AMO systems for dark matter detection

- An incomplete but (hopefully) inspirational overview by a quantum optics theorist

Swati Singh
University of Delaware,

Aug 10, 2022

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

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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)

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} *atomic/ spin systems*

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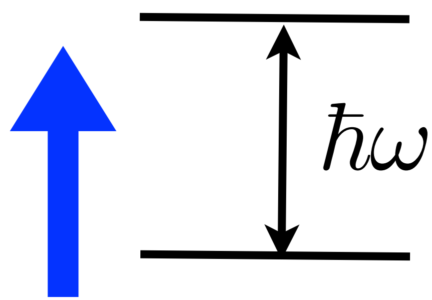
  Nature Nano ***7*** *301 (2012)*

} *harmonic oscillator systems*

Two simple models in AMO physics

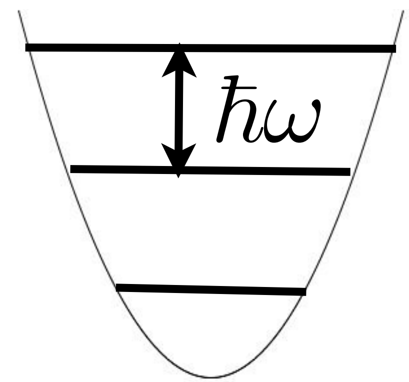
Spin 1/2



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

captures transitions between 2 discrete energy states

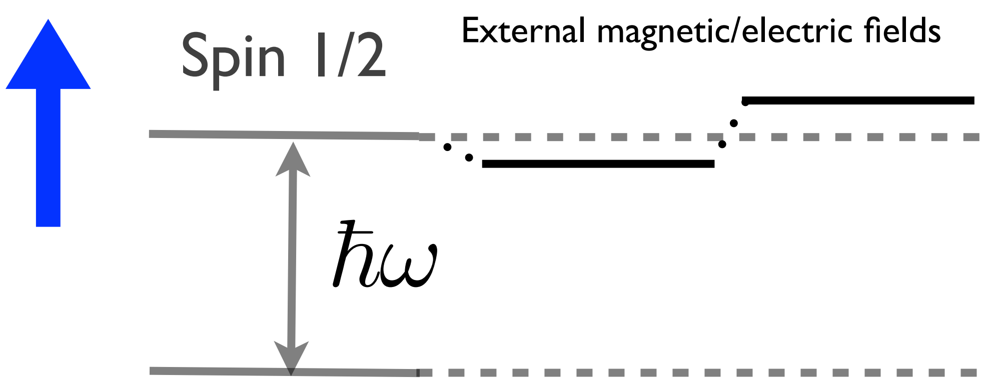
Harmonic Oscillator



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

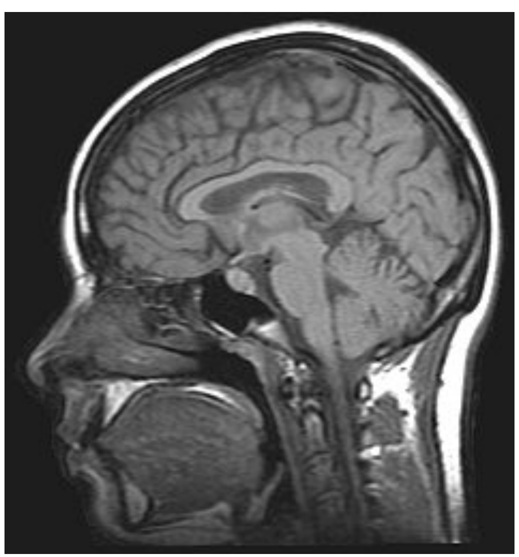
captures small changes around equilibrium

Measuring fields via spin based sensors

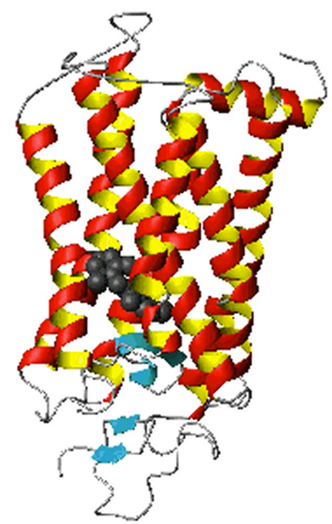


Susceptibility of energy difference to various environmental factors makes spins versatile sensors

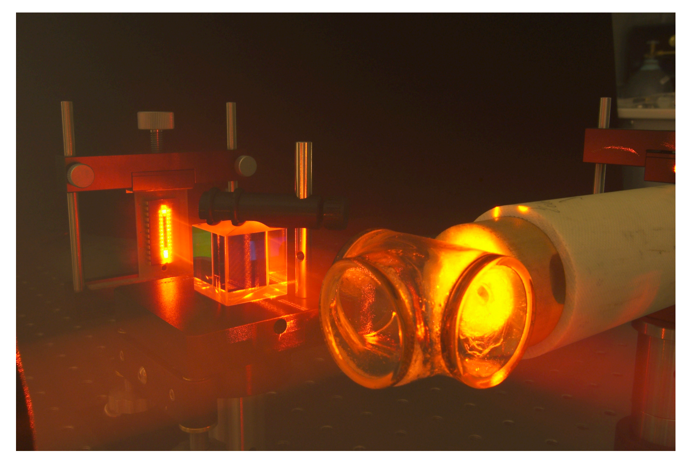
NMR/MRI



Protein Structure



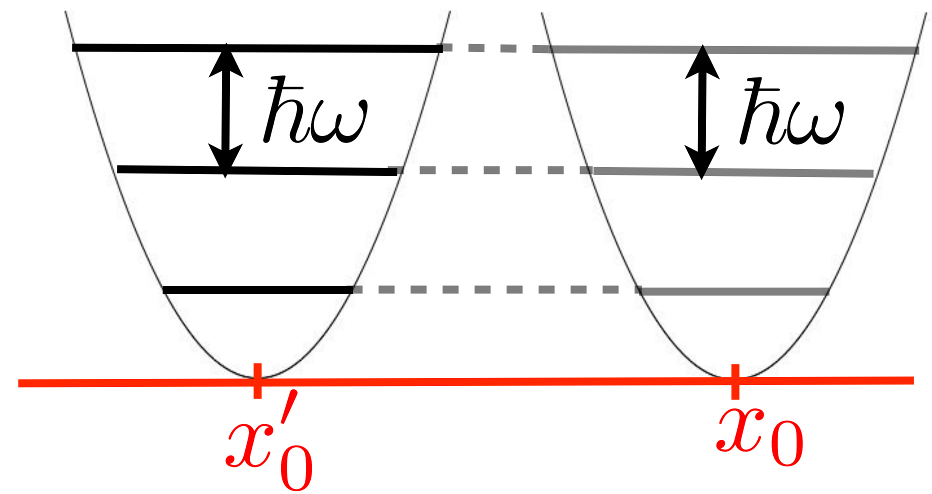
Magnetometers



Measuring weak forces via Harmonic

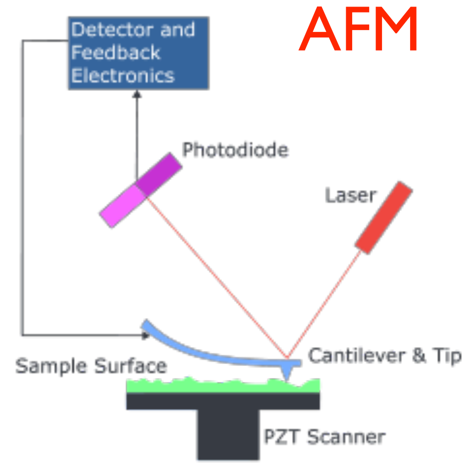
Harmonic Oscillator

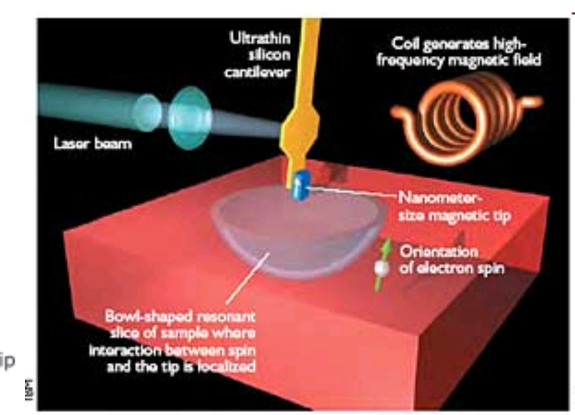
Susceptibility of equilibrium position to various environmental forces make harmonic oscillators versatile sensors



LIGO

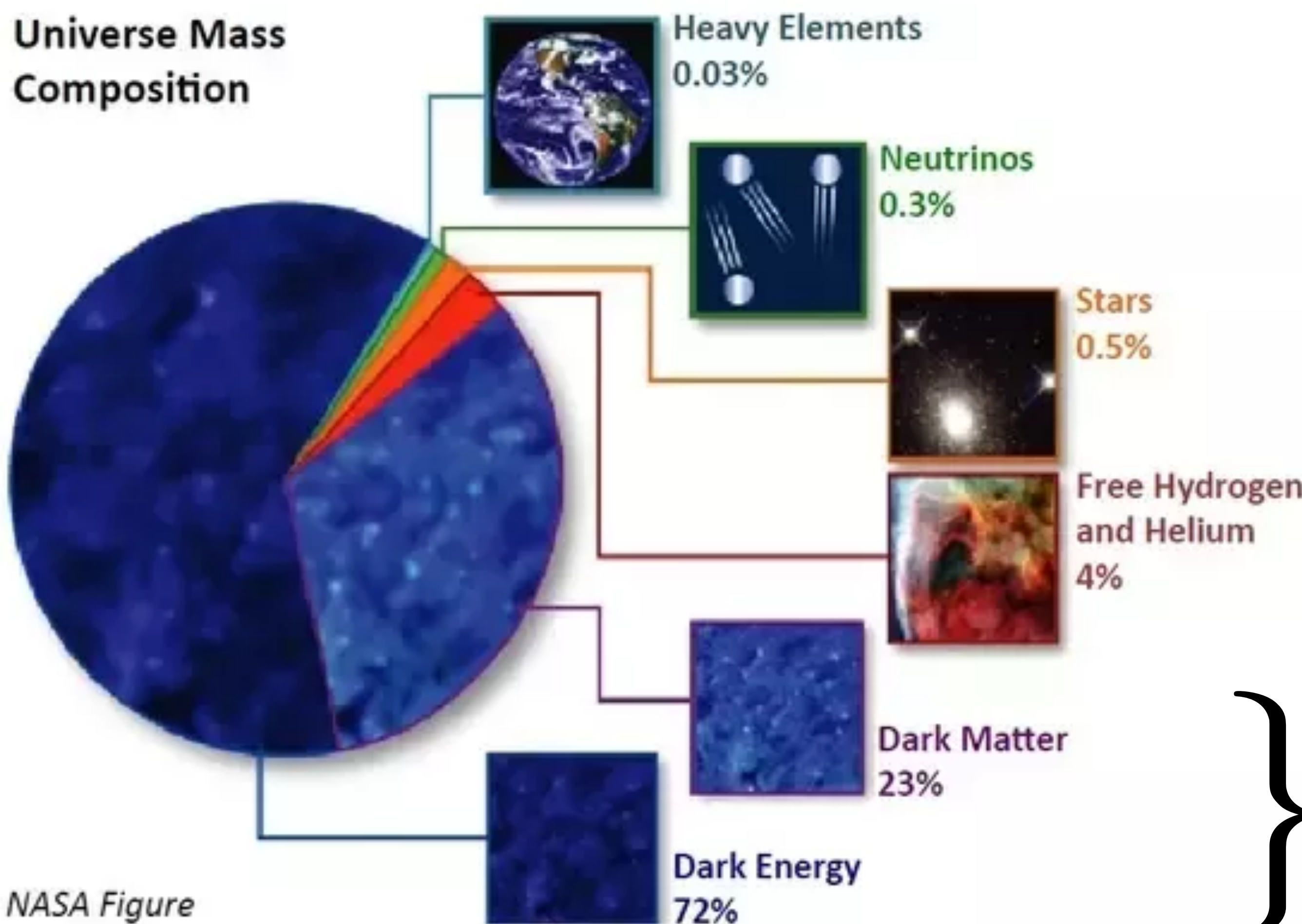
AFM





Single spin detection setup

The dark sector



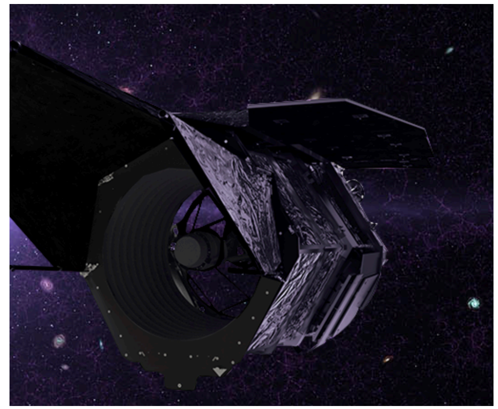
} >95% of our Universe

Image: NASA

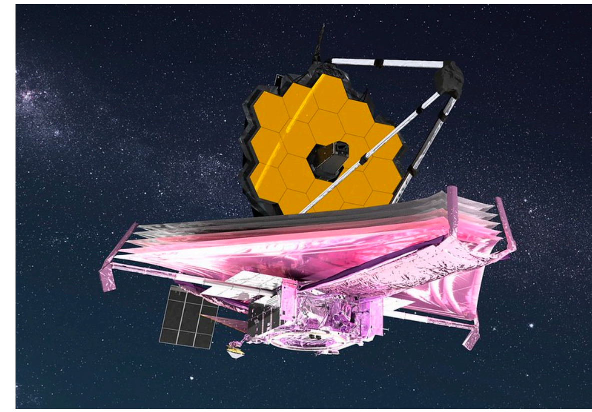
Shedding light on the dark sector

- **Look outside:** better astrophysical surveys

Victor Blanco Telescope

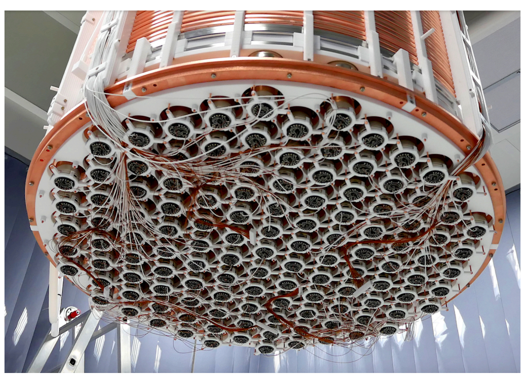


Roman Space Telescope

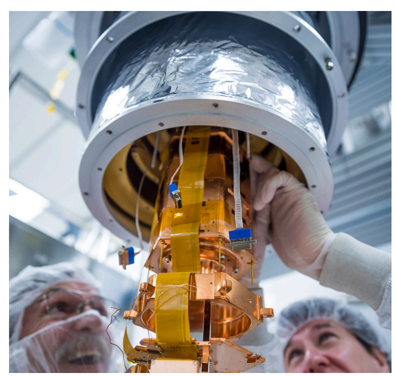


James Webb Telescope

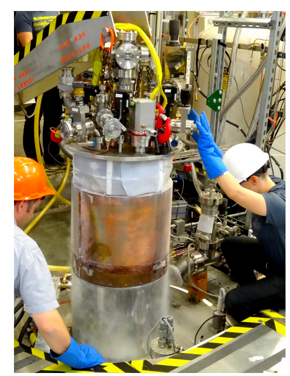
- **Look inside:** direct detection experiments



XENON 1T experiment



Super CDMS



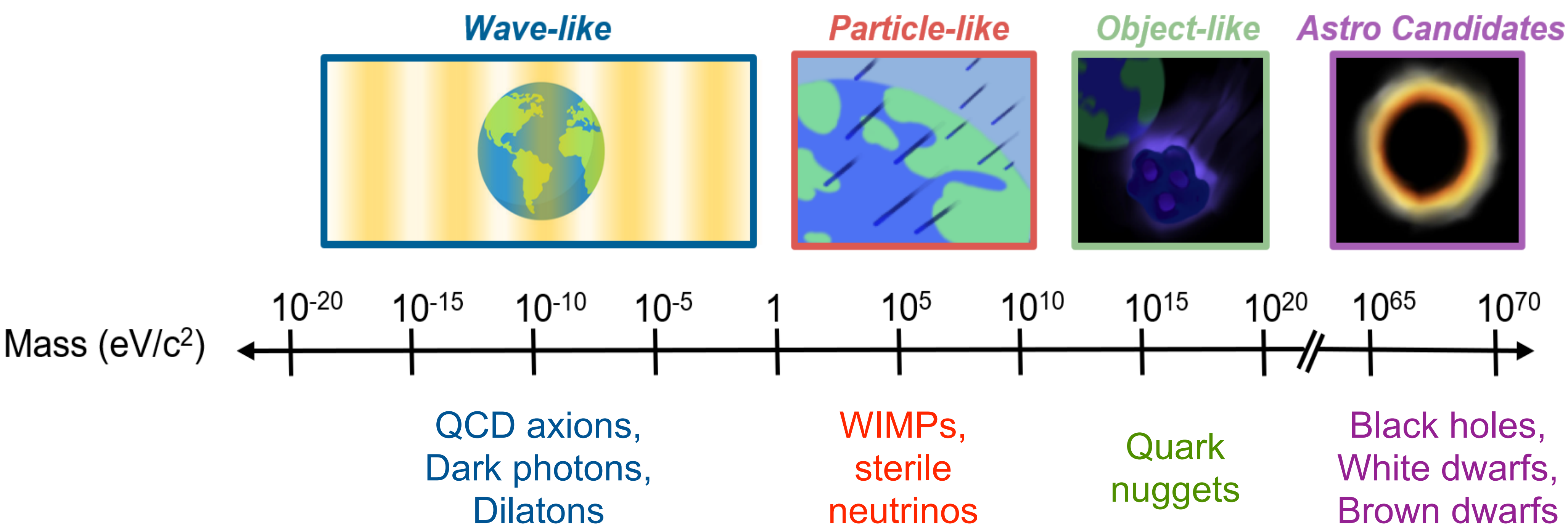
ADMX

Table-top precision measurement experiments

Image: Various websites..

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

How much Dark Matter is around me?

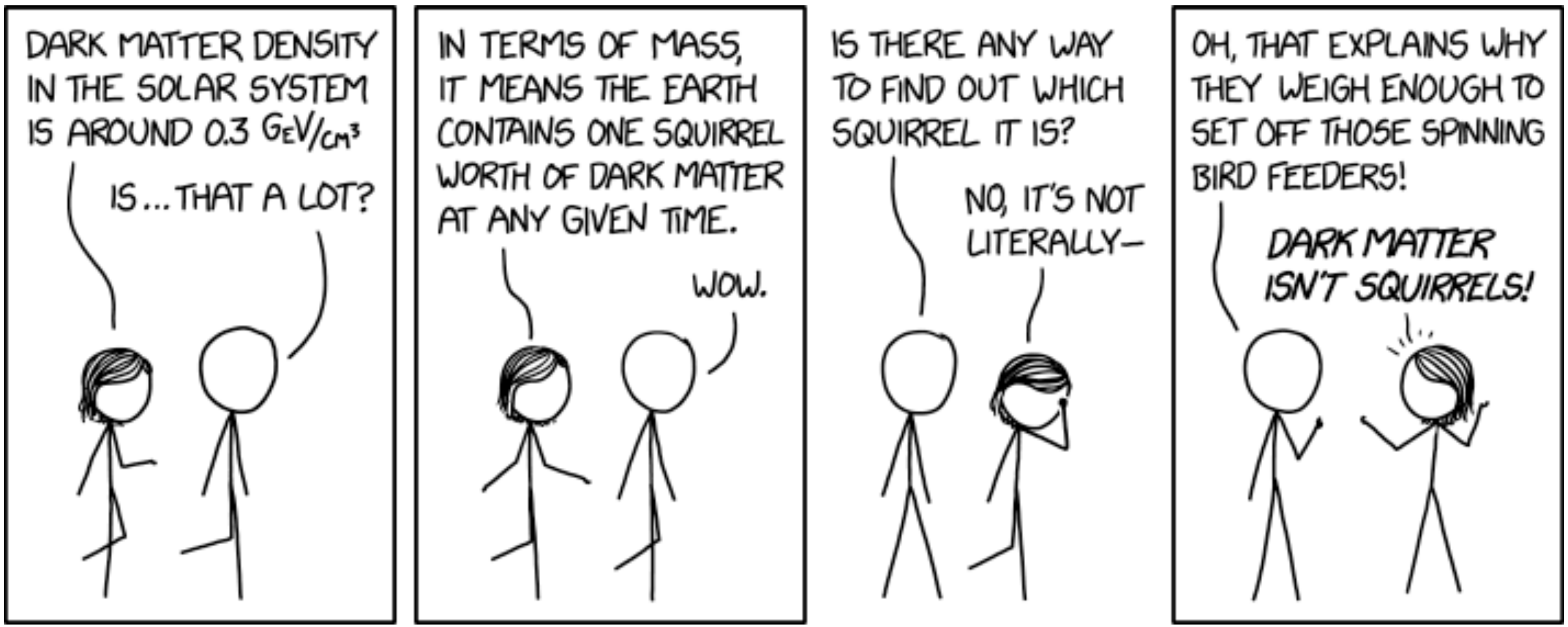


Image: https://xkcd.com/2186/

Dark matter detectors -overview

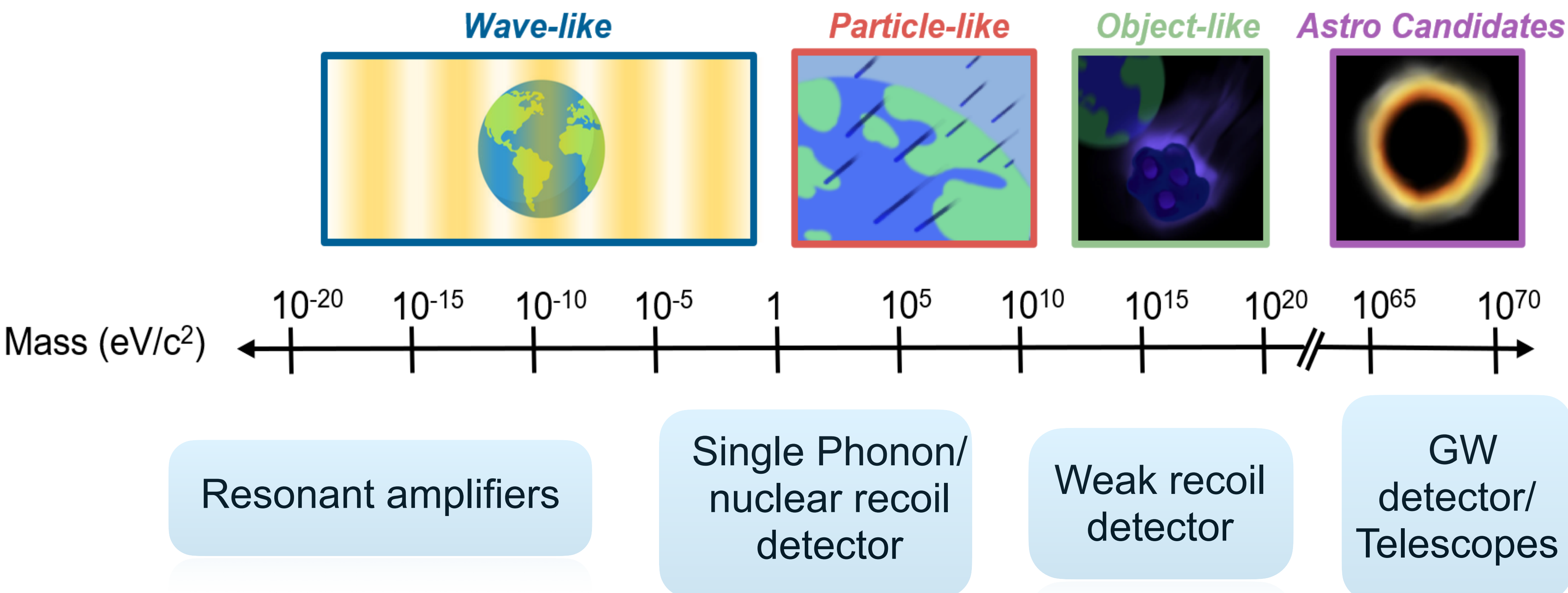


Image: Natalie Schmidt

Ultralight Dark Matter

- For mass <1 eV/c² , 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: $$\phi_0 = \frac{\hbar}{m_\phi c}\sqrt{2\rho_{DM}}$$ $$\rho_{DM} \approx 0.3 \text{ GeV/cm}^3$$

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

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

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

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

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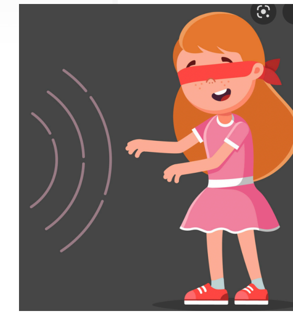
- It's always there!
- The signal oscillates at angular freq. given by DM mass
- Locally coherent over ~10^6 oscillations

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

How to think of “dark photons”

(Kind of works for all ultralight particles)

How do we know (normal) photons exist?



How to think of “dark photons”

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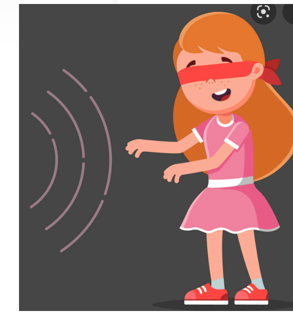

How do we know (normal) photons exist?

- Photons as real particles directly do something measurable

  (e.g. Photoelectric effect)

- Photons as virtual particles mediate electrostatic forces

  (e.g. Coulomb’s law)

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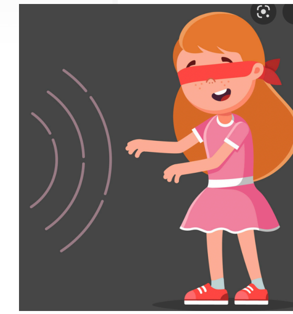

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  Dark photon search example: haloscope experiments

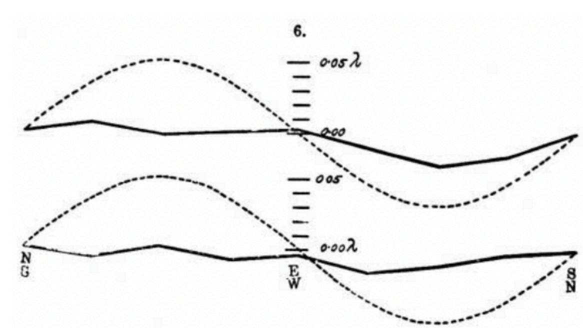
- Photons as virtual particles mediate electrostatic forces

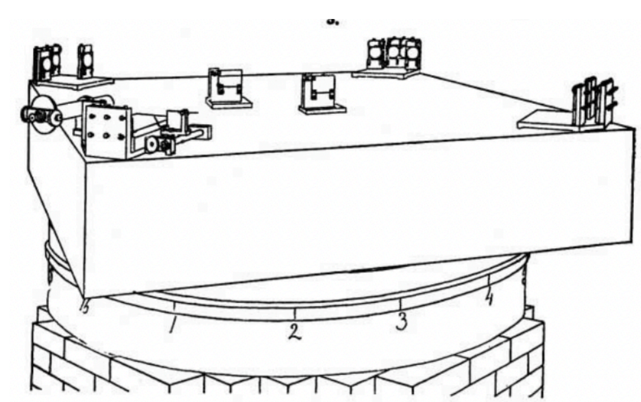
  (e.g. Coulomb’s law)

  Dark photon search example: EP violation experiments

Return of the “ether”

-Differential measurement scheme requirement



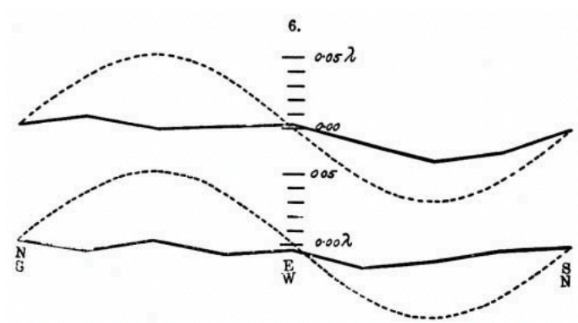


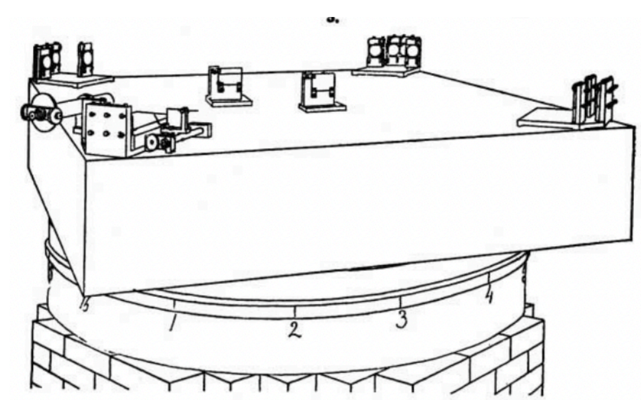
On the relative motion of the Earth and the Luminiferous Ether,
A. A. Michelson and E. W. Morley, American Journal of Science 34, 203, 36 (1887).

Return of the “ether”

-Differential measurement scheme requirement

vs.





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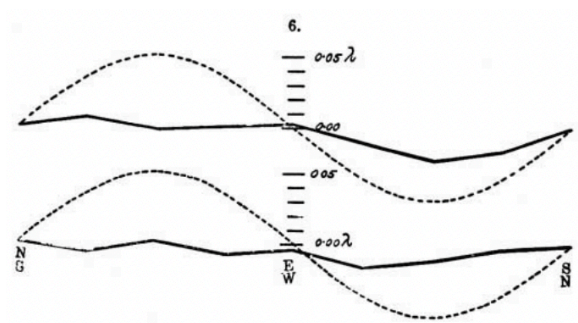
Return of the “ether”

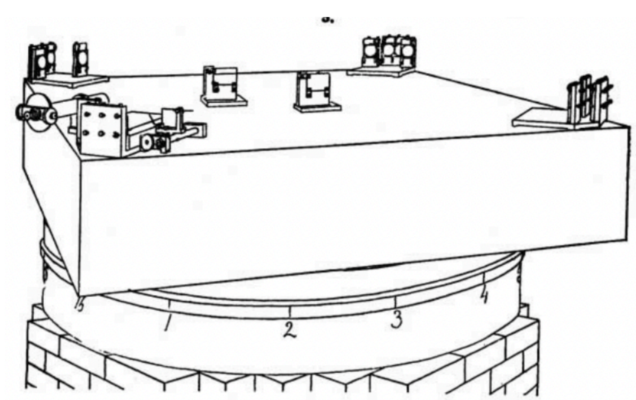
-Differential measurement scheme requirement

vs.

Need a “ruler” that does not interact with dark matter

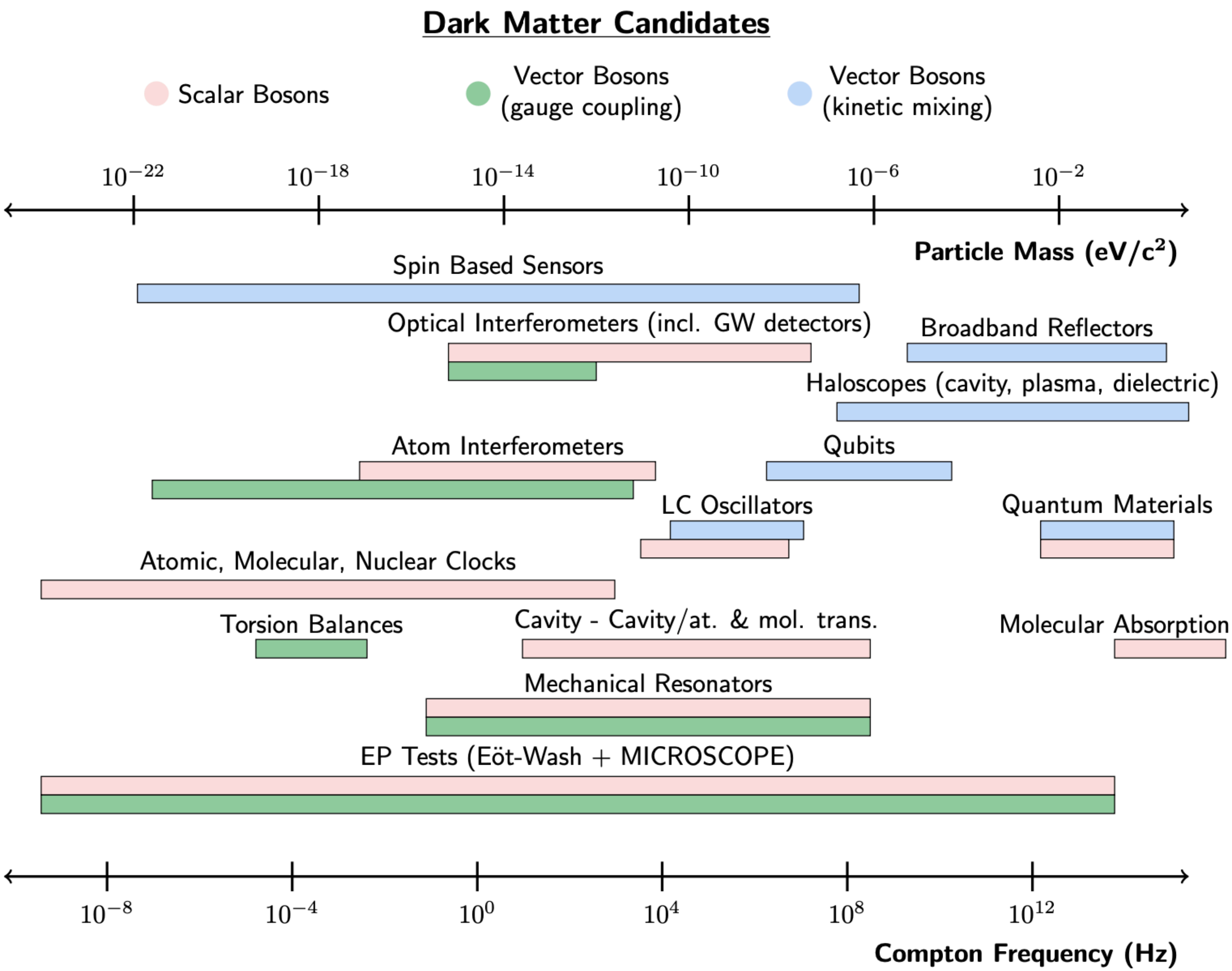
Need a “ruler” that interacts differently with dark matter than you





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).

Searches for ultralight DM

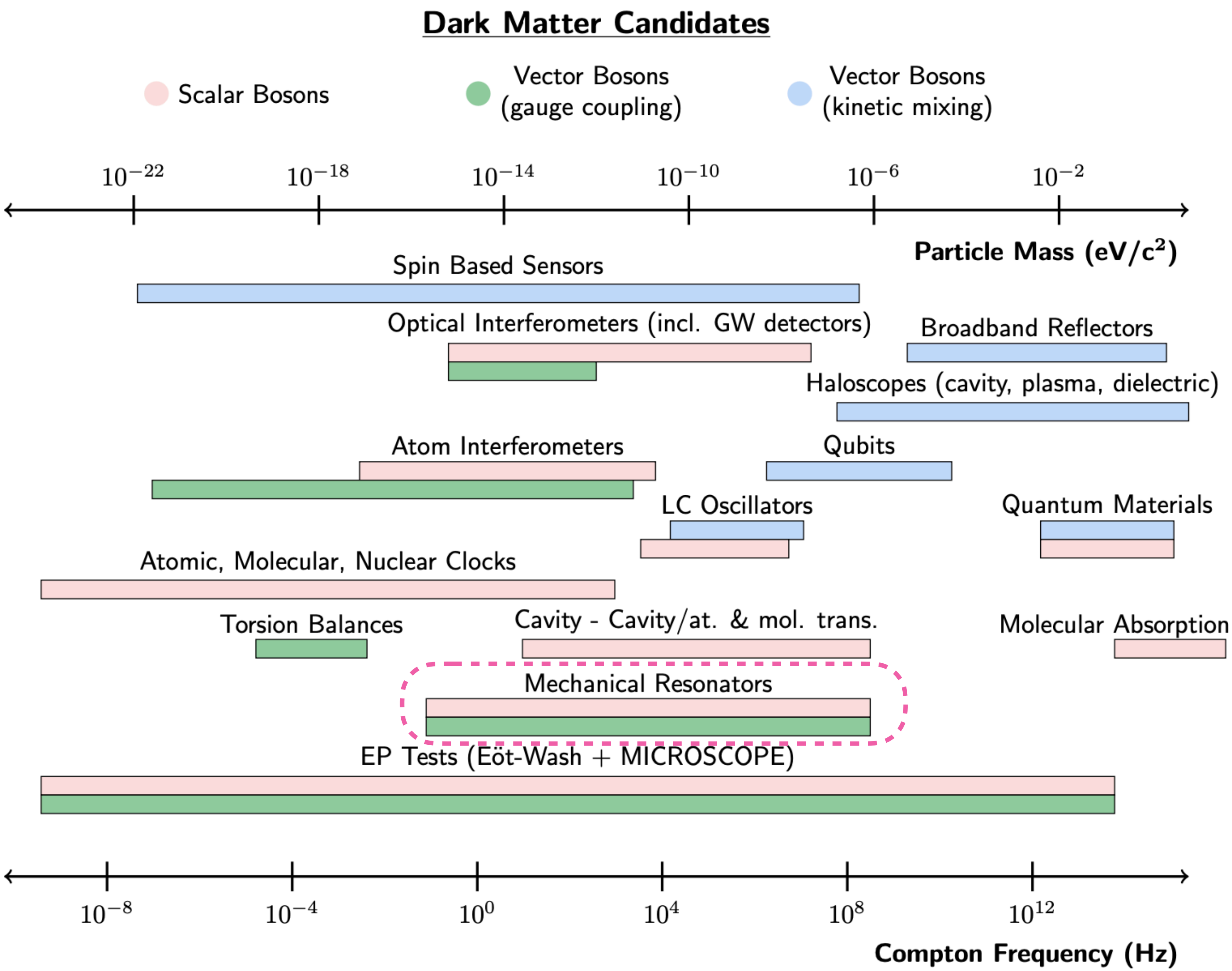


M. Safronova + SS

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

Searches for ultralight DM



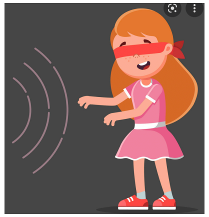
M. Safronova + SS

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

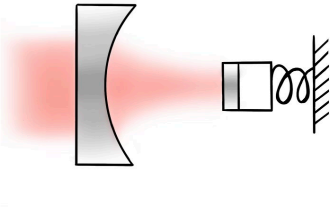
Image: Joey Betz, SS

Overview

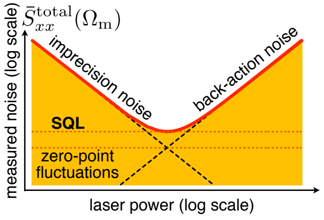
- Overview of ultralight DM detection philosophy



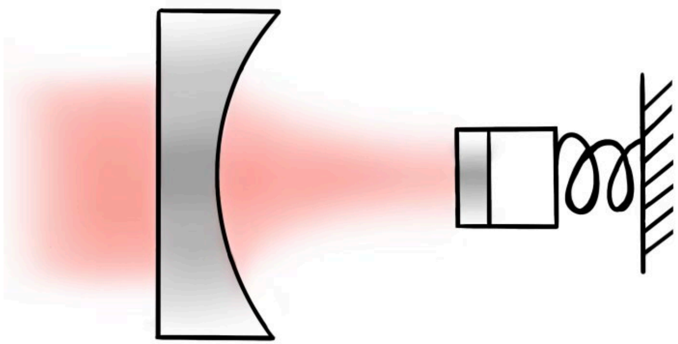
- Overview of mechanical dark matter detectors

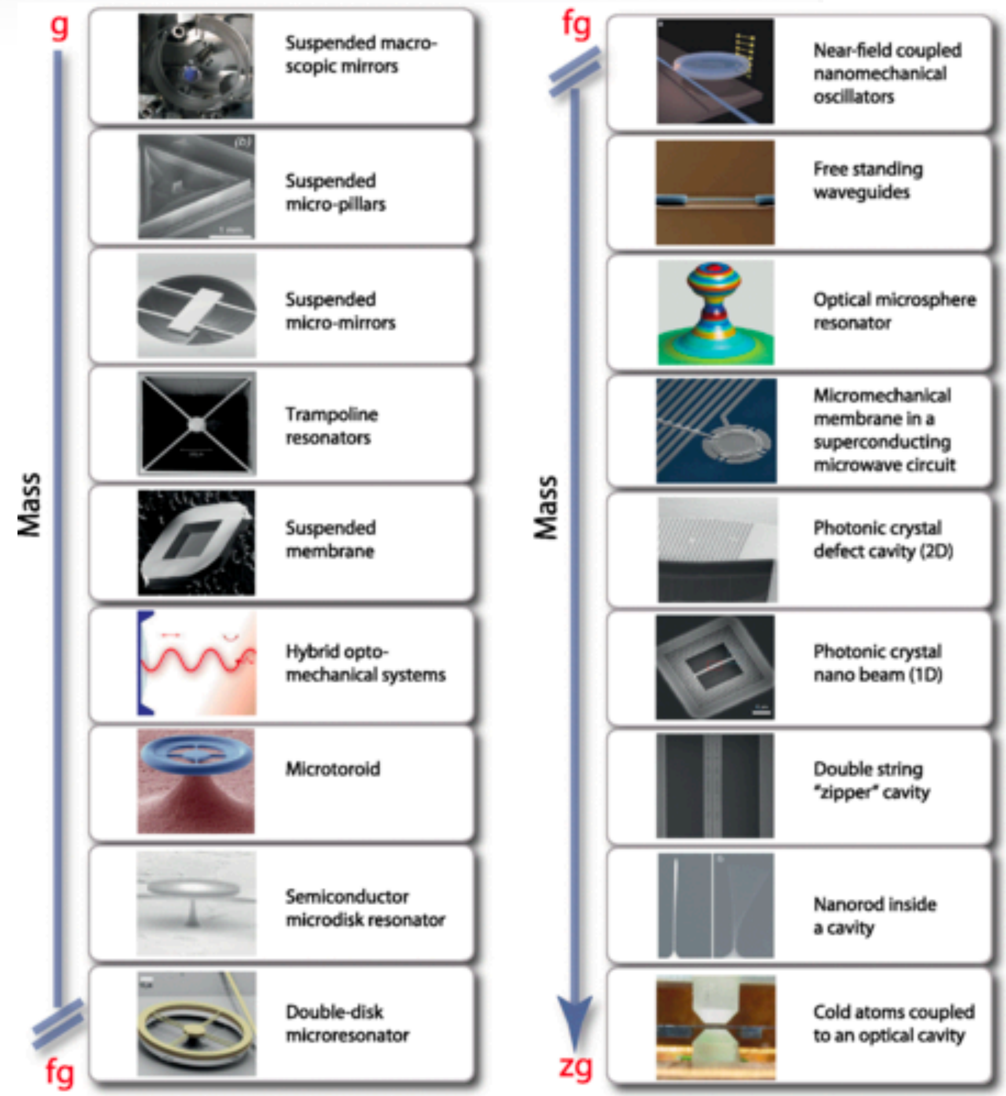


- Overview of quantum optics for dark matter detectors



Cast of characters: harmonic oscillators





State of the art sensitivities[1]

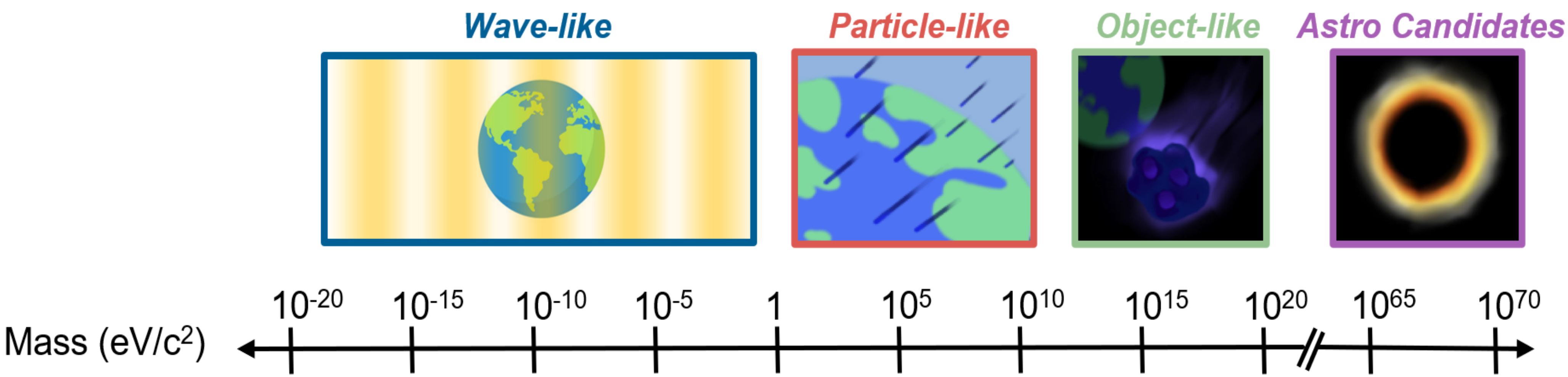
- Force: $10^{-20}\ N/\sqrt{Hz}$
- Acceleration: $10^{-15}\ g/\sqrt{Hz}$
- Strain: $10^{-21}\ /\sqrt{Hz}$

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 dark matter detectors- overview



Resonant amplifier of a continuous signal

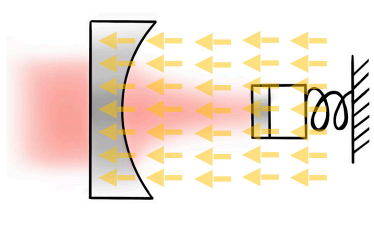


Image: Natalie Schmidt

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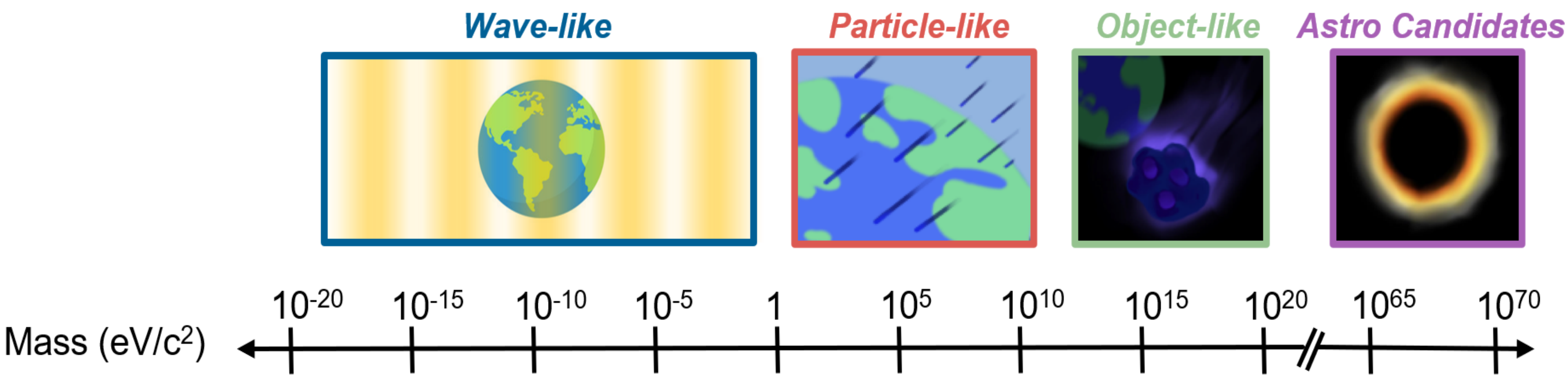
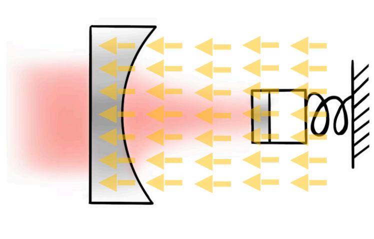


Resonant amplifier of a continuous signal

Single phonon detector



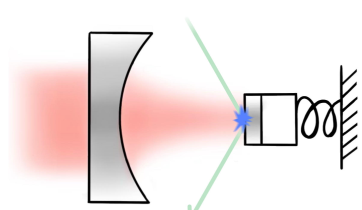


Image: Natalie Schmidt

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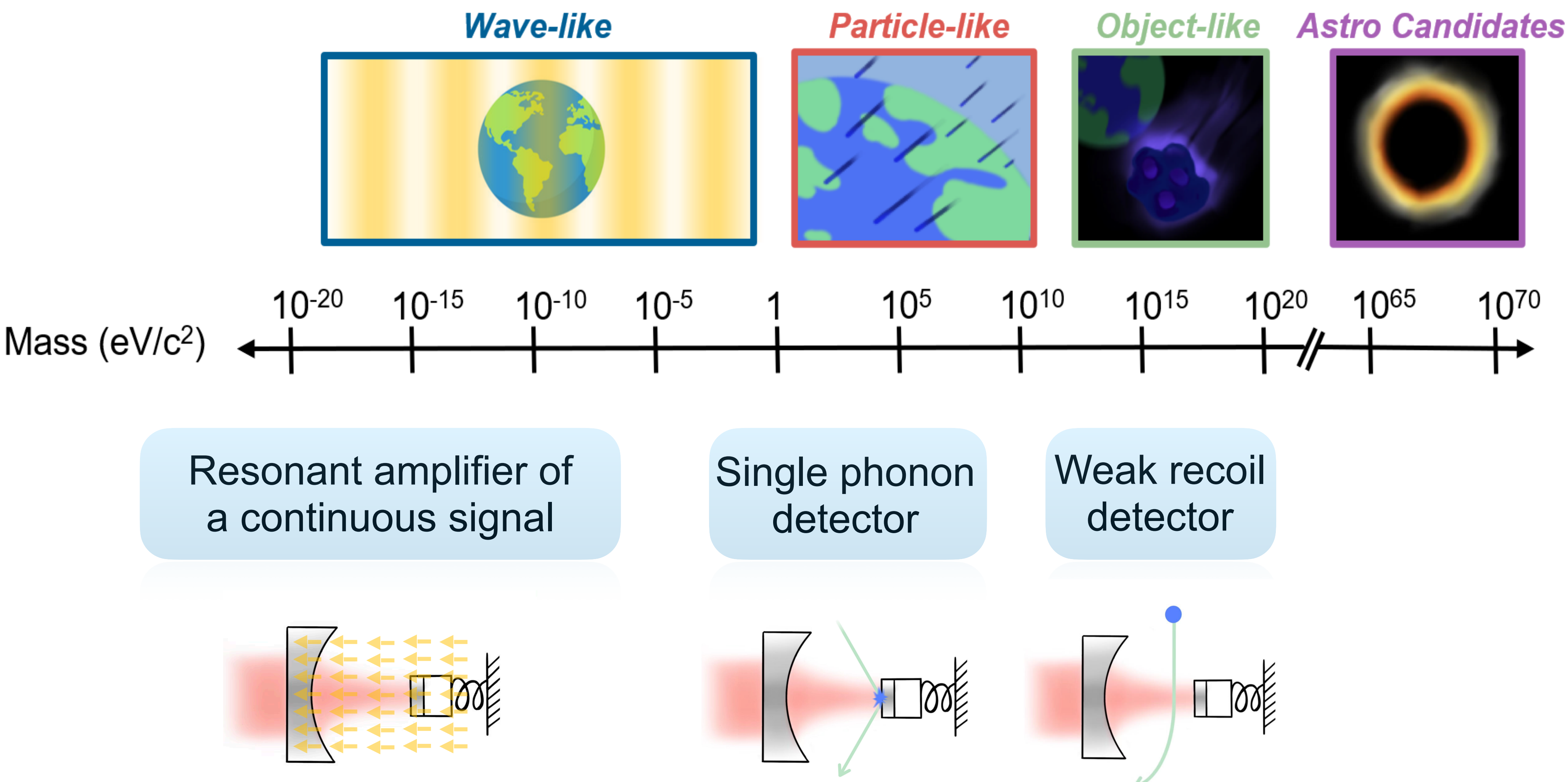

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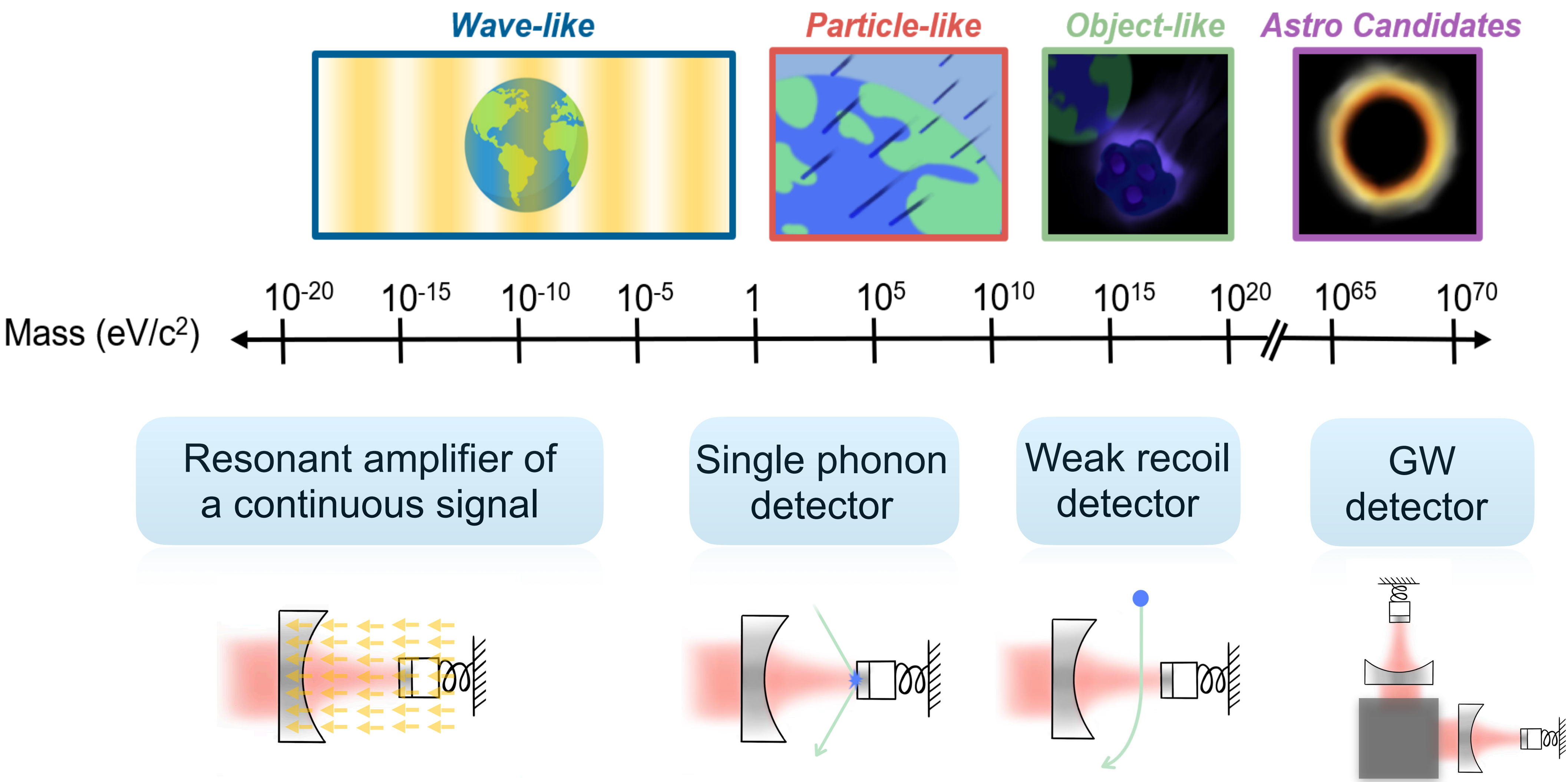
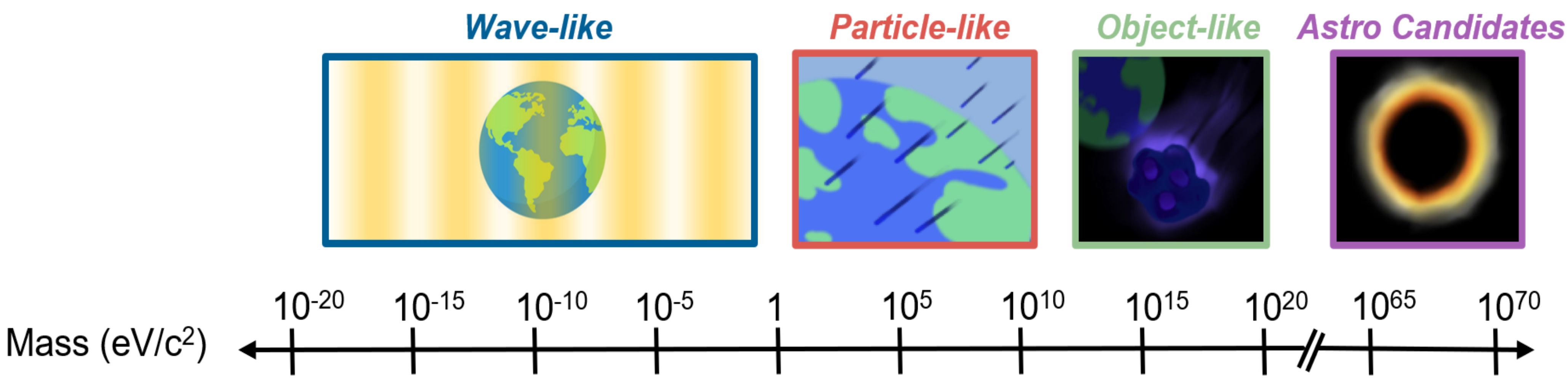


Image: Natalie Schmidt

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

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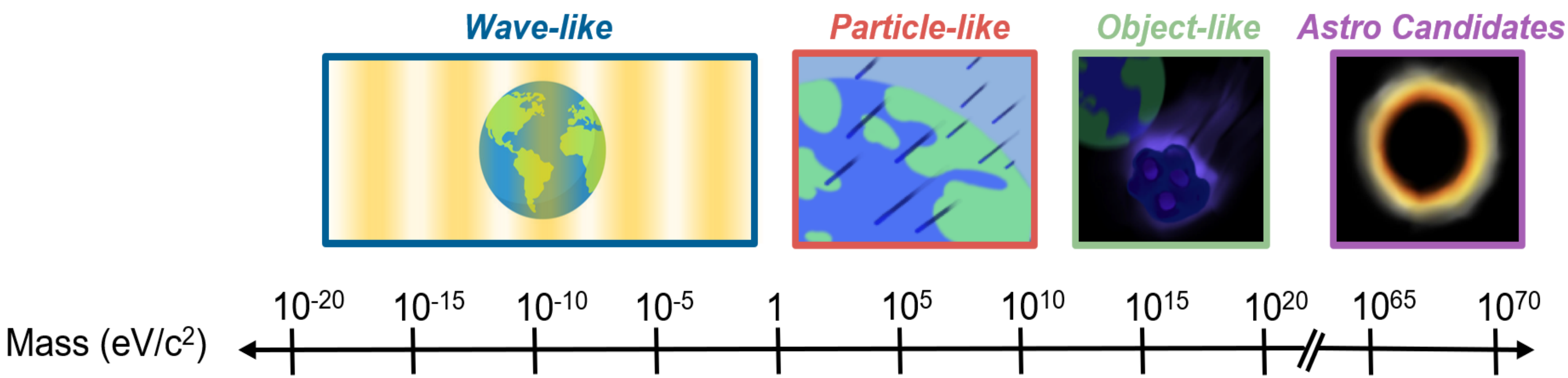

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Eliminating the LIGO bounds on primordial black hole dark matter

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

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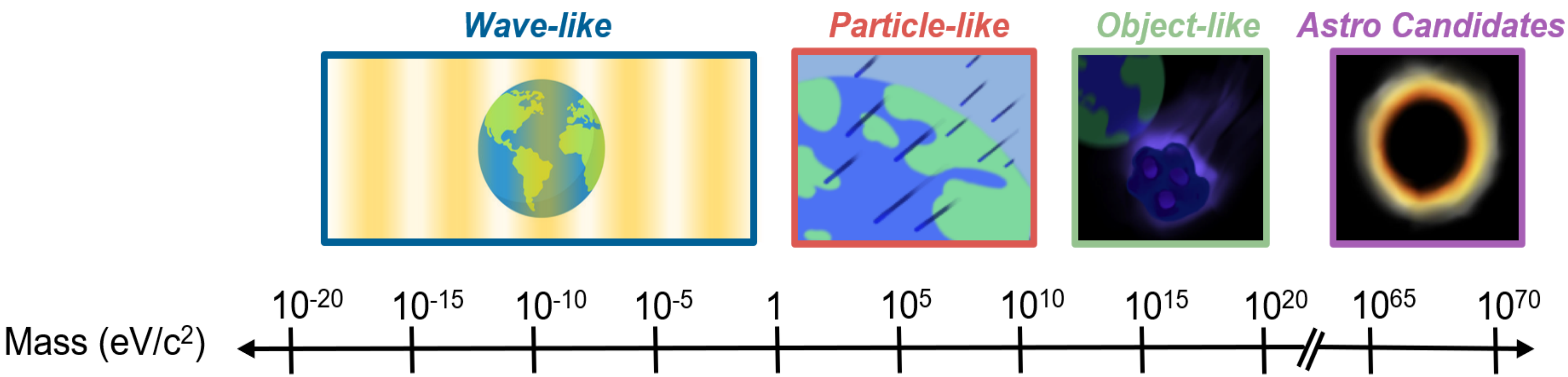

Levitated microspheres

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

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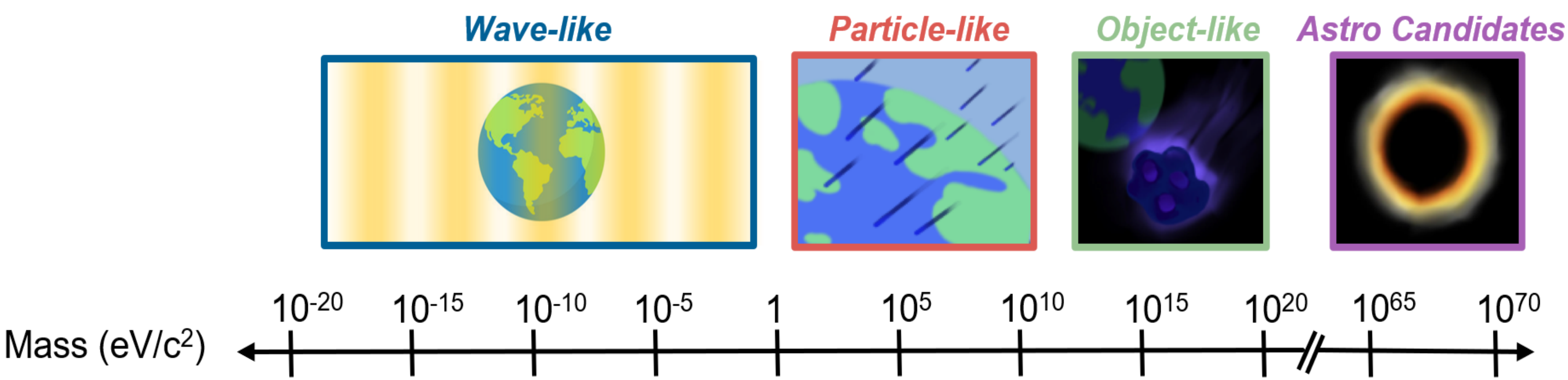

Phonon recoil detectors

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

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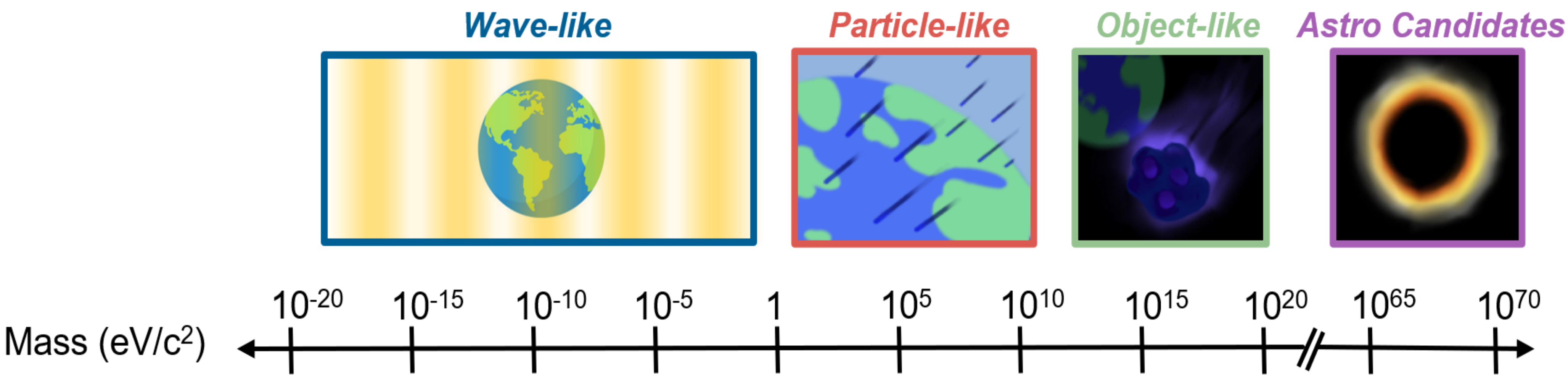


(primarily) Cavity-based searches

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

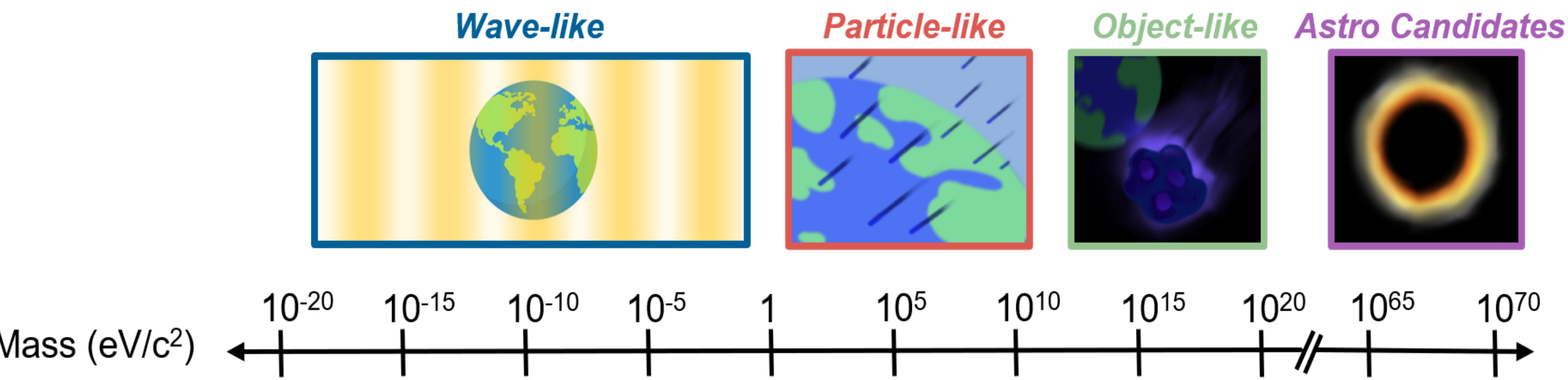
Searching for Dark Matter with an Optical Cavity and an Unequal-Delay Interferometer

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

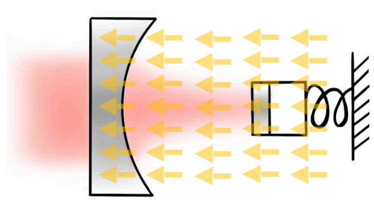
Searching for Scalar Dark Matter via Coupling to Fundamental Constants with Photonic, Atomic, and Mechanical Oscillators

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

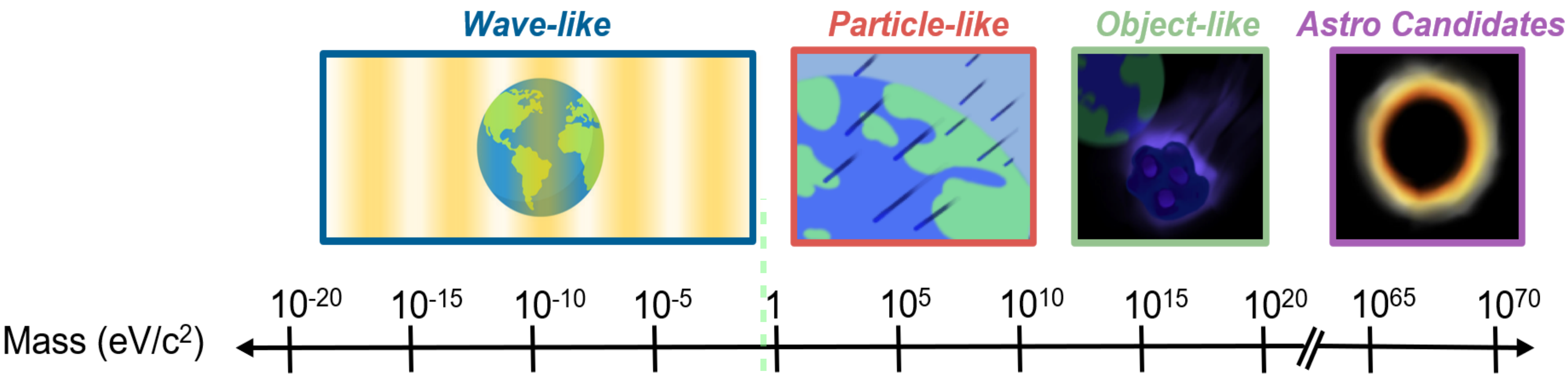
Mechanical detectors of ultralight DM



Resonant amplifier of
a continuous signal



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).

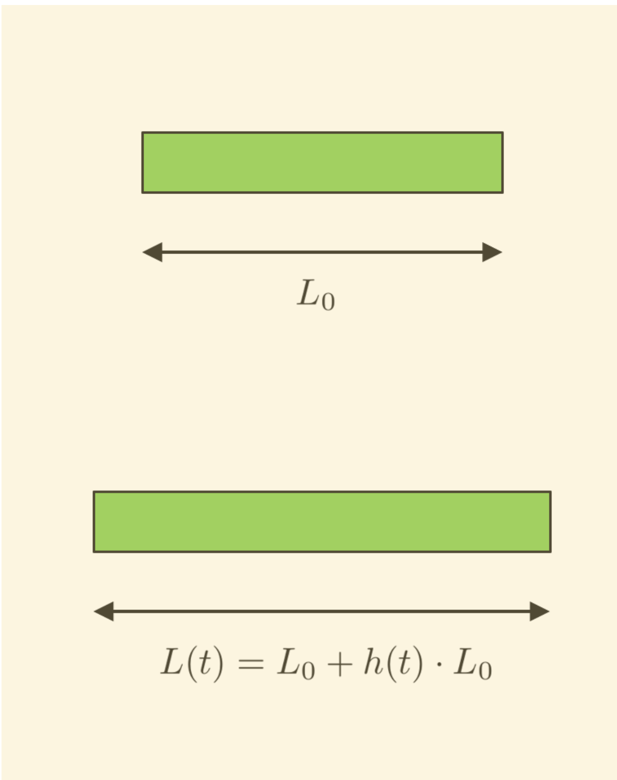
Carney et al. NJP **23** 023041 (2021).

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

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

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

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

- Amplified in a macroscopic solid
- Amplified on acoustic resonance

Mechanical detectors

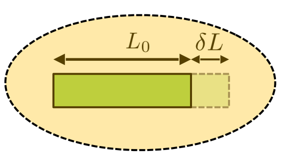
- Vermeulen et al. *Nature* **600**, 424-428 (2021) (GEO600)
- Branca et al. *PRL* **118**, 021302 (2017) (AURIGA)

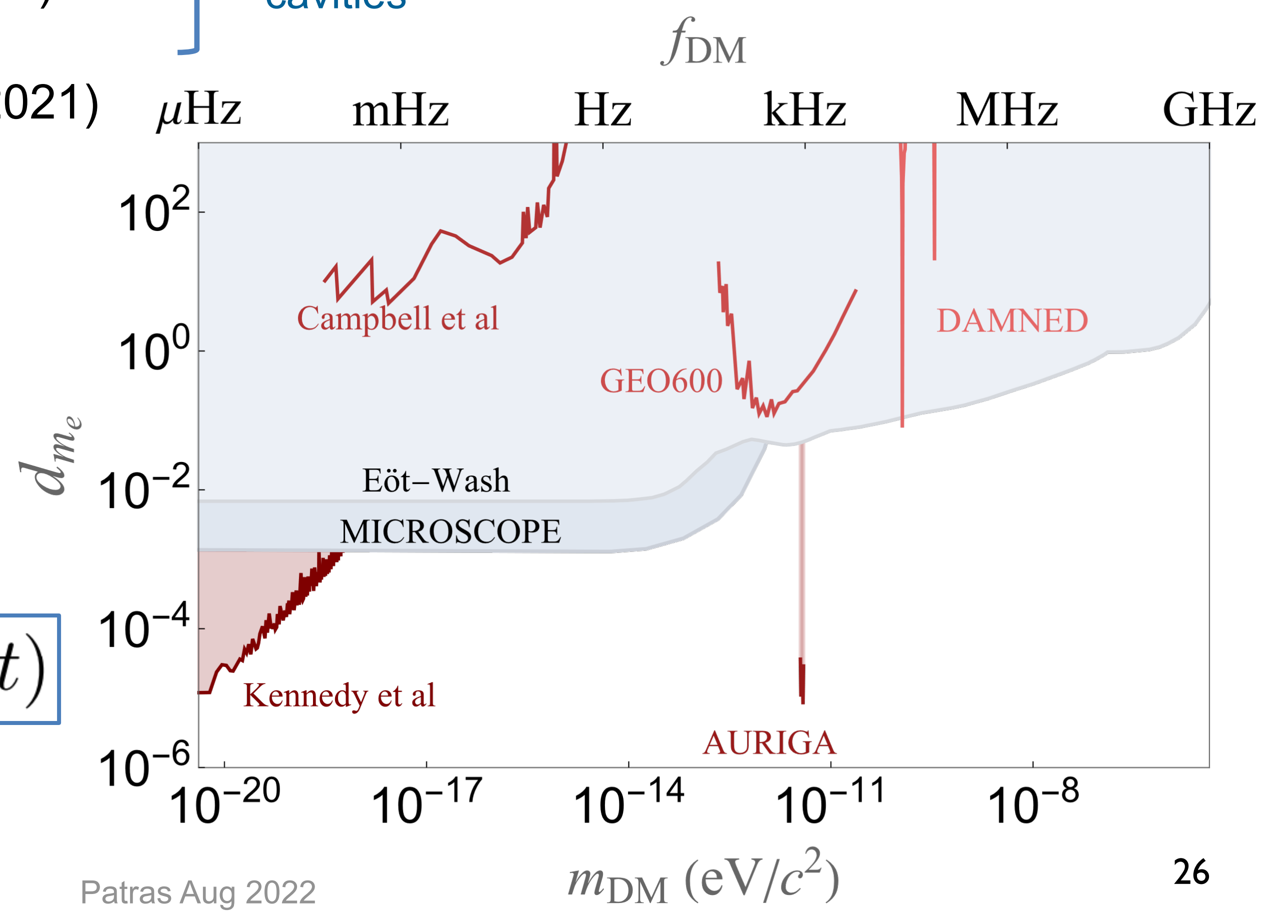
} GW detectors

- 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

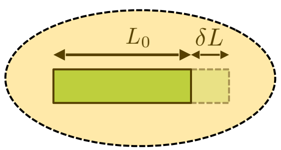
$$h(t) = -d_{m_e} \varphi_0 \cos\left(\omega_{\rm DM} t\right)$$

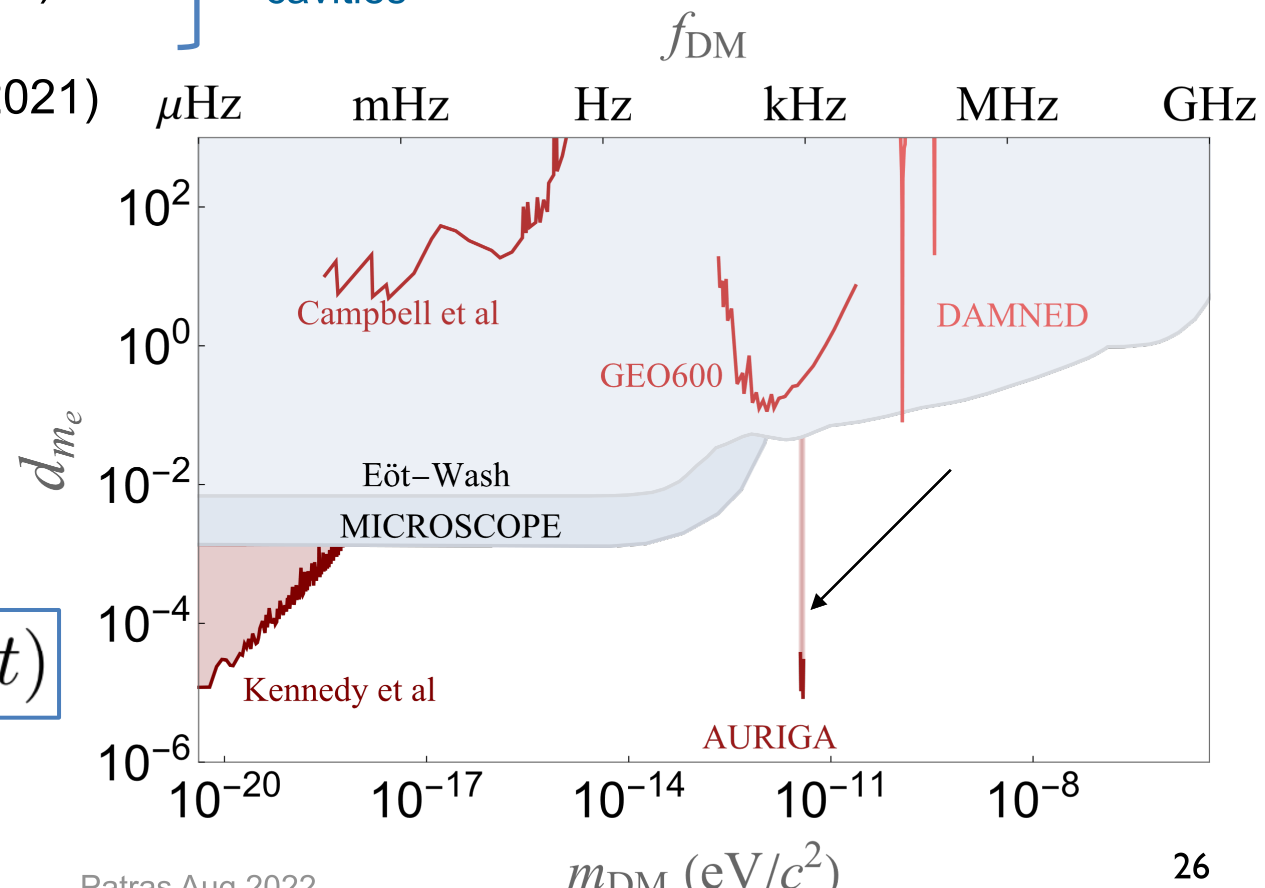
Mechanical detectors

- Vermeulen et al. *Nature* **600**, 424-428 (2021)
  (GEO600)
- Branca et al. *PRL* **118**, 021302 (2017)
  (AURIGA)
- Kennedy et al. *PRL* **125**, 201302 (2020)
- Savalle et al. *PRL* **126**, 051301 (2021)
  (DAMNED)
- Campbell et al. *PRL* **126**, 071301 (2021)

GW detectors

Optical cavities

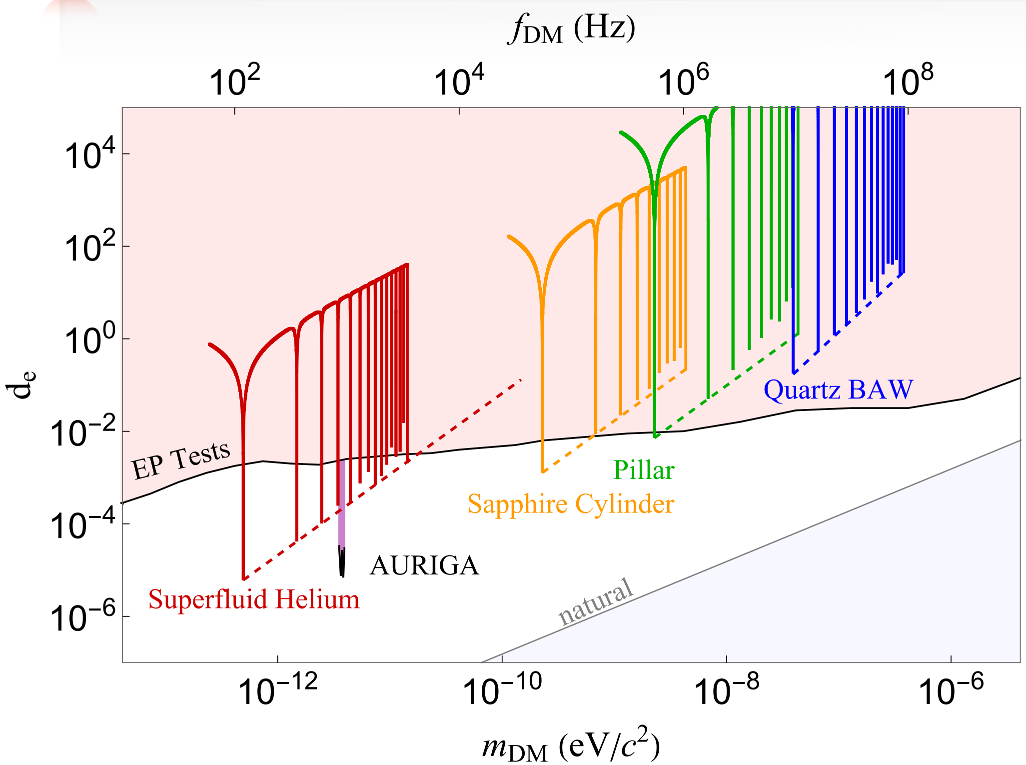


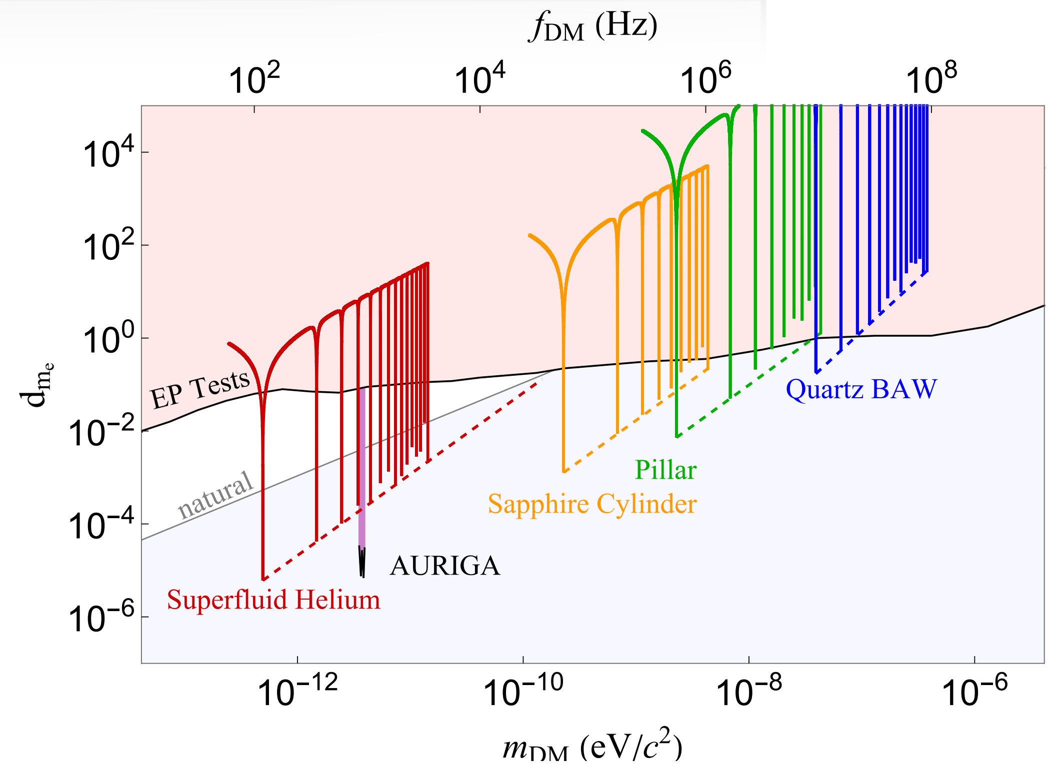


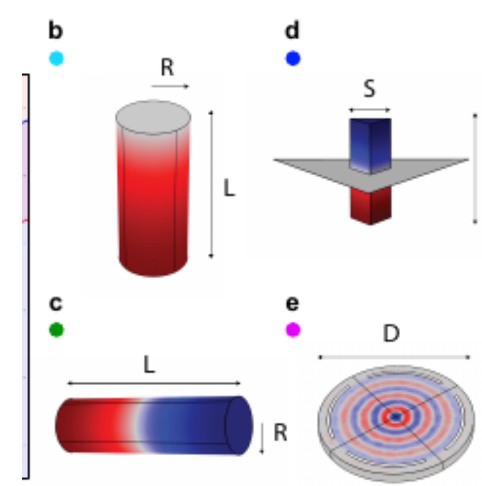
Strain Signal

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

Compact mechanical resonators







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

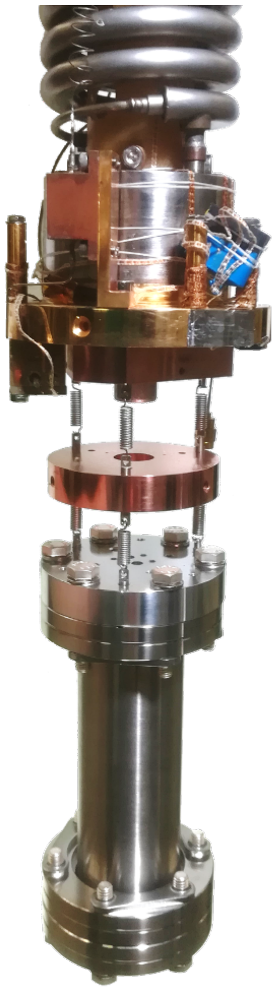
Searching for Scalar Dark Matter with Compact Mechanical Resonators

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)

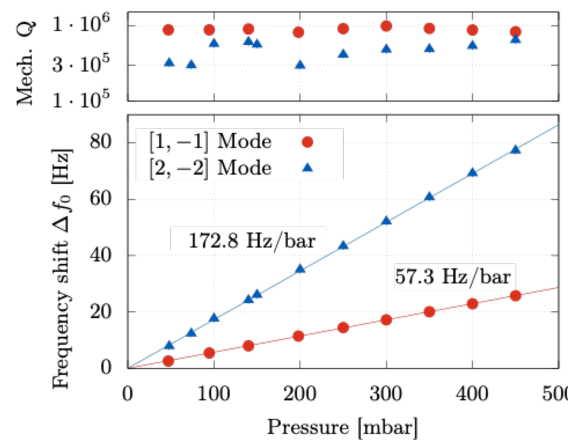
Superfluid helium detector for DM

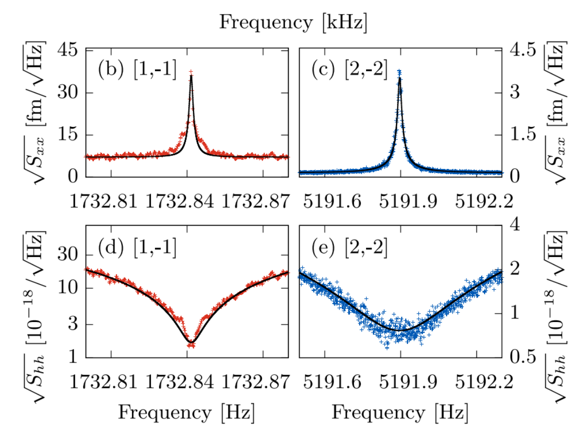
Tunable resonant mass detector for high frequency (continuous) gravitational waves, and ultralight scalar dark matter detection:



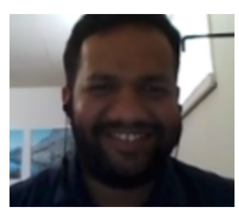
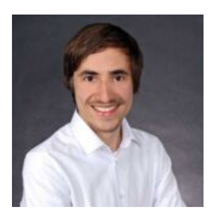
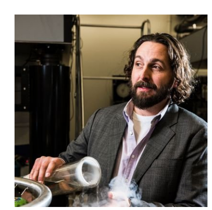
HELIOS: superfluid helium based ultralight dark matter optomechanical sensor

- ➢High-Q
- ➢Tunable
- ➢Thermally-limited





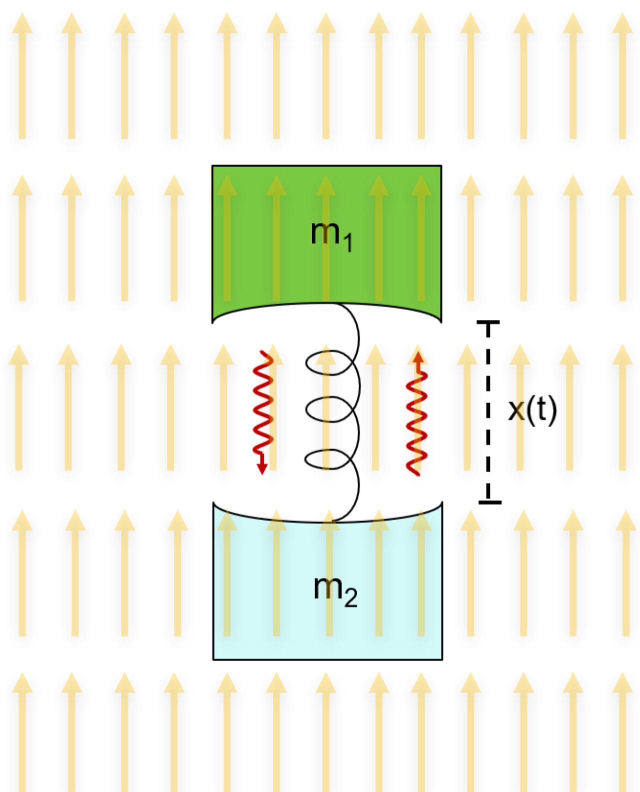
John Davis group @ UNIVERSITY OF ALBERTA

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

Image: Marvin Hirschel

Vector coupling: experimental signature



Differential acceleration signal

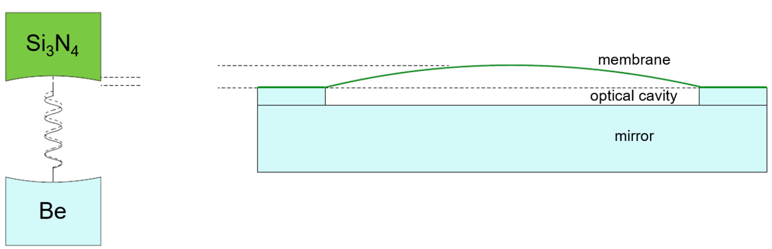
$$\Delta a(t) = a_1(t) - a_2(t) \approx g' \left(\frac{N_1{}'}{m_1} - \frac{N_2{}'}{m_2} \right) F_0 \cos\left(\omega_{\rm dm} t\right)$$

- 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).

SiN membrane detector

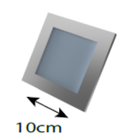
For vector gauge bosons (dark photons) coupling to B-L “charge”:

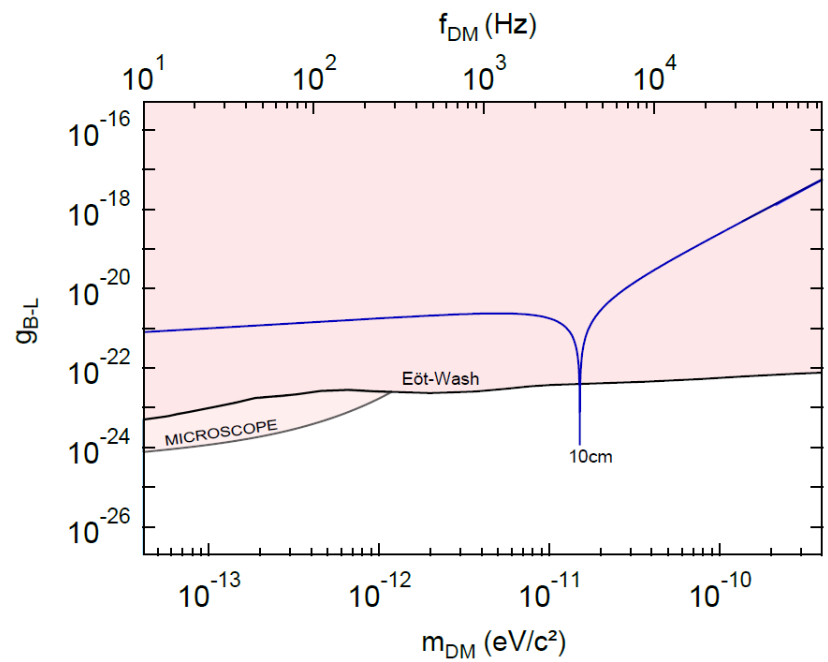


$$\Delta \boldsymbol{a}(t) \approx g_{\text{B-L}} \left[\left(\frac{N_{\text{n}}}{m}\right)_1 - \left(\frac{N_{\text{n}}}{m}\right)_2 \right] \boldsymbol{F}_0 \cos\left(\omega_{\text{dm}} t\right)$$

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

laser shot $\quad S_{xx}^{\text{imp}} = \dfrac{\pi \hbar c \lambda}{64 \mathcal{F}^2 P}$, $\quad S_{aa}^{\text{ba}} = \dfrac{\hbar^2}{m^2 S_{xx}^{\text{imp}}}$





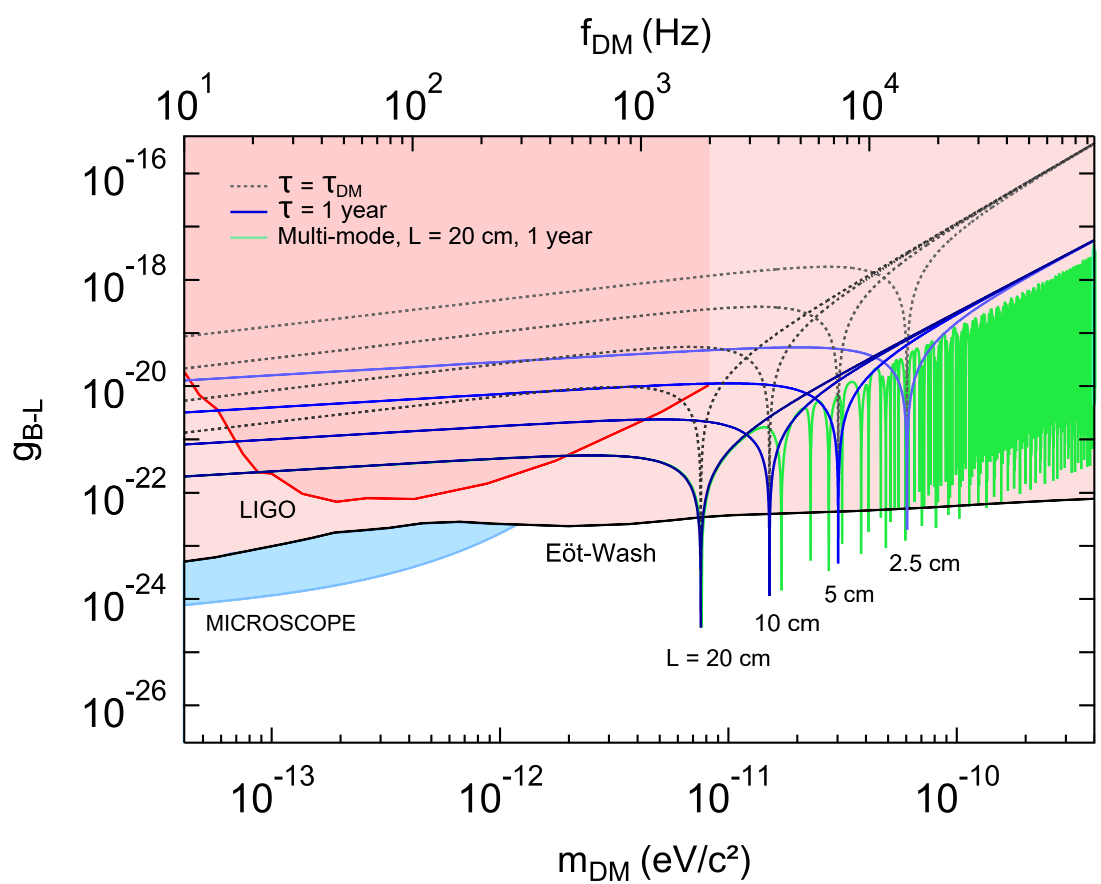
Searching for vector dark matter with an optomechanical accelerometer,
J. Manley, M. D. Choudhary, D. Grin, S. Singh and D. J. Wilson, PRL **126**, 061301 (2021).

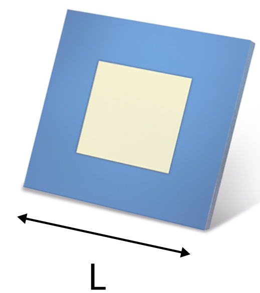
Wagner et al. Classical and Quantum Gravity 29.18 (2012): 184002.

Touboul et al. Physical review letters 119.23 (2017): 231101.

Mechanical detectors for vector Dark Matter

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

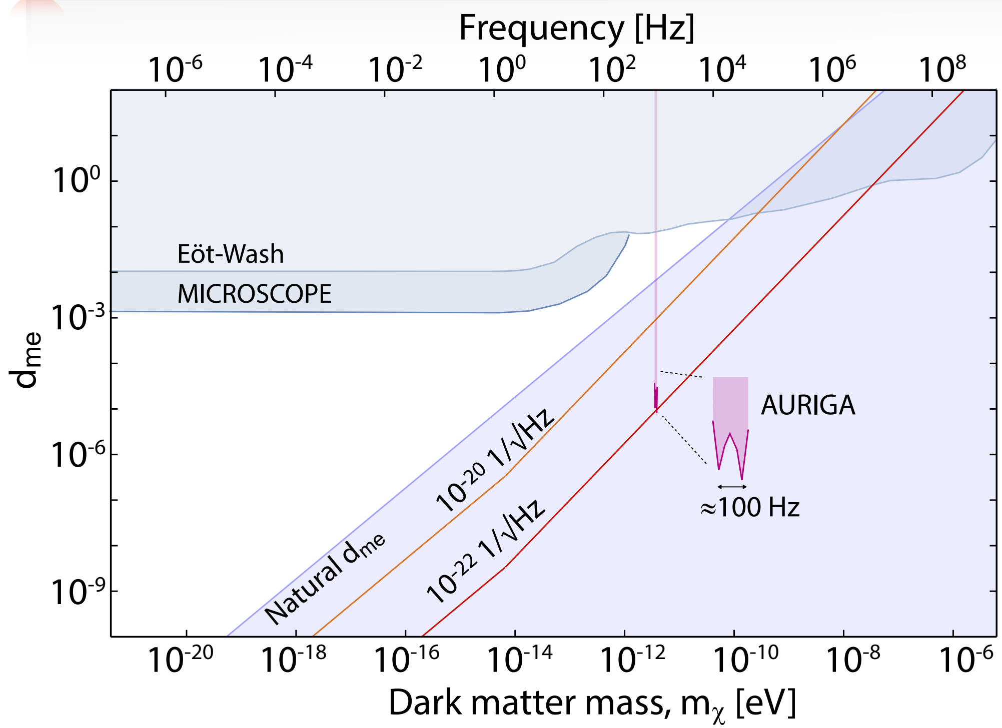




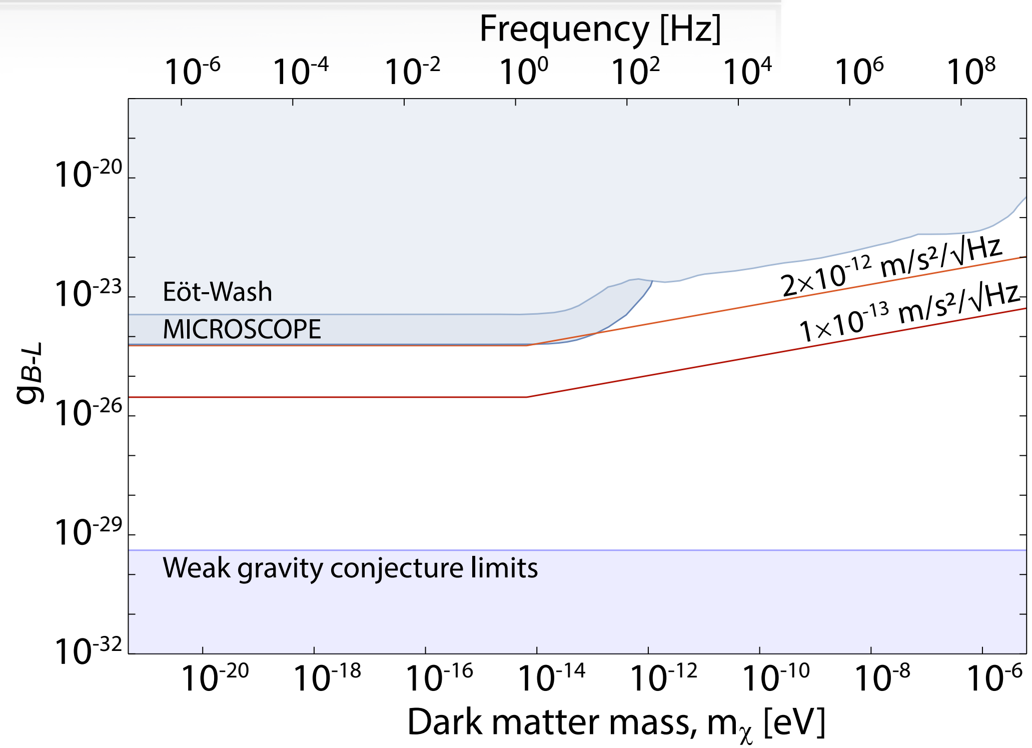
Dalziel Wilson group @ THE UNIVERSITY OF ARIZONA

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) .

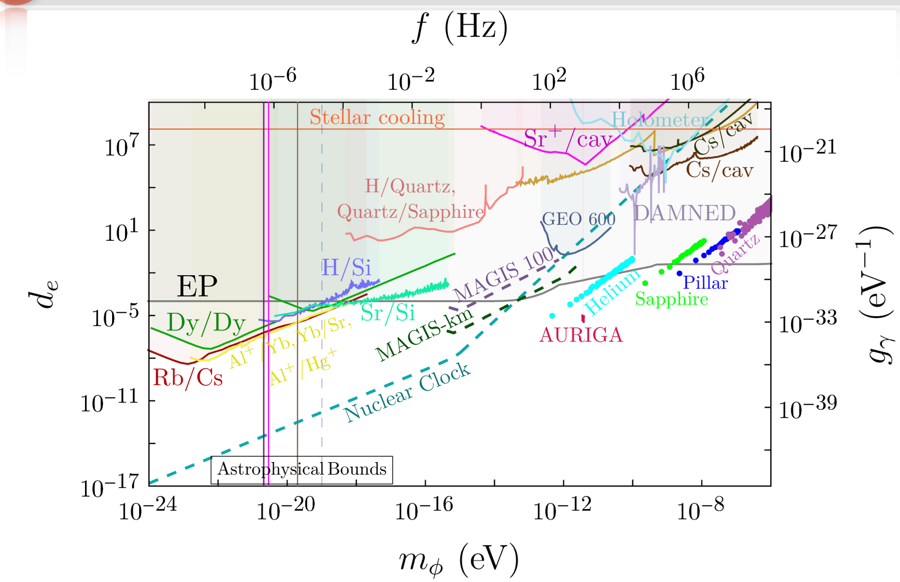
D. Carney

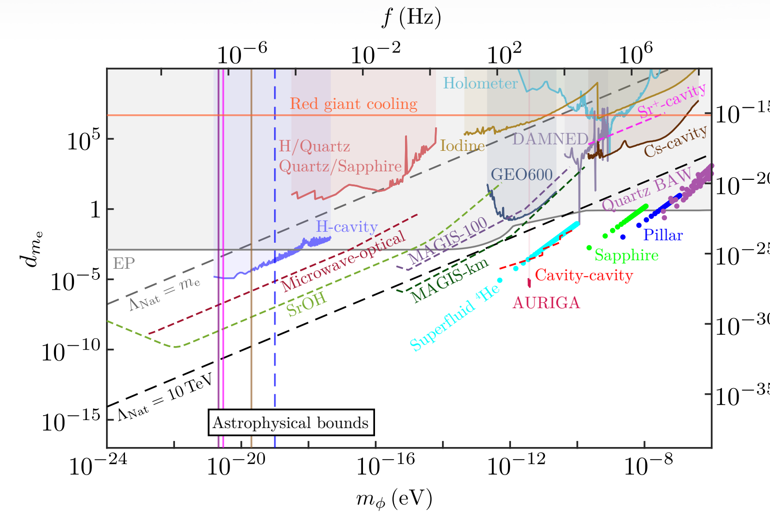
G. Krnjaic

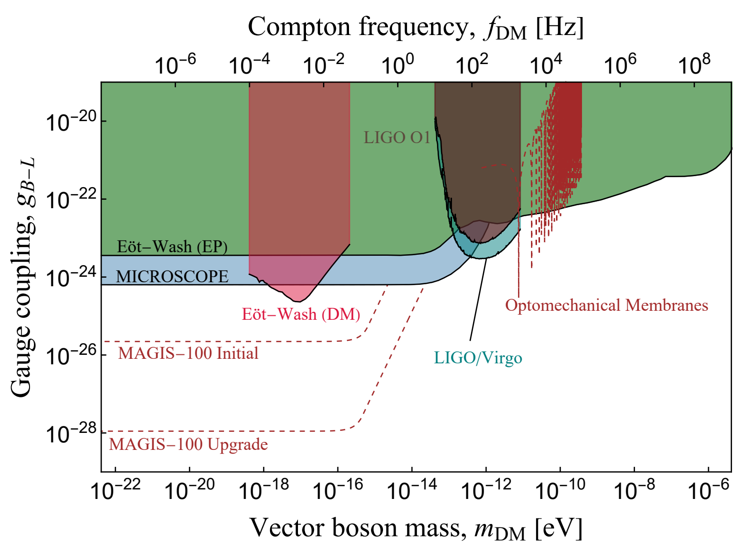
D. Moore

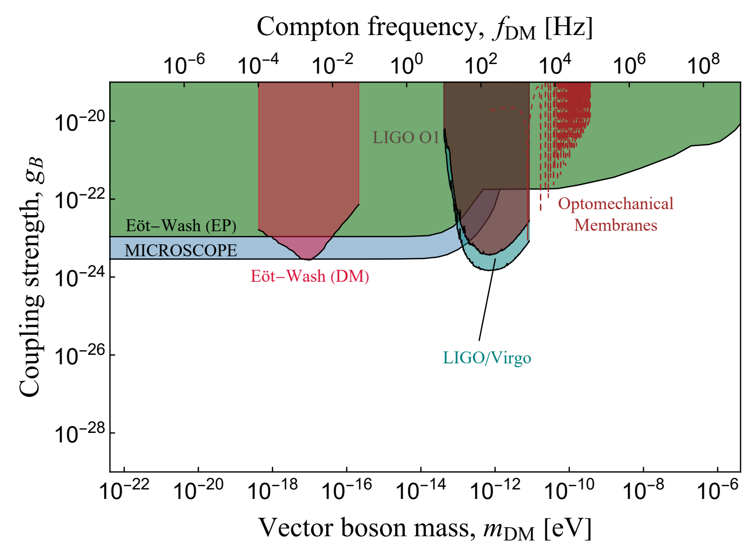
C. Regal

Ultralight scalar and vector DM constraints







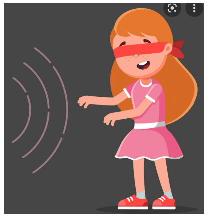


Parameter plots Credit: Abhishek Banerjee, Tejas Deshpande, Sumita Ghosh, Jack Manley, Ciaran, O'Hare

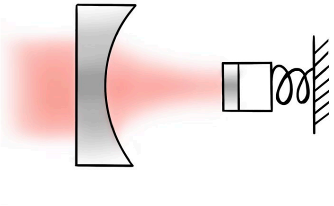
New Horizons: Scalar and Vector ultralight dark matter
Snowmass Proceedings of the US community study on the Future of Particle Physics (arXiv:2203.14915)

Overview

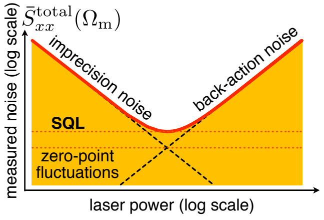
- Overview of ultralight DM detection philosophy



- Overview of mechanical dark matter detectors

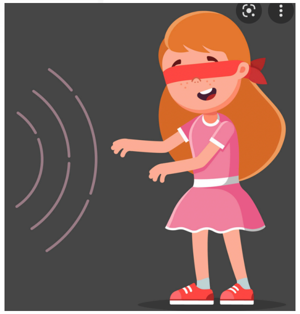


- Overview of quantum optics for dark matter detectors



How to think of “dark photons”— think again

(Kind of works for all ultralight particles)



How do we know (normal) photons exist?

- Photons as real particles directly do something measurable
  (e.g. Photoelectric effect)

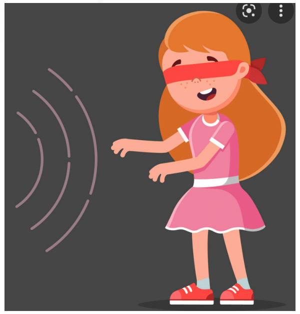
  Dark photon search example: haloscope experiments

- Photons as virtual particles mediate electrostatic forces
  (e.g. Coulomb’s law)

  Dark photon search example: EP violation experiments

How to think of “dark photons”— think again

(Kind of works for all ultralight particles)



How do we know (normal) photons exist?

- Photons as real particles directly do something measurable
  (e.g. Photoelectric effect)

Dark photon search example: haloscope experiments

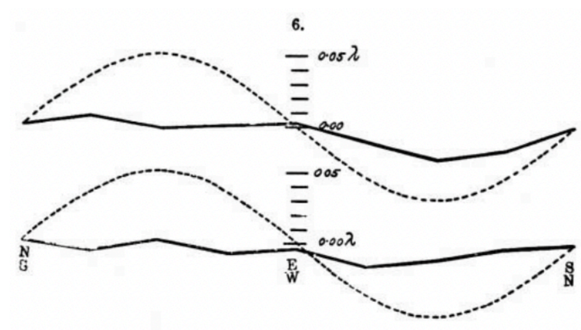
Much weaker signal than their “bright photon” counterpart!

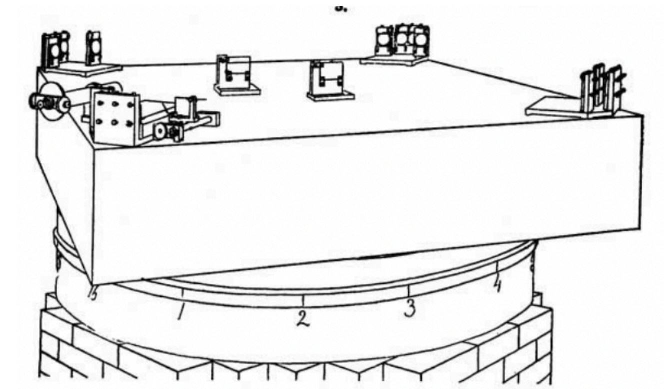
- Photons as virtual particles mediate electrostatic forces
  (e.g. Coulomb’s law)

Dark photon search example: EP violation experiments

How to measure weak signals

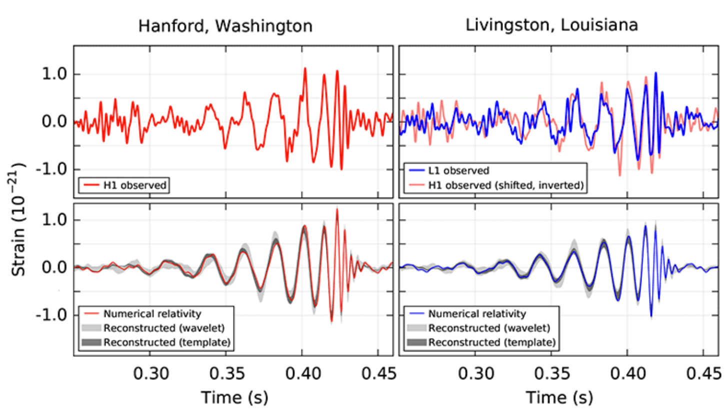
(In particle physics, today's signal is tomorrow's noise floor)





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).

129 years later!



Observation of Gravitational Waves from a Binary Black Hole Merger,
B.P. Abbott et. al, Phys. Rev. Lett 116, 061102 (2016).

How to measure weak signals

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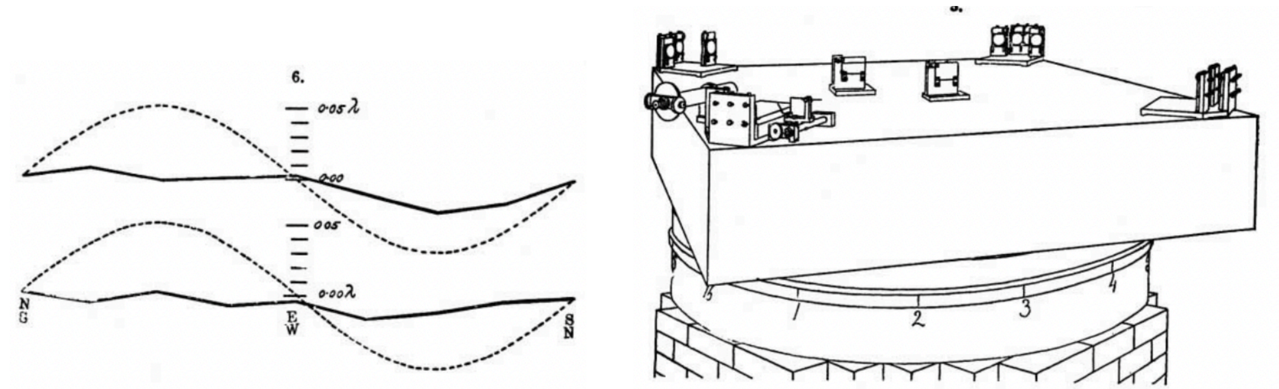
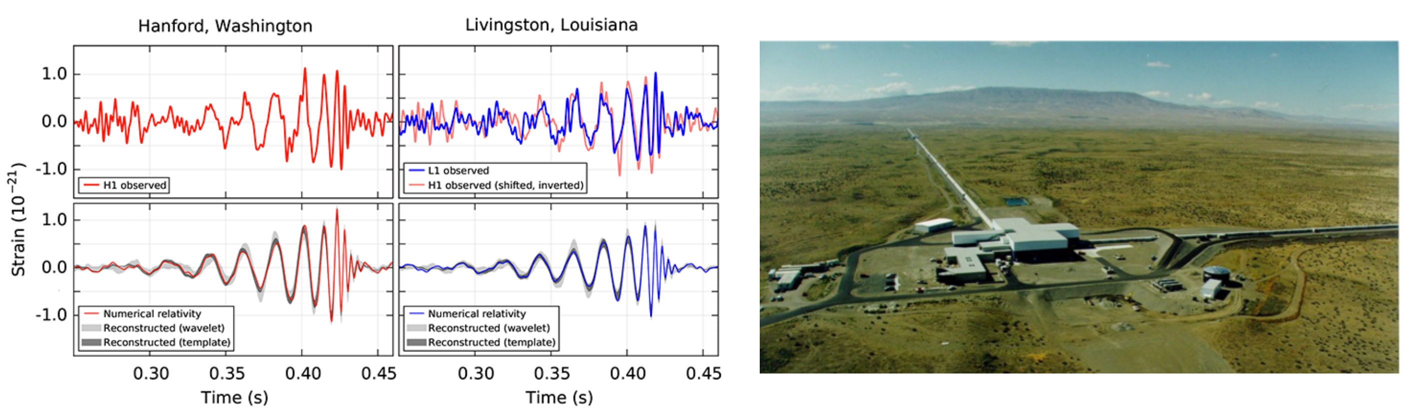


On the relative motion of the Earth and the Luminiferous Ether,
A. A. Michelson and E. W. Morley, American Journal of Science 34, 203, 36 (1887).

129 years later!

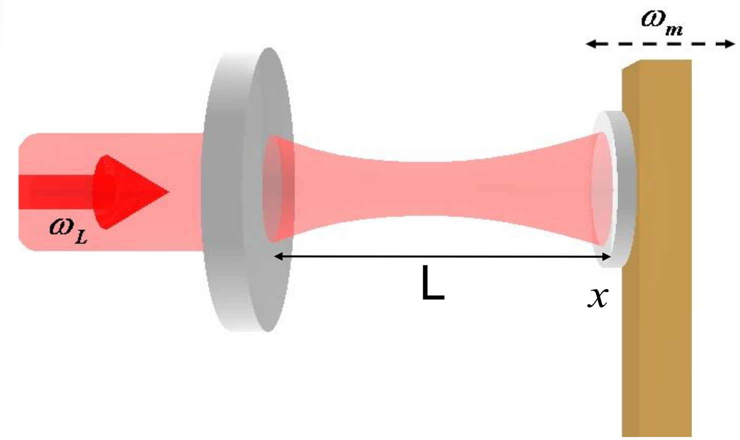
A very small fractional change in position



Observation of Gravitational Waves from a Binary Black Hole Merger,
B.P. Abbott et. al, Phys. Rev. Lett 116, 061102 (2016).

Back action of a position measurement

For a quantum oscillator $[\hat{x}, \hat{p}] = i\hbar$

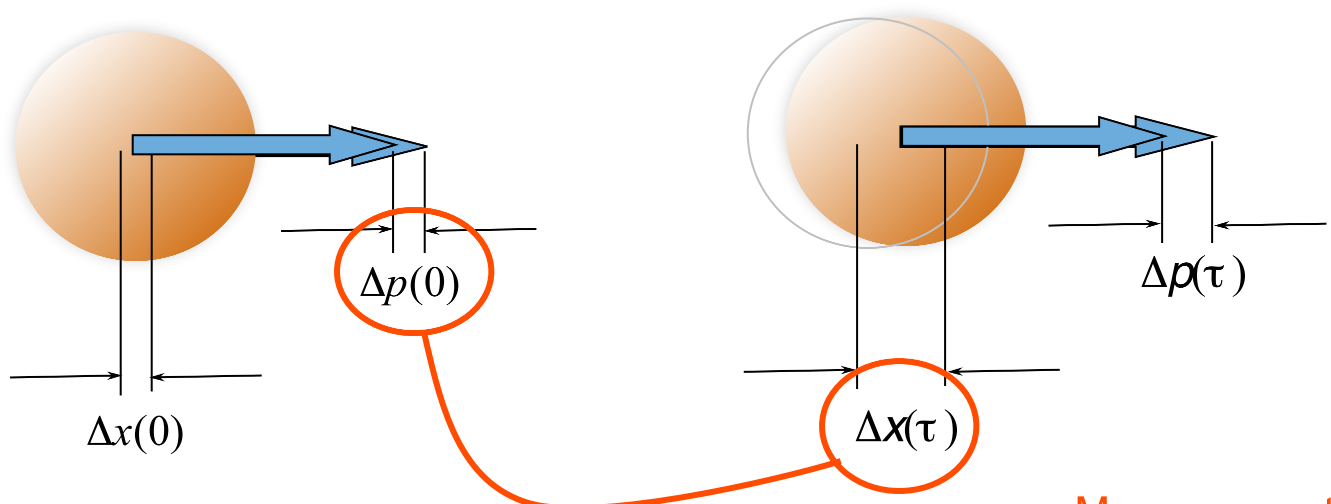


Heisenberg uncertainty relation

$$\Delta\hat{x}\Delta\hat{p} \geq \frac{\hbar}{2} \longrightarrow \boxed{\Delta\hat{p} \geq \frac{\hbar}{2\Delta\hat{x}}}$$

Measuring $\hat{x}$ perturbs $\hat{p}$, which in turn perturbs subsequent measurement of $\hat{x}$

$$\Delta x(\tau) = \Delta x(0) + \tau \times \frac{\Delta p(0)}{m}$$



Measurement back-action

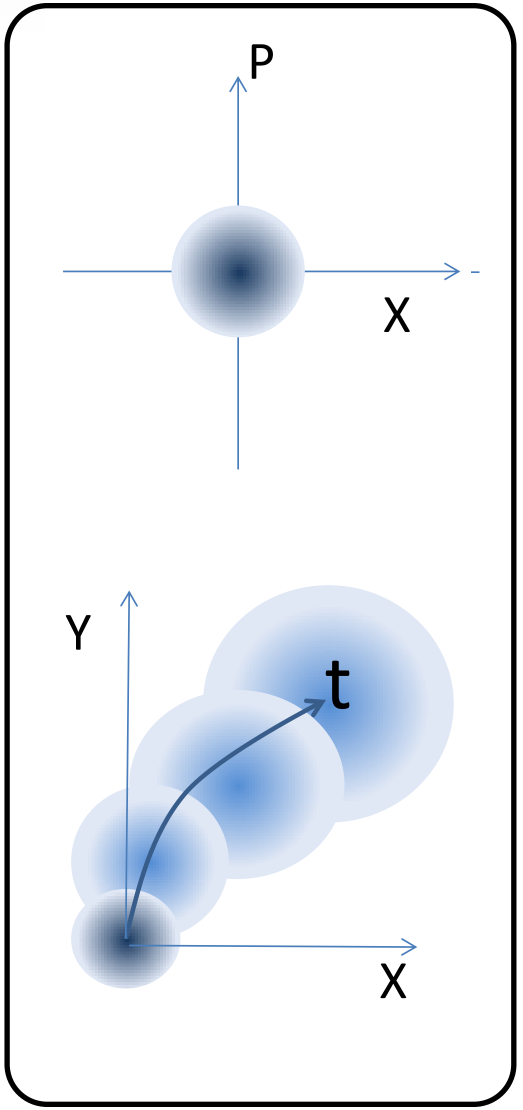
Position Measurement Back action

$$\Delta x(\tau) = \Delta x(0) + \tau \times \frac{\Delta p(0)}{m}$$

In general,

$$H = \frac{1}{2} m\omega^2 \hat{x}^2 + \frac{1}{2m}\hat{p}^2$$

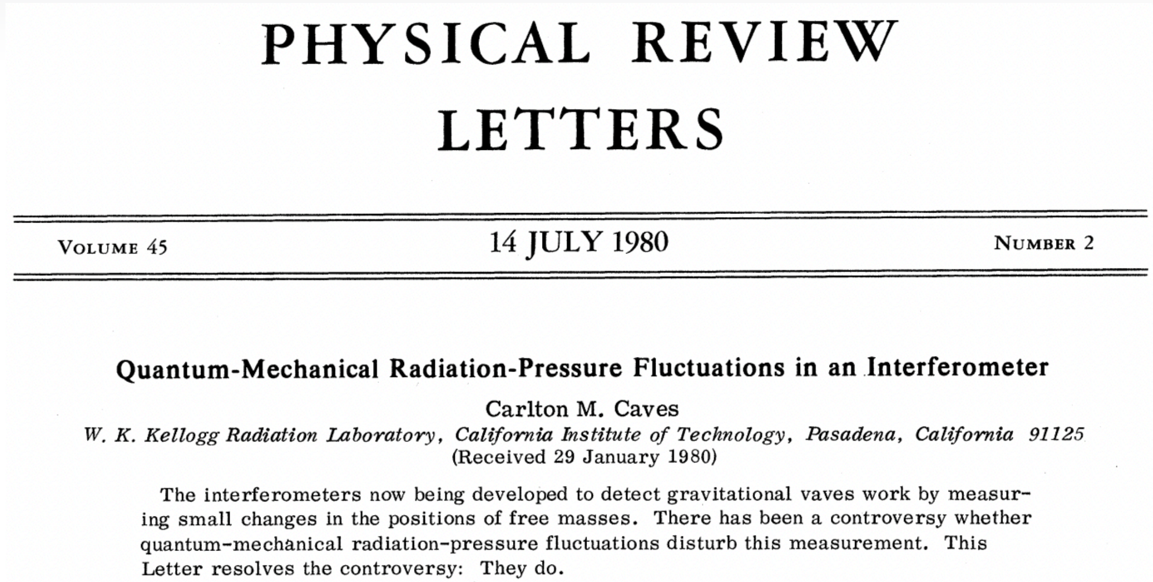
$$\frac{d\hat{x}}{dt} = \frac{i}{\hbar}[\hat{H}, x] = \frac{\hat{p}}{m}$$



Backaction effects are built up by repeated measurements

"Trajectories without quantum uncertainties",
E. S. Polzik and K. Hammerer, Annalen der Physik, (2014).

Standard Quantum Limit of Position


PHYSICAL REVIEW LETTERS

VOLUME 45 — 14 JULY 1980 — NUMBER 2

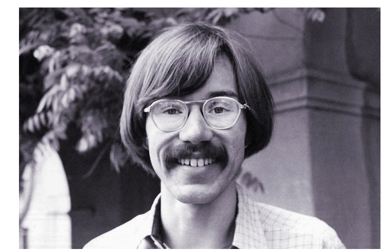
Quantum-Mechanical Radiation-Pressure Fluctuations in an Interferometer

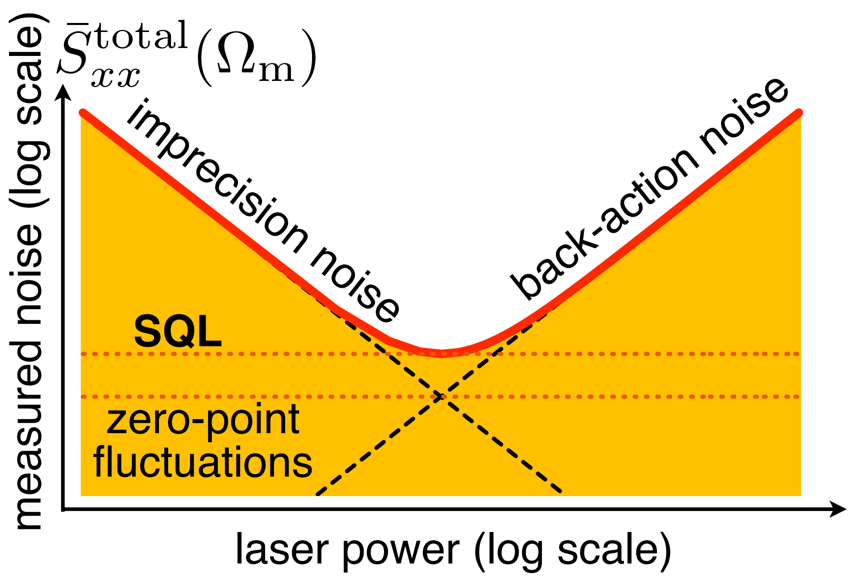
Carlton M. Caves

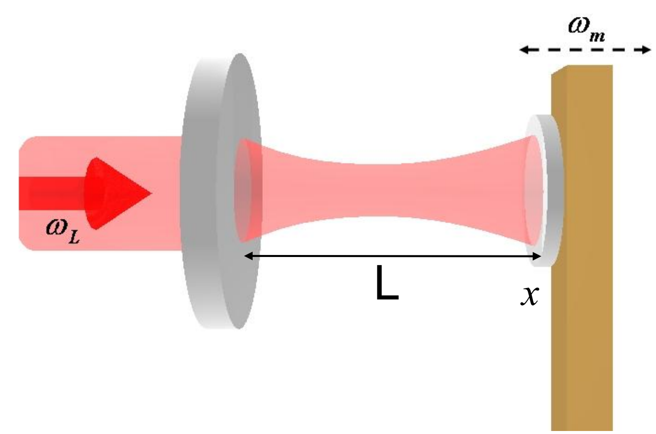
W. K. Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California 91125

(Received 29 January 1980)

The interferometers now being developed to detect gravitational vaves work by measuring small changes in the positions of free masses. There has been a controversy whether quantum-mechanical radiation-pressure fluctuations disturb this measurement. This Letter resolves the controversy: They do.







"Quantum optomechanics",

M. Aspelmeyer, T. J. Kippenberg and F. Marquardt RMP 86, 1391(2014).

Beyond the Standard Quantum Limit

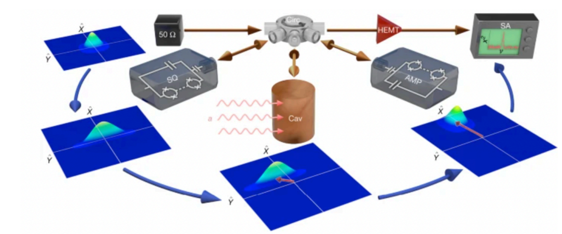
In quantum optics, there are no problems, only features.

- Inject squeezed vacuum

A quantum enhanced search for dark matter axions

https://doi.org/10.1038/s41586-021-03226-7
Received: 24 July 2020
Accepted: 8 December 2020
Published online: 10 February 2021

K. M. Backes[1,6 ✉], D. A. Palken[2,3,6], S. Al Kenany[4], B. M. Brubaker[2,3], S. B. Cahn[1], A. Droster[4], Gene C. Hilton[5], Sumita Ghosh[1], H. Jackson[4], S. K. Lamoreaux[1], A. F. Leder[4], K. W. Lehnert[2,3,5], S. M. Lewis[4], M. Malnou[2,5], R. H. Maruyama[1], N. M. Rapidis[4], M. Simanovskaia[4], Sukhman Singh[1], D. H. Speller[1], I. Urdinaran[4], Leila R. Vale[5], E. C. van Assendelft[1], K. van Bibber[4] & H. Wang[1]



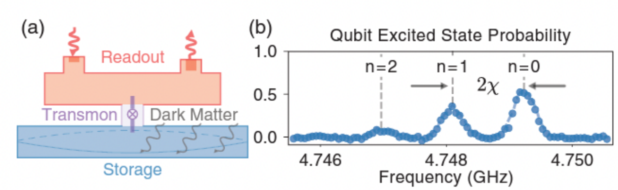
- Measure a commuting observable

PHYSICAL REVIEW LETTERS **126**, 141302 (2021)

Featured in Physics

Searching for Dark Matter with a Superconducting Qubit

Akash V. Dixit,[1,2,3,*] Srivatsan Chakram,[1,2,4] Kevin He,[1,2] Ankur Agrawal,[1,2,3] Ravi K. Naik,[5] David I. Schuster,[1,2,6] and Aaron Chou[7]



Patras Aug 2022

Beyond the Standard Quantum Limit

- Coherent backaction noise cancelation

  Couple to another harmonic oscillator, but with a negative mass

Coherent Quantum-Noise Cancellation for Optomechanical Sensors

Mankei Tsang and Carlton M. Caves
Phys. Rev. Lett. **105**, 123601 – Published 13 September 2010

All-optical coherent quantum-noise cancellation in cascaded optomechanical systems

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(Dated: August 4, 2022)

Exciting times ahead!

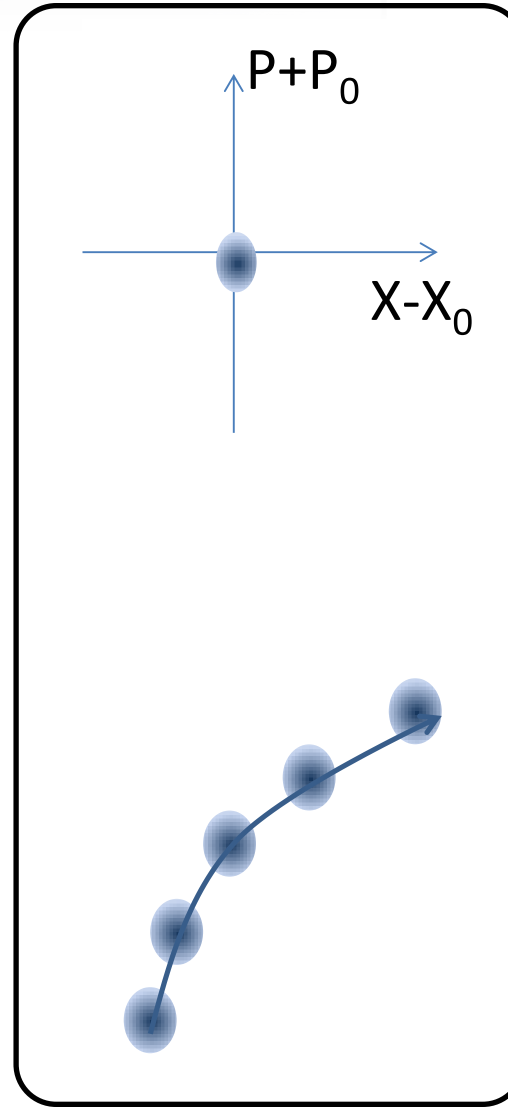


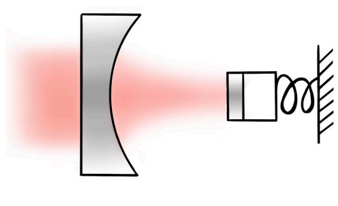
Figure from: "Trajectories without quantum uncertainties",
E. S. Polzik and K. Hammerer, Annalen der Physik, (2014).

"Atom-based coherent quantum-noise cancellation in optomechanics,"
F. Bariani, H. Seok, S. Singh, M. Vengalattore, P. Meystre, Phys. Rev. A 92, 043817 (2015).

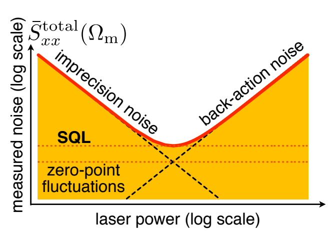
Overview

- Overview of ultralight DM detection philosophy

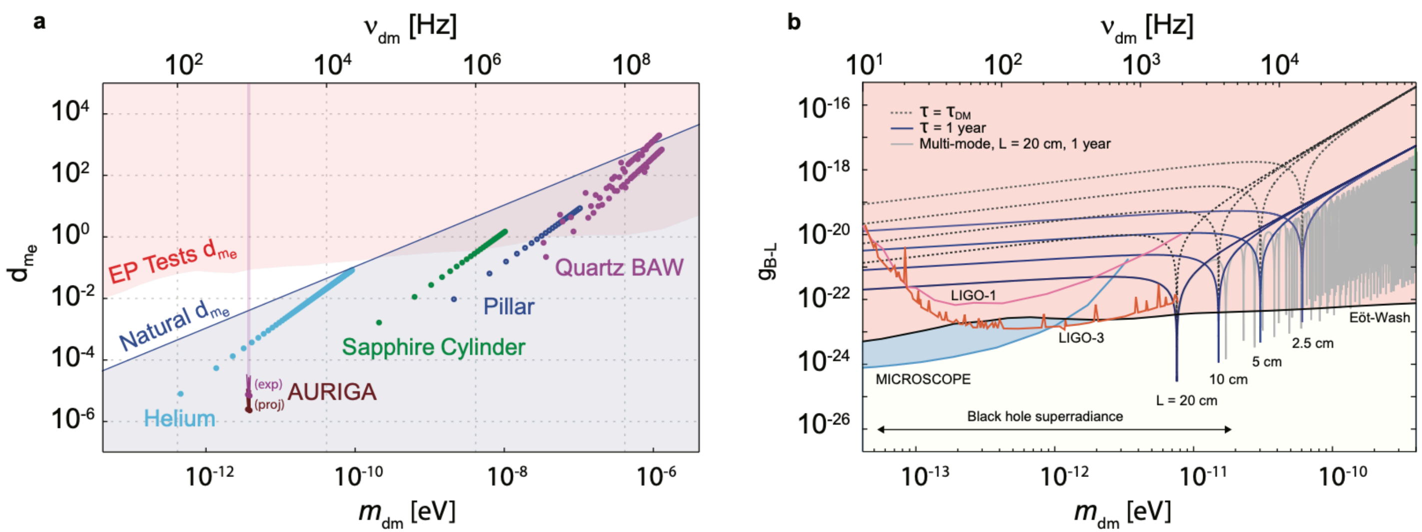
- Overview of mechanical dark matter detectors



- Overview of quantum optics for dark matter detectors



AMO measurement techniques



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

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

Heroic experiments!

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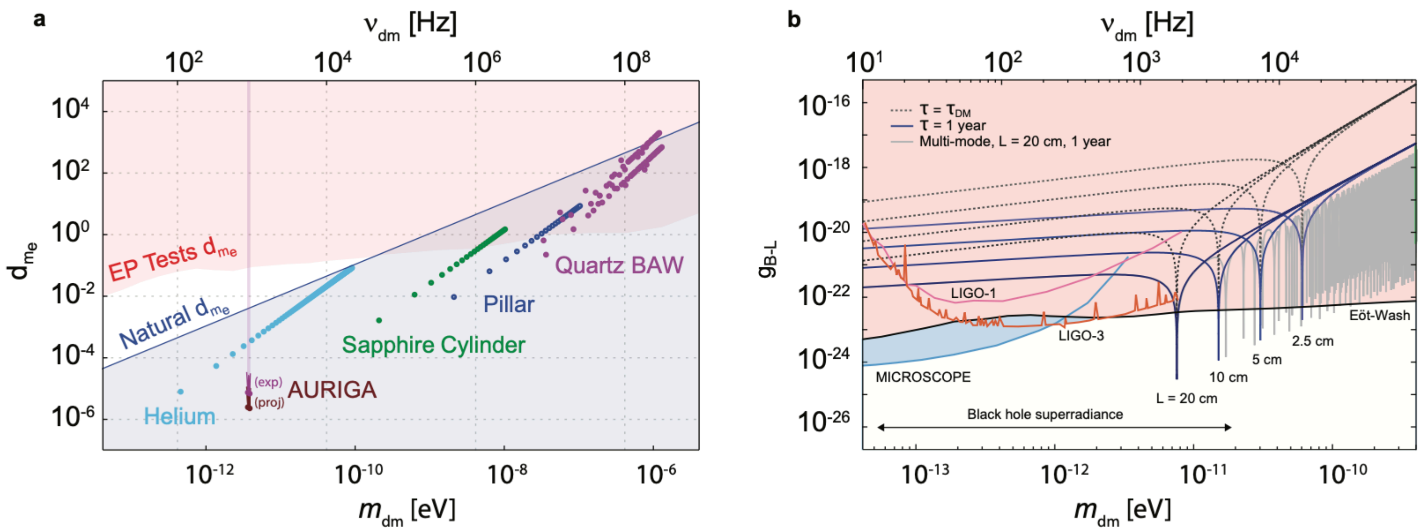

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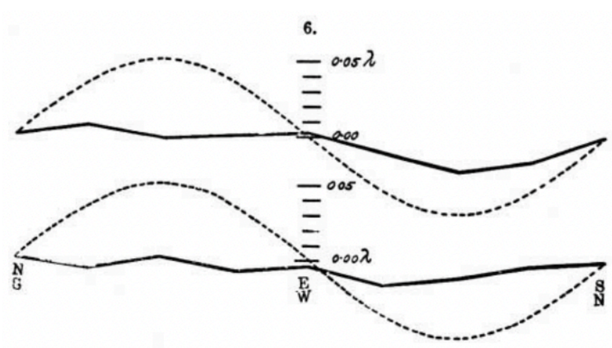
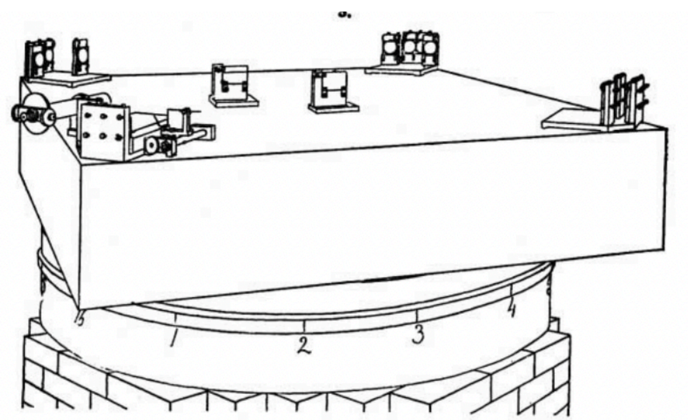
Heroic experiments!

What if dark matter is not ultralight?

Return of the "ether" philosophy

Return of the “ether” philosophy

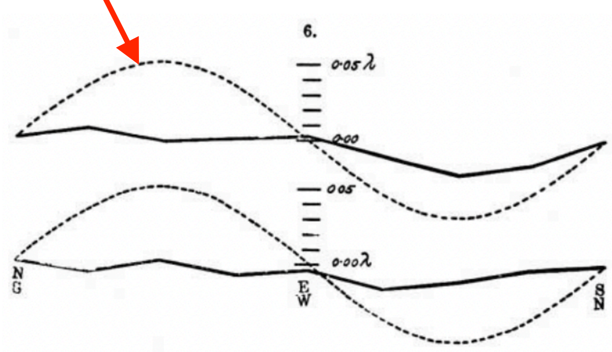


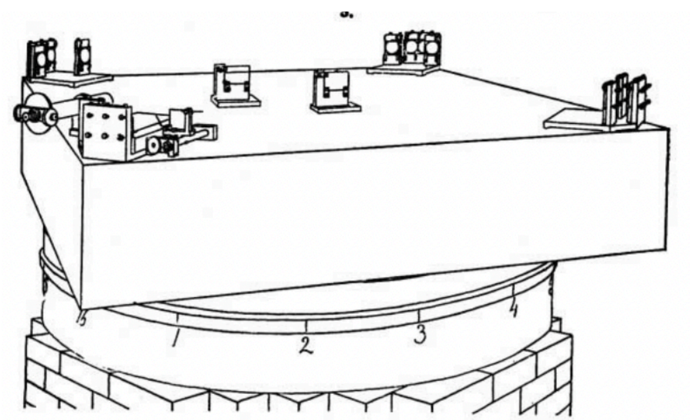


On the relative motion of the Earth and the Luminiferous Ether,
A. A. Michelson and E. W. Morley, American Journal of Science 34, 203, 36 (1887).

Return of the "ether" philosophy

Not measuring this signal led to a better understanding of the nature of light





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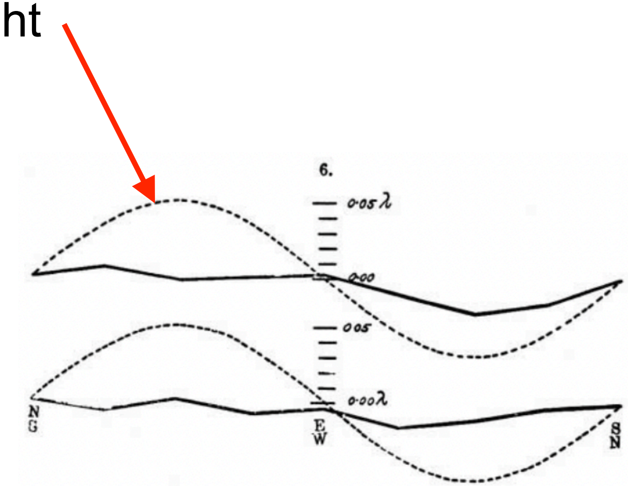

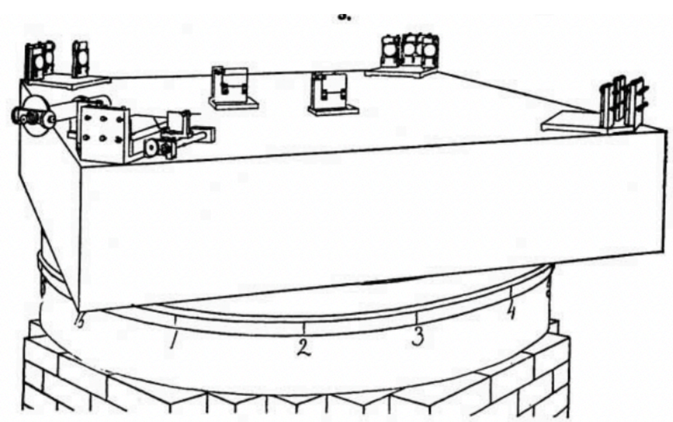

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A. A. Michelson and E. W. Morley, American Journal of Science 34, 203, 36 (1887).

Constraining the available parameter space for dark matter will lead to a better understanding of properties of dark matter.

Acknowledgements

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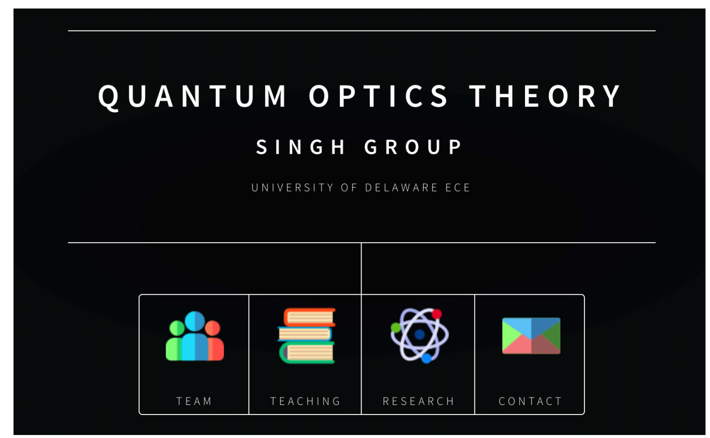
Ewan Wright (U Arizona)



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:

Backup Slides

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 — $\phi(t)$; coupling strength — d_i; SM term — $\mathcal{O}_{\mathrm{SM},i}$

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.

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

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

- This leads to a force:

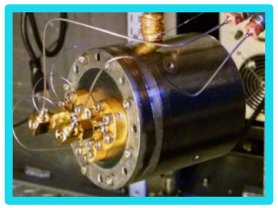
$$F(t) \approx g'N'F_0\cos\left(\omega_{\mathrm{dm}}t\right)$$

coupling strength — number of dark charges

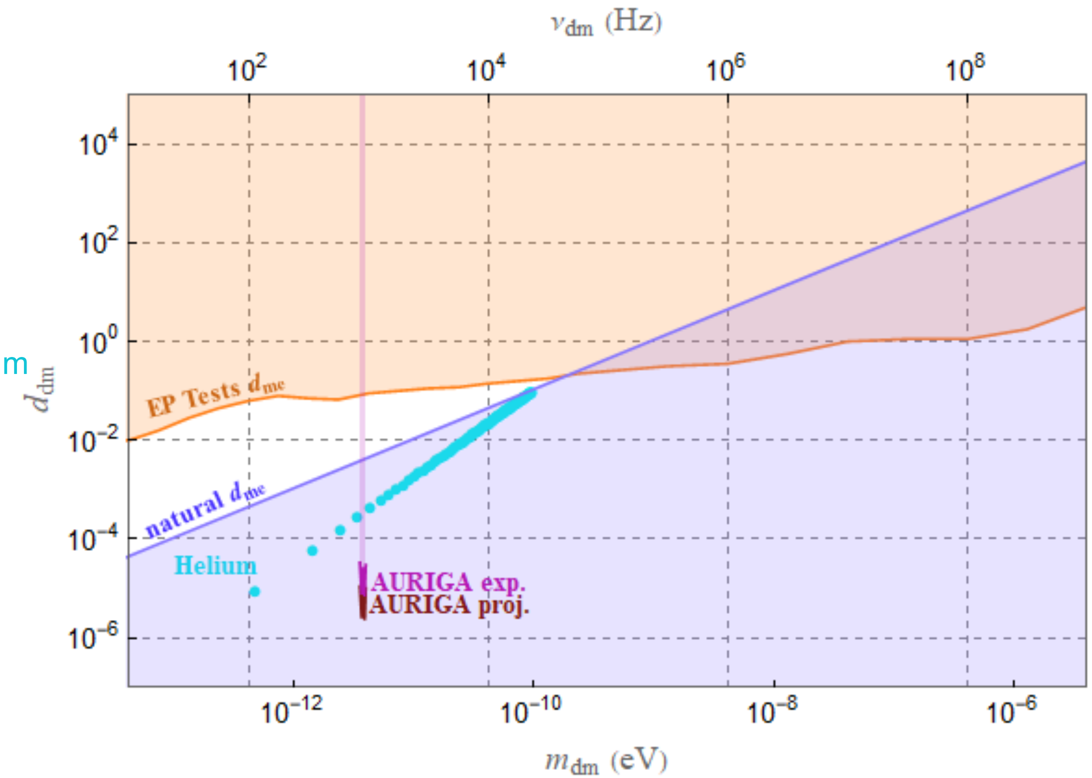
$$F_0 \equiv \sqrt{2\frac{e^2\rho_{\mathrm{DM}}}{\epsilon_0}} \approx 6\times10^{-16}\ \mathrm{N}$$

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

Scalar DM parameter space

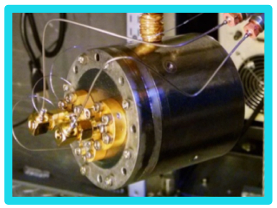


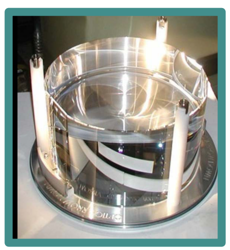
- 2.7 kg Superfluid helium (Niobium shell)
- 11cm radius
- 50cm length
- Q=10^9
- T=10mK



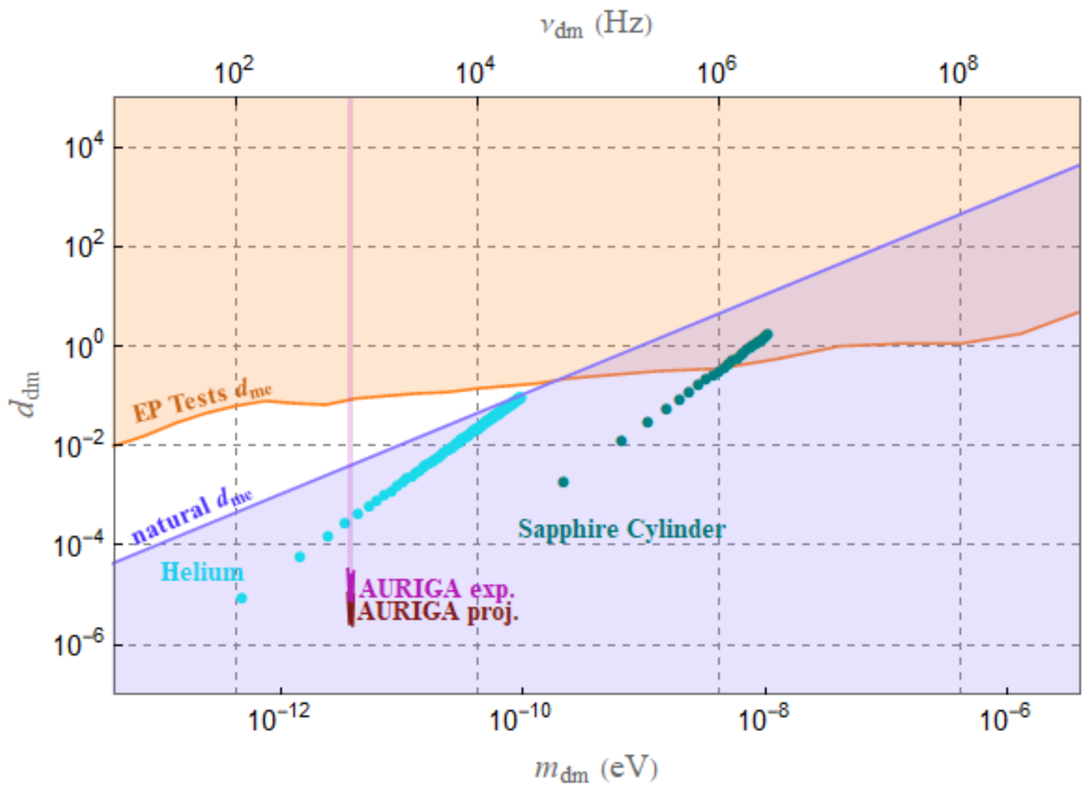
L. De Lorenzo and K. Schwab, *Journal of Low Temperature Physics* 186, 233 (2017)

Scalar DM parameter space



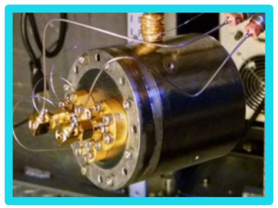


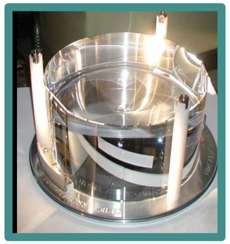
- Sapphire test mass
- 15 mm radius
- 10cm length
- Q=10^9
- T=10 K

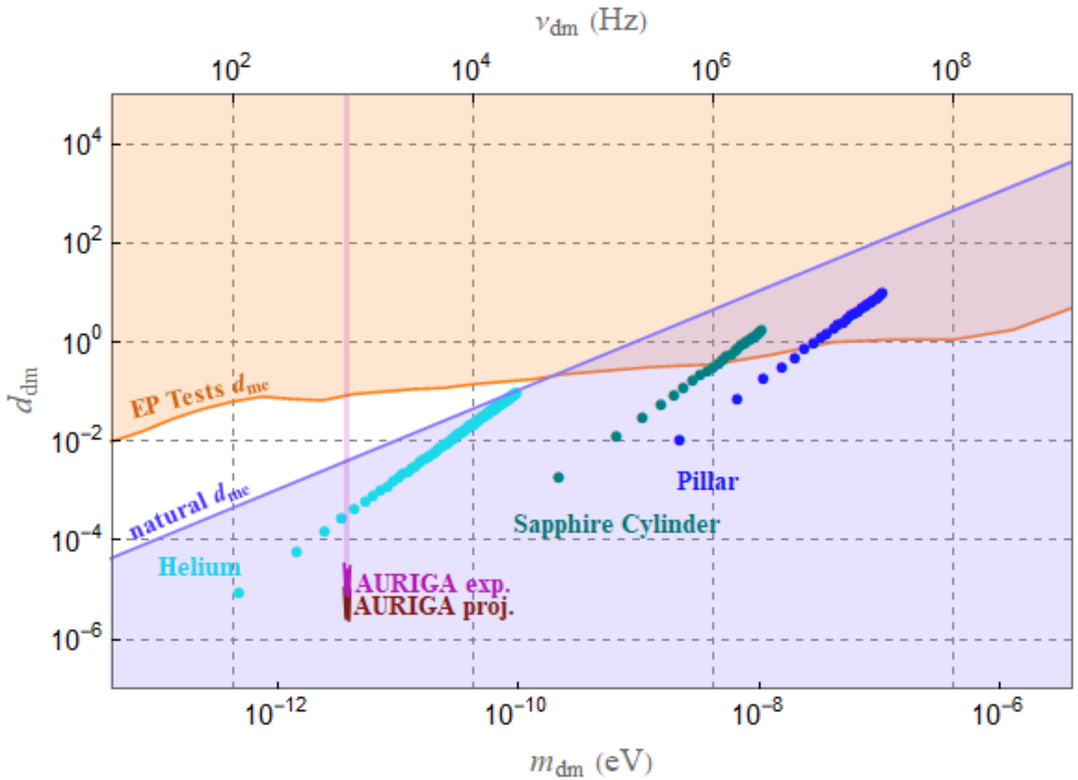


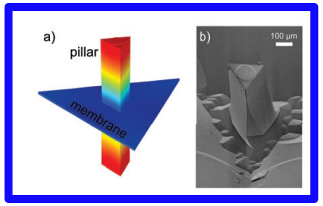
Rowan et al. *Physics Letters A* 265.1-2 (2000): 5-11.

Scalar DM parameter space





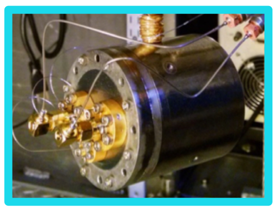


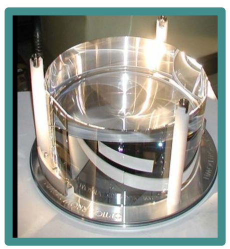


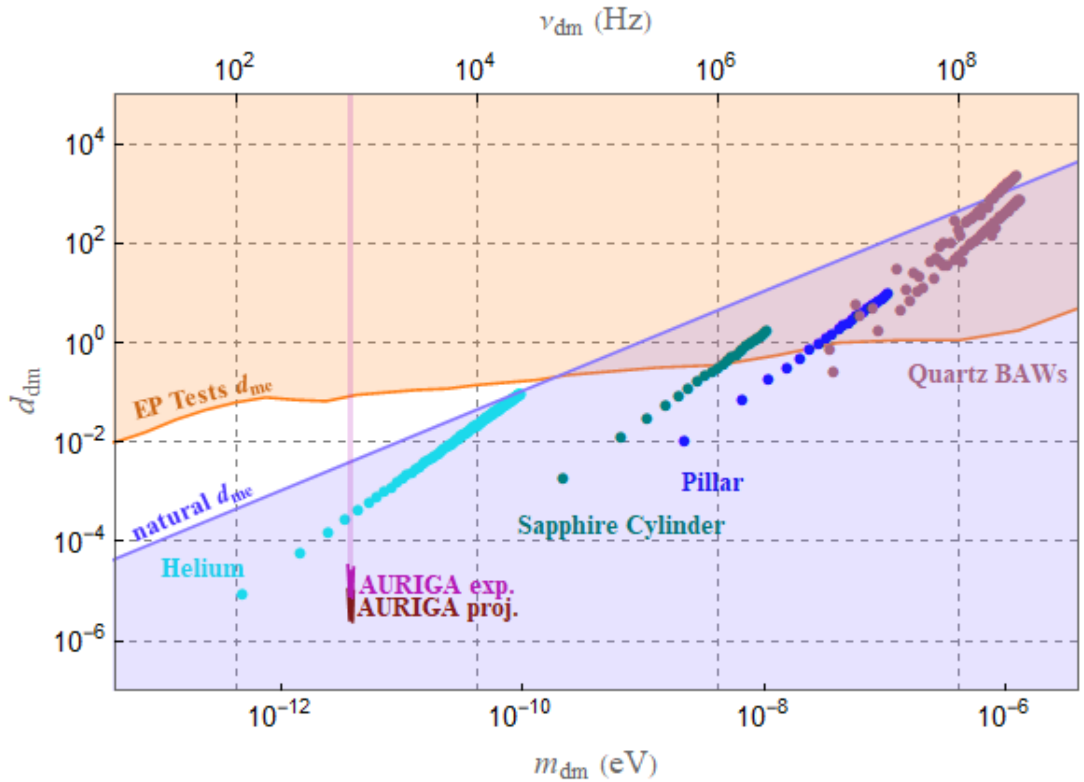
- Sapphire micropillar
- 0.3 g mass
- 1 cm length
- Q=10^9
- T=10mK

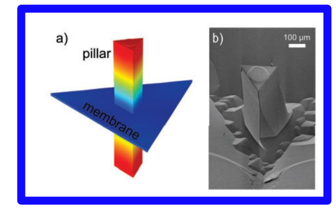
L. Neuhaus, *Cooling a macroscopic mechanical oscillator close to its quantum ground state*, Ph.D. thesis, Universite Pierre et Marie Curie - Paris VI (2016).

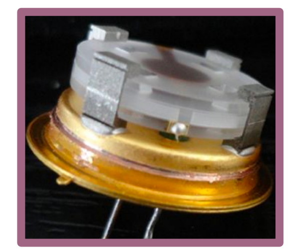
Scalar DM parameter space









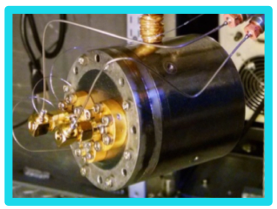


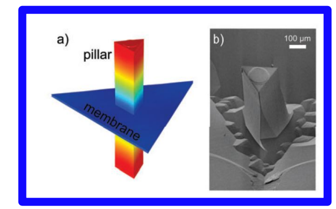
- Quartz BAW resonator
- 15 mm radius
- 1 mm length
- $Q\sim10^9$
- T=10mK

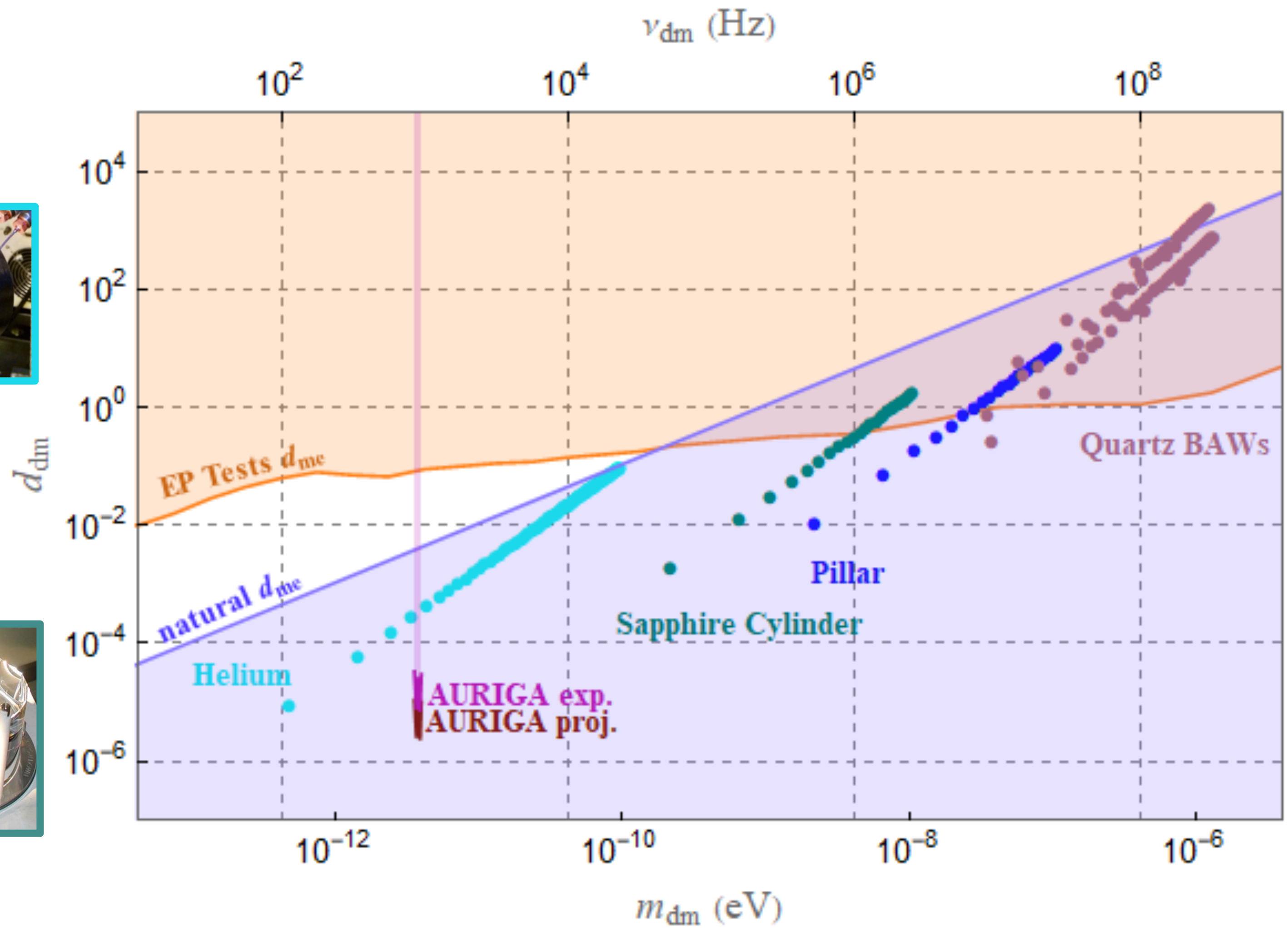
M. Goryachev and M. E. Tobar. *Phys. Rev. D* 90, 102005 (2014).
S. Galliou et al. *Scientic reports* 3, 2132 (2013).
M. Goryachev et al. *Applied Physics Letters* 100, 243504 (2012).
Arvanitaki et al. Physical review letters 116.3 (2016): 031102.

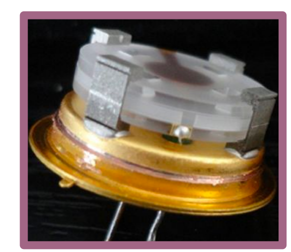
Mechanical detectors for scalar Dark Matter

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









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