Dark Matter Scattering in Optomechanical Experiments

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16th PATRAS Workshop on Axions, WIMPs and WISPs

Mostly based on collaborations with
Outline

- Introduction
- Particle Physics Approach
- Gravitational Wave Astronomy Approach
- Summary and Conclusions
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WIMP Searches

Time to think again?! Light WIMPs?
Gravitational Wave Detectors
Gravitational Wave Detectors

- Decade long R&D efforts
- Impressive sensitivities
- Impressive results
- Nobelprize 2017
- Other uses for this technology?

(Similar motivation to the talks from Jun'ya Kume, Sander Vermeulen and Doris Todorović)

[Courtesy Caltech/MIT/LIGO Laboratory 2016]
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Dark Brownian Motion

- Any target mass in a bath of DM
- DM scatterings induce Brownian Motion
- Measure the position of a light target mass with high precision
- Look for time-dependent asymmetries

[Cheng, Primulando, MS '19]
Potential Setup

Inspired by [Valerie Domcke and Martin Spinrath, 2017]

Assume the motion of the mirror without external force is well understood.
The Asymmetry Factor

- The Asymmetry Factor:
  \[ A = \frac{N_+ - N_-}{N_+ + N_-} = p_+ - p_- \]

- Uncertainty of A:
  \[ \sigma_A = \frac{2}{\sqrt{N}} \sqrt{p_+ p_-} \]

\( A, p_\pm \) are independent of DM mass
Backgrounds

• Many potential backgrounds for our proposal
  • seismic noise, nearby traffic, radioactivity, etc.

• In the paper we discuss two examples
  • Neutrinos (negligible $O(10^{-14})$ events per sec)
  • Hits from residual gas (after momentum cutoff $O(10^{-9})$ events per sec)
Sensitivity Estimate

\[
\frac{\langle A \rangle^2}{\sigma_A^2 + \sigma_{bkg}^2} = 4
\]

\[M_T = 10^{-3} \text{ g of carbon}\]
\[\Delta t = 10 \text{ min}\]
\[q_{\text{min}} = 2 \times 10^{-23} \text{ kg m/s}\]

\[\sigma_{\text{DM-N}} [\text{cm}^2]\]

\[M_{\text{DM}} [\text{GeV/c}^2]\]
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Toy Model: Damped Harmonic Oscillator

• We want to study a simple toy model first

\[
m \ddot{x}_c + k_c (1 + i \phi) x_c = \frac{F_{\text{ext},c}}{L}
\]

• The experimental output

\[
x_{\text{tot},c}(t) = x_{\text{th},c}(t) + x_{\text{qu},c}(t) + x_{\text{DM},c}(t)
\]

  \[\text{Suspension Thermal Noise} \quad \text{Quantum Noise} \quad \text{DM Signal}\]

• We neglect here some noise components
Toy Model: Strain Amplitudes

Assume KAGRA-like parameters and $q_R = 1 \text{ GeV/c}^2 \times 220 \text{ km/s}$
Signal-to-Noise Ratio

- The optimal SNR is given by

\[ \varphi^2 = \int_{f_{\text{min}}}^{f_{\text{max}}} df \frac{4|\tilde{x}_{\text{DM}}(2\pi f)|^2}{S_n(2\pi f)} \]

- Near the peak (FWHM) neglect quantum noise

\[ \varphi_{\text{th}}^2 = \frac{1}{2\pi} \frac{q_R^2}{m k_B T} = \frac{1}{2\pi} \frac{E_R}{E_{\text{th}}} = 4.09 \times 10^{-24} \]

- Need light, cold targets!

[Lee, Nugroho, MS '20; Moore, Cole, Berry '14]

Numbers as in previous figure
DM Signal at KAGRA

[Lee, Nugroho, MS '20]

DM Hit in the KAGRA TM

KAGRA Total Noise

Strain Amplitude in $\sqrt{1/\text{Hz}}$

$q_R$ in vertical direction

$q_R$ in horizontal direction

$q_R = 1 \text{ GeV/c}^2 \times 220 \text{ km/s}$

Frequency in Hz
Current Reality

- Optically levitated mass
- Target mass 1 ng
- Temperature 200 μK
- Several days exposure
- Experimental threshold 0.15 GeV
Lots of R&D


<table>
<thead>
<tr>
<th>Physical device</th>
<th>Mass</th>
<th>Frequency</th>
<th>Temp.</th>
<th>Quantum limit</th>
<th>Sensitivity, e.g. acceleration, strain, force...</th>
</tr>
</thead>
<tbody>
<tr>
<td>BAW/Weber bar [41]</td>
<td>1000 kg</td>
<td>1 kHz</td>
<td>4 K</td>
<td>$h_s \sim 10^{-21}/\sqrt{\text{Hz}}$</td>
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<tr>
<td>HBAR phonon counting [76]</td>
<td>50 µg</td>
<td>10 GHz</td>
<td>10 mK</td>
<td>single phonon</td>
<td>$\sigma_E \sim 30 \mu\text{eV}$</td>
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<td>$h_s \sim 10^{-15}/\sqrt{\text{Hz}}$</td>
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<td>$h_s \sim 10^{-19}/\sqrt{\text{Hz}}$ broadband below res.</td>
</tr>
<tr>
<td>superfluid helium cavities [52]</td>
<td>1 ng</td>
<td>300 MHz</td>
<td>50 mK</td>
<td>single phonon</td>
<td>$\sigma_E \sim 1 \mu\text{eV}$</td>
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<td>Resonant and below-resonance detectors:</td>
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<tr>
<td>cantilever optomechanical accelerometer [77]</td>
<td>25 mg</td>
<td>10 kHz</td>
<td>300 K</td>
<td>$\sqrt{\Delta f} \sim 3 \times 10^{-9} \text{g}/\sqrt{\text{Hz}}$</td>
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<td></td>
<td>($\sqrt{\Delta f} \sim 10^{-7} \text{g}/\sqrt{\text{Hz}}$ broadband below res)</td>
</tr>
<tr>
<td>SiN suspended test mass accelerometer [78, 79]</td>
<td>10 mg</td>
<td>10 kHz</td>
<td>300 K</td>
<td>$\sqrt{\Delta f} \sim 10^{-7} \text{g}/\sqrt{\text{Hz}}$</td>
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<td>($\sqrt{\Delta f} \sim 10^{-6} \text{g}/\sqrt{\text{Hz}}$ broadband below res)</td>
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<td>membrane optomechanics [80-86]</td>
<td>10 ng</td>
<td>1.5 MHz</td>
<td>100 mK</td>
<td>at SQL</td>
<td>$\sqrt{\Delta f} \sim 10^{-17} \text{N}/\sqrt{\text{Hz}}$</td>
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<tr>
<td>crystalline cantilever for force sensing [87]</td>
<td>0.2 ng</td>
<td>1 kHz</td>
<td>200 mK</td>
<td>$\sqrt{\Delta f} \sim 3 \times 10^{-7} \text{g}/\sqrt{\text{Hz}}$</td>
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<td></td>
<td>$\sqrt{\Delta f} \sim 10^{-18} \text{N}/\sqrt{\text{Hz}}$</td>
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<td>Pendula above resonance:</td>
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<td>LIGO mirror [88]</td>
<td>10 kg</td>
<td>10 Hz – 10 kHz</td>
<td>300 K</td>
<td>SN limited above 100 Hz</td>
<td>$\sqrt{\Delta f} \sim 4 \times 10^{-15} \text{g}/\sqrt{\text{Hz}}$ at 100 Hz</td>
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<td>$\sqrt{\Delta f} \sim 10^{-19} \text{m}/\sqrt{\text{Hz}}$</td>
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<tr>
<td>suspended mg mirror [89-91]</td>
<td>1 mg</td>
<td>1 – 10 kHz</td>
<td>300 K</td>
<td>Factor of 20 in displacement from (off-resonant) SQL</td>
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<td></td>
<td>$\sqrt{\Delta f} \sim 7 \times 10^{-15} \text{g}/\sqrt{\text{Hz}}$ at 600 Hz</td>
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<td>$\sqrt{\Delta f} \sim 5 \times 10^{-17} \text{m}/\sqrt{\text{Hz}}$</td>
</tr>
<tr>
<td>crystalline cantilever [92]</td>
<td>50 ng</td>
<td>10 – 100 kHz</td>
<td>300 K</td>
<td>at (off-resonant) SQL</td>
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<td>$\sqrt{\Delta f} \sim 2 \times 10^{-7} \text{g}/\sqrt{\text{Hz}}$ at 20 kHz</td>
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<td></td>
<td>$\sqrt{\Delta f} \sim 10^{-16} \text{m}/\sqrt{\text{Hz}}$</td>
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<td>Levitated and free-fall systems:</td>
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<tr>
<td>LISA pathfinder [93]</td>
<td>1.5 kg</td>
<td>1 – 30 mHz</td>
<td>300 K</td>
<td>$\sqrt{\Delta f} \sim 10^{-15} \text{g}/\sqrt{\text{Hz}}$</td>
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<tr>
<td>nm magneto-levitated sphere [94]</td>
<td>4 mg</td>
<td>20 Hz</td>
<td>5 K</td>
<td>$\sqrt{\Delta f} \sim 2 \times 10^{-7} \text{g}/\sqrt{\text{Hz}}$</td>
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<td></td>
<td>$\sqrt{\Delta f} \sim 8 \times 10^{-12} \text{N}/\sqrt{\text{Hz}}$</td>
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<tr>
<td>sub-mm magneto-levitated sphere [95]</td>
<td>0.25 µg</td>
<td>1 – 20 Hz</td>
<td>laser cool to &lt; 9 K</td>
<td>$\sqrt{\Delta f} \sim 10^{-7} \text{g}/\sqrt{\text{Hz}}$</td>
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<td>$\sqrt{\Delta f} \sim 2 \times 10^{-16} \text{N}/\sqrt{\text{Hz}}$</td>
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<tr>
<td>optically trapped microsphere [96]</td>
<td>1 ng</td>
<td>10 – 100 Hz</td>
<td>laser cool to 50 µK</td>
<td>Factor of 100 in displacement from (off-resonant) SQL</td>
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<td>$\sqrt{\Delta f} \sim 10^{-7} \text{g}/\sqrt{\text{Hz}}$</td>
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<td></td>
<td>$\sqrt{\Delta f} \sim 10^{-18} \text{N}/\sqrt{\text{Hz}}$</td>
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<tr>
<td>optically trapped nanosphere [97, 98] (rotational [99])</td>
<td>3 fg</td>
<td>300 kHz</td>
<td>laser cool to 12 µK</td>
<td>ground state</td>
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<td>$\sqrt{\Delta f} \sim 7 \times 10^{-4} \text{g}/\sqrt{\text{Hz}}$</td>
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<td></td>
<td>$\sqrt{\Delta f} \sim 2 \times 10^{-20} \text{N}/\sqrt{\text{Hz}}$</td>
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<td></td>
<td></td>
<td>$\sqrt{\Delta f} \sim 10^{-27} \text{Nm}/\sqrt{\text{Hz}}$</td>
</tr>
<tr>
<td>trapped ion crystal [18]</td>
<td>$10^{-16}$ fg</td>
<td>1 MHz</td>
<td>$\sqrt{\Delta f} \sim 50 \text{g}/\sqrt{\text{Hz}}$</td>
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<td>$\sqrt{\Delta f} \sim 4 \times 10^{-22} \text{N}/\sqrt{\text{Hz}}$</td>
</tr>
</tbody>
</table>

TABLE I. Examples of currently-available mechanical sensors. Sensitivities for continuous sensing are represented by the relevant noise power spectral densities (e.g. $S_a$ is the acceleration noise power), or threshold ($\sigma_E$ is the single-phonon detection threshold). Here we summarize solid-state mechanical detectors, although atom interferometers can be characterized by similar metrics.
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Summary and Conclusions

- Gravitational Wave Astronomy has just begun
- Impressive new technologies
- Can we use them to find DM?
  - Maybe.
- We need more research
A bit of Advertisement

The Future is DARK Workshop
29th of June - 1st of July
Free registration
- Neutrinos
- Dark Matter
- Gravitational Waves