Advances in Optomechanics

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11/09/2025

Croatian Science Foundation

Hybrid Optomechanical Technologies

OMT
OPTOMECHANICAL TECHNOLOGIES

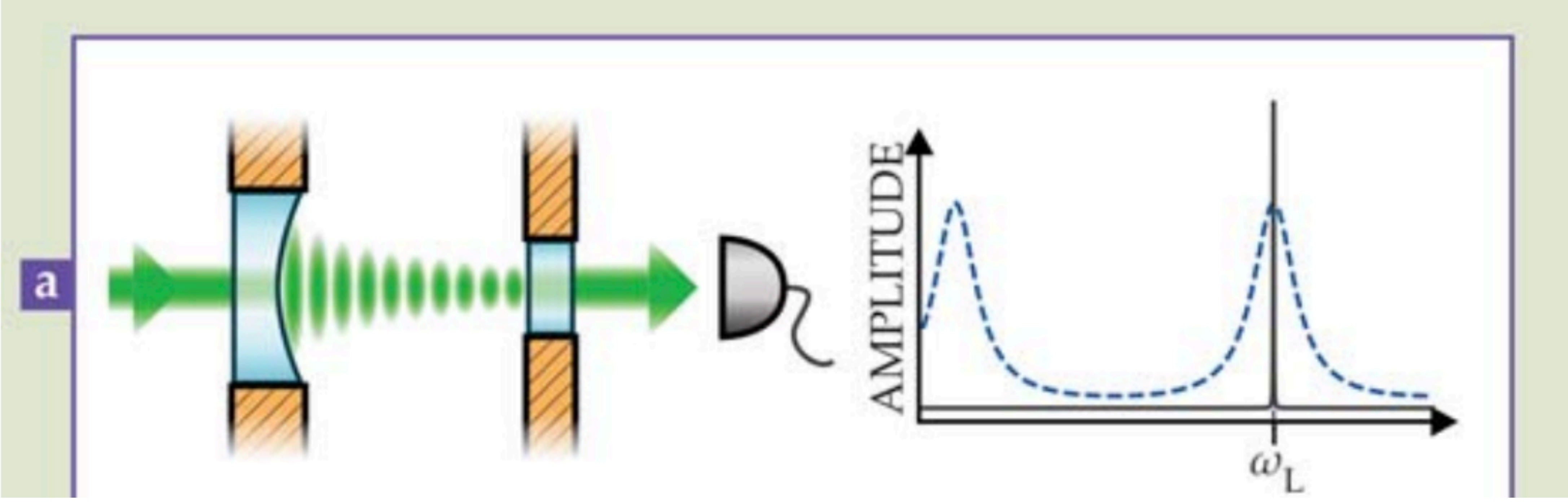
erc

FNSNF

Danmarks Grundforskningsfond
Danish National Research Foundation

European Commission

Optomechanics: introduction



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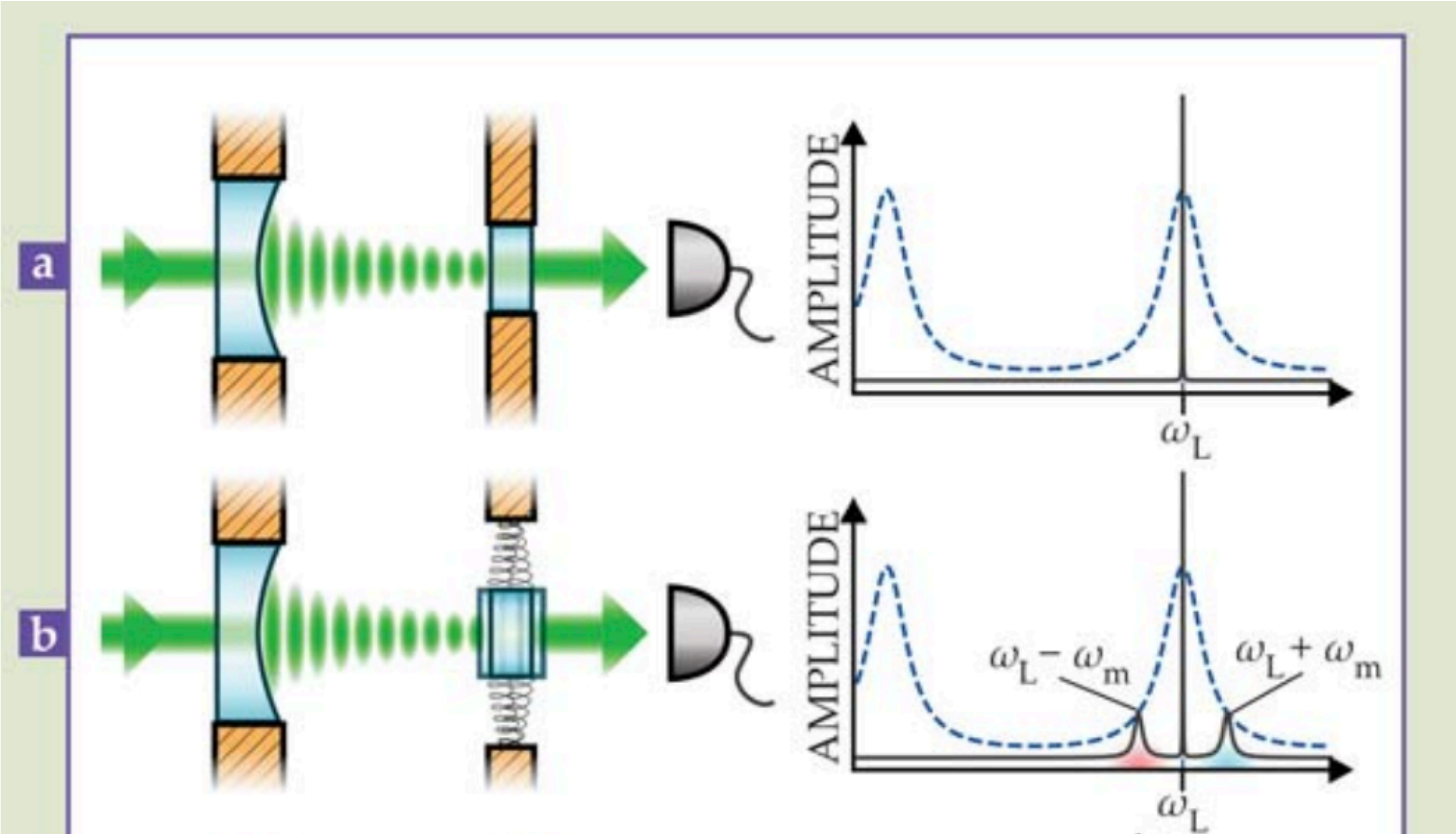

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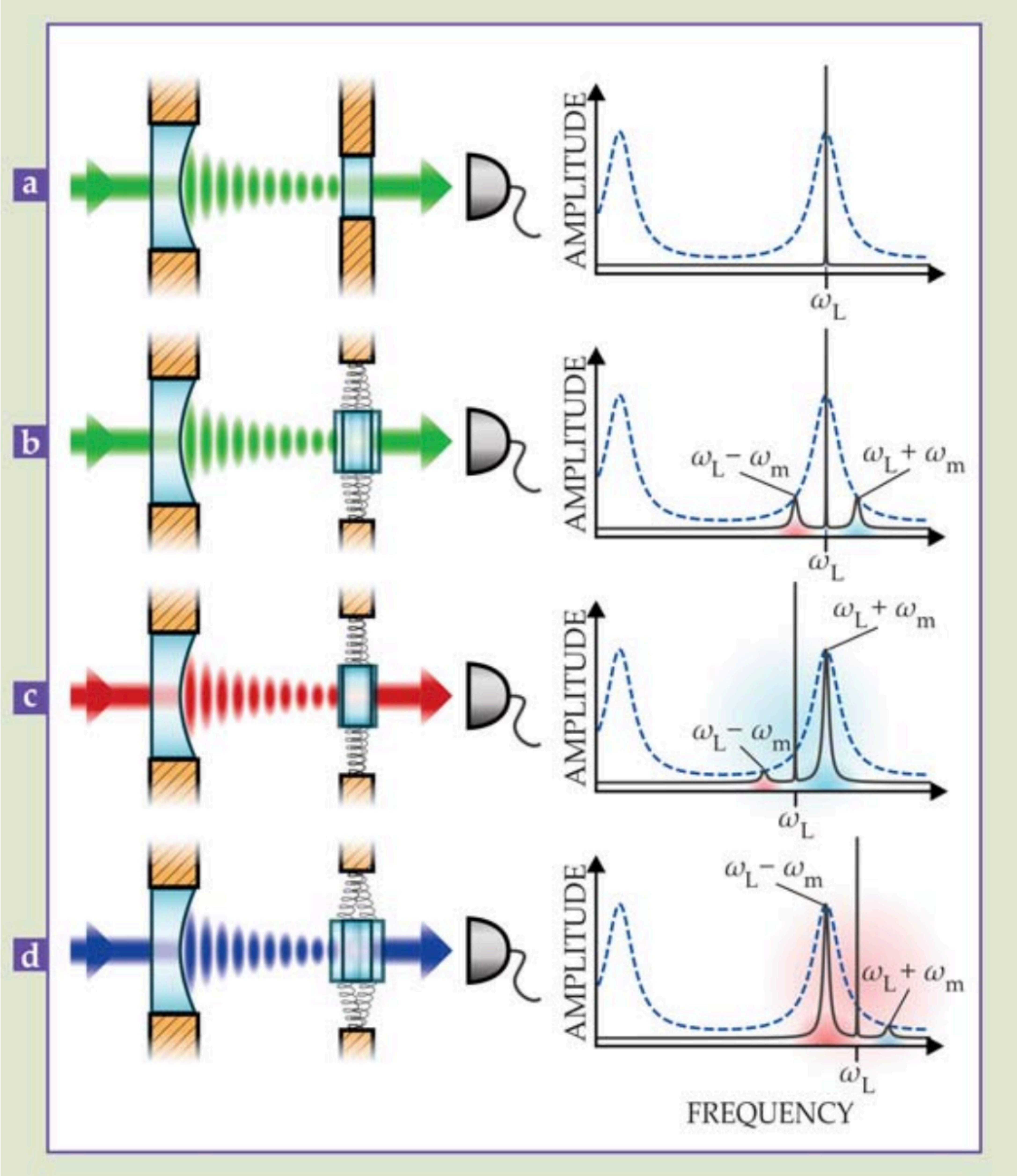
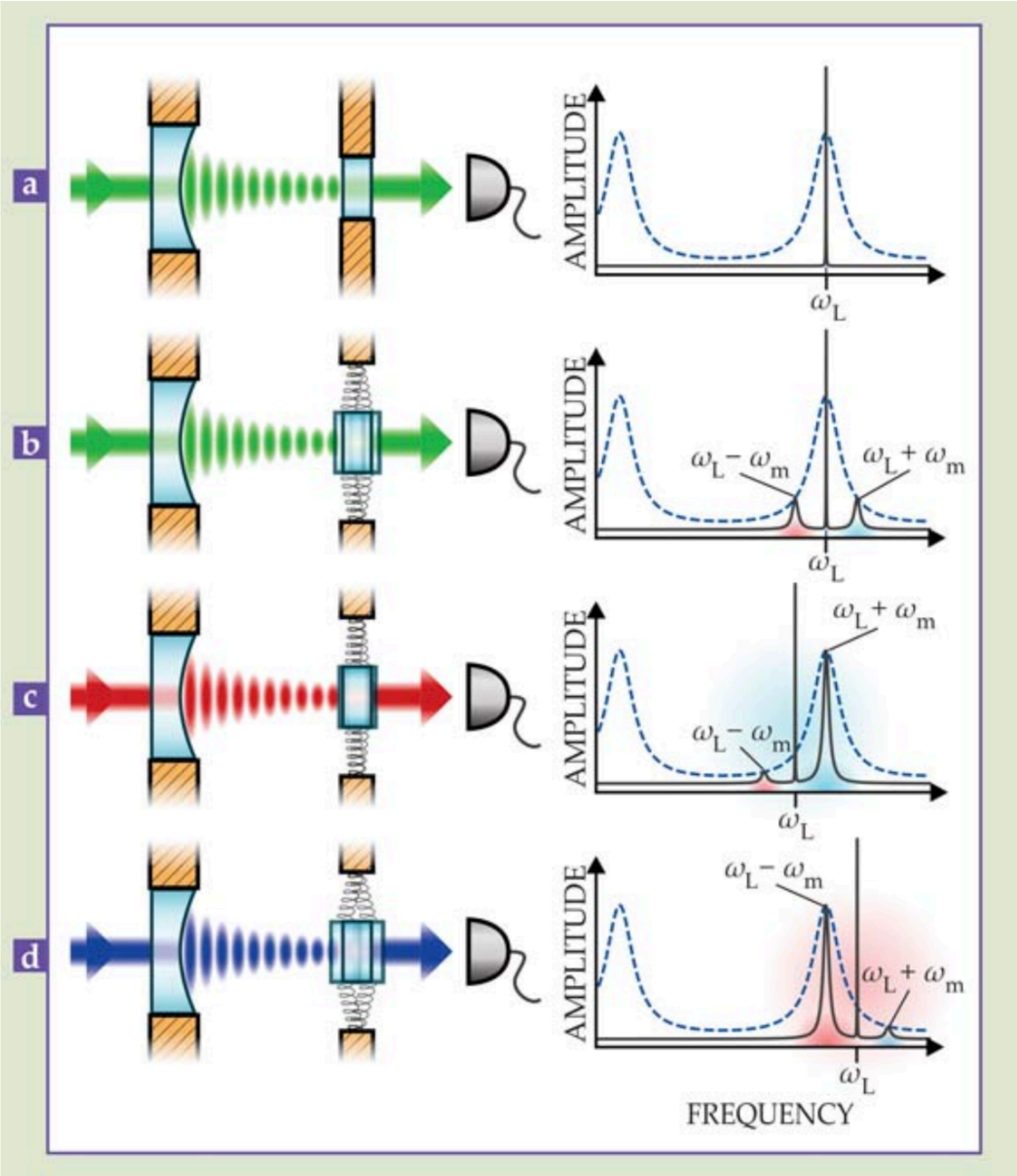
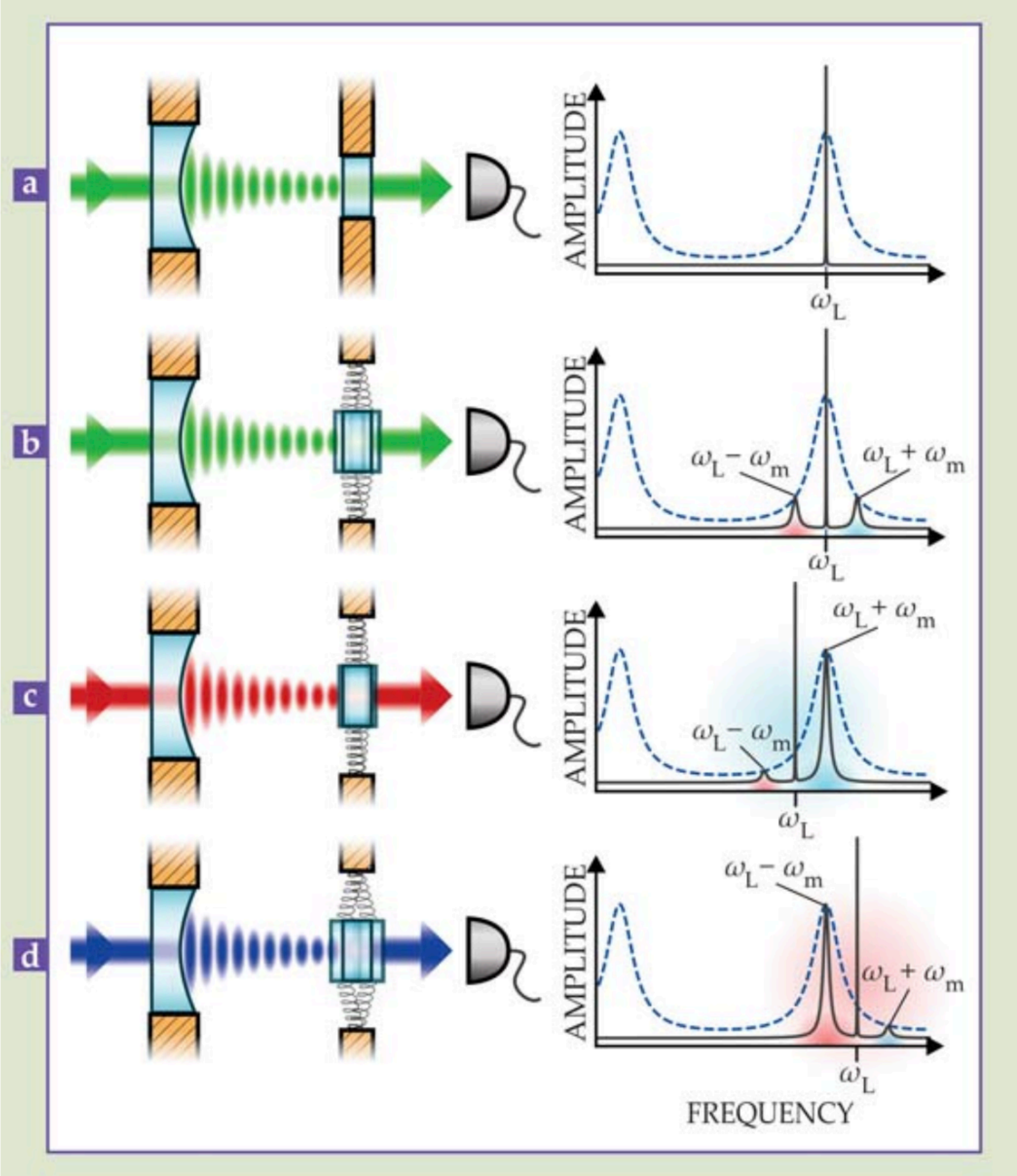




$$H_I = \hbar g_0 \sqrt{\bar{n}_{\mathrm{cav}}}(a + a^\dagger)(b + b^\dagger)$$

$$H_I \propto a^\dagger b + a^\dagger b^\dagger + \mathrm{c.c.}$$



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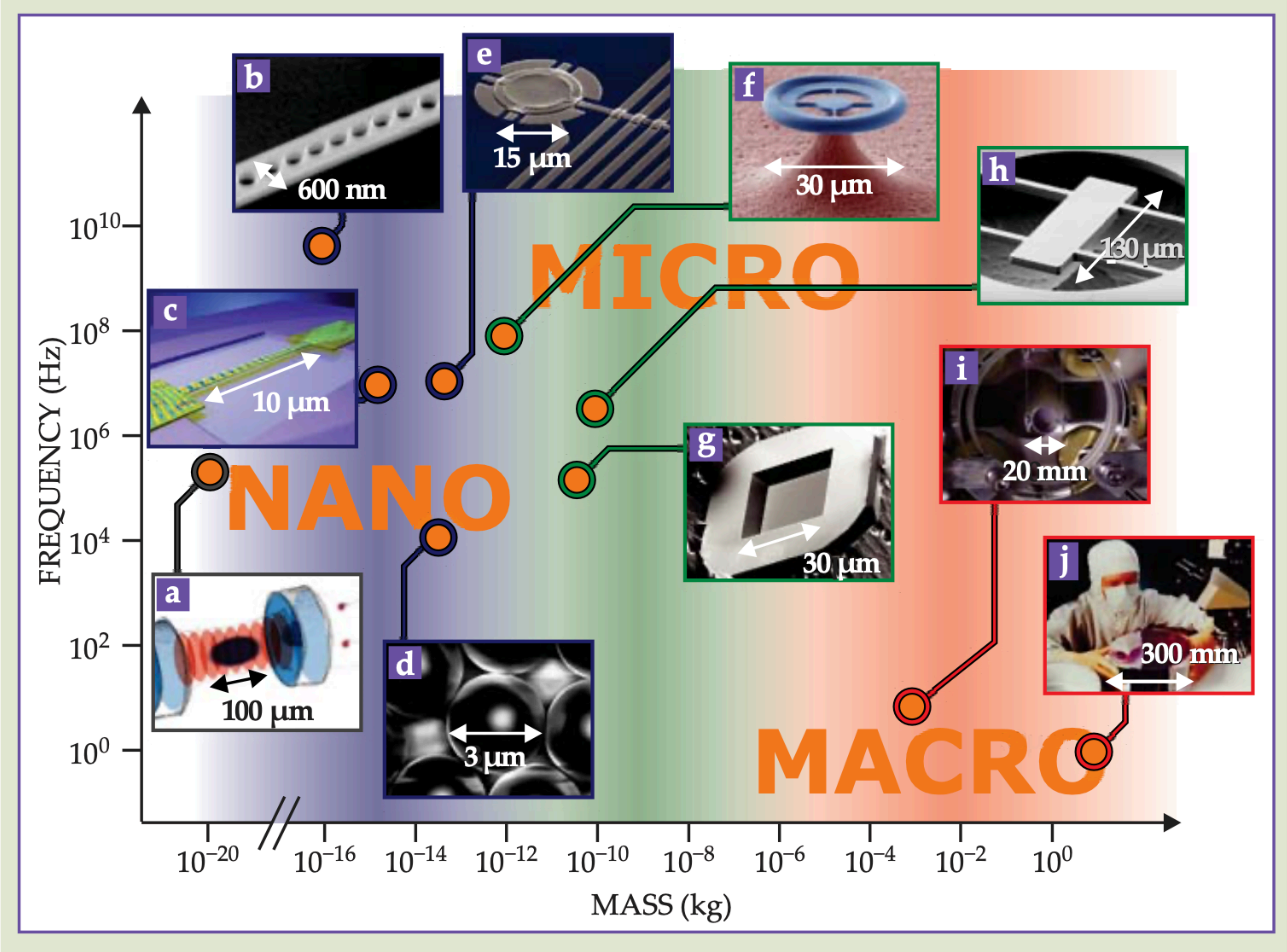
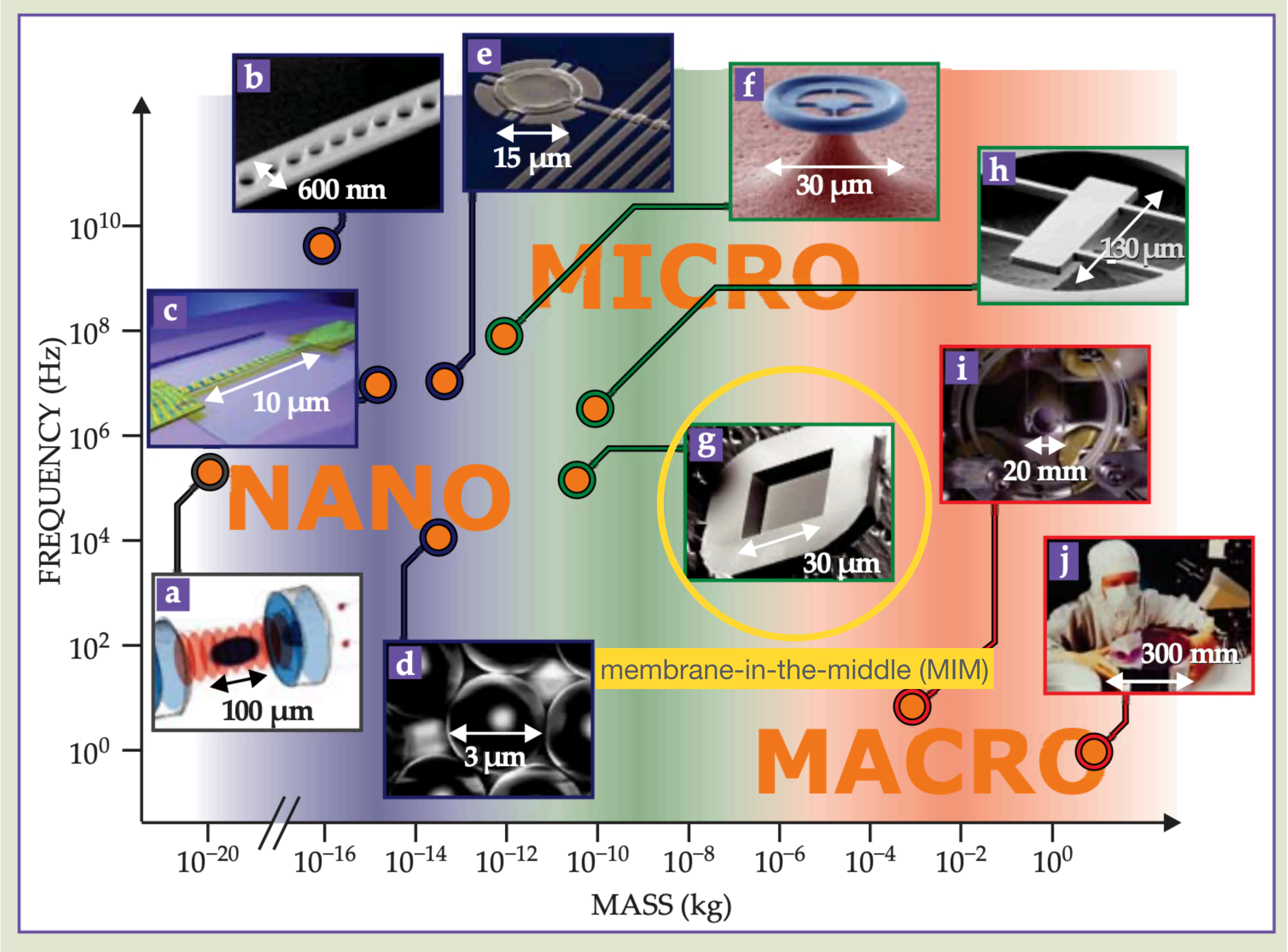
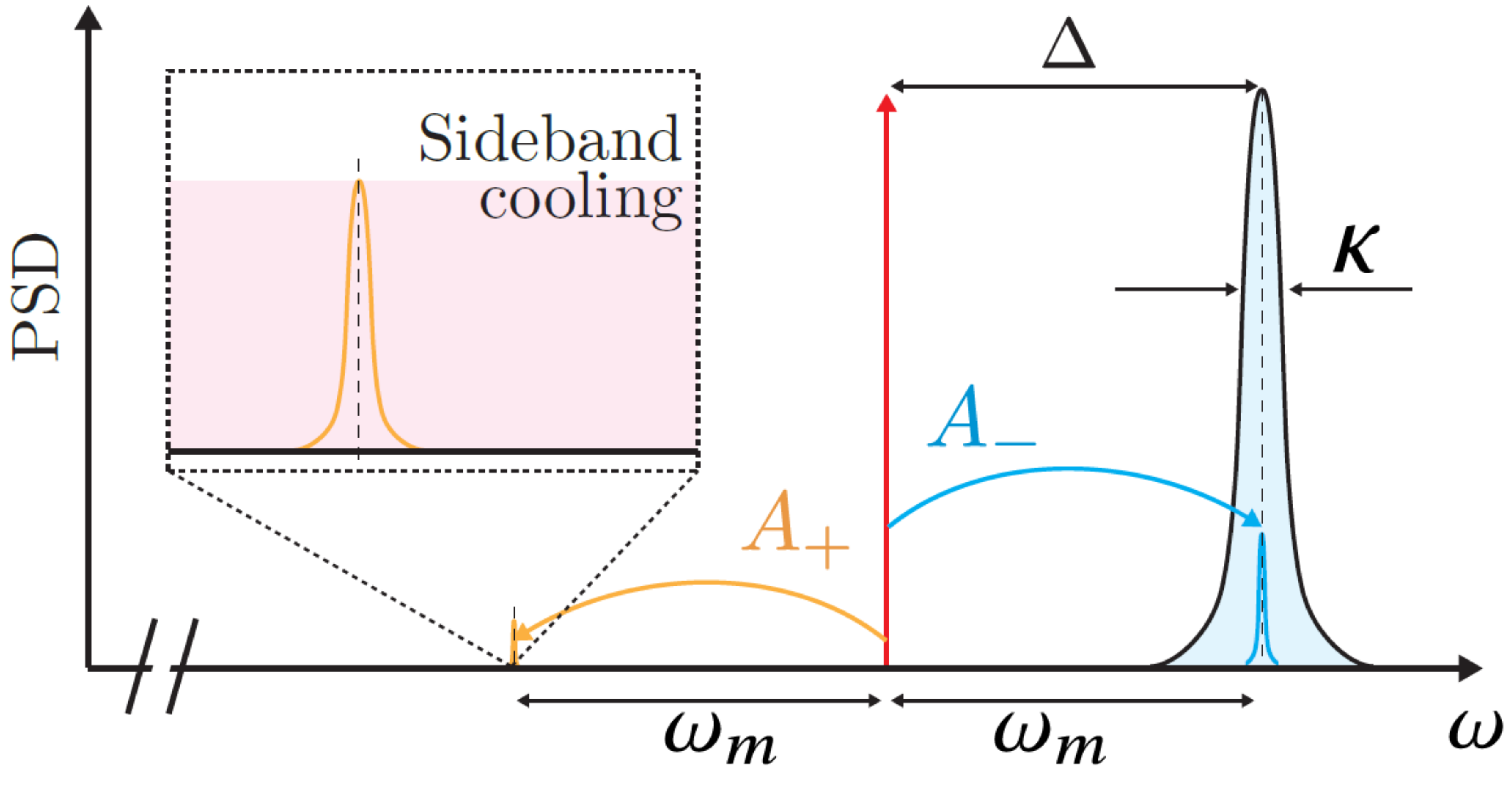
Braginsky first interested in instabilities (blue-detuned regime)!

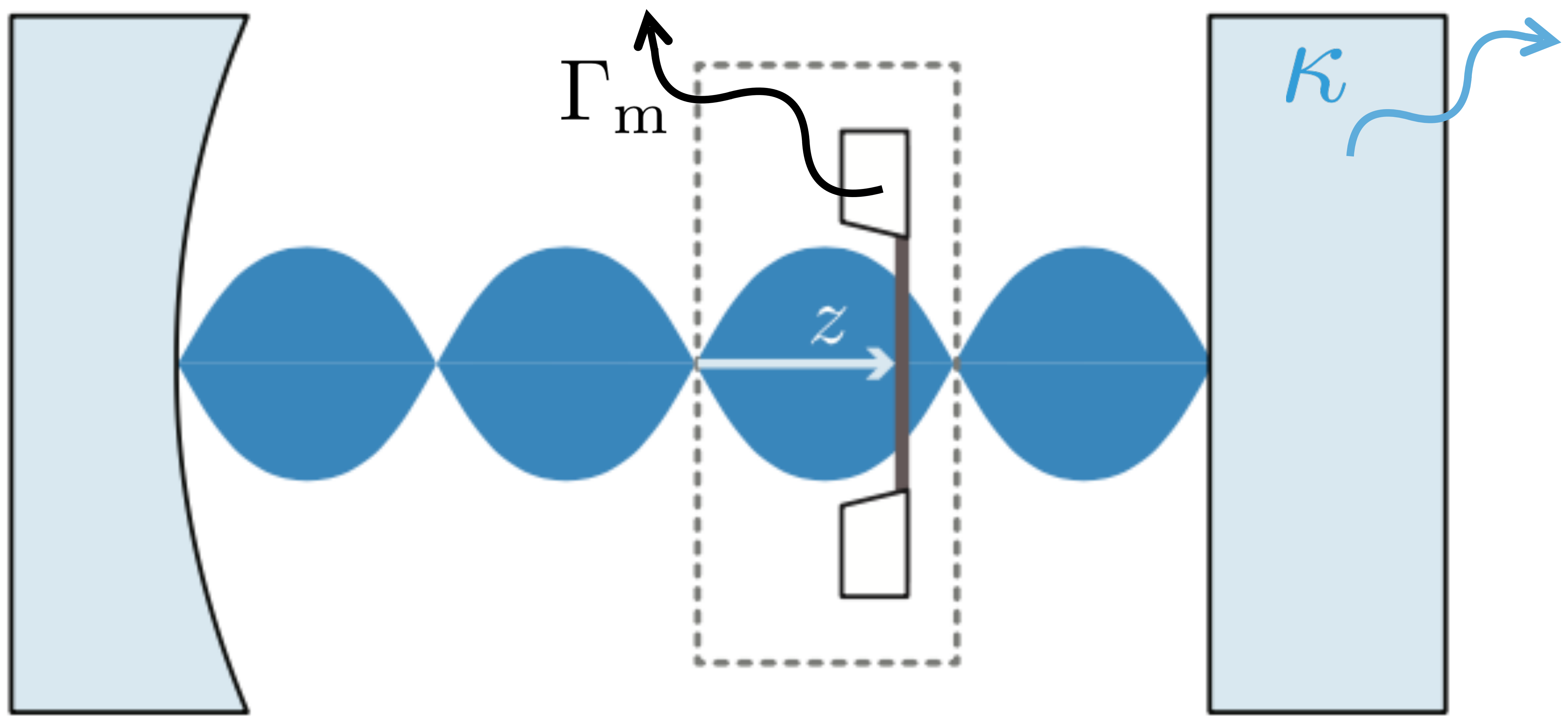

b
600 nm
e
15 μm
f
30 μm
h
130 μm
c
10 μm
MICRO
NANO
g
30 μm
i
20 mm
j
300 mm
a
100 μm
d
3 μm
MACRO
FREQUENCY (Hz)
10^{10}
10^8
10^6
10^4
10^2
10^0
10^{-20}
10^{-16}
10^{-14}
10^{-12}
10^{-10}
10^{-8}
10^{-6}
10^{-4}
10^{-2}
10^0
MASS (kg)

Optomechanics: introduction



$$\Gamma_{\rm opt} = A_- - A_+$$





Jack Harris: **membrane-in-the-middle, separate objects, higher Qs**

$$\bar{n}_{\rm f} = \frac{\Gamma_{\rm m}\bar{n}_{\rm th} + \Gamma_{\rm opt}\bar{n}_{\rm min}}{\Gamma_{\rm opt} + \Gamma_{\rm m}} \qquad \bar{n}_{\rm f} \approx \frac{1}{C_{\rm q}} + \bar{n}_{\rm min}$$

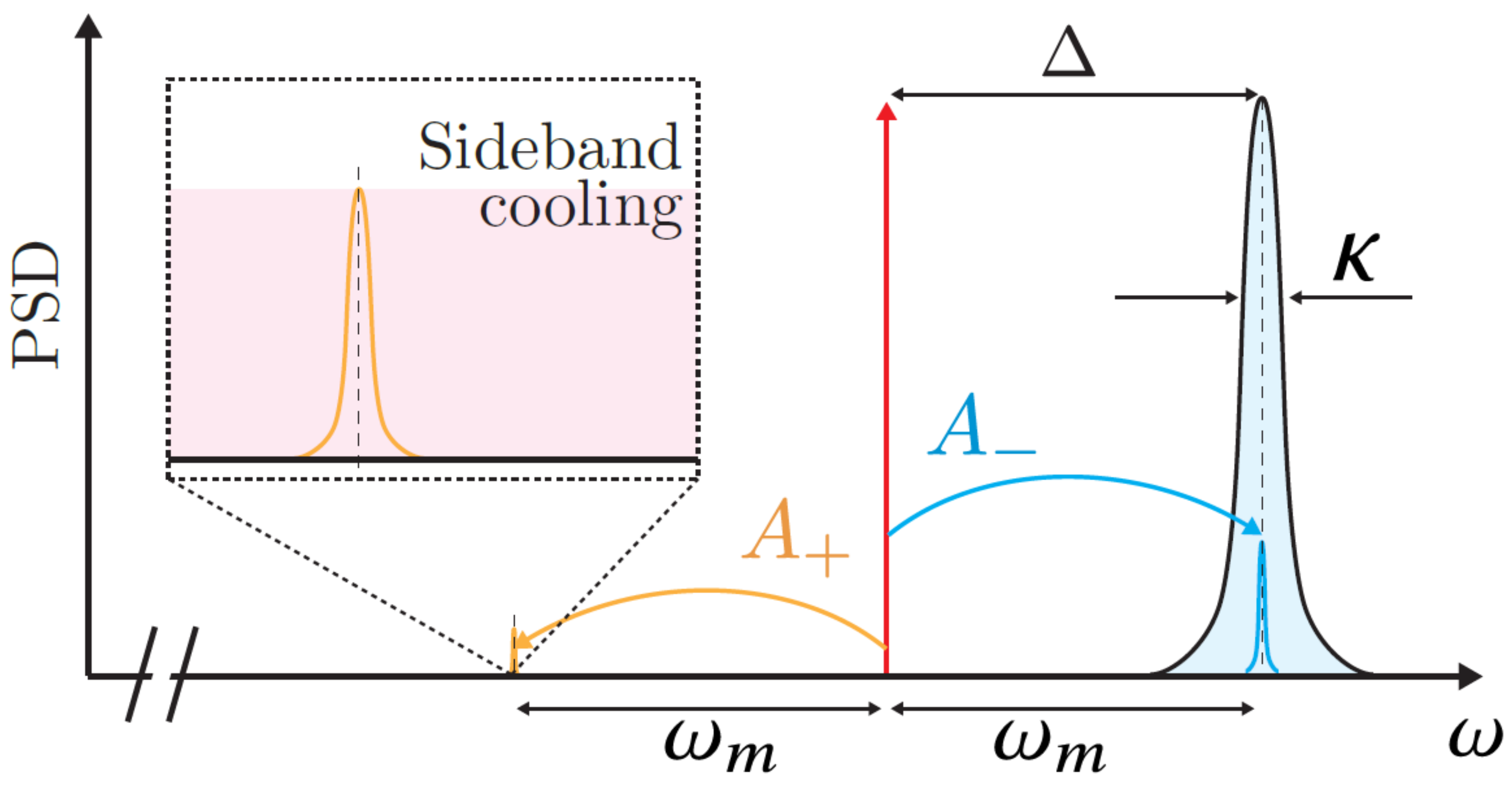
$$C_{\rm q} = \frac{\Gamma_{\rm opt}}{\Gamma_{\rm th}} = \frac{4g_0^2\,\bar{n}_{\rm cav}}{\kappa\,\Gamma_{\rm m}\,\bar{n}_{\rm th}}$$

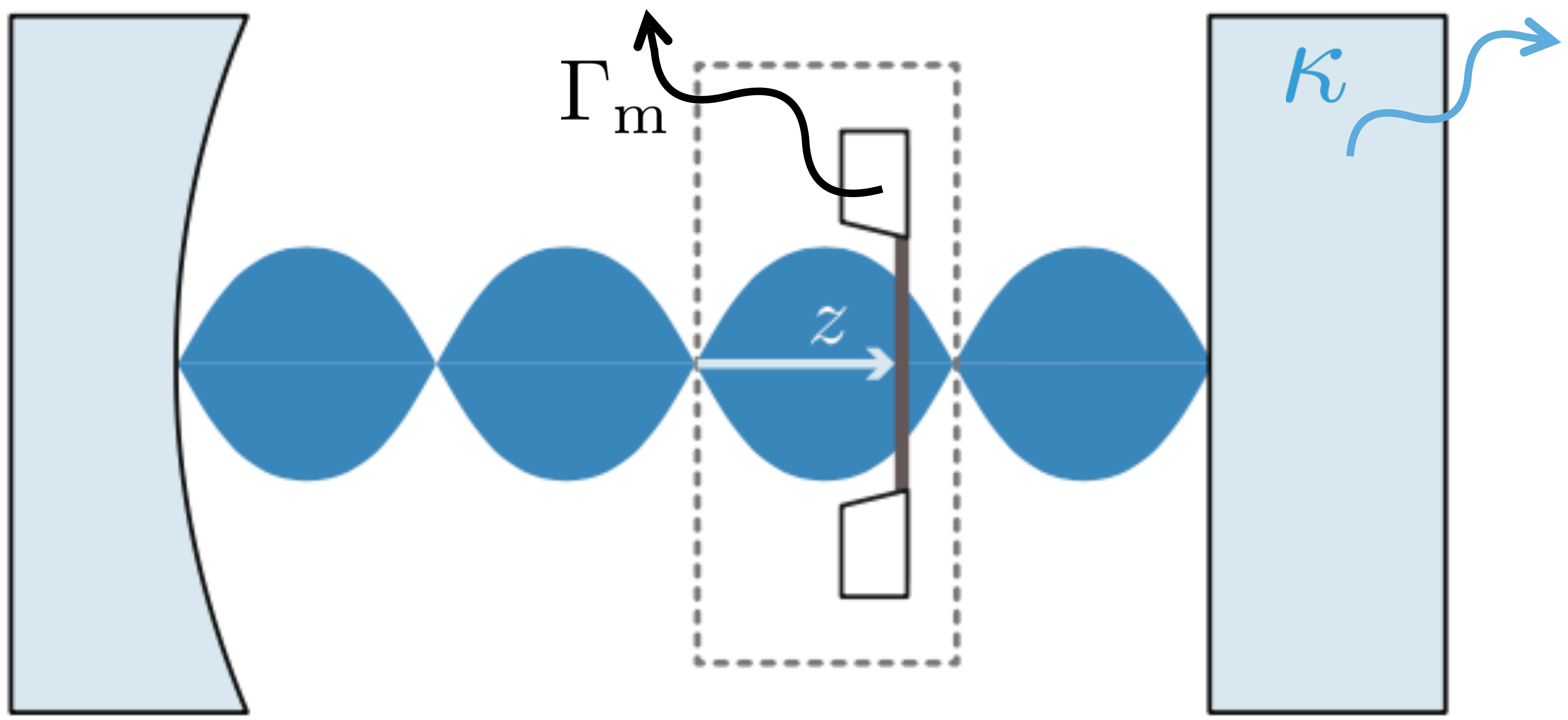
quantum cooperativity

$$g_0 = \left.\frac{d\omega_{\rm cav}}{dz}\right|_{z=z_0} \sqrt{\frac{\hbar}{2m_{\rm eff}\,\Omega_{\rm m}}}\,\Theta^{ij}_{mn}$$

- **high-finesse cavity**
- **high-Q oscillator**
- **cryogenic environment**

$$\Gamma_{\mathrm{opt}} = A_- - A_+$$





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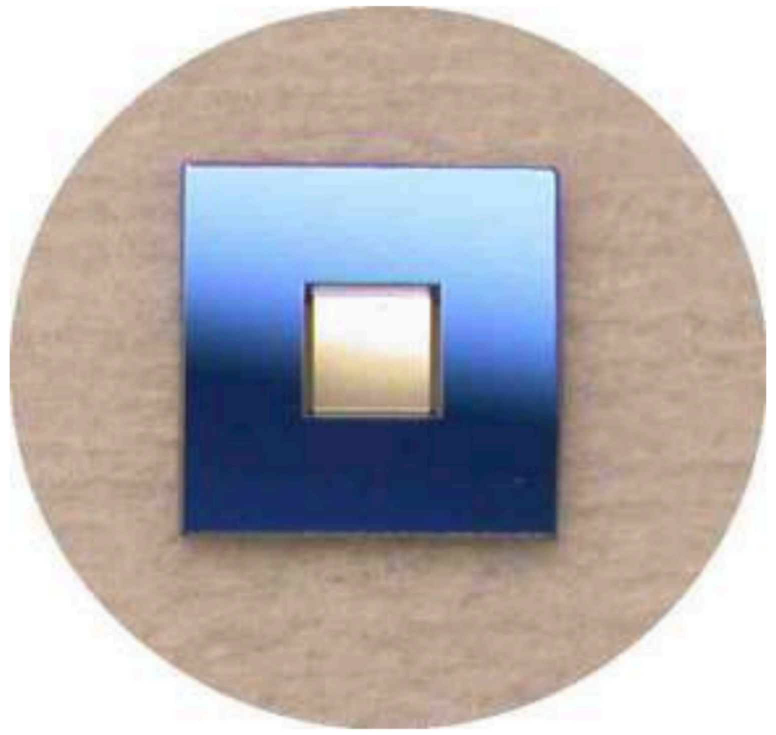
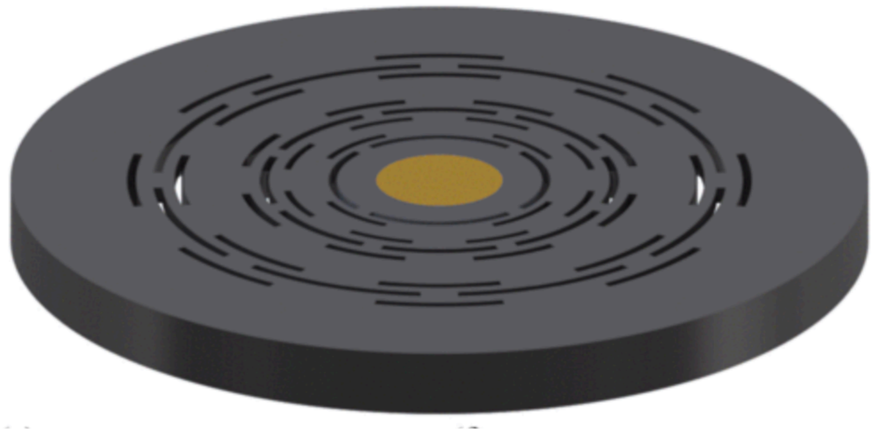
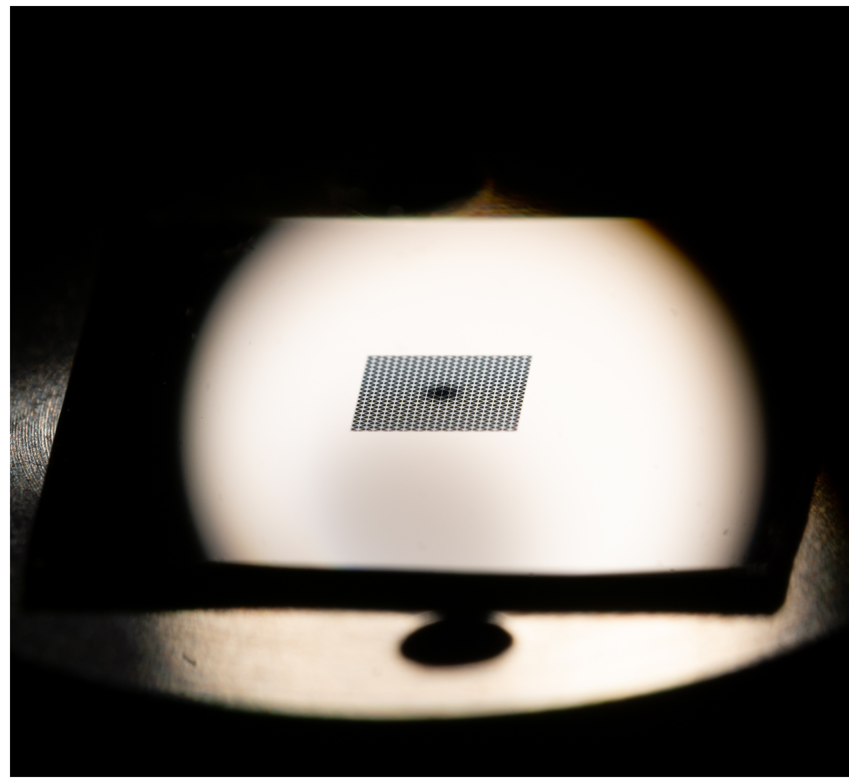




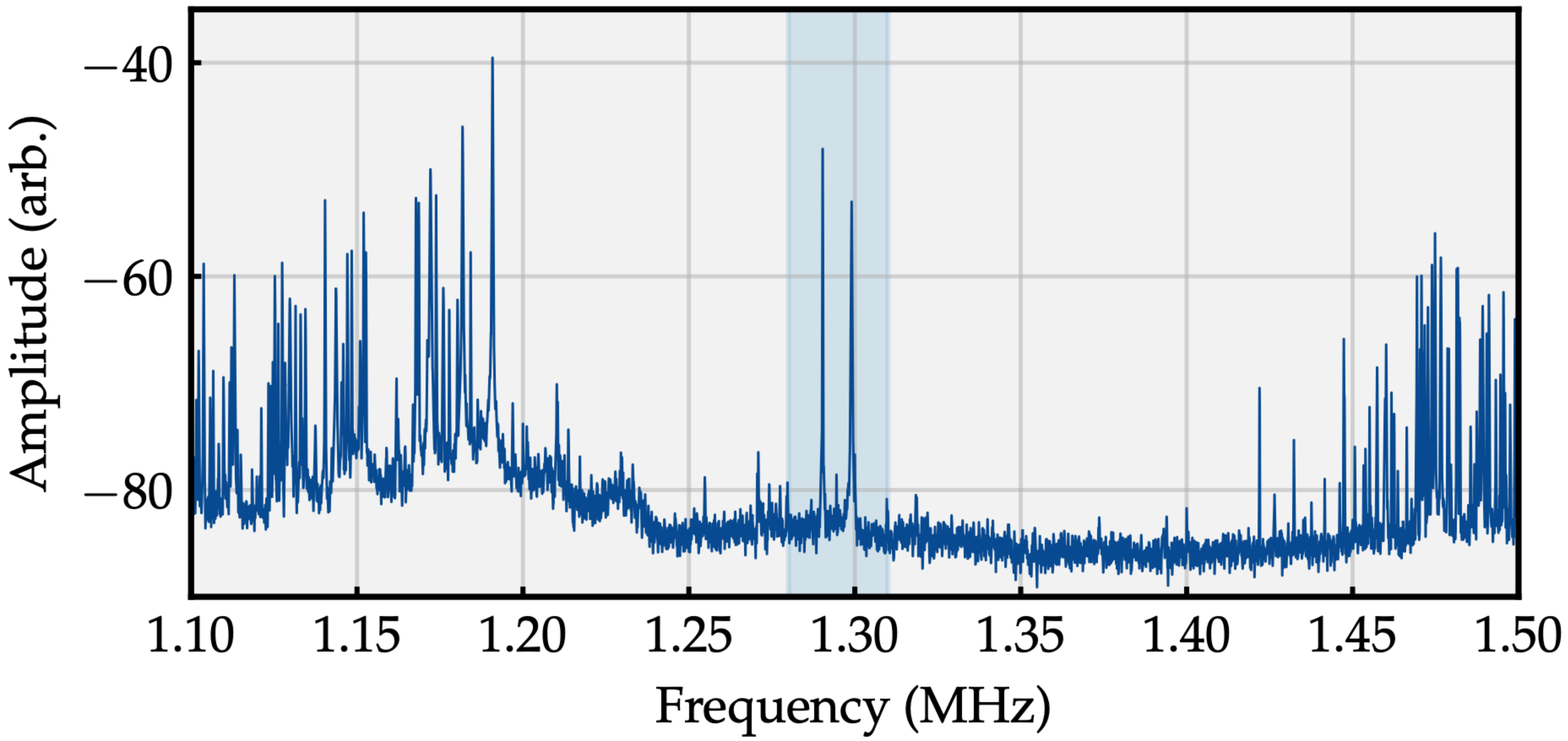


three generations:
1. dissipation dilution
2. phononic bandgap
3. soft clamping

- soft-clamped membranes

Y. Tsaturyan et al., Nature Nanotechnol. 12, 776-783 (2017)

$\Omega_m/(2\pi) = 1.3\,\text{MHz}$ $Q_m = 1.4 \times 10^8$ at RT



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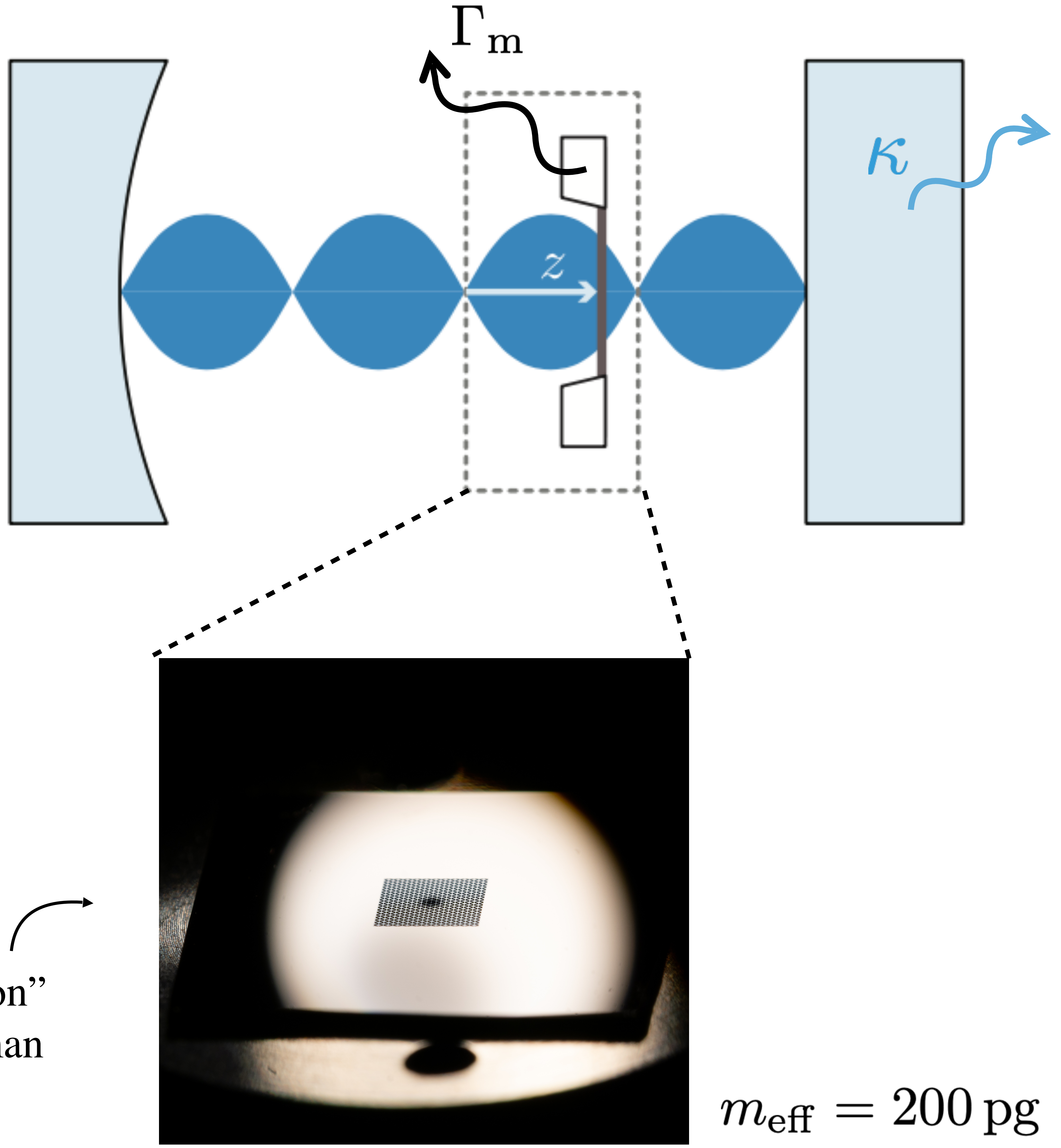
low-mass “Dandelion” design by E. Langman



$m_{eff} = 200\,\text{pg}$

$d = 30\,\mu\text{m}$

M. Rossi et al., Nature 563, 53-58 (2018)

J. Chen et al., Nat. Commun. 11, 943 (2020)

adapted from: D. Hälg et al., Phys. Rev. Applied 15 (2 2021), p. L021001

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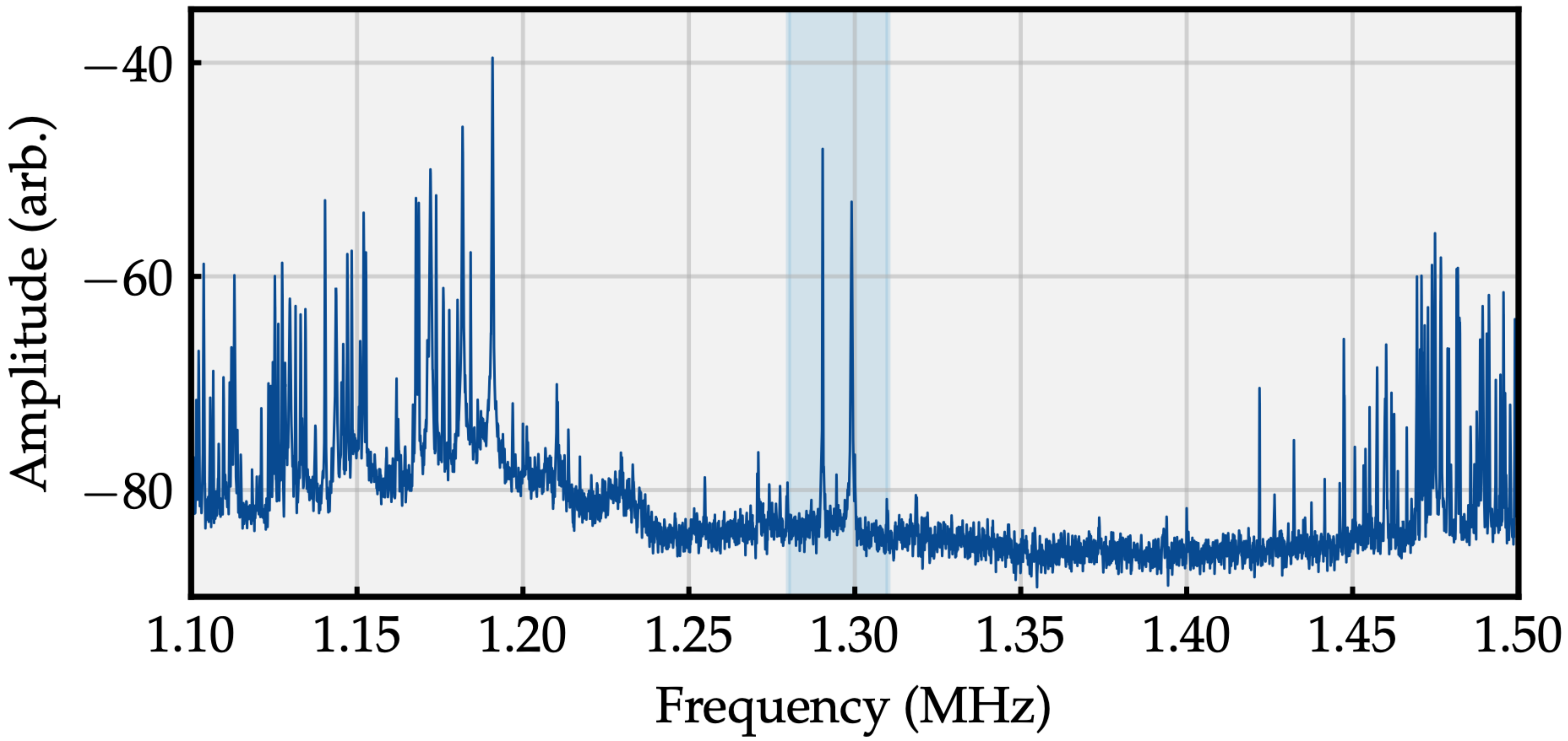

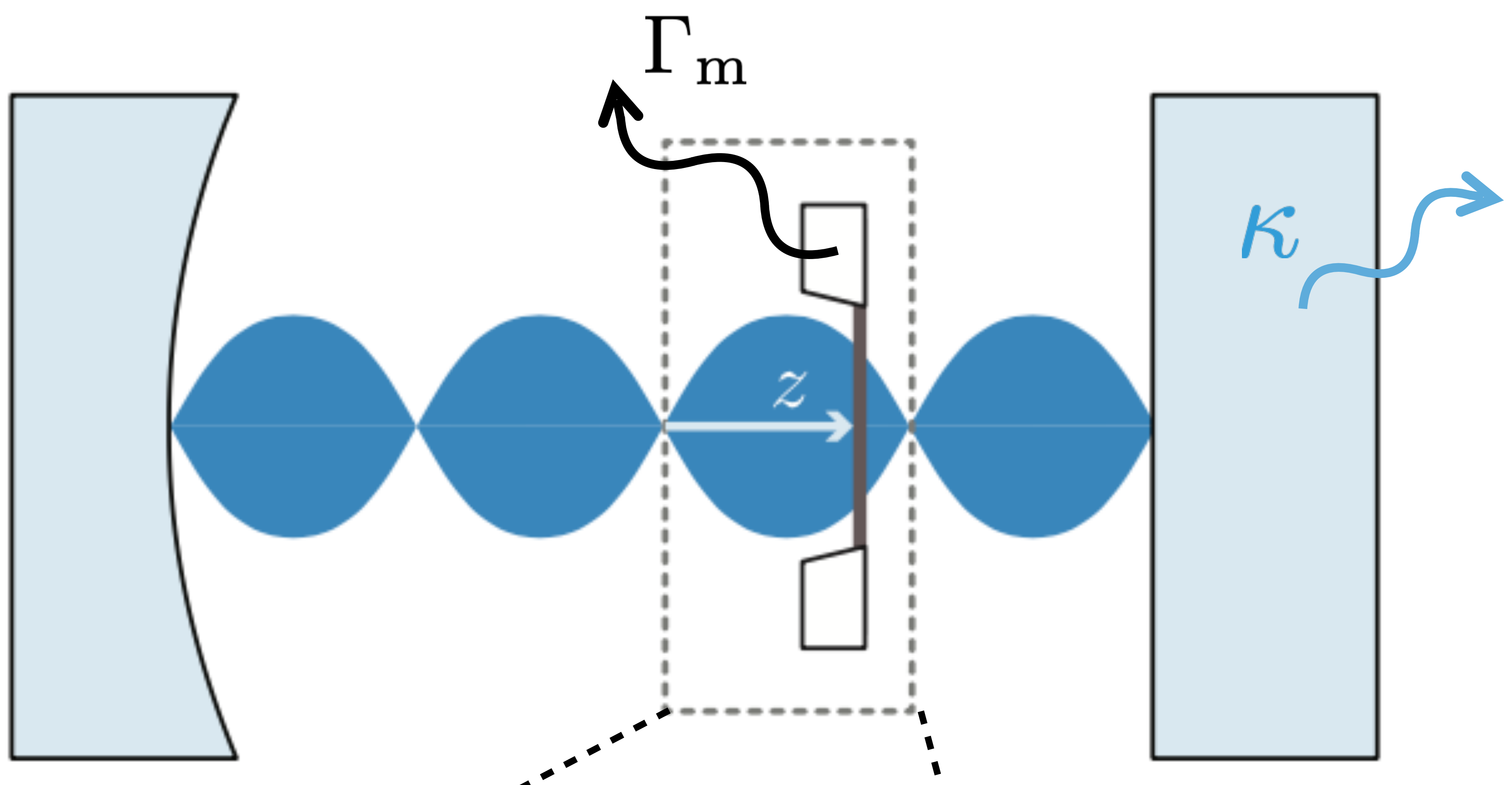

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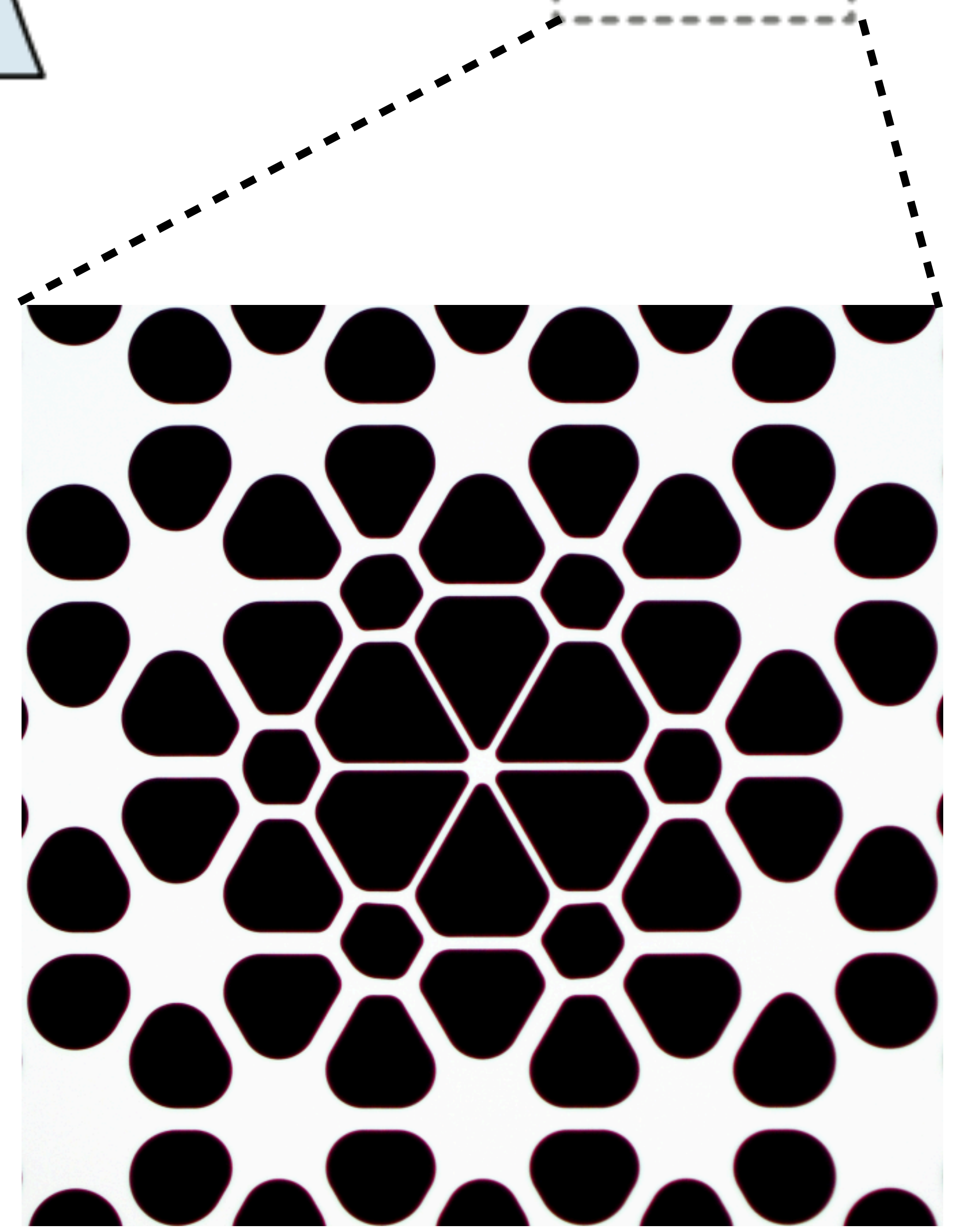

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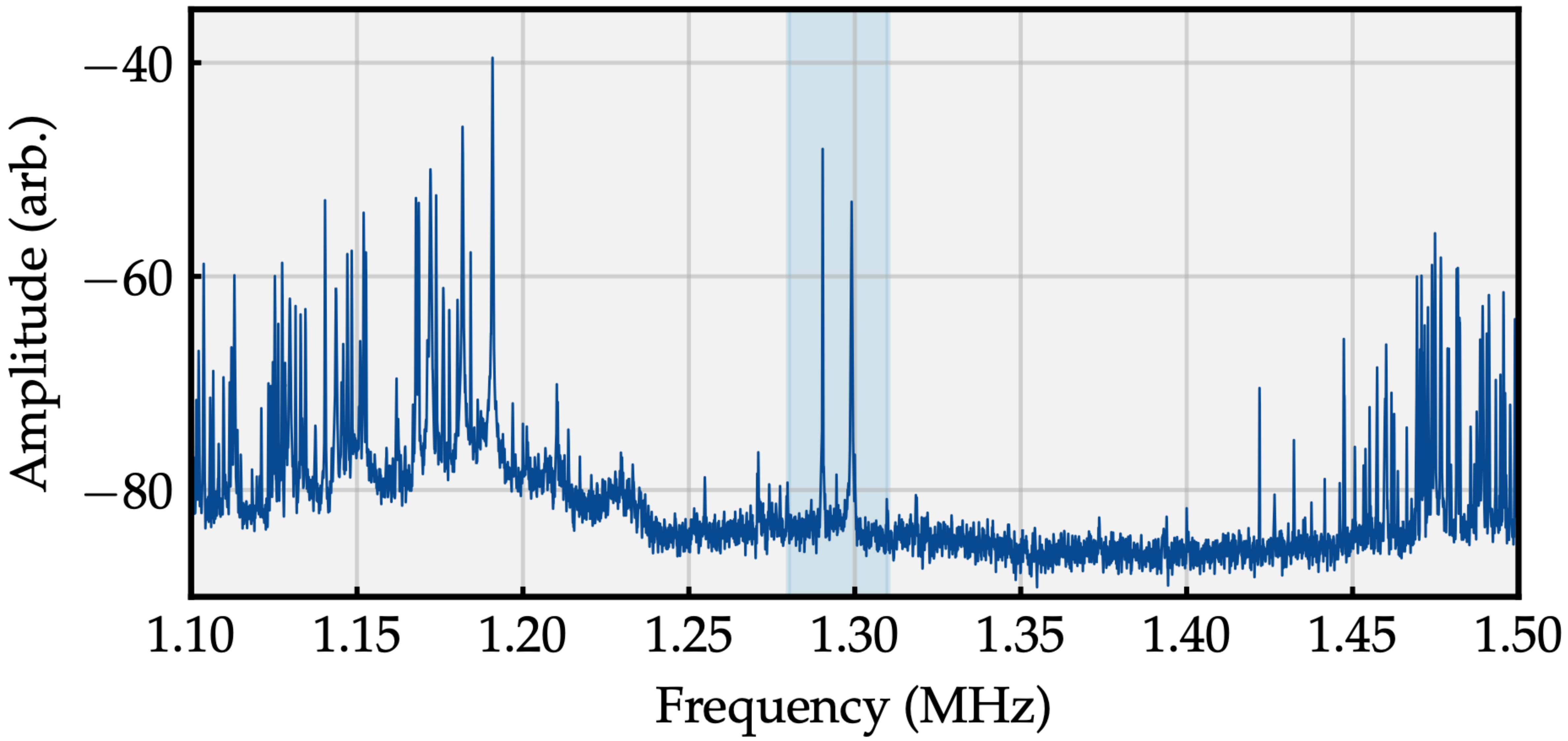

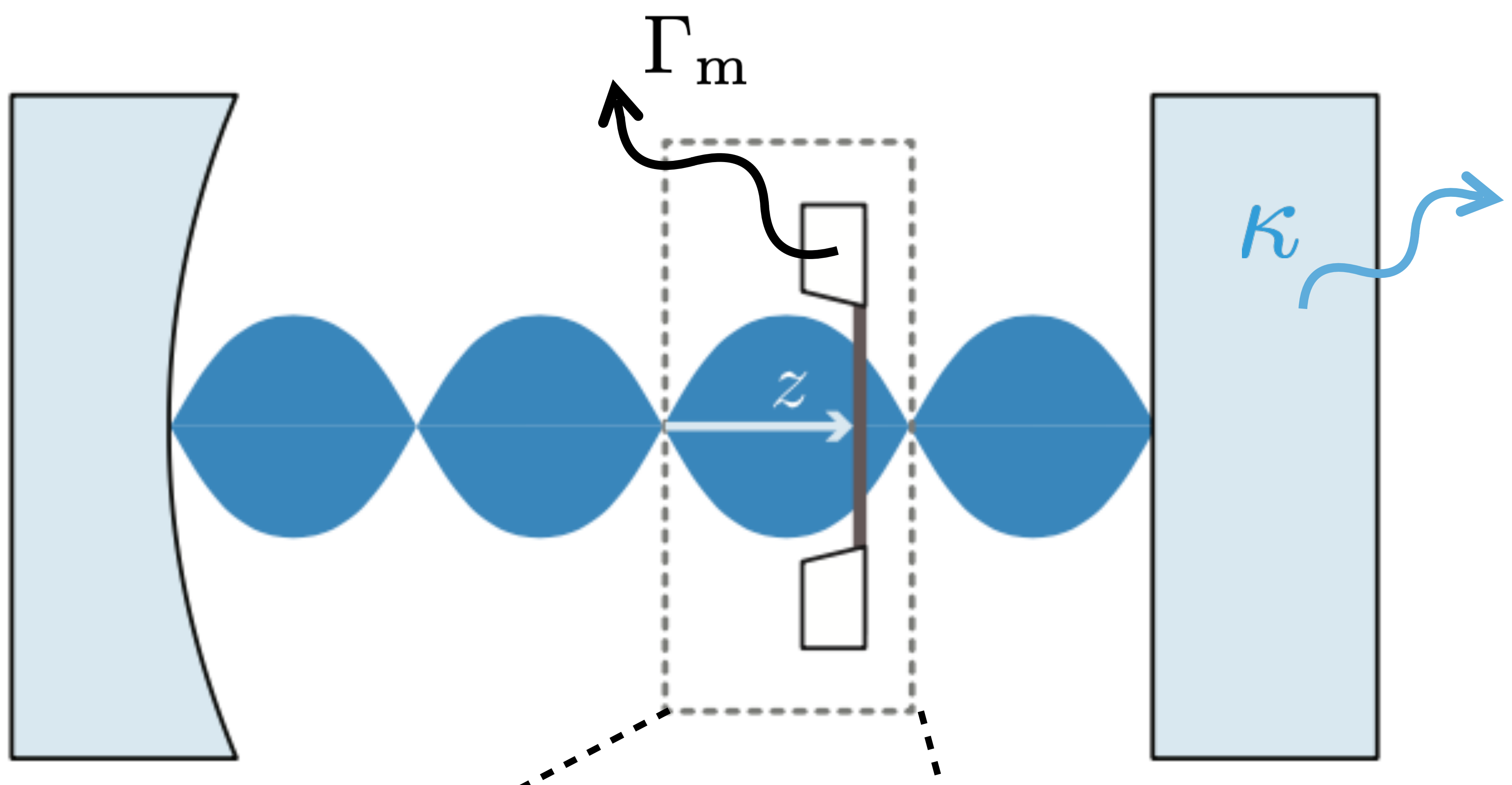

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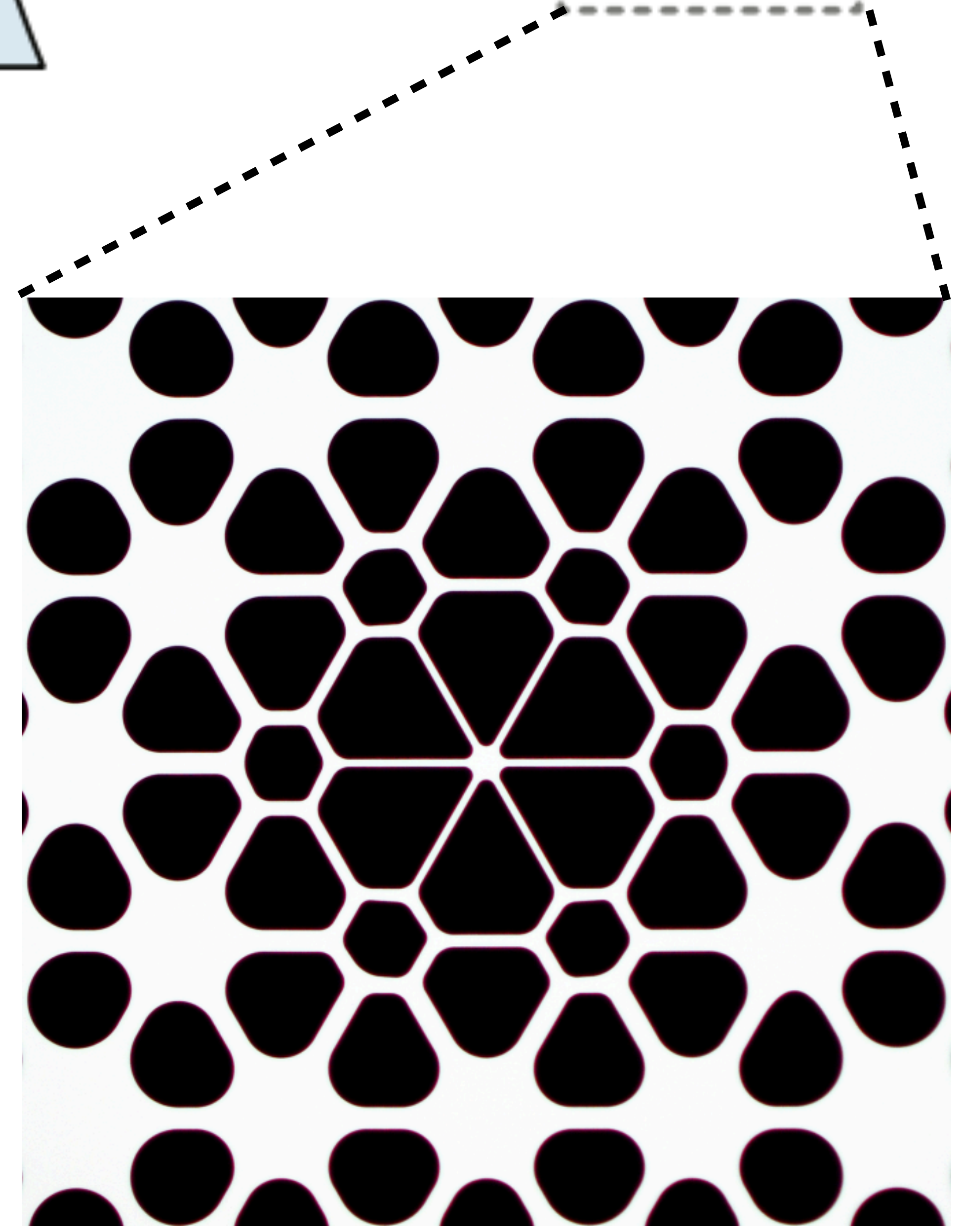

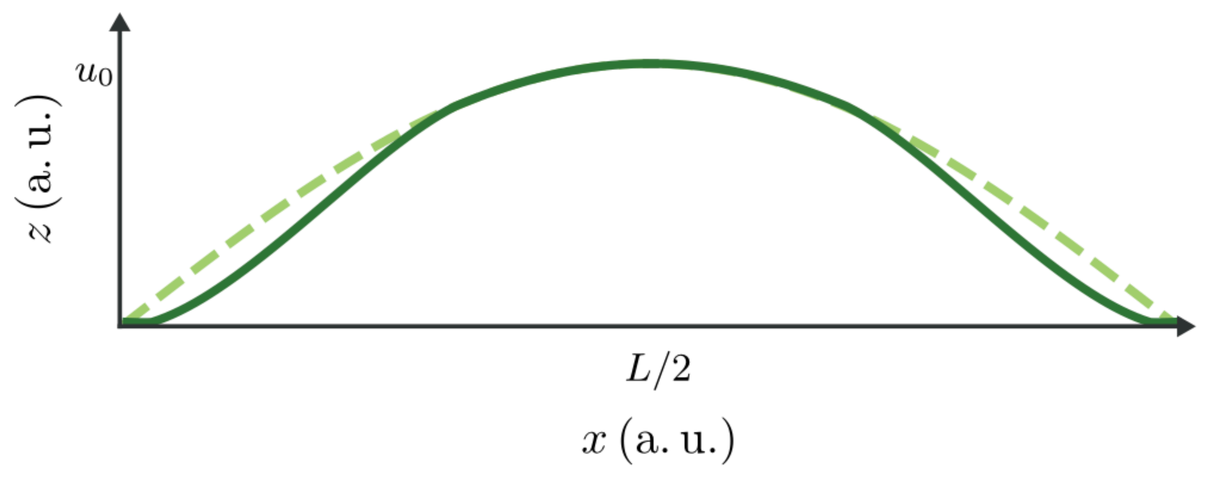

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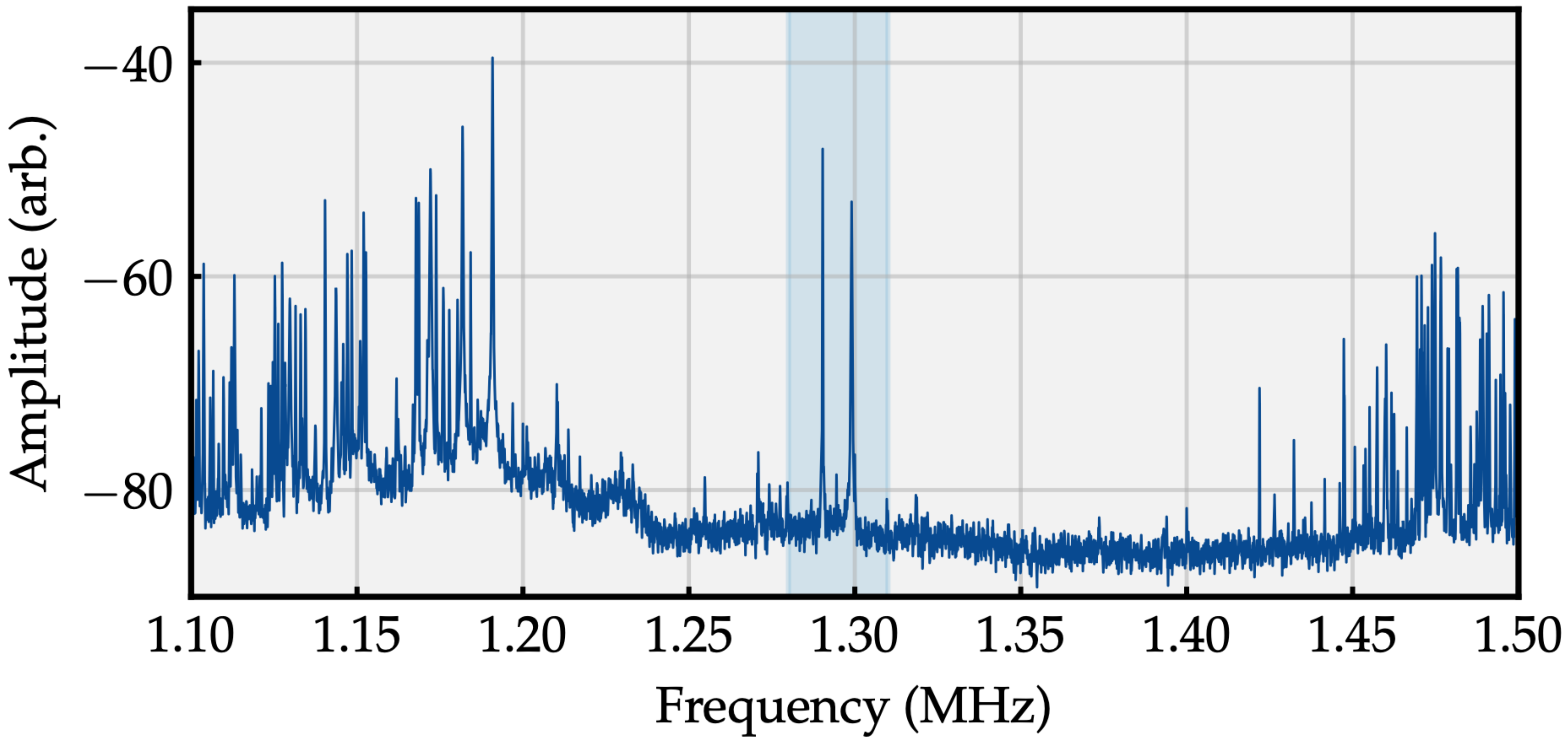

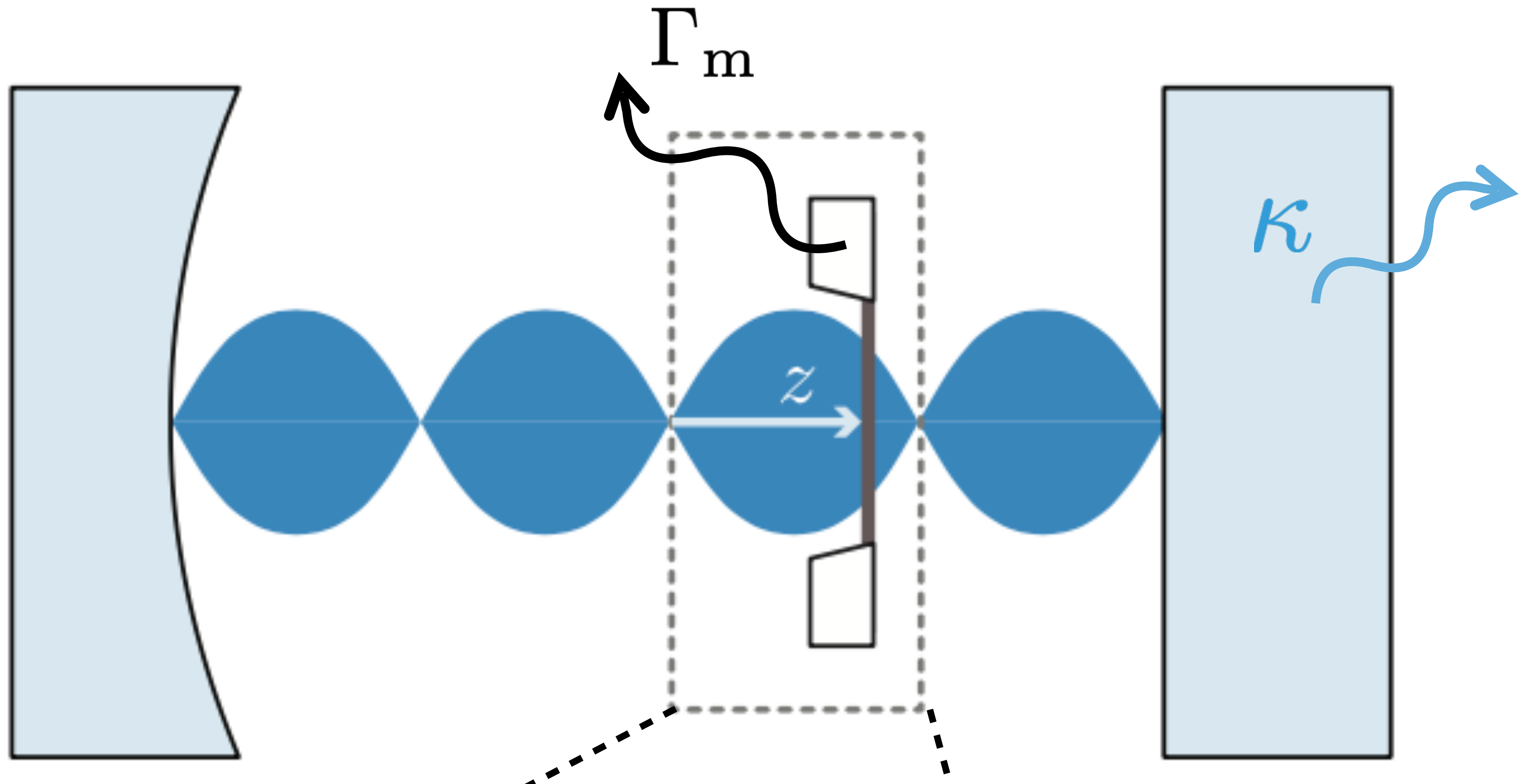

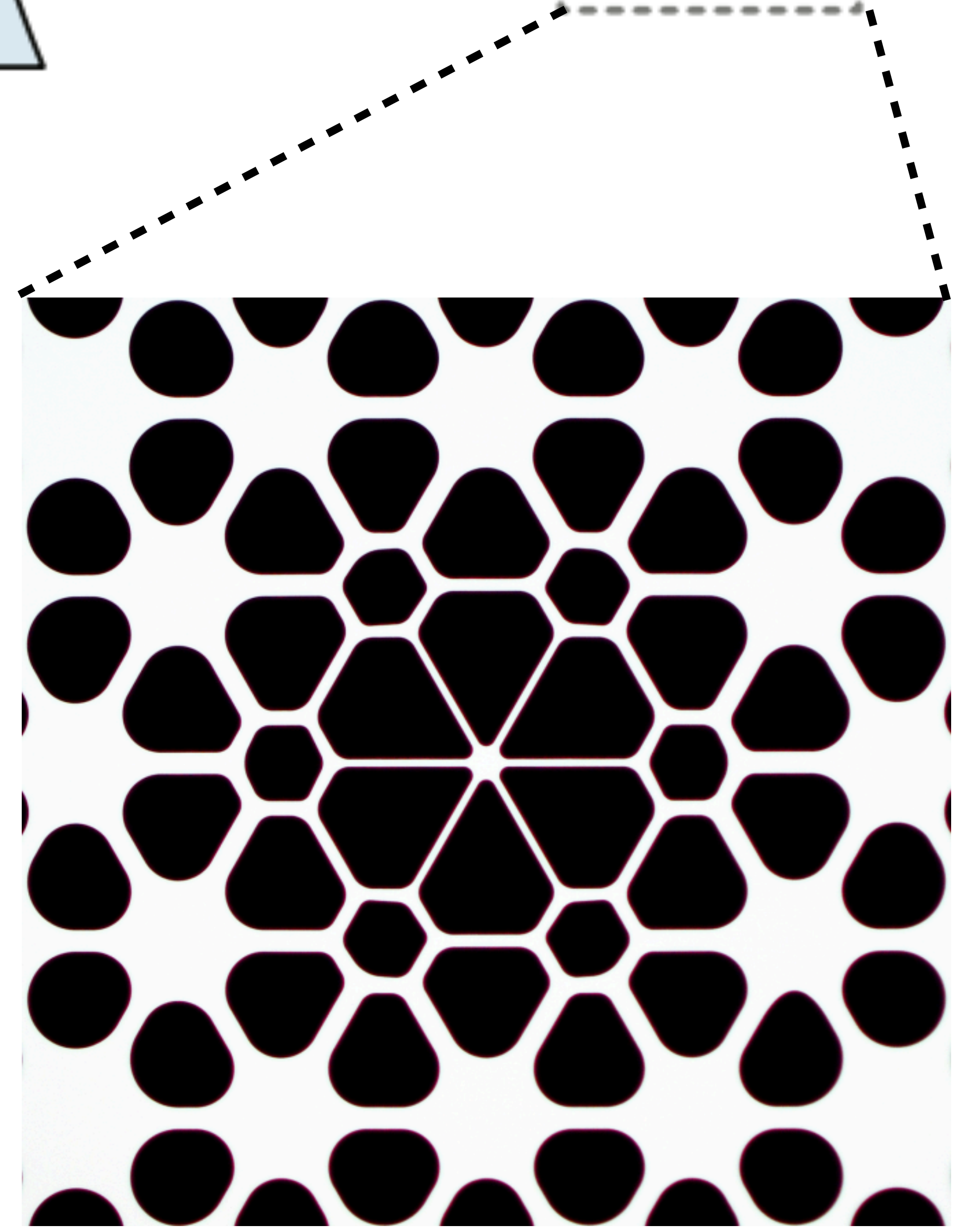

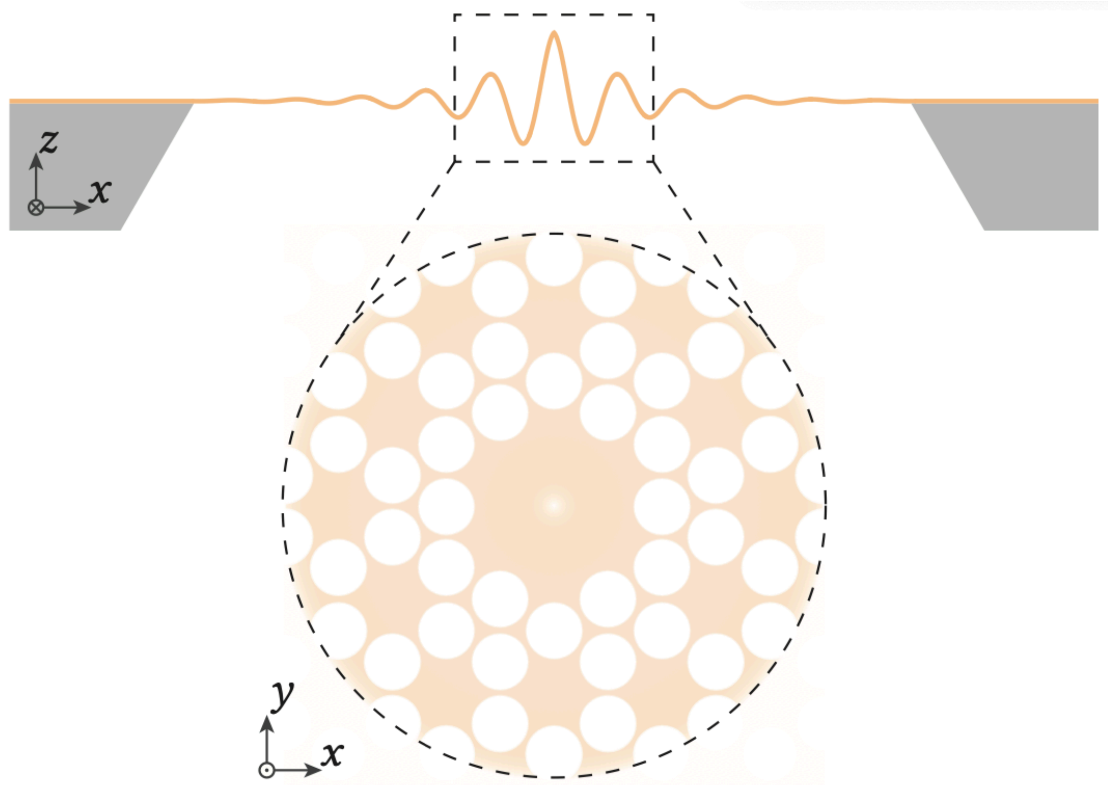

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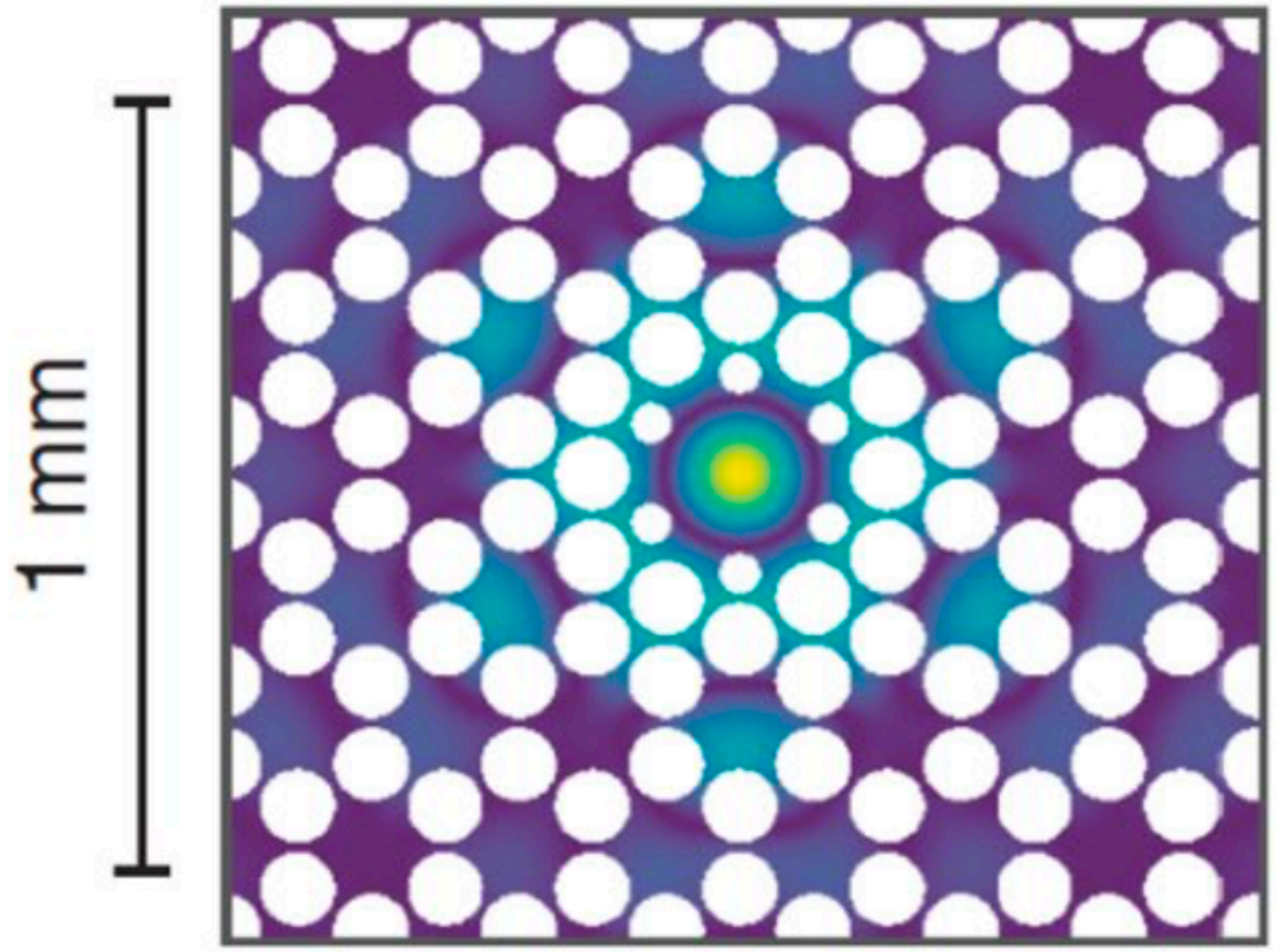
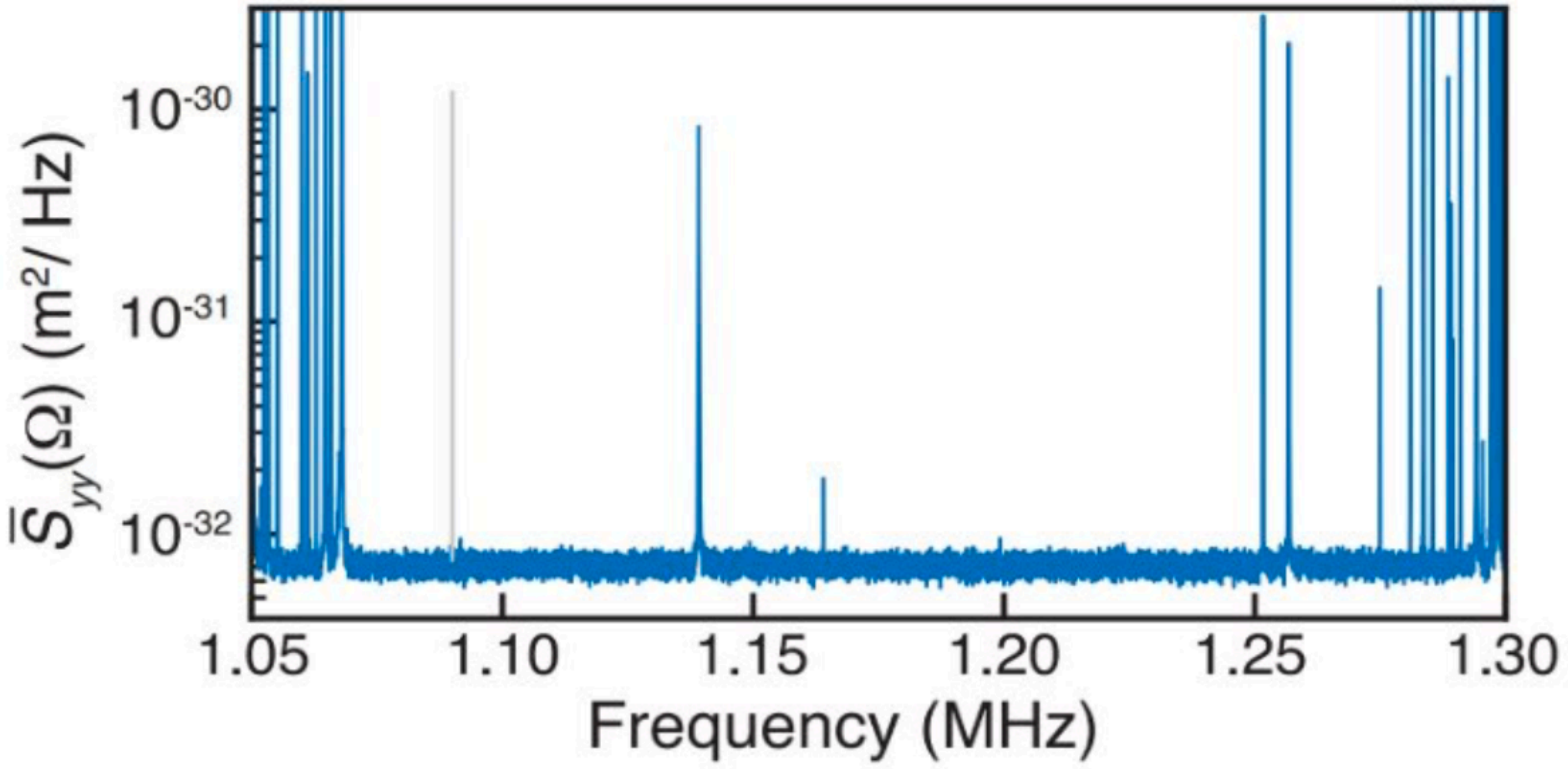
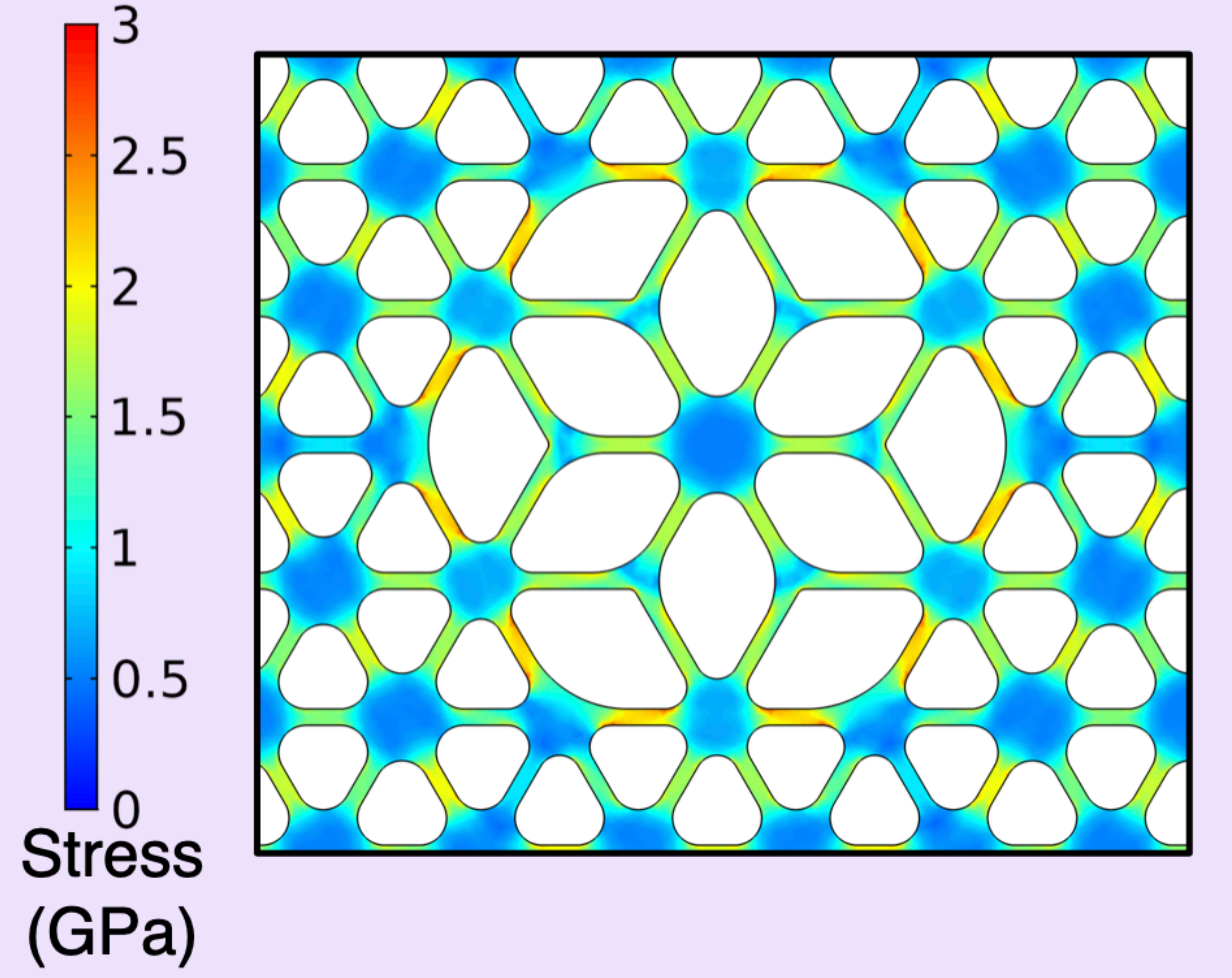




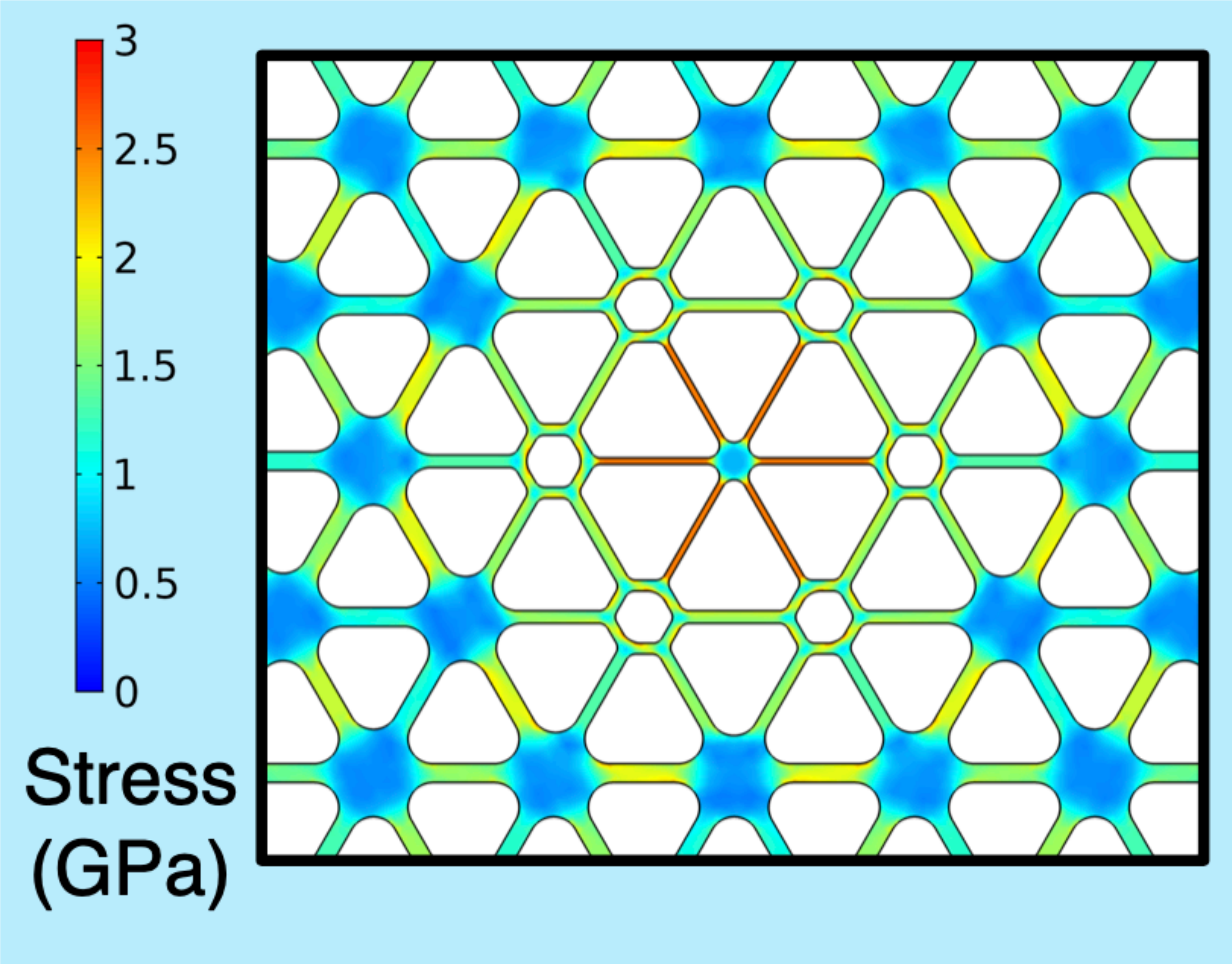
Qfactory

https://qfactory.dk/

The Single-Mode Lotus



The Low-Mass Dandelion



$$S_{\mathrm{FF}} = \sqrt{\frac{4 m_{\mathrm{eff}} k_B T \Omega}{Q}}$$

Qfactory

https://qfactory.dk/

$$S_{\mathrm{FF}}(@300\,\mathrm{K}) \sim 30\,\mathrm{aN}/\sqrt{\mathrm{Hz}}$$

$$S_{\mathrm{FF}}(@4\,\mathrm{K}) \sim 2\,\mathrm{aN}/\sqrt{\mathrm{Hz}}$$

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Y. Tsaturyan et al., Nature Nanotechnol. 12, 776-783 (2017)

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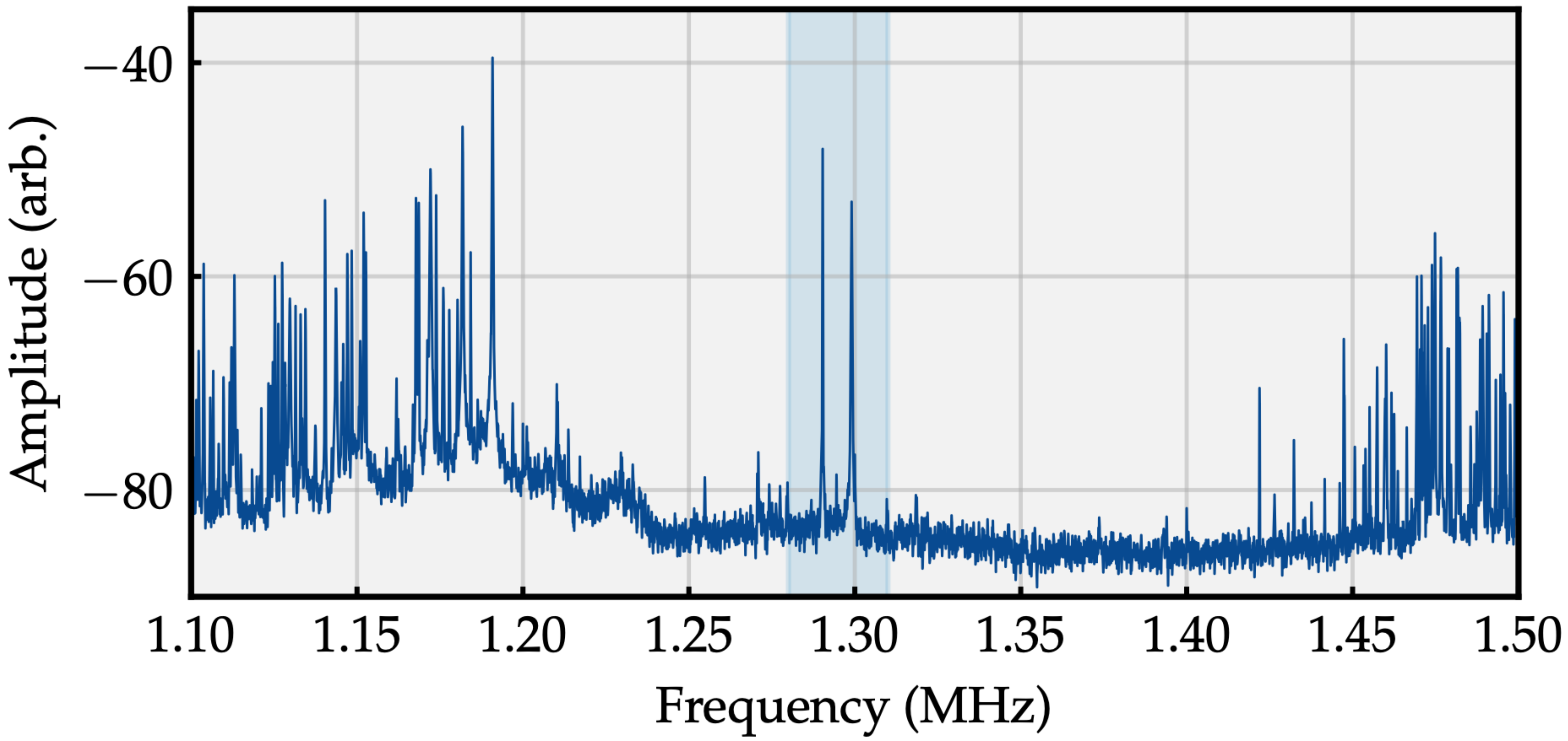

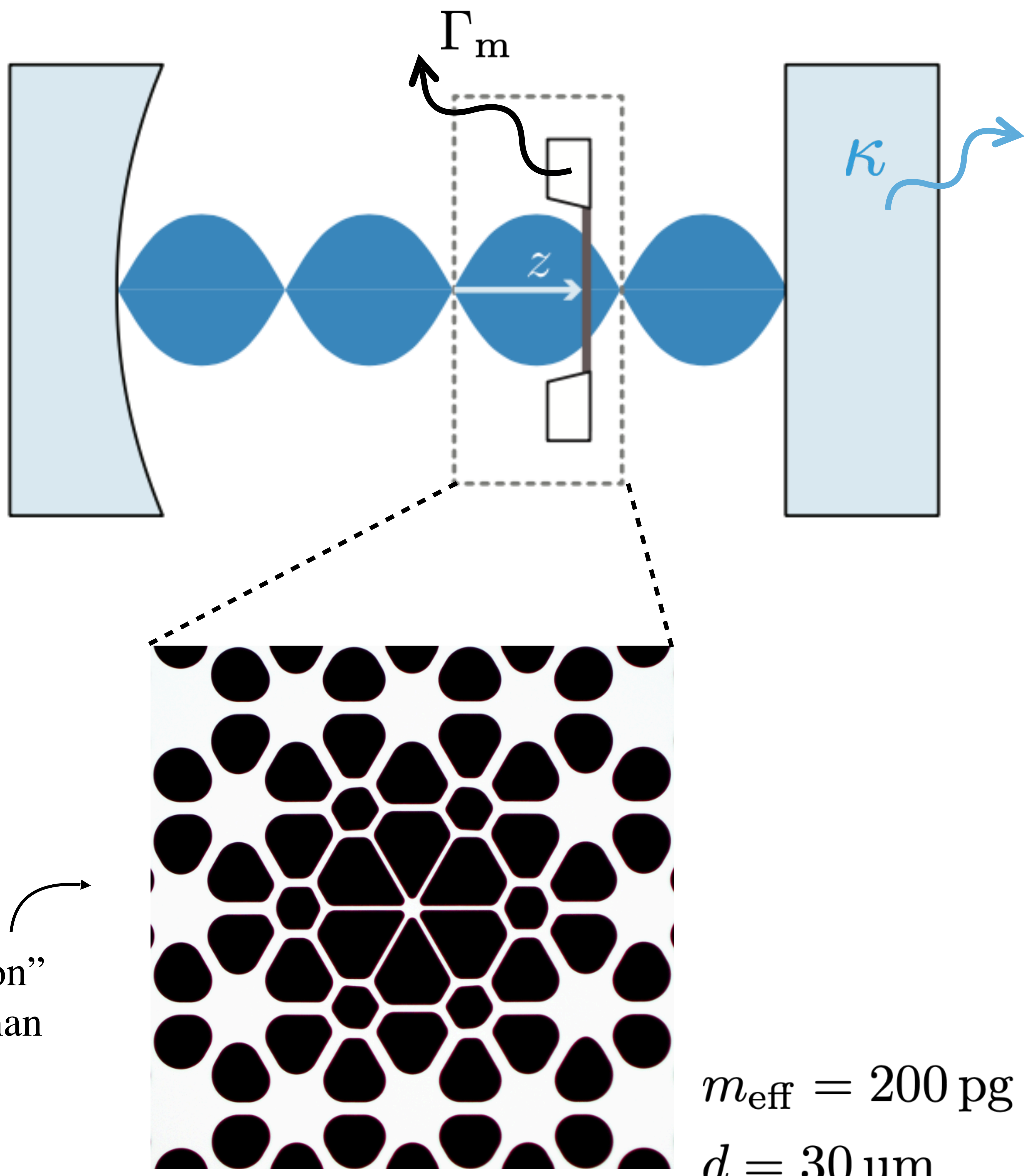

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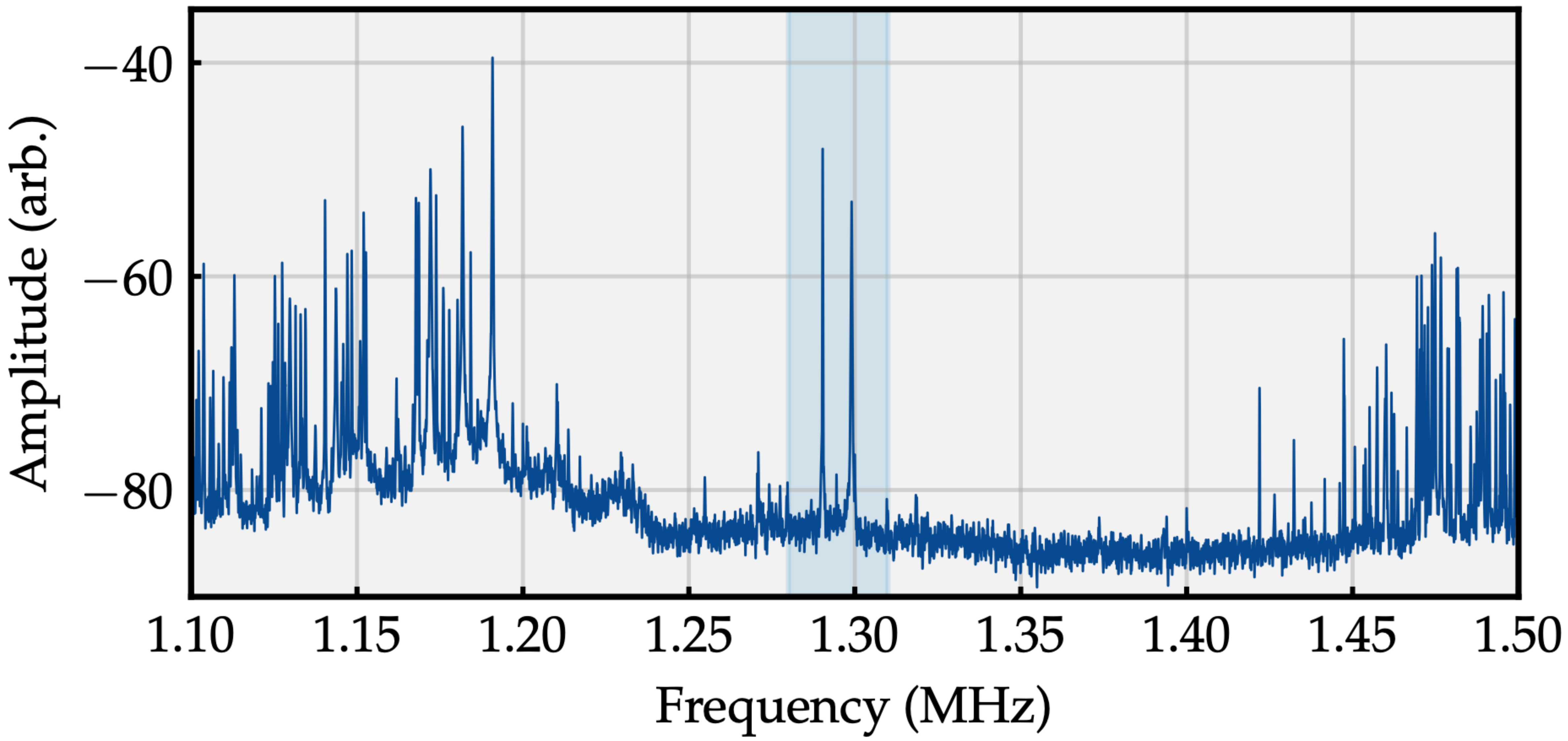

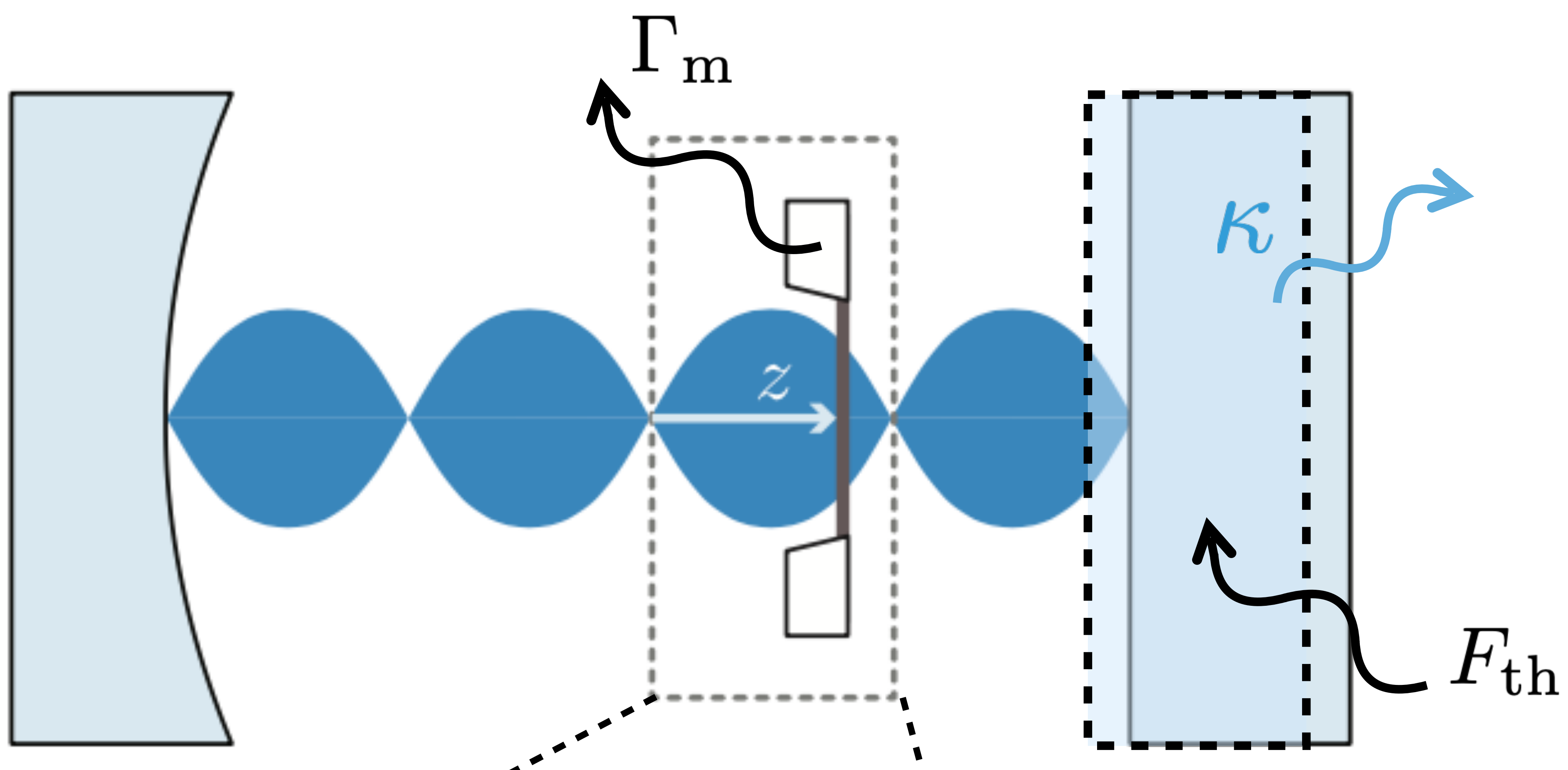

mirror noise!

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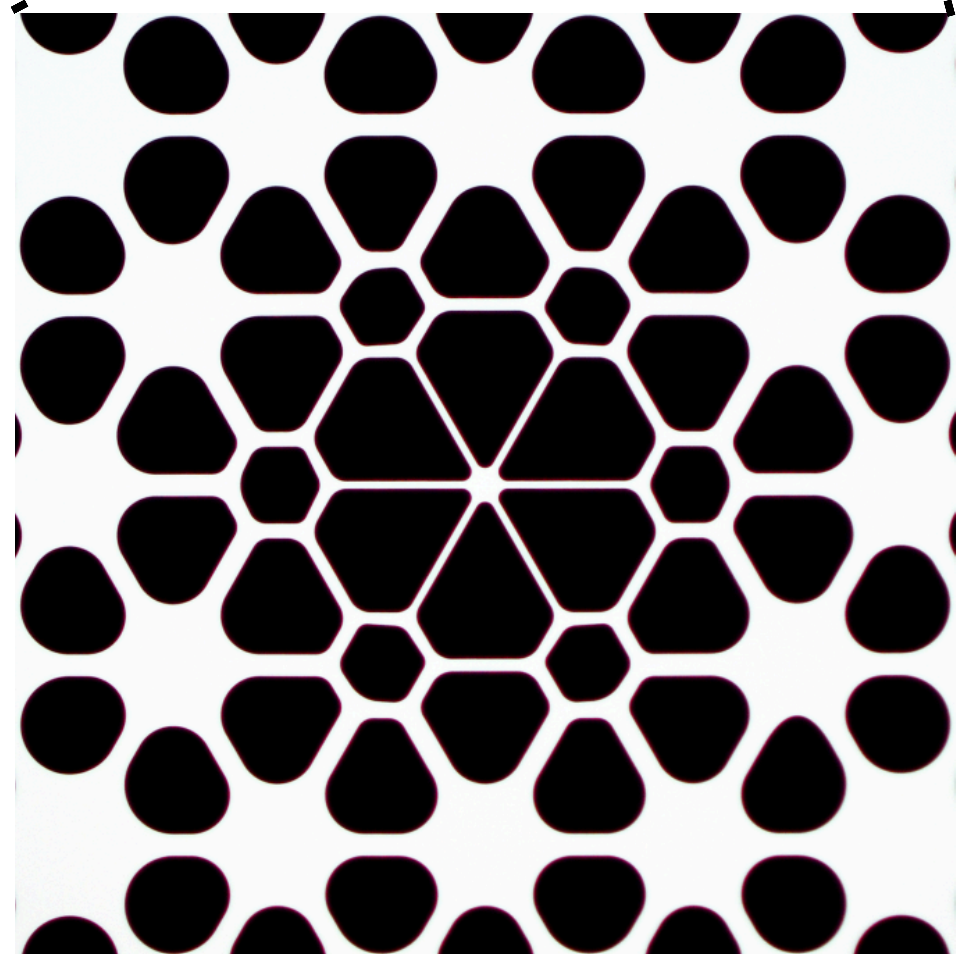

to reach ground state:

$$\bar{S}_{\omega\omega}(\Omega_{\mathrm{m}}) \leq \frac{g_0^2}{k_B\,T/\hbar\,Q_{\mathrm{m}}}$$

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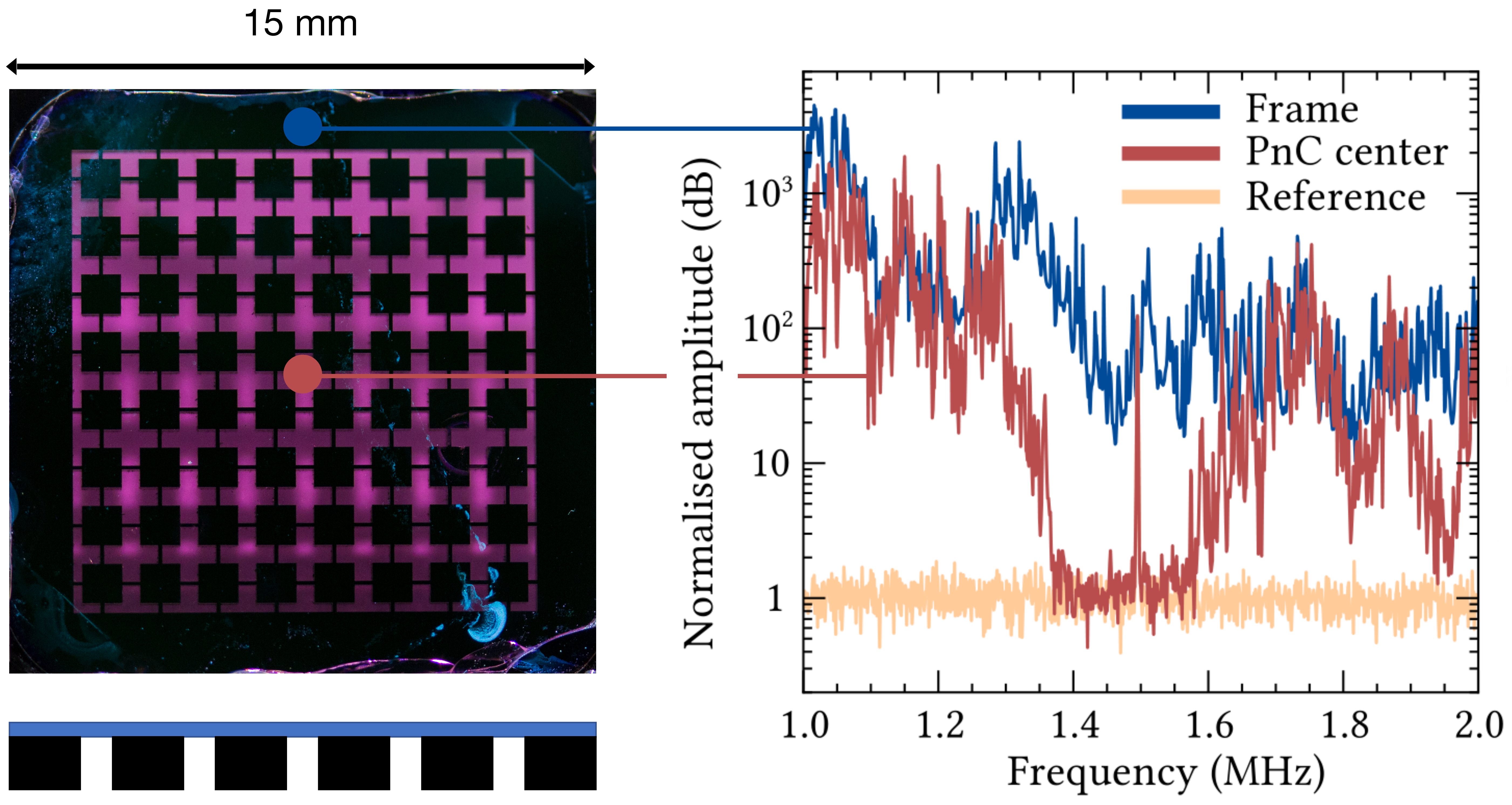
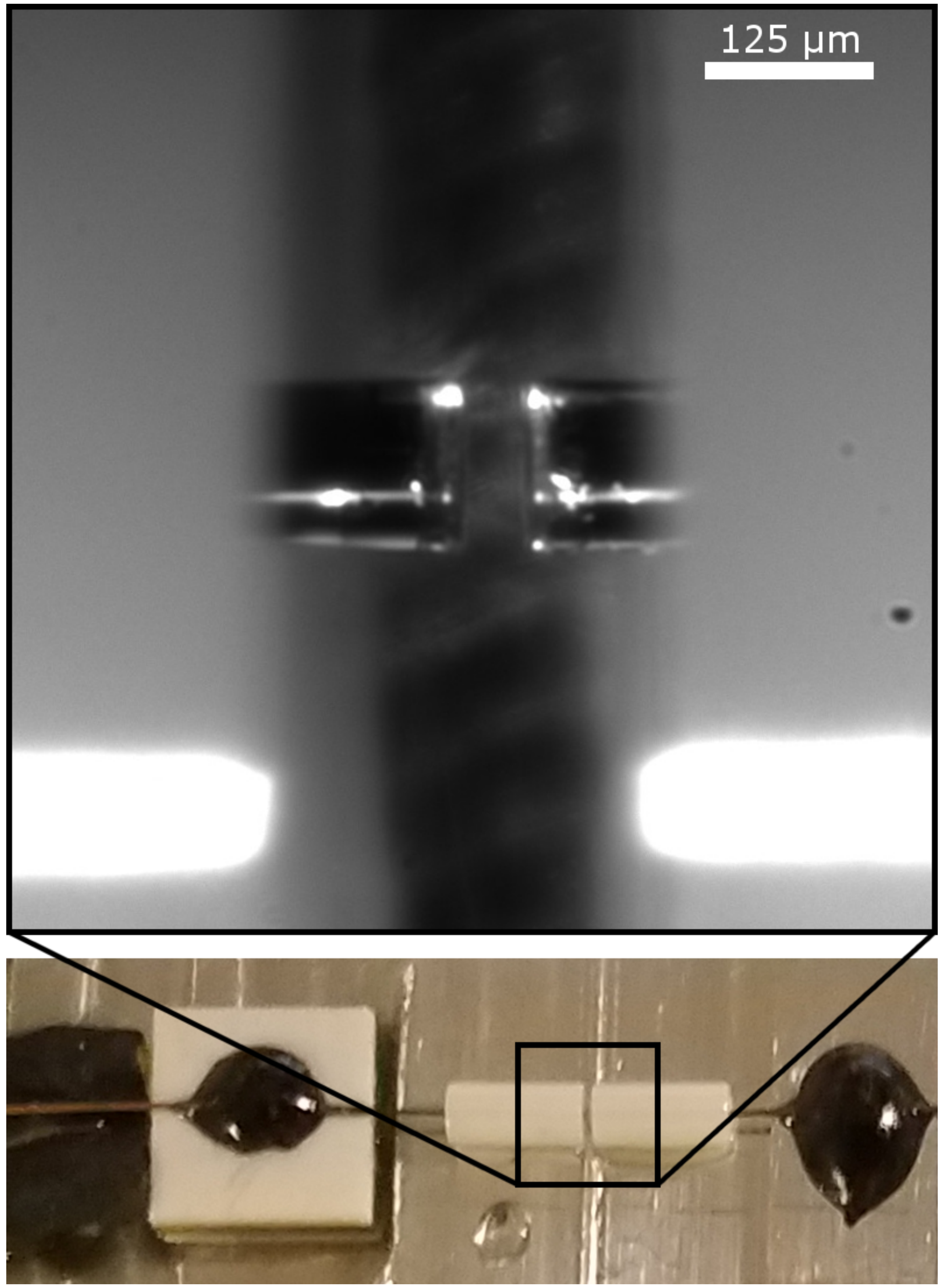
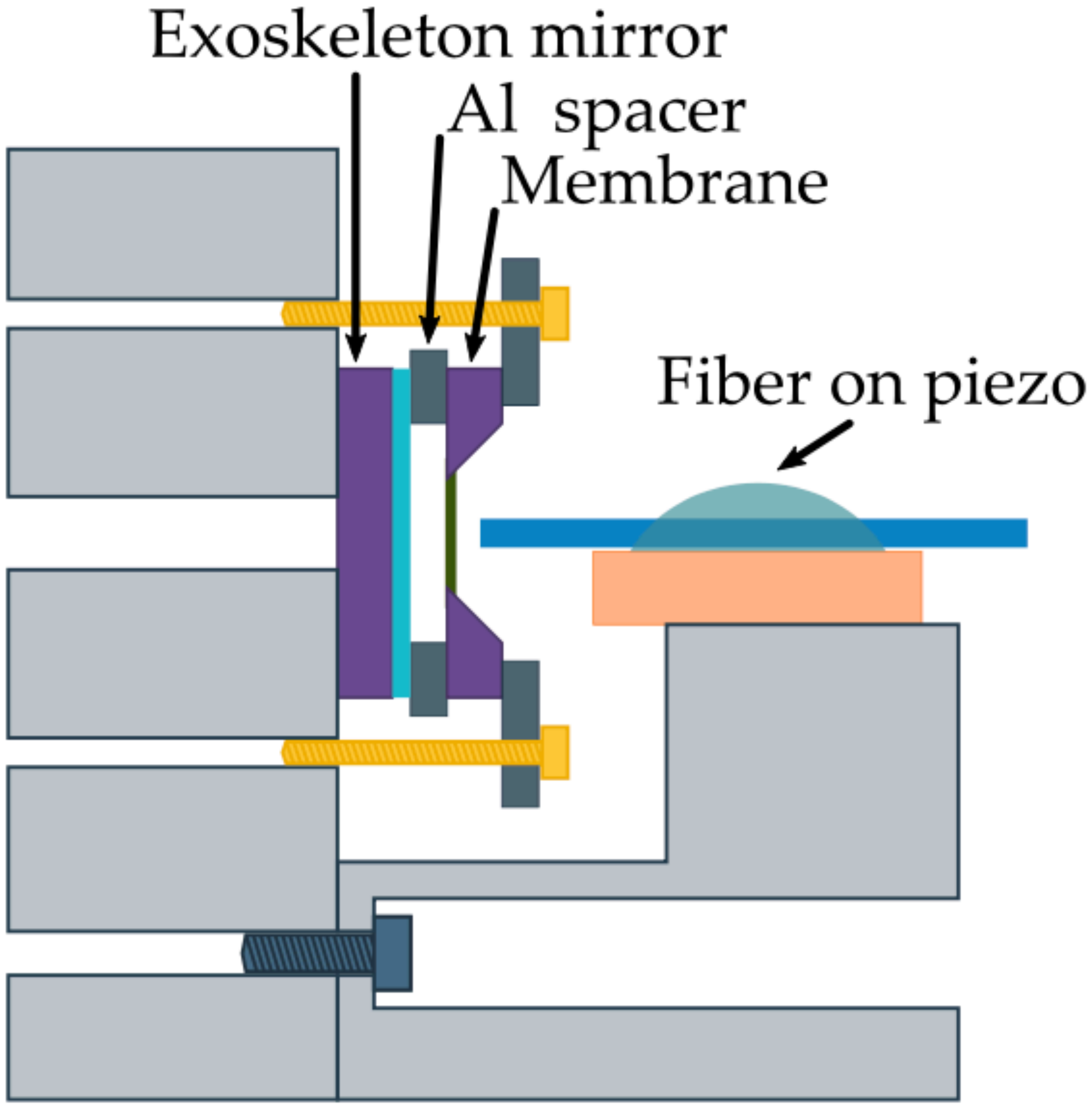
- two strategies:
  - reduce mirror size: fiber mirrors
  - create a bandgap: “exoskeleton” mirror

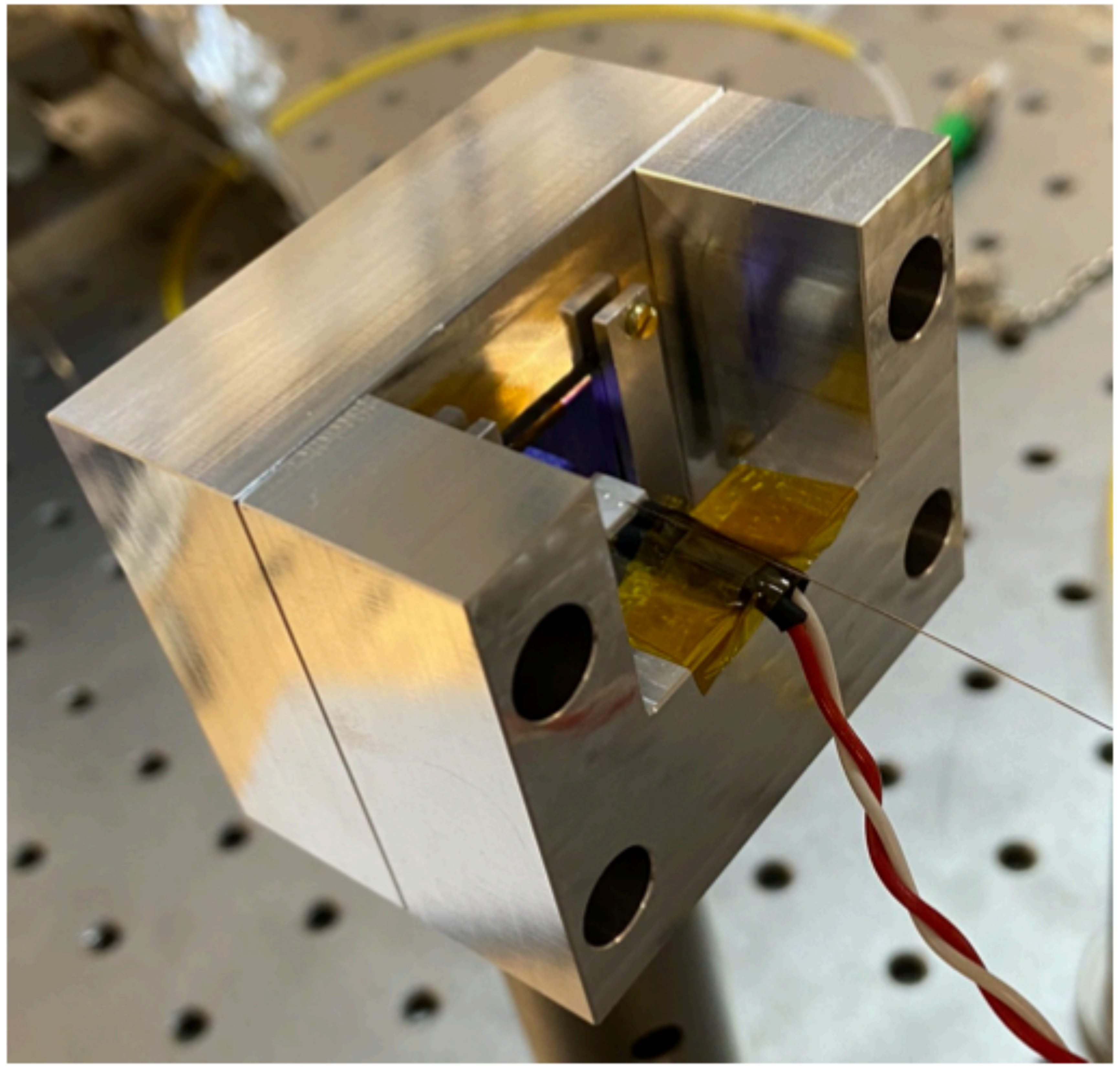


Y. Tsaturyan, PhD thesis, University of Copenhagen (2019)



Quantum optomechanics at room temperature





$\Omega_m/(2\pi) = 1.3\,\text{MHz}$

$\kappa/(2\pi) = 340\,\text{MHz}$

$L = 97\,\mu\text{m}$

$\mathcal{F} \approx 4850$

$\eta_c = 0.895$

$$\bar{n}_{min} = \frac{\kappa}{4\Omega_m}$$

$g_0/(2\pi) = 2.3\,\text{kHz}$

- apparent displacement:

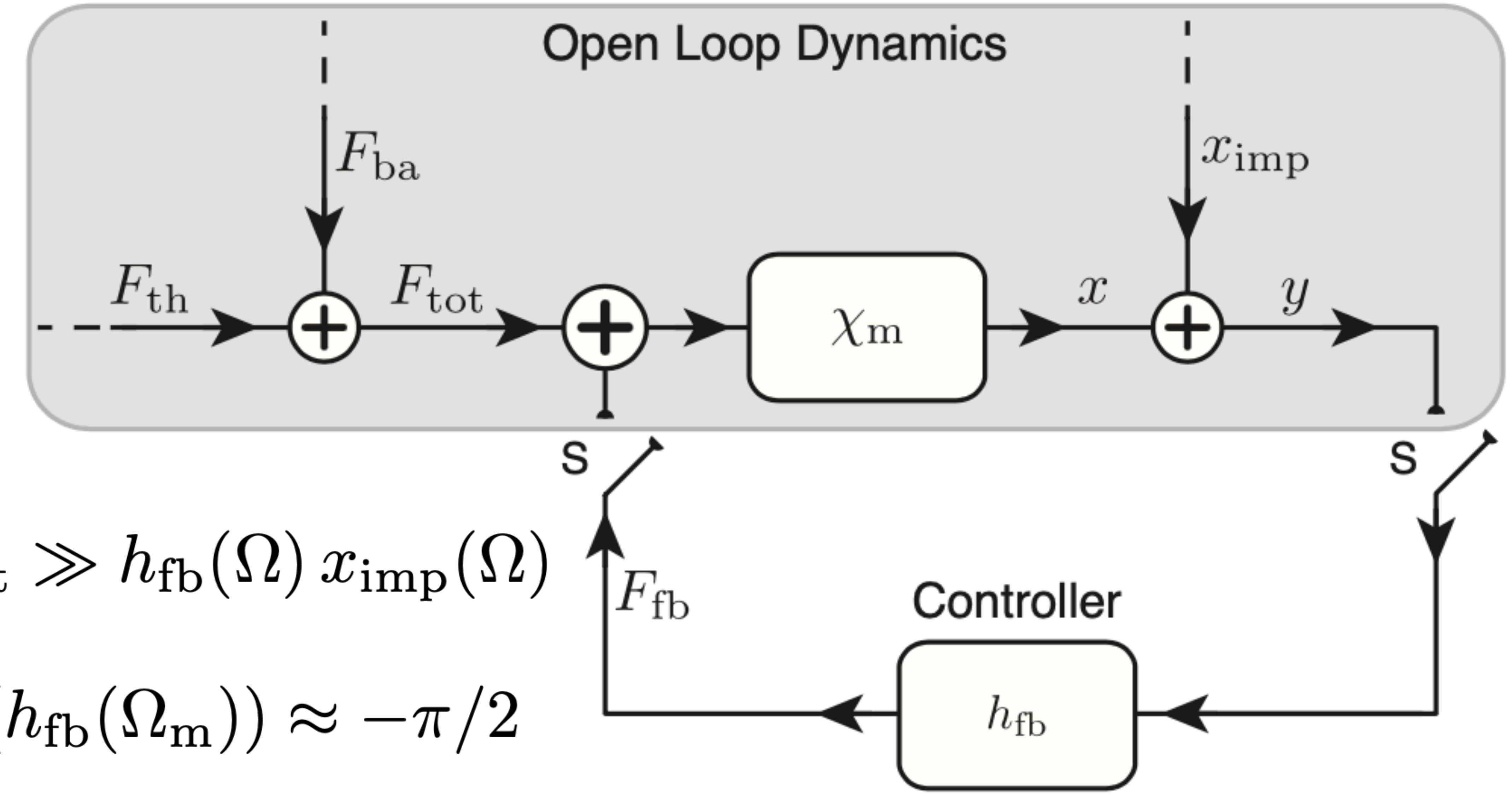
$$y = x + x_{\mathrm{imp}}$$

- measurement efficiency:

$$\eta = \frac{\Gamma_{\mathrm{meas}}}{\Gamma_{\mathrm{th}} + \Gamma_{\mathrm{opt}}} = \frac{\eta_{\mathrm{det}}}{1 + 1/C_{\mathrm{q}}}$$

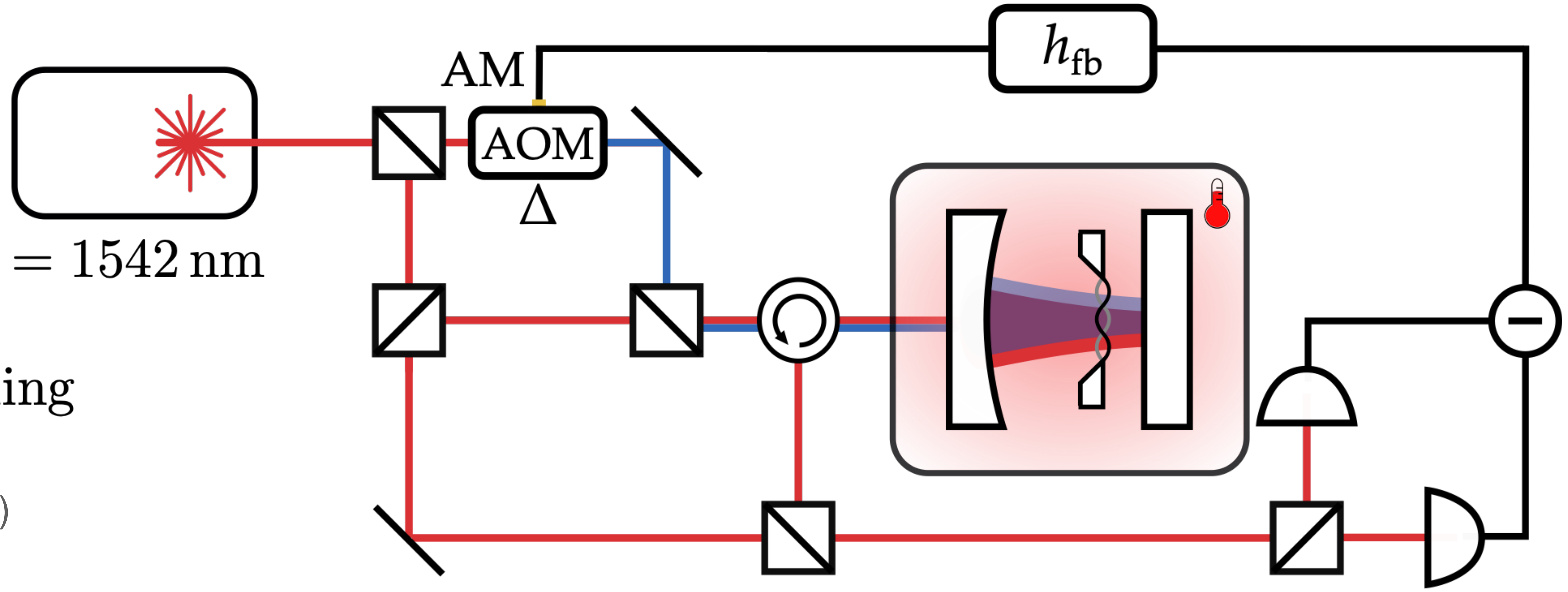
- ideal filter:

$$\bar{n}_{\mathrm{est}} \approx \frac{1}{2}\left(\sqrt{\frac{1}{\eta}} - 1\right)$$



$$F_{\mathrm{tot}} \gg h_{\mathrm{fb}}(\Omega)\, x_{\mathrm{imp}}(\Omega)$$

$$\arg(h_{\mathrm{fb}}(\Omega_{\mathrm{m}})) \approx -\pi/2$$

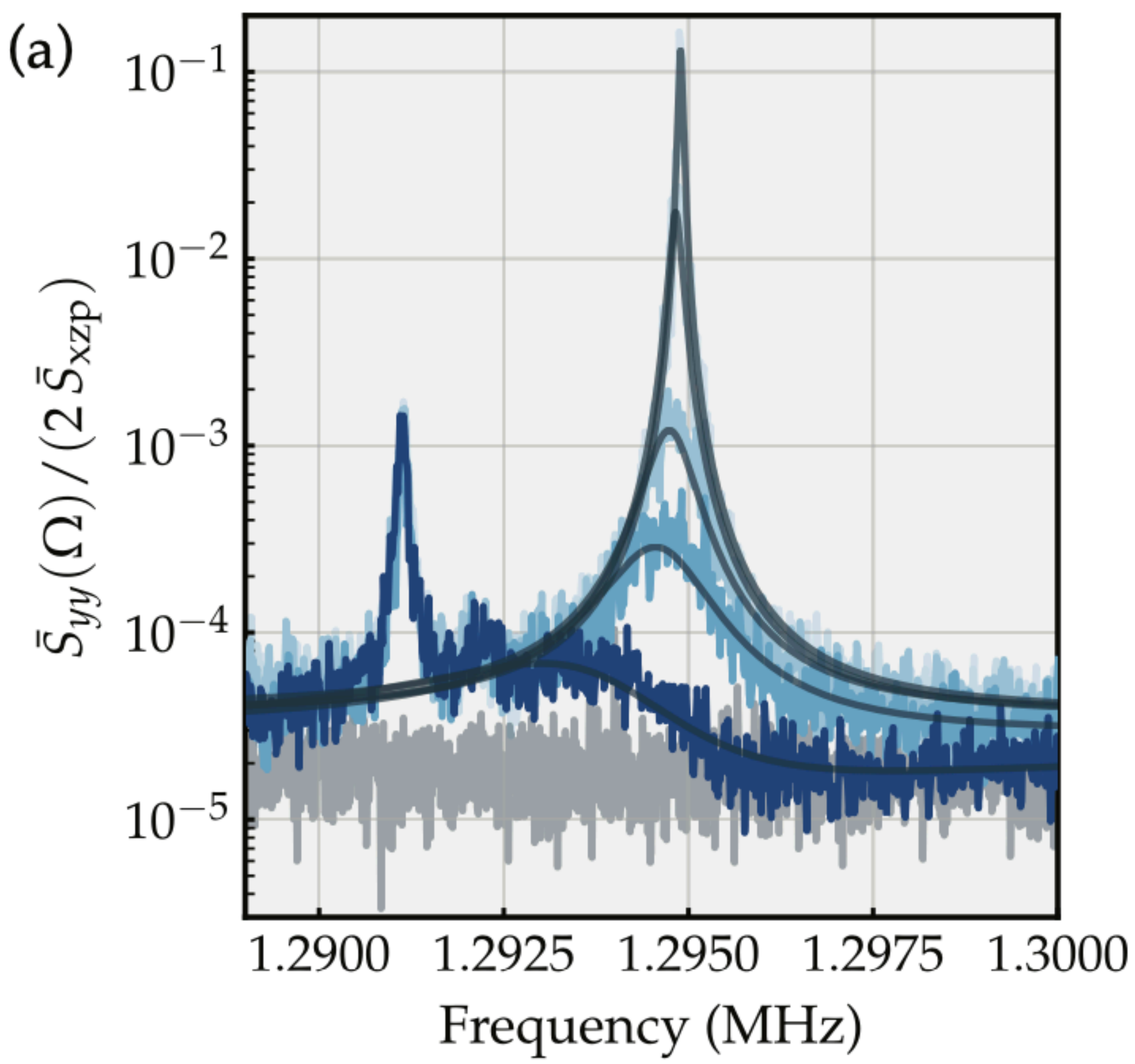


$\Delta = 0$, readout, locking (red)

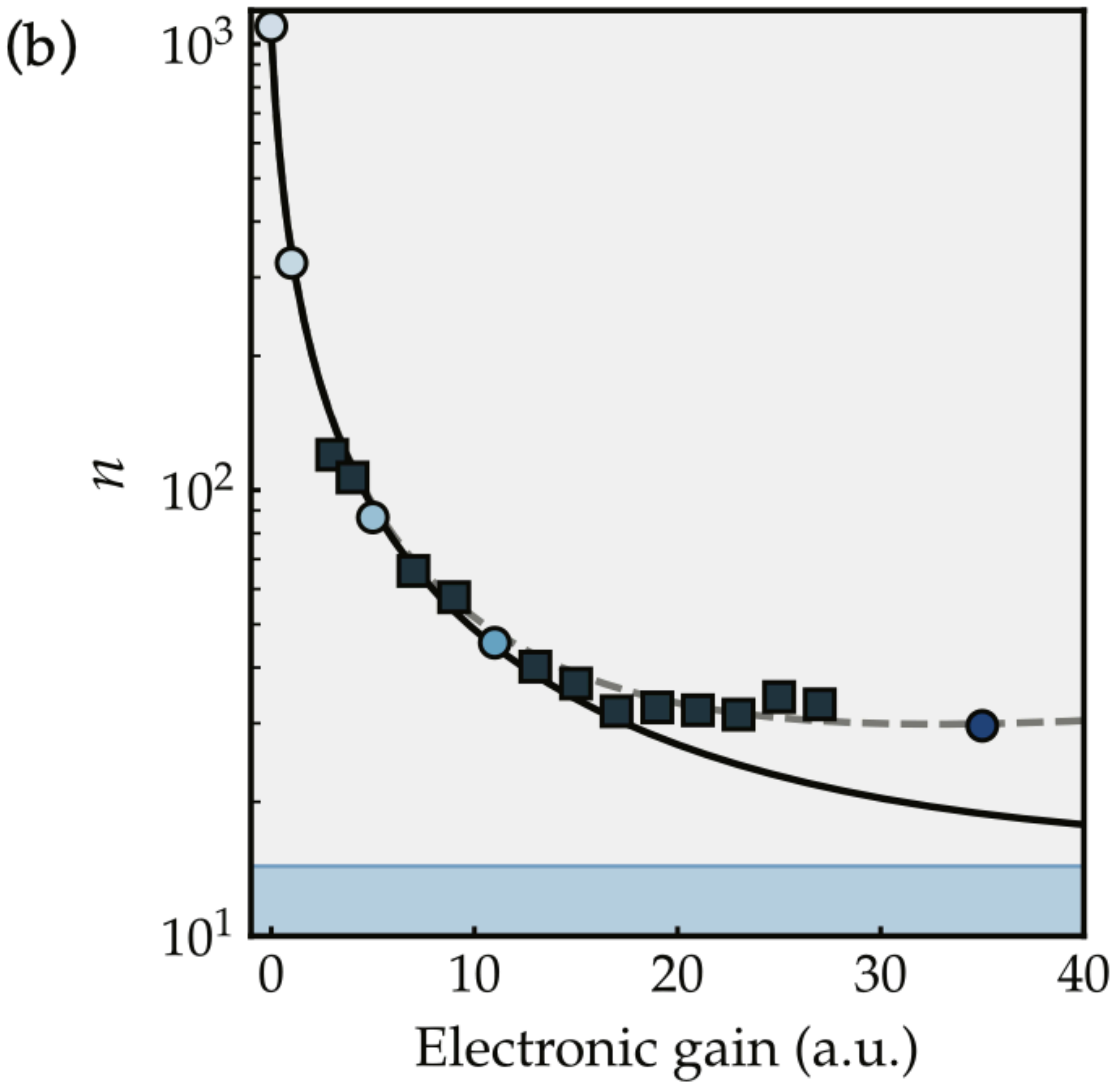
$\Delta = -80\,\mathrm{MHz}$, feedback, cooling (blue)

S. Saarinen, N. Kralj et al., Optica 10 (3), 364-372 (2023)

Quantum optomechanics at room temperature



$$C_{\mathrm{q}} = 0.1$$



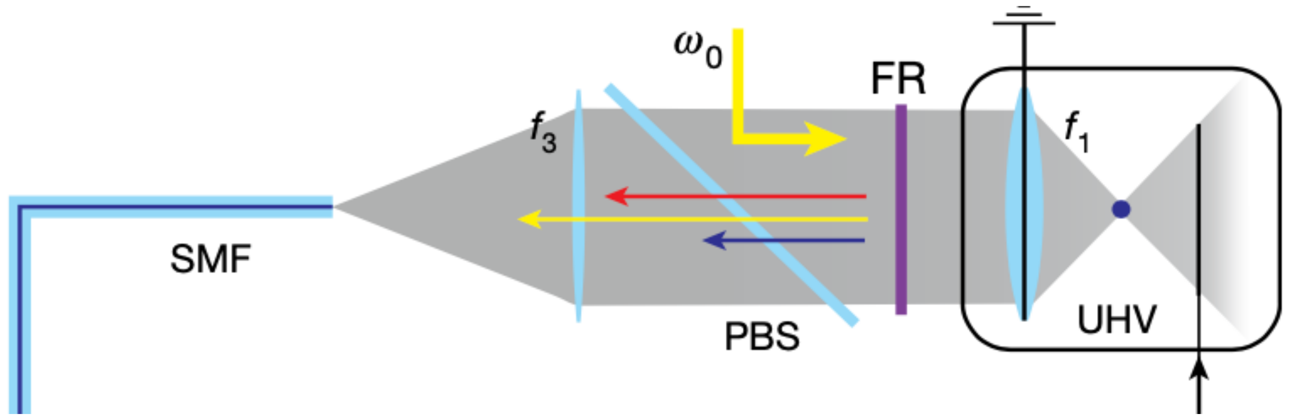
$$\bar{n}_{\mathrm{f}} = 30 \pm 8$$

but unity quantum cooperativity not prohibited by bistability!

S. Saarinen, N. Kralj et al., Optica 10 (3), 364-372 (2023)

Article

Real-time optimal quantum control of mechanical motion at room temperature



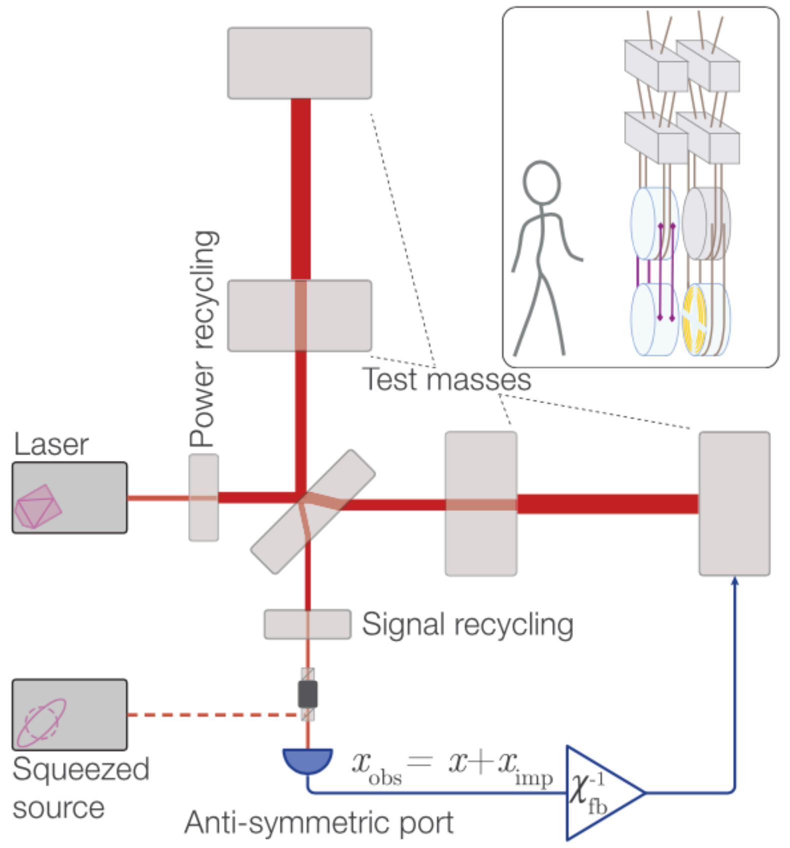
L. Magrini et al., Nature 595, 373-377 (2021)

OPTOMECHANICS

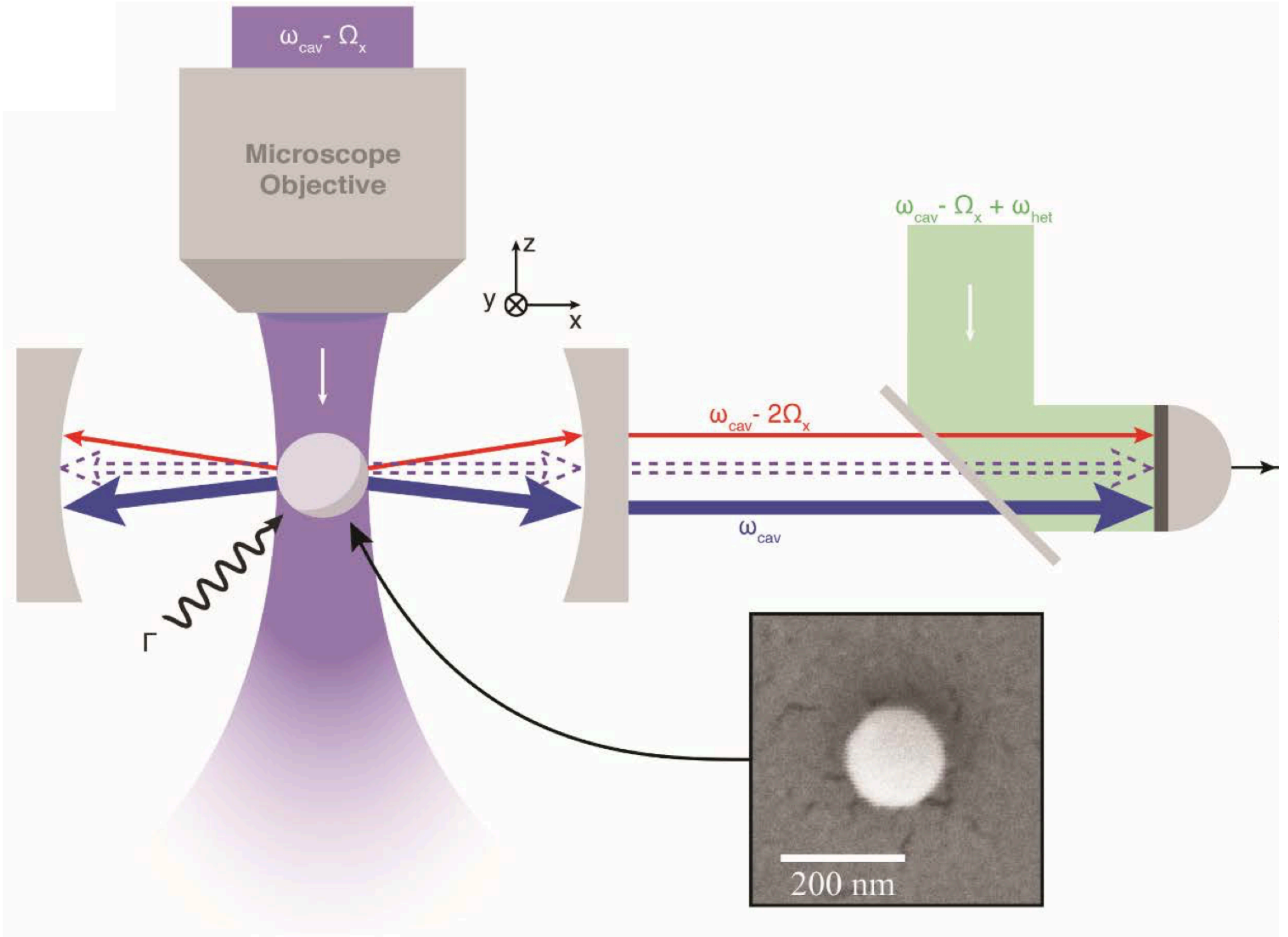
Approaching the motional ground state of a 10-kg object

C. Whittle et al., Science, Vol. 372, Issue 6548, pp. 1333-1336 (2021)

$$\bar{n}_{\mathrm{f}} \approx 10$$

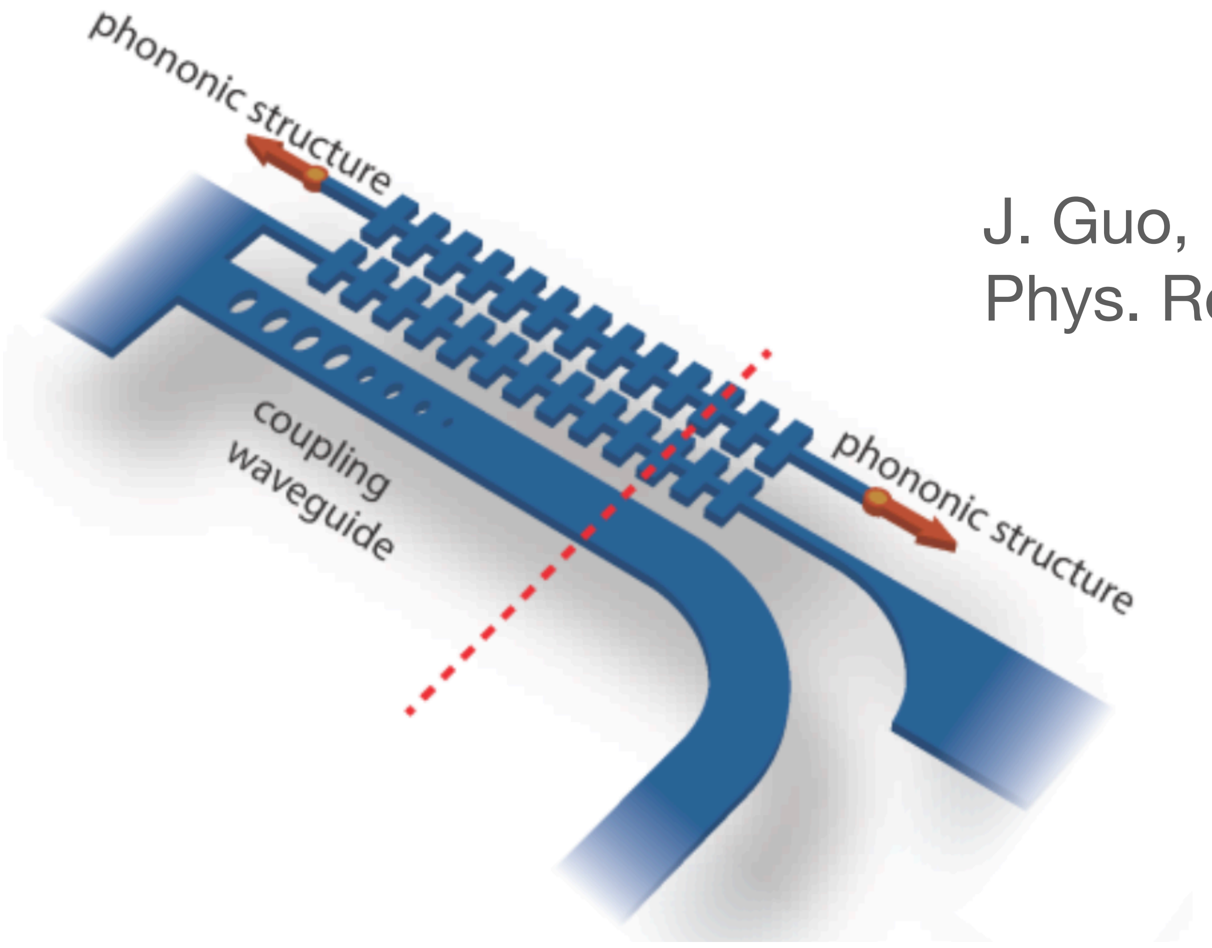


Cooling of a levitated nanoparticle to the motional quantum ground state



U. Delić et al., Science, Vol. 367, Issue 6480, pp. 892-895 (2020)

Feedback Cooling of a Room Temperature Mechanical Oscillator close to its Motional Ground State



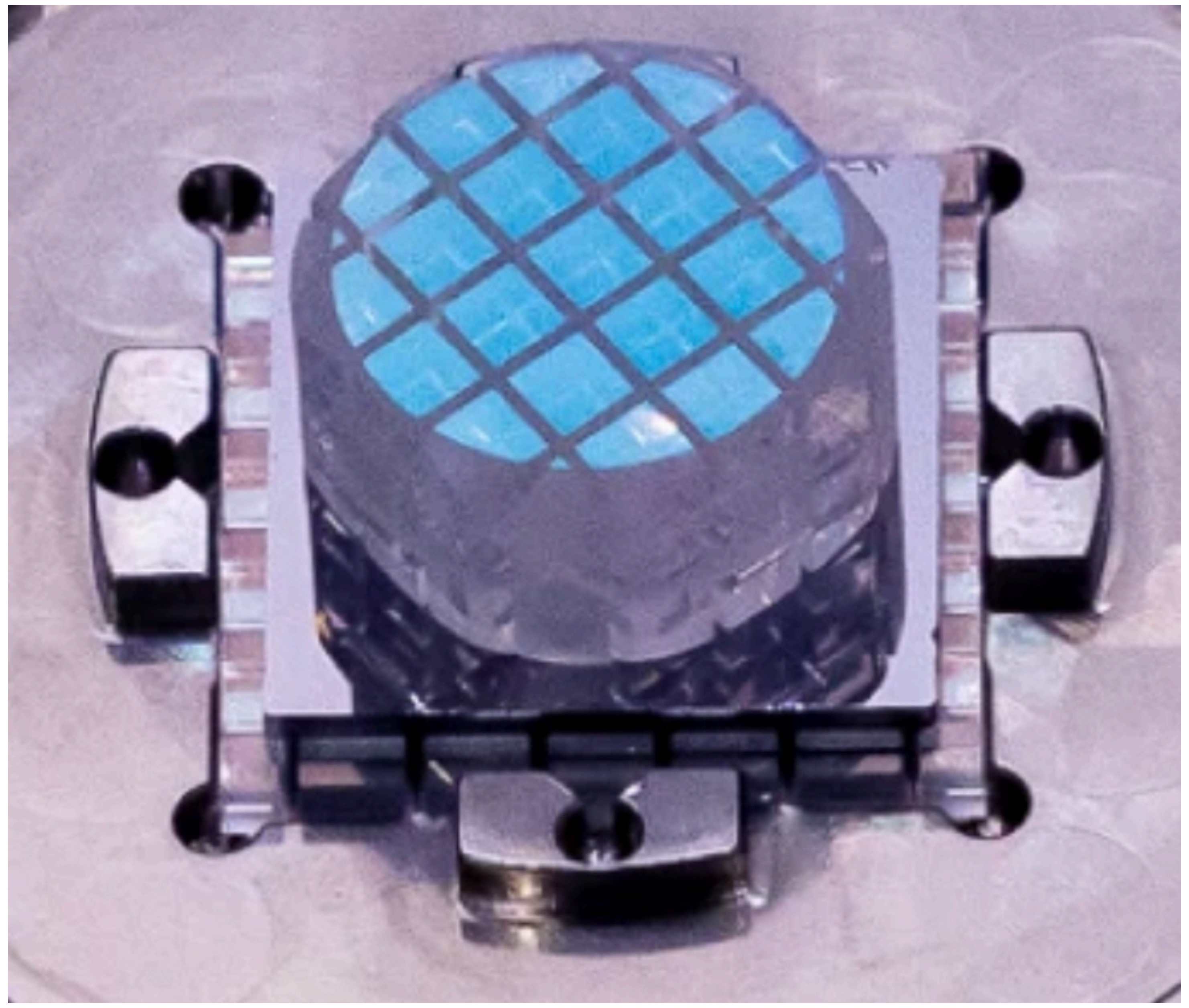
J. Guo, R. Norte and S. Gröblacher, Phys. Rev. Lett. 123, 223602 (2019)

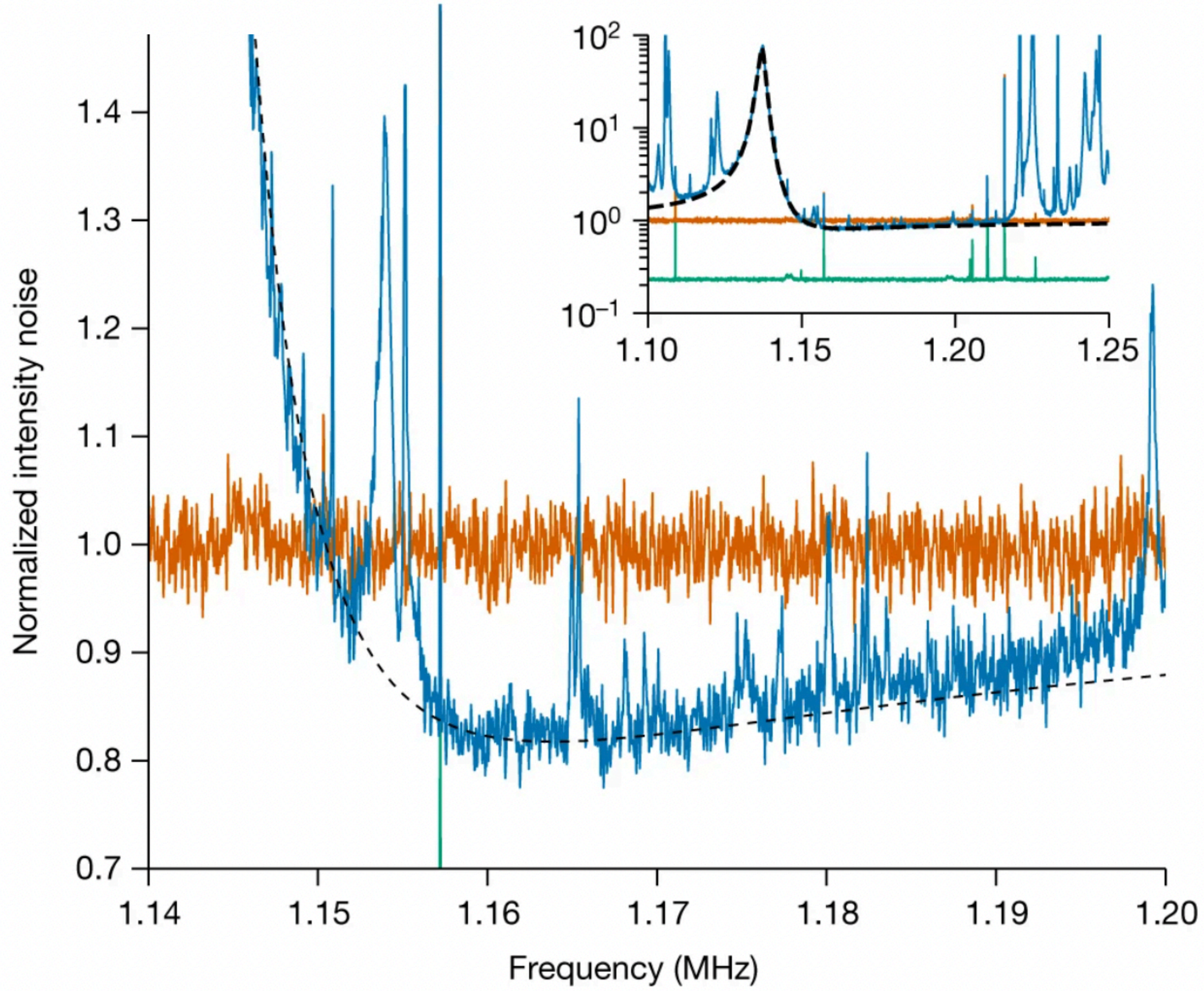
$$\bar{n}_{\mathrm{f}} \approx 27$$

$$m_{\mathrm{eff}} = 73.6\,\mathrm{pg}$$

$$@1550\,\mathrm{nm}$$

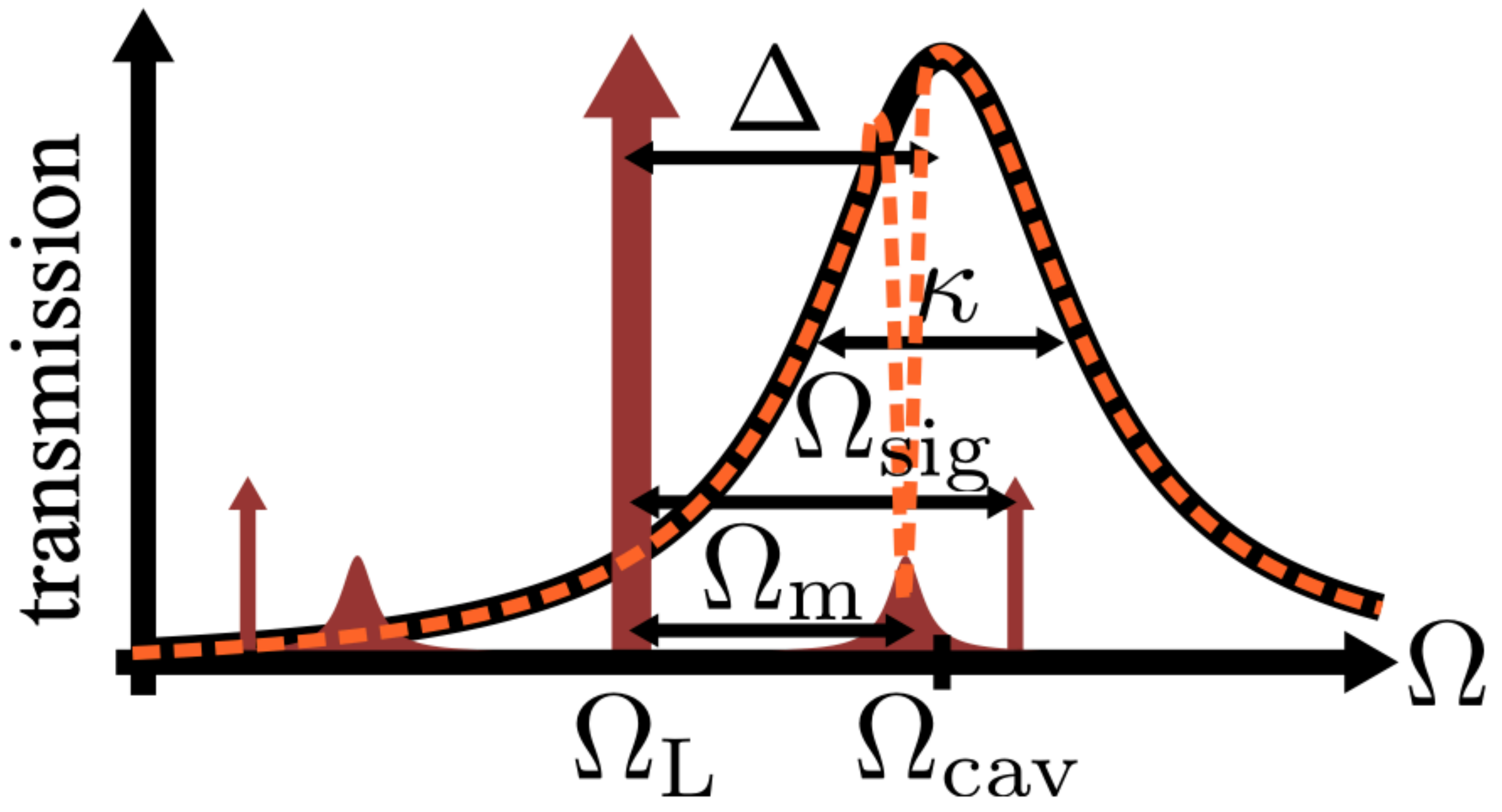
Room-temperature quantum optomechanics using an ultralow noise cavity

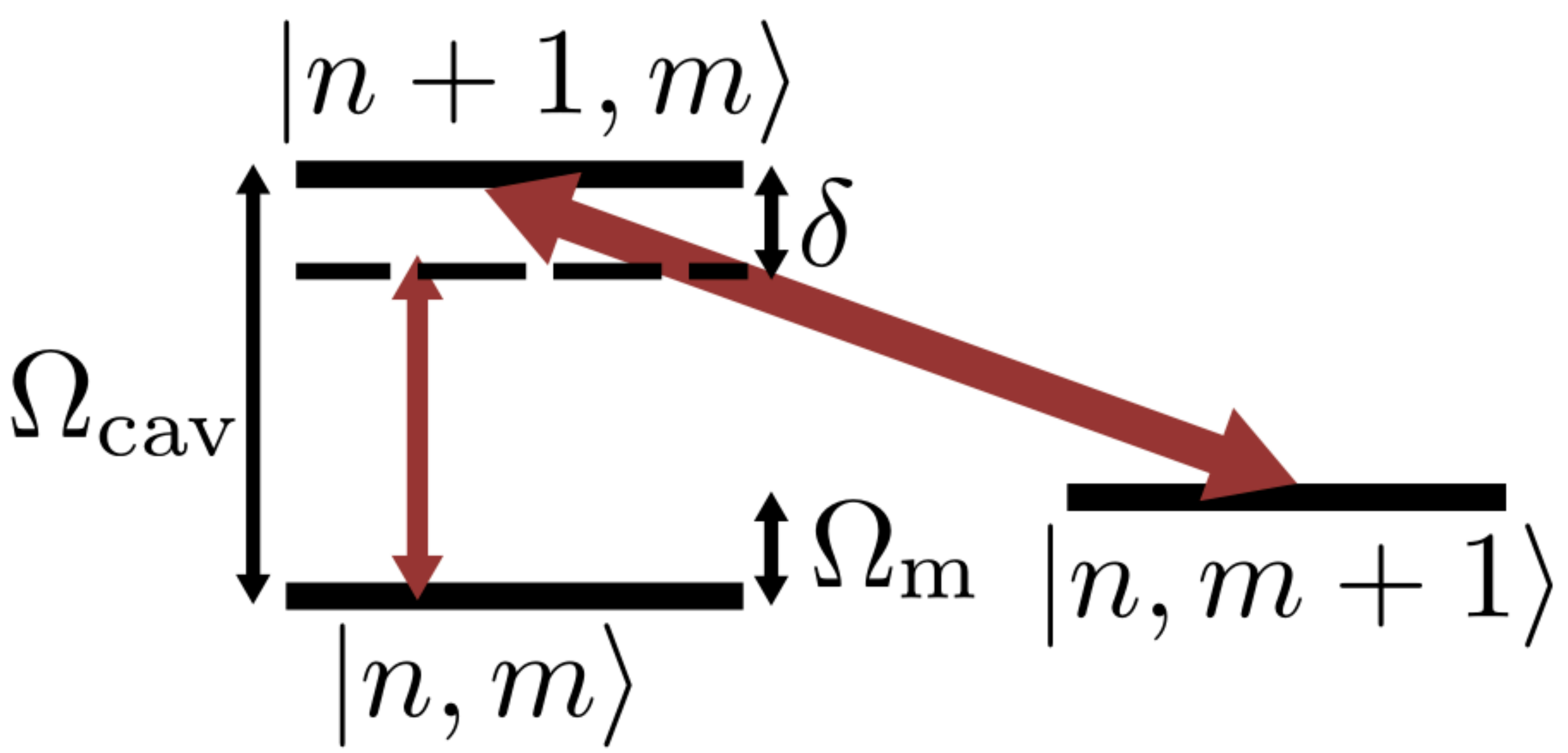




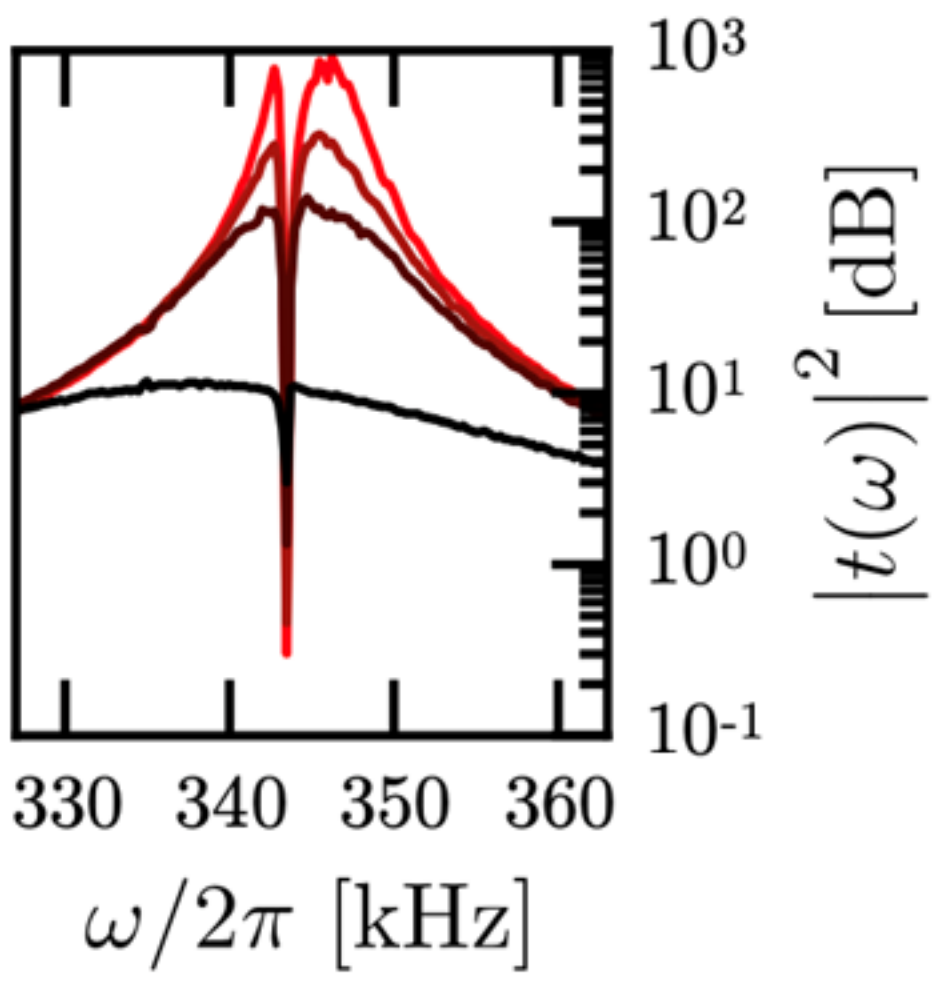
G. Huang et al., Nature 626, 512 (2024)

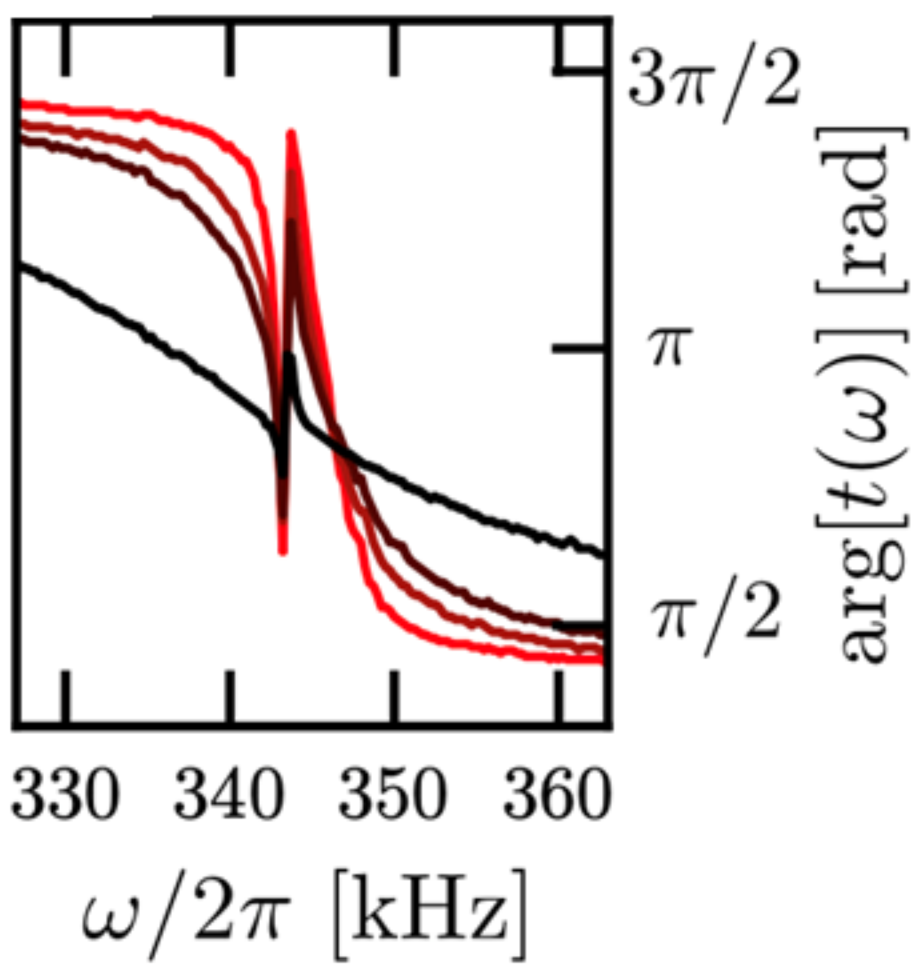
OMIT-based mechanical memory for single photons





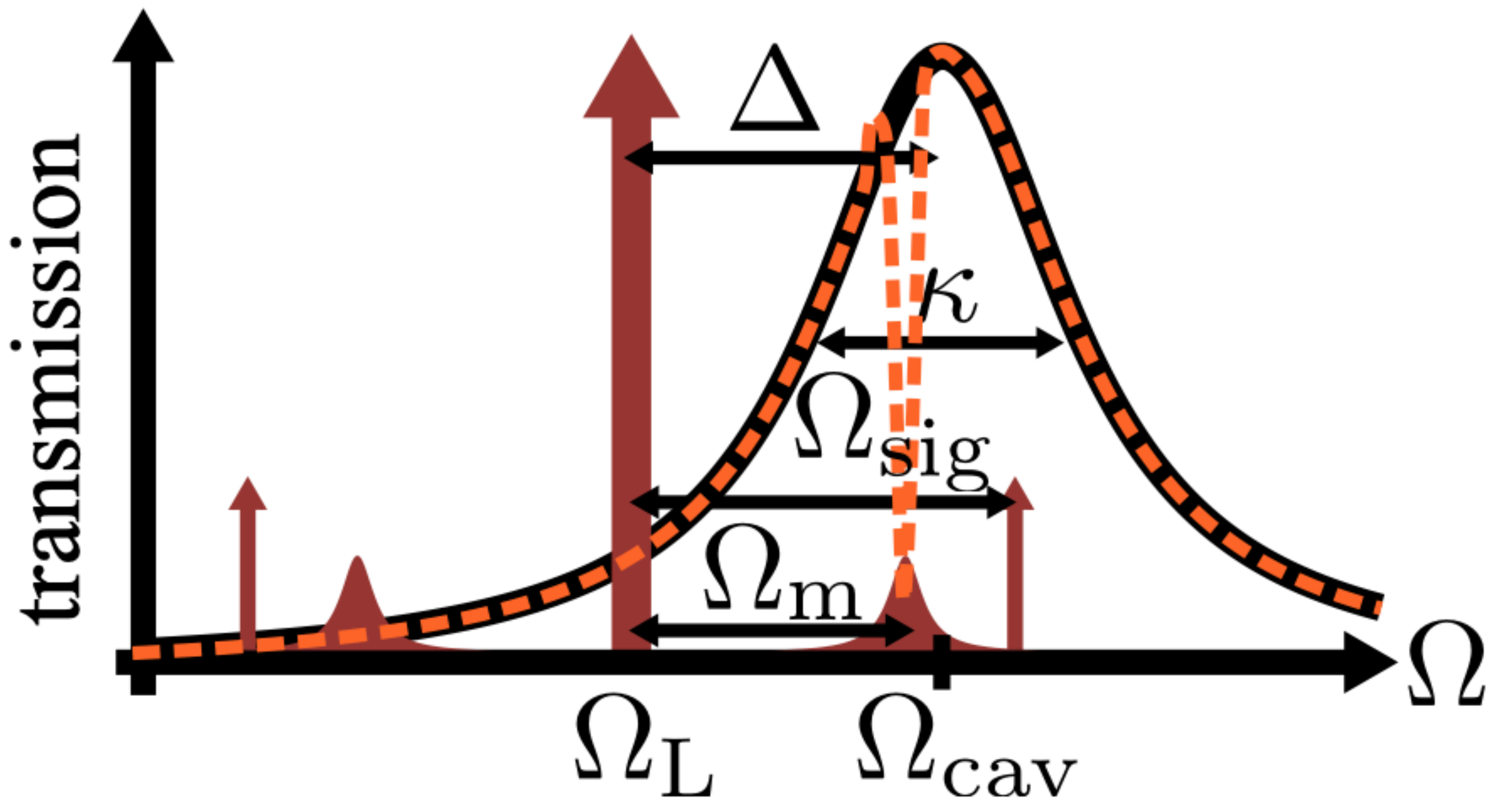
ideal memory:
- high efficiency
- long coherence time
- telecom operation
- on-demand readout





$$v_g(\omega) = \frac{c}{n_R(\omega) + \omega\, dn_R/d\omega}$$

OMIT-based mechanical memory for single photons



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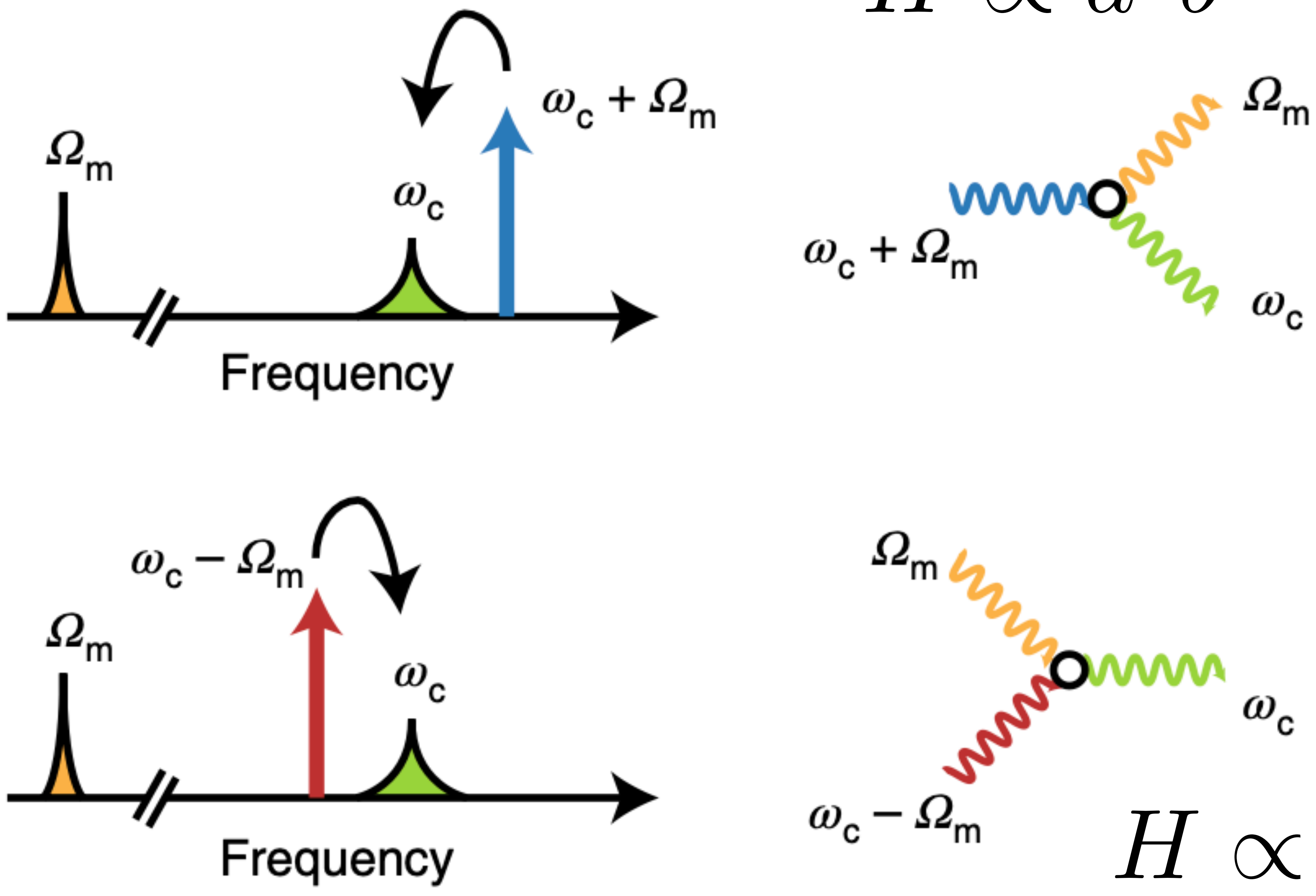
Wallucks et al. (Gröblacher group)

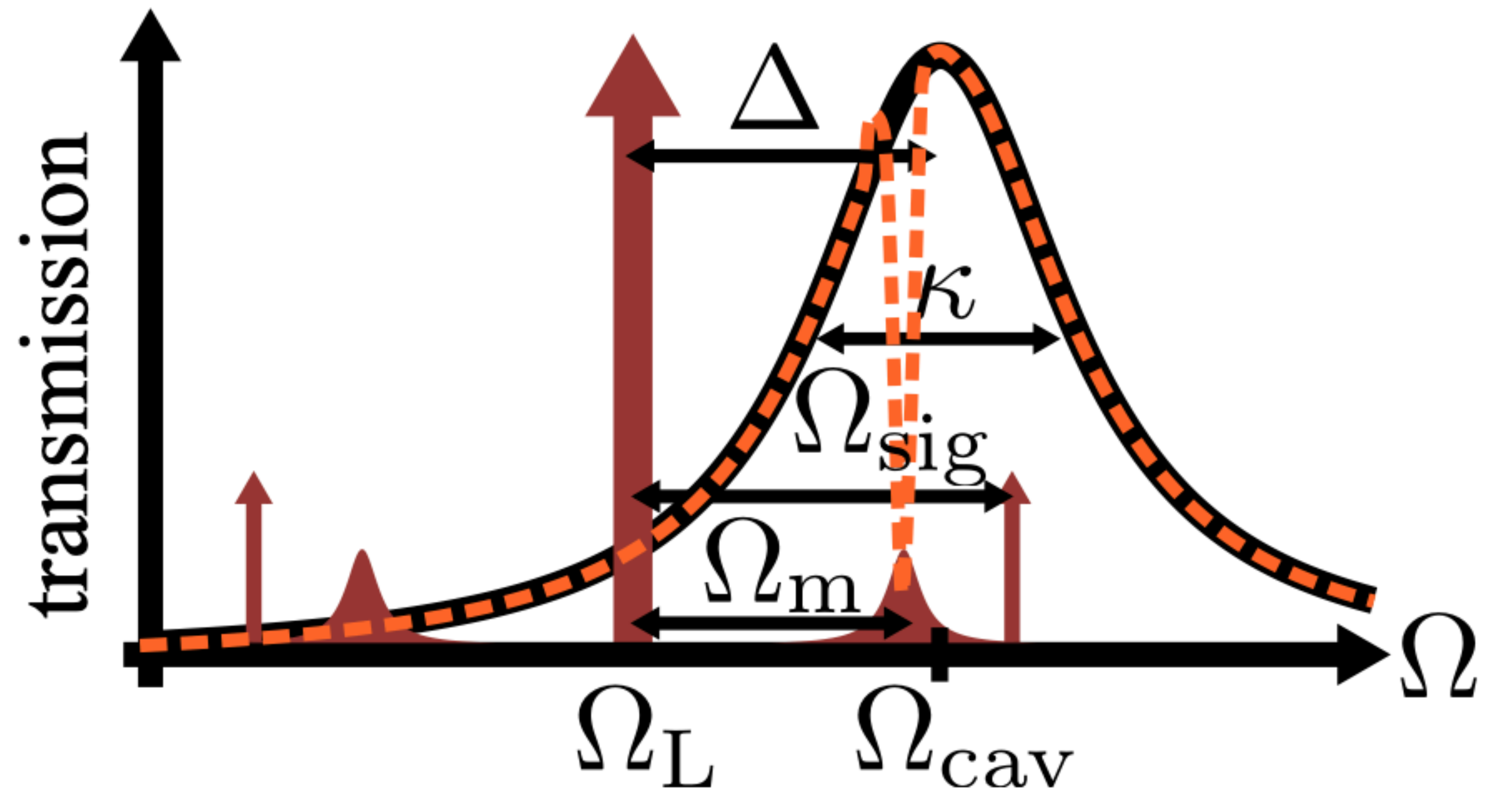


$$H \propto a^\dagger b^\dagger + \text{c.c.}$$

$$H \propto a^\dagger b + \text{c.c.}$$

$$H \propto g_0 \sqrt{\bar{n}_{cav}} (a + a^\dagger)(b + b^\dagger)$$

OMIT-based mechanical memory for single photons



$$C_q \equiv \frac{\Gamma_{opt}}{\Gamma_{th}} \geq 1$$

ideal memory:
- high efficiency
- long coherence time
- telecom operation
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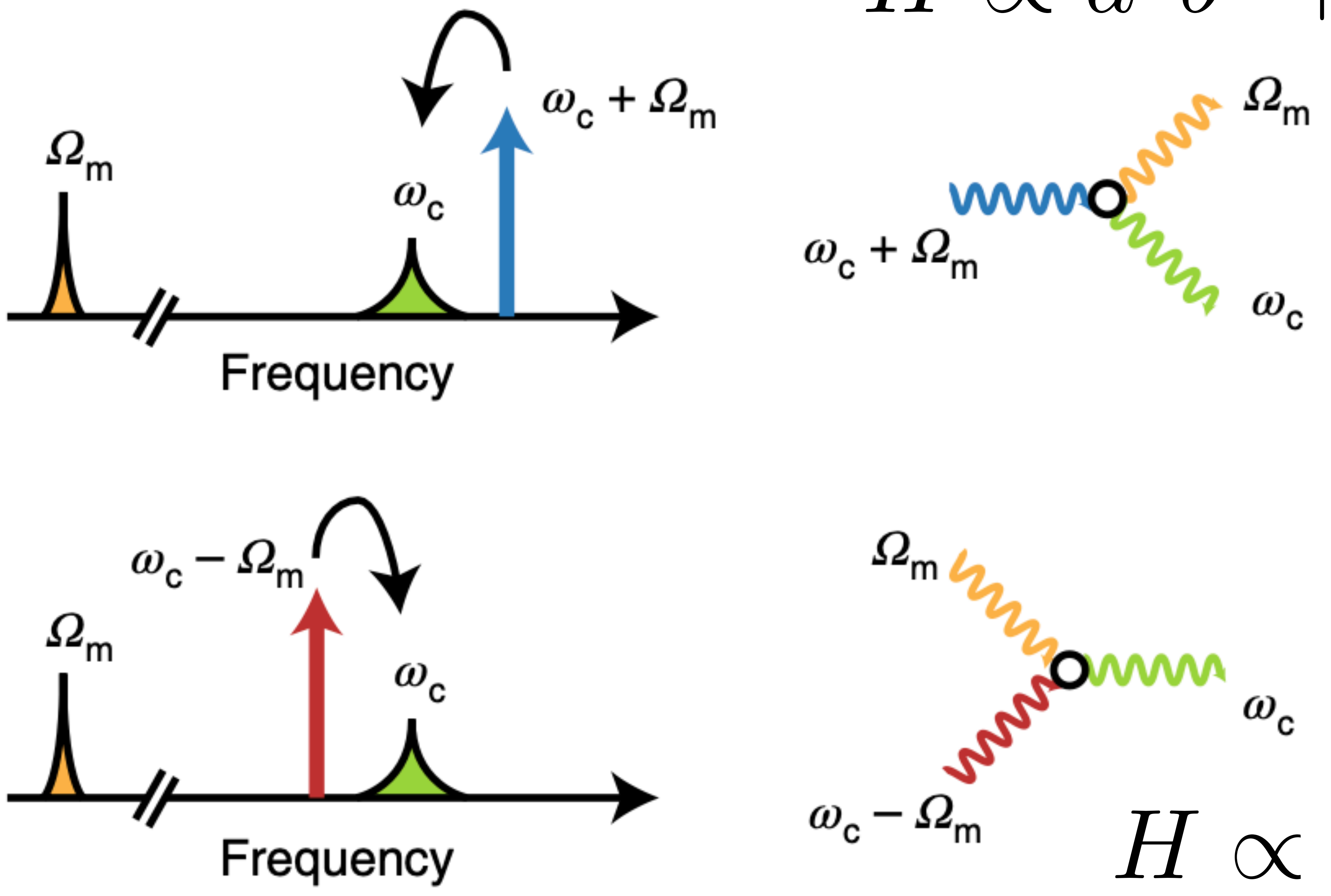
Wallucks et al. (Gröblacher group)

$$H \propto a^\dagger b^\dagger + \text{c.c.}$$



$$H \propto a^\dagger b + \text{c.c.}$$

$$H \propto g_0 \sqrt{\bar{n}_{cav}} (a + a^\dagger)(b + b^\dagger)$$

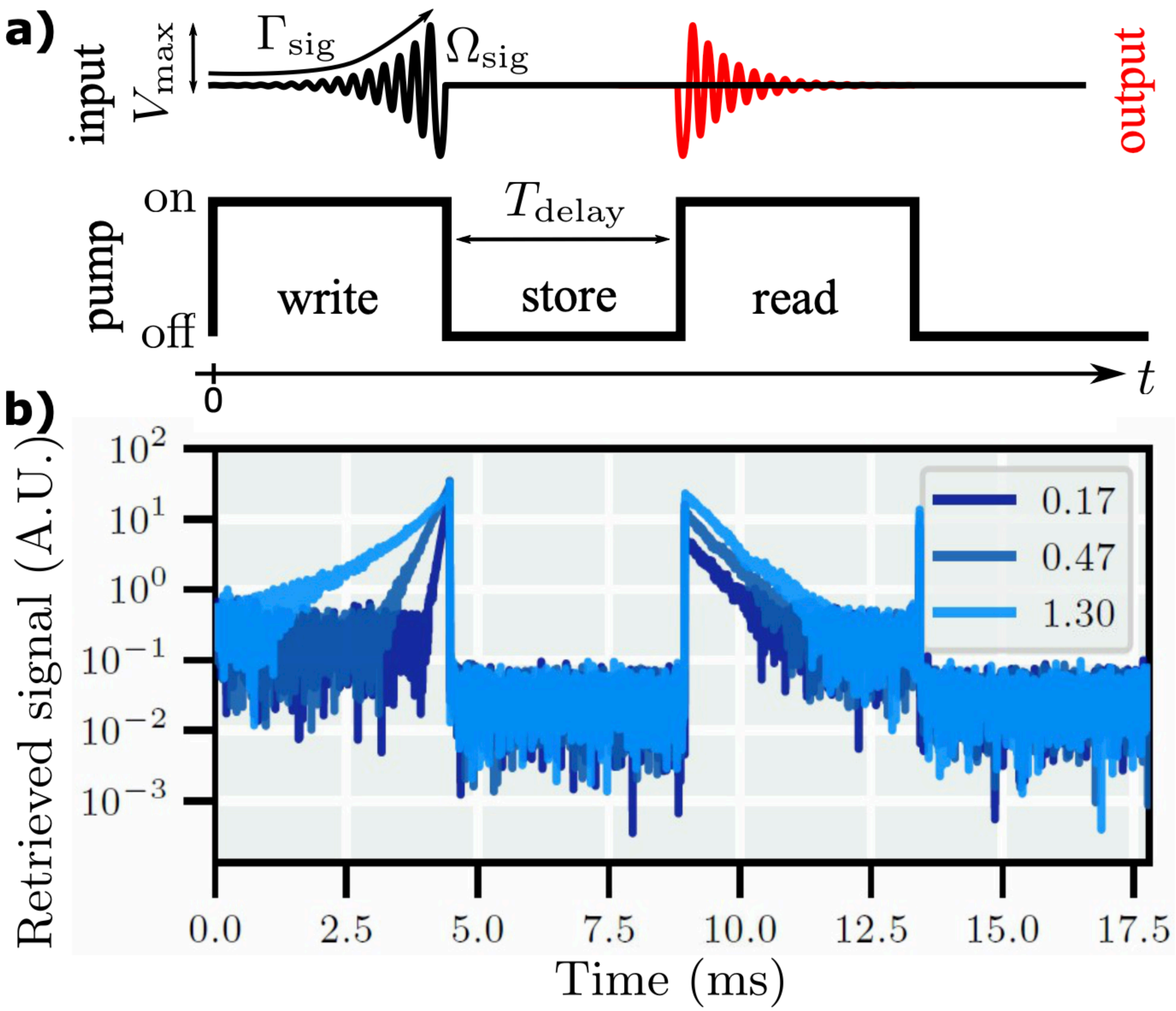
$$V_{\mathrm{EOM}}(t) = V_{\max} \sin(\Omega_{\mathrm{sig}} t) e^{(\Gamma_{\mathrm{sig}} t/2)}$$

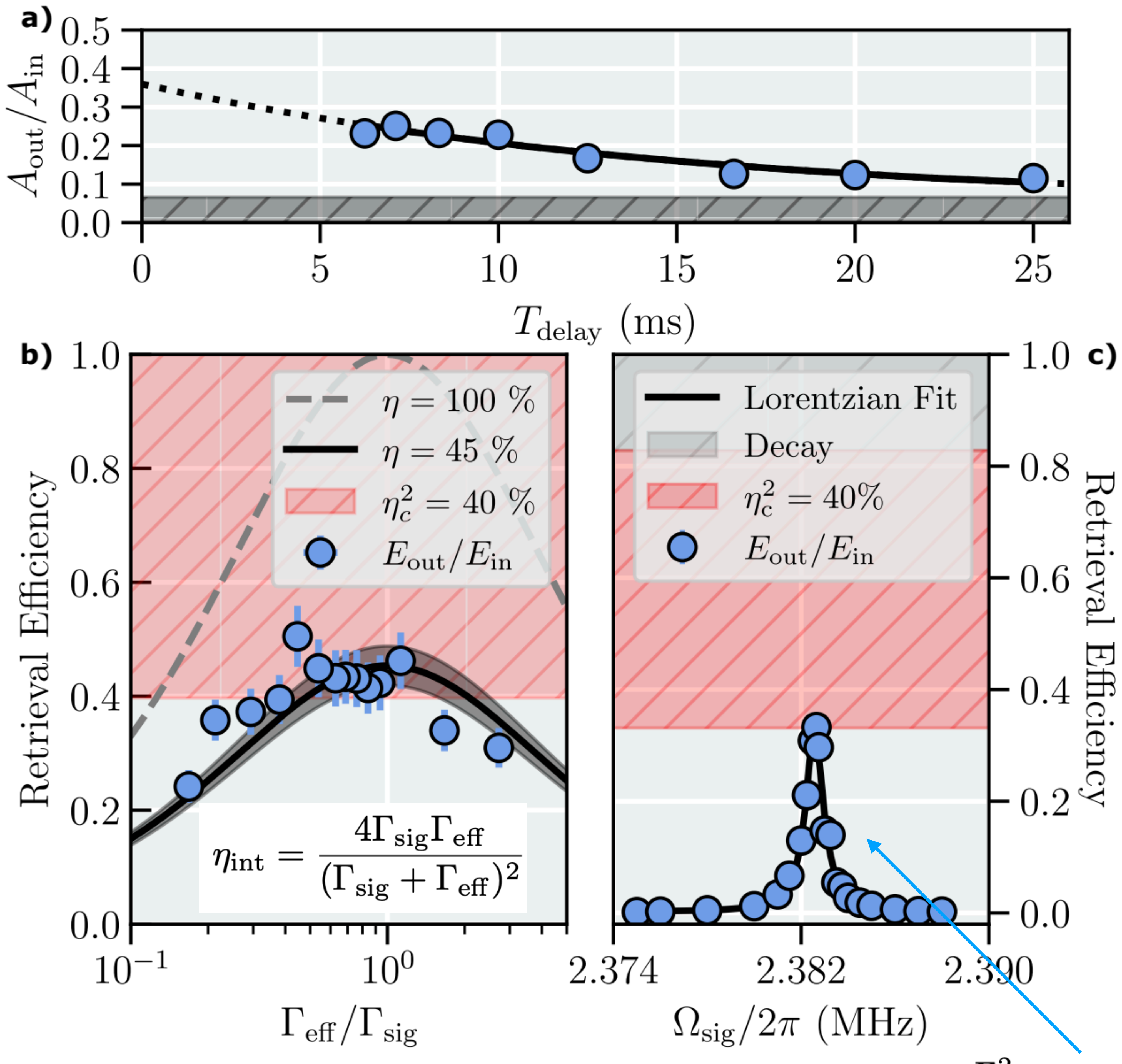
$$\Gamma_{\mathrm{eff}} = 1/(2T_1)$$

$$\eta = \eta_c^2 \, \eta_{\mathrm{int}}$$

$$T_1 = 23\,\mathrm{ms}$$

$$\eta \approx 40\,\%$$





$$\eta = \eta_c^2 \cdot \frac{\Gamma_{\mathrm{eff}}^2}{\delta^2 + \Gamma_{\mathrm{eff}}^2} \cdot e^{-\frac{T_{\mathrm{delay}}}{T_1}}$$

$$Q = 100(3) \times 10^6 \qquad \Omega_{\mathrm{m}}/2\pi = 2.4\,\mathrm{MHz}$$

M. Bjeregaard Kristensen, N. Kralj et al., Phys. Rev. Lett. 132, 100802 (2024).

FIZRI

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$$\Gamma_{\mathrm{pht}} \ll \Gamma_{\mathrm{OMIT}} \ll \kappa \ll \Omega_{\mathrm{m}}$$

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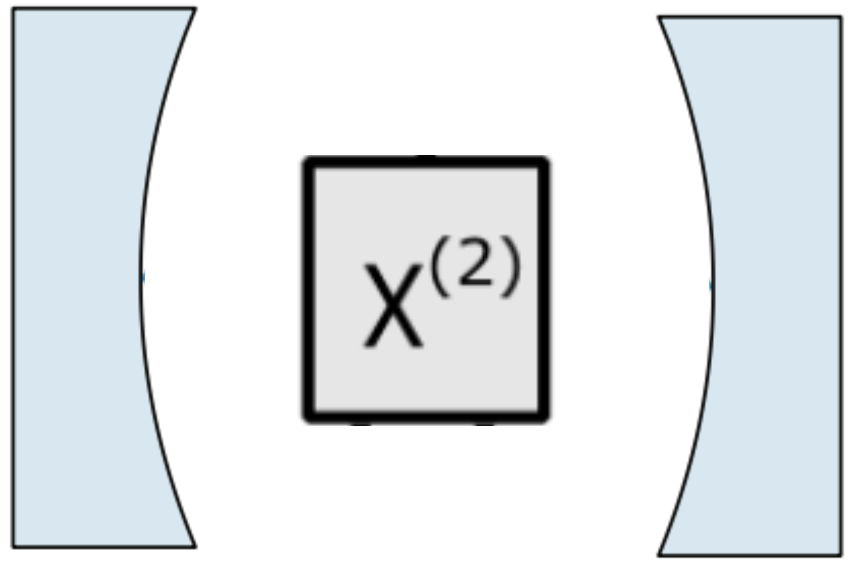

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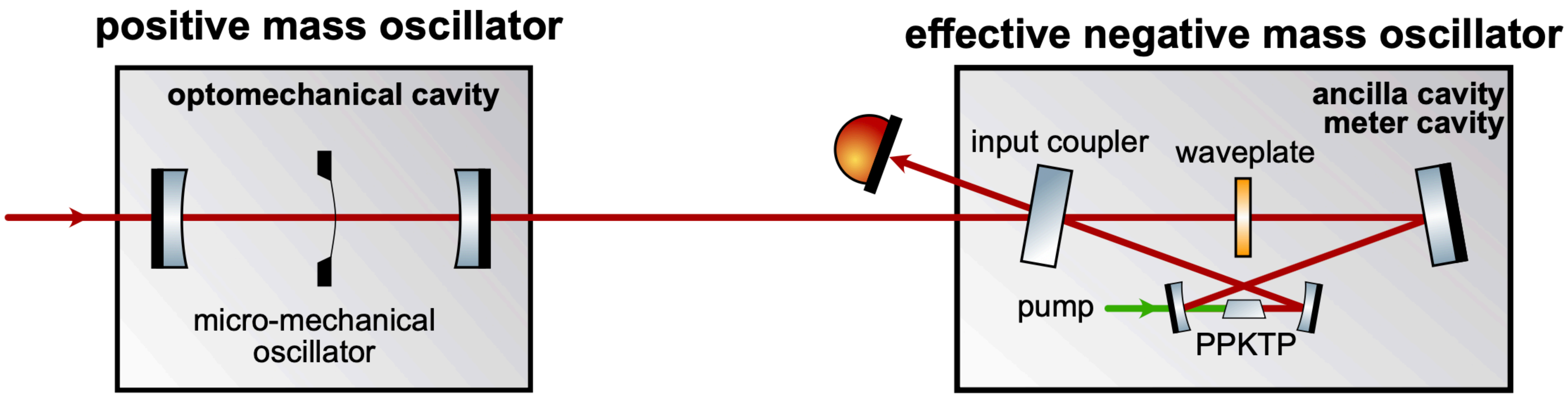

based on idea by M. Tsang and C.M. Caves, Phys. Rev. Lett. 105, 123601 (2010).