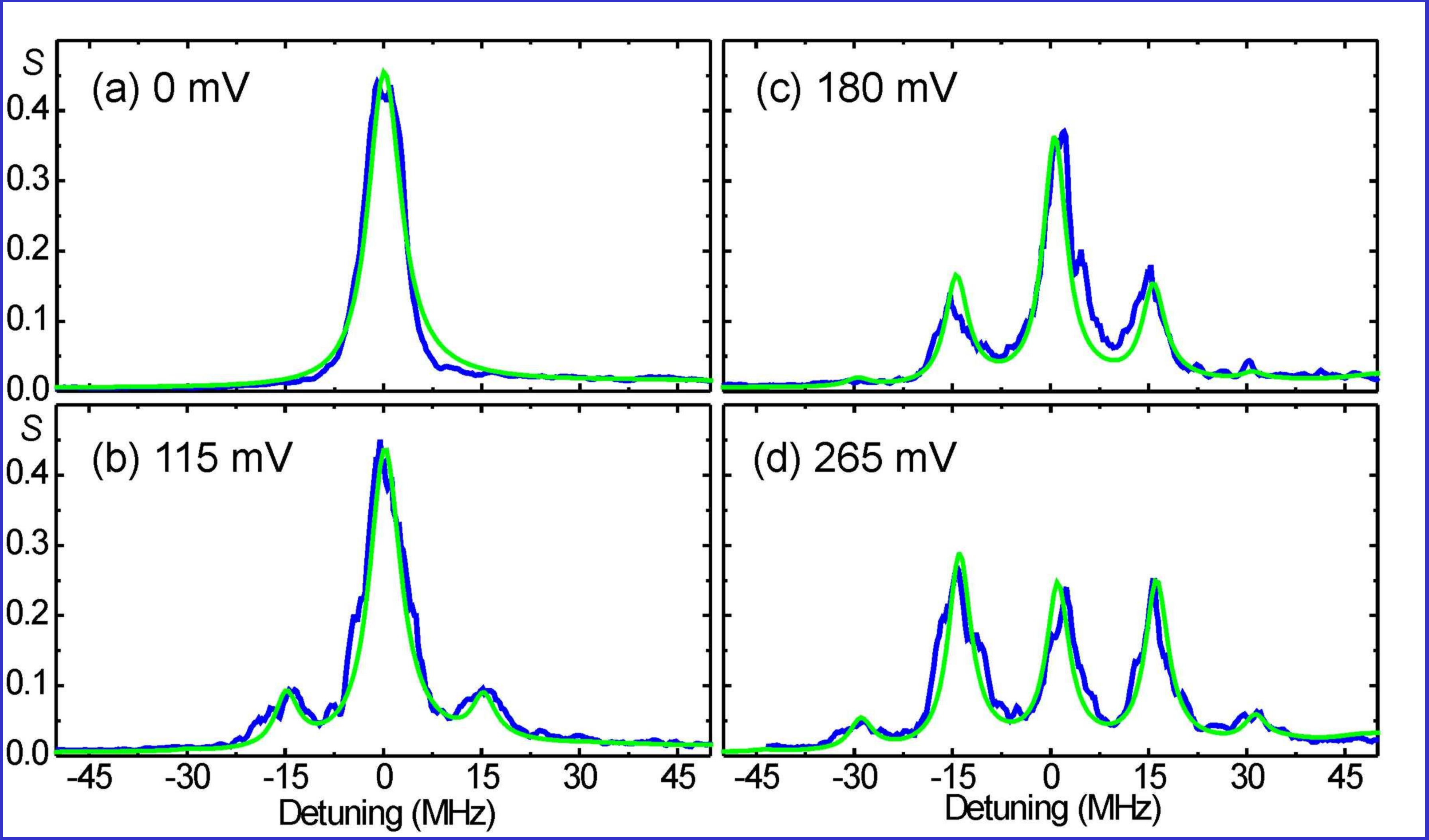


Interaction of any Rydberg atoms with large principal quantum number can be converted from van der Waals to resonant dipole-dipole using radio-frequency assisted Förster resonances with $\omega < 1$ GHz !

How to observe Floquet sidebands at laser excitation



Floquet sidebands at 15 MHz rf-modulation of the 37*P* state



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

PHYSICAL REVIEW A **94**, 062307 (2016)

Two-qubit gates using adiabatic passage of the Stark-tuned Förster resonances in Rydberg atoms

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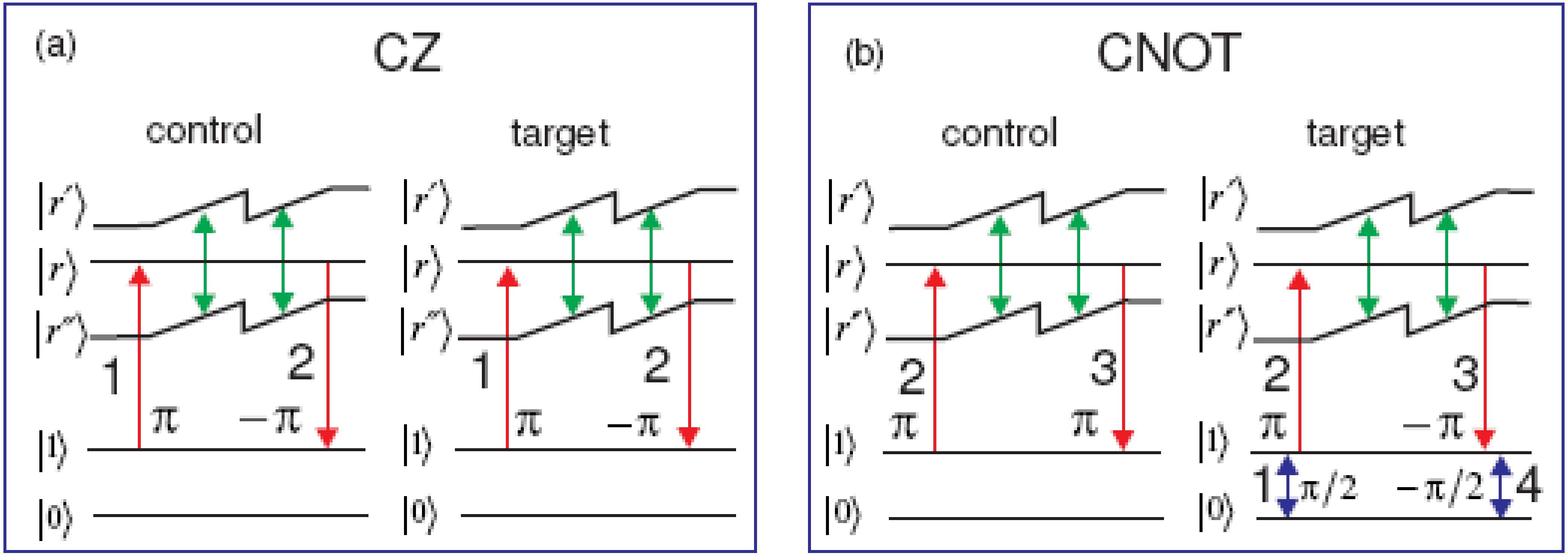

*I.I.Beterov et al., Phys. Rev. A **94**, 062307 (2016)*
*I.I.Beterov et al., Quantum Electronics **47**, 455 (2017)*

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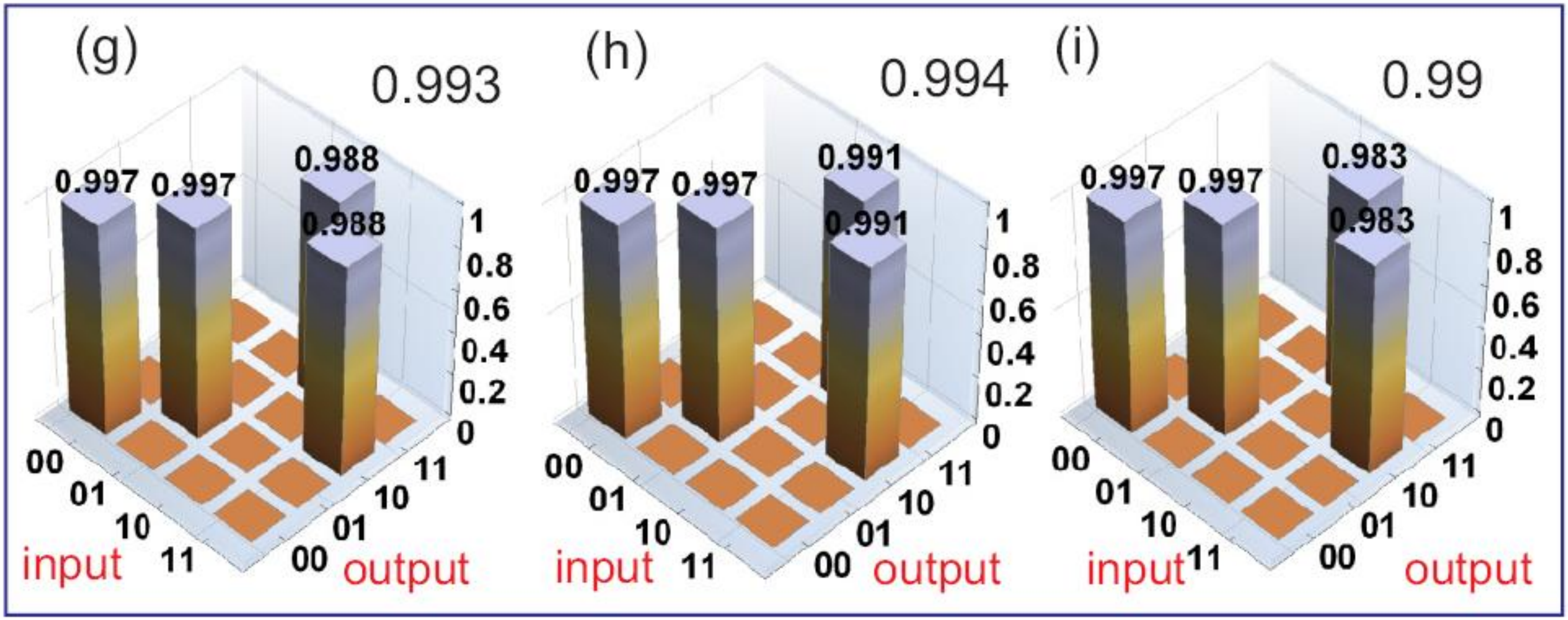

(g), (h), (i) Calculated truth tables of a CNOT gate for $R = 24, 25$, and $26\ \mu$m, respectively. The overlap with the ideal truth table is shown above each plot.

Adiabatic passage of radiofrequency-assisted Förster resonances in Rydberg atoms for two-qubit gates and generation of Bell states

I. I. Beterov,[1,2,3,*] G. N. Hamzina,[1,3] E. A. Yakshina,[1,2] D. B. Tretyakov,[1,2] V. M. Entin,[1,2] and I. I. Ryabtsev[1,2]

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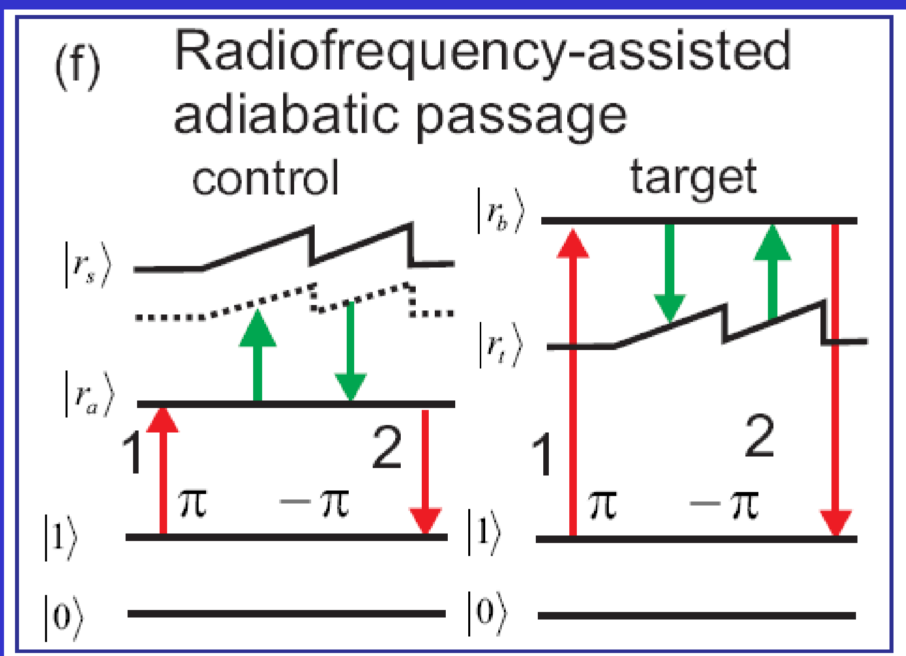

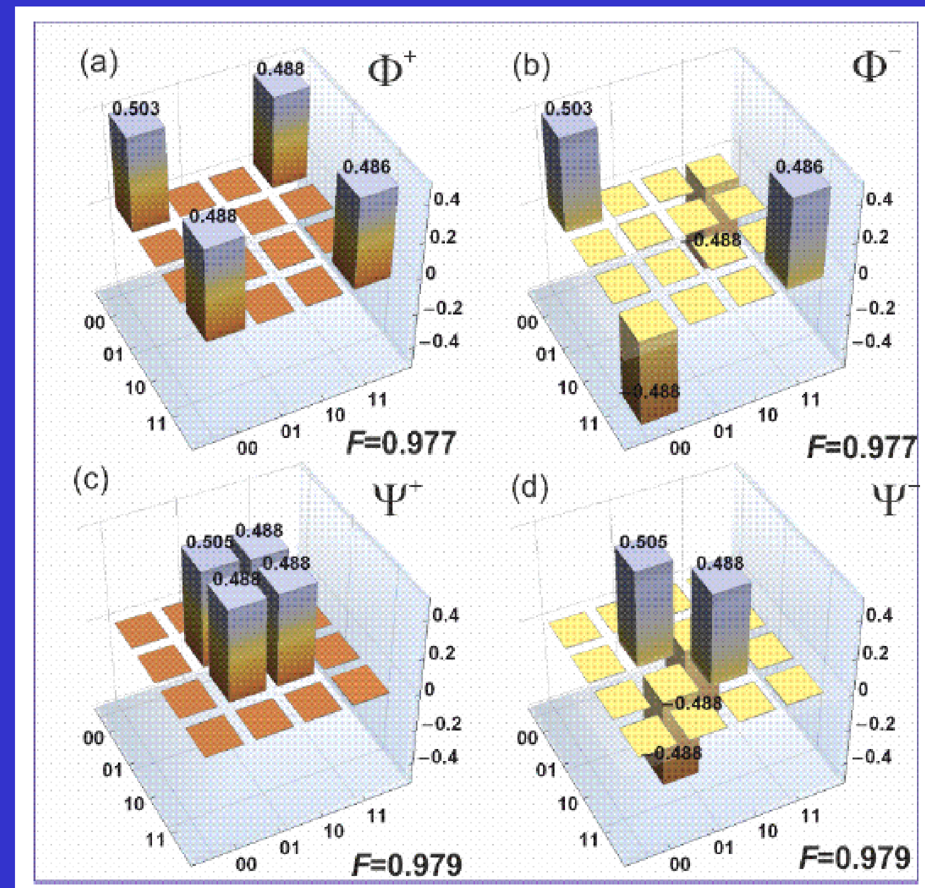

I.I.Beterov et al., arXiv:1710.04384v1

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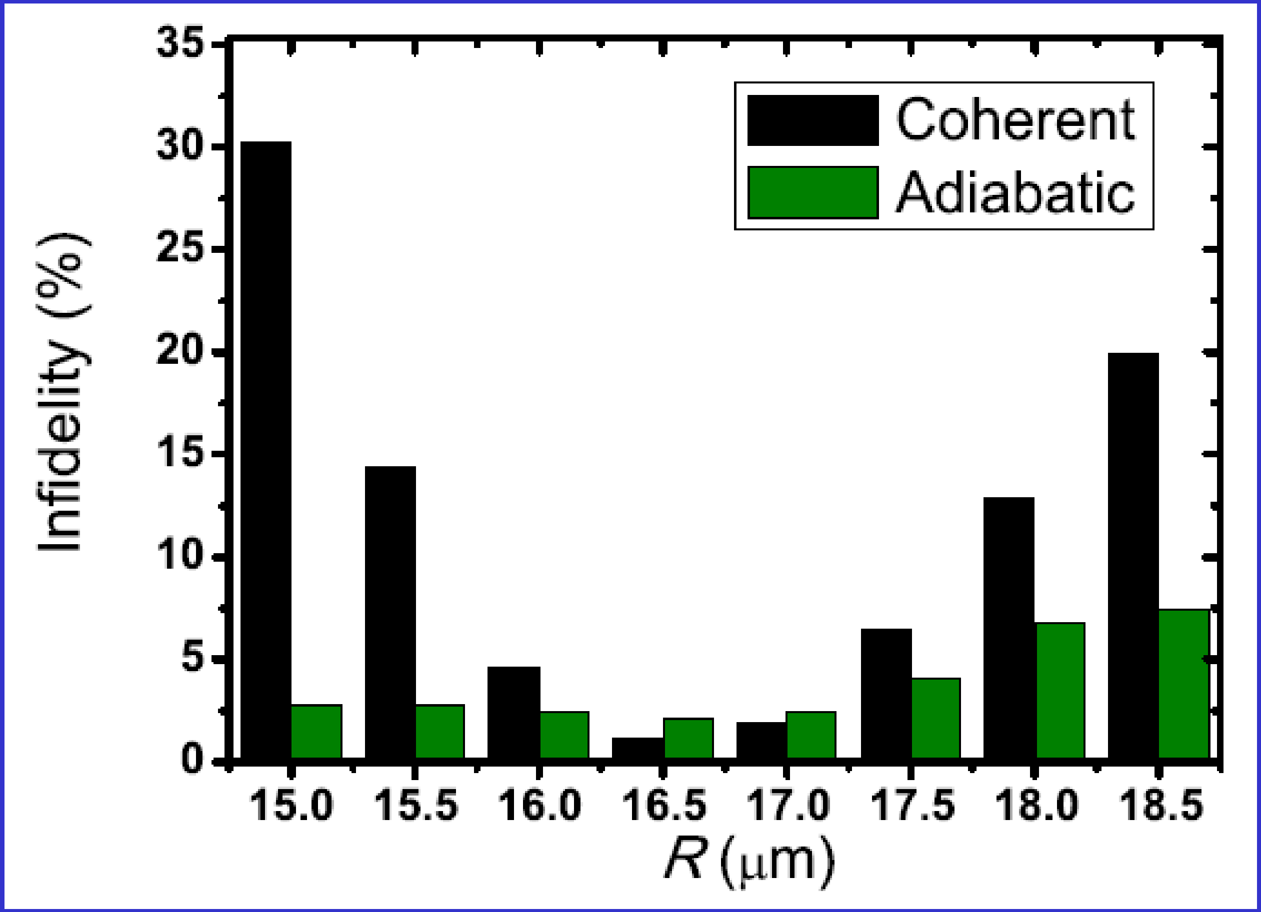
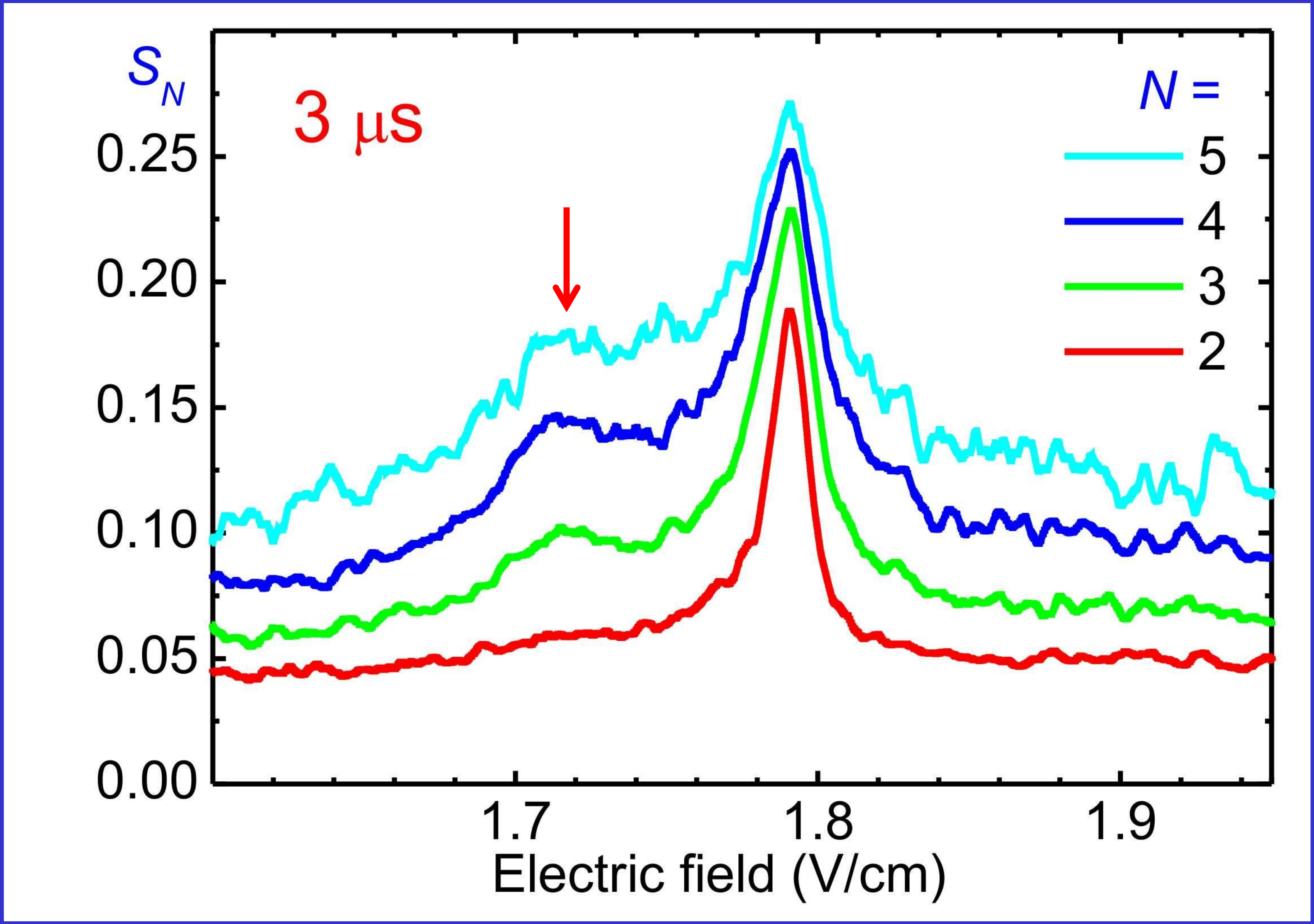


I.I.Beterov et al., arXiv:1710.04384v1

Three-body Förster resonance?



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ARTICLE

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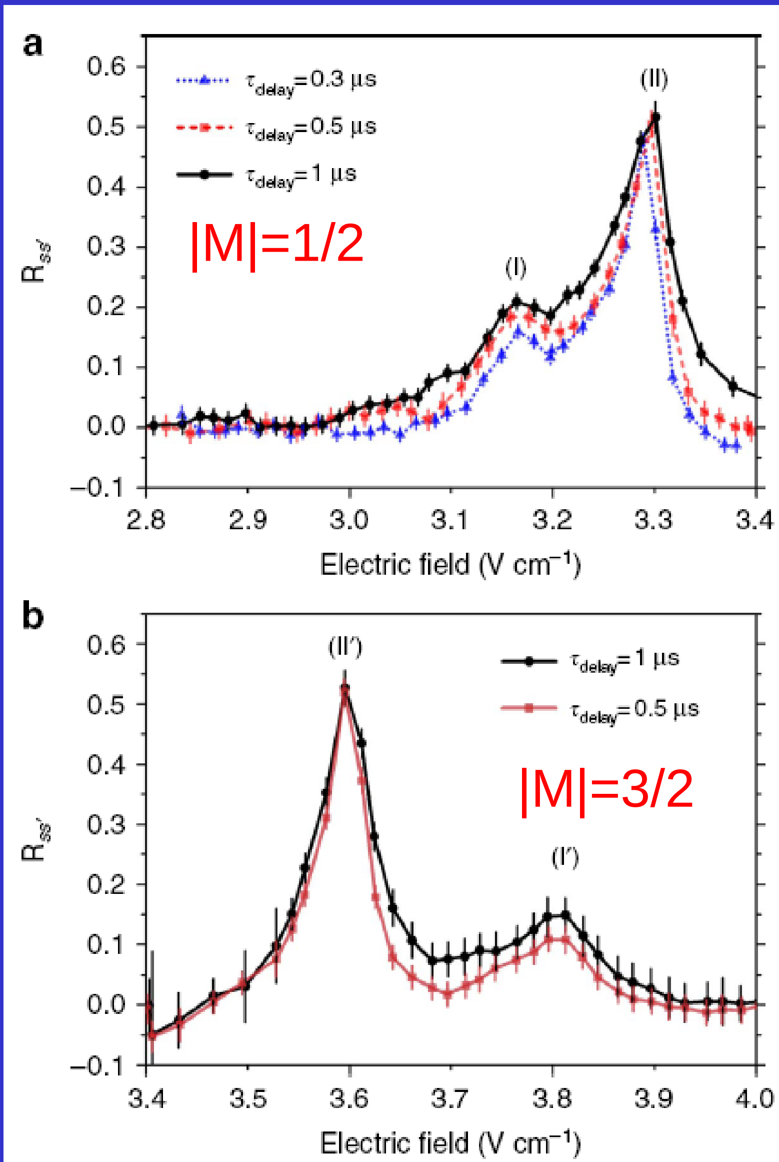
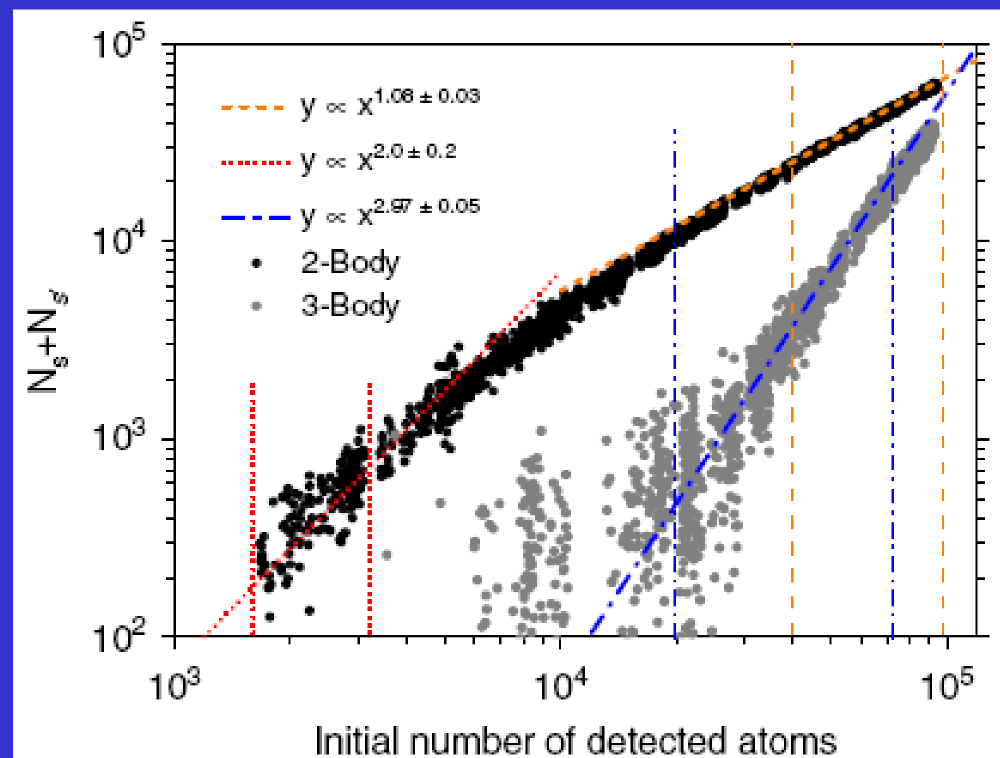
Borromean three-body FRET in frozen Rydberg gases

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



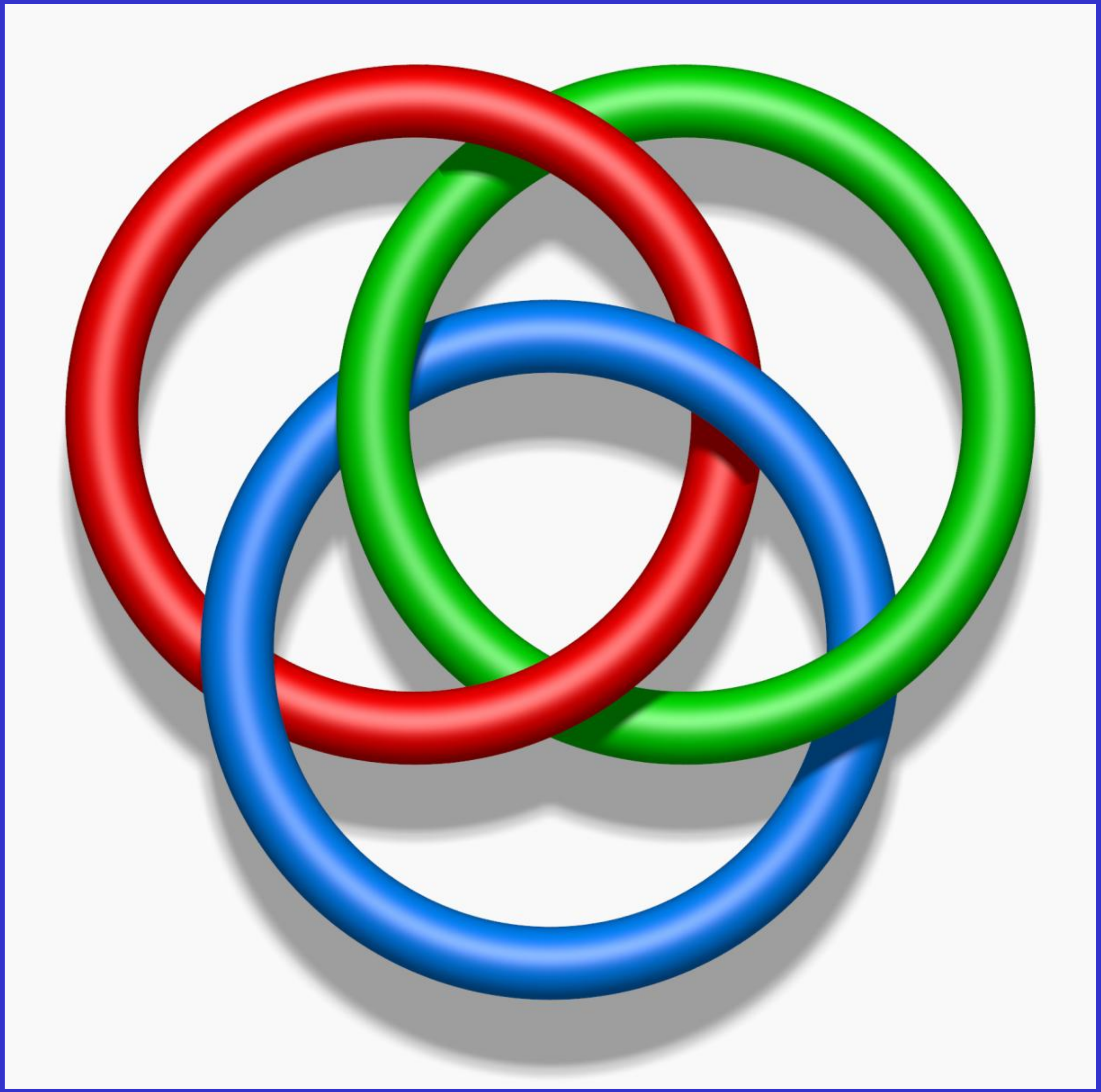
~10^5 Cs($35P_{3/2}$) atoms in the volume of ~200 µm in size



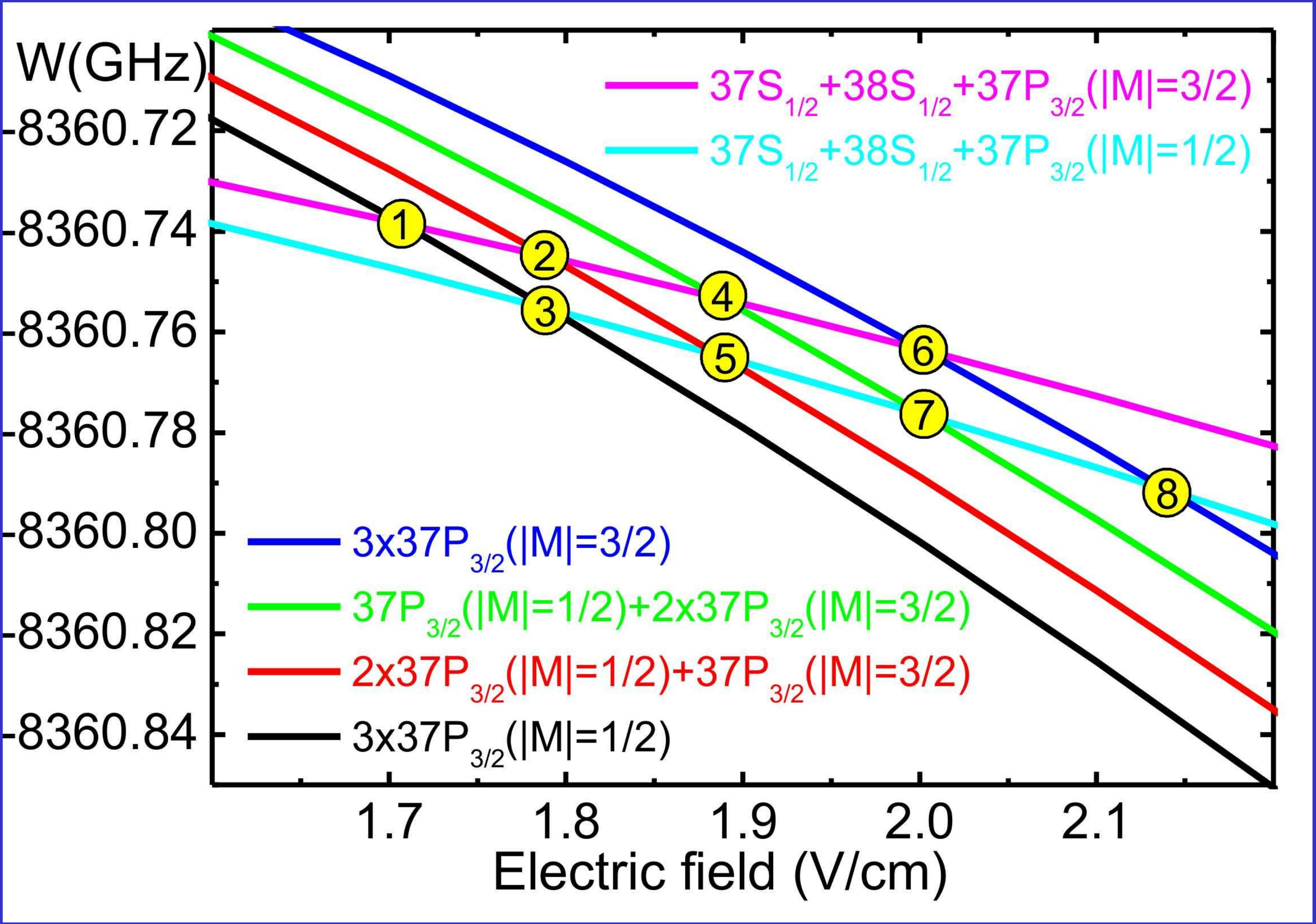
Borromean three-body interactions of Rydberg atoms

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.

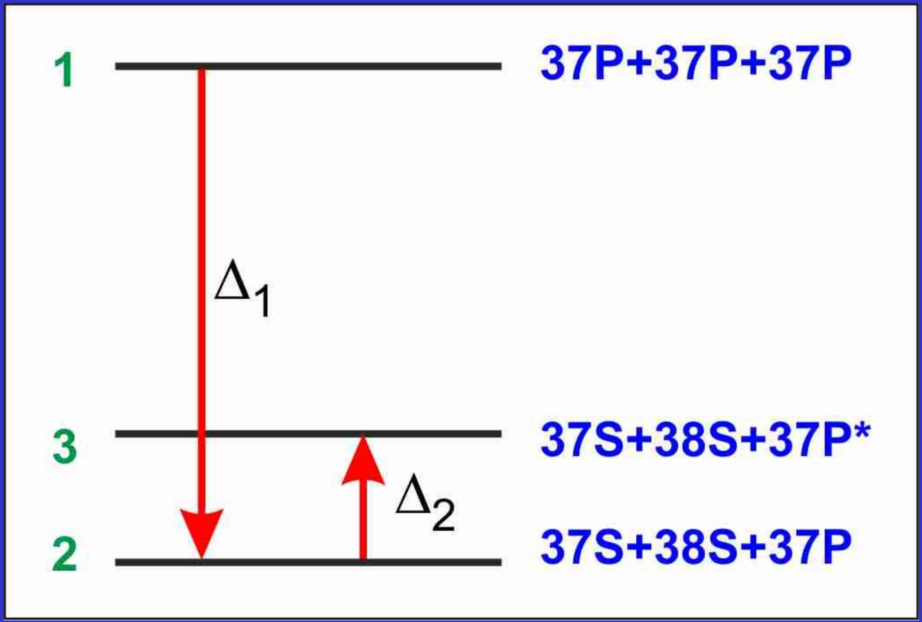


Three-body Förster resonances for Rb($37P_{3/2}$) atoms



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)*

Simple theoretical model with perturbation theory



$$i\dot{a}_1 = 6\Omega a_2 e^{-i\Delta_1 t}$$
$$i\dot{a}_2 = \Omega a_1 e^{i\Delta_1 t} + 2\Omega^* a_3 e^{i\Delta_2 t}$$
$$i\dot{a}_3 = 2\Omega^* a_2 e^{-i\Delta_2 t}$$

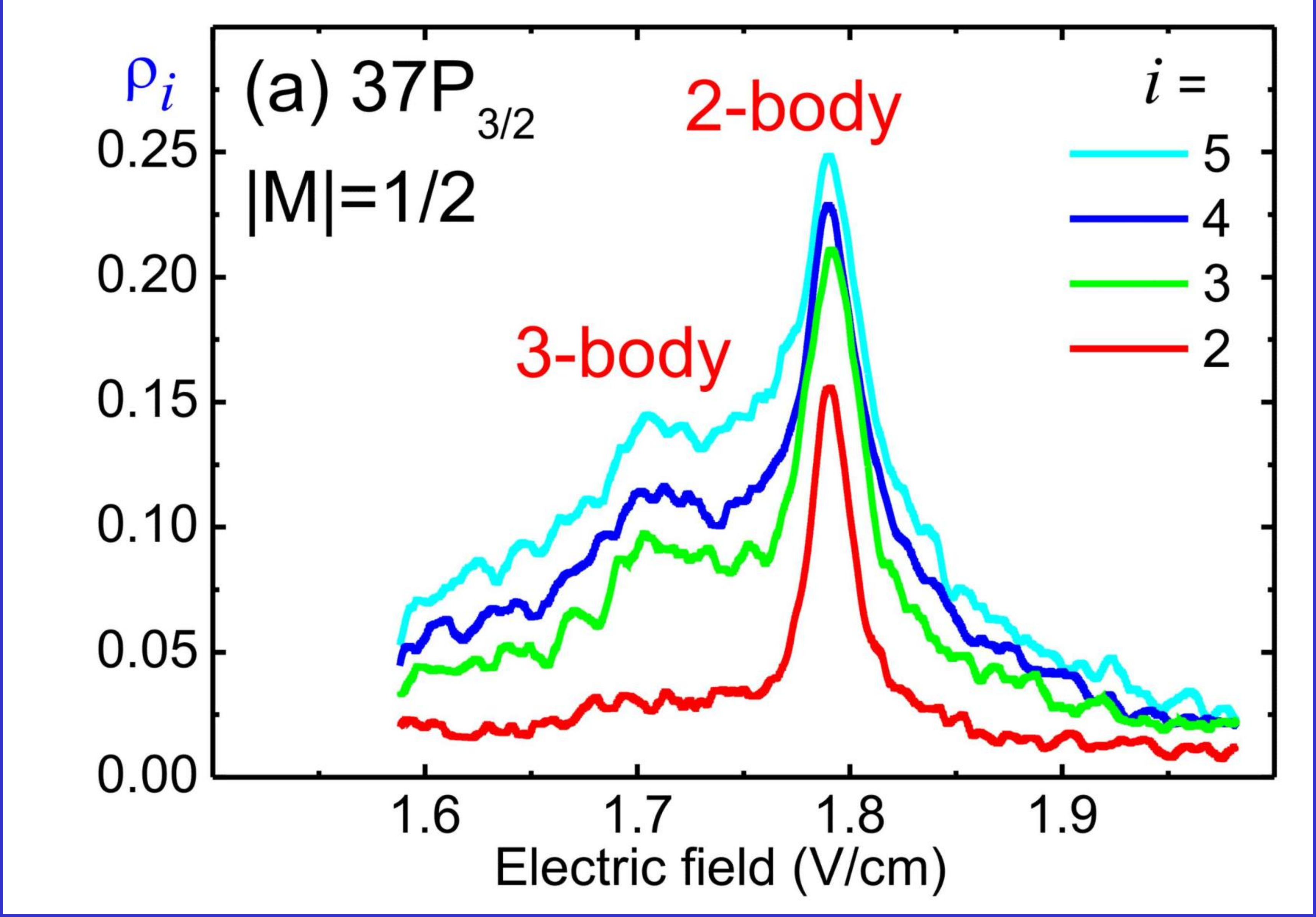
$$\rho_3 = (6|a_2|^2 + 6|a_3|^2)/3$$

Perturbation theory for weak DD interaction: $a_1 \approx 1$, $a_2, a_3 << 1$

$$\rho_3 \approx \frac{8\Omega^2}{\Delta_1^2}\sin^2\left[\frac{\Delta_1 t}{2}\right] + 32\Omega^2\Omega^{*2} \times \left\{ \frac{1}{\Delta_1\Delta_2(\Delta_1-\Delta_2)^2}\sin^2\left[\frac{(\Delta_1-\Delta_2)t}{2}\right] + \frac{1}{\Delta_1\Delta_2^2(\Delta_1-\Delta_2)}\sin^2\left[\frac{\Delta_2 t}{2}\right] - \frac{1}{\Delta_1^2\Delta_2(\Delta_1-\Delta_2)}\sin^2\left[\frac{\Delta_1 t}{2}\right] \right\}$$

*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)*

Observation of three-body Förster resonances in Rb



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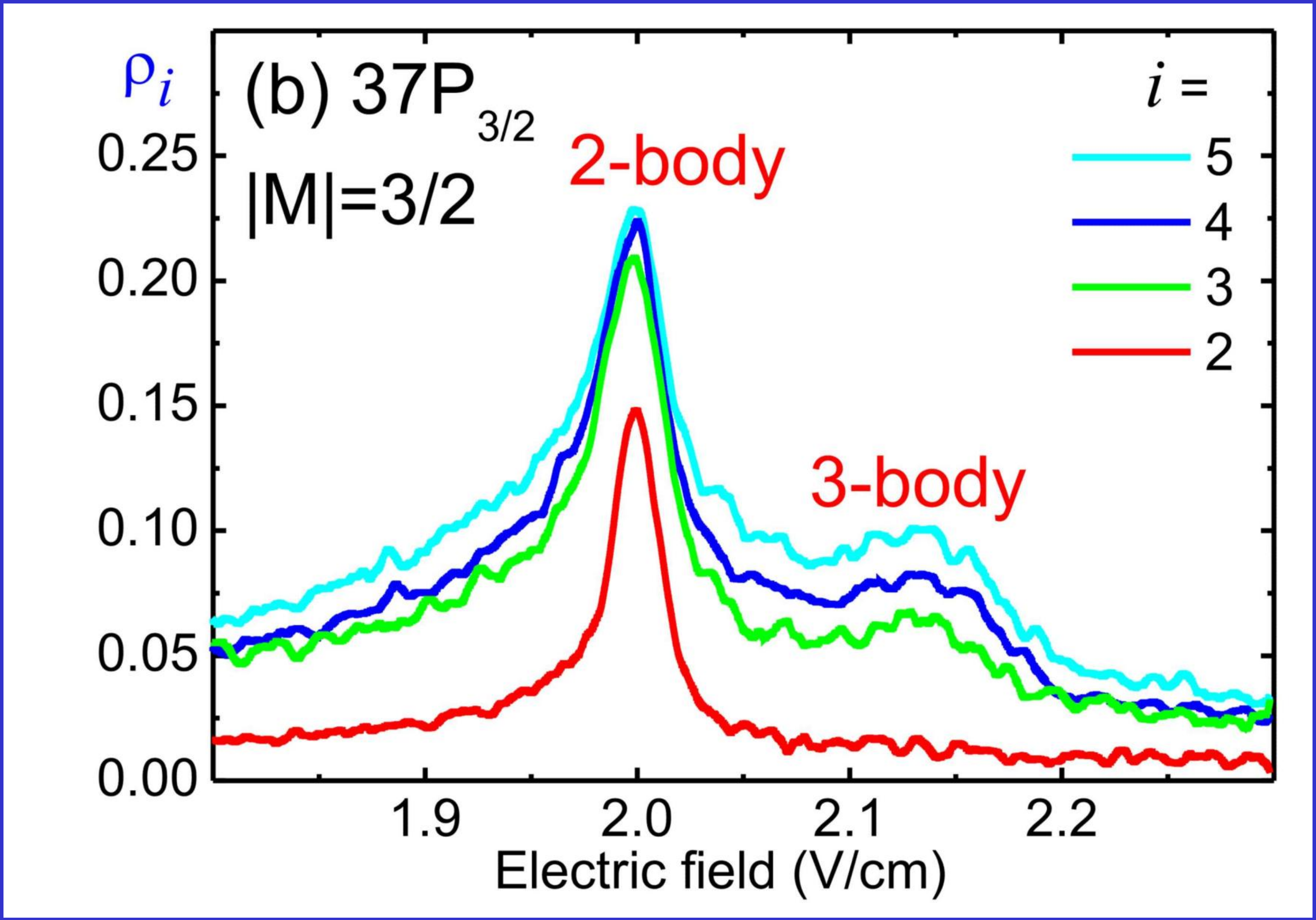

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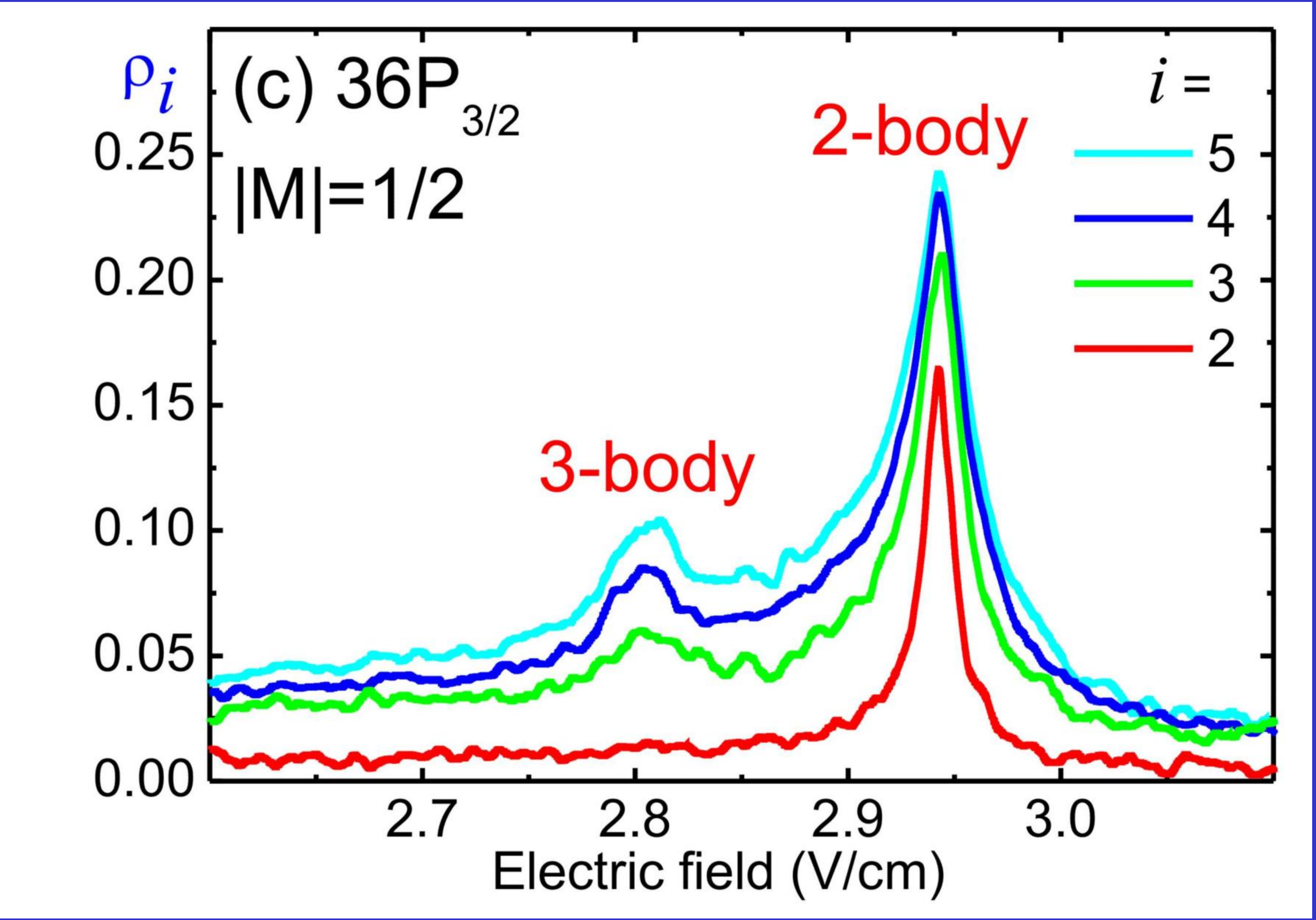

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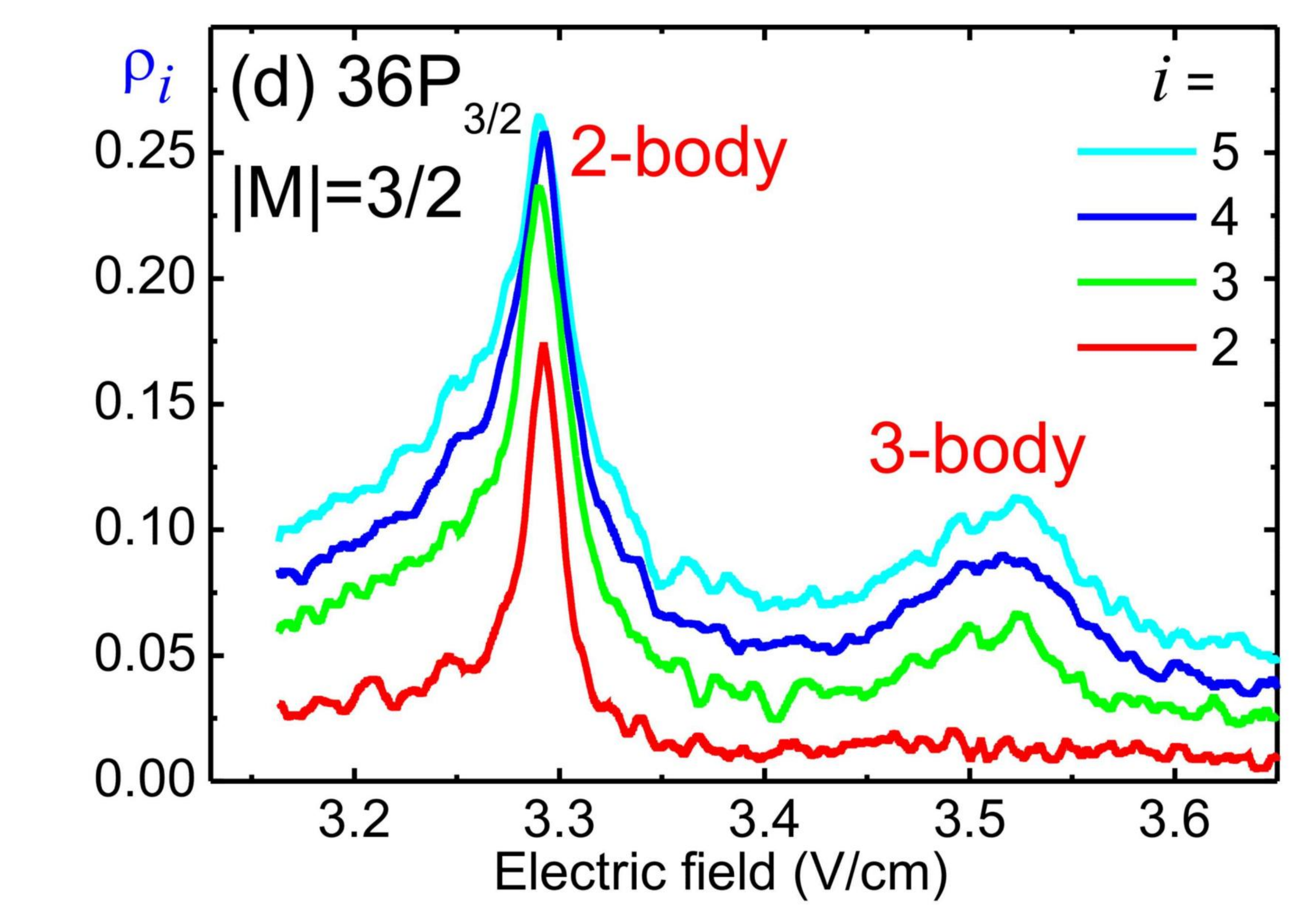

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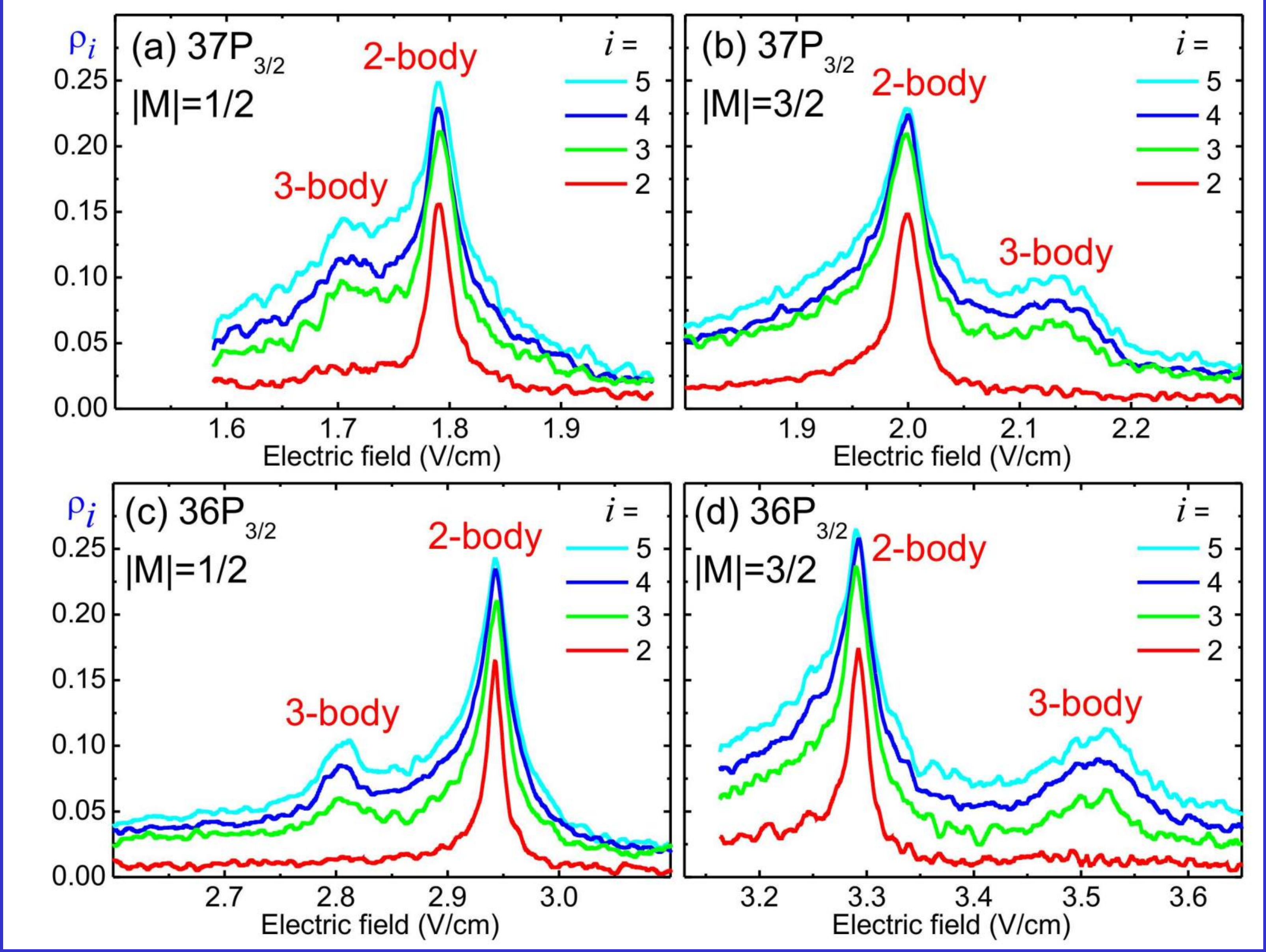

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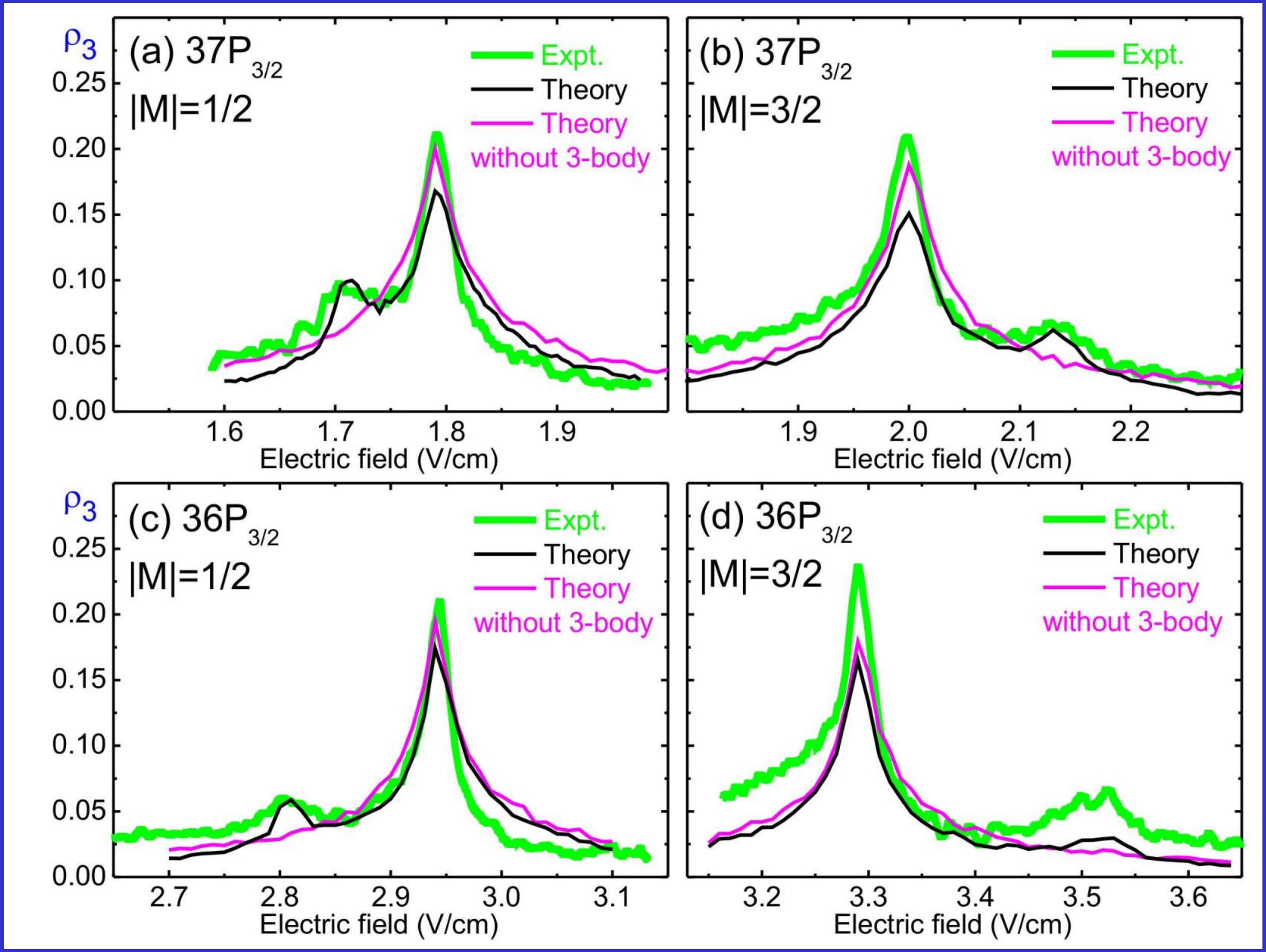
Comparison with numerical simulations for 3 disordered atoms



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SUMMARY

- Stark-tuned Förster resonances provide fine and flexible control of the interactions between Rydberg atoms
- Stark-switching technique is efficiently used to control both Rydberg laser excitation and Förster resonances
- Line shape of the Förster resonances strongly depends on the shape of the controlling electric-field pulses
- Broadening and time dynamics of the Förster resonances are well described by the density-matrix phase-diffusion theoretical model
- RF-assisted transitions can be induced both for the "accessible" Förster resonances, which are tuned by the dc electric field, and for those which cannot be tuned and are "inaccessible"
- The van der Waals interaction of almost arbitrary high Rydberg states can be efficiently tuned to resonant dipole-dipole interaction using the rf-field with frequencies below 1 GHz
- There is no signature of the Borromean three-body Förster resonances for exactly two interacting Rydberg atoms, while it is present for the larger number of atoms. It represents an effective three-body operator, which can be used to directly control the three-body interactions

Recent papers

- D.B.Tretyakov et al., Phys. Rev. Lett. **119**, 173402 (2017)
- I.I.Beterov et al., arXiv:1710.04384
- I.I.Beterov et al., Quantum Electronics 47, 455 (2017)
- I.I.Ryabtsev et al., Physics – Uspekhi **59**, 196 (2016)
- E.A.Yakshina et al., Phys. Rev. A 94, 043417 (2016)
- I.I.Beterov et al., Phys. Rev. A 94, 062307 (2016)
- D.B.Tretyakov et al., Phys. Rev. A **90**, 041403(R) (2014)
- V.M.Entin et al., JETP **116**, 721 (2013)

Future studies

- RF-resonances for high states
- Enhanced dipole blockade
- Optical dipole traps
- Coherent DD interaction
- Two-qubit logic gates
- Controlled many-body interactions