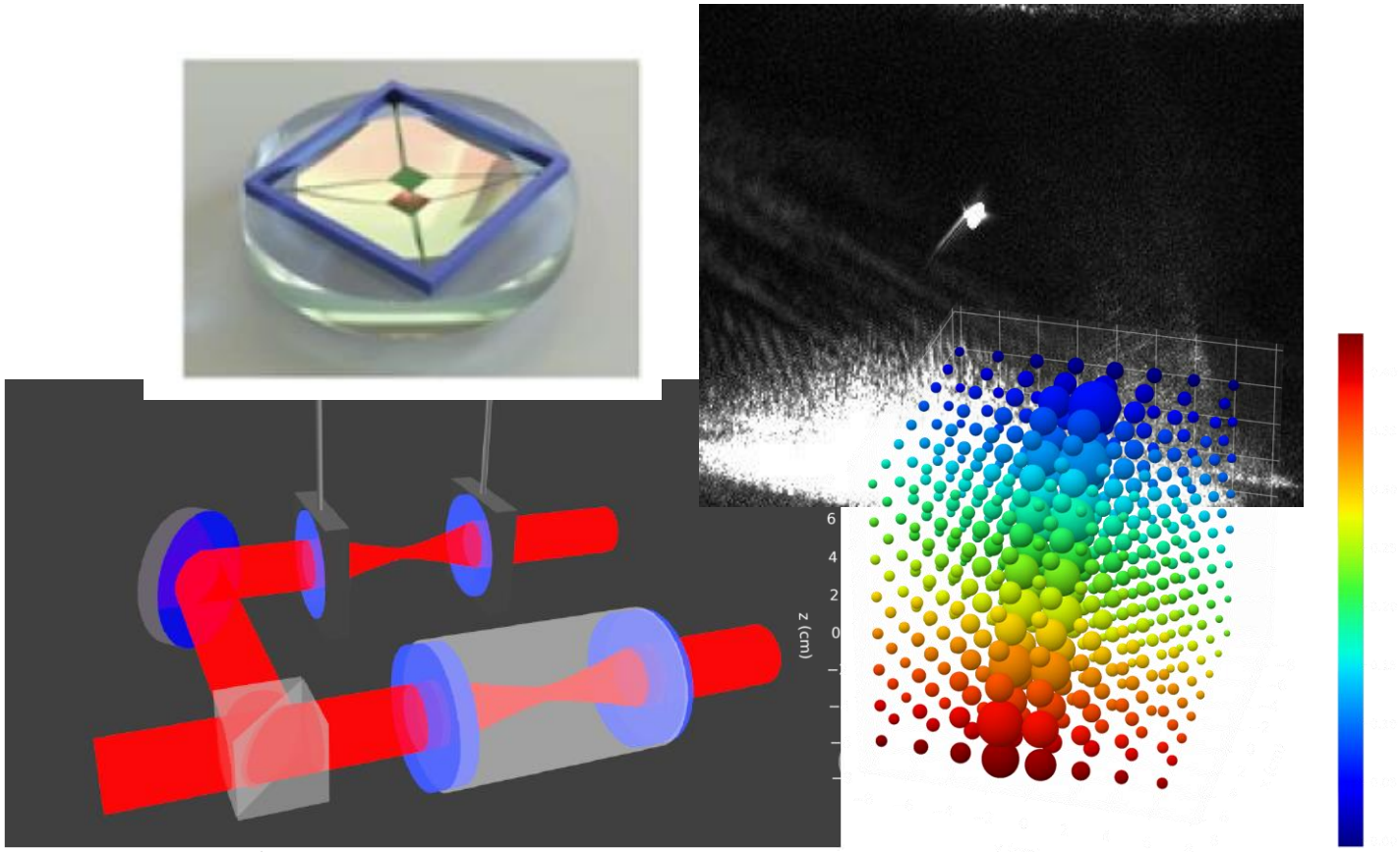
Primer: Optomechanical systems for dark matter, gravity, and fundamental physics



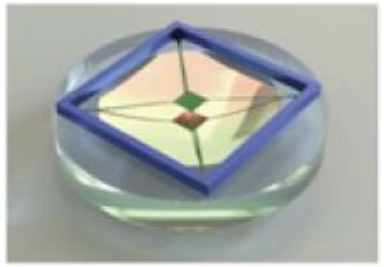
A.Geraci

Northwestern University

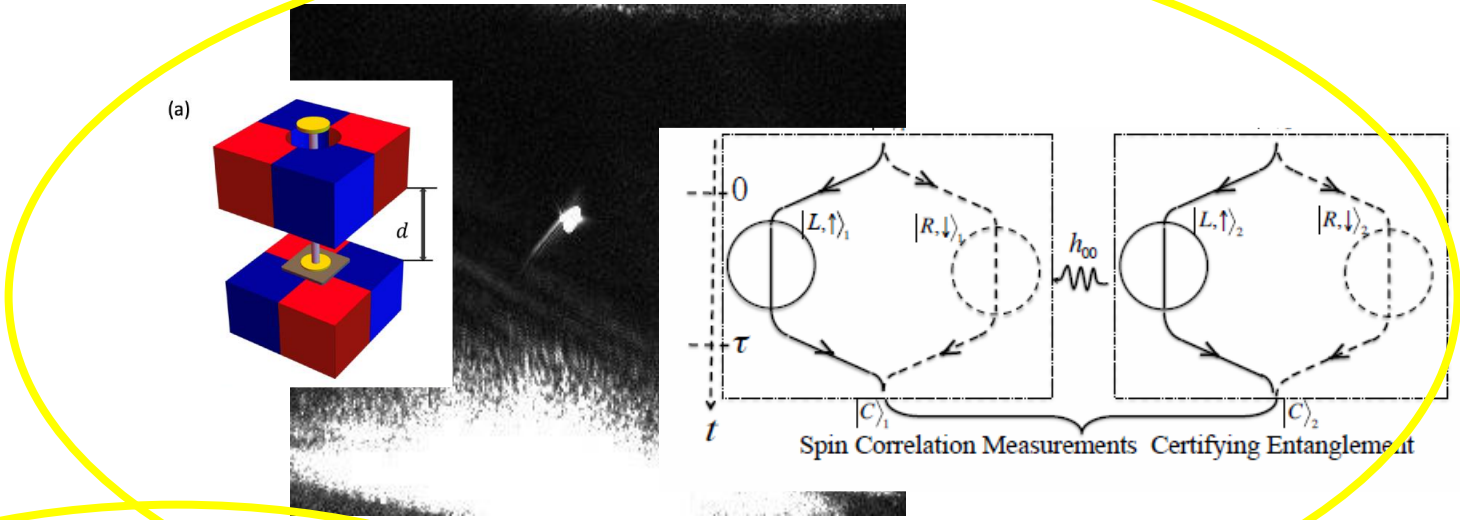
Center for Fundamental Physics (CFP)

DRD5 Collaboration meeting 31 Oct 2025 – WP 5 talk

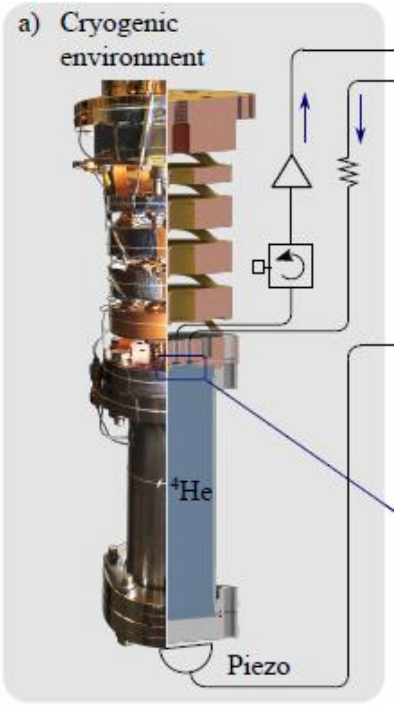
Optomechanical sensors for dark matter and gravity



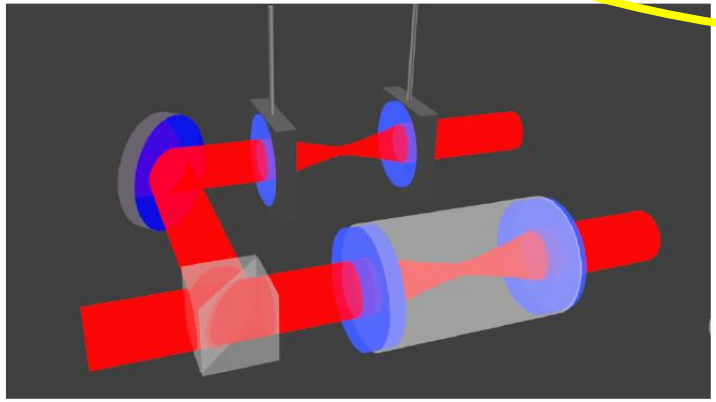
Nanofabricated and bulk mechanical sensors



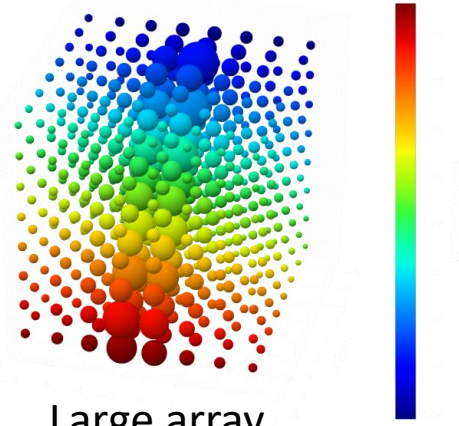
Levitated (opto)-mechanical sensors



Superfluid Helium dark Matter detectors



Optical cavity based dark matter detectors



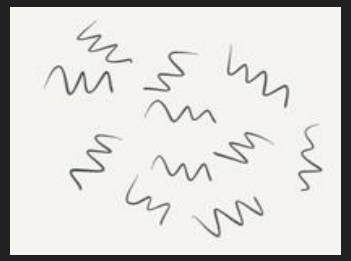
Large array mechanical detectors

Also talks: WP-5 and WP-4 (Tues: Mazumdar, Higgins, Wed: Wilson, Datta, Marino)

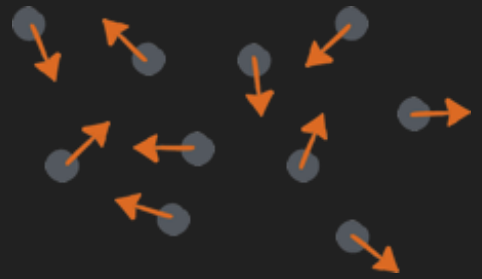
Outline

- Wavelike DM
  - -Scalar-like: Optical-cavity-based detectors
  - -Vector-like: Accelerometer detectors
- Particle/extended-object DM
  - -Gravitational Wave detectors for DM (also Axions)
  - -Levitated microspheres
- Tests of Gravity in quantum systems
- Future directions

Dark Matter



Field-like



Particle-like

$1eV/c^2$

Hubble

Planck

Neutrinos
Dark Energy

Standard
Model

LHC

10^{-33} 10^{-21} 10^{-3} 10^{5} 10^{11} 10^{28}

Axions
~10^{-2}eV to 10^{-11}eV

WIMPs
~10-1000 GeV

10^{-22}

Possible Dark Matter Mass Range

Ultra-light scalar Dark Matter

- Dark Matter mass scales:

  $>10^{-22}$ eV (size of dwarf galaxies)

➢ Ultralight DM looks like coherent field rather than particle

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

$$\phi_0 = \hbar\sqrt{2\rho_{\mathrm{DM}}}/\left(m_\phi c\right)$$

➢ Techniques for detecting oscillating scalar DM:

- Atomic clocks
- Bar detectors
- Torsion Balances
- Atom Interferometers

Asimina Arvanitaki, Savas Dimopoulos, and Ken Van Tilburg, Phys. Rev. Lett. **116**, 031102 (2016)
Asimina Arvanitaki, Junwu Huang, and Ken Van Tilburg, Phys. Rev. D 91, 015015 (2015)
Asimina Arvanitaki, Peter W. Graham, Jason M. Hogan, Surjeet Rajendran, and Ken Van Tilburg
Phys. Rev. D 97, 075020 (2018)
Peter W. Graham, David E. Kaplan, Jeremy Mardon, Surjeet Rajendran, William A. Terrano
Phys. Rev. D 93, 075029 (2016)

Ultra-light scalar DM

$$\phi(t,\mathbf{r}) \approx \frac{\hbar}{m_\phi c}\sqrt{2\rho_{\rm DM}}\cos\left[2\pi f_\phi t - \mathbf{k}_\phi\cdot\mathbf{r} + ...\right]$$

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

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

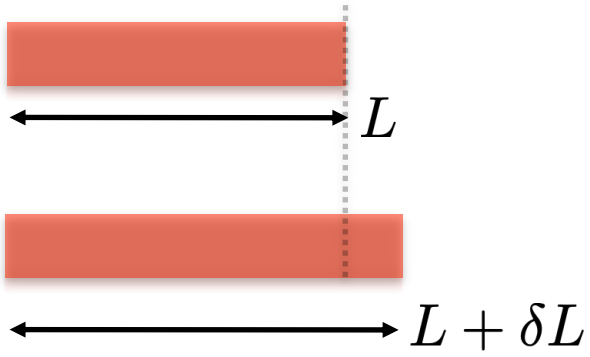
Wavenumber: $k_\phi = m_\phi v/\hbar$ $\qquad v = 10^{-3}c$

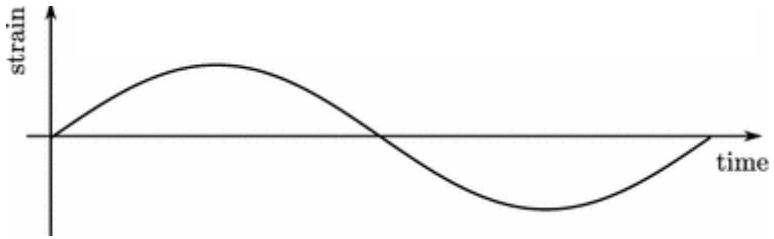
Coherence time: $\tau_c \approx \frac{10^6}{\omega_{\rm dm}}$

$$\frac{\delta m_e(t,\mathbf{r})}{m_{e,0}} = d_{m_e}\sqrt{4\pi\hbar c}E_P^{-1}\phi(t,\mathbf{r})$$

$$\frac{\delta\alpha(t,\mathbf{r})}{\alpha_0} = d_e\sqrt{4\pi\hbar c}E_P^{-1}\phi(t,\mathbf{r})$$

Isotropic strain in material objects due to variation of atomic size





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

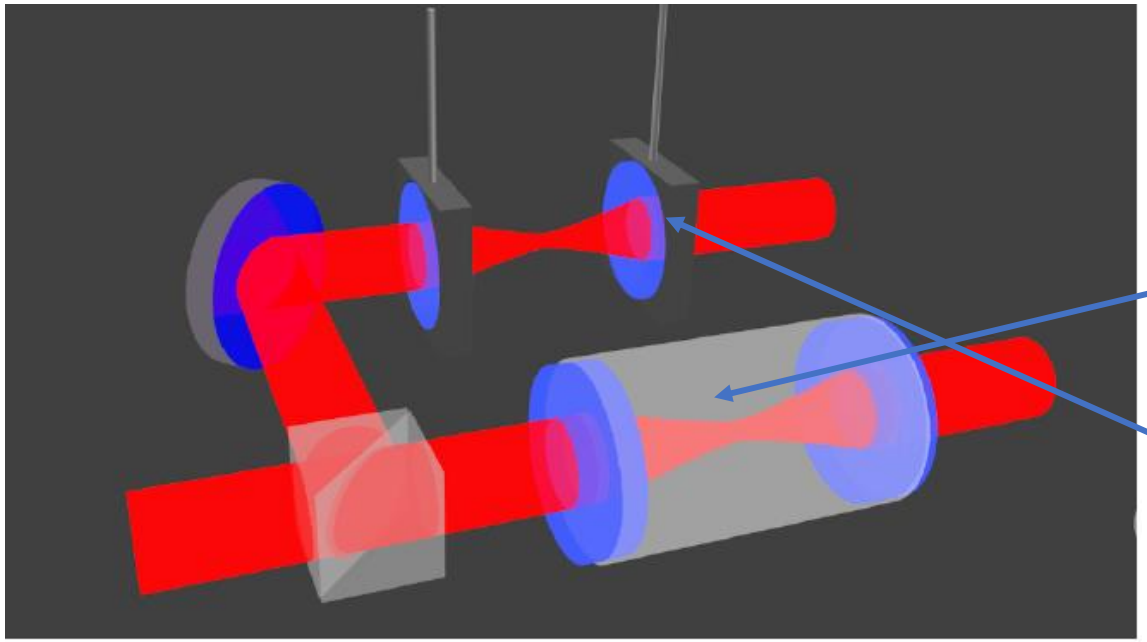
Detecting ultra-light scalar dark matter with optical cavities

$$\phi(t,\mathbf{r}) \approx \frac{\hbar}{m_\phi c}\sqrt{2\rho_{\rm DM}}\cos\left[2\pi f_\phi t - \mathbf{k}_\phi\cdot\mathbf{r} + ...\right]$$

$$\frac{\delta m_e(t,\mathbf{r})}{m_{e,0}} = d_{m_e}\sqrt{4\pi\hbar c}E_P^{-1}\phi(t,\mathbf{r})$$

$$\frac{\delta\alpha(t,\mathbf{r})}{\alpha_0} = d_e\sqrt{4\pi\hbar c}E_P^{-1}\phi(t,\mathbf{r})$$

oscillations in size of atoms (and strain in material objects)



Dark matter field causes strain in rigid cavity at f_ϕ

Suspended cavity cannot respond quickly enough for f_ϕ in audio-band (100 Hz- 100 kHz)

AG, C. Bradley, W. Gao, J. Weinstein, A. Derevianko, PRL (2019)

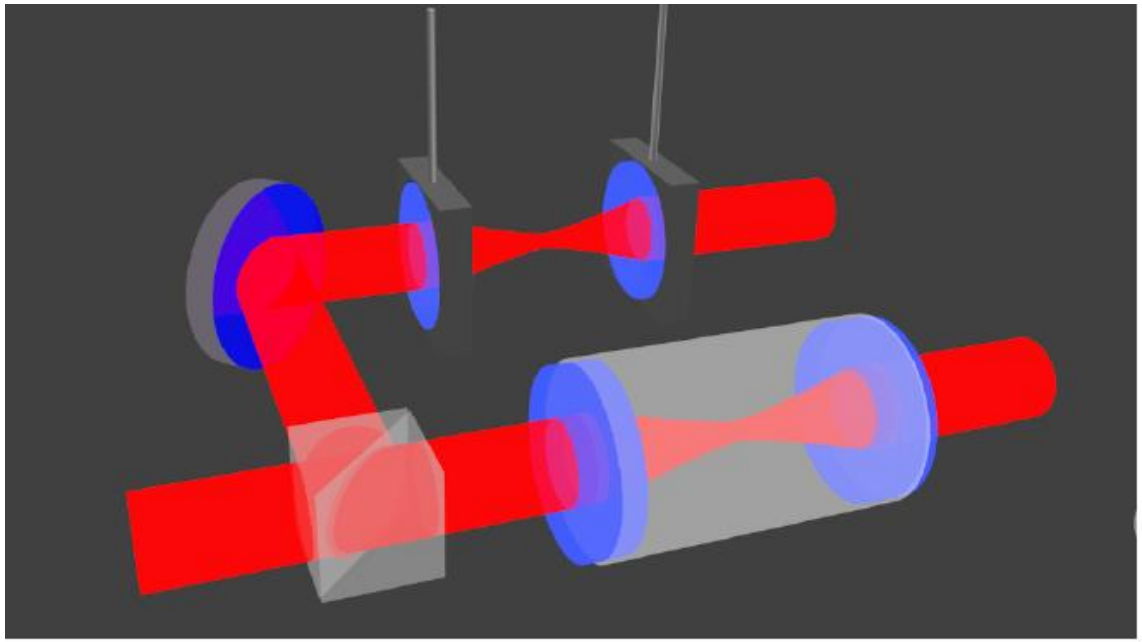
Detecting ultra-light scalar dark matter with optical cavities

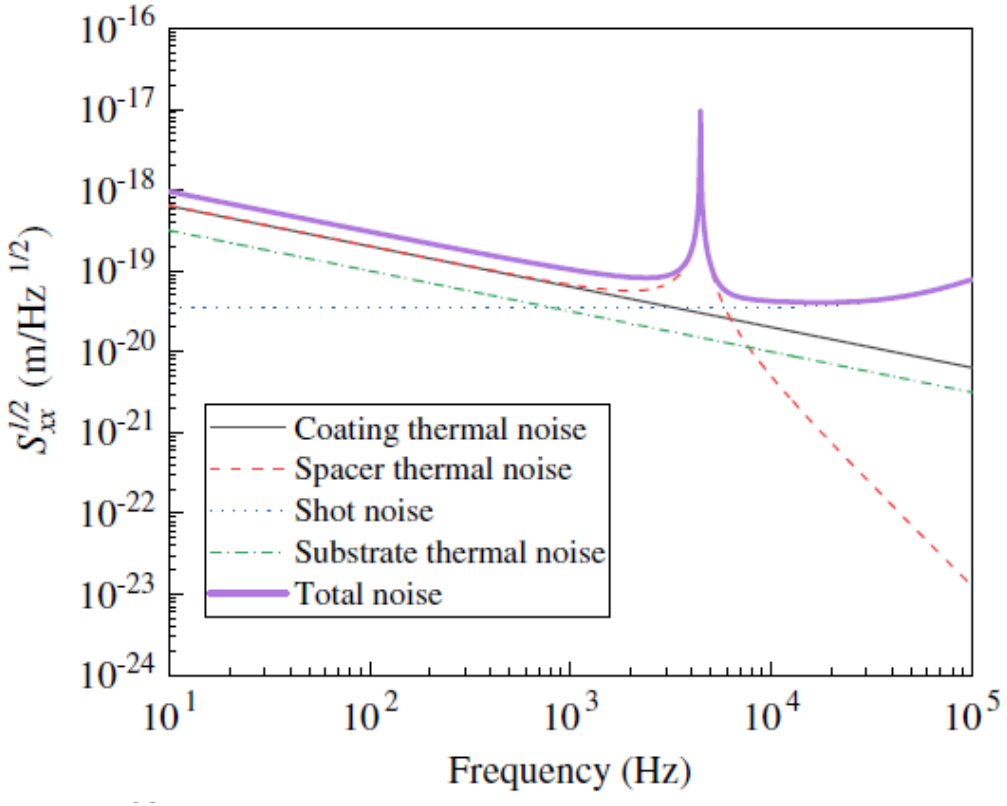
$$\phi(t,\mathbf{r}) \approx \frac{\hbar}{m_\phi c}\sqrt{2\rho_{\rm DM}}\cos\left[2\pi f_\phi t - \mathbf{k}_\phi\cdot\mathbf{r} + ...\right]$$

$$\frac{\delta m_e(t,\mathbf{r})}{m_{e,0}} = d_{m_e}\sqrt{4\pi\hbar c}E_P^{-1}\phi(t,\mathbf{r})$$

$$\frac{\delta\alpha(t,\mathbf{r})}{\alpha_0} = d_e\sqrt{4\pi\hbar c}E_P^{-1}\phi(t,\mathbf{r})$$

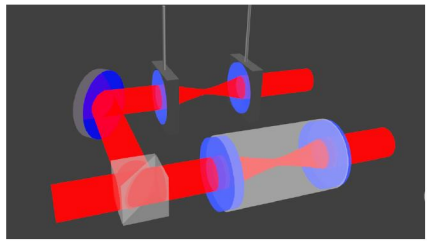
oscillations in size of atoms (and strain in material objects)

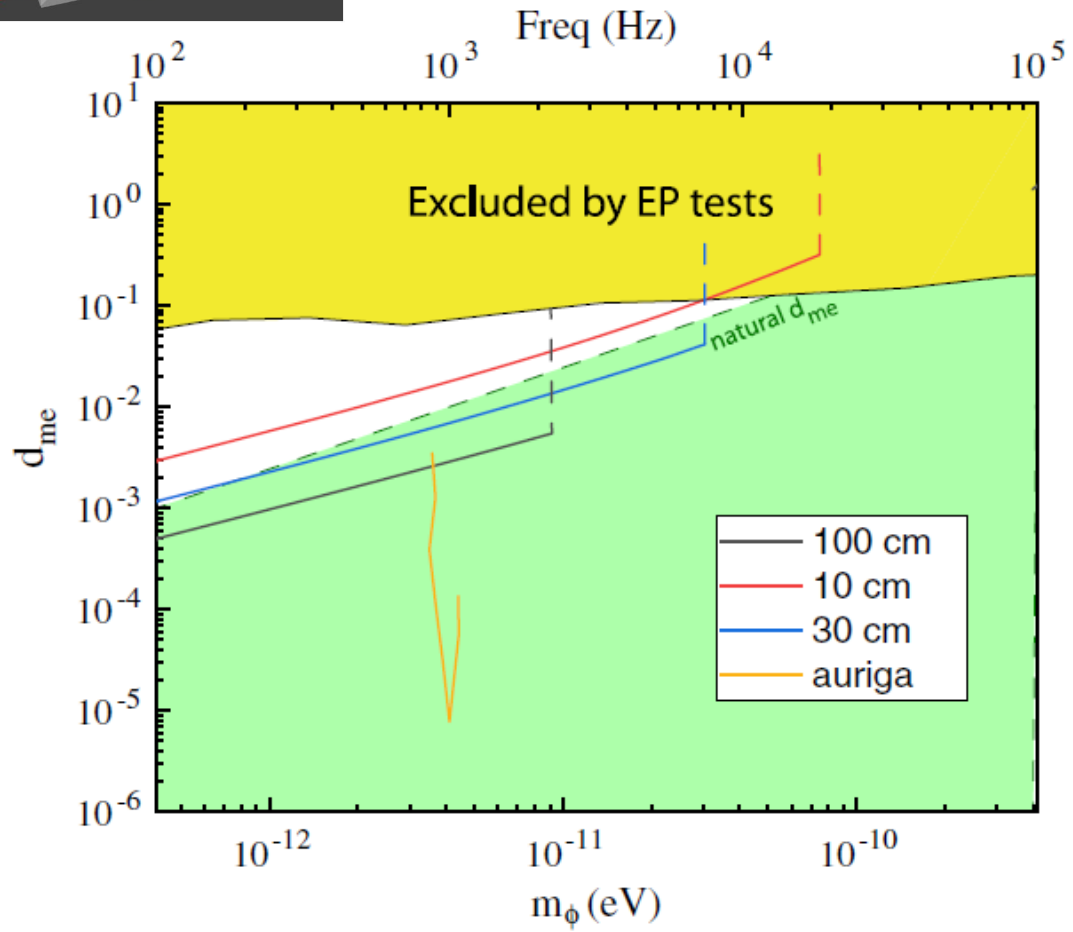




AG, C. Bradley, W. Gao, J. Weinstein, A. Derevianko, PRL (2019)

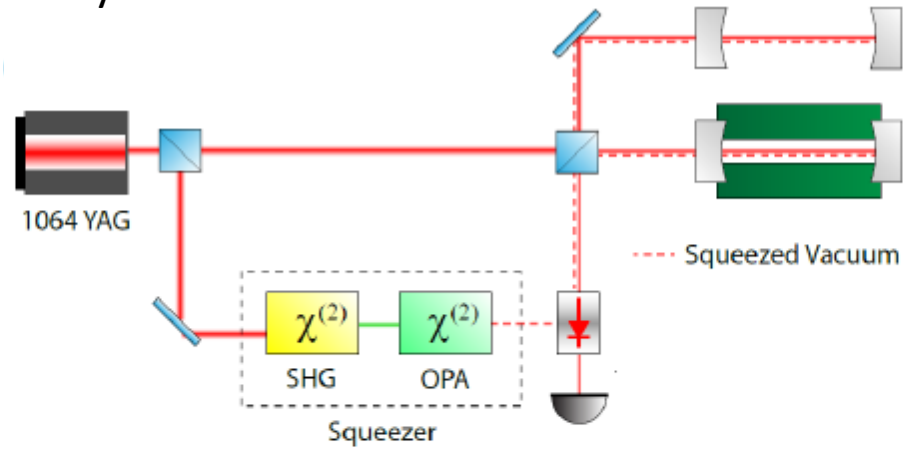
Reach for variation of electron mass d_{me}



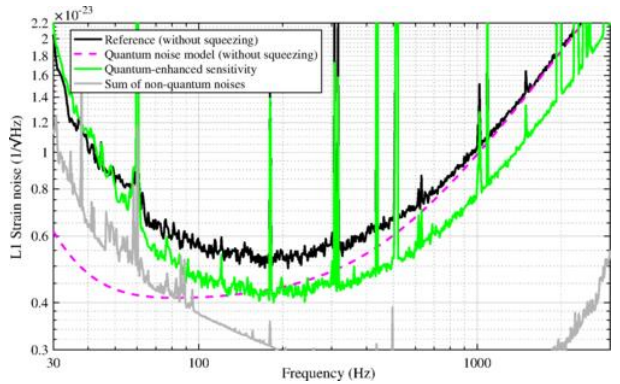


AG, C. Bradley, W. Gao, J. Weinstein, A. Derevianko, PRL (2019)

-Cryogenic experiment for low thermal noise to reach the shot noise limit
- quantum squeezing techniques can improve sensitivity >1 kHz

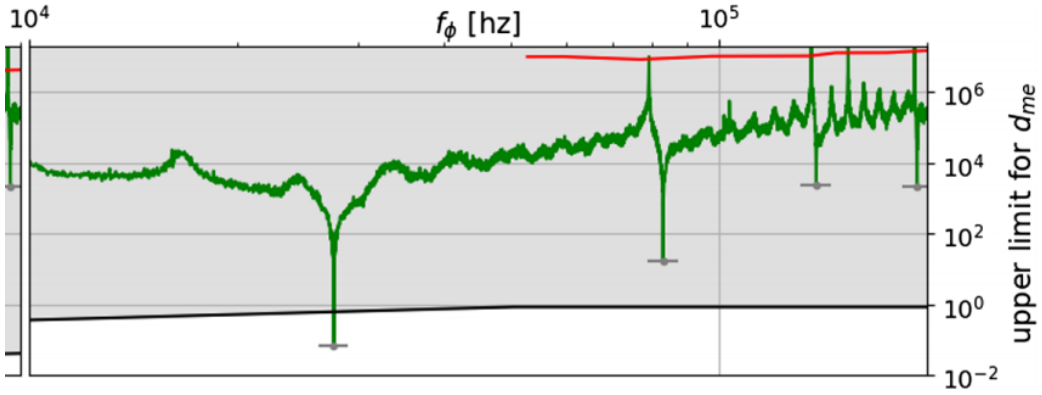


Borrow proven methods from GW community (LIGO, VIRGO):

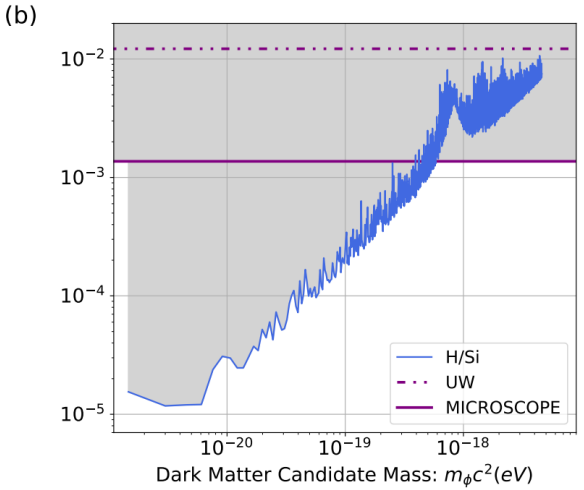


Recent DM limits from other cavity experiments

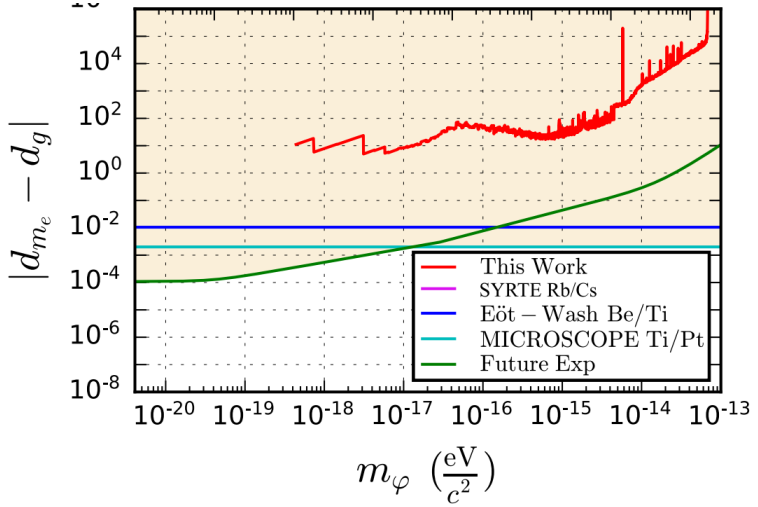
Experiments are **already** constraining scalar dark matter!



Savalle et al. PRL **126**, 051301 (2021).

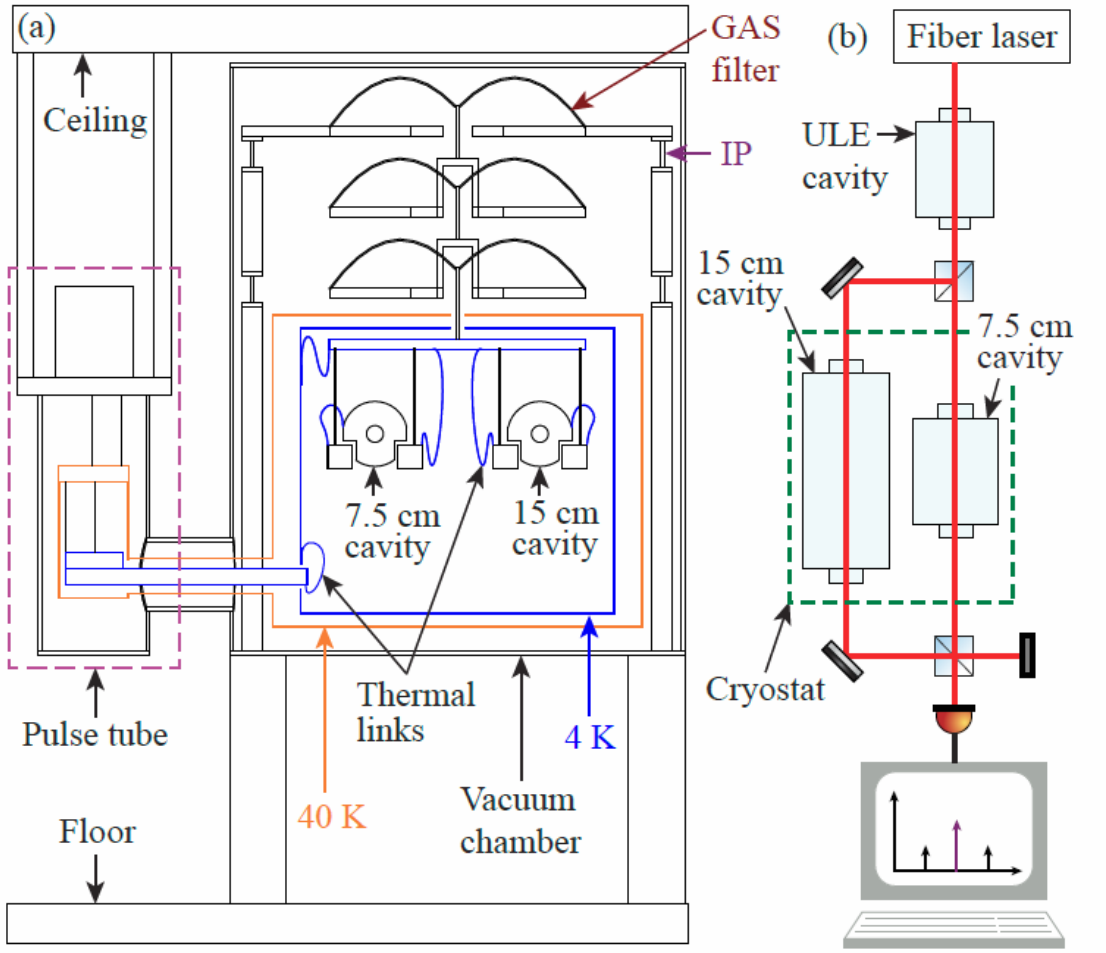


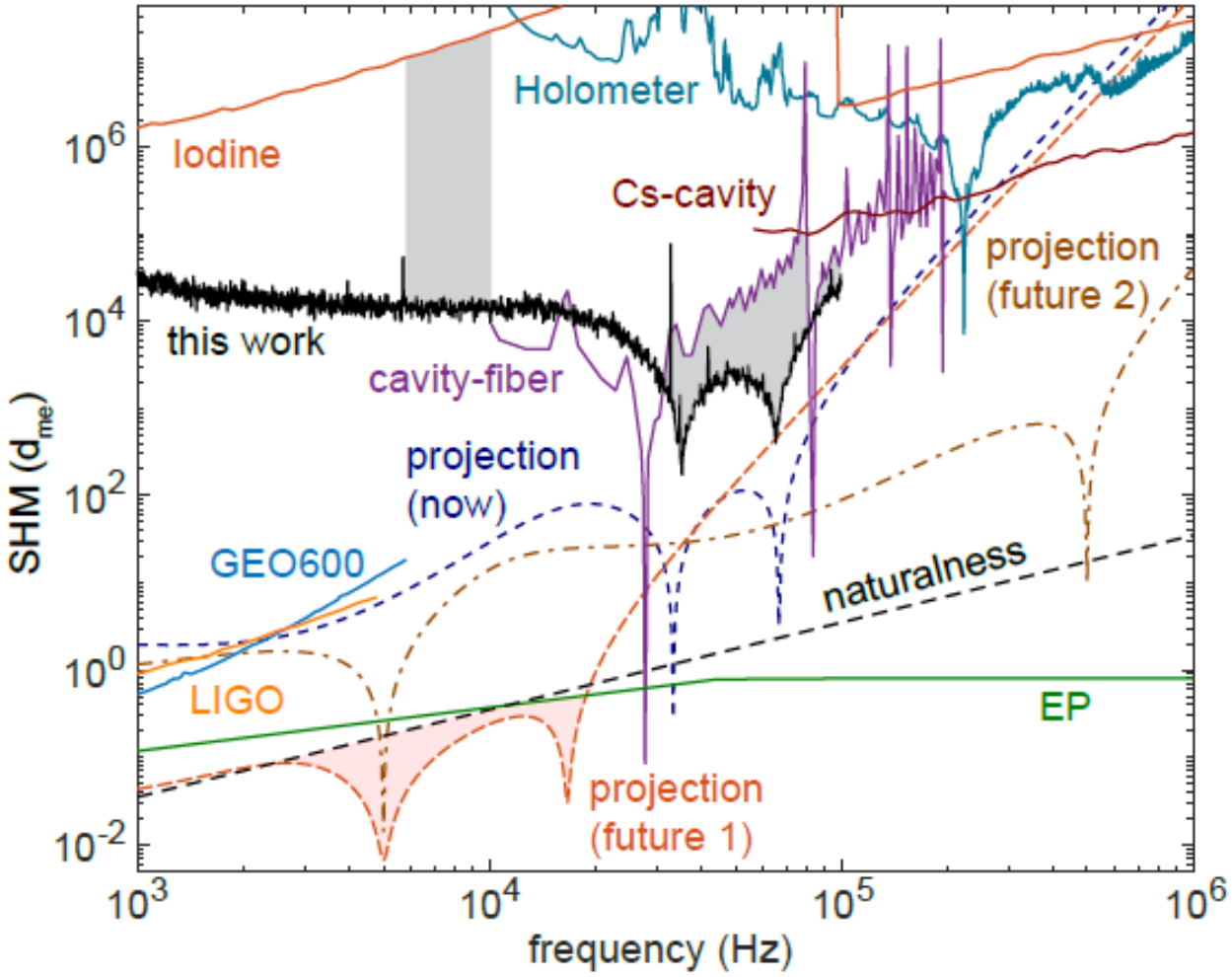
Kennedy et al. PRL **125**, 201302 (2020).



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

Recent results from cavity comparison DM search

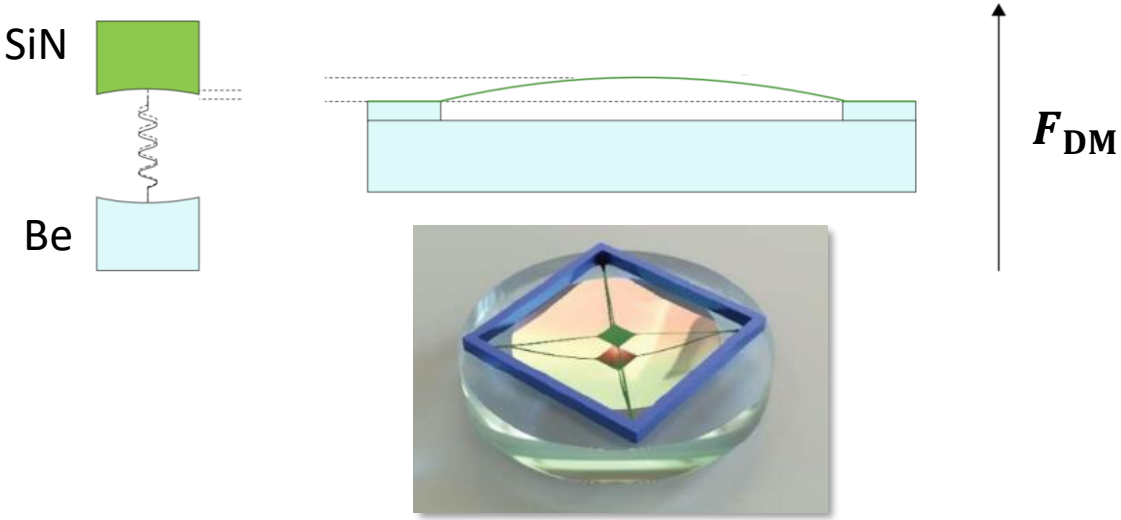


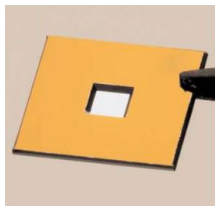


T. Deshpande, A.Ionescu, N. Miller, Z. Wang,G.Gabrielse, AG, T. Kovachy, arxiv: 2412.20623

A membrane-based dark photon detector

Differential acceleration between materials (e.g. if coupled to B-L)





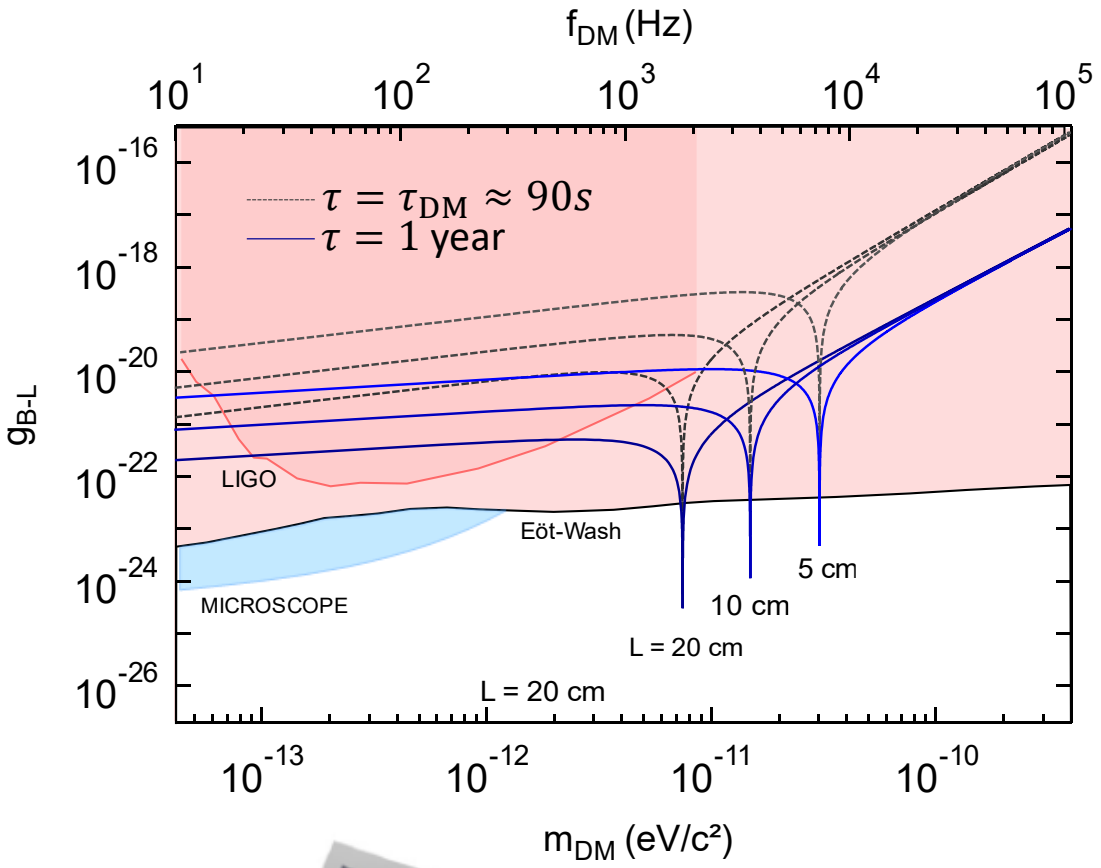
Si_3N_4 membrane
($Q \sim 10^9$)

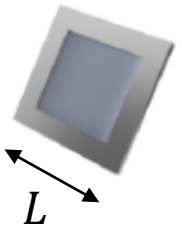
+

Be Mirror
(Webb telescope)

+

Cryogenics
(100 mK)

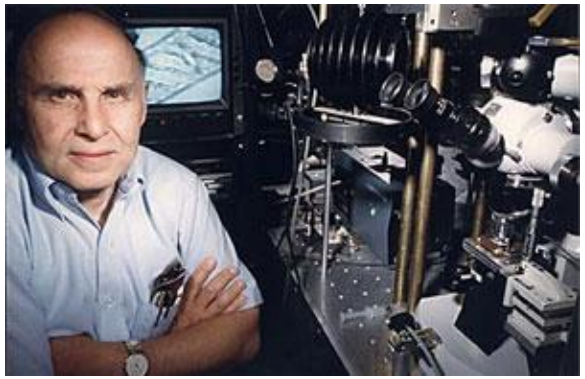


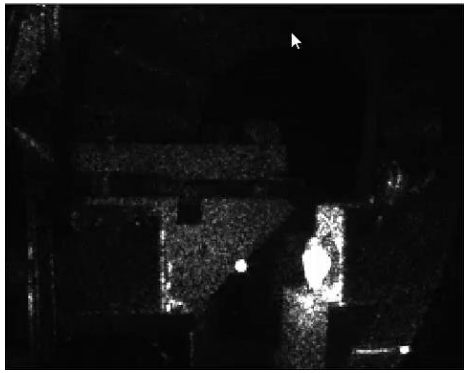


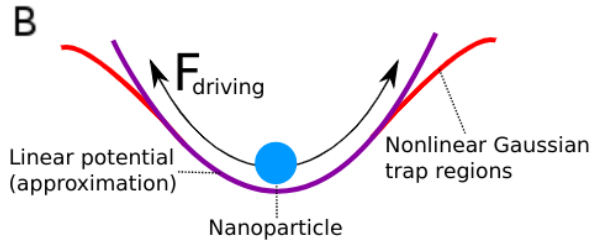
Manley et. al. PRL 126 061301 (2021)

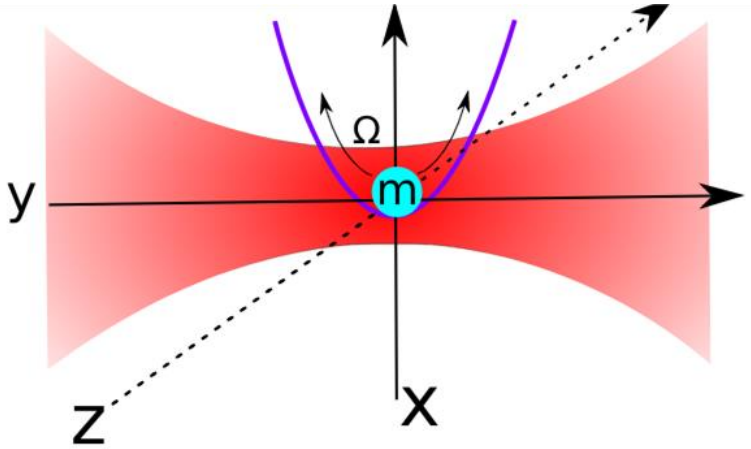
Levitated optomechanics - brief introduction

- Ashkin, Bell Labs, 1970s Optical tweezers → biology, biophysics
- Ashkin (76) Levitation in high vacuum









1. Polarisable neutral glass particles act as high field seekers - trapped in laser focus
2. High Q factors ~ 10^12 → excellent force sensors
3. Can reduce the effective motional 'temperature' of such objects through feedback schemes

(Ground) state of the art:

Dynamical backaction:

Measurement based cooling:

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REPORT

Cooling of a levitated nanoparticle to the motional quantum ground state

Uroš Delić[1,2,*], Manuel Reisenbauer[1], Kahan Dare[1,2], David Grass[1,†], Vladan Vuletić[3], Nikolai Kiesel[1], ...

+ See all authors and affiliations

Science 21 Feb 2020:
Vol. 367, Issue 6480, pp. 892-895
DOI: 10.1126/science.aba3993

A nanoparticle trapped and cooled

Cooling massive particles to the quantum ground state allows fundamental tests of quantum mechanics to be made; it would provide an experimental probe of the boundary between the classical and quantum worlds. Delić *et al.* laser-cooled an optically trapped solid-state object (a ~150-nanometer-diameter silic a nanoparticle) into its quantum ground state of motion starting from room temperature. Because the object is levitated using optical forces, the experimental configuration can be switched to free fall, thereby providing a test bed for several macroscopic quantum experiments.

Science, this issue p. **892**

nature

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Article | Published: 14 July 2021

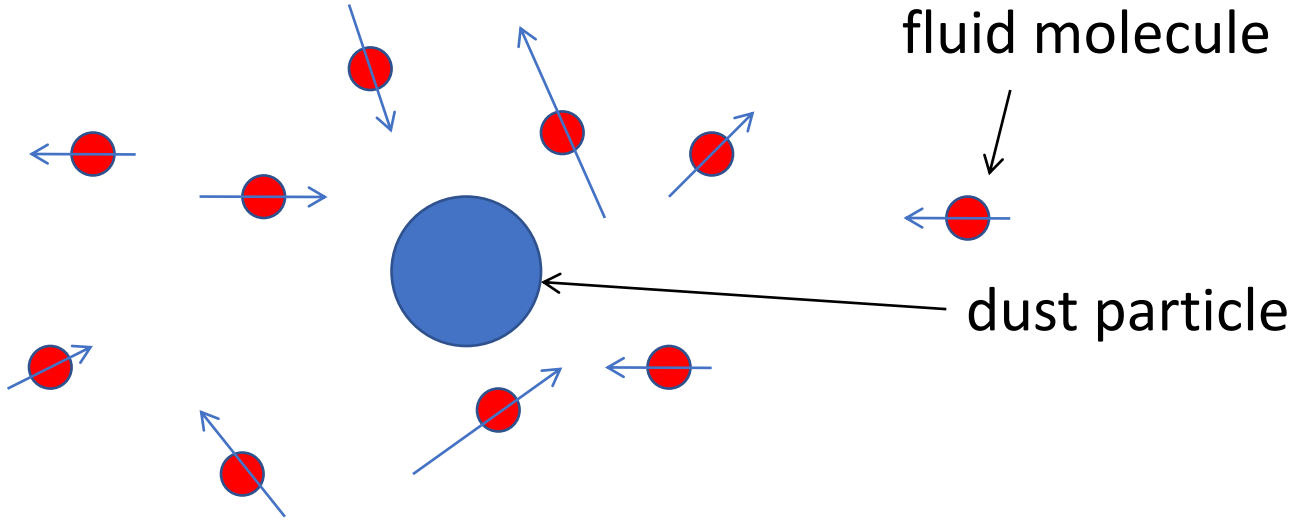
Quantum control of a nanoparticle optically levitated in cryogenic free space

Felix Tebbenjohanns, M. Luisa Mattana, Massimiliano Rossi, Martin Frimmer & Lukas Novotny

Nature **595**, 378–382 (2021) | Cite this article

Fundamental limitation: thermal noise

Brownian motion – random "kicks" given to particle due to thermal bath



- Random "kicks" are given to sensor due to finite T of oscillator

$$\frac{1}{2}k\langle x^2\rangle = \frac{1}{2}k_B T \quad \Longrightarrow \quad F_{\min} = \left(\frac{4kk_B Tb}{Q\omega_0}\right)^{1/2}$$

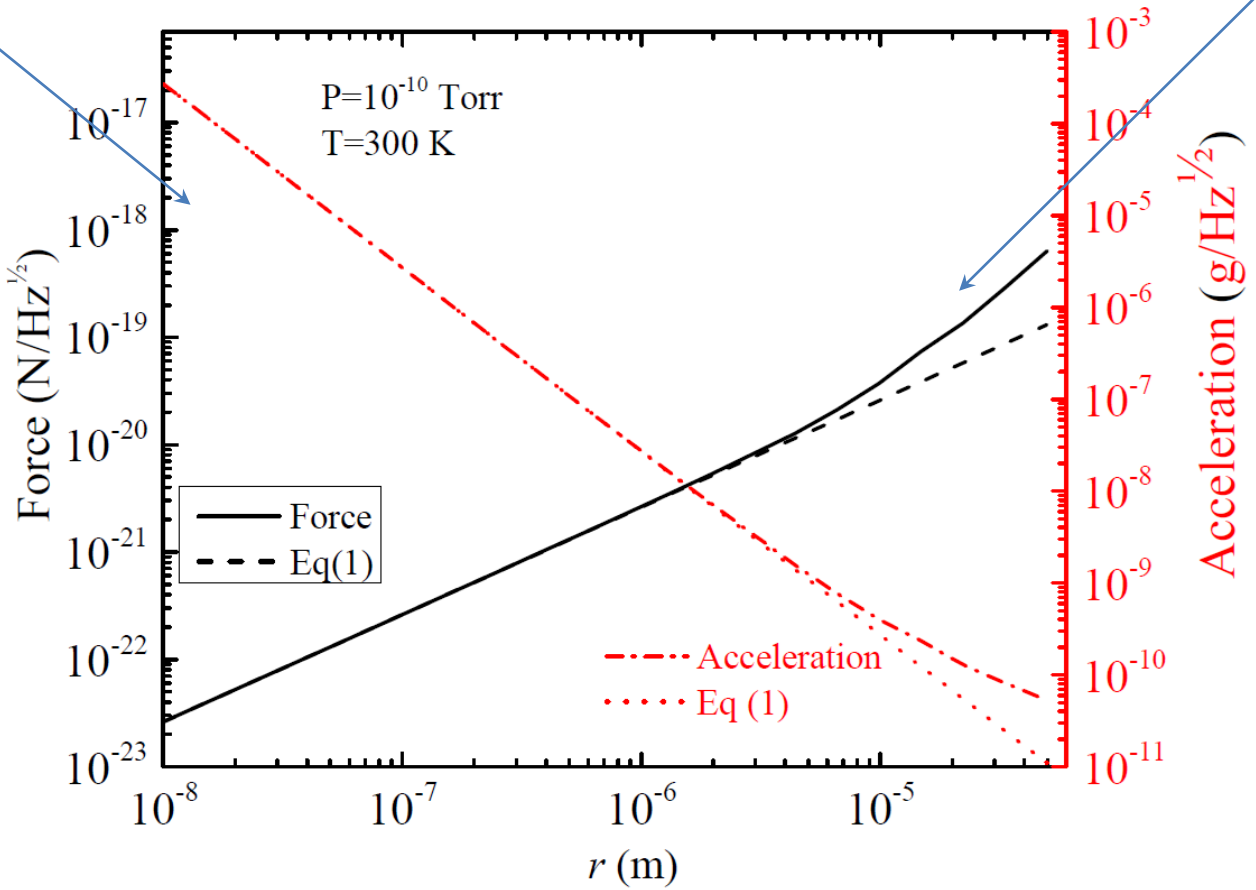
Projected Force sensitivity

Cantilever sensors

$$F_{\min} = \left(4 k_B T \gamma m\right)^{1/2} \quad (1)$$

Photon recoil heating

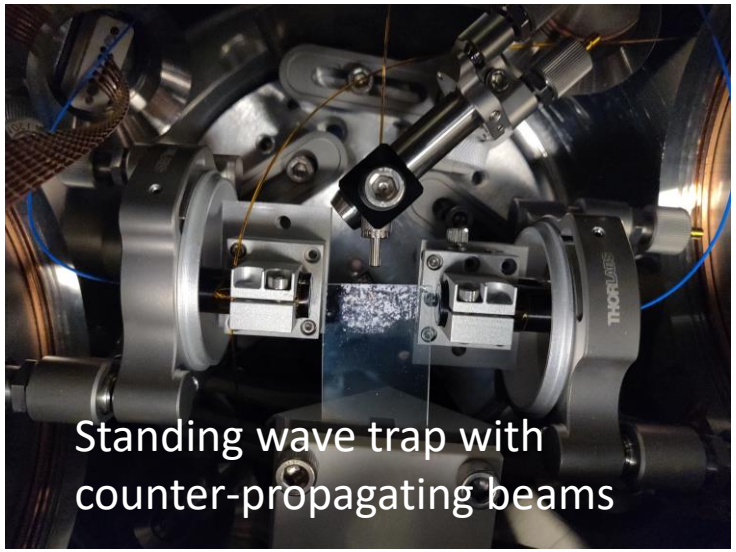
Seen recently by Novotny group V. Jain et. al., PRL 116, 243601 (2016)

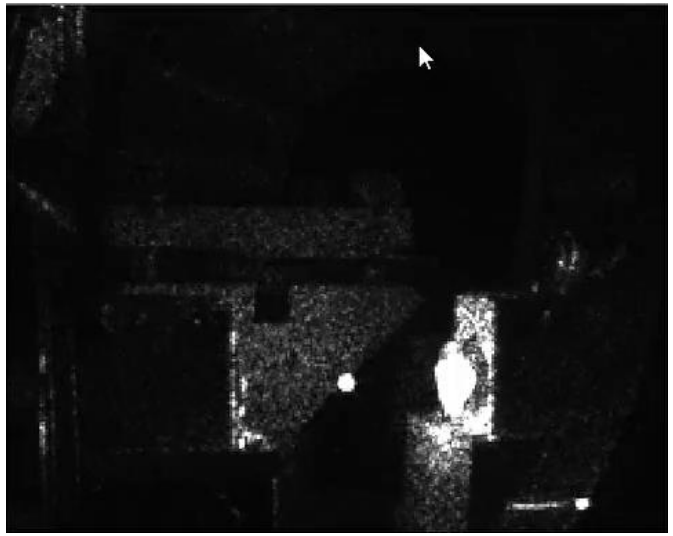


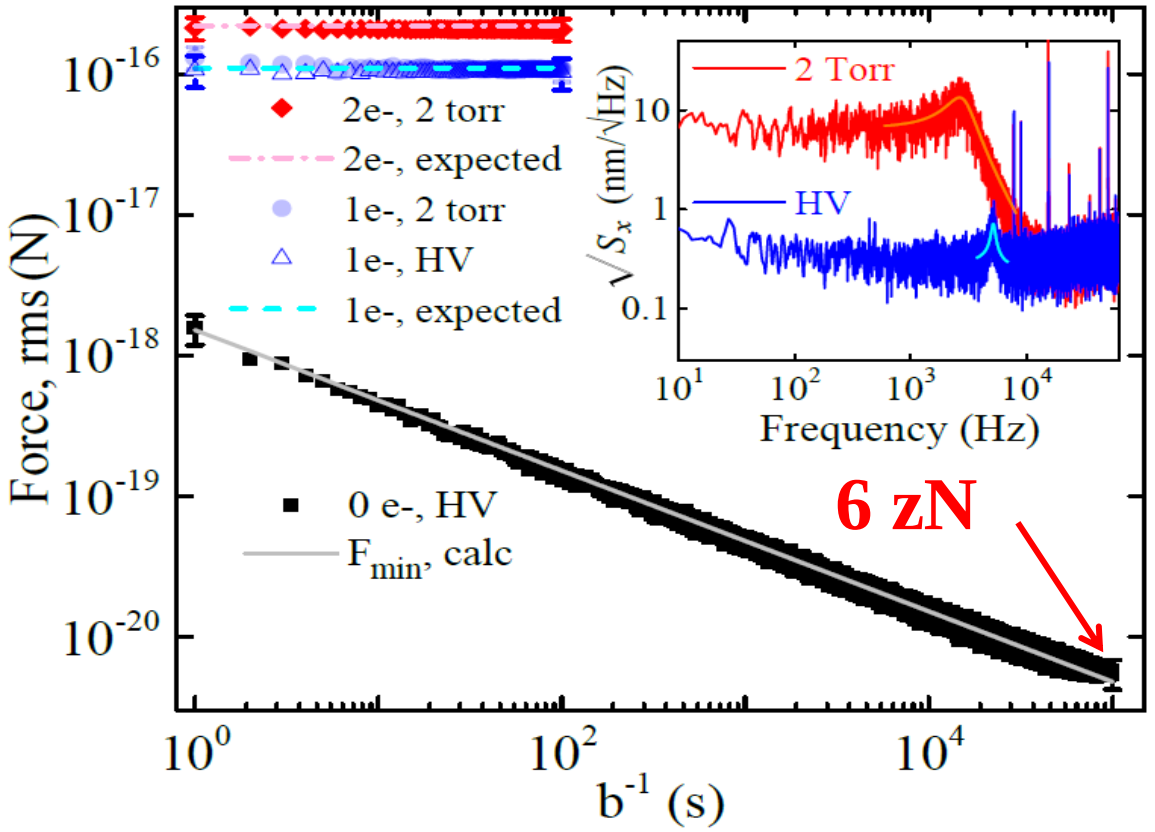
20 zN/Hz$^{1/2}$ Gieseler, Novotny, Quidant (Nature Phys. 2013)

Z. Yin, A. Geraci, T. Li, Int. J. Mod. Phys. B 27,1330018 (2013).

Calibrated zN force sensitivity



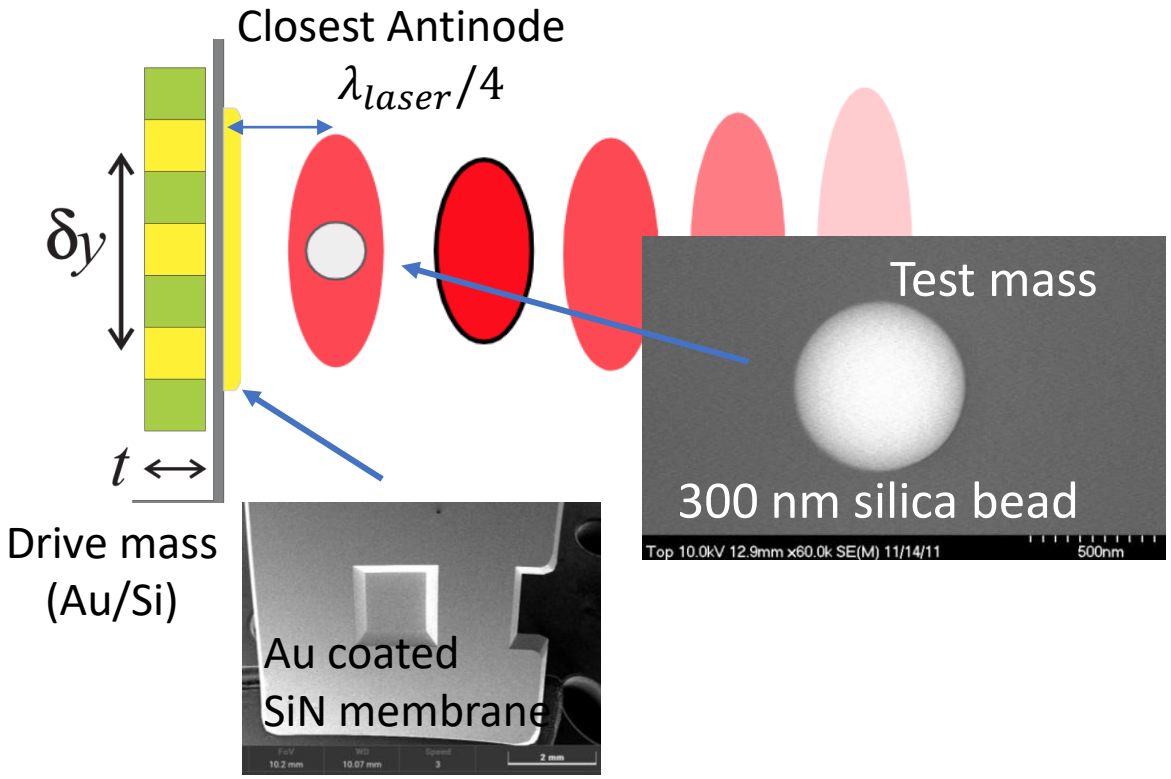




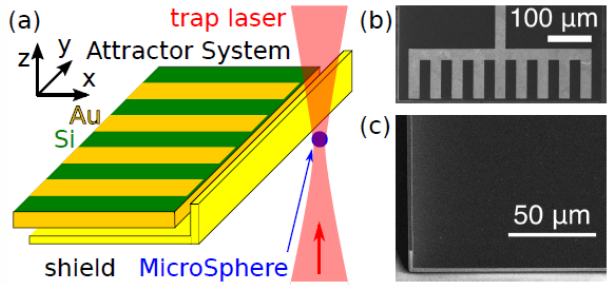
zeptonewton sensitivity in a standing wave trap w/ 3-D laser feedback cooling –

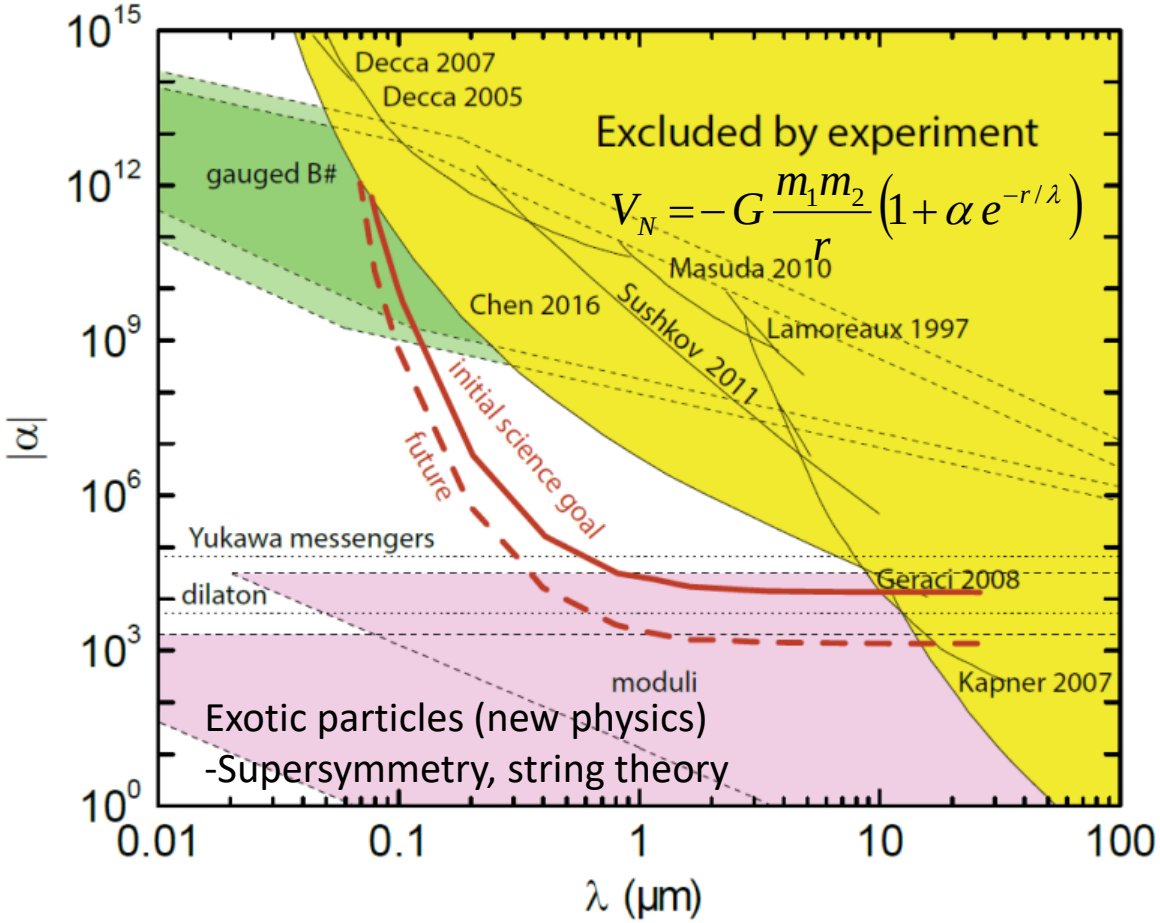
G. Ranjit, et.al. , *Phys. Rev. A*, 93, 053801 (2016)

Levitated nanospheres – testing gravity at um-range



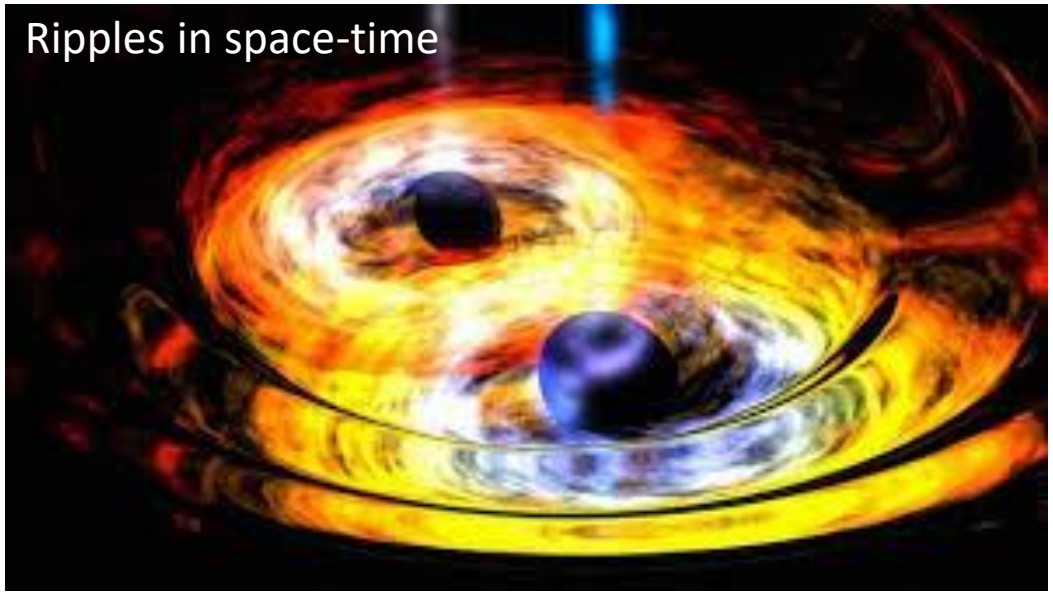
Also work at
Stanford,Yale



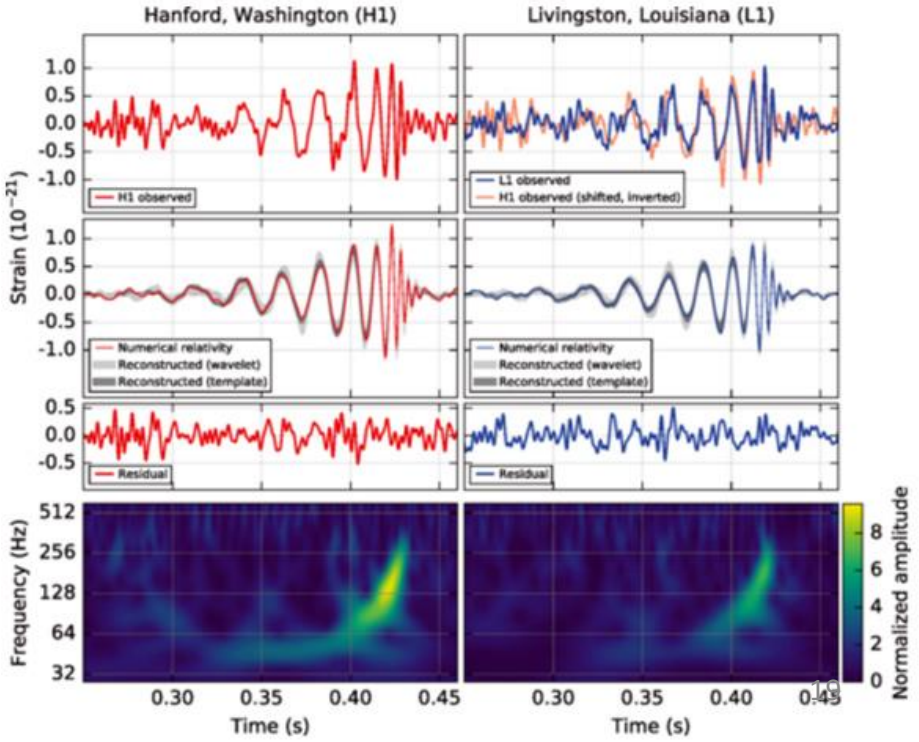


AG, S.B. Papp, and J. Kitching, *Phys. Rev. Lett*. **105**, 101101 (2010)

Gravitational waves



- Discovered by LIGO Sep 2015 !!
- Sources:
  - Inspirals of astrophysical objects
  - Inflation, Phase transitions, etc.



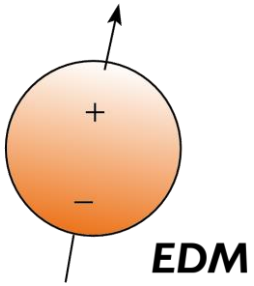
B. P. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration) Phys. Rev. Lett. **116**, 061102 (2016).

The Dark Sector

- GW detectors are a probe of the Dark Sector

→Axions

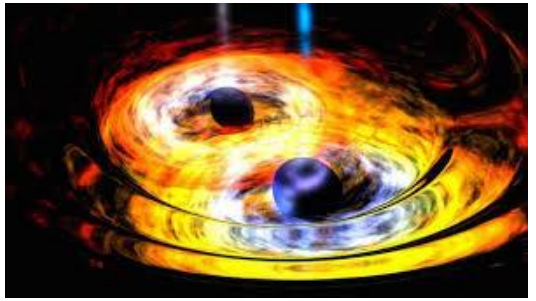
- Peccei-Quinn Axion (QCD) solves "strong-CP problem" $\theta_{QCD} < 10^{-10}$
- Dark matter candidate



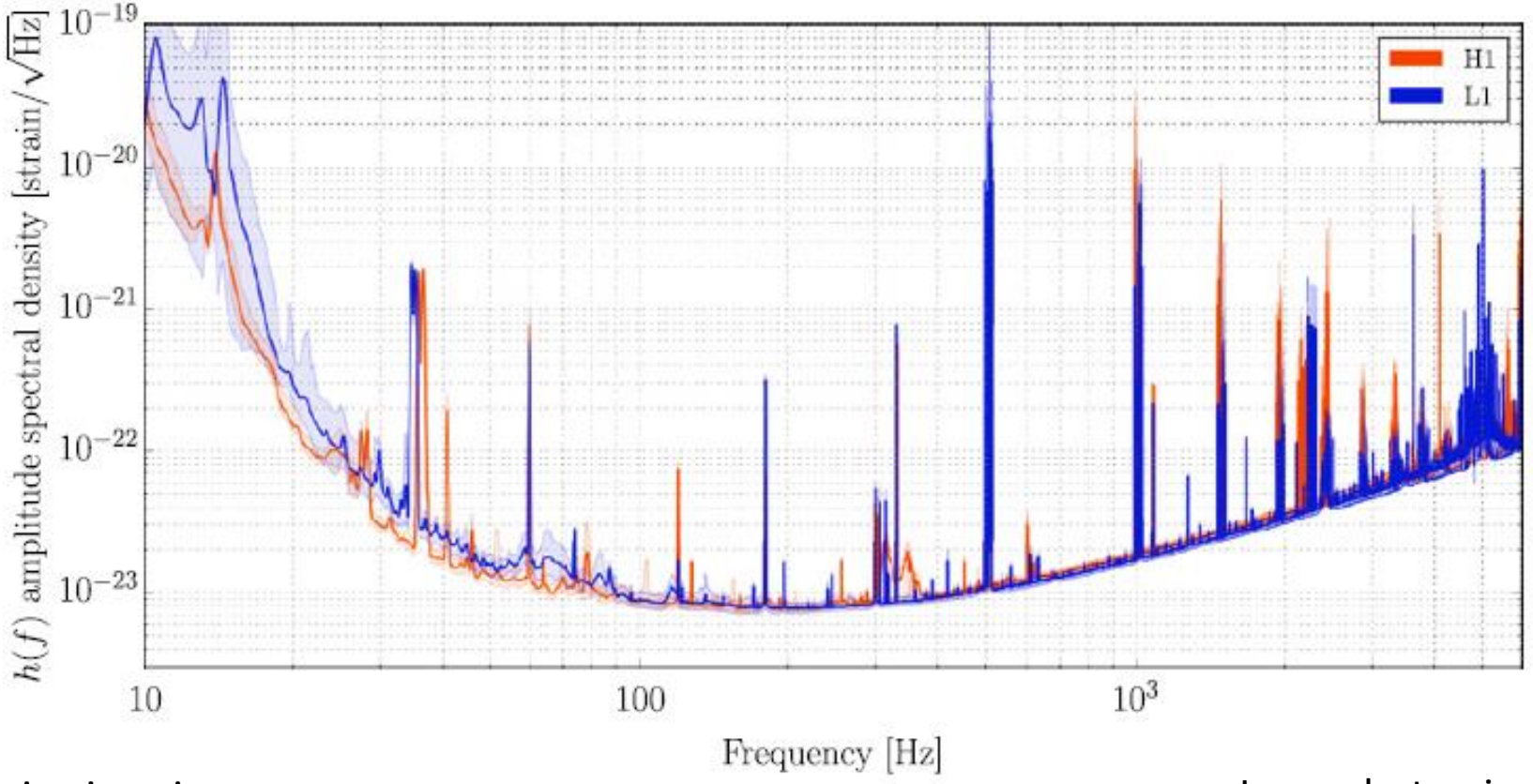
R. D. Peccei and H. R. Quinn, Phys. Rev. Lett. 38, 1440 (1977); S. Weinberg, Phys. Rev. Lett. 40, 223 (1978); F. Wilczek, Phys. Rev. Lett. 40, 279 (1978).

→Primordial Black Holes (PBHs)

- Remnant from early universe
- Wide range of possible masses (sub-M_{sun})



GWs from Dark Matter?



Seismic noise

Coating thermal noise

Laser shot noise

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

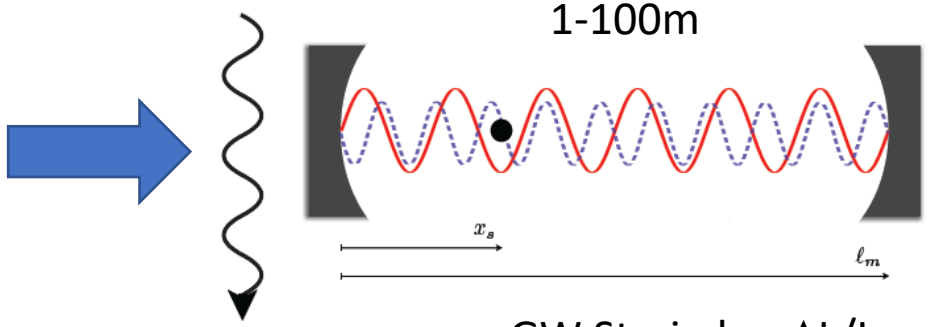
Céline Bœhm[1], Archil Kobakhidze[1], Ciaran A.J. O'Hare[1], Zachary S.C. Picker[1] and Mairi Sakellariadou[2]

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

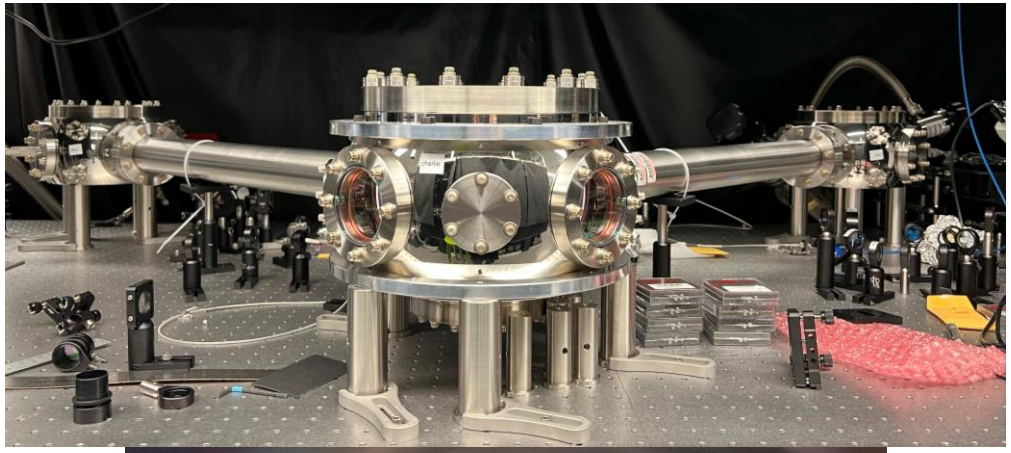
Journal of Cosmology and Astroparticle Physics, Volume 2021, March 2021

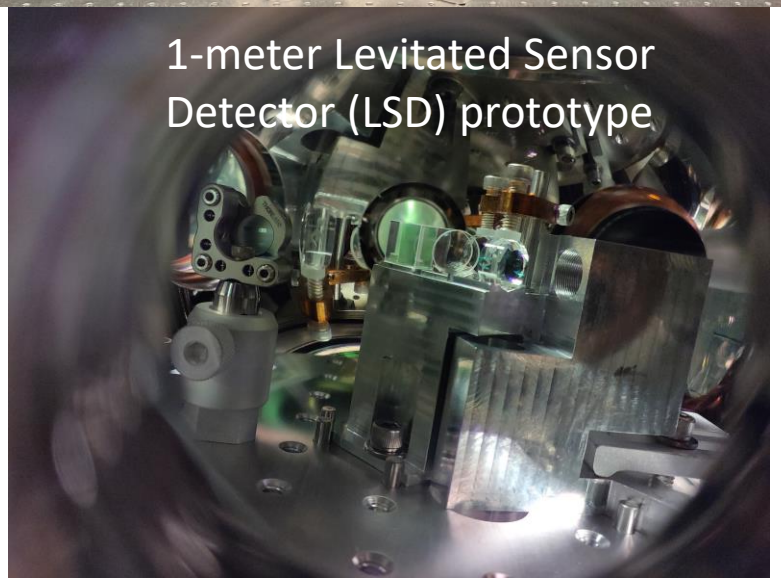
Citation Céline Bœhm *et al* JCAP03(2021)078

Novel gravitational wave detector for > 10 kHz



GW Strain h = ΔL/L



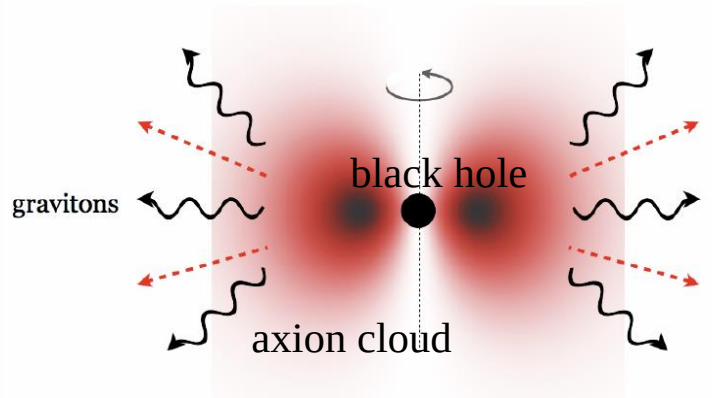


- Laser intensity changed to match trap frequency to GW frequency
- For a 10m cavity, $h \sim 10^{-22}$ Hz $^{-1/2}$ at high frequency (100kHz)
- Novelty: Limited by thermal noise in sensor (not laser shot noise) → much better at high frequency!

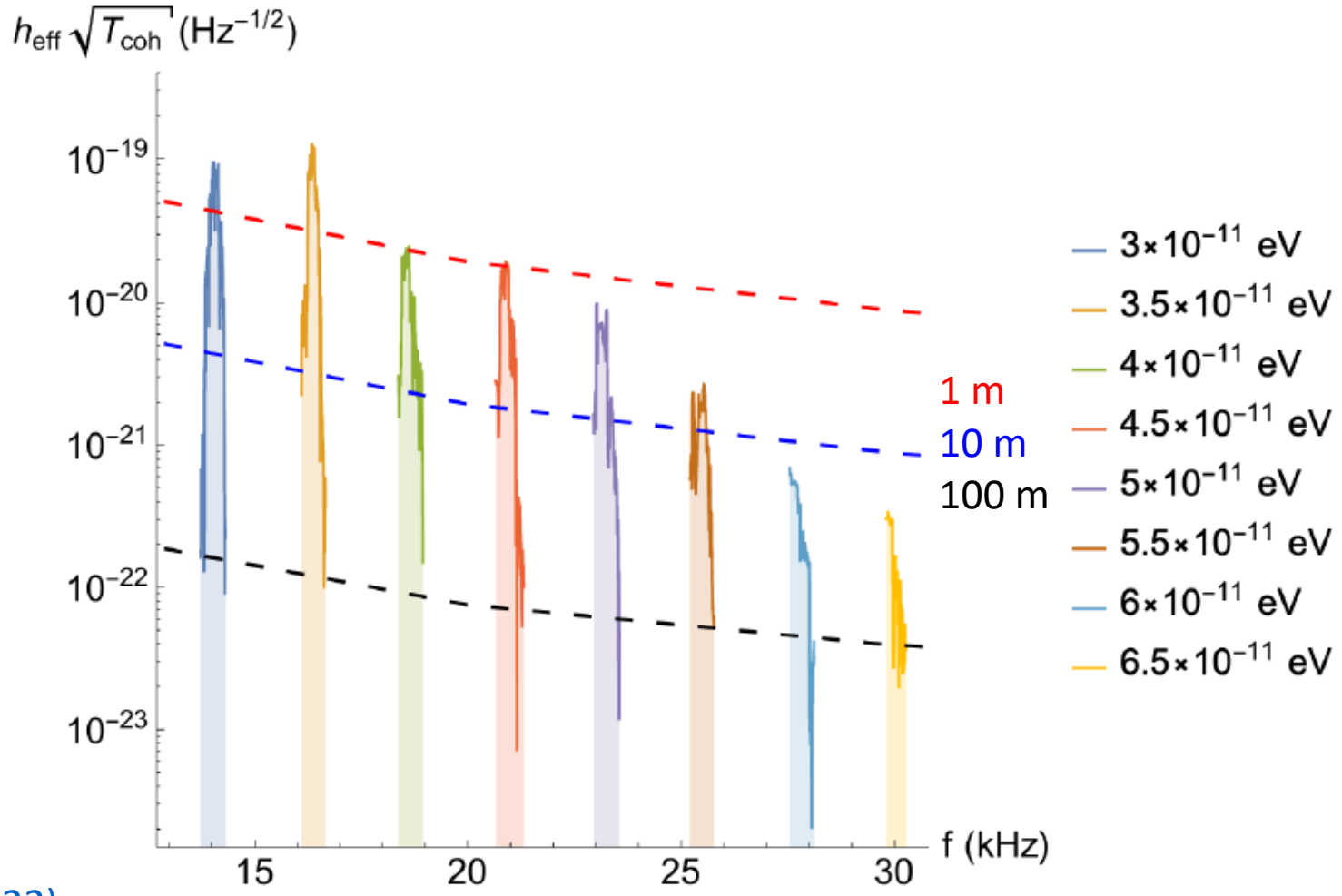
A. Arvanitaki and AG, Phys. Rev. Lett. 110, 071105 (2013), Aggarwal et. al., Phys. Rev. Lett. **128**, 111101 (2022).

High frequency gravitational waves probe dark sector

Estimated signals from axion annihilation in BH superradiance



Distance to source: 10 kpc
(within our galaxy)

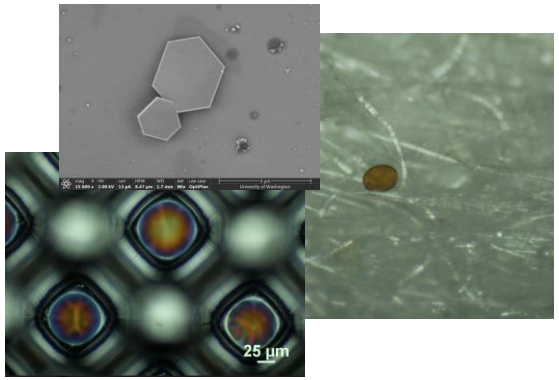


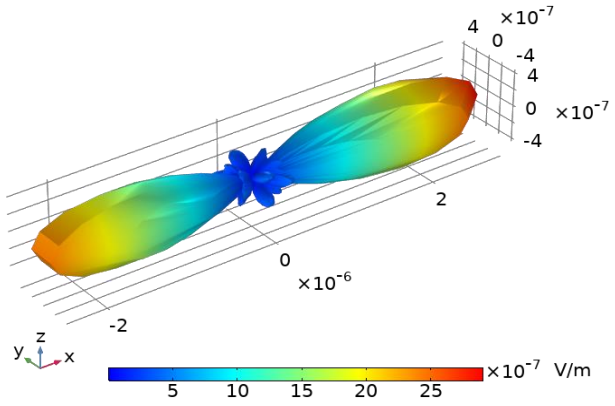
J. Sprague et.al, arXiv:2409.03714

Aggarwal et. al., Phys. Rev. Lett. **128**, 111101 (2022).

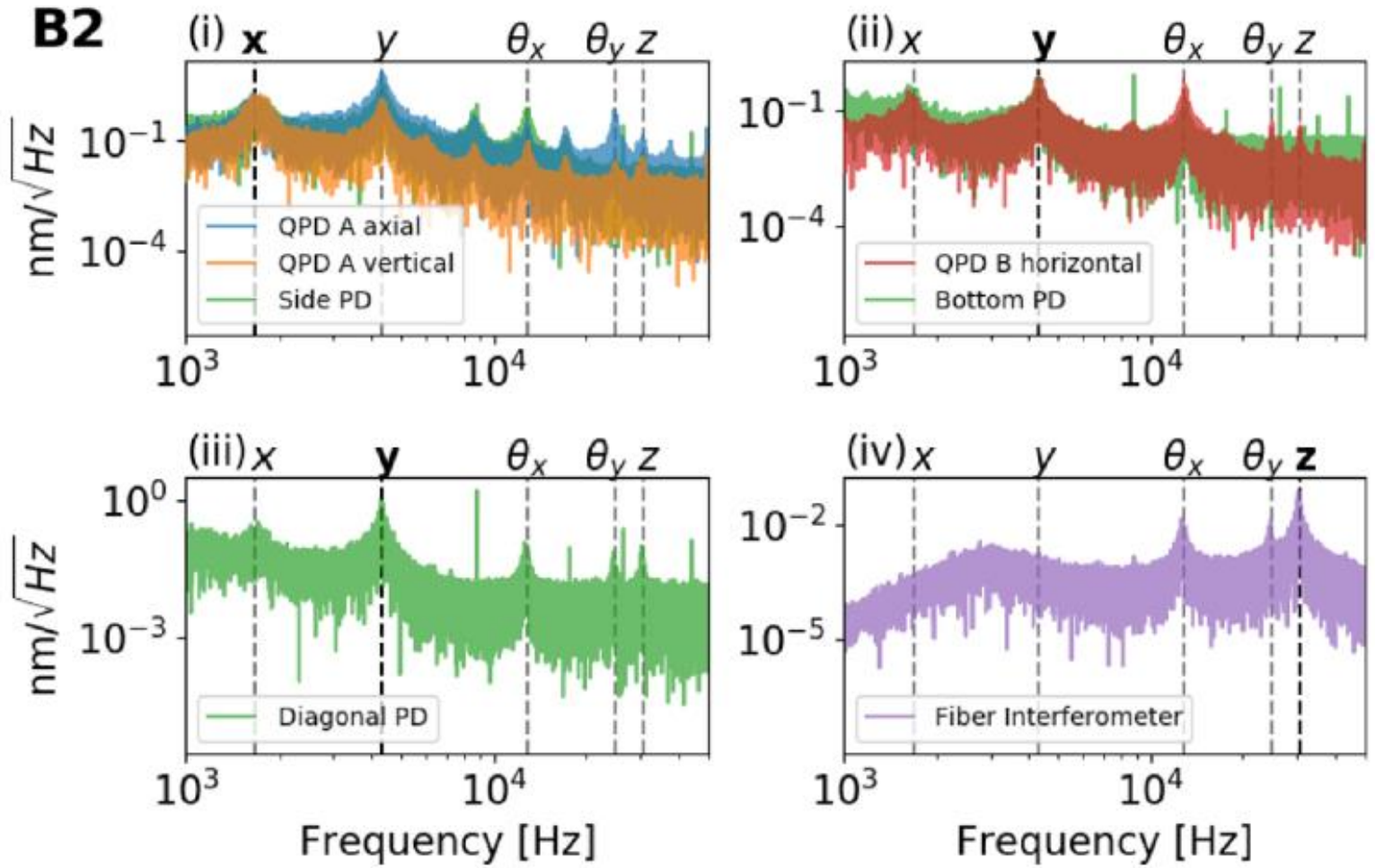
Levitated object optimization: disc/plate vs sphere

SiO2 disks &
NaYF hexagons





Ideal sensor: high mass, high frequency, low photon recoil

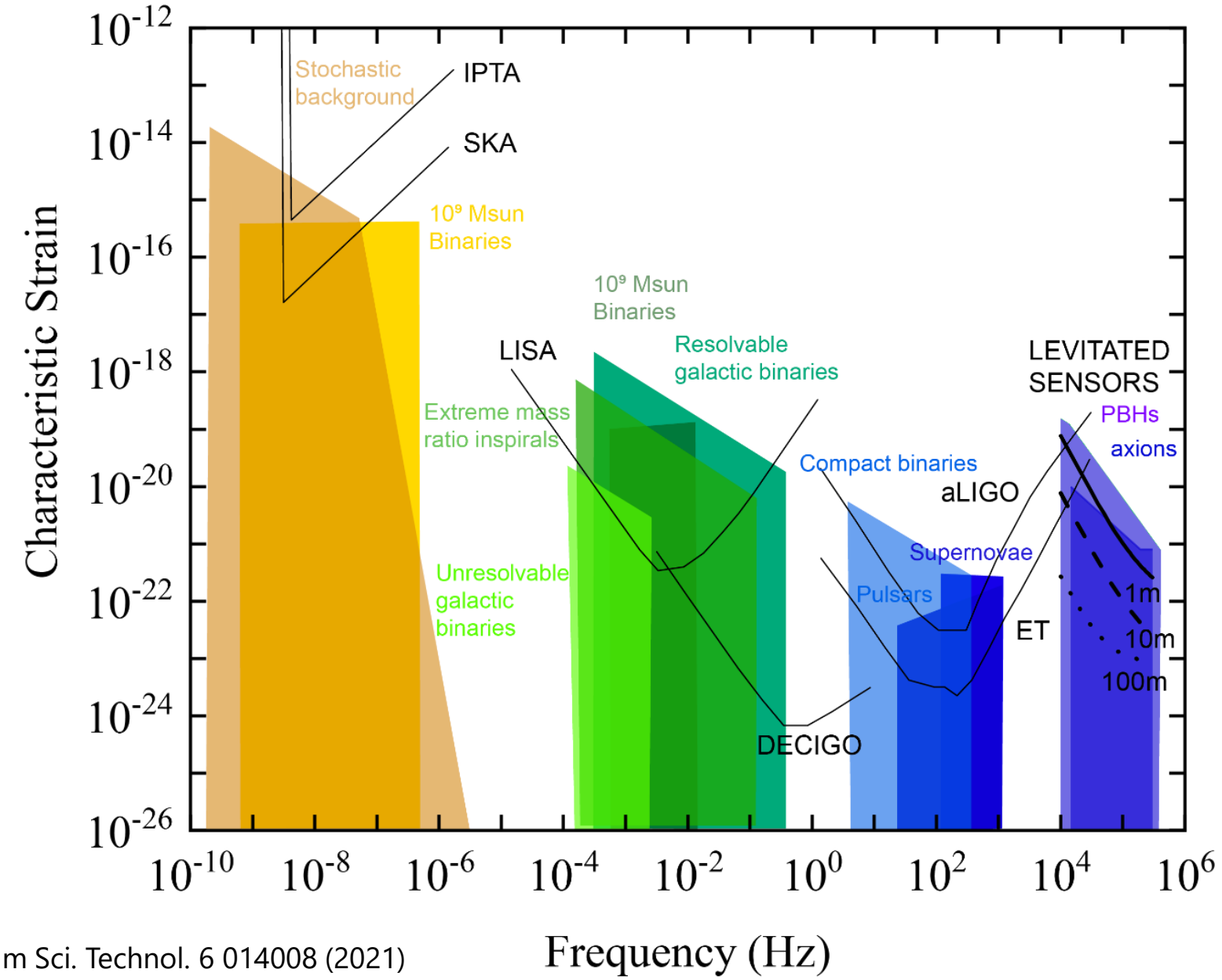


- Less isotropic scattering reduces photon recoil noise

Aggarwal et. al., Phys. Rev. Lett. **128**, 111101 (2022).

G. Winstone et.al., Phys. Rev. Lett. **129**, 053604 (2022)

Vision for HF gravitational wave astronomy



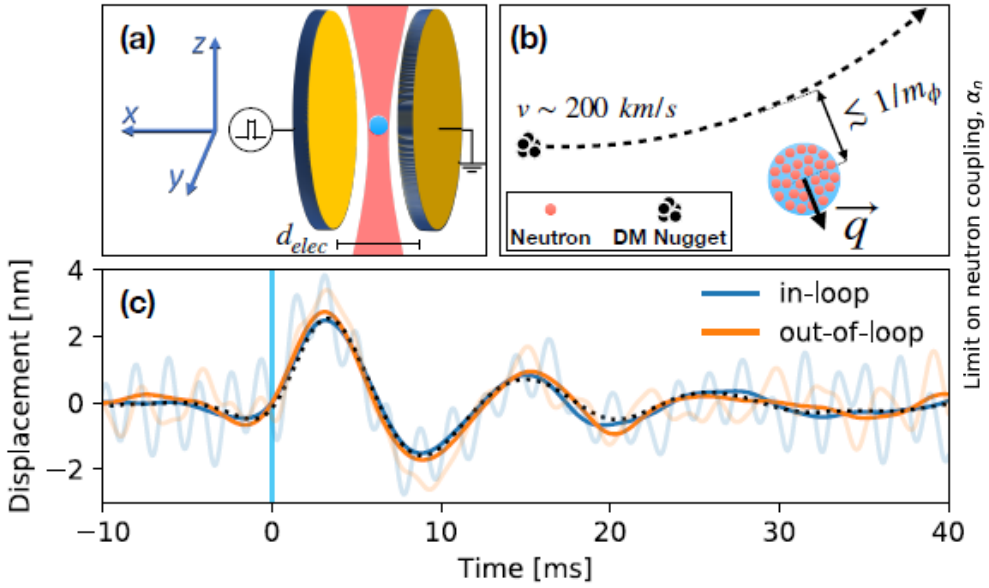
Need a network of detectors!

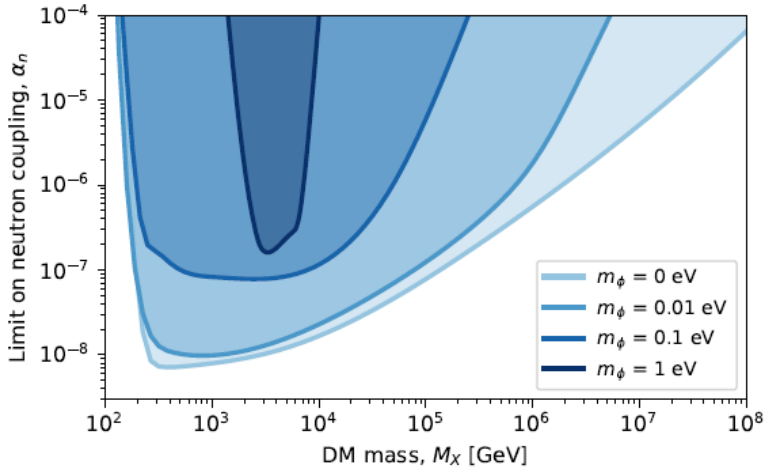
D.C. Moore and AG, Quantum Sci. Technol. 6 014008 (2021)

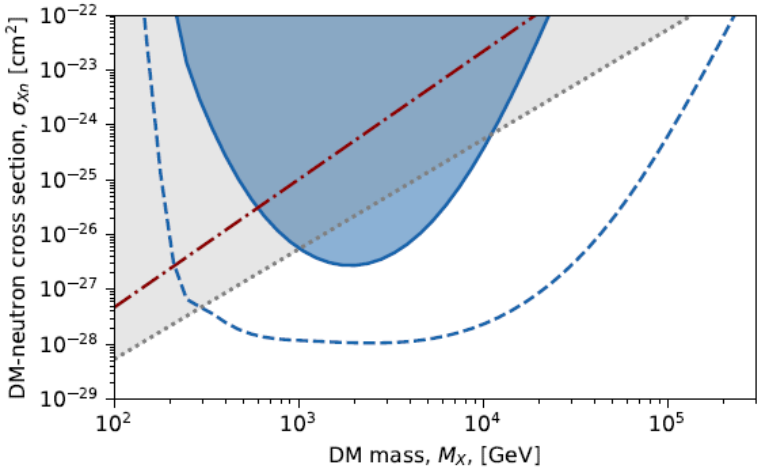
Composite DM search with Levitated microspheres

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





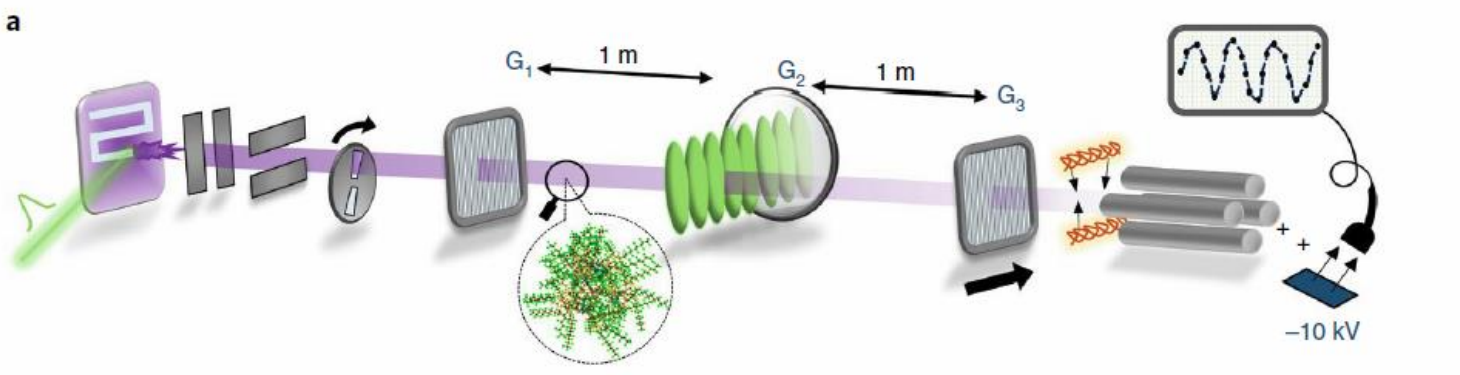


Quantum Regime: Matter wave interference

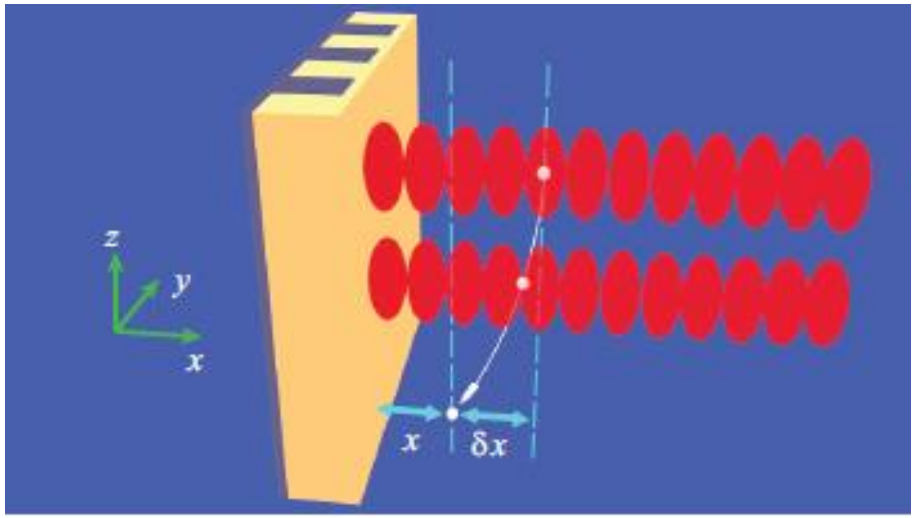
LETTERS
https://doi.org/10.1038/s41567-019-0663-9
nature physics

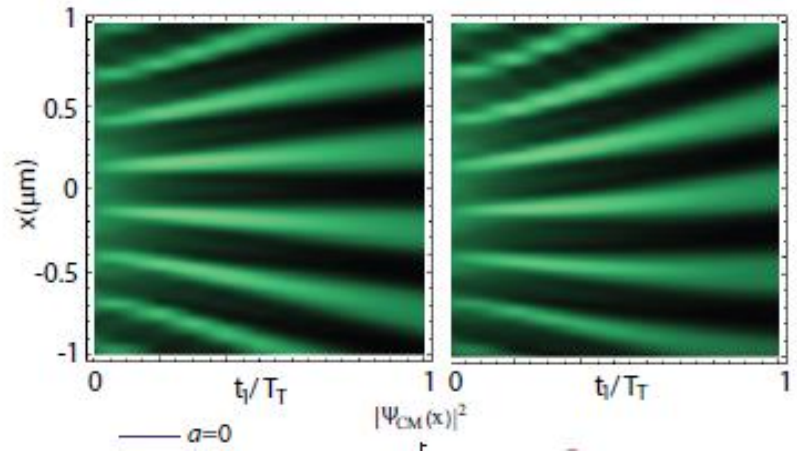
Quantum superposition of molecules beyond 25 kDa

Yaakov Y. Fein[1], Philipp Geyer[1], Patrick Zwick[2], Filip Kiałka[1], Sebastian Pedalino[1], Marcel Mayor[2,3,4], Stefan Gerlich[1] and Markus Arndt[1*]

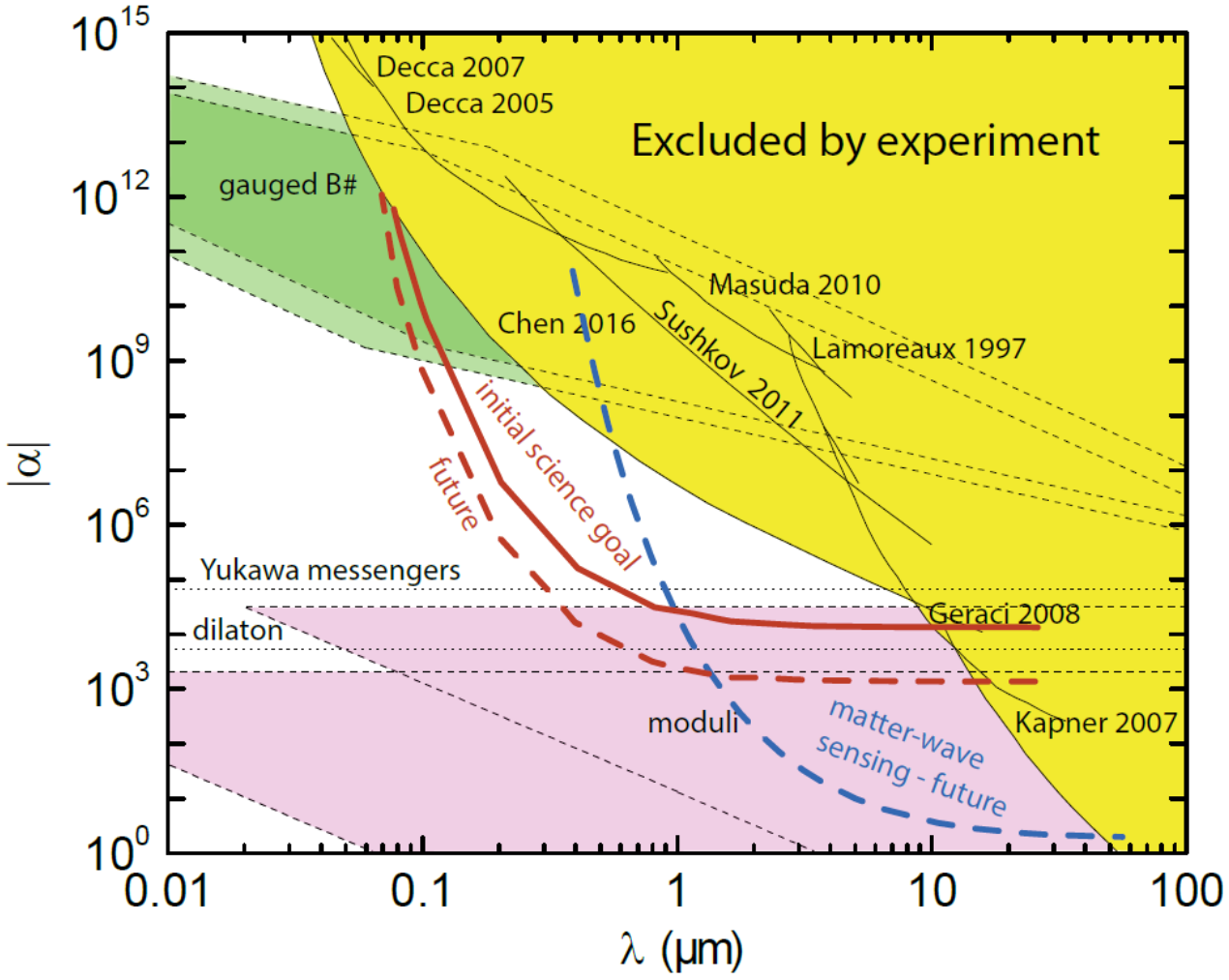


Quantum Regime: Matter-wave interferometry



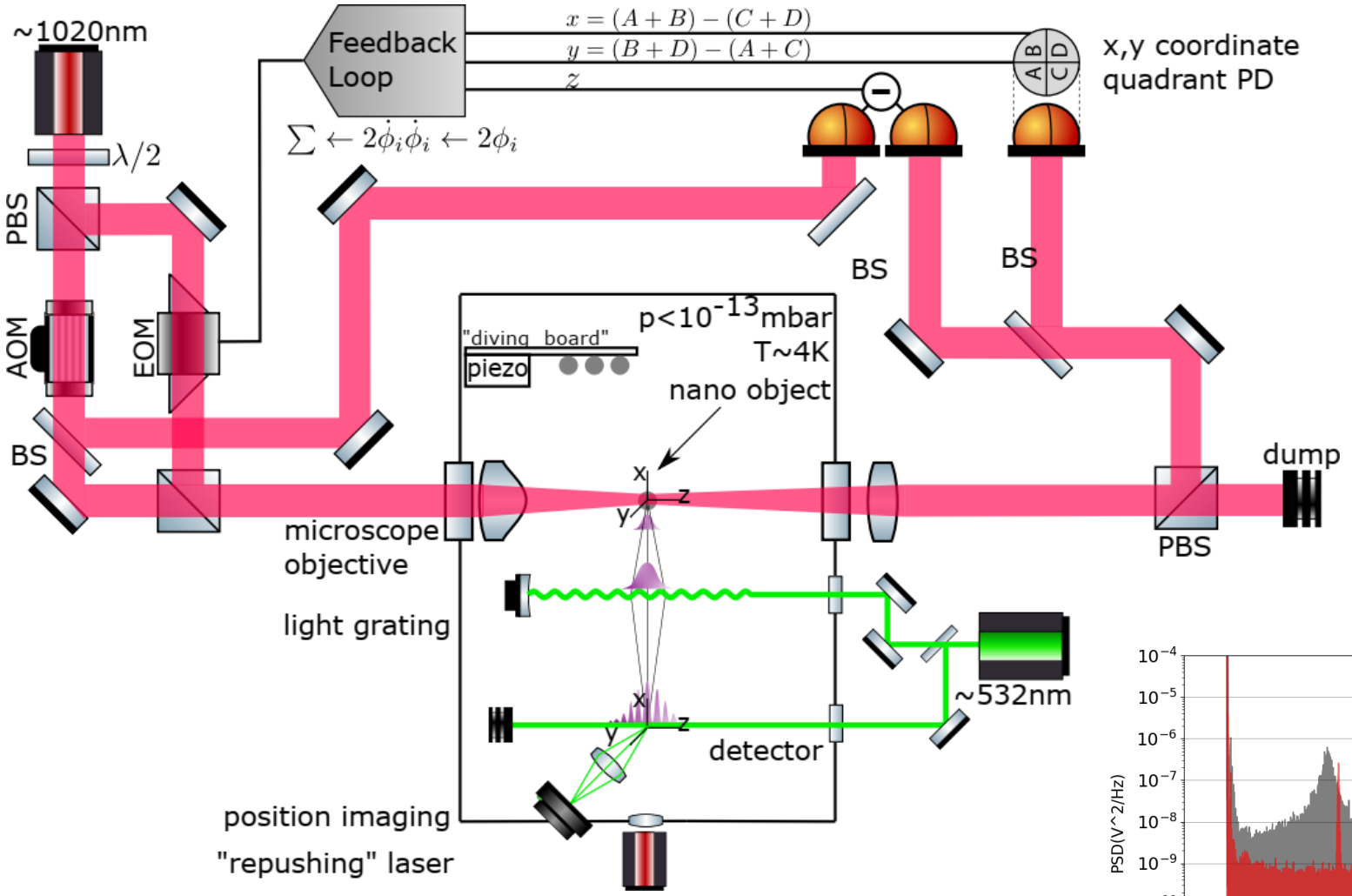


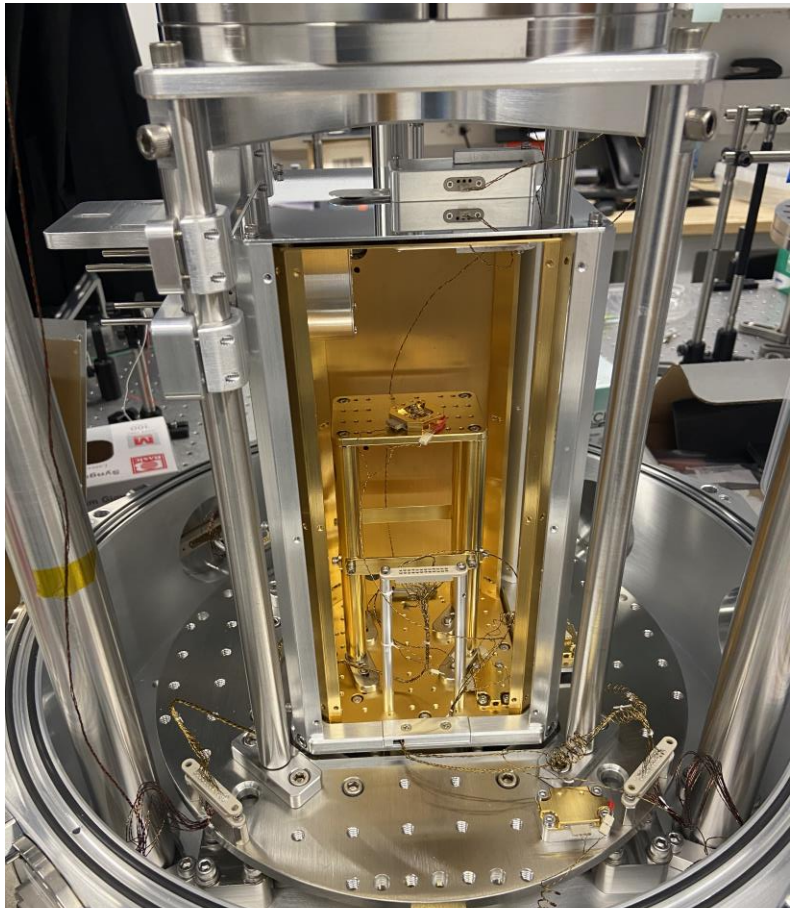
Nano-g acceleration sensing



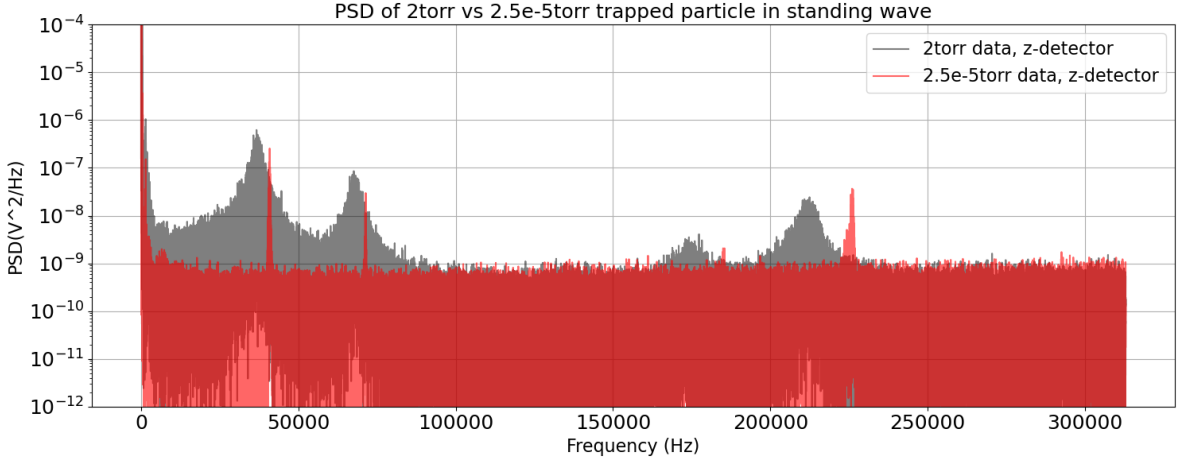
A.G. and H. Goldman, Phys. Rev. D 92, 062002 (2015).

Experimental layout

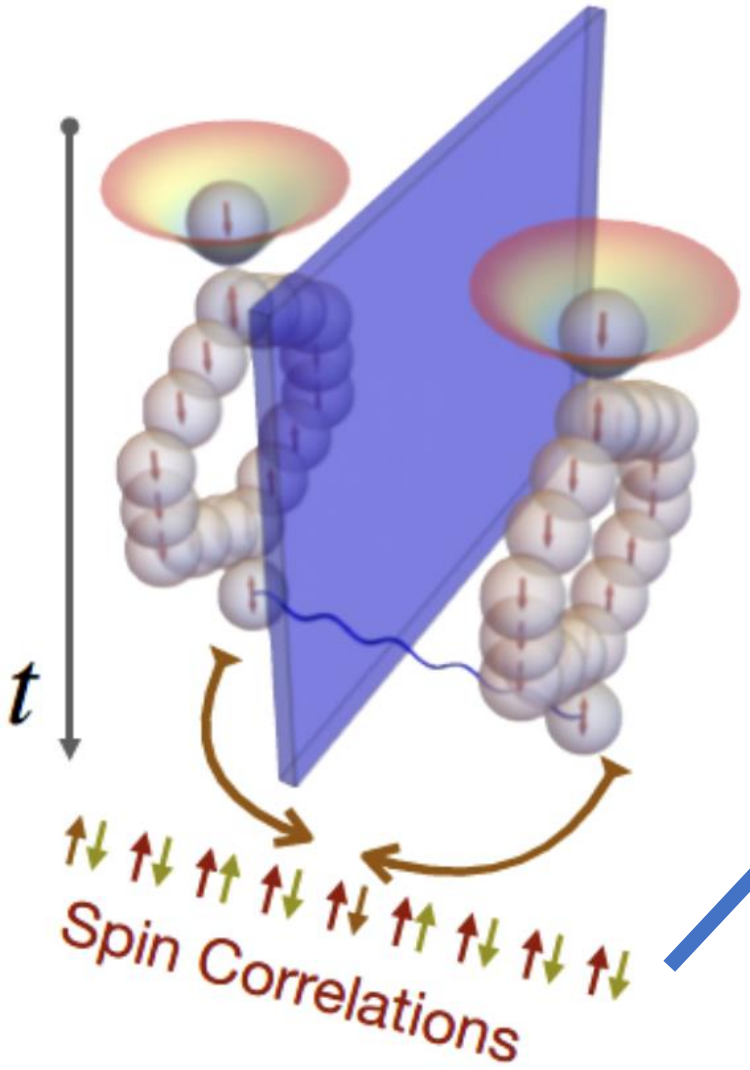




PSD of 2torr vs 2.5e-5torr trapped particle in standing wave



Does Gravity participate in Quantum Entanglement?



Gravity entangles in less than a second for micro-diamonds for $\Delta x \sim 10\mu\mathrm{m}$ superposition!

Gravitational Interaction is Quantum

Space-time is Quantum

S. Bose, A. Mazumdar, G. W. Morley, H. Ulbricht, M. Toroš, M. Paternostro, AG, P. F. Barker, M. S. Kim, and G. Milburn (PRL 2017)

Elahi, Schut, Grinin, Dana, AG, Bose, Mazumdar (arxiv:2024)

Schut, AG, Bose, Mazumdar, Phys.Rev.Res. (2024)

Summary

- Optomechanical detection of DM looks very promising

 - narrowband mechanical resonators/accelerometers

 - broadband cavities

 - gravitational wave searches for the Dark Sector (axions, PBHs)

 - search for composite or Planck mass DM with levitated microspheres or arrays of sensors (e.g. Windchime)

(also torsion balances, atom interferometers, superfluid He…)

→ Opportunities for networking detectors for e.g. coincidence detection/spatial correlation, scaling up arrays of sensors

- Massive quantum superpositions could test quantum behavior of gravity

→ Technical limiting factors in many (opto)-mechanical experiments (external vibration, gravity gradient noise) could be addressed by suitable shared underground facilities (cavity experiments, torsion balances, matter wave interferometers)

→ Exciting road ahead in coming decade(s)!

Acknowledgements

From left to right: Alexey Grinin (PD), Nancy Aggarwal (UC Davis), William Eom (G), Nia Burrell (G), Aaron Zhiyuan Wang (G), Chethn Galla (G), Andrew Geraci (PI), Cris Montoya (PD), George Winstone (PD), Chloe Lohmeyer (G), Shelby Klomp (G), Evan Weisman (PD), Andrew Poverman (G), Eduardo Alejandro (G), Andrew Laeuger (UG)

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Peter Barker (UCL)
Peter Pauzauskie (UW)

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Masha Baryakhtar (Perimeter)
Mae Hwee Teo (Stanford)
Shane Larson (NU)
Vicky Kalogera (NU)