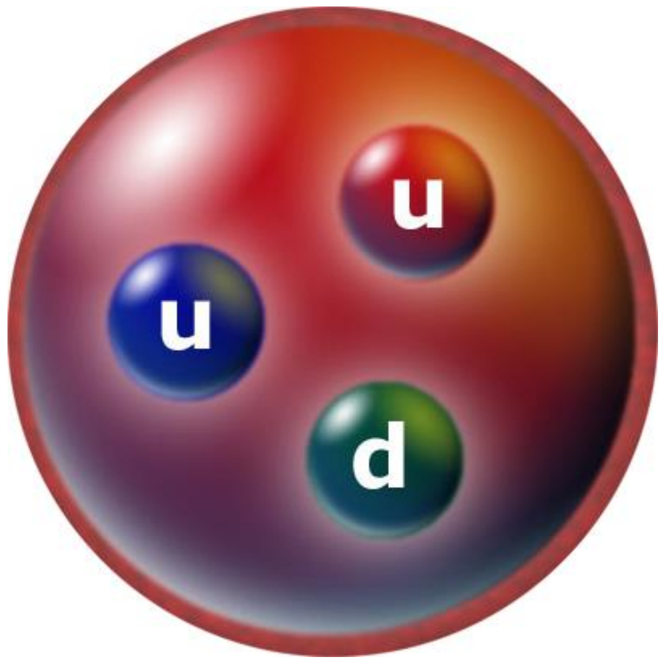
Precision spectroscopy of atomic hydrogen and the proton charge radius puzzle



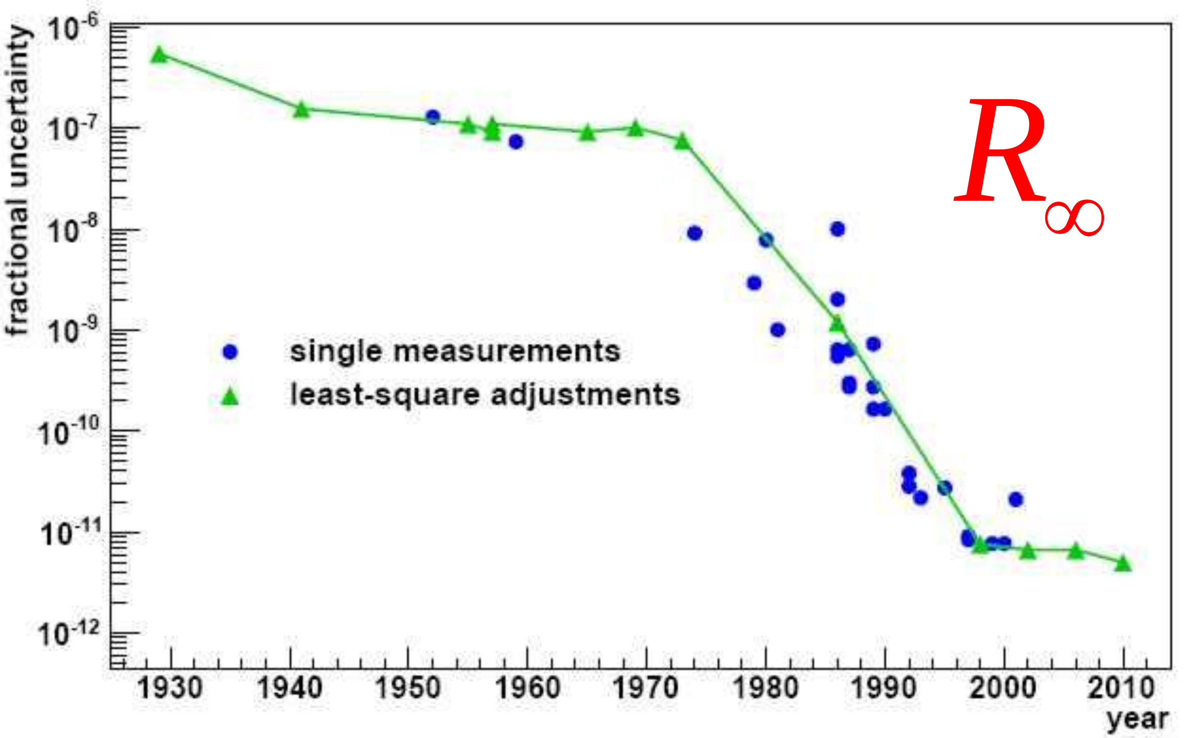
N. Kolachevsky

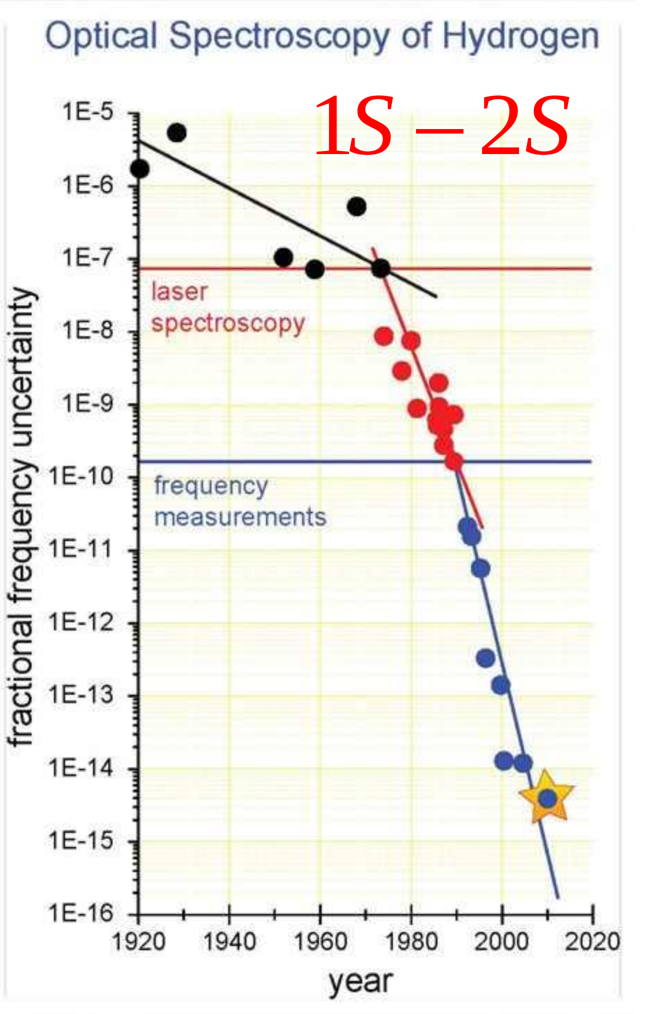
MPQ

MPQ

Why proton charge radius is so important?

- needed for accurate Rydberg constant determination





Hydrogen atomic levels

Schrödinger (atomic units):

$$E_{\mathrm{Bohr}} = -\frac{1}{n^2}$$

QED:

$$E_{\mathrm{QED}} = -\frac{1}{n^2} + \frac{3(2j+1) - 8n}{4(2j+1)n^4}\,\alpha^2 + \ldots$$

$$= -\frac{1}{n^2} + a_2\alpha^2 + a_4\alpha^4 + a_{50}\alpha^5 + a_{51}\alpha^5 ln(\alpha^{-2}) + \ldots$$

recoil:

$$+\frac{m_r}{2(M+m_e)}[f(n,j)-1]^2 + \frac{(Z\alpha)^4 m_r^2}{2n^3 M^2}\left[\frac{1}{j+1/2} - \frac{1}{l+1/2}\right](1-\delta_{l0})$$

nuclear size correction:

$$+\frac{2\pi(Z\alpha)}{3}\langle r_p^2\rangle|\psi(0)|^2$$

Fundamental constants

$$E_n = R_\infty \, F\left(\alpha,\ m_e/M\,,\ \langle r_p^2 \rangle\right)$$

Relative uncertainties:

$$\alpha : \quad 3\times10^{-10}$$

$$m_e/M : \quad 4\times10^{-10}$$

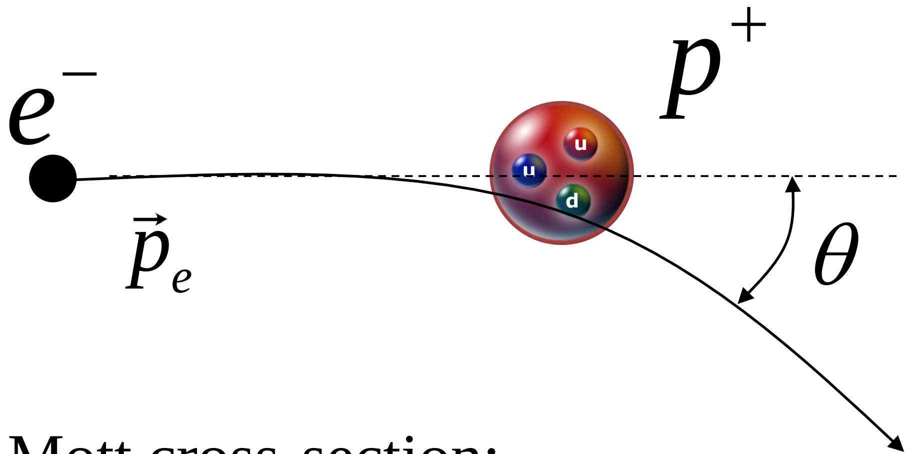
Do not contribute (small corrections!)

$$\langle r_p^2 \rangle : \quad 1\%$$

Leading uncertainty!

L_{1S}	self-energy	vacuum pol.	r_p	total
e p	8 383 MHz	-215 MHz	1.253(50) MHz	8 172 MHz

Method 1: Electron scattering



Measured value $\dfrac{d\sigma}{d\Omega}$

Mott cross-section:

Transferred momentum

$$\left.\frac{d\sigma}{d\Omega}\right|_{\text{point}} = \frac{\alpha^2}{4p_e^2 \sin^4\frac{\theta}{2}}\left(\cos^2\frac{\theta}{2} - \frac{q^2}{2m_p^2}\sin^2\frac{\theta}{2}\right)$$

Non point-like proton:

$$\frac{d\sigma}{d\Omega} = \left.\frac{d\sigma}{d\Omega}\right|_{\text{point}} |F(q^2)|^2$$

form-factor

For small q

$$F(0) = 1$$

impact parameter >> proton size

Form-factor and charge radius

Form-factor is the Fourier transformation of the charge distribution

$$F(q^2) = \int \rho(\vec{x}) e^{i\vec{q}\cdot\vec{x}} d^3x$$

Mean proton charge radius

$$\rho(r) = \rho_0 e^{-r/r_0}, \qquad r_0 \approx 0.8 \text{ fm}$$

Since proton possesses anomalous magnetic moment :

$$\frac{d\sigma}{d\Omega} = \frac{\alpha^2}{4E_1^2 \sin^4\frac{\theta}{2}} \frac{E_3}{E_1} \left\{ \left(F_1^2 - \frac{\kappa_p^2 q^2}{4m_p^2} F_2^2 \right) \cos^2\frac{\theta}{2} - \frac{q^2}{2m_p^2} (F_1 + \kappa_p F_2)^2 \sin^2\frac{\theta}{2} \right\}$$

F_1 – "Dirac" charge form-factor

F_2 – "Anomalous" magnetic form-factor

$$\mu_p = \frac{(1+\kappa_p)e}{2m_p}$$

$$\kappa_p = 1.79$$

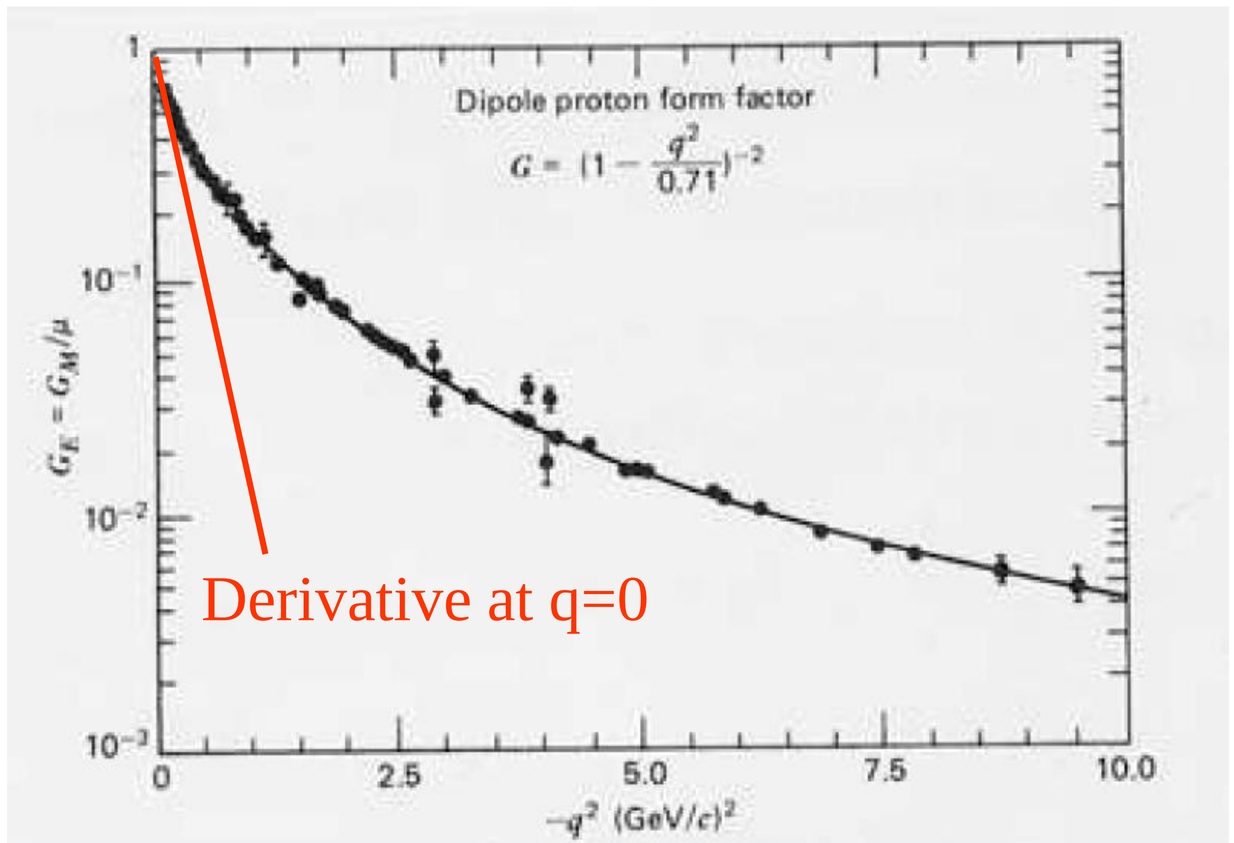
Electric and magnetic form-factors

$$G_E = F_1 + \frac{\kappa q^2}{4m_p^2} F_2 \qquad G_M = F_1 + \kappa F_2$$

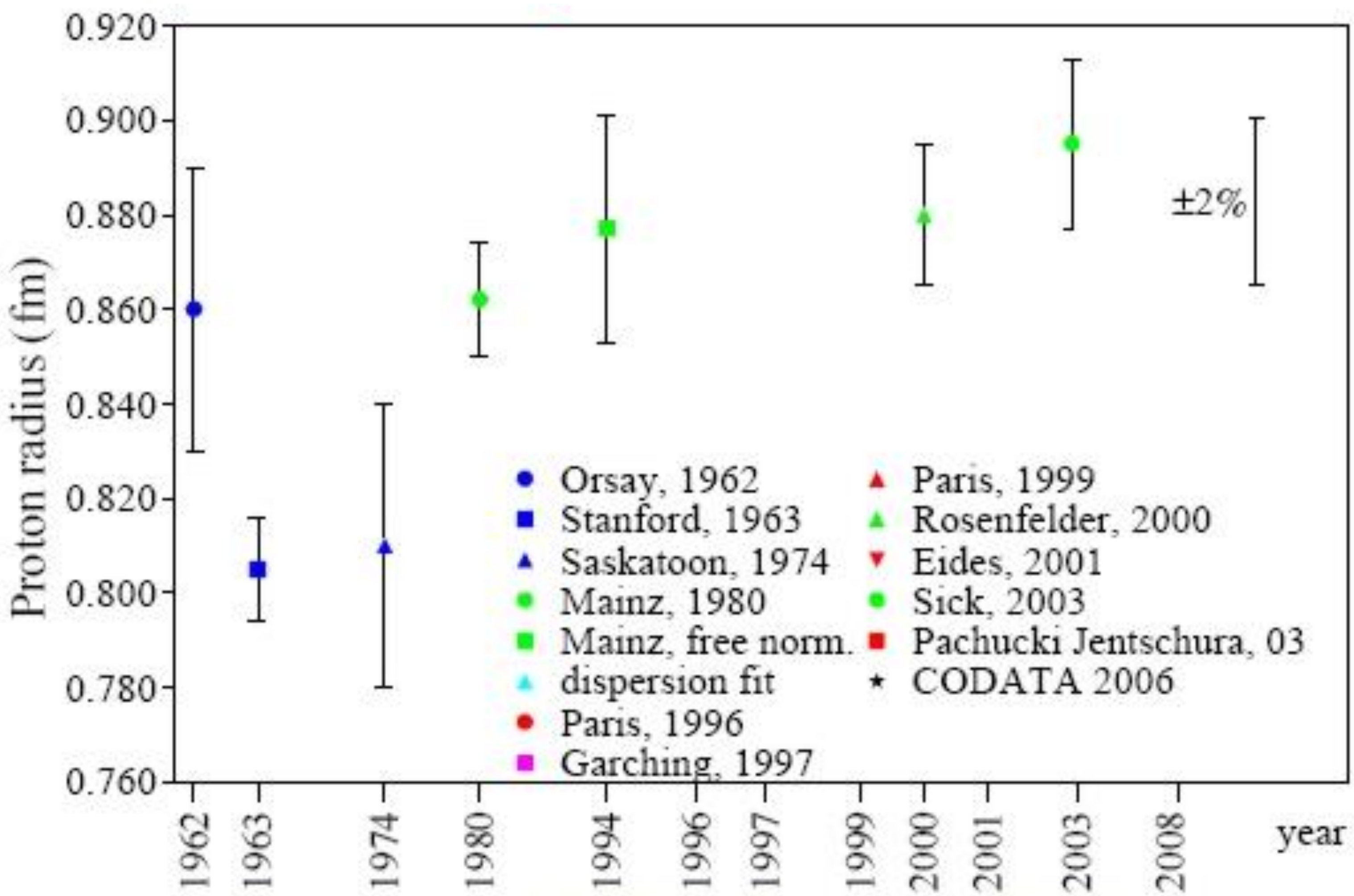
Electric

Magnetic

$$\left\langle r_p^2 \right\rangle = -6\hbar^2 \frac{dG_E^2(q^2)}{dq^2}\bigg|_{Q=0}$$



e-p scattering results



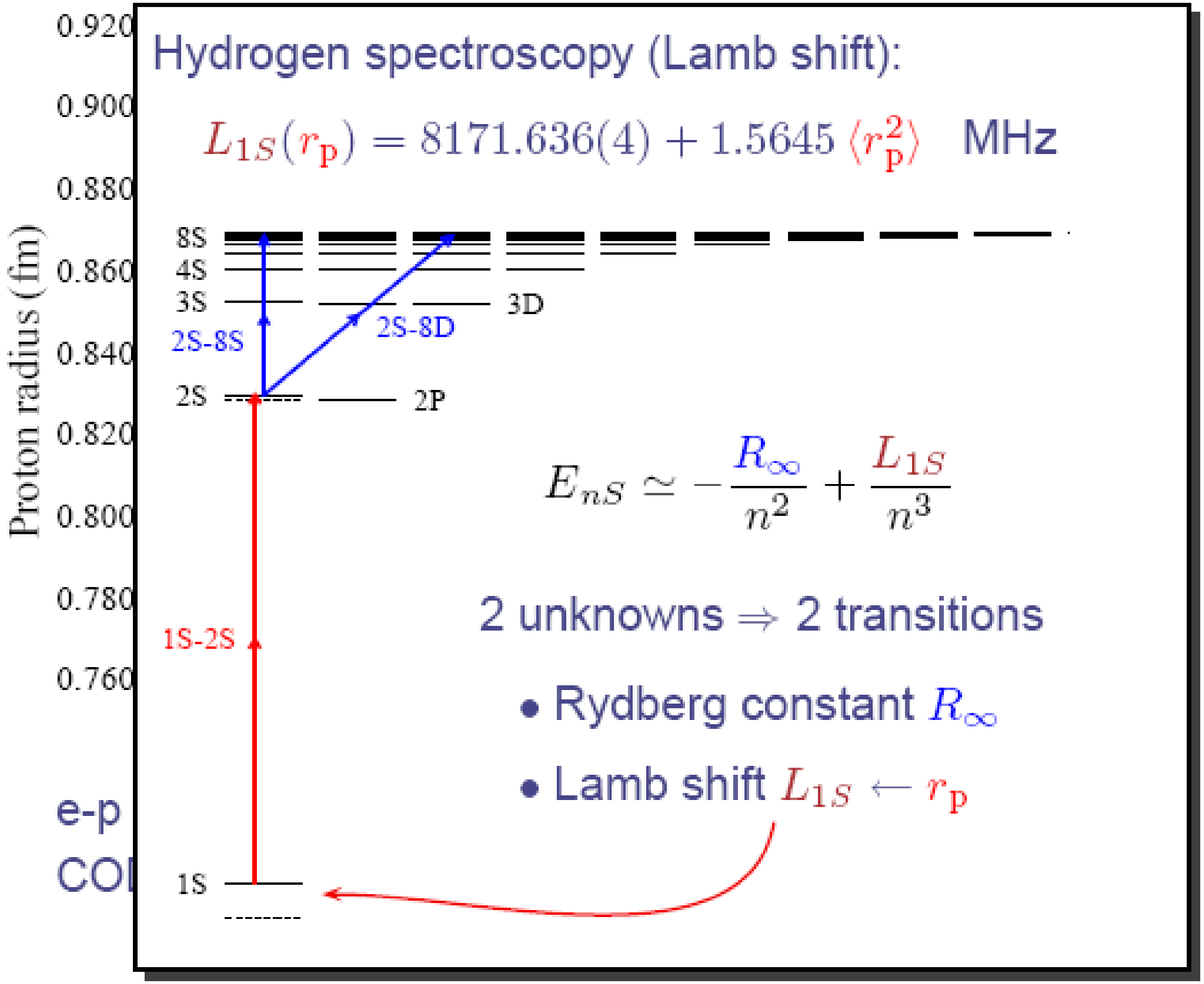
e-p scattering: r_p = 0.895(18) fm $(u_r = 2\,\%)$

Hydrogen spectroscopy

$$E_n = R_\infty \, F\left(\alpha,\ m_e/M\,,\ \langle r_p^2 \rangle\right)$$

Two unknowns $\Rightarrow$

Two equations necessary!



Hydrogen spectroscopy: limitations

Precision spectroscopy in H:

- ALL levels except 2S promptly decay

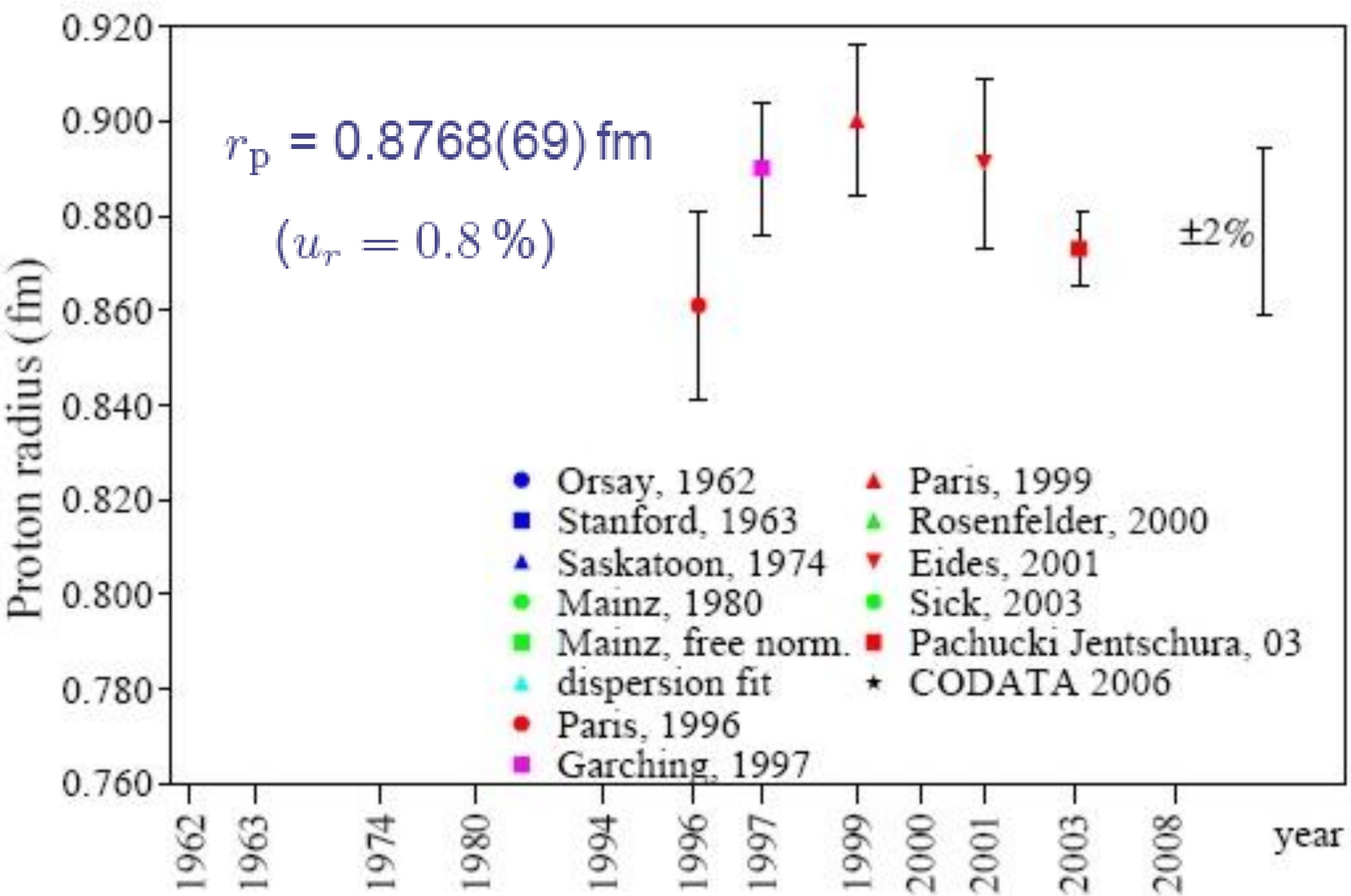
$$\gamma\left(3S\right) \sim \gamma\left(3P\right) \sim \gamma(4P) \sim 10\ \text{MHz}$$

- Natural linewidth of Rydberg states reduces, but they become sensitive to electric fields (Stark effect)

$$\Delta E_{DC} \sim n^{7}$$

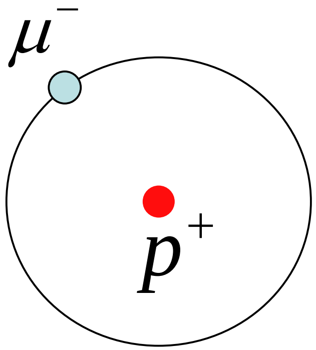
Scattered electric field at the level of 1V/m is hard to control!

Hydrogen spectroscopy: results



Dominating uncertainty results from spectroscopy of higher excited states (not 2S)

Muonic hydrogen μp



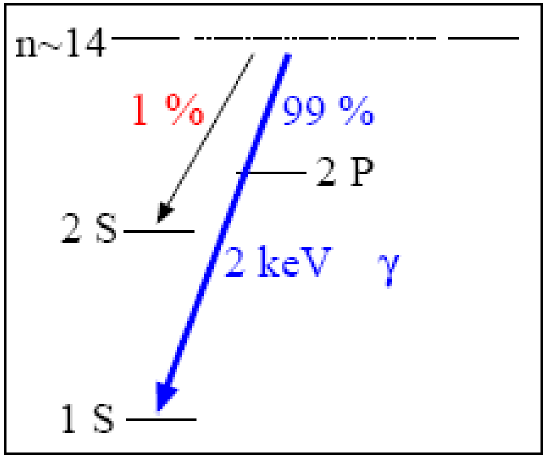
$m_\mu / m_e \approx 200$

		Hydrogen	Muonic hydrogen
Bohr radius	$\hbar / mc\alpha$	50 pm	0.25 pm
Lyman-α	$3mc^2\alpha^2/8$	121 nm (10 eV)	2 keV

L_{2S}	self-energy	vacuum pol.	r_p	total
e p	1 085 MHz	-27 MHz	0.14 MHz	1 057 MHz
μ p	0.1 THz	-45 THz	0.93 THz	-49 THz

Spectroscopy of 2S-2P transition in μp

"prompt" ($t \sim 0$)



μ^- stop in H_2 gas
$\Rightarrow$ μp* atoms formed ($n \sim 14$)

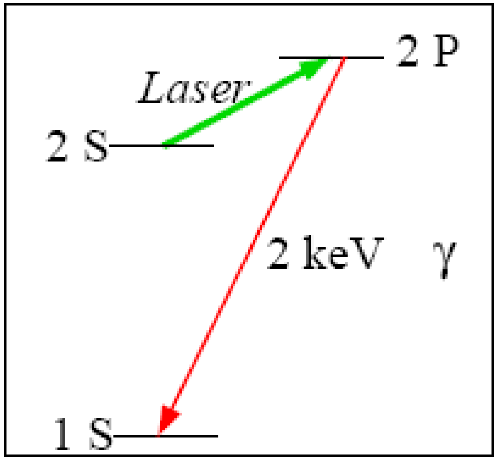
99%: cascade to μp(1S),
emitting prompt K_α, K_β ...

1%: long-lived μp(2S) atoms

lifetime $\tau_{2S} \approx 1\,\mu$s at 1 mbar H_2

R. Pohl et. al., Phys. Rev. Lett. 97, 193402 (2006).

"delayed" ($t \sim 1\,\mu$s)

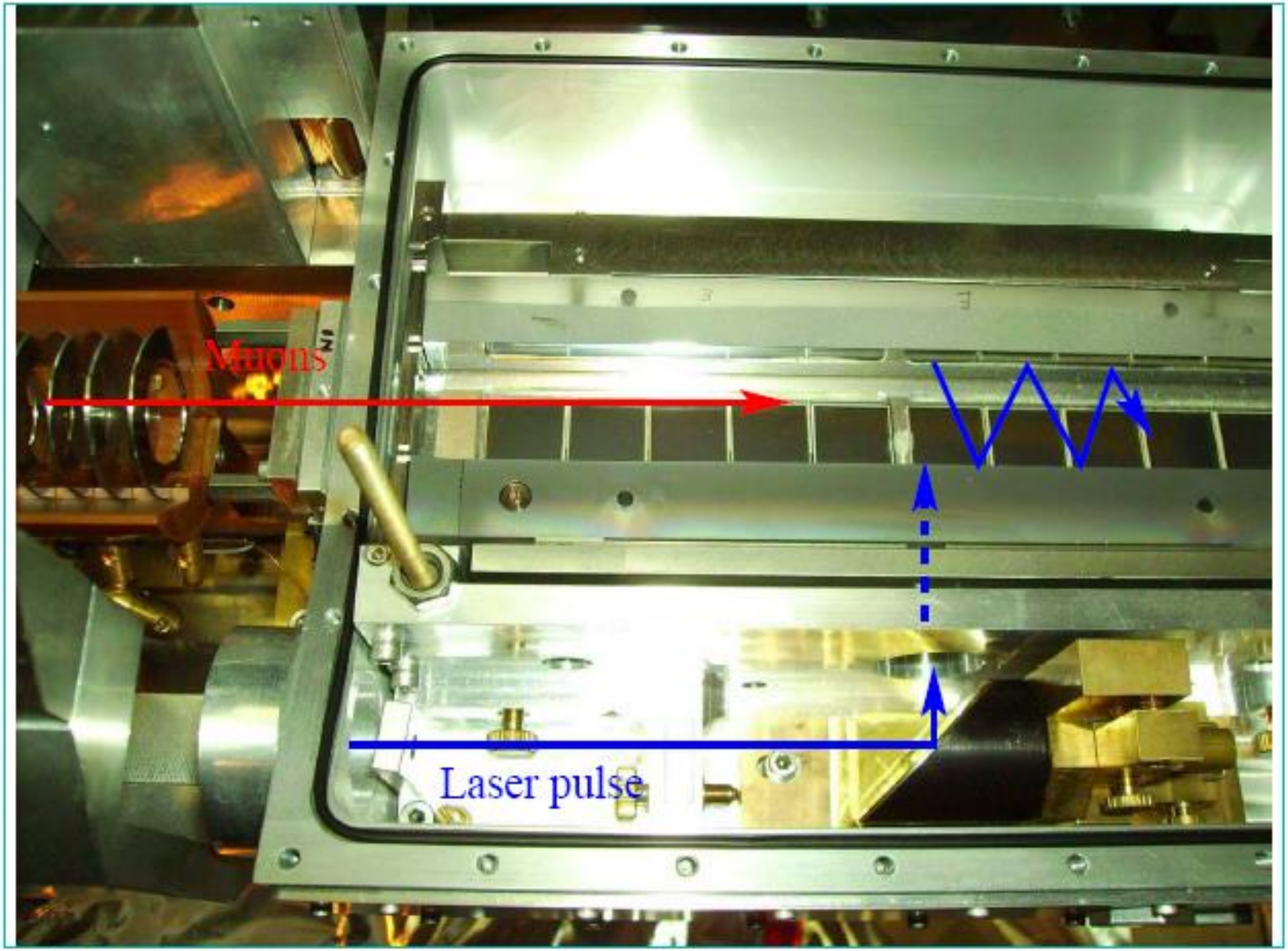


fire laser ($\lambda \approx 6\,\mu$m, $\Delta E \approx 0.2$ eV)

$\Rightarrow$ induce μp(2S) $\rightarrow$ μp(2P)

Transition line width 10 GHz
Goal – uncertainty of 1 GHz
(1999)

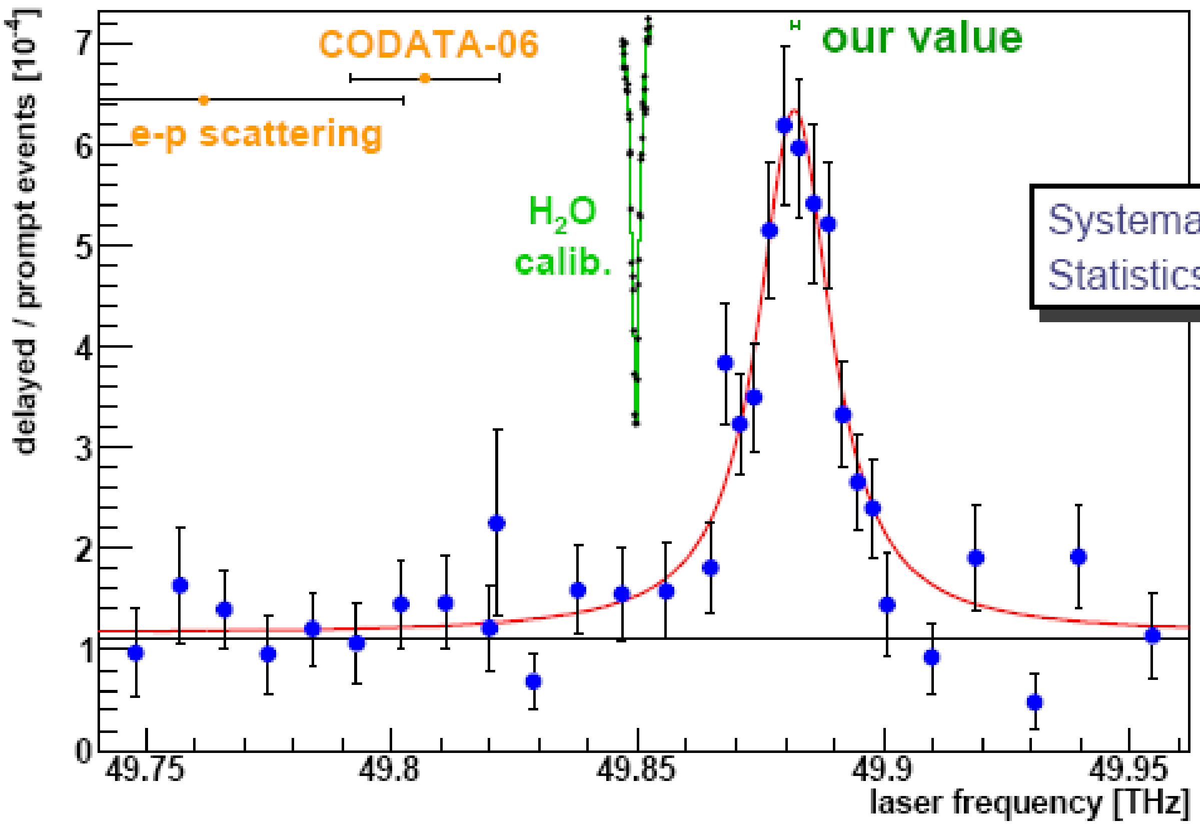
Target (H_2)



Resonance line 2S-2P in μp

Water-line/laser wavelength:
300 MHz uncertainty

$\Delta\nu$ water-line to resonance:
200 kHz uncertainty



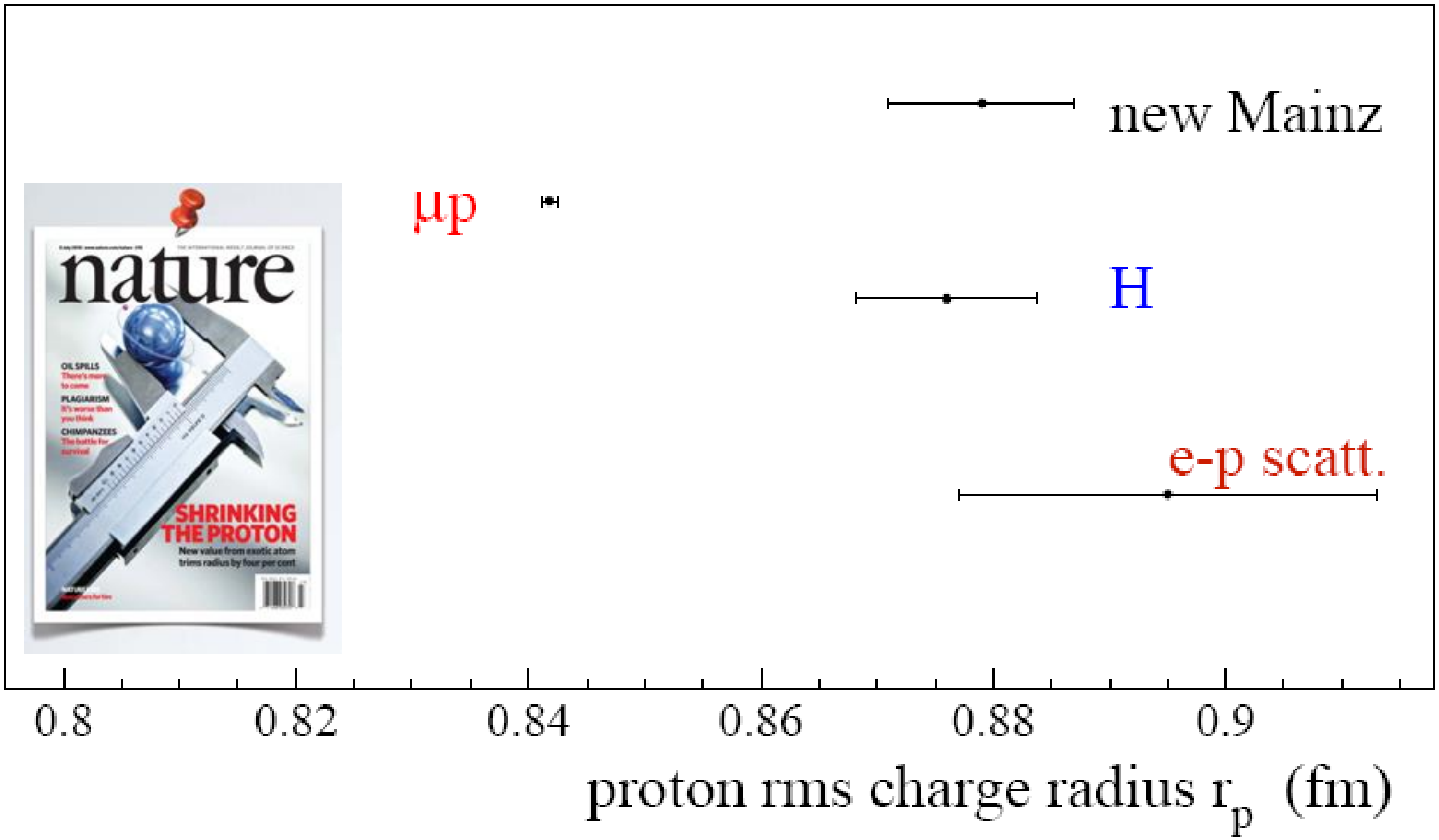
Systematics: 300 MHz
Statistics: 700 MHz

Discrepancy:
$5.0\,\sigma \leftrightarrow 75\ \mathrm{GHz} \leftrightarrow \delta\nu/\nu = 1.5\times 10^{-3}$

R. Pohl *et al.*, Nature 466, 213 (2010).

Proton radius 2010

$r_p = 0.84184\,(36)_{exp}(56)_{theo}$ fm



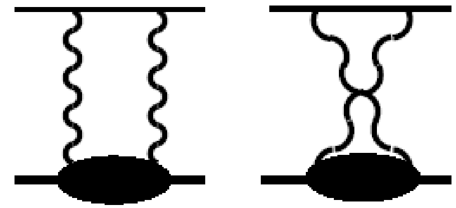
R. Pohl *et al.*, Nature 466, 213 (2010).

Where the problem resides ?!

-Errors in QED calculations are excluded at such level of discrepancy

“New” physics?

proton polarizability aka. two-photon exchange



Seems to be the only contribution which *might* be able to solve the proton size puzzle by changing theory in μp.

Keep in mind:

Discrepancy: 0.31 meV

Polarizability: 0.015(4) meV   20 times smaller!

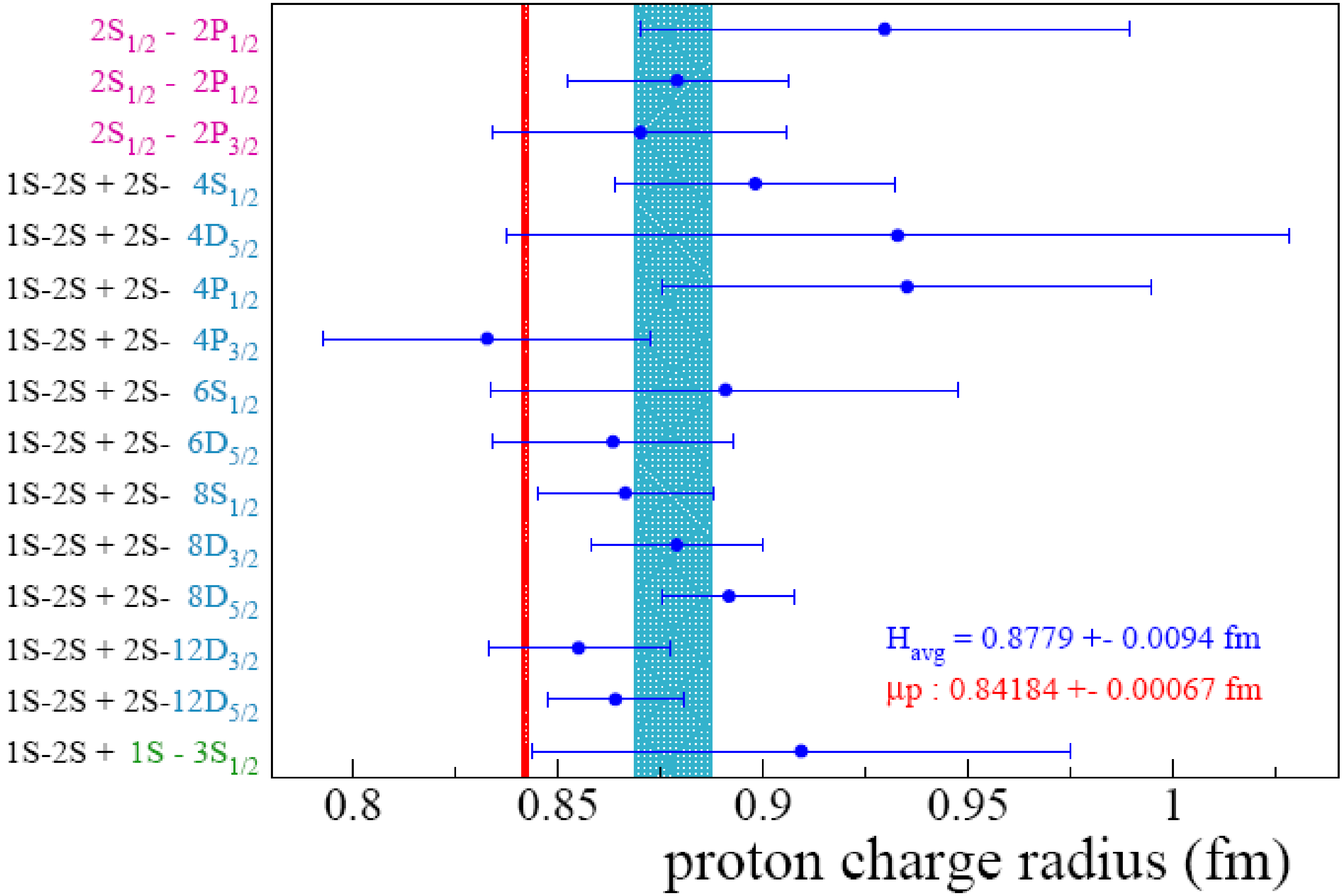
Are

- e-p scatteing experiments

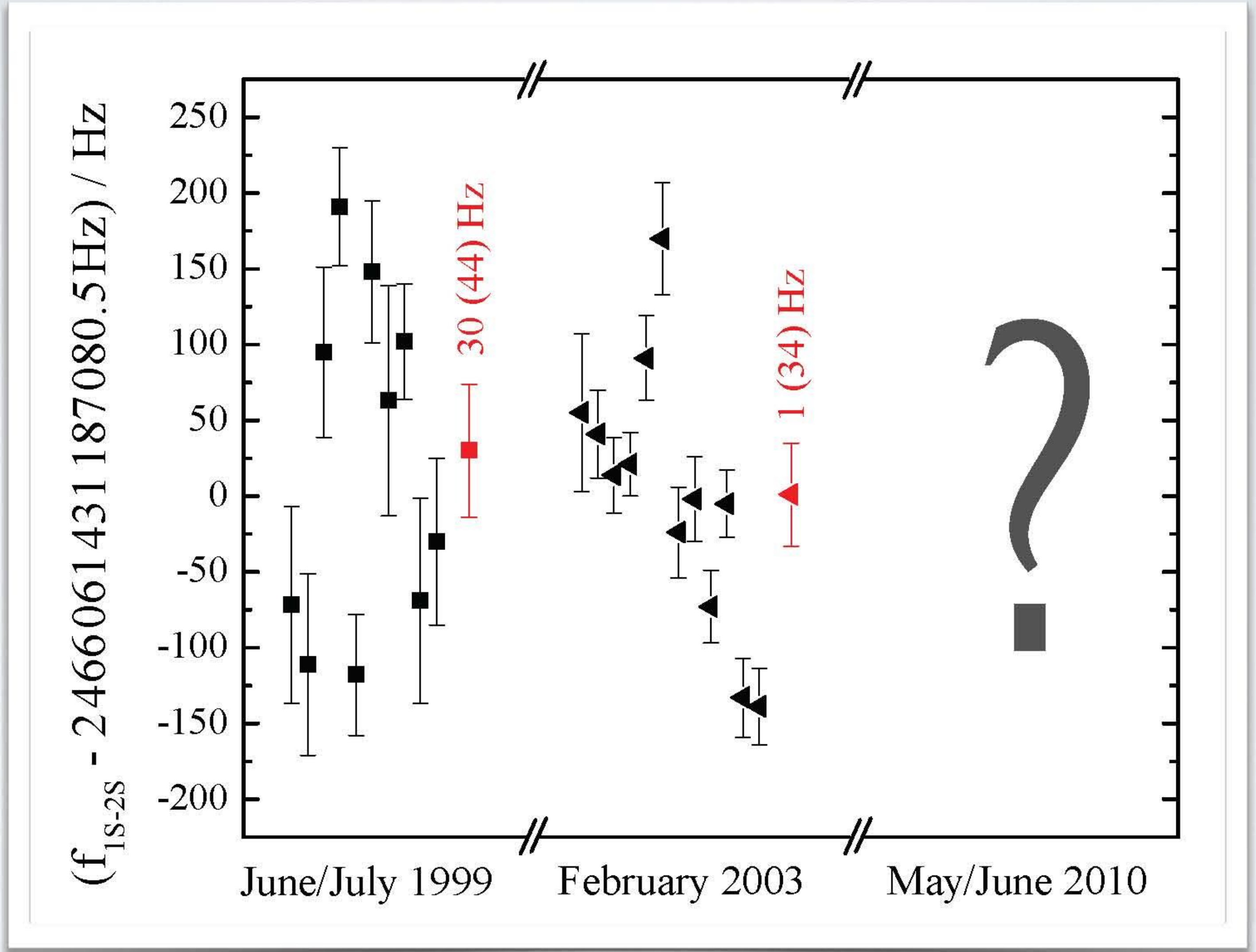
- H spectroscopy results

flawless?

Hydrogen spectroscopy



Measurements of the 1S-2S transition



Fischer et. al, Phys. Rev. Lett. **92**, 230802 (2004)

The Team

Hydrogen

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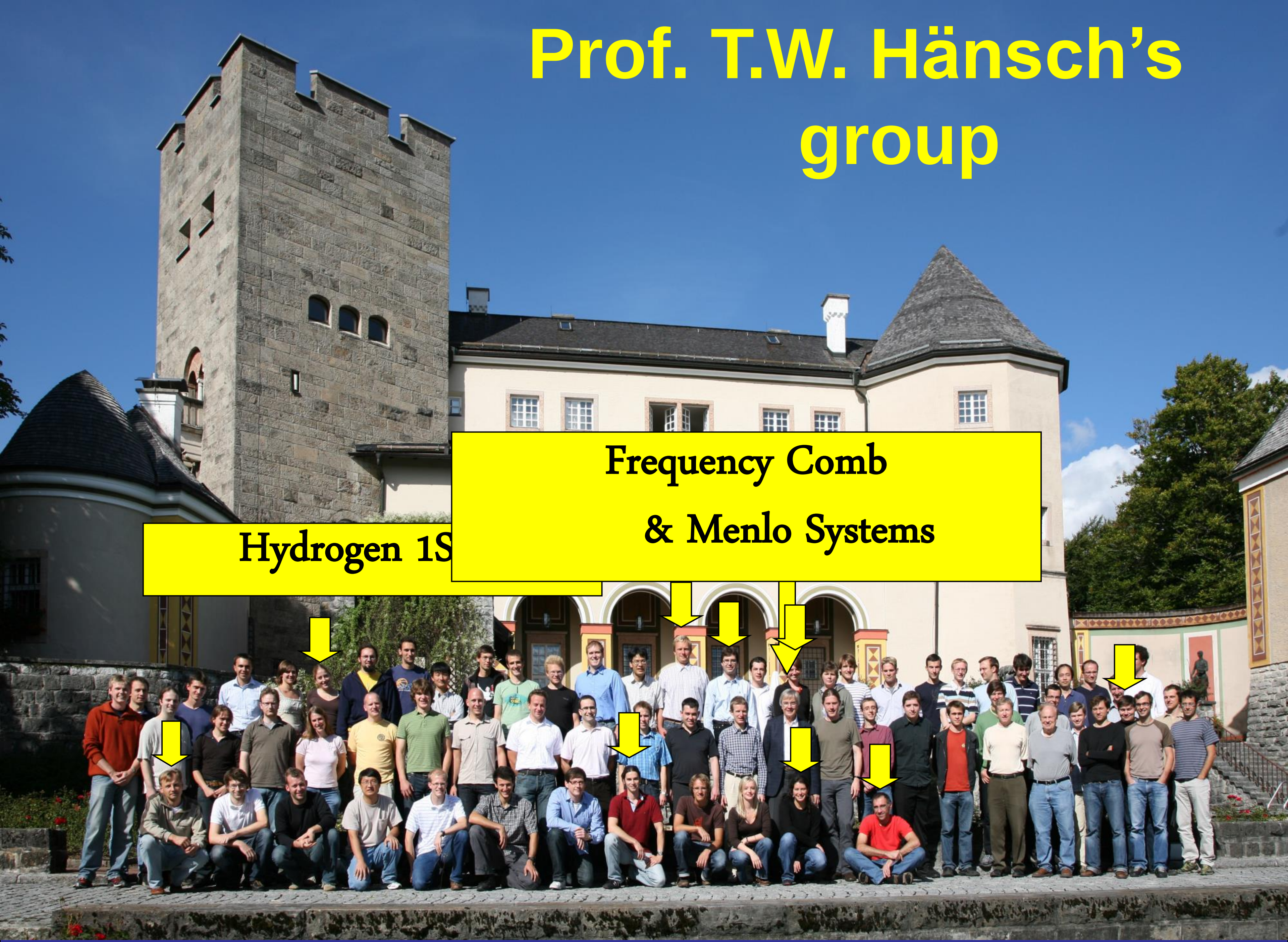

The team 2009-

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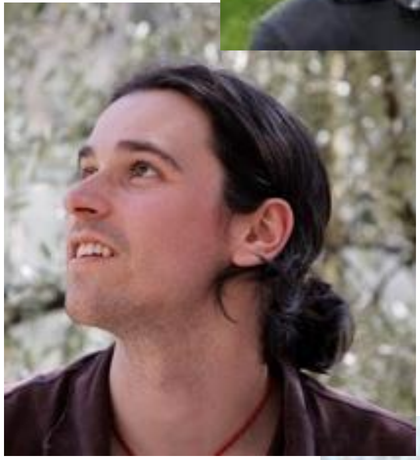
T.W. Hänsch



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Th. Udem

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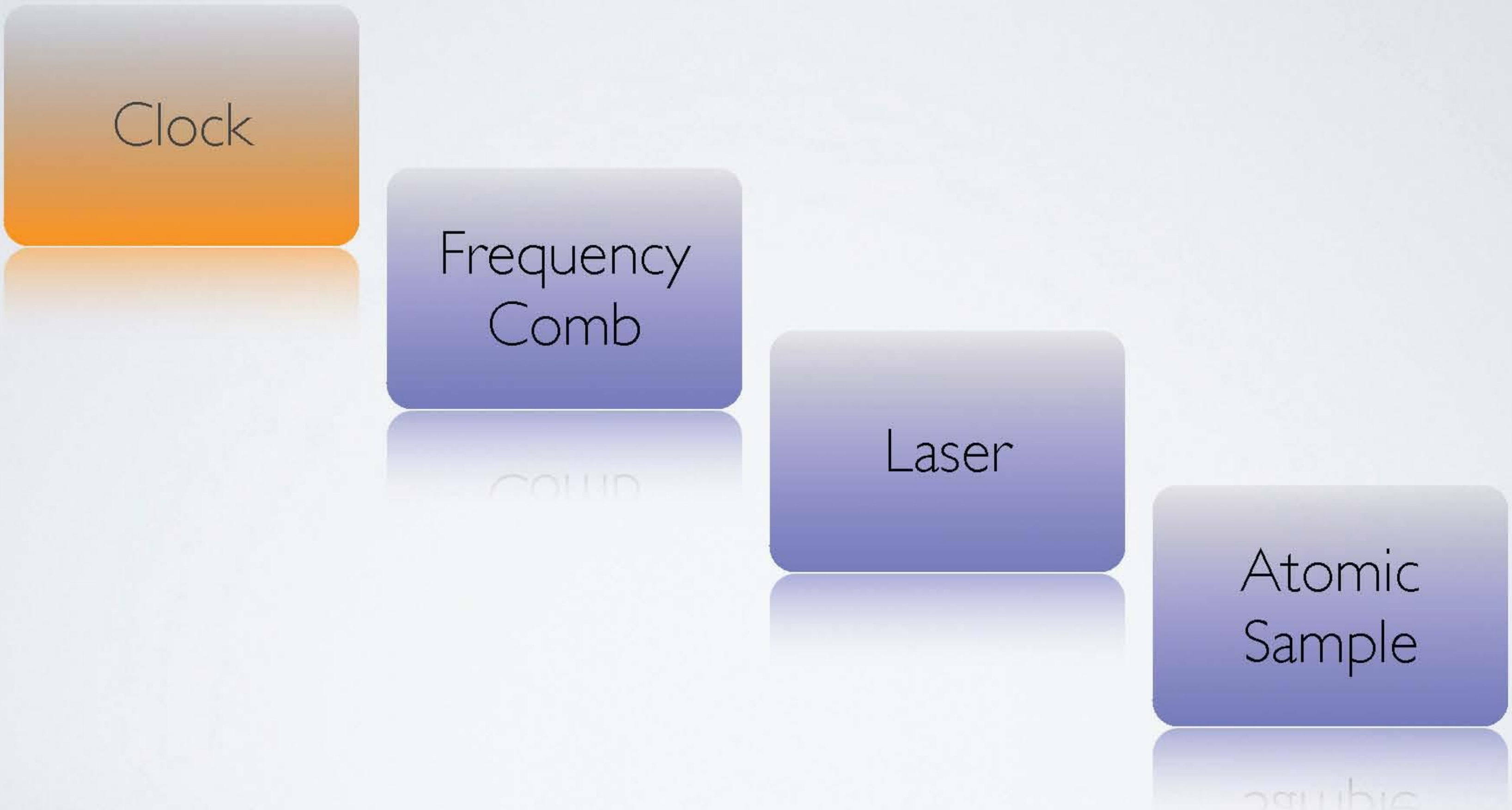
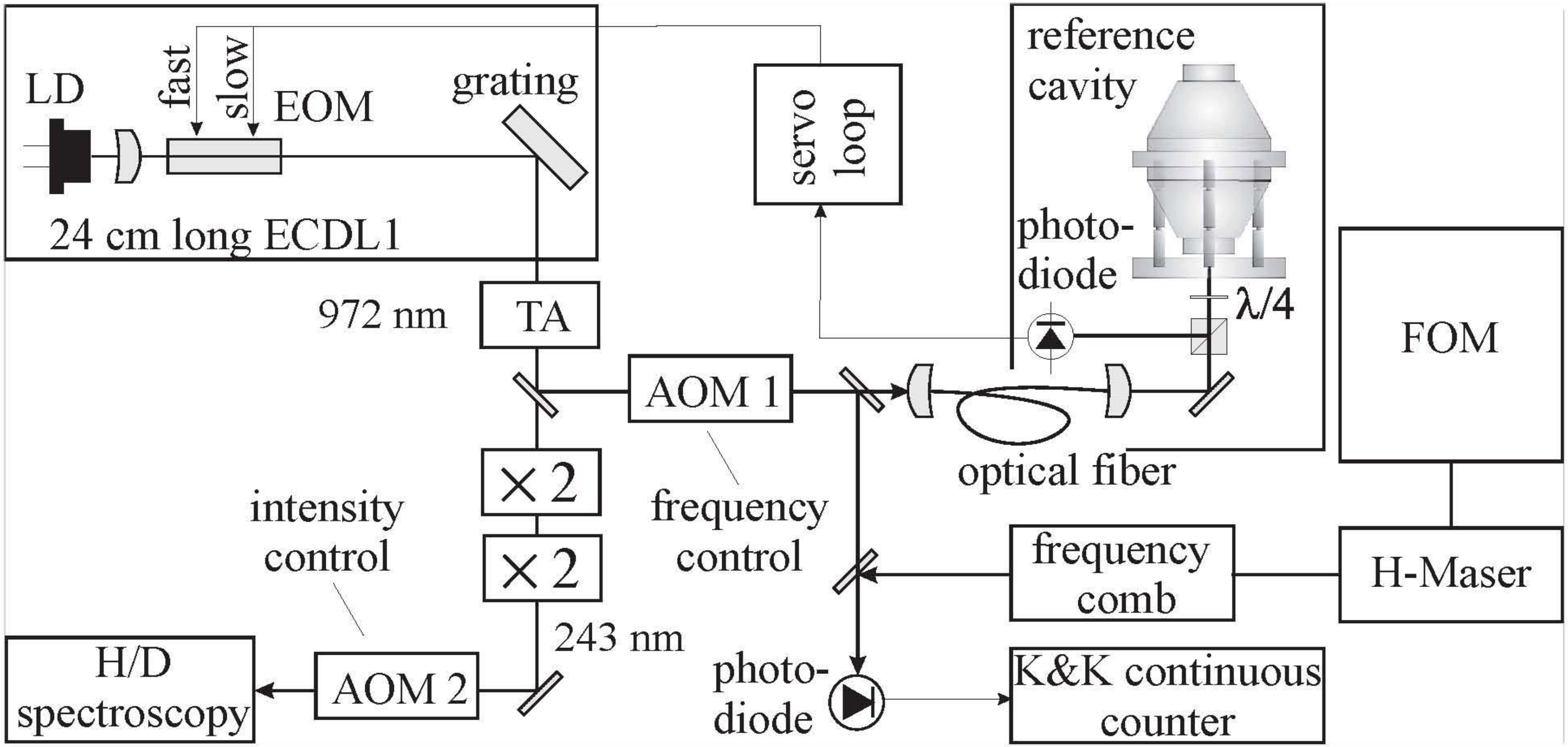
Experiment Overview

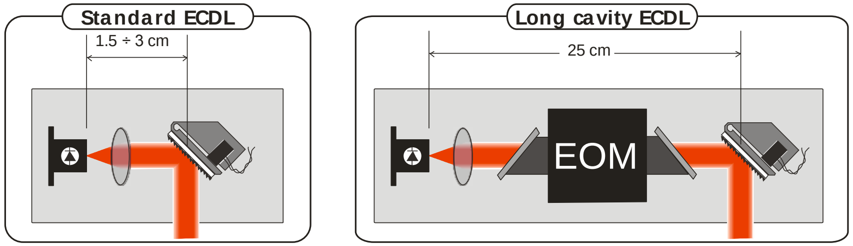


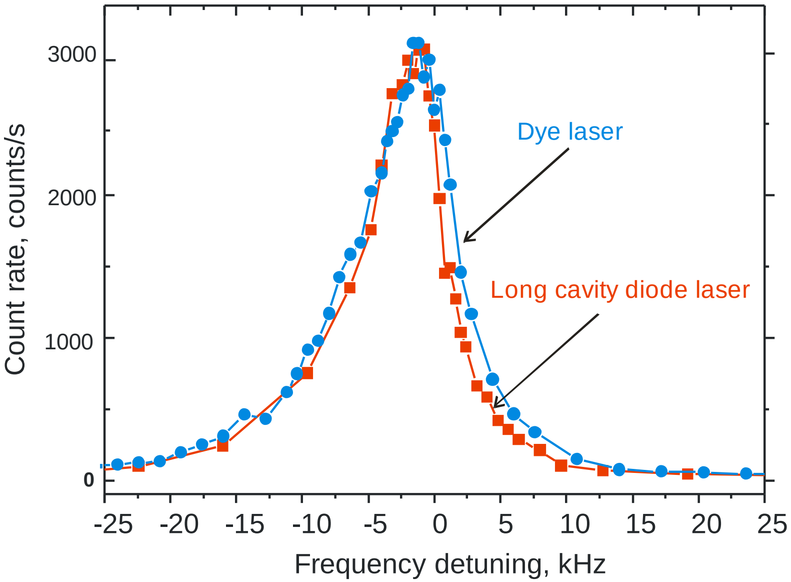
Setup



N. Kolachevsky et al., Opt. Lett. 36, 4299 (2011)

Master oscillator

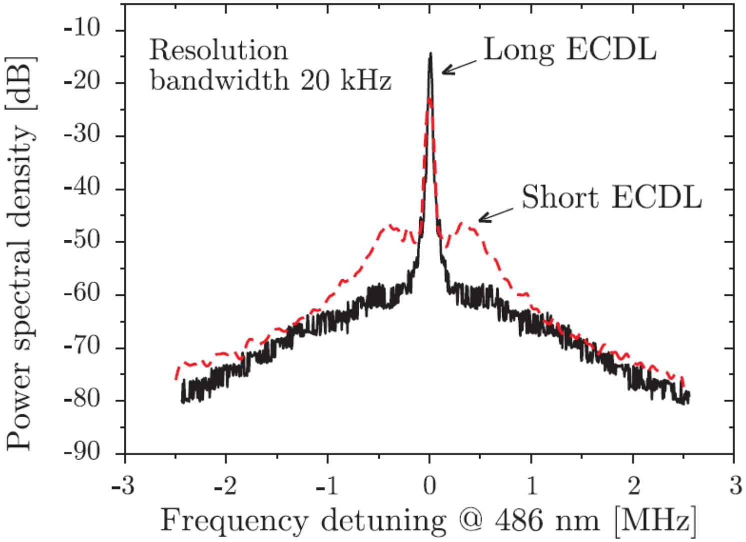




$$\eta = \exp\left(-\varphi_{rms}^2\right)$$ **at 972 nm**

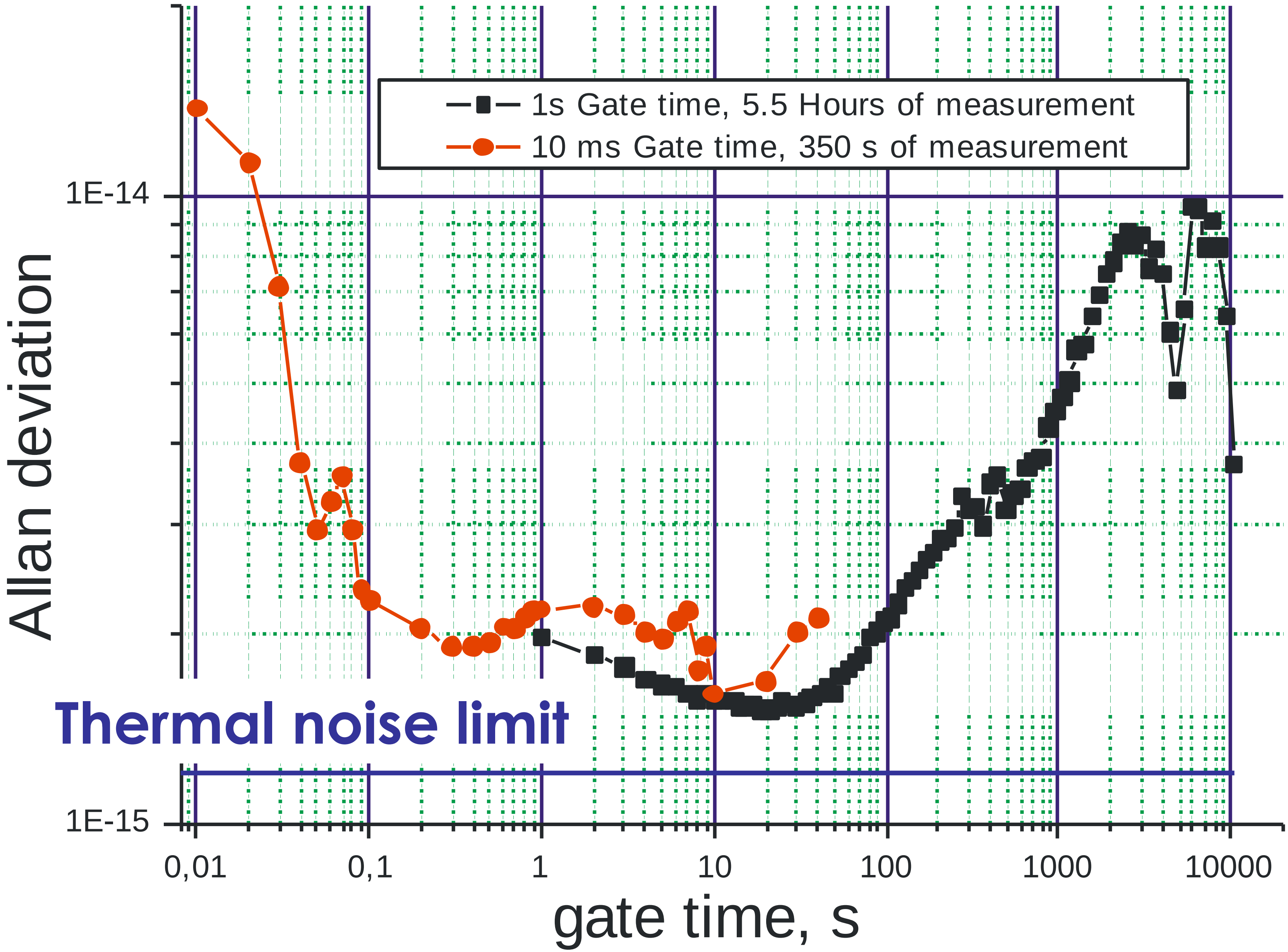
8-photon process => $\eta_{eff} = \eta_{IR}^{64}$

Beat note diode - dye laser

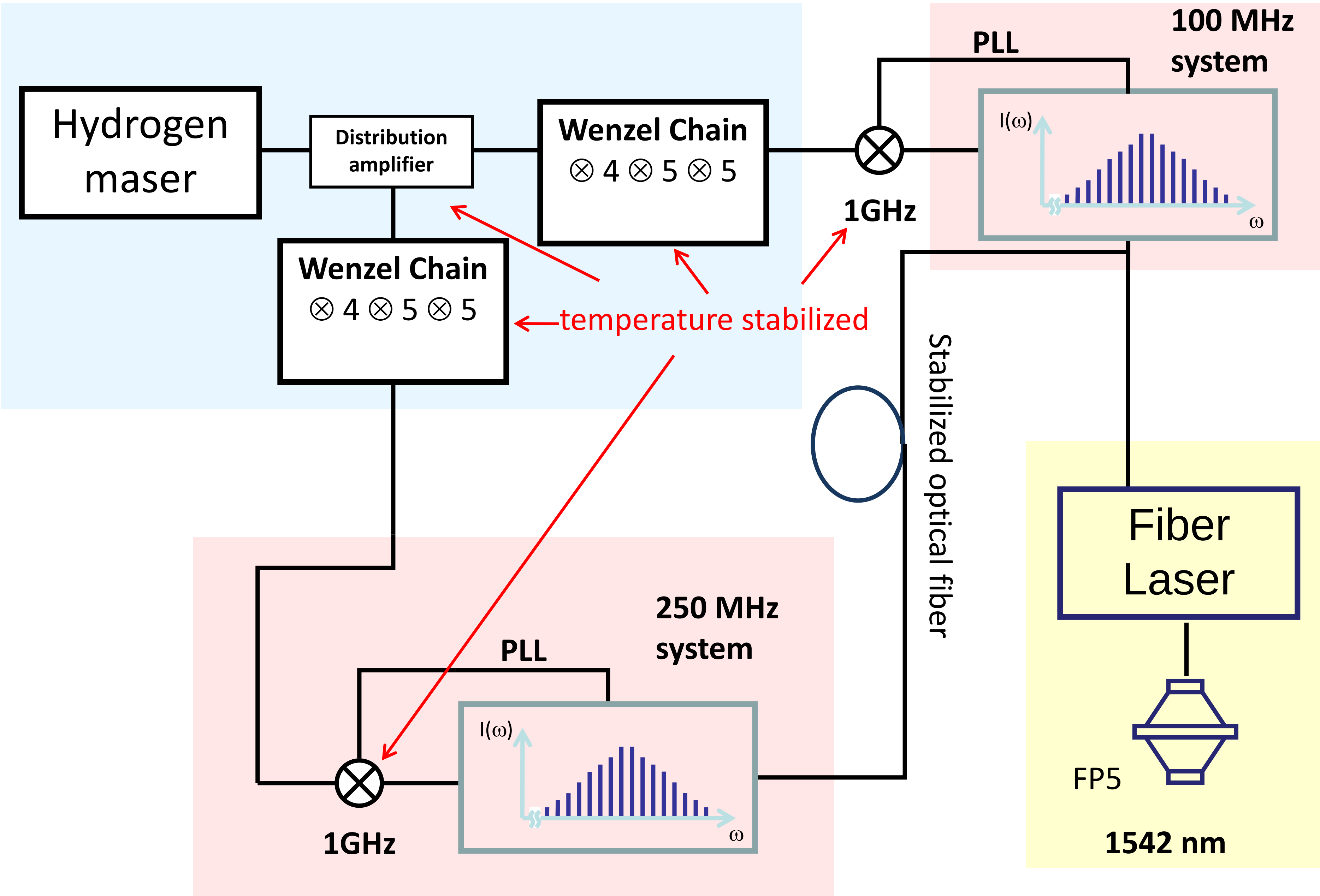


972 nm diode laser with a 20 cm long external resonator and intra-cavity EOM

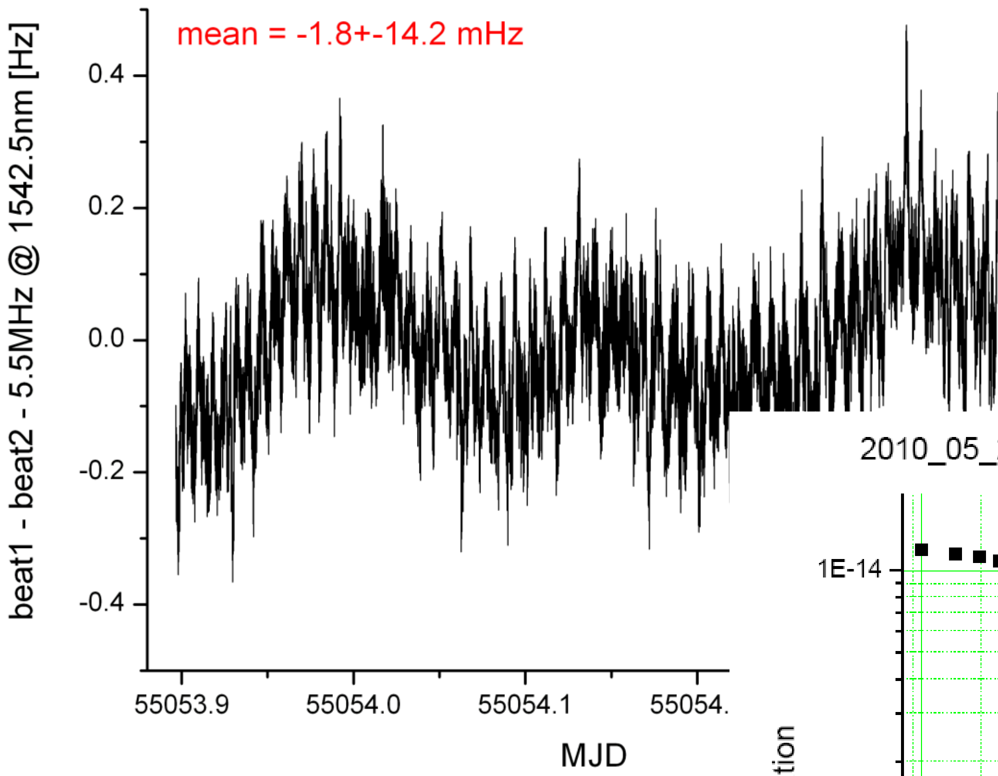
FP1-FP2 Allan deviation



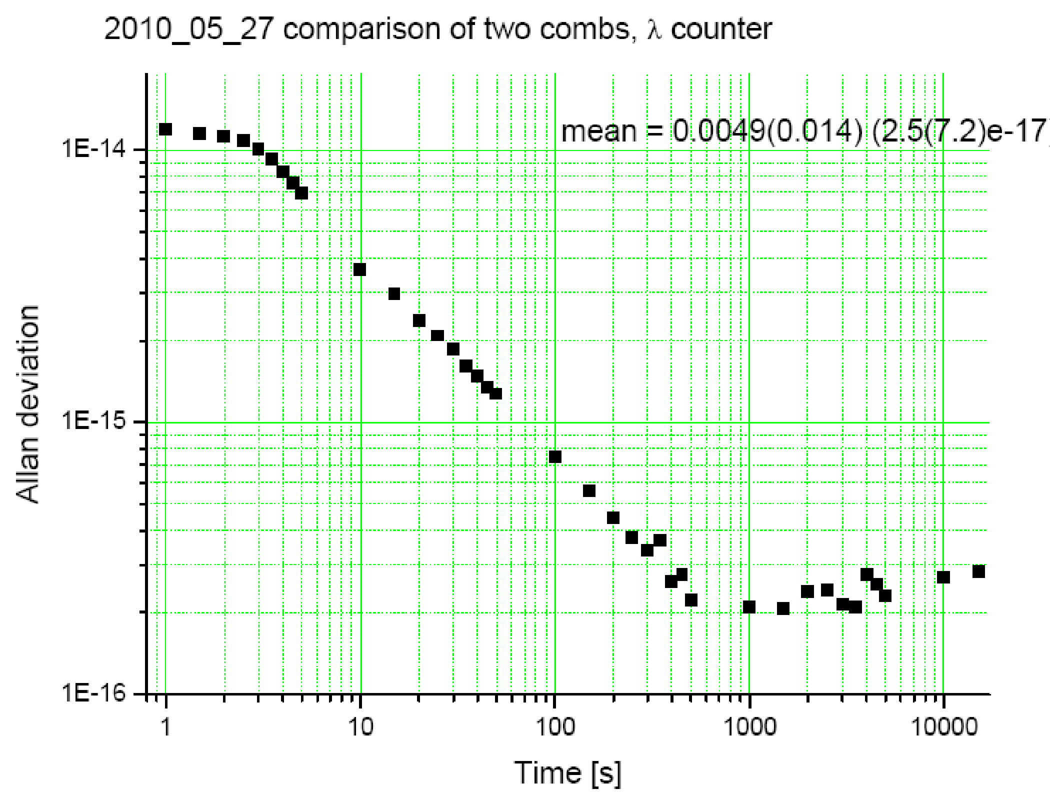
Comb-comb comparison setup



Comb-comb comparison: result

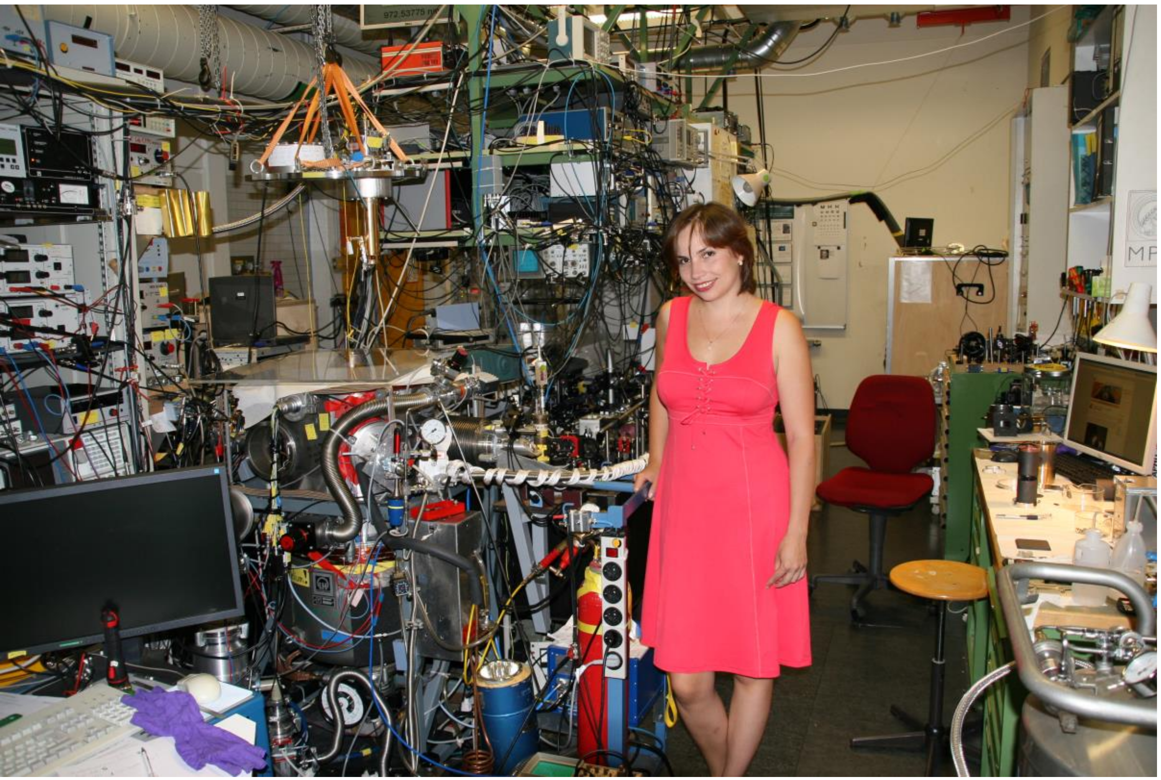


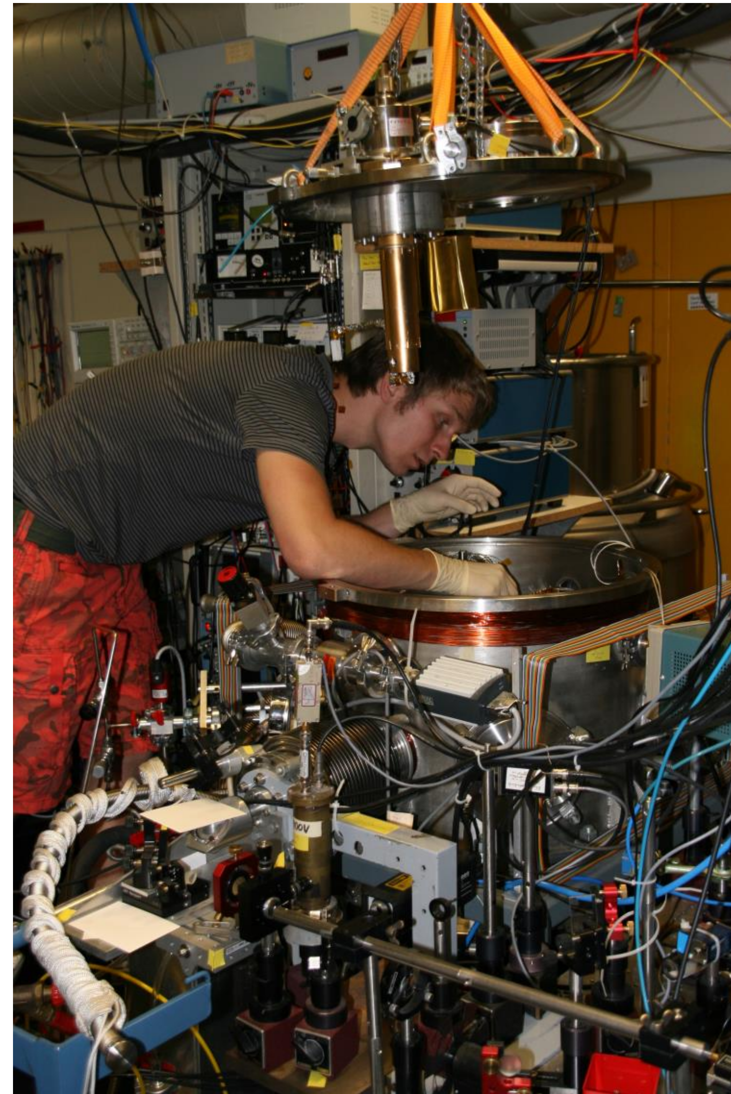
$$2mHz / 200THz = 7 \times 10^{-17}$$



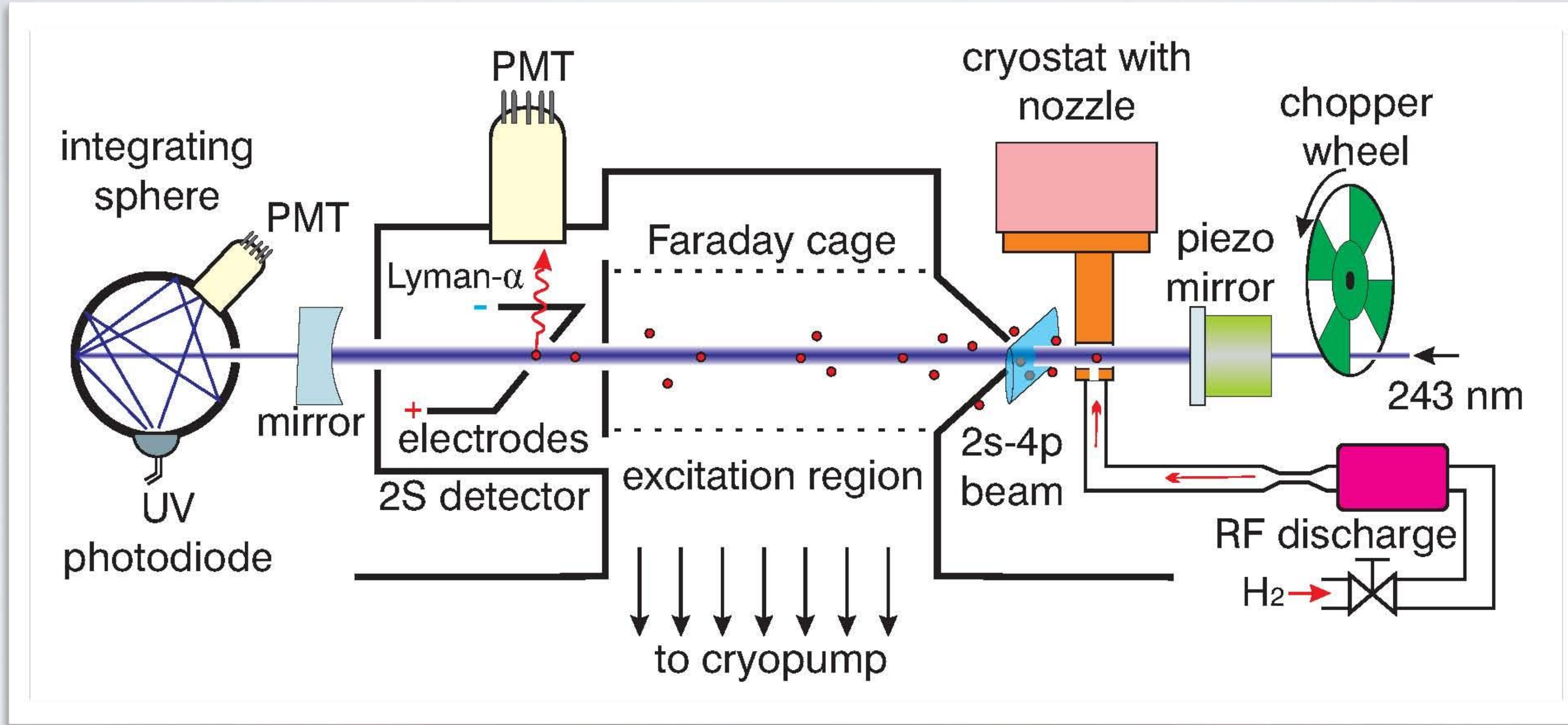
The Hydrogen spectrometer

1S-2S spectrometer



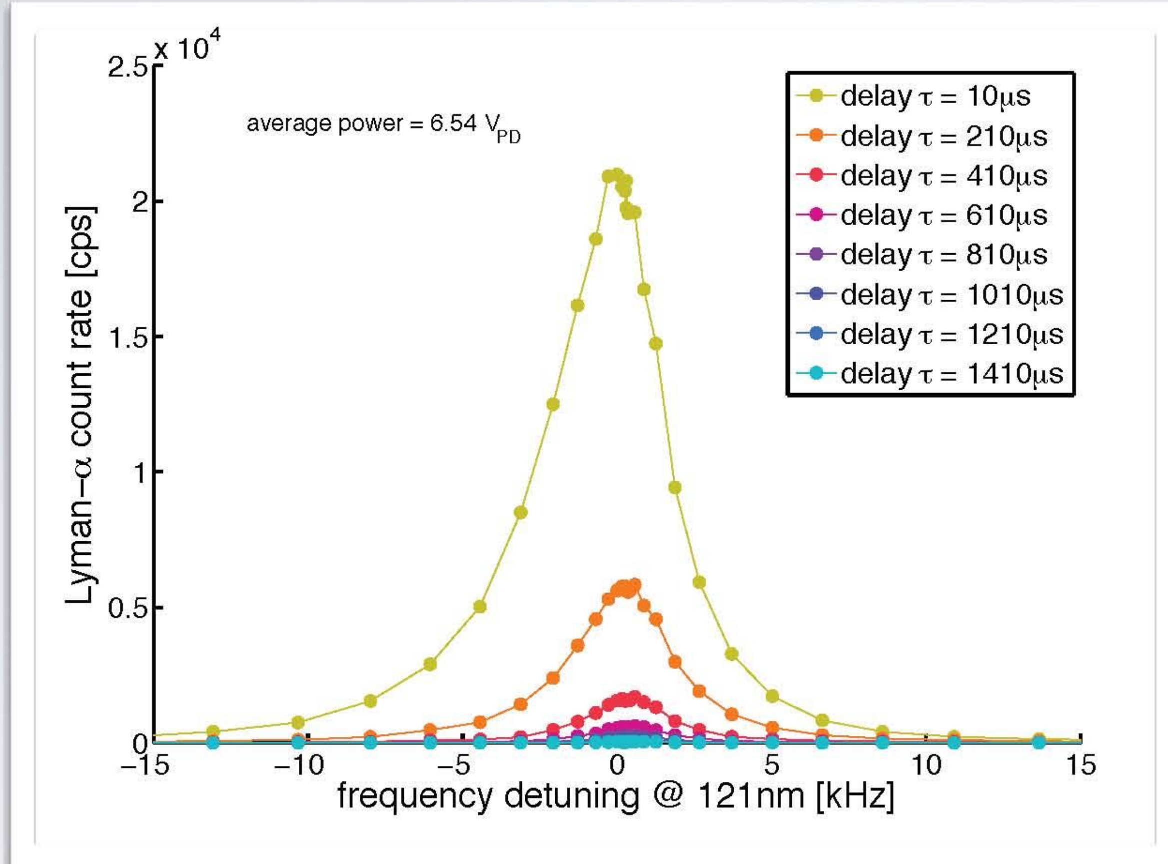


Setup

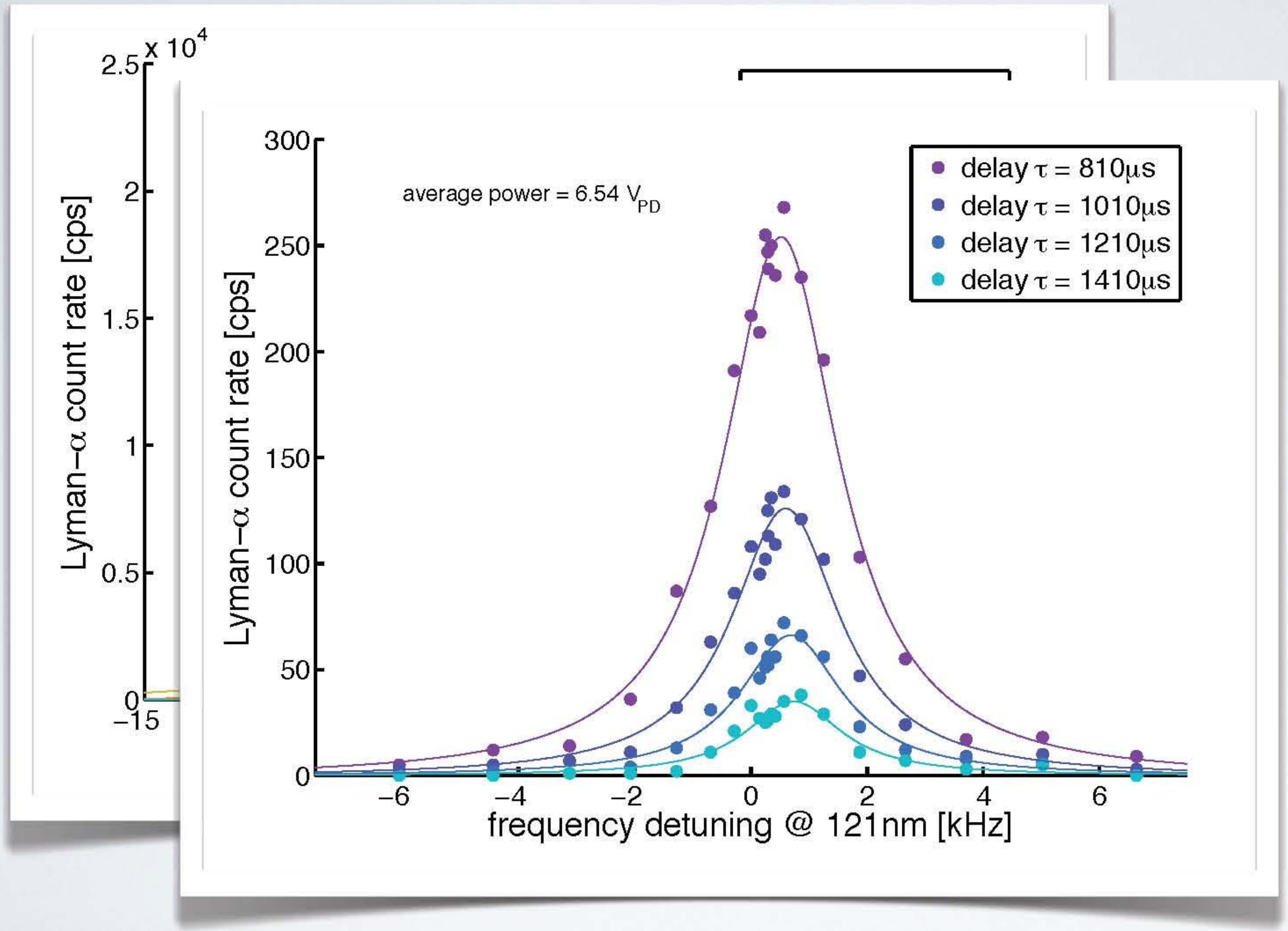


PMT
cryostat with nozzle
chopper wheel
integrating sphere
PMT
Faraday cage
piezo mirror
Lyman-α
-
mirror
+
electrodes
243 nm
2s-4p beam
2S detector
excitation region
UV photodiode
RF discharge
H2
to cryopump

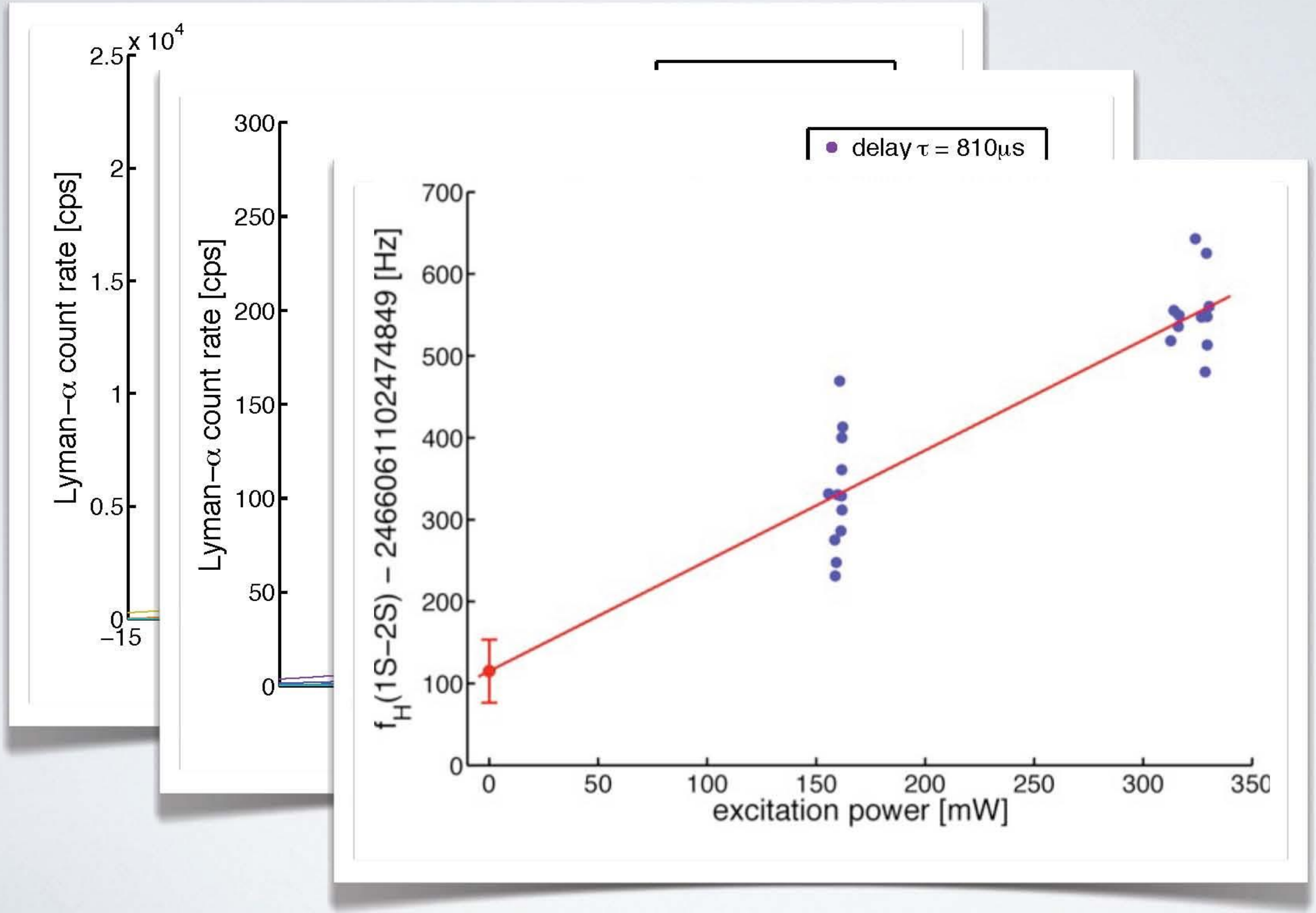
Line Profile



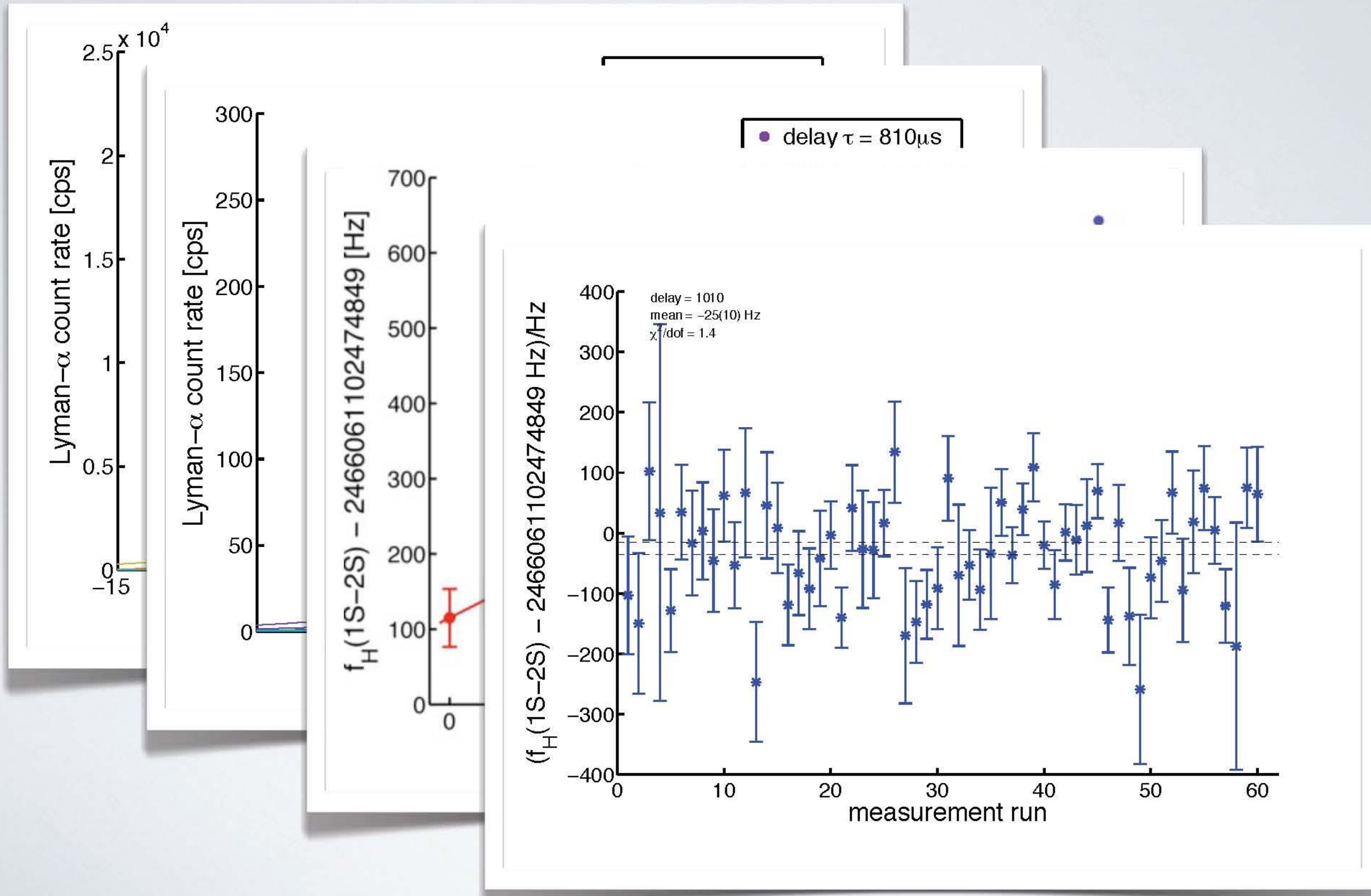
Line Profile



Line Profile



Line Profile



Uncertainty Budget

	uncertainty [Hz]	rel. uncertainty [10^{-15}]
statistics	6.3	2.6
2nd order Doppler effect	5.1	2.0
line shape model	5.0	2.0
quadratic ac Stark shift (243 nm)	2.0	0.8
ac Stark shift, 486 nm quench light	2.0	0.8
hyperfine correction	1.7	0.69
dc Stark effect	1.0	0.4
ac Stark shift, 486 nm scattered light	1.0	0.4
Zeeman shift	0.93	0.38
pressure shift	0.5	0.2
blackbody radiation shift	0.3	0.12
power modulation AOM chirp	0.3	0.11
rf discharge ac Stark shift	0.03	0.012
higher order modes	0.03	0.012
line pulling by $m_F = 0$ component	0.004	0.0016
recoil shift	0.009	0.0036
FOM	2.0	0.81
gravitational red shift	0.04	0.077
total	10.4	4.2

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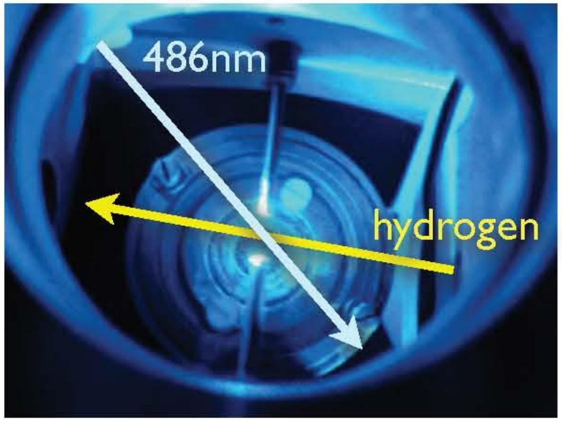
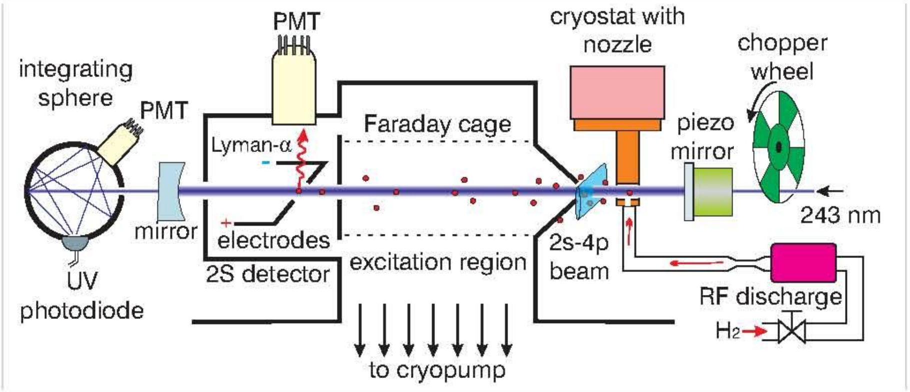
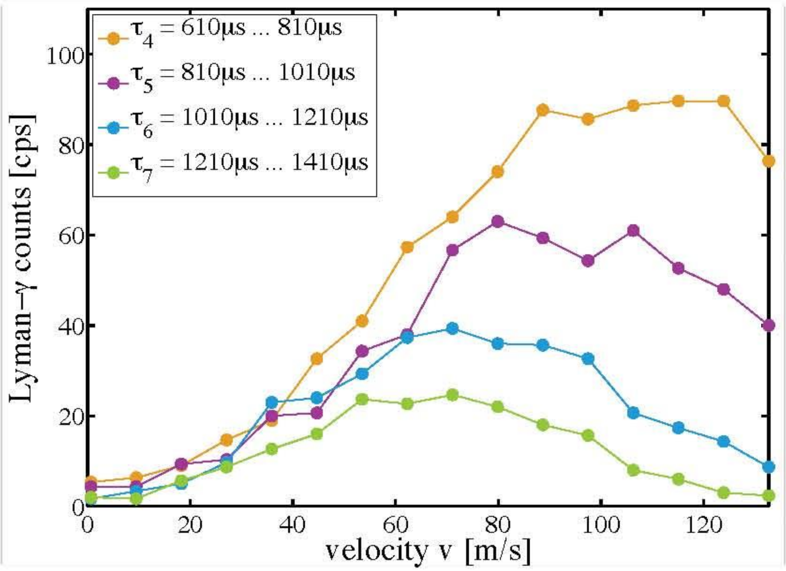
line pulling by $m_F = 0$ component	0.004	0.0016
recoil shift	0.009	0.0036
FOM	2.0	0.81
gravitational red shift	0.04	0.077
total	10.4	4.2

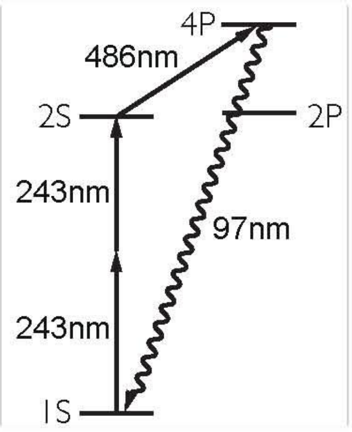
Second Order Doppler Effect



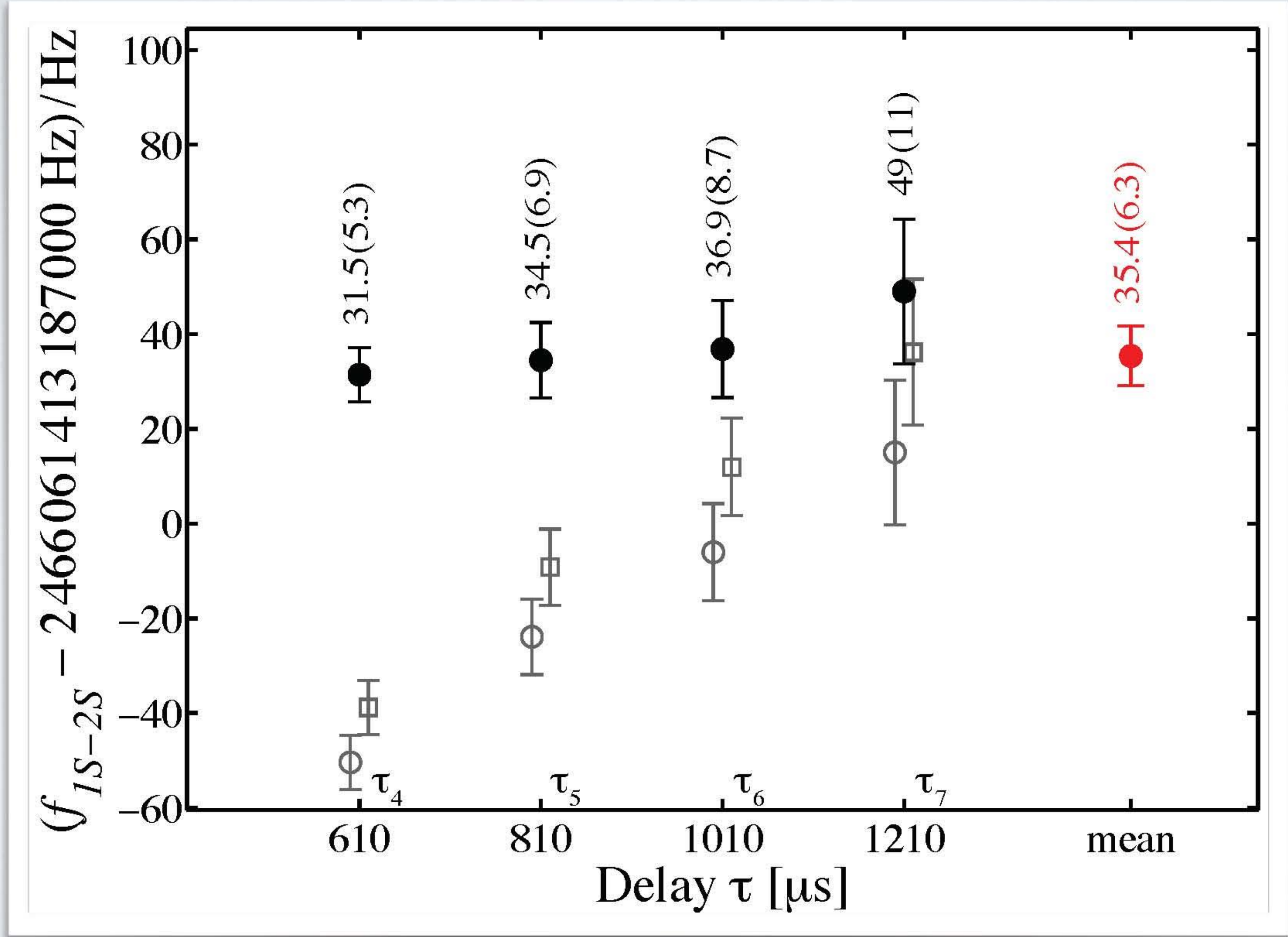


$$\Delta f_{\mathrm{dp}} = -v^2/(2c^2) \cdot f1S - 2S$$



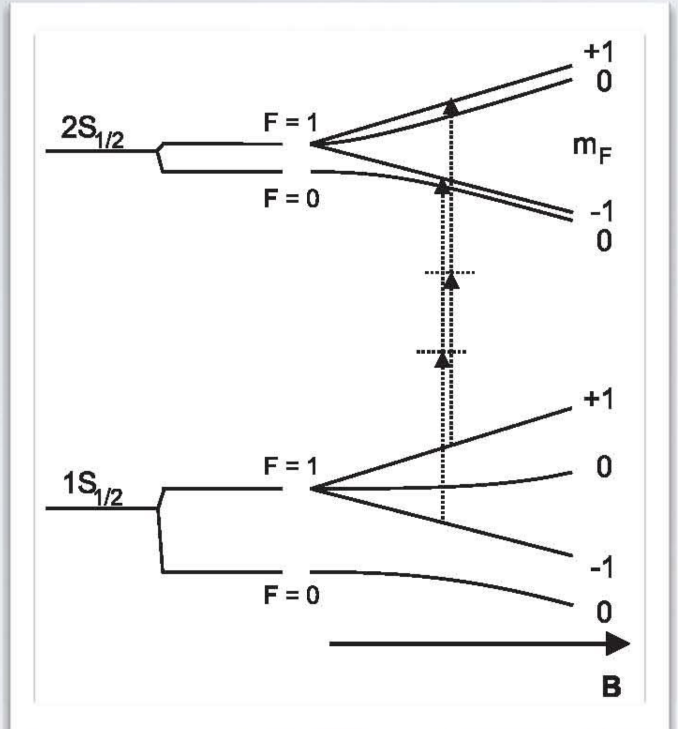


Result

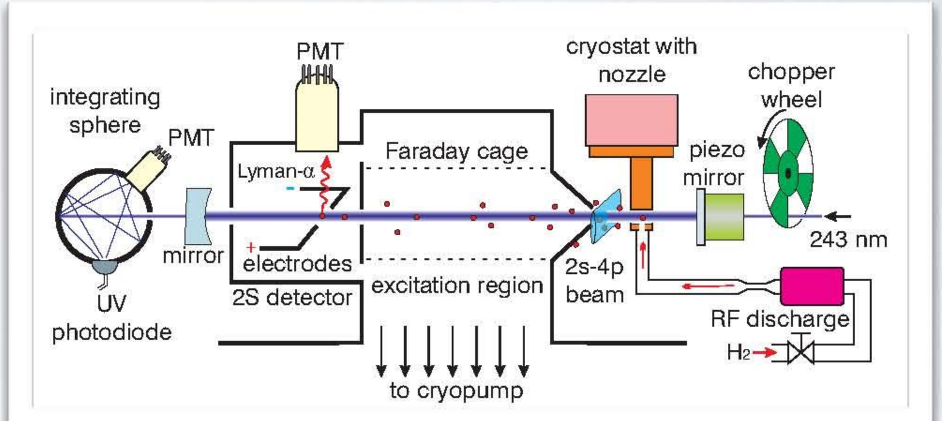


$(f_{1S-2S} - 2466061413187000\ \mathrm{Hz})/\mathrm{Hz}$
100
80
60
40
20
0
−20
−40
−60
31.5(5.3)
34.5(6.9)
36.9(8.7)
49(11)
35.4(6.3)
τ_4
τ_5
τ_6
τ_7
610
810
1010
1210
mean
Delay τ [µs]

Zeeman Shift



$$\Delta f(m_F = \pm 1) = \pm B \cdot 36\,\mathrm{Hz/G}$$
$$B = 5G$$

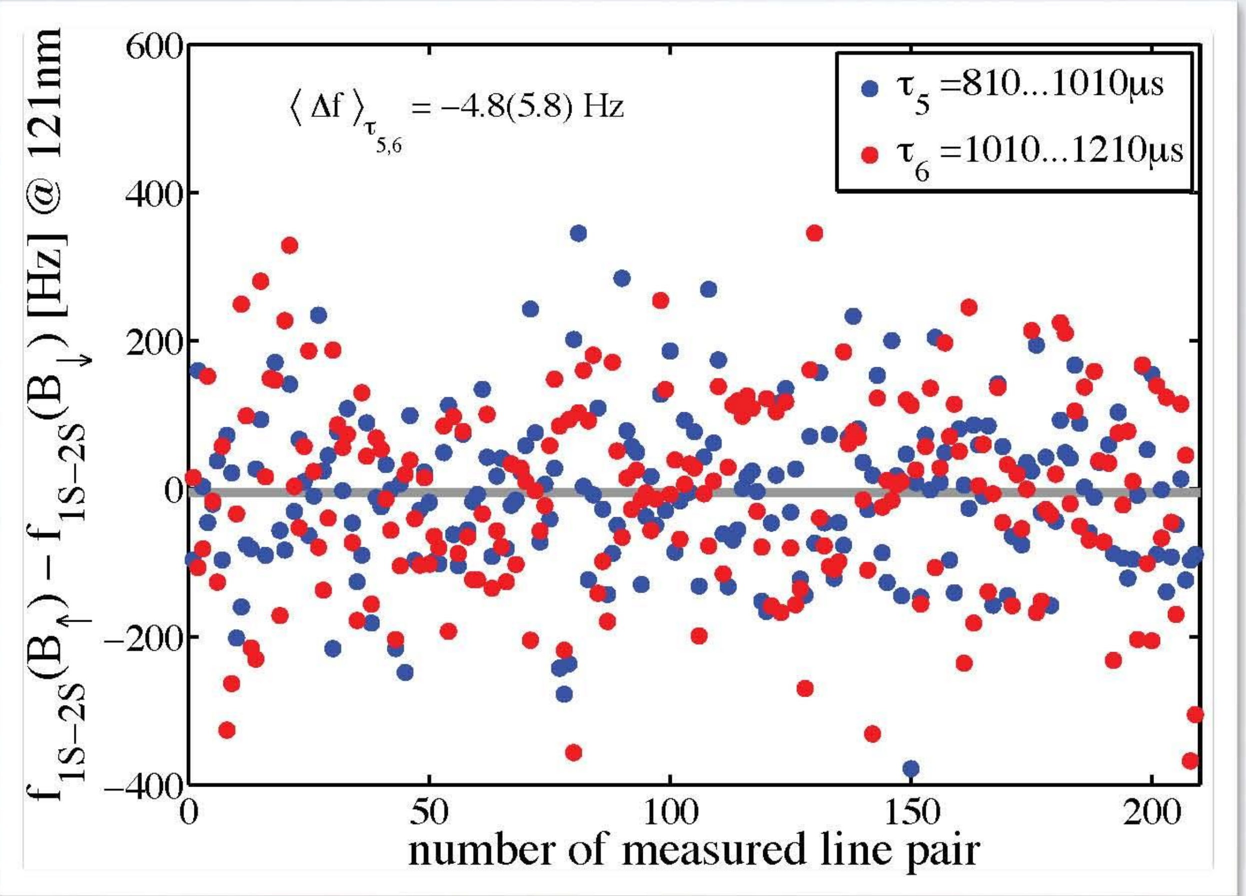


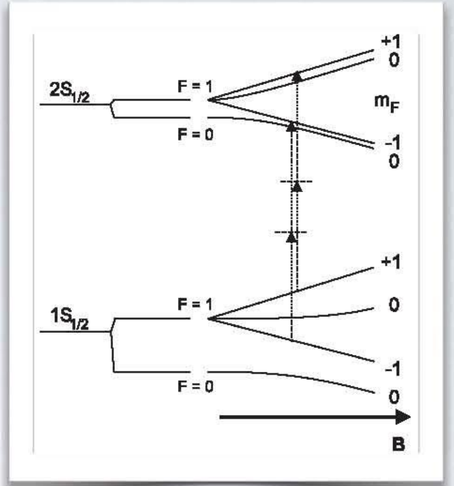
Differential measurement:

30 winding 100 windings

$$I \to \pm I$$

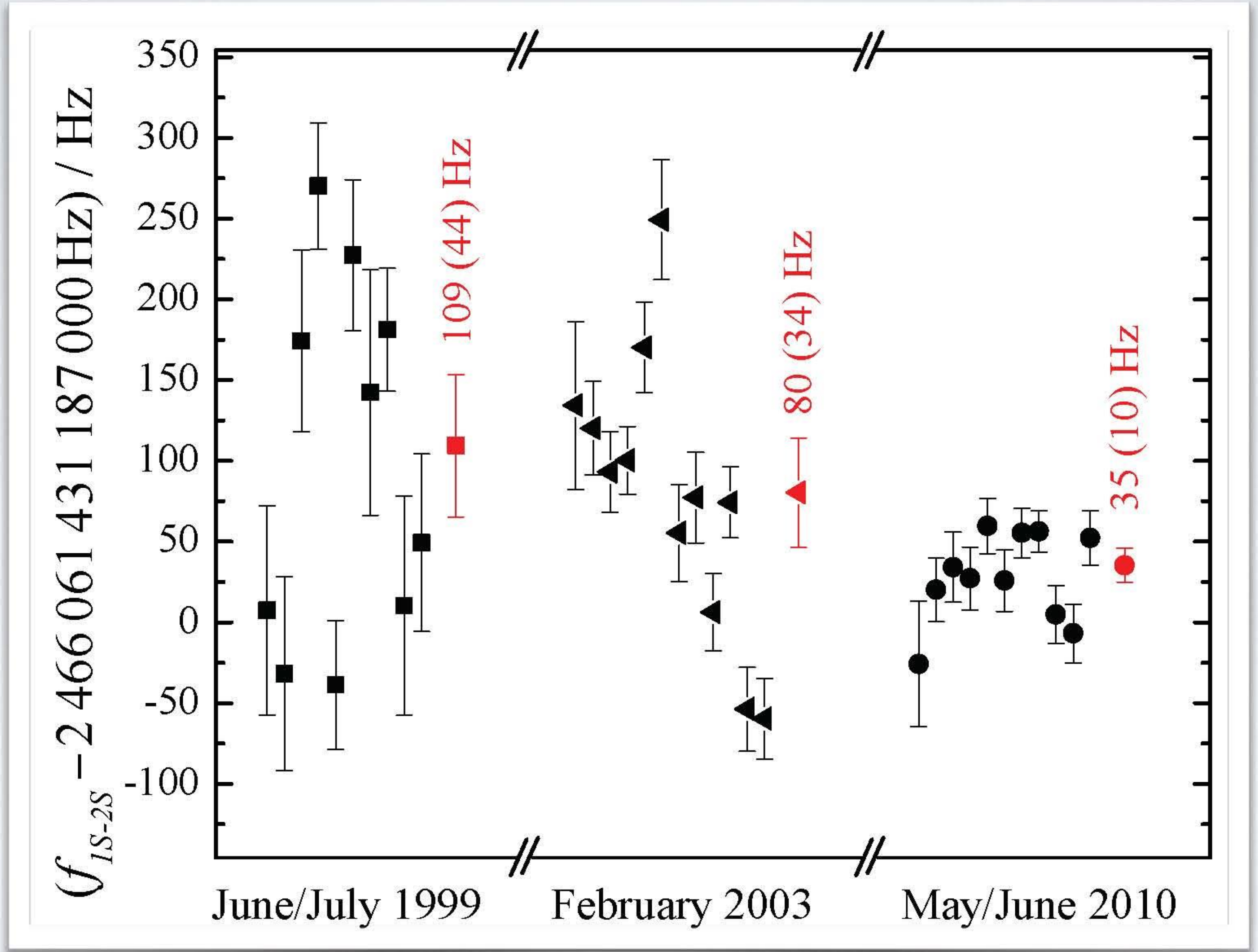
Zeeman Shift





$$5.8\,\mathrm{Hz}/6.25 = 0.93\,\mathrm{Hz} \quad (0.38 \times 10^{-15})$$

Result

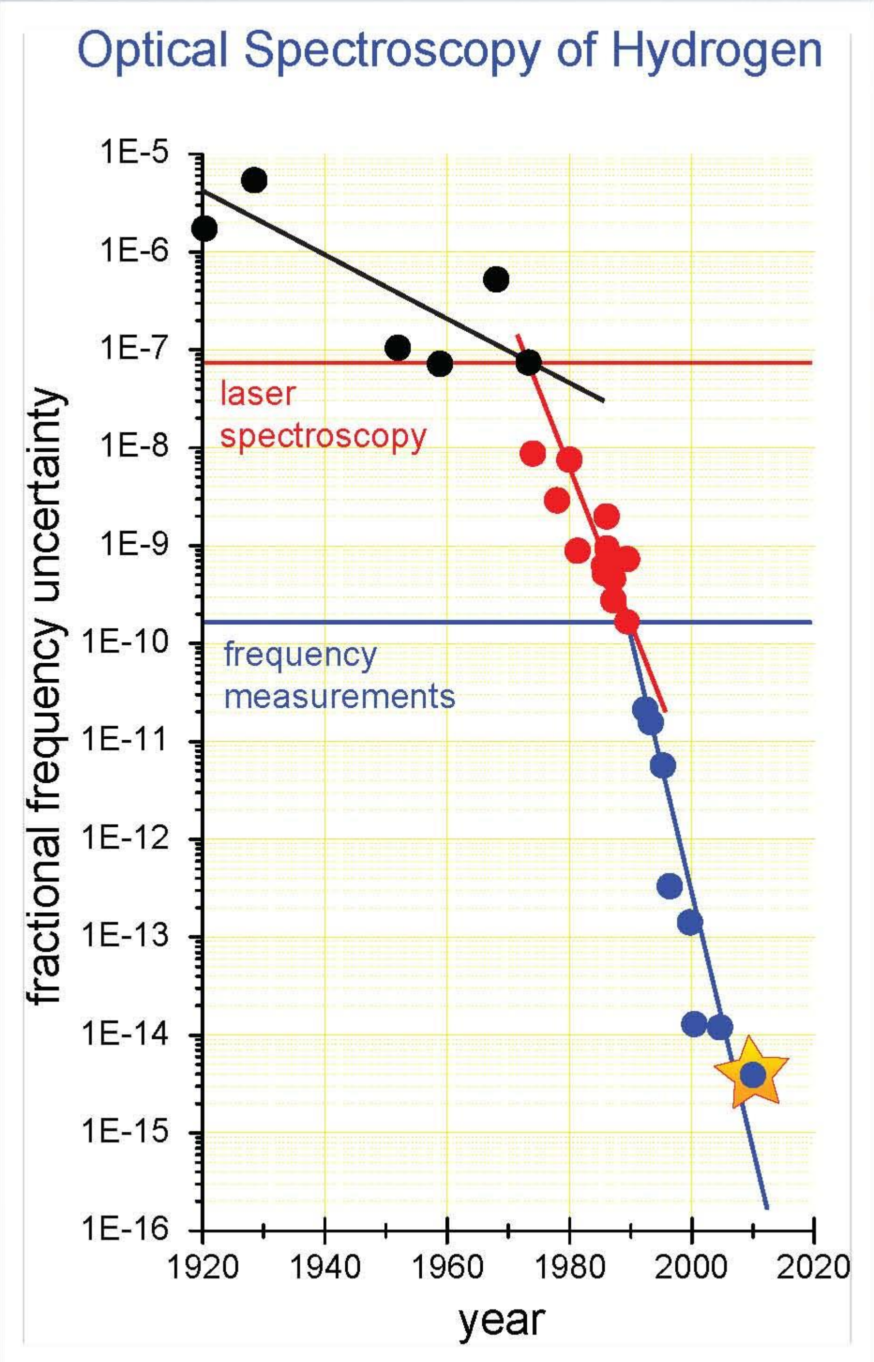


C.G. Parthey et al., PRL 107, 203001 (2011)

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

4.2×10^{-15}

C.G. Parthey et al., PRL 107, 203001 (2011)

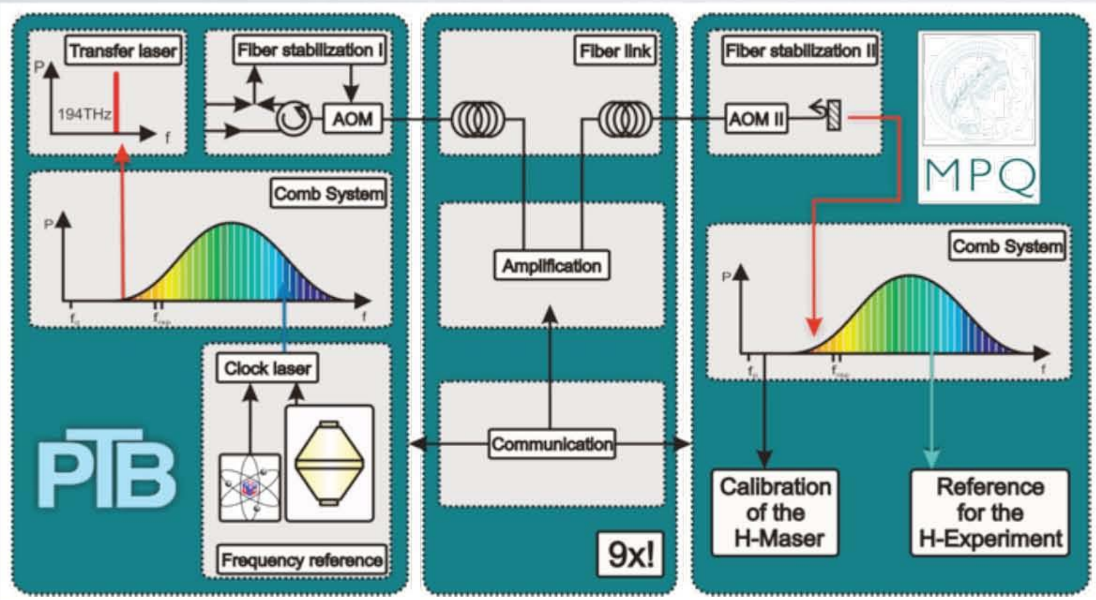


187 035(10) Hz

4.2×10^{-15}

C.G. Parthey et al., PRL 107, 203001 (2011)

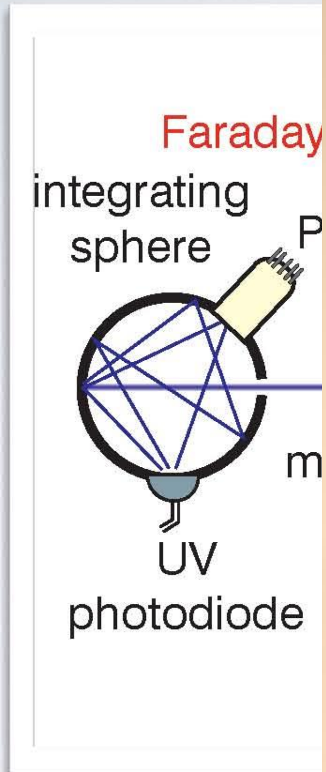
900 km Optical Fiber Link to PTB

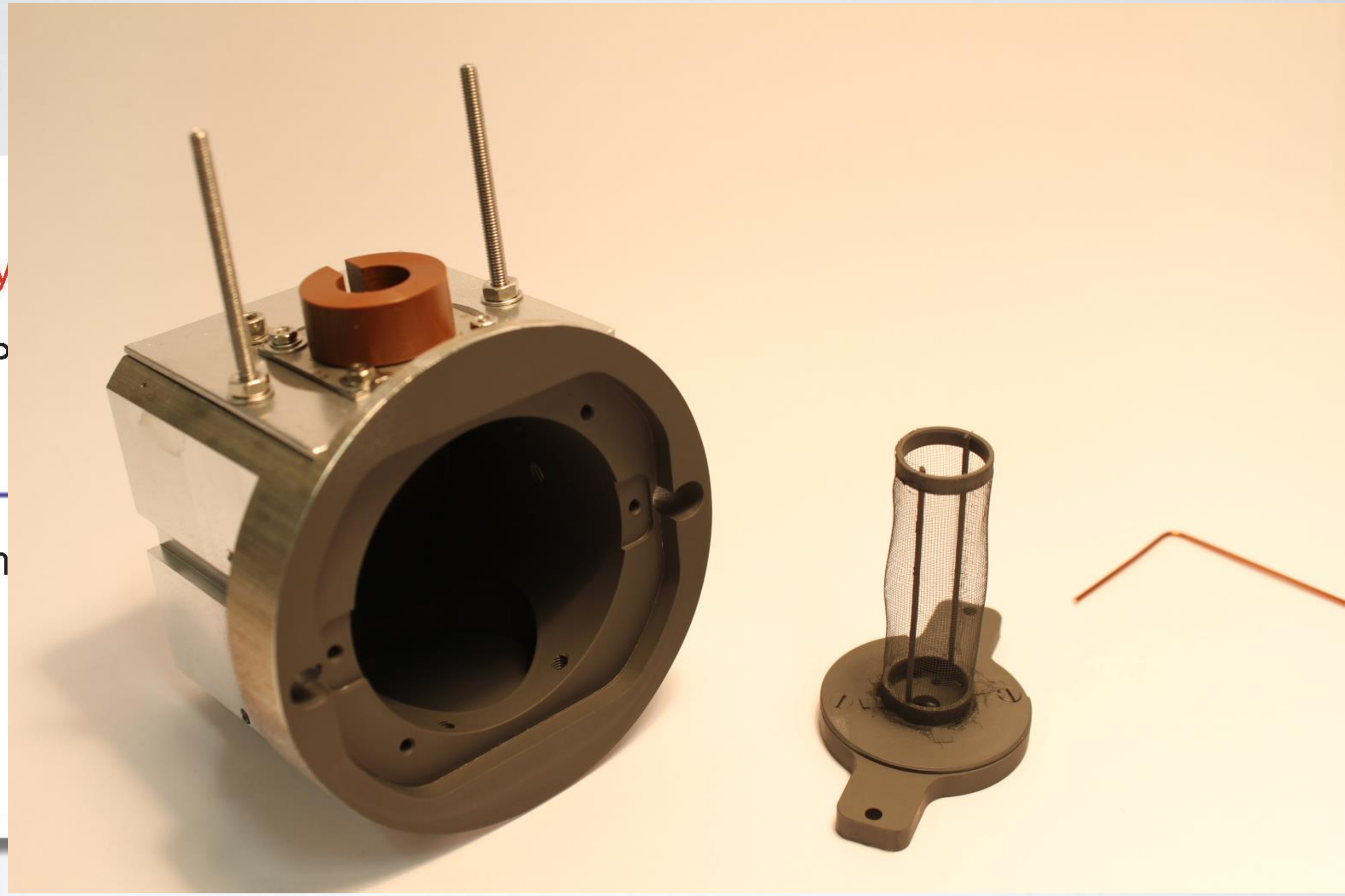


gravitational red shift

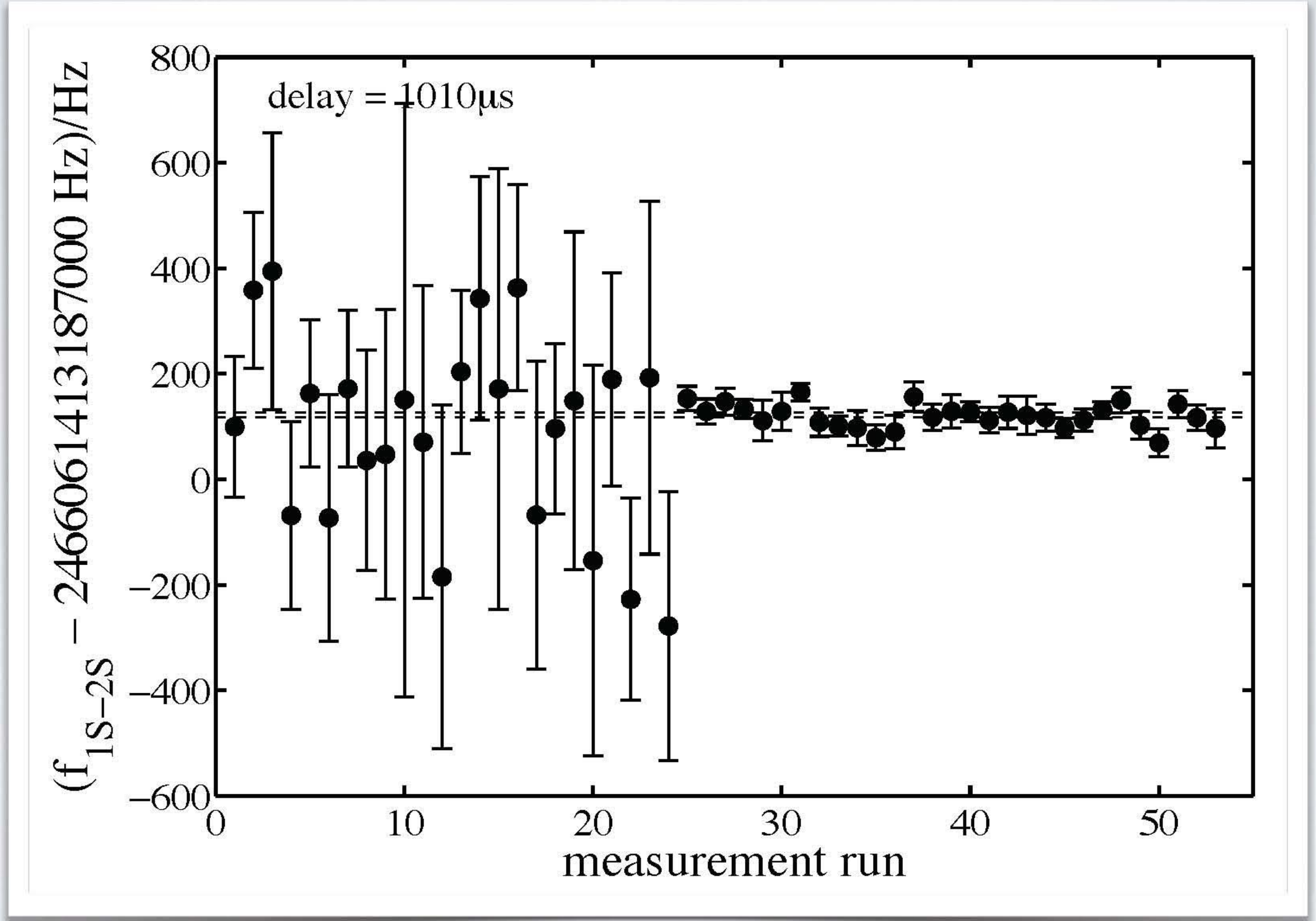
$$\frac{\Delta f}{f} = \frac{\Delta h g}{c^2} = 4.4 \times 10^{-14}$$

New detector

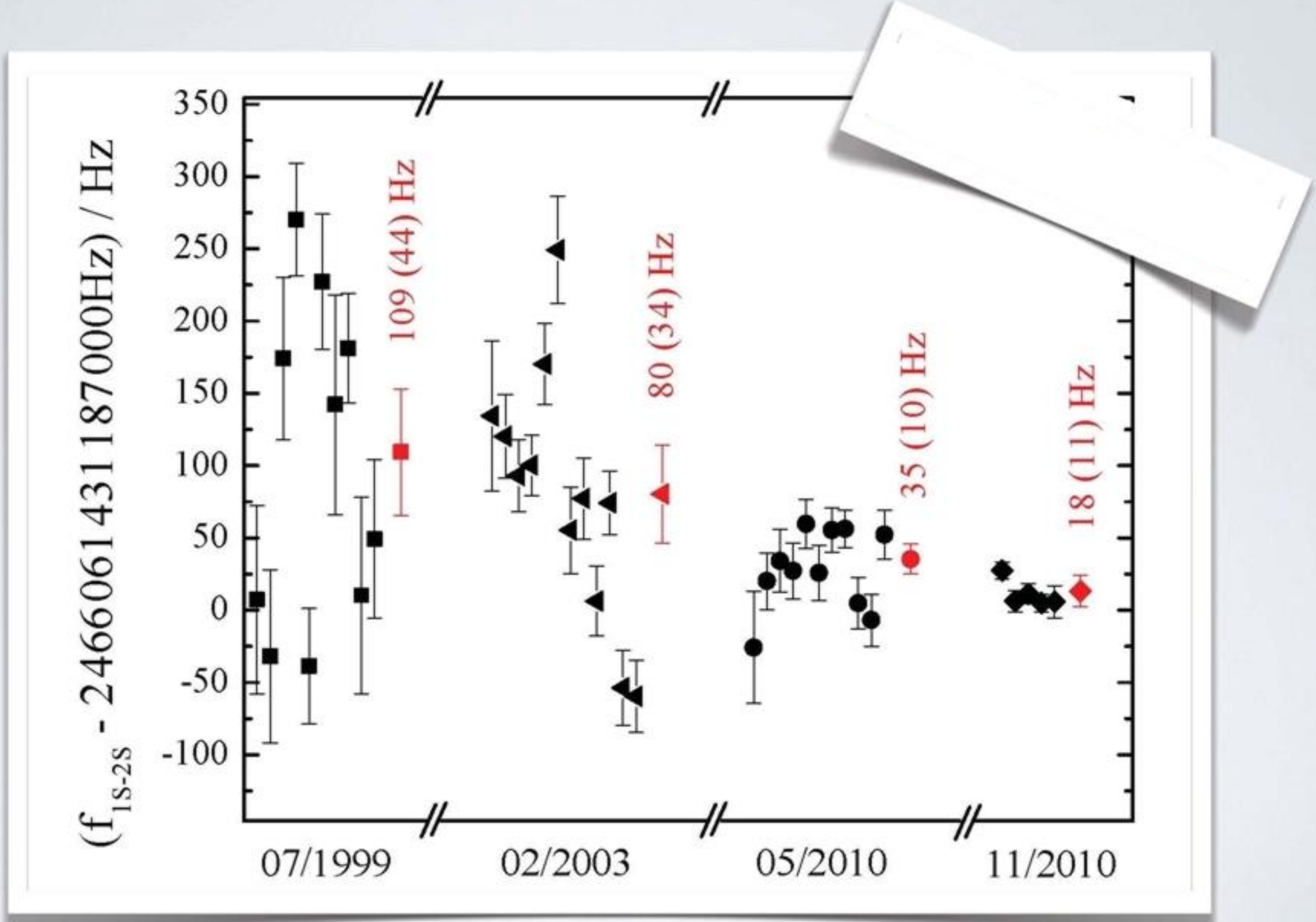




New Detector



Result - Link Measurement



Uncertainly in the 1S-2S transition cannot solve the proton charge radius puzzle

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

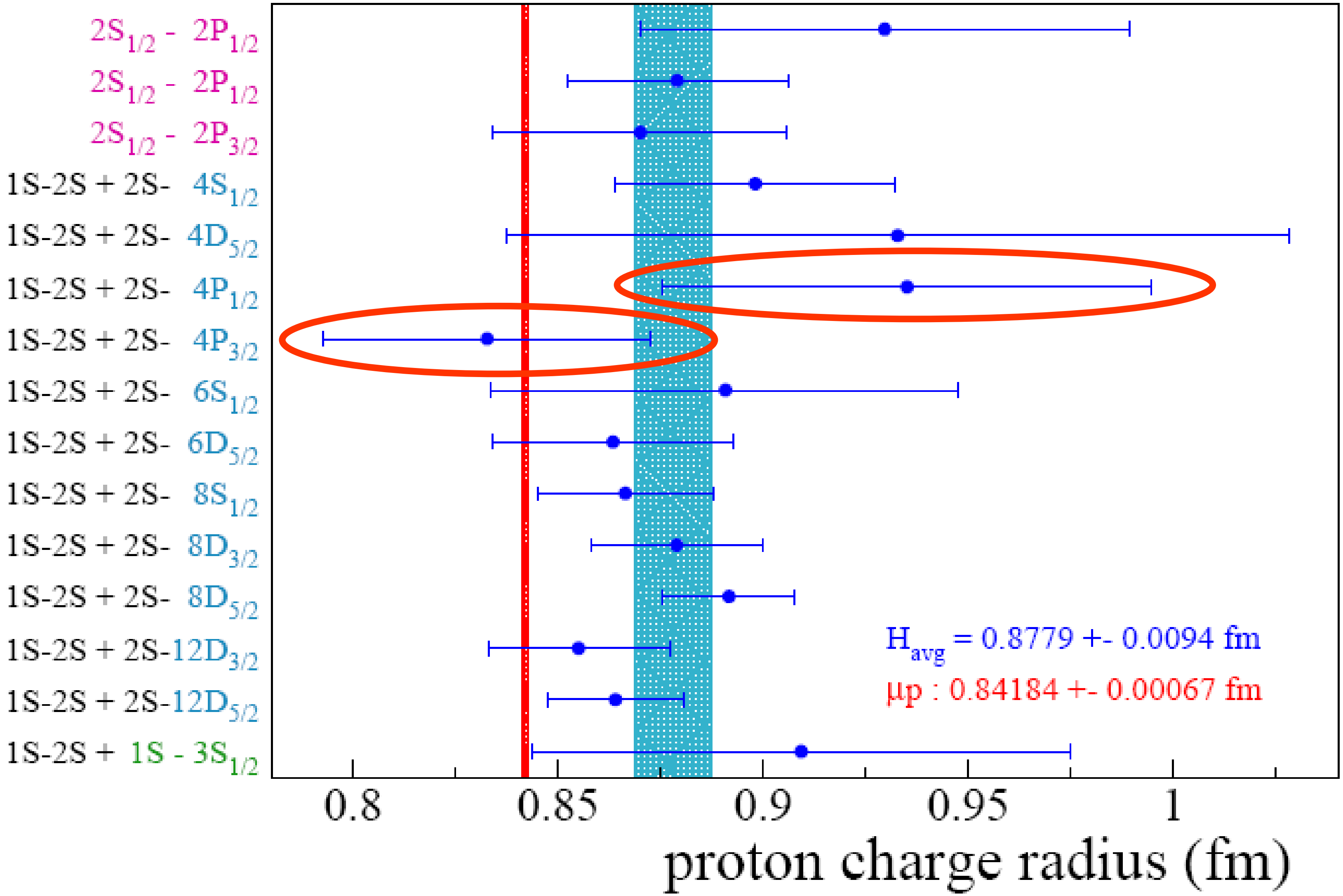
$$4.2 \times 10^{-15}$$

Parthey et al., arXiv:1107.3101v1

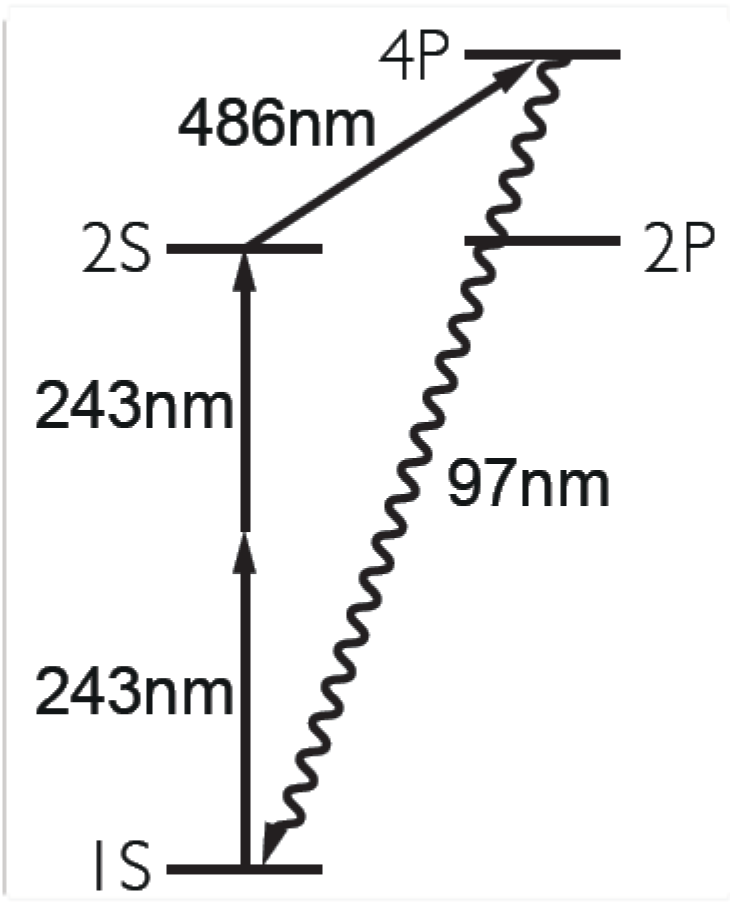
It is desirable to measure independently other transitions in H with higher accuracy

We already use a laser to excite 2S-4P (486 nm) transition in a cold atomic beam of H

2S-4P transition measurements (Yale'95)



2S-4P spectroscopy at MPQ

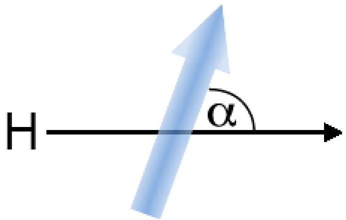


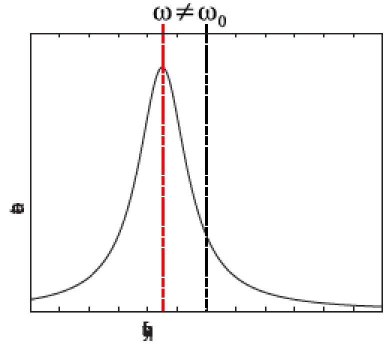
Cold beam of metastable atoms (4 K)

Optically populated only one hyperfine sublevel 2S (F=0)

Velocity selective detection, typical velocities down to 100 m/s

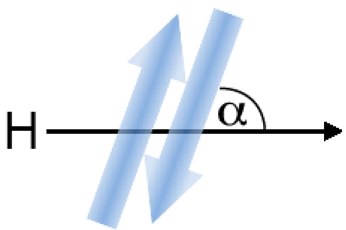
Frequency measurement is reliable

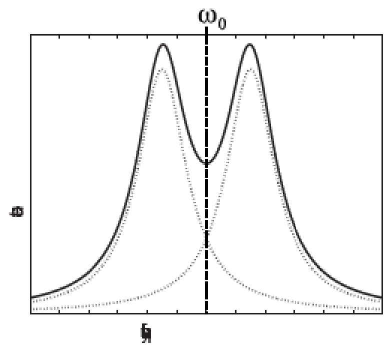


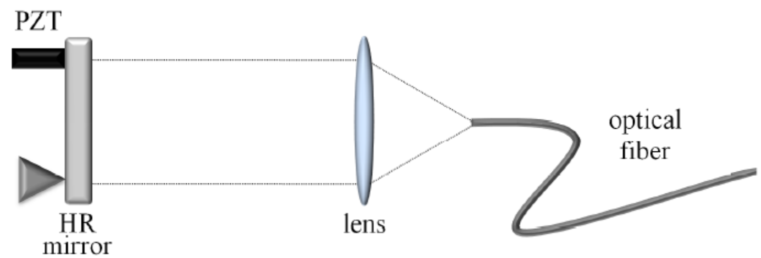


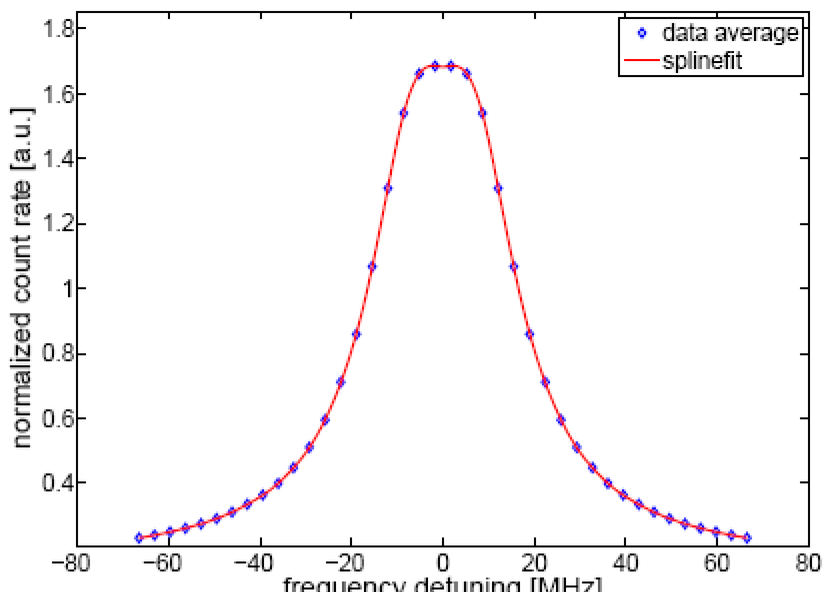
Natural line width of the 4P level

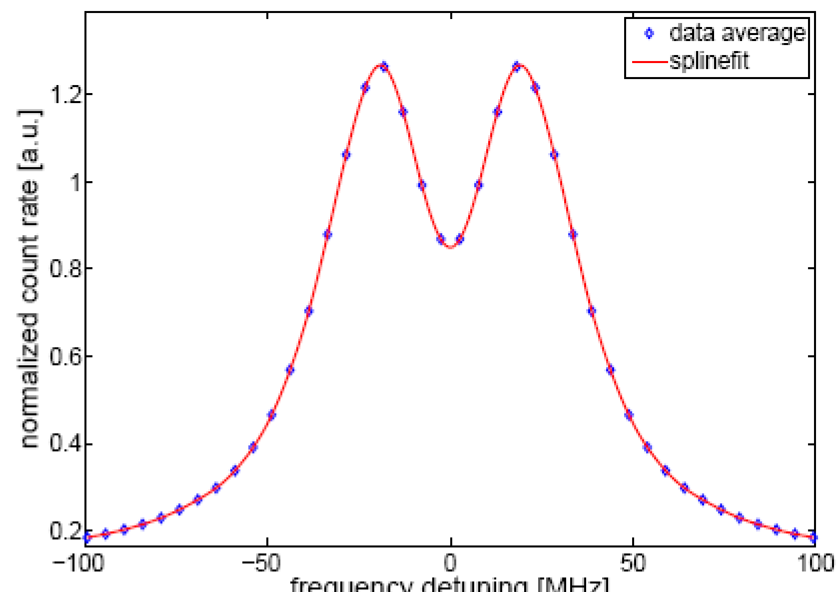
13 MHz



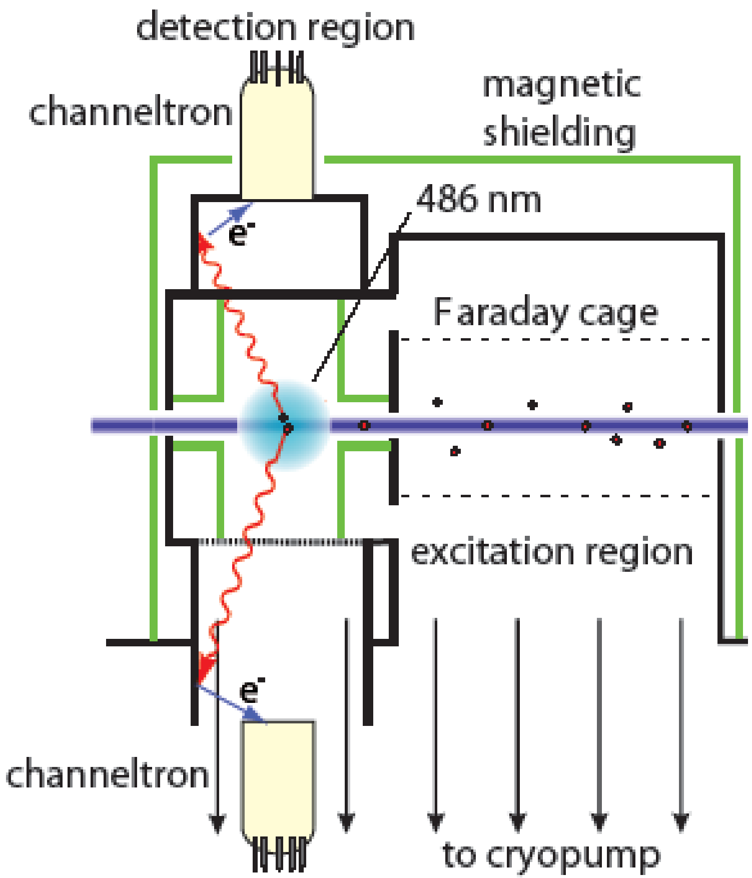


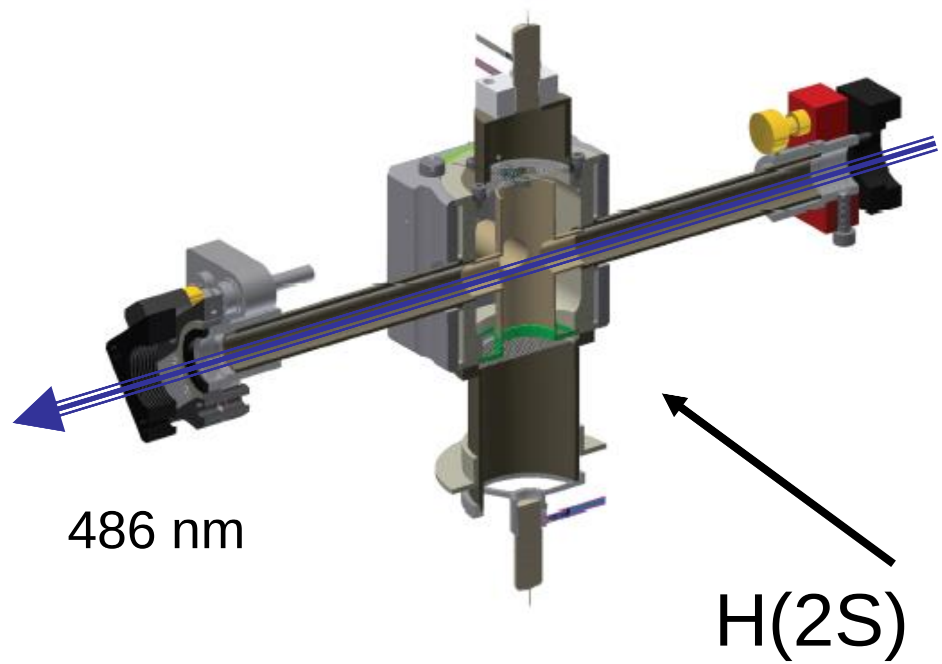






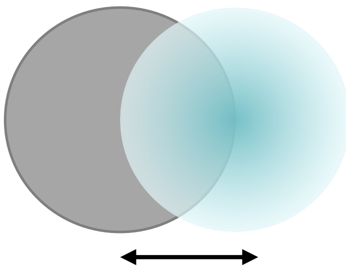
2S-4P experimental setup



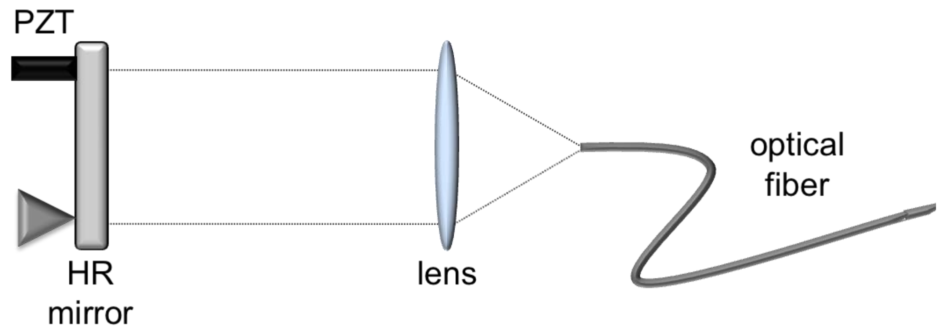


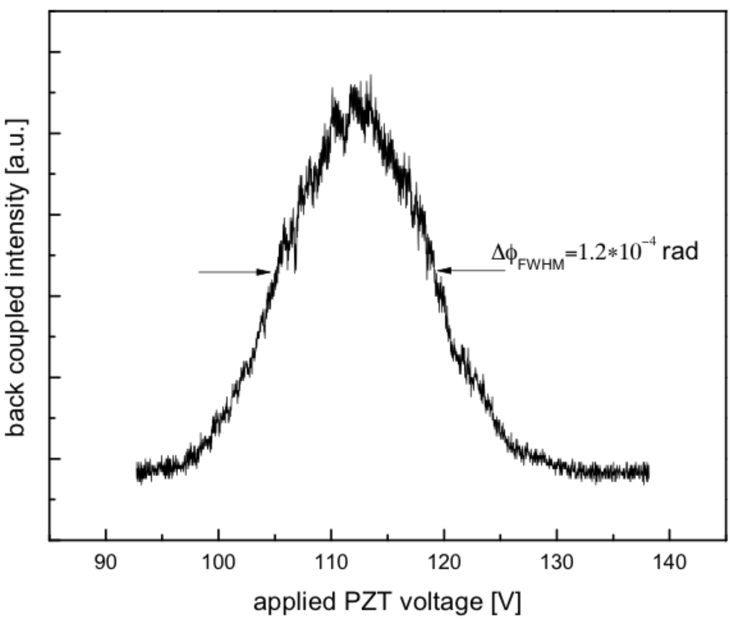
Antiparallel Beams

Active fiber-based retroreflector:



$\Delta x_{1/2}$





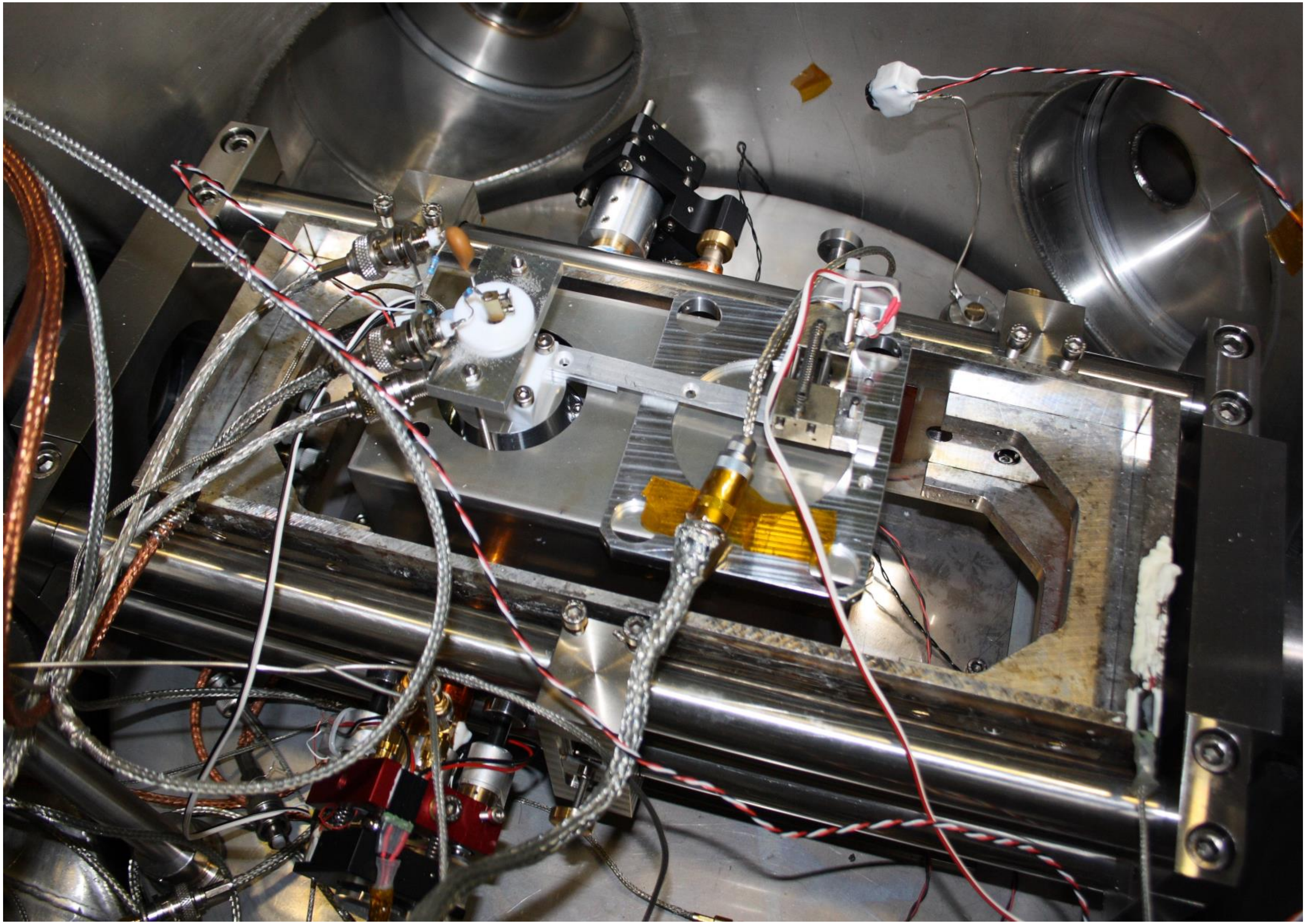
$$\tan(\theta) \approx \theta = \frac{\Delta x}{f}$$

$$\Delta x \simeq 3\mu\mathrm{m}$$

$$\Rightarrow \phi_{1/2} \simeq 5 \cdot 10^{-5}\mathrm{rad}$$

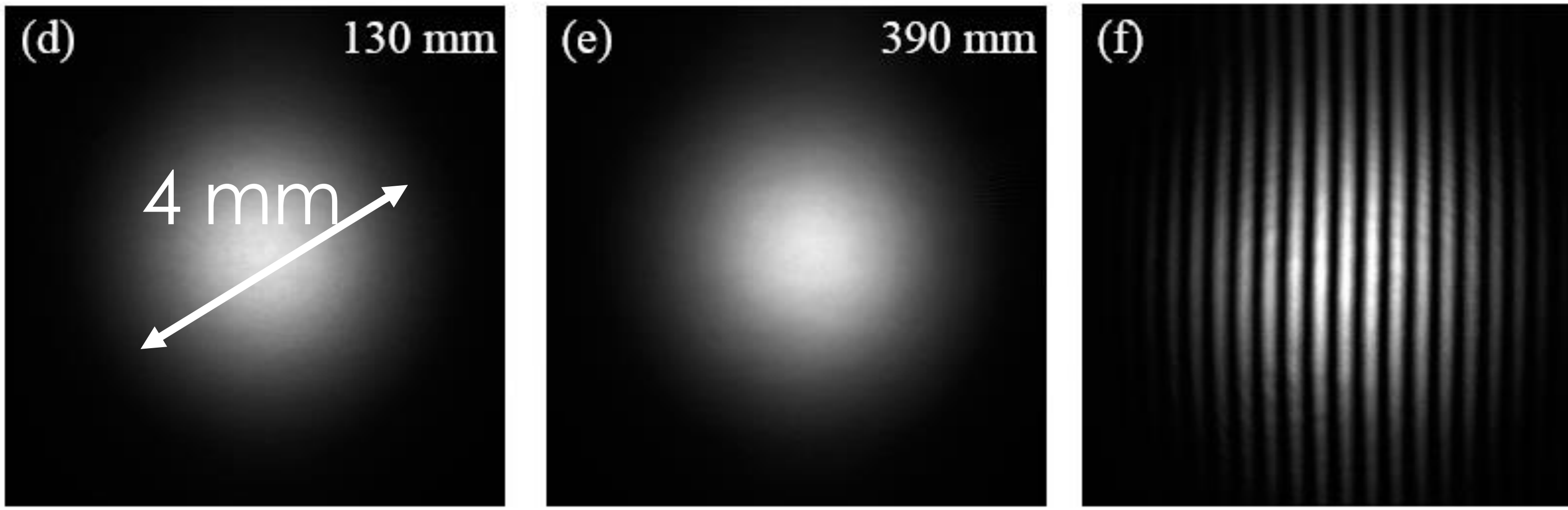
$$\phi_{\mathrm{FWHM},exp} \simeq 1.2 \cdot 10^{-4}\mathrm{rad}$$

Inside the chamber

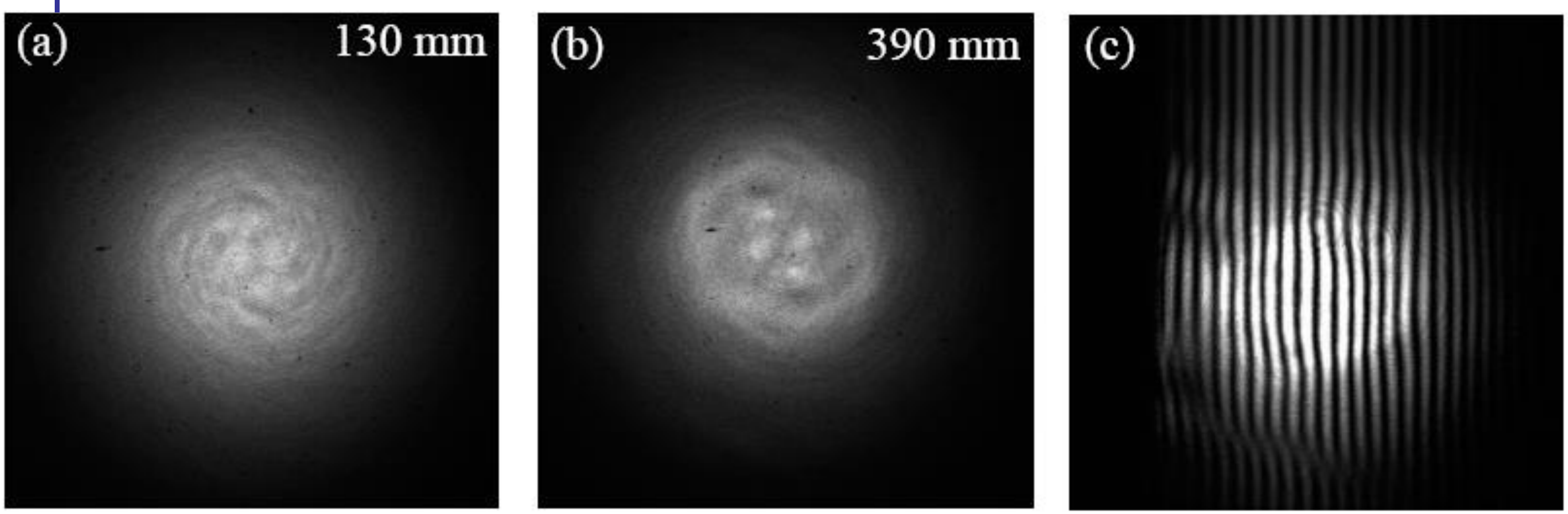


Gaussian beam

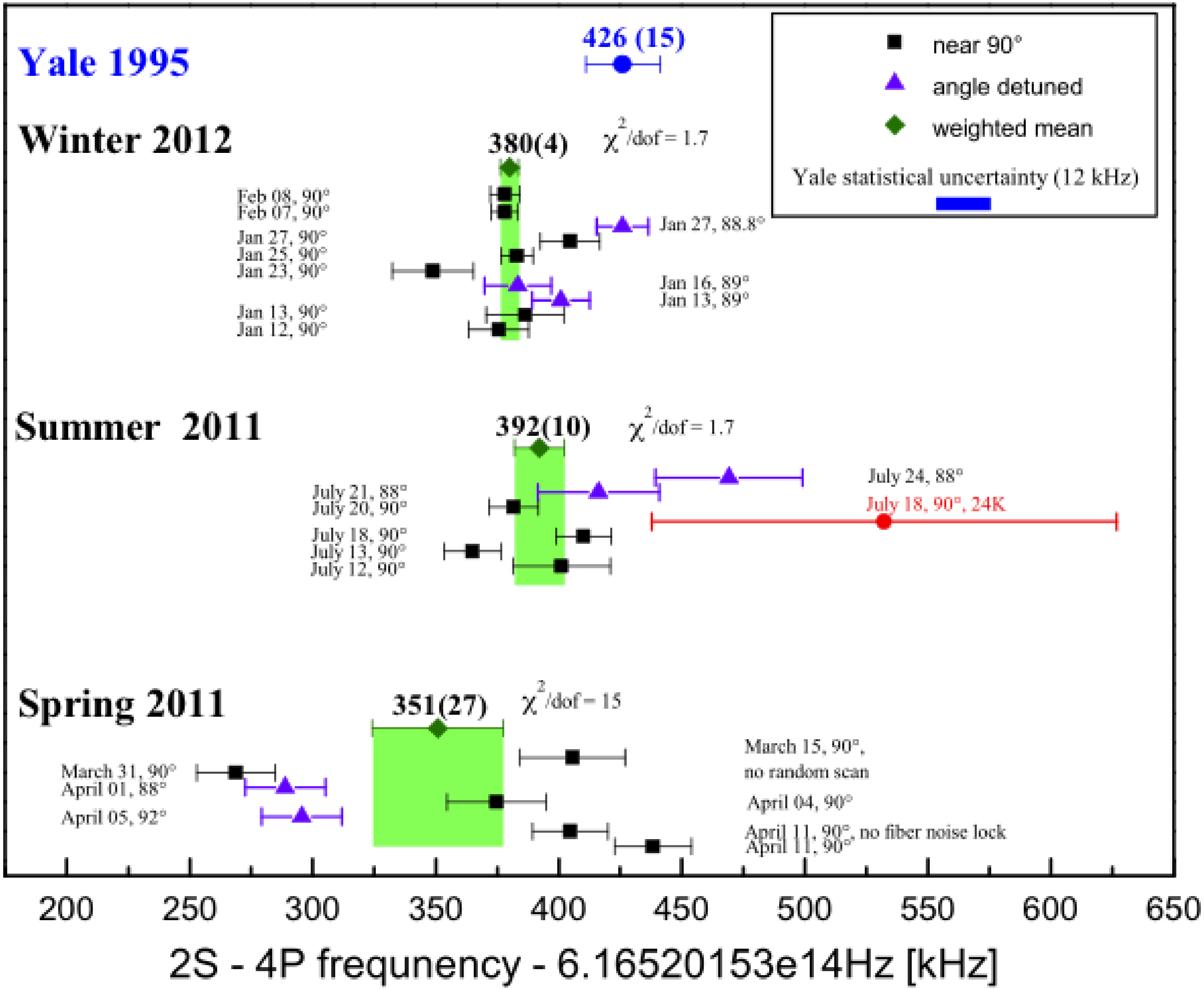
Assembly of spherical lenses



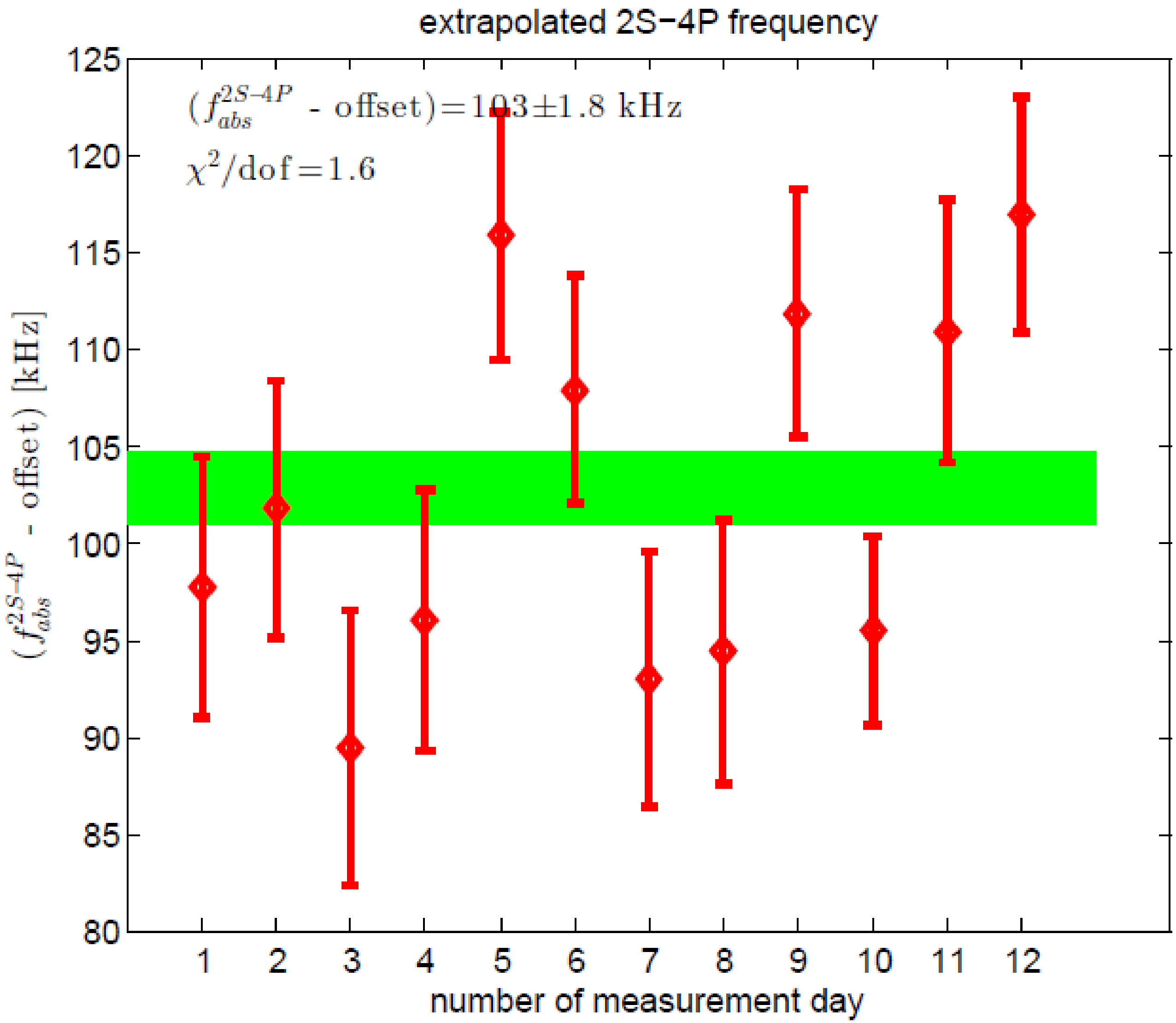
Aspherical lens



Data evaluation



Data scattering (polarization dependent?)



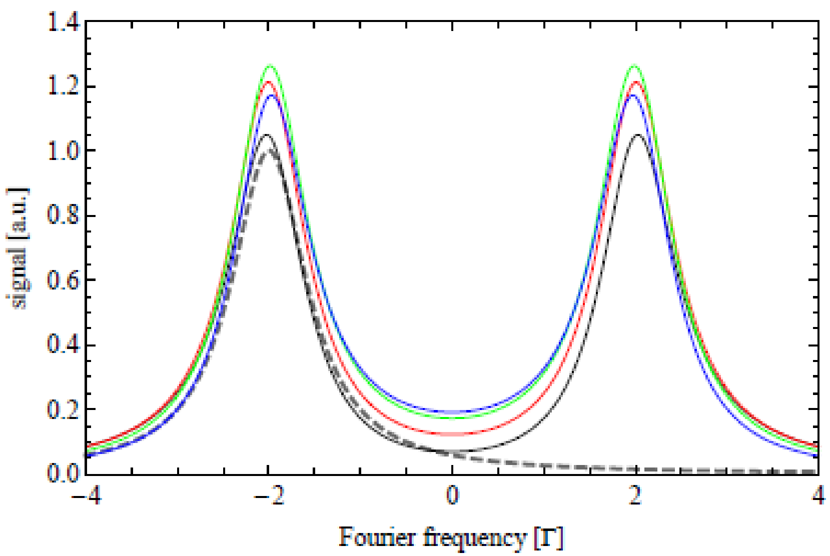
Cross damping: coherent and incoherent parts

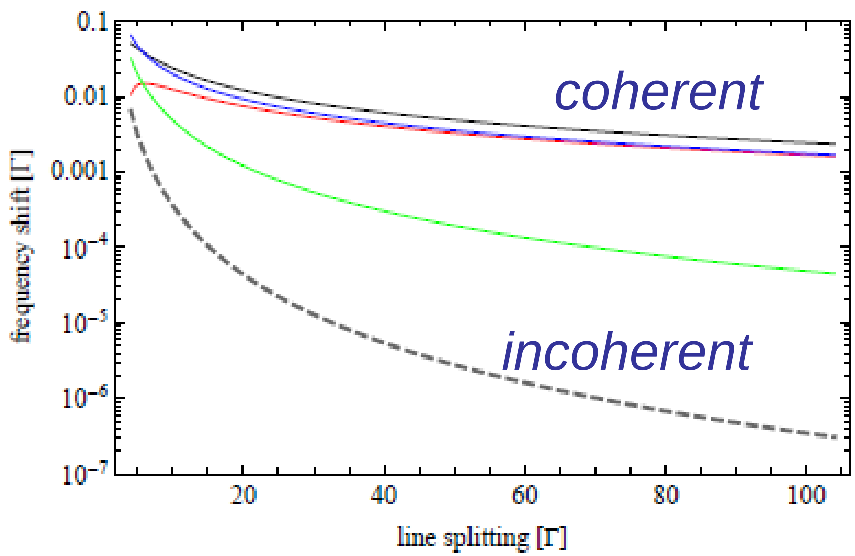
$$\vec{d}(t) = \vec{d}_1 e^{i\omega_1 t - \Gamma_1/2t} + \vec{d}_2 e^{i\omega_2 t - \Gamma_2/2t + i\varphi}$$

$$\left|\tilde{\vec{d}}(\omega)\right|^2 = \left|\frac{\vec{d}_1}{i(\omega-\omega_1)+\Gamma_1/2} + \frac{\vec{d}_2 e^{i\varphi}}{i(\omega-\omega_2)+\Gamma_2/2}\right|^2 \quad (3)$$

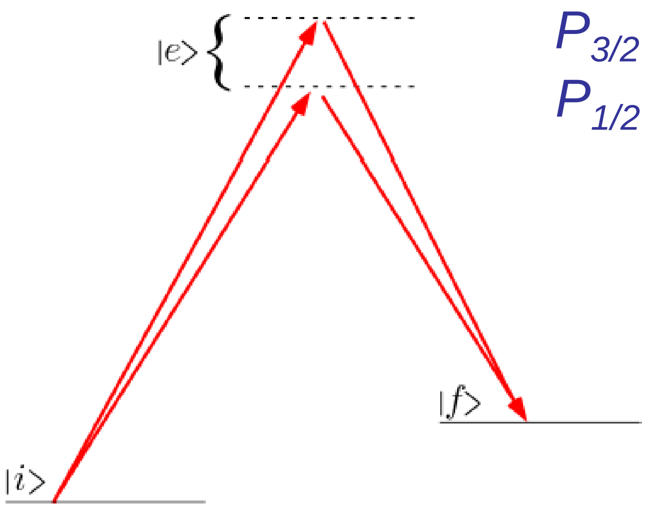
$$= \underbrace{\frac{|\vec{d}_1|^2}{(\omega-\omega_1)^2+(\Gamma_1/2)^2} + \frac{|\vec{d}_2|^2}{(\omega-\omega_2)^2+(\Gamma_2/2)^2}}_{\text{incoherent}}$$

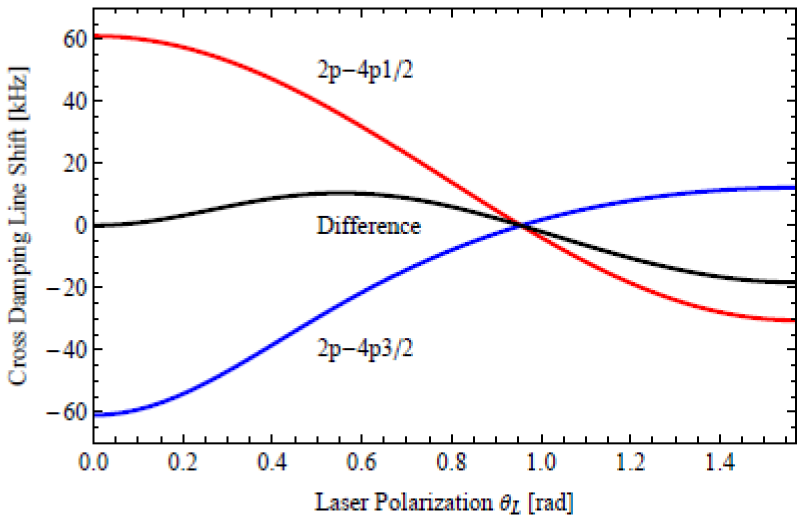
$$\underbrace{+\,\vec{d}_1\cdot\vec{d}_2\,\frac{\cos(\varphi)\left[\Gamma_1\Gamma_2/2+2(\omega-\omega_1)(\omega-\omega_2)\right]+\sin(\varphi)\left[(\omega-\omega_1)\Gamma_2-(\omega-\omega_2)\Gamma_1\right]}{\left[(\omega-\omega_1)^2+(\Gamma_1/2)^2\right]\,\left[(\omega-\omega_2)^2+(\Gamma_2/2)^2\right]}}_{\text{coherent}}$$





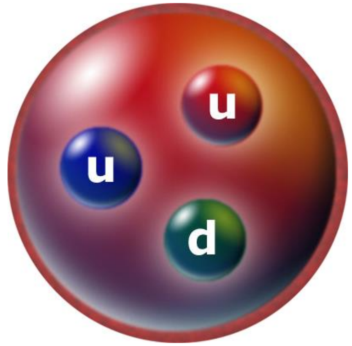
Cross damping problem in the 2S-4P experiment





Simple rule: if one wants to split the line by the factor of N, the perturbing line should be further away as $N\gamma$

Analysis of systematic
effects is
still in progress



Thank you for attention!

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