« Mise en pratique » of the new kelvin with a direct link to the primary time-frequency standard

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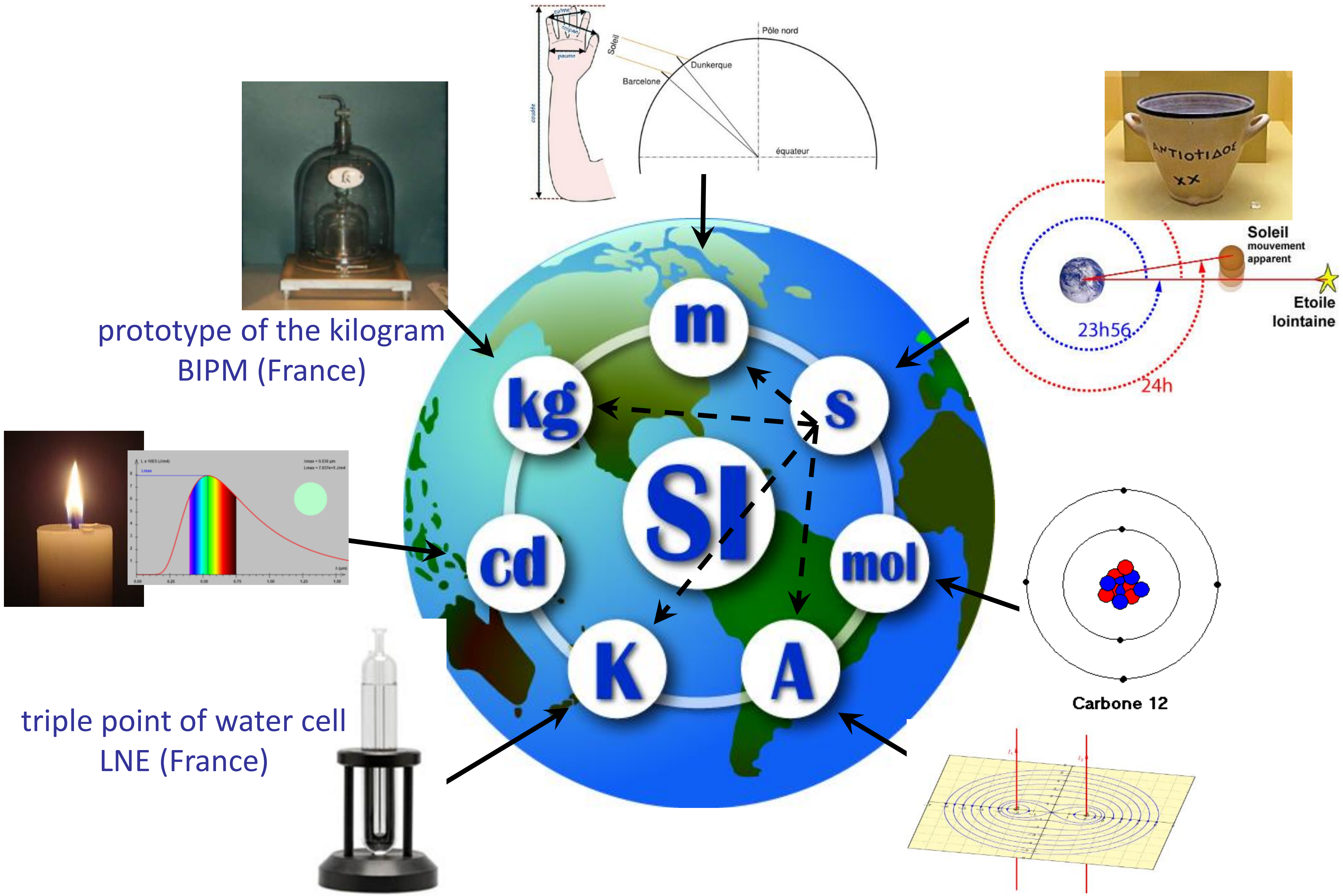
10 Octobre 2019

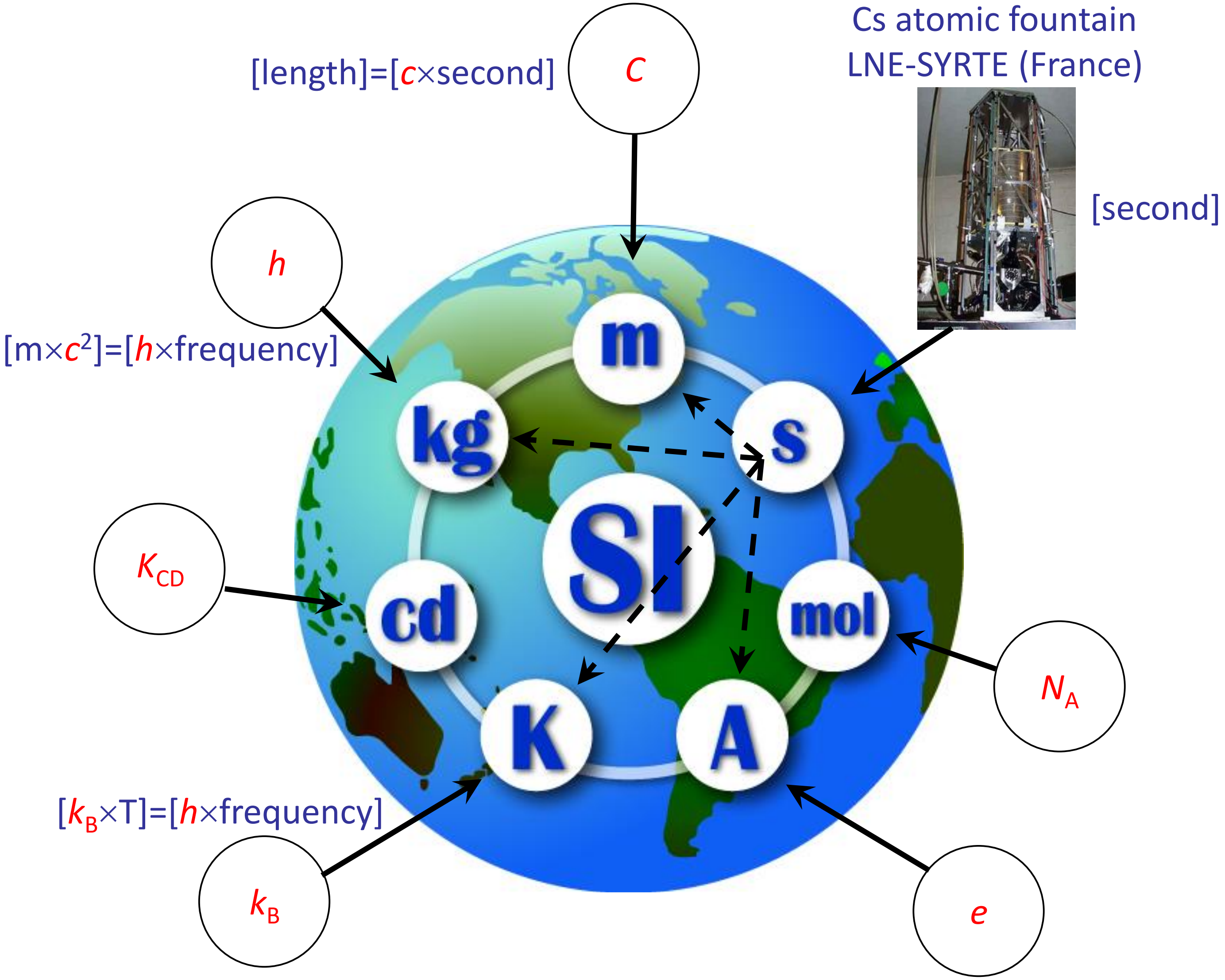
Context: redefinition of the International System of Units (SI)



Context: redefinition of the International System of Units (SI)

- **11/2018:** approval by the 26th General Conference on Weights and Measures (CGPM, Versailles)
- **20/05/2019:** new SI came into effect (World Metrology Day)

- Redefine units by fixing the value of some fundamental constants
- Discard macroscopic artifacts
- Link all other units to the second

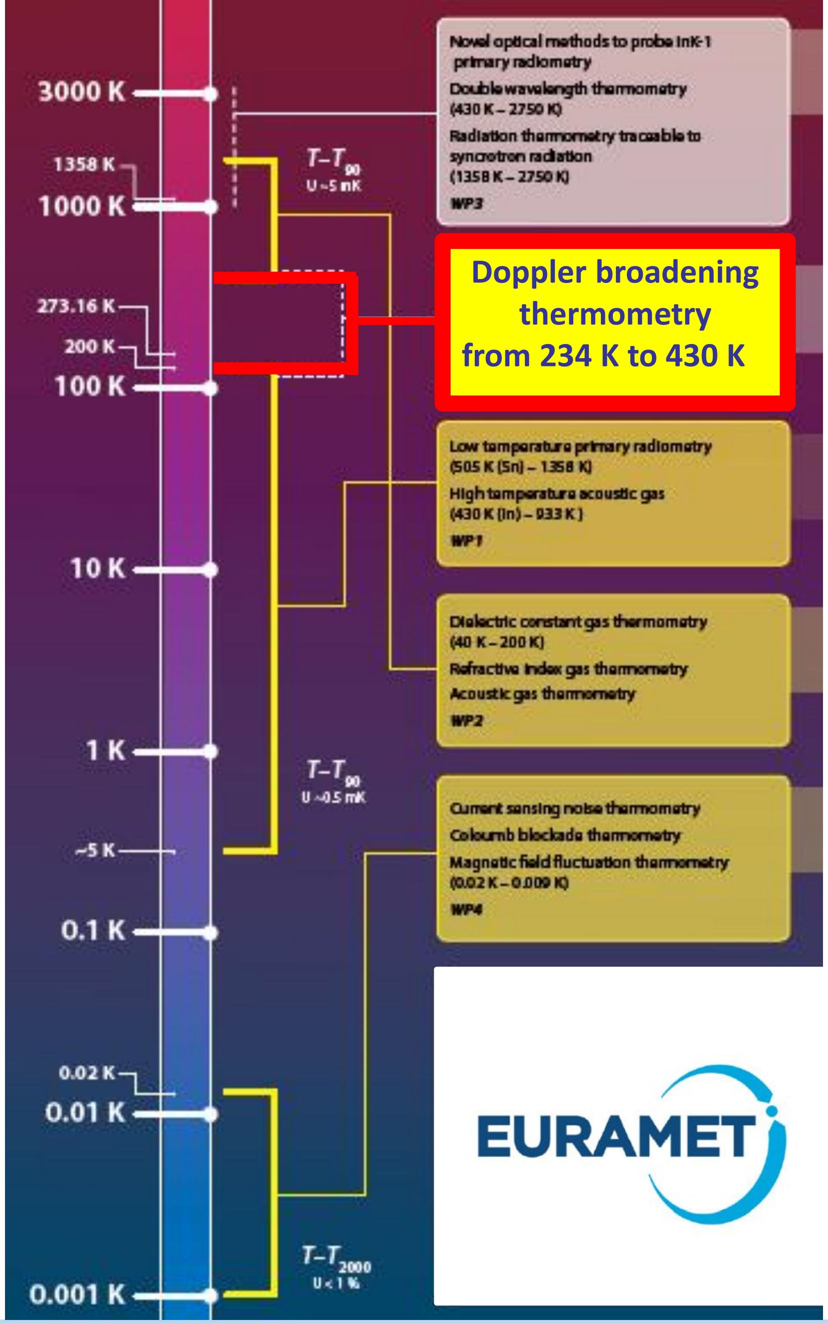


Context: Temperature measurement

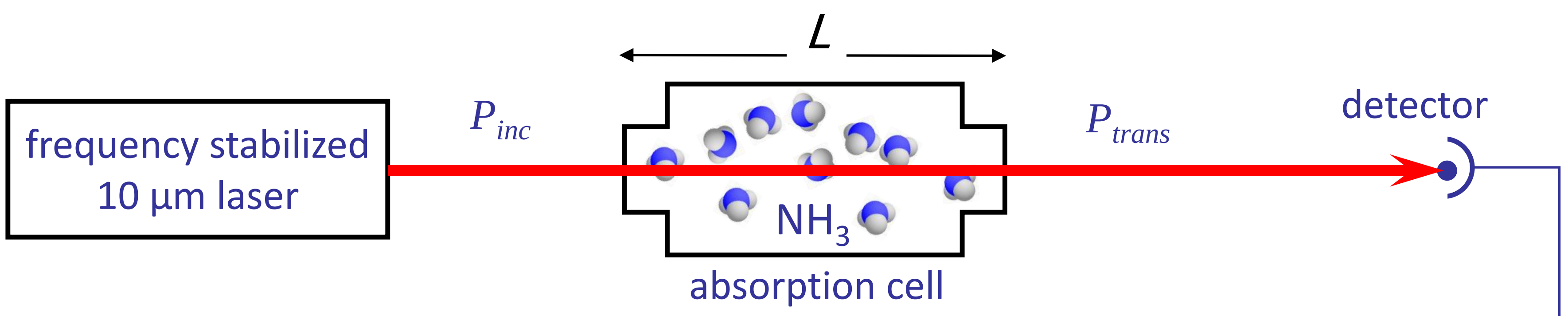
Doppler Broadening Thermometry (DBT) as a <u>novel primary method</u> in the frame of European Joint Research Project <u>« Implementing the New Kelvin 2 »</u>

<u>Temperature range</u> :

- from the Hg triple point (234 K) to In freezing point (430 K)
- Compare our new technique to old ITS-90 measurement

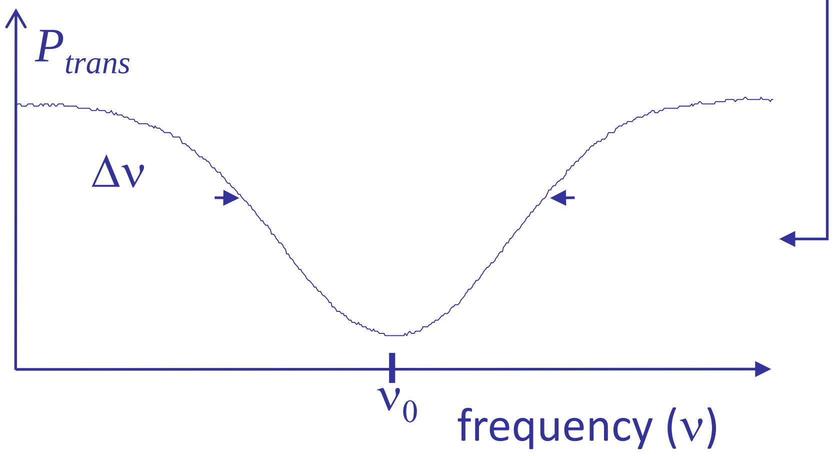


The Doppler Broadening Technique



<u>Beer law :</u>

$$P_{trans} = P_{inc} exp(-\alpha(\nu)L)$$

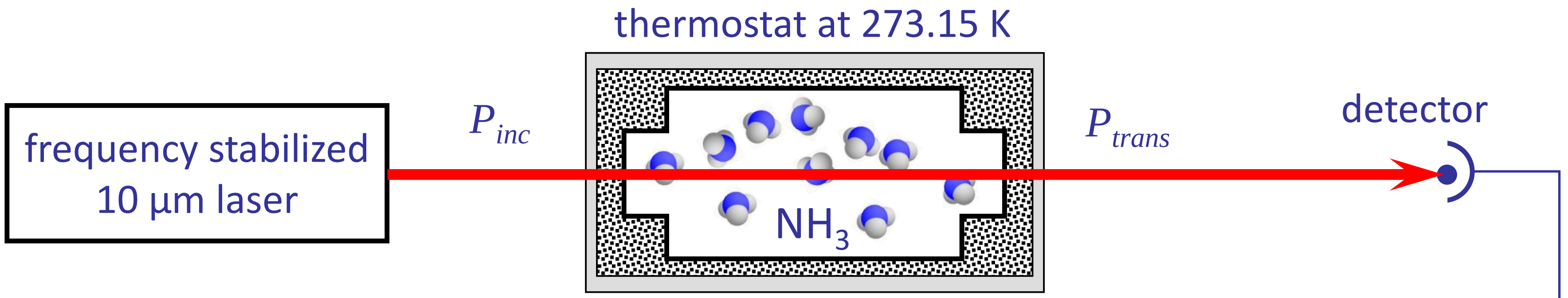


$$k_B T = \frac{m}{2}\left(\frac{\Delta \nu_D}{\nu_0} c\right)^2$$

record the absorption profile

extract $k_B T$, k_B or T

The Doppler Broadening Technique



Beer law :

$$P_{trans} = P_{inc} exp(-\alpha(\nu)L)$$

$\alpha(\nu)$
- Doppler broadening
- Collisional broadening
- Speed dependent effect
- Dicke narrowing
- Hyperfine structure
- …

$k_B = 1.380704(69) \times 10^{-23}\, J.K^{-1}$

$50\ ppm$ combined uncertainty, $\approx 10\ ppm$ statistical uncertainty

Now Few ppm systematic effects

$$k_B T = \frac{m}{2}\left(\frac{\Delta\nu_D}{\nu_0}c\right)^2$$

record and model the absorption profile

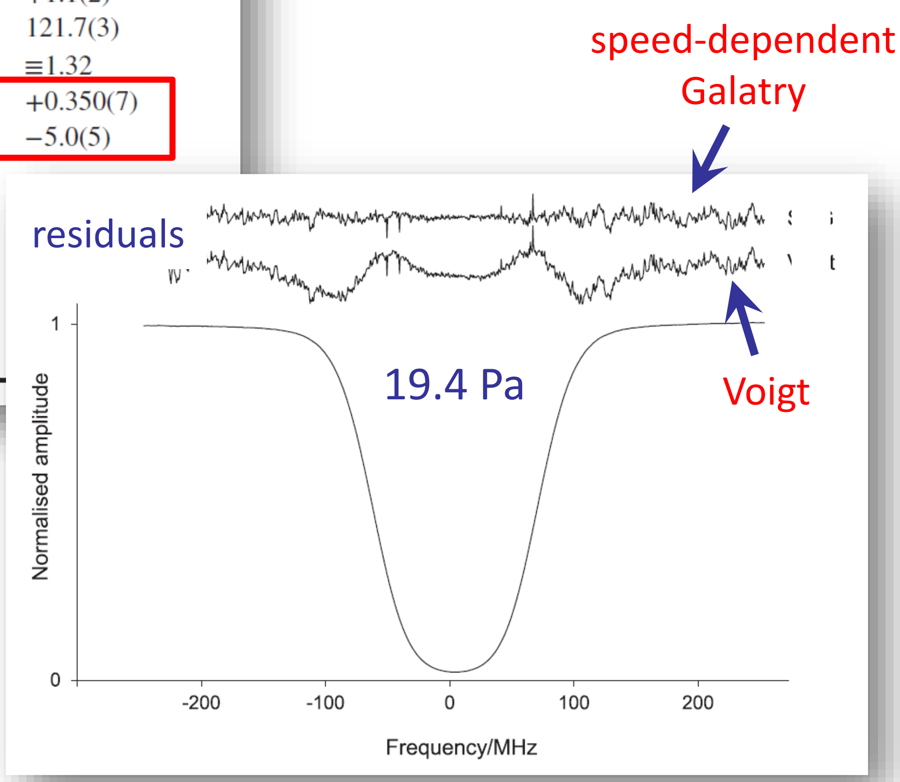
to extract k_B: control and measure the temperature ⇒ thermostat at 273.15 K

[1] Fisher *et al.*, Metrologia **55**, R1-R20 (2018)

Line shape

Table 1. Line shape spectroscopic parameters (and their standard uncertainties) derived from various line profiles for the self-broadened ν_2 saQ(6,3) line of NH_3 around 273.15 K, for a cell length $L \cong 37$ cm (frequencies shifted by 28 953 690 MHz).

Parameter	Unit	Voigt profile	Galatry profile	speed-dependent Voigt profile	speed-dependent Galatry profile
			This work		
A_0	MHz Pa^{-1}	18.143(3)	18.209(4)	18.205(4)	18.208(4)
ν_0	MHz	3.924(2)	3.925(2)	3.918(3)	3.918(3)
δ_0	kHz Pa^{-1}	+1.7(2)	+1.7(2)	+1.1(2)	+1.1(2)
γ_0	kHz Pa^{-1}	117.9(3)	122.4(4)	121.5(3)	121.7(3)
β_G	kHz Pa^{-1}	0	23.8(4)	0	≡1.32
m	—	0		+0.350(7)	+0.350(7)
n	—	0		−5.0(5)	−5.0(5)
			From [29]		
δ_0	kHz Pa^{-1}	+0.99(4)	+1.01(4)	+1.2(1)	
γ_0	kHz Pa^{-1}	106 to 130	120.9(3)	120(3)	
β_G	kHz Pa^{-1}	0	14 to 32	0	
m	—	0	0	+0.360(7)	
n	—	0	0	−3.8(3)	



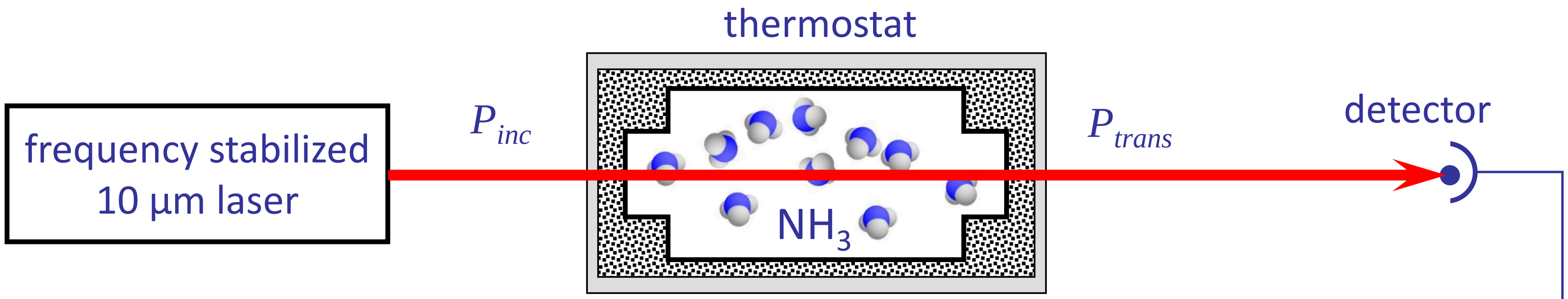
Fit with various models:

- speed-dependent effects essential
- velocity-changing collisions negligible, fixed

- uncertainty on speed-dependent collisional parameters ⇒ uncertainty on $k_B T$: 1.8×10^{-6}

M. Triki *et al.*, Phys. Rev. A (2012); Mejri *et al.*, Metrologia (2015)

The Doppler Broadening Technique



Beer law :

$$P_{trans} = P_{inc} exp(-\alpha(\nu)L)$$

$\alpha(\nu)$
- Doppler broadening
- Collisional broadening
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- Hyperfine structure
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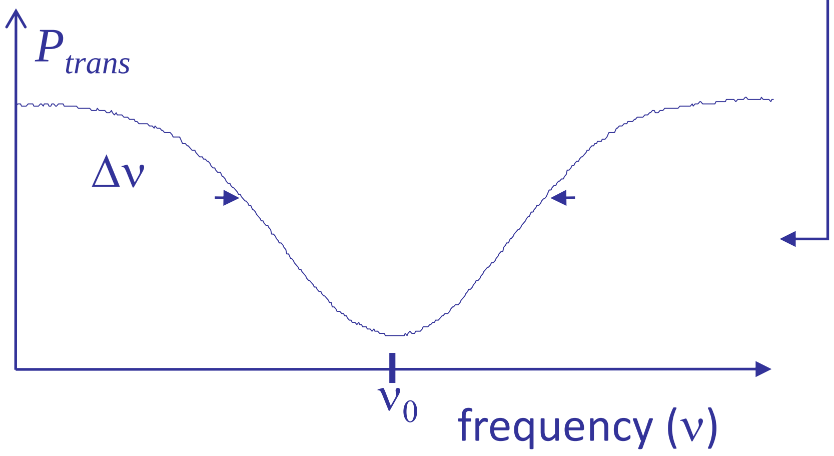
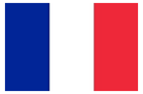
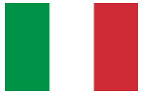
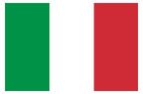


$$k_B T = \frac{m}{2}\left(\frac{\Delta\nu_D}{\nu_0}c\right)^2$$

record and model the absorption profile

once k_B fixed $\Rightarrow$ extract T

The Doppler Broadening Technique in 2019

	Group	Species	Wavelength
	Our group [1]	NH_3	10.3 µm
	L. Gianfrani et al. [1,2]	CO_2 , H_2O , C_2H_2	2 µm / 1.39 µm
	A.Luiten et al. [3]	Rb , Cs	0.8-0.9 µm
	M.Marangoni, L. Gianfrani et al. [4]	CO_2	1.6 µm
	C.-F. Cheng et al. [5]	CO , C_2H_2	1.6 / 0.8 µm
	J. Kitching et al. [6]	Rb , Cs	0.8 - 0.9 µm
	Y. Pan et al. [7]	Cs	0.9 µm

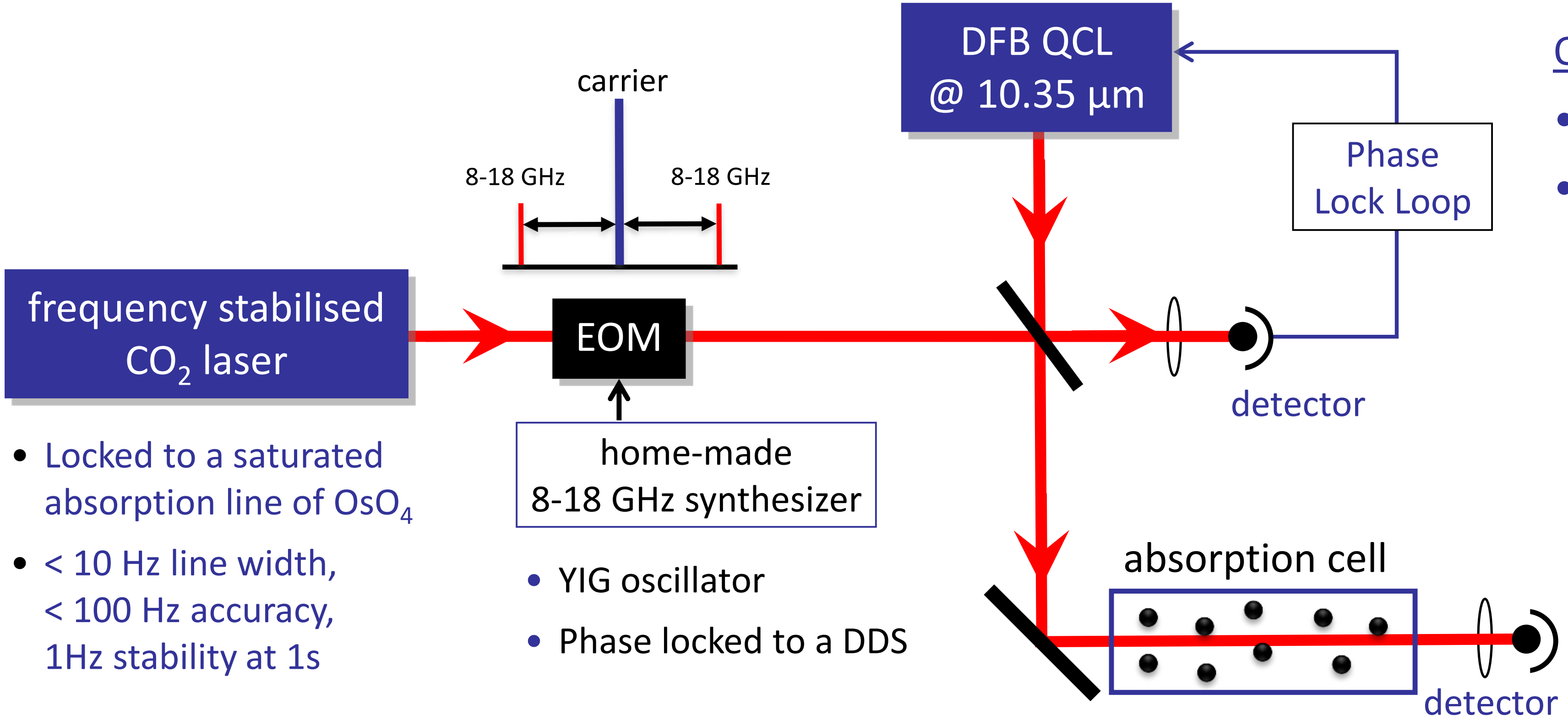
Conventional Linear absorption spectroscopy

Using cavity ring-down spectrocopy

Absorption
(practical or chip-scale)

[1] Fisher *et al.*, Metrologia **55**, R1-R20 (2018)
[2] Gianfrani et al., Phys. Rev. applied (2019)
[3] Truong *et al.*, Nat. Commun. **6,** 8345 (2015)
[4] Gotti *et al.*, Phys. Rev. A **97**, 12512 (2018)
[5] Cheng *et al.*, Metrologia **52**, S385 (2015)
[6] Kitching *et al.,* J.Phys.Conf.Ser. 723 012056 (2016)
[7] Pan *et al.*, Tempmeko 2019

The frequency stabilized 10 µm source

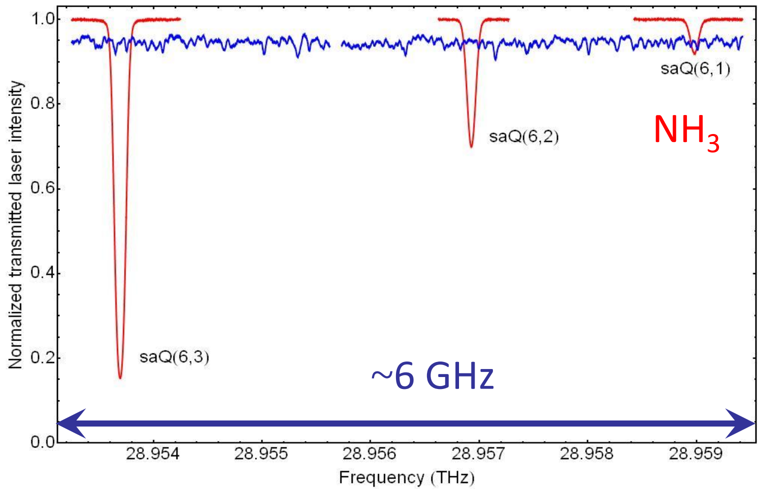


- Locked to a saturated absorption line of OsO_4
- < 10 Hz line width, < 100 Hz accuracy, 1Hz stability at 1s

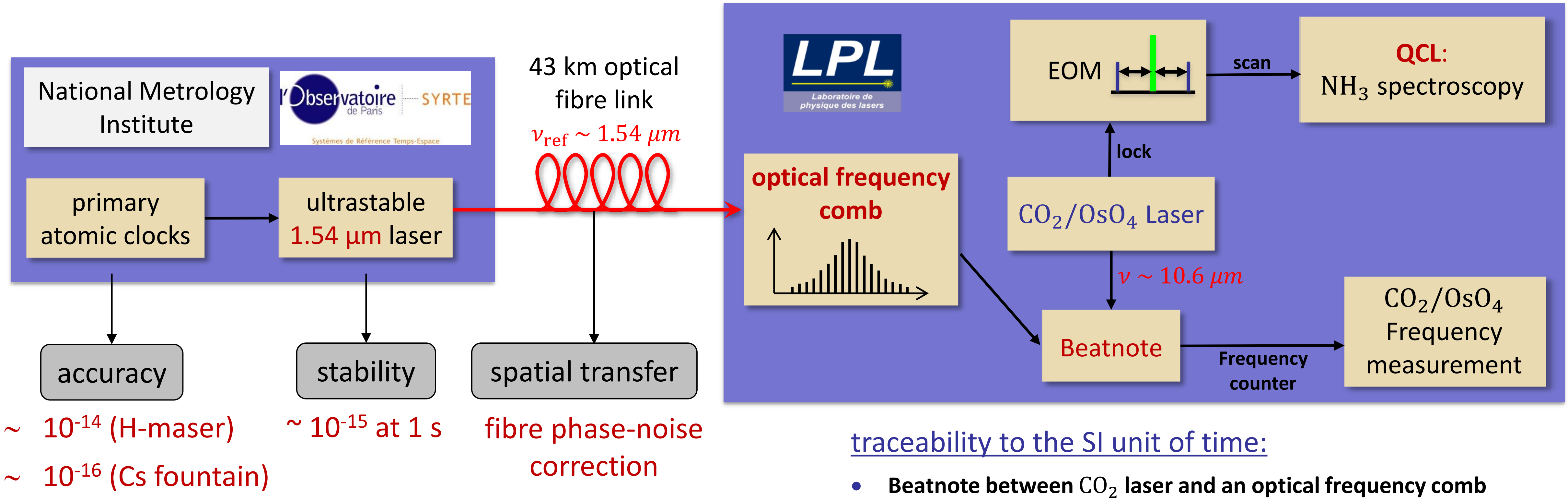
- YIG oscillator
- Phase locked to a DDS

QCL:

- < 10 Hz linewidth, 1 Hz stability at 1 s
- Continuously tuneable over 10 GHz around each CO_2 laser line



Link to the SI unit of time



$$\nu_{OsO_4/CO_2} = \frac{n}{N}\left(\nu_{ref} + \Delta\right) + \text{Beatnote}$$

Measured at SYRTE **PLL frequency shifts**

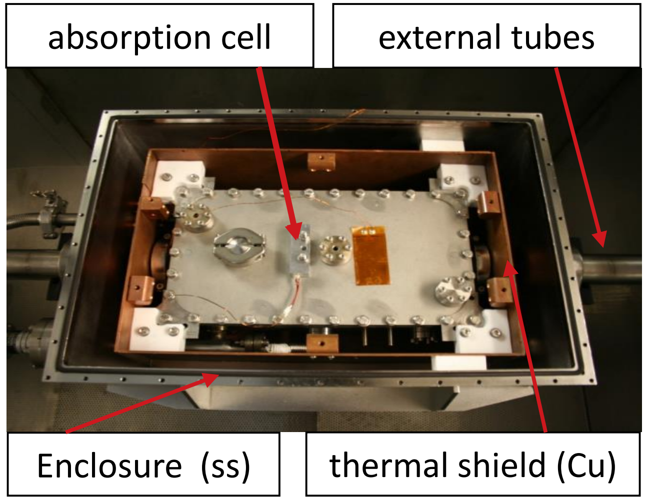
traceability to the SI unit of time:

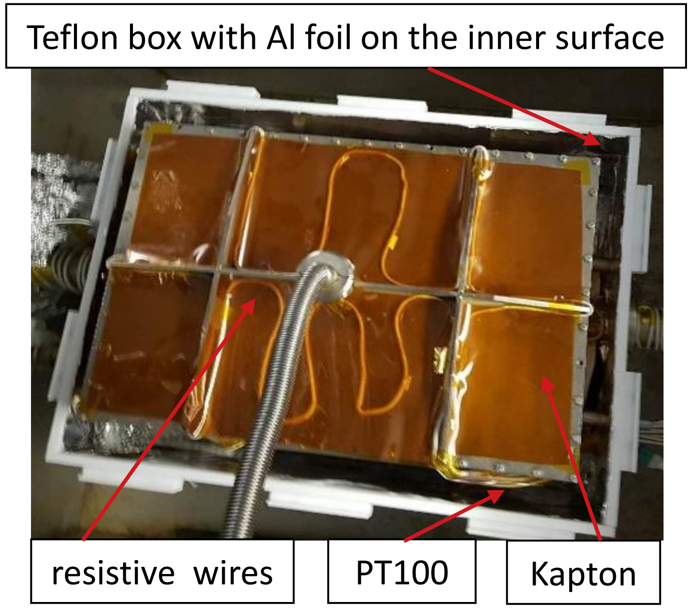
- **Beatnote between CO_2 laser and an optical frequency comb**
- **Count Beatnote Frequency**

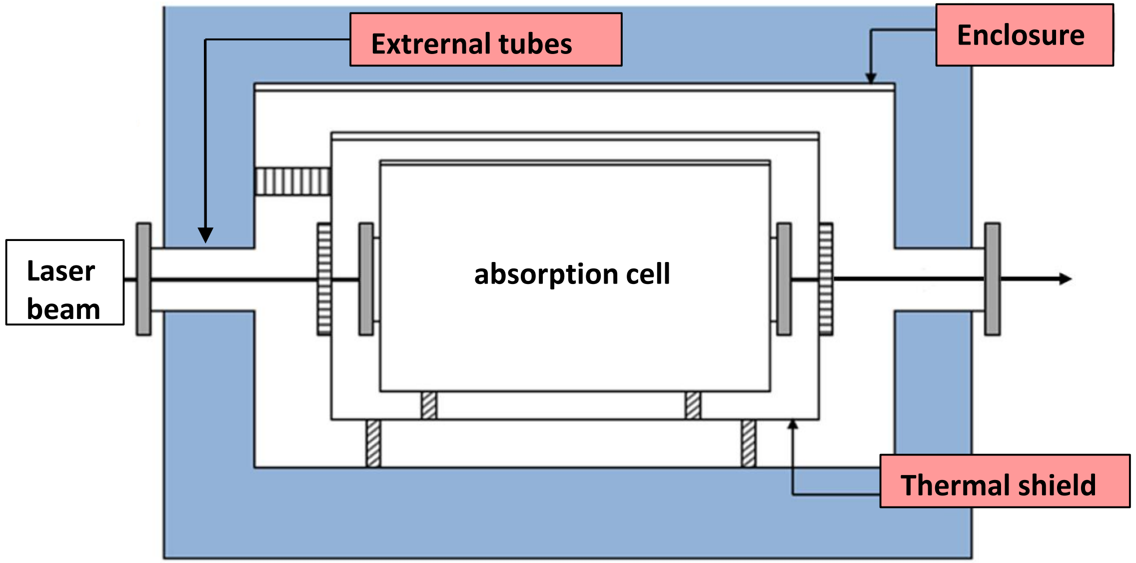
Uncertainty on the QCL absolute frequency:

- **Sub-100 Hz contribution from the CO_2/OsO_4laser**
- **<0.1 Hz contribution from the µW driving the EOM**

Thermostat



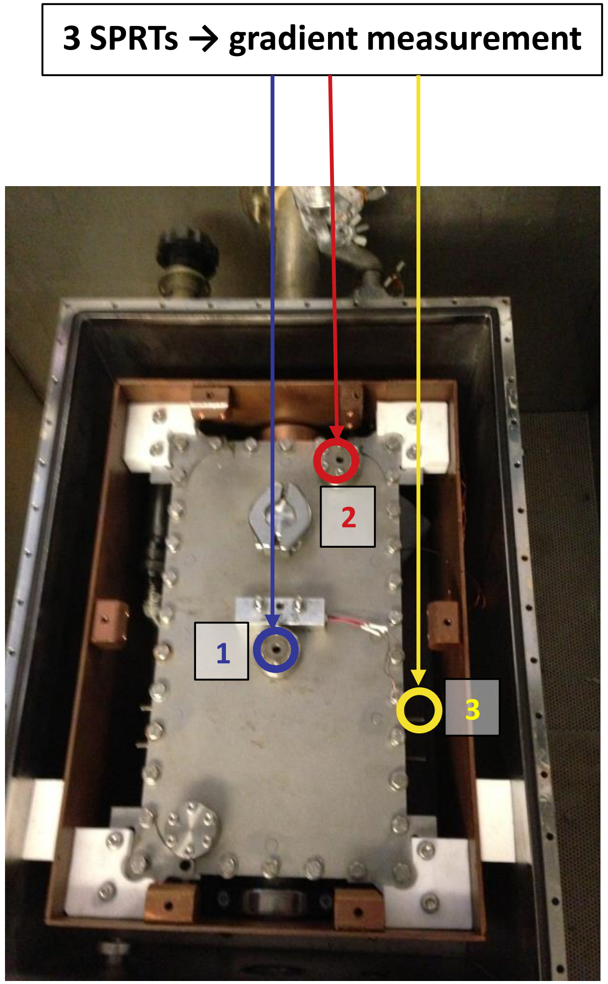




<u>Temperature stabilization:</u>

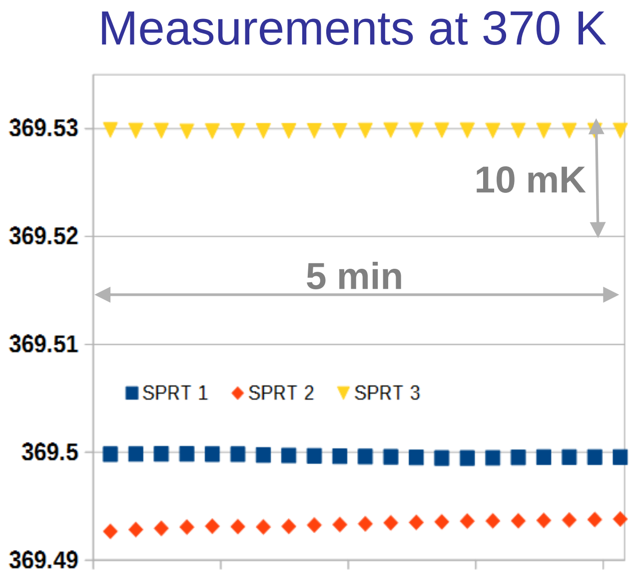
- 2 PI controllers for enclosure and external tubes
- PT100 for the temperature control of the thermostat

Thermostat characterization and ITS-90 measurement



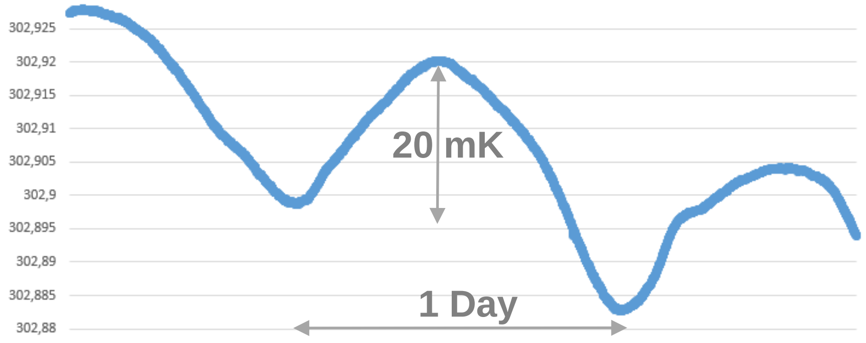
<u>Gradient measurements:</u>

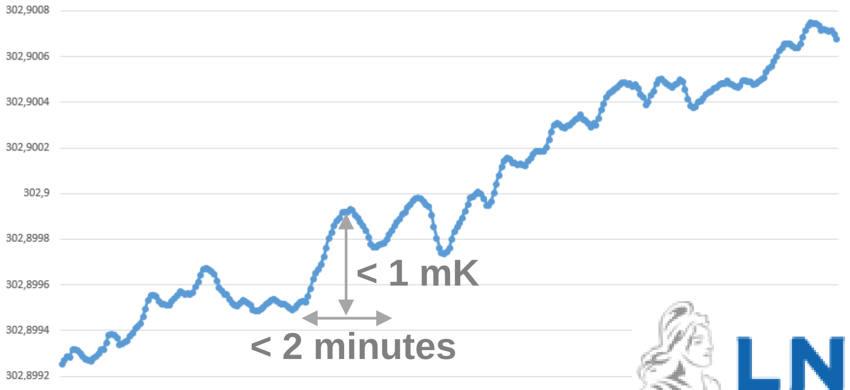
- **SPRT 1** and **SPRT 2** are in wells at the center and near the edge.
- **SPRT3 stuck on the wall**



<u>Stability measurements:</u>

- Day/Night cycle
- Typical stability <50 mK over several days at 370 K





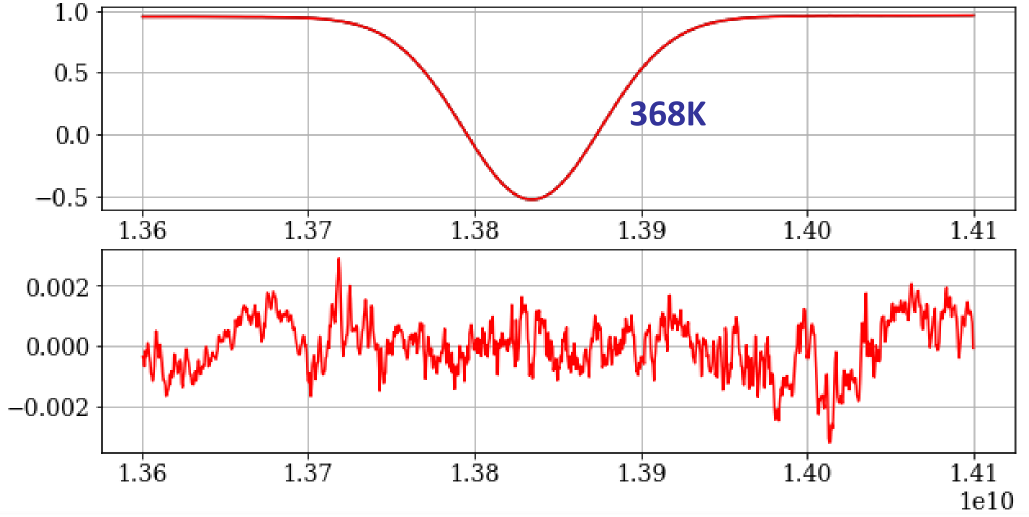
Le progrès, une passion à partager

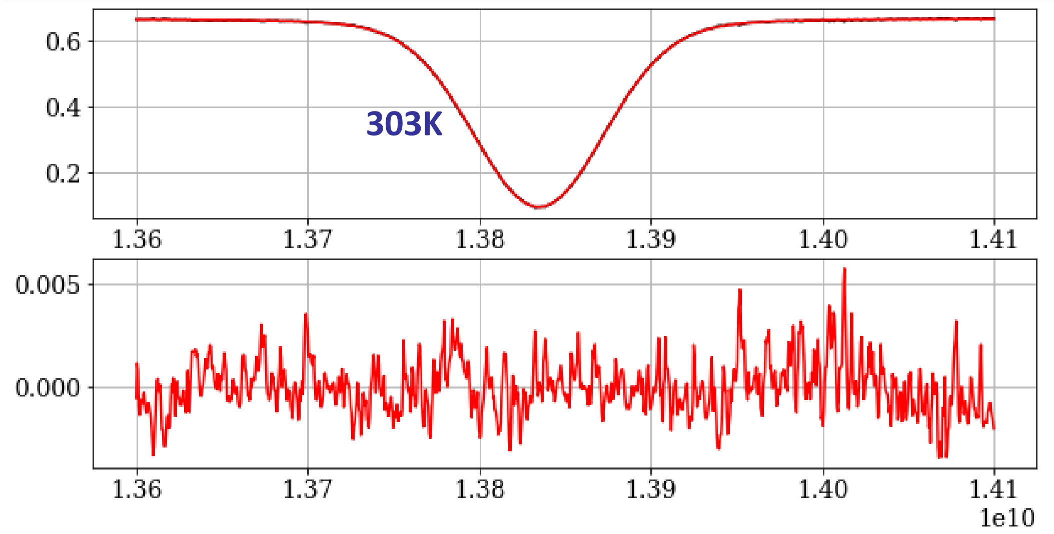
ITS-90 measurement - Uncertainty budget

		T = 303 K	T = 370 K	
origin	**uncertainty components**	**value, mK**	**value, mK**	**comments**
cell temperature	cell homogeneity	**0.8**	**1.7**	gradient inside the cell
	cell temperature fluctuations	**10.1**	**14.4**	typical fluctuation over several days
calibration chain	SPRT calibration uncertainty	**0.4**	**1.0**	calibration with uncertainty propagation a, Ro
detection chain	measurement resolution	**negl.**	**negl**	negligible
	measurement repeatability	**0.5**	**0.5**	typical noise over 1 spectrum
	reference resistance calibration	**negl.**	**negl.**	negligible
	reference resistance stability	**0.1**	**0.1**	temperature fluctuations of the oil bath
	SPRT self-heating	**1.5**	**1.5**	not corrected for, uncertainty taken equal to the shift
Combined uncertainty k=1, mK		**10.3**	**14.7**	

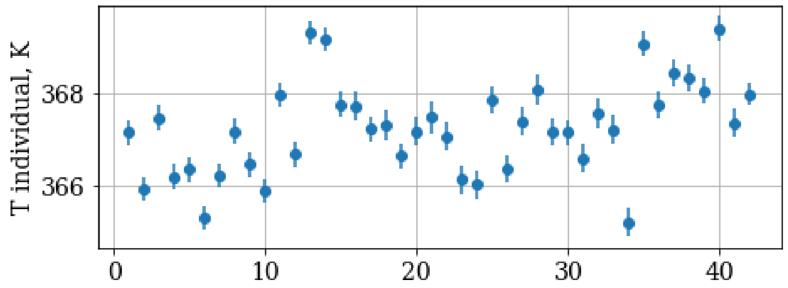
Thermodynamic temperature : First spectra at 368K and 303K

- **Typical spectra fitted with Voigt profile:**

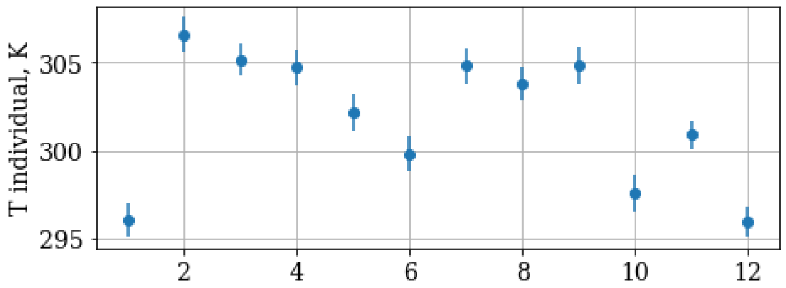




42 Spectra at 368K



20 Spectra at 302K



NEXT STEPS:

- **Spectrum S/N improvement**
- **More spectrum acquisitions**
- **Improve fitting procedure: collaboration with F. Rohart**

Perspectives

- Acquire spectra at 303K -> 50ppm uncertainty (1 week)
- Acquire spectra at 370K -> 50ppm uncertainty (1 week)
- Link the measurements to time-frequency standard

Thank you for your attention