



Riding Dark Matter Waves at Windchime

TAUP 2023

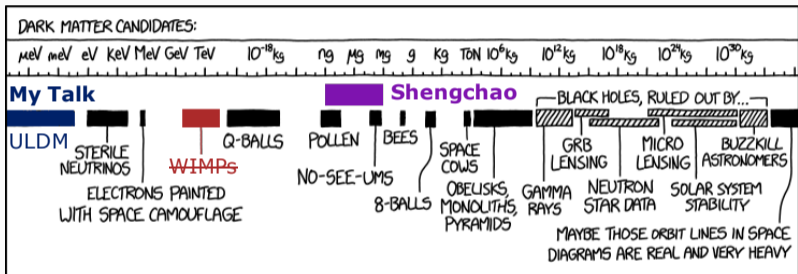
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Windchime Collaboration

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The Vast Dark Matter Landscape



Adapted from xkcd

Ultralight Dark Matter: The Cosmic Ocean

- In ultralight regime, dark matter occupation number is macroscopic

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

- 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 $U(1)_X$ gauge symmetry (**fifth force**)
- We consider a new particle coupling to $X = B - L$ charge

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**

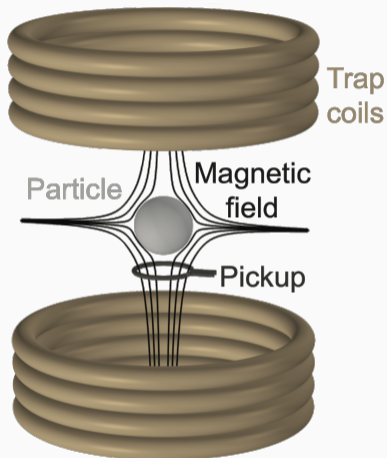
Jack Manley et al. **2007.04899**

- Windchime will employ precisely such detectors!
- Leads to a natural question...



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

Acceleration Sensing with Magnetically Levitated Spheres

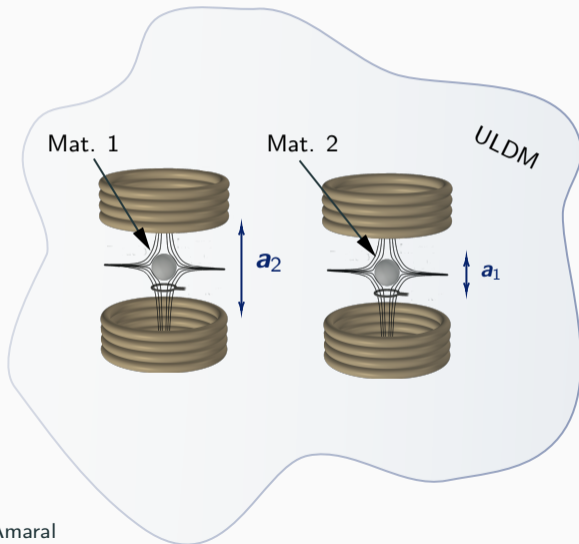


- Sensor concept: **Superconducting particle trapped in a magnetic field**
- Excellent mechanical sensor:
 - Can measure particle motion very precisely using quantum circuitry
 - **Excellent isolation from background**—mK temperatures, ultrahigh vacuum, vibration isolation

Potential of such sensors in ULDM search not yet tapped!

See Gerard Higgins' poster and
Joachim Hofer et al. **2211.06289**

Submerging Windchime in Dark Matter



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

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

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

Setting Limits

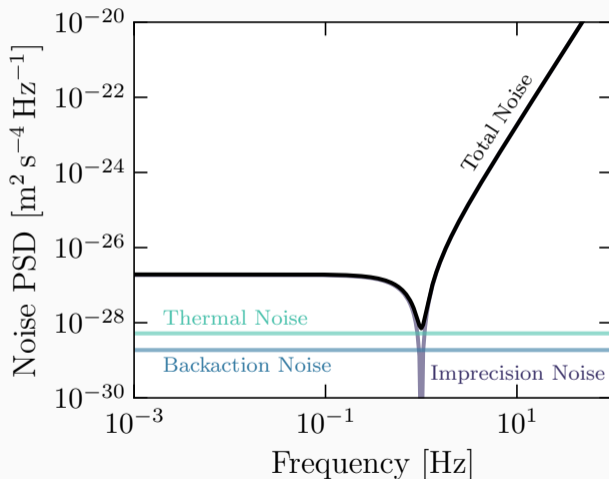
1. Assume we observe no signal—only noise (Asimov data set for asymptotic limit)
2. Characterise data via a likelihood (here a non-central χ^2)
3. Build test statistic based on this likelihood (here log-likelihood ratio)
4. Exclude coupling at 95% confidence level using this statistic

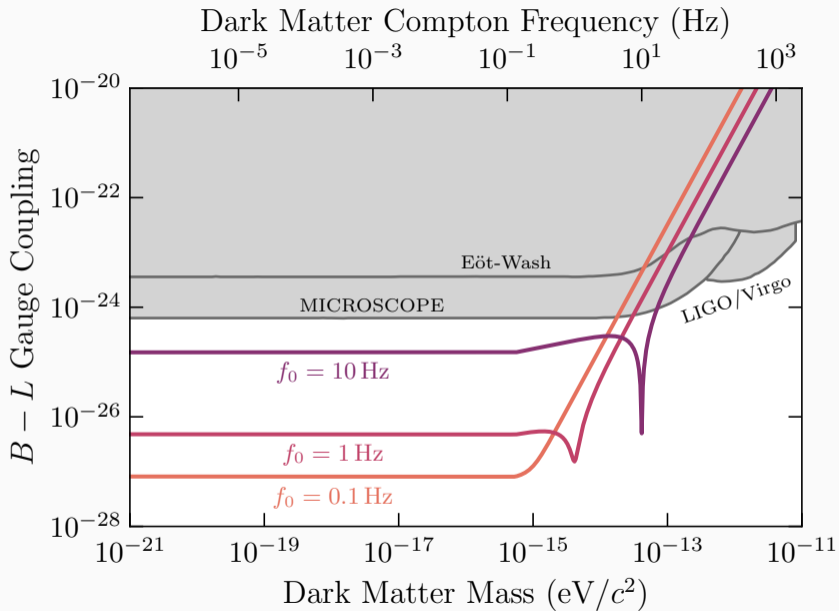
The MagLev Configuration

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





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

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

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

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

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