Towards the Detection of Ultralight Dark Photon Dark Matter Using Optomechanical Sensors

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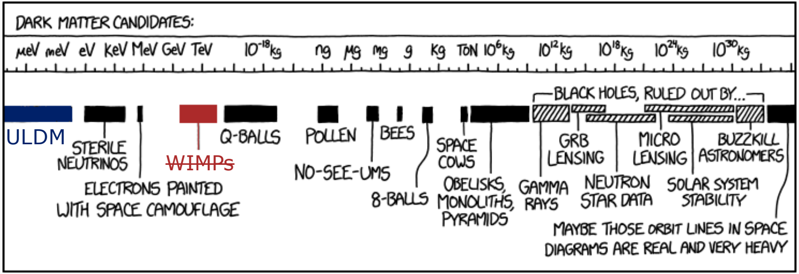
Beyond the WIMP Paradigm

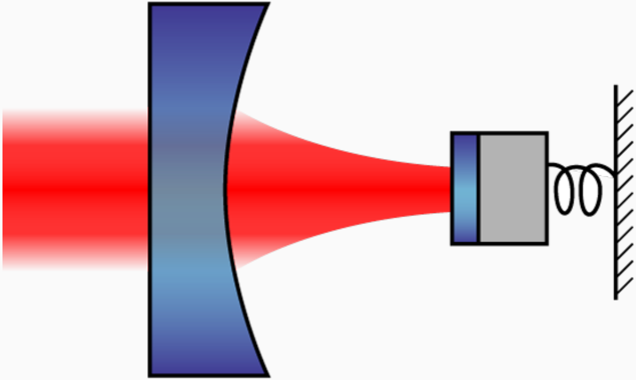


Adapted from xkcd

$B-L$ Dark Photon Dark Matter

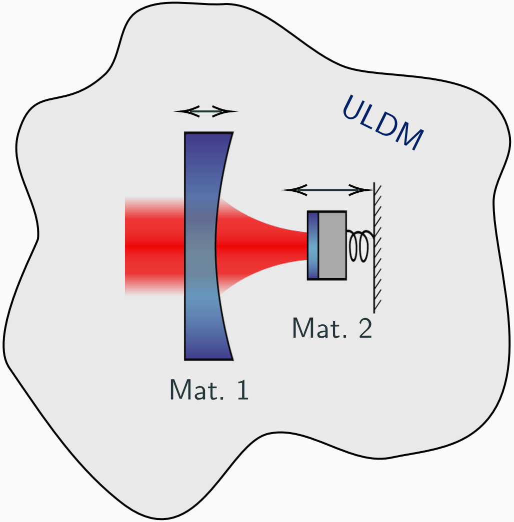
- Dark photon from a new gauged $U(1)_{B-L}$ symmetry is a popular BSM extension
- Characterised by two parameters: coupling (g_{B-L}) and mass (m_{DM})
- Ultralight dark photons lead to an ever-present, **oscillating** background **dark electric field**
- This leads to a very small differential acceleration between materials with different charge-mass ratios!

The Optomechanical Sensor



Wikipedia

Detecting Ultralight Dark Matter



- Sensor constantly immersed in **oscillating dark electric field**
- If mirrors made of different materials, get **differential acceleration**

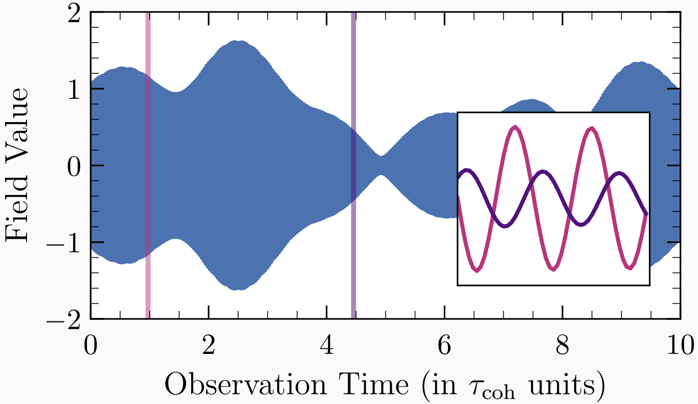
Amplitude related to DM field

$$\Delta a = g_{B-L}\Delta_{B-L}\boldsymbol{a_0}\cos(\omega_{\mathrm{DM}})\underbrace{\hat{\varepsilon}\cdot\hat{\boldsymbol{m}}}_{\text{DM Polarisation Projection}}$$

a_0 and $\hat{\varepsilon}\cdot\hat{\boldsymbol{m}}$ are inherently stochastic!

The Stochastic Field

$$A_m(t) \sim \sum_{i=1}^{N_{\mathrm{waves}}} \frac{\sqrt{2\rho_{\mathrm{DM}}}}{m_{\mathrm{DM}}} \mathrm{Re}\left(e^{i m_{\mathrm{DM}}(1+\frac{1}{2}v_i^2)t+\varphi_i}\right) \hat{\varepsilon} \cdot \hat{\boldsymbol{m}}$$



Our Goal

- Cavity accelerometers have been used to draw limits on $B - L$ dark photon DM
  Peter W. Graham et al. **1512.06165**, Daniel Carney et al. **1908.04797**, Jack Manley et al. **2007.04899**

- **However**, a likelihood-led treatment incorporating stochastic field properties and DM signal shape is lacking

- Want to develop this treatment in contact with experimentalists in **Windchime Collaboration**!

How does field stochasticity impact projected limits?

Towards a Statistical Limit-Setting Treatment

- Previously: Limits set using $\mathrm{SNR} = 1$

$$d \equiv \frac{\text{Signal Power Spectral Density}}{\text{Noise Power Spectral Density}} \stackrel{!}{=} 1$$

- **Problem**: Does not account for statistics of problem and stochasticity of field!

- We can quantify departure from simple SNR treatment via a correction factor, $\boldsymbol{\kappa}$

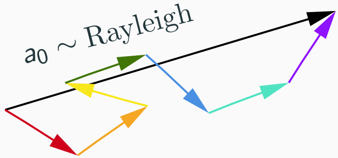
$$g_{B-L} = \kappa \, g_{B-L}^{\mathrm{SNR}}$$

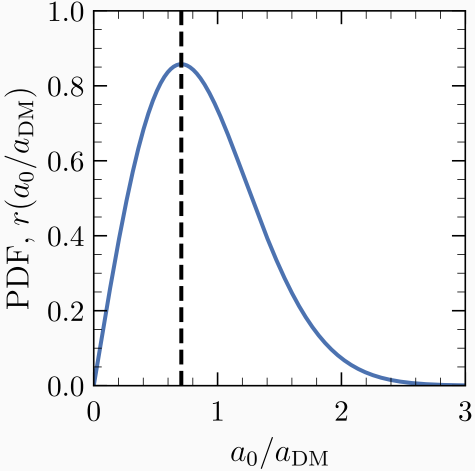
The Stochastic Field: Field Amplitude

- Randomness in field amplitude due to random DM phase, $\varphi \sim \mathrm{U}(0, 2\pi)$

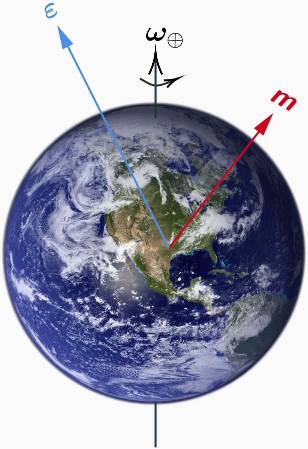
$$a_0 \propto \sum_{i}^{N_{\rm waves}} e^{i\varphi_i}$$

- Amplitude distribution follows from statistics of a 2D random walk





The Stochastic Field: Polarisation Projection

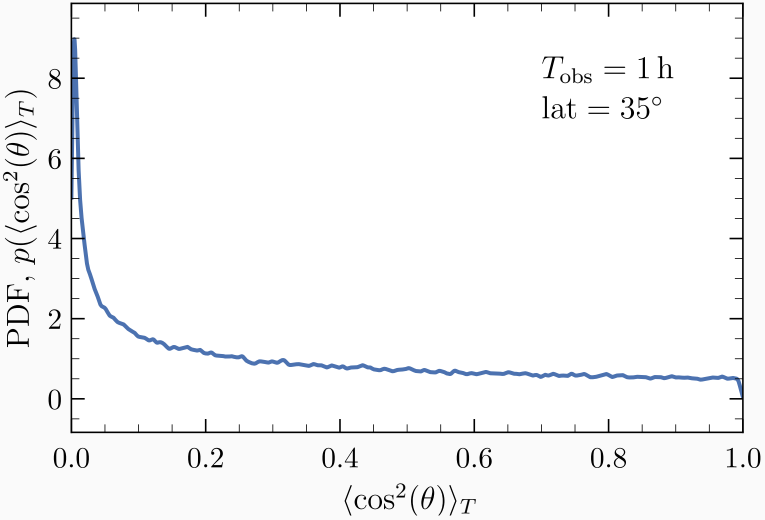


- Signal dependent on **time-averaged** projection of **random** DM polarisation onto sensor sensitivity axis Andrea Caputo et al. **2105.04565**

$$\text{Signal} \propto \langle |\hat{\varepsilon} \cdot \hat{\boldsymbol{m}}(t)|^2 \rangle_T \equiv \langle \cos^2(\theta) \rangle_T$$

- Depends on
  - Observation time (T_{obs})
  - Direction of sensitivity axis ($\hat{\boldsymbol{m}}$)
  - Location of experiment (lat)

The Polarisation Projection PDF



Towards a Statistical Limit-Setting Treatment: The Likelihoods

1. Get **deterministic** likelihood. Takes care of inherent statistics of problem

$$\mathcal{L}_{\mathrm{det}}(d) = \chi^2_{\mathrm{nc}}\,(d;\, \lambda_{\mathrm{nc}}(g_{B-L}),\, k=2)$$

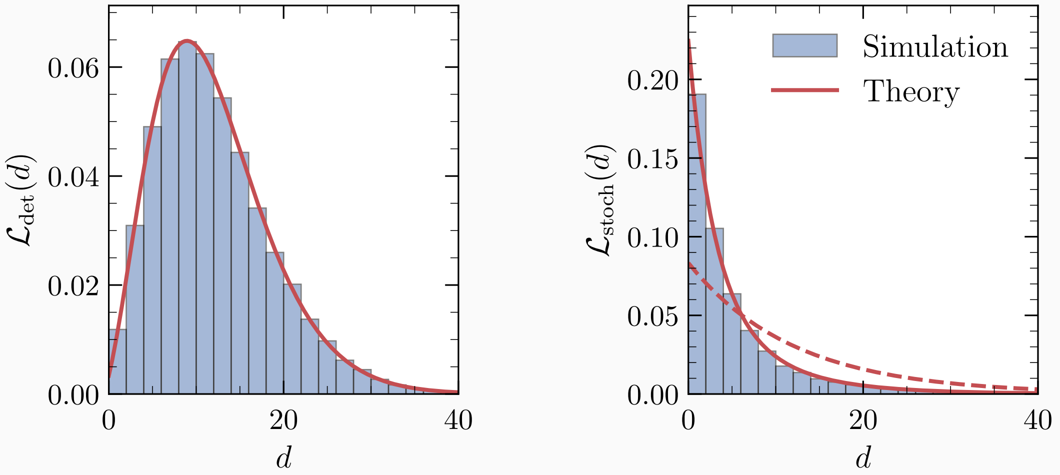
2. Account for stochasticity. We handle this via a marginalised likelihood[1]

$$\mathcal{L}_{\mathrm{stoch}}(d) = \int_\Omega \mathcal{L}_{\mathrm{det}}\, r(x)\, p(\langle \cos^2(\theta)\rangle_T)\, \mathrm{d}x\, \mathrm{d}\langle \cos^2(\theta)\rangle$$

3. Find that g_{B-L} for which we can exclude $g_{B-L} = 0$ to 95% confidence level

[1] Similar approach in Gary P. Centers et al. **1905.13650** but only for amplitude stoch.

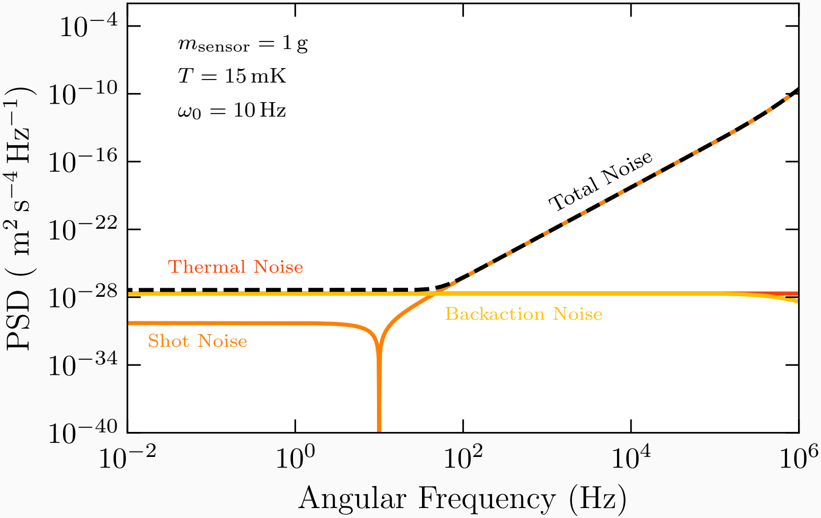
Visualising the Likelihoods



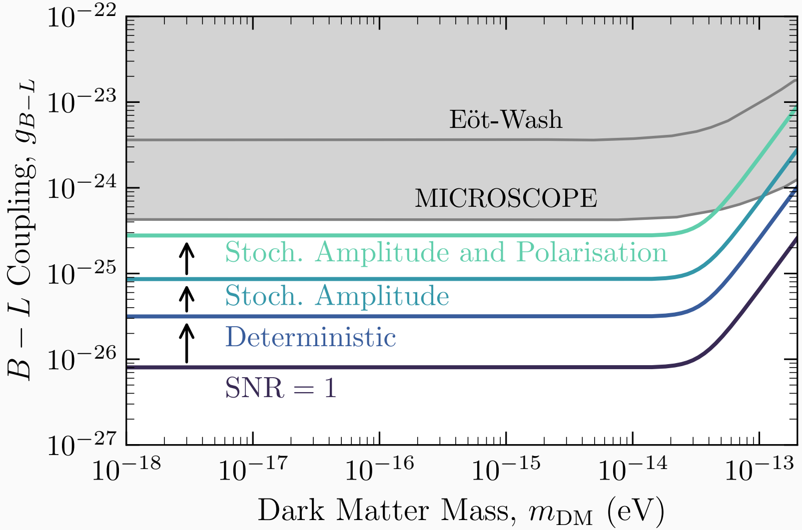
Correcting for Stochasticity

Effect	**Correction Factor, κ**
Likelihood Treatment (Det.)	3.9
w/ Stochastic Amplitude	11
w/ Stochastic Amplitude and Polarisation	35

Making Contact with Experiment



The Stochastic Field: Short Observation Time

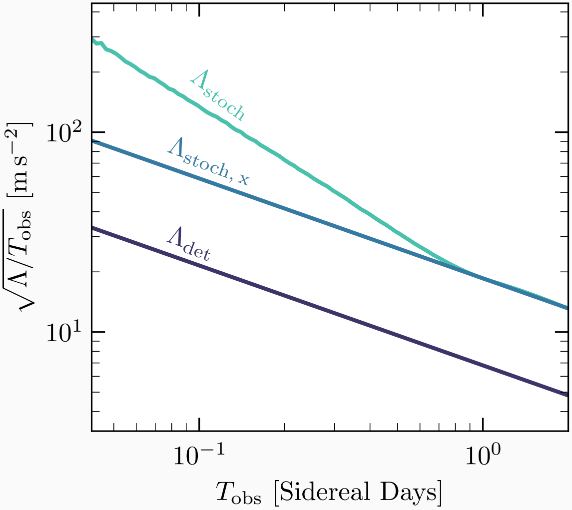


Summary

- Ultralight $B-L$ vector is a **well-motivated DM candidate**
- Optomechanical sensors are up to task of measuring effects of dark electric field
- However, it is **crucial** to account for field stochasticity
- This can lead to $\mathcal{O}(10\text{–}100)$ effects in limit projections

Optomechanical sensors are powerful probes of ultralight $B-L$ dark matter, but we cannot ignore a proper statistical treatment!

Dependence on Observation Time



Backgrounds

$$S_{aa}^{\mathrm{Th}} \equiv \frac{4k_B T\gamma}{m_s}$$

$$S_{aa}^{\mathrm{SN}}(\omega) \equiv \frac{\hbar\kappa L^2}{2\omega_L P_L}|\chi_c(\omega)|^{-2}|\chi_m(\omega)|^{-2}$$

$$S_{aa}^{\mathrm{BA}}(\omega) \equiv \frac{2\hbar\omega_L P_L}{m_s^2 L^2 \kappa}|\chi_c(\omega)|^{2}$$

$$|\chi_m(\omega)|^{-2} = (\omega^2 - \omega_0^2)^2 + \gamma^2\omega^2$$

$$|\chi_c(\omega)|^{-2} = \frac{\omega^2 + \kappa^2/4}{\kappa}\,.$$

Statistics

1. Solve for d_{lim} under null hypothesis (Type-I error step)

$$\int_0^{d_{\mathrm{lim}}} \mathcal{L}(d|g_{B-L}=0)\mathrm{d}d = 1-\alpha$$

2. Solve for $g_{B-L} > 0$ in alternative hypothesis (Type-II error step)

$$\int_0^{d_{\mathrm{lim}}} \mathcal{L}(d|g_{B-L})\mathrm{d}d = 1-\beta \equiv \alpha$$