1S-3S CW spectroscopy on deuterium atoms

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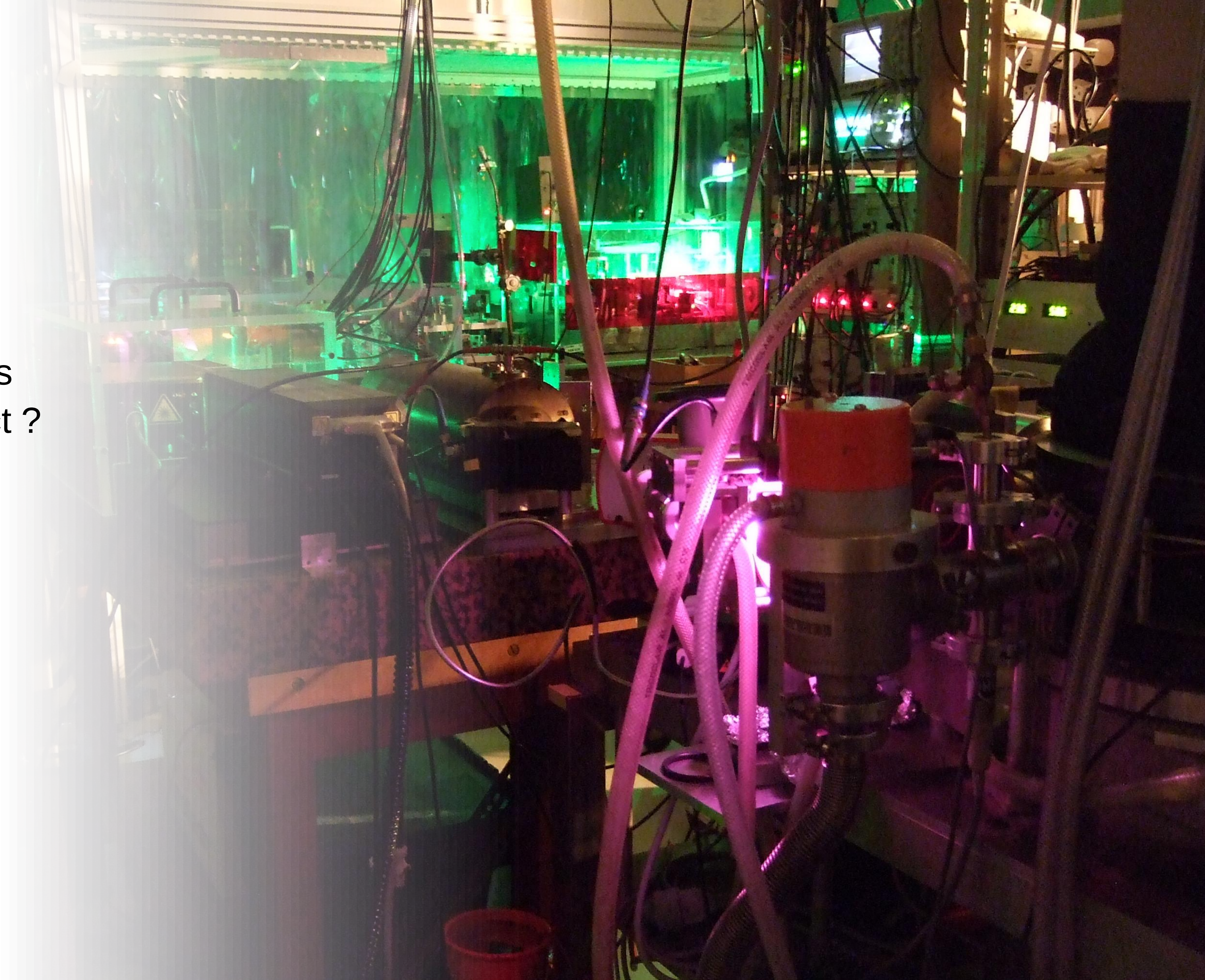
PREN - June 2023

Overview

- The experiment
- Dealing with systematics
- A new systematics effect ?
- Preliminary result ?



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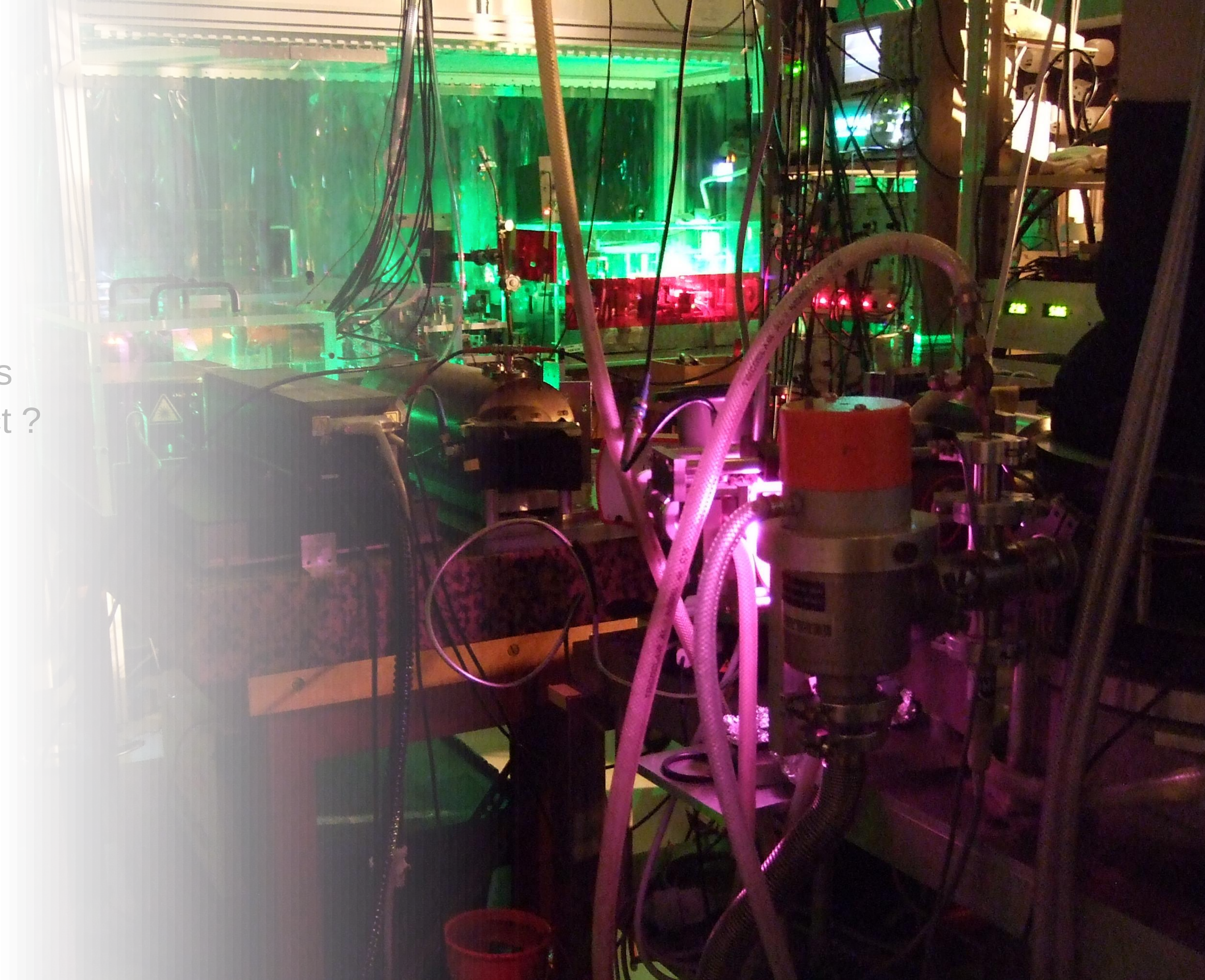
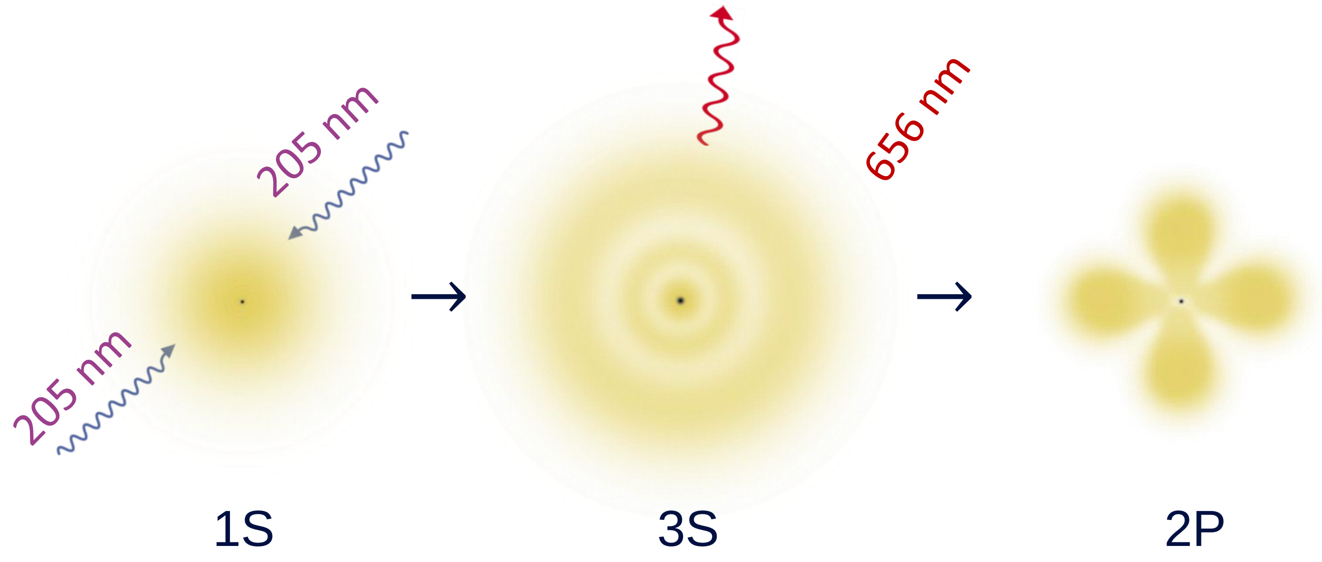
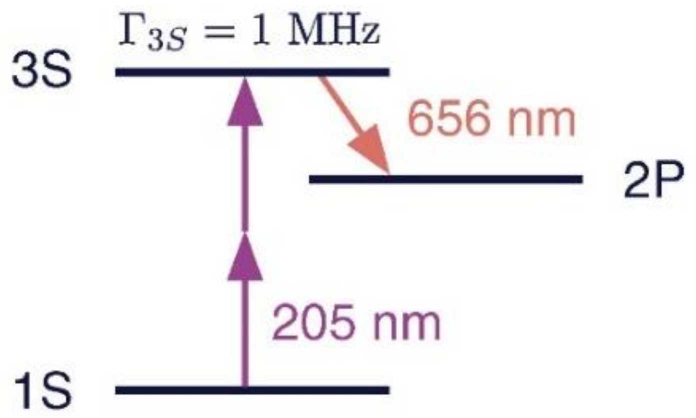
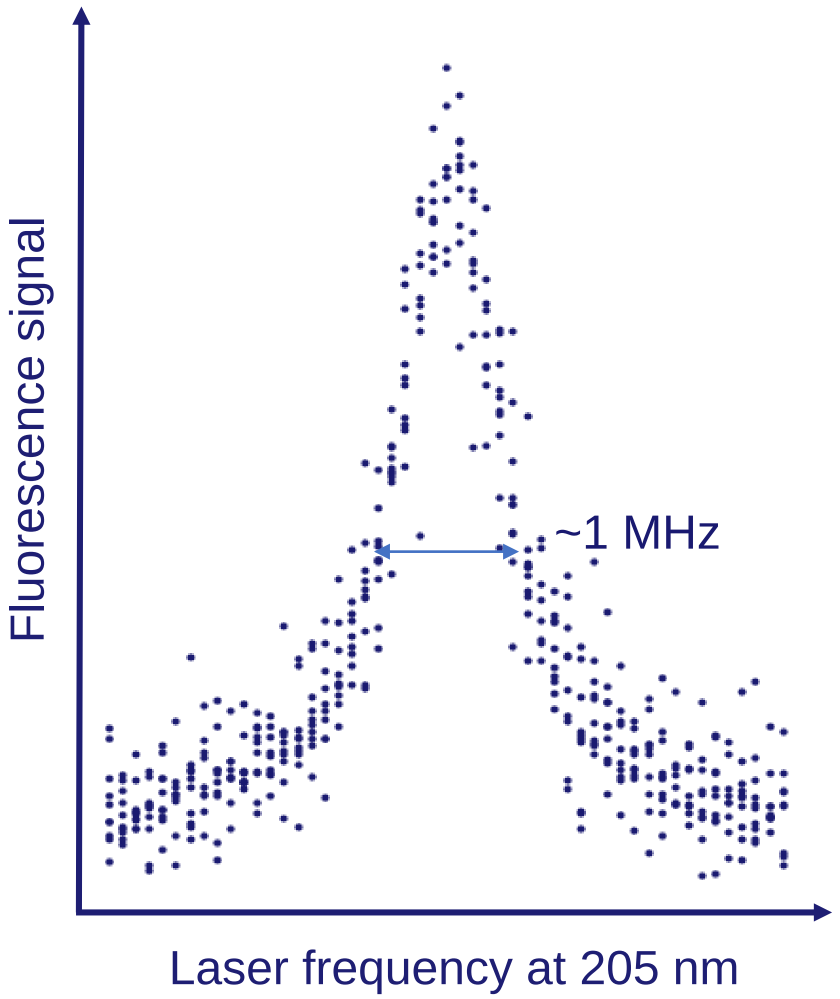


1S–3S Hydrogen CW spectroscopy

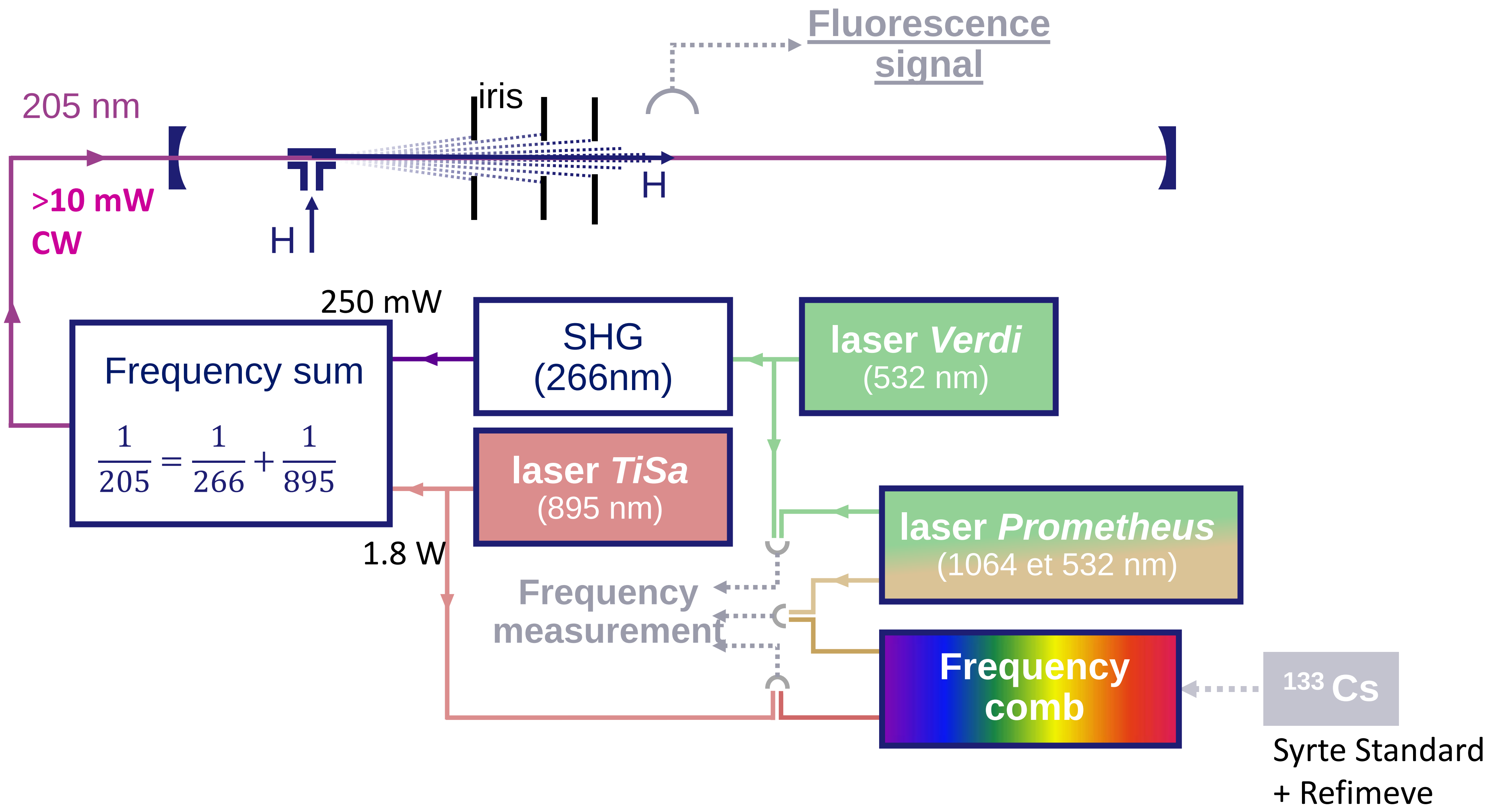






Slide – courtesy of S. Thomas

Overview of the experiment



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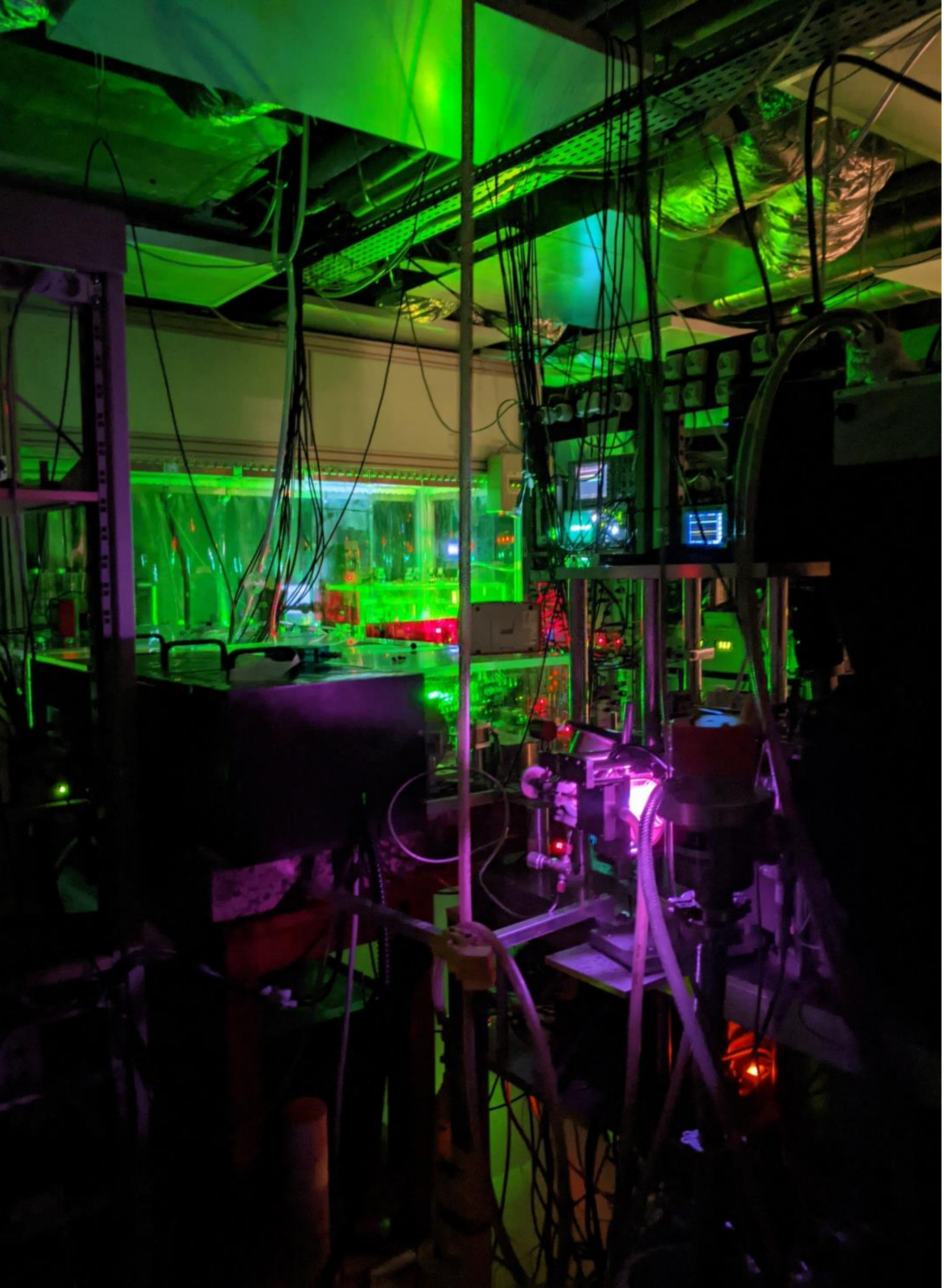

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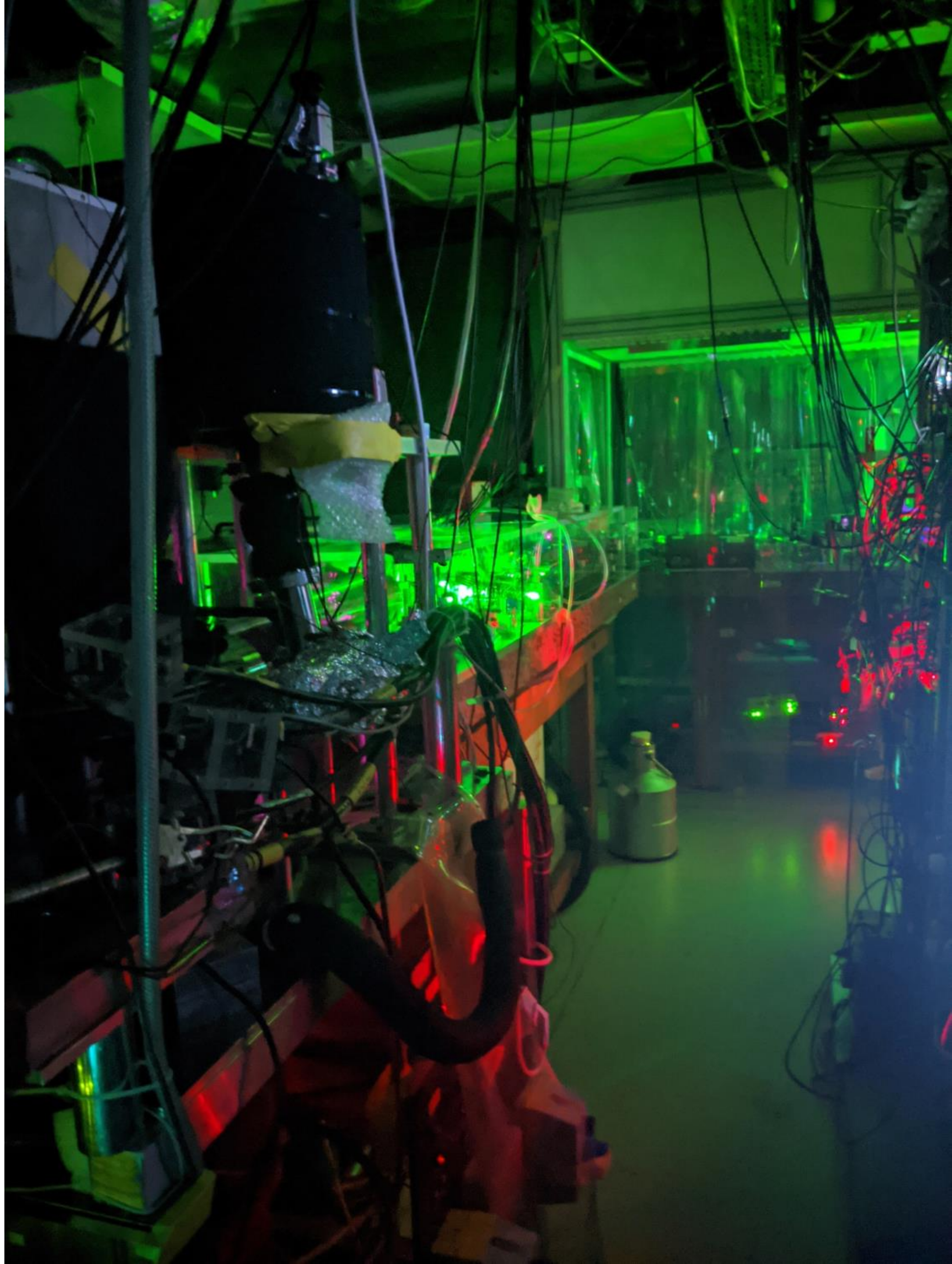

Spectroscopy 1S-3S on Deuterium

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

Based on the 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) ***(new B field at "low" 20G)***
— measurement of the laser intensity (AC. Stark shift estimation)

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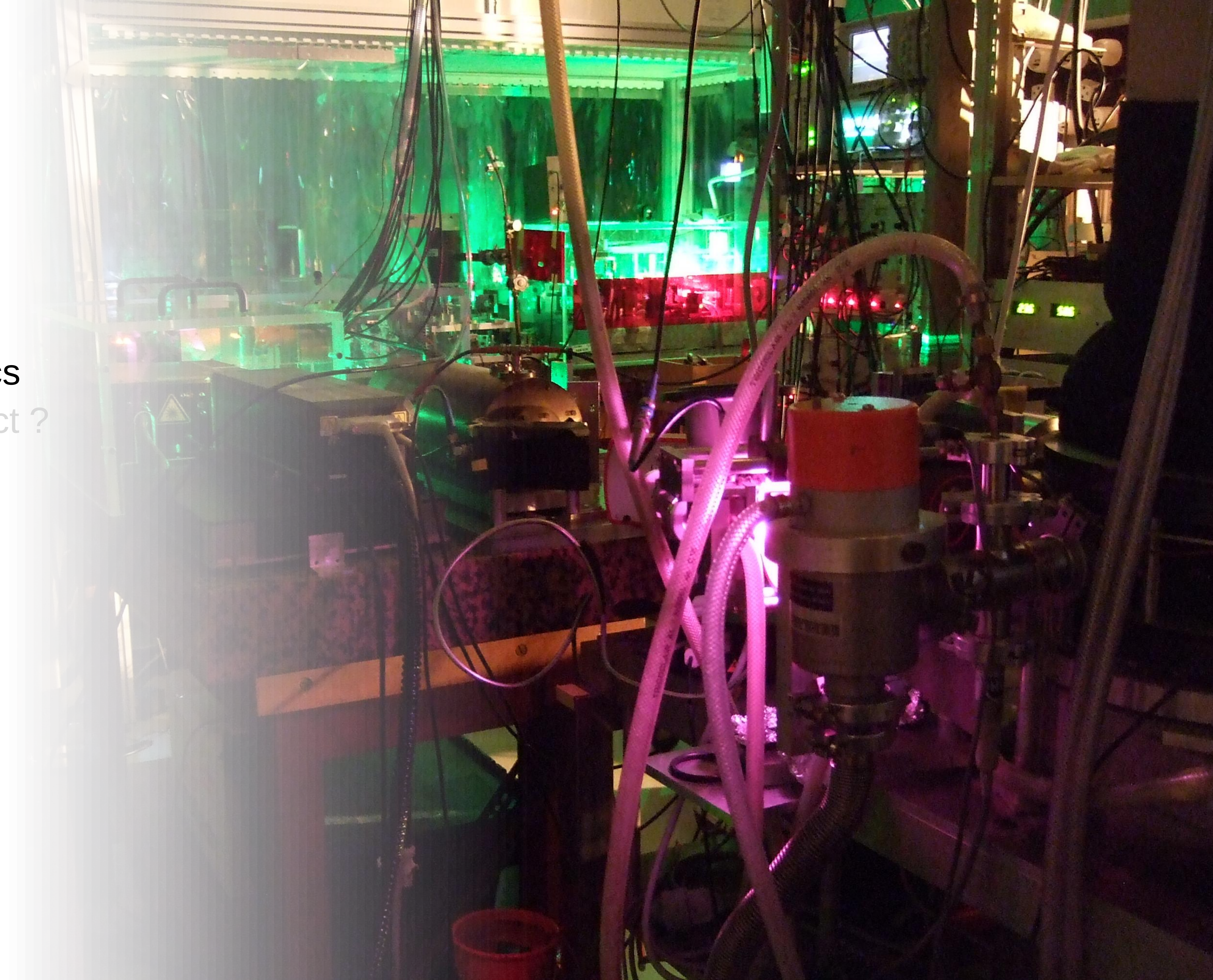


Dealing with systematics …

1S - 3S spectroscopy on electronic Deuterium:

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

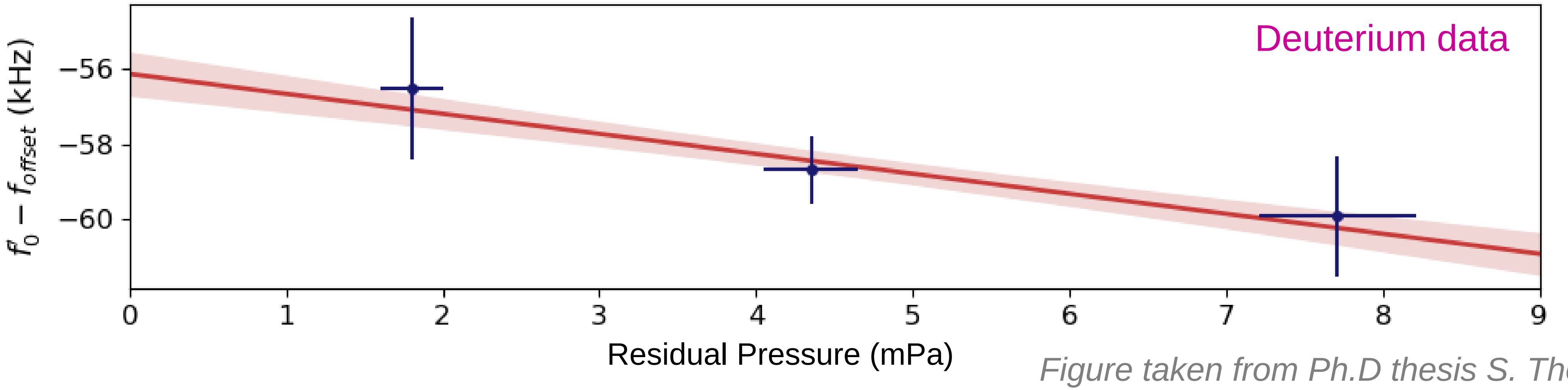


Figure taken from Ph.D thesis S. Thomas (2021)

$$f_0' - f_{offset} = -0,527\,(344) \times P_f$$

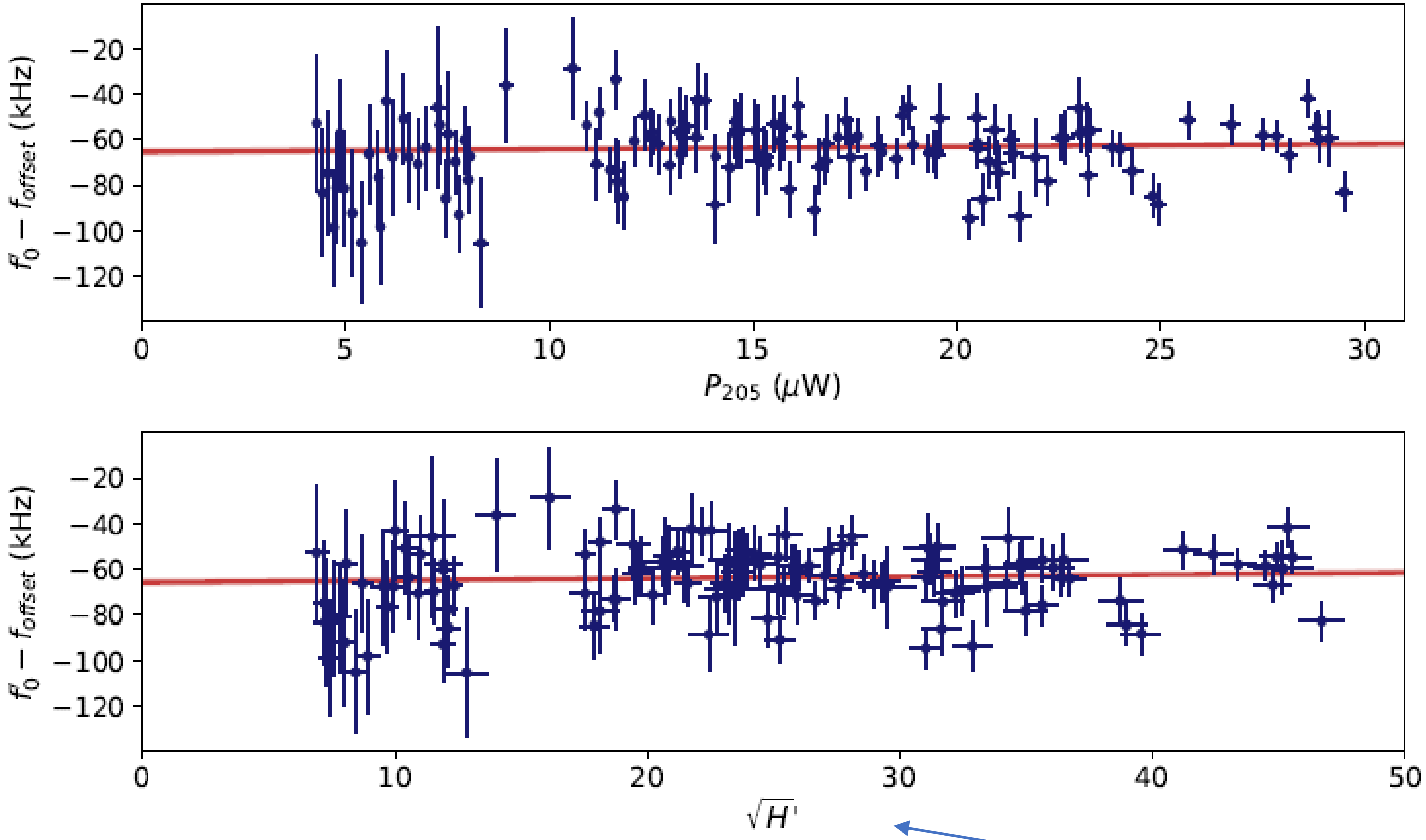
kHz/mPa

Pressure inside the vacuum chamber (mPa)

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



Deuterium data

$$f_0' - f_{offset} = 0,115\,(176) \times P_{205}$$

kHz/µW

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

$$f_0' - f_{offset} = 0,088\,(112) \times \sqrt{H'}$$

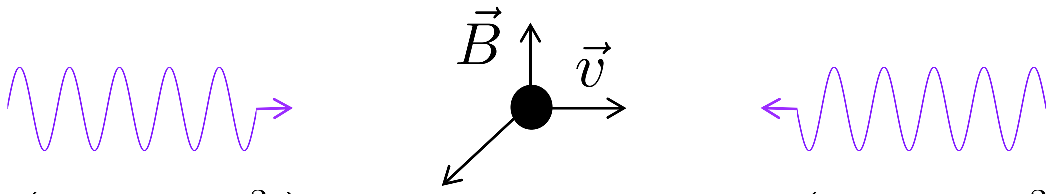
kHz/$\sqrt{counts/s}$

Height of the signal (counts/s)

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

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

2sd Order Doppler effect frequency shift



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

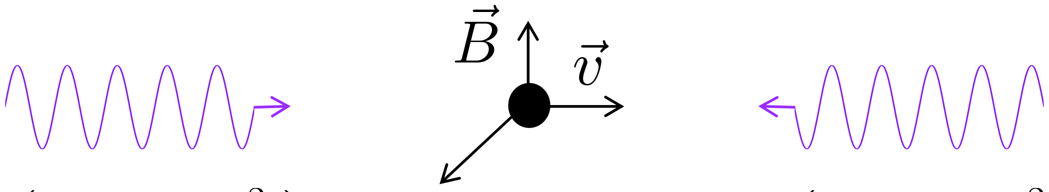
$$\boxed{\delta^{(2)}_{Doppler} = -\nu_{at}\frac{v^2}{2c^2}}$$

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

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

2^{sd} Order Doppler effect

Compensating it ?



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

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

Idea principle: inducing a Motional Stark effect $\boxed{\delta_{Stark} = \frac{E^2}{\Delta\nu_{SP}} = \frac{v^2B^2}{\Delta\nu_{SP}}}$

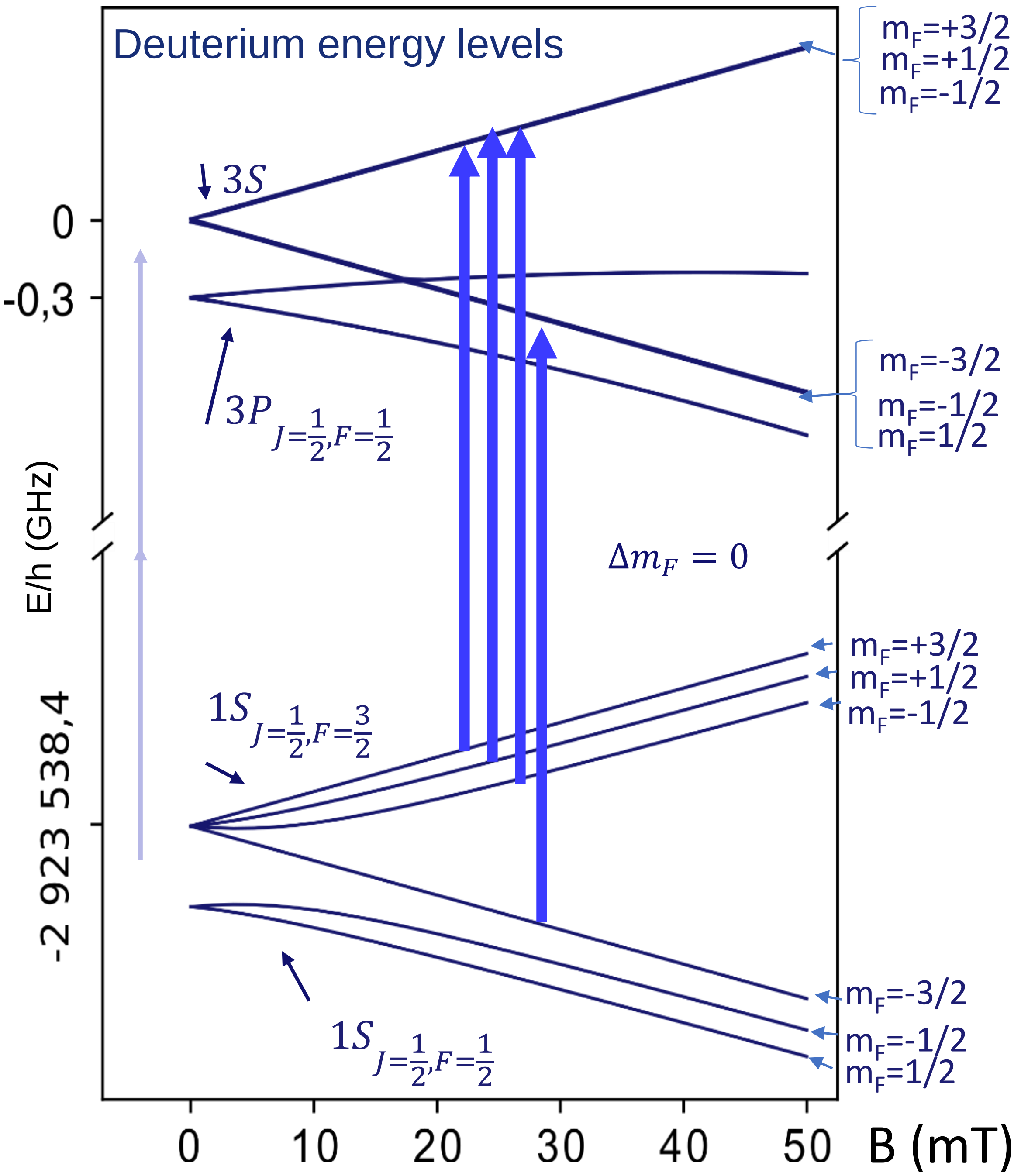
To compensate 2^{nd} order Doppler

2^{sd} Order Doppler effect

Avoiding it ?

Let's zoom in hyperfine structure

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



2sd Order Doppler effect

Avoiding it ?

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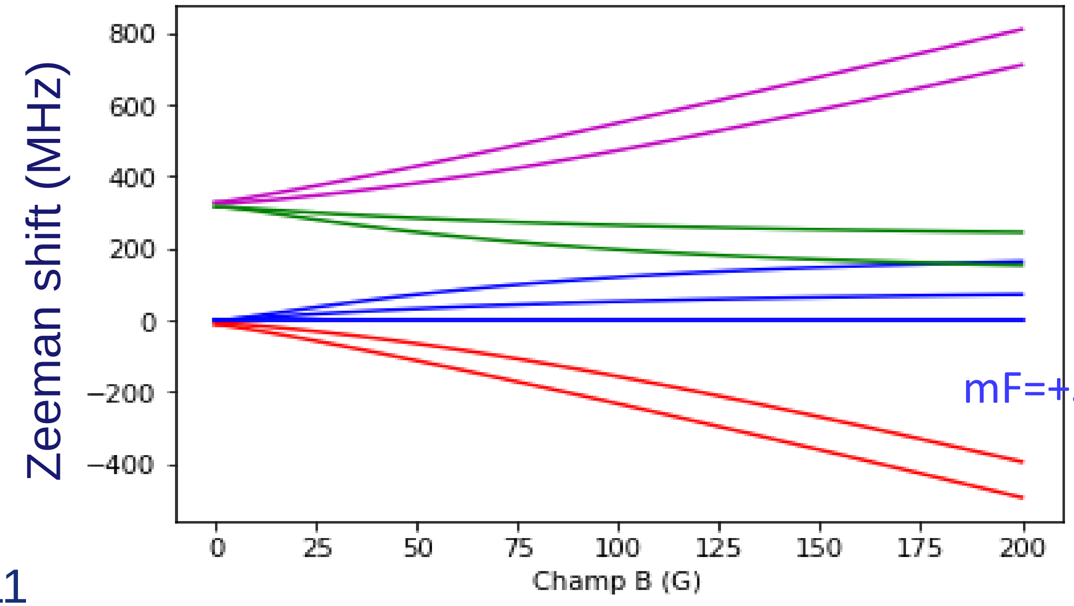
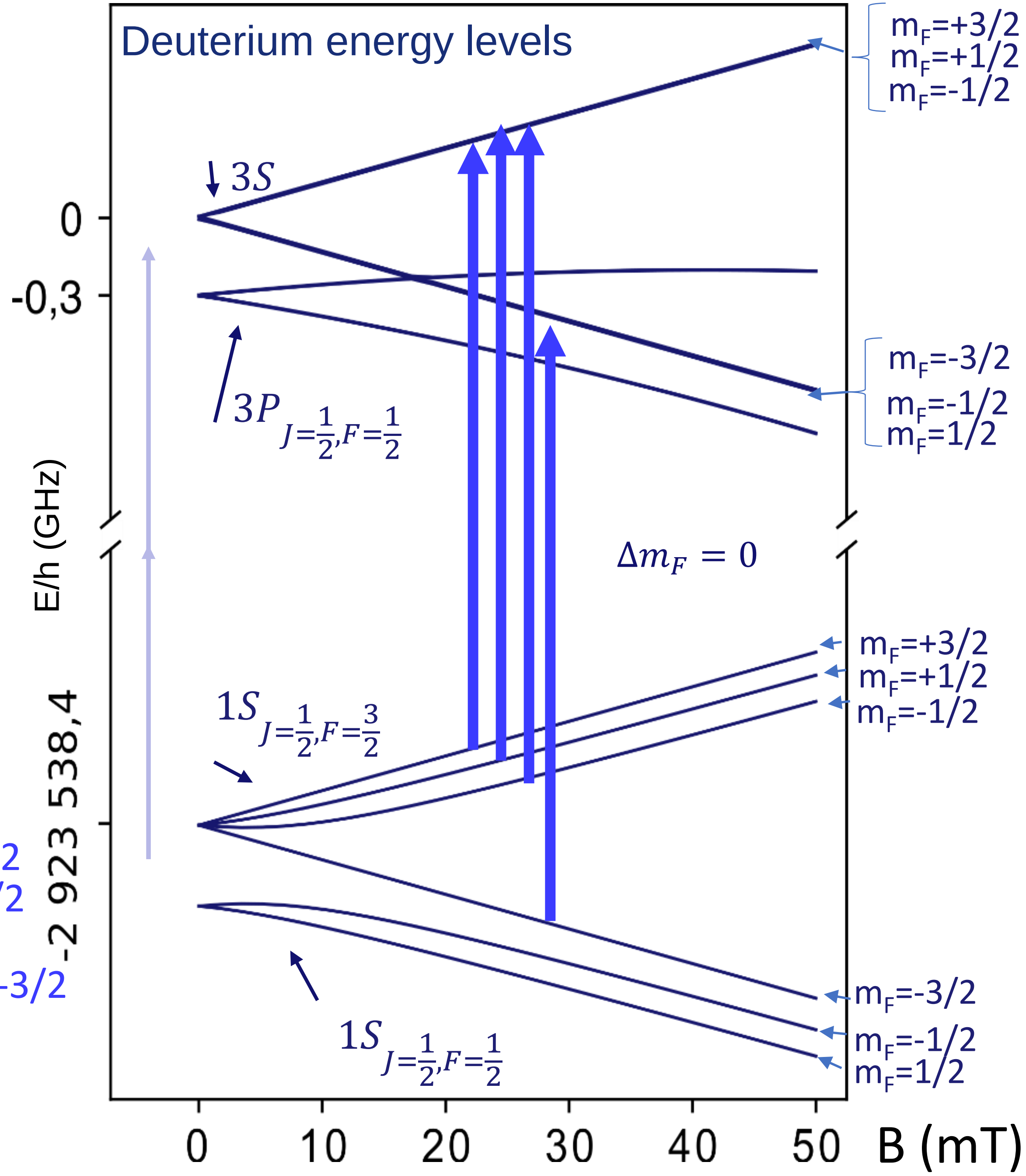
Transitions 1S F=3/2 ⇔ 3S F=3/2

Position of the 1S-3S transitions lines ($\Delta mF = 0$)





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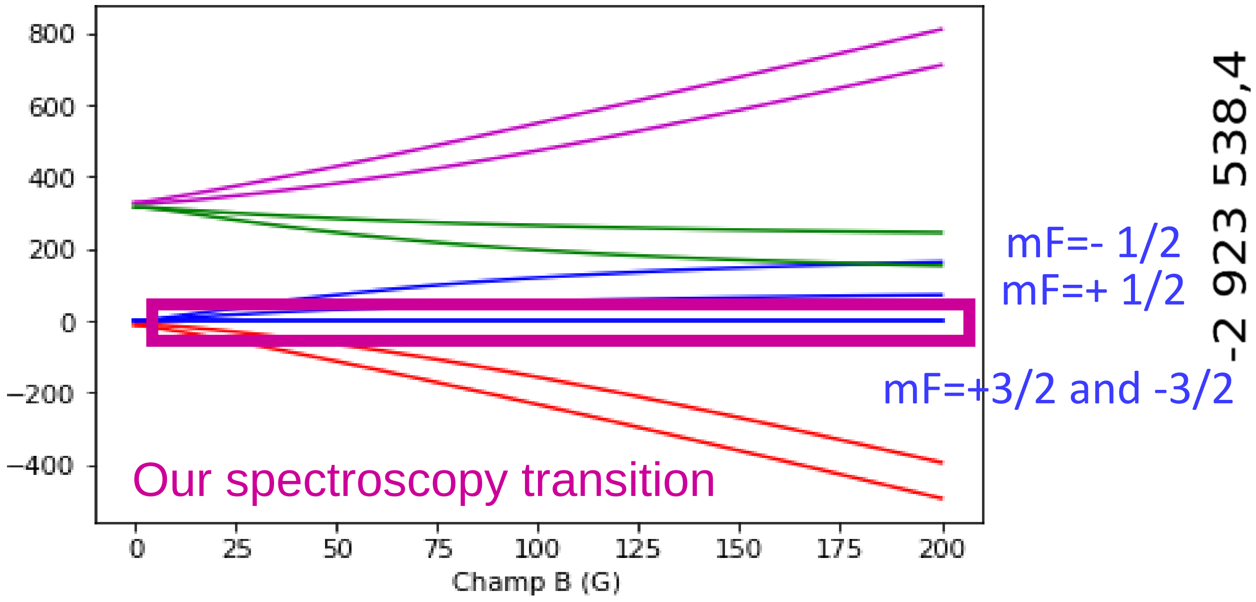

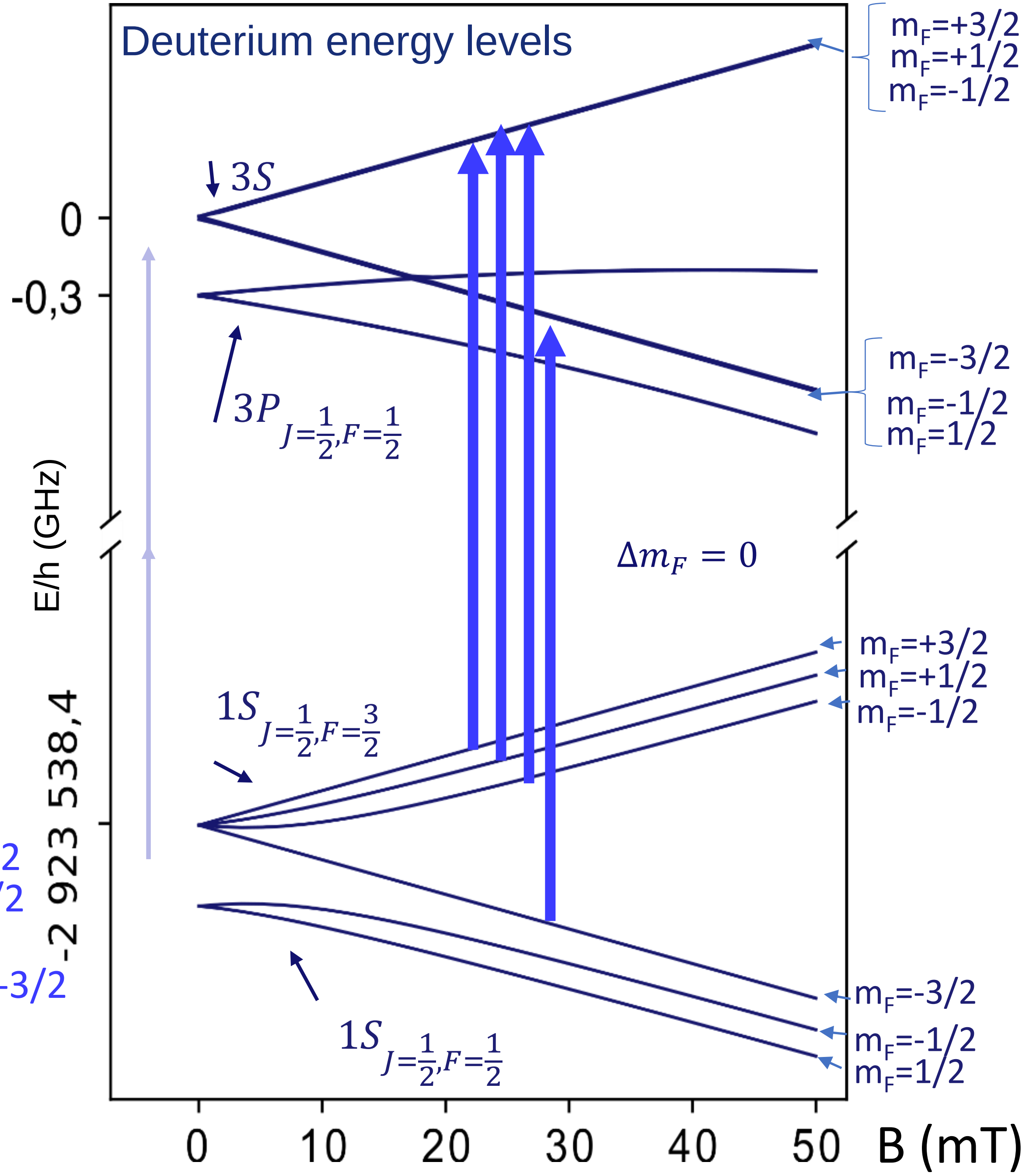

2^{sd} Order Doppler effect

Avoiding it ?

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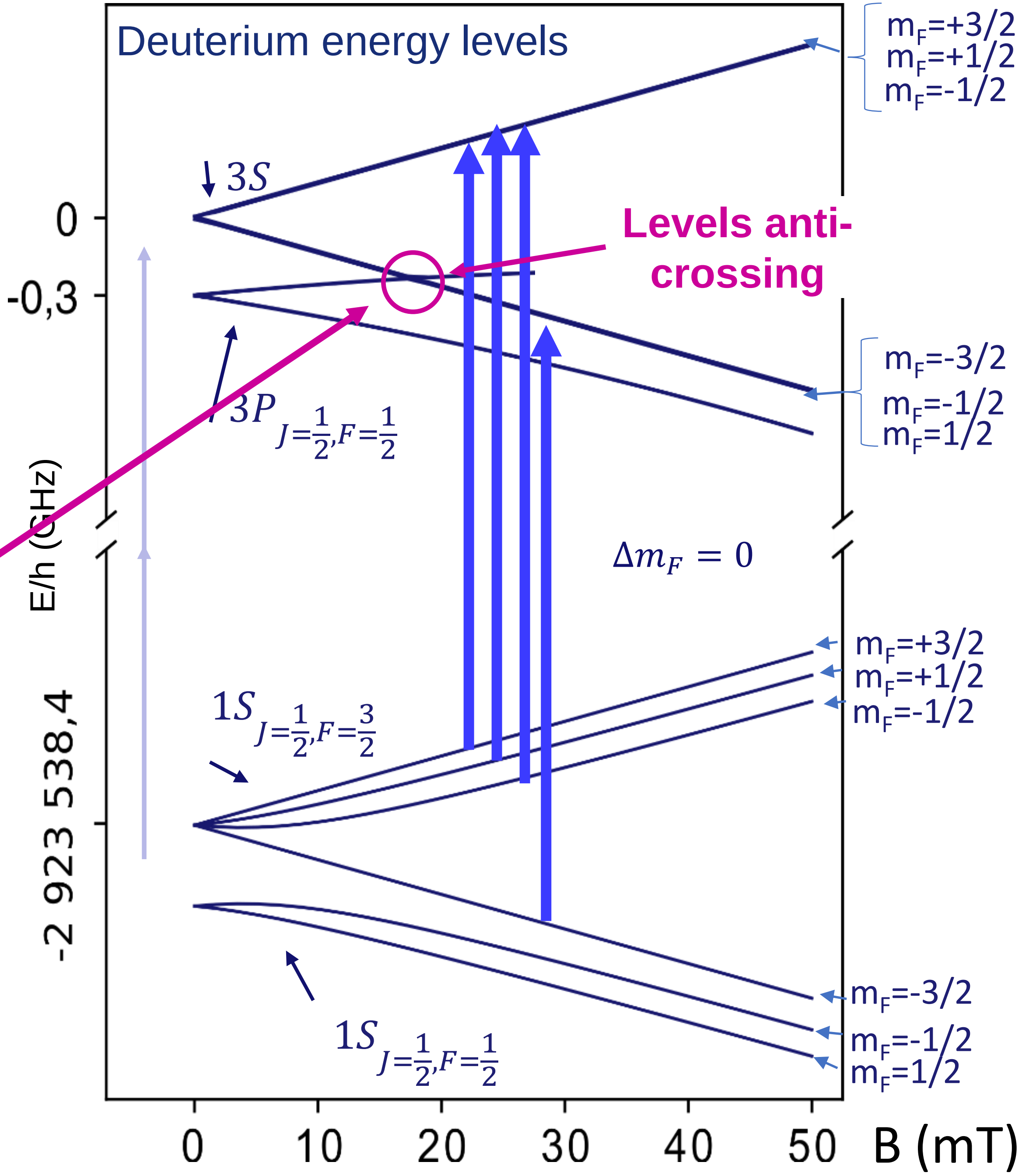
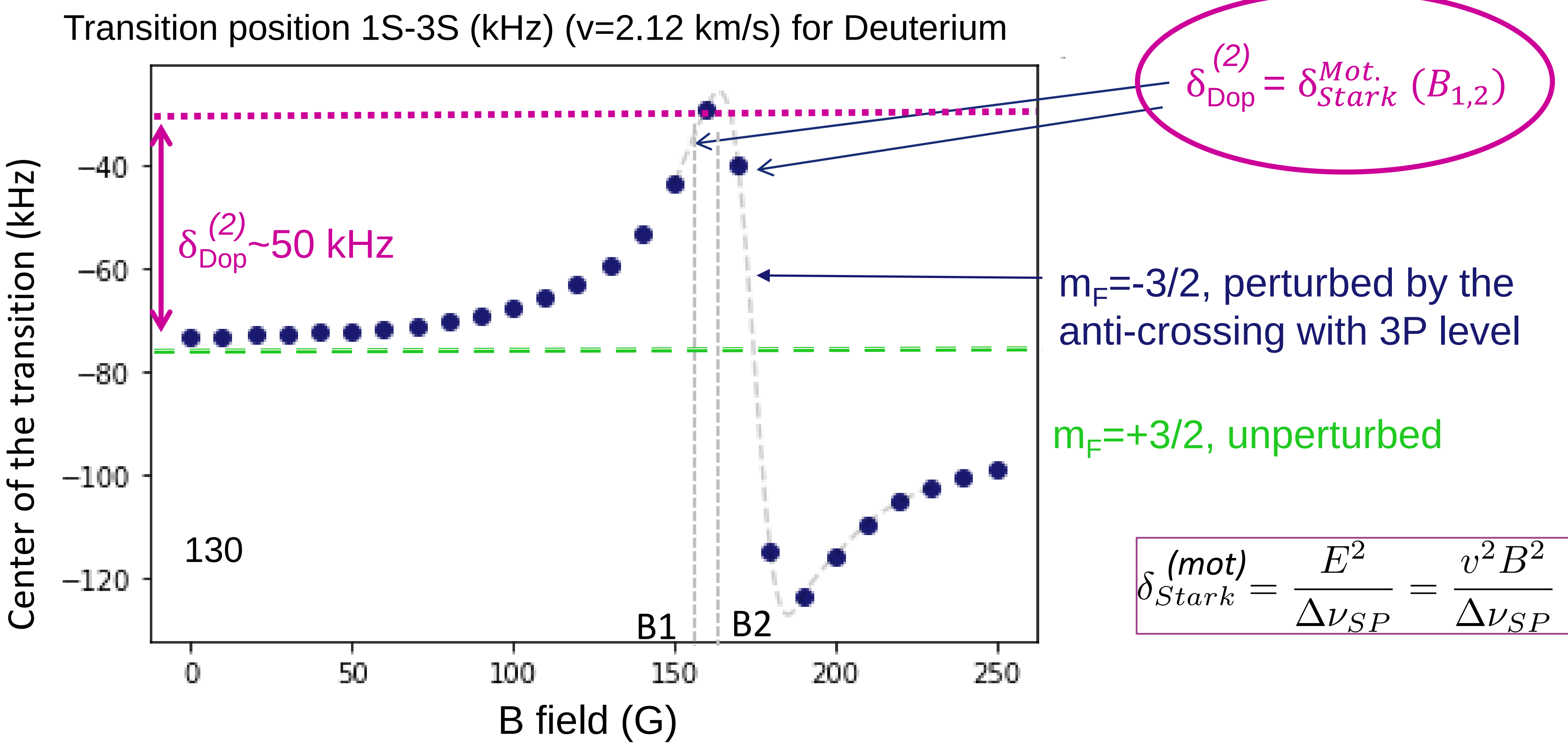
Transitions 1S F=3/2 ⇔ 3S F=3/2

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

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



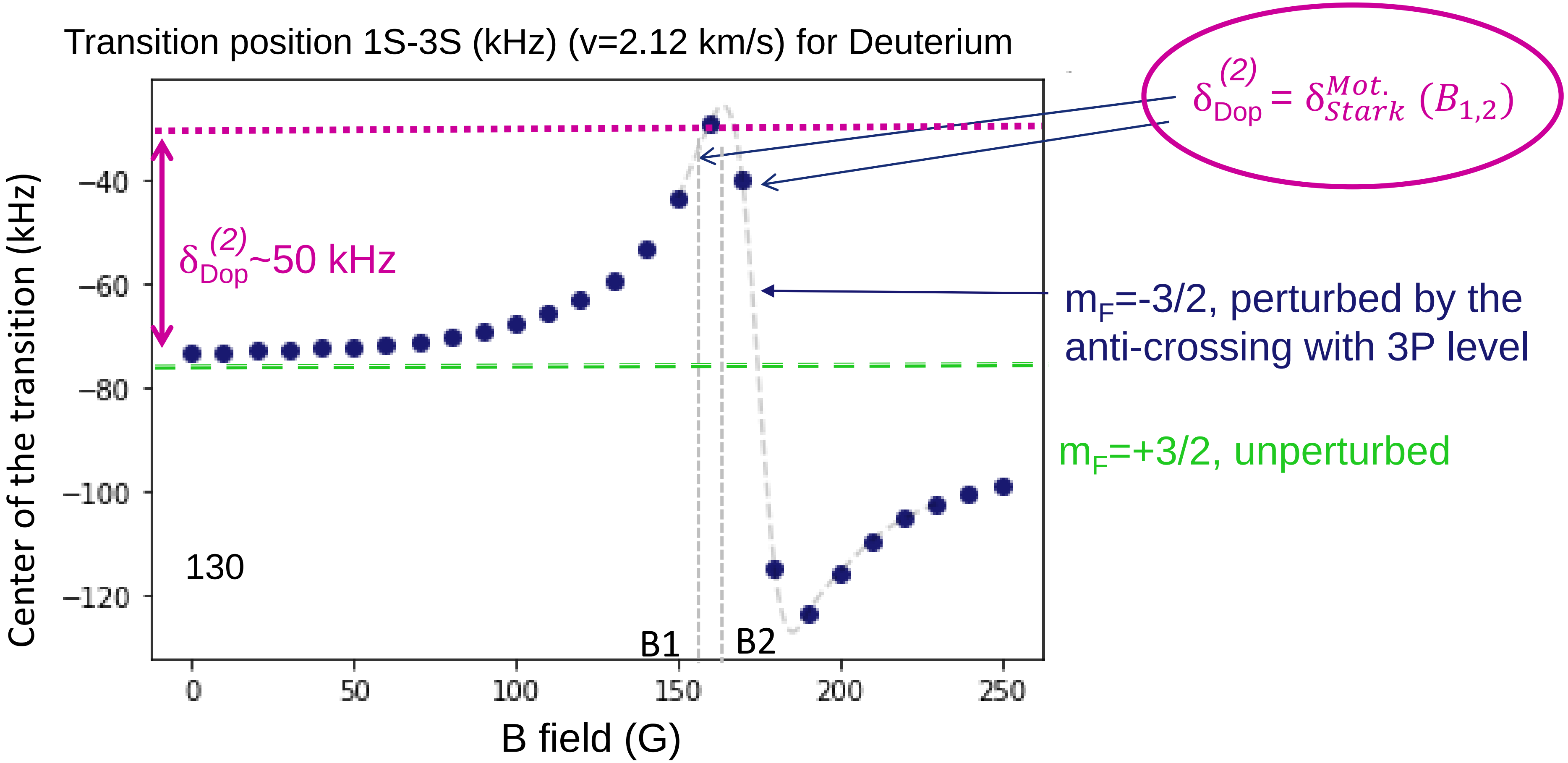
Avoiding 2nd order Doppler effect



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

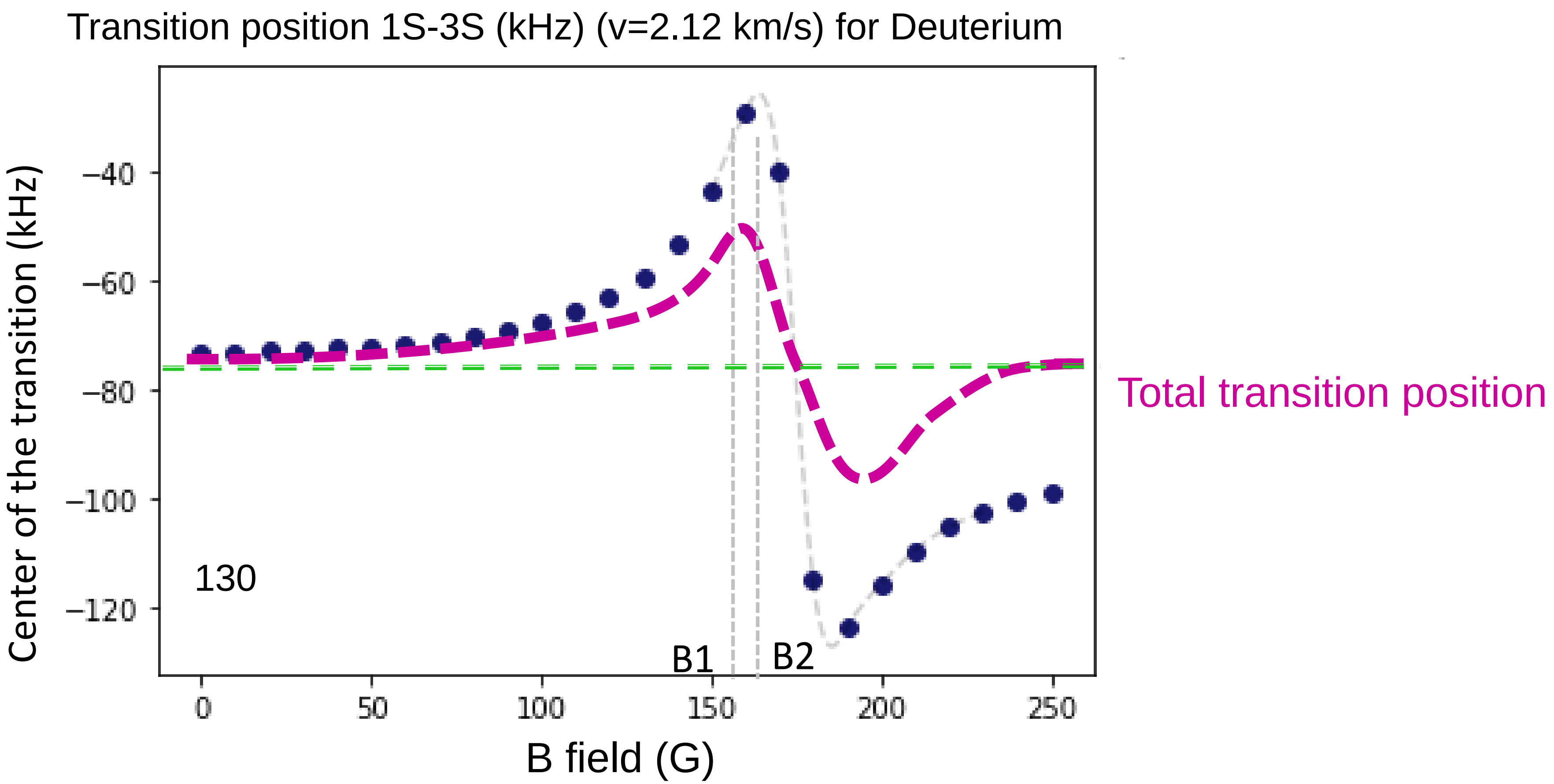
- *Total compensation of 2sd Ord. Doppler for B = B1 and B2 for mF=-3/2 transition*

Avoiding 2nd order Doppler effect



- *Total compensation of 2sd Ord. Doppler for B = B1 and B2 for mF=-3/2 transition*
- For v= 2.3 km/s: the transitions m_F=-3/2 and m_F=3/2 are split by ~50 kHz for B = B1 and B2.
- The 3S natural bandwith ~1 MHz ⇒ **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 (« pink» profile)

Examples of fits to extract the best velocity distribution

Our theoretical fluorescence lines: take into account:

- Zeeman, Motional Stark, 2^{sd} Doppler effects
- Integrated over all the velocity distribution.

Fits give the “zero field” frequency *(corrected from the above shifts)*

The theoretical lines depend on:

- B field
- Velocity distribution of the H beam (2 parameters to model it)

Protocol: it our data sets for each recorded B field, with various velocity distribution parameters.

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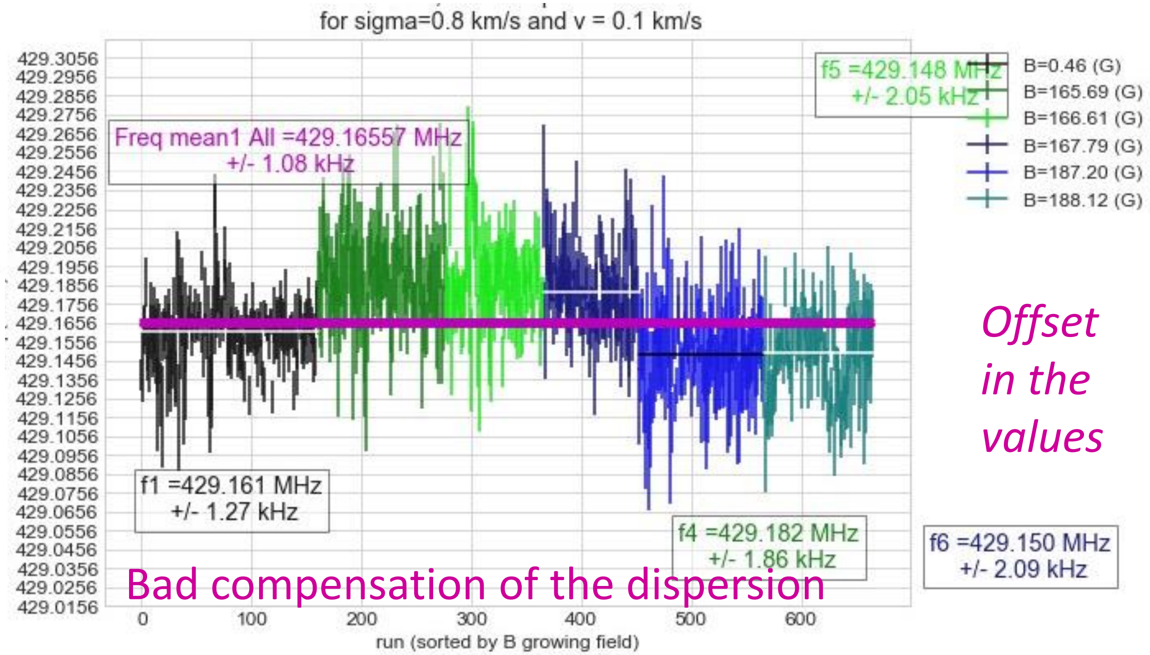

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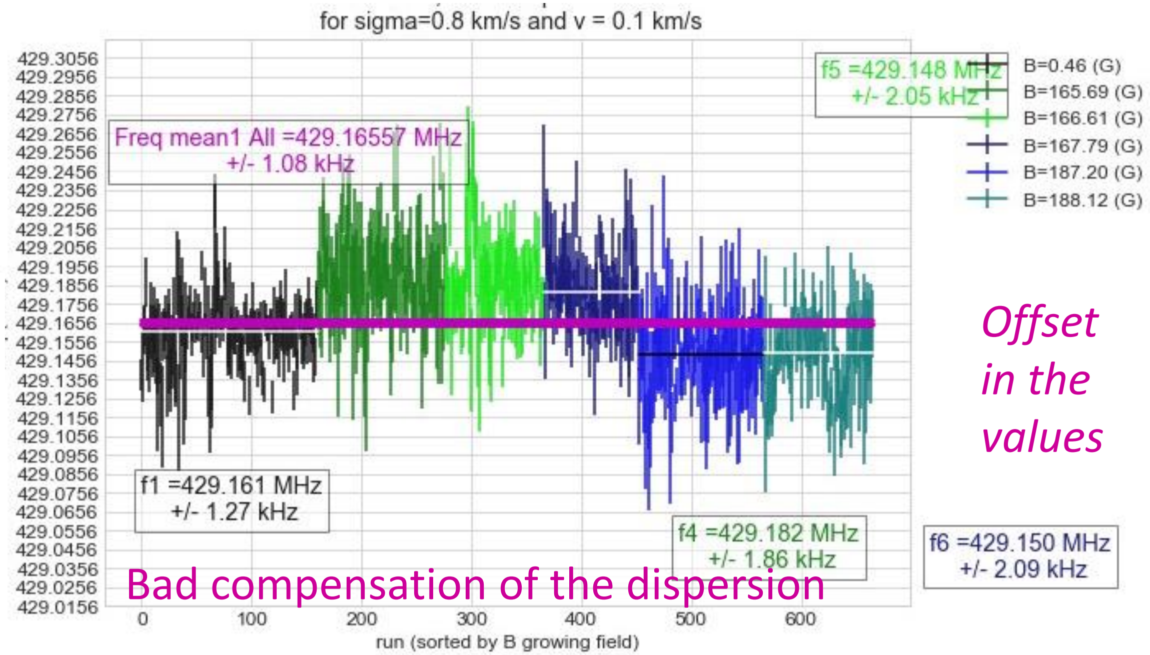
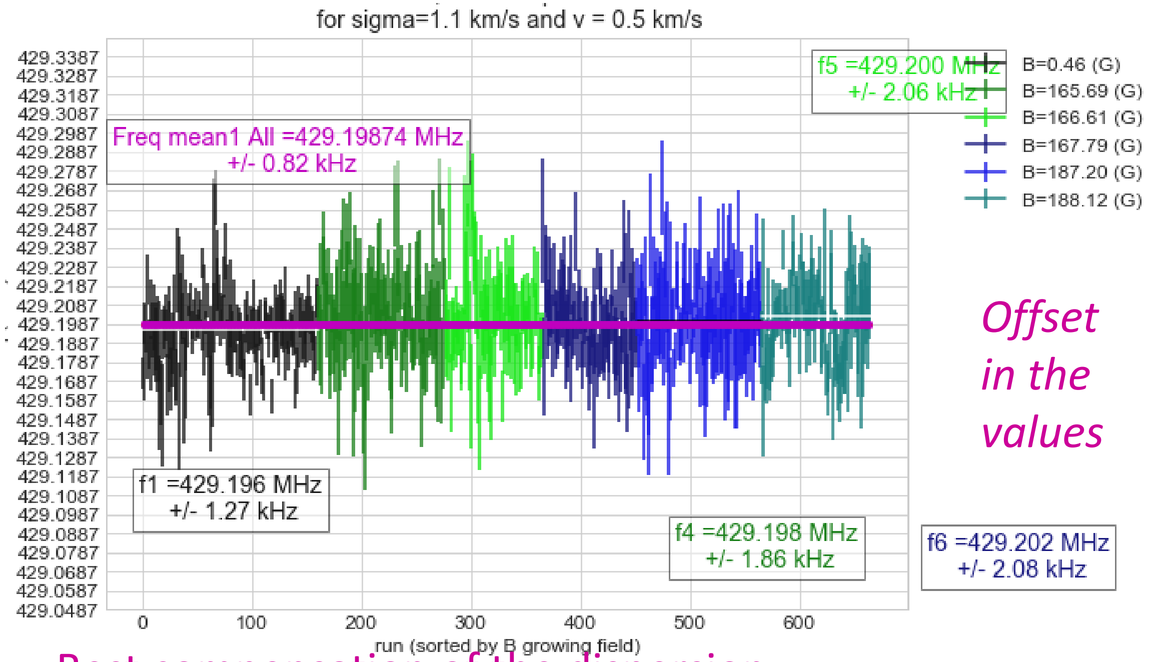
Extracted transition frequency (MHz)



Bad compensation of the dispersion

Offset in the values

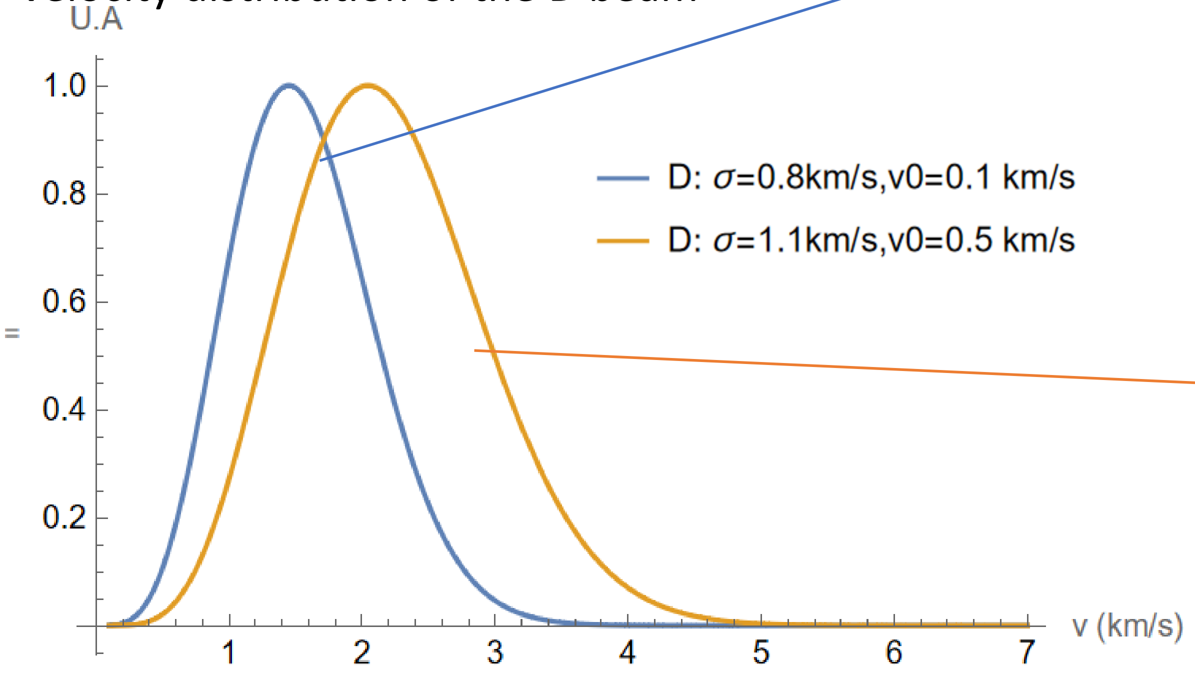


Best compensation of the dispersion

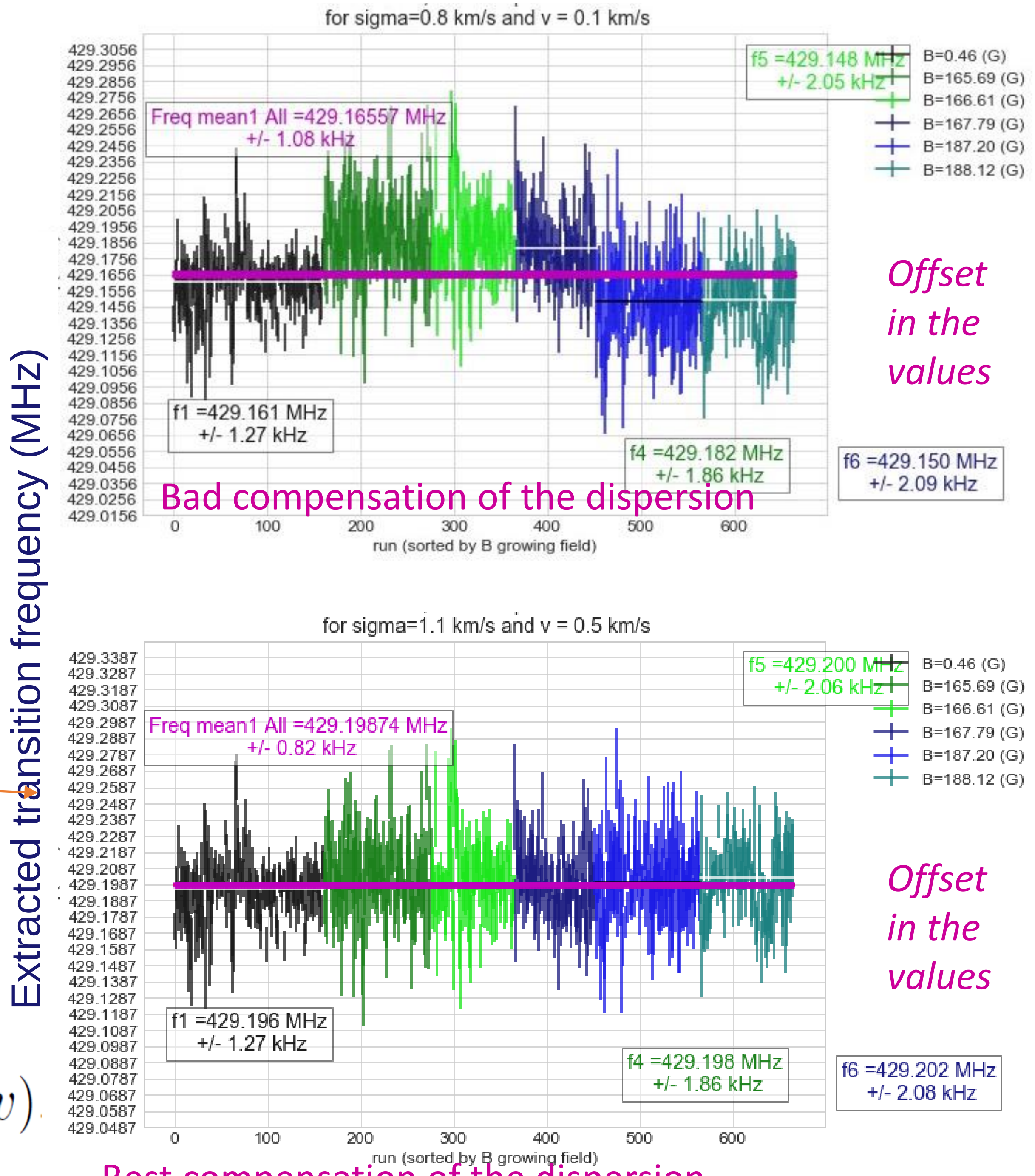
Offset in the values

Examples of fits to extract the best velocity distribution

Velocity distribution of the D beam



$$f(v,\sigma,v_0) \propto v\ f_M(v,\sigma)\ P[\Psi(z),\mathrm{Kn}]\ \exp(-v_0/v)$$



Best compensation of the dispersion

Offset in the values

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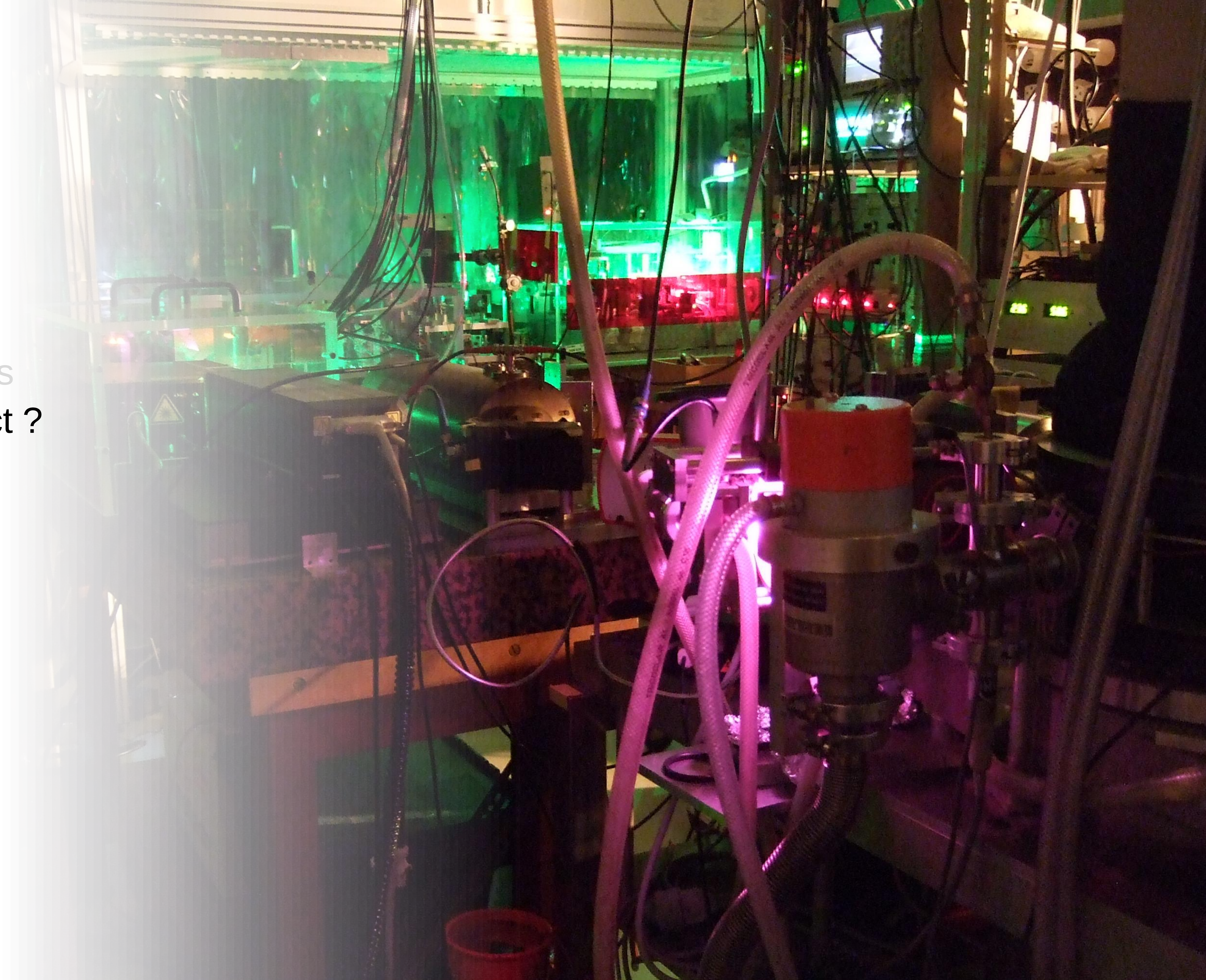
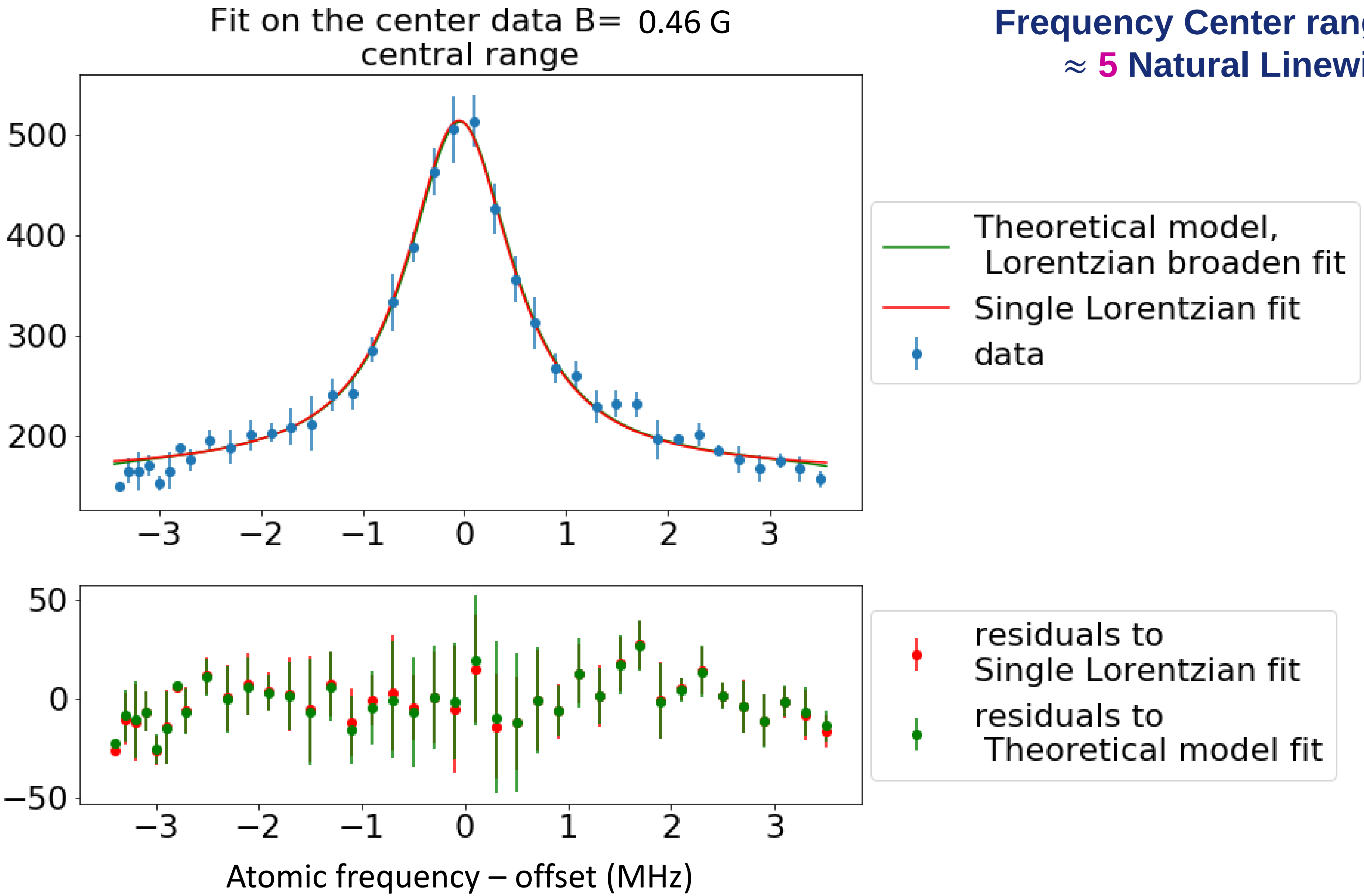


For the campaign, we recorded data over [-3,3] MHz range



Frequency Center range scan
≈ 5 Natural Linewidth

Improvements of the experiment during the last years

- Recent 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)*

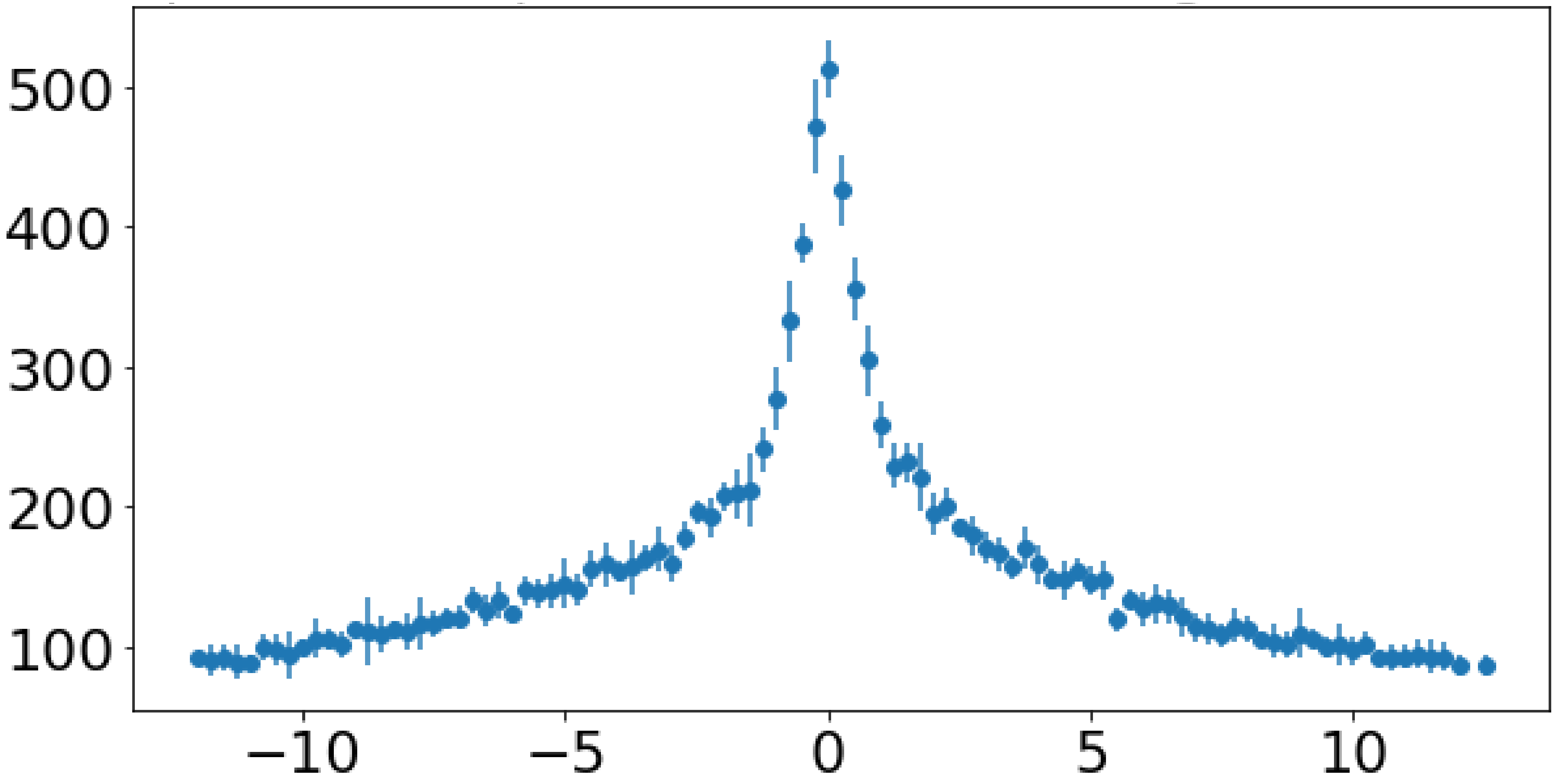
  - possible up to $\pm$ 5 MHz ($\approx$ **10** Natural Linewidth) – ~ *11 min*

  - ***New* system:** $\pm$**10** – 30 MHz scan possible ($\approx$ **20** – **60** Natural Linewidth**)** ~ *20 min* $\Rightarrow$ *A few "wide" scans recorded*

With a wider laser frequency scan:

Deuterium spectrum
14/12/2020, run 38
B=0.46 G

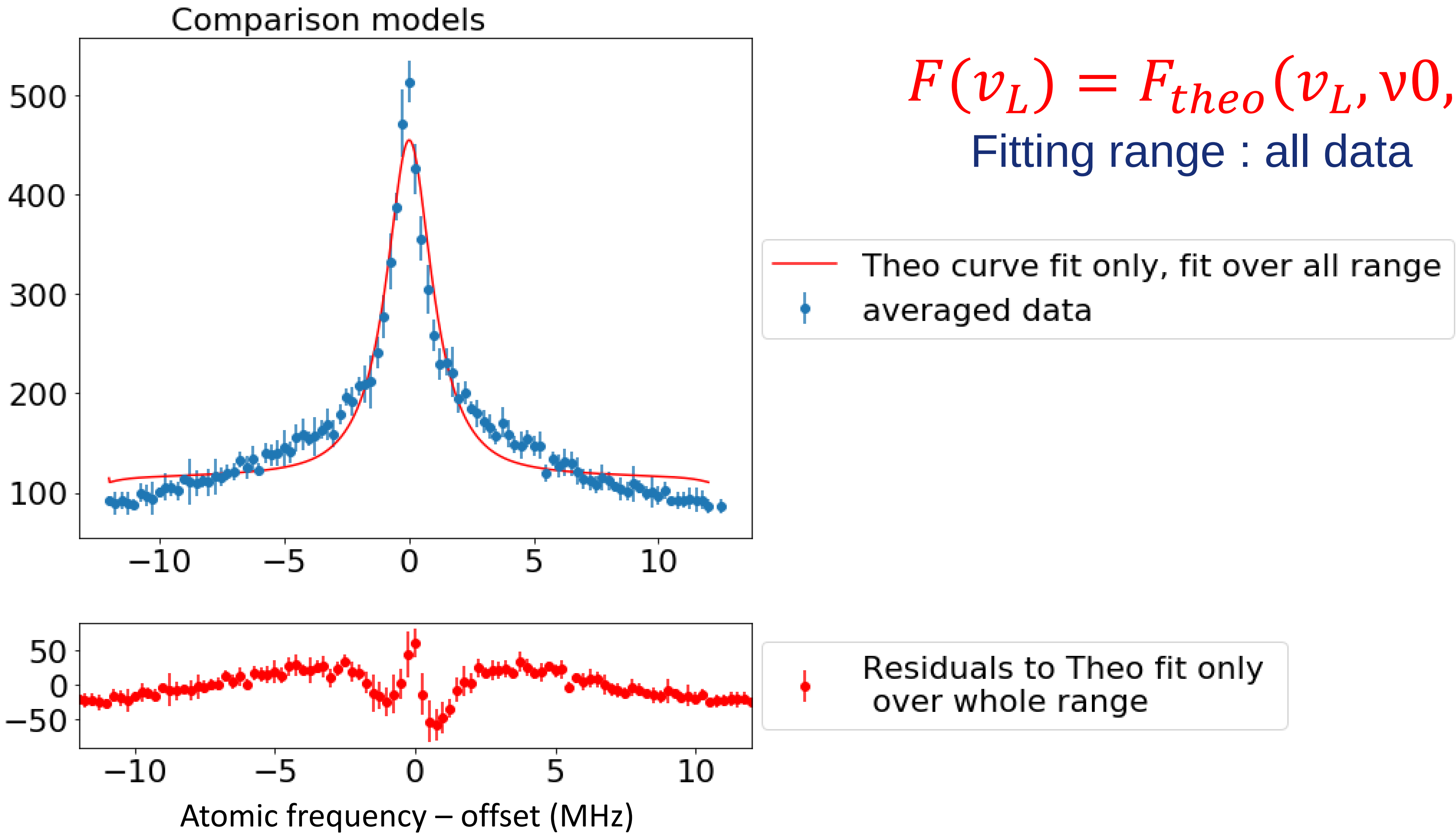
Wide spectrum, recorded for B=0.46 G



Atomic frequency – offset (MHz)

Averaged
1 run
(10 scans)

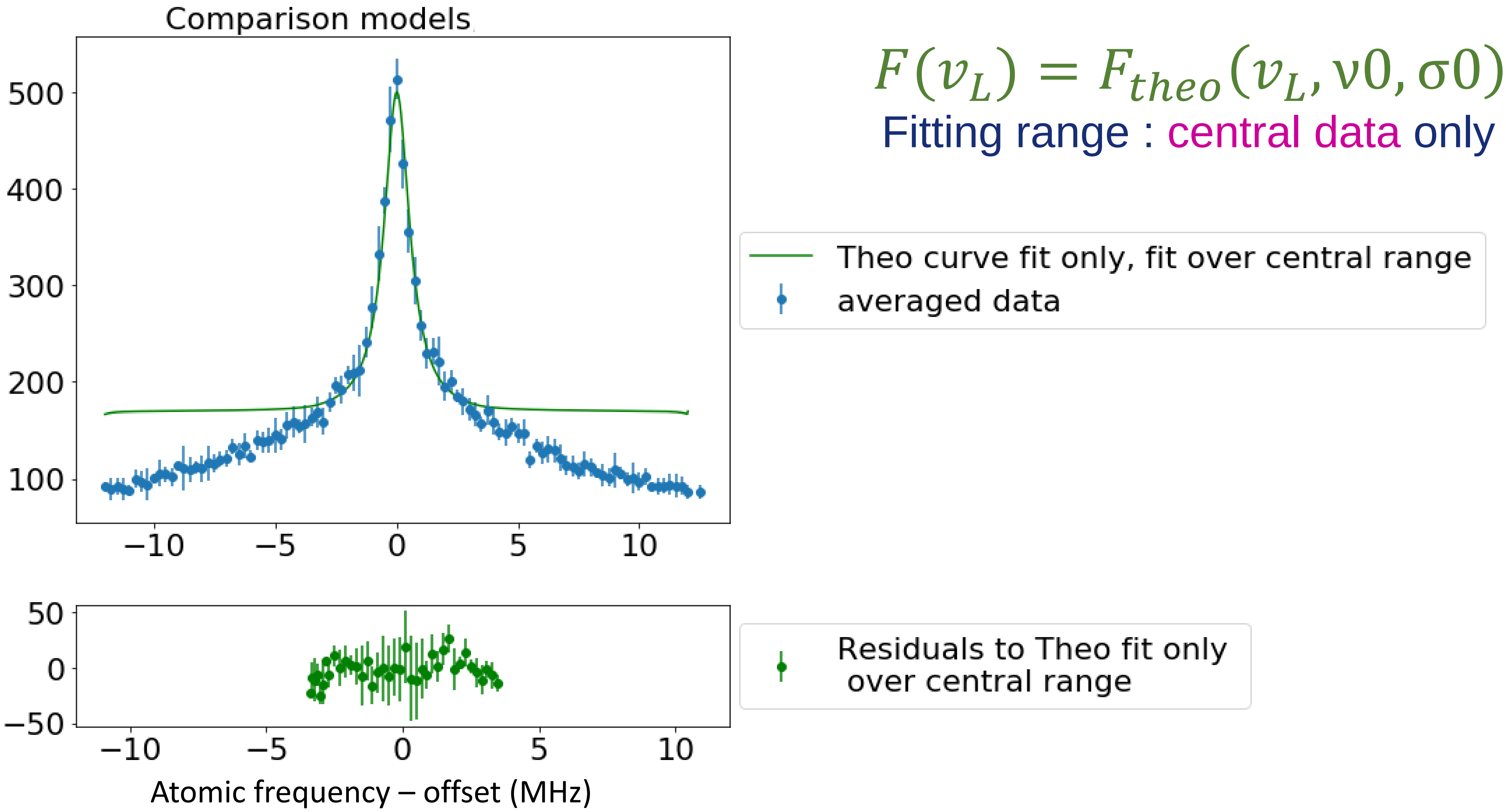
Which fit model ?



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

Fitting range : all data

Which fit model ?



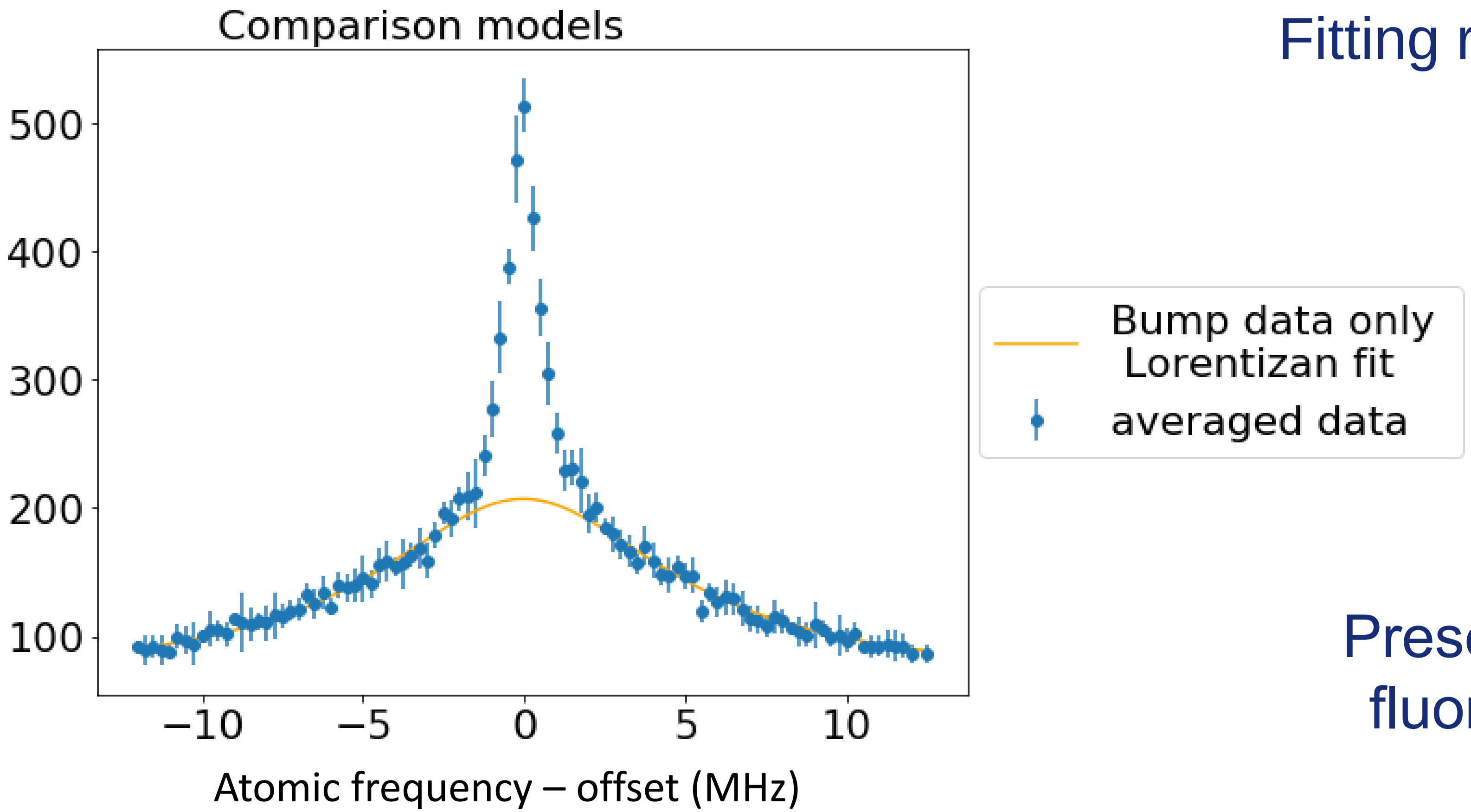
$$F(v_L) = F_{theo}(v_L, \nu 0, \sigma 0)$$

Fitting range : central data only

Which fit model ?

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

Fitting range : edge data only

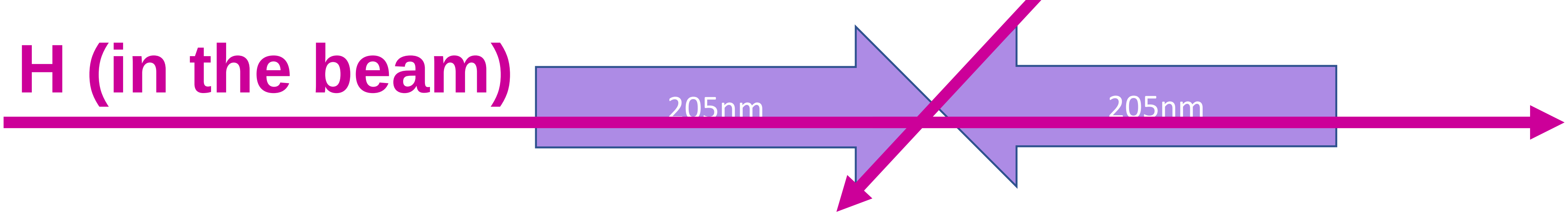


Presence of a "Pedestal fluorescence signal" = "Bump" signal

Which fit model ?

Origin of this pedestal ?

Presence of residual H gas in the chamber.



$\Rightarrow$ Contribution to a **broaden** fluorescence signal due to **short interaction time**

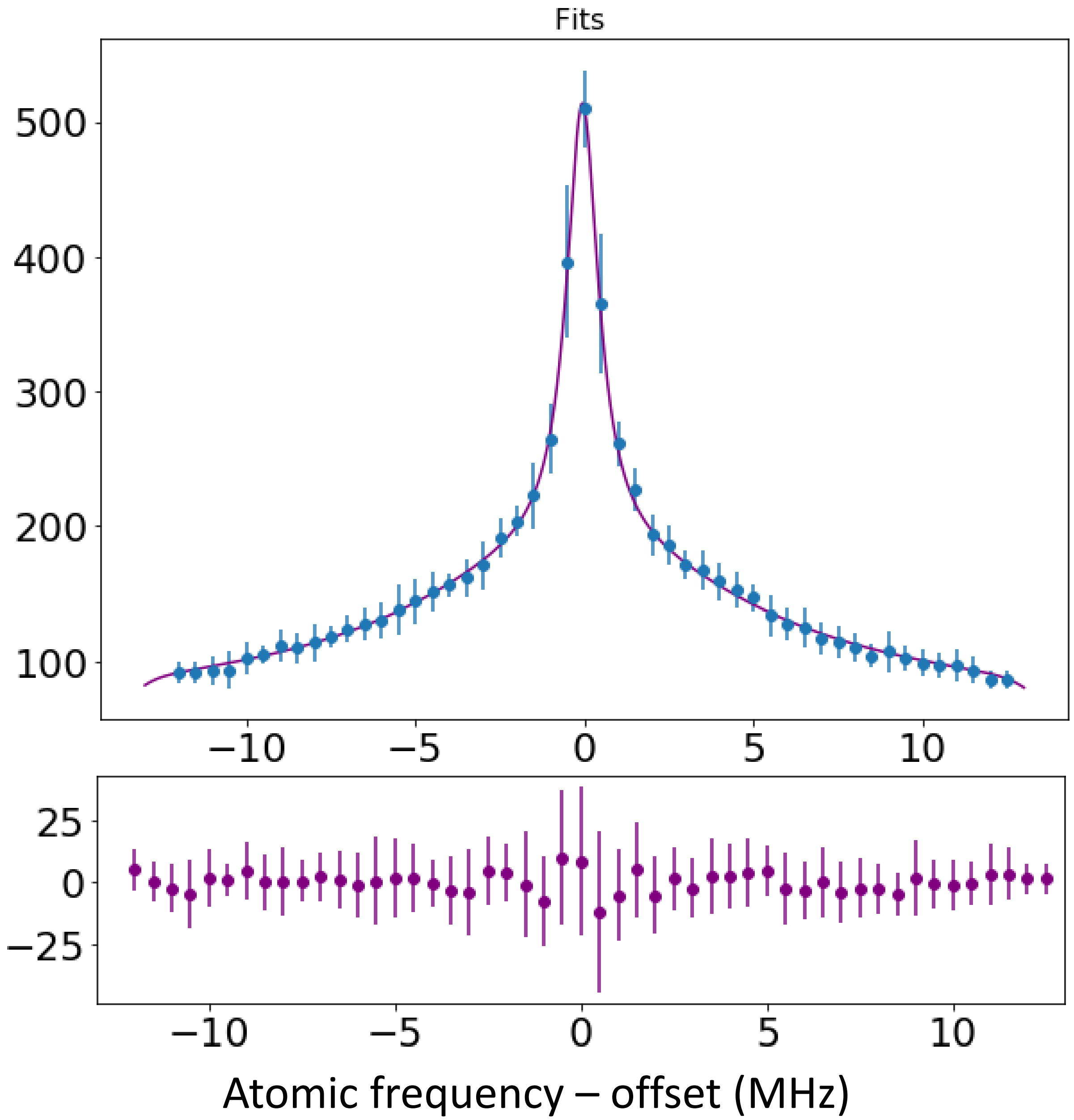
New model to fit:

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

Which fit model ?

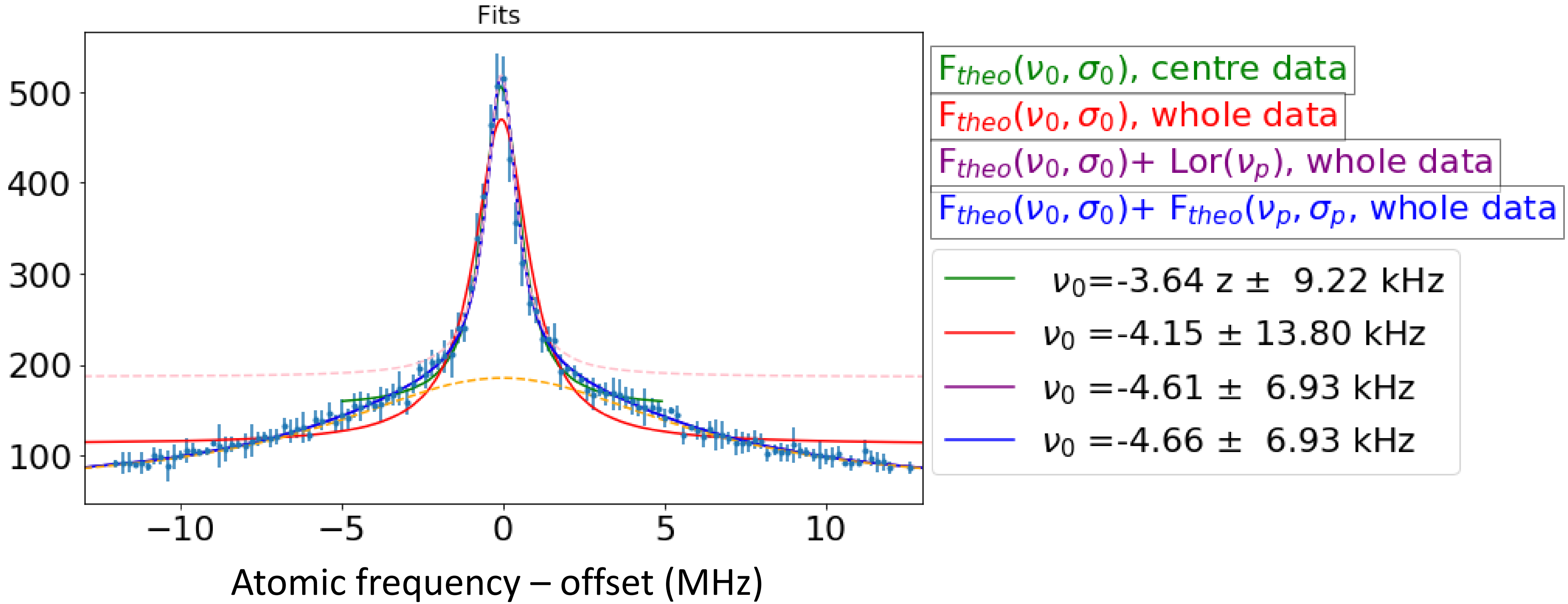
$$F(\nu_L) = F_{theo}(\nu_L, \nu 0, \sigma 0) + F_{theo}(\nu_L, \nu B, \sigma B)$$

Fitting range : all data

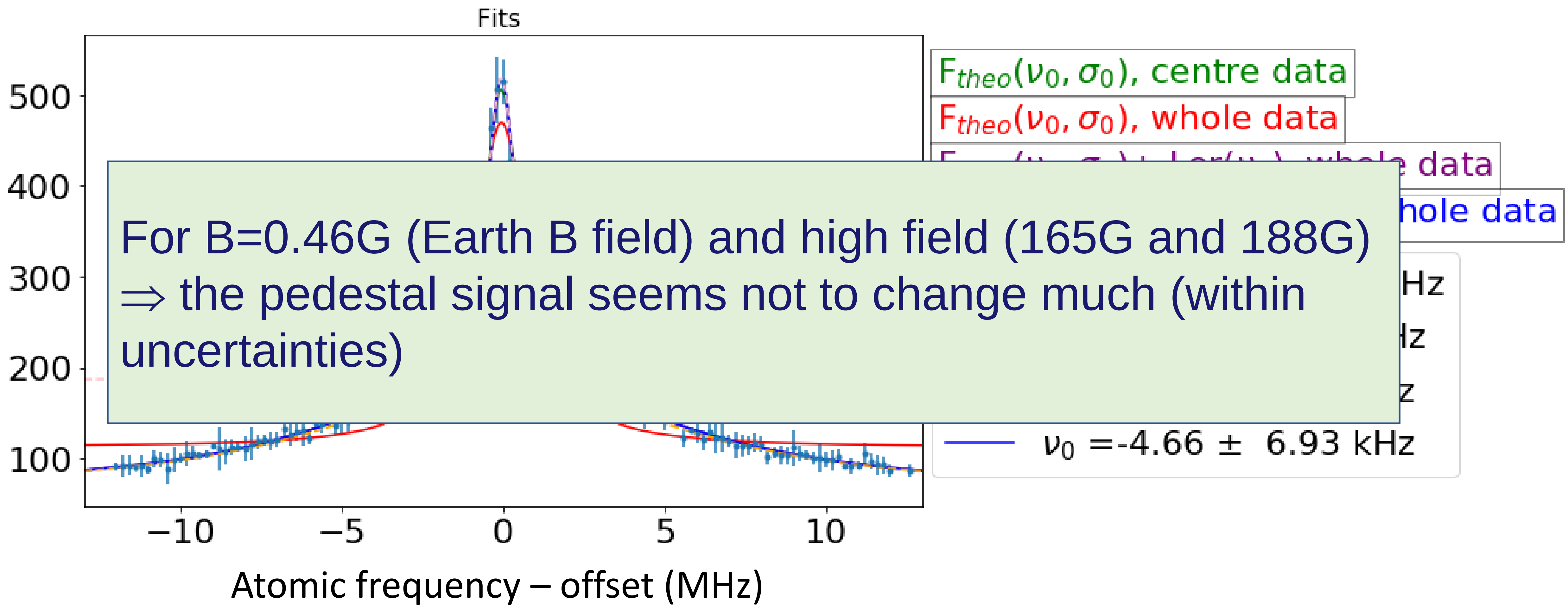


Theo curve + Extra broaden Theo curve for Bump, whole data

What does it change for the fitted centre frequency?



What does it change for the fitted centre frequency?

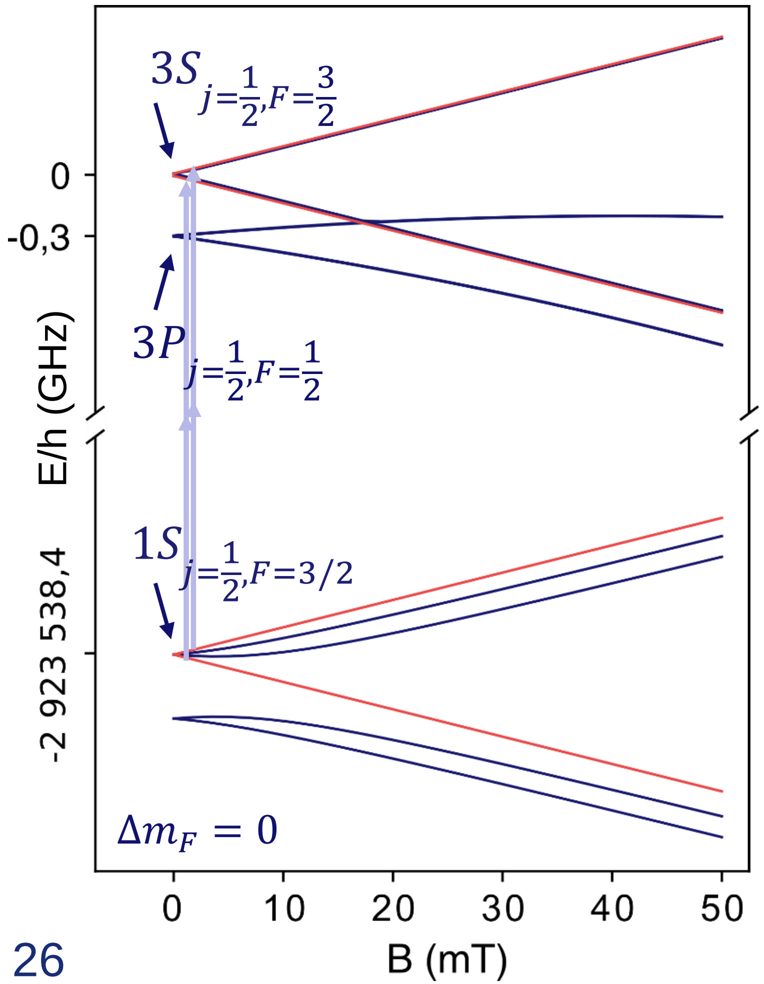


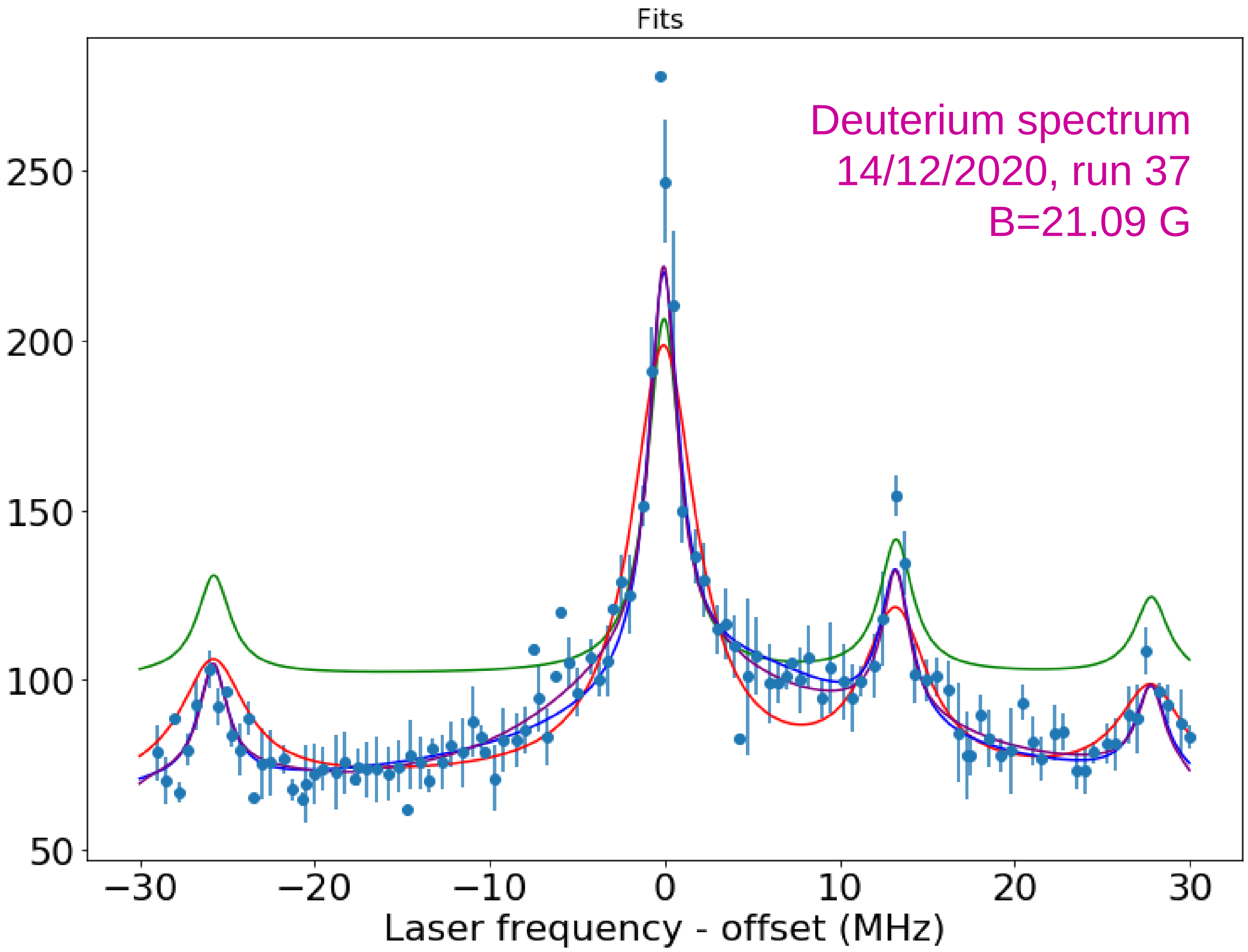
For B=0.46G (Earth B field) and high field (165G and 188G)
⇒ the pedestal signal seems not to change much (within uncertainties)

Issue with the new "low" field data …

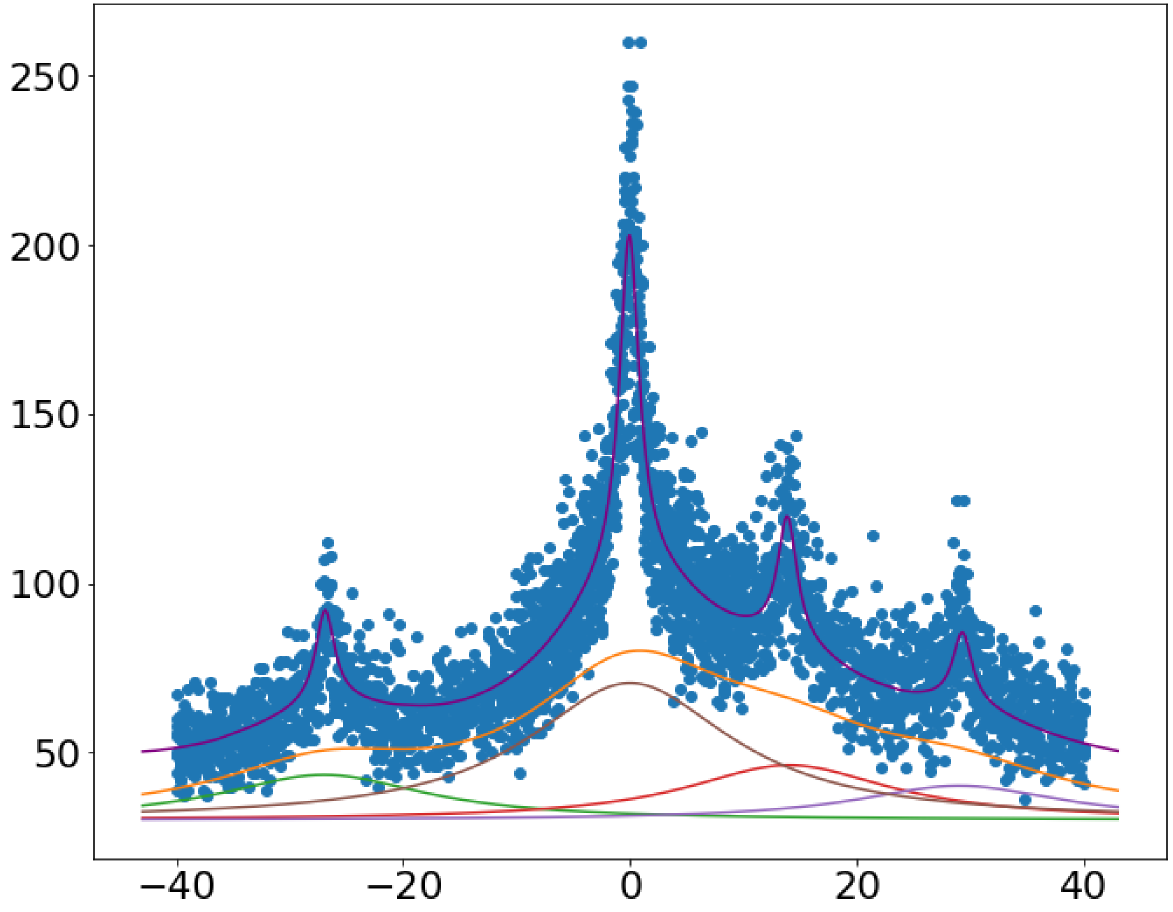
Story more complex at weak B field: B ~ 20 G

Deuterium Energy levels

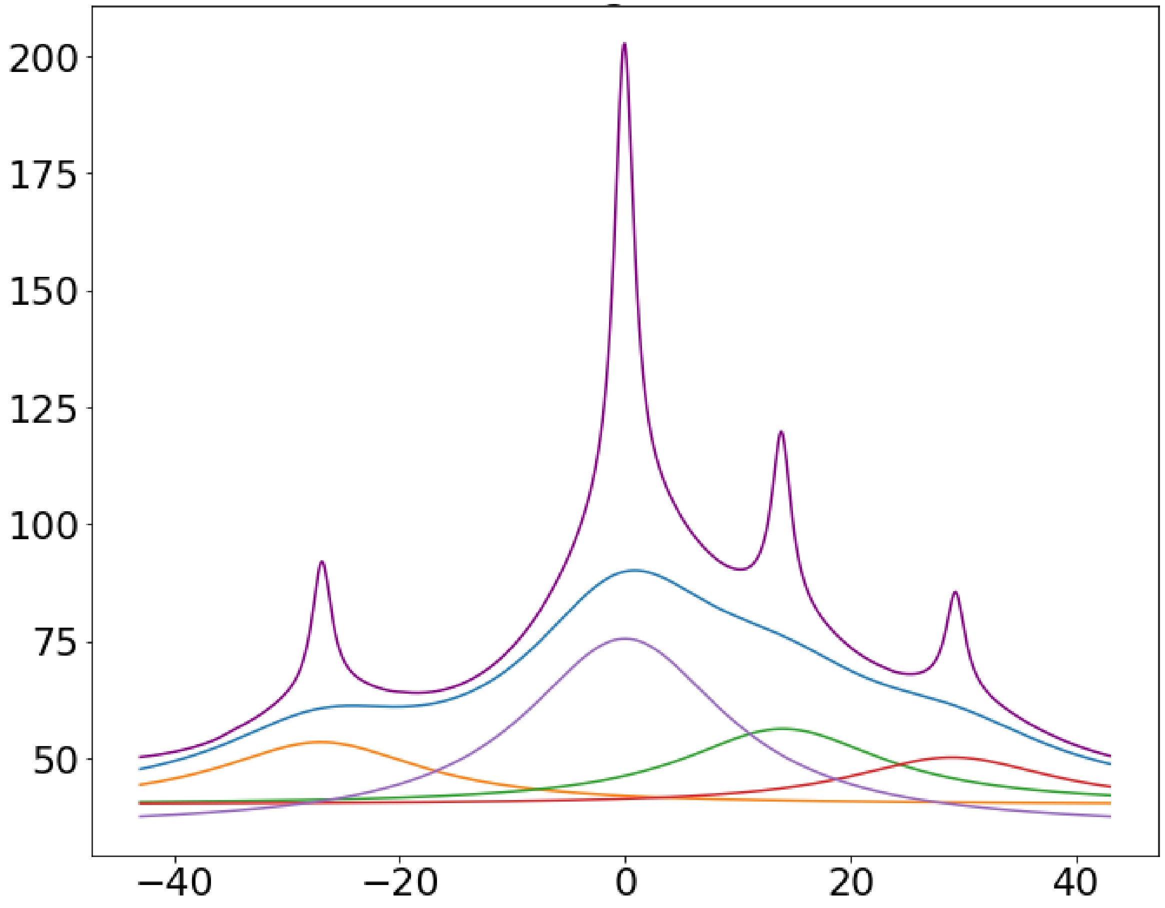




Asymmetry of the pedestal due to neighbouring lines at B~20 G



Atomic frequency (MHz)

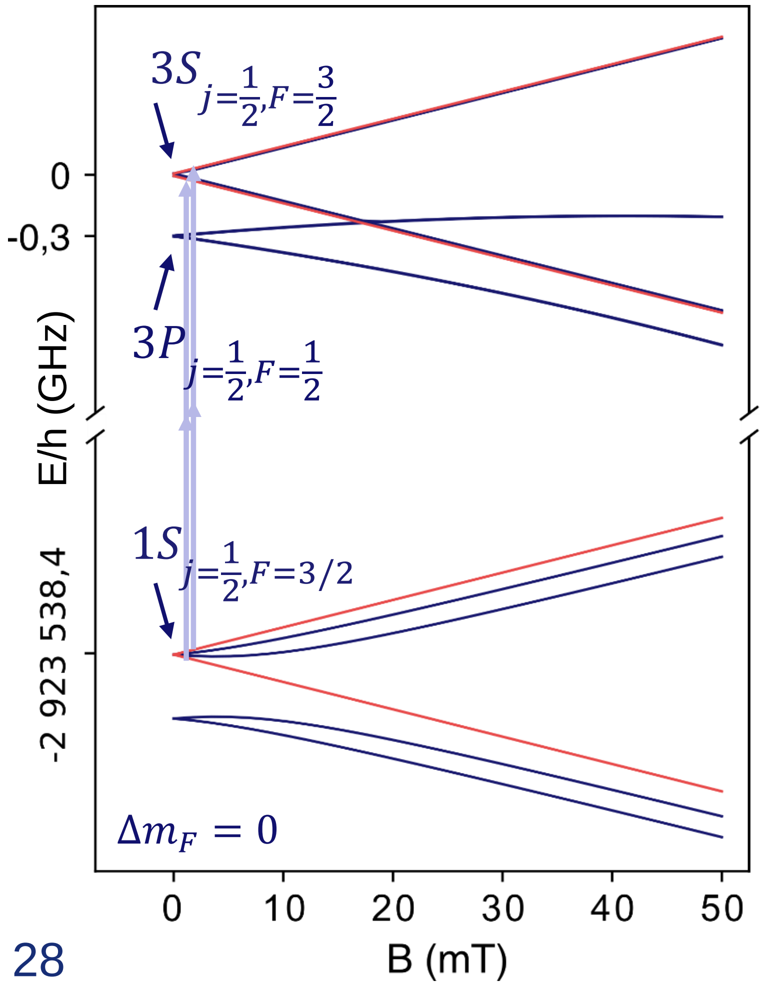


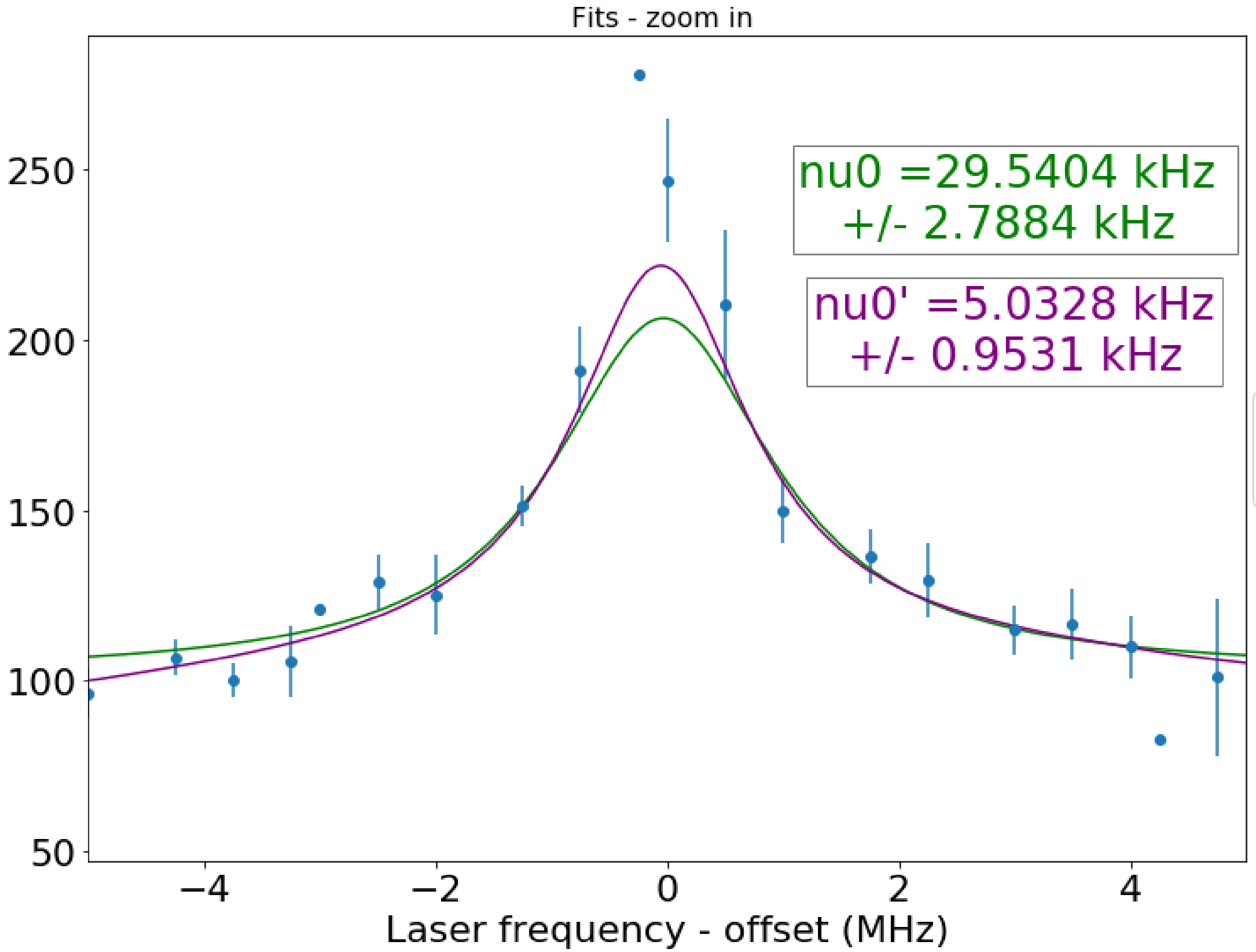
Atomic frequency (MHz)

Issue with the new “low” field data …

Story more complex at weak B field: like 20 G

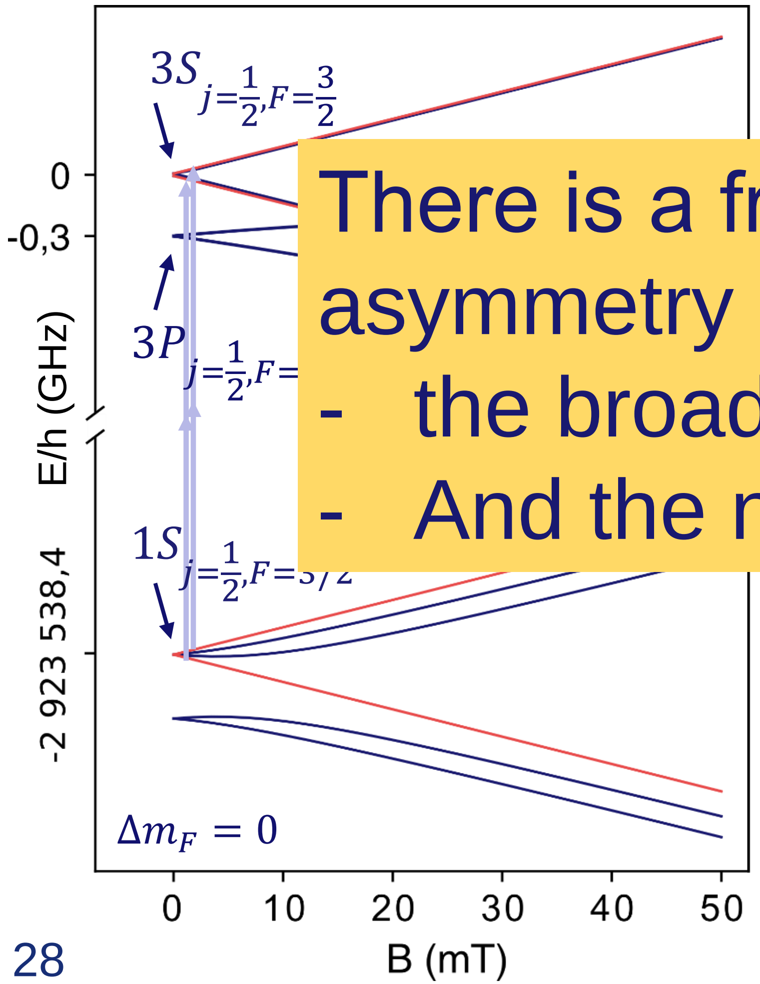
Deuterium Energy levels

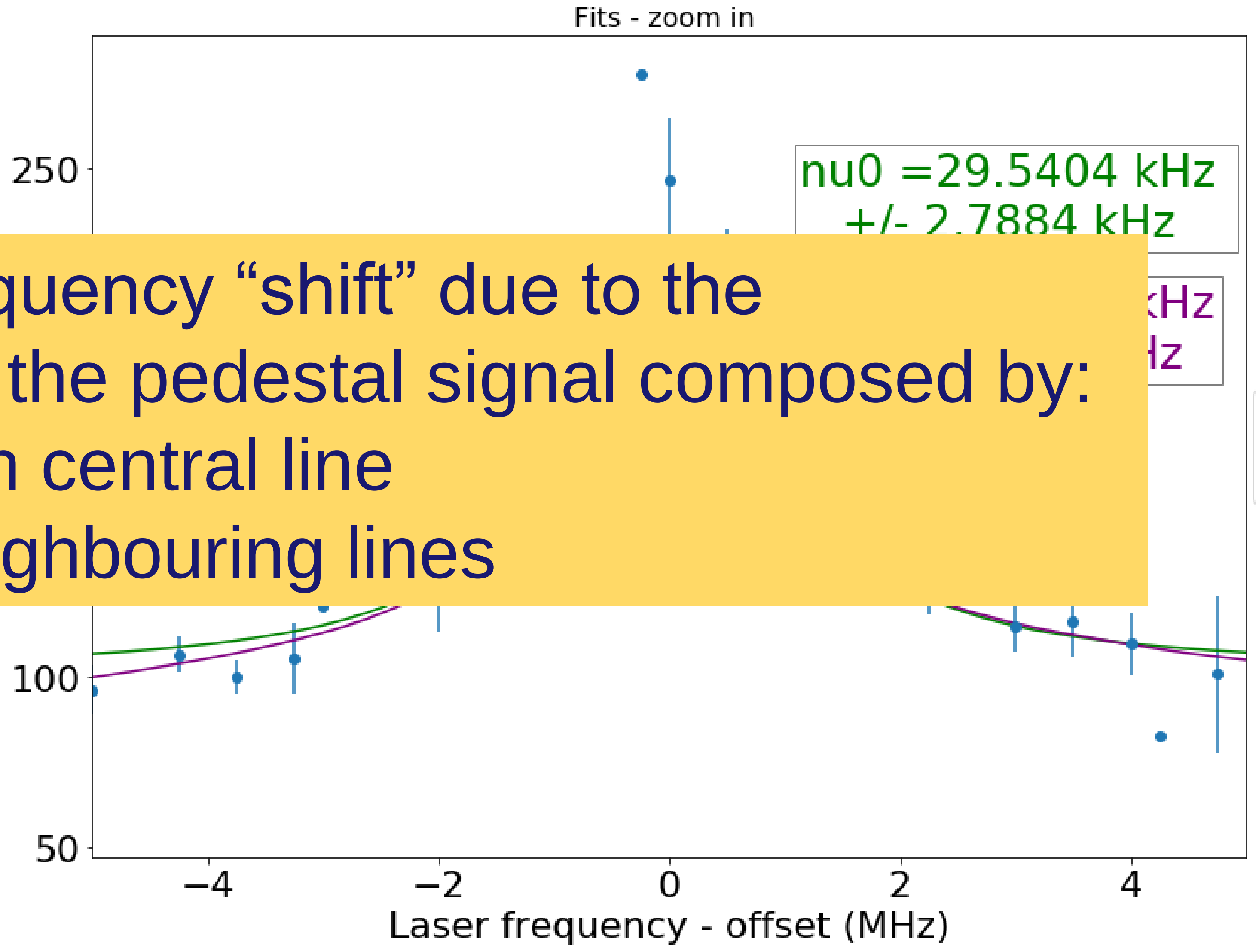




Issue with the "low" field data

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





There is a frequency "shift" due to the asymmetry of the pedestal signal composed by:

- the broaden central line
- And the neighbouring lines

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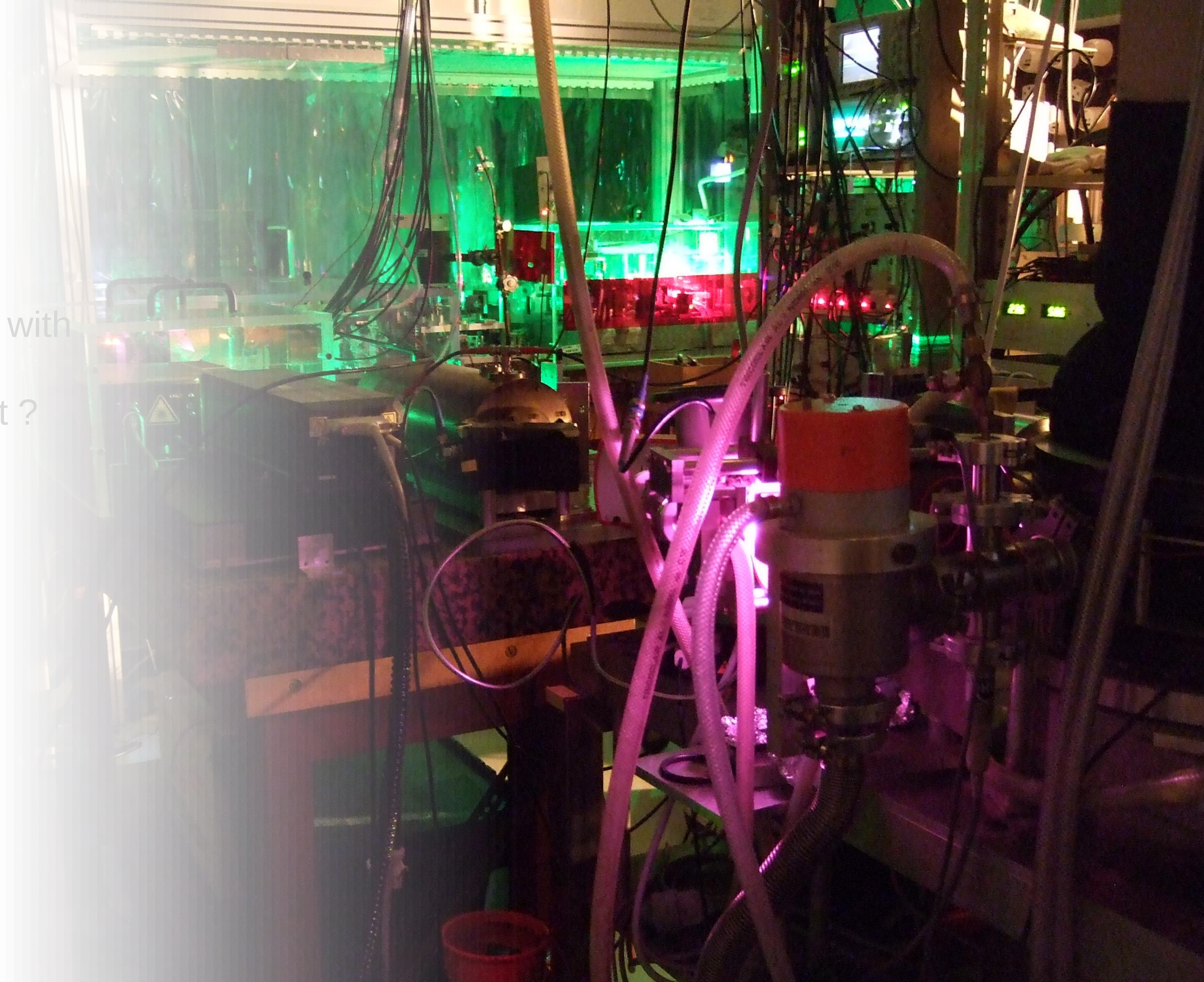


Data analysis

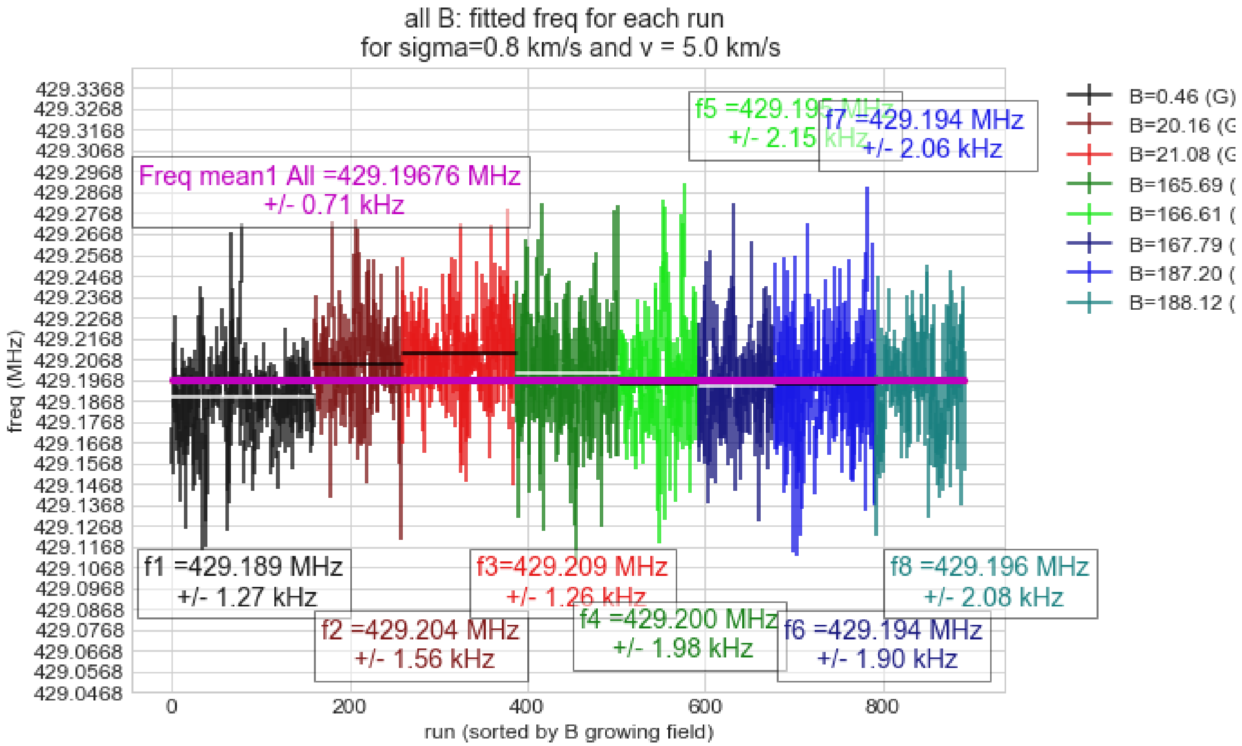
- From 20 October to 17 December 2020 – B field recorded:

-0.46 **, +20.16, -21.09**, +165.99, -166.91,-167.80, +187.20,

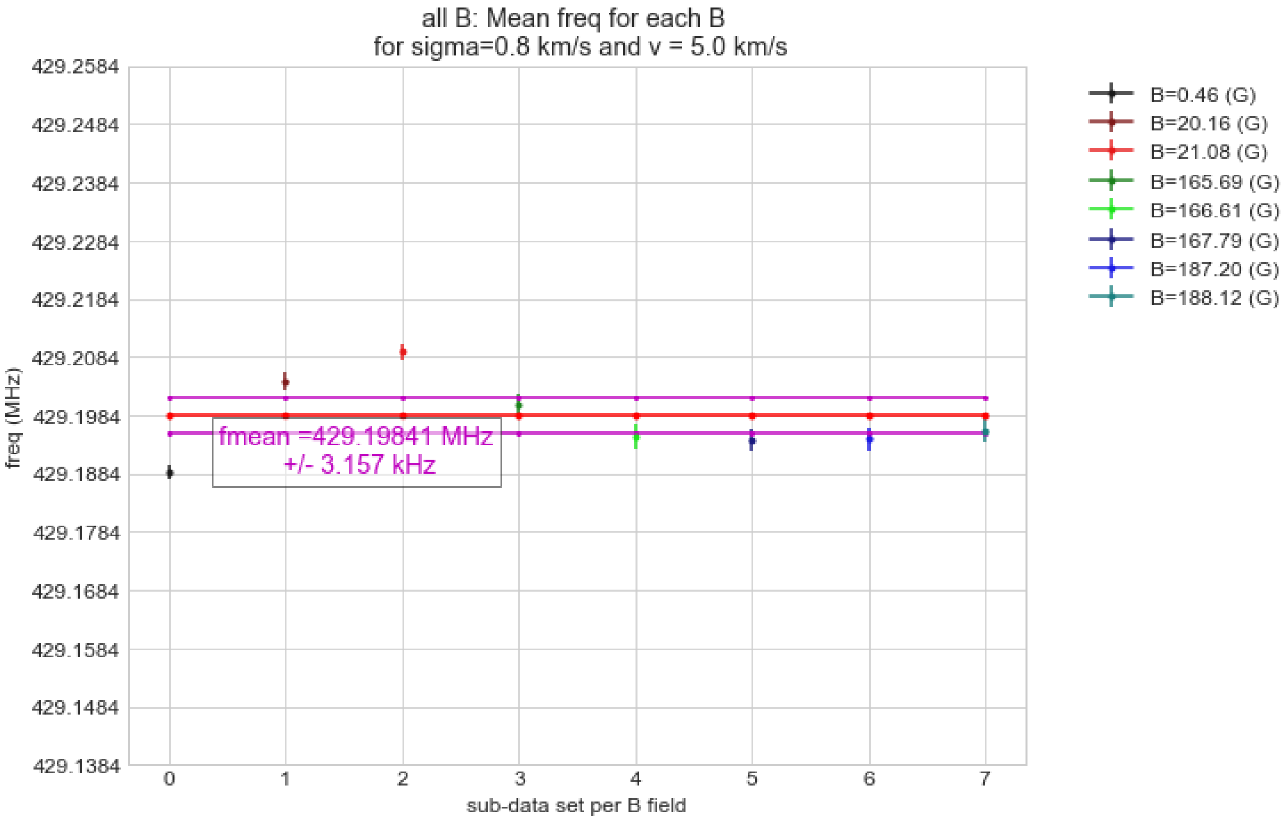
-188.12 G

- Data recorded over [-3,3] MHz atomic frequency range $\Rightarrow$ impossible to well determine the pedestal parameters in such a short frequency range (centre, bandwidth, amplitude) for the fits.
- Issues in the fits for the B=20.16 and B=-21.09 G because of the neighbouring lines (asymmetrical pedestal signal leads to a wrong positioning of the centre line)

Example of the issue with the B=20G data

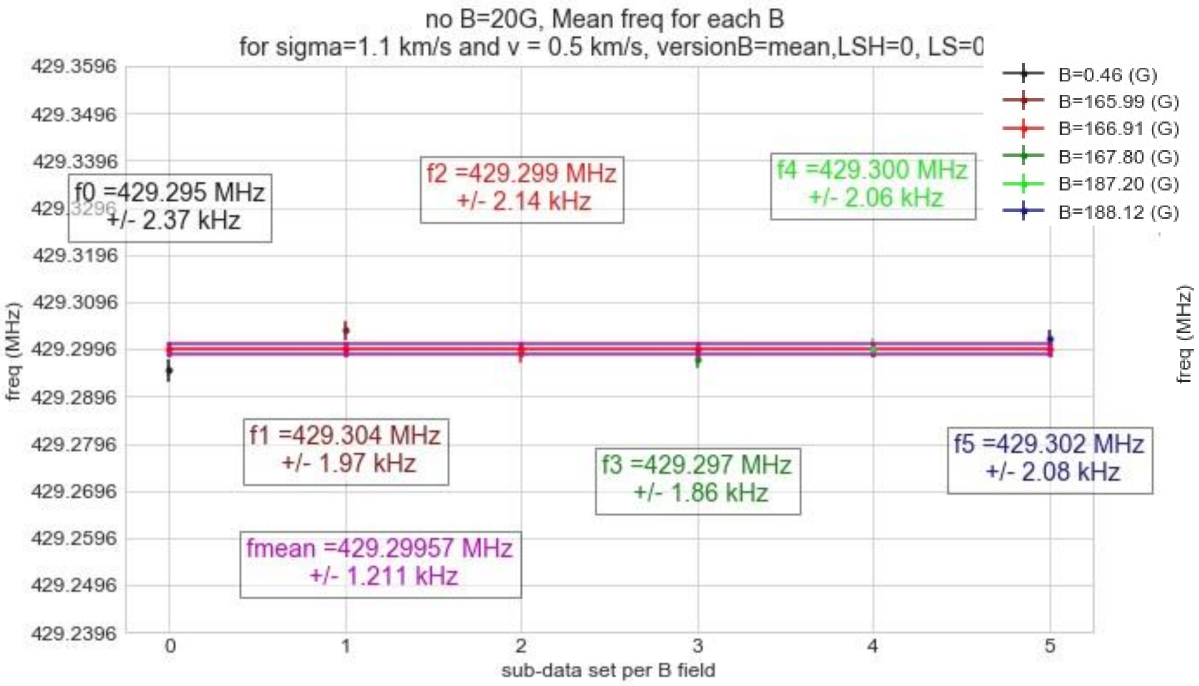


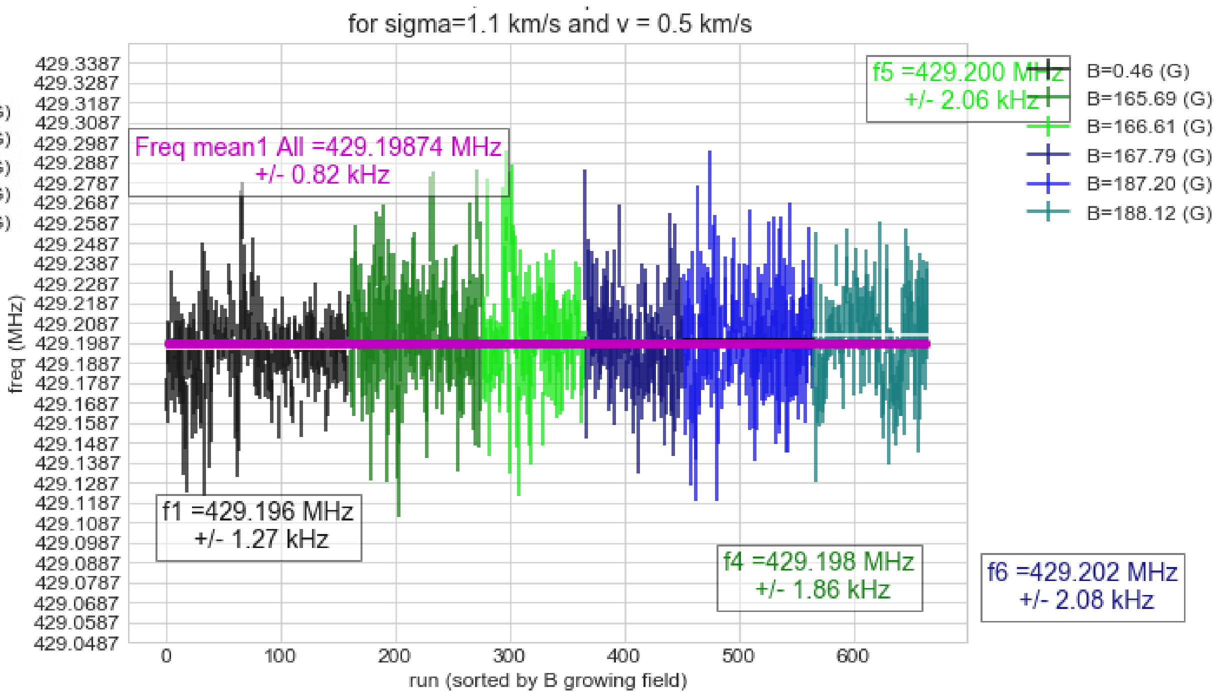
Best velocity distribution (sigma=0.8 km/s, v0=5 km/s)



Even for the "best parameters" that minimize χ^2 of the determination of velocity distribution: not a "good" correction of dispersion type profile of the data separated by B fields

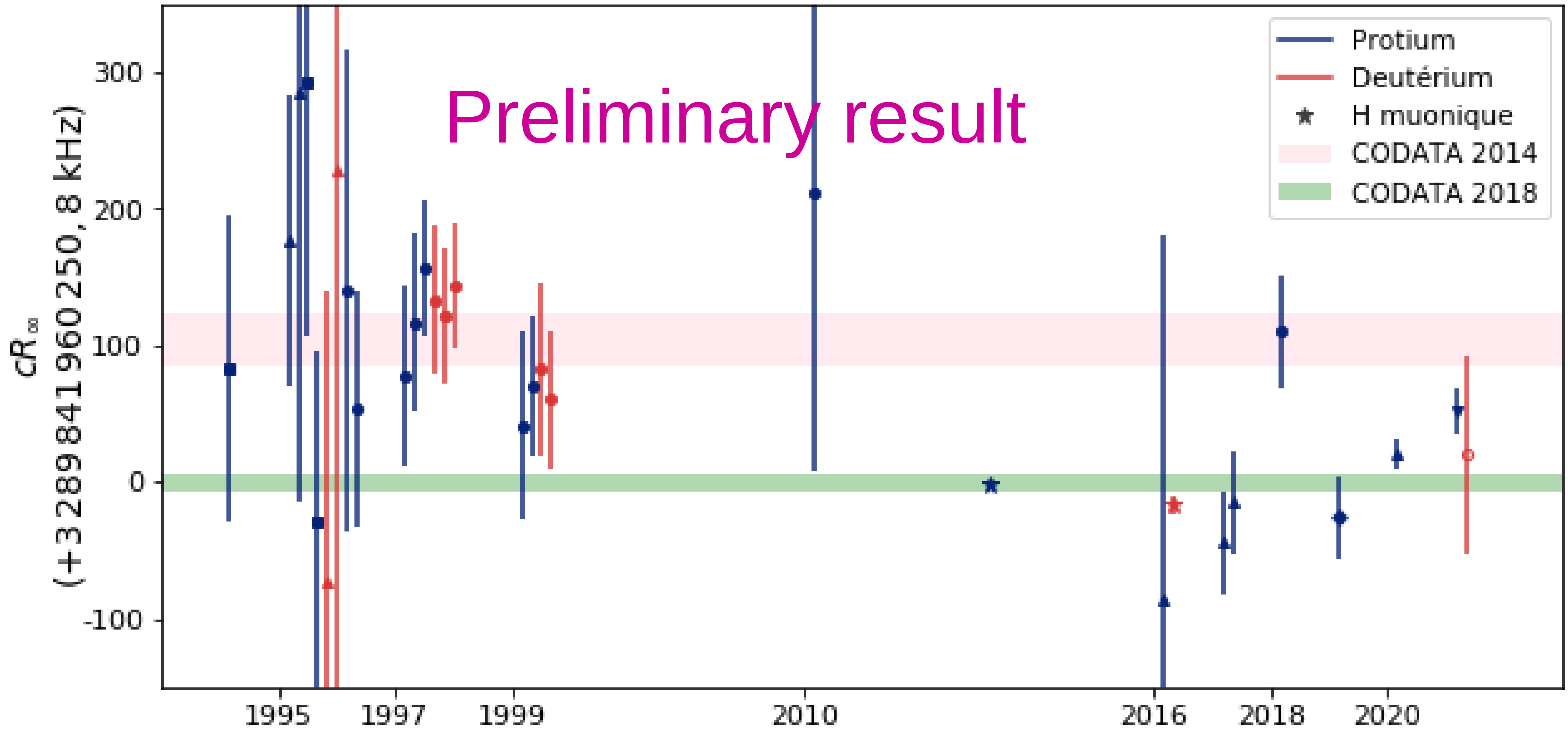
Whereas, excluding the B=20 G data

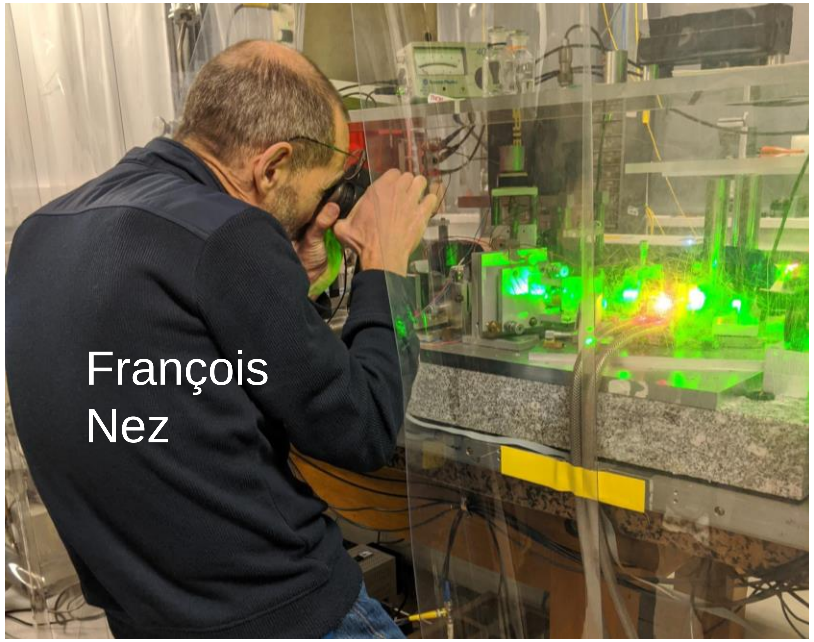


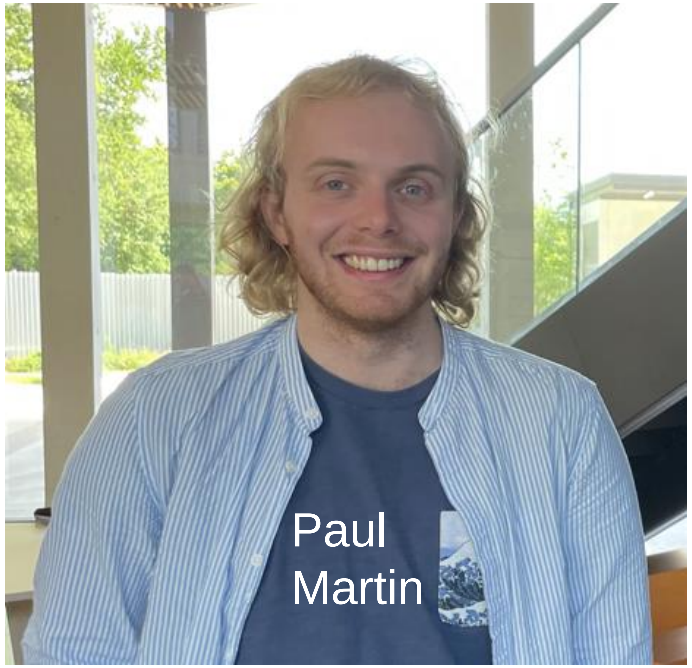


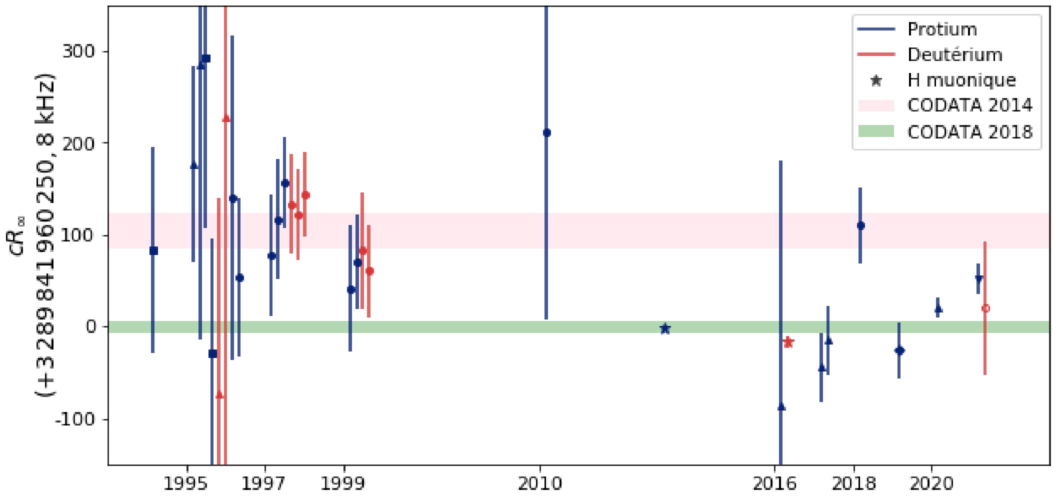
Preliminary result

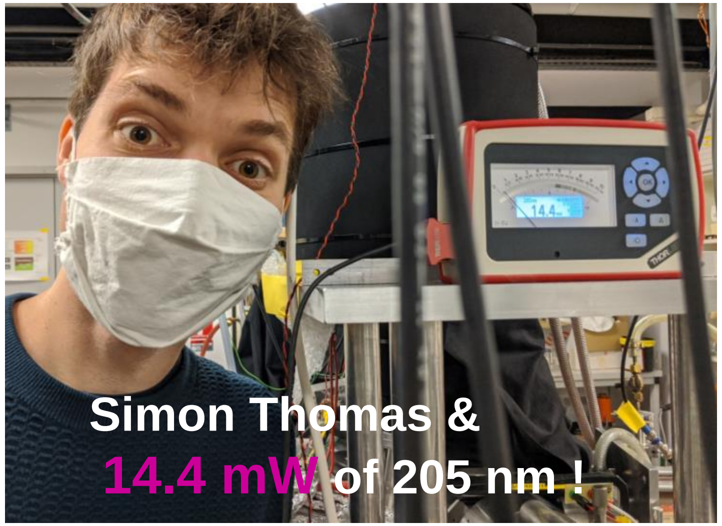
contributions	In frequencies	comments
ν_{fit} ($\delta\nu_{fit}$) 1S-3S F=3/2 -> F=3/2	2 923 538 429 299.7 (1.5) kHz	Take into account the - the SOD, the Zeeman effect, and the motional Stark shifts - Statistical uncertainty - Uncertainty of the ν_{mean}(B=0.46G) due to 20mG uncertainty
$\Delta\nu_{pressure\ shift}$ ($\delta\nu_{PS}$)	+2.6 (0.9) kHz	
$\Delta\nu_{light\ shift}$($\delta\nu_{LS}$)	-2.5 (3.0) kHz	
$\Delta\nu_{quantum\ interference}$($\delta\nu_{QI}$)	+0.6 (0.2) kHz	H. Fleurbaey, et al Phys. Rev. A **95**, 052503 (2017).
$\Delta\nu_{correctionSyrte}$	-0.171(<0.010) kHz	From Syrte (maser drift in time)
$\Delta\nu_{Bump}$(δ_{Bump})	0.0 (3.0) kHz	To be investigated
Tot 1S-3S F=3/2 -> F=3/2	2 923 538 429 300.1 (4.5) kHz	Not corrected of the HFS


Preliminary result
Protium
Deutérium
H muonique
CODATA 2014
CODATA 2018
cR_∞
(+3 289 841 960 250,8 kHz)
300
200
100
0
-100
1995
1997
1999
2010
2016
2018
2020





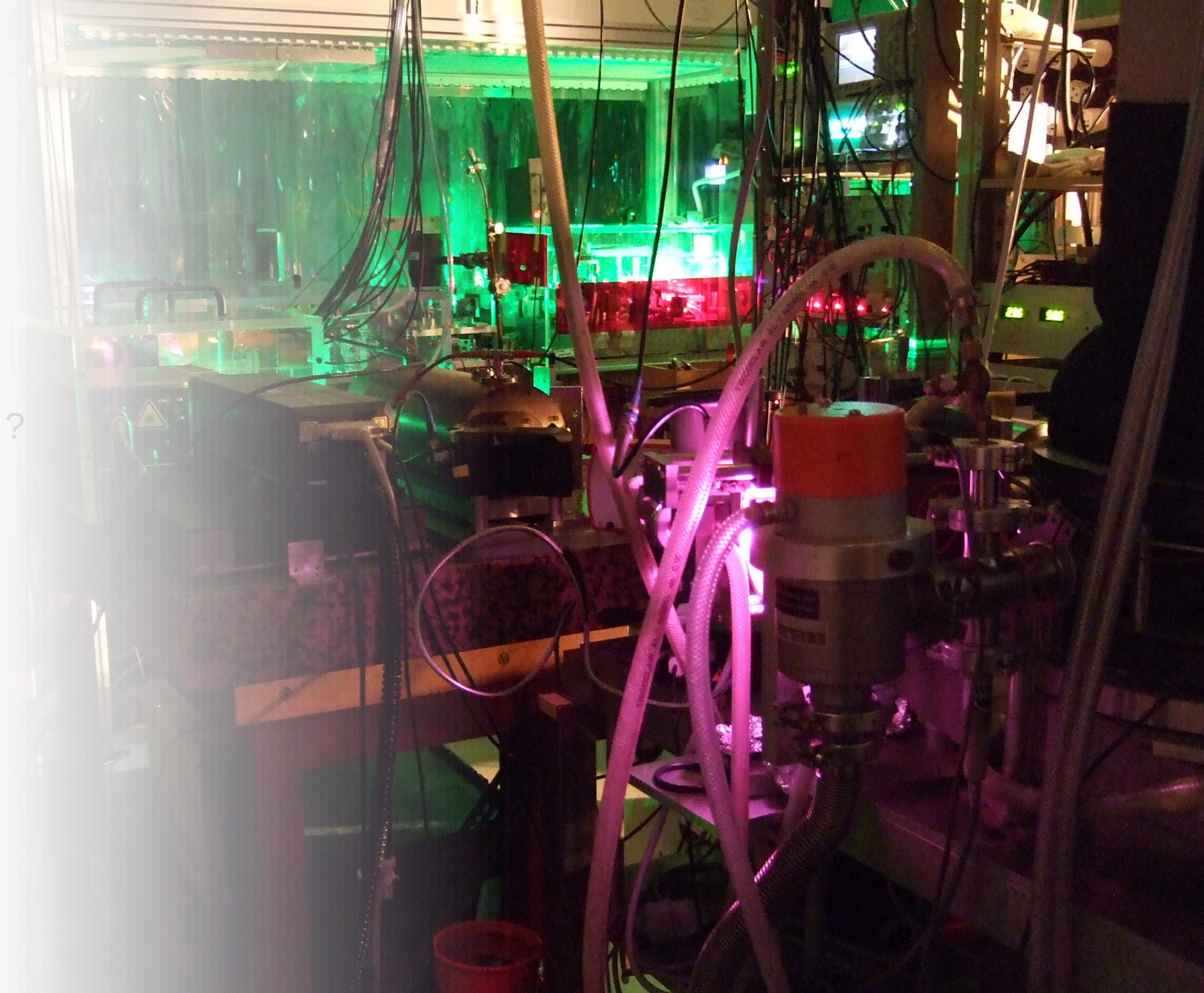




Thanks for your attention

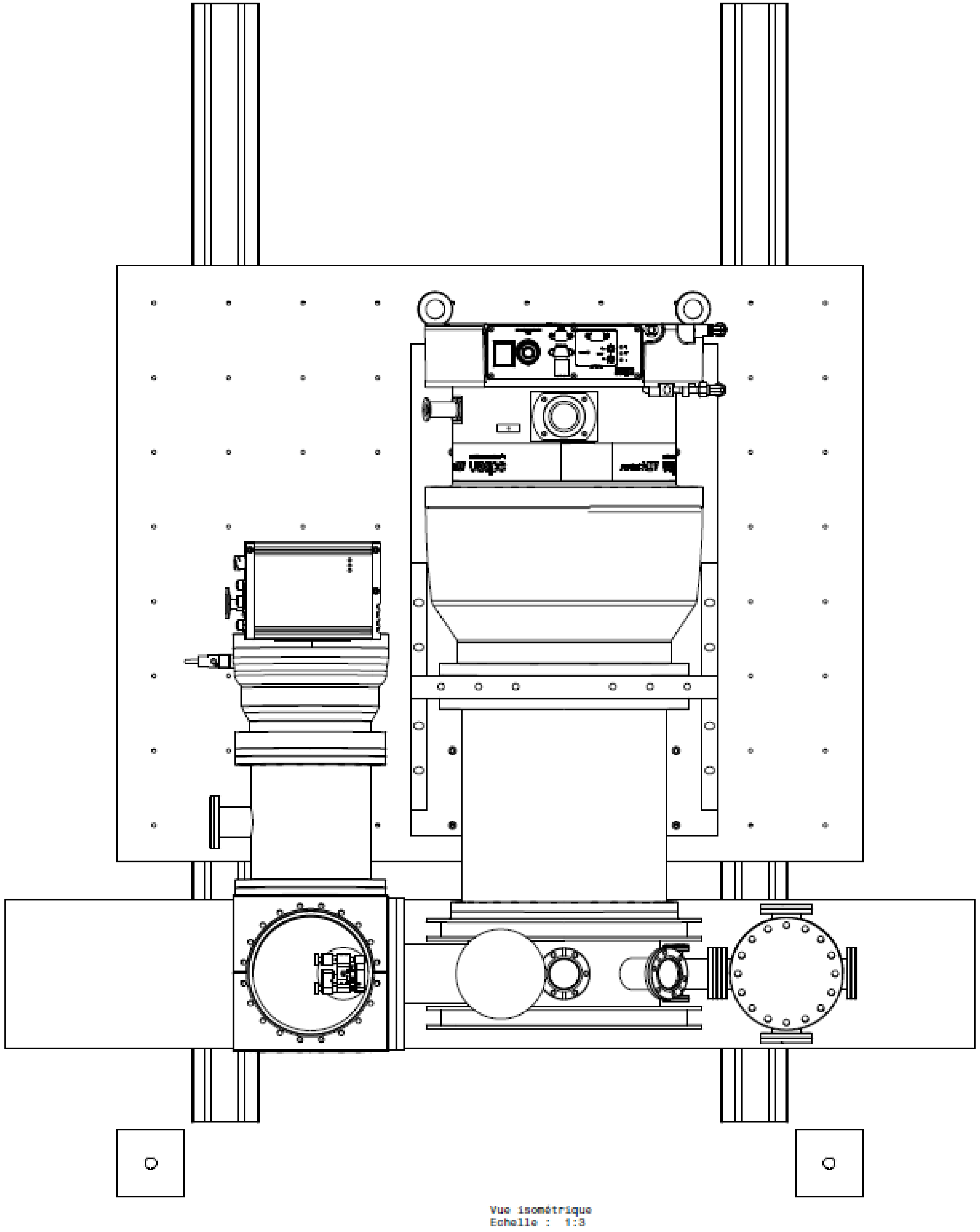
Overview

- The experiment
- Dealing with systematics
- A new systematics effect ?
- Preliminary result ?
- What next ?



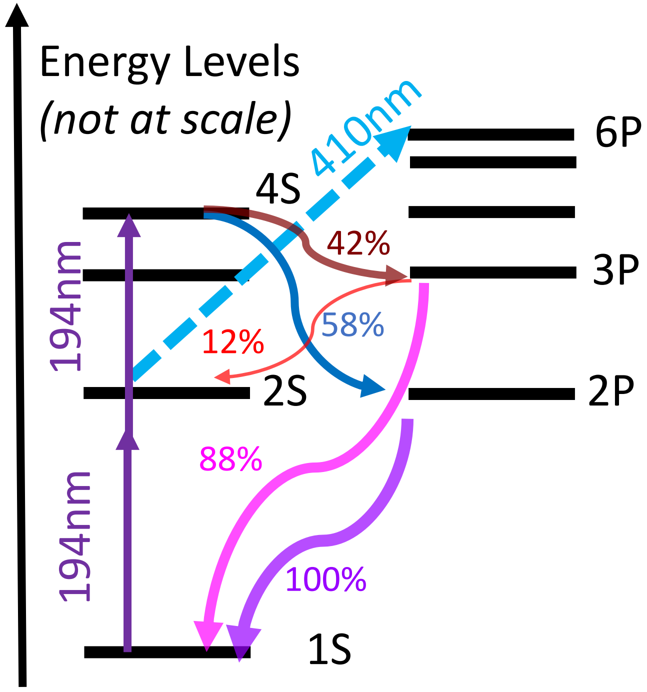
The new H beam experiment

- Based on dry pumps ! ✓
- New design to decoupled the mirrors' cavity of the 205 nm from the vibrations of the turbo pumps ✓
- Better power supplies for the coils and compensating Earth-B field coils ✓
- Wider laser frequencies scans to investigate better the pedestal signal ✓
- Better laser stability ✓
- New design of the

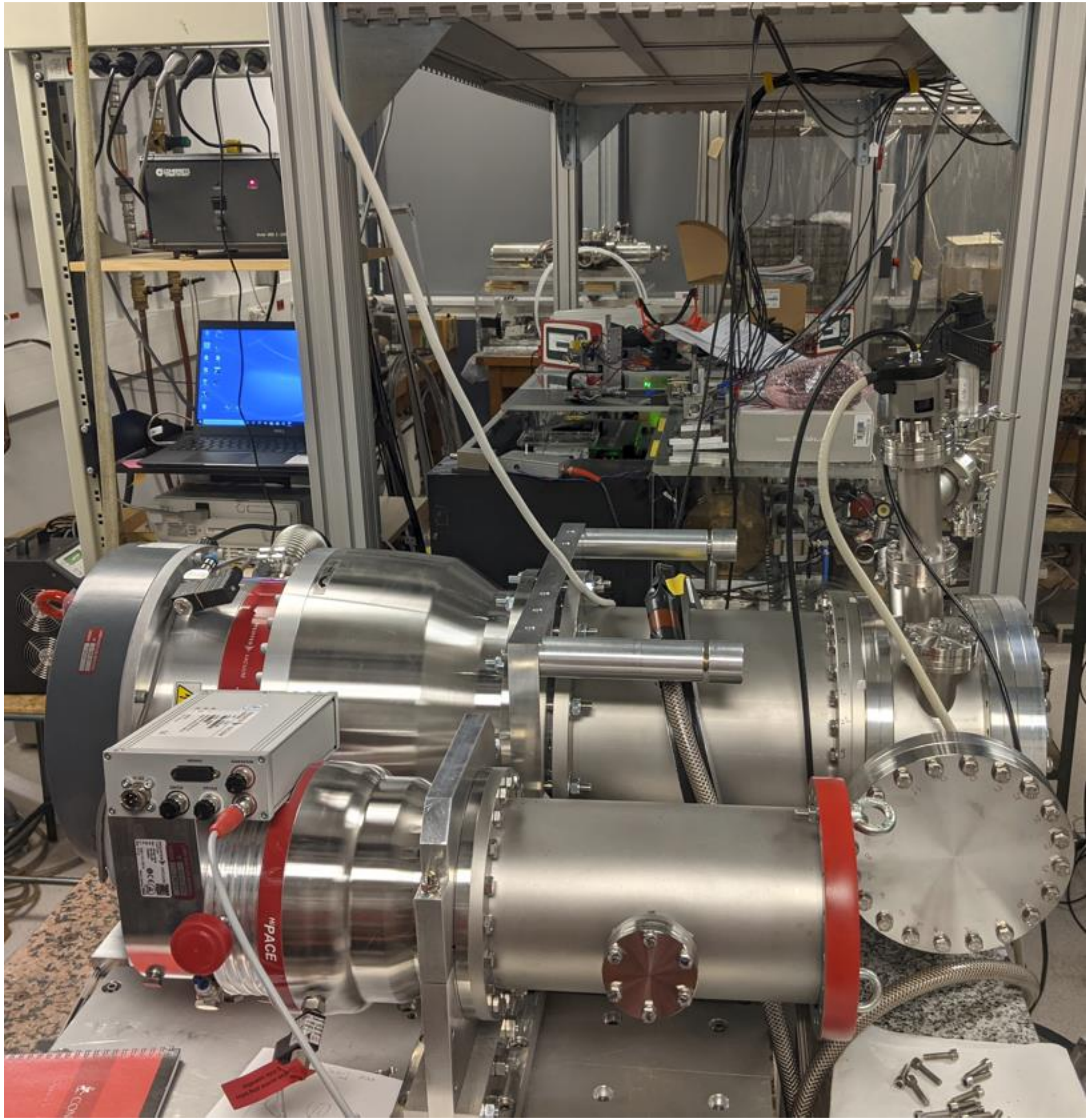


The new H beam experiment

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

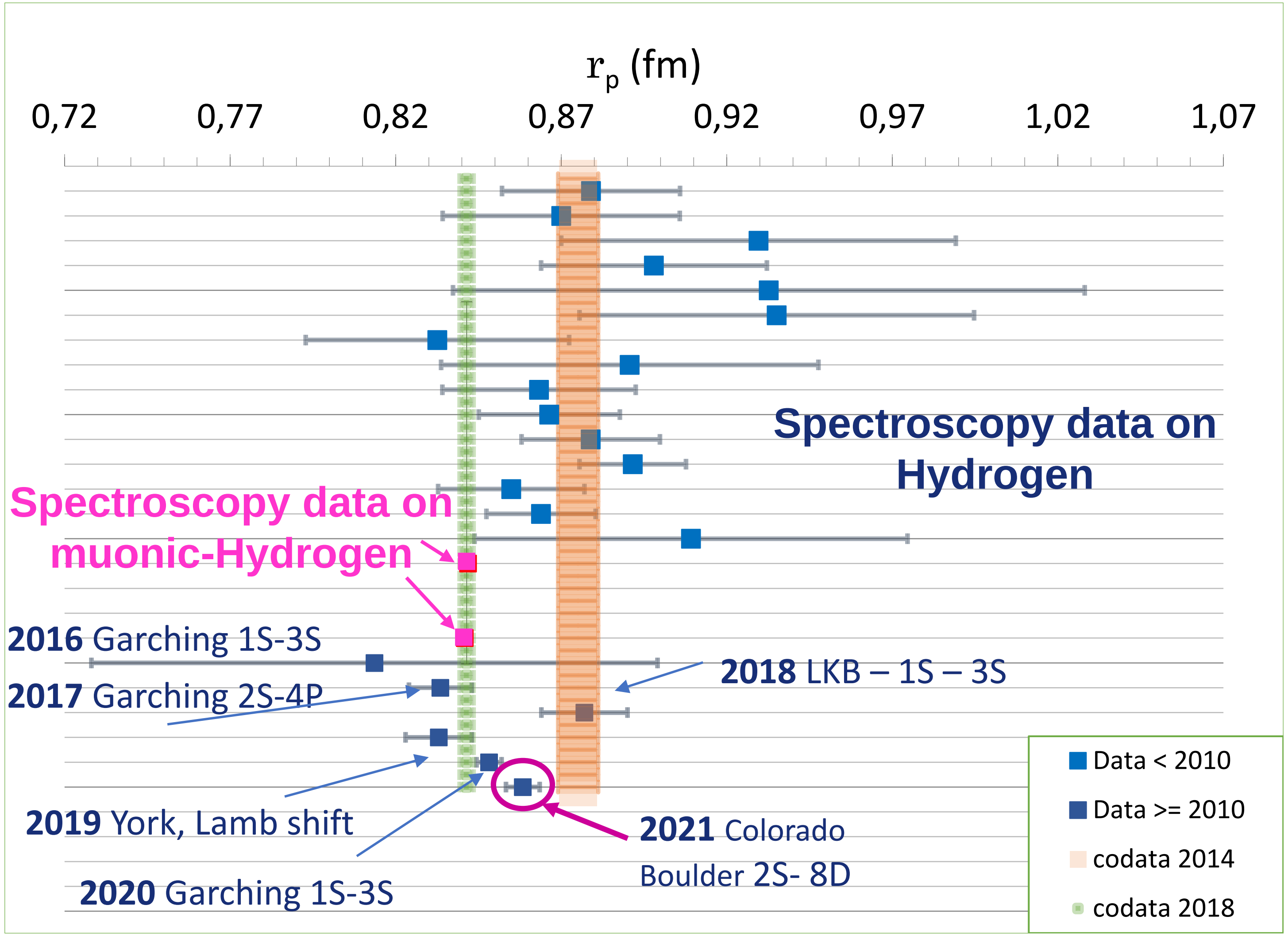


1S-4S spectroscopy

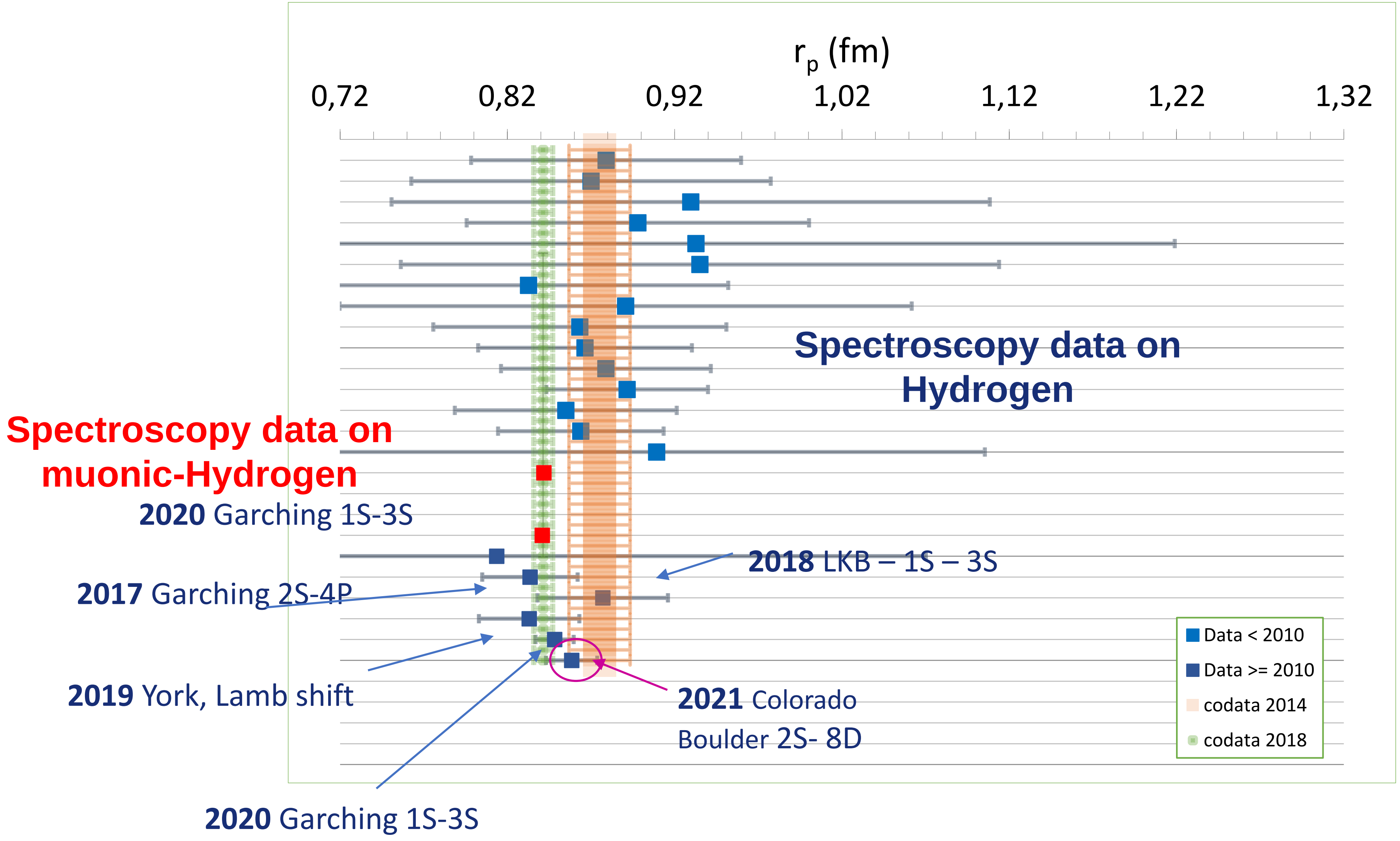


Back up

The proton radius puzzle ? 1 sigma



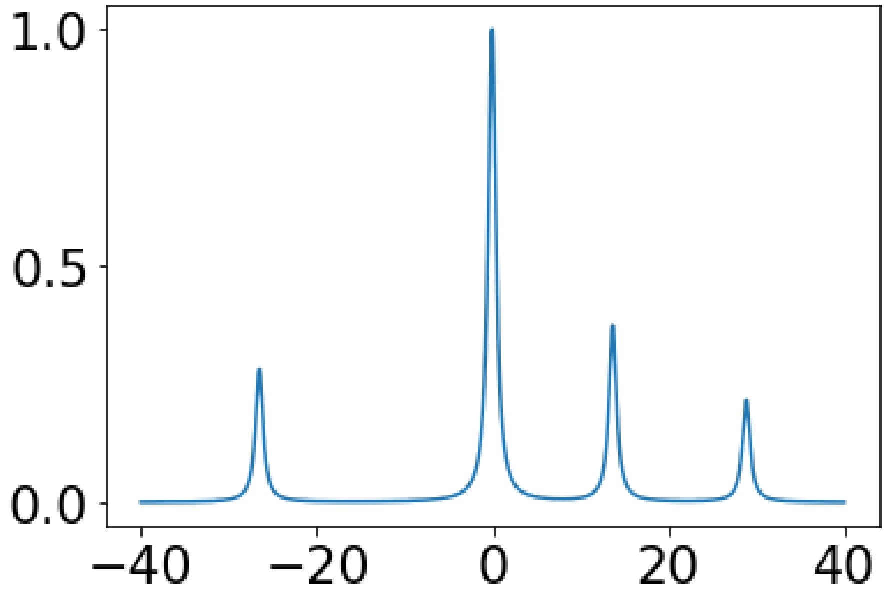
The proton radius puzzle ? 3 sigmas

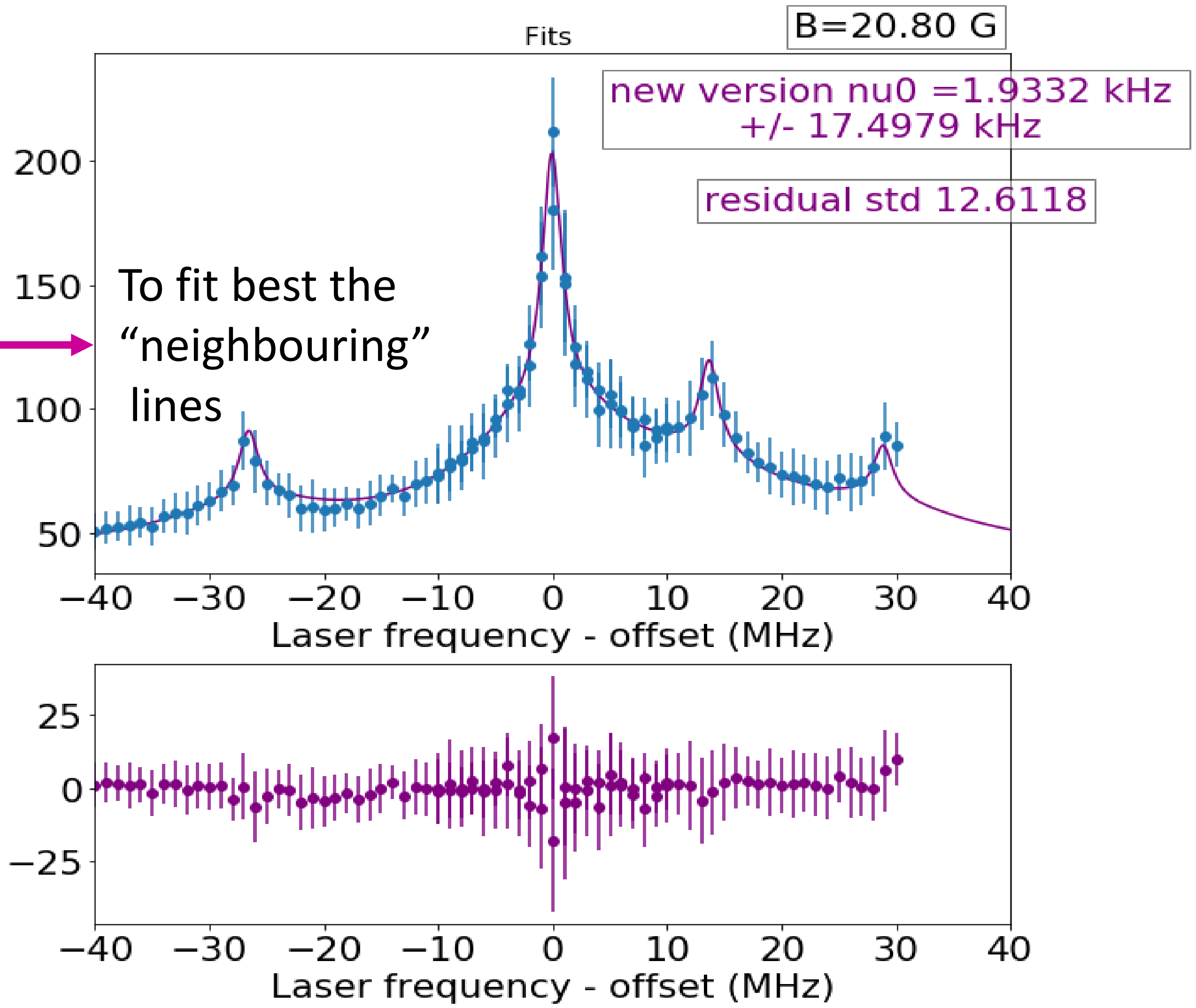


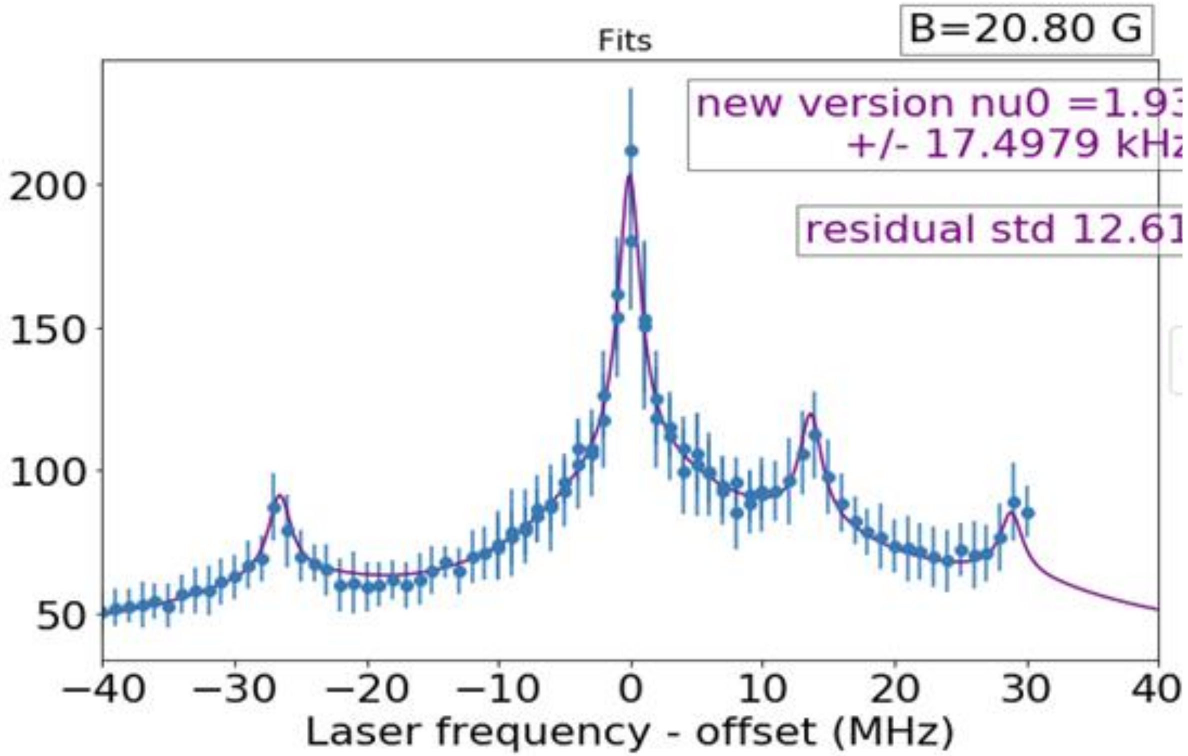
Calibration of B fields – 2 methods

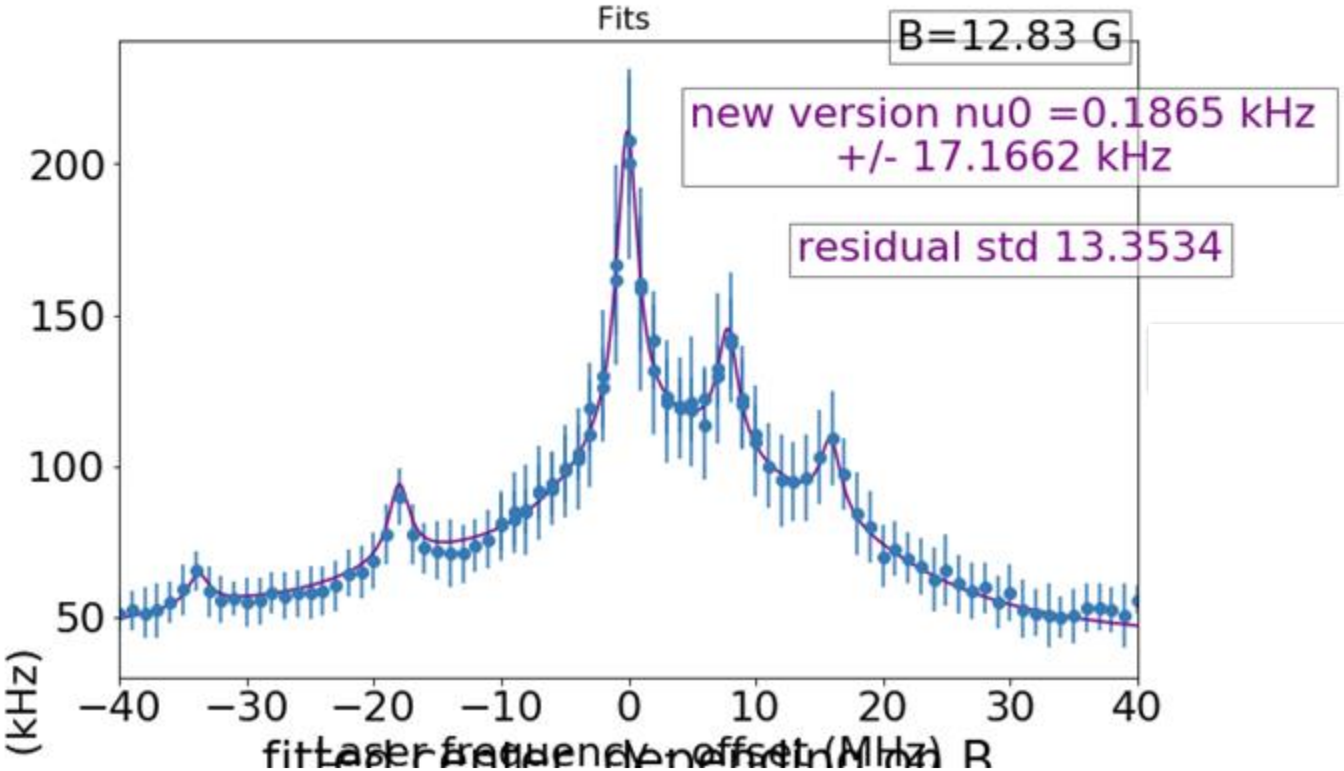
- 1) Over one Zeeman shifted line
- 2) With neighbouring lines at low B field

Theory curve

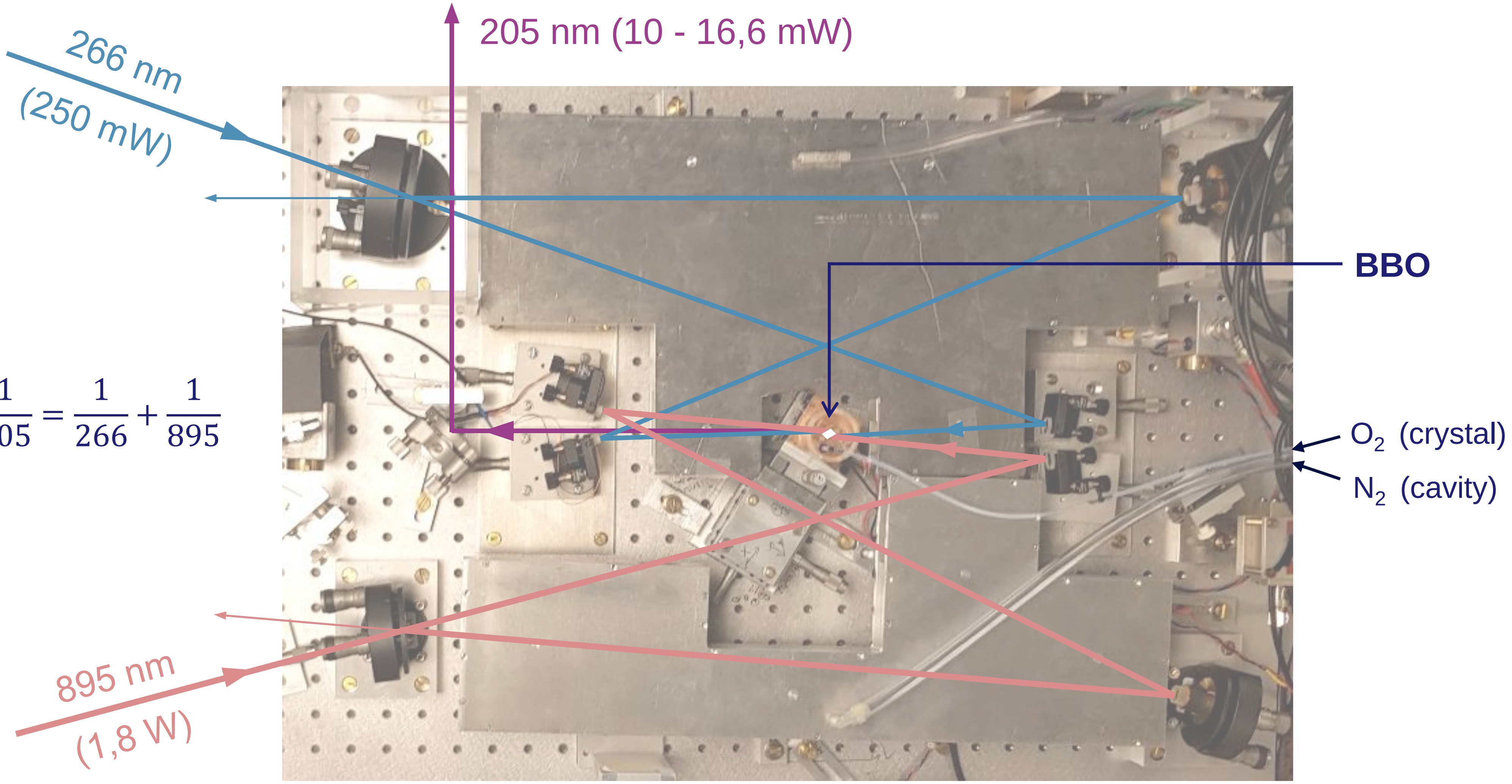





Fits
B=20.80 G
new version nu0 =1.93
+/- 17.4979 kHz
residual std 12.61
Laser frequency - offset (MHz)

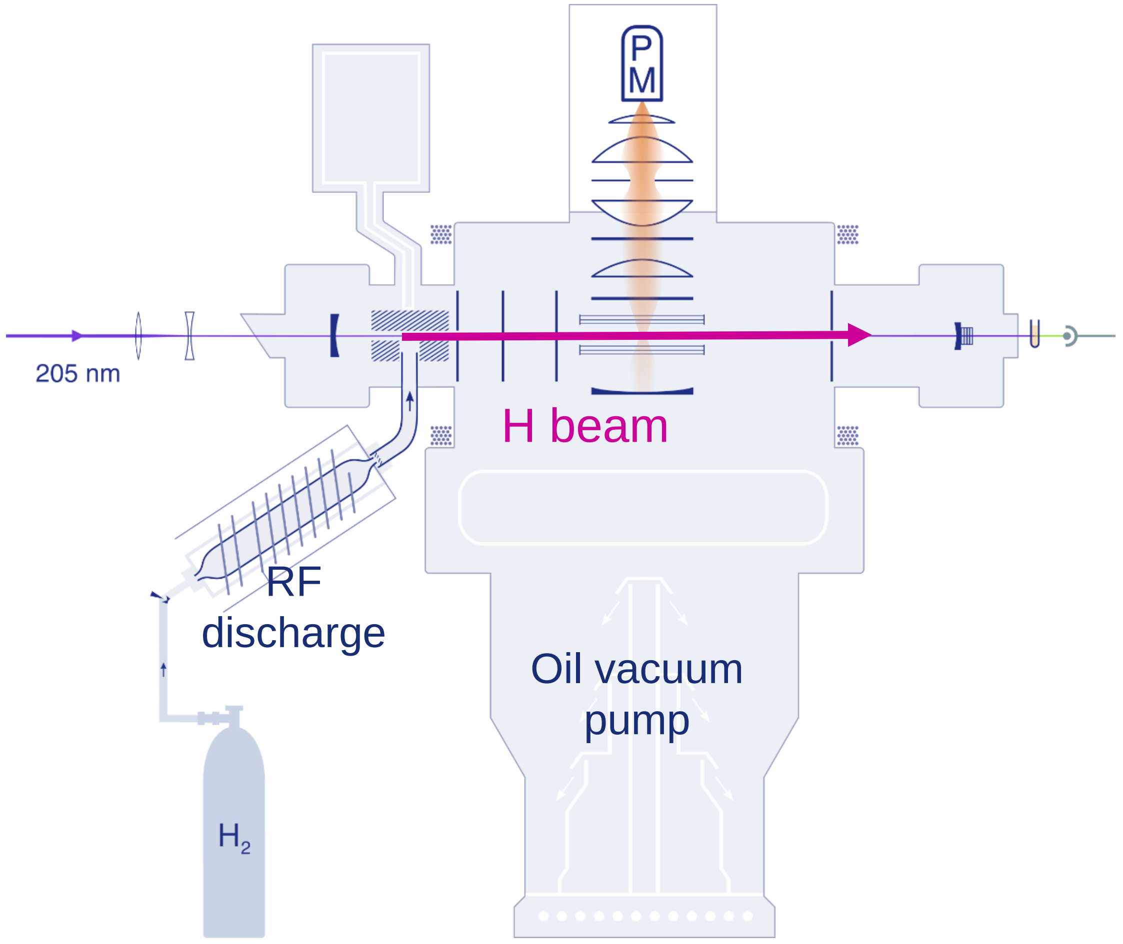

Fits
B=12.83 G
new version nu0 =0.1865 kHz
+/- 17.1662 kHz
residual std 13.3534
Laser frequency - offset (MHz)

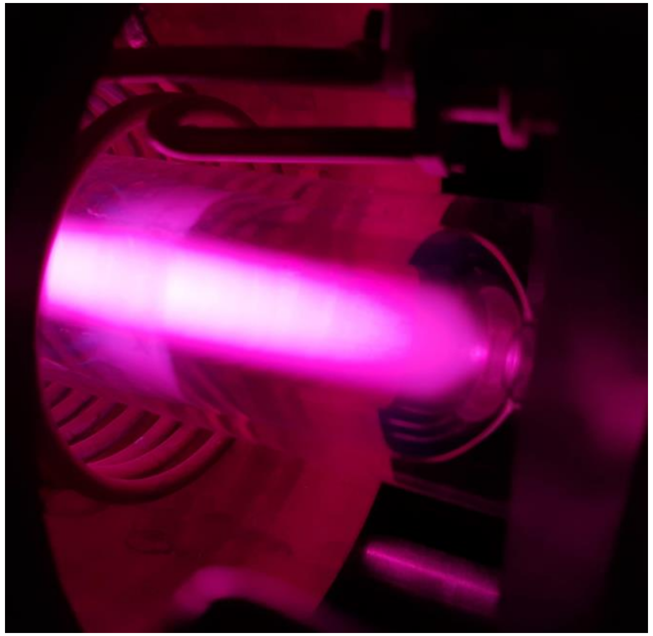
CW 205nm laser generation



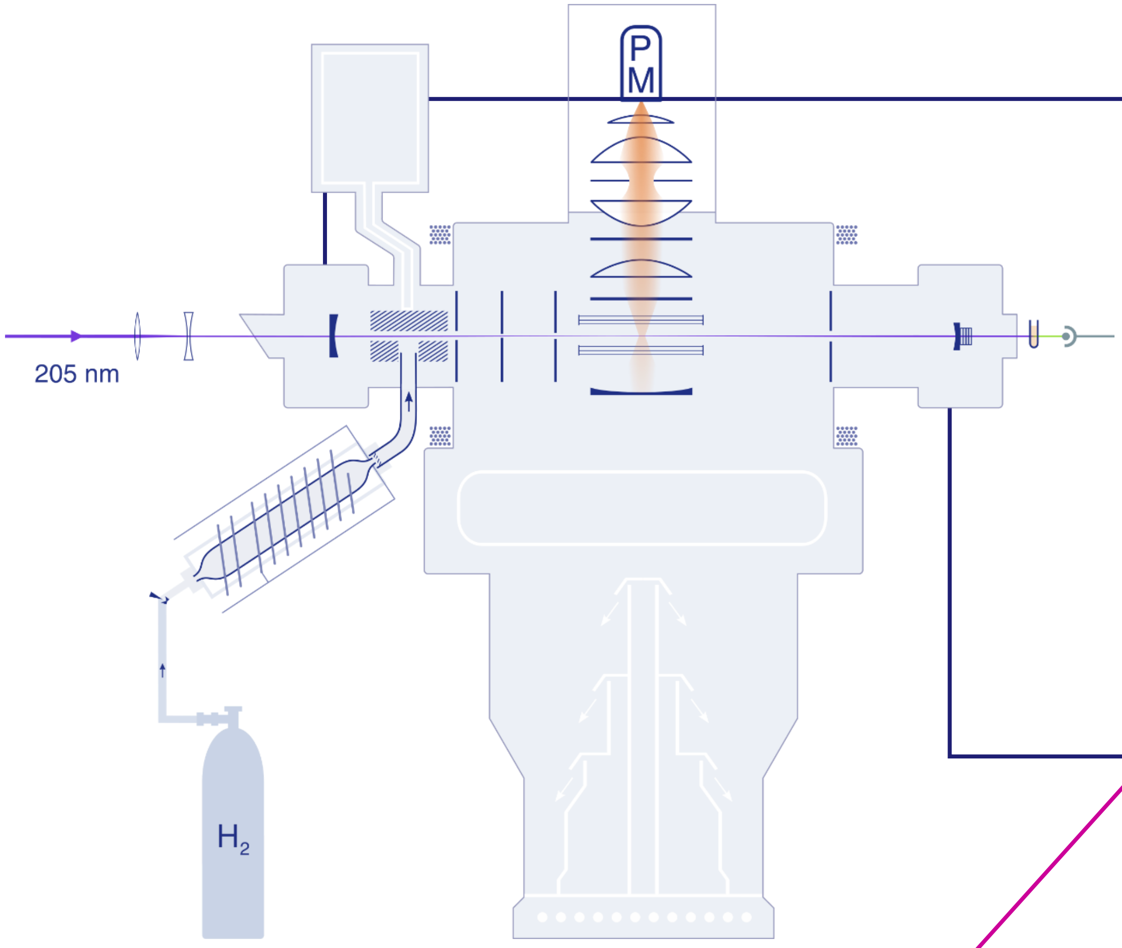
$$\frac{1}{205} = \frac{1}{266} + \frac{1}{895}$$

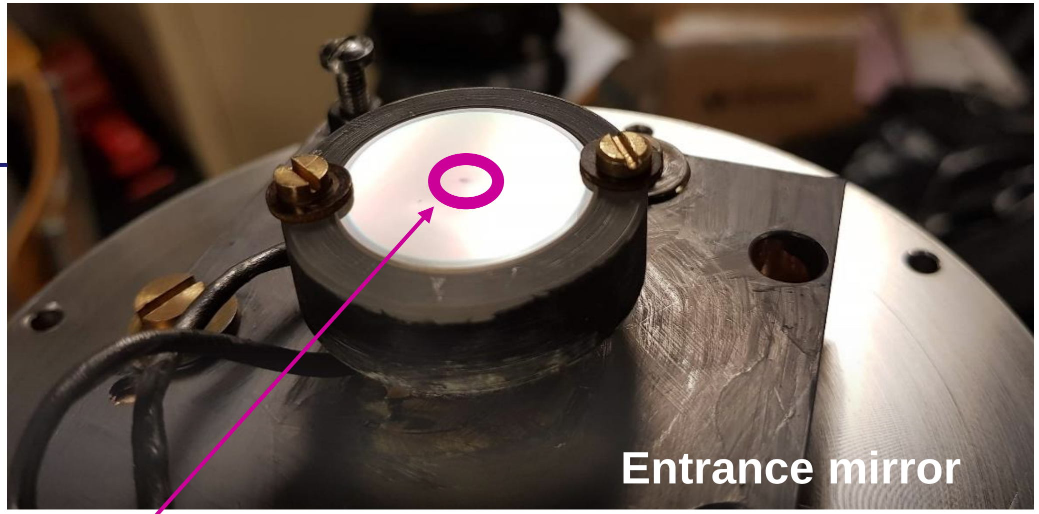
Schematic of the «old » H beam experiment

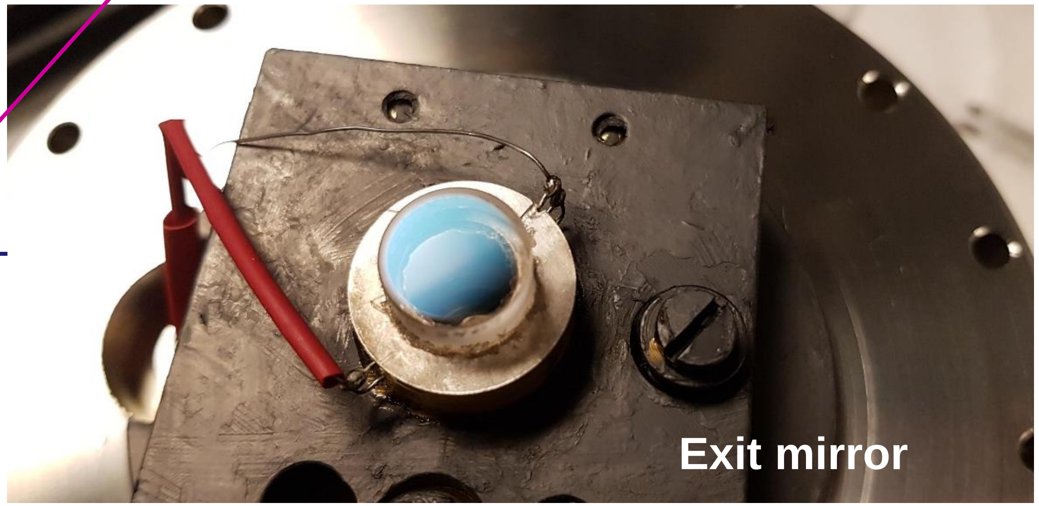




Schematics of the «old » H beam experiment





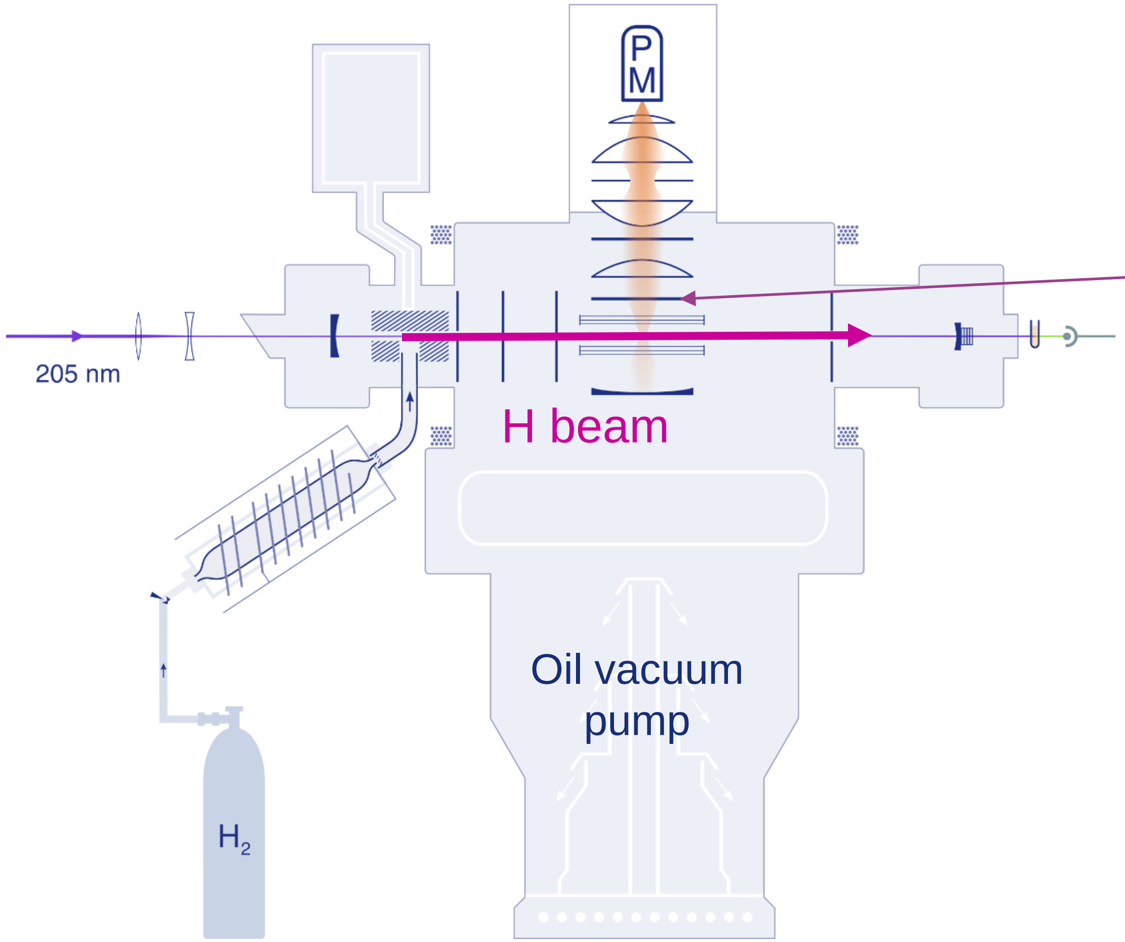


Pollution of the mirrors $\Rightarrow$ breaking vacuum every 2 days to clean

Slide – courtesy of S. Thomas

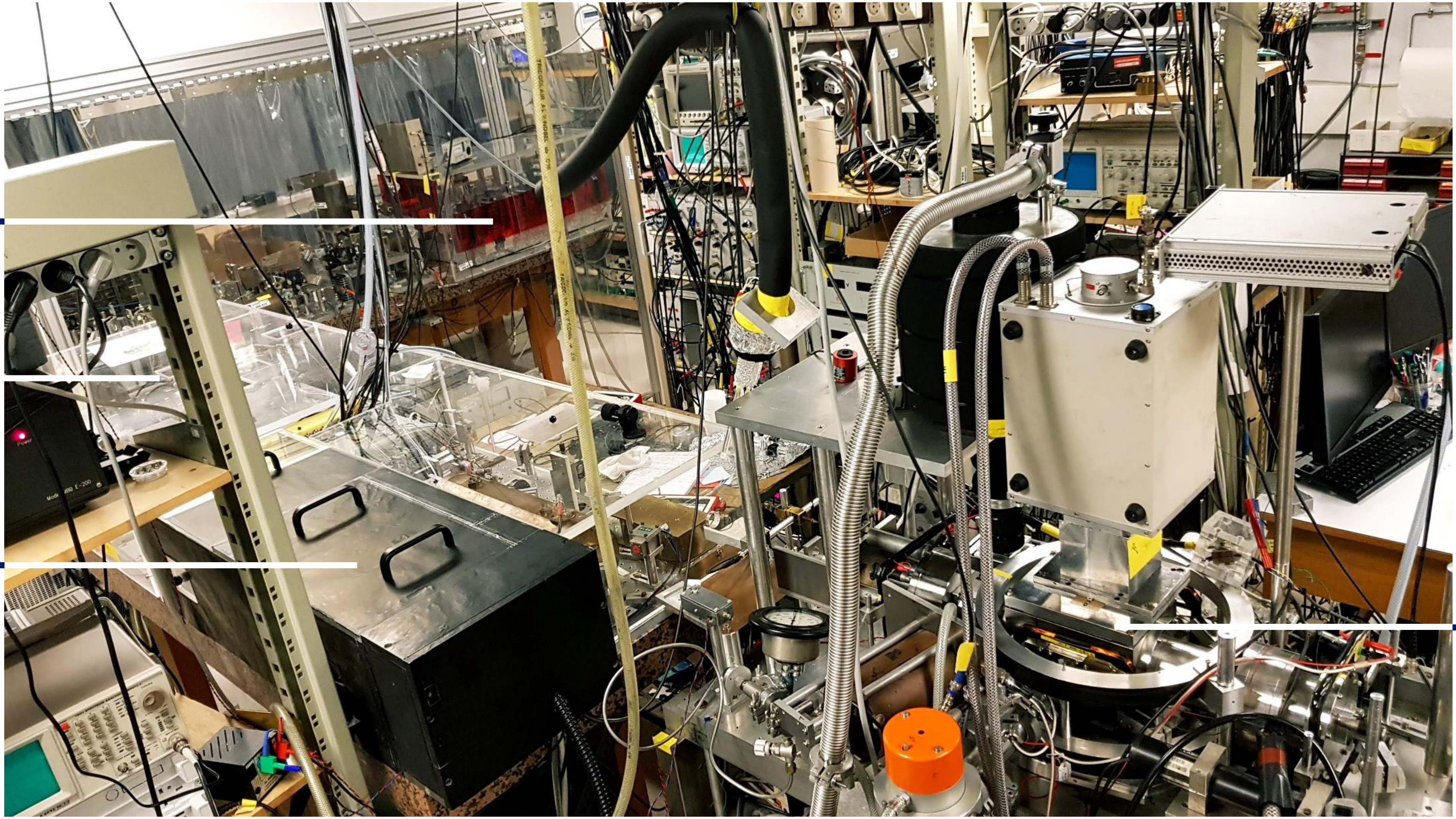
Schematic of the «old » H beam experiment

B= 0.46G



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

With some light ON



Picture – courtesy of S. Thomas

Velocity distribution of the D beam