Searching for high-frequency (10 kHz-MHz) gravitational waves with Levitated Sensor Detector (LSD)

Northwestern
WEINBERG COLLEGE OF ARTS & SCIENCES
Center for Fundamental Physics

CIERA
CENTER FOR INTERDISCIPLINARY EXPLORATION AND RESEARCH IN ASTROPHYSICS

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Geraci Group

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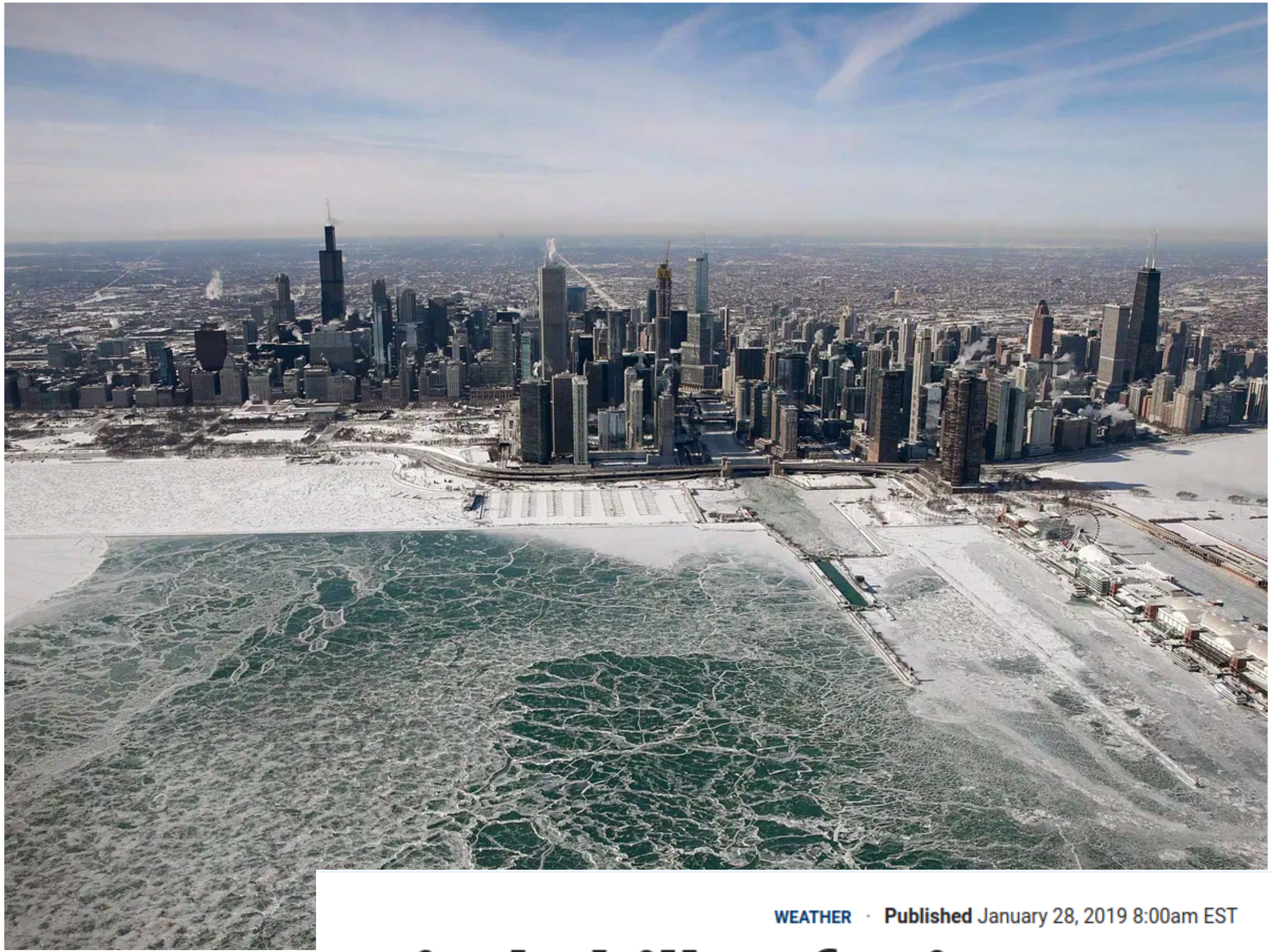
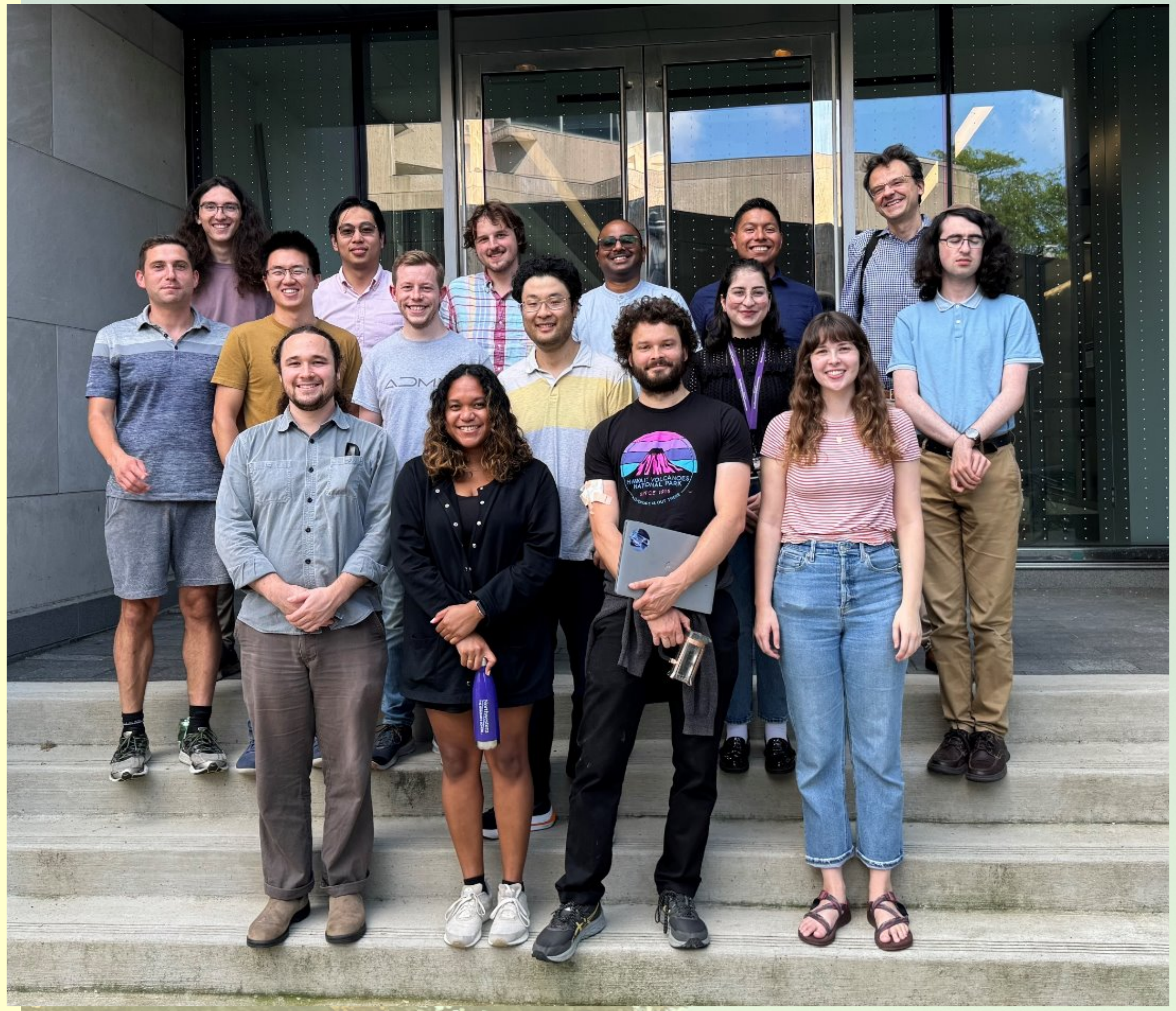


WEATHER · **Published** January 28, 2019 8:00am EST

Wind chills of minus-45 to minus-60 expected in Chicago, much of upper Midwest



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LSD Collaboration

Prof. Andrew Geraci, Prof. Nancy Aggarwal (Davis), Prof. Shane Larson (Clarkson) and Prof. Vicky Kalogera

Office of Naval Research ONR Science & Technology

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Clarkson University Technology

The University of California Davis

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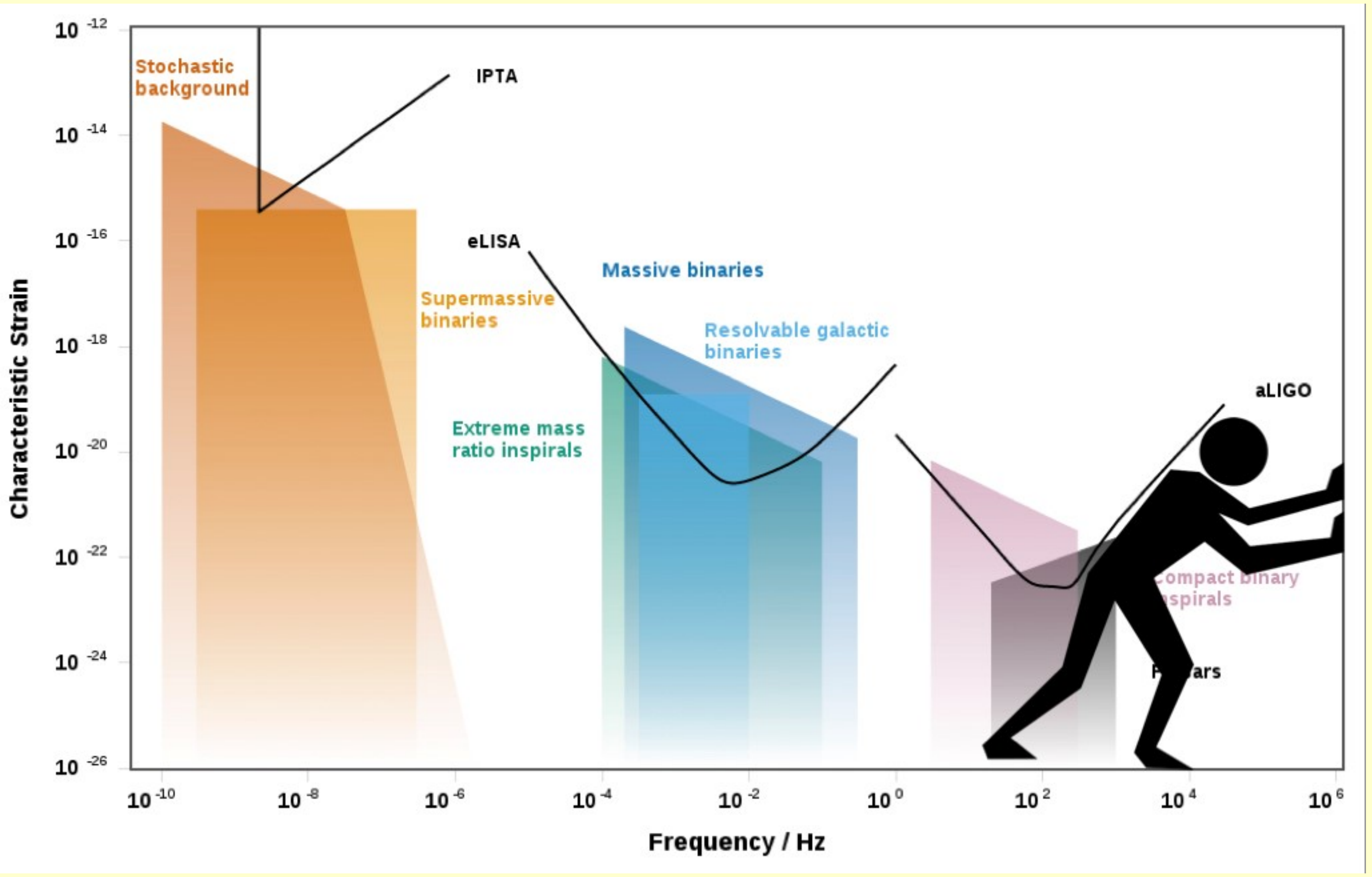
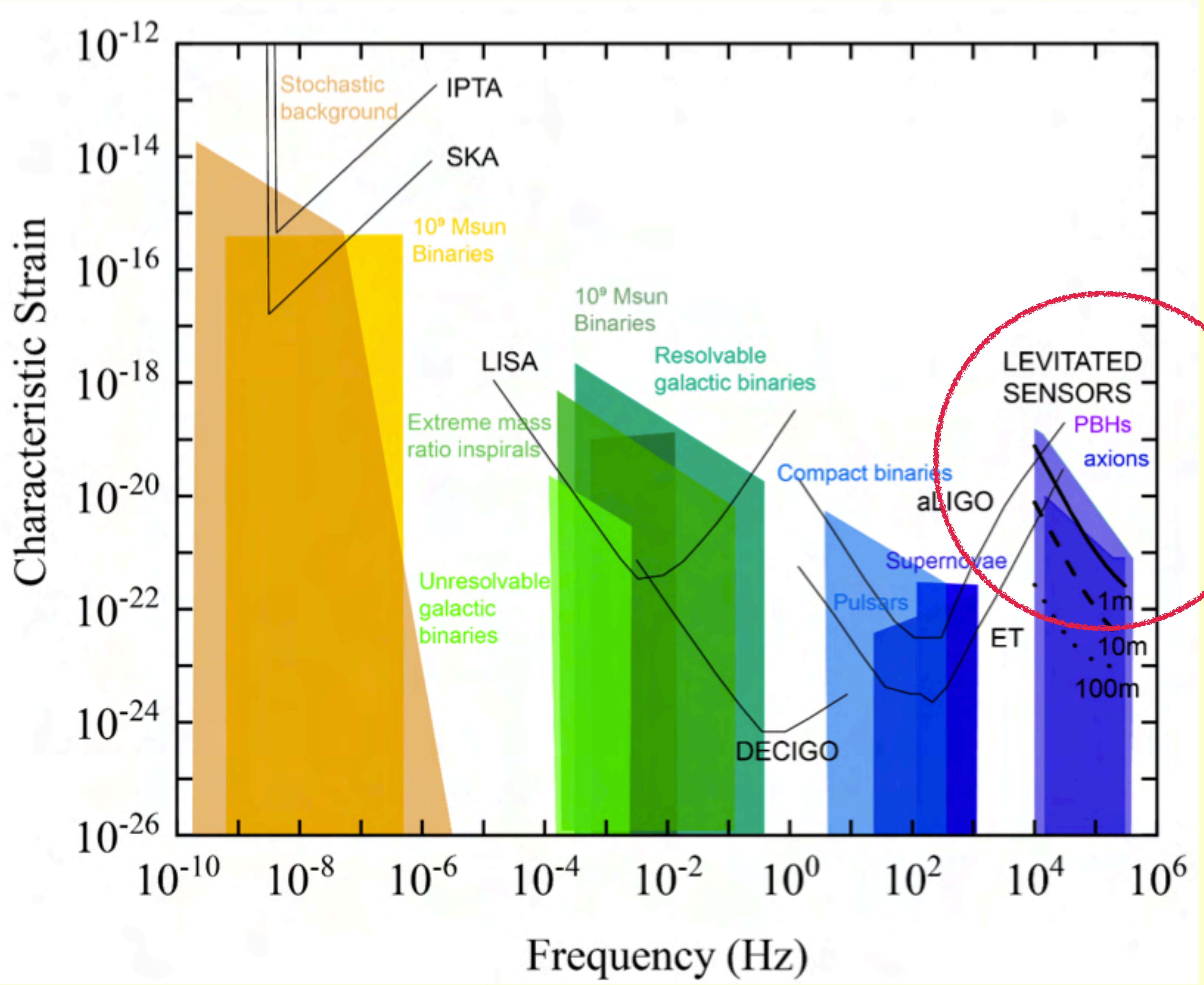
Gravitational Wave Astronomy

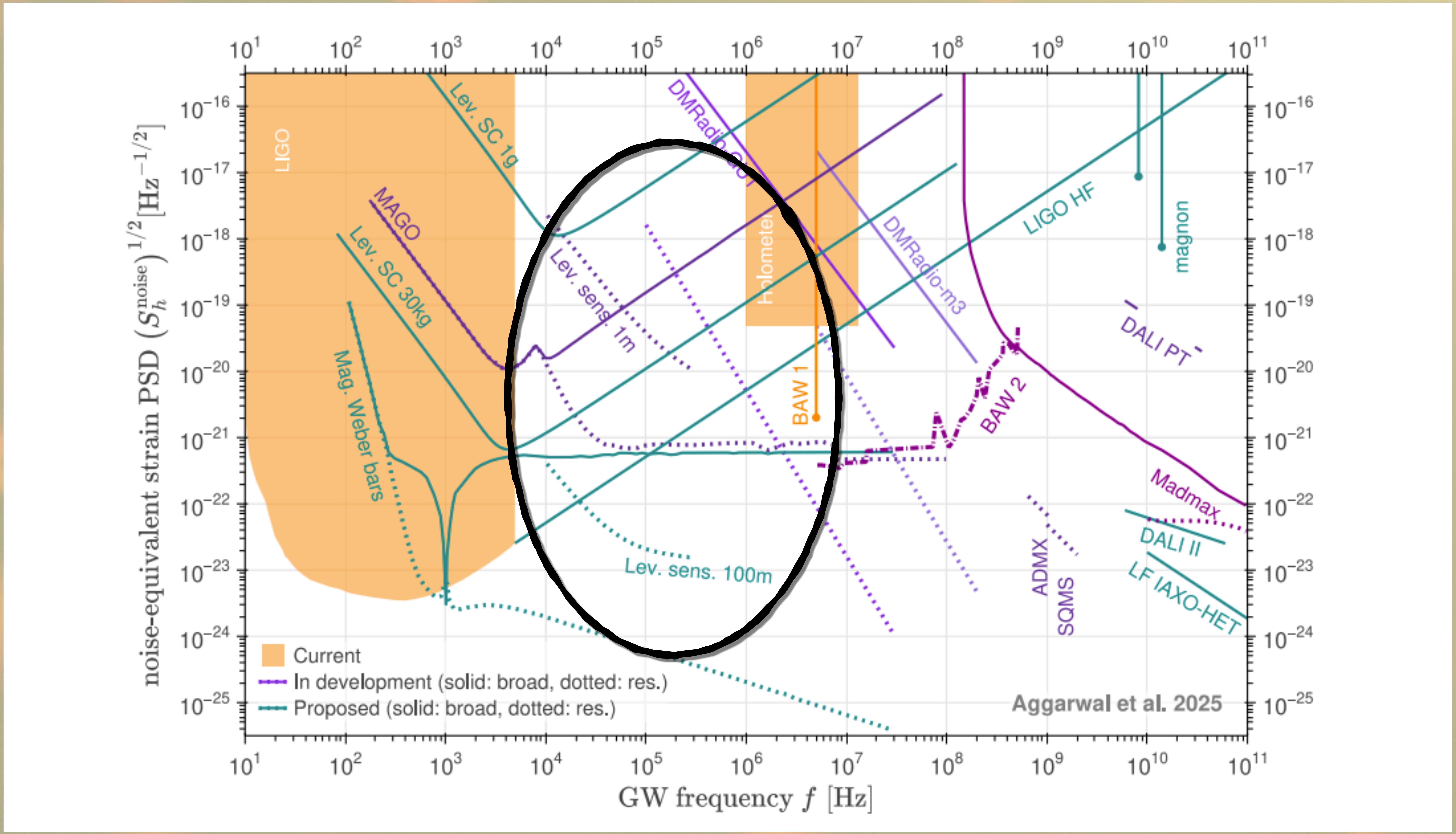




LIGO-like experiments are shot noise limited at HF

David C. Moore , Andrew A. Geraci Quantum Sci. Technol. 6 014008 (2021)

HF GW Astronomy: Sneak peak into the BSM Physics



Aggarwal et. Al. Challenges and Opportunities of Gravitational Wave Searches above 10 kHz

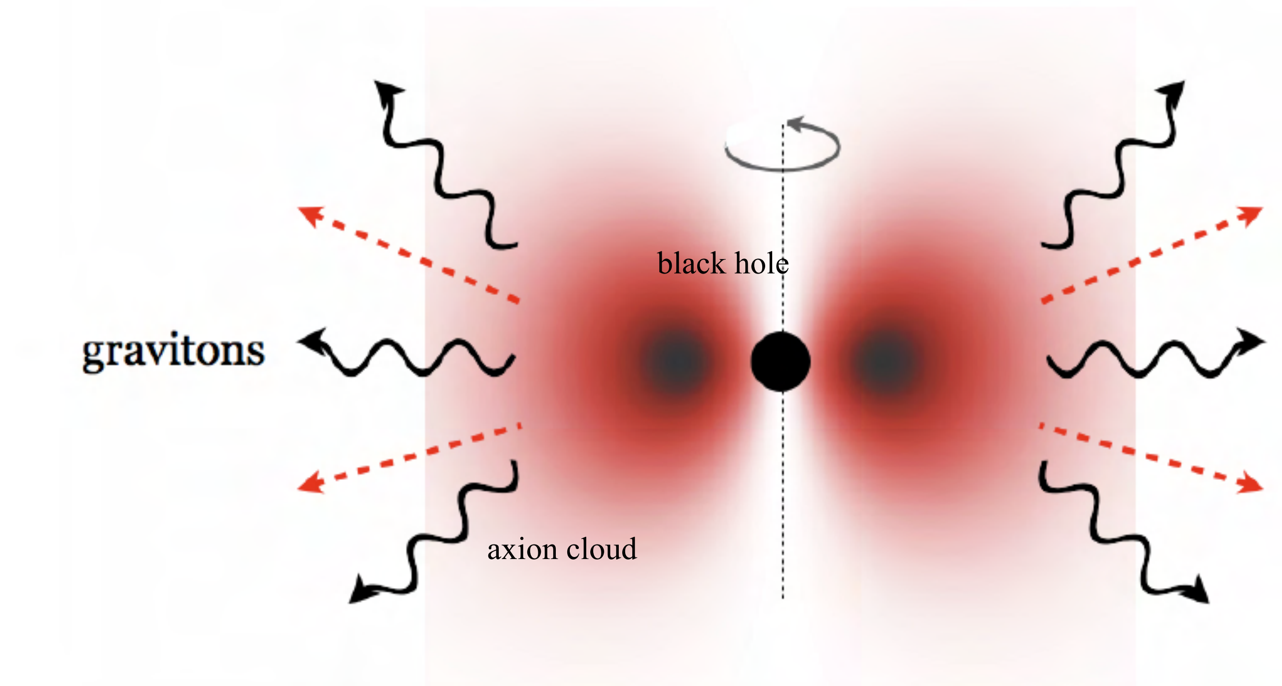
HFGWs : Potential Sources

Probing both particle and wave like dark matter at the same time!

Well motivated dark matter candidates

- Mergers of **Primordial Black Holes**
- **QCD axions around rotating Black Holes**
- Exotic compact objects like Boson stars
- Unknown BSM sources
- String cosmology
- **Uncharted regime—> don't know what we'll find!**

Also solve the Strong CP problem



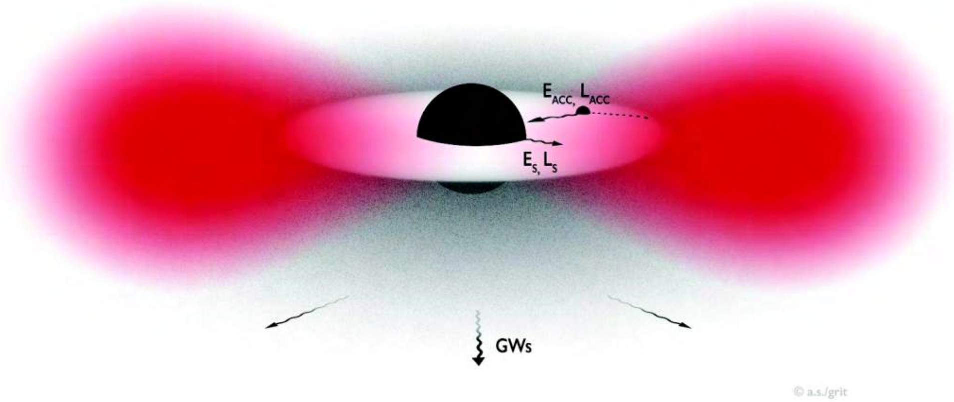
LSD Searches for GWs in 10kHz-MHz Band

Searching for New Physics with a Levitated-Sensor-Based Gravitational-Wave Detector

Nancy Aggarwal, George P. Winstone, Mae Teo, Masha Baryakhtar, Shane L. Larson, Vicky Kalogera, and Andrew A. Geraci

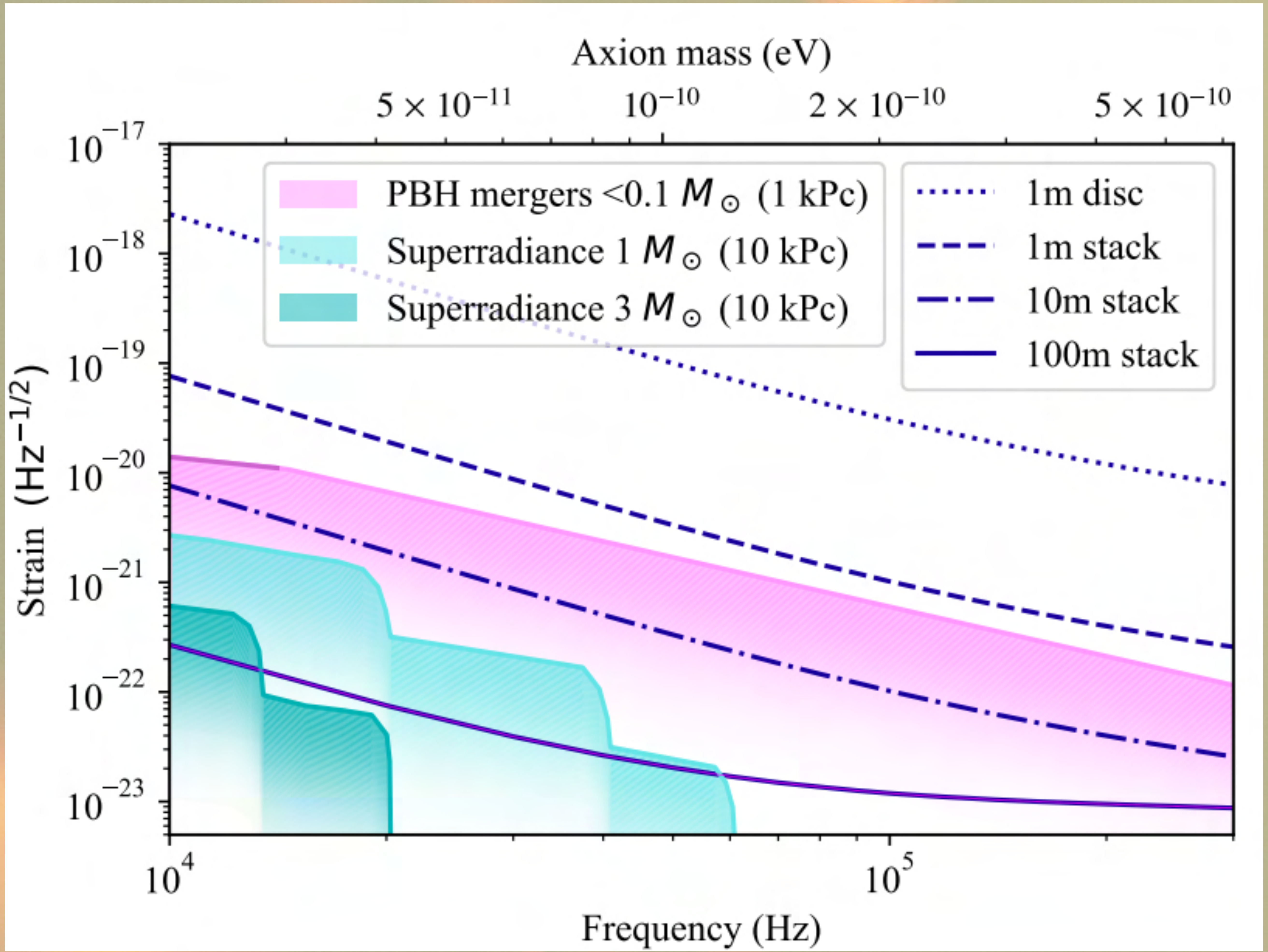
Phys. Rev. Lett. **128**, 111101 – Published 16 March 2022

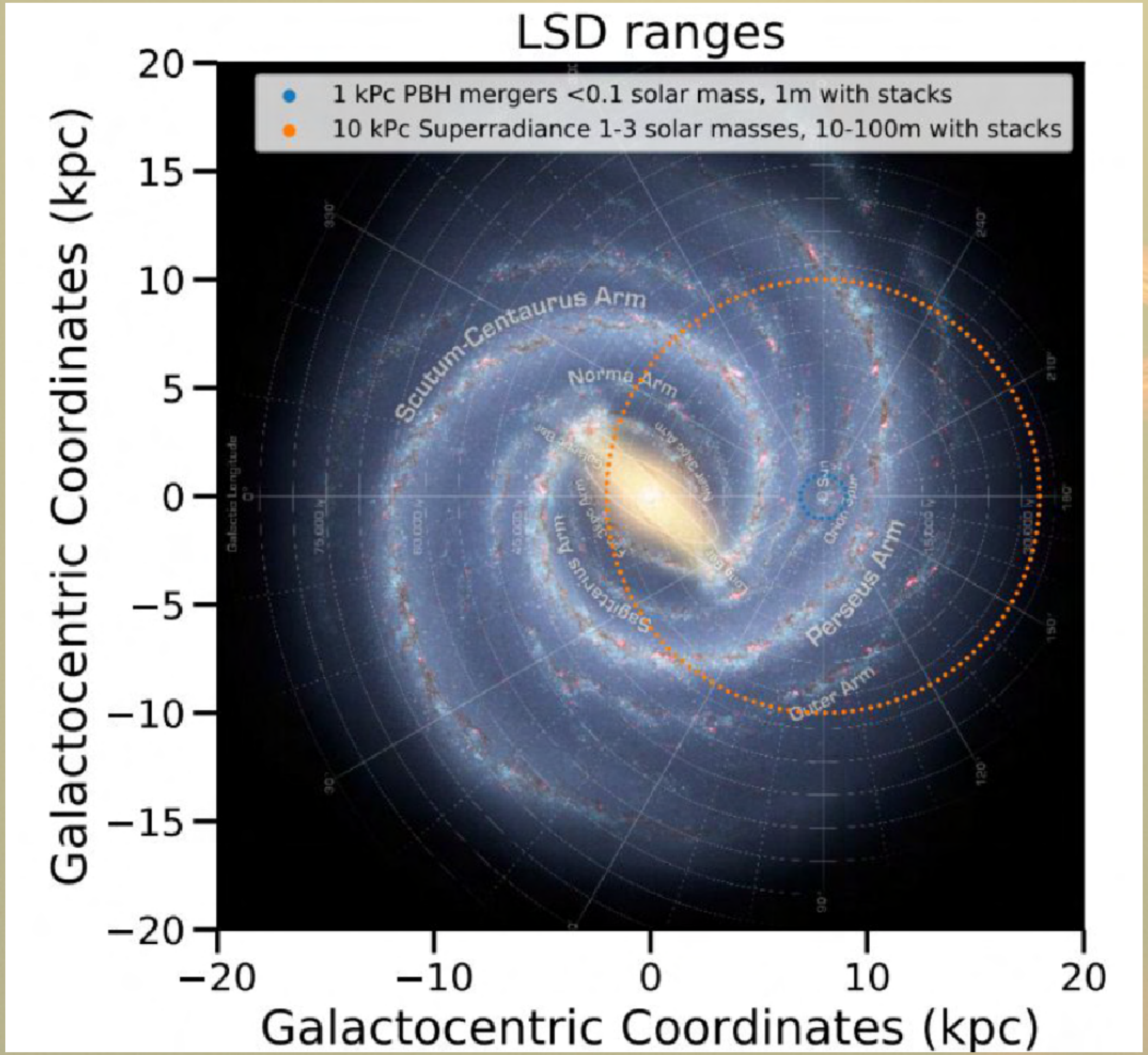
○ Gravitational atom in the sky



- Ultra-light scalar field like QCD axion bound to a rotating BH by gravity
- Extracts angular mom. from BH via Penrose process—> specific states get super radiantly amplified—>macroscopic boson cloud
- Annihilate to gravitons—>emission of monochromatic GW waves

LSD Searches for GWs in 10 kHz-MHz Band





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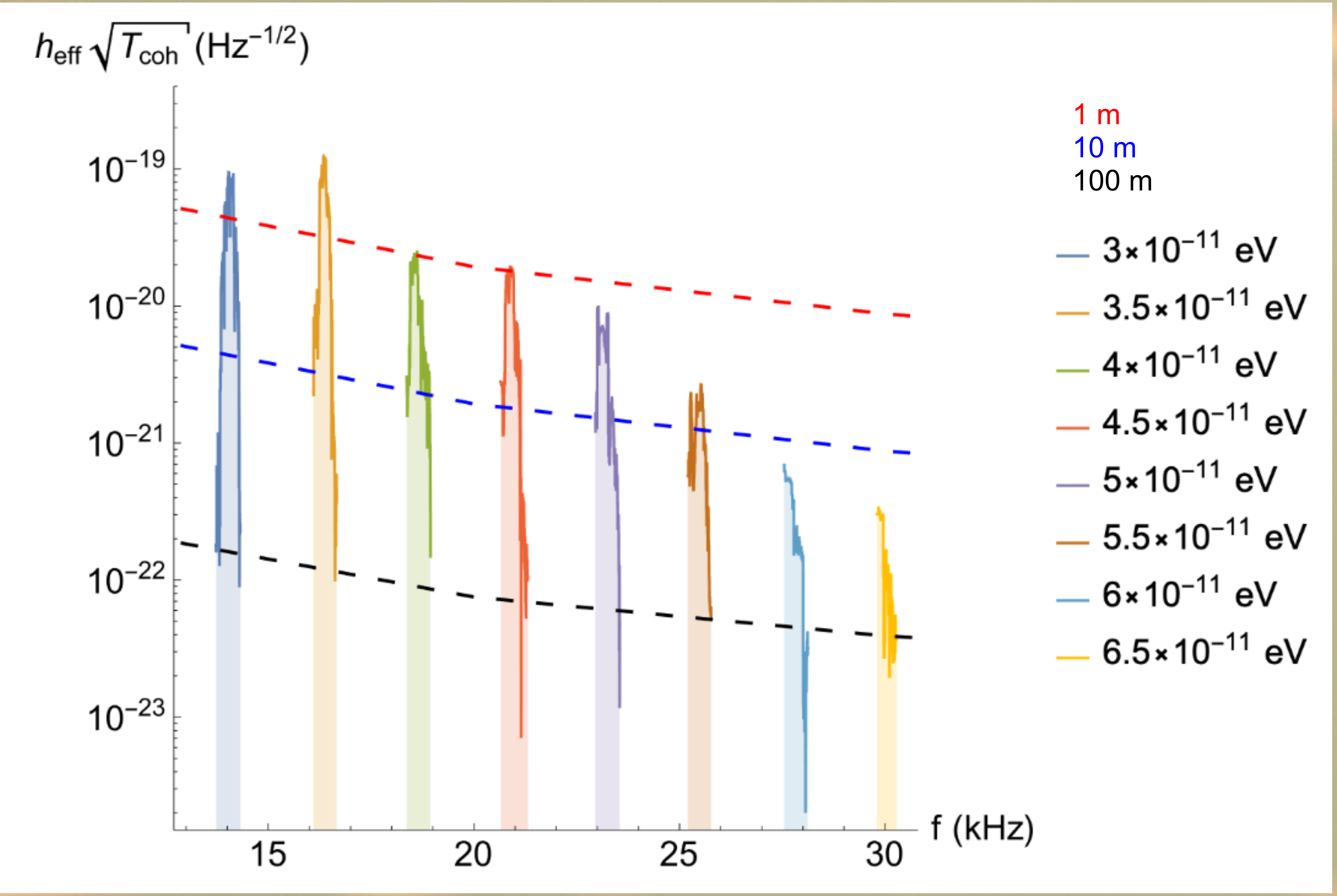
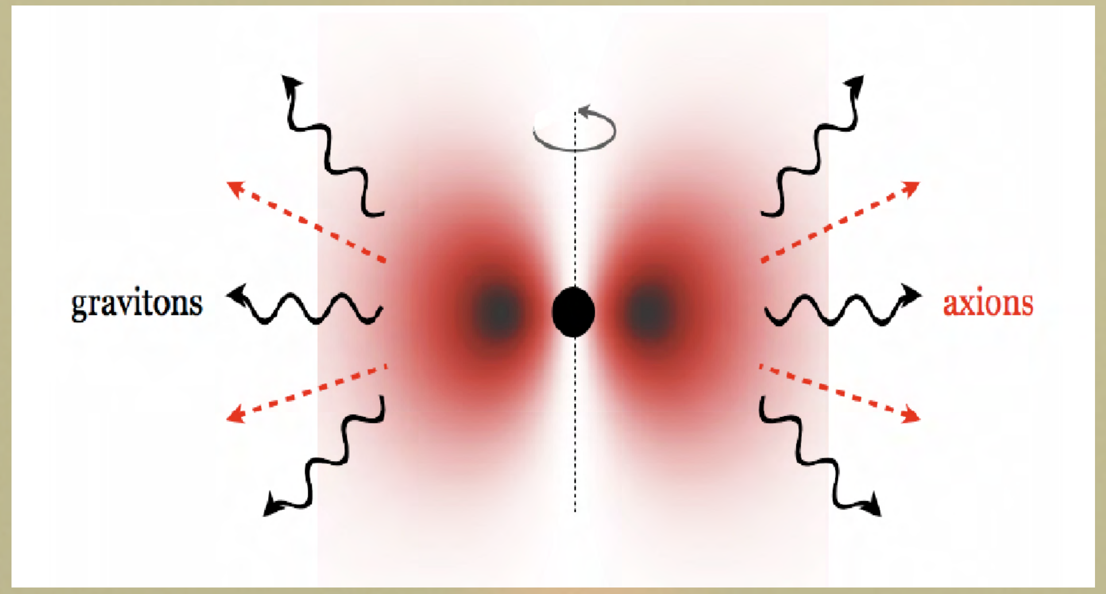
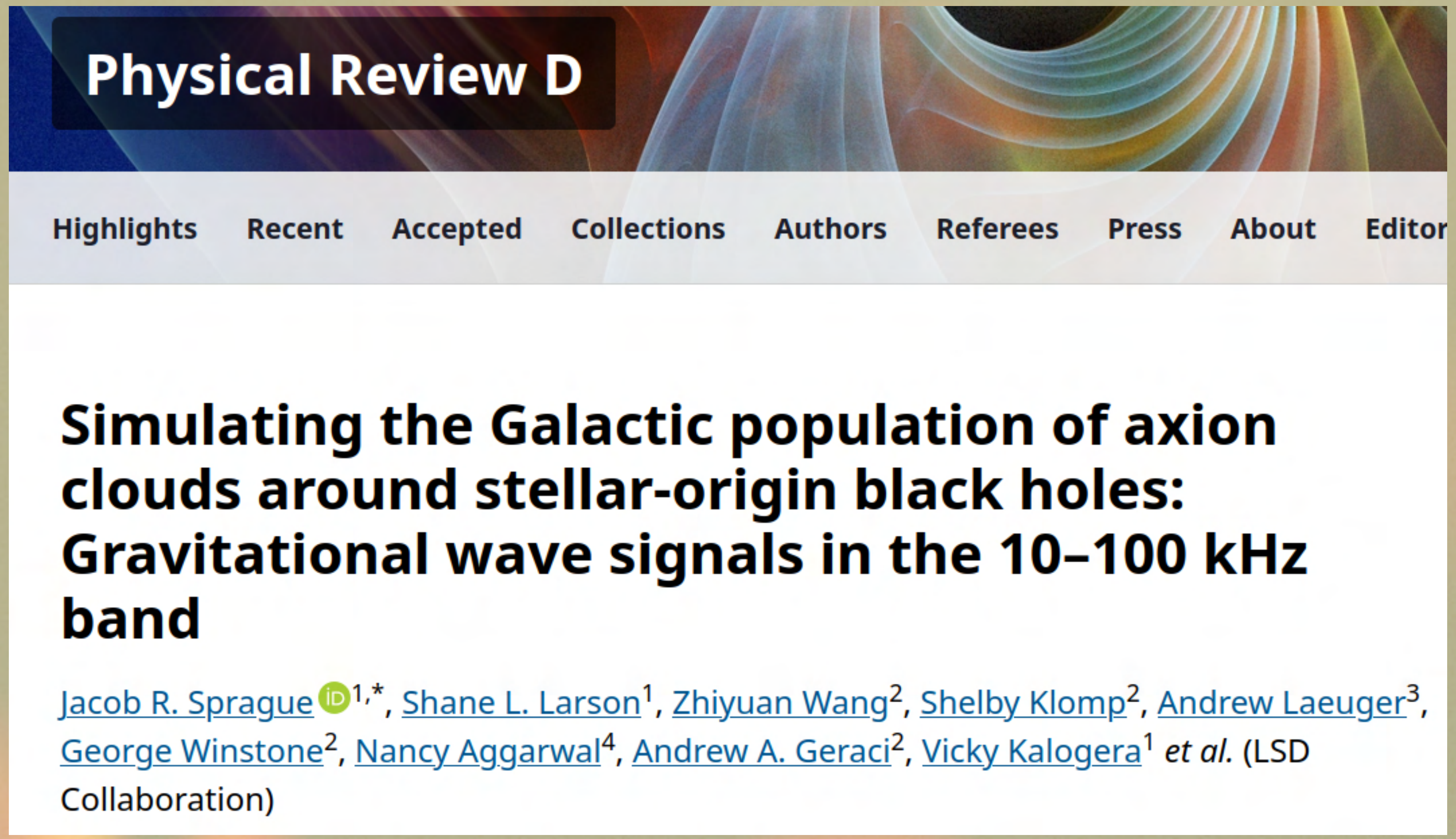
LSD Searches for GWs in 10 kHz-MHz Band

1-m prototype may see the signal from the annihilation of $\sim 3.5 \times 10^{-11}\ eV$ axions !



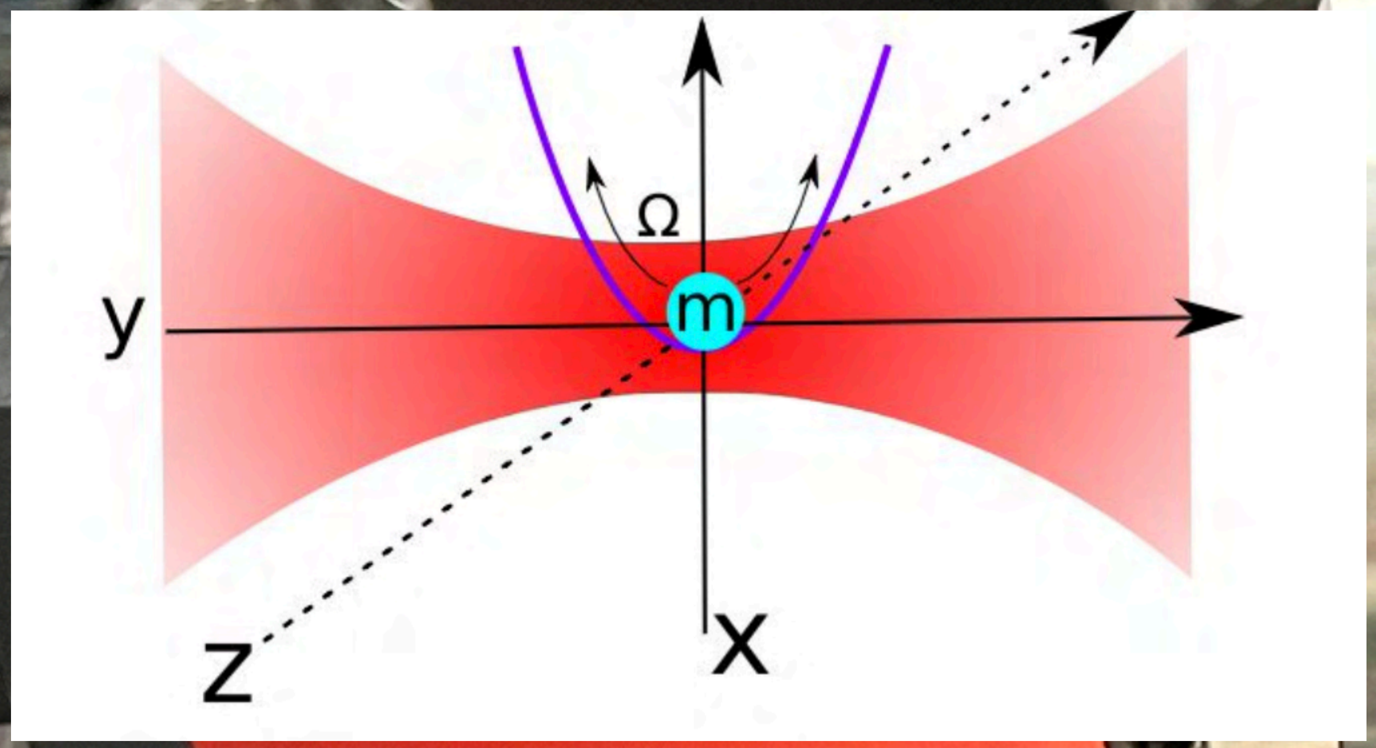




Levitated Sensor Detector (LSD)

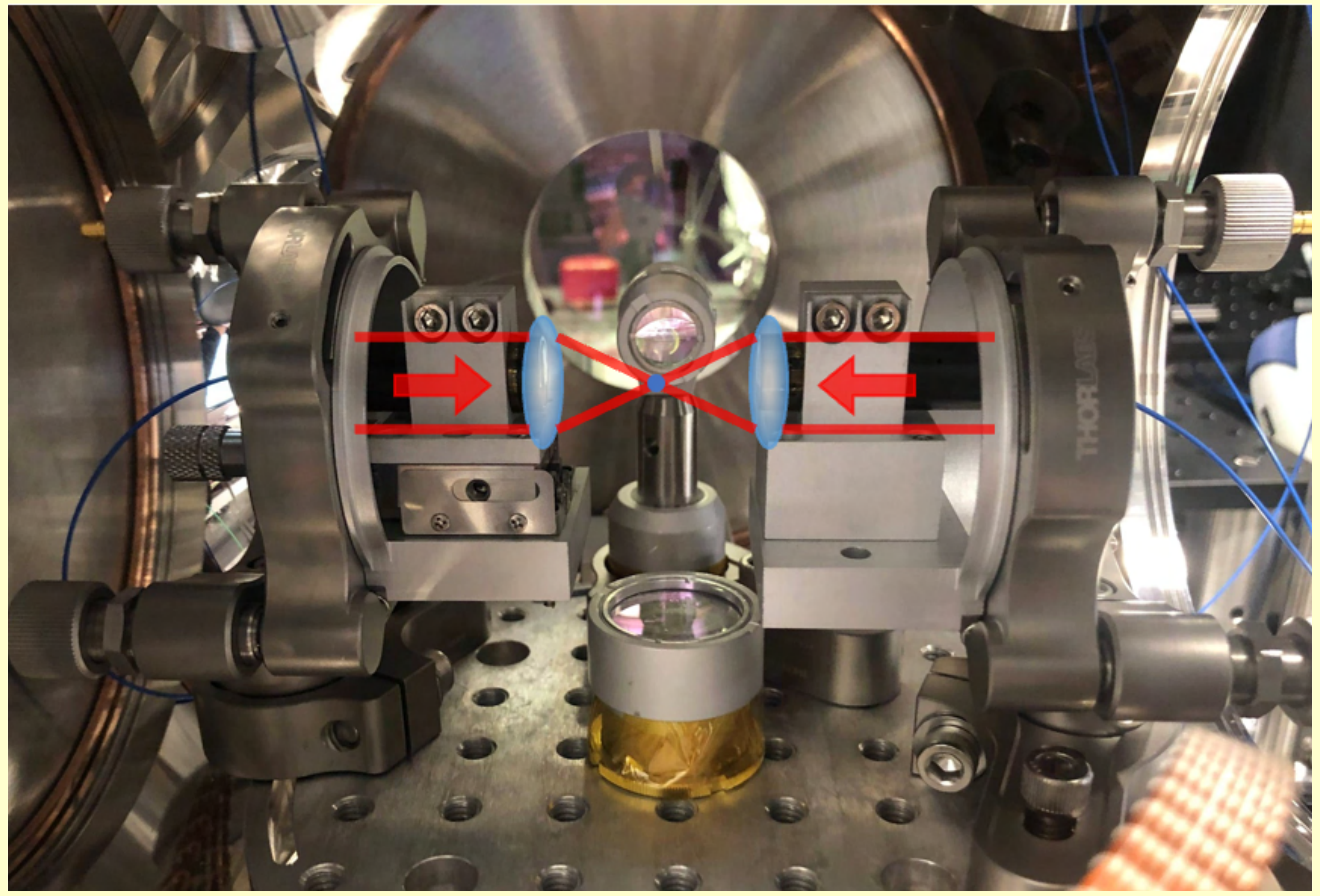
1-m prototype resonant gravitational wave detector with two Fabry-Perot arms

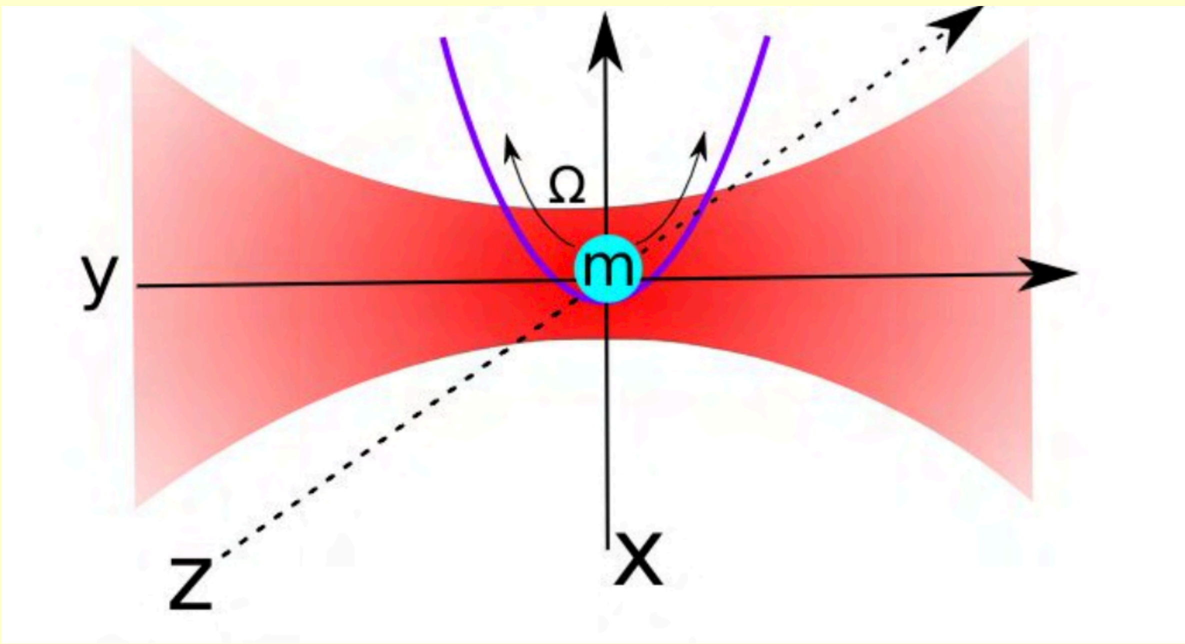
Levitated Optomechanics with a damped driven harmonic oscillator as a force sensor

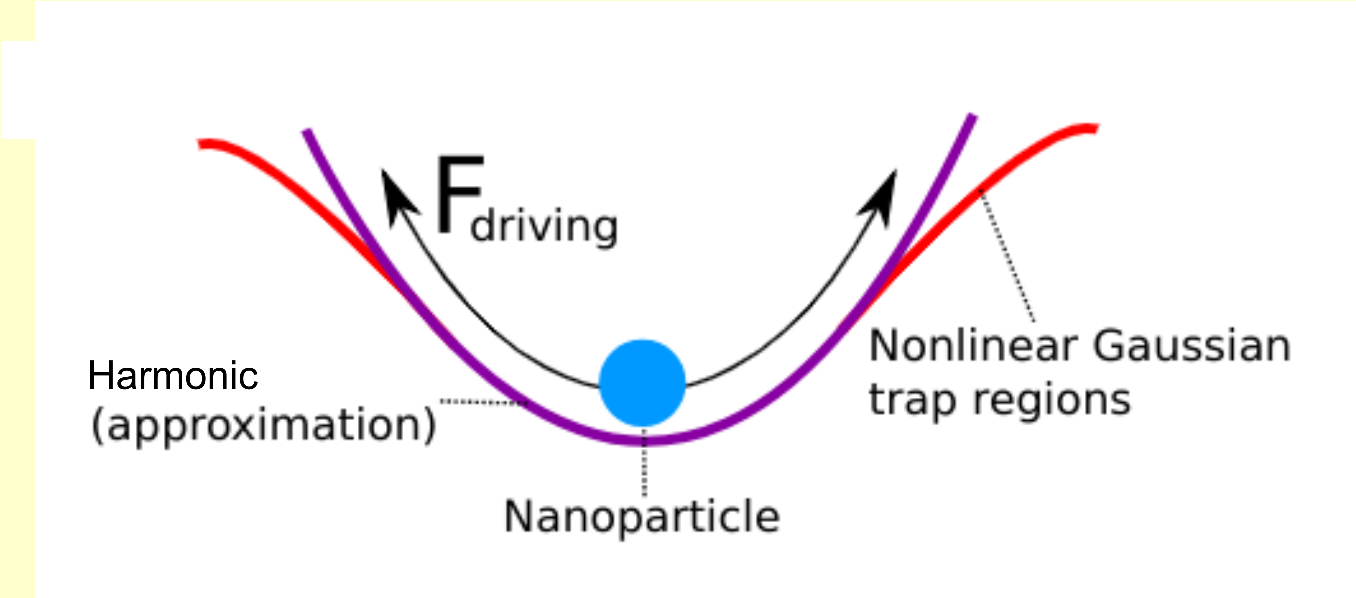


Optical Trapping : Brief Overview

- Nm-micron sized polarizable dielectric particles (e.g. silica, NaYF) act as high field seekers - trapped at the laser focus
- Confined in three axes by radiation pressure ($\propto I$) and dipole forces ($\propto \Delta I$)



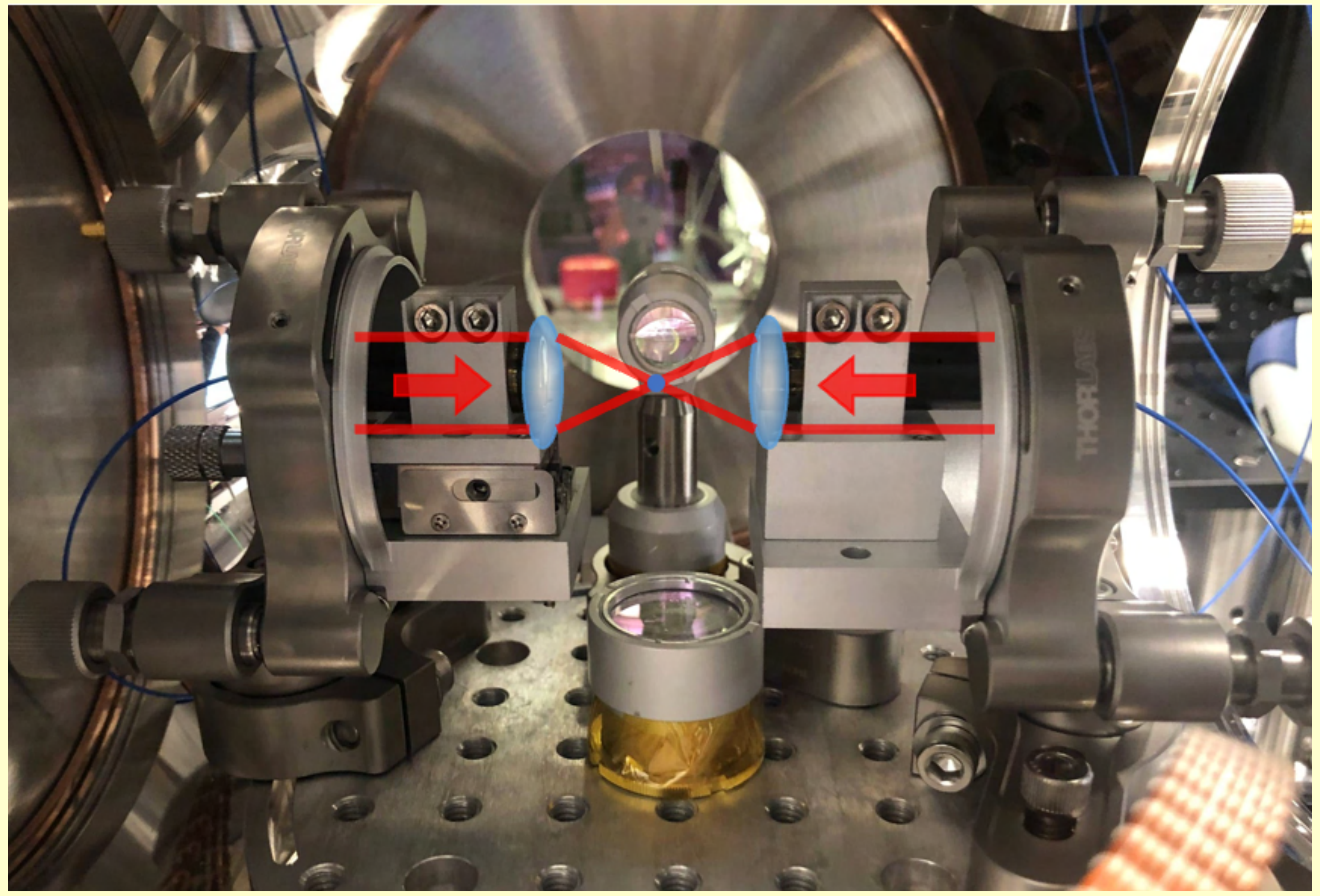




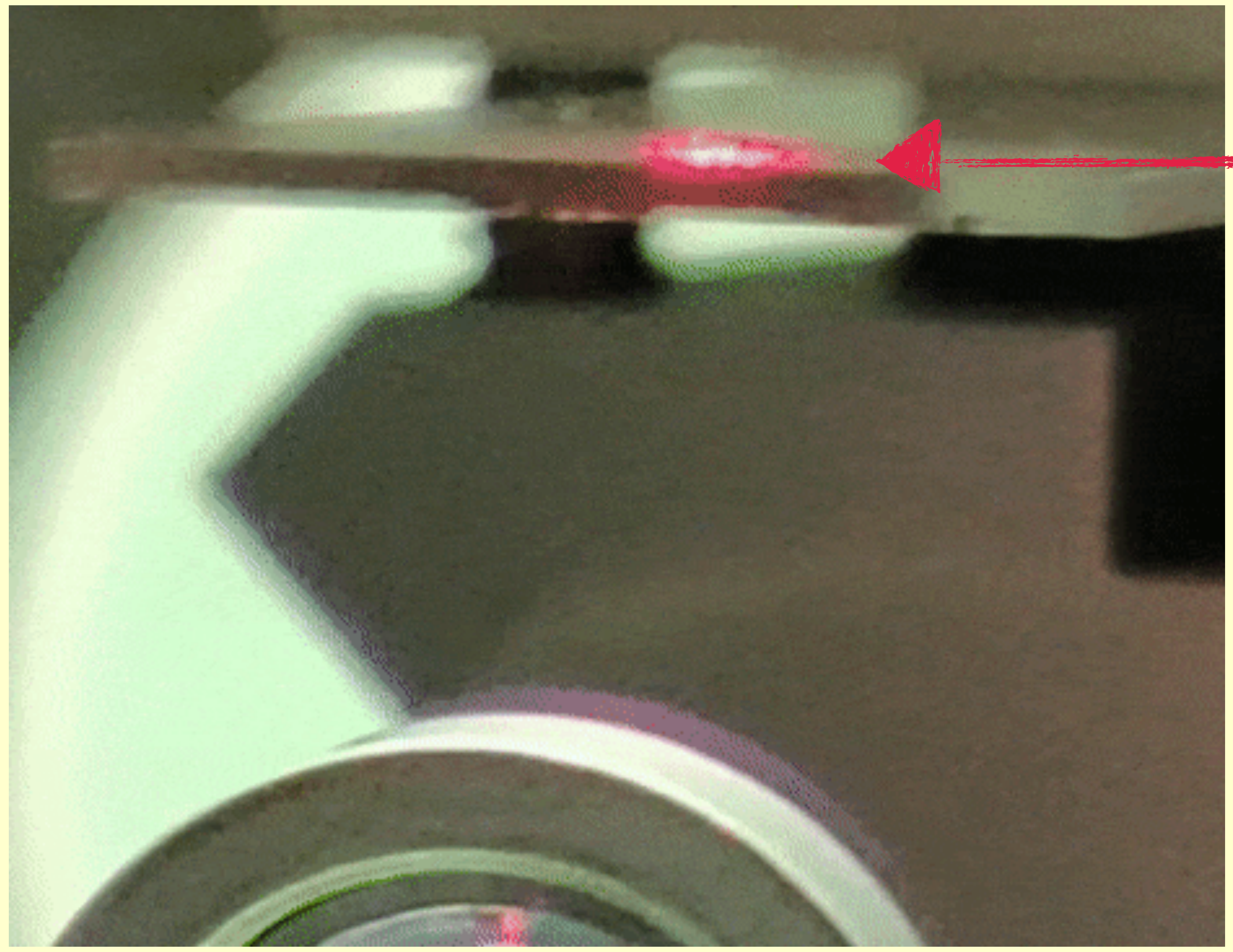
- Particle behaves like a 3-D harmonic oscillator: trap depth & trap stiffness (k) depend on particle size, polarizability, laser power, beam focusing

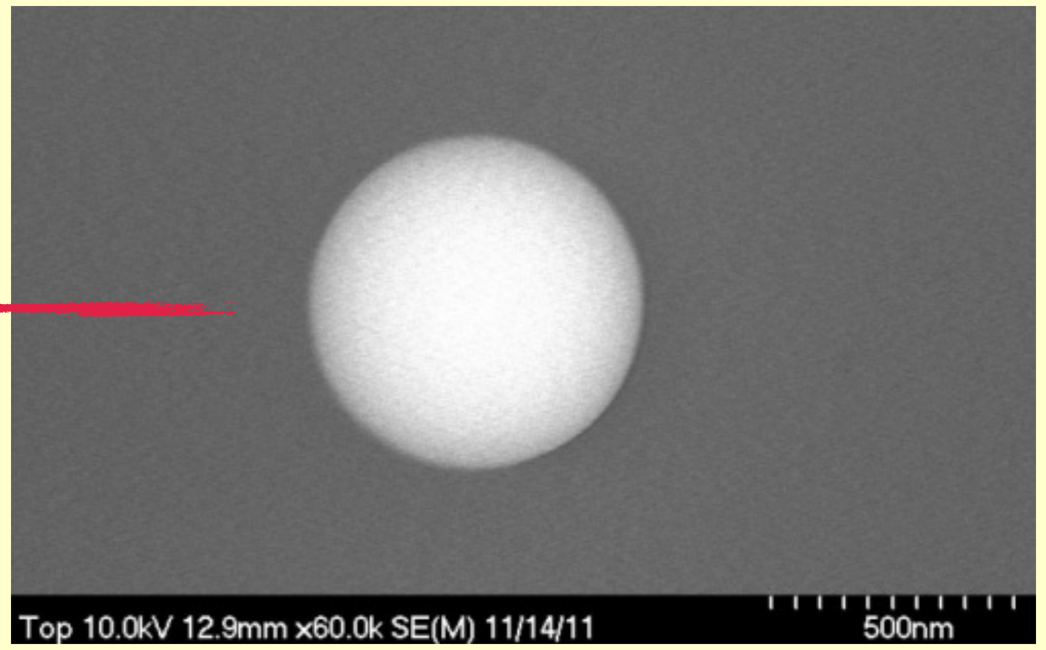
Optical Trapping : Brief Overview

Piezo driven slide acts as a dive-board for the particles

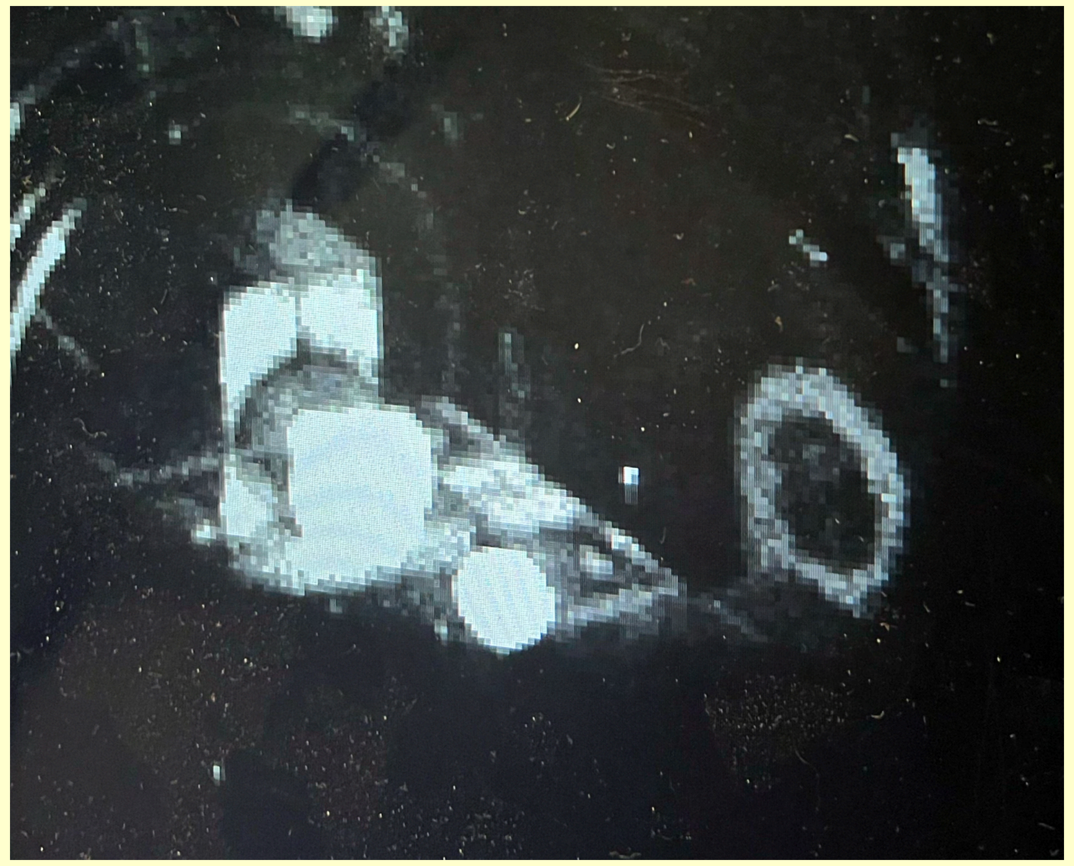


1550 nm Dual-Beam Optical Trap





SEM image of a Silica nanosphere



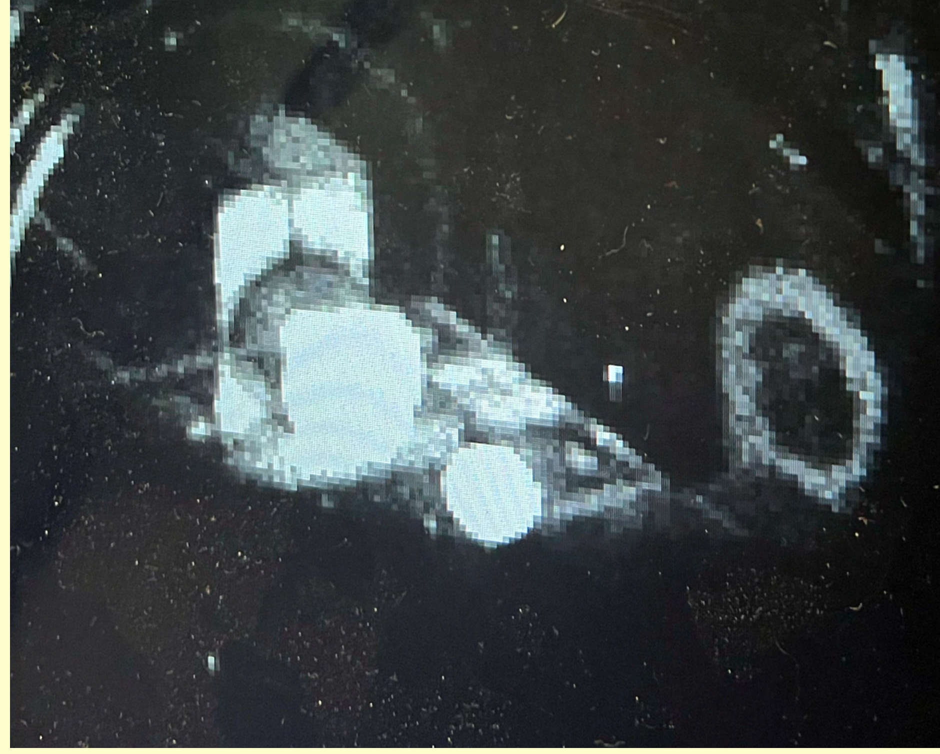
View from IR Camera

RESEARCH ARTICLE | NOVEMBER 29 2022

An apparatus for in-vacuum loading of nanoparticles into an optical trap

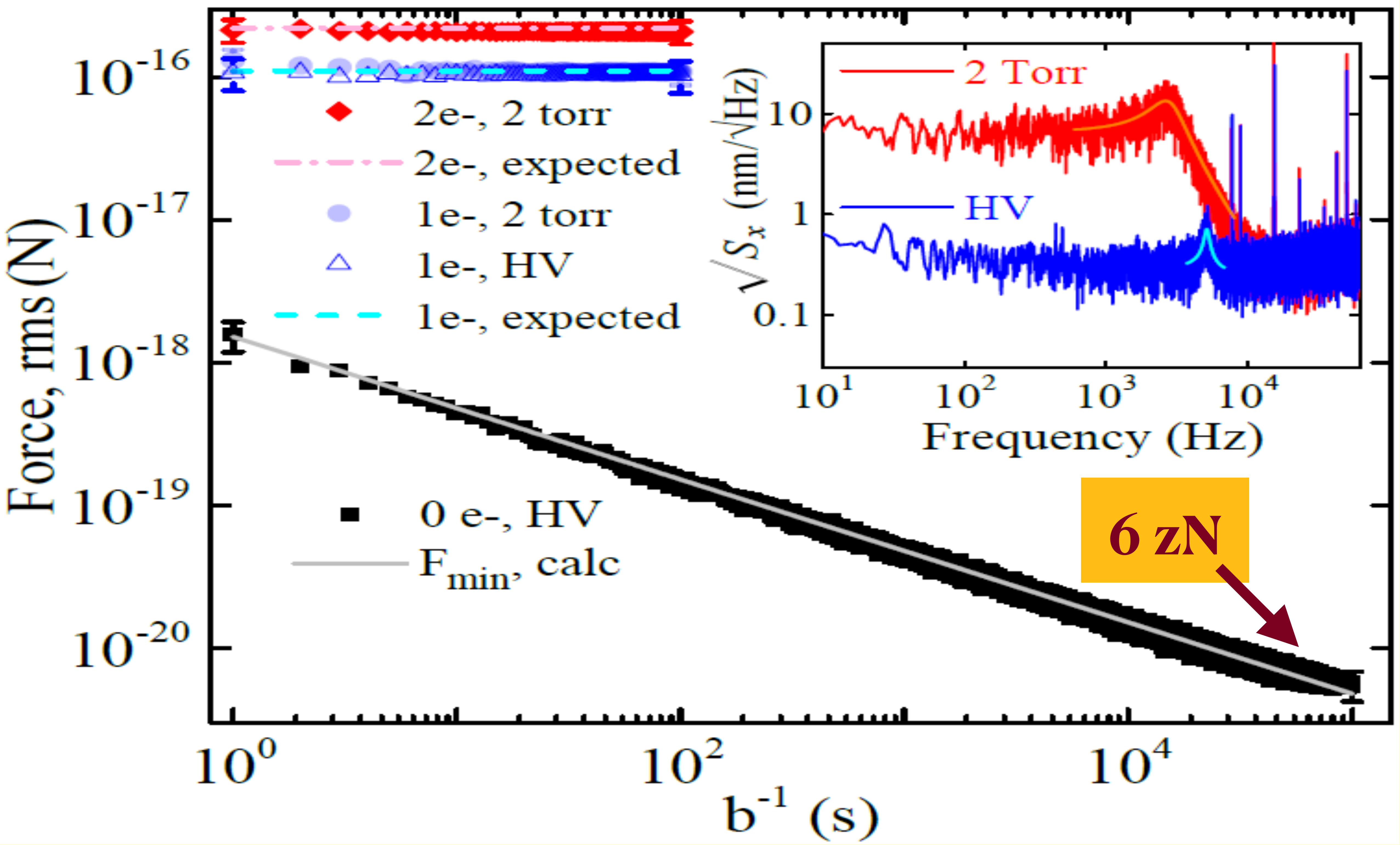
Evan Weisman; Chethn Krishna Galla; Cris Montoya; Eduardo Alejandro; Jason Lim; Melanie Beck; George P. Winstone; Alexey Grinin; William Eom; Andrew A. Geraci

Optical Trapping : Brief Overview



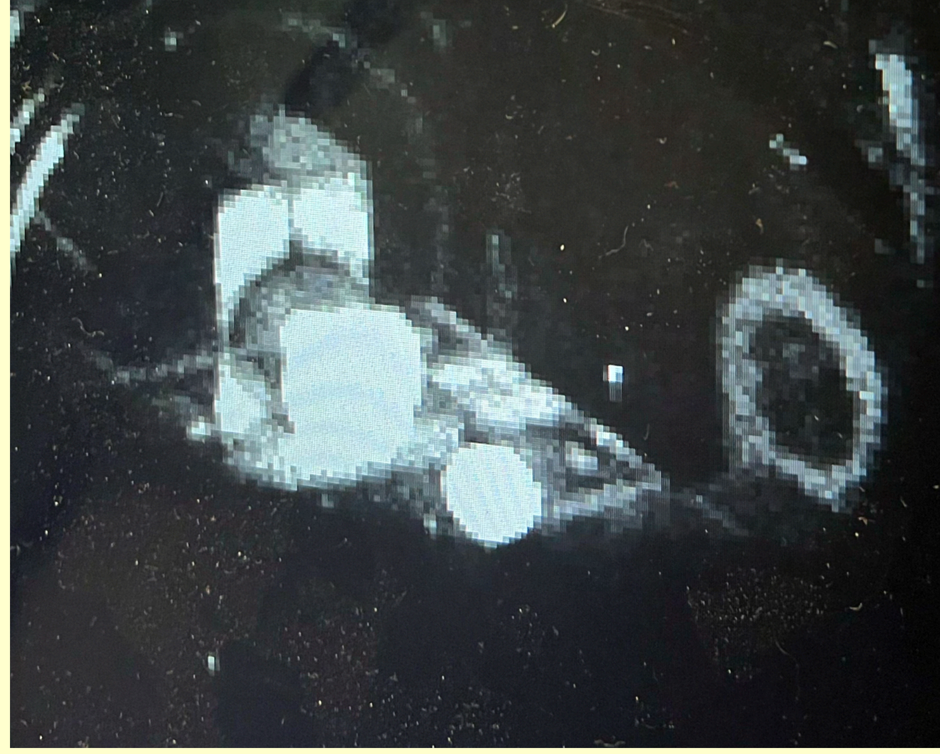
- COM motion decoupled from environment – no clamping $\Longrightarrow$ less dissipation
- High Q- factors (energy stored per cycle/ energy dissipated) achieved (10^{10})——> ultra sensitive force detection (Zepto-Newton) demonstrated in our group.

$$F_{min} = S_F^{1/2} b^{1/2} = \sqrt{\frac{4k_B T b k}{\omega_0 Q}}$$

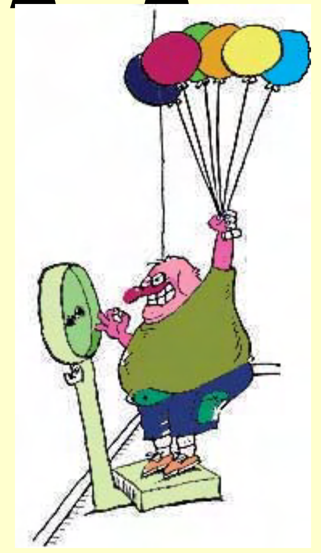


G. Ranjit, et.al. , *Phys. Rev. A*, 93, 053801 (2016).

Optical Trapping : Brief Overview



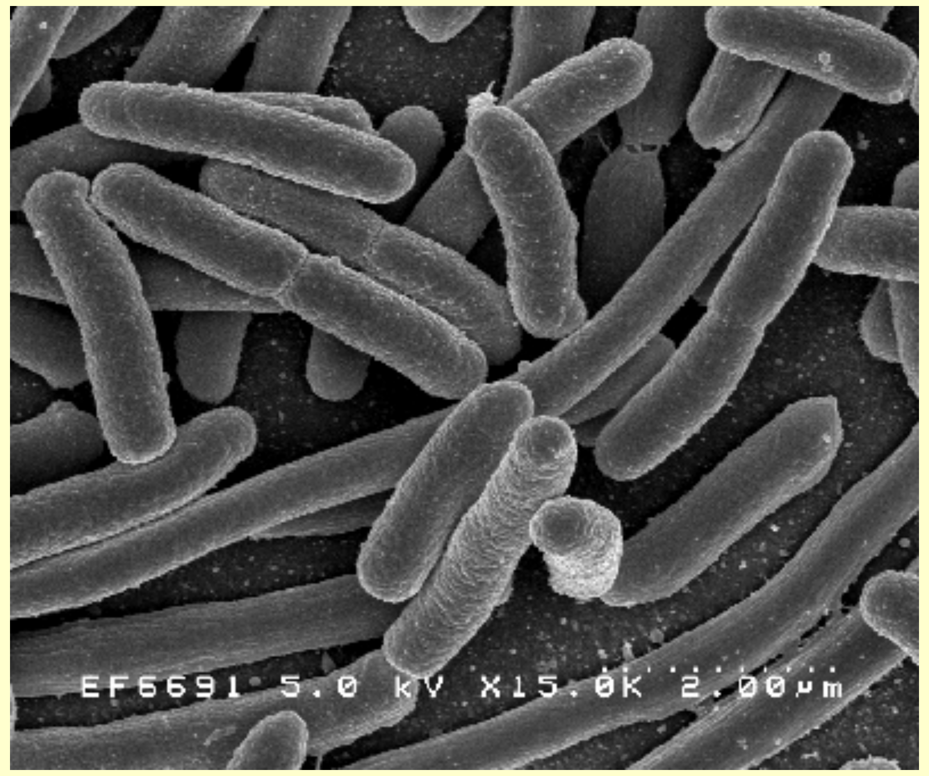
Bathroom scales measure 10^{-1} N



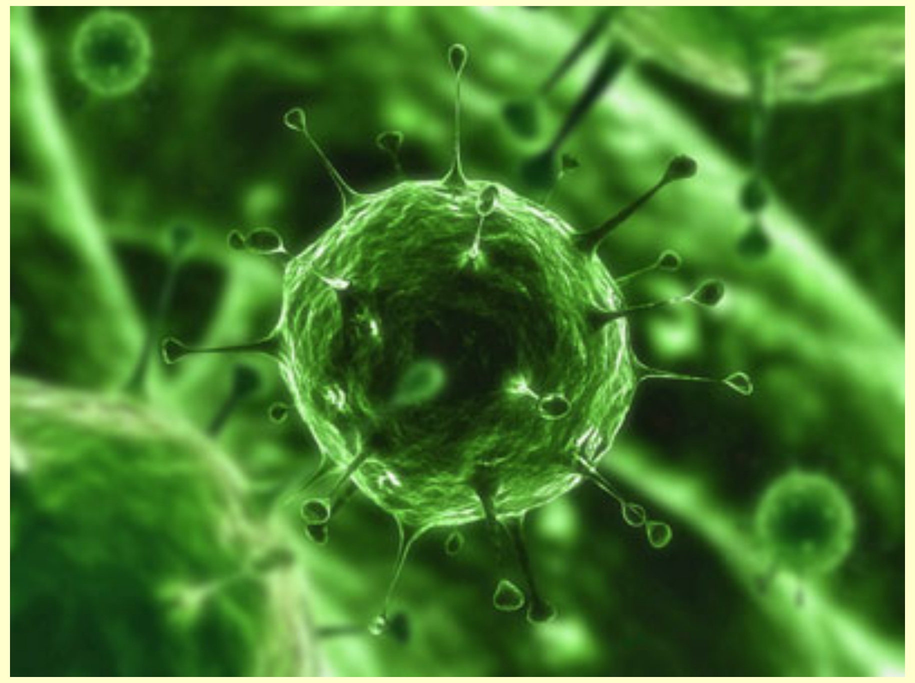
70 kg ~ 700 N

Dust mite 10^{-7} N

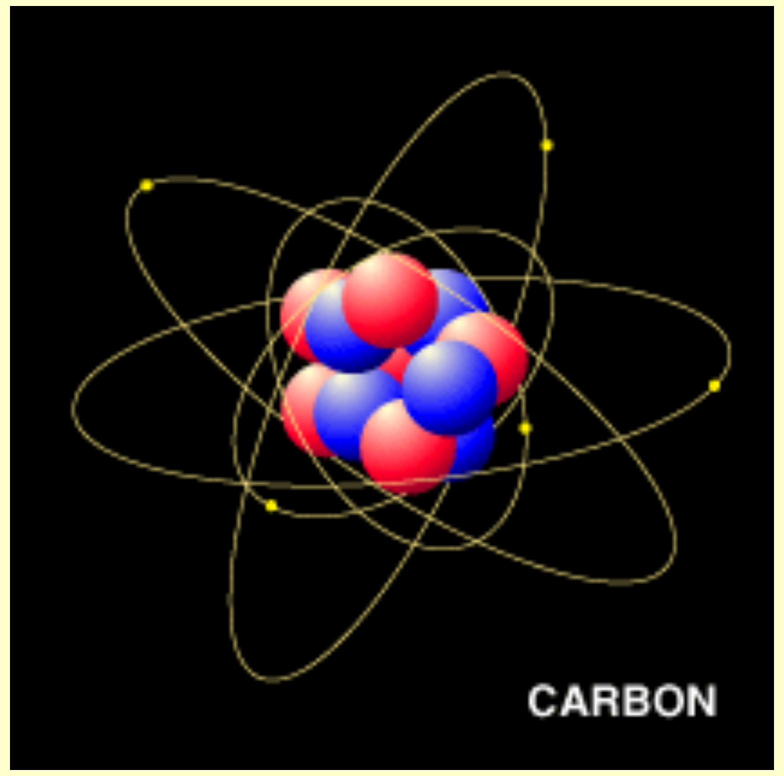
E. coli 10^{-15} N

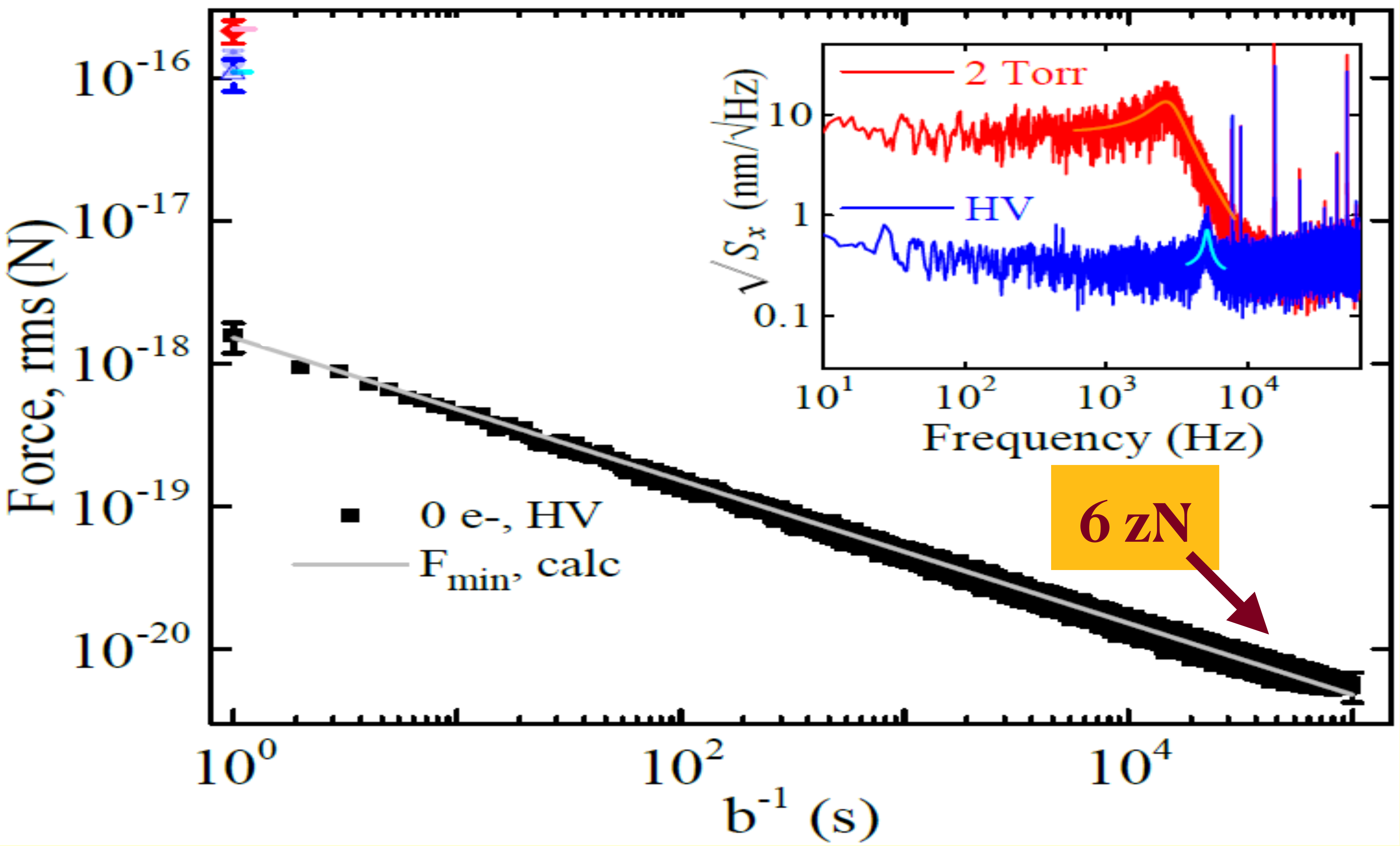


Virus 10^{-19} N



Carbon atom 10^{-25} N





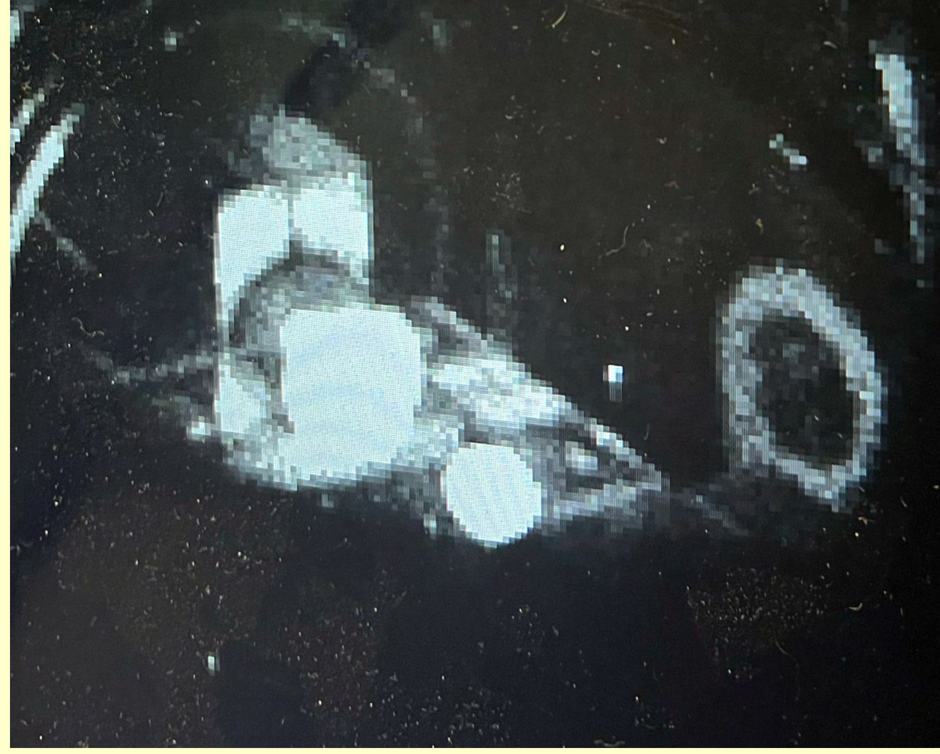
G. Ranjit, et.al. , *Phys. Rev. A*, 93, 053801 (2016).

Optical Trapping

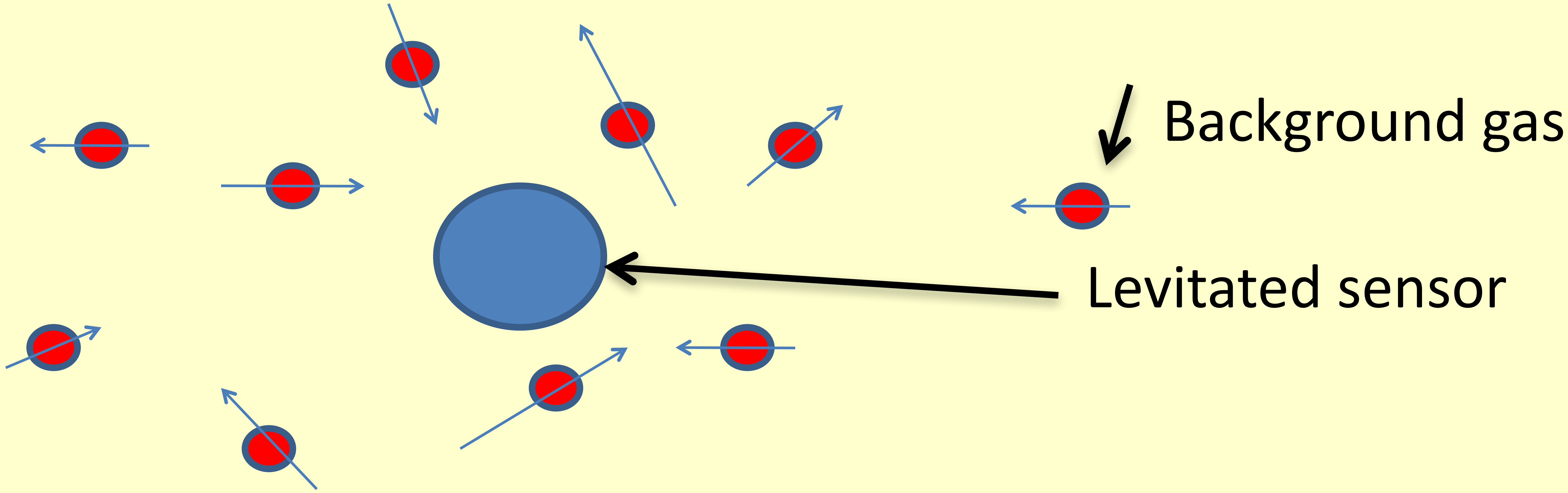
Limiting Noise Sources and ways to mitigate them

1. **Thermal Noise**
2. **Photon recoil heating**
3. **Displacement sensing noise**

Optical Trapping : Thermal noise



- Force sensitivity is thermal noise limited.



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

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

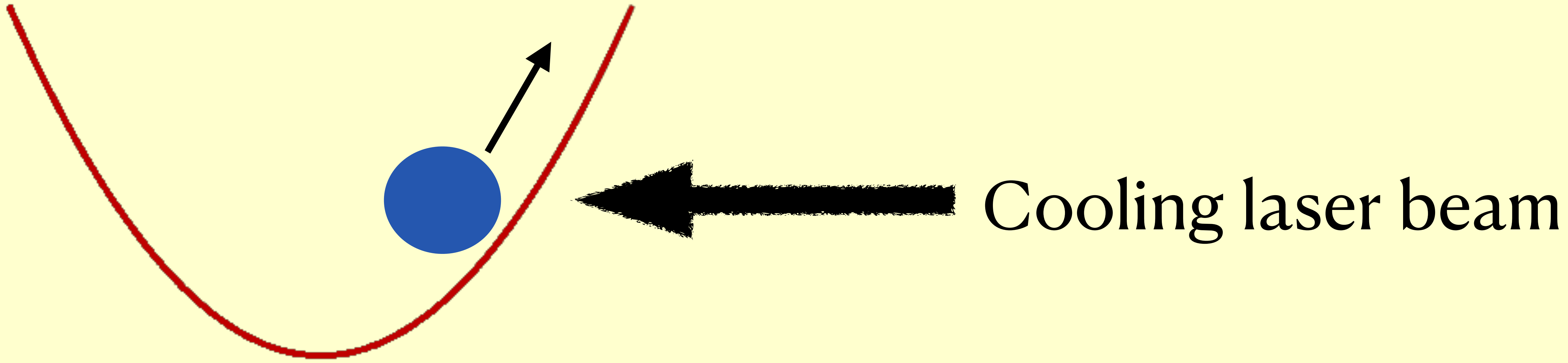
Optical Trapping : Linear Feedback cooling

Go to UHV to improve F_{min} and use modulated light to damp the oscillations

- Introduce velocity dependent damping force (F_{damp})

$$m\ddot{x}(t) - \gamma_g \ \dot{x}(t) + k \ x(t) = F_{damp}(t) + F_{ext}(t), \ \text{where } F_{damp}(t) \propto -\dot{x}(t)$$

- F_{damp} applied using additional lasers to cool the COM motion of the particle.

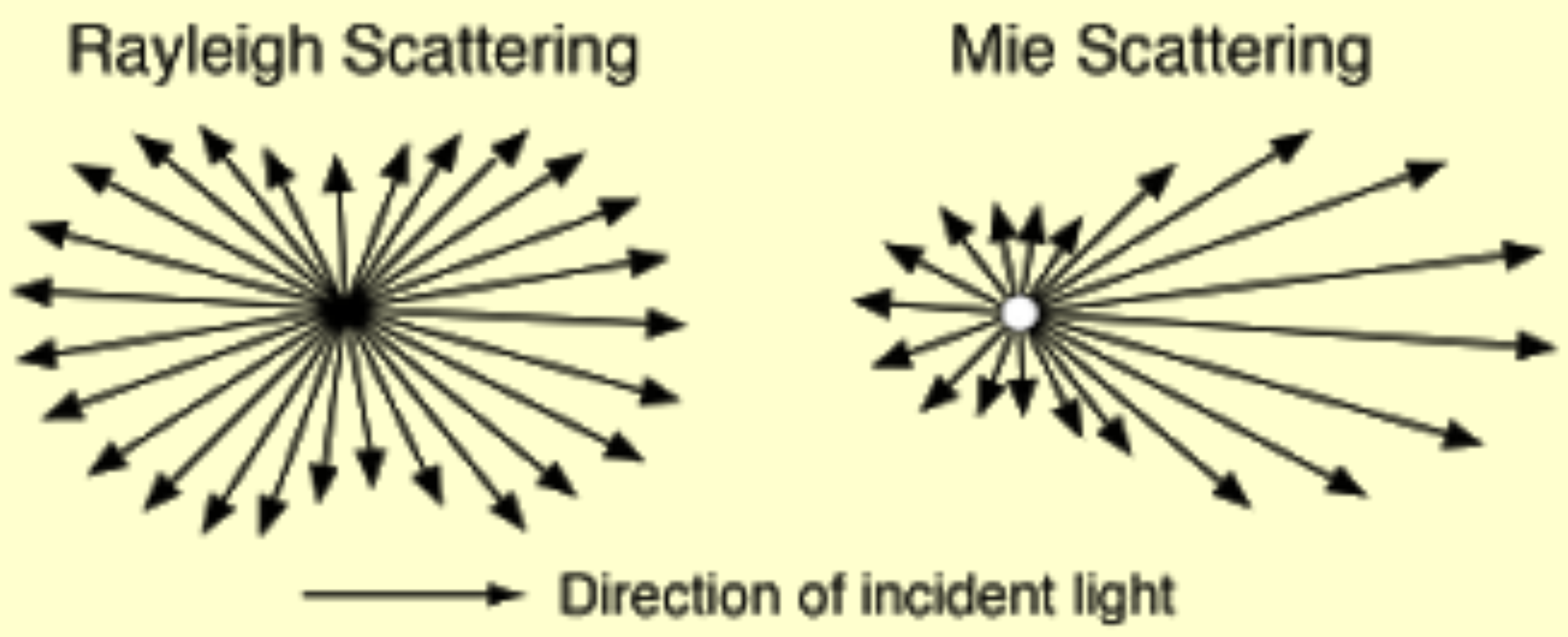


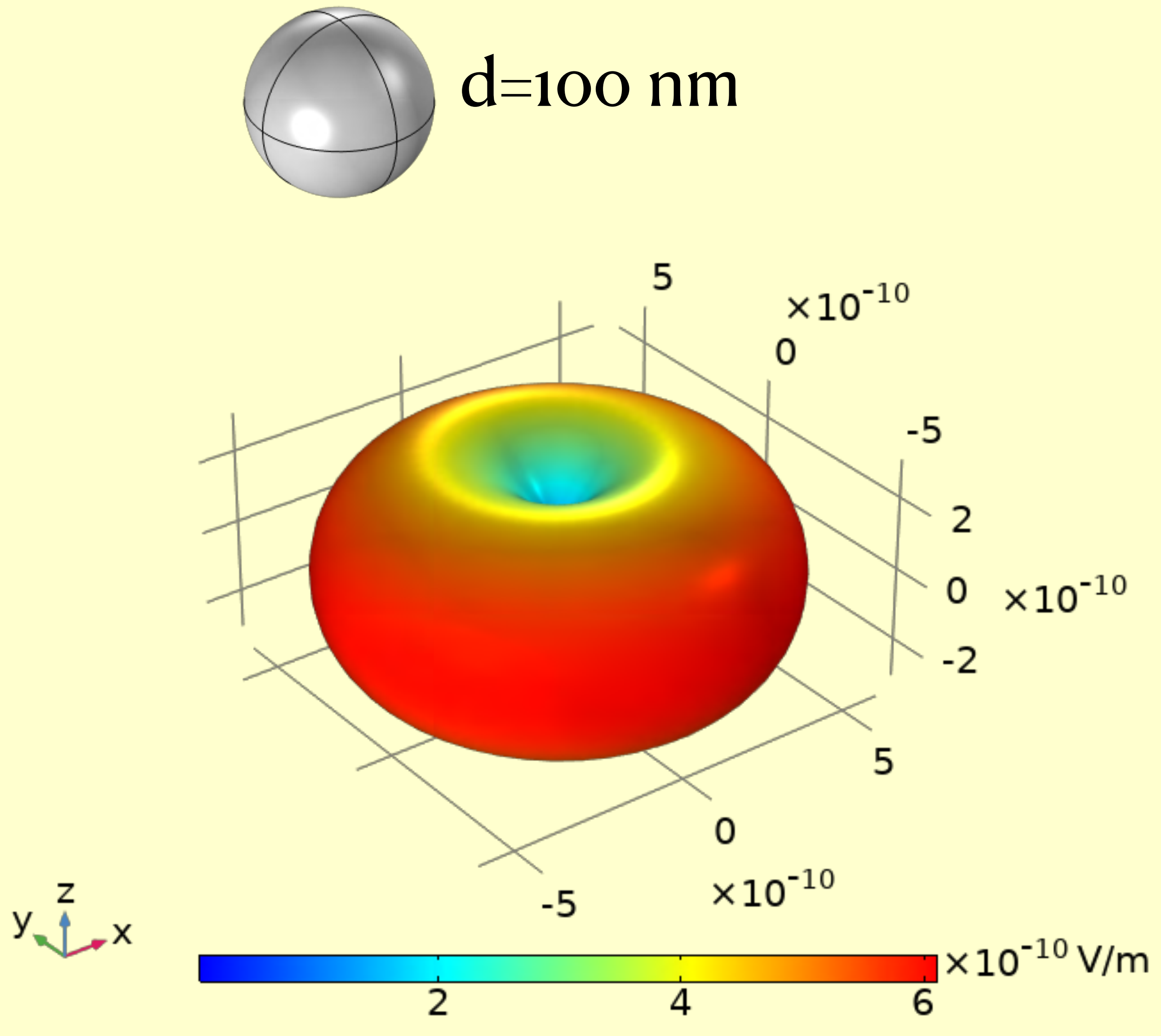
Apply radiation pressure force at frequency proportional to particle's motion

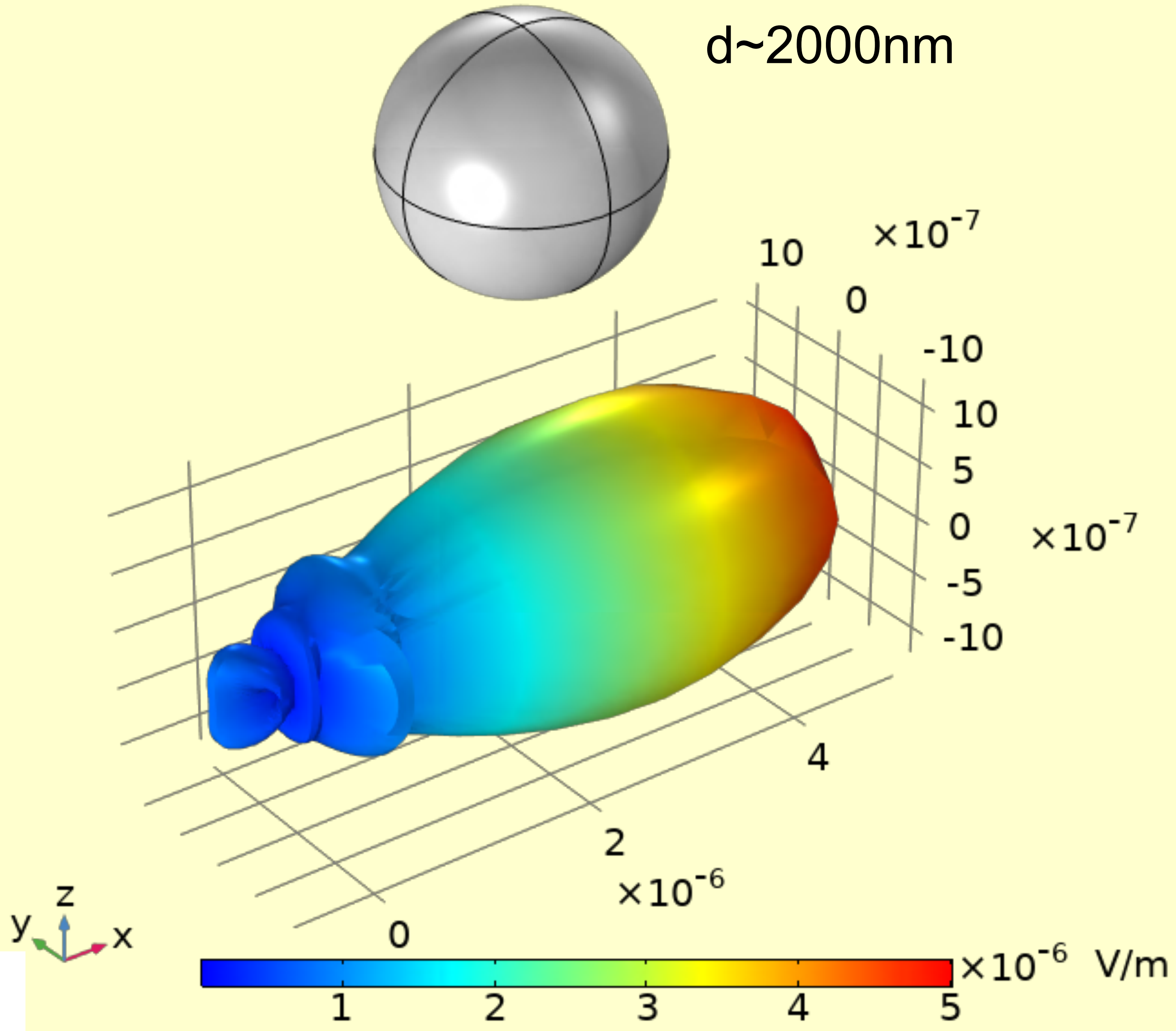
Optical Trapping: Photon Recoil heating (PRH)

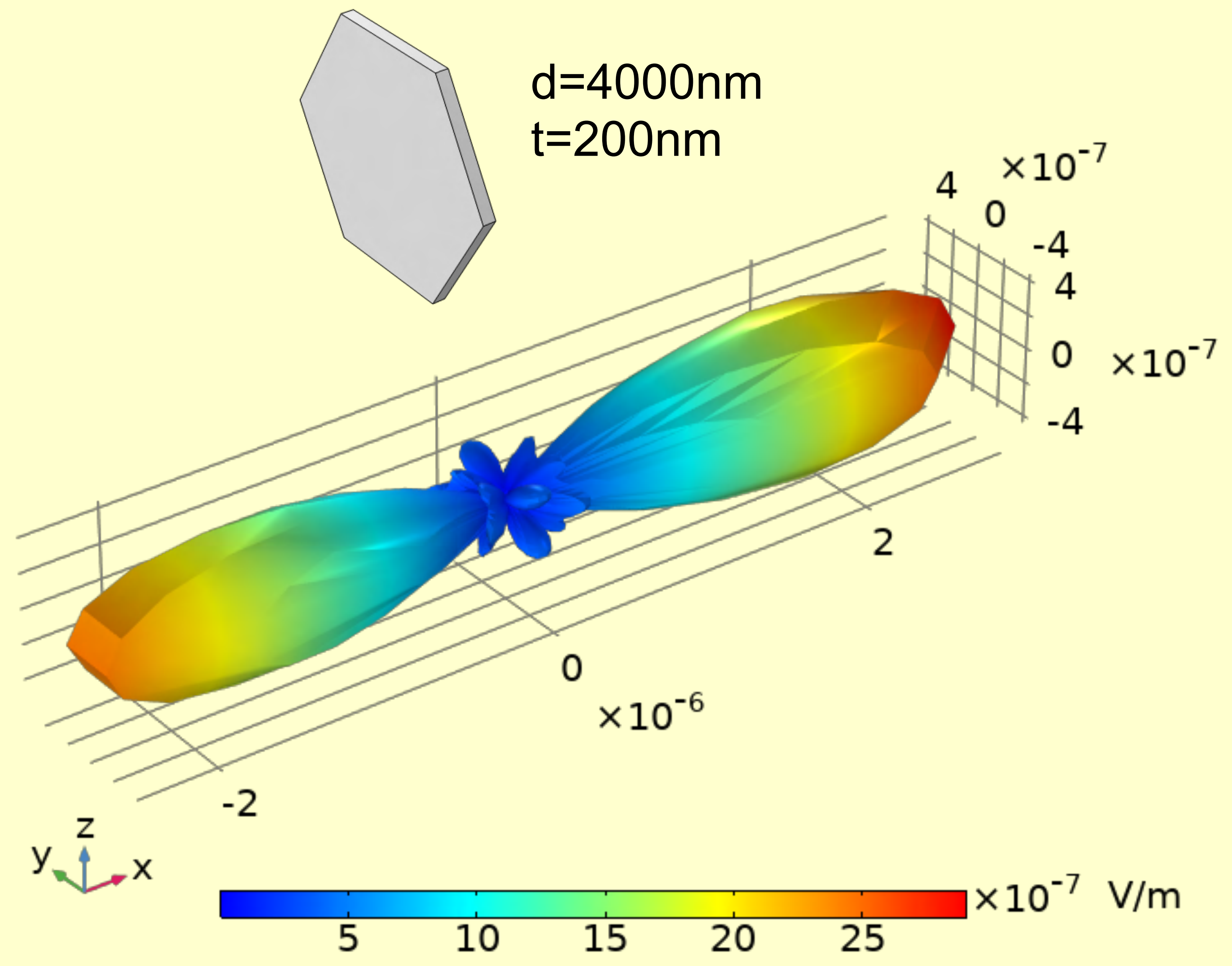
Flat discs have a more directional scattering into the cavity mode, reducing PRH

- Small spheres (r<<λ) scatter isotropically (Rayleigh)
- Larger spheres (r~λ) get more complicated (Mie)
- Different shapes produce different patterns





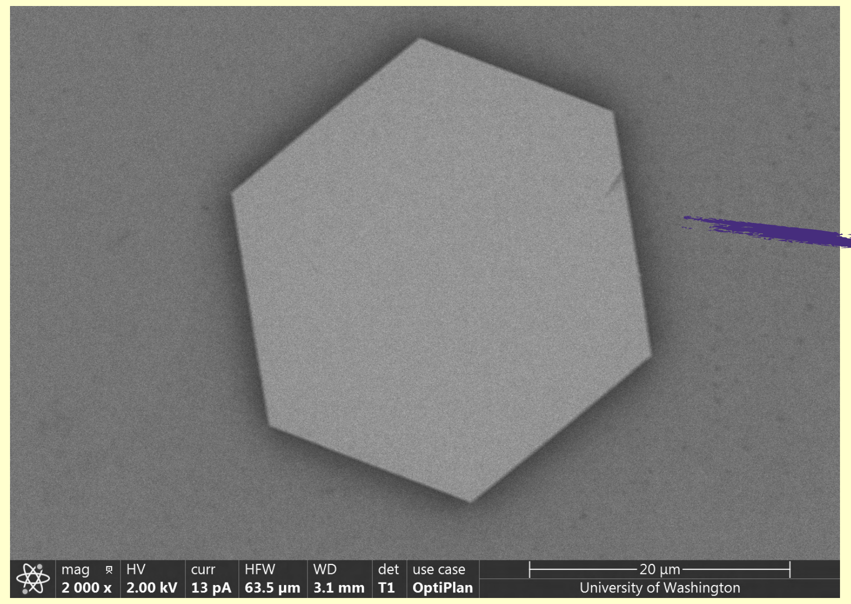


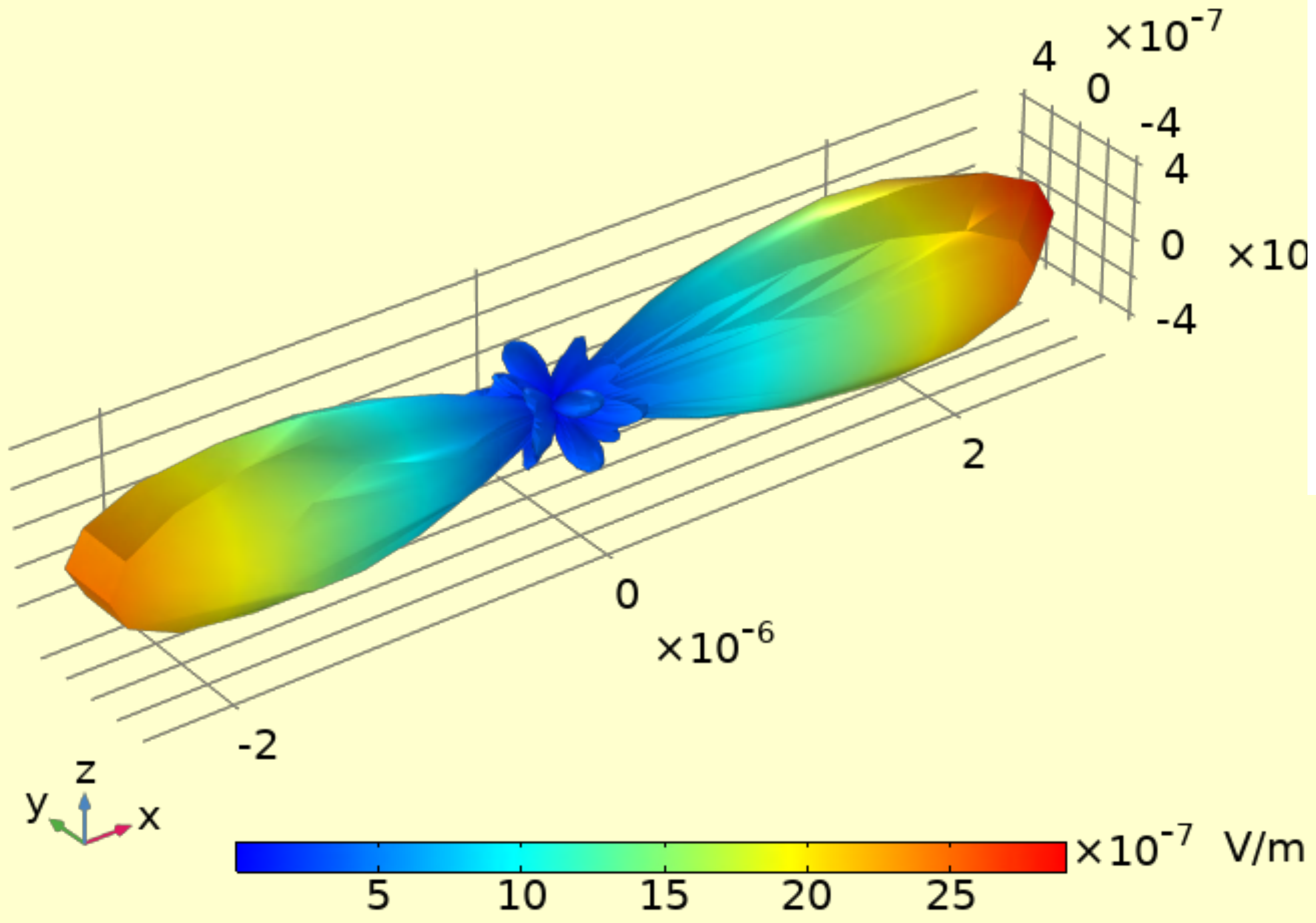


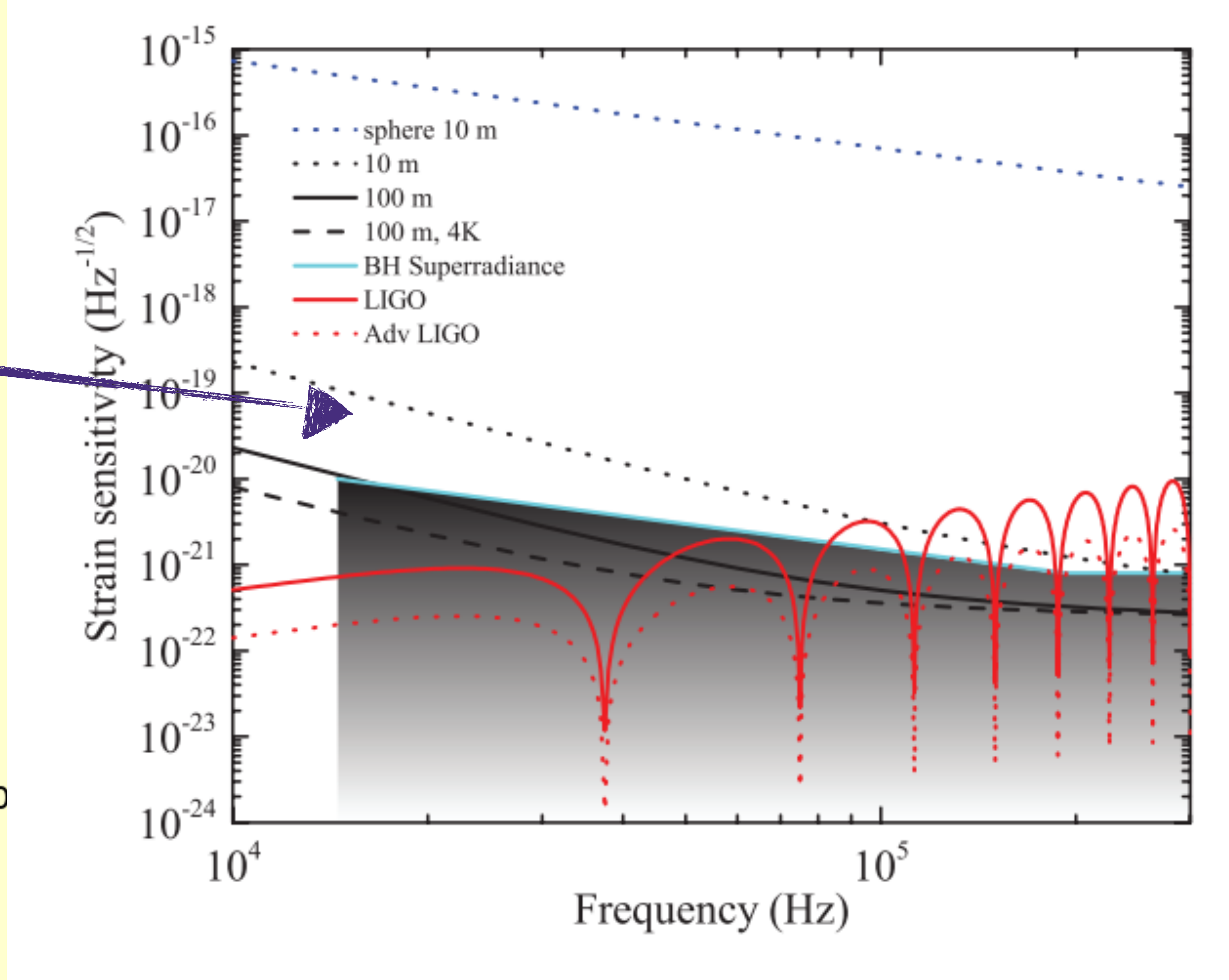
Optimal displacement detection of arbitrarily-shaped levitated dielectric objects using optical radiation

Shaun Laing,[1] Shelby Klomp,[2] George Winstone,[2] Alexey Grinin,[2] Andrew Dana,[2] Zhiyuan Wang,[2] Kevin Seca Widyatmodjo,[2] James Bateman,[1] and Andrew A. Geraci[3]

Optical Trapping :Photon Recoil heating (PRH)







PRL **110,** 071105 (2013) PHYSICAL REVIEW LETTERS week ending 15 FEBRUARY 2013

Detecting High-Frequency Gravitational Waves with Optically Levitated Sensors

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(Received 18 July 2012; published 14 February 2013)

Disc fabrication

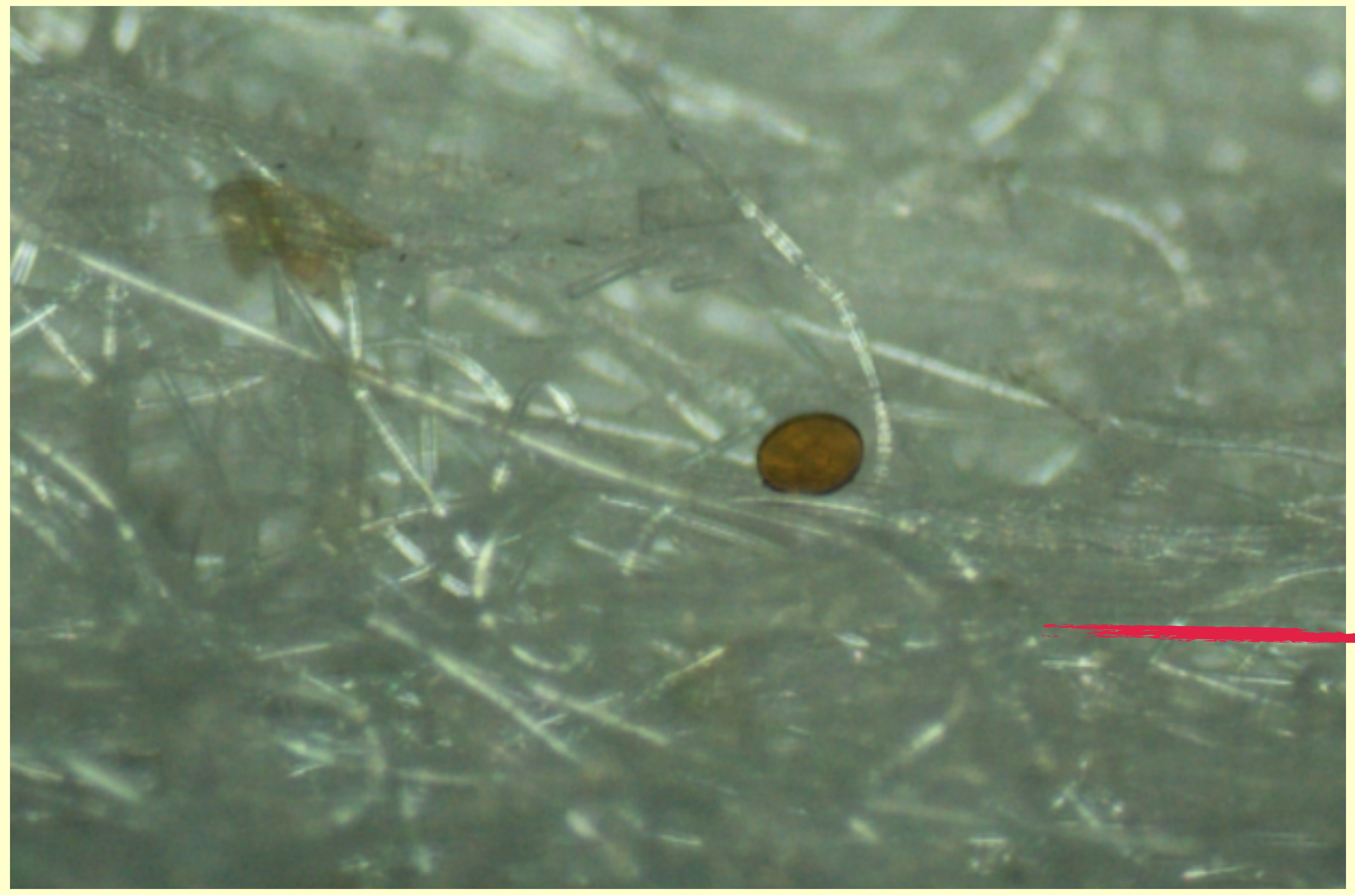
Prof. Peter J. Pauzauskie

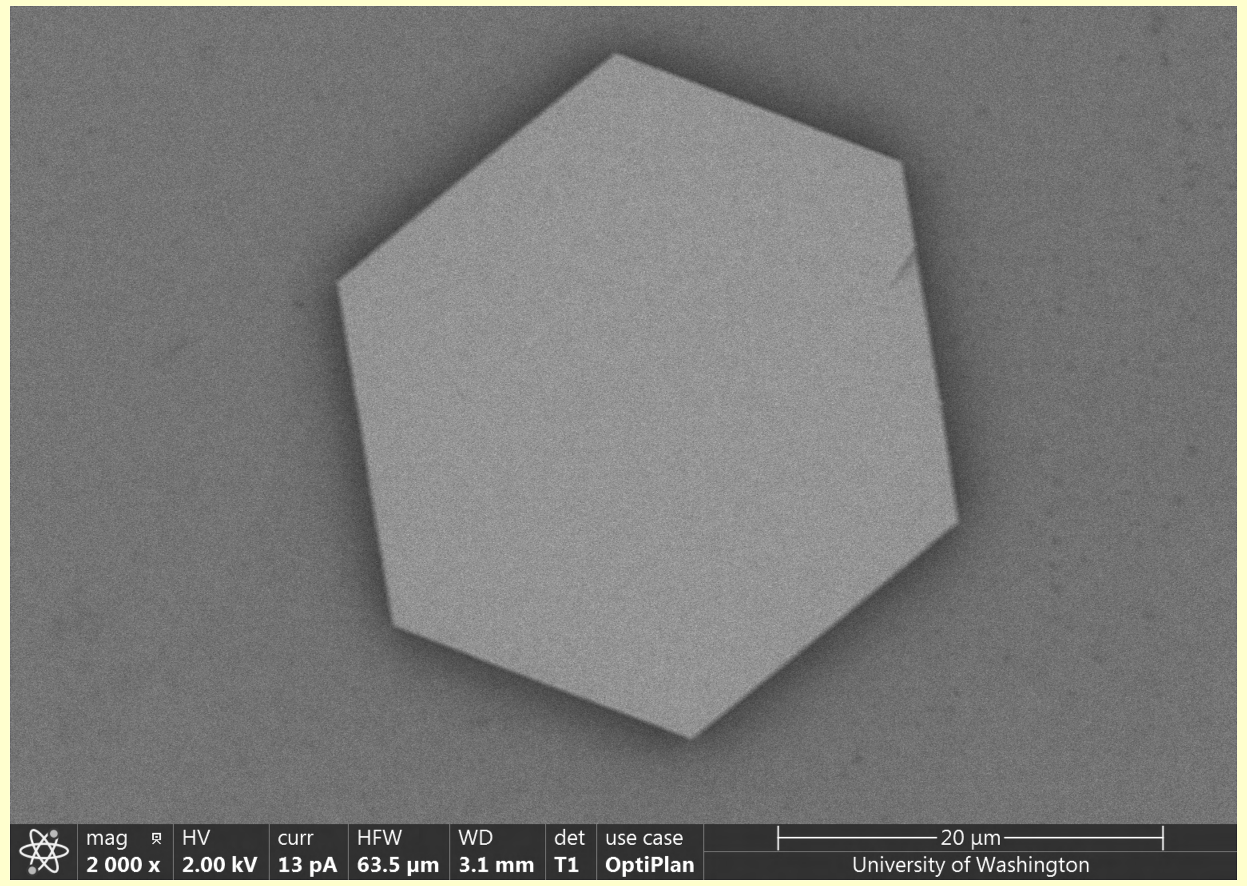
Lars Forberger **Greg Felsted**

UNIVERSITY of WASHINGTON

Levitated object optimization

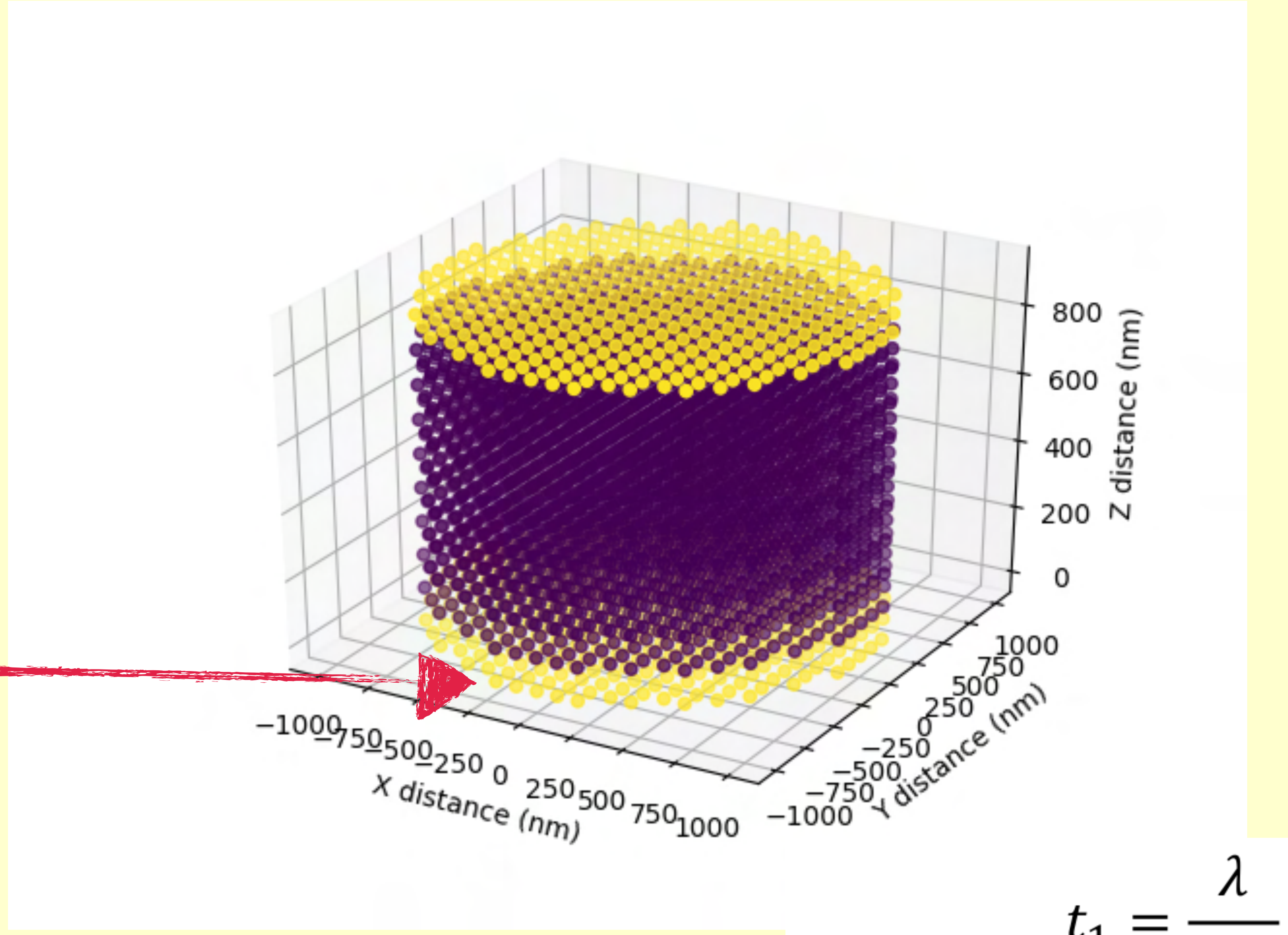
SiO2 Microdisc / NAYF Microhexagon

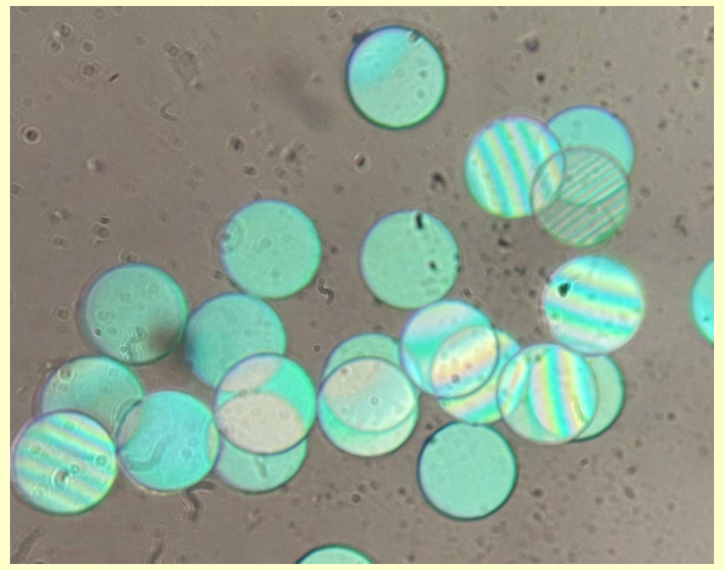


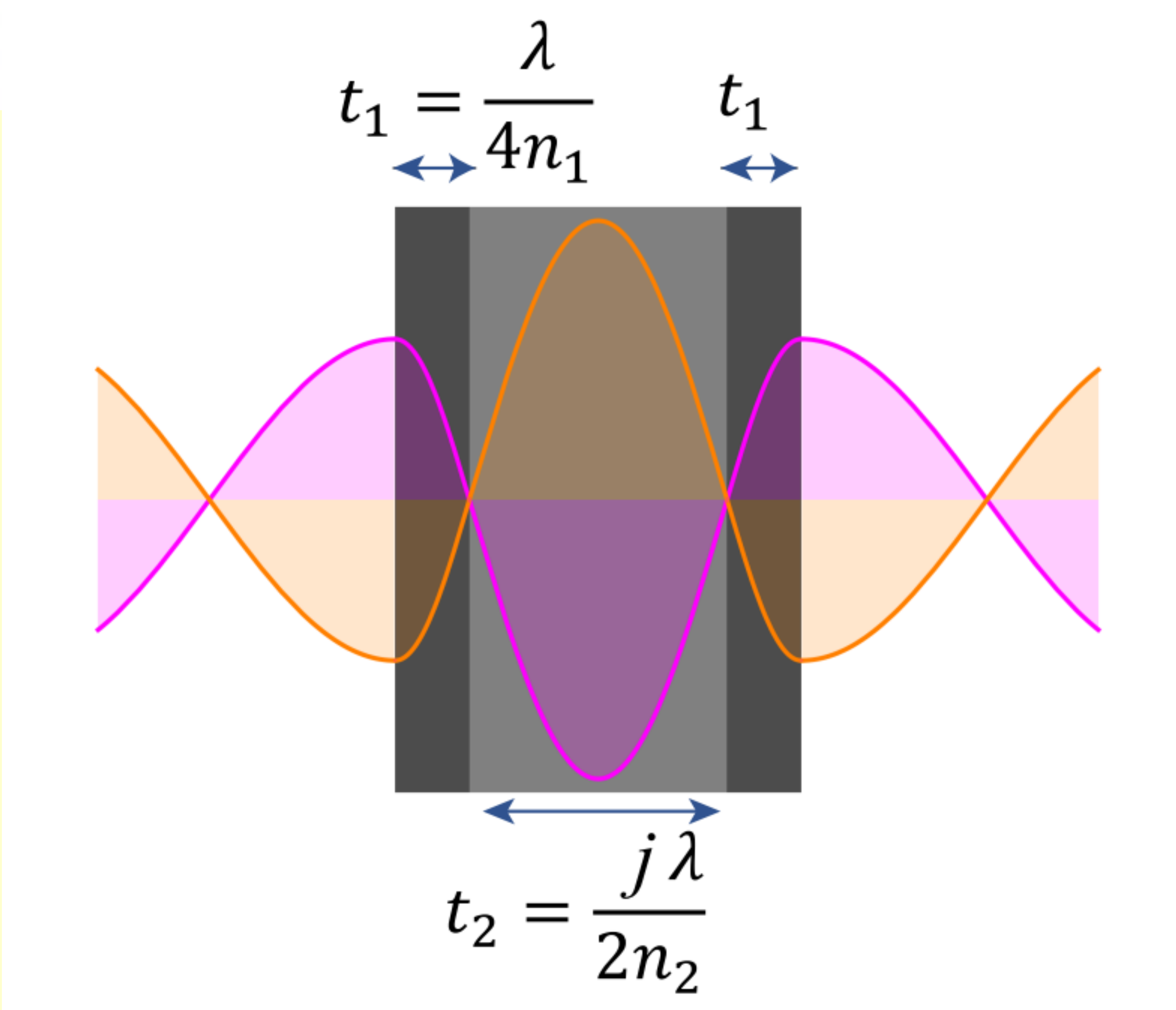


Future

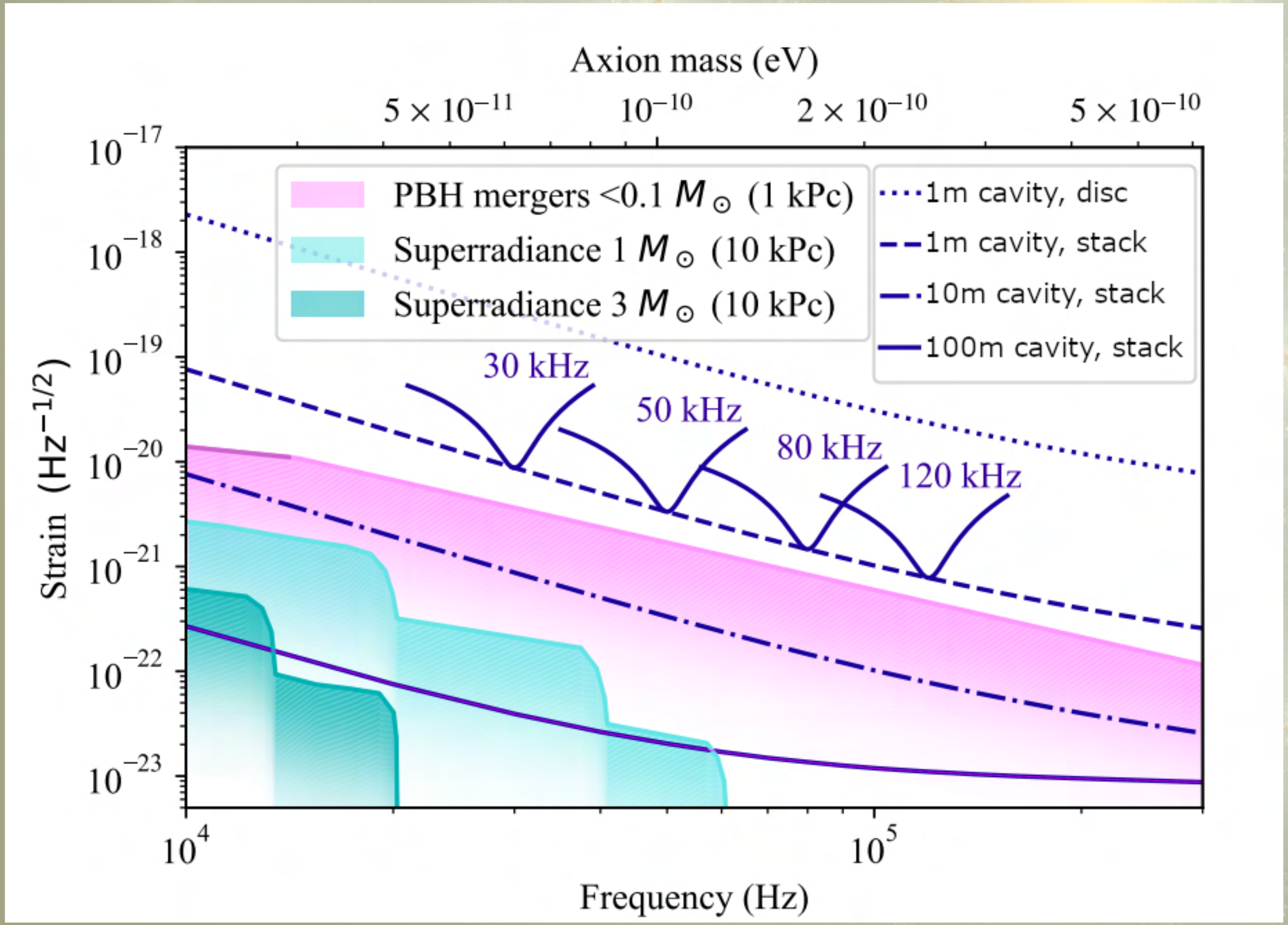
Si/SiO2/Si Nanostack

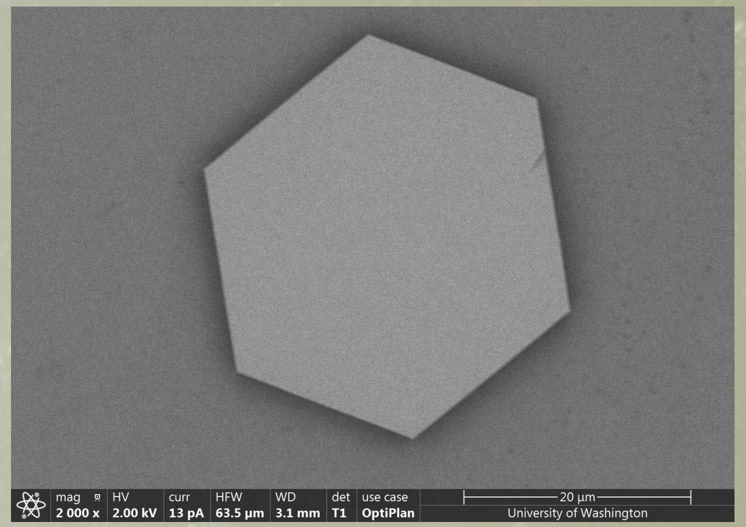


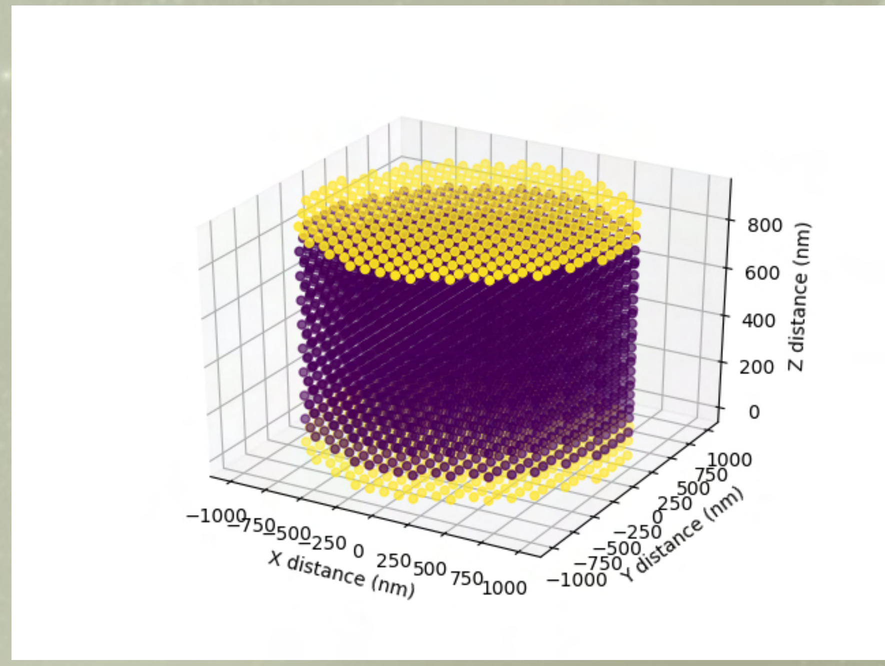




Levitated object optimization



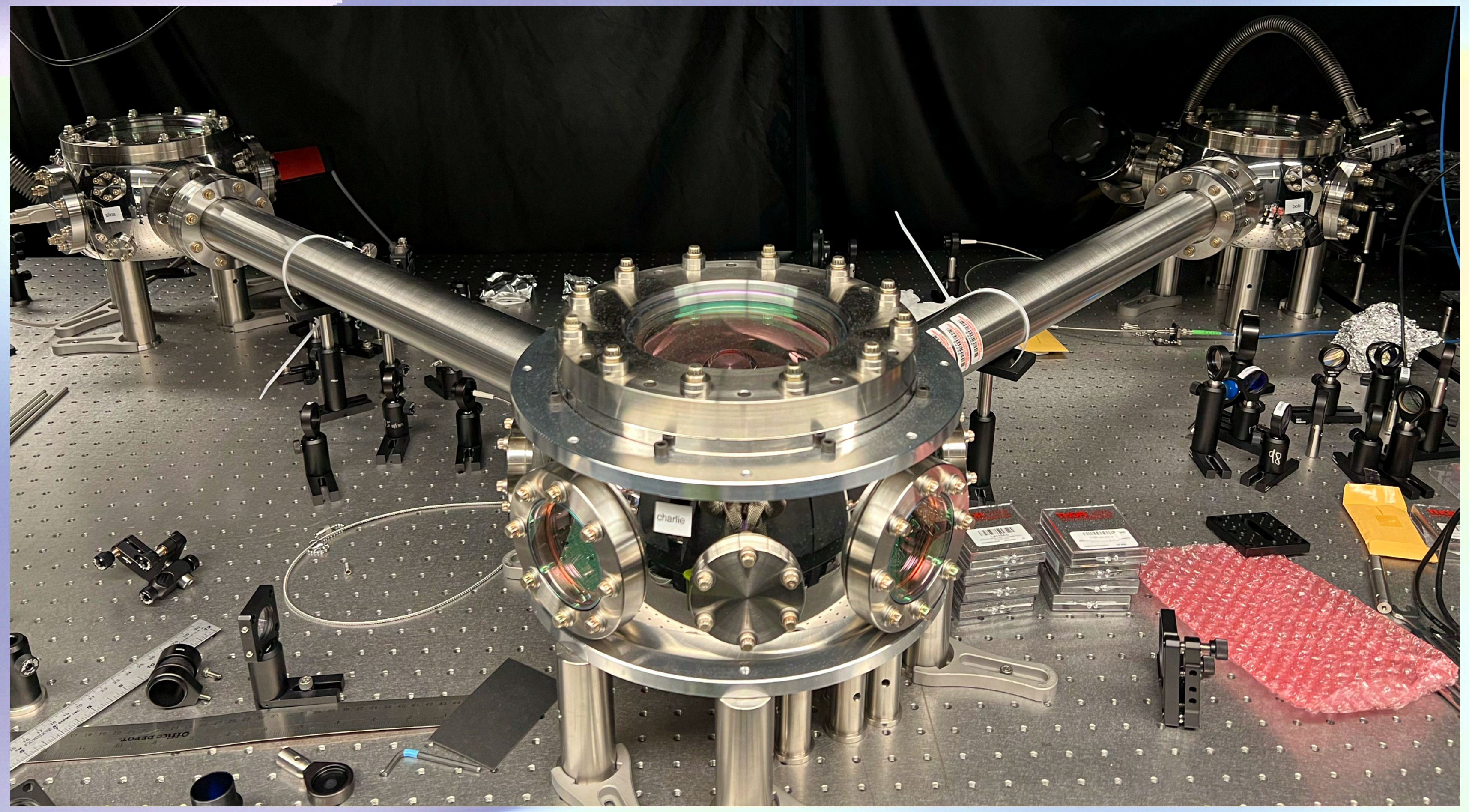


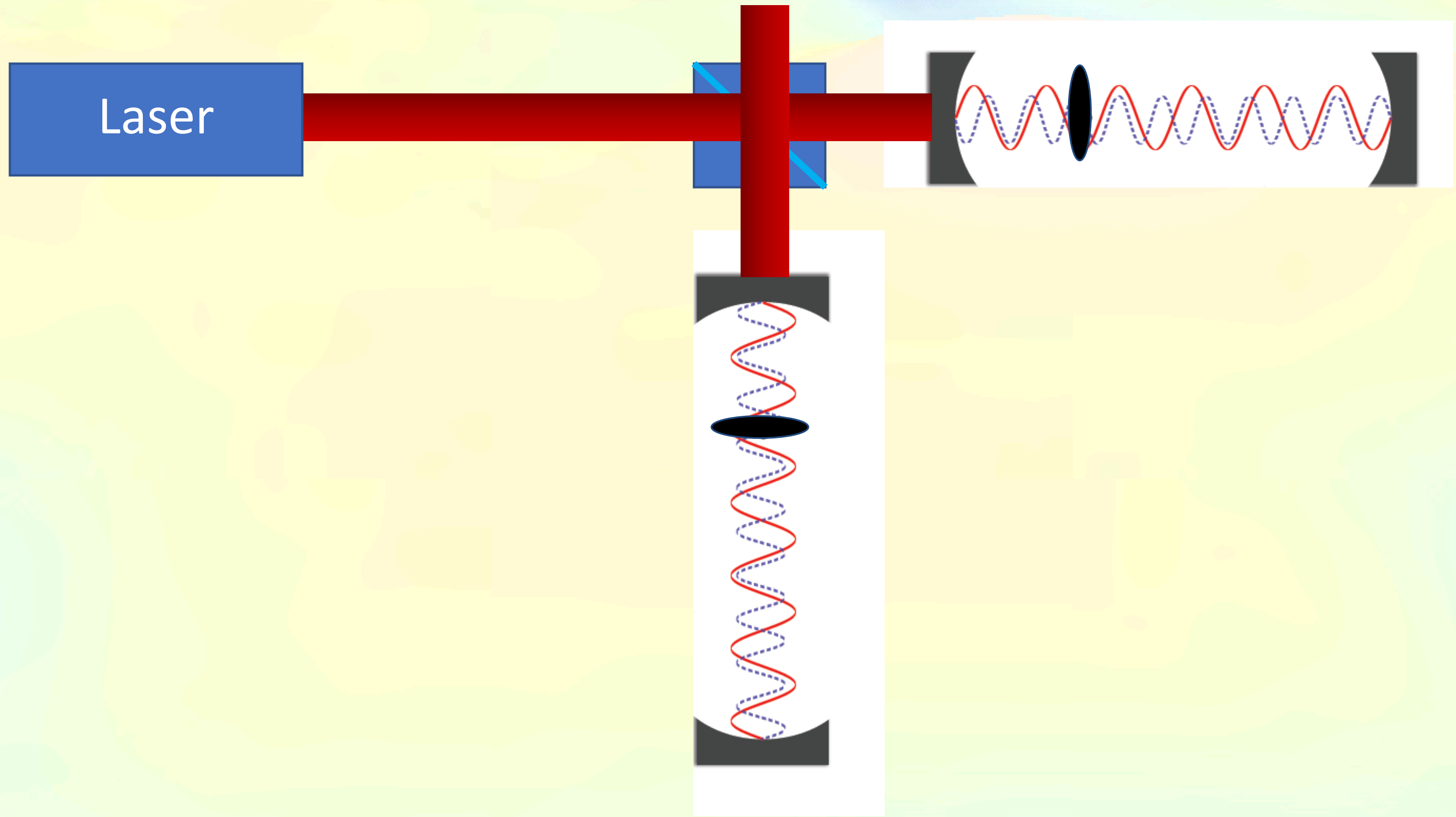


For best sensitivity, particles should be:

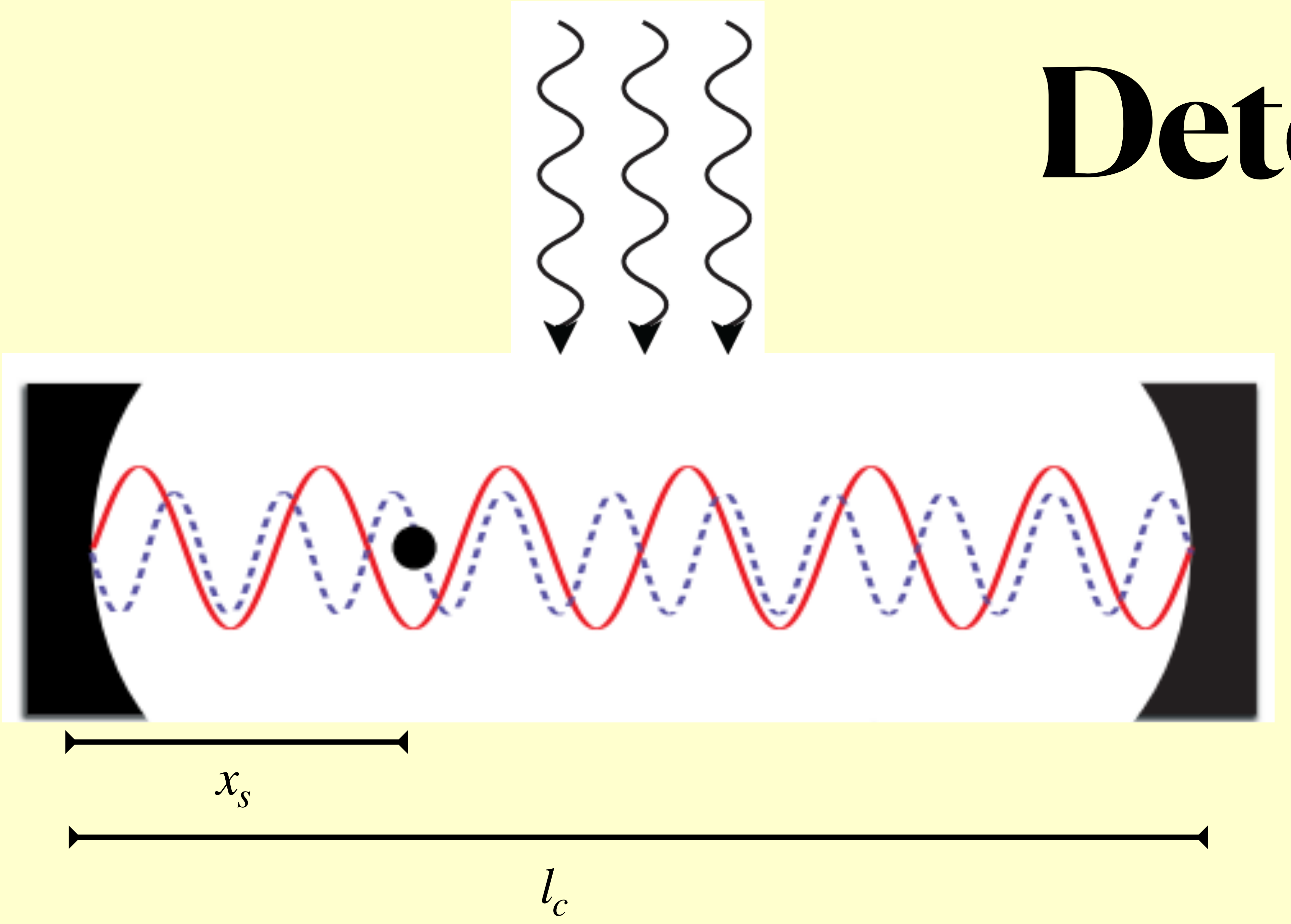
- Large & flat (to reduce photon recoil)
- High mass (to be more sensitive to GWs)
- Layered (to trap at high frequencies)

How does LSD detect gravitational waves?





Detection Principle



x_s : position of the particle w.r.t. the input mirror

l_c: length of the cavity

x_{min} : trap position of the particle: fixed by the anti-node of the trapping beam

- **As a GW passes, the proper length between the particle and the input mirror as well as the input mirror and the end mirror changes**

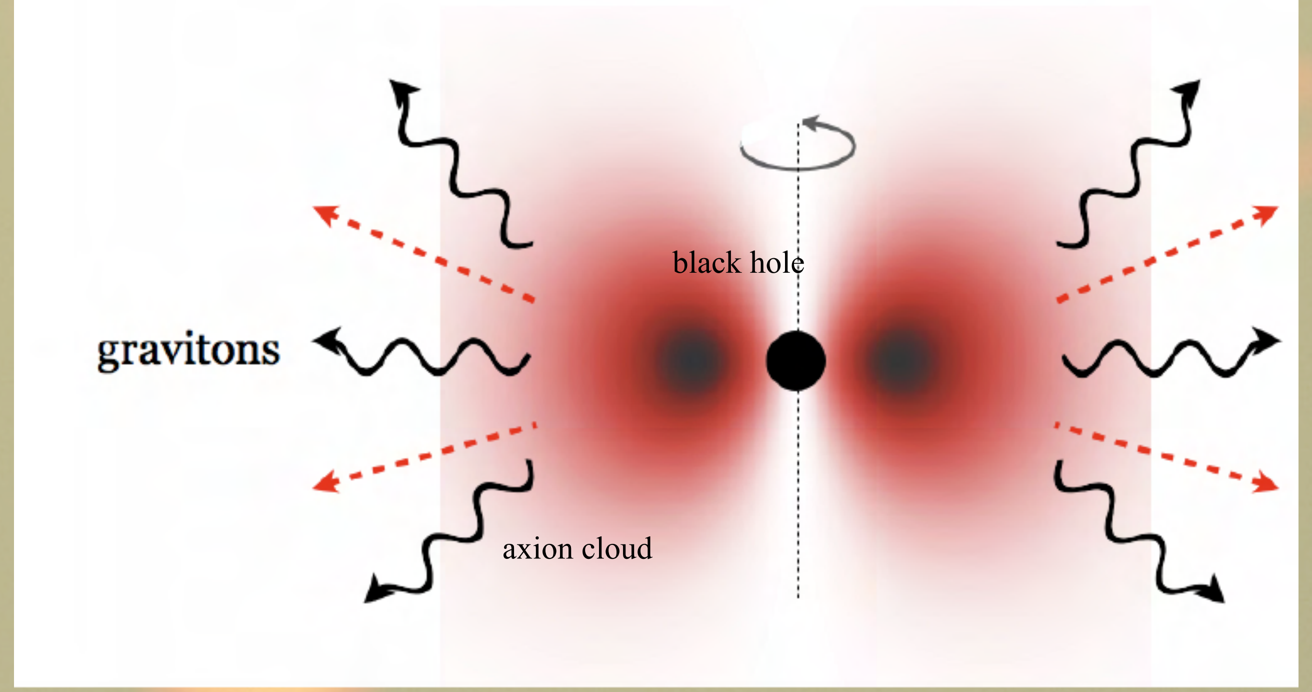
$$L_c = \left(1 + \frac{1}{2}h\right) l_c$$

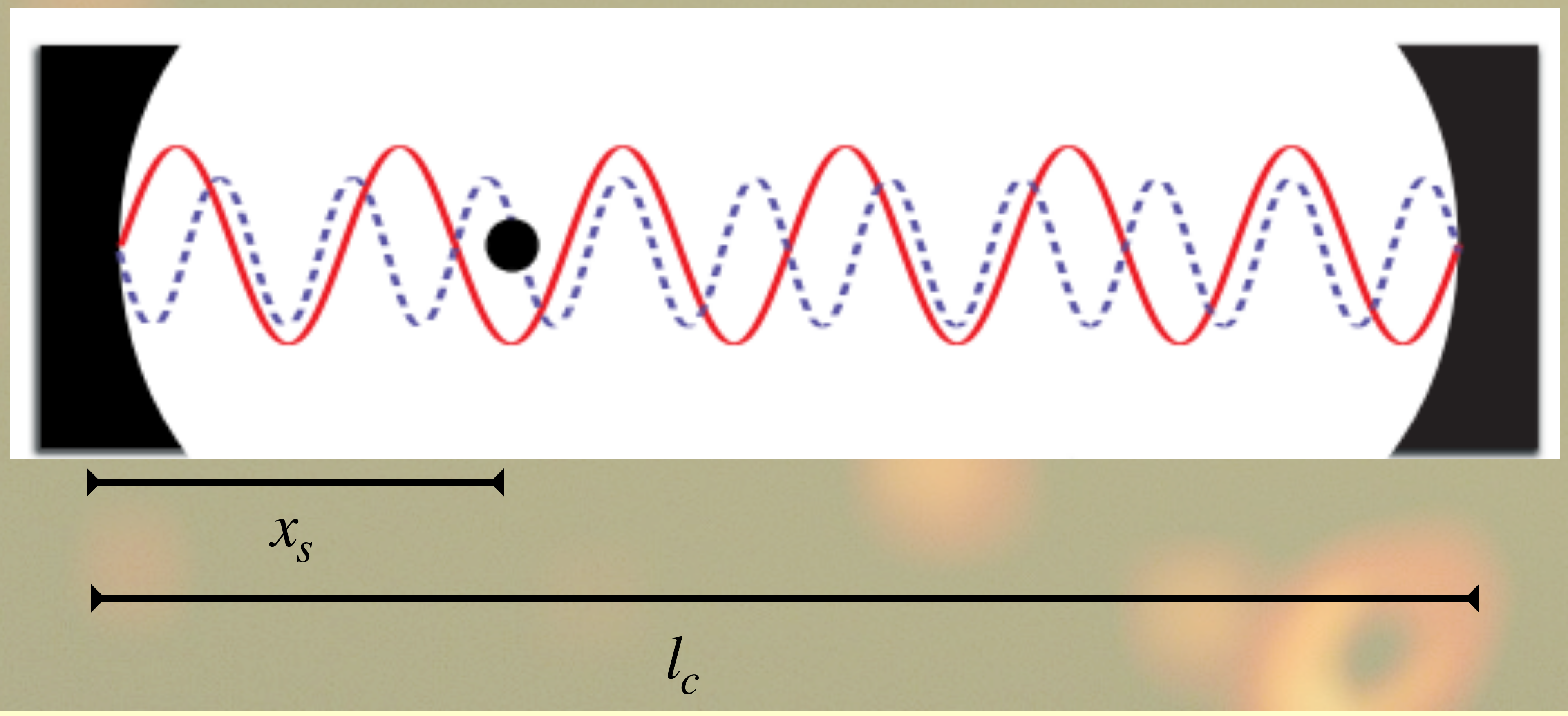
$$X_s = \left(1 + \frac{1}{2}h\right) x_s$$

Displacement from trap min:

$$\Delta X = \frac{1}{2}\, h \left(x_S - l_c\right)$$

Detection Principle





- Passing monochromatic GW acts as an oscillatory driving force on the sensor: $\mathbf{F_{GW}} = -\frac{\mathbf{m}\omega_{\mathbf{GW}}^2}{\mathbf{2}}\mathbf{h_o}\ \mathbf{cos}\left(\omega_{\mathbf{GW}}\mathbf{t} + \boldsymbol{\Delta}\phi\right)$
- Mechanical frequency of the trapped particle is tuned to GW frequency

——> resonant detection (**wide tunability! Frequency depends on the laser power**)

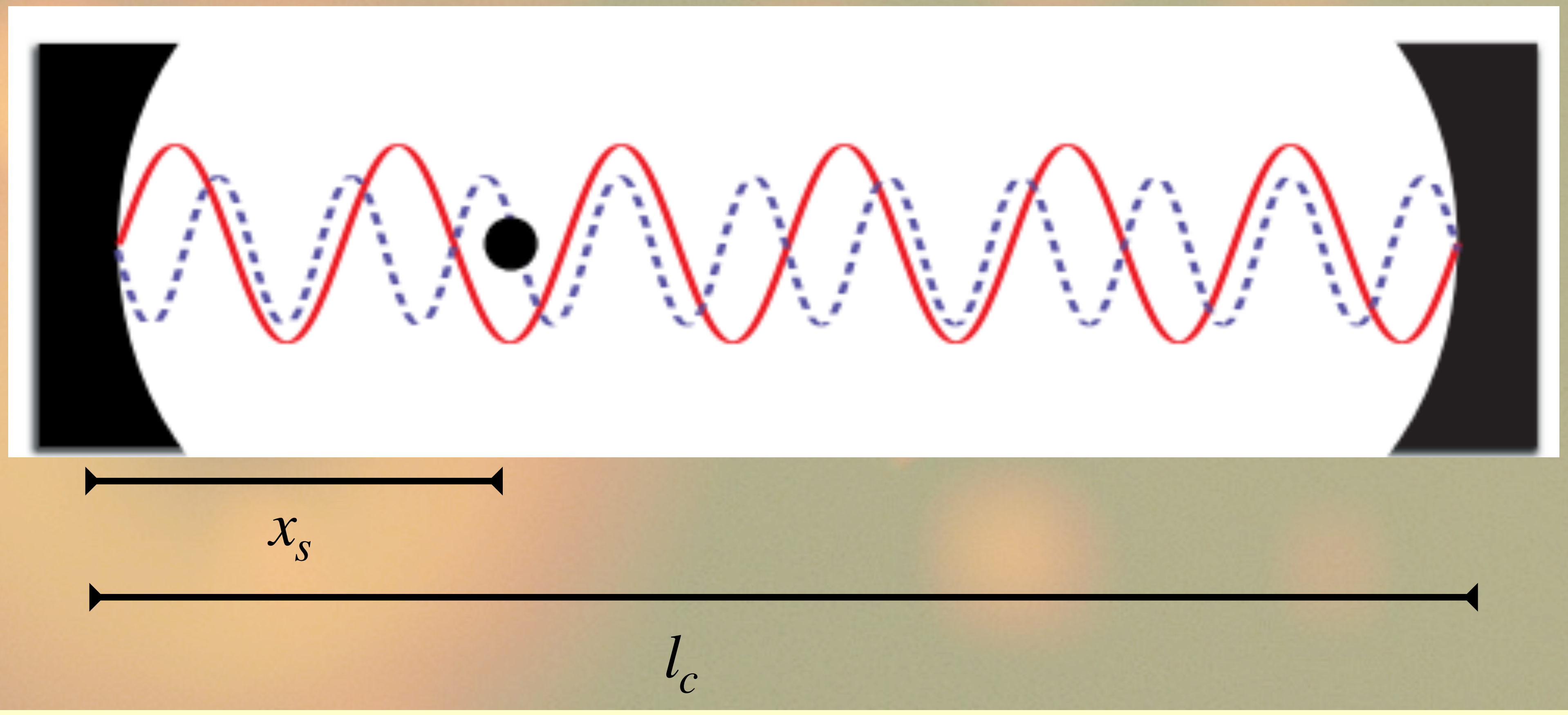
—> Passing GW wave changes the length of the cavity—> this shifts the trap position

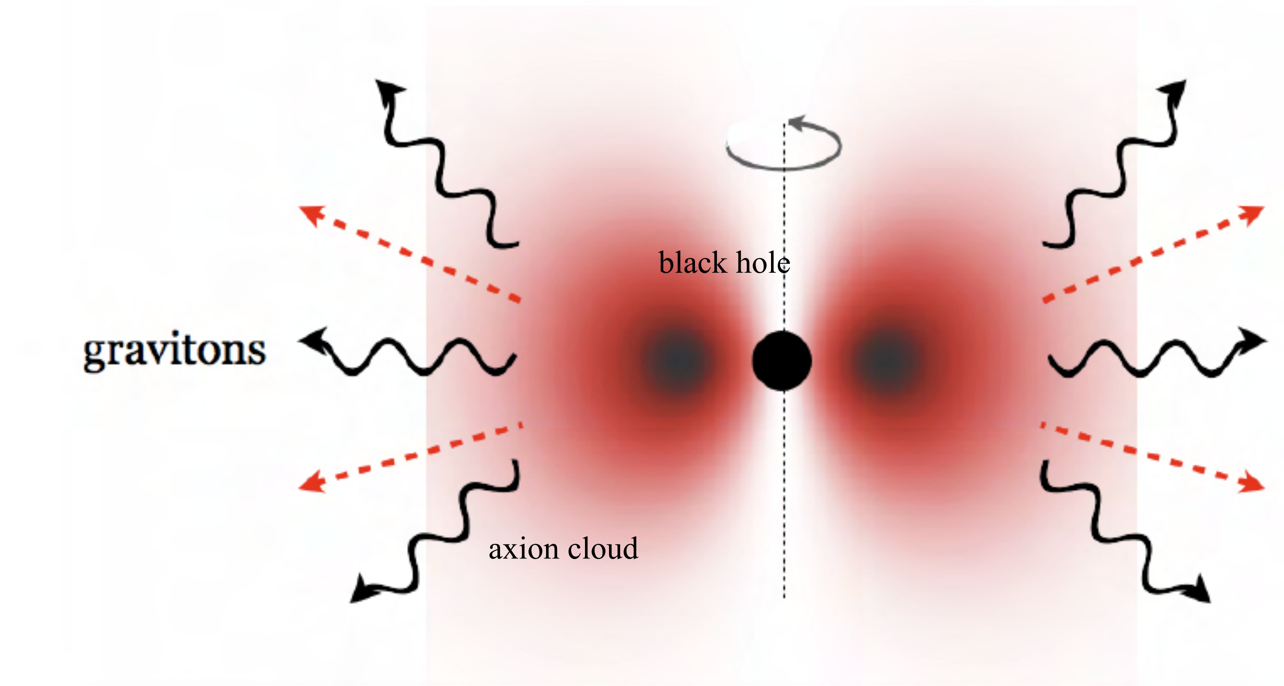
—> Particle gets displaced due to this optical force

—> This shift can be detected using our imaging system

- **Length change from gravitational wave transduced to (resonant) optical force on levitated sensor!**

Detection Principle





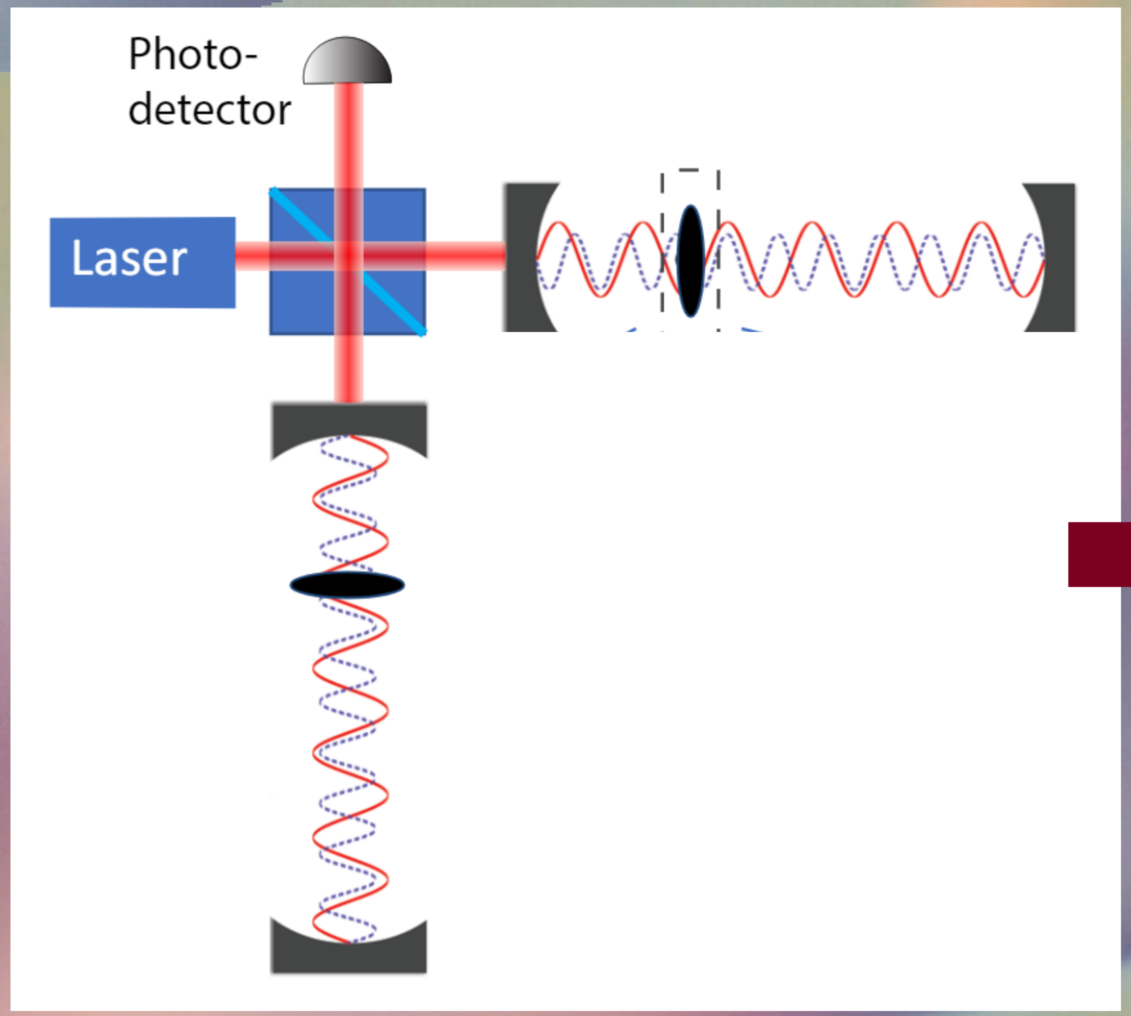
- Minimum detectable strain due to a passing GWs:

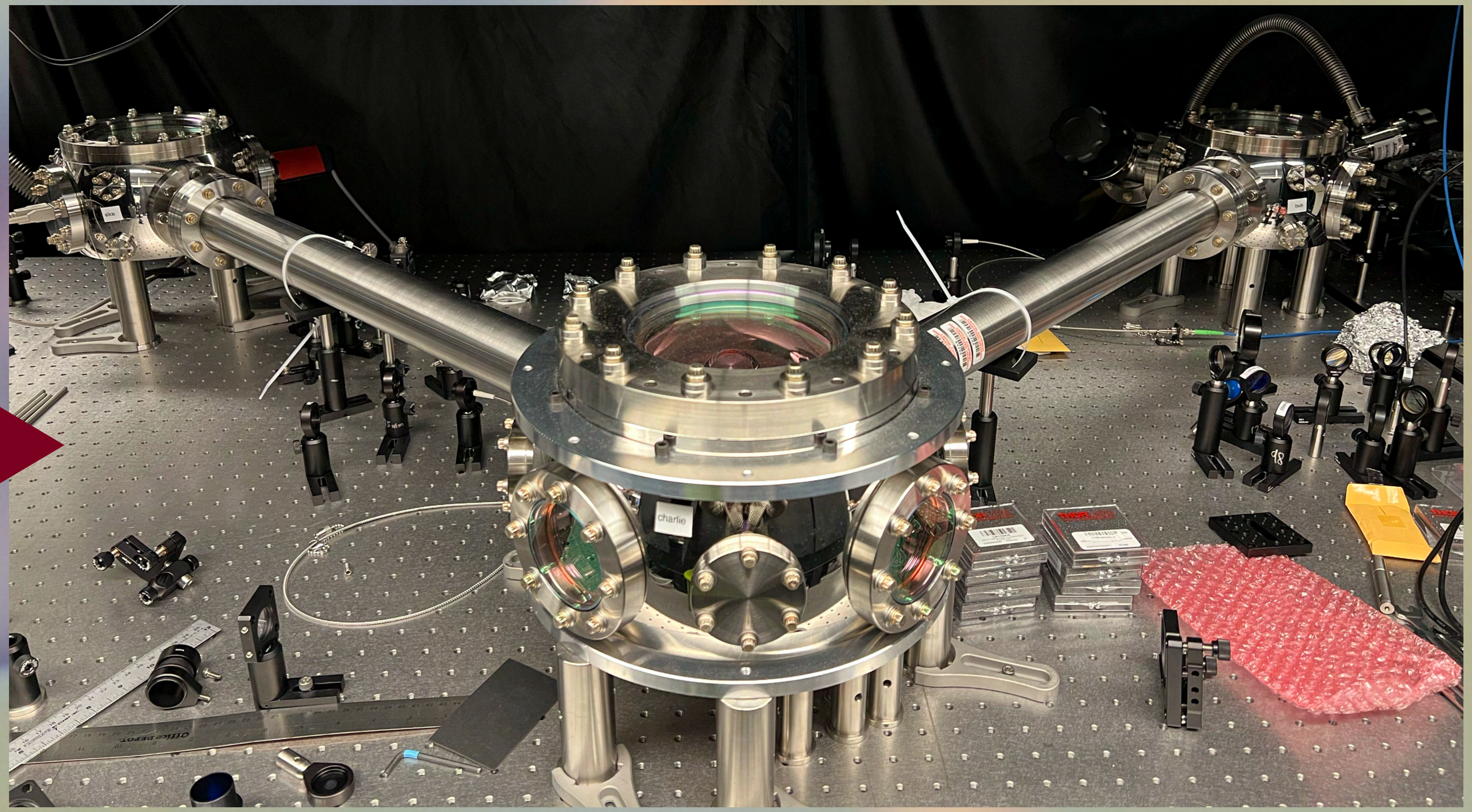
$$h_{limit} = \frac{4}{\omega_o^2 l_c}\sqrt{\frac{k_B T_{CM}\gamma_g b}{m}\left[1 + \frac{\gamma_{sc} + R_+}{N_i \gamma_g}\right]} H(\omega_o)$$

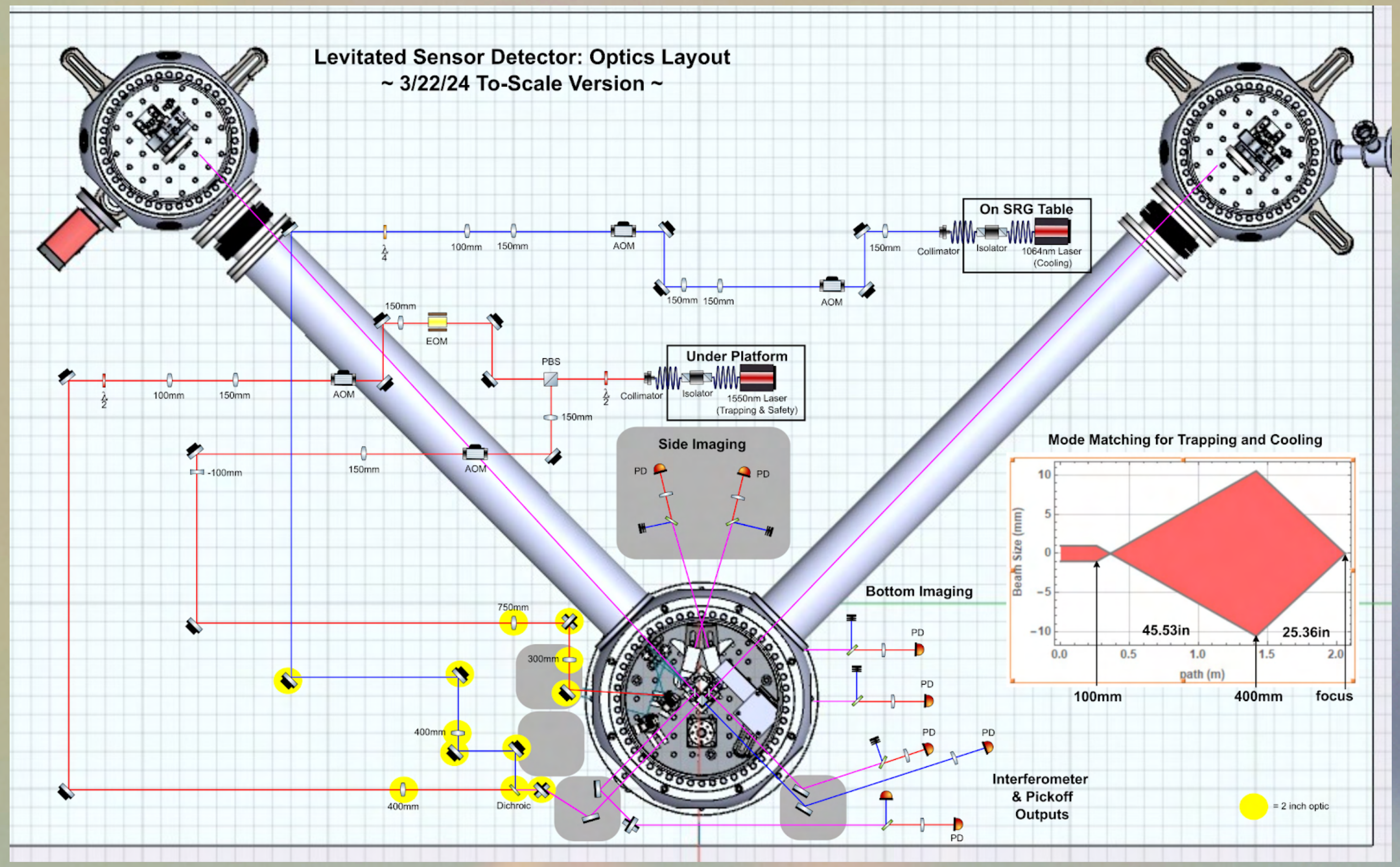
For a 10m cavity, $h \sim 10^{-22}\sqrt{Hz}$ at high frequency (100kHz)

trapping frequency ω_0
cavity arm length l_c
center of mass temperature of particle T_{CM}
gas damping rate $\gamma_g = 32P/\pi\bar{v}\rho t$
bandwidth b
particle mass m
photon recoil heating rate $\gamma_{sc} = (V_c\lambda\omega_0/4l_c)\{1/\int dV(\epsilon - 1)\}(1/\mathcal{F}_{disc})$
mean initial phonon occupation number of the CM motion $N_i = k_b T_{CM}/\hbar\omega_0$
cavity response function $H(\omega) \approx \sqrt{1 + 4\omega^2/\kappa^2}$

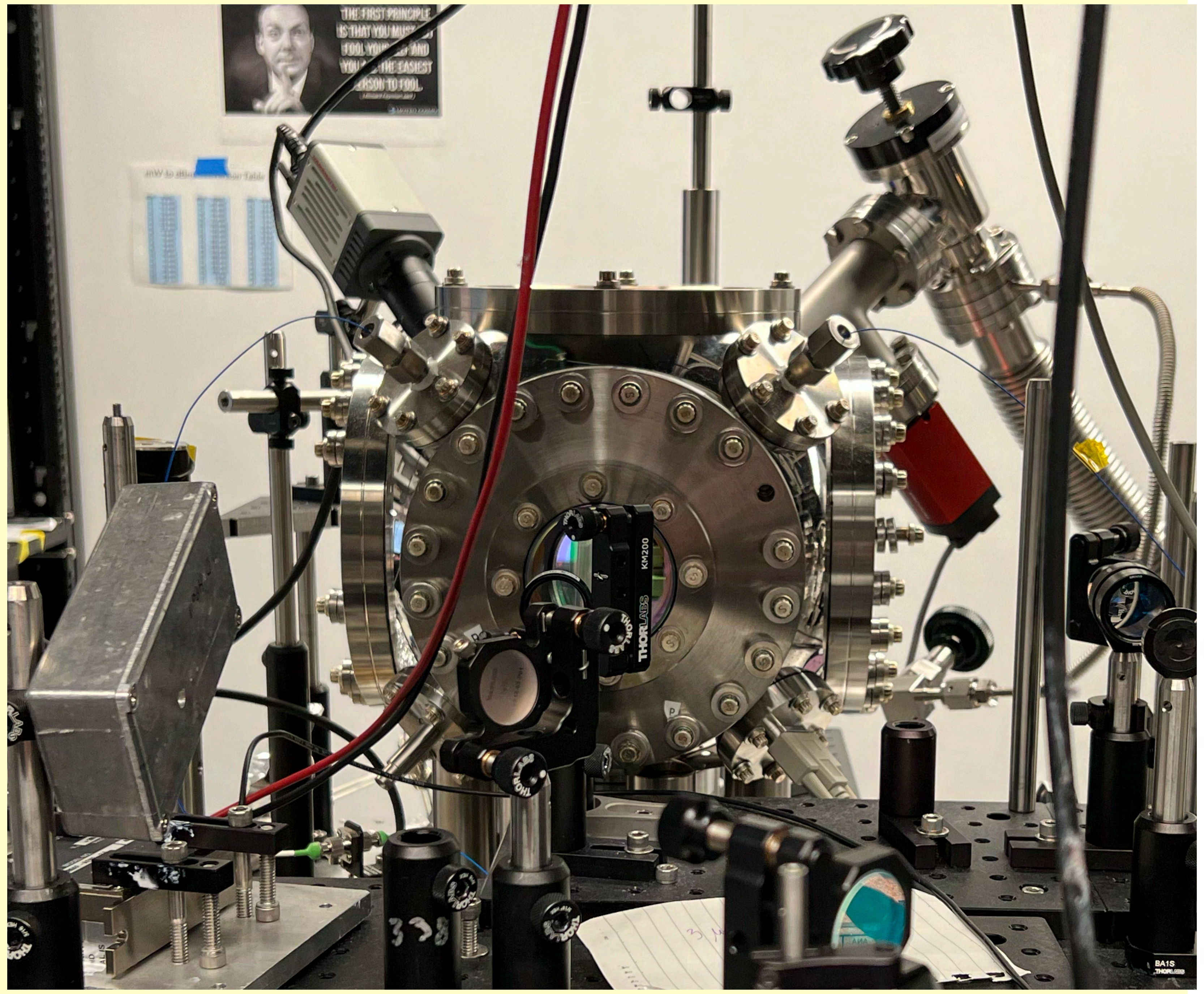
Current status



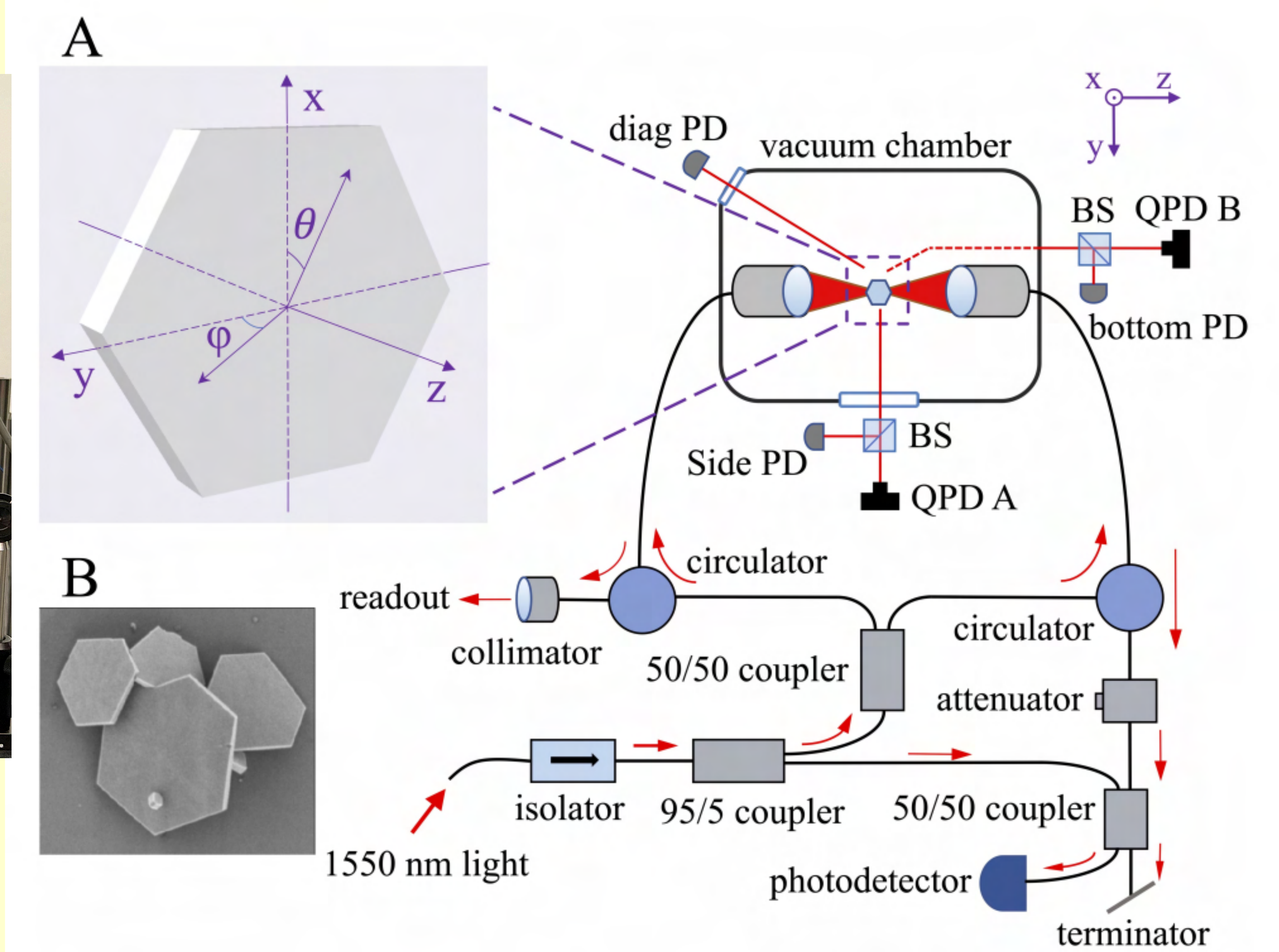


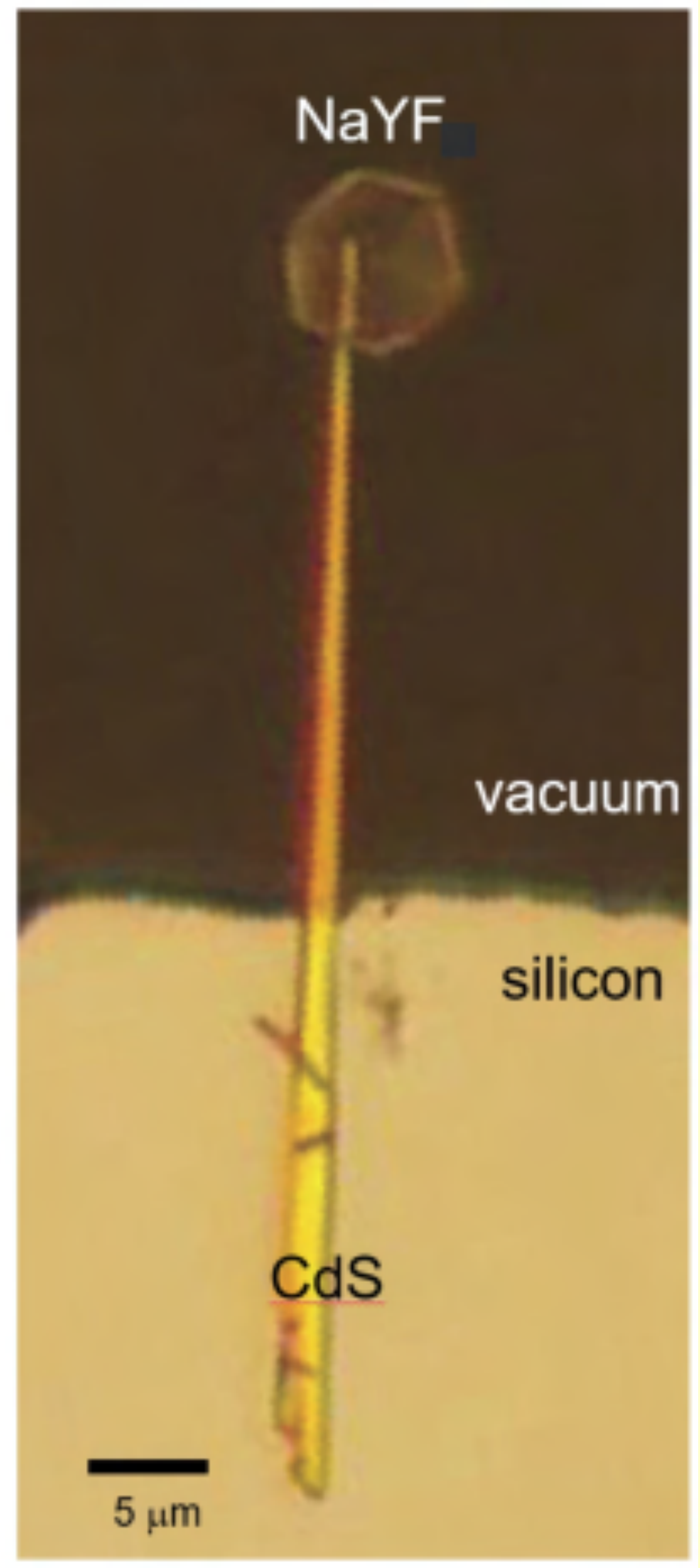


Trapping of Hexagons



ONR Test chamber





Deterministic launcher for hexagons

Optical Trapping of High-Aspect-Ratio NaYF Hexagonal Prisms for kHz-MHz Gravitational Wave Detectors

George Winstone, Zhiyuan Wang, Shelby Klomp, Greg R. Felsted, Andrew Laeuger, Chaman Gupta, Daniel Grass, Nancy Aggarwal, Jacob Sprague, Peter J. Pauzauskie, Shane L. Larson, Vicky Kalogera, and Andrew A. Geraci (LSD Collaboration)

Phys. Rev. Lett. **129**, 053604 – Published 28 July 2022

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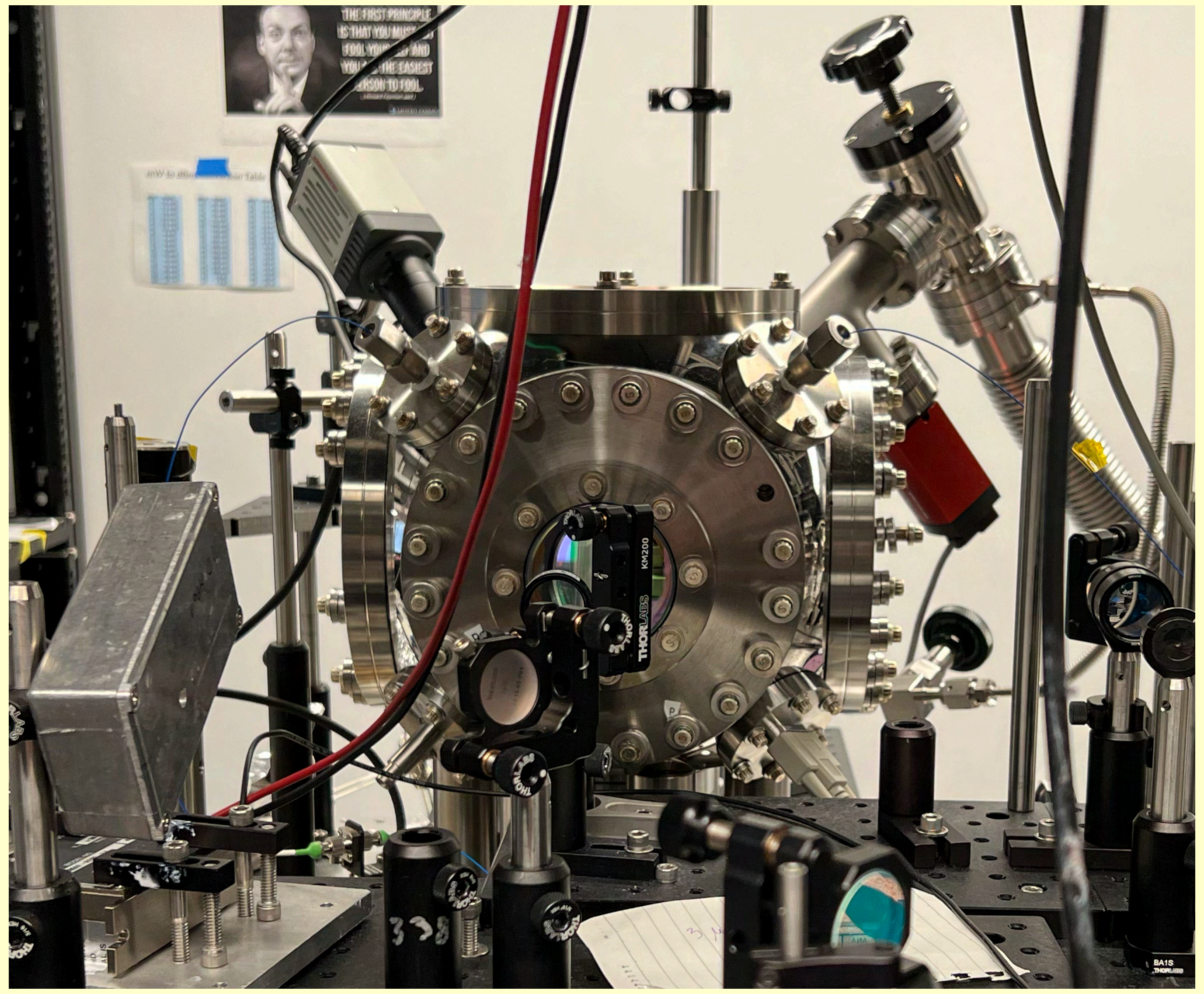
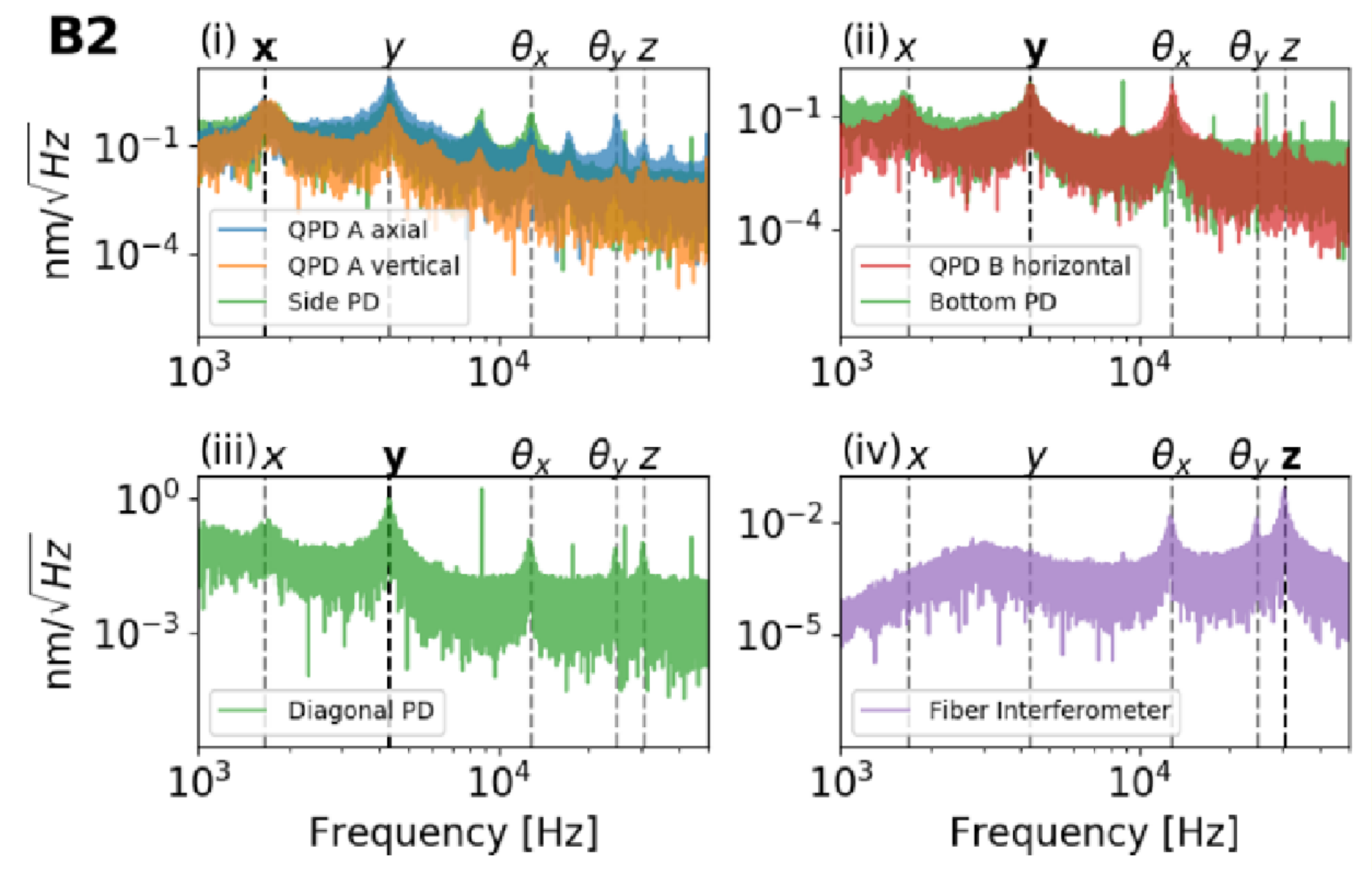
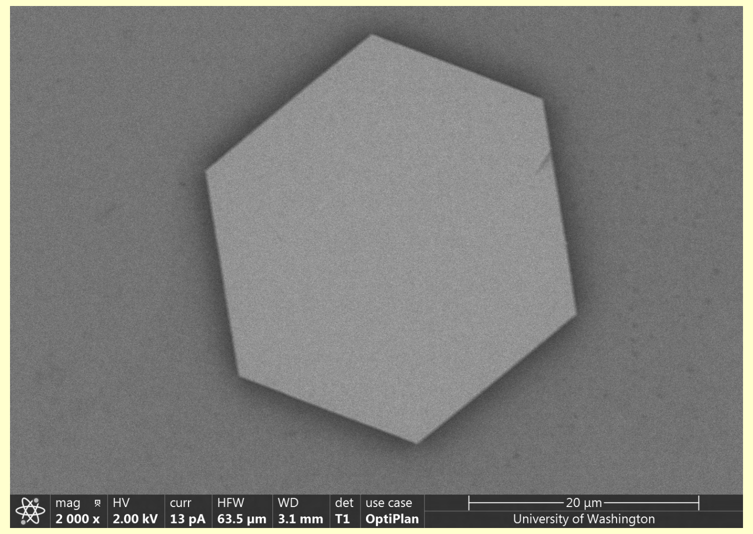
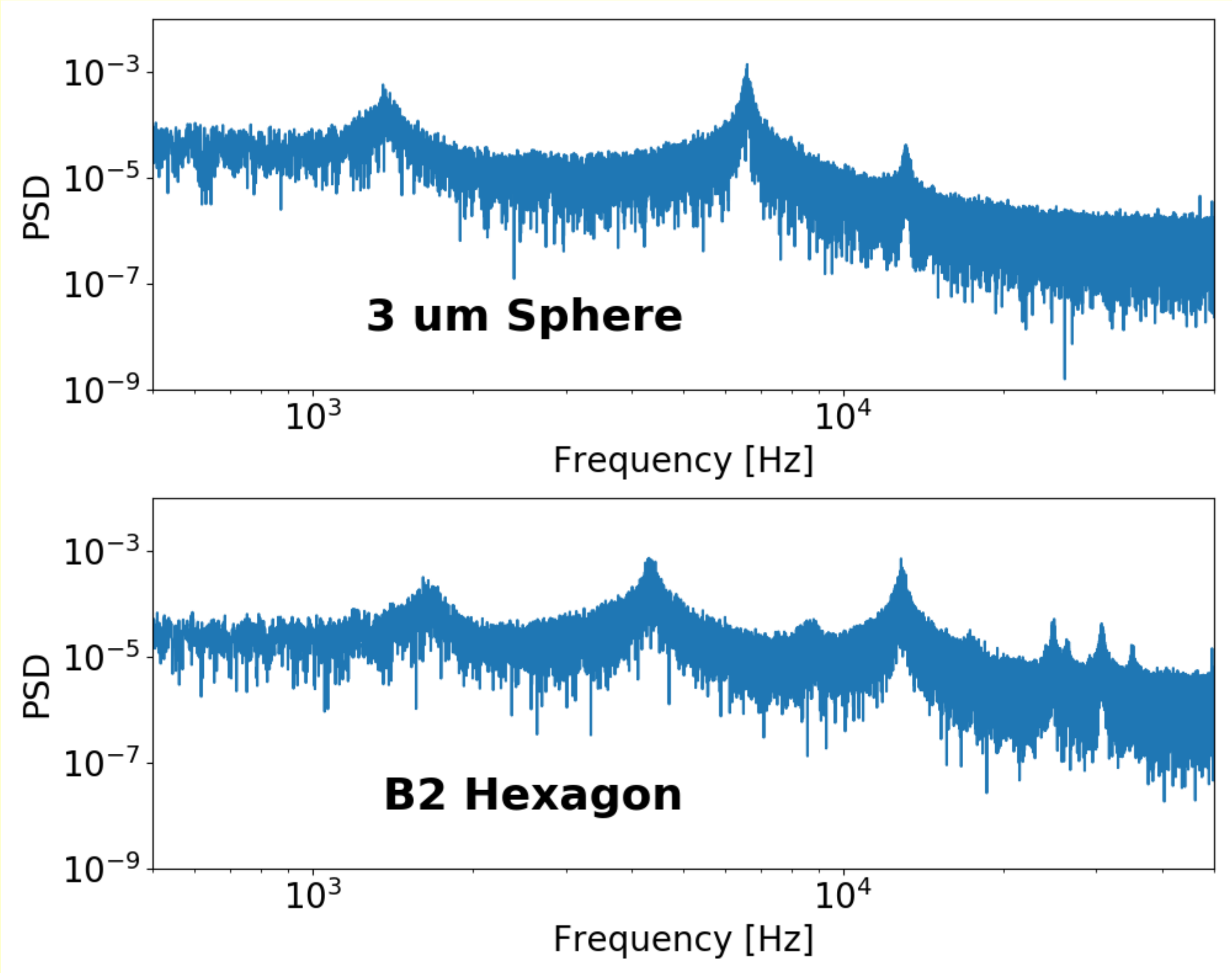
Trapping of Hexagons



ONR Test chamber



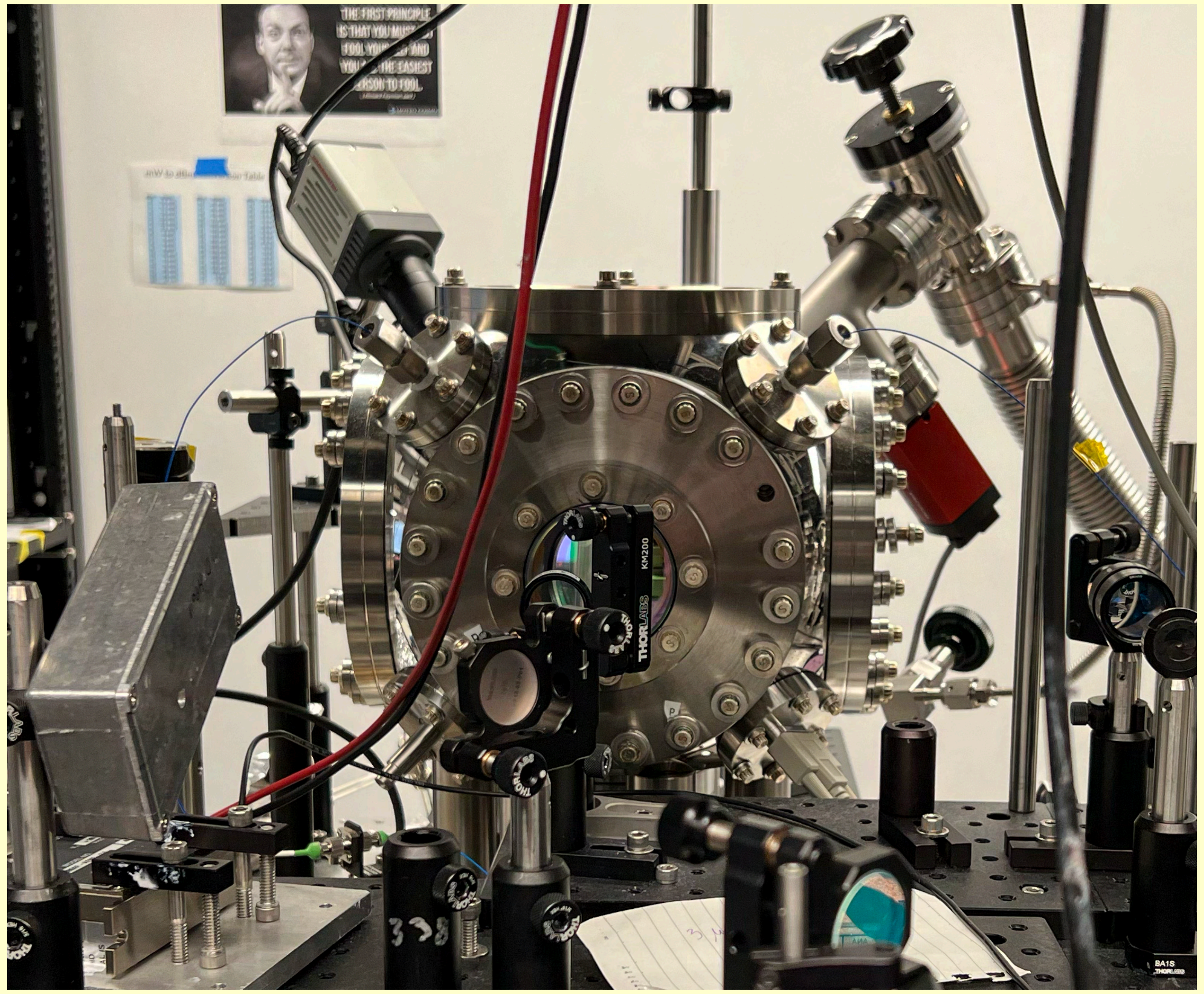




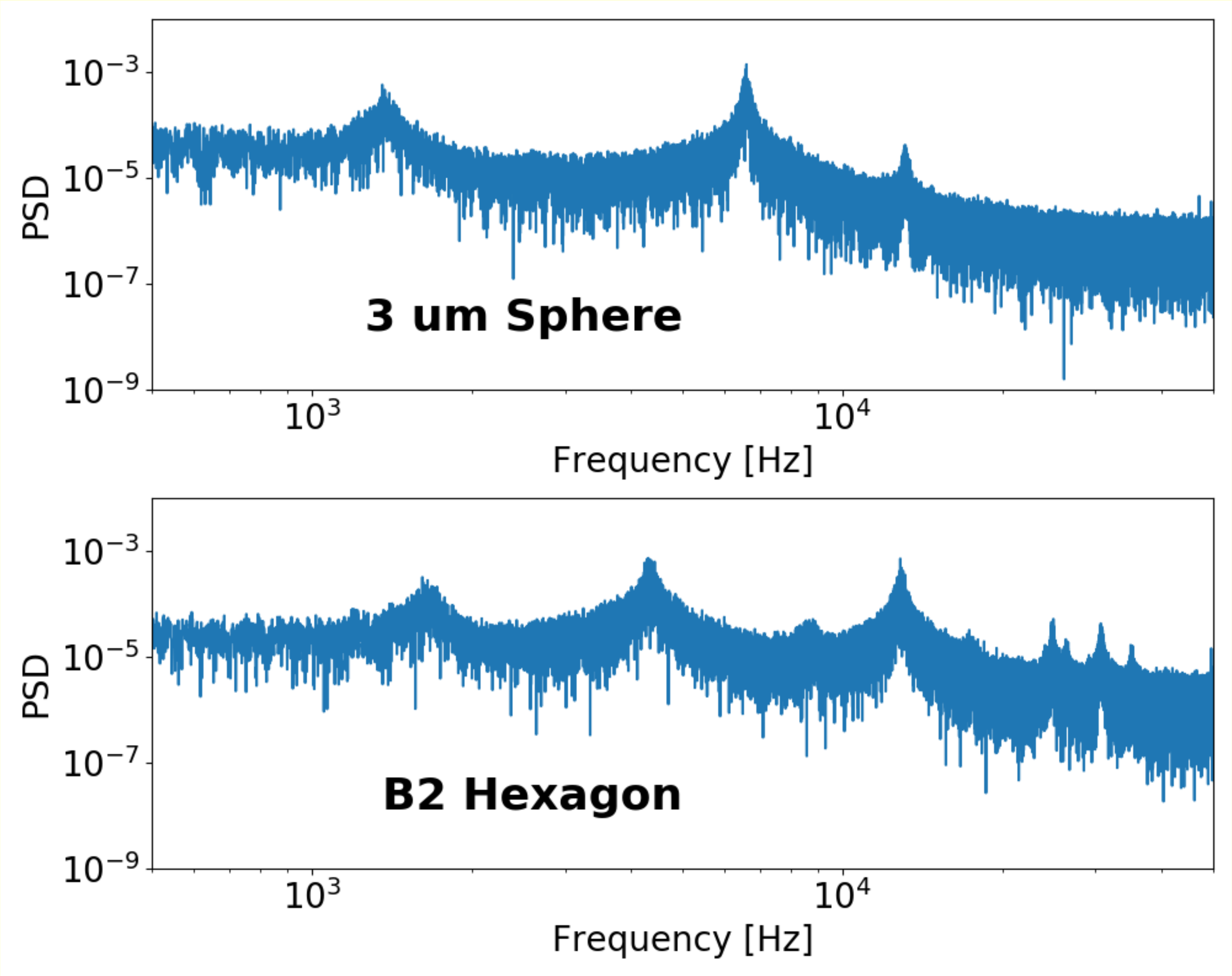
- Scattered light on a detector with FFT allows us to analyze motion
- Peaks in the spectra correspond to different oscillations of the particle in the trap

Trapping and Cooling of Hexagons

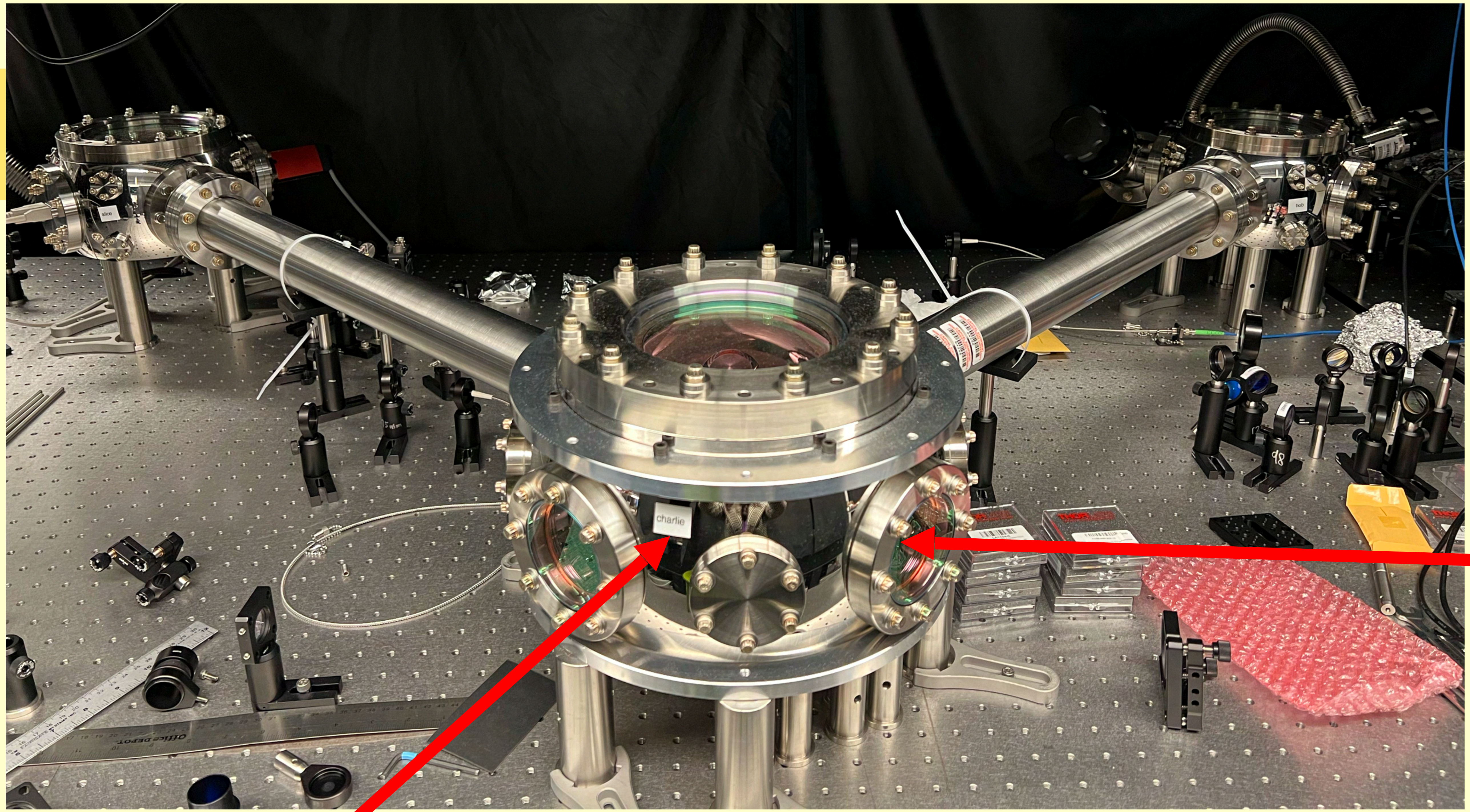
Currently attempting and optimizing linear damping on hexagons

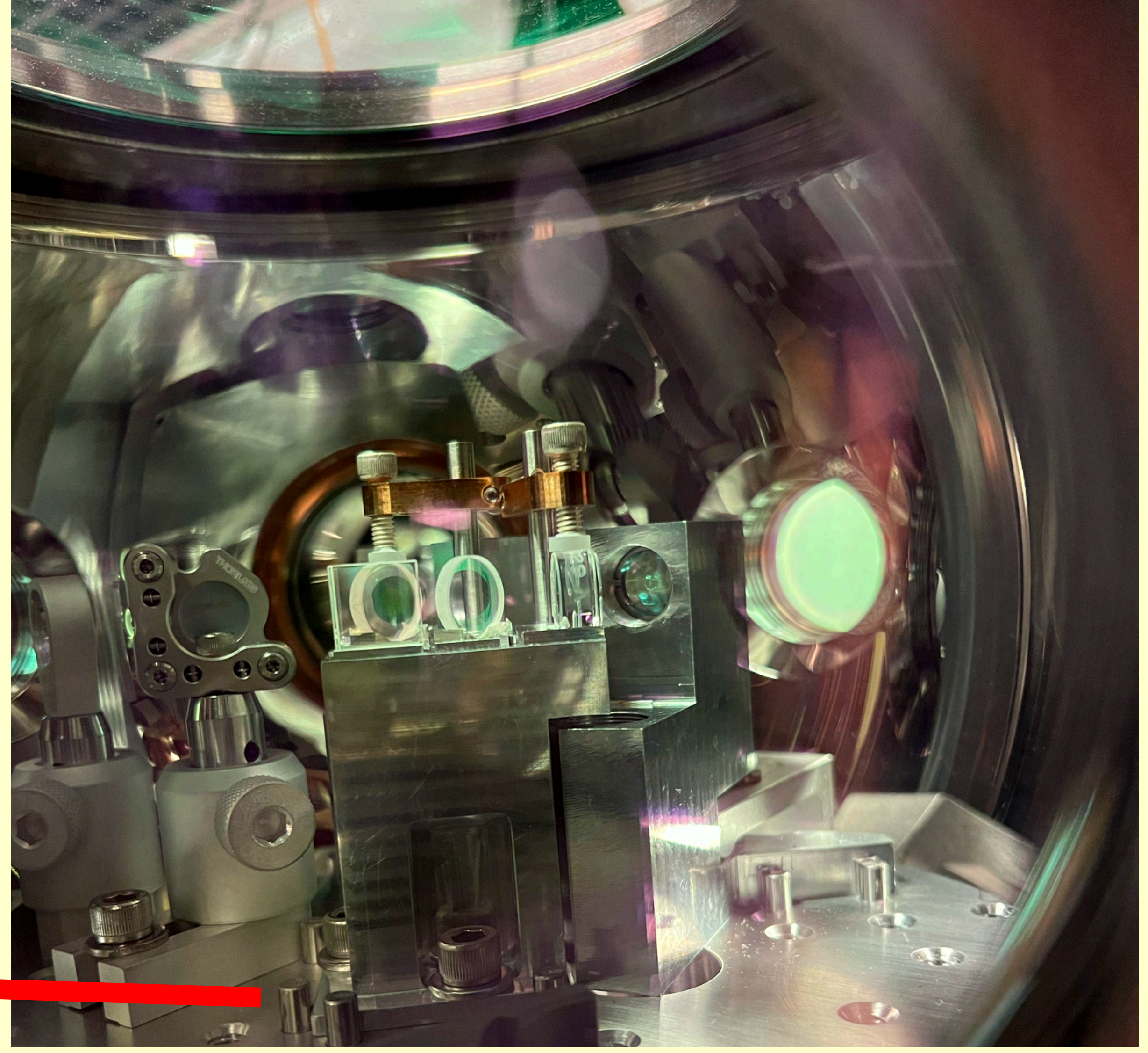


ONR Test chamber



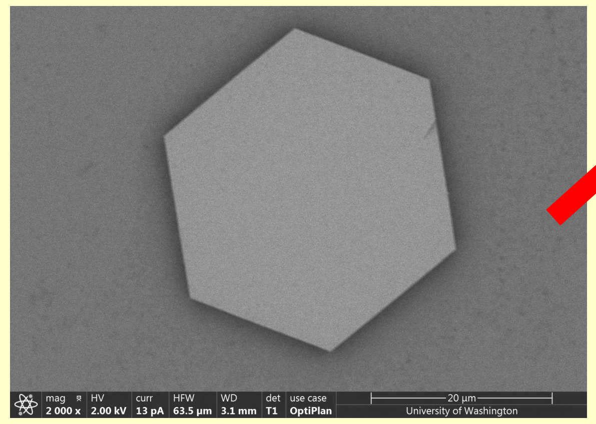
LSD phase 1 construction



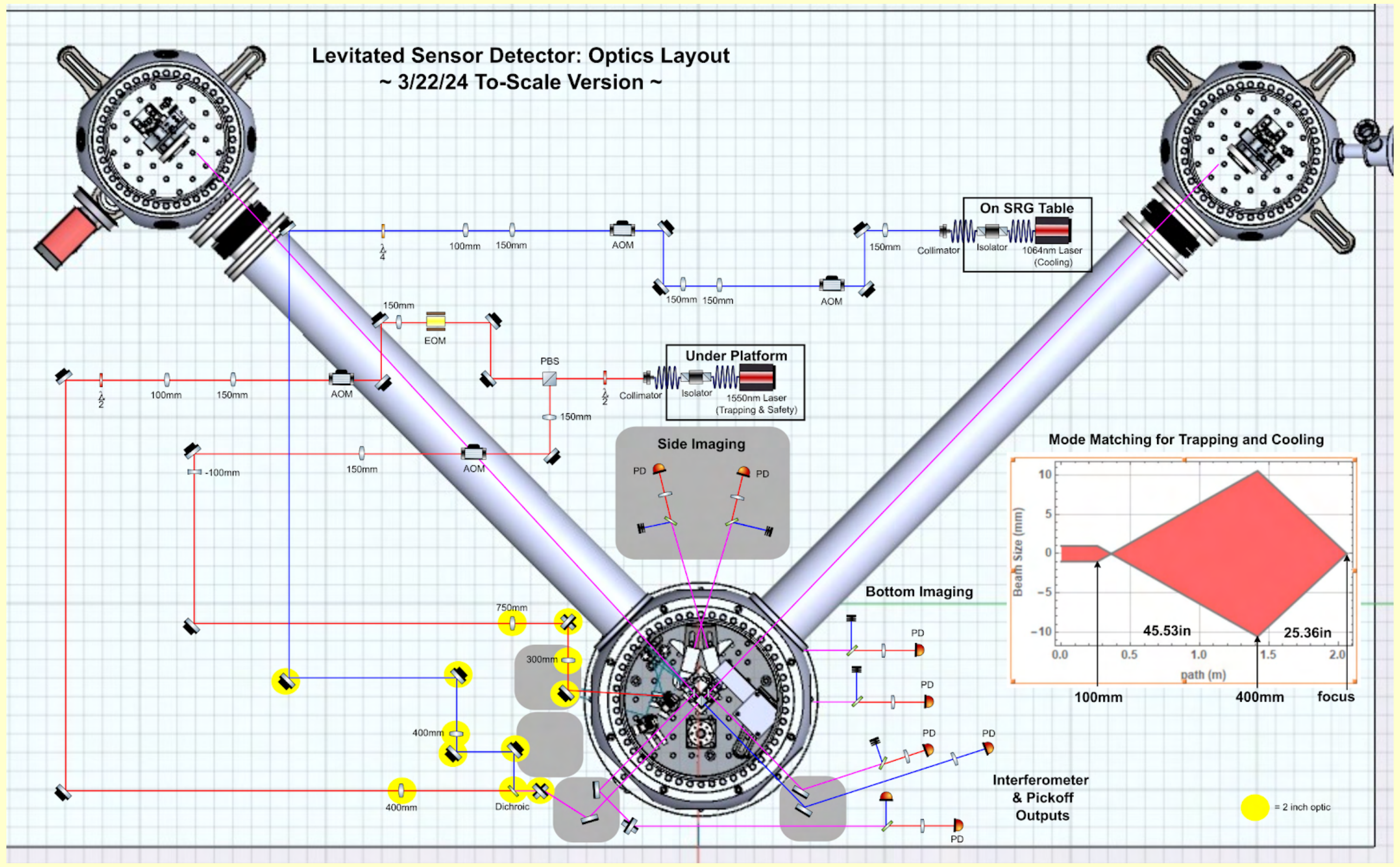


Locking 1-m cavity

Get disc-like sensors into 1m cavity



- Waveform modelling
- Complete noise budget (sub-dominant)
- Setting up our data acquisition system



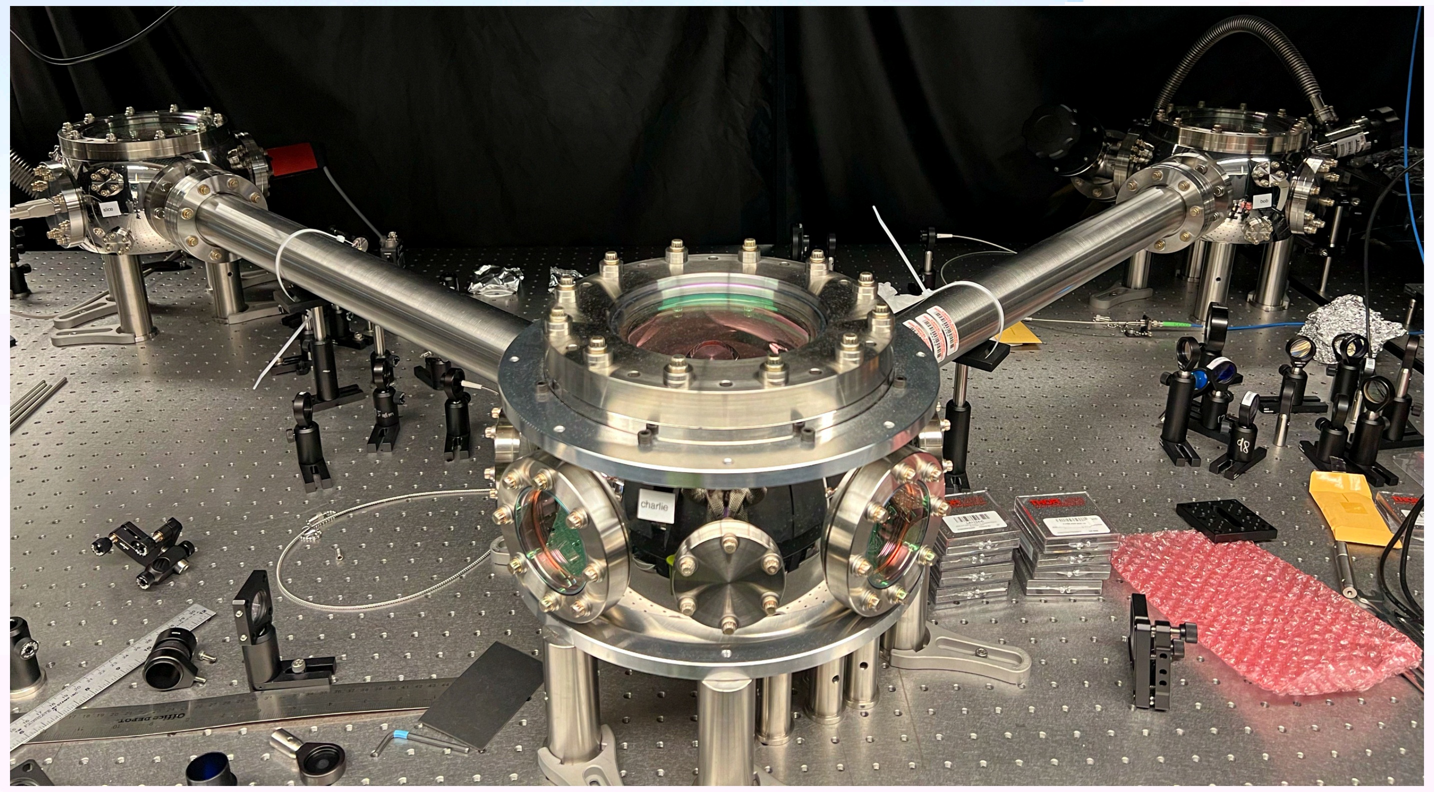
LSD Network (under construction)

LSD node 2 at UC Davis

PI: Dr. Nancy Aggarwal

LSD node 1 at Northwestern

PI: Prof. Andrew Geraci



Interesting review papers

Optomechanics of optically-levitated particles: A tutorial and perspective

GEORGE WINSTONE,[1], ALEXEY GRININ,[1] MISHKAT BHATTACHARYA,[2] ANDREW A. GERACI,[1,*] TONGCANG LI,[3] PETER J. PAUZAUSKIE,[4,5] AND NICK VAMIVAKAS[6]

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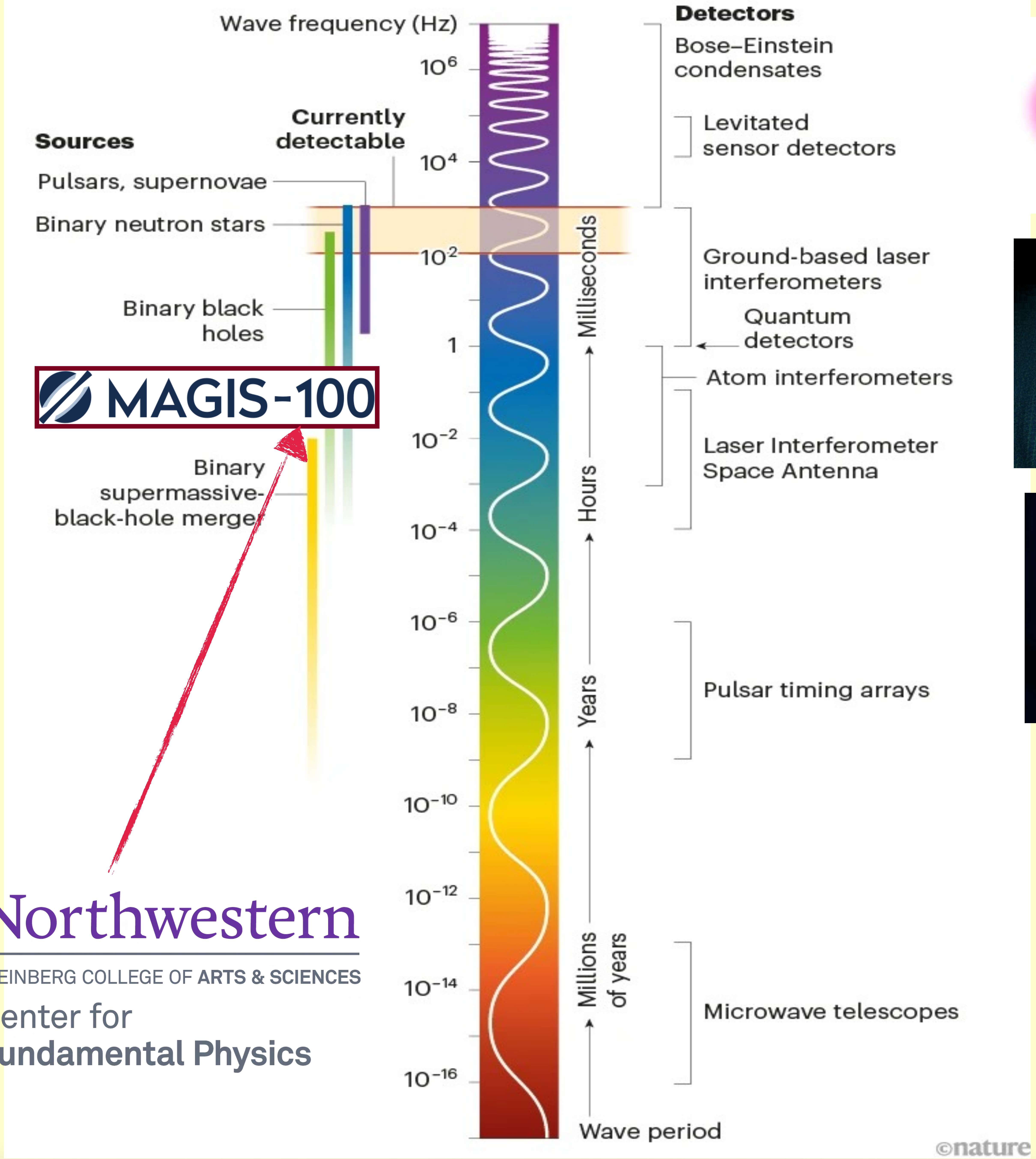
[2] *School of Physics and Astronomy, Rochester Institute of Technology, 84 Lomb Memorial Drive, Rochester, 14623 NY*
[3] *Department of Physics and Astronomy and Elmore Family School of Electrical and Computer Engineering, Purdue University, West Lafayette, IN, USA*
[4] *Department of Materials Science and Engineering, University of Washington, Seattle, WA*
[5] *Physical and Computational Sciences Directorate, Pacific Northwest National Laboratory, Richland, WA*
[6] *Department of Physics, University of Rochester, Rochester, NY, 14627*
[*] *andrew.geraci@northwestern.edu*

Challenges and Opportunities of Gravitational Wave Searches above 10 kHz

Nancy Aggarwal[a] · Odylio D. Aguiar[b] · Diego Blas[c,d] · Andreas Bauswein[e] · Giancarlo Cella[f] · Sebastian Clesse[g] · Adrian Michael Cruise[h] · Valerie Domcke[i,*] · Sebastian Ellis[j,*] · Daniel G. Figueroa[k] · Gabriele Franciolini[i,*] · Camilo Garcia-Cely[k] · Andrew Geraci[a] · Maxim Goryachev[l] · Hartmut Grote[m] · Mark Hindmarsh[n,o] · Asuka Ito[p,q] · Joachim Kopp[i,r,*] · Sung Mook Lee[i,*] · Killian Martineau[s] · Jamie McDonald[t] · Francesco Muia[u] · Nikhil Mukund[v] · David Ottaway[w] · Marco Peloso[x,y] · Krisztian Peters[z] · Fernando Quevedo[u,α] · Angelo Ricciardone[f,β] · Andreas Ringwald[z] · Jessica Steinlechner[γ,δ,ϵ] · Sebastian Steinlechner[γ,δ] · Sichun Sun[ζ] · Carlos Tamarit[r] · Michael E. Tobar[l] · Francisco Torrenti[η] · Caner Ünal[θ,λ] · Graham White[μ]



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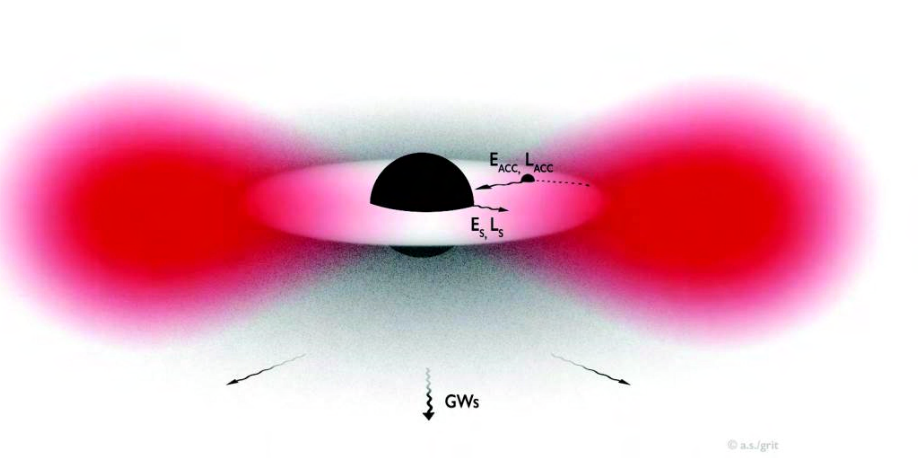

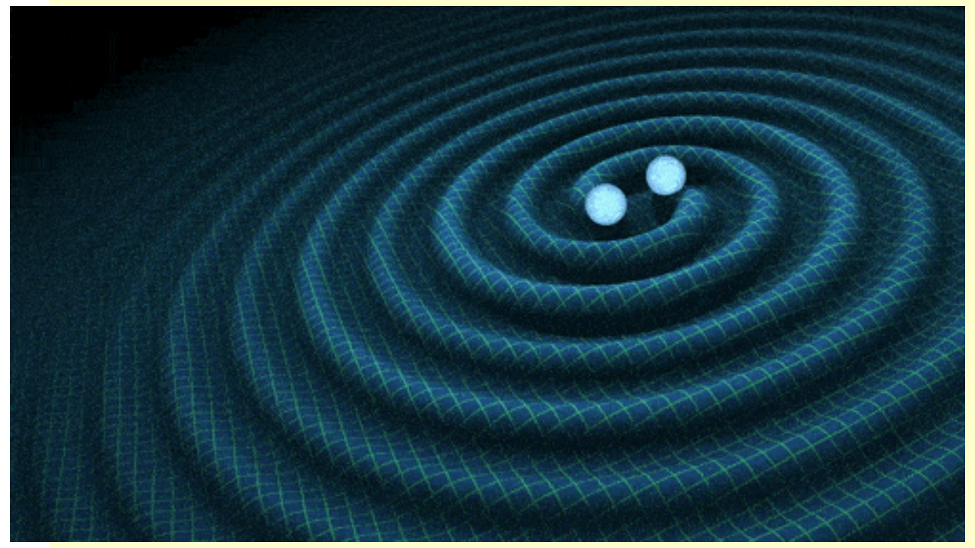

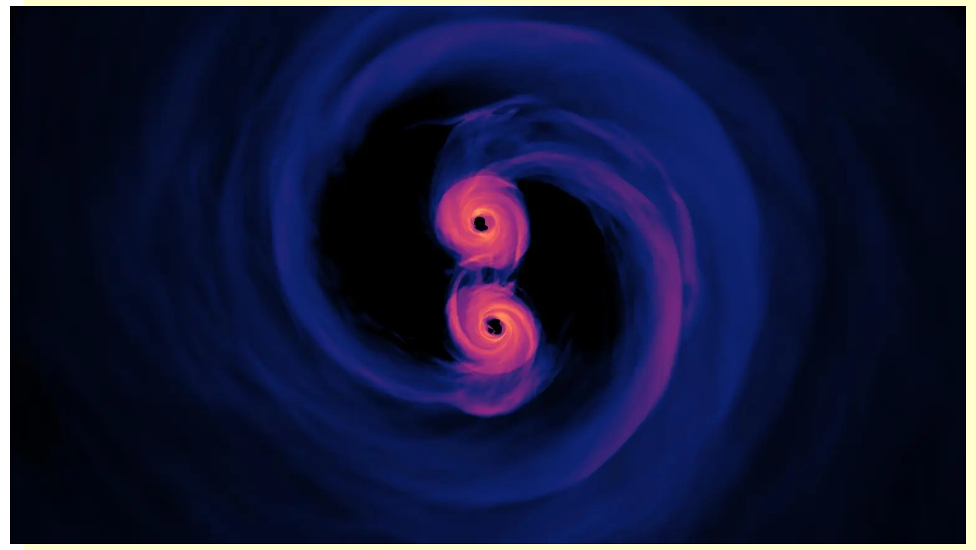

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NEWS FEATURE | 27 June 2024

Five new ways to catch gravitational waves — and the secrets they'll reveal

Observatories, experiments and techniques are being developed to spot ripples in space-time at frequencies that currently can't be detected.

Gravitational wave spectrum