Dark matter Scalar field search with Optical Cavity and an Unequal-Delay Interferometer

The DAMNED Experiment

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Scalar field theory action

The theory relies on an action where φ is the massive scalar field :

$$S = \int d^4x \frac{\sqrt{-g}}{c} \frac{c^4}{16\pi G} \underbrace{\left[R - 2g^{\mu\nu}\partial_\mu\varphi\partial_\nu\varphi - V(\varphi)\right]}_{\text{General Relativity + scalar field}}$$

$$+ \int d^4x \frac{\sqrt{-g}}{c} \underbrace{\left[\mathcal{L}_{SM}[g_{\mu\nu}, \Psi_i] + \mathcal{L}_{int}[g_{\mu\nu}, \varphi, \Psi_i]\right]}_{\text{Standard Model + scalar field}}$$

General relativity action part

$$S = \int d^4x \frac{\sqrt{-g}}{c} \frac{c^4}{16\pi G} \underbrace{\left[R - 2g^{\mu\nu}\partial_\mu\varphi\partial_\nu\varphi - V(\varphi)\right]}_{\text{General Relativity + scalar field}}$$

Field oscillation

Least action principle and Klein Gordon equation

$$-2g^{\mu\nu}\partial_\mu\varphi\partial_\nu\varphi + V(\varphi)$$
$$\Downarrow$$
$$\varphi(t) = \varphi_0 \cos\left(\omega_\varphi t\right)$$

Dark matter field

Energy-impulsion tensor and local density

$$T^{\mu\nu}(\varphi) \Rightarrow \rho_\varphi = \rho_{DM}$$
$$\Downarrow$$
$$\varphi_0 = \frac{\sqrt{8\pi G \rho_{DM}}}{\omega_\varphi c}$$

T. Damour et al. - PRD (2010), A. Arvanitaki et al. - PRD (2015) and Y.V. Stadnik et al. - PRL (2015)

Standard Model action part

$$S = \int d^4x \frac{\sqrt{-g}}{c} \underbrace{\left[\mathcal{L}_{SM}[g_{\mu\nu}, \Psi_i] + \mathcal{L}_{int}[g_{\mu\nu}, \varphi, \Psi_i]\right]}_{\text{Standard Model + scalar field}}$$

Lagrangien of the scalar field interaction with Standard Model

$$\mathcal{L}_{int} = \varphi \left[d_e \frac{e^2 c}{16\pi\hbar\alpha} F^2 - d_g \frac{\beta_3}{2g_3} \left(F^A\right)^2 - c^2 \sum_{k=e,u,d} \left(d_{m_k} + \gamma_{m_k} d_g\right) m_k \bar{\psi}_k \psi_k \right]$$

The constants d_x characterize the interaction between the scalar field φ and the different Standard Model sectors.

T. Damour et al. PRD 82,084033, A. Arvanitaki et al. PRD 91,015015 and Y.V. Stadnik et al. PRL 115,201301

Fine structure constant variation

For example, when considering only the electromagnetic effect, the effective lagrangien $\mathcal{L}_{int} + \mathcal{L}_{SM}$ leads to variation of the fine structure constant :

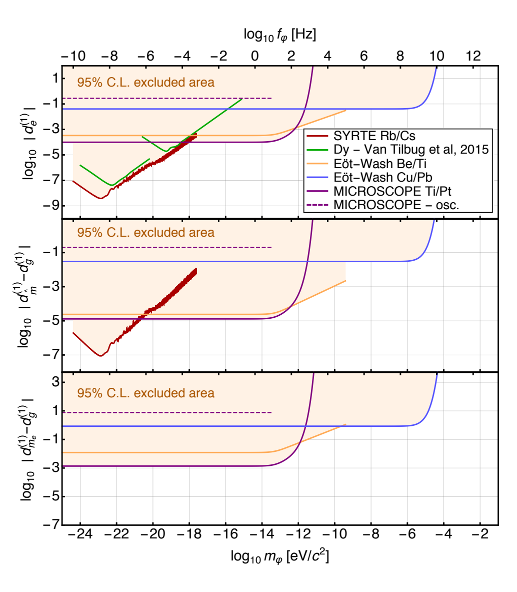
$$\mathcal{L}_{eff}^{EM} = \underbrace{-\frac{e^2 c}{16\pi\hbar\alpha}F^2}_{\substack{\text{Electromagnetism}\\ \text{from Standard Model}}} \underbrace{+d_e\varphi\frac{e^2 c}{16\pi\hbar\alpha}F^2}_{\substack{\text{Electromagnetism}\\ \text{from scalar field}}} \simeq \frac{-e^2 c}{16\pi\hbar\alpha\left(1+d_e\varphi\right)}F^2$$

Variation of the fundamental constants

A fundamental constant X varies with φ through a coupling constant d_X

$$X_{(t,\vec{r})} = X\left(1 + d_X\varphi_{(t,\vec{r})}\right)$$

- the fine structure constant $\{\alpha, d_e\}$,
- the electron mass $\left\{m_e, d_{m_e}\right\}$ and average quark mass $\left\{m_q, d_{m_q}\right\}$,
- the QCD mass scale $\left\{\Lambda_3, d_g\right\}$.



A. Hees et al. PRD 98,064051

Atomic clock comparison

Sensitive (mainly) to fine structure constant variation :

$$\{\alpha, d_e\},\ \{m_q/\Lambda_3, d_{m_q} - d_g\}$$

Test masses

Sensitive to normalized mass variation and α:

$$\{m_x/\Lambda_3, d_{m_x} - d_g\},\ \{\alpha, d_e\}$$

New experiment ?

Sensitive to mass variation :

$$\{m_x, d_{m_x}\}$$

Fondamental constants oscillations

$$X(t) = X\left[1 + d_X \frac{\sqrt{8\pi G\rho_{DM}}}{\omega_\varphi c}\cos\left(\omega_\varphi t\right)\right] = X + \delta X(t)$$

Fine structure constant and electron mass

$$\frac{\delta\alpha(t)}{\alpha} = d_e\varphi_0\cos\left(\omega_\varphi t\right) \qquad \frac{\delta m_e(t)}{m_e} = d_{m_e}\varphi_0\cos\left(\omega_\varphi t\right)$$

Bohr radius

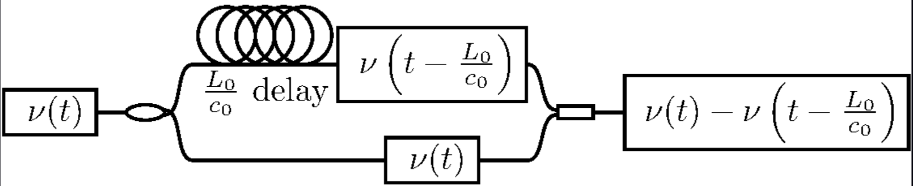
$$a_0 = \frac{\hbar}{\alpha m_e c}$$

Object length

$$L(t) \equiv N a_0(t) \simeq L_0\left[1 - (d_e + d_{m_e})\varphi_0\cos\left(\omega_\varphi t\right)\right]$$

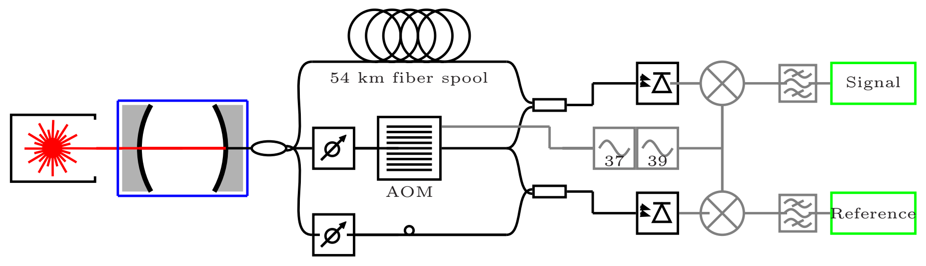
DArk Matter from Non Equal Delays

"DAMNED" allows to compare an ultrastable cavity to itself in the past.



Unequal-arm length Mach-Zender interferometer

Blueprint



Source

$1542nm$ laser source stabilized on an ultra stable cavity, unevenly distributed in three arms.

Delay

Long delay line of $50 \rightarrow 125km$
Short delay line of $1m$
AOM for detection

Detection

Beatnotes
Self-heterodyne
Photodiodes
Ettus X310

Bohr radius oscillation

The fundamental constants oscillation leads to Bohr radius oscillation :

$$a_0 = \frac{\hbar}{m_e c \alpha} \Rightarrow \frac{\delta a_0}{a_0} = -\frac{\delta \alpha}{\alpha} - \frac{\delta m_e}{m_e} = -\left(d_e + d_{m_e}\right)\varphi$$

DAMNED setup oscillations

The two main things affected by the fundamental constants oscillations in our experiment are :

- the cavity ouput frequency : $\omega \propto L_{cavity}^{-1} \propto a_0^{-1}$
- the delay lines $T = nL/c$ decomposed in :
  - the fiber length $L \propto a_0$
  - the fiber refractive index n

C. Braxmaier et al. PRD 64,042001

Cavity frequency oscillation

$$\omega(t) = \omega_0 + \Delta\omega(t) + \delta\omega \sin\left(\omega_\varphi t\right)$$

Color code

Nominal value
Noise
Dark matter effect

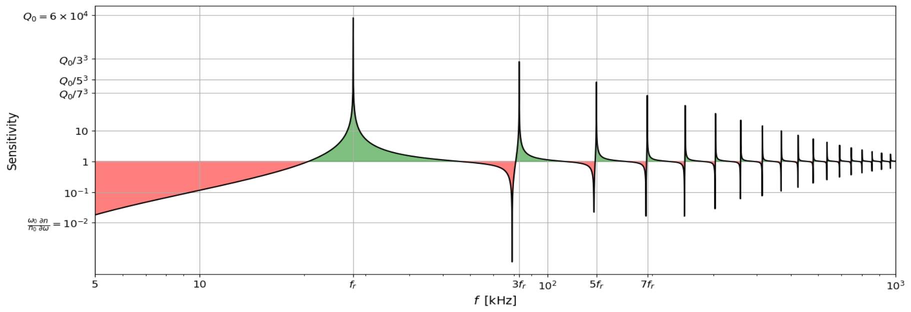
Fiber delay oscillation

$$T(t) = T_0 + \int_{t-T_0}^{t} \frac{\Delta T(t')}{T_0} \mathrm{d}t' + \delta T \sin\left(\omega_\varphi t - \omega_\varphi \frac{T_0}{2}\right) \operatorname{sinc}\left(\omega_\varphi \frac{T_0}{2}\right)$$

Phase difference between the delayed and non delayed signals

$$\Delta\Phi(t) = \omega_0 T_0 + \omega_0 \int_{t-T_0}^{t} \left(\frac{\Delta T(t')}{T_0} + \frac{\Delta\omega(t')}{\omega_0}\right) \mathrm{d}t'$$
$$+ \omega_0 T_0 \left(\frac{\delta T}{T_0} + \frac{\delta\omega}{\omega_0}\right) \sin\left(\omega_\varphi t - \omega_\varphi \frac{T_0}{2}\right) \operatorname{sinc}\left(\omega_\varphi \frac{T_0}{2}\right)$$

Full sensitivity



Link to the coupling constants

$$\left(\frac{\delta\omega}{\omega_0} + \frac{\delta T}{T_0}\right) \simeq d_e \varphi_0 \text{"Sensitivity"}$$

$$\text{or} \simeq d_{m_e} \varphi_0 \text{"Sensitivity"}$$

Data acquisition

12 days acquisition at 500 kHz for "Signal" & "Reference" data streams.

Fourier Transform

To overcome memory limitation, we had to split the 2TB time domain file in smaller chunck to perform an FFT.

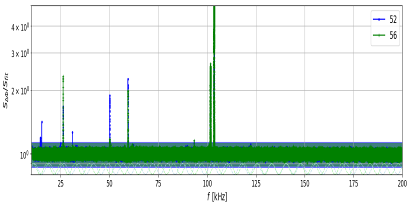
Signal & Reference

Exclusion of peaks present in both data sets.

Limiting noise modelisation

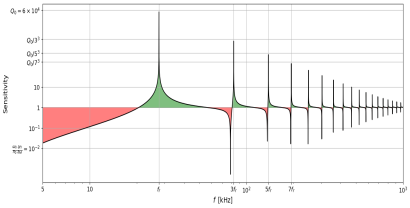
The cavity instabilities are the limiting noise in the experiment.

Experimental data



+

Sensitivity



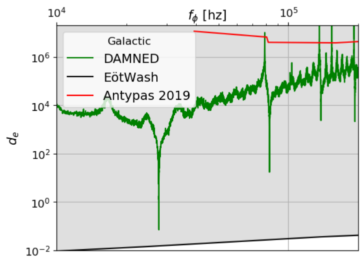
~~Heesian~~ Bayesian analysis

$$-\ln \mathcal{P}(d_x|s) = \sum_{k=1}^{N} \frac{\frac{|\tilde{s}_k|^2}{2Nf_sS_k}}{1 + d_x^2 \frac{NA_k^2}{4f_sS_k}} + \ln\left(1 + d_x^2 \frac{NA_k^2}{4f_sS_k}\right)$$

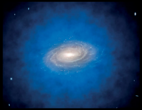
A. Derevianko - PRA (2018)

E.S. et al. - PRL (2021)

α

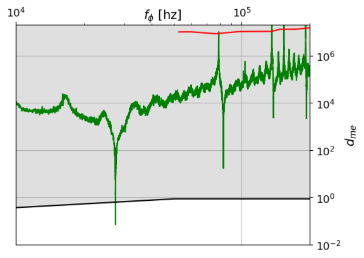


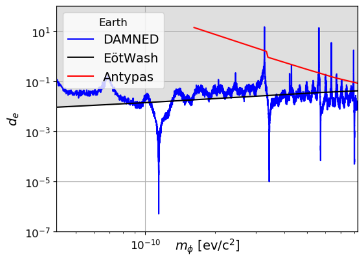
Galactic halo



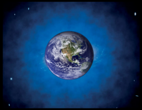
$\rho_{DM} = 0.4 GeV/cm^3$.

m_e

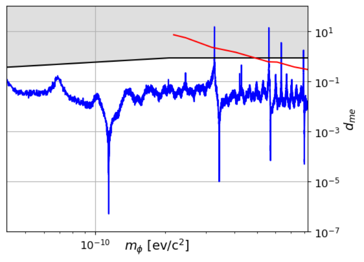




Earth halo



$\rho_{DM}^{Earth} >> \rho_{DM}^{galactic}$.



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Thank you for your attention !