

# Određivanje broja hladnih atoma u magneto-optičkoj stupici

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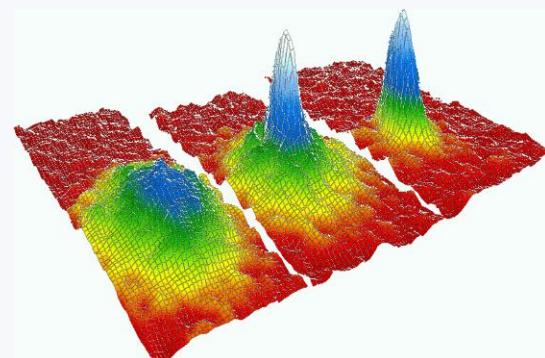
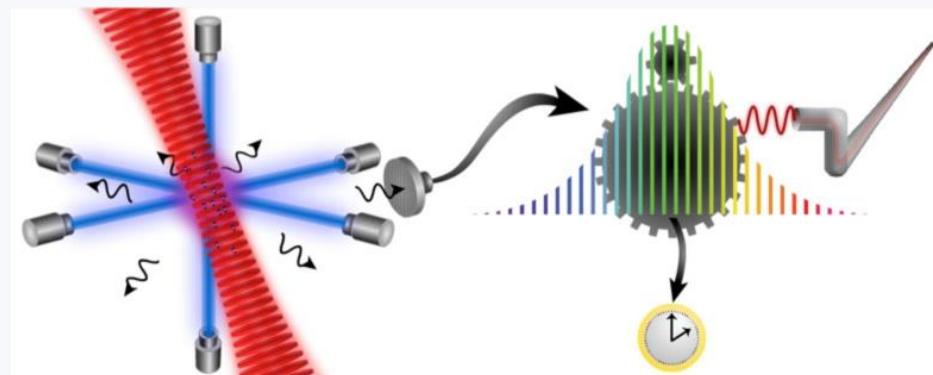
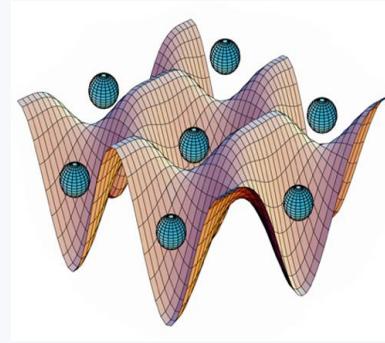
# Uvod

- magneto-optička stupica (eng. *Magneto Optical Trap*, MOT) – lasersko hlađenje i zarobljavanje atoma
- 1987. god.- prva eksperimentalna izvedba

# Uvod

## PRIMJENA:

- proučavanje hladnih sudara
- stvaranje hladnih molekula
- visokoosjetljivi senzori
- atomski satovi
- stvaranje Bose-Einsteinovog kondenzata
- kvantna računala...

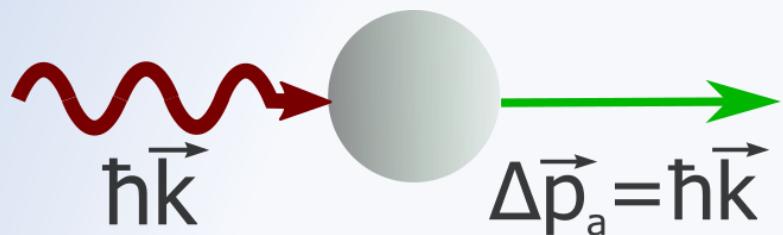


# Lasersko hlađenje

- prijenos impulsa u ciklusima apsorpcije i spontane emisije
- atomi s dva energijska stanja

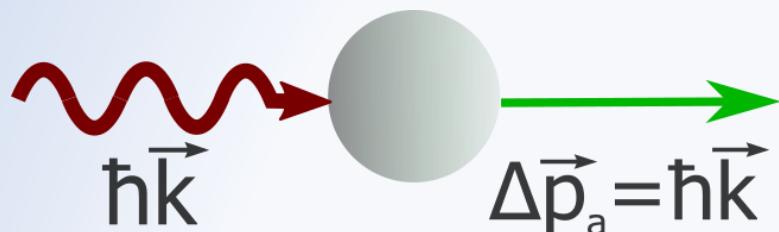
# Lasersko hlađenje

apsorpcija:

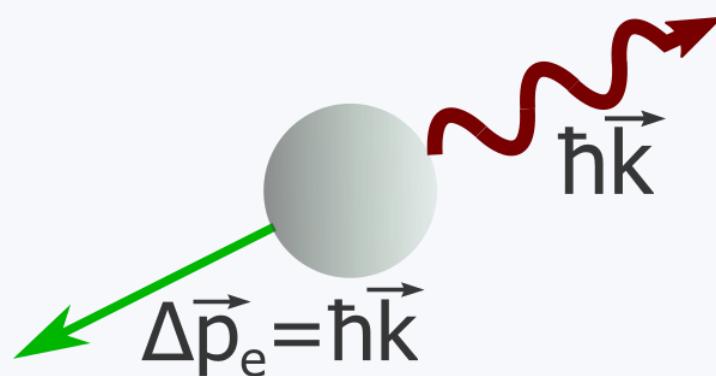


# Lasersko hlađenje

apsorpcija:

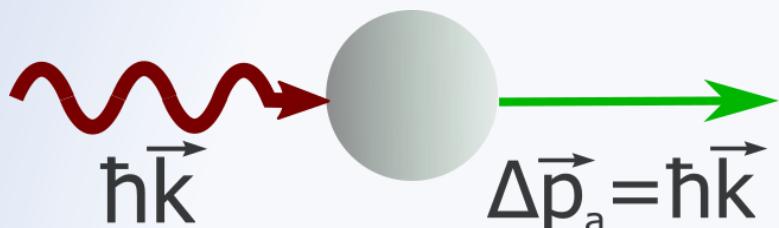


spontana emisija:

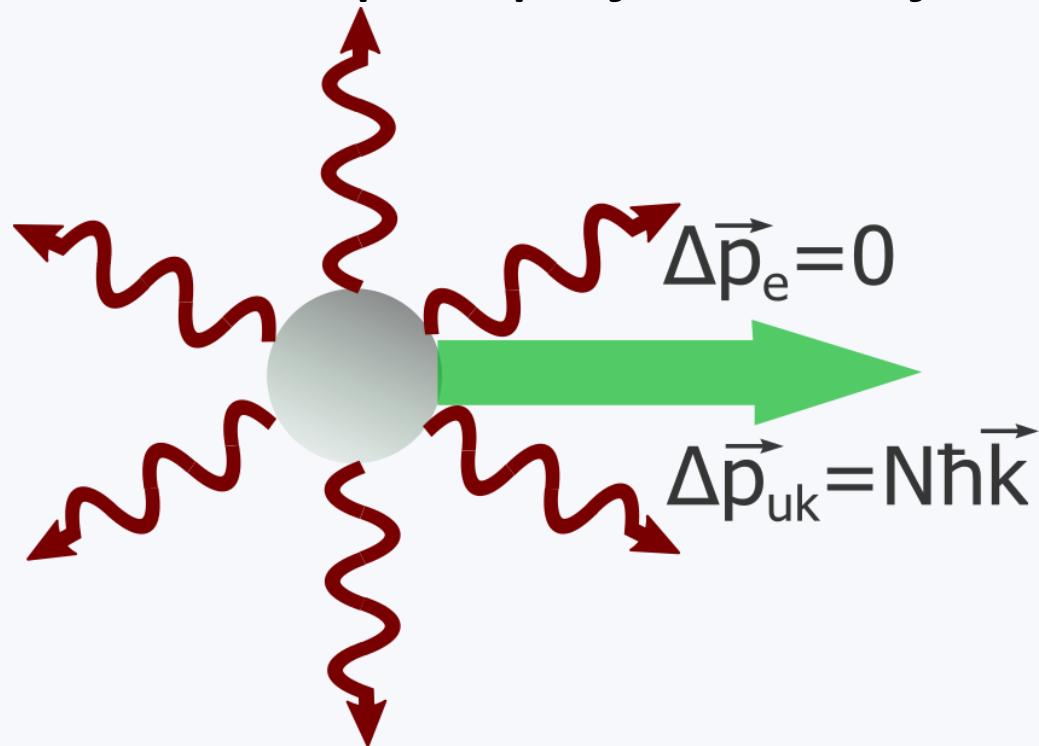


# Lasersko hlađenje

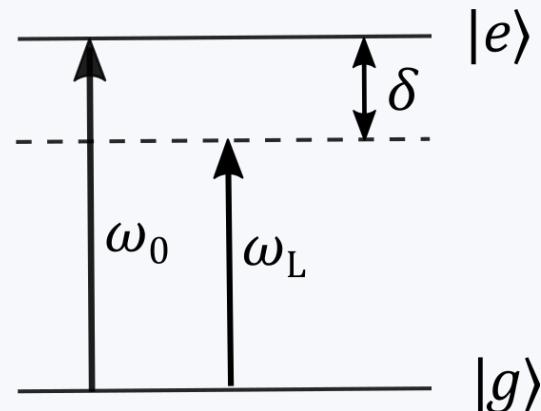
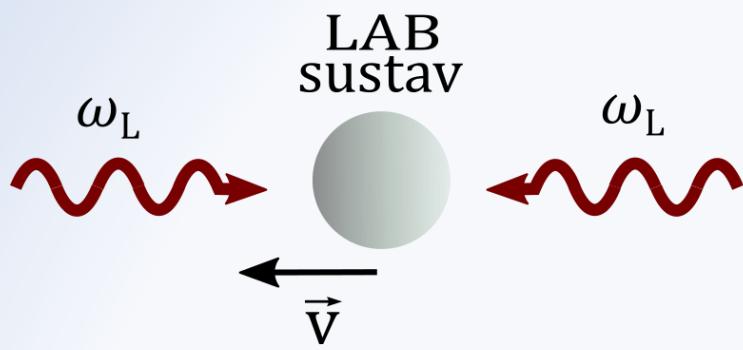
apsorpcija:



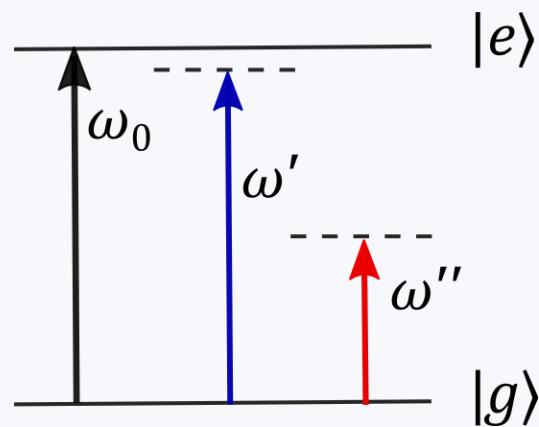
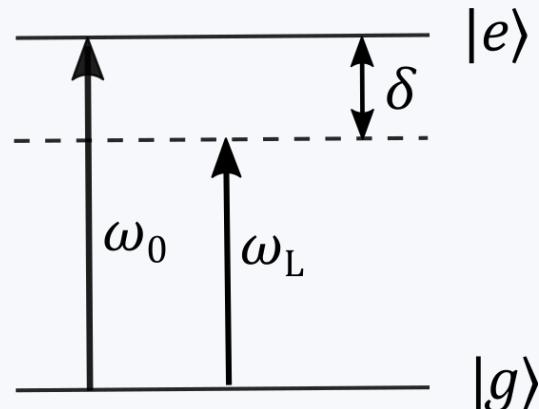
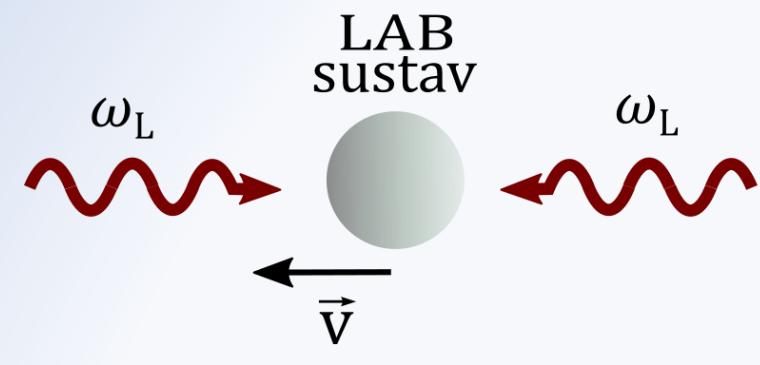
N ciklusa absorpcije i emisije:



# Lasersko hlađenje

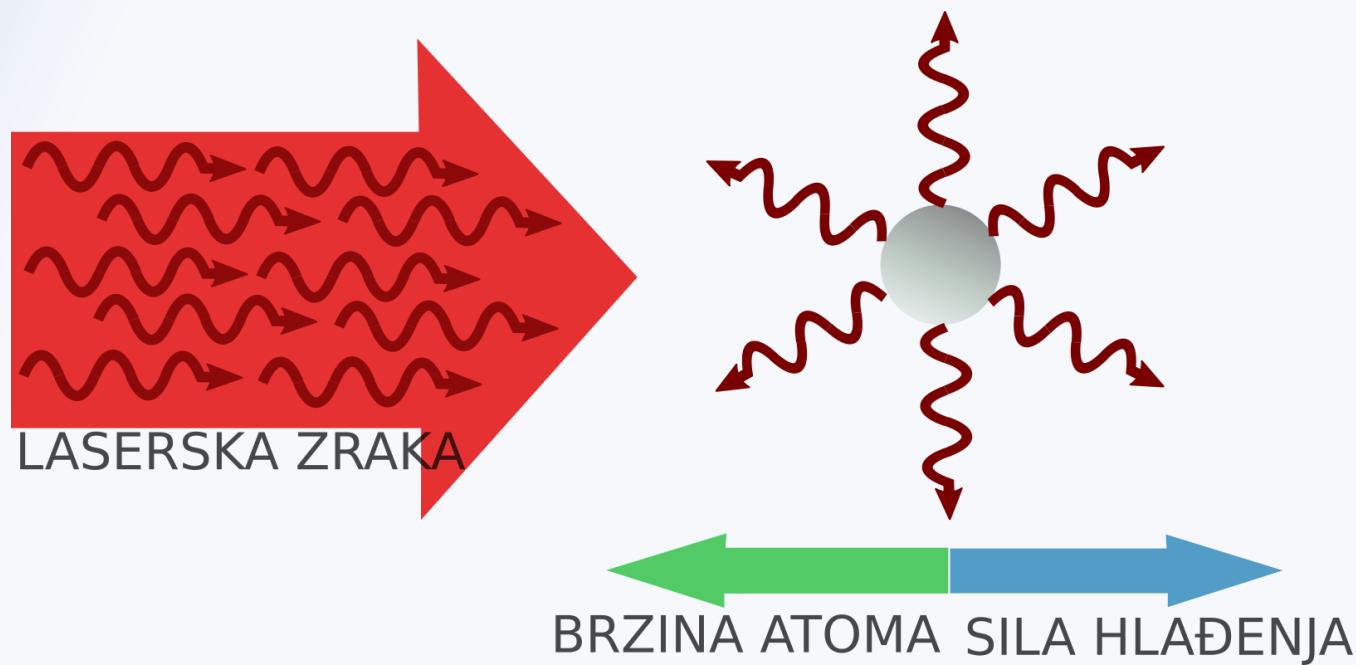


# Lasersko hlađenje

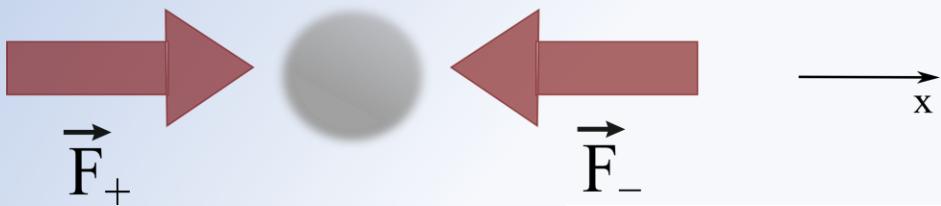


# Lasersko hlađenje

- $\delta = \omega_L - \omega_0 < 0$
- prijenos impulsa

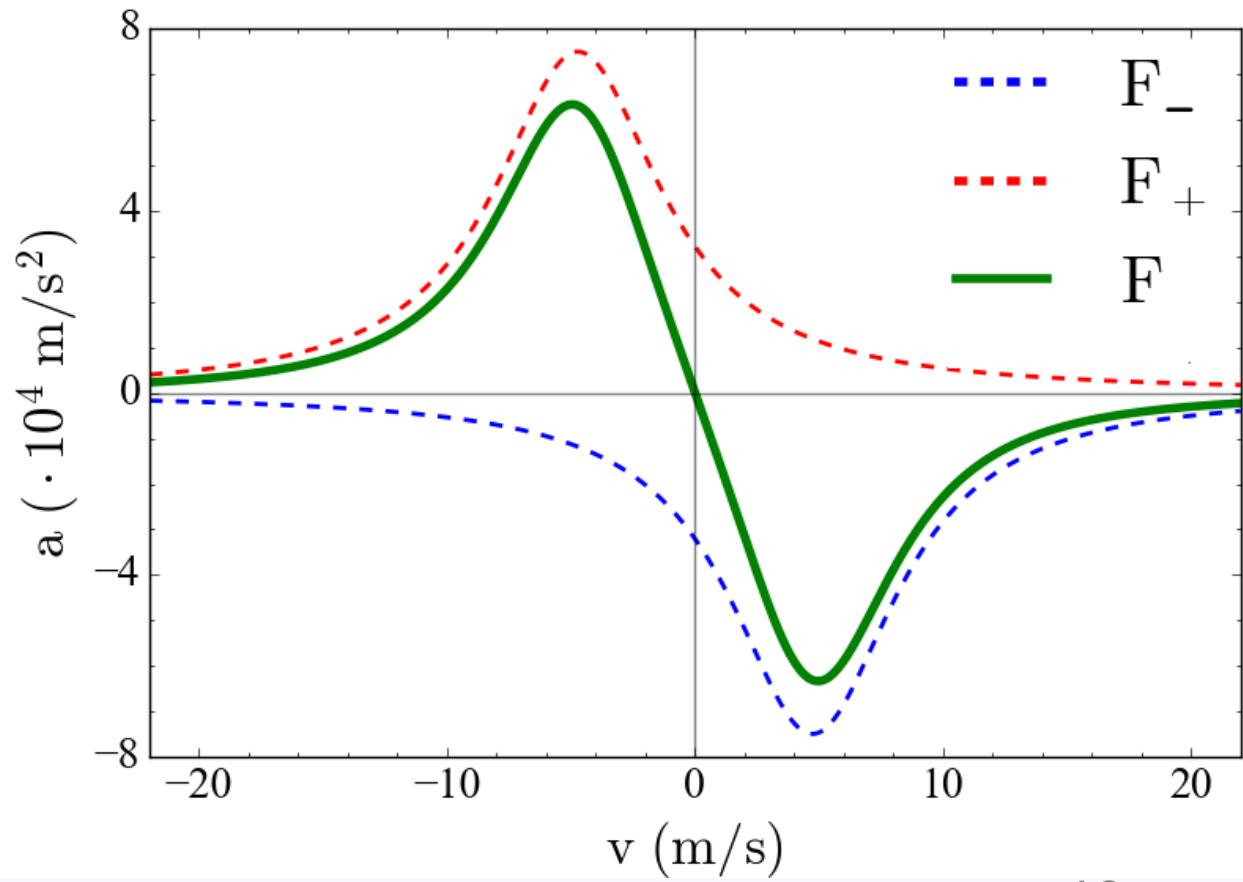


# 1D optička melasa

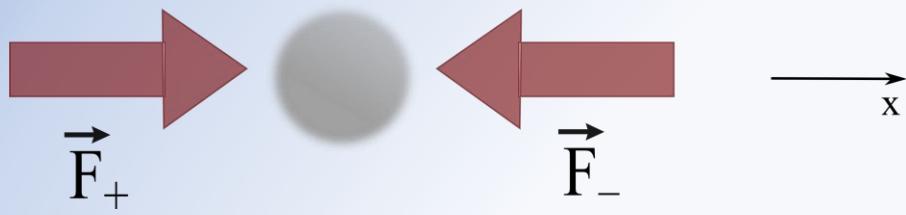


$$\vec{F} = \vec{F}_+ + \vec{F}_-$$

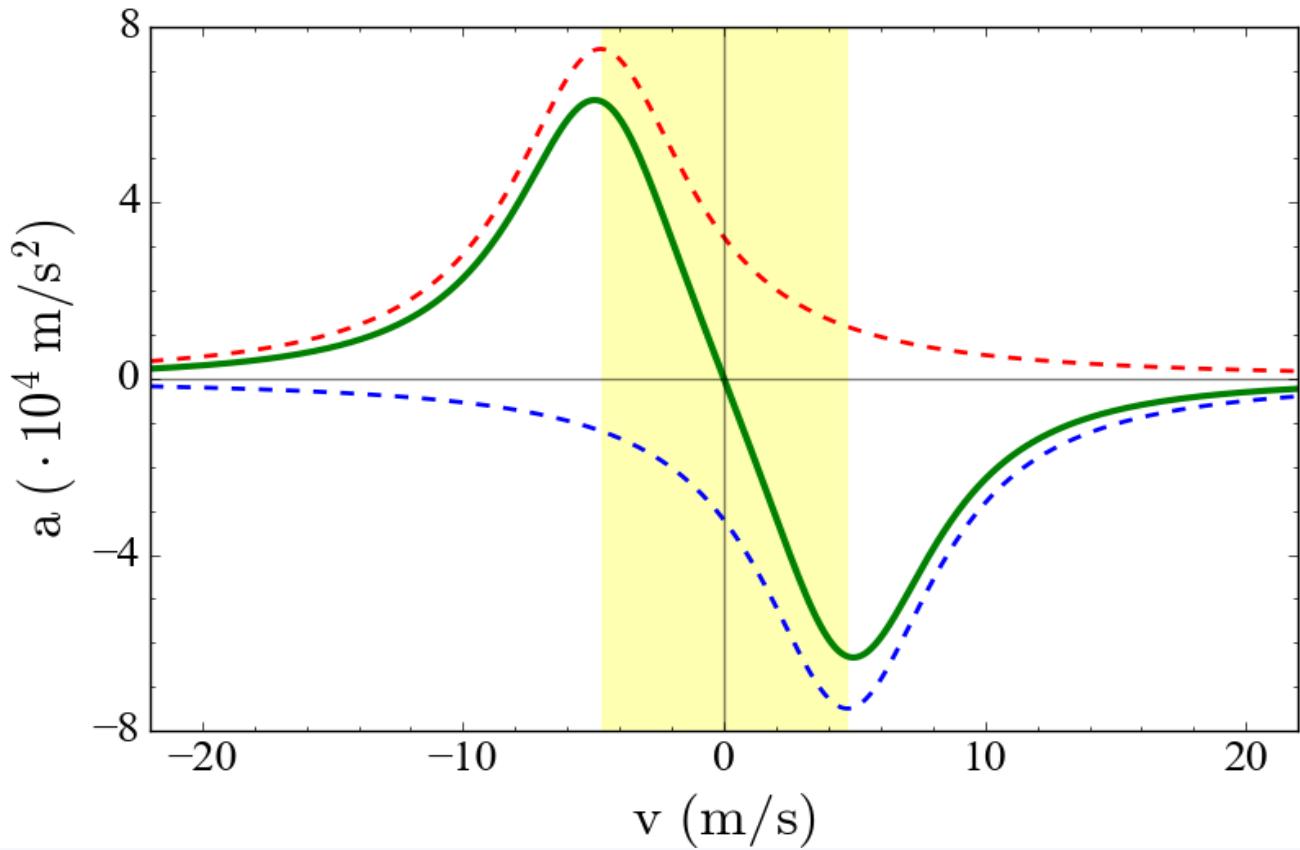
$$87\text{Rb}$$
  
$$\delta = -\Gamma$$



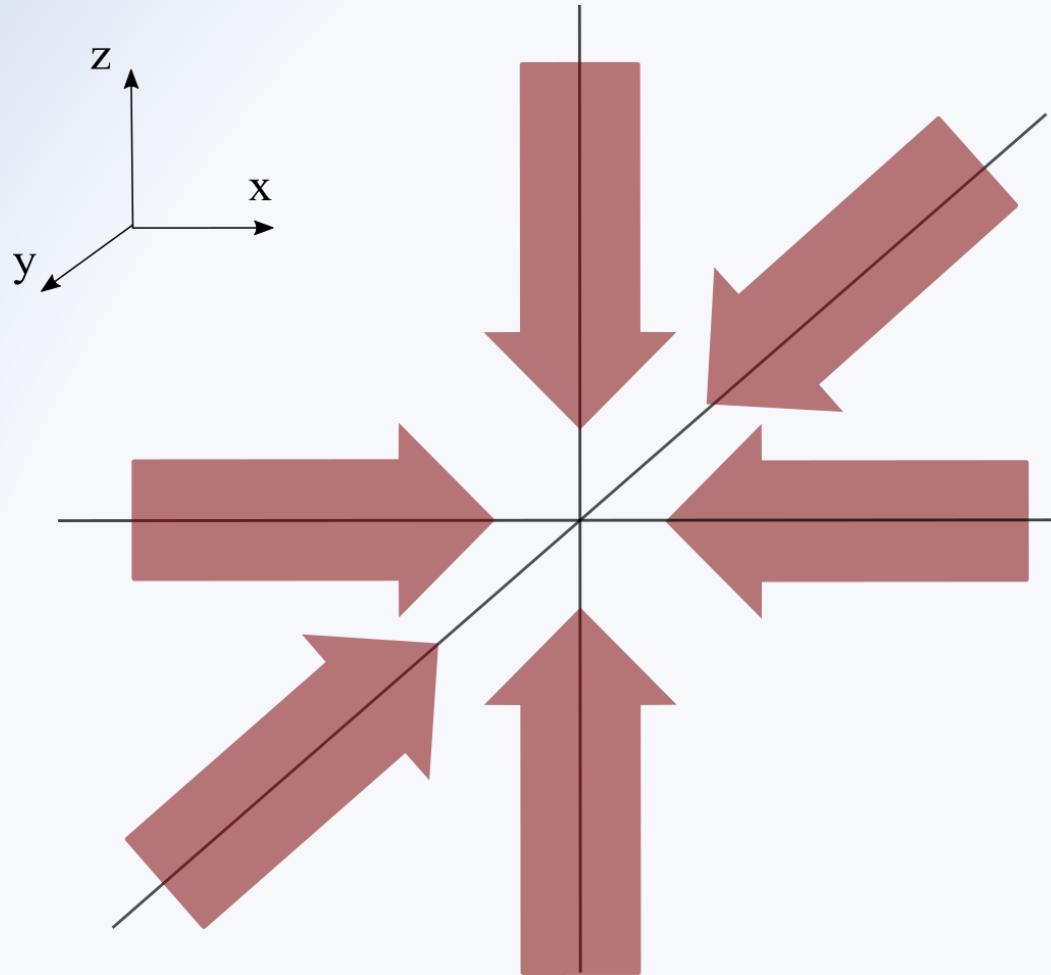
# 1D optička melasa



$$\vec{F} = -\beta \vec{v}$$

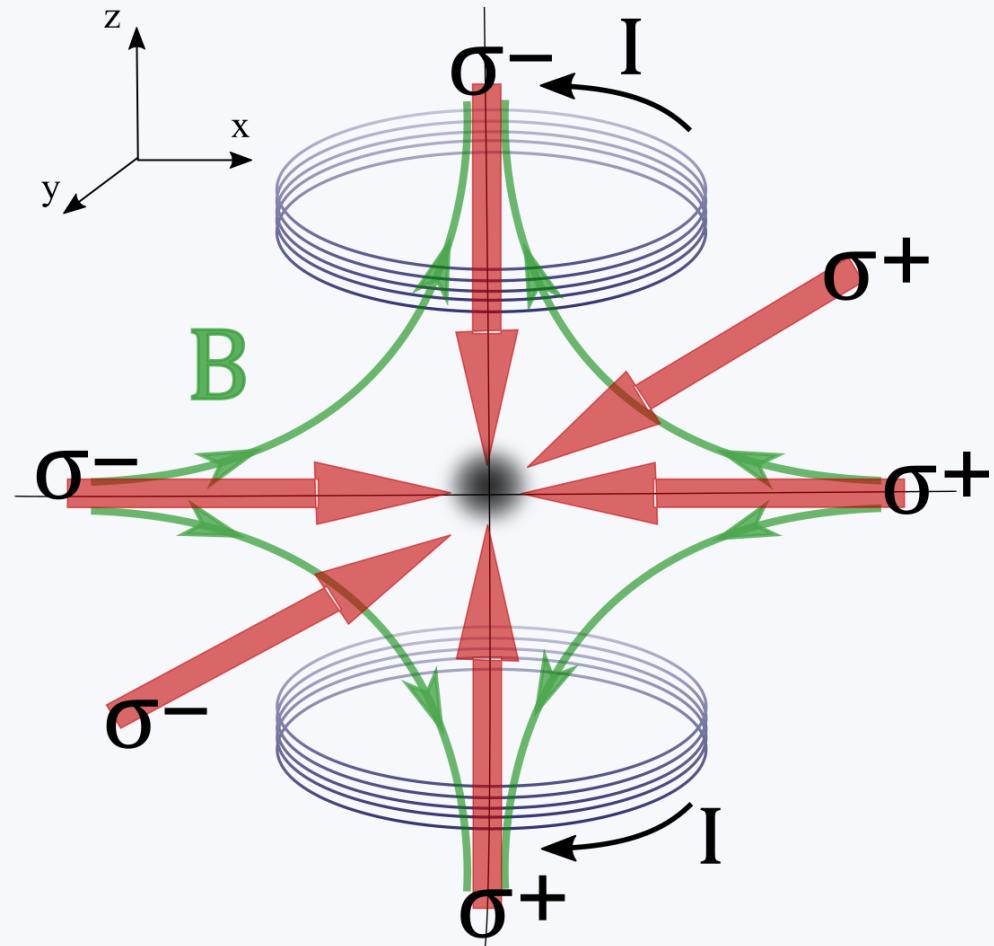


# 3D optička melasa

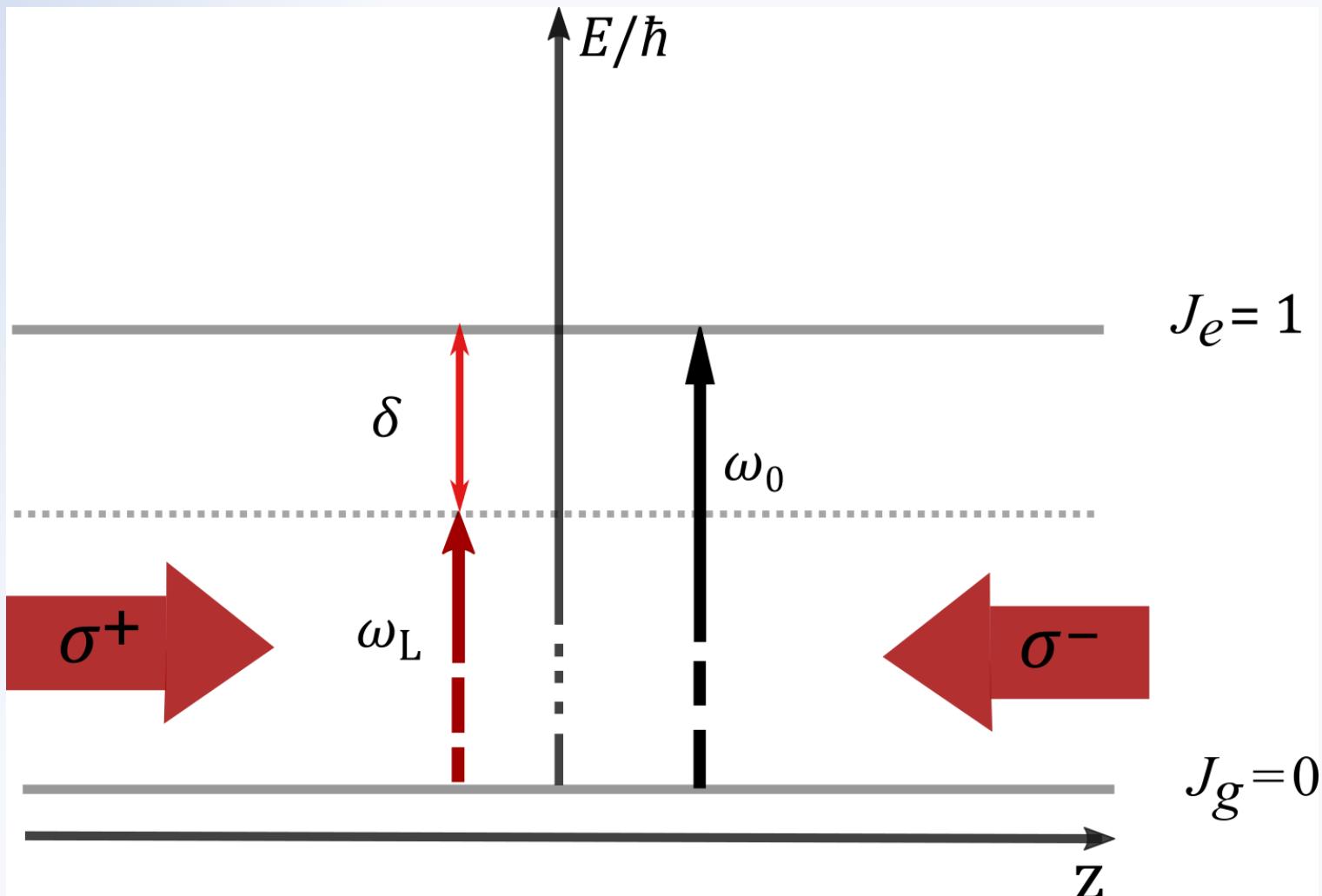


# Magneto-optička stupica, MOT

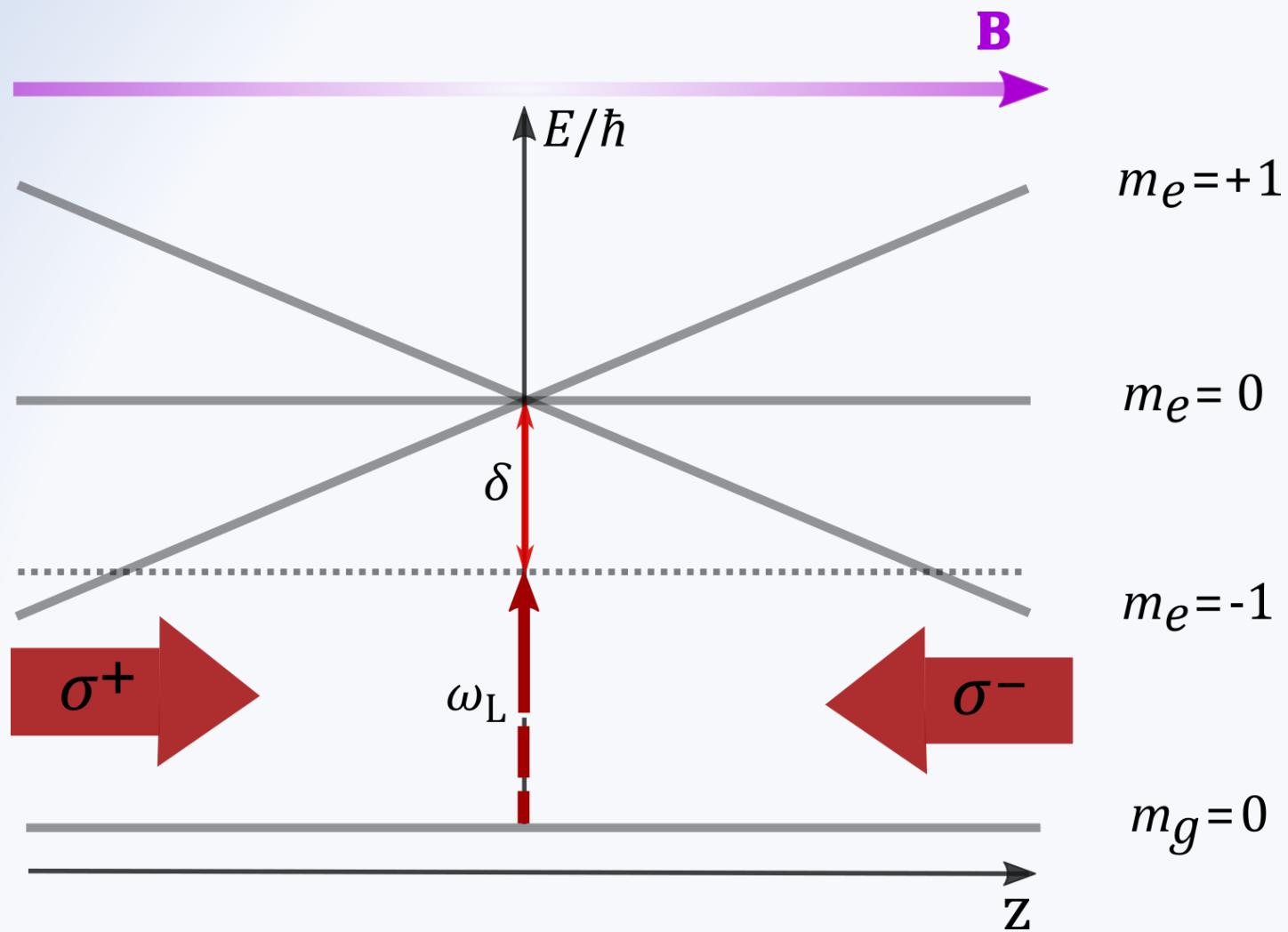
- prostorno zatočenje hladnih atoma
- kružno polarizirano  $\sigma^+$  i  $\sigma^-$  lasersko zračenje + magnetsko polje
- male udaljenosti od centra stupice:  
$$B(z) = Az,$$
  
$$A = \partial B / \partial z$$



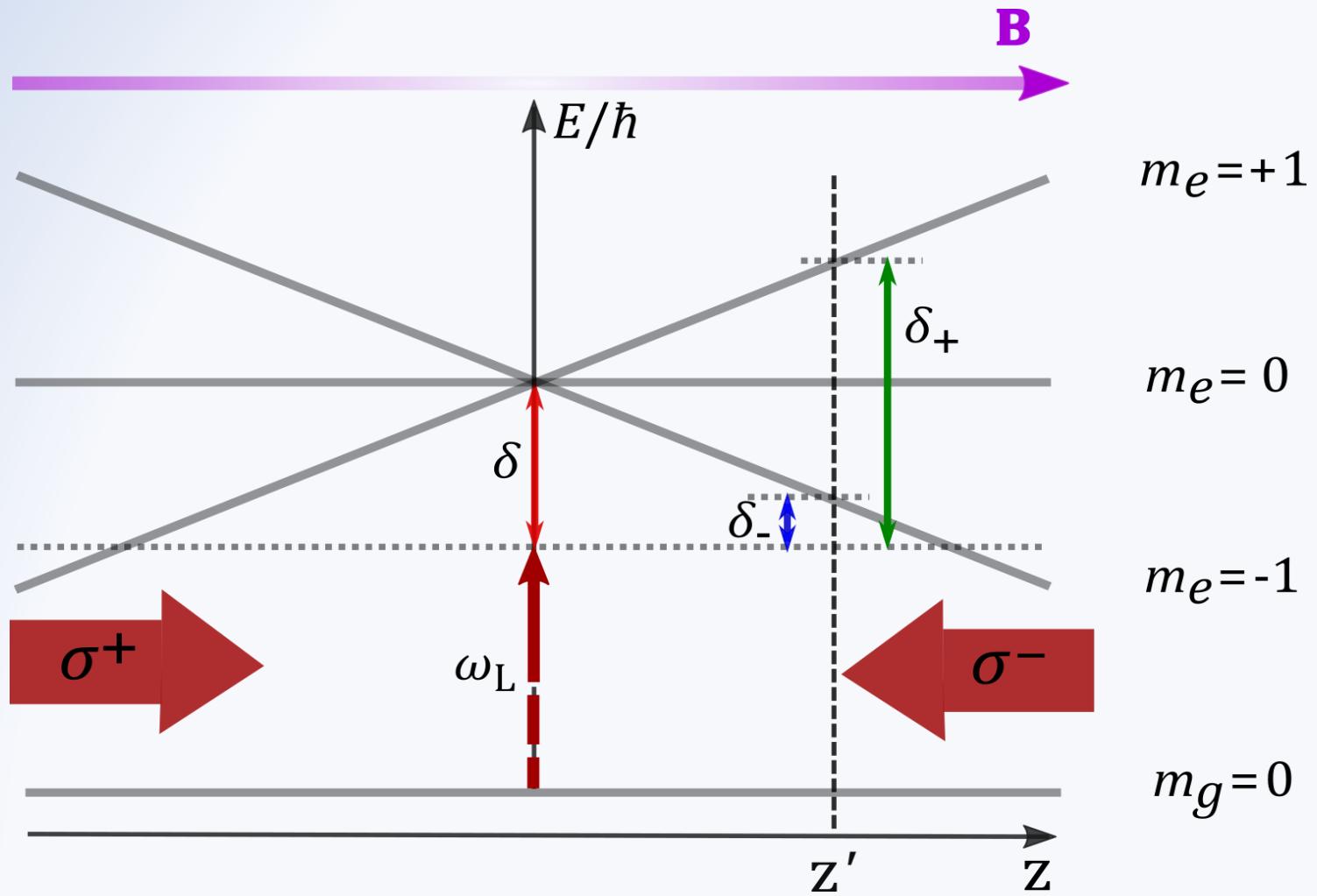
# Magneto-optička stupica, MOT



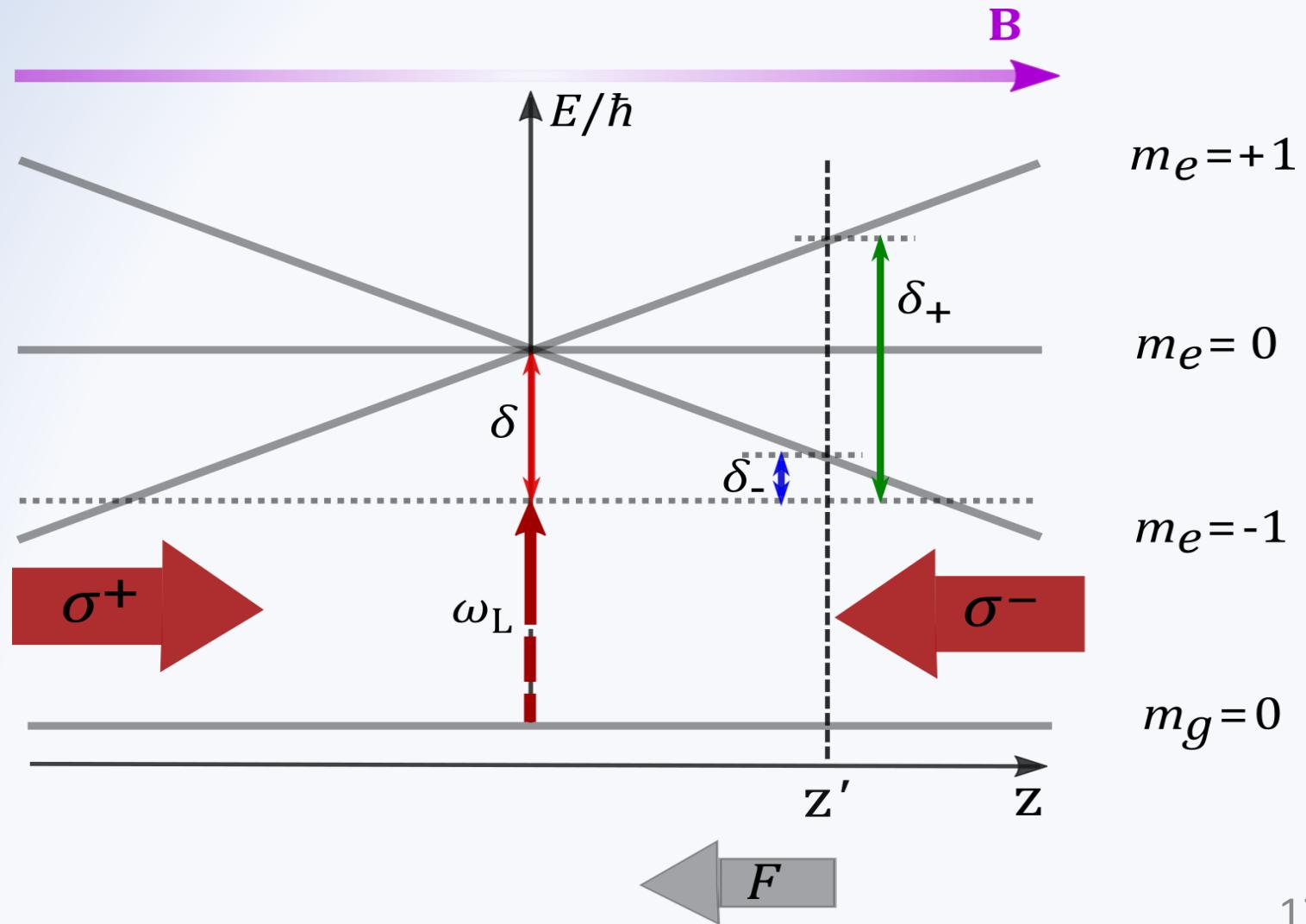
# Magneto-optička stupica, MOT



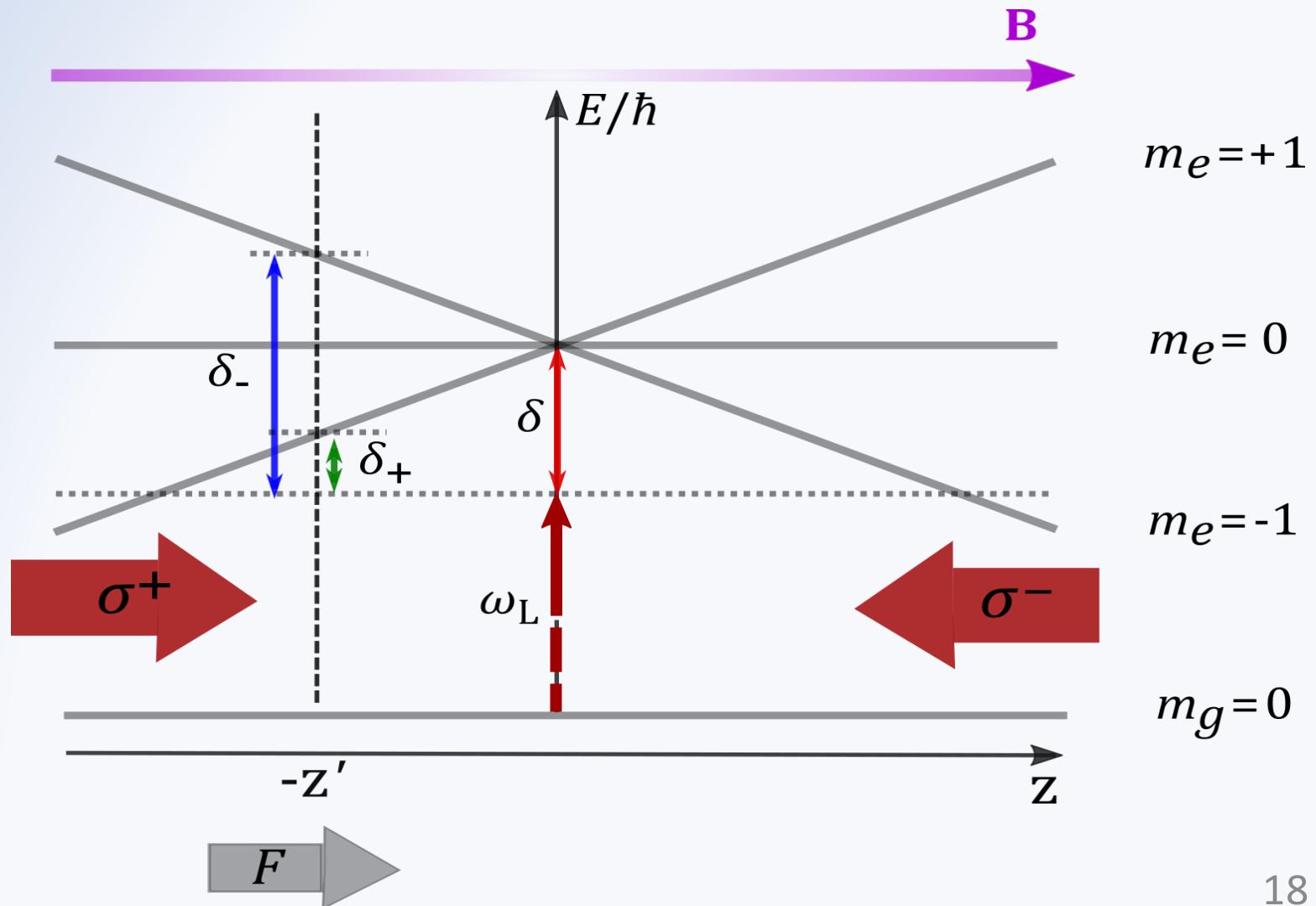
# Magneto-optička stupica, MOT



# Magneto-optička stupica, MOT



# Magneto-optická stupica, MOT

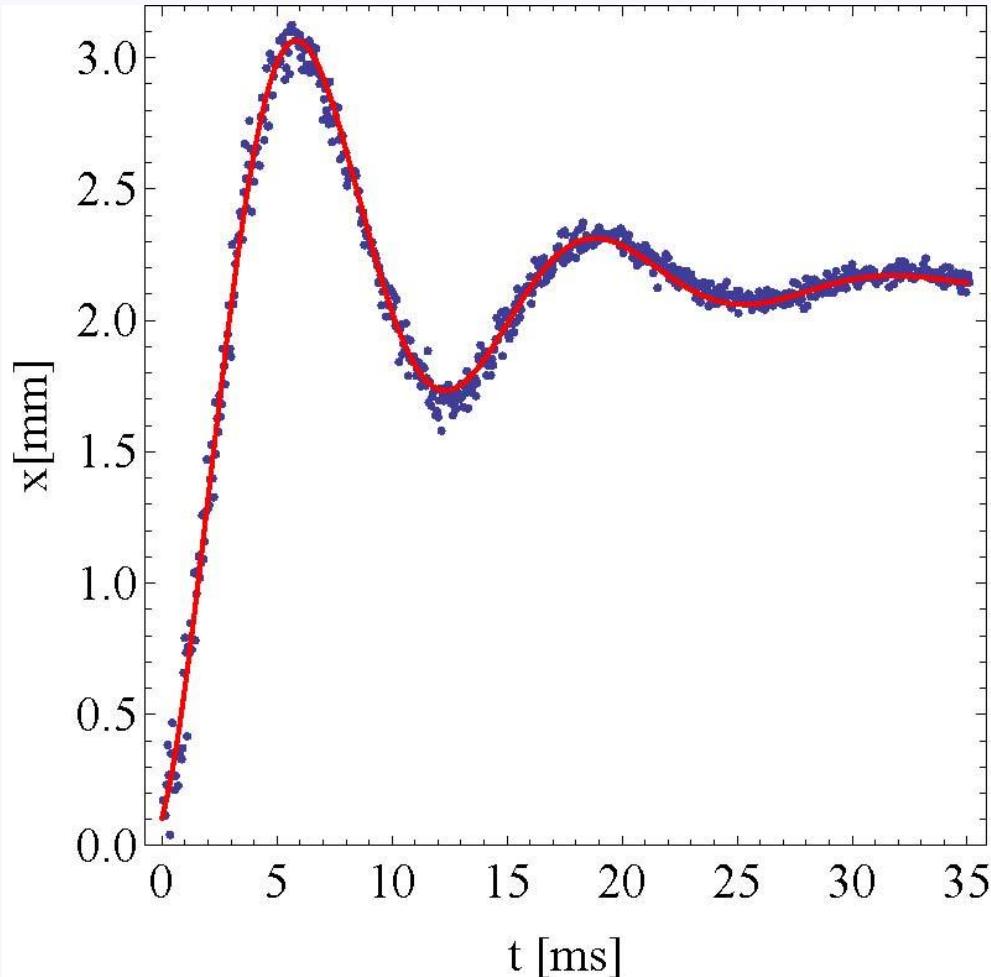


# Magneto-optička stupica, MOT

- ukupna sila na atom u MOT-u:

$$\vec{F} = -\beta \vec{v} + \kappa \vec{z}$$

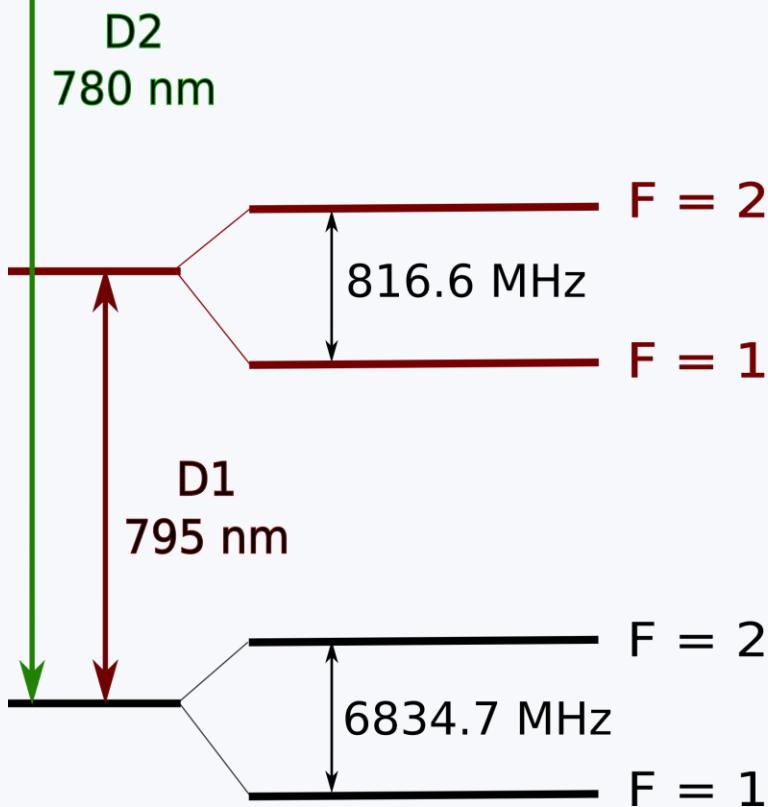
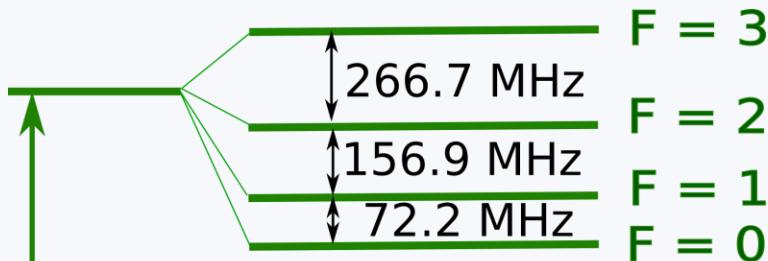
SILA GUŠENOGL  
HARMONIČKOG  
OSCILATORA



# atom $^{87}\text{Rb}$ -realizacija sistema s dva stanja

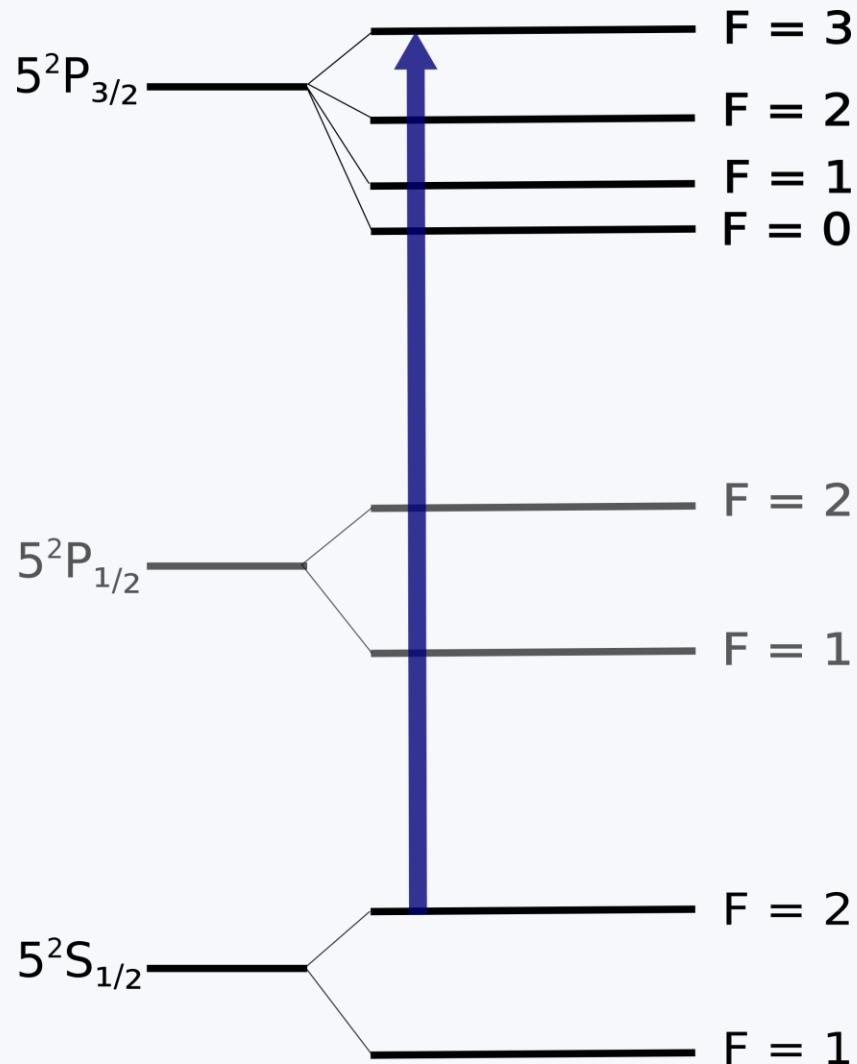
- fina struktura
- hiperfina struktura

$$\mathbf{F} = \mathbf{I} + \mathbf{J}$$



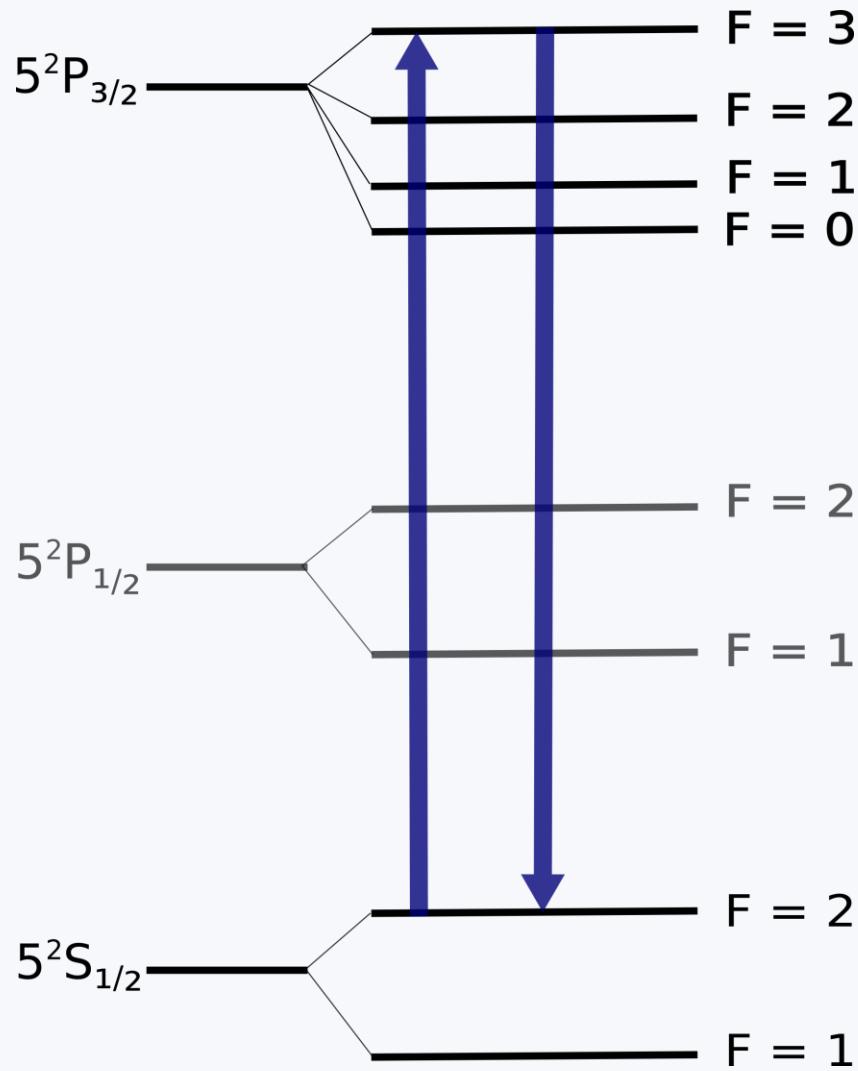
# atom $^{87}\text{Rb}$ -realizacija sistema s dva stanja

- prijelaz za hlađenje-  
zatvoreni prijelaz



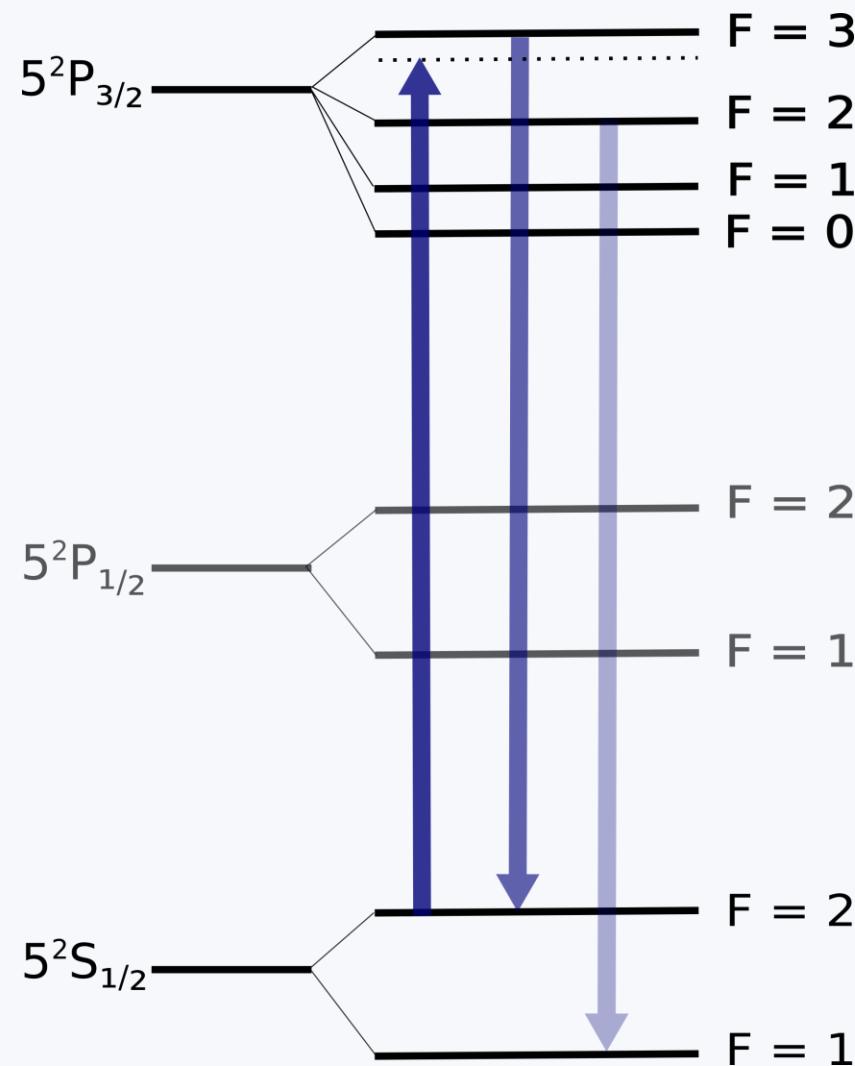
# atom $^{87}\text{Rb}$ -realizacija sistema s dva stanja

- prijelaz za hlađenje-  
zatvoreni prijelaz
- $\Delta F = 0, \pm 1$



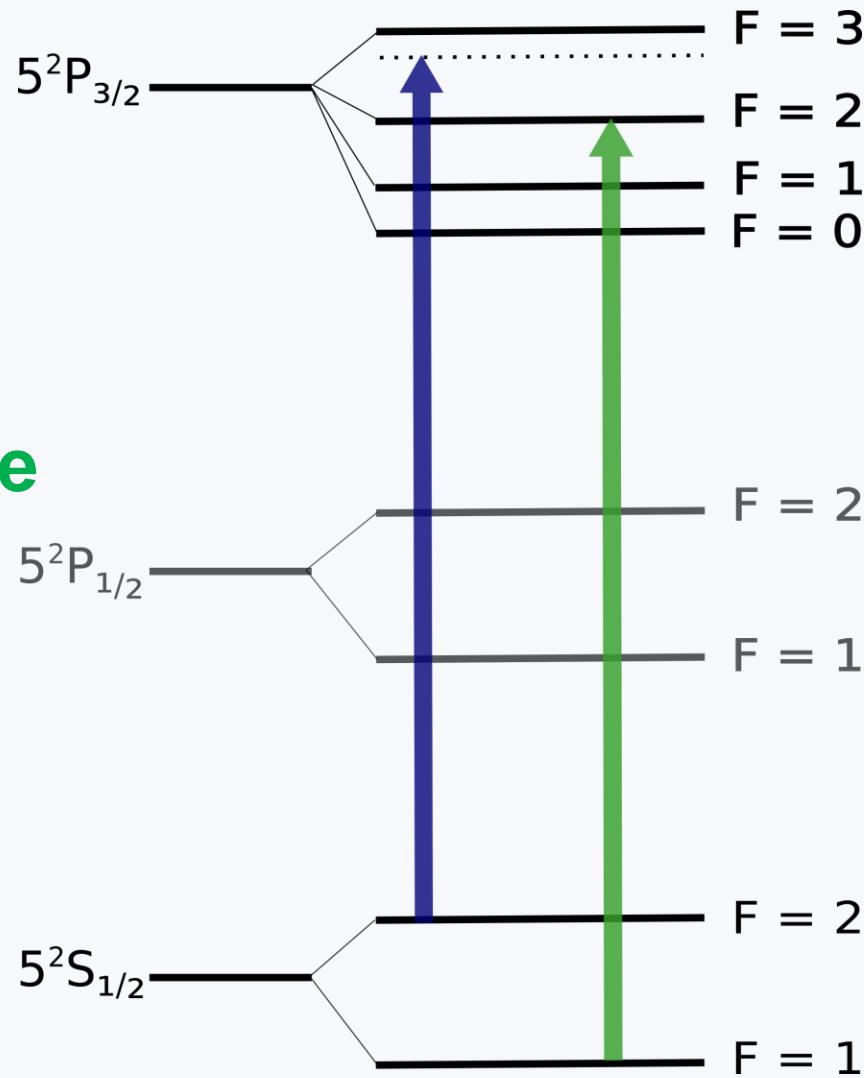
# atom $^{87}\text{Rb}$ -realizacija sistema s dva stanja

- **laser za hlađenje**



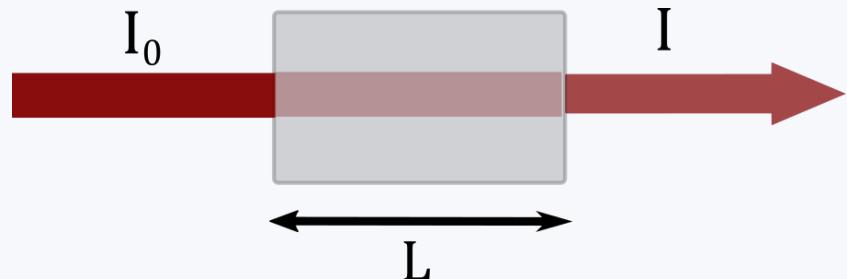
# atom $^{87}\text{Rb}$ -realizacija sistema s dva stanja

- laser za hlađenje
- laser za naseljavanje



# Beer-Lambertov zakon

$$I = I_0 e^{-n\sigma_{12}L}$$



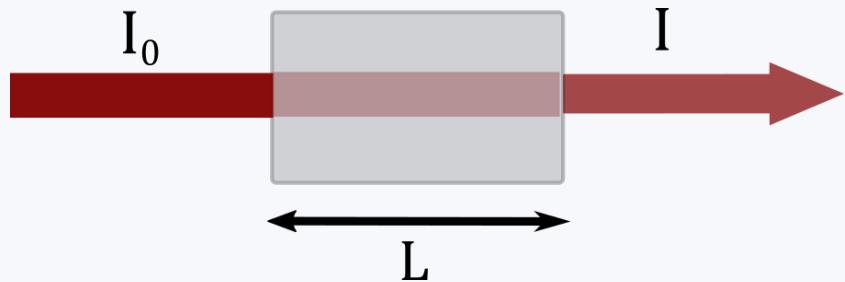
$n$  koncentracija atoma koji  
apsorbiraju zračenje

$\sigma_{12}$  apsorpcijski udarni presjek

$L$  duljina apsorbirajućeg  
medija

# Beer-Lambertov zakon

$$I = I_0 e^{-n\sigma_{12}L}$$



- apsorpcijski udarni presjek  
 $\sigma_{12}(\nu)$

$$\sigma_{12}(\nu = \nu_{12}) = \frac{e^2 f_{12}}{2\pi \epsilon_0 m_e c \Gamma}$$

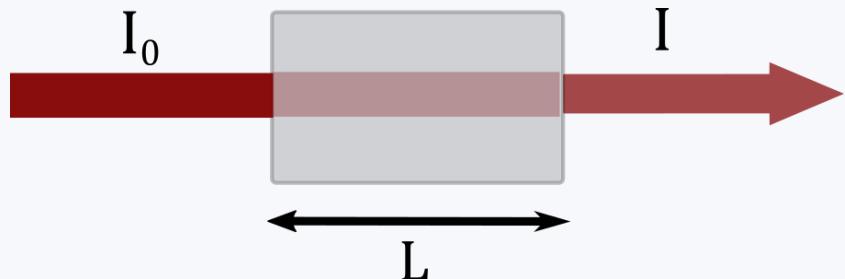


FREKVENCIJA PRIJELAZA

$f_{12}$  oscilatorna jakost  
 $\Gamma$  prirodna širina linije

# Beer-Lambertov zakon

$$I = I_0 e^{-n\sigma_{12}L}$$

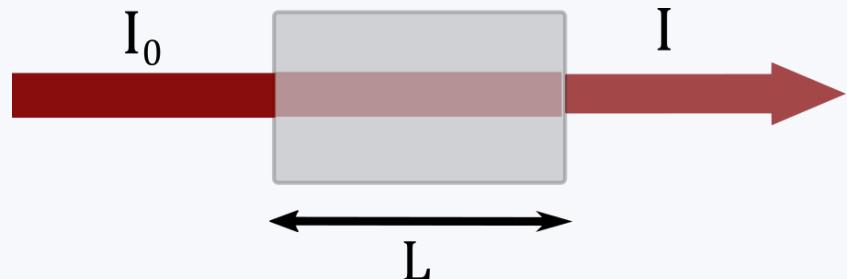


- koncentracija atoma

$$n = \frac{2\pi\varepsilon_0 m_e c \Gamma}{e^2 f_{12} L} \ln(I_0/I)$$

# Beer-Lambertov zakon

$$I = I_0 e^{-n\sigma_{12}L}$$

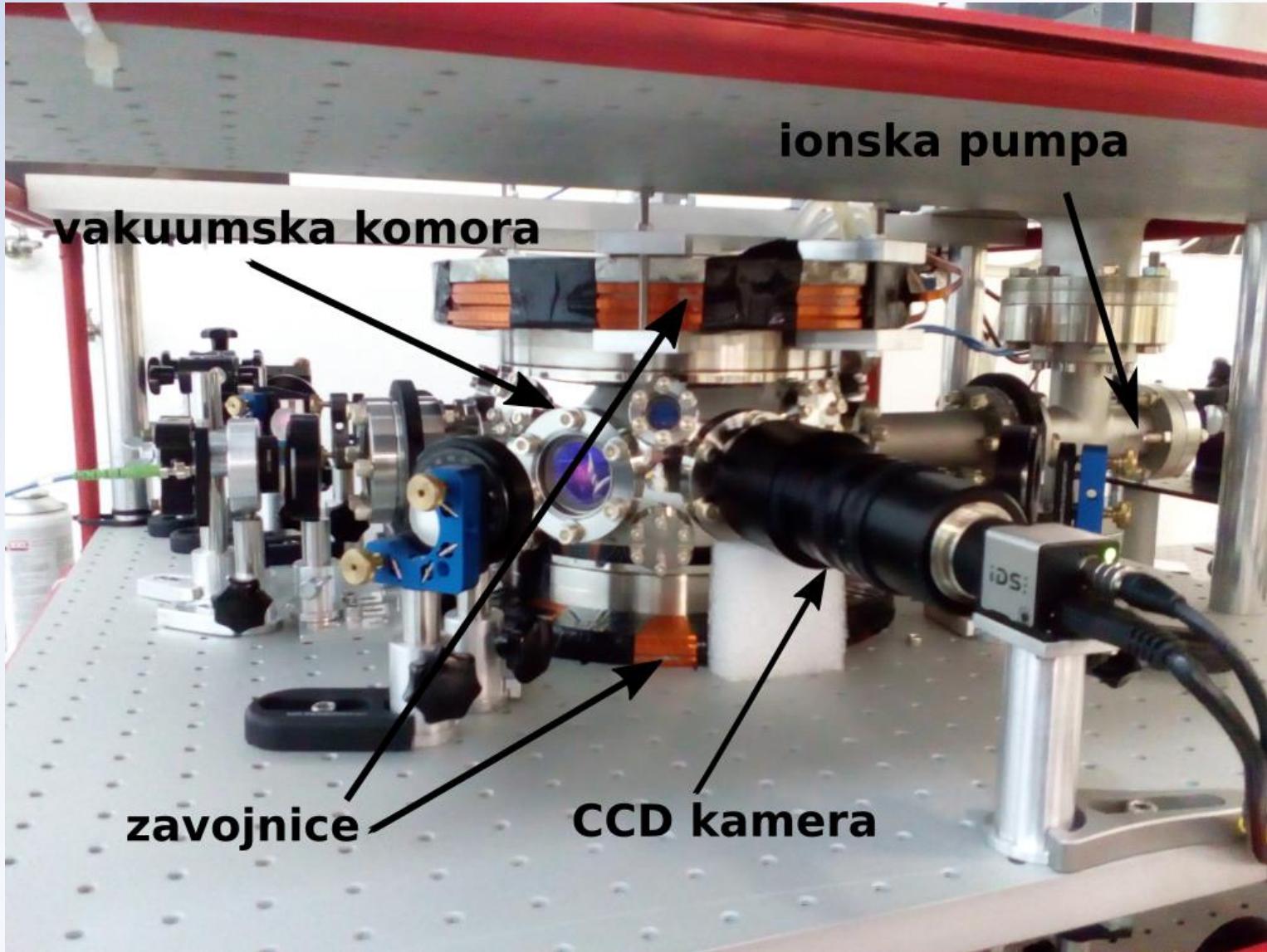


- koncentracija atoma

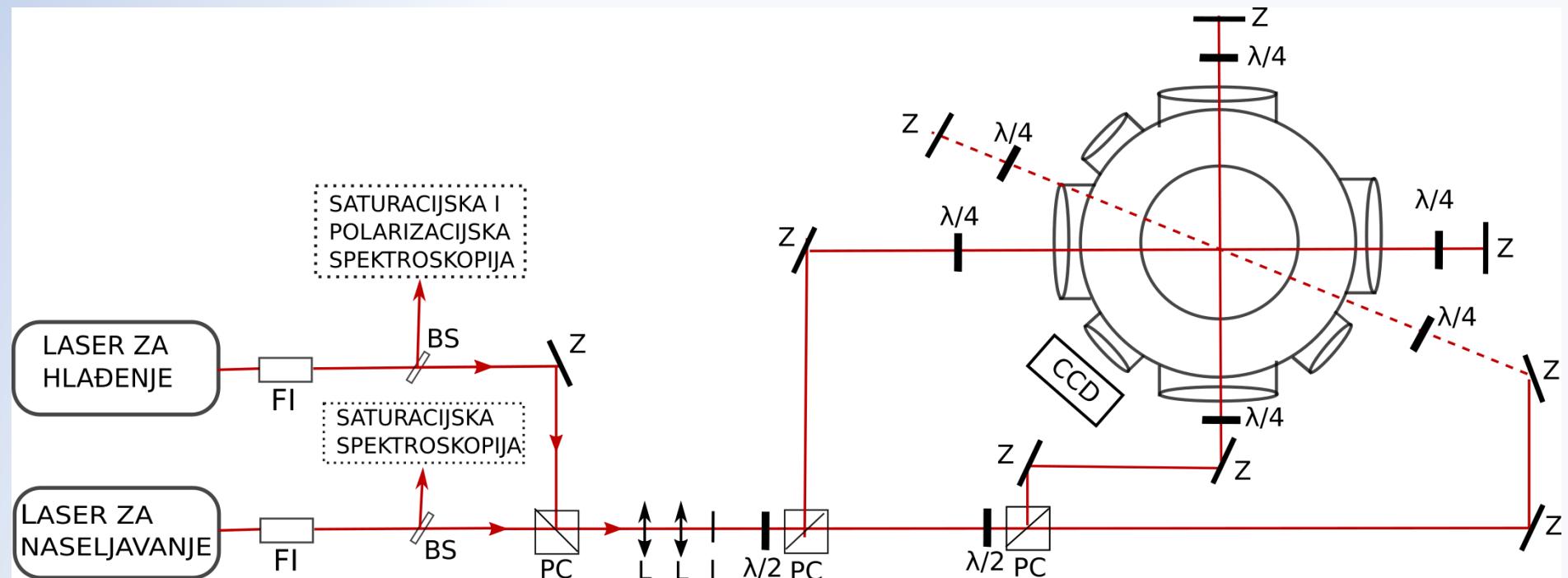
$$n = \frac{2\pi\varepsilon_0 m_e c}{e^2 f_{12} L} \Gamma \ln(I_0/I)$$

OPTIČKA DEBLJINA  
OD =  $\ln(I_0/I)$

# Eksperimentalni postav

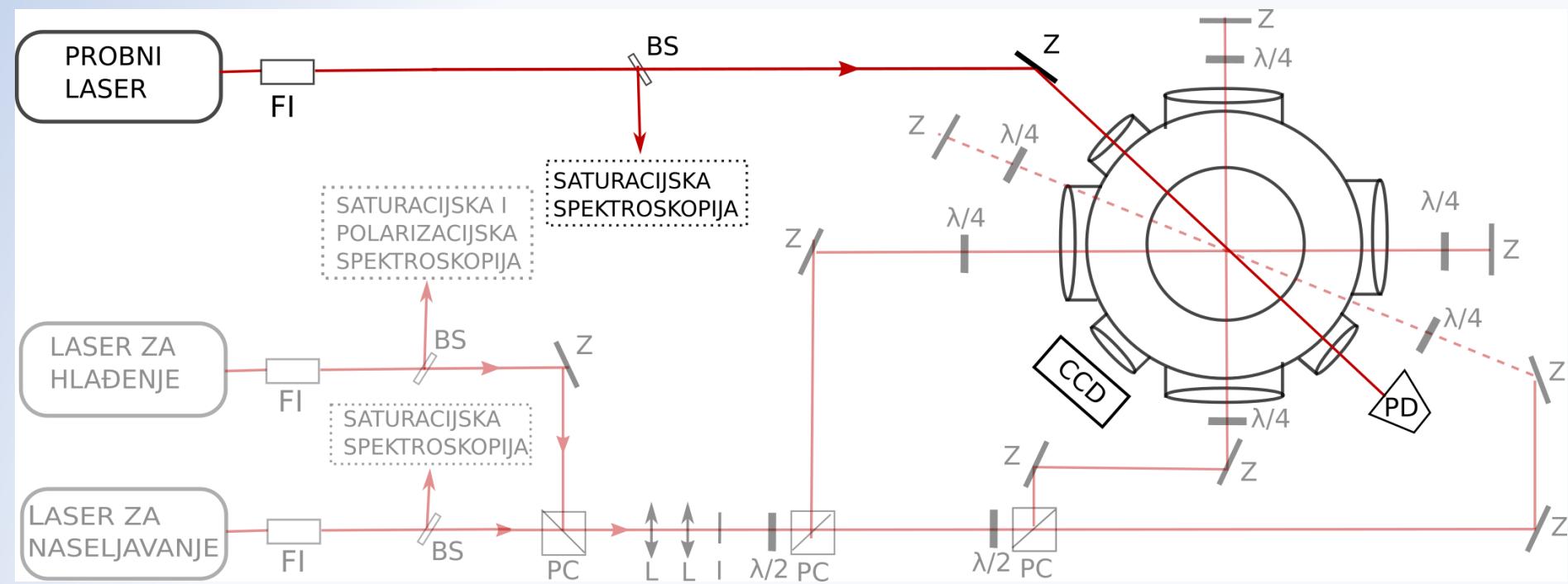


# Realizacija MOT-a



Oznake: Z - zrcalo;  $\lambda / 2$  i  $\lambda / 4$  - polarizacijske pločice; BS - djelitelj snopa; PC - polarizacijska kocka; L - leća; I - iris; FI - Faradayev izolator; PD - fotodioda.

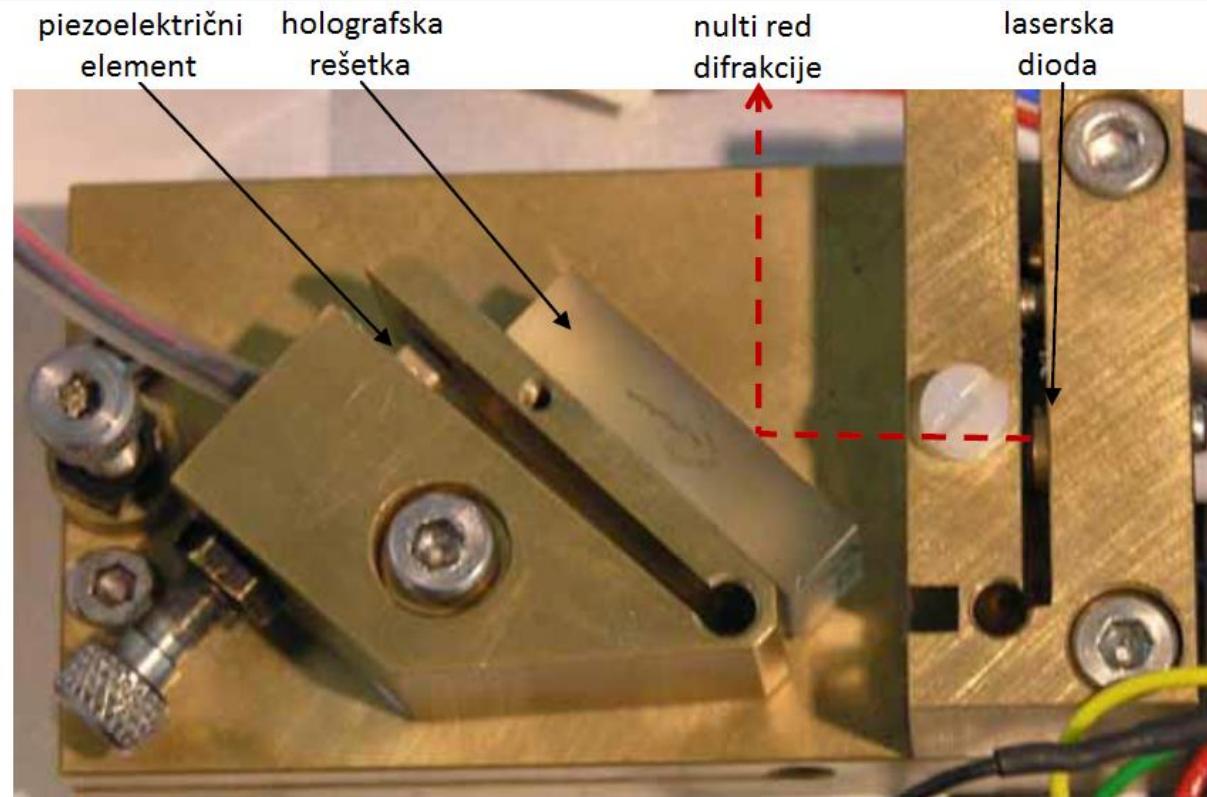
# Mjerenje transmisijske



Oznake: Z - zrcalo;  $\lambda / 2$  i  $\lambda / 4$  - polarizacijske pločice; BS - djelitelj snopa; PC-polarizacijska kocka; L - leća; I - iris; FI - Faradayev izolator; PD - fotodioda.

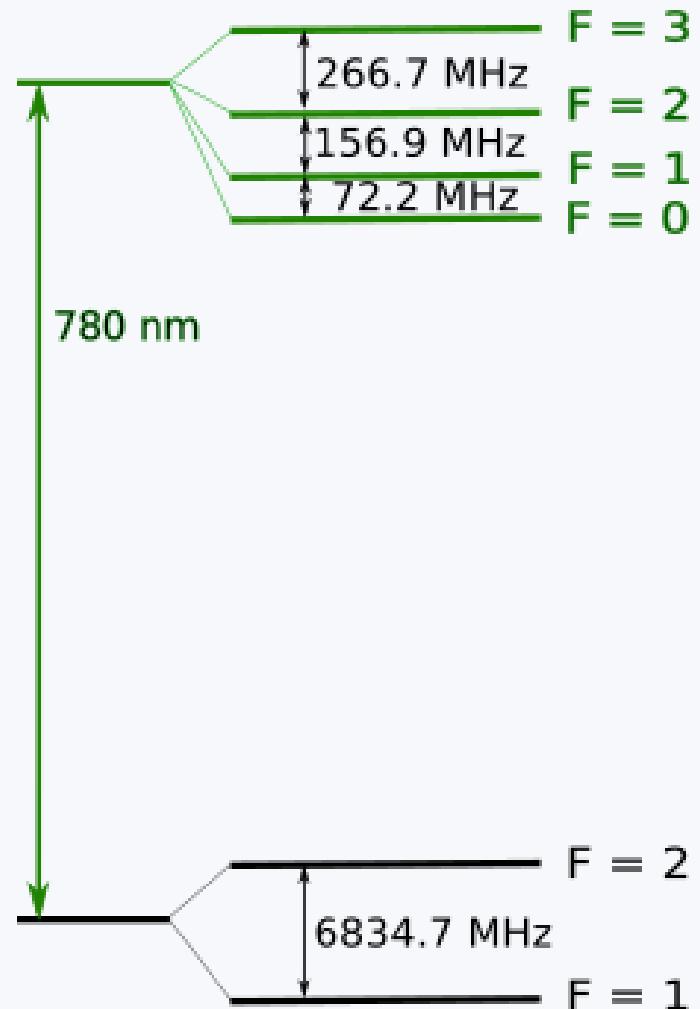
# Laserski sistem

- Poluvodički laseri s vanjskim rezonatorom (eng. *External cavity diode laser, ECDL*) – 780 nm
- valna duljina:
  - struja
  - temperatura
  - položaj optičke rešetke
- piezoelektrični element-kontinuirano mijenjanje valne duljine

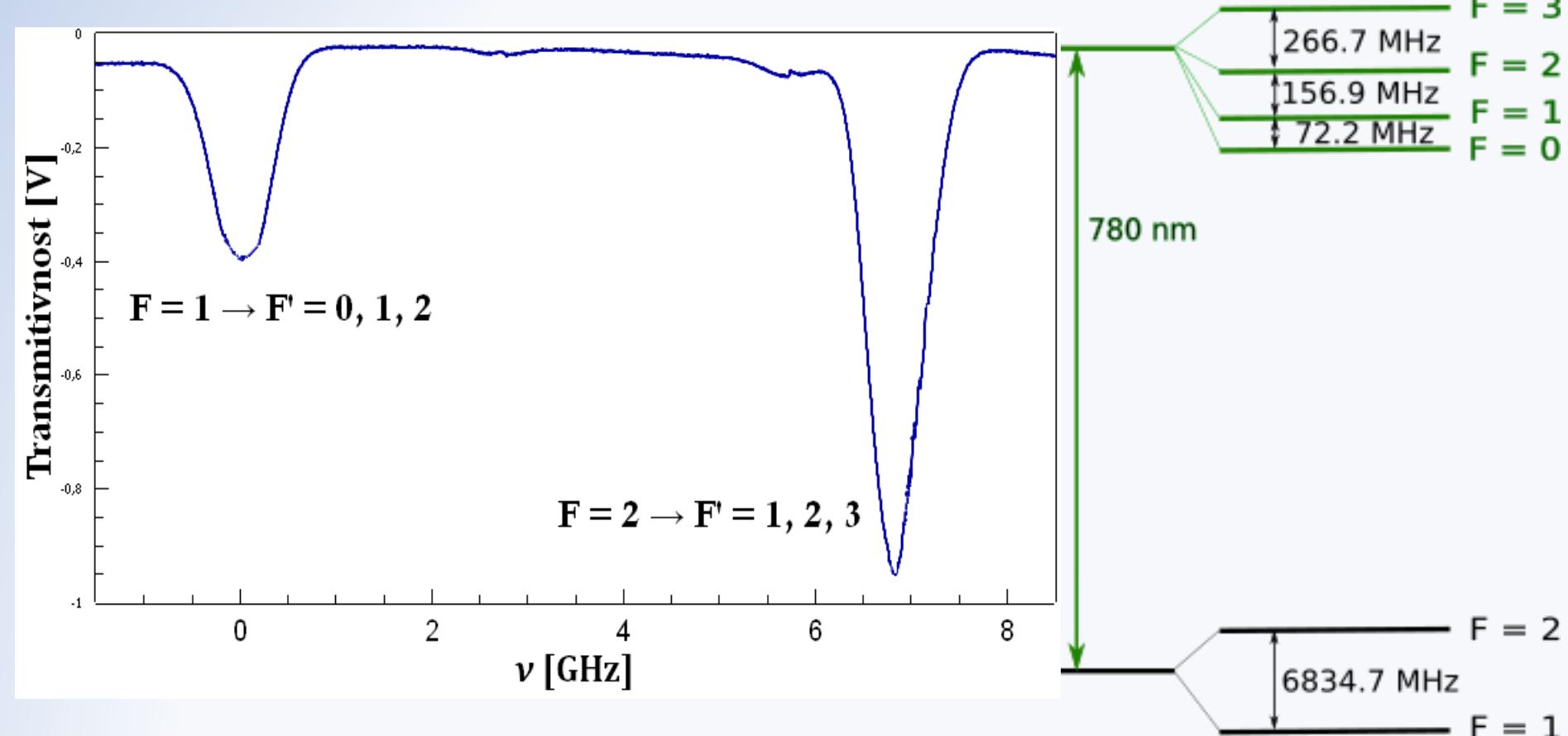


# Kako postaviti frekvencije lasera na frekvencije HF prijelaza?

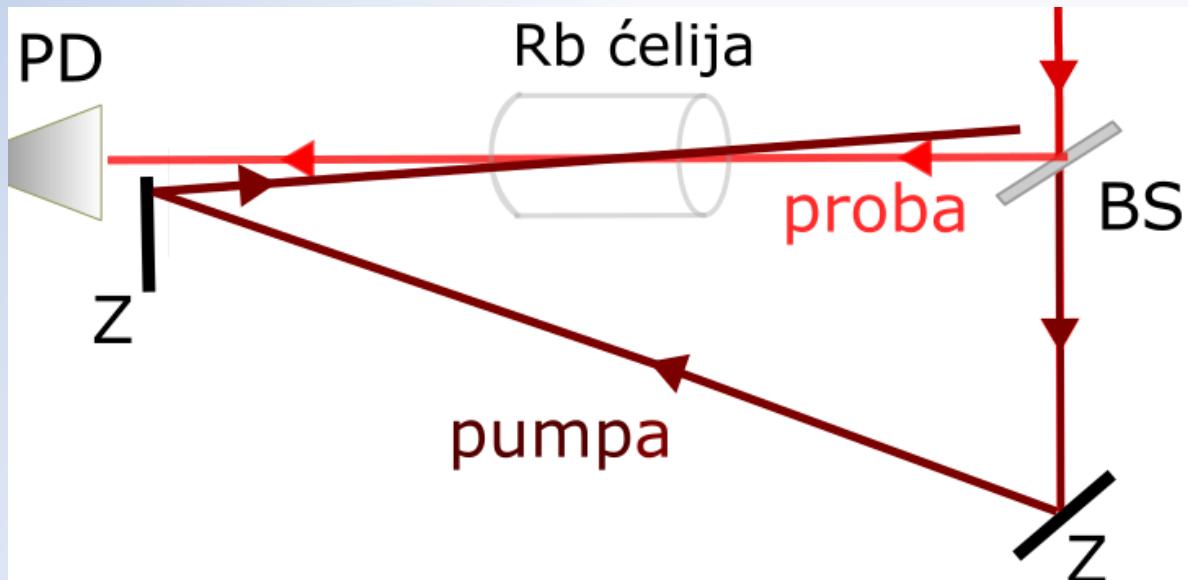
- termalno gibanje atoma i Dopplerov efekt → **Dopplerovo širenje spektralnih linija**
- $^{87}\text{Rb}$  na sobnoj temperaturi:  
Dopplerova širina linije  
 $\Delta\nu_D \approx 513 \text{ MHz} \rightarrow \text{linije hiperfine strukture nisu razlučive}$



# Kako postaviti frekvencije lasera na frekvencije HF prijelaza?

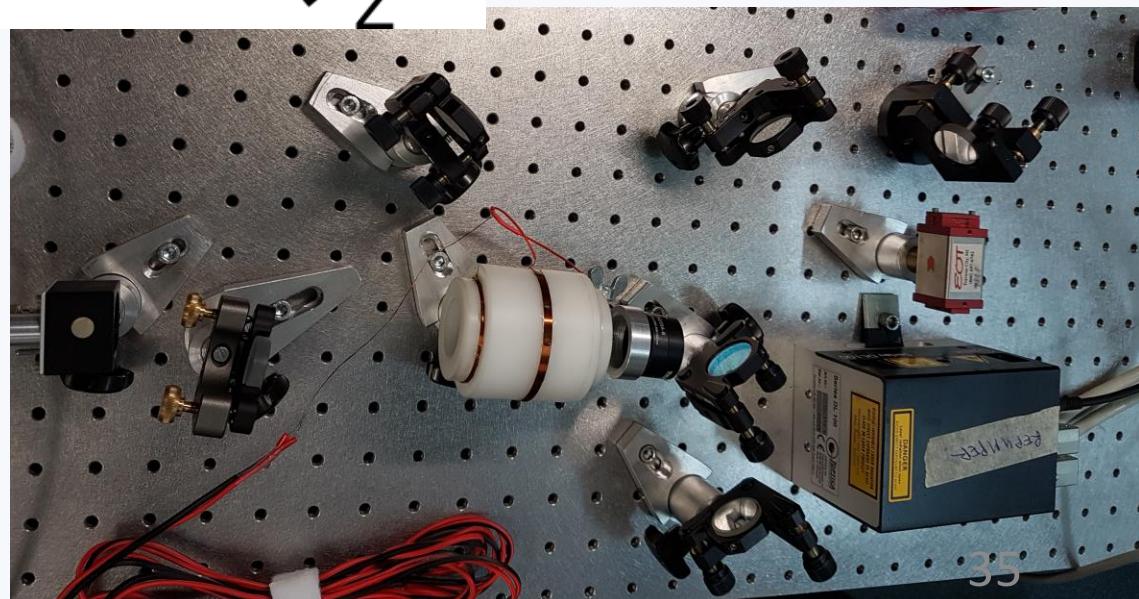


# Saturacijska apsorpcijska spektroskopija



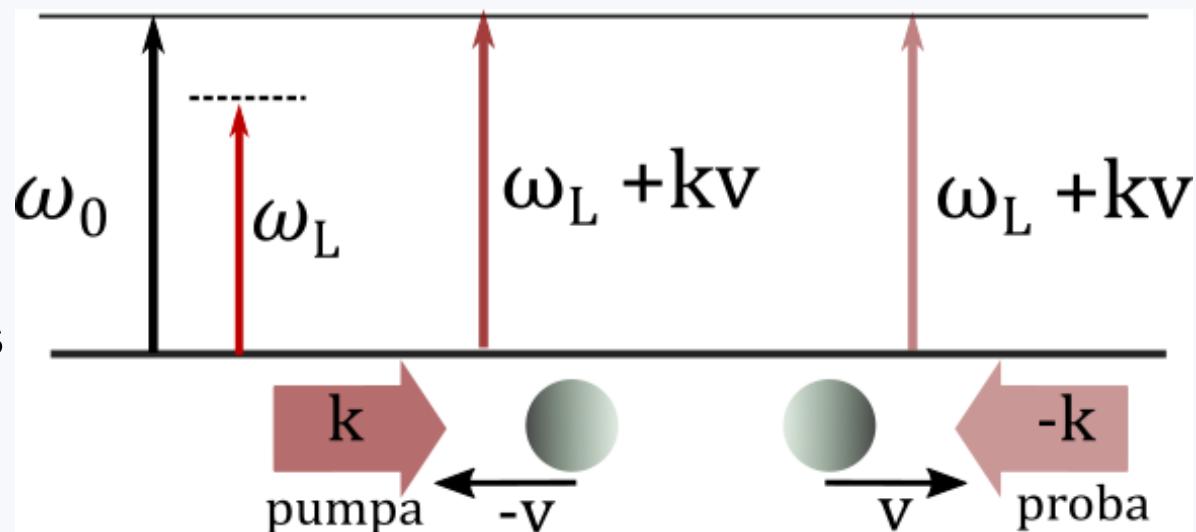
- **pumpa**- promjena naseljenosti stanja
- **proba** - detekcija promjena

Oznake: Z-zrcalo; BS- djelitelj zrake; PD-fotodioda



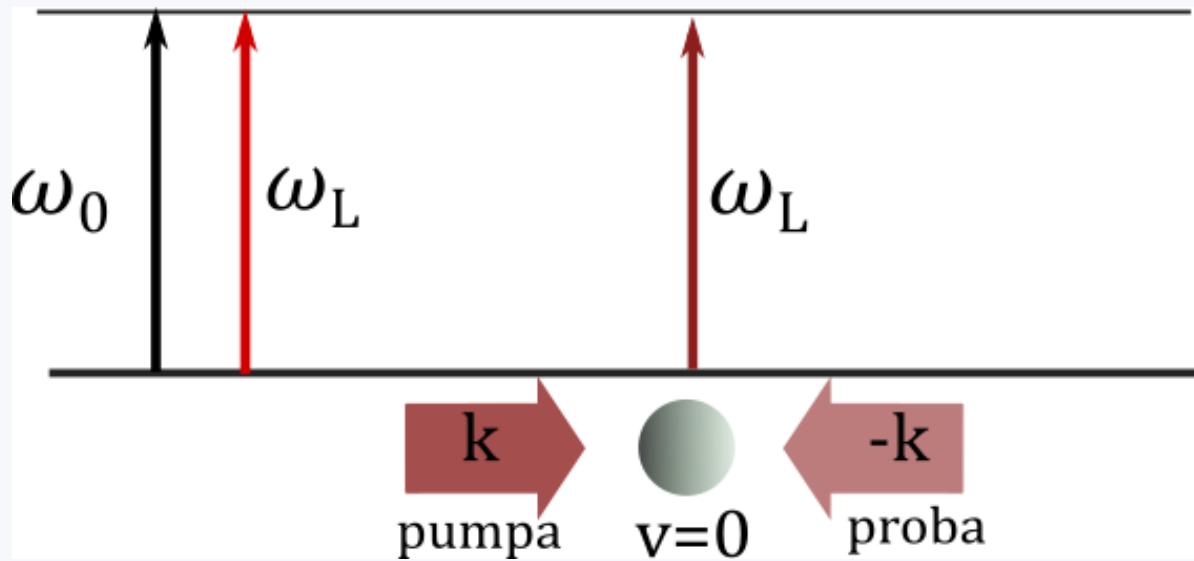
# Saturacijska apsorpcijska spektroskopija

- Dopplerov efekt
- $\vec{k}_{\text{pumpa}} = -\vec{k}_{\text{proba}}$
- $\omega_L \neq \omega_0 \rightarrow$  interakcija s **različitim** brzinskim grupama atoma  $\rightarrow$  nema utjecaja na transmisiju probne zrake

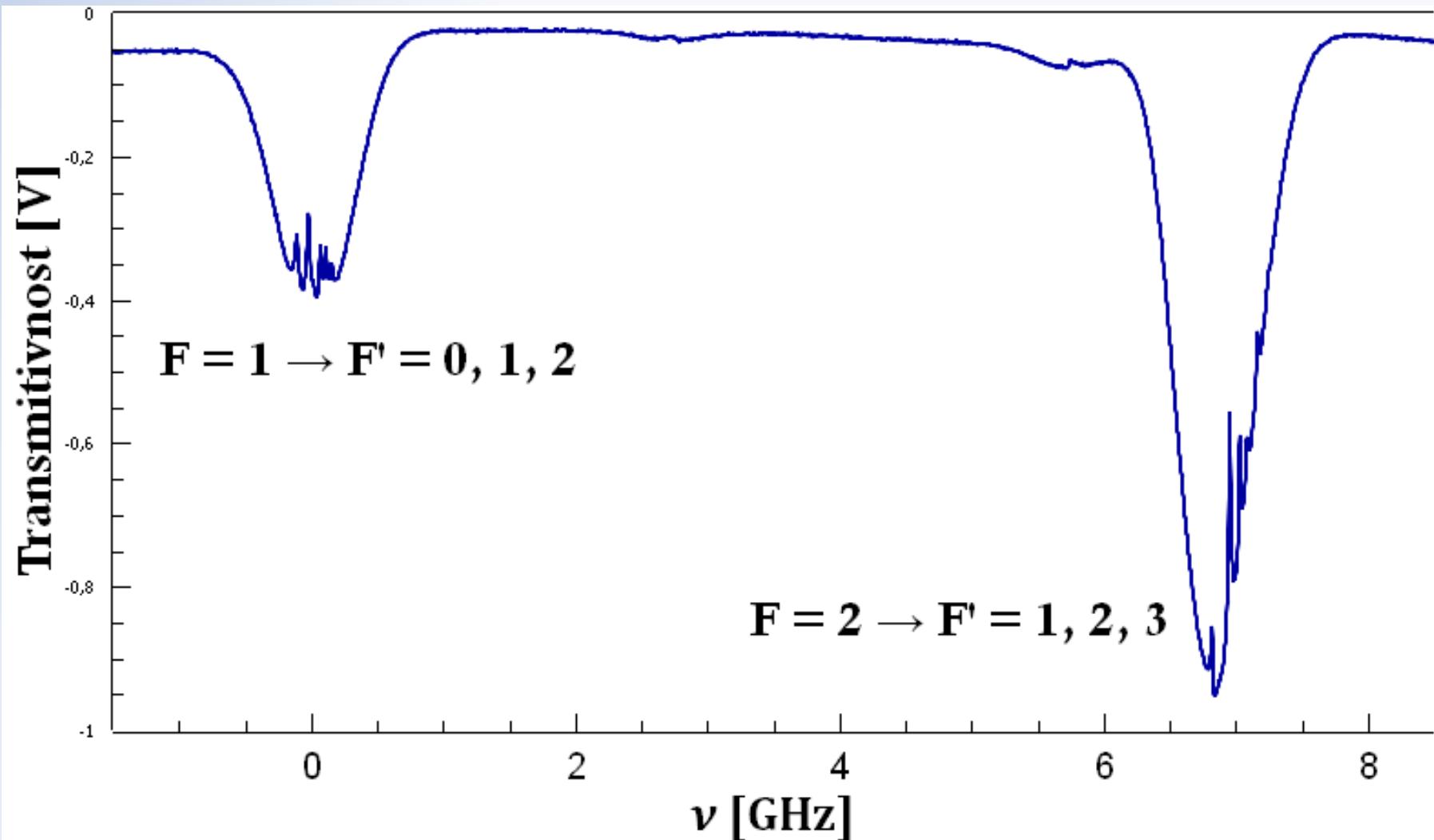


# Saturacijska apsorpcijska spektroskopija

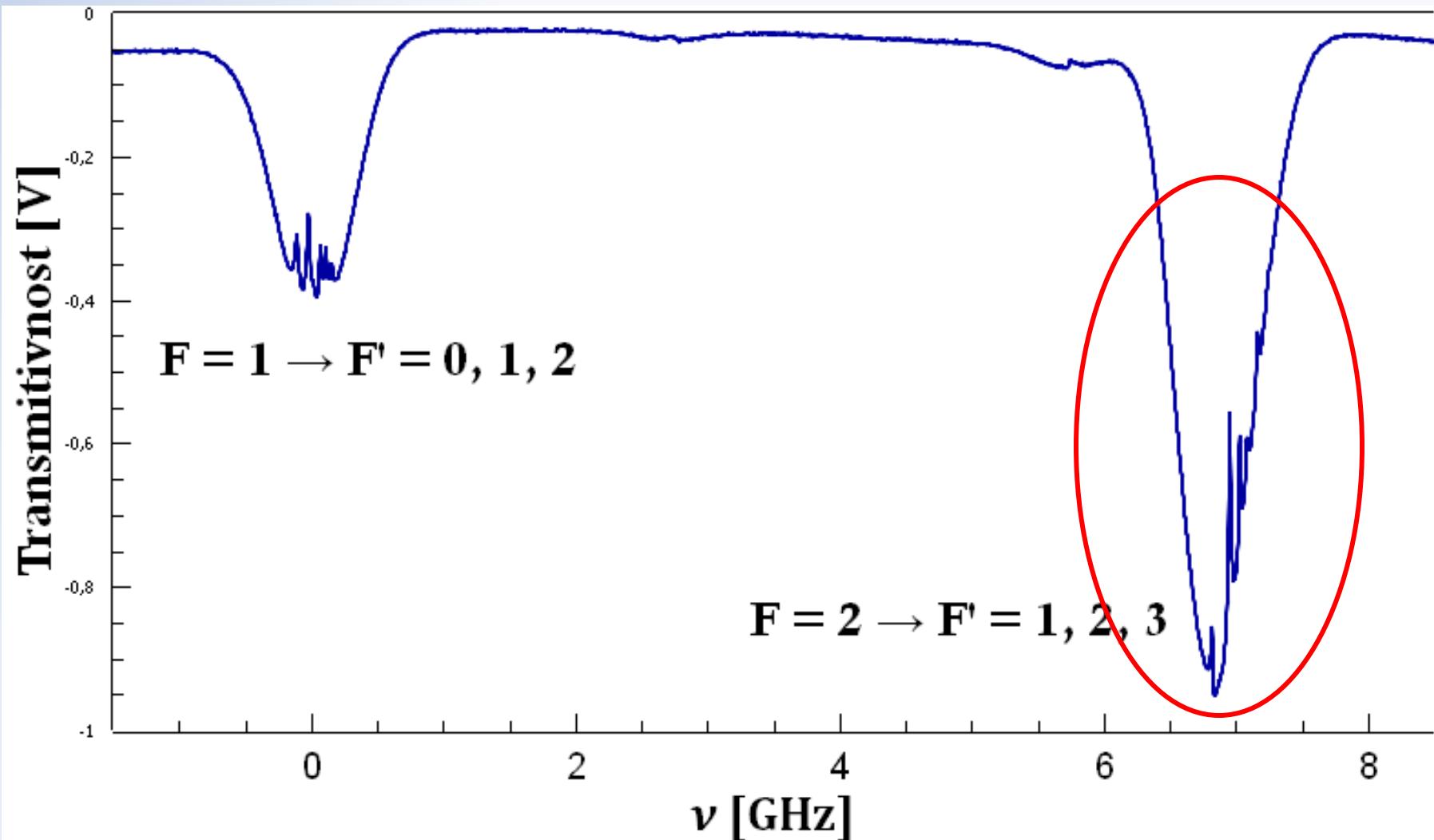
- Dopplerov efekt
- $\vec{k}_{\text{pumpa}} = -\vec{k}_{\text{proba}}$
- $\omega_L = \omega_0 \rightarrow$  interakcija s **istom** brzinskom grupom atoma  
 $(v=0) \rightarrow$  **povećanje transmisije** probe



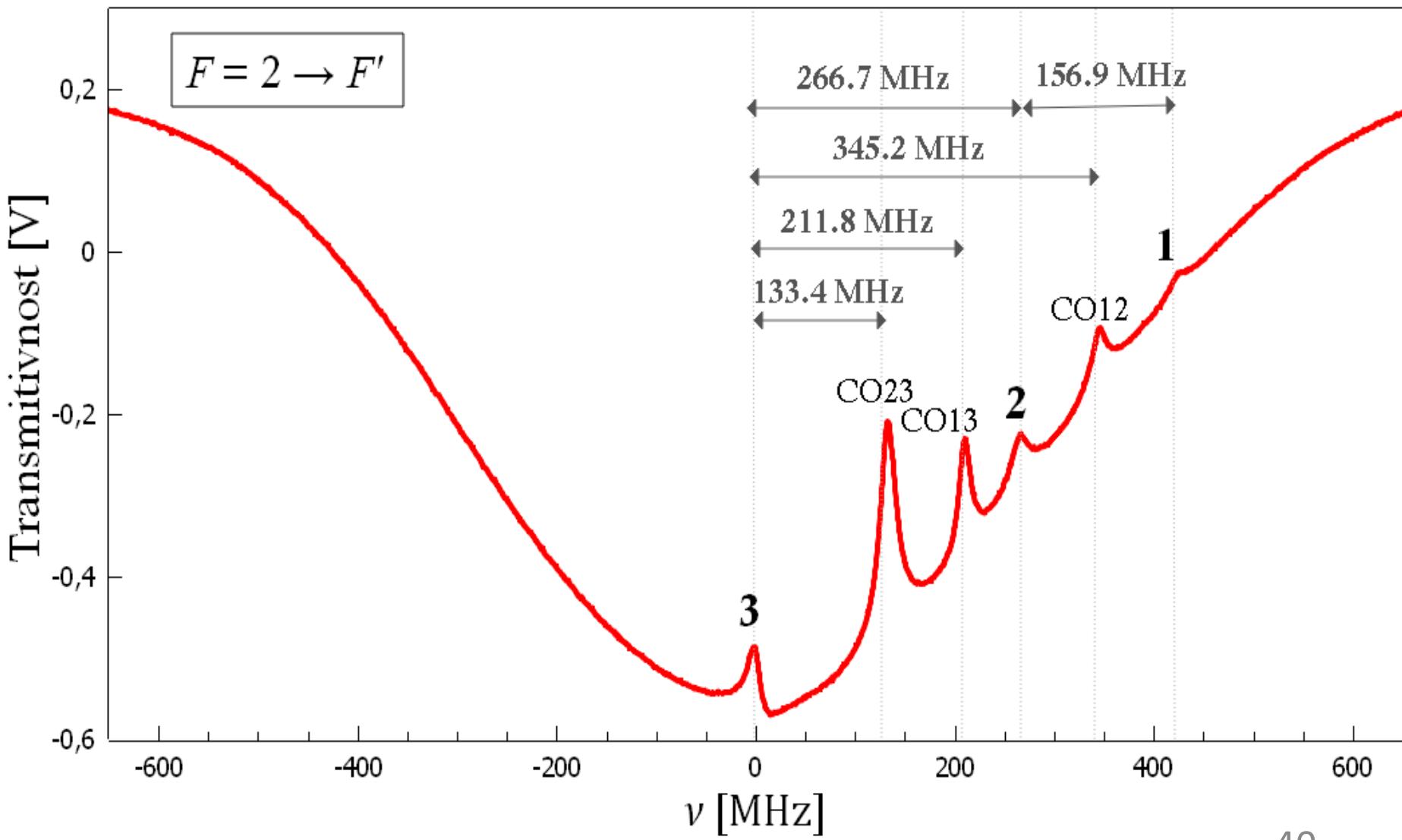
# Saturacijska apsorpcijska spektroskopija



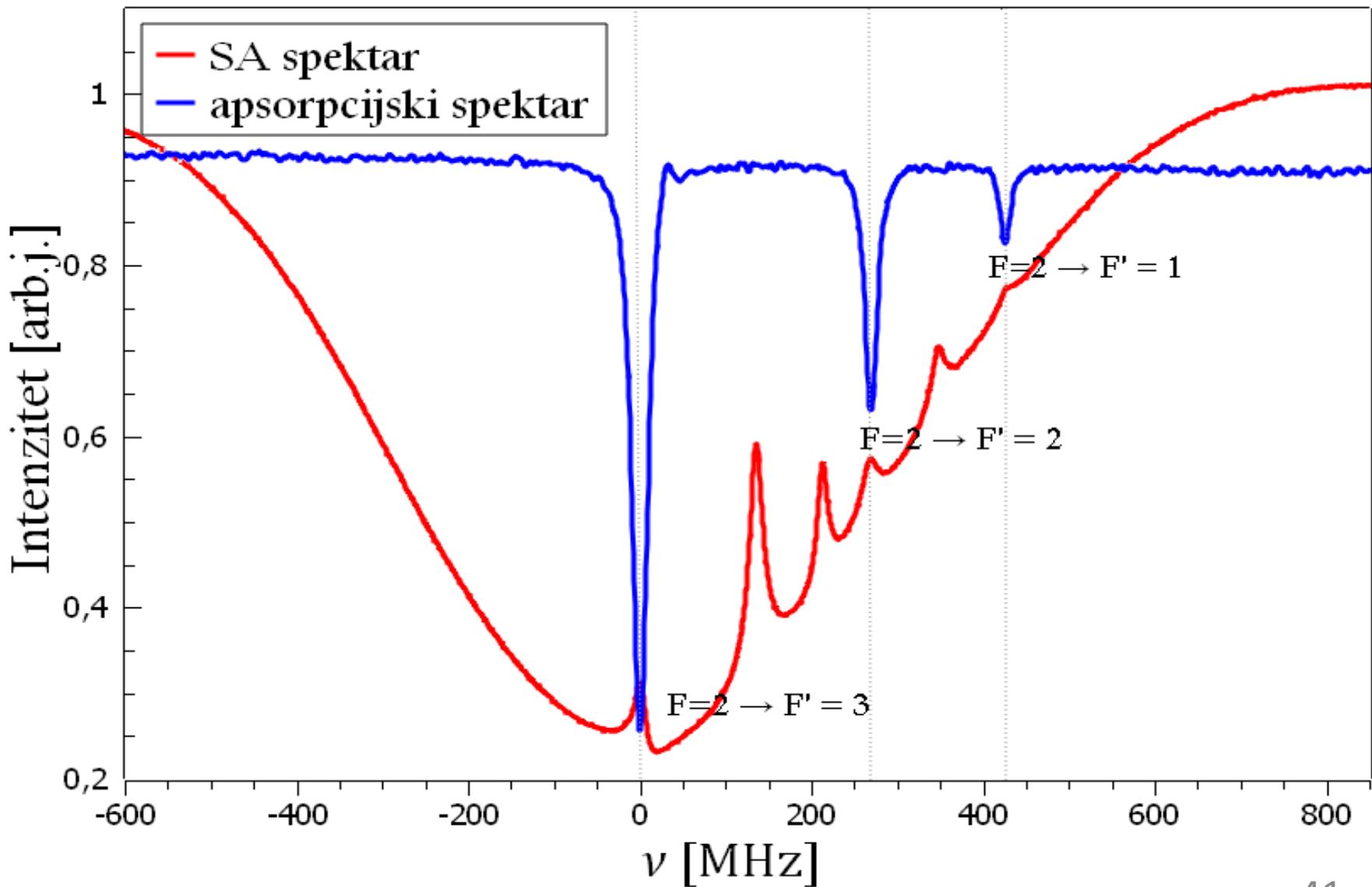
# Saturacijska apsorpcijos spektroskopija



# Saturacijska apsorpcijska spektroskopija

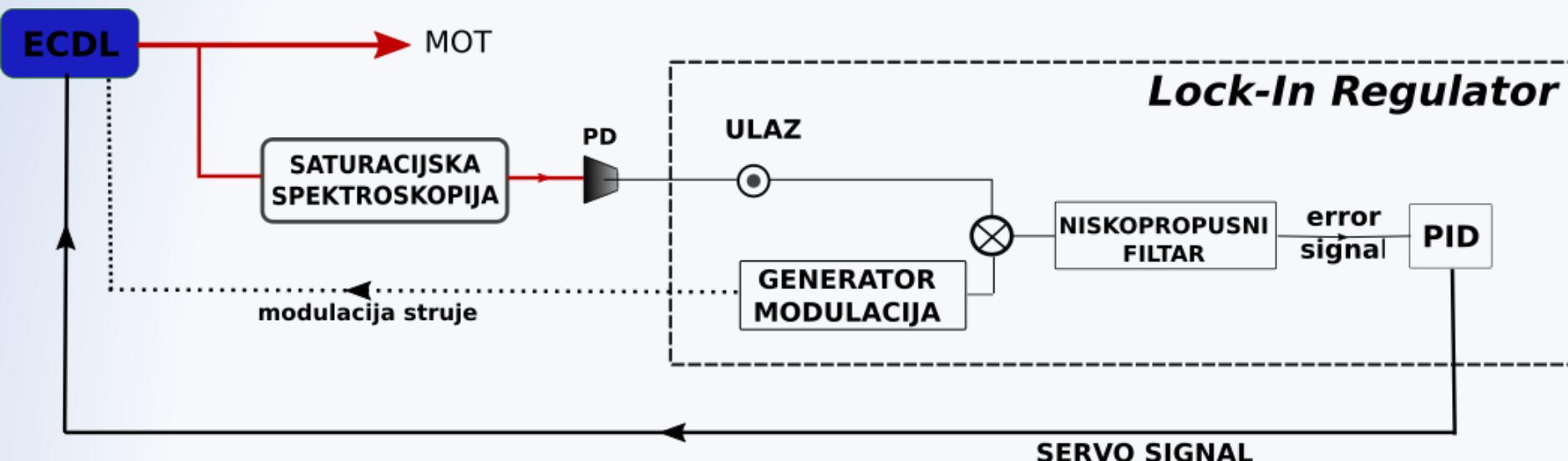


# Saturacijska apsorpcijska spektroskopija



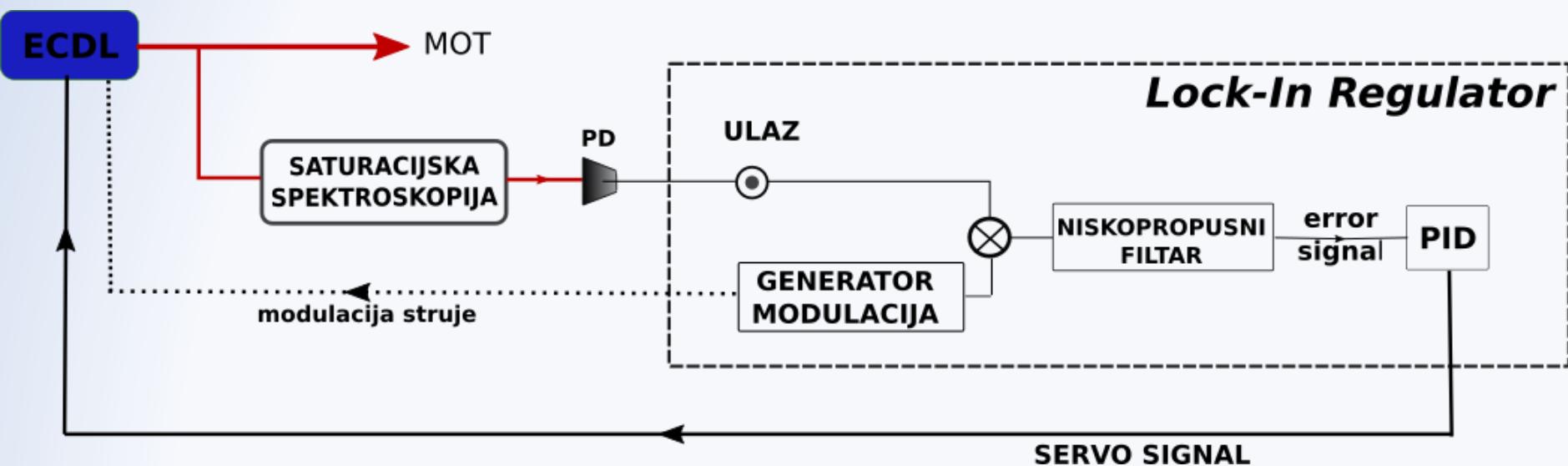
# Frekventna stabilizacija lasera

- ECDL-osjetljivi na promjene u okolini (temperatura, tlak, vlažnost, mehaničke vibracije i sl.) → frekvencija lasera klizi s vremenom → potrebna frekventna stabilizacija lasera
- stvaranje negativne povratne veze
- frekventna modulacija laserske frekvencije

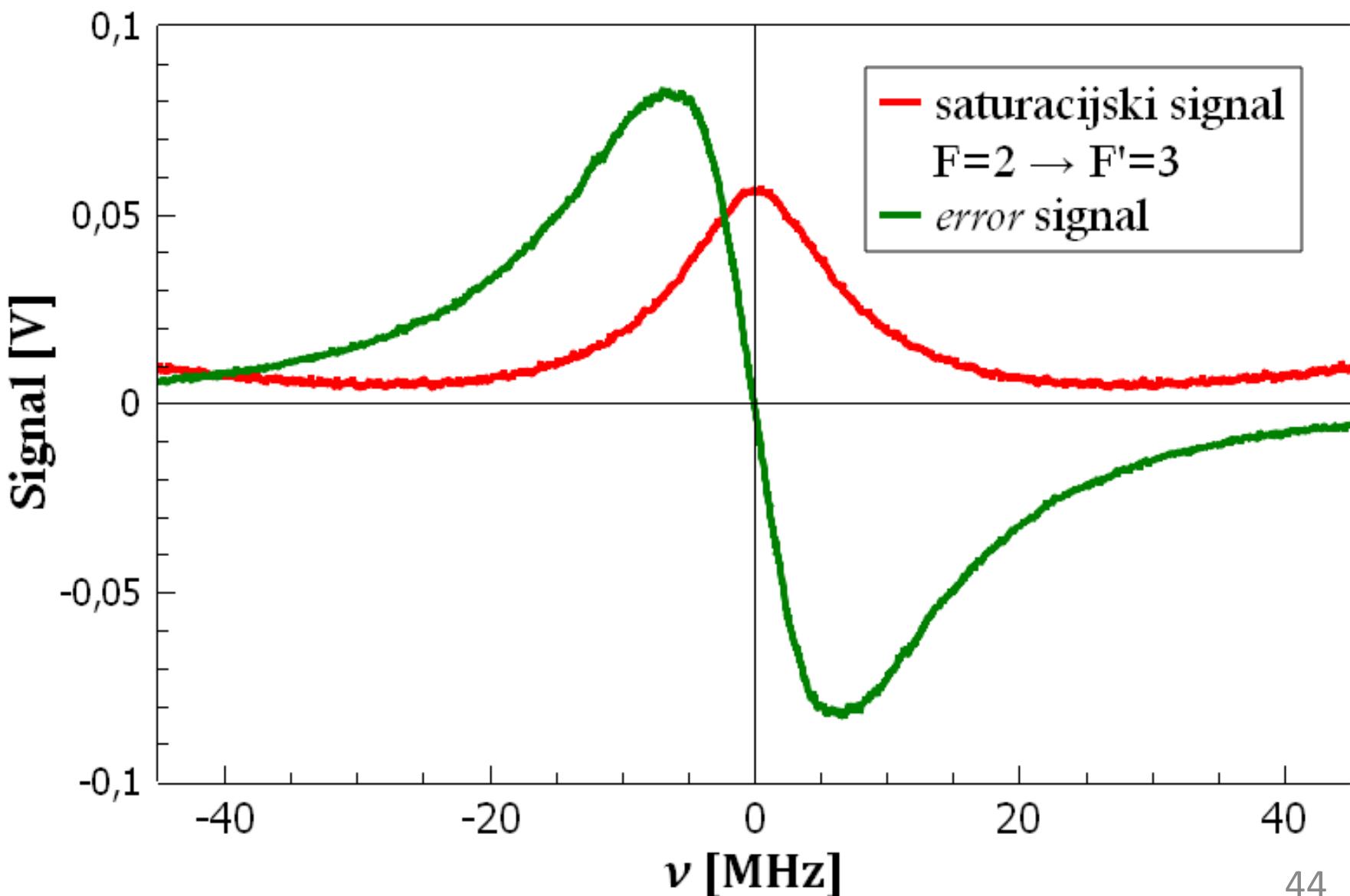


# Frekventna stabilizacija lasera

$$\text{Error signal} \propto S'(\omega_L)$$



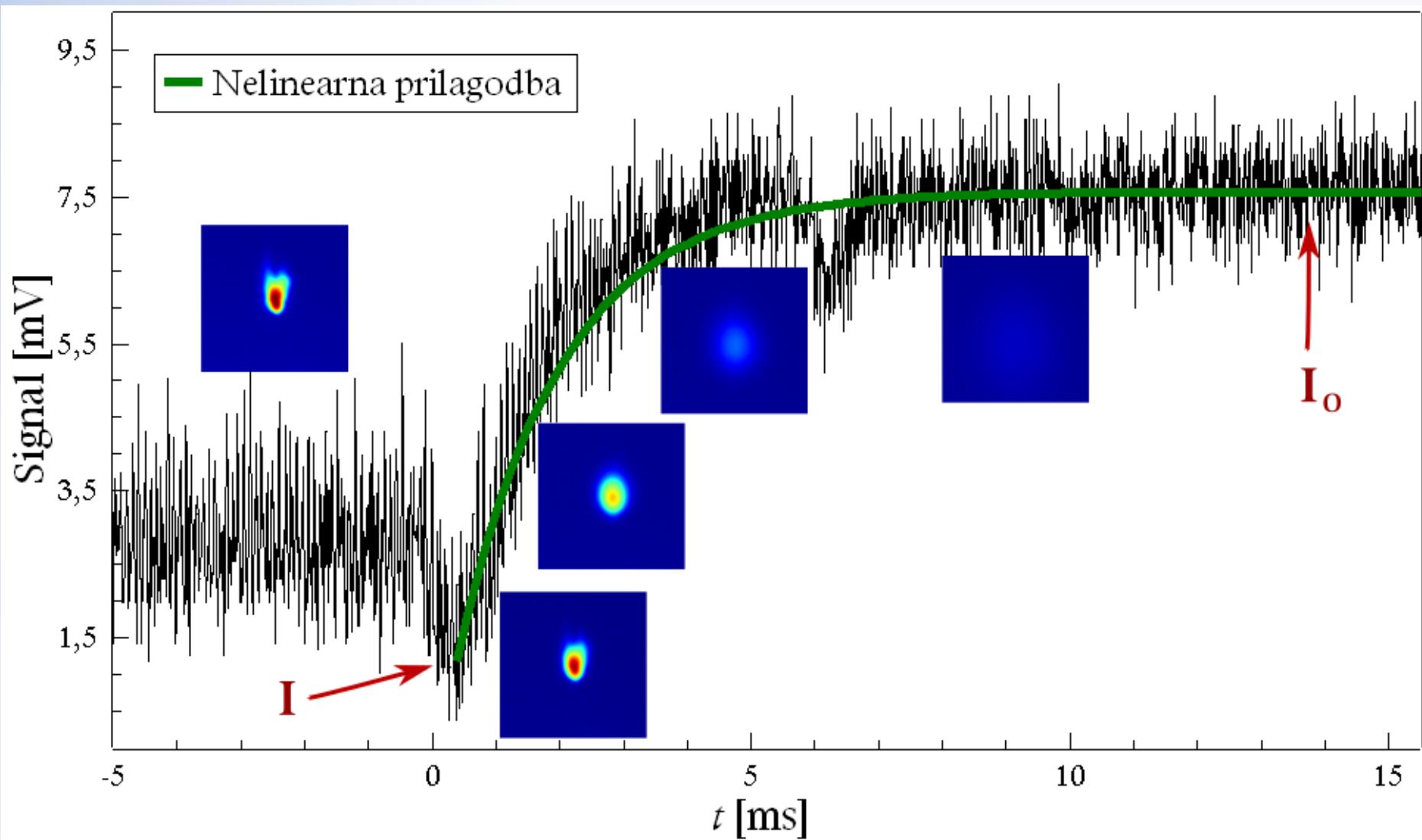
# Frekventna stabilizacija lasera



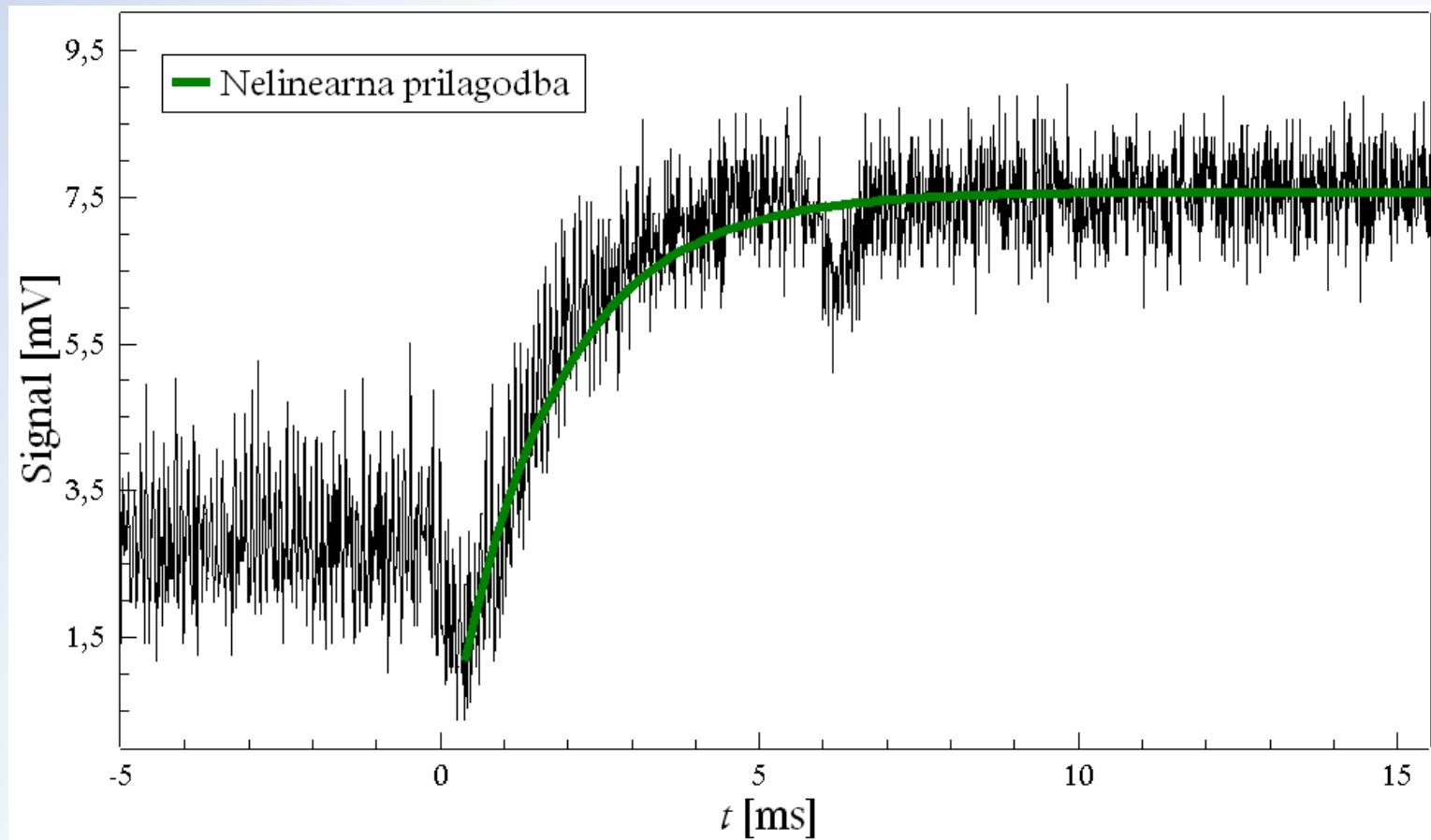
# Mjerenje

- $P_{PR} = 4.95 \mu\text{W}$ ,  $P_{HL} = 6.25 \text{ mW}$ ,  $\delta = -16 \text{ MHz}$ ,  
 $\partial B / \partial z \approx 13 \text{ G/cm}$
- probni laser: HF prijelaz  ${}^{87}\text{Rb } F=2 \rightarrow F'=3$
- gašenje MOT-a: ekspanzija oblaka

# OPTIČKA DEBLJINA

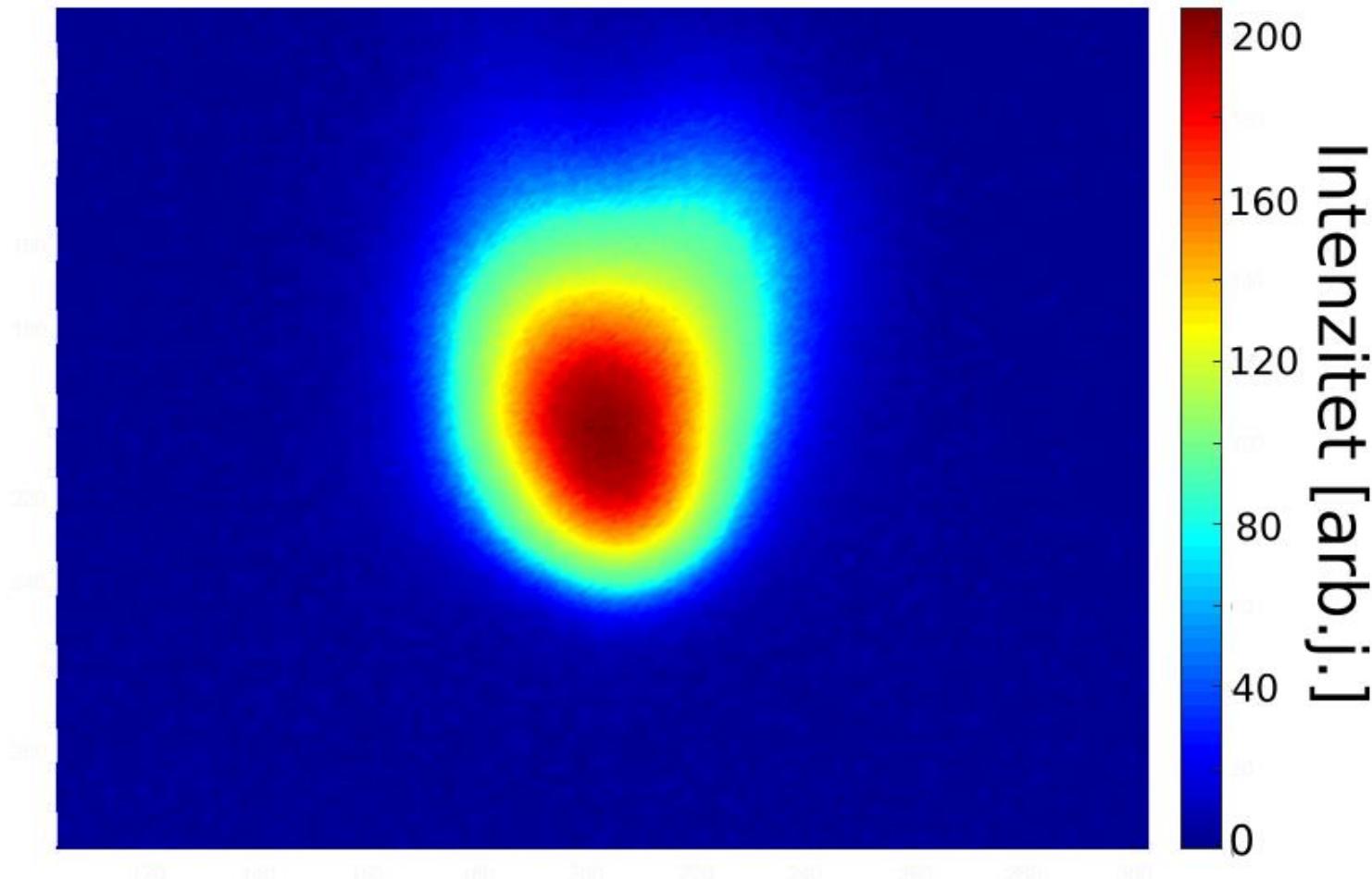


# OPTIČKA DEBLJINA

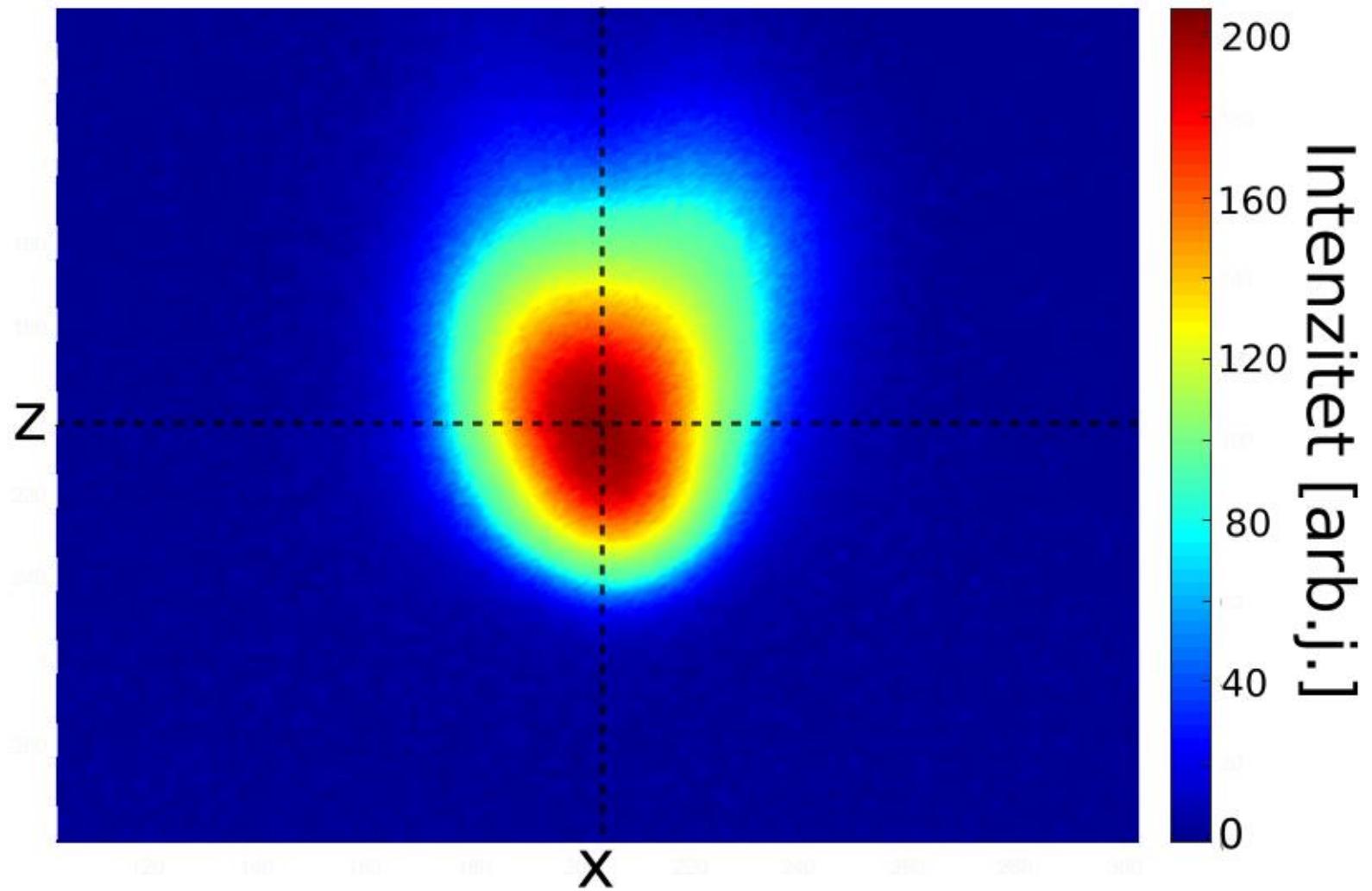


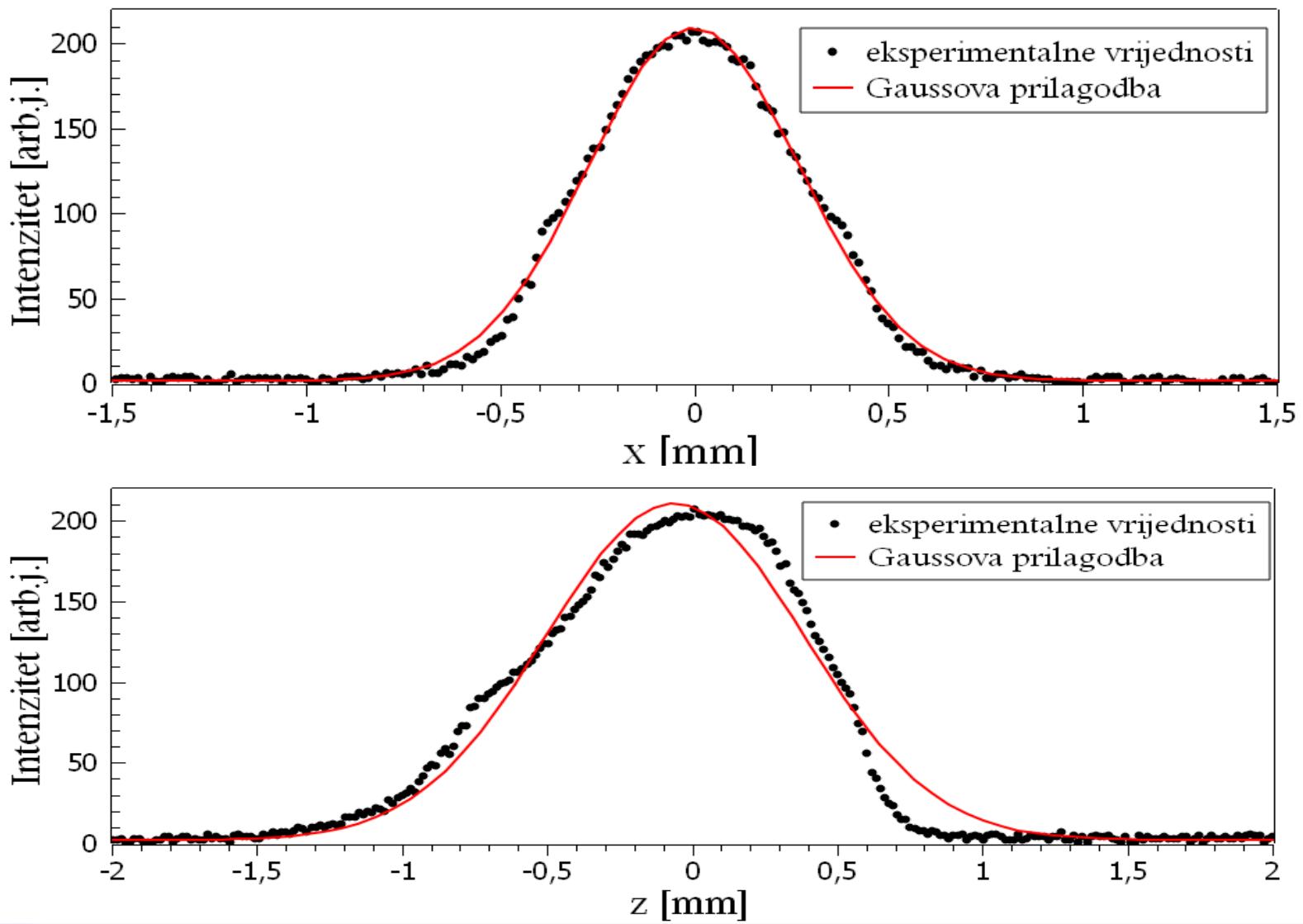
$$\text{OD} = \ln(I_0/I) = 1.9 \pm 0.1$$

# VELIČINA OBLAKA



# VELIČINA OBLAKA





$$\sigma_x = (0.35 \pm 0.01) \text{ mm}$$

$$\sigma_z = (0.51 \pm 0.04) \text{ mm}$$

# VELIČINA OBLAKA

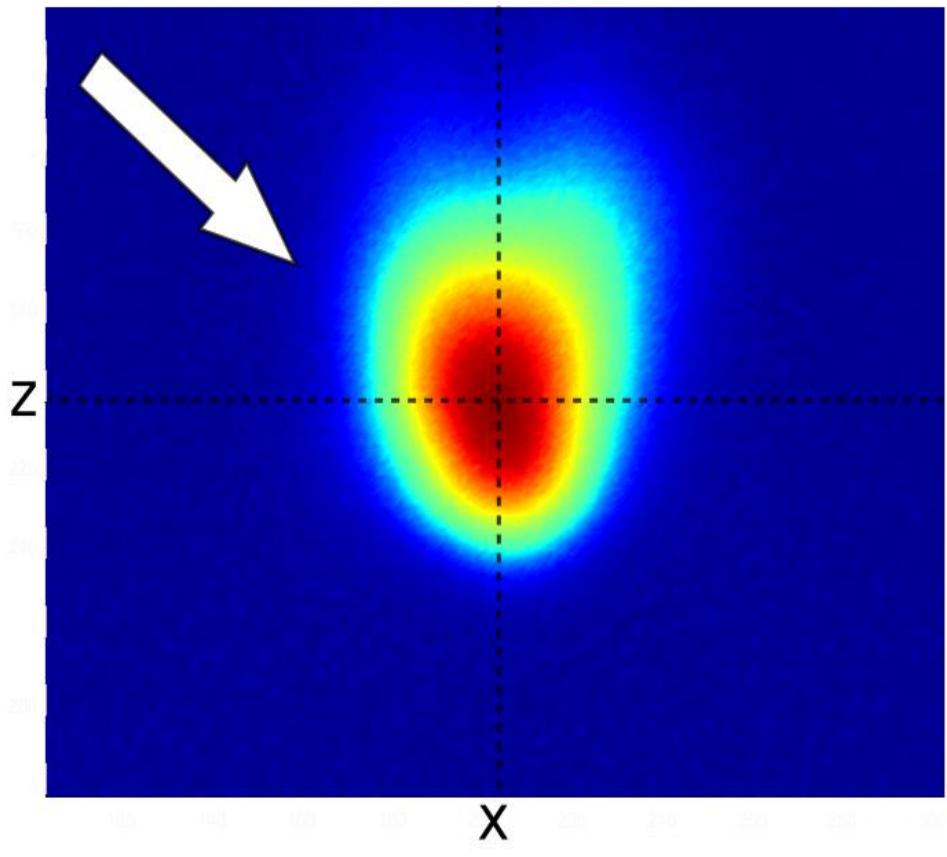
- volumen oblaka hladnih atoma  
= volumen rotacijskog elipsoida s poluosima  $\sigma_x$  i  $\sigma_z$

$$V = 4\pi\sigma_x^2\sigma_z/3$$

$$V = (0.26 \pm 0.03) \text{ mm}^3$$

- duljina apsorpcijskog puta:

$$L = 2\sigma_x = (0.70 \pm 0.02) \text{ mm}$$



# Rezultati

$$n = \frac{2\pi\varepsilon_0 m_e c \Gamma}{e^2 f L} \ln(I_0/I)$$

$$n = (2.0 \pm 0.1) \cdot 10^{10} \text{ cm}^{-3}$$

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$P_{PR} = 4.95 \mu\text{W}$ ,  $P_{HL} = 6.25 \text{ mW}$ ,  $\delta = -16 \text{ MHz}$ ,  
 $\partial B / \partial z \approx 13 \text{ G/cm}$

# Zaključak

- određivanje broja hladnih atoma na temelju transmisije laserske zrake koja prolazi kroz oblak ohlađenih atoma
- saturacijska spektroskopija i frekventna modulacija laserske frekvencije
- Beer-Lambertov zakona
- veličina oblaka
- nedostatak: određivanje volumena oblaka i duljine apsorpcijskog puta