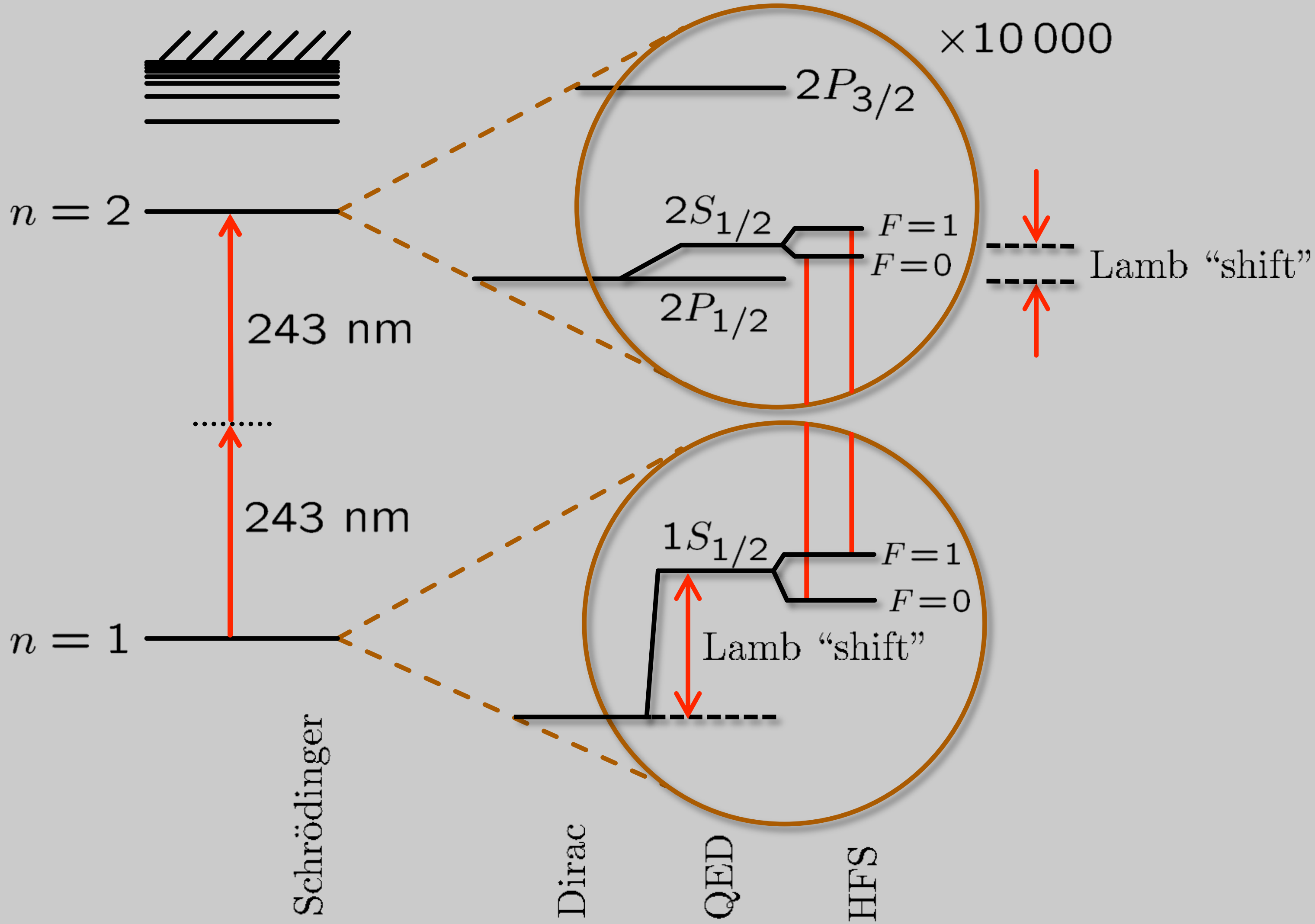
MPQ

Precision Spectroscopy of the 2S-4P Transition Frequency in Atomic Hydrogen

A. Beyer, L. Maisenbacher, K. Khabarova, A. Matveev,
R. Pohl, Th. Udem, T. W. Hänsch and N. Kolachevsky
Tuesday, June 3rd 2014

Hydrogen Energy Levels



Hydrogen Energy Levels

Full recoil and QED in SI units:

$$E = R_\infty \left(-\frac{1}{n^2} + A_{20}\alpha^2 + A_{30}\alpha^3 + A_{31}\alpha^3 ln(\alpha) + A_{40}\alpha^4 + \ldots \right.$$
$$\left. + \frac{2}{3}\frac{(2\pi)^2}{n^3}\frac{m_e^2 c^2 \alpha^3}{h^2}\, r_p^2\, \delta_{l0} \right)$$

Parameters involved in the theory of atomic hydrogen energy levels:

- Rydberg constant (unit converter) R_∞
- fine structure constant α
- electron-to-proton mass ratio m_e/m_p
- proton r.m.s. charge radius r_P

… and many more.

Complete collection of coefficients in P. Mohr *et al.*, Rev. Mod. Phys. **84**, 1527 (2012)

Hydrogen Energy Levels

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R_∞: 5x10^{-12}

r_p: 6x10^{-3}

Determination of α from electron g-factor

Hanneke *et al.*, PRL **100**, 120801 (2008)

Determination of α from atomic recoil shift

Bouchendira *et al.*, PRL **106**, 080801 (2011)

α: 3x10^{-10}

Determination of m_e/m_P from cyclotron frequency — 5x10^{-10}

see P. Mohr *et al.*, Rev. Mod. Phys. **84**, 1527 (2012) and Refs. therein

Effectively two parameters left to us: R_∞ and r_p.

Hydrogen Energy Levels

Full recoil and QED in SI units:

$$E = R_\infty \left(-\frac{1}{\cdot} + A_{20}\alpha^2 + A_{30}\alpha^3 + A_{31}\alpha^3 ln(\alpha) + A_{40}\alpha^4 + \ldots \right.$$

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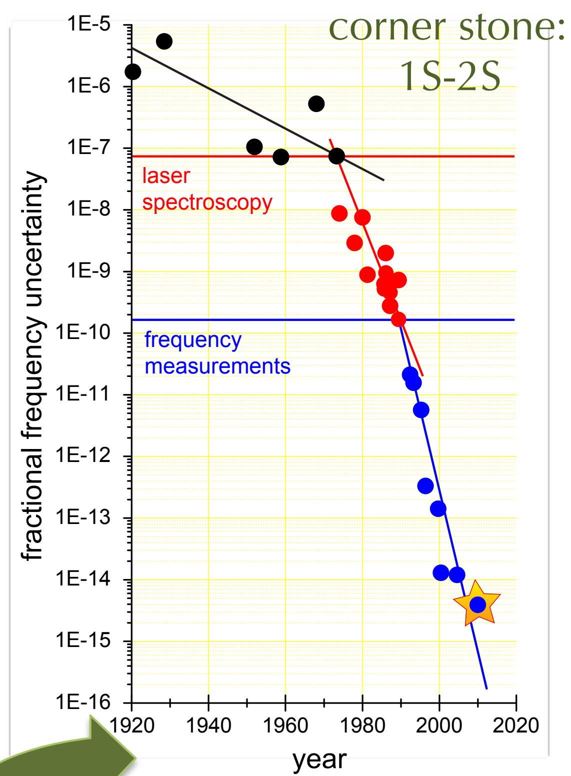
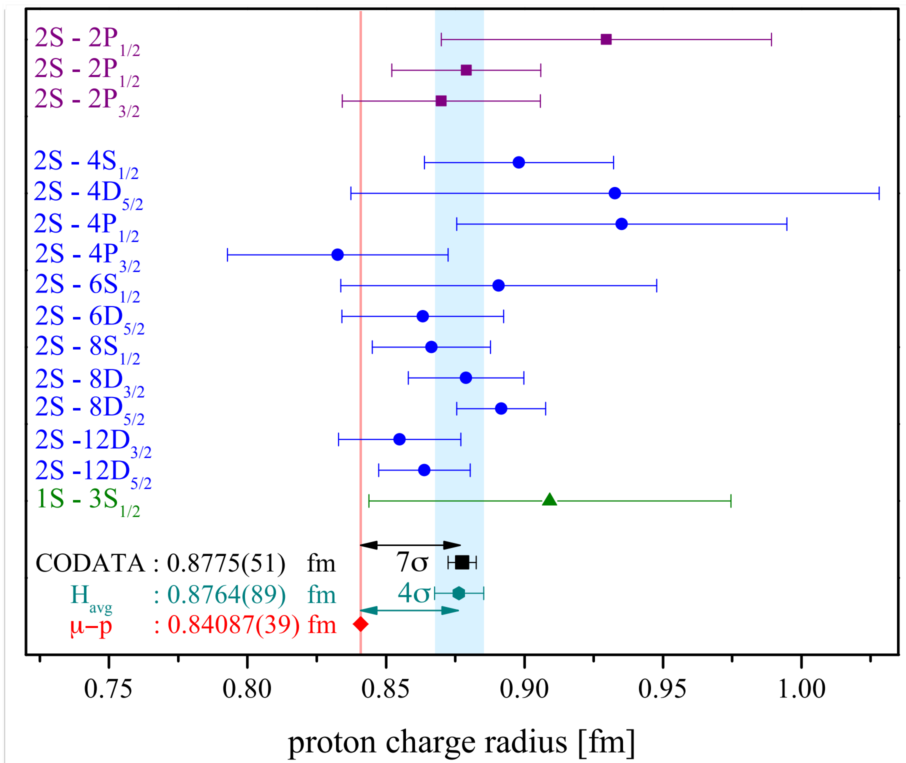
Term of the Lamb shift	Value for the 1S level	Uncertainties
Self-energy (one-loop)	8 383 339.466 kHz	0.083 kHz
Vacuum polarization (one-loop)	−214 816.607 kHz	0.005 kHz
Recoil corrections	2 401.782 kHz	0.010 kHz
Proton size	1 253.000 kHz	50 kHz
Two-loop corrections	731.000 kHz	3.300 kHz
Radiative recoil corrections	−12.321 kHz	0.740 kHz
Vacuum polarization (muon)	−5.068 kHz	<0.001 kHz
Vacuum polarization (hadron)	−3.401 kHz	0.076 kHz
Proton self-energy	4.618 kHz	0.160 kHz
Three-loop corrections	1.800 kHz	1.000 kHz
Nuclear size corrections to SE and VP	−0.149 kHz	0.011 kHz
Proton polarization	−0.070 kHz	0.013 kHz
1S Lamb shift	8 172 894(51) kHz	

F. Biraben, Euro. Phys. J. **172**, 2009

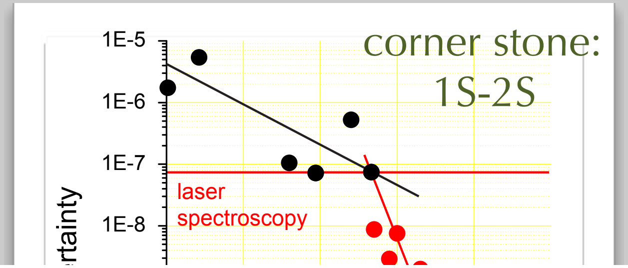
Hydrogen Energy Levels

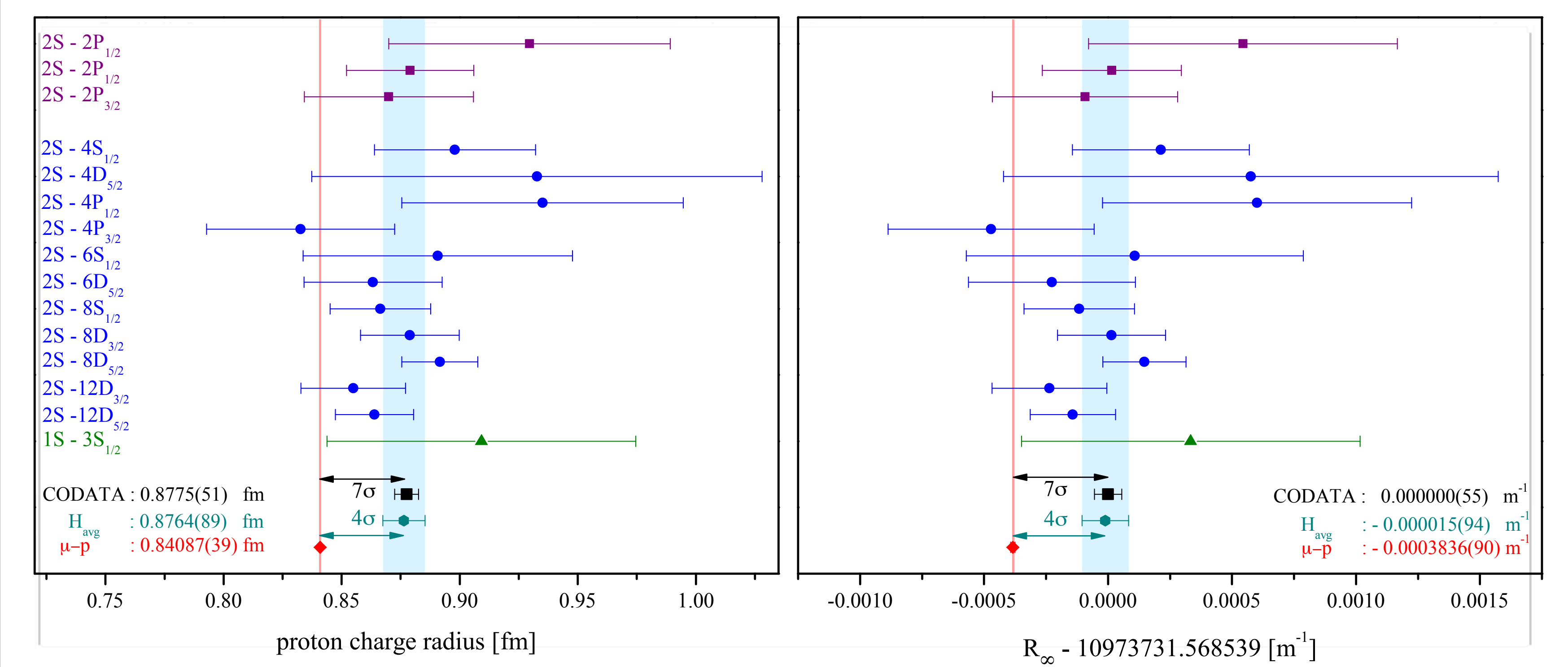




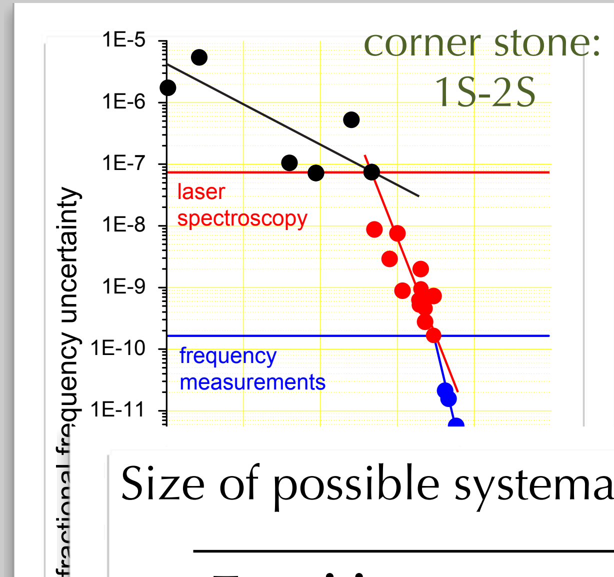
Effectively two parameters left to us: R_∞ and r_p.

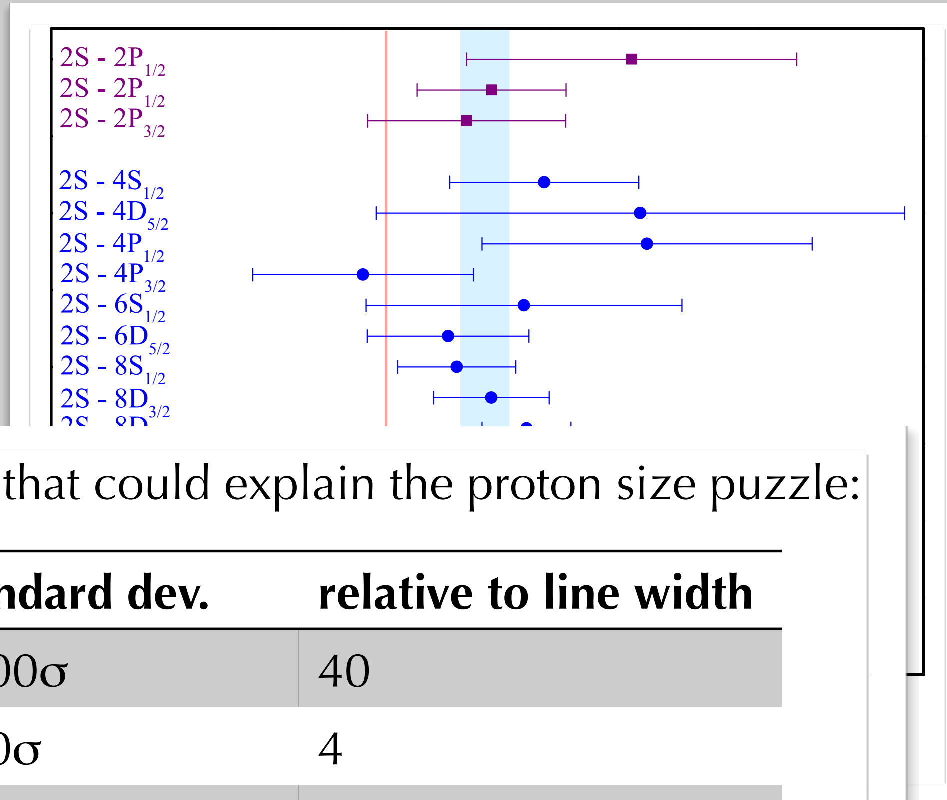
Hydrogen Energy Levels





Hydrogen Energy Levels





Size of possible systematics that could explain the proton size puzzle:

Transition	standard dev.	relative to line width
H 1S-2S	4000σ	40
μ−p	100σ	4
H $2S-4P_{1/2}$	< 1.5σ	$7x10^{-4}$
H $2S-4P_{3/2}$	< 0.5σ	$7x10^{-4}$

Hydrogen 1S-2S

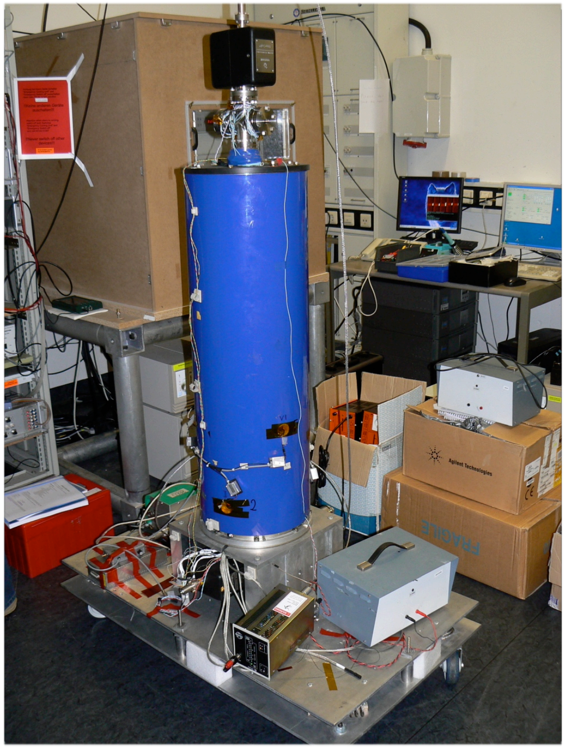
Clock

Frequency Comb

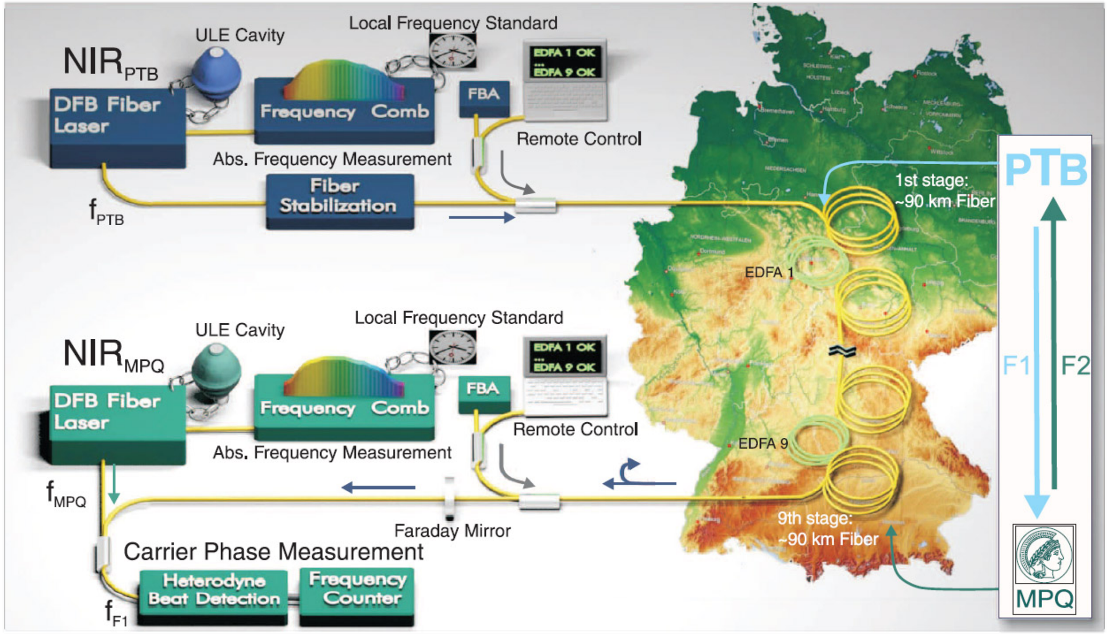
Laser

Atomic Sample

Hydrogen 1S-2S

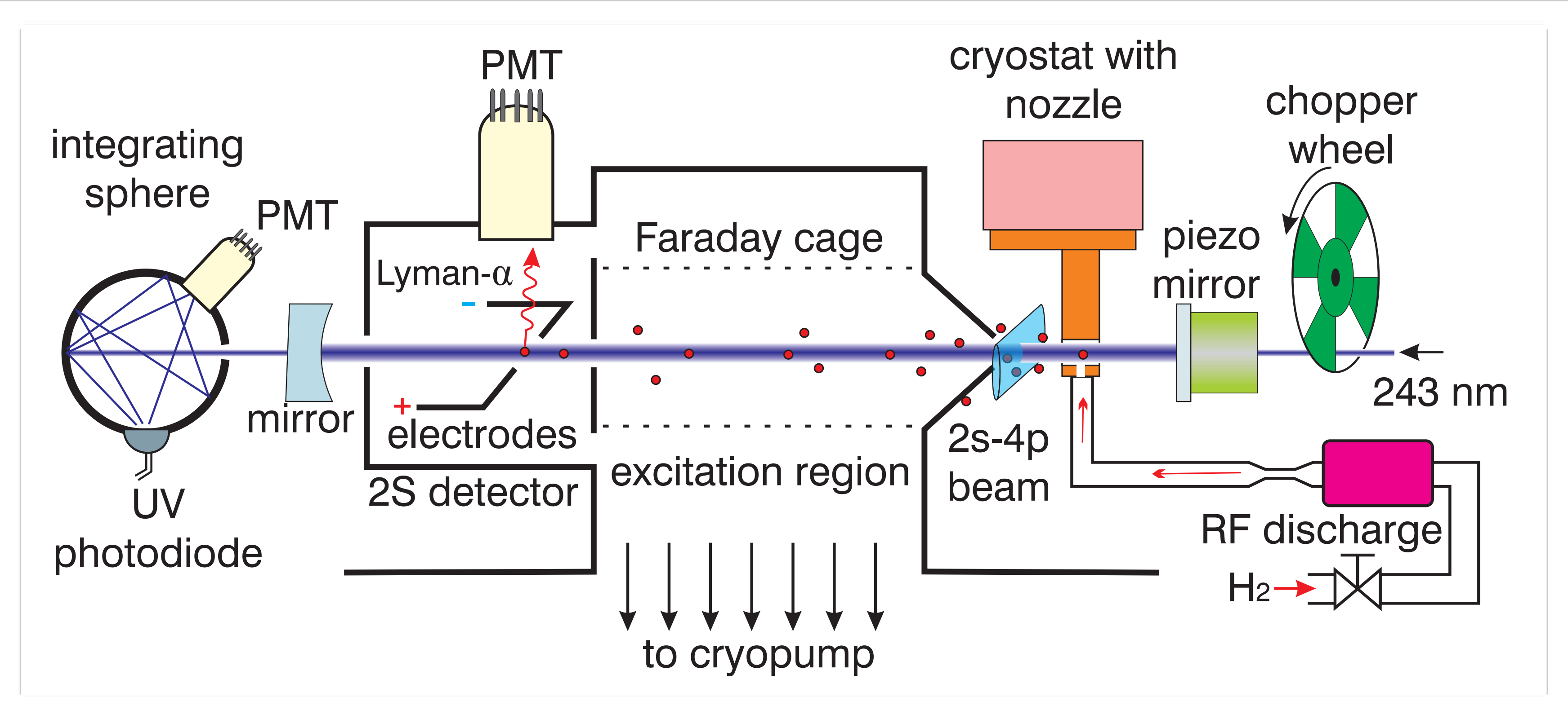


Frequency references



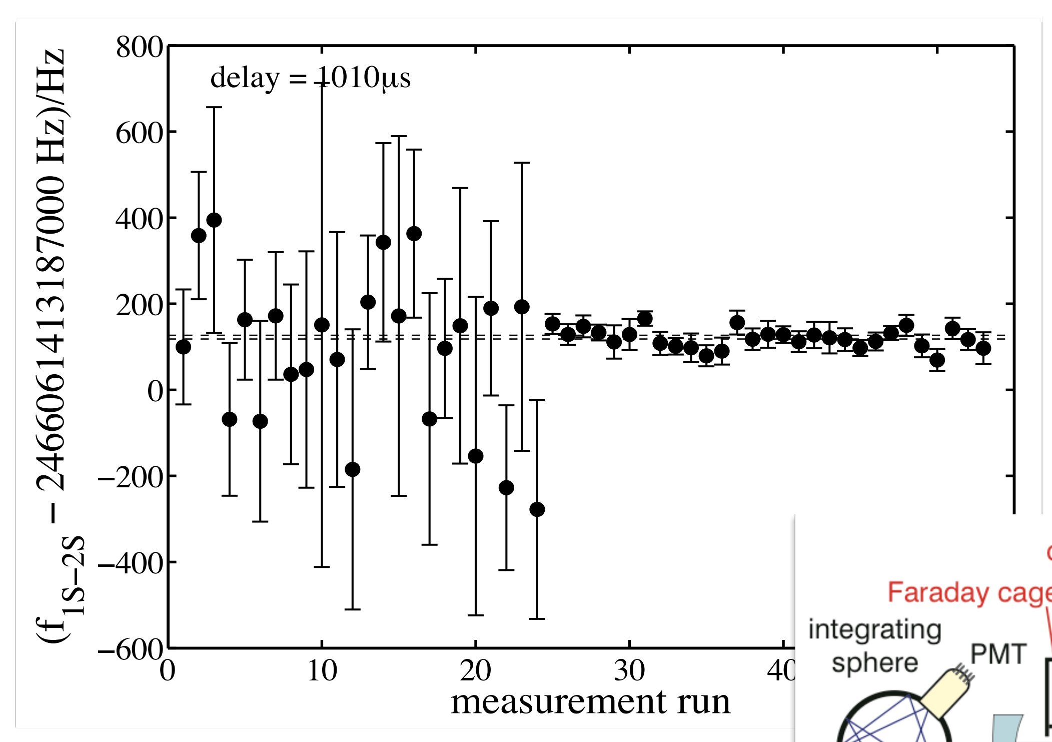
J. Guena *et al.*, IEEE Trans. Ultrason., Ferroelectr., Freq. Control **59**, 391 (2012)
K. Predehl *et al.*, Science **336**, 441 (2012)

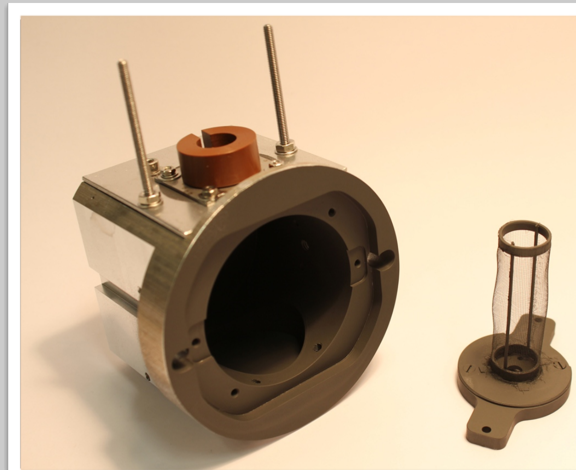
Hydrogen 1S-2S

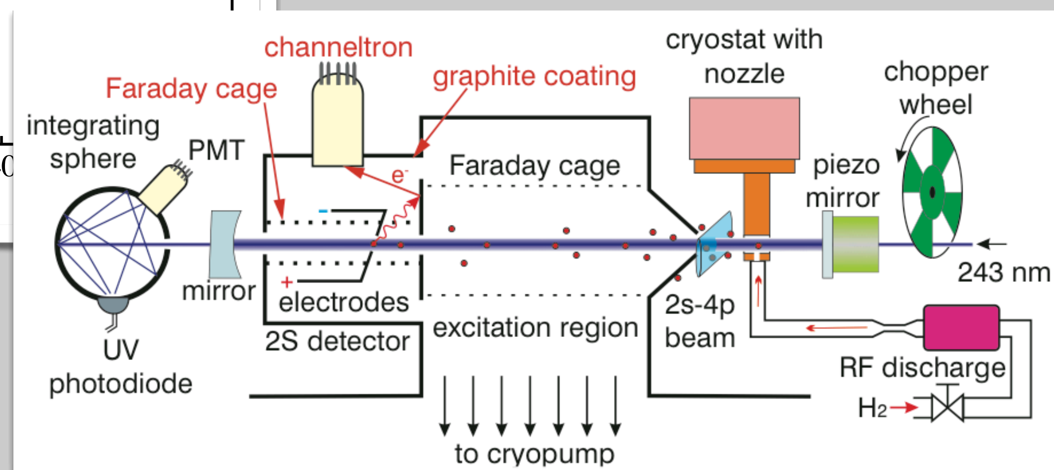


C.G. Parthey et al., Phys. Rev. Lett. **107**, 203001 (2011)

Hydrogen 1S-2S

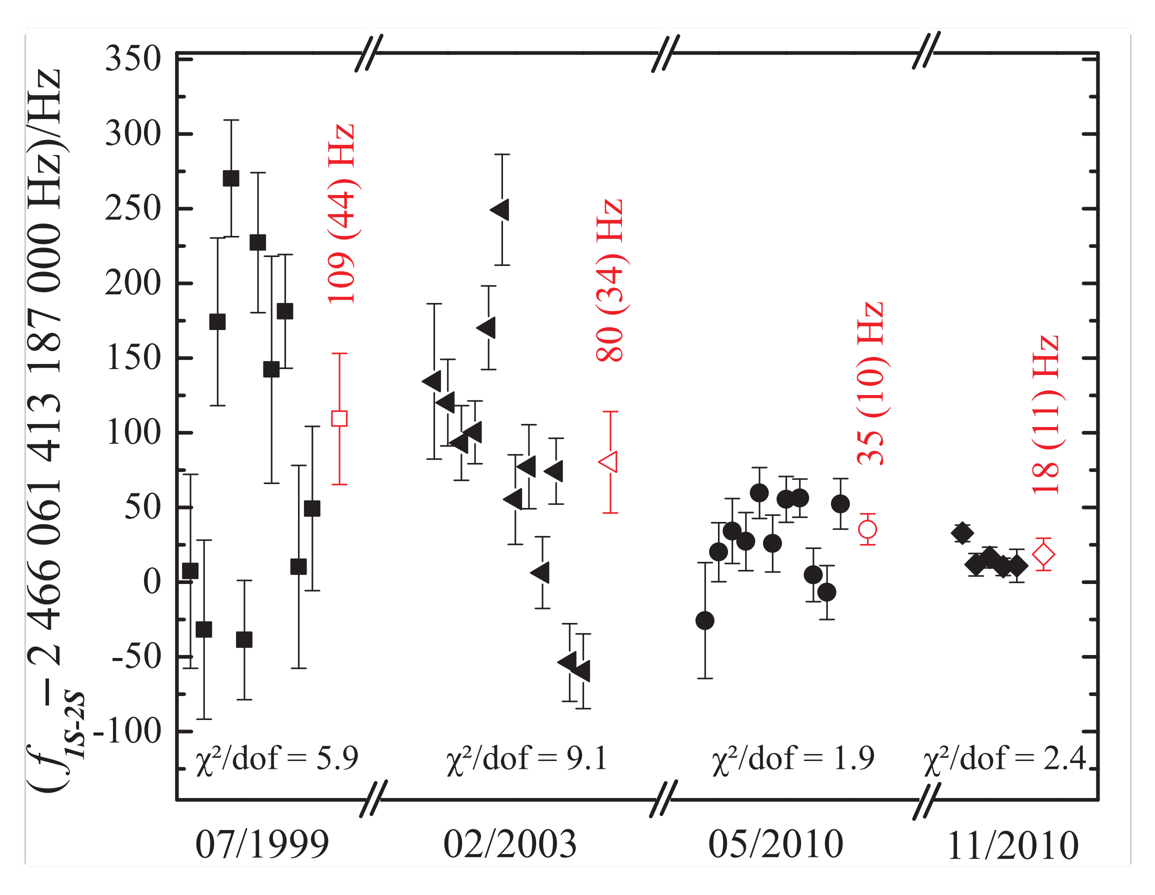






A. Matveev *et al.*, Phys. Rev. Lett. **110**, 230801 (2013)

Hydrogen 1S-2S



$$2\,466\,061\,413\,187\,035(10)\ \text{Hz}$$

New experiments

New experiments on the way:

Scattering experiments:

- Jlab E12-11-106: e - p (2014-15)
- MUSE at PSI: $\mu^{+/-}$ - p (2017-2018)

Spectroscopy of exotic atoms:

- ETH, Zurich (in preparation):
  - positronium (e^+e^-)
  - muonium (μ^+e^-)
- PSI, Villingen: μHe^+

Spectroscopy of electronic Atoms and Ions:

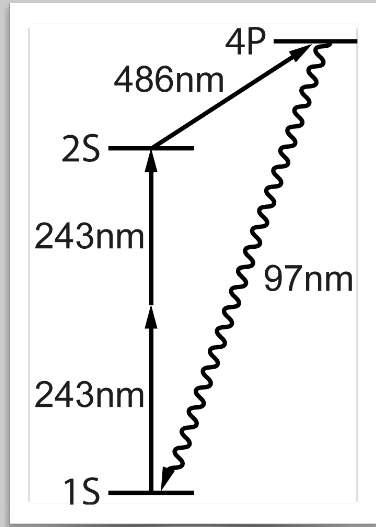
- NPL, London: 2S-6S/D in atomic hydrogen
- MPQ, Garching:
  - 2S-4P in atomic hydrogen
  - 1S-3S in atomic hydrogen (comb)
  - He^+ (in preparation)
- LKB, Paris: 1S-3S in atomic hydrogen (cw)
- YU, Toronto: 2S-2P „Lamb shift“

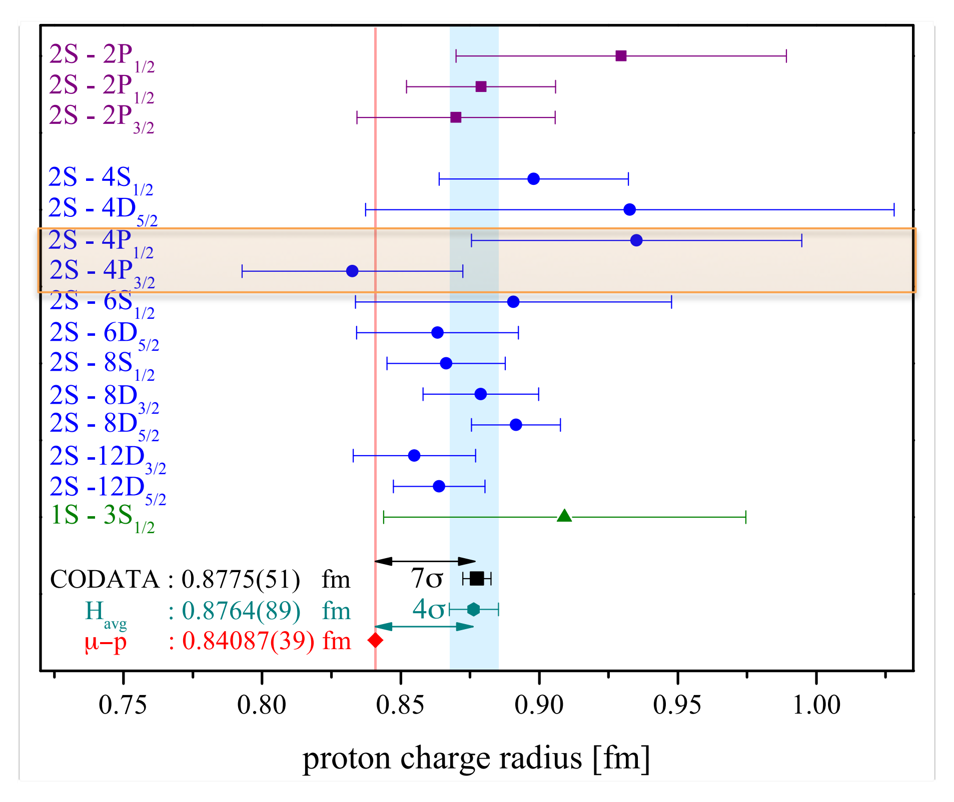
- VU, Amsterdam: He^+ (in preparation)
- NIST, Gaithersburg: highly charged ions

Hydrogen 2S-4P

2S-4P transition:

- one photon transition
  - ➢ low power required
  - ➢ need to deal with 1st and 2nd order Doppler Shift
- small principal quantum number *n*:
  - ➢ natural line width 13 MHz
  - ➢ DC Stark effect small compared higher transitions





difference in 2S-4P transition frequency
using r_p from μ-p or H:
only about 8.9kHz

1st Order Doppler Shift

$$\Delta\omega = \vec{v} \cdot \vec{k}$$

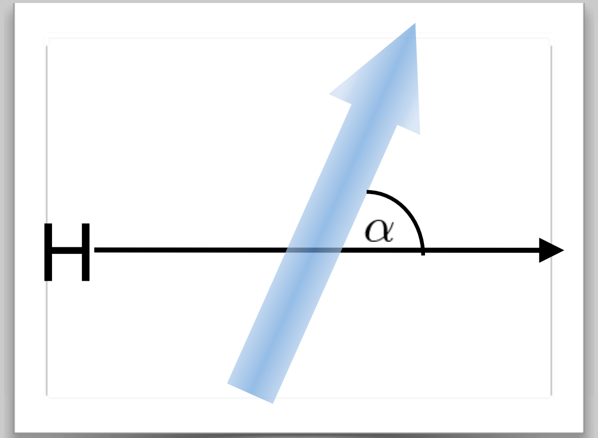
Typical numbers in our experiment:

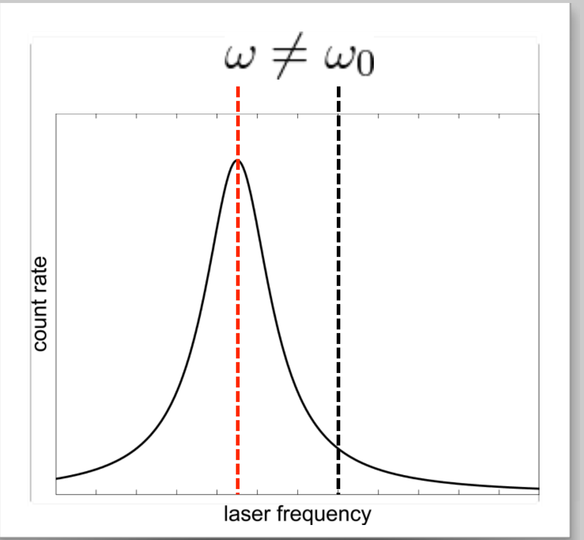
$$T = 6\mathrm{K} \Rightarrow v_r \approx 300\mathrm{m/s}$$

Frequency shift for deviation from 90° configuration:

$$1^\circ \Rightarrow 12\mathrm{MHz}$$

$$1.5 \times 10^{-6}\mathrm{rad} \Leftarrow 1\mathrm{kHz}$$





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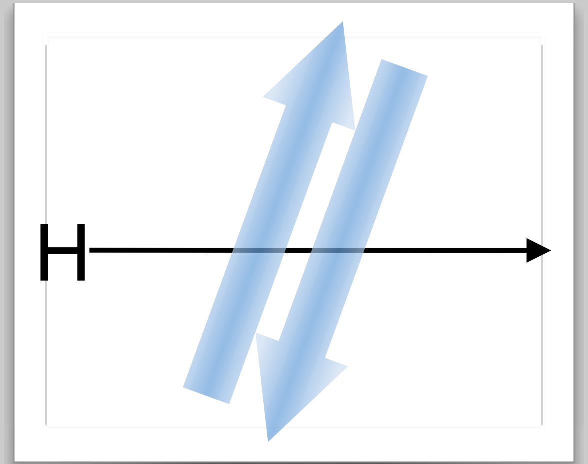

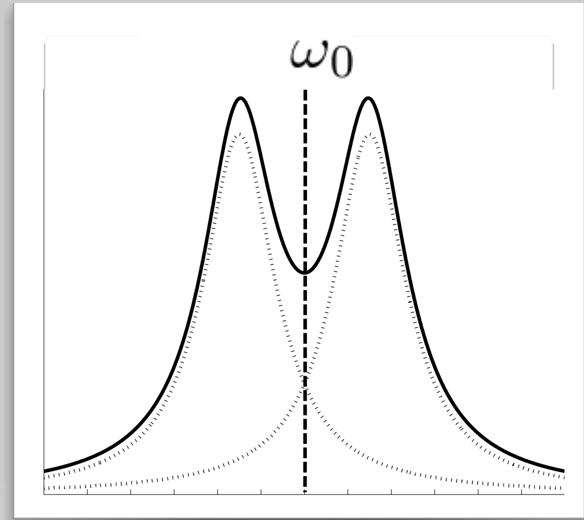

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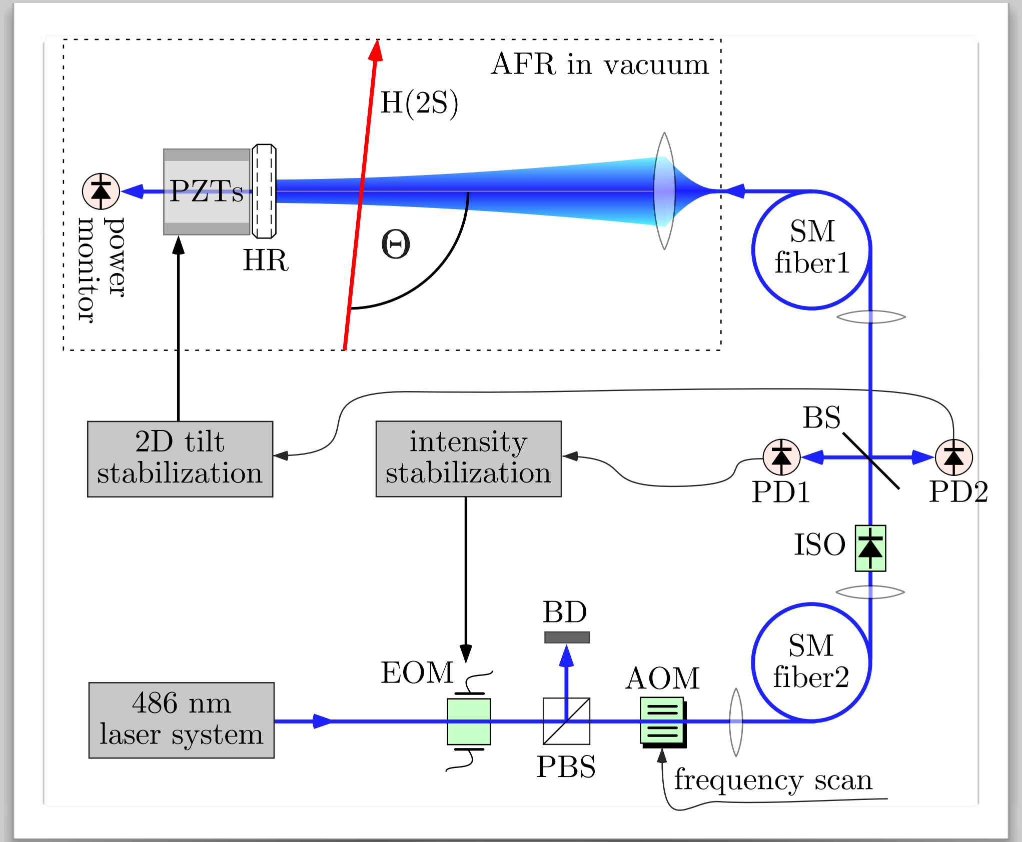
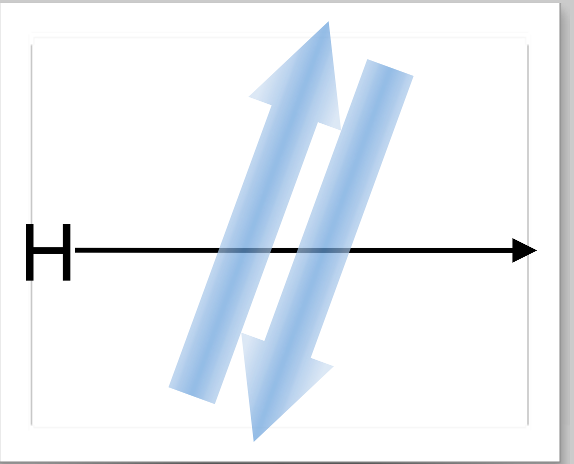
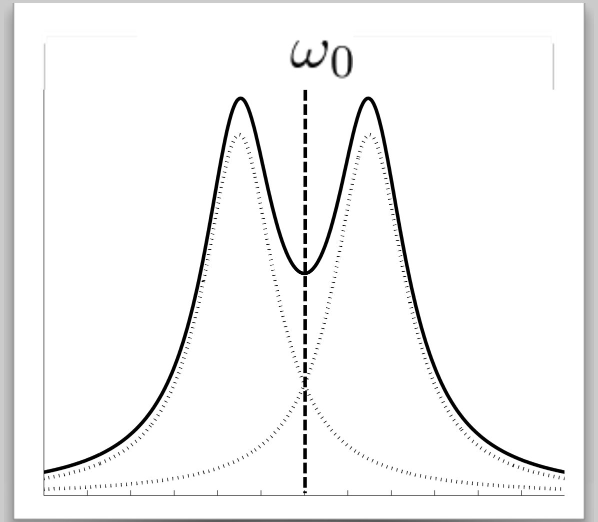
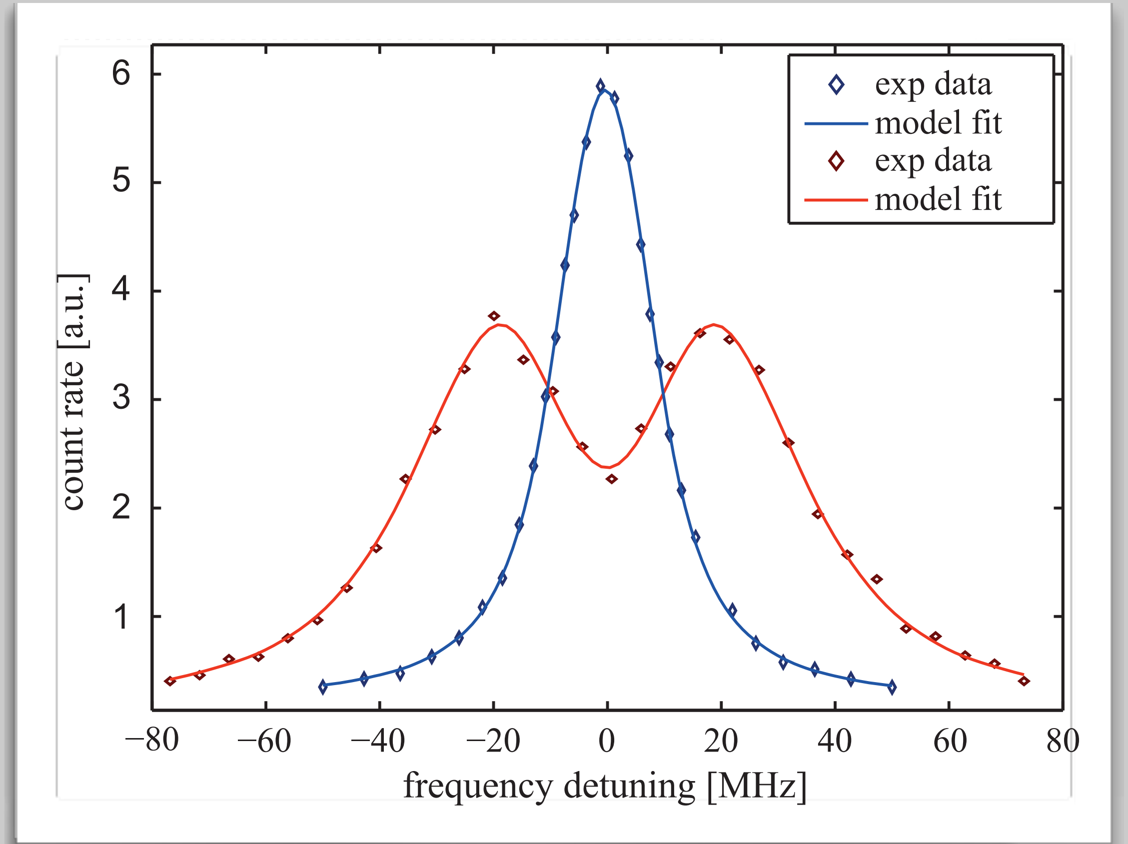


A. Beyer *et al.*, 10.1002/andp.201300075 (2013)





1^{st} Order Doppler Shift



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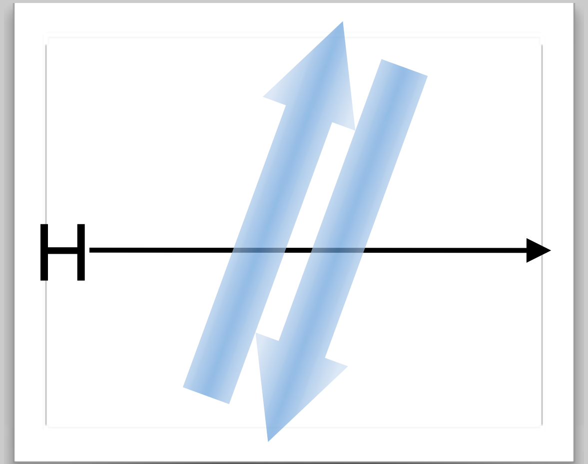
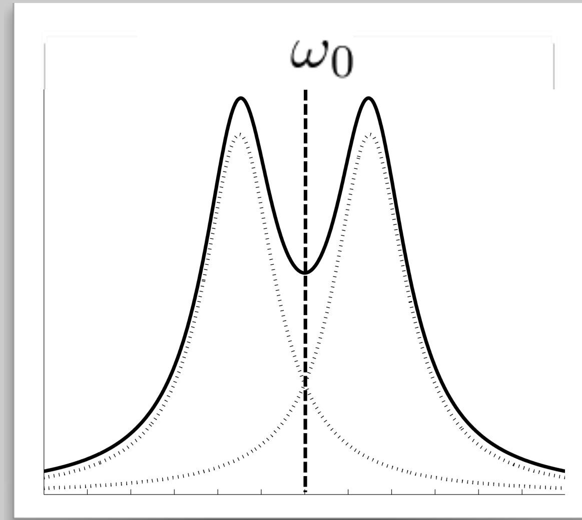
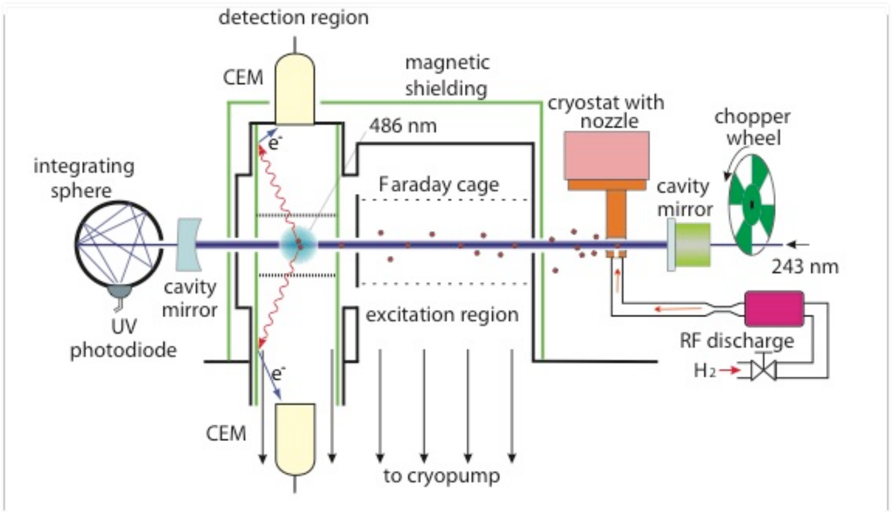
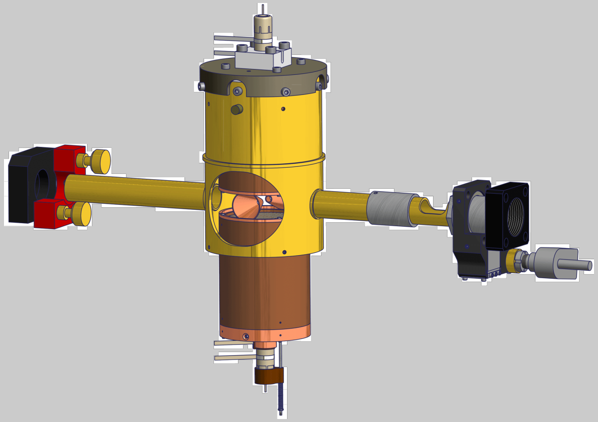
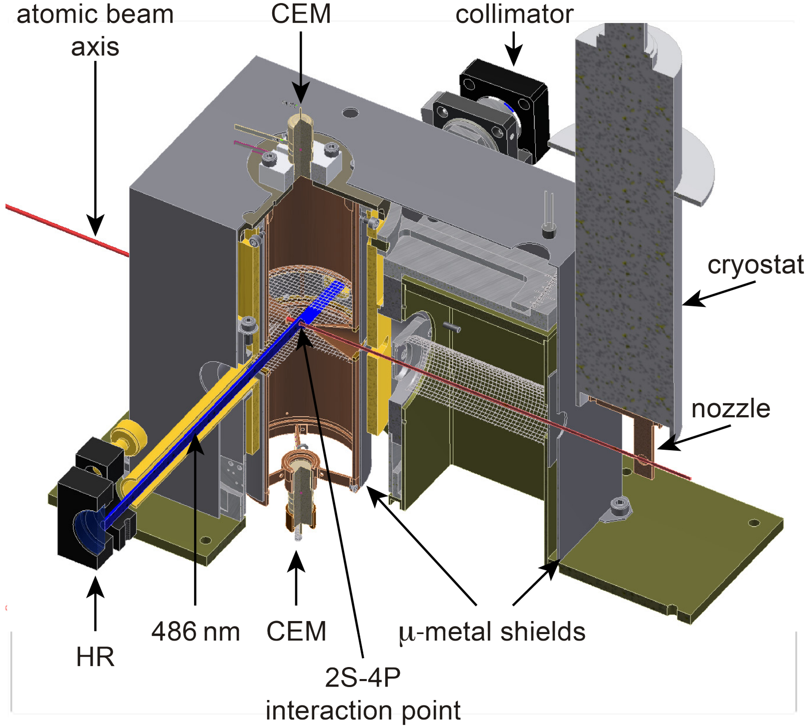




Beam Apparatus







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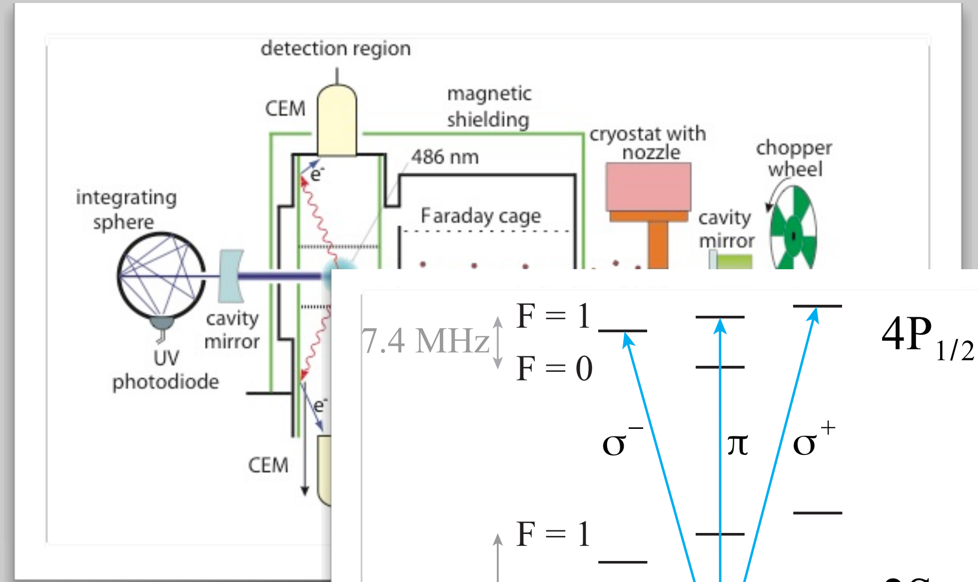

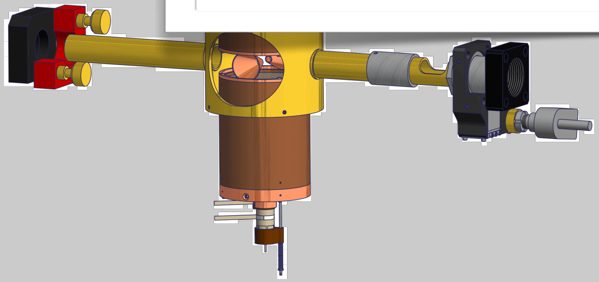

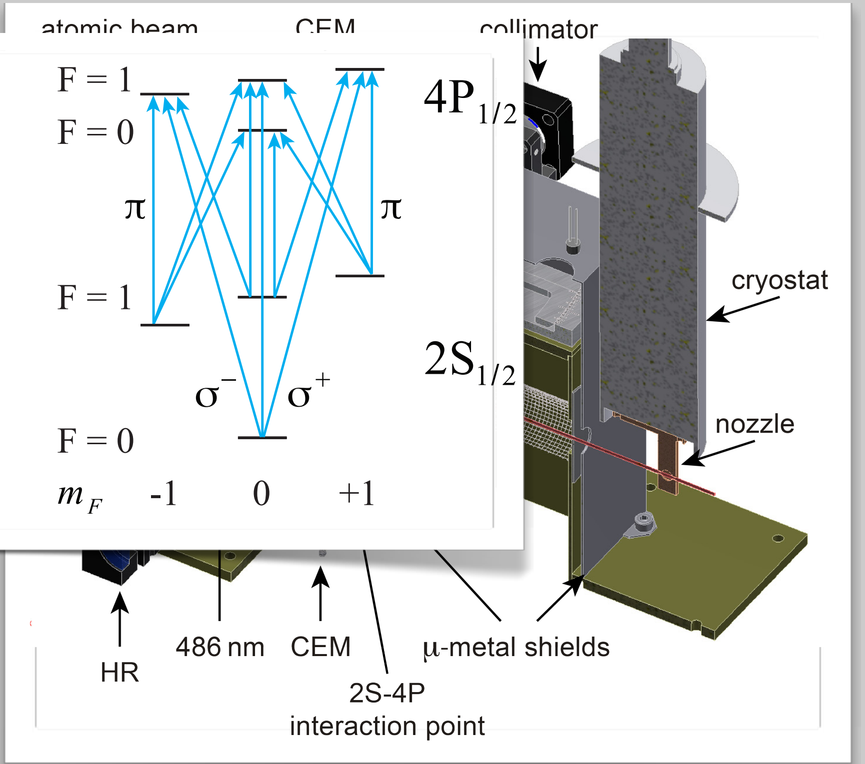

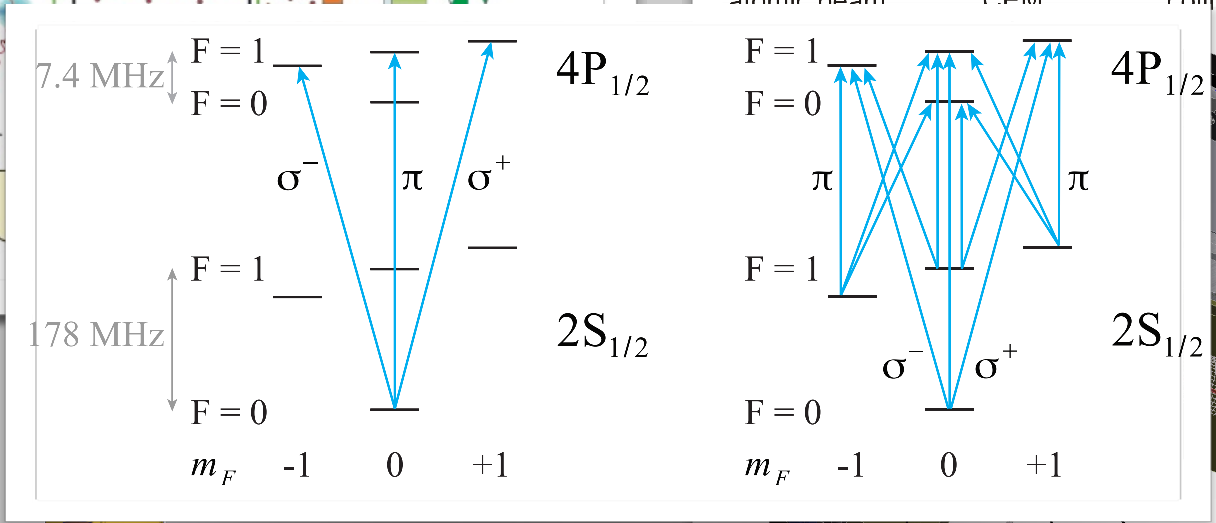

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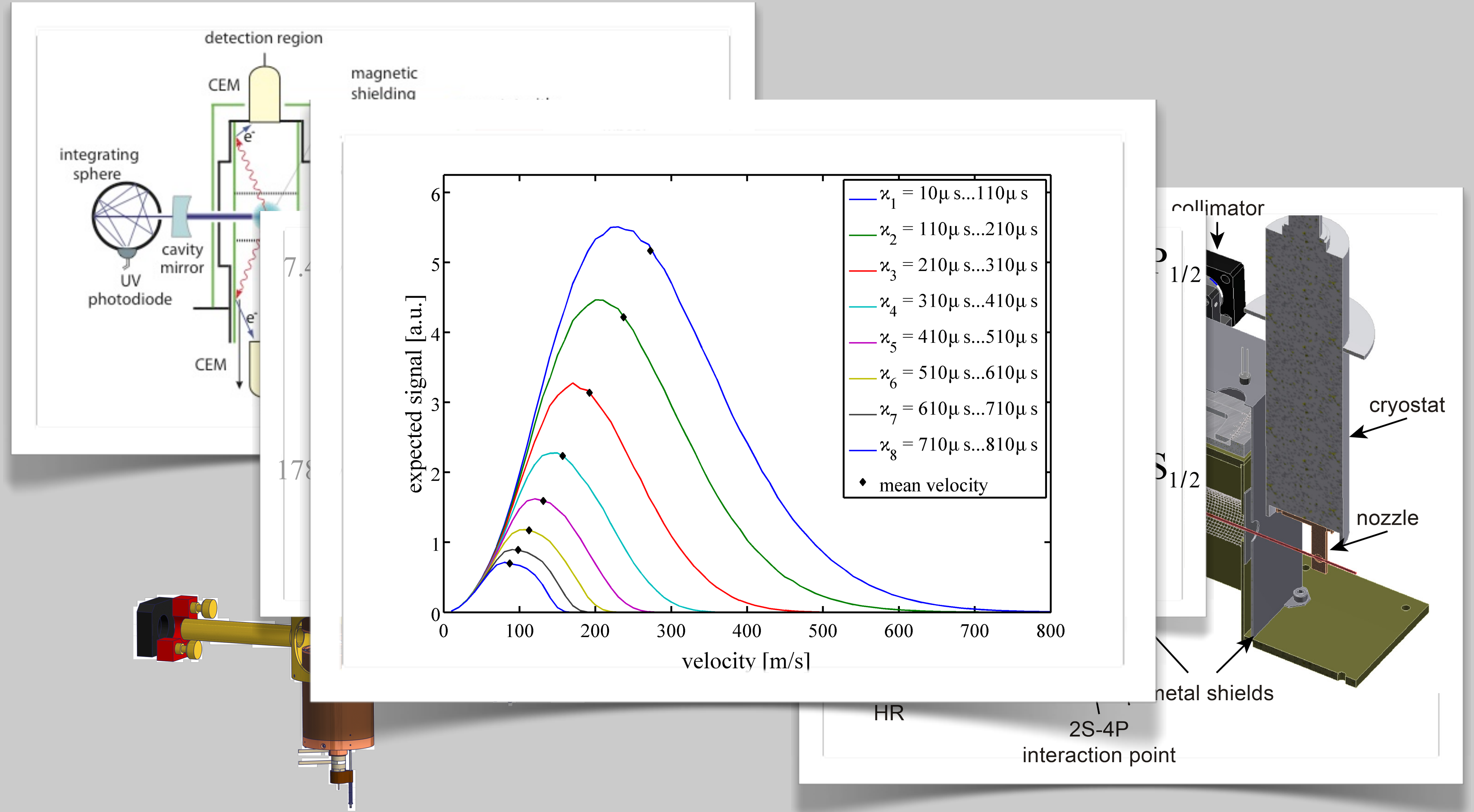
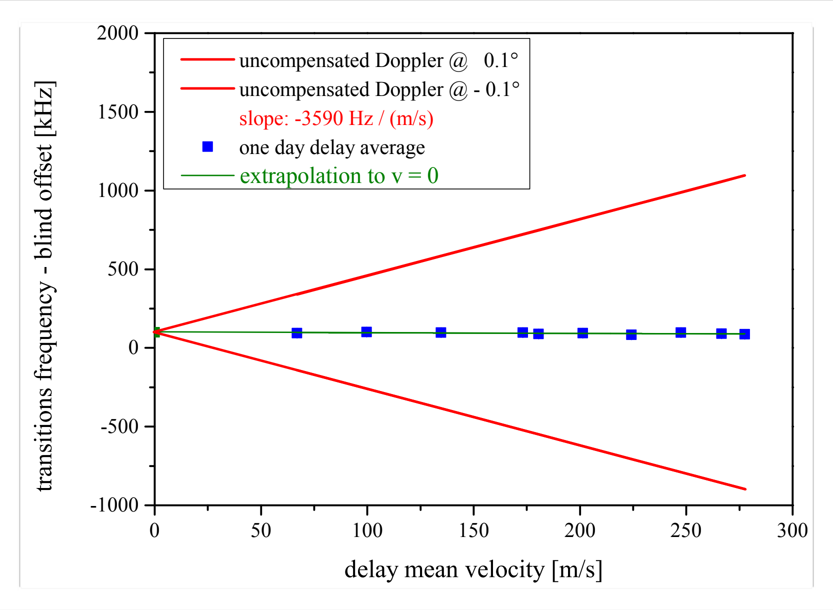
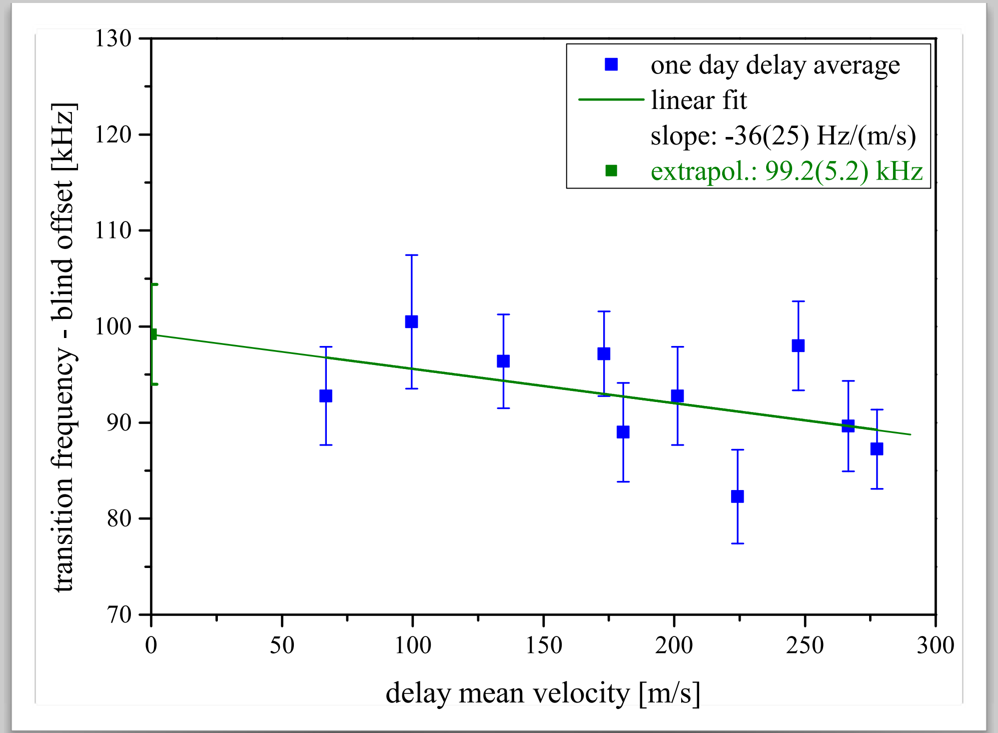
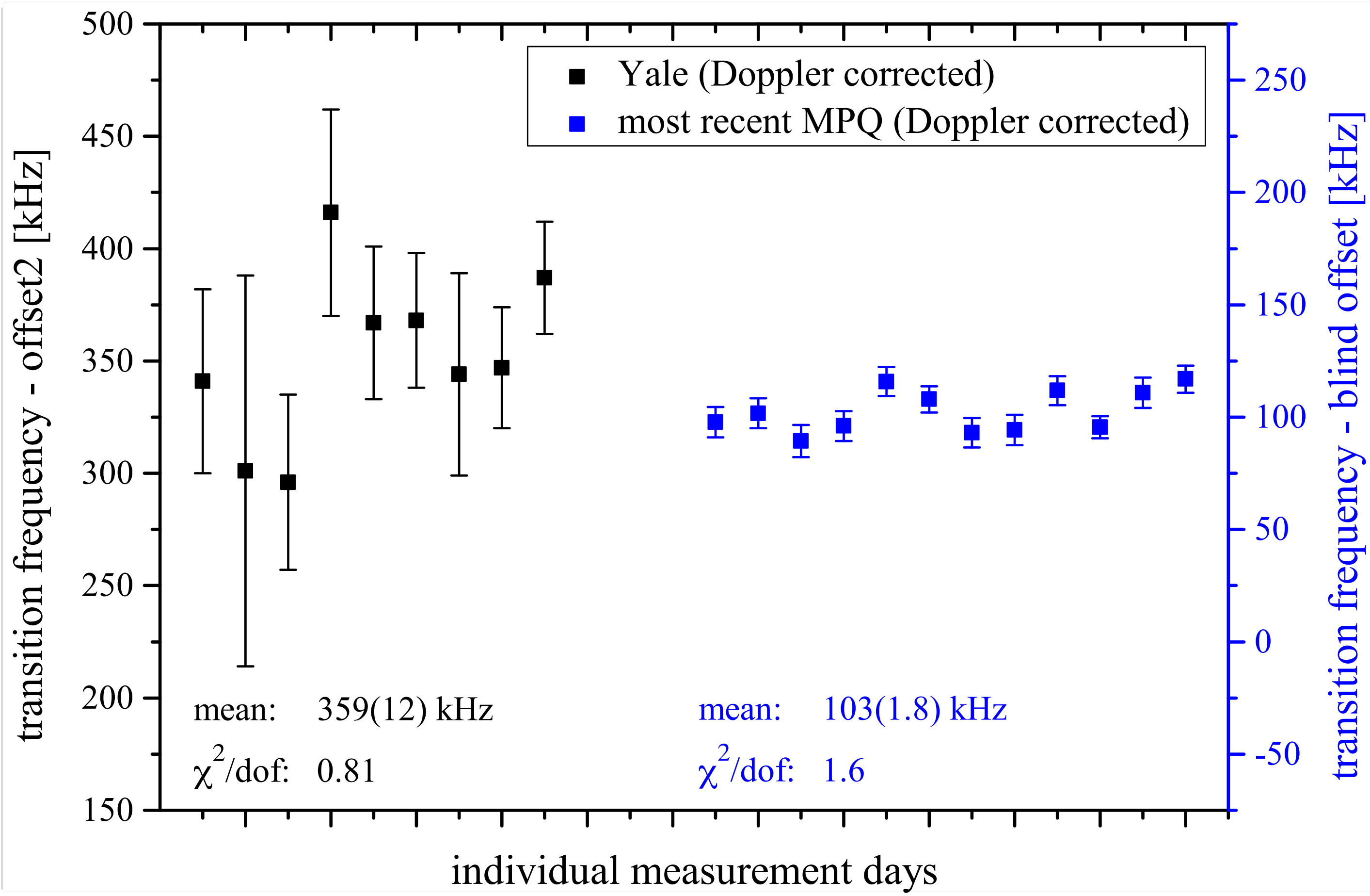


Last Year...

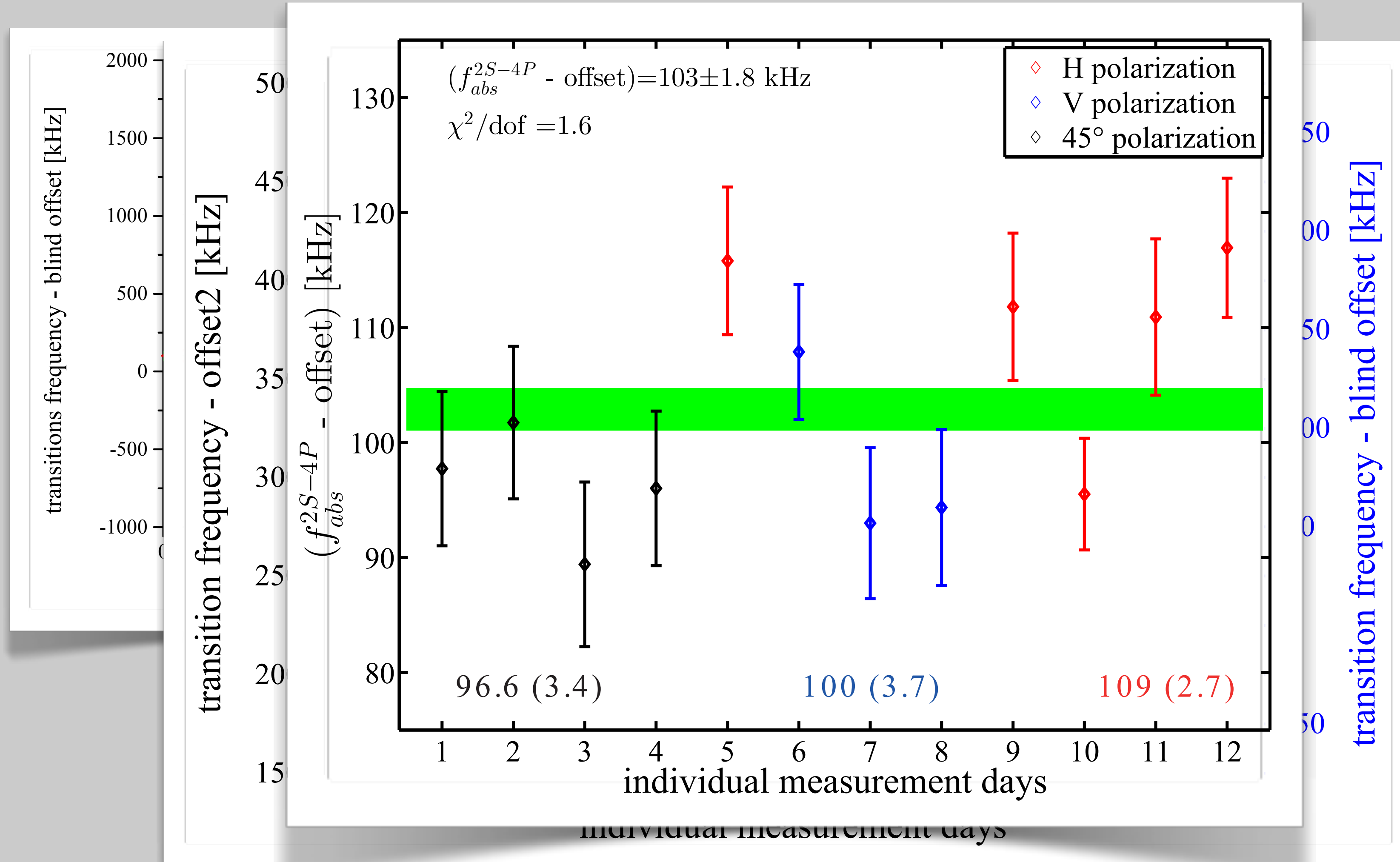

uncompensated Doppler @ 0.1°
uncompensated Doppler @ - 0.1°
slope: -3590 Hz / (m/s)
one day delay average
extrapolation to v = 0
transitions frequency - blind offset [kHz]
delay mean velocity [m/s]
2000
1500
1000
500
0
-500
-1000
0
50
100
150
200
250
300


one day delay average
linear fit
slope: -36(25) Hz/(m/s)
extrapol.: 99.2(5.2) kHz
transition frequency - blind offset [kHz]
delay mean velocity [m/s]
130
120
110
100
90
80
70
0
50
100
150
200
250
300

Last Year...

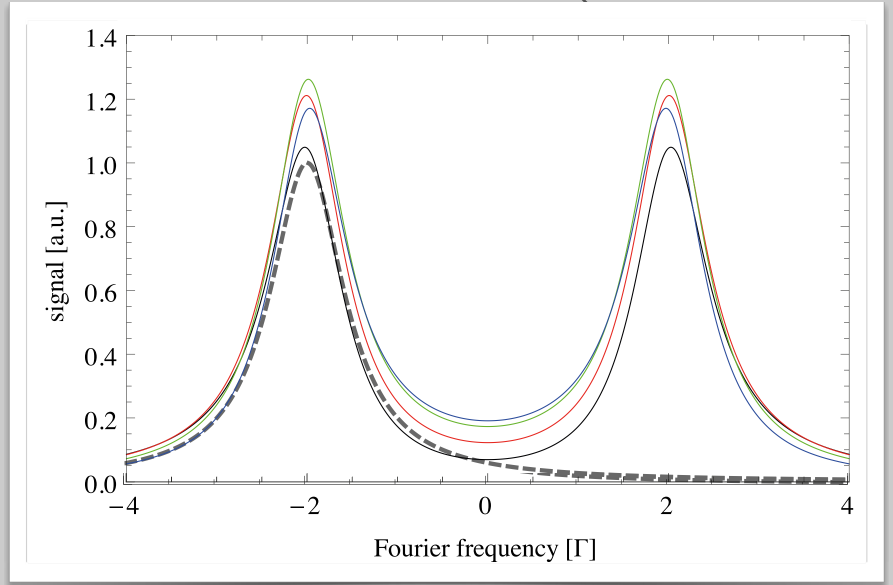

transition frequency - offset2 [kHz]
500
450
400
350
300
250
200
150
Yale (Doppler corrected)
most recent MPQ (Doppler corrected)
250
200
150
100
50
0
-50
transition frequency - blind offset [kHz]
mean: 359(12) kHz
χ2/dof: 0.81
mean: 103(1.8) kHz
χ2/dof: 1.6
individual measurement days

Last Year…


$(f_{abs}^{2S-4P}$ - offset)=103±1.8 kHz
χ^2/dof =1.6
H polarization
V polarization
45° polarization
96.6 (3.4)
100 (3.7)
109 (2.7)
$(f_{abs}^{2S-4P}$ - offset) [kHz]
individual measurement days
transition frequency - offset2 [kHz]
transitions frequency - blind offset [kHz]
transition frequency - blind offset [kHz]

Cross Damping / Interference

If the line is to be split by γ/N, the additional, geometry dependent cross term becomes important if the next resonance is closer than Nxγ



$$I(\omega) \propto \left| \frac{\vec{d}_s \cdot \vec{d}_1}{\omega - \omega_1 + i\Gamma_1} + \frac{\vec{d}_s \cdot \vec{d}_2}{\omega - \omega_2 + i\Gamma_2} \right|^2$$

$$= \frac{(\vec{d}_s \cdot \vec{d}_1)^2}{(\omega - \omega_1)^2 + \Gamma_1^2} + \frac{(\vec{d}_s \cdot \vec{d}_2)^2}{(\omega - \omega_2)^2 + \Gamma_2^2} + 2Re\left(\frac{(\vec{d}_s \cdot \vec{d}_1)(\vec{d}_s \cdot \vec{d}_2)^*}{(\omega - \omega_1 + i\Gamma_1)(\omega - \omega_2 - i\Gamma_2)} \right)$$

M. Horbatsch & E.A. Hessels, PRA 82, 052519 (2010)
R.C. Brown et al., PRA 87, 032504 (2013)

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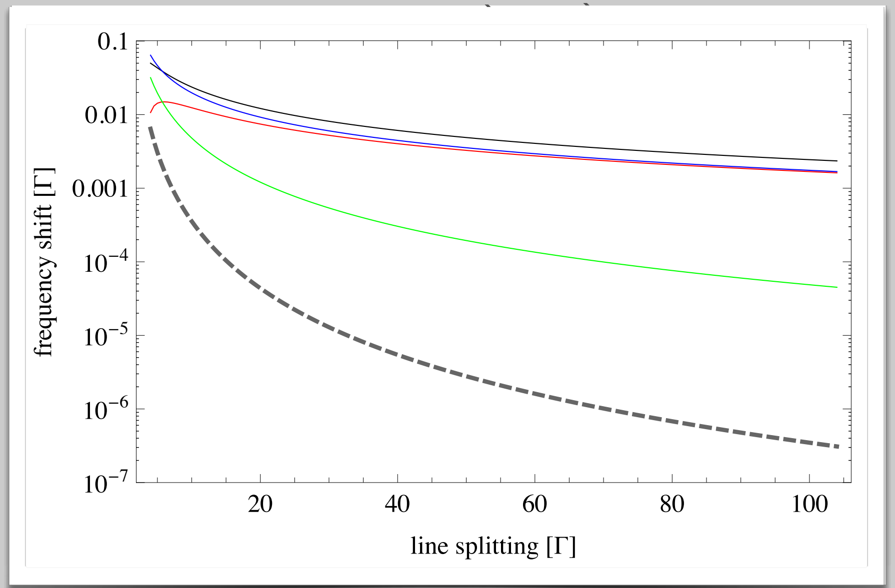

$$I(\omega) \propto \left| \frac{\vec{d}_s \cdot \vec{d}_1}{\omega - \omega_1 + i\Gamma_1} + \frac{\vec{d}_s \cdot \vec{d}_2}{\omega - \omega_2 + i\Gamma_2} \right|^2$$

$$= \frac{(\vec{d}_s \cdot \vec{d}_1)^2}{(\omega - \omega_1)^2 + \Gamma_1^2} + \frac{(\vec{d}_s \cdot \vec{d}_2)^2}{(\omega - \omega_2)^2 + \Gamma_2^2} + 2Re\left(\frac{(\vec{d}_s \cdot \vec{d}_1)(\vec{d}_s \cdot \vec{d}_2)^*}{(\omega - \omega_1 + i\Gamma_1)(\omega - \omega_2 - i\Gamma_2)} \right)$$

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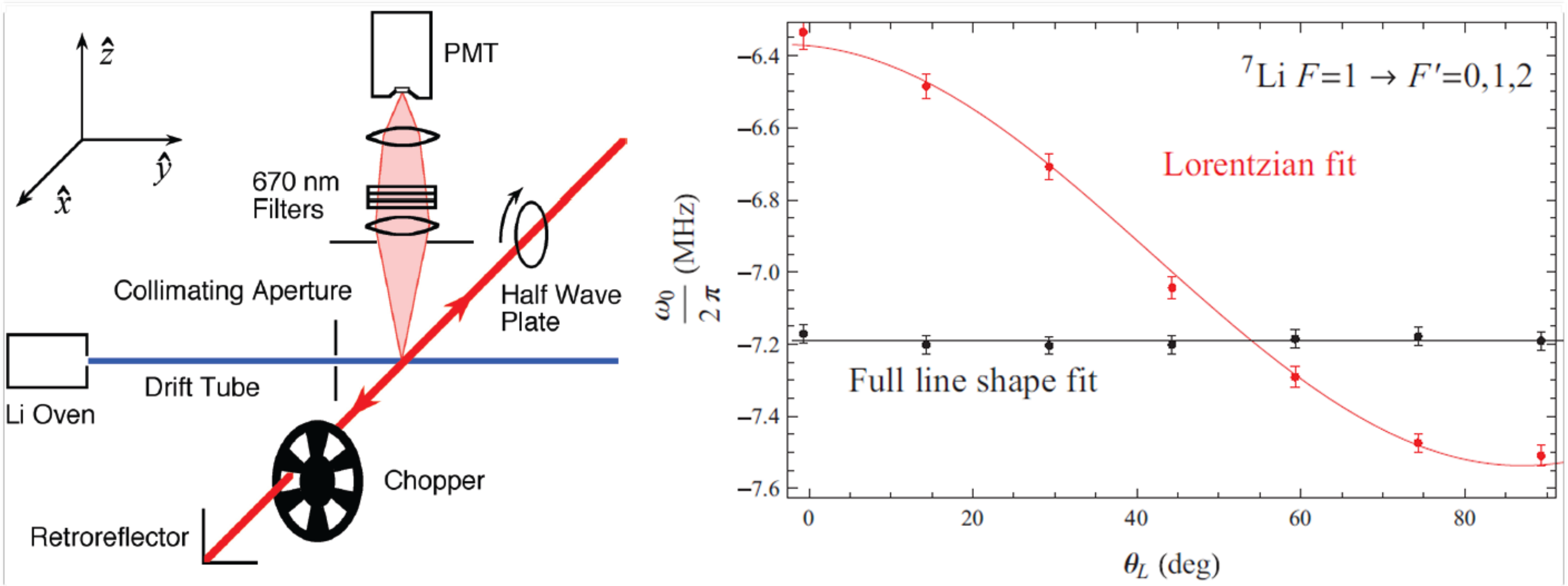
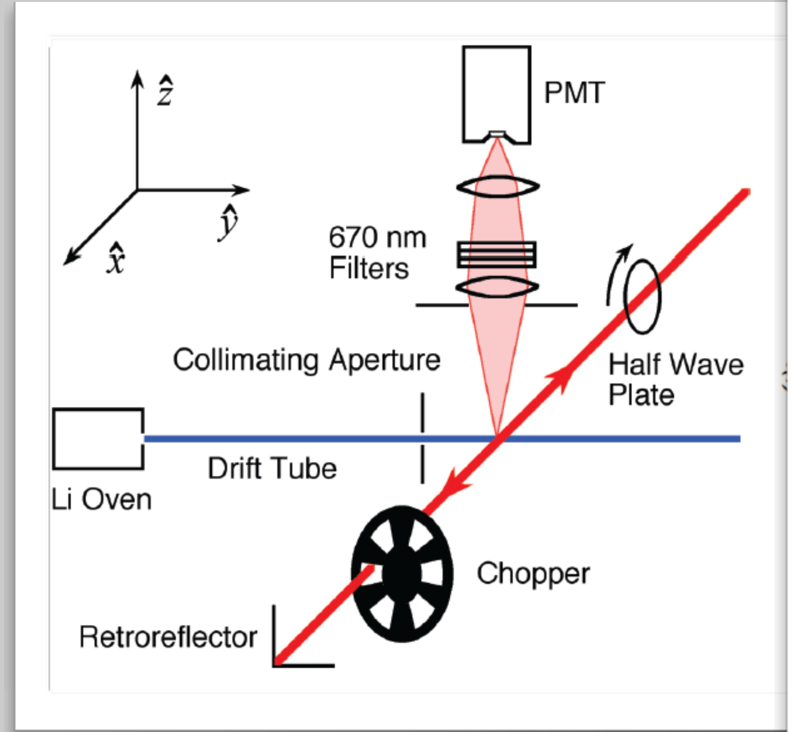
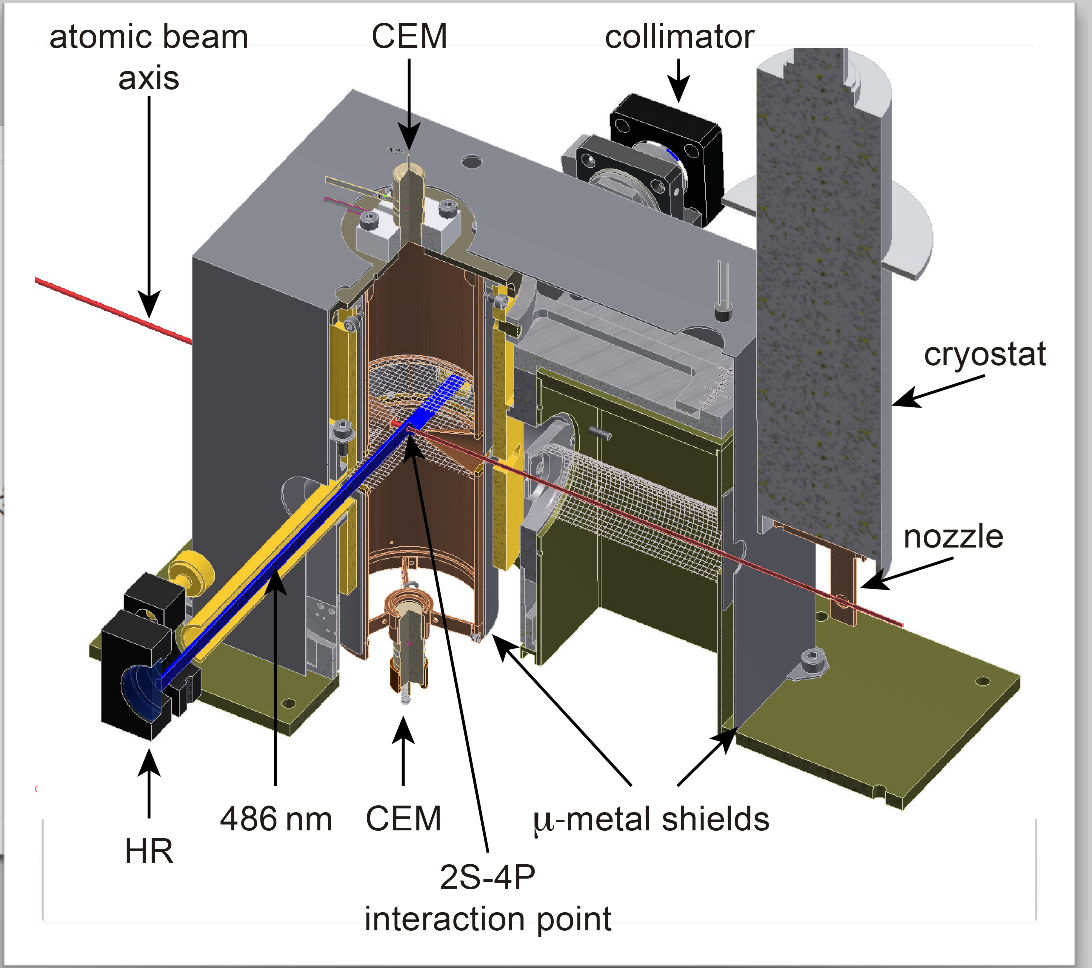
R.C. Brown et al., PRA 87, 032504 (2013)



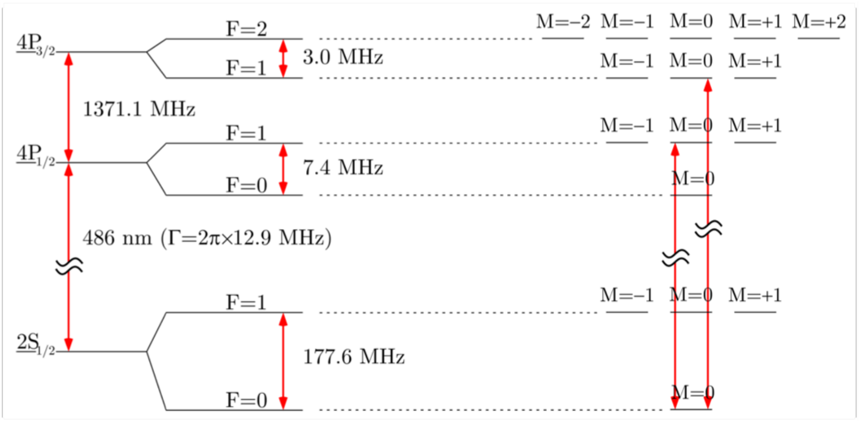
Cross Damping / Interference

R.C. Brown et al., PRA 87, 032504 (2013)



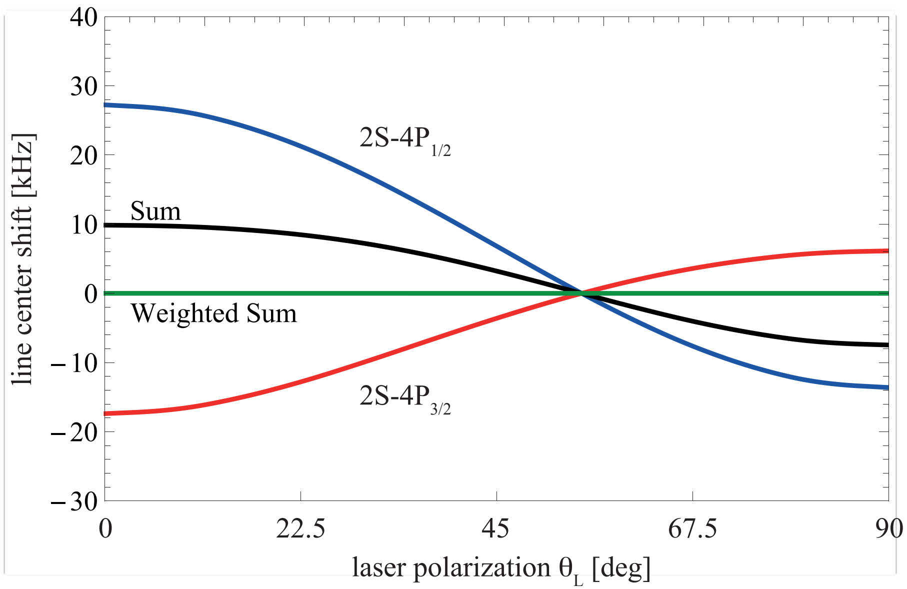


Cross Damping / Interference



effect depends on geometry and detection scheme of experiment

simulation of interference effect using perturbative approach presented by in R.C. Brown et al., PRA 87, 032504 (2013)



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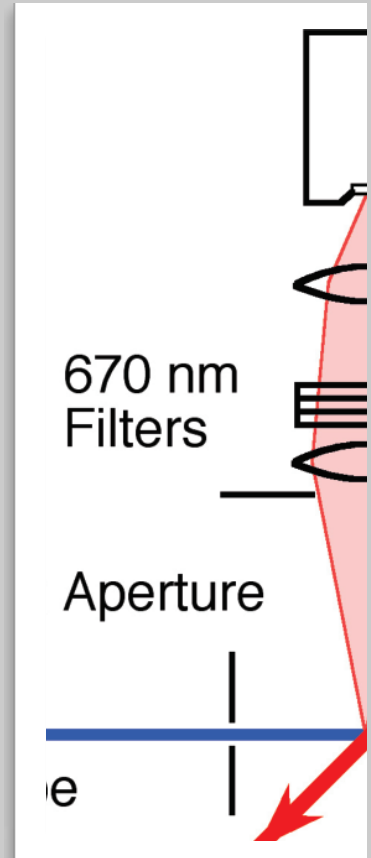
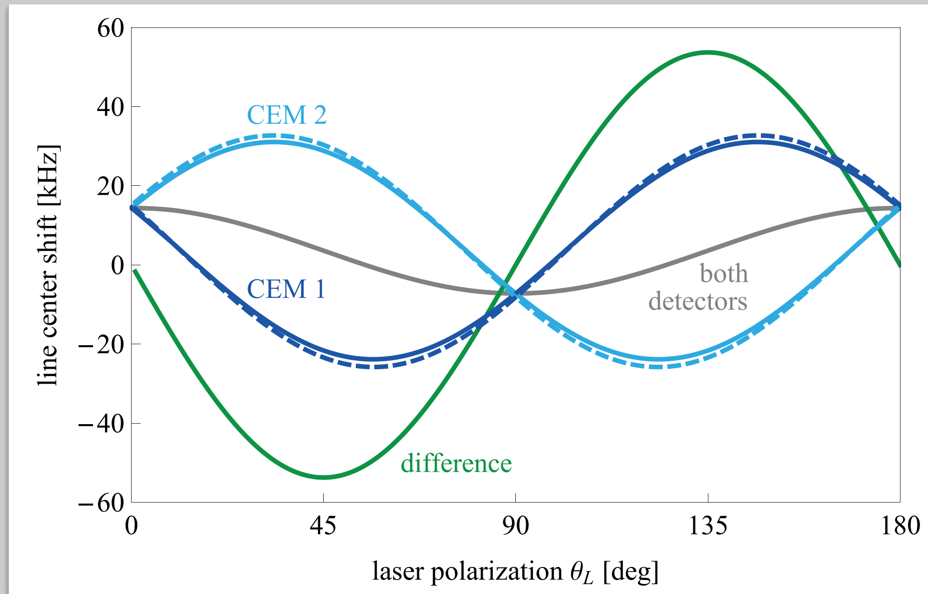
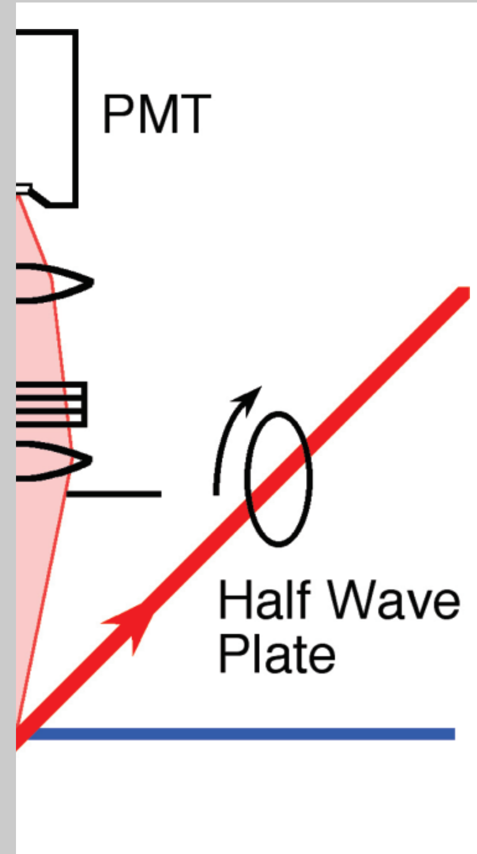


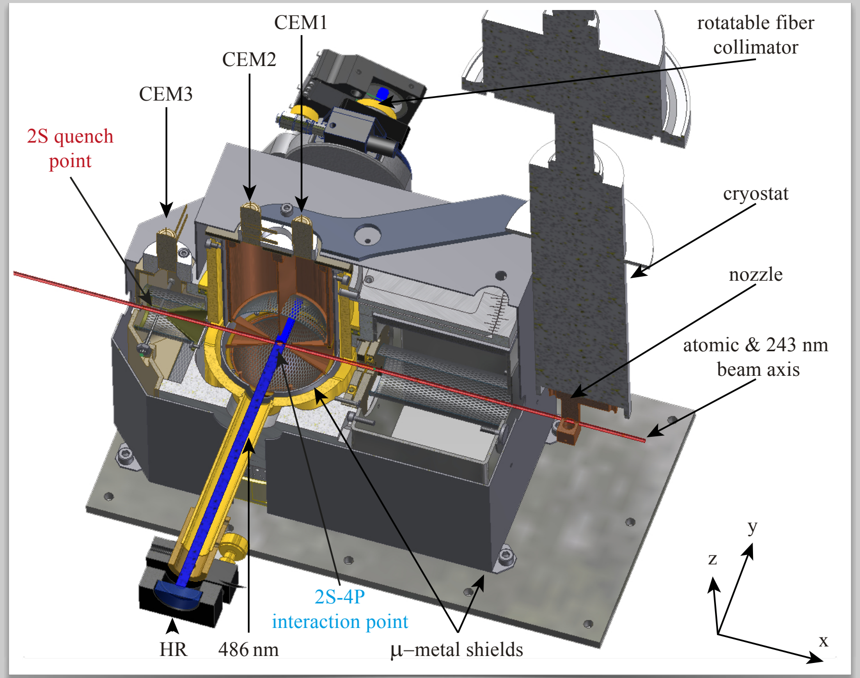


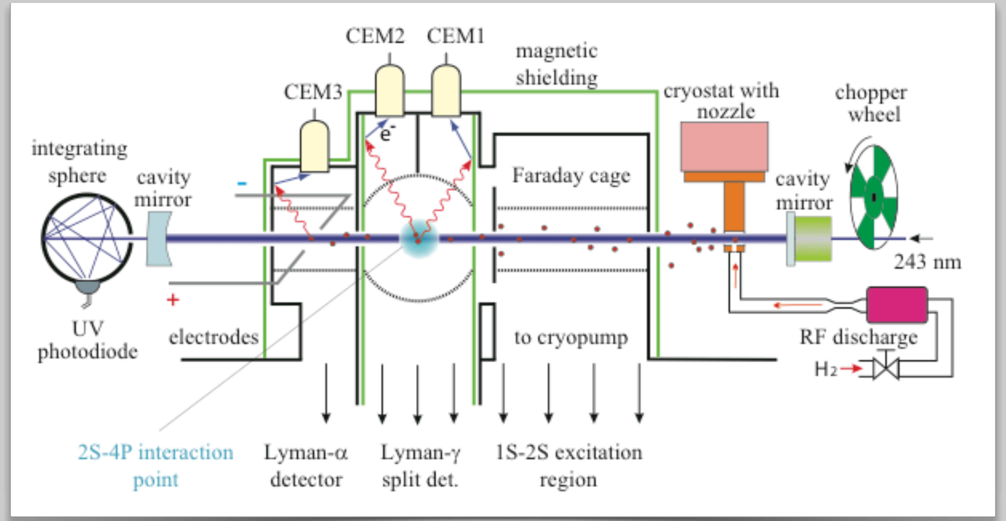


dashed: numerical integration of optical Bloch equations

→ 2707 coupled partial differential equations

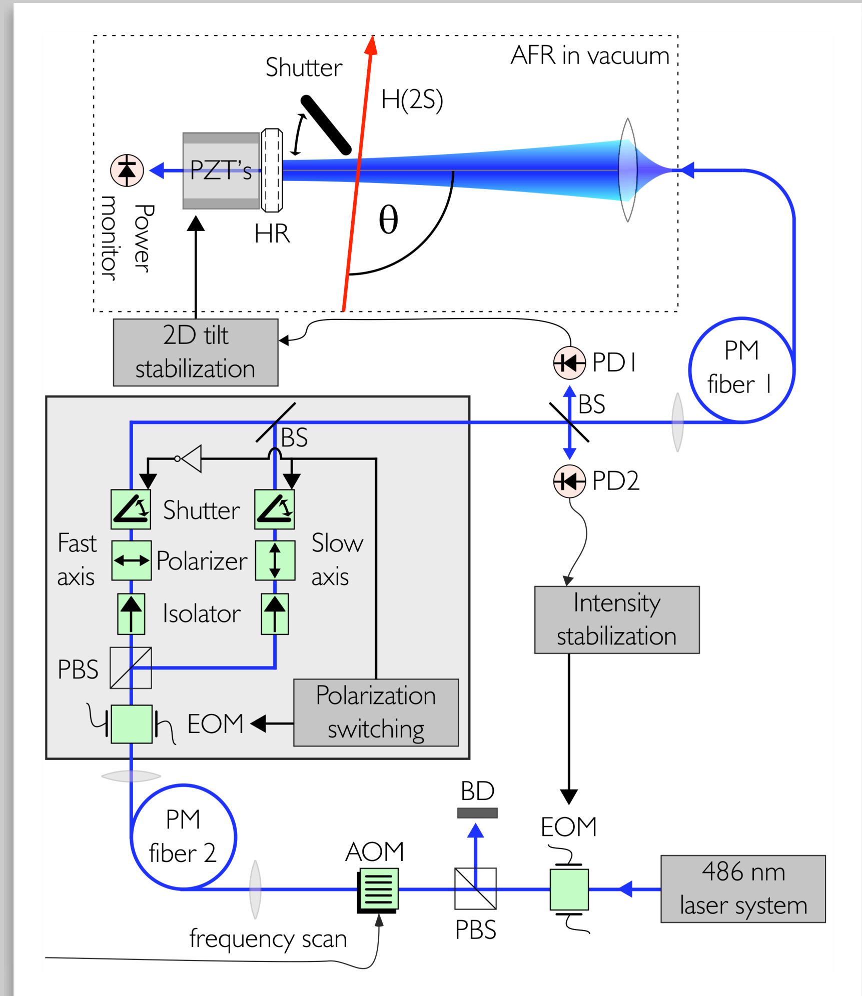
Detector Upgrade

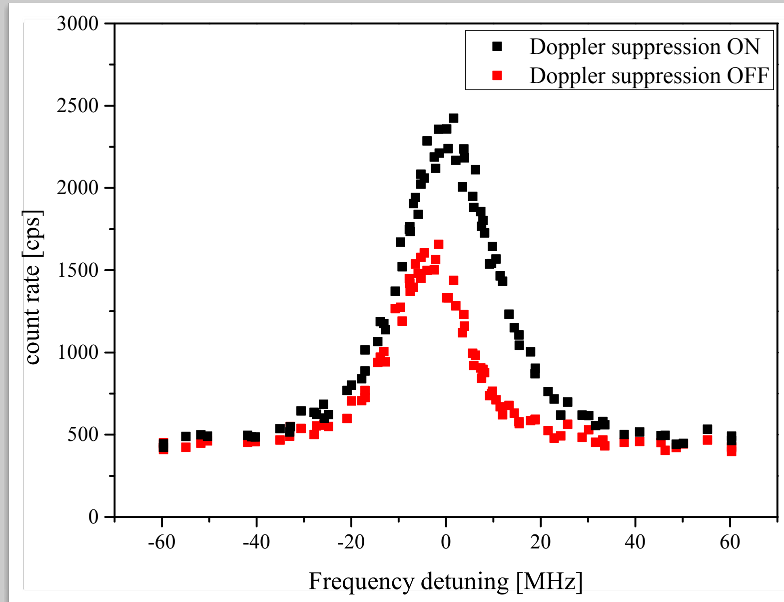




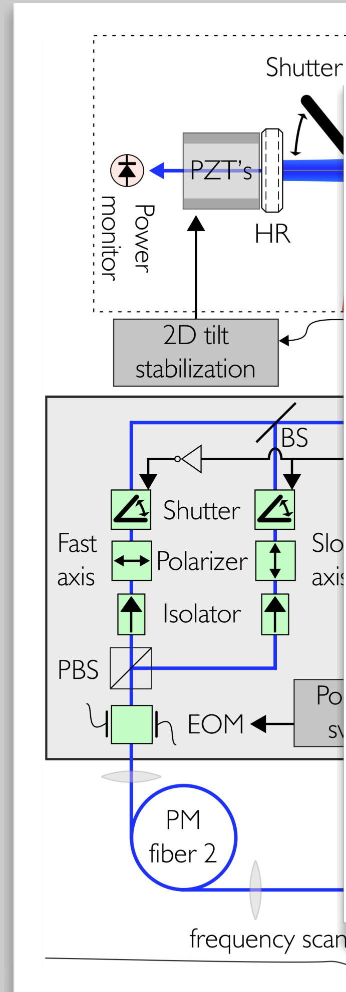
Detector Upgrade

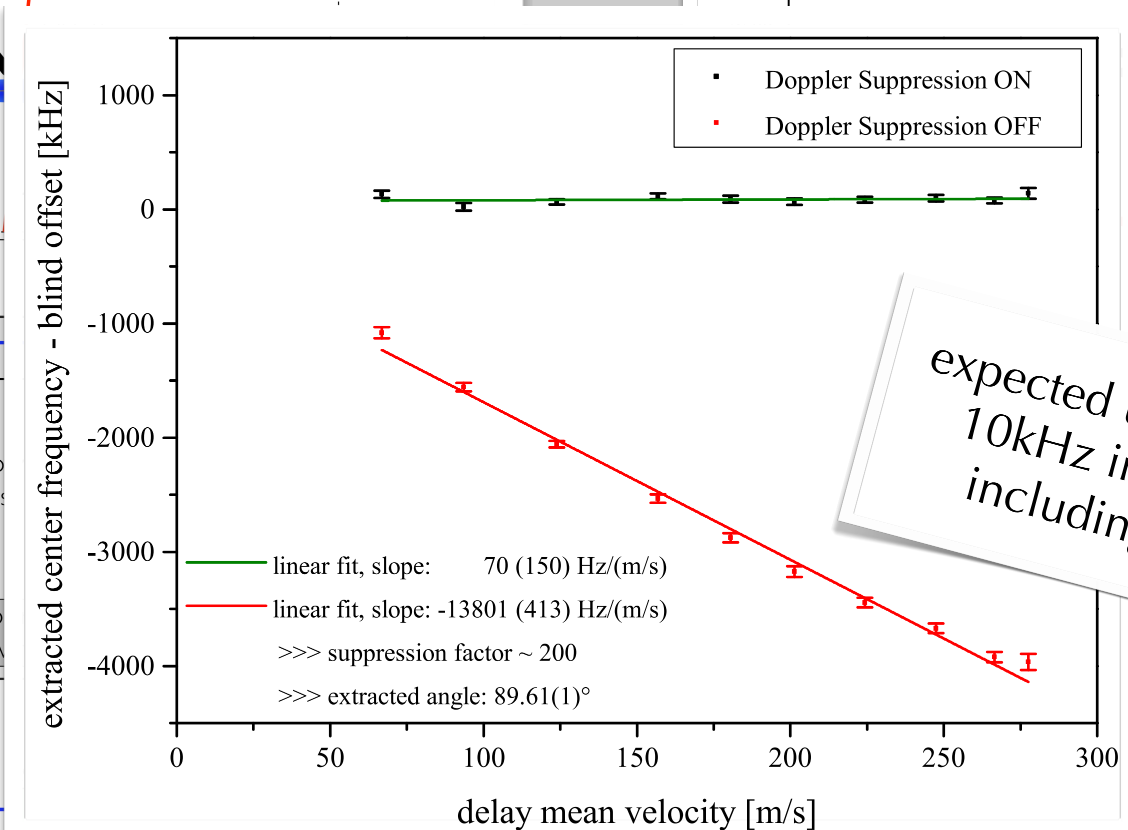
Optical Beam Path Upgrade

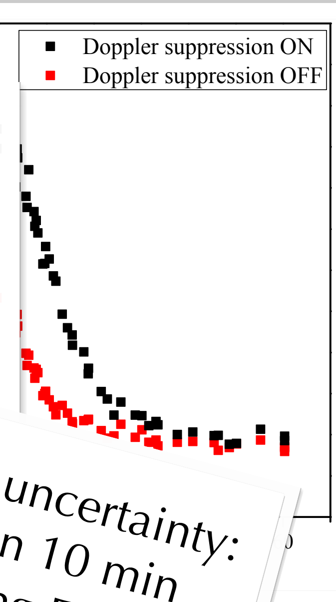




Optical Beam Path Upgrade

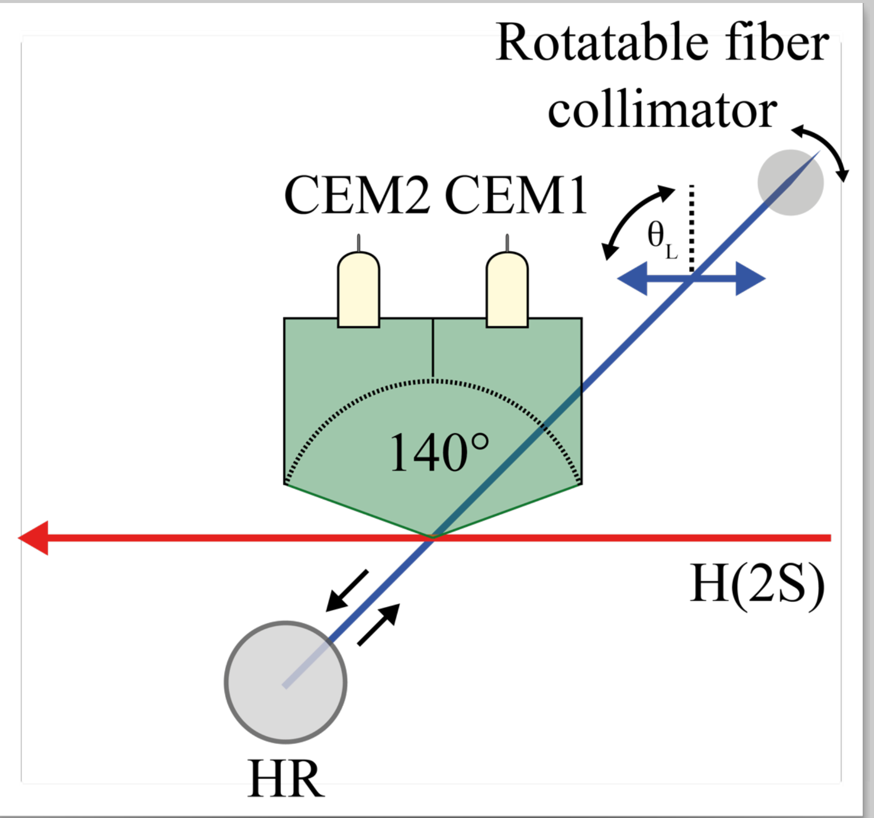


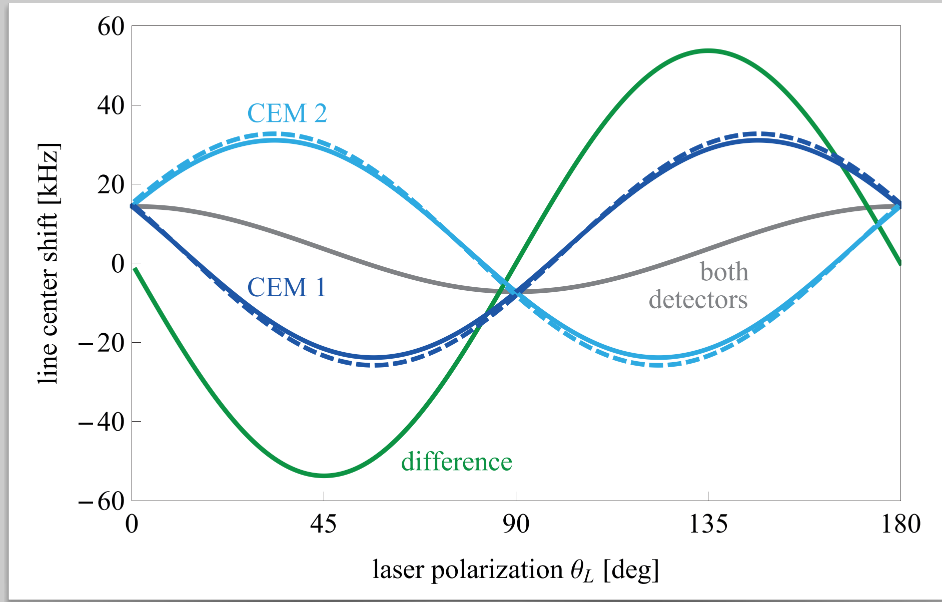




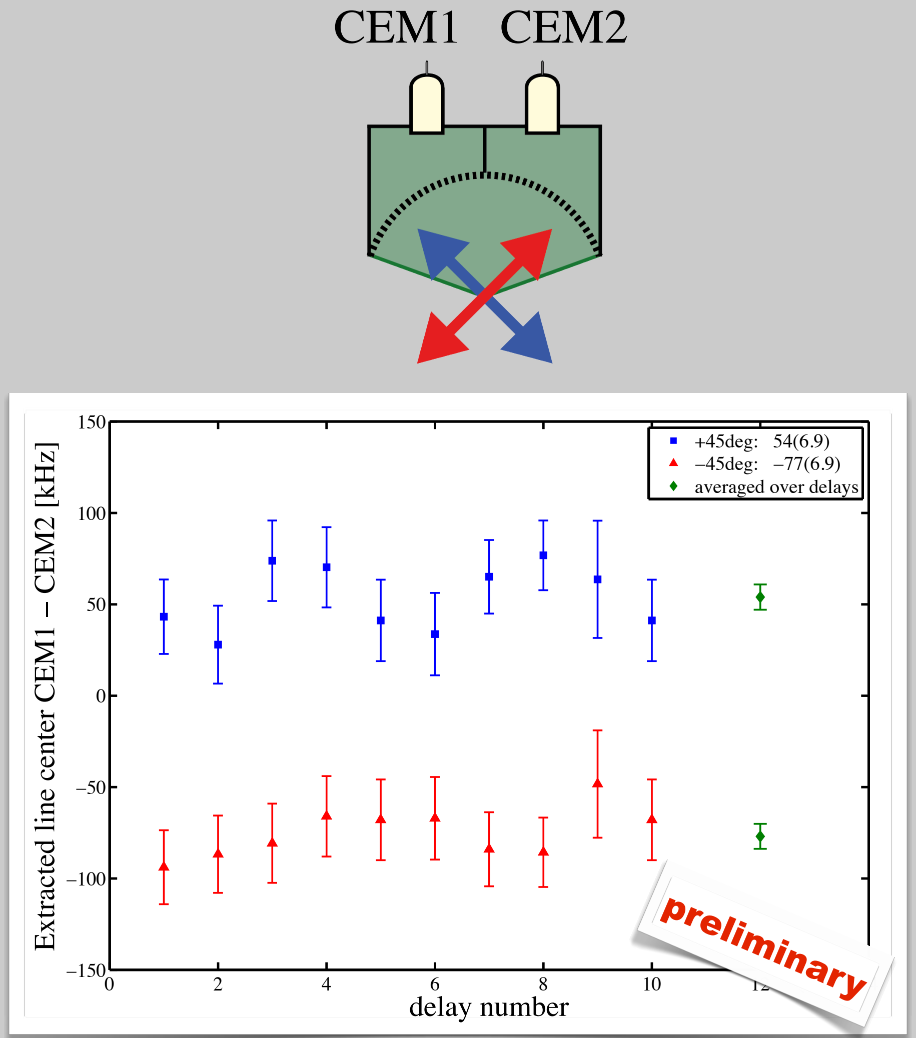
expected uncertainty:
10kHz in 10 min
including FOD

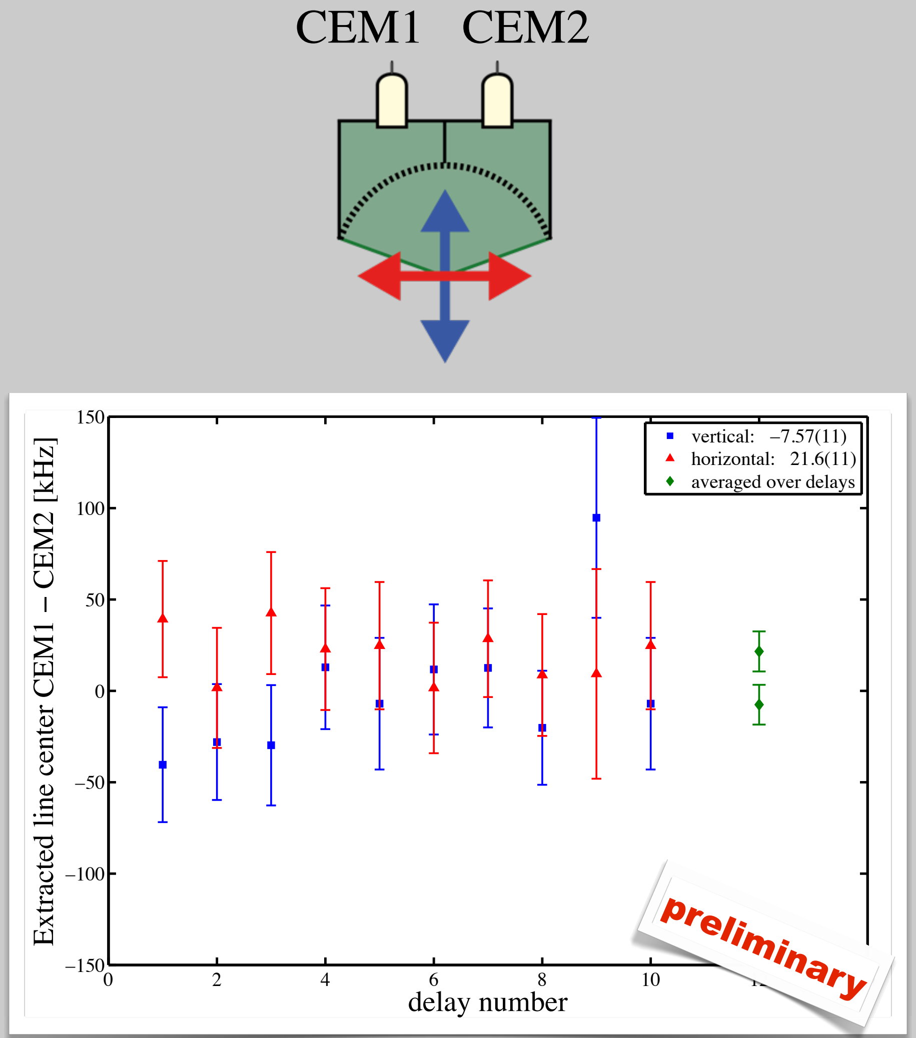
Detector Upgrade



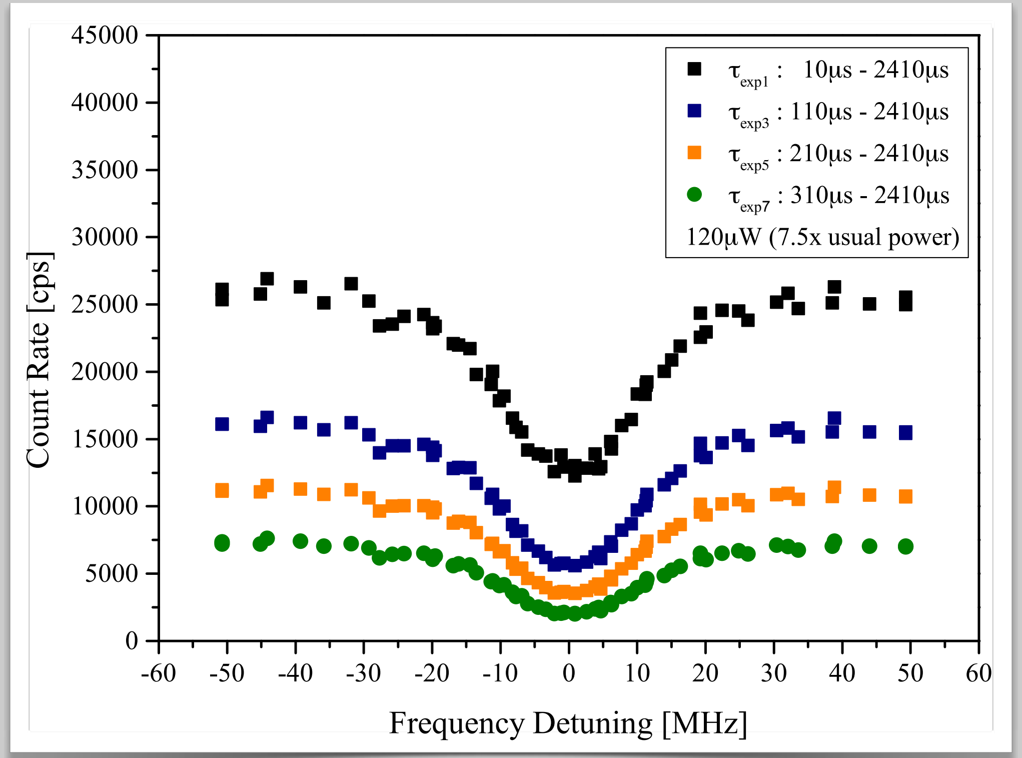


Detector Upgrade





Outlook: Lyman-α Detector

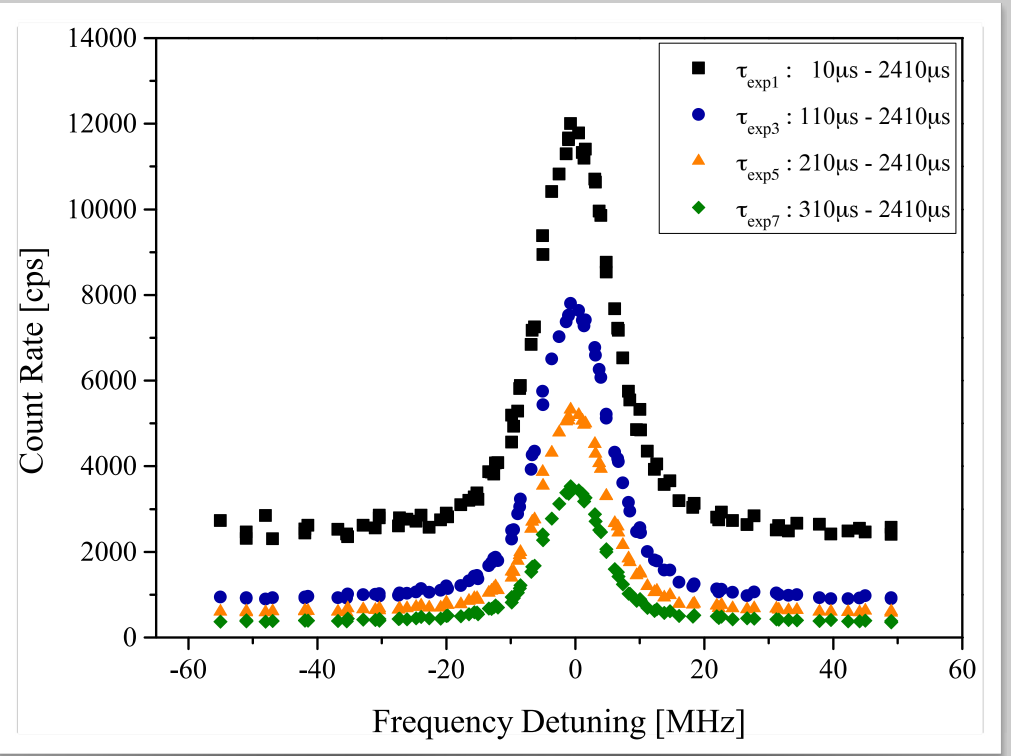


Lyman-α detector:

- monitor number of remaining 2S atoms after interaction
- intrinsically worse statistics
- ca. 2.5 times prolonged measurement time

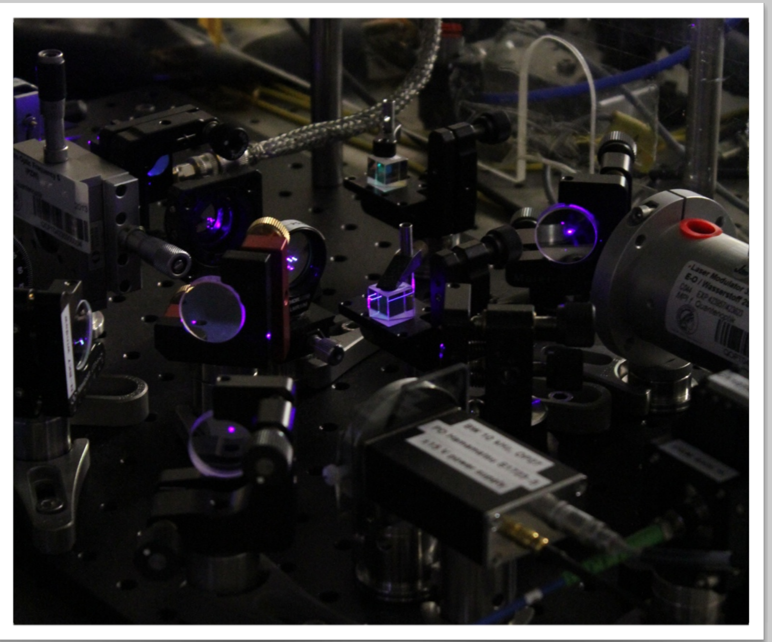
- but:
  - insensitive to interference effect
  - direct online measurement of 2S atom flux

Outlook: 2S-6P Transition

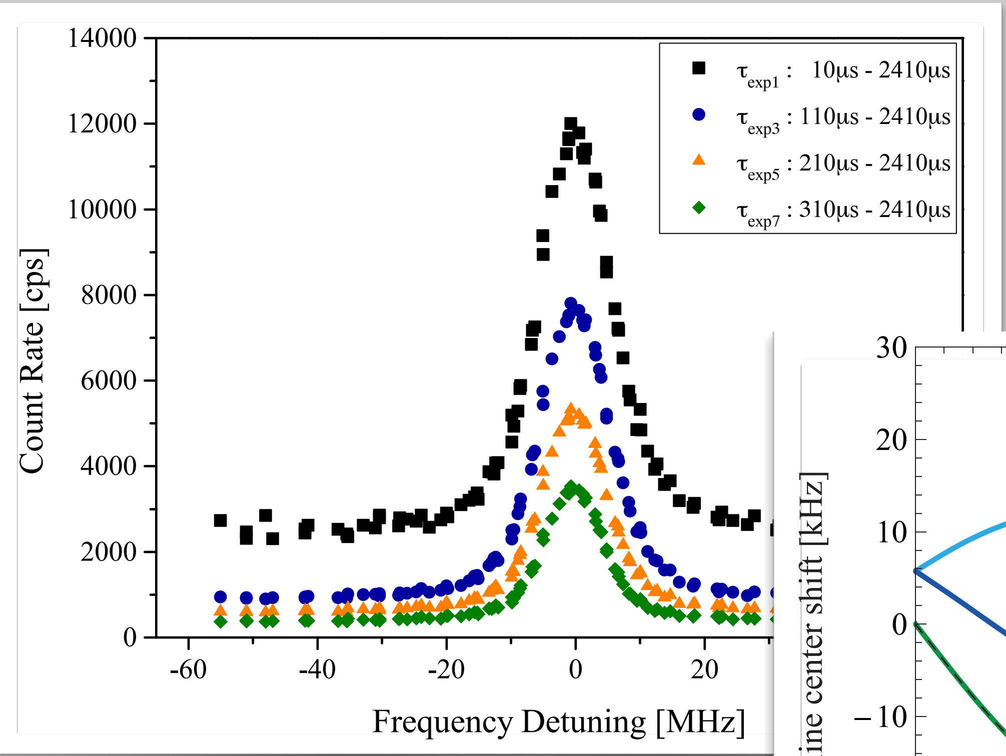


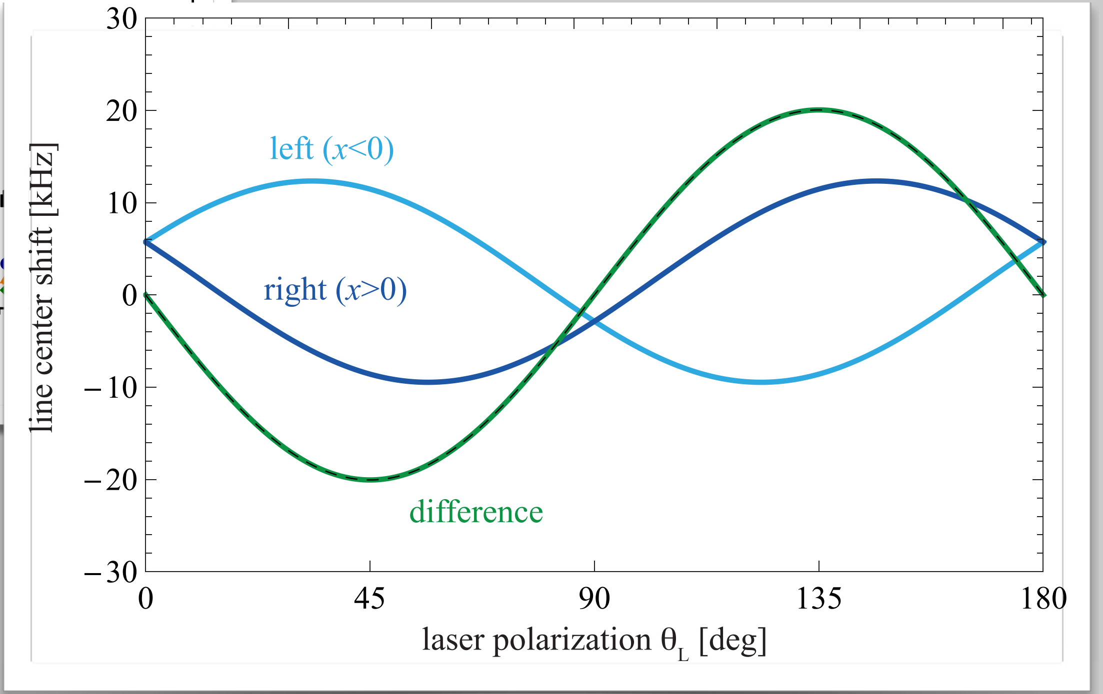
2S-6P transition @ 410nm:

1. study electric fields for 2S-4P
2. absolute freq. measurement



Outlook: 2S-6P Transition





2S-6P transition @ 410nm:

1. study electric fields for 2S-4P
2. absolute freq. measurement

Summary

- Precision spectroscopy of the 2S-4P transition on a cryogenic beam of optically excited 2S atoms
  - $2S\text{-}4P_{1/2}$ and $2S\text{-}4P_{3/2}$
  - 1.8kHz uncertainty for $2S\text{-}4P_{1/2}$ (statistics and FOD)
- good statistics essential to identify systematic effects on the order of the discrepancy between H and mup
- interference effect seems to be crucial for our contribution to the proton size puzzle

What's next?

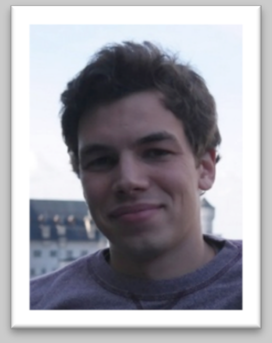
- further improve statistics by direct measurement of FOD
- characterization of interference effect in new detector configuration (exp. & theo.)
- characterization of the DC Stark effect by 2S-6P spectroscopy
- new measurements of the $2S\text{-}4P_{1/2}$ and $2S\text{-}4P_{3/2}$ transition frequency with upgraded system
- apply experimental scheme to higher 2S-*n*P transitions

  (*n* = 6, 8, 9,10)

Acknowledgment

K. Khabarova

R. Pohl



L. Maisenbacher

A. Matveev

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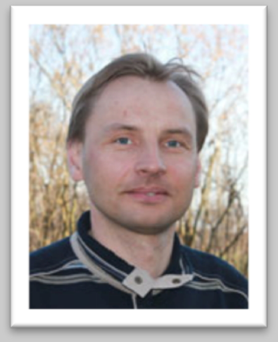
T. W. Hänsch



N. Kolachevsky


Thank you for your attention!