Mesures de précision et tests fondamentaux :

- La mesure de la constante de structure fine
- La détermination de la distribution de charge du proton

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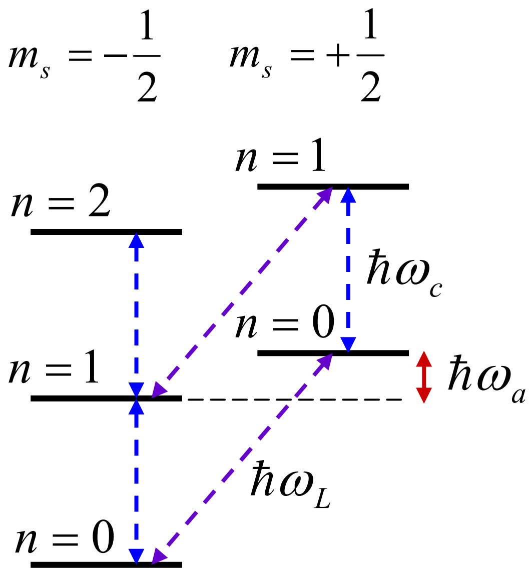
COLLÈGE DE FRANCE 1530

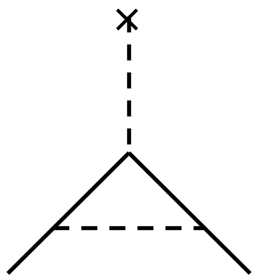
CNRS

Two effects of the quantum electrodynamics

Electron anomaly

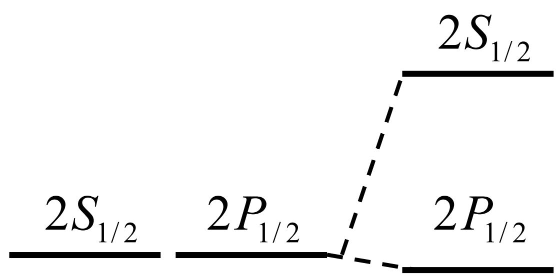
Kusch and Foley
Phys. Rev. **72**, 1256 (1947)





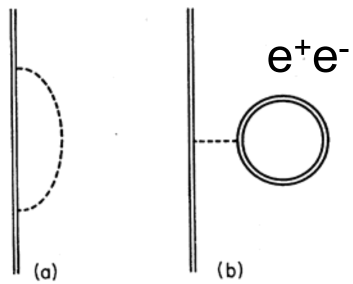
Lamb shift

Lamb and Retherford,
Phys. Rev. **72**, 241 (1947)



Self energy

Vacuum polarization

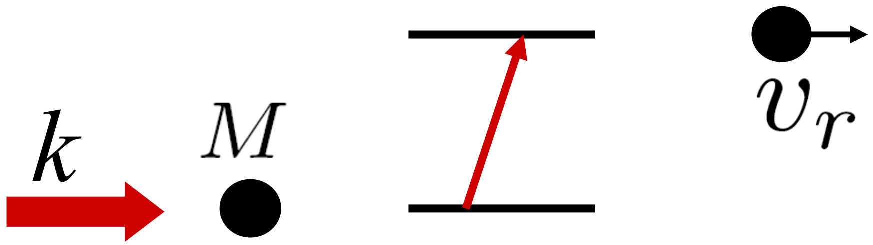


Bloch oscillations

Determination of the fine structure constant

Measurement of the ratio h/M
Determination of the fine structure constant

h/M is given by the recoil effect



$$v_r = \frac{\hbar k}{M}$$

Alpha is deduced from the ratio h/M

Rydberg constant in terms of energy :

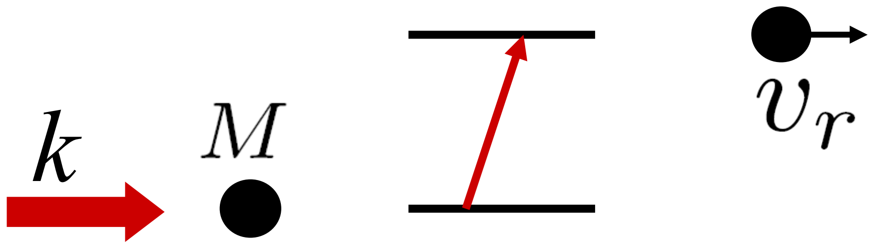
$$h\,c\,R_\infty = \frac{1}{2} m_e c^2\,\alpha^2$$

The measurement of *h/M* allows to determine α

$$\alpha^2 = \frac{2\,R_\infty}{c} \times \frac{h}{m_e}$$

Measurement of the ratio h/M
Determination of the fine structure constant

h/M is given by the recoil effect



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The measurement of *h/M* allows to determine α

$$\alpha^2 = \frac{2R_\infty}{c} \times \frac{M}{m_p} \times \frac{m_p}{m_e} \times \frac{h}{M}$$

Relative uncertainty on each term :

- Rydberg constant : 5×10^{-12}
- mass ratio M/m_p : $1{,}2\times10^{-10}$
- mass ratio $m_\mathrm{p}/m_\mathrm{e}$: $4{,}1\times10^{-10}$

Experiments : Cs atoms (Stanford)
Rb atoms (Paris)

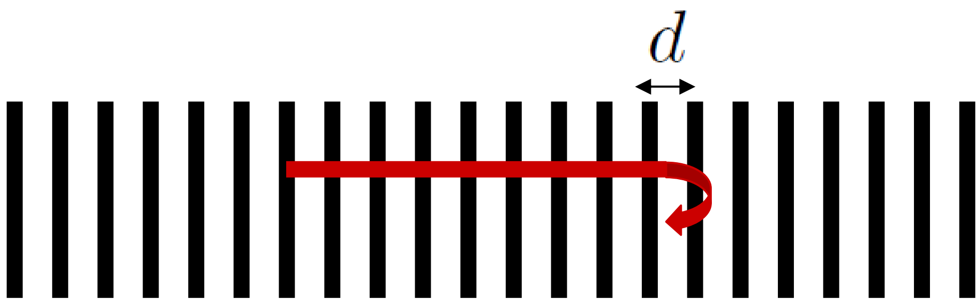
Bloch oscillations

In a periodic potential, a particle oscillates

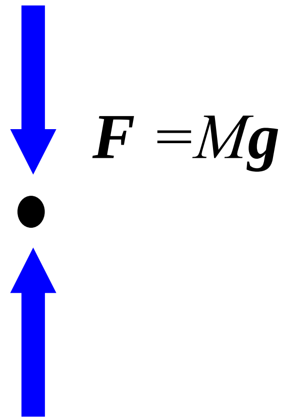
$$mv = h/\lambda_{DB}$$

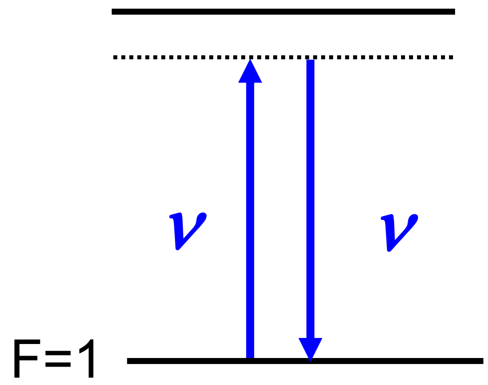
$$mv = Ft$$

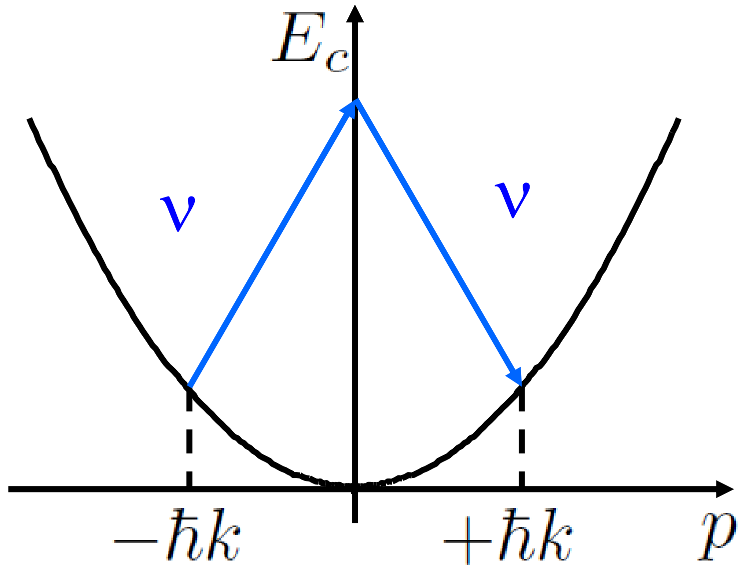
$$\tau_B = \frac{h}{Fd}$$



Atoms in a vertical standing wave

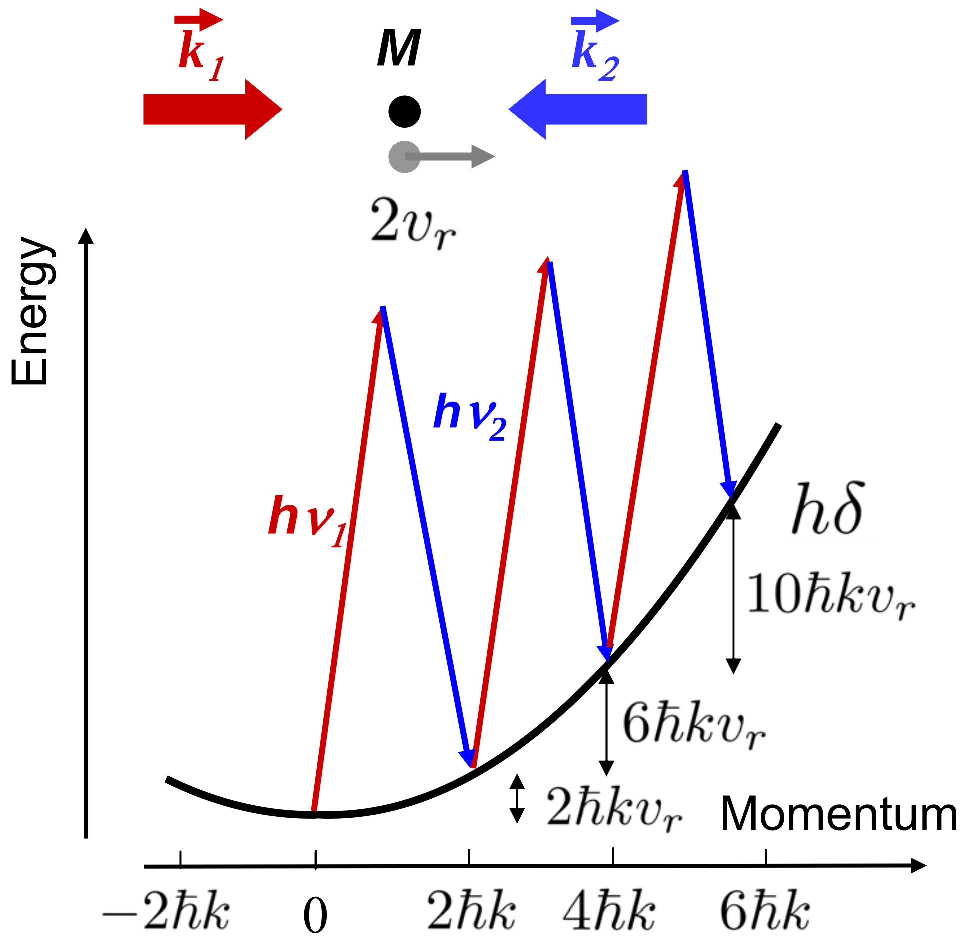


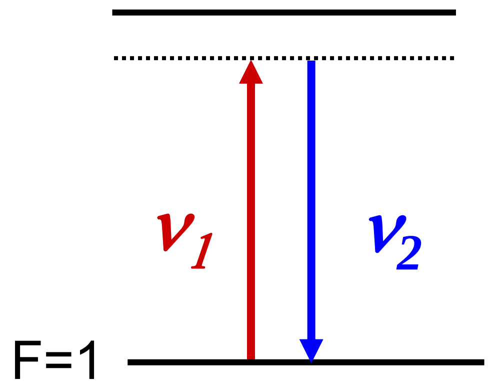




Coherent acceleration

Succession of stimulated Raman transitions
(same hyperfine level)





$2\hbar k$ par cycle

$\delta = \nu_1 - \nu_2 \propto t$

The atom is placed in an accelerated standing wave: in its frame, the atom is submitted to an inertial force

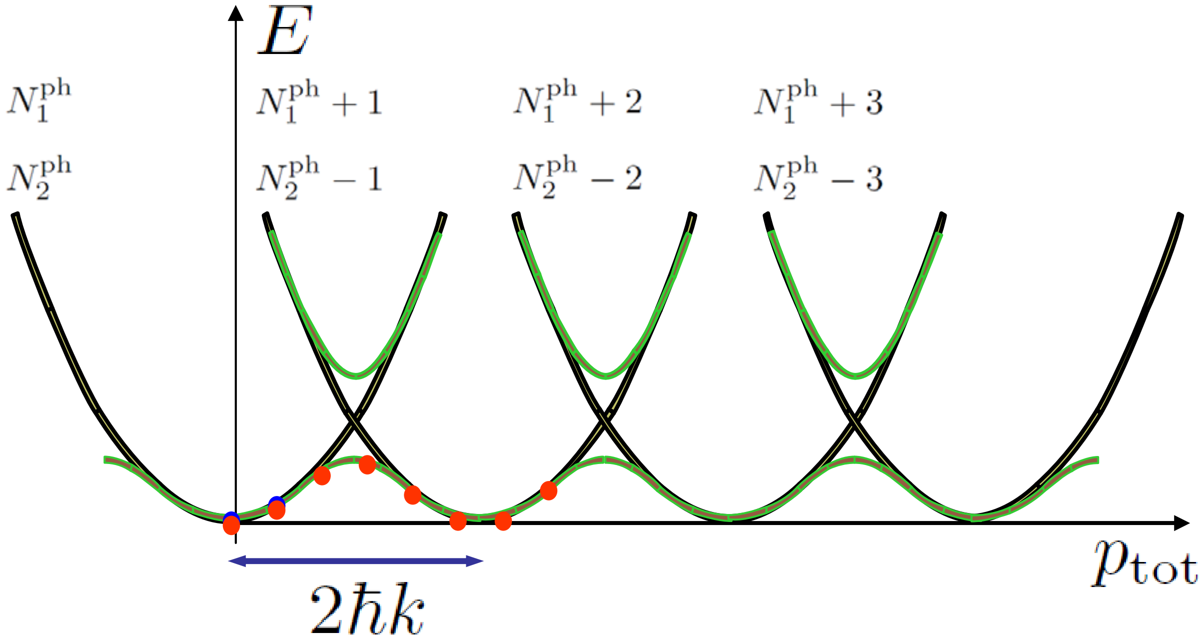
Bloch oscillations
in a periodic potential

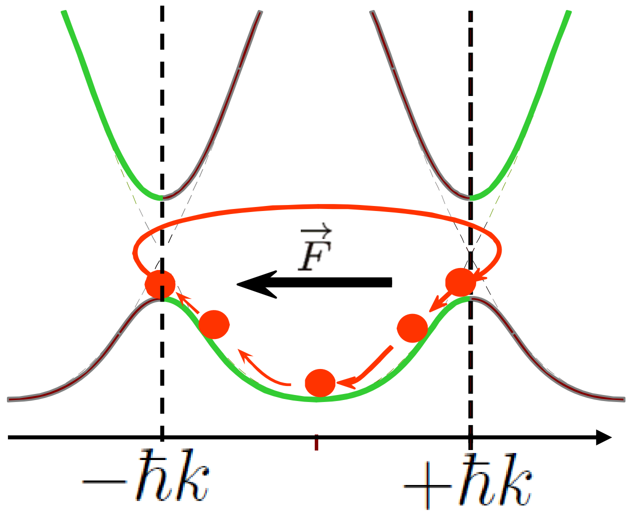
M. Ben Dahan, E. Peik, J. Reichel, Y. Castin and C. Salomon , *PRL. 76 (1996) 4508.*

S.R. Wilkinson, C.F. Bharucha, K.W. Madison, Quian Niu and G.M. Raizen*, PRL 76 (1996) 4512.*

Band structure

$$\left| p, N_1^{\text{ph}}, N_2^{\text{ph}} \right\rangle$$

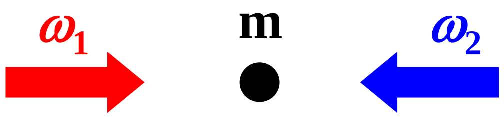




Accélération ⇔ oscillations de Bloch dans la bande fondamentale

$2\hbar k$ par oscillation
Grande efficacité (99.95%)

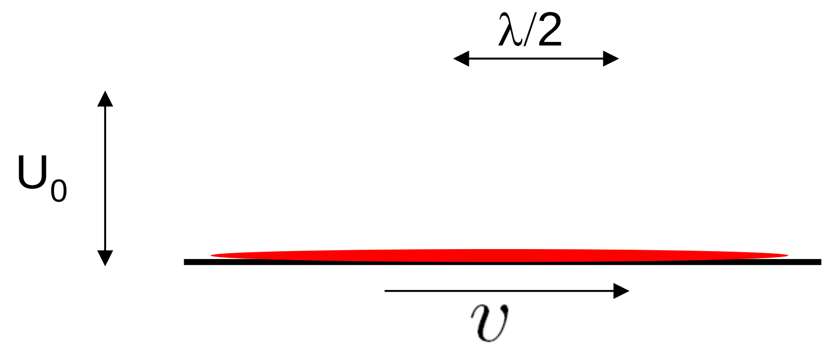
Atom in an accelerated lattice



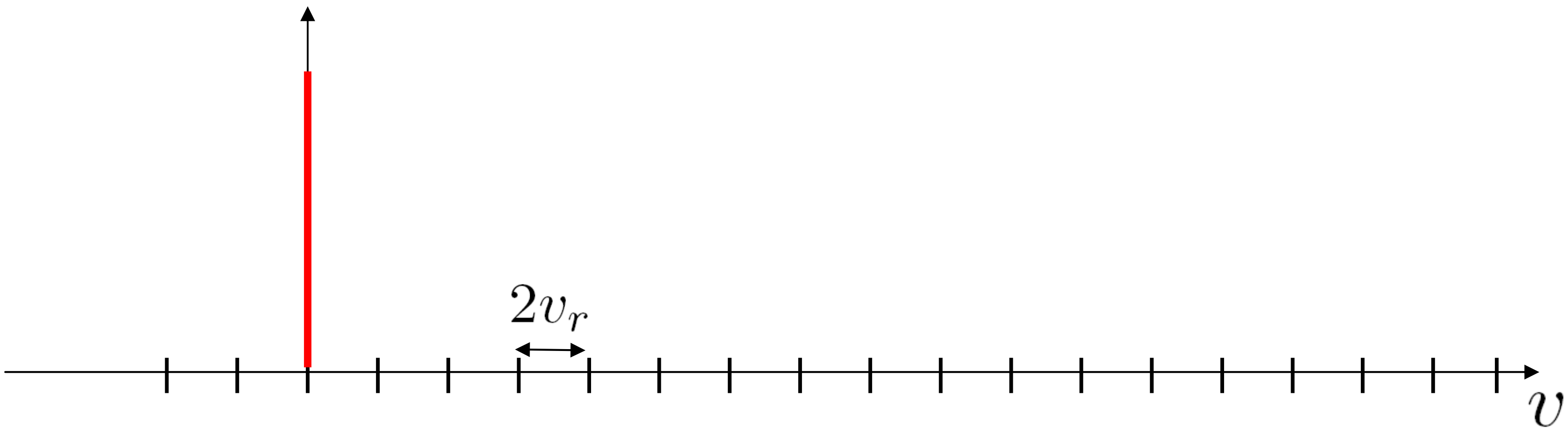
Light shifts: periodic potential

$$U(x,t) = \frac{U_0}{2}\cos(2k(x - vt))$$

Velocity of the lattice: $v = (\omega_1 - \omega_2)/2k$



Velocity distribution



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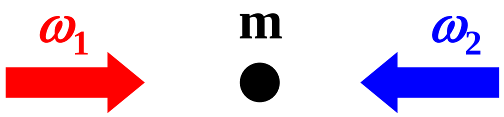

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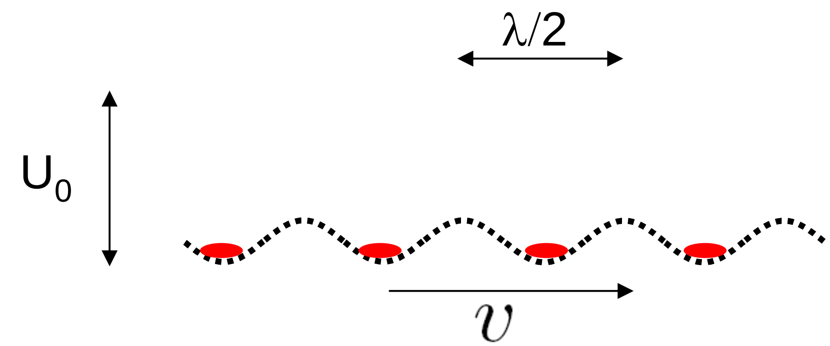
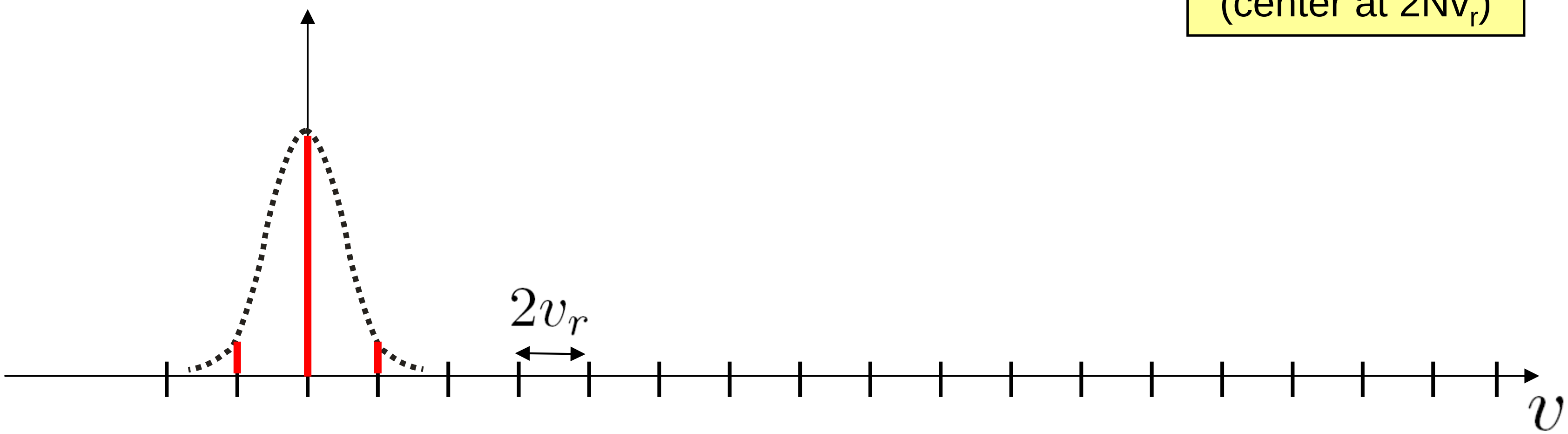


Velocity distribution

Wannier function (center at $2Nv_r$)



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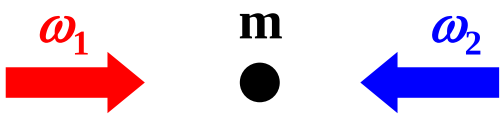

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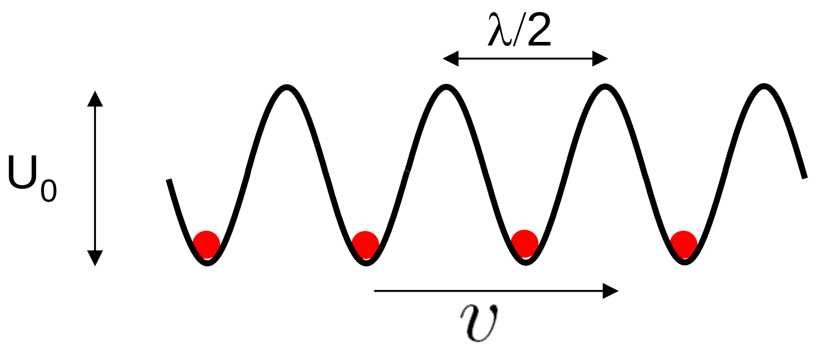

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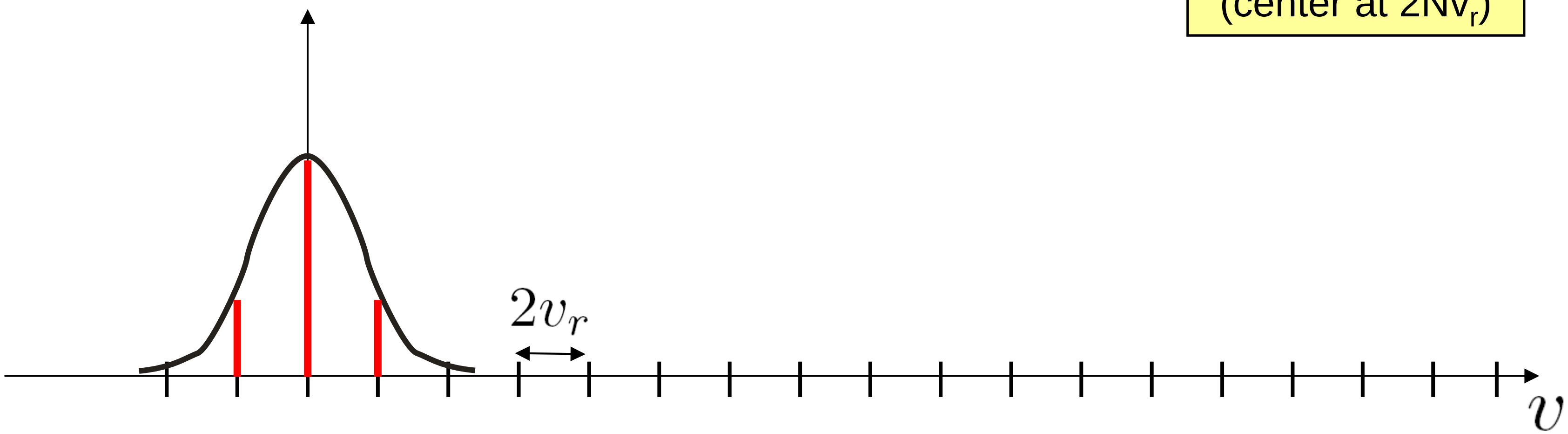

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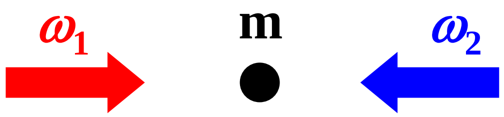

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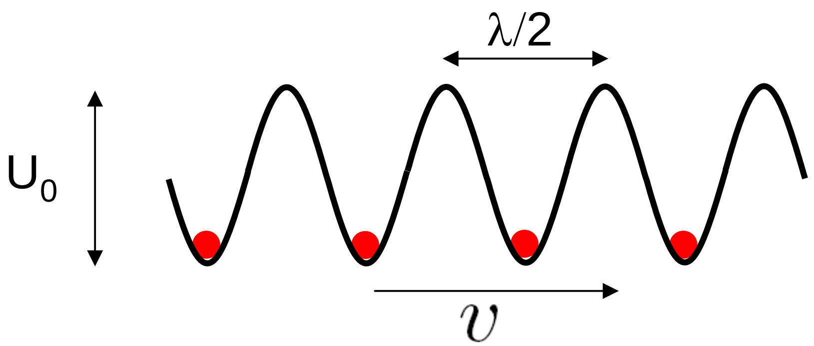

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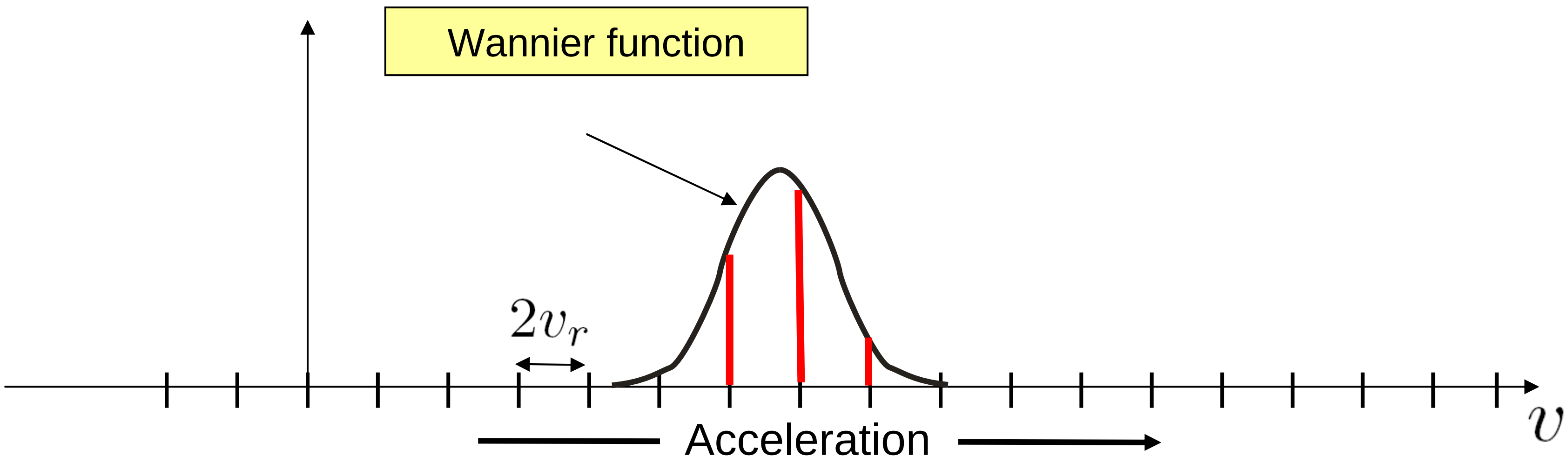

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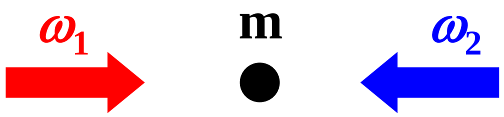

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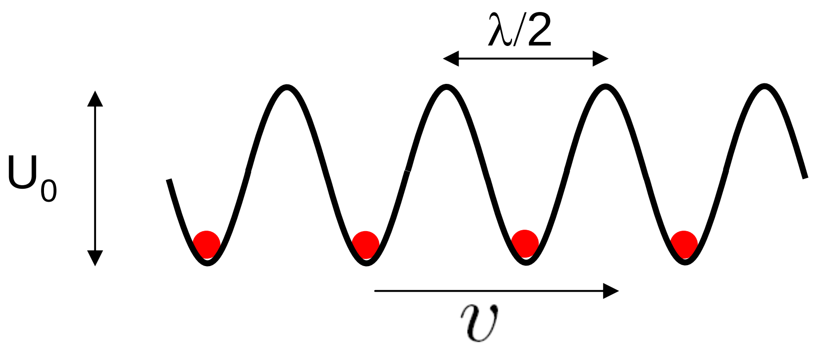

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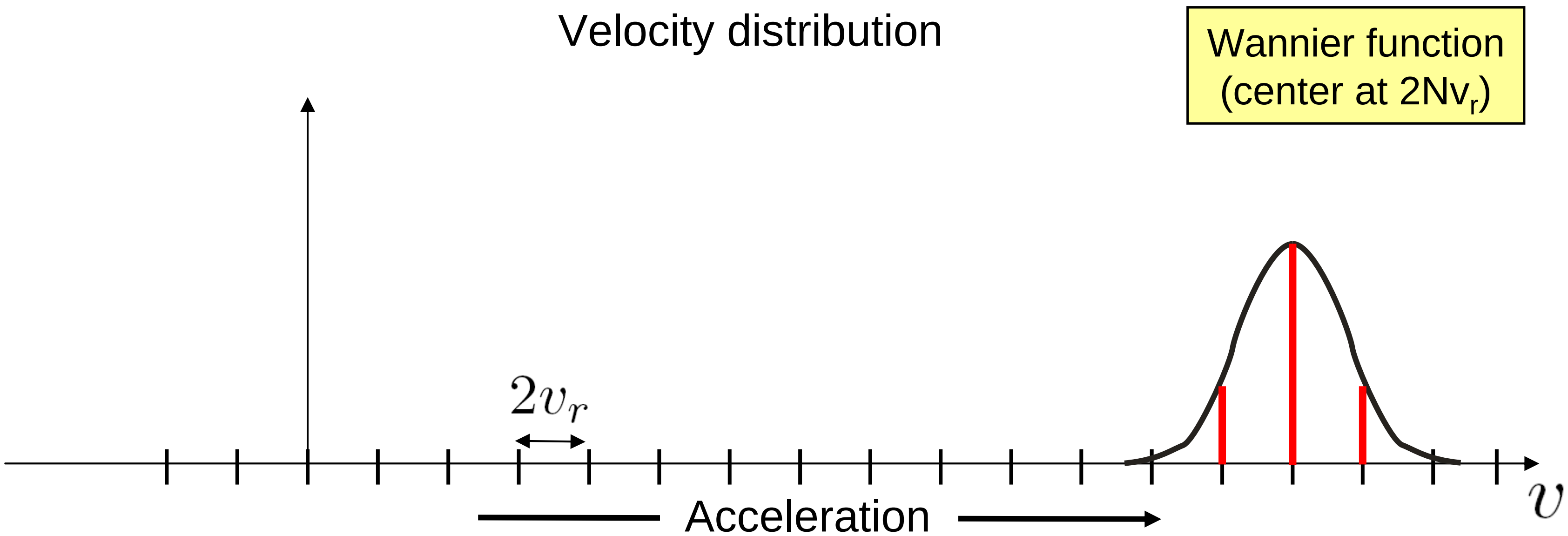

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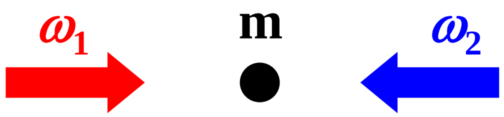

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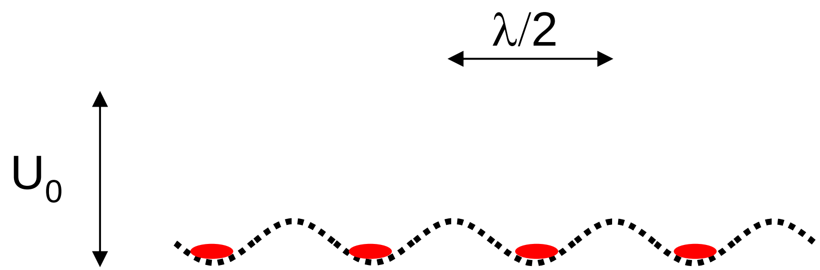

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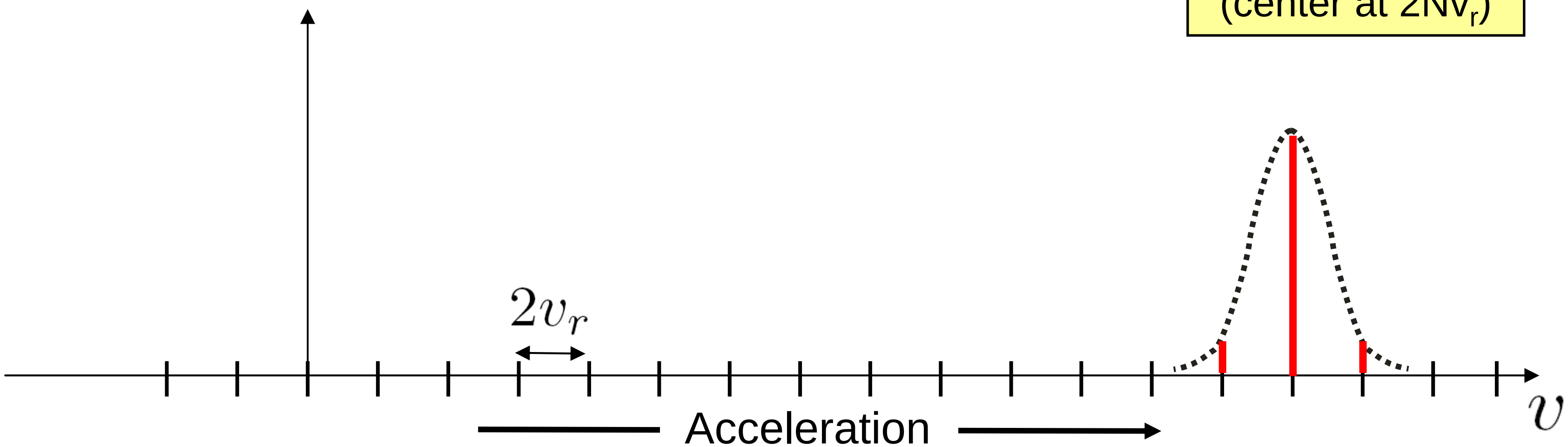

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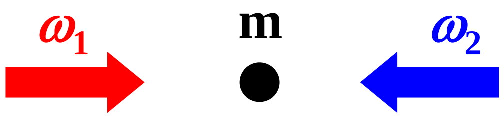

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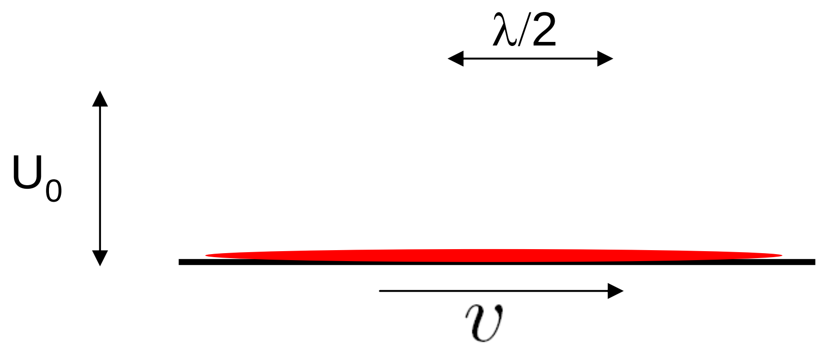

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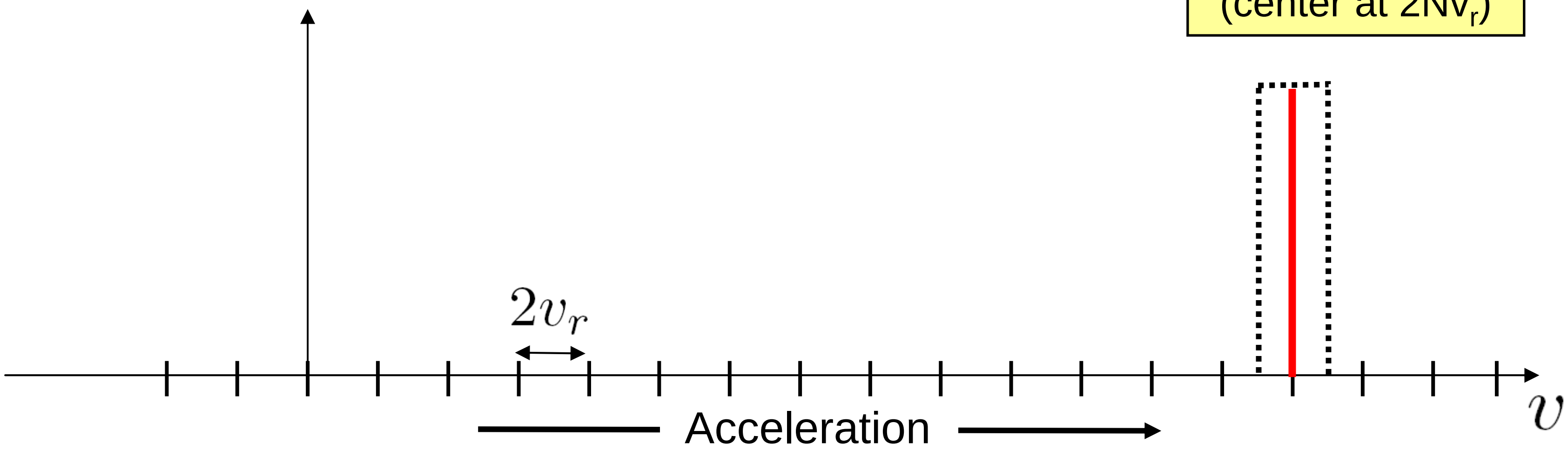

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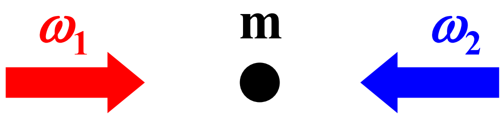

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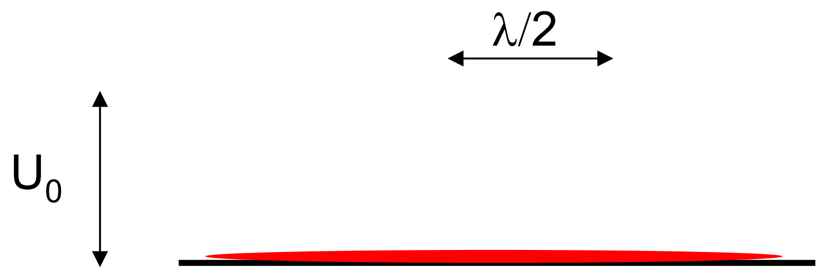

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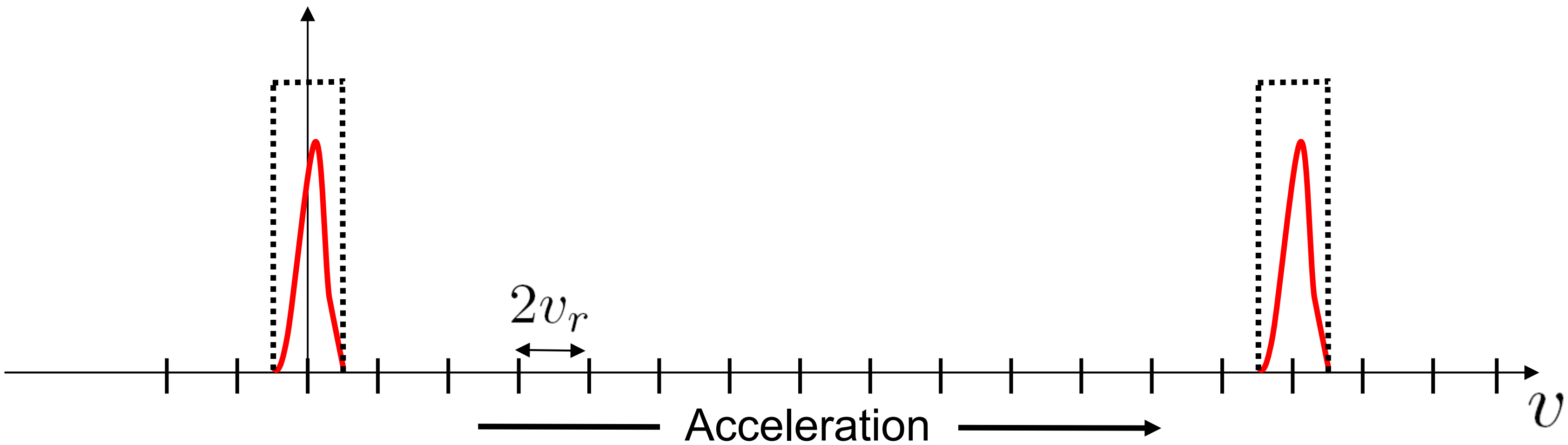
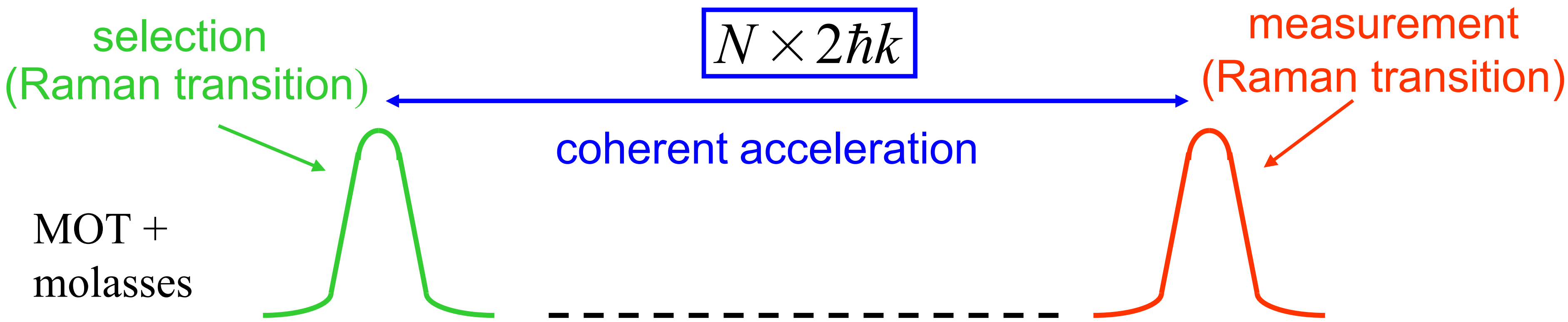
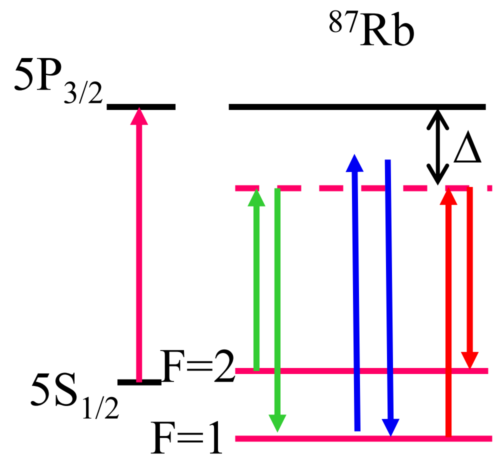


Principle of our experiment



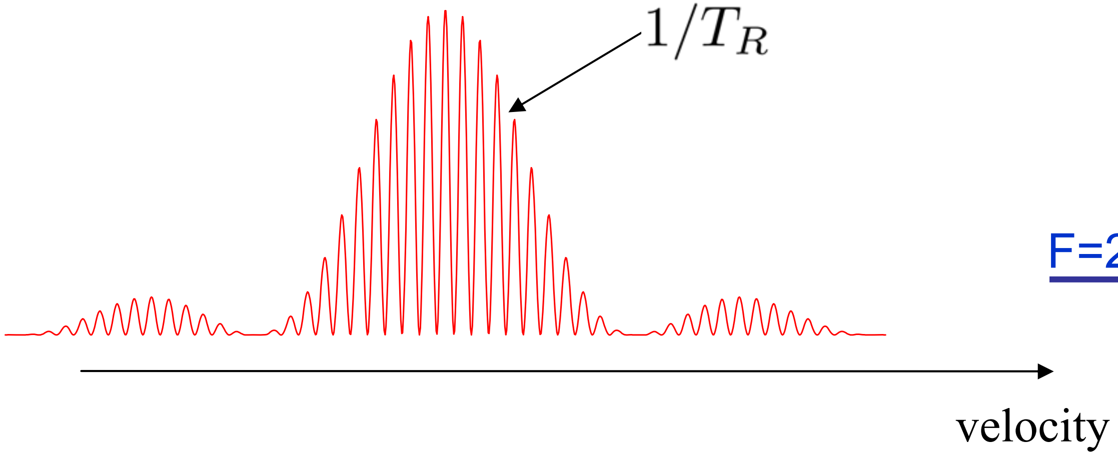


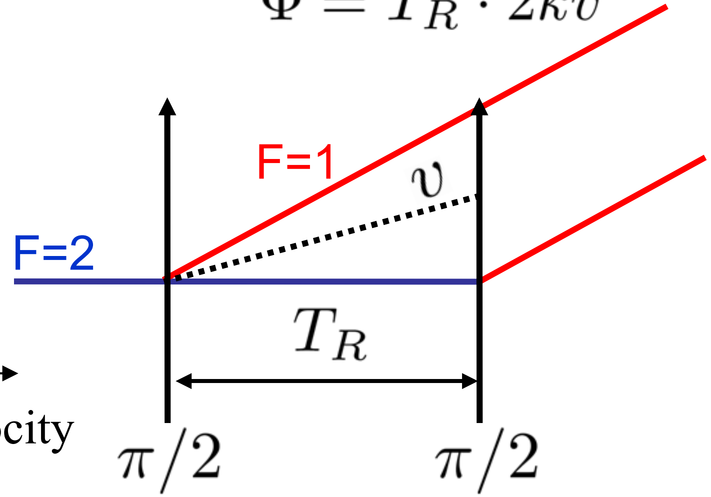
- selection of an initial sub-recoil velocity class
- coherent acceleration : *N* Bloch oscillations, momentum transfer $2N\hbar k$
- measurement of the final velocity class

$$\sigma_{v_r} = \sigma_v / 2N$$

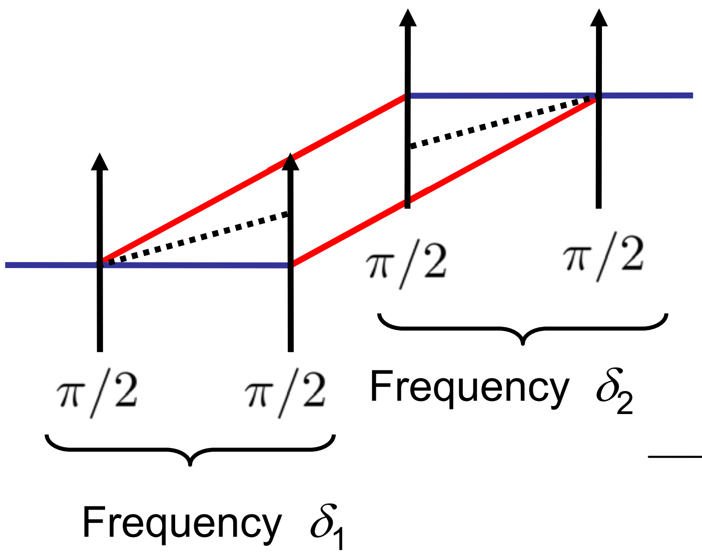
Ramsey velocity selection

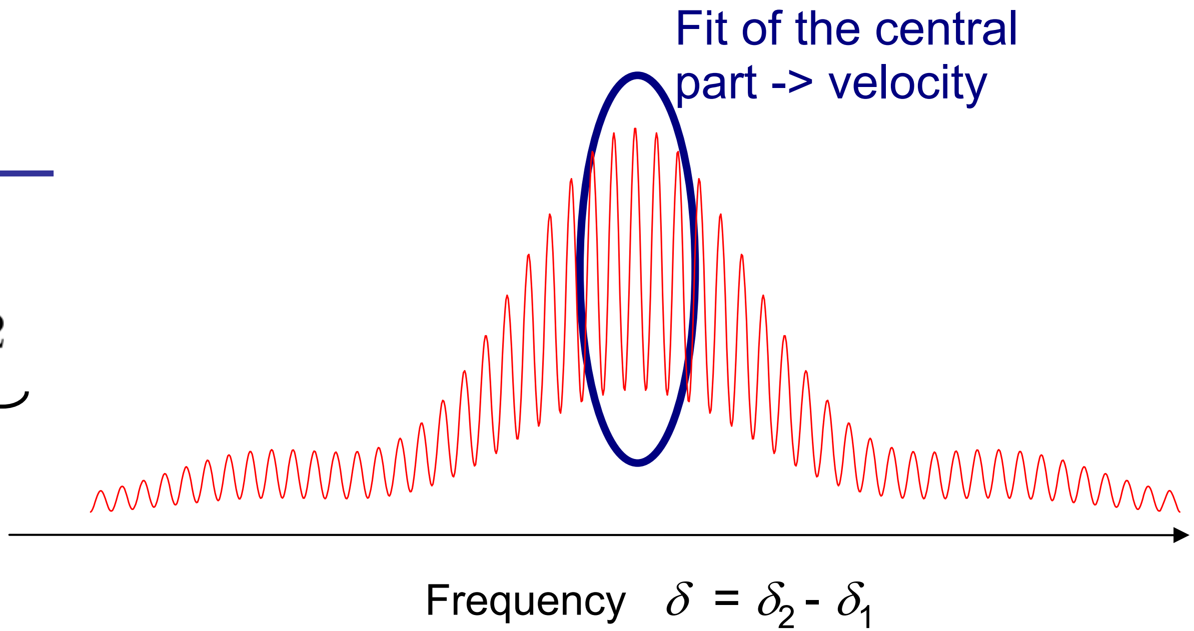
$$v = (v_1 + v_2)/2$$
$$\Phi = T_R \cdot 2kv$$





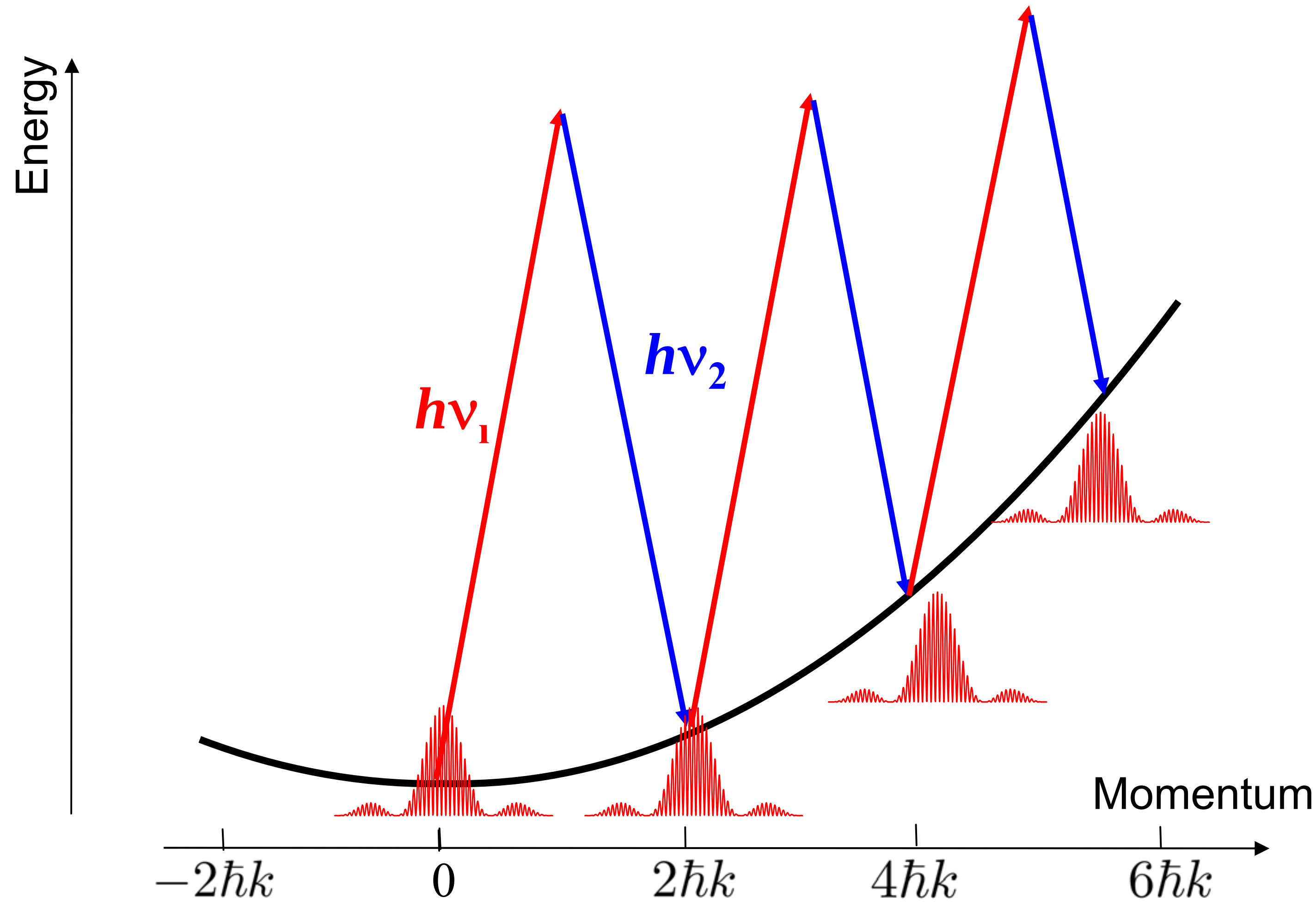
Convolution of the two Ramsey patterns



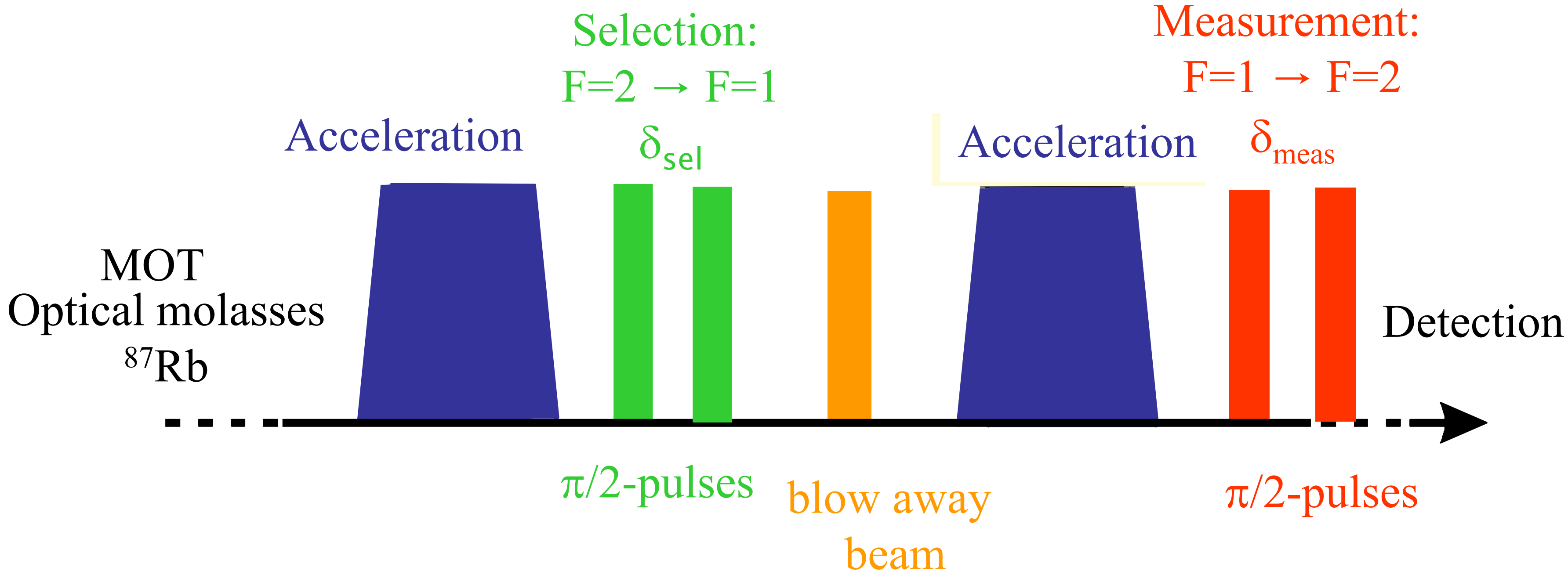


Combining Bloch oscillations with interferometry

Bloch oscillations are a coherent process
Tranfer of recoils to any velocity distribution that fit into the first Brillouin zone



Measurement of the recoil velocity : determination of h/m (I)



Velocity variation

$$\Delta V^{\pm} = gt \pm 2N v_r$$

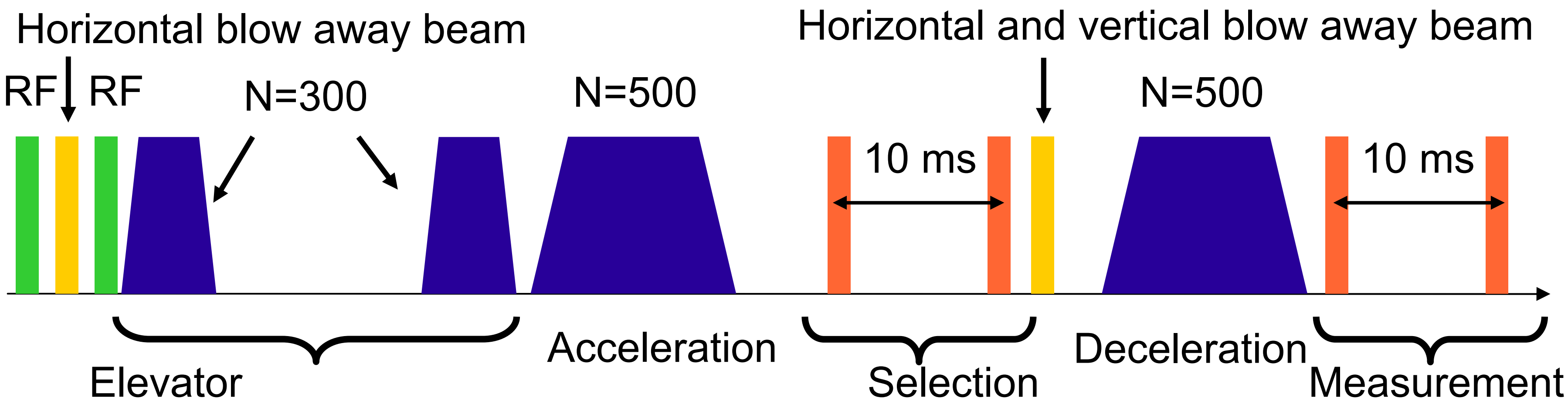
t : time between the two Raman pulses

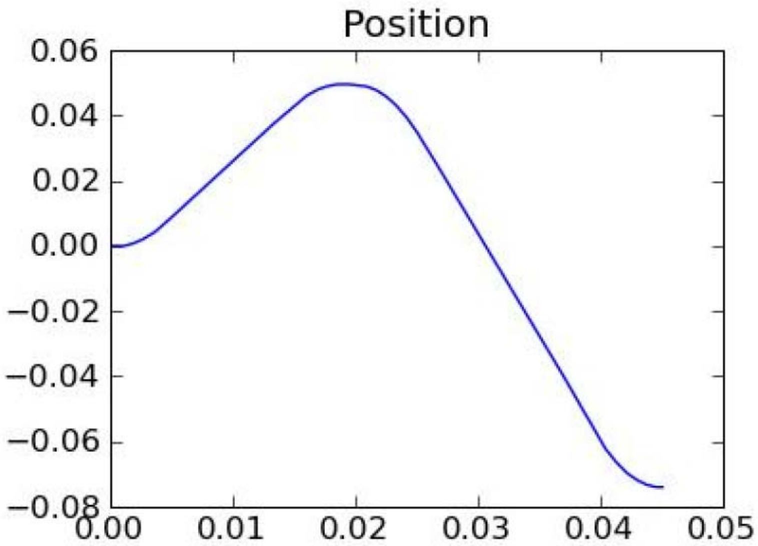
N: Number of Bloch oscillations

Acceleration in both opposite directions

$$v_r = \frac{\Delta V^{+} - \Delta V^{-}}{4N}$$

Measurement of the recoil velocity : determination of h/m (II)



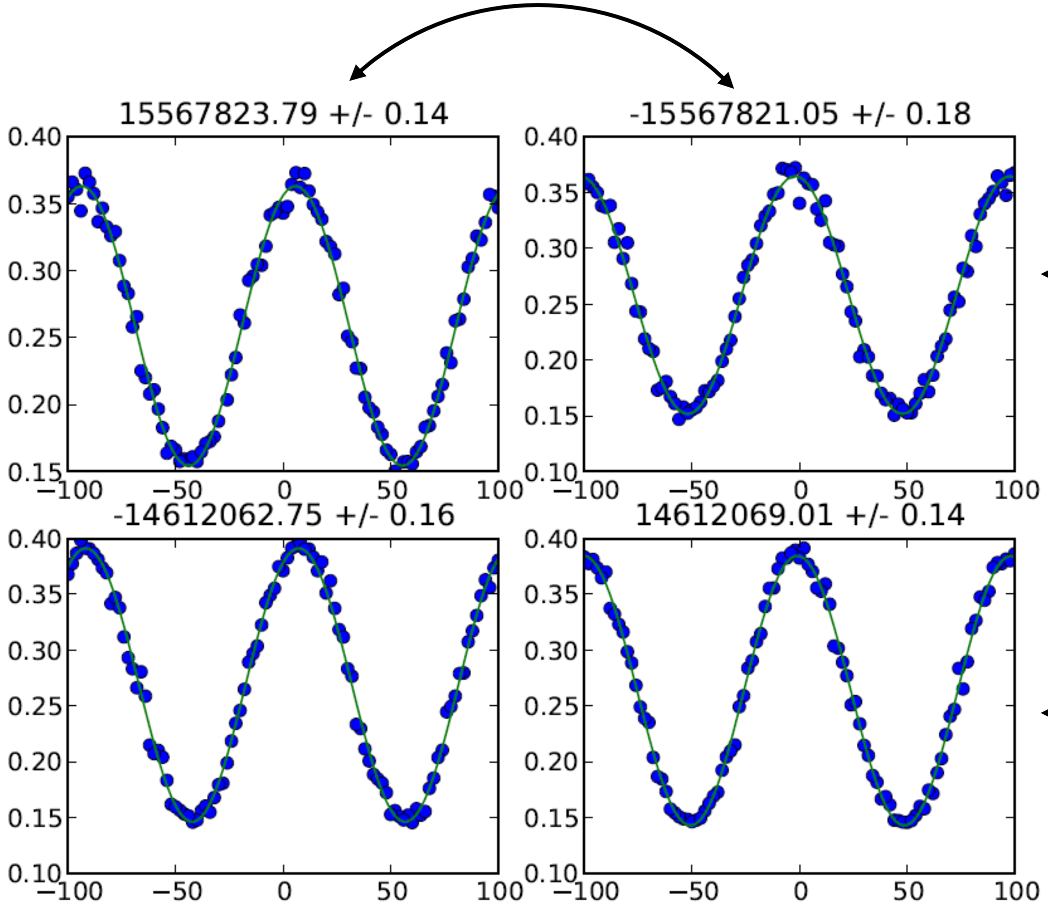


Δ_{Raman} = 130 GHz

Δ_{Bloch} = 25 GHz

Observation of the interference fringes

Inversion of the Raman beams



Upward trajectory
500 Bloch oscillations

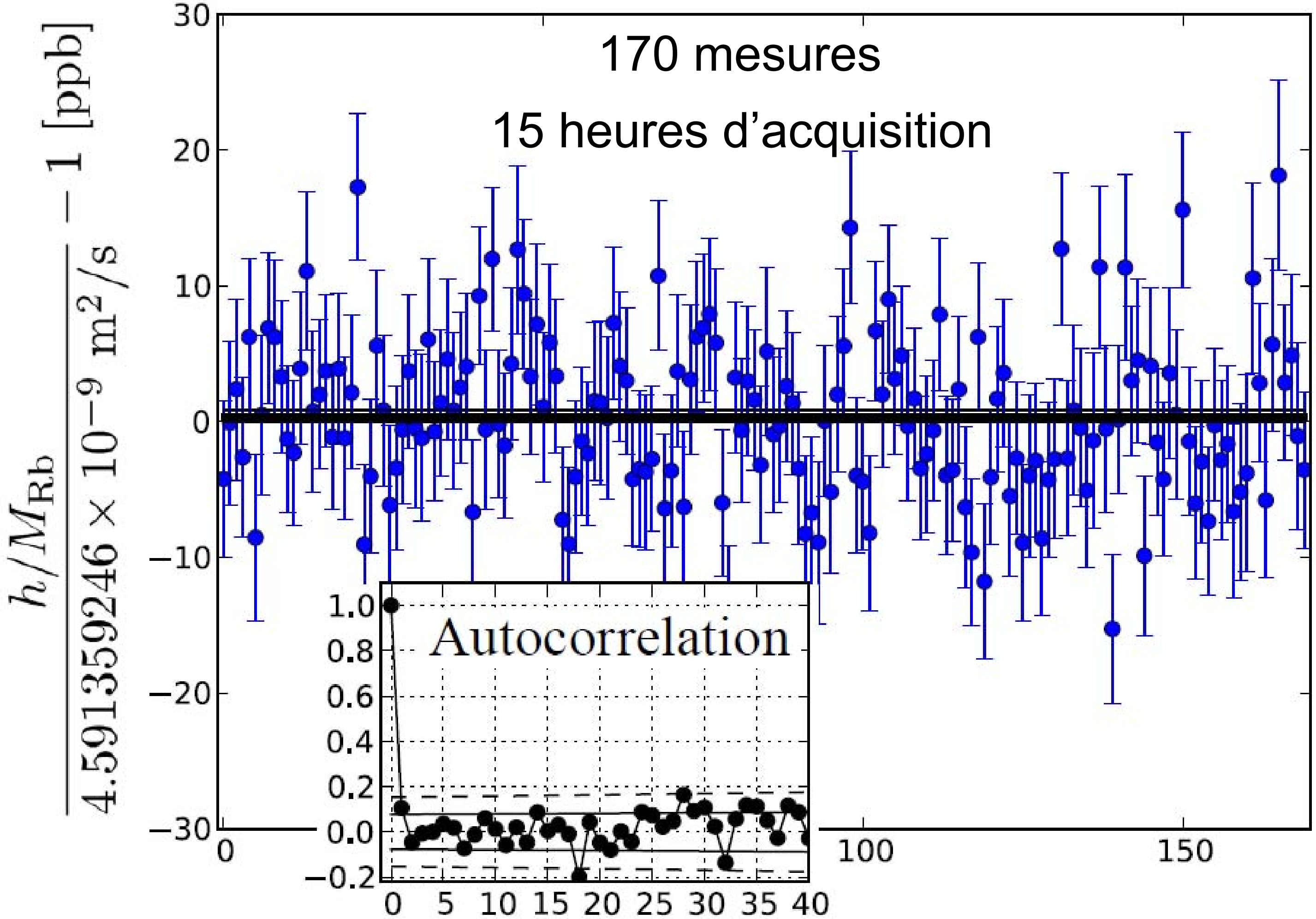
2000
recoil velocities

Downward trajectory
500 Bloch oscillations

Data acquisition time: 5 minutes

Relative uncertainty on h/m: $5.2\times10^{-9} \rightarrow 2.6\times10^{-9}$ on α

Results of one night acquisition



Relative uncertainty on h/m: 4.4×10^{-10} and 2.2×10^{-10} on α

Very good reliability of the experiment

Uncertainty budget

Source	Correction (α^{-1})(ppb)	Uncertainty (ppb)
Laser frequencies		0,13
Laser beams alignement	-0,33	0,33
Wave front curvature and Gouy phase	-2,51	0,3
Second order Zeeman effect	0,4	0,3
Light shift (1 photon)		0,01
Light shift(2 photon)		0,001
Light shift (Bloch)		0,05
Gravity gradient	-0,2	0,02
Refraction index of atom cloud and interactions		0,2
Total of the systematic effects	-2,64	0,59
Statistics		0,2
Rydberg constant and mass ratio		0,22
Final uncertainty		0,66

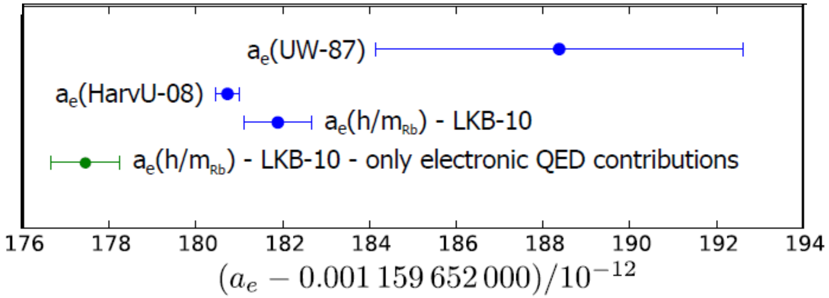
Electron anomaly and QED test

$$a_e = C_1\left(\frac{\alpha}{\pi}\right) + C_2\left(\frac{\alpha}{\pi}\right)^2 + C_3\left(\frac{\alpha}{\pi}\right)^3 + C_4\left(\frac{\alpha}{\pi}\right)^4 + a\left(m_e/m_\mu, m_e/m_\tau, weak, hadron\right) + \ldots$$

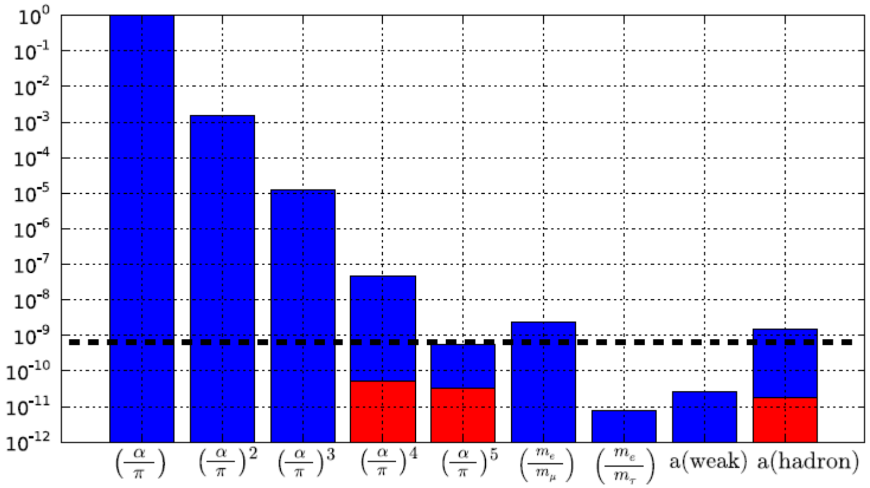
Expérience (Harvard University, 2008) : $\Longrightarrow$ $a_e = 0.001\ 159\ 652\ 180\ 73(28)$

LKB-10 (Paris) $1/\alpha = 137.035\ 999\ 037(91)$ $\Longrightarrow$ $a_e = 0.001\ 159\ 652\ 181\ 88(78)$

$$a_e(\mathrm{Exp}) - a_e(\mathrm{Theo}) = -1.09(0.83) \times 10^{-12}$$



Première vérification des contributions muonique et hadronique à a_e



T. Aoyama, M. Hayakawa, T. Kinoshita, and M. Nio, *Phys. Rev. Lett*. **109**, 111807 (2012).

D. Hanneke, S. Fogwell, and G. Gabrielse, *Phys. Rev. Lett*. **100**, 120801 (2008).

Spectroscopy of atomic hydrogen

From the Rydberg constant to the size of the proton

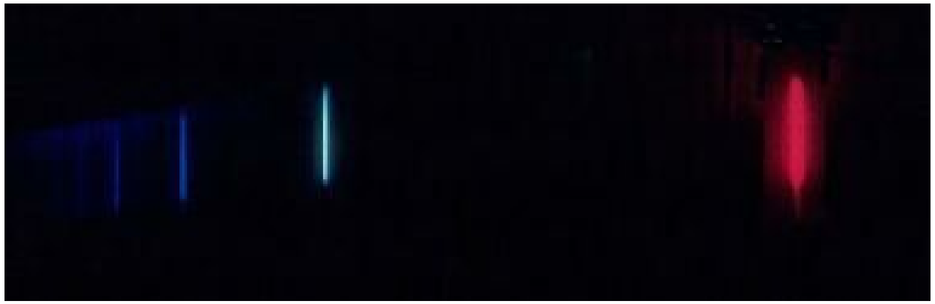
A brief history

The simplest atom in nature : proton + electron
involved in major advances of atomic physics and quantum mechanics

19th century

Optical spectrum
(Balmer 1885)

Hβ Hα



Balmer-Rydberg formula
(1889)

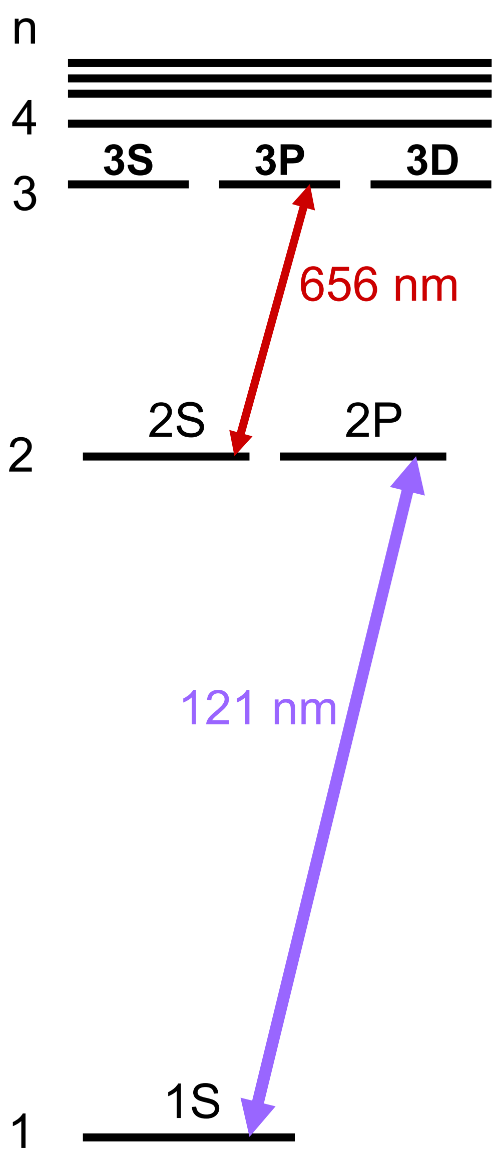
$$\frac{1}{\lambda} = R\left(\frac{1}{n^2} - \frac{1}{p^2}\right)$$

n and p integers

R : Rydberg constant

Balmer lines : $n = 2$

The energy levels of hydrogen atom



First explanation

Hydrogen is made with a nucleus and an electron (Rutherford 1911)

Bohr's model (1913): the frequency of the light is determined by the difference in energy between two states. The electron follows a circular orbit and the angular momentum is quantized: $n\hbar$

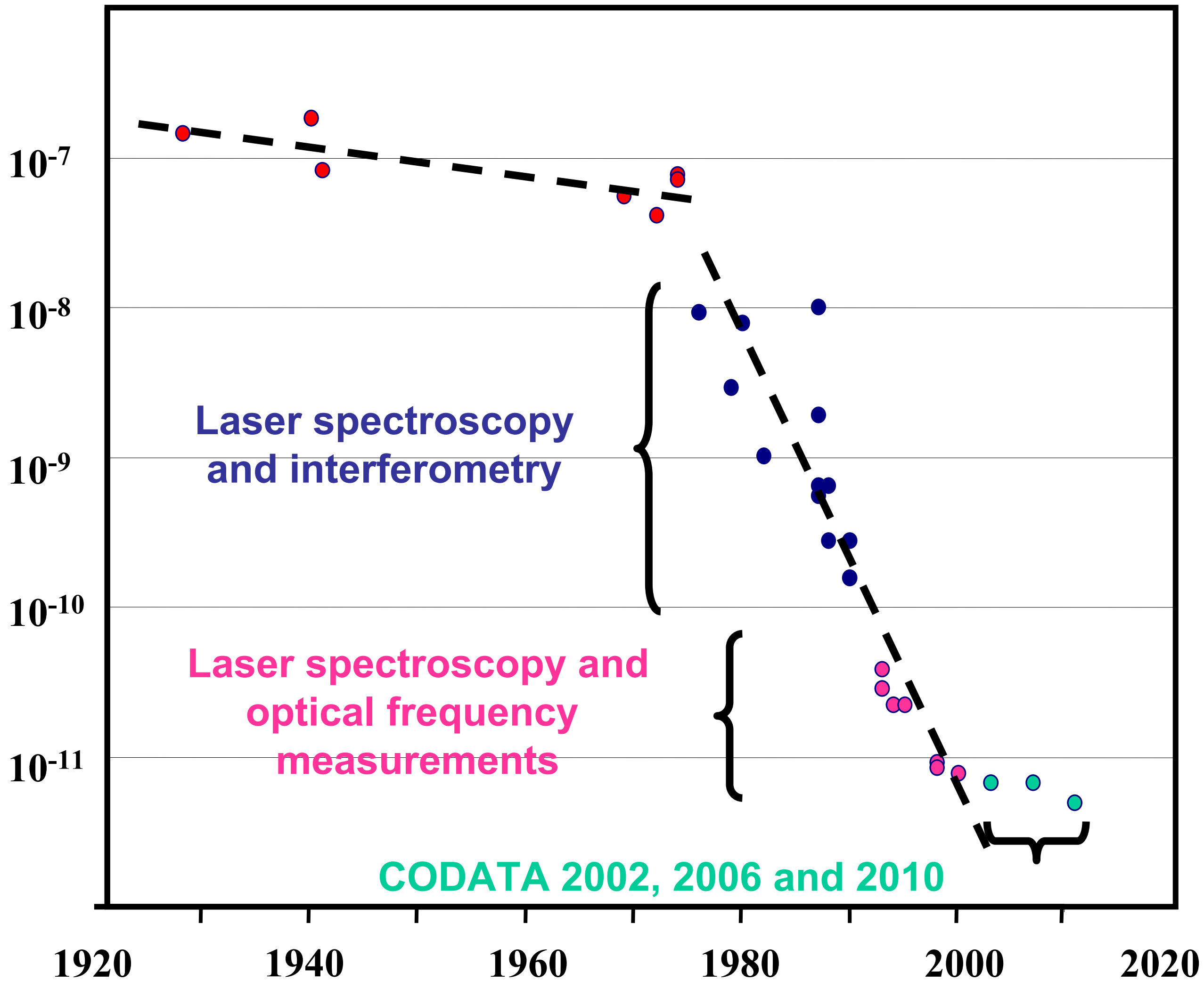
$$E = -\frac{R_H hc}{n^2}$$

$$R_H = R_\infty \left(1 + m_e / m_p\right)^{-1}$$

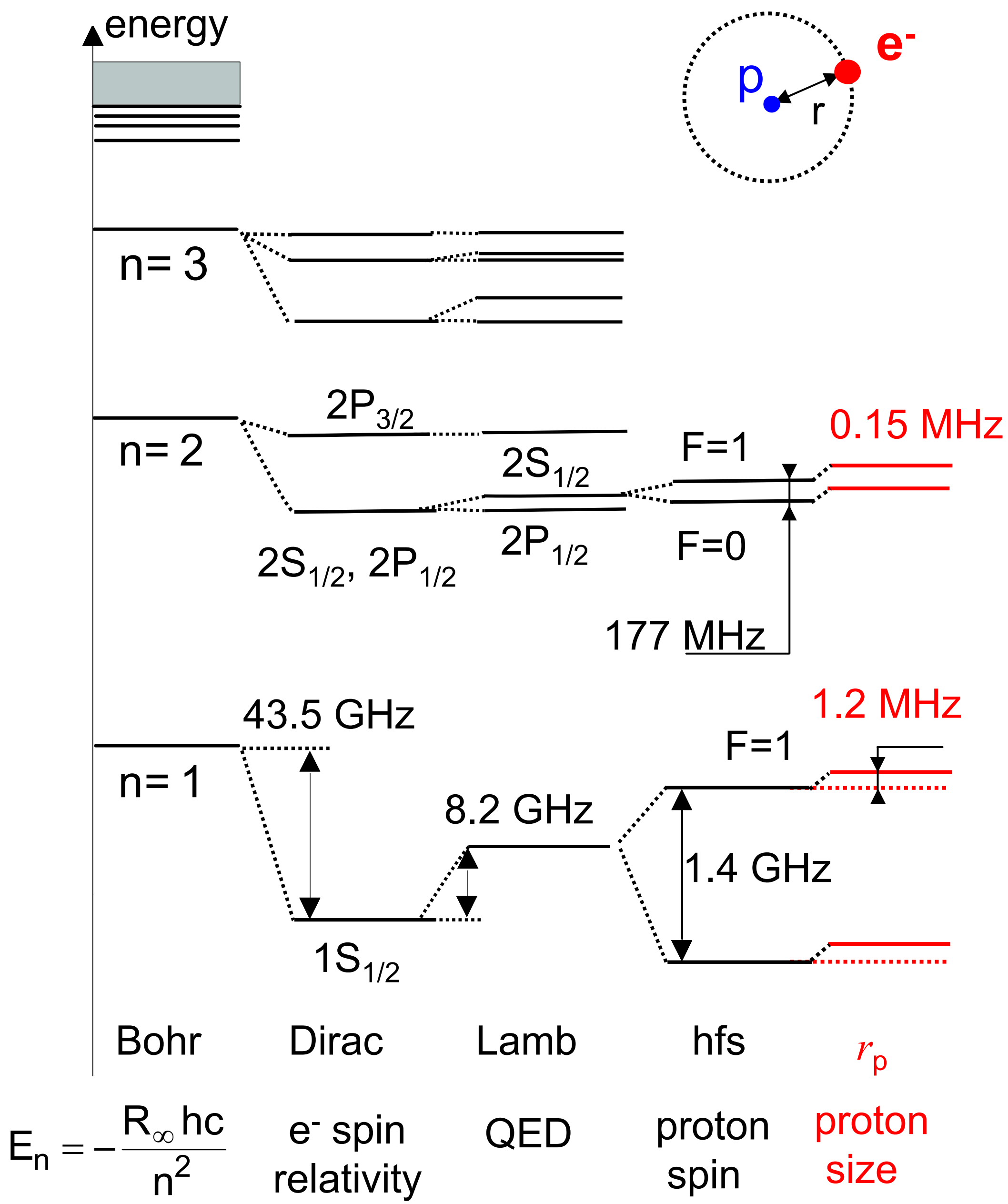
The Rydberg constant is linked to other fundamental constants

$$R_\infty = \frac{m_e e^4}{8\varepsilon_0{}^2 h^3 c}$$

Rydberg constant: relative uncertainty



The energy levels of hydrogen atom

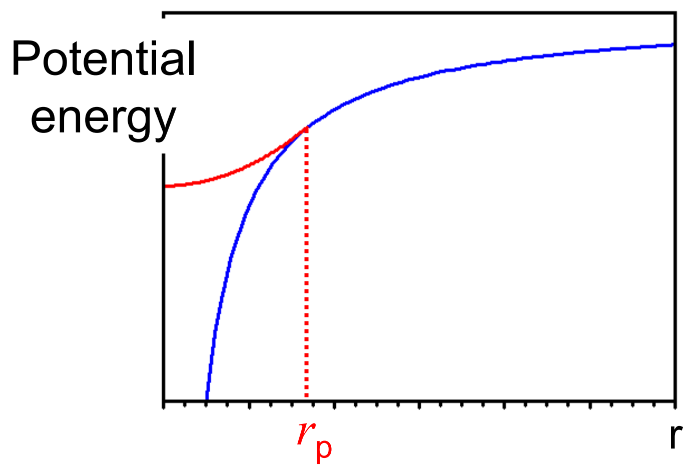


$E(n,l,j)$ = Dirac + recoil + $L(n,l,j)$

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

exact — not well known

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



$L^{theo}(1S_{1/2})$ = 8172.847 (3) (22) MHz

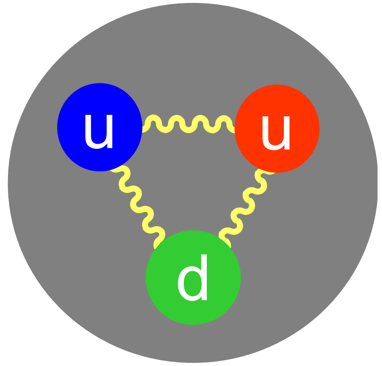
QED

scattering proton size

Proton

Structure

2 quarks up (2/3 e) + 1 quark down (-1/3 e) + strong interaction (gluons)



Proton charge radius : r_p

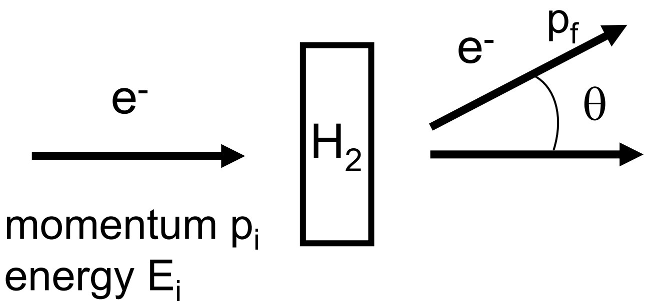
$$r_p = \sqrt{\langle r^2 \rangle} \qquad \langle r^2 \rangle = \frac{\int r^2 \rho(r)\, d^3r}{\int \rho(r)\, d^3r}$$

$\rho(r)$: proton charge distribution

QCD Calculations

- proton mass (< 4%)
- r_p (< 5%)

Electron-proton scattering



$$\vec{q} = \vec{p}_f - \vec{p}_i \qquad q = 2p\sin\left(\frac{\theta}{2}\right)$$

$$\frac{d\sigma}{d\Omega}(E_i,\theta) \approx \underbrace{\left[\frac{d\sigma}{d\Omega}(E_i,\theta)\right]}_{\text{Rutherford}} G(q^2)$$

$$G(q^2) = \int d^3r\, e^{iqr} \frac{\rho(r)}{4\pi} \approx 1 - \frac{r_p^2}{6} q^2$$

Limiting factor

Calculation of the Lamb shift

The table below gives the various contributions to the Lamb shift

Term of the Lamb shift	Value for the 1S level	Uncertainties
Self-energy (one-loop)	8 383 339.472 kHz	0.008 kHz
Vacuum polarization (one-loop)	− 214 816.607 kHz	0.001 kHz
Recoil corrections	2 401.701 kHz	0.780 kHz
Proton size	1 209.000 kHz	22 kHz ←
Two-loop corrections	727.700 kHz	2.000 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	− 0.143 kHz	0.011 kHz
Proton polarization	− 0.070 kHz	0.013 kHz
1S Lamb shift	8 172 847(23) kHz	

The uncertainties of the one-loop corrections are mainly due to α

The theoretical uncertainty (QED) is ~ 2.5 kHz

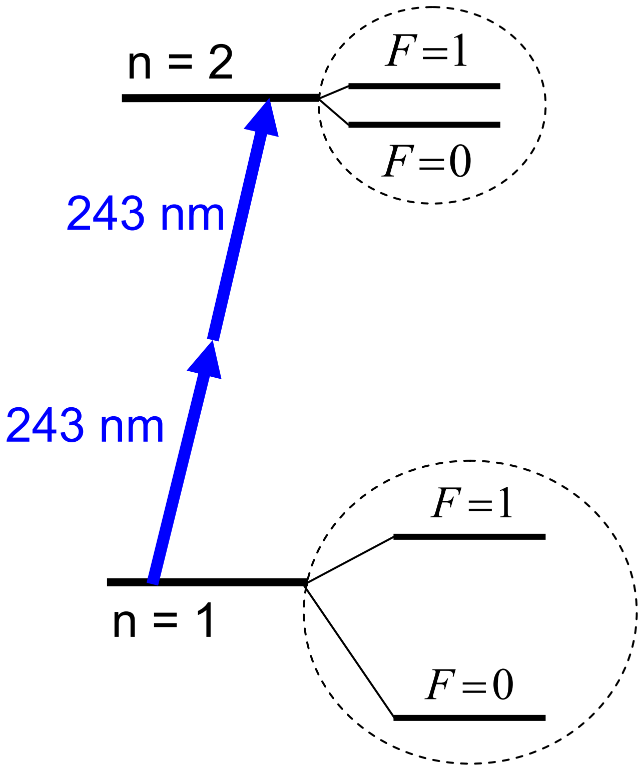
Optical spectroscopy of hydrogen gives a test of QED until the two-loop corrections if the proton radius is known

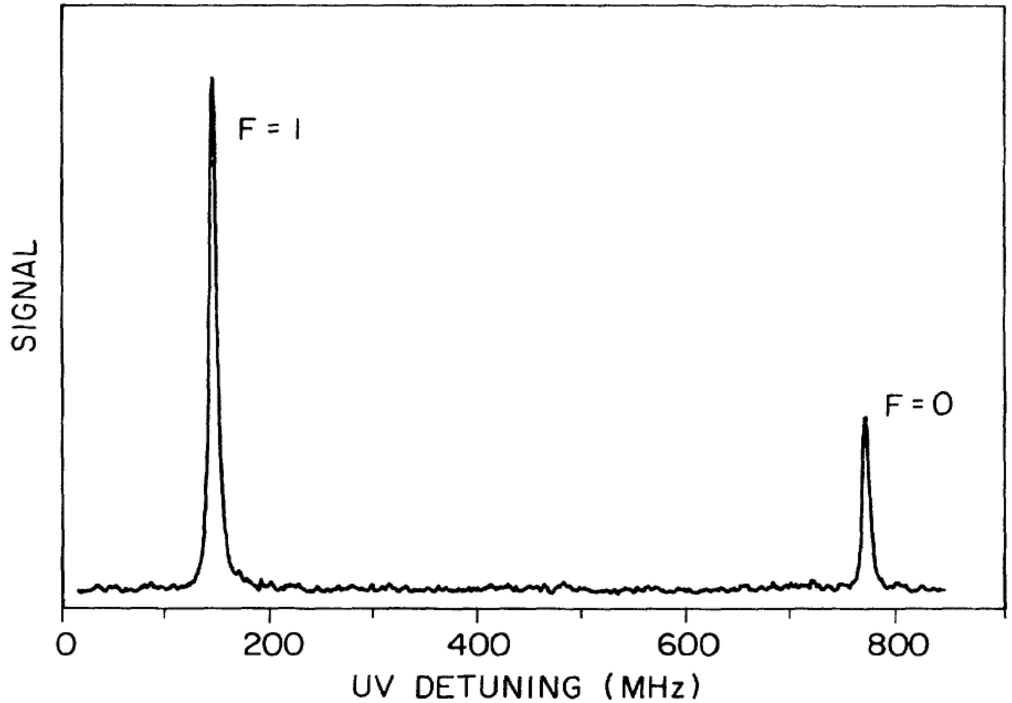
Two-photon spectroscopy of the 1S-2S transition

This transition has been extensively studied by the T.W. Hänsch's group
first in Stanford and then in Garching

natural width : 1.3 Hz !

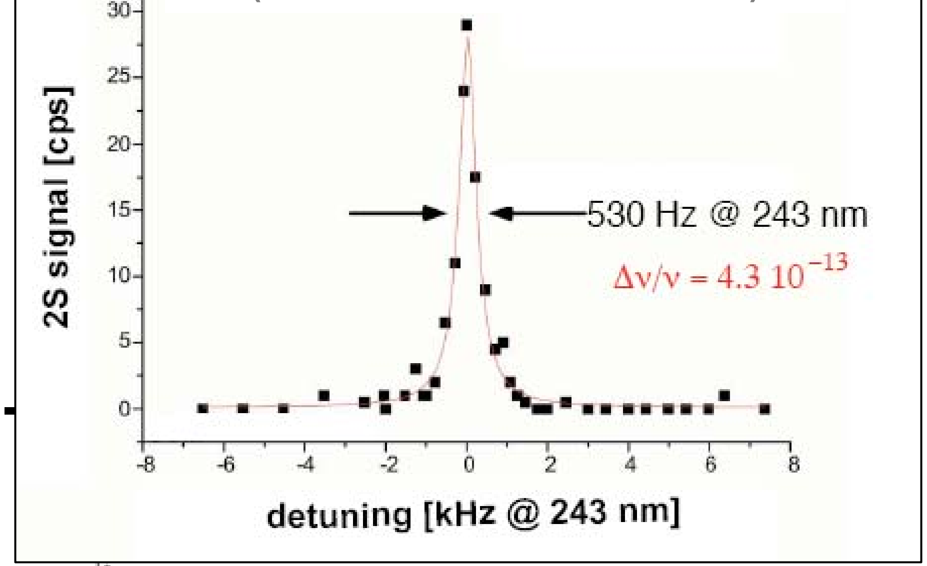
First observation
with a cw laser : C.J. Foot, B. Couillaud, R.G. Beausoleil and T.W. Hänsch
Phys. Rev. Lett. 54, 1913 (1985)

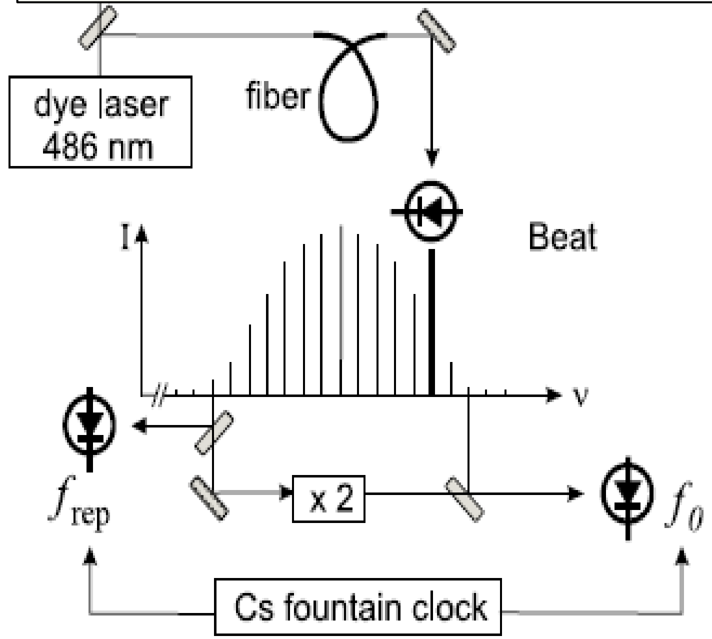




Absolute frequency measurement of the 1S-2S hydrogen transition

(Hänsch's Nobel conference)





Nobel Prize 2005 half awarded jointly to J. L. Hall and T.W. Hänsch

> *"for their contributions to the development of laser-based precision spectroscopy, including the optical frequency comb technique"*

Frequency measurement:

2466 061 413 187 018 (11) Hz

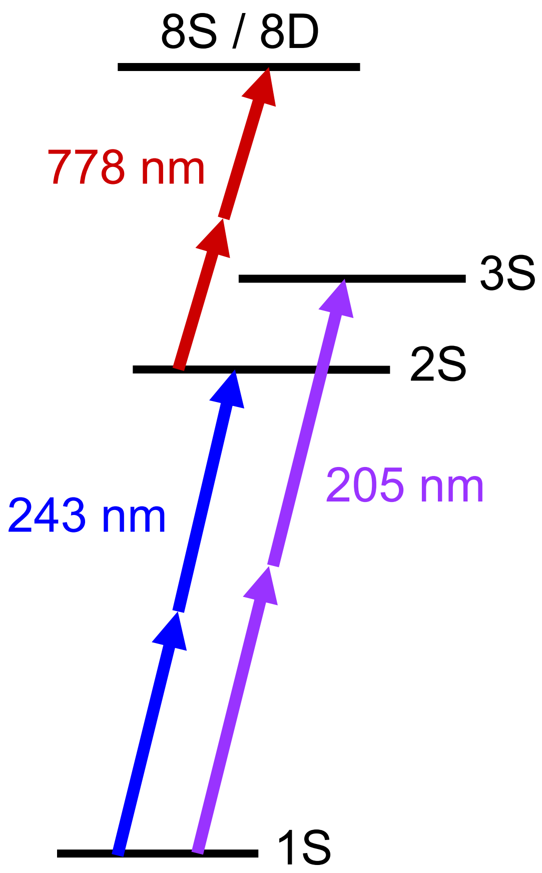
accuracy of 4.5×10^{-15}

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

Test of the stability of fundamental constants : no drift observed at a level of 10^{-15} per year

Two-photon spectroscopy in hydrogen

The 1S-2S two-photon transition has been measured at a very high level of precision
but the determination of the Rydberg constant and of the Lamb shifts
needs the comparison of different optical frequencies



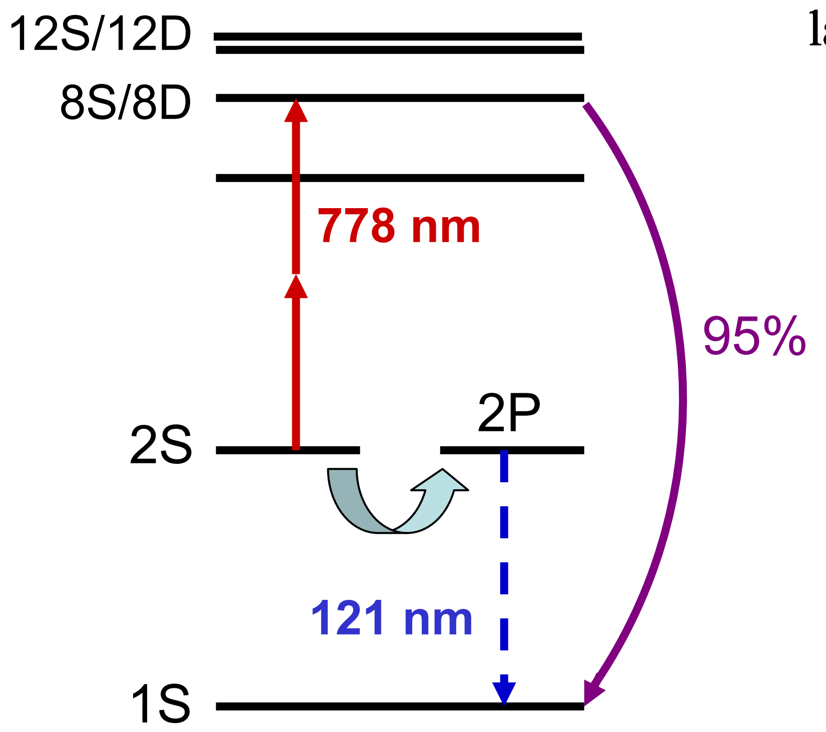
Our group in Paris has studied :

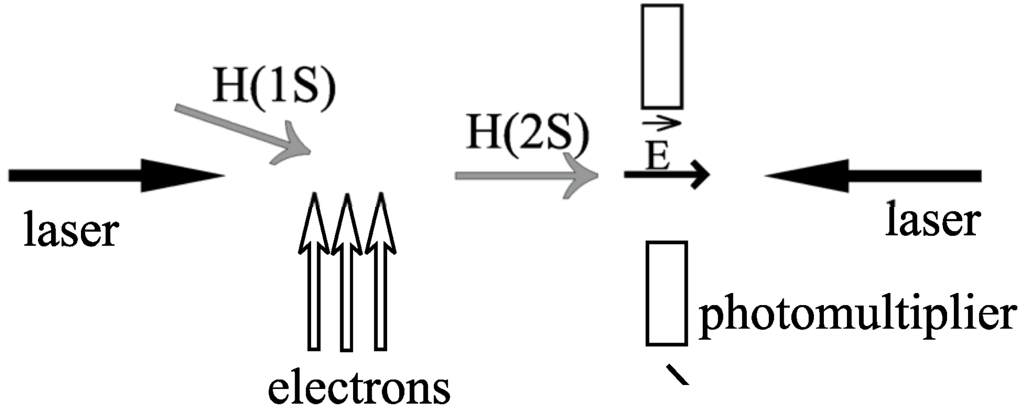
the 2S-nS et 2S-nD two-photon transitions
from the metastable state
towards the n = 8 and 12 levels

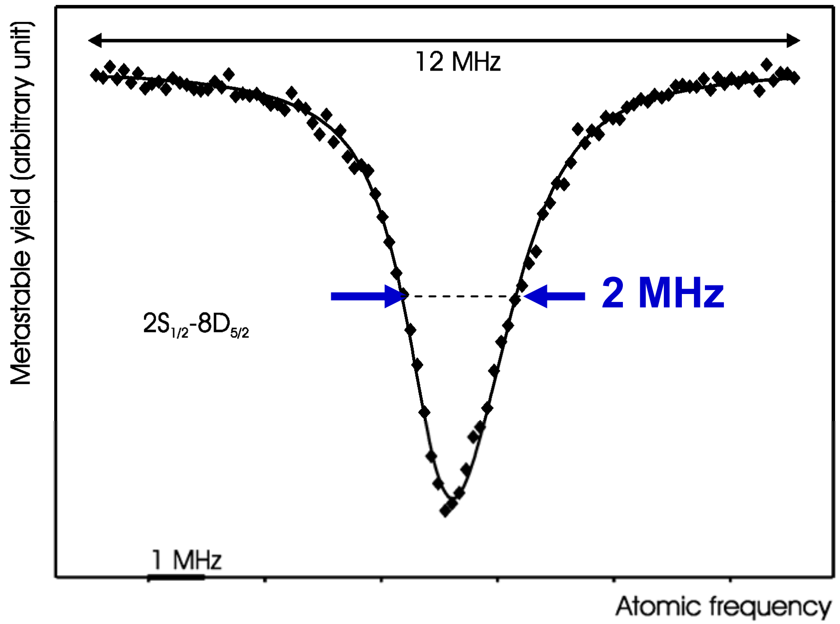
and the 1S-3S two-photon transition
from the ground state

The 2S-nS and 2S-nD transitions

studied in Paris (LKB)





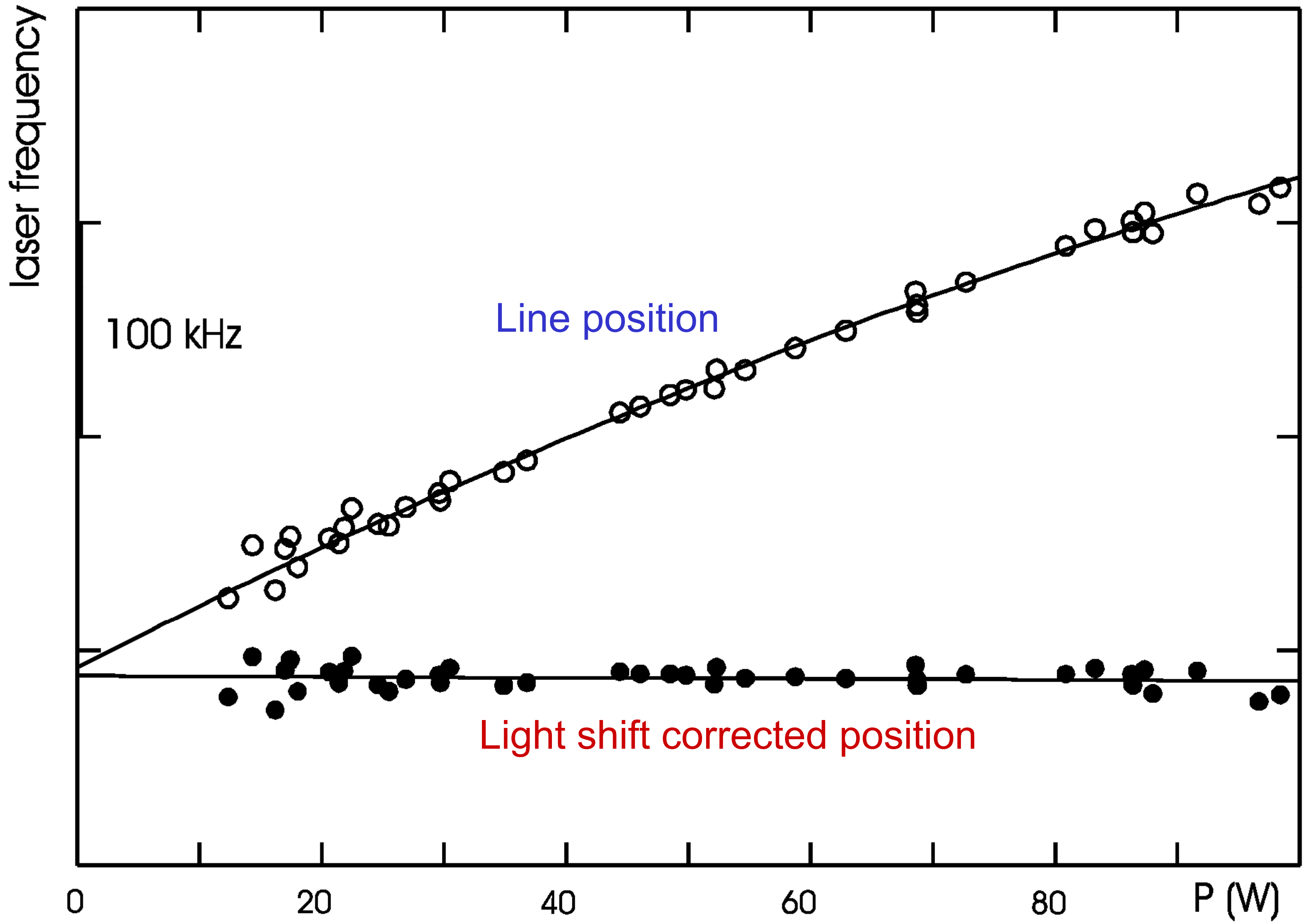


Natural width : 100 - 500 kHz

Typical line width : 1 to 2 MHz

mainly due to inhomogenous light shift

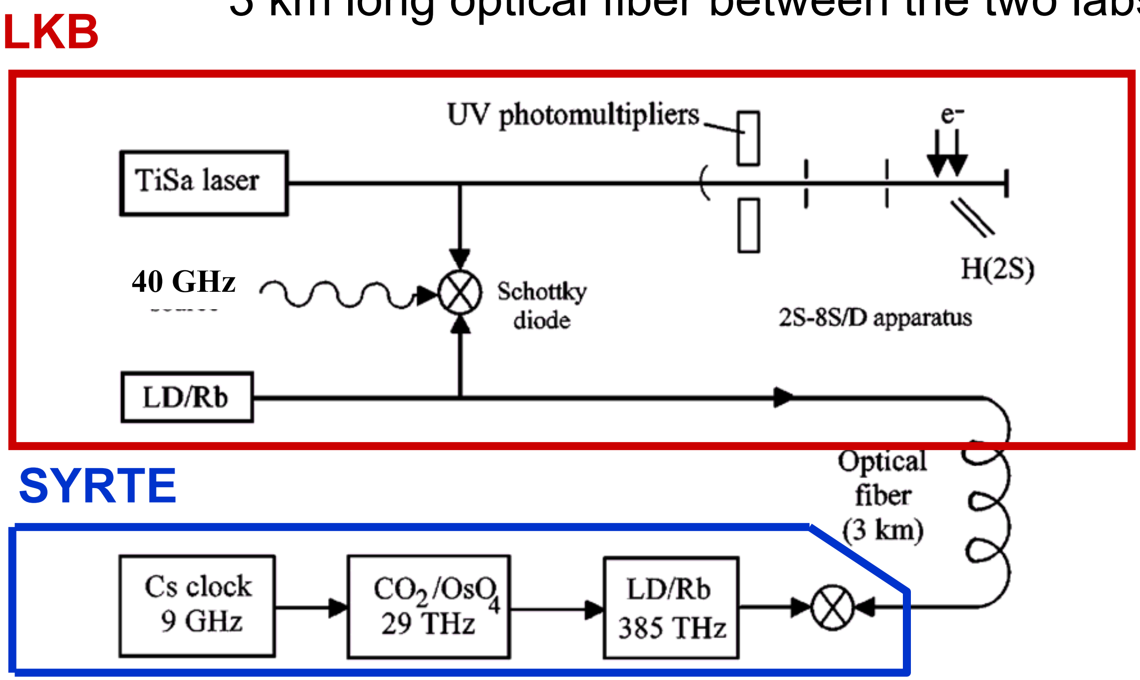
Light shift of the $2S_{1/2}$-$8D_{5/2}$ transition



Measurement of the 2S-8S and 2S-8D frequencies (SYRTE-LKB)

First pure frequency measurement in 1993

Use of a two-photon rubidium frequency standard
3 km long optical fiber between the two labs



B. de Beauvoir *et al.*, Phys. Rev. Lett. 78, 440 (1997)
and Eur. Phys. J. D 12, 61 (2000)

$f\,(2S_{1/2}\text{-}8D_{5/2})$ = 770 649 561 584.2 (6.4) kHz

relative uncertainty 8.3 x 10^{-12}

How determine the Rydberg constant?

There are several way to deduce the Rydberg constant from the 1S-2S interval, the 2S-nD interval or from their combination

B. de Beauvoir *et al*, Eur. Phys. J. D 12, 61 (2000)

F. Biraben et al., in « The Hydrogen atom : precision physics of simple atomic systems » Springer (2001)

F. Biraben, Eur. Phys. J. Special topics 172, 109 (2009)

- From the 1S-2S frequency, using Lamb shifts deduced from QED calculations
  → uncertainty ~9 x 10^{-12} mainly limited by the proton size

- From the 2S-nD frequencies, using the 2S Lamb shift from QED calculations
  → uncertainty ~7 x 10^{-12} mainly limited by the frequency measurement and the proton size

- From the 2S-nD frequency, using the measured 2S Lamb shift
  → uncertainty ~10.6 x 10^{-12} mainly limited by 2S Lamb shift mesurement
  independent from the proton size

Determination of the Rydberg constant

- From the 1S-2S and 2S-nD intervals, using the scaling law of the Lamb shift

The Lamb shifts vary aproximatively as $1/n^3$; the deviation from this law is given by Δ_2

$$\Delta_2 = L_{1S_{1/2}} - 8L_{2S_{1/2}}$$

This quantity has been calculated very precisely and is independent from the proton size

S.G. Karshenboim, J. Phys. B 29, L29 (1996) ; Z. Phys. D 39, 103 (1997)

A. Czarnecki, U.D. Jentschura and K. Pachucki, Phys. Rev. Lett. 95, 180404 (2005)

It is then possible to form a linear combination to eliminate these Lamb shifts

$$7f\left(2S_{1/2} - 8D_{5/2}\right) - f\left(1S_{1/2} - 2S_{1/2}\right) \approx \left(\frac{57}{64}\right) c R_\infty + 7L_{8D_{5/2}} + \Delta_2$$

This method gives together the Rydberg constant and the 1S and 2S Lamb shifts
and is applicable to hydrogen and deuterium

The results in hydrogen are :

$R_\infty = 10\,973\,731.568\,505(97)\ \text{cm}^{-1}$ [8.8×10^{-12}]
$L_{1S} = 8172.834\ (25)\ \text{MHz}$
$r_p = 0.8742\ (94)\ \text{fm}$

Determination of the Rydberg constant

- From a least square adjustment
  - it can be done using only the hydrogen data

    the values of α and m_e/m_p being given a priori
  - or including data concerning all the fundamental constants

Since 1998, the CODATA (Committee on Data for Science and Technology) uses this method to determine the Rydberg constant

P.J. Mohr and B.N. Taylor, Rev. Mod. Phys. 72, 351 (2000)
Rev. Mod. Phys. 77, 1 (2005)
P.J. Mohr, B.N. Taylor and D.B. Newell, Rev. Mod. Phys. 80, 633 (2008)

The results obtained in the 2010 CODATA adjustment are :

$$R_\infty = 10\,973\,731.568\,539\,(55)\ \text{cm}^{-1}$$

with a relative uncertainty of 5.0×10^{-12}

$$r_\text{p} = 0.8775\,(51)\ \text{fm}$$

P.J. Mohr, B.N. Taylor and D.B. Newell, Rev. Mod. Phys. 84,1527 (2012)

Spectroscopy of muonic hydrogen determining the proton charge radius

F.D Amaro, A. Antognini, F.Biraben, J.M.R. Cardoso, D.S. Covita, A. Dax, S. Dhawan, L.M.P. Fernandes, A. Giesen, T. Graf, T.W. Hänsch, P. Indelicato, L.Julien, C.-Y. Kao, P.E. Knowles, F. Kottmann, J.A.M. Lopes, E. Le Bigot, Y.-W. Liu, L. Ludhova, C.M.B. Monteiro, F. Mulhauser, T. Nebel, F. Nez, R. Pohl, P. Rabinowitz, J.M.F. dos Santos, L.A. Schaller, K. Schuhmann, C. Schwob, D. Taqqu, J.F.C.A. Veloso

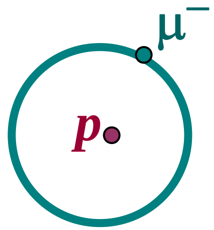
CREMA (Charge Radius Experiment with Muonic Atoms) collaboration

http://muhy.web.psi.ch http://www.lkb.ens.fr/-Metrologie-Quantique-

Principle of the experiment :
measurement of the 2S-2P Lamb shift in muonic hydrogen μ-p

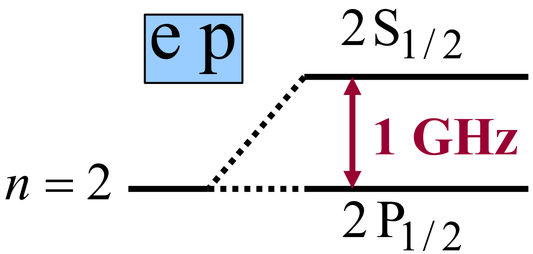
$$\frac{m_\mu}{m_e} \approx 207$$

Bohr radius : $a_0/207$



Lamb shift = self-energy + vacuum polarization + proton radius

2S-2P	self-energy	vacuum pol.	r_p	total
e p	1085.8 MHz	-26.9 MHz	0.146 MHz	1057.8 MHz
μ p	0.16 THz	-49.94 THz	0.93 THz	-49.05 THz



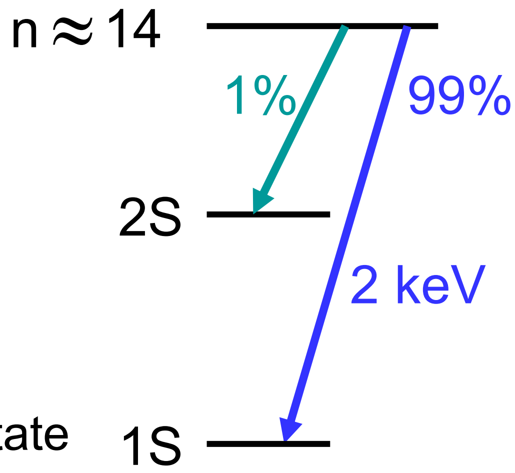
$$\frac{f_{\mu-p}}{f_{e-p}} \propto \left(\frac{1}{207}\right)^3 \approx 10^{-7}$$

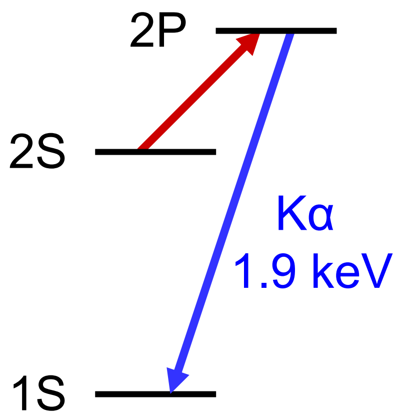
Production of muonic hydrogen in the 2S metastable state …

- the muon is captured in a highly excited state which decays at 99 % to the ground state emitting a « prompt » X ray (Kα, Kβ,…)

- X rays are detected with LAAPDs (large area avalanche photodiodes) placed above and below the muon stop volume

- 1% of the stopped muons decay to the long-lived 2S state

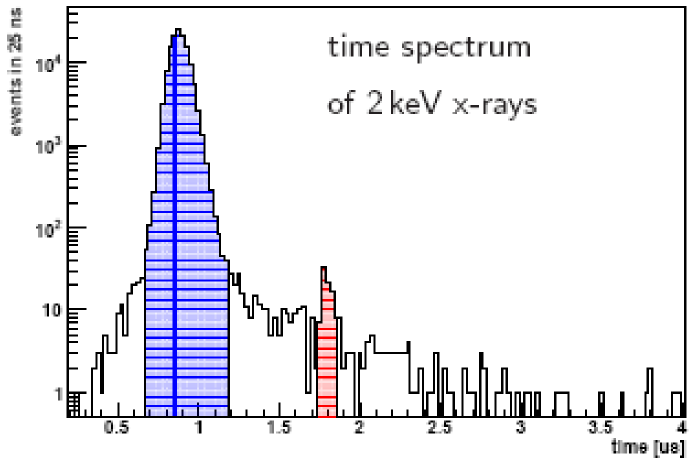




… and excitation of the transition

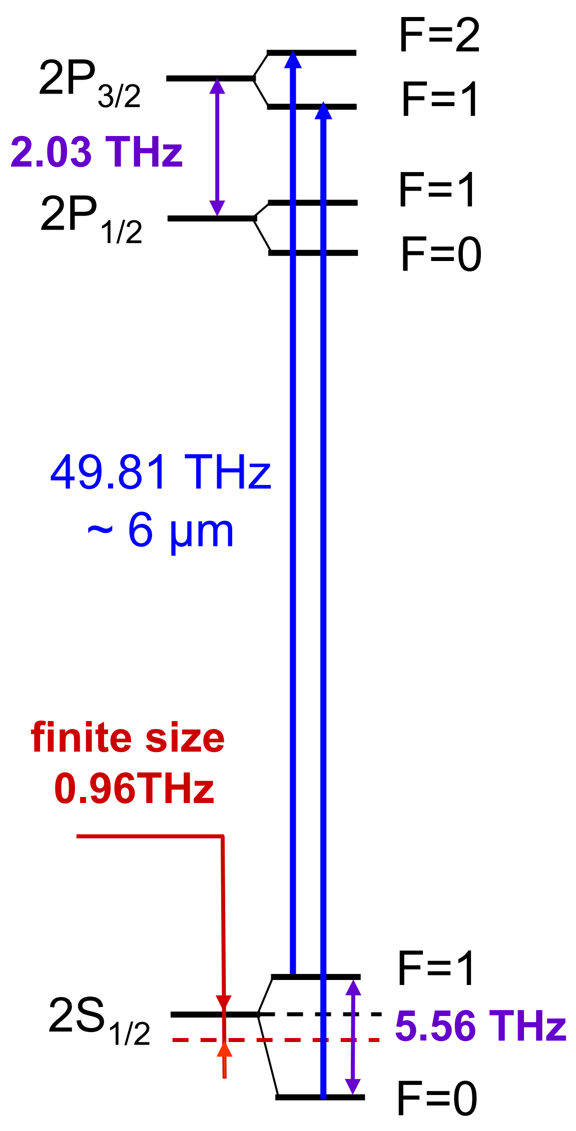
A short laser pulse at 6 μm drives the 2S-2P transition

- the transition is detected through the 1.9 keV Kα decay of the 2P state (« delayed » X ray)

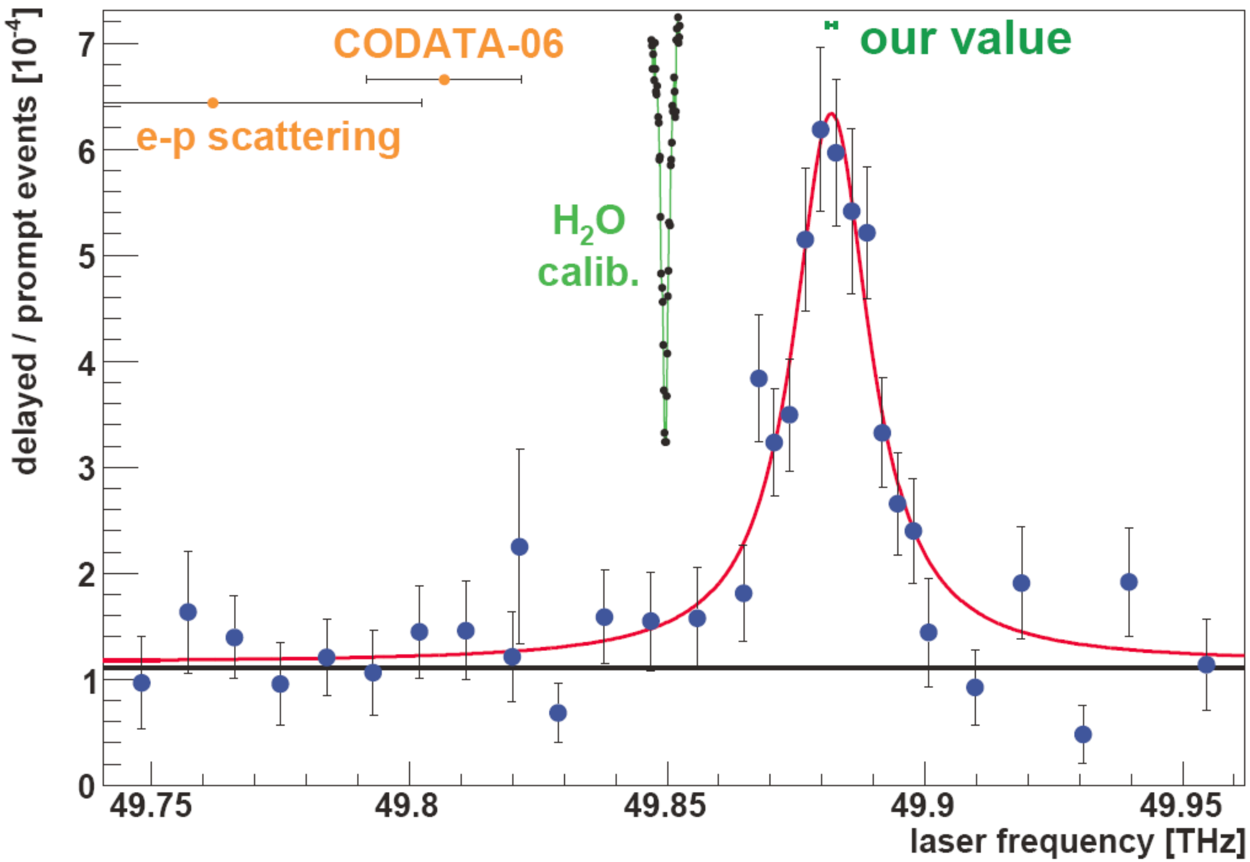


The signature of the signal is the detection of Kα, in time coincidence with the laser excitation, and of the electron originating from the muon decay (muon lifetime is 2.2 μs)

$2S_{1/2}(F=1)$ - $2P_{3/2}(F=2)$ transition observed in muonic hydrogen in 2009



- 550 events measured
- 155 backgrounds
- 31 FP fringes
- 250 hours



→ proton charge radius (~ 0.1%)

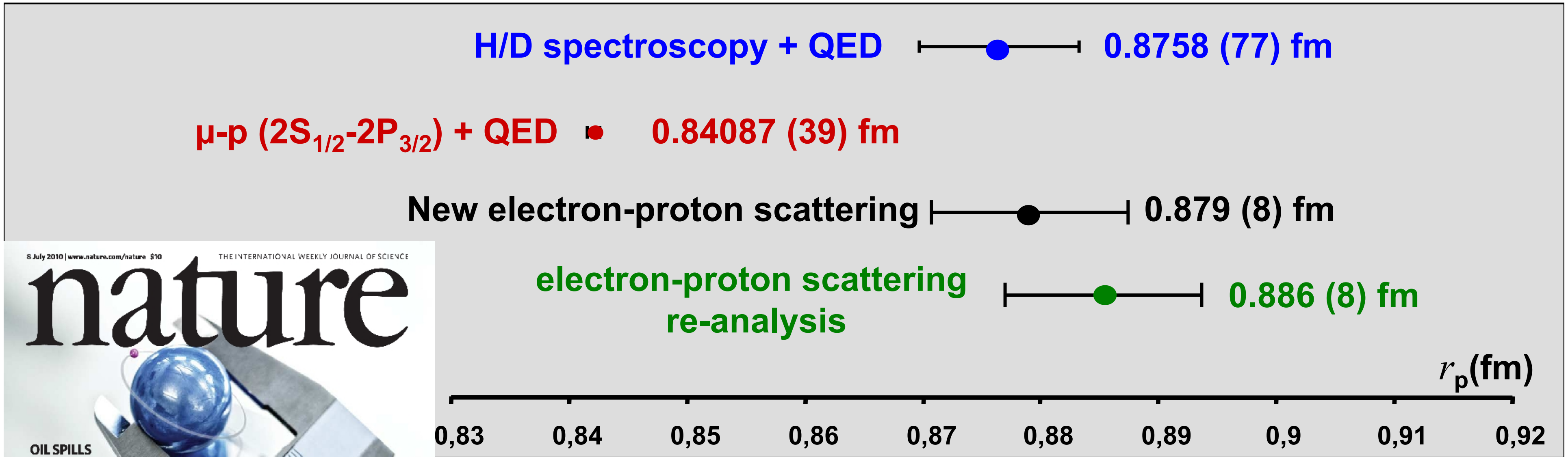
Result and comparison with other best determinations

ν (μ-p : $2S_{1/2}(F=1)$- $2P_{3/2}(F=2)$) = 49 881.35 (65) GHz

ν (μ-p : $2S_{1/2}(F=0)$- $2P_{3/2}(F=1)$) = 54 611.16 (1.05) GHz

ν_{theor}= 49818.70 (36) – 1264.00 (24) $r_p^{\,2}$ + $\Delta\nu_{TPE}$ GHz

r_p= 0.84087(26)(29) fm



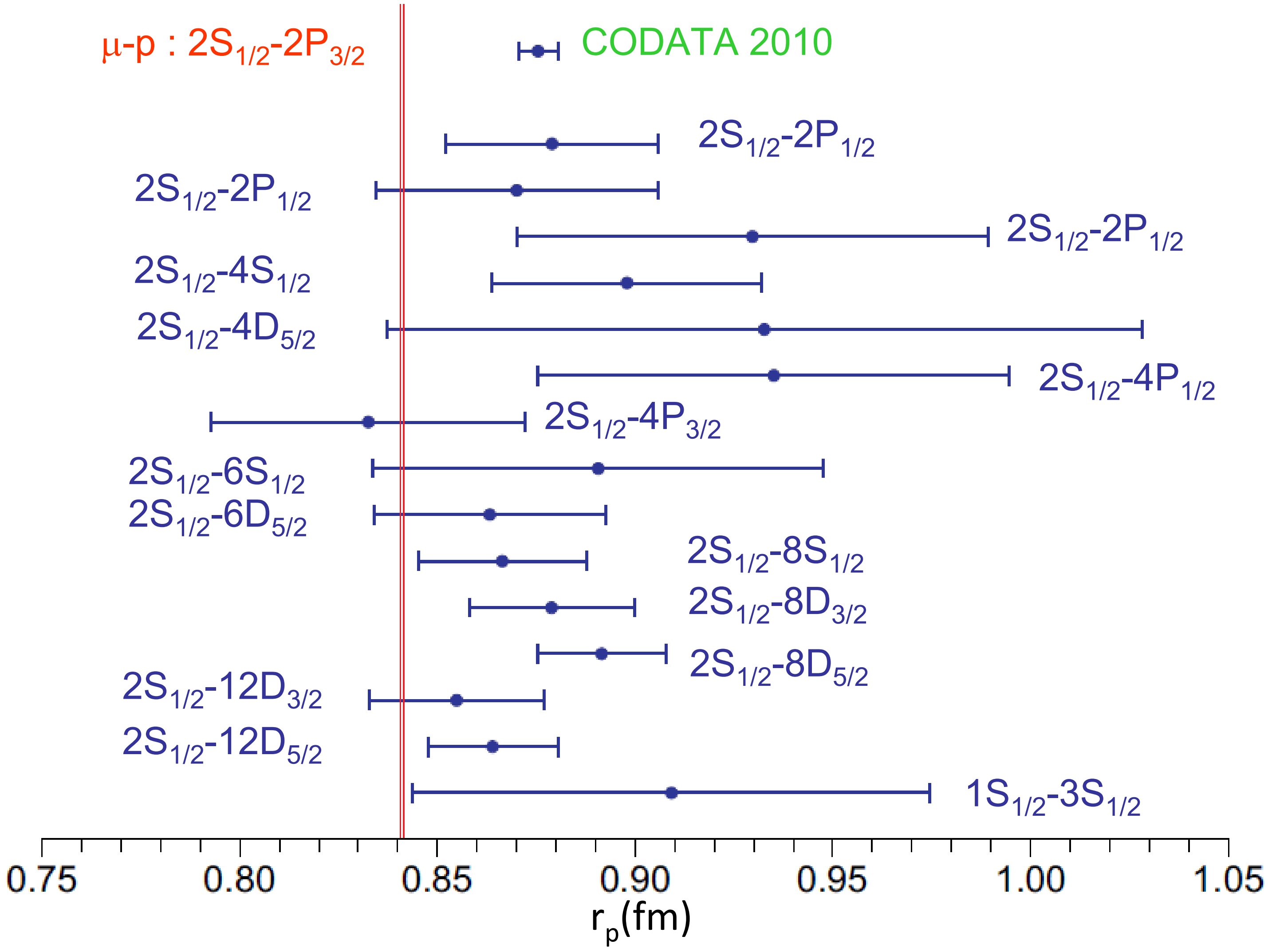
The result on μ-p : R. Pohl *et al.* , Nature **466**, 213 (2010)
A. Antognini et al, Science **339**, 417 (2013)

(Mainz)

New e^-- p^+ scattering : J.C. Bernauer *et al.* ,
Phys. Rev. Lett. 105, 242001 (2010)

7 σ discrepancy with the 2010 CODATA value

Determination of the proton radius from hydrogen frequencies



Ongoing experiments

2S-2P transition York university (E. Hessels) : "Ramsey method"

Measured @ 9kHz Lundeen and Pipkin PRL 72, 1172 (1994)
Γ(2S-2P)=100MHz proton radius : 11 kHz i.e. 10^{-4} of the linewidth

Advantages : 2S-2P mainly QED weak dependence on the Rydberg constant
RF source well known
Difficulty : large line width 100MHz, lineshape controlled at 10^{-4} !

$^{20}Ne^{9+}$ Rydberg states NIST : U. D. Jentschura et al, PRL 100, 160404 (2008)

Advantages : Rydberg states : high energy levels

- no contribution of the nucleus structure, QED well known ($1/n^3$)
- Direct measurement of the Rydberg constant

Difficulty : production of the ion $^{20}Ne^{9+}$

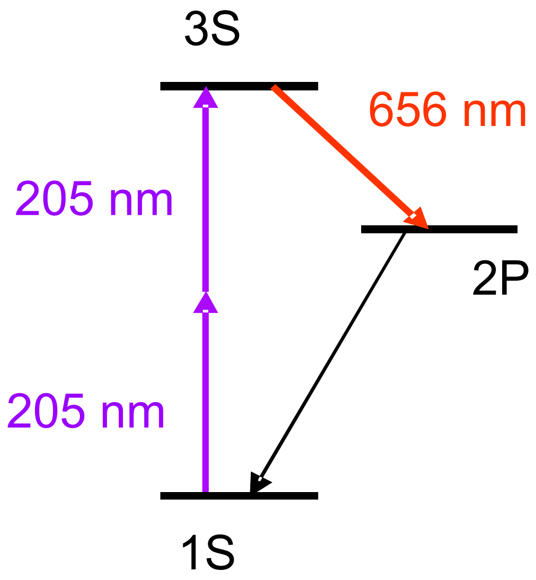
2S-4P transition MPQ Garching : Ann. Phys. (Berlin) 525 n°8-9 671-679 (2013)

Aim few kHz Γ(2S-4P)=13 MHz i.e. 10^{-3} of the linewidth

Advantages : cold hydrogen source
one ph transition weak laser power needed

Difficulty : transverse excitation but seems to be controlled
controlled of the linewidth @ 10^{-3}

Study of the 1S - 3S transition



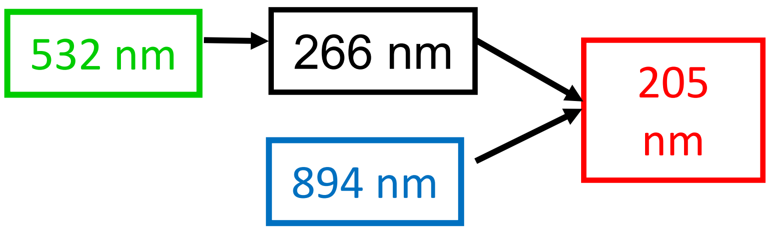
Advantages

More atoms in 1S beam compared to 2S H-beam

Difficulties

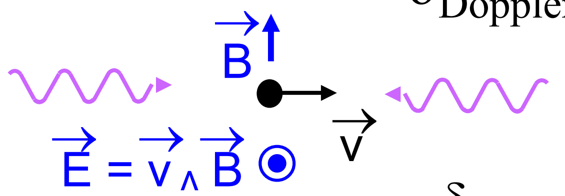
- Laser @ 205nm
- No "easy" optical transition for Doppler spectroscopy
- Aim for 1S-3S frequency 1kHz i.e. 10^{-3} linewidth

CW laser source @ 205 nm 15mW



Compensation of 2nd order Doppler effect

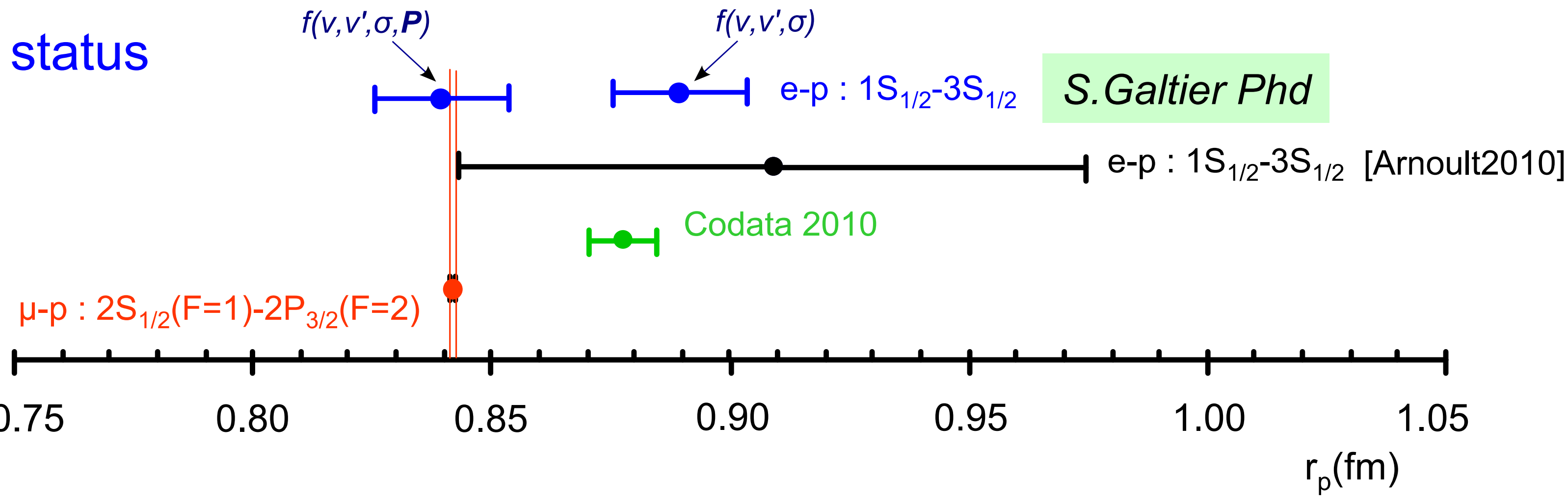
$$\delta_{Doppler} = -\nu_{atomic} \frac{v^2}{2c^2}$$



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

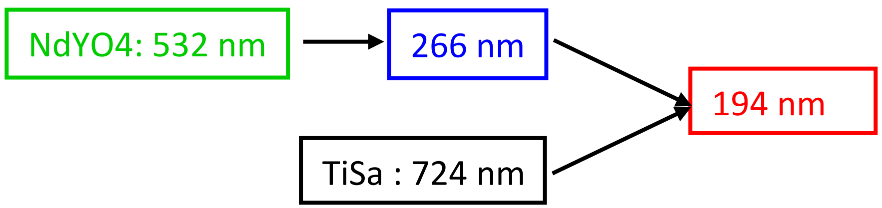
Study of the 1S - 3S transition

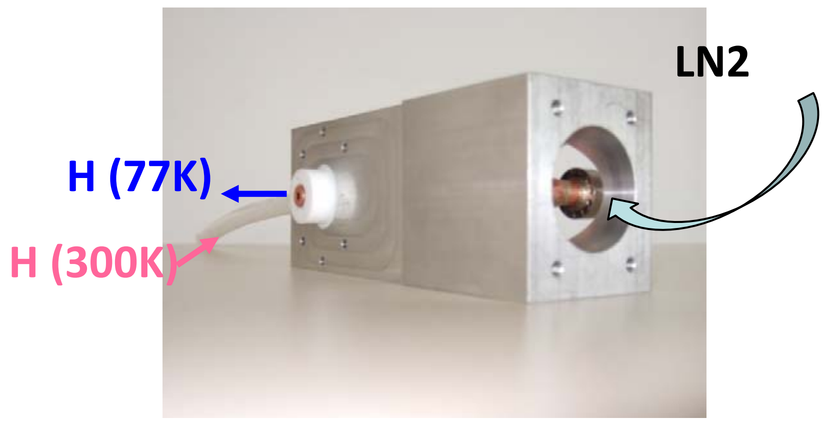
Current status



Prospects

-Study of the velocity distribution versus pressure (current)
-LN_2 (77K) cooled hydrogen source
-1S-2P with Lyman-⟨ laser (LAC Orsay)
-1S-4S transition





Proton radius puzzle

Assume the experiments are ok

C.E. Carlson, Progress in Particle and Nuclear Physics 82 (2015) 59-77

Introduction...“The reasons for this (i.e. proton radius puzzle) are not yet clear”

•Unexpected QCD corrections : “haywire” hadronic behaviour

…one is still left with an implausible 600MeV electromagnetic contributions to individual nucleon masses…

• Exotic explanations : new particles as $(g\text{-}2)_\mu$ (theo) ≠ $(g\text{-}2)_\mu$ (exp)

…constrains from K decay ($K^\pm \rightarrow \mu^\pm \nu$), from hfs in muonium,…

• Pb with the full collection of elec measurements (i.e. H spectroscopy, e-p scatt.)

…e-p scattering uncertainty larger than quoted…

Remerciements

Doctorants

J.-C. Garreau (1989)

F. Nez (1993)

S. Bourzeix (1995)

B. Chatel (1996)

G. Hagel (2001)

R. Battesti (2003)

P. Cladé (2005)

O. Arnoult (2006)

M. Cadoret (2008)

R. Bouchendira (2012)

S. Galtier (2014)

M. Andia

R. Jannin

C. Courvoisier

H. Fleurbay

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C. Schwob (1998-2008)

L. Julien

P. Cladé

S. Guellati-Khélifa

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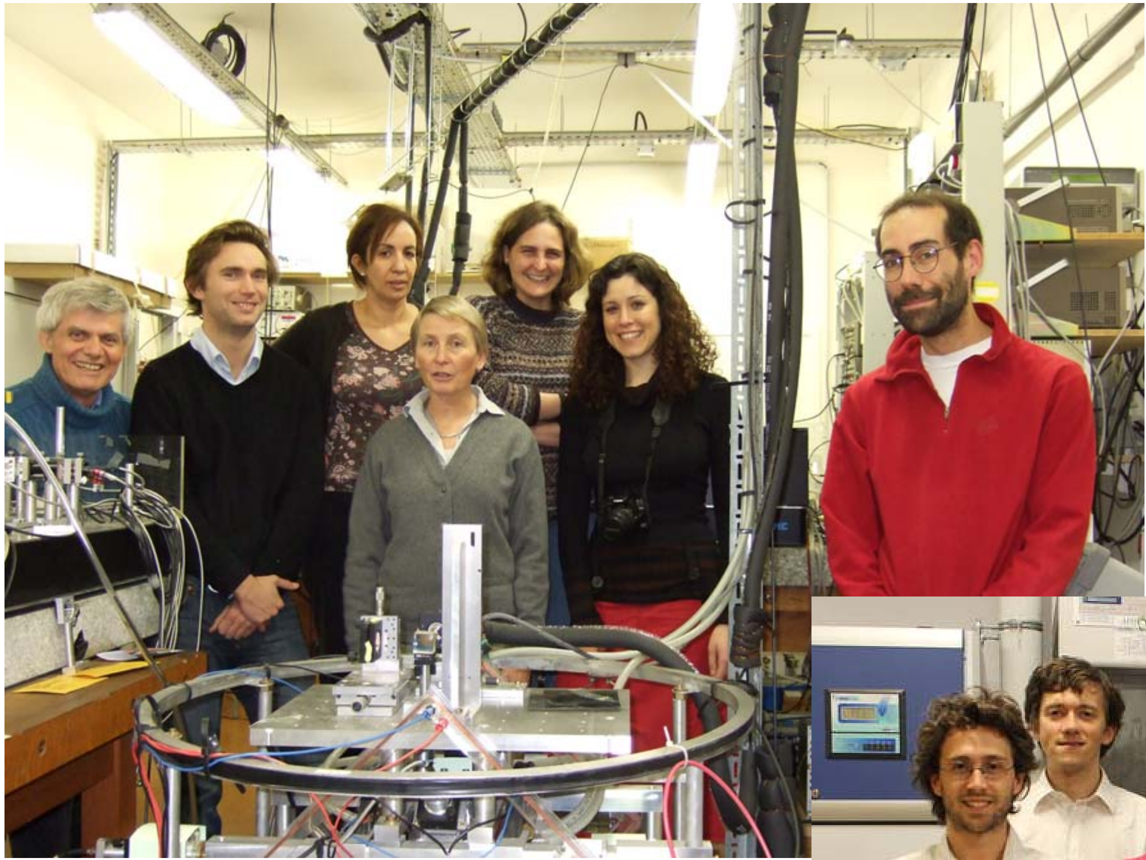
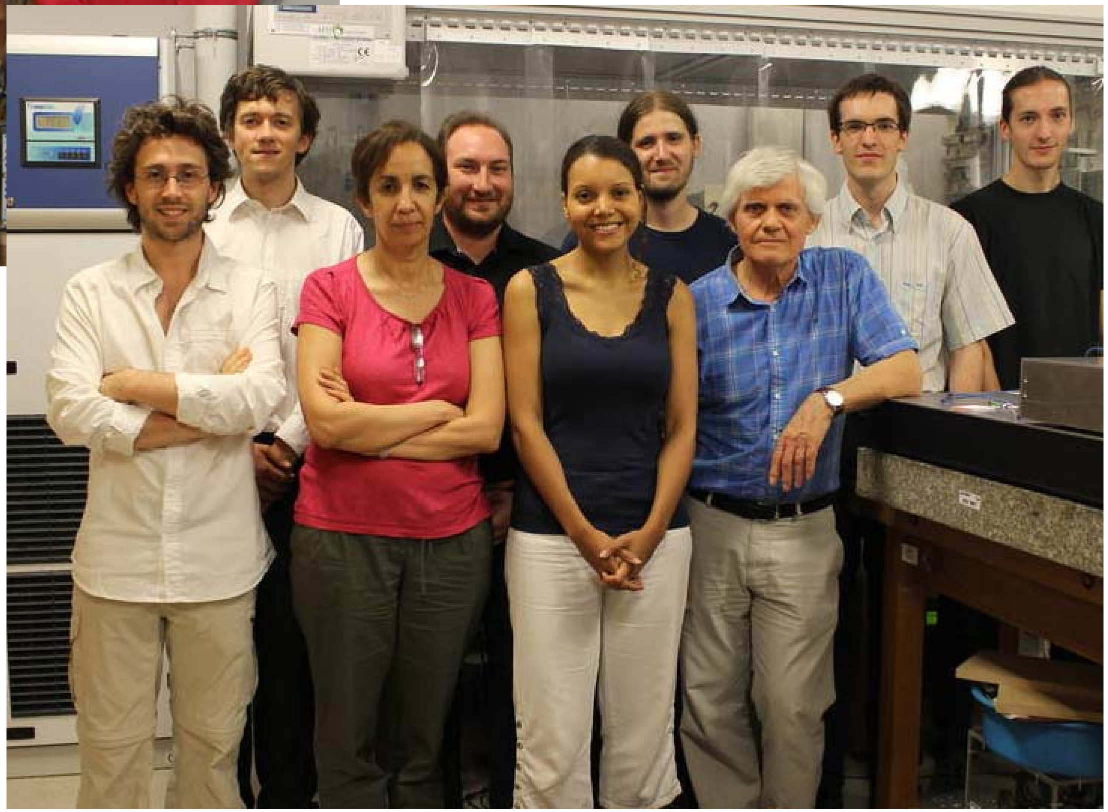
L. Jozefowsky (1997-1998)

E. de Mirandes (2006- 2007)



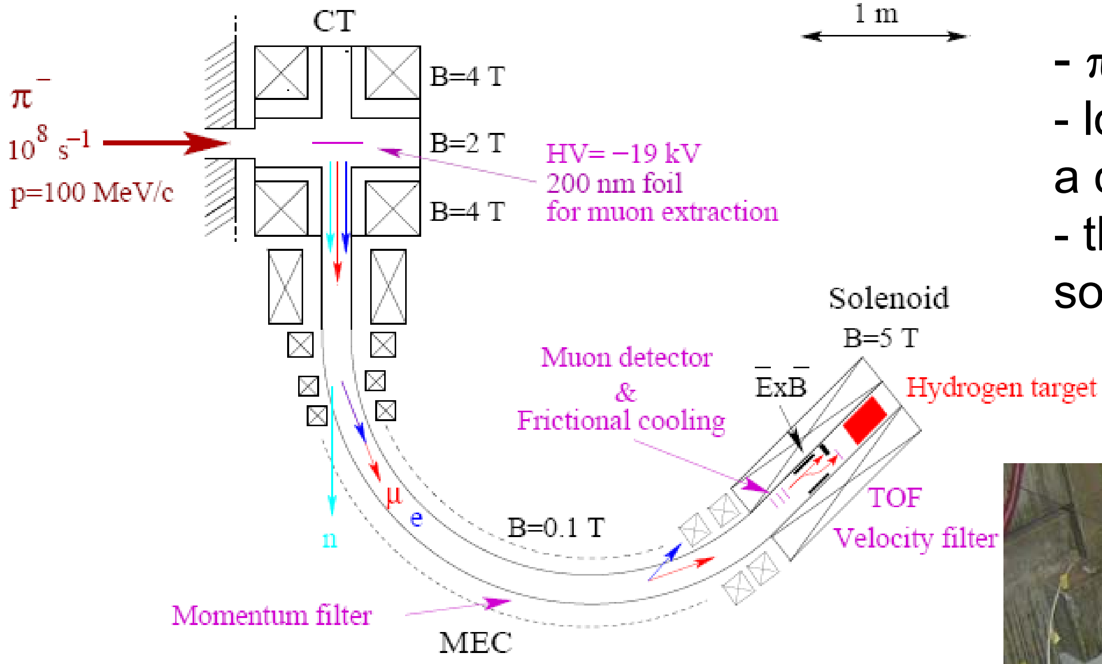
2007



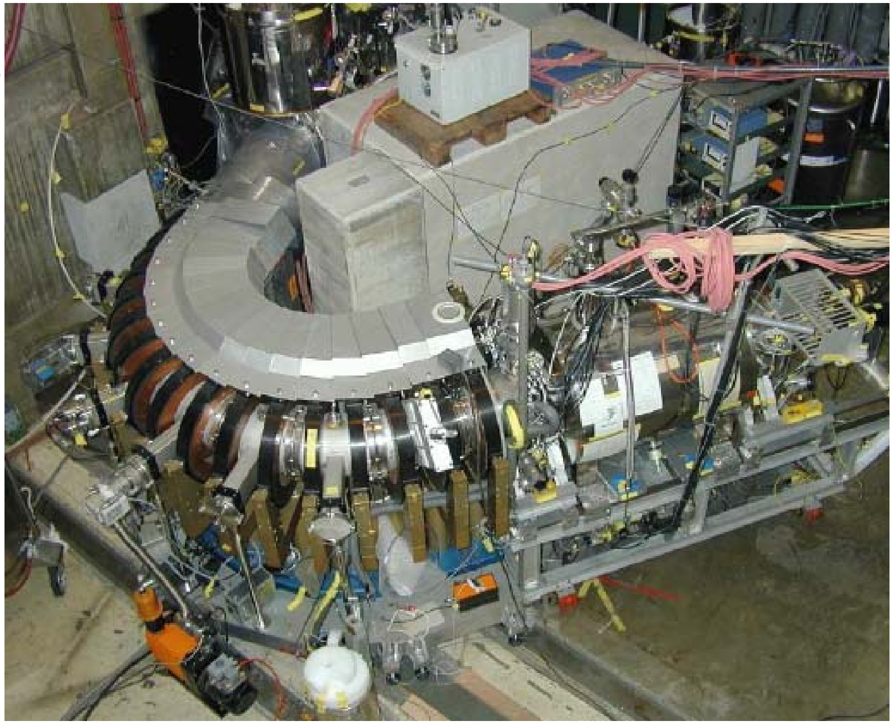
2014

Production of muonic hydrogen

CREMA collaboration



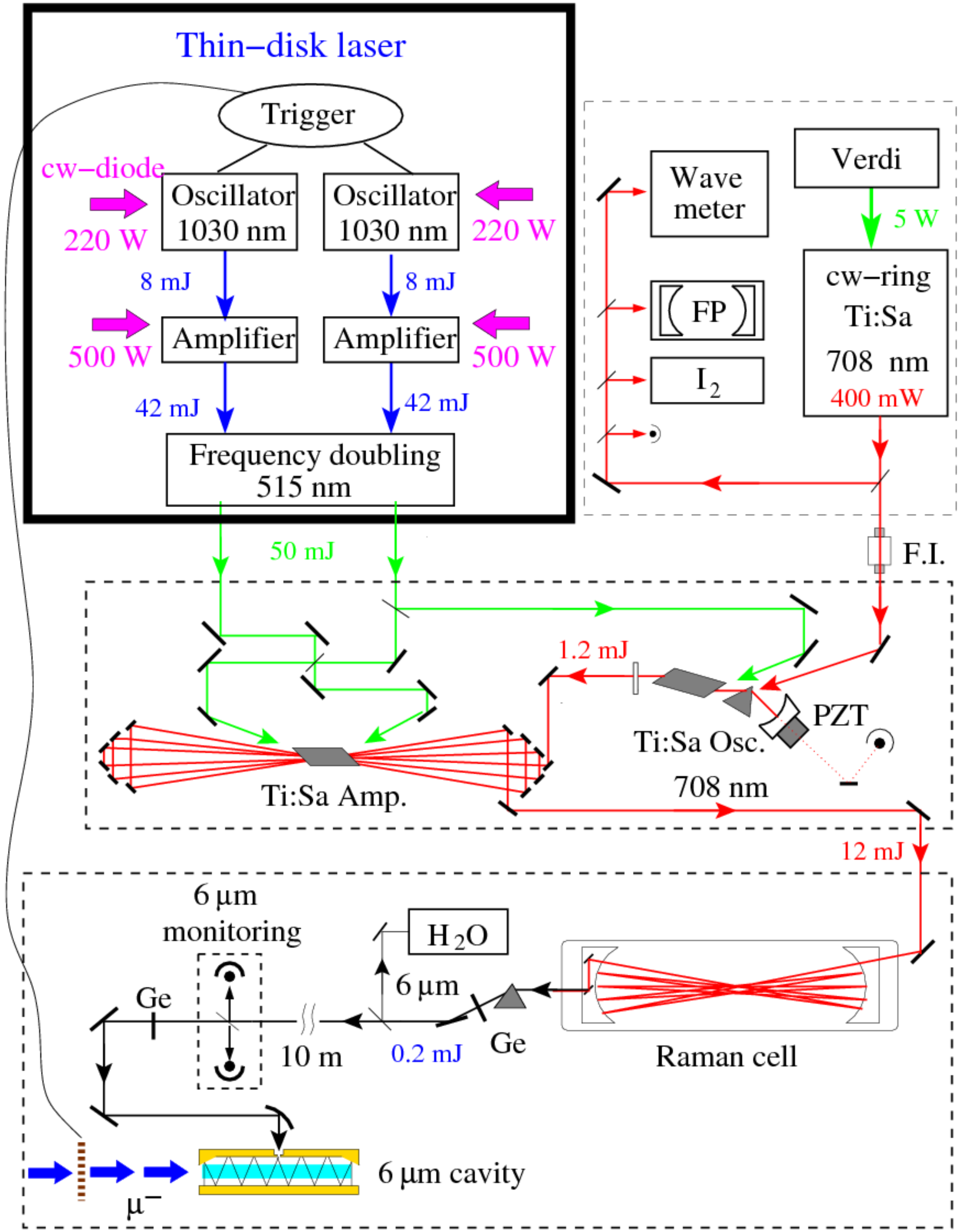
- πE5 line at PSI
- low energy muons are produced in a cyclotron trap
- they are transported in a curved solenoid (muon extracted channel)…



- detected by two fast detectors
  (stacks of ultra-thin carbon foils)
  rate of muons : 300 /s

signal used to trigger the laser pulse

- and stopped in the H_2 target
  (1 mbar)



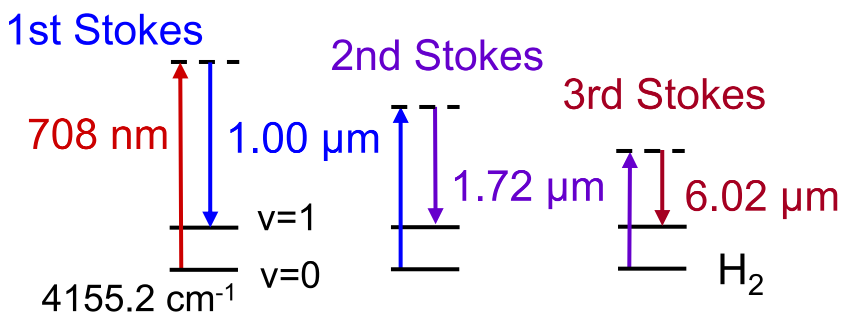
The laser chain

to produce a 6 µm tunable laser pulse

- **thin disk laser (1030 nm)**
  µ⁻ triggered
  + LBO (515 nm)

- **pulsed TiSa oscillator + amplifier (cw TiSa seeded at 708 nm)**

- **Raman cell for frequency conversion**



- **Multipass cavity at 6 µm surrounding the H_2 target**