Searching for dark matter using mechanical systems

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Mar 19th 2021

https://www.eecis.udel.edu/~swatis/

Some of the smallest things measured (so far)

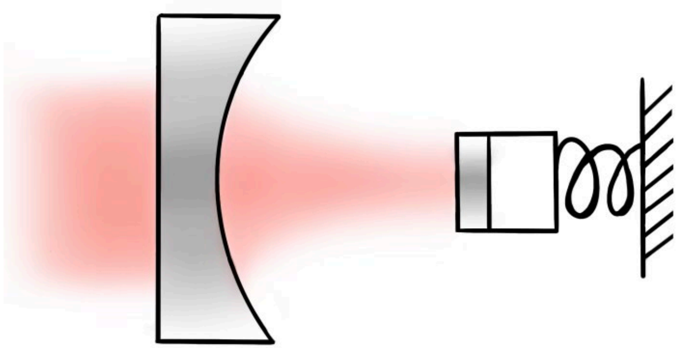
- Attosecond time-keeping (10^{-18} s)
  Nat. Comm. ***6*** *6896 (2015), PRL* ***116*** *063001 (2016)*
- Attotesla magnetic field sensing (10^{-18} T)
  PRL ***110*** *160802 (2013)*

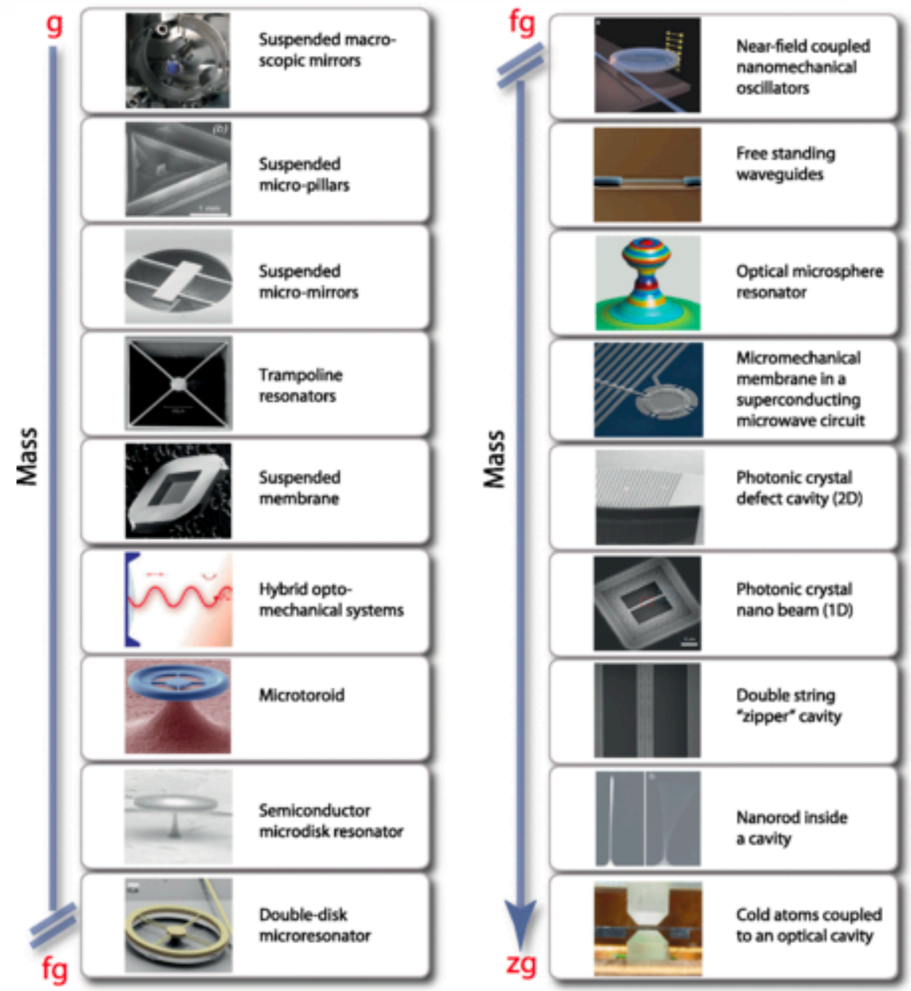
atomic/ spin systems

- Yoctonewton Force sensing (10^{-24} N)
  Science ***344*** *1486 (2014)*
- Attometer displacement sensing (10^{-18} m)
  PRL ***97,*** *133601(2006), NJP* ***10****, 095015 (2008)*
- Yoctogram mass sensing (10^{-24} g)
  Nature Nano ***7*** *301 (2012)*

harmonic oscillator systems

Cast of characters: harmonic oscillators





State of the art sensitivities[1]

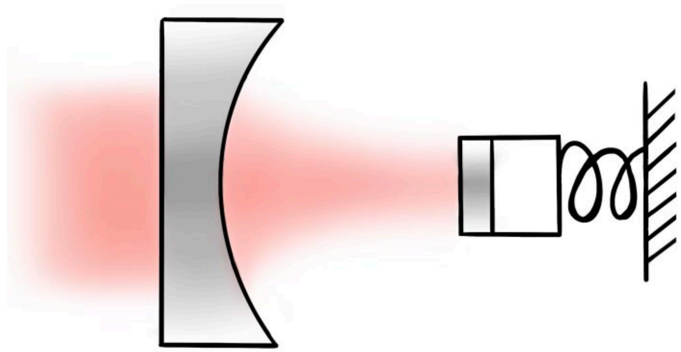
- Force: $10^{-20}\ N/\sqrt{Hz}$
- Acceleration: $10^{-15}\ g/\sqrt{Hz}$
- Strain: $10^{-21}\ /\sqrt{Hz}$

An isolated mode of a floppy mechanical oscillator

Image: Cavity *Optomechanics*, M. Aspelmeyer, T.J. Kippenberg and F. Marquardt, RMP **86**, 1391(2014).

1: Carney et. al, arXiv:2008.06074 (2020) .

A theorist's viewpoint



$$m\ddot{x} + m\frac{\gamma}{2}\dot{x} + m\omega^2 x = F_{\rm signal} + F_{\rm noise}$$

due to DM field

thermal,
imprecision,
measurement
back action

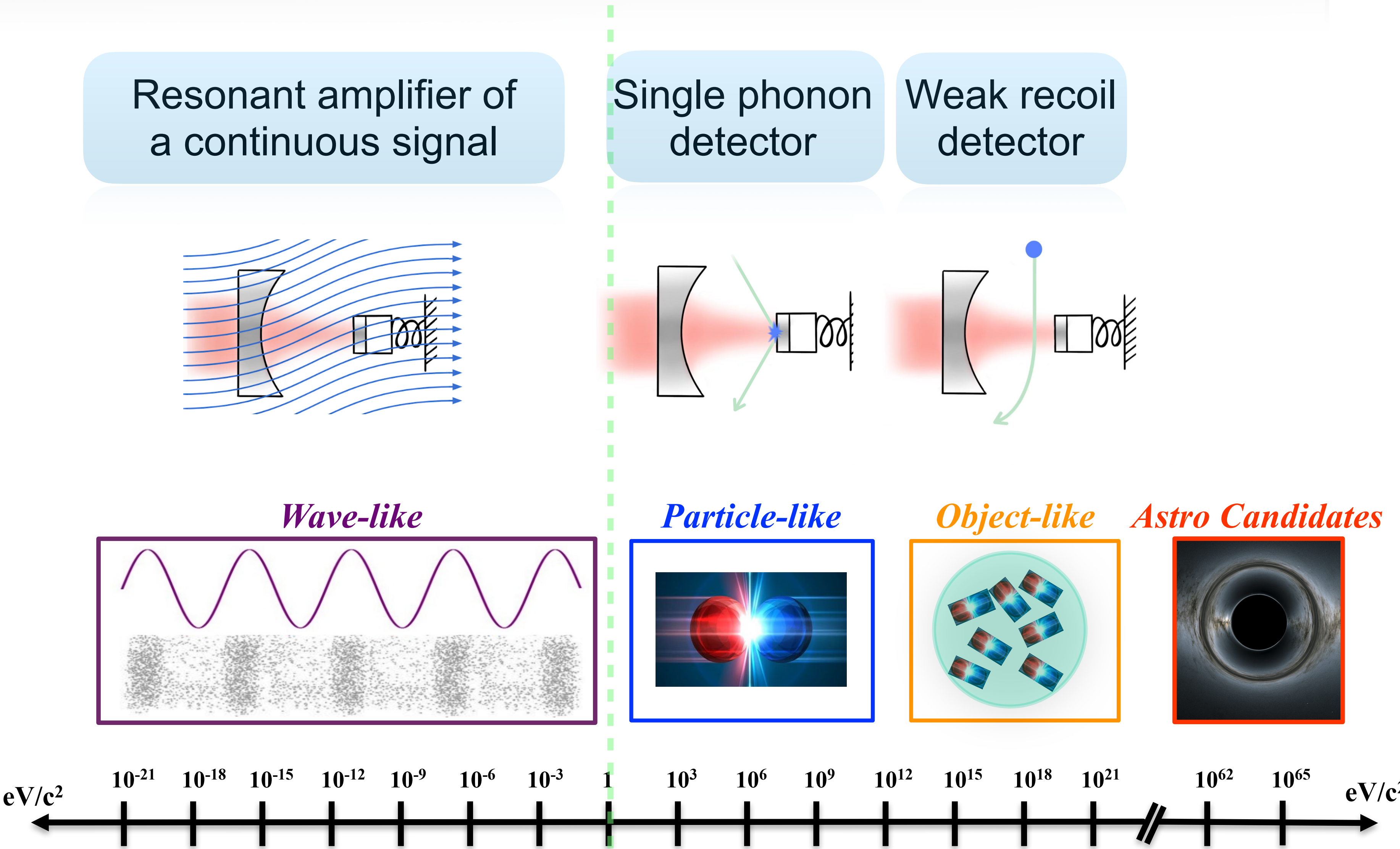
$$H = \hbar\omega_c \hat{a}^\dagger \hat{a} + \hbar\omega_m \hat{b}^\dagger \hat{b} - \hbar g_0 \hat{a}^\dagger \hat{a}\left(\hat{b} + \hat{b}^\dagger\right)$$

optical cavity

mechanical
oscillator

interaction

Mechanical DM detectors- overview



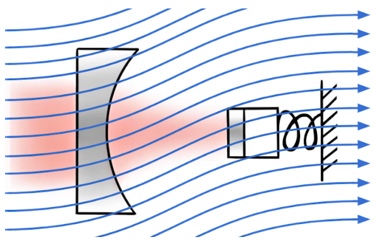
Mechanical quantum sensing in the search for dark matter, Carney et. al, arXiv:2008.06074 (2020) .

Mechanical DM detectors- overview

1 eV

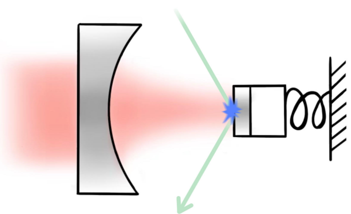
Wave-like

Amplifier of a continuous signal



Particle-like

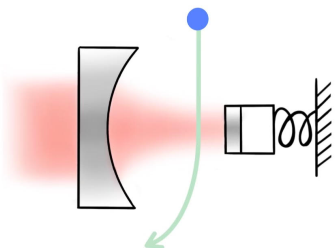
Single phonon detector



(Under progress in other groups)

Object-like

Weak recoil detector



Arvanitaki et al. PRL **116**, 031102 (2016).

Graham et al. PRD **93**, 075029 (2016).

Branca et al. PRL **118** 021302 (2017).

Geraci et al. PRL **123**, 031304 (2019).

Guo et al. Comm. Phys **2**, 1-7 (2019).

Manley et al. PRL **124**, 151301 (2020).

Kennedy et al. PRL **125**, 201302 (2020).

Carney et al. NJP **23** 023041 (2021).

Manley et al. PRL **126**, 061301 (2021).

Campbell et al. PRL **126**, 071301 (2021)…

Proposal for gravitational direct detection of dark matter
Daniel Carney, Sohitri Ghosh, Gordan Krnjaic, and Jacob M. Taylor
Phys. Rev. D **102**, 072003 – Published 13 October 2020

Search for Composite Dark Matter with Optically Levitated Sensors
Fernando Monteiro, Gadi Afek, Daniel Carney, Gordan Krnjaic, Jiaxiang Wang, and David C. Moore
Phys. Rev. Lett. **125**, 181102 – Published 28 October 2020

Ultralight Dark Matter

- For mass <1 eV, DM must be bosonic
- These DM particles of mass m_ϕ will behave like a coherent wave

$$\phi(\mathbf{r},t) \approx \phi_0 \cos\left(\omega_\phi t - \mathbf{k}_\phi.\mathbf{r} + \ldots\right)$$

Amplitude: $\phi_0 = \frac{\hbar}{m_\phi c}\sqrt{2\rho_{DM}}$ $\rho_{DM} \approx 0.3\ \mathrm{GeV/cm^3}$

Frequency: $\omega_\phi = m_\phi c^2/\hbar$

Wavenumber: $k_\phi = m_\phi v/\hbar$ $v = 10^{-3}c$

Coherence time: $\tau_\mathrm{c} \approx \frac{10^6}{\omega_\mathrm{dm}}$

- It's always there! $\rho_{DM} \approx 0.3\ \mathrm{GeV/cm^3}$
- The signal oscillates at angular freq. given by DM mass
- Locally coherent over ~10^6 oscillations

Detecting dark-matter waves with a network of precision-measurement tools, A. Derevianko, Phys. Rev. A **97**, 042506 (2018).

Ultralight Dark Matter: Parameter space

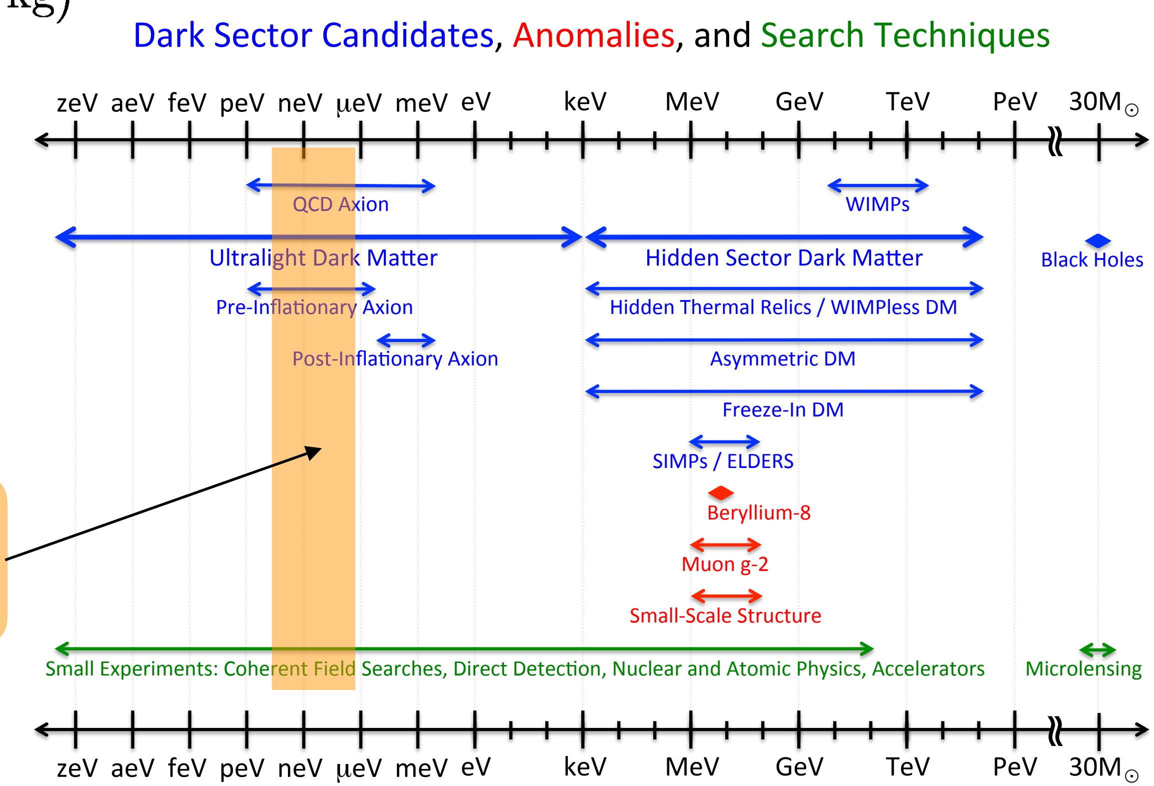
- We focus on Dark Matter candidates in the mass range

$$10^{-12}\ \mathrm{eV/c^2} \lesssim m_{\mathrm{dm}} \lesssim 10^{-6}\ \mathrm{eV/c^2}$$

$$(10^{-48}\,\mathrm{kg} \lesssim m_{\mathrm{dm}} \lesssim 10^{-42}\,\mathrm{kg})$$

≈spatially uniform

$$\phi(\cancel{\mathbf{x}}, t) \approx \phi_0 \cos\left(\omega_\phi t - \cancel{\mathbf{k}_\phi\cdot\mathbf{r}} + \dots\right)$$



- This corresponds to signal in the frequency range

$$100\ \mathrm{Hz} \lesssim \frac{\omega_{\mathrm{dm}}}{2\pi} \lesssim 100\ \mathrm{MHz}$$

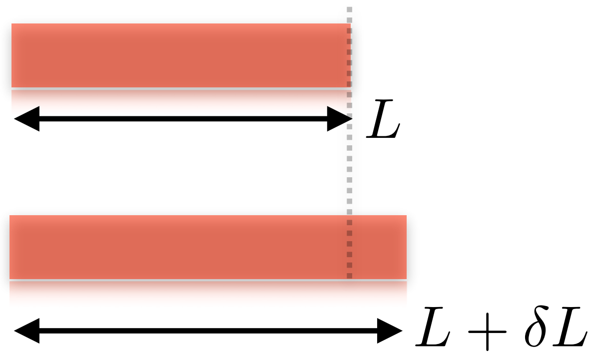
mechanical devices!

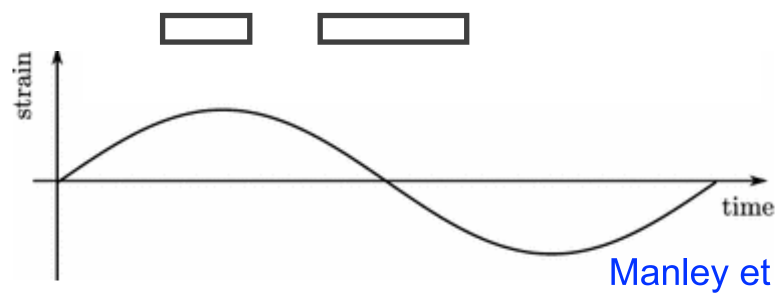
$$1\,\mathrm{km} \lesssim \lambda_{\mathrm{dm}} \lesssim 10^6\,\mathrm{km}$$

US Cosmic Visions: New Ideas in Dark Matter 2017 : Community Report, arXiv:1707.04591 [hep-ph]

Mechanical effects due to DM couplings

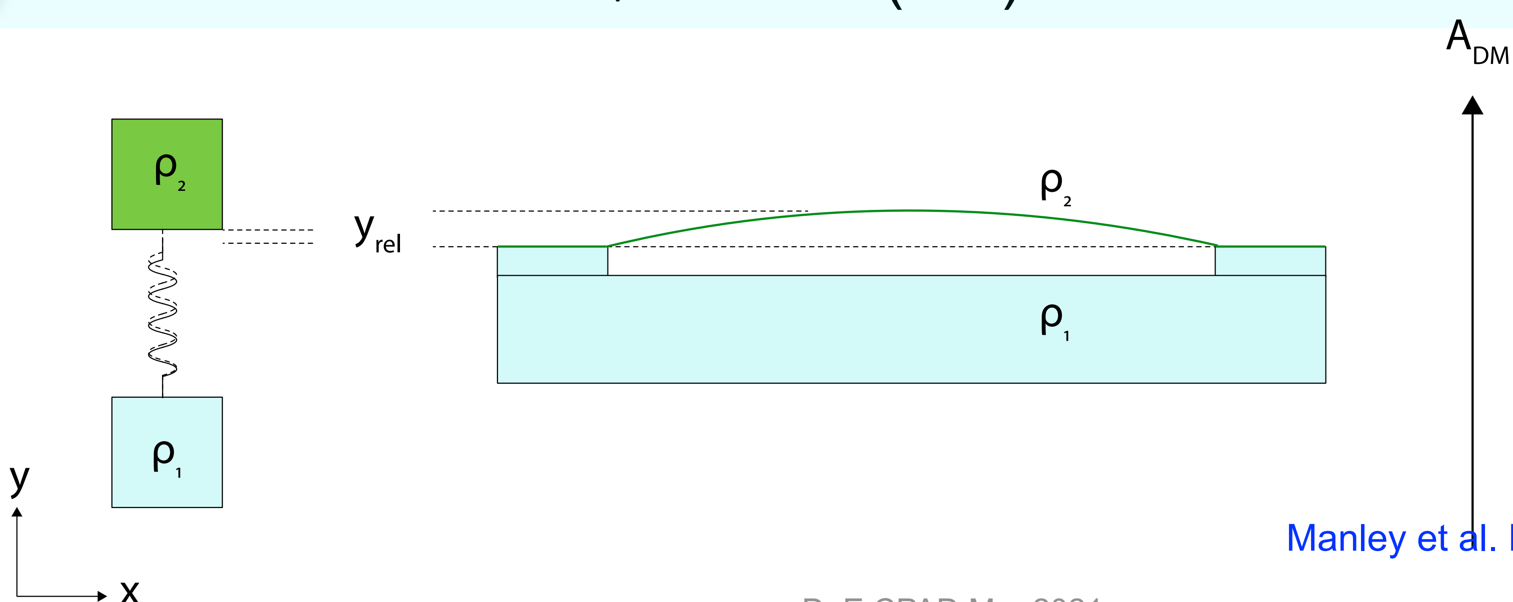
- Scalar dark matter $\longrightarrow$ isotropic strain field $\longrightarrow$ displacement signal





Manley et al. PRL **124**, 151301 (2020).

- Vector dark matter $\longrightarrow$ Lorentz (like) force $\longrightarrow$ differential acceleration



Manley et al. PRL **126**, 061301 (2021).

Scalar coupling: experimental signature

- Linear scalar couplings to SM Lagrangian terms:

$$\mathcal{L} \supset \sqrt{\frac{4\pi G}{c^4}}\phi(t)d_i\mathcal{O}_{\mathrm{SM},i}$$

scalar field — coupling strength — SM term

Consider couplings to

EM field: $d_e \frac{c^2\epsilon_0}{4}F_{\mu\nu}F^{\mu\nu}$

electron mass: $-d_{m_e}m_{e,0}c^2\bar{\psi}_e\psi_e$

- Leads to modulation of fundamental constants:

fine-structure constant

$$\alpha(t) \approx \alpha_0\left(1+\sqrt{\frac{4\pi G}{c^4}}d_e\phi(t)\right)$$

electron mass

$$m_e(t) \approx m_{e,0}\left(1+\sqrt{\frac{4\pi G}{c^4}}d_{m_e}\phi(t)\right)$$

Bohr radius

$$a = \frac{\hbar}{\alpha m_e c}$$

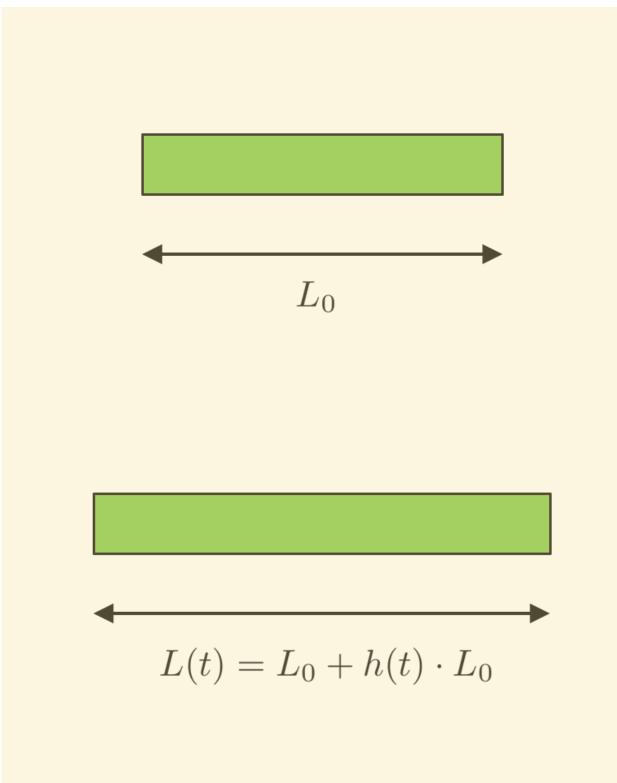
→ **scalar DM strains atoms**

A. Derevianko. Physical Review A 97.4 (2018): 042506.

A. Arvanitaki et al. Physical review letters 116.3 (2016): 031102.

Scalar coupling: experimental signature

scalar DM field



$$\text{strain:}\ \ h \equiv \frac{\Delta L}{L_0}$$

$$h(t) = \frac{\delta a(t)}{a_0} \approx -\frac{\delta m_e(t)}{m_{e,0}} - \frac{\delta \alpha(t)}{\alpha_0}$$

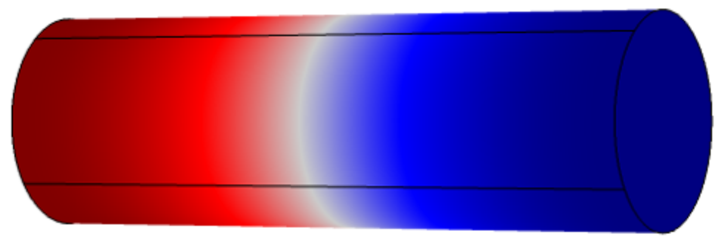
Strain signal

$$h(t) \approx -h_0 \cos\left(\omega_{\mathrm{dm}} t\right)$$

- Amplified in a macroscopic solid
- Amplified on acoustic resonance

(Classical) Harmonic oscillators in theory..

Simple Acoustic Resonator



(pressure mode)

- For a point mass,

$$m\ddot{x} + m\frac{\gamma}{2}\dot{x} + m\omega^2 x = F_{\text{signal}} + F_{\text{noise}}$$

- For an extended elastic object,

$$m_n\ddot{x_n} + m_n\frac{\gamma_n}{2}\dot{x_n} + m_n{\omega_n}^2 x_n = F_{\text{signal}} + F_{\text{noise}}$$

effective mass

dissipation

eigenfrequency

due to DM field

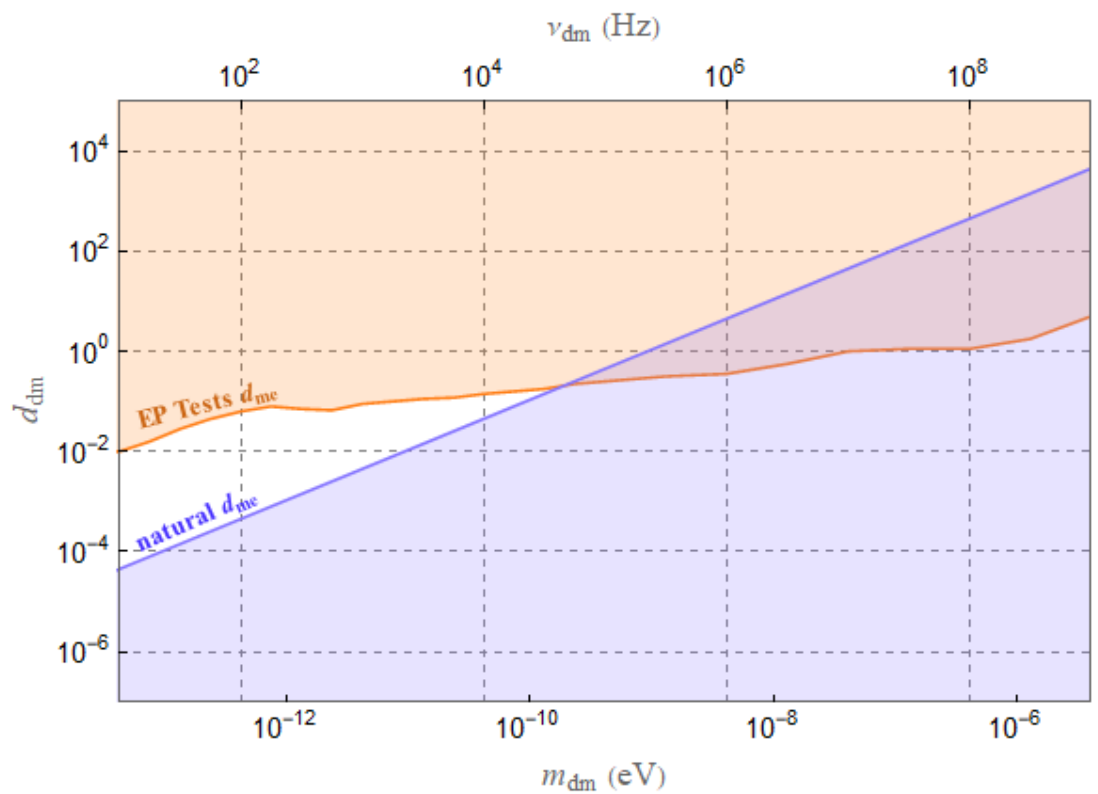
thermal

Scalar DM parameter space

Signal

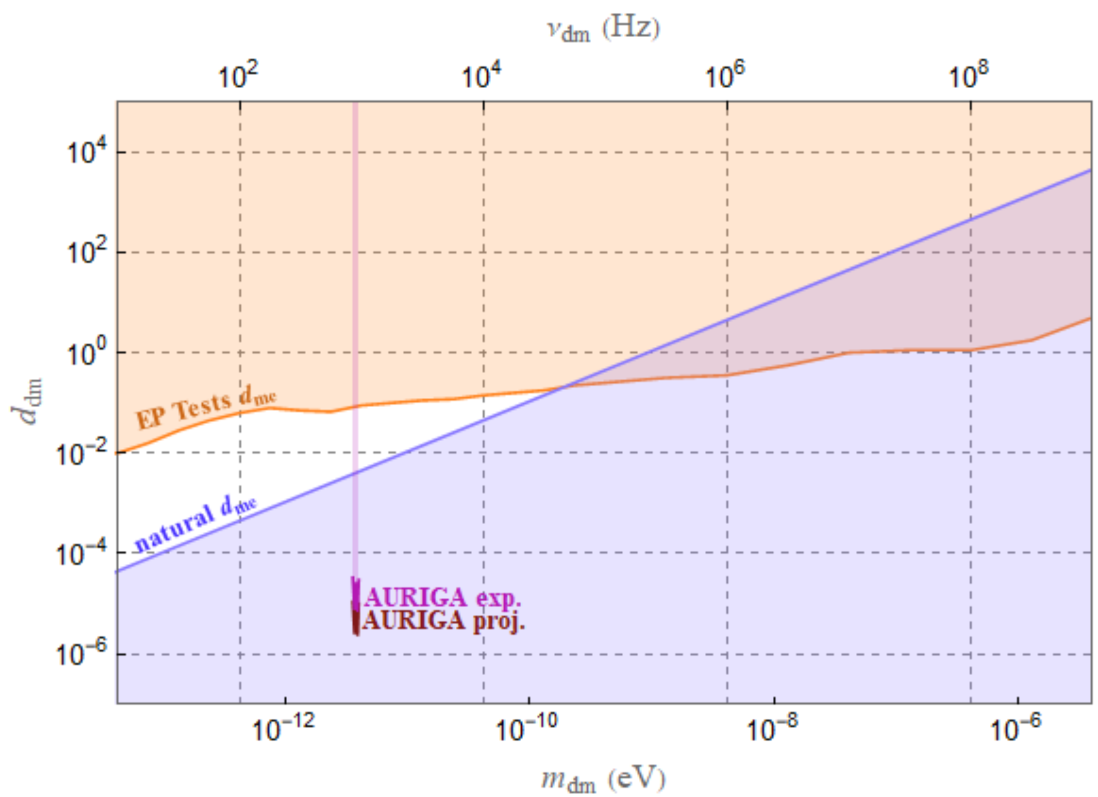
$$h(t) \approx d_{\mathrm{dm}} h_0 \cos\left(\omega_{\mathrm{dm}} t\right)$$

unknown parameters

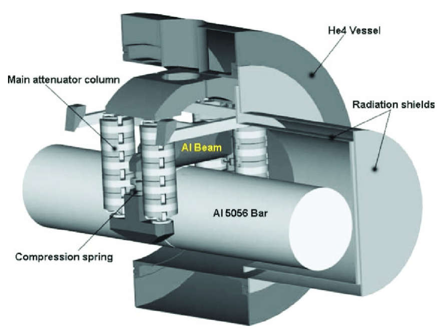


T. Wagner et al. *Classical and Quantum Gravity* 29.18 (2012): 184002.
Arvanitaki et al. Physical review letters 116.3 (2016): 031102.

Scalar DM parameter space

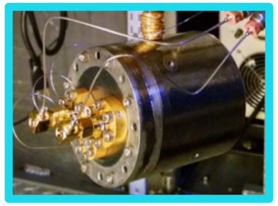


AURIGA

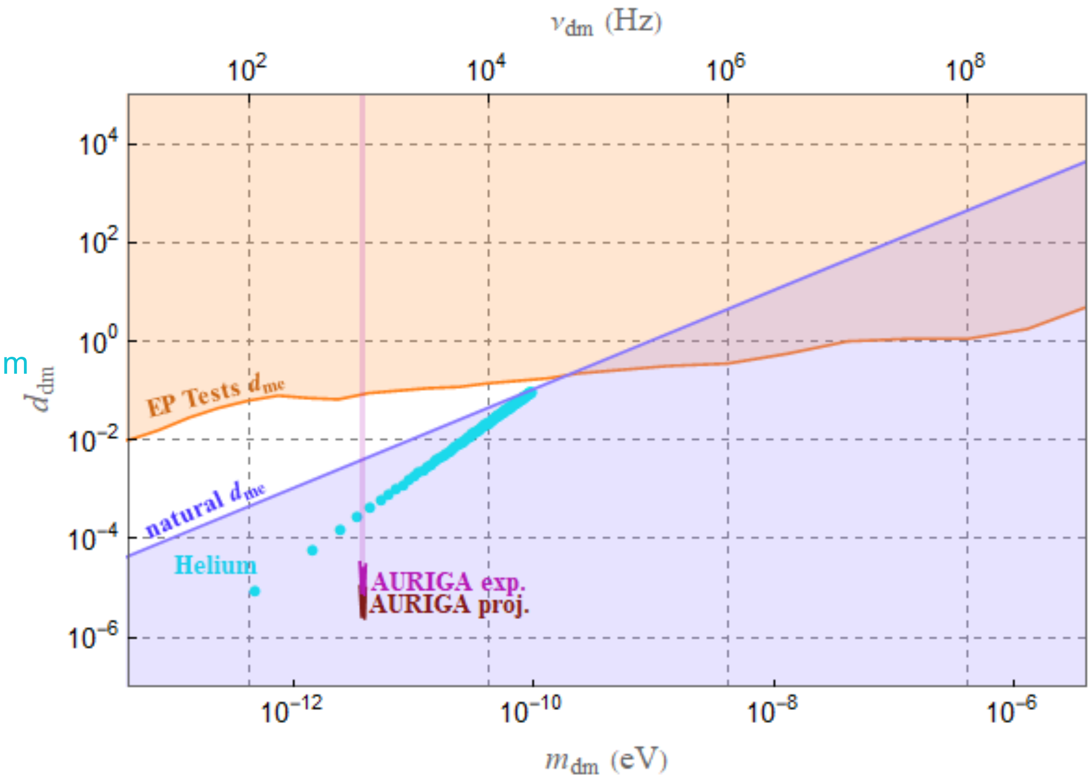


A. Branca et al. Physical review letters 118.2 (2017): 021302.

Scalar DM parameter space

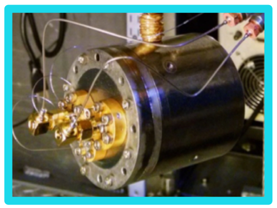


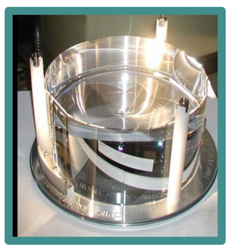
- 2.7 kg Superfluid helium (Niobium shell)
- 11cm radius
- 50cm length
- Q=10^9
- T=10mK



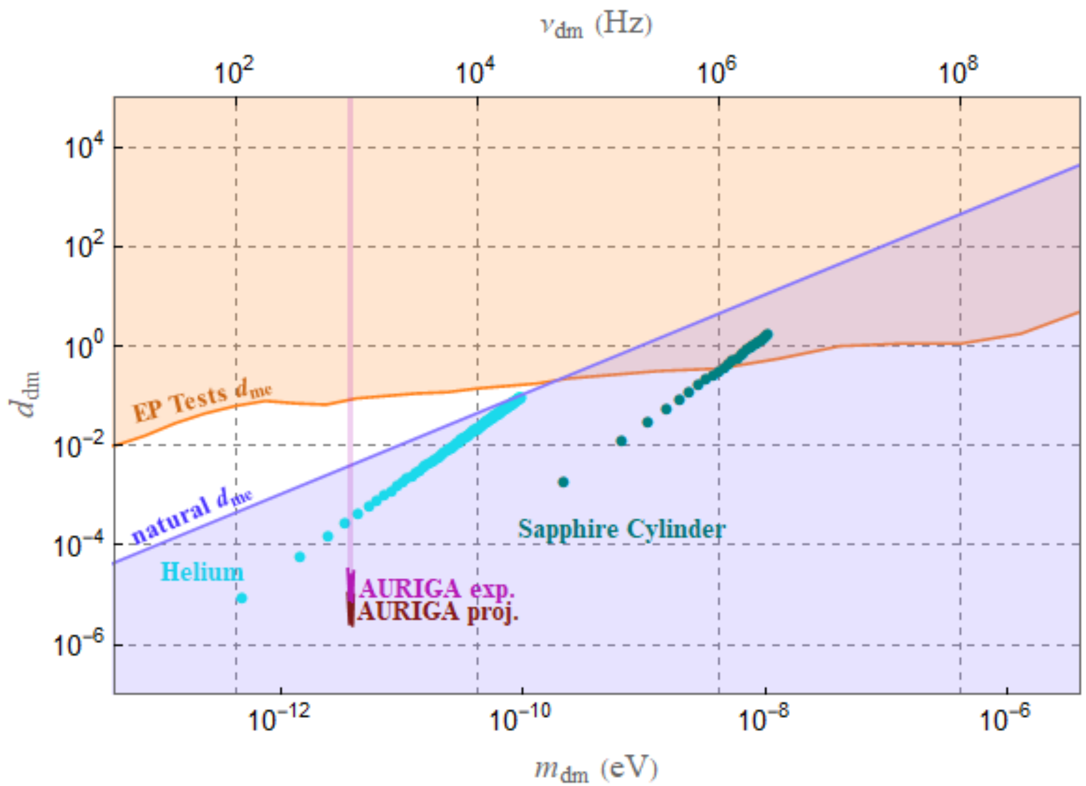
L. De Lorenzo and K. Schwab, *Journal of Low Temperature Physics* 186, 233 (2017)

Scalar DM parameter space



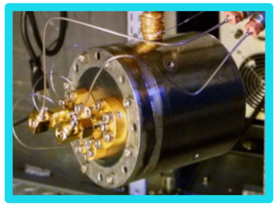


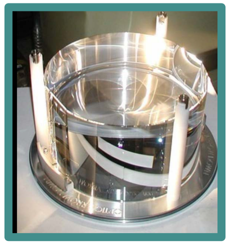
- Sapphire test mass
- 15 mm radius
- 10cm length
- Q=10^9
- T=10 K

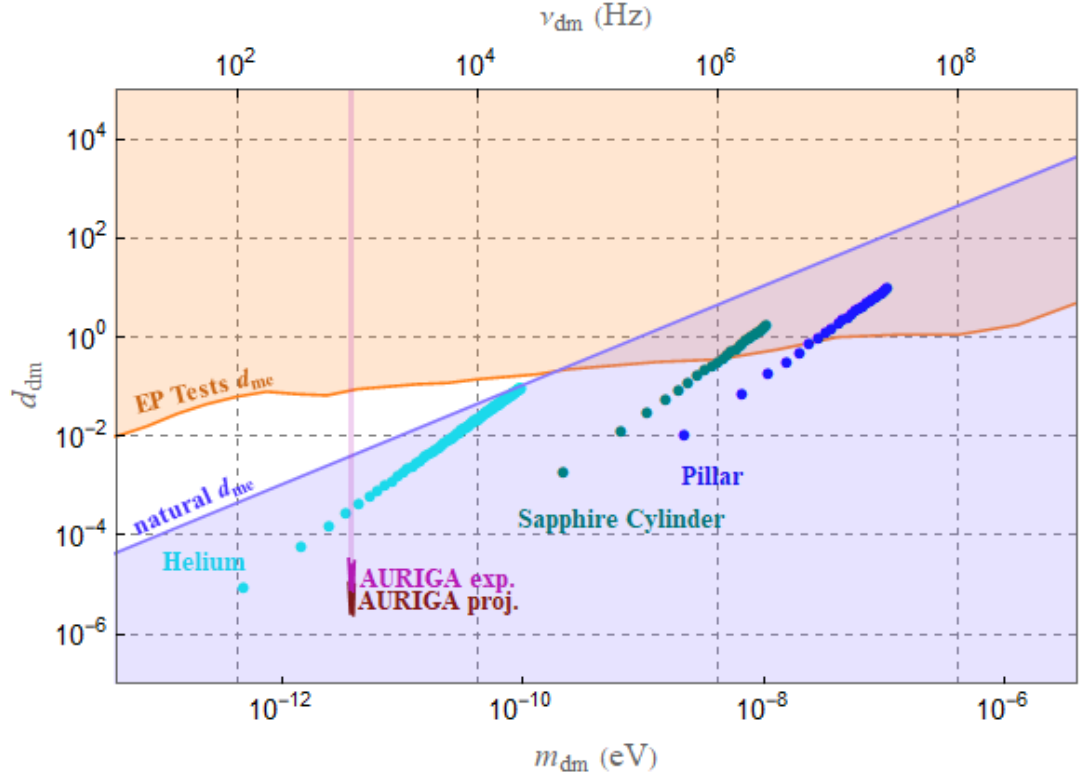


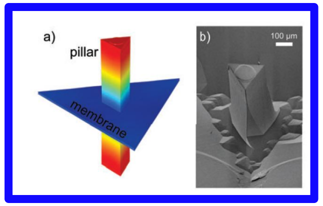
Rowan et al. *Physics Letters A* 265.1-2 (2000): 5-11.

Scalar DM parameter space





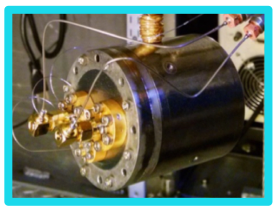


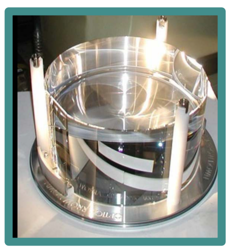


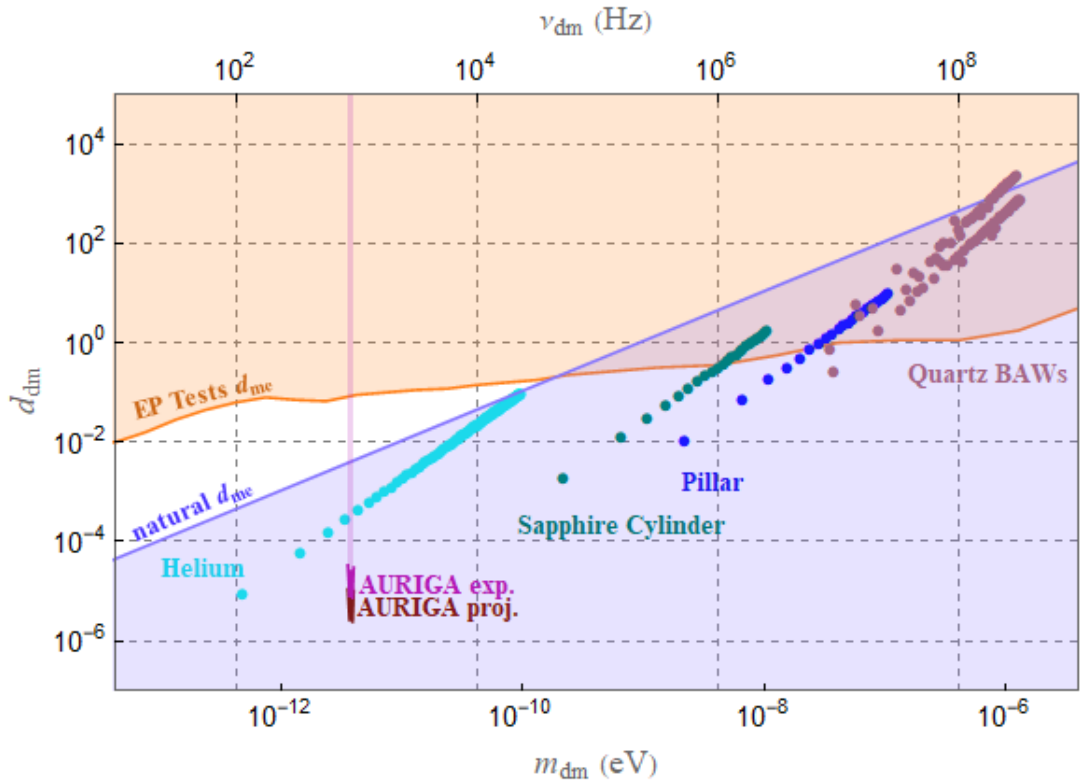
- Sapphire micropillar
- 0.3 g mass
- 1 cm length
- $Q=10^9$
- T=10mK

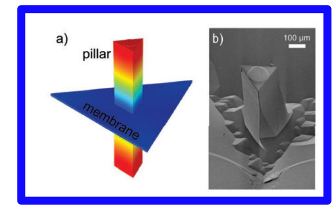
L. Neuhaus, *Cooling a macroscopic mechanical oscillator close to its quantum ground state*, Ph.D. thesis, Universite Pierre et Marie Curie - Paris VI (2016).

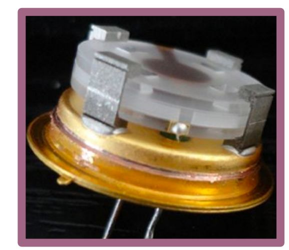
Scalar DM parameter space









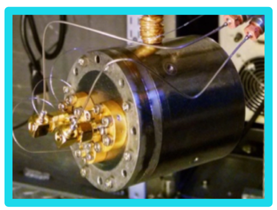


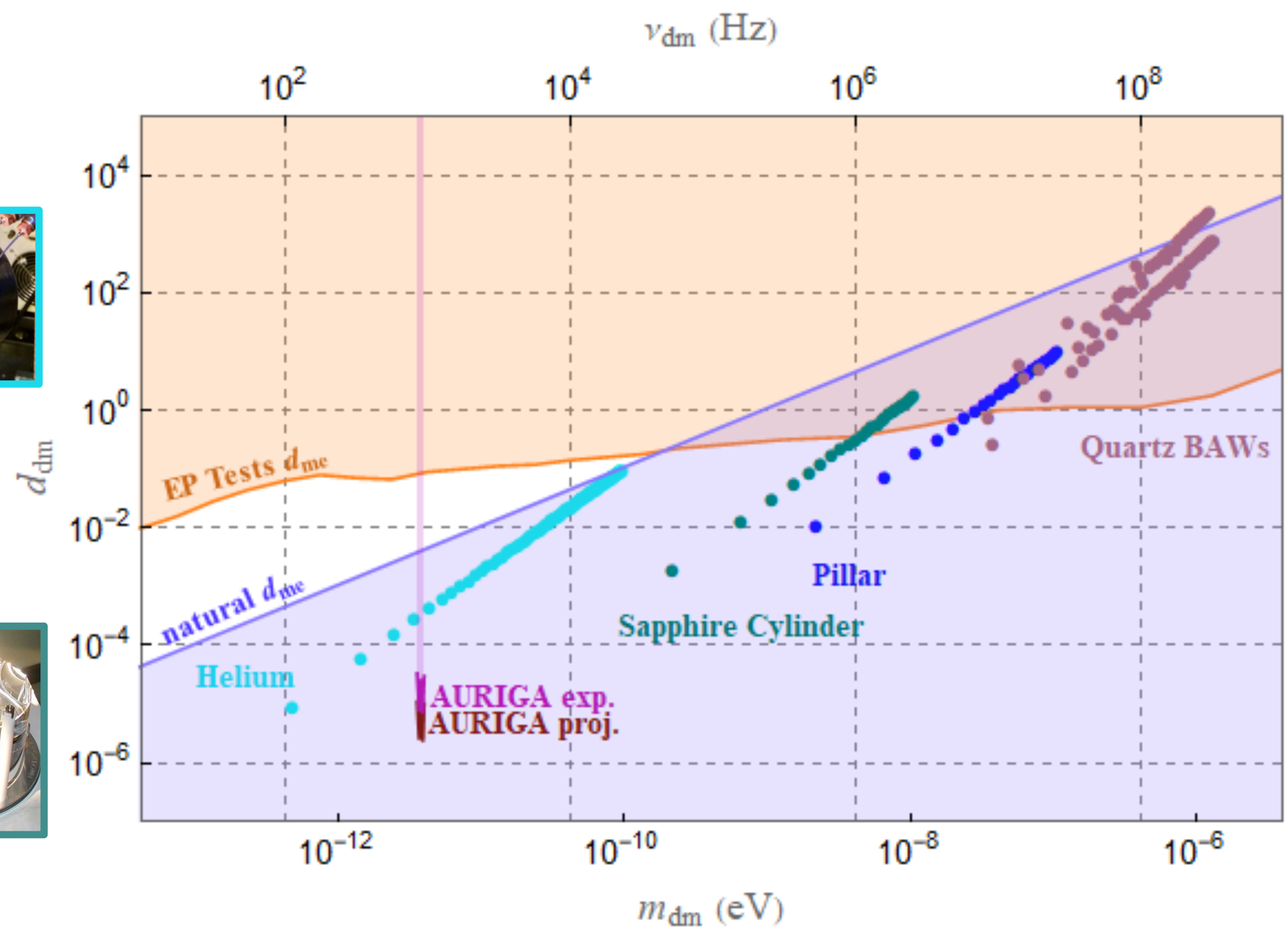
- Quartz BAW resonator
- 15 mm radius
- 1 mm length
- Q~10^9
- T=10mK

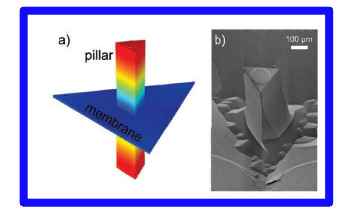
M. Goryachev and M. E. Tobar. *Phys. Rev. D* 90, 102005 (2014).
S. Galliou et al. *Scientic reports* 3, 2132 (2013).
M. Goryachev et al. *Applied Physics Letters* 100, 243504 (2012).
Arvanitaki et al. Physical review letters 116.3 (2016): 031102.

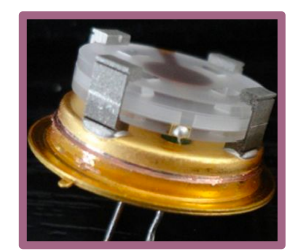
Mechanical detectors for scalar Dark Matter

For scalar bosons (dilatons) modulating the mass of electron:





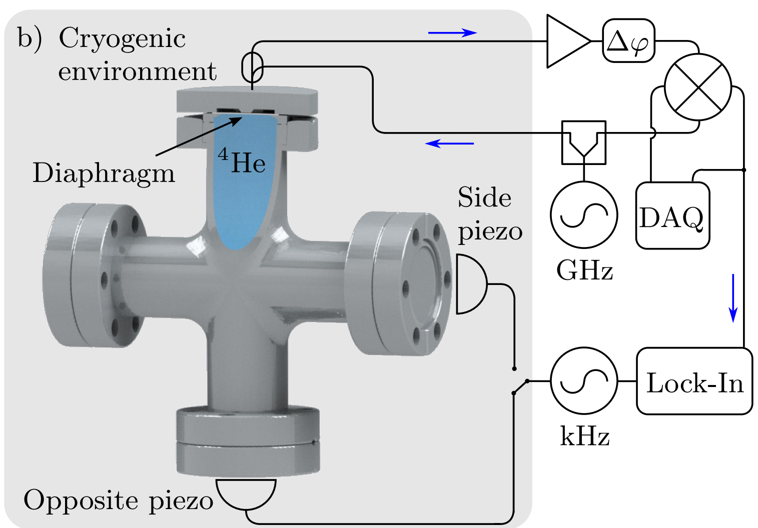


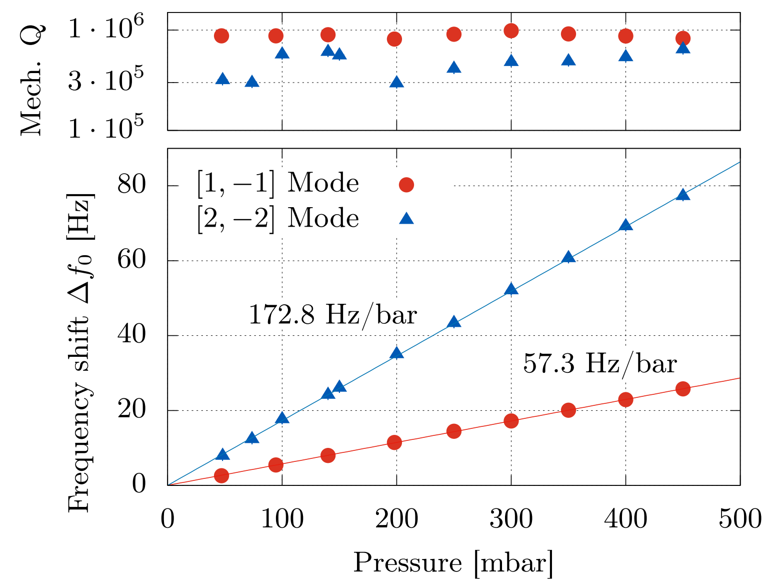


Searching for scalar dark matter with compact mechanical resonators,
J. Manley, D. Wilson, R. Stump, D. Grin and S. Singh, PRL **124** 151301 (2020) .

Superfluid helium detector for GWs and DM

Tunable resonant mass detector for high frequency (continuous) gravitational waves, and ultralight scalar dark matter detection:





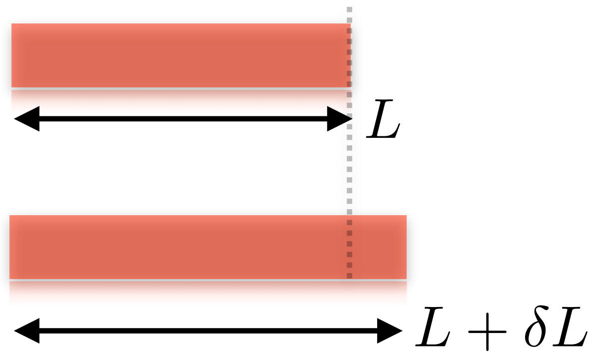
John Davis group @ UNIVERSITY OF ALBERTA

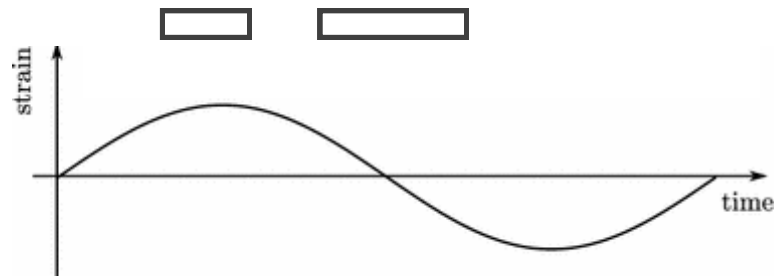
“Detecting continuous gravitational waves with superfluid ^{4}He”
S. Singh, L.A. De Lorenzo, I. Pikovski, K. C. Schwab, NJP **19**, 073023 (2017).

“Prototype superfluid gravitational wave detector”
V. Vadakkumbatt, M. Lasetzki, J. Manley, S. Singh, J. P. Davis, To be submitted (2021).

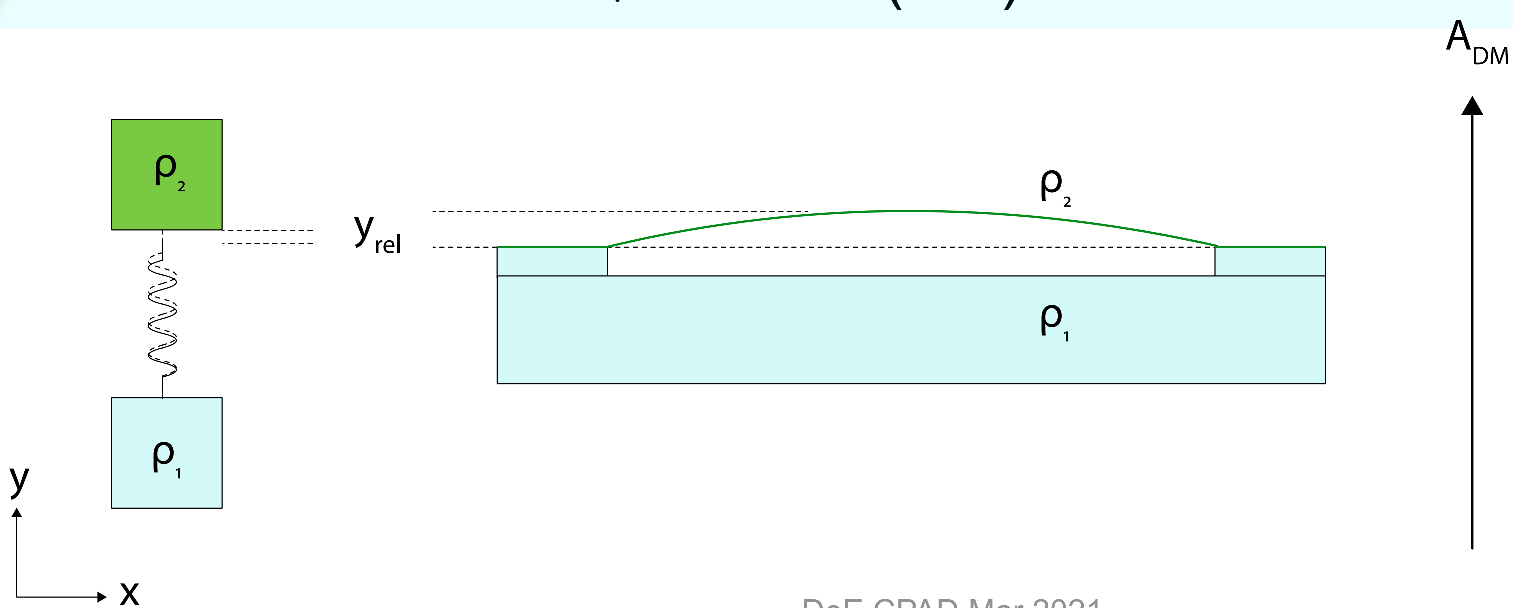
Mechanical effects due to DM couplings

- Scalar dark matter $\longrightarrow$ isotropic strain field $\longrightarrow$ displacement signal





- Vector dark matter $\longrightarrow$ Lorentz (like) force $\longrightarrow$ differential acceleration



Vector coupling: experimental signature

- Lagrangian density for massive vector field:

$$\mathcal{L}' = -\frac{c^2\epsilon'}{4}F'^{\mu\nu}F'_{\mu\nu} + \frac{c^2\epsilon'}{2\lambda_c^2}A'^{\nu}A'_{\nu} - J'^{\nu}A'_{\nu}$$

kinetic term — mass term — coupling term

- Consider DM as a vector field in vacuum:

Plane waves

$$A'^{\nu} \approx A_0'^{\nu} \sin\left(\omega_{\rm dm} t\right)$$

- This leads to a force:

$$F(t) \approx g' N' F_0 \cos\left(\omega_{\rm dm} t\right)$$

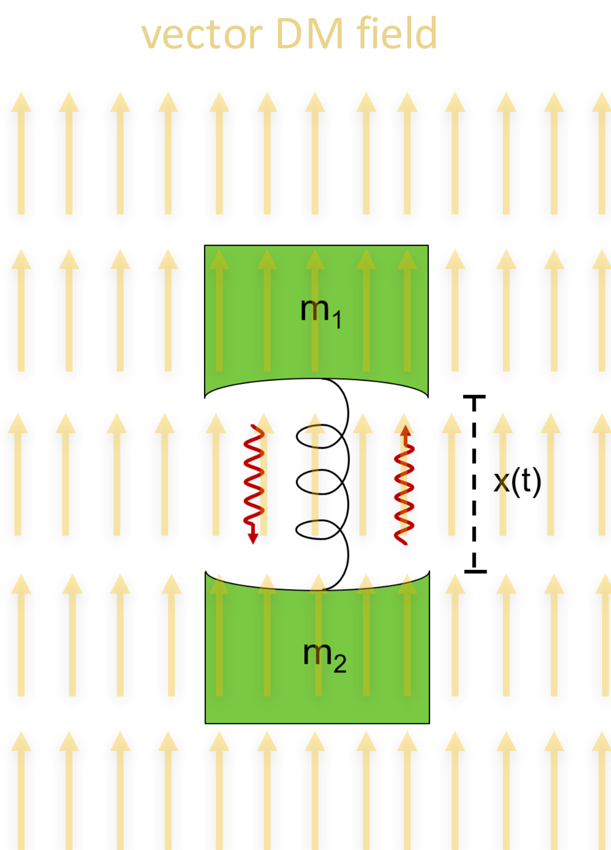
coupling strength — number of dark charges —

$$F_0 \equiv \sqrt{2\frac{e^2\rho_{\rm DM}}{\epsilon_0}} \approx 6\times 10^{-16}\ {\rm N}$$

J. Manley et. al, arXiv:2007.04899 (2020) .

Carney et al, arXiv:1908.04797 (2019).

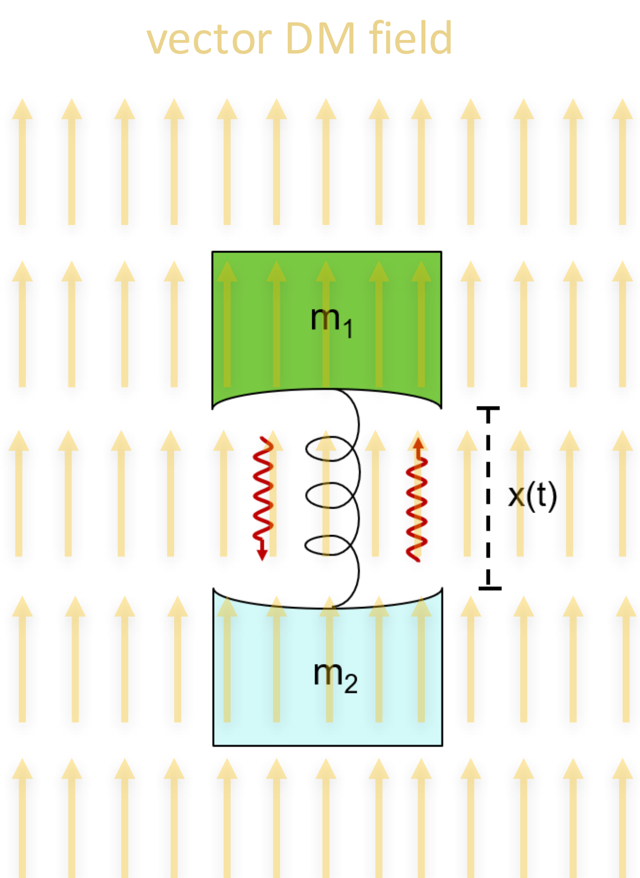
Vector coupling: experimental signature



$$a_i(t) \approx g_{\text{B-L}} \left(\frac{N_{\text{n}}}{m}\right)_i F_0 \cos\left(\omega_{\text{dm}} t\right)$$

acceleration proportional to charge to mass ratio

Vector coupling: experimental signature



$$a_i(t) \approx g' \frac{N_i'}{m_i} F_0 \cos(\omega_{\rm dm} t)$$

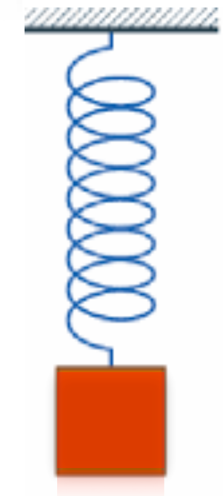
Differential acceleration signal

$$\Delta a(t) = a_1(t) - a_2(t) \approx g' \left(\frac{N_1'}{m_1} - \frac{N_2'}{m_2} \right) F_0 \cos(\omega_{\rm dm} t)$$

- Depends on charge-to-mass ratio
- Amplified on acoustic resonance

finite coherence time: $\tau_c \approx \frac{10^6}{\omega_{\rm dm}}$

(Classical) Harmonic oscillators in theory..



- For a point mass,

$$m\ddot{x} + m\frac{\gamma}{2}\dot{x} + m\omega^2 x = F_{\text{signal}} + F_{\text{noise}}$$

- For an extended elastic object,

$$m_n\ddot{x_n} + m_n\frac{\gamma_n}{2}\dot{x_n} + m_n{\omega_n}^2 x_n = F_{\text{signal}} + F_{\text{noise}}$$

effective mass

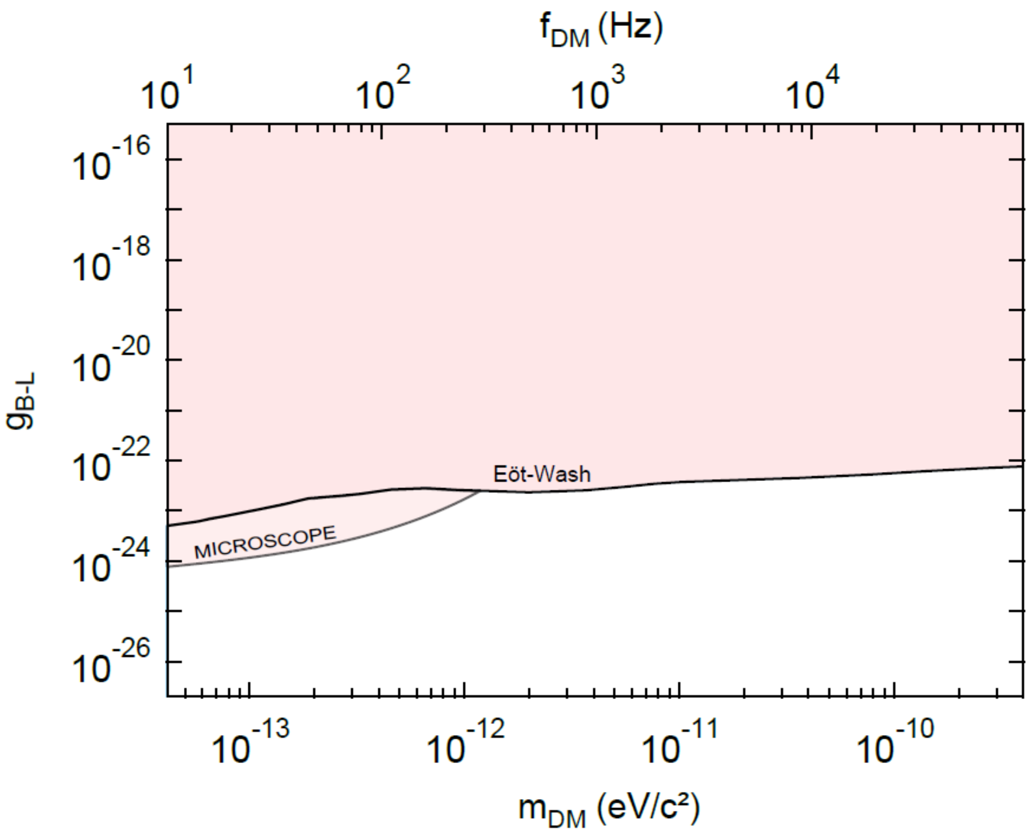
dissipation

eigenfrequency

due to DM field

thermal,
imprecision,
measurement
back action

Vector DM parameter space



Signal

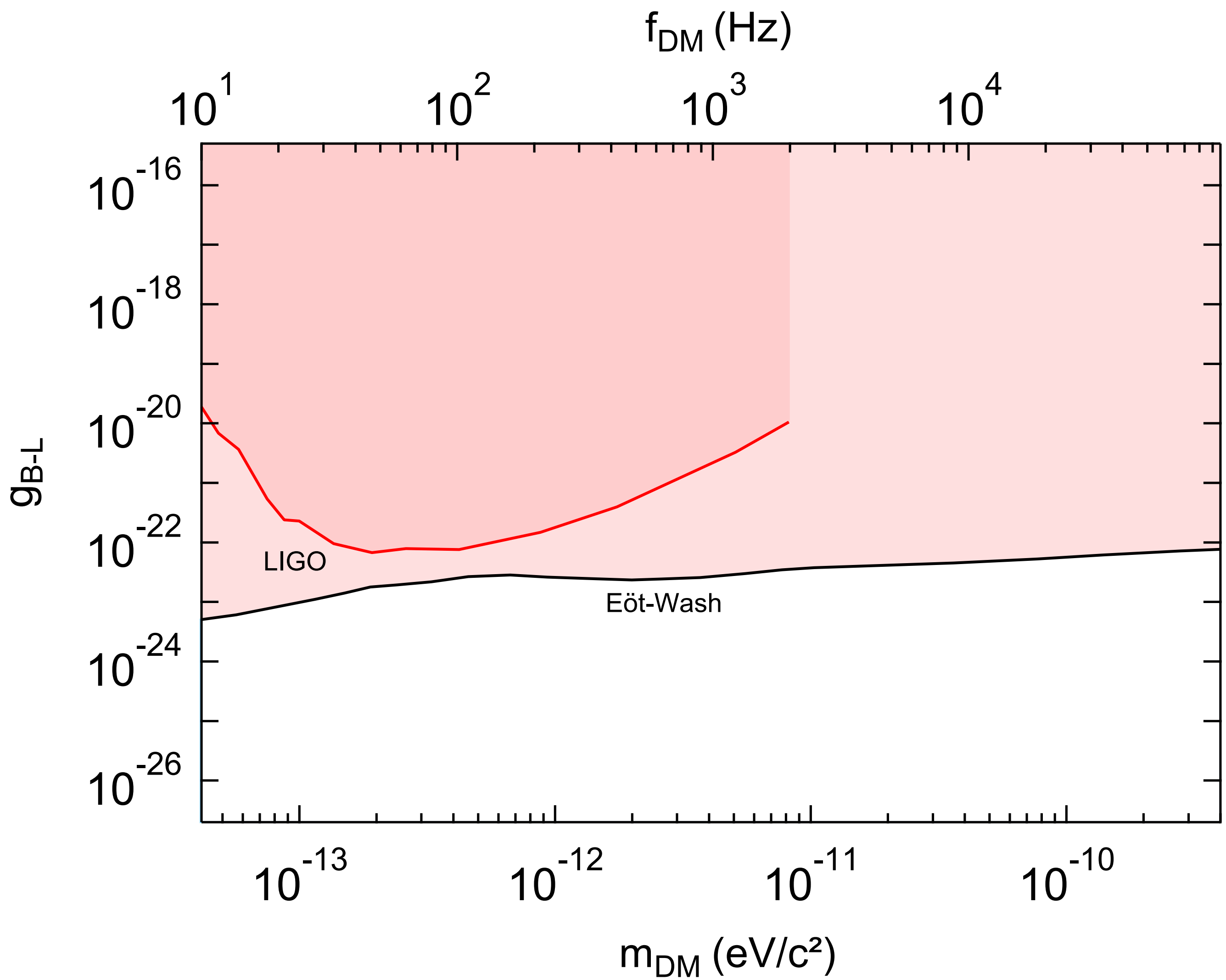
$$\Delta \boldsymbol{a}(t) \approx g_{\text{B-L}} \left[\left(\frac{N_{\text{n}}}{m} \right)_1 - \left(\frac{N_{\text{n}}}{m} \right)_2 \right] \boldsymbol{F_0} \cos(\omega_{\text{dm}} t)$$

unknown parameters

Wagner et al. Classical and Quantum Gravity 29.18 (2012): 184002.
Touboul et al. Physical review letters 119.23 (2017): 231101.

Vector DM parameter space

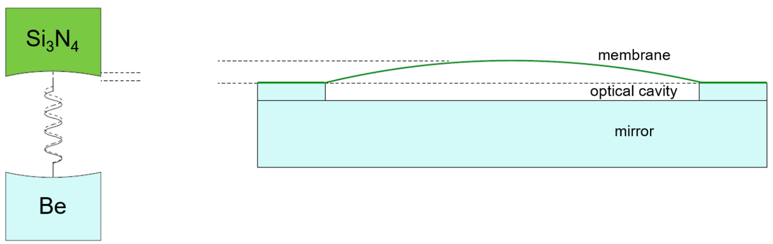
For vector gauge bosons (dark photons) coupling to B-L "charge":



Guo et al. Communications Physics 2.1 (2019): 1-7

SiN membrane detector

For vector gauge bosons (dark photons) coupling to B-L "charge":



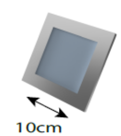
$$\Delta \boldsymbol{a}(t) \approx g_{\text{B-L}} \left[\left(\frac{N_\text{n}}{m} \right)_1 - \left(\frac{N_\text{n}}{m} \right)_2 \right] \boldsymbol{F_0} \cos(\omega_\text{dm} t)$$

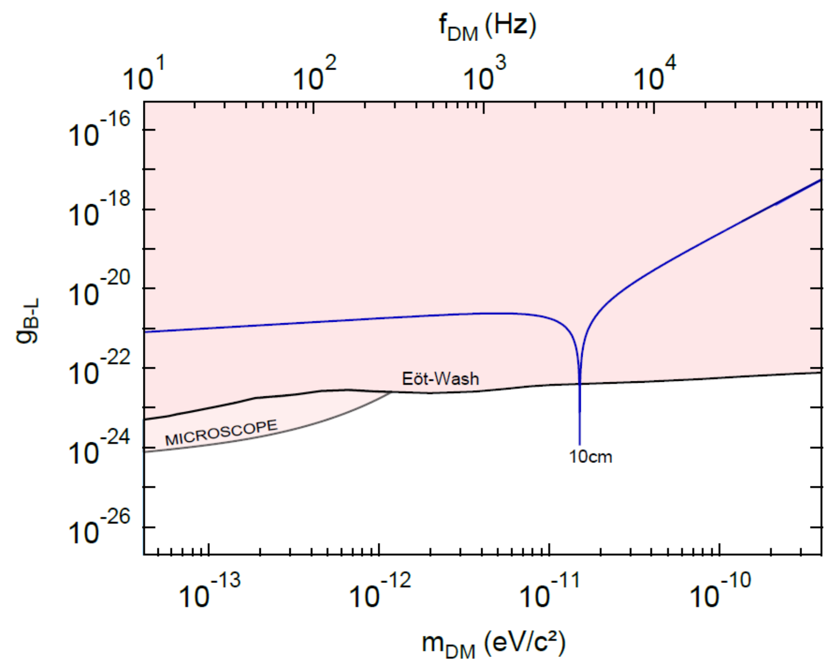
Thermal $$S_{aa}^{\text{th}} = \frac{4 k_\text{B} T \omega_0}{m Q_0}$$

laser shot

$$S_{xx}^{\text{imp}} = \frac{\pi \hbar c \lambda}{64 \mathcal{F}^2 P}$$

$$S_{aa}^{\text{ba}} = \frac{\hbar^2}{m^2 S_{xx}^{\text{imp}}}$$

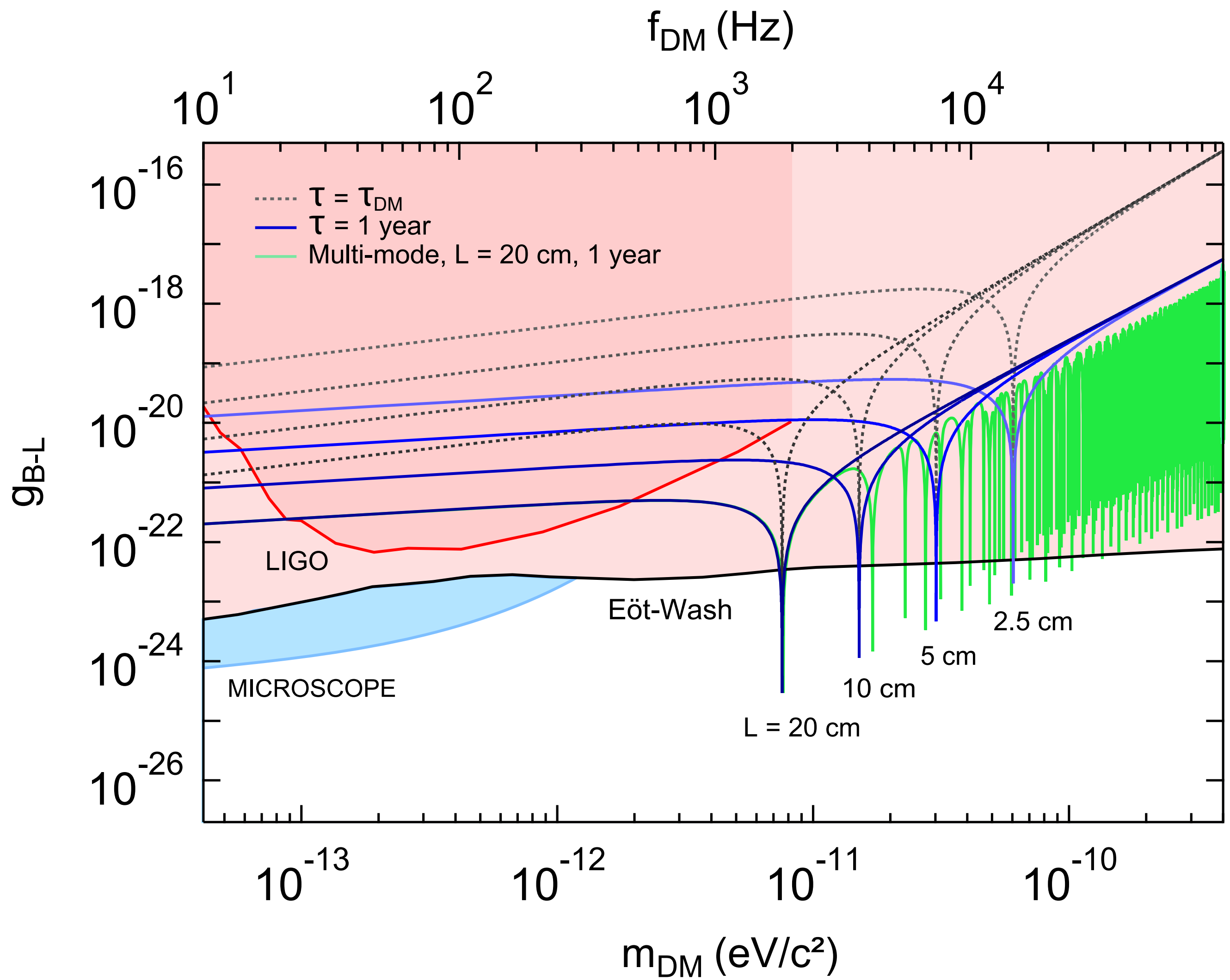


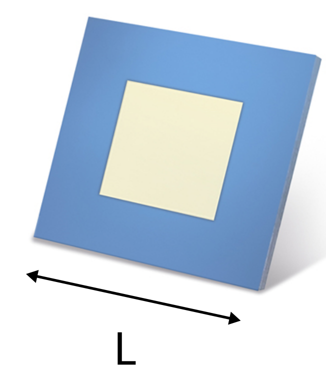


Searching for vector dark matter with an optomechanical accelerometer,
J. Manley, M. D. Choudhary, D. Grin, S. Singh and D. J. Wilson, PRL **126**, 061301 (2021).

Mechanical detectors for vector Dark Matter

For vector gauge bosons (dark photons) coupling to B-L "charge":





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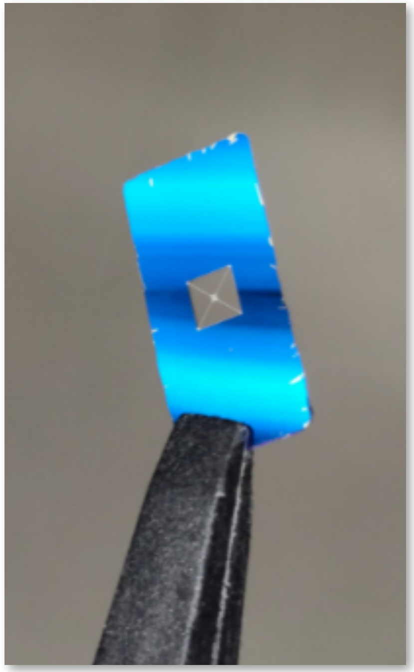
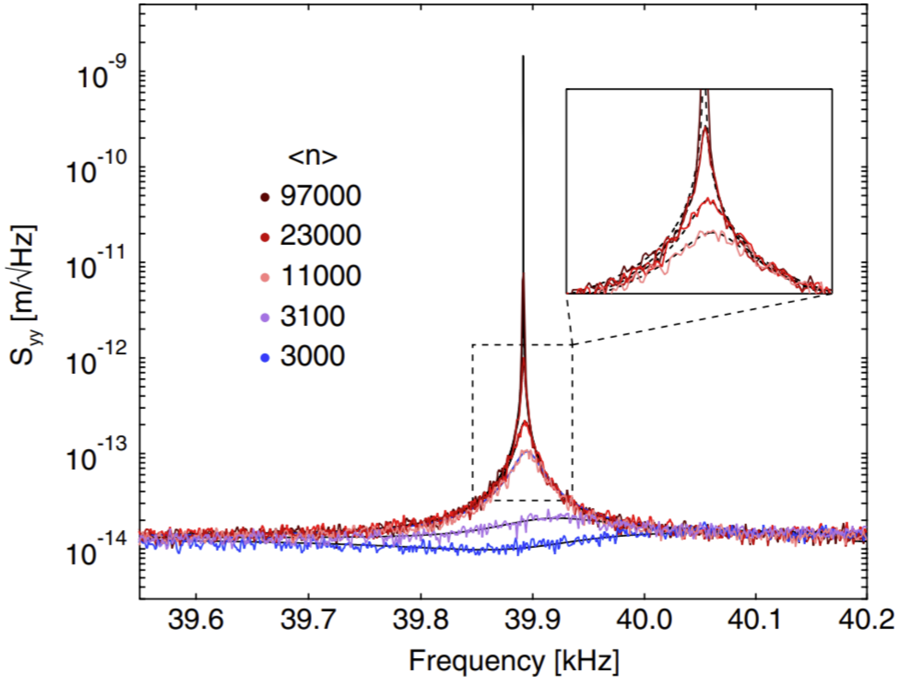
SiN membrane detector for vector DM



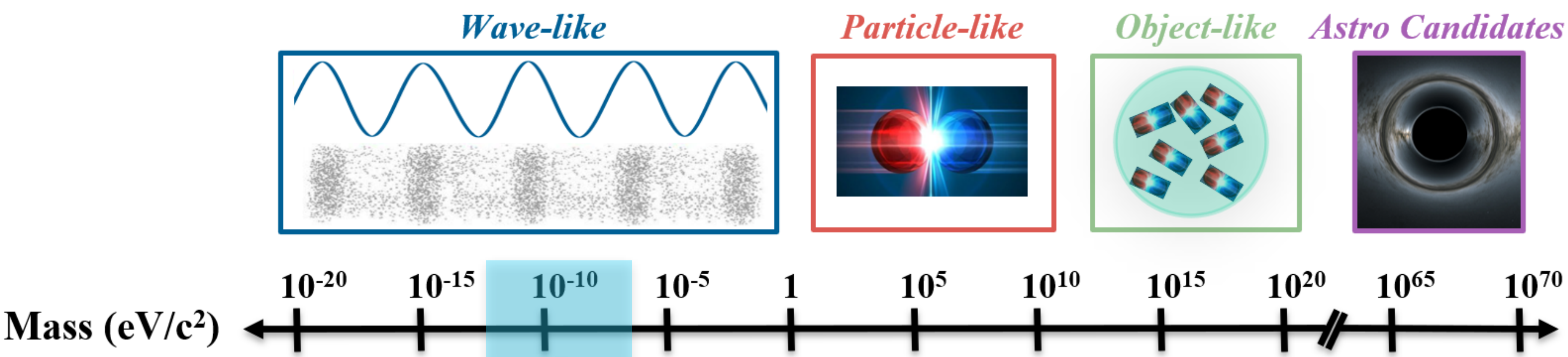


Dalziel Wilson group @ THE UNIVERSITY OF ARIZONA

Searching for vector dark matter with an optomechanical accelerometer,
J. Manley, M. D. Choudhary, D. Grin, S. Singh and D. J. Wilson, PRL **126**, 061301 (2021).

Towards cavity-free ground-state cooling of an acoustic-frequency silicon nitride membrane,
C. M. Pluchar, A. R. Agrawal, E. Schenk, and D. J. Wilson, *Applied Optics*, *59*(22), G107-G111 (2020).

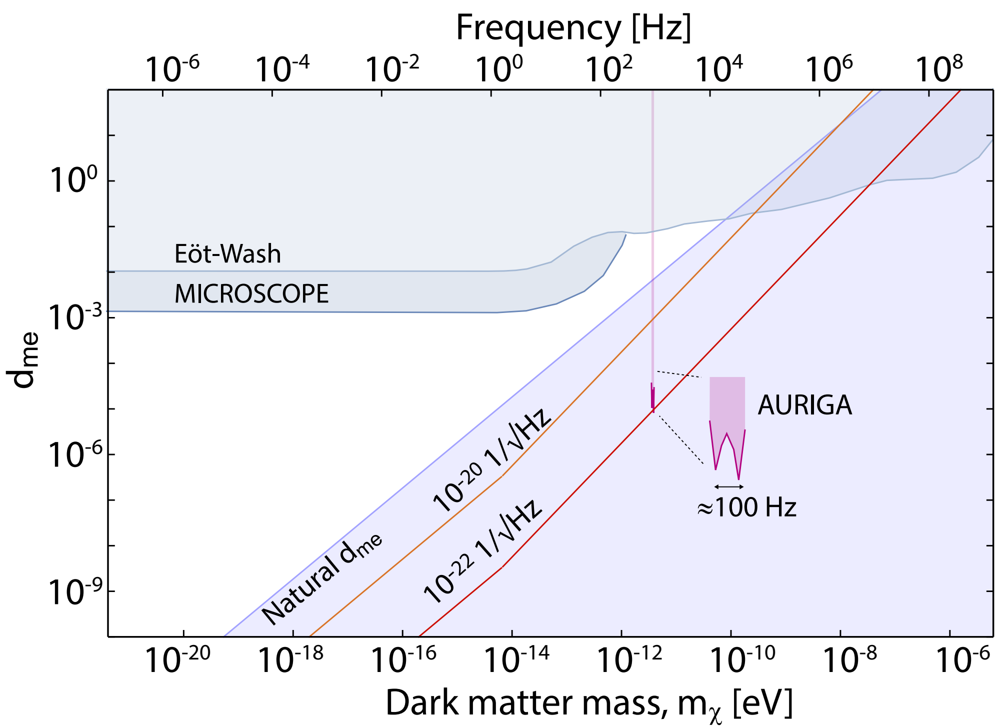
Conclusion

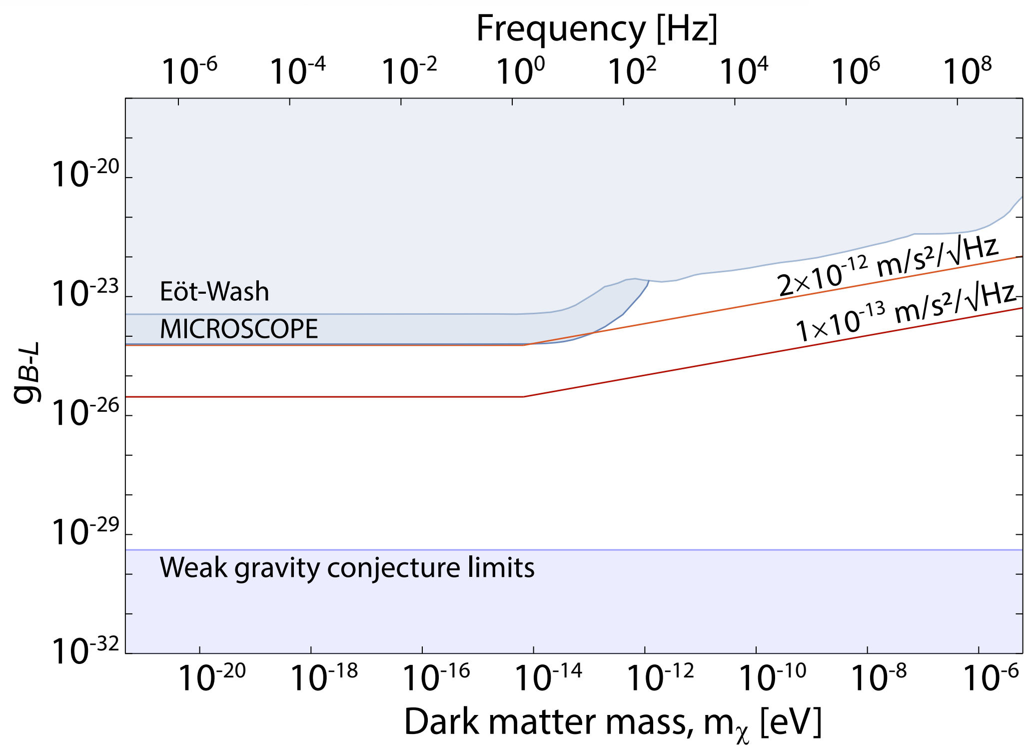


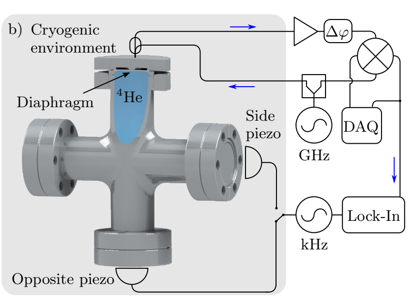
- pseudo-scalar (axions)
- scalar (dilatons)
- vector (dark photons)
- …

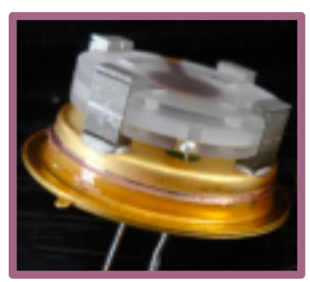
detectable with optomechanical systems

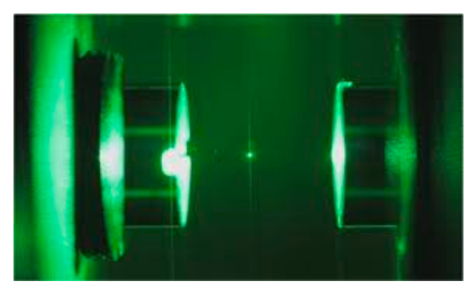
Mechanical sensing of ultralight dark matter

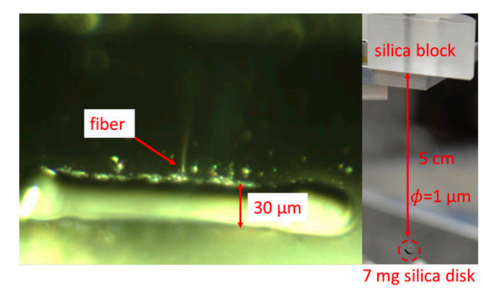












Mechanical quantum sensing in the search for dark matter,
Carney et. al, arXiv:2008.06074 (2020) .

Future work

- Broadband, tunable detection schemes for DM

  similar issues as haloscope detectors such as ADMX, HAYSTAC

- Other astrophysical sources of weak forces

  high freq. GWs, exotic DM candidates, chameleon DE fields

- Using quantum features (QND, BAE measurements) to make better sensors

  similar to optical squeezing in LIGO, QND detectors in HAYSTAC

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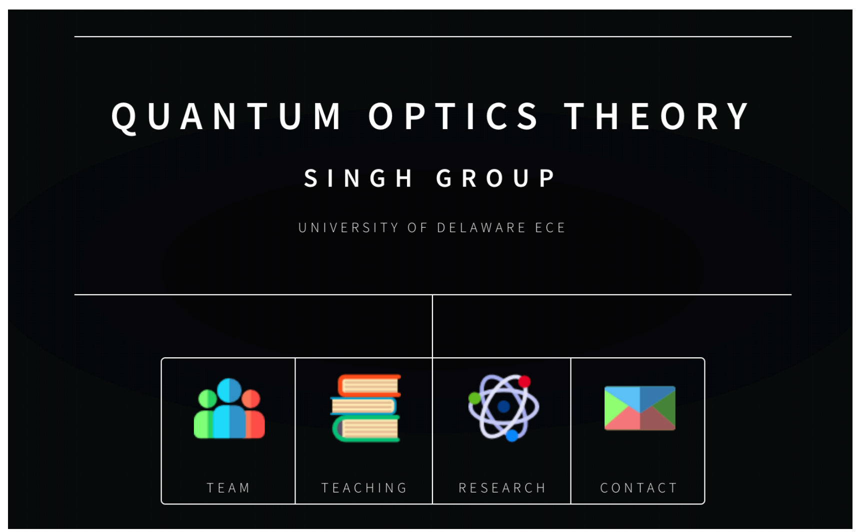
(U Arizona)

Daniel Grin
(Haverford)



https://www.eecis.udel.edu/~swatis/

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