Towards Probing Ultralight Dark Matter Couplings with Acetylene Spectroscopy

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Oral presentation at *Journées Scientifiques du Programme National GRAM* 2023

1) From UDM couplings to SM to frequency variations of AMO resonances

2) Potential from infrared precision measurements with $^{12}C_2H_2$
-Modelisation and measurement of a $^{12}C_2H_2$ transition at 1.55 µm
-Constraints on UDM couplings to SM

3) Potential from frequency measurements of a MW acetylene clock
-Acetylene MW transitions with enhanced sensitivity to µ-variation
-Molecular theory and metrological performances of a MW clock
-Constraints from frequency measurements of a MW acetylene clock

4) Conclusion

1) Variation of fundamental constants from precision measurements

• Objectives

- State-of-the-art molecular theory and precision measurements

Global Hamiltonian models : Herman and Perry, PCCP 15, 9970 (2013); Lyulin and Perevalov, JQSRT 177, 59 (2016)
Ab-initio theory : Chubb *et al*, JQSRT 204, 42 (2018)
Instrumentations for high-resolution spectroscopy; spectroscopic data; molecular databases HITRAN, GEISA, …
Cold molecules research : Aiello *et al*, Nat. Commun. 13, 7016 (2022)

- Search for variability of fundamental constants; understand nature of dark matter

Uzan, Living Rev. Relativity 14, 2 (2011) Safronova *et al*, Rev. Mod. Phys. 90, 025008 (2018)

• Applications of the acetylene molecular theory and spectroscopy

- Atmospheric science

Whitby and Altwicker, Atmos. Environ. 12, 1289 (1978)

- Astrophysics

Didriche and Herman, Chem. Phys. Lett. 496, 1 (2010)

- Frequency metrology

Recommandation *Comité Consultatif des Longueurs* 1, 2009; Riehle *et al*, Metrologia 55, 188 (2018)

- Probe variations of fundamental constants

Constantin, Vibrational Spectroscopy 85, 228 (2016)

- Photonic-molecular integration

Tharpa *et al*, Opt. Lett. 31, 2489 (2006); Takiguchi *et al*, Opt. Lett. 36, 1254 (2011)
Zektzer *et al*, Laser Photonics Rev. 14, 1900414 (2020)

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- The Standard Model and the General Relativity : FC are free parameters of the theory

Uzan, C. R. Physique 16, 576 (2015)

- CODATA 2018 recommended values of fundamental constants

https://physics.nist.gov/cuu/Constants/index.html

- Variability from couplings to cosmology and to local fields

- UDM: sub-eV scalar field $\phi(t) = \phi_0 \cos(\omega_\phi t)$; pulsation $\omega_\phi \cong \frac{m_\phi c^2}{\hbar}$; amplitude $\phi_0 = \sqrt{\frac{4\pi G \rho_{DM}}{\omega_\phi^2 c^2}}$

- Galactic halo model : $\rho_{DM} = 0.4\ \mathrm{GeV/cm^{-3}}$; $v \cong 230\ \frac{\mathrm{km}}{\mathrm{s}}$; $\sigma_v \cong 10^{-3} c$; $\tau_c = 10^{-4}/\omega_\phi$

Arvanitaki *et al*, PRD 91, 015015 (2015); Stadnik *et al*, PRL 115, 201301 (2015); Freese *et al*, RMP 85,1561 (2013)

=> DM-field induced variation of fundamental constants

- fermion X=(e,u,d,s) masses : $m_X(\phi) = m_X\left(1 + d_{m_X} \cdot \phi/\sqrt{c\hbar/8\pi G}\right)$

- fine structure constant : $\alpha(\phi) = \alpha\left(1 + d_\alpha \cdot \phi/\sqrt{c\hbar/8\pi G}\right)$

- QCD scale parameter : $\Lambda_{QCD}(\phi) = \Lambda_{QCD}\left(1 + d_g \cdot \phi/\sqrt{c\hbar/8\pi G}\right)$

- $\mu(m_e, \Lambda_{QCD}, m_X) = m_p/m_e$: $\mu(\phi) = \mu\left(1 - \left(d_{m_e} + d_g + 0.036 d_{\hat{m}}\right) \cdot \phi/\sqrt{c\hbar/8\pi G}\right)$

Damour and Donoghue, PRD 82, 084033 (2010)

=> Sensitivity of atomic, molecular and optical cavity resonance frequency:

$$\frac{\Delta f_{C,A,M}}{f_{C,A,M}} = Q_{\alpha}^{C,A,M}\frac{\Delta\alpha}{\alpha} + Q_{\mu}^{C,A,M}\frac{\Delta\mu}{\mu} + Q_{q}^{C,A,M}\frac{\Delta(\hat{m}/\Lambda_{QCD})}{\hat{m}/\Lambda_{QCD}}$$

- atomic optical transition $f_{A,opt} = C_{A,opt}\frac{\alpha^2 m_e c^2}{4\pi\hbar}\cdot F_{opt}\,(\alpha)$
- atomic hyperfine transition $f_{A,HF} = C_{A,HF}\frac{\alpha^2 m_e c^2}{4\pi\hbar}\left(g_i(m_q/\Lambda_{QCD})\times m_e/m_p\right)\cdot F_{HF}(\alpha)$
- vibrational molecular transition : $f_{vib} = C_{vib}\frac{\alpha^2 m_e c^2}{4\pi\hbar}\sqrt{m_e/m_p}$
- rotational molecular transition : $f_{rot} = C_{rot}\frac{\alpha^2 m_e c^2}{4\pi\hbar}m_e/m_p$
- optical cavity resonance : $f_C = C_C\frac{\alpha m_e c^2}{\hbar}\cdot F_C\,(\alpha, m_X, \Lambda_{QCD}\,)$

• Searches for UDM with atoms and molecules

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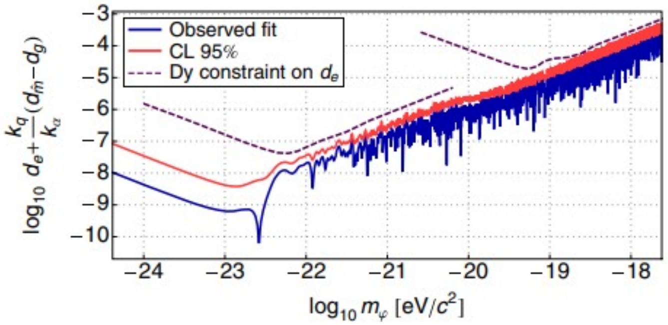
=> Atomic clocks comparisons

- oscillations from scalar fields of Rb/Cs clocks

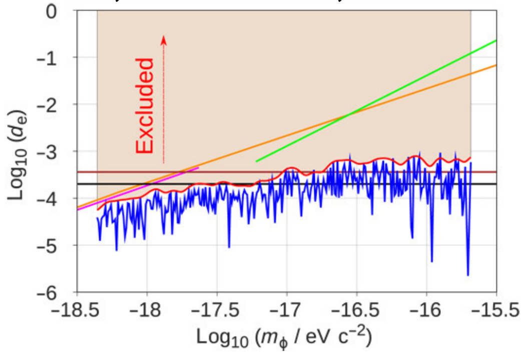
Hees *et al*, Phys. Rev. Lett. 117, 061301 (2016)



=> Atomic clocks/cavity comparisons

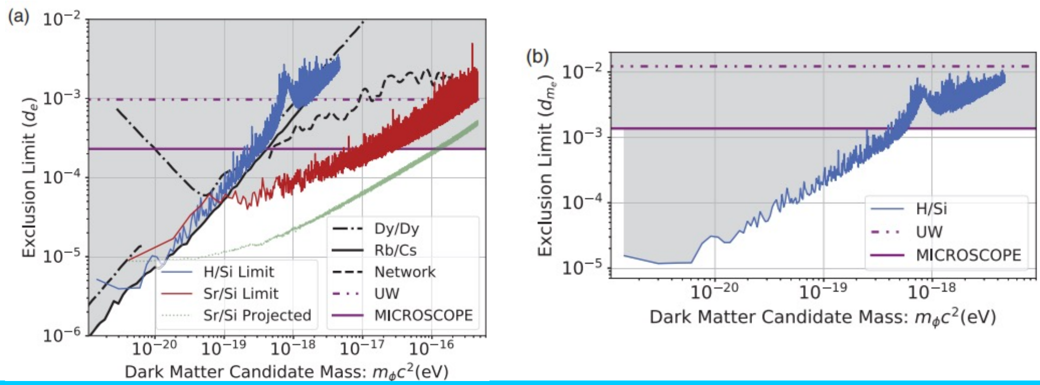
- Sr clock/cavity network comparison by GPS

Wcislo *et al*, Sci. Adv. 4, eaau4869 (2018)



- Sr clock/cavity/H maser comparisons

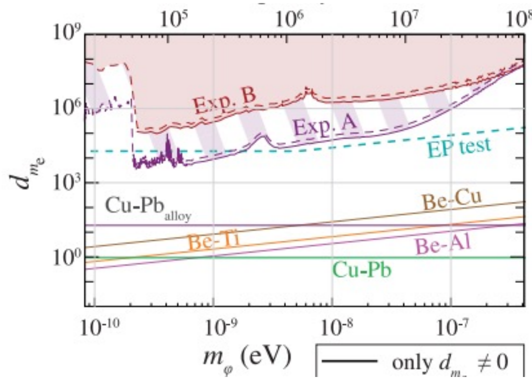
Kennedy *et al*, 125, 201302 (2020)



=> Spectroscopy experiments

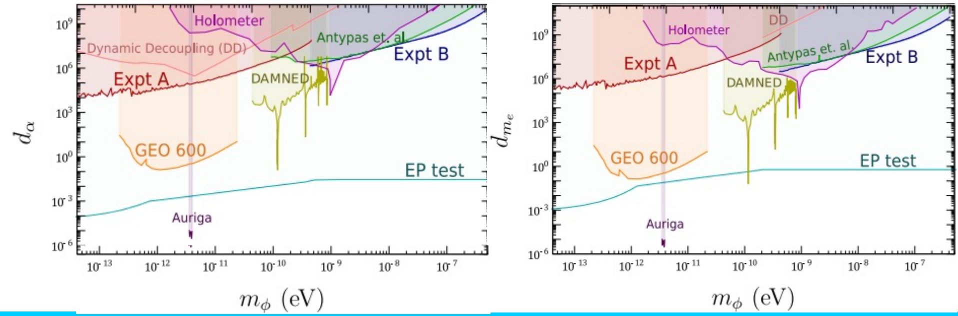
- Cs polarization spectroscopy

Tretiak *et al*, Phys. Rev. Lett. 129, 031301 (2022)



- I_2 Doppler/Doppler-free spectroscopy

Oswald *et al*, Phys. Rev. Lett. 129, 031302 (2022)



2) Potential from infrared precision measurements with $^{12}C_2H_2$

• Acetylene molecular theory

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Fundamental vibrational modes

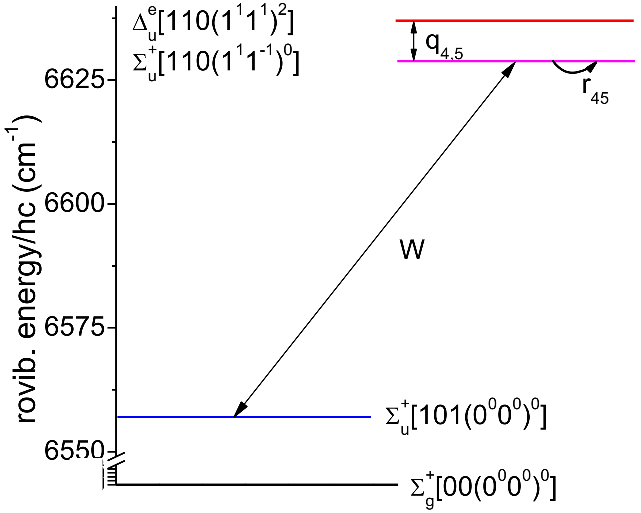
	v_1	3401.15 cm^{-1}	Symmetric CH stretching
	v_2	1982.68 cm^{-1}	Symmetric CC stretching
	v_3	3313.20 cm^{-1}	Antisymmetric CH stretching
	v_4	608.99 cm^{-1}	Trans-bending
	v_5	729.21 cm^{-1}	Cis-bending

Polyads

$$(v_1, v_2, v_3, v_4^{l_4}, v_5^{l_5})$$
$$k = l_4 + l_5; \quad J$$
$$N_s = v_1 + v_2 + v_3$$
$$N_r = 5v_1 + 3v_2 + 5v_3 + v_4 + v_5$$

Hermann, Mol. Phys. 105, 2217 (2007)

Energy levels ~196 THz



Effective Hamiltonian

Vibrational term: $G_v[v] = \sum_s \omega_s (v_s + g_s/2) + \sum_{s \le s'} x_{ss'} (v_s + g_s/2)(v_{s'} + g_{s'}/2) + \sum_{k \le k'} g_{kk'} l_k l_{k'}$

Rotational term: $F_r(J,k) = B[v](J(J+1) - k^2) - D[v](J(J+1) - k^2)^2 + H[v](J(J+1) - k^2)^3$

Hamiltonian matrix:

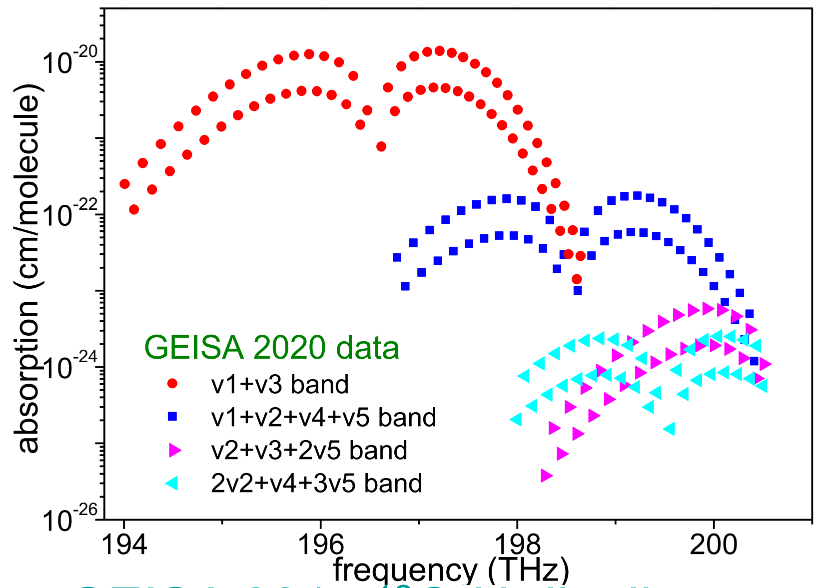
$$\begin{pmatrix} E[110(1^11^1)^2, J] + \frac{\rho_{45}}{4} J(J+1)(J(J+1)-2) & \frac{q_4+q_5}{2}\sqrt{J(J+1)(J(J+1)-2)} & 0 \\ \frac{q_4+q_5}{2}\sqrt{J(J+1)(J(J+1)-2)} & E[110(1^11^1)^0, J] + r_{45} & W \\ 0 & W & E[101(0^00^0)^0, J] \end{pmatrix}$$

Unperturbed energy levels:

$$E[110(1^11^1)^2, J] = (v_2 + g_{45}) + (B_2 + \gamma^{45})(J(J+1) - 4) - (D_2 + \delta^{45})(J(J+1) - 4)^2 + (H_2 + h^{45})(J(J+1) - 4)^3$$
$$E[110(1^11^1)^0, J] = (v_2 - g_{45}) + (B_2 - \gamma^{45})J(J+1) - (D_2 - \delta^{45})(J(J+1))^2 + (H_2 - h^{45})(J(J+1))^3$$
$$E[101(0^00^0)^0, J] = v_1 + B_1 J(J+1) - D_1 (J(J+1))^2 + H_1 (J(J+1))^3$$
$$E[000(0^00^0)^0, J] = B_0 J(J+1) - D_0 (J(J+1))^2 + H_0 (J(J+1))^3$$

Keppler *et al*, JMS 175, 411 (1996)

High-resolution spectroscopy



=> GEISA 2015 $^{12}C_2H_2$ linelist

Jacquinet-Husson *et al*, JMS 327, 31 (2016)

• Sensitivity of the parameters to a variation of μ

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Constant	Value (GHz)	K_A	Constant	Value (GHz)	K_A
B_0	35.274974565(42)	- 0.9974937(4)	x_{14}	-416.1(42)	- 1
D_0 ($\times 10^6$)	48.77824(39)	- 2.01457(5)	x_{15}	-315.4(48)	- 1
H_0 ($\times 10^{12}$)	57(18)	- 3	x_{22}	-223.4(21)	- 1
α_1 ($\times 10^3$)	206.986(33)	- 1.5	x_{23}	-184.7(33)	- 1
α_2 ($\times 10^3$)	185.308(39)	- 1.5	x_{24}	-381.6(30)	- 1
α_3 ($\times 10^3$)	176.332(33)	- 1.5	x_{25}	-45.9(22)	- 1
α_4 ($\times 10^3$)	-40.5780(26)	- 1.5	x_{33}	-828.3(36)	- 1
α_5 ($\times 10^3$)	-66.9159(12)	- 1.5	x_{34}	-300.4(42)	- 1
γ^{44} ($\times 10^4$)	-19.720(33)	- 2	x_{35}	-280.0(48)	- 1
γ^{55} ($\times 10^4$)	-32.954(15)	- 2	x_{44}	103.7(16)	- 1
γ^{45} ($\times 10^4$)	-67.641(12)	- 2	x_{45}	-66.9(30)	- 1
β_1 ($\times 10^8$)	-42.45(27)	- 2.5	x_{55}	-71.2(16)	- 1
β_2 ($\times 10^8$)	5.93(44)	- 2.5	g_{44}	23.42939(27)	- 1
β_3 ($\times 10^8$)	-40.99(40)	- 2.5	g_{45}	198.00315(24)	- 1
β_4 ($\times 10^8$)	103.13(23)	- 2.5	g_{55}	104.21008(19)	- 1
β_5 ($\times 10^8$)	77.76(18)	- 2.5	r_{45}	-187.03212(33)	- 1
δ^{44} ($\times 10^{10}$)	-517(18)	- 3	r_{J45} ($\times 10^4$)	58.565(19)	- 2
δ^{45} ($\times 10^{10}$)	-1184(22)	- 3	ρ_{45} ($\times 10^8$)	-52.79(90)	- 2
δ^{55} ($\times 10^{10}$)	-446(17)	- 3	q_{04} ($\times 10^3$)	-157.3485(36)	- 1.5
B_1	34.8877668(57)	- 0.991972(1)	q_{05} ($\times 10^3$)	-139.7165(36)	- 1.5
D_1 ($\times 10^6$)	47.8852(39)	- 2.0061(2)	q_{44} ($\times 10^5$)	53.45(33)	- 2
B_2	35.002840(20)	- 0.993256(1)	q_{45} ($\times 10^5$)	-237.3(1.3)	- 2
D_2 ($\times 10^6$)	48.107(60)	- 2.0277(36)	q_{54} ($\times 10^5$)	-330.1(1.4)	- 2
ν_1	196576.8494(18)	- 0.47159(9)	q_{55} ($\times 10^5$)	-113.86(36)	- 2
ν_2	198922.7020(21)	- 0.48114(7)	q_{J4} ($\times 10^8$)	117.82(19)	- 2.5
x_{11}	-743.8(66)	- 1	q_{J5} ($\times 10^8$)	115.351(69)	- 2.5
x_{12}	-350.2(39)	- 1	W	193.87198(96)	- 1
x_{13}	-3223(16)	- 1	W_J ($\times 10^5$)	-101.93(60)	- 2

sensitivity coefficient

$$K_A = d \ln A / d \ln \mu$$

Dependence on molecular structure parameters => sensitivity to μ-variation

Constantin, Vibrational Spectr. 85, 228 (2016)

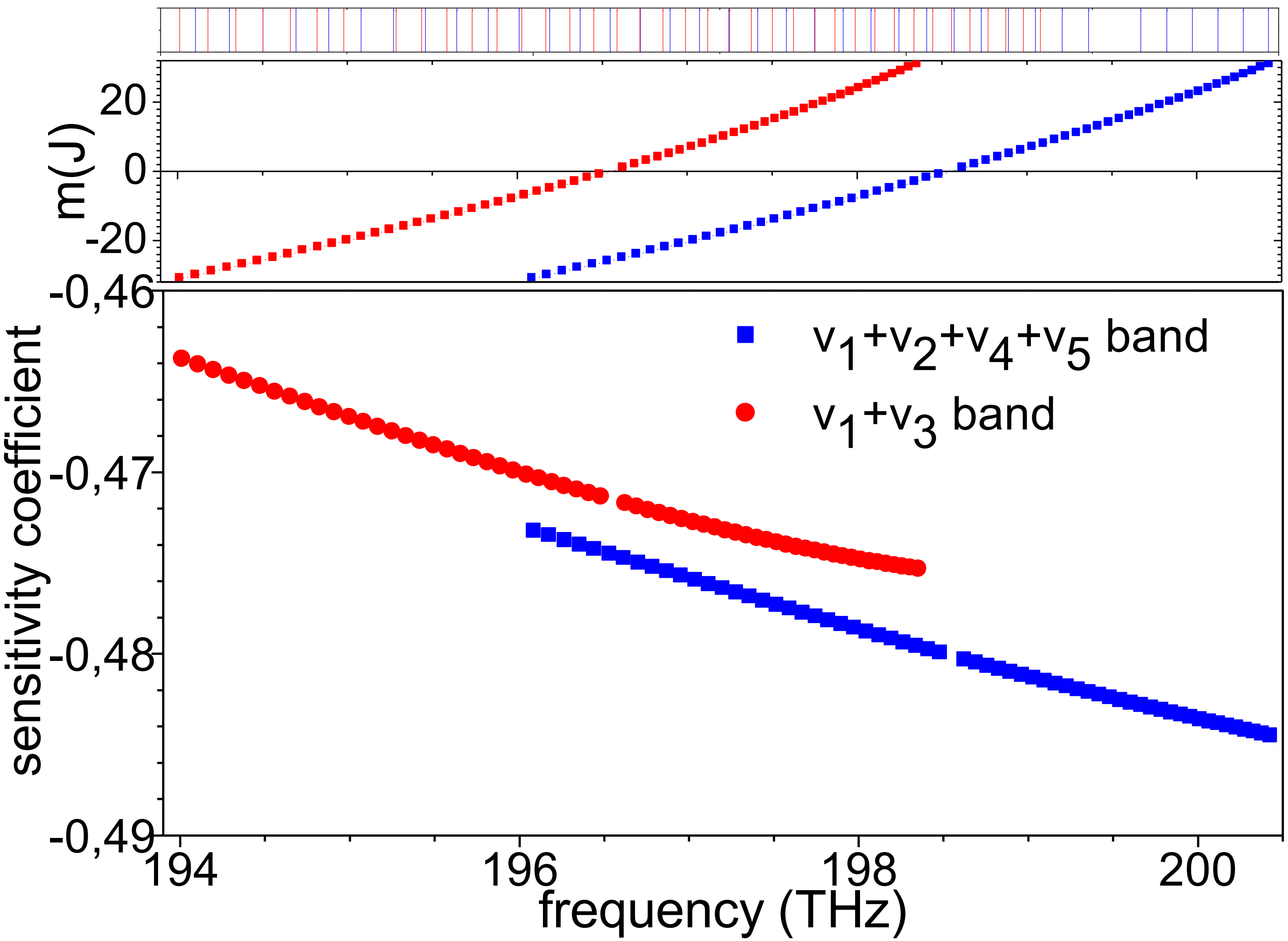
• Sensitivity of the transitions to a variation of μ

-Hamiltonian approach to calculate sensitivity to μ-variation of $^{12}C_2H_2$ reference transitions

Constantin, Vibrational Spectr. 85, 228 (2016)

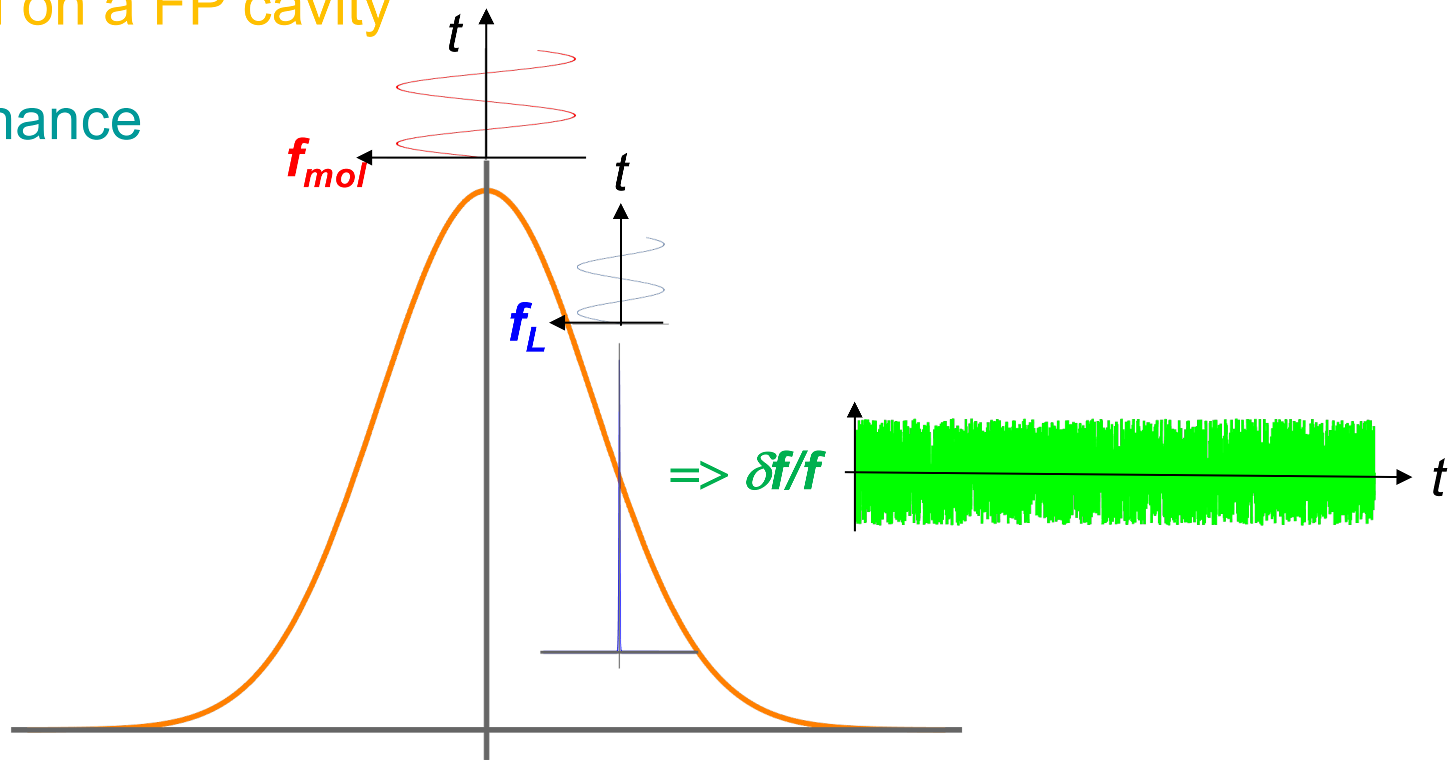
Prediction of acetylene frequency in function of μ & derivative of simulated data

=>Sensitivity of reference transition P(16) of the v_1+v_3 band of $^{12}C_2H_2$: K_μ=-0.468



• Principle of the experiment

- Laser stabilized on a FP cavity
- Molecular resonance



$$\frac{f_L(t)-f_{mol}(t)}{f_L(t)} = \left(Q_\alpha^L h^L(f_\phi) - Q_\alpha^{mol} h^{mol}(f_\phi)\right)\frac{\Delta\alpha(t)}{\alpha} + \left(Q_\mu^L h^L(f_\phi) - Q_\mu^{mol} h^{mol}(f_\phi)\right)\frac{\Delta\mu(t)}{\mu}$$

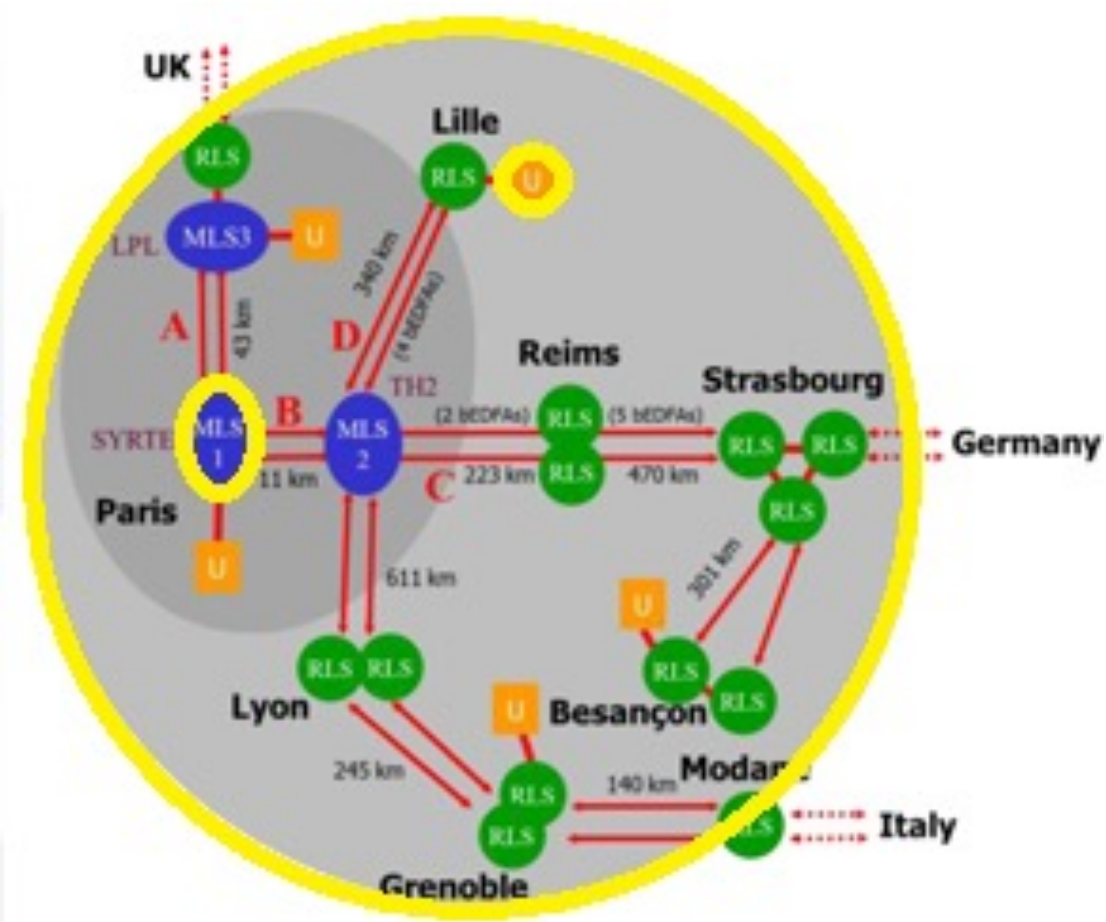
- Sensitivity coefficients : $Q_\alpha^L \cong 1; Q_\mu^L \cong 0;\ Q_\alpha^{mol} = 2;\ Q_\mu^{mol} = -0.47$

Pašteka *et al*, PRL 122, 160801 (2019); Constantin, Vibrational Spectr. 85, 228 (2016)

- Response functions $h^L,\ h^{mol}$ with high-frequency cutoffs

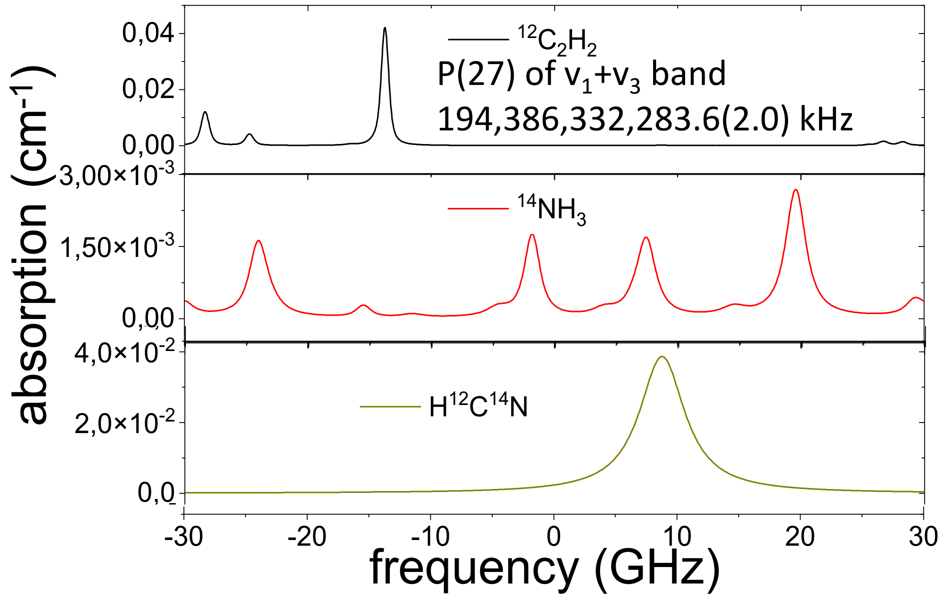
-frequency cutoffs : linewidth of the molecular line, delay in propagation of sound in the ULE spacer, …

- REFIMEVE network :
•1542 nm laser locked to ULE cavity/H maser
•phase-stabilized fiber link
Cantin *et al*, New J. Phys. 23, 053027 (2021)



=> fractional stability $<10^{-15} (\tau/1s)^{-1/2}$
=> fractional uncertainty $<10^{-14}$

=> Signal to PhLAM almost continuously at
194,400,084,500.000(25) kHz



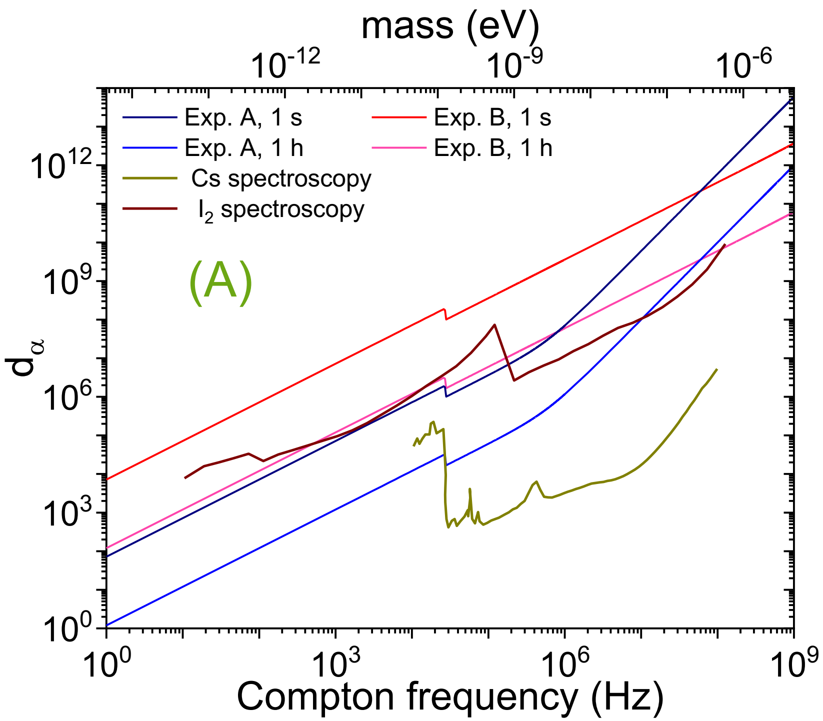
- Broadband tuning with optical modulators
-$LiNbO_3$ photonic platform
- Fast data acquisition at 1 Gsa/s level
-fast DAQ and data storage
- Low-noise absorption detection
-differential detection, noise-eater implementation,…

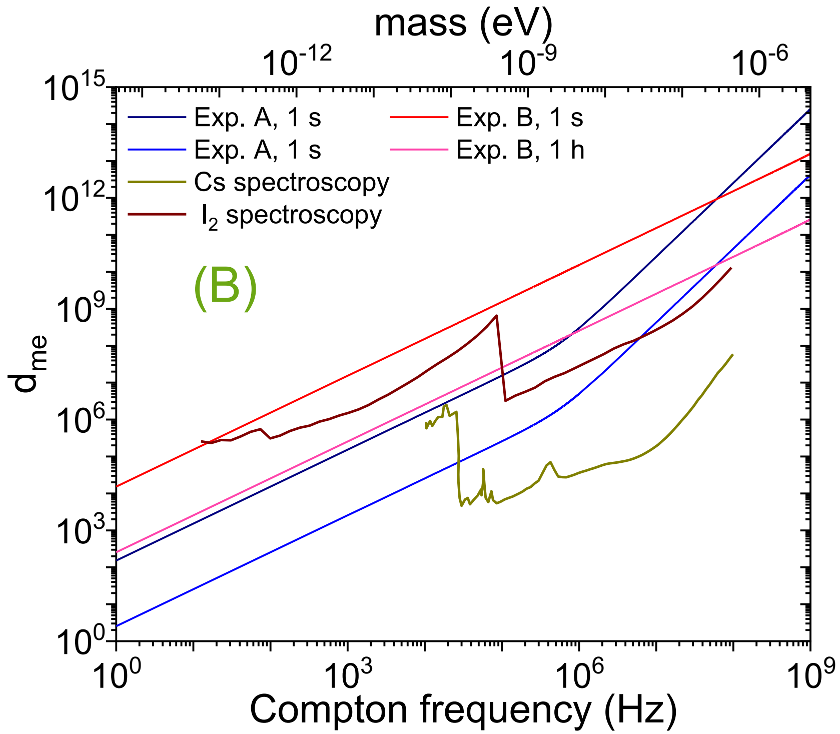
=> compact/robust molecular spectrometer
=> integration into the optical fiber network
Constantin, Proc. IFCS-EFTF 2023 Paper Id 7354

• Estimated sensitivity of the experiment

- Exp. A : recording a Doppler-free molecular line with $\delta f/f=10^{-14}\,(\tau/1\mathrm{s})^{-1/2}$
- Exp. B : recording a linear absorption molecular line with $\delta f/f=10^{-12}\,(\tau/1\mathrm{s})^{-1/2}$
- High-frequency cutoffs in the response of the experimental setup

- Sound propagation in ULE spacer f_{c1}=27 kHz
- Molecular transition sub-Doppler f_{c2A}=100 kHz and linear absorption f_{c2B}=4 GHz linewidths





=>improved limits on Compton frequencies domain by one order of magnitude

=>potential to improve the state-of-the-art constraints at low frequencies by averaging

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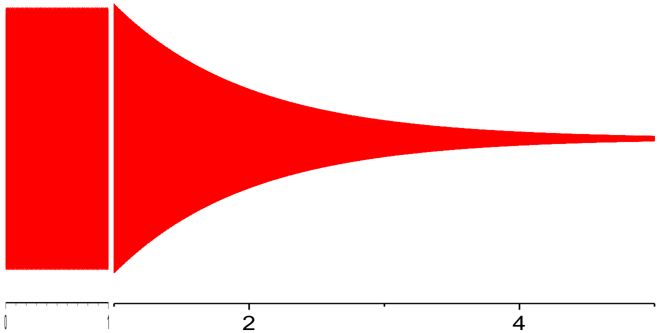
2) Potential from frequency measurements of a MW acetylene clock

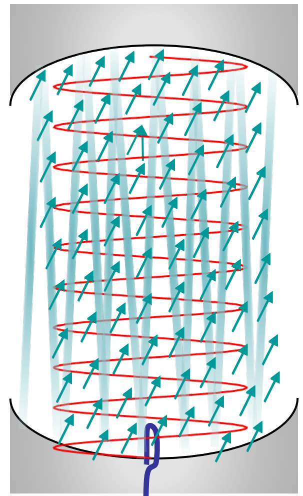
Measurement of a MW transition with enhanced sensitivity coefficient to μ-variation

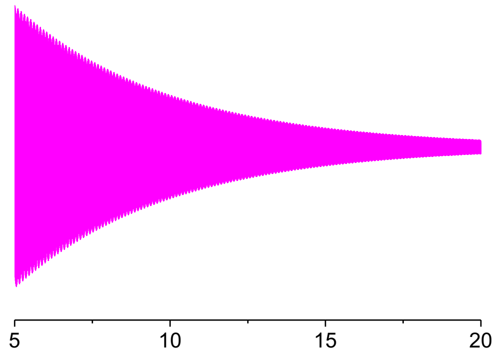
Constantin, Proc. CLEO-Europe/EQEC paper ED-1.4 (2023)

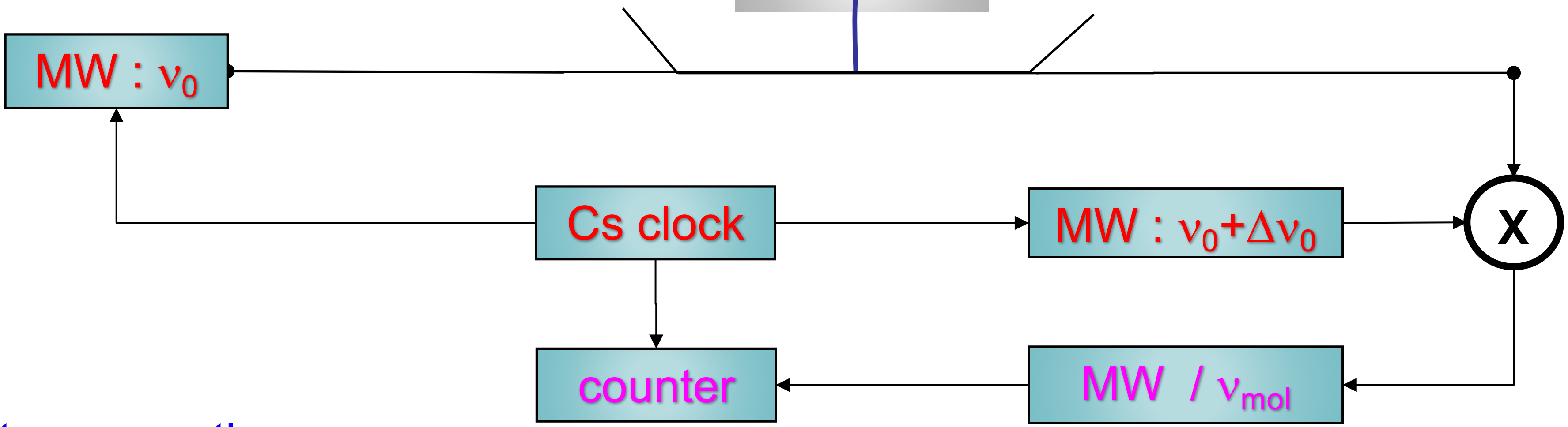
$$E_{cav} = E_0 \cdot cos(2\pi\upsilon_0 t)\ for\ 0 < t < \tau_p;$$
$$E_0 \cdot e^{-(t-\tau_p)/\tau_{cav}} cos\left(2\pi\upsilon_0\left(t-\tau_p\right)\right) for\ t \geq \tau_p$$

$$E_{FID} = exp\left(-2\pi\Delta\upsilon_{HWHM}^{press} t - \left(\pi\Delta\upsilon_{HWHM}^{Doppler} t\right)^2 / ln(2)\right)$$
$$\times E_{mol} \cdot cos\left(2\pi\upsilon_{mol}\left(t-\tau_p-4\tau_{cav}\right)+\theta\right)$$









State preparation
- heating
- optical pumping
- MW $\pi/2$ pulse

Cavity ringdown
Molecular FID

Heterodyne mixing
FFT+MW osc. locking

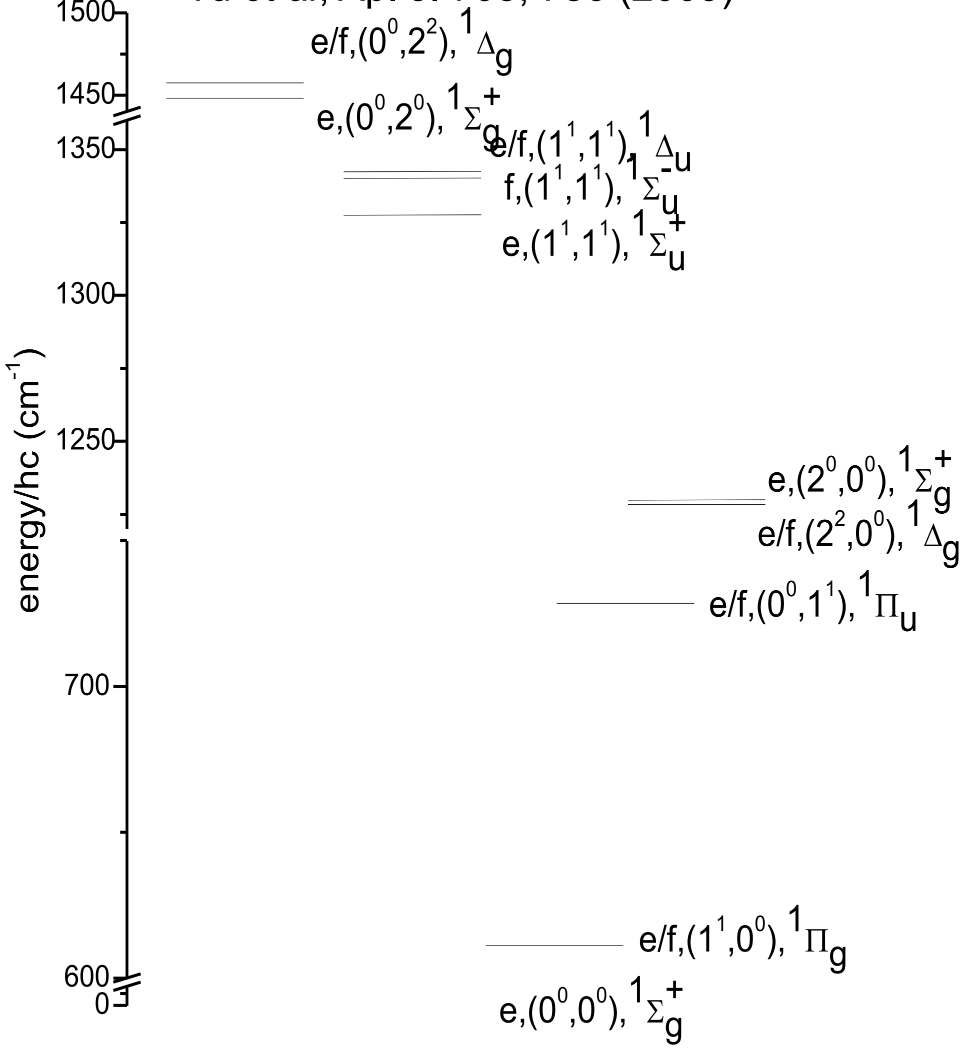
C_2H_2/Cs frequency measurement

Vibrational energy: v_4^{l4}, v_5^{l5}

$$E_V/hc = \sum_{i=4}^{5} \omega_i \left(v_i + \frac{d_i}{2}\right)$$
$$+ \sum_{i,j=4}^{5} x_{ij} \left(v_i + \frac{d_i}{2}\right)\left(v_j + \frac{d_j}{2}\right) +$$
$$\sum_{i,j=4}^{5} g_{ij} \left(l_i + \frac{d_i}{2}\right)\left(l_j + \frac{d_j}{2}\right) + \ldots$$

$\omega_i \sim 1/\sqrt{\mu}\,;\, x_{ij} \sim 1/\mu\,;\, g_{ij} \sim 1/\mu, \ldots$

Yu *et al*, Ap. J. 705, 786 (2009)



• $^{12}C_2H_2$ low energy levels and rovibrational interactions

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Vibrational energy: v_4^{l4}, v_5^{l5}

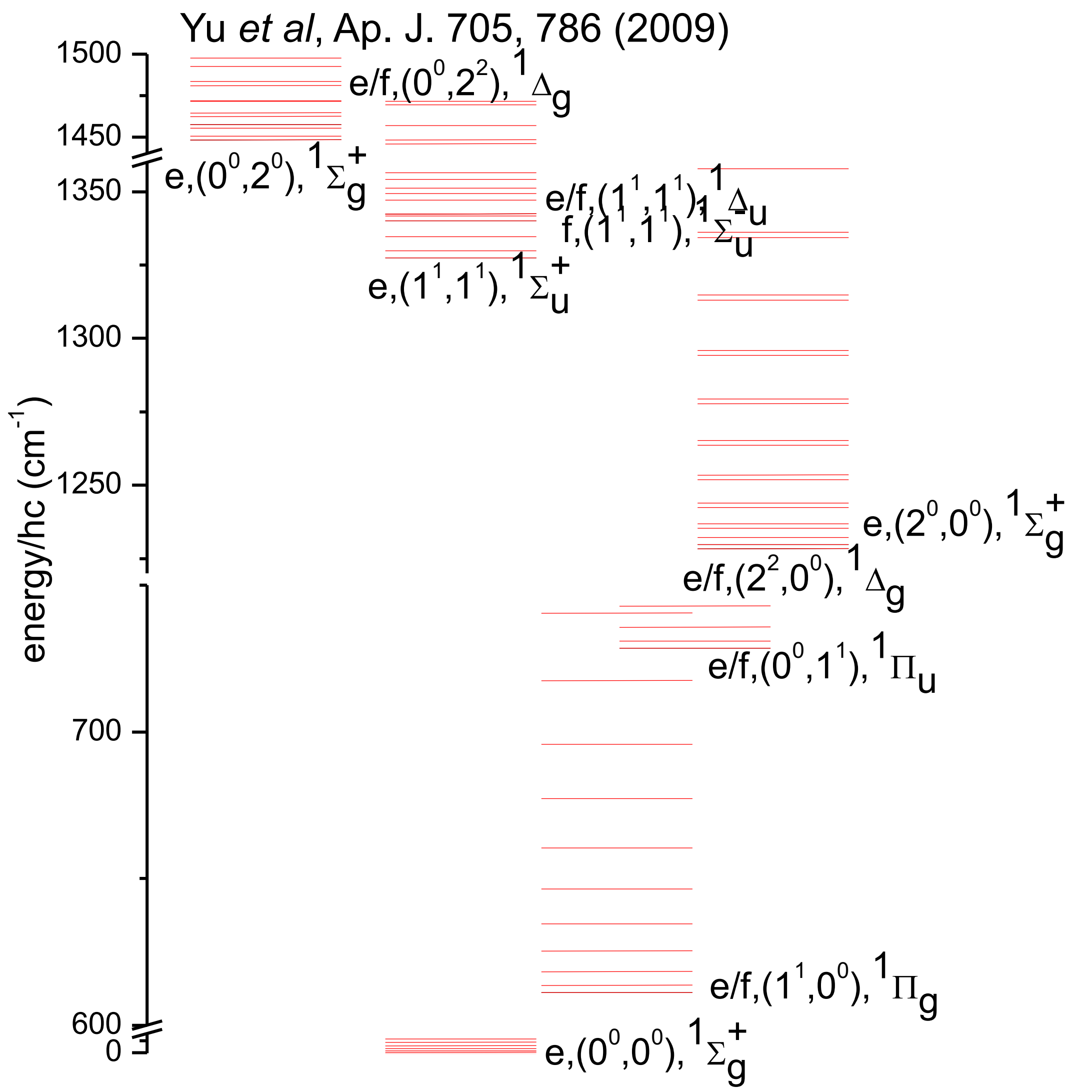
$$E_V/hc = \sum_{i=4}^{5} \omega_i \left(v_i + \frac{d_i}{2}\right)$$
$$+ \sum_{i,j=4}^{5} x_{ij} \left(v_i + \frac{d_i}{2}\right)\left(v_j + \frac{d_j}{2}\right) +$$
$$\sum_{i,j=4}^{5} g_{ij} \left(l_i + \frac{d_i}{2}\right)\left(l_j + \frac{d_j}{2}\right) + \dots$$

$\omega_i \sim 1/\sqrt{\mu}\,;\, x_{ij} \sim 1/\mu\,;\, g_{ij} \sim 1/\mu, \dots$

Rotational energy: J, $k=l_4+l_5$

$$E_R/hc = B\left(v_4^{l_4}, v_5^{l_5}\right)[J(J+1) - k^2]$$
$$+ D\left(v_4^{l_4}, v_5^{l_5}\right)[J(J+1) - k^2]^2 + \cdots$$
$$B\left(v_4^{l_4}, v_5^{l_5}\right) = B_0 - \sum_{i=4}^{5} \alpha_i \left(v_i + \frac{d_i}{2}\right) + \cdots$$
$$D\left(v_4^{l_4}, v_5^{l_5}\right) = D_0 + \sum_{i=4}^{5} \beta_i \left(v_i + \frac{d_i}{2}\right) + \cdots$$

$B \sim 1/\mu\,;\, D \sim 1/\mu^2;\, \alpha \sim 1/\mu^{3/2};\, \beta \sim 1/\mu^{5/2}$



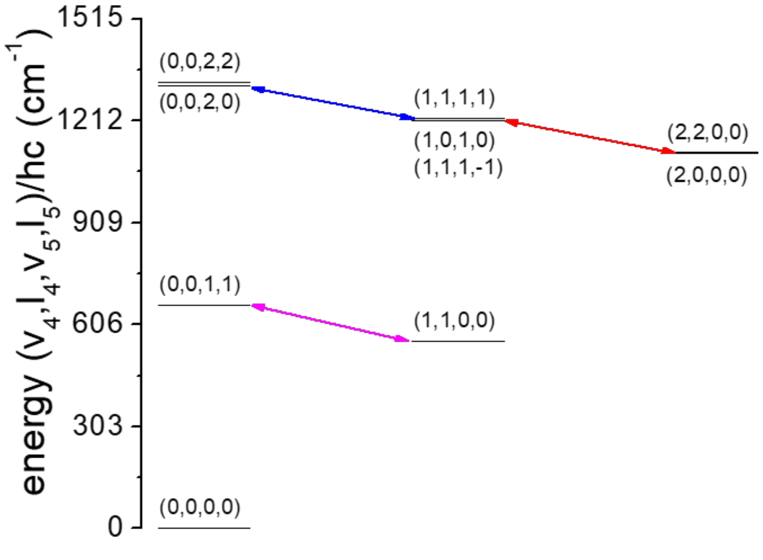
Rotational & vibrational l-type interactions and doublings

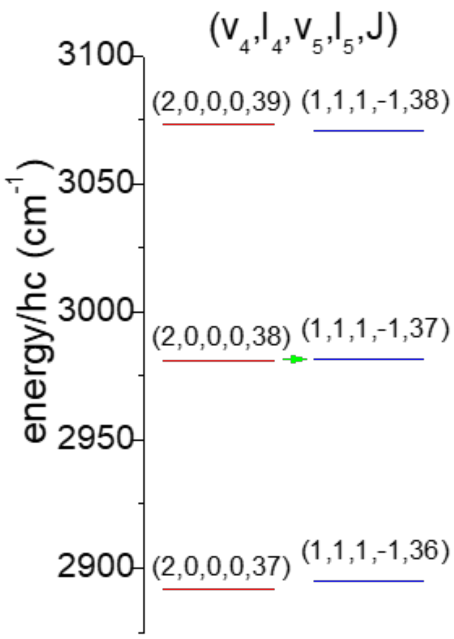
For exemple $M = J(J+1) - k^2$:

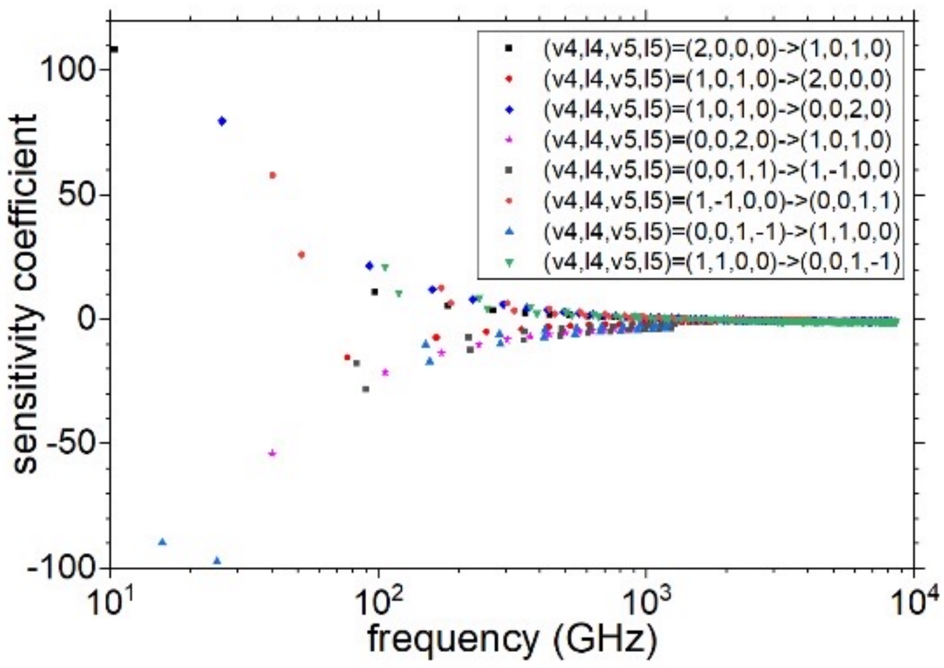
$$\begin{pmatrix} E_R(J,0) + E_V(2^{0,\pm 2}, 0^0) & \left(\sqrt{2}\, hcq_4(2,0)/2\right)\sqrt{M(M-2)} \\ 0 & E_R(J,0) + E_V(2^{0,\pm 2}, 0^0) \pm (hc\rho_4/2)M(M-2) \end{pmatrix}$$

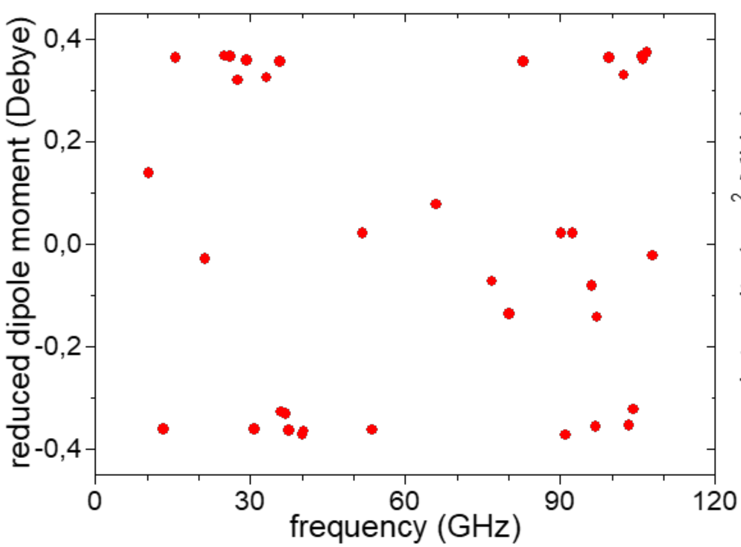
=> Energy level prediction with 10^3-10^7 Hz accuracy ; estimation of the μ-sensitivity

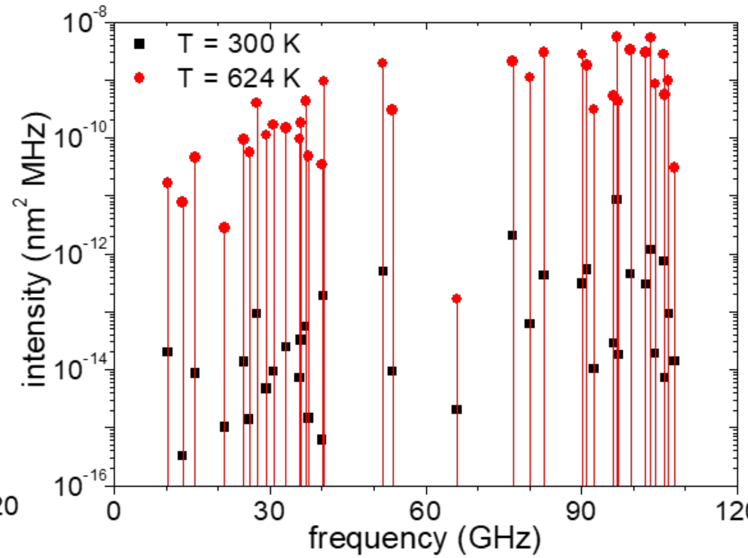
•MW transitions with enhanced sensitivity to μ-variation











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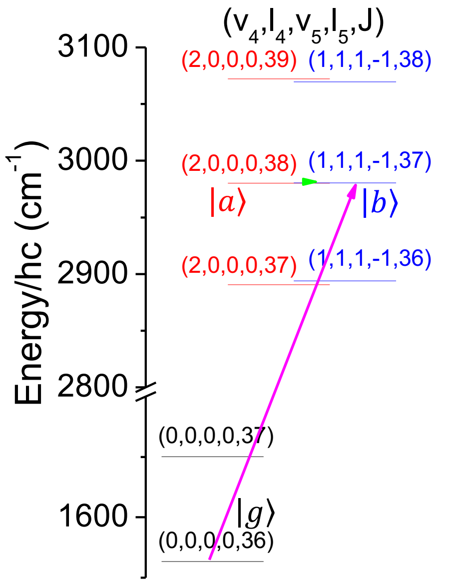
Transition $\left(v_4^{l_4}, v_5^{l_5}, J, sym\right) = \left(2^0, 0^0, 38, e\ {}^1\Sigma_g^+\right) \rightarrow \left(1^1, 1^{-1}, 37, e\ {}^1\Sigma_u^+\right)$

Exp. param. : ν_{mol} = 10363 MHz, L = 1 m, w_0 = 0.1 m, $Q_0 = 10^5$

π/2 MW pulse; full population transfer from |g> to |b>

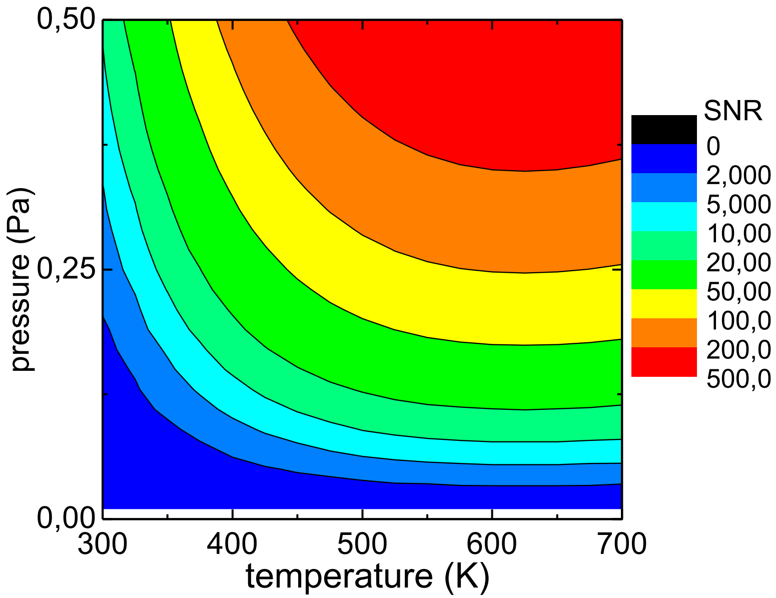


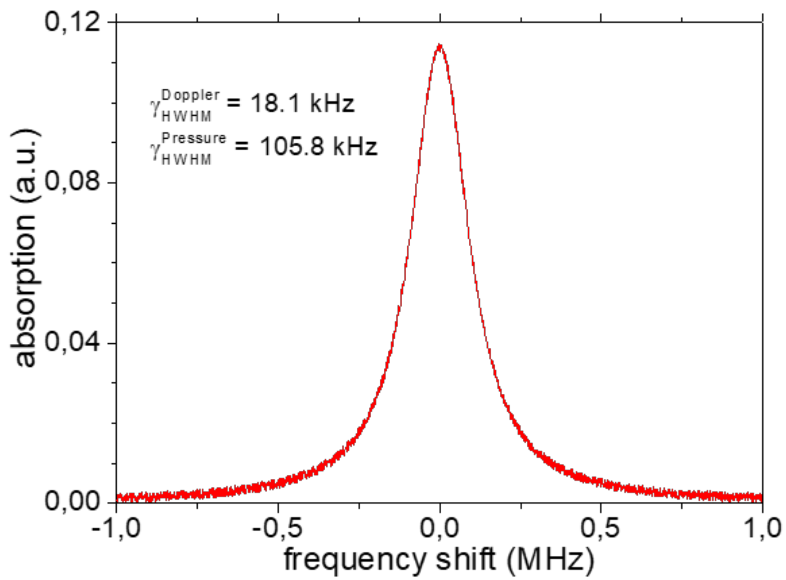
FID power : $P_{FID} = \frac{16}{9}\pi^2 Q_0 \nu_0 (\mu_{ab}\Delta N_0)^2\ \pi w_0^2 L \left(\frac{\int_0^{\kappa E_0 \tau_p} J_1(u)du}{\kappa E_0 \tau_p}\right)^2$

Campbell *et al*, J. Chem. Phys. 74, 813 (1980)

Noise power : $P_{noise} = kT_{noise}B \approx kT_{exp}/\tau_{cav}$

Optimization with constraint $B = \gamma_{cav} \sim \gamma_{mol}$ => T_{exp} = 624 K; P_{exp}=0.24 Pa; SNR = 94





=>Allan fractional instability : $\sigma_{\delta f_{mol}/f_{mol}}(\tau) \approx \frac{P_{FID}/P_{noise}}{Q_{mol}}\sqrt{\frac{T_c}{\tau}} \cong \frac{2.1\times10^{-10}}{\sqrt{\tau/1s}}$

• Systematic frequency shifts of a $^{12}C_2H_2$ microwave line

Transition $(v_4^{l_4}, v_5^{l_5}, J, sym)$= $(2^0, 0^0, 38, e\ {}^1\Sigma_g^+) \rightarrow (1^1, 1^{-1}, 37, e\ {}^1\Sigma_u^+)$ at 10363 MHz

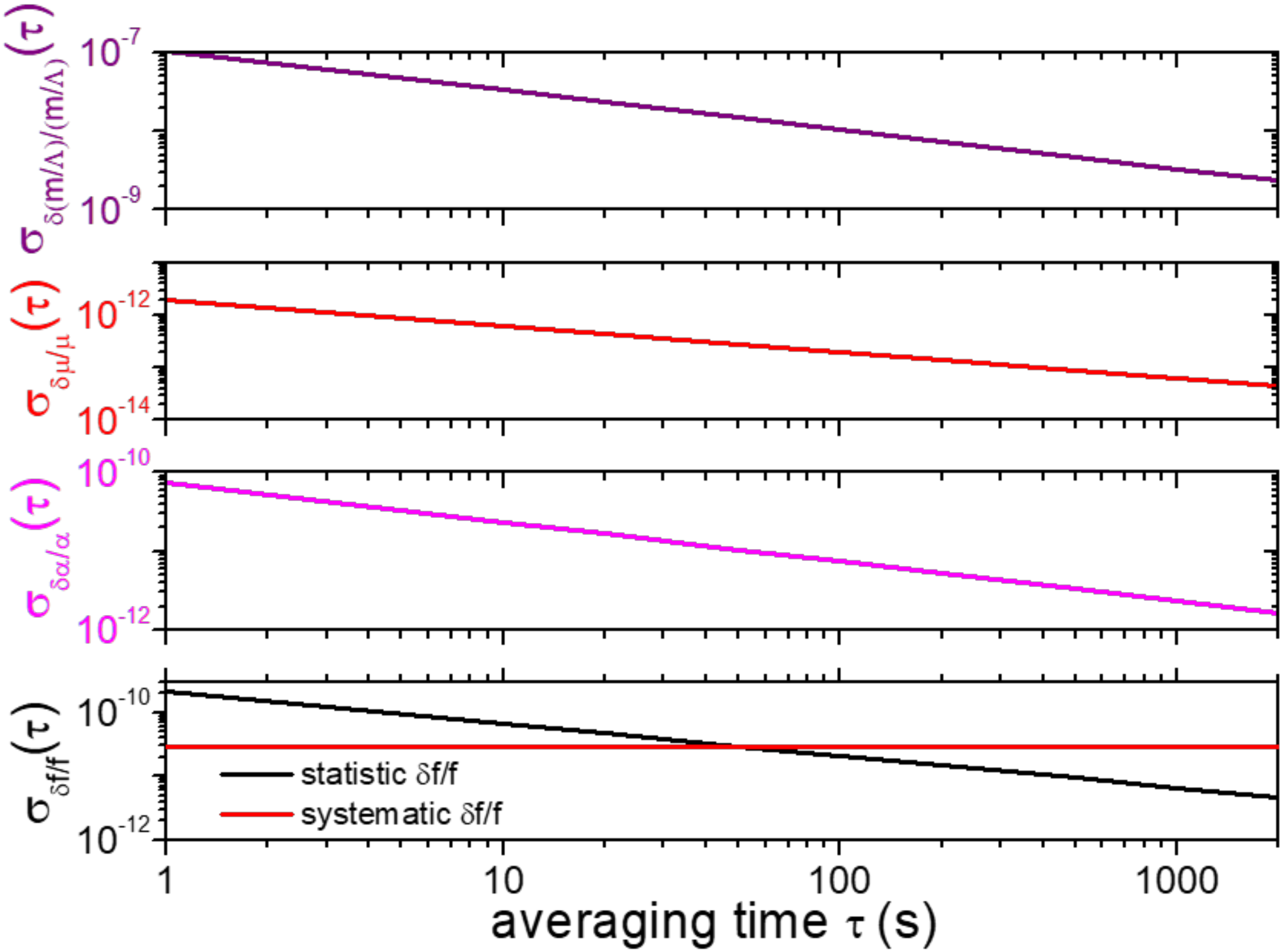
Systematic effect		***value***	***unc.***
Cavity pulling		44 kHz	0.22 Hz
$f_{mol} - f_{mol,0} = (f_{cav} - f_{mol})\times(Q_{cav}/Q_{mol})^2$			
param.:	α_T = 5 x 10^(-6)/°C		
uncertainty:	ΔT=1 °C $(f_{cav} - f_{mol}) = \Delta\nu/10$		
Viennet *et al*, IEEE TIM 21, 204 (1972)			
Pressure shift		246 Hz	0.19 Hz
extrapolation meas. v4+v5 band at high T and low p			
param.:	T=624 K; p=0.24 Pa; no J-dependence		
uncertainty:	ΔT=1 K		
Dhyne *et al*, JQSRT 112, 969 (2011)			
Zeeman shift		28 Hz	86 mHz
extrapolation meas. MVCD v4&v5 band; eval. M=J states			
param.:	B=48 µT		
uncertainty:	ΔB=0.15 µT		
Tam *et al*, J. Chem. Phys. 104, 1813 (1996)			

Systematic effect		***value***	***unc.***
DC Stark shift		6.4 µHz	1.3 µHz
1st order perturbation theory, eval. for M=0 states			
param.:	E=1 V/m		
uncertainty:	Δµ/µ=20%		
Barnes *et al*, Chem. Phys. Lett. 237, 437 (1995)			
BBR shift		1.4 mHz	9 µHz
ab-initio scalar polarizabilities, eval. for M=J states			
param.:	T=624 K		
uncertainty:	ΔT=1 K		
Russell and Spackman, Mol. Phys. 88, 1109 (1996)			
SODE shift		-34.3 mHz	55 µHz
param.:	T=624 K		
uncertainty:	ΔT=1 K		
Recoil doubling		negligible	
Autler-Townes doubling		negligible	

• Sensitivity to variations of fundamental constants

$$\frac{\Delta(f_{MW/mol}/f_{Cs})}{f_{MW/mol}/f_{Cs}} = \left(Q_{\alpha}^{mol} - Q_{\alpha}^{Cs}\right)\frac{\Delta\alpha}{\alpha} + \left(Q_{\mu}^{mol} - Q_{\mu}^{Cs}\right)\frac{\Delta\mu}{\mu} + \left(Q_{q}^{mol} - Q_{q}^{Cs}\right)\frac{\Delta(\hat{m}/\Lambda)}{\hat{m}/\Lambda}$$

• Sensitivity coefficients : $Q_{\alpha}^{Cs} = 2.83; Q_{\mu}^{Cs} = -1; Q_{q}^{Cs} = 0.002; Q_{\alpha}^{mol} = 0;\ Q_{\mu}^{mol} = 109; Q_{q}^{mol} = 0$



• Conclusion

- Accurate theory for modeling frequency & frequency shifts of $^{12}C_2H_2$ transitions
- Accurate determination of sensitivity coefficients to μ-variation
- Enhanced sensitivity coefficients for MW transitions between near-resonant levels

- Development of spectrometers at 194 THz using the REFIMEVE network with precision at levels of $(\delta f/f)^{\text{Doppler-free}} = 10^{-14}\,(\tau/1\text{s})^{-1/2}$ and $(\delta f/f)^{\text{Doppler}} = 10^{-12}\,(\tau/1\text{s})^{-1/2}$
- Microwave molecular clock with $(\delta f/f)^{A} = 2.1\times10^{-10}\,(\tau/1\text{s})^{-1/2}$ and $(\delta f/f)^{B} = 2.9\times10^{-11}$

- Potential to improve constraints on UDM couplings to SM particles

Thank you for your attention !

Acknowledgements

GRAM – Gravitation Références Astronomie Métrologie

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