Isolating the Sound of Dark Matter

Our HELIOS Suspension

Noah Baker, CASST 2022 Presentation

UNIVERSITY OF ALBERTA

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HeLIOS
Helium UltraLIght Dark Matter Optomechanical Sensor

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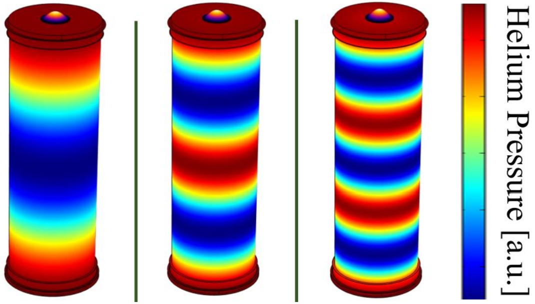
Ultralight Scalar Dark Matter



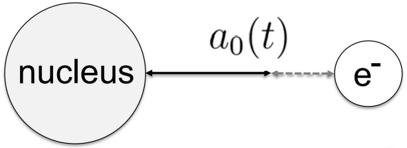
Time-dependent variations in the **fine structure constant** and **fermion mass** according to their respective DM coupling constants *g* [1]:

$$\alpha \rightarrow \frac{\alpha}{1 - g_\gamma \phi} \approx \alpha(1 + g_\gamma \phi)\,, \quad m_\psi \rightarrow m_\psi + g_\psi \phi$$

A **detectable, isotropic** strain induced on **all** condensed objects [2-4]:

$$h(t) = \underbrace{d_{\mathrm{DM}} \frac{\sqrt{8\pi G \varrho}}{\omega c}}_{h_0} \cos(\omega t)$$

Modulation of the atoms' **Bohr radius** [2-3]: $a_0(t) = \dfrac{\hbar}{c\, m_e(t)\, \alpha(t)}$



Circuit Modelling

- Mechanical suspension systems generally **simulated directly**.
- Can actually map **mechanical quantities** to **electrical ones**.
  - Reduces the problem to a **circuit** which can be **solved analytically** [5].

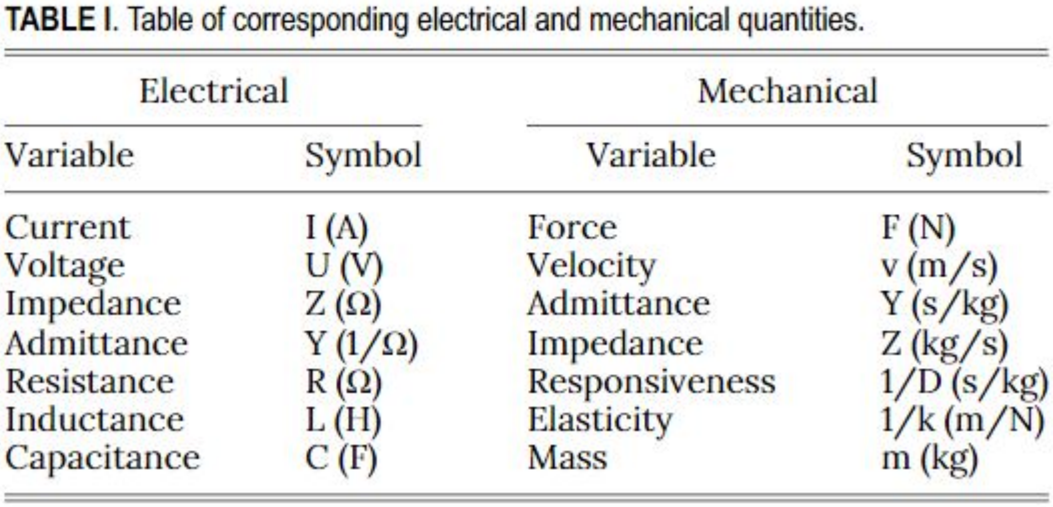
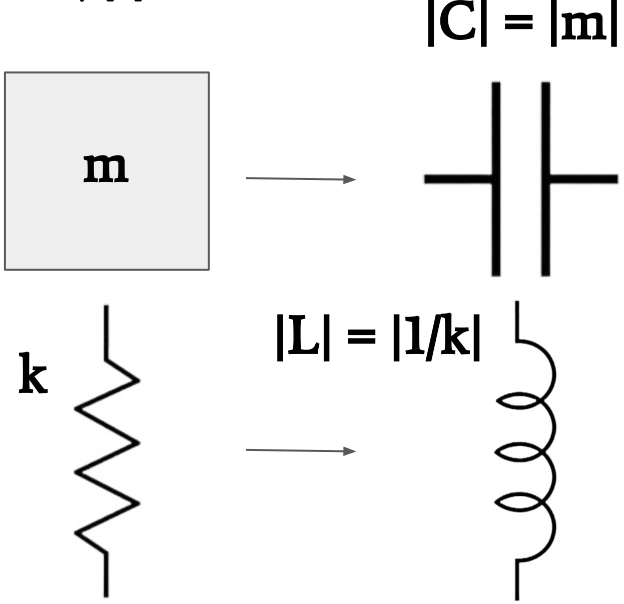


TABLE I. Table of corresponding electrical and mechanical quantities.

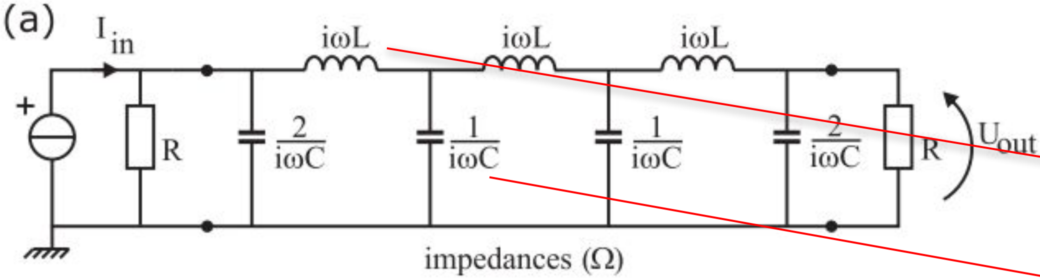
Electrical		Mechanical	
Variable	Symbol	Variable	Symbol
Current	I (A)	Force	F (N)
Voltage	U (V)	Velocity	v (m/s)
Impedance	Z (Ω)	Admittance	Y (s/kg)
Admittance	Y (1/Ω)	Impedance	Z (kg/s)
Resistance	R (Ω)	Responsiveness	1/D (s/kg)
Inductance	L (H)	Elasticity	1/k (m/N)
Capacitance	C (F)	Mass	m (kg)

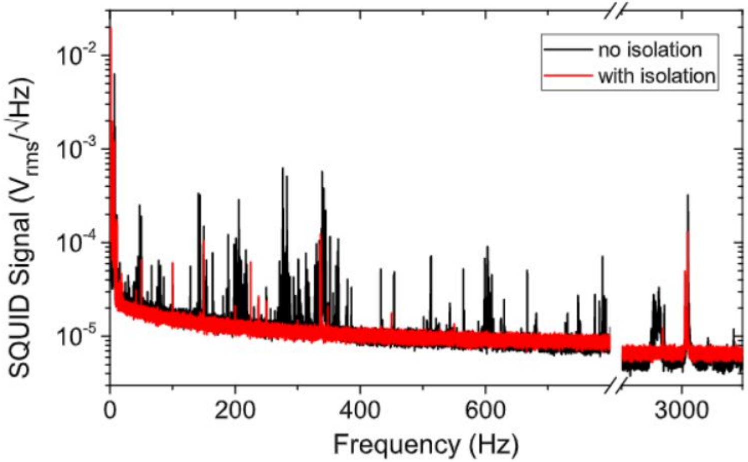


$|C| = |m|$

$|L| = |1/k|$

Mapping to a Mechanical Filter [5]





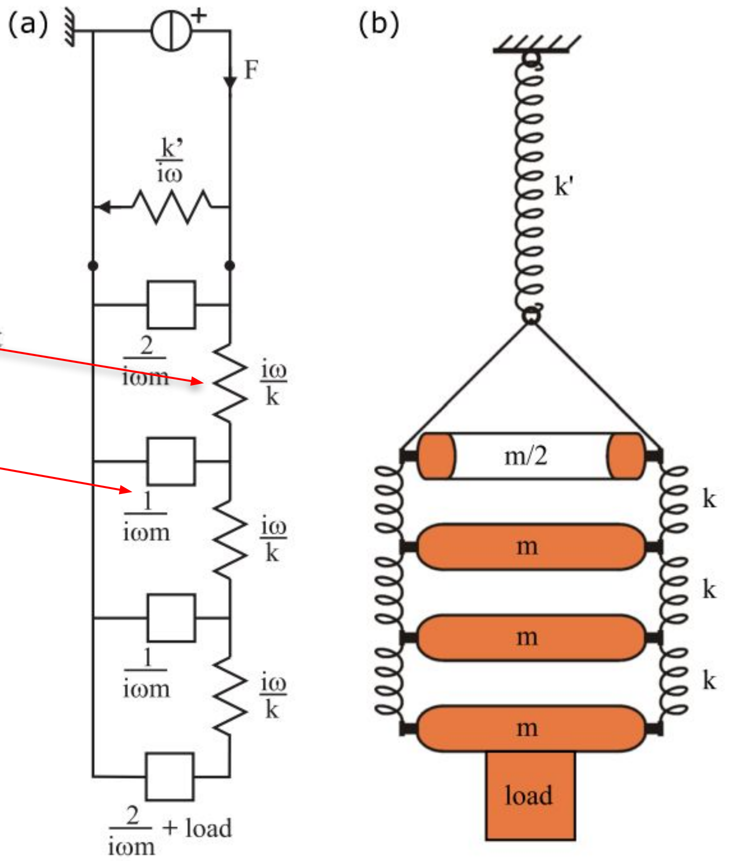
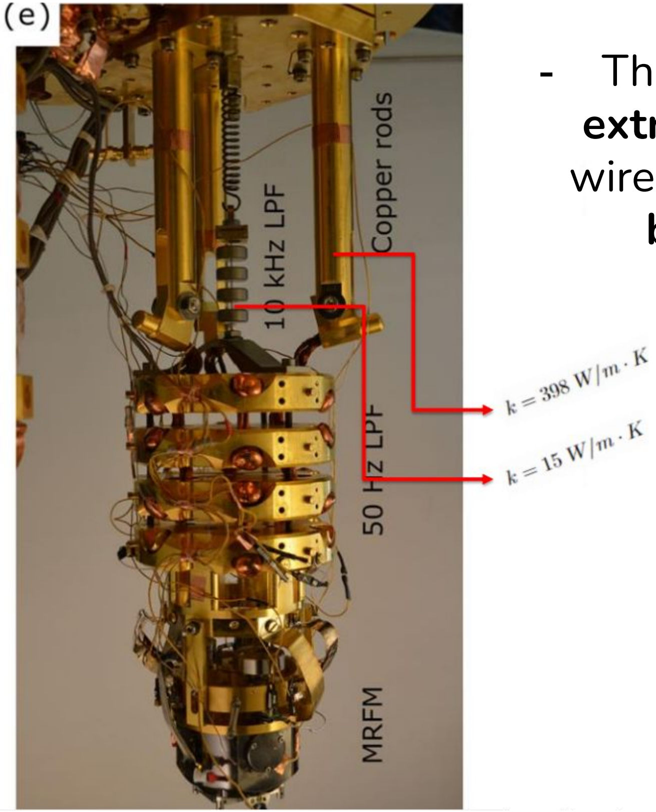


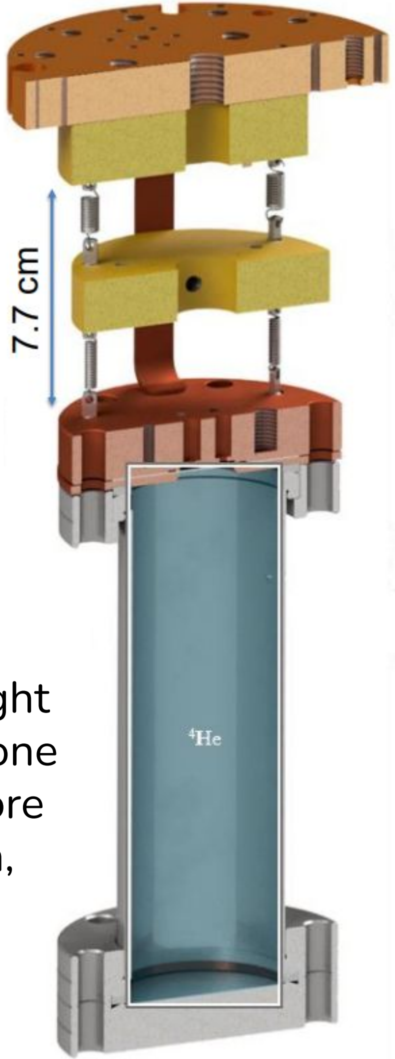
FIG. 3. (a) Circuit diagram and (b) schematic overview of the mechanical low-pass filter based on the outlined theory. Note that the damper at the input is missing.

Direct Implementation Issues



- Thermal conductivity of steel is **extremely poor**, meaning **copper** wires/rods were used to **thermally bypass** the suspension [5].

- We had **10-11 cm** in vertical height to fit the **entire suspension**. Just one stage was **7.7 cm long**. Since more stages means more attenuation, **we needed a new design**.

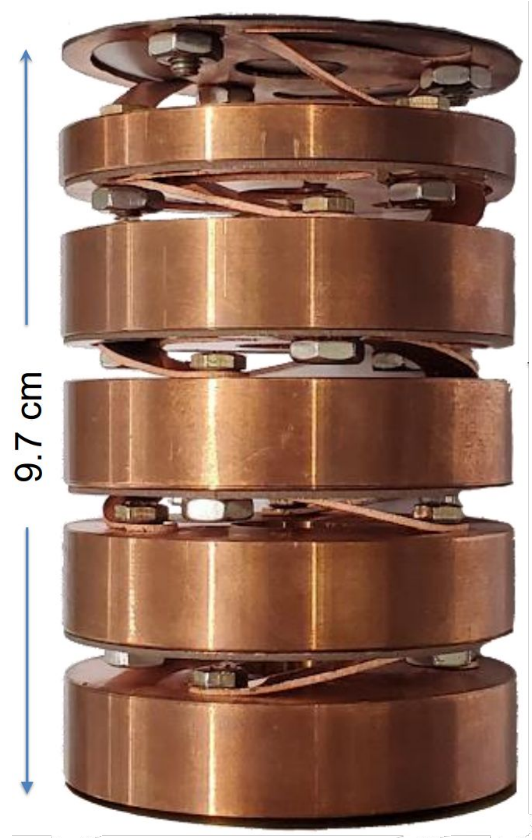


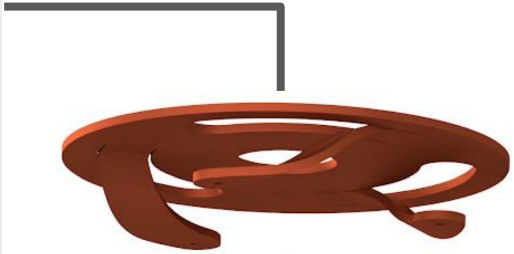
Copper Catherine Wheel Springs

- These springs have a **drastically smaller** rest length.

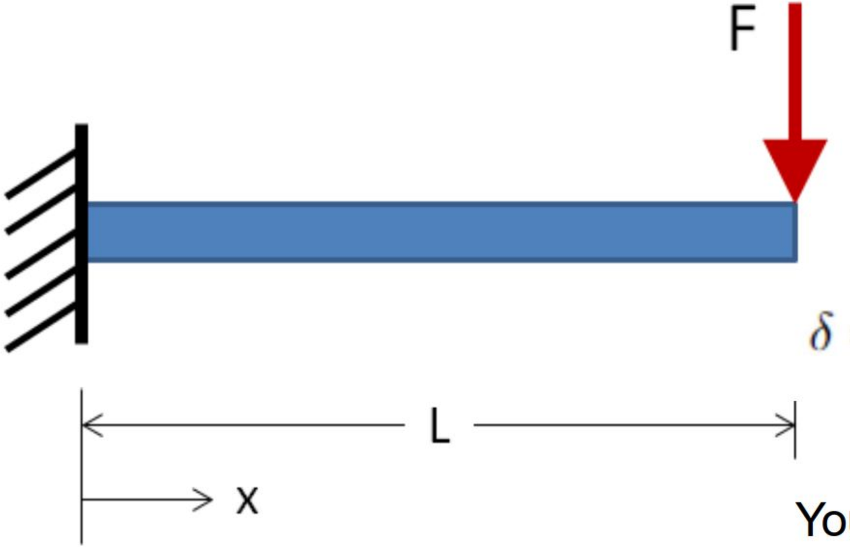
- As the oscillations are also very small, they take up **almost no vertical height**.

- Since they’re also **made out of copper**, additional heat conducting wires are rendered **unnecessary**.





Mapping Springs to Cantilever Arms



Deflection *δ(x)* induced on cantilever arm given some applied force *F(x)* (one fixed end):

$$\delta = -\frac{Fx^2}{6EI}(3L - x) \xrightarrow{x=L} -\frac{L^3F}{3EI} = -\frac{4L^3F}{EwT^3}$$

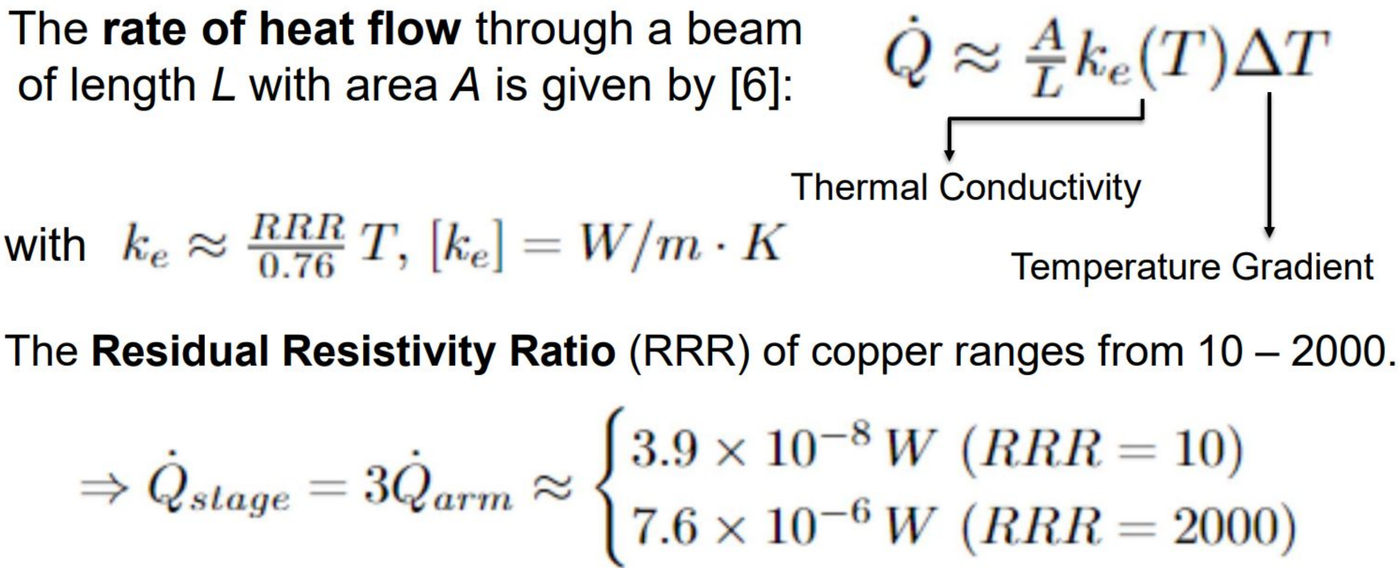
Young's Modulus

Moment of Inertia, $I = \frac{1}{12}wT^3$

Want deflection *δ* to be equal to deflection *x* in equivalent spring:

$$x = -\frac{F}{k} = \delta = -\frac{4L^3F}{EwT^3} \Leftrightarrow \boxed{k = \frac{EwT^3}{4L^3}}$$

Thermal Conductivity Through the Arms



The **rate of heat flow** through a beam of length *L* with area *A* is given by [6]:

$$\dot{Q} \approx \frac{A}{L} k_e(T) \Delta T$$

Thermal Conductivity

Temperature Gradient

with $k_e \approx \frac{RRR}{0.76} T,\ [k_e] = W/m \cdot K$

The **Residual Resistivity Ratio** (RRR) of copper ranges from 10 – 2000.

$$\Rightarrow \dot{Q}_{stage} = 3\dot{Q}_{arm} \approx \begin{cases} 3.9 \times 10^{-8}\, W \ \ (RRR = 10) \\ 7.6 \times 10^{-6}\, W \ \ (RRR = 2000) \end{cases}$$

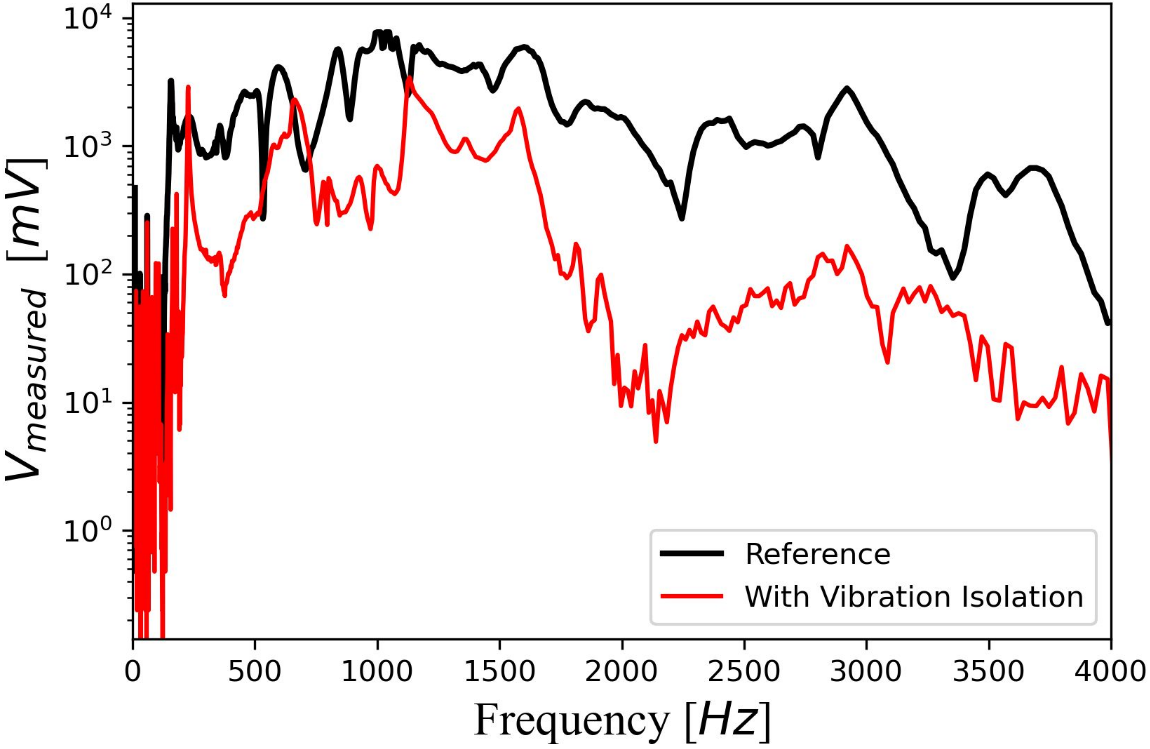
By these estimates, even the **minimum possible heat flow rate** would be sufficient to cool the detector to the 10 **mK range**. We also used **OFHC copper**, meaning an **even higher heat flow rate**.

Suspension Performance

- **1-2 orders of magnitude** of attenuation in desired frequency range (~2 kHz).

- Performance **on par** with the suspension built in the paper.

- Need to test in **proper environment** (at low temp. on fridge) to definitively say.



Outlook and Future Plans

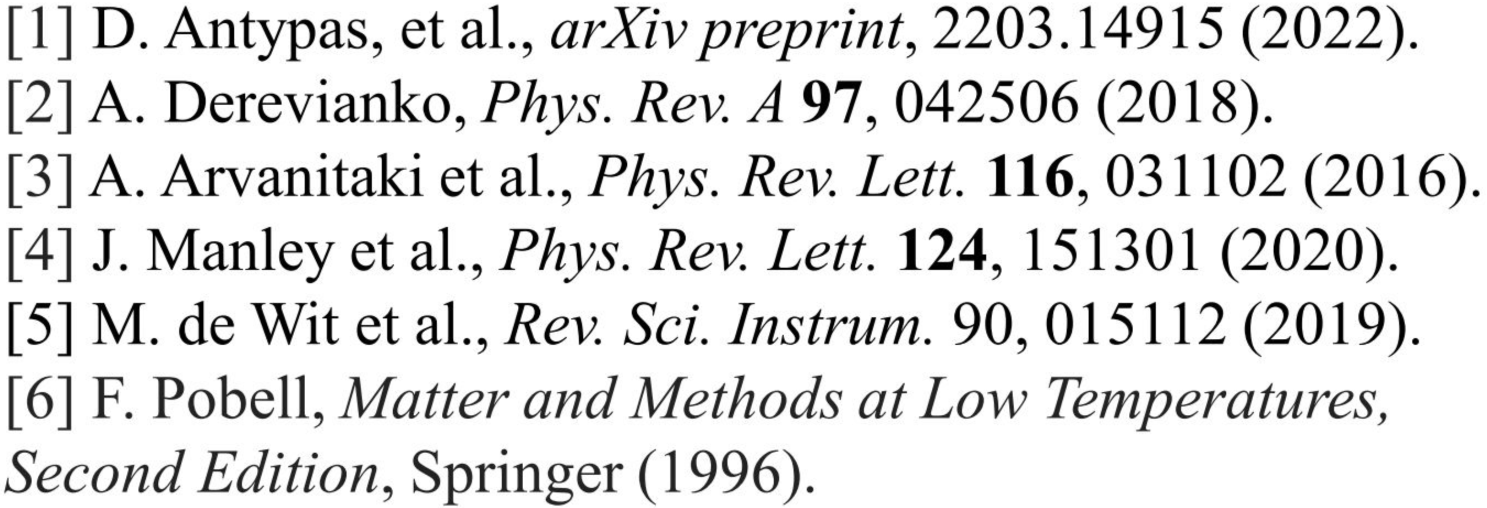
- The suspension **appears to work**, though **proper characterization** and **resonance identification** must still be performed.
- **Proper thermal characterization** is still to come.
- **Optimization** of the material (**brass screws**, **gold plating** the copper, etc.).

⋮

- Detect dark matter.

Thank you!

References



[1] D. Antypas, et al., *arXiv preprint*, 2203.14915 (2022).

[2] A. Derevianko, *Phys. Rev. A* **97**, 042506 (2018).

[3] A. Arvanitaki et al., *Phys. Rev. Lett.* **116**, 031102 (2016).

[4] J. Manley et al., *Phys. Rev. Lett.* **124**, 151301 (2020).

[5] M. de Wit et al., *Rev. Sci. Instrum.* 90, 015112 (2019).

[6] F. Pobell, *Matter and Methods at Low Temperatures, Second Edition*, Springer (1996).