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

The DAMNED Experiment

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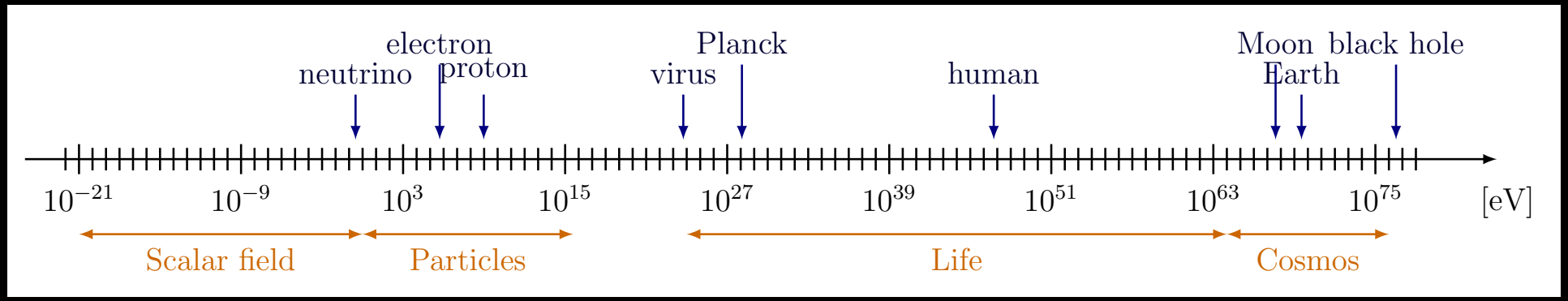
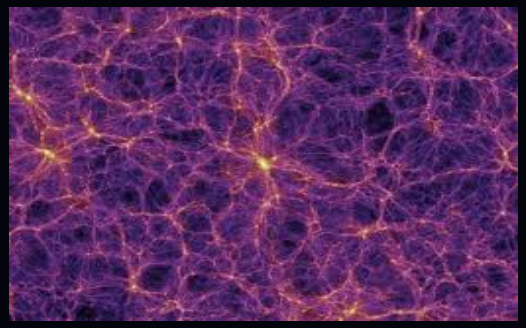
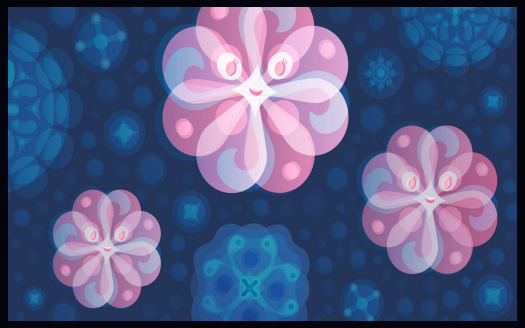


Scalar field



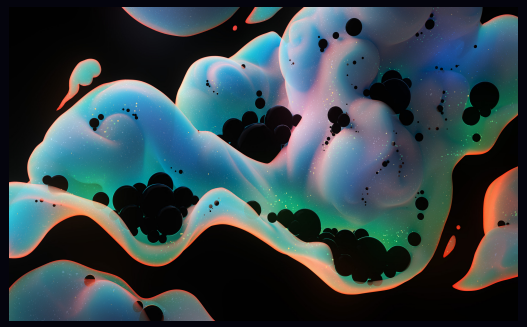
Ultra-light

Particles



WIMPs

Cosmological scale



Black holes

US Cosmic Visions, arXiv (2017)

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

1. Scalar field additional terms create a field oscillation :
$$\varphi(t) = \varphi_0 \cos(\omega_\varphi t),$$
2. Dark matter local density gives the field amplitude :
$$\frac{\sqrt{8\pi G \rho_{DM}}}{\omega_\varphi c}.$$

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 :

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

Variation of the fine stucture constant

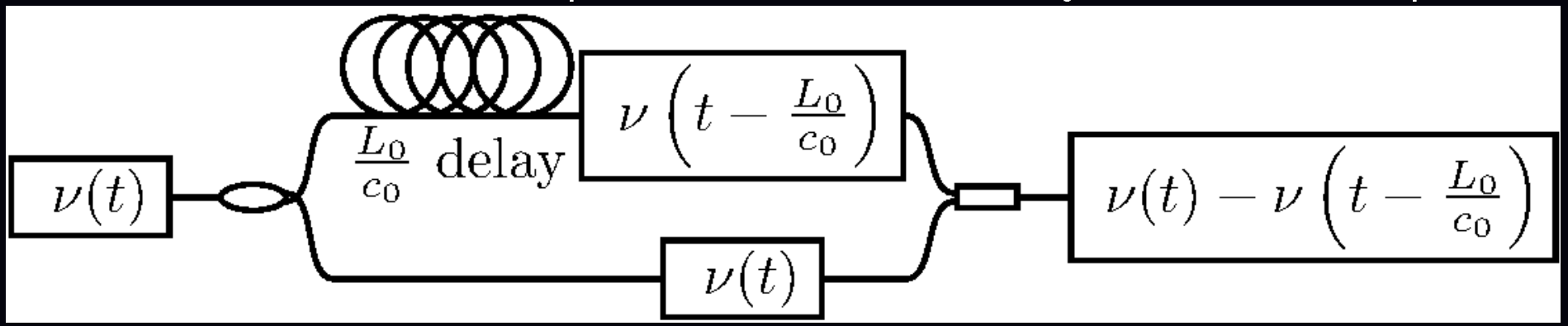
$$\alpha_{(t)} = \alpha\left(1 + d_e\sqrt{\frac{8\pi G\rho_{DM}}{\omega_\varphi c^2}}\cos(\omega_\varphi t)\right)$$

Variation of the length of an object

$$L(t) \propto \frac{\hbar}{\alpha(t)m_e c} \equiv L_0\left(1 + d_e\varphi_0\cos(\omega_\varphi)\right)$$

DArk Matter from Non Equal Delays

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



Unequal-arm length Mach-Zender interferometer

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

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

Color code

Nominal value
Noise
Dark matter effect

Fiber delay oscillation

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

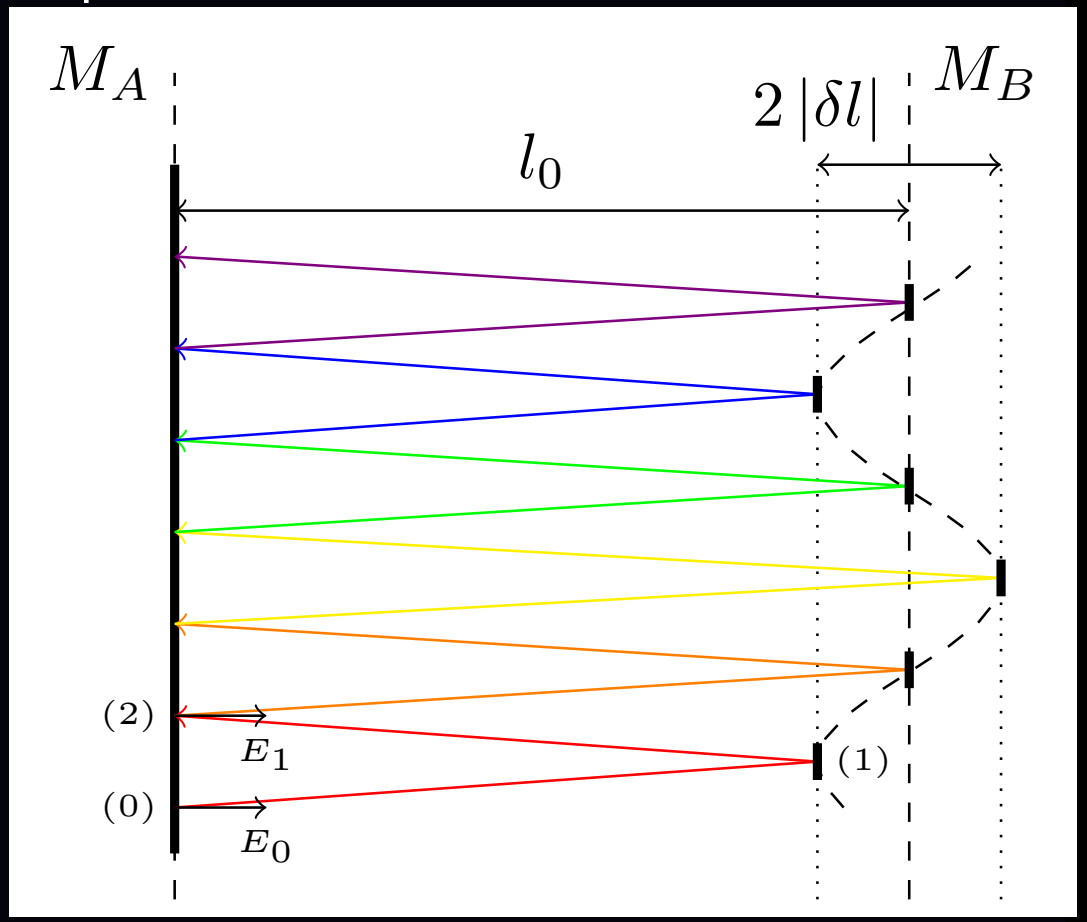
Phase difference between the delayed and non delayed signals

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

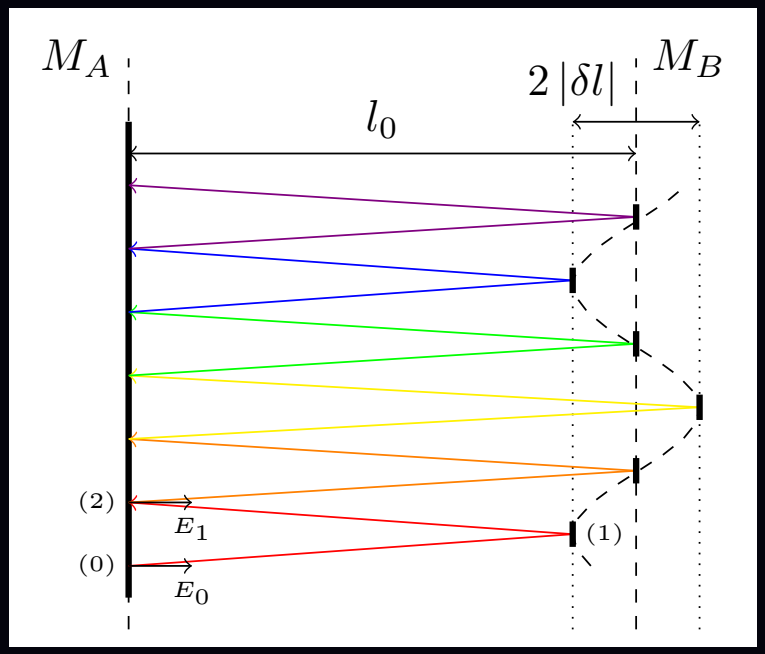
Let's model $\frac{\delta\omega}{\omega_0}$ and $\frac{\delta T}{T_0}$

Spacer length oscillation

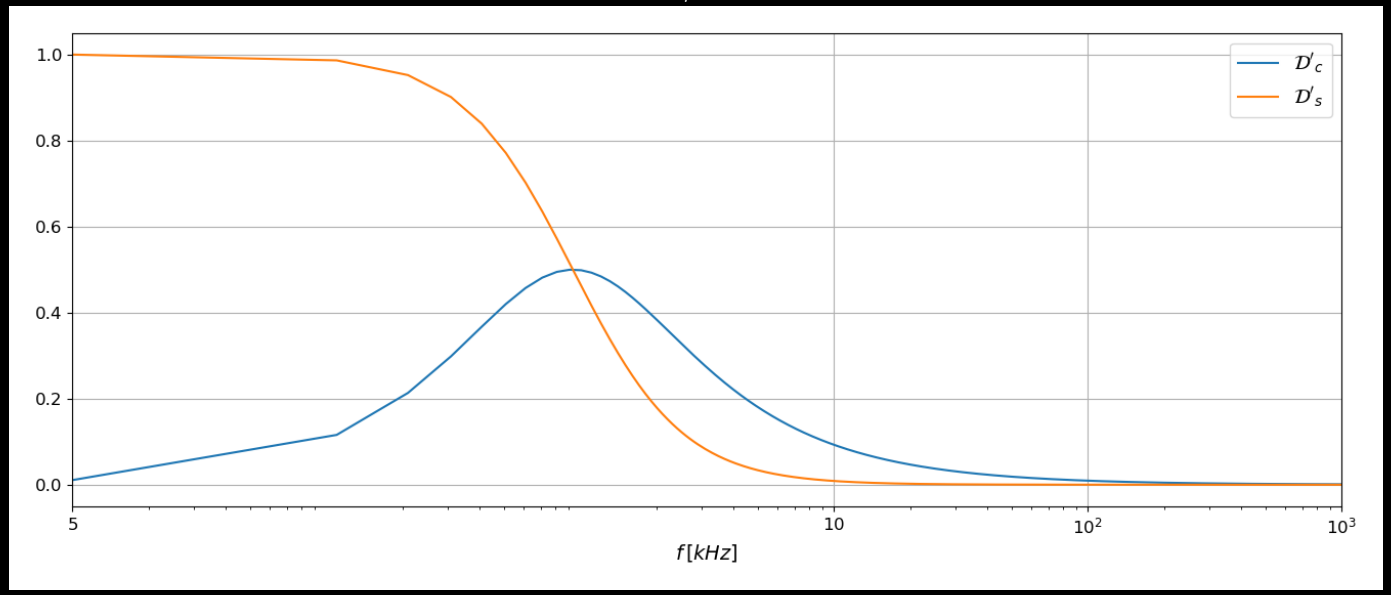
The mirrors position are oscillating in response to the scalar field.



Photon phase oscillation



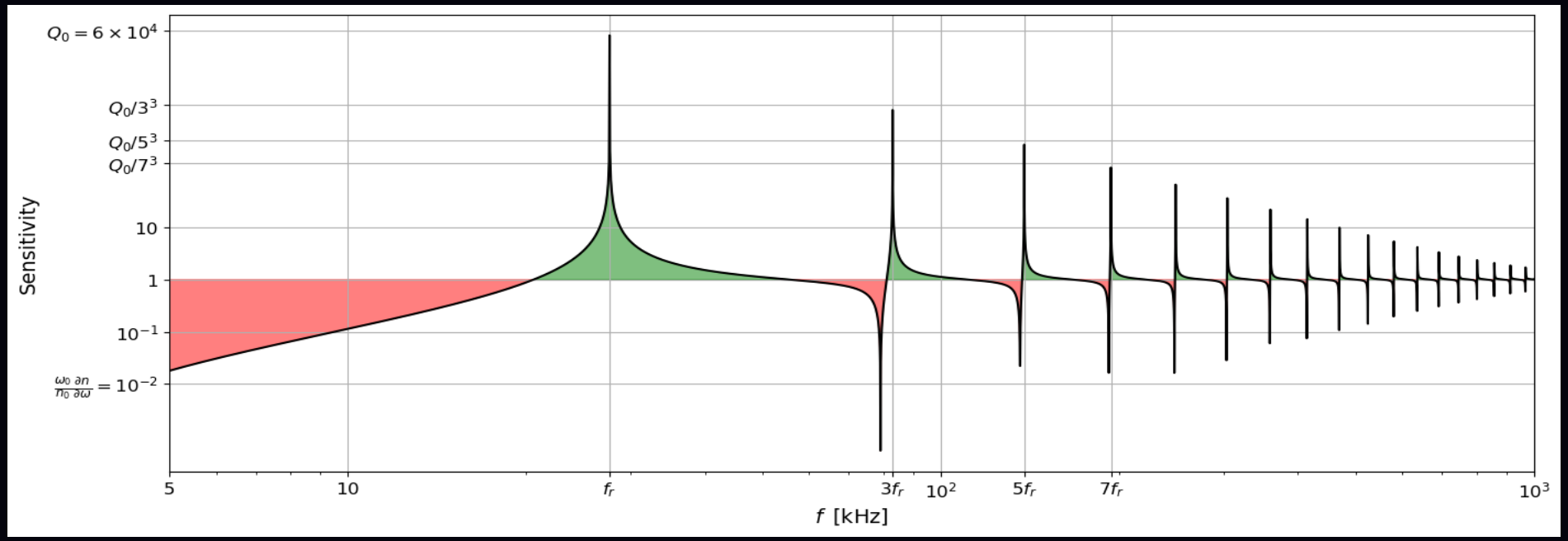
Let's model $\frac{\delta\omega}{\omega_0} \propto \frac{\delta\phi}{\phi_0}$



Fiber oscillations

$$\frac{\delta T}{T_0} \propto \frac{\delta L}{L_0} \text{ and } \frac{\delta T}{T_0} \propto \frac{\delta n}{n_0}$$

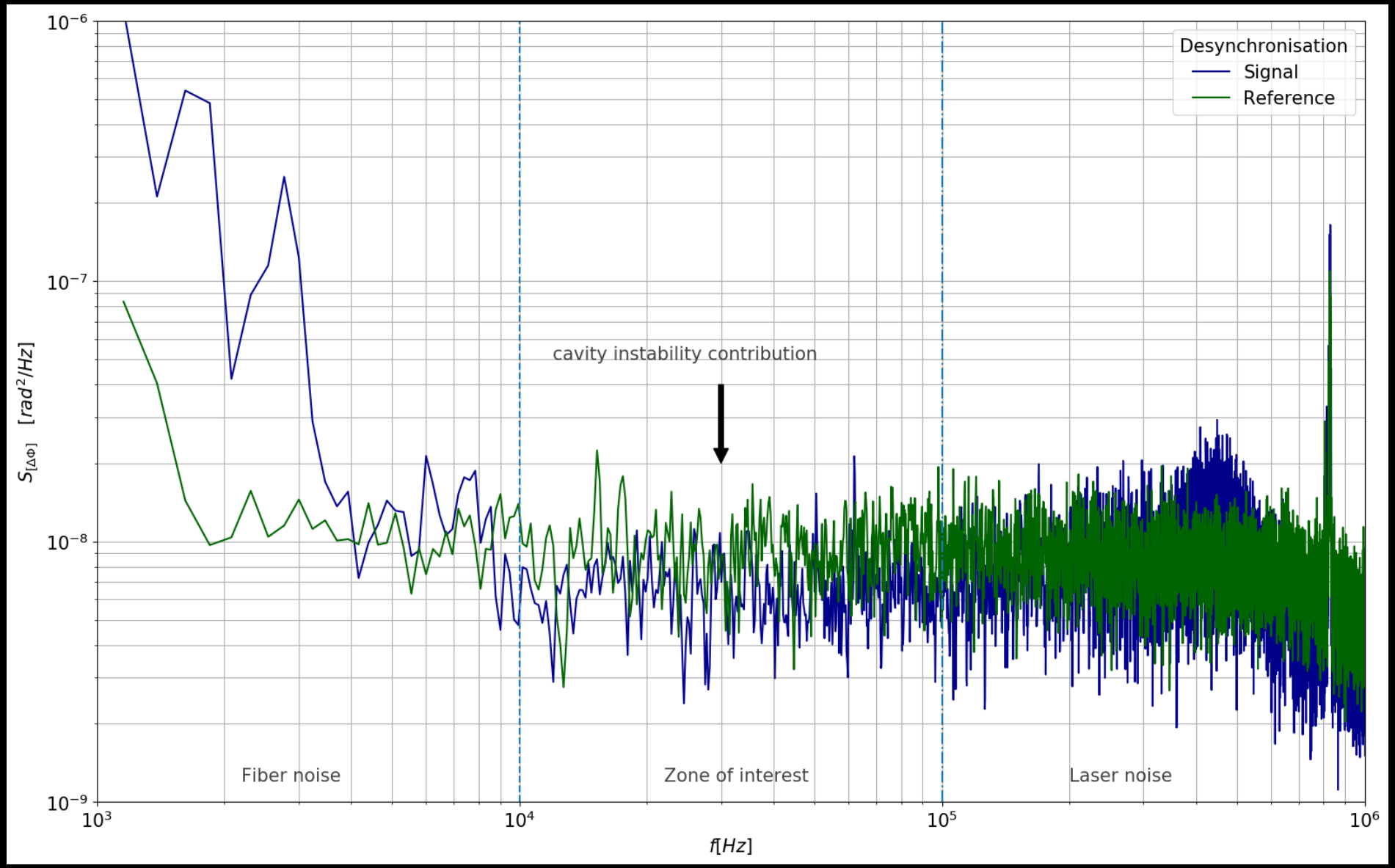
Full sensitivity



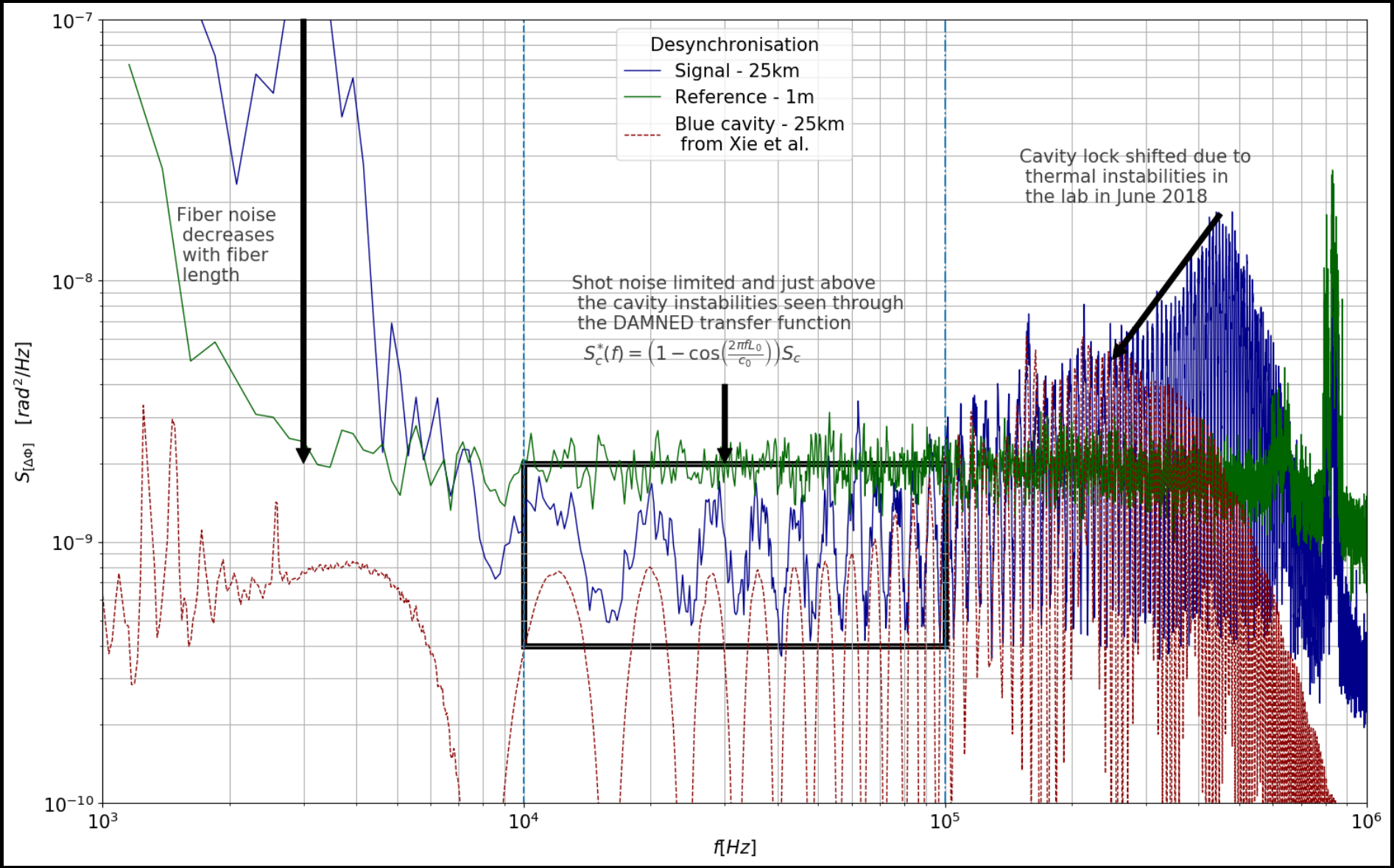
Link to the coupling constants

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

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



5 ms acquisition at 2 MHz with a 50km fiber



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

Data acquisition

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

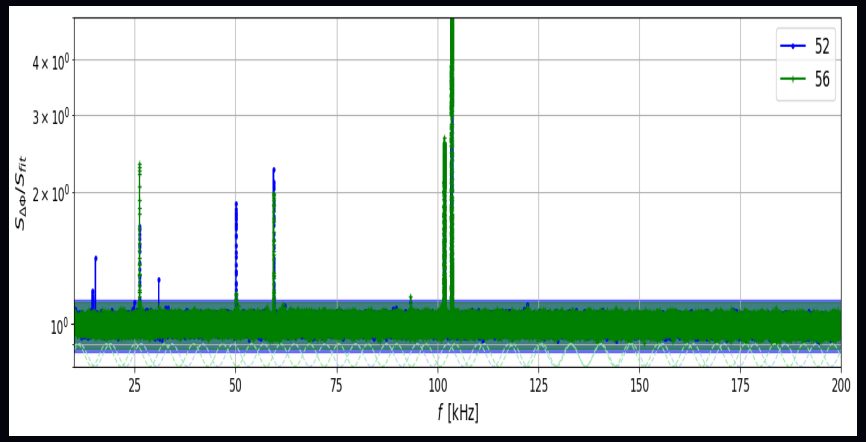
Fourier Transform

To overcome memory limitation, we had to split the $\simeq 2$ TB time domain file in smaller chunck to perform an FFT. The chunk had to be long enough to cover multiple coherence time of the stochastic signal.

Signal & Reference

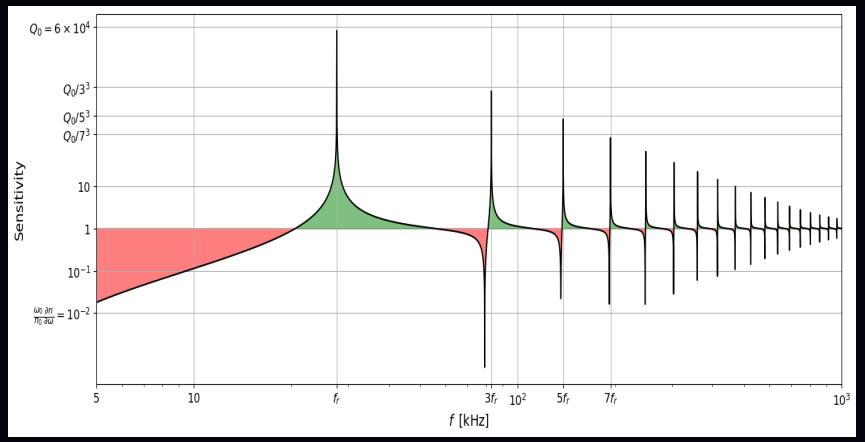
Exclusion of peaks present in both data sets.

Experimental data



+

Sensitivity



~~Heesian~~ Bayesian analysis

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

A. Derevianko - PRA (2018)

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

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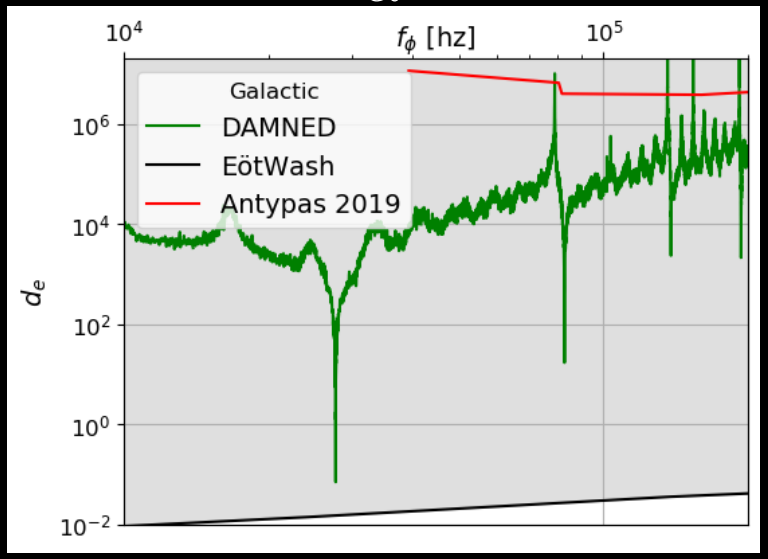
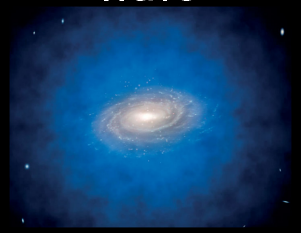
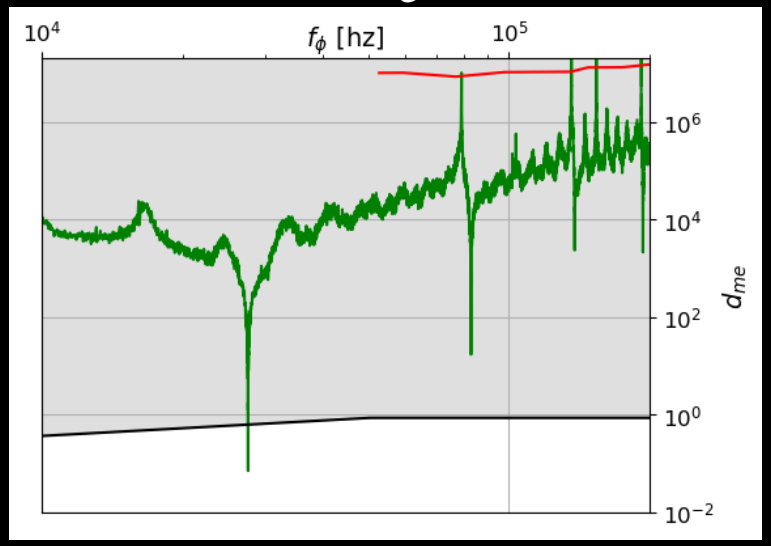


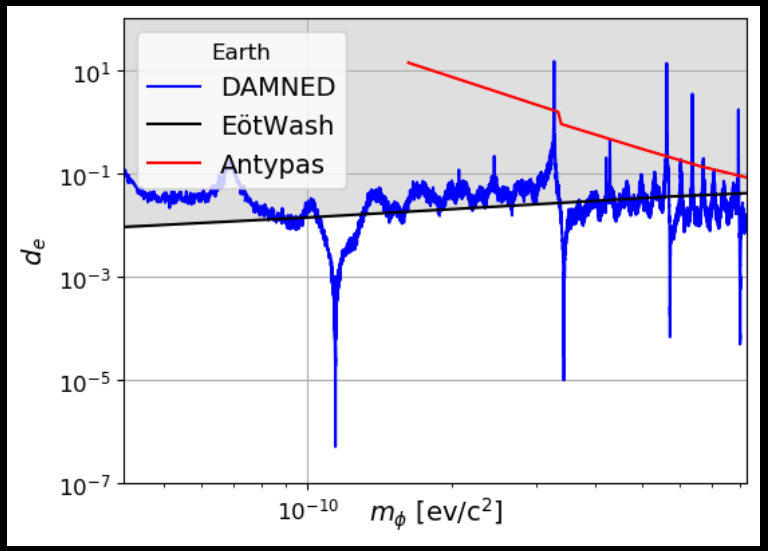
Galactic halo



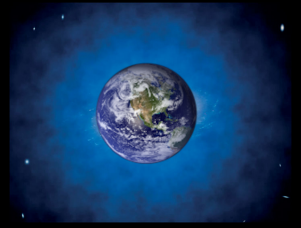
$\rho_{DM} = 0.4 GeV/cm^3$

m_e

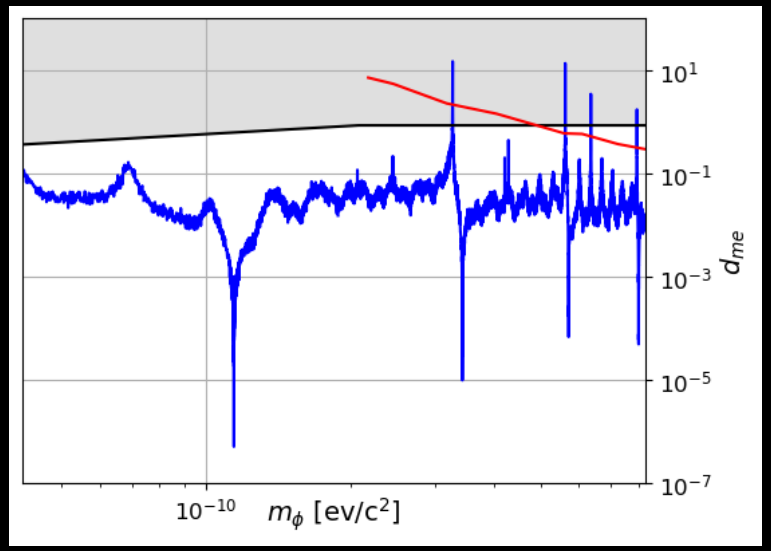




Earth halo



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



Thank you for your attention !