The DAMNED experiment !

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Abstract

The theory of ultralight scalar field assumes the existence of an oscillation of the fundamental constants (FC) as a consequence of dark matter (DM) coupling. In order to look for these FC oscillations, we proposed a new experiment that compares the frequency of a clock to itself in the past, by "storing" photons in a fibre delay line, which thus makes it sensitive to a relative variation of the constants. Although we report no dark matter evidence, the DAMNED experiment improves the constraints on the intensity of the putative DM coupling to normal matter.

Dark matter

Dark matter (DM) is known to constitute around 85 % of our universe total mass but it does not directly interact with light. The lack of evidence for the existence of the favorite candidates (WIMPs or axions) turns the spotlight onto a diversity of other DM-models. Recent theoretical and experimental works are focused on ultra-light dark matter detection using the outstanding atomic clocks accuracy.

Scalar fields theory

The scalar fields theory relies on an action in which appears φ the scalar field :

$$S=\frac{1}{c}\int d^4x\sqrt{-g}\Bigg[\underbrace{\frac{R-2g^{\mu\nu}\partial_\mu\varphi\partial_\nu\varphi-V(\varphi)}{2\kappa}}_{\text{General relativity + Scalar field}}+\underbrace{\mathcal{L}_{\rm SM}[g_{\mu\nu},\Psi_i]}_{\text{Standard Model}}+\underbrace{\mathcal{L}_{\rm int}[g_{\mu\nu},\varphi,\Psi_i]}_{\text{Field interaction with Standard Model}}\Bigg] \quad (1)$$

where $\mathcal{L}_{\rm SM}$ is the lagrangian density of the Standard Model and $\mathcal{L}_{\rm int}$ caracterizes the interaction between standard model fields and the scalar field such that :

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

The constants d_j characterize the interaction between the scalar field φ and the different SM sectors. If we only consider the electromagnetic effect, the effective lagrangien $\mathcal{L}_{\rm int}+\mathcal{L}_{\rm SM}$ yields a variation of the fine structure constant :

$$\mathcal{L}^{\rm EM}_{\rm eff}=-\frac{e^2c}{16\pi\hbar\alpha}F^2+d_e\varphi\frac{e^2c}{16\pi\hbar\alpha}F^2\simeq-\frac{e^2c}{16\pi\hbar\alpha\left(1+d_e\varphi\right)}F^2\Rightarrow\alpha(t)=\alpha\left(1+d_e\varphi\right) \quad (3)$$

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

Oscillation of the length of solids

Solving the Klein-Gordon equation leads to an oscillation of the massive field φ with a pulsation ω_φ and amplitude φ_0 that depends on the local dark matter density ρ_{DM} :

$$\varphi(t)=\sqrt{\frac{8\pi G\hbar^2\rho_{DM}}{m_\varphi^2c^6}}\sin\left(\frac{m_\varphi c^2}{\hbar}t\right)=\phi_0\sin\left(\omega_\varphi t\right) \quad (4)$$

This yields oscillations in a fundamental constant X and the corresponding coupling constant d_x so that

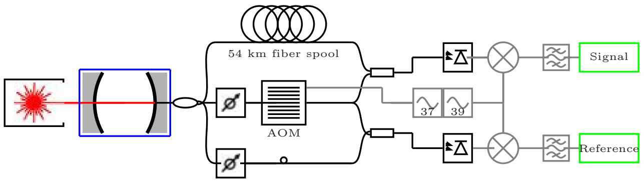
$$X(t)=X_0\left[1+d_X\phi_0\sin\left(\omega_\varphi t\right)\right] \quad (5)$$

where $\{X,d_x\}$ can be the fine structure constant $\{\alpha,d_e\}$, the electron mass $\{m_e,d_{m_e}\}$ and average quark mass $\{m_q,d_{m_q}\}$, and/or the QCD mass scale $\{\Lambda_3,d_g\}$.

We can expect a change in the length of solids L which follows the Bohr radius $a_0=\hbar/(\alpha m_e c)$ oscillation :

$$L(t)\propto a_0(t)=L_0-L_0\left(d_e+d_{m_e}\right)\varphi(t) \quad (6)$$

DAMNED blueprint

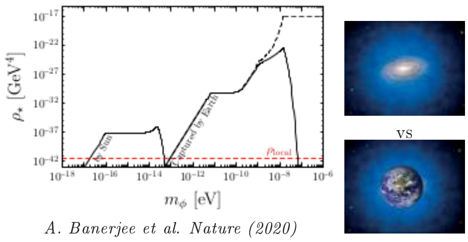


A 1542 nm laser source locked onto an ultrastable cavity is unevenly distributed in the an unequal arm length Mach-Zender interferometer (top part) as well as in an equal arm length interferometer. The two optical beatnotes are measured through a photodiode with a high sampling frequency phasemeter.

The use of the two interferometers makes it possible to isolate the putatitve DM signal (solid length oscillation) detected in the "Signal" arm from the systematic effects and noise characterized in the "Reference" arm.

Dark matter density

In the classical dark matter galactic halo, the dark matter density ρ_{DM} is equal to 0.4 GeV/c^2. From recent simulations of our Universe formation, some models predict the existence of dark matter halos that would have formed around the bodies of the Solar System, thus increasing the local dark matter density.



A. Banerjee et al. Nature (2020)

DAMNED model

The dark matter scalar field creates a cavity frequency $\omega(t)$ variation due to the change in the Bohr radius $a_0=\frac{\hbar}{m_e c\alpha}$ which yields an oscillation in the cavity length L_c. In the same time, the fiber delay $T=n_0L_0/c$ varies with the refractive index n_0 and the fiber length L_0. We can model these two effects as follows :

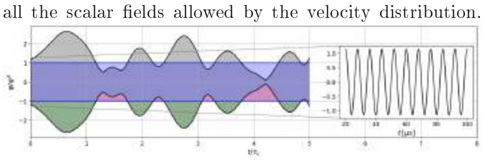
$$\omega(t)=\omega_0+\underbrace{\Delta\omega(t)}_{\text{Noise}}+\underbrace{\delta\omega\sin\left(\omega_\varphi t\right)}_{\text{Dark matter}}\qquad T(t)=T_0+\underbrace{\int_{t-T_0}^{t}\frac{\Delta T(t')}{T_0}{\rm d}t'}_{\textit{Noise}}+\underbrace{\frac{2}{\omega_\varphi}\frac{\delta T}{T_0}\sin\left(\omega_\varphi t-\omega_\varphi\frac{T_0}{2}\right)\sin\left(\omega_\varphi\frac{T_0}{2}\right)}_{\textit{Darkmatter}} \quad (7)$$

Both of this effect creates an oscillation in the desynchronisation between the delayed and non delayed signal :

$$\Delta\Phi(t)=\underbrace{\omega_0T_0}_{\Delta\Phi_0}+\underbrace{\omega_0T_0\left(\frac{\delta T}{T_0}+\frac{\delta\omega}{\omega_0}\right)\sin\left(\omega_\varphi t-\omega_\varphi\frac{T_0}{2}\right){\rm sinc}\left(\omega_\varphi\frac{T_0}{2}\right)}_{\text{Dark matter induced oscillations}}+\underbrace{\omega_0\int_{t-T_0}^{t}\left(\frac{\Delta T(t')}{T_0}+\frac{\Delta\omega(t')}{\omega_0}\right){\rm d}t'}_{\text{DAMNED noise}} \quad (8)$$

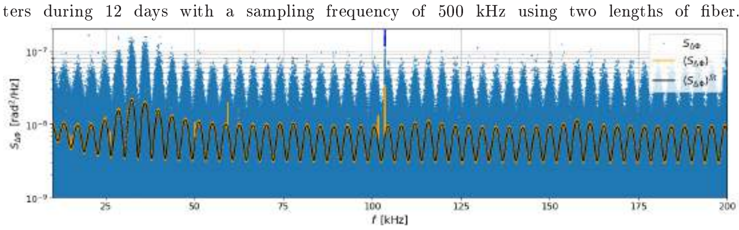
Stochastic scalar field

With the Earth movement through the dark matter halo, the Compton frequency of the scalar field is broaden because of the DM velocity distribution. This broadening introduces a coherence time τ_c which implies that the scalar field has a stochastic component from the sum of all the scalar fields allowed by the velocity distribution.

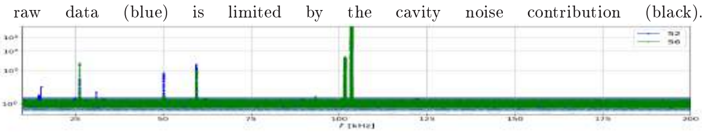


DAMNED experimental results

In order to increase sensitivity and account for the stochastic nature of the signal, we acquired the phase desynchronisation for the "Signal" and "Reference" interferometers during 12 days with a sampling frequency of 500 kHz using two lengths of fiber.



The transfer function of the unequal-arm length interferometer is responsible for the valved shaped of the PSD while the overall level in the raw data (blue) is limited by the cavity noise contribution (black).



Although we can see peaks in the residuals ("Signal" - "Reference" - cavity noise model), all of them can be attributed to systematics effects and we report no evidence of a DM signal with the DAMNED experiment.

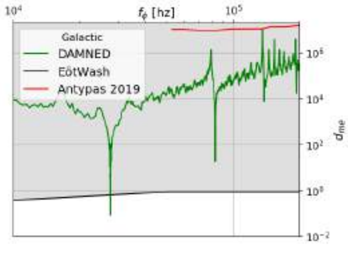
Data analysis

The data analysis and the experiment sensitivity are detailed in our paper.

Conclusion - Physical Review Letter 126 051301

Our experiment sets new constraints on the coupling parameters to the fine structure constants d_e (in paper) and the electron mass d_{m_e}.

In the standard galactic halo model, only a marginal improvement is made on the d_{m_e} parameter thanks to a resonance mechanism in the optical cavity.



In the Earth relaxation halo, we benefit strongly from the increase of the local dark matter density to the detriment of the Eöt-Wash torsion balance experiment which is not sensitive to it.