Detecting Ultralight Dark Photon Dark Matter Using Optomechanical Sensors

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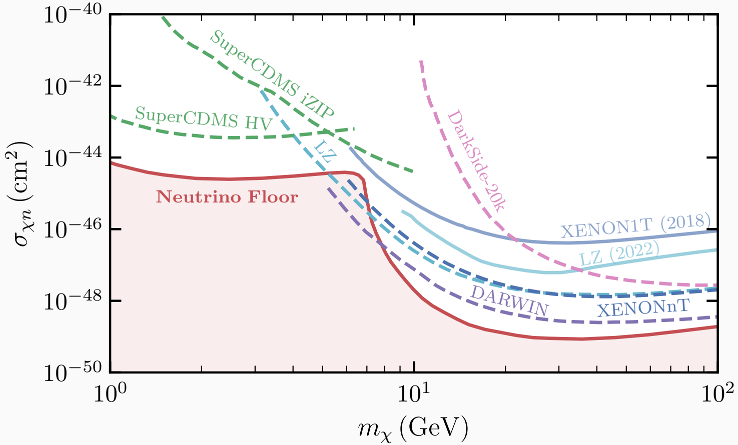
The WIMP Era in Distress



The WIMP Era in Distress (According to ChatGPT)

WIMPs retreat, unseen,
Alternatives now emerge,
Mysteries persist.

— ChatGPT

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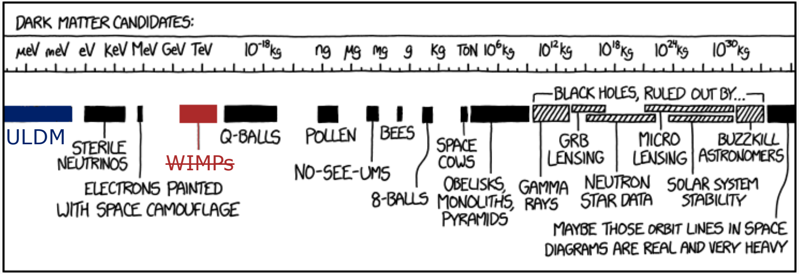
Beyond the WIMP Paradigm



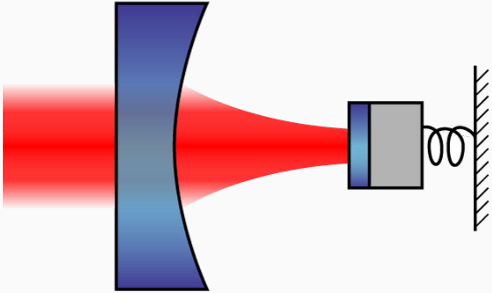
Adapted from xkcd

$B-L$ 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

- Sensors use coupling between optical and mechanical modes to measure quantities very precisely
- Incredible developments due to gravitational wave efforts!
- Important parameters:
  - Mechanical resonant frequency (ω_0)
  - Temperature of surroundings (T)
  - Sensor mass (m_{sensor})
  - Mode decay rates

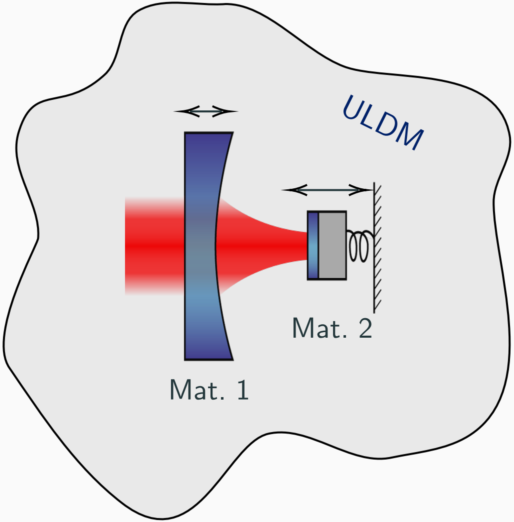


Wikipedia

Detecting Ultralight Dark Matter

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

$$\Delta a \sim \overset{\text{Coupling}}{\overset{\downarrow}{g}}_{B-L} \underbrace{\left| \frac{N_1}{A_1} - \frac{N_2}{A_2} \right|}_{\text{Diff. } q-m \text{ ratio}} a_0 \cos(\overset{\text{DM Frequency}}{\overset{\downarrow}{\omega_{\mathrm{DM}}}} t)$$



Our Goal

- Cavity accelerometers have been used to draw limits on $B - L$ dark photon DM

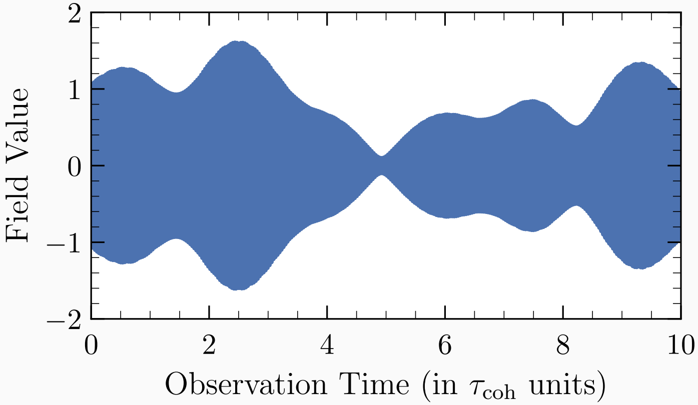
  Peter W. Graham et al. **1512.06165**, Daniel Carney et al. **1908.04797**, Jack Manley et al. **2007.04899**

- **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 can optomechanical sensors help us to learn more about the nature of ULDM?

The Stochastic Field: Long Observation Time



- Net field a superposition of many partial waves oscillating at slightly different frequencies

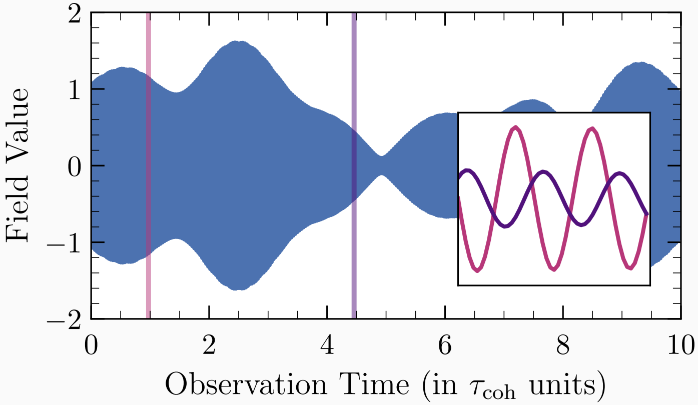
$$\omega_{\mathrm{DM}} = m_{\mathrm{DM}} + \frac{1}{2} m_{\mathrm{DM}} v^2$$

- Leads to 'beat-like' effect on timescales

$$\tau_{\mathrm{coh}} = \frac{1}{m_{\mathrm{DM}} v^2} \sim \frac{10^6}{m_{\mathrm{DM}}}$$

- For $T_{\mathrm{obs}} \gg \tau_{\mathrm{coh}}$, our sensor samples many coherent patches

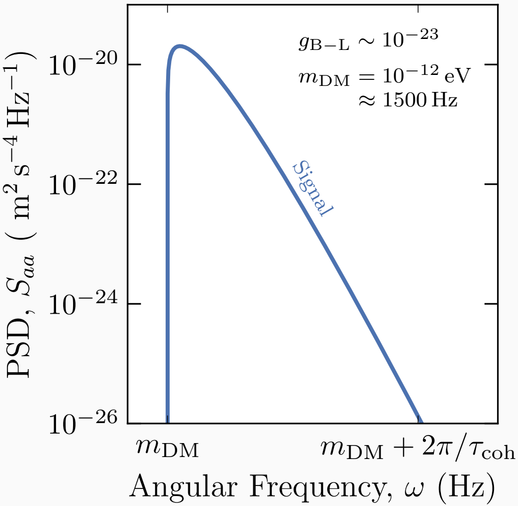
The Stochastic Field: Short Observation Time



- For $T_{\mathrm{obs}} \ll \tau_{\mathrm{coh}}$, our sensor samples one coherent patch
- We observe a clean sinusoid in time series
- But now the amplitude is **stochastic**!

Focus here on $T_{\mathrm{obs}} \gg \tau_{\mathrm{coh}}$

ULDM in Frequency Space

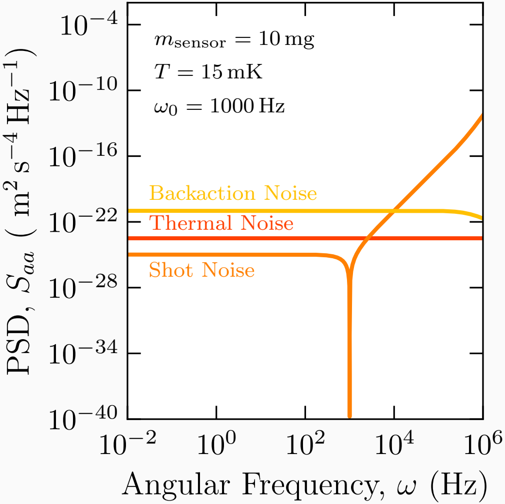


- Fourier space is best place to do our inferencing
- We consider the **power spectral density**, PSD (power per frequency)
- In $T_{\mathrm{obs}} \gg \tau_{\mathrm{coh}}$ case, signal appears as a **broadened peak** at $\omega \approx m_{\mathrm{DM}}$
- Each frequency bin is exponentially distributed

  Joshua W. Foster et al. **1711.10489**

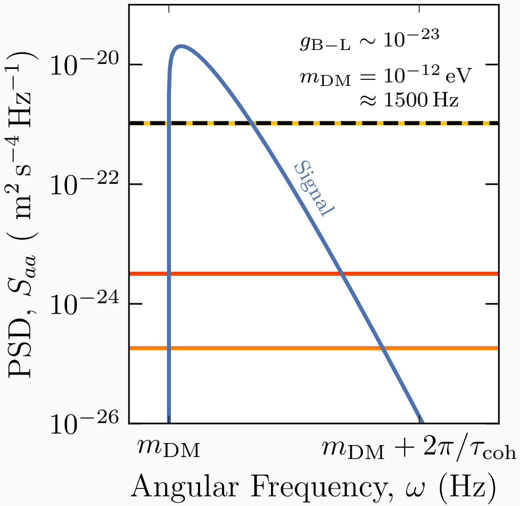
$$\mathrm{Likelihood}(\text{data}) \sim \mathrm{Exp}(\langle\text{signal}\rangle)$$

ULDM in Frequency Space: Signal vs Background



- We have to distinguish this peak from many background sources:
    - Thermal noise
    - Shot noise
    - Backaction noise

ULDM in Frequency Space: Signal vs Background



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Excluding Ultralight Dark Photon Dark Matter

Frequentist Limit Setting

1. Assume we see nothing: ‘generate’ Asimov background data set

2. For a given m_{DM}, construct signal given a $g_{B-L} \neq 0$

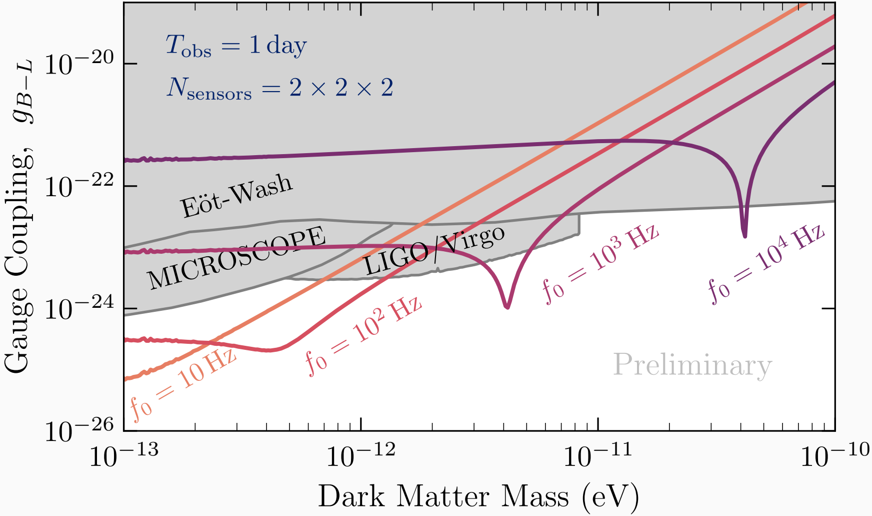
3. Consider log-likelihood ratio test statistic

$$q = -2\ln\left[\frac{\mathcal{L}(\text{data}\,|\,g_{B-L},\, m_{\mathrm{DM}})}{\mathcal{L}(\text{data}\,|\,g_{B-L}=0,\, m_{\mathrm{DM}})}\right]$$

   (Likelihood for axions developed by Joshua W. Foster et al. **1711.10489**):

4. Use q to exclude coupling at desired confidence level! (90%)

Limits


$T_{\mathrm{obs}} = 1$ day
$N_{\mathrm{sensors}} = 2 \times 2 \times 2$
Eöt-Wash
MICROSCOPE
LIGO/Virgo
$f_0 = 10$ Hz
$f_0 = 10^2$ Hz
$f_0 = 10^3$ Hz
$f_0 = 10^4$ Hz
Preliminary
Gauge Coupling, g_{B-L}
10^{-20}
10^{-22}
10^{-24}
10^{-26}
10^{-13}
10^{-12}
10^{-11}
10^{-10}
Dark Matter Mass (eV)

Summary

- WIMPs are facing an **existential crisis**
- Ultralight $B - L$ dark photons are a **well-motivated DM candidate**
- Optomechanical sensors at up to the task of measuring effects of dark electric field
- A **small** array could quickly **exclude new parameter space**!

Optomechanical sensors will form powerful probes of ultralight dark photon dark matter!

Constructing Field

$$A_x \sim \sum_{i=1}^{N_{\mathrm{waves}}} \frac{\sqrt{\rho_{\mathrm{DM}}}}{m_{Z'}} \mathrm{Re}\left(e^{im_{\mathrm{DM}}(1+\frac{1}{2}v_i^2)t+\theta_i}\right) \hat{\varepsilon} \cdot \hat{\boldsymbol{x}}$$

$$v \sim f_{\mathrm{SHM}}(\boldsymbol{v})$$

$$\theta \sim \mathrm{U}(0,\, 2\pi)$$

$$\hat{\varepsilon} \sim \text{Unit Sphere}$$

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

$$q = 2\sum_k \left[S^k_{aa} \left(\frac{1}{\lambda_k(\boldsymbol{\theta})} - \frac{1}{\lambda_k(\hat{\boldsymbol{\theta}})} \right) + \ln \left(\frac{\lambda_k(\boldsymbol{\theta})}{\lambda_k(\hat{\boldsymbol{\theta}})} \right) \right]$$

$$p \equiv \int_{q^{\mathrm{lim}}}^{\infty} f(q)\,\mathrm{d}q = 1 - \alpha\,,$$

$$f(q) = \frac{1}{2}\delta(0) + \frac{1}{2}\chi^2_{k=1}(q)\,.$$