Limits on oscillating fundamental constants from laser spectroscopy of molecular ensembles

R. Oswald, A. Nevsky, V. Vogt, S. Schiller
Heinrich-Heine-Universität Düsseldorf (Germany)

N. L. Figueroa, Ke Zhang, O. Tretiak, D. Antypas, D. Budker*
Johannes Gutenberg-Universität Mainz (Germany)
Helmholtz-Institut, GSI Helmholtzzentrum für Schwerionenforschung (Germany)

A. Banerjee, G. Perez
Department of Particle Physics and Astrophysics, Weizmann Institute of Science (Israel)

* *also: Department of Physics, University of California, Berkeley (USA)*

DM and oscillating fundamental constants

- DM may consist of light bosons. These form a classical field Φ, which coherently oscillates at their Compton frequency $f_C = m_\Phi\, c^2/h$ $\langle\Phi\rangle = \frac{\sqrt{2\rho_{DM}}}{m_\Phi} \cos 2\pi f_C t$
- Φ may have scalar interactions with the SM fields
- The fundamental constants (FC) may be expectation values of SM fields
- The coupling of Φ to SM fields may lead to oscillating fundamental constants

<u>Low-energy effective lagrangian with linear coupling:</u>

$$\mathcal{L}_{\rm eff} \supset \frac{\phi}{M_{\rm Pl}} \left(\sum_{f=e,u,d,s} d_{m_f} m_f \bar{f} f + \frac{d_\alpha \alpha}{4} FF + \frac{d_g \beta(g_s)}{2 g_s} GG \right)$$

F : electromagnetic field tensor
G: gluon field tensor
f: fermion fields (electron, up-quark, down-quark, strange quark)
d: dimensionless coupling constants to the DM field Φ
α: fine-structure constant
β: beta function, describes the running of the coupling constant with energy
$\alpha_s = g_s^2/4\pi$, strong force coupling constant; for 3 massless quarks, $\beta/2g_s = -9\alpha_s/8\pi$

DM and oscillating fundamental constants

$$m_f(\phi) = m_f \left[1 + d_{m_f} \frac{\phi}{M_{\rm Pl}}\right], \; \alpha(\phi) \simeq \alpha \left[1 - d_\alpha \alpha \frac{\phi}{M_{\rm Pl}}\right], \; \alpha_s(\phi) \simeq \alpha_s \left[1 - \frac{2 d_g \beta(g_s)}{g_s} \frac{\phi}{M_{\rm Pl}}\right]$$

$$\frac{\partial \ln \Lambda_{\rm QCD}}{\partial \phi} = -\frac{g_s}{2\beta(g_s)} \frac{\partial \ln \alpha_s}{\partial \phi} = \frac{d_g}{M_{\rm Pl}} \qquad \frac{\delta M_{\rm nuc}}{M_{\rm nuc}} = \frac{\delta \Lambda_{\rm QCD}}{\Lambda_{\rm QCD}} + 0.093 \frac{\delta \hat{m}}{\hat{m}} + 0.043 \frac{\delta m_s}{m_s},$$

$$\hat{m} = (m_u + m_d)/2$$

- Observables of light scalar DM may come from FC oscillations
- A series of experiments on oscillating FC has already been performed [1]
- Also: Equivalence-Principle (EP)-violating/5th force accelerations searches for non-SM fields. Experiments have already set tight bounds [2]

[1]
For references see: D. Antypas et al. Qu. Sci. and Techn. 6, 034001 (2021) for a list of references

see also M. Tobar, this workshop

[2]
P. W. Graham, et al., Phys. Rev. D 93, 075029 (2016).
A. Hees, et al., Phys. Rev. D 98, 064051 (2018).
G. L. Smith, et al., Phys. Rev. D 61, 022001 (1999).
S. Schlamminger, et al., Phys. Rev. Lett. 100, 041101 (2008).
P. Touboul et al., Phys. Rev. Lett. 119, 231101 (2017).
J. Bergé, et al., Phys. Rev. Lett. 120, 141101 (2018).

An open search

Which fundamental constants?

All?

Magnitude?

Period?

Make an encompassing search

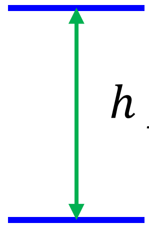
$\rightarrow$ All constants

$\rightarrow$ All frequencies

Approach

Frequency metrology

- Transition frequency f between internal levels of a quantum system



$$E_2 = E_2(\alpha, m_e, \Lambda_{QCD}, \dots.)$$

$$h\,f = E_2 - E_1$$

$$E_1 = E_1(\alpha, m_e, \Lambda_{QCD}, \dots.)$$

- Transition frequency between levels of a spin in an external magnetic field

- Mode frequency of an electromagnetic resonator

- Mode frequency of a mechanical resonator

The frequency ratio of two dissimilar oscillators is measured as a function of time

High quality factor of the transitions/modes lead to:

high sensitivity

but *slow reaction – low bandwidth*

→ Trade-off

Some dependencies

- Optical transition frequency $f \propto m_e c^2 \alpha^2 H(\alpha)$
- Hyperfine transition frequency $f \propto m_e c^2 \alpha^4 F(\alpha) \left(\frac{m_e}{m_p}\right) \mu_{nuc}$
- Molecular vibrational transition frequency $f \propto m_e c^2 \alpha^2 \left(\frac{m_e}{M_{nuc}}\right)^{\frac{1}{2}} G\left(\frac{m_e}{M_{nuc}}\right)$
- Electromagnetic cavity mode frequency (empty cavity) $f \propto m_e c^2 \alpha$
- Mechanical mode frequency $f \propto m_e c^2 \alpha^2 \left(\frac{m_e}{M_{nuc}}\right)^{\frac{1}{2}}$

$$\frac{\delta M_{\rm nuc}}{M_{\rm nuc}} = \frac{\delta \Lambda_{\rm QCD}}{\Lambda_{\rm QCD}} + 0.093 \frac{\delta \hat{m}}{\hat{m}} + 0.043 \frac{\delta m_s}{m_s}, \qquad \hat{m} = (m_u + m_d)/2$$

$\mu_{\rm nuc}$ has a small/modest dependence on $m_{\rm s}$ (~0.01) and on $\hat{m}$ (~0.1)

Classes of systems and their performance

Recent experiments

	frac. accuracy/stability	f_{max} (Hz)
Atomic clocks		
optical transitions (electronic)	$10^{-18}/10^{-18}$	1
microwave transitions (hyperfine)	$10^{-16}/10^{-16}$	1
Atomic spectroscopy		
optical transitions (electronic)	$10^{-14}/10^{-14}$	10^{7}
microwave (hyperfine)	$10^{-14}/10^{-14}$	10^{3}
Molecular standards/spectroscopy		
optical transitions (electronic)	$10^{-14}/10^{-15}$	10^{7}
mid-infrared transitions (vibrational)	$10^{-15}/10^{-15}$	10^{6}
THz transitions (rotational)	$10^{-11}/10^{-11}$	10^{4}
Other		
Mass spectrometers (mass ratios)	10^{-11}	0.1
Atom interferometers (h/mass)	10^{-10}	1
g-factors of electron, positron, nuclei	10^{-12}	0.1
Electromagnetic resonators		
Microwave resonators	--/10^{-16}	10^{4}
Optical resonators	--/10^{-17}	10^{4}
Mechanical resonators		
quartz crystals	--/10^{-13}	10^{3}

Note: rough estimates

Opportunity

Experiments so far have not addressed:

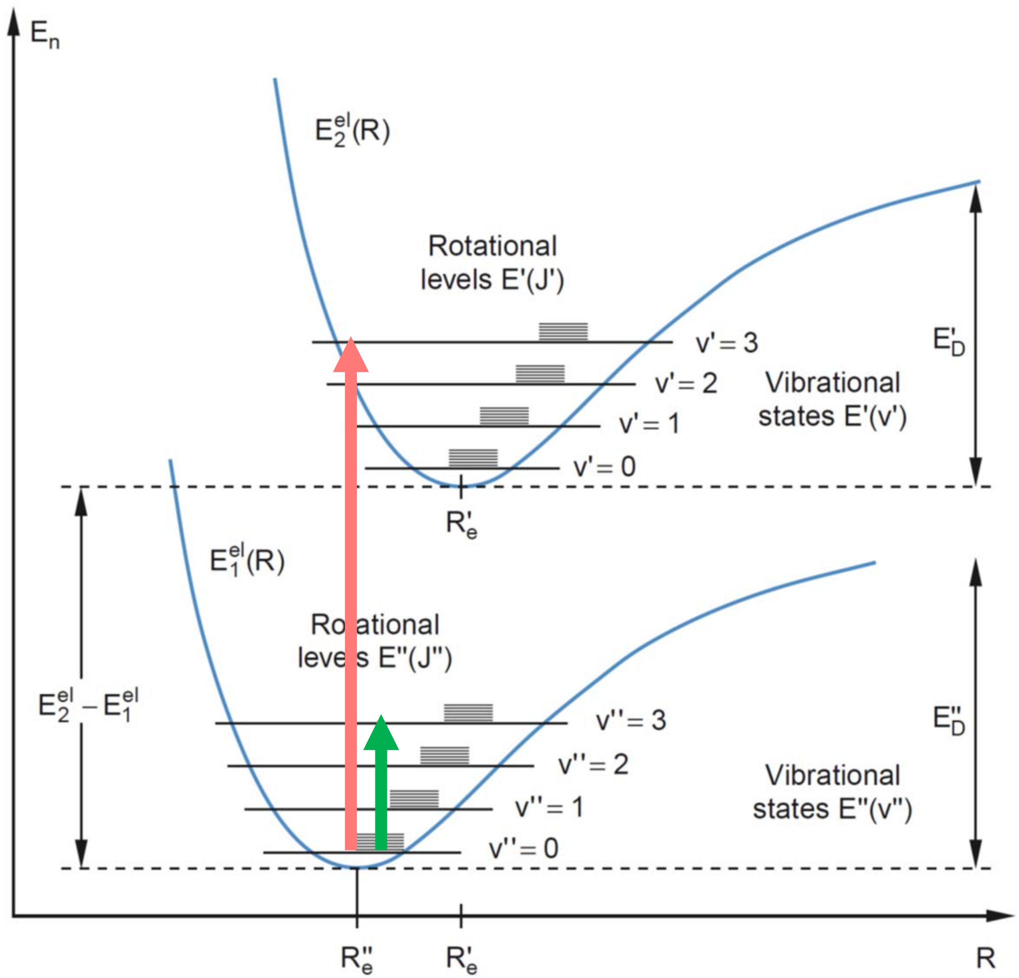
Oscillations of nuclear mass with frequencies > 1 Hz

Optical spectroscopy is well suited for this purpose!

Proposal:
D. Antypas et al.
„*Probing fast oscillating scalar dark matter with atoms and molecules*"
Quantum Science and Technology 6, 034001 (2021)

Optical transitions in molecules

Rotational and vibrational levels
in two different electronic states of a diatomic molecule



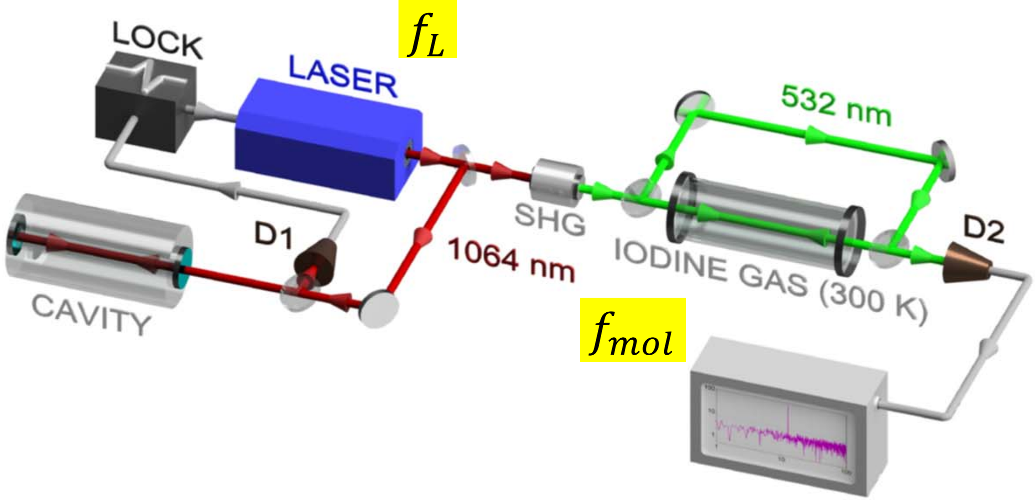
Electronic transition:
contribution from vibration to transition frequency is small (~ 0.1)

Vibrational transition:
full contribution from vibration

From: W. Demtröder
Atoms, Molecules and Photons

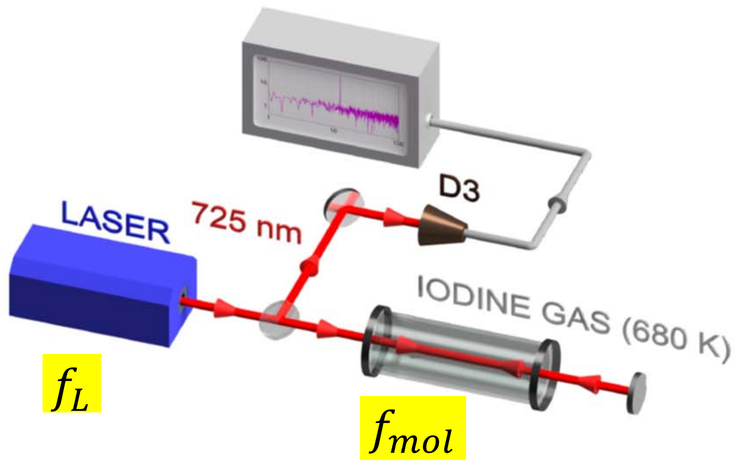
Experimental setups

Experiment A Saturation spectroscopy



100 Hz < f < 0.1 MHz

Experiment B Absorption spectroscopy

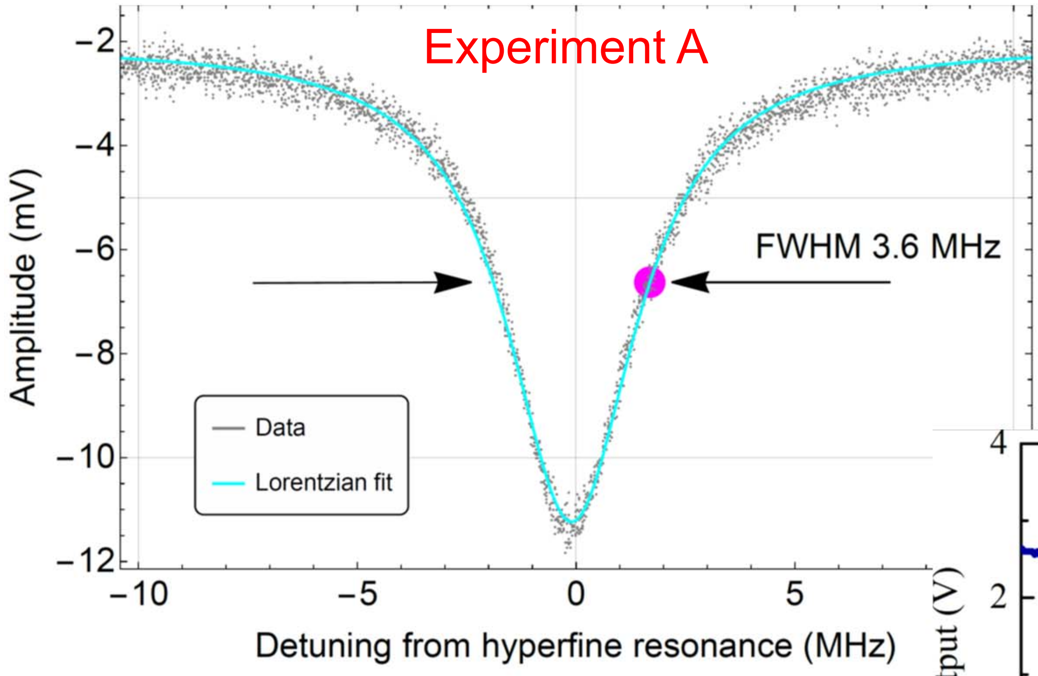


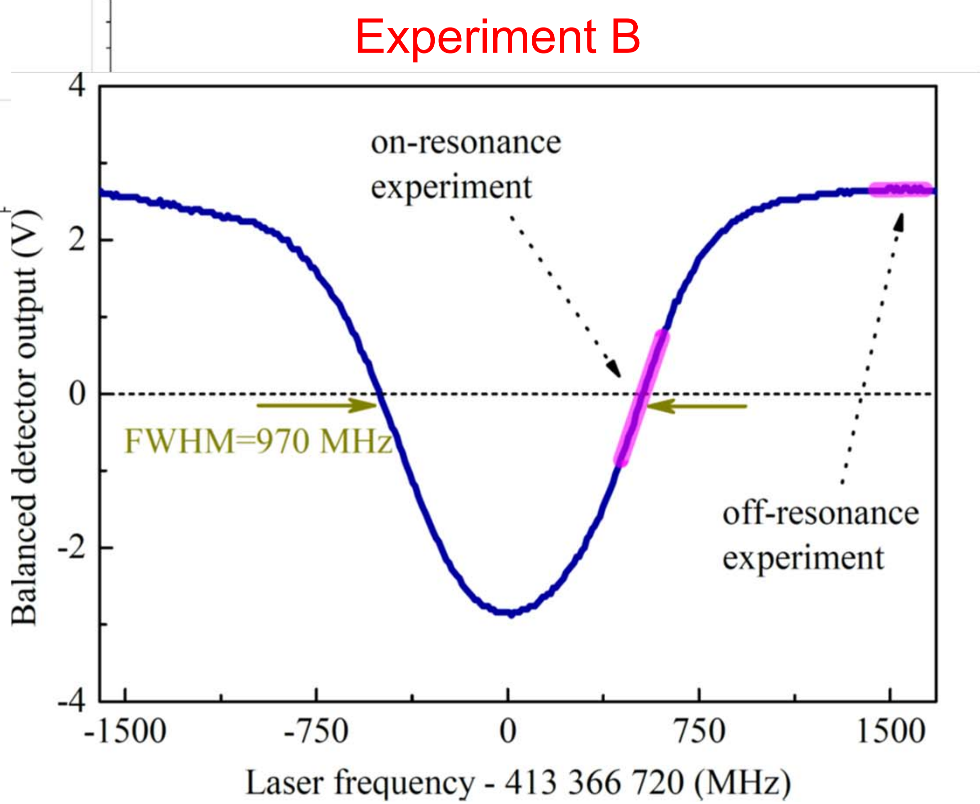
0.1 MHz < f < 100 MHz

$$\frac{\delta(f_{\mathrm{mol}} - f_{\mathrm{L}})}{f_{\mathrm{mol}}} = \begin{cases} \frac{\delta\alpha}{\alpha} + \frac{f_{\mathrm{vib}}}{2f_{\mathrm{mol}}}\frac{\delta m_e}{m_e} - \frac{f_{\mathrm{vib}}}{2f_{\mathrm{mol}}}\frac{\delta M_{\mathrm{nuc}}}{M_{\mathrm{nuc}}}, & f \le f_{\mathrm{cut}} \\ 2\frac{\delta\alpha}{\alpha} + \left(1 + \frac{f_{\mathrm{vib}}}{2f_{\mathrm{mol}}}\right)\frac{\delta m_e}{m_e} - \frac{f_{\mathrm{vib}}}{2f_{\mathrm{mol}}}\frac{\delta M_{\mathrm{nuc}}}{M_{\mathrm{nuc}}}, & f \ge f_{\mathrm{cut}} \end{cases}$$

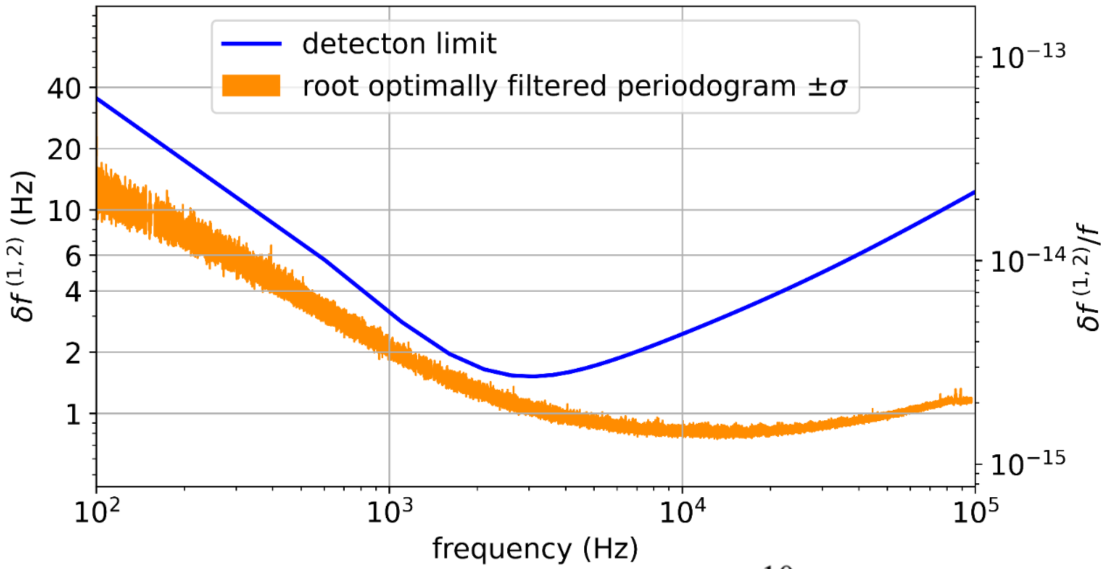
Experiment is sensitive to 6 fundamental constants!

Iodine transition lines



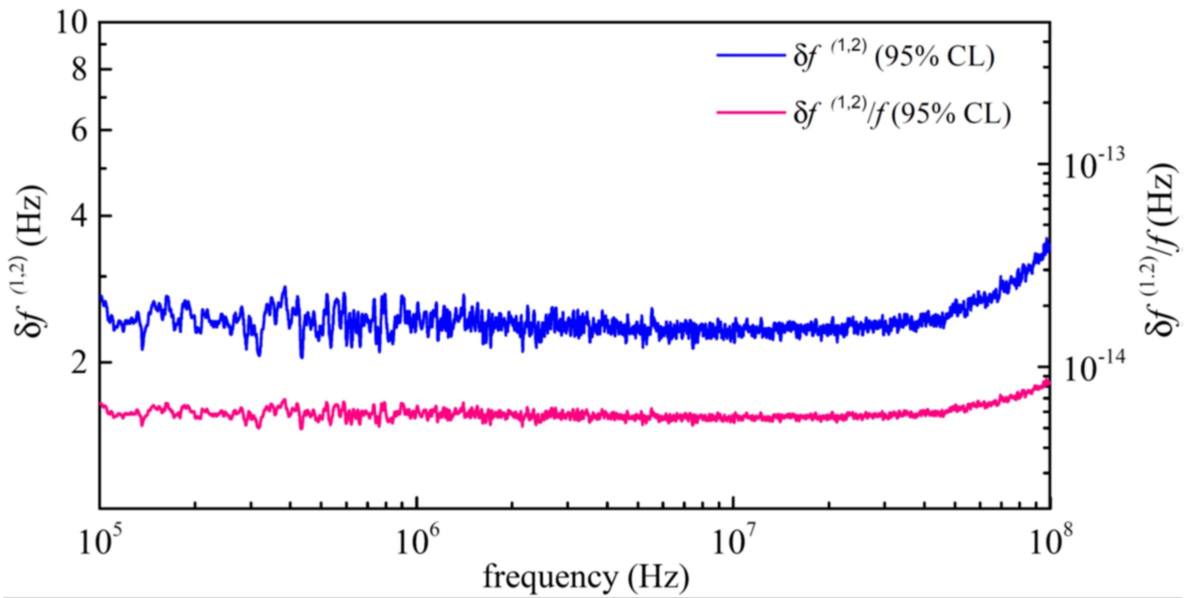


Experimental limits



Experiment A
19 h of data

Experiment B 60 h of data



- No evidence for oscillations
- Analysis takes axion lineshape into account
- Results are limited by technical noise

Analysis

effectively:

$$\frac{\delta|f_{\mathrm{mol}} - f_{\mathrm{L}}|}{f_{\mathrm{mol}}} = \left|\frac{f_{\mathrm{vib}}}{2f_{\mathrm{mol}}}\right| \frac{\delta M_{\mathrm{nuc}}}{M_{\mathrm{nuc}}}.$$

$$\frac{\delta M_{\mathrm{nuc}}}{M_{\mathrm{nuc}}} = \frac{\delta \Lambda_{\mathrm{QCD}}}{\Lambda_{\mathrm{QCD}}} + 0.093 \frac{\delta \hat{m}}{\hat{m}} + 0.043 \frac{\delta m_s}{m_s} \; ,$$

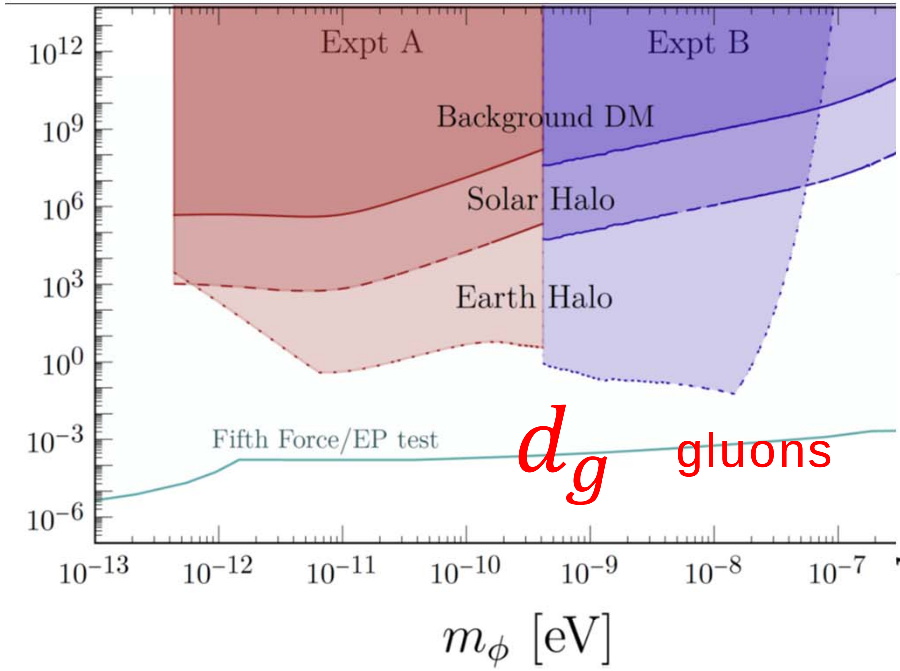
Dependence of nuclear mass on the DM field:

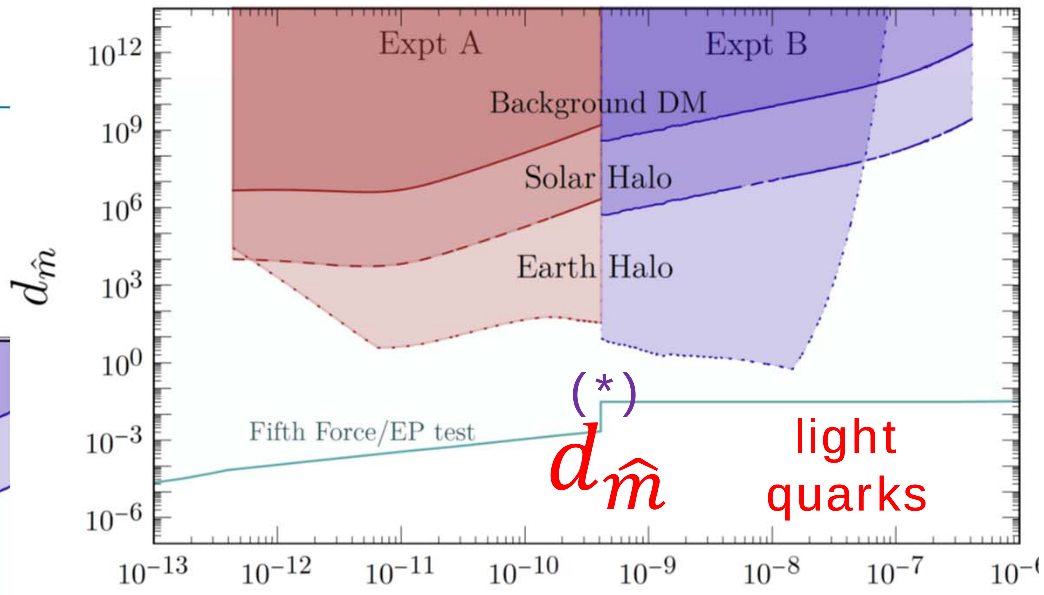
$$\frac{\delta M_{nuc}}{M_{nuc}} = \left(d_g + 0.093 d_{\hat{m}} + 0.043 d_{m_s}\right) \frac{\langle \Phi \rangle}{M_{Pl}}$$

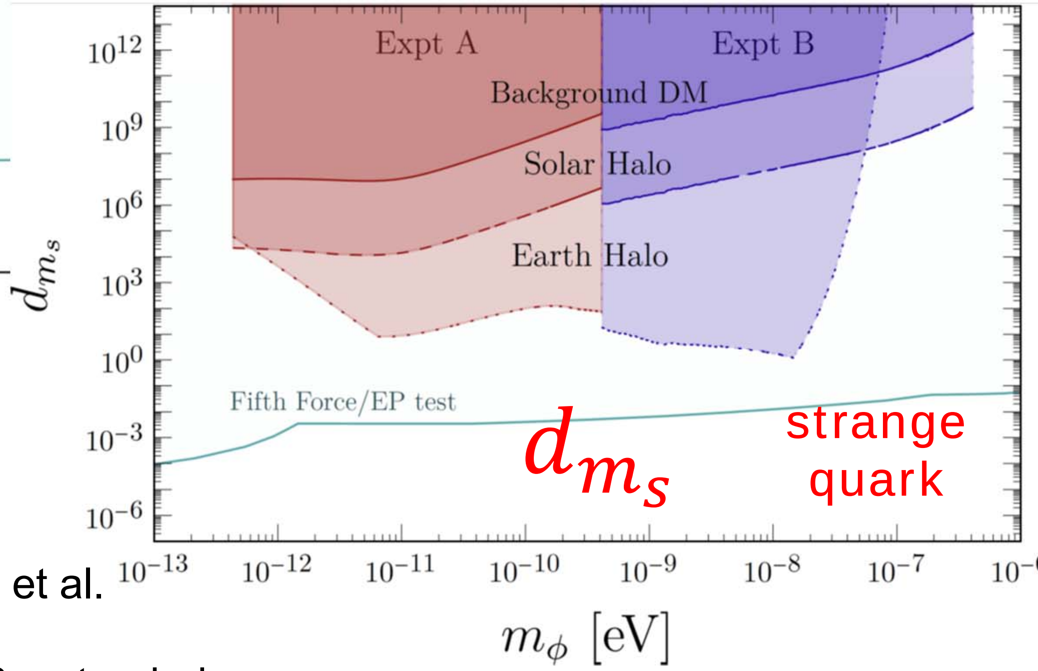
$$\langle \Phi \rangle = \frac{\sqrt{2\rho_{DM}}}{m_\Phi} \cos 2\pi f_C t$$

Bounds

preliminary







Earth halo limits: based on model in Banerjee et al. Comm. Physics 3, 1 (2020)

Solar halo limits: based on model 2007.11016; extended

(*) accidental

Summary and conclusion

- A search for oscillating nuclear mass is feasible in a wide spectrum using standard molecular spectroscopy of gas: sub-kHz to 100 MHz
- Experimental bounds on modulation of molecular transition frequency are at several $\times\ 10^{-15}$
- We set bounds on the coupling of light DM scalar field to gluons and quark masses at level 10^{6} (Galactic halo model)

- Improvement of bounds by several orders appears feasible, with effort

1-loop result

$$\Lambda_{QCD} \sim \mu \; e^{2\pi/(\beta_0 \, \alpha_s(\mu^2,\Phi))}$$

μ: renormalization-running-energy scale
β_0: leading-order beta function
α_s: strong force coupling constant;
here it also depends on Φ due to the inner coupling added to the GG term

EP-violation/5th force experiments

- These do not depend on Φ having a background value or being DM.
- Because Φ is light it mediates a long-range force between two SM objects that couple to Φ
- the force can be tested via 5th-force-EP-type experiments.
- Example: m_Φ = 1 neV $\rightarrow f$ = 240 kHz, Λ = 1.2 km

$$\mathcal{L} \subset y_{nuc} \frac{\Phi}{M_{Pl}} m_{nuc} \bar{N} N$$

y_{nuc}: Effective coupling constant
N: nucleon field

$$F(r) = {y_{nuc}}^2 \frac{{m_{nuc}}^2}{{M_{Pl}}^2} \frac{e^{-r/\Lambda}}{4\pi\, r}$$

Λ: Compton wavelength $h/m_\Phi c$
F: nucleon-nucleon 5th force

Models of ultra-light DM:

- 1405.2925 the DM is the dilaton (the Goldstone boson of scale invariance)
- 1810.01889 (the DM is ALP and due to spontaneous breaking of CP mixes with the Higgs)