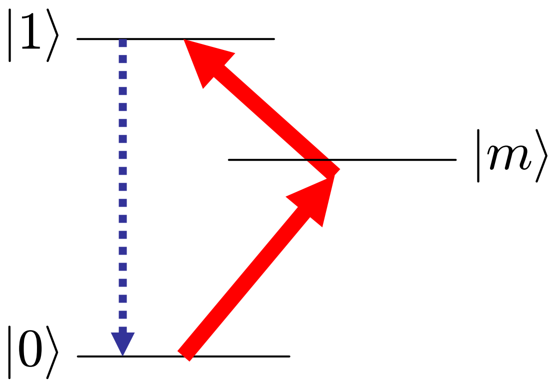
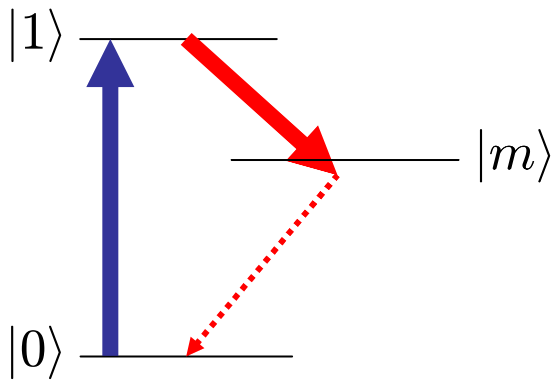
W drugim rzędzie



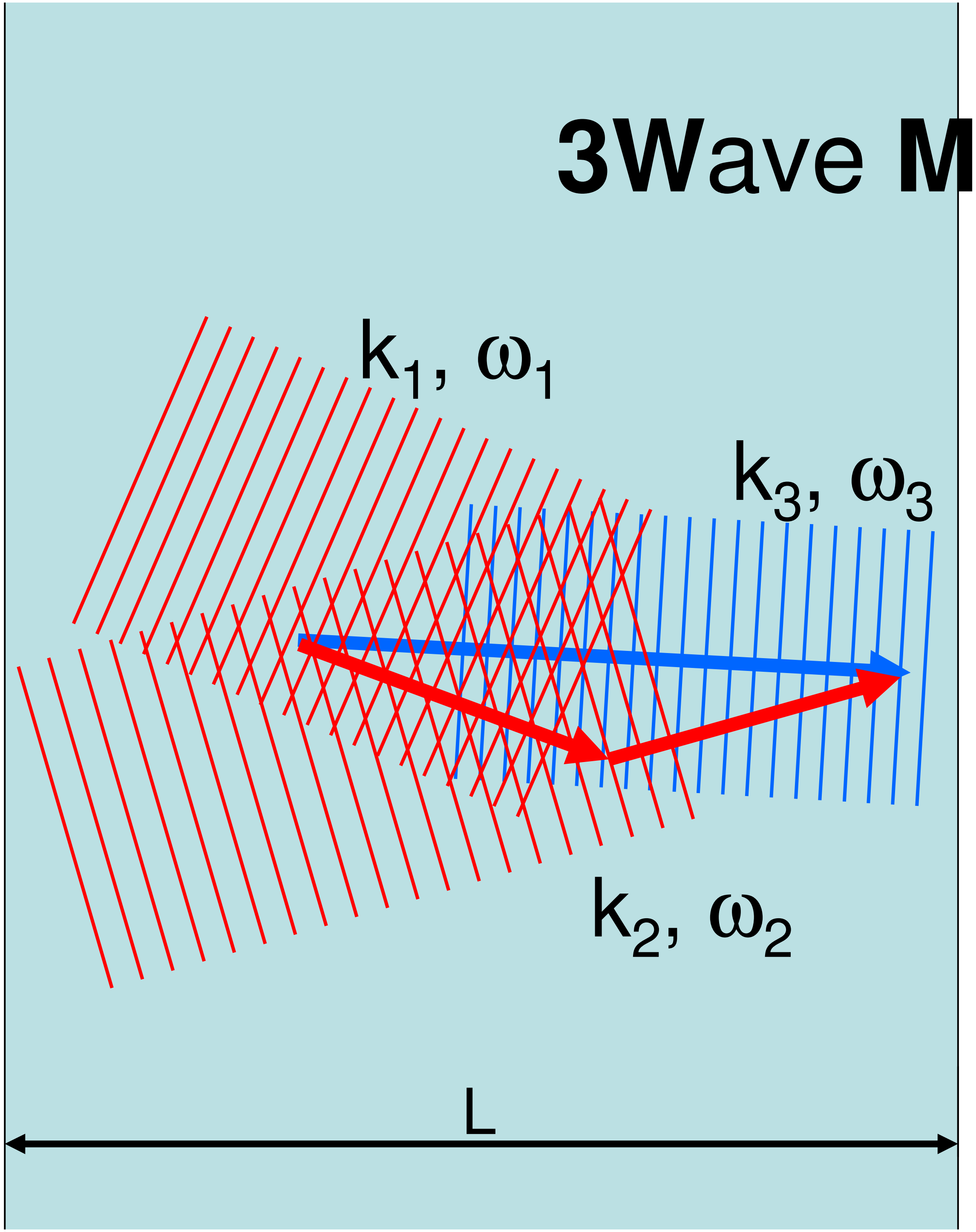
SHG
SFG



DFG
PDC

■ ■ ■

3Wave Mixing



$$\omega_3 = \omega_1 + \omega_2$$

$$k_{3\perp} = k_{1\perp} + k_{2\perp}$$

sprawność
$\sim \mathrm{sinc}^2[\Delta k L/2]$

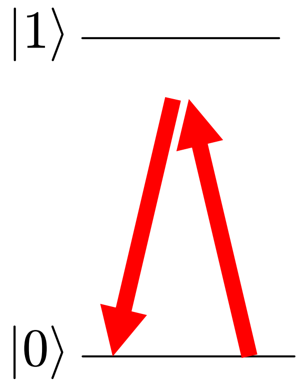
$$\Delta k = k_{3z} - k_{1z} - k_{2z}$$

2

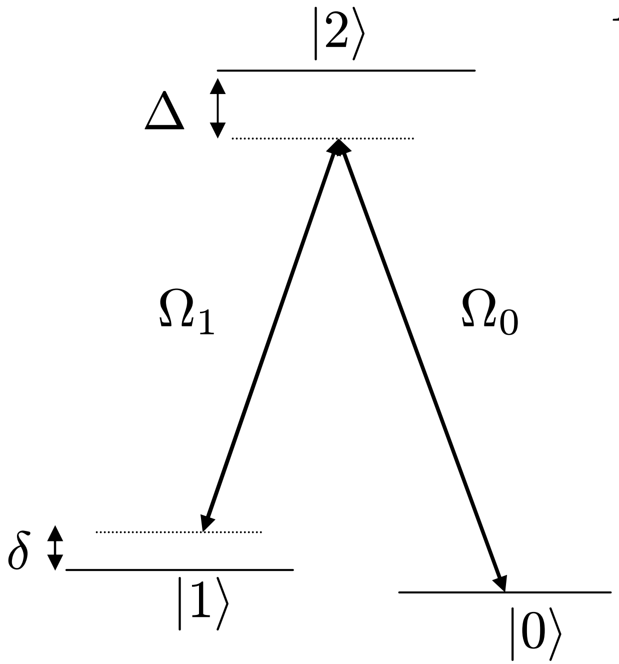
Efekty wielofotonowe: życie atomów

Raman. EIT.

Lightshift



Λ-system



$$H = -\frac{\hbar}{2}\begin{pmatrix} -2\omega_{02} & 0 & \Omega_0 e^{-i\omega_0 t} \\ 0 & -2\omega_{12} & \Omega_1 e^{-i\omega_1 t} \\ \Omega_0 e^{i\omega_0 t} & \Omega_1 e^{i\omega_1 t} & -2\Delta \end{pmatrix}$$

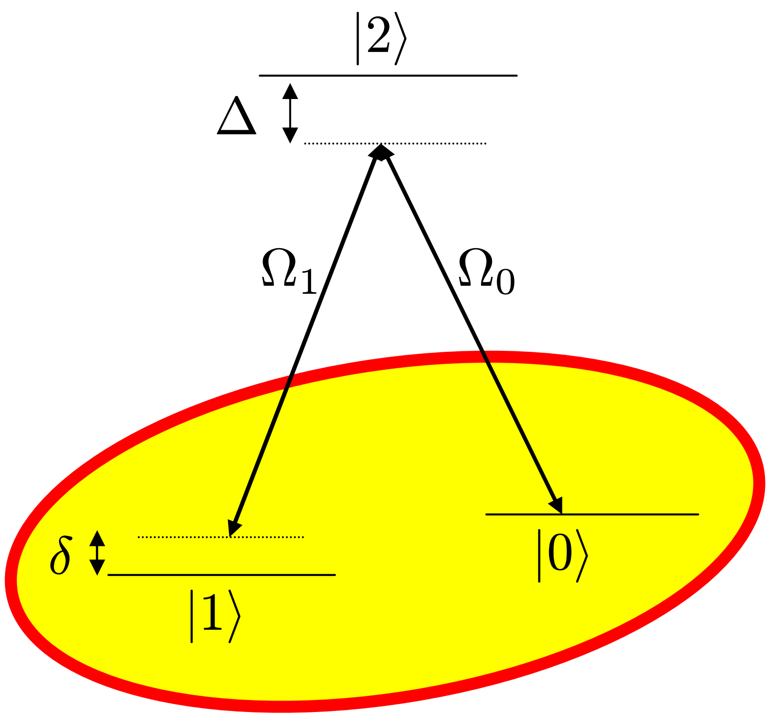
$$\tilde{H}_{int} = -\frac{\hbar}{2}\begin{pmatrix} 0 & 0 & \Omega_0 \\ 0 & 2\delta & \Omega_1 \\ \Omega_0 & \Omega_1 & -2\Delta \end{pmatrix}$$

przejście do układu wirującego
wraz z falami optycznymi

$$|\psi\rangle = \alpha|0\rangle + \beta e^{-i(\omega_0-\omega_1)t}|1\rangle + \gamma e^{-i\omega_0 t}|2\rangle$$

Eliminacja adiabatyczna

$$|\psi\rangle = \alpha|0\rangle + \beta e^{-i(\omega_0-\omega_1)t}|1\rangle + \gamma e^{-i\omega_0 t}|2\rangle$$



$$\begin{cases} i\dot{\alpha}(t) = \frac{\Omega_0^*}{2}\gamma \\ i\dot{\beta}(t) = -\delta\beta + \frac{\Omega_1^*}{2}\gamma \\ i\dot{\gamma}(t) = \frac{\Omega_0}{2}\alpha + \frac{\Omega_1}{2}\beta + \Delta\gamma \end{cases}$$

=0

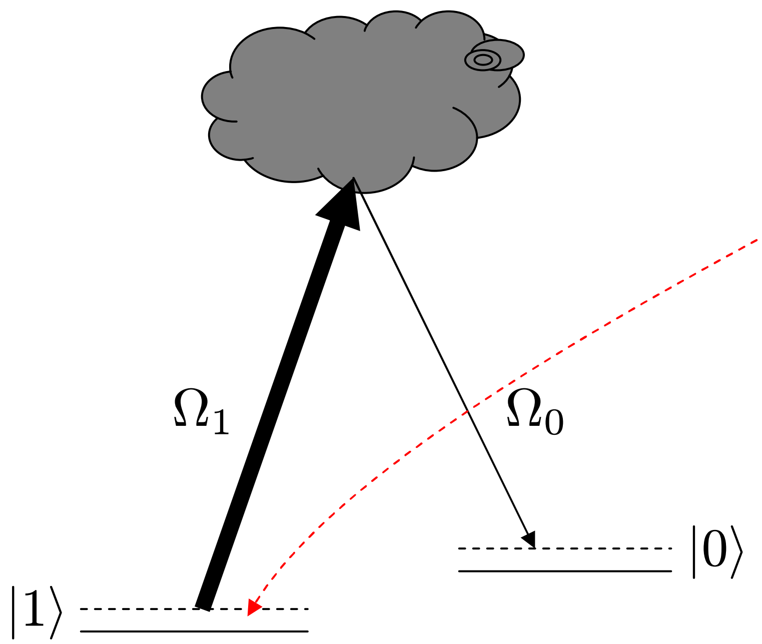
$$\gamma = -\frac{\Omega_0}{2\Delta}\alpha - \frac{\Omega_1}{2\Delta}\beta$$

$$H_{eff} = -\hbar \begin{bmatrix} \frac{|\Omega_0|^2}{4\Delta} & \frac{\Omega_R^*}{2} \\ \frac{\Omega_R}{2} & -\delta + \frac{|\Omega_1|^2}{4\Delta} \end{bmatrix}$$

$$\Omega_R \equiv \frac{\Omega_0\Omega_1^*}{2\Delta}$$

E Brion *et al* 2007 *J. Phys. A: Math. Theor.* **40** 1033

Rozpraszanie Ramana

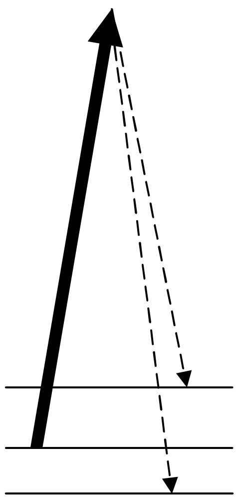


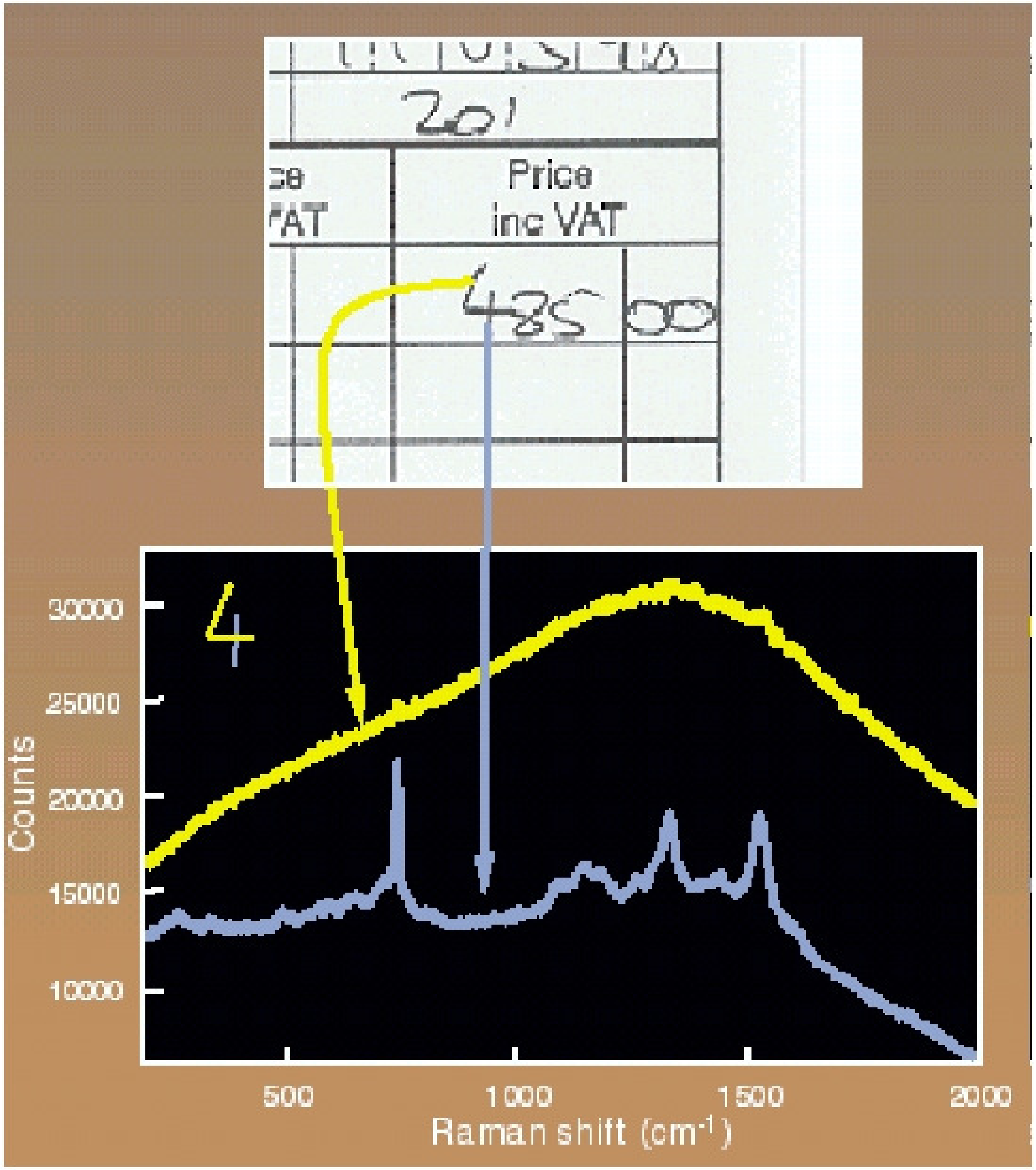
$$H_{eff} = -\hbar \begin{bmatrix} \frac{|\Omega_0|^2}{4\Delta} & \frac{\Omega_R^*}{2} \\ \frac{\Omega_R}{2} & -\delta + \frac{|\Omega_1|^2}{4\Delta} \end{bmatrix}$$

$$\Omega_R \equiv \frac{\Omega_0 \Omega_1^*}{2\Delta}$$

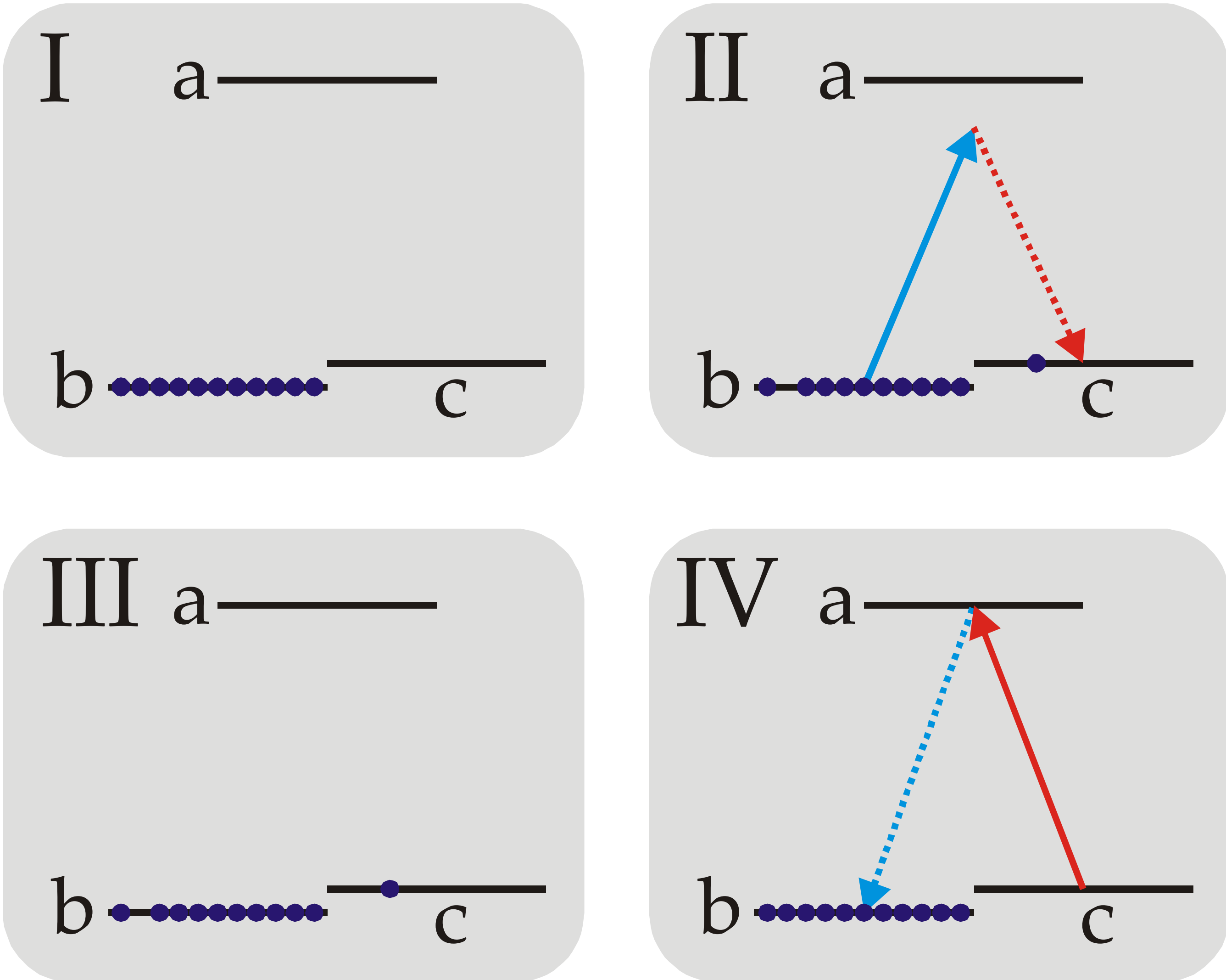
$$\Omega = \frac{Ed}{\hbar} \to \kappa \hat{a}$$

Zastosowania Ramana

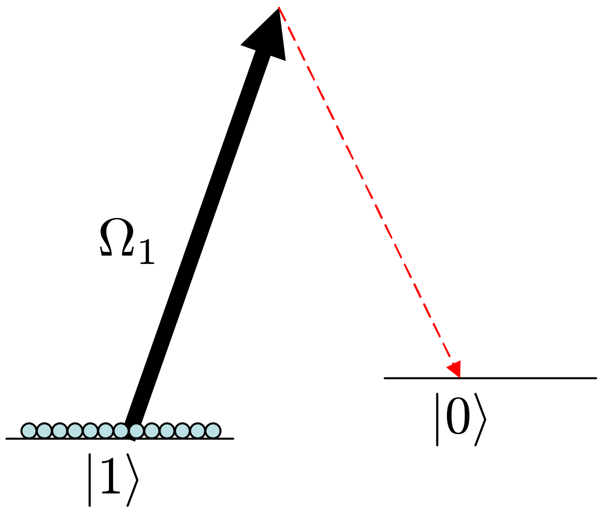


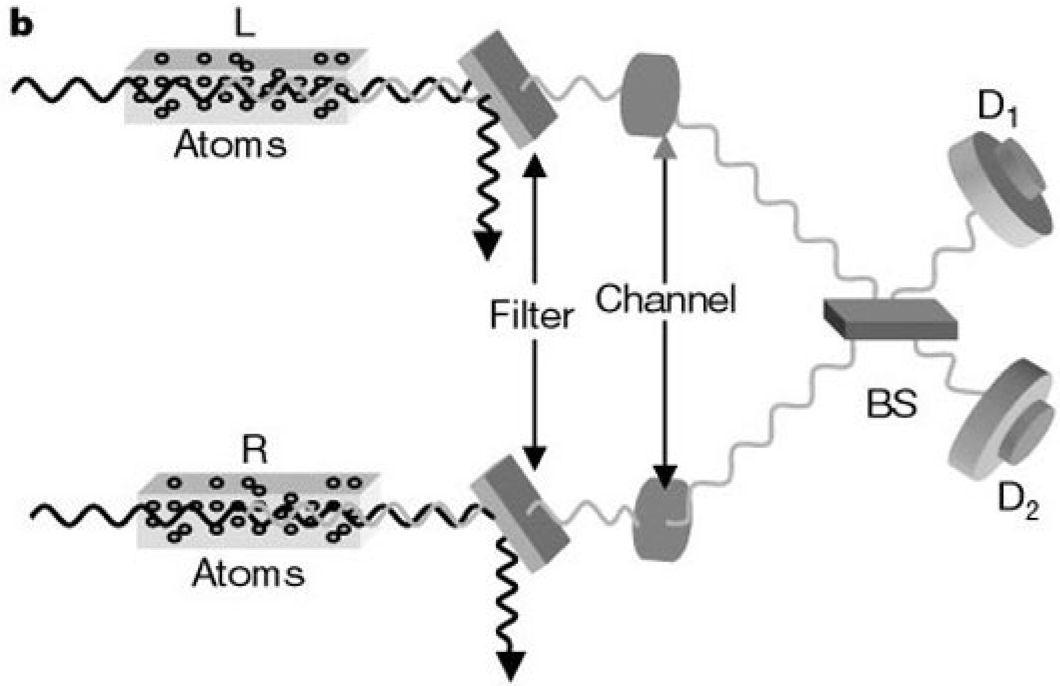


Działo fotonowe



Protokół DLCZ

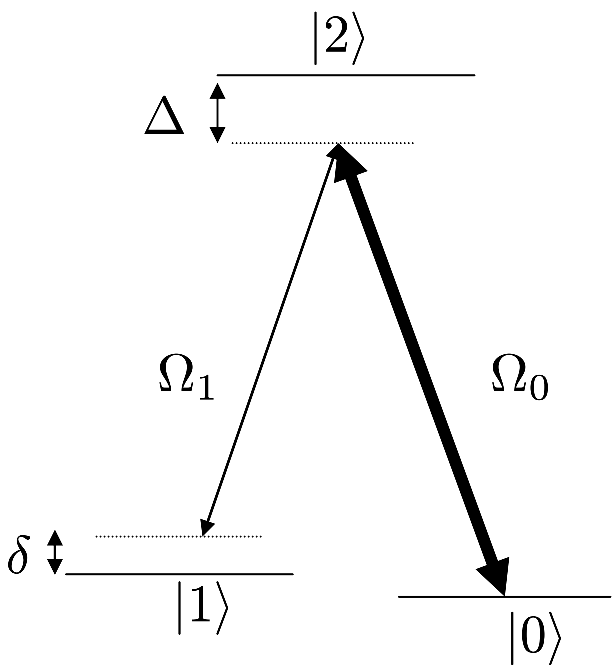




$$|1_a\rangle|0_E\rangle + \sqrt{p}|0_a\rangle|1_E\rangle + \ldots$$

Duan, Lukin, Cirac, Zoller. *Nature* **414**, 413 (2001).

Coherent Population Trapping



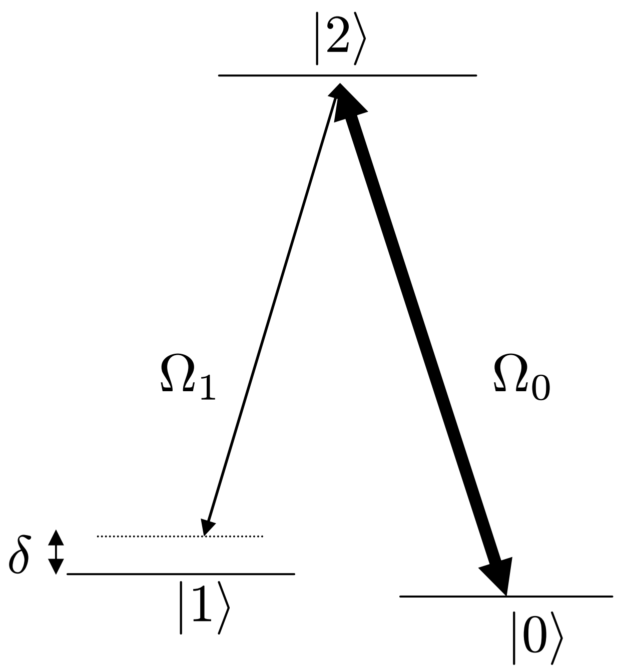
$$\tilde{H}_{int} = -\frac{\hbar}{2}\begin{pmatrix} 0 & 0 & \Omega_0 \\ 0 & 2\delta & \Omega_1 \\ \Omega_0 & \Omega_1 & -2\Delta \end{pmatrix}$$

dla $\delta = 0$

$$|a_0\rangle = \frac{\Omega_1|0\rangle - \Omega_0|\tilde{1}\rangle}{\sqrt{|\Omega_1|^2 + |\Omega_0|^2}}$$

stan ciemny

Electromagnetically Induced Transparency



$$\tilde{H}_{int} = -\frac{\hbar}{2}\begin{pmatrix} 0 & 0 & \Omega_0 \\ 0 & -2\delta & \Omega_1 \\ \Omega_0 & \Omega_1 & 0 \end{pmatrix}$$

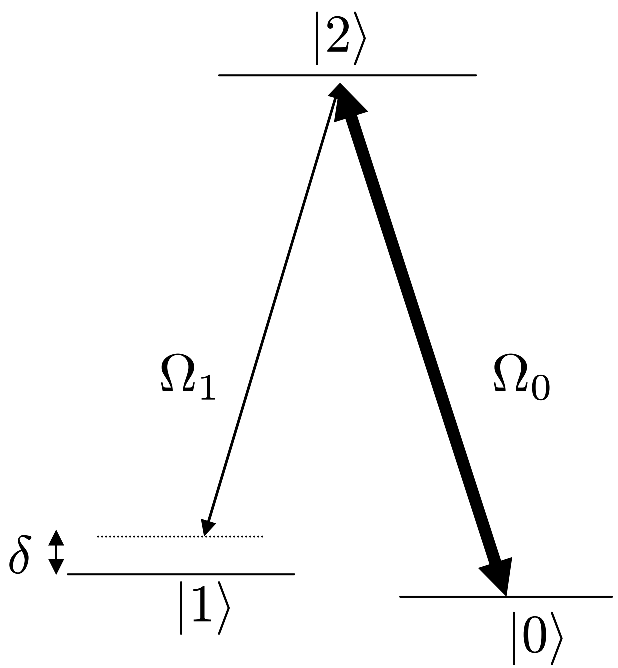
dla $\delta = 0$

$$|a_0\rangle = \frac{\Omega_1|0\rangle - \Omega_0|\tilde{1}\rangle}{\sqrt{|\Omega_1|^2 + |\Omega_0|^2}}$$

dla $\delta \simeq 0,\ \Delta = 0$

$$|a_0'\rangle = |a_0\rangle - 2\delta\frac{\Omega_1\Omega_0}{(\Omega_1^2 + \Omega_0^2)^{3/2}}|\tilde{2}\rangle$$

Electromagnetically Induced Transparency



$$\tilde{H}_{int} = -\frac{\hbar}{2}\begin{pmatrix} 0 & 0 & \Omega_0 \\ 0 & -2\delta & \Omega_1 \\ \Omega_0 & \Omega_1 & 0 \end{pmatrix}$$

$$|a_0'\rangle = |a_0\rangle - 2\delta\frac{\Omega_1\Omega_0}{(\Omega_1^2+\Omega_0^2)^{3/2}}|\tilde{2}\rangle$$

Odstrojenie

Pole

$$\langle a_0'|\vec{r}|a_0'\rangle \simeq 2\frac{\delta\Omega_1}{\Omega_0^2}\langle 1|\vec{r}|2\rangle e^{-i\omega_1 t} + c.c.$$

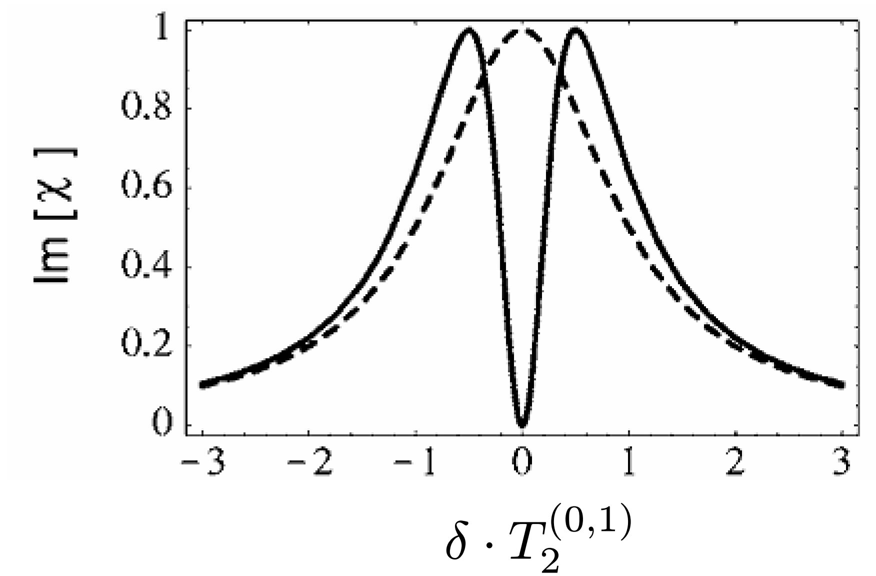
Polaryzacja

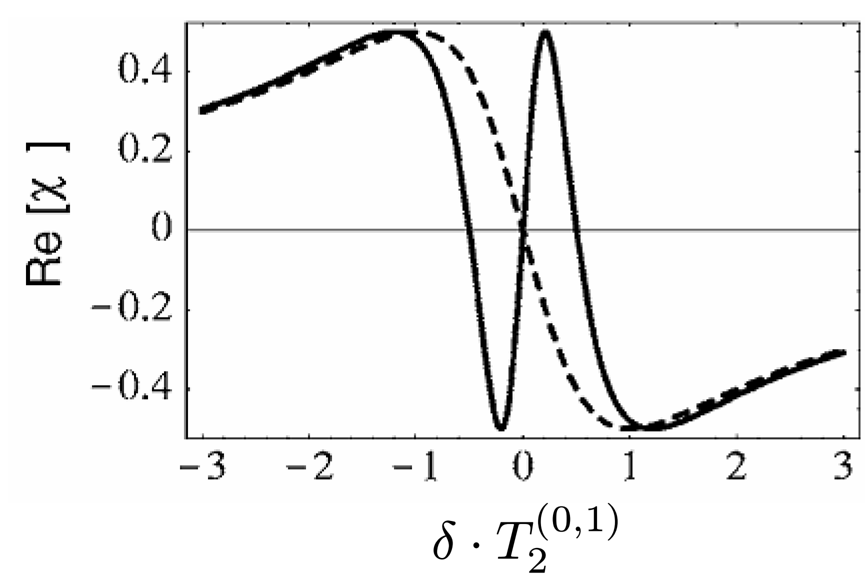
Kontrola

$$\chi \propto \delta/\Omega_0^2$$

Slow Light

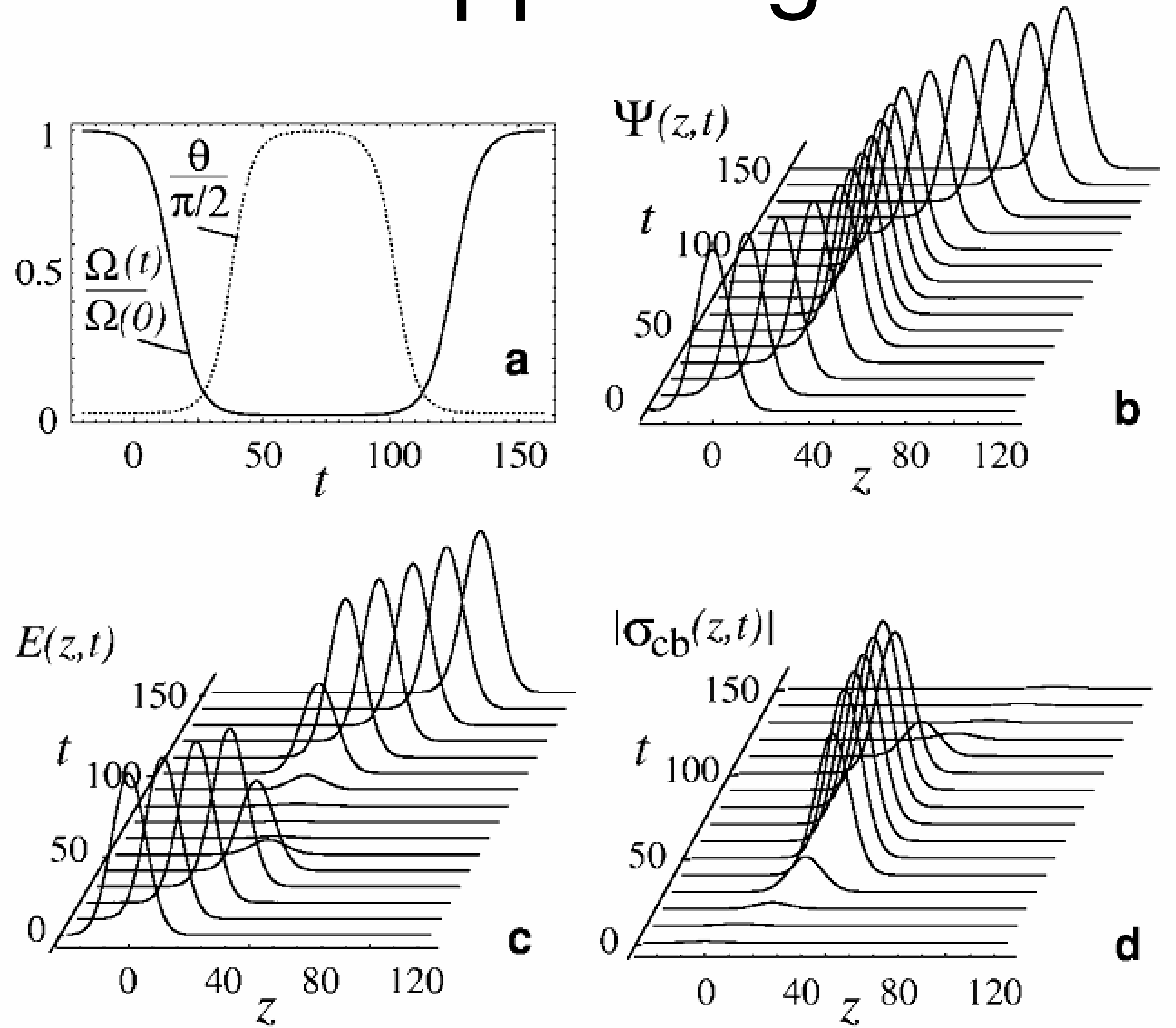
$$\chi \propto \delta/\Omega_0^2 \longrightarrow \frac{\partial k}{\partial \omega} \propto 1/\Omega_0^2$$





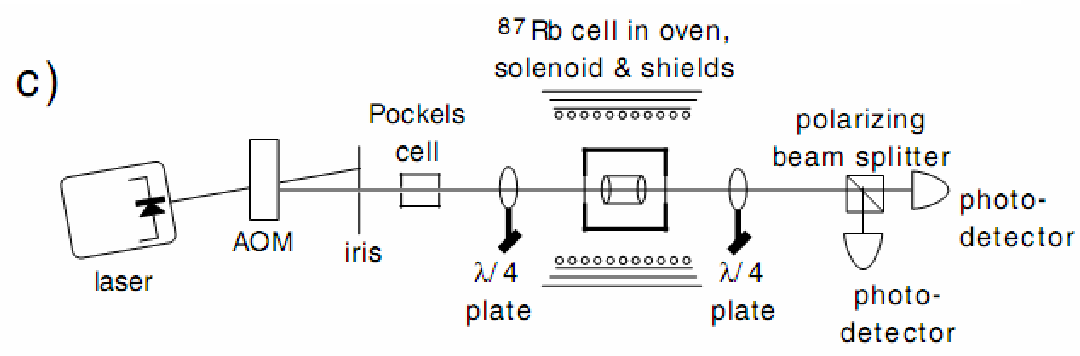
Fleischhauer, Imamoglu, and Marangos:
Electromagnetically induced transparency, RMP 77, 633 (2005)

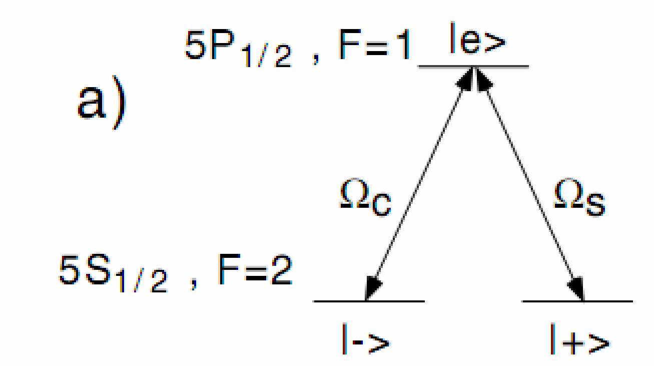
Stopped light

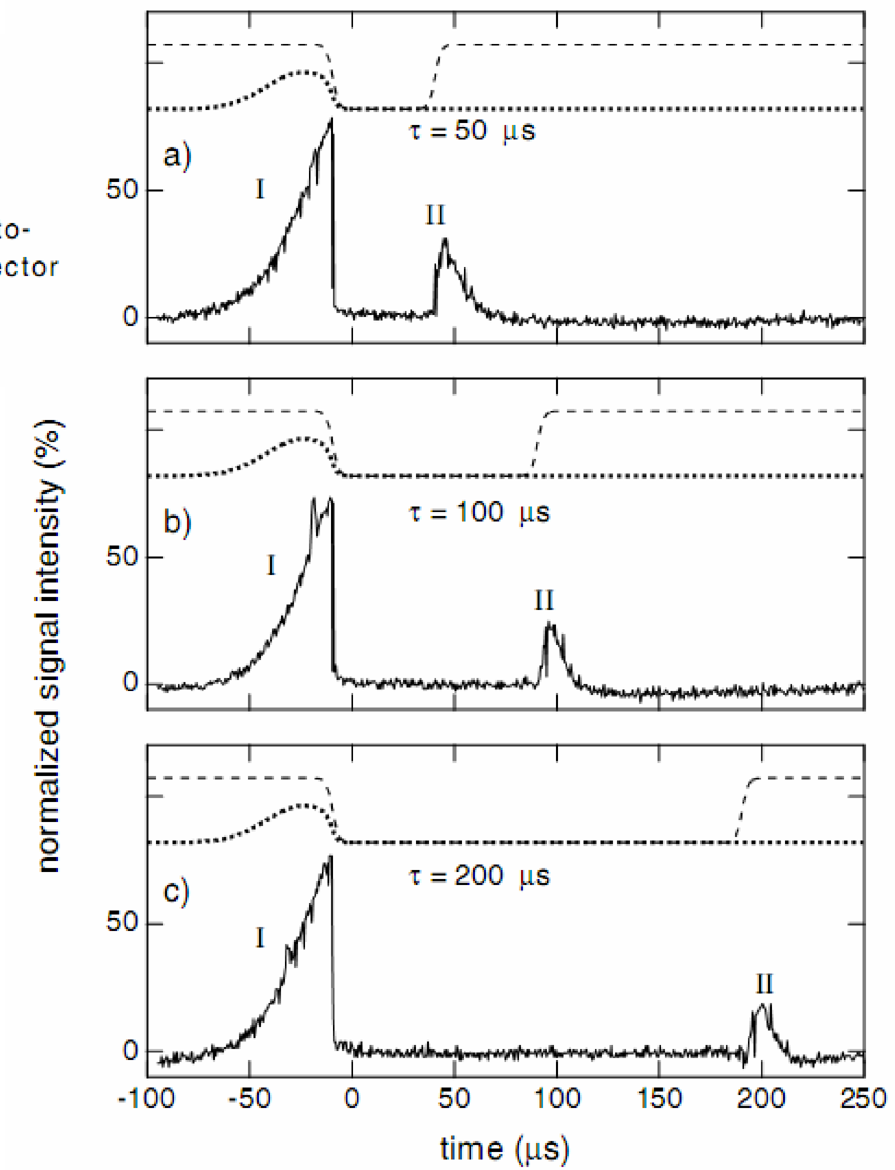


Fleischhauer, Lukin, PRL **84**, 5094 (2000)

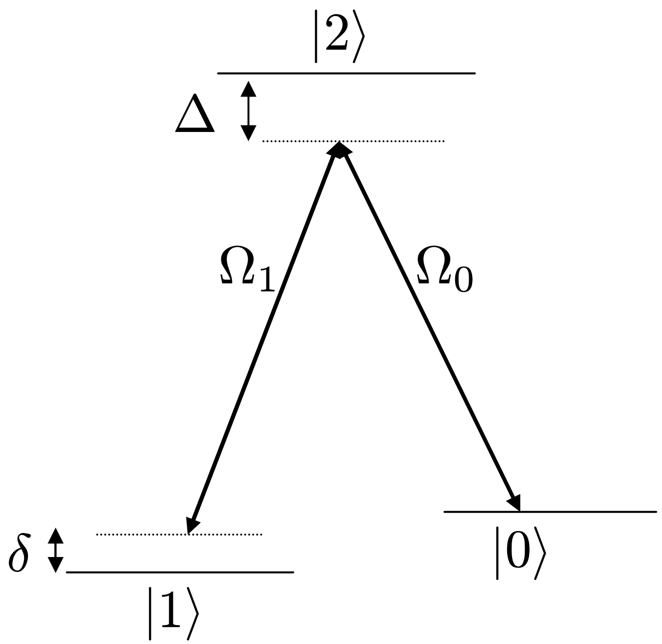
Eksperyment







Do domu



Dany jest układ Λ, w chwili początkowej atom jest w stanie 0. Wyjaśnij jak przenieść go z pewnością do poziomu 1, używajac:

1. najpierw impulsu na przejściu 0-2 a następnie na 2-1
2. jednocześnie obu impulsów z Δ dużym i δ małym
3. wykorzystując przejście adiabatyczne przez stany ciemne
4. Czy potrafisz ocenić które podejście daje nam najwięcej czasu?

Pojedyncze jony w pułapce Paula

Komputer kwantowy

Blatt & Wineland, *Nature* **453**, 1008 (2008)

Komputery kwantowe

QC Approach	The DiVincenzo Criteria: Quantum Computation #1	#2	#3	#4	#5		QC Networkability #6	#7
NMR	red	yellow	yellow	green	yellow		red	red
Trapped Ion	yellow	green	yellow	green	green		yellow	yellow
Neutral Atom	yellow	green	yellow	yellow	yellow		yellow	yellow
Cavity QED	yellow	green	yellow	yellow	green		yellow	yellow
Optical	yellow	yellow	green	yellow	yellow		yellow	green
Solid State	yellow	yellow	yellow	yellow	yellow		red	red
Superconducting	yellow	green	yellow	yellow	yellow		red	red
Unique Qubits	This field is so diverse that it is not feasible to label the criteria with "Promise" symbols.							

Legend: (green) = a potentially viable approach has achieved sufficient proof of principle

(yellow) = a potentially viable approach has been proposed, but there has not been sufficient proof of principle

(red) = no viable approach is known

The column numbers correspond to the following QC criteria:

#1. A scalable physical system with well-characterized qubits.

#2. The ability to initialize the state of the qubits to a simple fiducial state.

#3. Long (relative) decoherence times, much longer than the gate-operation time.

#4. A universal set of quantum gates.

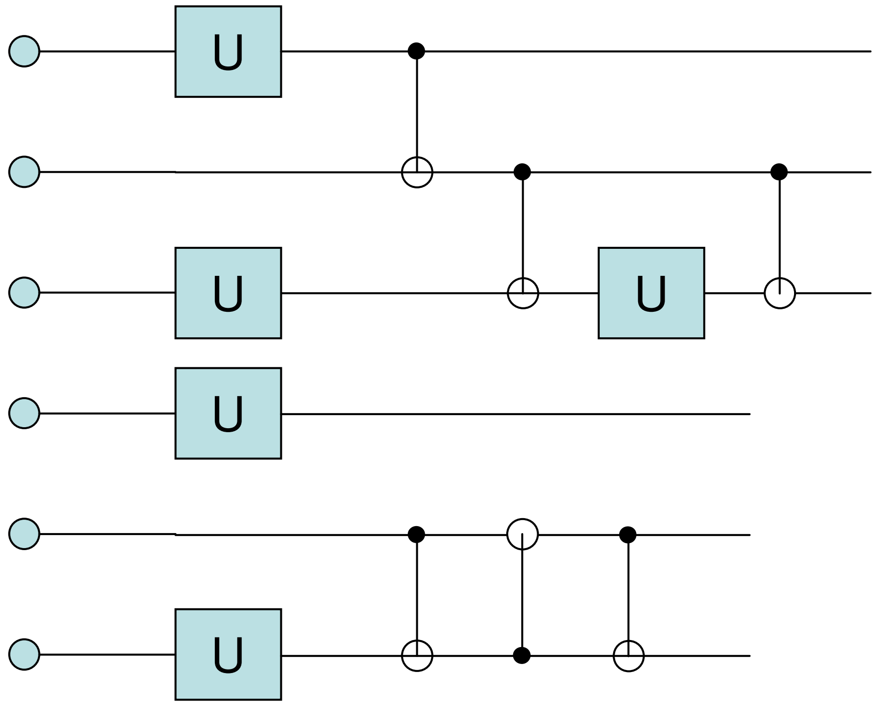
#5. A qubit-specific measurement capability.

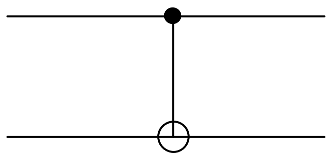
#6. The ability to interconvert stationary and flying qubits.

#7. The ability to faithfully transmit flying qubits between specified locations.

http://qist.lanl.gov/

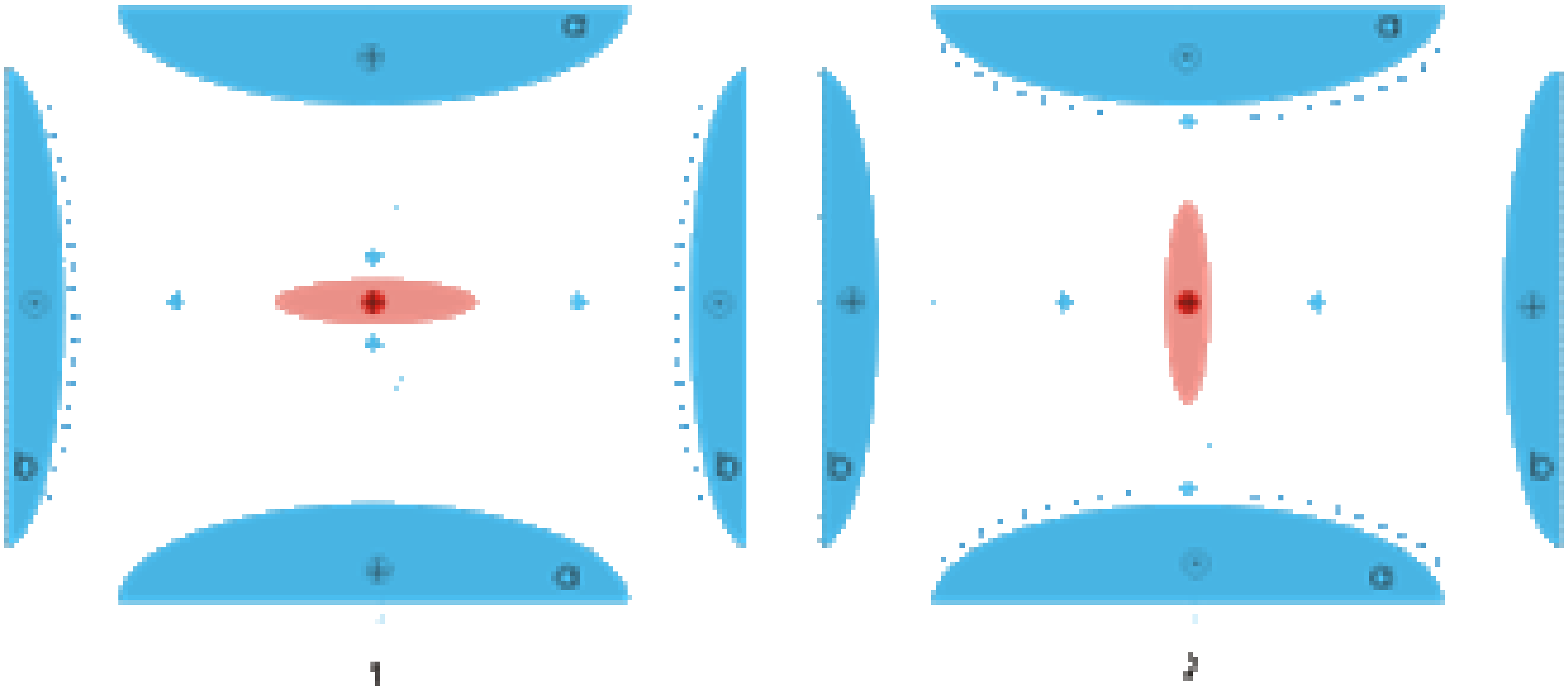
Uniwersalny komputer kwantowy: SU(2)+C-NOT



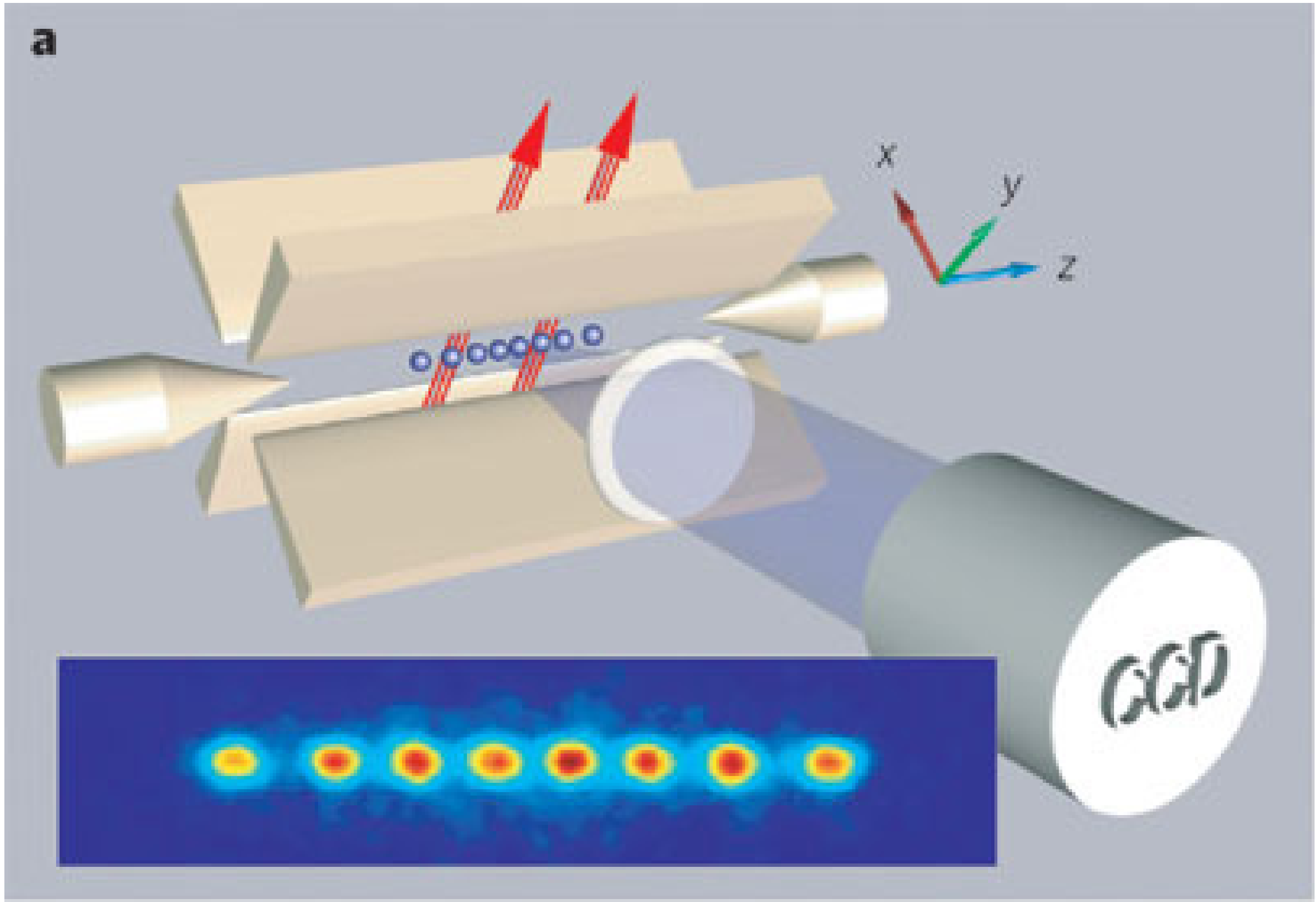


$$|0\rangle|0\rangle \rightarrow |0\rangle|0\rangle$$
$$|0\rangle|1\rangle \rightarrow |0\rangle|1\rangle$$
$$|1\rangle|0\rangle \rightarrow |1\rangle|1\rangle$$
$$|1\rangle|1\rangle \rightarrow |1\rangle|0\rangle$$

Pułapka Paula

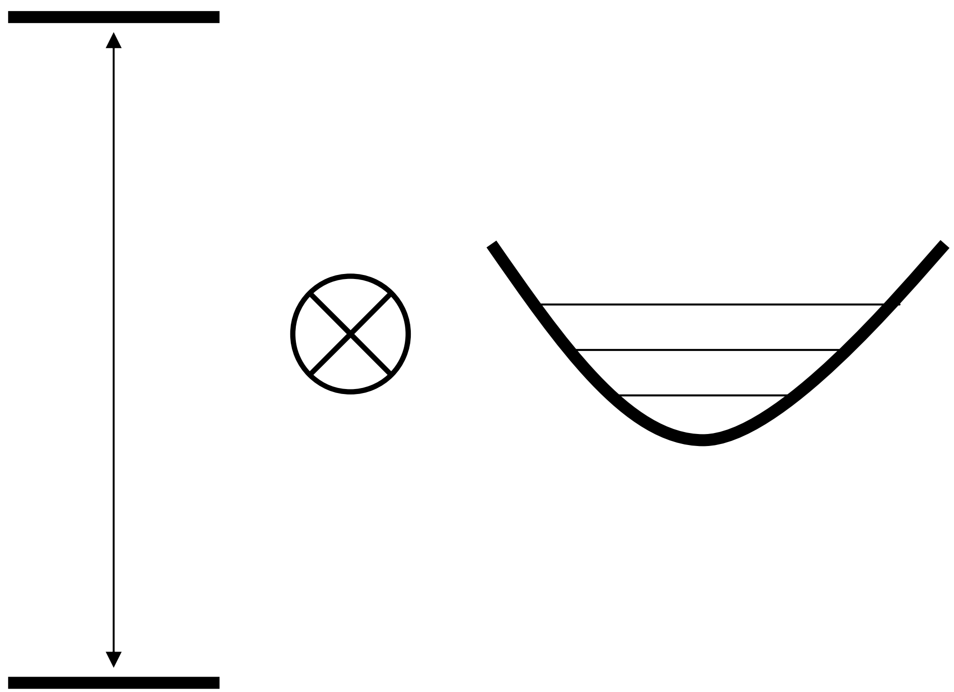


Liniowa pułapka Paula



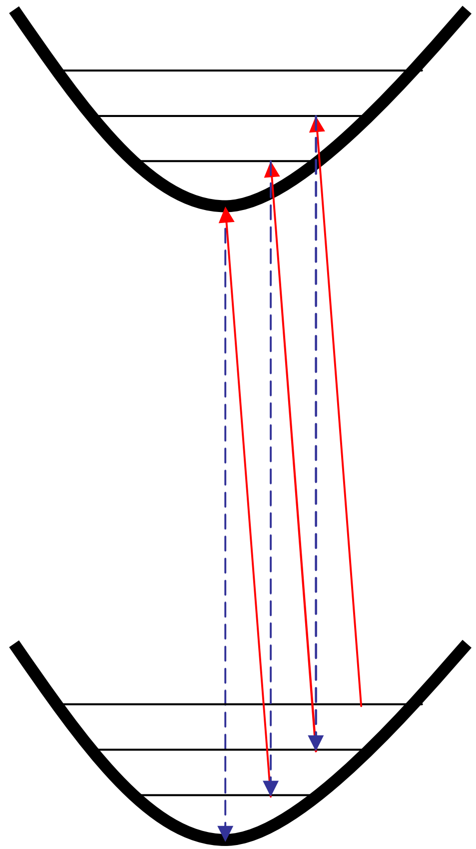
Blatt & Wineland, *Nature* **453**, 1008 (2008)

Sytuacja

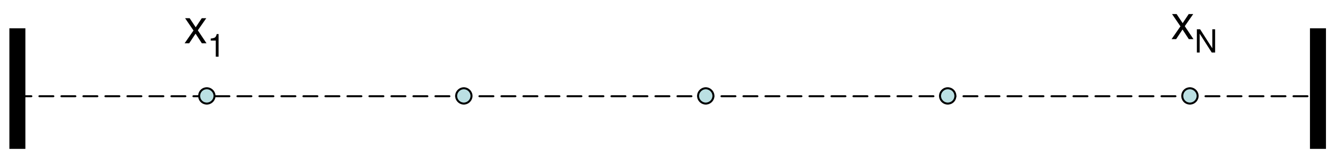


ruch elektronu　　　　ruch całego jonu

Sideband cooling



Fonony na łańcuszku



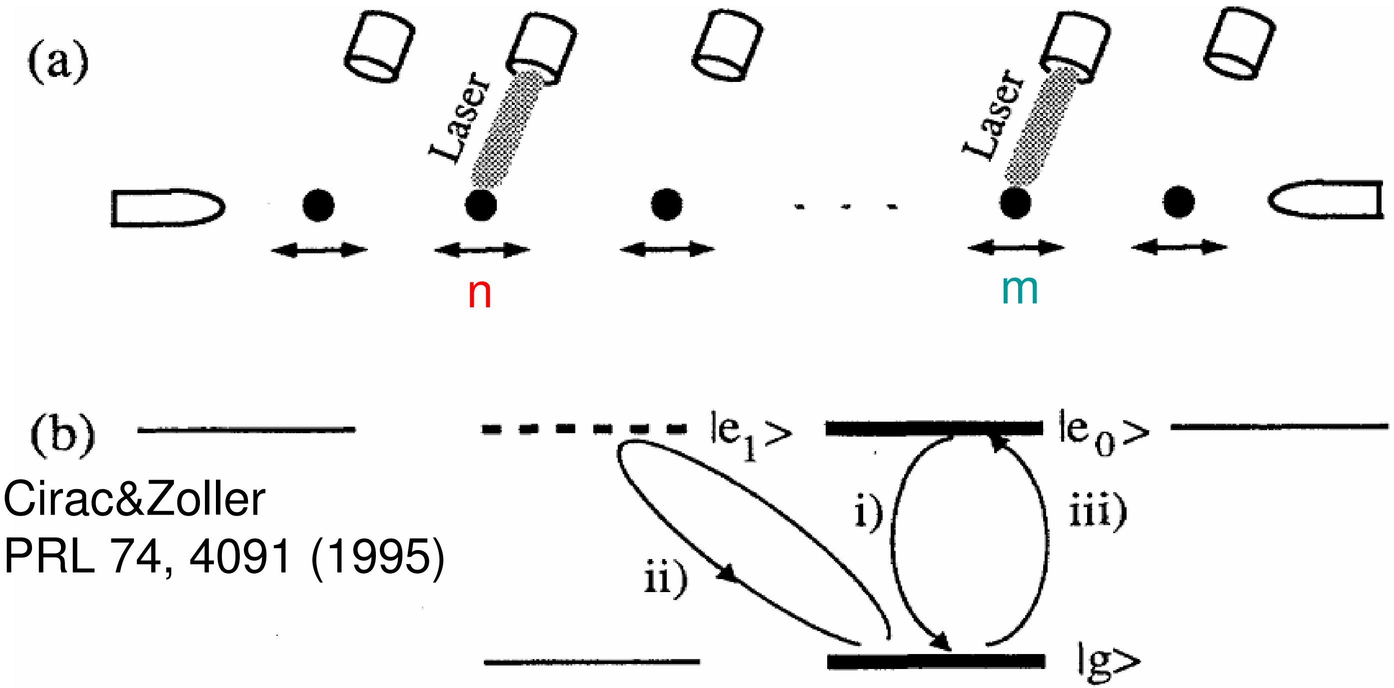
$$x_n = A_{nm} Q_m$$

mody normalne

suma N oscylatorów harmonicznych

$$\hat{H}_{mot} = \sum_{m=0}^{N-1} \hbar \omega_m \hat{a}^\dagger a$$

C-NOT na jonach

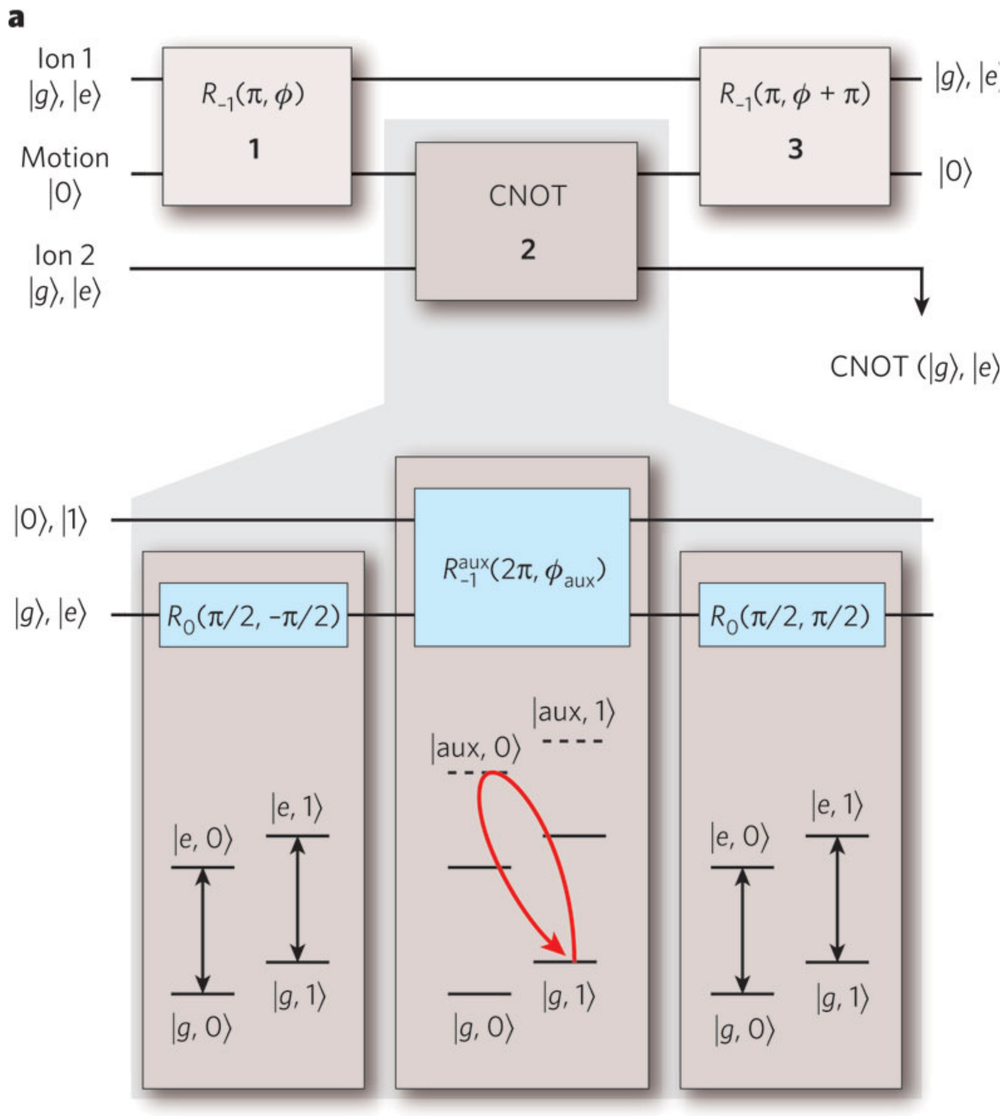


Cirac&Zoller
PRL 74, 4091 (1995)

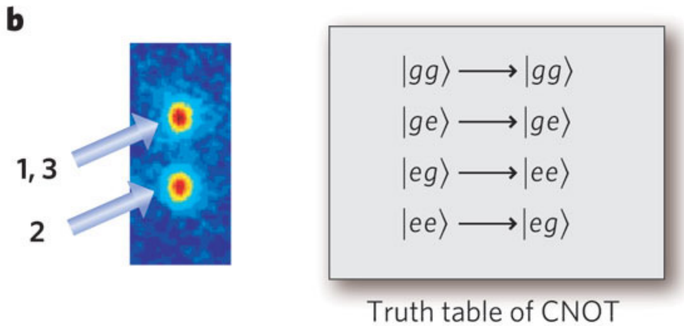
$$
\begin{array}{lllllll}
|g\rangle_m|g\rangle_n|0\rangle & \longrightarrow & |g\rangle_m|g\rangle_n|0\rangle & \longrightarrow & |g\rangle_m|g\rangle_n|0\rangle & \longrightarrow & |g\rangle_m|g\rangle_n|0\rangle\,, \\
|g\rangle_m|e_0\rangle_n|0\rangle & \longrightarrow & |g\rangle_m|e_0\rangle_n|0\rangle & \longrightarrow & |g\rangle_m|e_0\rangle_n|0\rangle & \longrightarrow & |g\rangle_m|e_0\rangle_n|0\rangle\,, \\
|e_0\rangle_m|g\rangle_n|0\rangle & \longrightarrow & -i|g\rangle_m|g\rangle_n|1\rangle & \longrightarrow & i|g\rangle_m|g\rangle_n|1\rangle & \longrightarrow & |e_0\rangle_m|g\rangle_n|0\rangle\,, \\
|e_0\rangle_m|e_0\rangle_n|0\rangle & \longrightarrow & -i|g\rangle_m|e_0\rangle_n|1\rangle & \longrightarrow & -i|g\rangle_m|e_0\rangle_n|1\rangle & \longrightarrow & -|e_0\rangle_m|e_0\rangle_n|0\rangle\,.
\end{array}
$$

C-NOT na jonach

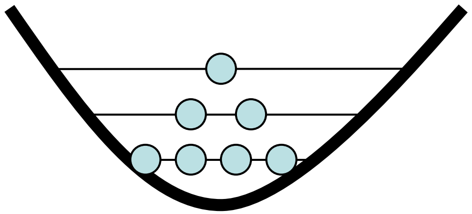
$$|\downarrow\rangle|\uparrow\rangle|0\rangle \rightarrow |\downarrow\rangle|\uparrow\rangle|0\rangle$$



Cirac&Zoller
PRL 74, 4091 (1995)



Kondensat Bosego-Einsteina



100Hz

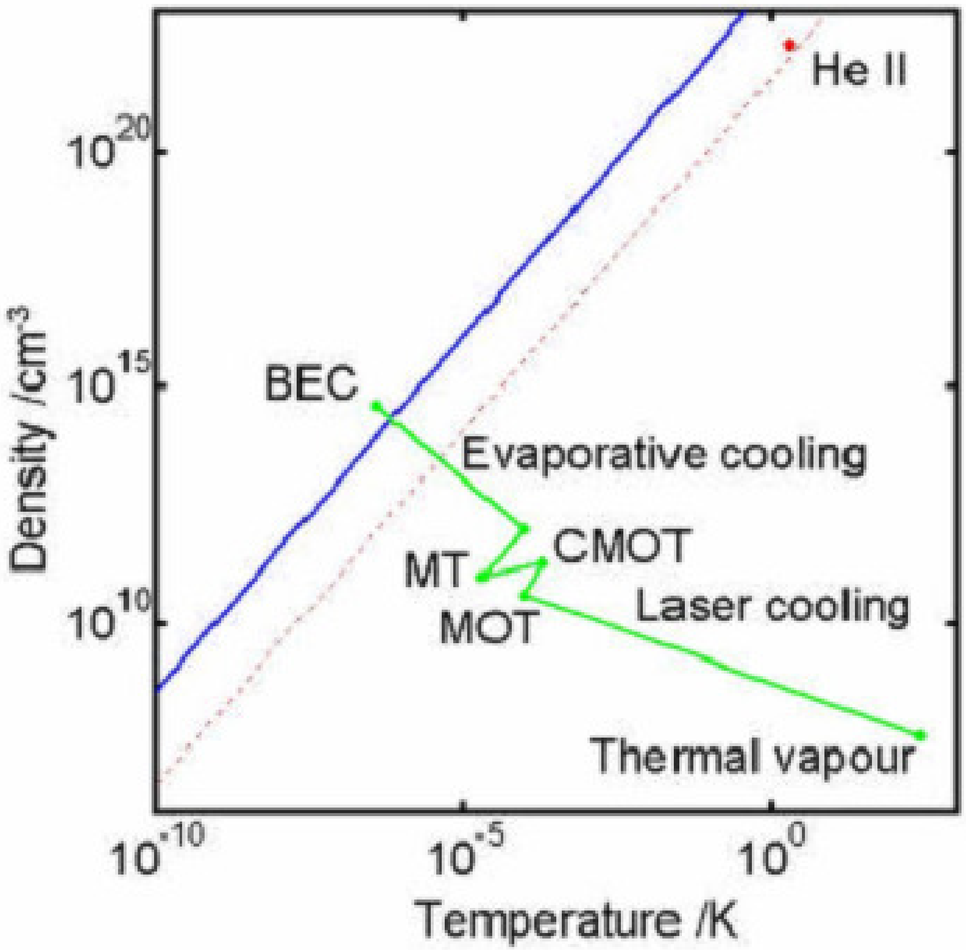
$$T_c = \left(\frac{n}{\zeta(3/2)}\right)^{2/3} \frac{2\pi\hbar^2}{mk_B}$$

310nK – 90% kondensatu

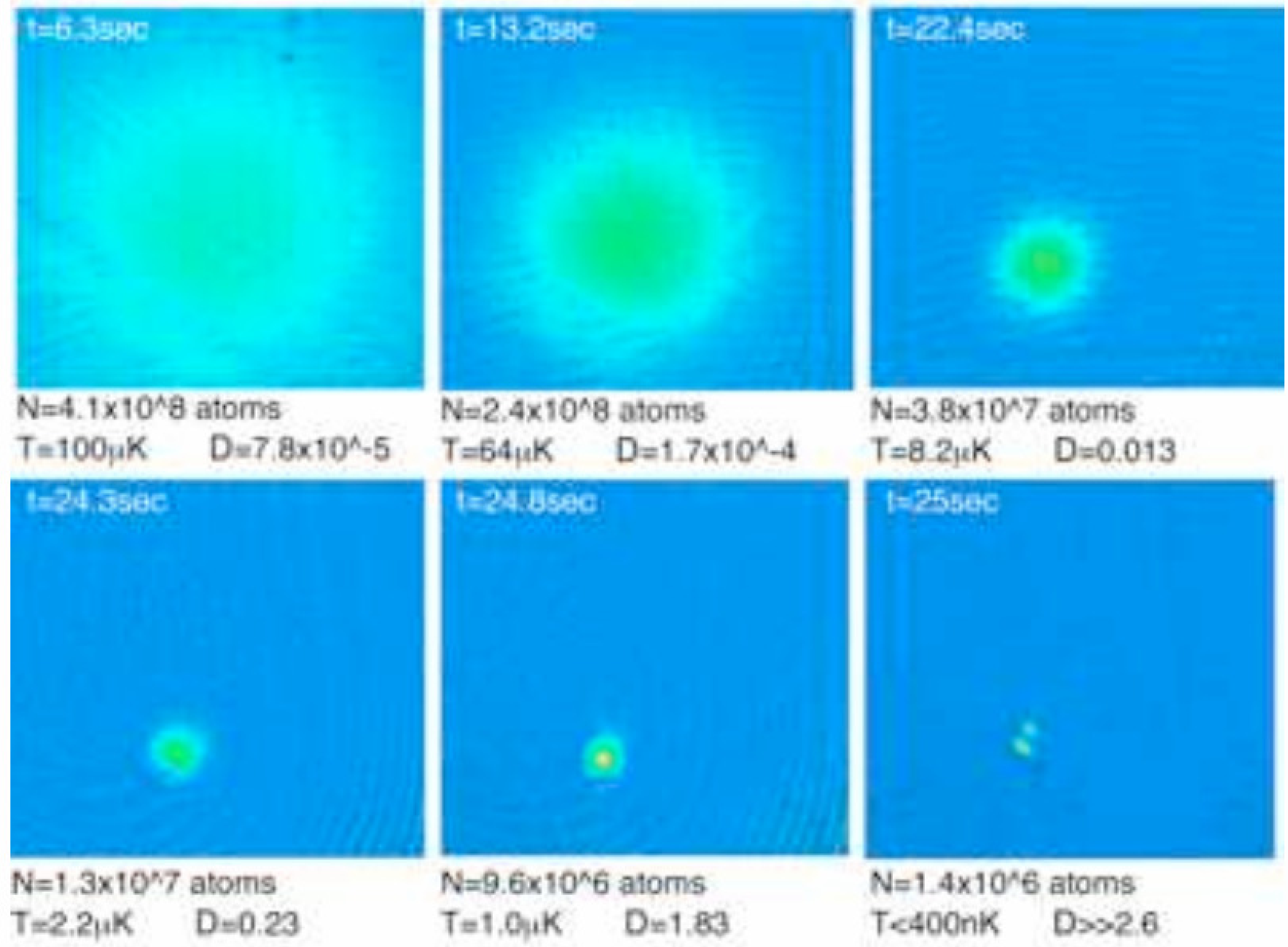
(Planck's constant * 100 Hertz) / Boltzmann constant
= 4.799237 × 10-9 kelvin

Droga do BEC

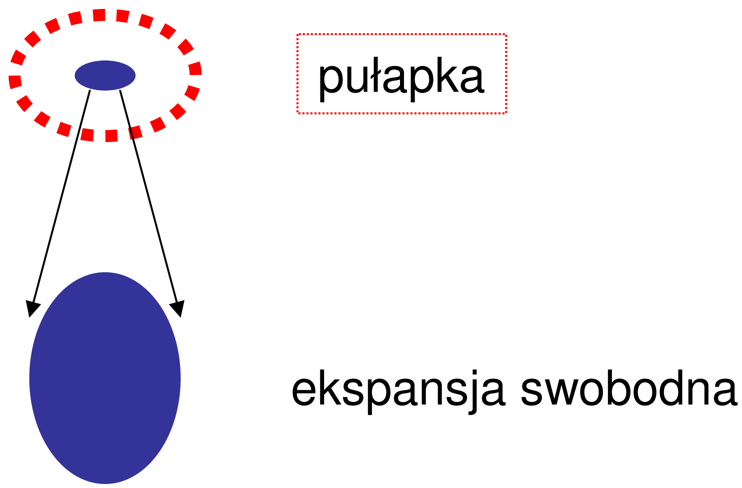
Fig. 25. *The route to BEC: Density against temperature plot illustrating how a Bose-Einstein condensate is produced using a sequence of laser cooling followed by evaporative cooling. The solid line, corresponding to* $\lambda_{dB} = 1.4\ n^{-1/3}$ *for* ^{87}Rb*, indicates the phase transition. The dotted line is the phase transition for* ^{4}He *The cooling sequence is as follows: 1. Room temperature atoms are laser cooled and confined in a MOT. The trap is compressed by increasing the magnetic field gradient (CMOT). 2. The magnetic field is turned off to allow a short period of sub-Doppler cooling (optical molasses) before transferring the cloud to a purely magnetic trap (MT). 3. The magnetic field is increased to compress the cloud. 4. An rf field is applied to evaporate hot atoms. The rf frequency is reduced until the transition to BEC (solid line) is crossed.*



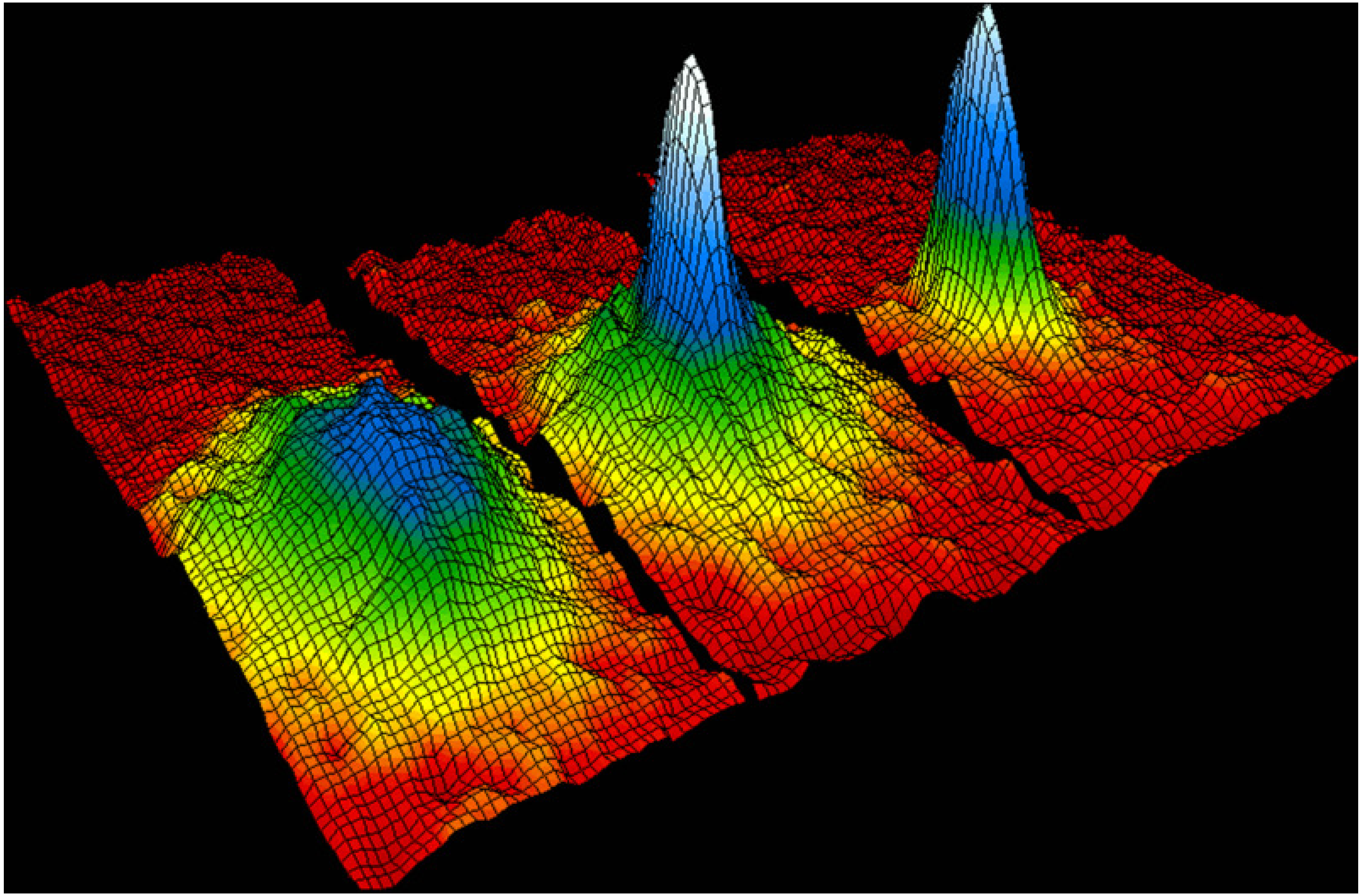
Logarithmic Evaporative Cooling Ramp



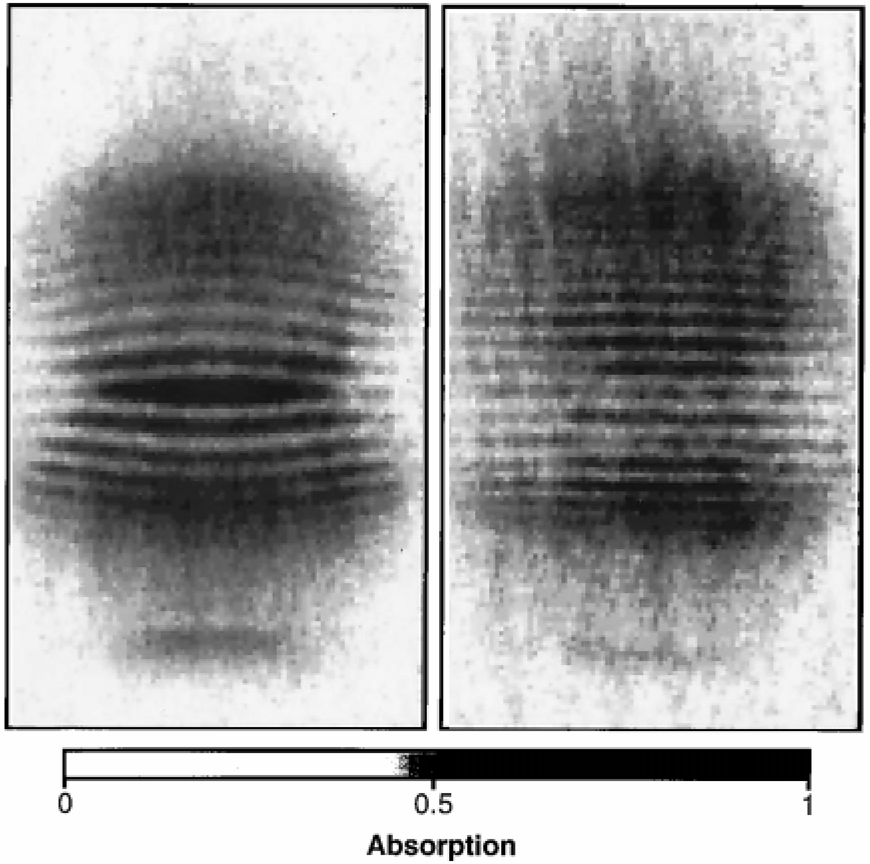
Obserwacja BEC



Formowanie BEC

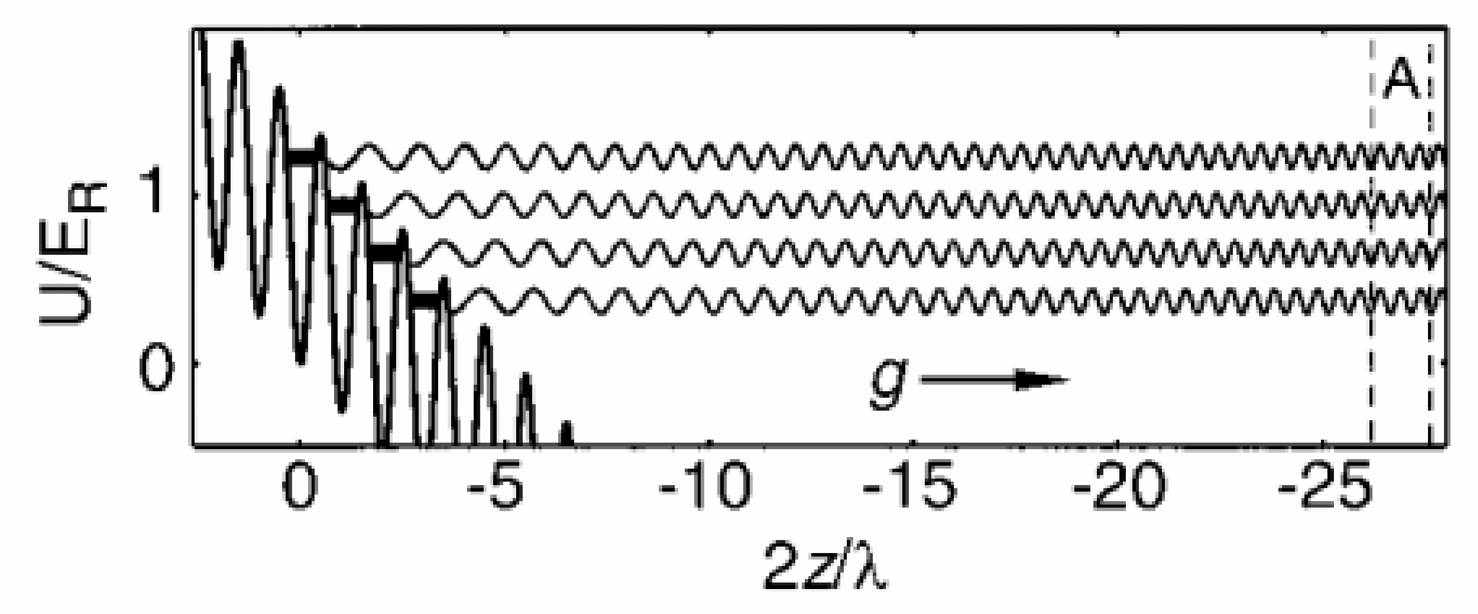


Interferencja kondensatów



M. R. Andrews, et al. Science 275, 637 (1997);

Interferencja kondensatu



B. P. Anderson, et al. Science 282, 1686 (1998);

Interferencja kondensatu