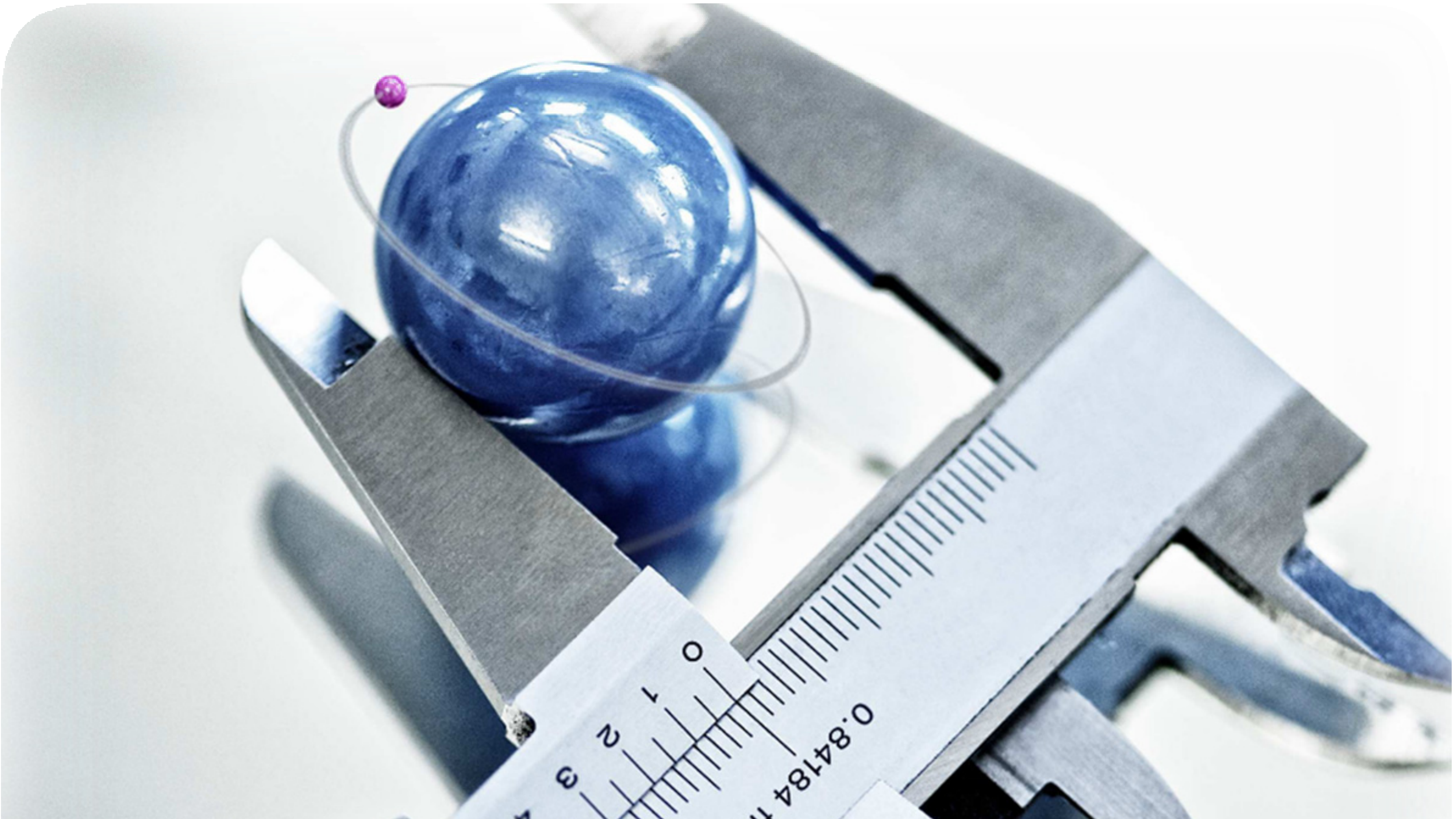
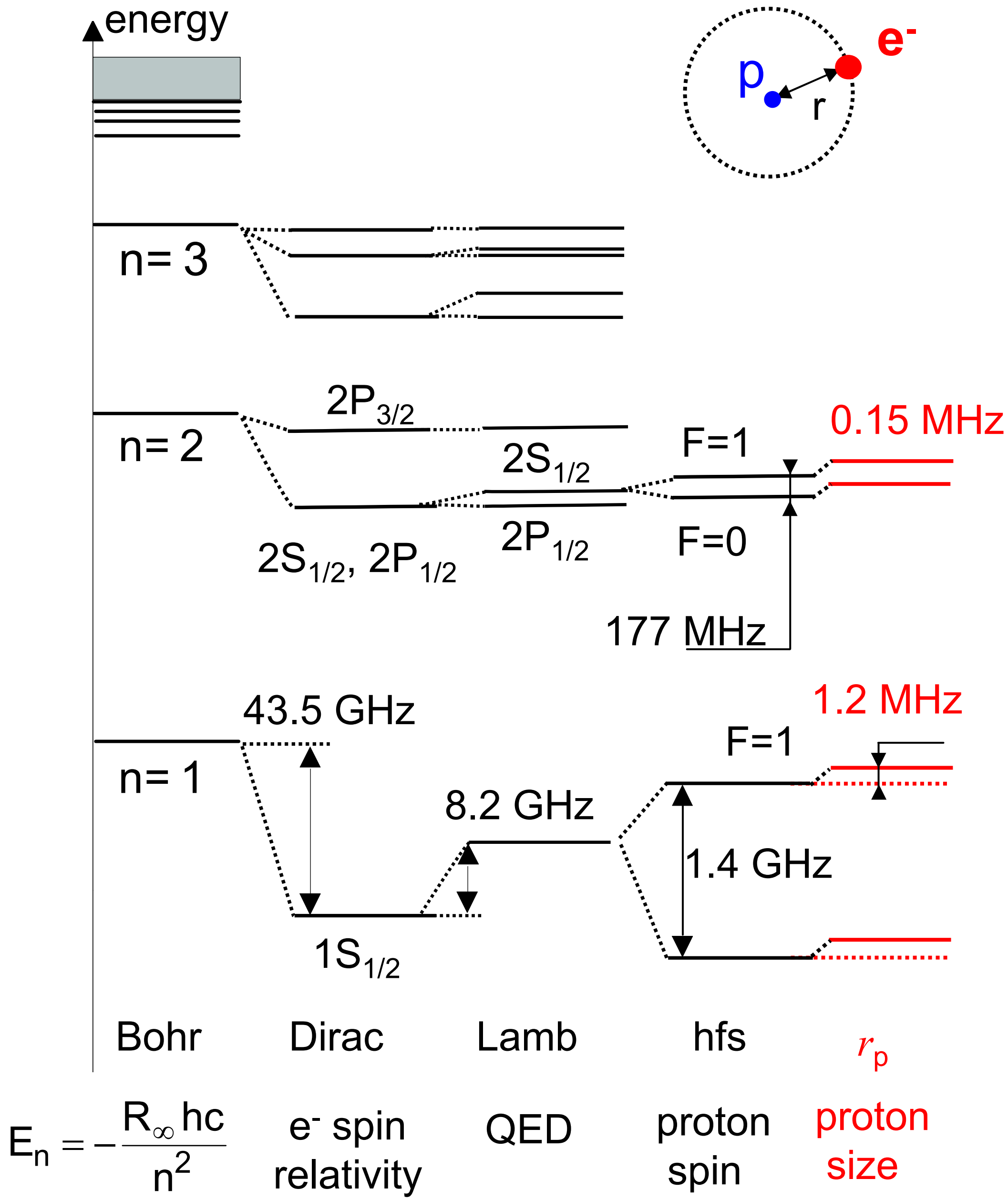
Hydrogen 1S-3S spectroscopy to contribute to the proton charge radius puzzle



S. Galtier, H. Fleurbaey, F. Nez, L. Julien, F. Biraben
Laboratoire Kastler Brossel CNRS, UPMC, ENS

Hydrogen energy levels



$E(n,l,j)$ = Dirac + recoil + $L(n,j)$

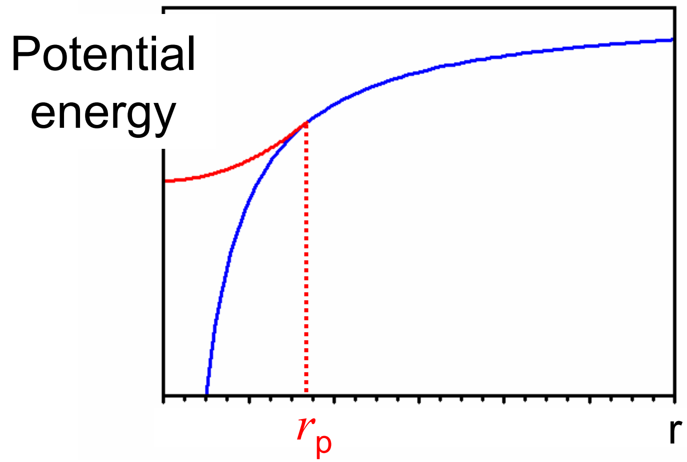
$hcR_\infty\, f(\alpha,\, m_e/m_p,\, n,l,j)$

exact

not well known

$$\Delta E^{FS} = \frac{2(Z\alpha)^4}{3n^3} m_r^3\, r_p^2\, \delta_{l0}$$

- QED corrections ($1/n^3$)
- relativistic recoil
- charge radius of the proton ($1/n^3$)



$L^{theo}(1S_{1/2})$ = 8172.903 (4) (50) MHz

QED

scattering proton size

H spectroscopy : R_∞ and L_{1S} determination

$$E(n,l,j) = hcR_\infty\, f(,\alpha,\, m_e/m_p,\, n,l,j) + \text{recoil} + L(n,j,r_p) \approx \frac{R_\infty}{n^2} + L(n,r_p)$$

MPQ Garching $\quad \nu(1S-2S) = (1-\frac{1}{4})R_\infty + L(1S) - L(2S)$

LKB Paris $\quad \nu(2S-8S) = (\frac{1}{4}-\frac{1}{64})R_\infty + L(2S) - L(8S)$

S. Karshenboim
K. Pachucki $\quad L(1S) - 8L(2S) = \text{precisely calculated}$

Linear combinations $\rightarrow$ R_∞, $L^{exp}(1S)$

$L^{exp}(1S)$ = 8172.840 (19) kHz + QED $\rightarrow$ r_p (1%)

cR_∞ = 3 289 841 960 360.9 (21.9) kHz (6.6×10^{-12})

proton radius from H spectroscopy

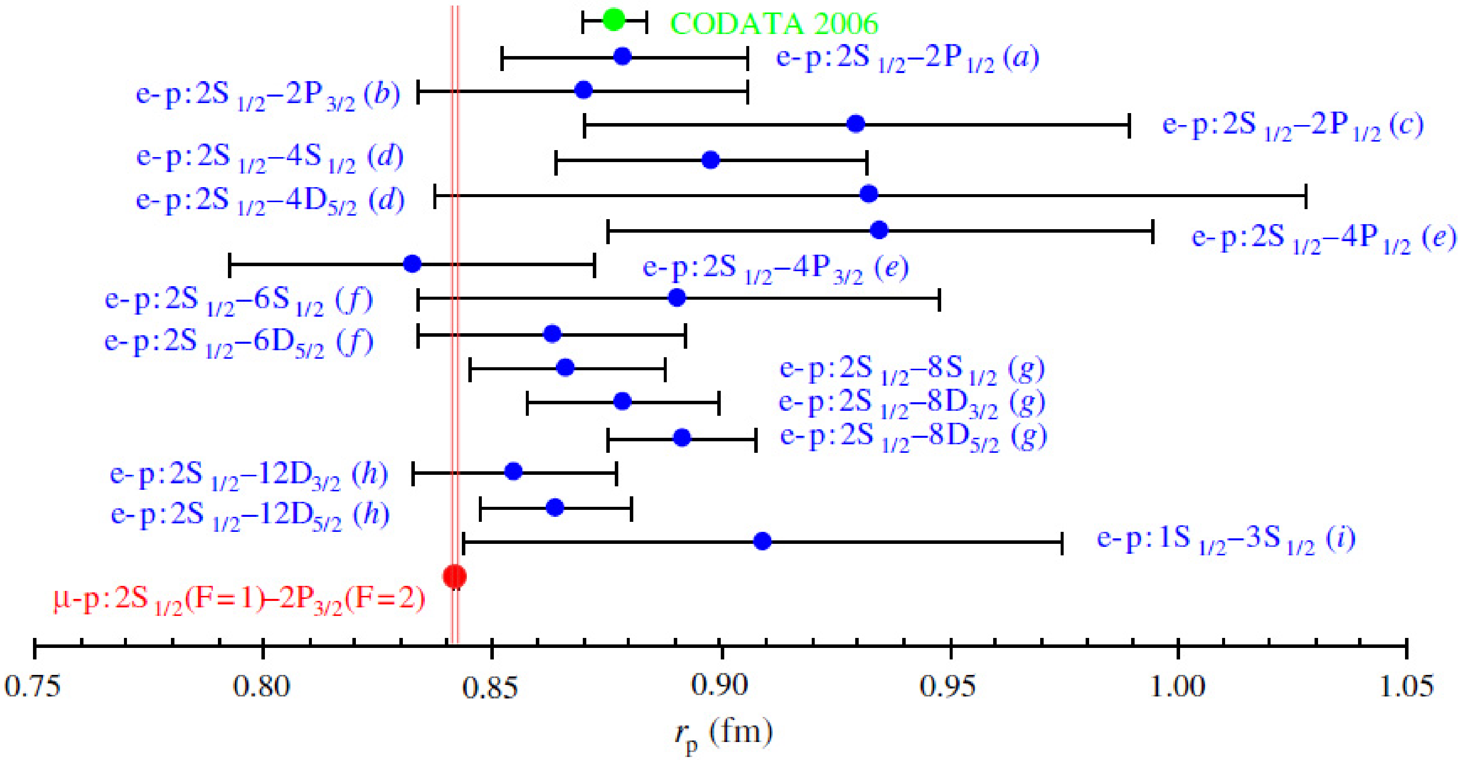
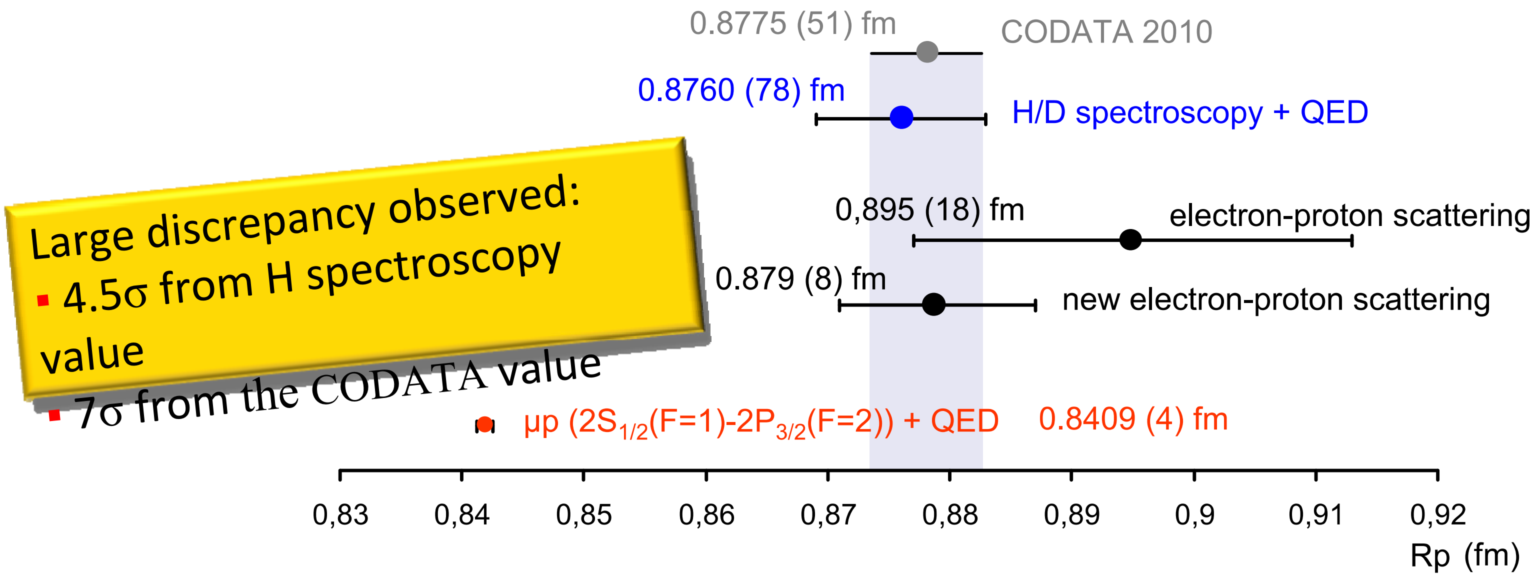


Figure 5. Comparison of various determinations of the proton radius from hydrogen spectroscopy. Each value is obtained from the 1S–2S transition frequency, the $1/n^3$ law and one of the other hydrogen experimental data from 2S–n(S,P,D). ((*a*) From Lundeen & Pipkin [55], (*b*) from Hagley & Pipkin [56], (*c*) from Newton *et al.* [57], (*d*) from Weitz *et al.* [58], (*e*) from Berkeland *et al.* [59], (*f*) from Bourzeix *et al.* [60] combined with Arnoult *et al.* [53], (*g*) from de Beauvoir *et al.* [24], (*h*) from Schwob *et al.* [61], and (*i*) from Arnoult *et al.* [53]). The double line corresponds to the uncertainty of the proton radius determination obtained from muonic hydrogen spectroscopy. (Online version in colour.)

Phil. Trans. R. Soc. A (2011) 369, 4064-4077

« Proton radius puzzle »



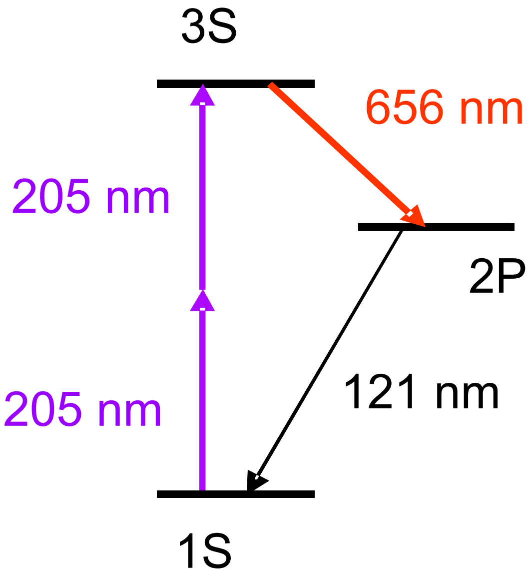
- Improve precision measurements on hydrogen:

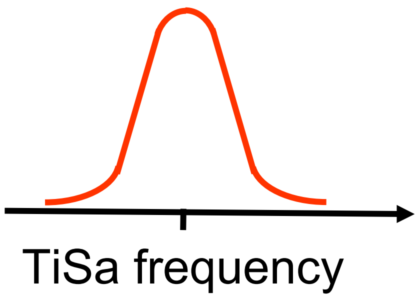
1S-2S (*MPQ Garching*) , *1S-3S* (*LKB and MPQ G.), 2S-6S (NPL), 2S-2P (York)*

- Improve electron-proton scattering experiment (*Newport News,Va and Mainz*)
- Improve the uncertainty of R_∞ (*$^{20}Ne^{9+}$ Rydberg states at NIST-Gaithersburg*)

- Perform muon-proton scattering experiment (*MUSE project at PSI*)
- Perform μ-He+ spectrocopy (*CREMA collaboration at PSI: 2S-2P*)
- Perform precise He+ spectrocopy (1S-2S *MPQ Garching and LaserLab Amsterdam)*

1S-3S/2S-8S spectroscopy of hydrogen





- 1S atomic beam (10^{14} at/cm^3) (~10^{11}at/s)

  2S atomic beam 17 at/cm^3 ! (2×10^6 at/s)

- transition probability $\gamma_{fi} \propto \Gamma_f \gamma^2$

  1S-3S: γ =2.14 a.u.
  Γ_f= 1 MHz

  2S-8S: γ =14.921 a.u.
  Γ_f= 144 kHz

  1S-2S: γ =7.85 a.u.
  Γ_f= 1.2 Hz

- 205 nm laser (<1mW) (820 nm $\rightarrow$ 410 nm $\rightarrow$ 205 nm)

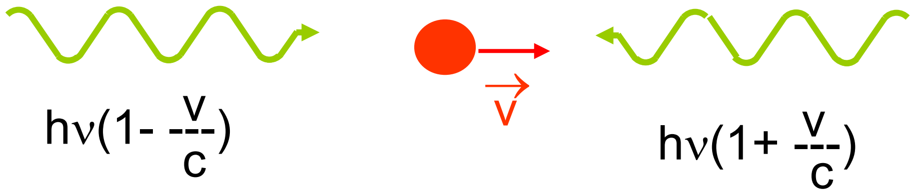
  2S-8S 778 nm 1.6W !

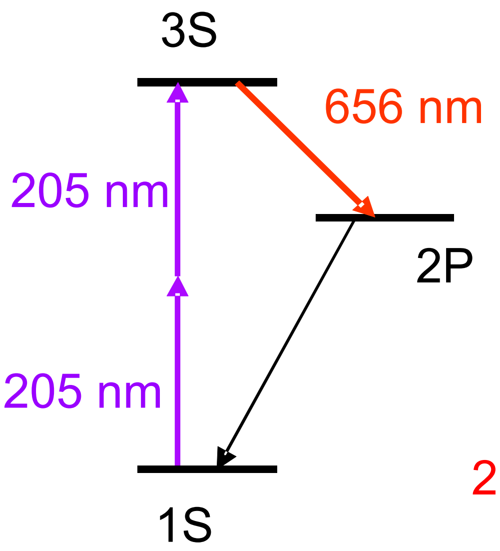
- Velocity distribution measurement :

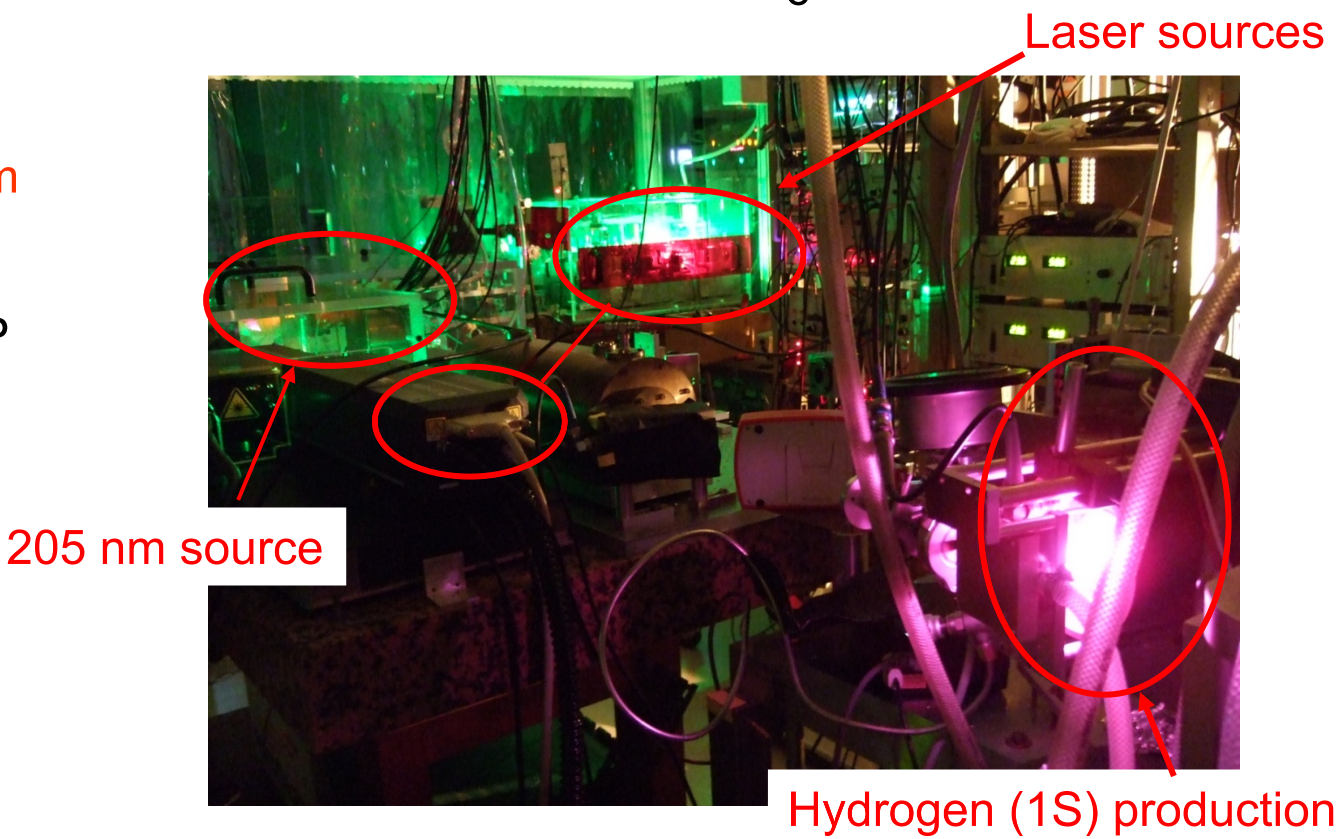
  No "easy" optical transition for Doppler spectroscopy
  (1S-2P : 121 nm !)

1S-3S spectroscopy of hydrogen

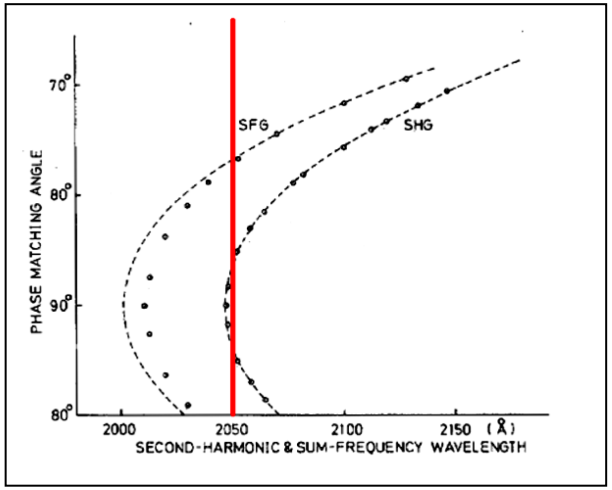
Two photon spectroscopy : first order Doppler effect compensation







The 205 nm cw light source



- **Two doubling stages** :

TiSa: 820 nm → 410 nm in LBO → 205 nm in BBO

< 1 mW quasi-continuous

- **Frequency mixing in BBO**:

NdYO4: 532 nm → 266 nm

266 nm + TiSa : 896 nm → 205 nm

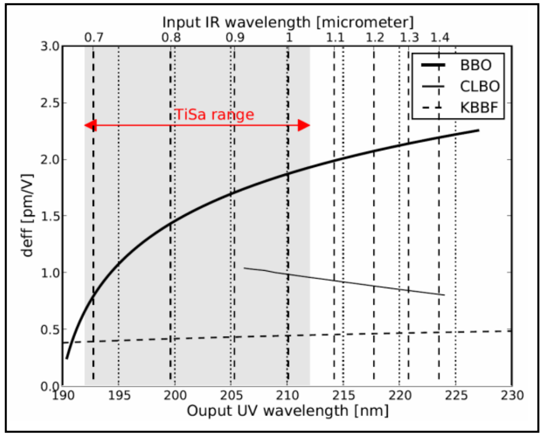
15 mW cw

- Two-photon absorption probability proportional to **P²**:
  → Enhancement of the S/N ratio of the resonance signal

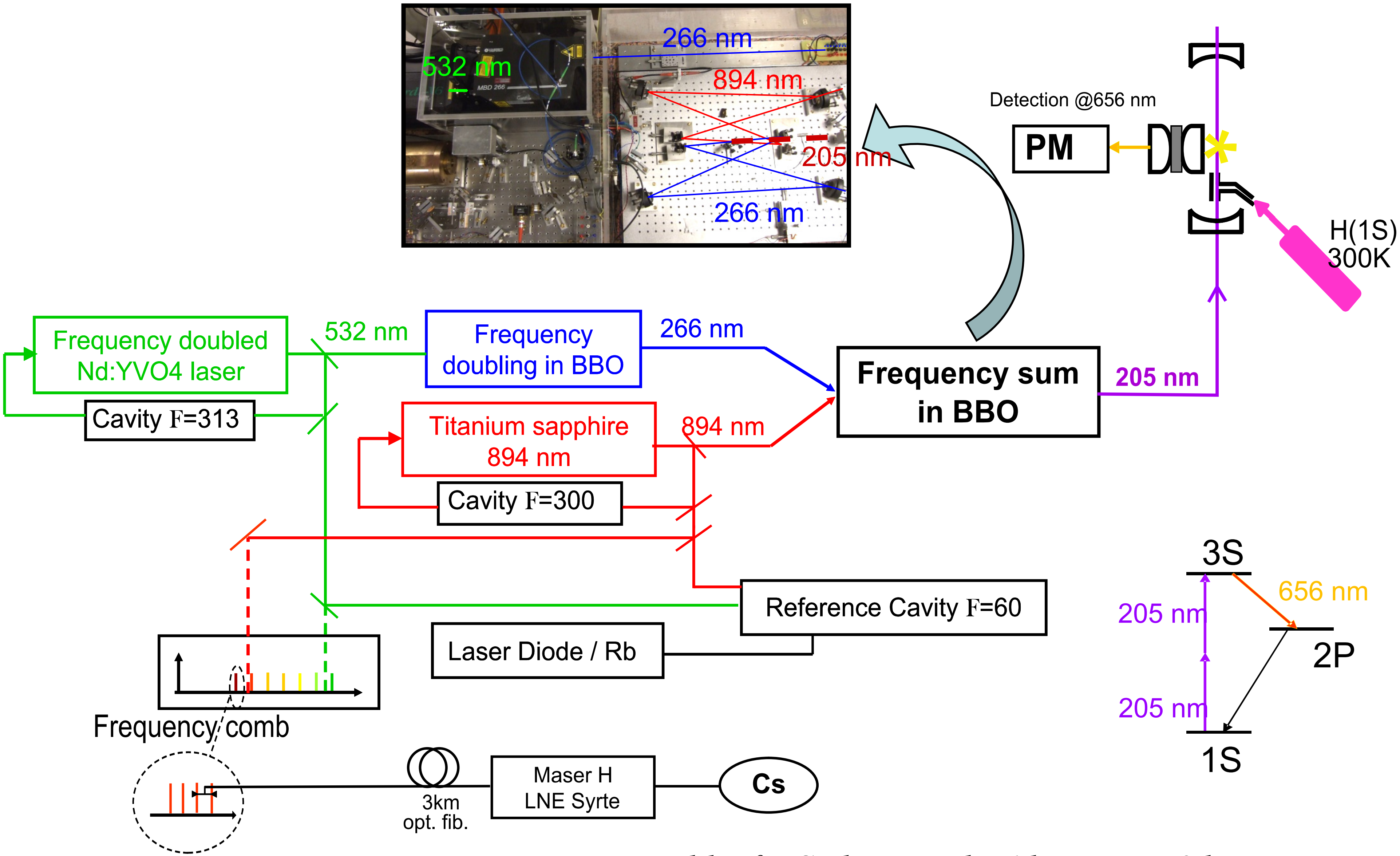
- **Continuous** laser beam:
  → Easier spectroscopy (less systematic compared to pulsed spectroscopy)

- Possibility of generating 194 nm (1S-4S)

S. Galtier, F. Nez, L. Julien and F. Biraben, Opt. Comm. 324 (2014) p.34-37 : "Ultraviolet continuous-wave laser source at 205 nm for hydrogen spectroscopy".

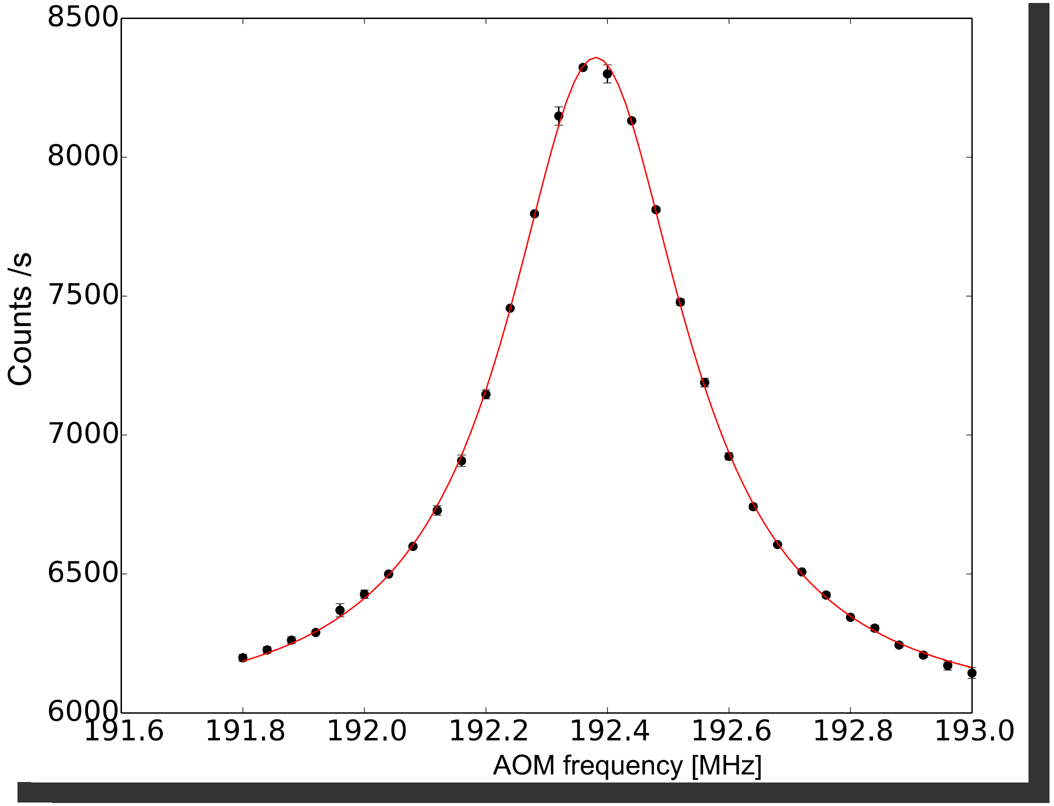


The experimental setup



Linewidth of TiSa laser and V6 laser : < 40 kHz

The resonance signal

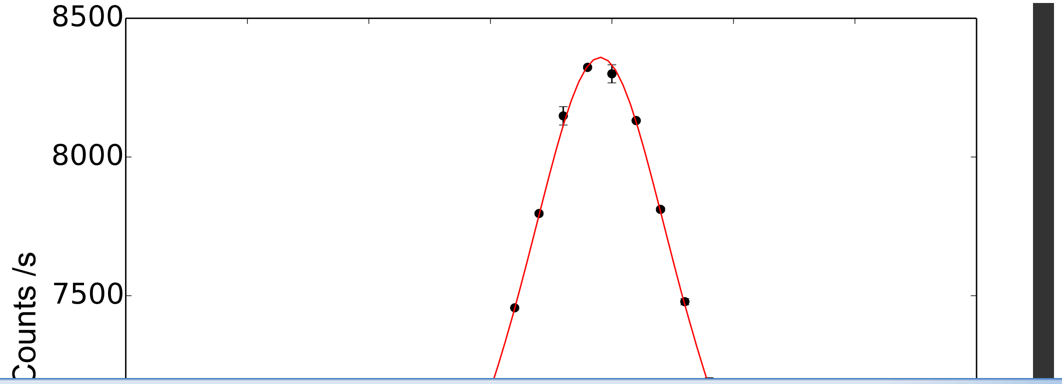


- The TiSa laser frequency is scanned over 2.4 MHz, with step of 80 kHz.
  → curve obtained with an integration time of about 3.5 hours.

- fitted with a lorentzian function: Γ =1.5 MHz (1S-3S natural linewidth: 1MHz)

(lorentzian fit on line sophisticated fit after…)

The resonance signal



Frequency shifts sources:

- **Second order Doppler effect**
  - **Light shift**
    - **Collisional shift (thermal beam!)**

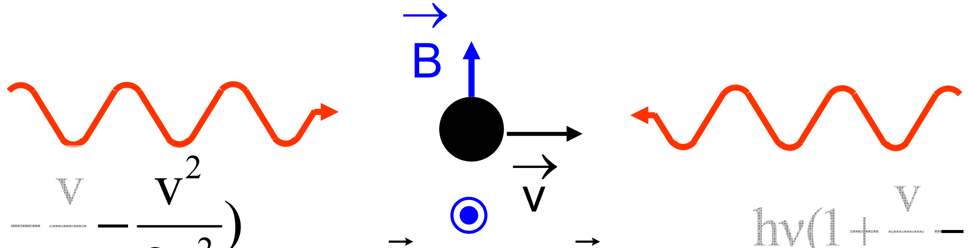
- We scan the TiSa laser frequency over 2.4 MHz, with step of 80 kHz.
  → curve obtained with an integration time of about 3.5 hours.

- fitted with a lorentzian function: Γ =1.5 MHz   (1S-3S natural linewidth: 1MHz)

(lorentzian fit on line   sophisticated fit after…)

The 2nd order Doppler effect compensation

- **Relativistic effect**
- v = 3km/s → δ_{dop}= 120 kHz !
- **Principle**: motional Stark effect for opposite parity levels (ex. S and P)



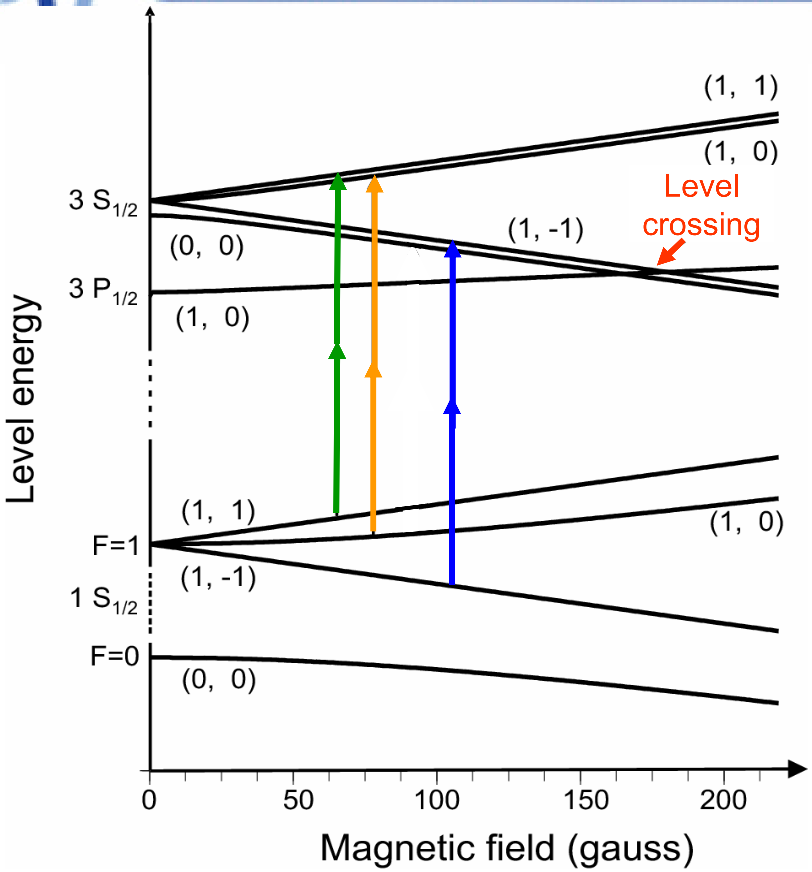
$$h\nu\left(1-\frac{v}{c}-\frac{v^2}{2c^2}\right) \qquad \vec{E}=\vec{v}\wedge\vec{B} \qquad h\nu\left(1+\frac{v}{c}-\frac{v^2}{2c^2}\right)$$

$$\delta_{Stark}=\frac{E^2}{\Delta\nu_{SP}}=\frac{v^2B^2}{\Delta\nu_{SP}}$$

$$\delta_{dop}=-\nu_{at}\frac{v^2}{2c^2}$$

F. Biraben, L. Julien, J. Plon and F. Nez, Europhys. Lett., 15 (1991) p.831 :
"Compensation of the second Doppler effect in two photon spectroscopy of atomic hydrogen".

The 2nd order Doppler effect compensation



- **Two photon spectrocopy: ΔF = 0 and ΔmF = 0**

$1S_{1/2}$ (F=1) → $3S_{1/2}$ (F=1)

- **Zeeman splitting:**

$1S_{1/2}$ (F=1, mF=1) → $3S_{1/2}$ (F=1, mF =1)

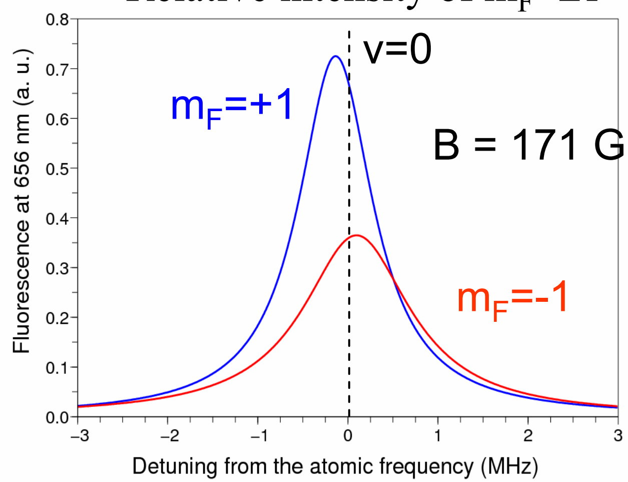
$1S_{1/2}$ (F=1, mF=-1) → $3S_{1/2}$ (F=1, mF =-1)

$1S_{1/2}$ (F=1, mF=0) → $3S_{1/2}$ (F=1, mF =0)

- **Motional Stark effect - Level crossing 180G:**

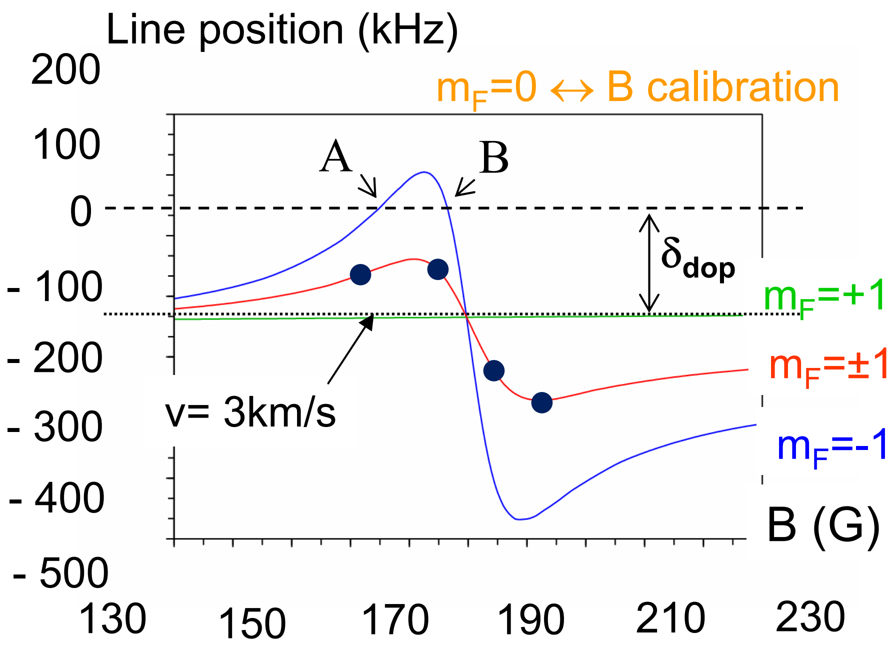
$3S_{1/2}$ (F=1, mF = -1) coupled to $3P_{1/2}$

Relative intensity of m_F=±1



G. Hagel, R. Battesti, F. Nez, L. Julien and F. Biraben, Phys. Rev. Lett. 89 (2002) p.203001 : "Observation of a motional Stark effect to determine the second order Doppler effect".

The 2nd order Doppler effect compensation



- **Two photon spectroscopy: ΔF = 0 and ΔmF = (**

$1S_{1/2}$ (F=1) → $3S_{1/2}$ (F=1)

- **Zeeman splitting:**

$1S_{1/2}$ (F=1, mF=1) → $3S_{1/2}$ (F=1, mF =1)

$1S_{1/2}$ (F=1, mF=-1) → $3S_{1/2}$ (F=1, mF =-1)

$1S_{1/2}$ (F=1, mF=0) → $3S_{1/2}$ (F=1, mF =0)

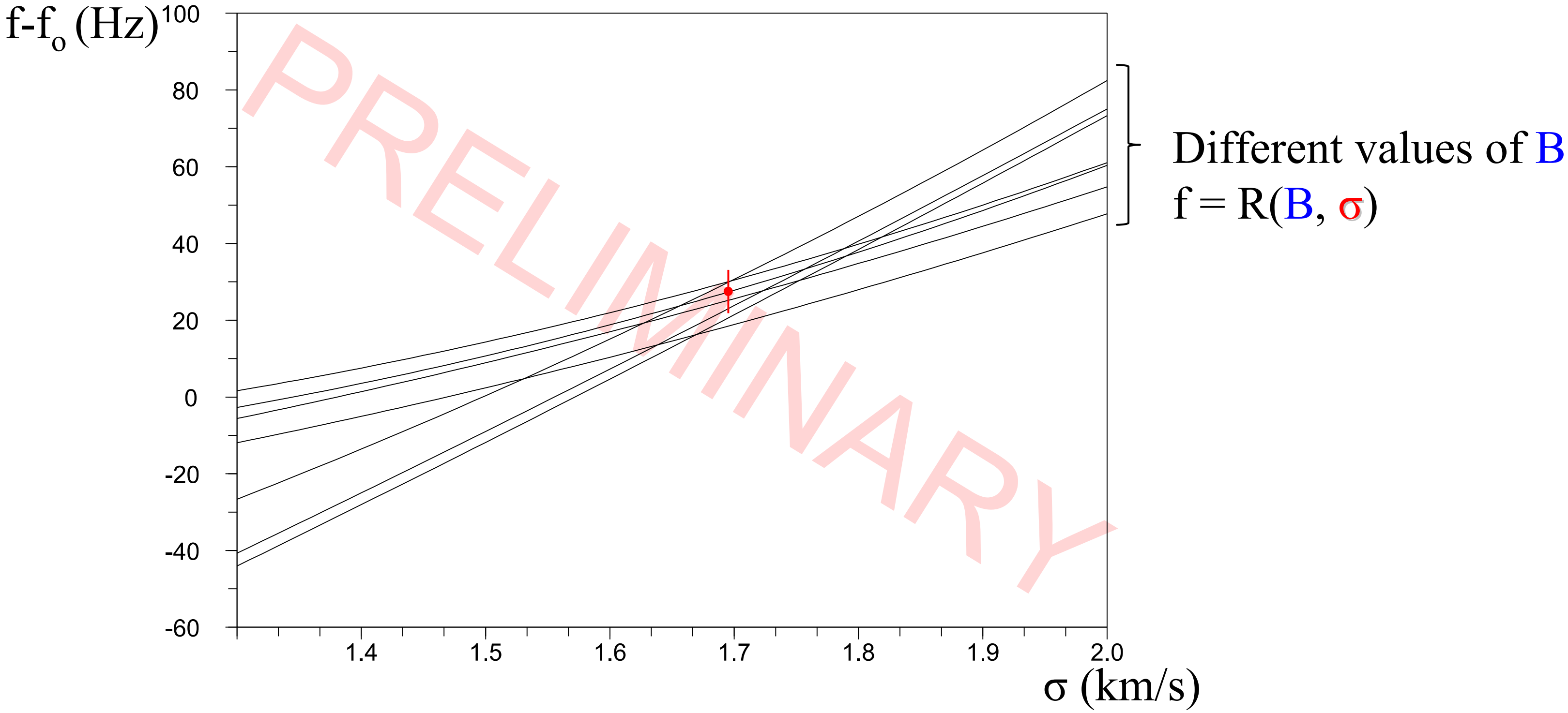
- **Motional Stark effect - Level crossing 180G:**

$3S_{1/2}$ (F=1, mF = -1) coupled to $3P_{1/2}$

Partial compensation at 171G
→ 2nd order Doppler effect determination
for a given velocity distribution

G. Hagel, R. Battesti, F. Nez, L. Julien and F. Biraben, Phys. Rev. Lett. 89 (2002) p.203001 : "Observation of a motional Stark effect to determine the second order Doppler effect".

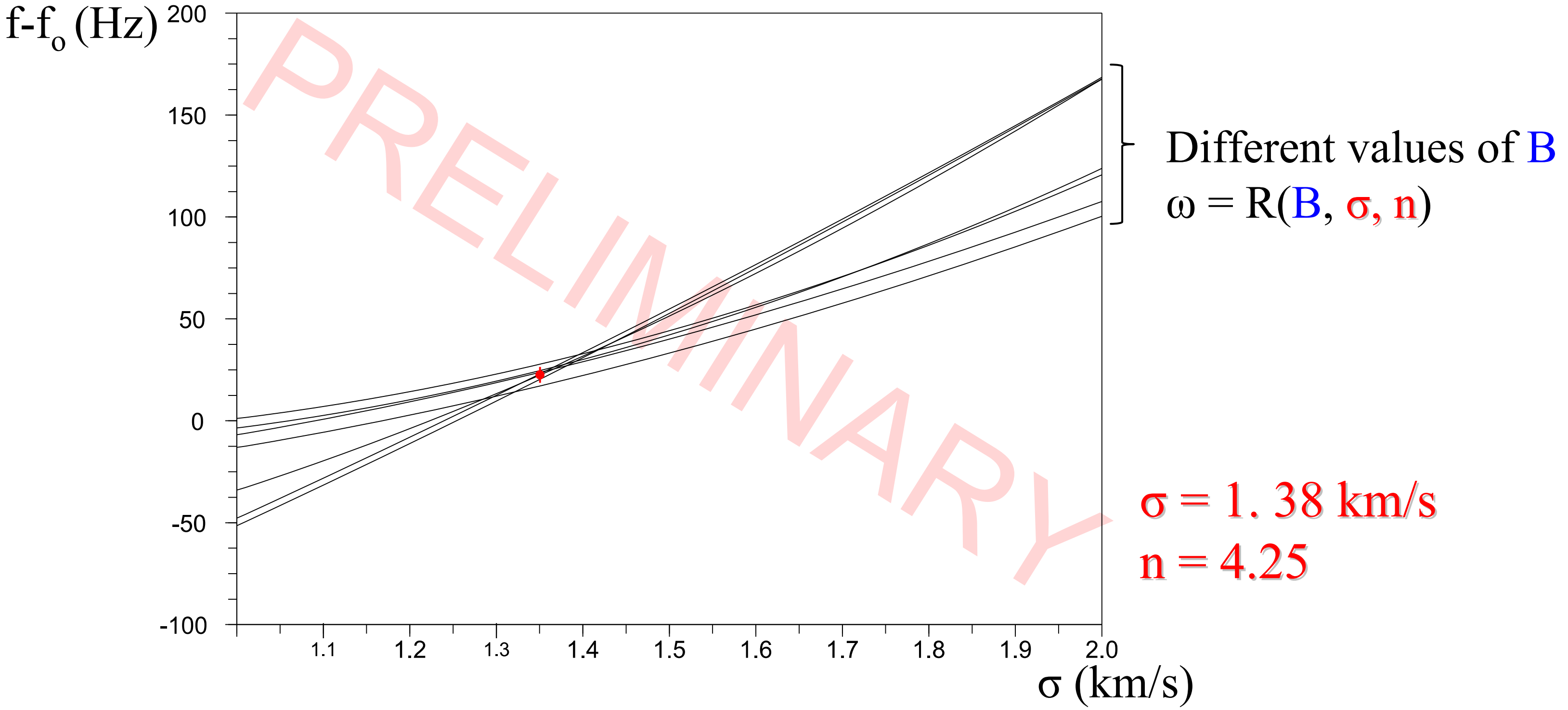
2014 first results



Velocity distribution?

Effusive jet: $f(\mathrm{v},\sigma) = \mathrm{v}^3 \exp(-\mathrm{v}^2 / 2\sigma^2)$

2014 first results



Velocity distribution?

~~Effusive jet:~~ $f(\mathrm{v},\sigma) = \mathrm{v}^3 \exp(-\mathrm{v}^2/2\sigma^2)$ (3 → n)

The velocity distribution

→ fast atoms pull along slower one:

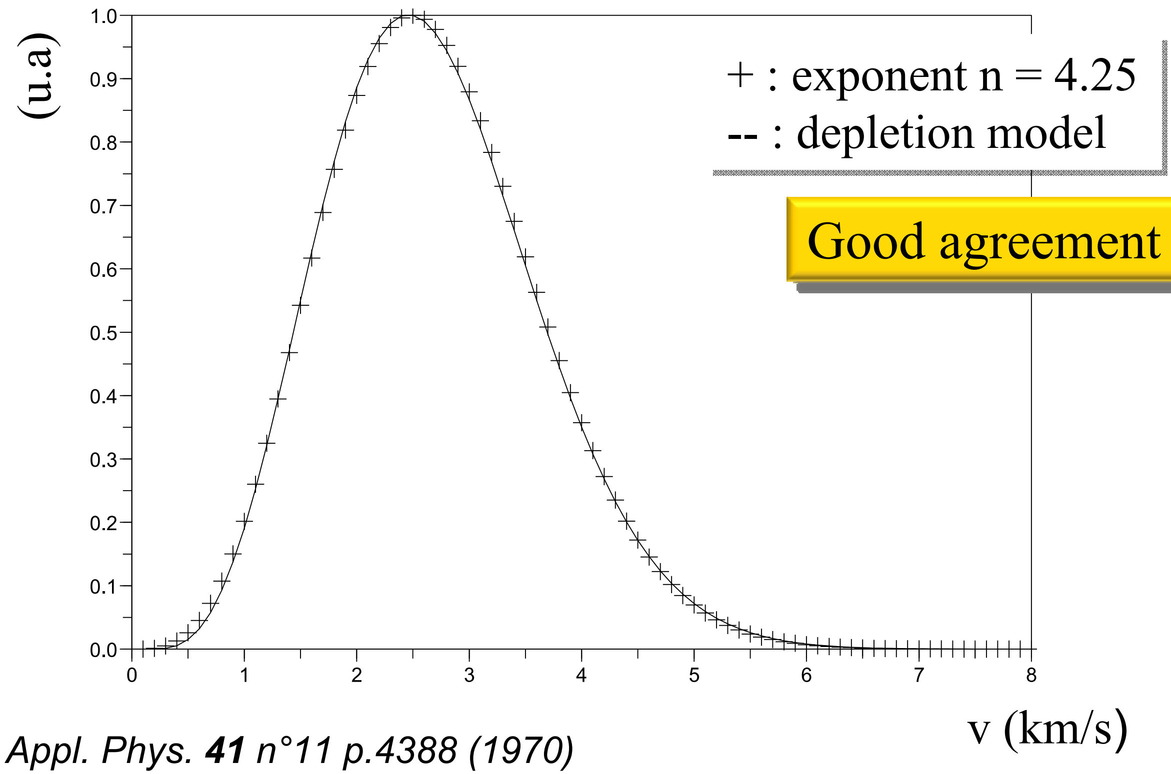
$$f_M(\sigma)P(l_{res.},\mathrm{L},\mathrm{v})\exp(-\mathrm{v}_0(p,\mathrm{L}')/\mathrm{v})$$

Maxwellian distribution → $f_M(\sigma)$

Velocity-dependant mean-free path after a pipe → $P(l_{res.},\mathrm{L},\mathrm{v})$

Total depletion of slow atoms → $\exp(-\mathrm{v}_0(p,\mathrm{L}')/\mathrm{v})$

l_{res}=mean-free path in atomic reservoir
L = pipe length
L’ = distance between the pipe and the interaction zone

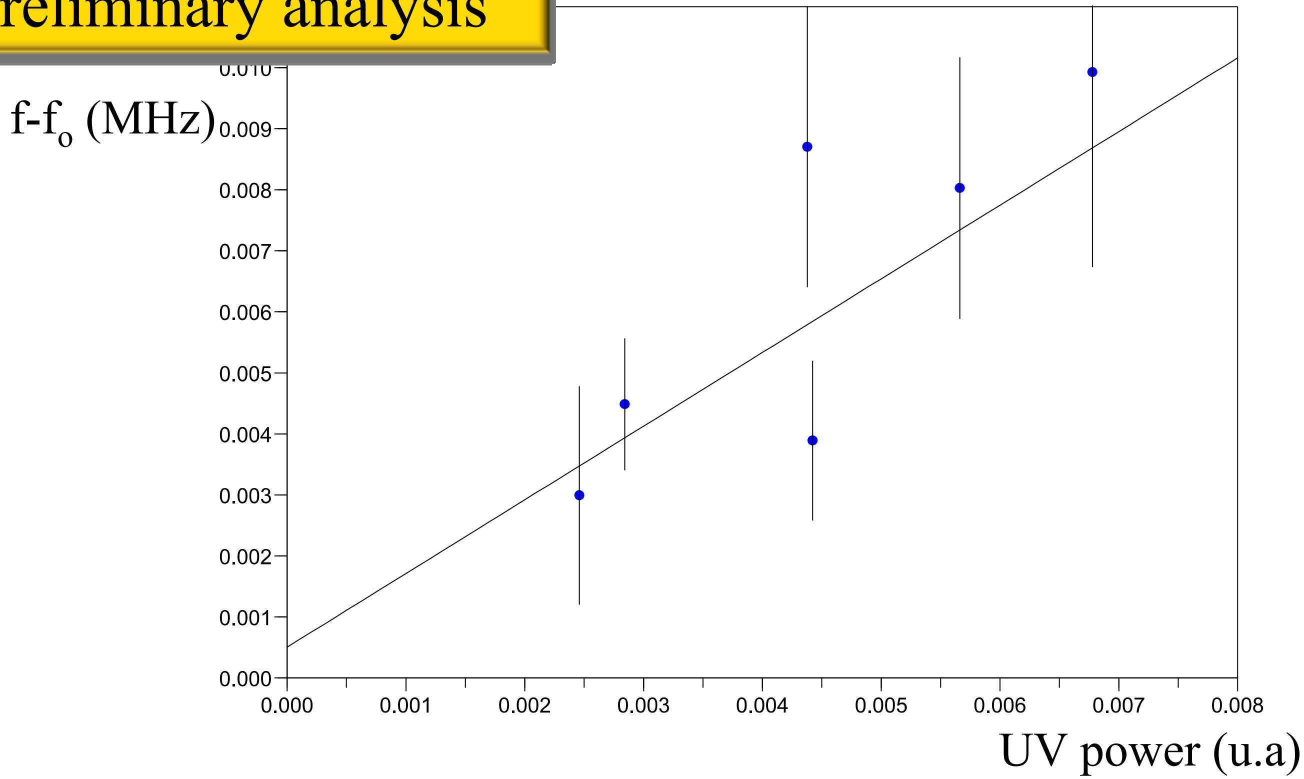


Good agreement !

D.R. Olander et al. J. Appl. Phys. ***41*** *n°11 p.4388 (1970)*
see also A. Huber et al Phys Rev A 59 1844 (1999)

The light shift

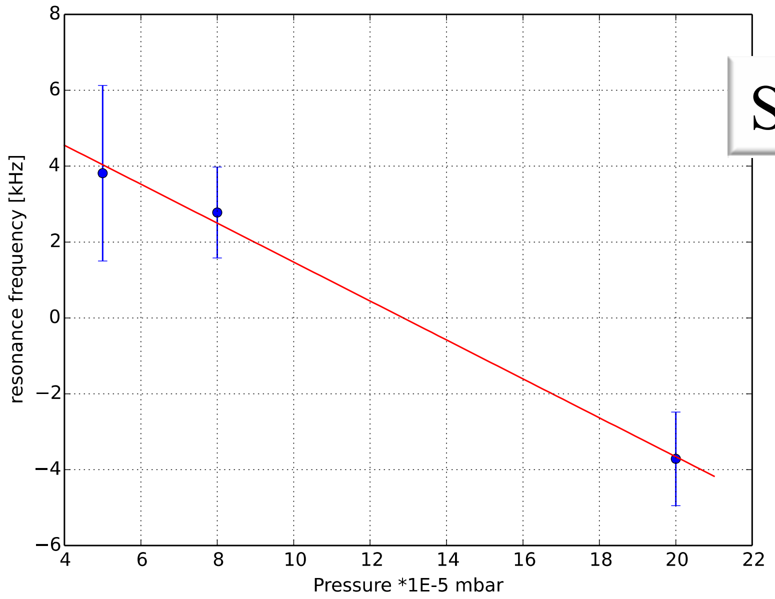
Preliminary analysis



Light shift correction □ $u_r \lesssim 10^{-12}$ (3 kHz)

$\Longrightarrow$ Monitoring of the transmitted UV light from the FP cavity with a PMT instead of a UV-Si photodiode

The collisional shift and conclusion



Shift at 8.10^{-5} mbar ≈ 4(2) kHz

- Very preliminary results
- Collisional shift = the limiting effect!
  Improving the vacuum (1×10^{-4}mbar currently).
- Cooling down the atomic jet (N_2).
- Better UV power estimation

- Analysis on going
- next step: 1S-4S transitions at 194 nm (Γ=700 kHz).
  Laser to be checked

Comments

Which precision on 1S-3S transition to solve the proton puzzle ?

Taking into account the measured 1S-2S frequency:

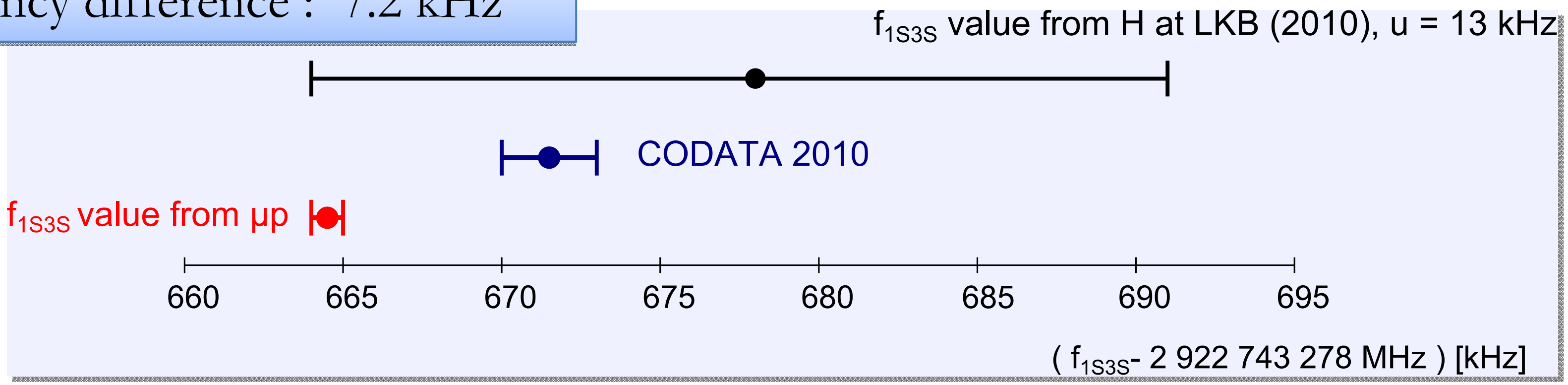
- with r_p deduced from hydrogen+scattering experiment (CODATA)

  $\nu[1S_{1/2}\text{-}3S_{1/2}]$ = 2 922 743 278.6716 (14) MHz   (4.8×10^{-13})

- with r_p deduced from μp spectroscopy:

  $\nu[1S_{1/2}\text{-}3S_{1/2}]$ = 2 922 743 278.6644 (5) MHz   (1.7×10^{-13})

Frequency difference : 7.2 kHz



I thank you
for your attention!
Still missing
pieces…
Bound state QED….
Proton structure
Experiments…
New theory…
cnrs
dépasser les frontières
AGENCE NATIONALE DE LA RECHERCHE
ANR
FIRST TF
UPMC
SORBONNE UNIVERSITÉS

Codata Rydberg constant versus time

1998 :	109 737.315 685 9 (16) cm-1	without LKB
1998 :	109 737.315 685 3 (10) cm-1	without MPQG
1998 :	109 737.315 685 6 (96) cm-1	H only
1998 :	109 737.315 683 9 (13) cm-1	D only
1998 :	109 737.315 685 21 (81) cm-1	Codata
2002 :	109 737.315 685 59 (85) cm-1	H only
2002 :	109 737.315 683 9 (13) cm-1	D only
2002 :	109 737.315 685 25 (73) cm-1	Codata
2006 :	109 737.315 685 62 (85) cm-1	H only
2006 :	109 737.315 683 9 (13) cm-1	D only
2006 :	109 737.315 685 27 (73) cm-1	Codata
2010 :	109 737.315 685 61 (60) cm-1	H only
2010 :	109 737.315 683 7 (13) cm-1	D only
2010 :	109 737.315 685 39 (73) cm-1	Codata
2010 :	109 737.315 681 75 (12) cm-1	with µp

2006

TABLE XLV. Summary of the results of some of the least-squares adjustments used to analyze the input data related to R_∞. The values of R_∞, R_p, and R_d are those obtained in the indicated adjustment, N is the number of input data, M is the number of adjusted constants, $\nu = N - M$ is the degrees of freedom, and $R_B = \sqrt{\chi^2/\nu}$ is the Birge ratio. See the text for an explanation and discussion of each adjustment, but, in brief, 4 is the final adjustment; 7 is 4 with the input data for R_p and R_d deleted; 8 is 4 with just the R_p datum deleted; 9 is 4 with just the R_d datum deleted; 10 is 4 but with only the hydrogen data included; and 11 is 4 but with only the deuterium data included.

Adj.	N	M	ν	χ^2	R_B	R_∞/m^{-1}	$u_r(R_\infty)$	R_p/fm	R_d/fm
4	135	78	57	65.0	1.07	10 973 731.568 527(73)	6.6×10^{-12}	0.8768(69)	2.1402(28)
7	133	78	55	63.0	1.07	10 973 731.568 518(82)	7.5×10^{-12}	0.8760(78)	2.1398(32)
8	134	78	56	63.8	1.07	10 973 731.568 495(78)	7.1×10^{-12}	0.8737(75)	2.1389(30)
9	134	78	56	63.9	1.07	10 973 731.568 549(76)	6.9×10^{-12}	0.8790(71)	2.1411(29)
10	117	68	49	60.8	1.11	10 973 731.568 562(85)	7.8×10^{-12}	0.8802(80)	
11	102	61	41	54.7	1.16	10 973 731.568 39(13)	1.1×10^{-11}		2.1286(93)

2010

TABLE XXXVIII. Summary of the results of some of the least-squares adjustments used to analyze the input data related to R_∞. The values of R_∞, r_p, and r_d are those obtained in the indicated adjustment, N is the number of input data, M is the number of adjusted constants, $\nu = N - M$ is the degrees of freedom, and $R_B = \sqrt{\chi^2/\nu}$ is the Birge ratio. See the text for an explanation and discussion of each adjustment. In brief, adjustment 6 is 3 but the scattering data for the nuclear radii are omitted; 7 is 3, but with only the hydrogen data included (no isotope shift); 8 is 7 with the r_p data deleted; 9 and 10 are similar to 7 and 8, but for the deuterium data; 11 is 3 with the muonic Lamb-shift value of r_p included; and 12 is 11, but without the scattering values of r_p and r_d.

Adj.	N	M	ν	χ^2	R_B	R_∞ (m^{-1})	$u_r(R_\infty)$	r_p (fm)	r_d (fm)
3	149	82	67	58.1	0.93	10 973 731.568 539(55)	5.0×10^{-12}	0.8775(51)	2.1424(21)
6	146	82	64	55.5	0.93	10 973 731.568 521(82)	7.4×10^{-12}	0.8758(77)	2.1417(31)
7	131	72	59	53.4	0.95	10 973 731.568 561(60)	5.5×10^{-12}	0.8796(56)	
8	129	72	57	52.5	0.96	10 973 731.568 528(94)	8.6×10^{-12}	0.8764(89)	
9	114	65	49	46.9	0.98	10 973 731.568 37(13)	1.1×10^{-11}		2.1288(93)
10	113	65	48	46.8	0.99	10 973 731.568 28(30)	2.7×10^{-11}		2.121(25)
11	150	82	68	104.9	1.24	10 973 731.568 175(12)	1.1×10^{-12}	0.842 25(65)	2.128 24(28)
12	147	82	65	74.3	1.07	10 973 731.568 171(12)	1.1×10^{-12}	0.841 93(66)	2.128 11(28)

1998

TABLE XVIII. Summary of the results of some of the least-squares adjustments used to analyze the input data related to R_∞ given in Tables XIV.A.1 and XIV.A.2. The values of R_∞, R_p, and R_d are those obtained in the indicated adjustment, N is the number of input data, M is the number of adjusted constants, $\nu = N - M$ is the degrees of freedom, $R_B = \sqrt{\chi^2/\nu}$ is the Birge ratio, and $Q(\chi^2|\nu)$ is the probability that the observed value of χ^2 for ν degrees of freedom would have exceeded that observed value.

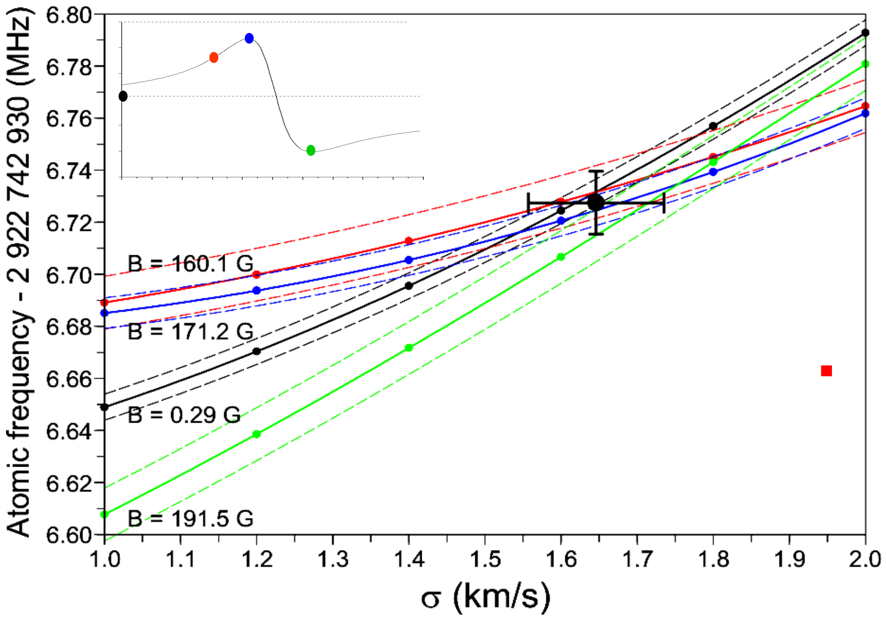
Adj.	N	M	ν	χ^2	R_B	$Q(\chi^2\|\nu)$	R_∞/m^{-1}	$u_r(R_\infty)$	R_p/fm	R_d/fm
1	50	28	22	12.7	0.76	0.94	10 973 731.568 521(81)	7.3×10^{-12}	0.859(10)	2.1331(42)
2	48	28	20	10.4	0.72	0.96	10 973 731.568 549(83)	7.5×10^{-12}	0.907(32)	2.153(14)
3	31	18	13	7.4	0.75	0.88	10 973 731.568 556(96)	8.7×10^{-12}	0.908(33)	
4	16	11	5	2.1	0.65	0.84	10 973 731.568 32(30)	2.7×10^{-11}		2.133(28)
5	36	28	8	4.8	0.78	0.78	10 973 731.568 59(16)	1.5×10^{-11}	0.910(35)	2.154(15)
6	39	25	14	8.5	0.78	0.86	10 973 731.568 53(10)	9.2×10^{-12}	0.903(35)	2.151(16)

2002

TABLE XXIV. Summary of the results of some of the least-squares adjustments used to analyze the input data related to R_∞. The values of R_∞, R_p, and R_d are those obtained in the indicated adjustment, N is the number of input data, M is the number of adjusted constants, $\nu = N - M$ is the degrees of freedom, and $R_B = \sqrt{\chi^2/\nu}$ is the Birge ratio.

Adj.	N	M	ν	χ^2	R_B	R_∞/m^{-1}	$u_r(R_\infty)$	R_p/fm	R_d/fm
4	105	61	44	31.2	0.84	10 973 731.568 525(73)	6.6×10^{-12}	0.8750(68)	2.1394(28)
7	103	61	42	29.0	0.83	10 973 731.568 511(82)	7.5×10^{-12}	0.8736(77)	2.1389(32)
8	104	61	43	29.7	0.83	10 973 731.568 490(78)	7.1×10^{-12}	0.8717(74)	2.1381(30)
9	104	61	43	30.2	0.84	10 973 731.568 546(76)	6.9×10^{-12}	0.8769(71)	2.1402(29)
10	87	36	51	27.1	0.87	10 973 731.568 559(85)	7.8×10^{-12}	0.8782(80)	
11	72	28	44	20.9	0.86	10 973 731.568 39(13)	1.1×10^{-11}		2.1285(93)

2010 Results



- **Velocity distribution:**

$$f(\mathrm{v},\sigma) = \mathrm{v}^3 \exp(-\mathrm{v}^2 / 2\sigma^2)$$

- **Line shape:**

$$\mathrm{R}(\omega_{\mathrm{laser}}, \sigma, \mathrm{B})$$

→ **σ = 1.646 (89) km/s**

LKB	$\nu[1S_{1/2}\text{-}3S_{1/2}]$ = 2 922 743 278.6783 (**130**) MHz	(4.6×10^{-12})
NIST (data base)	$\nu[1S_{1/2}\text{-}3S_{1/2}]$ = 2 922 743 278.6716 (14) MHz	(4.8×10^{-13})

We deduce: **r_p = 0.911 (65) fm**

O. Arnoult, F. Nez, L. Julien, and F. Biraben, Eur. Phys. J. D 60 p.243 (2010)

The velocity distribution

$$P[Kn,\psi(z)]=\frac{(\pi)^{1/2}}{2}\frac{\mathrm{erf}[\psi(z)/2Kn]^{1/2}}{[\psi(z)/2Kn]^{1/2}}.$$

- $$\psi(z)=\frac{z\exp(-z^2)+[(\pi)^{1/2}/2](1+2z^2)\ \mathrm{erf}(z)}{(2\pi)^{1/2}z^2}.$$

Ψ(x) as for the mean number of collisions per second ***Z*** experienced by a molecule of speed c= xα (where α is the most probable speed) is given by:

$$Z=\sqrt{\pi}N\sigma^2\alpha\frac{\Psi(x)}{x},$$

[6] E. H. Kennard, *Kinetic Theory of Gases* (McGraw-Hill, New York, 1938), pp. 97–113.

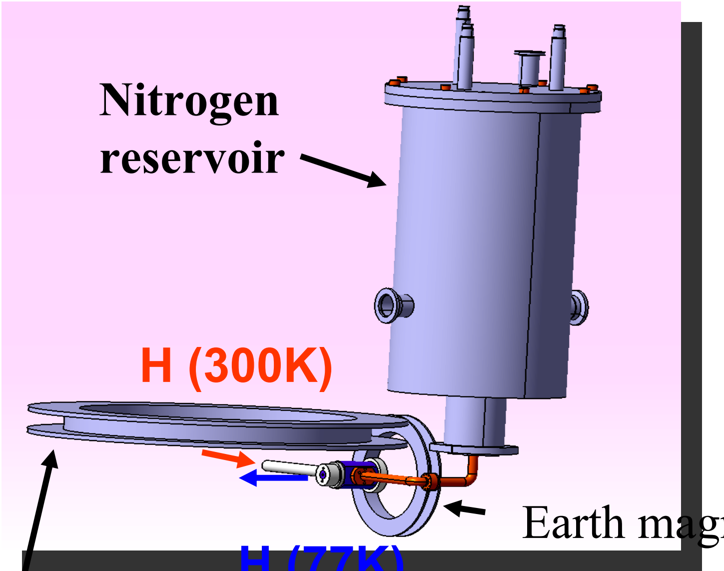
- $Kn=\lambda_s/L.$

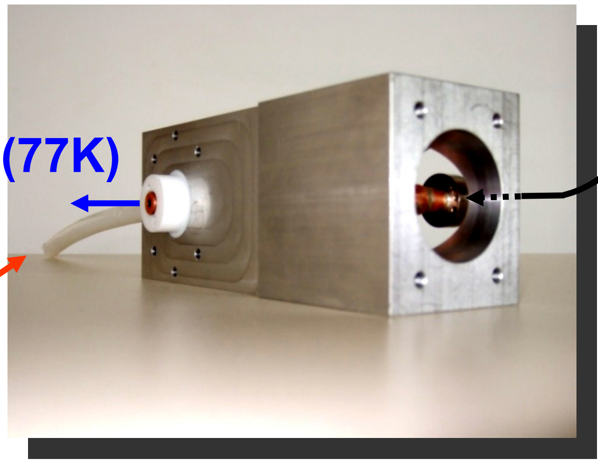
The **Knudsen** number : ***L***, the length of the circular tube from where escape the atoms.
λ_s, the mean-free path in the source reservoir.

If ***Kn* > 1** → the velocity distribution deviates from a Maxwellian distribution → more fast atoms

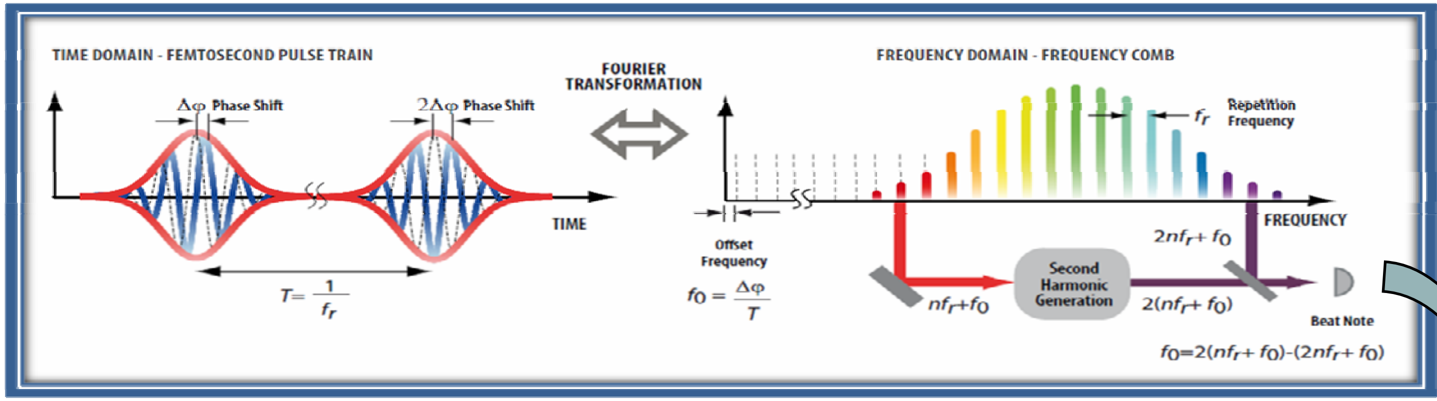
D.R. Olander et al. J. Appl. Phys. 41 n°11 p.4388 (1970)

Prospect :cooling down the hydrogen beam



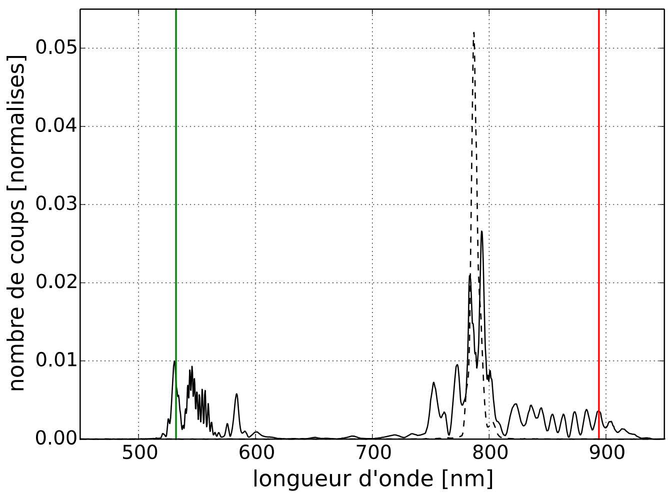


The frequency comb



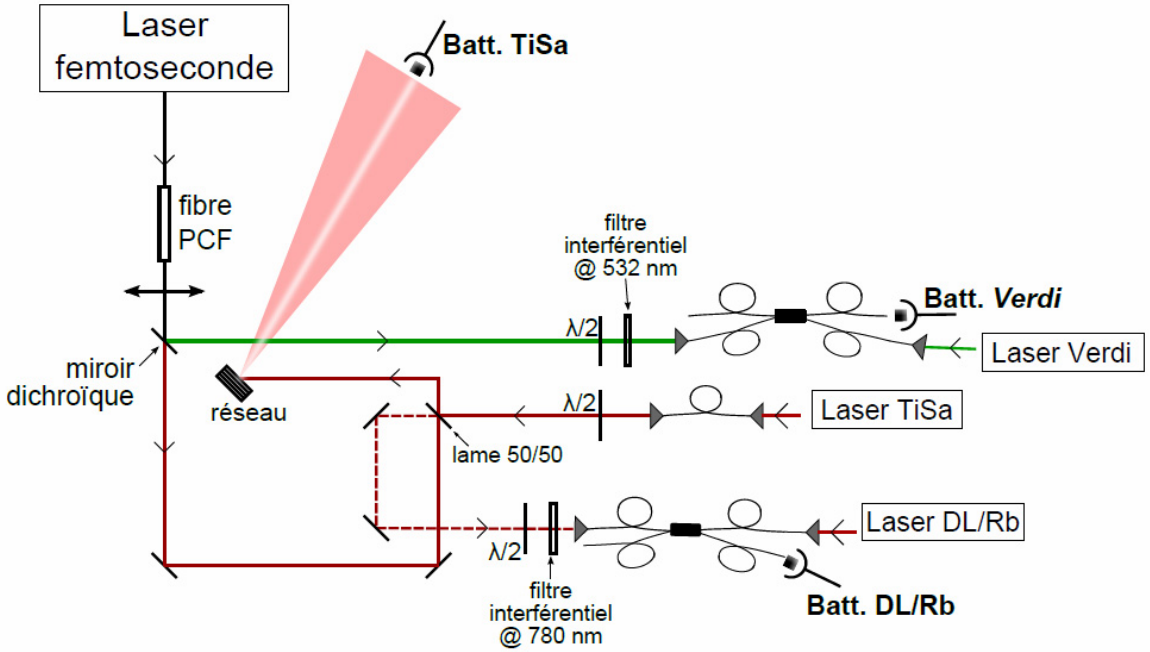
Sum frequency $\Longrightarrow$ simultaneous measurement of two laser frequencies

- Two photonic crystal fiber (PCF) spectrum:



Fiber laser frequency comb (MenloSystems)

Absolute frequency measurements



Beat notes:

- TiSa laser:
free space beat
→ 30 dB with 1MHz RBW

- Verdi laser:
fiber coupler
→ 25 dB with 1MHz RBW

- Absolute frequency of the two lasers:

TiSa laser: f_{TiSa} = 334 797 895 352, 900 ± 0, 994 kHz

Verdi laser: f_{Verdi} = 563 286 978 440, 6 ± 2, 6 kHz

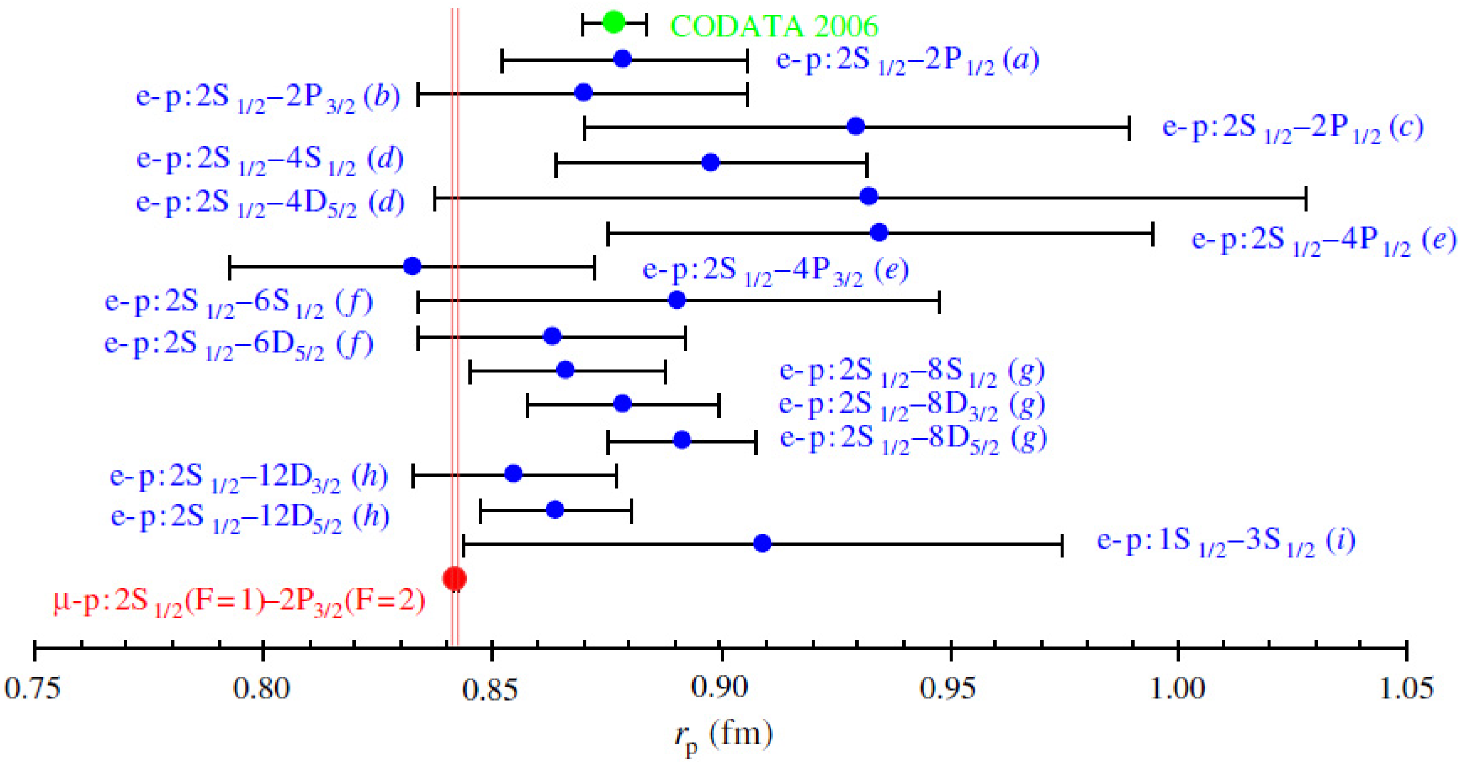


Figure 5. Comparison of various determinations of the proton radius from hydrogen spectroscopy. Each value is obtained from the 1S–2S transition frequency, the $1/n^3$ law and one of the other hydrogen experimental data from 2S–n(S,P,D). ((*a*) From Lundeen & Pipkin [55], (*b*) from Hagley & Pipkin [56], (*c*) from Newton *et al.* [57], (*d*) from Weitz *et al.* [58], (*e*) from Berkeland *et al.* [59], (*f*) from Bourzeix *et al.* [60] combined with Arnoult *et al.* [53], (*g*) from de Beauvoir *et al.* [24], (*h*) from Schwob *et al.* [61], and (*i*) from Arnoult *et al.* [53]). The double line corresponds to the uncertainty of the proton radius determination obtained from muonic hydrogen spectroscopy. (Online version in colour.)

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