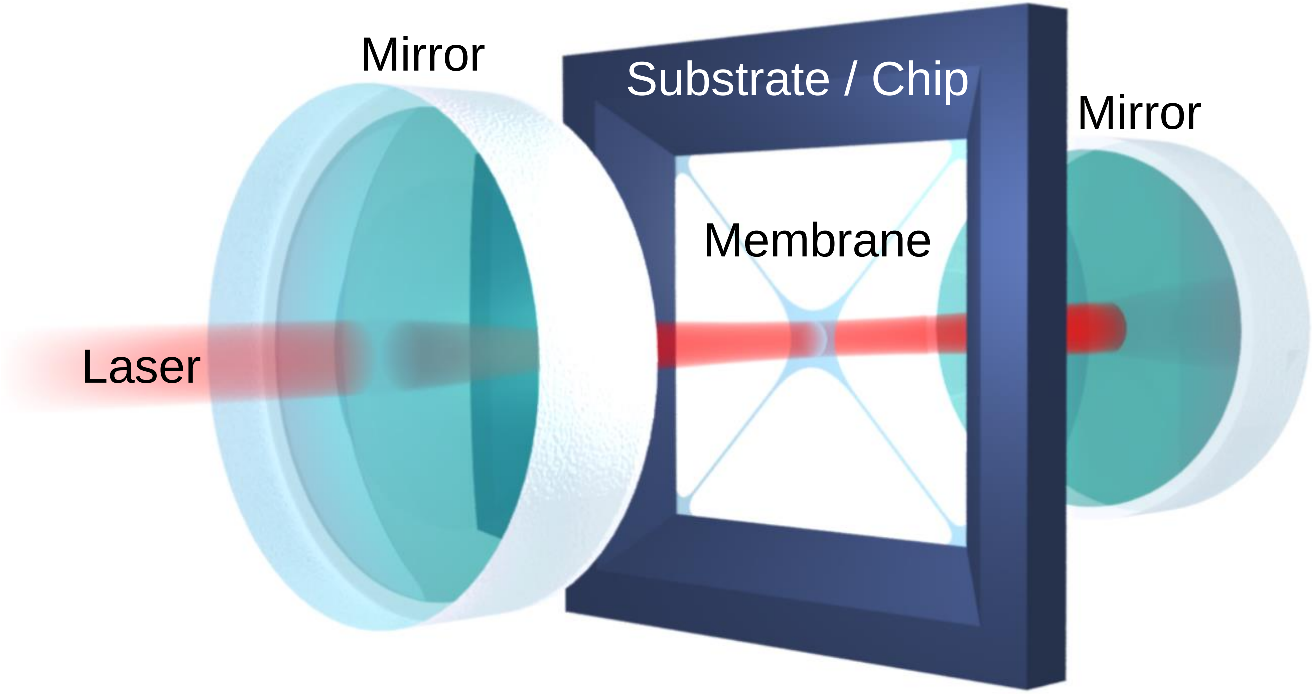
Partially-levitated membranes for high-frequency gravitational wave detection

Ultra-high frequency gravitational wave workshop

CERN, December 5, 2023

Christoph Reinhardt
(DESY, FH-ALPS)

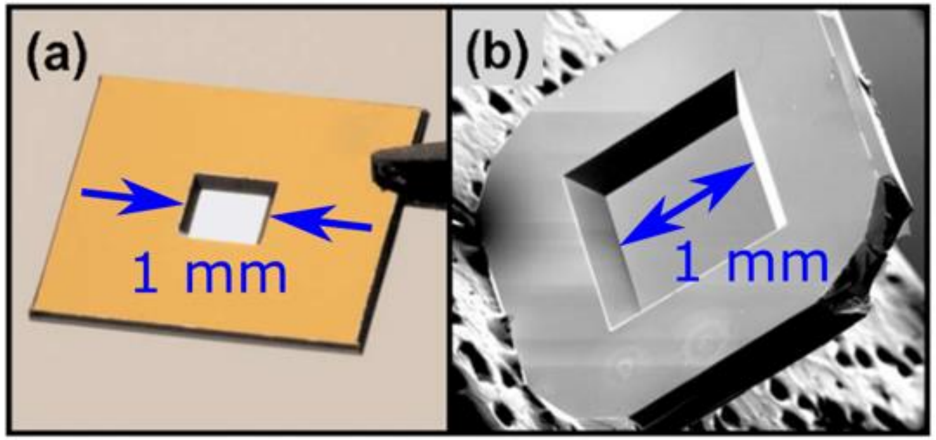


HELMHOLTZ

DESY.

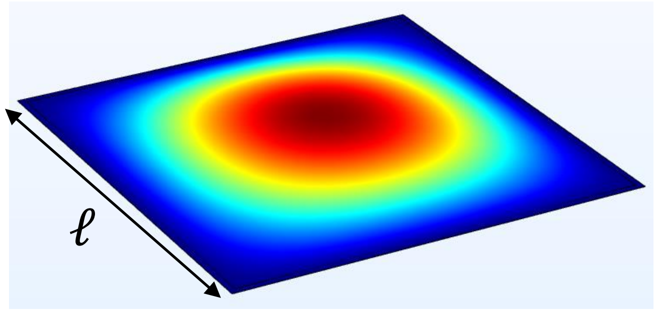
Mechanical membrane oscillators / resonators

Microscope & SEM images

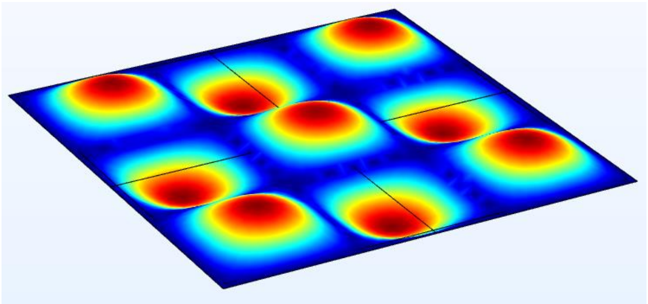


Silicon nitride (SiN) membrane [1]
(typically 10 to 100 nm thick)

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)

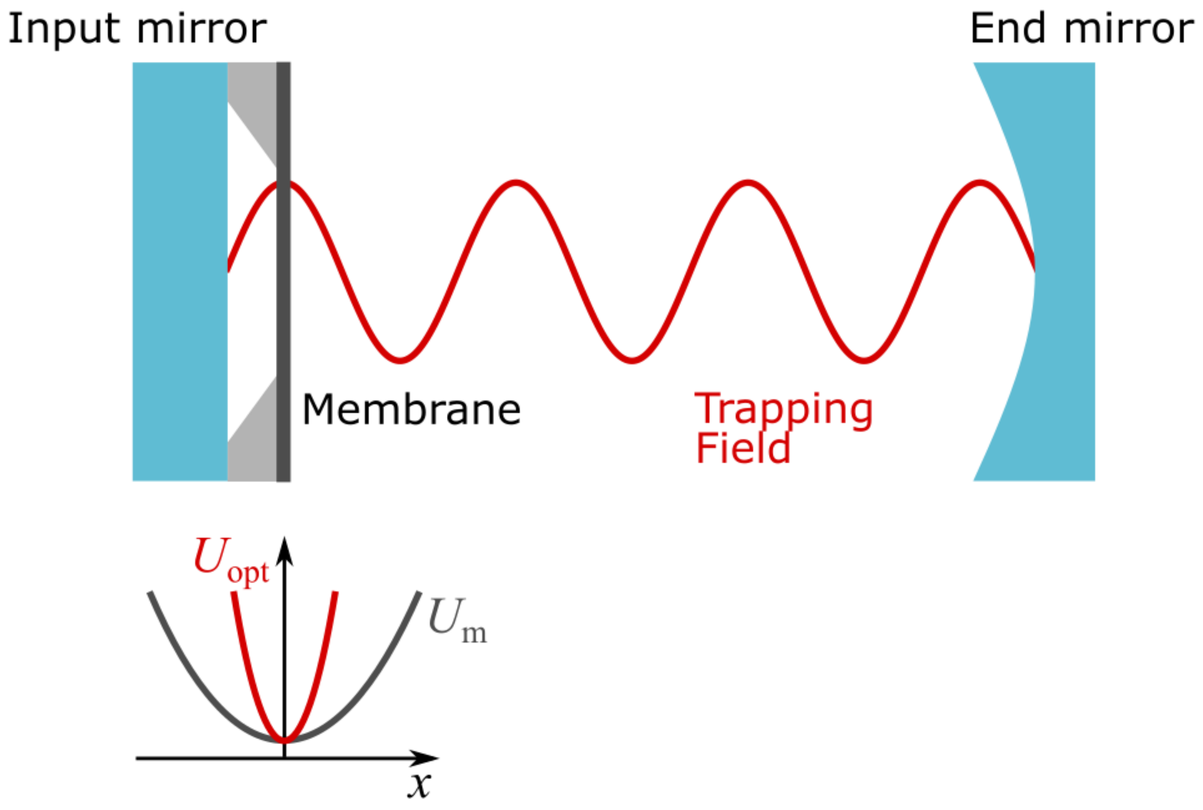
Partial optical leviation

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

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

- 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

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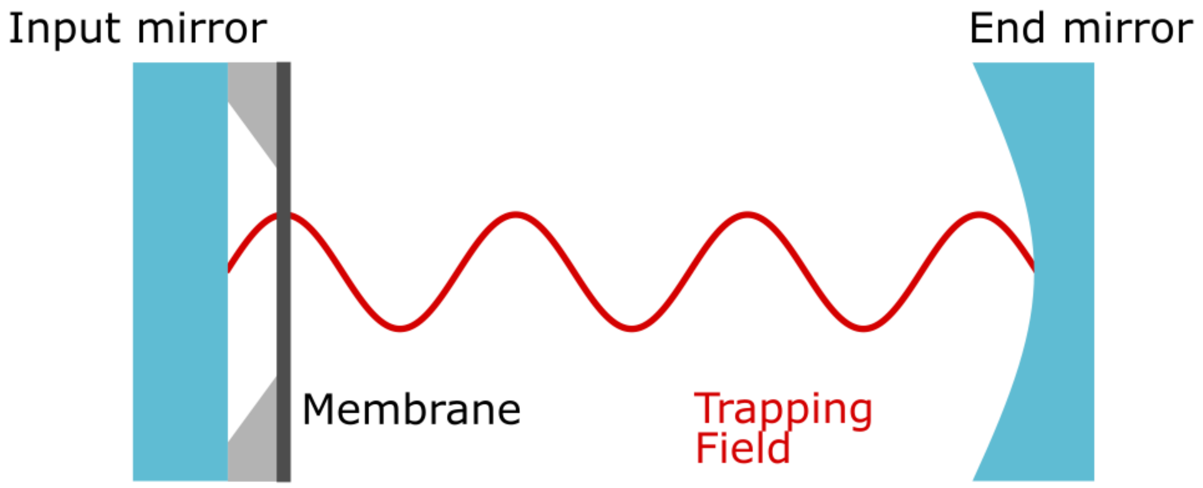

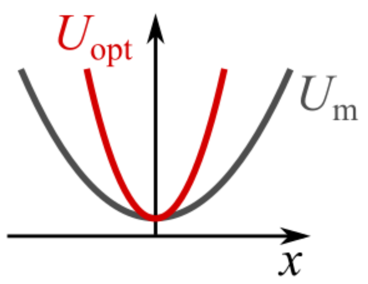

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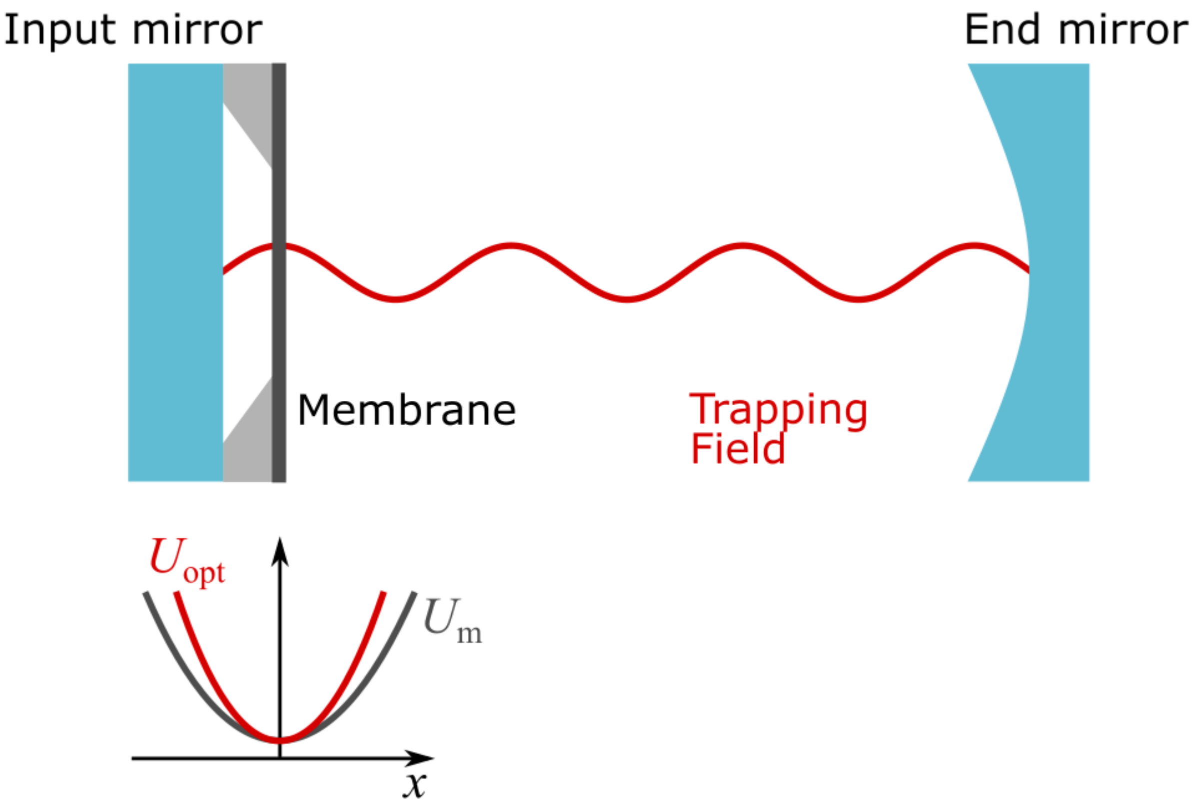
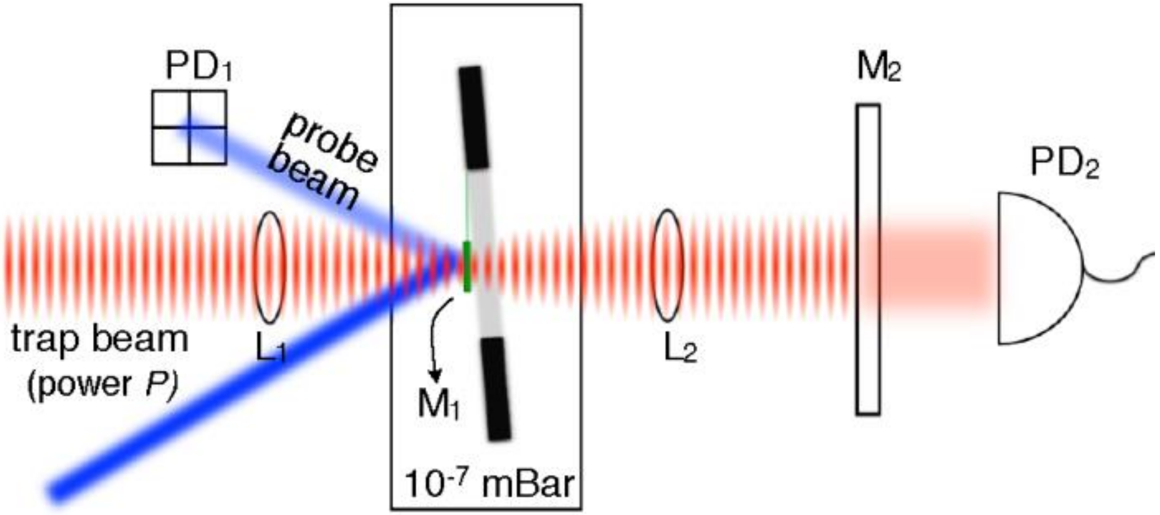
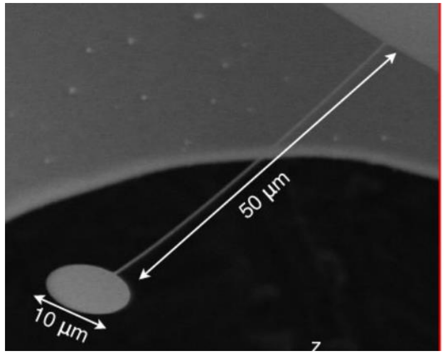


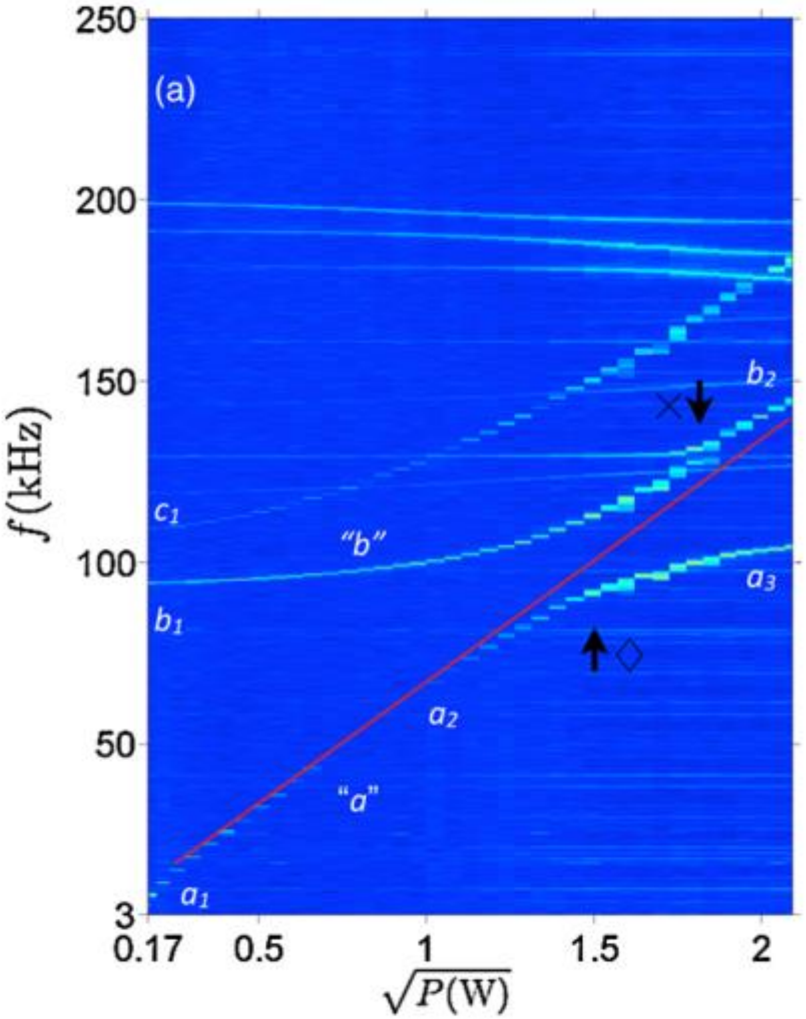
[2] Chang, D. E., Ni, K. K., Painter, O., & Kimble, H. J. (2012). Ultrahigh-Q mechanical oscillators through optical trapping. *New Journal of Physics*, *14*(4), 045002

Optical trapping of mechanical thin-film oscillator

Optical trapping of glas pendulum [3]

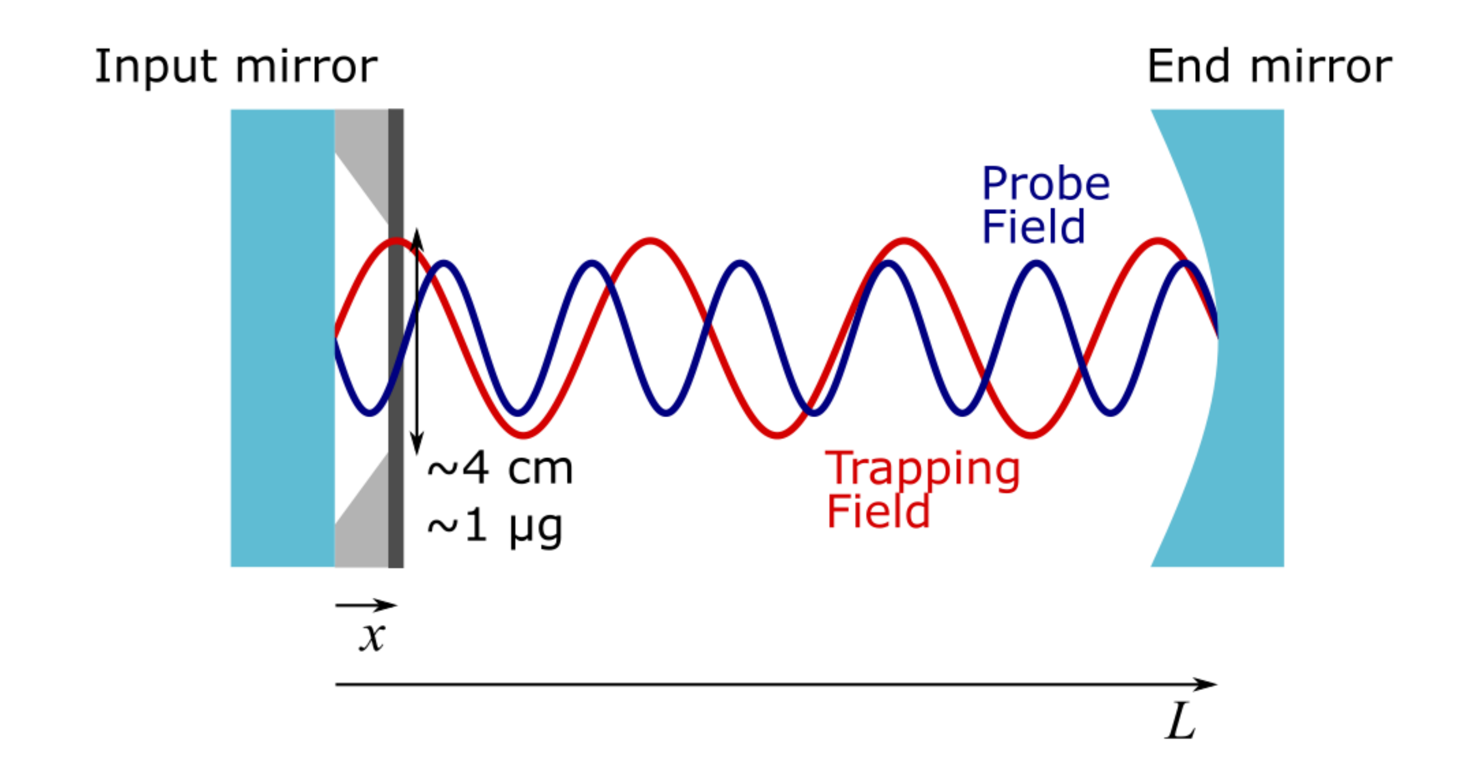






[3] K. K. Ni et al., Phys. Rev. Lett. (2012)

Detector sensitivity



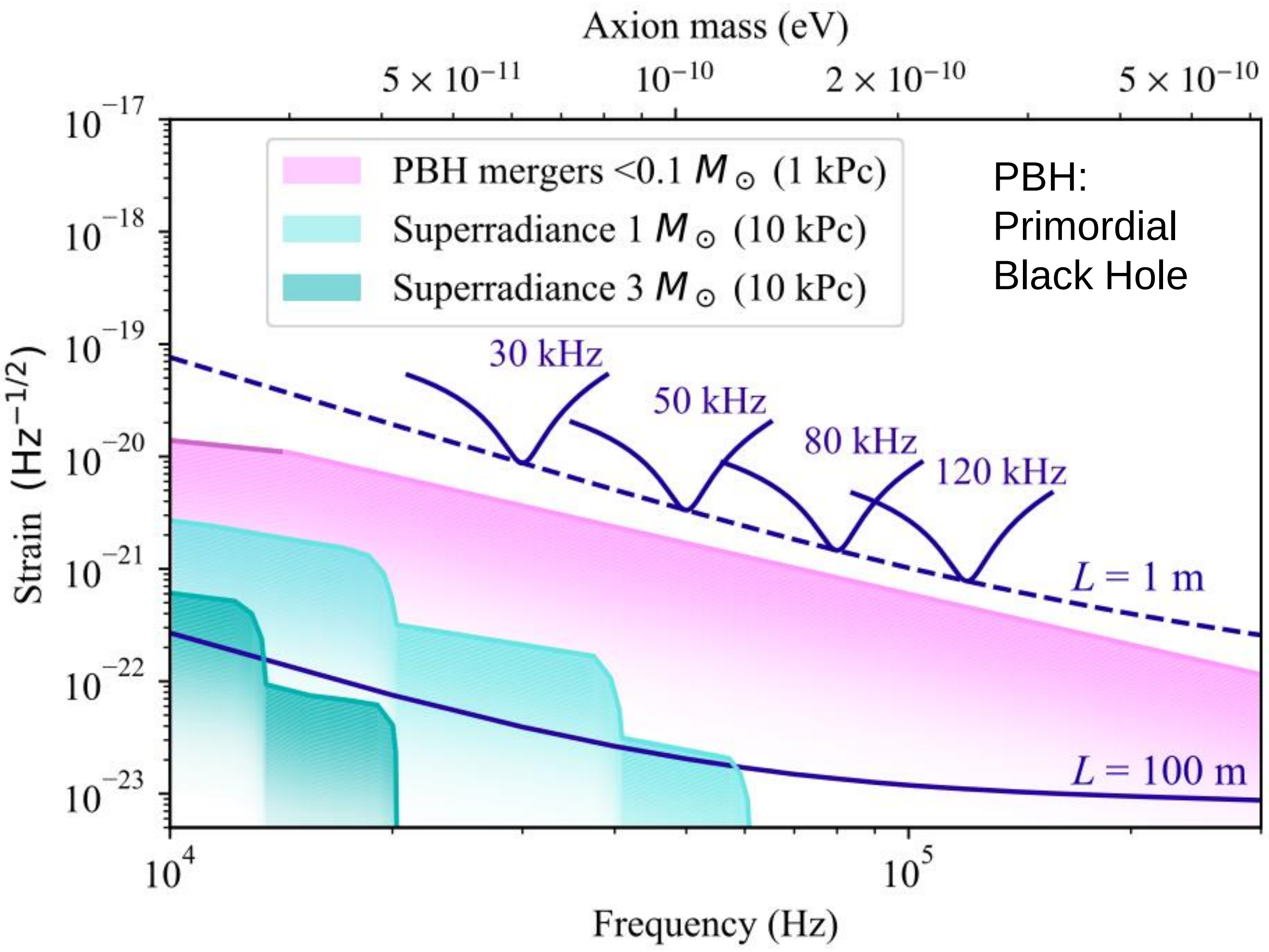
Ultra-high-vacuum: pressure ~ 10^{-11} mbar (mechanical $Q \sim 10^{13}$)

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

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

Predicted sensitivity & signals

Goal: similar sensitivity to Levitated Sensor Detector [5] (Andrew Geraci‘s talk this morning):

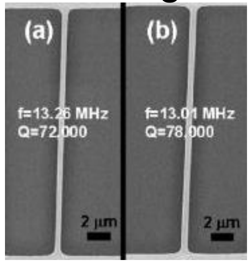


PBH: Primordial Black Hole

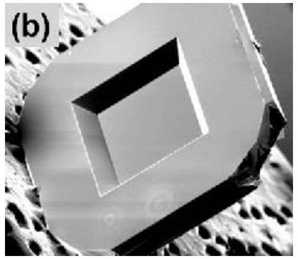
[5] Aggarwal, et al. *Physical review letters* 128.11 (2022): 111101

Evolution of mechanical thin-film oscillators

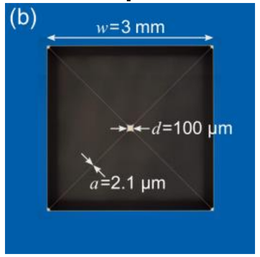
String



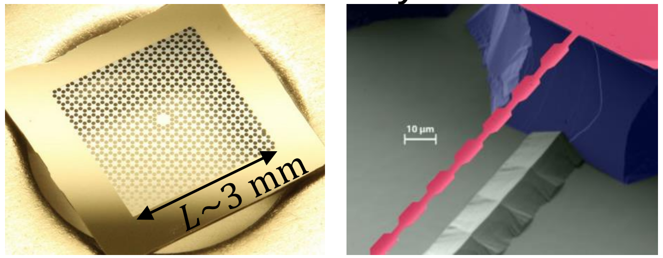
Membrane



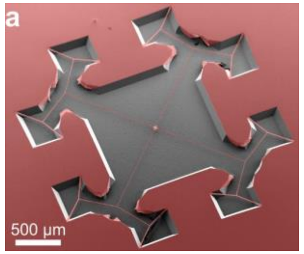
Trampoline



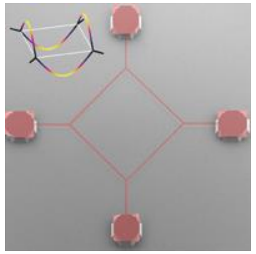
Phononic Crystal



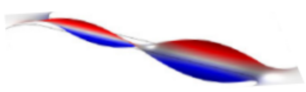
Hierarchical

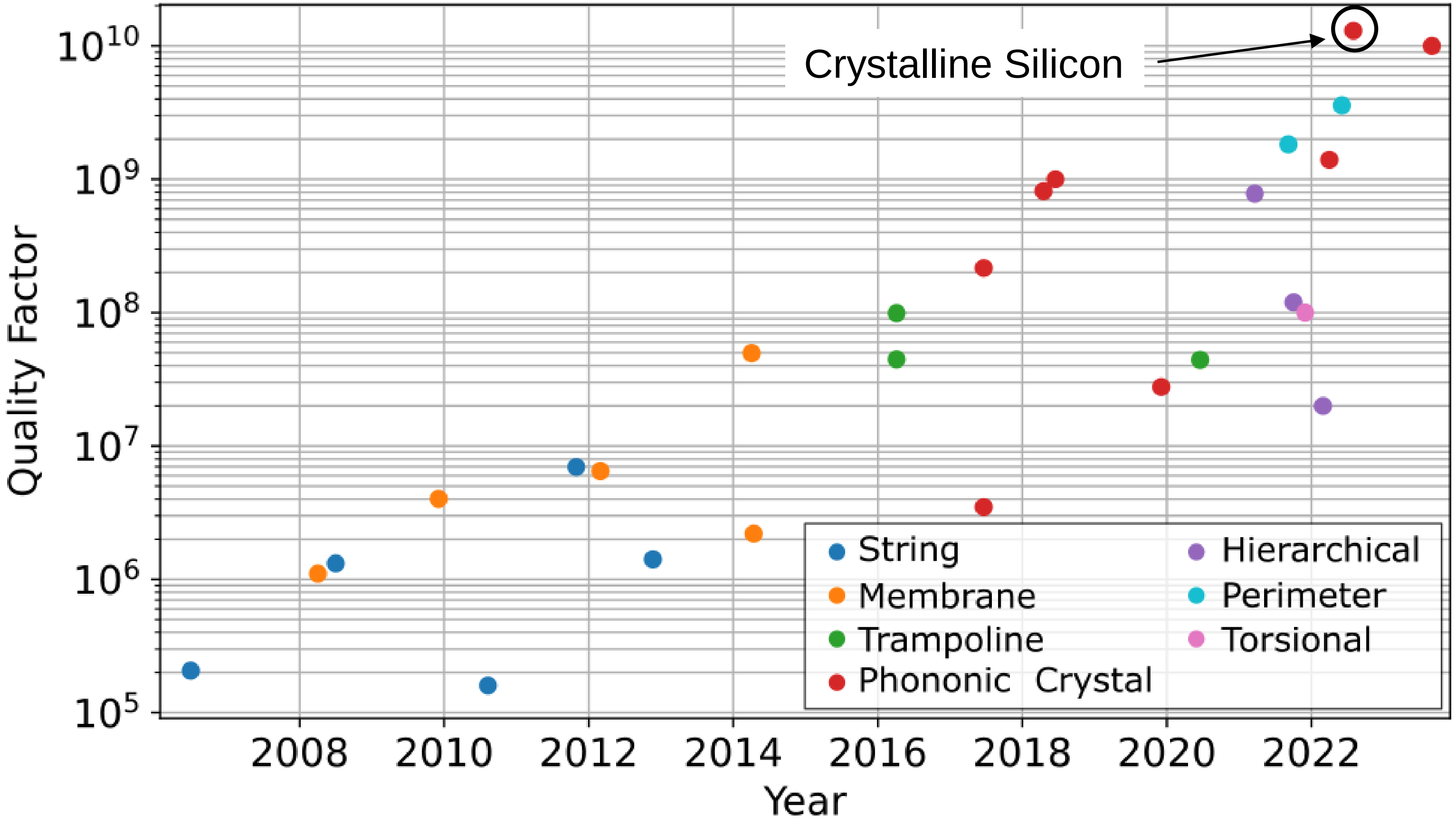


Perimeter



Torsional



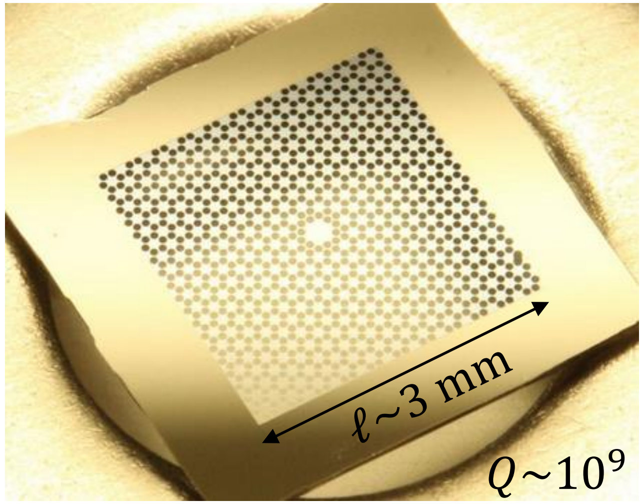


Images (left to right):

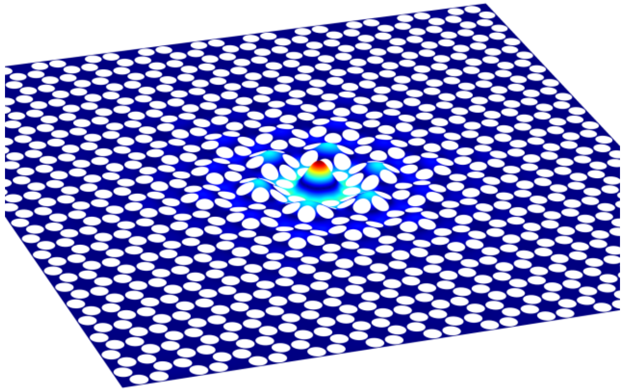
Verbridge et al., Appl. Phys Lett. (2006)
Thompson et al., Nature (2008)
Reinhardt et al., Phys. Rev. X (2016)
Tsaturyan et al., Nat. Nano (2017)
Ghadimi et al., Science (2018)
Bereyhi et al., Nature Comm. (2022)
Bereyhi et al., Phys. Rev. X (2022)
Pratt et al., Phys. Rev. X (2023)

Phononic crystal PnC membrane

Photo of PnC membrane chip [6]



Simulated mode profile of
1st defect mode



Mechanical quality factor scales with ℓ^2:

$$Q = \xi \frac{\ell^2}{d^2} \frac{\sigma}{E_2}$$

Geometry

Material Parameters

$\ell \sim 3$ cm, Si instead of SiN → $Q > 10^{12}$

Tunability of defect mode up to factor 2 [8]:

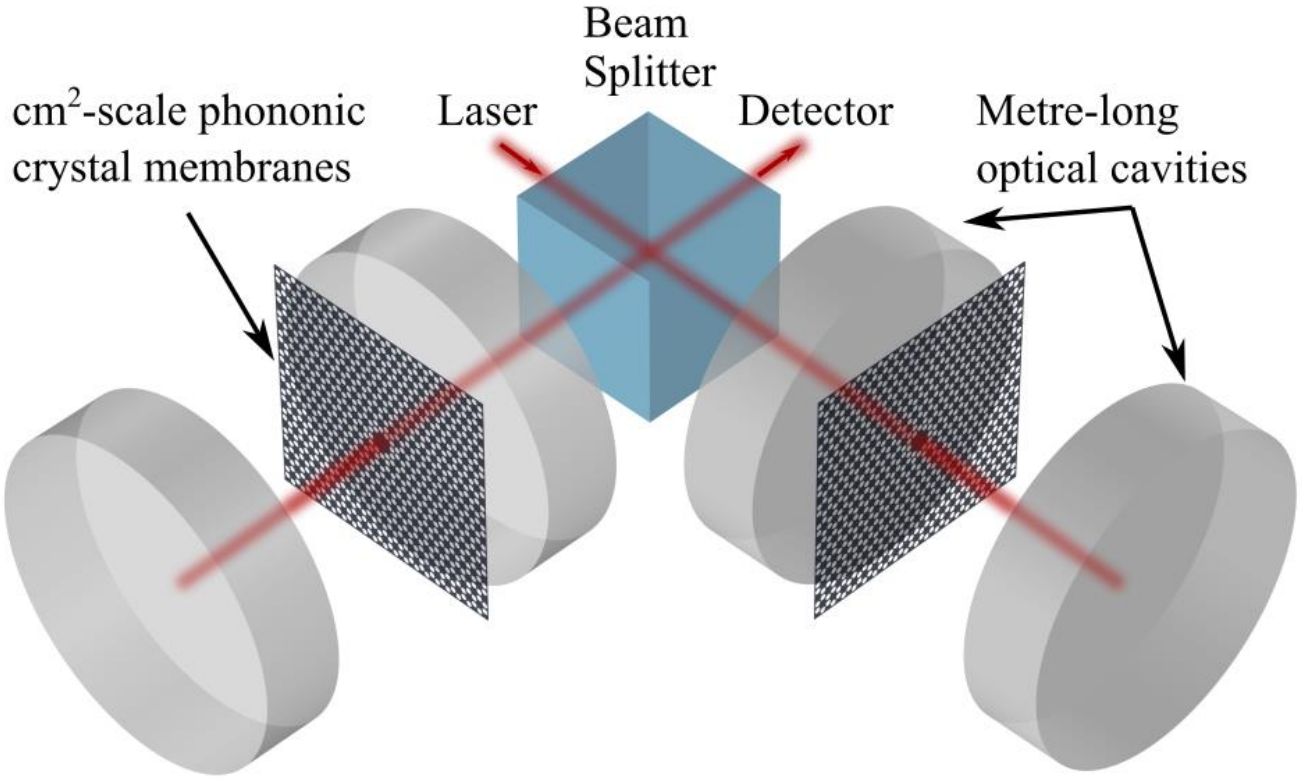
→ cover frequency range from 30 kHz to 300 kHz with 5 PnC membranes

[6] Tsaturyan, Yeghishe, et al. "Ultracoherent nanomechanical resonators via soft clamping and dissipation dilution." *Nature nanotechnology* 12.8 (2017): 776-783
[7] https://nbi.ku.dk/english/research/quantum-optics-and-photonics/quantum-optomechanics/ultracoherent-mechanical-devices/
[8] Barasheed, Abeer Z., Tina Müller, and Jack C. Sankey. "Optically defined mechanical geometry." *Physical Review A* 93.5 (2016): 053811

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



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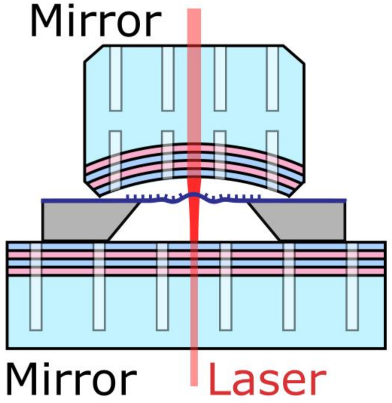
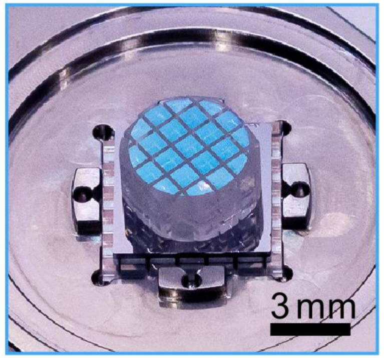
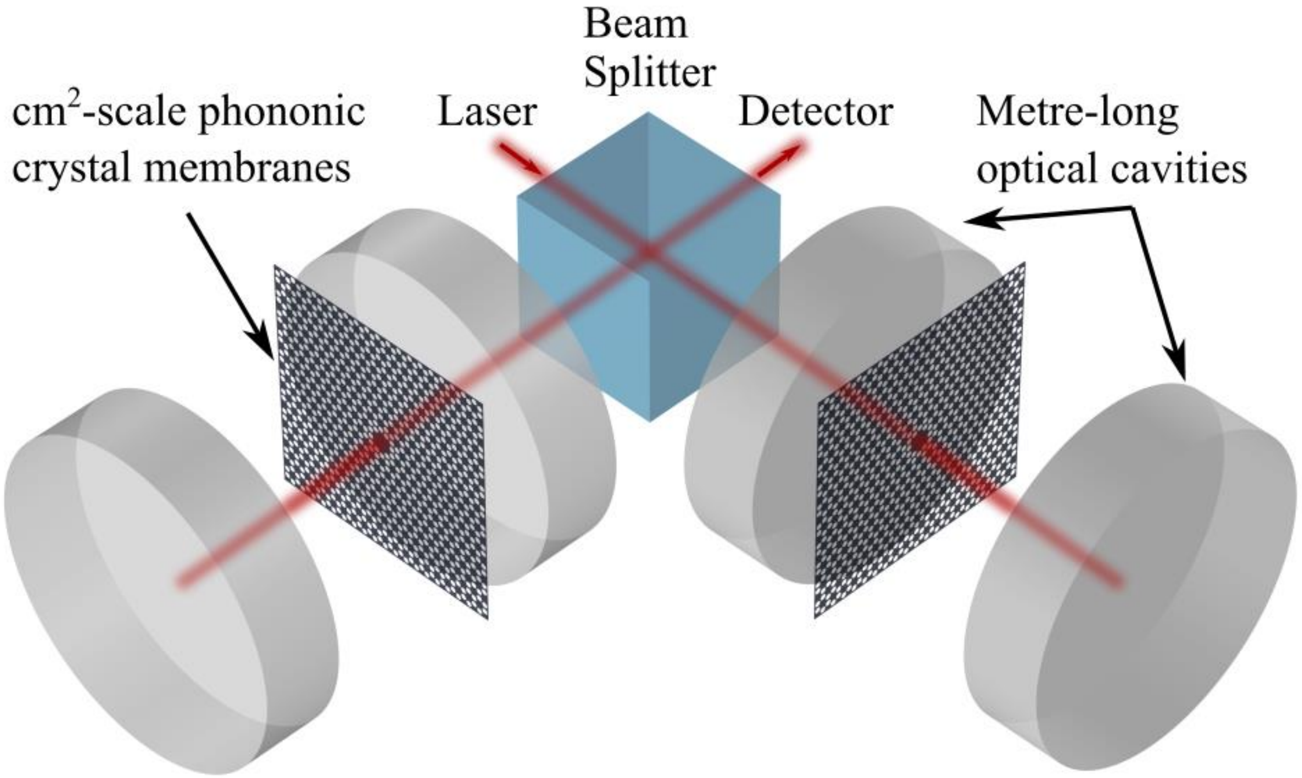




Huang, et al., arXiv:2309.15051 (2023)



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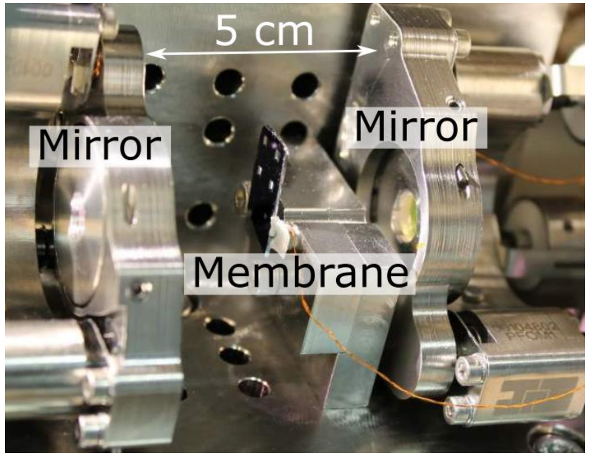
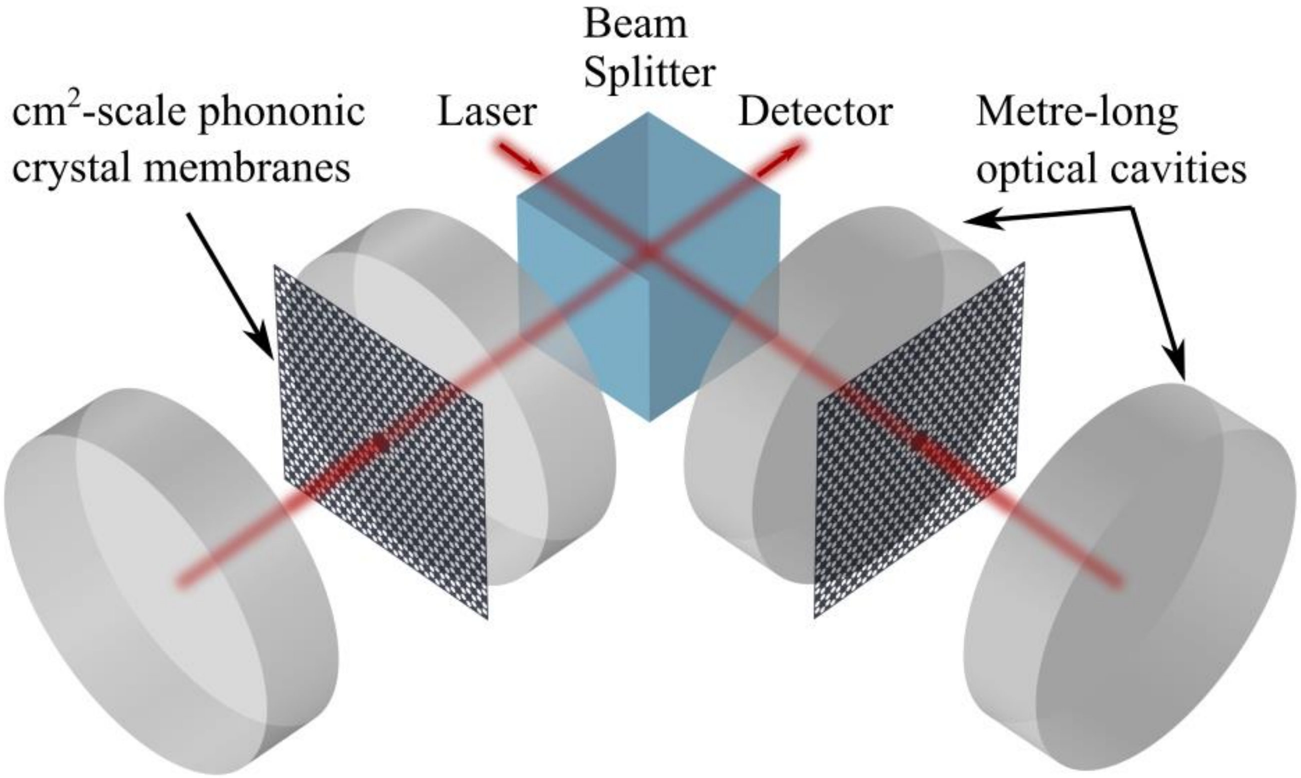


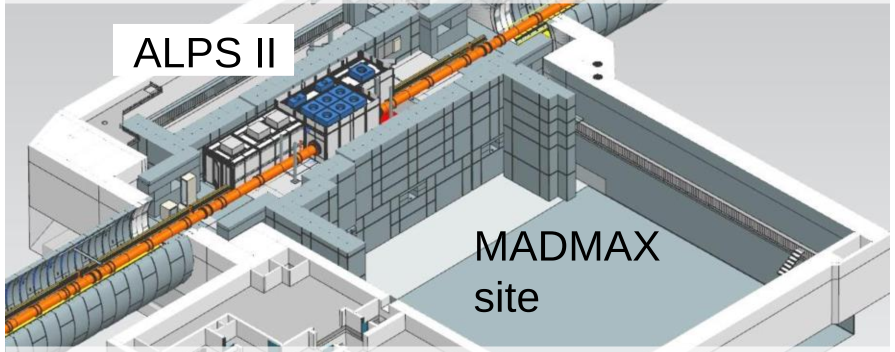
Reinhardt, McGill University (2018)



Current status & possible next steps

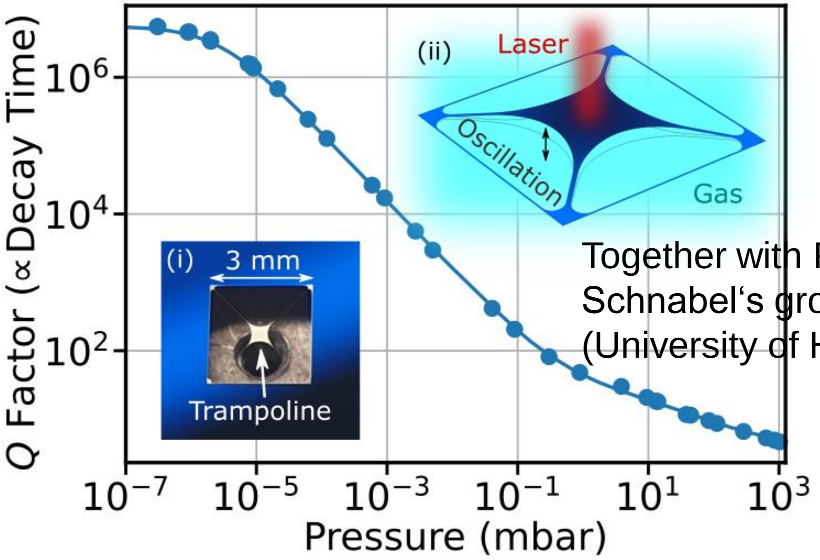
- Submitted grant application to develop membranes for HFGW detection, together with Albert Schliesser‘s group (Niels Bohr Institute) and Benno Willke‘s group (Albert Einstein Institute)
- Working towards grant application for prototype detector
- Current ALPS II / cryoplatform infrastructure could enable a cryogenic 100-m-scale experiment
- Available expertise at DESY: optics, control systems vacuum, cryogenics, nanoparticles / levitated-nanoparticles and on partially-levitated membranes

ALPS II / cryoplatform infrastructure at DESY



See Axel Lindner’s talk tomorrow 15:30

Synergies: membrane pressure sensor [9]



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

[9] Reinhardt, et al. *arXiv:2309.12044* (2023)

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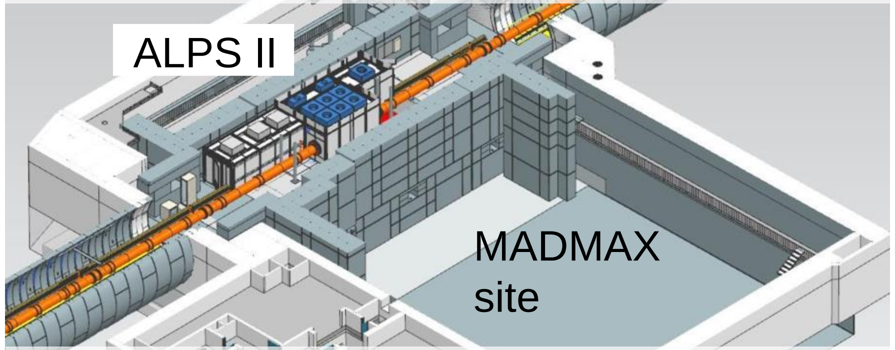

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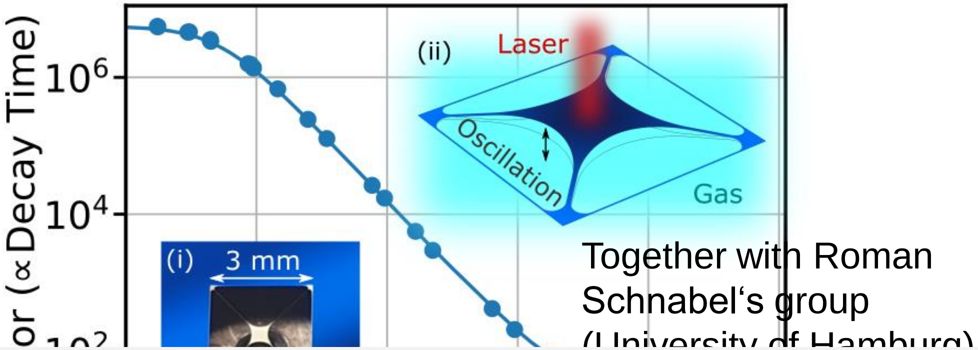

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Thank you

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[9] Reinhardt, et al. *arXiv:2309.12044* (2023)