Cold Magnesium Atoms for an Optical Clock

Tanja Mehlstäubler

Jan Friebe
Volker Michels
Karsten Moldenhauer
Nils Rehbein
Dr. Hardo Stöhr
Dr. Ernst-Maria Rasel
Prof. Dr. Wolfgang Ertmer

Institute of Quantum Optics
University of Hannover
Welfengarten 1
D-30159 Hannover
Germany

The Mg - Atom Interferometry group in Hannover

Jan Friebe
Volker Michels
Tanja Mehlstäubler
Karsten Moldenhauer
Nils Rehbein

Dr. Hardo Stöhr
Dr. Ernst-Maria Rasel
Prof. Wolfgang Ertmer

former members:

Holger Wolf
Dr. Jochen Keupp
Dr. Albane Douillet

Outline

- Brief history of frequency standards
- Ramsey-Bordé interferometery in Mg
- How to get to µK temperatures ?
  - (A) ^{25}Mg and heating in MOT
  - (B) Quench cooling
  - (C) 2-photon resonances
- Summary & Outlook

A brief history of frequency standards

- **microwave standards**

1950 : Ramsey develops seperated field method

→ atomic beam clocks surpass quarz

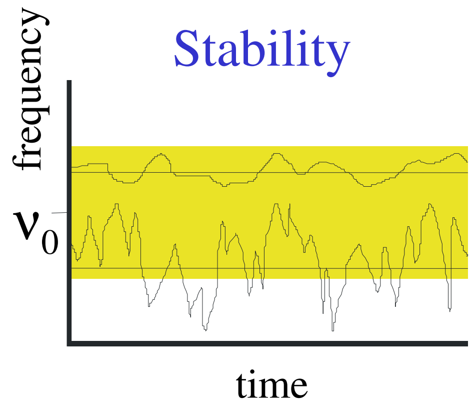
1989 : "a Mg atomic beam frequency standard"

Bava et al., Appl. Phys. B, 48, p.495, (1989)

1989 : first fountain (Na): $\Delta\nu = 2$ Hz

Kasevich et al., PRL, 63, p.612, (1989)

$\delta\nu/\nu_0 = 7\times10^{-16}$
$\sigma_y = 1.6\times10^{-14}$ in 1s
(Cs/Rb fountains)



$$\sigma_y^2(\tau) = \frac{1}{\pi Q \frac{S}{N}\left(\frac{\tau}{T}\right)^{1/2}}, \quad Q = \frac{\nu}{\Delta\nu}$$

- **optical standards**

neutral alkaline-earth (like) atoms → high S/N

1992 : "the Mg Ramsey interferometer"

Sterr et al., Appl. Phys. B, 54, p.341, (1992)

1999 : narrow line cooling in Sr : $\rho \sim 10^{-2}$ in MOT

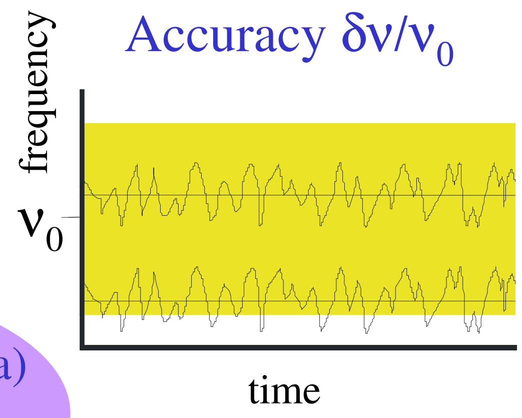
Katori et al., PRL, 82, p.1116, (1999)

2001 : quench cooling in Ca: $T_{MOT} \sim 6\ \mu K$

Binnewies et al., PRL, 87, 123002, (2001)
Curtis et al., Phys. Rev. A, 64, 031403, (2001)

2003 : Yb BEC via narrow line cooling !

Takasu et al., PRL, 91, 040404, (2003)

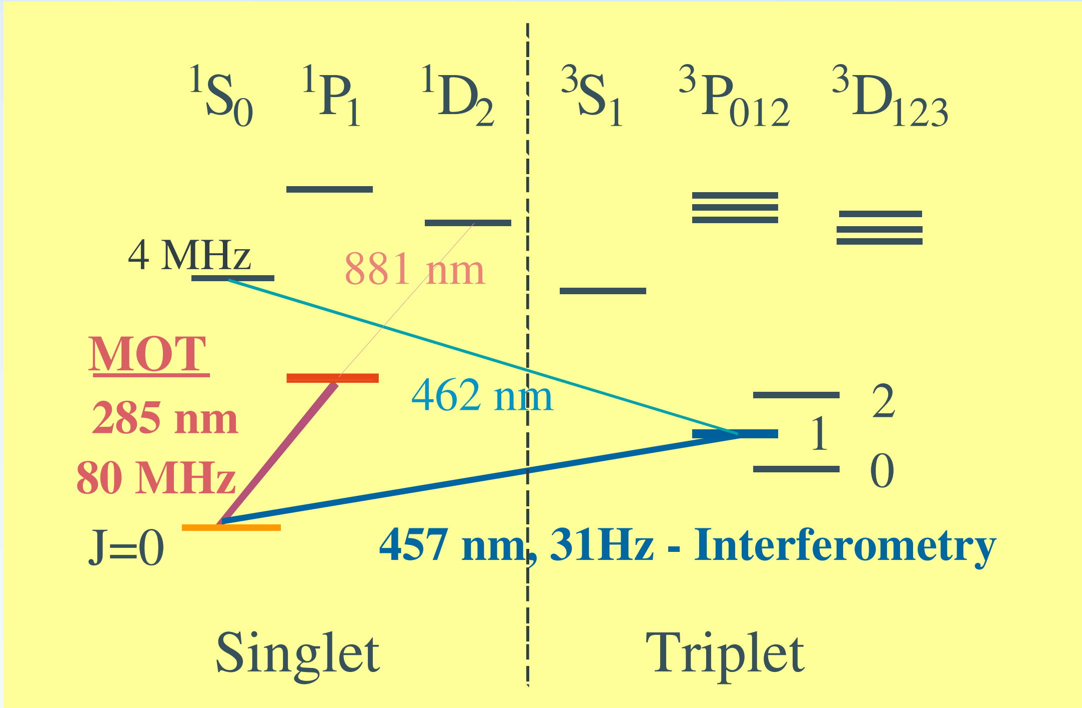


$\delta\nu/\nu_0 = 1.2\times10^{-14}$ (Ca)
$\sigma_y = 7\times10^{-15}$ in 1s
(Ca/Hg^+ comparison)

^{24}Mg

- **457 nm clock transition**
  - **atomic quality factor $Q=2\times10^{13}$**
  - **potential for $T < \mu K$[1]**

- **285 nm cooling transition**
  - **strong light forces**
  - **high $T_D \sim 2$ mK**

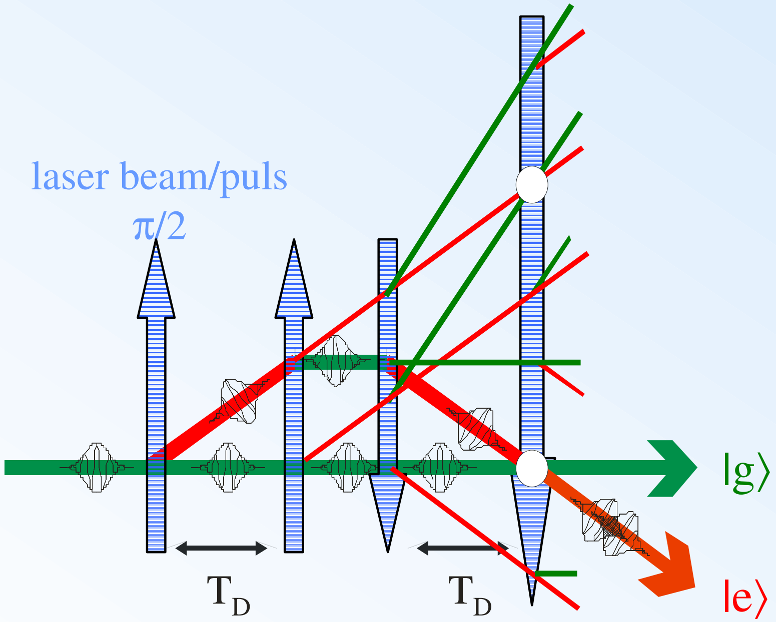


(1) H. Wallis and W. Ertmer, J.Opt.Soc.Am. B **6**, 2211 (1989)

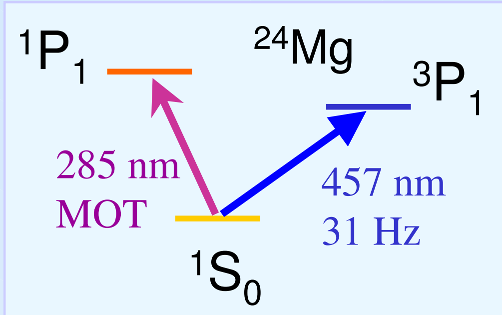
Ramsey-Bordé Interferometry

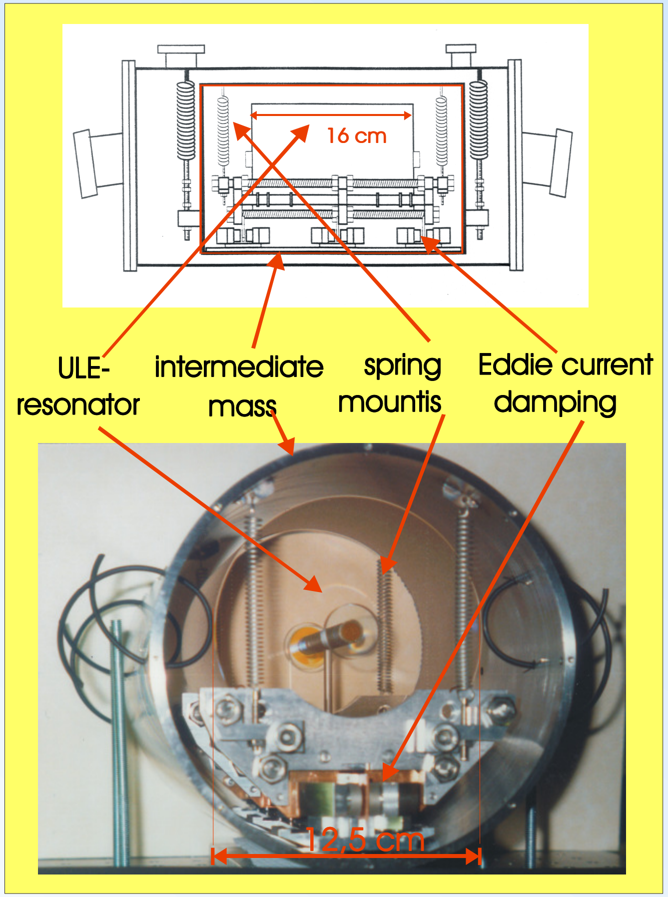
- **Doppler free Ramsey spectroscopy**

Ch. Bordé, C.R. Acad. Sci. Ser. B, 284, p.101 (1977)



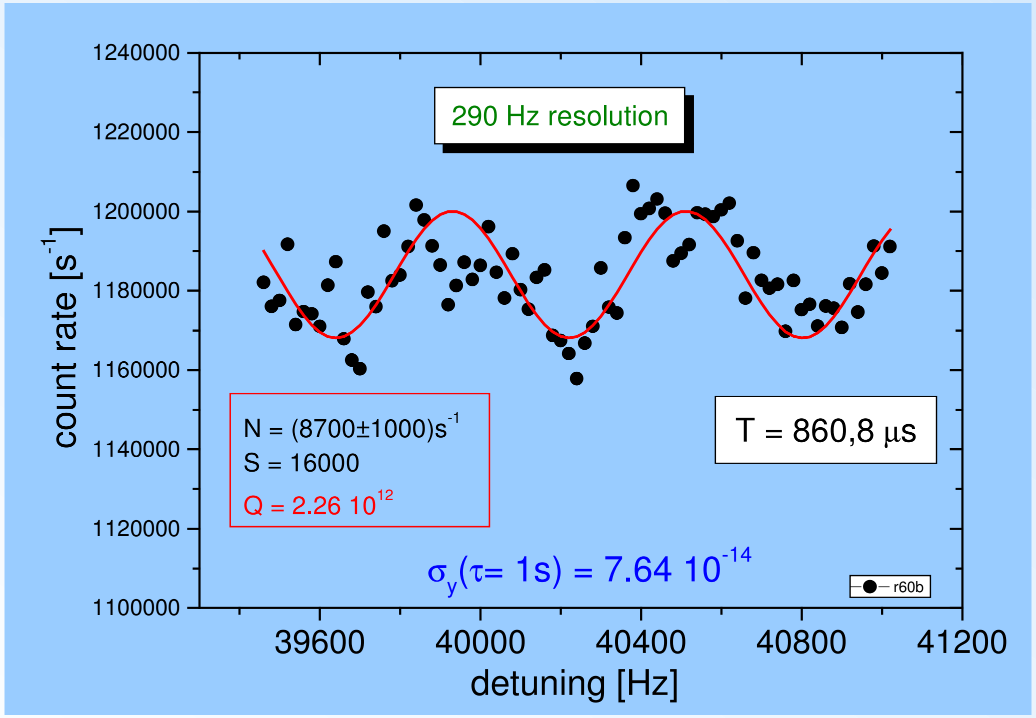
$$P_{ex} \propto \cos(2T_D(\Delta+\delta_{rec}))$$

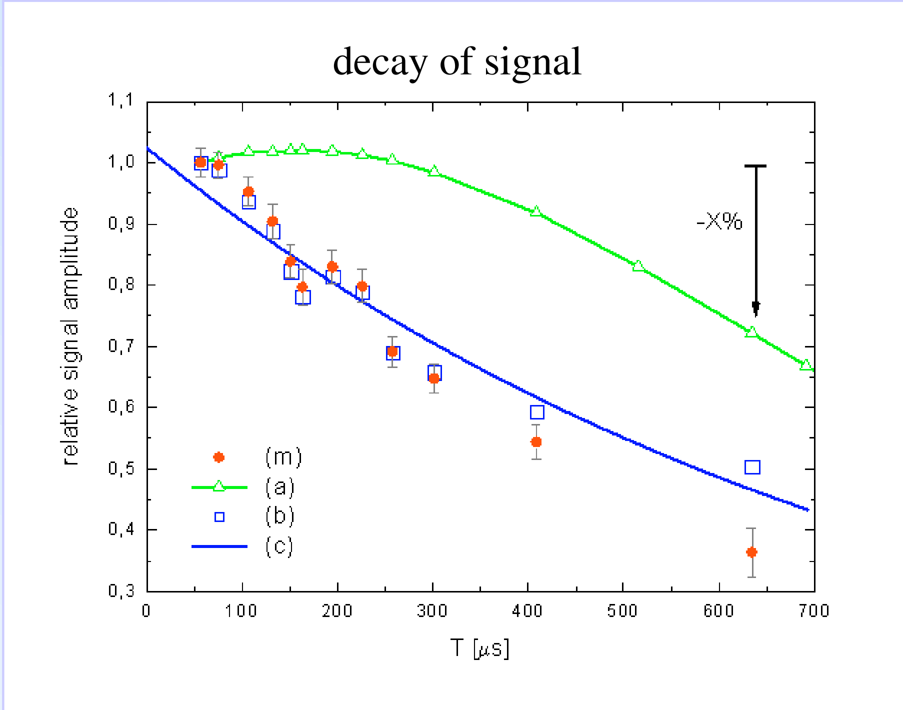




- **140 mW at 457 nm with dye laser**
- **stabilized to high finess cavities**

Ramsey-Bordé Interferometry





- resolution 280 Hz
- potential stability $\sigma_y = 8 \times 10^{-14}$
- laser line width $\Delta\upsilon_{Laser} \leq (170 \pm 15)$ Hz

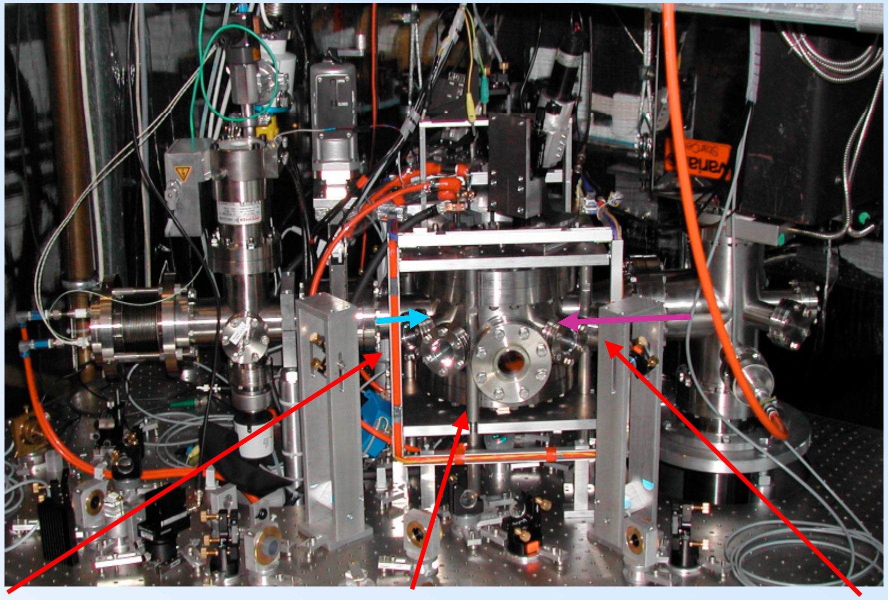
$\Longrightarrow$ atomic motion limits stability

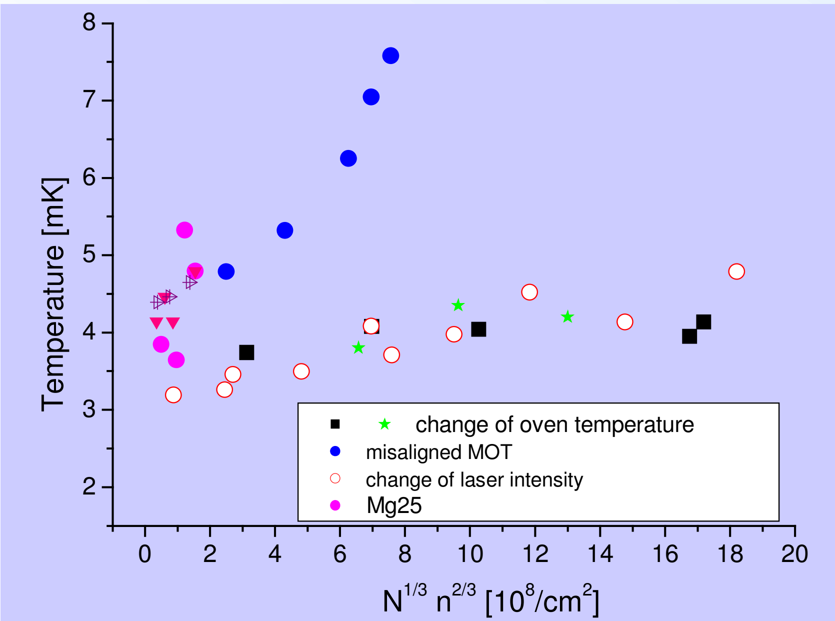
$T_{MOT} = 3.8$ mK

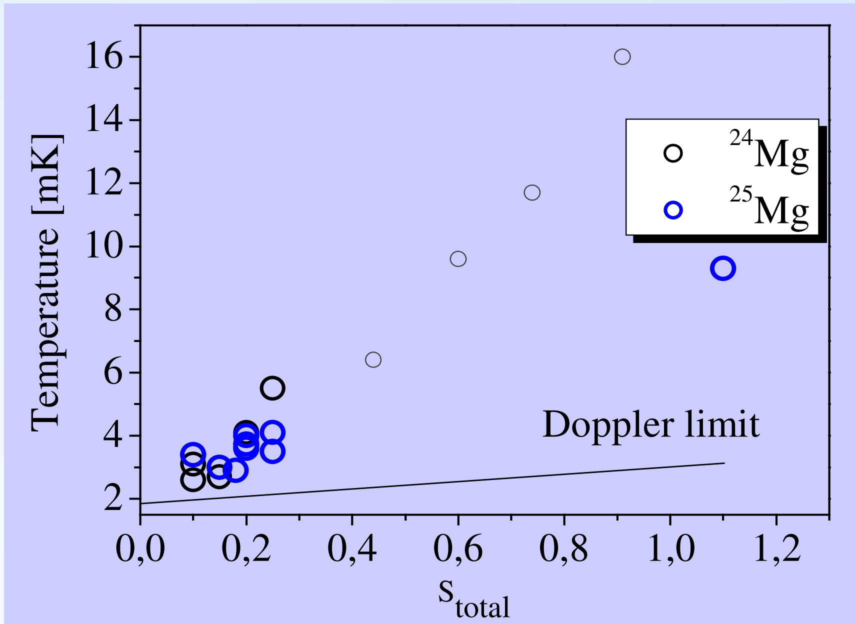
$\Longrightarrow$ only 8 % of atoms are excited ($\tau_{Pulse} = 4$ µs)

Temperatures in MOT

- new set up to study cooling techniques
- optical access for UV, quenching, interferometry, dipole trapping
- up to10^8 atoms



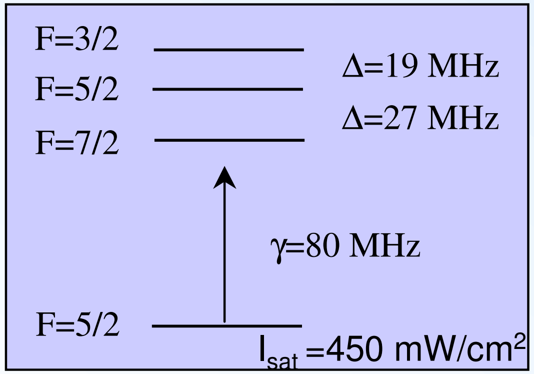


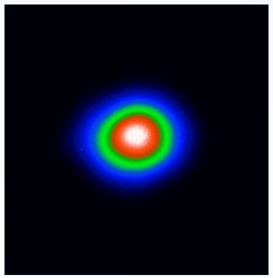


Sub-Doppler forces in ^{25}Mg

Sub-Doppler cooling of ^{25}Mg ?
(Coop. J.Dunn, J.Ye, NIST)

^{25}Mg

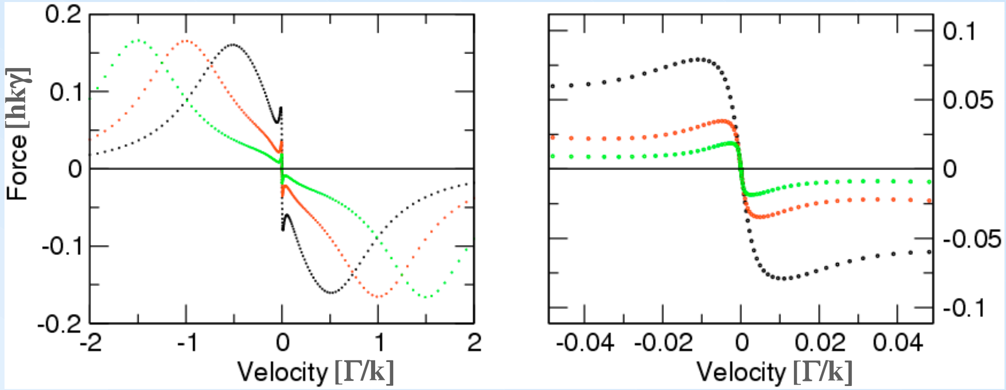




> 10^5 atoms in MOT

Hyperfine Quenching of clock transition $^1S_0 \rightarrow {}^3P_0$:
90 μHz → 0.44 mHz
(Porsev u. Derevianko, physics/0312006, Dez.2003)

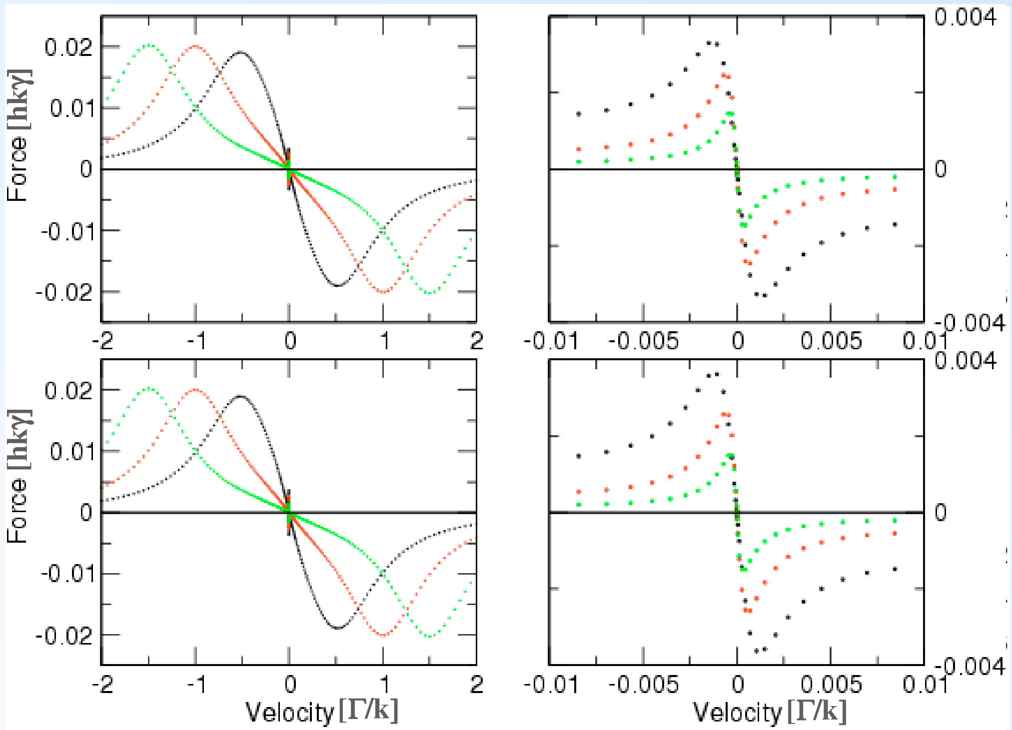
^{87}Sr
Ω/Γ=1



^{25}Mg
Ω/Γ=0.25

B=16 MHz

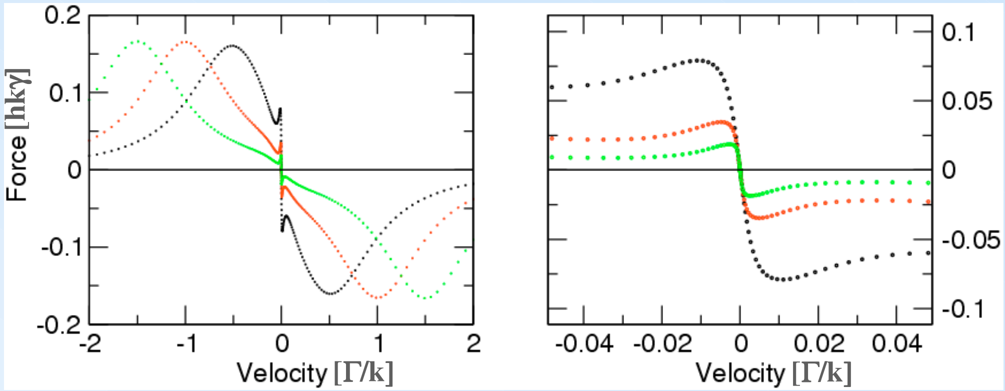
B=0 MHz



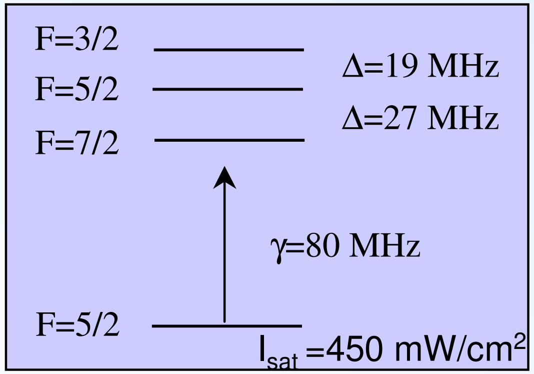
Sub-Doppler forces in ^{25}Mg

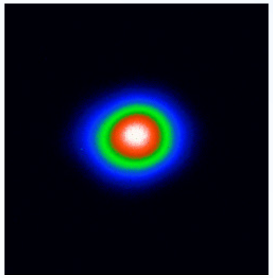
Sub-Doppler cooling of ^{25}Mg ?
(Coop. J.Dunn, J.Ye, NIST)

^{87}Sr
$\Omega/\Gamma=1$



^{25}Mg



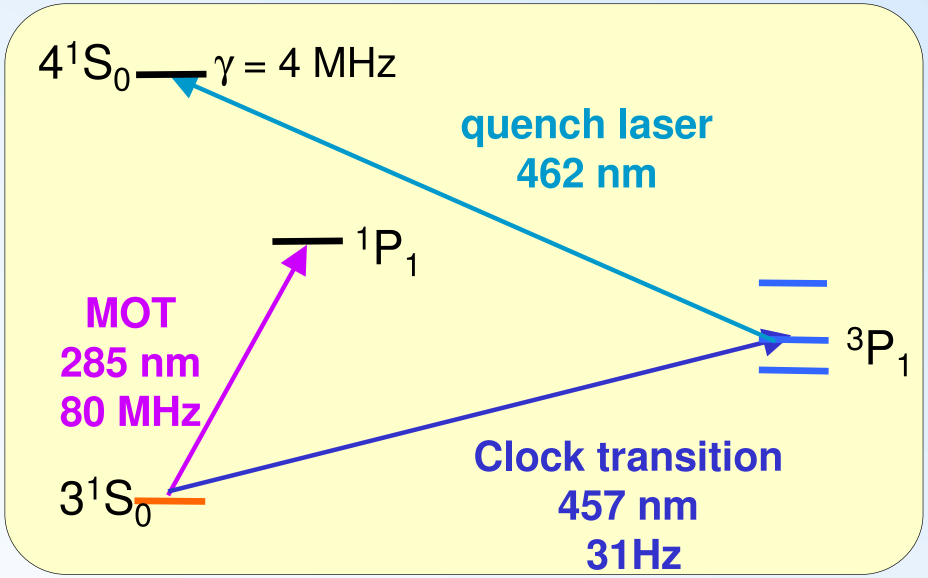


> 10^5 atoms in MOT

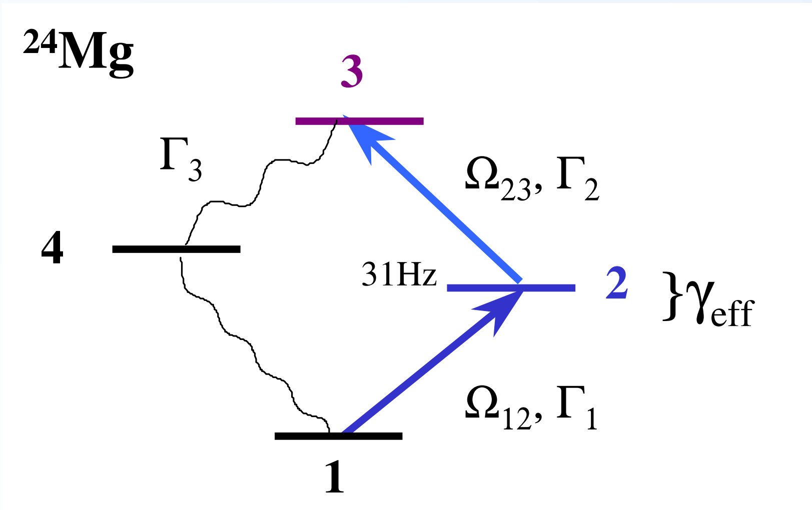
	^{87}**Sr**	^{25}**Mg**
(s = 2)	v_c ~ 0.07 m/s	v_c ~ 0.22 m/s
(s=0.13)		v_c ~ 0.02 m/s
	v_{rec}= 0.01 m/s	v_{rec}= 0.06 m/s
in MOT:	v_{rms}= 0.4 m/s	v_{rms}= 1.1 m/s

Hyperfine Quenching of clock transition $^1S_0 \rightarrow {}^3P_0$:
90 µHz → 0.44 mHz
(Porsev u. Derevianko, physics/0312006, Dez.2003)

Quench cooling in ^{24}Mg



- cooling on narrow lines
- $3^1S_0 \rightarrow 3^3P_1$: $T_{rec} = 3.8\ \mu K >> T_{Dopp}$
- $mg<F_{light} \rightarrow \gamma_{min}$~90 Hz
- quench transition $3^3P_1 \rightarrow 4^1S_0$
  200 mW @ 462 nm with Ti:Sapph
  doubled with PPKTP



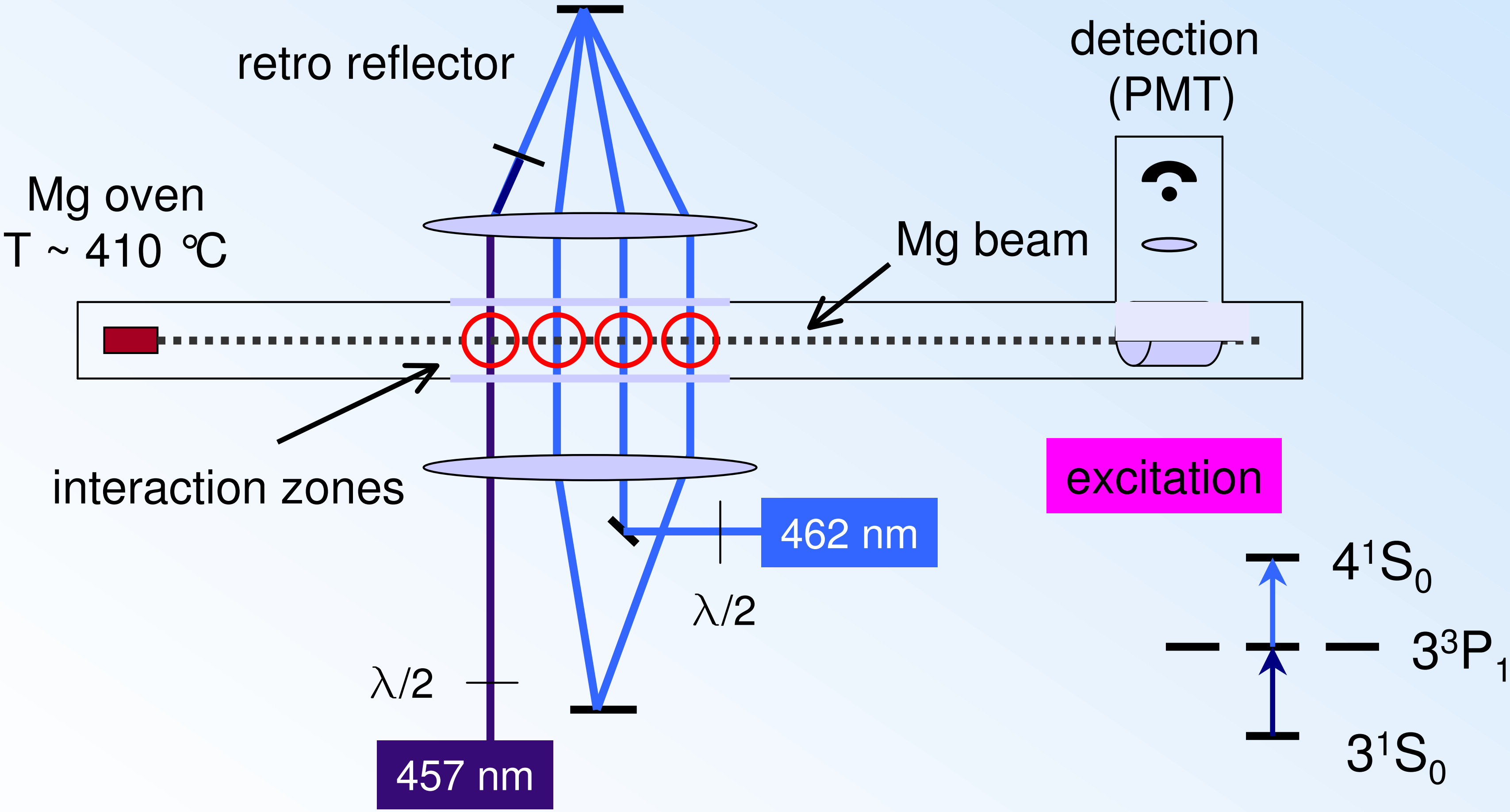
$$\rho_{22}\Gamma_{eff} = \rho_{22}\Gamma_1 + \rho_{33}\Gamma_3$$

for $s_3 <<1$: $$\rho_{33} = \rho_{22} \times \frac{\Omega_{23}^2}{\Gamma_3^2}$$

$$\Gamma_{eff} = \Gamma_1 + \frac{\Omega_{23}^2}{\Gamma_3} \propto \frac{\Gamma_2}{\Gamma_3} I_{Laser}$$

T.E. Mehlstäubler *et al.*, J.O.B **5**, p.183 (2003)

Search for the quenching transition

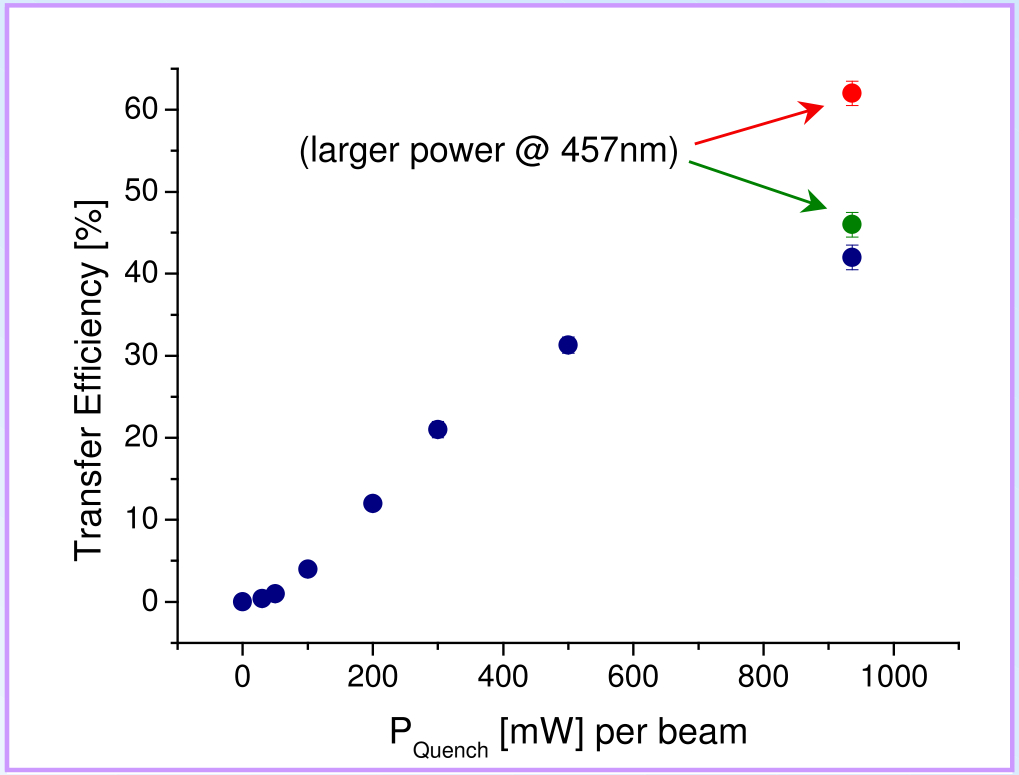


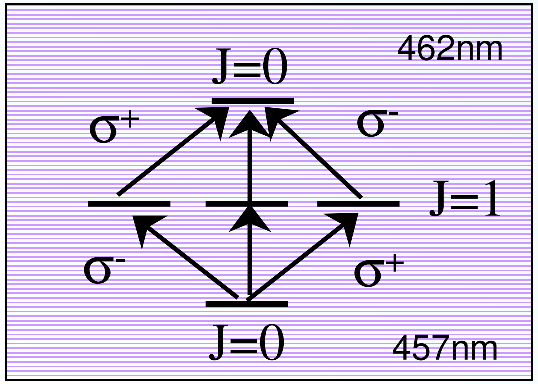
Quench cooling in ^{24}Mg

Kuruzc: $\Gamma_2 = 3.21\ 10^3\ s^{-1}$

new ab initio calculations:
Pal'chikov, Derevianko, Fischer(3)
$\Gamma_2 = 2.0 \times 10^2\ s^{-1}$

our measurement:
$\Gamma_2 \sim 1 \times 10^2\ s^{-1}$

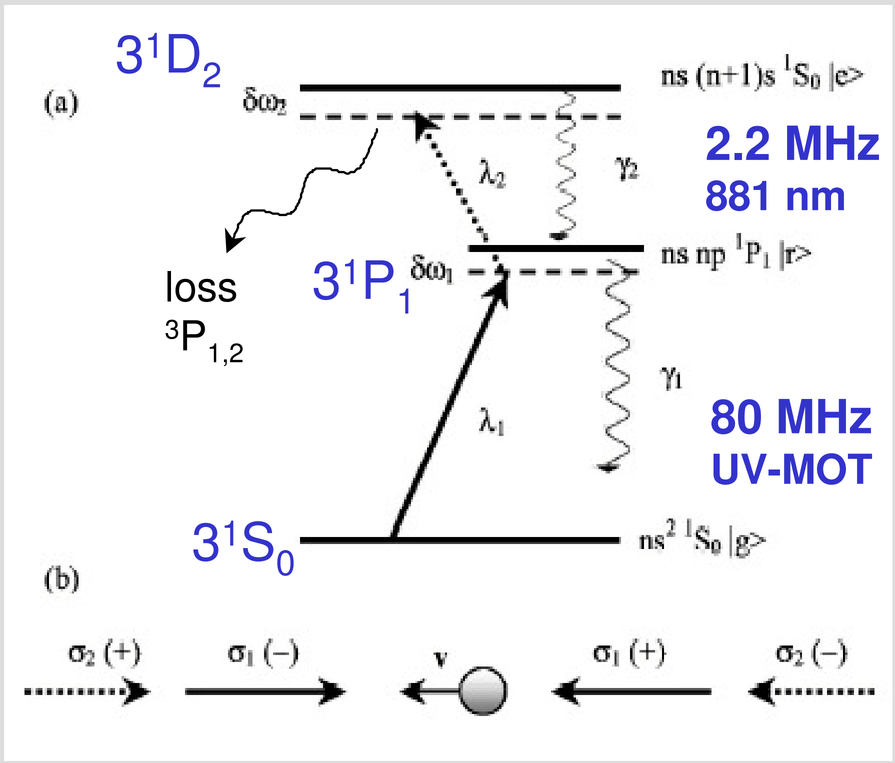




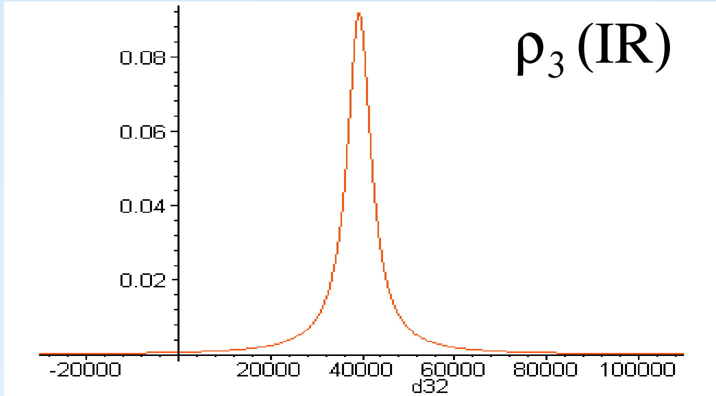
→ theo. transfer efficiency ~ 1%
→ x • 10^4 atoms expected @ T=10µK
→ 8% of 10^5 atoms, 70% of x • 10^4 atoms
→ lower duty cycle of interferometry

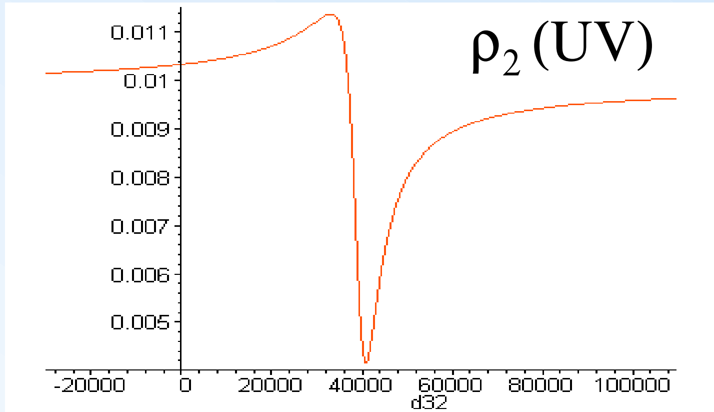
(3) private communications, to be published

2-Photon resonances in ^{24}Mg



exact solution of the Bloch equations for a 3 level system

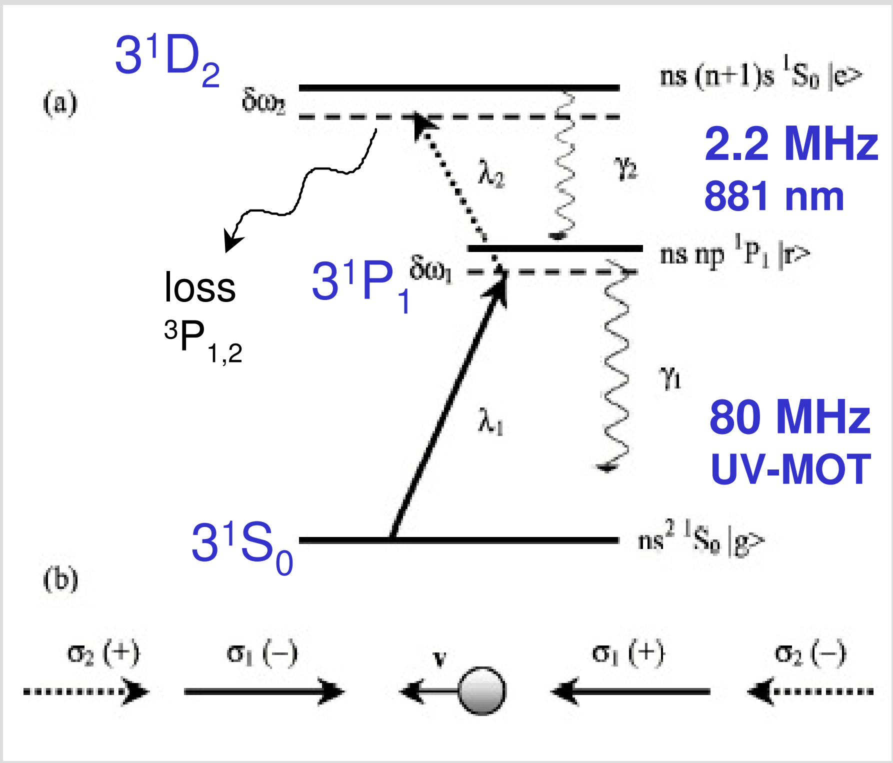


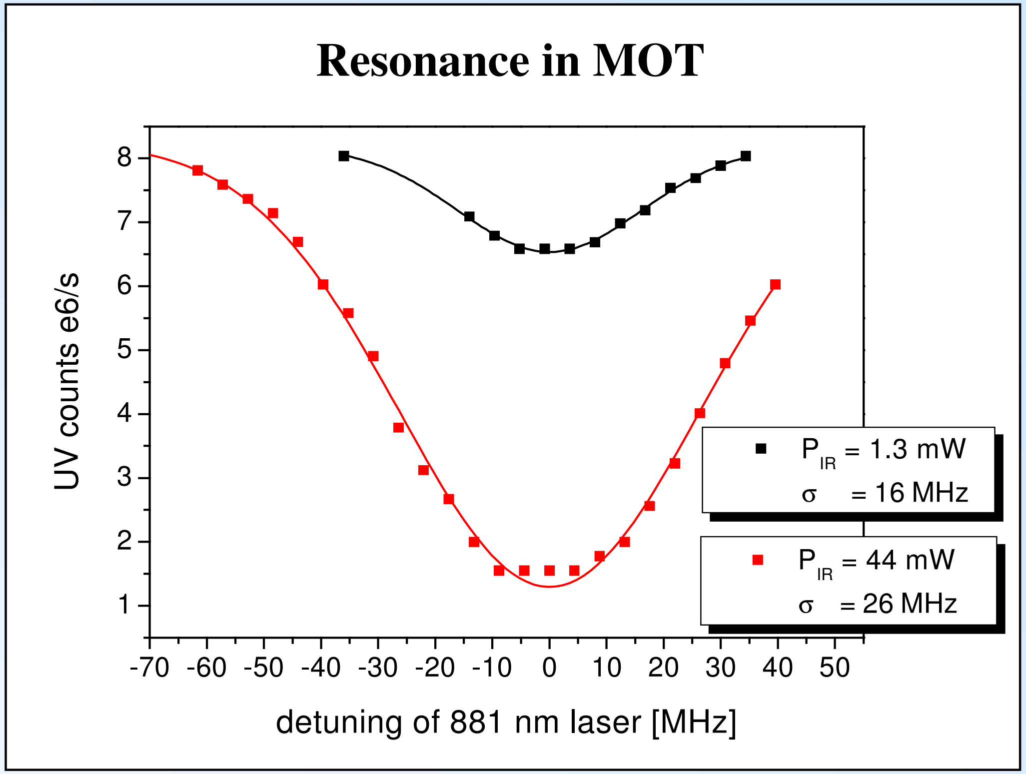


- 2-photon process more efficient than 1 photon ?

W.C. Magno *et al.*, Phys. Rev. A 67, 043407 (2003)

2-Photon resonances in ^{24}Mg

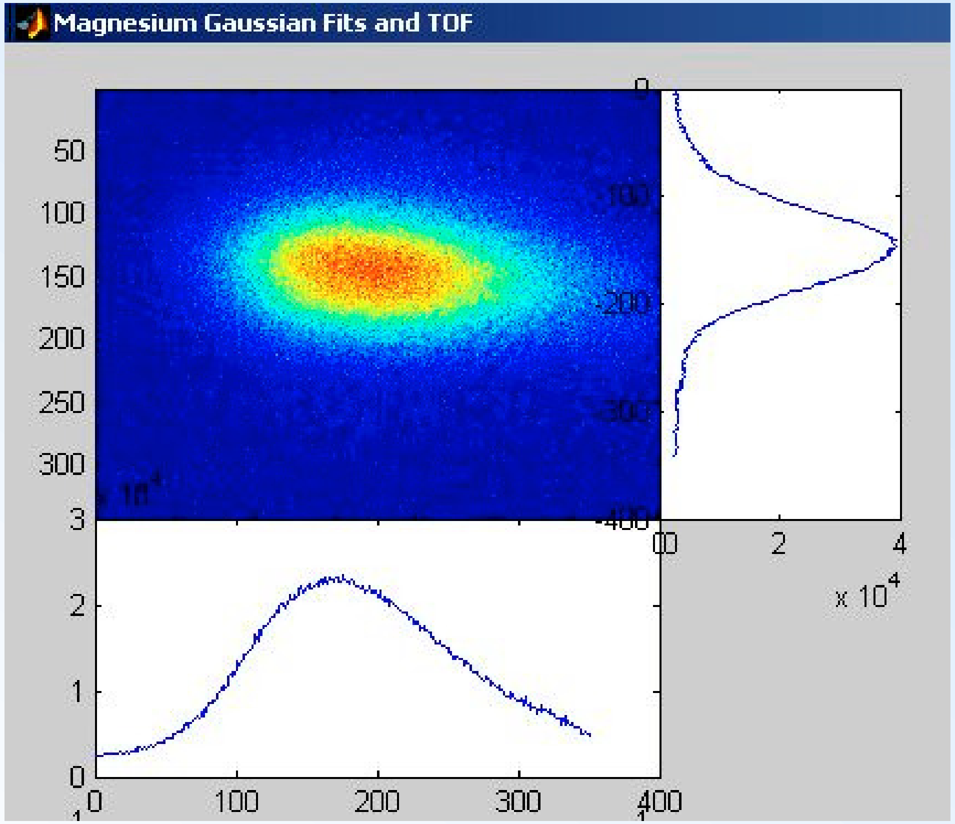




- 2-photon process more efficient than 1 photon ?

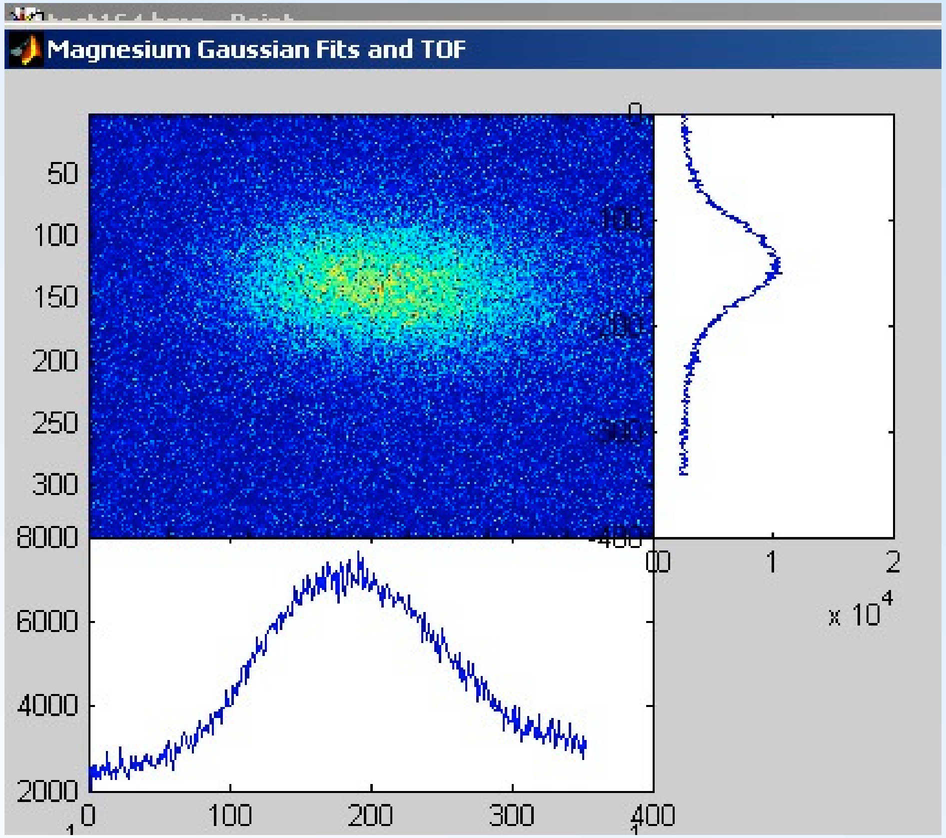
W.C. Magno *et al.*, Phys. Rev. A 67, 043407 (2003)

2-Photon resonances in ^{24}Mg



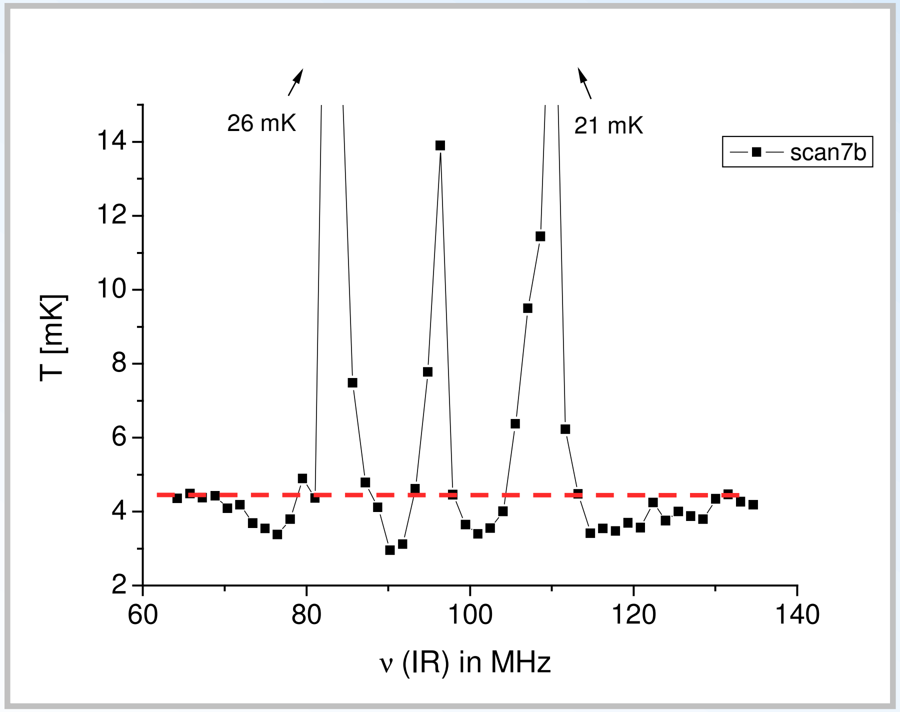
resonances in 1D molasses

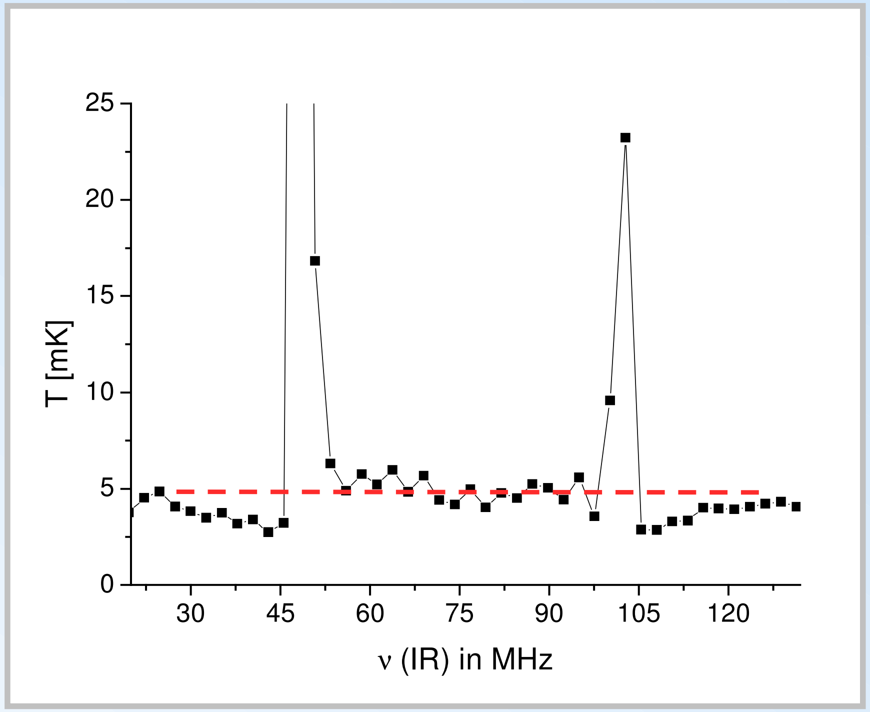
2-Photon resonances in ^{24}Mg



resonances in 1D molasses

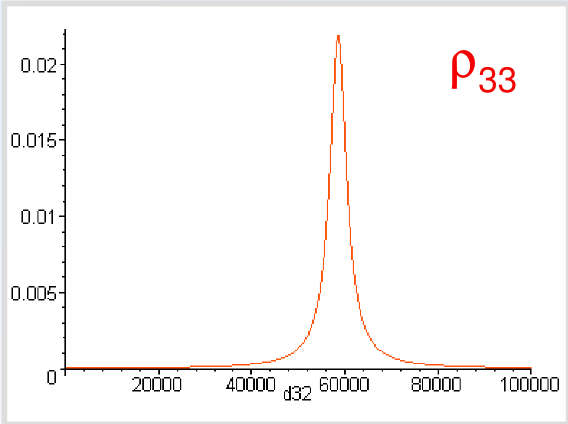
Temperature across 2-photon resonance

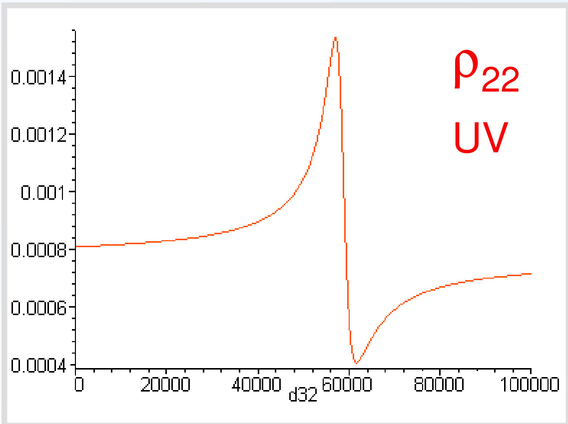


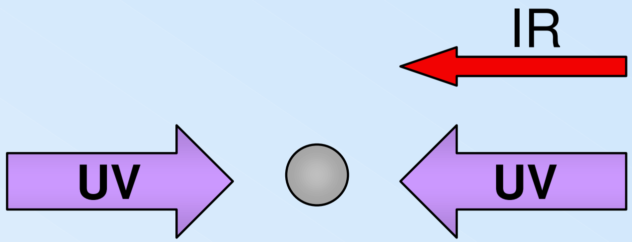


2-Photon resonances in ^{24}Mg

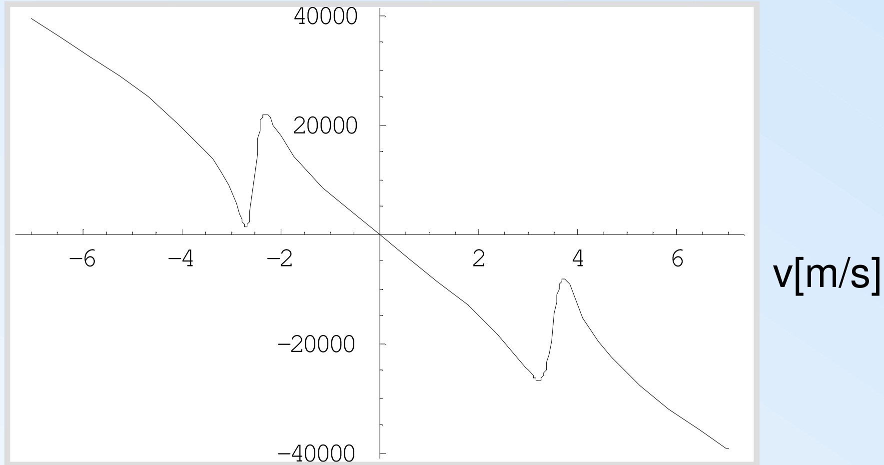
Populations in excited states







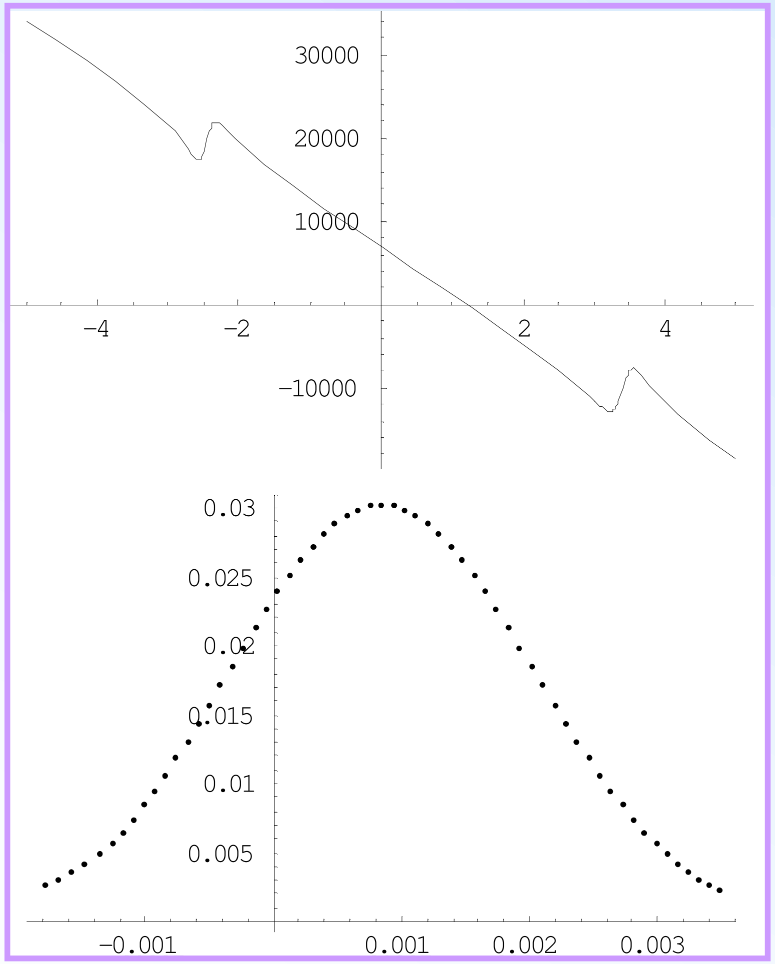
⇒ force at UV transition:

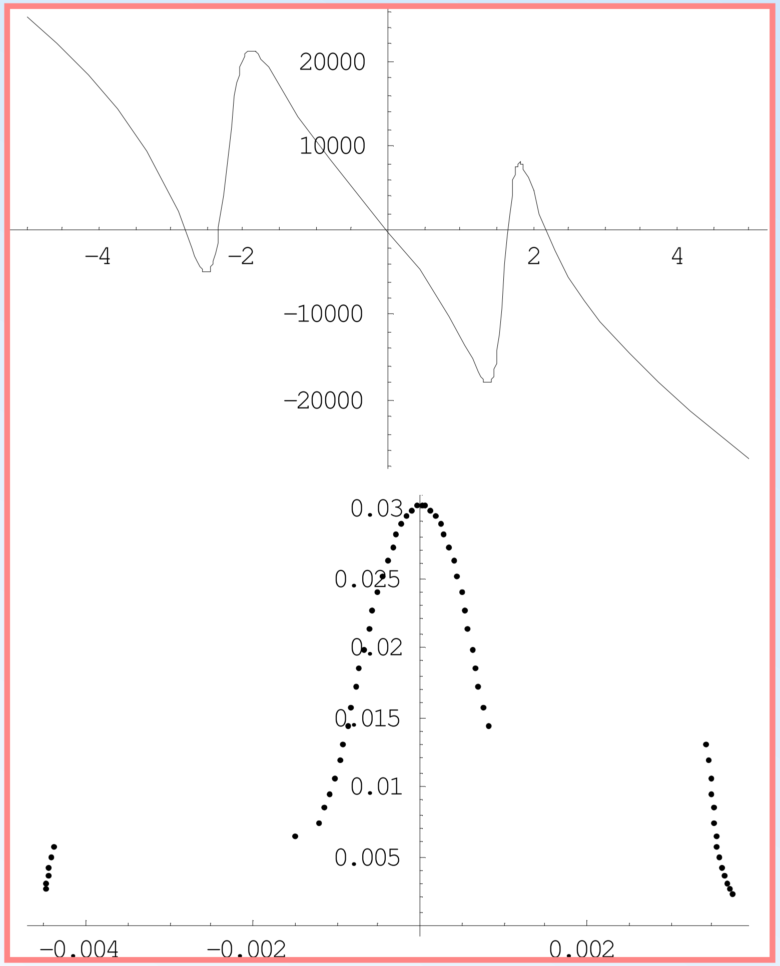


- **positive feedback on faster atoms (bunching)**
- **higher friction for low velocities**

• force at UV transition
⇒ dv = a(v) dt

e.g. for balanced molasses



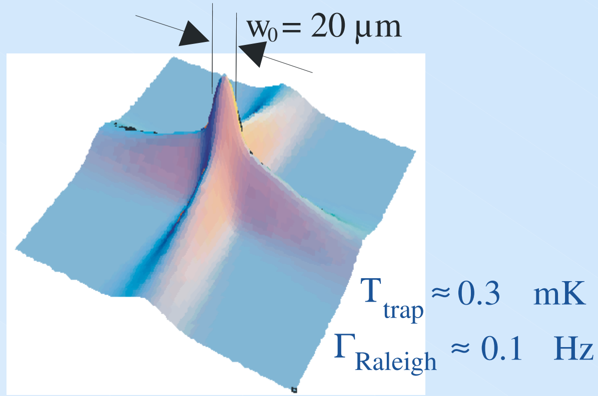


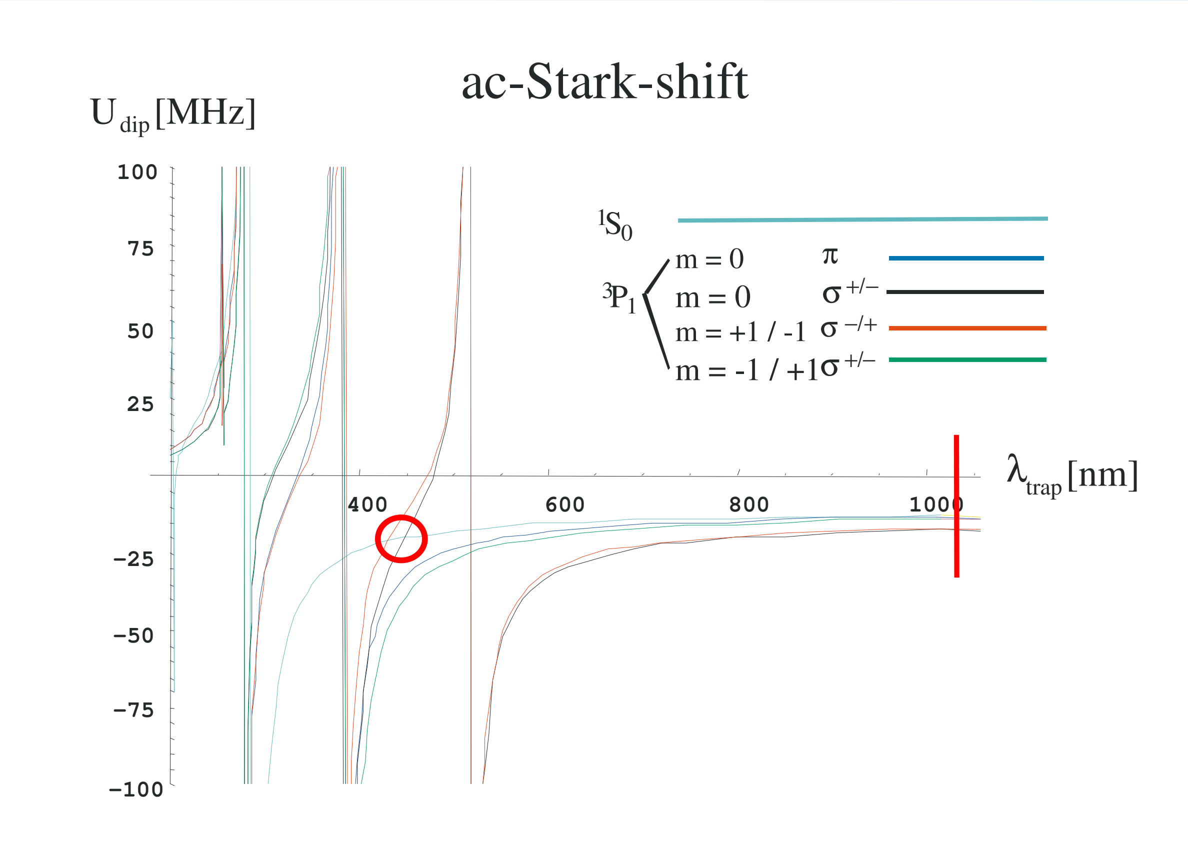
• integrating eqs. of motion
• TOF after 100μs molasses

T < 100 μK ?

Summary & Outlook

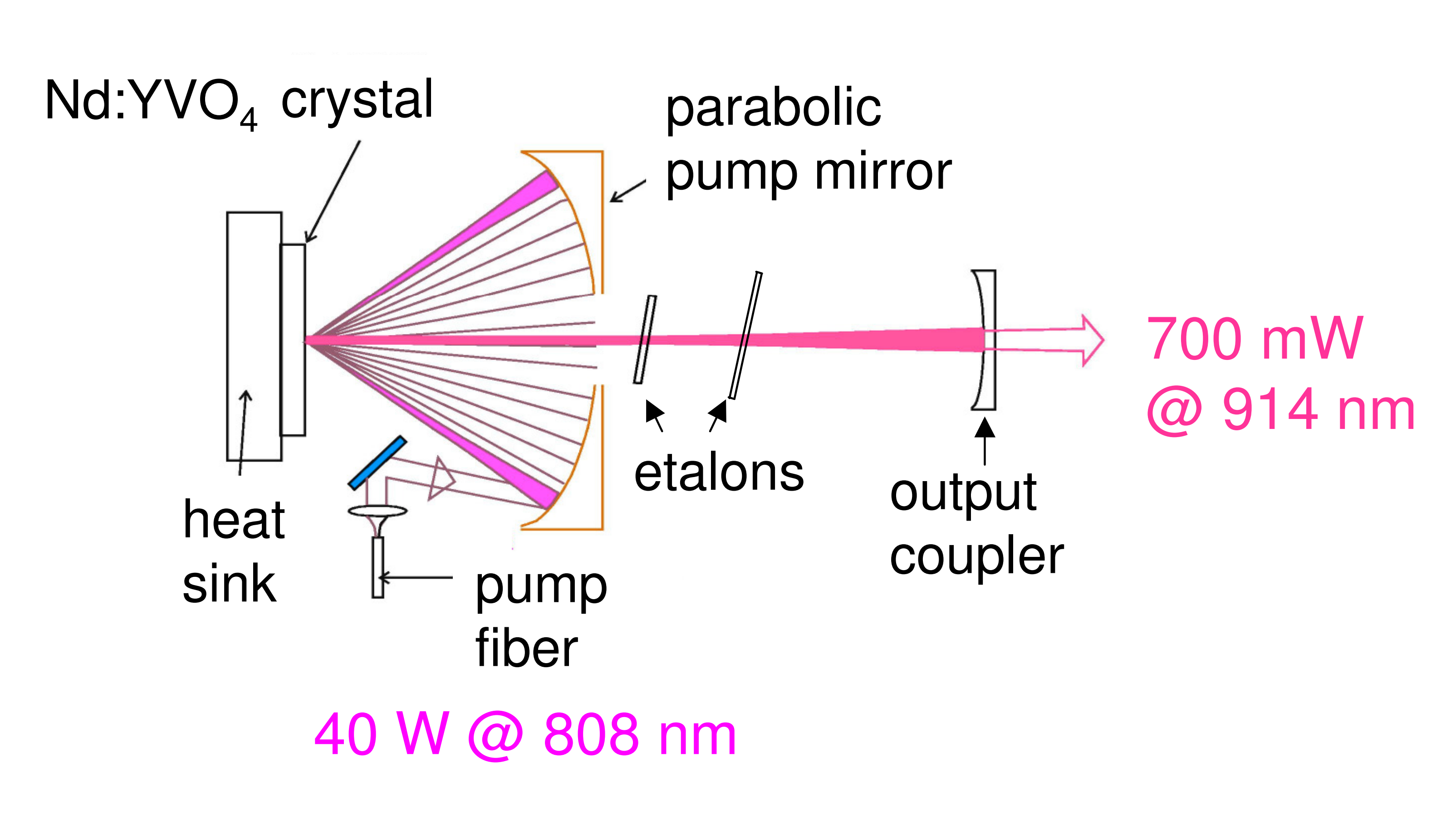
- Mg interferometry limited by temperature of atoms
- Sub-Doppler cooling forces in ^{25}Mg are not sufficient
- Quenching transition @ 462 nm measured
  → load 1% of atoms into QMOT at 9 µK ?
- 2-photon resonances observed
  → Sub-Doppler temperatures possible in 3D-molasses ?
  → Channel to populate meta-stable states !
- Combination with dipole trap ?



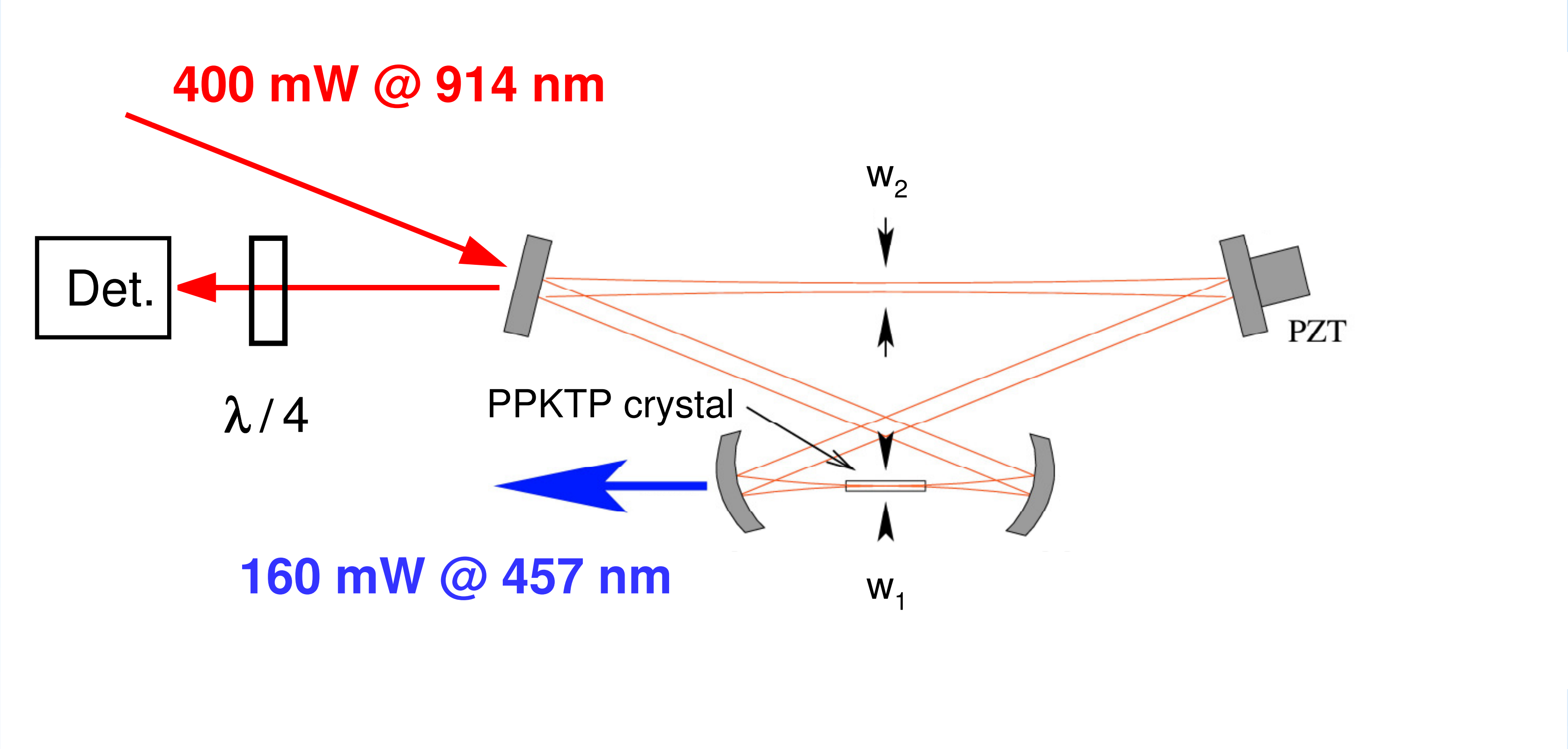


- **Yb:YAG 25 W @ 1030 nm**
- **quench cooling into dipole trap**
- **study of collisions**

- **trap potentials only identical at crossing → λ = 446 nm**



- Laser active medium : thin disk (~320 µm)
- multiple pump light passes through the laser active medium
- single frequency with 2 etalons : d = 0,6 mm und 4 mm



Cavity:
Hänsch-Couillaud lock

w_1~49 μm
w_2~147μm
cavity length = 34 cm
incoupling efficiency: 85 %
conversion efficieny: 47 %