Surfing Dark Matter Waves at the Windchime Experiment

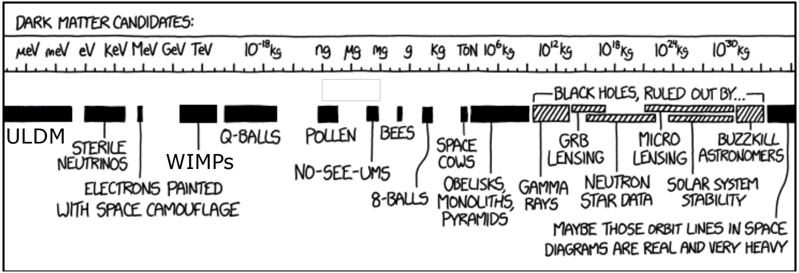
TACOS 2023

Dorian Amaral[1]

October 10th, 2023

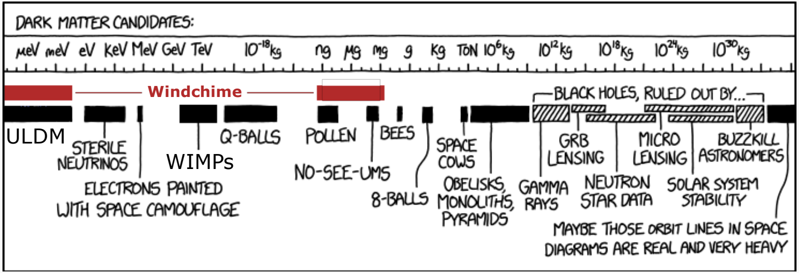
[1]**Rice University**

The Vast Dark Matter Landscape



Adapted from xkcd

The Vast Dark Matter Landscape



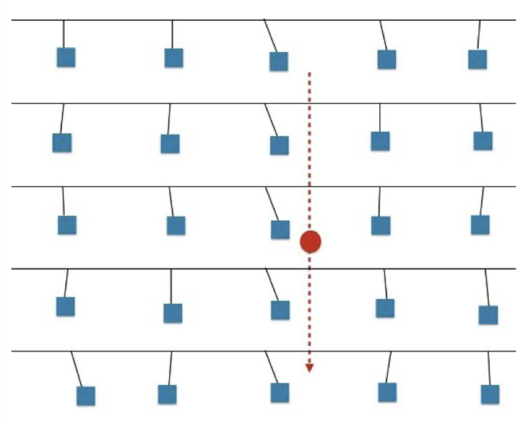
Adapted from xkcd

The Windchime Experiment

- Original idea: levarage advancements in quantum sensing techniques to **gravitationally detect dark matter**
  Daniel Carney et al. **1903.00492**

- Windchime would see an **array** of **accelerometers** being employed in search for a passing dark matter particle

- Impulses along a track would be our dark matter signature!



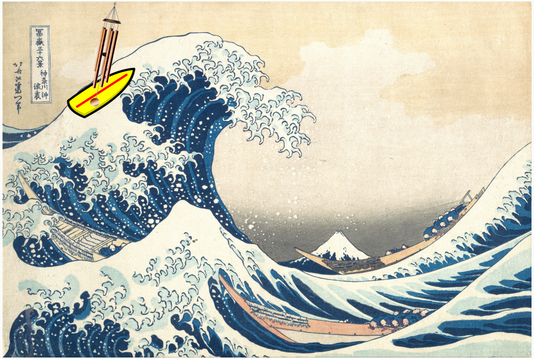
Alaina Attanasio et al. **2203.07242**

Surfing Dark Matter at Windchime

- Power of acceleration-sensing instruments already shown for ULDM
  Peter W. Graham et al. **1512.06165**
  Daniel Carney et al. **1908.04797**
  Jack Manley et al. **2007.04899**

- Windchime will employ precisely such detectors!

- Leads to a natural question...



How can Windchime teach us about the nature of ultralight dark matter?

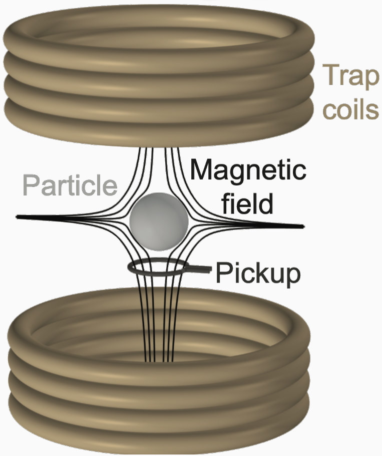
Ultralight Dark Matter: The Cosmic Ocean

- In ultralight regime, dark matter occupation number is macroscopic

$$N = n_{\mathrm{DM}} \lambda_{\mathrm{dB}}^3 \sim 10^{23} \left(\frac{10^{-5}\,\mathrm{eV}}{m_{\mathrm{DM}}} \right)^4$$

- This allows us to treat **bosonic** dark matter as wavelike!
- Entire universe host to an 'ocean' of dark matter
- DM candidate can arise from new $\mathrm{U}(1)_X$ gauge symmetry (**fifth force**)
- We consider a new particle coupling to $X = B - L$ charge

Acceleration Sensing with Magnetically Levitated Spheres

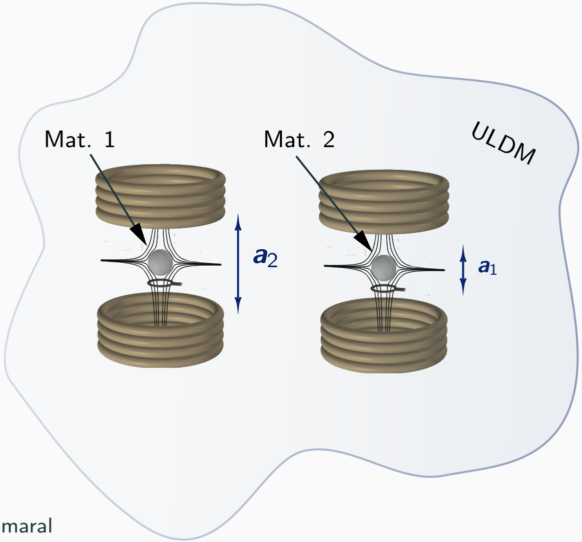


Joachim Hofer et al. **2211.06289**

- Sensor concept: **Superconducting particle trapped in a magnetic field**
- Excellent mechanical sensor:
  - Can measure particle motion very precisely using quantum circuitry
  - **Excellent isolation from background**—mK temperatures, ultrahigh vacuum, vibration isolation

Potential of such sensors in ULDM search not yet tapped!

Submerging Windchime in Dark Matter



- Have two sensors constantly immersed in **oscillating dark field**
- If spheres made of different materials, get **differential acceleration**

$$\Delta a \sim \frac{\sqrt{2\rho_{\rm DM}}}{m_n} \underbrace{g_{B-L}}_{\text{Coupling}} \overbrace{\Delta_{B-L}}^{\text{Differential } q-m} \cos(\underset{\substack{\uparrow \\ \text{DM Mass}}}{m_{\rm DM}}\, t)$$

Signal is a sharp peak in Fourier space at $\omega = m_{\rm DM}$!

The Limit-Setting Game

Setting Limits

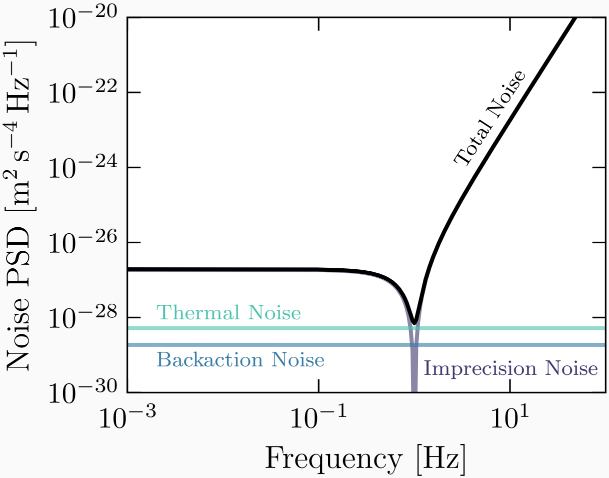
1. Assume we observe no signal—only noise (Asimov data set for asymptotic limit)
2. Characterise data via a likelihood (here a non-central χ^2)
3. Build test statistic based on this likelihood (here log-likelihood ratio)
4. Exclude coupling at 95% confidence level using this statistic

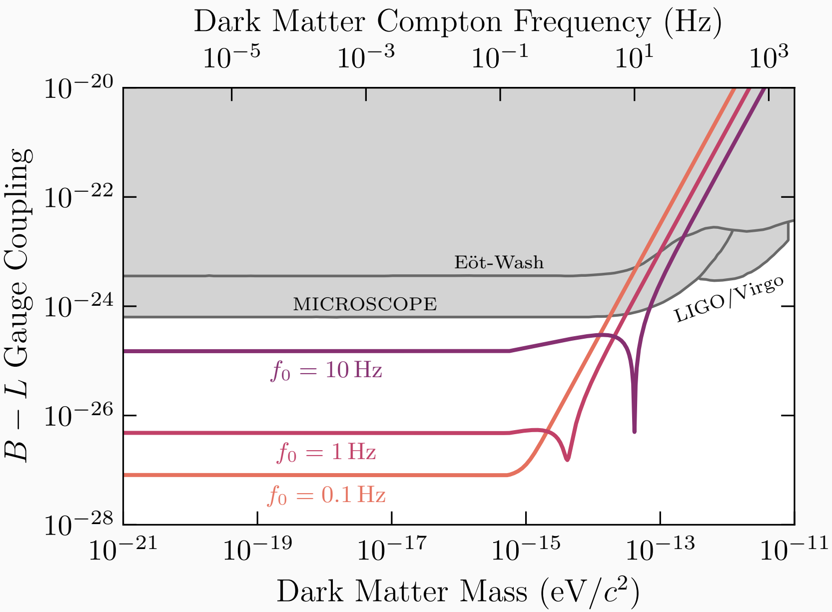
The MagLev Configuration

Quantity	Value
Resonance Frequency (f_0)	0.1 Hz, 1 Hz and 10 Hz
Damping Rate (γ)	$2\pi \times 10^{-8}$ Hz
Bath temperature (T)	15 mK
Integration time (T_{int})	2 weeks
Sensor mass (m_s)	1 g

Noises to Compete With

- Noise captured by noise power spectral density (PSD)
- Have three noise terms:
  - **Thermal** noise
  - **Backaction** noise
  - **Imprecision** noise





Dark Matter Compton Frequency (Hz)
10^{-5}
10^{-3}
10^{-1}
10^{1}
10^{3}
10^{-20}
10^{-22}
10^{-24}
10^{-26}
10^{-28}
$B - L$ Gauge Coupling
Eöt-Wash
MICROSCOPE
LIGO/Virgo
$f_0 = 10\,\mathrm{Hz}$
$f_0 = 1\,\mathrm{Hz}$
$f_0 = 0.1\,\mathrm{Hz}$
10^{-21}
10^{-19}
10^{-17}
10^{-15}
10^{-13}
10^{-11}
Dark Matter Mass (eV/c^2)

Takeaways

- Ultralight dark matter is a well-motivated, **wavelike** DM candidate
- **Magnetically levitated setups** are powerful to probe such ULDM
- Ultralight dark matter sensitivity is an attractive **near-term goal** for Windchime

Windchime is set to be a versatile dark matter detector, tackling the dark matter puzzle from both mass extremes

Backgrounds

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

$$S_{aa}^{\mathrm{IN}}(\omega) \sim \frac{\hbar}{m_s^3 \gamma \omega_0 |\chi_m(\omega)|^2}$$

$$S_{aa}^{\mathrm{BA}}(\omega) \sim \frac{\hbar\gamma}{m_s}$$

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