1S-3S Spectroscopy on hydrogen/deuterium atoms

Pauline Yzombard, Paul Martin, Simon Thomas, Hugo Tortel, Lucile Julien, François Biraben, François Nez

Laboratoire Kastler Brossel
Physique quantique et applications

Sorbonne Université, CNRS, ENS, Collège de France

PREN - June 2022

Interest of H-like atoms spectroscopy ?
In short

Ultra-accurate theory ⇔ highly resolved experiments

Proportional to R_∞

Internal energy of an atom: E= h f ≈ (E_{Dirac} + E_{QED} + $E_{nucleous\_radius\_effect}$)

⇒ Spectroscopist point of view: 3 unknowns (R_∞ , QED, r_N)

- *α, me/mp, me/h very-well known by other experimental measurements*

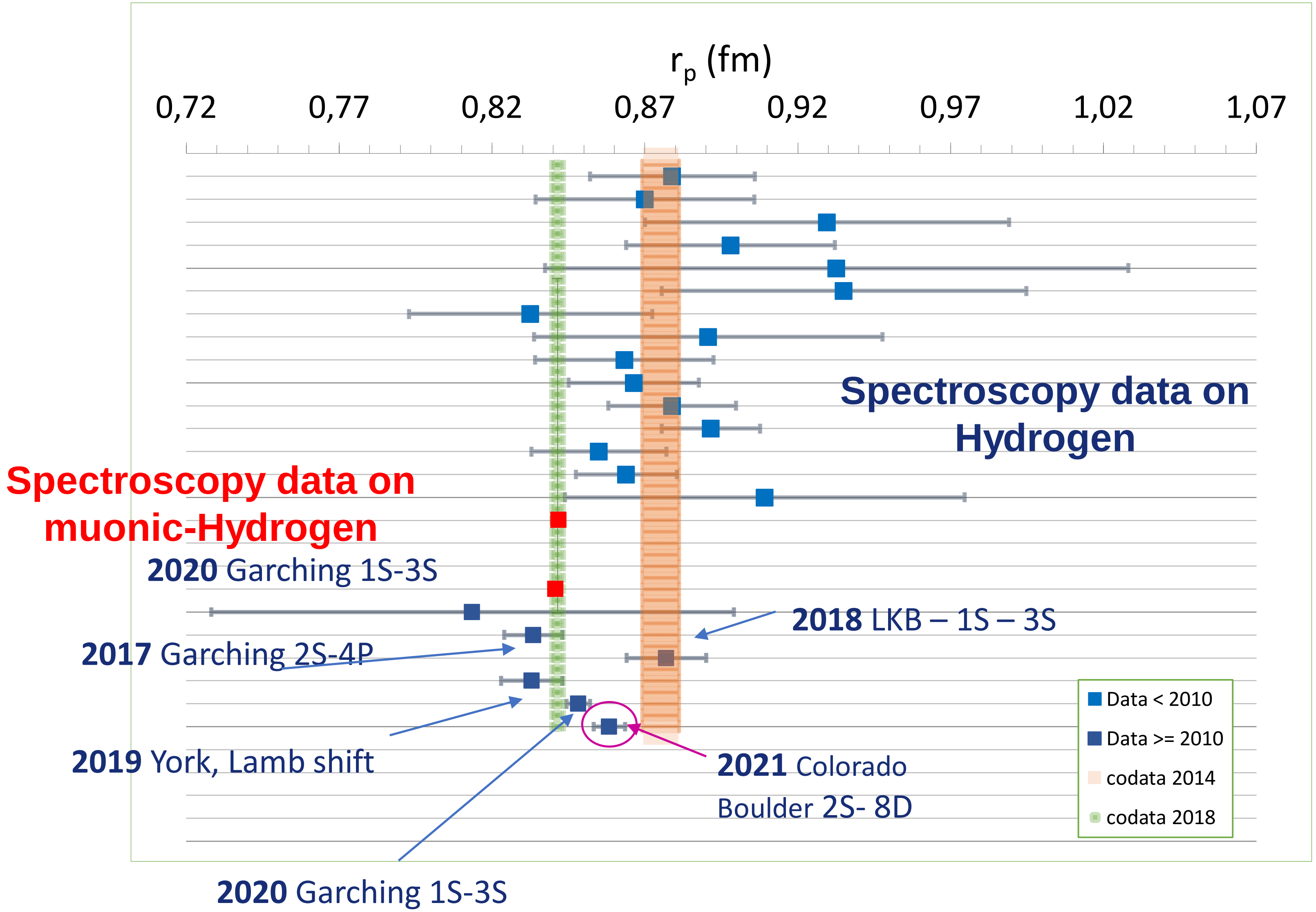
If QED exact (so fixed) ⇒ 2 unknows left: R_∞ and r_N

$$f_{a-b} + f_{c-d} \Rightarrow R_\infty + r_N$$

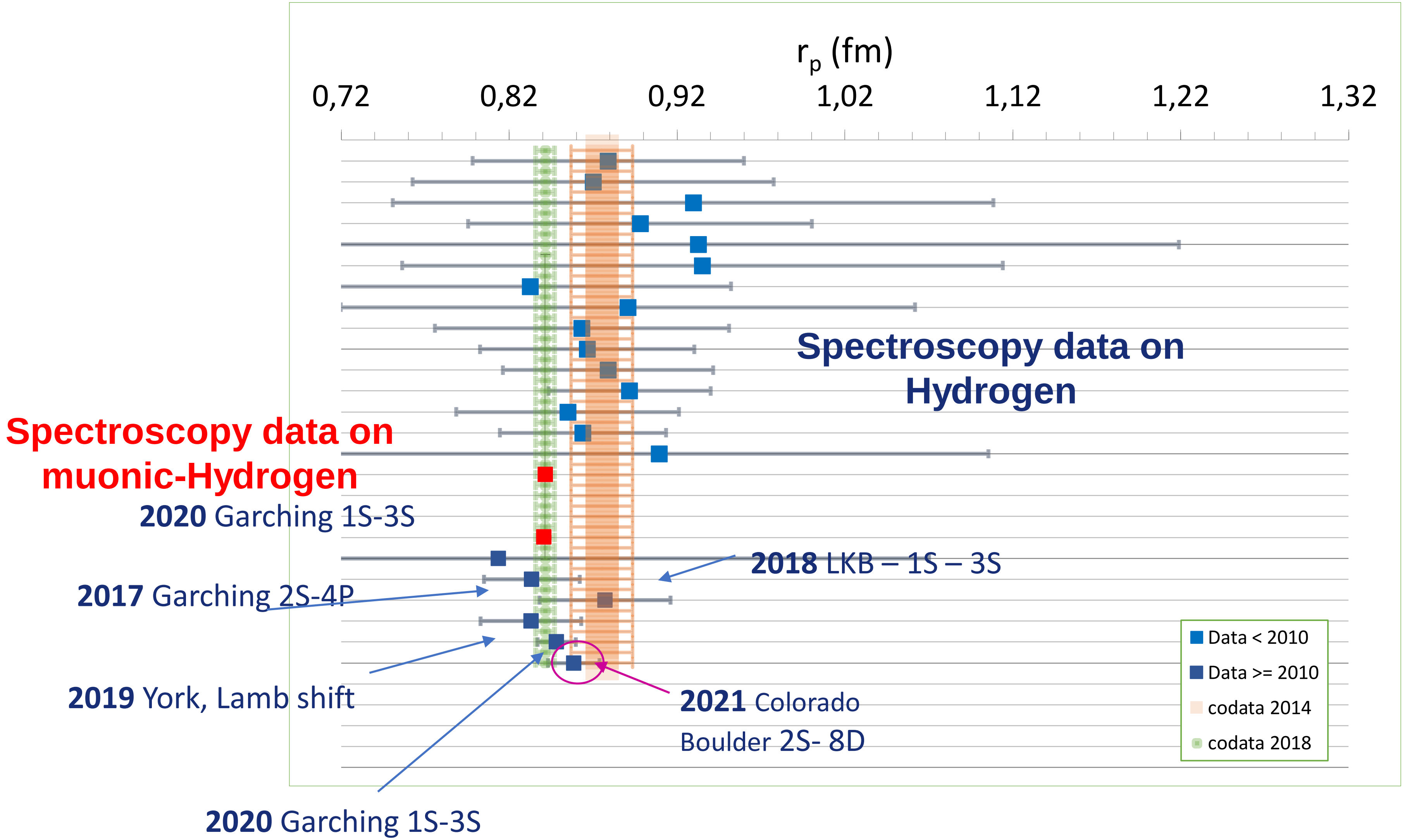
⇒ Requires only 2 transitions to be determined

⇒ With 3 and more: tests on consistancies can be done !

The proton radius puzzle ? 1 sigma

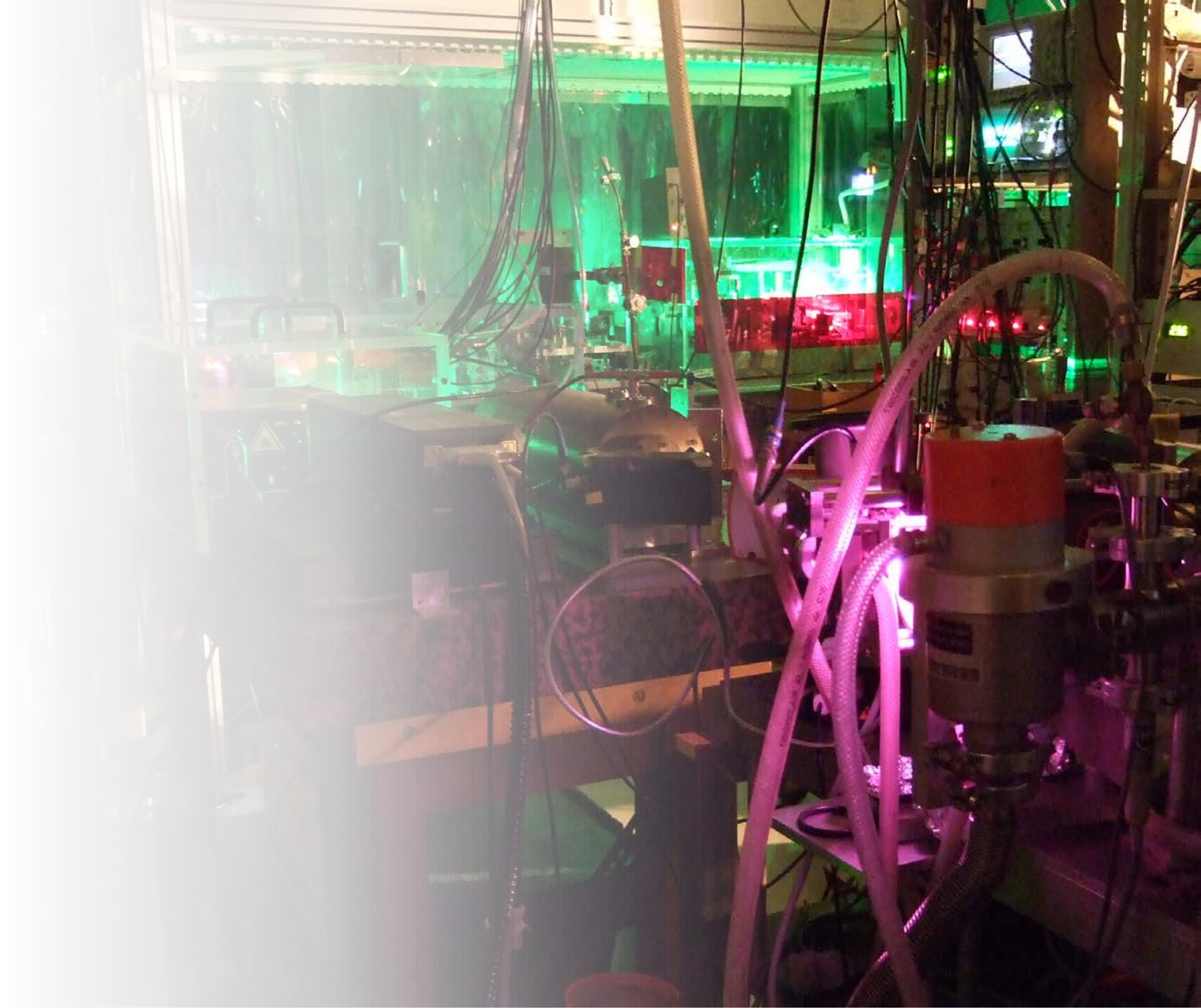


The proton radius puzzle ? 3 sigmas



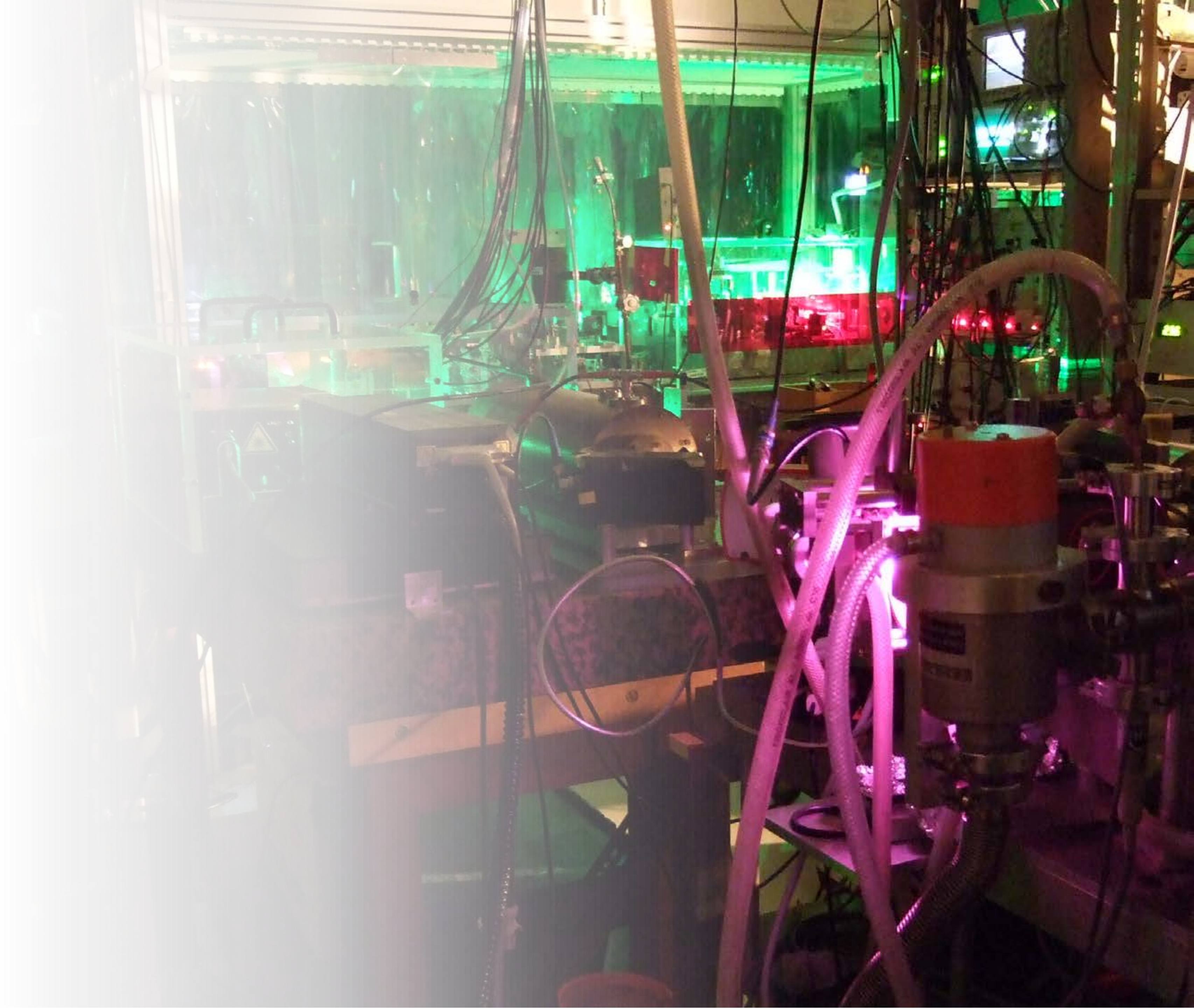
Overview

- 1S-3S Hydrogen spectroscopy
  - The experiment and some of the latest improvements
  - Dealing with systematics
  - A new systematics effect ?
  - What next ?

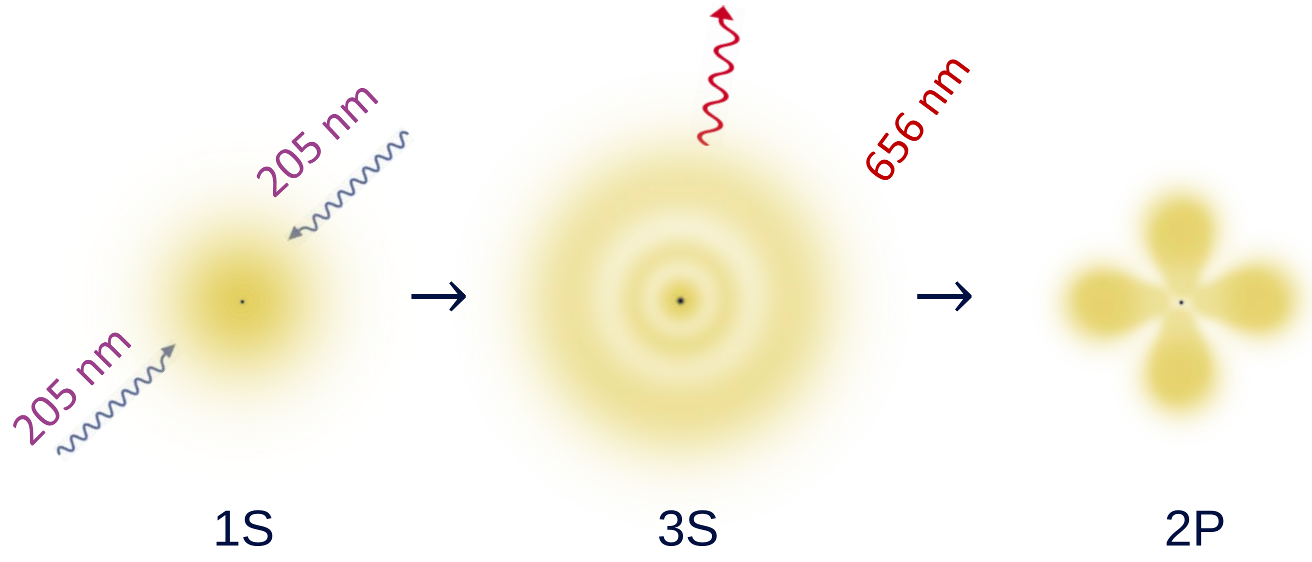


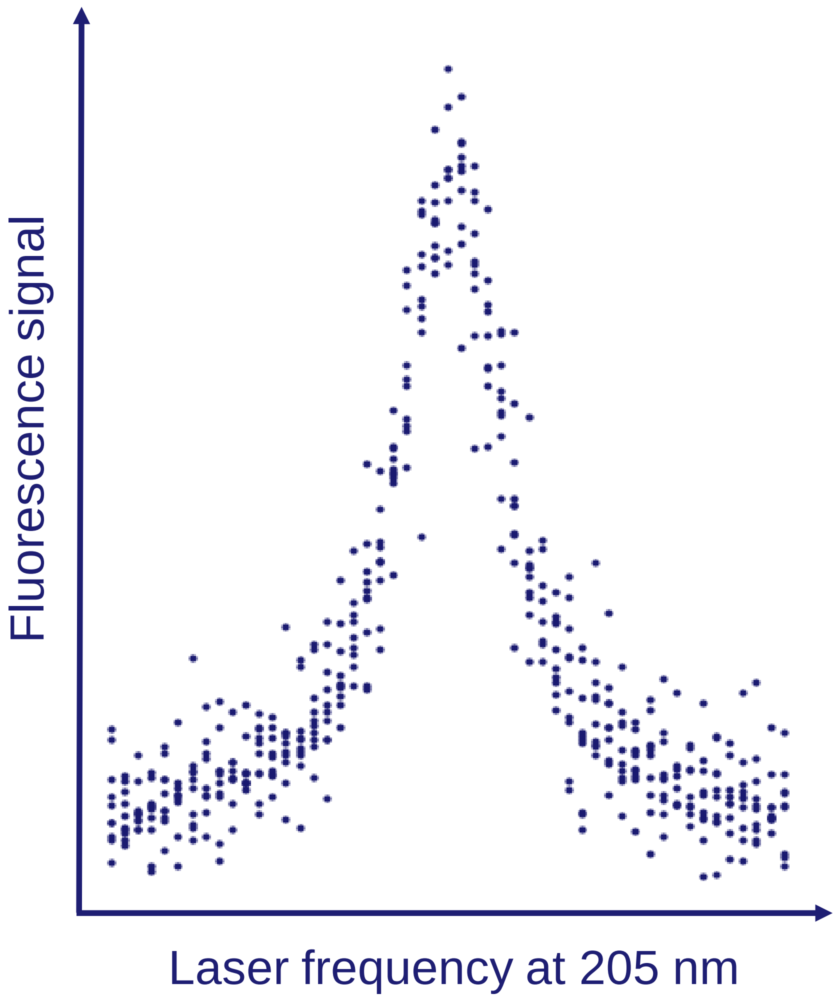
Overview

- 1S-3S Hydrogen spectroscopy
  - The experiment and some of the latest improvements
  - Dealing with systematics
  - A new systematics effect ?
  - What next ?



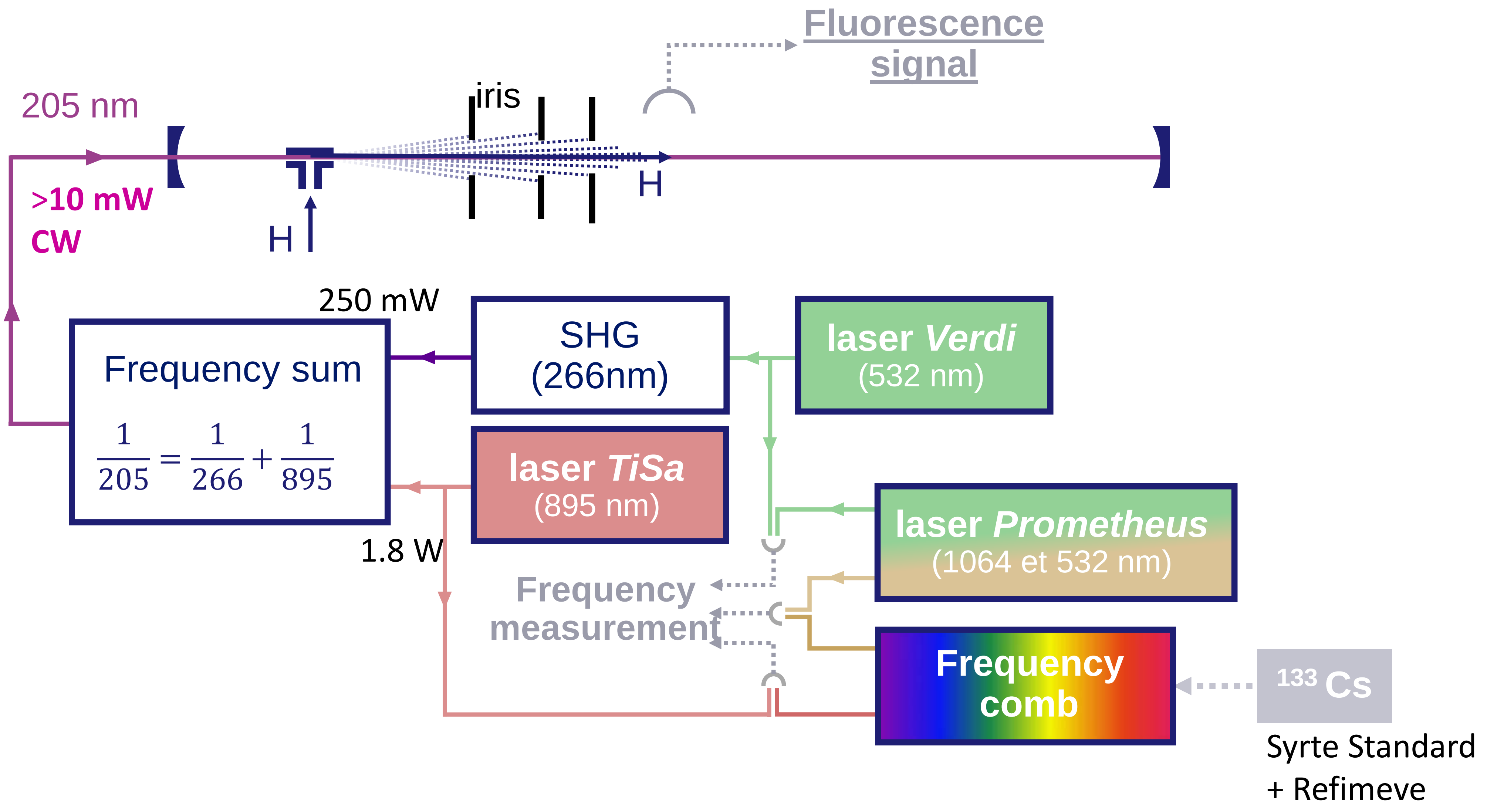
1S–3S Hydrogen CW spectroscopy



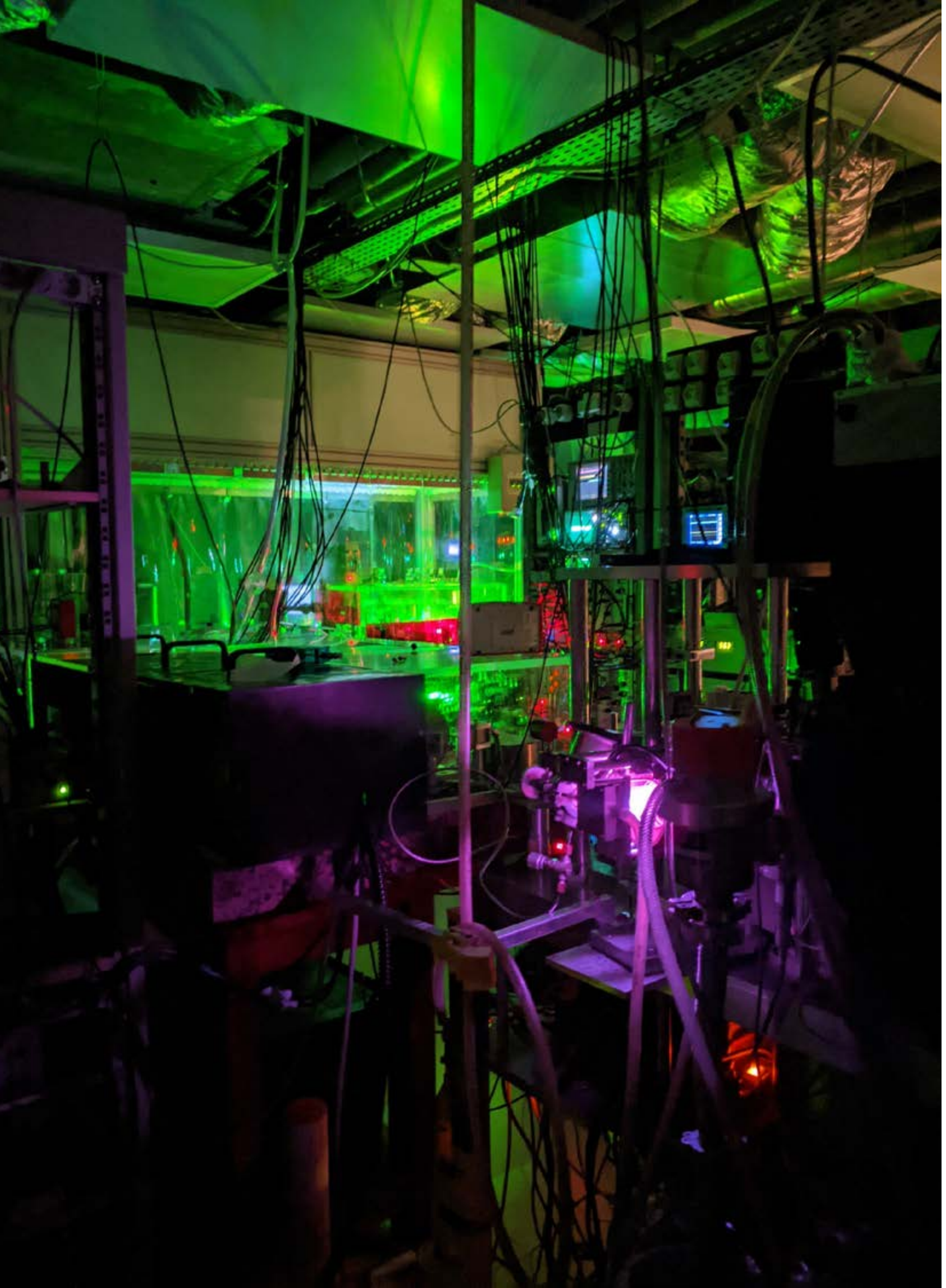


Slide – courtesy of S. Thomas

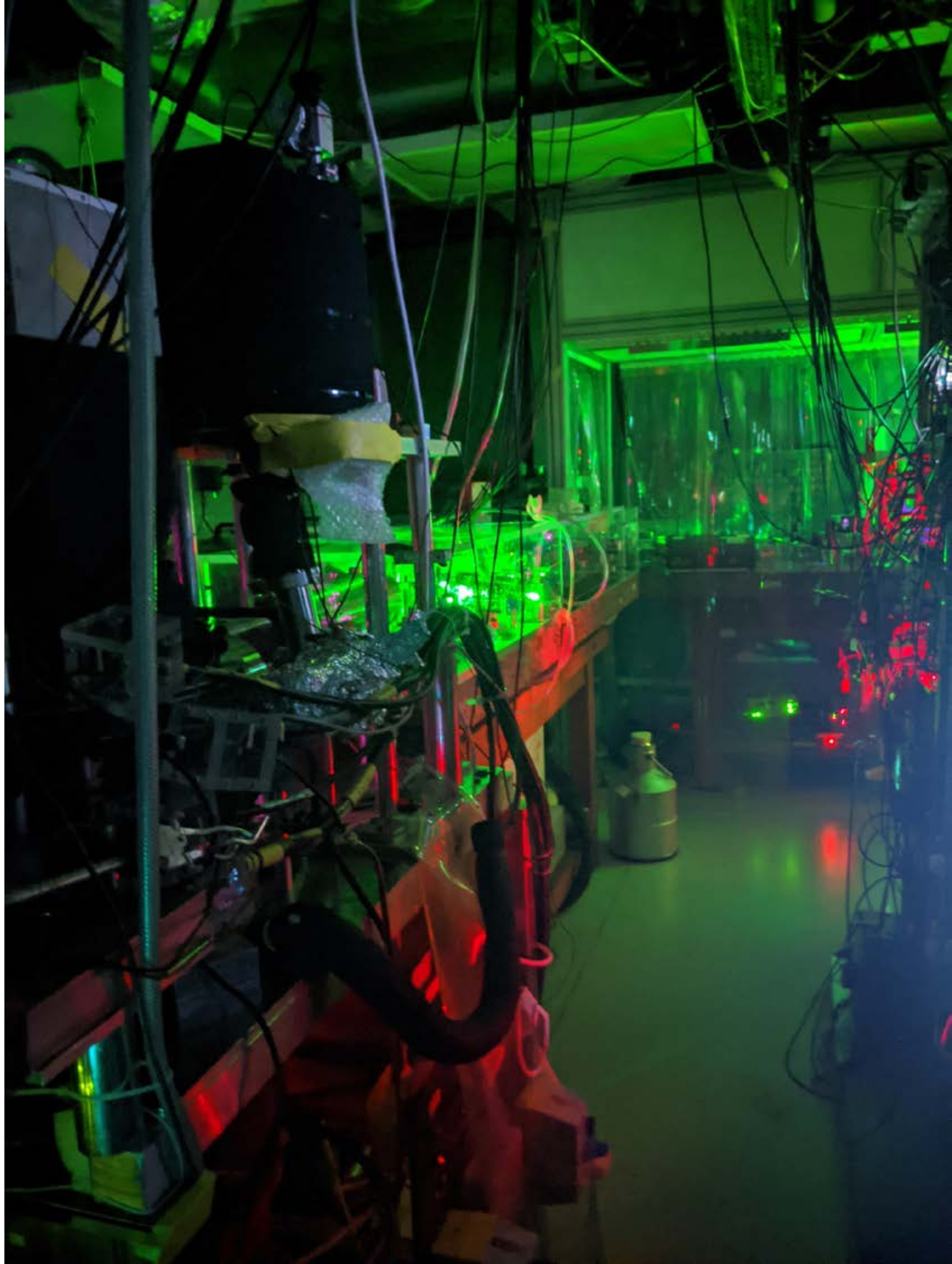
Overview of the experiment



Slide – courtesy of S. Thomas



Overview of the experiment

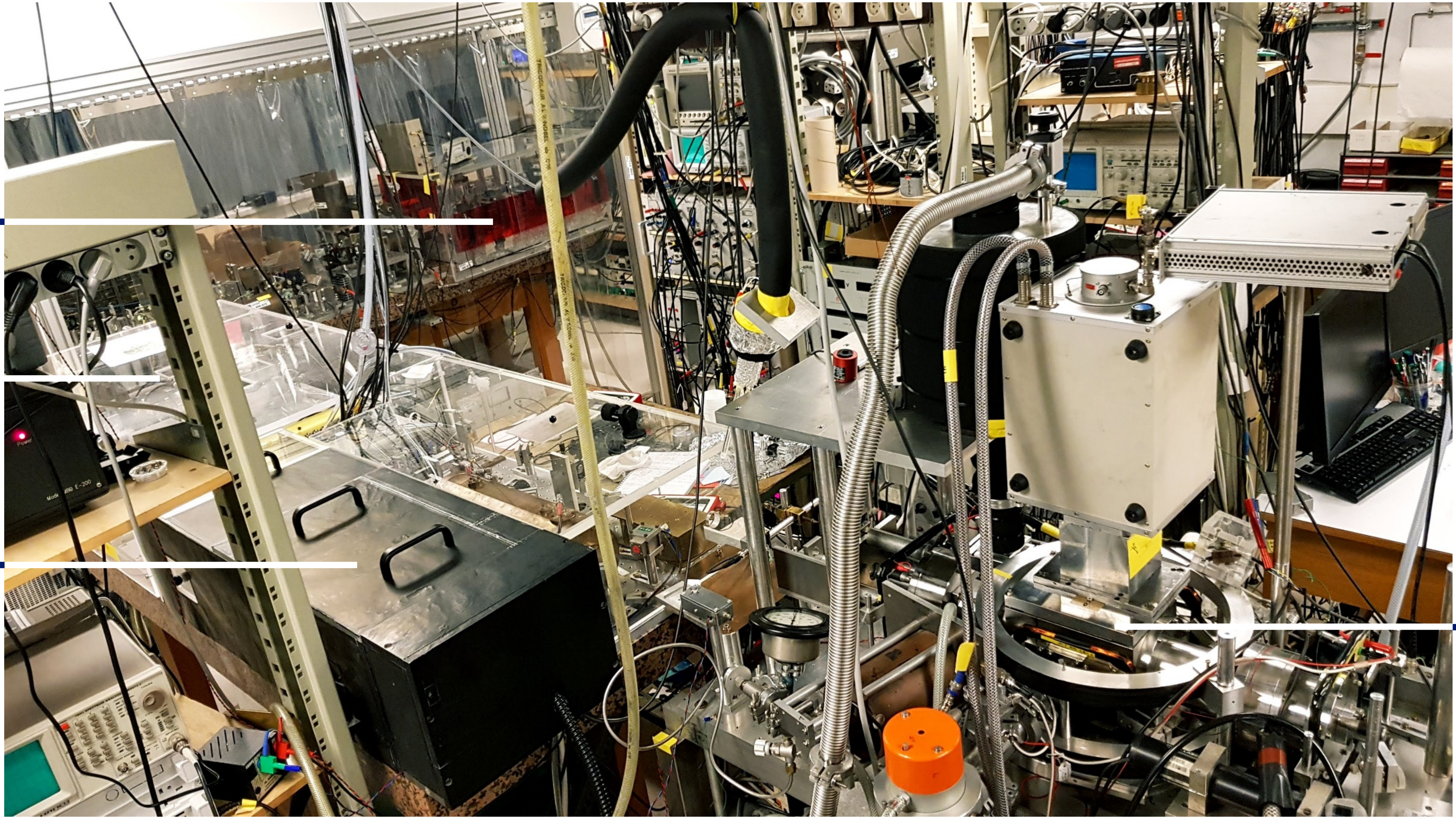


With some light ON

TiSa
895nm

205nm
generation

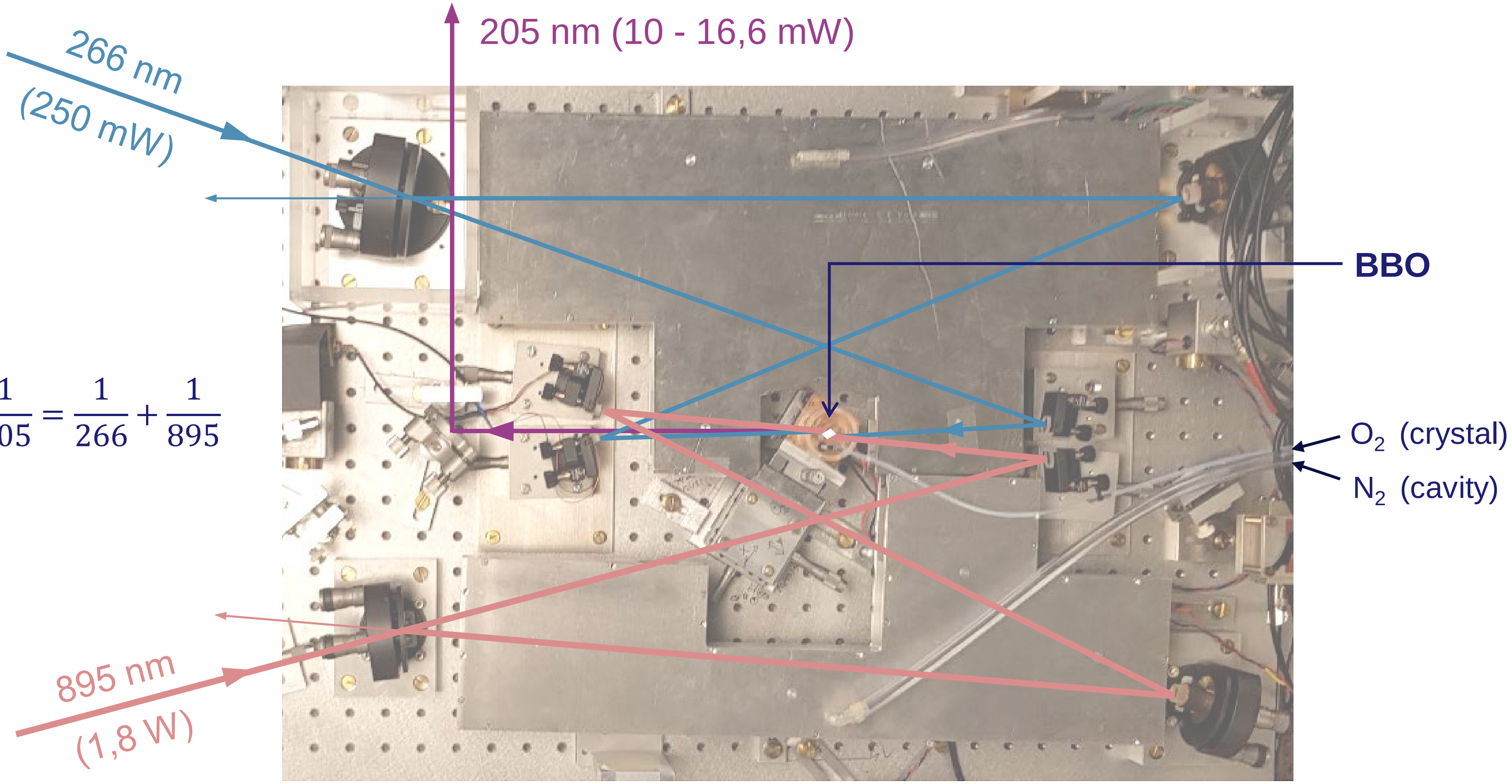
Verdi
266nm



(old) H
beam

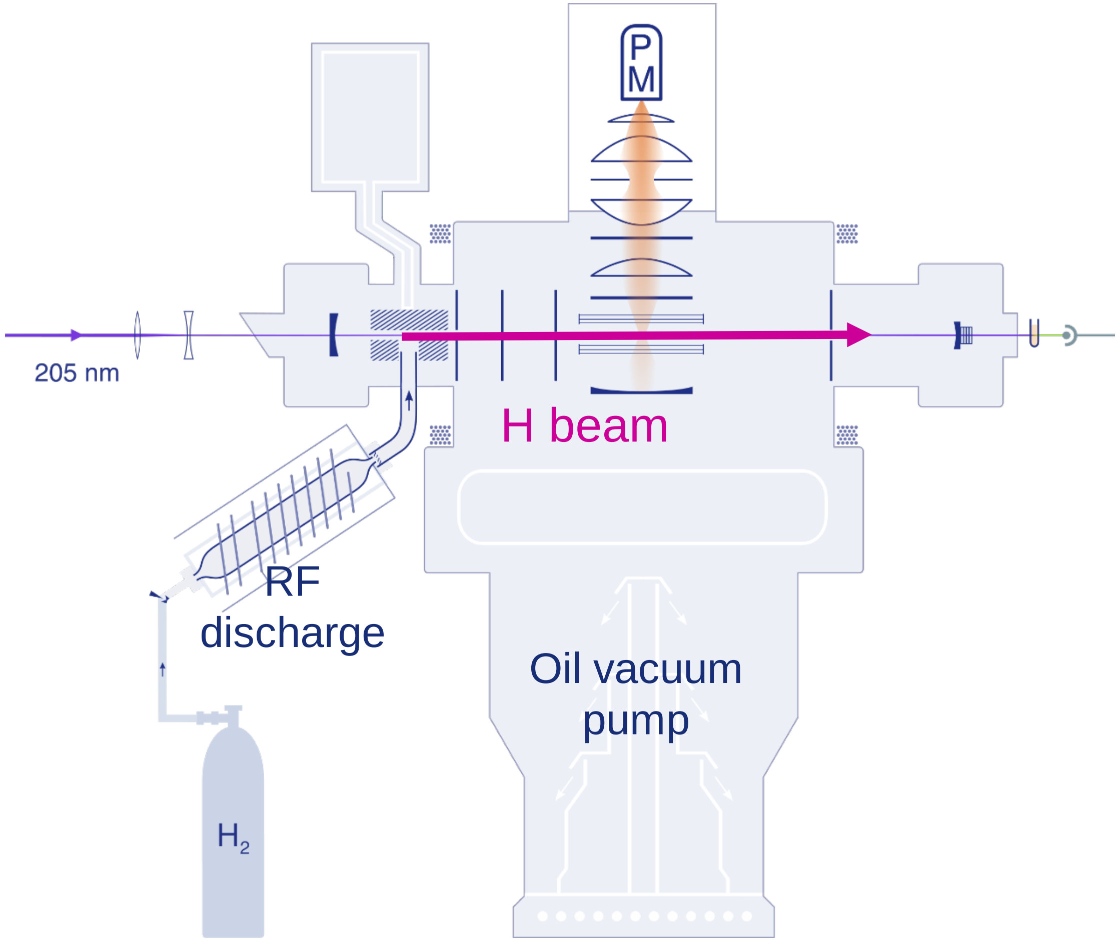
Picture – courtesy of S. Thomas

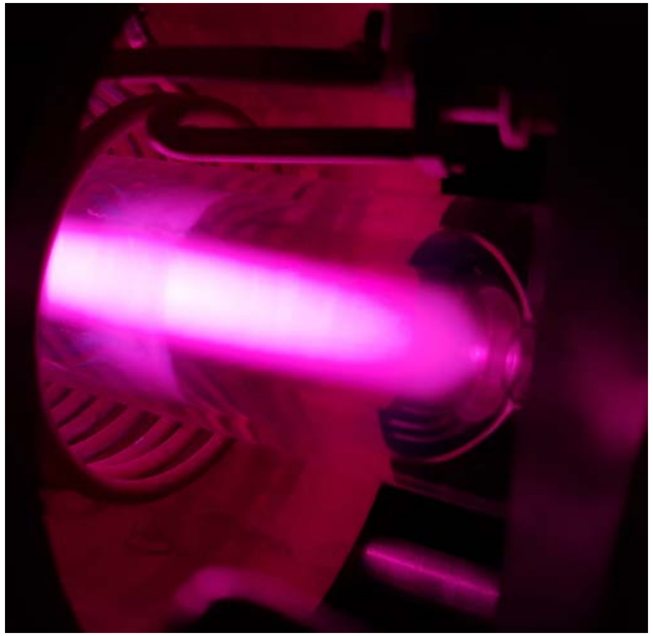
CW 205nm laser generation



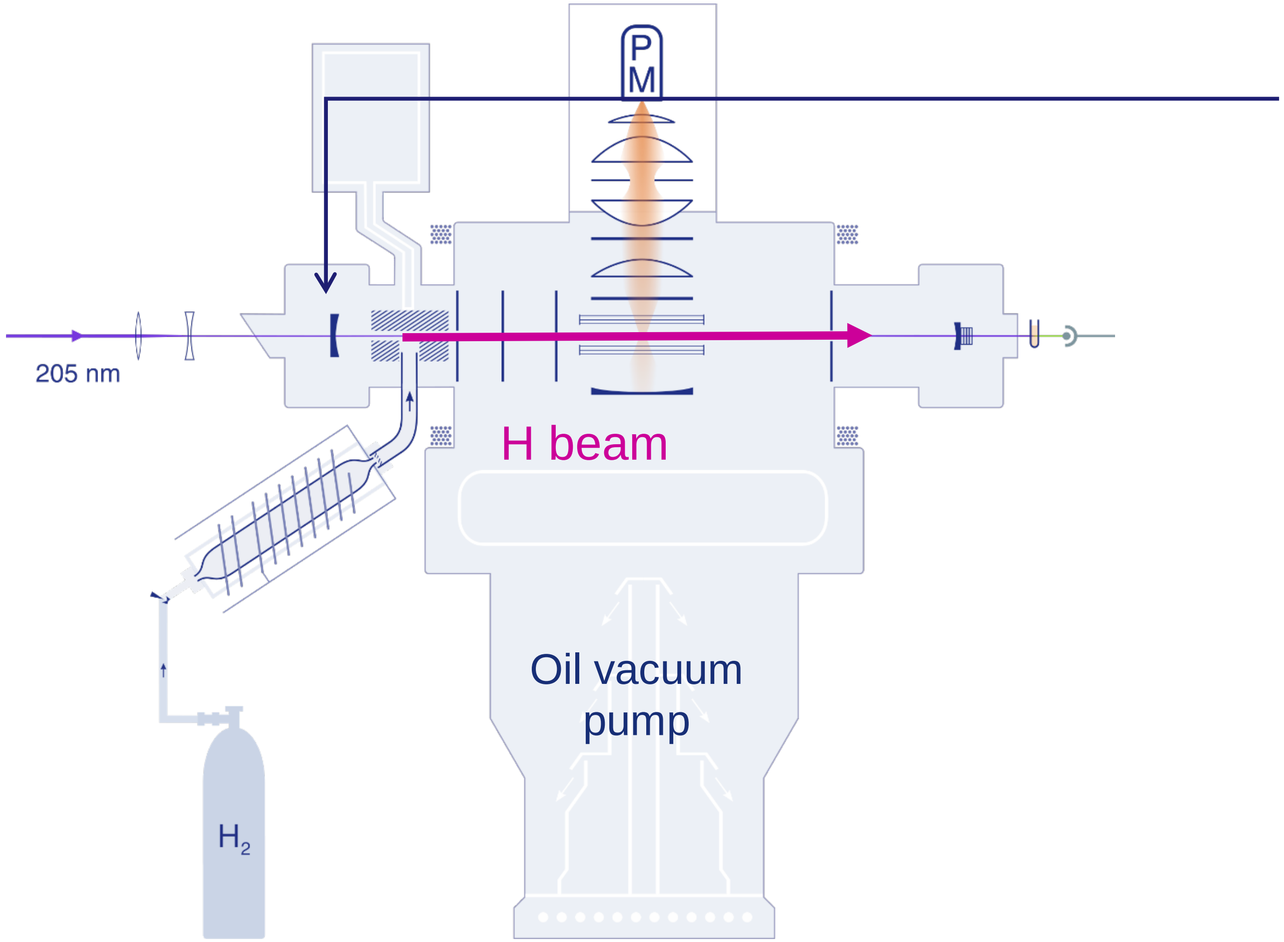
$$\frac{1}{205} = \frac{1}{266} + \frac{1}{895}$$

Schematic of the «old » H beam experiment





Schematic of the «old » H beam experiment



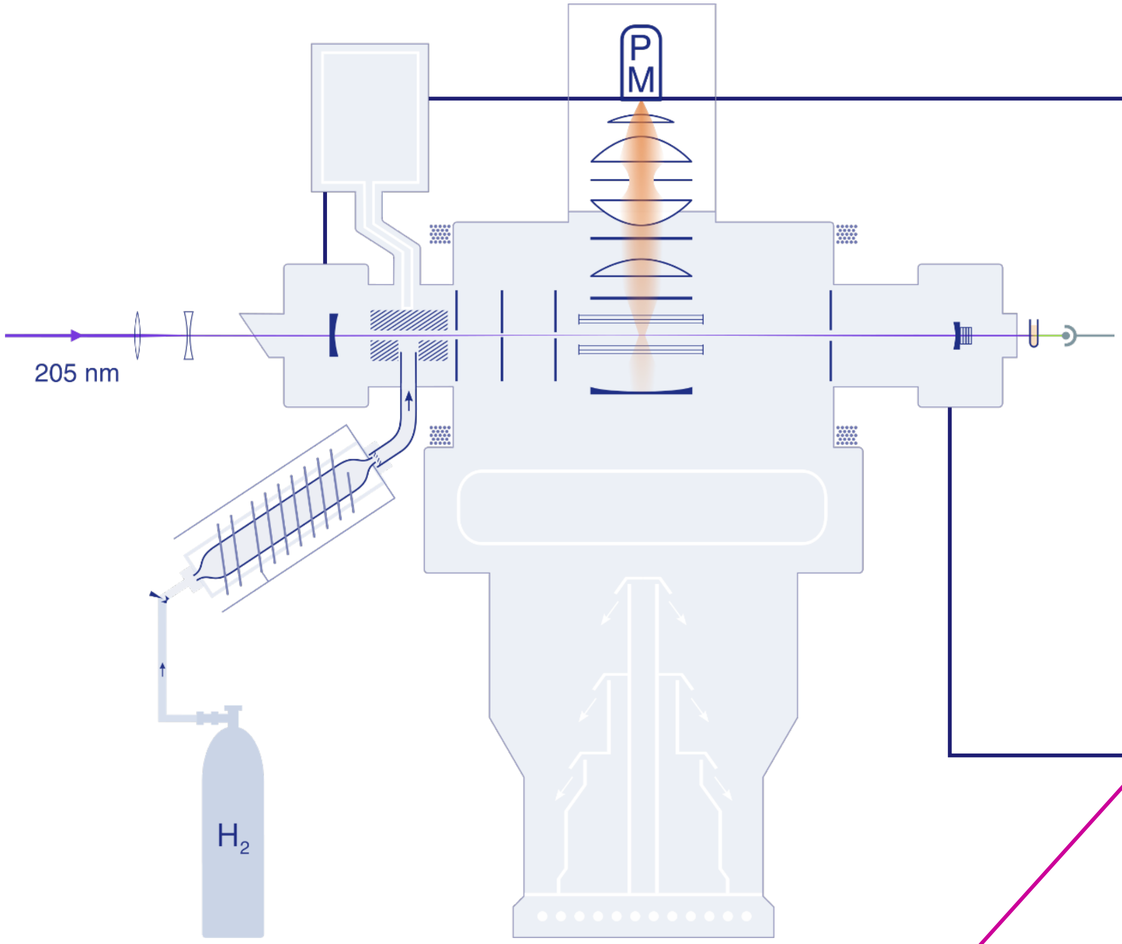
Crucial point:
the enhancement 205nm cavity (Fabry Perot) is under vacuum

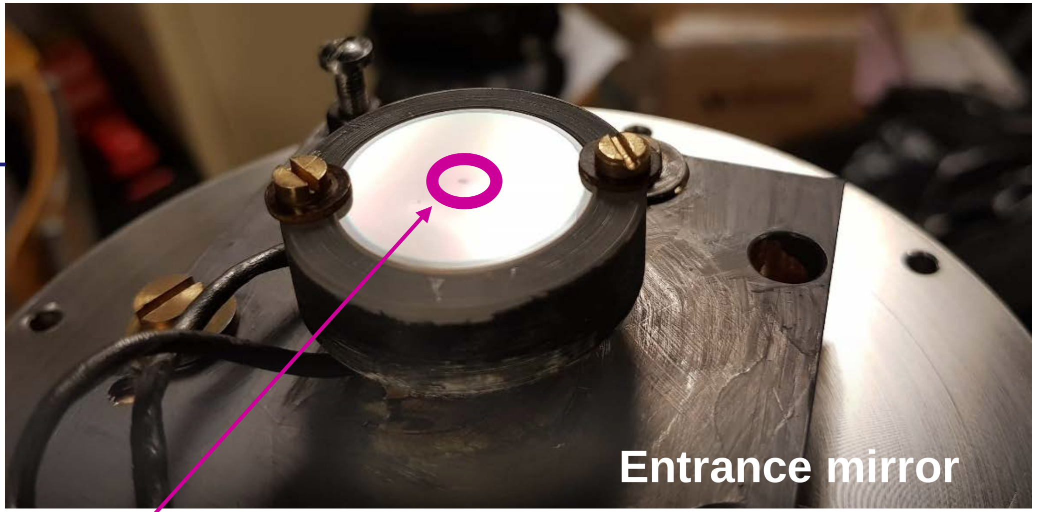
Theoretical power build-up factor

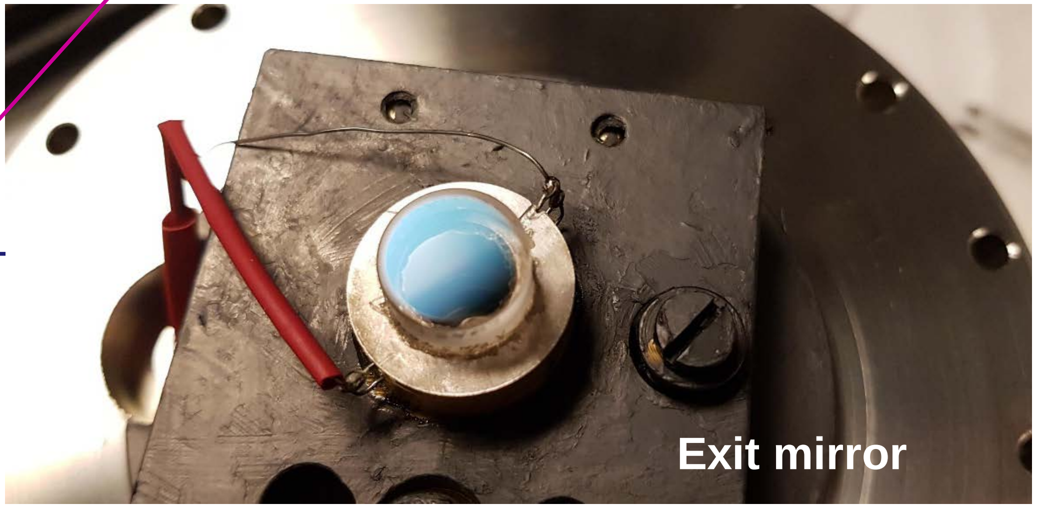
$$S = T_e / \left(1 - \sqrt{R_e R_s}\right)^2 \approx 40$$

But using UV degrades the mirrors…

Schematics of the «old » H beam experiment



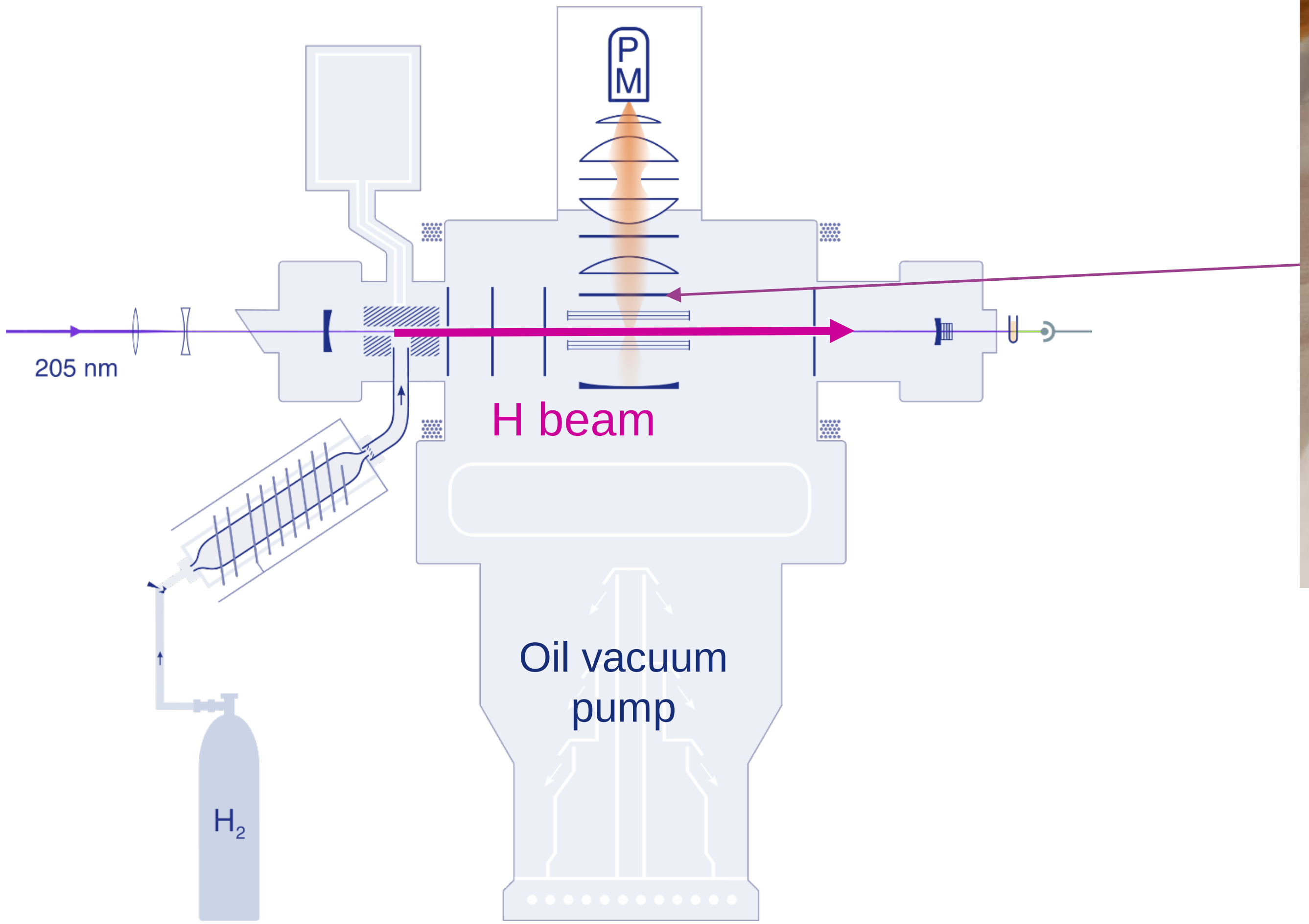




Pollution of the mirrors ⇒ breaking vacuum every 2 days to clean

Slide – courtesy of S. Thomas

Schematic of the «old » H beam experiment



⇒ Blocks the fluorescence due to 205 nm
⇒ drastic reduction of the background signal !

Spectroscopy 1S-3S on Deuterium

Some of the results obtained during the *PhD thesis S. Thomas - dec. 2021*

Based on a new campaign measurement on Deuterium atoms:

From 20 October to 17 December 2020

— 9434 spectra

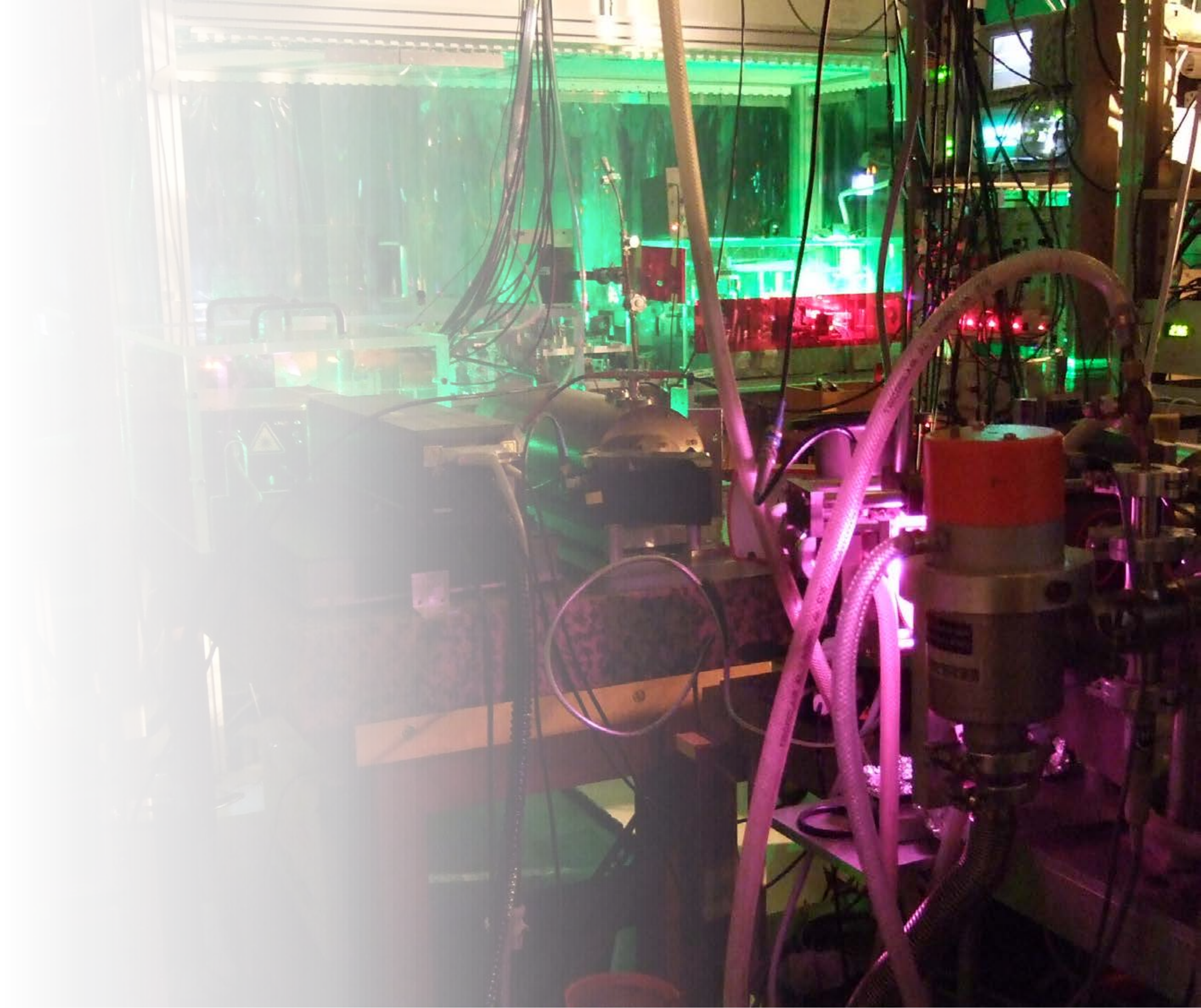
— 3 values of pressure

— 4 values of magnetic field (x 2 direction): **a new B weak field B~20G**

— measurement of the laser intensity (AC. Stark shift estimation)

Overview

- 1S-3S Hydrogen/Deuterium spectroscopy
  - The experiment and some of the latest improvements
  - Dealing with systematics
  - A new systematics effect ?
  - What next ?



Dealing with systematics …

1S - 3S spectroscopy on electronic hydrogen:

A few 10^{-12} relative uncertainty targeted

One of the main works: identifying systematics effects and try to compensate or characterize them !

Pressure shift

Origin: Collisions with rest gas in the chamber

=> broadening ~2 kHz << negligible (natural linewidth 1 MHz)

=> non negligible shift of the center of the line

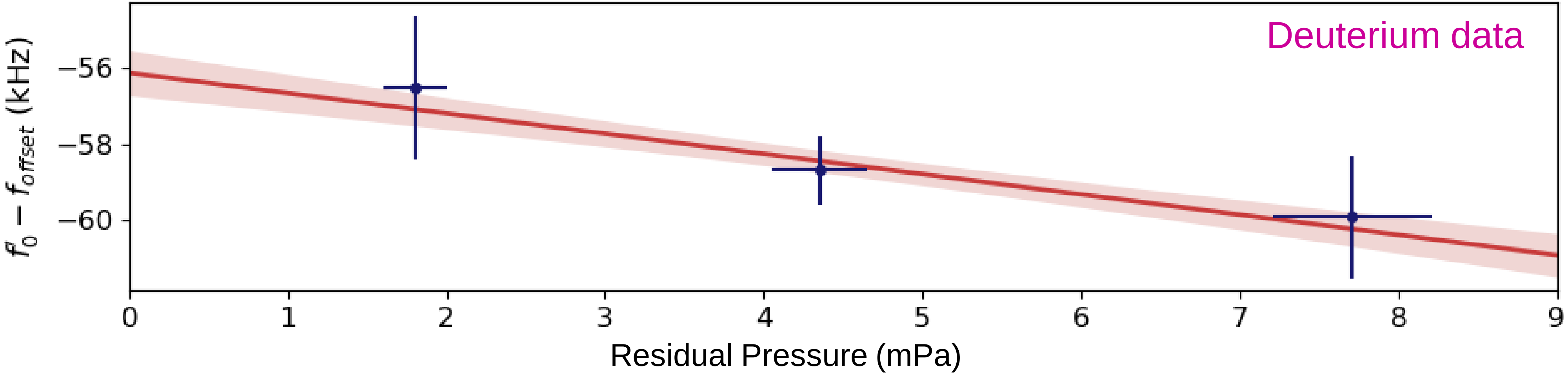


Figure taken from Ph.D thesis S. Thomas (2021

$$f_0' - f_{offset} = -0,527\,(344) \times P_f - 56,1\,(1,97)\,\mathrm{kHz}$$

For our Deuterium data at 4.35 (10) mPa : $\Delta f_{col} = 2,32\,(1,51)\,\mathrm{kHz}.$

See also: Ph.D thesis H. Fleurbaey (2017) https://tel.archives-ouvertes.fr/tel-01633631

Light shift (AC Stark shift)

- Proportional to the laser intensity inside the interaction chamber

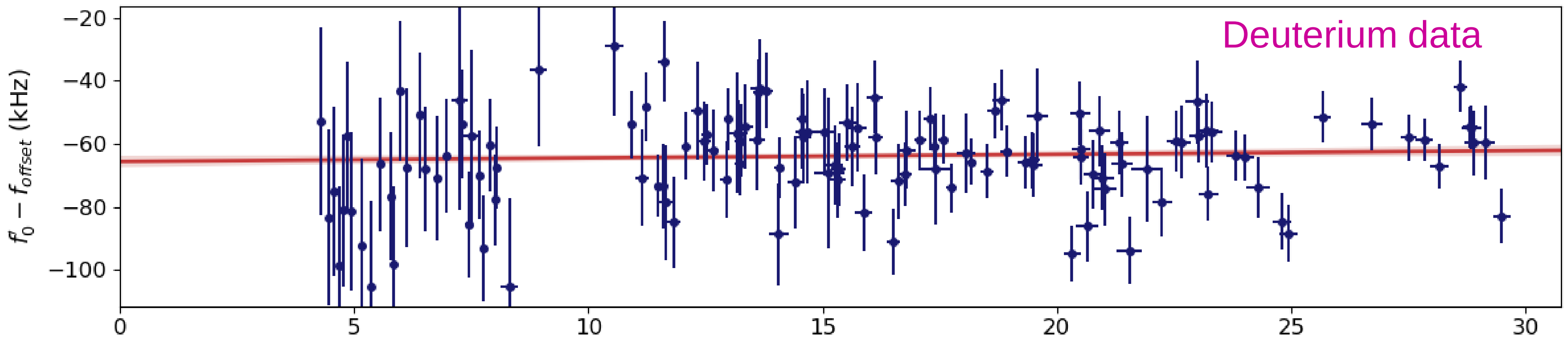


Figure taken from Ph.D thesis S. Thomas (2021)

$$f_0' - f_{offset} = 0,115\,(176) \times P_{205} - 65,57\,(3,51)\,\text{kHz (pour } P_{205} \text{ en } \mu\text{W)}$$

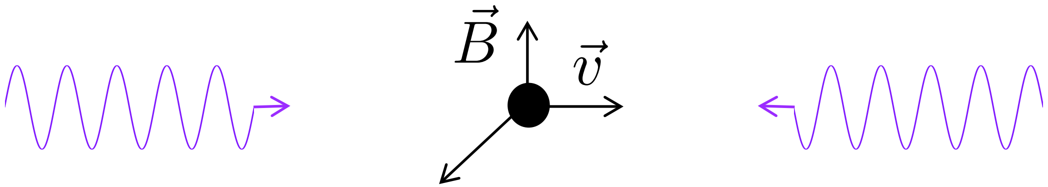
Transmitted 205nm light (through the exit mirror of the Fabry Perot cavity & pickup window)

$\Rightarrow$ Typically ~ 1-2 kHz shift

See also Ph.D thesis H. Fleurbaey (2017) https://tel.archives-ouvertes.fr/tel-01633631

2^{sd} Order Doppler effect

Our main source of uncertainty



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

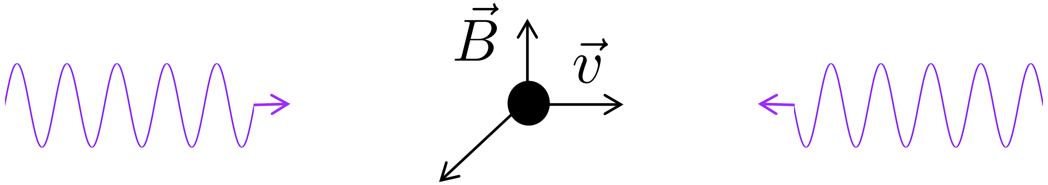
$$\delta^{(2)}_{Doppler} = -\nu_{at}\frac{v^2}{2c^2}$$

Need to determine the **velocity distribution** of the H beam …

And no 1-photon transition easily achievable (121nm laser) for 1^{st} order Doppler broadening measurement

2^{sd} Order Doppler effect

Compensating it ?



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

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

$$\delta^{(2)}_{Doppler} = -\nu_{at}\frac{v^2}{2c^2}$$

$$\vec{E} = \vec{v} \times \vec{B}$$

Idea principle: inducing a Motional Stark effect

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

To compensate 2^{nd} order Doppler

2^{sd} Order Doppler effect

Avoiding it ?

Hydrogen energy levels

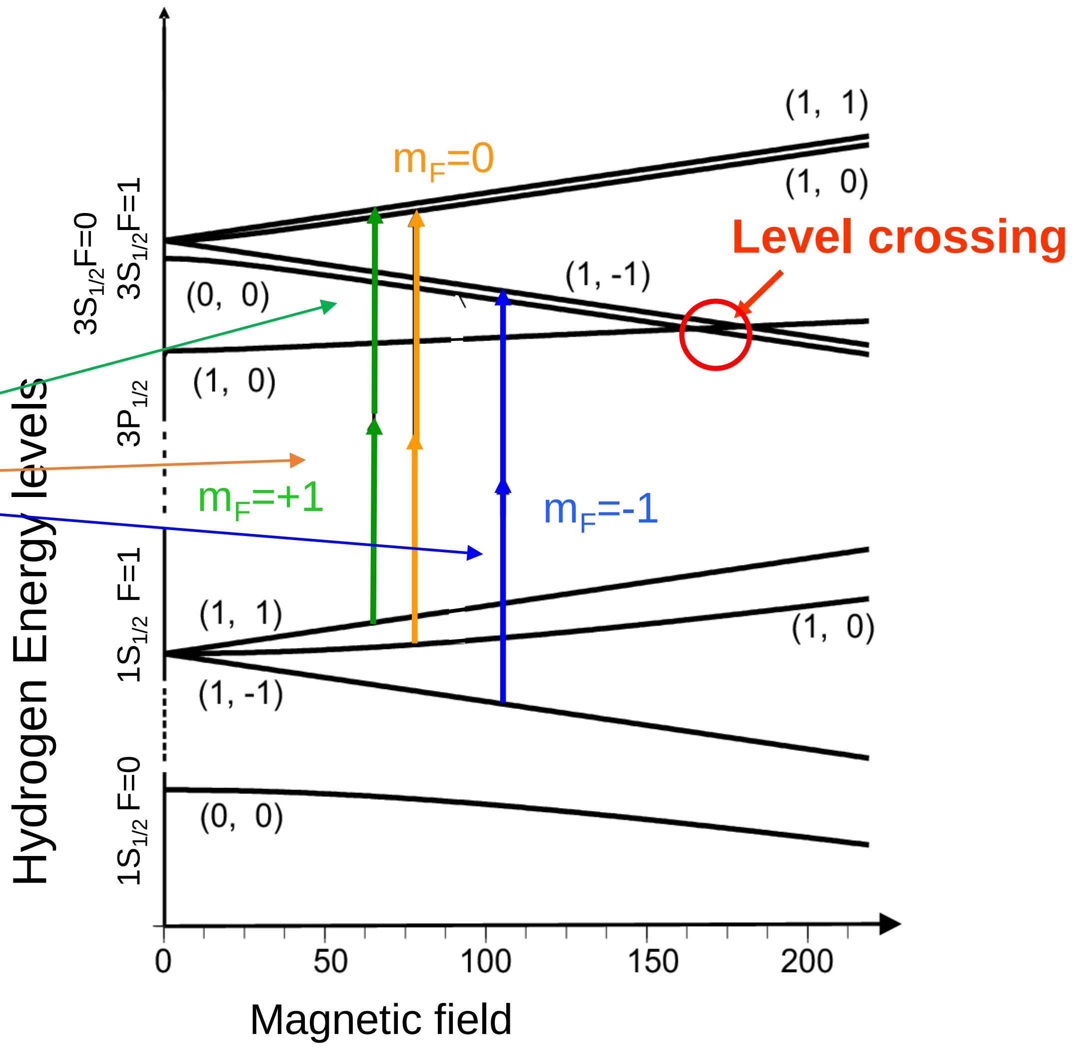
But Zeeman effect has to be taken into account !

2-γ transition Selection rules

$$\Delta mF = 0$$

⇒ 3 transitions driven

m_F=0 m_F=+1 m_F=-1



2sd Order Doppler effect

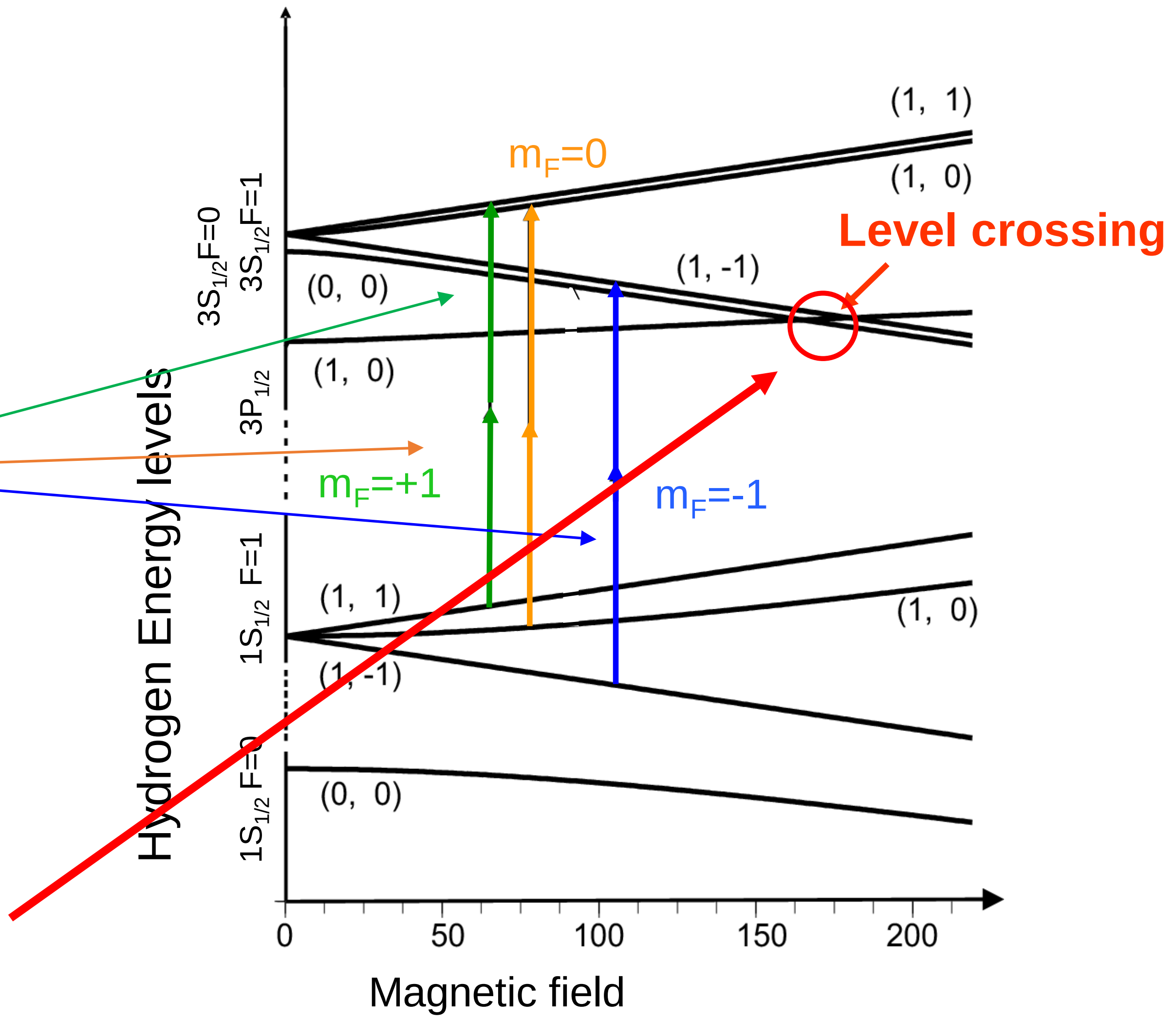
Hydrogen energy levels

But Zeeman effect has to be taken into account !

2-γ transition Selection rules
$\Delta mF = 0$

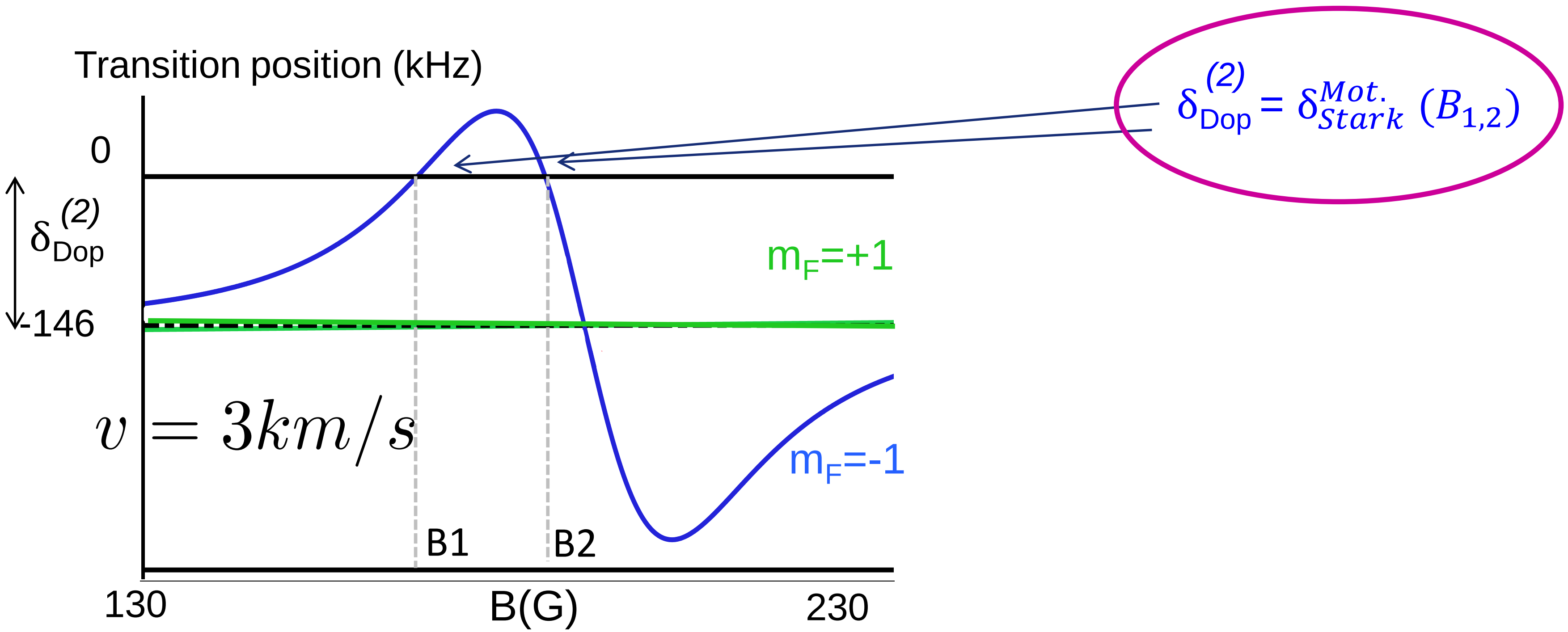
⇒ 3 transitions driven

m_F=0 m_F=+1 m_F=-1



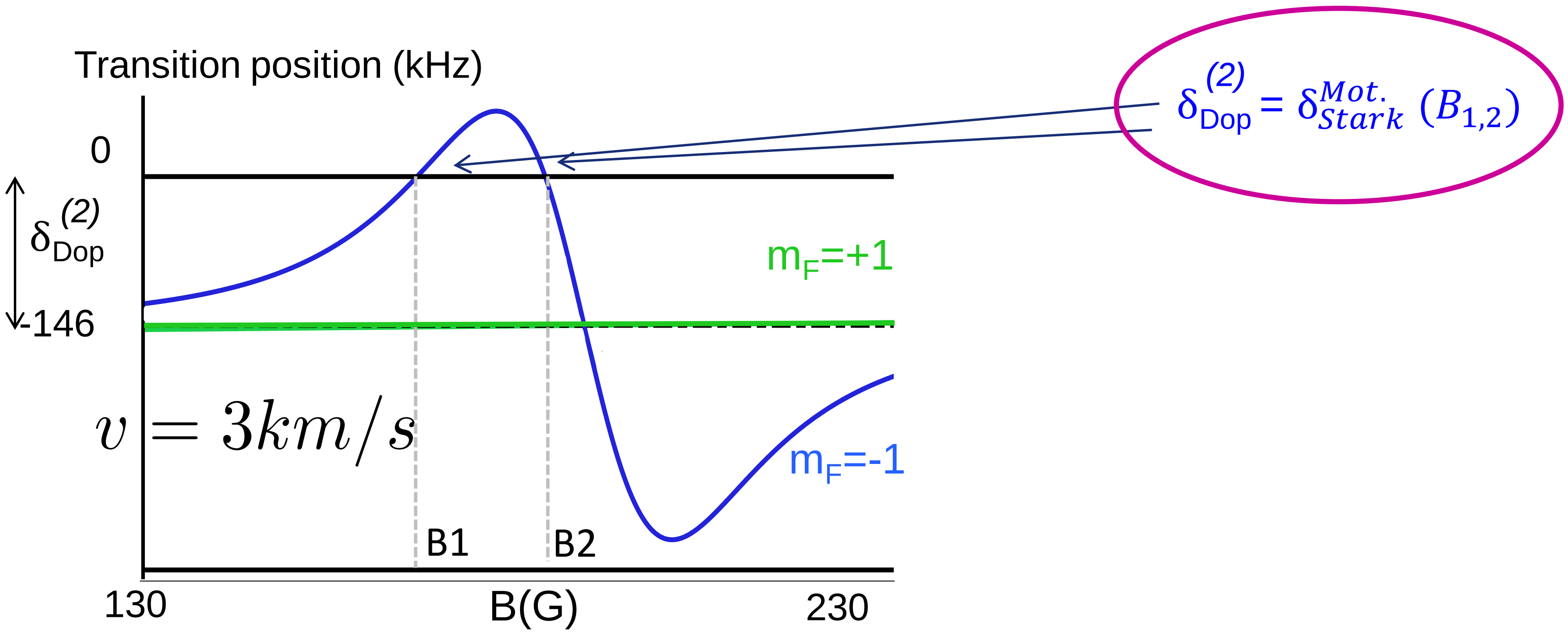
Motional Stark:
mixing S – P states = anti-crossing

Avoiding 2nd order Doppler effect



- *Total compensation of 2^{sd} Ord. Doppler for B = B1 and B2 for mF=-1 transition*

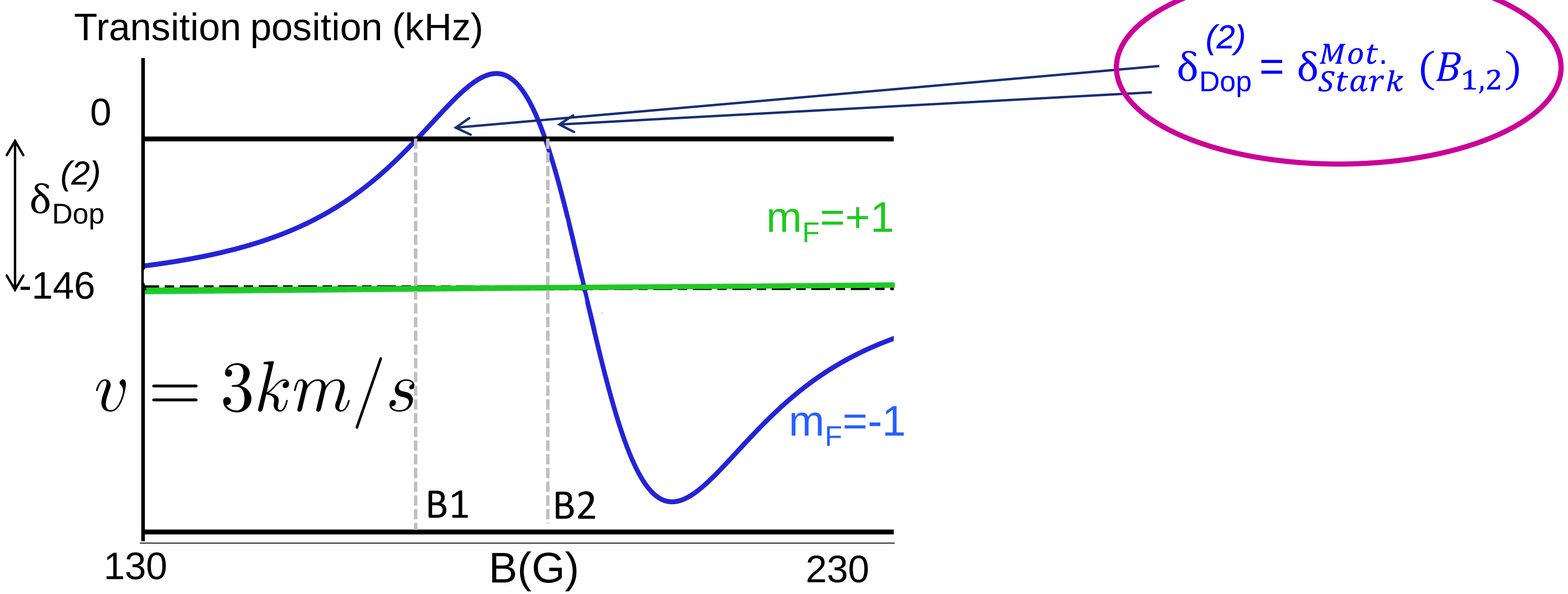
Avoiding 2nd order Doppler effect



- *Total compensation of 2sd Ord. Doppler for B = B1 and B2 for mF=-1 transition*

- For v= 3 km/s: the transitions m_F=-1 and m_F=1 are split by ~146 kHz for B = B1 and B2.

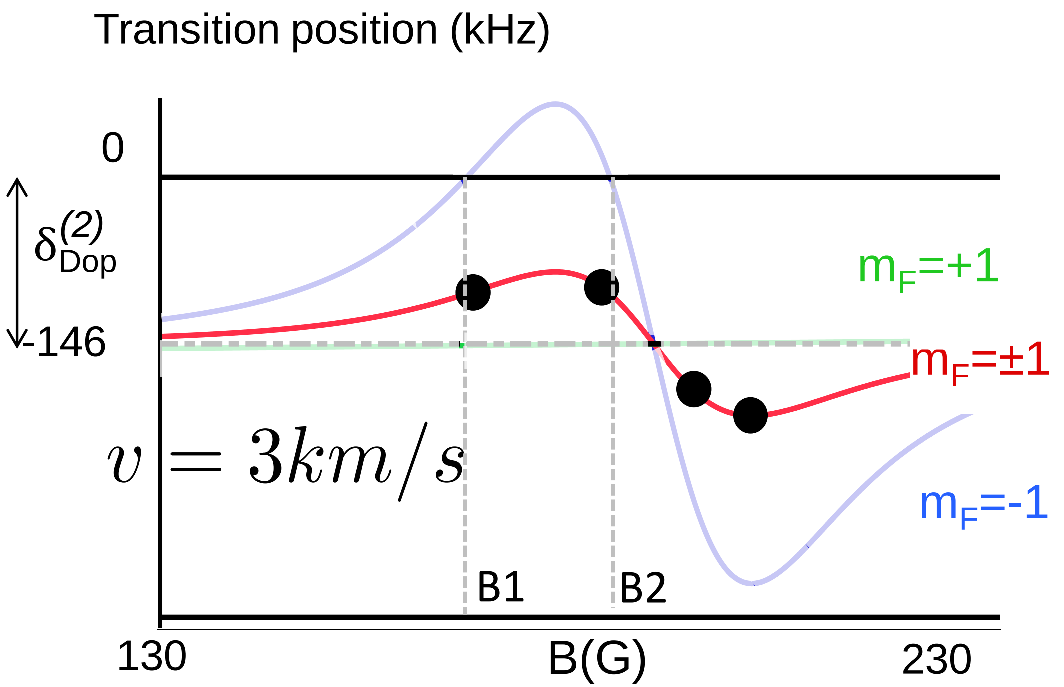
Avoiding 2nd order Doppler effect



- *Total compensation of 2sd Ord. Doppler for B = B1 and B2 for mF=-1 transition*

- For v= 3 km/s: the transitions m_F=-1 and m_F=1 are split by ~146 kHz for B = B1 and B2.
- The 3S natural bandwith ~1 MHz
- The two lines cannot be resolved ⇒ **Both lines are excited**

Avoiding 2nd order Doppler effect

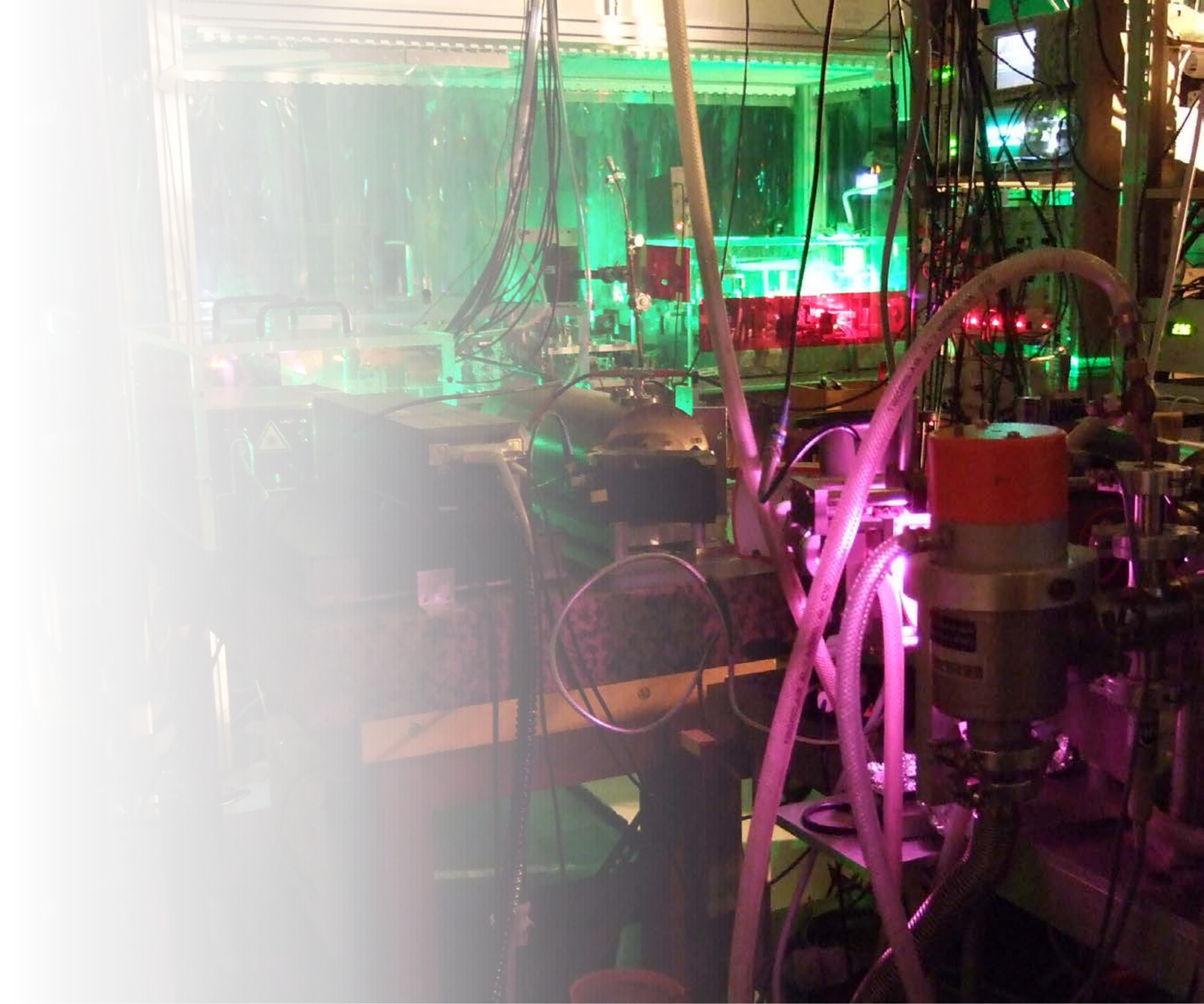


The two lines cannot be resolved ⇒ **partial compensation only** due to Motional Stark

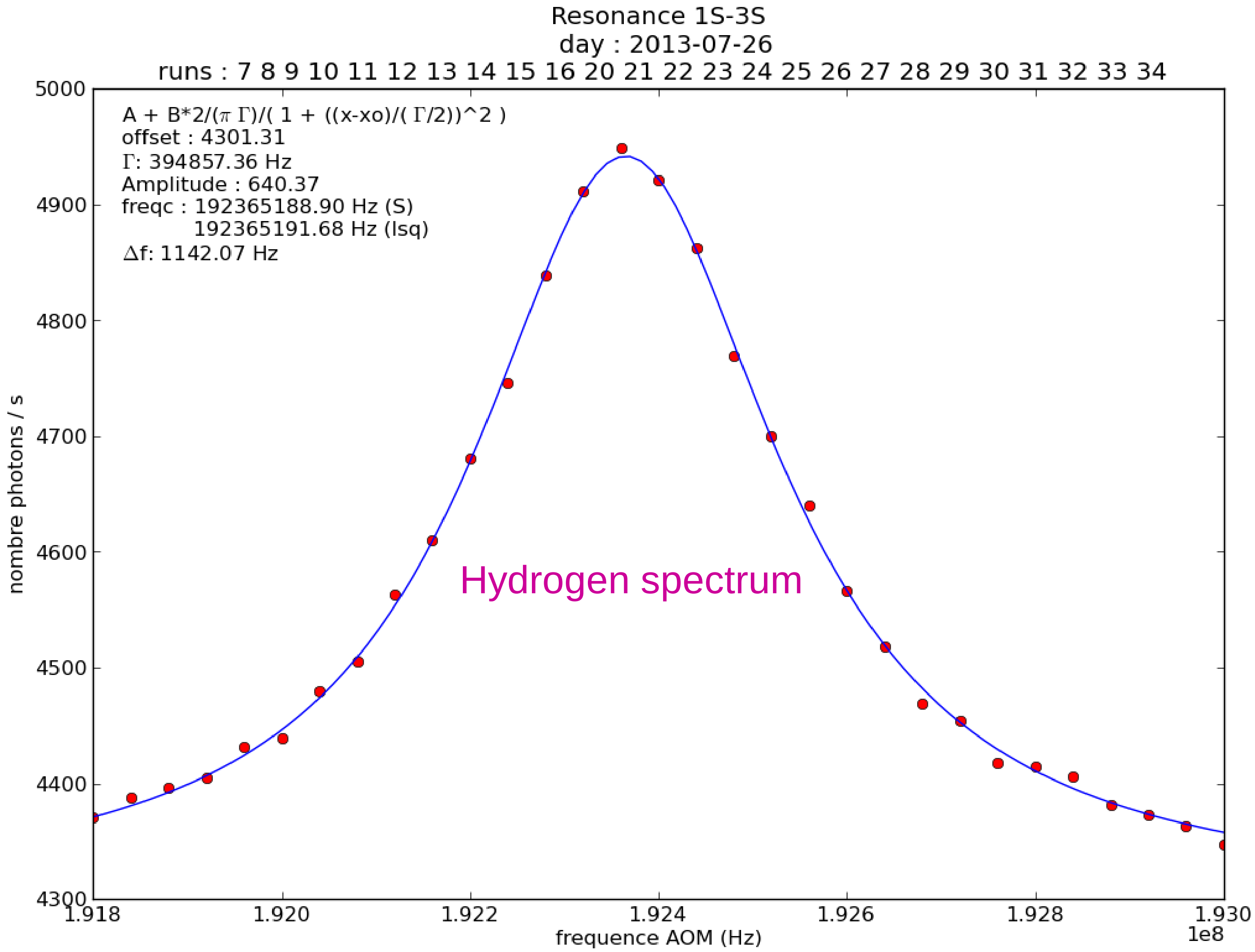
⇒ **Determination of the velocity distribution** by fitting the dispersion curve with several data points for different B (« red » profile)

Overview

- 1S-3S Hydrogen/Deuterium spectroscopy
  - The experiment and some of the latest improvements
  - Dealing with systematics
  - A new systematics effect ?
  - What next ?



Typical signal of the 1S-3S transition – in the past



On day average

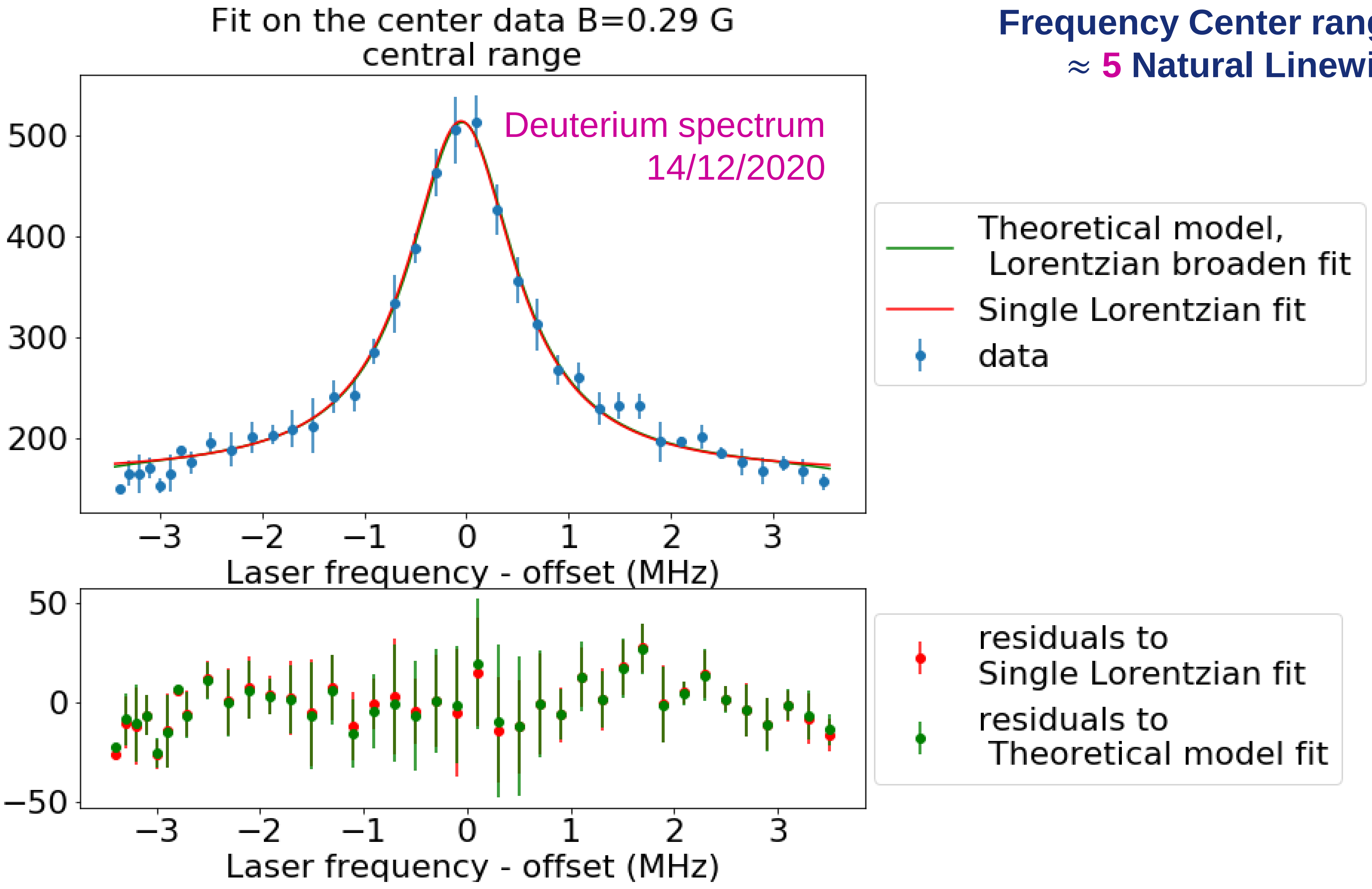
Improvements of the experiment during the last years

- Work to reduce the Background signal:

$\Rightarrow$ installation of a dichroic mirror to block the 205nm fluorescence detection system (collection optics)

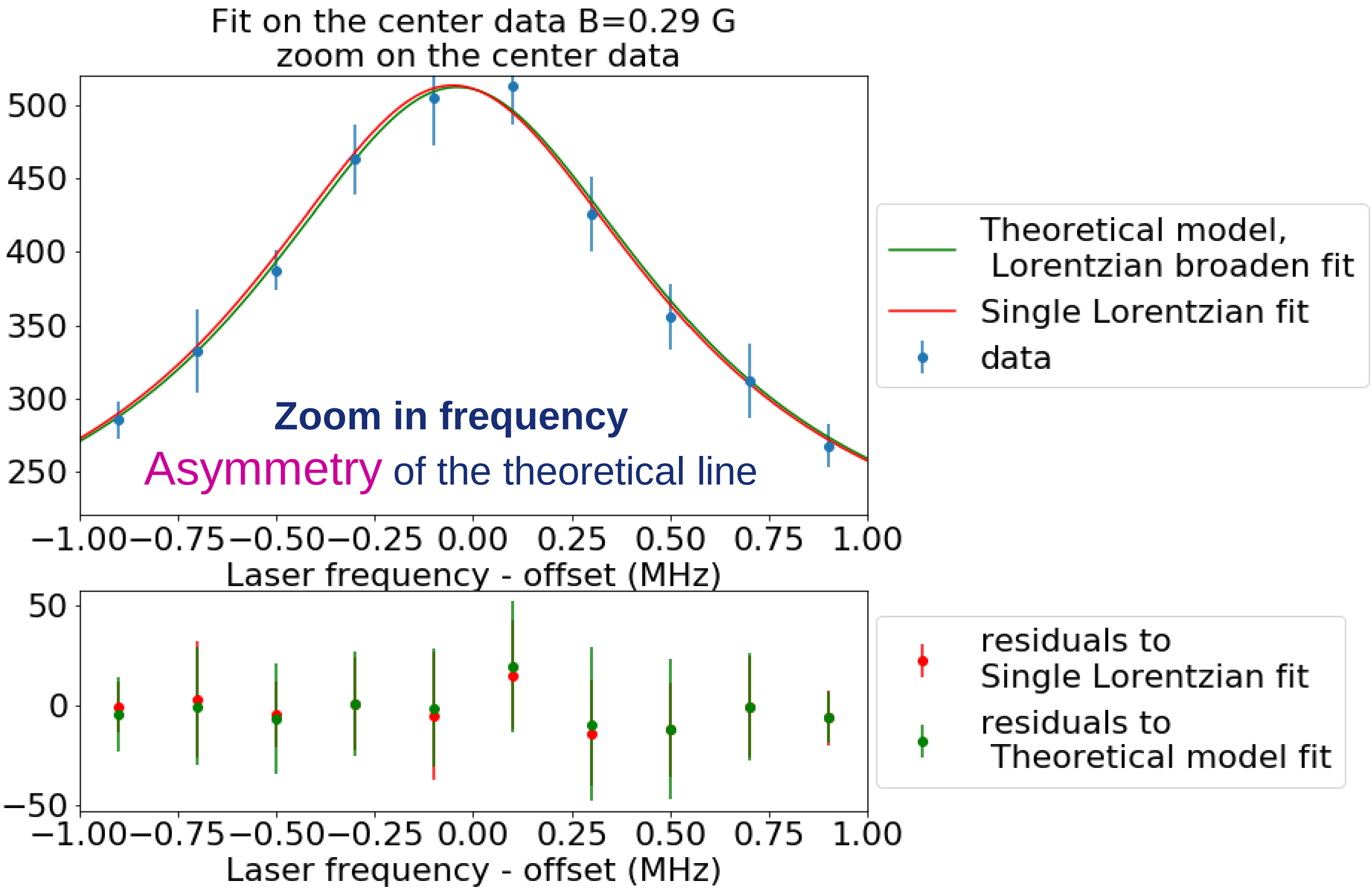
Good background reduction

Frequency Center range scan
≈ 5 Natural Linewidth



Good background reduction

Deuterium spectrum
14/12/2020, run 38
B=0.29 G



Improvements of the experiment during the last years

- Work to increase the frequency stability and tunability of the laser

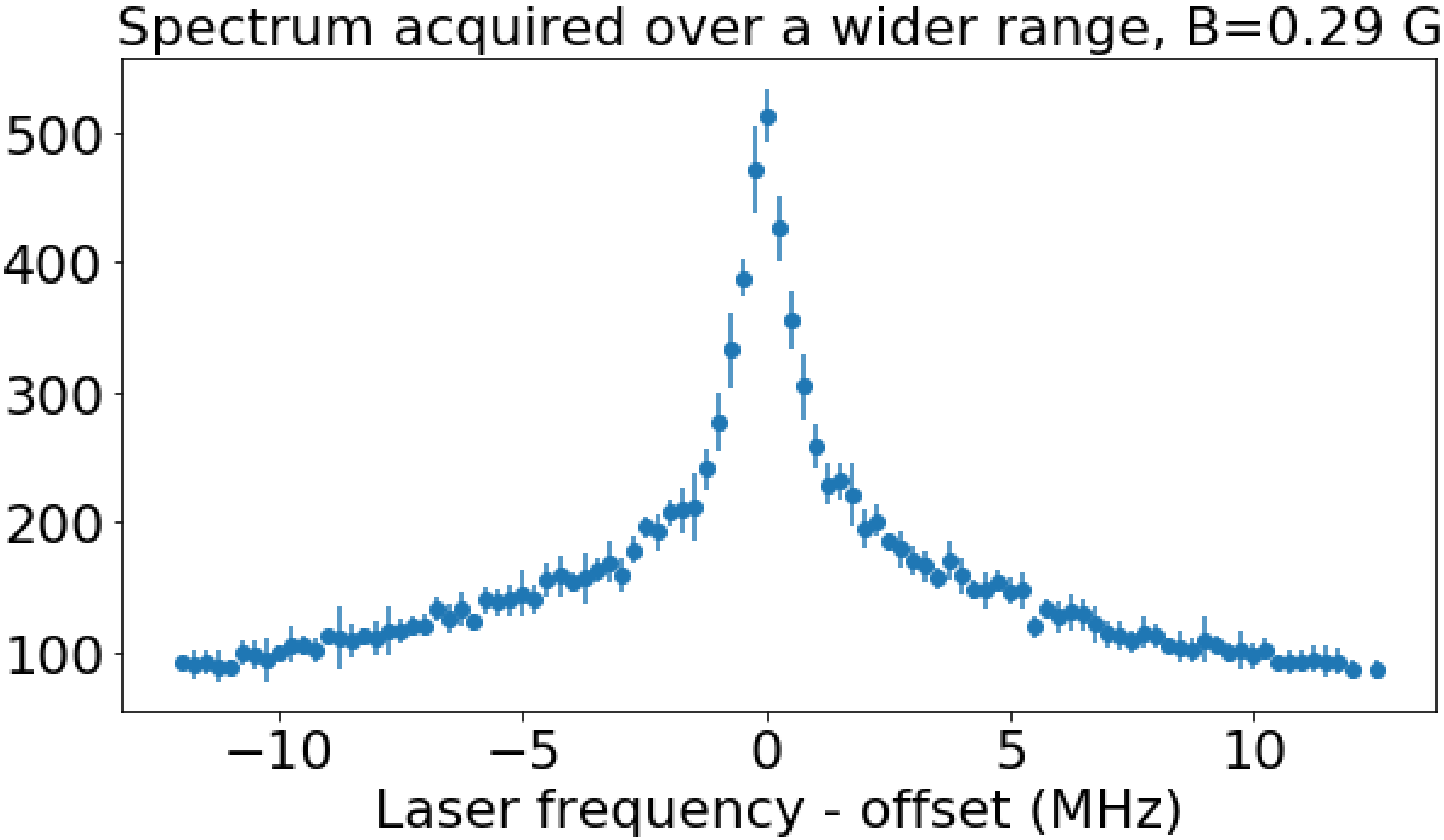
  - ***Before***: **usual** scan $\pm$ 2.5 - 3 MHz scan ($\approx$ **5** Natural Linewidth**) –** *~ 6 min for 1 run (= 10 scans)*

  - possible up to $\pm$ 5 MHz ($\approx$ **10** Natural Linewidth) – *~ 11 min*

  - ***New* system:** $\pm$**10** – 30 MHz scan possible ($\approx$ **20** – **60** Natural Linewidth**)** ~ *20 min*

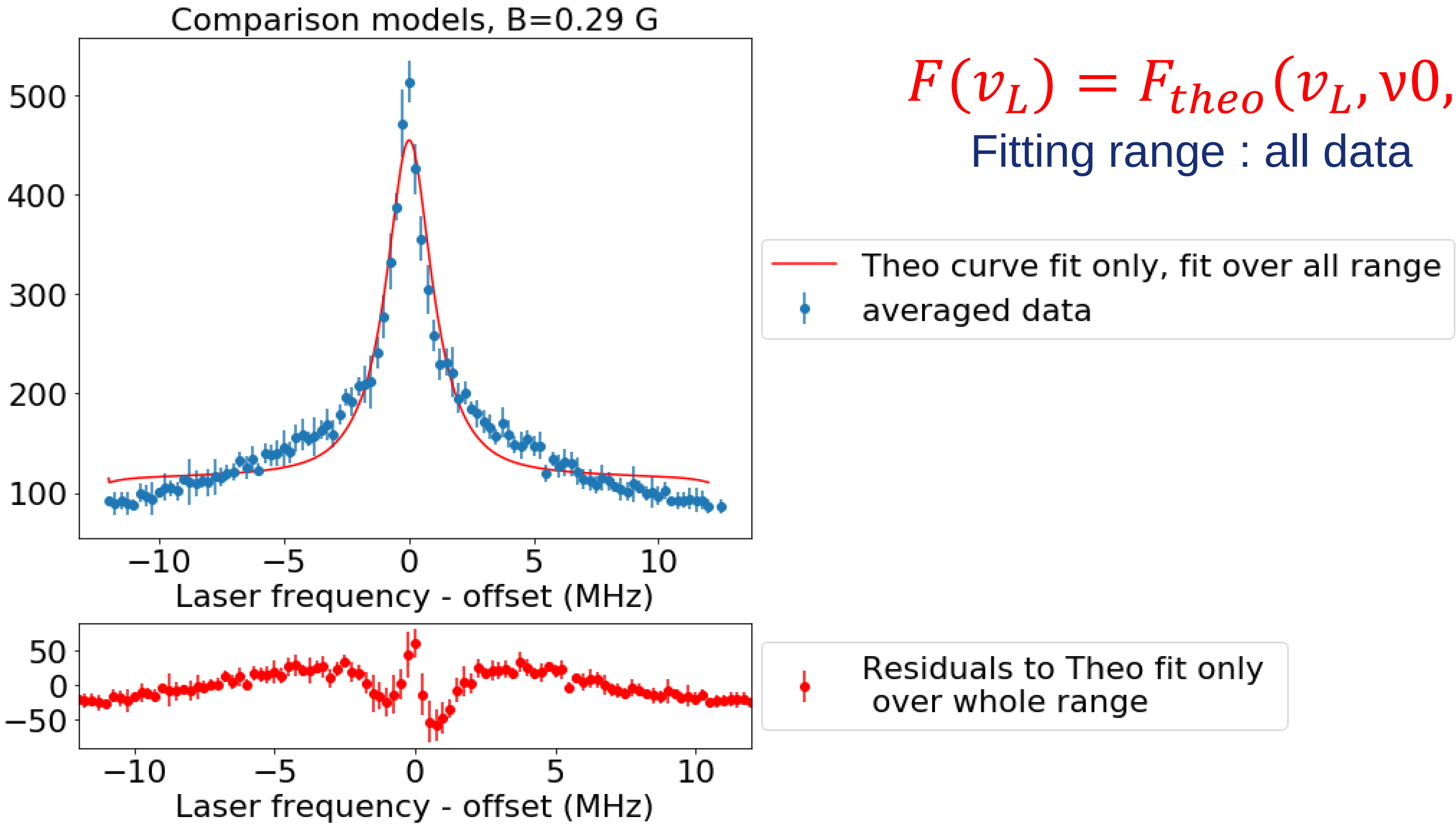
With a wider laser frequency scan:

Deuterium spectrum
14/12/2020, run 38
B=0.29 G



Averaged
1 run
(10 scans)

Which fit model ?



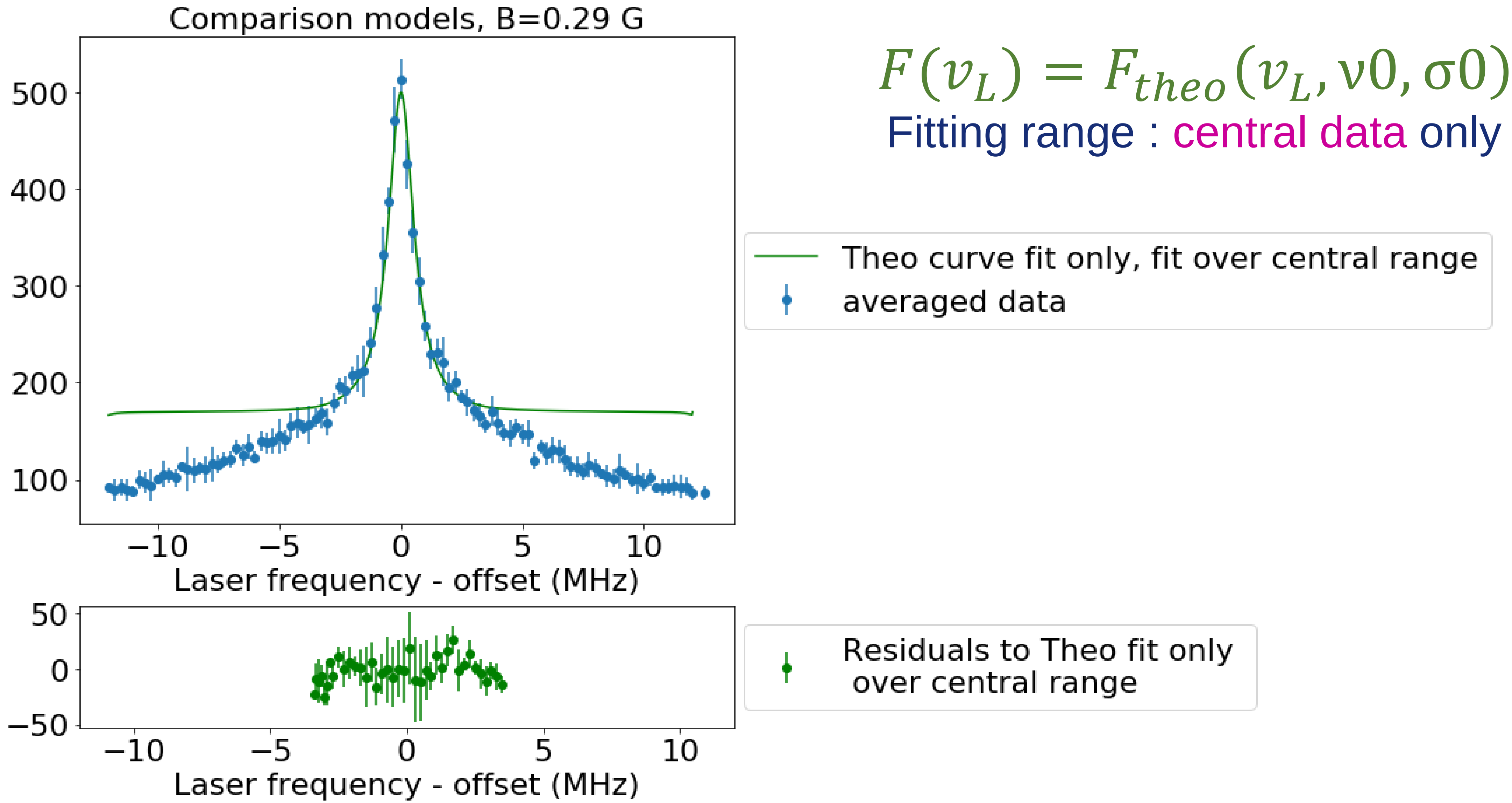
$$F(\nu_L) = F_{theo}(\nu_L, \nu 0, \sigma 0)$$

Fitting range : all data

Which fit model ?

$$F(\nu_L) = F_{theo}(\nu_L, \nu 0, \sigma 0)$$

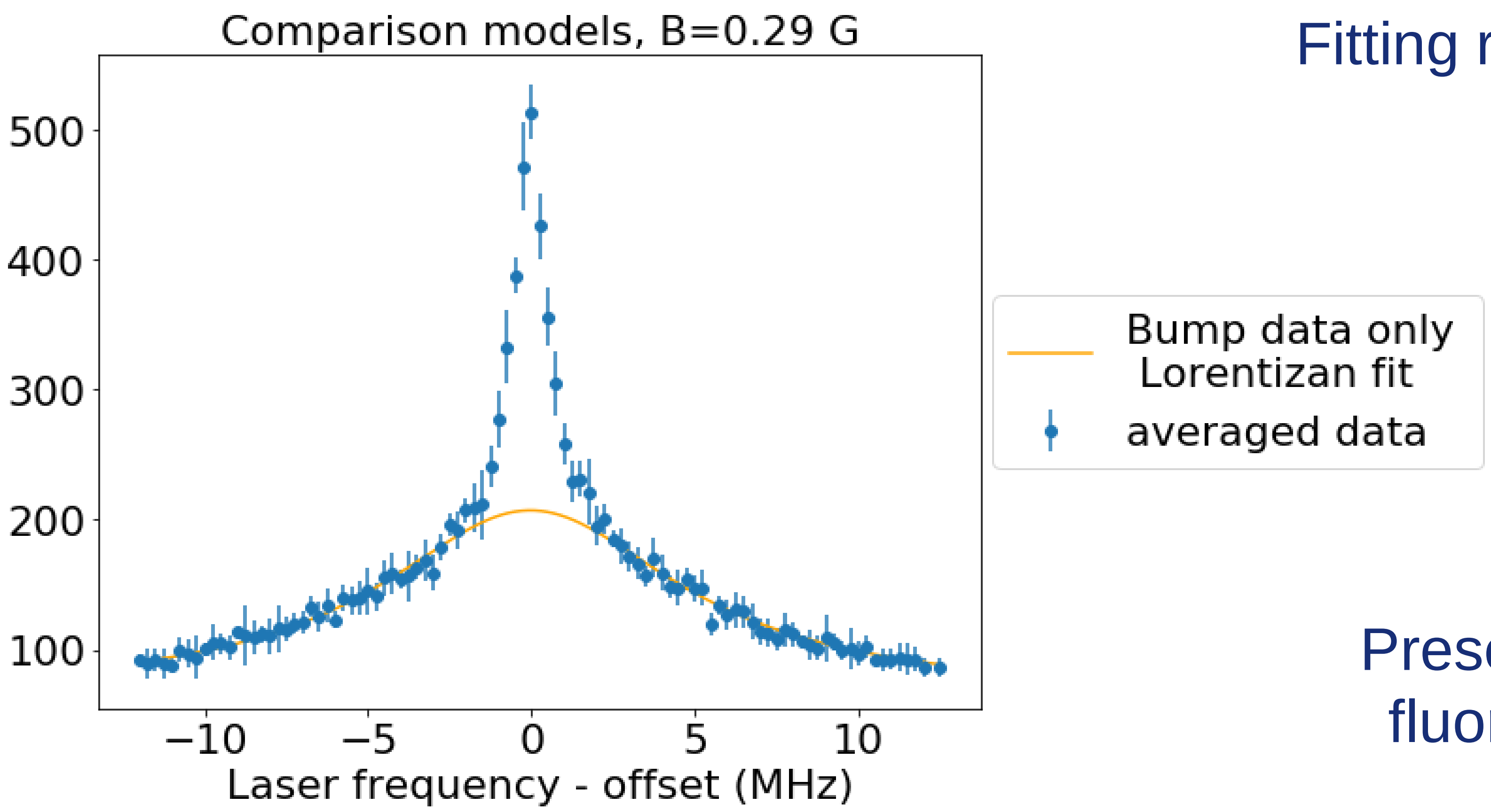
Fitting range : central data only



Which fit model ?

$$F(\nu_L) = Lor(\nu_L, \nu_{Bump}, \Gamma_{Bump})$$

Fitting range : edge data only



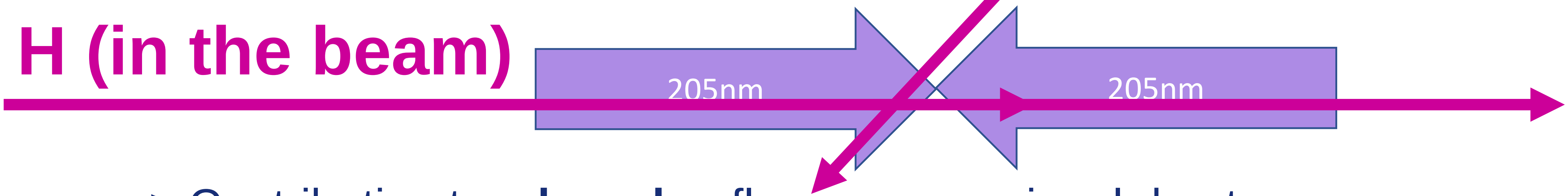
Presence of a “Pedestal fluorescence signal” = “Bump” signal

Which fit model ?

Origin of this pedestal ?

H (residual gas in the chamber)

Presence of residual H gas in the chamber.



=> Contribution to a **broaden** fluorescence signal due to **short interaction time**

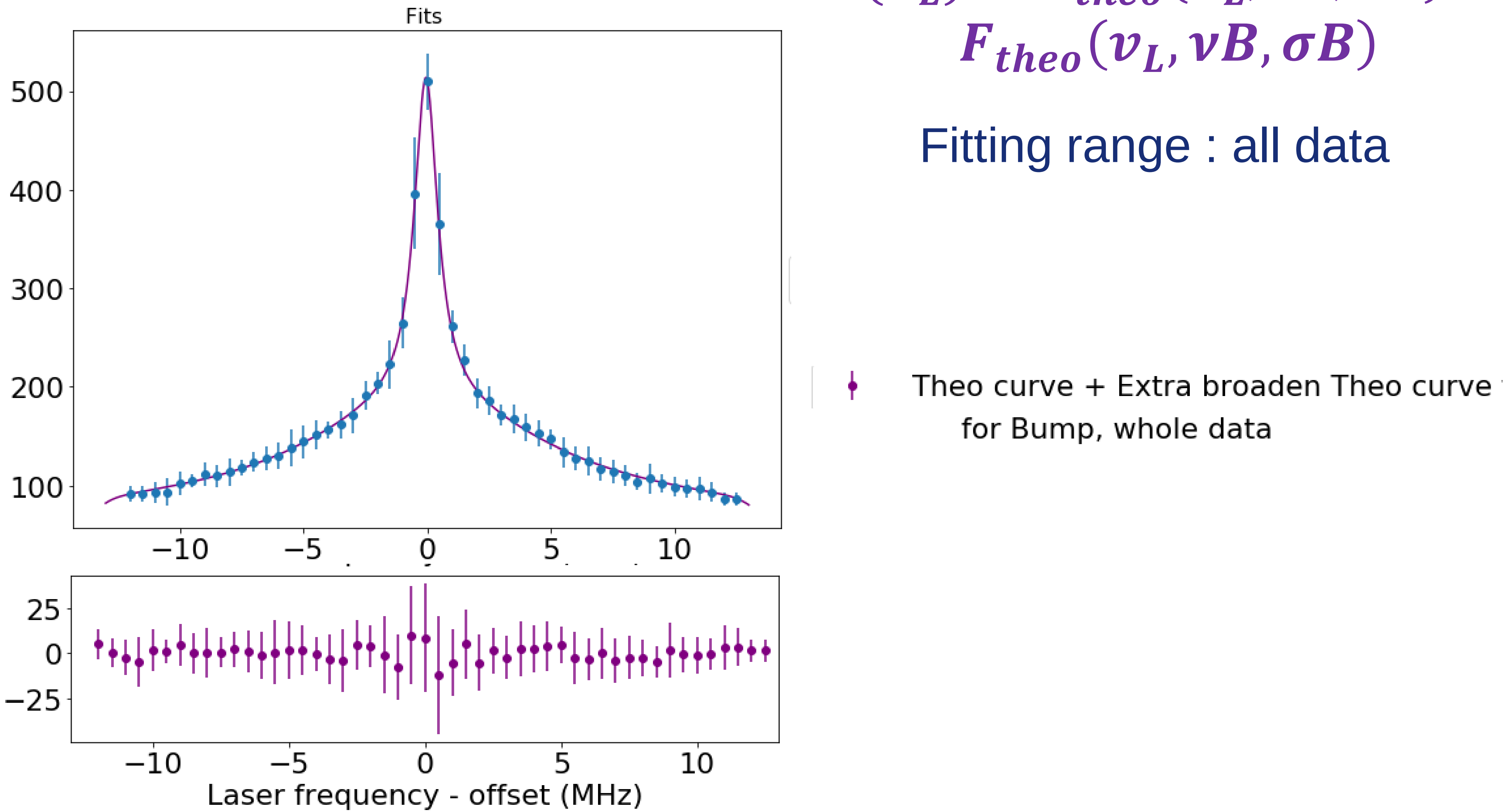
New model to fit:

$$F(v_L) = F_{theo}(v_L, \nu0, \sigma0) + F_{theo}(v_L, \nu B, \sigma B) + B$$

Which fit model ?

$$F(\nu_L) = F_{theo}(\nu_L, \nu 0, \sigma 0) + F_{theo}(\nu_L, \nu B, \sigma B)$$

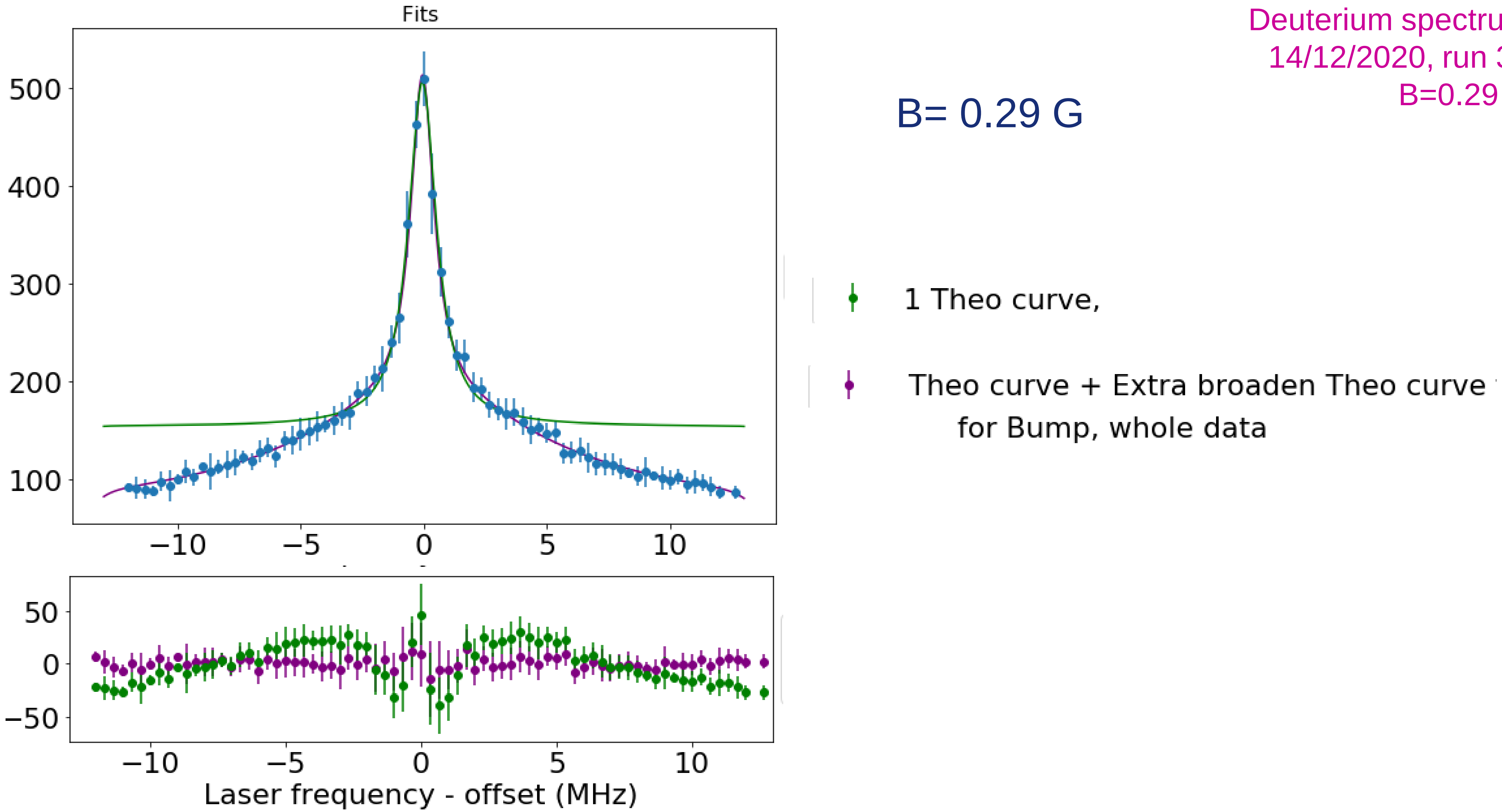
Fitting range : all data



Difference in the fit result of the different models ?

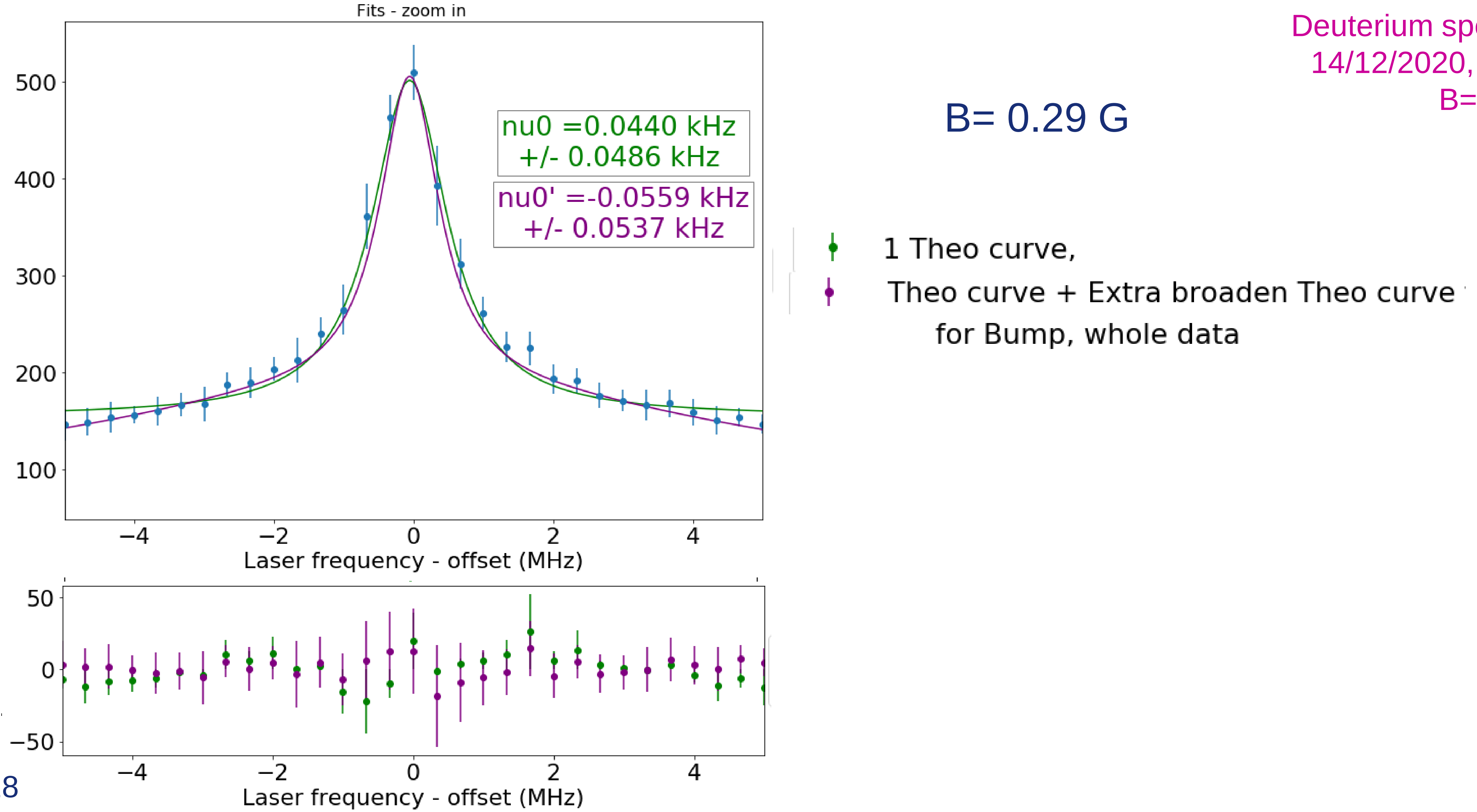
Deuterium spectrum
14/12/2020, run 38
B=0.29 G

B= 0.29 G



Difference in the fit result of the different models ?

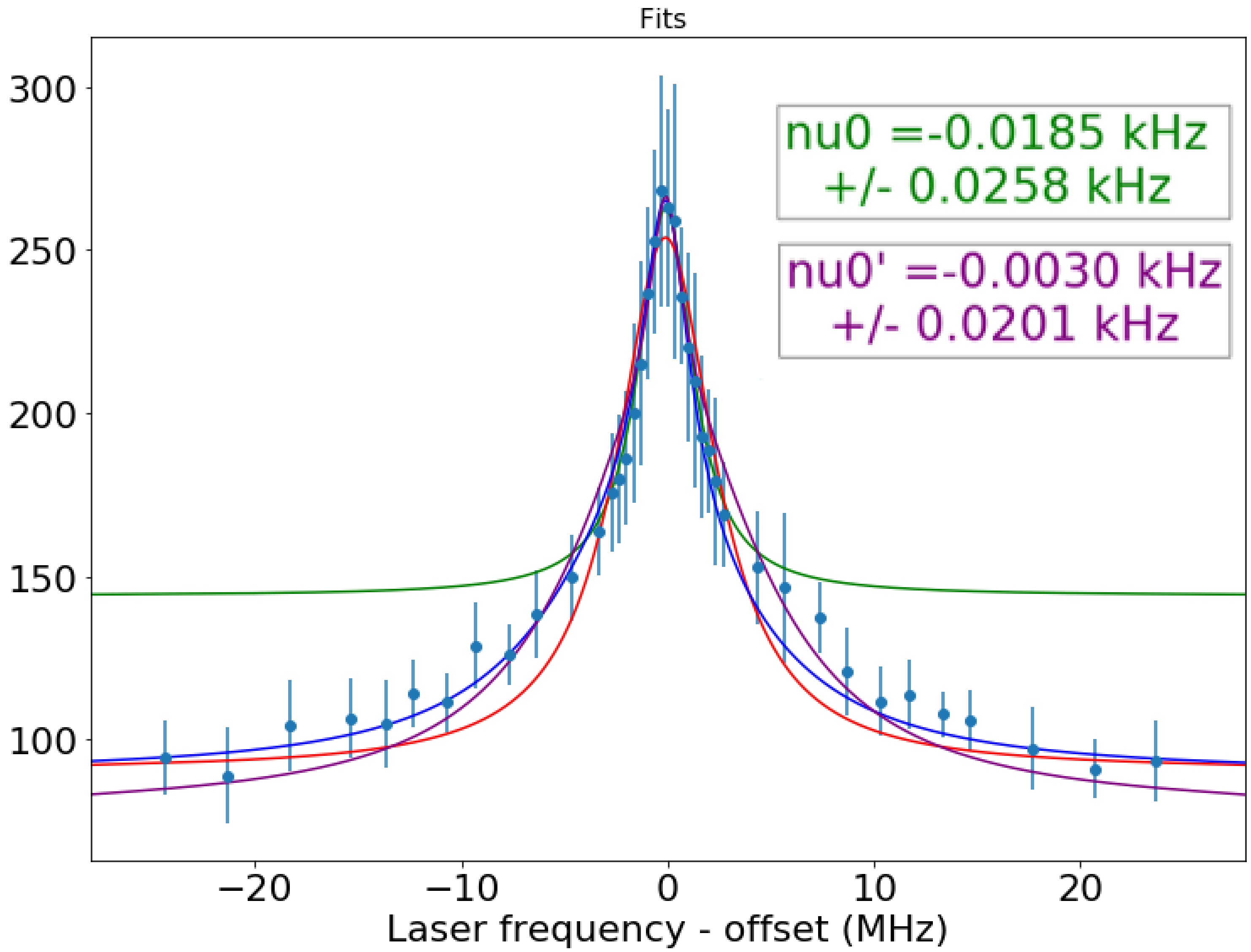
Deuterium spectrum
14/12/2020, run 38
B=0.29 G



B= 0.29 G

Difference in the fit result of the different models ?

Deuterium spectrum
26/11/2020, run 17
B=186 G



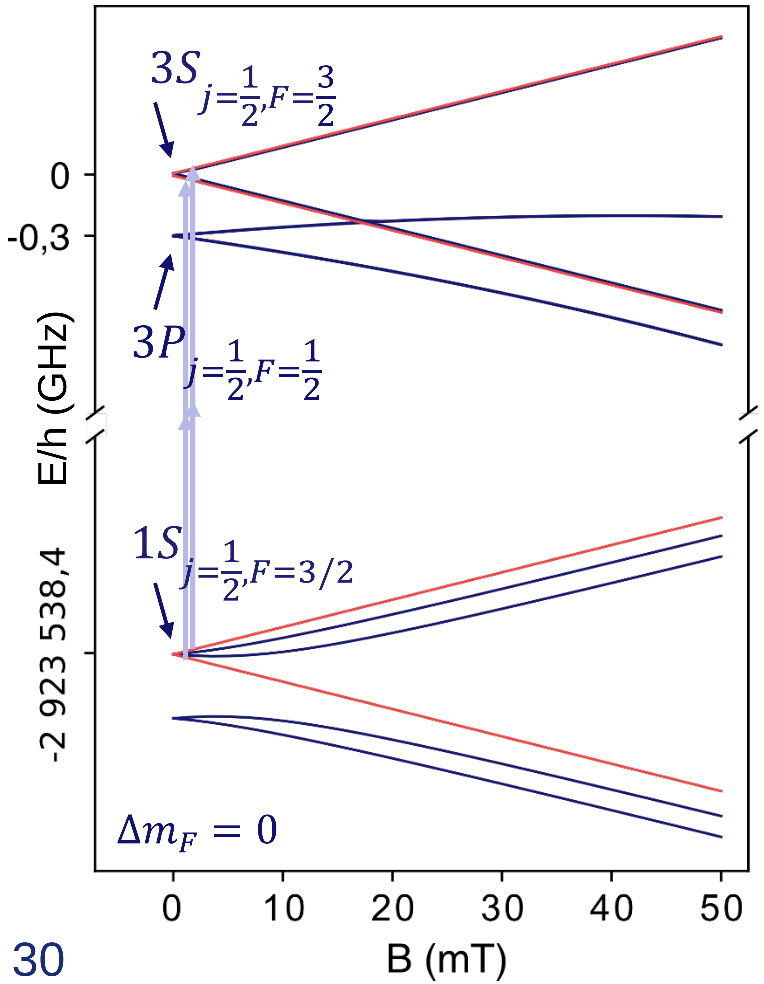
B= 186 G

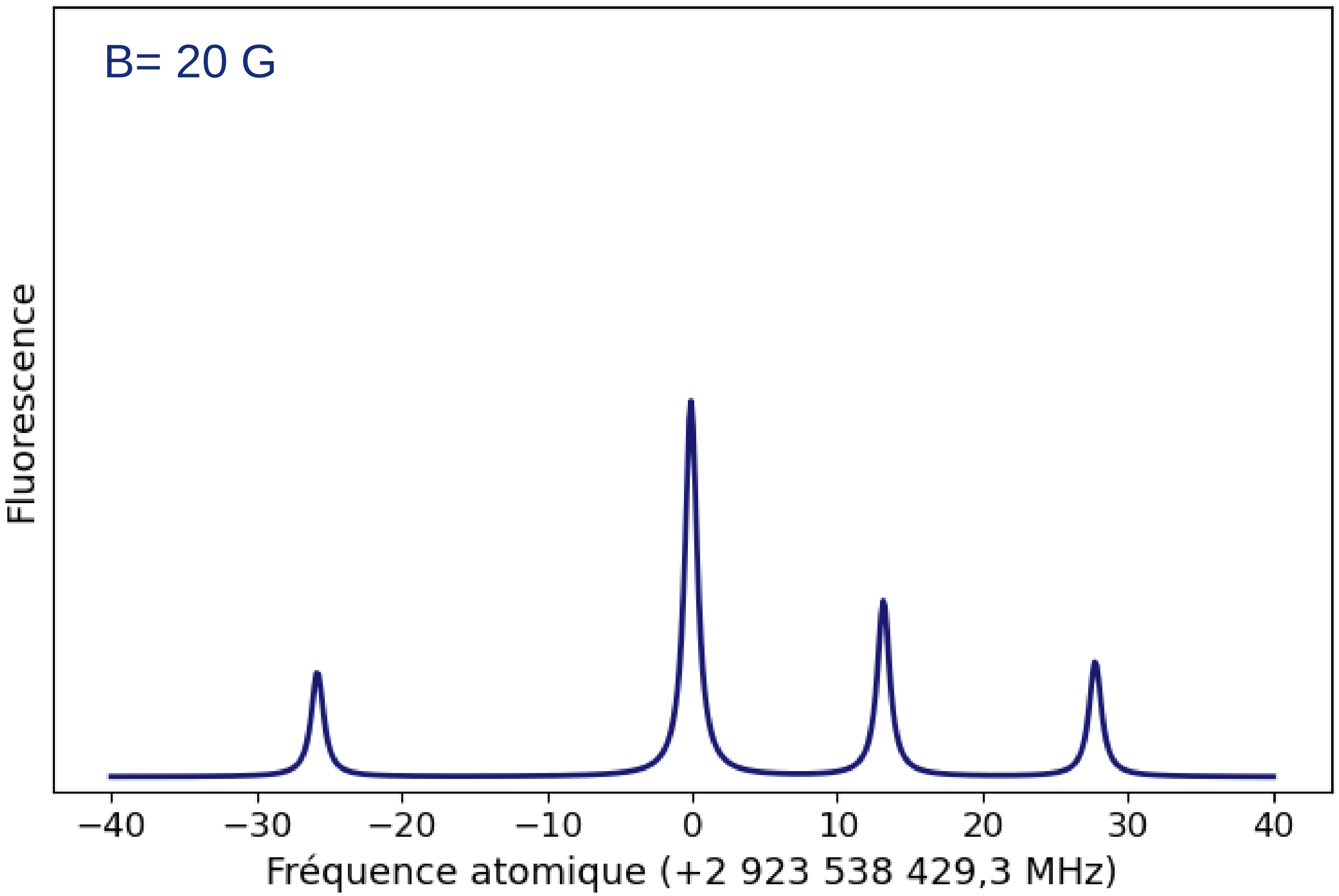
- 1 Theo curve , on center data
- 1 Theo curve, on whole data
- 1 Theo curve + Extra broaden Lorentzian
- Theo curve + Extra broaden Theo curve for Bump, whole data

Difference in the fit result of the different models ?

Story more complex at weak B field: B ~ 20 G

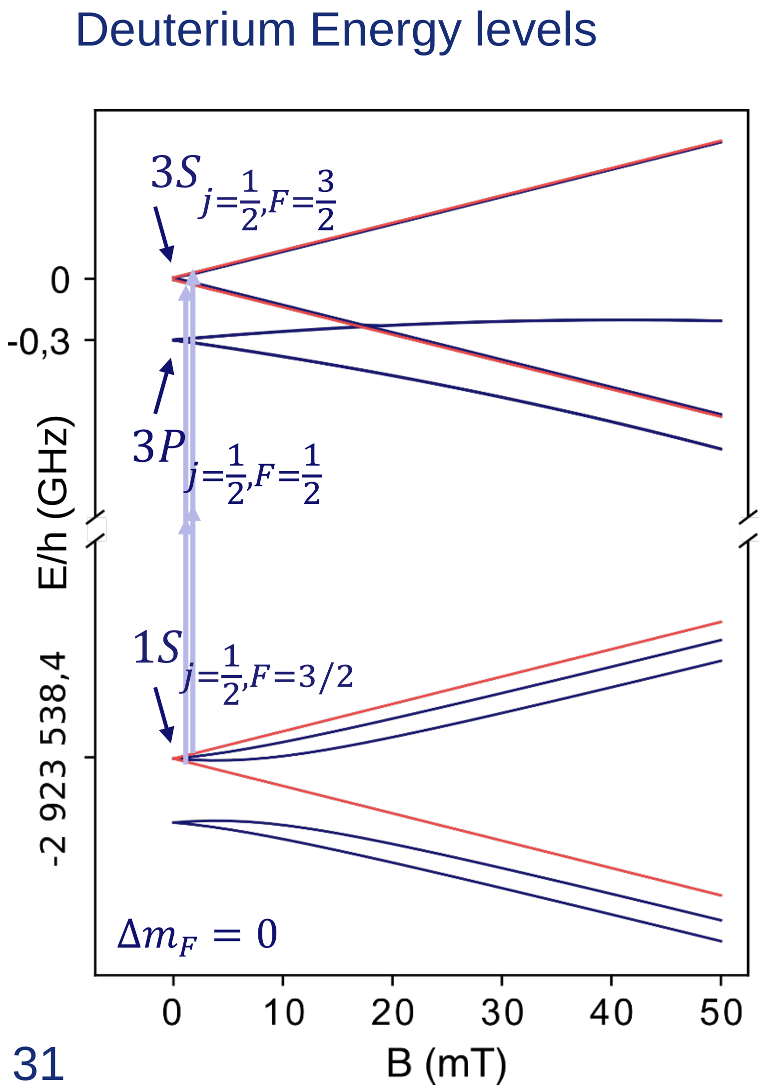
Deuterium Energy levels

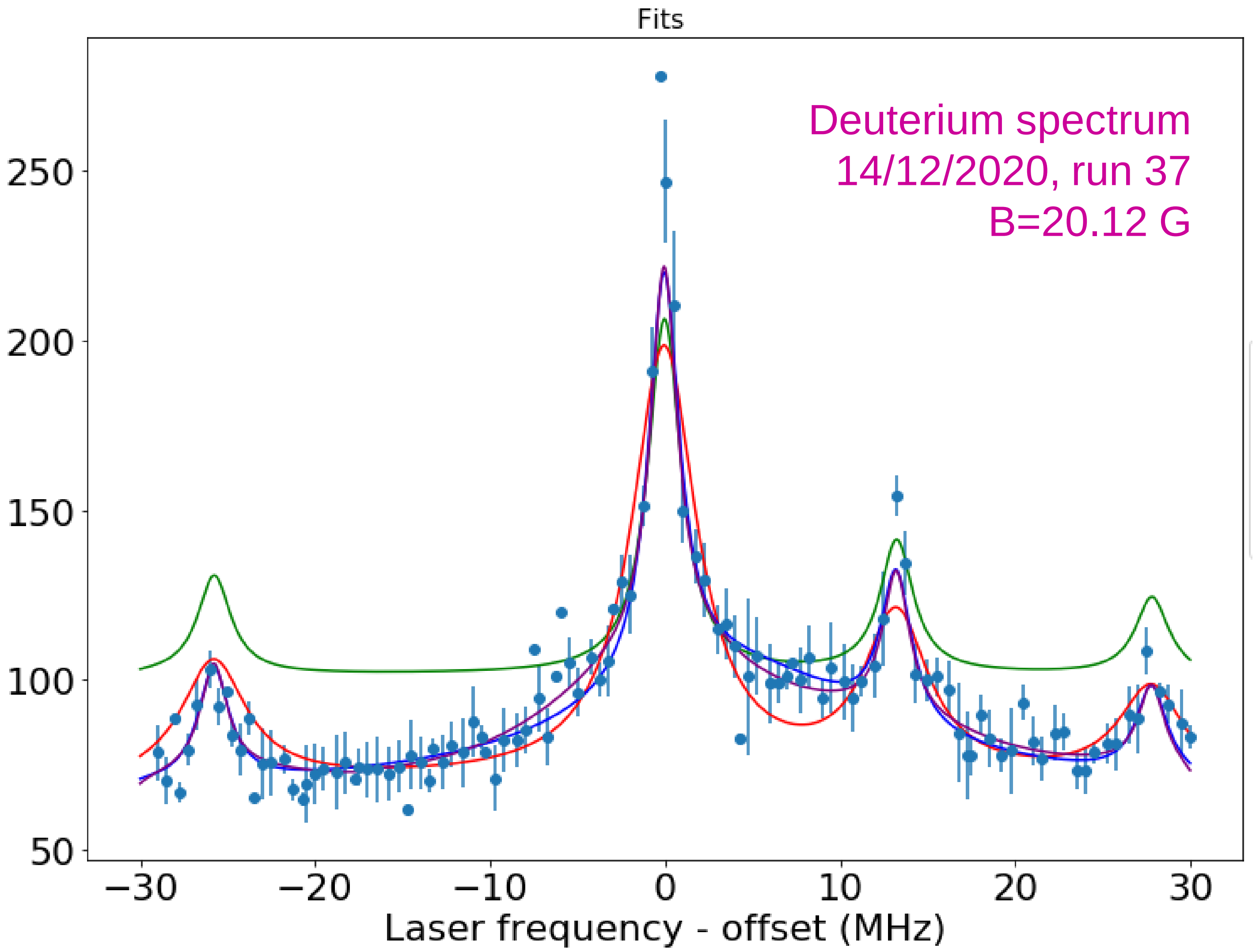




Difference in the fit result of the different models ?

Story more complex at weak B field: B ~ 20 G

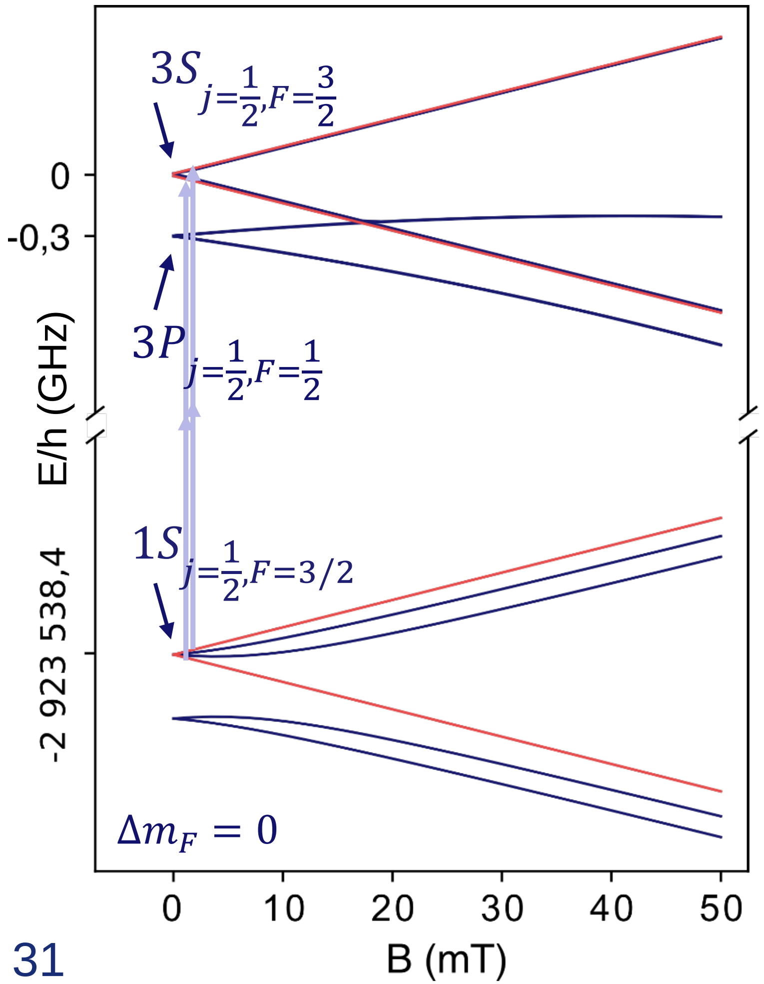


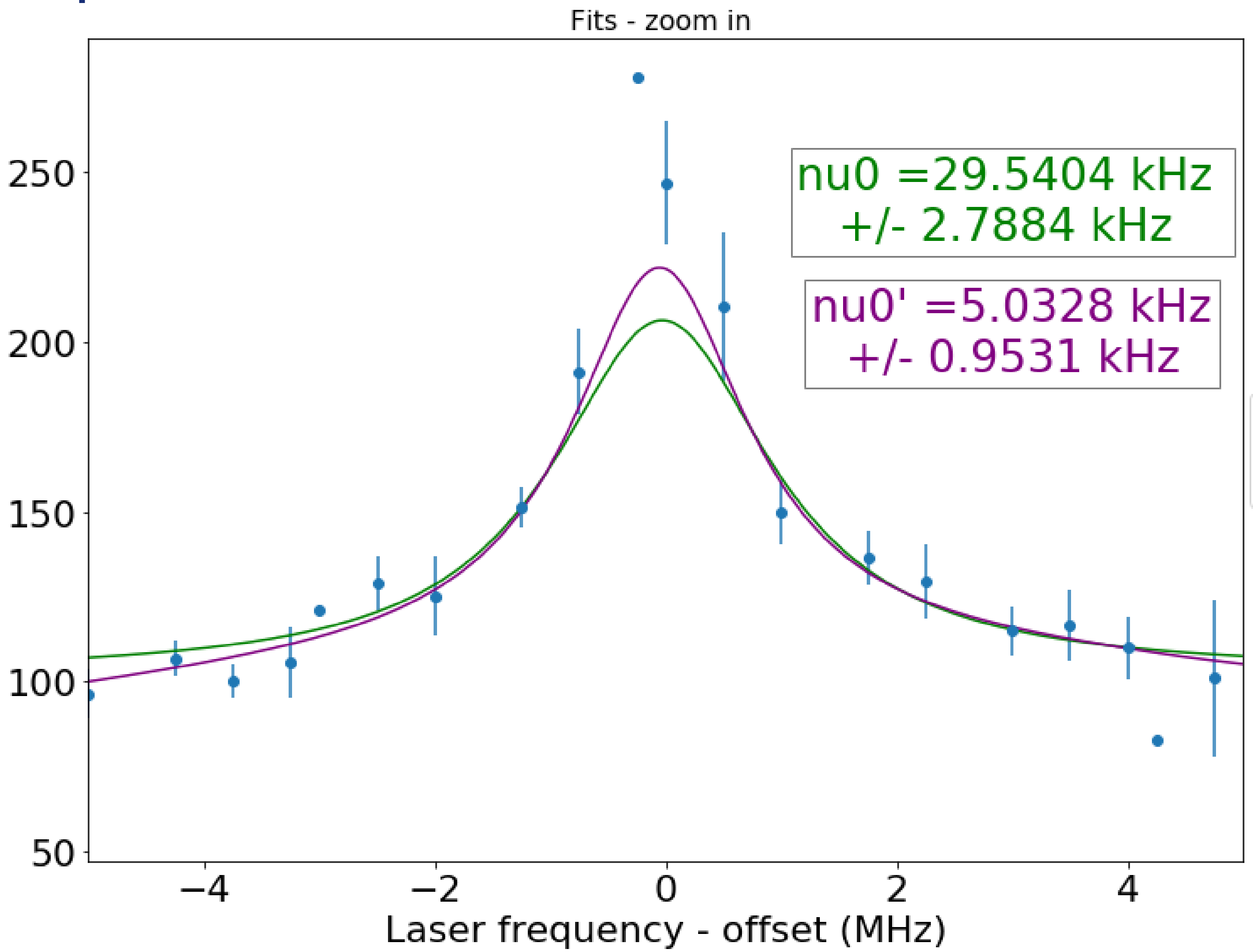


Difference in the fit result of the different models ?

Story more complex at weak B field: like B 20 G

Deuterium Energy levels

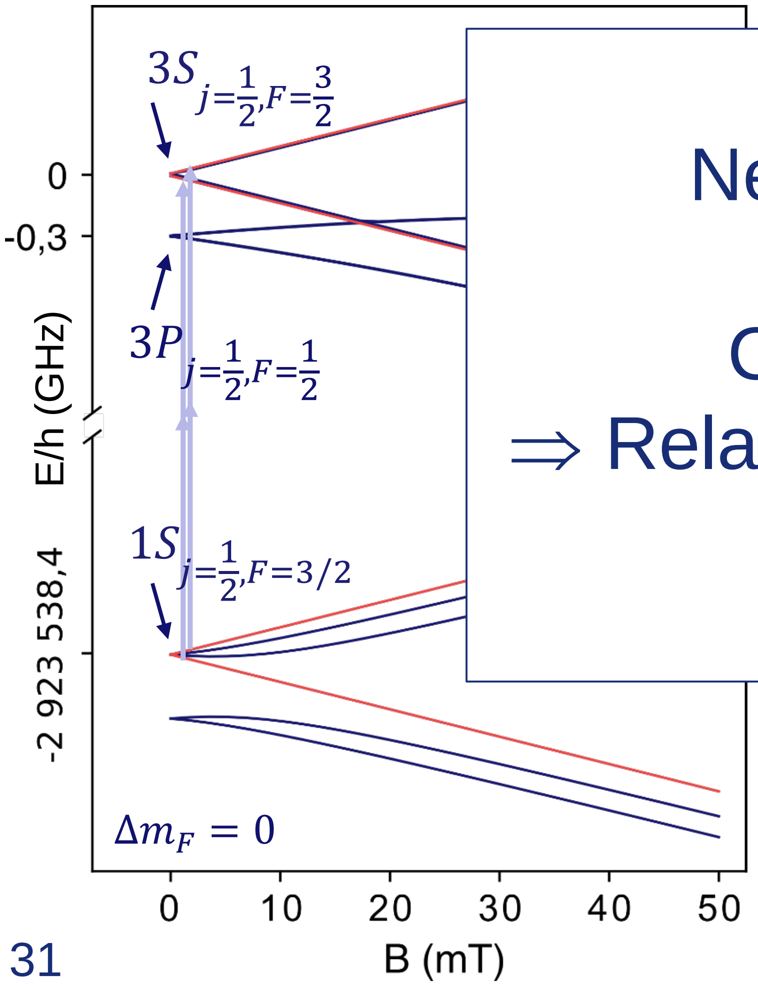


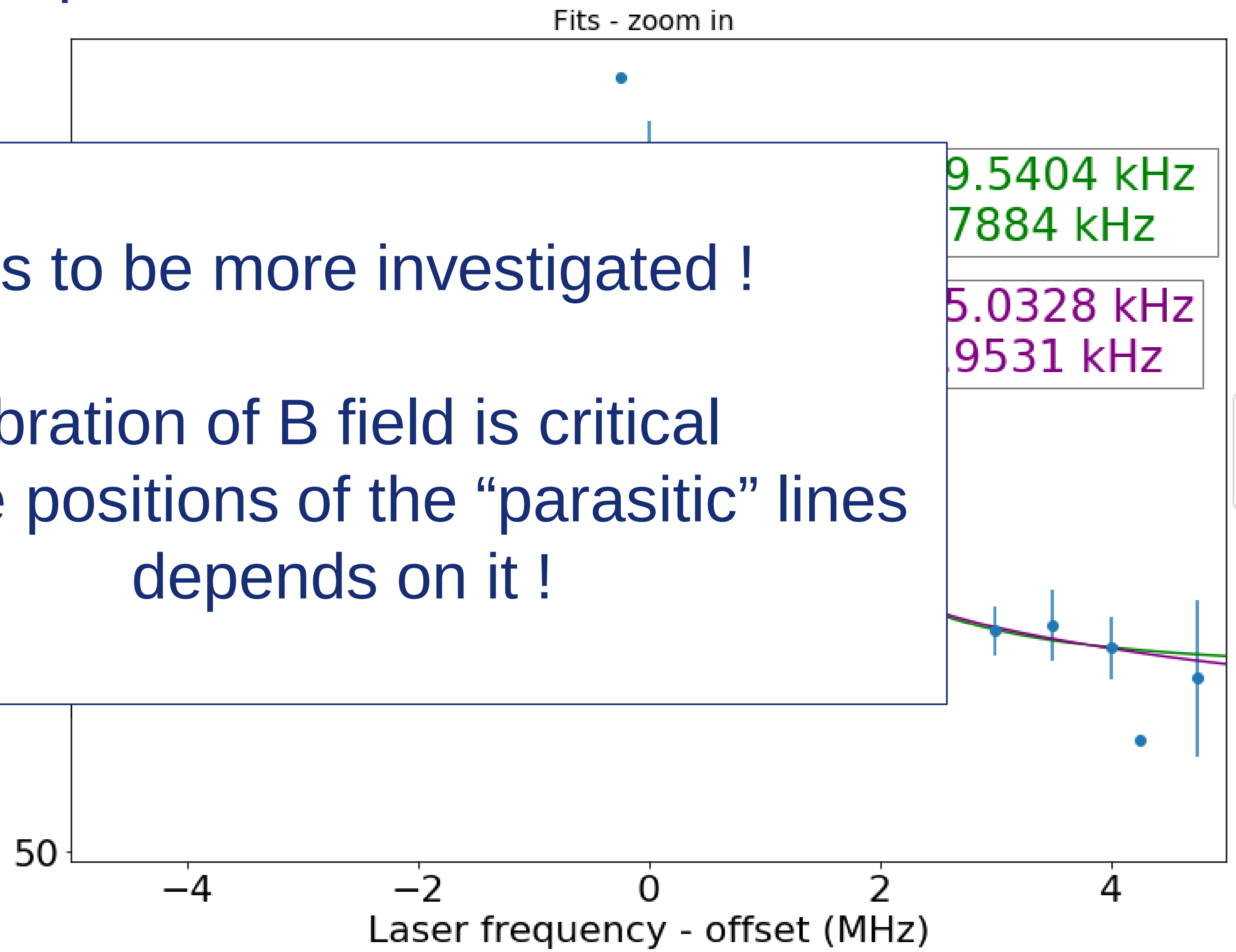


Difference in the fit result of the different models ?

Story more complex at weak B field: like B 20 G

Deuterium Energy levels





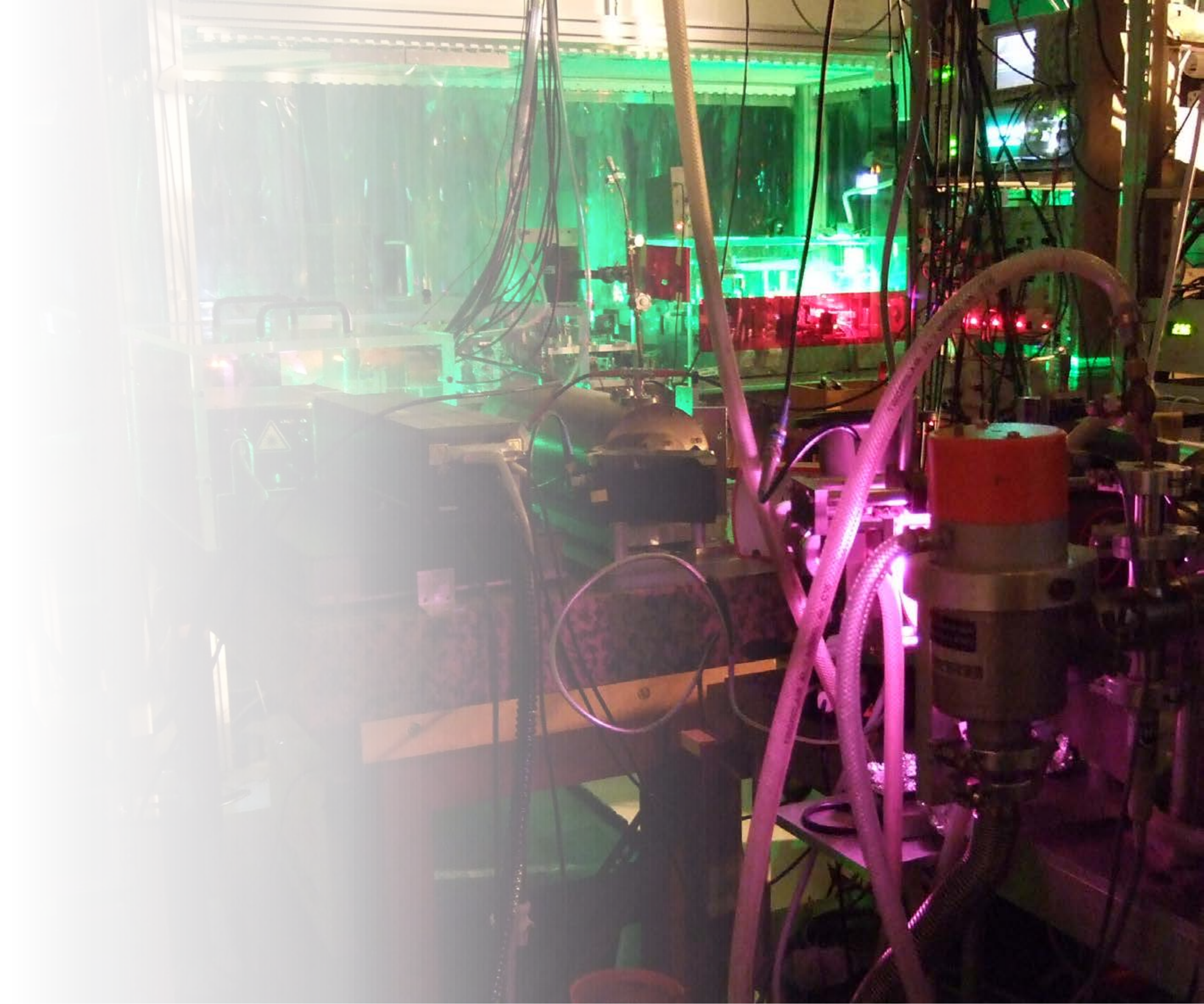
Needs to be more investigated !

Calibration of B field is critical

$\Rightarrow$ Relative positions of the “parasitic” lines depends on it !

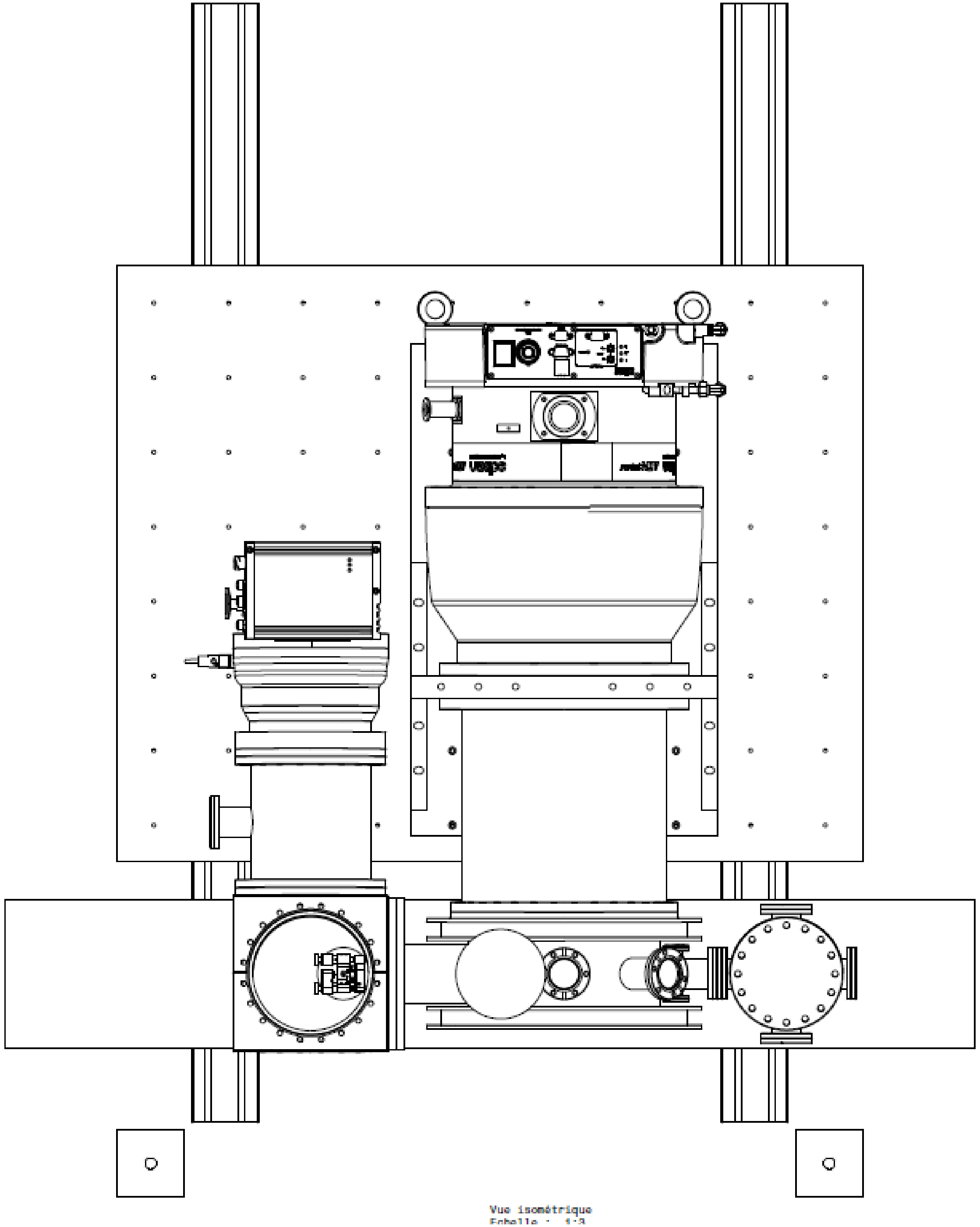
Overview

- 1S-3S Hydrogen spectroscopy
  - The experiment and some of the latest improvements
  - Dealing with systematics
  - A new systematics effect ?
  - What next ?



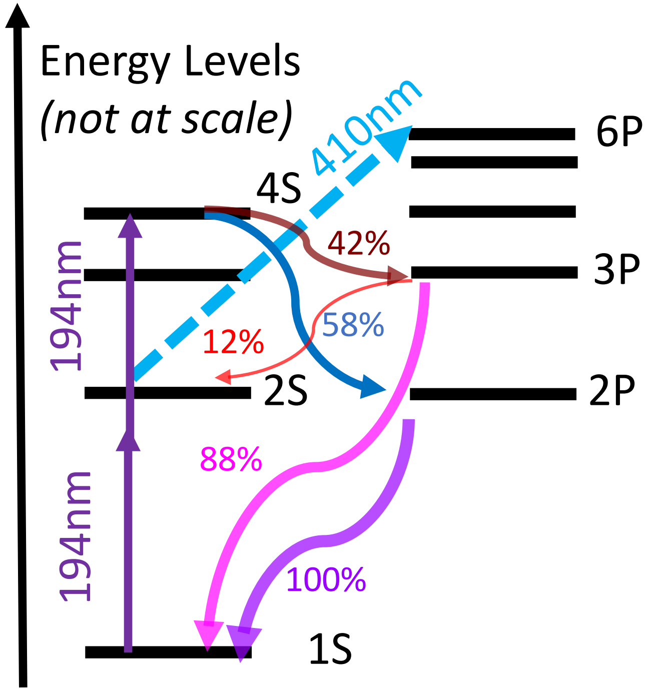
The new H beam experiment

- Based on dry pumps !
- New design to decoupled the mirrors' cavity of the 205nm from the vibrations of the turbo pumps

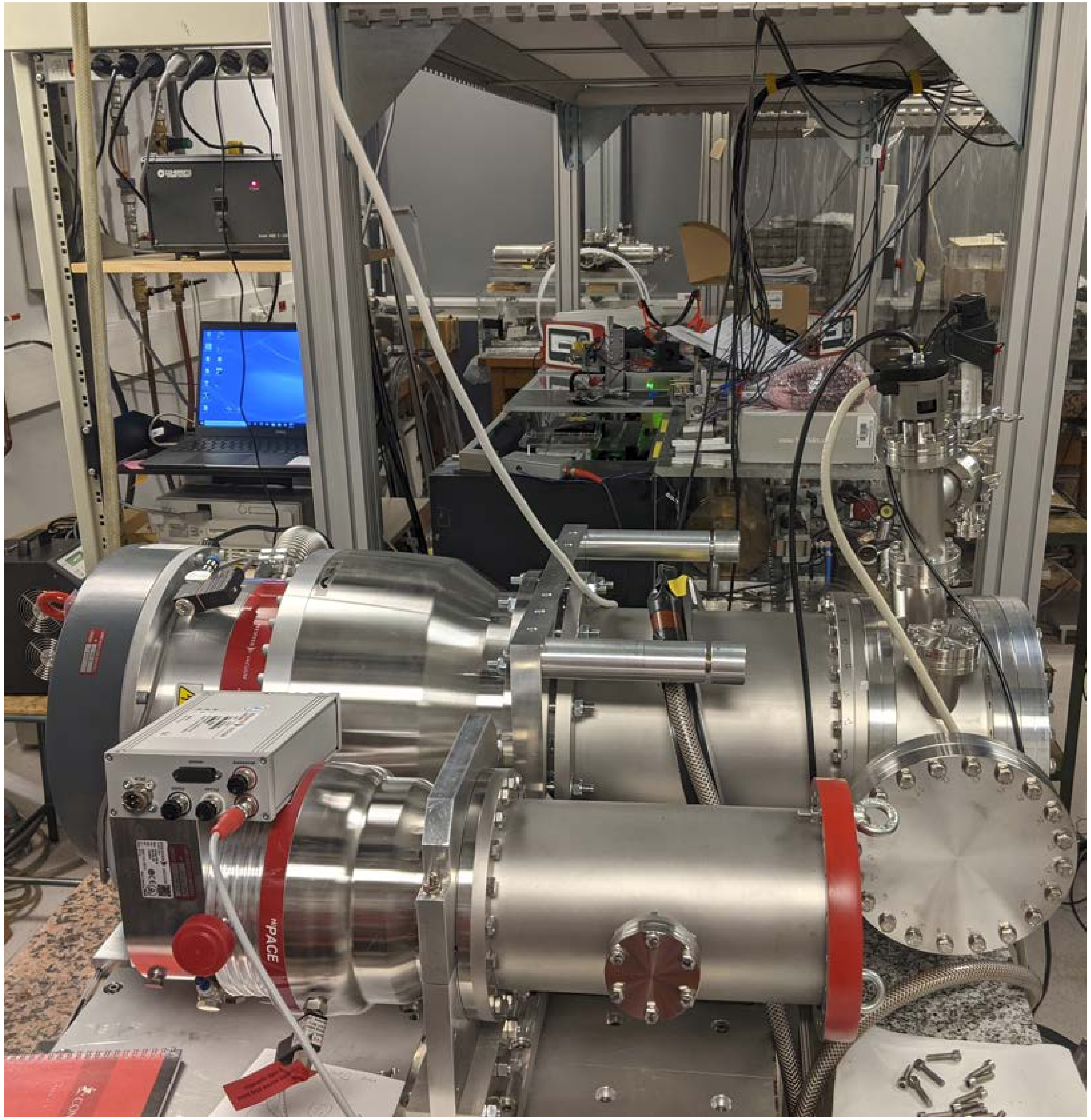


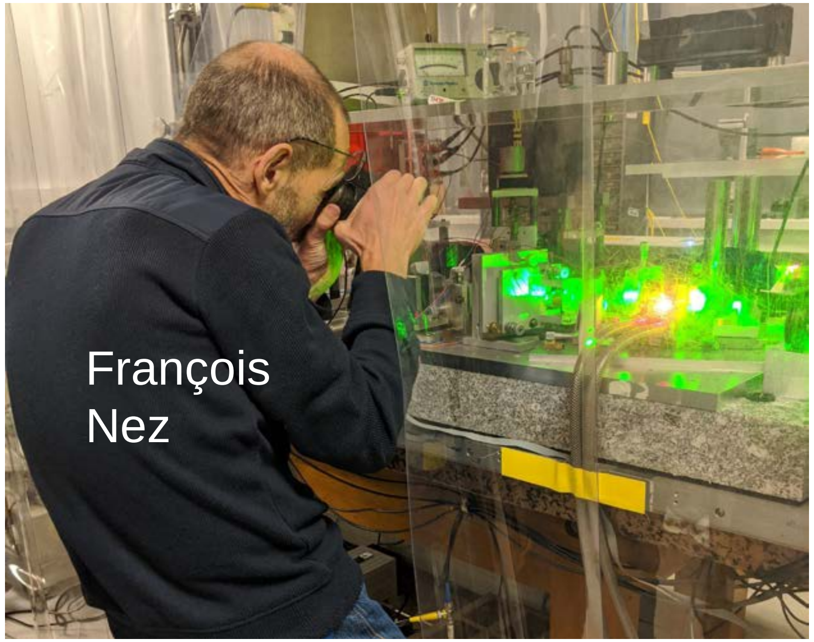
The new H beam experiment

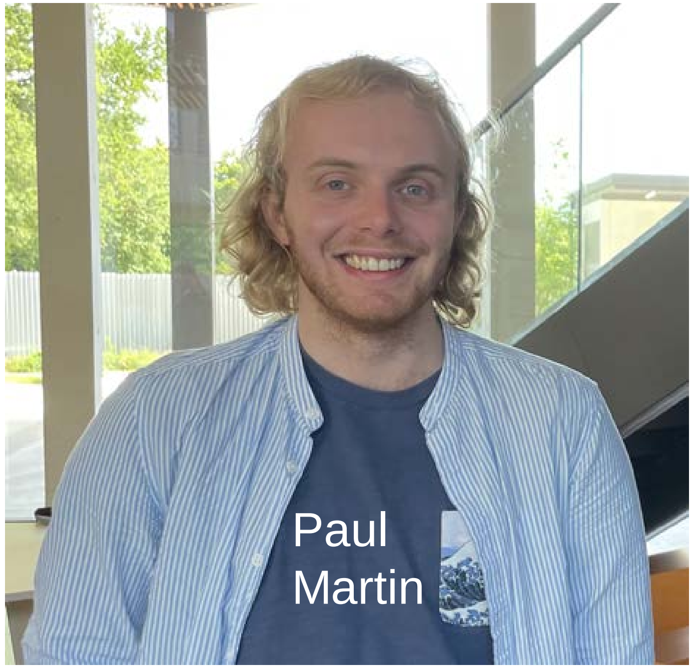
- For 1S-3S then 1S-4S

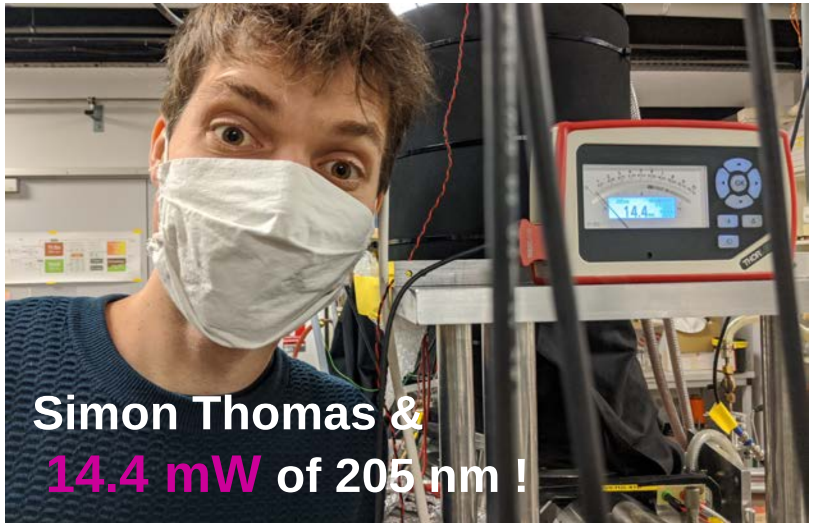


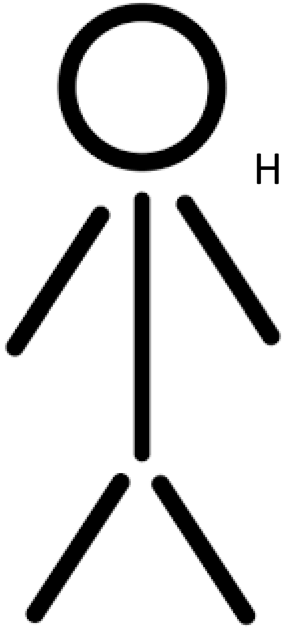
1S-4S spectroscopy











Hugo Tortel

Thanks for your attention