Spectroscopie 1S-3S de l'atome d'hydrogène en vue de la détermination de constantes fondamentales et du rayon du proton

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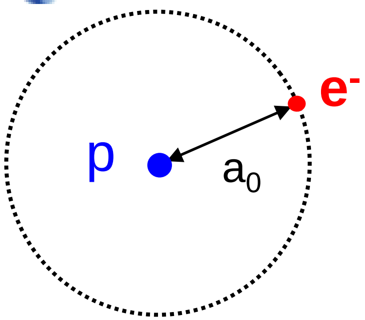
Assemblée générale du Labex FIRST-TF

8-9 juin 2017

Hydrogen theory



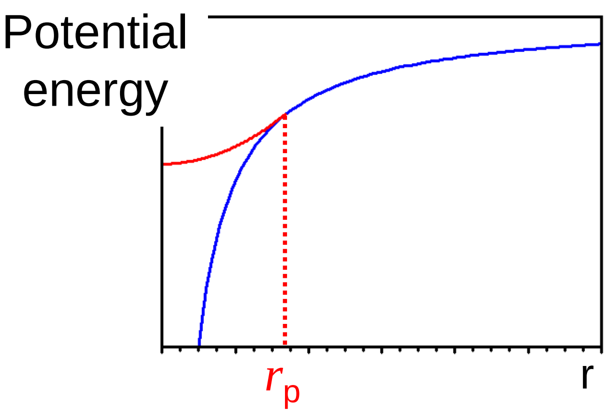
$$E = hcR_\infty f(\alpha, \frac{m_e}{m_p}, n, l, j) + L_n(n, l, j, r_p)$$

exact

- Dirac equation
- recoil effect

not well known

- QED corrections ($1/n^3$)
- proton charge radius ($m_r^3 r_p^2/n^3$)



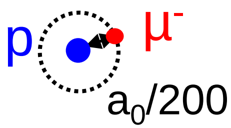
- Unknown quantities : R_∞ and L_n

⇨ linear combinations of exp. data

MPQ Garching	$\nu(1S-2S) = (1-\frac{1}{4})R_\infty + L(1S) - L(2S)$	
LKB Paris	$\nu(2S-8S) = (\frac{1}{4}-\frac{1}{64})R_\infty + L(2S) - L(8S)$	R_∞, $L^{exp}(1S)$ + QED → r_p
S. Karshenboim / K. Pachucki	$L(1S) - 8L(2S) =$ precisely calculated	

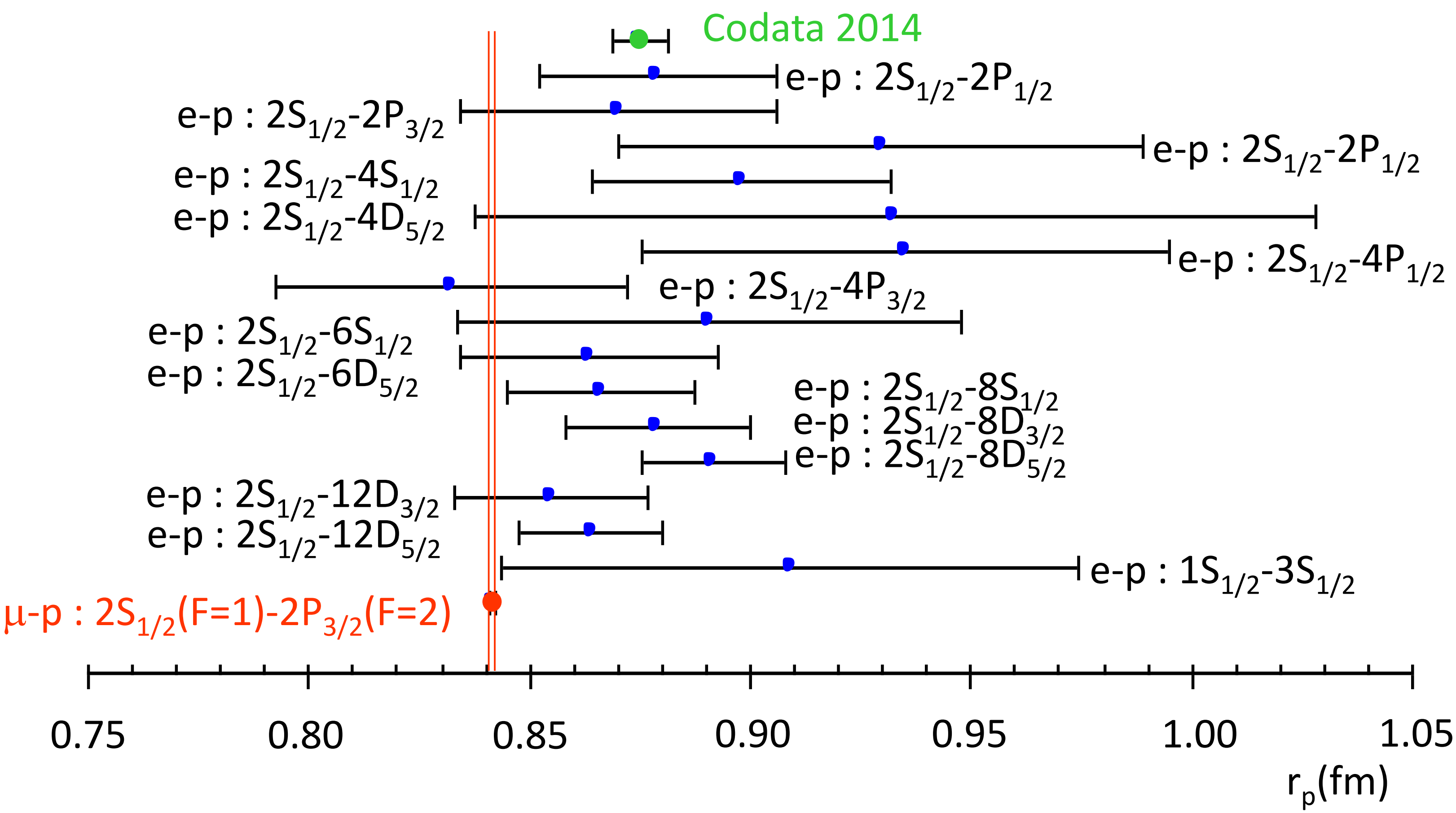
Actually, least squares adjustment of all data available (CODATA)

The « proton radius puzzle »



- 2S-2P in muonic hydrogen μ-p (Paul Scherrer Institute)
- $m_\mu \sim 200\ m_e$ ⇒ $\Delta E_\mu(r_p) \sim 10^7\ \Delta E_e(r_p)$: 2% of $\nu_{2S\text{-}2P}(\mu\text{-p})$

⇒ more precise r_p, but smaller !



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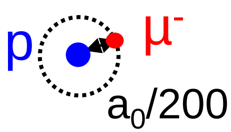
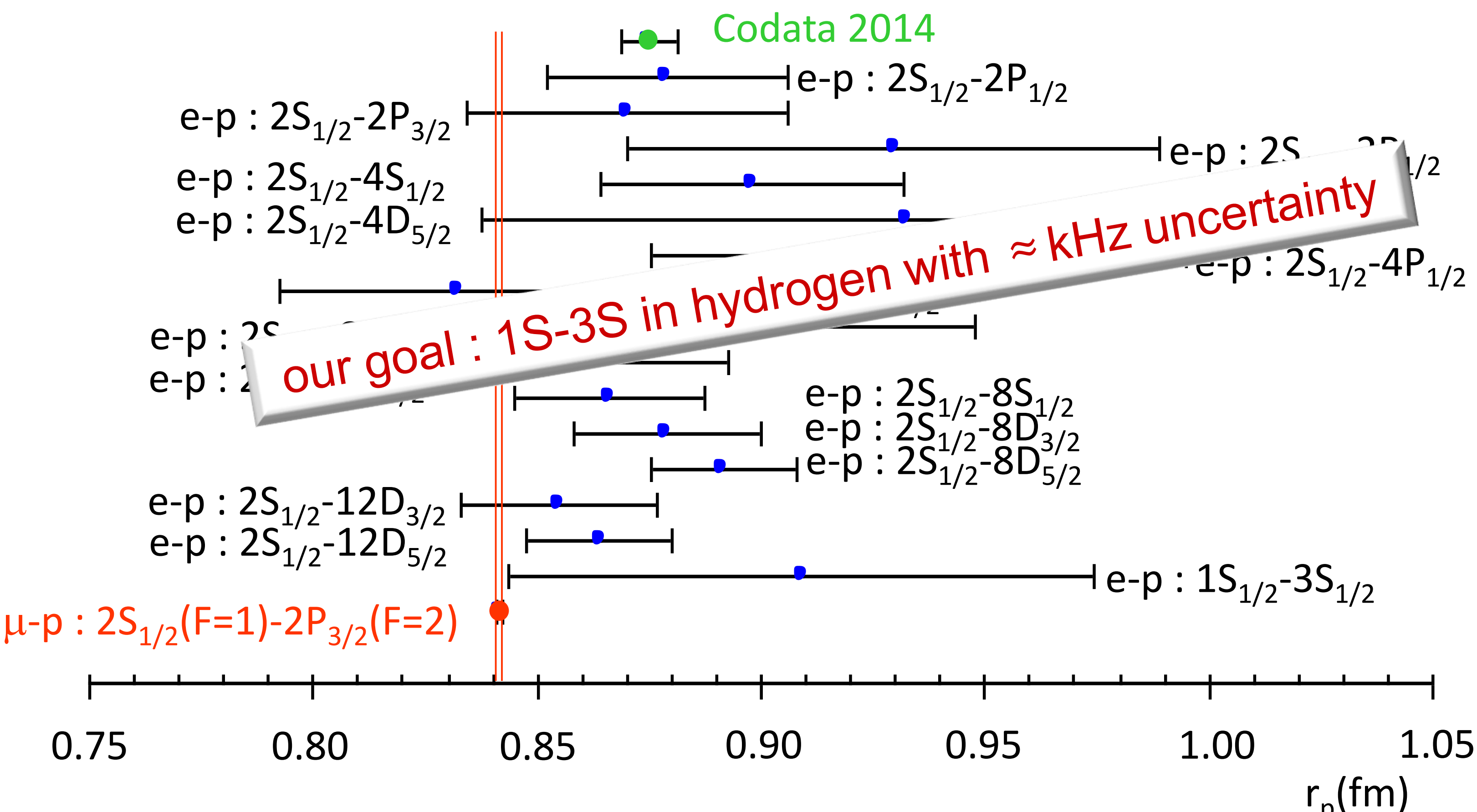
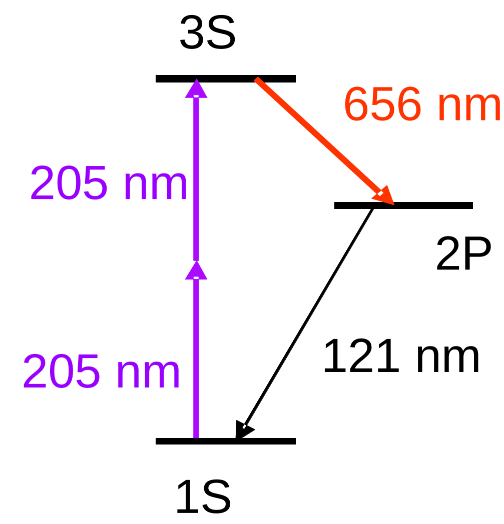
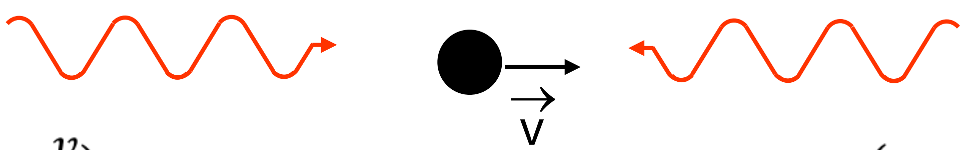




1S-3S spectroscopy

- Two-photon transition
  - ⇨ No first order Doppler effect

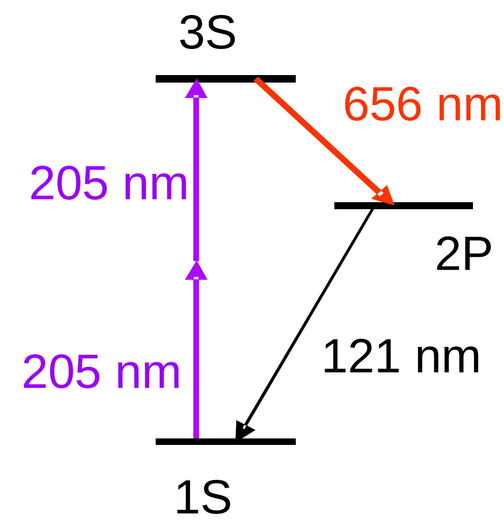


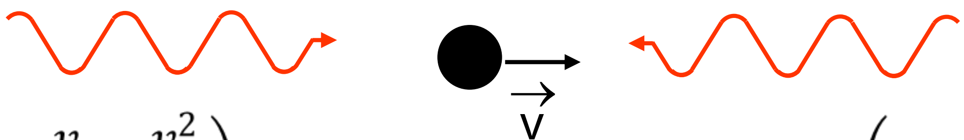


$$\omega_L\left(1-\frac{v}{c}\right) \qquad \omega_L\left(1+\frac{v}{c}\right)$$

1S-3S spectroscopy

- Two-photon transition
  ⟹ No first order Doppler effect
- 2nd order Doppler effect



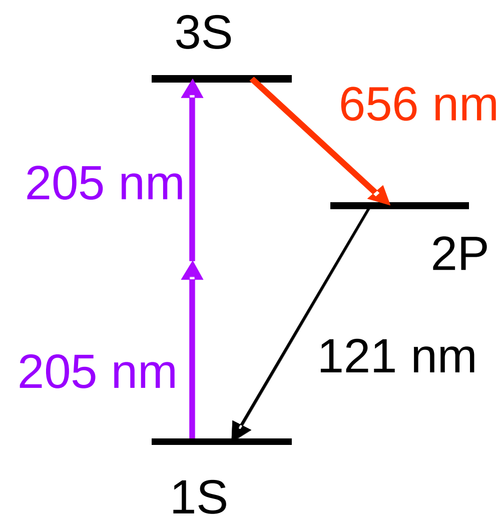


$$\omega_L\left(1-\frac{v}{c}+\frac{v^2}{2c^2}\right)$$

$$\omega_L\left(1+\frac{v}{c}+\frac{v^2}{2c^2}\right)$$

$$\delta_{Doppler}\approx-\frac{\omega_0 v^2}{2c^2}$$

1S-3S spectroscopy

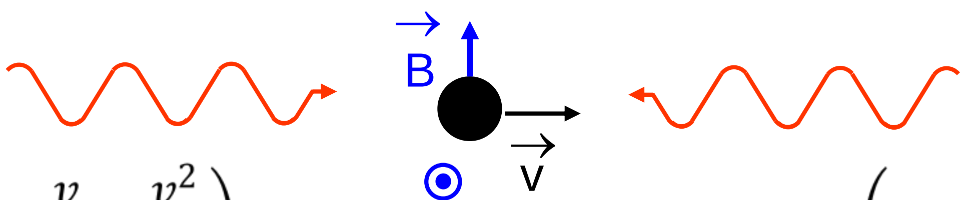


- Two-photon transition

  ⇒ No first order Doppler effect

- 2nd order Doppler effect
  - No easy one-photon transition from 1S

  ⇒ Compensation with quadratic Stark effect

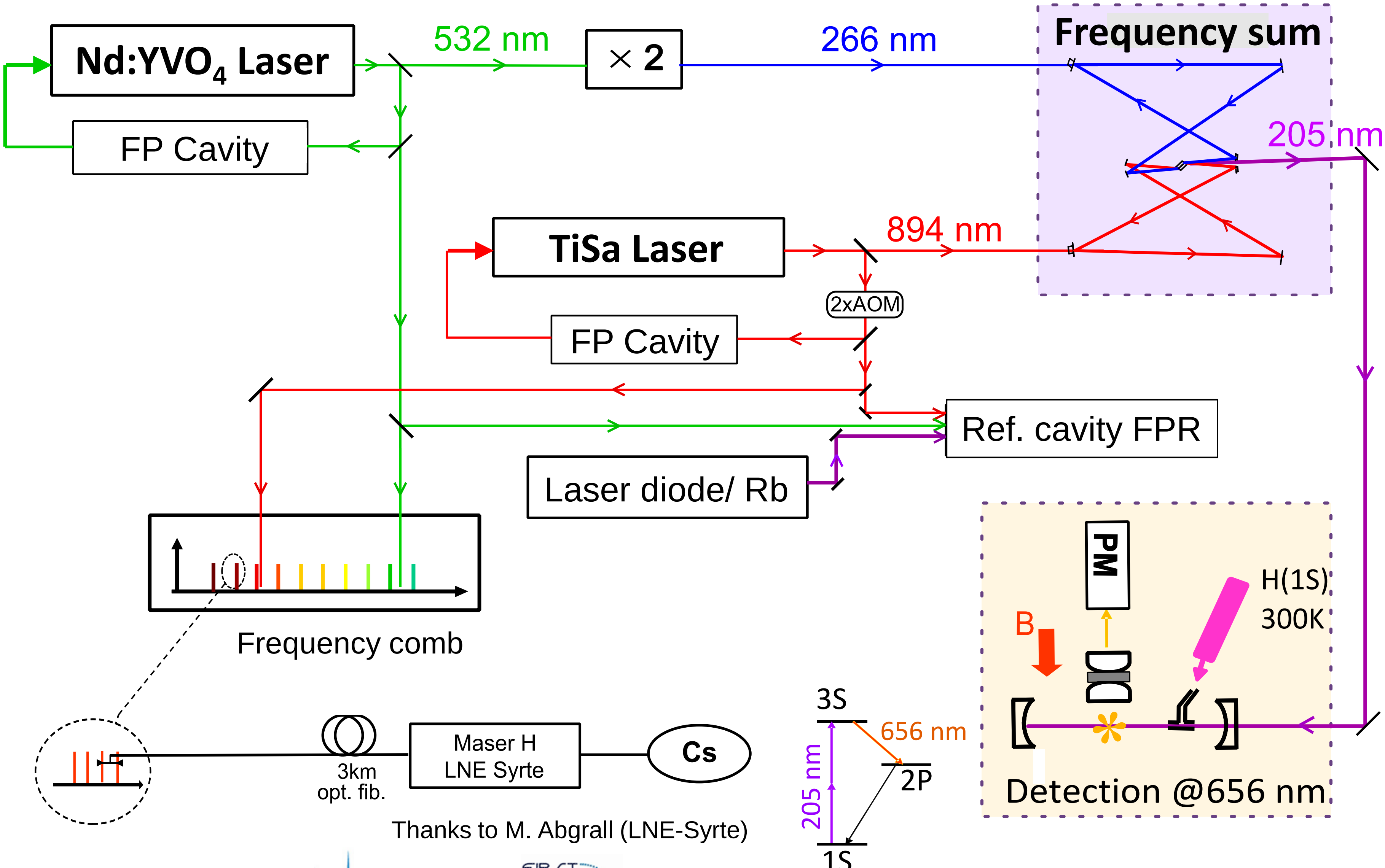


$$\omega_L\left(1-\frac{v}{c}+\frac{v^2}{2c^2}\right) \qquad \vec{E}=\vec{v}\wedge\vec{B} \qquad \omega_L\left(1+\frac{v}{c}+\frac{v^2}{2c^2}\right)$$

$$\delta_{Doppler}\approx-\frac{\omega_0 v^2}{2c^2} \Longleftrightarrow \delta_{Stark}\propto\frac{v^2B^2}{\Delta\nu_{SP}}$$

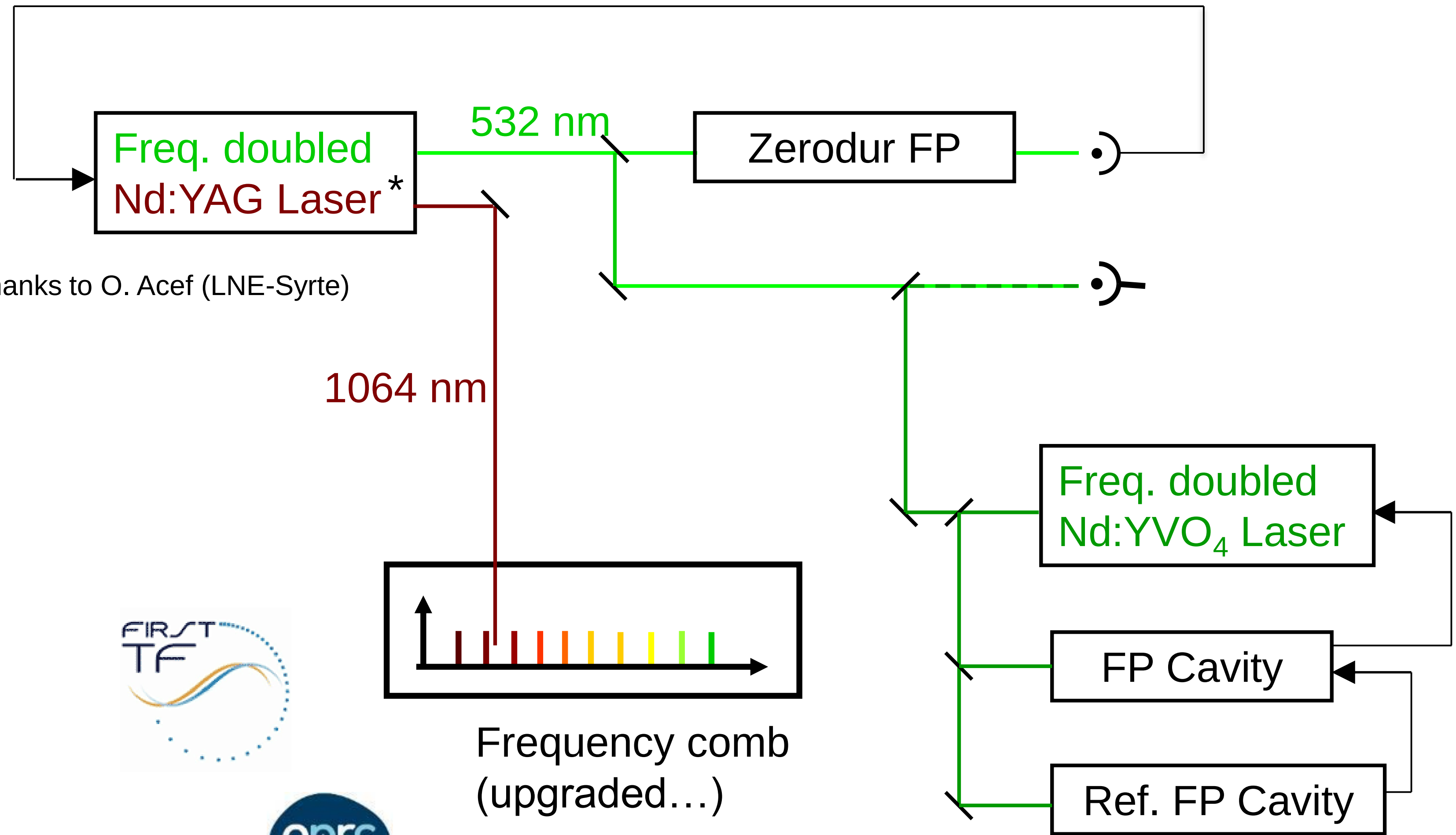
- In practice: only partial compensation
  - Fit for various B values ⇒ velocity distribution estimation

Experimental setup



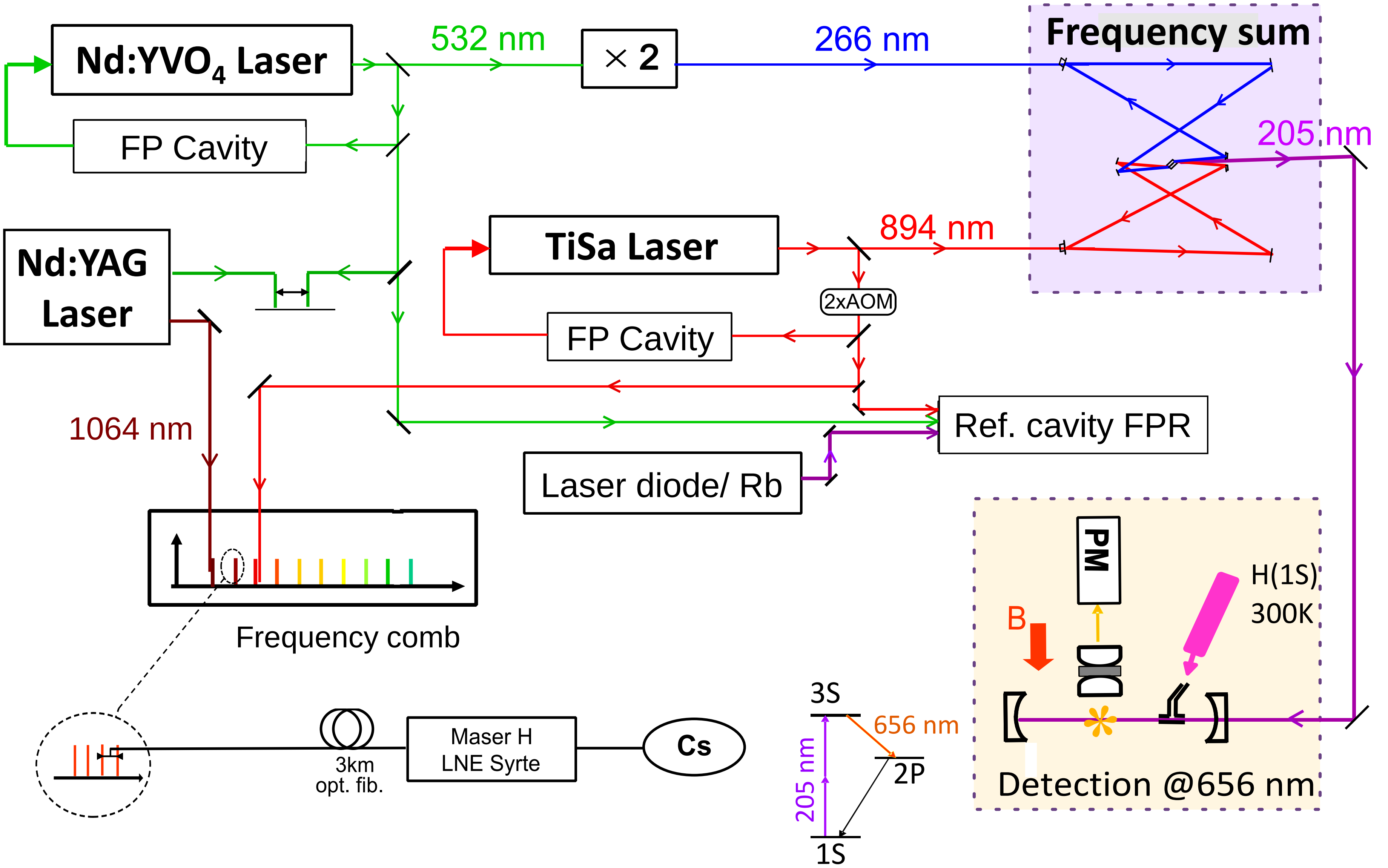
Thanks to M. Abgrall (LNE-Syrte)

Improving the 532 nm frequency measurement



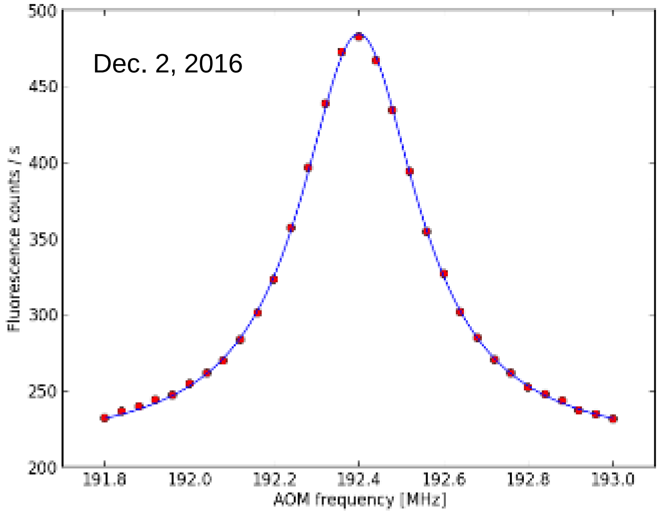
* Thanks to O. Acef (LNE-Syrte)

Experimental setup : update



Data analysis

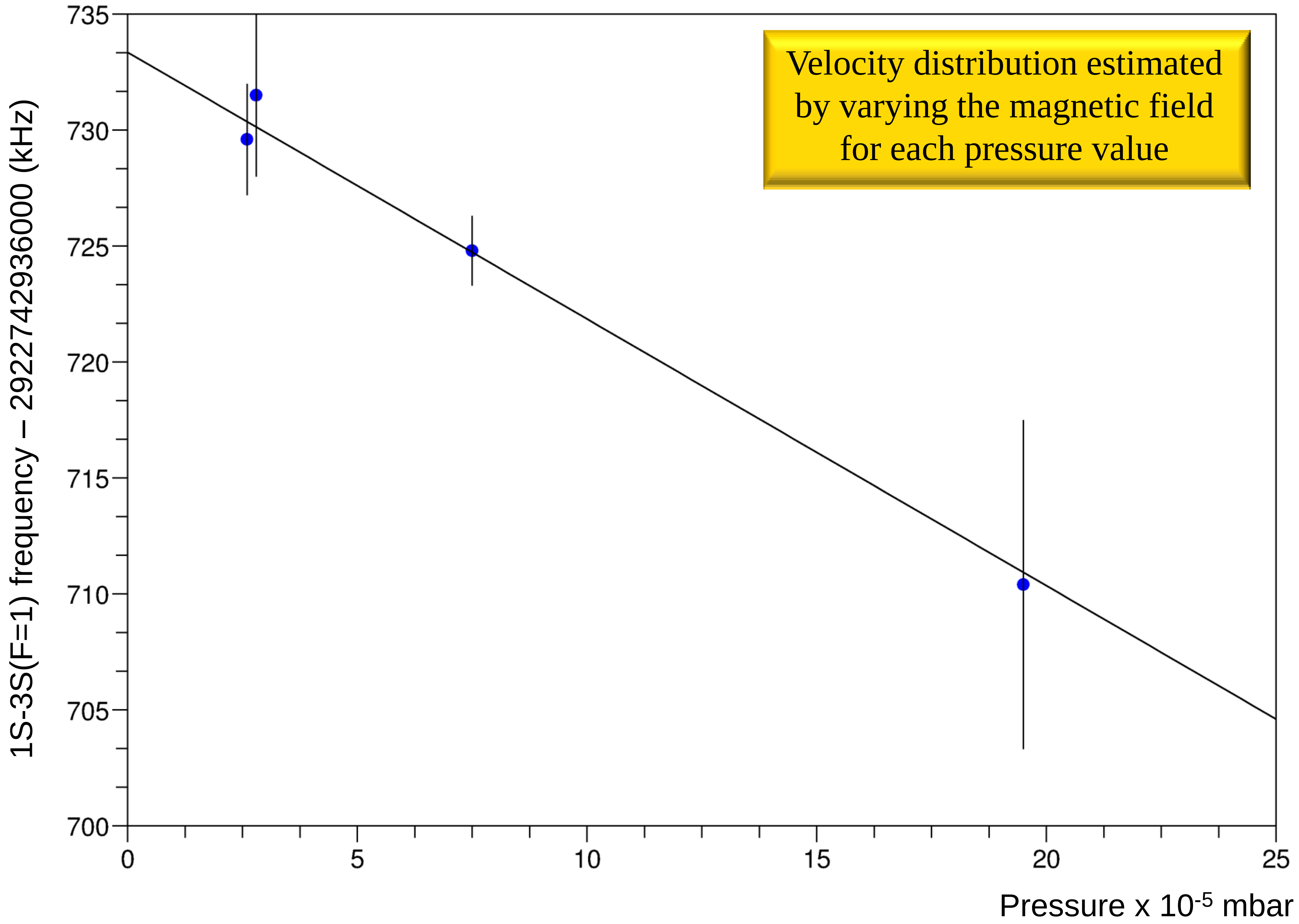
- Data acquisition:
  - frequency $f_{1S-3S} = 2\left(2\times f_{verdi}^{FPR} + \left(f_{tisa}^{FPR} - 2\times f_{AOM}\right)\right)$
  - fluorescence
  - UV intensity, …
- for several B field values
  - and 3 different pressures



Integration time : 4h
P_{205} = 6.5 mW
Pressure = 3×10^{-5} mbar
B = -0.3 G

- Analysis:
  - fit with theoretical profile
  - estimate velocity distribution
- Systematic effects:
  - pressure shift
  - light shift
  - quantum interference

Pressure shift

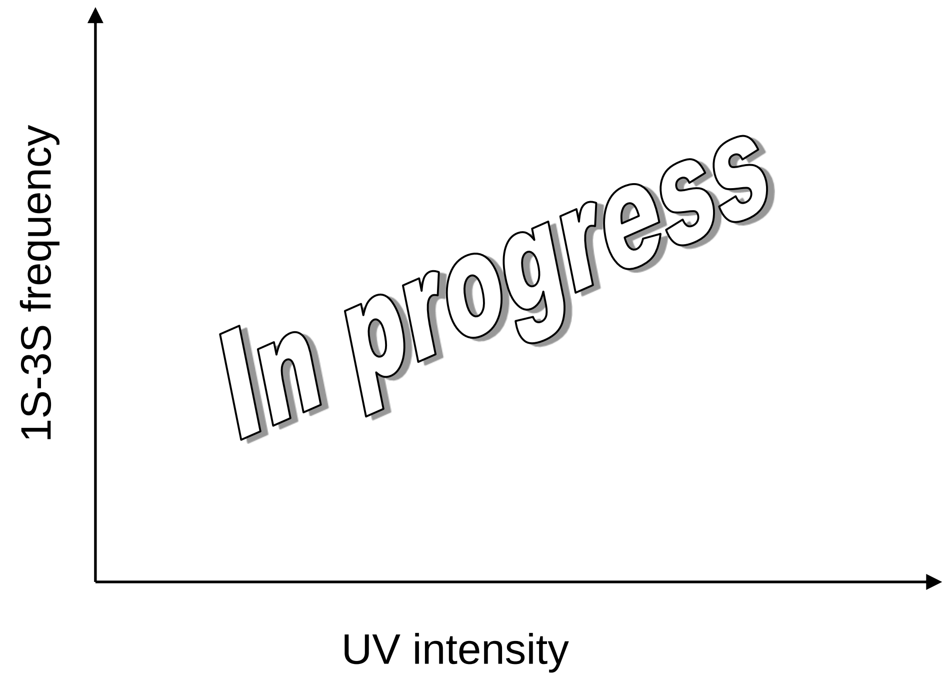


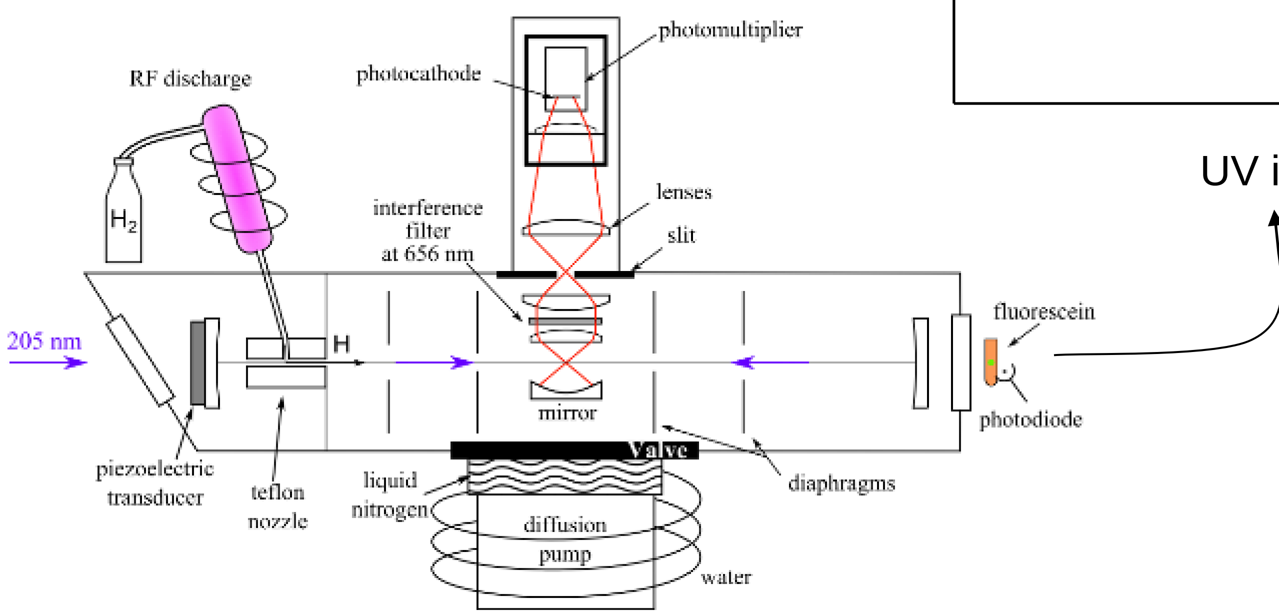
Light shift

- Large effect (several kHz)
- Hard to measure

- Monitor the UV power
  - Photodiodes with fluorescein

- Analysis in progress





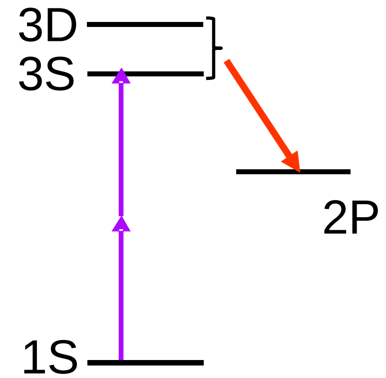
Quantum interference

- Same initial and final state

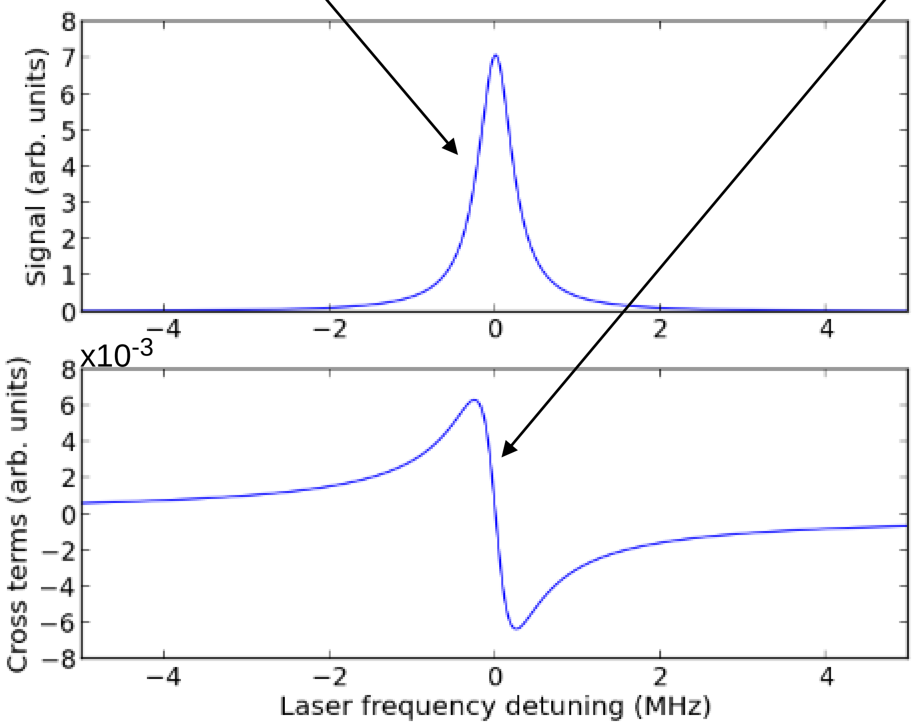
⇨ Interference between different paths

- Coherent sum

⇨ $$P = \left|A_{3S} + A_{3D}\right|^2$$
$$= \left|A_{3S}\right|^2 + \left|A_{3D}\right|^2 + \underbrace{A_{3S}A_{3D}^* + c.c.}$$



Γ_{3S} = 1 MHz
$\Delta\nu_{3S\text{-}3D}$ = 3 GHz



- Frequency shift depends on detection geometry:

- for point-like detector: max shift < 1000 Hz

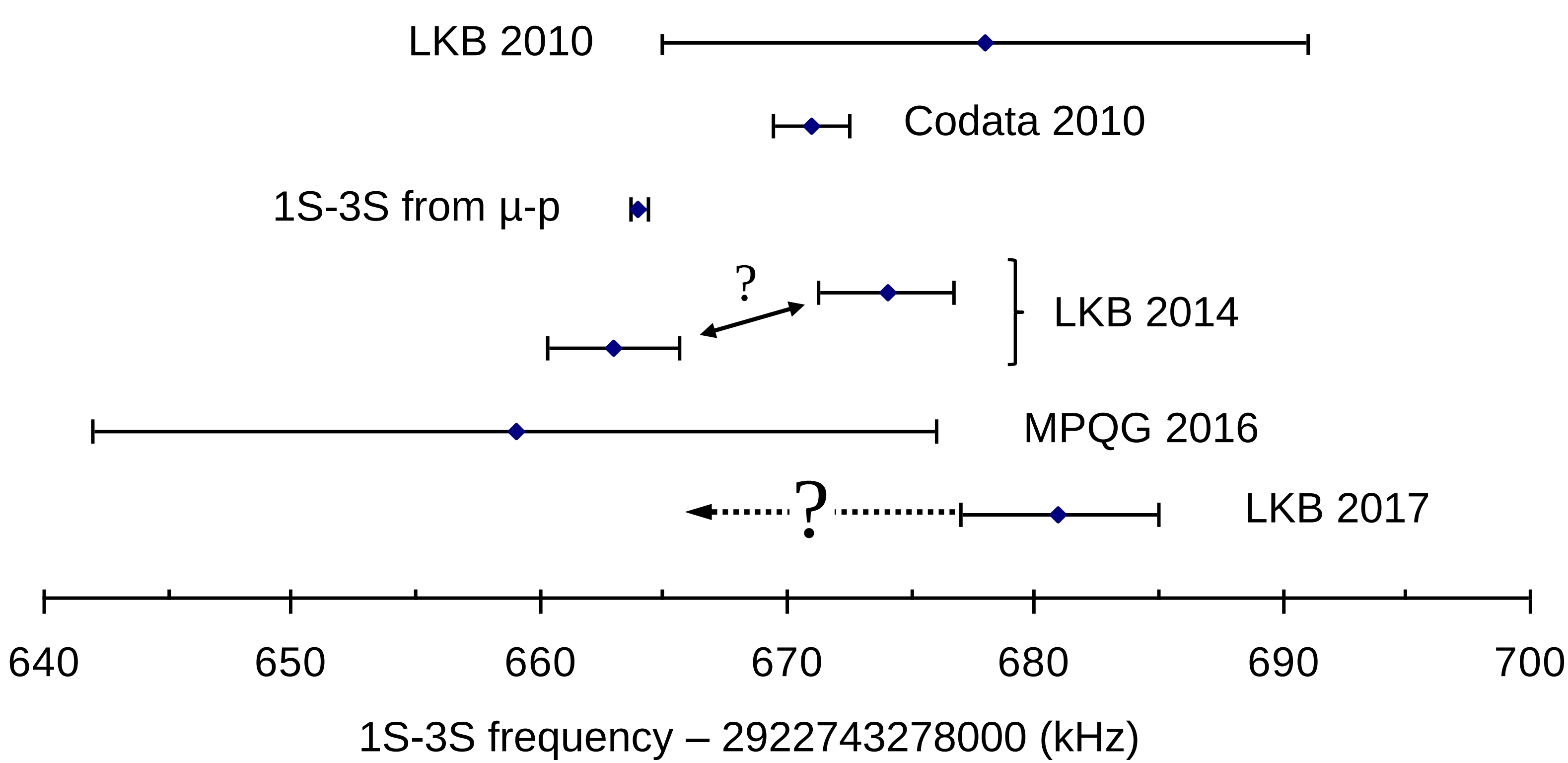
- integrate over detection cone: shift < 600 Hz

H. Fleurbaey, F. Biraben, L. Julien, J.-P. Karr and F. Nez, PRA 95 (2017) 052503

Conclusion & perspectives

⇨ Our goal : 1S-3S transition frequency with ≈ kHz uncertainty

- Shed light on the “proton radius puzzle”



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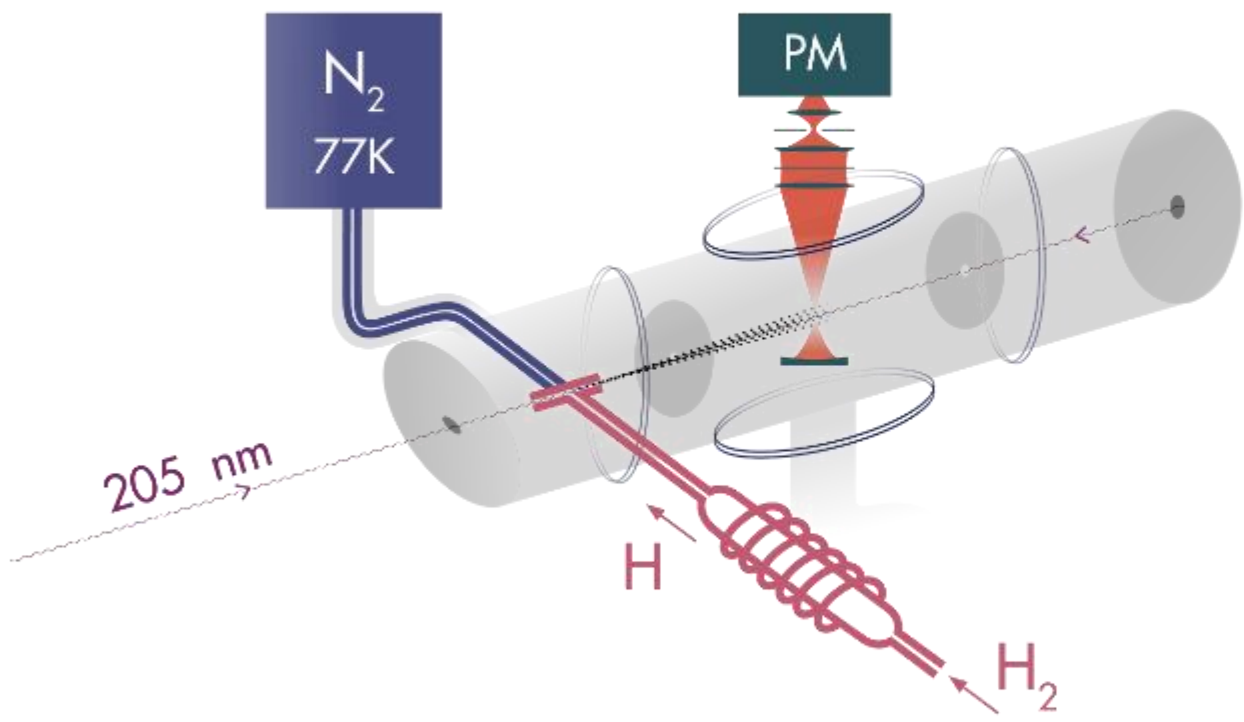

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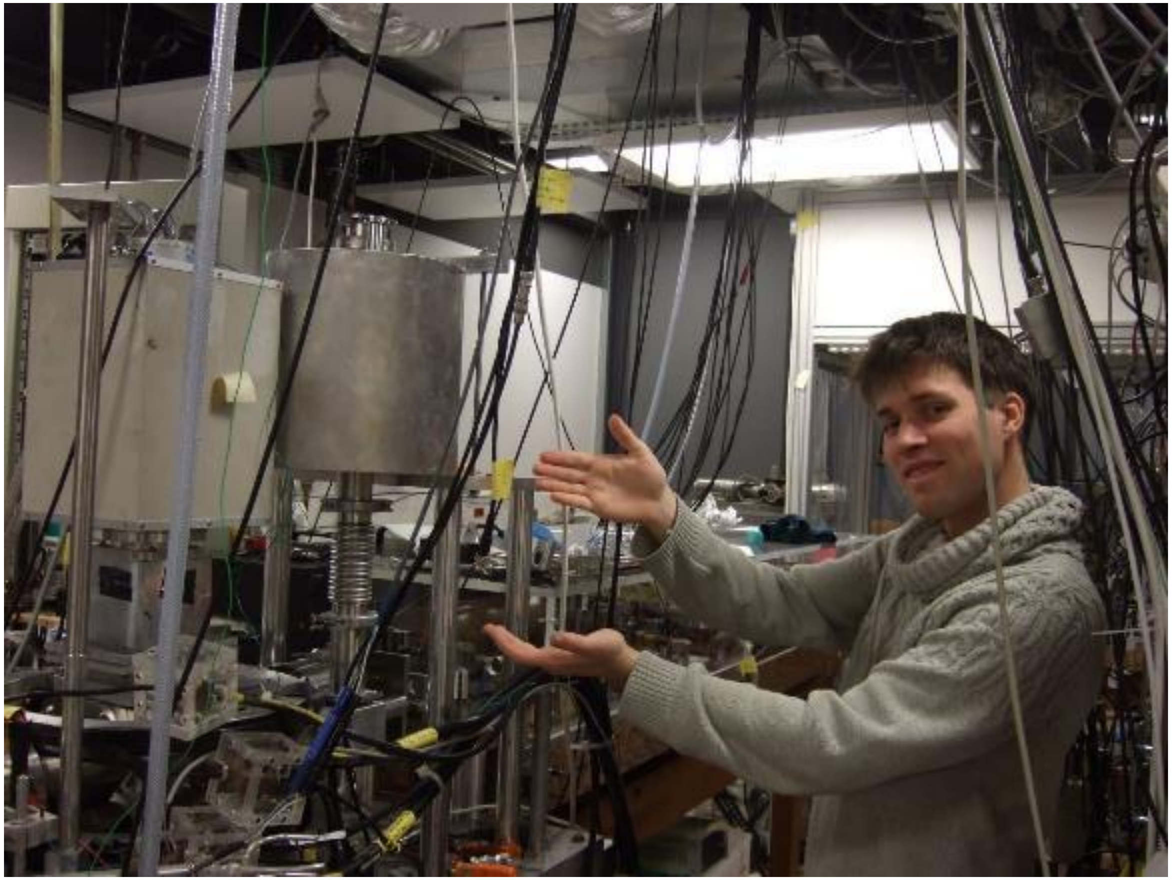

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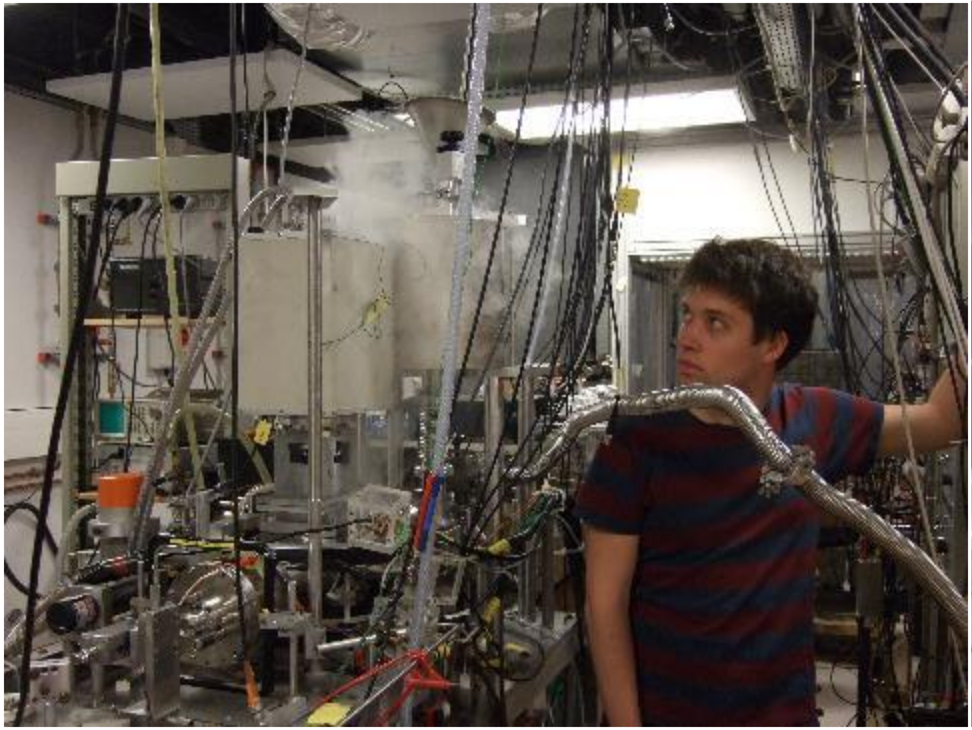

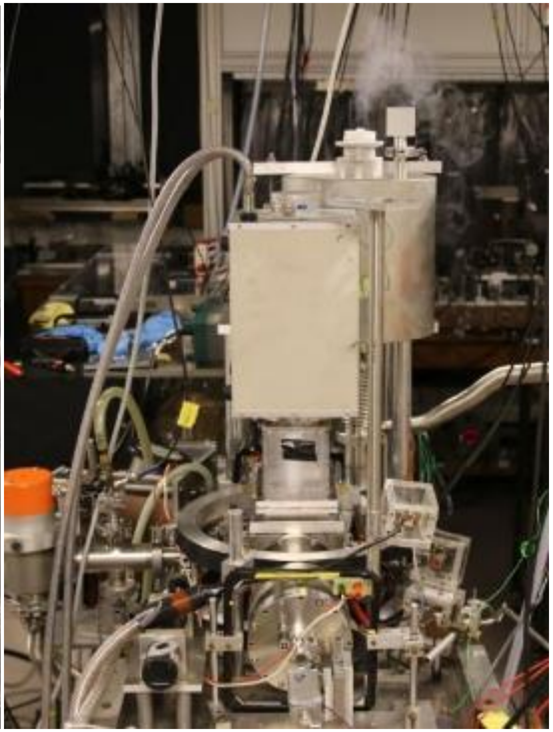

⇨ Long-term perspective

- 1S-4S transition (194 nm)

THANK YOU