# Optically-trapped membranes for high-frequency gravitational wave detection

**Quantum Sensing for Fundamental Physics**

November 20, 2024

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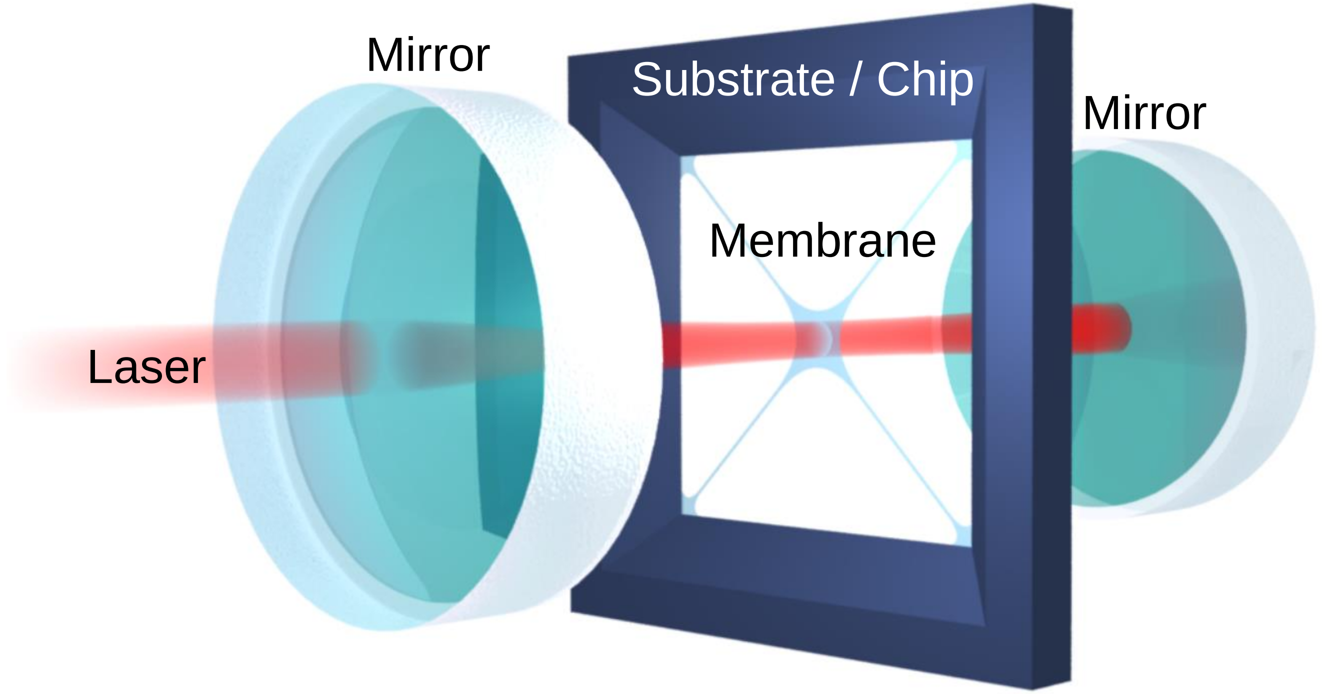
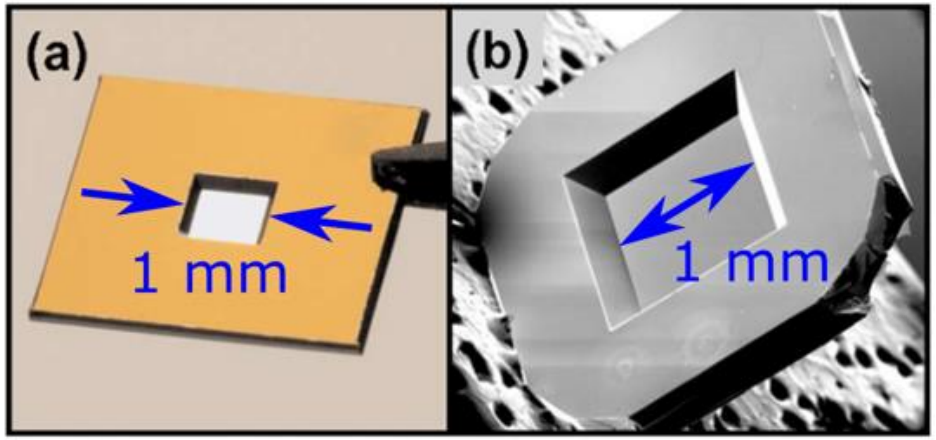
(DESY, FH-ALPS)




HELMHOLTZ

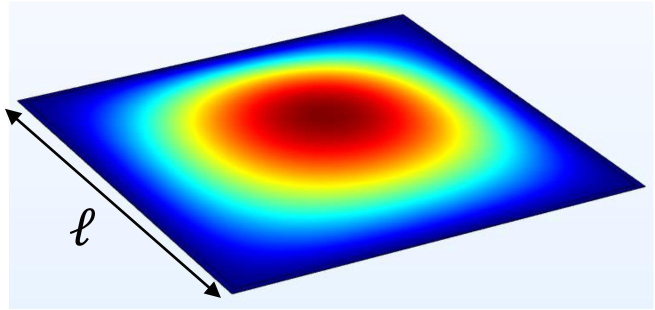
# Nanomechanical membrane resonators

### Microscope & SEM images

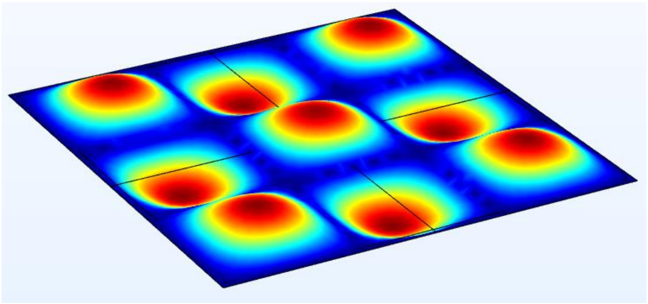



Silicon nitride (SiN) membrane [1]
(typically 10 to 100 nm thick)

### Mechanical resonances




$m = n = 1$, $f_{11} = 0.4\ \mathrm{MHz}$



$m = n = 3$, $f_{33} = 1.2\ \mathrm{MHz}$

$$f_{mn} = \frac{1}{2\ell}\sqrt{\frac{\sigma}{\rho}(m^2 + n^2)}$$

Mechanical stress: $\sigma = 1\ \mathrm{GPa}$

Mass density: $\rho = 3000\ \mathrm{kg/m^3}$

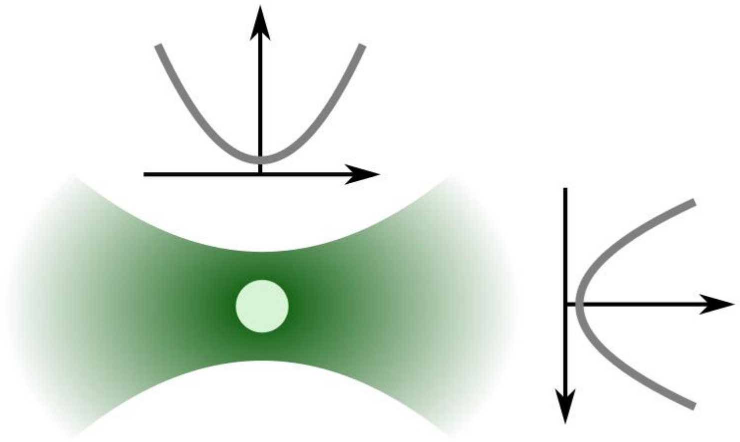
[1] B. M. Zwickl, et al. *Applied Physics Letters* 92.10 (2008)

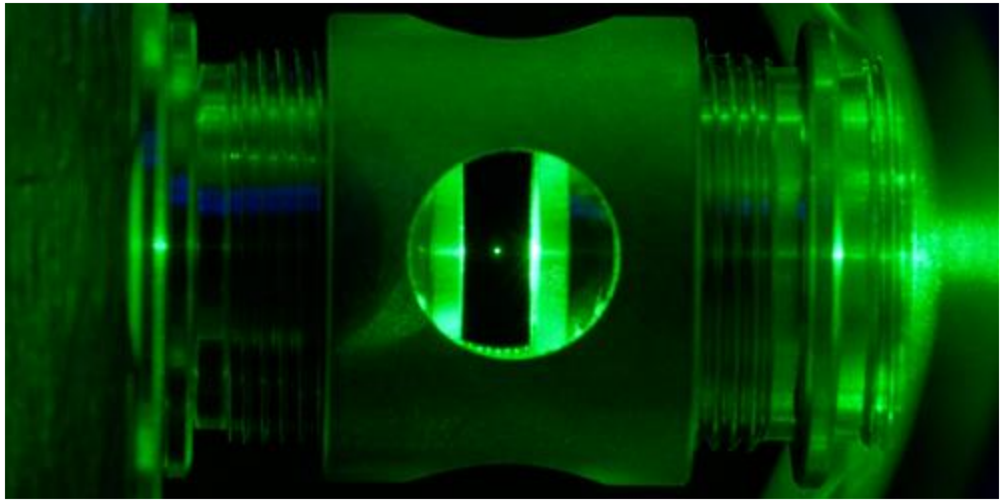
# Optical trapping of a glass sphere

**Dielectric (polarizable) particle is attracted to region of maximum field**

$$U(x) = -\frac{1}{2}\alpha\, E^2(x)$$

$$f_{\mathrm{trap}} = \frac{1}{2\pi}\sqrt{\frac{1}{m}\frac{d^2U}{dx^2}}$$





https://physics.aps.org/articles/v13/s4

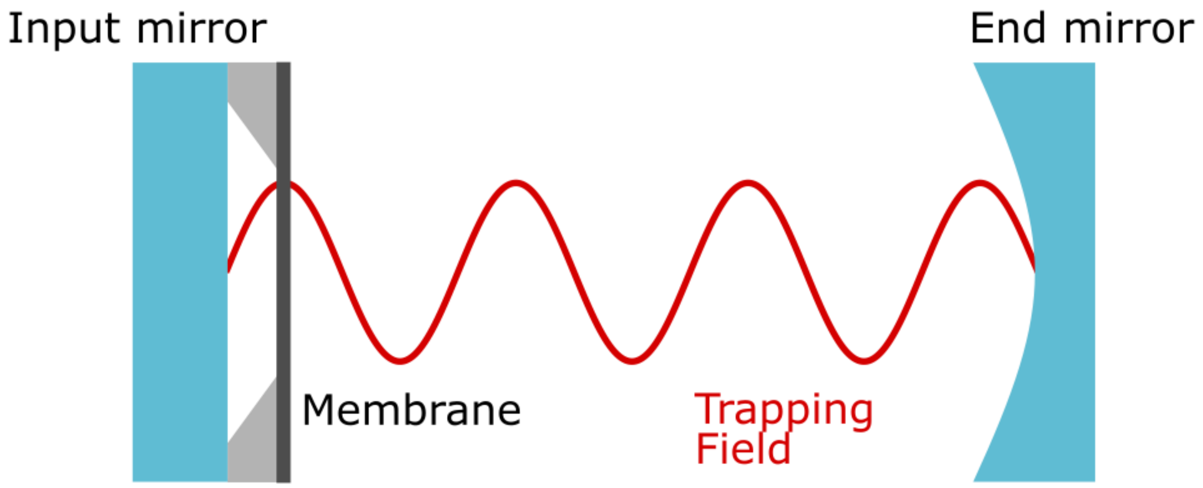
# Optical trapping of a membrane

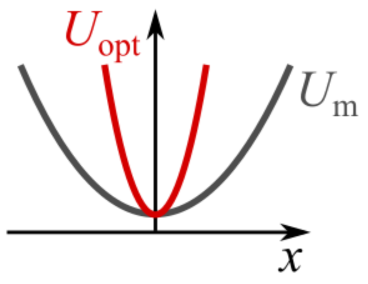
- Straight-forward installation of membrane chip inside cavity
- Optical standing wave inside cavity provides a harmonic potential for membrane
  → optical spring constant [2-4]

$$k_{\text{opt}} = \frac{d^2 U_{\text{opt}}}{dx^2} = \frac{16\pi}{\lambda} \frac{\mathcal{P}}{c} \frac{|r|}{|t|}$$

- Membrane's oscillation frequency depends on optical power

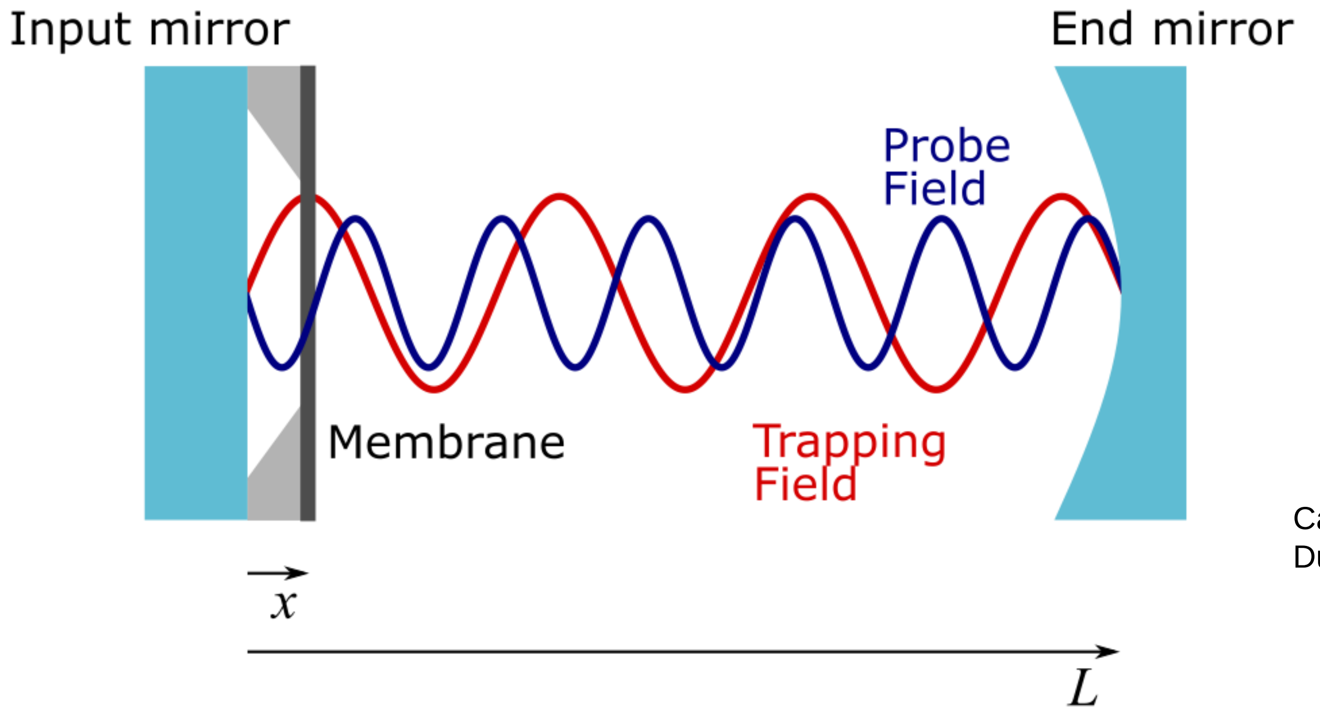
$$f_{\text{tot}}(\mathcal{P}) = \sqrt{\frac{k_{\text{m}} + k_{\text{opt}}(\mathcal{P})}{m_{\text{eff}}}}$$




[2] Chang, D. E., Ni, K. K., Painter, O., & Kimble, H. J. (2012). Ultrahigh-Q mechanical oscillators through optical trapping. *New Journal of Physics*, *14*(4), 045002
[3] Ni, K. K., Norte, R., Wilson, D. J., Hood, J. D., Chang, D. E., Painter, O., & Kimble, H. J. (2012). Enhancement of mechanical Q factors by optical trapping. *Physical review letters*, *108*(21), 214302
[4] Barasheed, Abeer Z., Tina Müller, and Jack C. Sankey. "Optically defined mechanical geometry." *Physical Review A* 93.5 (2016): 053811

# High-frequency gravitational wave detector



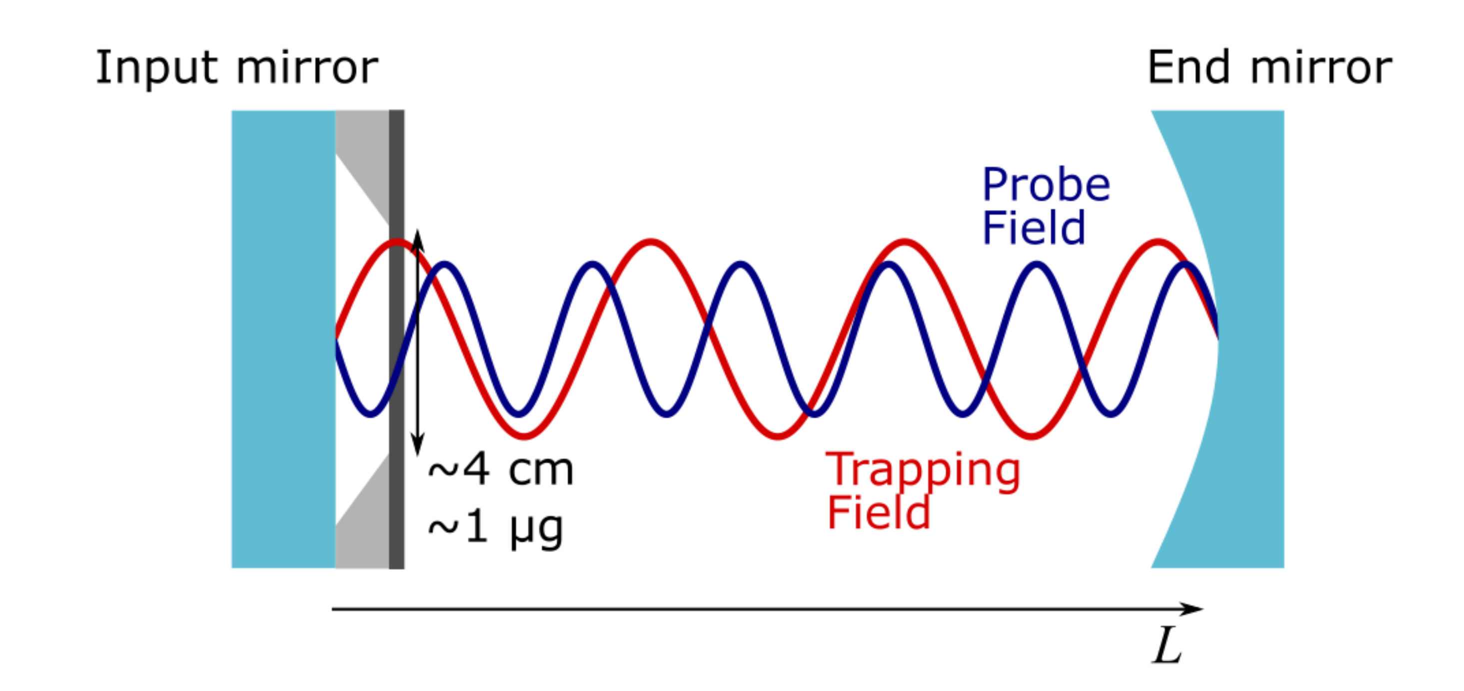

Cavity with membrane close to input mirror: Dumont, et al. *Optics express* (2019)

$$\Delta L = \frac{h}{2} L \qquad \Delta x = \frac{h}{2} x \qquad \Delta x_{\mathrm{GW}} = \frac{h}{2}(x - L) \rightarrow \frac{h}{2} L$$

Resonant enhancement if frequency of membrae and gravitational wave coincide $f_{\mathrm{m}} = f_{\mathrm{GW}}$


[5] Arvanitaki, et al. *Physical review letters* 110.7 (2013): 071105
[6] Aggarwal, et al. *Physical review letters* 128.11 (2022): 111101

# Detector sensitivity



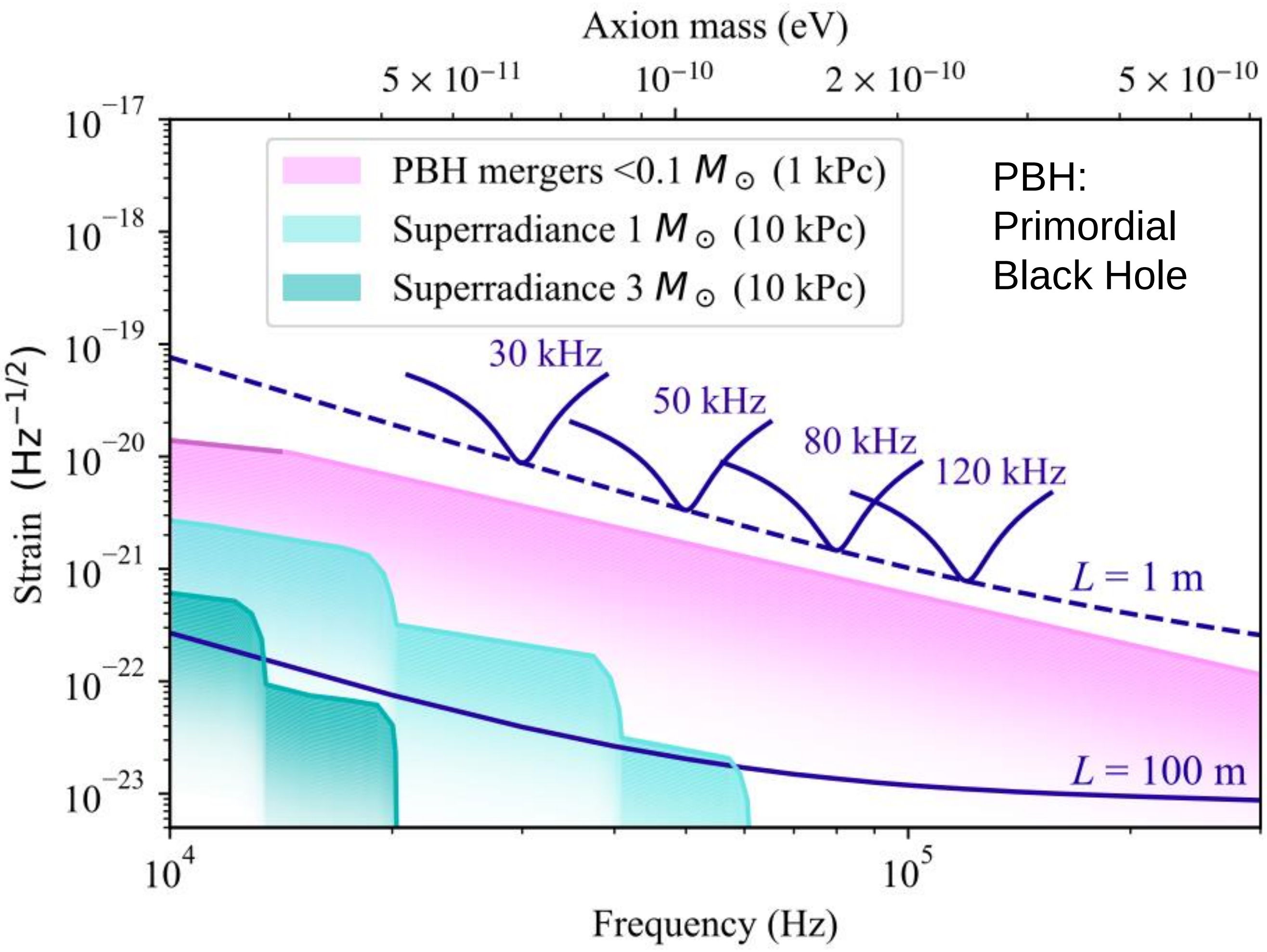

Ultra-high-vacuum: pressure ~ $10^{-11}$ mbar (mechanical $Q \sim 10^{13}$)

Thermal noise-limited strain sensitivity on resonance: $h \approx \frac{4}{L}\left[k_B \frac{T}{m(2\pi f_{\mathrm{GW}})^3 Q}\right]^{1/2}$


[5] Arvanitaki, et al. *Physical review letters* 110.7 (2013): 071105
[6] Aggarwal, et al. *Physical review letters* 128.11 (2022): 111101

# Predicted sensitivity & signals

**Goal: similar sensitivity to Levitated Sensor Detector [6]**



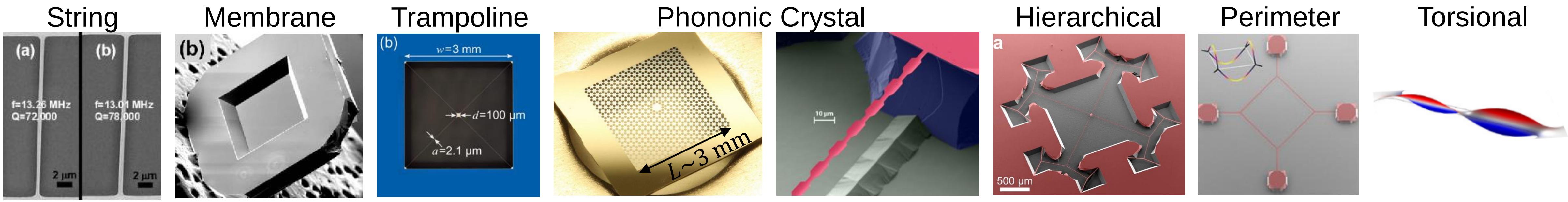

PBH: Primordial Black Hole

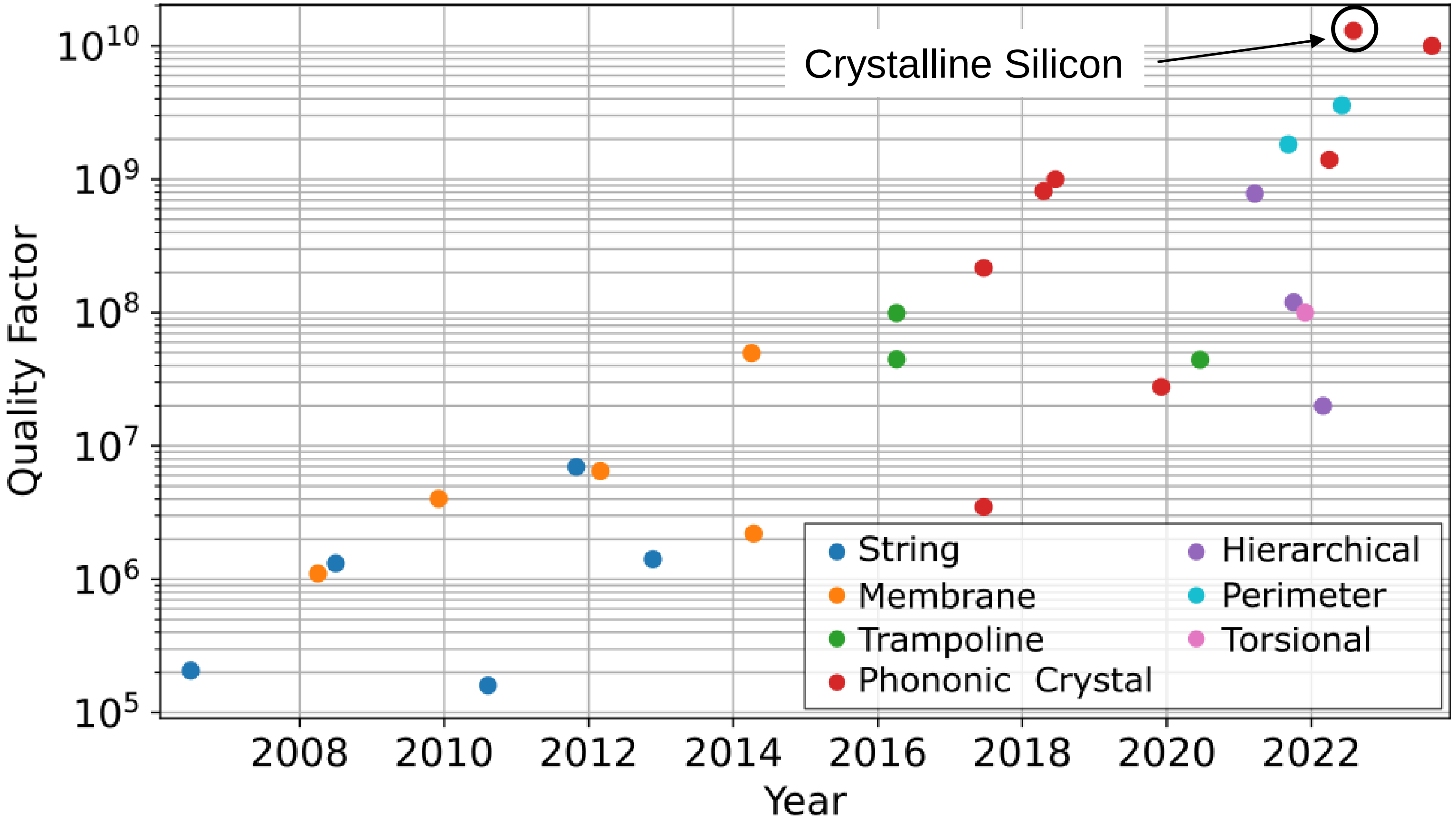
(300 K)

(4 K)

[6] Aggarwal, et al. *Physical review letters* 128.11 (2022): 111101

# Evolution of mechanical thin-film resonators

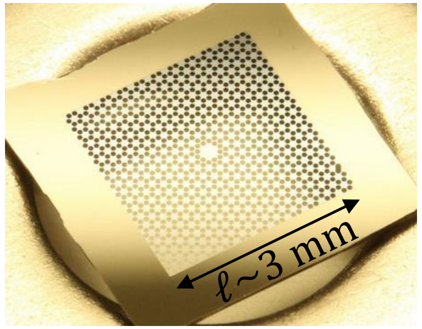


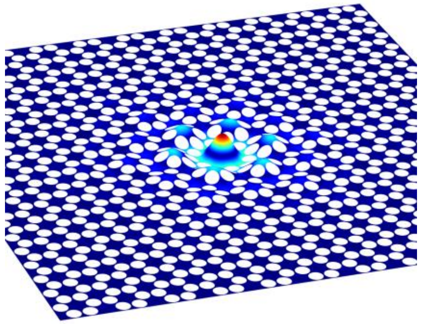




**Images (left to right):**
Verbridge et al., Appl. Phys Lett. (2006)
Thompson et al., Nature (2008)
Reinhardt et al., Phys. Rev. X (2016)
Tsaturyan et al., Nat. Nano (2017)
Ghadimi et al., Science (2018)
Bereyhi et al., Nature Comm. (2022)
Bereyhi et al., Phys. Rev. X (2022)
Pratt et al., Phys. Rev. X (2023)

# Design target: ten times larger membranes & SiN → Si

## Phononic crystal membrane [7,8]



**Demonstrated**

$\ell \sim 3$ mm

$f \sim 10^6$ Hz

$Q \sim 10^9$

**Target**

$\sim 10\,\ell$

$f \sim 10^4 \ldots 10^5$ Hz

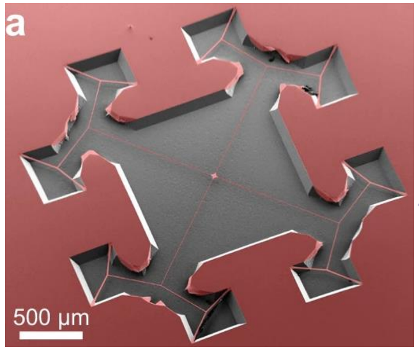
$Q > 10^{12}$

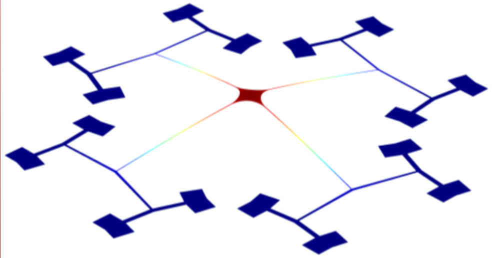
**Scaling**

$f \propto \ell^{-1}$

$Q \propto \ell^2$

## Branched trampoline [9]



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[7] Tsaturyan, Yeghishe, et al. "Ultracoherent nanomechanical resonators via soft clamping and dissipation dilution." *Nature nanotechnology* 12.8 (2017): 776-783
[8] https://nbi.ku.dk/english/research/quantum-optics-and-photonics/quantum-optomechanics/ultracoherent-mechanical-devices/
[9] Bereyhi, Mohammad J., et al. "Hierarchical tensile structures with ultralow mechanical dissipation." *Nature Communications* 13.1 (2022): 3097

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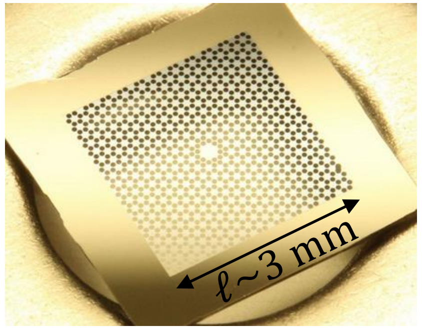


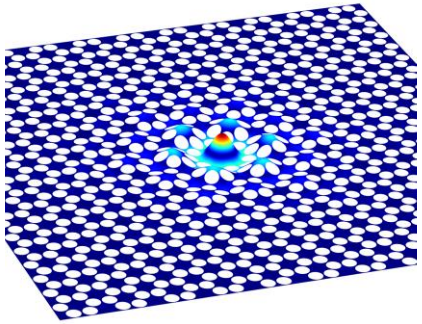

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Superradiance
e.g., Sprague, et al., 2409.03714

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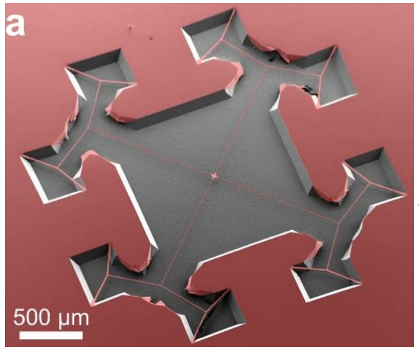


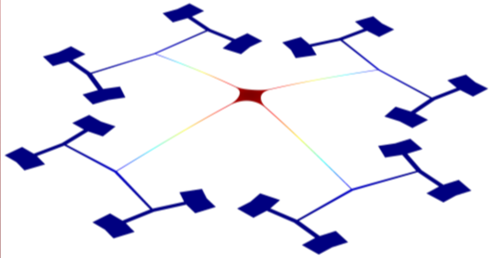

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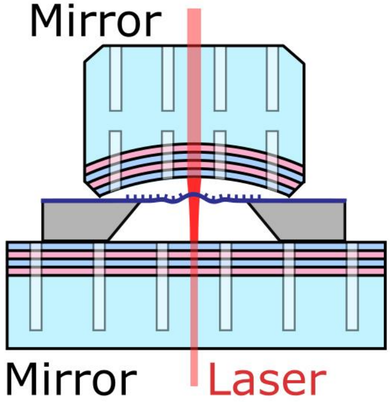
Neutron star mergers
e.g., Ecker, et al., 2403.0324

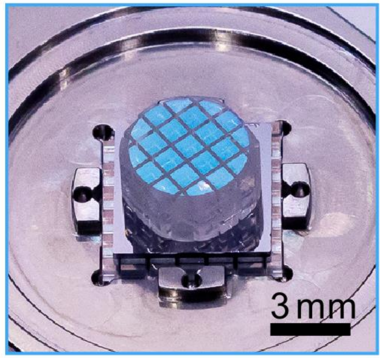

[7] Tsaturyan, Yeghishe, et al. "Ultracoherent nanomechanical resonators via soft clamping and dissipation dilution." *Nature nanotechnology* 12.8 (2017): 776-783
[8] https://nbi.ku.dk/english/research/quantum-optics-and-photonics/quantum-optomechanics/ultracoherent-mechanical-devices/
[9] Bereyhi, Mohammad J., et al. "Hierarchical tensile structures with ultralow mechanical dissipation." *Nature Communications* 13.1 (2022): 3097

# Towards a prototype detector

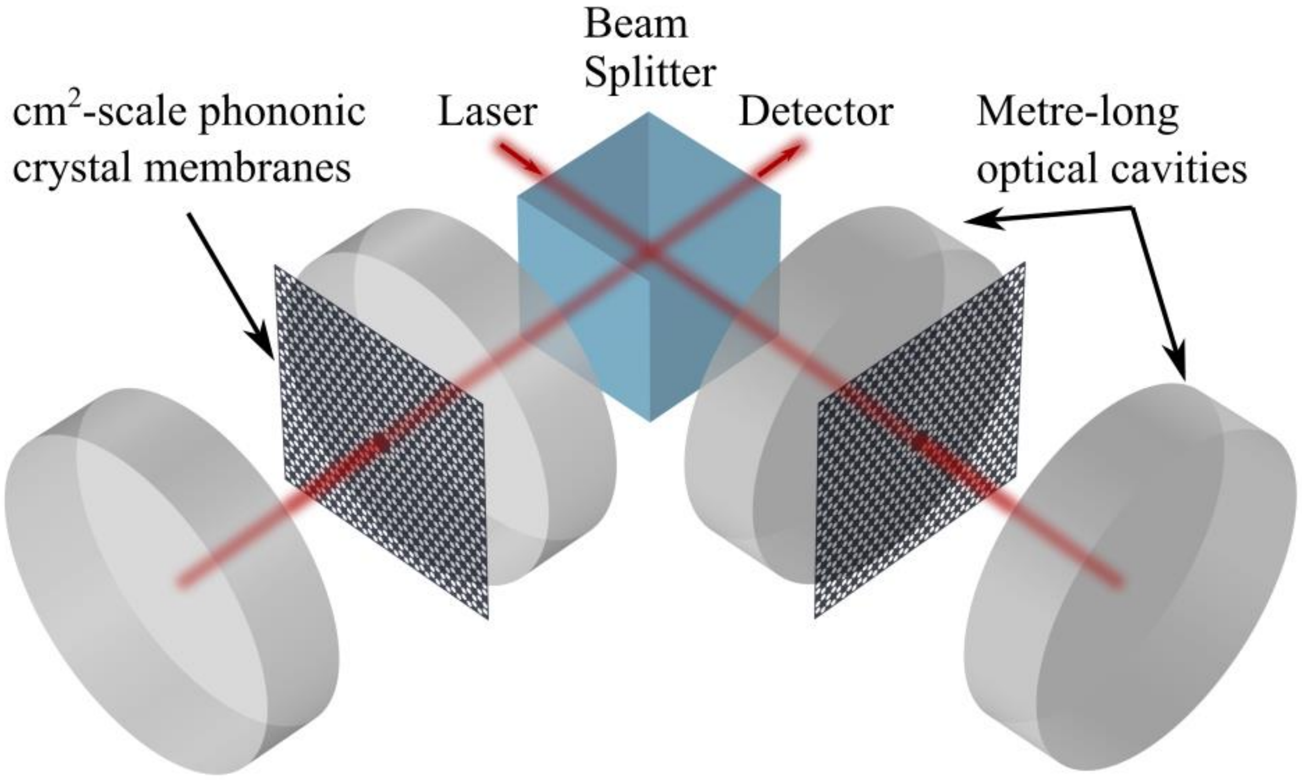
**Goal: table-top prototype**

- Meter-scale optical cavities
- cm$^2$ scale membranes made out of crystalline silicon with $Q > 10^{12}$
- Cryogenically cooled to 10 K




Huang, et al., *Nature* 626, 512–516 (2024)



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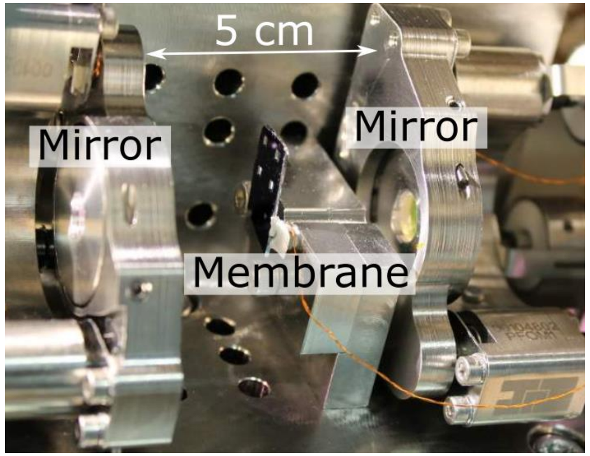
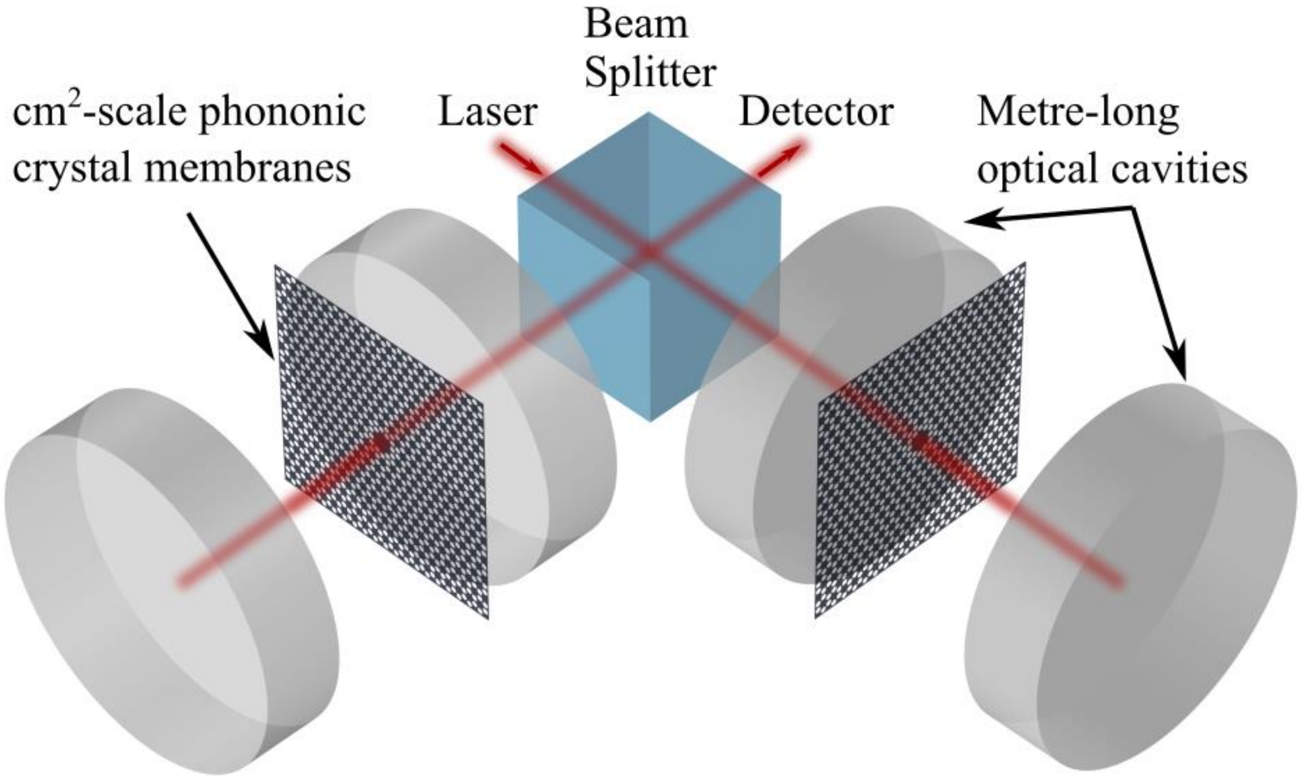
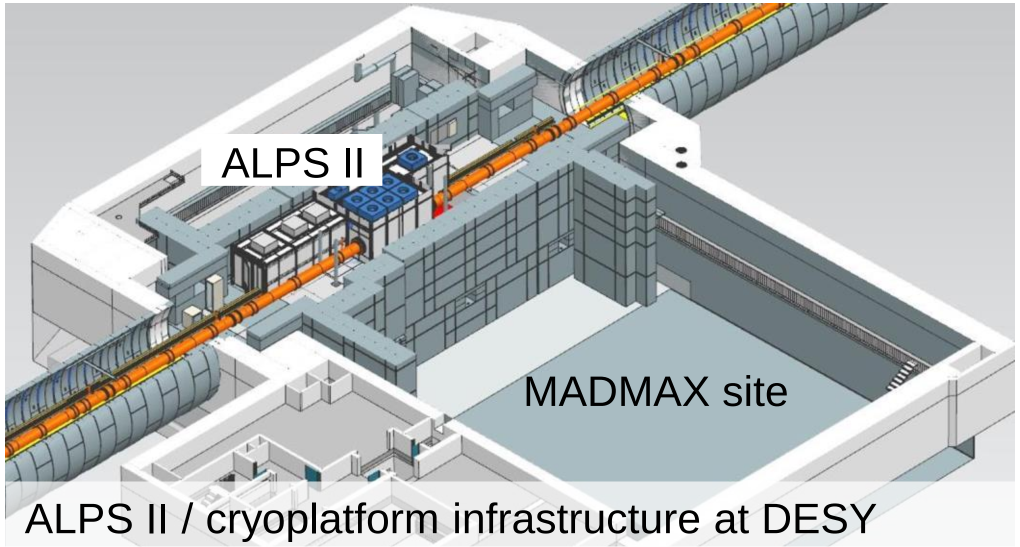



Reinhardt, McGill University (2018)



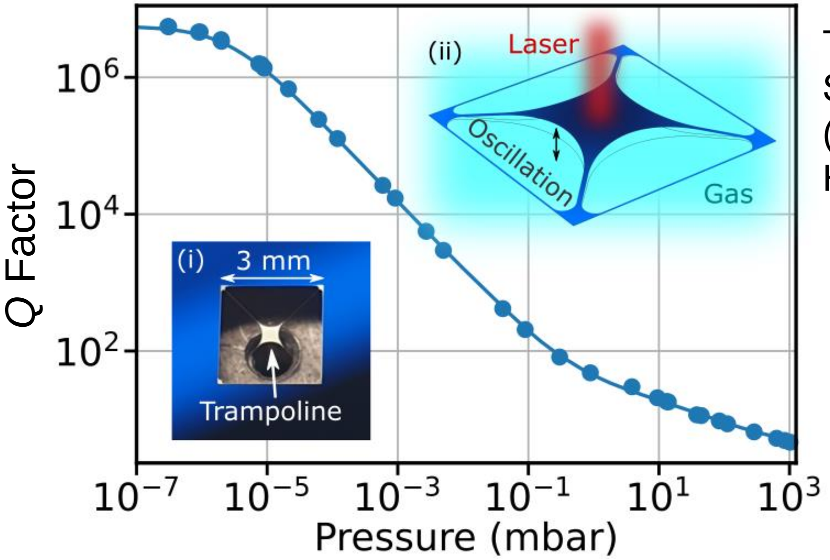
# Closing remarks

Available infrastructure and expertise at DESY could enable a cryogenic 100-m-scale experiment





Synergies: membrane pressure sensor [9] (unprecedented 10 decade measurement range)




Together with Roman Schnabel‘s group (University of Hamburg)

DESY GENERATOR PROGRAM.
DFG "Quantum Universe" - 390833306
PIER
Partnership of Universität Hamburg and DESY
PIF-2021-08

[10] Reinhardt, et al. *ACS Photonics,* 11(4), 1438-1446 (2024)
[11] Reinhardt, et al. EU Patent Application, EP4446714, (2023)

**Thank you**

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