Импульсная оптическая дипольная ловушка атомов фемтосекундной длительности

А.Е. Афанасьев, А.М. Машко, А.А. Мейстерсон, В.И. Балыкин

Outlook

Introduction

- Laser cooling and trapping in UV region
- Laser cooling with pulsed lasers
- Laser trapping with pulsed lasers (picosecond)

Trapping with femtosecond laser

- Heating channels
- Experimental setup
- Rb cell as a notch-filter for pulsed trapping
- Lifetime of trapped atoms

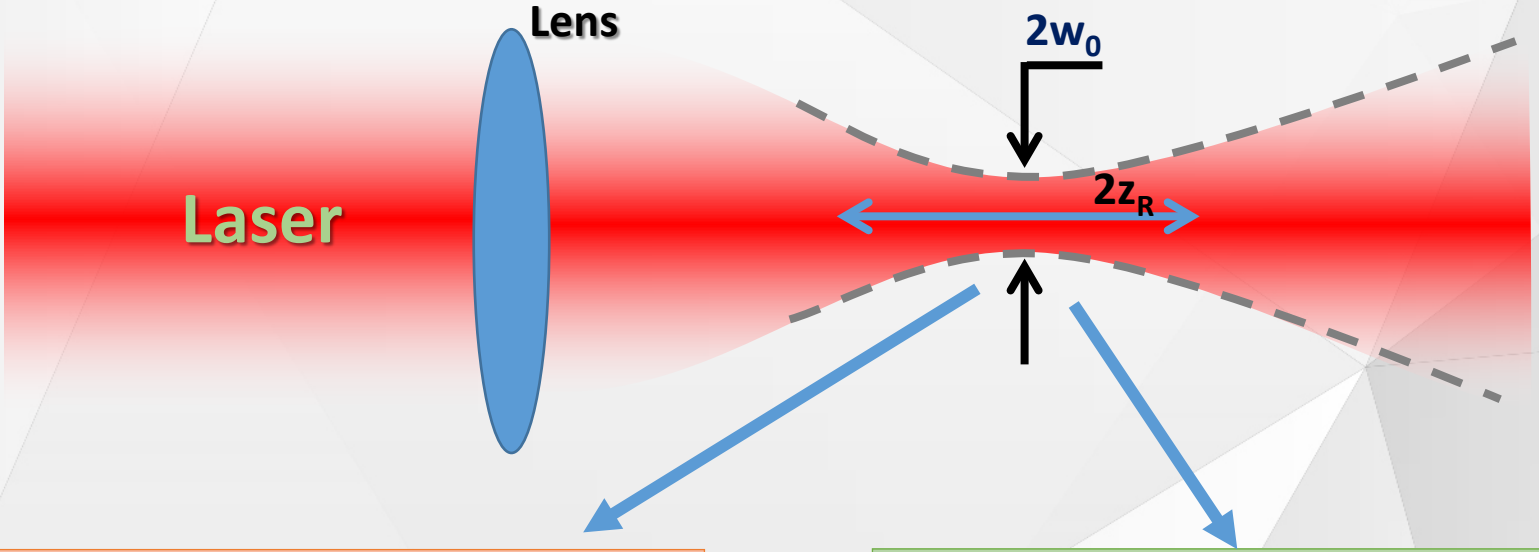
Spectroscopy of trapped atoms

- Spectroscopy with selective heating
- Experimental results
- Theoretical calculations

Conclusion

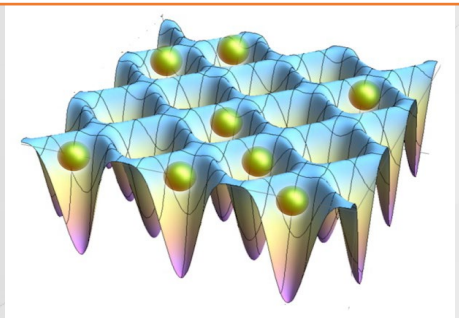
Extreme trapping

$$F_{gr} = -\frac{1}{2}\hbar(\delta - kv)\frac{\nabla G(r)}{1 + G(r) + (\delta - kv)^2/\Gamma^2},$$

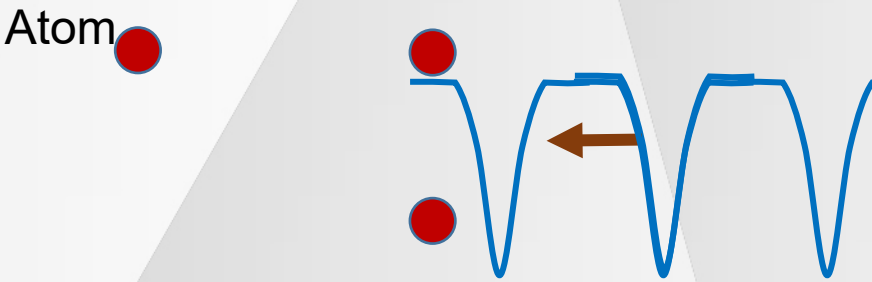


Trapping in a small region w_0~1 μm
Spatial extreme localization

- Single atom localization
- Quantum simulations
- Quantum computation (Qubit)



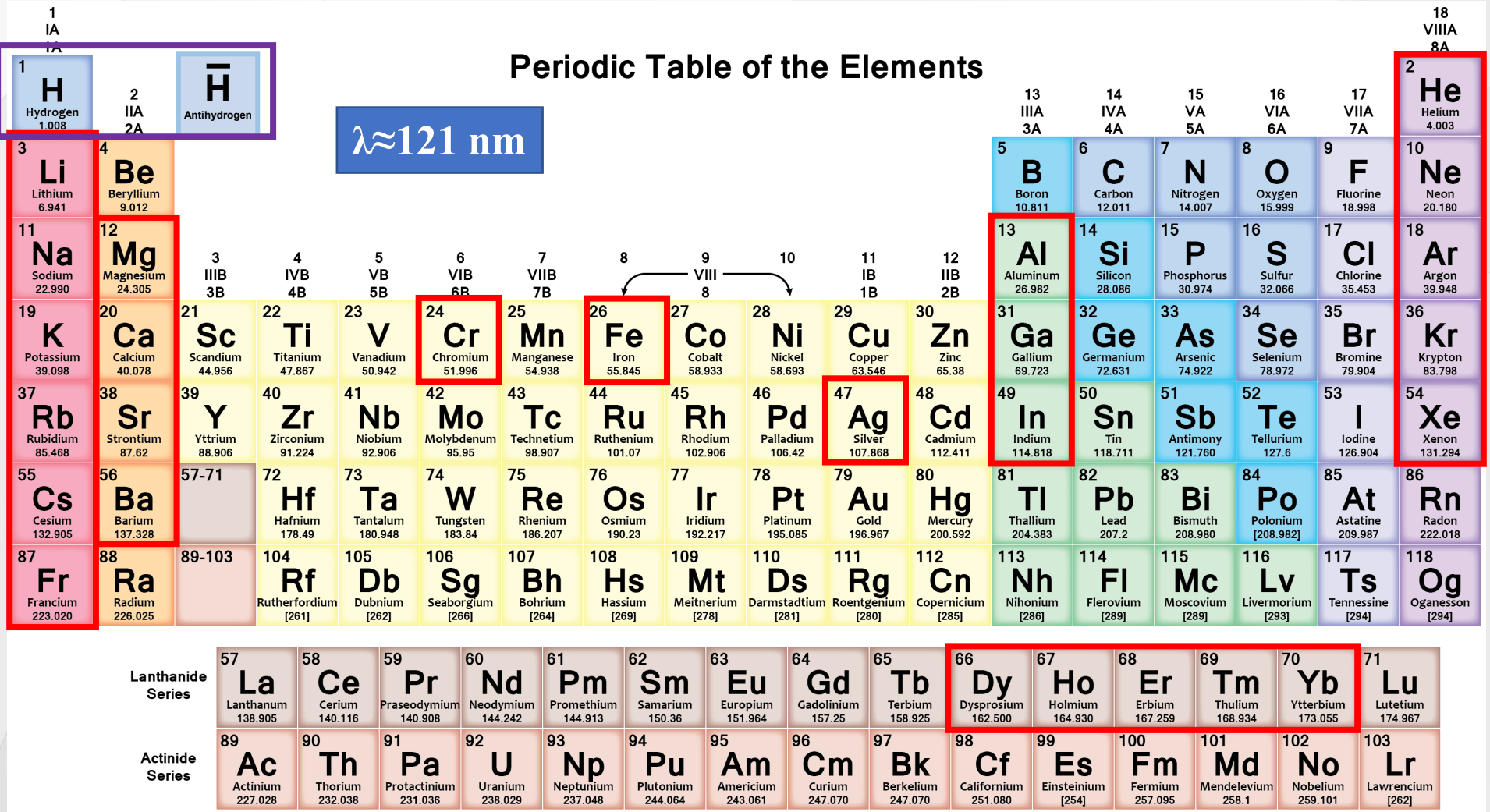
Trapping with a short pulse
Temporal extreme localization



The time of localization ~ 50 fs

V.S. Letokhov, B.D. Pavlik, Appl. Phys., 9, 229 (1976)

Motivation

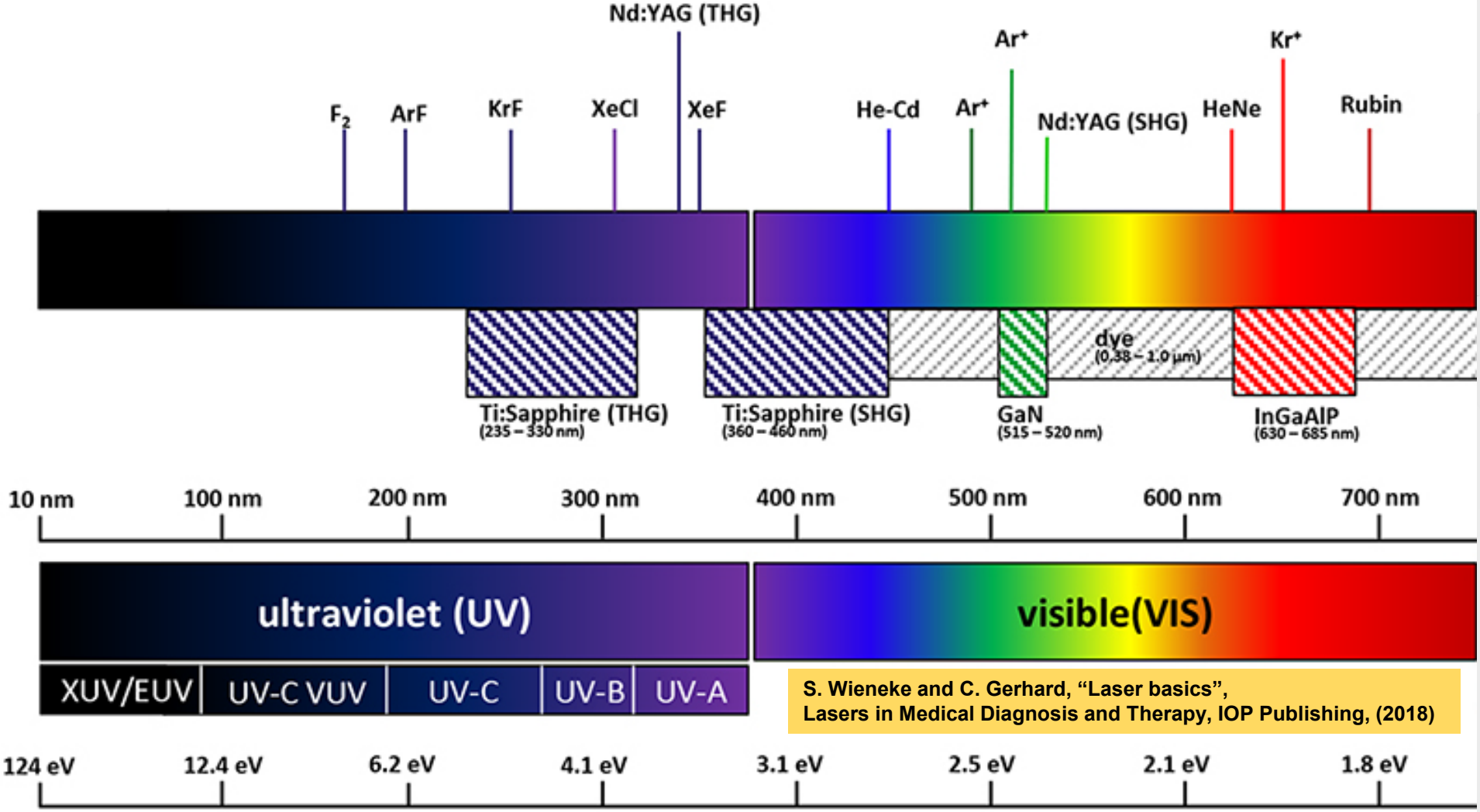


- Laser-cooled atoms

Fundamental investigations:

1. Equivalence principle
2. Fundamental constants

Available laser sources

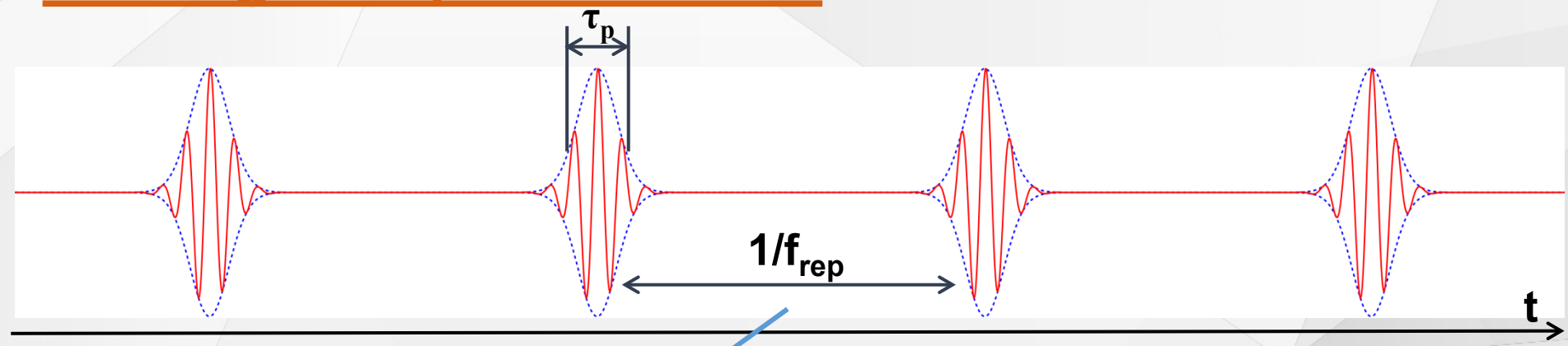


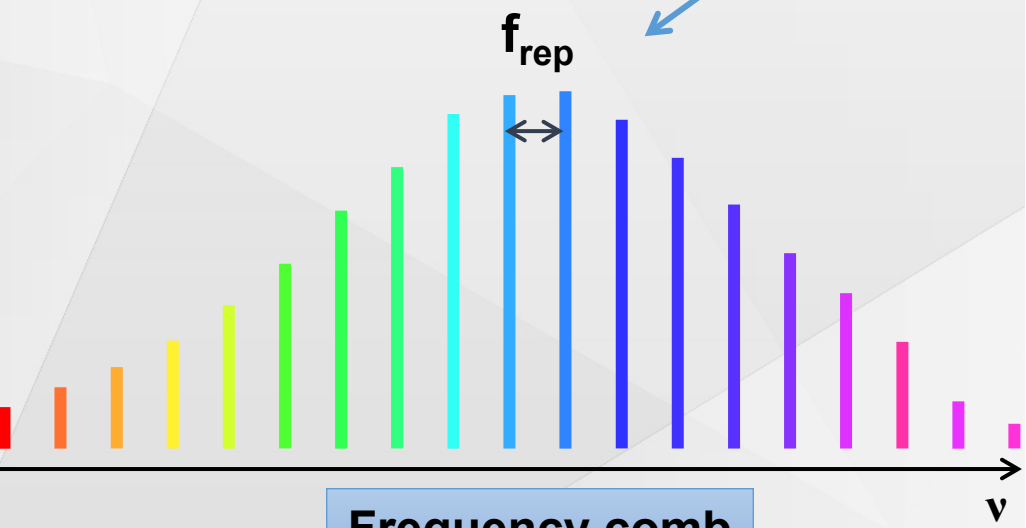
S. Wieneke and C. Gerhard, "Laser basics",
Lasers in Medical Diagnosis and Therapy, IOP Publishing, (2018)

Lasers of UV range are mostly pulsed

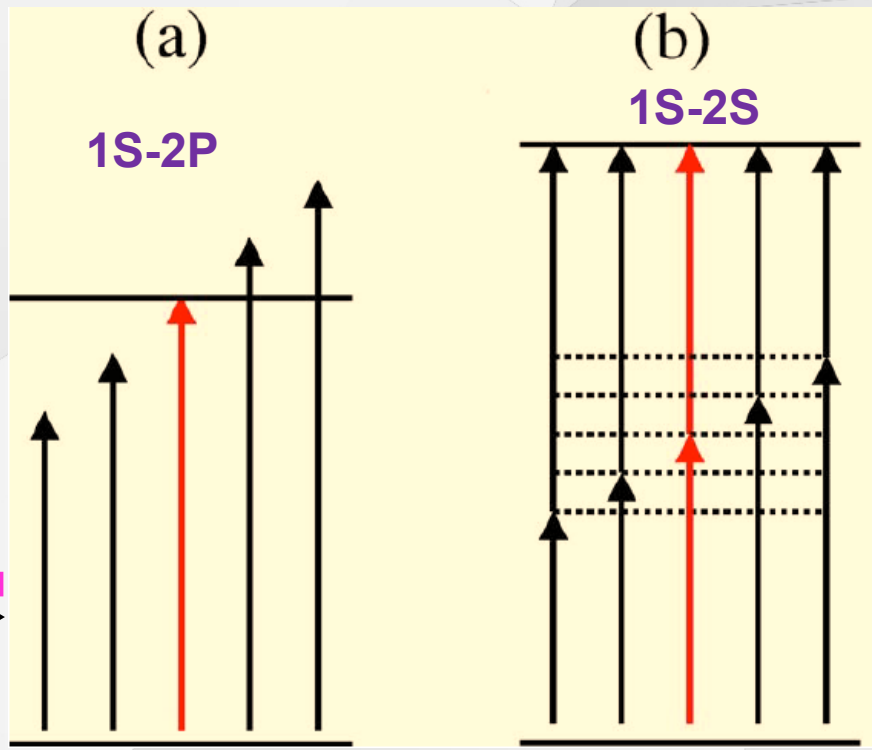
Efficiency of harmonic generation depends on the peak laser intensity

Cooling with pulsed lasers





Frequency comb



Single-photon transition

Two-photon transition

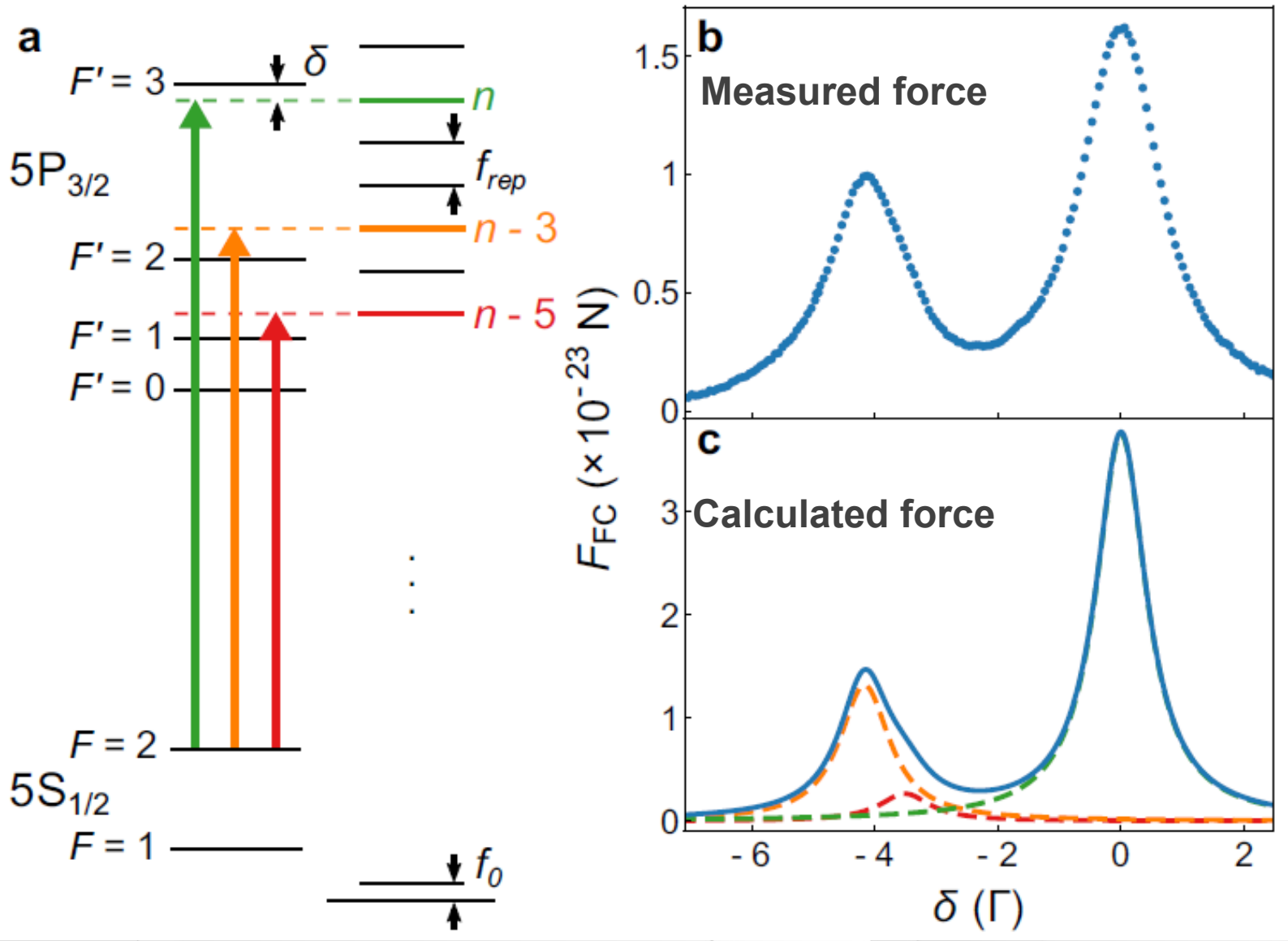
D. Kielpinski, Physical Review A 73, 063407 (2006)

Cooling with pulsed lasers

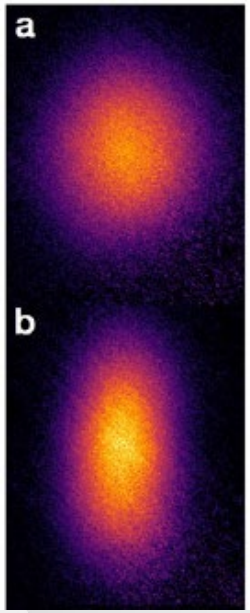
Single-photon transition

Rb

$$F_{rp} = \hbar k \Gamma \frac{G(r)}{1 + G(r) + (\delta - kv)^2/\Gamma^2}$$



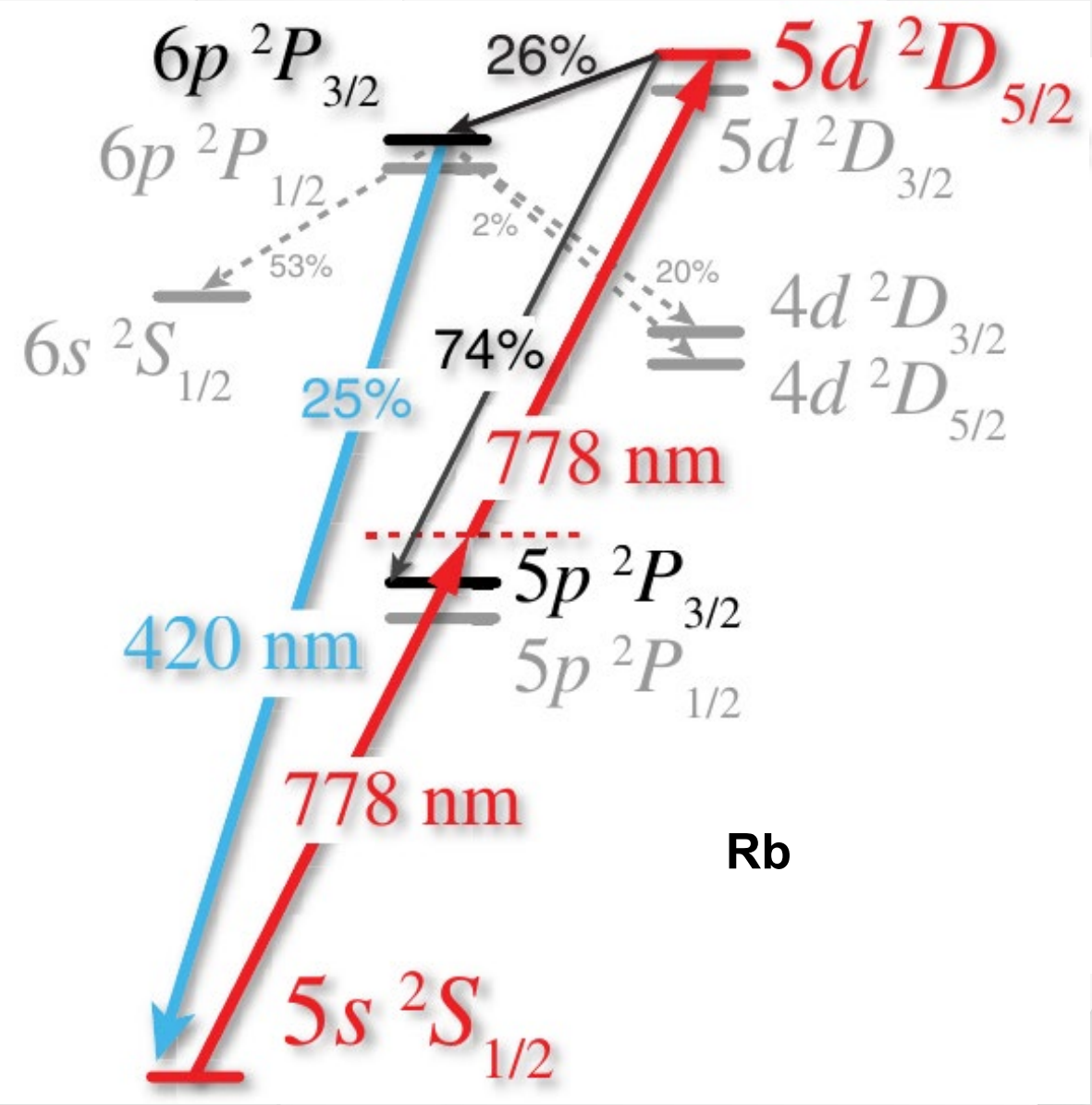
T_i=240 μK



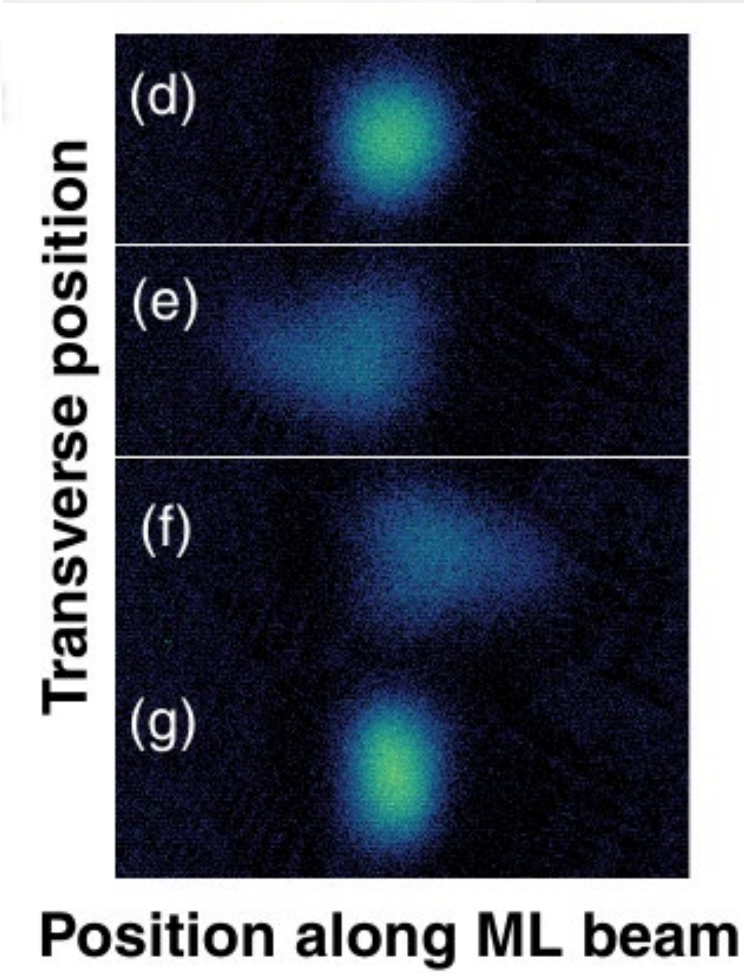
T=155 μK

N. Šantić, et. al, Scientific Reports, 9, 2510 (2019)

Cooling with pulsed lasers



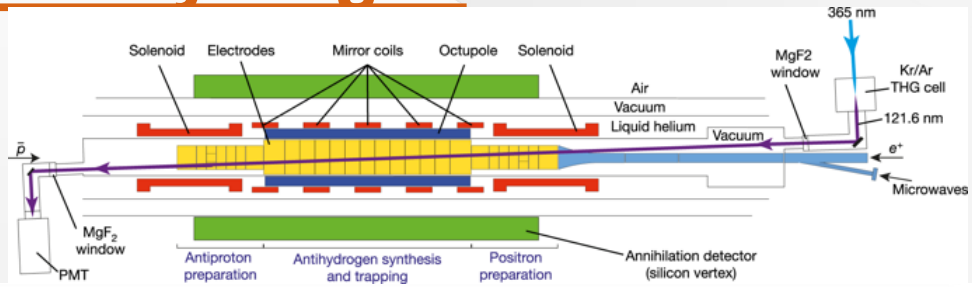
T_i=110 μK

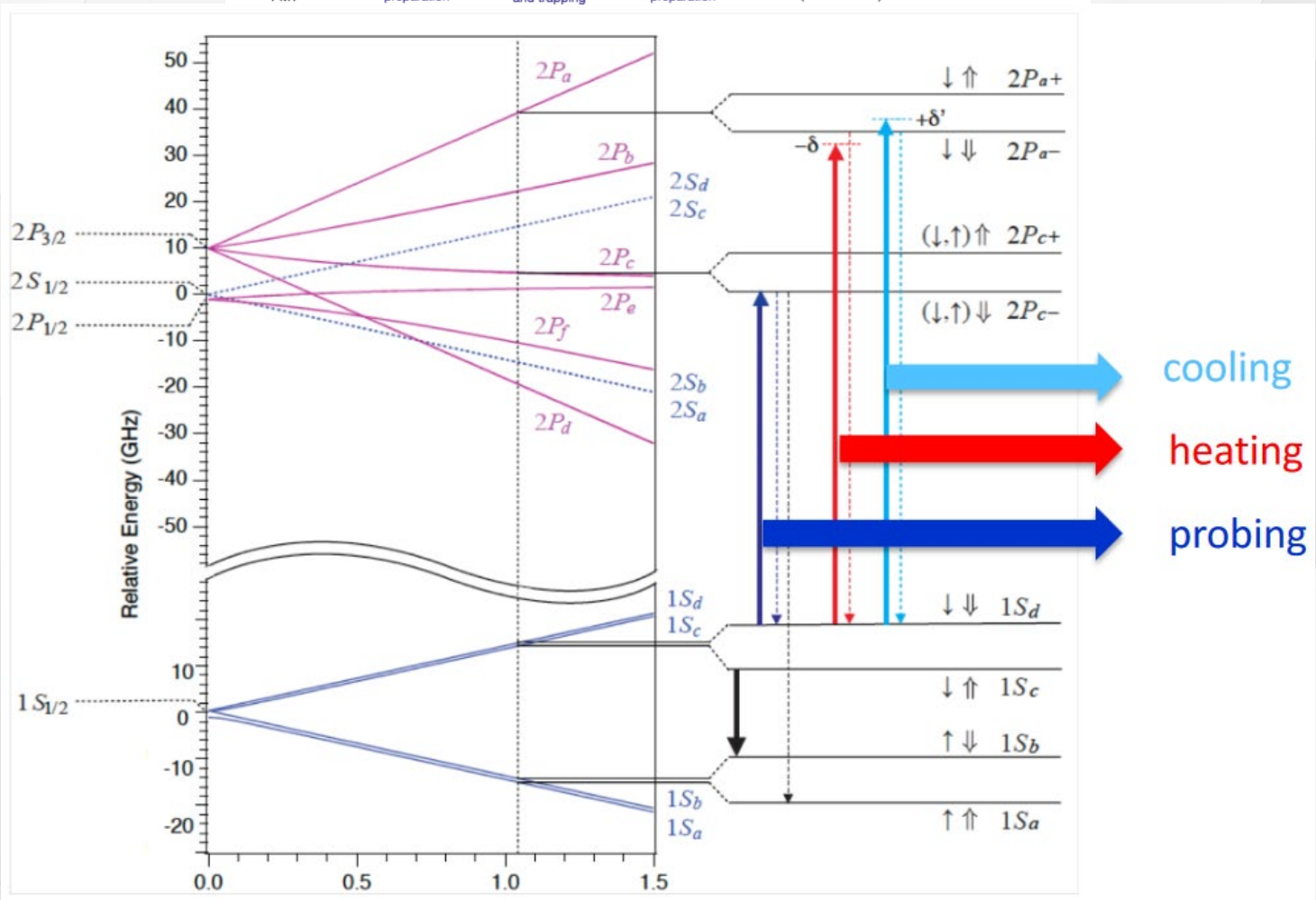


T=57 μK

A. M. Jayich, X. Long, and W. C. Campbell, Phys.Rev. X, 6, 041004 (2016)

Cooling of anti-hydrogen

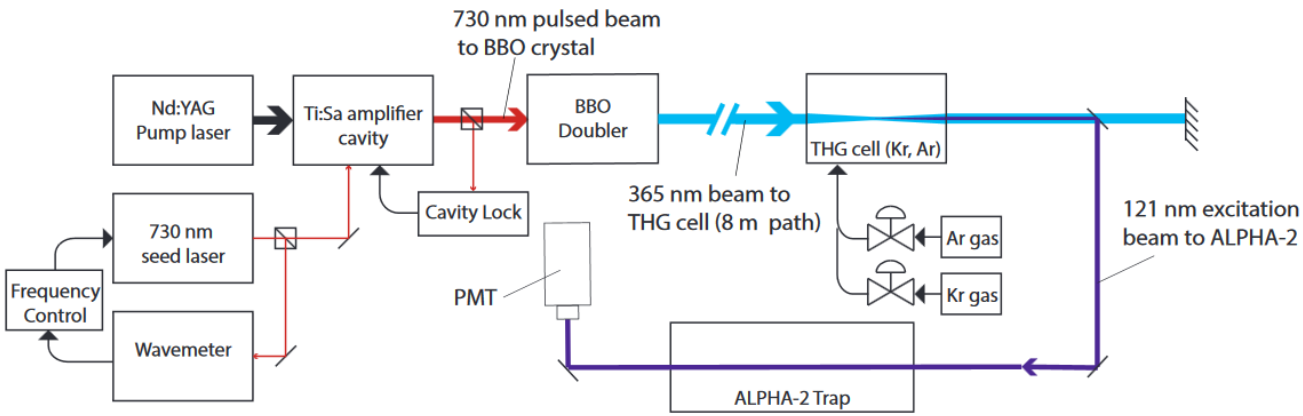




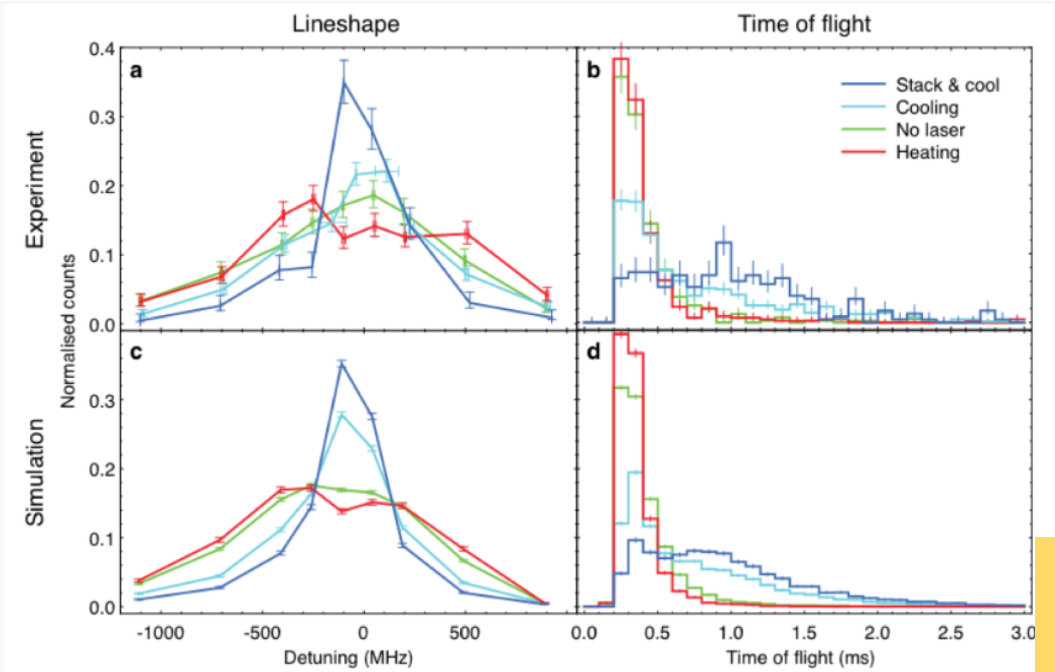
Ahmadi, M., Alves, B.X.R., Baker, C.J. et al. Investigation of the fine structure of antihydrogen. Nature 578, 375–380 (2020)

Cooling of anti-hydrogen

- 121.5 nm pulsed laser: THG of a 365 nm laser in a Kr/Ar gas cell (500 pJ, 20 ns/pulse)



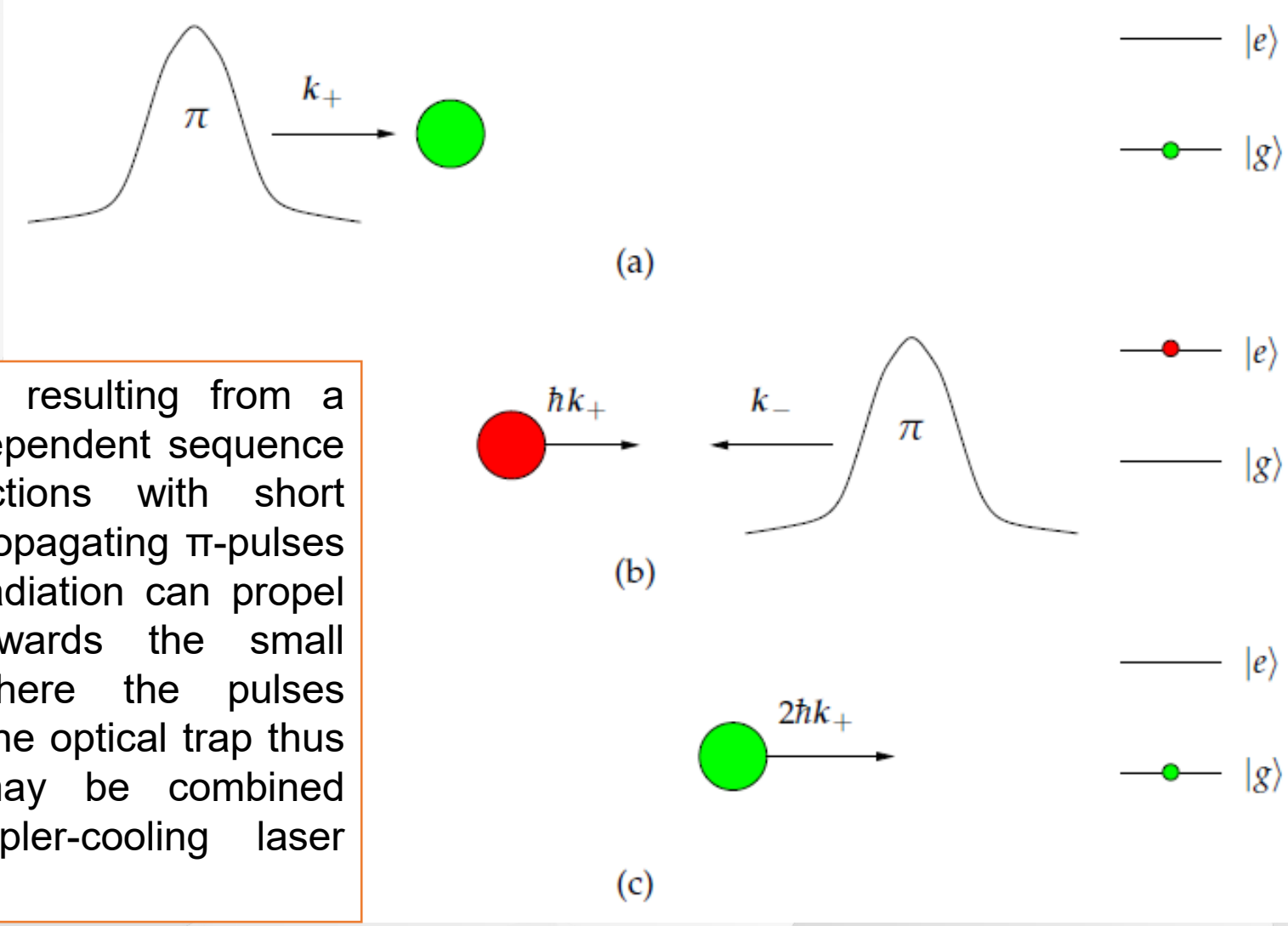
- cooling reduces the Doppler contribution to the linewidth and results in more atoms annihilating at later times (qualitative agreement with simulations)



Ahmadi, M., Alves, B.X.R., Baker, C.J. et al. Investigation of the fine structure of antihydrogen. Nature 578, 375–380 (2020)

Localization in pulsed traps

Localization with π pulses



The force resulting from a position-dependent sequence of interactions with short counter-propagating π-pulses of laser radiation can propel atoms towards the small region where the pulses overlap. The optical trap thus formed may be combined with Doppler-cooling laser beams.

T.G.M. Freegarde, J. Walz, and T.W. Hänsch., Opt. Comm., **117,** 262 (1995)
A.P. Kazantsev. The acceleration of atoms by light. JETP, **39**: 784 (1974).
L.C. Karssen, Trapping cold atoms with ultrafast laser pulses. Ph.D. thesis, Utrecht University (2008)

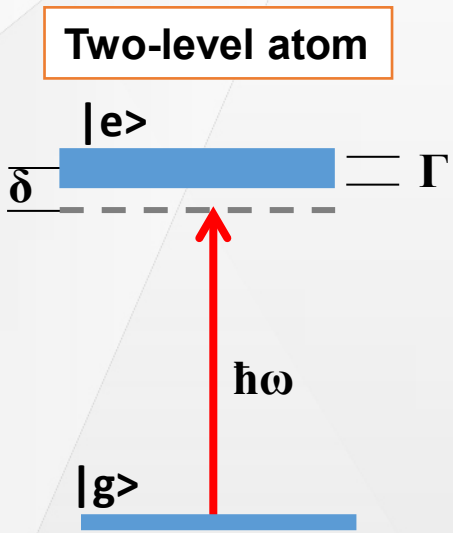
Optical dipole trapping

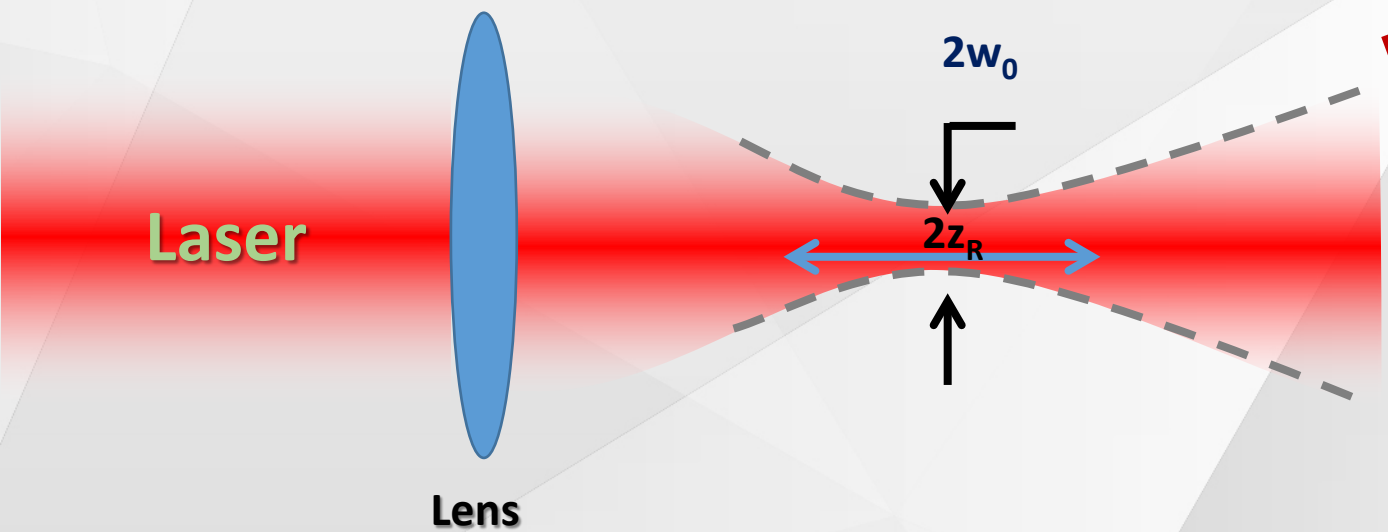
$$U = \langle V \rangle = -\langle \boldsymbol{D} \rangle \boldsymbol{E}$$

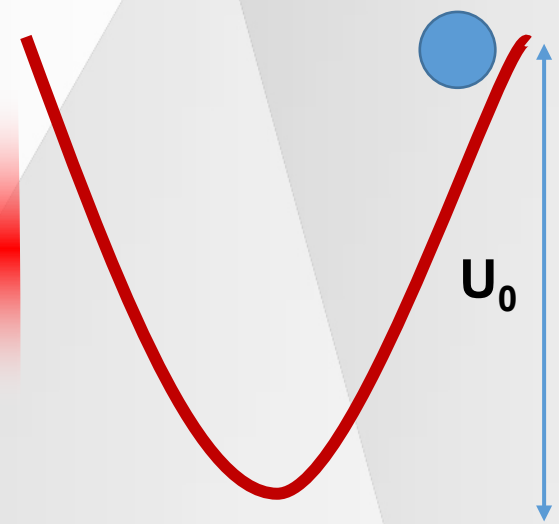
$$\boldsymbol{F} = \nabla U = \nabla(\langle \boldsymbol{D} \rangle \boldsymbol{E})$$

$$\boldsymbol{E} = e E_0(\boldsymbol{r}) \cos(\boldsymbol{k}\boldsymbol{r} - \omega t)$$

$$F_{gr} = -\frac{1}{2}\hbar(\delta - kv)\frac{\nabla G(r)}{1 + G(r) + (\delta - kv)^2/\Gamma^2},$$







$$|\delta| \gg \gamma, \Omega$$

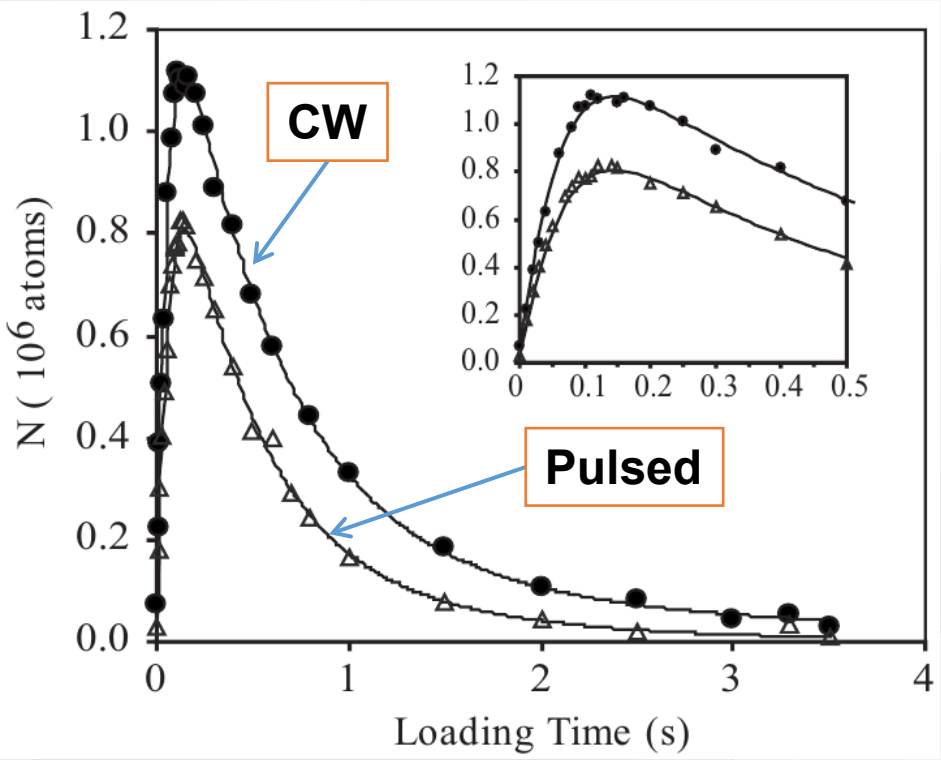
$$U_{\mathrm{gr}}(\boldsymbol{r}) = \hbar \frac{\Omega^2(\boldsymbol{r})}{\delta}$$

V.I. Balykin *et al.*, Rep. Prog. Phys. 63, 1429 (2000).
G. Rudolf et al. Adv. *Atom. Mol. Opt. Phys*, *42*, 95 (2000)

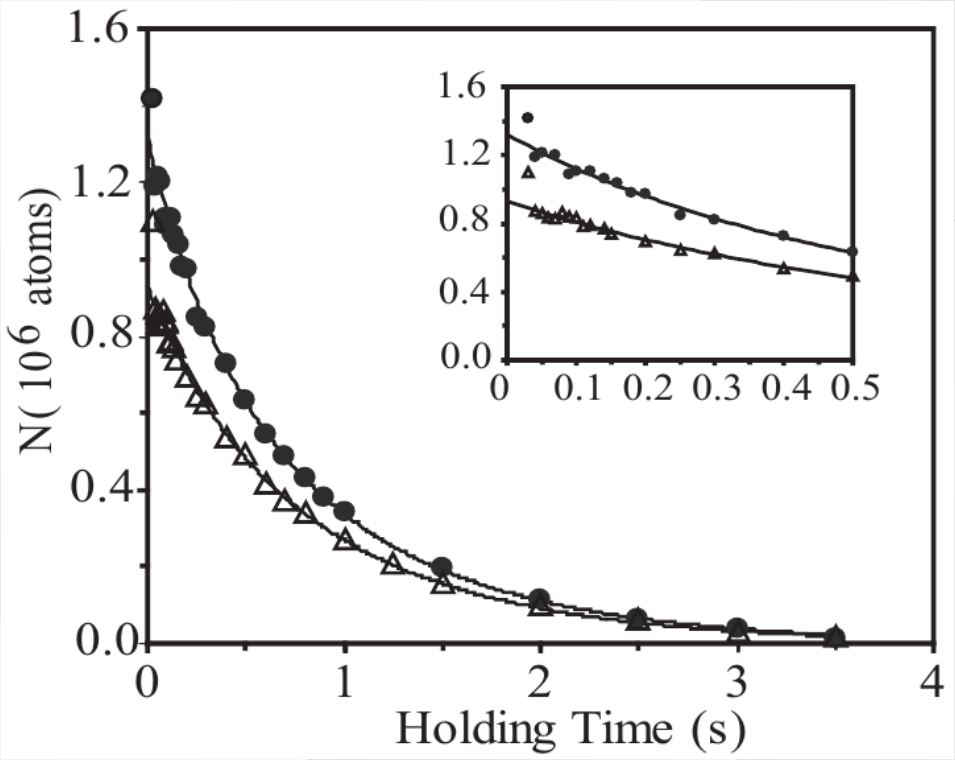
Trapping with pulsed laser

100 ps pulse duration

Loading



Lifetime

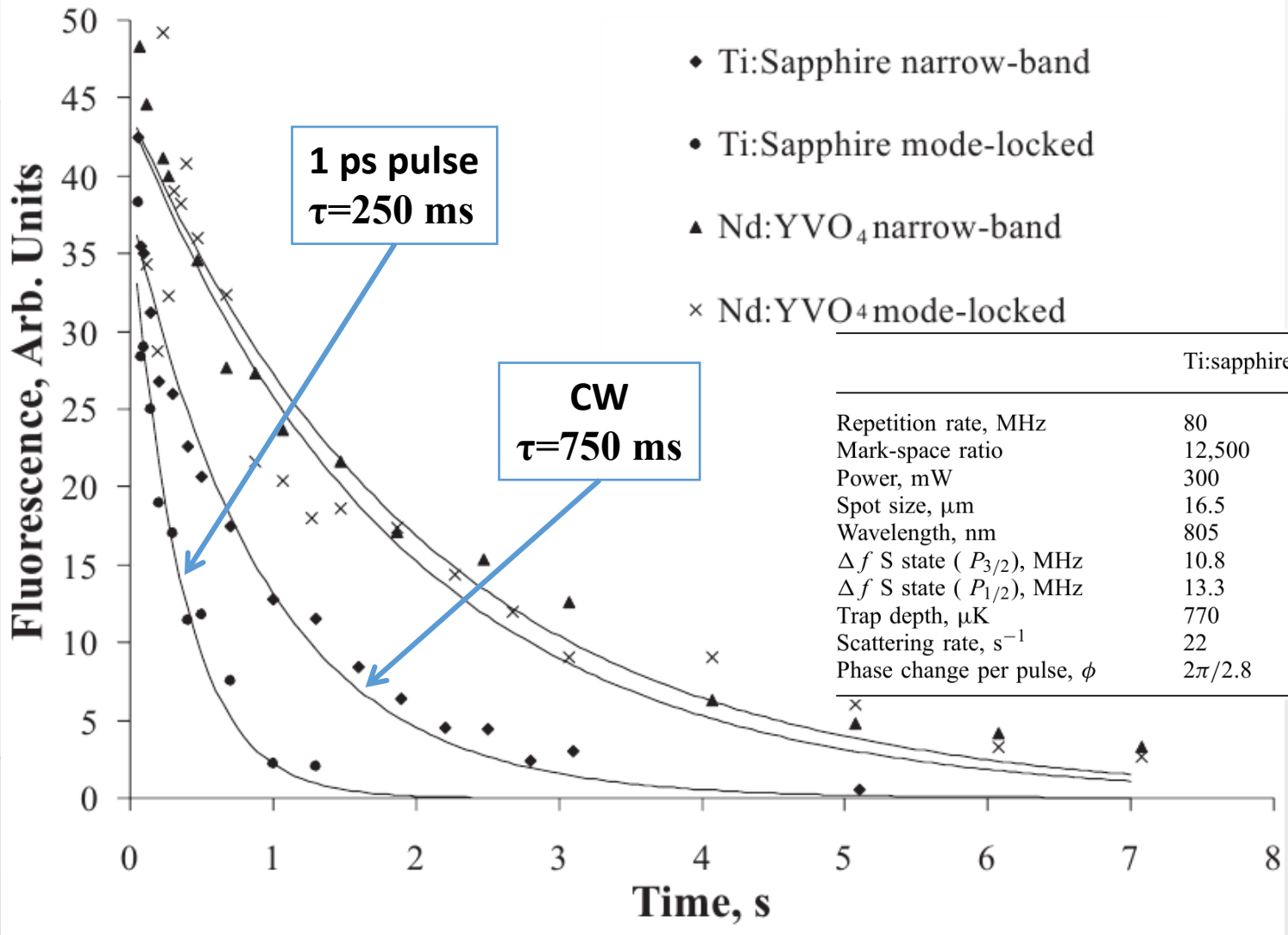


The properties of pulsed trap (*with picosecond pulse duration*) are the same as for CW trap (*if the average power the same*)

M. Shiddiq, et. al, Phys.Rev. A, 77, 045401 (2008)

Trapping with pulsed laser

1 ps pulse duration



	Ti:sapphire	$Nd:YVO_4$
Repetition rate, MHz	80	240
Mark-space ratio	12,500	130
Power, mW	300	2800
Spot size, μm	16.5	26.3
Wavelength, nm	805	1064
Δf S state ($P_{3/2}$), MHz	10.8	5.25
Δf S state ($P_{1/2}$), MHz	13.3	2.80
Trap depth, μK	770	260
Scattering rate, s^{-1}	22	0.47
Phase change per pulse, ϕ	$2\pi/2.8$	$2\pi/23$

The shorter lifetimes of pulsed trap is consistent with the losses due to **photoassociation** present in the wavelength region used (800–825 nm).

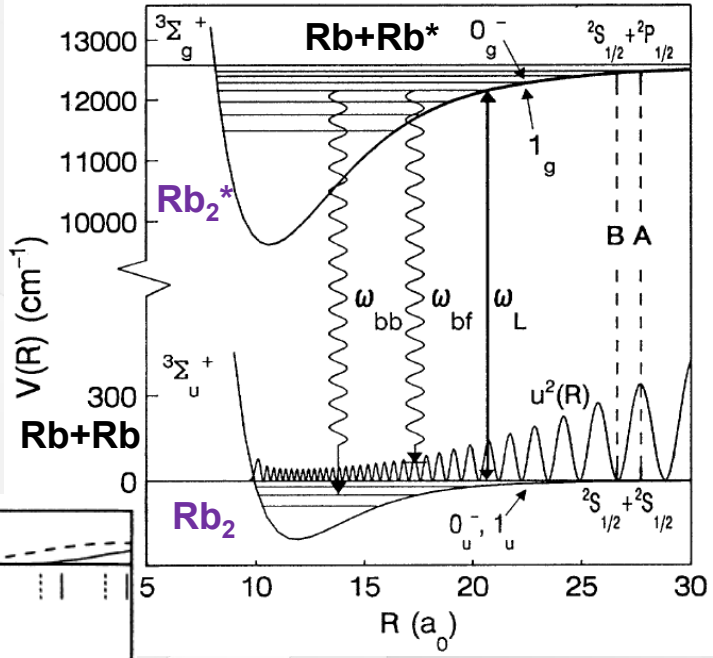
R.B.M. Clarke, T. Graf, E. Riis, Appl. Phys. B, 70, 695 (2000)

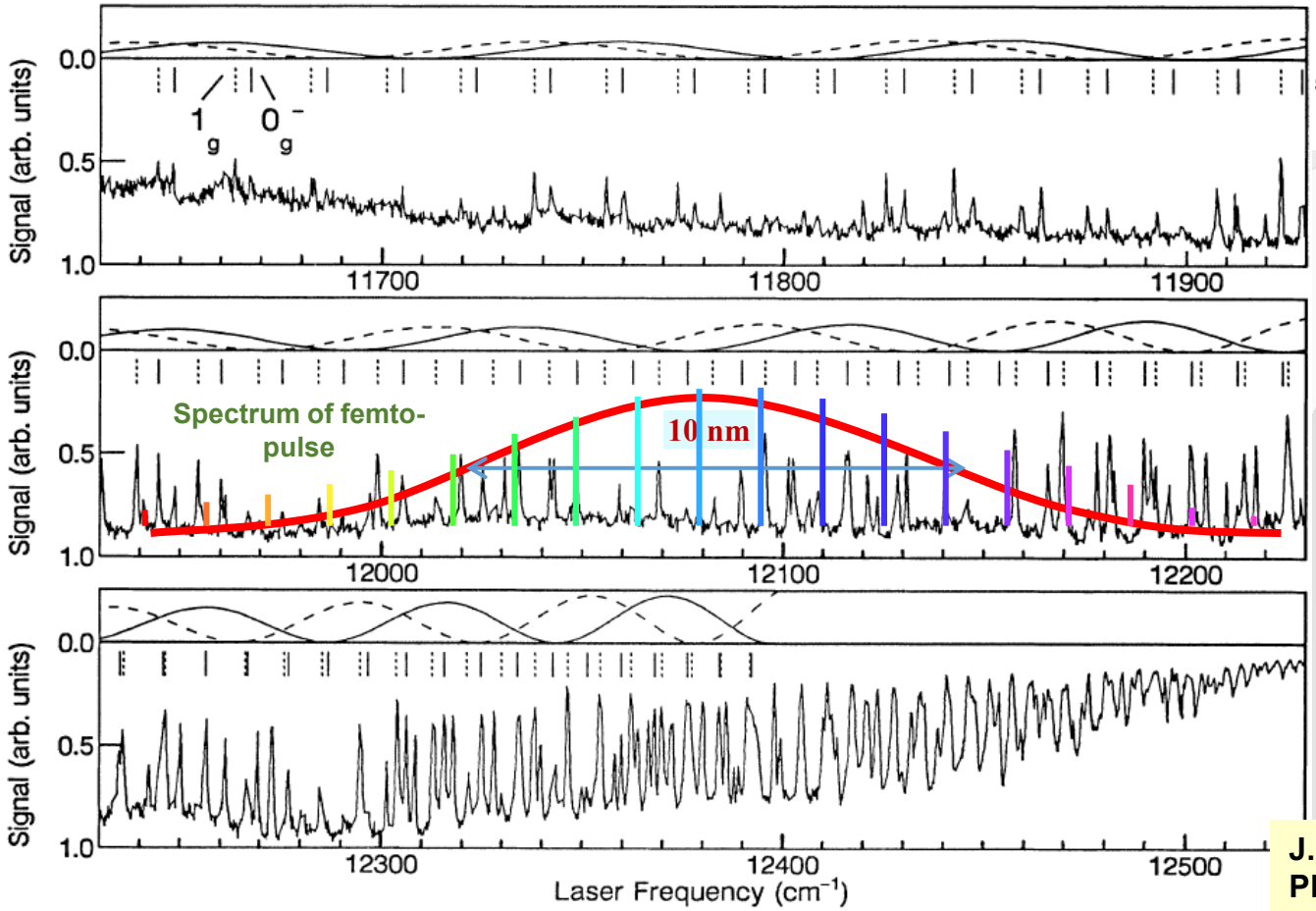
Photoassociation

$$Rb + Rb + \hbar\omega_L \rightarrow Rb_2^*$$

Escaping → $Rb_2 + \hbar\omega_{bb}$

Heating → $Rb + Rb + \hbar\omega_{bf}$





J. D. Miller, R. A. Cline, D. J. Heinzen, PRL, 71, 2204 (1993)

Lifetime of trapped atom

Losses:

$$\Gamma = \Gamma_{\text{Background}} + \Gamma_{\text{Photoassociation}} + \Gamma_{\text{Chaos}} + \Gamma_{\text{Momentum diffusion}}$$

$\Gamma_{\text{Background}}$ → From experiment with CW laser

$\Gamma_{\text{Photoassociation}}$ → Depends on the average laser intensity and width of laser spectrum

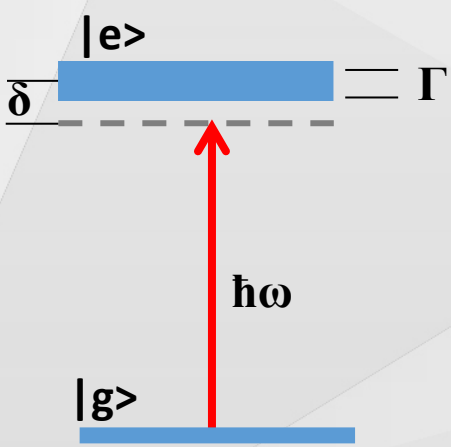
Γ_{Chaos} → Depends on the peak laser intensity and repetition rate

$\Gamma_{\text{Momentum diffusion}}$ → Depends on the peak laser intensity

Momentum diffusion

$$2D_p = \frac{d}{dt}\left(\langle \vec{P}\vec{P}\rangle - \langle \vec{P}\rangle\langle \vec{P}\rangle\right)$$

Fluctuation of spontaneous emission direction	Fluctuation of absorbed photons number	Fluctuation of stimulated emission
• Dominates in CW traps (s<<1) • $D_p \sim \Gamma \frac{s}{1+s}$	• Gives the Doppler limit of cooling	• Do not saturated with increasing intensity • $D_p \sim \frac{s^4}{(1+s)^3}, s > 1$



Saturation parameter

$$s = \frac{1}{2}\frac{\Omega^2}{\delta^2 + \Gamma^2/4}$$

Rabi frequency

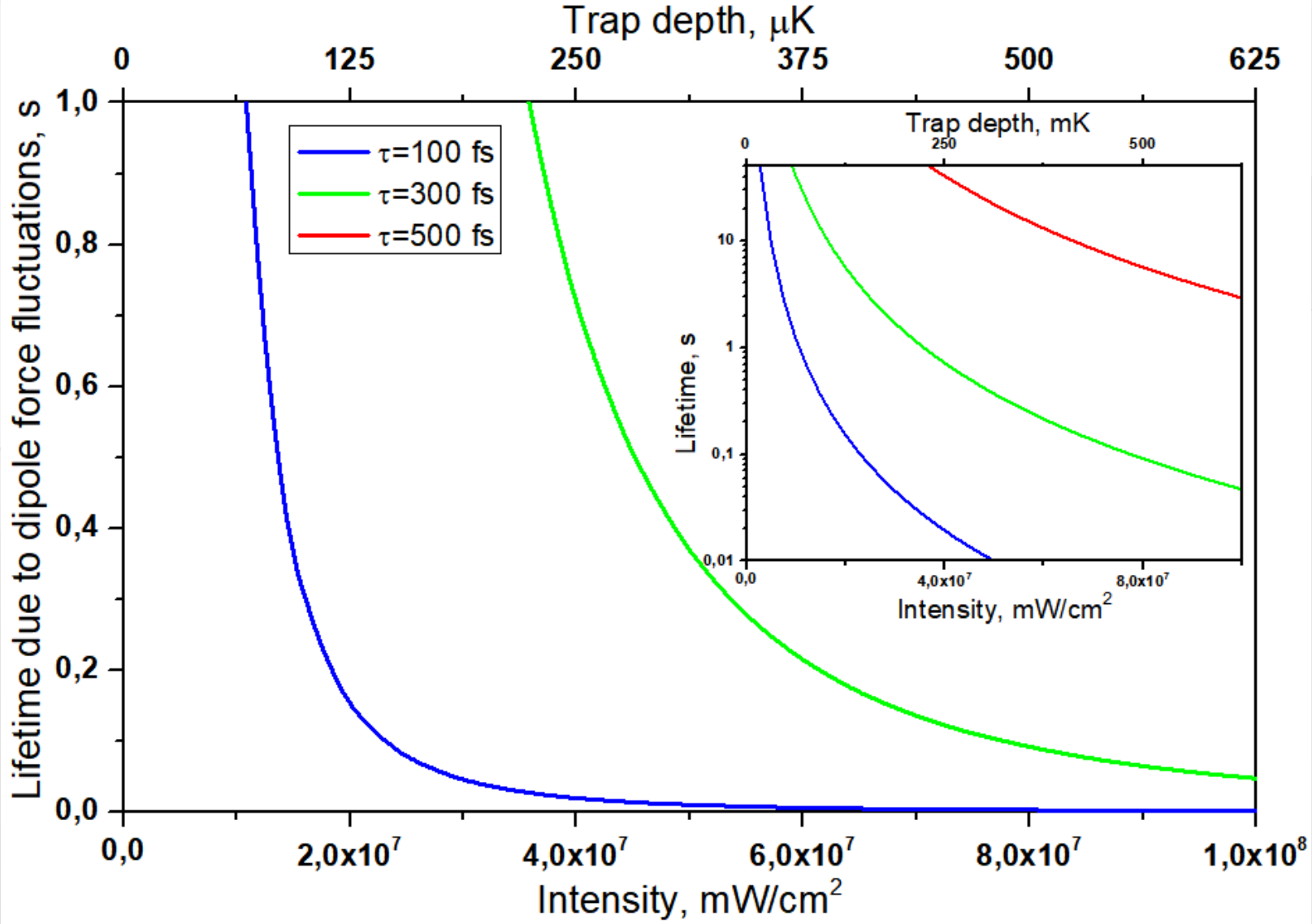
$$\Omega = \frac{dE}{\hbar}$$

The lifetime of an atom in a trap is defined as the time required for the atom to acquire energy equal to the depth of the potential well, by the momentum diffusion process

$$\tau_{trap} = mU_0/\langle D_{df}(r,t)\rangle$$

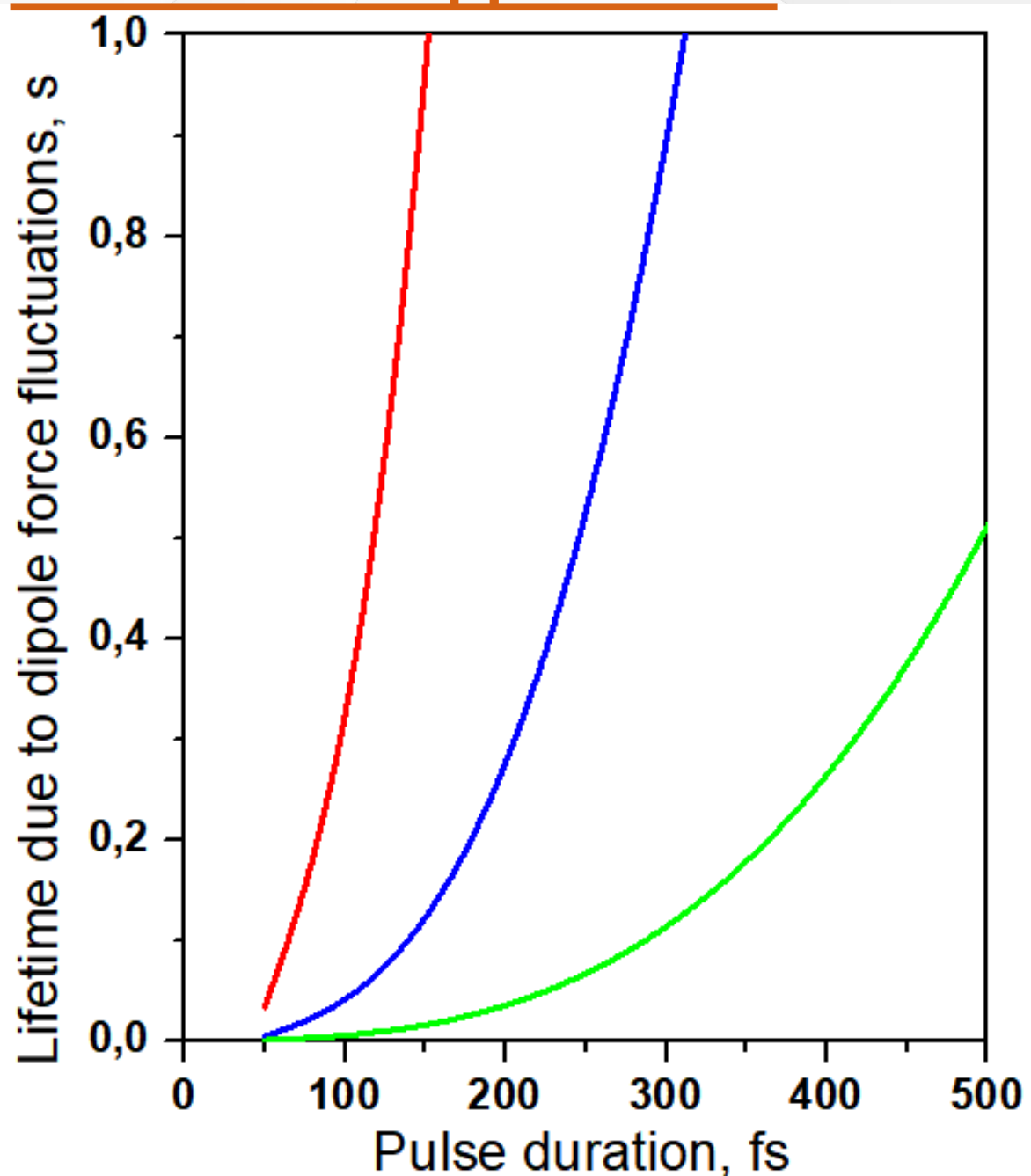
J.P. Gordon, A. Ashkin *Physical Review A*, ***21***, 1606 (1980)

Lifetime of trapped atom



τ_{life} ↑ ⇔ P ↓ ⇒ U_0 ↓

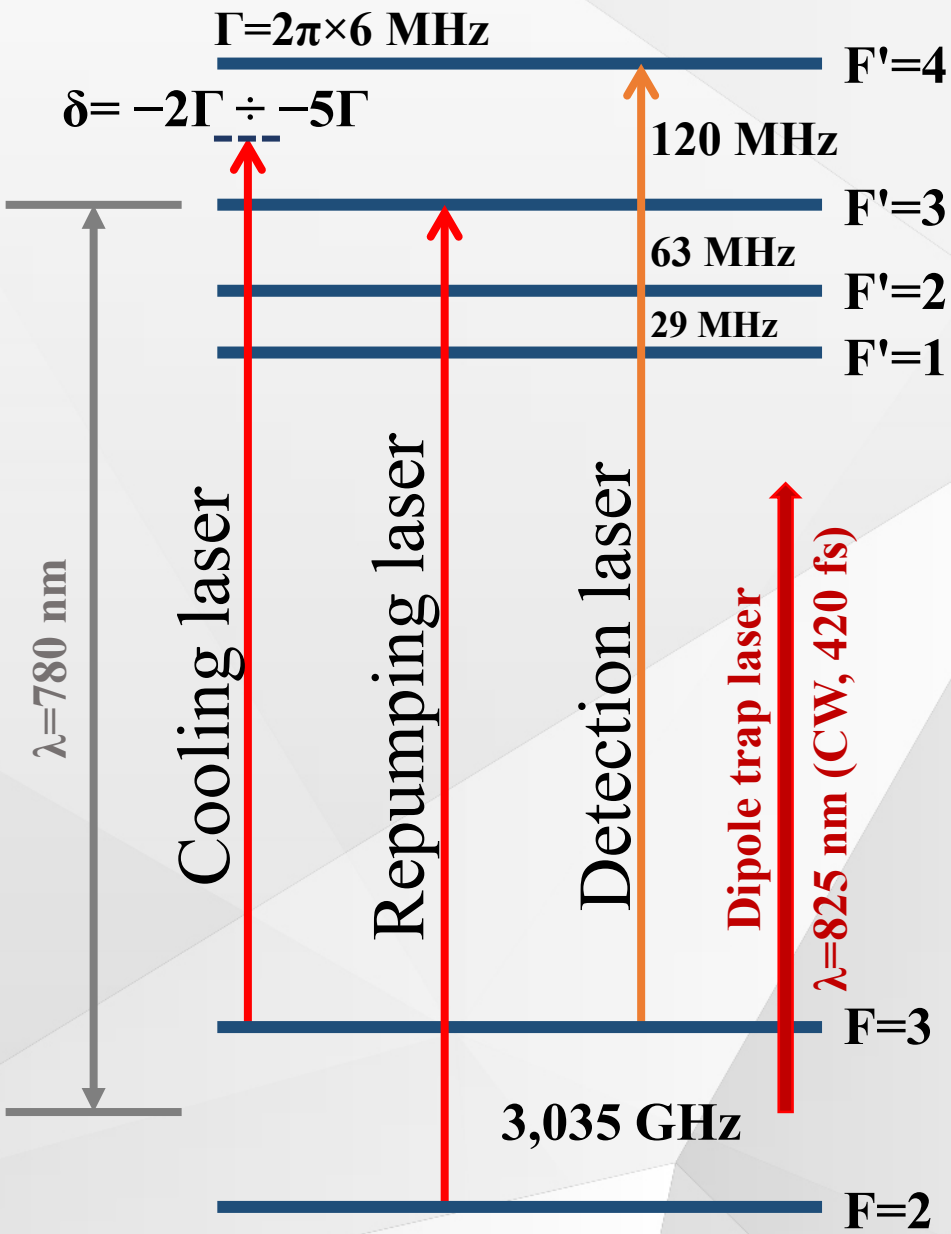
Lifetime of trapped atom



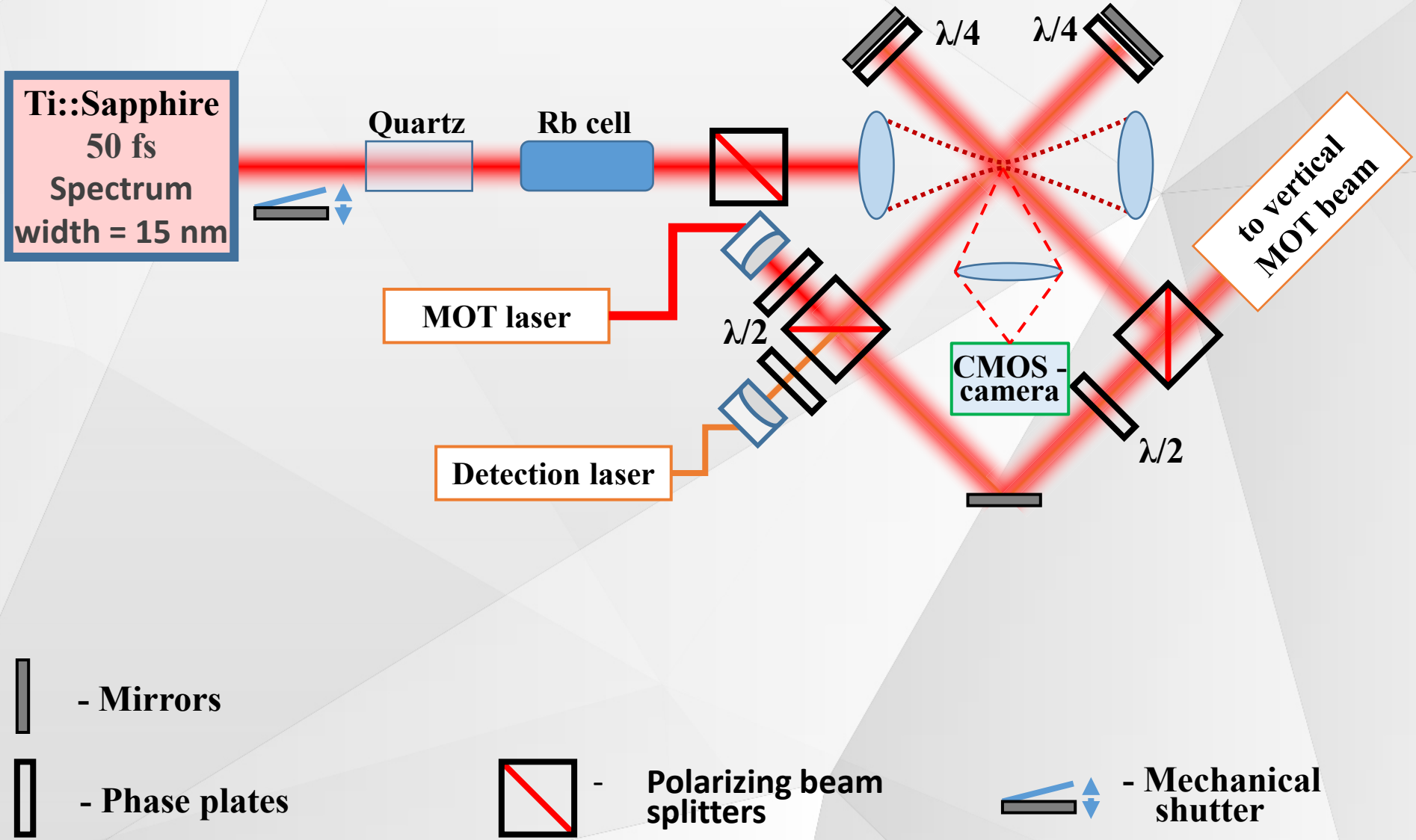
$\tau_{pulse}\uparrow \Rightarrow \tau_{life}\uparrow$

Experimental setup

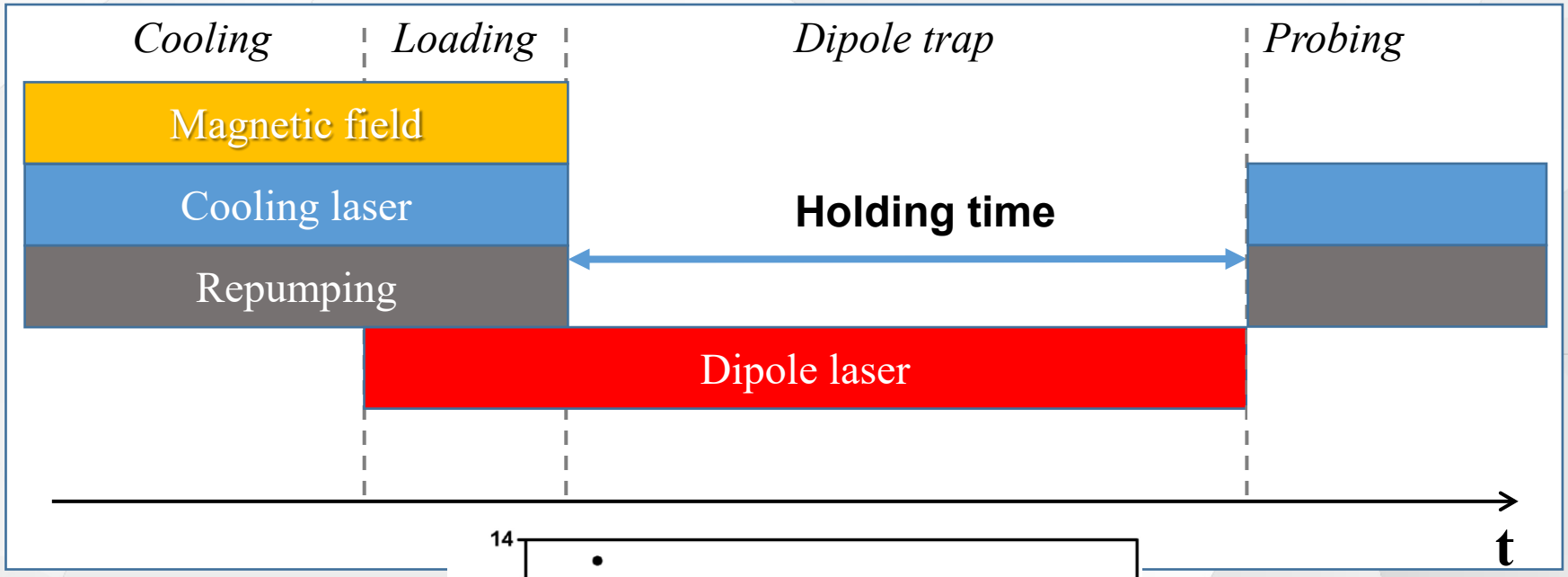
^{85}Rb energy levels D2 line

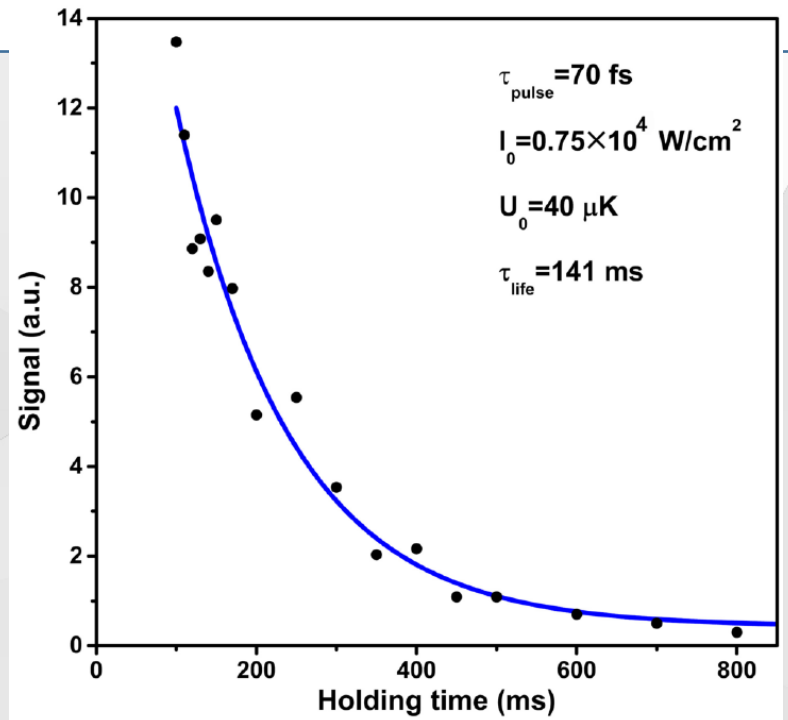


Experimental setup

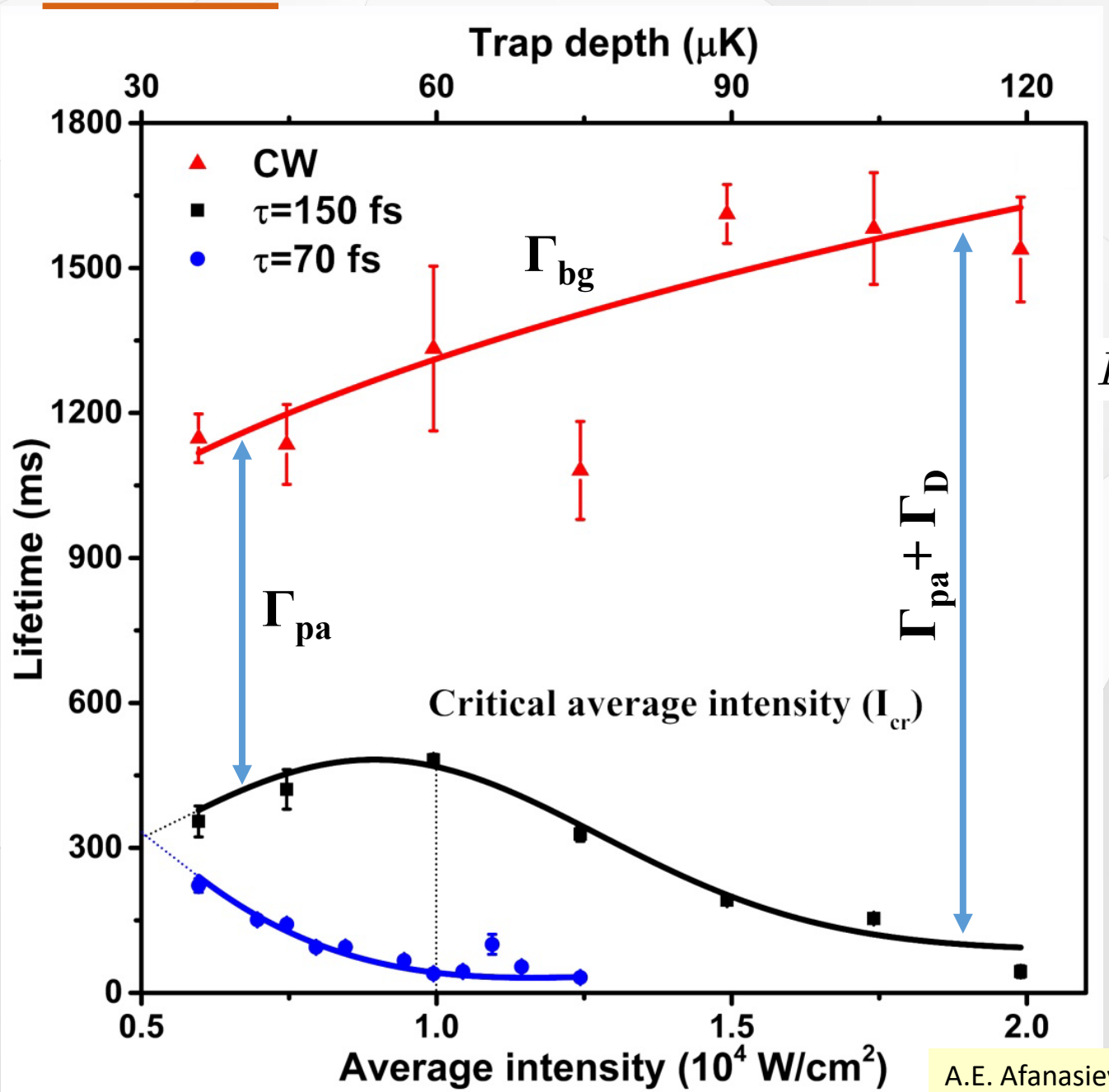


Lifetime measurements





Lifetime



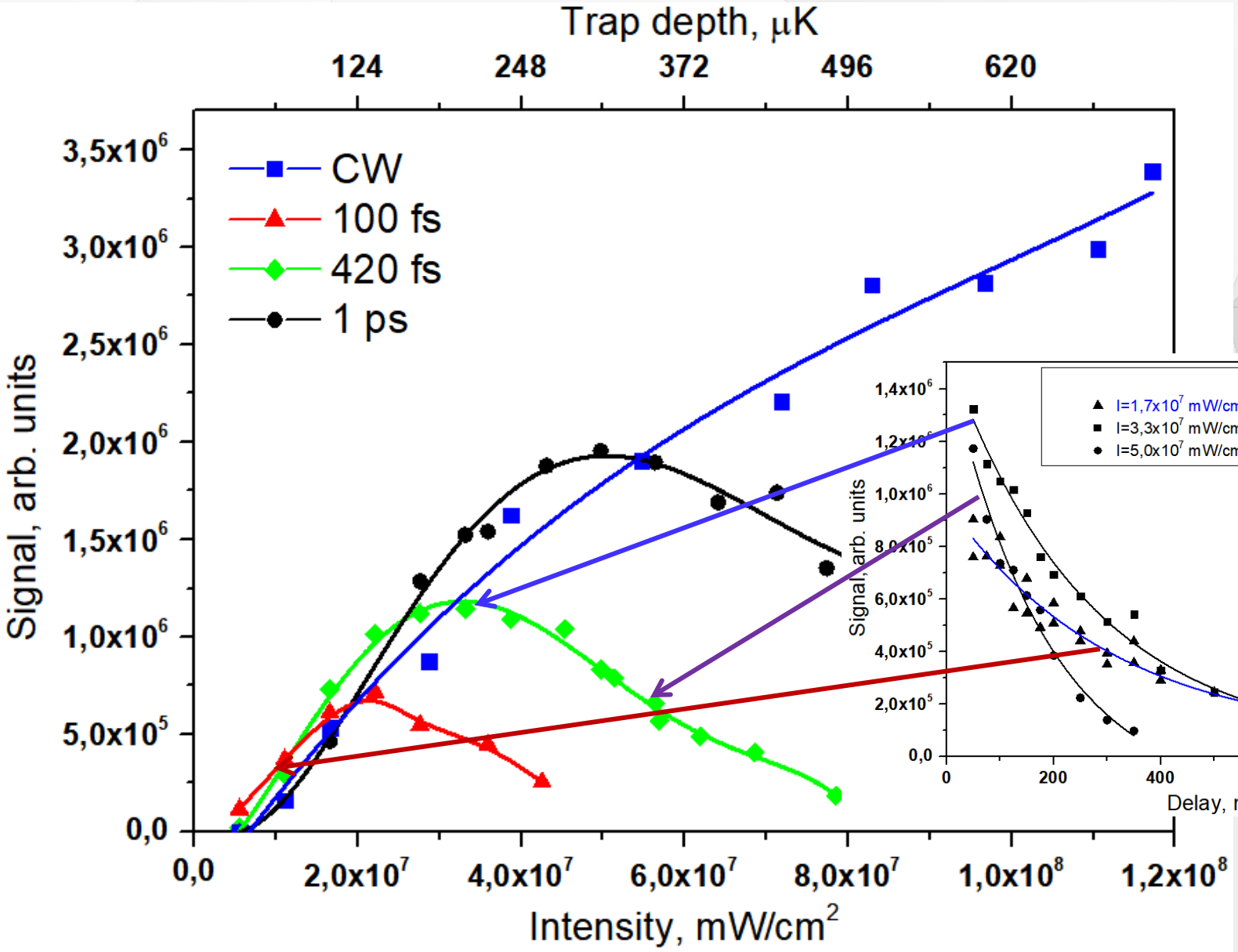
$$\Gamma_{bg} = 0.6\ \mathrm{s}^{-1}$$

$$\Gamma_{pa} = R_{pa} I = 4.3\ \mathrm{s}^{-1}$$

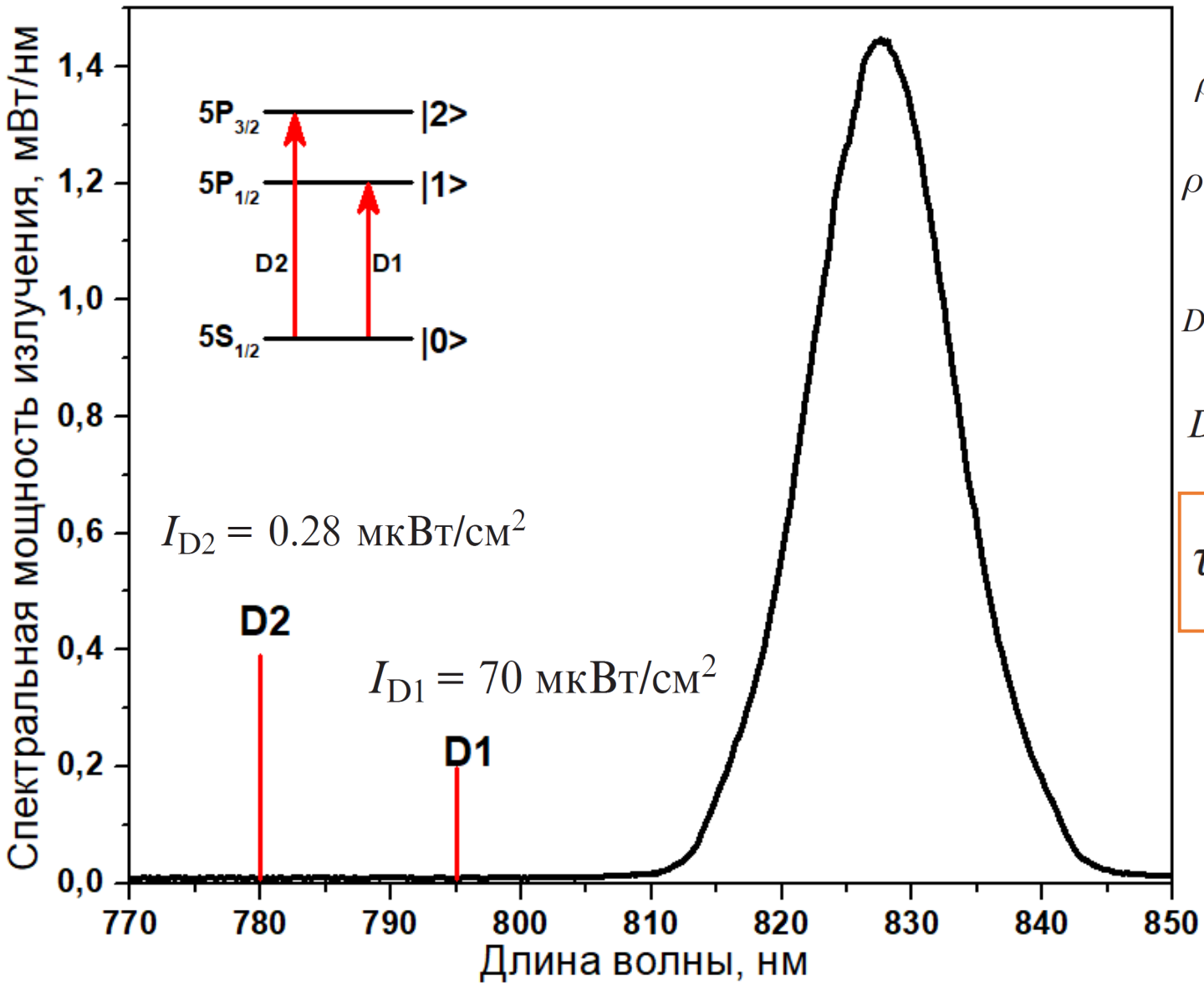
$$\Gamma_D = 6.2\ \mathrm{s}^{-1}$$

A.E. Afanasiev, et al. Appl. Phys. B, **126**, 26 (2020)

Efficiency of localization



Rb notch filter



$$\rho_{00} = \frac{(1+\frac{1}{2}s_1)(1+\frac{1}{2}s_2)}{(1+s_1+s_2+\frac{3}{4}s_1 s_2)},$$

$$\rho_{11} = \frac{\frac{1}{2}s_1(1+\frac{1}{2}s_2)}{(1+s_1+s_2+\frac{3}{4}s_1 s_2)},$$

$$\rho_{22} = \frac{\frac{1}{2}s_2(1+\frac{1}{2}s_1)}{(1+s_1+s_2+\frac{3}{4}s_1 s_2)}$$

$$D = D_1 + D_2 = \frac{1}{2}\sum_{i=1,2} R_i^{sc}(\hbar k_i)^2$$

$$D = 9.7 \times 10^{-50} \text{ Дж}\cdot\text{кг/с}$$

$$\tau = \frac{U_0 m}{D} = 1{,}5 \text{ ms}$$

Rb notch filter

28 °C
77 °C
104 °C

Transmittance

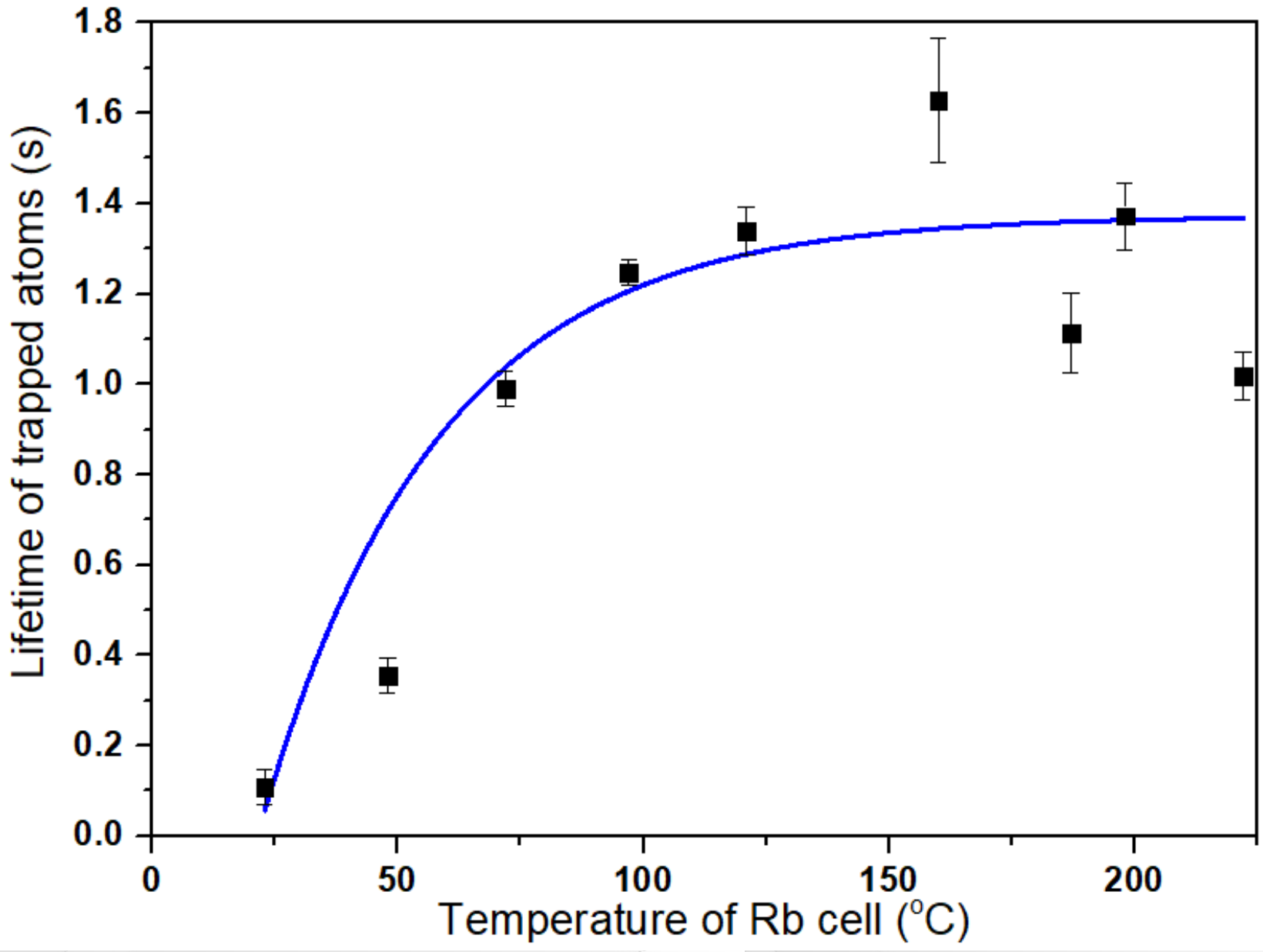
1.0
0.8
0.6
0.4
0.2
0.0

780.010
780.015
780.020
780.025
780.030
780.035

Wavelength (nm)

Rb notch filter

τ=420 fs

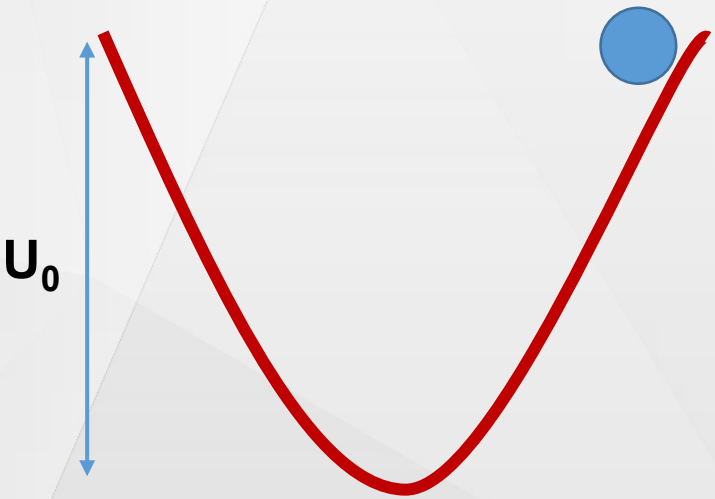


A.M. Mashko, et al. Quantum Electronics, **50**, accepted (2020)

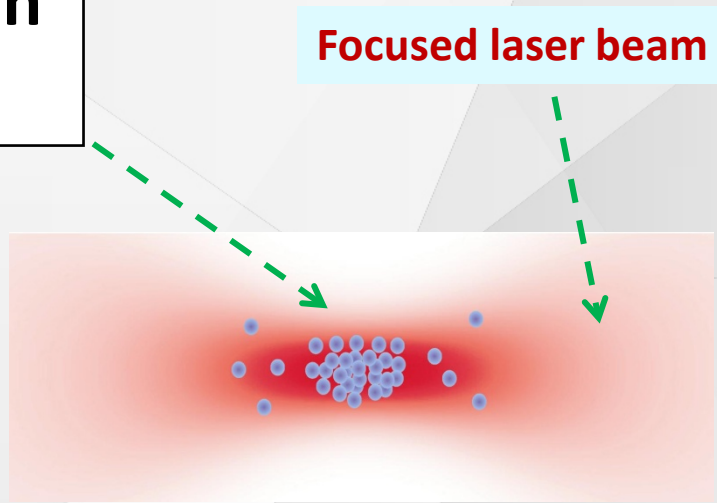
Spectroscopy of atoms trapped in pulsed traps

Spectral properties of trapped atom

Atom localization in dipole trap



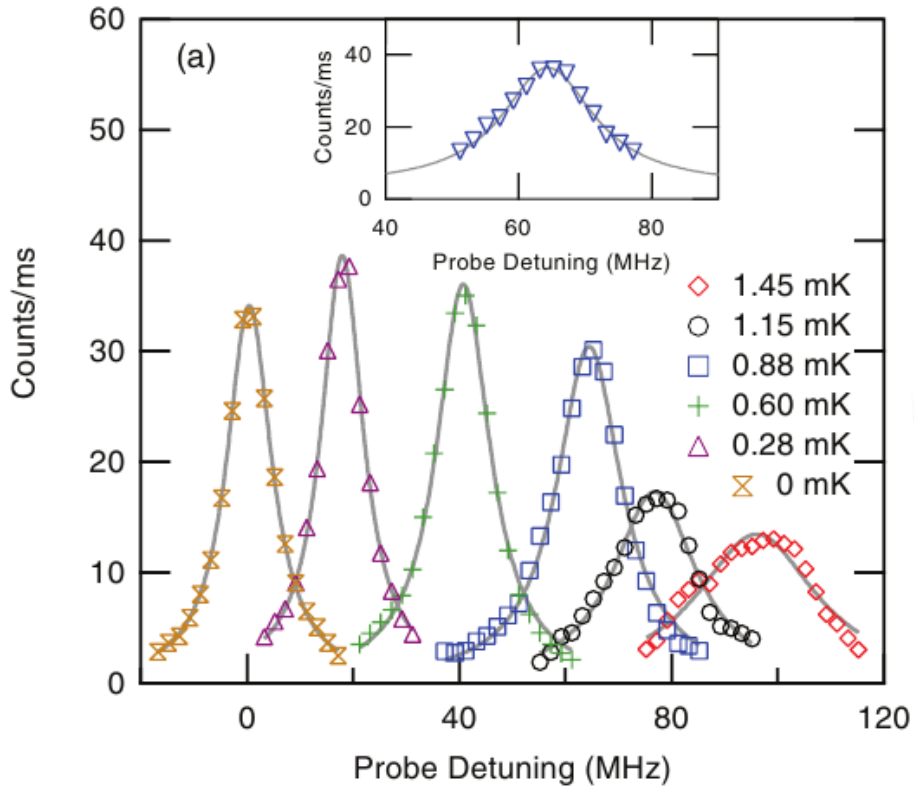
ac Stark

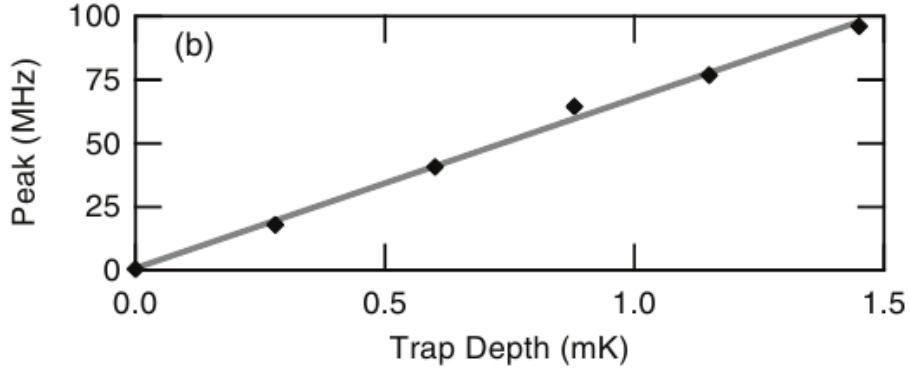


Spectrum shifting

Spectrum broadening

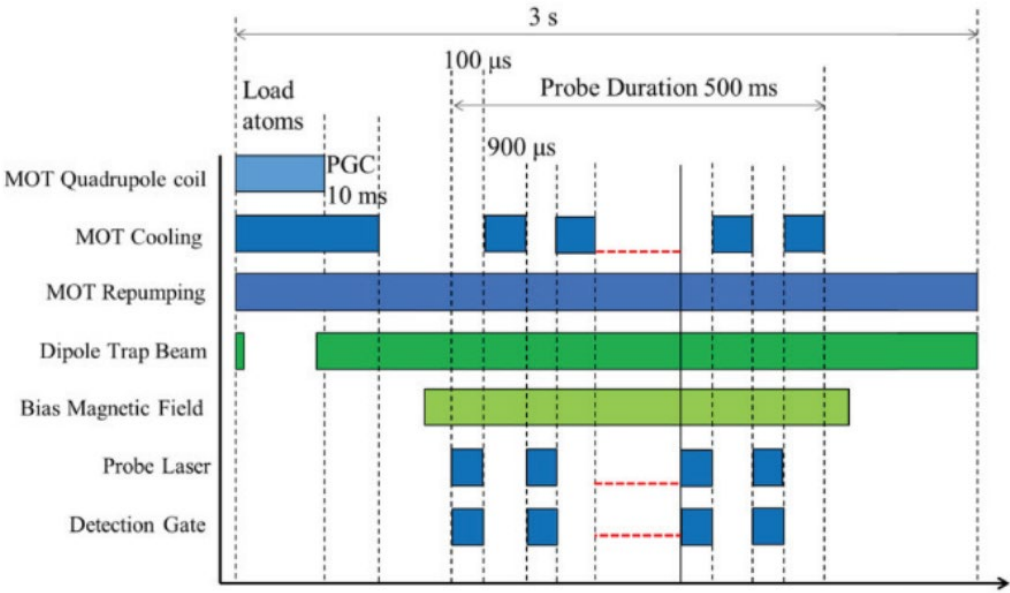
Detection of fluorescence





Gated probing-cooling technique

Additional cooling needs for compensation of heating from probing field



Chung-Yu Shin, M.S. Chapman, Phys.Rev. A, 87, 063408 (2013)
Bei Liu, et. al, Optics Express, 25, 15862 (2017)

Spectroscopy of trapped atoms by selective heating

Momentum diffusion due to photon scattering

$$D = \hbar^2 k^2 \frac{\Gamma}{4} \frac{I/I_{\mathrm{sat}}}{1 + I/I_{\mathrm{sat}} + 4(\delta/\Gamma)^2}$$

δ – detuning of probe laser

τ – lifetime of trapped atoms without probe field

τ_p – time of the atom interaction with the probe field

U_0 – potential depth

Number of atoms in the trap

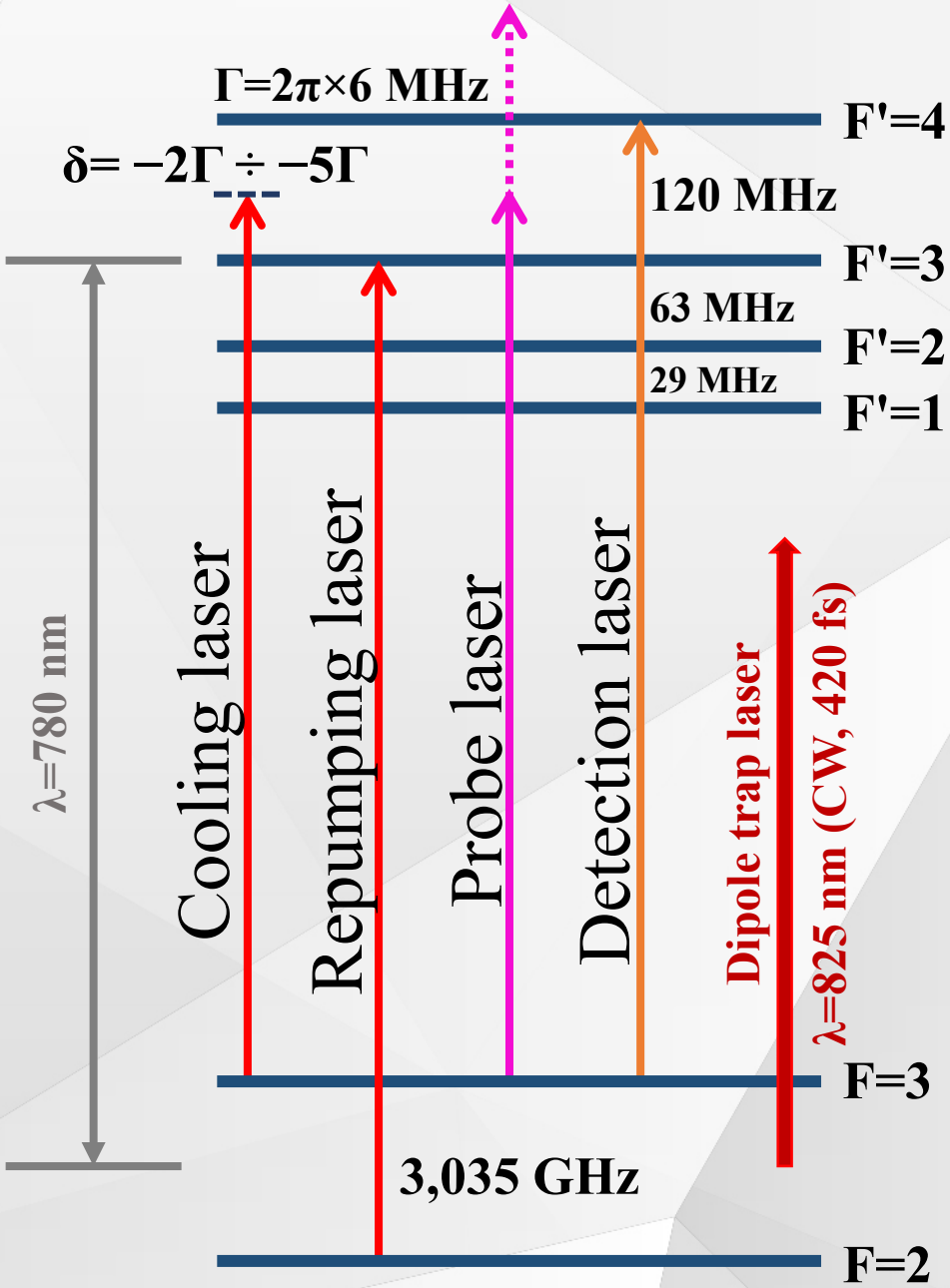
$$N_{\mathrm{p}}(t) = N_0 \mathrm{e}^{-t/\tau} \left(1 - D\tau_{\mathrm{p}}/(m U_0)\right)$$

Relative losses

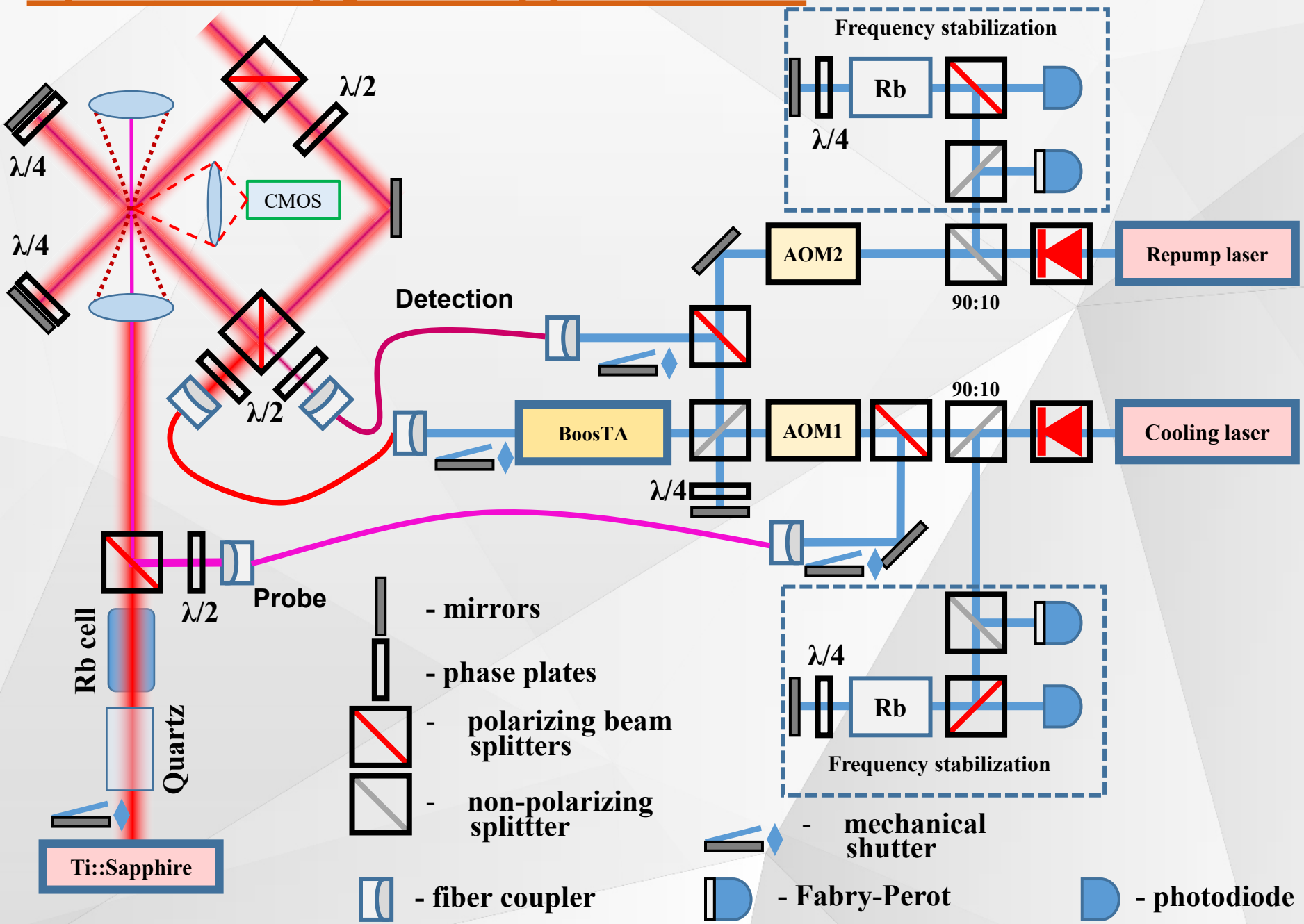
$$A = (N - N_{\mathrm{p}})/N = D\tau_{\mathrm{p}}/(m U_0)$$

A.E. Afanasiev, et al. Quantum Electronics, **50**, 206 (2020)

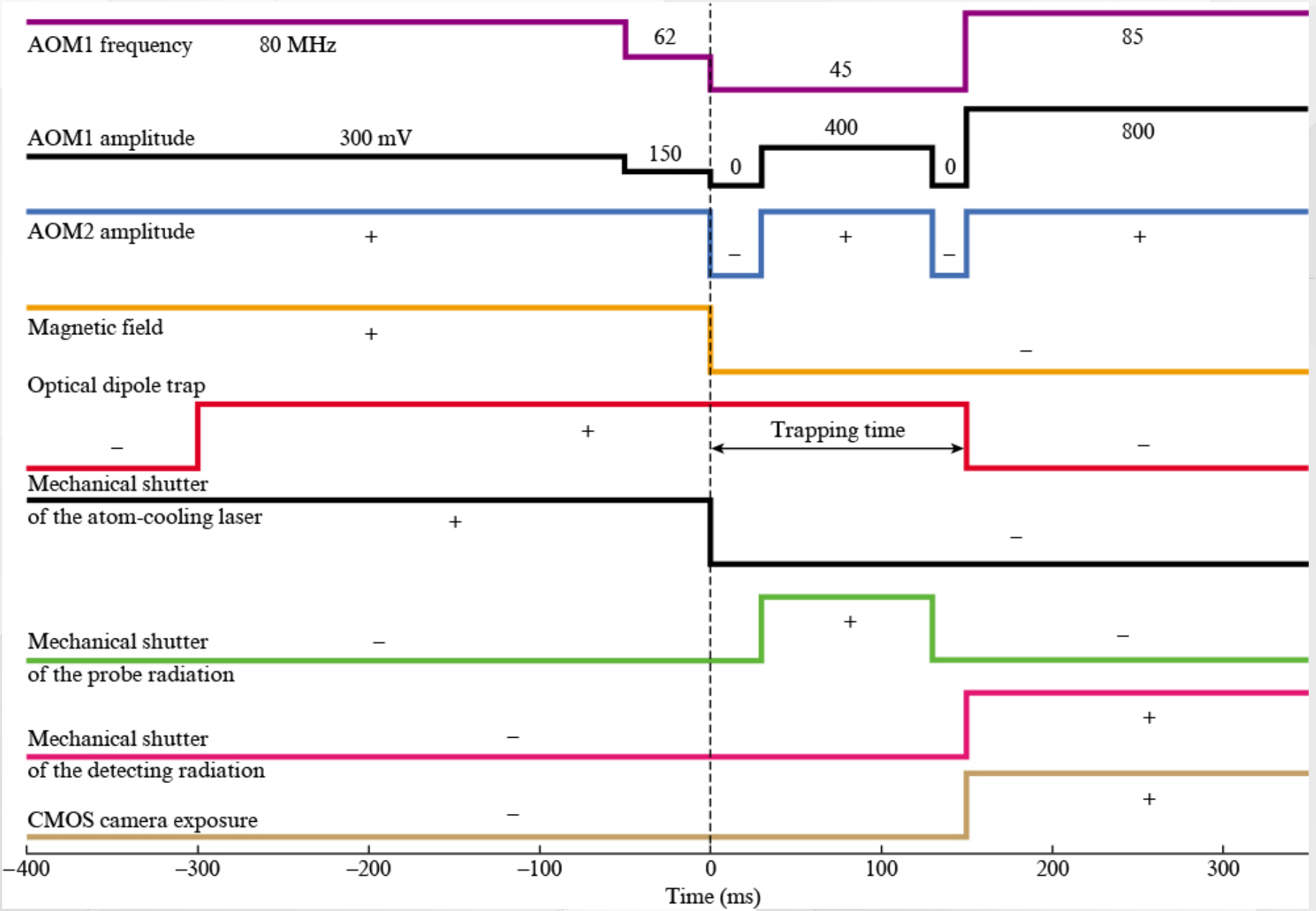
Spectroscopy of trapped atoms



Spectroscopy of trapped atoms

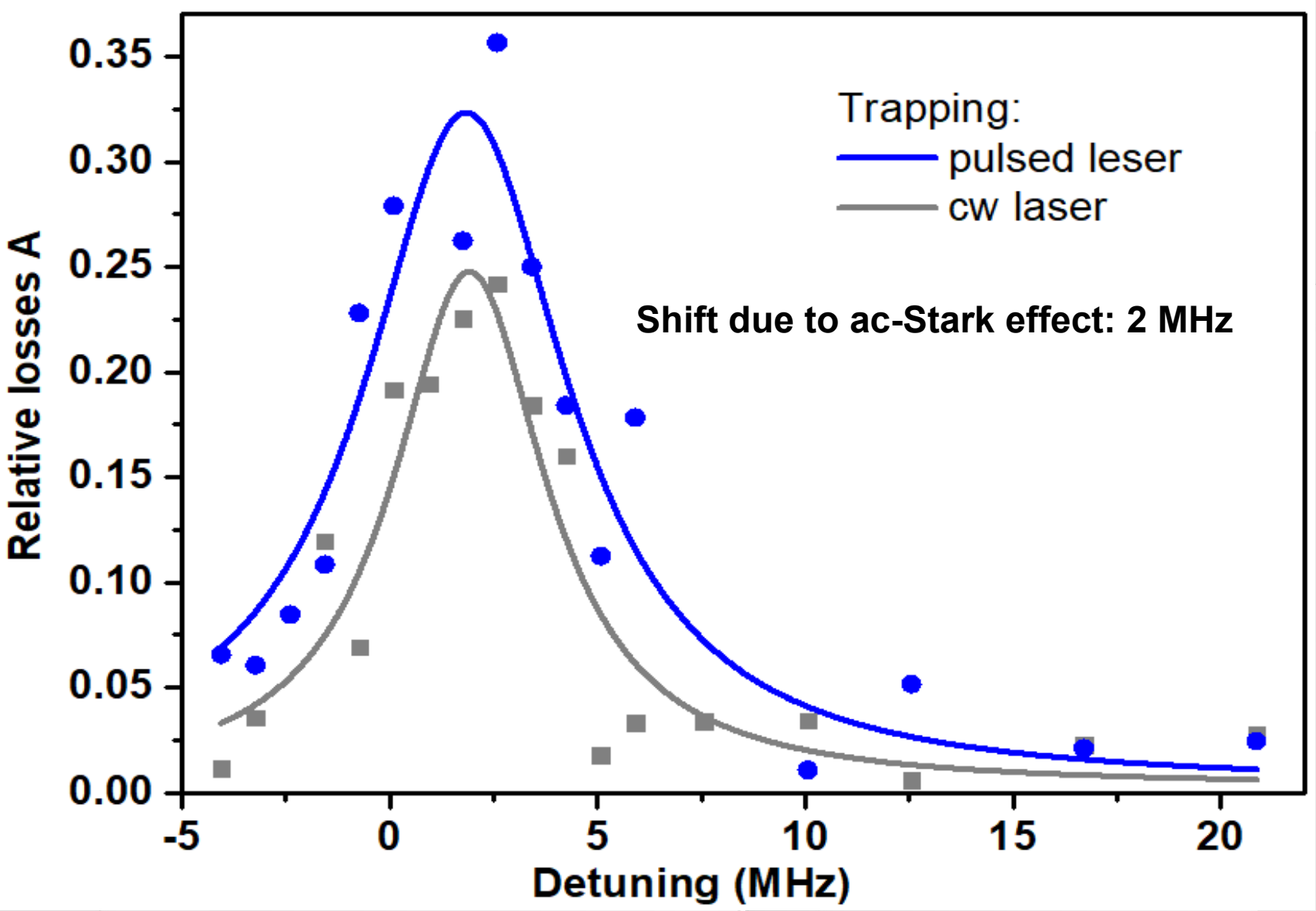


Spectroscopy of trapped atoms



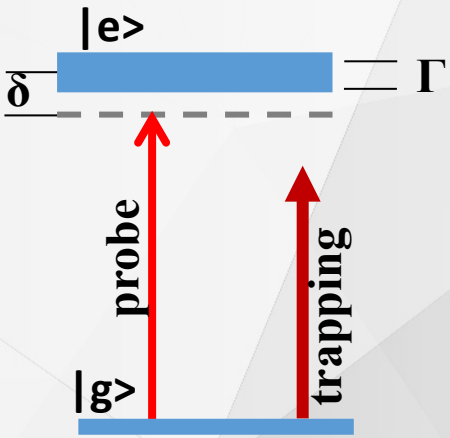
Spectroscopy of trapped atoms

τ=420 fs



A.E. Afanasiev, et al. JETP Lett., **111**, accepted (2020)

Spectroscopy of trapped atoms



Trapping field detuning

Probe field detuning

$$\rho_{gg}(t) + \rho_{ee}(t) = 1$$

$$\frac{d\rho_{ee}(t)}{dt} = i\Omega_p\left(\rho_{ge}(t)e^{-i\delta_p t} - \rho_{eg}(t)e^{i\delta_p t}\right) + i\Omega_d(t)\left(\rho_{ge}(t)e^{-i\delta_d t} - \rho_{eg}(t)e^{i\delta_d t}\right) - \rho_{\mathrm{ee}}\Gamma$$

$$\frac{d\rho_{ge}(t)}{dt} = i\left(\rho_{ee}(t) - \rho_{gg}(t)\right)\left(\Omega_p e^{i\delta_p t} + i\Omega_d(t)e^{i\delta_d t}\right) - \rho_{ge}\frac{\Gamma}{2},$$

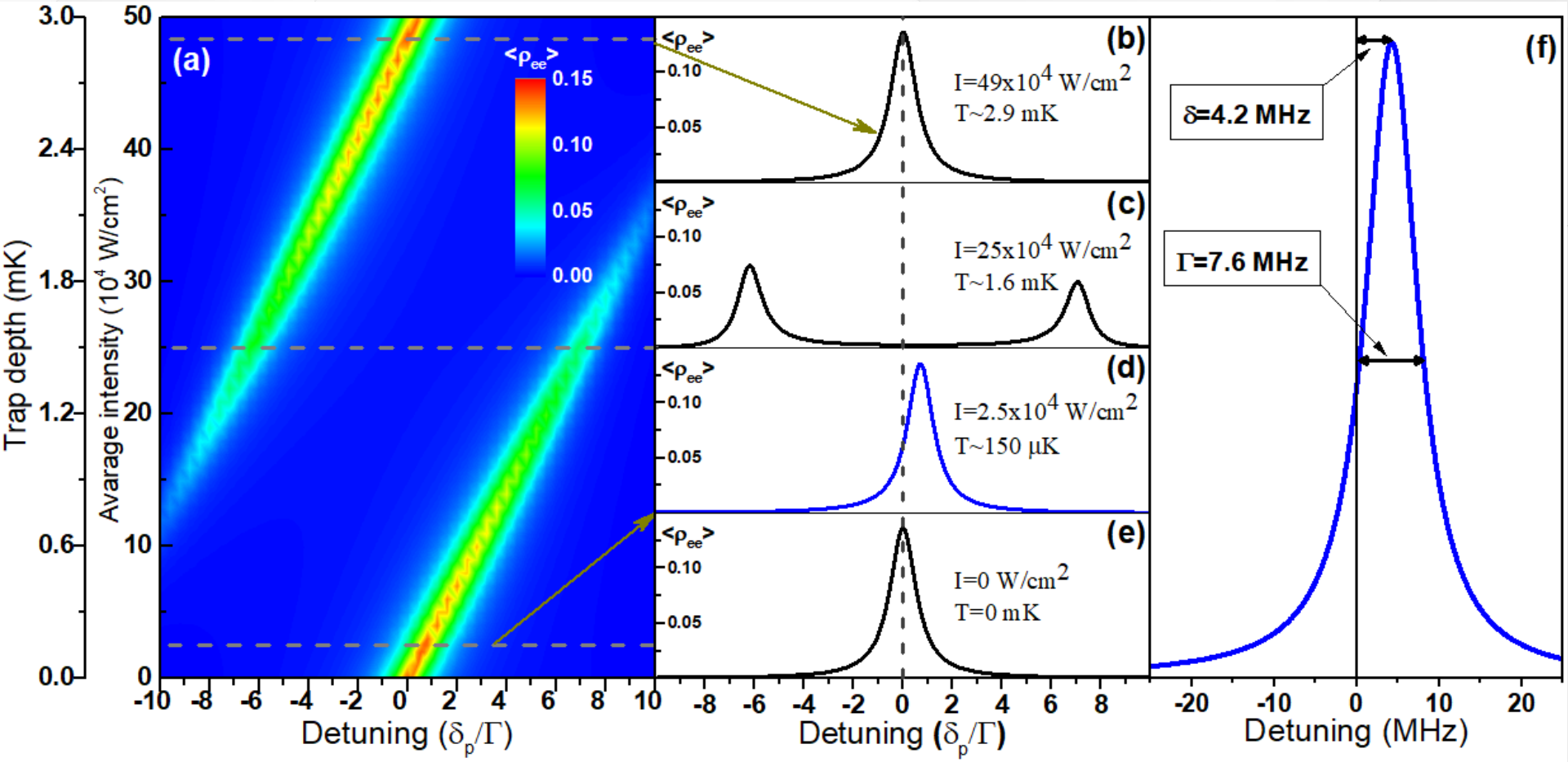
Probe field

Trapping pulsed field

$$\boldsymbol{\Omega} = \frac{\boldsymbol{dE}}{\boldsymbol{2\hbar}}$$

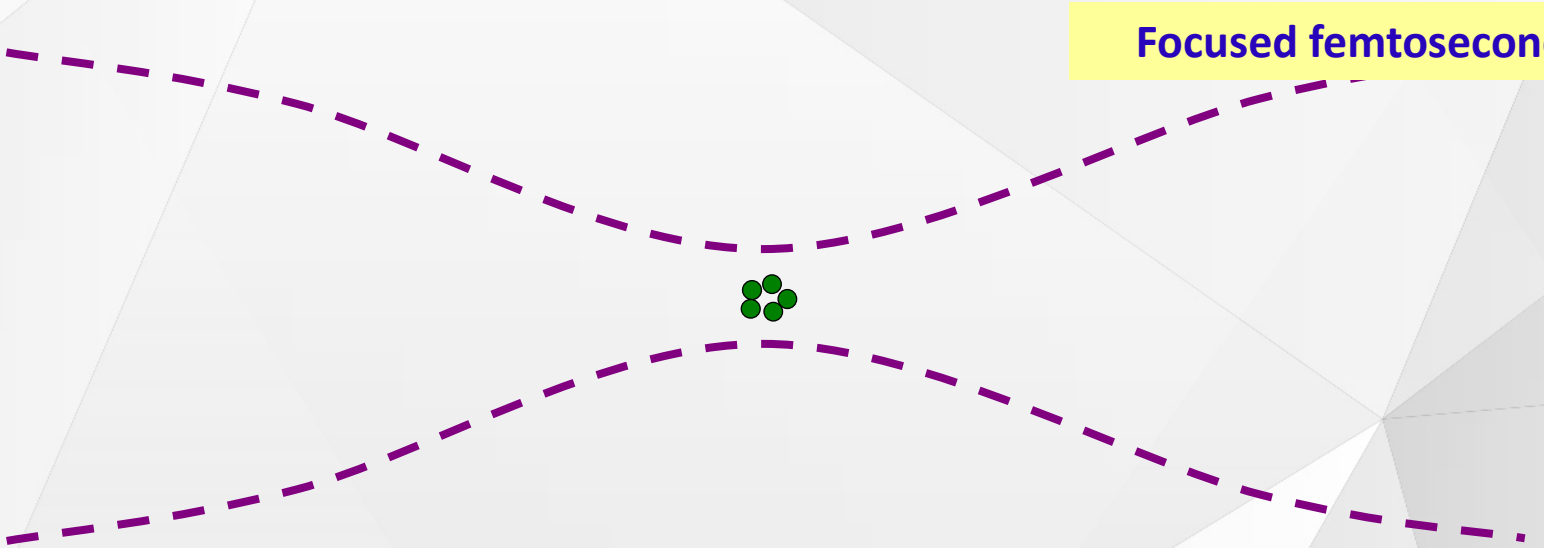
A.E. Afanasiev, et al. JETP Lett., **111**, accepted (2020)

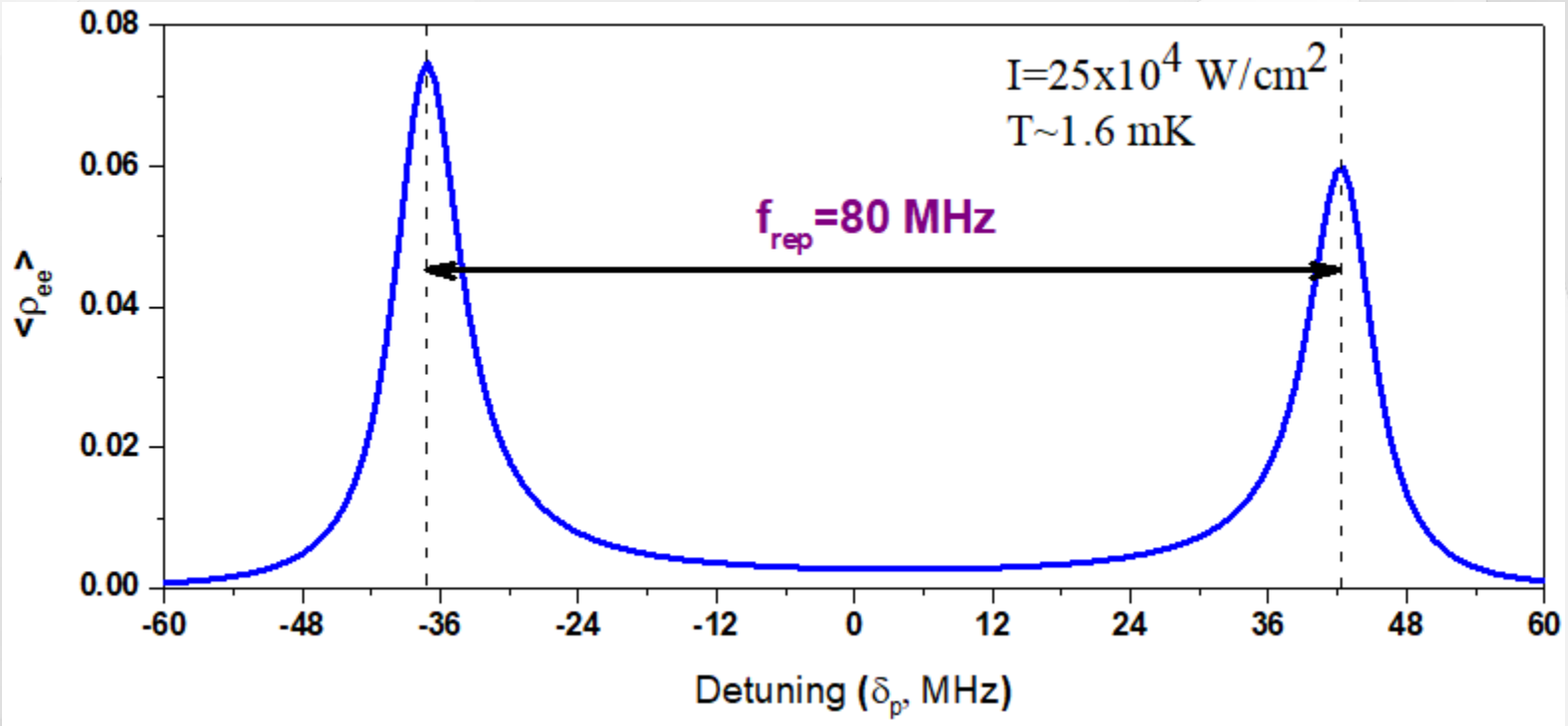
Spectrum calculation vs trapping field strength



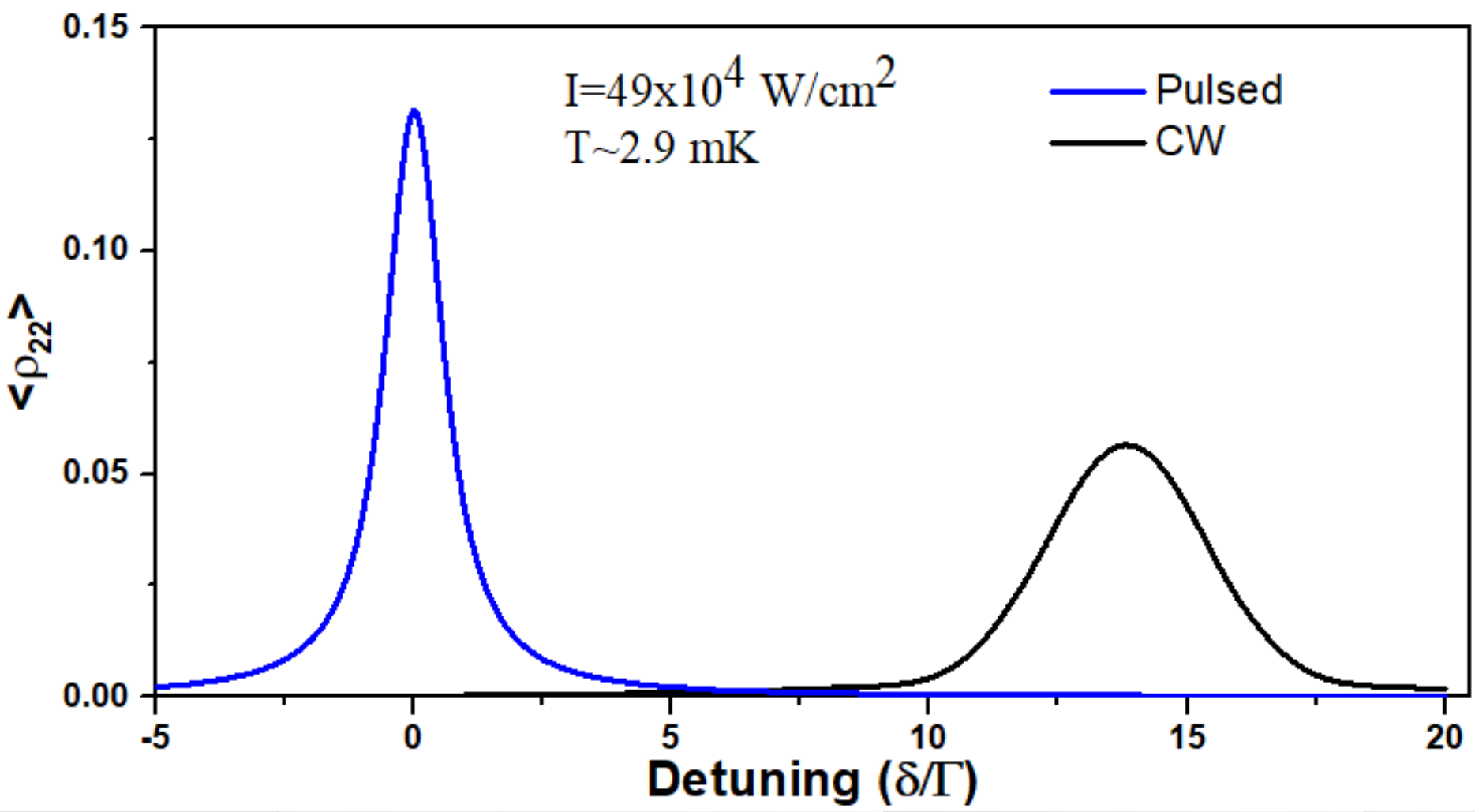
A.E. Afanasiev, et al. JETP Lett., **111**, accepted (2020)

Spectrum calculation vs trapping field strength

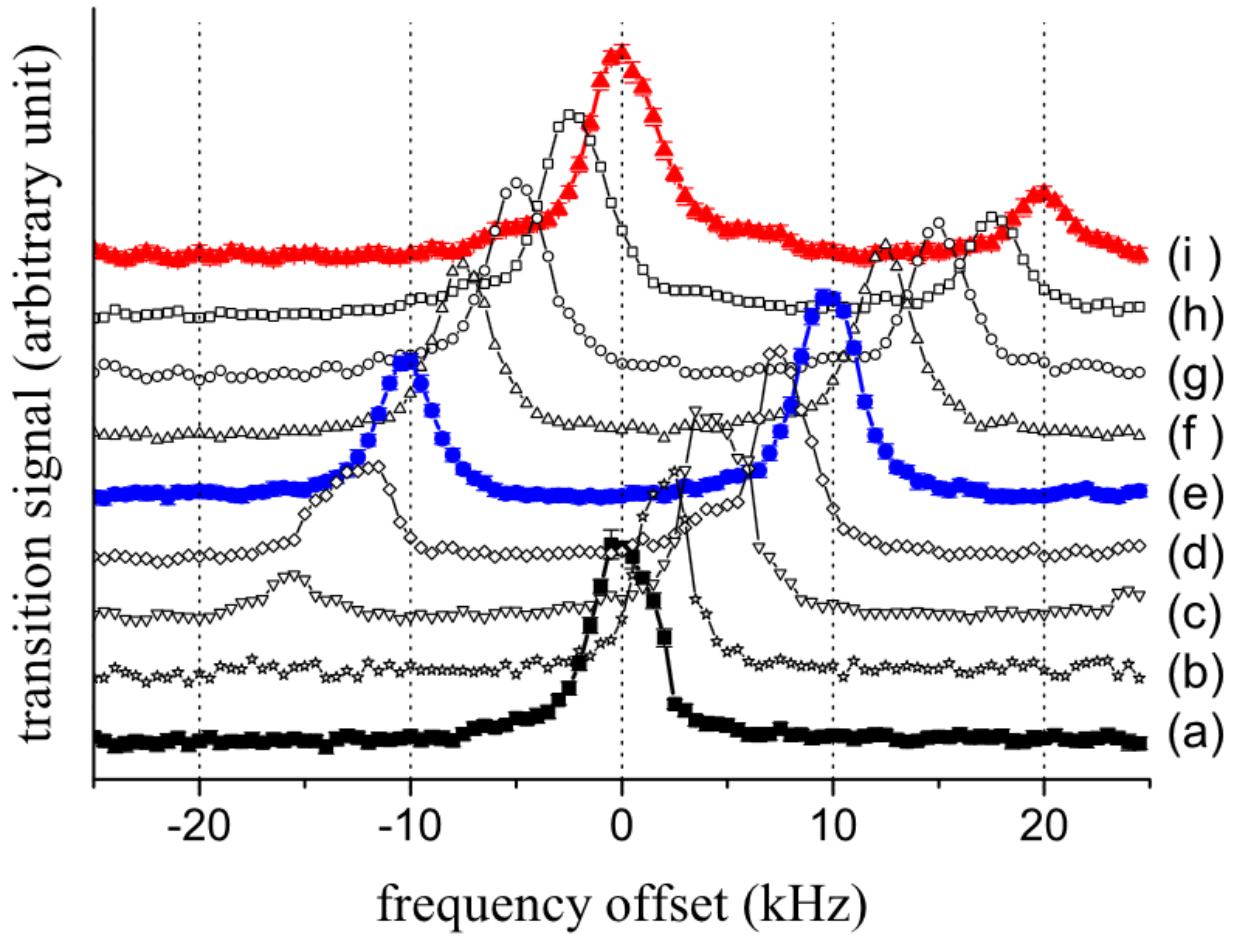




Line shift in CW trap



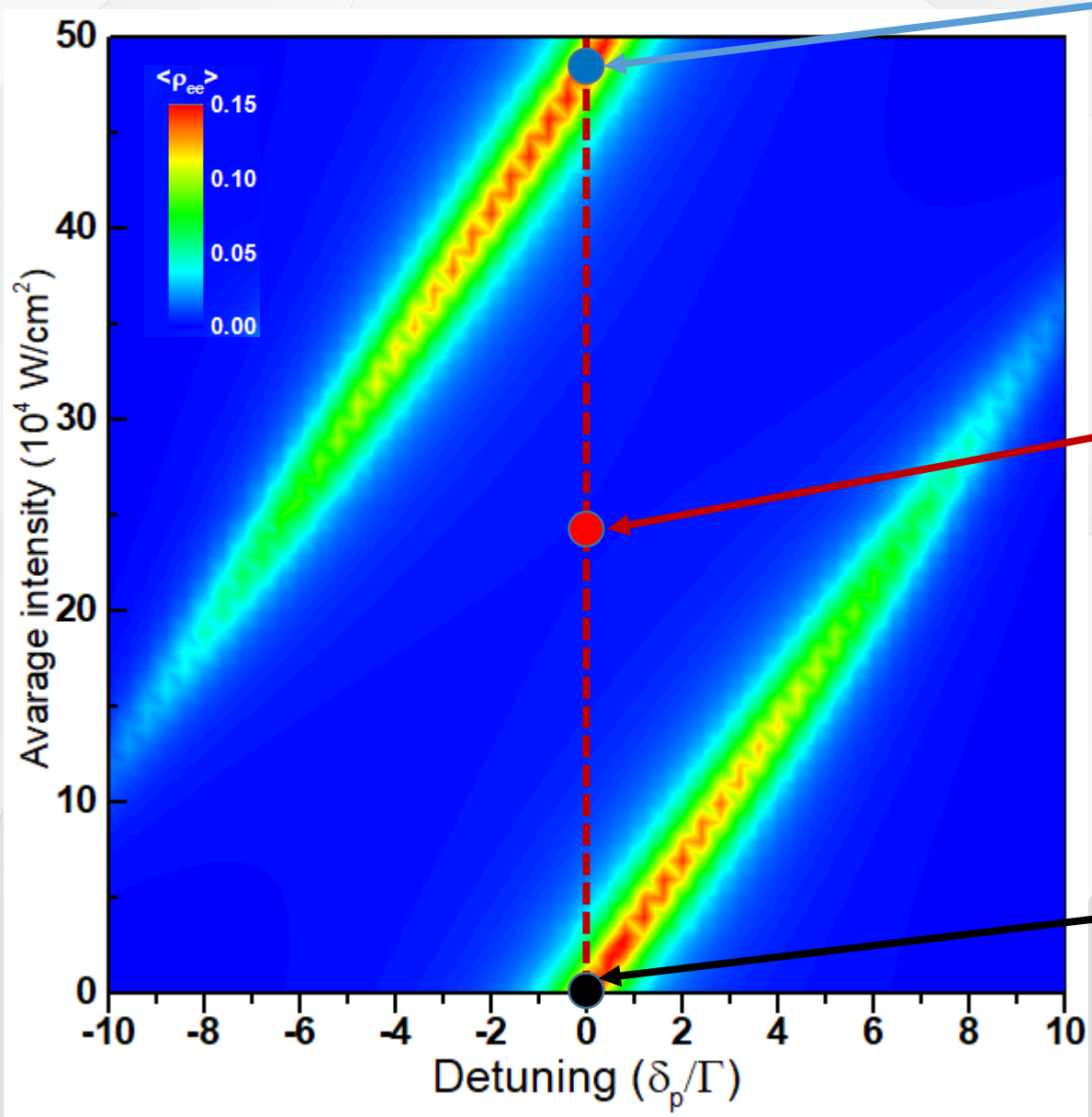
Spectrum in under pulsed perturbation

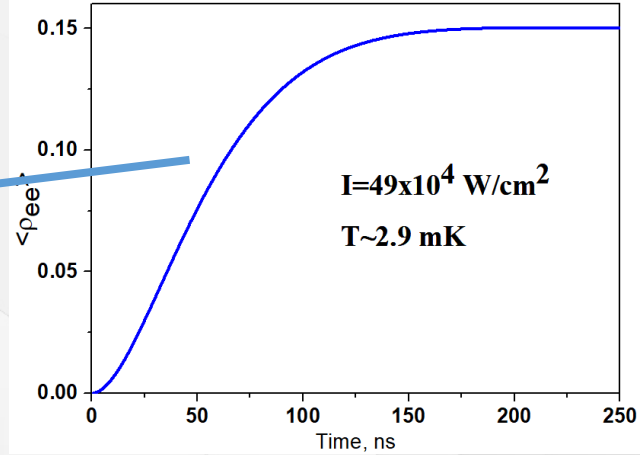


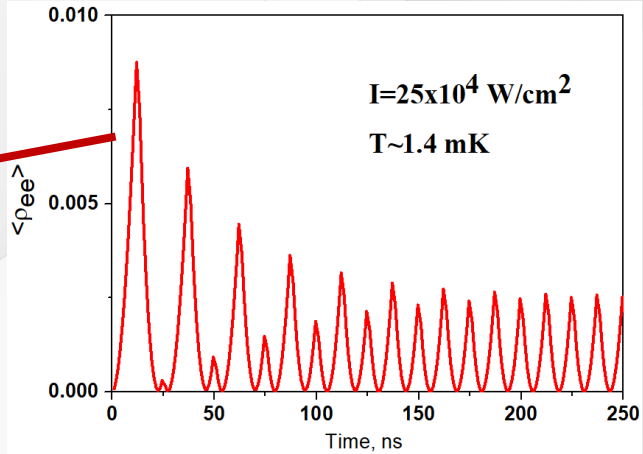
Experimental Rabi spectra under pulsed perturbations: (a) without a perturbation and (b) to (i) with increasing by $\pi/4$. In particular, (e) $\Delta\varphi = \pi$ and (i) $\Delta\varphi = 2\pi$

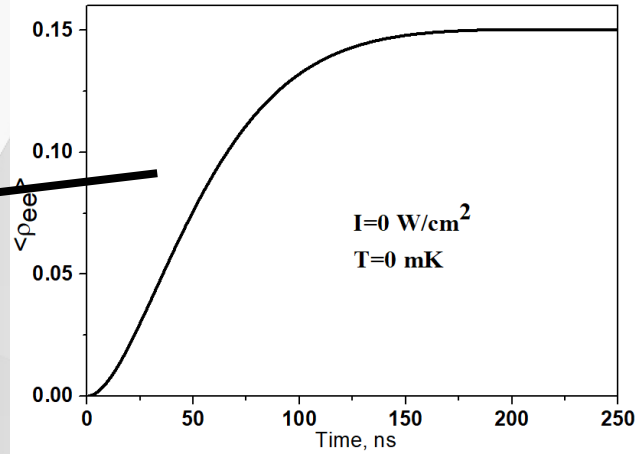
J. M. Choi, et al., Journal of the Korean Physical Society, **51**, 296 (2007)
J. M. Choi, et al., Physical Review A, **77**, 010501 (2008)

Position of the line









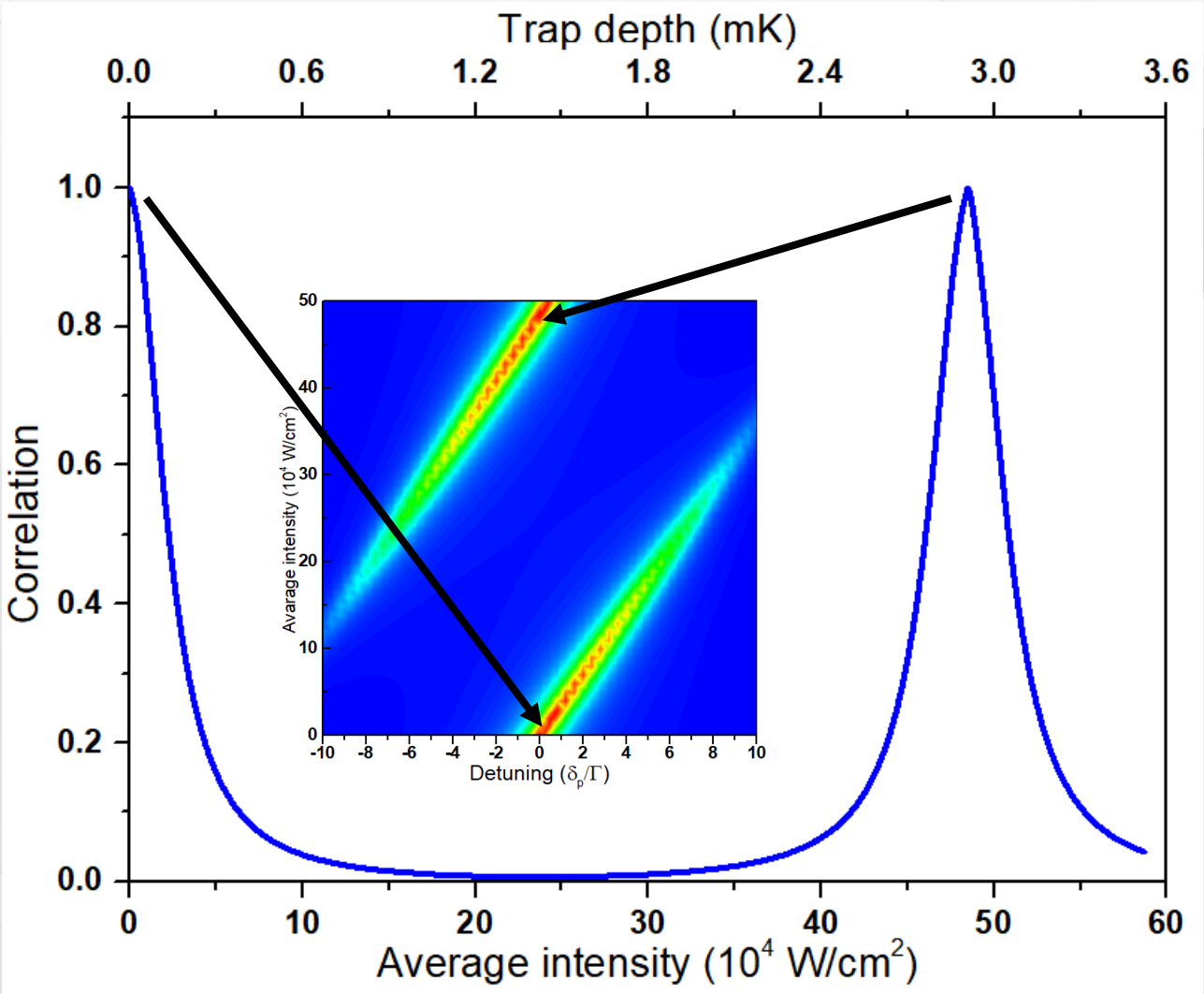
Correlation function

$\rho_{ee}(I_{trap}, t)$ – population of excited state of trapped atom

I_{trap} - average intensity of trapped field

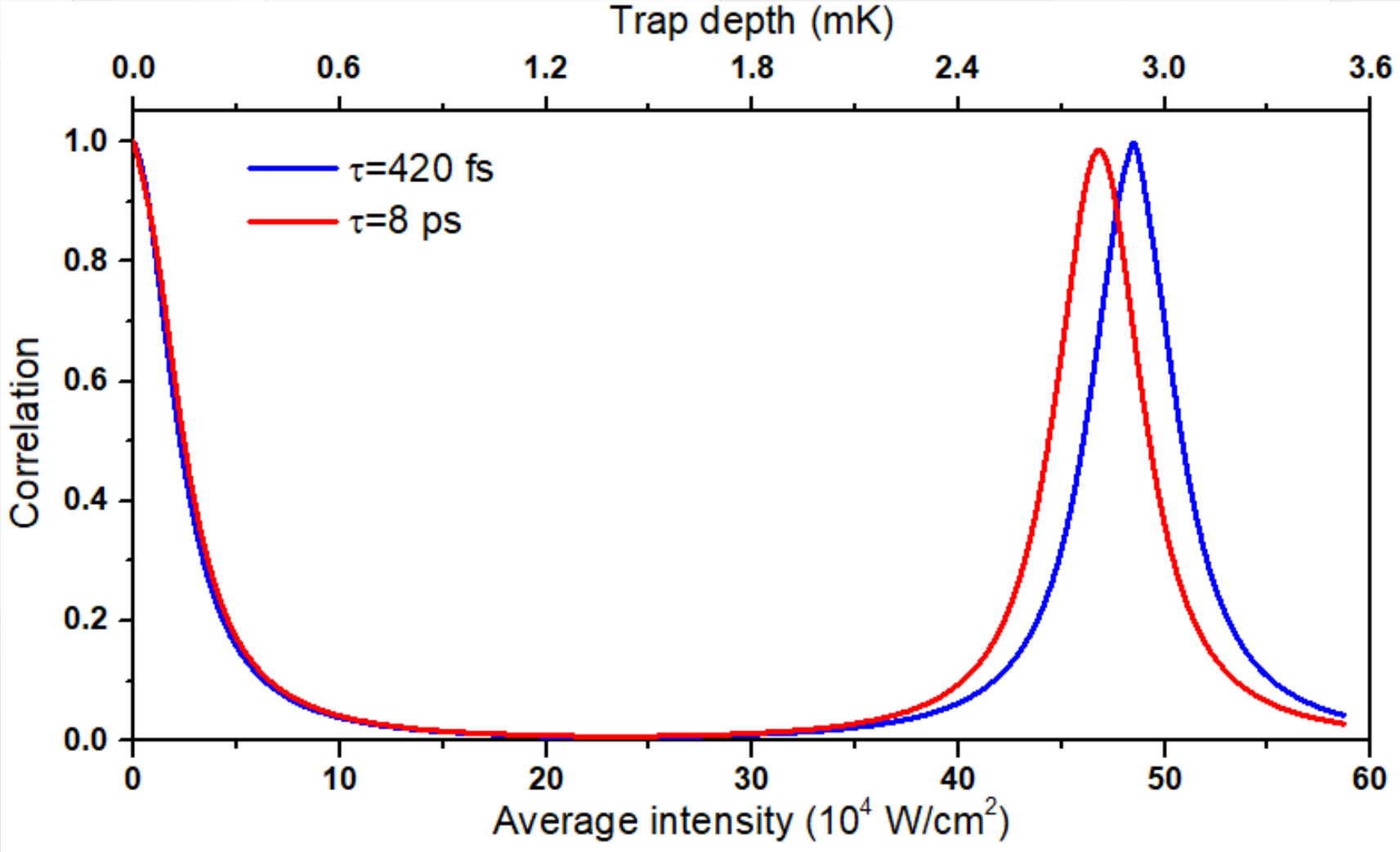
$$Correlation = \frac{\langle \rho_{ee}(I_{trap}, t)\rho_{ee}(0, t)\rangle}{\langle \rho_{ee}(0, t)\rho_{ee}(0, t)\rangle}$$

τ=420 fs



Correlation function

An ordinary condition for 2π pulse do not work!



Generalized Rabi frequency

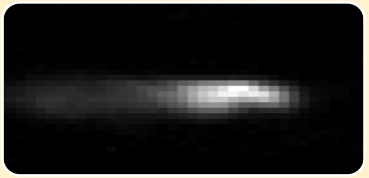
$$\tilde{\Omega} = \sqrt{\delta^2 + \Omega^2}$$

Rabi frequency

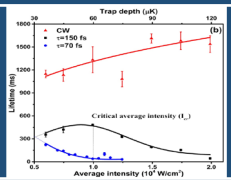
$$\Omega = \frac{dE}{\hbar}$$

$$\delta \gg \Omega$$

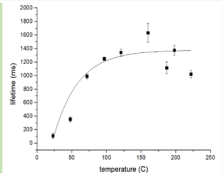
Key points



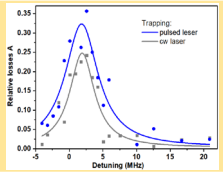
The atom dipole trap with pulsed laser radiation of 70 fs duration was firstly demonstrated



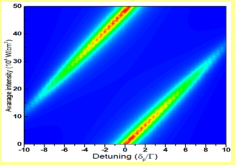
The dependence of the atom lifetime on the average intensity and pulse duration was investigated



The effect of the Rb notch filter on the lifetime of atoms was examined



Spectrum of trapped atoms has been measured and analyzed



It is possible to trap atoms without optical shift of absorption line

www.atomoptics.ru

List of publications

- V. I. Balykin, "Motion of an Atom under the Effect of Femtosecond Laser Pulses: From Chaos to patial Localisation", JETP Letters, Vol. 81, 209, (2005)
- D.N. Yanyshev, V.I. Balykin, Yu.V. Vladimirova, V.N. Zadkov, “Dynamics of atoms in a femtosecond optical dipole trap”, Physical review A, 87, 033411 (2013)
- A.E. Afanasiev, A.A. Meysterson, A.M. Mashko, P.N. Melentiev, V.I. Balykin, “Atom femto trap: experimental realization”, Appl. Phys. B, 126, 26 (2020)
- A.E. Afanasiev, A.M. Mashko, A.A. Meysterson, V.I. Balykin, "Spectroscopy of atoms in an optical dipole trap using spectrally selective heating by a probe laser field", Quantum Electronics, 50, 206 (2020)
- Машко А.М., Мейстерсон А.А., Афанасьев А.Е., Балыкин В.И., “Атомная дипольная импульсная ловушка со спектральной фильтрацией лазерного излучения”, Квантовая электроника, 50, принята к печати (2020)
- А.Е. Афанасьев, А.М. Машко, А.А. Мейстерсон, В.И. Балыкин, “Спектроскопия атомов рубидия в импульсной оптической дипольной ловушке фемтосекундной длительности”, Письма в ЖЭТФ, 111, принята к печати (2020)


Thank you for your attention!