The DAMNED Experiment

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Outline

1. Introduction
   - Dark matter
   - Ultralight dark matter scalar field theory
   - Co-located vs Space-time separated experiment
2. The DAMNED experiment
   - Experimental setup
   - Sensitivity to dark matter
   - Simulation
   - Preliminary results
   - Estimated constraints

Dark Matter search - What we know about it ?

Dark matter gravitational evidences

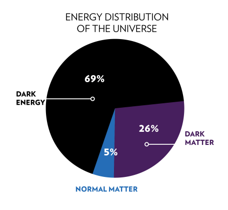
- Galaxy rotation curves
- Gravitational lensing
- Cosmic Microwave Background
- Structure formation

Dark matter caracteristics

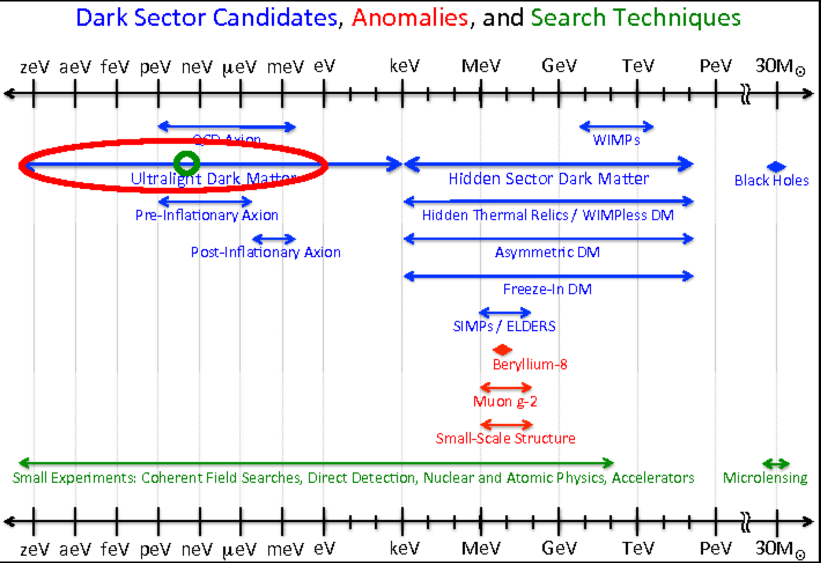
- Cold ($v \ll c$)
- Forms a galactic halo
- Virialized in the galaxy
- Typical density $\rho_{DM} = 0.4 GeV/cm^3$

Dark matter hopes

- DM interacts with standard model fields
- It will be detected and new physics will arise.



Dark Matter search - Where are we looking ?



arXiv:1707.04591

Scalar field theory - Effect on the fundamental constant

Fine structure constant variation

With a scalar field $\varphi_{(\vec{r},t)}$, the lagrangien of electromagnetism is modified :

$$\mathscr{L}_{eff}^{EM} = \underbrace{-\frac{e^2 c}{16\pi\hbar\alpha_0}F^2}_{\text{Electromagnetism - Standard Model}} \underbrace{+d_e\varphi_{(\vec{r},t)}\frac{e^2 c}{16\pi\hbar\alpha_0}F^2}_{\text{Electromagnetism - scalar field}} \simeq \frac{-e^2 c}{16\pi\hbar\alpha_0}F^2 \underbrace{\frac{\alpha_0}{\alpha_0\left(1+d_e\varphi_{(\vec{r},t)}\right)}}_{\text{Fine structure constant oscillation}}$$

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

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Time-only variation of the fundamental constants

A fundamental constant X varies with $\varphi_{(\vec{r},t)}$ through a coupling constant d_X

$$X_{(t)} = X_0 \left(1 + d_X \frac{\sqrt{8\pi G\hbar\rho_{DM}}}{m_\varphi c^3} \sin(\omega_m t)\right)$$

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

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

Co-located vs Space-time separated experiment

Bohr radius oscillation

$$a_0 = \frac{\hbar}{m_e c \alpha} \qquad \Rightarrow \qquad \frac{\delta a_0}{a_0} = -\frac{\delta \alpha}{\alpha} - \frac{\delta m_e}{m_e} = -(d_e + d_{m_e})\varphi_{(\vec{r},t)}$$

Anything made of atom will see its length oscillate in time.

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Colocated clocks

Comparison of different clocks at the same space and time :

$$\frac{\delta(\nu_A/\nu_C)}{(\nu_A/\nu_C)_0} = (d_e + (d_{m_e} - d_g))\varphi_{(\vec{r},t)}$$

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vs

Space-time separated clocks

Comparison of the same clocks at different space and/or time :

$$\frac{\delta(\nu_{A_1}/\nu_{A_2})}{(\nu_{A_1}/\nu_{A_2})_0} = (2d_e + d_{m_e})\varphi_{(\vec{r},t)}$$

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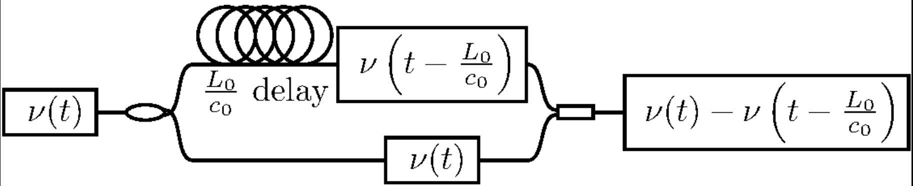
The DAMNED experiment

DArk Matter from Non Equal Delays

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



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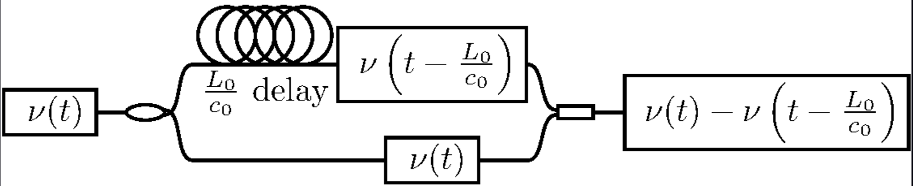

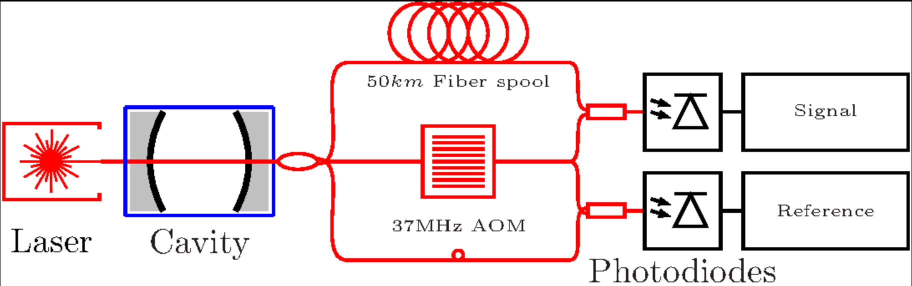

Dark matter effect on the setup

Fiber delay $T = nL/c$

C. Braxmaier et al. PRD 64,042001

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Fiber length oscillation	Fiber refractive index
$L \propto a_0 \propto (\alpha + m_e)^{-1}$	$n \propto (\alpha + m_e/m_N)$

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✓The spacer could be oscillating at mechanical resonance. It enhances ($Q = 6 \times 10^4$) the sensitivity at the harmonics frequencies.

E. Savalle et al. arXiv:1902.07192

Dark matter effect on the setup

Cavity frequency oscillation

$$\omega(t) = \omega_0 + \qquad +$$

Color code

Nominal value

Dark matter effect on the setup

Cavity frequency oscillation

$$\omega(t) = \omega_0 + \Delta\omega(t) +$$

Color code

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Noise

Dark matter effect on the setup

Cavity frequency oscillation

$$\omega(t) = \omega_0 + \Delta\omega(t) + \delta\omega \sin(\omega_m t)$$

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DM effect

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Fiber delay oscillation

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

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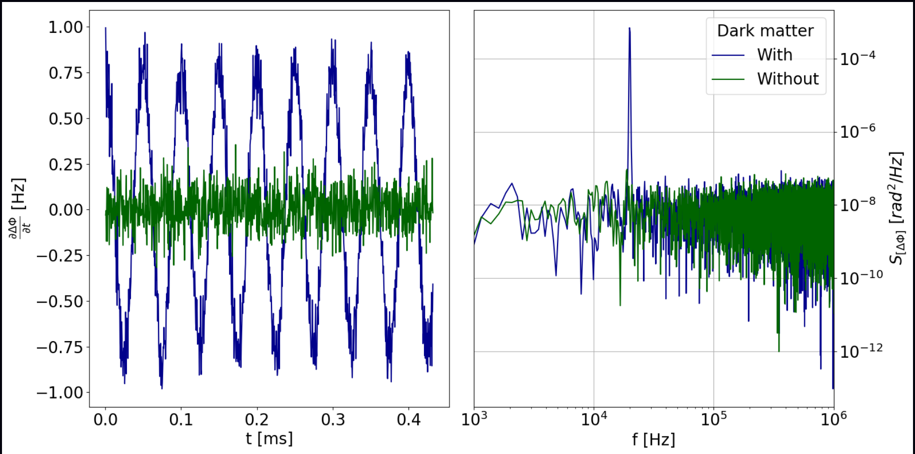
Phase difference between the delayed and non delayed signals

$$\Delta\Phi(t) = \omega_0 T_0 + \omega_0 \int_{t-T_0}^{t} \left(\frac{\Delta T(t')}{T_0} + \frac{\Delta\omega(t')}{\omega_0}\right) \mathrm{d}t'$$

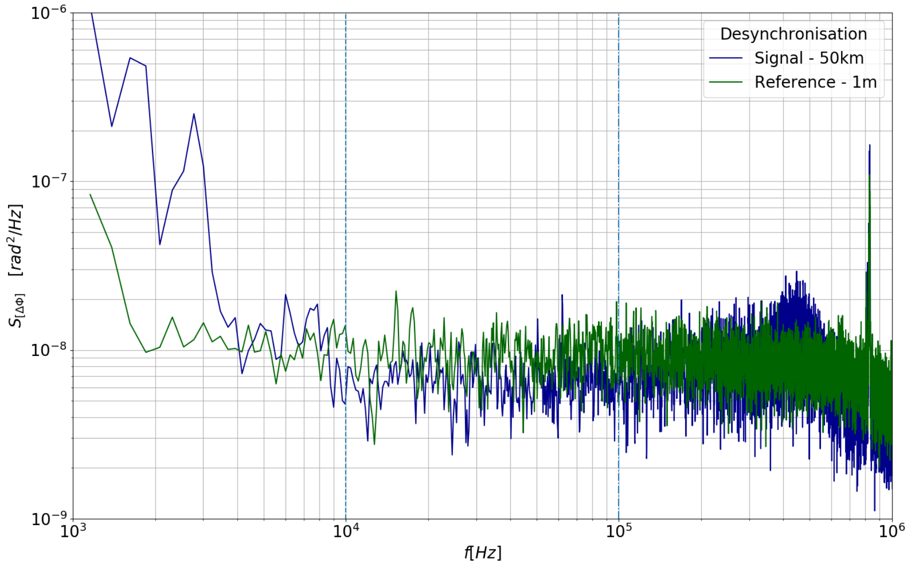
$$+ \omega_0 T_0 \left(\frac{\delta T}{T_0} + \frac{\delta\omega}{\omega_0}\right) \sin\left(\omega_m t - \omega_m \frac{T_0}{2}\right) \mathrm{sinc}\left(\omega_m \frac{T_0}{2}\right)$$

Signal simulation

What are we expecting with/without dark matter on the experiment ?



First experimental results



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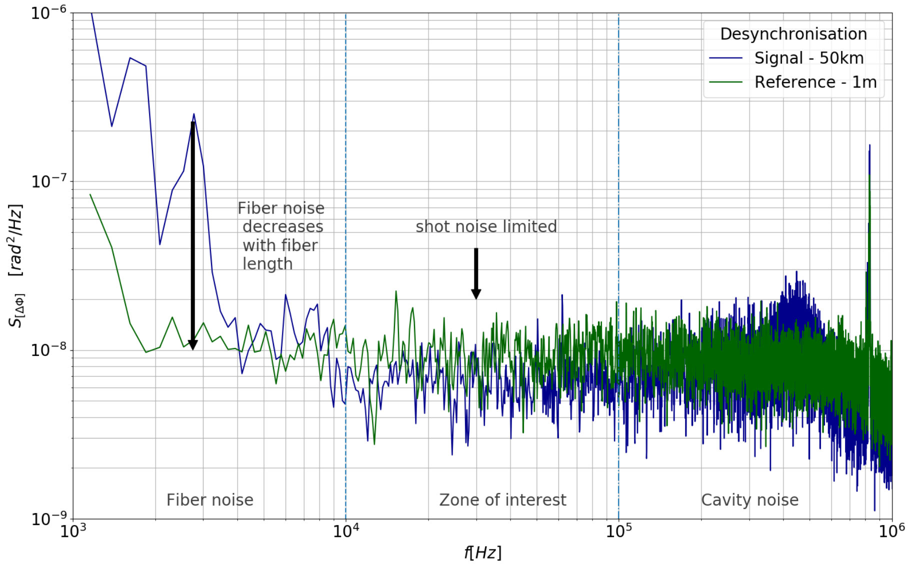
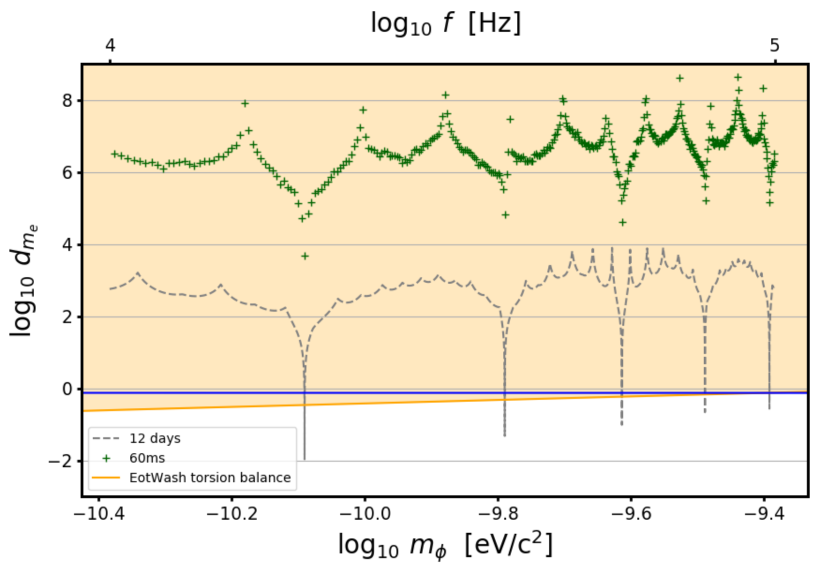


Estimated constraints



⚠Estimated constraints not actual constraints ⚠

Conclusion

Ongoing work

- Perform a FFT on 4TB of data.
- Improve the noise floor of the cavity.
- Search for the stochastic nature of the scalar field (A. Derevianko's presentation)

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DAMNED experiment

- There is no evidence for dark matter with this experiment (yet ?).
- It will allow us to decorellate the d_{m_e} coupling constant.
- It should be close to constraints of the torsion balance experiments.
- It will improve constraints by one or two orders of magnitude at the cavity resonance frequency.

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Thank you for your attention

Scalar field theory - General discussion

Scalar field theory action

The theory relies on an action where $\varphi_{(\vec{r},t)}$ is the massive scalar field :

$$S = \int d^4x \frac{\sqrt{-g}}{c} \Bigg[\underbrace{\frac{R}{2\kappa} - \frac{2g^{\mu\nu}\partial_\mu\varphi_{(\vec{r},t)}\partial_\nu\varphi_{(\vec{r},t)} + V(\varphi_{(\vec{r},t)})}{2\kappa}}_{\text{General relativity + Scalar field}} + \underbrace{\mathscr{L}_{SM}[g_{\mu\nu}, \Psi_i]}_{\text{Standard Model}} + \underbrace{\mathscr{L}_{int}[g_{\mu\nu}, \varphi_{(}}_{\text{Field intera... with Standar...}}$$

Lagrangien of the scalar field interaction with Standard Model

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

The constants d_x characterize the interaction between the scalar field $\varphi_{(\vec{r},t)}$ and the different Standard Model sectors.

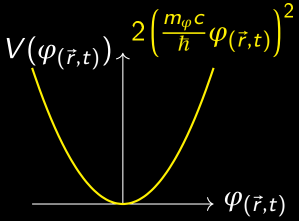
T. Damour et al. PRD 82,084033, A. Arvanitaki et al. PRD 91,015015 and Y.V. Stadnik et al. PRL 115,201301

Scalar field theory - Oscillating scalar field

How $\varphi_{(\vec{r},t)}$ varies with space-time ?

Deriving the field equation from the scalar field action with a quadratic potential, we get :

$$\Box\varphi_{(\vec{r},t)} + \left(\frac{m_\varphi c}{\hbar}\right)^2 \varphi_{(\vec{r},t)} = 0$$



Full $\varphi_{(\vec{r},t)}$ solution

$$\varphi_{(t,\vec{r})} = \frac{\sqrt{8\pi G\hbar\rho_{DM}}}{m_\varphi c^3}\sin\left(\omega_m t - \vec{k}_m.\vec{r}\right) - s_A\frac{GM_A}{c^2 r}e^{-r/\lambda_\varphi}$$

For more details and quadratic scalar field see : A. Hees et al. PRD 98,064051

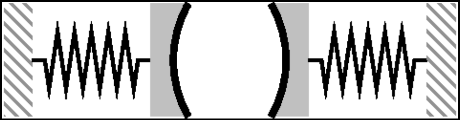
Time varying $\varphi_{(t)}$

$$\varphi_{(t)} = \varphi_0 \sin(2\pi f_m t)$$

Cavity acoustic resonance induced by dark matter

Cavity resonance

With the cavity length oscillation, one mirror is a mass on a spring.



Dampened driven parametric harmonic oscillator

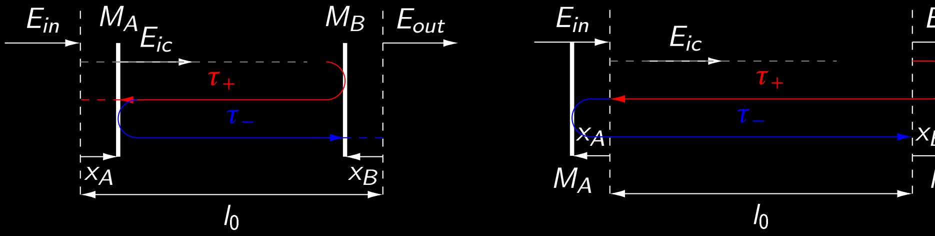
With δD the displacement induced by the resonant effect,

$$\underbrace{\frac{d^2\delta D_{(t)}}{dt^2} + \omega_0^2 \delta D_{(t)}}_{\text{Harmonic oscillator}} + \underbrace{\frac{\omega_0}{Q_0}\frac{d\delta D_{(t)}}{dt}}_{\text{Damping}} = \underbrace{\frac{\delta L}{L_0} L_0 \omega_m^2 \sin(\omega_m t)}_{\text{Parametric driving force}}$$

Solution

$$\delta D(t) = \frac{\delta L \omega_m^2}{(\omega_0^2 - \omega_m^2)^2 + \frac{\omega_0^2}{Q_0^2}} \left[\left(\frac{\omega_0^2}{\omega_m^2} - 1 \right) \sin(\omega_m t) - \frac{\omega_0}{\omega_m Q_0} \cos(\omega_m t) \right]$$

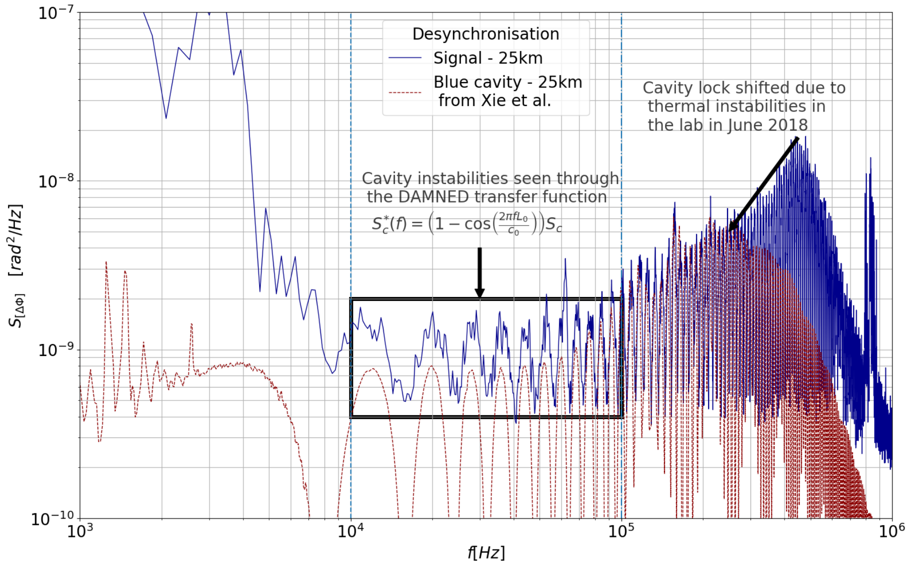
Cavity finesse



Phase in the cavity

$$\frac{\delta\omega}{\omega_0} = \frac{2\omega_m l_0/cr^2\,(1+r^2)\sin(\omega_m l_0/c)}{r^4 - 2r^2\cos(2\omega_m l_0/c)+1}$$

DAMNED noise



X. Xie et al. Opt. Lett 42,1217