Mechanical systems for exploring the dark sector

Swati Singh
University of Delaware,
July 5, 2022

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)*

- Yoctonewton Force sensing (10^{-24} N)

  Science ***344*** *1486 (2014)*

- Zeptometer displacement sensing (10^{-21} m)

  PRD ***93,*** *112004(2016)*

- Yoctogram mass sensing (10^{-24} g)

  Nature Nano ***7*** *301 (2012)*

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atomic/ spin systems

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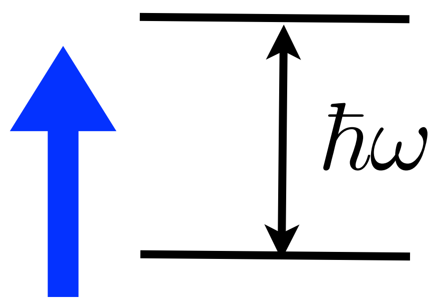
harmonic oscillator systems

Two simple models in quantum physics

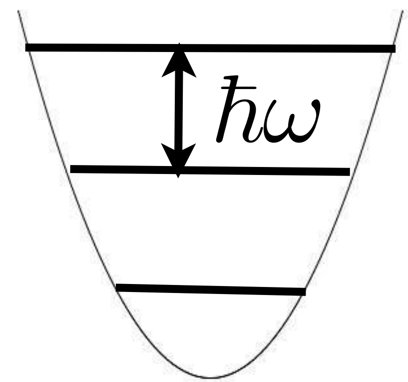
Spin 1/2



$$H = \hbar\frac{\omega}{2}\hat{\sigma}_z$$

captures transitions between
2 discrete energy states

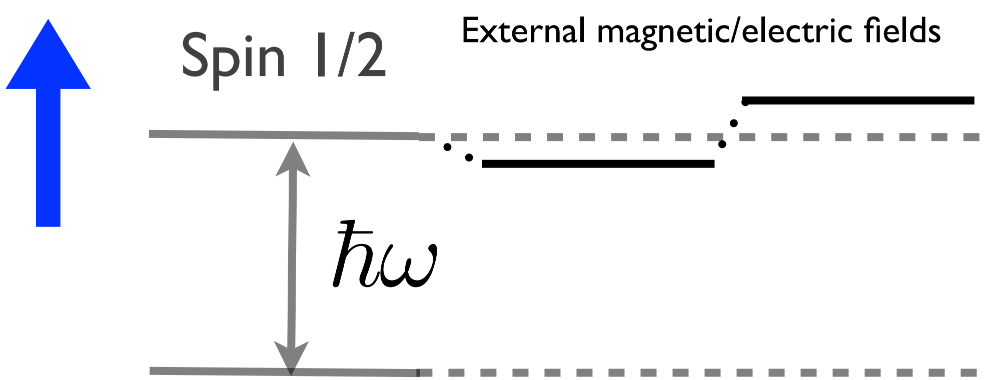
Harmonic Oscillator



$$H = \hbar\omega\left(\hat{a}^\dagger\hat{a} + \frac{1}{2}\right)$$

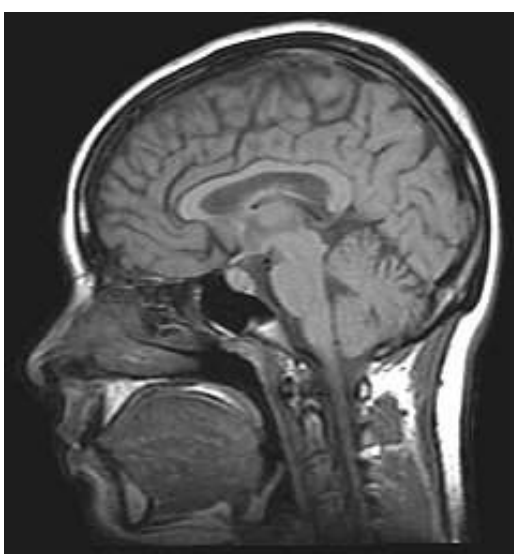
captures small changes
around equilibrium

Measuring fields via spin based sensors

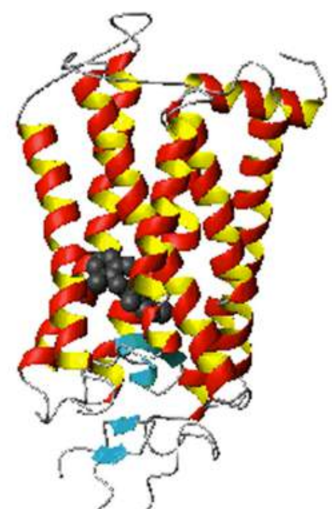


Susceptibility of energy difference to various environmental factors makes spins versatile sensors

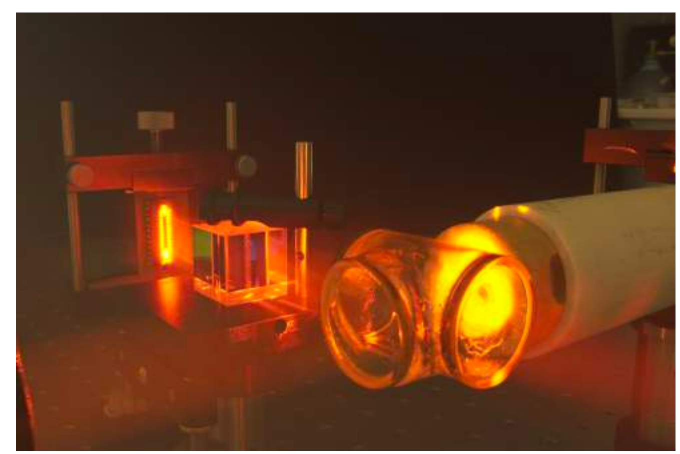
NMR/MRI



Protein Structure



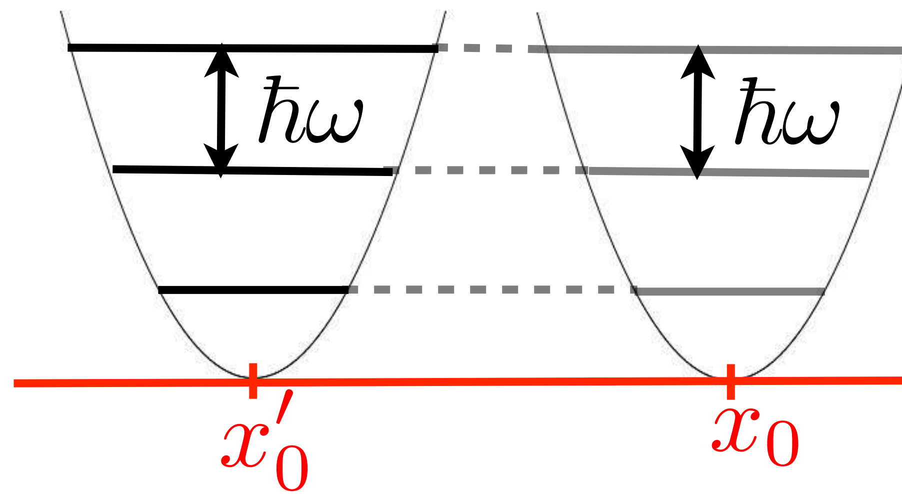
Magnetometers



Measuring weak forces via Harmonic

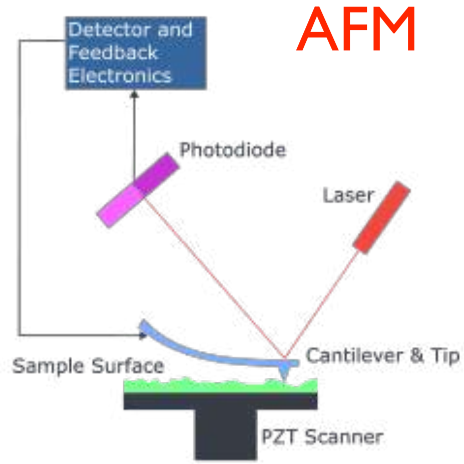
Susceptibility of equilibrium position to various environmental forces make harmonic oscillators versatile sensors

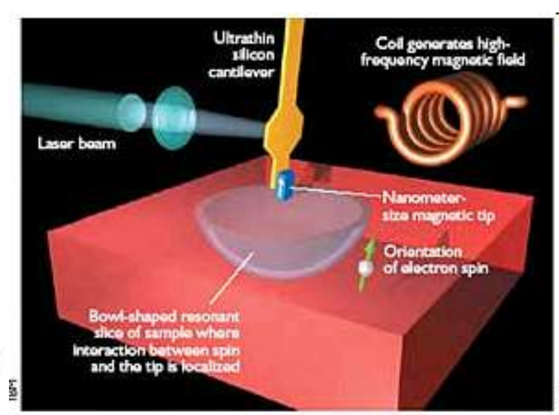
Harmonic Oscillator



LIGO

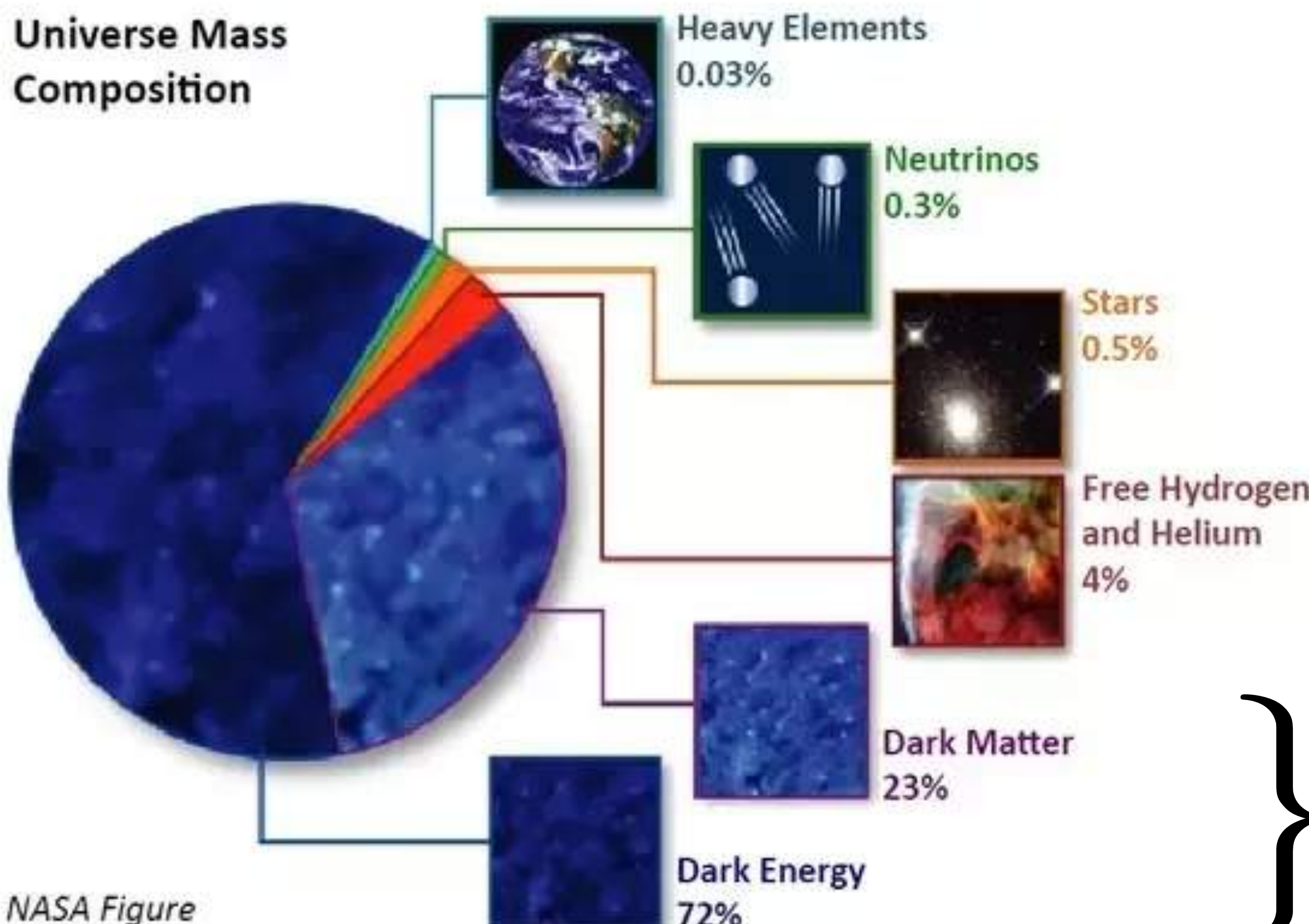
AFM





Single spin detection setup

The dark sector



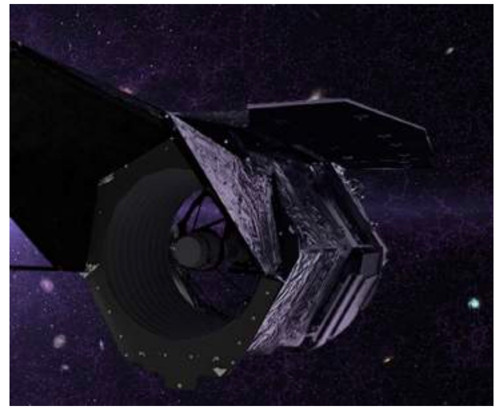
} >95% of our Universe

Image: NASA

Shedding light on the dark sector

- **Look outside:** better astrophysical surveys

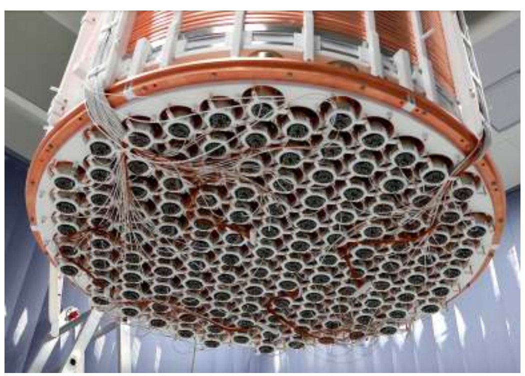
Victor Blanco Telescope



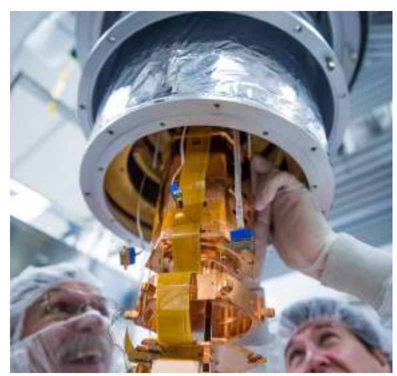
Roman Space Telescope

James Webb Telescope

- **Look inside:** direct detection experiments



XENON 1T experiment



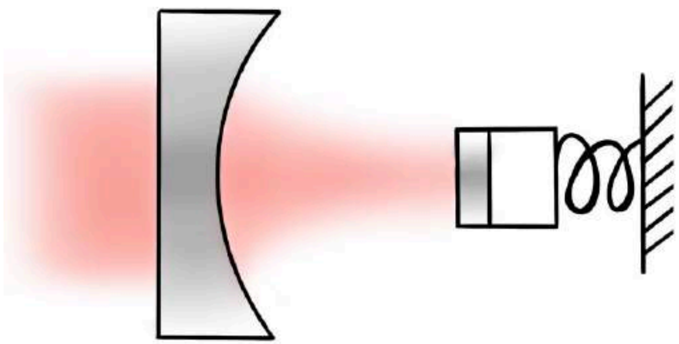
Super CDMS

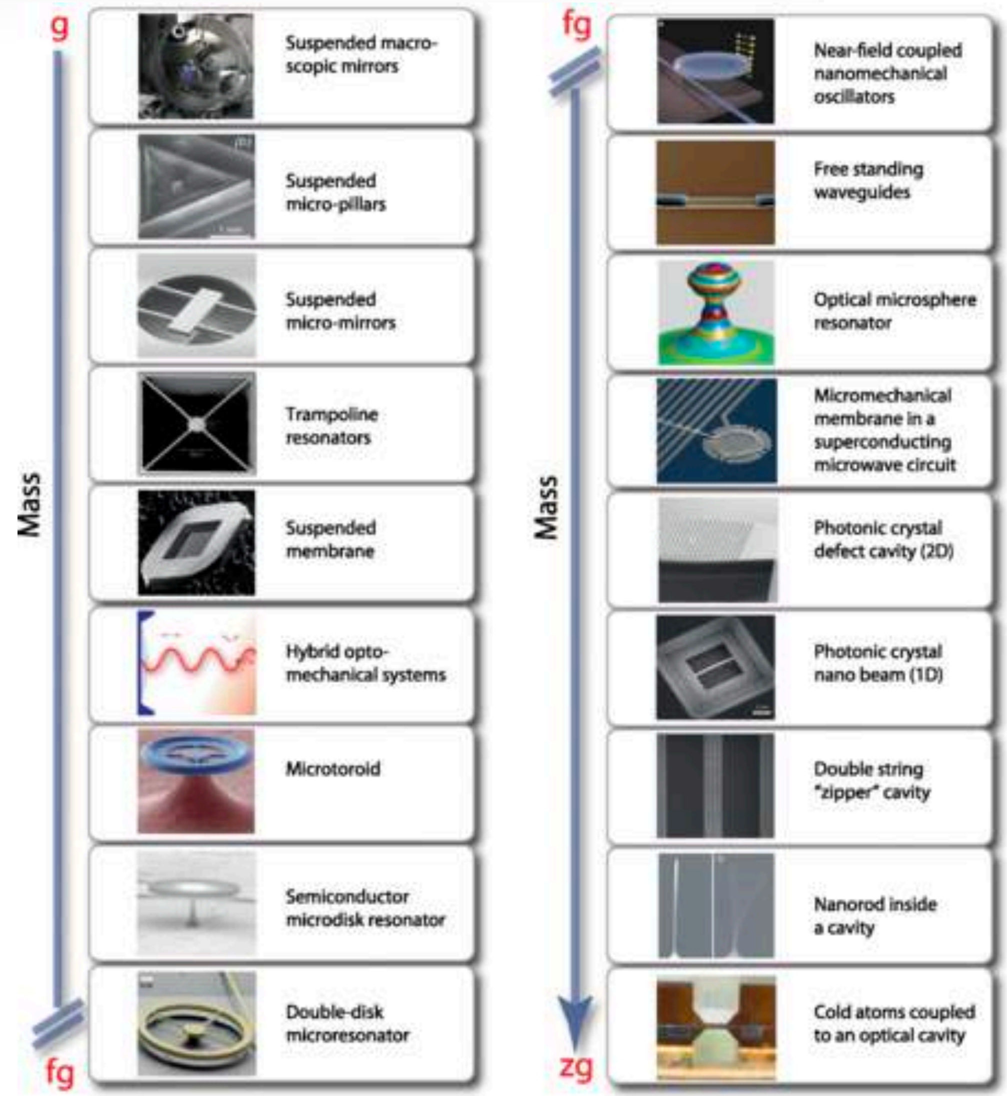
ADMX

Table-top precision measurement experiments

Image: Various websites..

Cast of characters: harmonic oscillators





State of the art sensitivities[1]

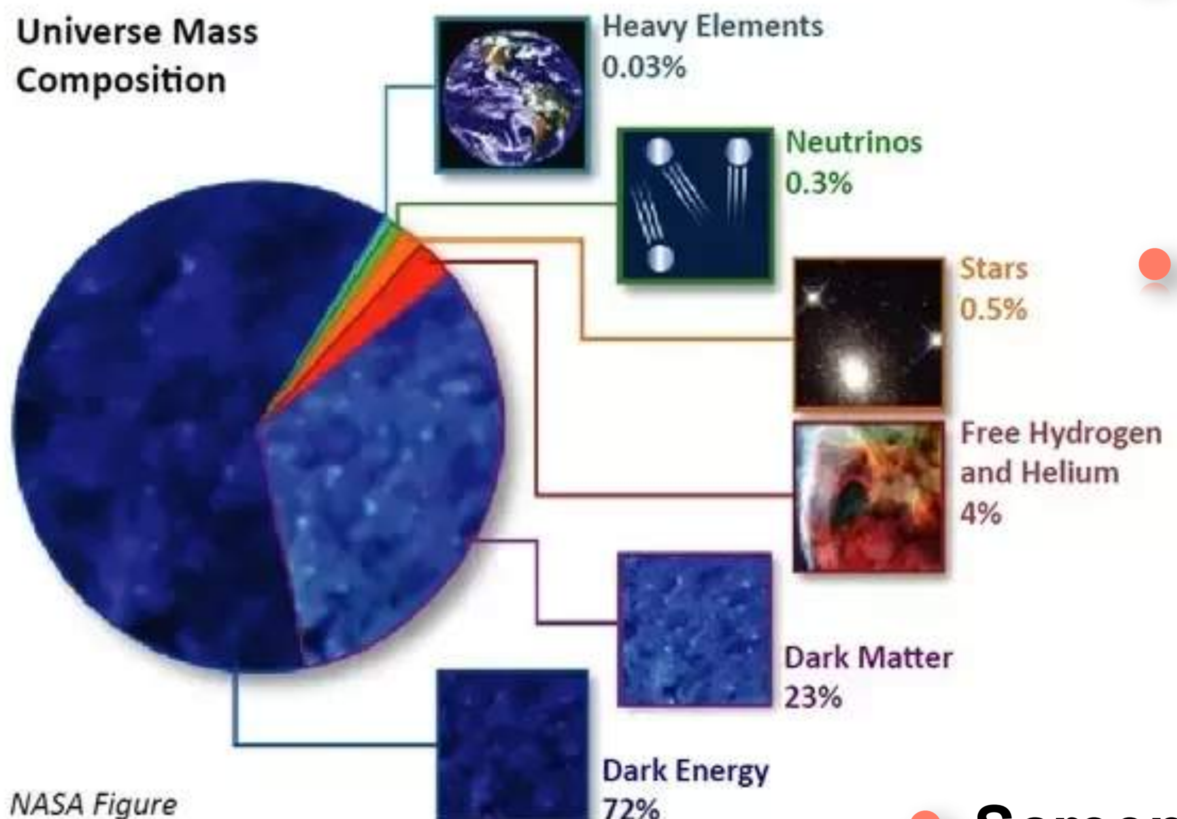
- Force: $10^{-20}\ N/\sqrt{Hz}$
- Acceleration: $10^{-15}\ g/\sqrt{Hz}$
- Strain: $10^{-21}\ /\sqrt{Hz}$

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) .

Mechanical signals from the dark sector



- **Scalar dark matter**
  - Isotropic strain field
  - Displacement signal
- **Vector dark matter**
  - Lorentz-like force
  - Differential acceleration signal
- **Screened-scalar dark energy**
  - Corrections to Newtonian gravity
  - Acceleration signal

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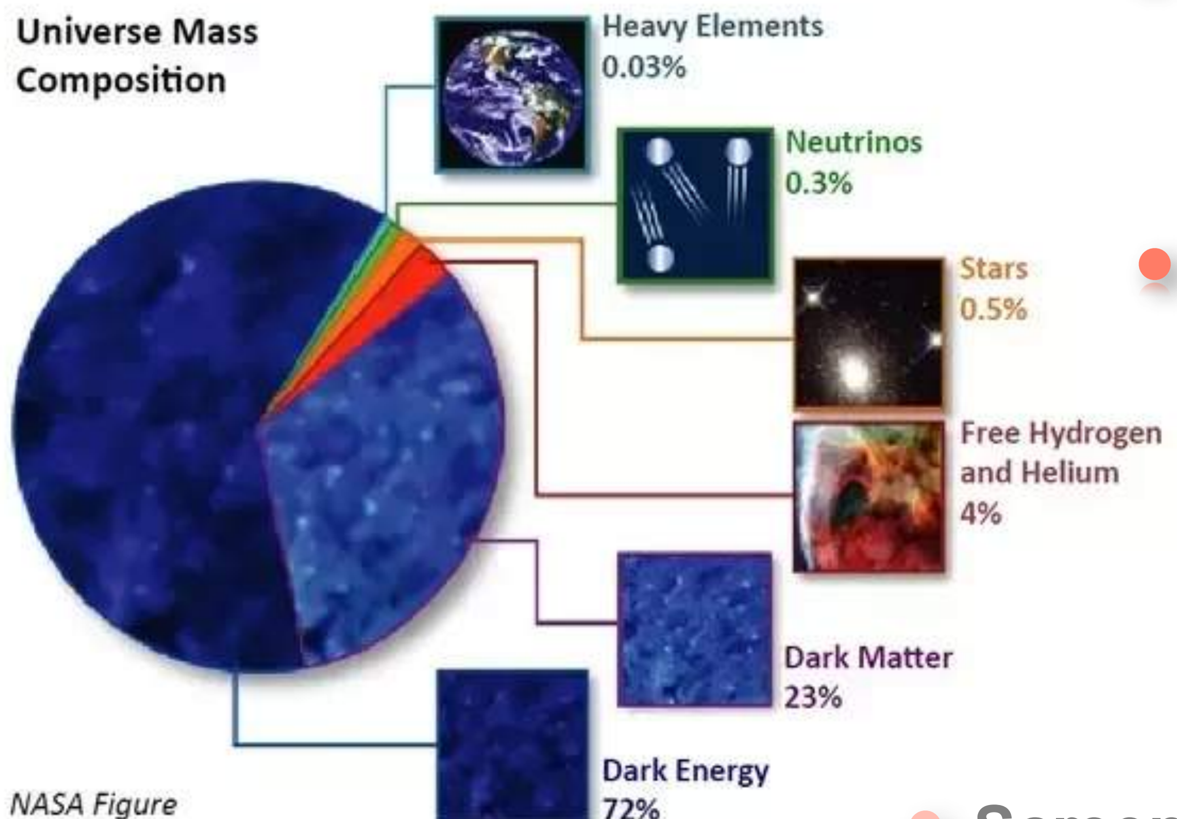

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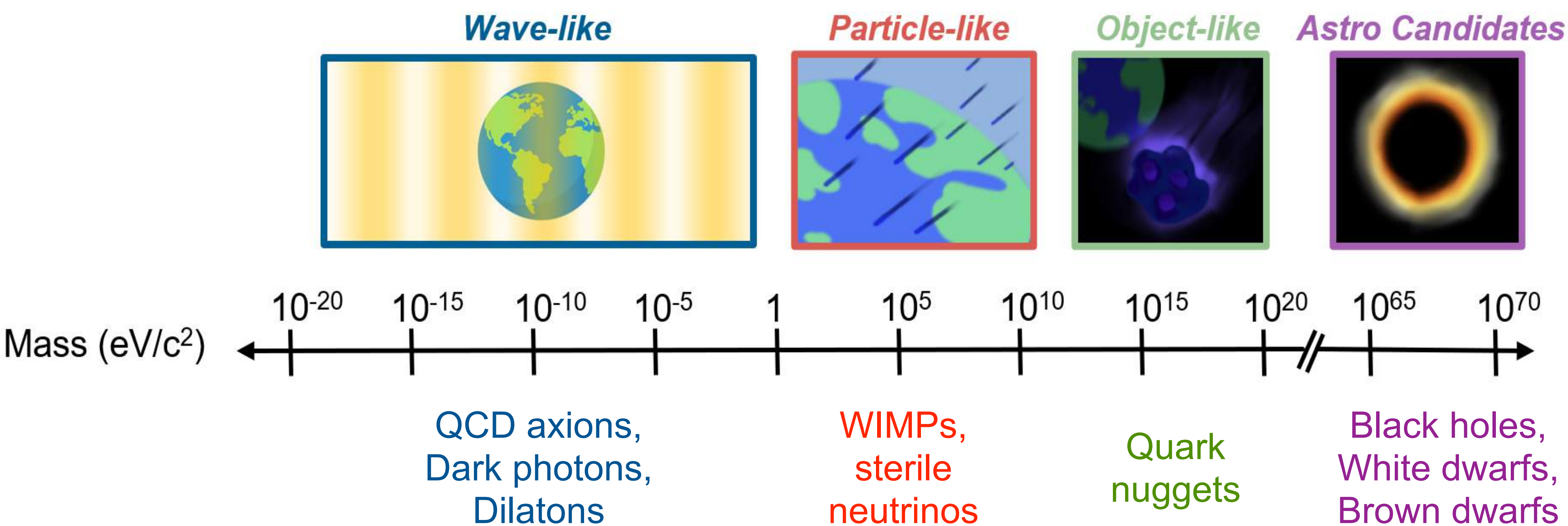
Dark Matter

- 23% of our universe is made of Dark Matter.
- 85% of the mass in typical galaxies is Dark Matter.
- There is ~90 orders of magnitude uncertainty in the composition of Dark Matter.



Note: $1\ \mathrm{eV/c^2} \approx 10^{-36}\ \mathrm{kg}$

Image help: Natalie Schmidt, Jack Manley

Mechanical dark matter detectors- overview

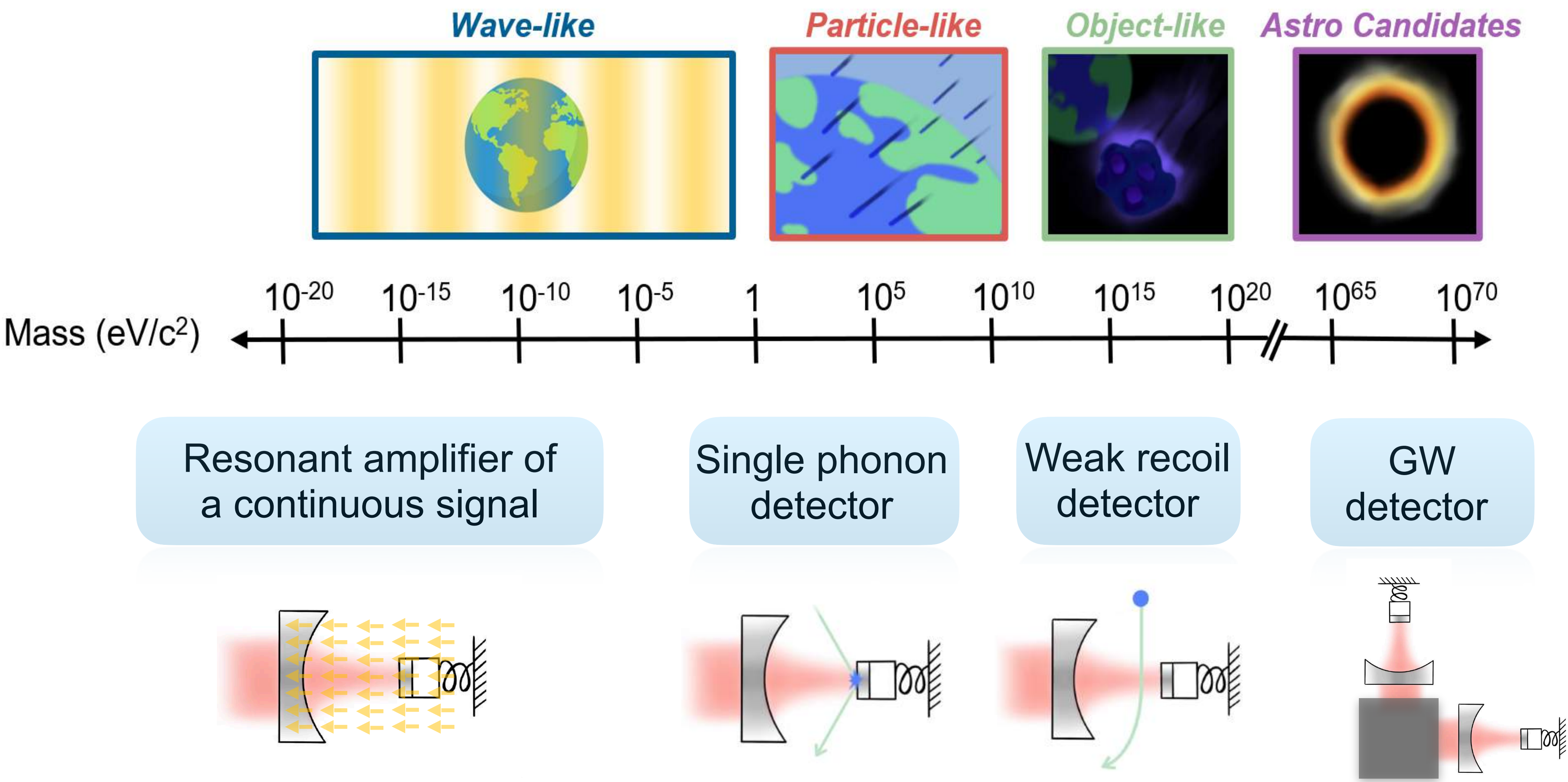
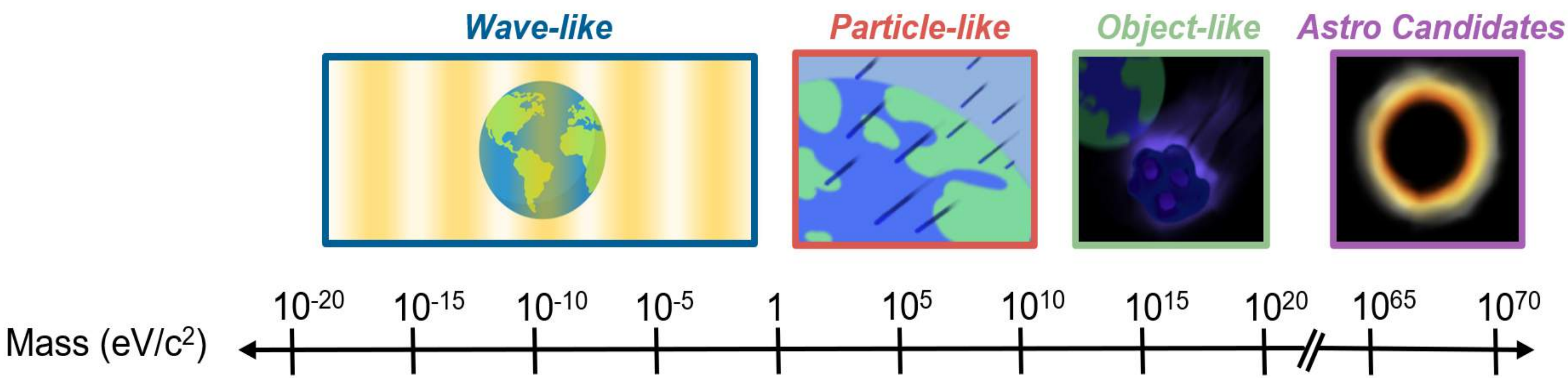


Image: Natalie Schmidt

Mechanical dark matter detection

Mechanical systems are **already** constraining dark matter



LIGO

Primordial black hole dark matter and the LIGO/Virgo observations

Karsten Jedamzik[1]

Published 14 September 2020 • © 2020 IOP Publishing Ltd and Sissa Medialab

Journal of Cosmology and Astroparticle Physics, Volume 2020, September 2020

Citation Karsten Jedamzik JCAP09(2020)022

Eliminating the LIGO bounds on primordial black hole dark matter

Céline Bœhm[1], Archil Kobakhidze[1], Ciaran A.J. O'Hare[1], Zachary S.C. Picker[1] and Mairi Sakellariadou[2]

Published 23 March 2021 • © 2021 IOP Publishing Ltd and Sissa Medialab

Journal of Cosmology and Astroparticle Physics, Volume 2021, March 2021

Citation Céline Bœhm *et al* JCAP03(2021)078

Mechanical dark matter detection

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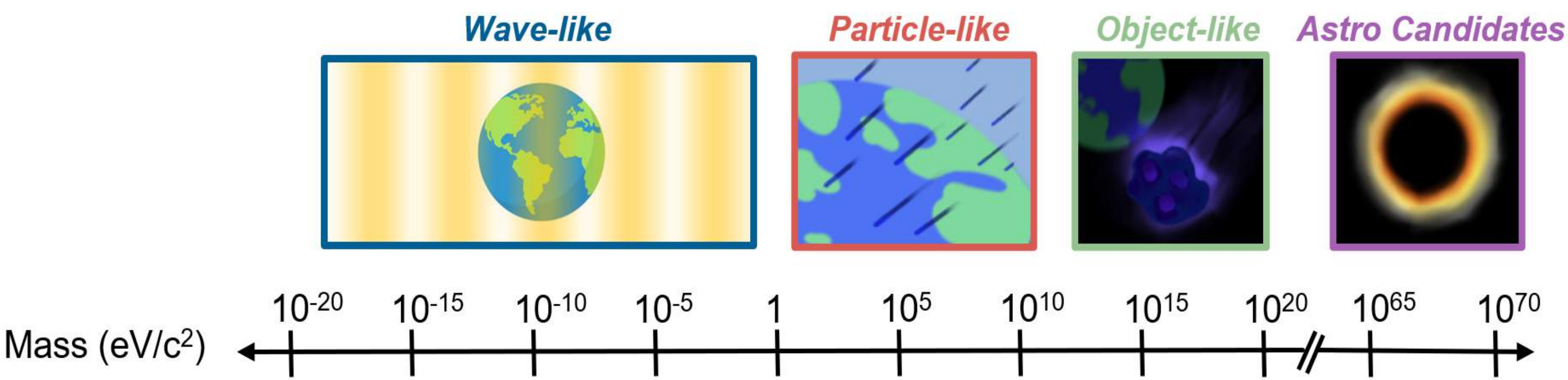


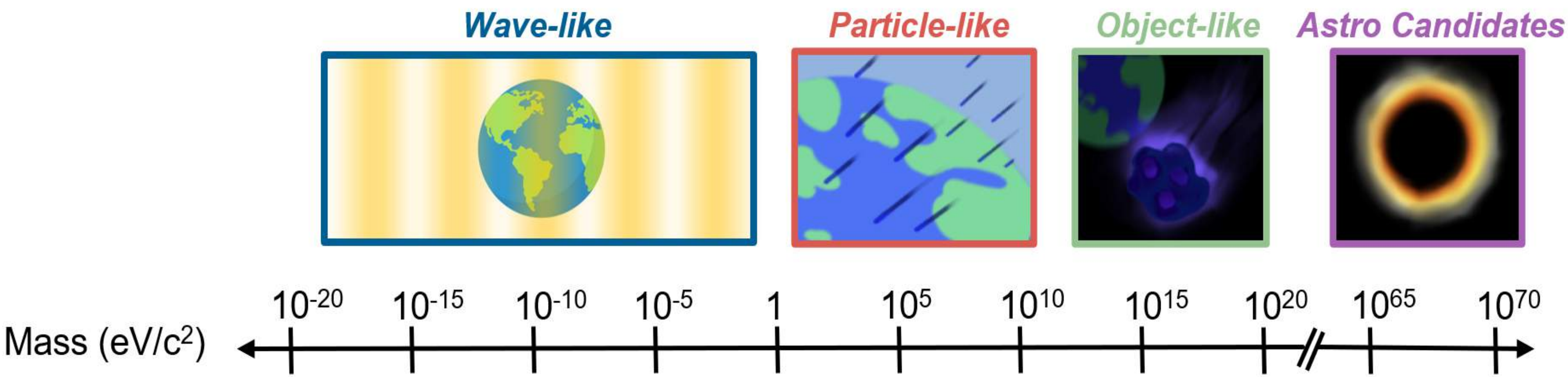
Levitated microspheres

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

Mechanical dark matter detection

Mechanical systems are **already** constraining dark matter



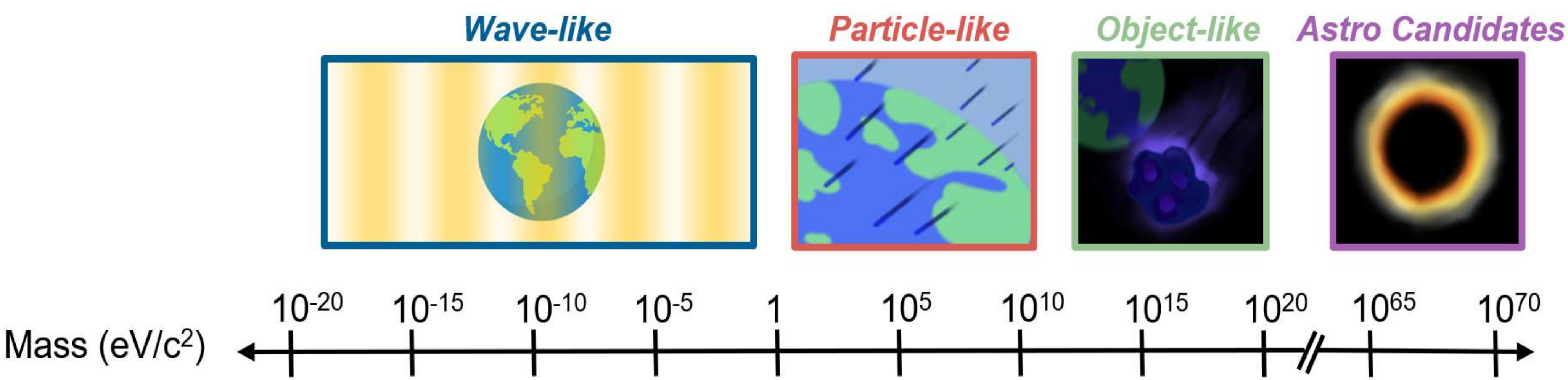
Phonon recoil
detectors

Coherent Scattering of Low Mass Dark Matter from Optically Trapped Sensors

Gadi Afek, Daniel Carney, and David C. Moore
Phys. Rev. Lett. **128**, 101301 – Published 9 March 2022

Mechanical dark matter detection

Mechanical systems are **already** constraining dark matter



(primarily) Cavity-based searches

Precision Metrology Meets Cosmology: Improved Constraints on Ultralight Dark Matter from Atom-Cavity Frequency Comparisons

Colin J. Kennedy, Eric Oelker, John M. Robinson, Tobias Bothwell, Dhruv Kedar, William R. Milner, G. Edward Marti, Andrei Derevianko, and Jun Ye
Phys. Rev. Lett. **125**, 201302 – Published 12 November 2020

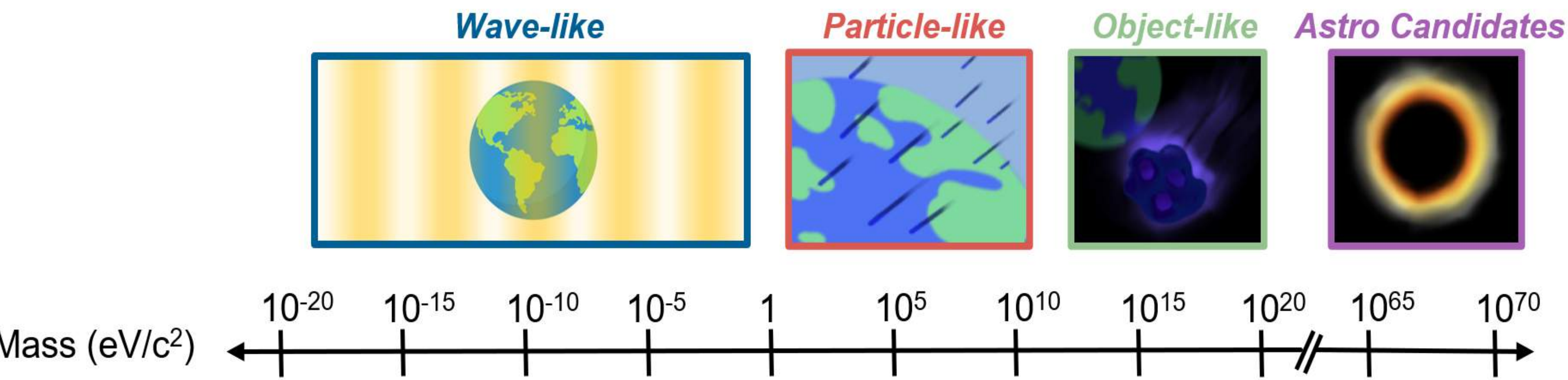
Searching for Dark Matter with an Optical Cavity and an Unequal-Delay Interferometer

Etienne Savalle, Aurélien Hees, Florian Frank, Etienne Cantin, Paul-Eric Pottie, Benjamin M. Roberts, Lucie Cros, Ben T. McAllister, and Peter Wolf
Phys. Rev. Lett. **126**, 051301 – Published 4 February 2021

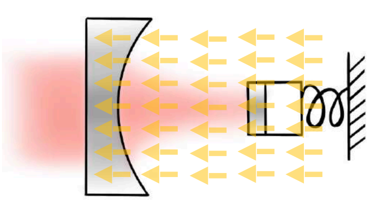
Searching for Scalar Dark Matter via Coupling to Fundamental Constants with Photonic, Atomic, and Mechanical Oscillators

William M. Campbell, Ben T. McAllister, Maxim Goryachev, Eugene N. Ivanov, and Michael E. Tobar
Phys. Rev. Lett. **126**, 071301 – Published 18 February 2021

Mechanical detectors of ultralight DM



Resonant amplifier of a continuous signal



Ultralight Dark Matter

- For mass <1 eV/c^2 , 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: $\omega_\phi = m_\phi c^2/\hbar$

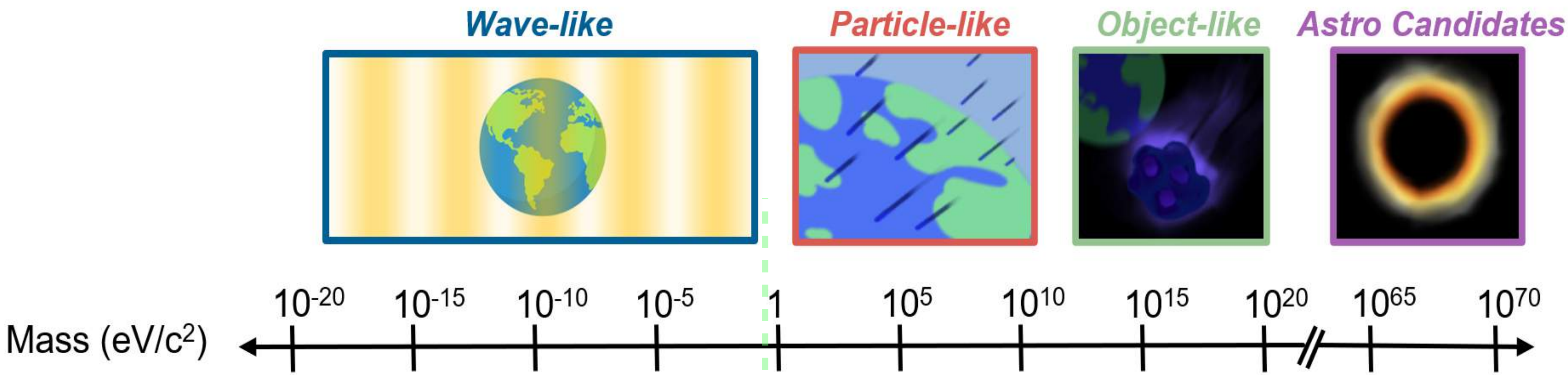
Wavenumber: $k_\phi = m_\phi v/\hbar$ $v = 10^{-3}c$

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

- It's always there!
- 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).

Mechanical DM detectors- overview



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).

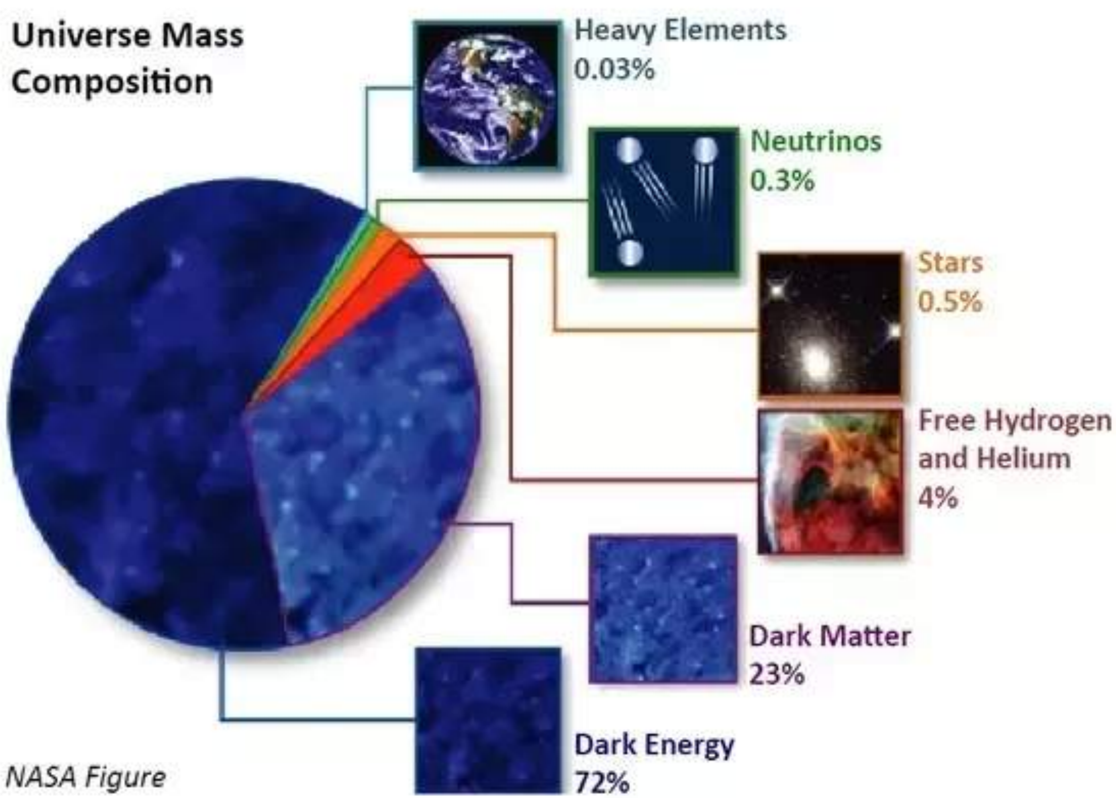
Carney et al. NJP **23** 023041 (2021).

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

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

Jack Manley

The dark matter problem



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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

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

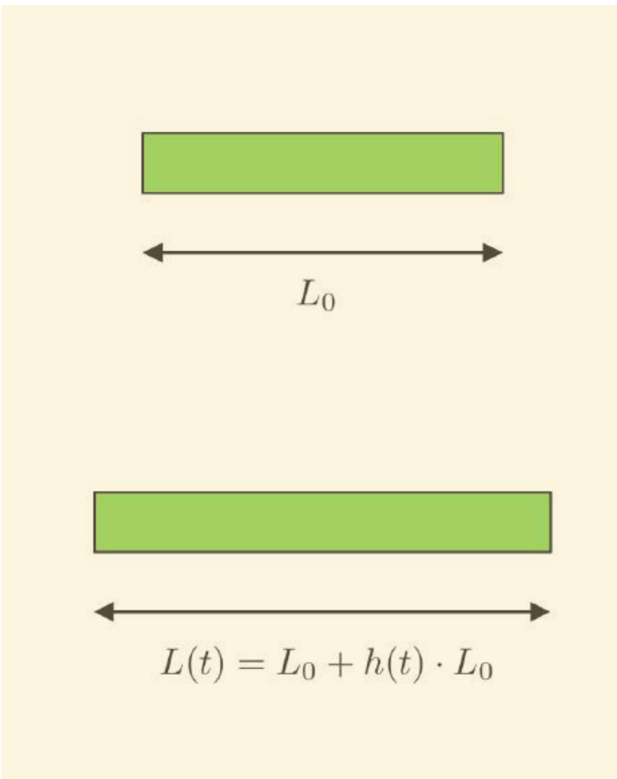
→ **scalar DM strains atoms**

A. Derevianko. PRA 97.4 (2018): 042506.

A. Arvanitaki et al. PRL 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

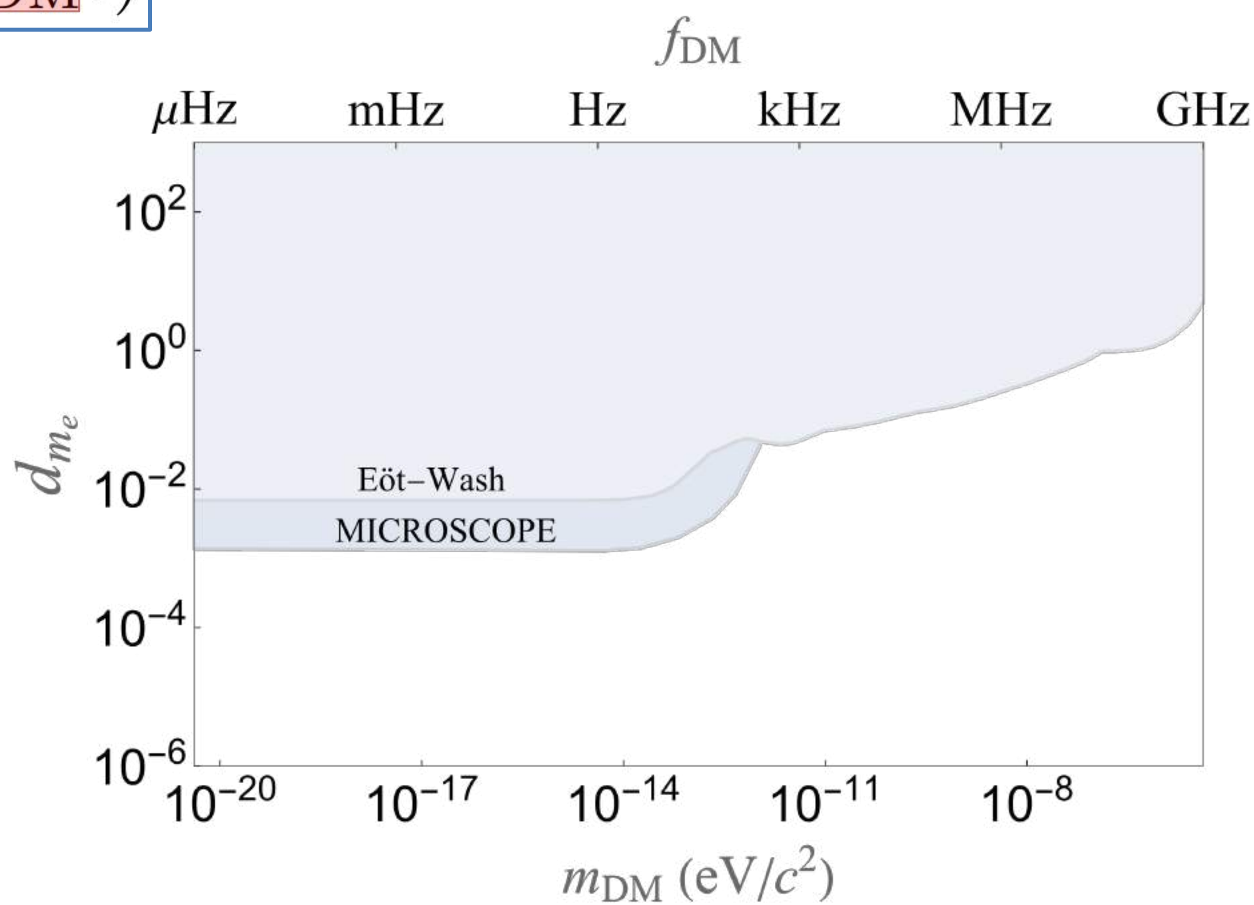
$$h(t) \approx -h_0 \cos\left(\omega_{\mathrm{dm}} t\right)$$

- Amplified in a macroscopic solid
- Amplified on acoustic resonance

Scalar DM parameter space

Strain Signal

$$h(t) = -d_{m_e} \varphi_0 \cos\left(\omega_{\rm DM} t\right)$$



Eöt-Wash: Wagner et al. *Classical and Quantum Gravity* 29, 184002, 2012.
MICROSCOPE: Berge et al. *Physical review letters*, 120(14):141101, 2018.

Mechanical detectors

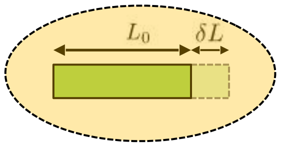
- Vermeulen et al. *Nature* **600**, 424-428 (2021) (GEO600)
- Branca et al. *PRL* **118**, 021302 (2017) (AURIGA)

GW detectors

- Kennedy et al. *PRL* **125**, 201302 (2020)
- Savalle et al. *PRL* **126**, 051301 (2021) (DAMNED)

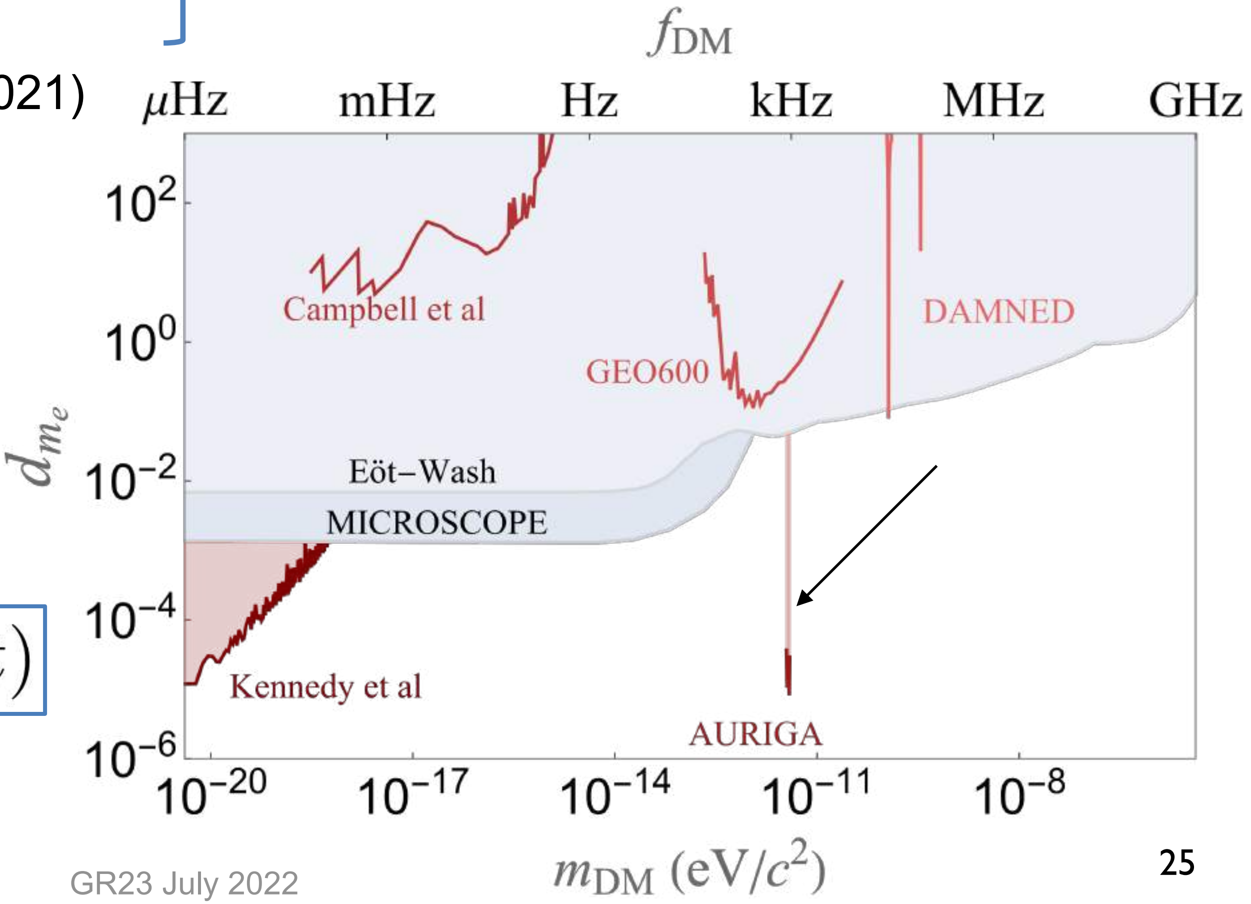
Optical cavities

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

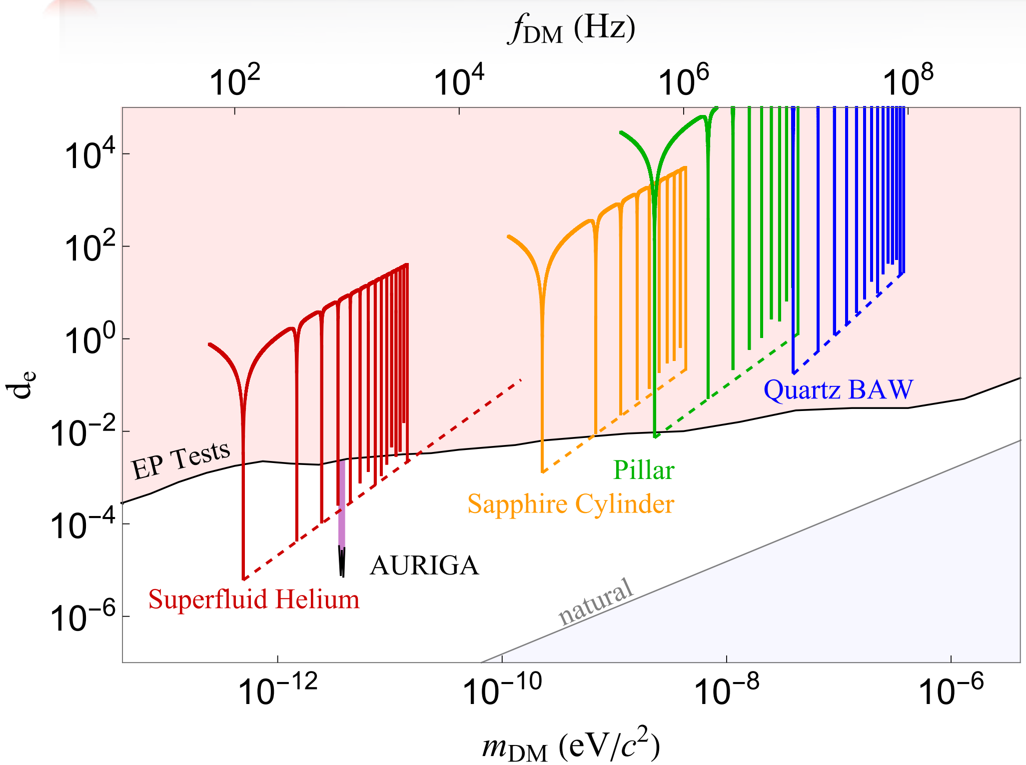


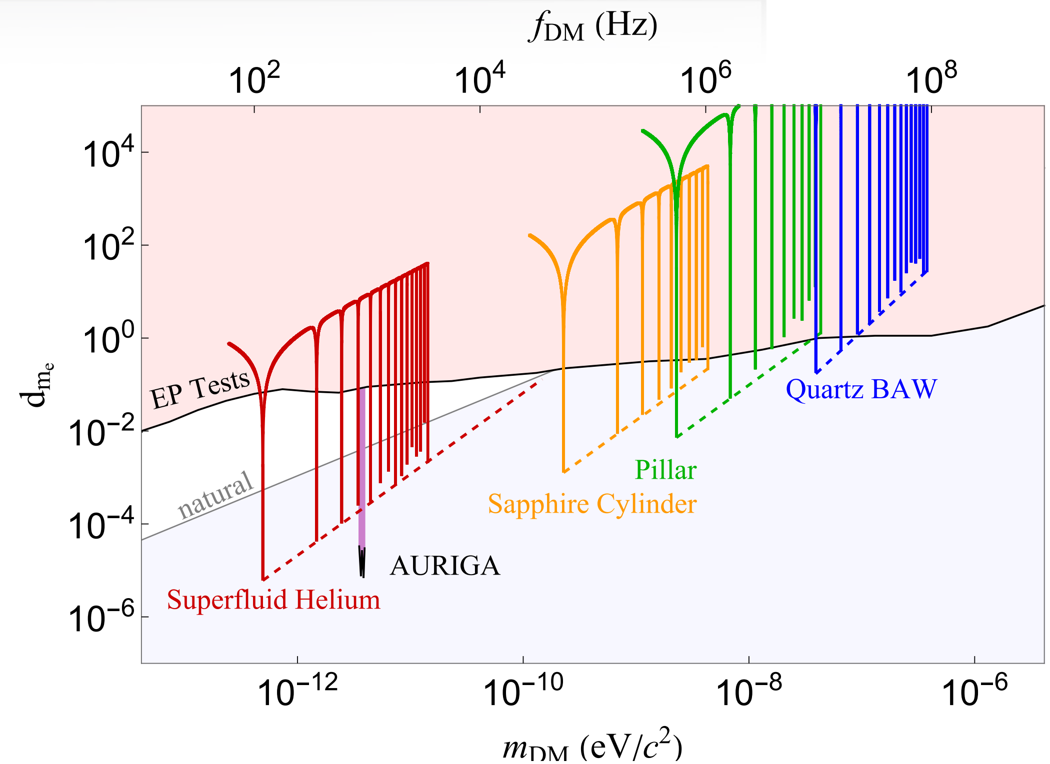
Strain Signal

$$h(t) = -d_{m_e} \varphi_0 \cos(\omega_{DM} t)$$



Compact mechanical resonators



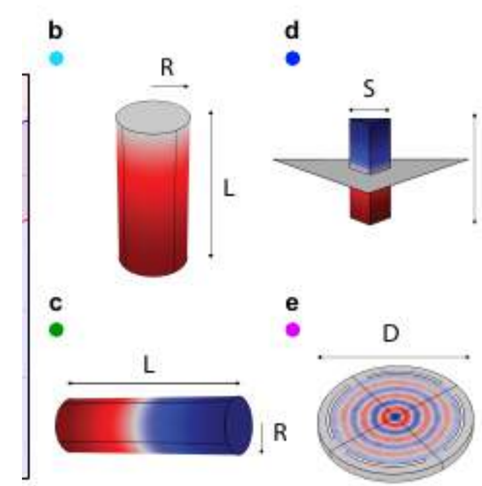


PHYSICAL REVIEW LETTERS **124,** 151301 (2020)

Searching for Scalar Dark Matter with Compact Mechanical Resonators

Jack Manley,[1] Dalziel J. Wilson,[2] Russell Stump,[1] Daniel Grin,[3] and Swati Singh[1,*]
[1]*Department of Electrical and Computer Engineering, University of Delaware, Newark, Delaware 19716, USA*
[2]*College of Optical Sciences, University of Arizona, Tucson, Arizona 85721, USA*
[3]*Department of Physics and Astronomy, Haverford College, Haverford, Pennsylvania 19041, USA*

(Received 21 November 2019; accepted 18 March 2020; published 16 April 2020)

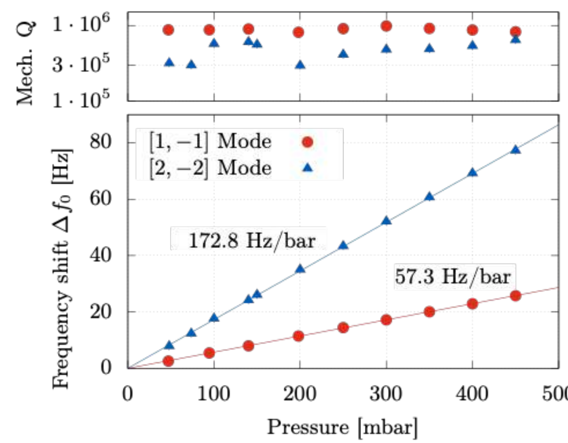


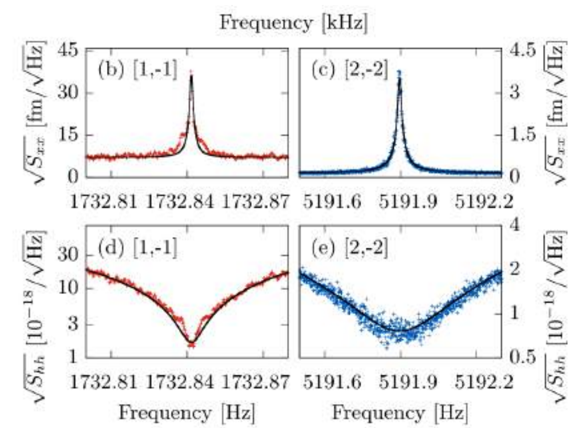
Superfluid helium detector for DM

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

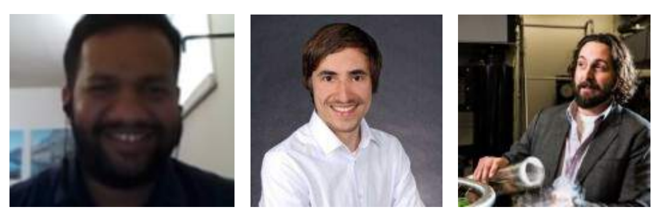
HELIOS: superfluid helium based ultralight dark matter optomechanical sensor

- High-Q
- Tunable
- Thermally-limited





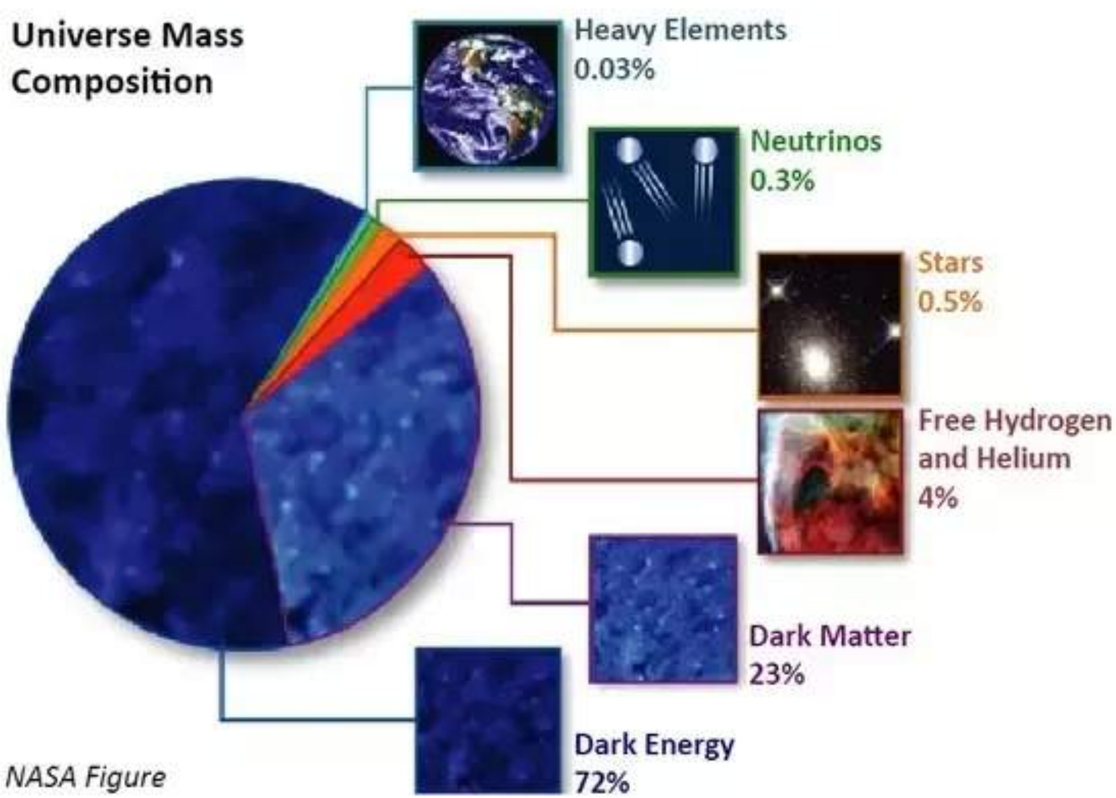
John Davis group @ UNIVERSITY OF ALBERTA



V. Vadakkumbatt, M. Hirschel, J. Manley, T. J. Clark, S. Singh, J. P. Davis, PRD 104 082001 (2021).

Image: Marvin Hirschel

The dark matter problem



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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:

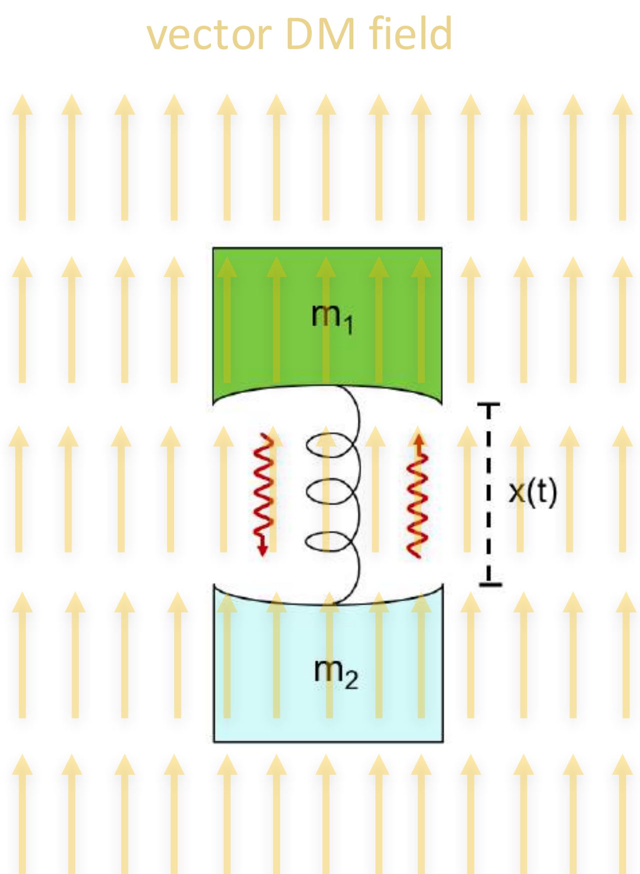
$$F(t) \approx g' N' F_0 \cos\left(\omega_{\rm dm} t\right)$$

g': coupling strength; N': number of dark charges; F_0:

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

D. Carney *et al* New J. Phys. **23** 023041 (2021).
J. Manley et al. PRL **126**, 061301 (2021).

Vector coupling: experimental signature



Differential acceleration signal

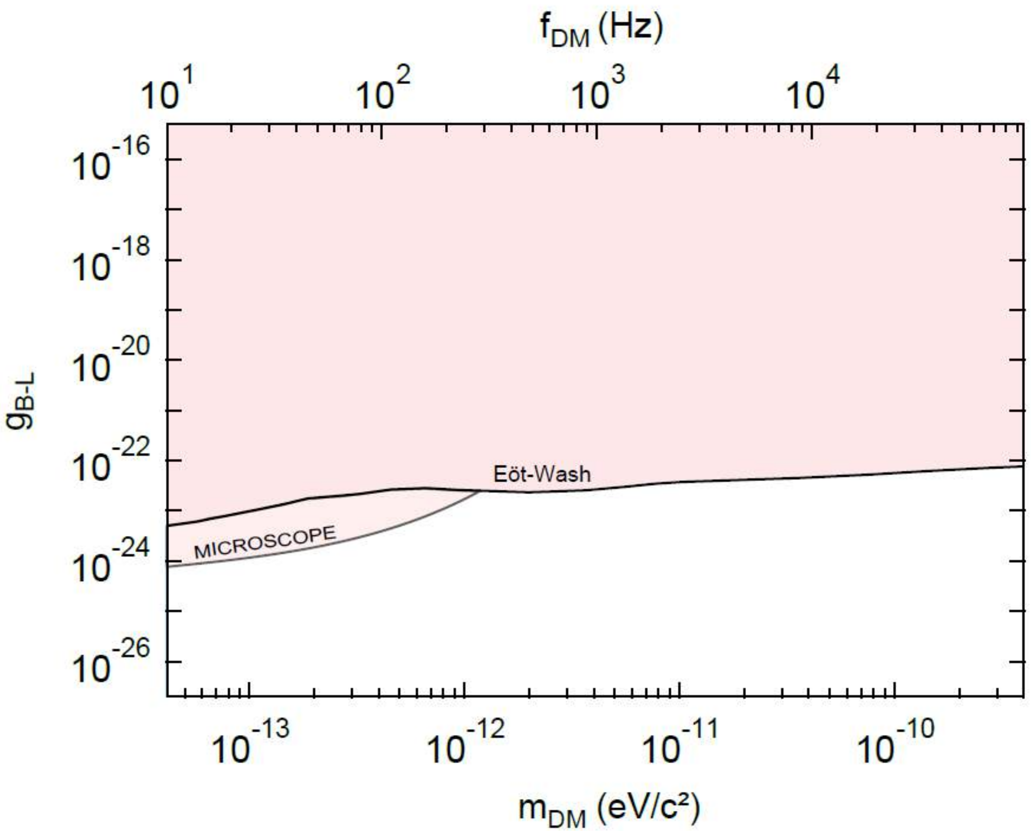
$$\Delta a(t) = a_1(t) - a_2(t) \approx g' \left(\frac{N_1'}{m_1} - \frac{N_2'}{m_2} \right) F_0 \cos\left(\omega_{\rm dm} t\right)$$

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

D. Carney *et al* New J. Phys. **23** 023041 (2021).
J. Manley et al. PRL **126**, 061301 (2021).

Vector DM parameter space

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



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.

SiN membrane detector

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

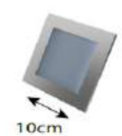
$$\Delta \boldsymbol{a}(t) \approx g_{\text{B-L}} \left[\left(\frac{N_{\text{n}}}{m} \right)_1 - \left(\frac{N_{\text{n}}}{m} \right)_2 \right] \boldsymbol{F}_0 \cos(\omega_{\text{dm}} t)$$

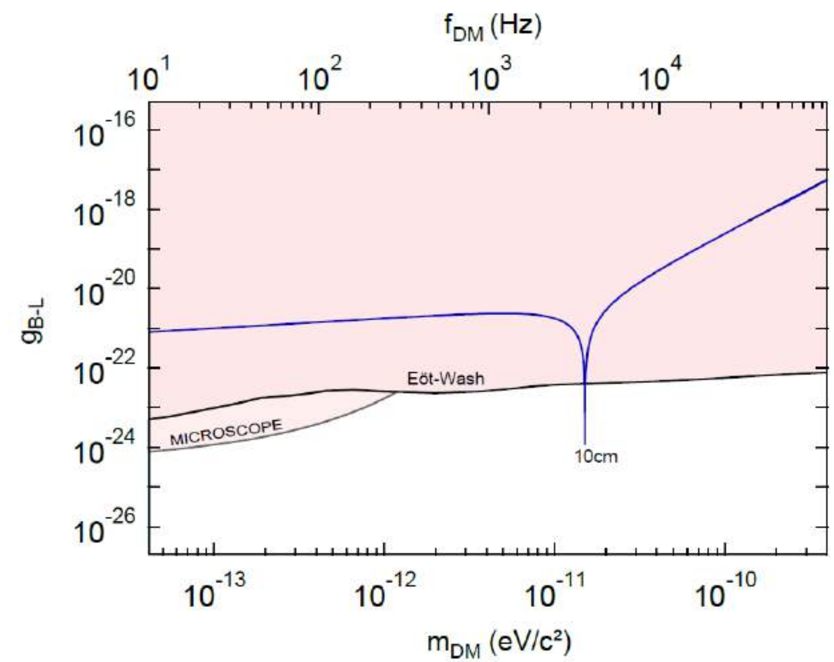
Thermal $\quad S_{aa}^{\text{th}} = \frac{4 k_{\text{B}} T \omega_0}{m Q_0}$.

laser shot

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

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

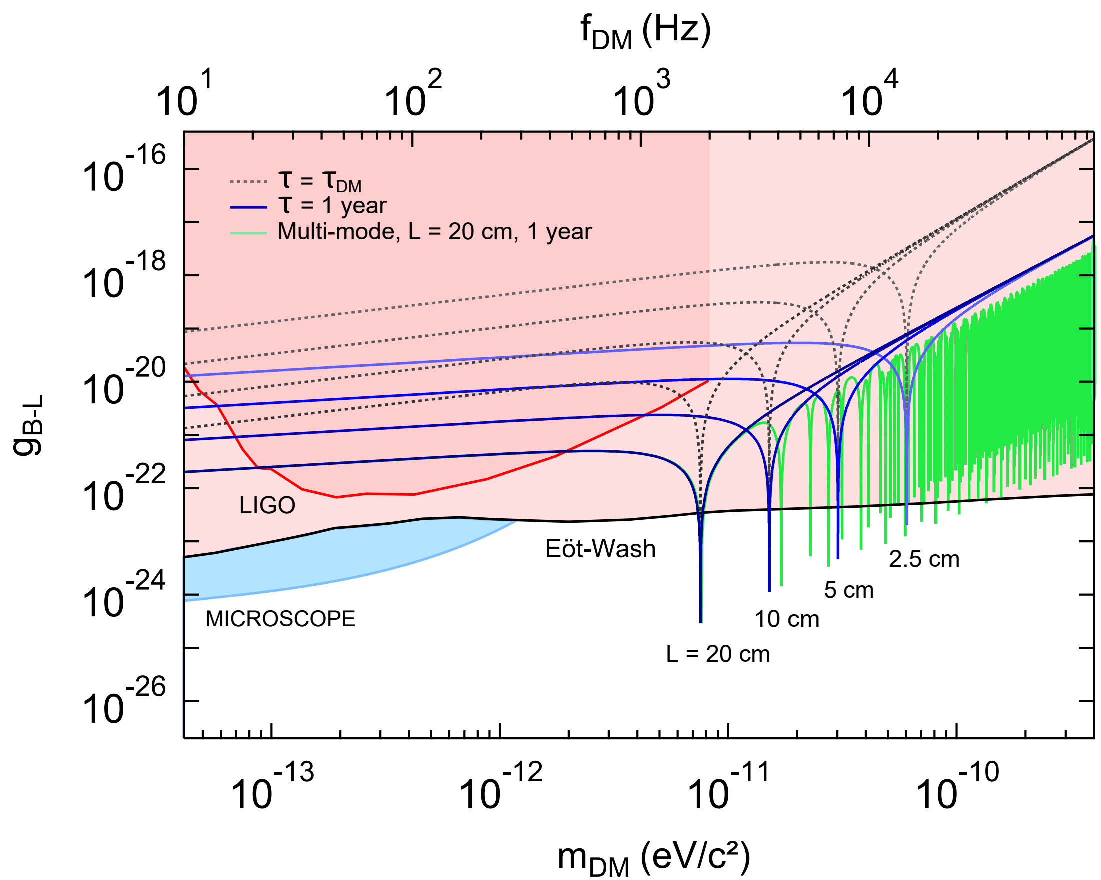


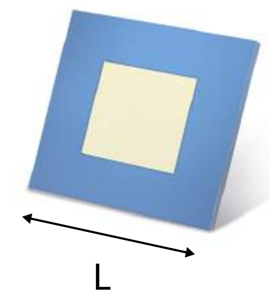


Searching for vector dark matter with an optomechanical accelerometer,
J. Manley, M. D. Choudhary, D. Grin, S. Singh and D. J. Wilson, PRL **126**, 061301 (2021).

Mechanical detectors for vector Dark Matter

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

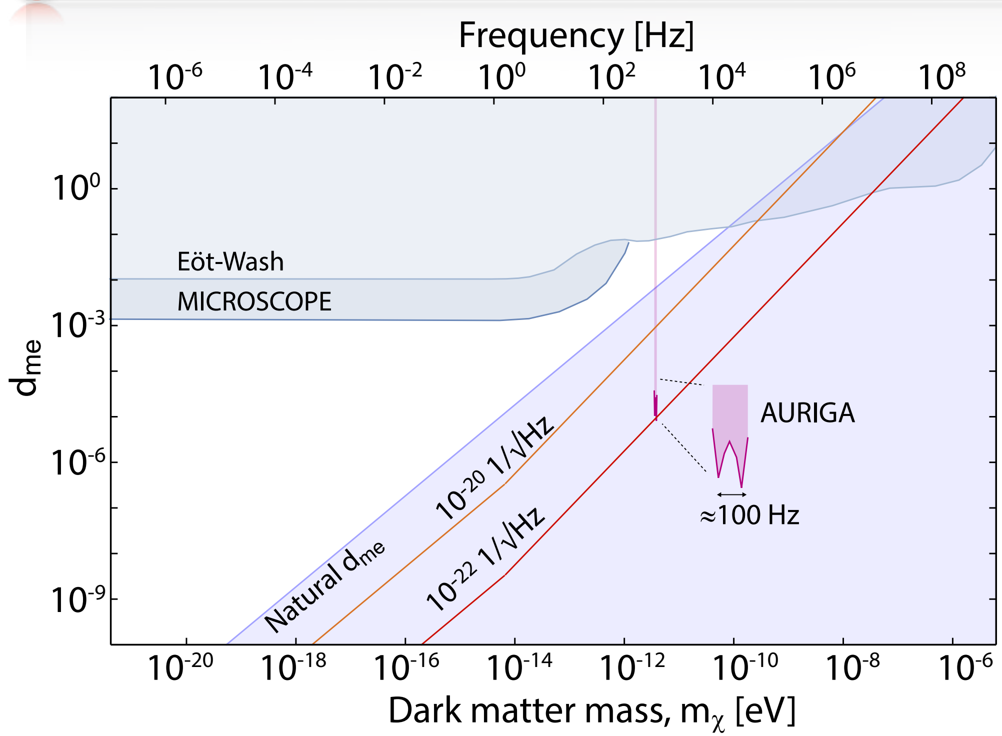




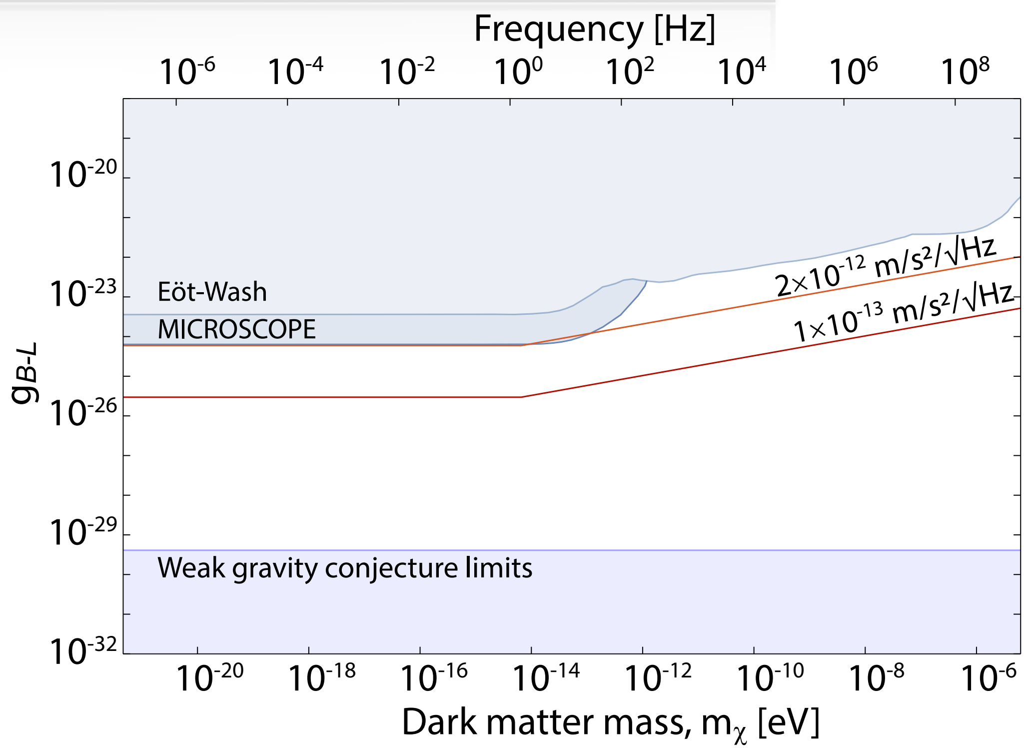
Dalziel Wilson group @ THE UNIVERSITY OF ARIZONA

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).

Mechanical sensing of ultralight dark matter



Scalar ultralight DM



Vector ultralight DM

Mechanical quantum sensing in the search for dark matter, Carney et. al, Quantum Sci. Technol. **6** 024002 (2021) .

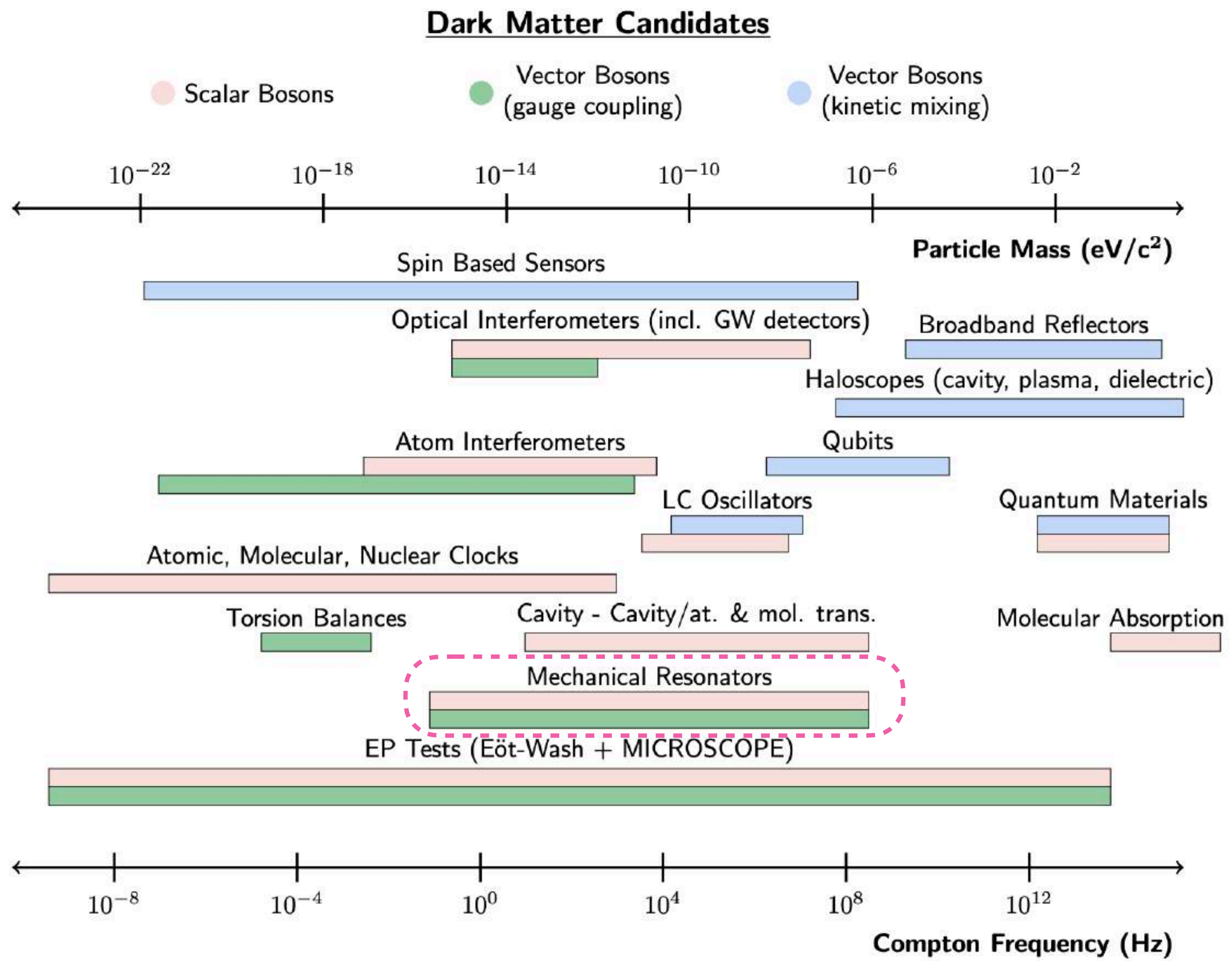
D. Carney

G. Krnjaic

D. Moore

C. Regal

Searches for ultralight DM

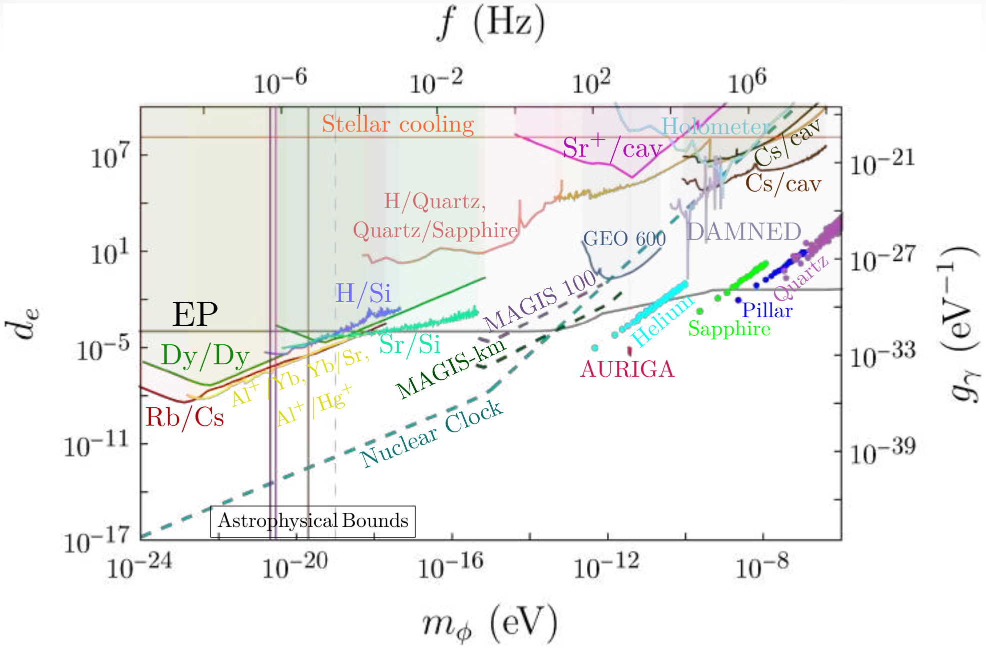


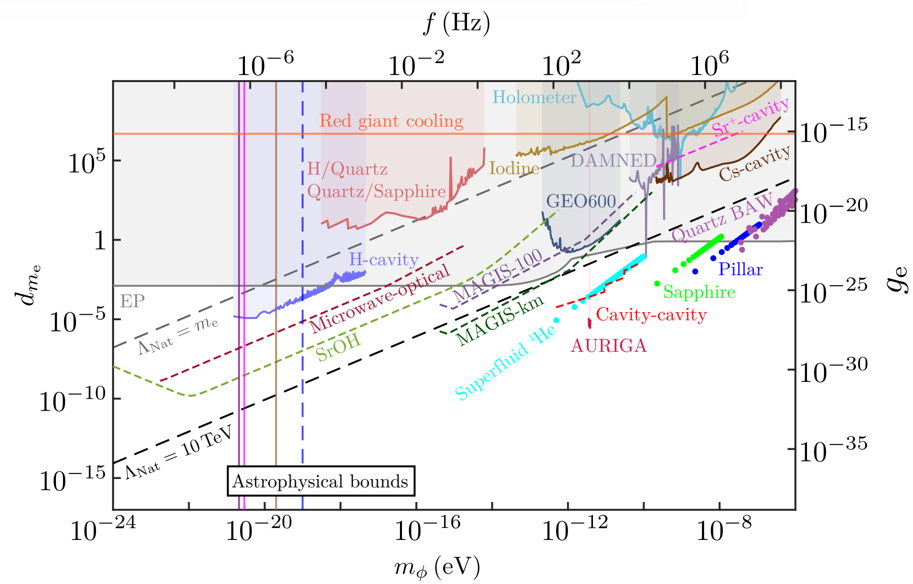
M. Safronova + SS

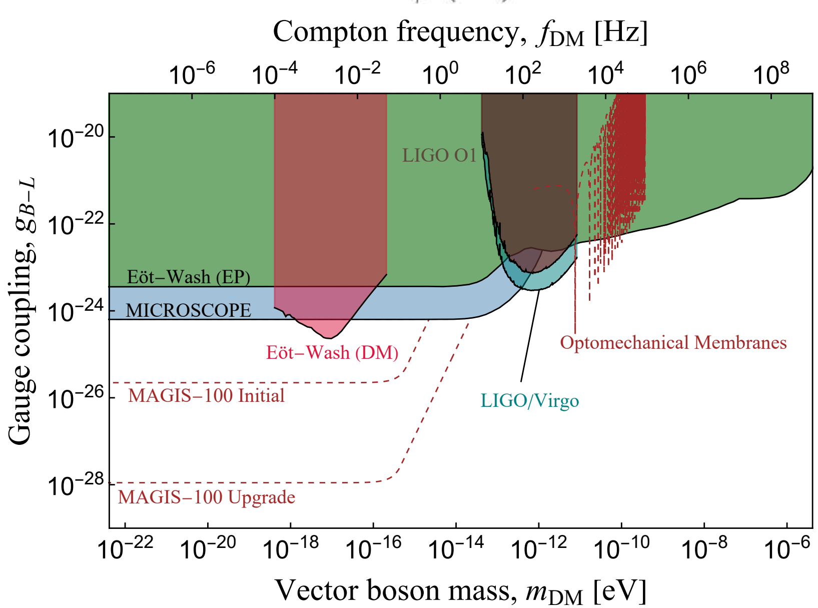
New Horizons: Scalar and Vector ultralight dark matter
Snowmass Proceedings of the US community study on the Future of Particle Physics (arXiv:2203.14915)

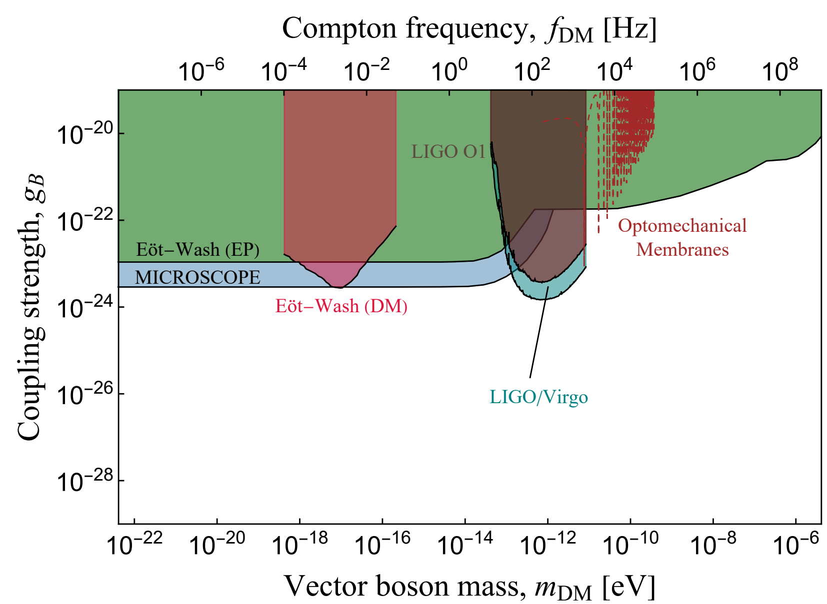
Image: Joey Betz, SS

Ultralight scalar and vector DM constraints



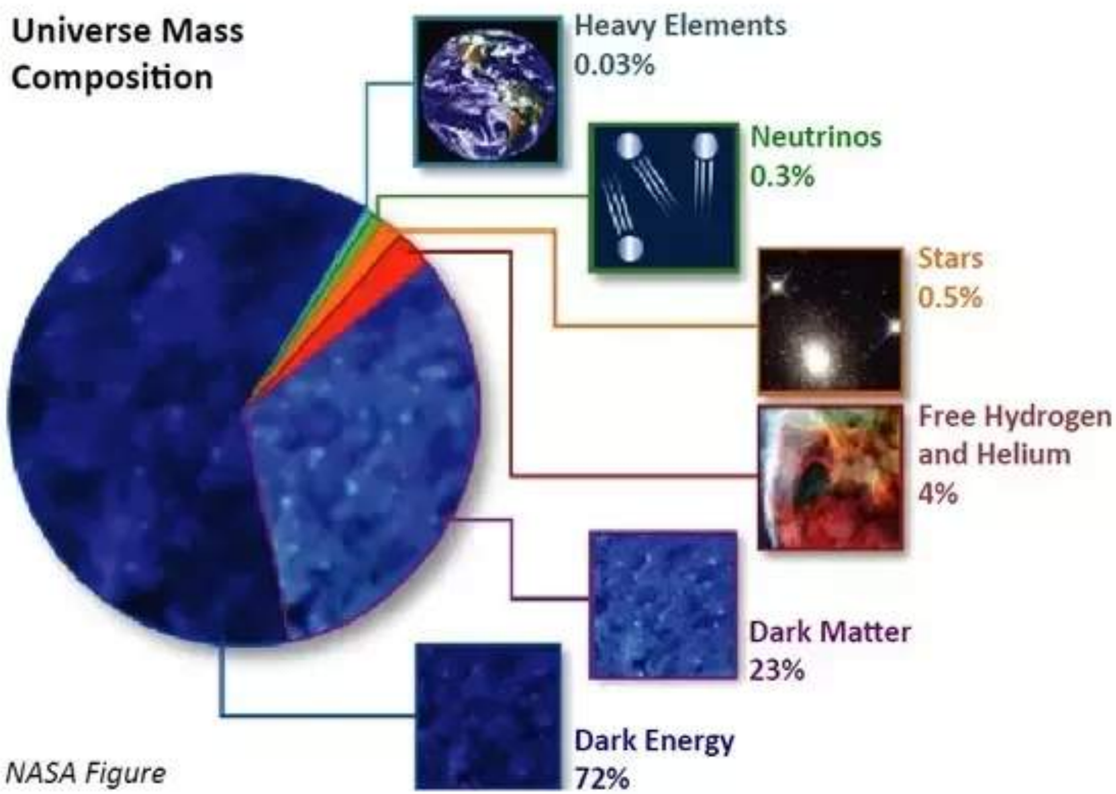






Parameter plots: Abhishek Banerjee, Tejas Deshpande, Sumita Ghosh, Jack Manley, Ciaran, O'Hare

The dark energy problem



- **Scalar dark matter**
  Isotropic strain field
  Displacement signal
- **Vector dark matter**
  Lorentz-like force
  Differential acceleration signal
- **Screened-scalar Dark energy**
  Corrections to Newtonian gravity
  Acceleration signal

The dark energy problem

- 72% of our universe is made of a constant energy density fluid with negative pressure.
- There is ~120 orders of magnitude discrepancy between its observed and calculated value.

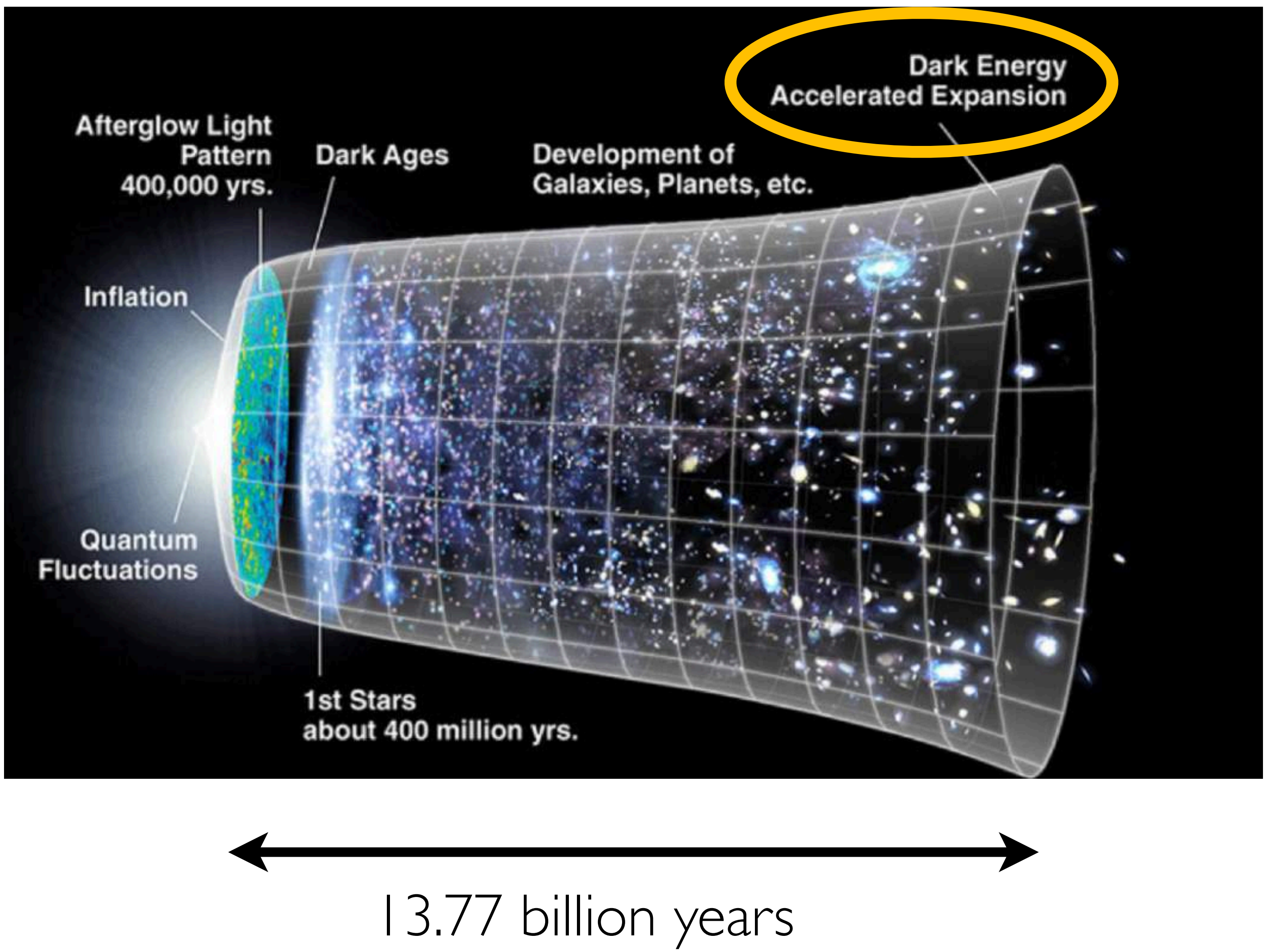
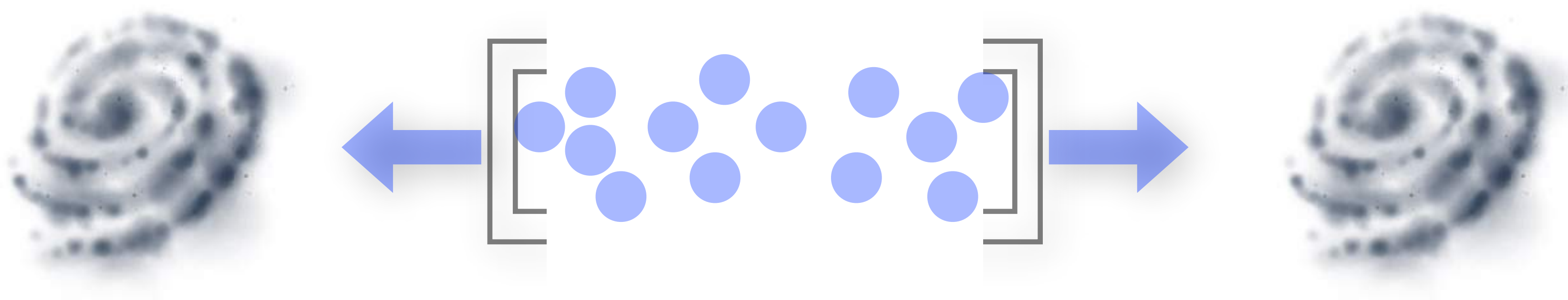


Image: NASA

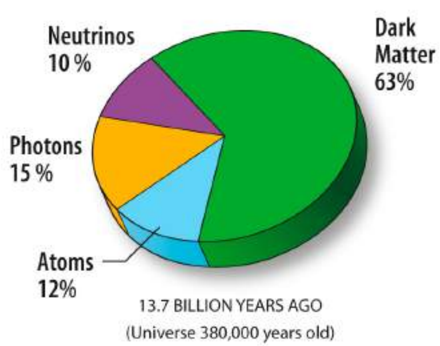
Quintessence fields

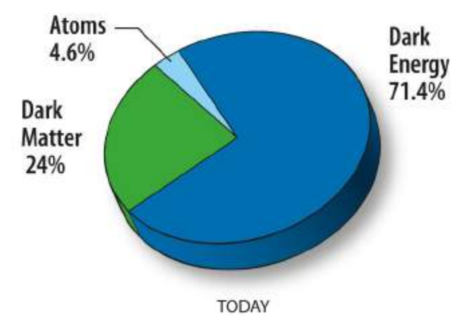
- A self-interacting scalar field is a form of matter that can have negative pressure.



- A quintessence field is characterized by the equation of state:

$$w = \frac{p}{\rho c^2} = \frac{\frac{1}{2}\dot{\phi} - V(\phi)}{\frac{1}{2}\dot{\phi} + V(\phi)} \qquad V(\phi) = \Lambda_{DE}^4 + \frac{\Lambda^{n+4}}{\phi^n}$$





Cosmology, M. Bartelmann
Image: Natalie Schmidt, NASA

Quintessence fields

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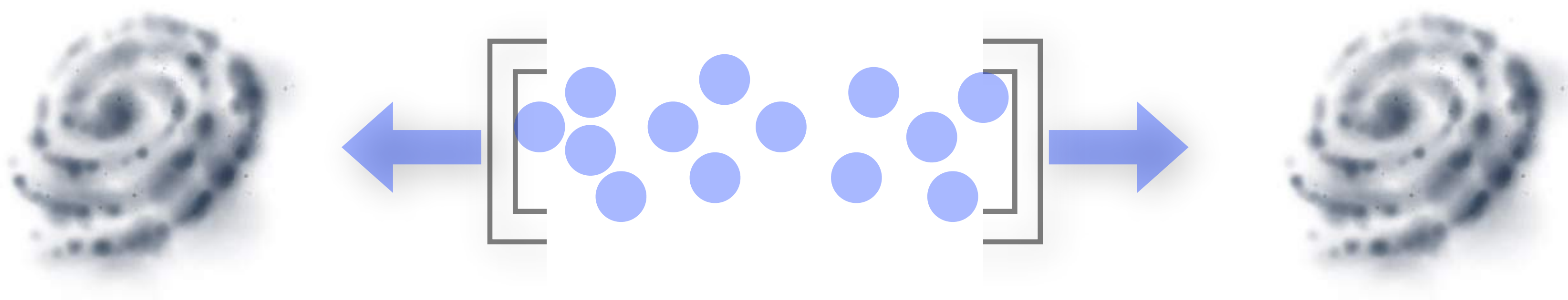

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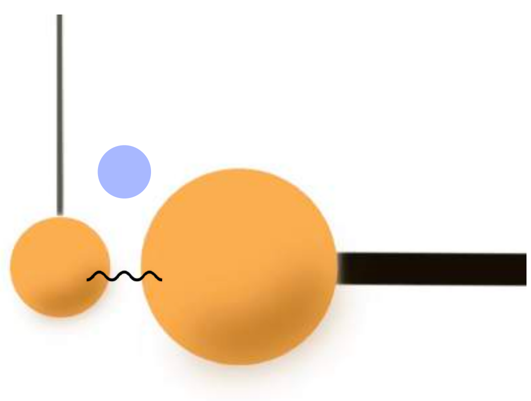
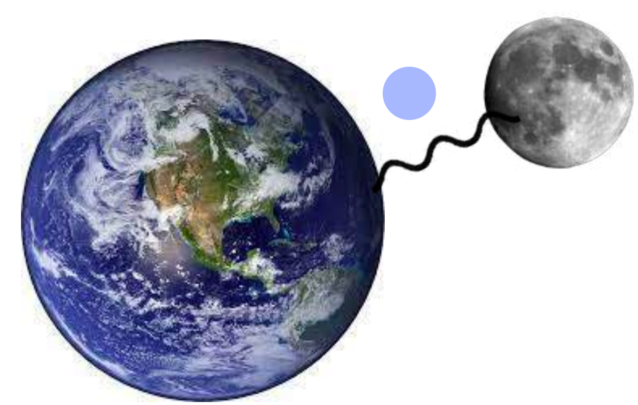


F_5

A fifth force!



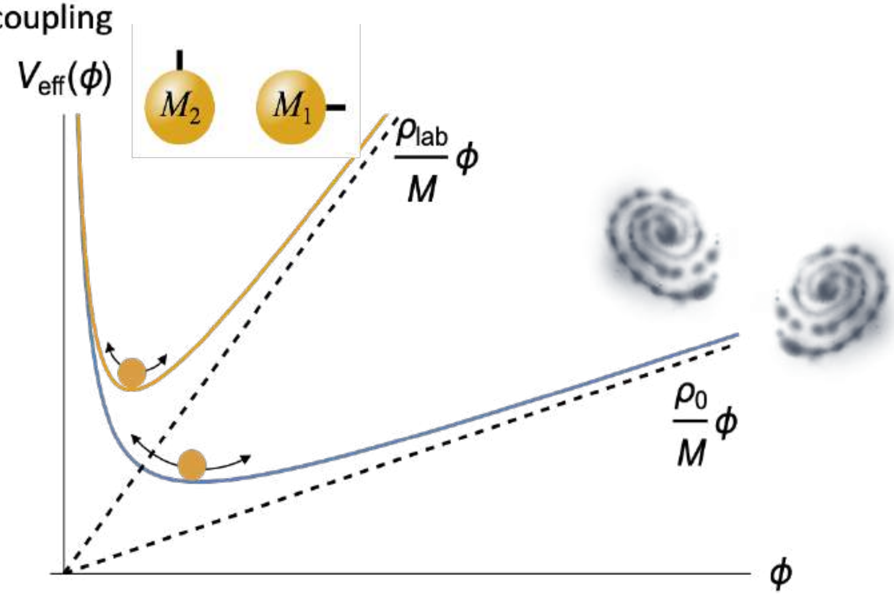
Cosmology, M. Bartelmann

Screened scalar fields: Chameleons

self coupling power law index

Effective potential: $V_{eff}(\phi) \approx \Lambda^4 \left(\frac{\Lambda}{\phi}\right)^n + \frac{\rho}{M}\phi$

matter coupling



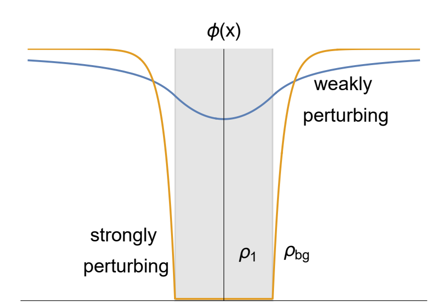
Equation of motion for the scalar field:

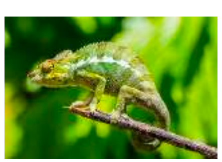
$$\nabla^2\phi = -\frac{\Lambda^{4+n}}{\phi^{n+1}} + \frac{\rho}{M}$$

Λ - self coupling

n - Power-law index

M - chameleon-matter coupling

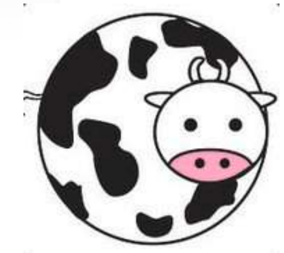


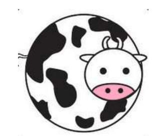


Tests of chameleon gravity, C. Burrage and J Sakstein, Living reviews in relativity **21**,1-58 (2018).

Chameleons: spherically symmetric solution

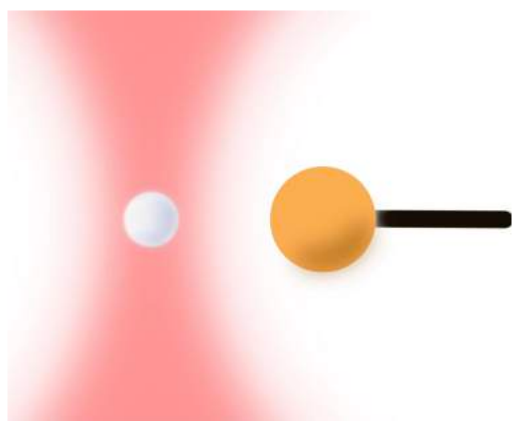
$$F_{\rm cham}(x) \approx 2\,\alpha \frac{G M_1 M_2}{x^2} \lambda_1 \lambda_2 \left(\frac{M_{\rm p}}{M}\right)^2$$



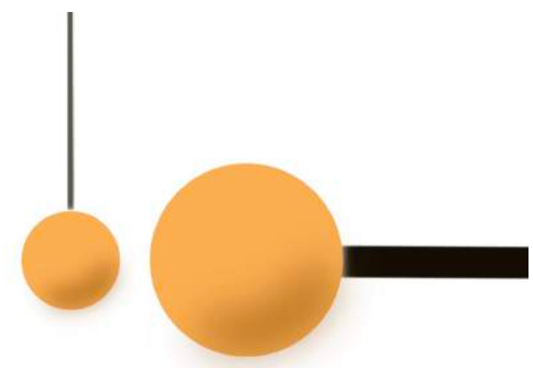


Screening parameters
(depends on density, size,
background vacuum)

Joey Betz



Levitated microspheres

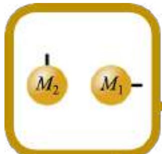


Torsion balance

Searching for chameleon dark energy with mechanical systems,
J. Betz, J. Manley, E. M. Wright, D. Grin, and S. Singh, arXiv:2201:12372 [astro-ph.CO] (2022).

Constraints on Matter coupling

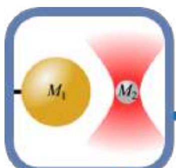
$$V(\phi) = \Lambda_{DE}^4 + \frac{\Lambda^{n+4}}{\phi^n} + \rho\frac{\phi}{M}$$



$R_1 \sim 10^{-4} m$

$R_2 \sim 10^{-4} m$

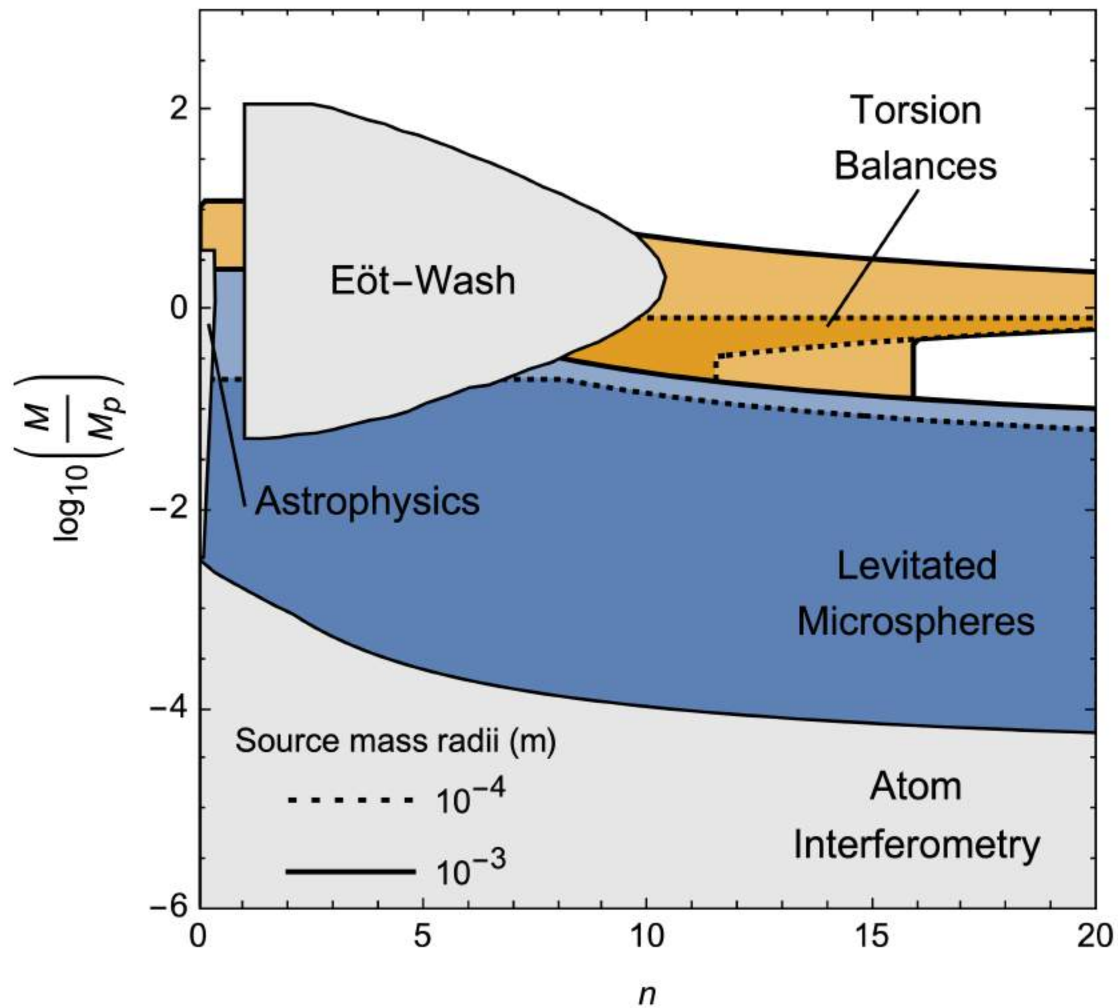
$F_{min} \approx 10^{-18}$N



$R_1 \sim 10^{-4} m$

$R_2 \sim 10^{-6} m$

$F_{min} \approx 10^{-21}$N



Probe unconstrained regions of matter- Chameleon field coupling using experiments operated at demonstrated sensitivities!

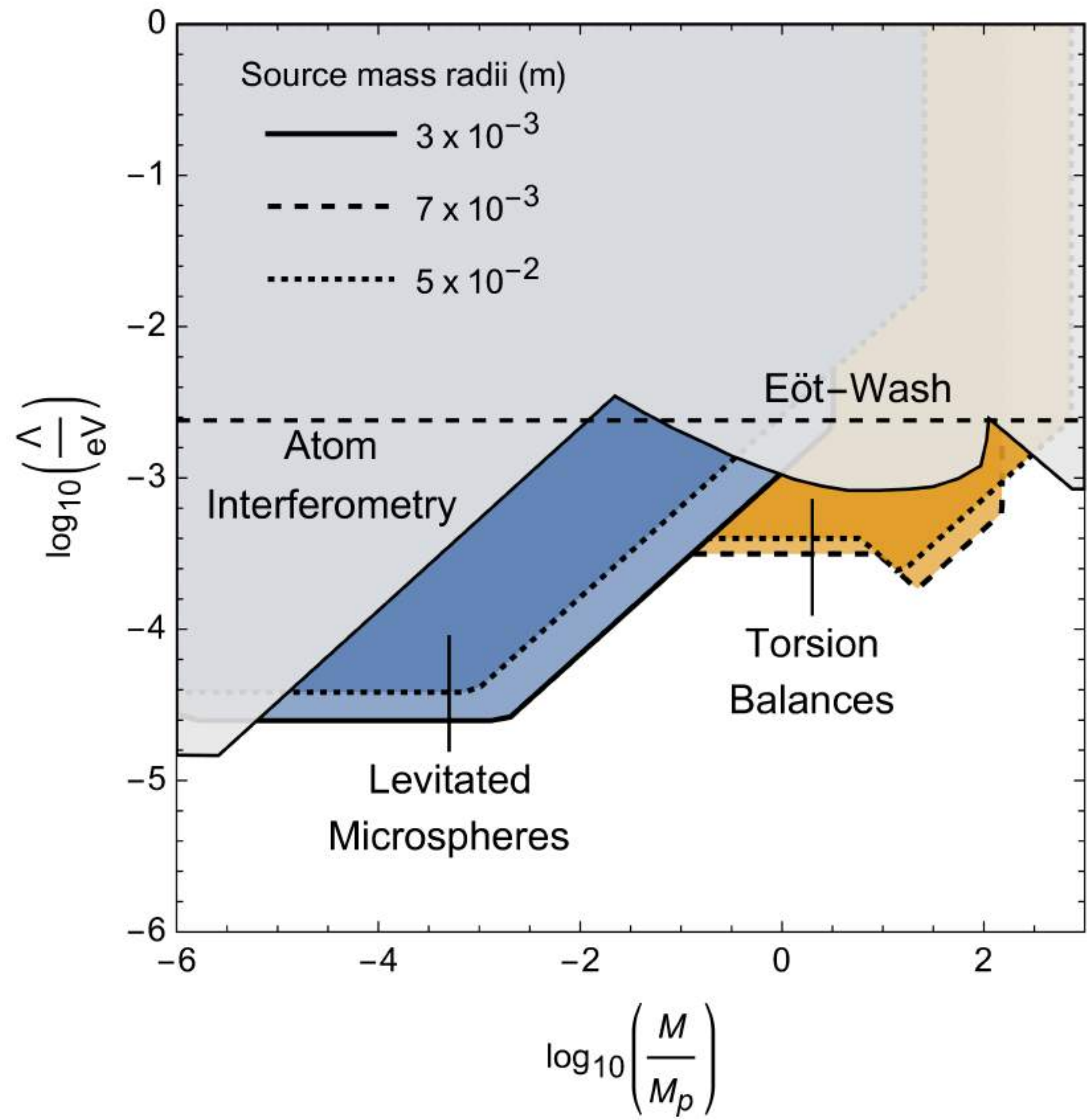
Searching for chameleon dark energy with mechanical systems,
J. Betz, J. Manley, E. M. Wright, D. Grin, and S. Singh, arXiv:2201:12372 [astro-ph.CO] (2022).

Constraints on Matter coupling

$$V(\phi) = \Lambda_{DE}^4 + \frac{\Lambda^{n+4}}{\phi^n} + \rho\frac{\phi}{M}$$

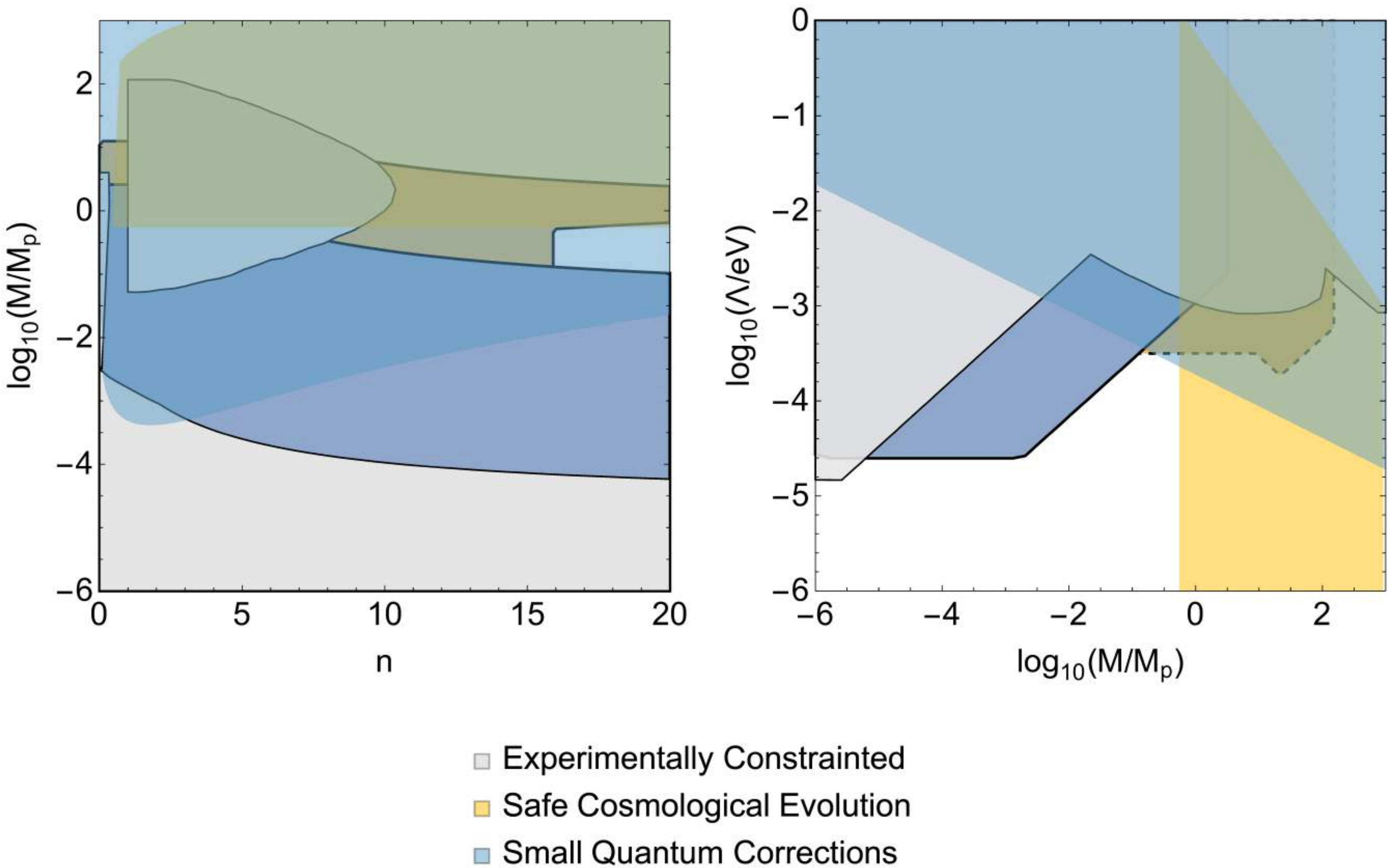
Fix $n = 1$

- Probe weaker coupling using larger masses
- Probe weaker self-interactions using better sensitivities.

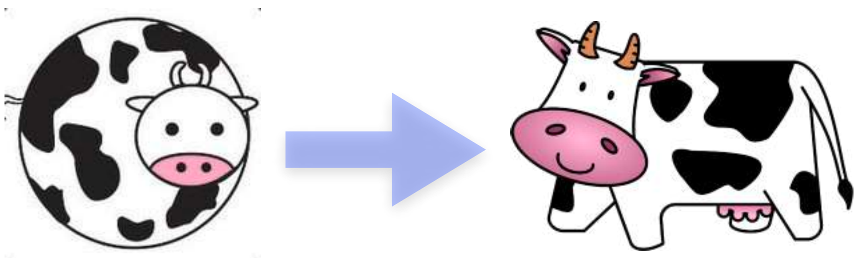


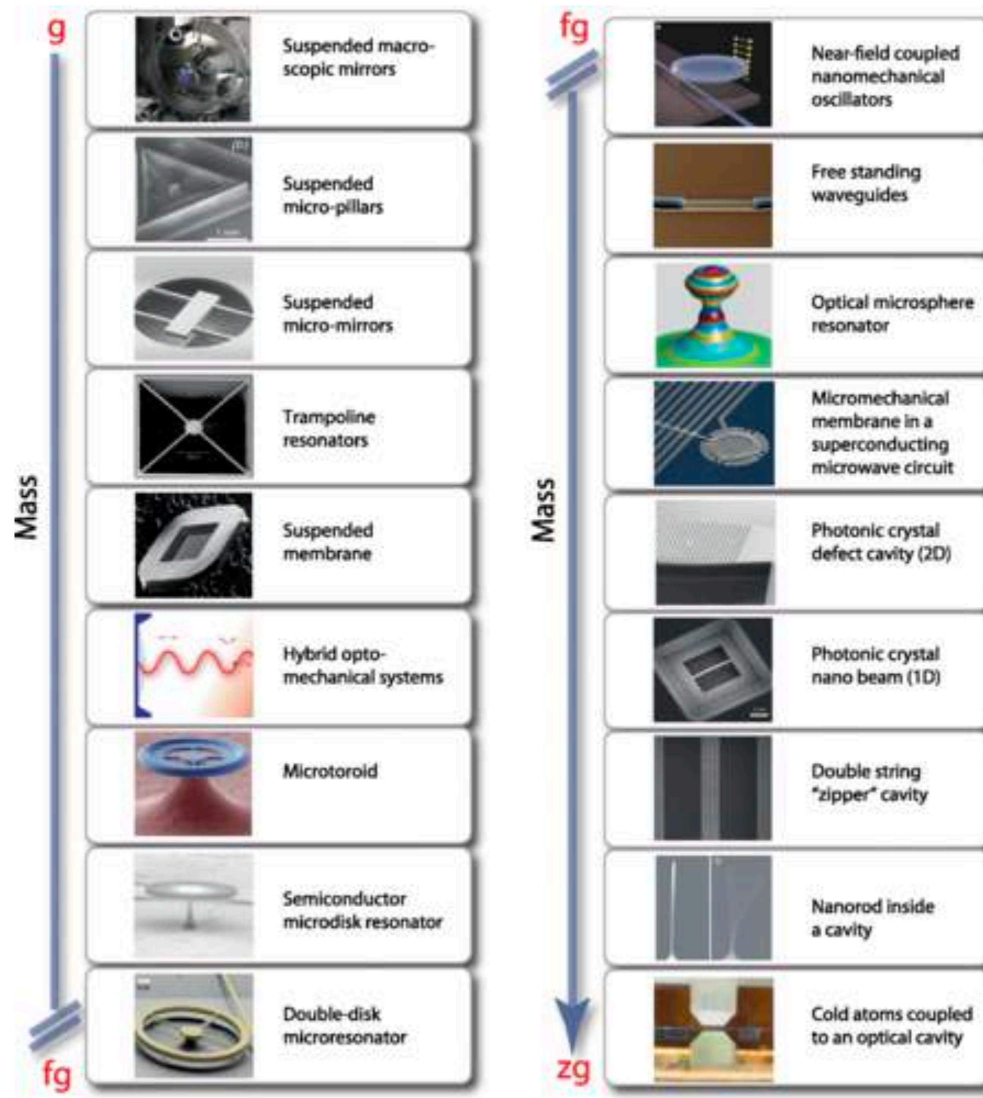
Searching for chameleon dark energy with mechanical systems,
J. Betz, J. Manley, E. M. Wright, D. Grin, and S. Singh, arXiv:2201:12372 [astro-ph.CO] (2022).

Theoretically motivated parameter space



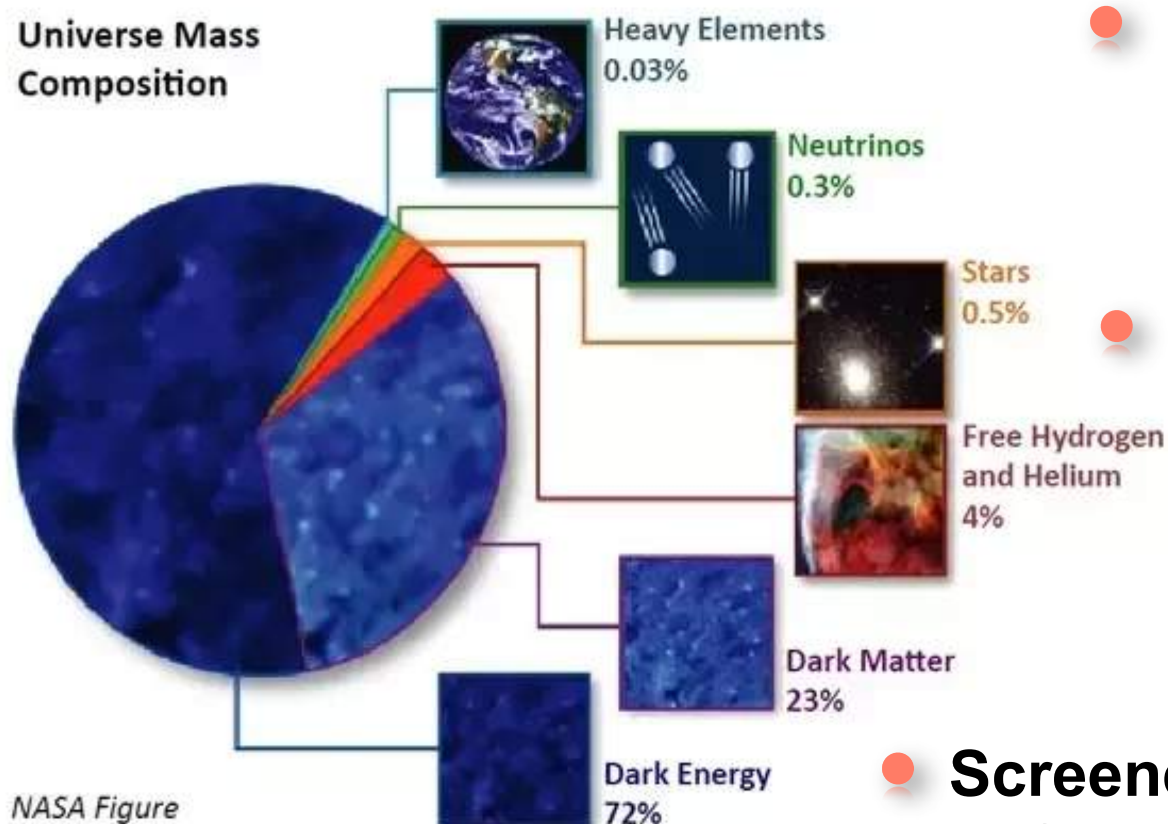
Mechanical systems to probe screened scalars





Due to the wide range of size and geometry of existing devices, mechanical systems are uniquely suited to probe screened-scalar fields

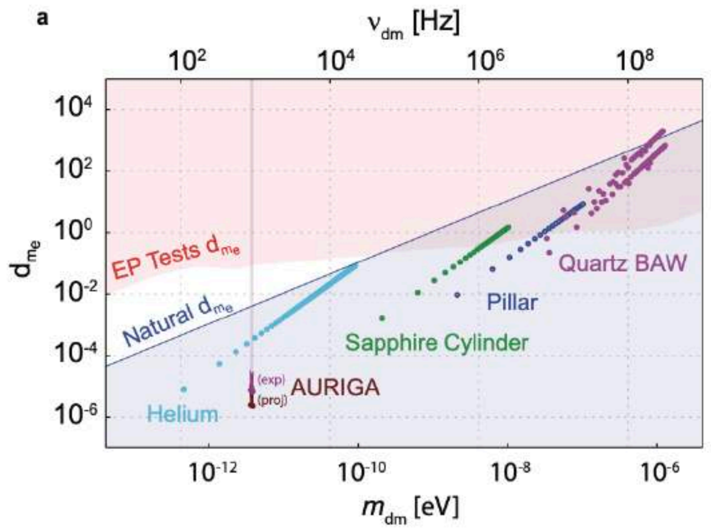
Mechanical signals from the dark sector

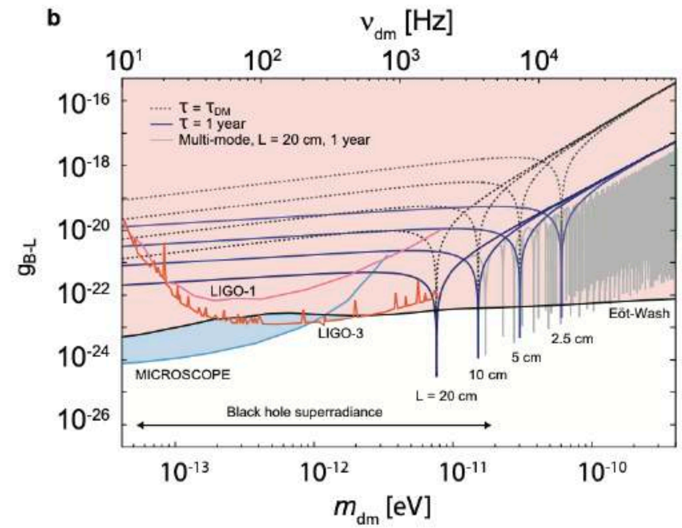


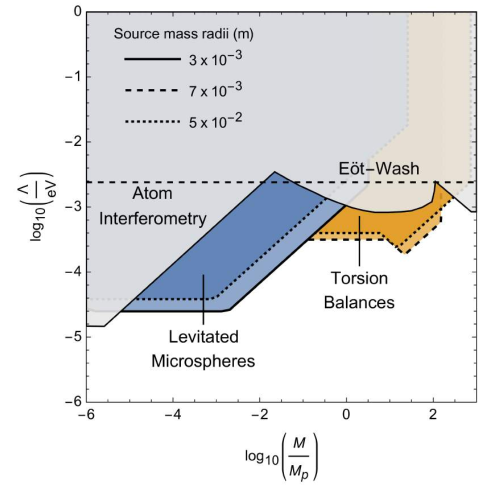
- **Scalar dark matter**
  - Isotropic strain field
  - Displacement signal
- **Vector dark matter**
  - Lorentz-like force
  - Differential acceleration signal
- **Screened-scalar Dark energy**
  - Corrections to Newtonian gravity
  - Acceleration signal

Optomechanical systems can set new bounds on the interaction of these dark sector candidates with normal matter.

Return of the “ether”



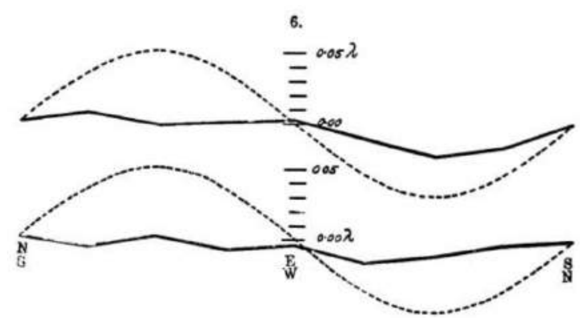


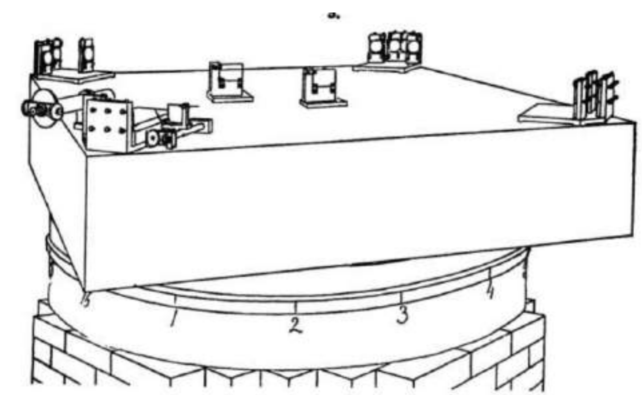


$$d_{m_e} \lesssim 10^{-2}\left(\frac{f}{1\ \text{Hz}}\right)^{1/4} \rightarrow \frac{\delta L}{L_0} \lesssim 10^{-20}\left(\frac{1\ \text{kHz}}{f}\right)^{3/4}$$

$$g_{B-L}a_0 \lesssim 10^{-11}\left(\frac{f}{1\ \text{kHz}}\right)^{1/4}\frac{\text{m}}{\text{s}^2}.$$

Heroic experiments!





On the relative motion of the Earth and the Luminiferous Ether,
A. A. Michelson and E. W. Morley, American Journal of Science 34, 203, 36 (1887).

Constraining these theories would lead to a better understanding of dark matter and dark energy

Acknowledgements

Jack Manley

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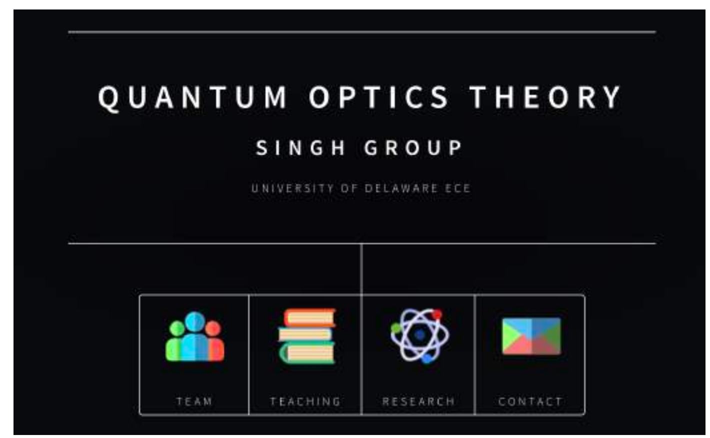
Ryan Petery

Daniel Grin
(Haverford)

Postdoc position open! Please email Swati

Dalziel Wilson (U Arizona)
John Davis (U Alberta)
Ewan Wright (U Arizona)



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

Email: swatis@udel.edu

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

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).

Searching for chameleon dark energy with mechanical systems, J. Betz, J. Manley, E. M. Wright, D. Grin, and S. Singh, arXiv:2201:12372 [astro-ph.CO] (2022).

Funding from: