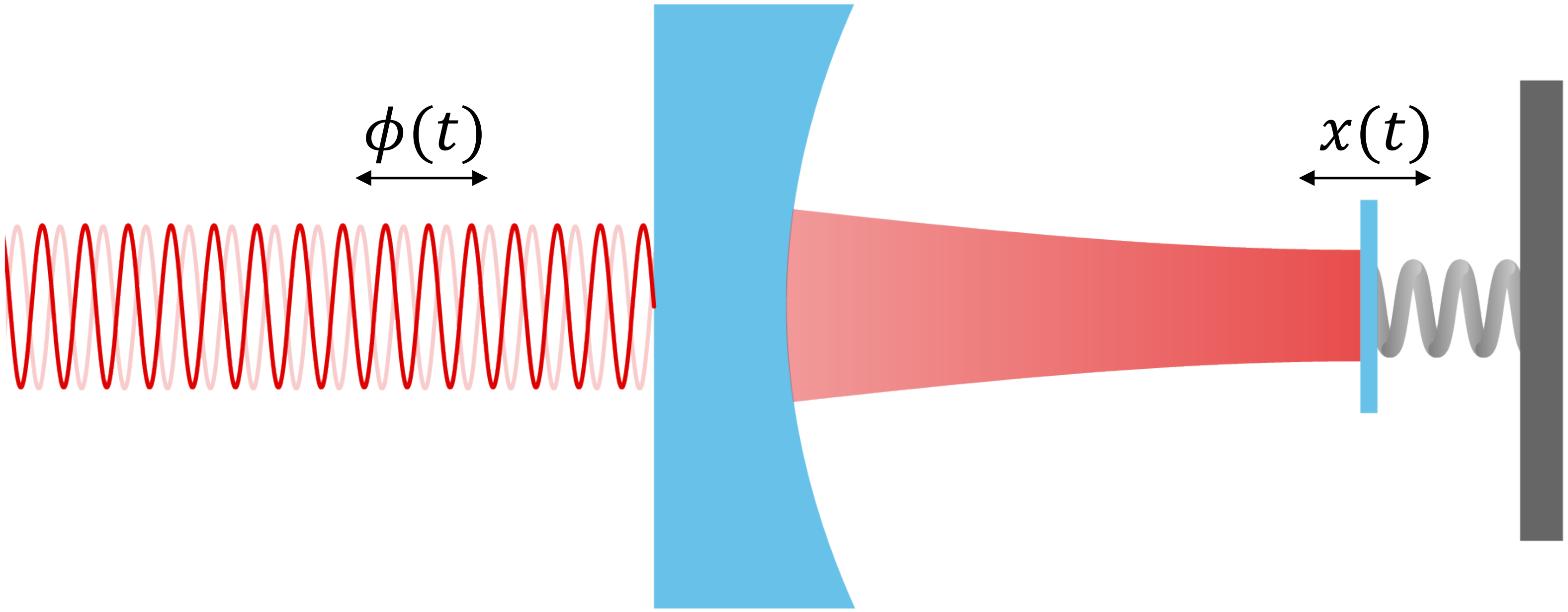
Ultracoherent mechanical resonators for quantum optomechanics

Nils J. Engelsen, Sergey A. Fedorov, Mohammad J. Bereyhi, Amir H. Ghadimi, Amirali Arabmoheghi, Alberto Beccari, Ryan Schilling, Dalziel J. Wilson, Tobias J. Kippenberg

Laboratory of Photonics and Quantum Measurements – EPFL, Switzerland

An idealized optomechanical system



- Mechanical oscillator position maps onto phase shift of light
- Radiation pressure from the light interacts with mechanical oscillator
- Cavity enhances interaction strength

M. Aspelmeyer, T. J. Kippenberg and F. Marquardt, Rev. Mod. Phys. **86**, 1391

History of optomechanics

EPFL

Quantum-Mechanical Radiation-Pressure Fluctuations in an Interferometer

Carlton M. Caves

W. K. Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California 91125

(Received 29 January 1980)

The interferometers now being developed to detect gravitational vaves work by measuring small changes in the positions of free masses. There has been a controversy whether quantum-mechanical radiation-pressure fluctuations disturb this measurement. This Letter resolves the controversy: They do.

The idea of light exerting pressure has existed since Kepler (comet tails)

Late 1960s: Seminal papers from Braginsky explore effects of radiation pressure on mechanical resonators

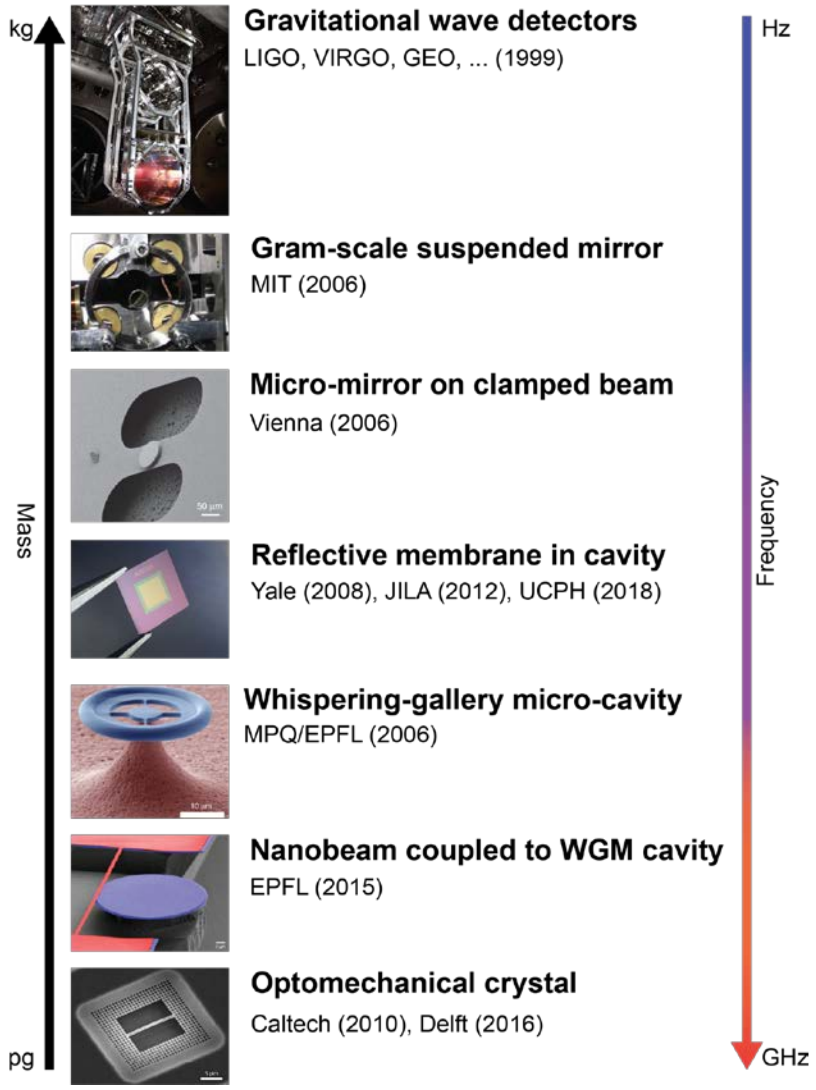
1980: First large interferometers (40m) built by Caltech

Rise of modern optomechanics

<u>2000s:</u> Techniques are developed to control mechanics with light

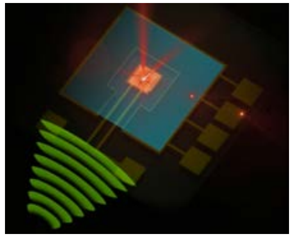
<u>2010:</u> First cooling to the quantum ground state of (macroscopic) mechanical resonators

<u>2010s:</u> Coupling to different systems, development of protocols for generating entanglement etc



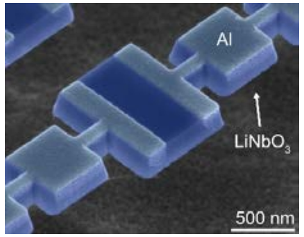
EPFL

Quantum technologies with optomechanics



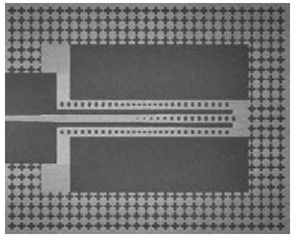
Optical RF detection

Bagci et al., Nature (2014)



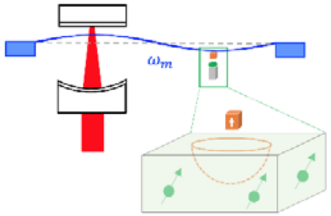
Quantum networking

Arrangoiz-Arriola et al., arXiv:1902.04681 (2019)



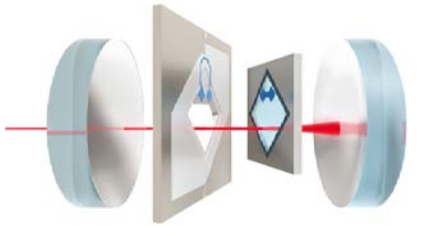
Quantum memory

MacCabe et al., arXiv:1901.04129 (2019)



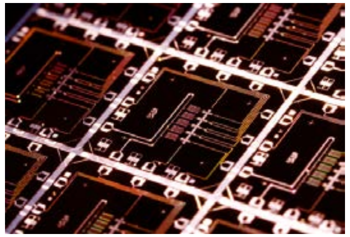
Spin detection (MRFM)

Fischer et al., NJP (2019)



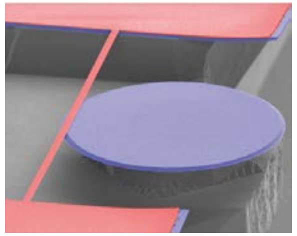
Low noise microwave-to-optical conversion

Higginbotham et al., Nat. Phys. (2017)



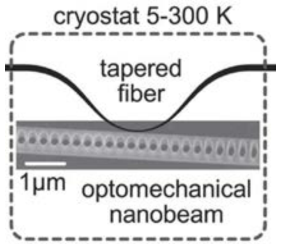
Coupling to qubits

Chu et al., *Science* **359,** 6373 (2017)



Room temperature optomechanics

Sudhir et al., Phys. Rev. X (2017)

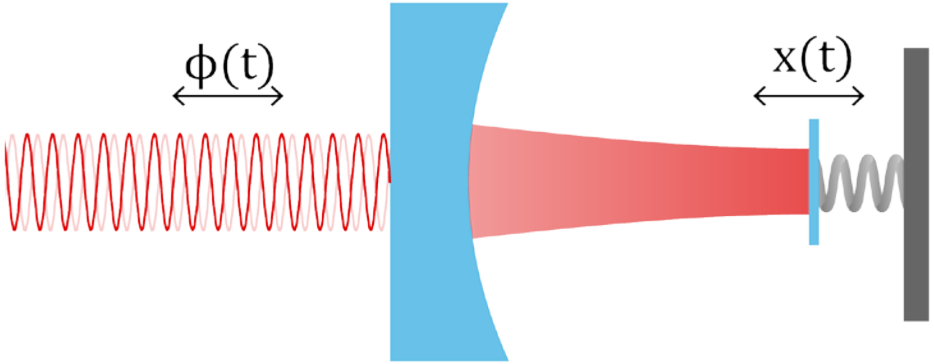


Quantum thermometry

Purdy et al., Science (2017)

Introduction to optomechanical interaction

$$\hat{H}_0 = \hbar\omega_{\mathrm{cav}}(x)\hat{a}^\dagger a + \hbar\omega_m \hat{b}^\dagger \hat{b}$$



$$\omega_{\mathrm{cav}}(x) = \omega_{\mathrm{cav}} + x\partial\omega_{\mathrm{cav}}/\partial x$$

$$\hbar\omega_{\mathrm{cav}}(x)\hat{a}^\dagger\hat{a} \approx \hbar(\omega_{\mathrm{cav}} - G\hat{x})\hat{a}^\dagger\hat{a}, \text{ where } G = -\partial\omega_{\mathrm{cav}}/\partial x$$

$$\hat{x} = x_{\mathrm{ZPF}}\left(\hat{b} + \hat{b}^\dagger\right), g_0 = G x_{\mathrm{ZPF}}$$

$$\hat{H} = -\hbar\Delta\hat{a}^\dagger a + \hbar\omega_m\hat{b}^\dagger\hat{b} - \hbar g_0\, \hat{a}^\dagger\hat{a}(\hat{b} + \hat{b}^\dagger) \qquad \Delta = \omega_L - \omega_{\mathrm{cav}}$$

M. Aspelmeyer, T. J. Kippenberg and F. Marquardt, Rev. Mod. Phys. **86**, 1391

A realistic optomechanical system

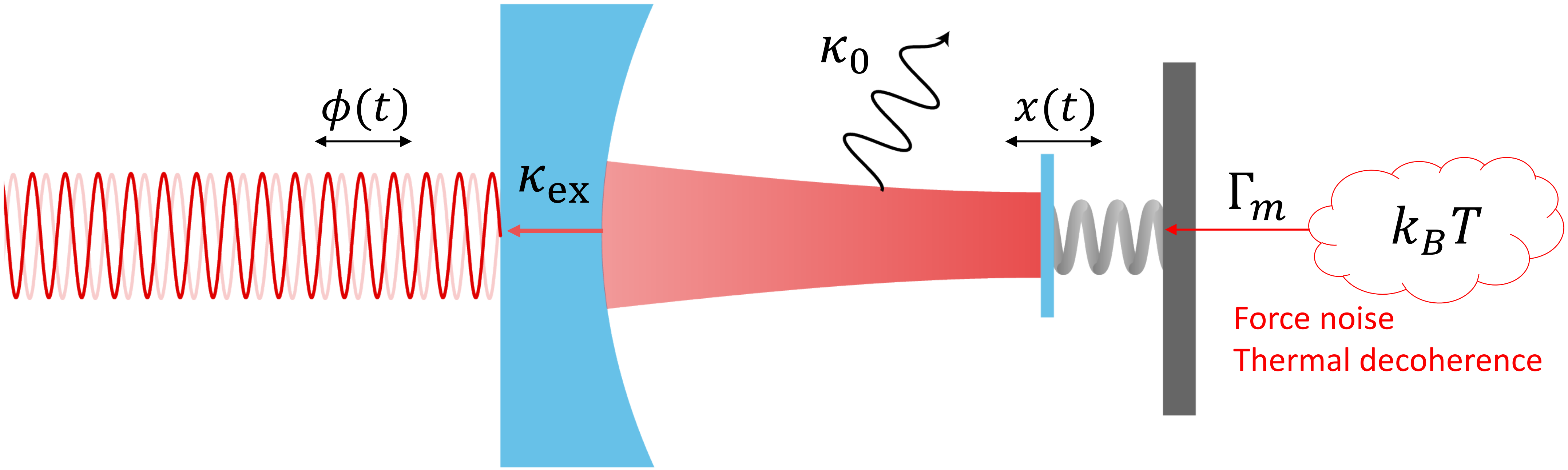


Figure of merit for optomechanical system (single-photon cooperativity): $C_0 = \frac{4g_0^2}{\kappa\Gamma_m}$

M. Aspelmeyer, T. J. Kippenberg and F. Marquardt, Rev. Mod. Phys. **86**, 1391

Equations of motion for optomechanical systems

$$\dot{\hat{a}} = -\frac{\kappa}{2}\hat{a} + i(\Delta + G\hat{x})\hat{a} + \sqrt{\kappa_{ex}}\hat{a}_{\text{in}} + \sqrt{\kappa_0}\hat{a}_{\text{vac}}$$

Cavity loss

Cavity-laser detuning

Optomechanical interaction

Cavity driving term

Vacuum fluctuations

$$\dot{\hat{b}} = \left(-\frac{\Gamma_m}{2} - i\Omega_m\right)\hat{b} + ig_0\hat{a}^\dagger\hat{a} + \sqrt{\Gamma_m}\hat{b}_{\text{in}}$$

Mechanical loss

Optomechanical interaction

Thermal bath

M. Aspelmeyer, T. J. Kippenberg and F. Marquardt, Rev. Mod. Phys. **86**, 1391

Linearized Hamiltonian and equations of motion

EPFL

- Consider a steady-state solution where we set $\hat{a} = \bar{\alpha} + \delta\hat{a}$, where $\bar{\alpha} = \sqrt{n_{\mathrm{cav}}}$, to get:

$$H_{\mathrm{int}} = -\hbar\sqrt{n_{\mathrm{cav}}}g_0\left(\delta\hat{a} + \delta\hat{a}^\dagger\right)\left(\hat{b} + \hat{b}^\dagger\right)$$

- Hamiltonian is now linear in the field operators with an effective interaction strength $g = \sqrt{n_{cav}}g_0$
- Linearized equations of motion:

$$\delta\dot{\hat{a}} = \left(-\frac{\kappa}{2} + i\Delta\right)\delta\hat{a} + ig\left(\hat{b} + \hat{b}^\dagger\right) + \sqrt{\kappa_{ex}}\delta\hat{a}_{\mathrm{in}} + \sqrt{\kappa_0}\hat{a}_{\mathrm{vac}}$$

$$\dot{\hat{b}} = \left(-\frac{\Gamma_m}{2} - i\Omega_m\right)\hat{b} + ig\left(\delta\hat{a} + \delta\hat{a}^\dagger\right) + \sqrt{\Gamma_m}\hat{b}_{\mathrm{in}}$$

M. Aspelmeyer, T. J. Kippenberg and F. Marquardt, Rev. Mod. Phys. **86**, 1391

Fundamental optomechanical interactions

- Can select different interactions with detuning

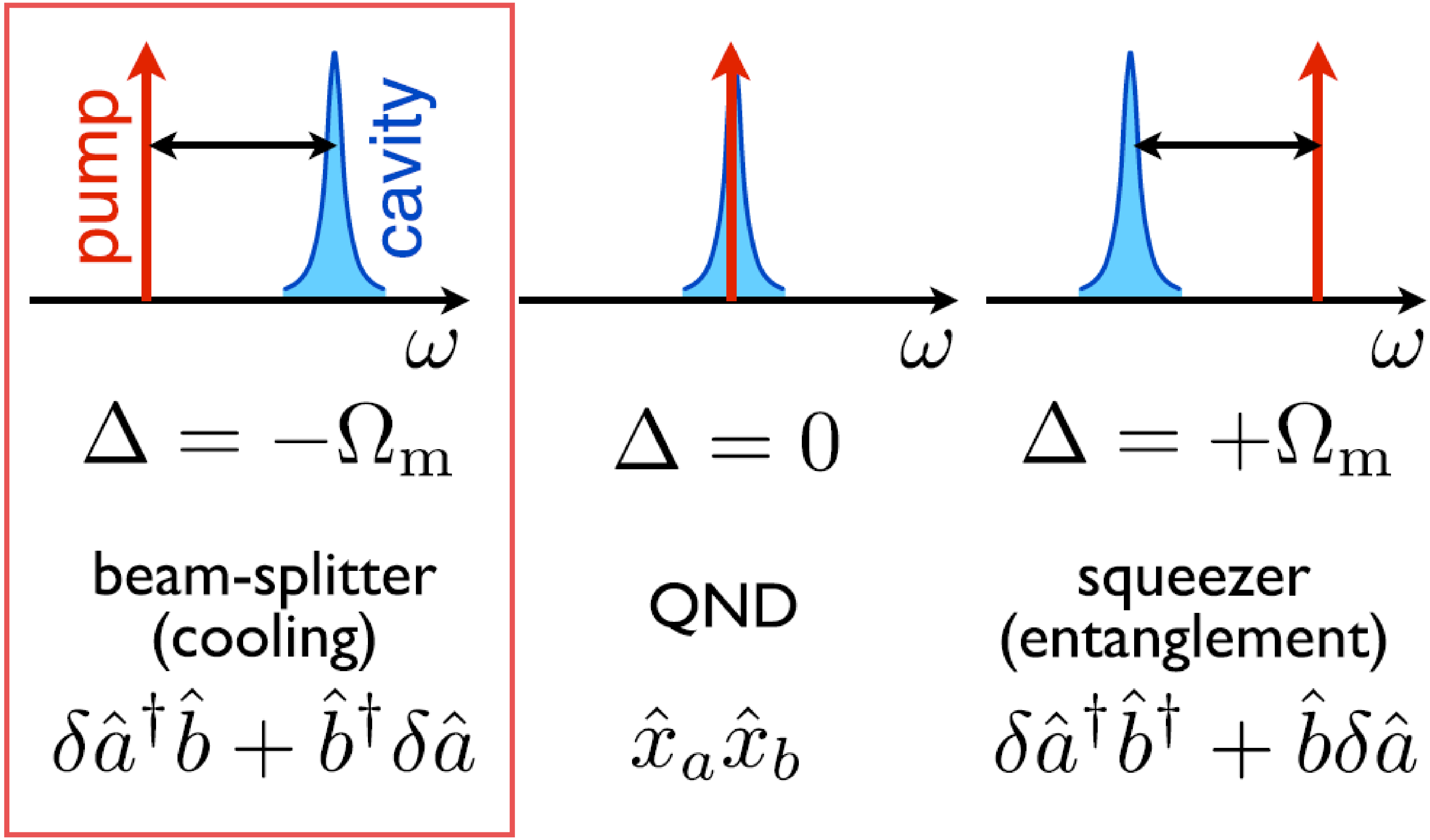


Figure from M. Aspelmeyer, T. J. Kippenberg and F. Marquardt, Rev. Mod. Phys. **86**, 1391

Dynamical backaction (cooling)

Interaction: $-\hbar\sqrt{n_{\mathrm{cav}}}g_0\hat{a}^\dagger\hat{b}$

Cooling rate: $\Gamma_{\mathrm{opt}} = n_{\mathrm{cav}}C_0\Gamma_m$

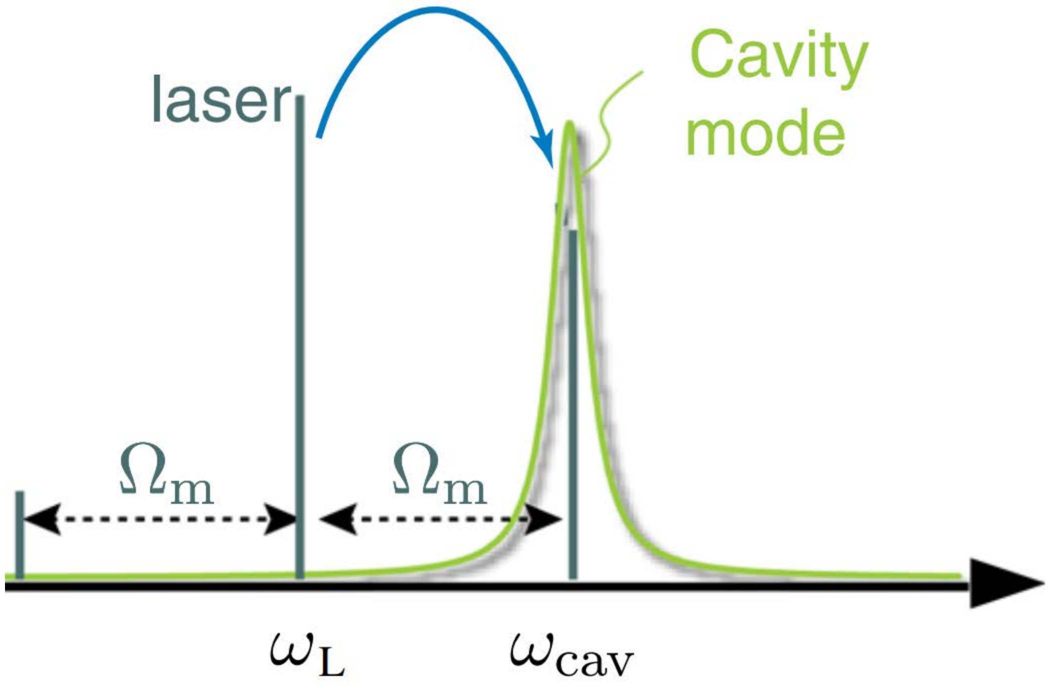
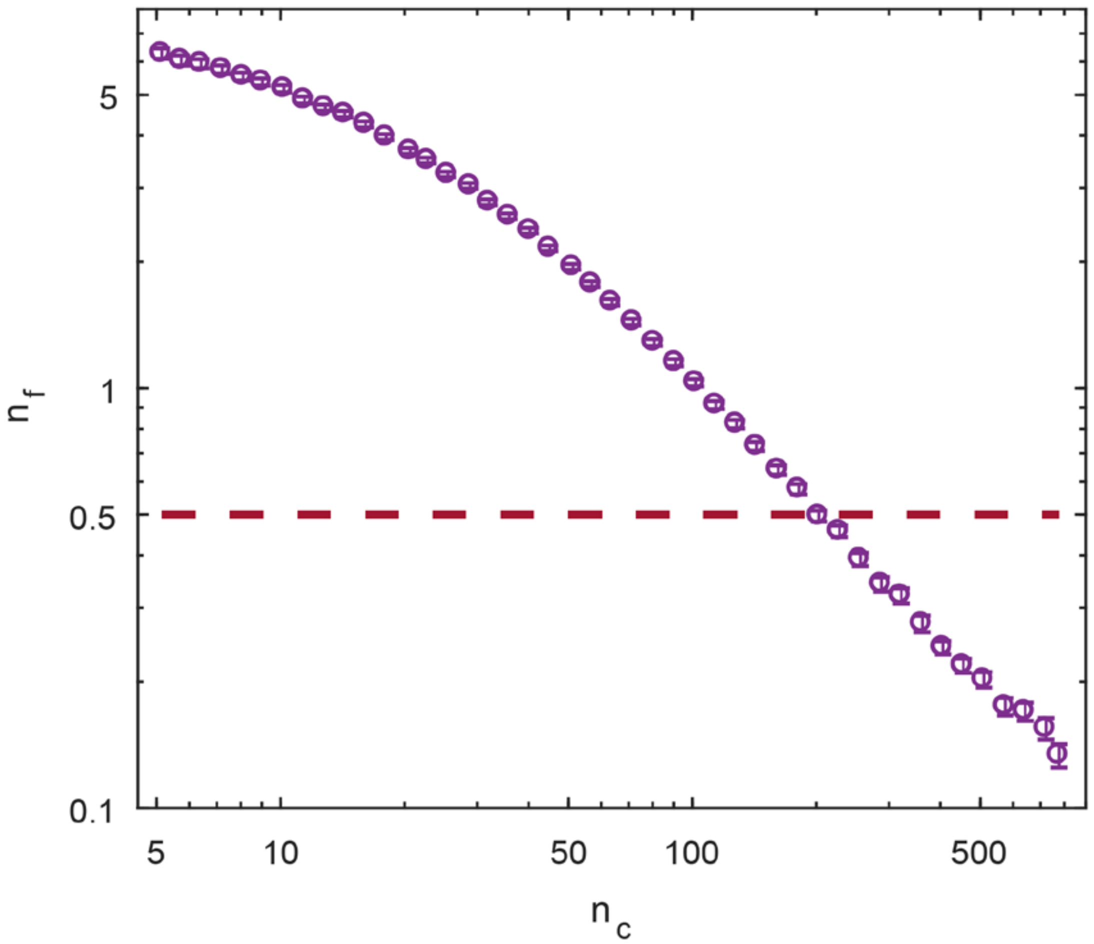


Figure from M. Aspelmeyer, T. J. Kippenberg and F. Marquardt, Rev. Mod. Phys. **86**, 1391

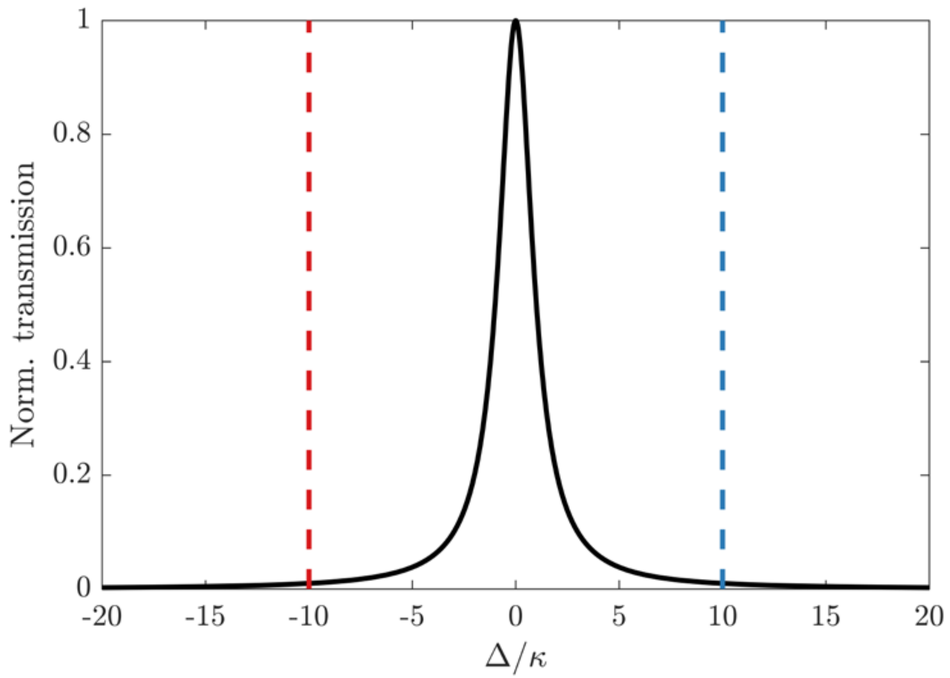


L. Qiu, I. Shomroni, T. J. Kippenberg (unpublished)

Two regimes of optomechanics

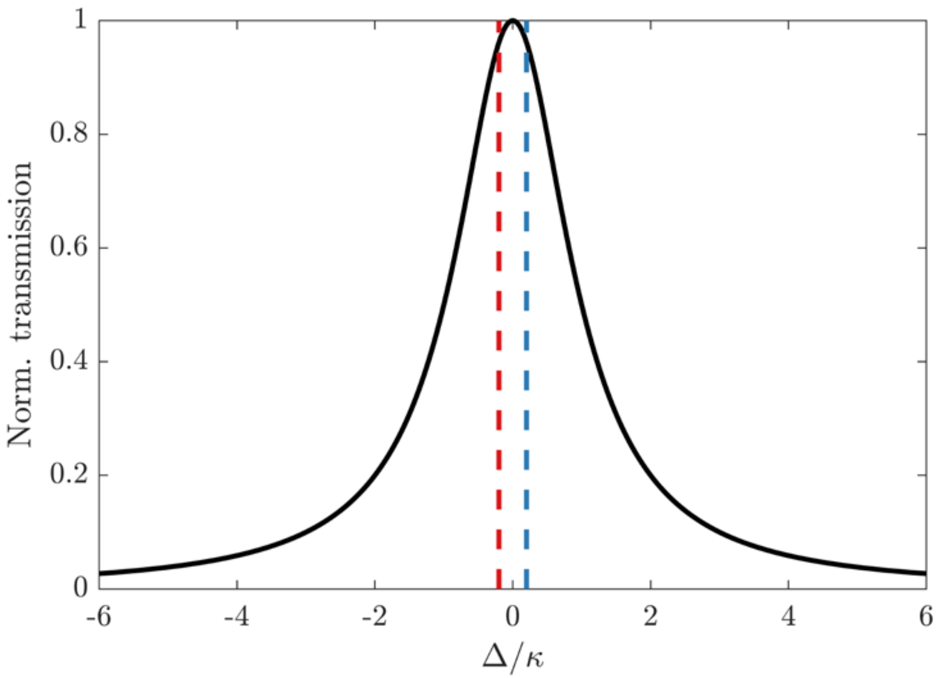
Resolved sideband: $\omega_m \gg \kappa$

- Can be sideband cooled to the ground state
- Coherent quantum state swaps between light and mechanics



Unresolved sideband: $\omega_m \ll \kappa$

- Can be feedback-cooled to the ground state
- Mechanical position can be measured in real time



Standard quantum limit for position measurements

EPFL

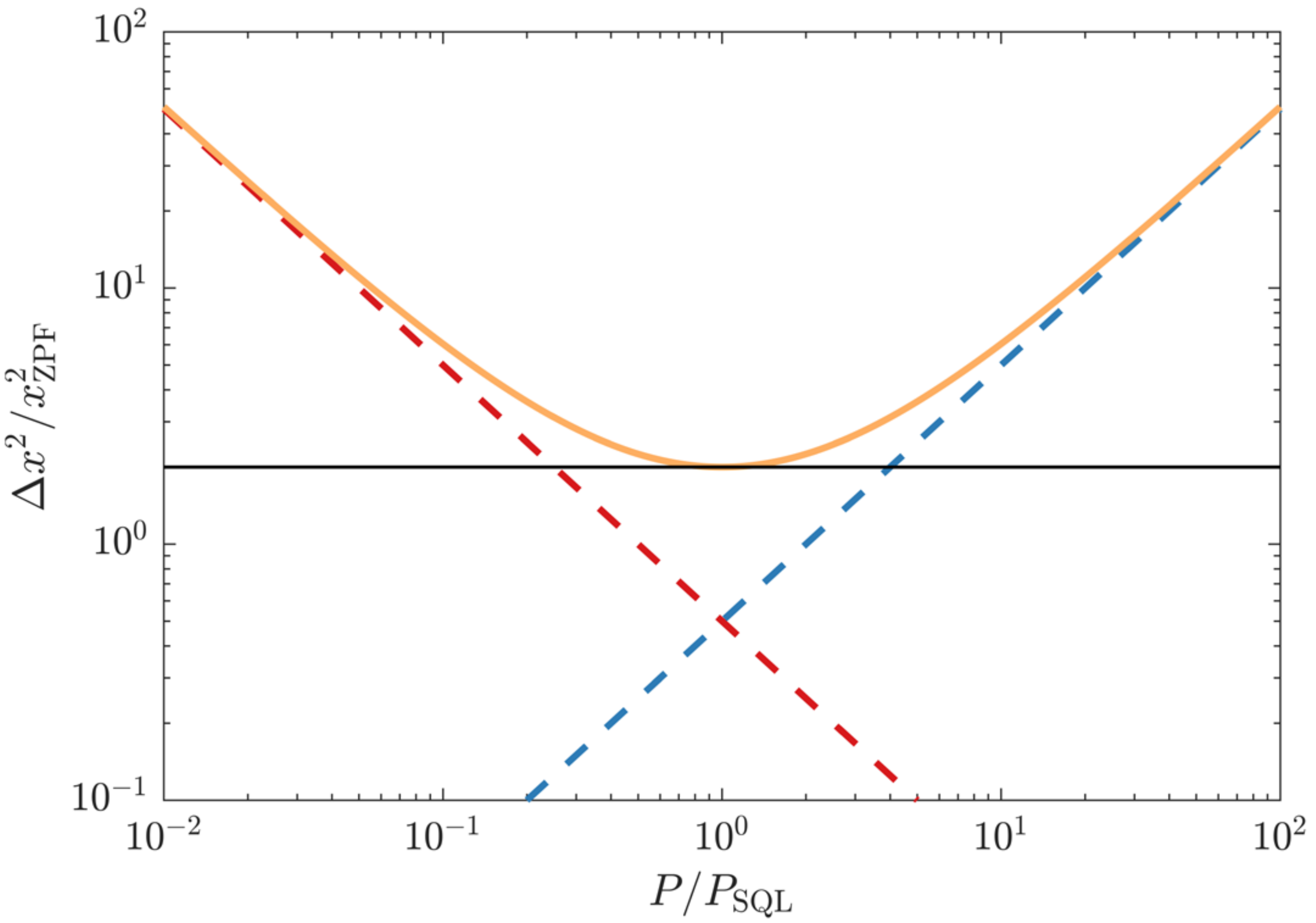
Arises from tradeoff between quantum backaction from radiation pressure and photon shot noise

Photon shot noise

Radiation pressure backaction

Sum

Standard quantum limit

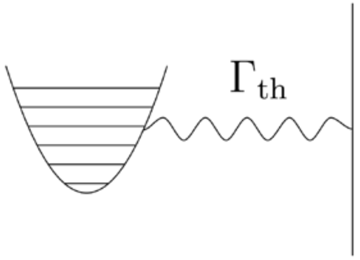


Quantum challenges for controlling mechanics

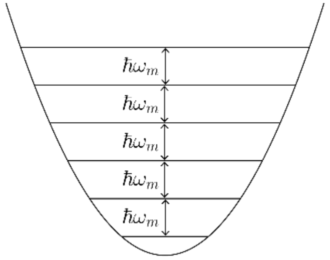
High thermal occupancy

$$n_{\text{th}} = \frac{k_B T}{\hbar \omega_m} \gg 1$$

Strong coupling to environment



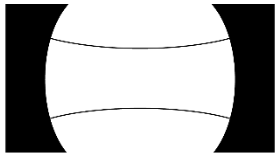
Lack of intrinsic nonlinearity



Sensitive readout required

$$x_{\text{ZPF}} \sim \text{fm}$$

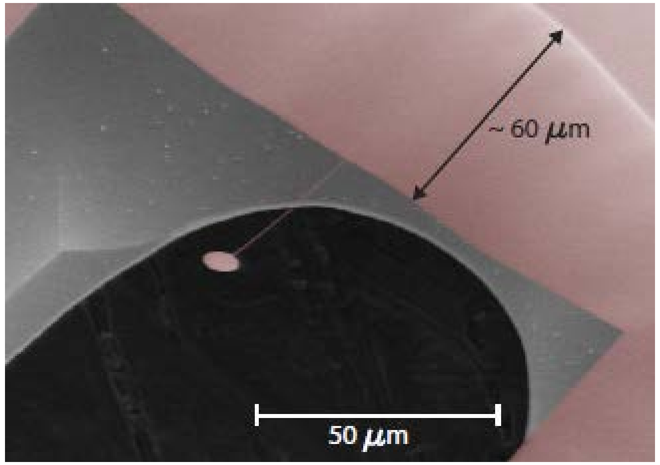
Hard to achieve strong coupling



M. Aspelmeyer, T. J. Kippenberg and F. Marquardt, Rev. Mod. Phys. **86**, 1391

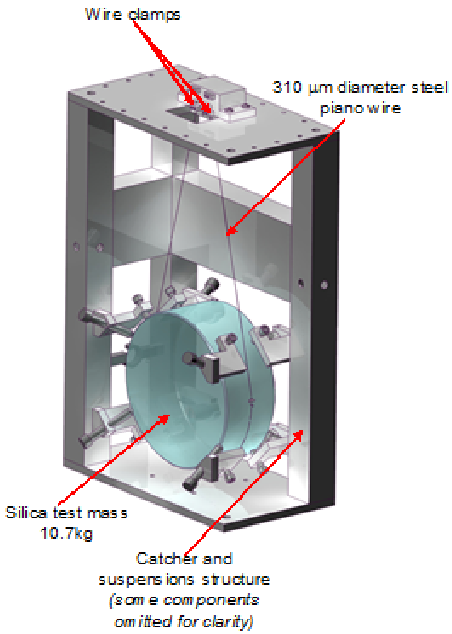
Dissipation dilution

Optical trapping



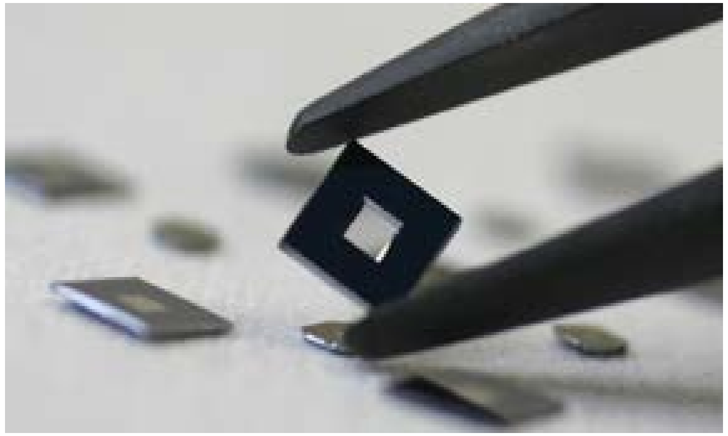
Ni et al., *Phys. Rev. Lett.* (2012)
Cripe et al., *Nature* (2019)

Gravitational potential



González and Saulson, *J. Acoust. Soc. Am.* (1994)

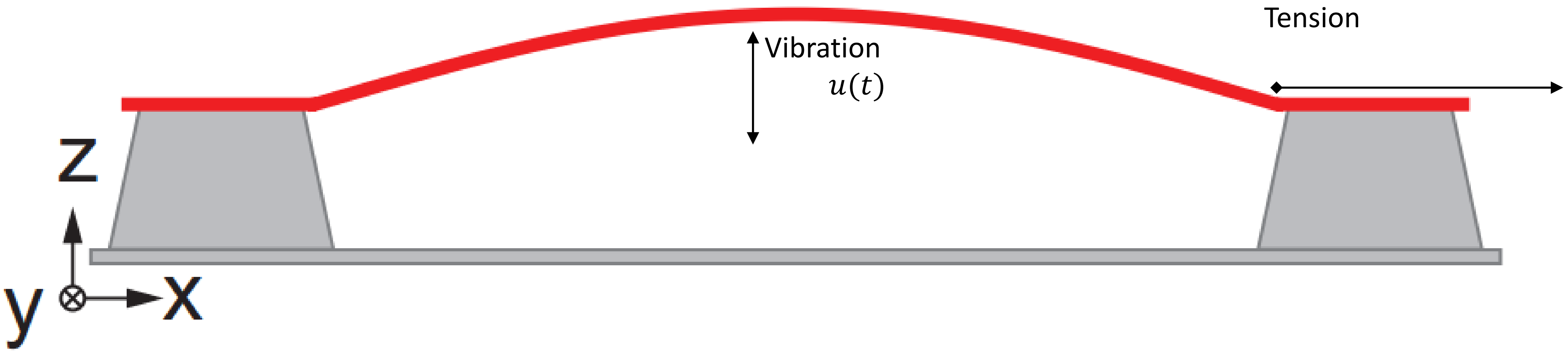
Nanomechanical resonators



Thompson et al., *Nature* (2008)

Dissipation dilution in strained materials

Key insight: Stress increases mechanical quality factors *regardless of the source of loss*

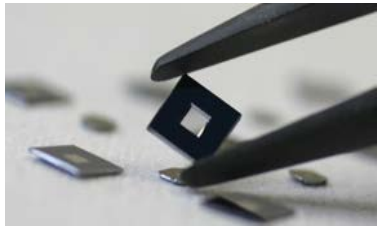


Therefore: Use a high deposition stress material such as Si_3N_4

Fedorov, Engelsen et al., Phys. Rev. B **99** (2019)
G.I. Gonzalez and P.R. Saulson, *J. Acoust. Soc. Am.* **96**.1(1994)
Q. P. Unterreithmeier, T. Faust, *Phys. Rev. Lett.* **105**, 027205 (2010)
P.-L. Yu, T.P. Purdy, C.A. Regal, *Phys. Rev. Lett.* **108**, 083603 (2012)

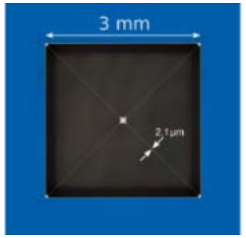
A timeline of Si_3N_4 mechanics

Millimeter-scale membranes



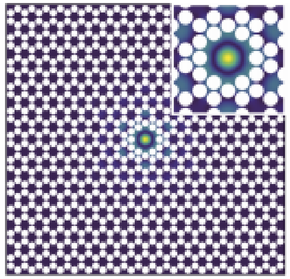
Thompson et al., *Nature* 452, 72-75 (2008)

Trampoline membranes



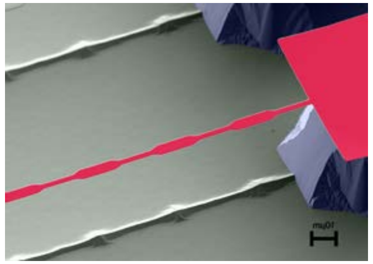
Sankey et al., *PRX* 6, 021001 (2016)

Soft-clamping



Y. Tsaturyan et. al. *Nat. Nano* 12, 776 (2017)

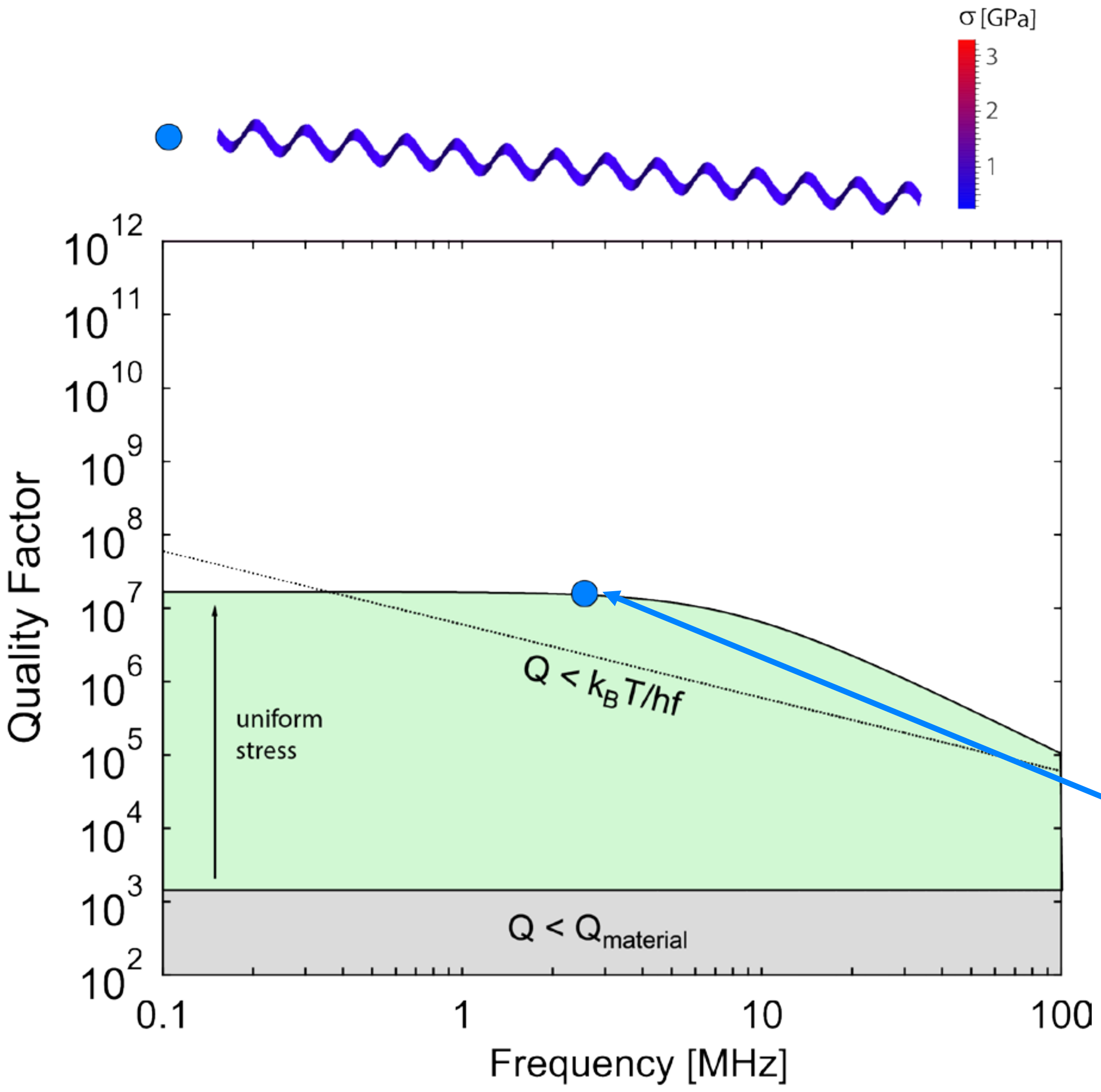
Strain engineering



Ghadimi et al., *Science* **360** (2017)

Higher aspect ratios and engineered geometry has enabled 100-1000 times higher mechanical quality factor

Increasing the Q with dissipation dilution

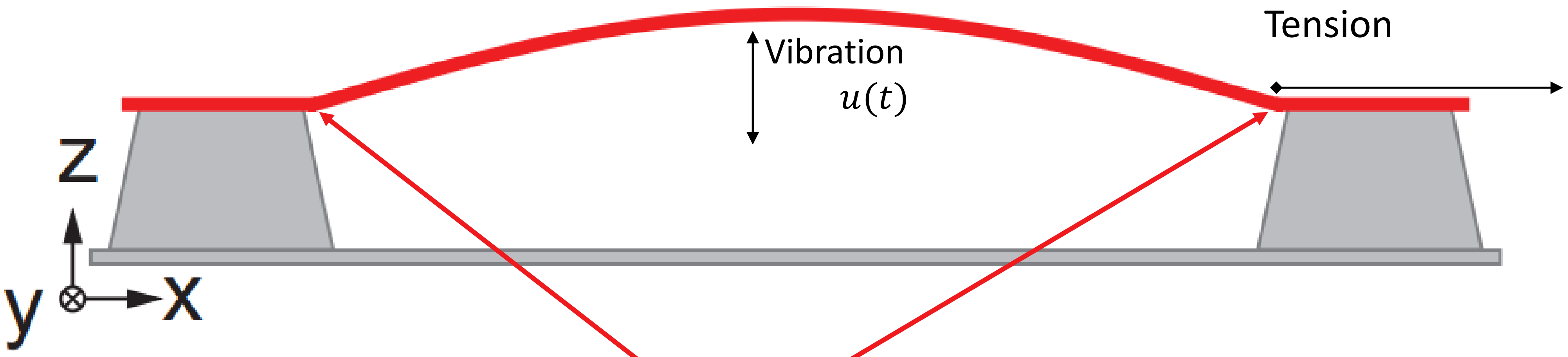


Deposition stress	1.1 Gpa
Thickness	20 nm
Length	3 mm

High stress material, Si_3N_4

Dissipation dilution

Key insight: Stress increases mechanical quality factors *regardless of the source of loss*



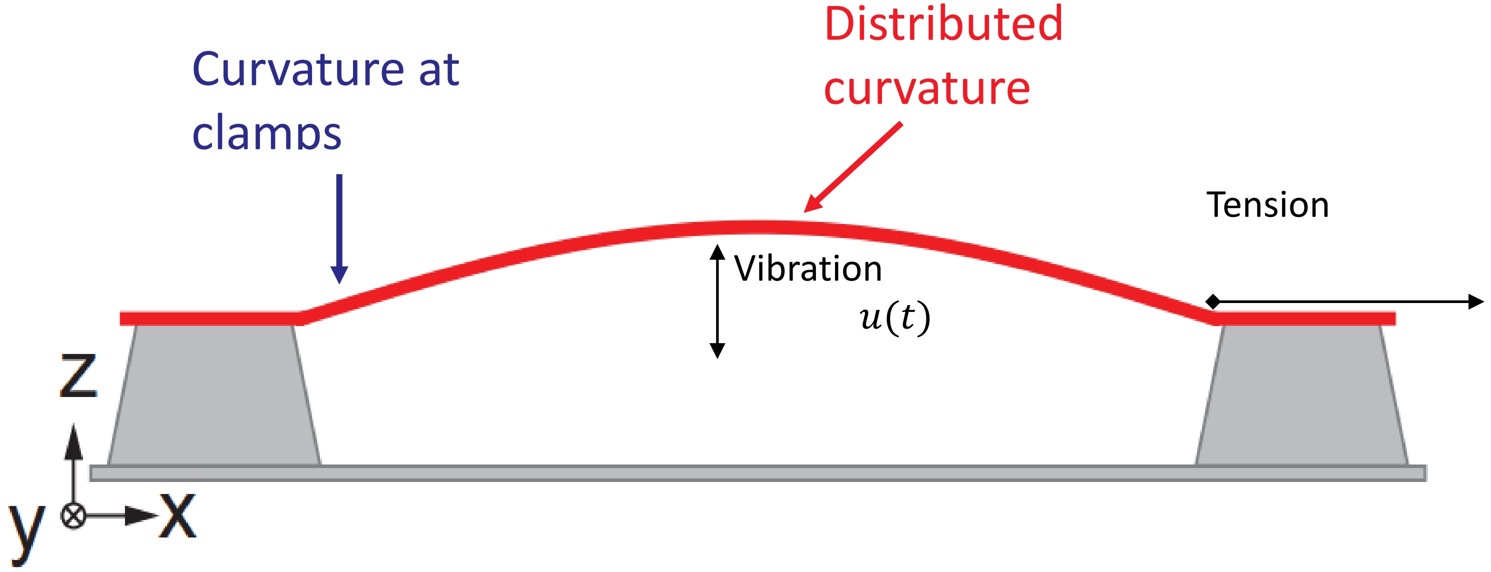
High curvature clamping region:
Main limitation on Q

Fedorov, Engelsen et al., *Phys. Rev. B* **99**, 054107 (2019)
Gonzalez and Saulson, *J. Acoust. Soc. Am.* **96**.1(1994)
Unterreithmeier et al., *Phys. Rev. Lett.* **105**, 027205 (2010)
Yu et al., *Phys. Rev. Lett.* **108**, 083603 (2012)

Dissipation dilution

EPFL

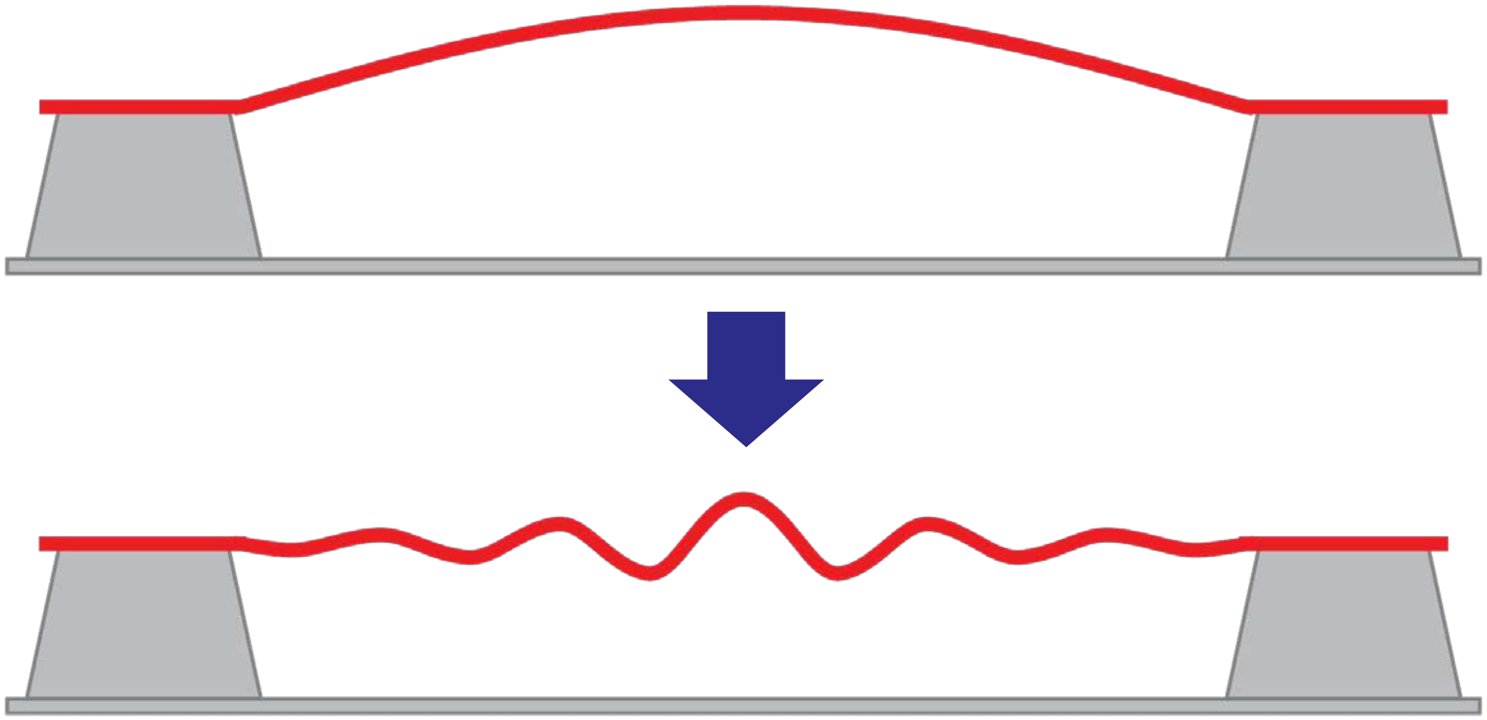
$$\frac{Q}{Q_{\text{int}}} = \frac{1}{2\lambda + n^2\pi^2\lambda^2} \qquad \lambda = \frac{h}{L}\sqrt{\frac{E_0}{12\sigma}} \ll 1$$

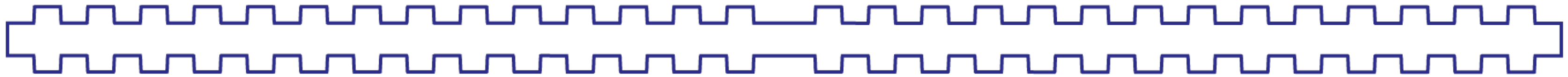


Q_{int} Intrinsic Q
n Mode number
h Thickness
L Length
E_0 Young's modulus
σ Material stress

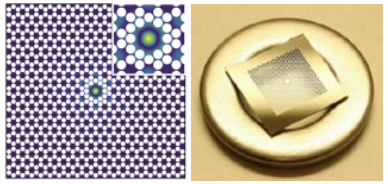
Fedorov, Engelsen et al., *Phys. Rev. B* **99**, 054107 (2019)
Gonzalez and Saulson, *J. Acoust. Soc. Am.* **96**.1(1994)
Unterreithmeier et al., *Phys. Rev. Lett.* **105**, 027205 (2010)
Yu et al., *Phys. Rev. Lett.* **108**, 083603 (2012)

Soft clamping





Pattern a phononic crystal on the beam with a defect in the center, creating a localized mode

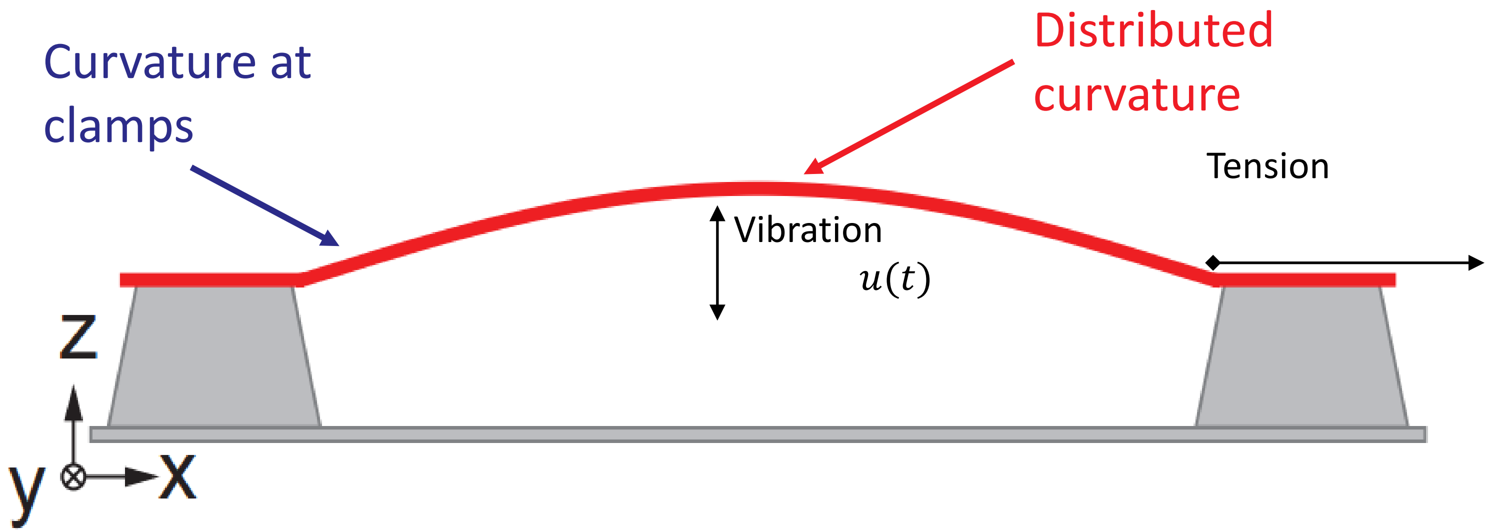


Y. Tsaturyan et. al. *Nature Nanotechnology* **12,** 776 (2017)

Dissipation dilution

$$\frac{Q}{Q_{\mathrm{int}}} = \frac{1}{\cancel{2\lambda} + n^2\pi^2\lambda^2} \qquad \lambda = \frac{h}{L}\sqrt{\frac{E_0}{12\sigma}} \ll 1$$

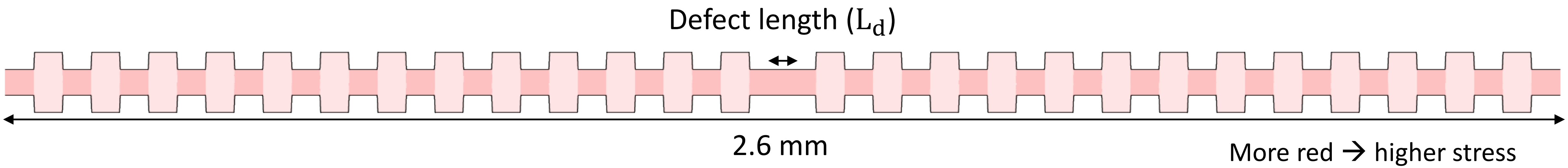
Soft clamping

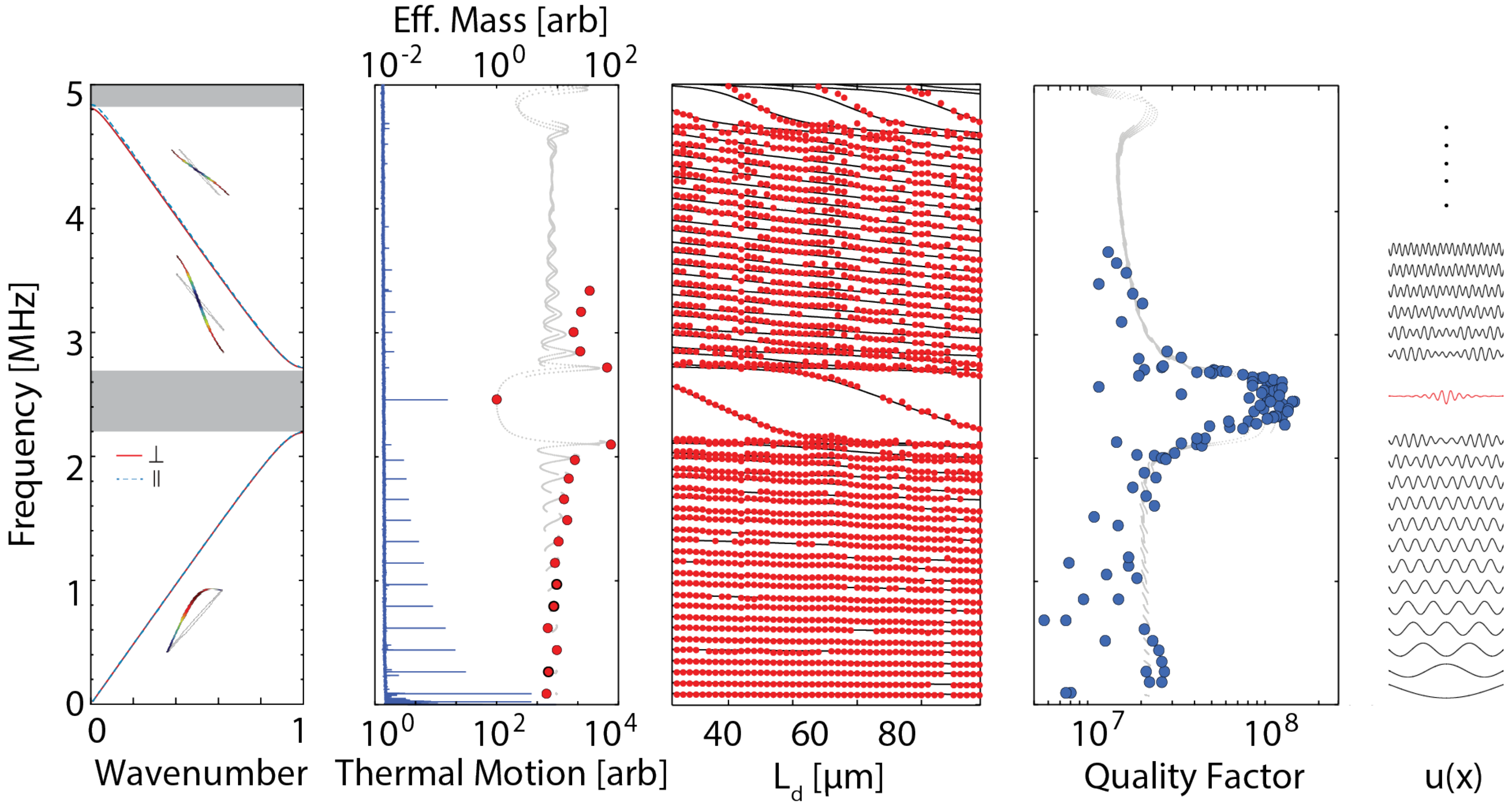


Q_{int} Intrinsic Q
n Mode number
h Thickness
L Length
E_0 Young's modulus
σ Material stress

Fedorov, Engelsen et al., *Phys. Rev. B* **99**, 054107 (2019)
Gonzalez and Saulson, *J. Acoust. Soc. Am.* **96**.1(1994)
Unterreithmeier et al., *Phys. Rev. Lett.* **105**, 027205 (2010)
Yu et al., *Phys. Rev. Lett.* **108**, 083603 (2012)

Soft clamped nanobeams

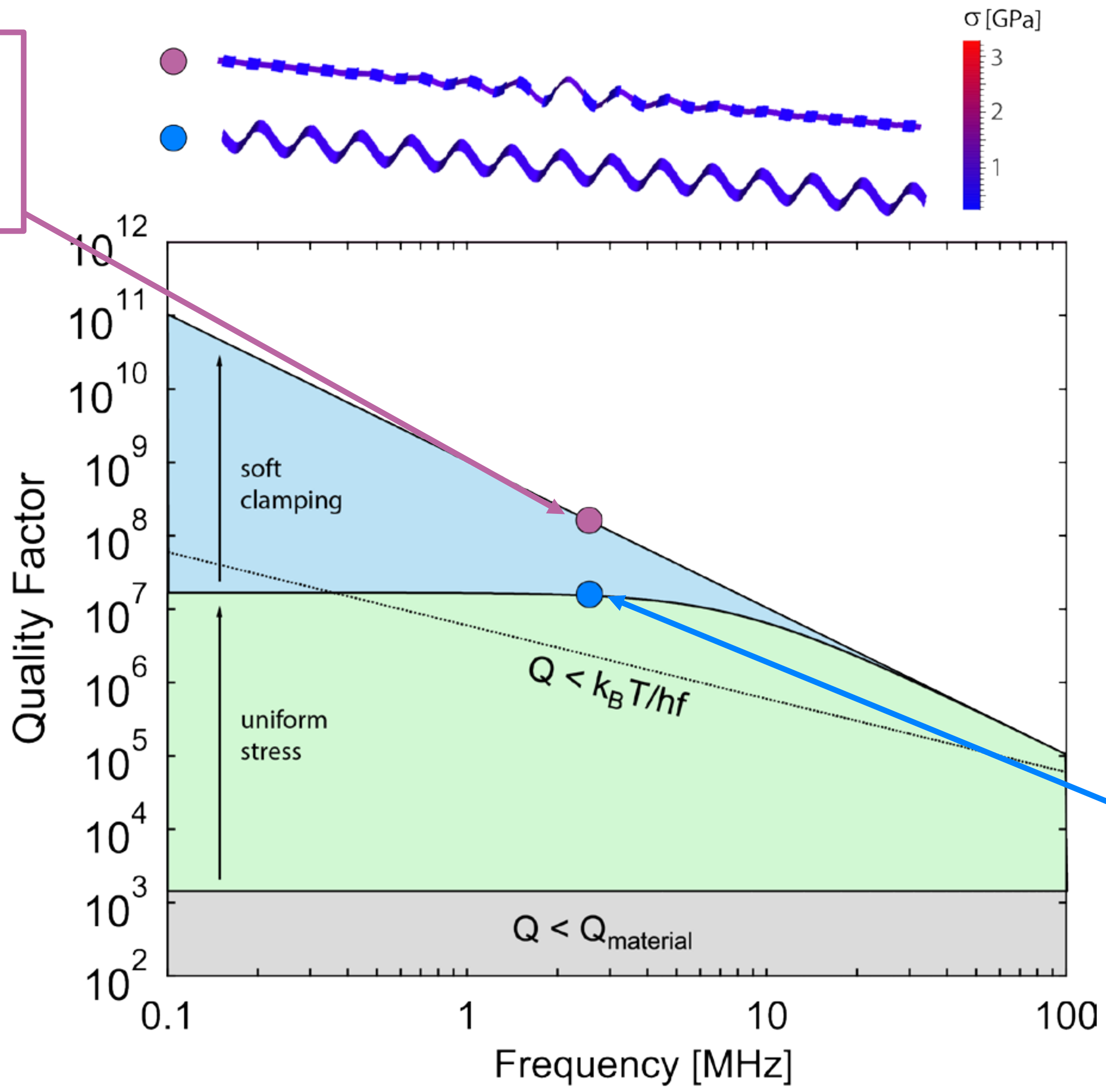




Localized modes with:
10x enhanced Q
20x reduction in m_{eff}

Increasing the Q with dissipation dilution

Soft clamping removes clamping losses



High stress material Si_3N_4

Dissipation dilution

EPFL

$$\frac{Q}{Q_{\mathrm{int}}} = \frac{1}{\cancel{2\lambda} + n^2\pi^2\lambda^2} \qquad \lambda = \frac{h}{L}\sqrt{\frac{E_0}{12\sigma}}$$

Soft clamping

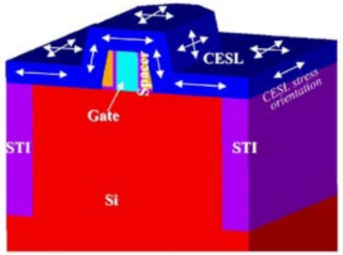
Now, minimize λ:

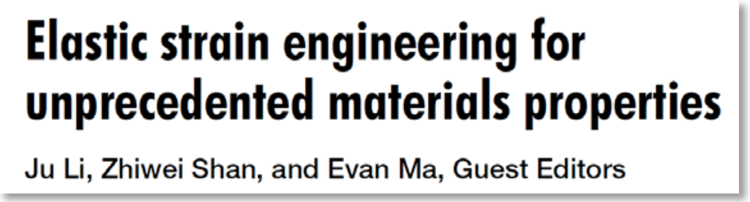
1. High aspect ratio (h/L)
2. High stress (σ)

Q_0	Intrinsic Q
n	Mode number
h	Thickness
L	Length
E_0	Young's modulus
σ	Material stress

Tsaturyan et. al. *Nature Nanotechnology* **12,** 776 (2017)
Fedorov, Engelsen et al., *Phys. Rev. B* **99**, 054107 (2019)

Elastic strain engineering




Elastic strain engineering for unprecedented materials properties
Ju Li, Zhiwei Shan, and Evan Ma, Guest Editors

Key insight: use geometry to locally increase the stress

More red → higher stress

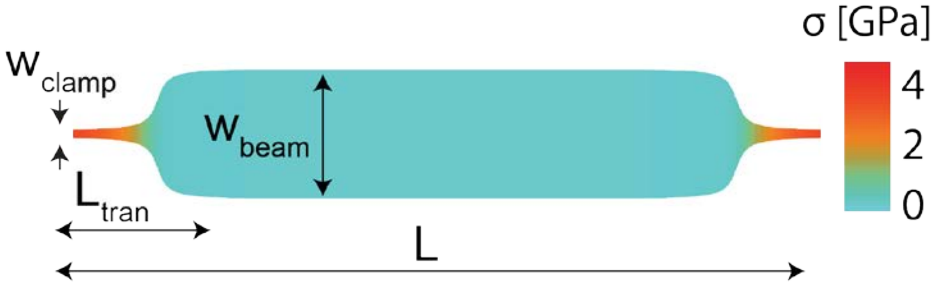
A simple taper increases the stress in the center...
...but loss near clamps will increase, leading to lower Q!

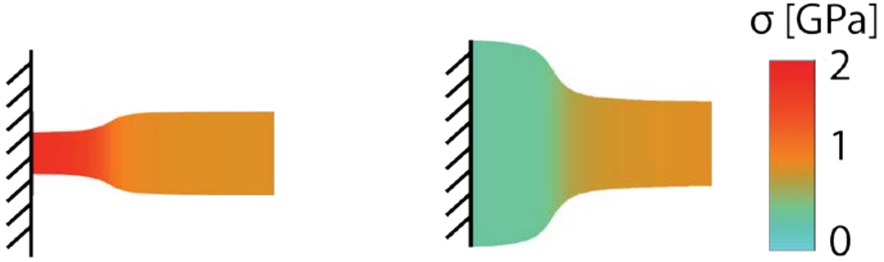
Li *et al.*, *MRS Bull.* **39**, 108-114 (2014)
Zhang *et al.*, *Appl. Phys. Lett.* **107,** 131110 (2015)

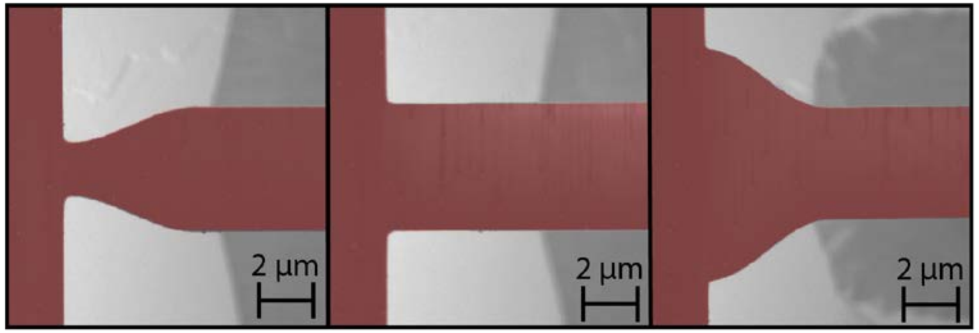
Clamp-tapering – a strain engineering technique

$$\frac{Q}{Q_{\mathrm{int}}} = \frac{1}{2\lambda_{\mathrm{cl}} + n^2\pi^2\lambda^2}$$

- Clamp taper increases stress at clamps → reduced loss at clamps
- Tapering enhances Q of lower-order modes including the *fundamental mode*
- Does not require increased device size

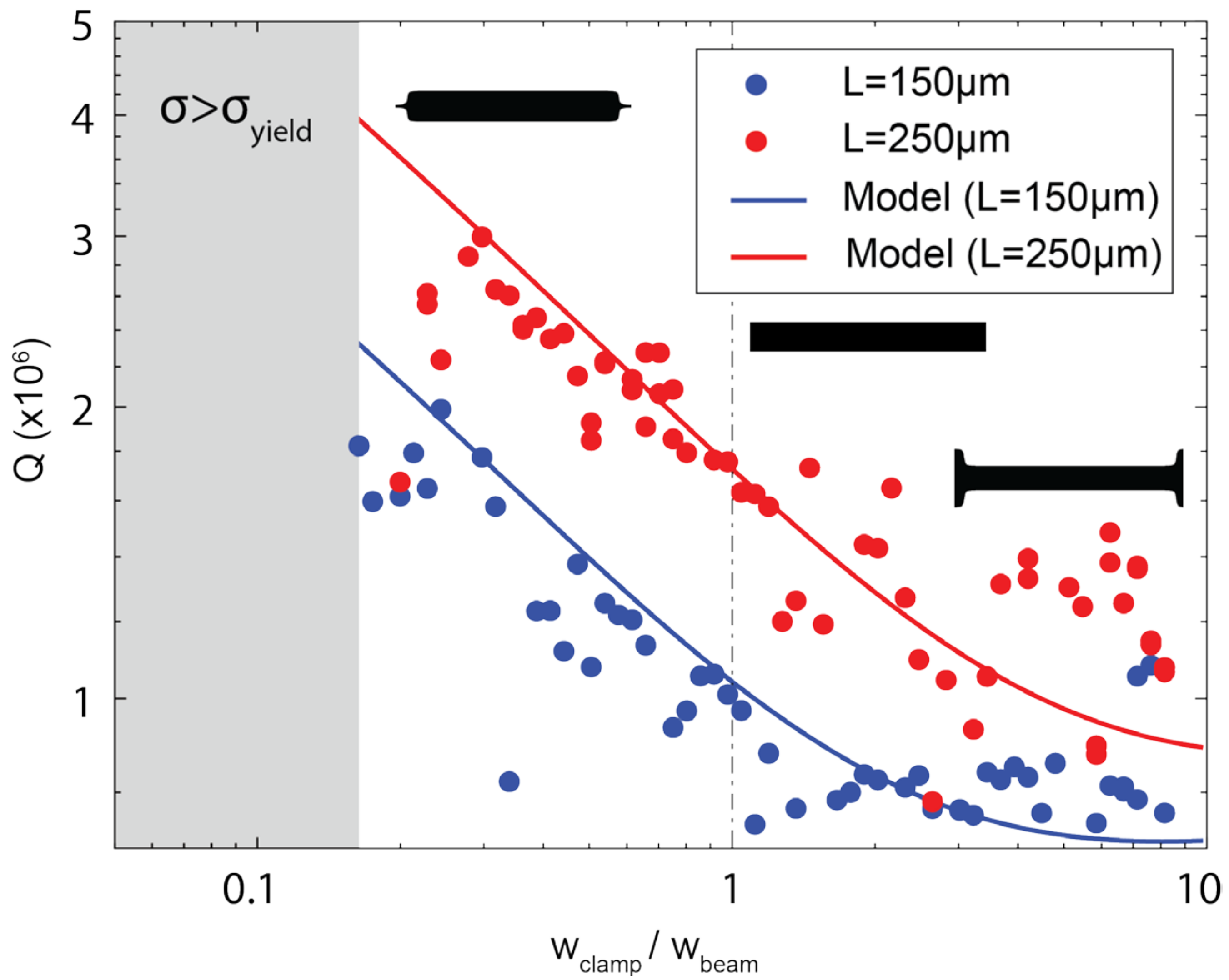


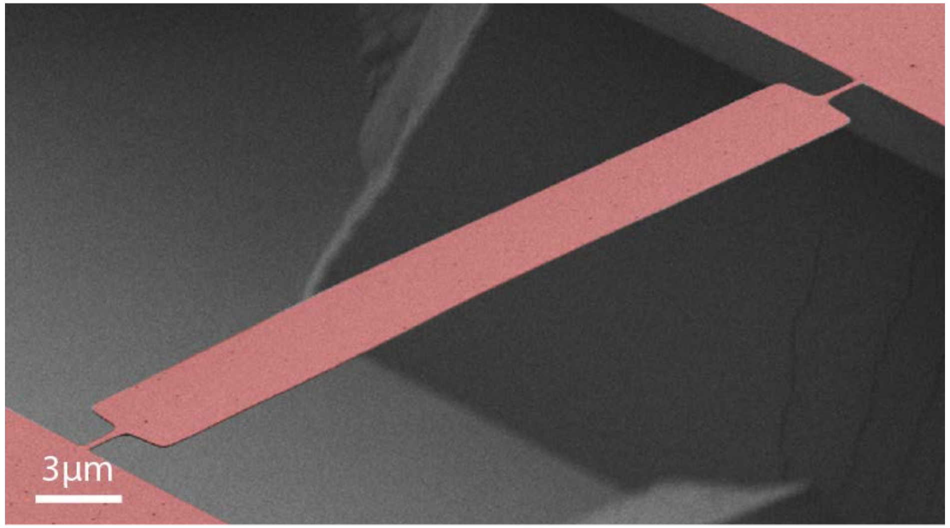




Bereyhi et al., *Nano Lett.* ***19****(4)*, 2019
Fedorov, Engelsen et al., *Phys. Rev. B* **99**, 054107 (2019)
Sadeghi et al., *arXiv:1905.06730* (2019)

Clamp-tapering for fundamental mode Q enhancement

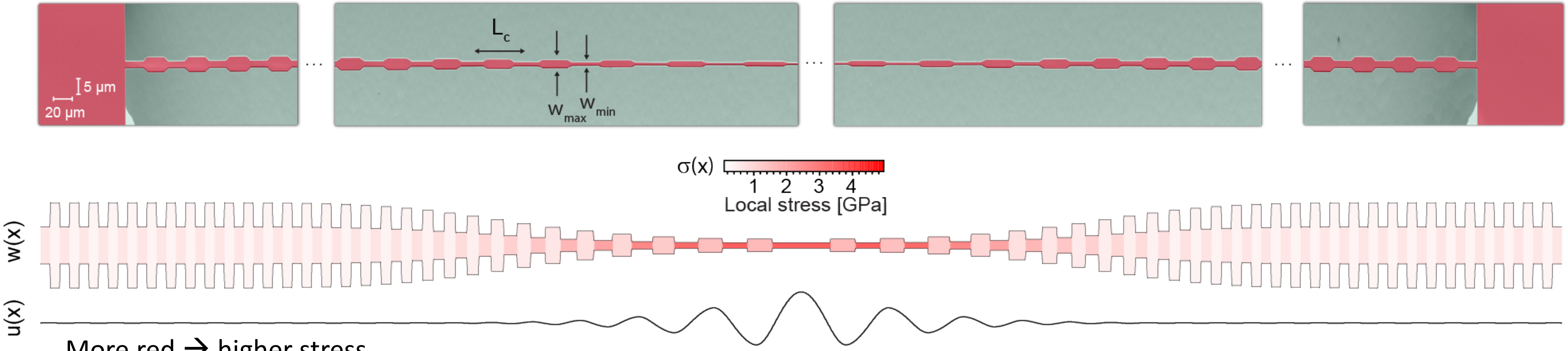




At yield stress, factor of ~2 enhancement for Si_3N_4

Bereyhi et al., *Nano Lett.* ***19****(4)*, 2019
Fedorov, Engelsen et al., *Phys. Rev. B* **99**, 054107 (2019)
Sadeghi et al., *arXiv:1905.06730* (2019)

Elastic strain engineering with soft clamping



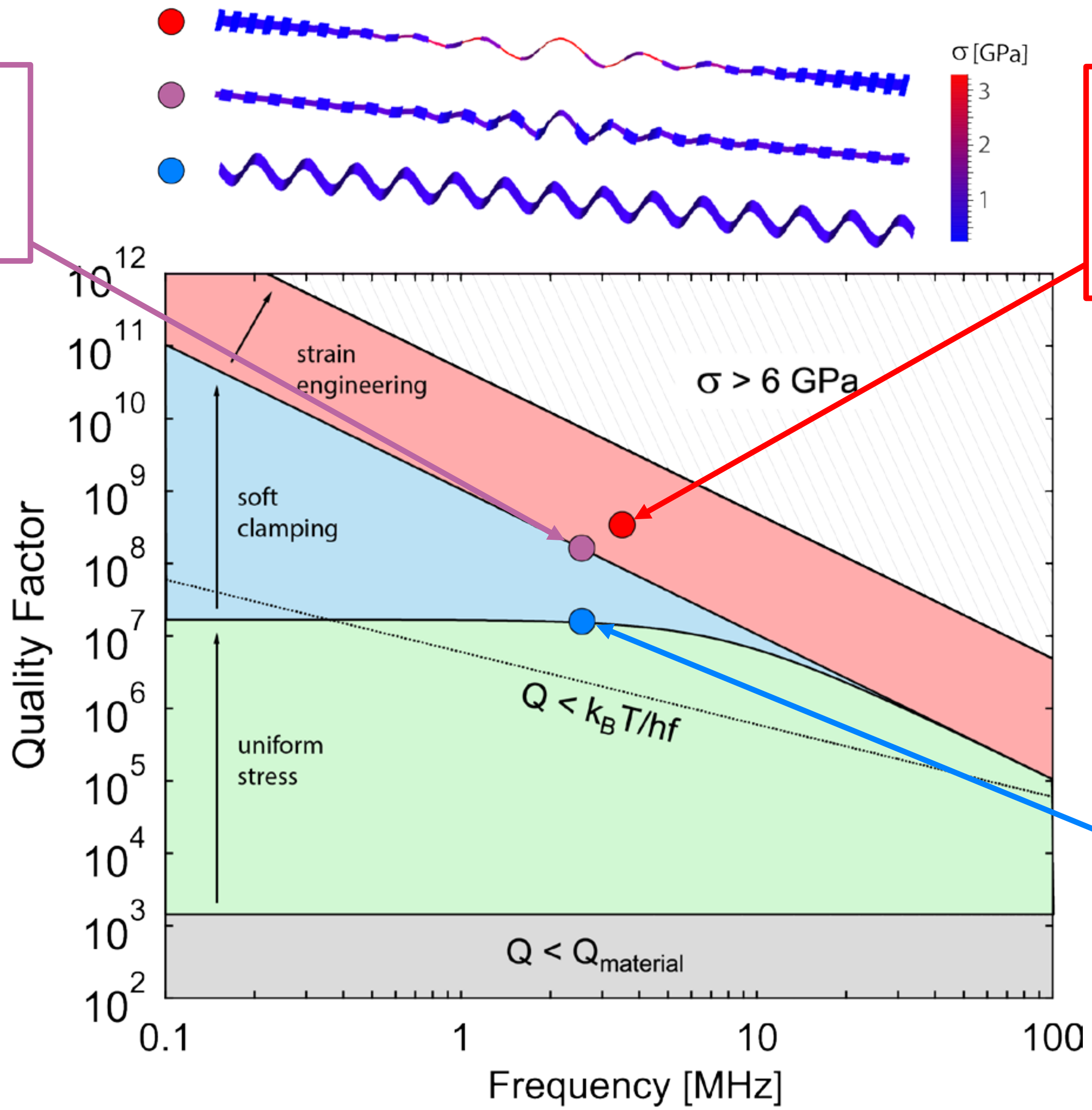
More red → higher stress

1. Localize the mechanical mode using soft clamping
2. Taper the beam to colocalize strain with the mechanical mode

Pitch of unit cells must be changed to maintain same bandgap throughout the beam

Increasing the Q with dissipation dilution

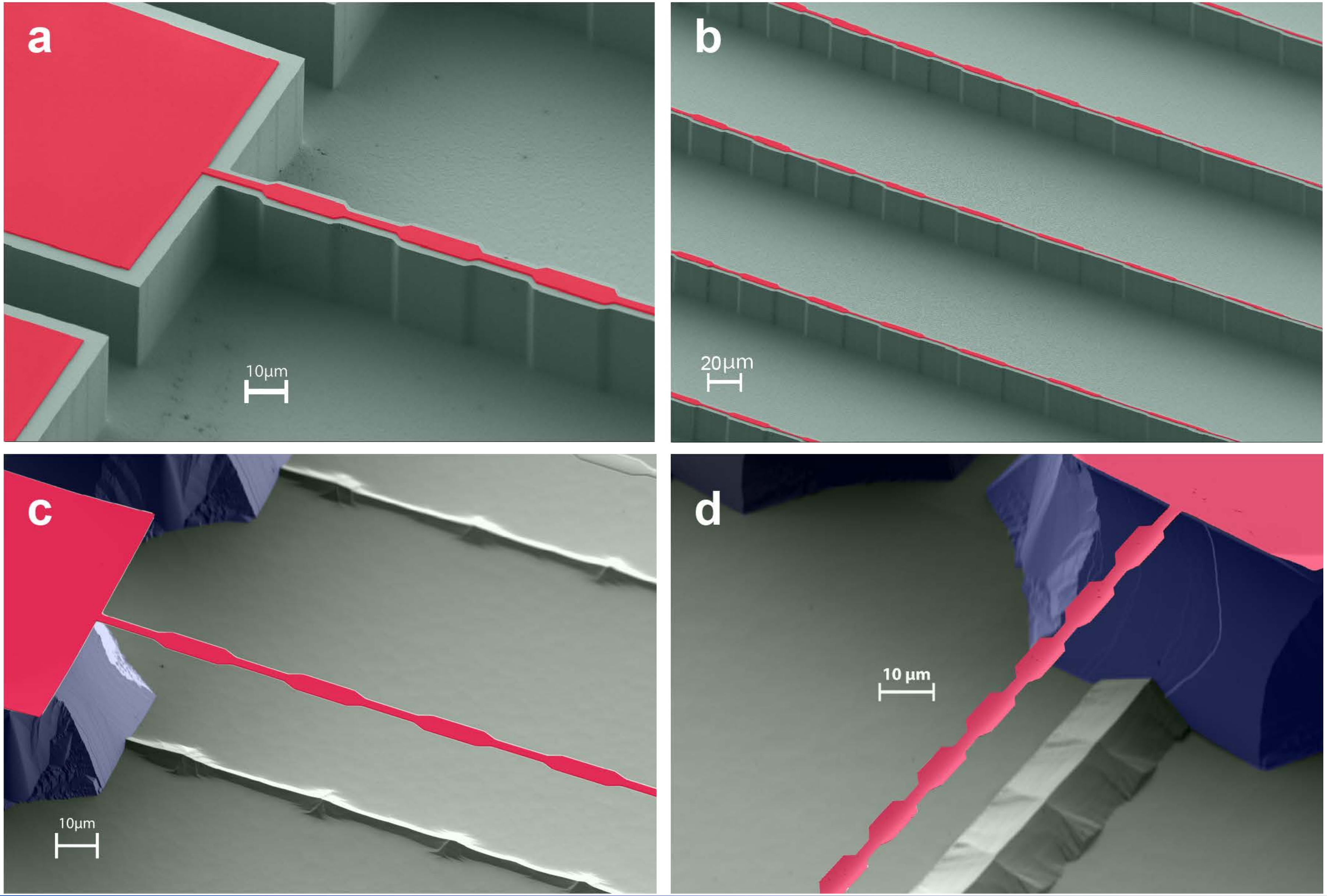
Soft clamping removes clamping losses



Geometric strain engineering further increases dissipation dilution

High stress material Si_3N_4

SEMs of fabrication process

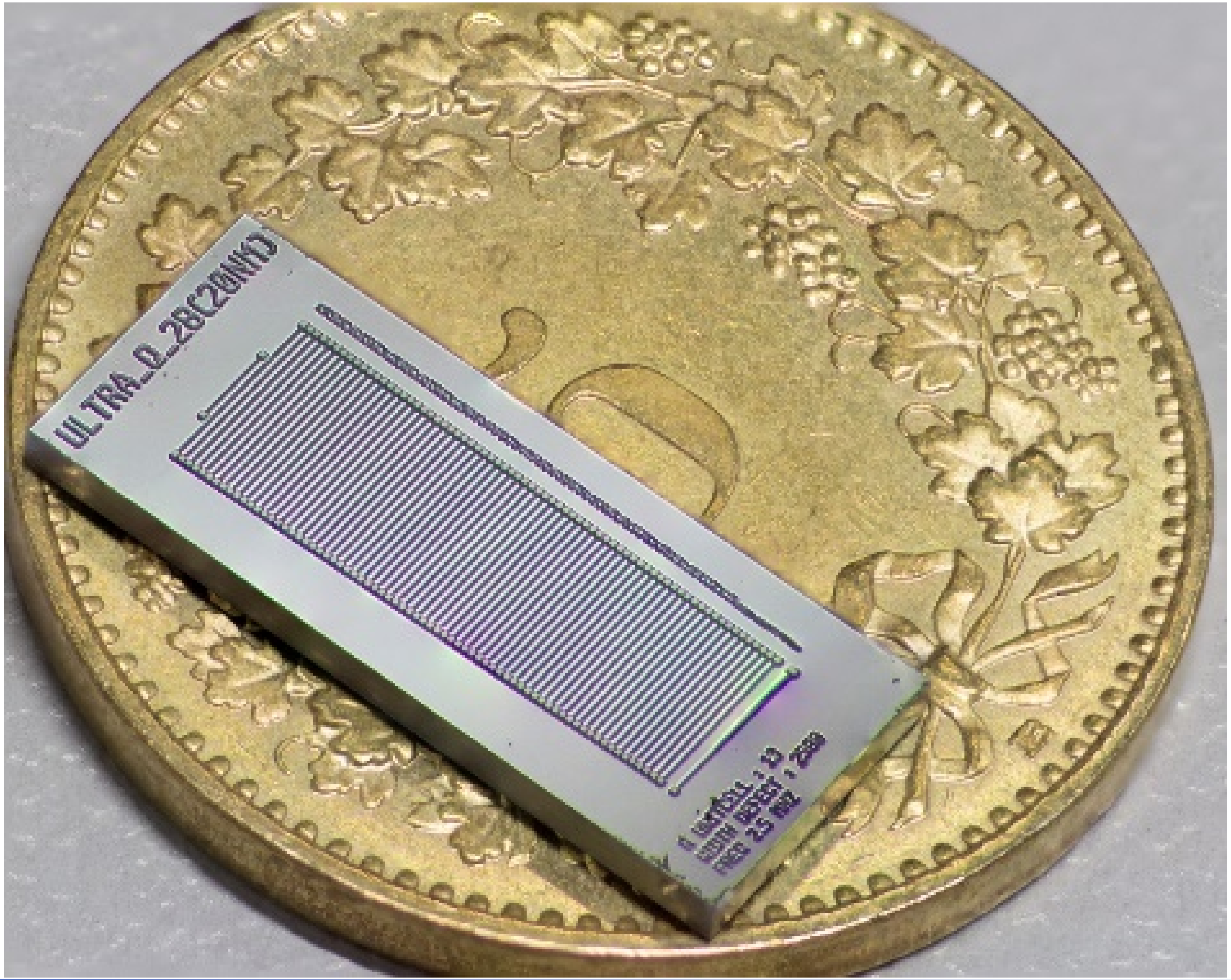


Red: Silicon nitride
Green: Silicon
Blue: Silicon pillar

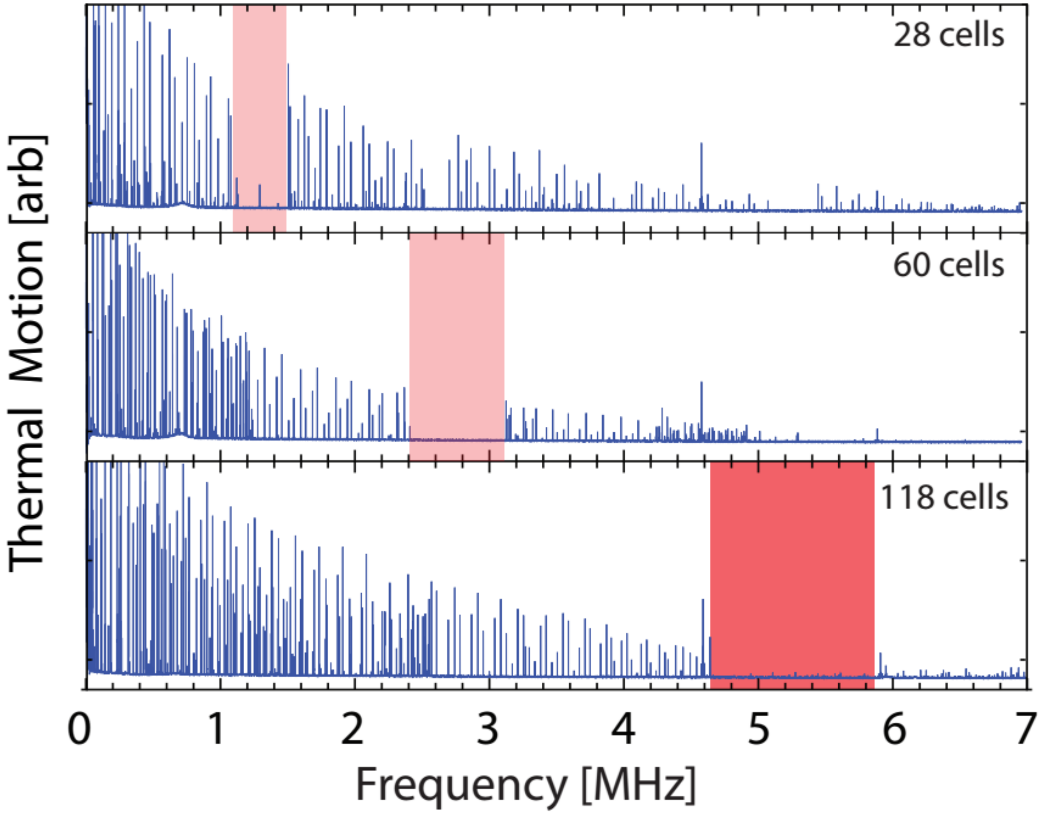
Fabrication outline

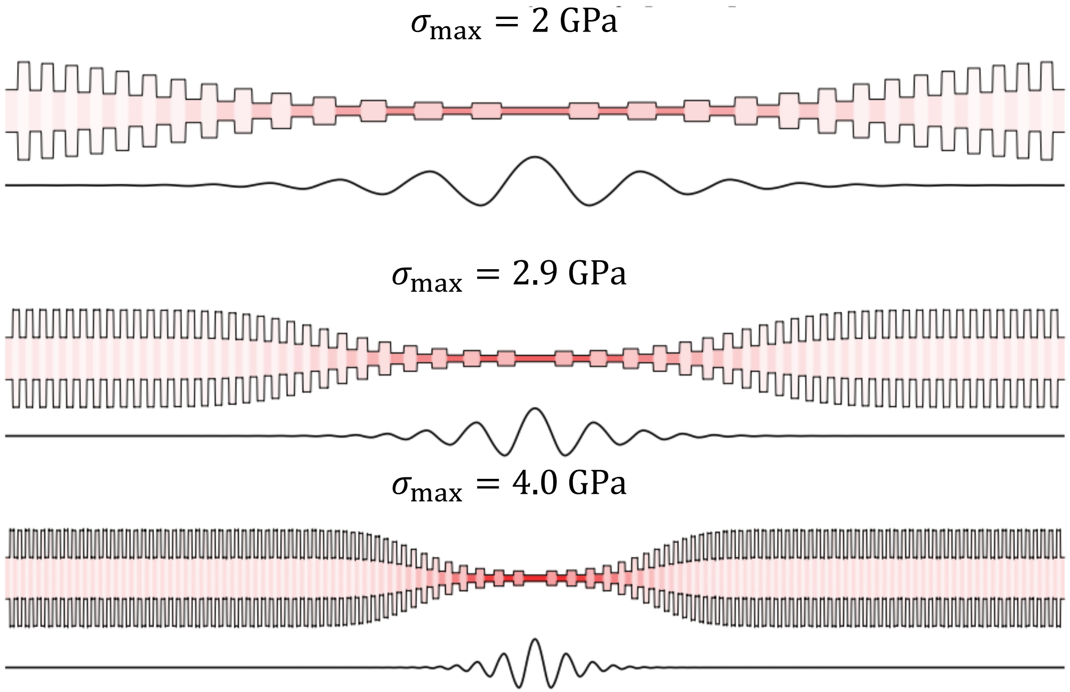
1. Ebeam lithography
2. Deep etch (RIE)
3. KOH undercut

Final devices: 20 nm thick and 3-8 mm long



Strain engineered beams - bandgaps



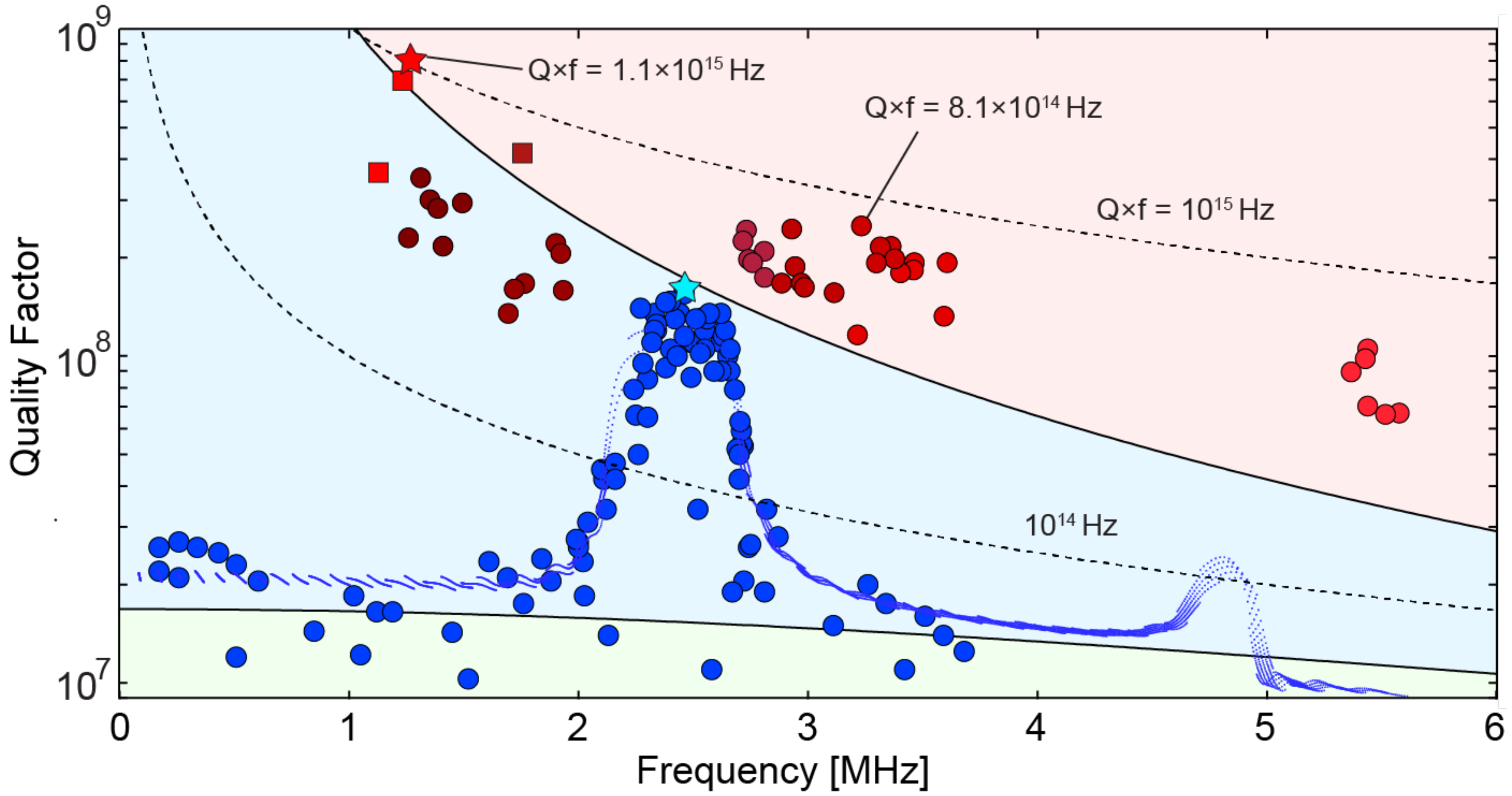


More red → higher stress

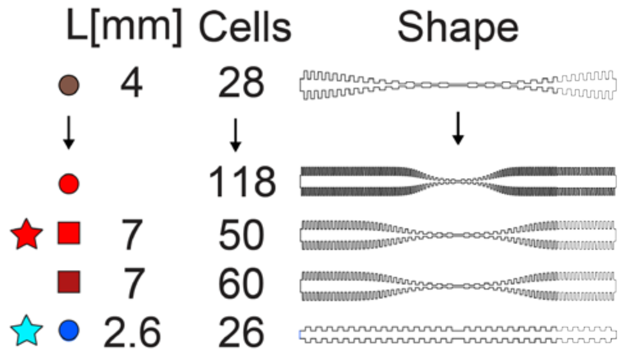
For fixed beam length (as high as limited by fabrication):

Higher strain → Smaller region of enhancement → Higher frequency mode

Strain engineered beams – quality factors



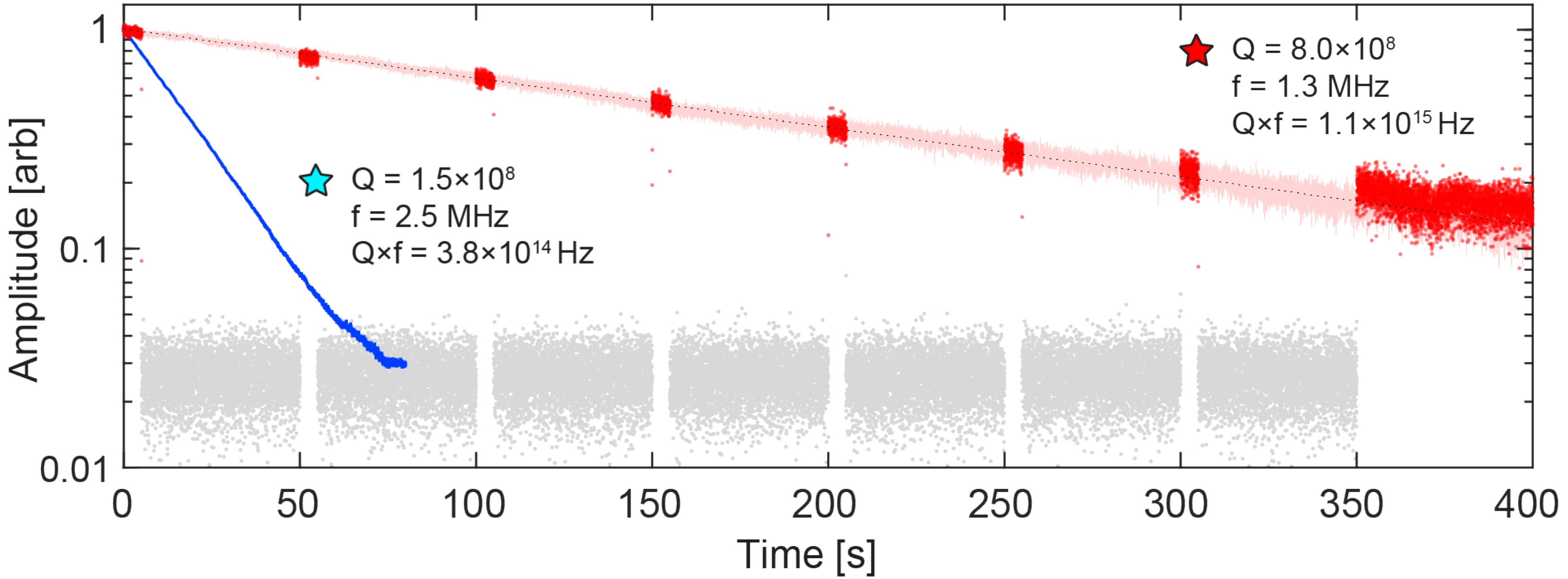
Strain engineering allows high $Qf\,(> 5 \times 10^{14}\ \text{Hz})$ for a wide range of frequencies



Ghadimi et al., *Science* 360, 2018

Q of 800 million at 1.3 MHz

EPFL



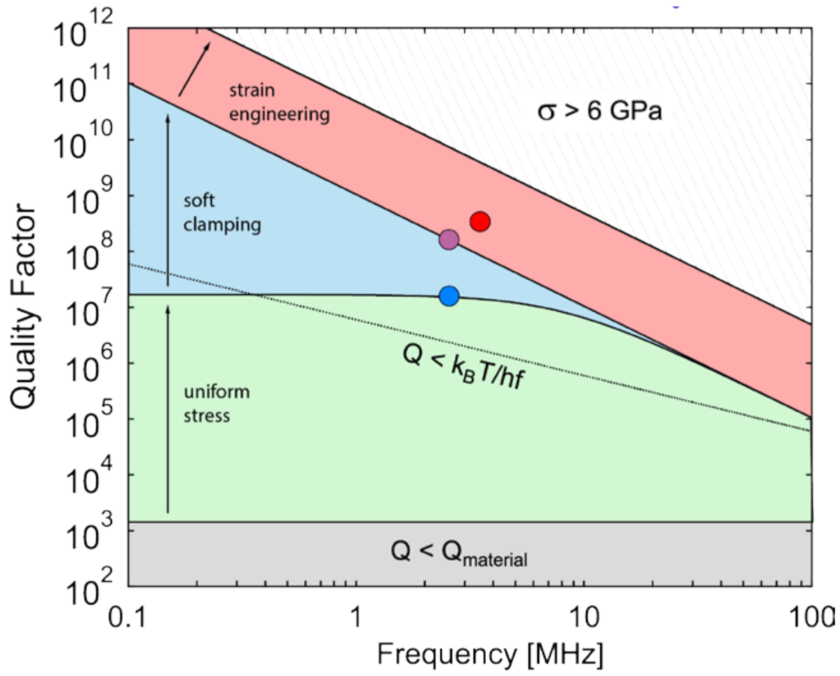
Unprecedented mechanical dissipation

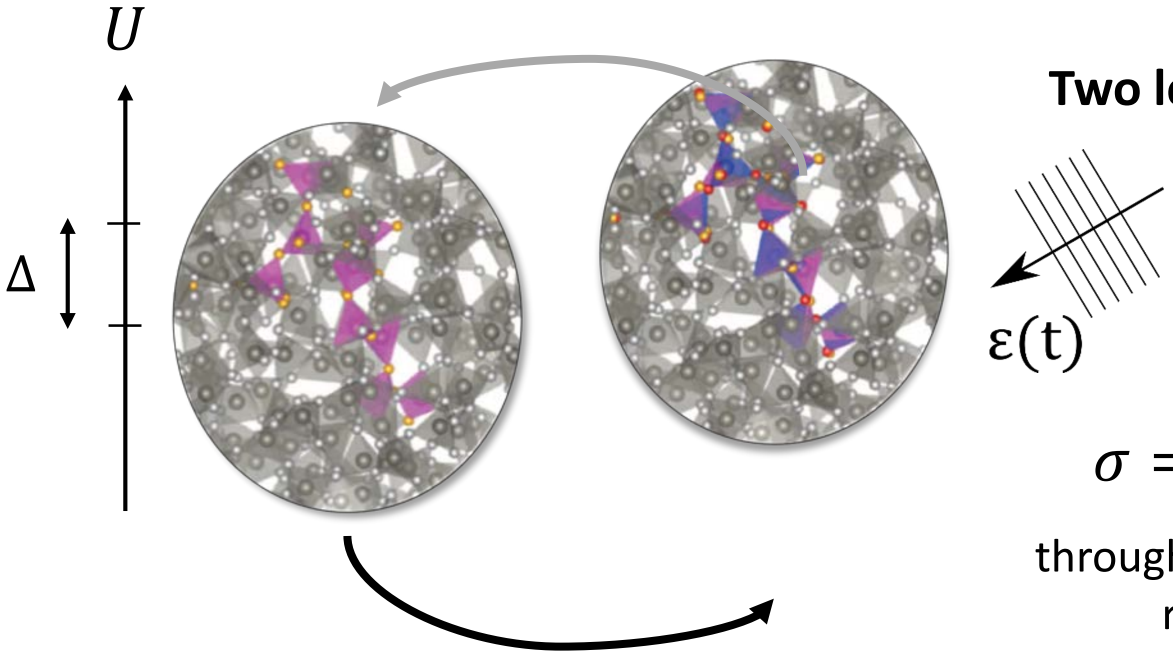
- Highest quality factor and Qf product achieved for a room temperature mechanical oscillator
- Stroboscopic measurement taken to control for photothermal anti-damping

Ghadimi et al., *Science* 360, 2018

How can we go beyond Si_3N_4?

$$\frac{Q}{Q_{\text{int}}} = \frac{1}{2\lambda + n^2\pi^2\lambda^2}$$





$$\sigma = E e^{i\phi} \epsilon$$

through strain-induced relaxation

Hamdan et al., *J. Chem. Phys.* **141**, 054501 (2014)
Faust et al., *Phys. Rev. B* **89**, 100-102 (2014)

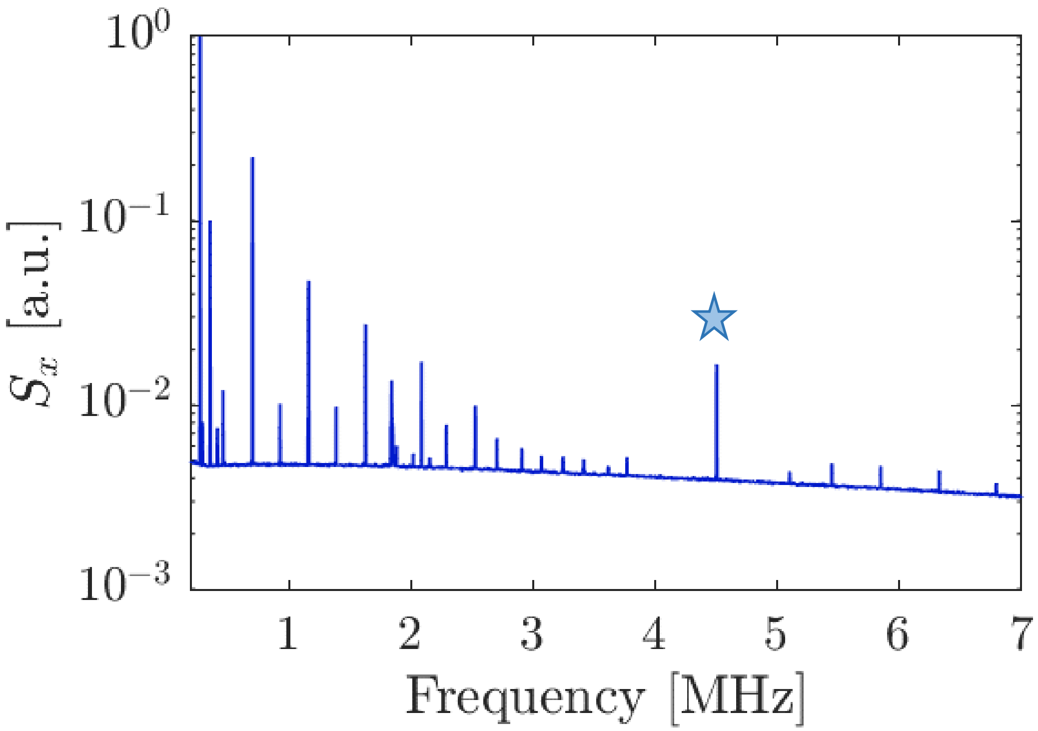
Soft-clamped devices of strained silicon

$L \approx 1\, mm,\, h \approx 10\, nm$ Aspect ratio $\approx 10^5$

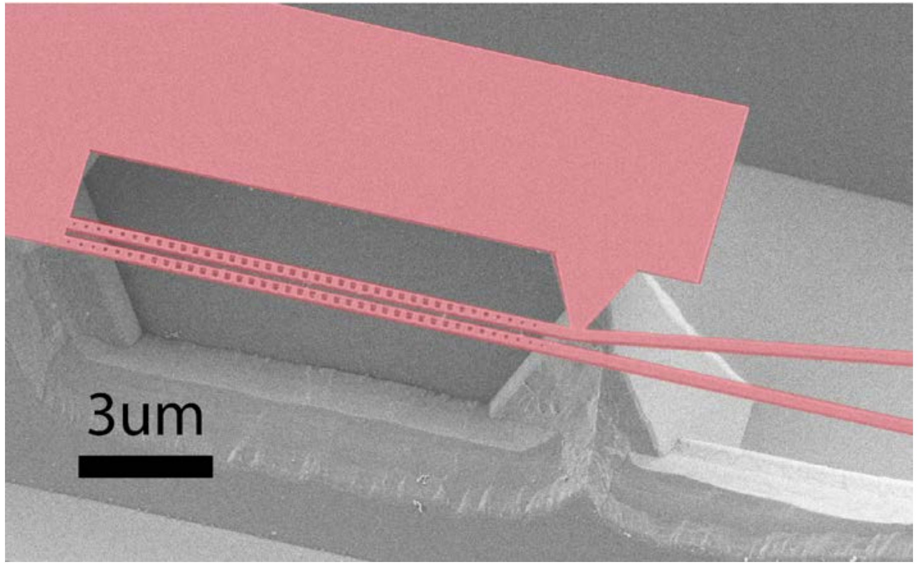
Fundamental mode quality factor

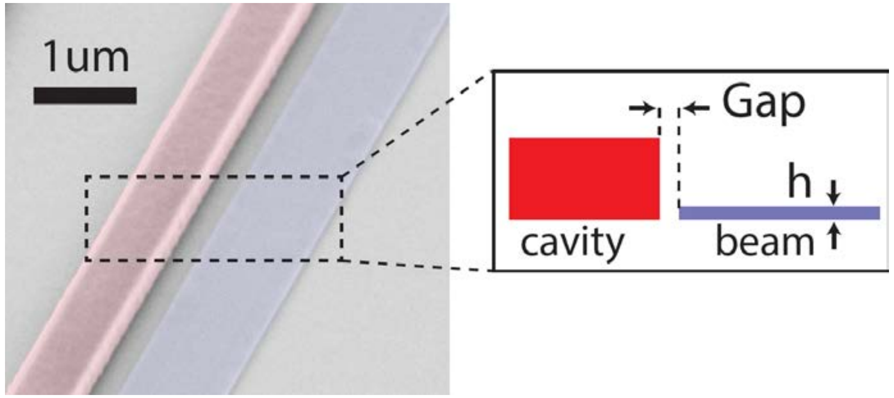
$Q \approx \{5.5, 9.8\} \cdot 10^5$ @ $T = \{300, 6\}\, K$
$f = 279\, kHz$

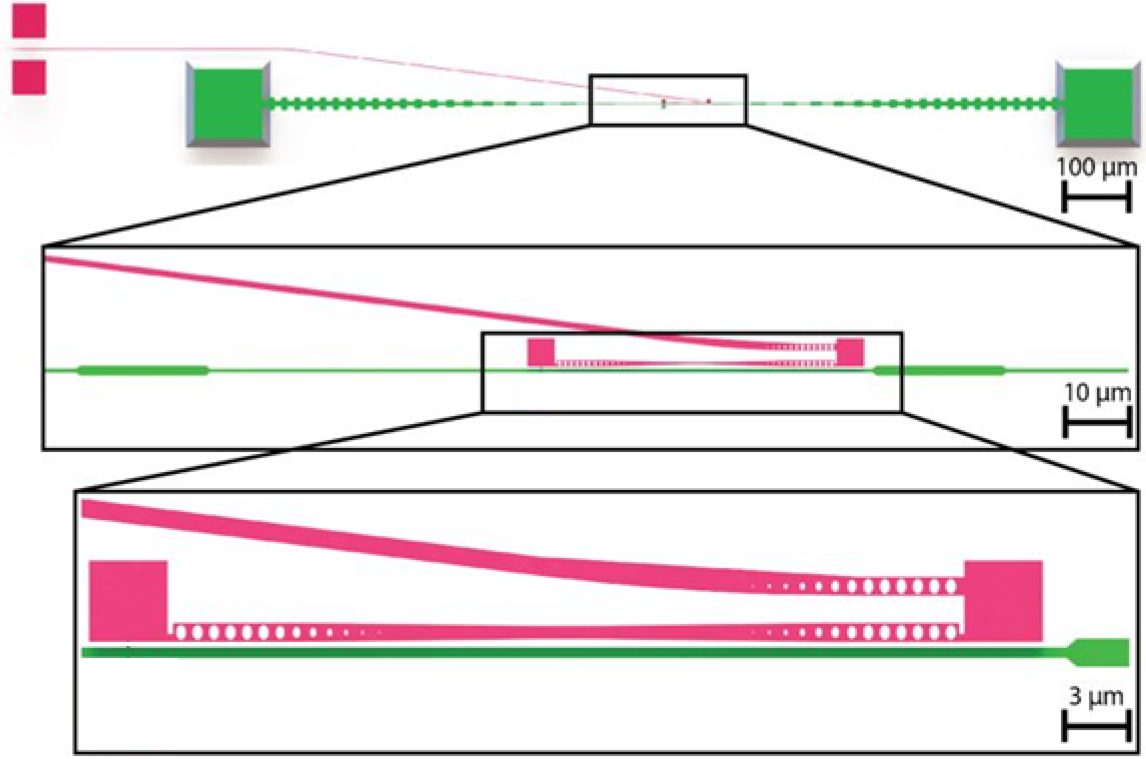
Single high order localized mode, $m_{\text{eff}} \approx 2.5\, pg$



Integration of high-aspect-ratio beams with 1D cavities

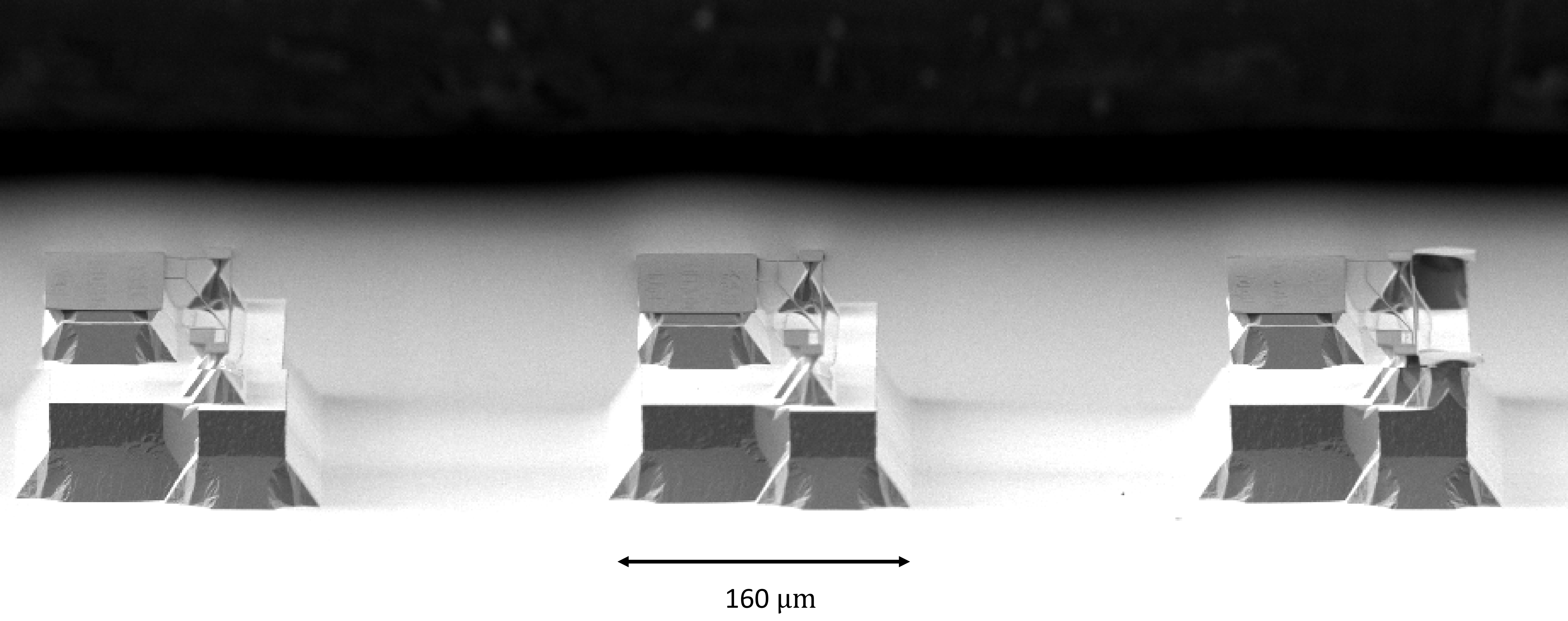






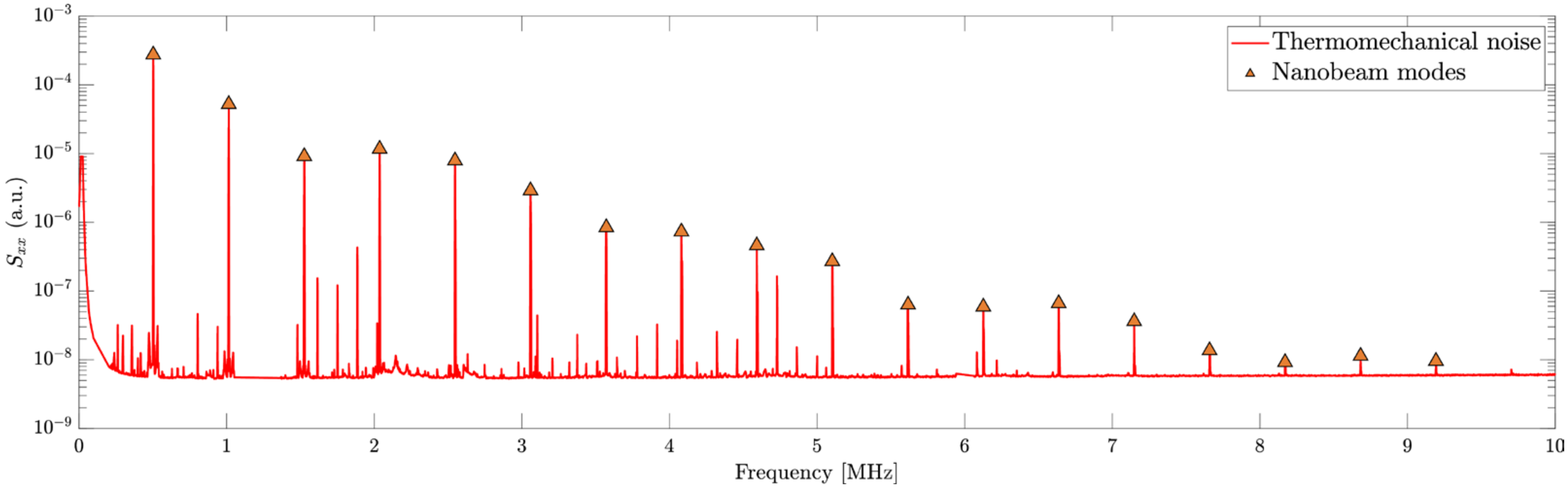
High-Q 1D Fabry-Pérot cavity on a waveguide with photonic crystal end mirrors ($Q_{int} > 35000$)

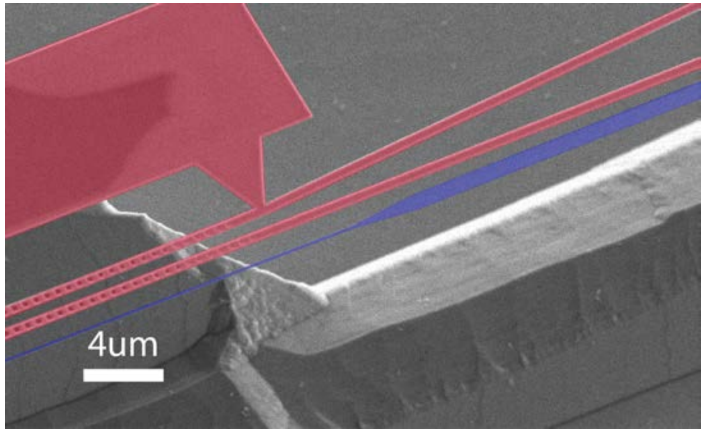
Simulations show g_0 ranging from 0.1-1 MHz



160 μm

Clamp-tapered beam integrated with 1D cavity



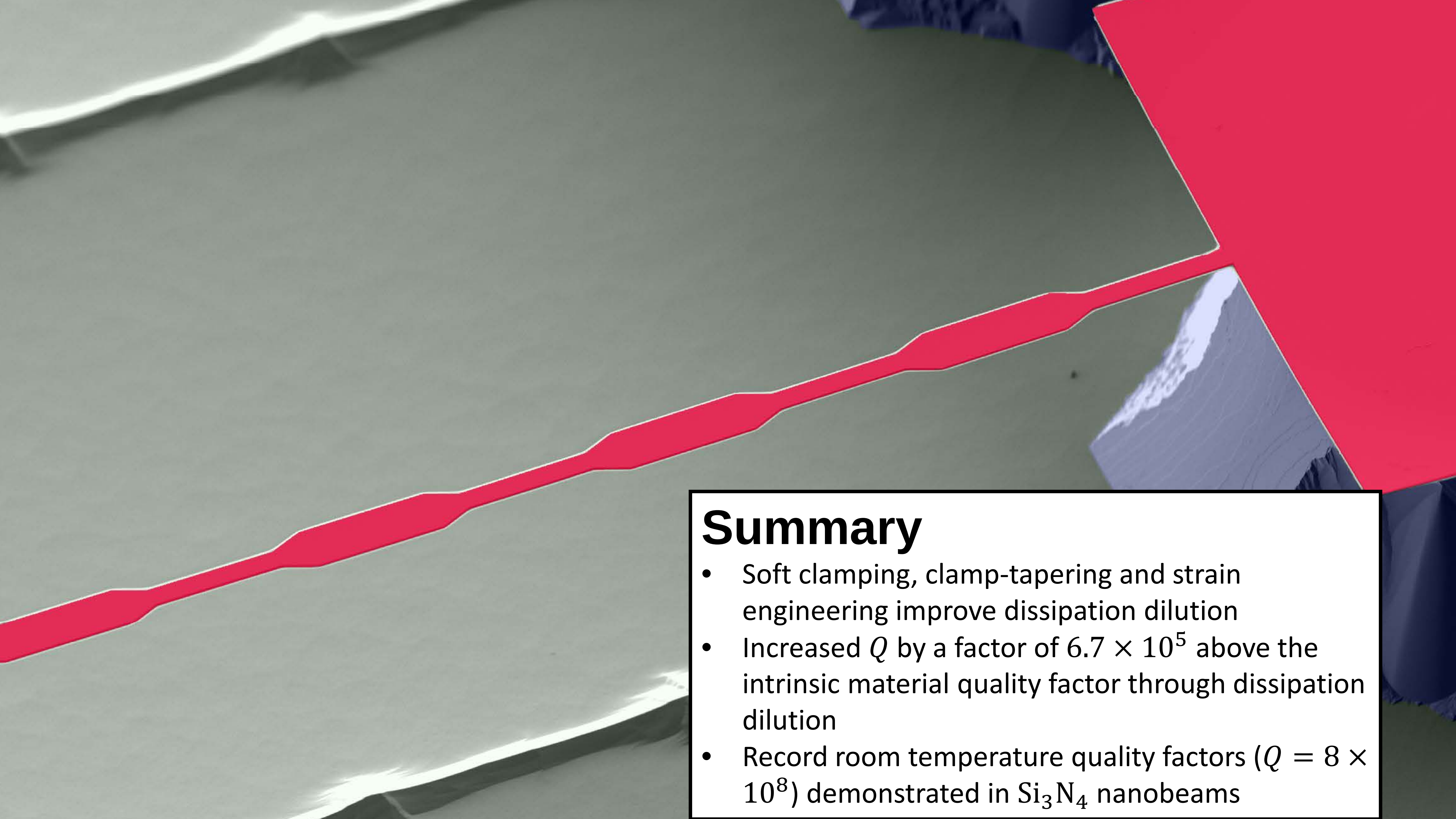


Recently measured device:

$\omega_m = 450$ kHz $\quad \Gamma_m = 2$ Hz

$g_0 = 180$ kHz $\quad \kappa = 14$ GHz

→ $C_0 \sim 2$



Summary

- Soft clamping, clamp-tapering and strain engineering improve dissipation dilution
- Increased Q by a factor of 6.7×10^5 above the intrinsic material quality factor through dissipation dilution
- Record room temperature quality factors ($Q = 8 \times 10^8$) demonstrated in Si_3N_4 nanobeams

The team

Sergey Fedorov

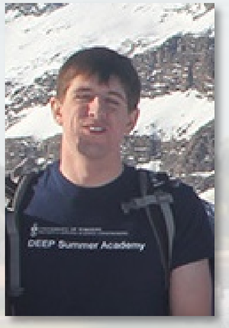
Alberto Beccari

Mohammad Bereyhi

Amir Ghadimi
(Now at CSEM)

Amirali Arabmoheghi

Ryan Schilling
(Now at IBM Watson)



Dalziel Wilson
(Now at Univ. Arizona)

Tobias Kippenberg

HOT Hybrid Optomechanical Technologies

MARIE CURIE ACTIONS

FNSNF
FONDS NATIONAL SUISSE
SCHWEIZERISCHER NATIONALFONDS
FONDO NAZIONALE SVIZZERO
SWISS NATIONAL SCIENCE FOUNDATION

BRIDGING THE GAP DARPA POWERED BY IDEAS

OMT OPTOMECHANICAL TECHNOLOGIES

Why do we care about dissipation?

EPFL

Dissipation (Γ_m) limits…

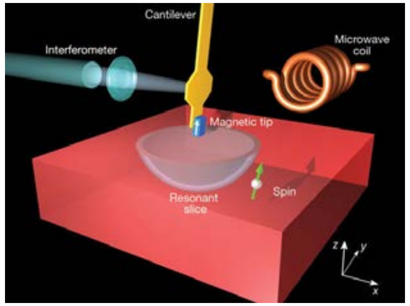
1. Force sensitivity $$\delta F_{\text{th}} = \sqrt{4k_B T m_{\text{eff}} \Gamma_m}$$

2. Frequency stability $$S_{\omega\omega}(\omega) = 2\frac{\langle X_{\text{th}}^2 \rangle}{\langle X_{\text{osc}}^2 \rangle} \frac{\omega^2}{\omega^2 + (\Gamma^2/2)^2} \Gamma_m$$

3. Mechanical coherence $$\Gamma_{\text{th}} = \frac{k_B T}{\hbar \omega_m} \Gamma_m$$

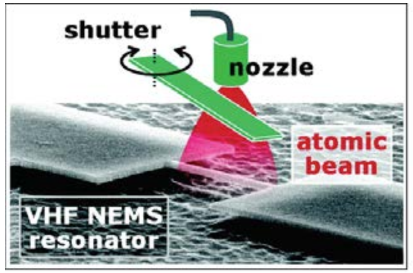
Force sensing

Rugar et al. *Nature* (2004)



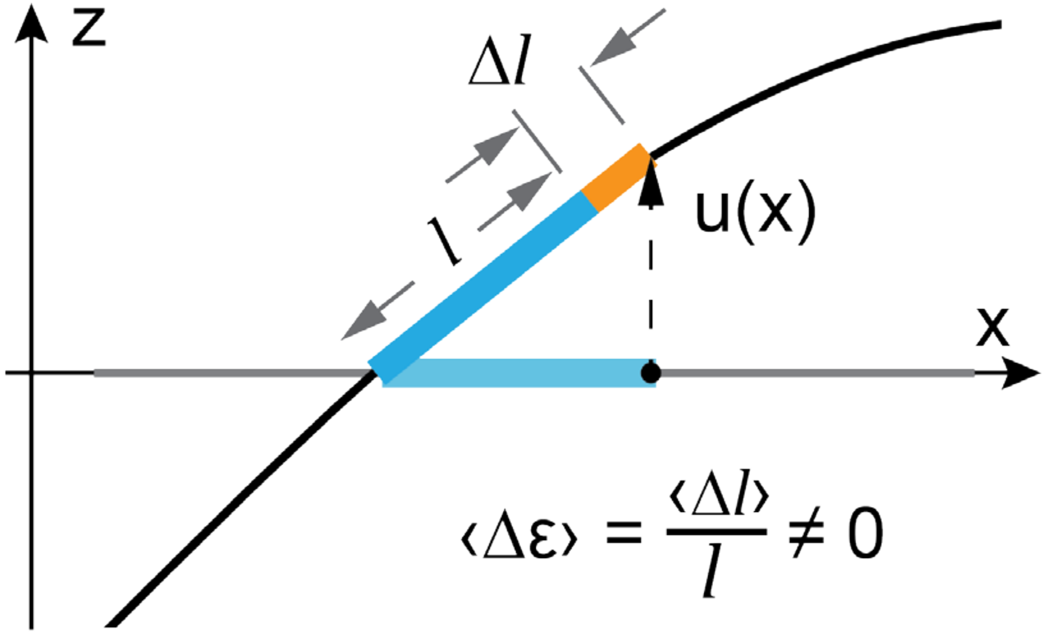
Mass sensing

R.W. Andrews et al., Nat. Phys. (2014)



Fong et al., *Phys. Rev. B* (2012)

Dissipation dilution requirements



$$\Delta l = \frac{1}{2}[u'(x,t)]^2$$

$\Delta\epsilon$	Change in strain
l	Segment length
Δl	Segment elongation
$u(x)$	Mode amplitude

Dissipation dilution requires:

1. Static strain
2. Geometric nonlinearity of strain

Especially strong for flexural (violin) modes

Fedorov, Engelsen et al., *Phys. Rev. B* **99** (2019)
Gonzalez and Saulson, *J. Acoust. Soc. Am.* **96**.1(1994)

Origin of dissipation dilution in stressed materials

Dissipation dilution: $$D_Q = \frac{Q}{Q_{\text{int}}} = 1 + \frac{\langle W_{\text{dil}}(t)\rangle}{\langle W_{\text{lossy}}(t)\rangle}$$

Increasing static strain increases the lossless potential more than the lossy potential

$$\sigma = E e^{-i\phi} \epsilon \qquad Q_{\text{int}} = 1/\phi$$

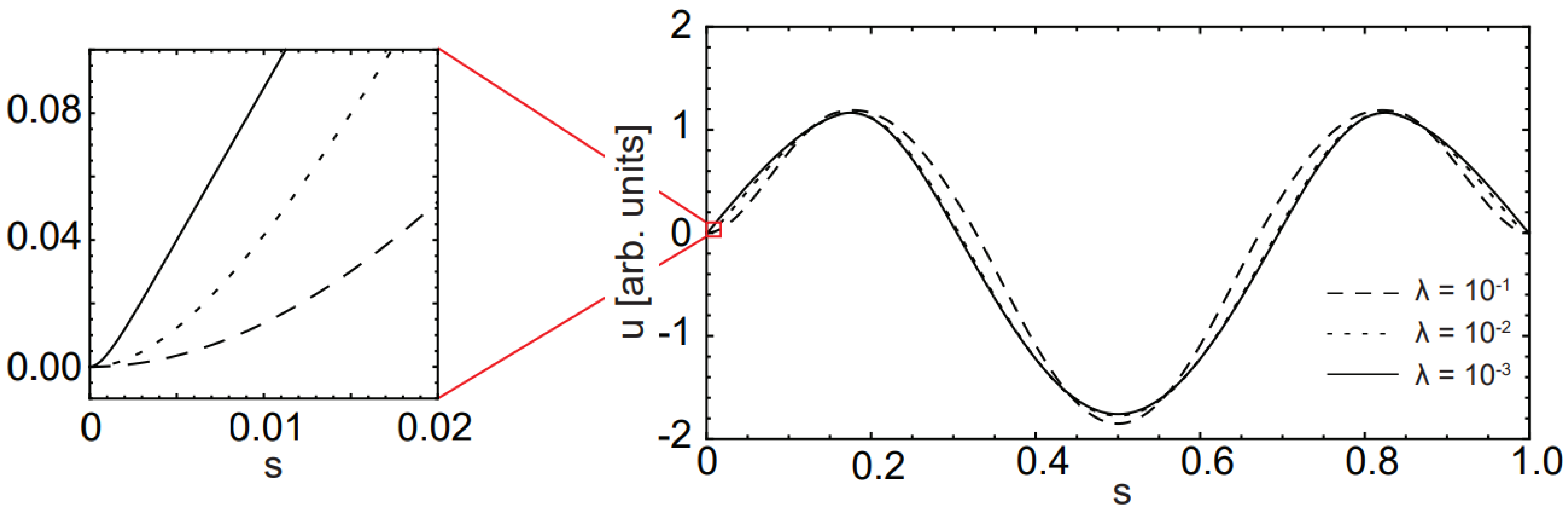
Lossless potential: $$\langle W_{\text{dil}}(t)\rangle = E \int \epsilon \,\langle \Delta\epsilon(t)\rangle \, dV$$

Lossy potential: $$\langle W_{\text{lossy}}(t)\rangle = \frac{E}{2} \int \langle [\Delta\epsilon(t)]^2 \rangle dV$$

Q_{int}	Intrinsic quality factor
E	Young's modulus
ϵ	Static strain
ϕ	Loss angle
σ	Stress
$\Delta\epsilon$	Change in strain

Fedorov, Engelsen et al., *Phys. Rev. B* **99** (2019)
Gonzalez and Saulson, *J. Acoust. Soc. Am.* **96**.1(1994)

Curvature in clamping region of uniform beam

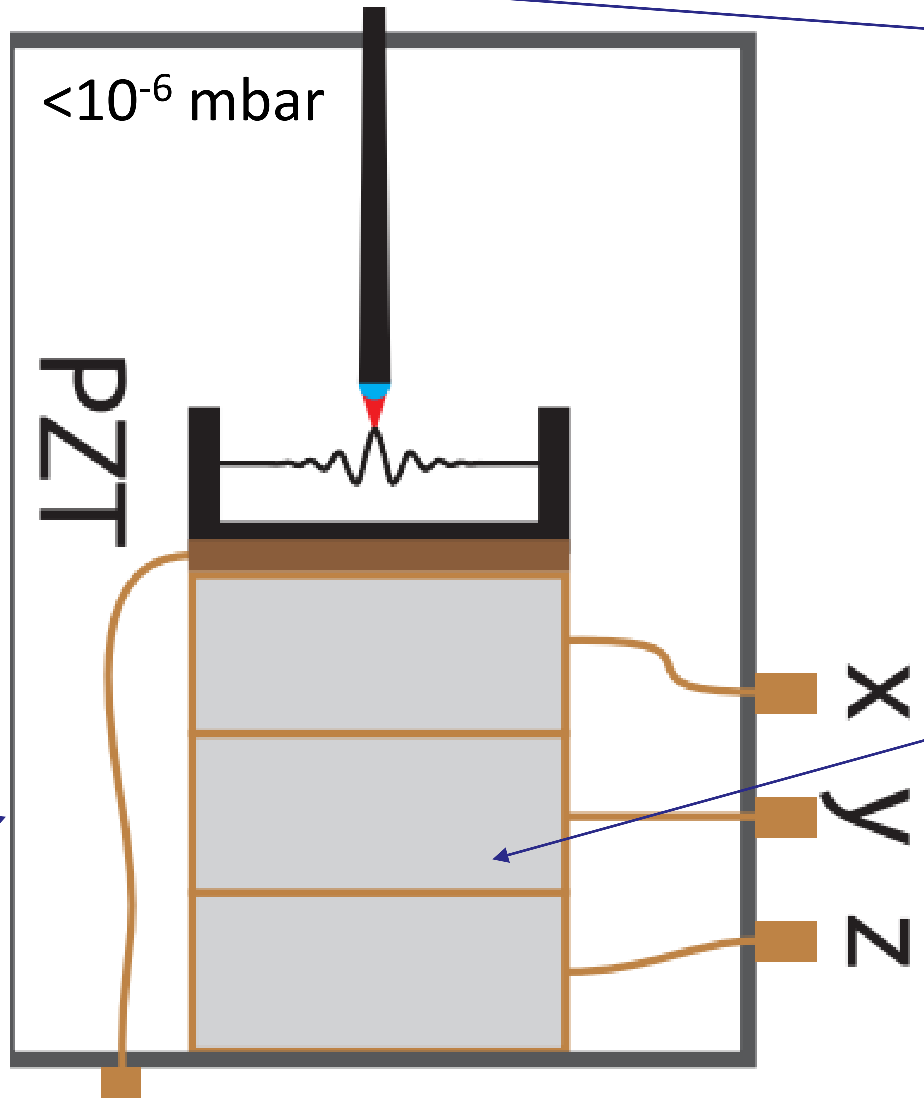


$s = \mathrm{x}/\mathrm{L}$: the normalized beam length

Note that the characteristic length of clamping region is proportional to λ

Mechanical characterization setup

Can resolve Brownian motion of mechanical modes



Reflected light sent to homodyne interferometer

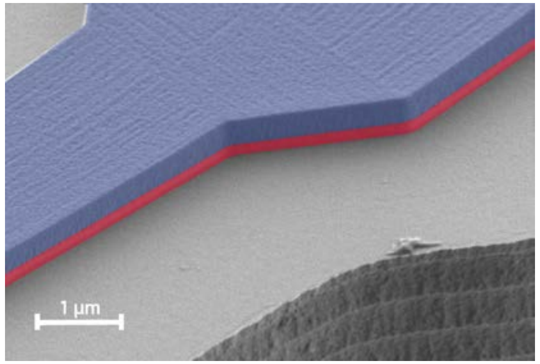
Nanopositioners used to position chip relative to lensed fiber

Ringdown measurement by driving mode with a piezoelectric element

Si_3N_4 nanobeam process flow

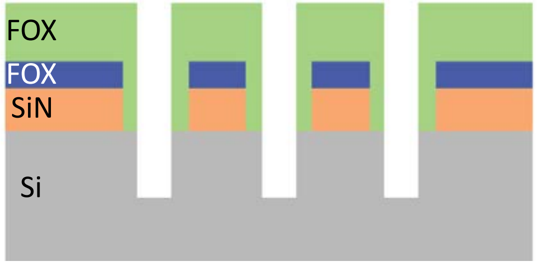
Patterning

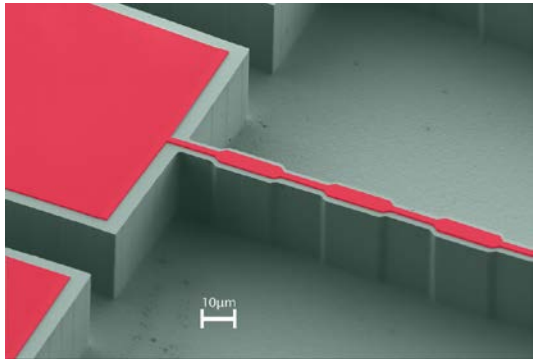
Structures are patterned using electron beam lithography



Gap definition

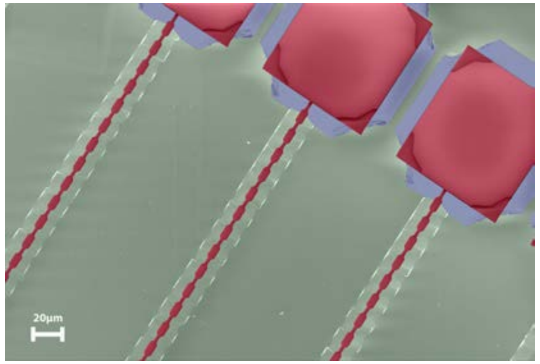
Upscaled version of the first lithography followed by deep reactive ion etching



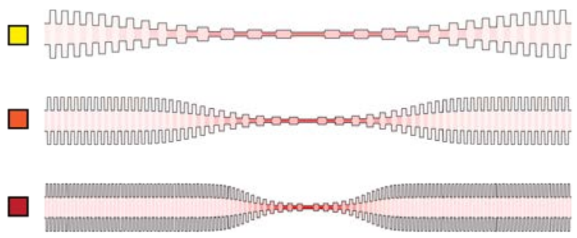


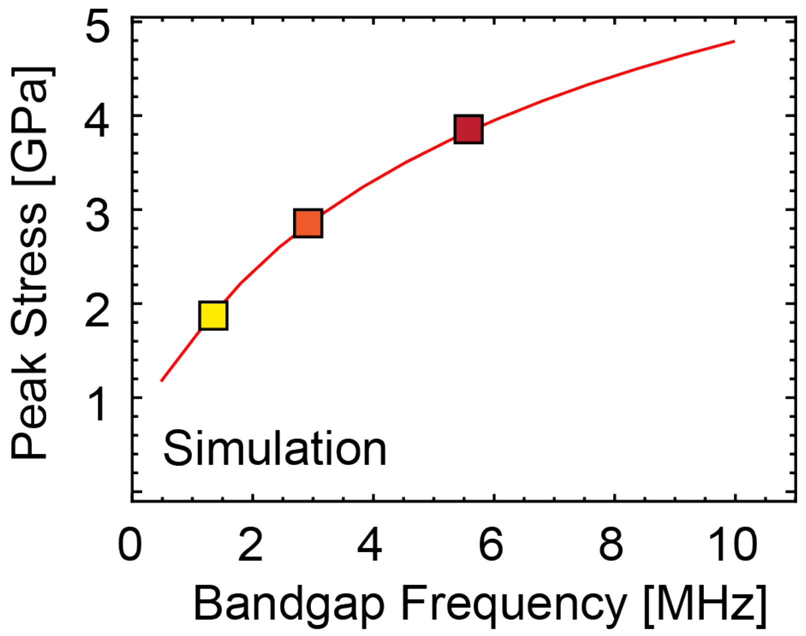
Undercut

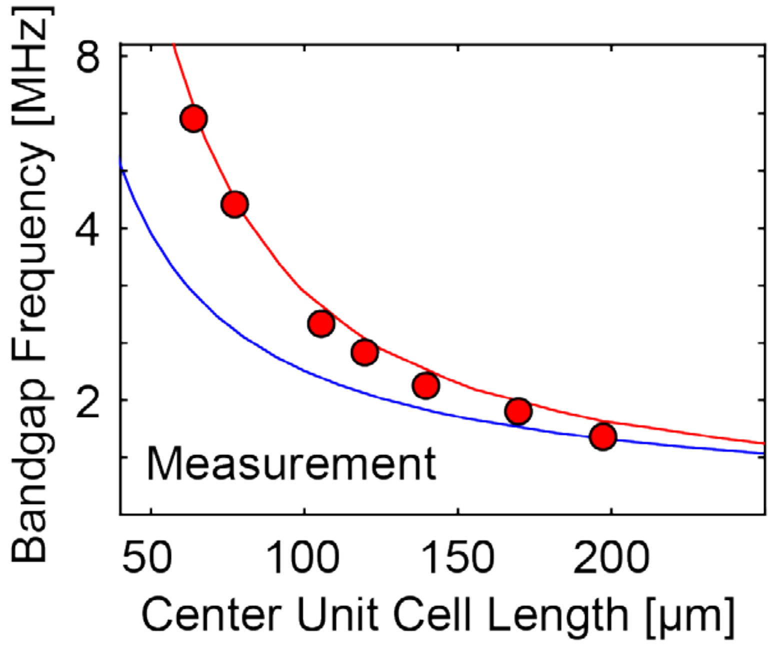
Si undercut using KOH



How do we know what stress we achieve?



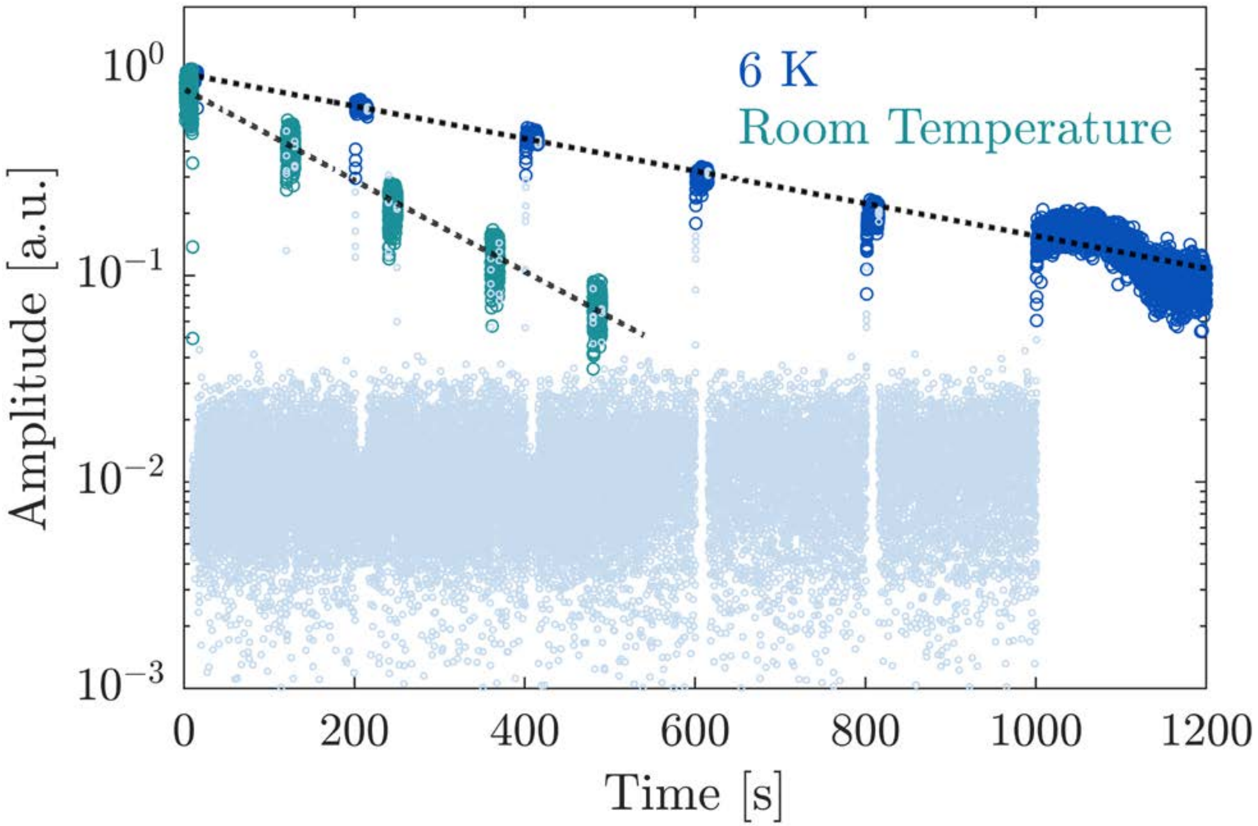


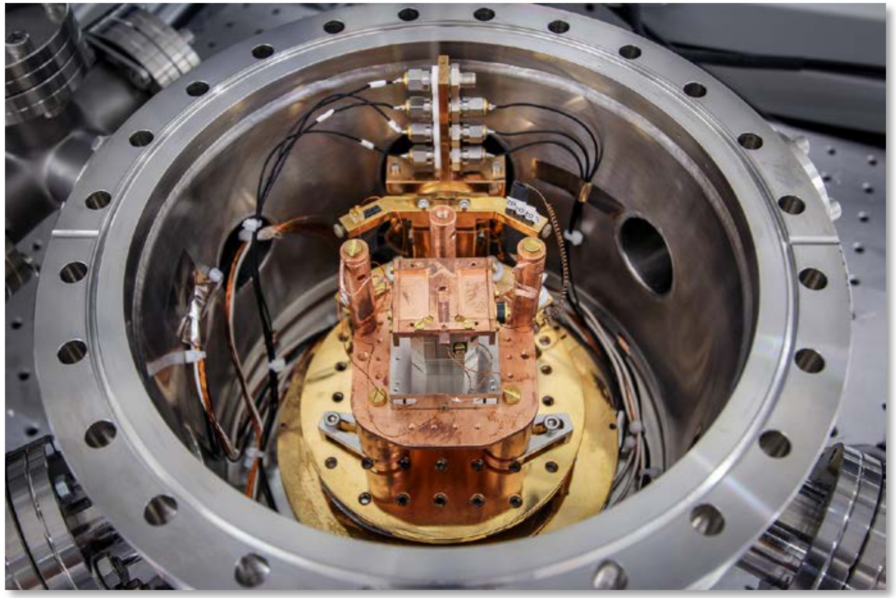


Expected bandgap frequency of the three geometries on the left shown as squares

- Blue line: expected bandgap frequency based on unit cell length
- Red line calculated including stress

Cryogenic characterization

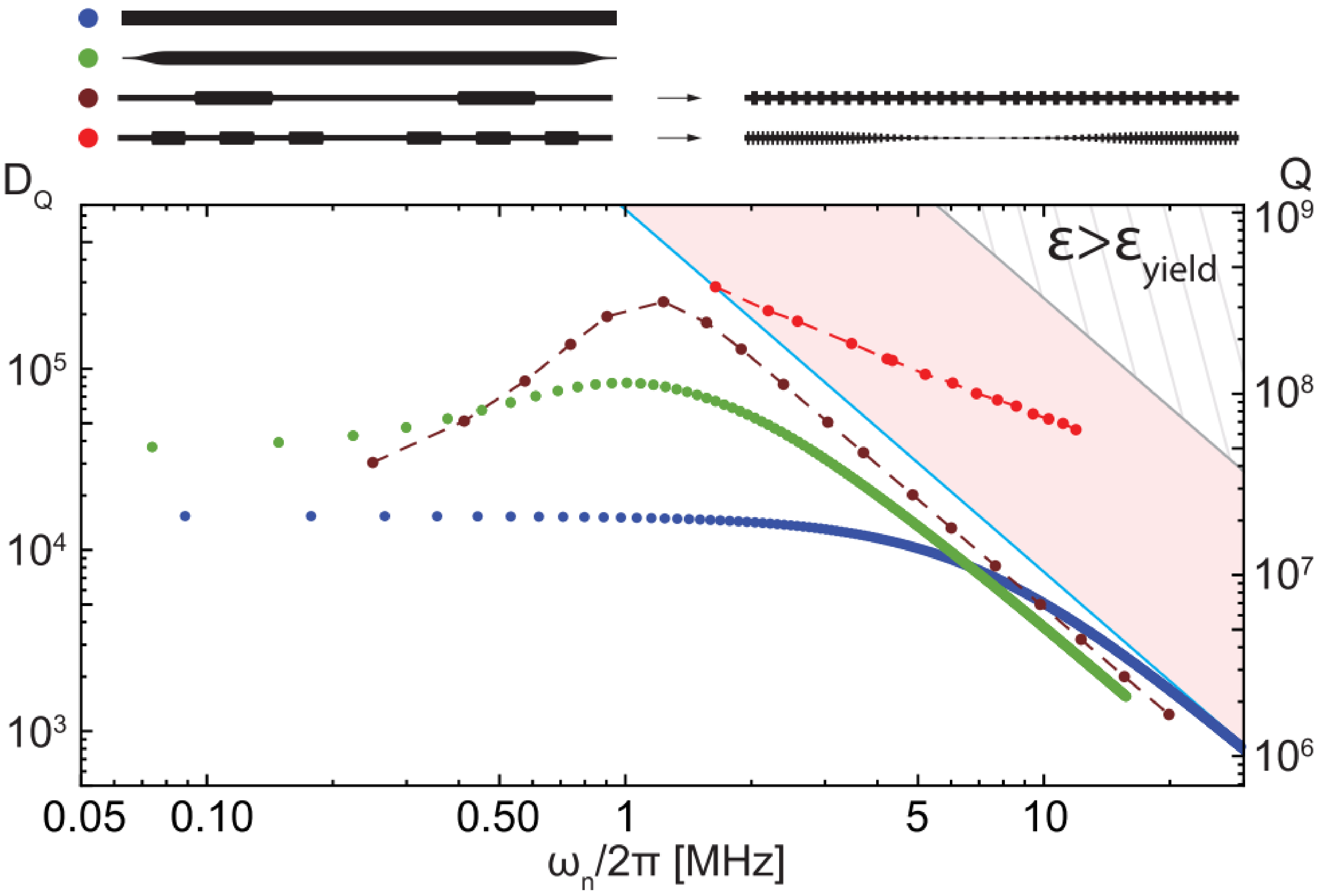




300 K		5.8 K	
$\Omega_m/2\pi$ [MHz]	Q $[\cdot 10^6]$	$\Omega_m/2\pi$ [MHz]	Q $[\cdot 10^6]$
1.020	650	0.985	**1480**
0.986	520	0.958	**1420**
0.848	130	0.823	**1340**
0.849	160	0.823	**1020**

- Enhancement factor ranging from 2-10
- Frequency shift likely due to thermal expansion mismatch

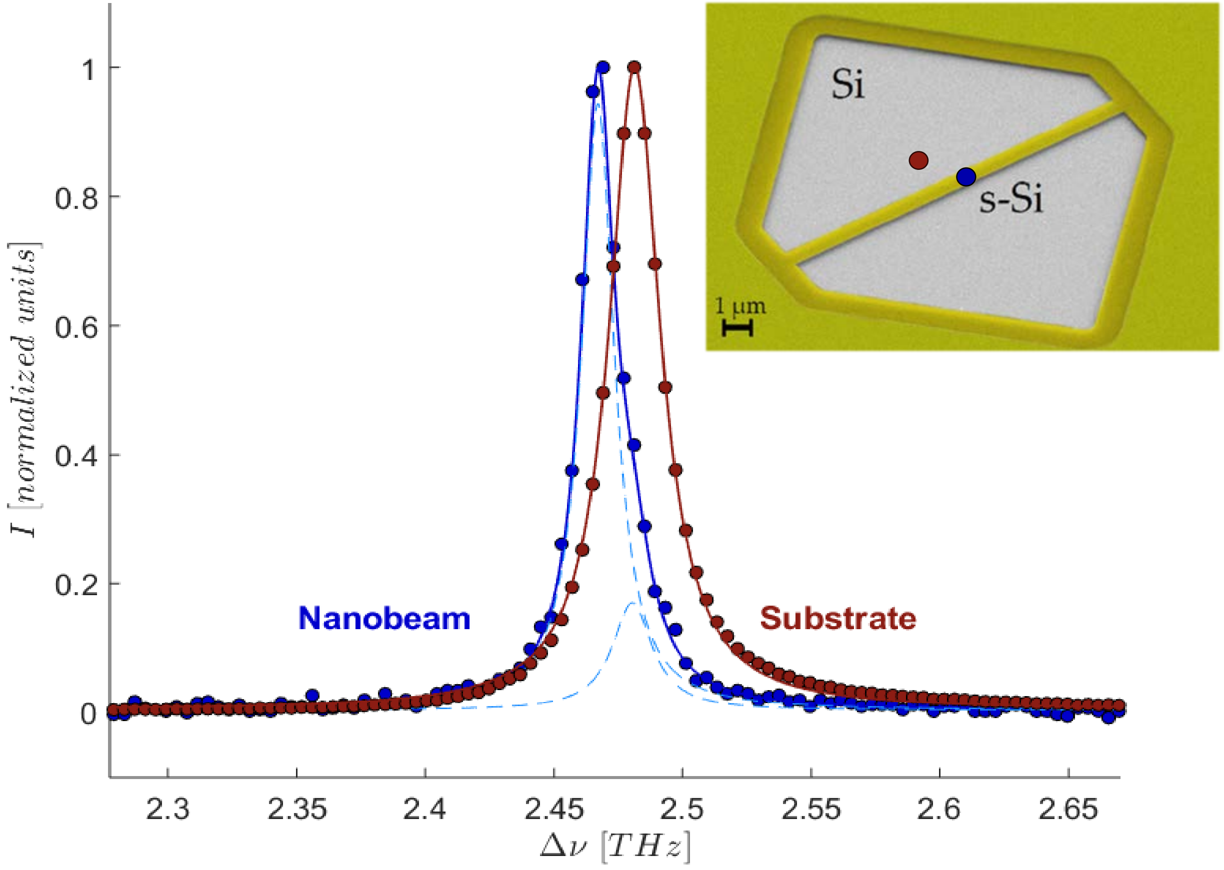
Overview of dissipation engineering techniques



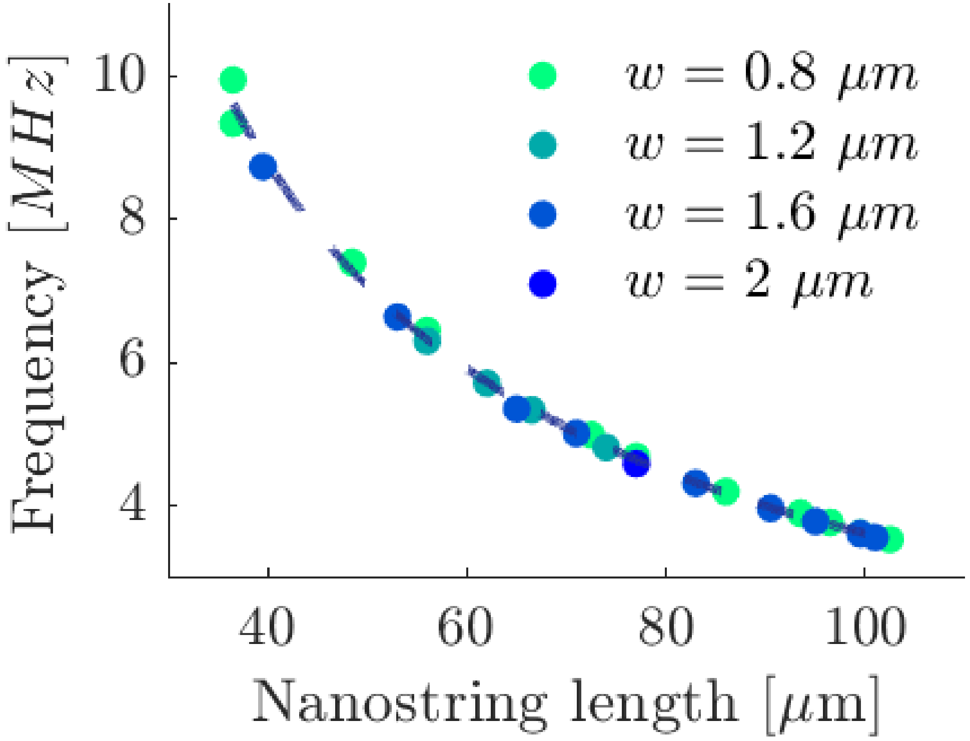
Values representative of 3-mm long, 20-nm thick Si_3N_4 beam

Fedorov, Engelsen et al., *Phys. Rev. B* **99**, 054107 (2019)

Strained silicon stress



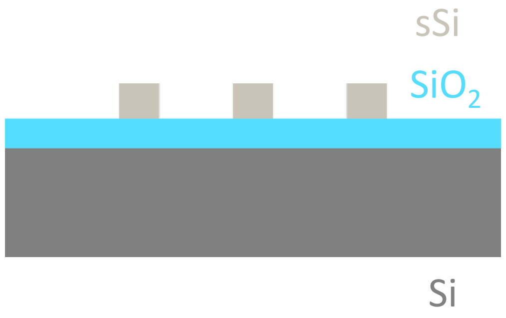
$$f_1 = \sqrt{\frac{\sigma(1-\nu)}{\rho}}\frac{1}{2L}$$

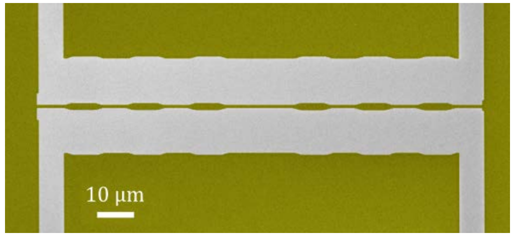


Verified that stress is in fact around 1.2 GPa after fabrication

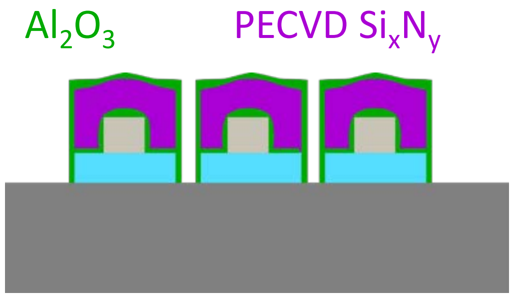
Strained silicon fabrication process

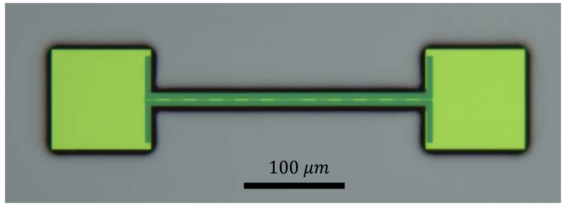
Patterning



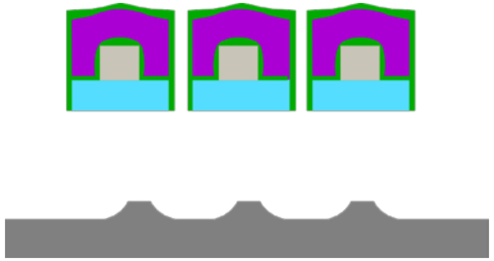


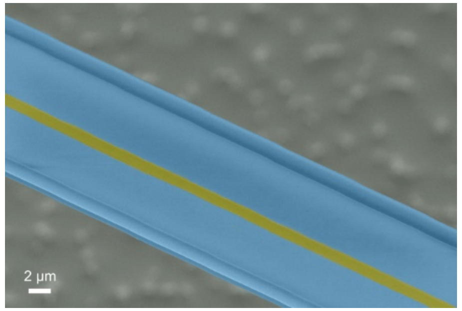
Encapsulation





Undercut





Selective etch