High resolution metrology of the 1S–3S transition frequency of the hydrogen atom

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Physique quantique et applications

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Metrology of the 1S–3S transition frequency

The fine structure of the hydrogen atom is acutely described by QED:

$$\frac{E_{nlj}}{hc} \approx R_\infty F_{nlj}\left(\alpha, \frac{m_e}{m_p}\right) + \frac{4}{3}\frac{(4\pi)^2 R_\infty^3}{n^3\alpha^2\left(1+\frac{m_e}{m_p}\right)^3} r_p^2 \delta_{l0} \quad \Bigg\}$$

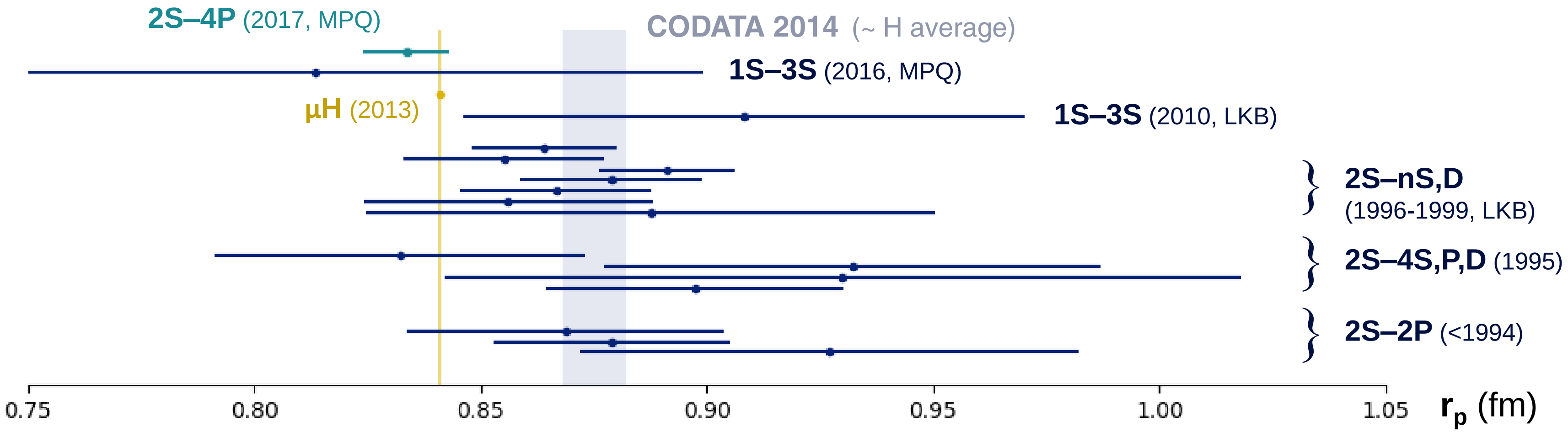
Dirac + recoil + Lamb shift

finite nucleus size

Assuming this expression to be exact, and $\alpha, m_e/m_p$ to be measured precisely enough:

$$f_{1S-3S},\ f_{1S-2S} \ \Rightarrow\ R_\infty,\ r_p$$

The consistency of different r_p determinations serves as a test of QED:



5.6σ discrepancy: the Proton Radius Puzzle©

The 1S–3S transition

To contribute to the Puzzle:
5.6 σ ↔ 7 kHz uncertainty.

Natural linewidth:
Γ_{1S-3S} = 1 MHz.

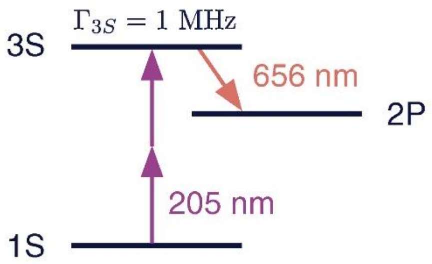
Two-photon transition:
Doppler-free spectro.

Two photons at 205 nm:
deep UV…

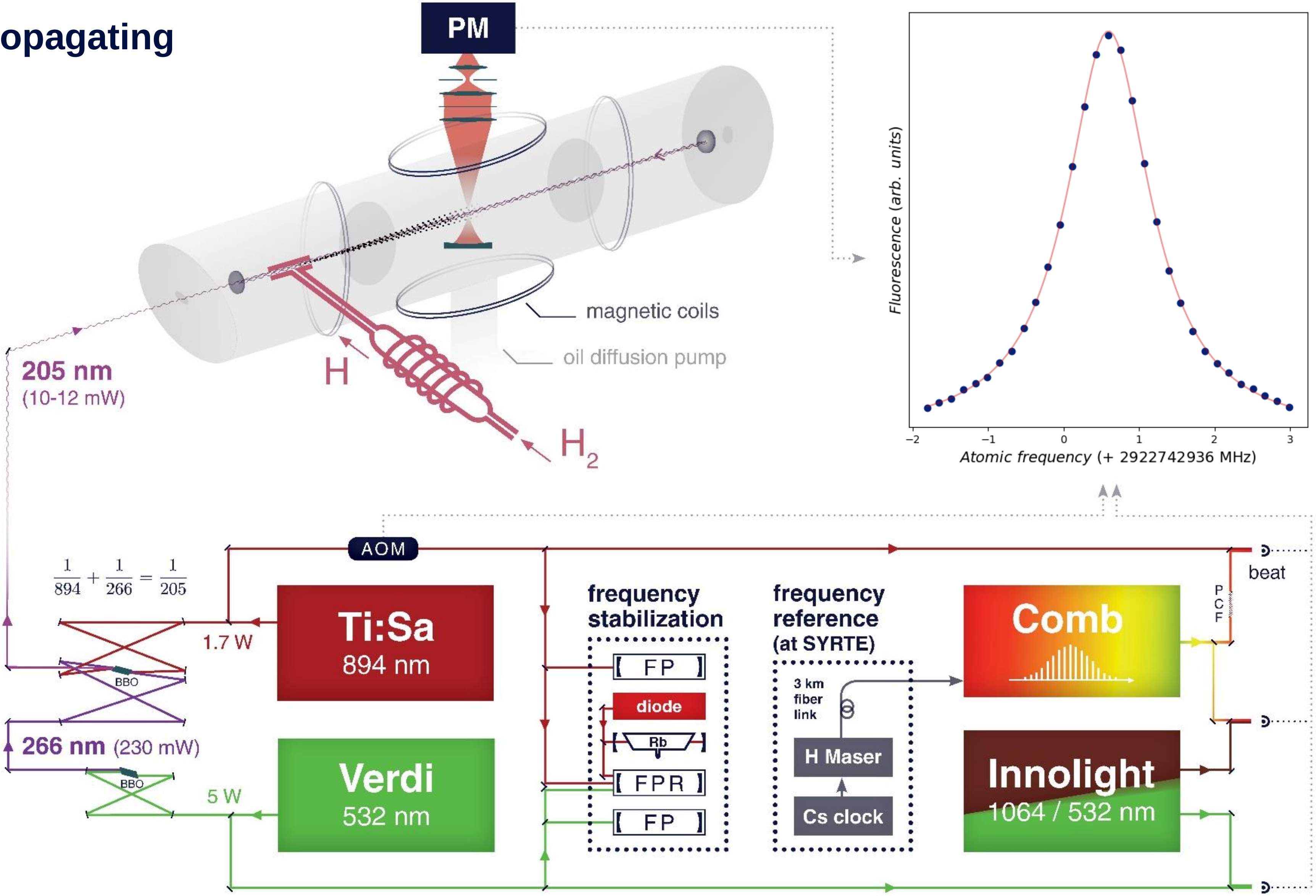
The 1S–3S experiment in Paris

Excitation by **two counter-propagating photons at 205 nm**

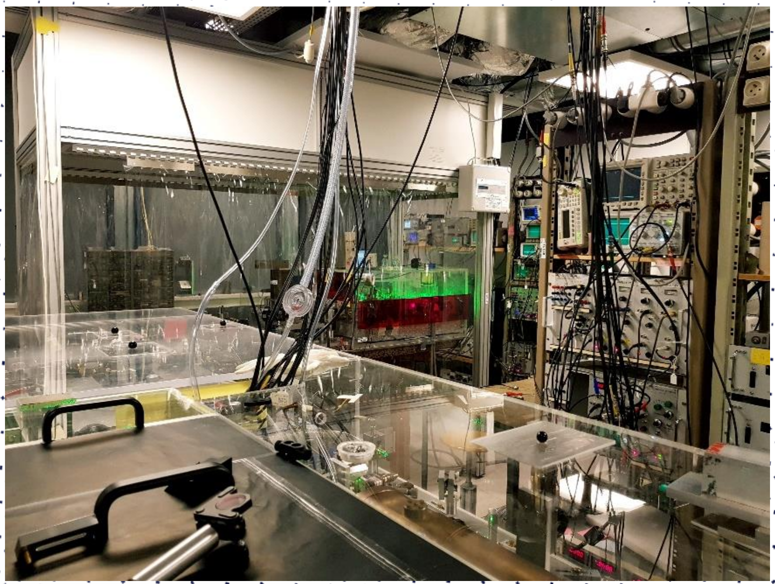
+ fluorescence detection

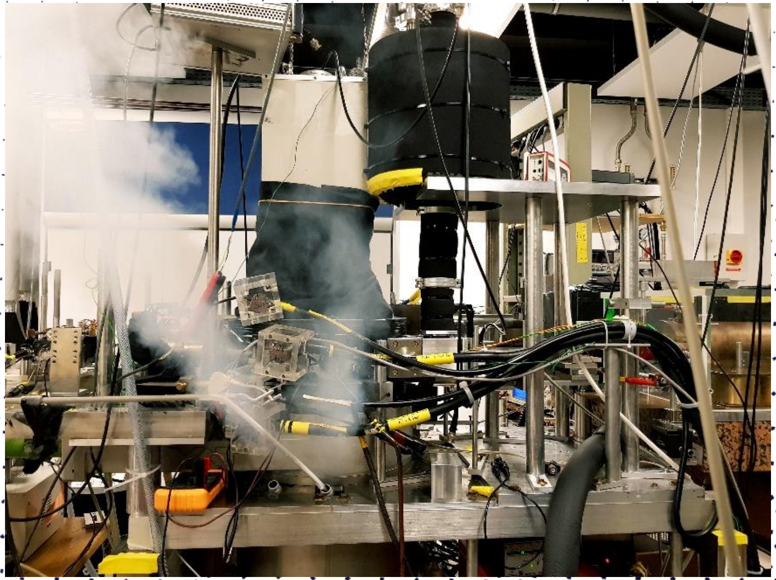


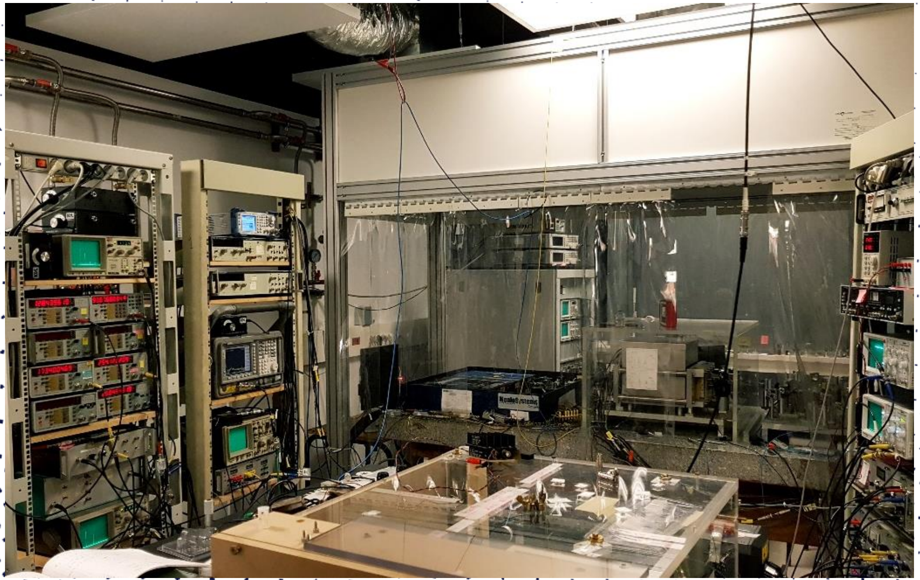
- atomic beam **colinear** to the laser beam, at **room temperature** before 2018
- **absolute** frequency measurement, referenced to the Cs clock at SYRTE.



The 1S–3S experiment in Paris







The 1S–3S team:


S. Galtier

Research director: François Nez
Emeriti: Lucile Julien & François Biraben

PhD students:
Simon Thomas (2017-…)
Hélène Fleurbaey (2014-2017)
Sandrine Galtier (2011-2014)

Data taking: 2013 & 2016-2017

Two recording sessions:

- by Sandrine Galtier,
  29 days in 2013;
- by Hélène Fleurbaey,
  59 days in 2016-2017.

Measurements repeated for different values of:

- UV power;
- hydrogen pressure;
- applied magnetic field.

→ systematics evaluated over 4 separate data sets.

Measurements repeated to reach a sufficient statistical uncertainty:

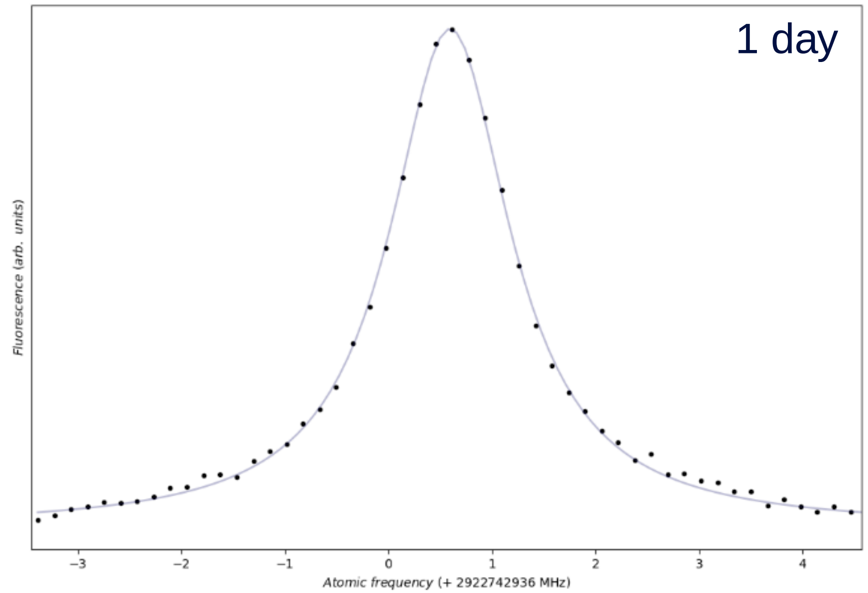
as an order of magnitude,

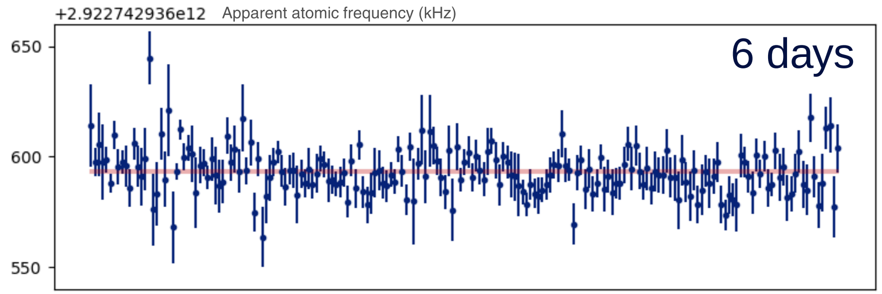
↳ u_{stat} ~10 kHz in 5 min

↳ u_{stat} ~1 kHz in 20 hours

(of integration time, on the absolute apparent frequency of the line at B=0 G)

→ systematics corrected for each run of 5 min.

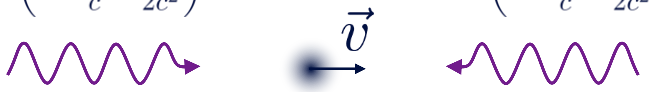




Systematics: 2nd order Doppler effect

Cancellation of 1st order Doppler effect

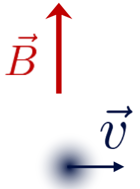
$\hbar\omega\left(1-\frac{v}{c}+\frac{v^2}{2c^2}\right)$ $\hbar\omega\left(1+\frac{v}{c}+\frac{v^2}{2c^2}\right)$



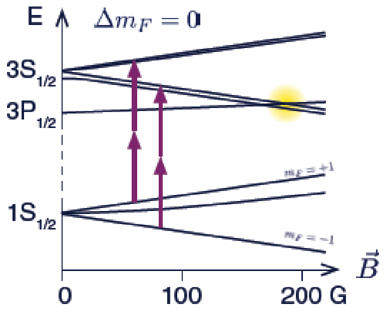
$$\longrightarrow \quad \delta_{Doppler}=\omega\frac{v^2}{c^2}$$

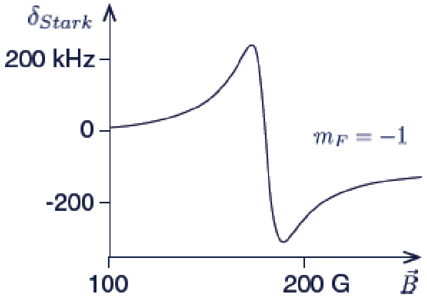
Application of a transverse $\vec{B}$ field $\longrightarrow$ quadratic Stark shift

motionnal Stark effect + Zeeman effect $\longrightarrow$ $\delta_{Stark}\propto\frac{|\vec{v}\wedge\vec{B}|^2}{\Delta_{3S-3P}}$



(B calibrated with m_F=0)





Fit of a theoretical atomic velocity distribution on the $\vec{v}$-dependant line shift

$$f_{\sigma,v_0}(v)\propto v^3 e^{-\frac{v^2}{2\sigma^2}-\frac{v_0}{v}}P(\tfrac{v}{\sigma})$$

slow atoms depletion

nozzle caracterization

via a theoretical lineshape:

$$\frac{\mathrm{d}\rho}{\mathrm{d}t}=i[\rho,\hat{H}]+\left\{\frac{\mathrm{d}\rho}{\mathrm{d}t}\right\}_{sp}$$

$$\begin{aligned}\hat{H}=\hat{H}_0&+\hat{H}_{Zeeman}(\vec{B})\\&+\hat{H}_{Stark}(\vec{v}\wedge\vec{B})\\&+\hat{H}_{2\gamma}([1+\tfrac{v^2}{c^2}]\omega t)\end{aligned}$$

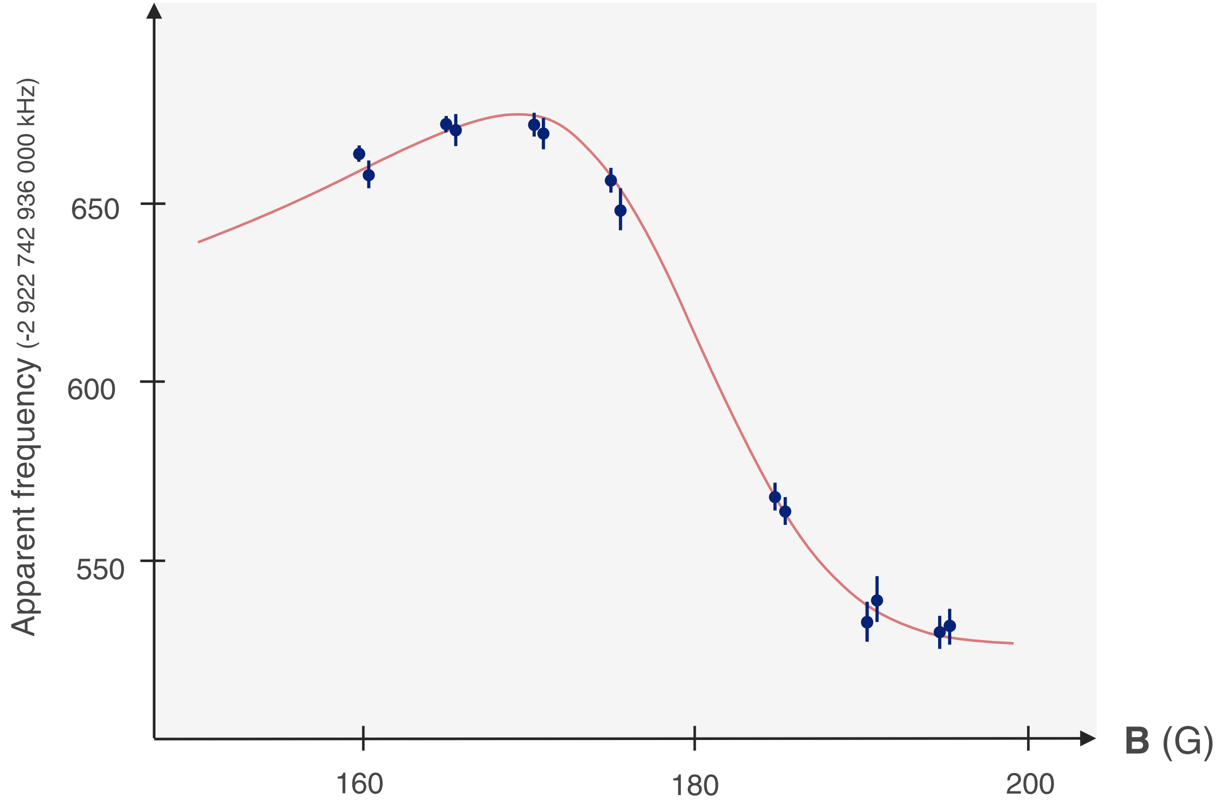
$$\rightarrow\ \Gamma(\omega,B)=\int\Gamma^{OBE}(\omega,v,B)\circledast\Gamma^{eff}(\omega)\ f_{\sigma,v_0}(v)dv$$

(calculations currently being improved)

(Arnoult et al., Eur. Phys. J. D **60**, 2010)

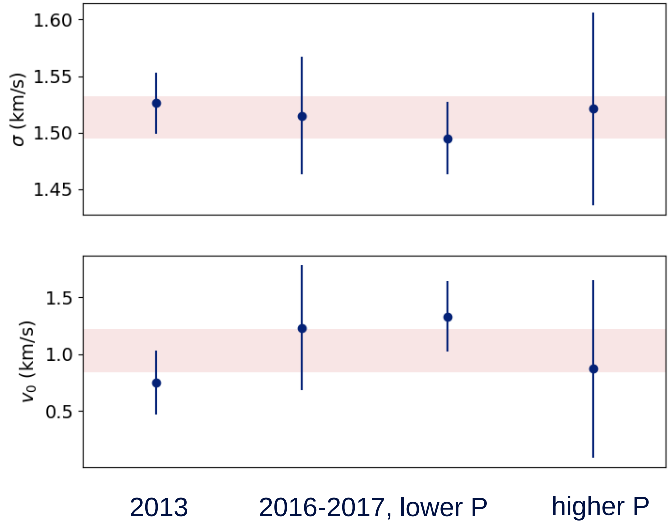
Systematics: 2^{nd} order Doppler effect

Fit of the velocity-dependent frequency shift:



→ typical correction of ~ 133 kHz.

Determination of σ and v_0:
no noticeable pressure dependency



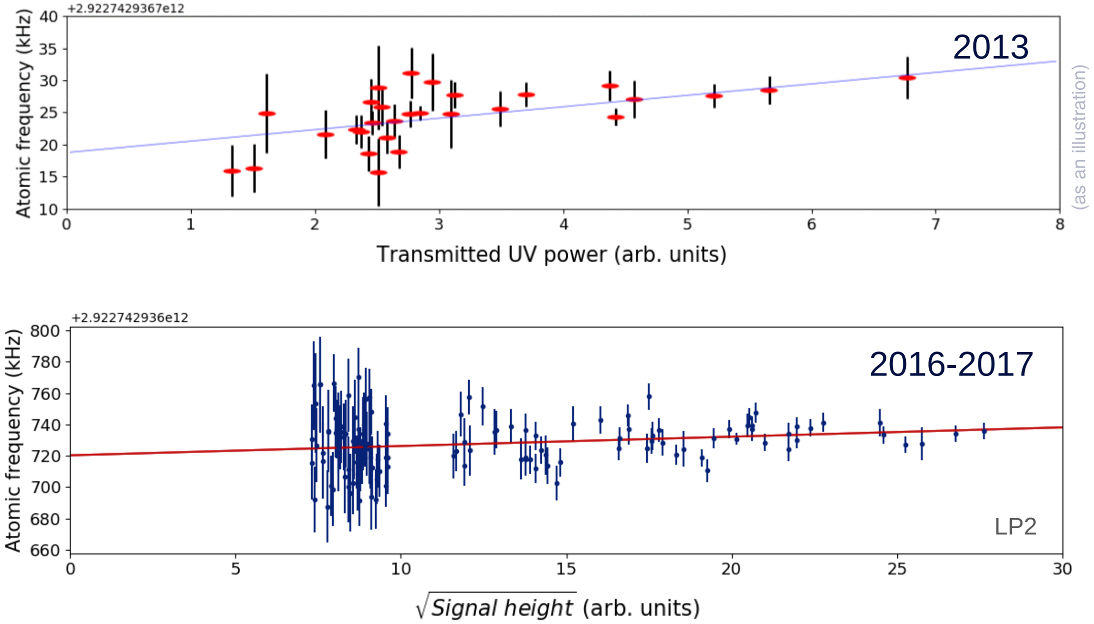
Test with different:

- velocity distribution models;
- broadening functions.

→ larger uncertainty, no apparent shift.

Systematics: light and collisional shifts

Extrapolation to zero UV power:

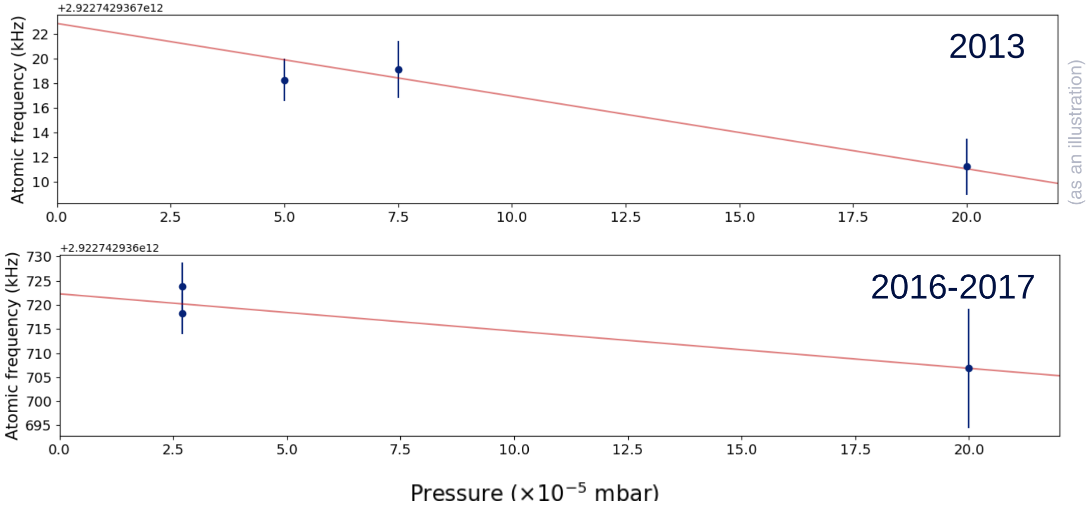


Agreement between different I_{UV} estimations:

- incident power;
- transmitted power (with fluorescein);
- √ signal height (corrected).

→ typical correction of ~ -6 kHz.

Extrapolation to zero pressure:



Relative pressure measurement (side of the vacuum chamber).

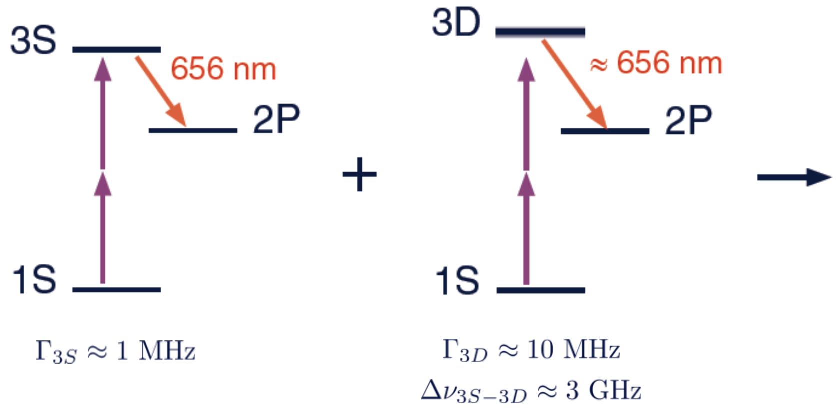
→ typical correction of ~ 4 kHz.

Agreement within the experimental uncertainties
after Doppler, light & pressure shifts correction,
of the results of the different data sets.

Systematics: cross damping effect, etc.

Interference between quantum paths

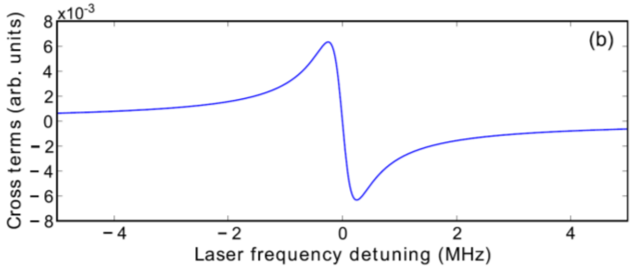
$$\frac{d\sigma}{d\Omega}(\omega) \propto \sum_{f=2P,\vec{\epsilon}} \left| \sum_{k=3S,3D} \frac{\hat{Q}_{ik}\hat{D}_{kf}}{\omega_{ik} - 2\omega - i\frac{\Gamma_k}{2}} \right|^2$$



$\Gamma_{3S} \approx 1$ MHz

$\Gamma_{3D} \approx 10$ MHz

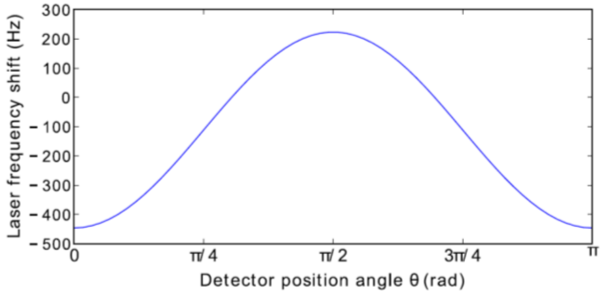
$\Delta\nu_{3S-3D} \approx 3$ GHz



Variation of the excitation probability.

Leading to a resonance frequency shift dependant on the detection geometry.

→ correction of 0.6(2) kHz.



Other systematics:

- H Maser drift
  (2013: -0.6 kHz)
- black body radiation*
- residual Stark shift*
- residual Zeeman shift*
- gaussian beam light-shift dependency*
- m_F ground states population difference*
- FP cavity modulation*
- SHG/SFG spectral asymmetry*

(*negligible to our knowledge)

(Fleurbaey et al., Phys. Rev. A **95**, 2017)

Our results

After hyperfine centroïd correction:

$$f^{2013}_{1S-3S} = 2\;922\;743\;278\;671.6\;(2.8)\;\text{kHz}$$

$$f^{2017}_{1S-3S} = 2\;922\;743\;278\;671.0\;(4.9)\;\text{kHz}$$

} estimated covariance: (1.6 kHz)²

(from the added uncertainty due to the $\vec{v}$-distribution determination)

Final result:

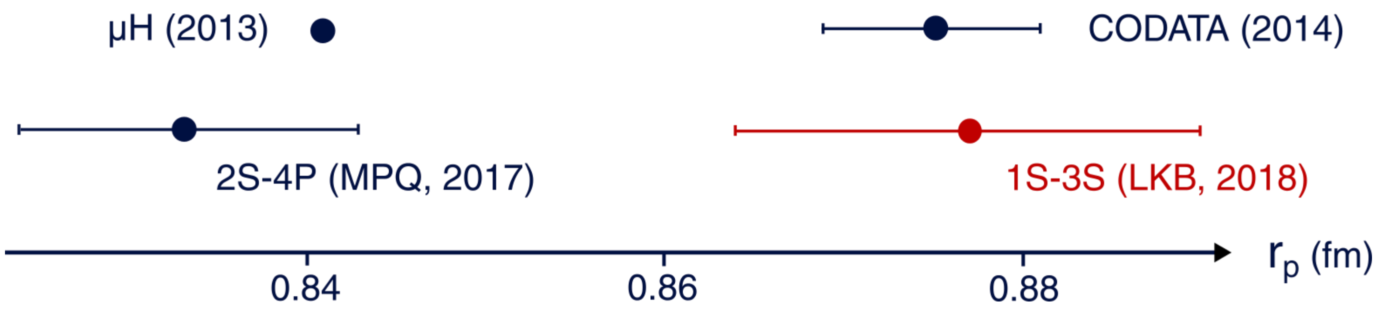
$$f_{1S-3S} = 2\;922\;743\;278\;671.5\;(2.6)\;\text{kHz}$$

When combined with $f_{1S–2S}$:

$$R_\infty = 10\;973\;731.568\;53(14)\;\text{m}^{-1} \qquad r_p = 0.877(13)\;\text{fm}$$

With the main sources of uncertainty being:

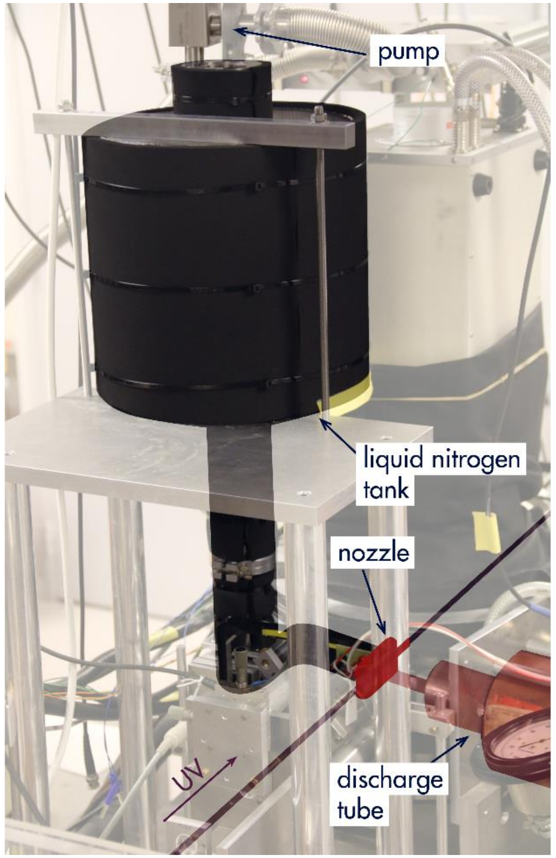
- Pressure shift (~2 kHz)
- Light shift (~1.3 kHz)
- 2nd order Doppler shift (~1.2 kHz)

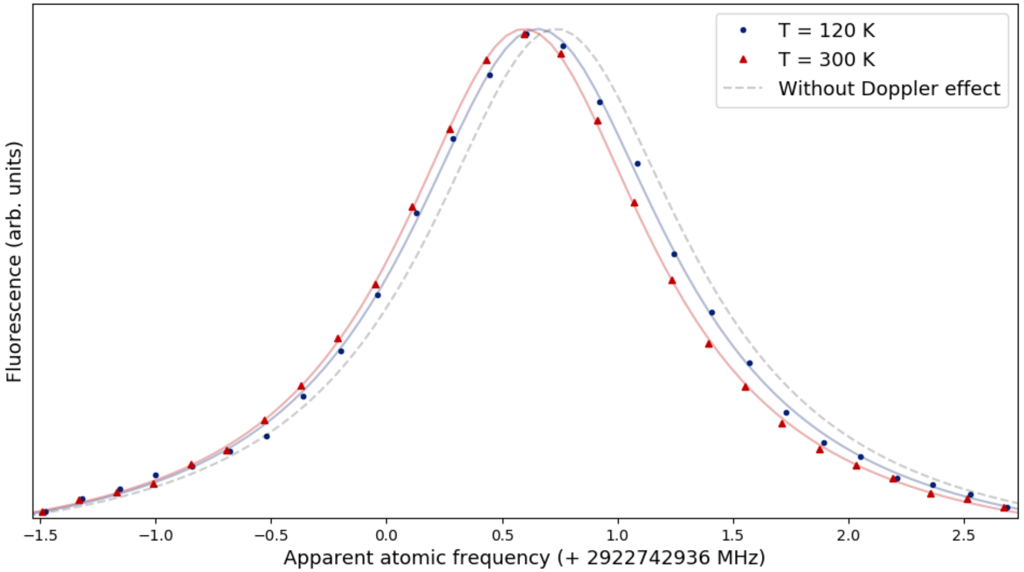


(Fleurbaey et al., Phys. Rev. Lett. **120**, 2018)

Since last year: fresh atoms

A new nozzle cooled down by liquid nitrogen





→ reduction of the 2nd order Doppler effect (~60%);

→ test of the $\vec{B}$ method with a different $\vec{v}$-distribution;

→ but longer measurement time…

What next?

→ 1S–3S in **deuterium**

- only already observed
- reduced Doppler effect

→ **1S–4S** in hydrogen

- yet to be observed
- $\Gamma_{1S\text{–}4S}$ = 0.7 MHz
- possible determination of the $\vec{v}$-distribution via the Doppler shift of a 2S–nP transition.

532 → 266 ↘

194 nm

724 ↗

Thank you for your attention!

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