Notes on interferometry with ALP dark matter

Sreemanti Chakraborti

I. OBTAINING LIMITS ON DARK MATTER INTERACTIONS FROM NOISE FLOOR ANALYSIS OF INTERFEROMETER DATA

GW detectors such as LIGO can be repurposed as laser interferometers to probe ultralight dark matter. The observable is the difference in the optical phase difference between the two interferometer arms, which results from the length variation in the interferometer beamsplitter. Oscillations of the fine structure constant and the electron mass cause shifts in the Bohr radius and the lattice spacing of the solid, causing variations in the length l and refractive index n of the beamsplitter.

In the oscillating ultralight dark matter background, the ratio of the optical path length variation can be written as[1]:

$$\frac{\delta l}{l} \simeq \left(\frac{\delta\alpha}{\alpha} + \frac{\delta m_e}{m_e}\right)$$
$$\frac{\delta n}{n} \simeq 5\times 10^{-3}\left(2\,\frac{\delta\alpha}{\alpha} + \frac{\delta m_e}{m_e}\right) \tag{1}$$

which is valid in the limit where the mechanical resonance frequency of the beamsplitter $f_{\rm mech}$ is much larger than the dark matter oscillation frequency $f_{\rm mech} \gg f$. These variations lead to a difference in the optical path length of the two arms defined by[2]

$$\delta(L_x - L_y) \approx L\left(\frac{\delta\alpha}{\alpha} + \frac{\delta m_e}{m_e}\right) \tag{2}$$

A. Dark matter interaction Lagrangian

$$\mathcal{L}_{\rm eff}^{D=6} \simeq C_E \frac{a^2}{f_a^2}\bar{e}e + C_\gamma \frac{a^2}{4f_a^2}F_{\mu\nu}F^{\mu\nu} \tag{3}$$

The above dim-6 Lagrangian will lead to ALP field (a)-dependent corrections to electron mass and fine-structure constant given by [1]:

$$\frac{\delta\alpha}{\alpha} = C_\gamma \frac{a^2}{f_a^2} \tag{4}$$
$$\frac{\delta m_e}{m_e} = C_E \frac{a^2}{f_a^2} \tag{5}$$

where in the oscillating DM background, the time-averaged quadratic ALP field is given by:

$$\langle a^2\rangle = \rho_{\rm DM}/m_a^2 \tag{6}$$

The time variation of the strain is given by:

$$h(t) = \frac{\delta(L_x - L_y)}{L} = (C_\gamma + C_E)\frac{\rho_{\rm DM}}{m_a^2 f_a^2} \tag{7}$$

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[1] coefficient for the refractive index shift is material/wavelength dependent
[2] Setting any instrument/geometry factor → 1.

B. Noise floor analysis

Since interferometers like LIGO have not observed any signal, the exclusion on the upper limit of the dark matter interaction strength comes from the rescaling of the noise floor in the frequency domain. This is obtained from the Amplitude Spectral Density (ASD) or the (Power Spectral Density(PSD))$^{1/2}$ of the strain.

95% strain limit from ASD is given by:

$$h_0^{95\%}(f) = \kappa \, \frac{h^0(f)}{\sqrt{T}} \tag{8}$$

where T denotes the integration time, $\kappa \sim 5$ for 95% CL and $h^0(f)$ is the ASD of the baseline strain (without signal) in units of $1/\sqrt{\mathrm{Hz}}$. This can be directly obtained from the displacement ASD in the frequency domain by the following relation by directly dividing by the interferometeric arm.

$$h^0(f)\,(\text{in } 1/\sqrt{\mathrm{Hz}}) = \frac{\delta L(f)\,(\text{in m}/\sqrt{\mathrm{Hz}})}{L} \tag{9}$$

The characteristic "bucket" shape of an interferometer sensitivity/noise curve [2] arises from the interplay of three dominant noise sources. At low frequencies, seismic noise from ground motion couples into the mirrors and suspensions, producing a steep rise that typically scales like $1/f^2$ or steeper. At high frequencies, shot noise dominates, reflecting the quantum nature of light: fewer photons per cycle lead to increasing phase fluctuations, giving a noise floor that rises roughly linearly with frequency. In between lies the thermal noise band, where Brownian motion in the mirror coatings, suspension fibers, and substrates drives displacement fluctuations; these fall with frequency but more slowly than seismic, and thus set the trough of the sensitivity curve. The crossover of these mechanisms produces the familiar bucket, with optimal sensitivity in the mid-band where seismic and shot noise are both suppressed but thermal noise is not yet overwhelming.

For details on interferometric analysis, see the review by Adhikari et. al [3].

C. Connection to dark matter parameter space

The bound on the 95% CL can be translated into the upper limit on the interaction strength as:

$$\frac{\sqrt{C_\gamma + C_E}}{f_a} \lesssim \left(h_0^{95\%}(f)\, \frac{m_a^2}{\rho_{\mathrm{DM}}} \right)^{1/2} \tag{10}$$

For quadratic couplings, the signal peaks at twice the Compton frequency of ALP dark matter $f_{\mathrm{sig}} = 2f$.

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[1] M. Bauer, S. Chakraborti, and G. Rostagni, JHEP **05**, 023 (2025), arXiv:2408.06412 [hep-ph].

[2] A. S. Göttel, A. Ejlli, K. Karan, S. M. Vermeulen, L. Aiello, V. Raymond, and H. Grote, Phys. Rev. Lett. **133**, 101001 (2024), arXiv:2401.18076 [astro-ph.CO].

[3] R. X. Adhikari, Rev. Mod. Phys. **86**, 121 (2014), arXiv:1305.5188 [gr-qc].