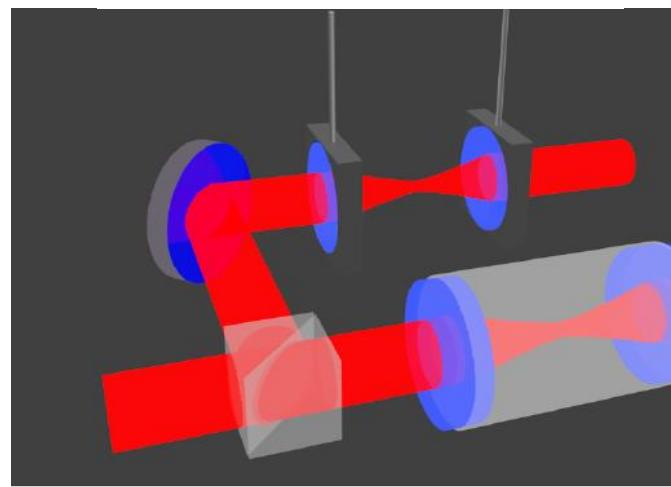
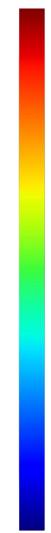
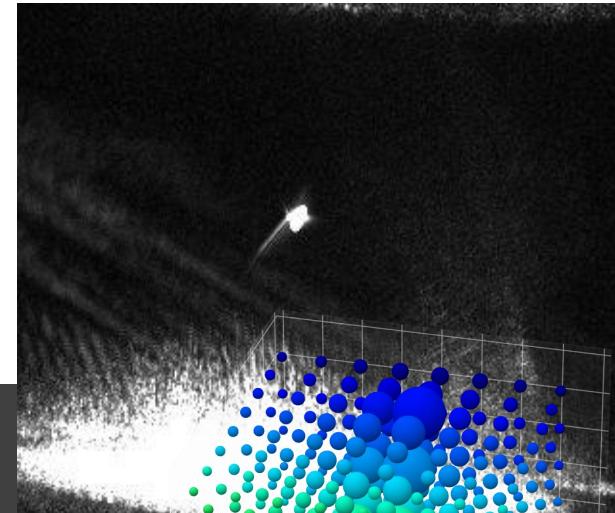


# (Opto)mechanical detectors for Dark Matter



A.Geraci

Northwestern University



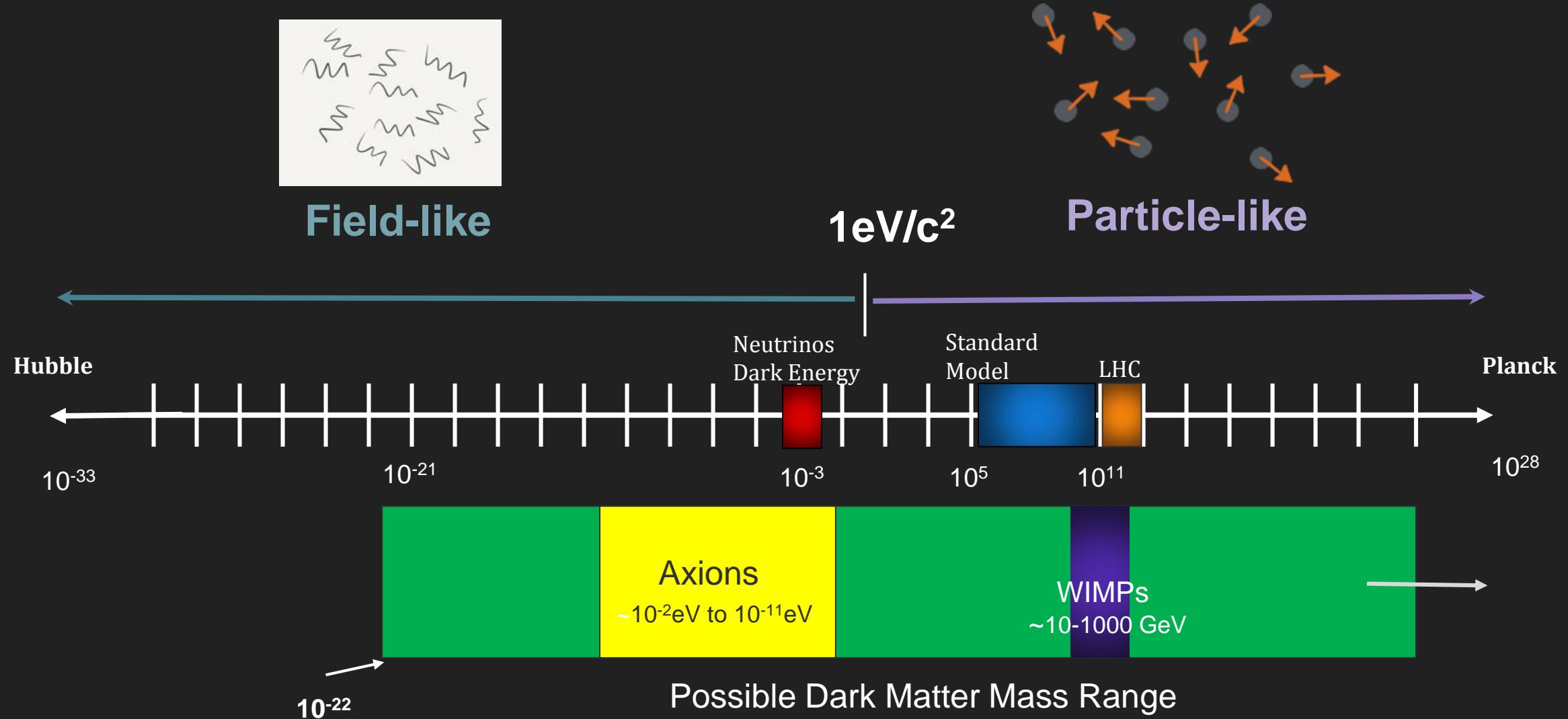
Center for Fundamental Physics (CFP)

ECFA Detector R&D Roadmap Symposium of Task Force 5  
Quantum and Emerging Technologies, Apr. 12, 2021

# 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
  - Windchime experiment
- Roadmap, Other techniques, and Discussion

# Dark Matter



# 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

$$\phi(\mathbf{r}, t) = \phi_0 \cos(\omega_\phi t - \mathbf{k}_\phi \cdot \mathbf{r} + \dots).$$

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

- Techniques for detecting oscillating scalar DM:

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)

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

# Ultra-light scalar DM

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

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

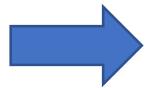
**Frequency:**  $\omega_\phi = m_\phi c^2 / \hbar$

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

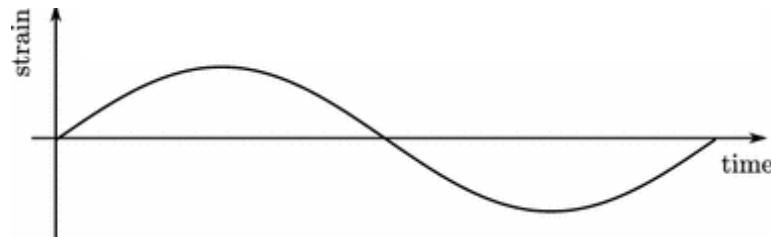
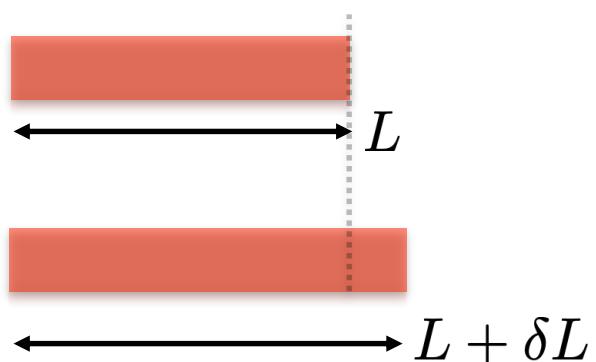
**Wavenumber:**  $k_\phi = m_\phi v / \hbar$        $v = 10^{-3}c$

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

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



Isotropic strain in material objects due to variation of atomic size



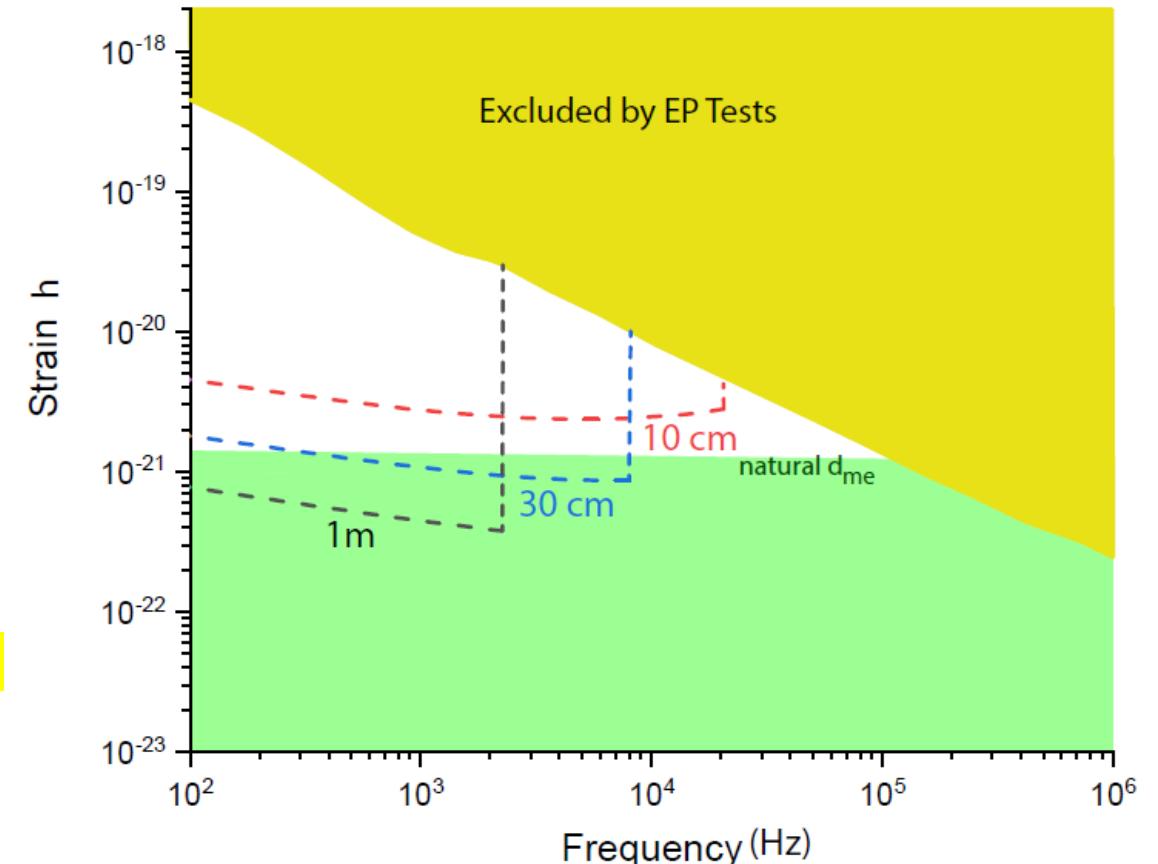
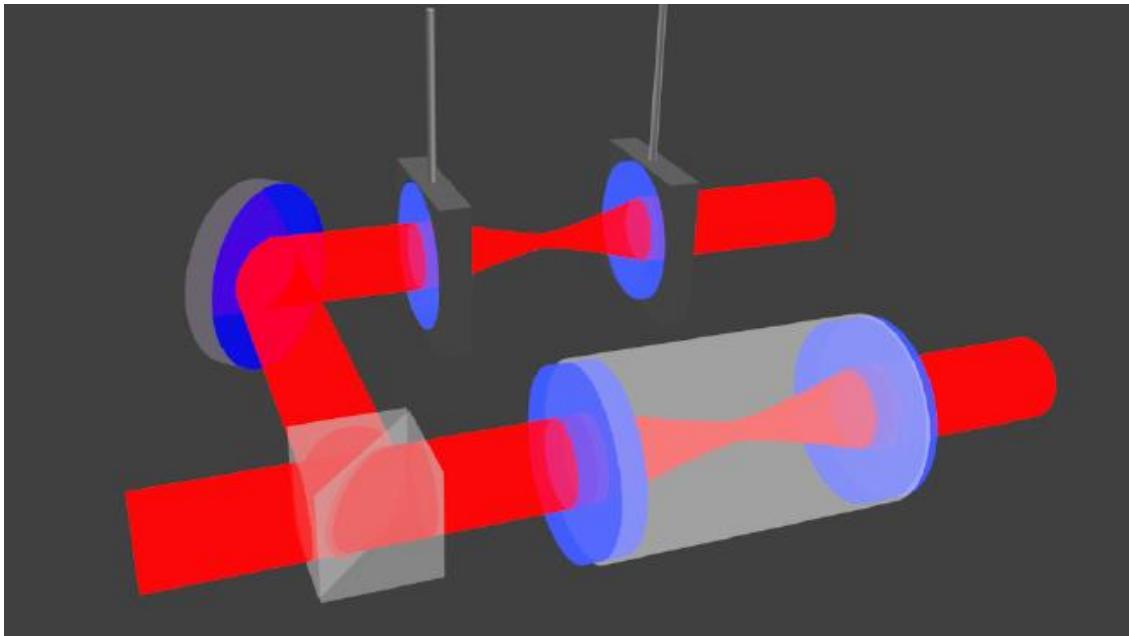
e.g. Manley et al. PRL 124, 151301 (2020).

# Detecting ultra-light Dark Matter with optical cavities

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

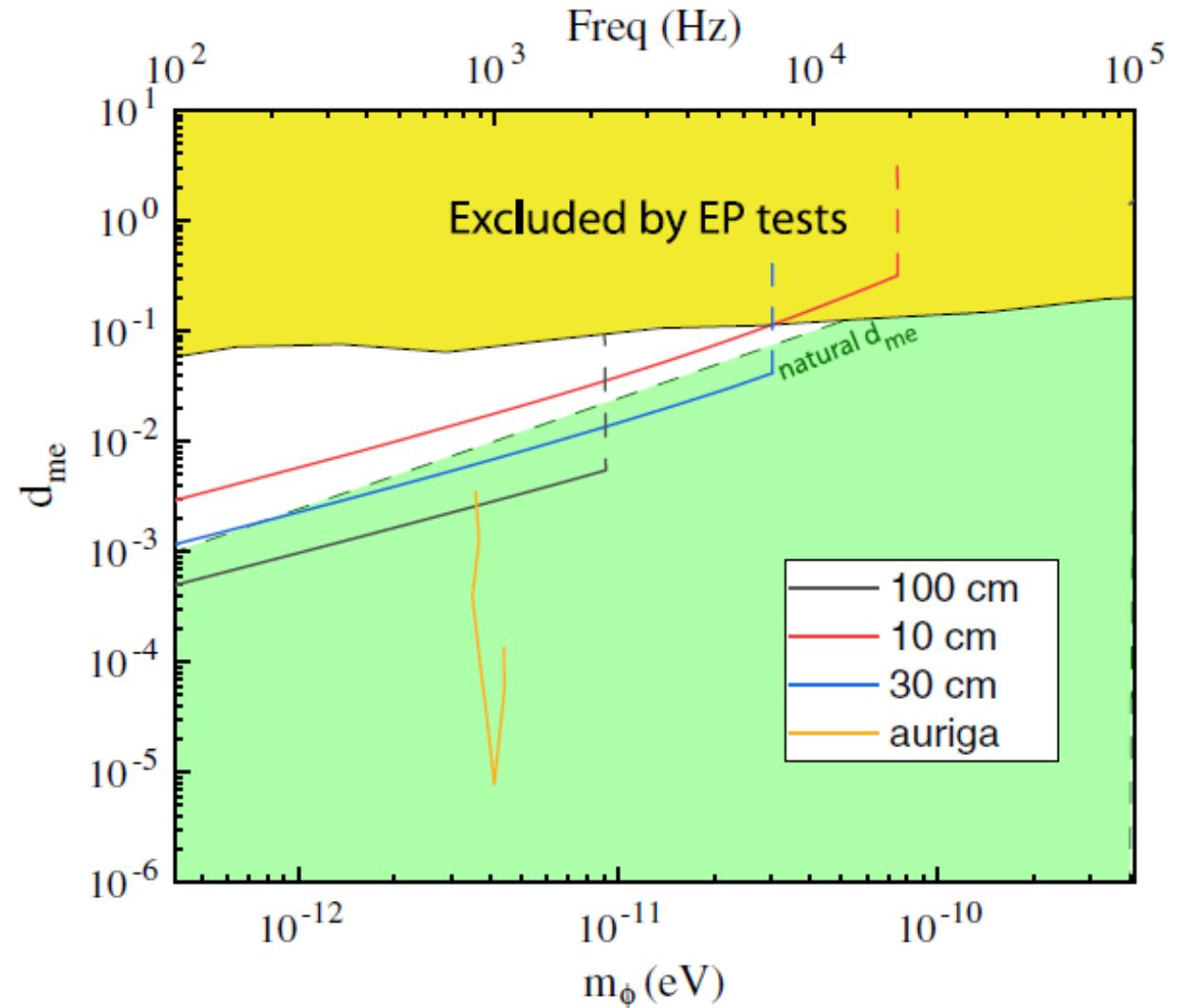
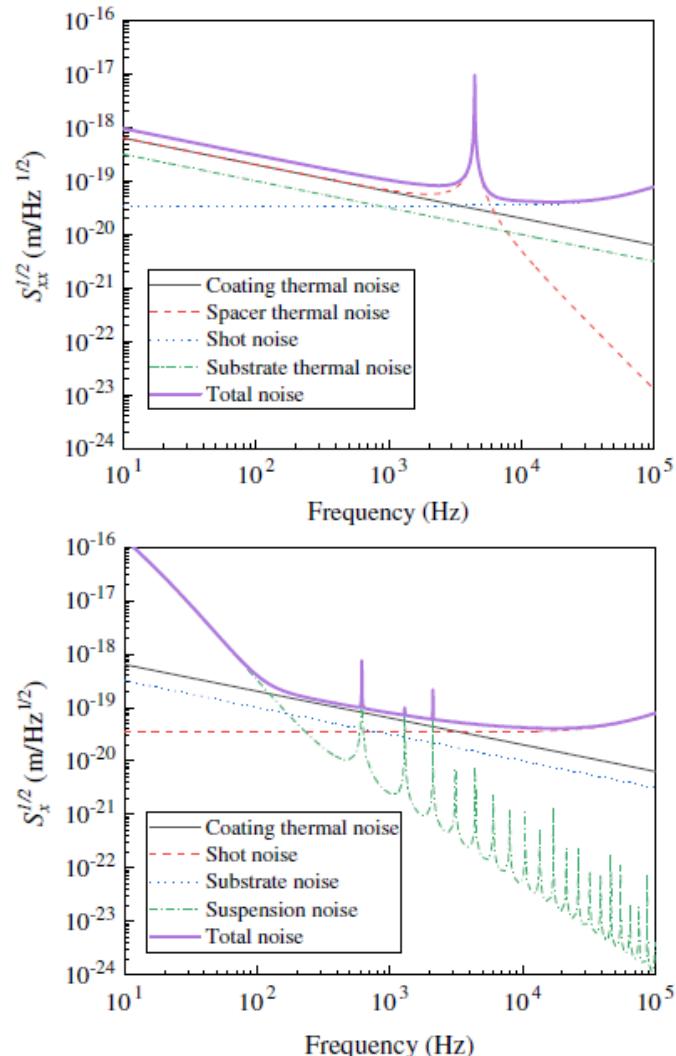


$$\frac{\delta m_e(t, \mathbf{r})}{m_{e,0}} = d_{m_e} \sqrt{4\pi\hbar c} E_P^{-1} \phi(t, \mathbf{r})$$
$$\frac{\delta \alpha(t, \mathbf{r})}{\alpha_0} = d_e \sqrt{4\pi\hbar c} E_P^{-1} \phi(t, \mathbf{r})$$



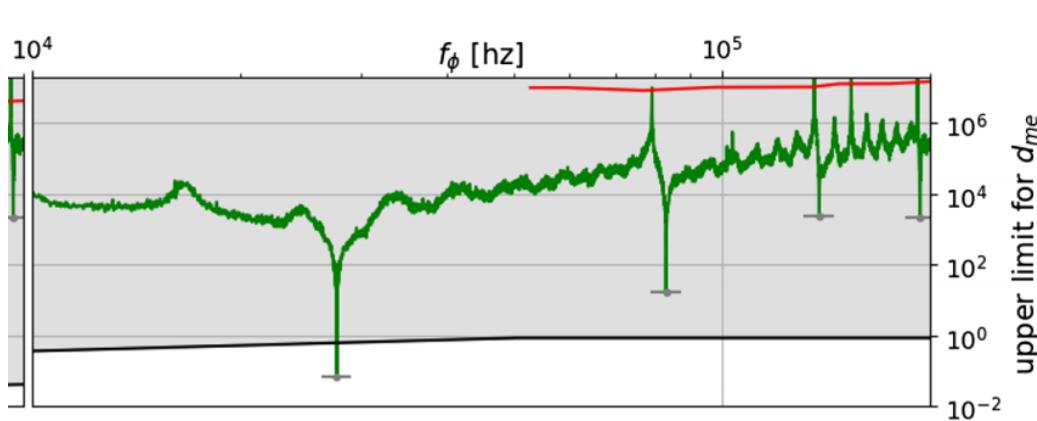
-Cryogenic testbed for low thermal noise to reach the shot noise limit, quantum squeezing techniques

# Reach for variation of electron mass $d_{me}$

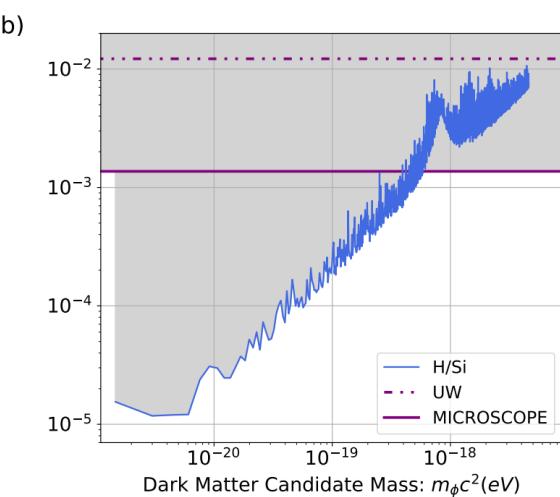


# Recent DM limits from other cavity experiments

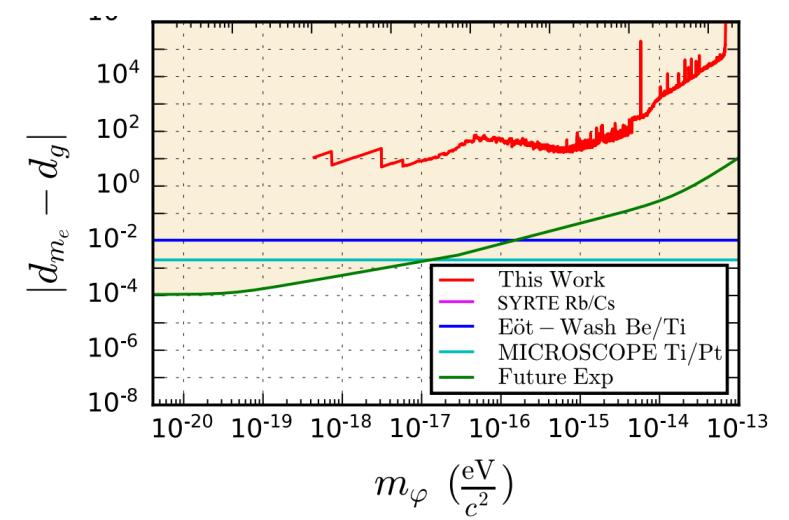
Experiments are **already** constraining scalar dark matter!



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



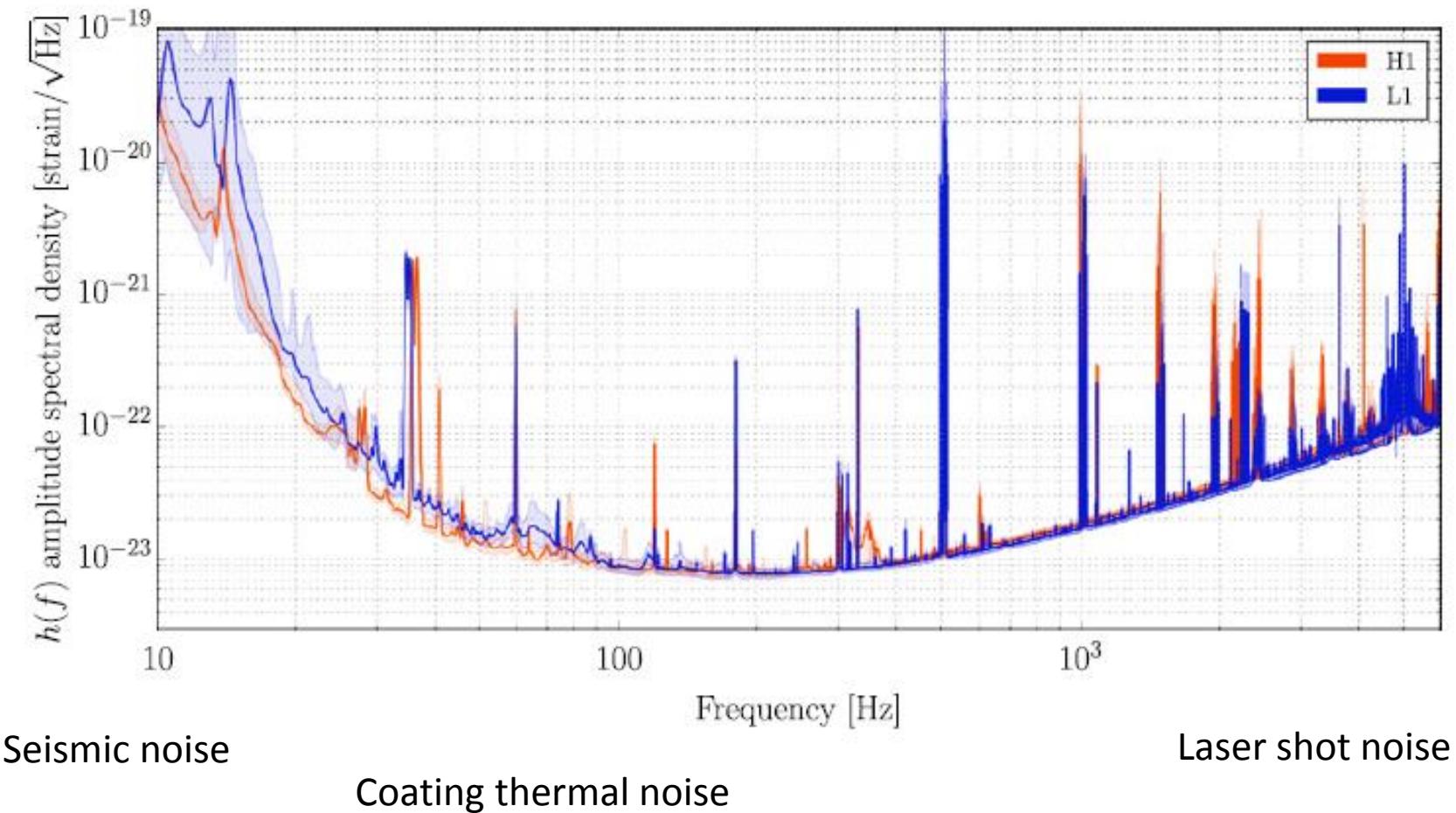
Kennedy et al. PRL **125**, 201302 (2020).



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

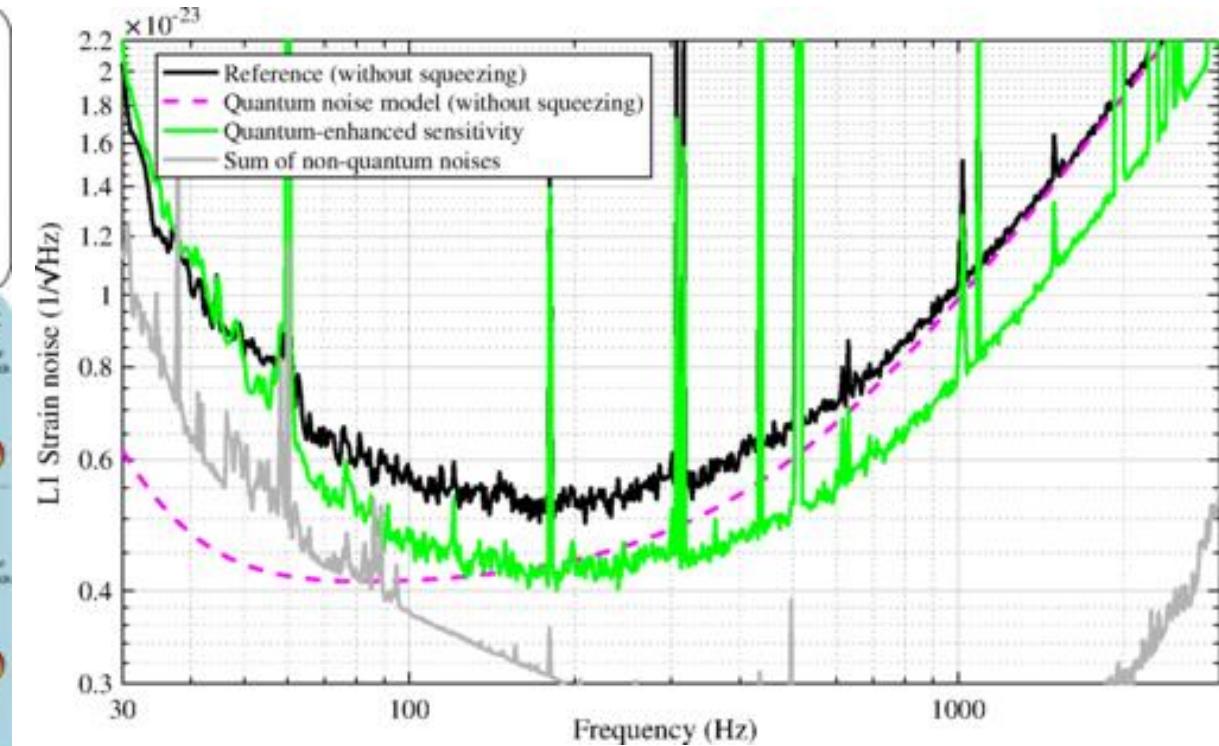
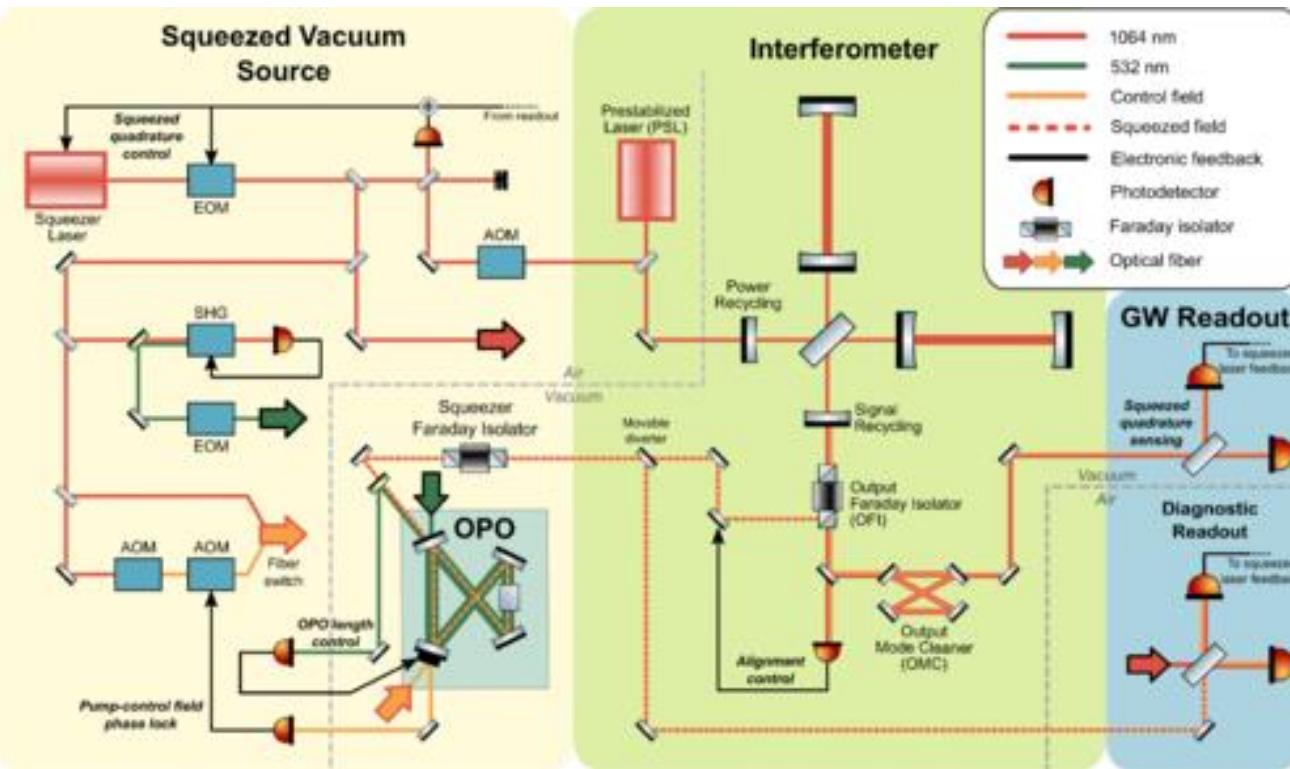
# Quantum enhanced sensing: Squeezed light for improved sensitivity $\sim 10\text{kHz}$

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



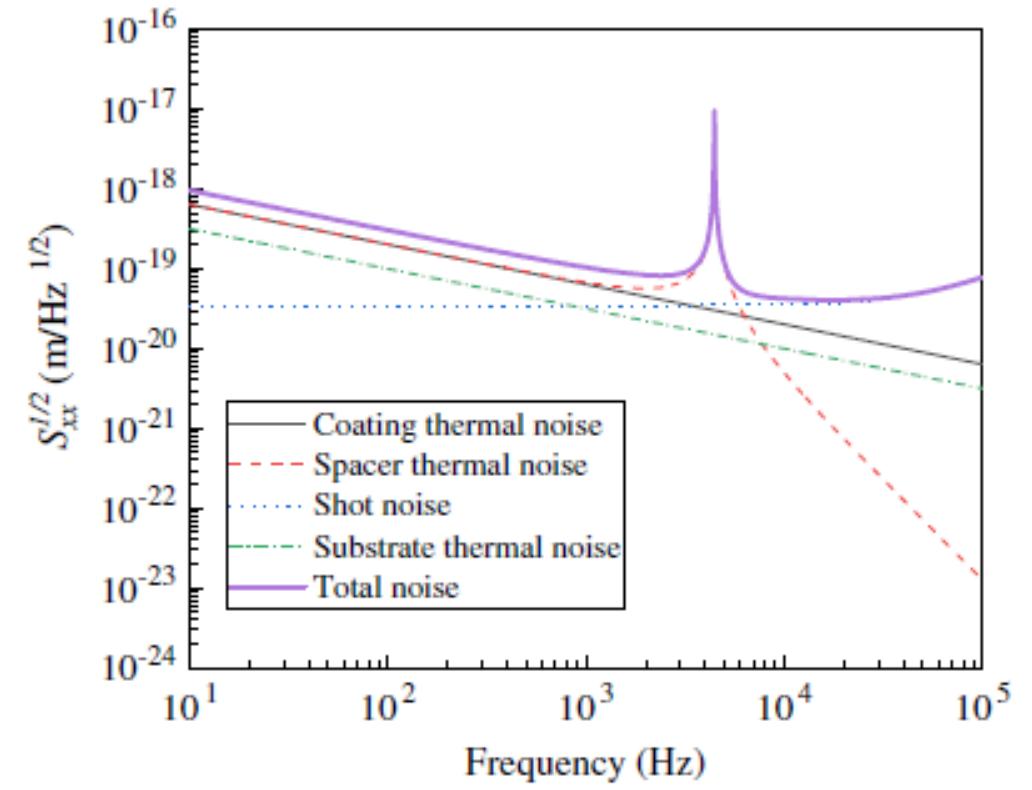
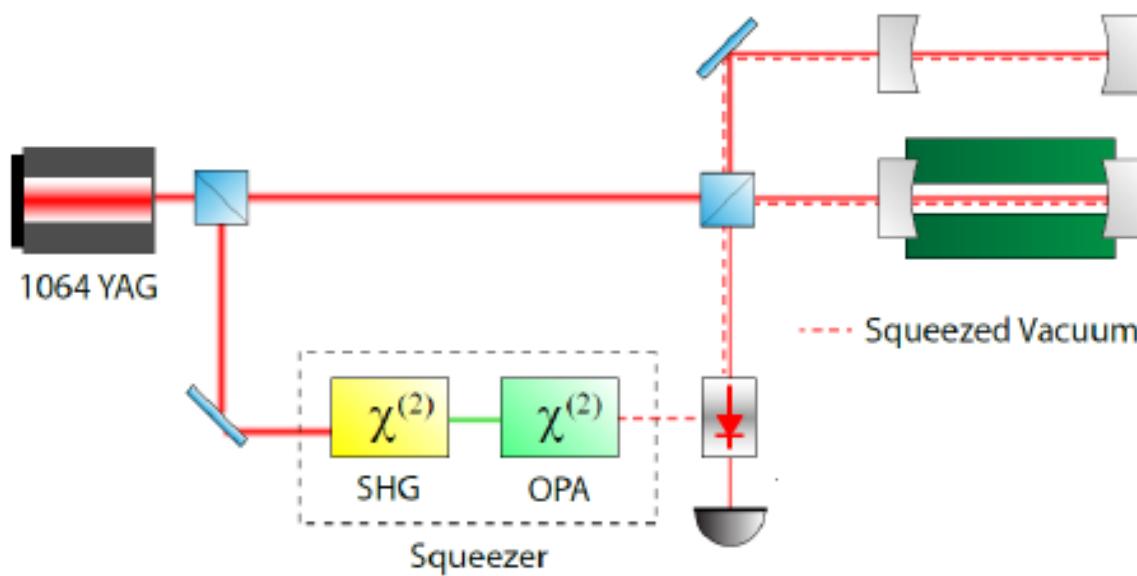
# Quantum enhanced sensing: Squeezed light for improved sensitivity $\sim 10\text{kHz}$

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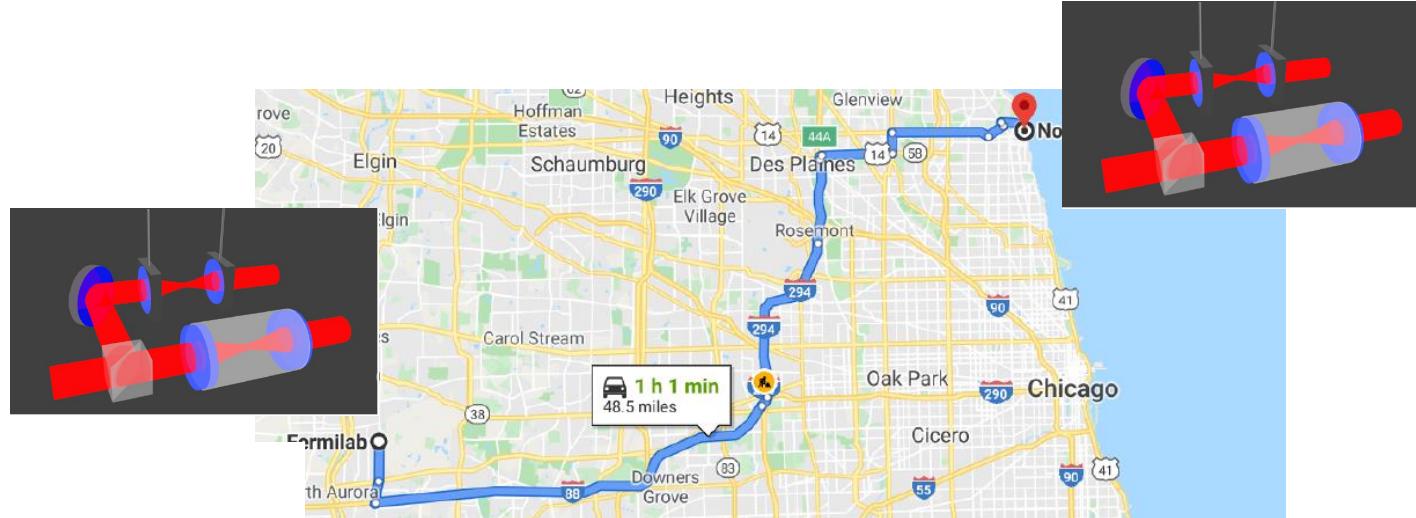


<https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.123.231107>  
<https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.123.231108>

# Quantum enhanced sensing: Squeezed light for improved sensitivity 1-100 kHz



# Under development: Cryogenic quantum-limited cavity network between Fermilab/NU



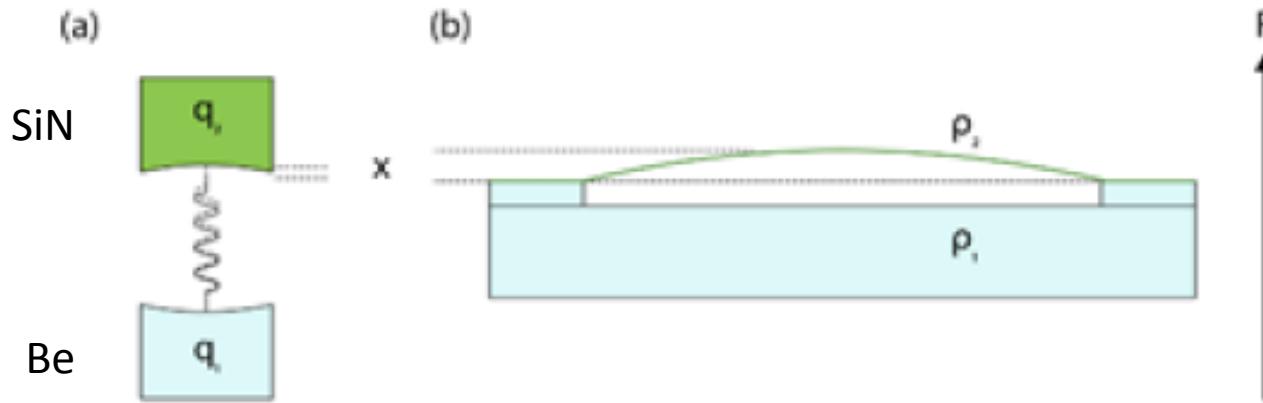
Center for Fundamental Physics (CFP)



- Most sensitive technique proposed so far to search for ultra-light scalar DM in the audioband 10 Hz- 100 kHz
- Able to determine spatial dependence of DM fields
- Search for correlations between distant experiments
- Search for transient DM signals passing through both sites

# Vector-like DM search using optomechanics

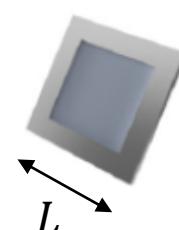
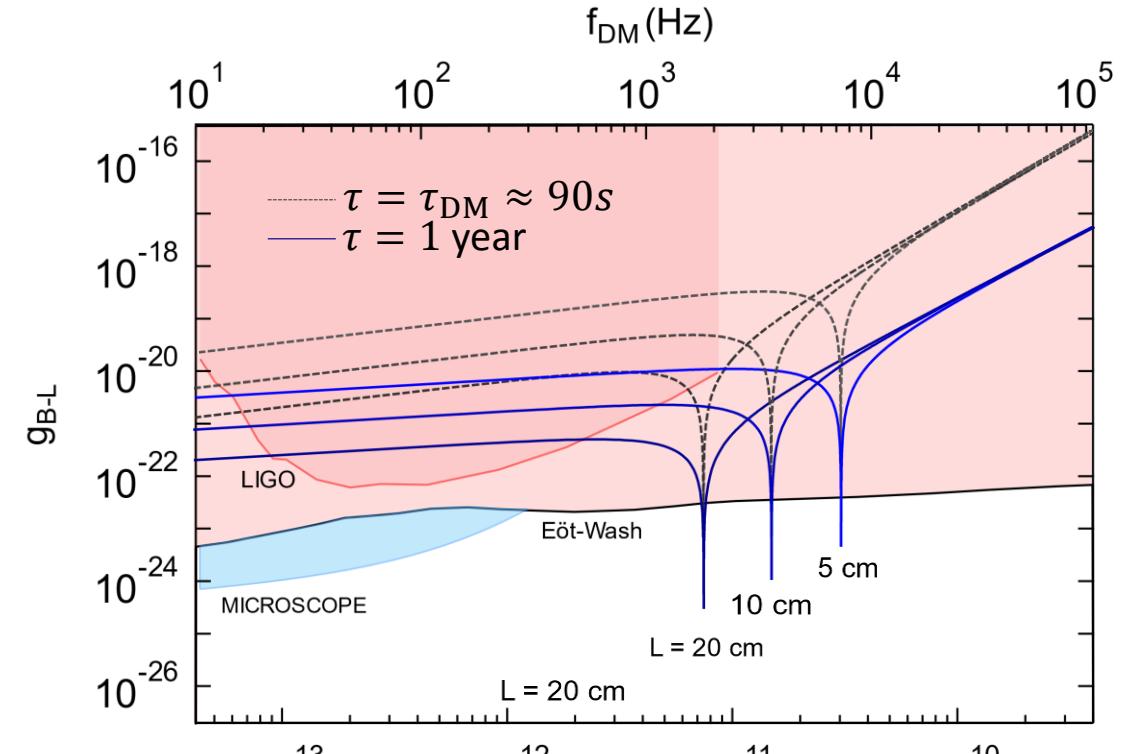
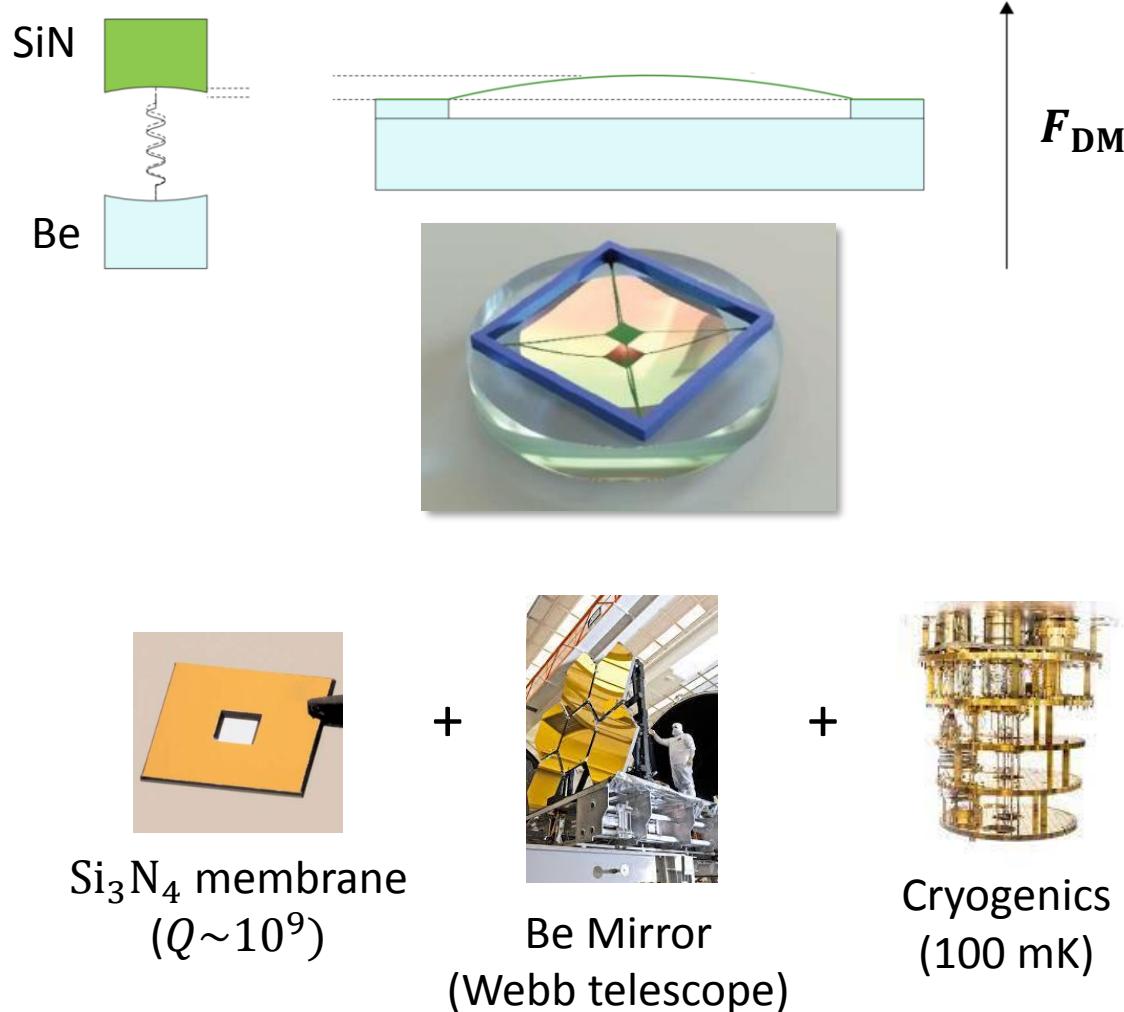
Differential acceleration between materials (e.g. if coupled to B-L)



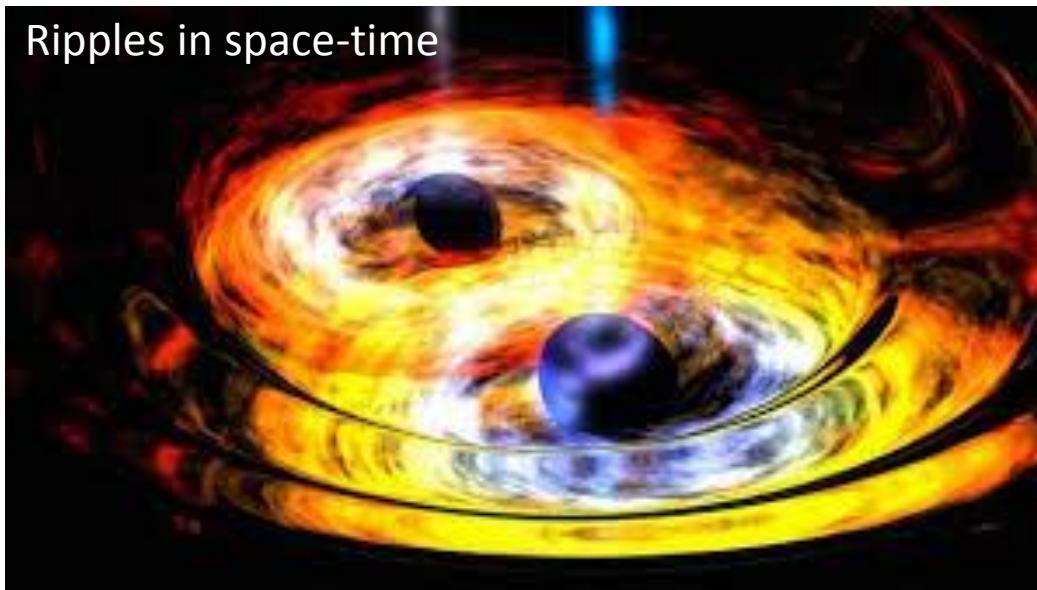
Manley et al. PRL 126, 061301 (2021).

# A membrane-based dark photon detector

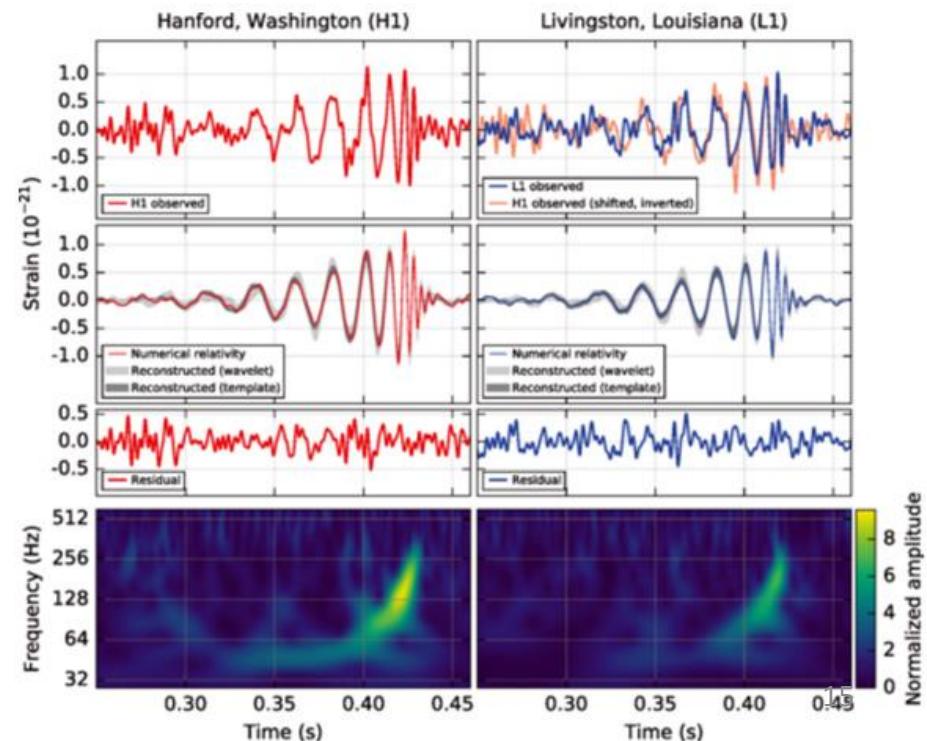
Differential acceleration between materials (e.g. if coupled to B-L)



# 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).

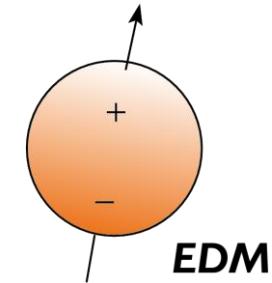
# The Dark Sector

- GW detectors are a probe of the Dark Sector

→Axions

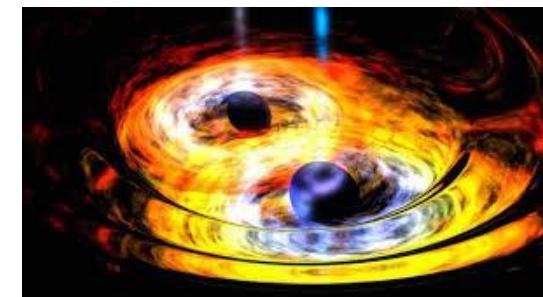
- Peccei-Quinn Axion (QCD) solves “strong-CP problem”  $\theta_{QCD} < 10^{-10}$
- Dark matter candidate

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).

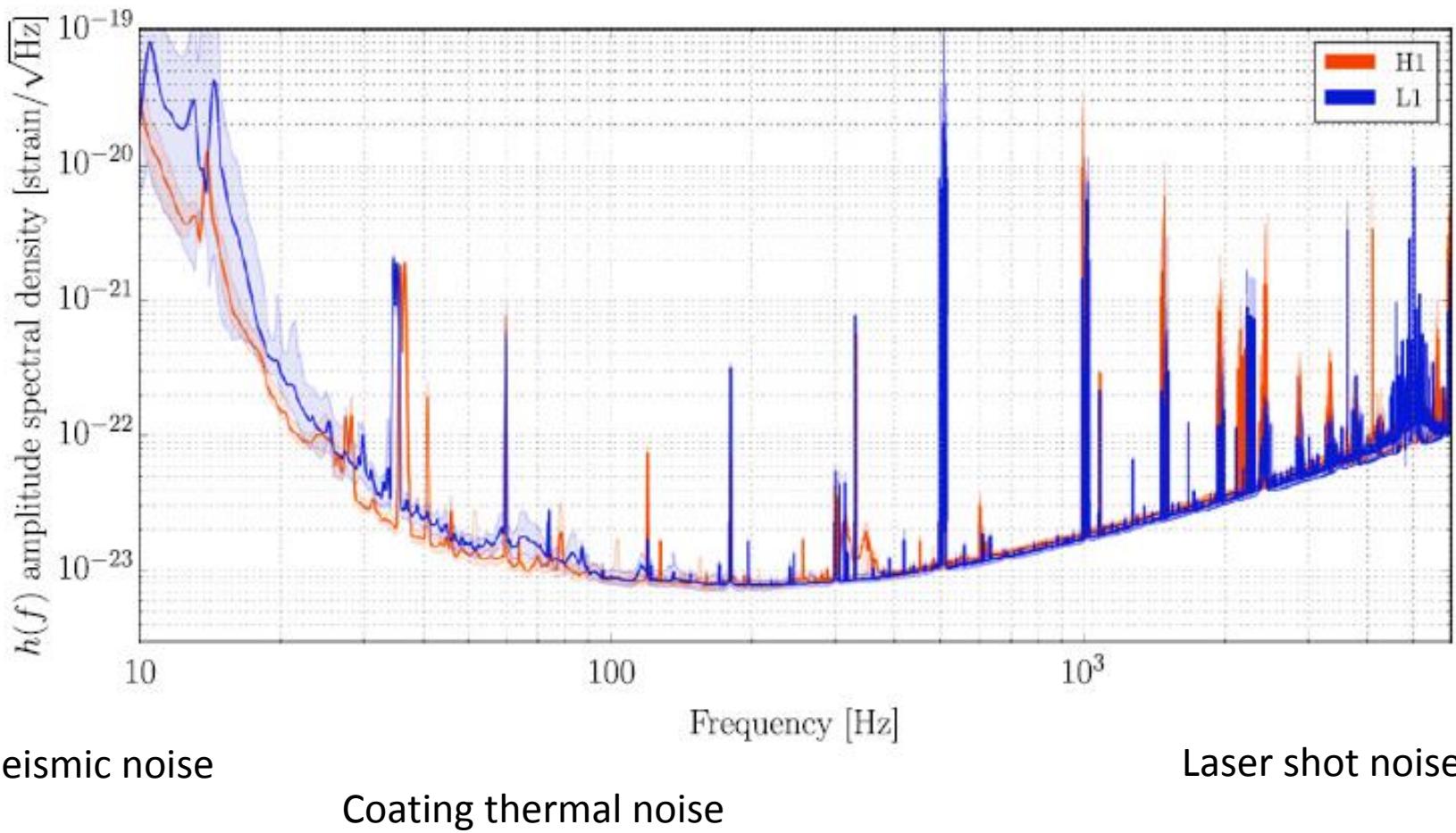


→Primordial Black Holes (PBHs)

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



# GWs from Dark Matter?



**LIGO**

Primordial black hole dark matter and the LIGO/Virgo observations

Karsten Jedamzik<sup>1</sup>

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<sup>1</sup>, Archil Kobakhidze<sup>1</sup>, Ciaran A.J. O'Hare<sup>1</sup>, Zachary S.C. Picker<sup>1</sup> and Mairi Sakellariadou<sup>2</sup>

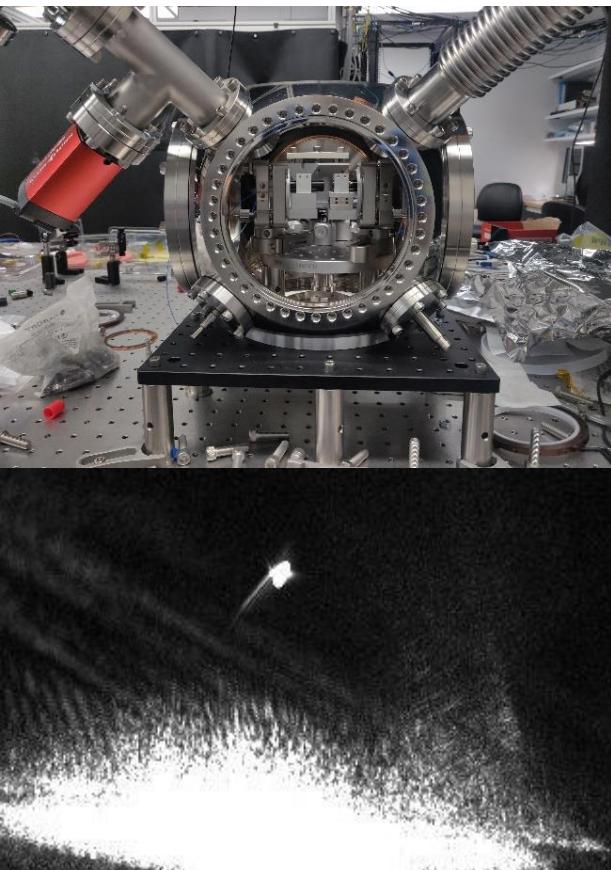
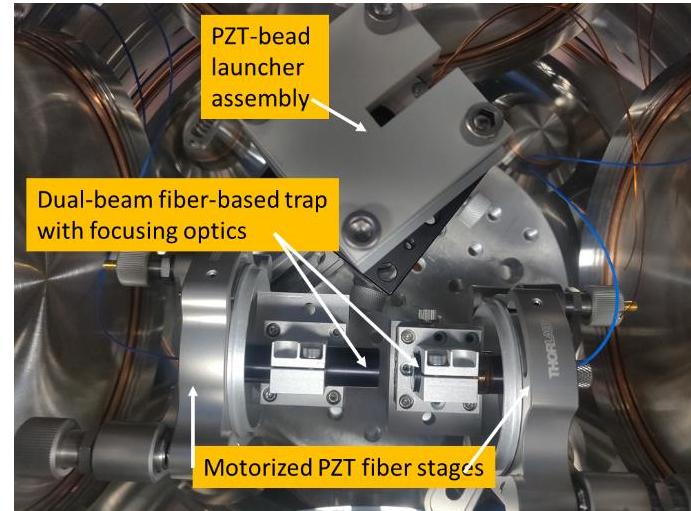
Published 23 March 2021 • © 2021 IOP Publishing Ltd and Sissa Medialab

[Journal of Cosmology and Astroparticle Physics, Volume 2021, March 2021](#)

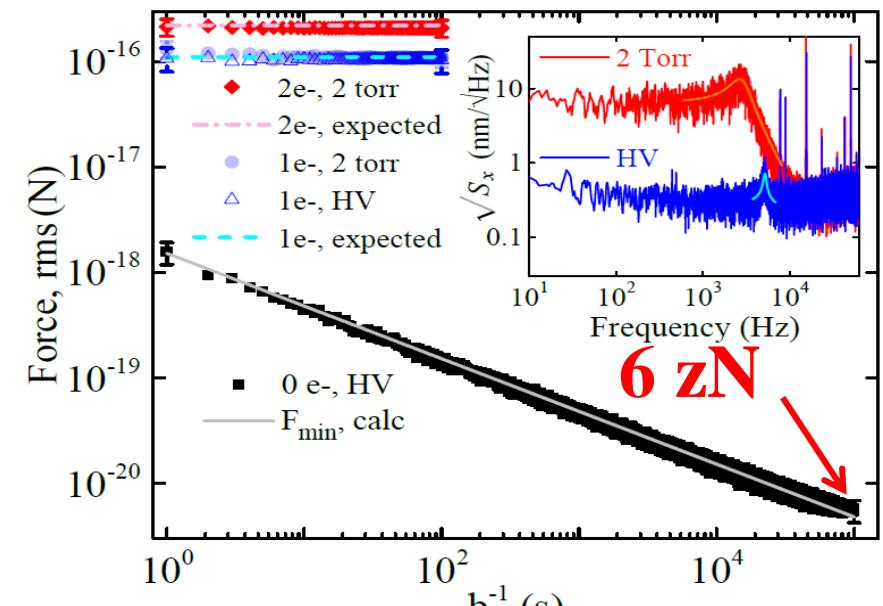
Citation Céline Bœhm et al JCAP03(2021)078

# Levitated optomechanical sensors

nanoparticle standing-wave trap (optical lattice) in UHV

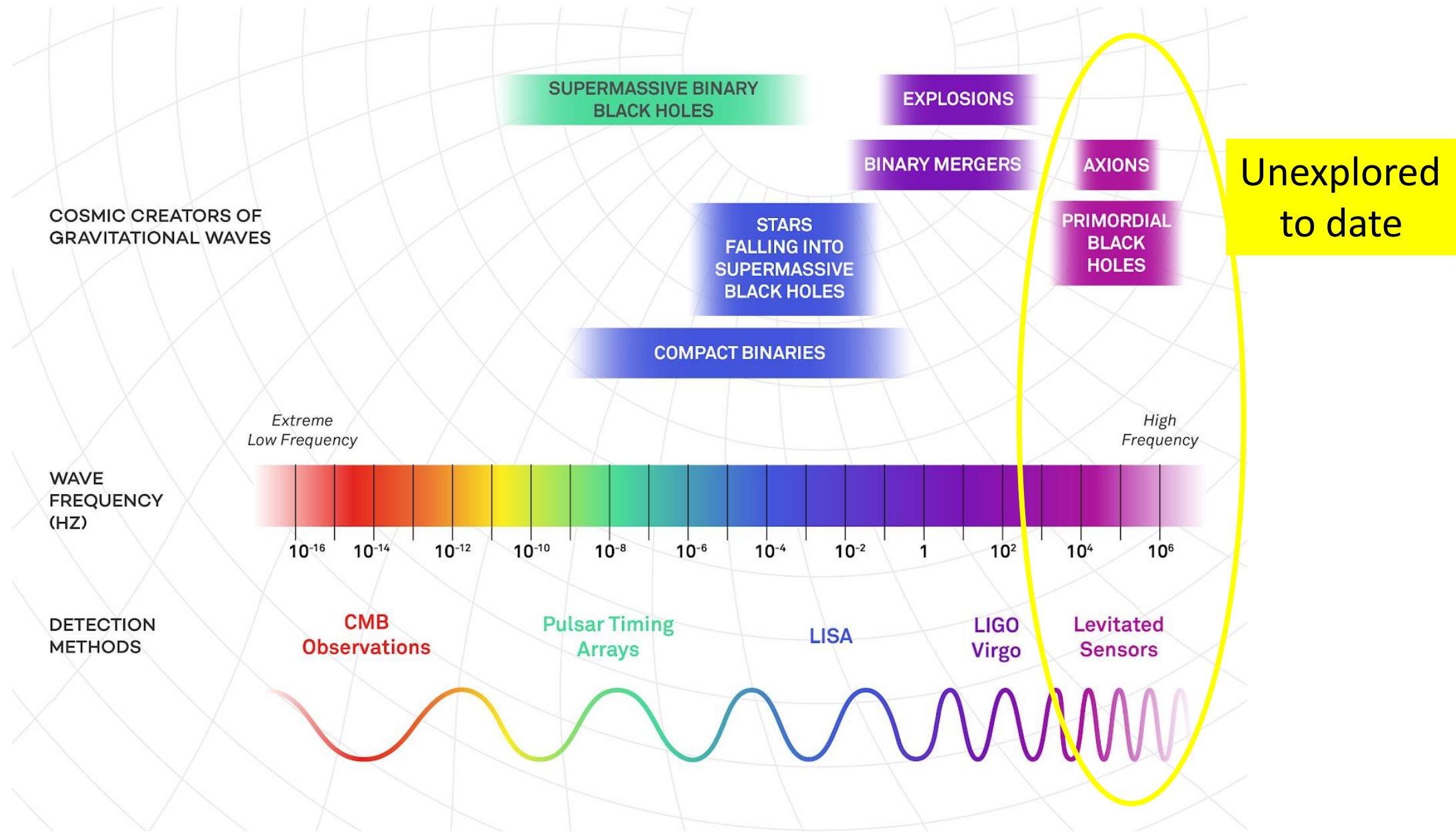


zeptonewton sensing

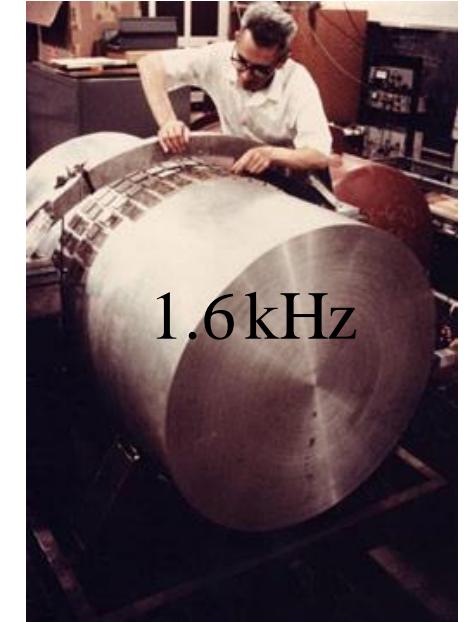
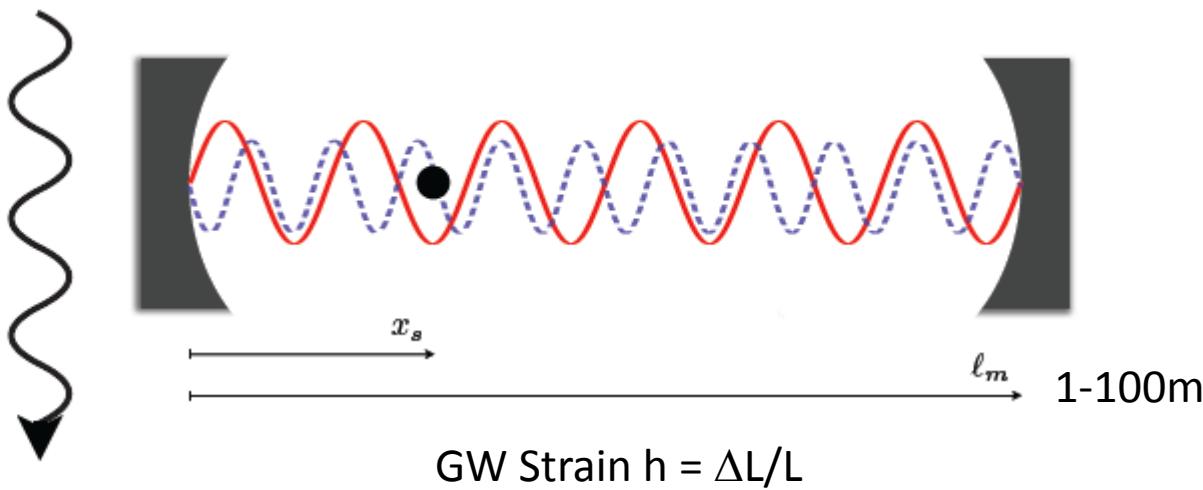


$$S_{F,x} = 1.63 \pm .37 \text{ aN}/\sqrt{\text{Hz}}$$

# Frequency landscape for gravitational waves

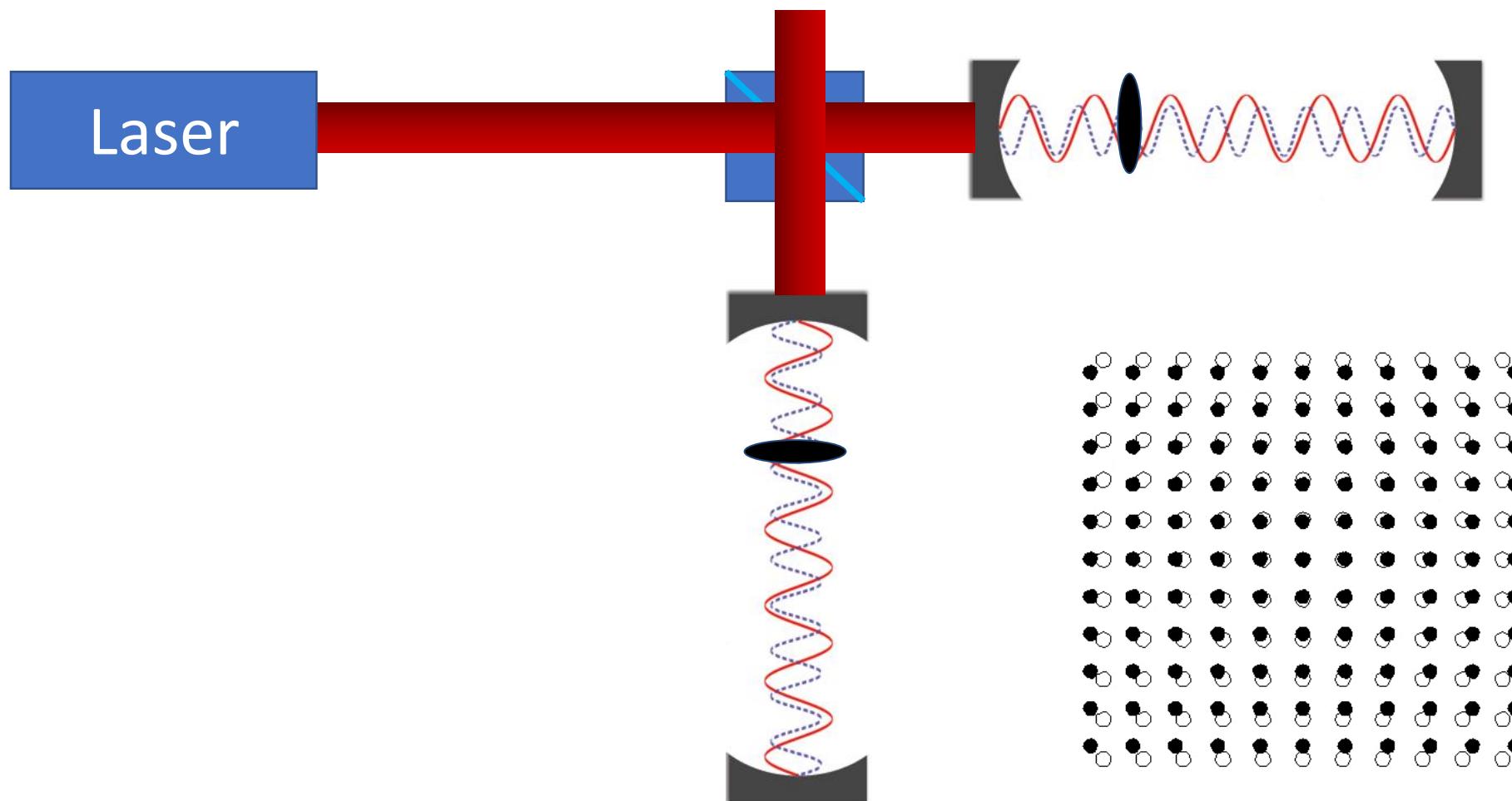


# A novel high-frequency GW detector

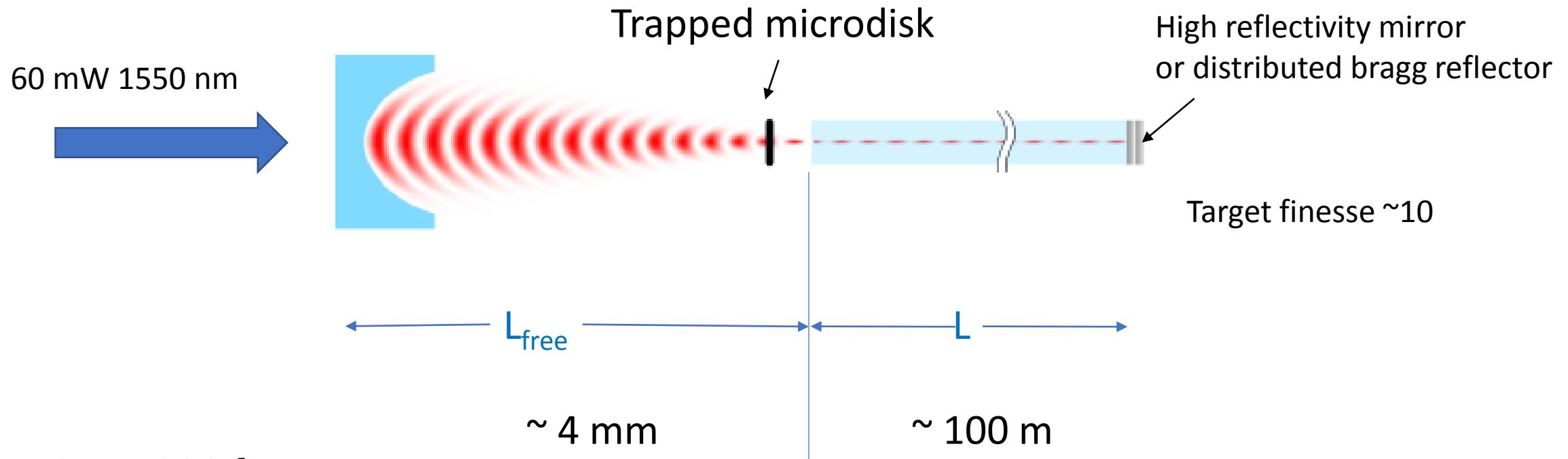


- Laser intensity changed to match trap frequency to GW frequency
- For a 10m cavity,  $h \sim 10^{-22} \text{ Hz}^{-1/2}$  at high frequency (100kHz)
- Limited by thermal noise in sensor (not laser shot noise) → much better at high frequency!!

# 1-m prototype detector layout



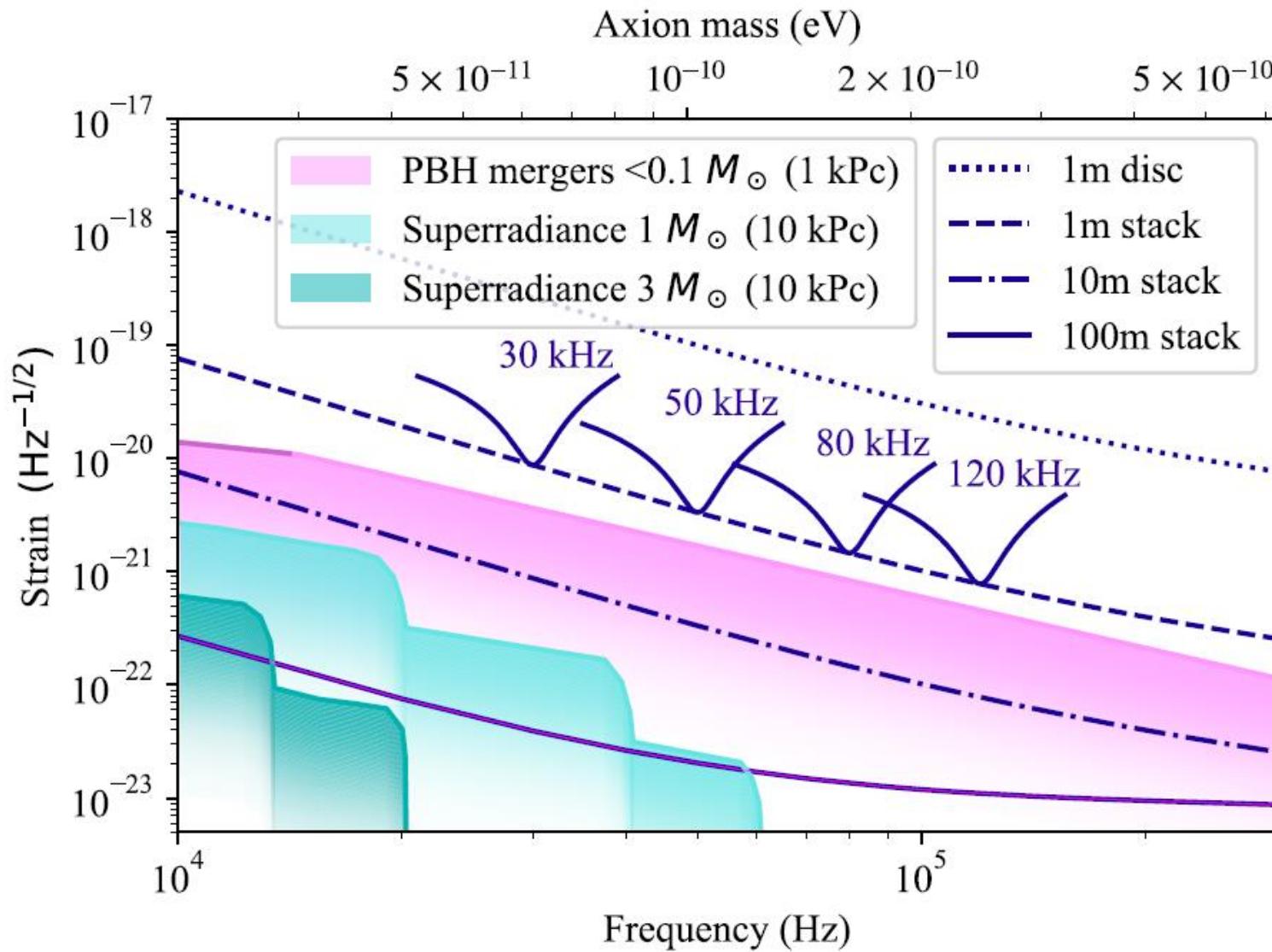
# Fiber based FP Cavity



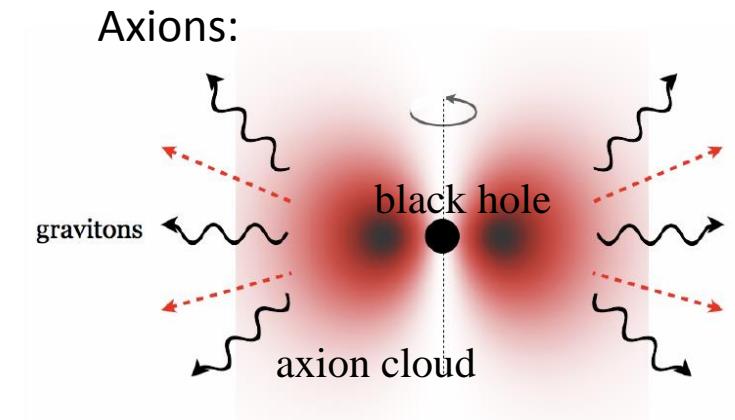
$$\omega = 2\pi \times 100 \text{ kHz}$$

$$\kappa = 2\pi \times 51 \text{ kHz}$$

# Dark Matter search – Axions and PBHs

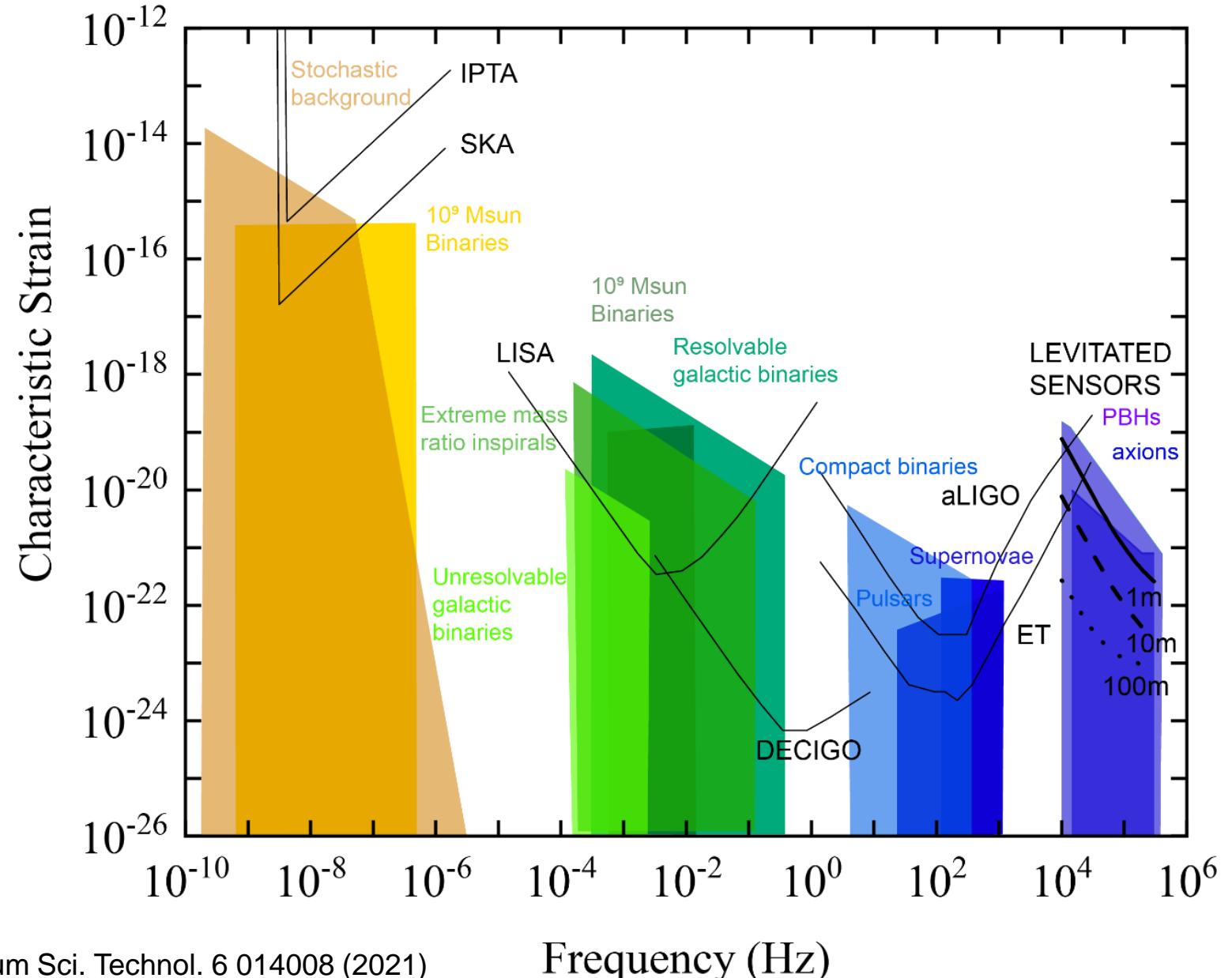


PBHs:  
Distance to source: 100 pc  
(within our galaxy)



Distance to source: 10 kpc  
(within our galaxy)  
Integration time:  $10^6$  sec

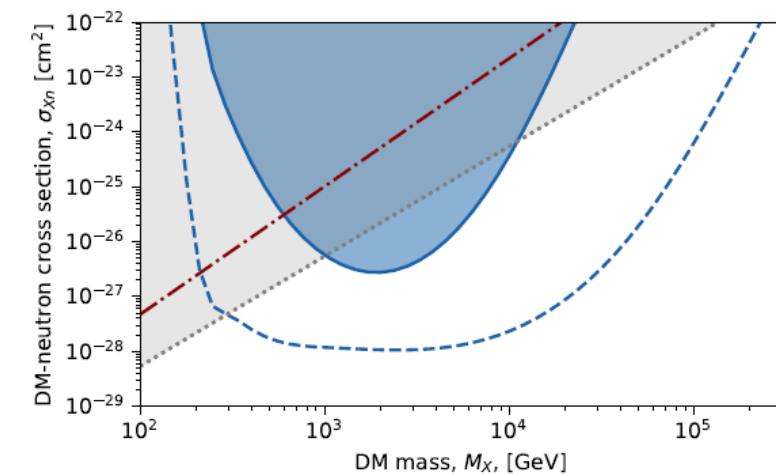
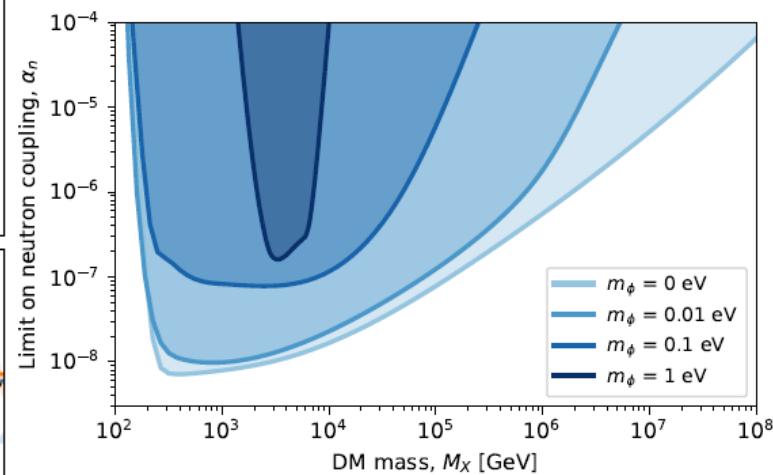
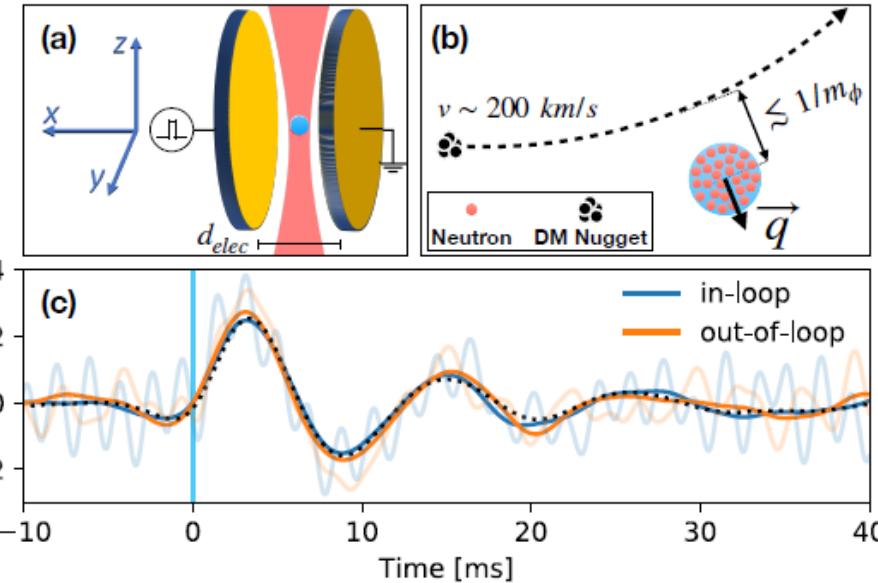
# Vision for HF gravitational wave astronomy



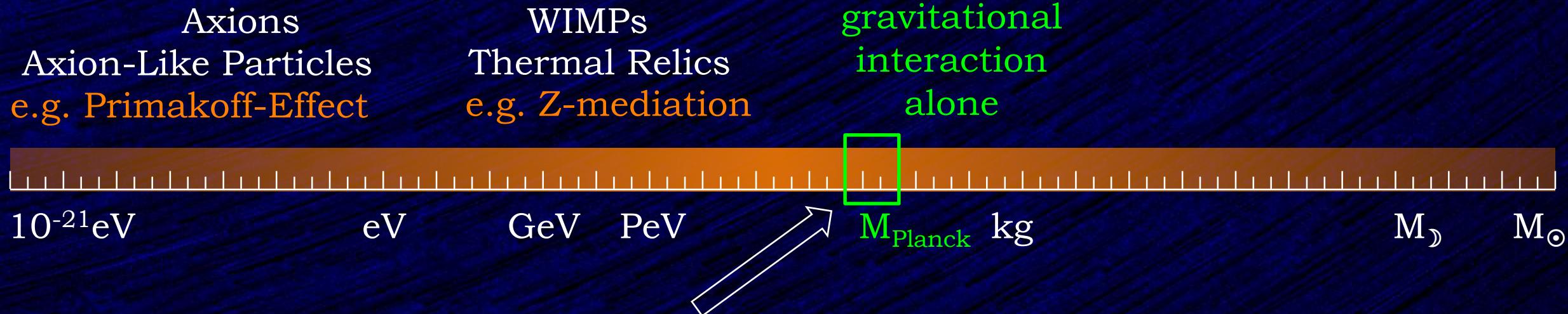
# Composite DM search with Levitated microspheres

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



# Dark Matter Direct Detection



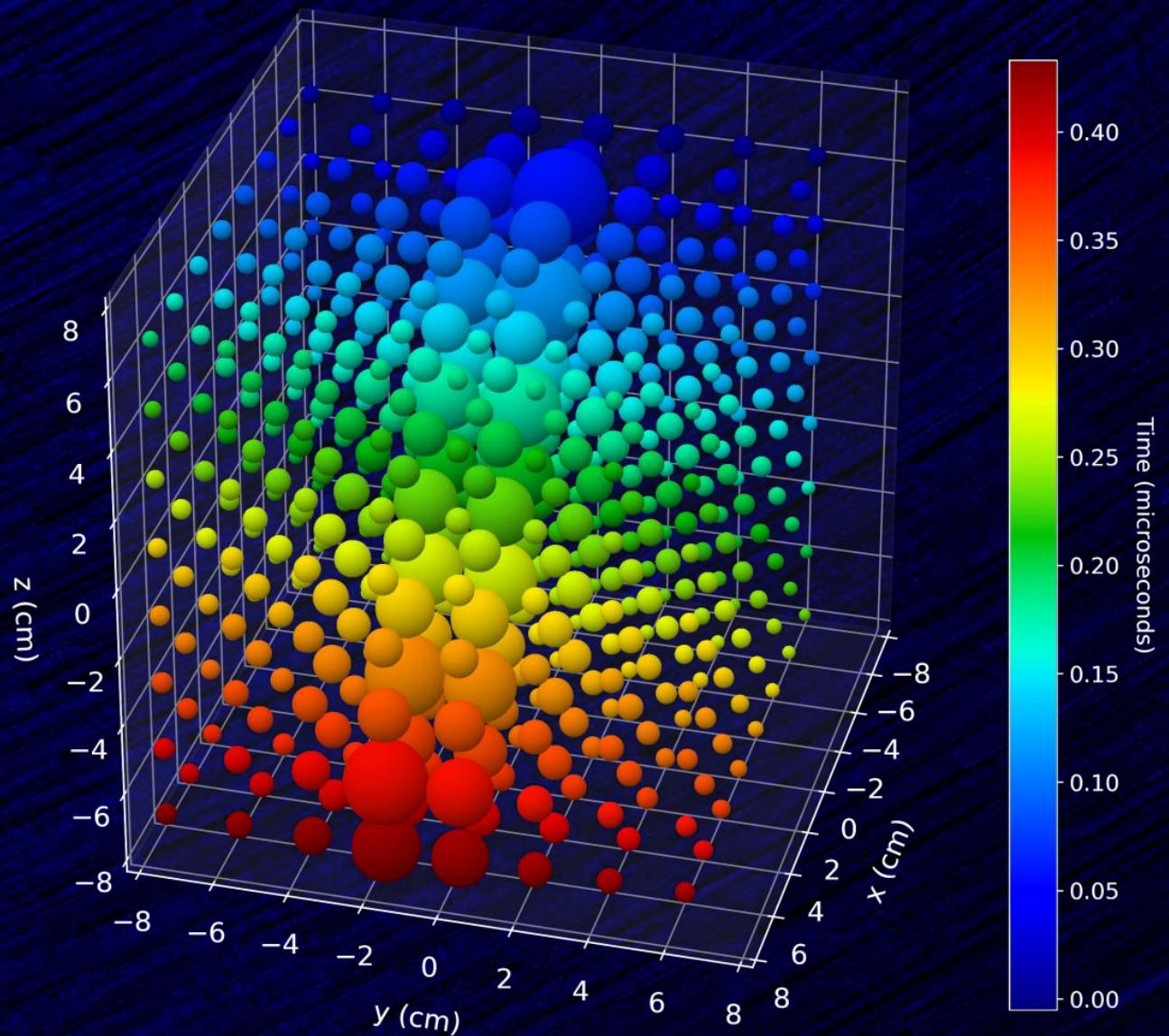
- Well-motivated parameter range
  - we know there's new physics at the Planck scale
  - gravitational interaction is guaranteed
- Dark Matter particle flux still accessible
  - mass density  $0.3 \text{GeV/cm}^3 \rightarrow \text{Flux} \sim 1/\text{m}^2/\text{year}$
- Experimentally not completely crazy
  - but difficult: long-term project
  - Carney+ 1903.00492, Ghosh+ 1910.11892

# Windchime: Array of Mechanical Accelerometers

Start with available sensor frame

Eventually, use quantum back-action evading impulse measurement

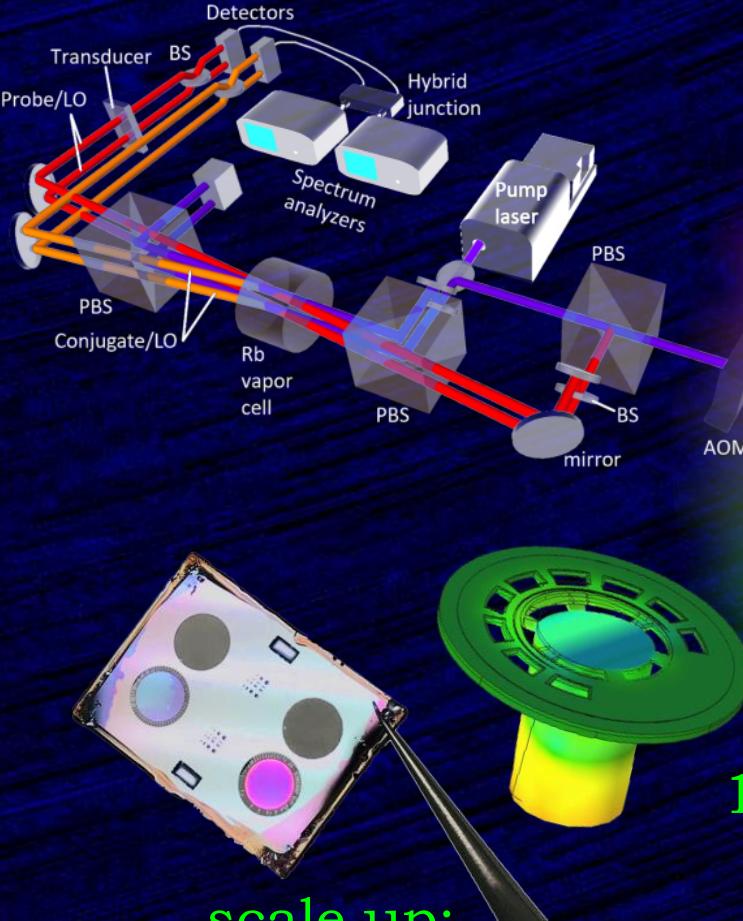
Challenges: scale, integration, noise, analysis



# Windchime: Gravitational Detection of Planck-Mass Dark Matter

quantum noise suppression:

short signals (neutrinos/sub-GeV)



scale up:  
ultralight dark matter

Rafael: Windchime

computing:

streaming analysis, ML-based design

ASIC

FPGA

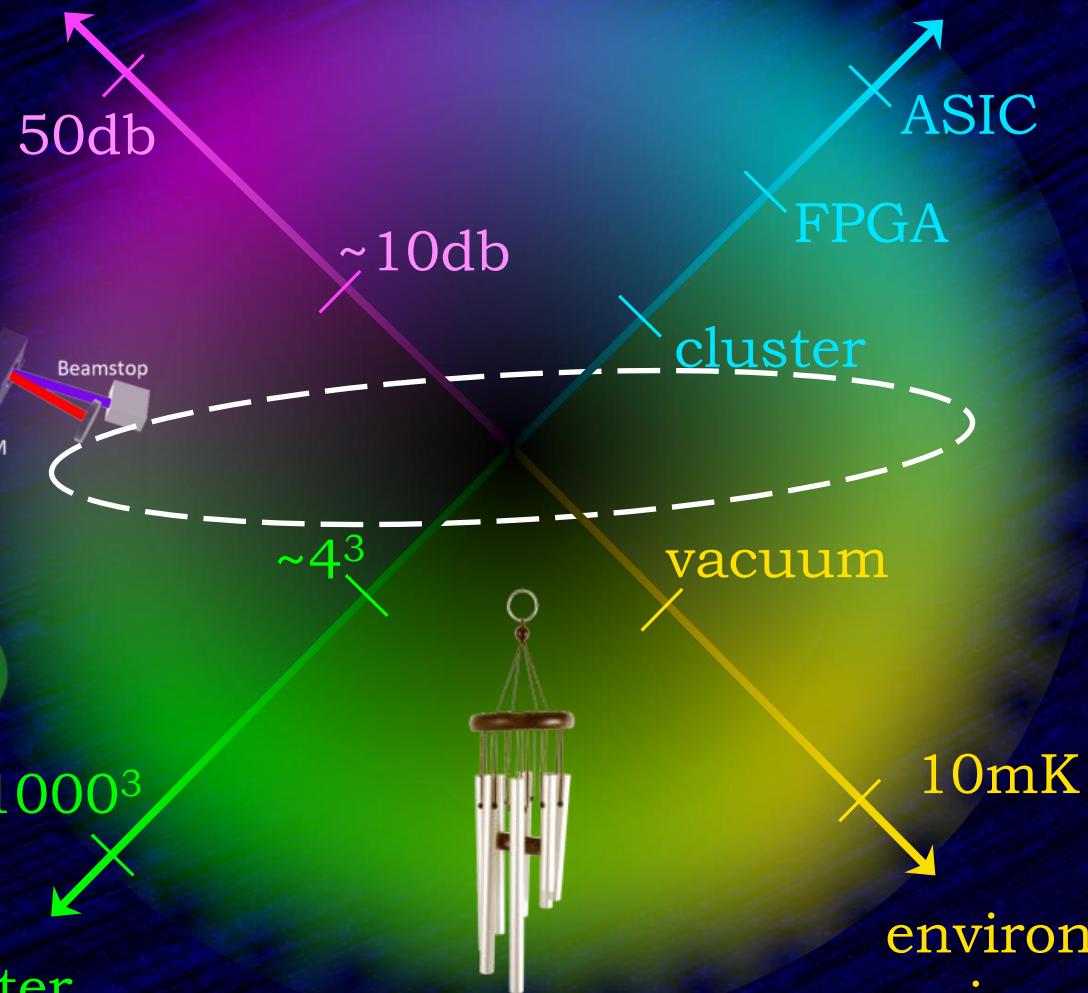
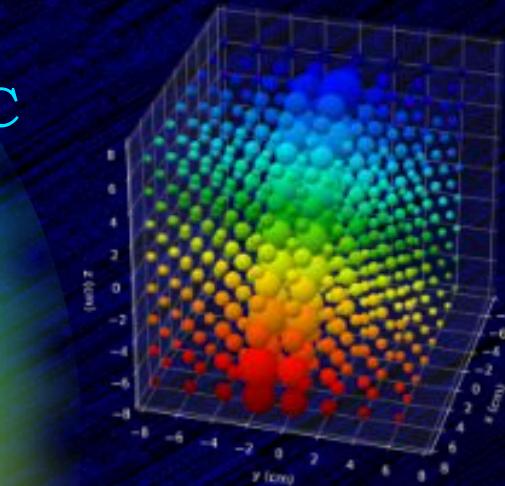
cluster

vacuum

$1000^3$

Windchime

$\sim 4^3$   
environmental isolation:  
impulse metrology



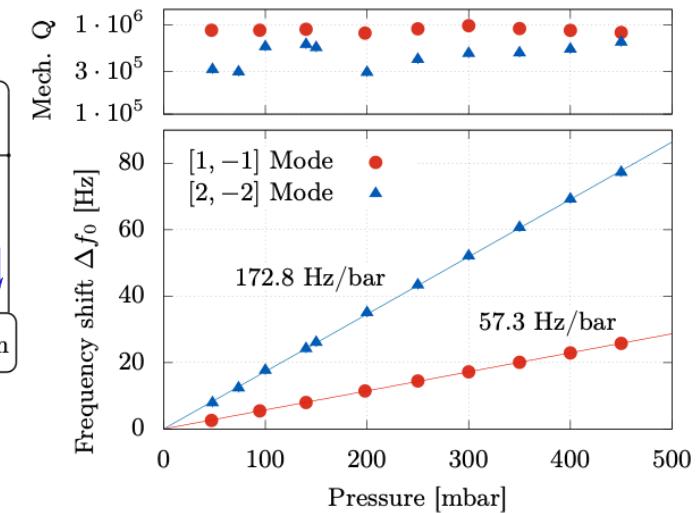
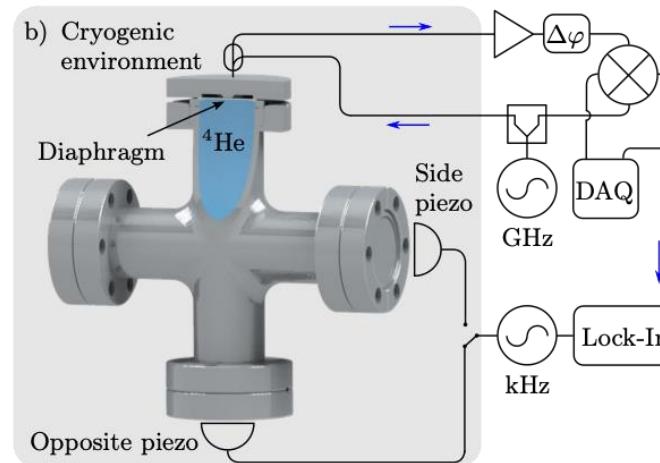
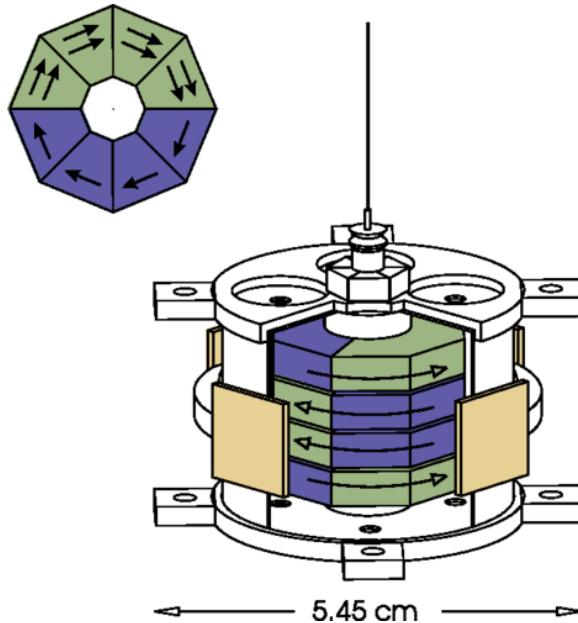
# Timeline for developments and physics reach

- next 20+ years of expected and necessary developments/challenges/milestones to reach scientific goals

Technology	3 yr	5 yrs	20 yrs
Cavity DM searches, Accelerometer sensors	Cryogenic methods 3 square decades scalar/vector DM parameter space	Squeezed light techniques 6 square decades parameter space scalar/vector DM	Lower-loss materials Improved squeezing, 10 square decades parameter space for scalar/vector DM
Levitated sensor GW detectors	1 m instrument >100 kHz axion, GW search, PBH search 0.1 kpc	10-m instruments >30 kHz axion, GW search PBH search 1 kpc	100-m instruments, Cryogenic, >5 kHz axion, GW search, PBH search 10 kpc
Particle DM detectors (Windchime, levitated particles)	Searches at TeV - Planck scale...isolation, noise suppression	Searches at TeV - Planck scale...isolation, noise suppression	Searches at TeV - Planck scale...isolation, noise suppression

# Other related physics topics and technologies

- Atom interferometer and matter-wave accelerometers for GWs and DM (see e.g. Jason's talk @17:15)
- Bar detectors Arvanitaki *et. al.* Phys. Rev. Lett. 116, 031102 (2016)
- Superfluid-helium based detectors for GWs and DM
- Torsion balances



John Davis group @



# 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...)*
- Exciting road ahead in coming decade(s)!



# Acknowledgements



Group Members (left to right): Chloe Lohmeyer (G), Evan Weisman (PD), George Winstone (PD), Nancy Aggarwal (PD), Cris Montoya (PD), Daniel Grass (UG), Chethn Galla (G), Eduardo Alejandro (G), William Eom (G), Andy Geraci (PI)



Center for Fundamental Physics (CFP)

Collaborators (GW):  
Peter Barker (UCL)

Astro Theory:  
Asimina Arvanitaki (Perimeter)  
Masha Baryakhtar (Perimeter)  
Mae Hwee Teo (Stanford)  
Shane Larson (NU)  
Vicky Kalogera (NU)