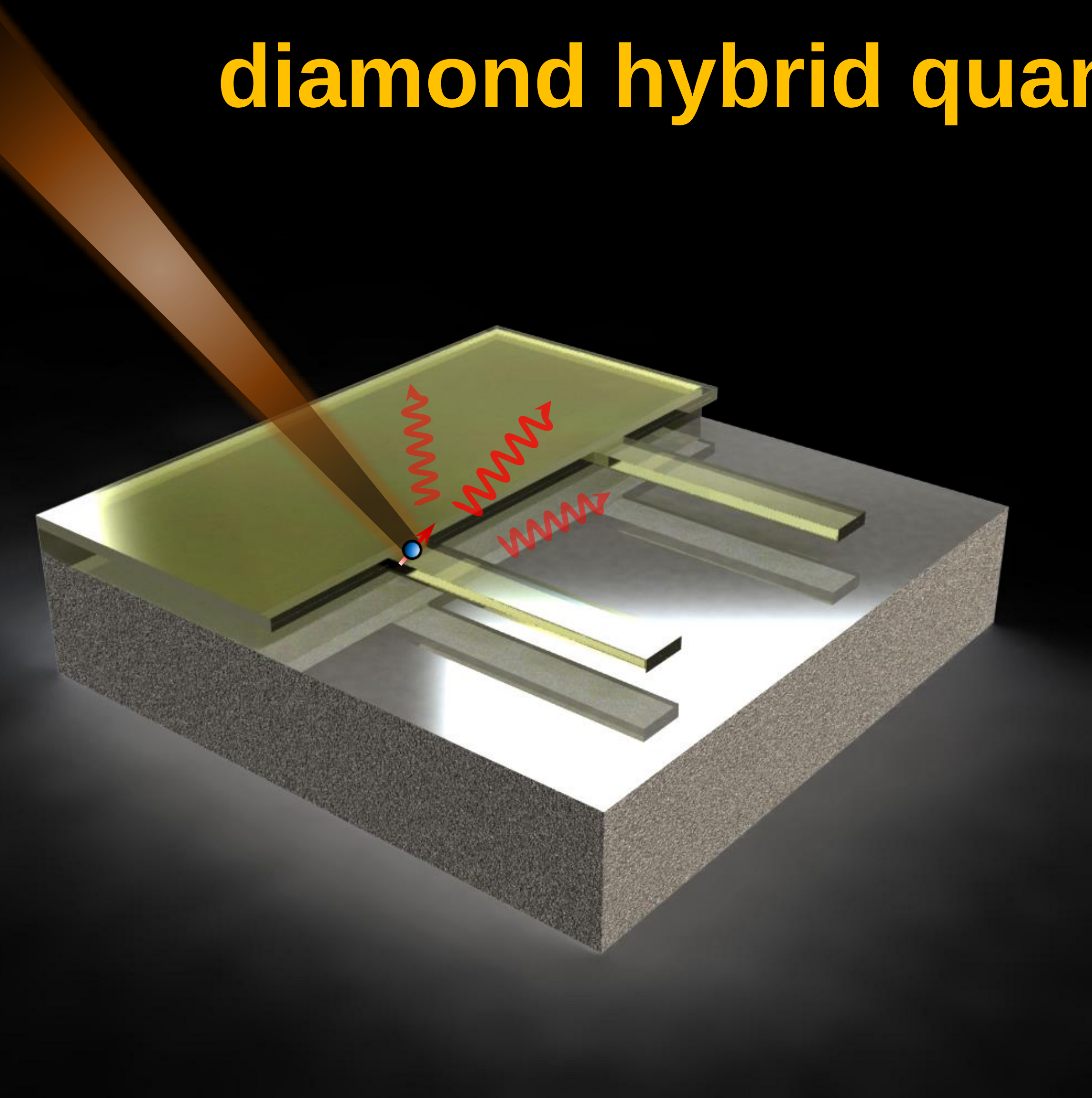
When Spin met Phonon: diamond hybrid quantum system



Donghun Lee

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SNU Colloquium May 10 2017

Selected for a Viewpoint in *Physics*
PRL **116**, 061102 (2016) PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016

Observation of Gravitational Waves from a Binary Black Hole Merger

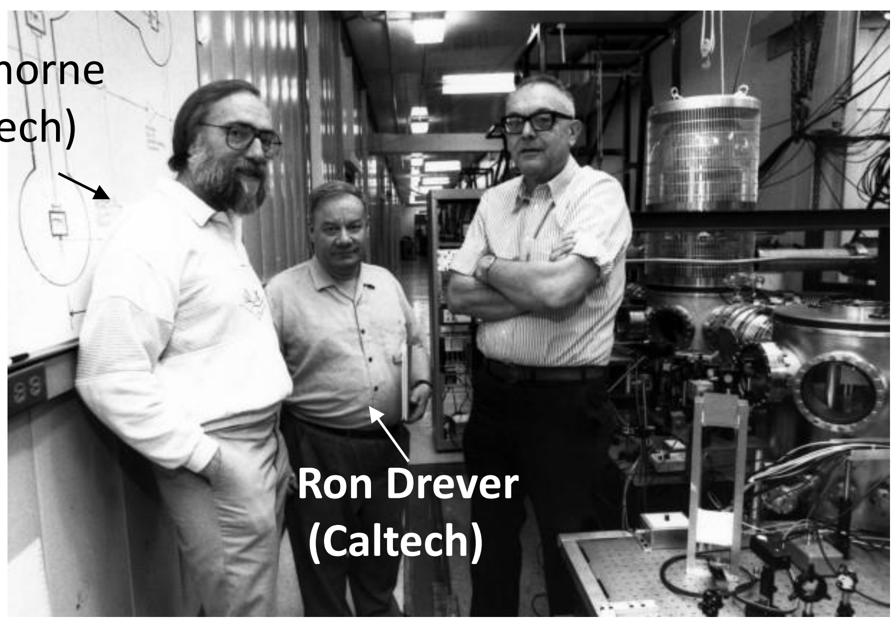
B. P. Abbott *et al.*[*]
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 21 January 2016; published 11 February 2016)

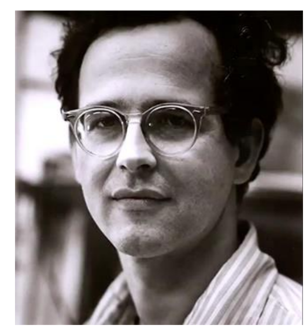
Citation ~ 850

On September 14, 2015 at 09:50:45 UTC the two detectors of the Laser Interferometer Gravitational-Wave Observatory simultaneously observed a transient gravitational-wave signal. The signal sweeps upwards in frequency from 35 to 250 Hz with a peak gravitational-wave strain of 1.0×10^{-21}. It matches the waveform predicted by general relativity for the inspiral and merger of a pair of black holes and the ringdown of the resulting single black hole. The signal was observed with a matched-filter signal-to-noise ratio of 24 and a false alarm rate estimated to be less than 1 event per 203 000 years, equivalent to a significance greater than 5.1σ. The source lies at a luminosity distance of 410^{+160}_{-180} Mpc corresponding to a redshift $z = 0.09^{+0.03}_{-0.04}$. In the source frame, the initial black hole masses are $36^{+5}_{-4} M_\odot$ and $29^{+4}_{-4} M_\odot$, and the final black hole mass is $62^{+4}_{-4} M_\odot$, with $3.0^{+0.5}_{-0.5} M_\odot c^2$ radiated in gravitational waves. All uncertainties define 90% credible intervals. These observations demonstrate the existence of binary stellar-mass black hole systems. This is the first direct detection of gravitational waves and the first observation of a binary black hole merger.

DOI: 10.1103/PhysRevLett.116.061102

Kip Thorne
(Caltech)

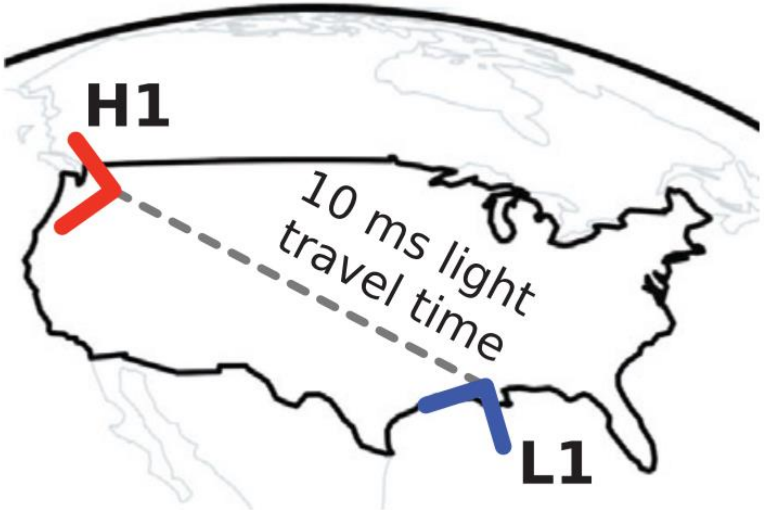




Rainer Weiss, MIT

LIGO (**L**aser **I**nterferometer **G**ravitational-Wave **O**bservatory)

LIGO Hanford



LIGO Livingston

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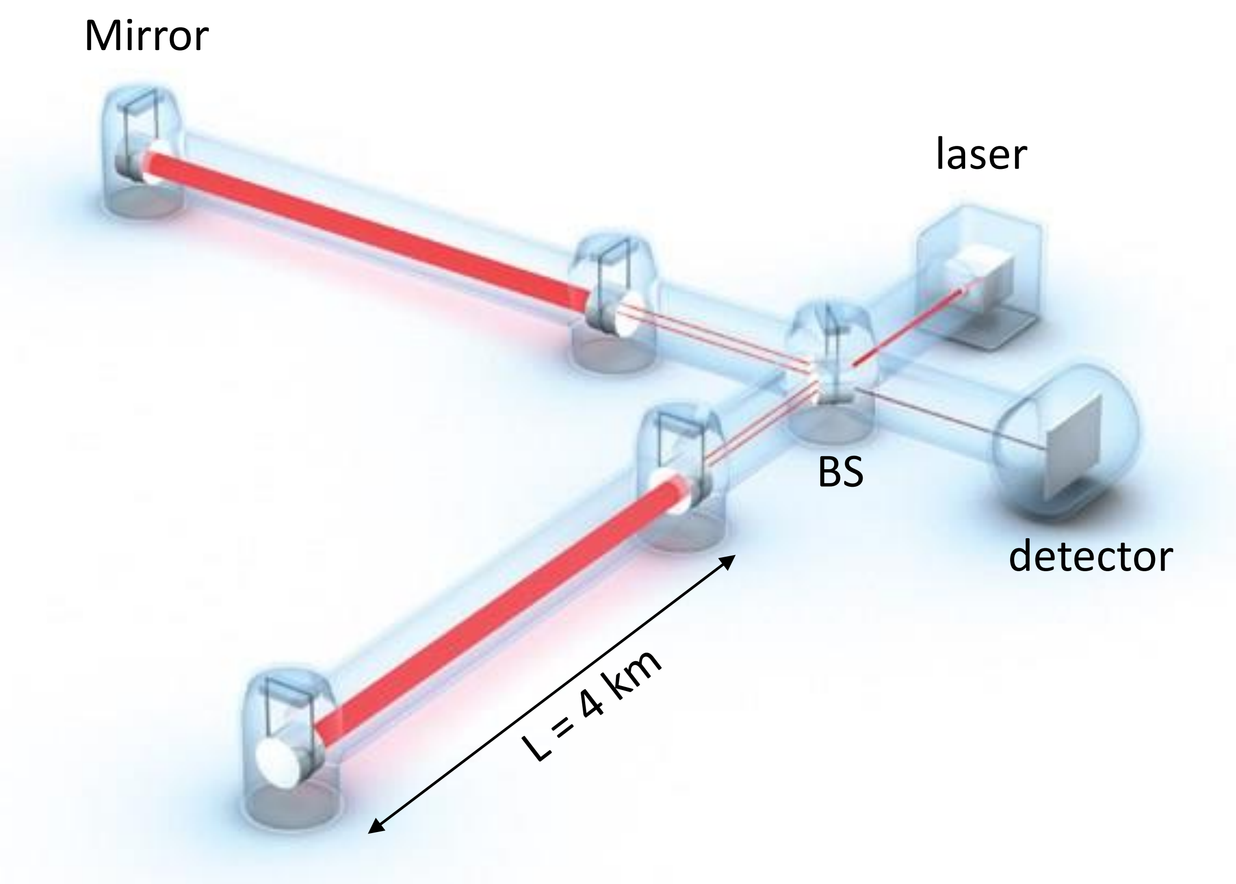

LIGO Livingston

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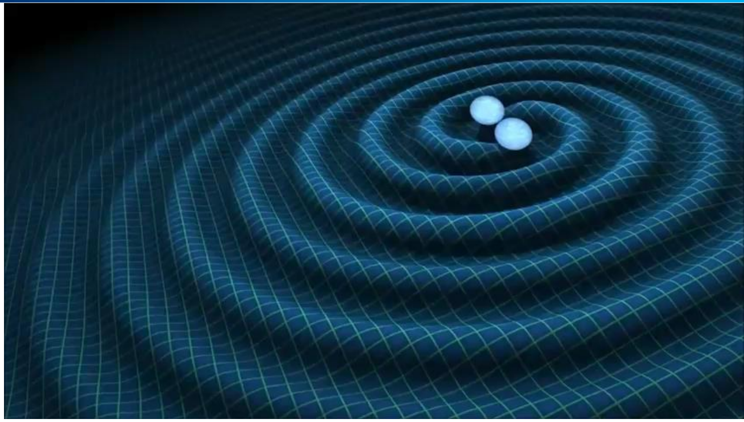
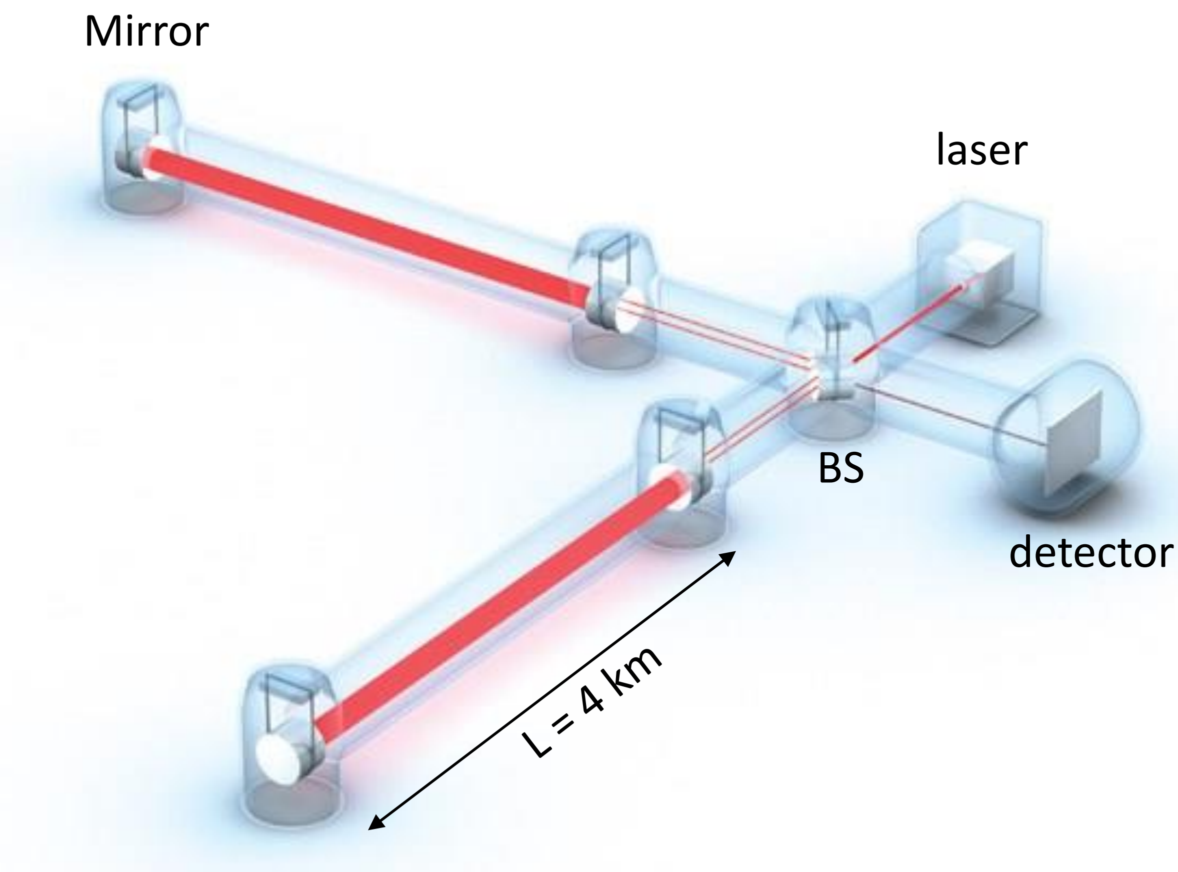


Binary black hole merger



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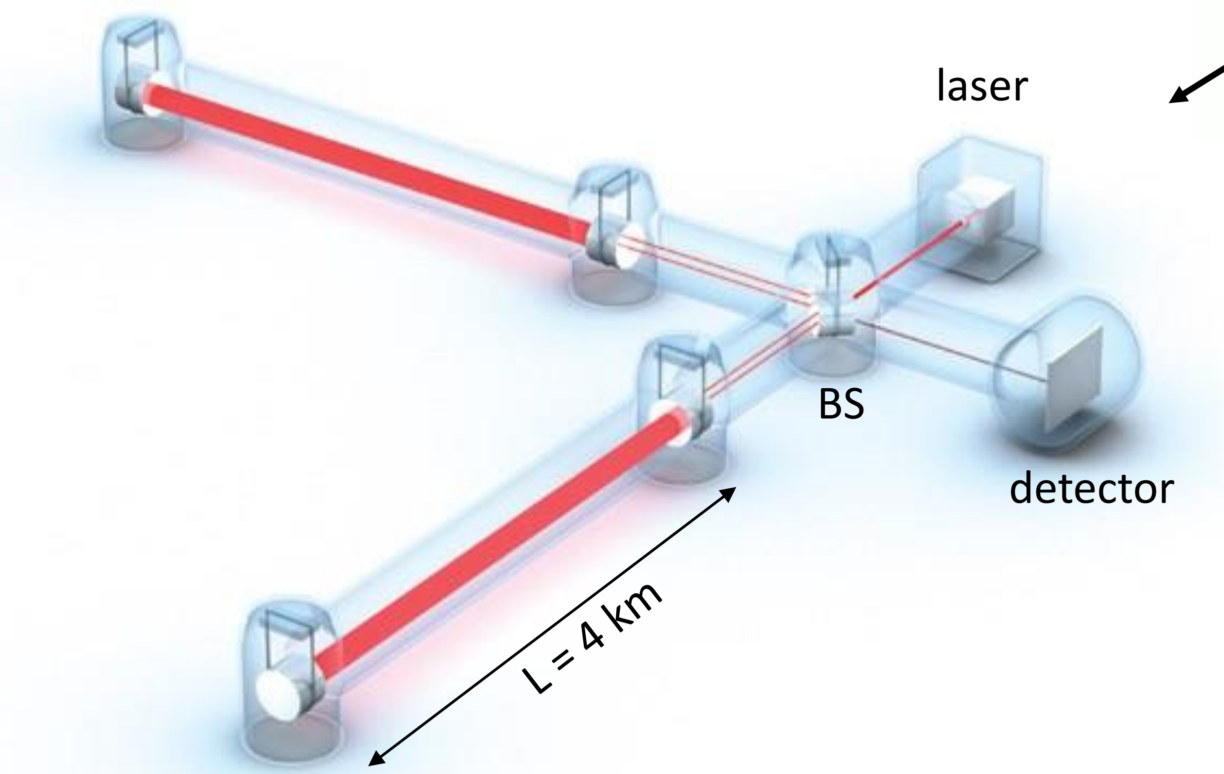

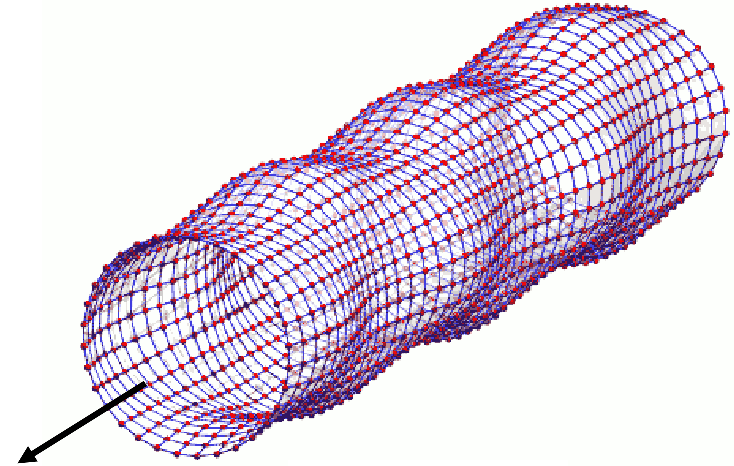

Gravitational waves

LIGO Livingston

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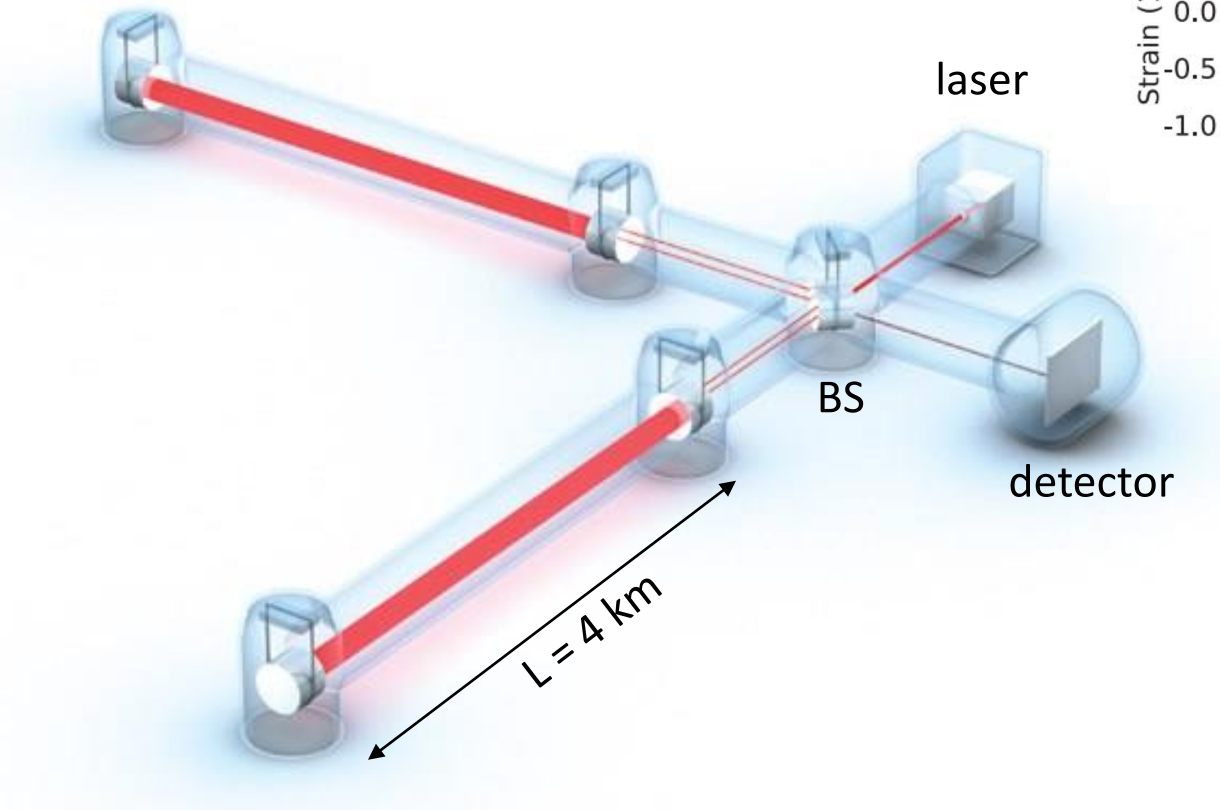

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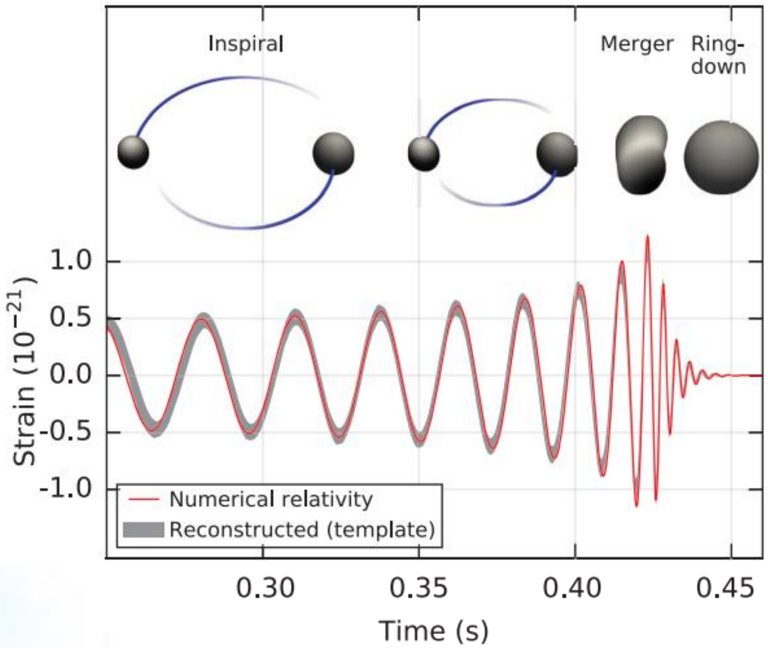

B.P. Abbott et al., PRL (2016)

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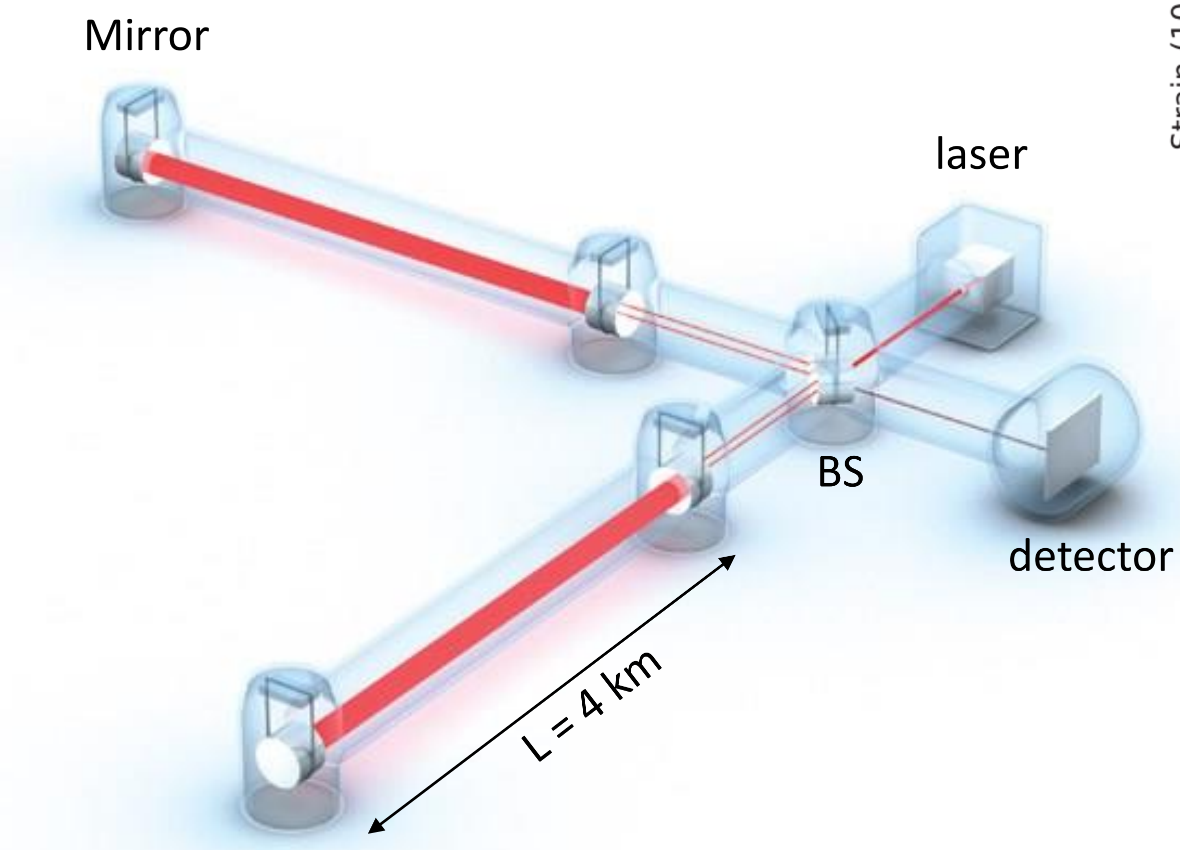
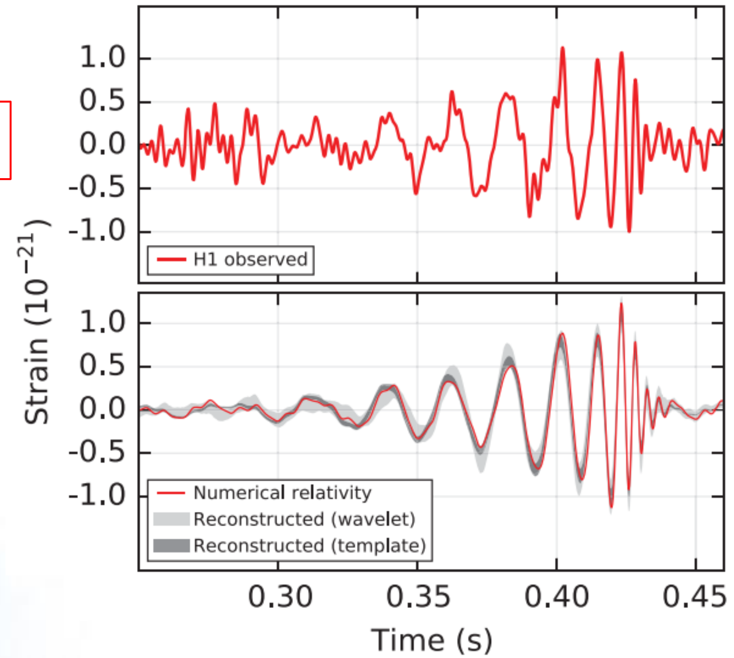
LIGO (**L**aser **I**nterferometer **G**ravitational-Wave **O**bservatory)

~ 10^{-18} m





B.P. Abbott et al., PRL (2016)

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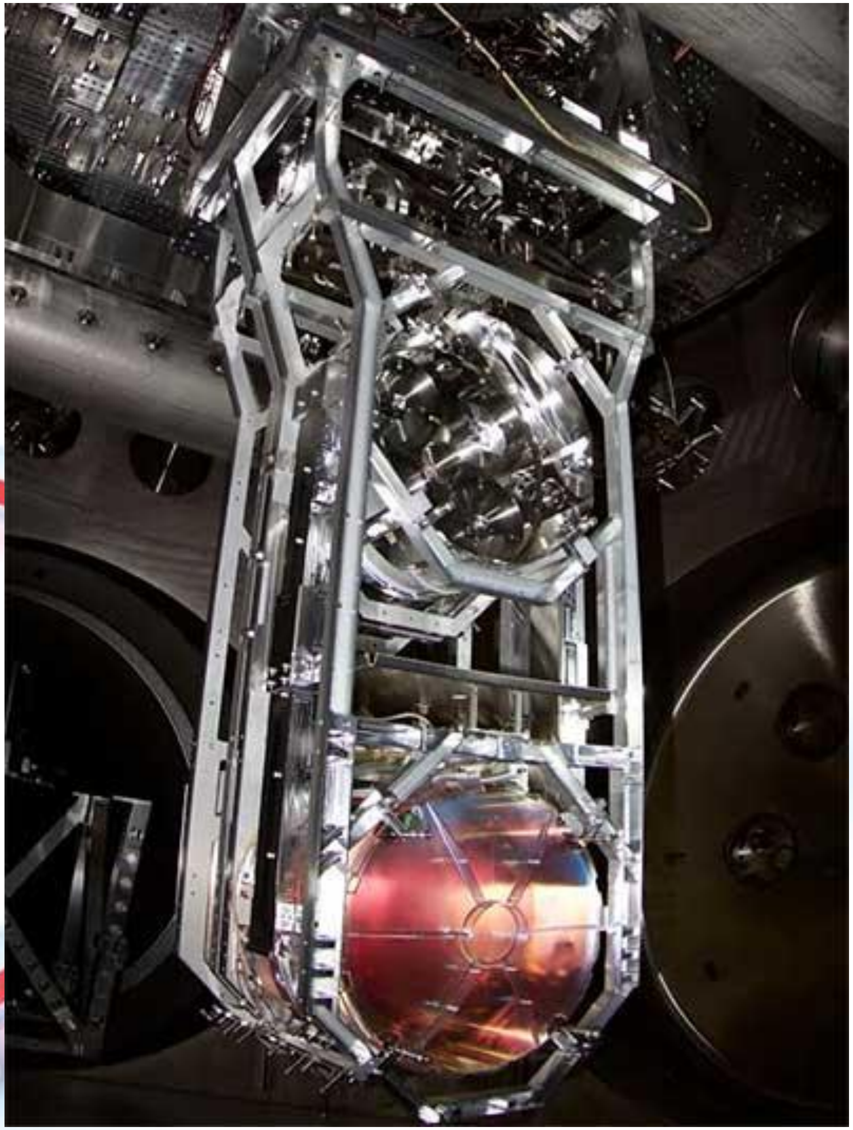

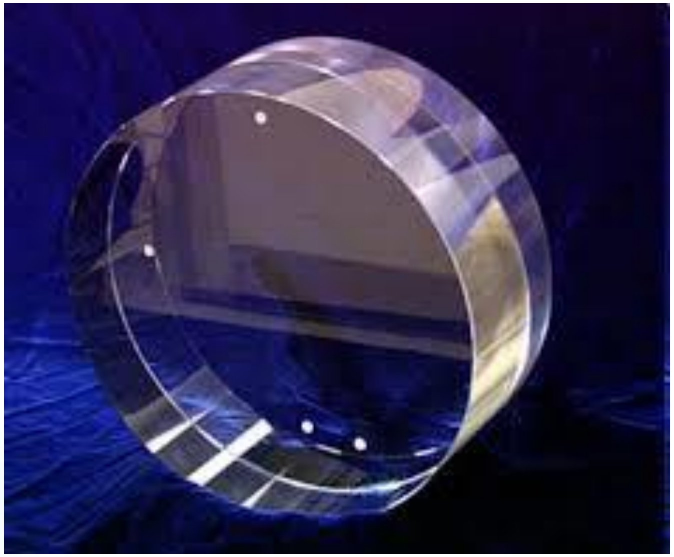

- 17 cm radius x 20 cm thickness
- mass = 40 kg

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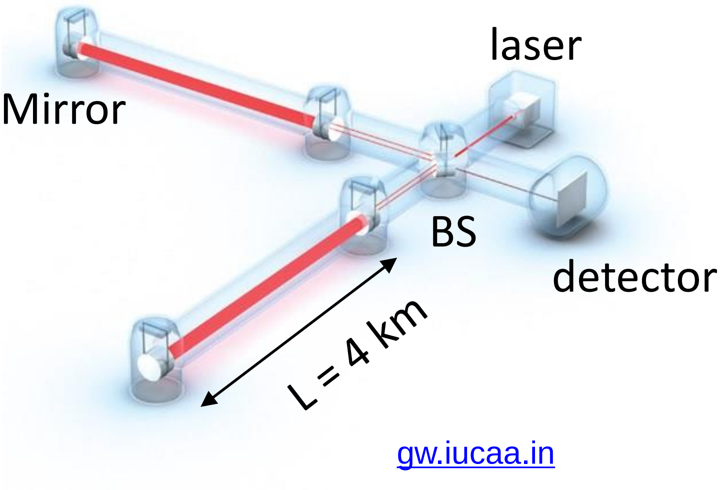
Nano mechanical systems for sensing

Mechanical sensing of displacement, force, mass, single spins…



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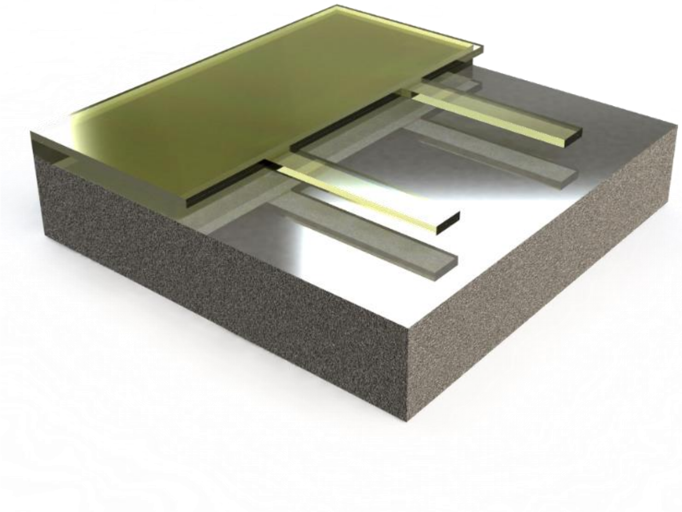
Nano mechanical systems
for practical applications

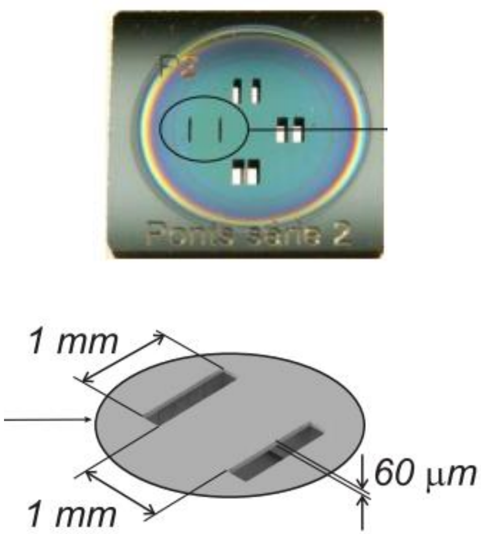


Nano mechanical systems in the quantum regime

1. Quantum-limited sensors based on nano mechanical systems

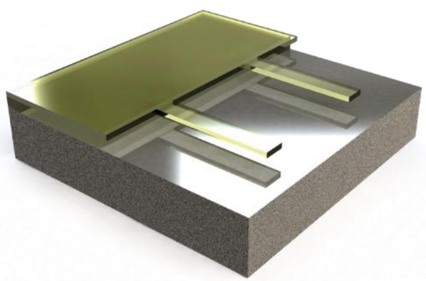
Mechanical sensing of displacement, force, mass, single spins…

Displacement sensitivity
attometer-scale (10^{-18} m)



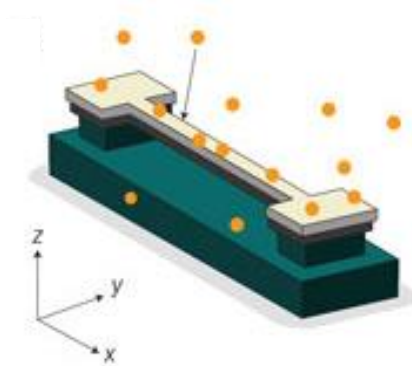
O. Arcizet et al.,
PRL 97, 133601 (2006)

Force sensitivity
zeptonewton-scale
(10^{-21} N)



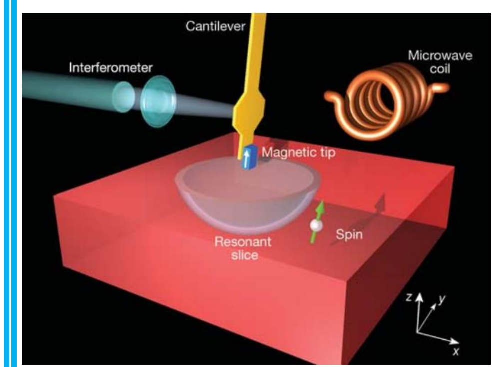
H. J. Mamin et al.,
APL 79, 3358 (2001)

Mass sensitivity
yoctogram-scale
(10^{-24} g)



A. K. Naik et al.,
Nature Nano. 4, 445 (2009)

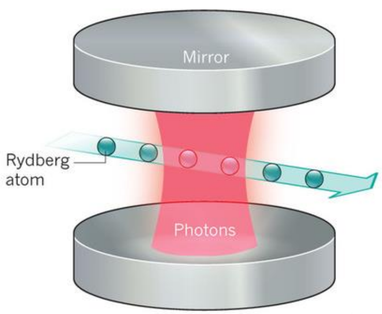
Magnetic sensitivity
single e spin-level

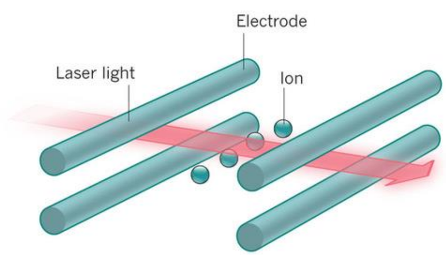


D. Rugar et al.,
Nature 430, 329 (2004)

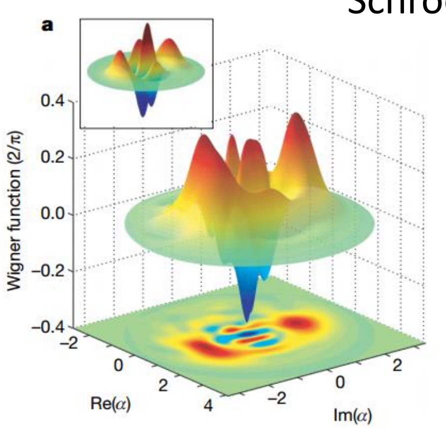
2. Quantum phenomena from macroscopic mechanical objects

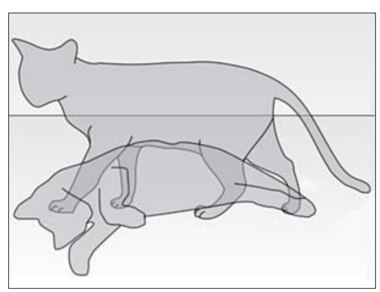
Quantum phenomena
at single atom, single photon level





Schrodinger cat state

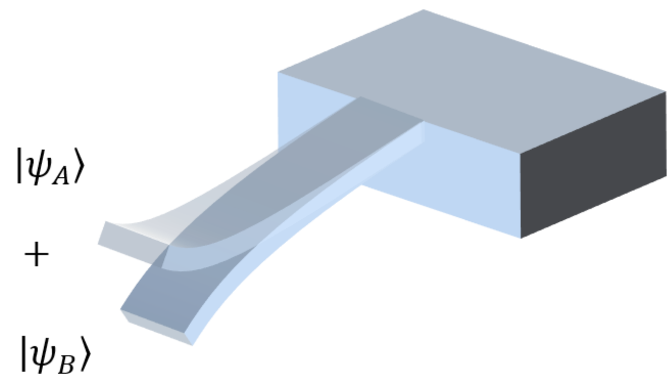




G. Nogues et al.,
Nature 400, 239 (1999)

C. J. Myatt et al.,
Nature 403, 269 (2000)

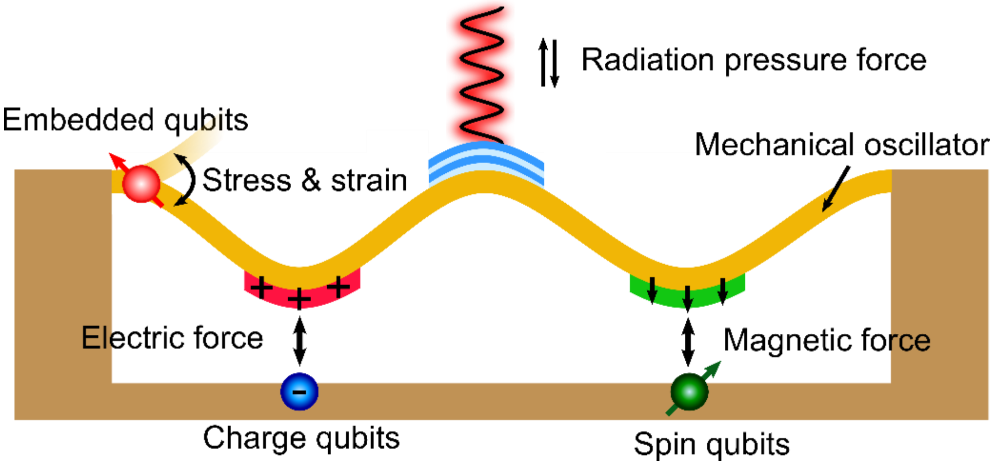
Quantum phenomena
from massive mechanical objects



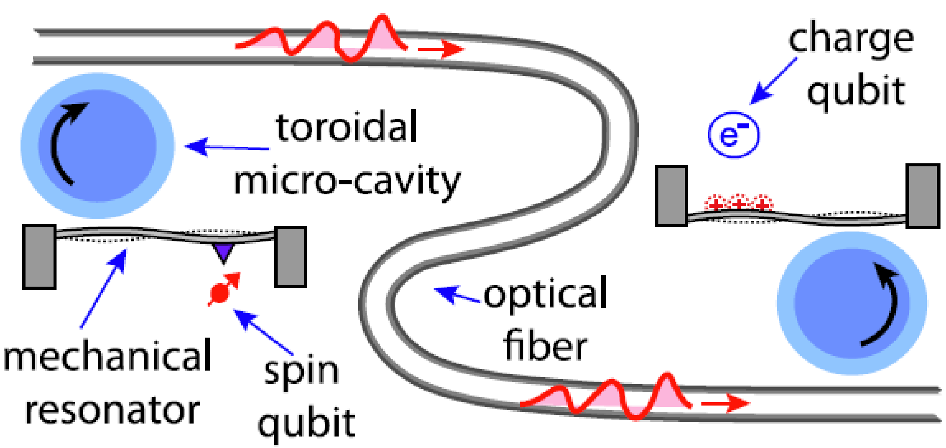
- Non-classical mechanical states
- Quantum decoherence mechanism
- Interface of QM/CM

Nano mechanical systems in the quantum regime

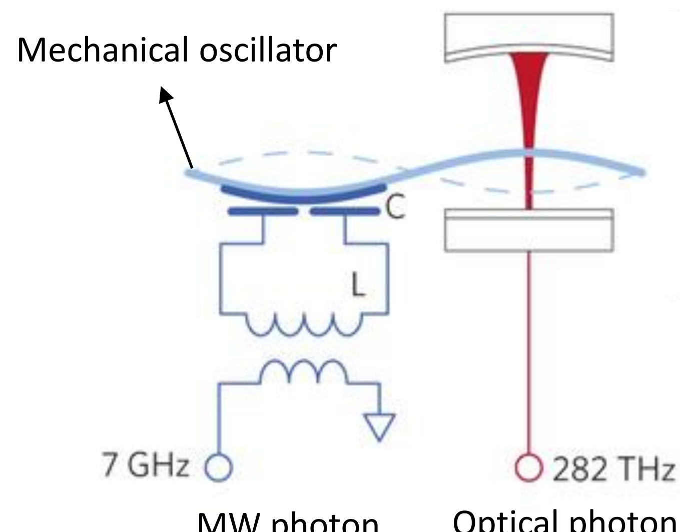
3. Universal quantum interface in hybrid quantum network



D. Lee *et al.*, JOP (2017)



K. Stannigel *et al.*, PRL (2010)

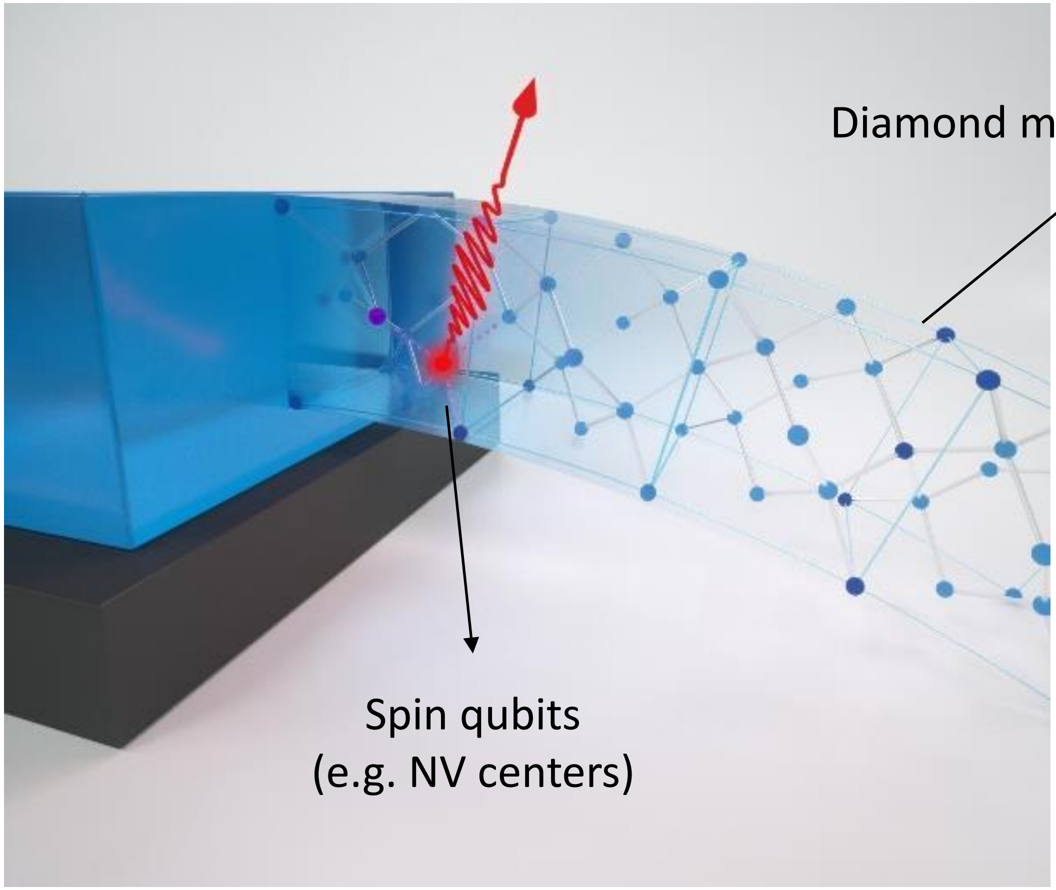


R. Andrews *et al.*, Nat. Phys. (2014)

Nano mechanical systems in the quantum regime

3. Universal quantum interface in hybrid quantum network

In this talk: diamond hybrid quantum system



Diamond mechanical oscillator

Spin qubits
(e.g. NV centers)

Outline

- When Phonon met Photon (Cavity Optomechanics)
  - Ground state cooling and sidebands asymmetry
  - Multimode optomechanics

- When Phonon met Spin (Diamond Hybrid System)
  - Strain-spin state coupling
  - Strain-orbital state coupling
  - Future applications

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  - Strain-orbital state coupling
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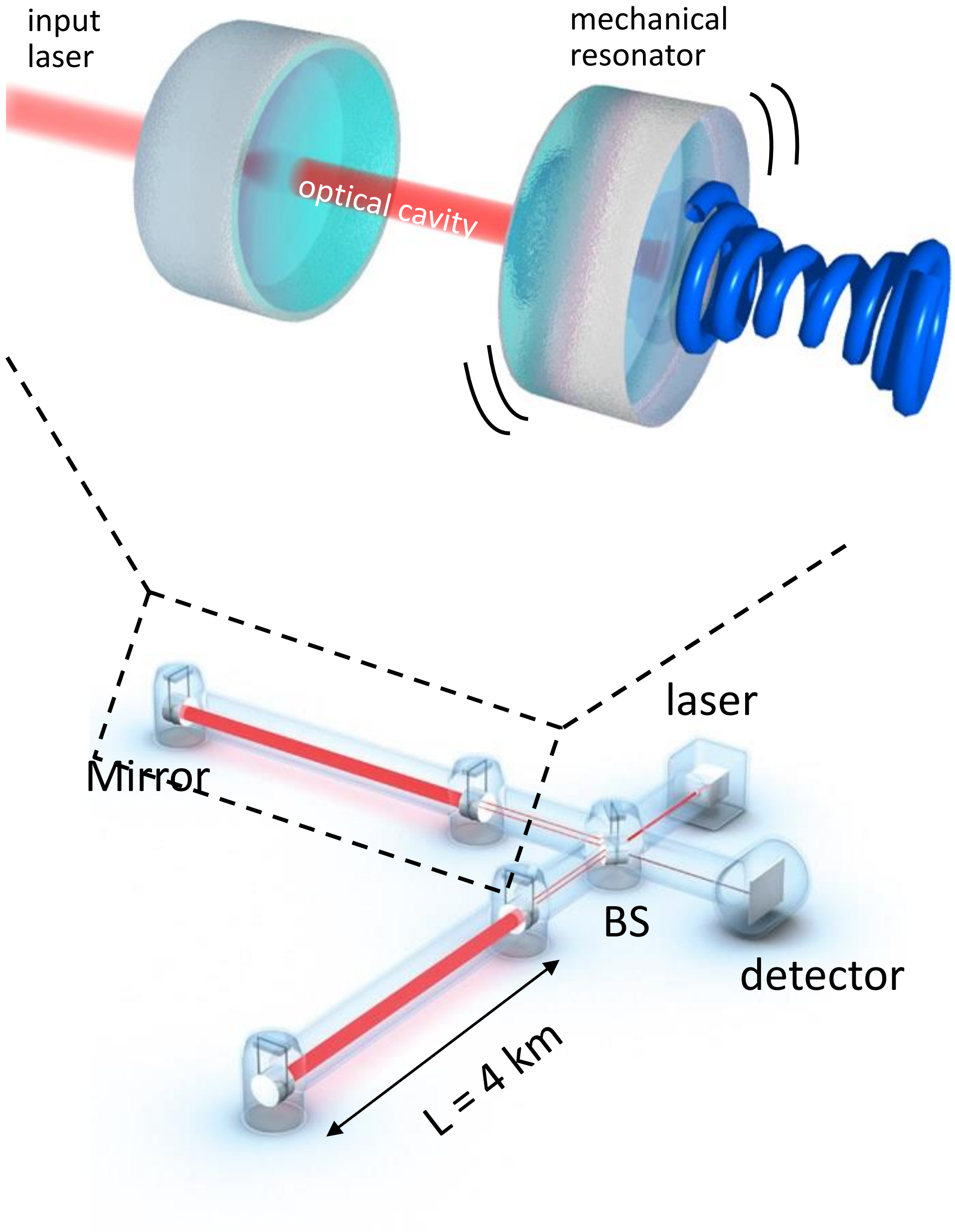
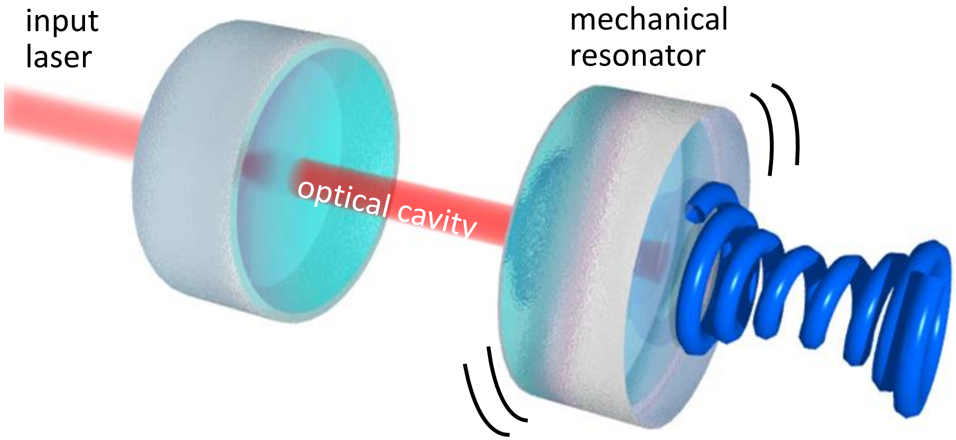
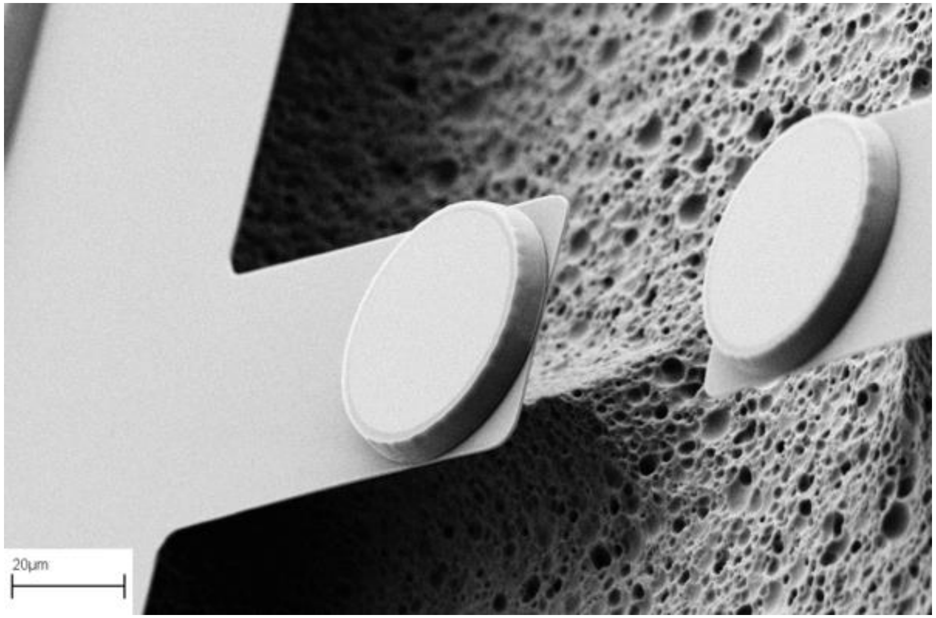
Cavity photons + mechanical oscillator



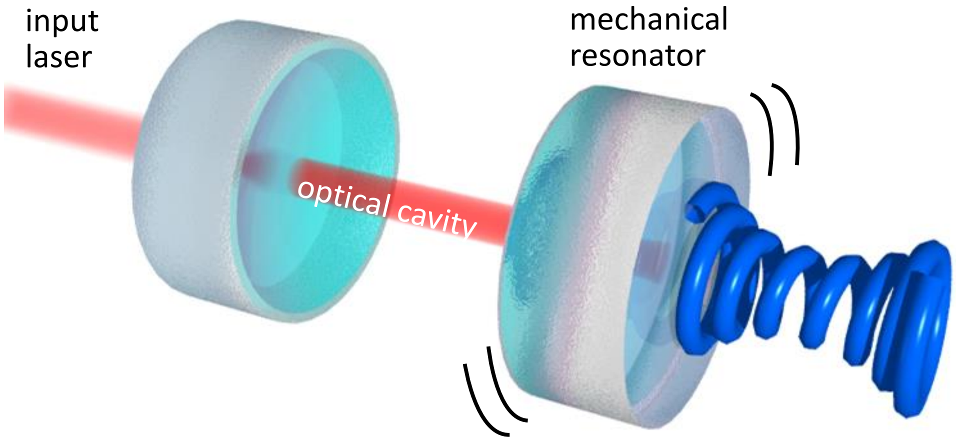
Cavity photons + mechanical oscillator

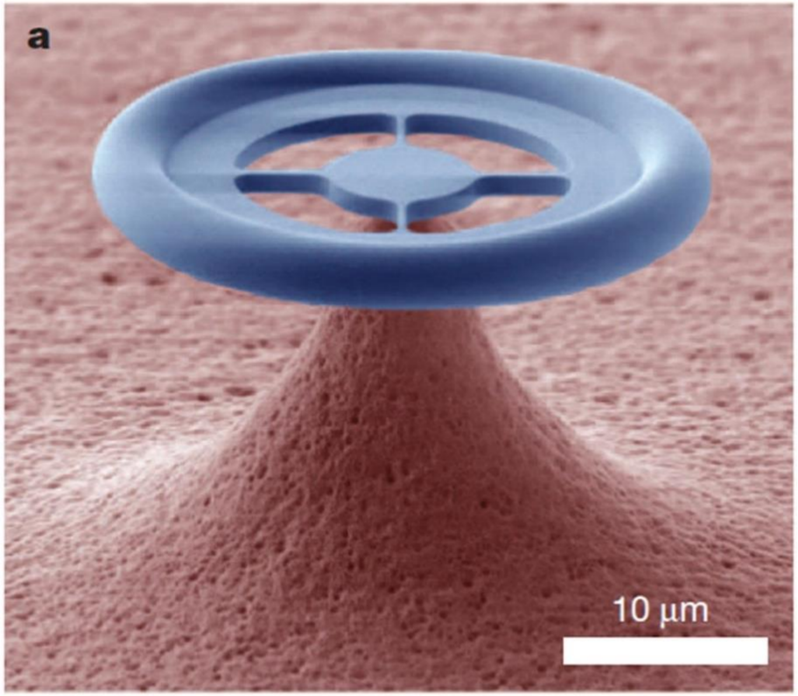




Micro-cantilever

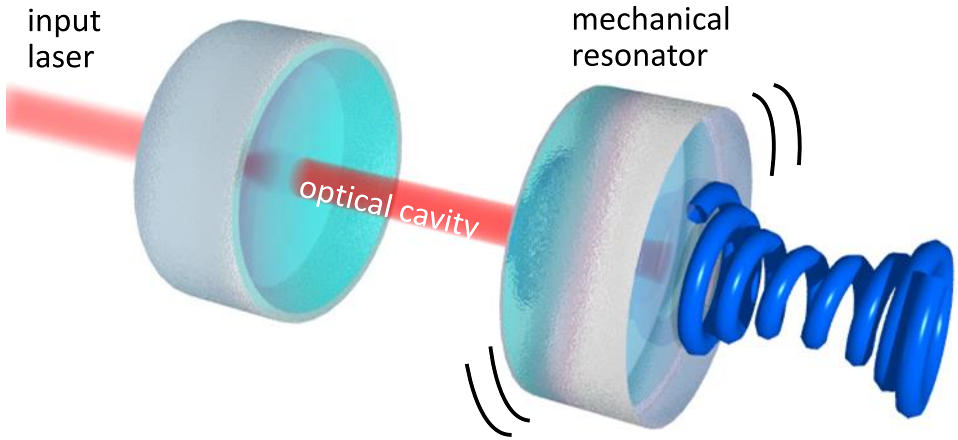
Cavity photons + mechanical oscillator

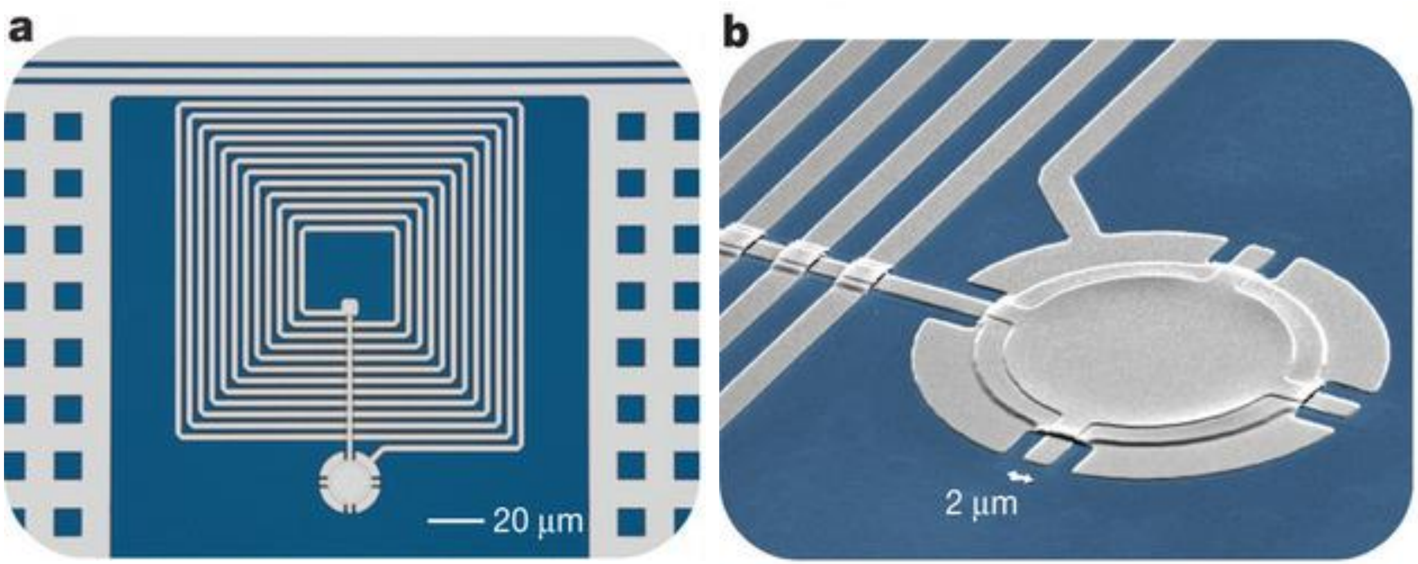




Micro-toroid

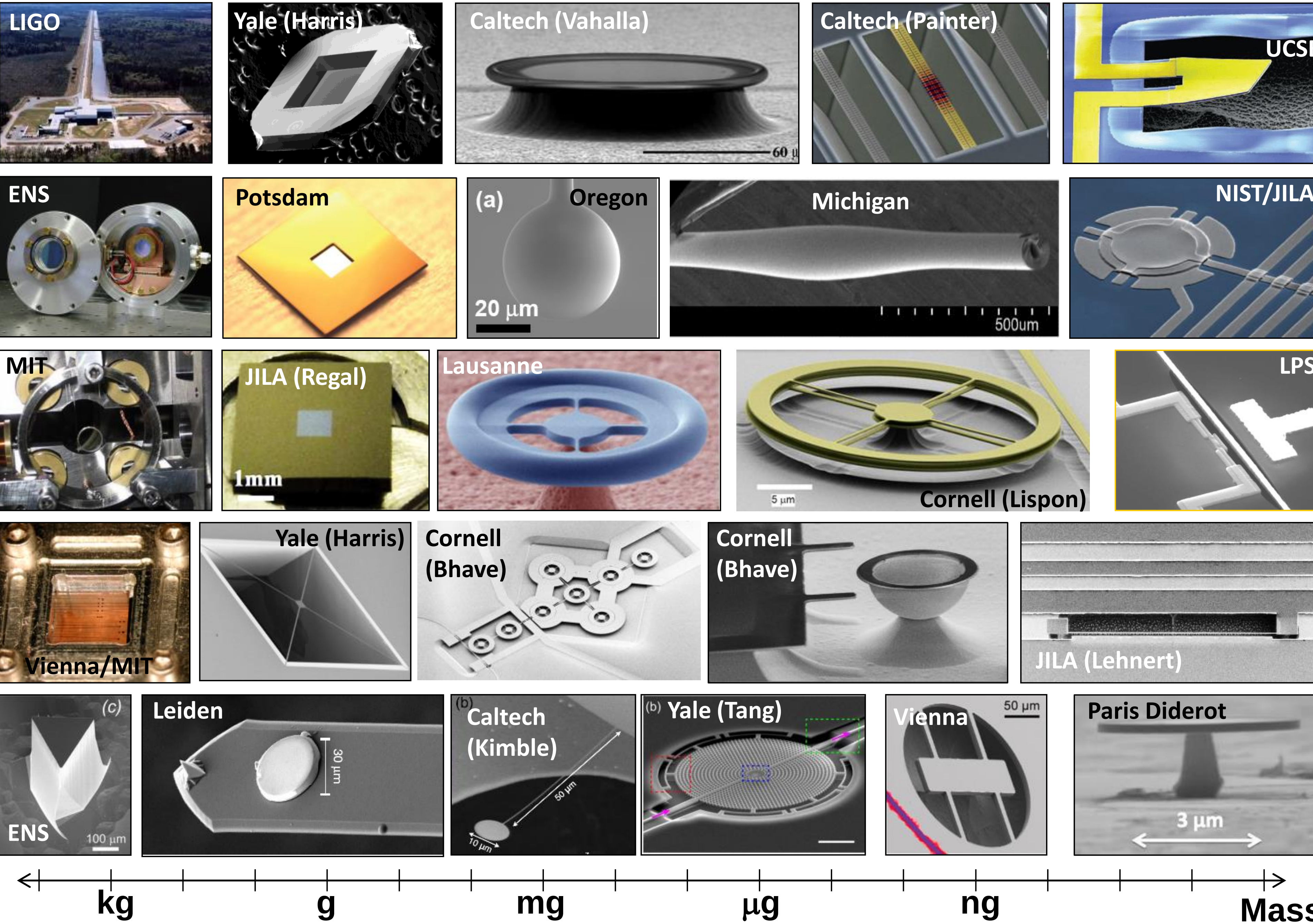
Cavity photons + mechanical oscillator





Microwave resonator

Various "optical cavity + mechanical oscillator" devices

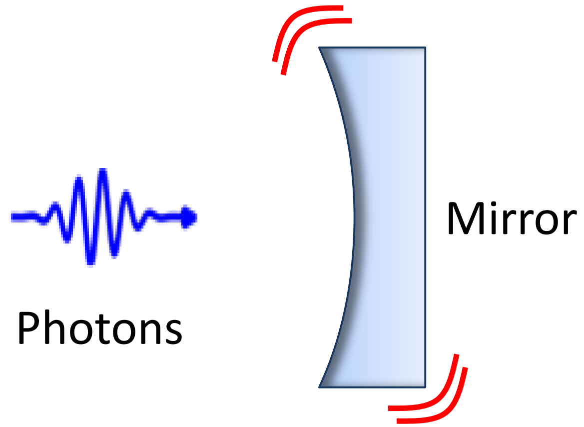


Cavity optomechanics

- **Radiation pressure:** very tiny force

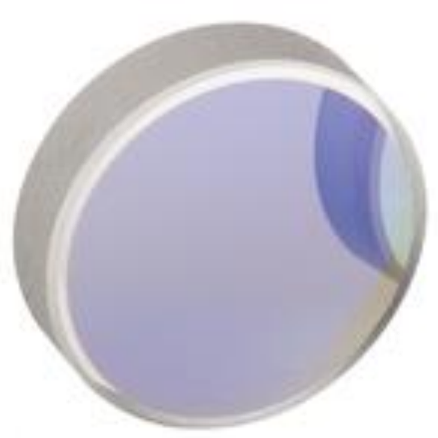
  e.g. Sunlight on a mirror ($1 kW/m^2$)

  → Radiation Pressure: 10^{-5} N/m^2

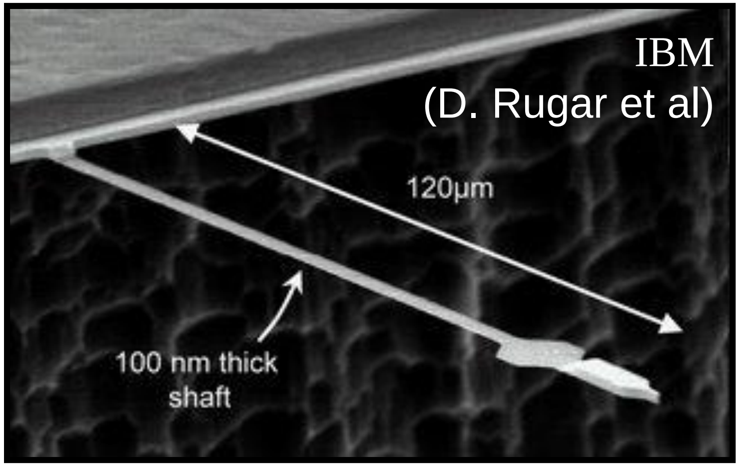


- **Solution:** "Optical Cavity" + "Micro-Mechanics"

  Many impacts/photon — *Enhanced response to small force*

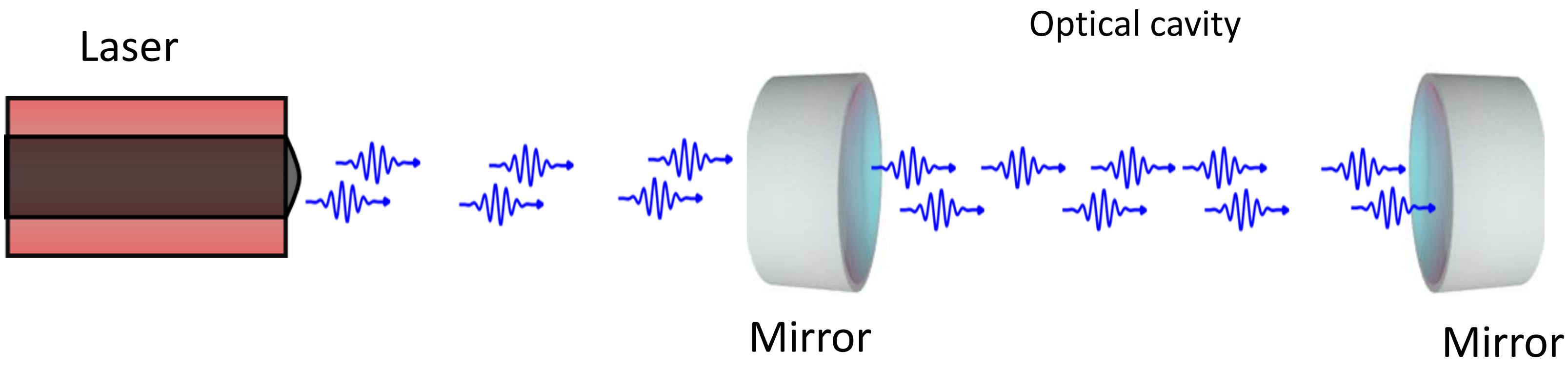


High reflectivity (99.999%)

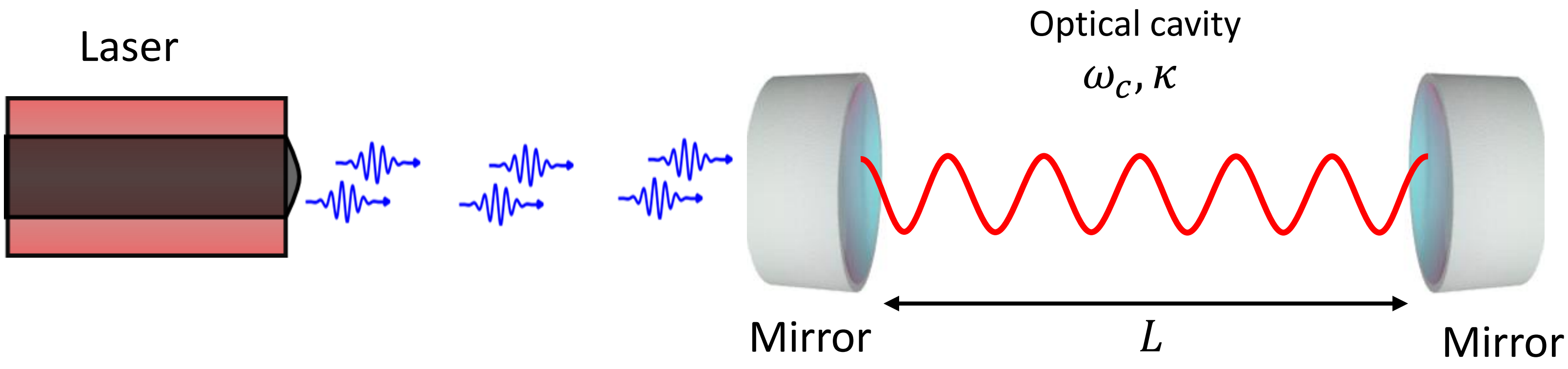


High force sensitivity (1 $aN/Hz^{½}$)

Basic concepts of cavity optomechanics



Basic concepts of cavity optomechanics

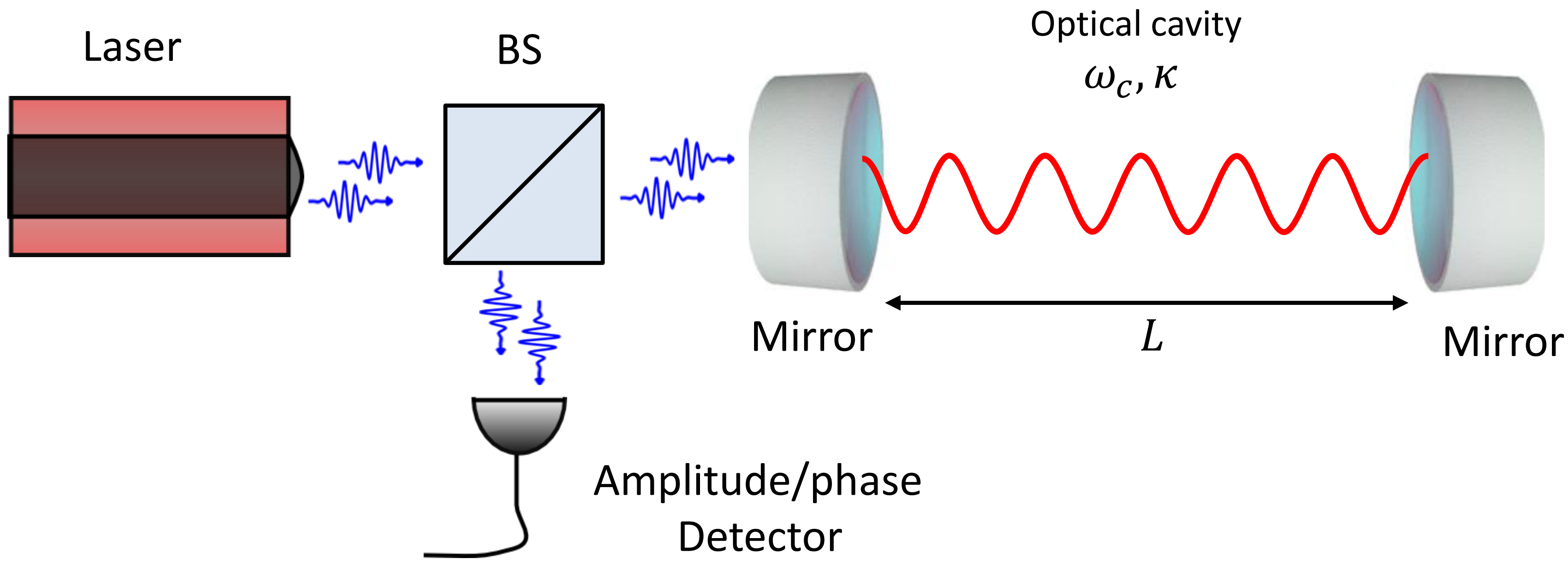


Optical Cavity:

- Resonance frequency,

$$\omega_c = 2\pi n \frac{c}{2L} = 2\pi n f_{FSR} \ \ (n = 1, 2 \ldots)$$

Basic concepts of cavity optomechanics



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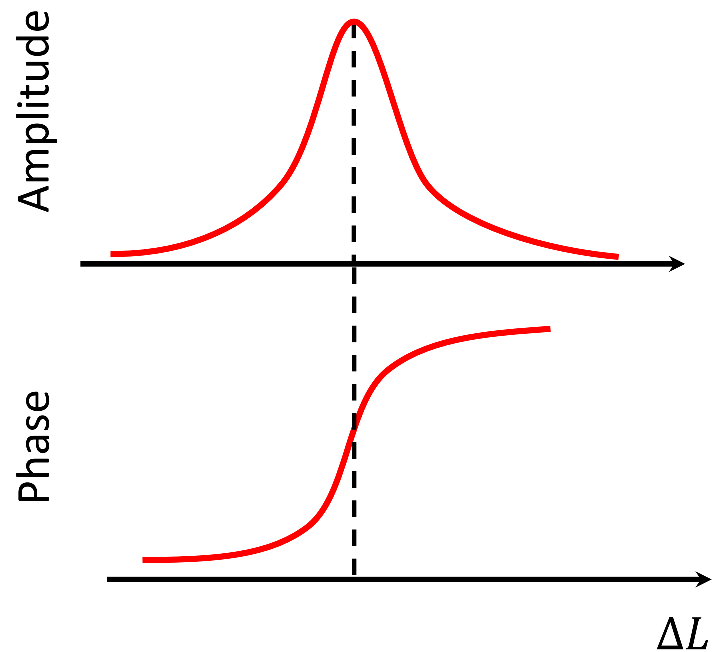

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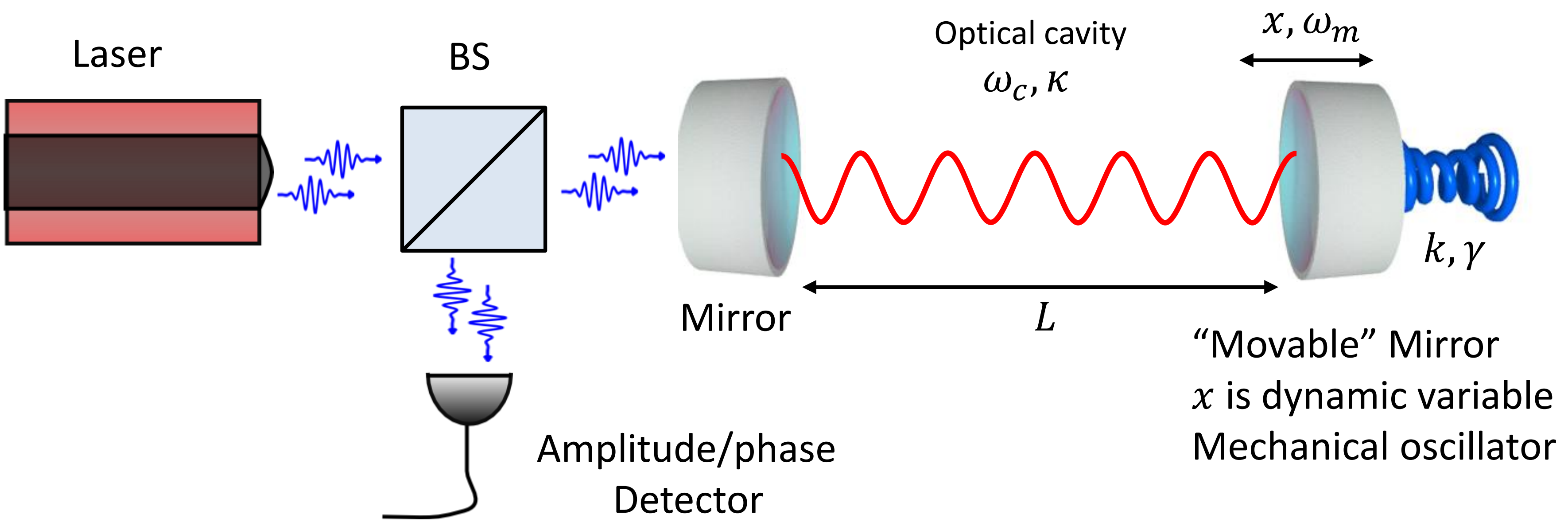

Optical Cavity:

- Resonance frequency,

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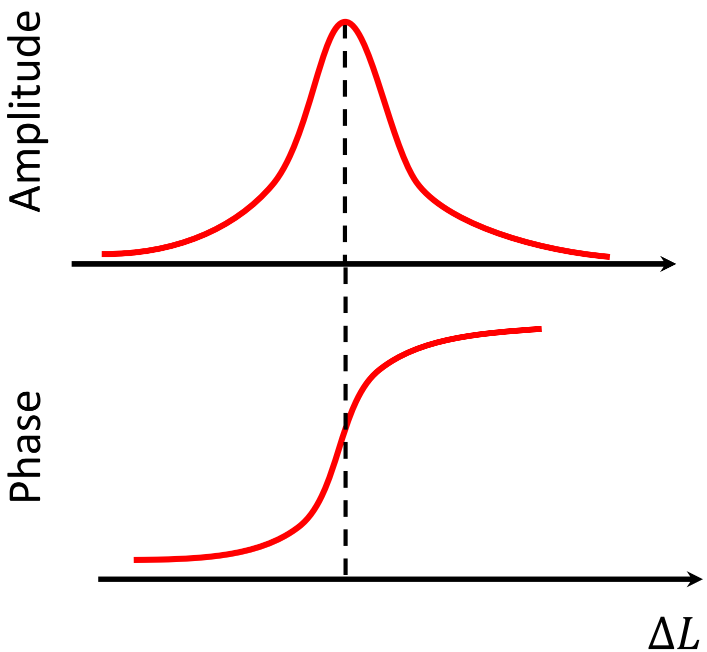
Mechanical Oscillator:

- Damped harmonic oscillator

$$m\frac{d^2x}{dt^2} + m\gamma\frac{dx}{dt} + kx = F_{RP}(t)$$



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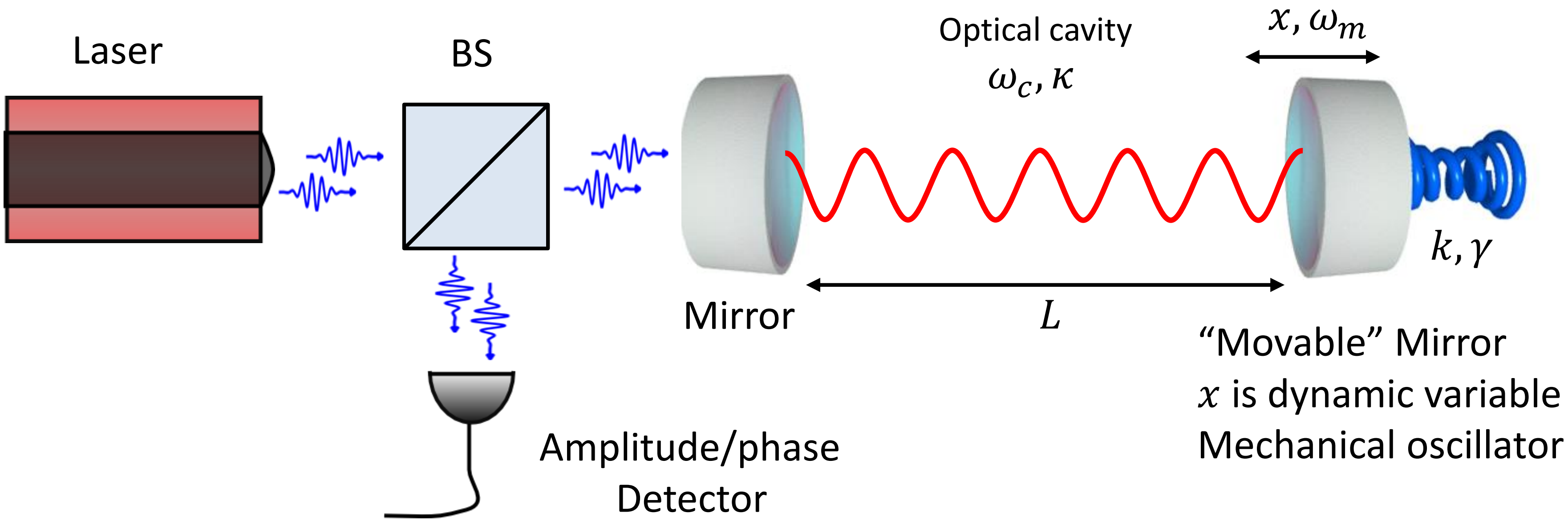

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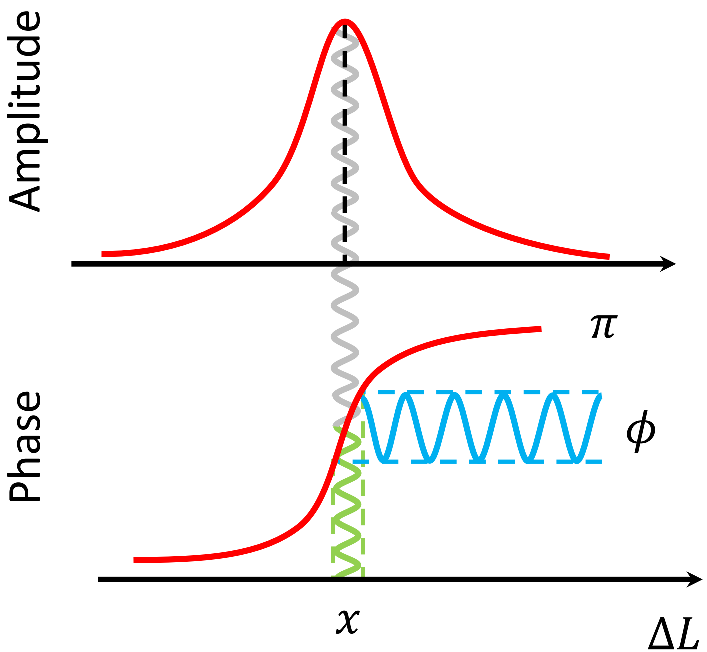
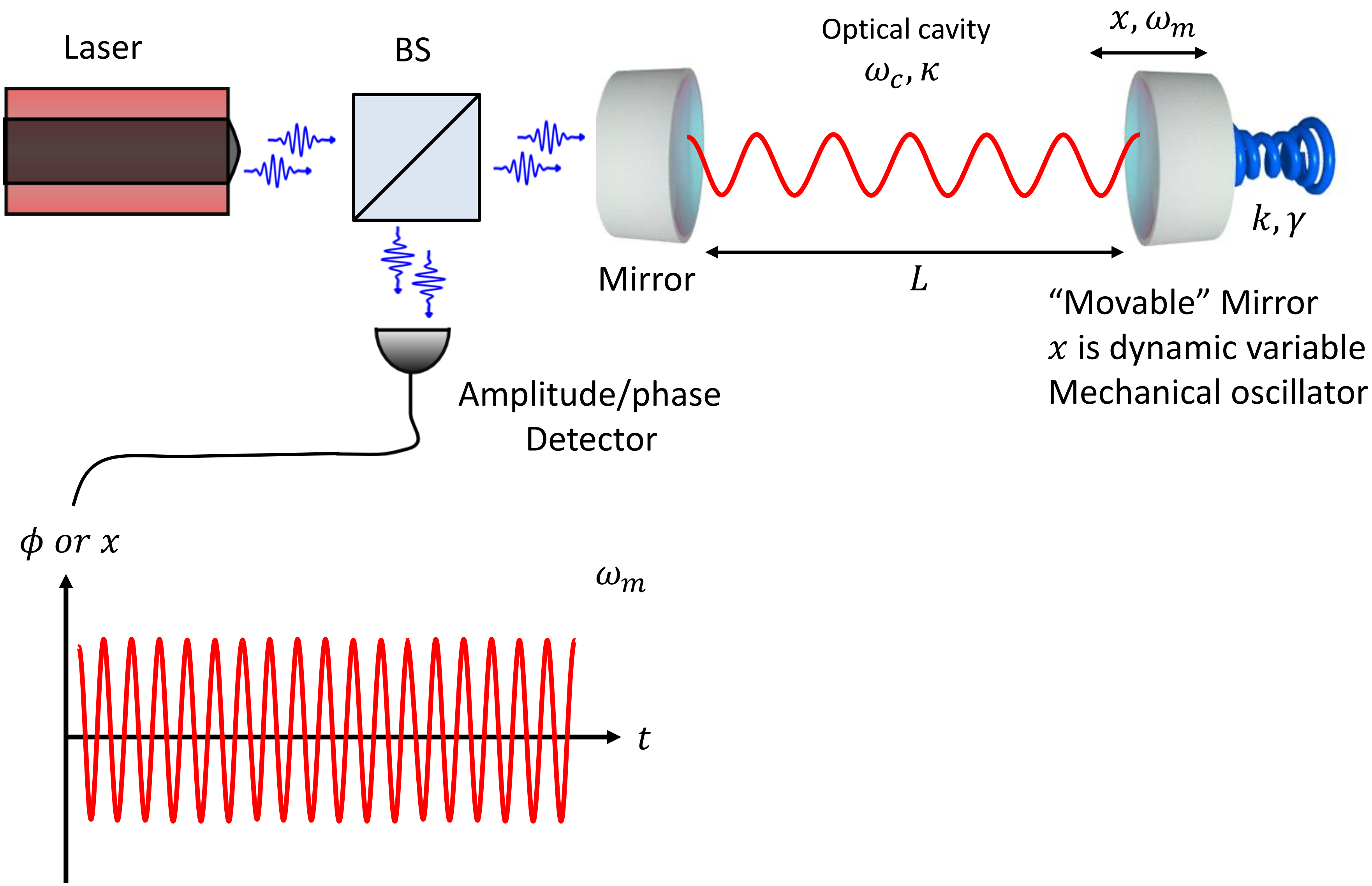


Optical reading of mechanical motion



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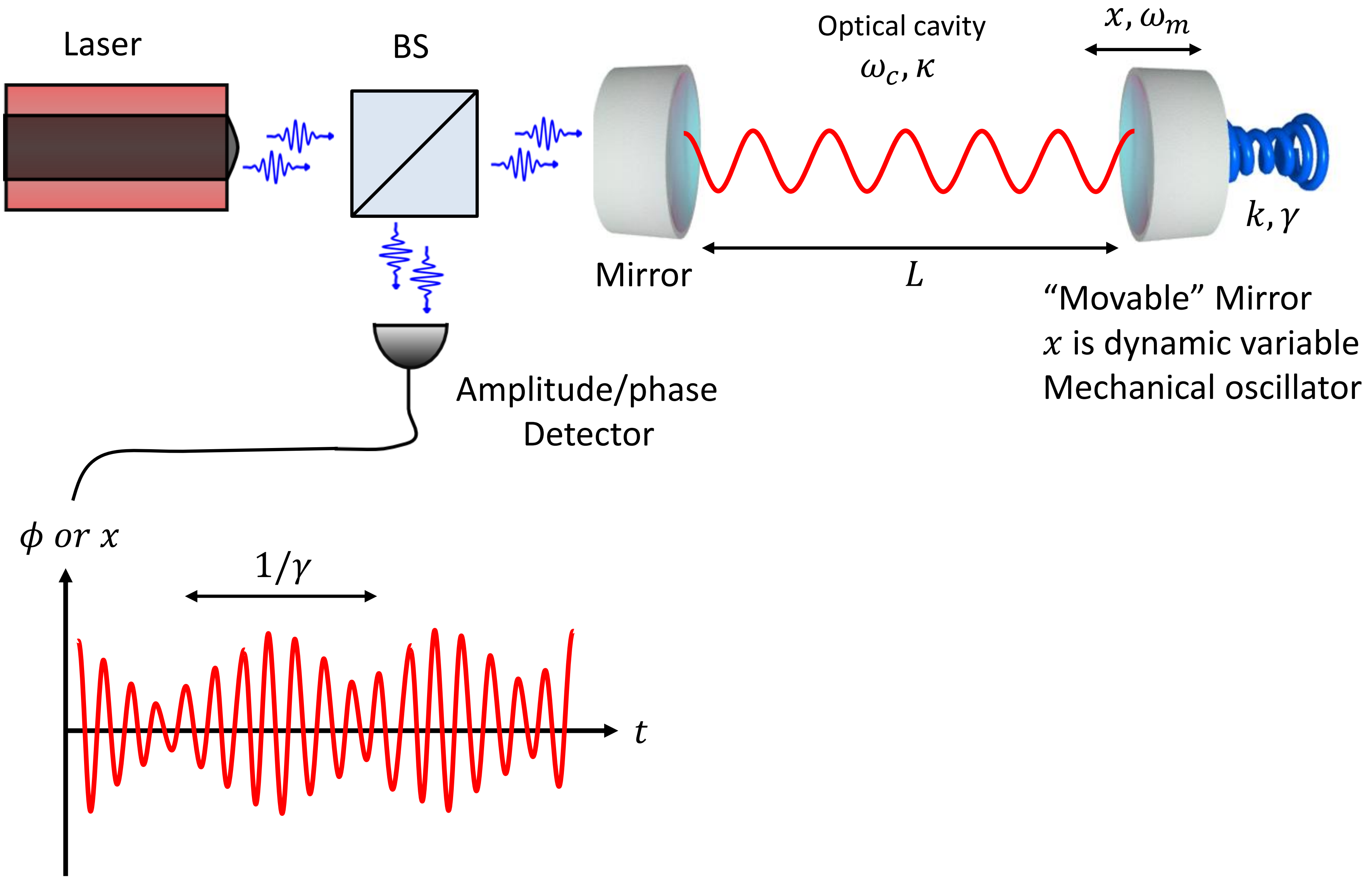

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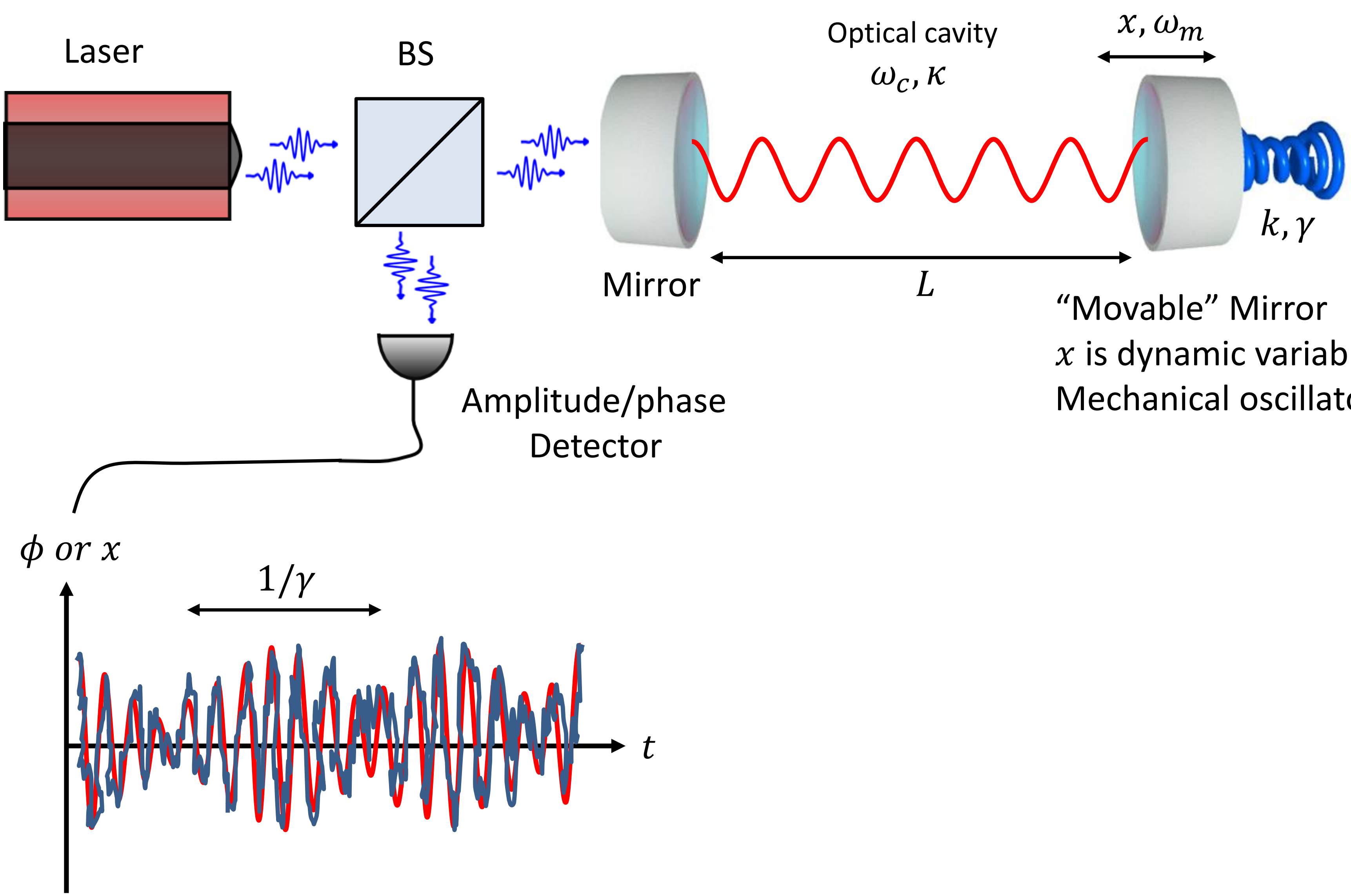

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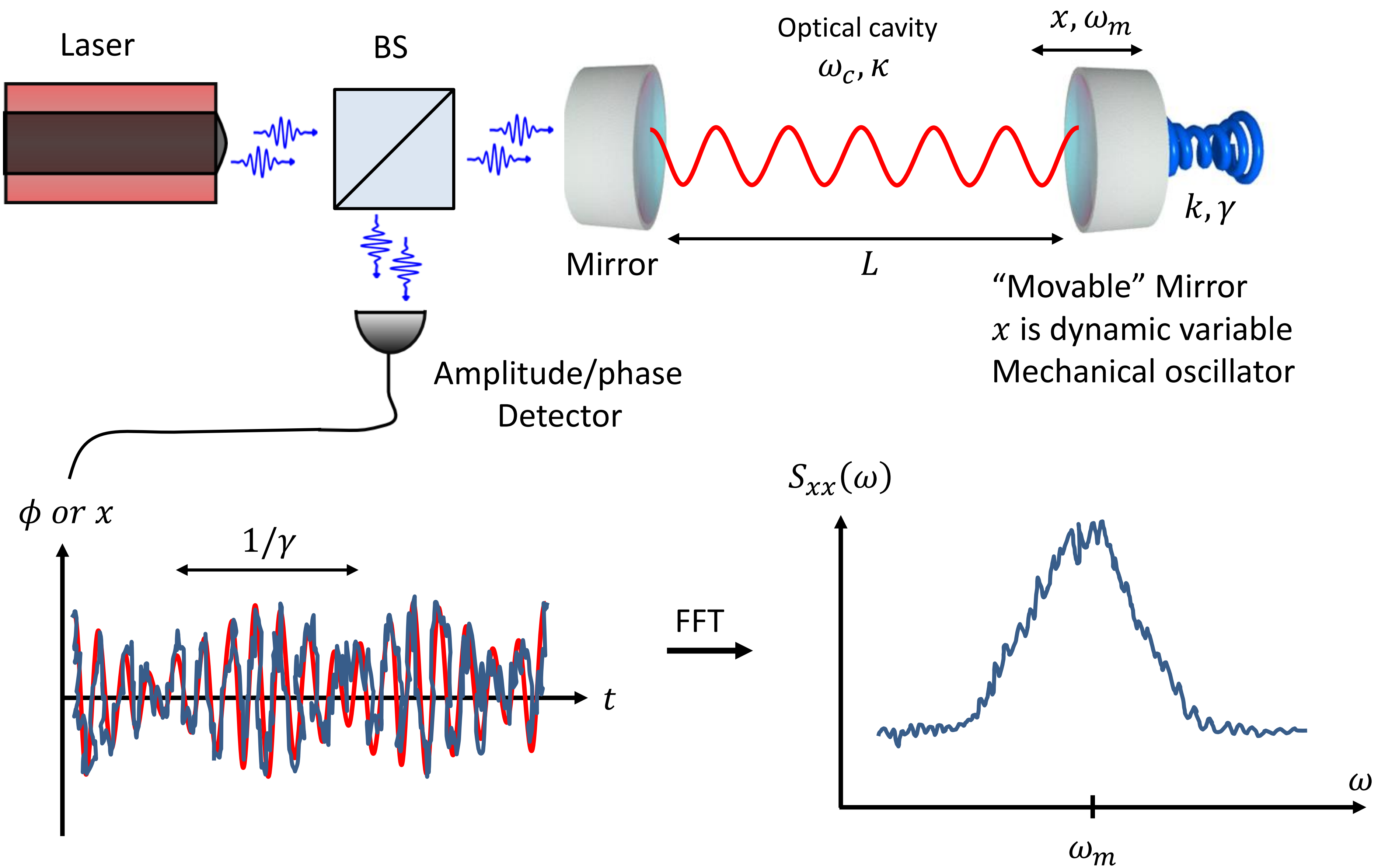
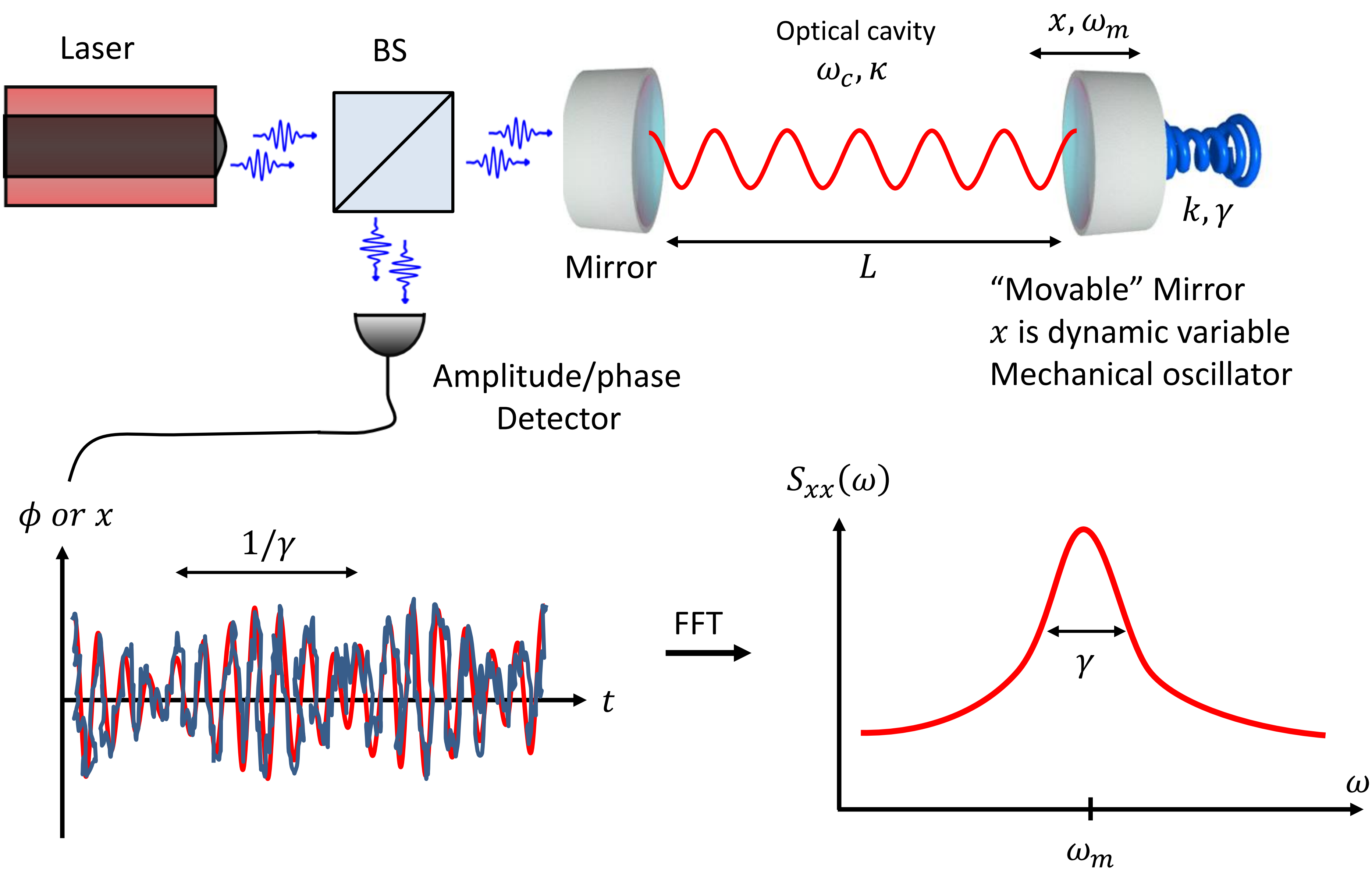
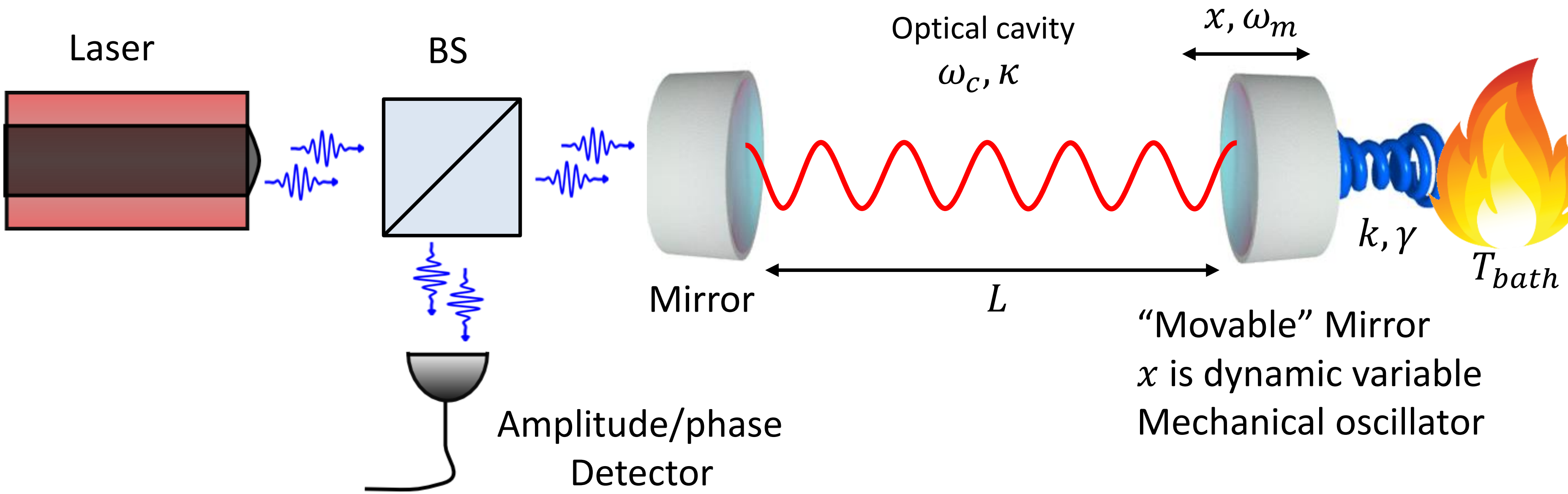


Optical reading of mechanical motion



Optical reading of mechanical motion



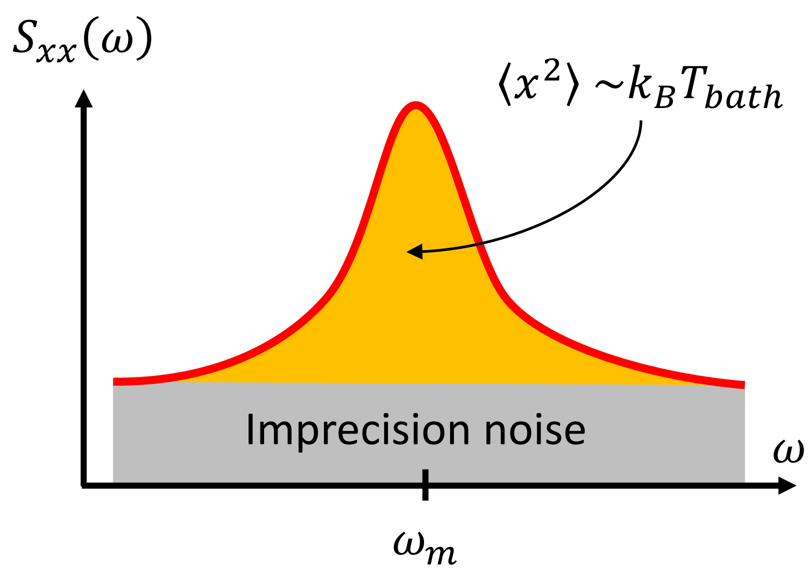
Equipartition theorem

$$\frac{1}{2} m {\omega_m}^2 \langle x^2 \rangle = \frac{1}{2} k_B T = \hbar \omega_m \left(\bar{n} + \frac{1}{2} \right)$$

Area underneath Brownian motion

~ mode temperature, T

~ phonon number, $\bar{n}$



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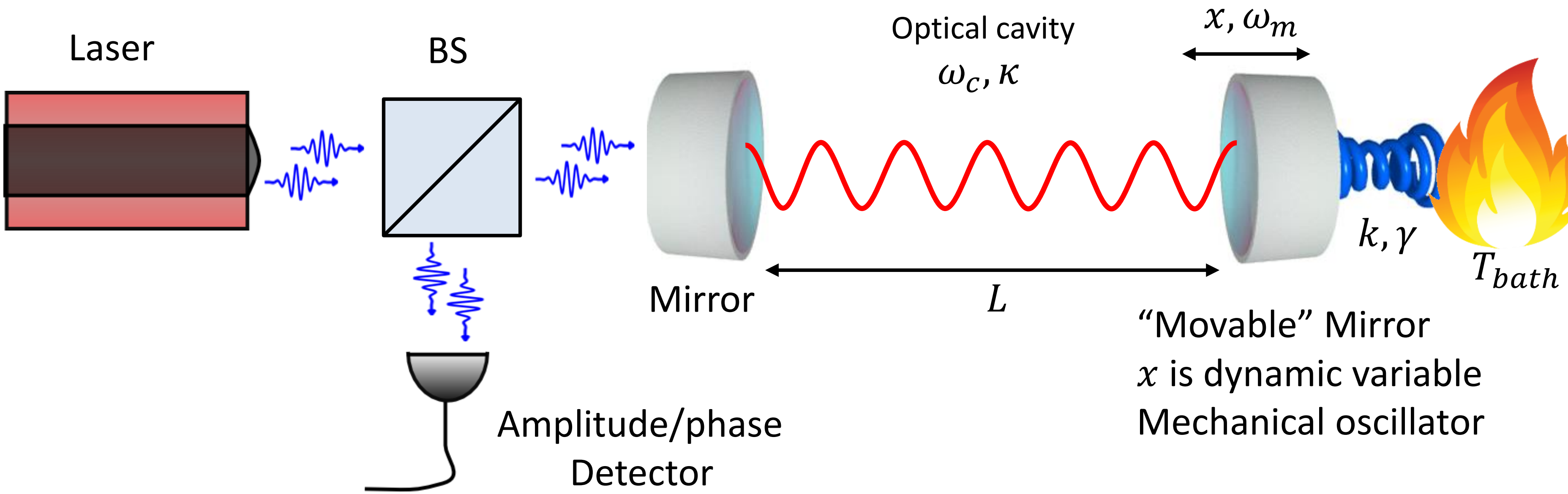
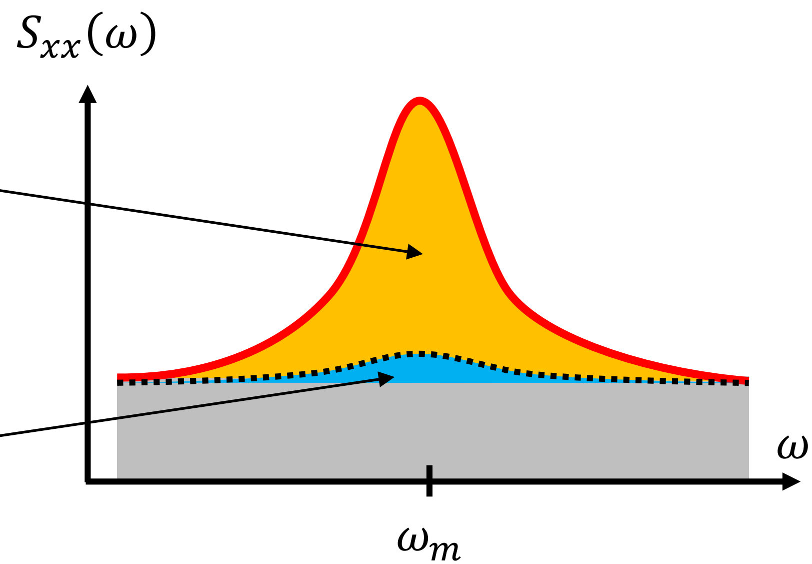


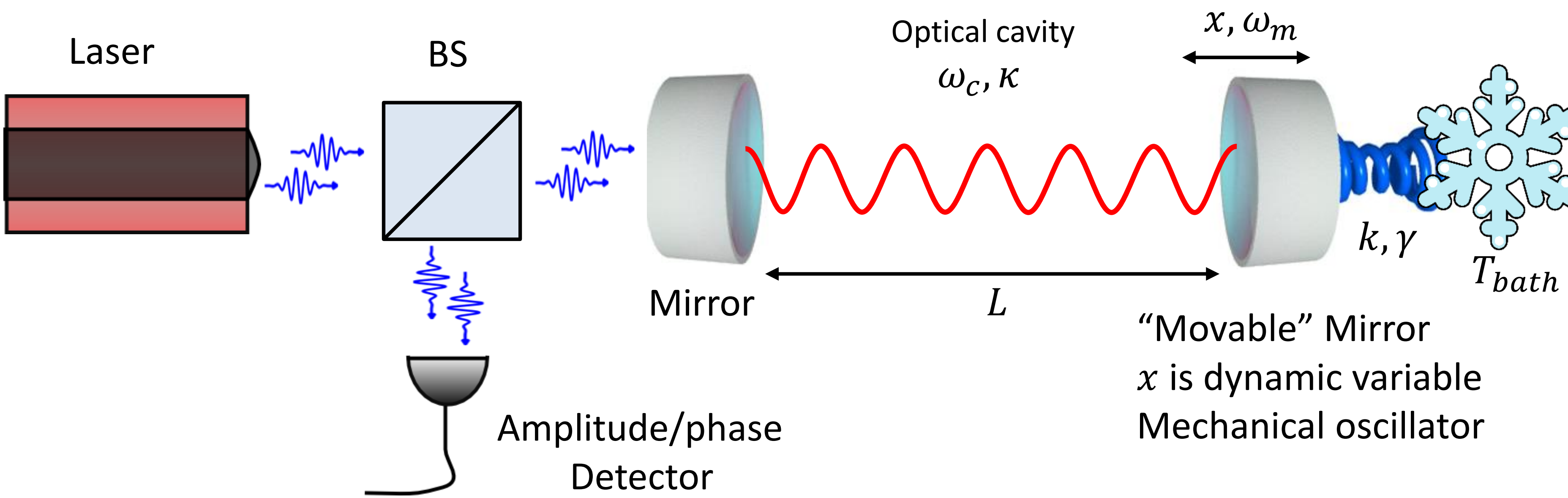
Brownian motion at T_{bath}

Quantum motion
(Zero point fluctuation)

$$x_{ZPF} = \sqrt{\frac{\hbar}{2m\omega_m}}$$

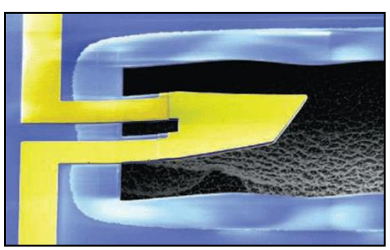


Controlling (e.g. cooling) of mechanical motion



Reduce Brownian motion by

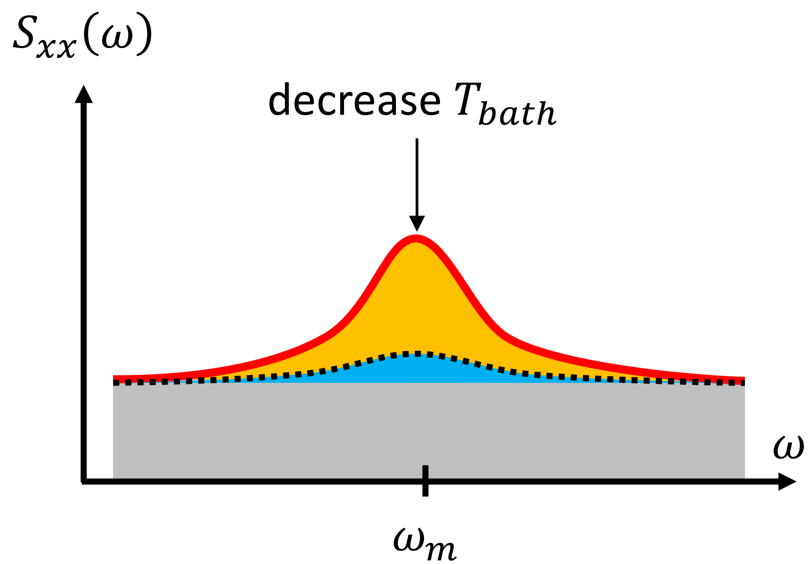
- lower bath temperature (refrigerator cooling)



$\omega_m/2\pi$ = 6 GHz, T = 25 mK

$\bar{n} \sim 0.1$

A. D. O'Connell *et al.*, Nature (2010)



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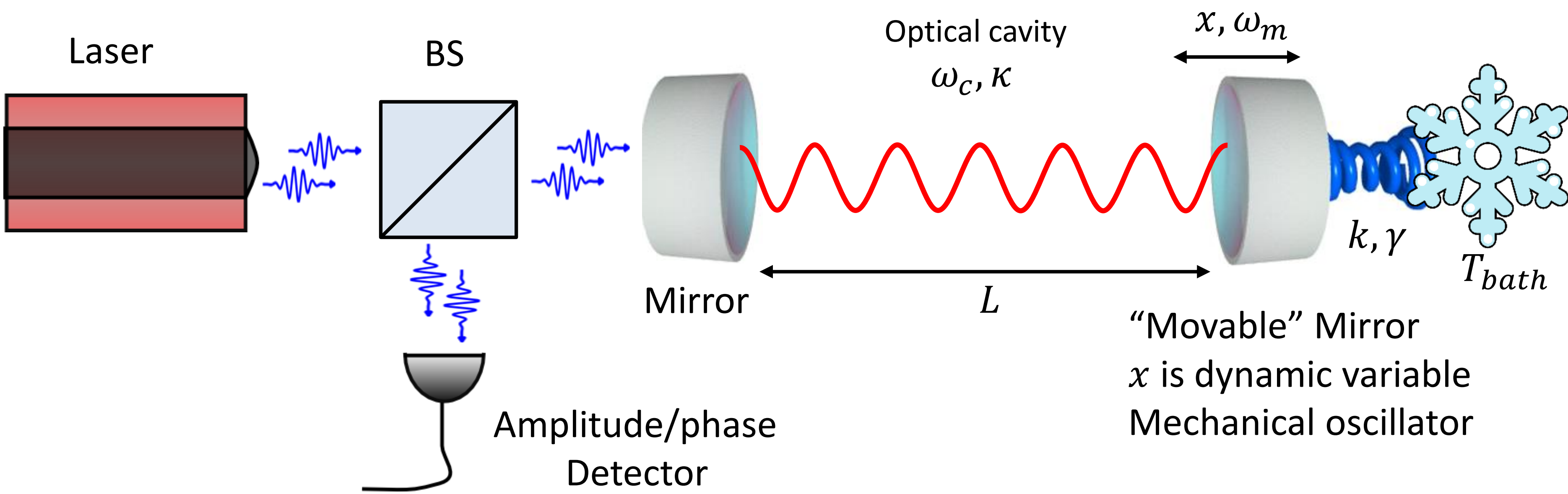
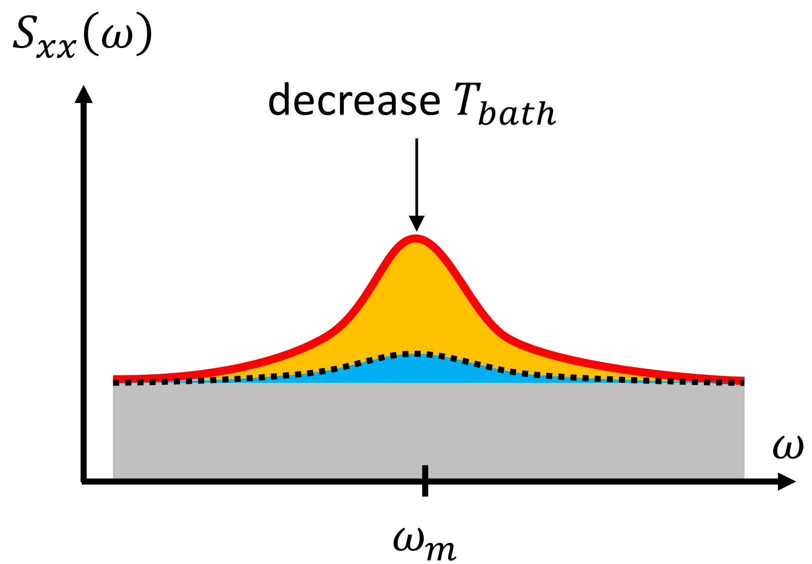
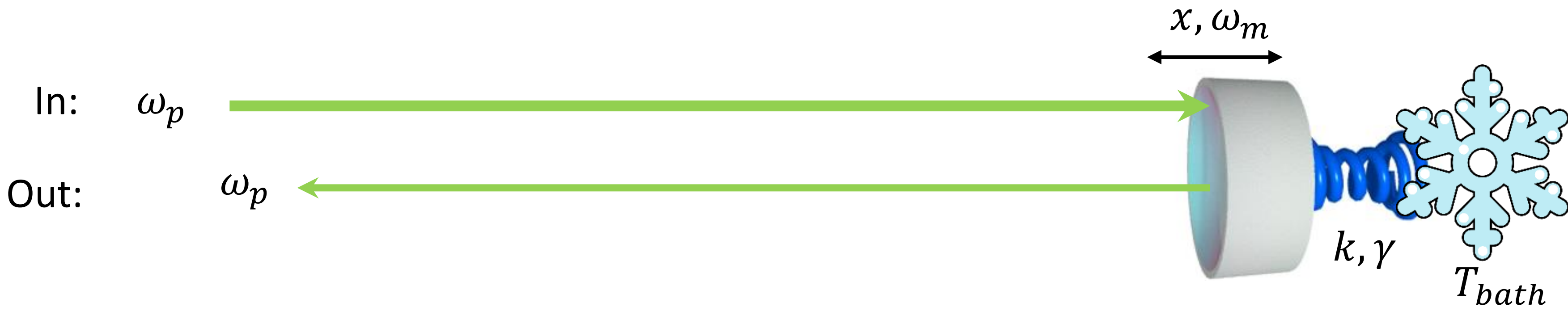


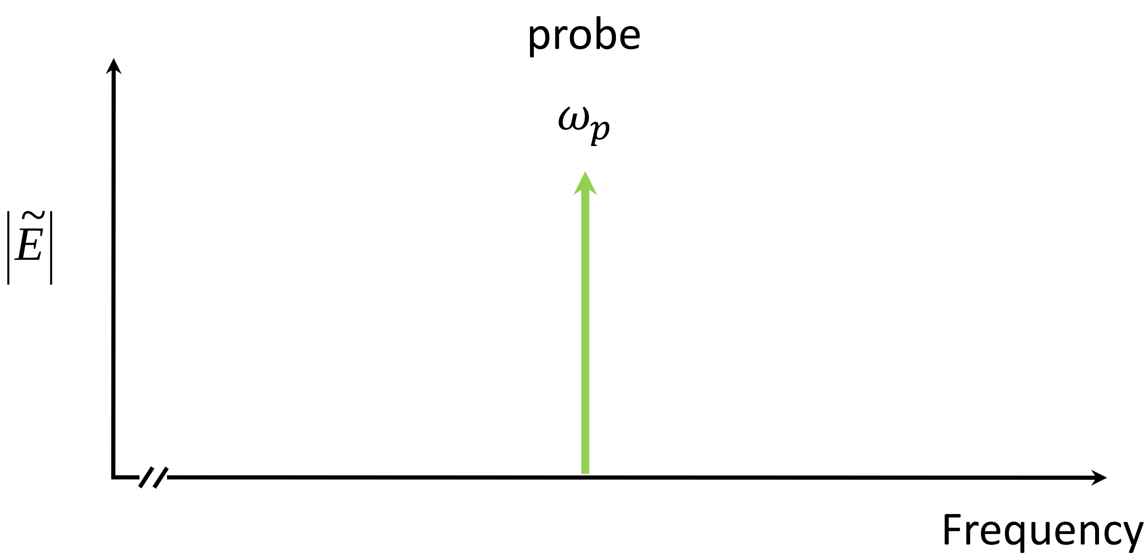
Reduce Brownian motion by

- lower bath temperature (refrigerator cooling)
- inelastic interaction with photons (laser cooling)

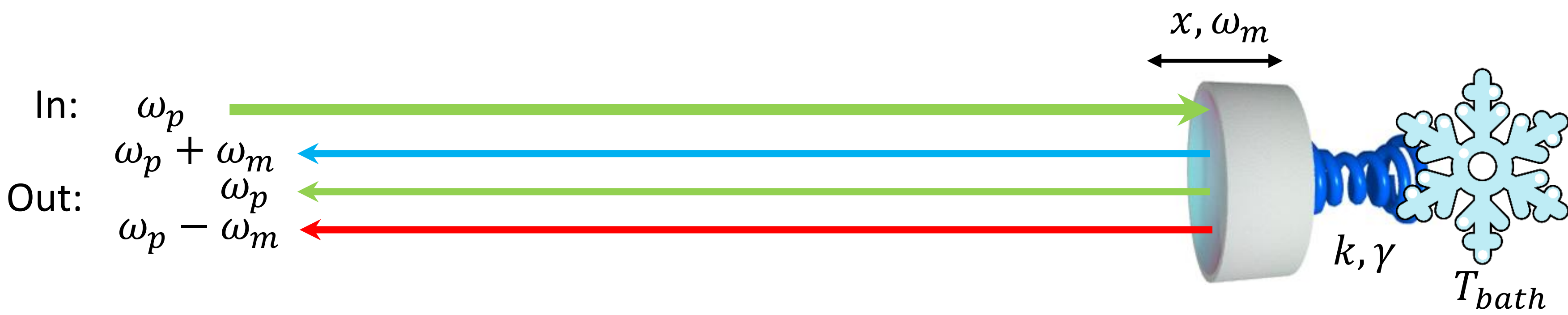


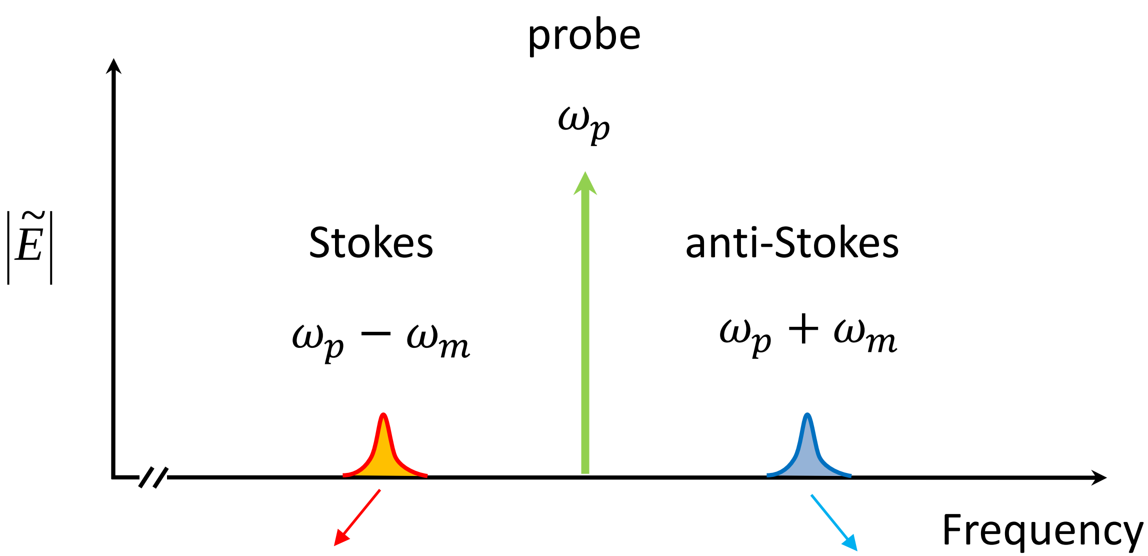
Laser cooling of mechanical motion





Laser cooling of mechanical motion

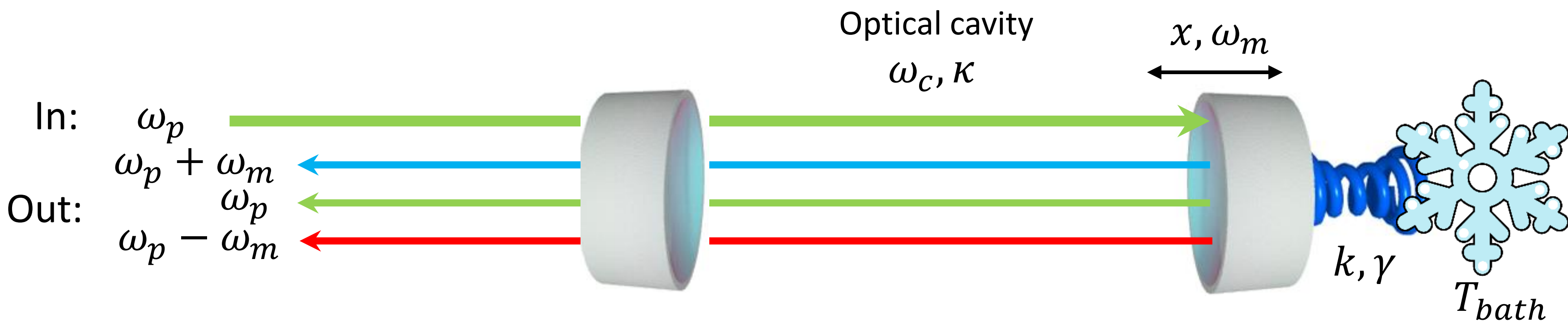


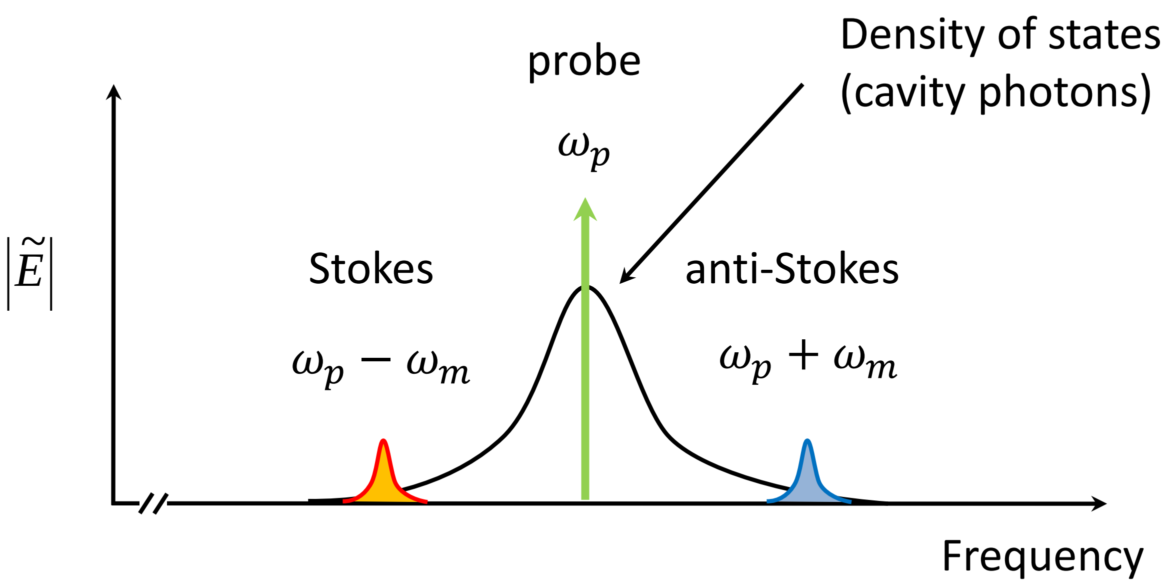


- Laser cooling
- Raises phonon number
- Signal proportional to $\bar{n} + 1$

- Laser heating
- Lowers phonon number
- Signal proportional to $\bar{n}$

Laser cooling of mechanical motion





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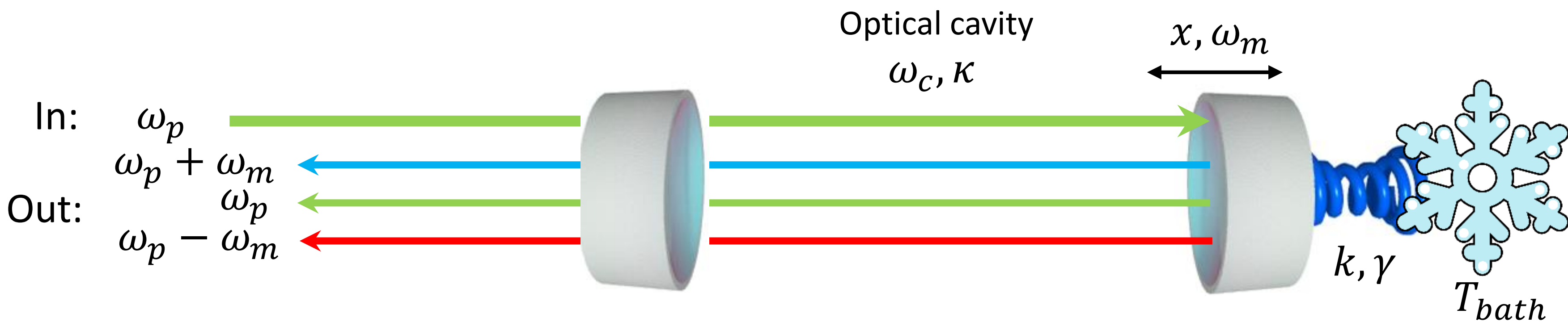
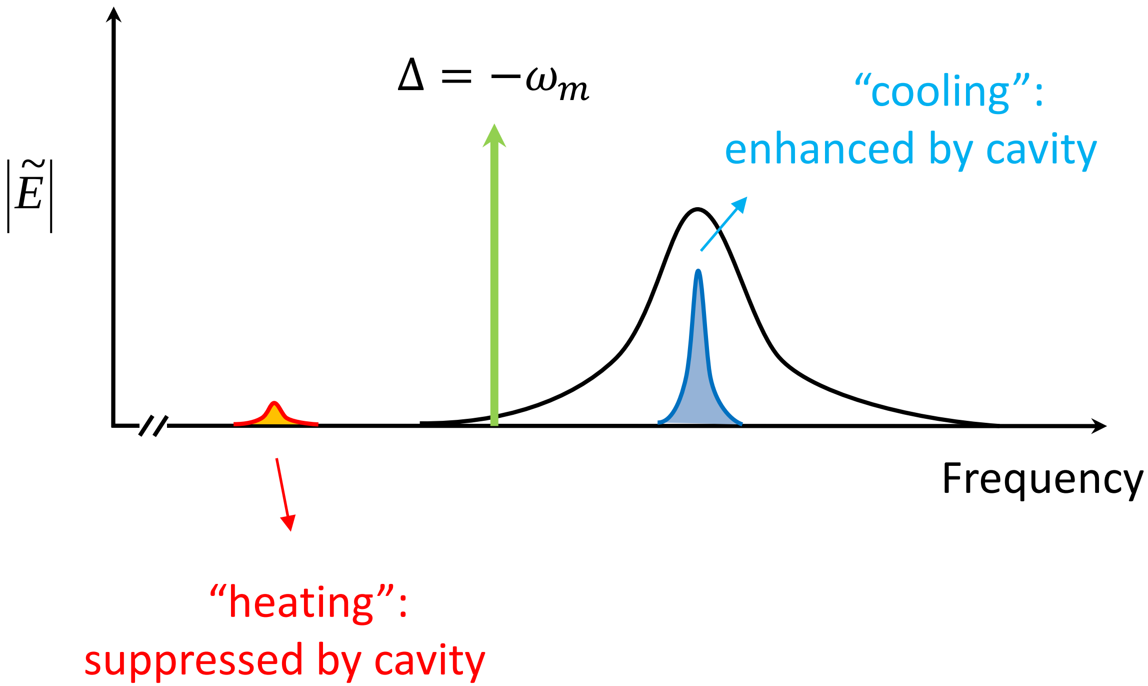
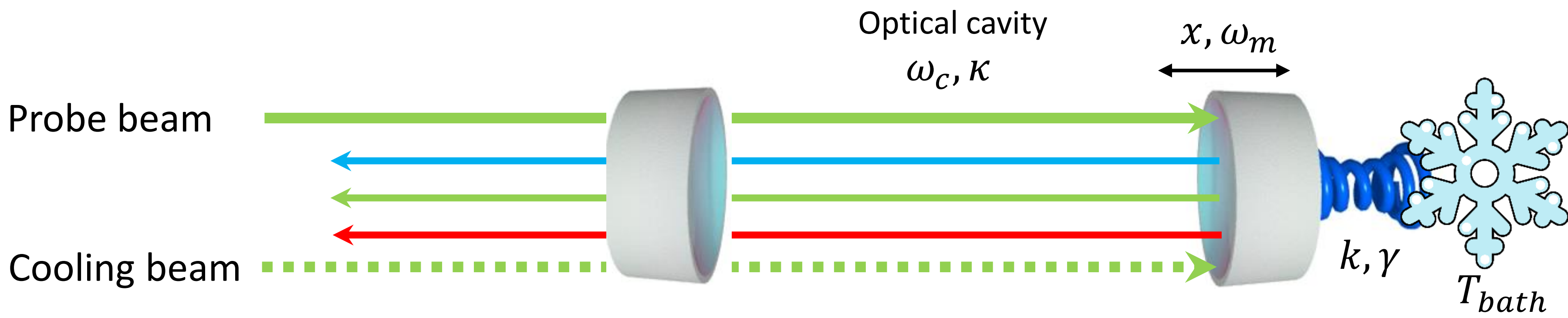
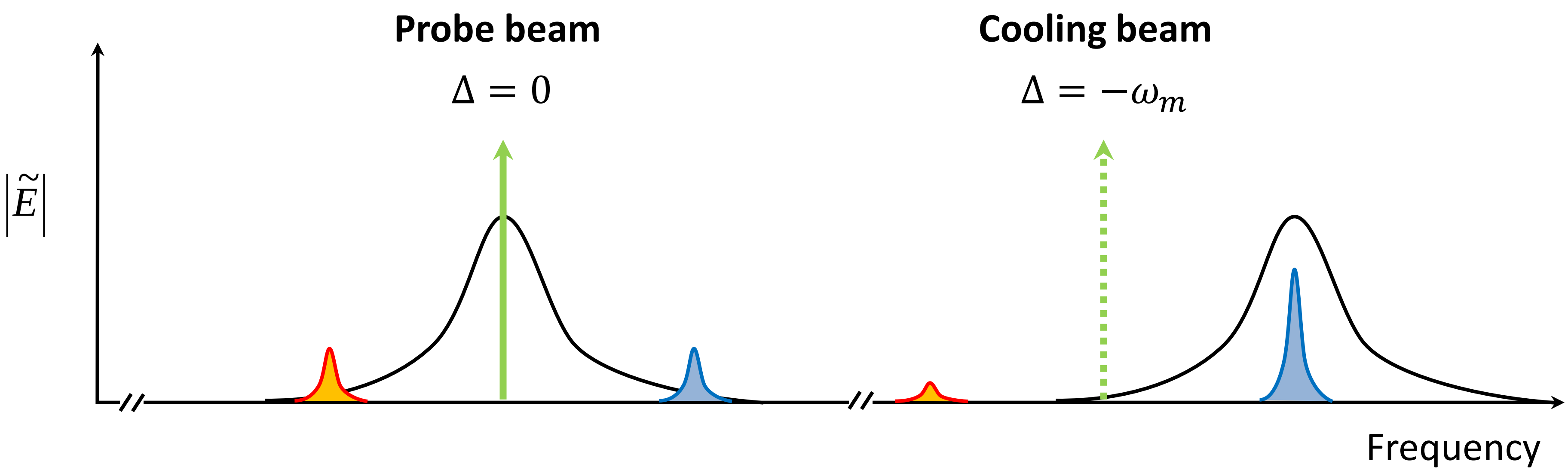


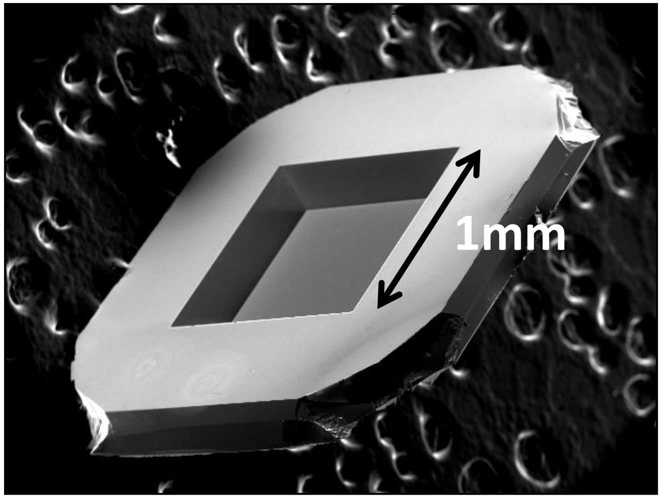


Laser cooling of mechanical motion



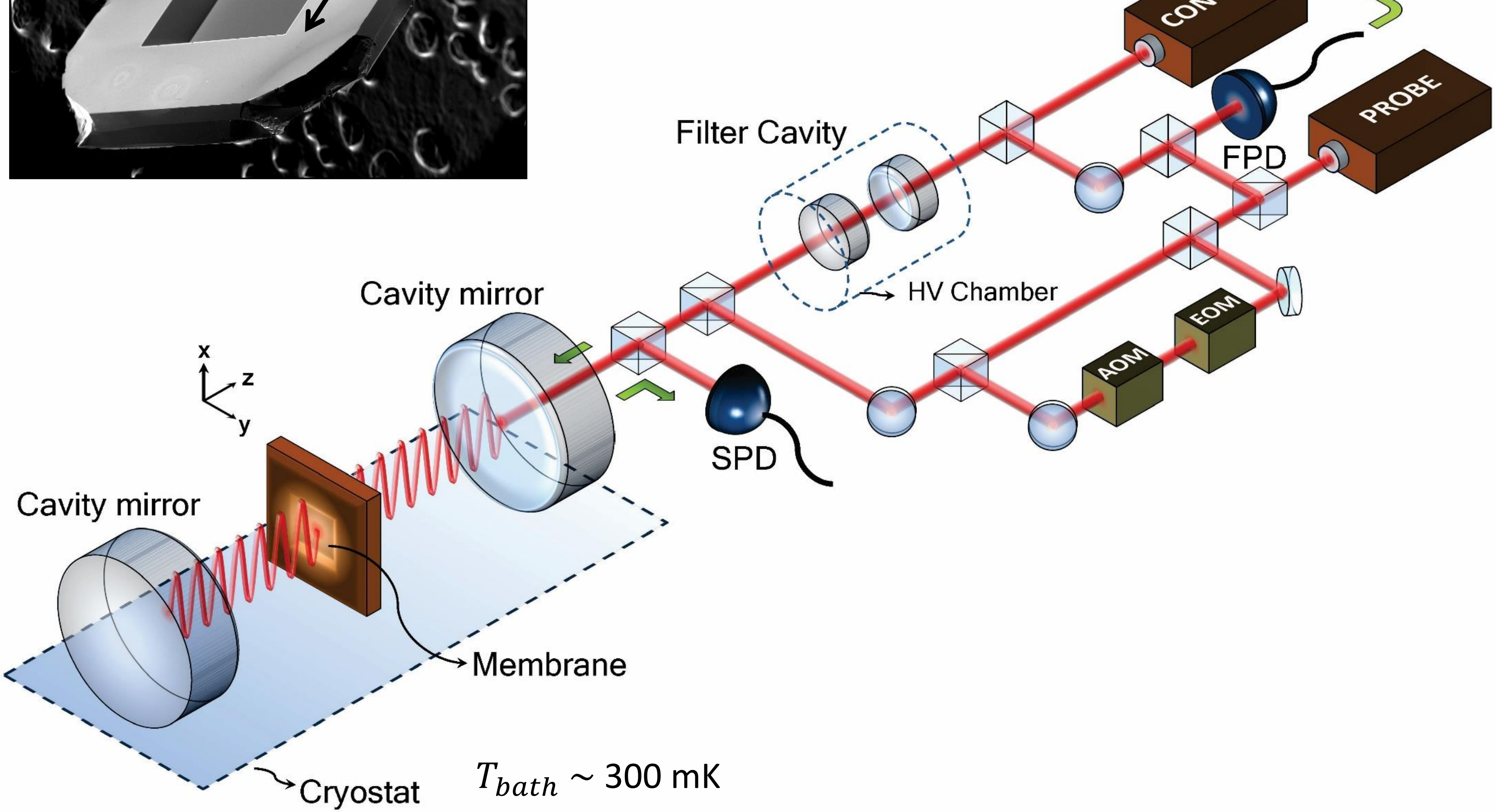


Outline of experimental set-up at Yale Univ. (Jack Harris group)



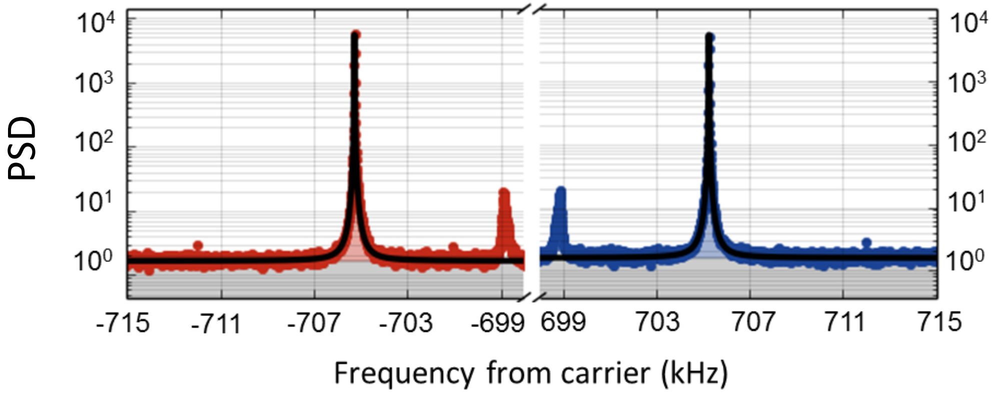
High Q Si_3N_4 membrane, $1\,mm \times 1\,mm\ \times 50\,nm$

$\omega_m/2\pi \sim 705\ \mathrm{kHz}\,, Q \sim 5 \times 10^6$



$T_{bath} \sim 300$ mK

Laser-assisted cooling of mechanical motion



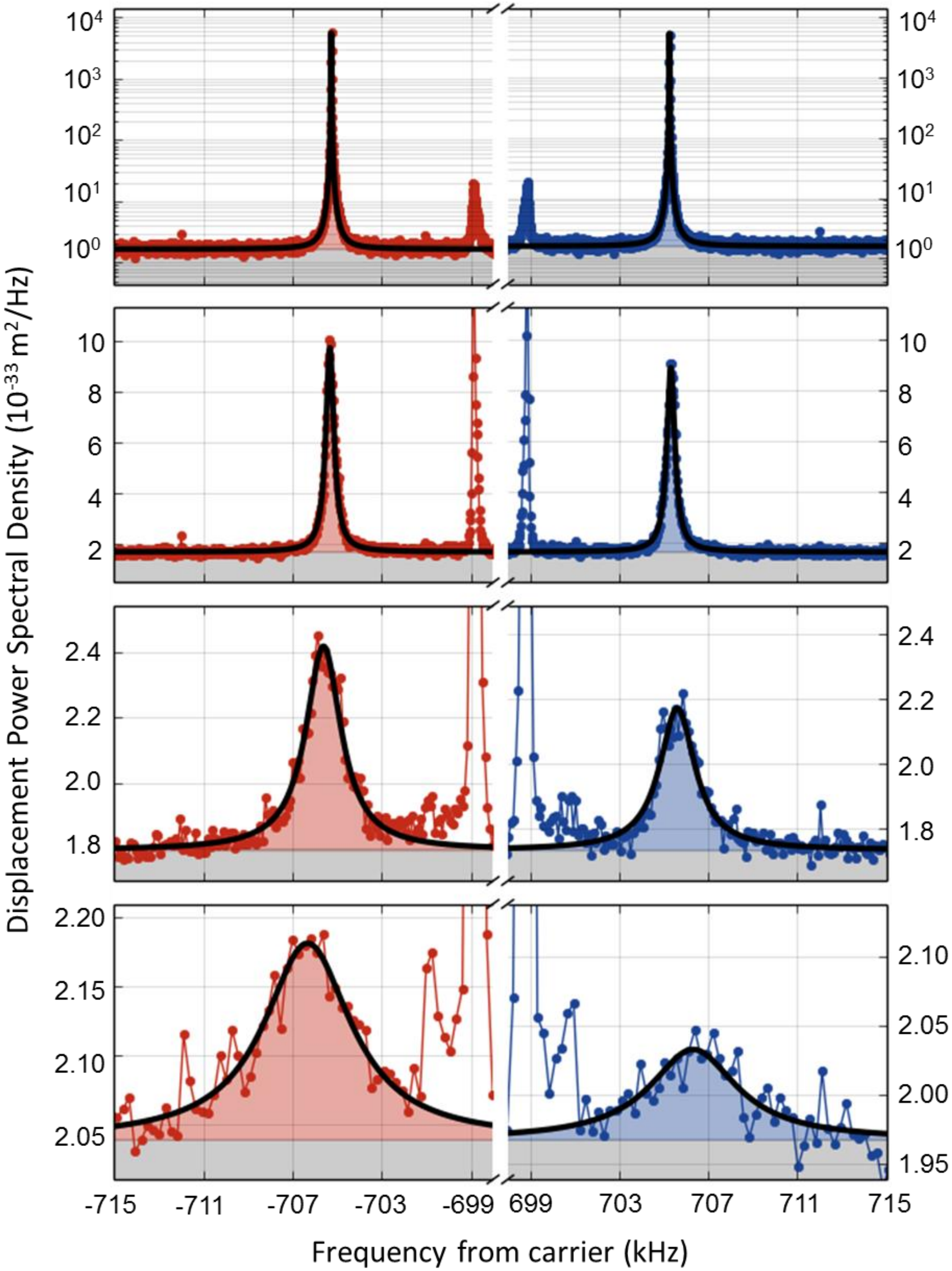
$P_{cool} = 0$

- **Blue sideband area:** $m\omega_m\langle x^2\rangle = \hbar\omega_m\bar{n}$

$\bar{n} = 192$

- **Red sideband area:** $m\omega_m\langle x^2\rangle = \hbar\omega_m(\bar{n}+1)$

Laser-assisted cooling of mechanical motion



$P_{cool} = 0$ $\bar{n} = 192$

$P_{cool} = 34\ \mu\text{W}$ $\bar{n} = 9.59$

$P_{cool} = 158\ \mu\text{W}$ $\bar{n} = 2.14$

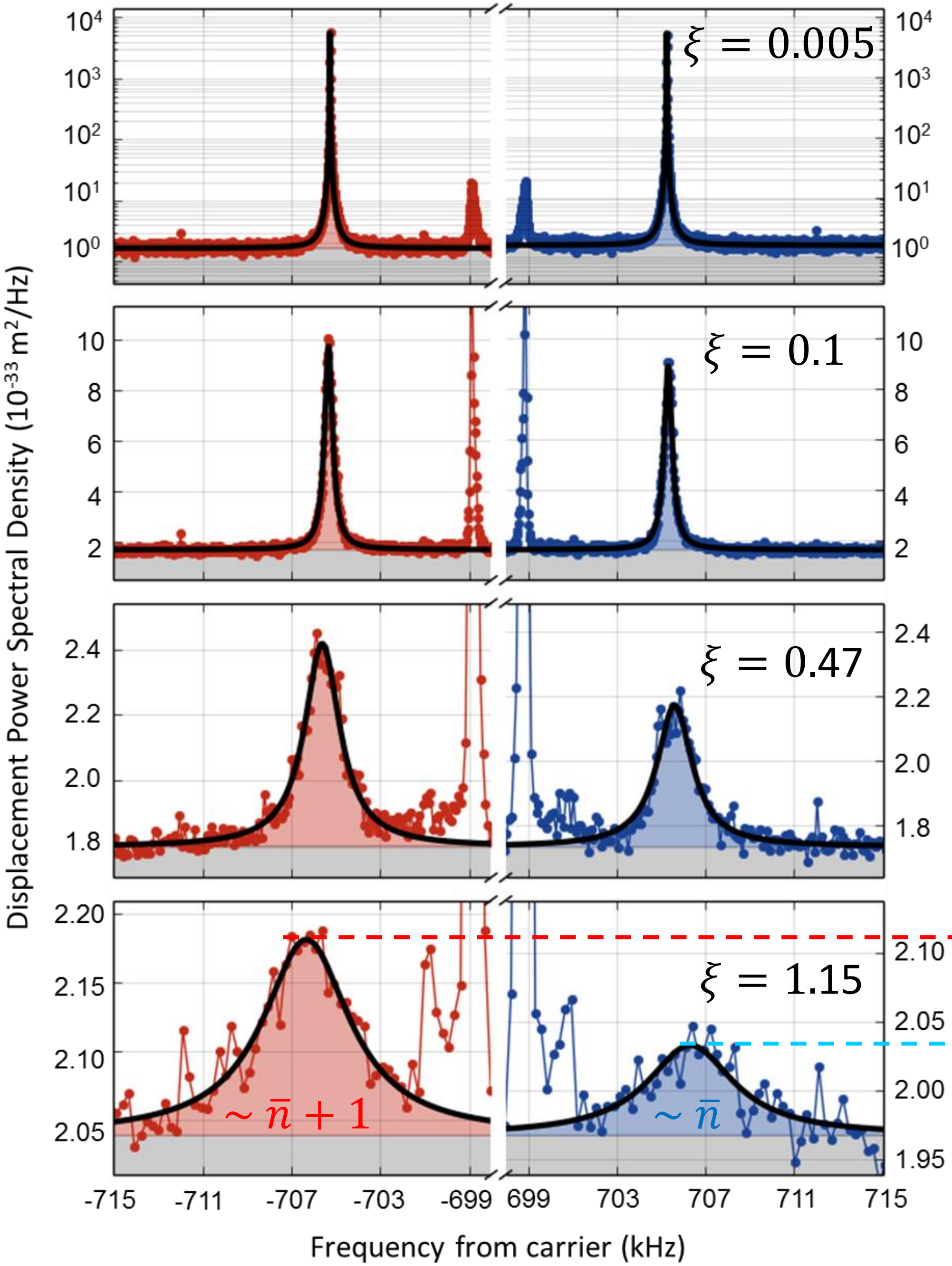
$P_{cool} = 415\ \mu\text{W}$

Ground state cooling!

$\boxed{\bar{n} = 0.84 \pm 0.22}$

M. Underwood *et al.*, PRA (2015)

Laser-assisted cooling of mechanical motion



- Ground state cooling
- Observation of sideband asymmetry (due to quantum motion)

- **Sideband asymmetry:**

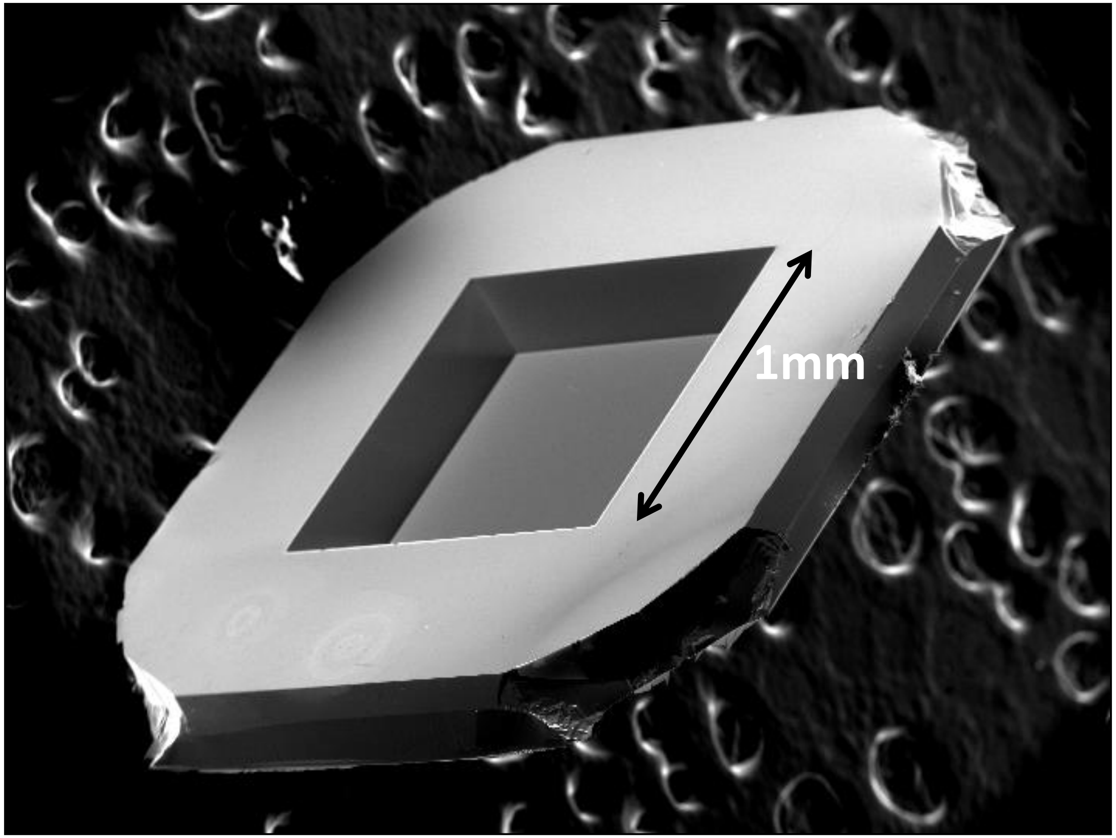
$$\xi = \left(\frac{A^{(r)}}{A^{(b)}} - 1\right) = \left(\frac{\bar{n}+1}{\bar{n}} - 1\right) = \frac{1}{\bar{n}}$$

Sideband asymmetry

M. Underwood *et al.*, PRA (2015)

Ground state cooling of macroscopic mechanical objects

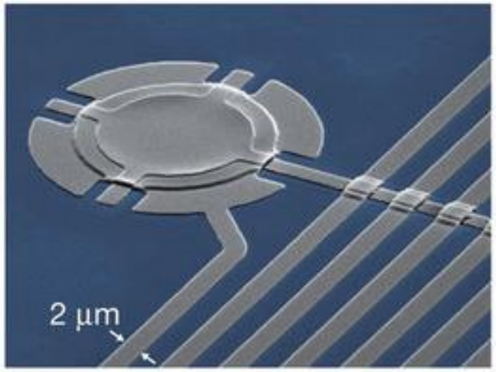
This work: laser cooling ~ 40 ng oscillator to $\bar{n} < 1$

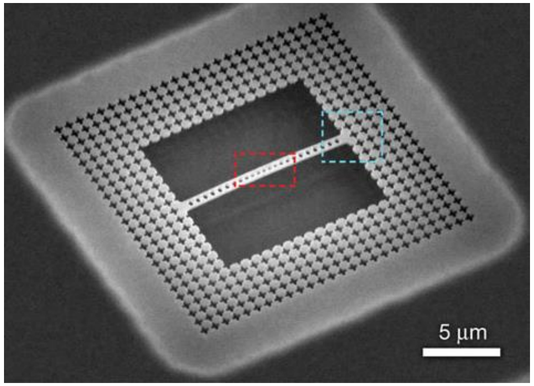


Similar results from
C. Regal (JILA/Boulder)

Simmonds/Teufel/Lehnert
(JILA/NIST/Boulder)

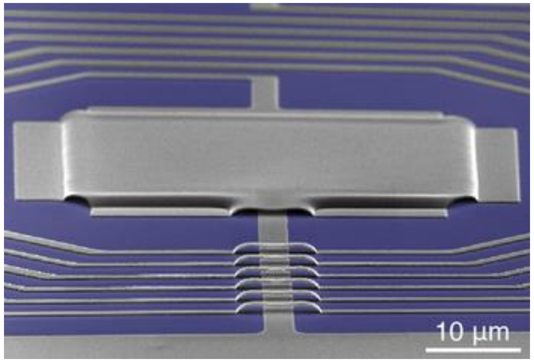
J. Teufel *et al*. Nature (2011)





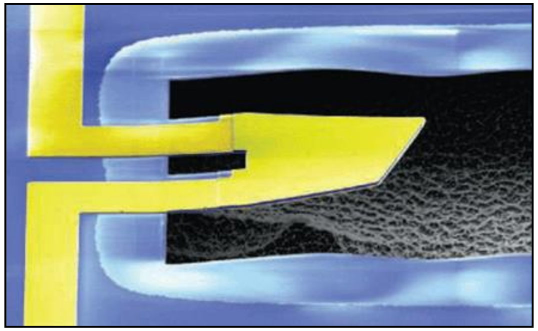
O. Painter (Caltech)

J. Chan *et al*. Nature (2011)



K. Schwab (Caltech)

J. Suh *et al*. Science (2014)



Cleland/Martinis (UCSB)

A.D. O'Connell *et al*. Nature (2010)

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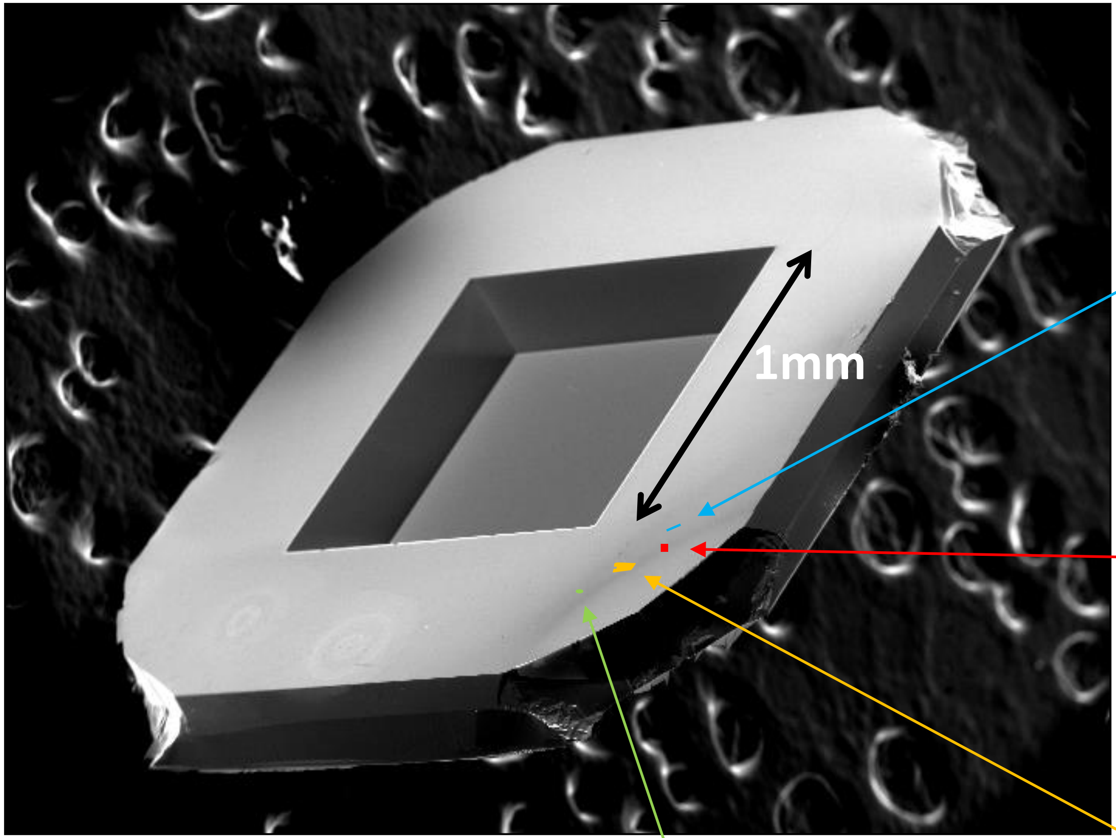

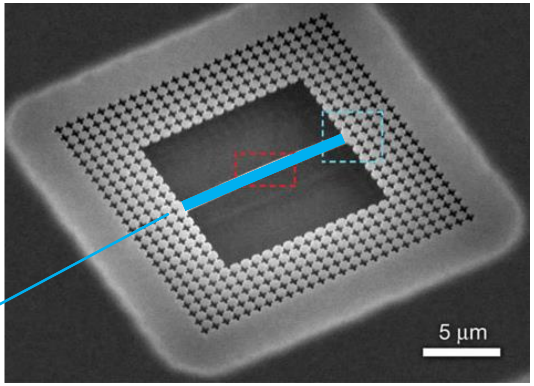

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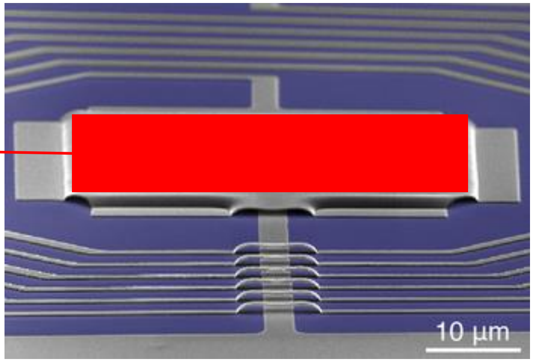

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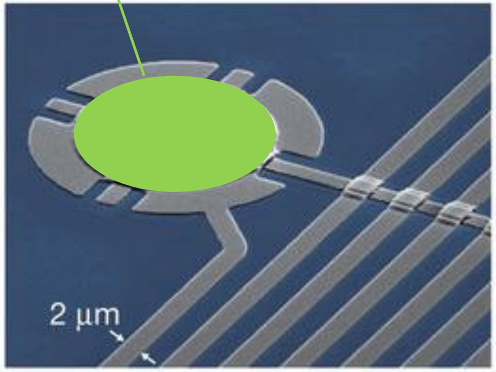
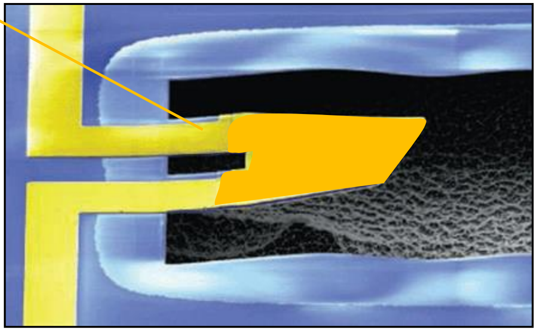


Simmonds/Teufel/Lehnert
(JILA/NIST/Boulder)

J. Teufel *et al*. Nature (2011)



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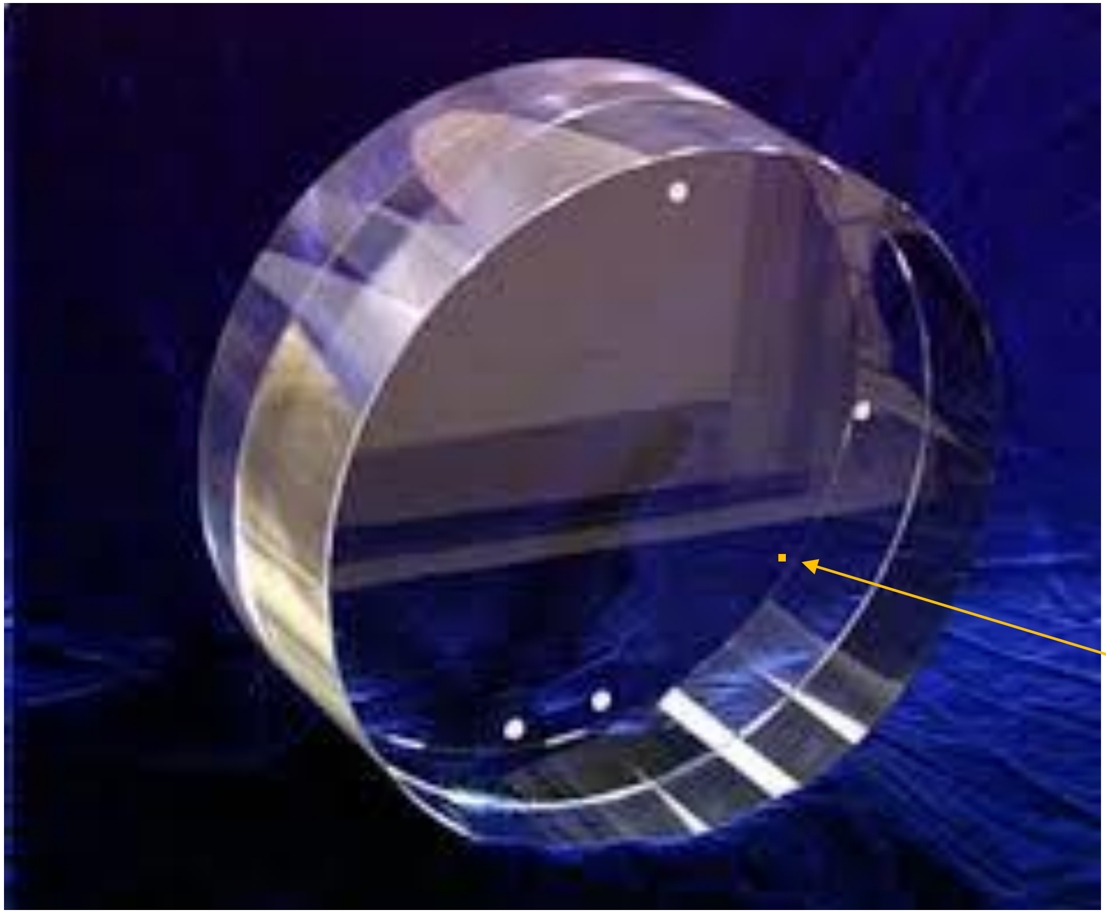
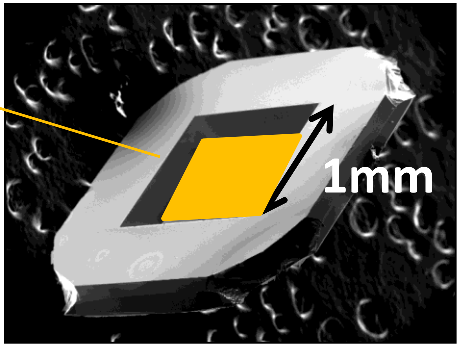
A.D. O'Connell *et al*. Nature (2010)

Ground state cooling of macroscopic mechanical objects

Quantum phenomena from LIGO mirrors or human size objects?





- 17 cm radius x 20 cm thickness
- mass = 40 kg

- 1mm
- mass = 40 ng

Recent progress in cavity optomechanics

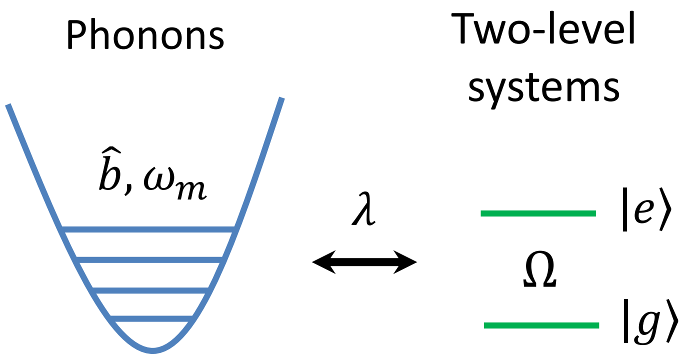
- Mechanical ground state (UCSB, JILA/NIST, Caltech, Yale)
- Entangled with qubits, photons (UCSB, JILA/NIST)
- Radiation pressure shot noise, squeezed light (Caltech, Berkeley, JILA, Yale)
- Back action evasion measurement (Caltech, JILA/NIST)
- Quantum squeezed mechanical states (Caltech, NIST, Aalto)
- Phonon counting (Caltech)
- Multimode optomechanics (Yale, Caltech)
- Topological energy transfer via exceptional points (Yale)
- …
- Hybrid quantum systems based on mechanical oscillators

Outline

- When Phonon Met Photon (Cavity Optomechanics)
  - Ground state cooling and sidebands asymmetry
  - Multimode optomechanics

- When Phonon met Spin (Diamond Hybrid System)
  - Strain-spin state coupling
  - Strain-orbital state coupling
  - Future applications

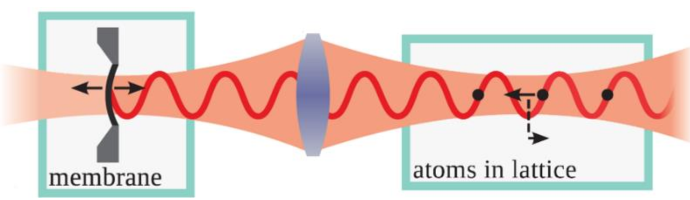
Various hybrid systems: mechanical oscillator + two-level systems



- non-linear interaction
- non-classical mechanical states

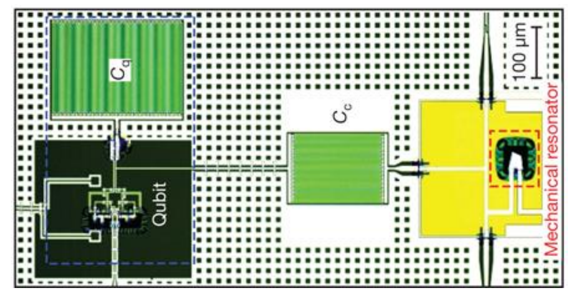
  e.g. Schrodinger cat states
- hybrid quantum systems

Mechanical oscillator ↔ Ultracold atoms



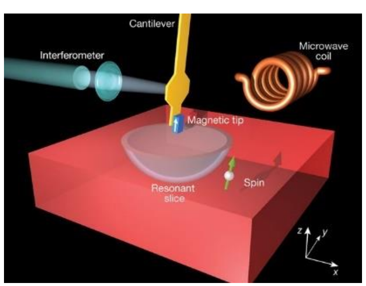
S. Camerer *et al.*, PRL (2011)

Mechanical oscillator ↔ Superconducting qubits

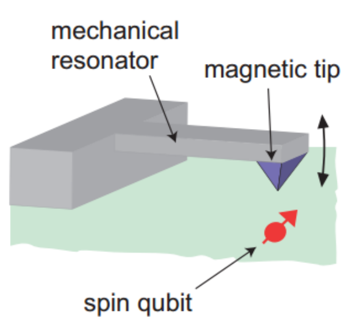


A. D. O'Connell *et al.*, Nature (2010)

Mechanical oscillator ↔ Solid-state defects or QDs

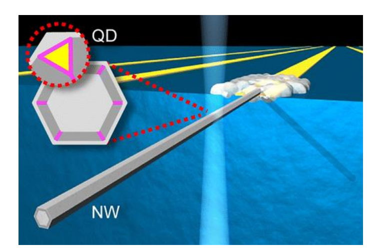


D. Rugar *et al.*,
Nature (2004)



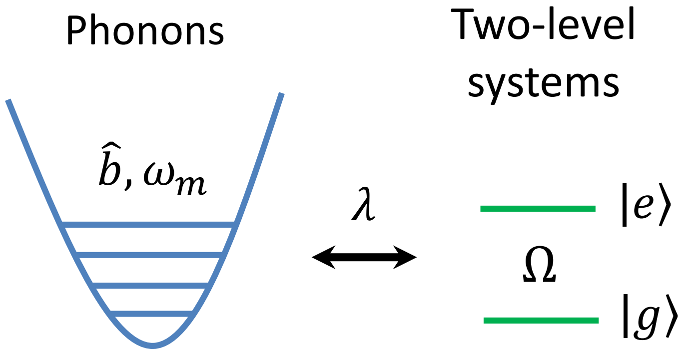
S. Kolkowitz *et al.*,
Science (2012)

I. Yeo *et al.*,
Nat. Nano. (2014)



M. Montinaro *et al.*,
Nano Lett. (2014)

Various hybrid systems: mechanical oscillator + two-level systems



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  e.g. Schrodinger cat states
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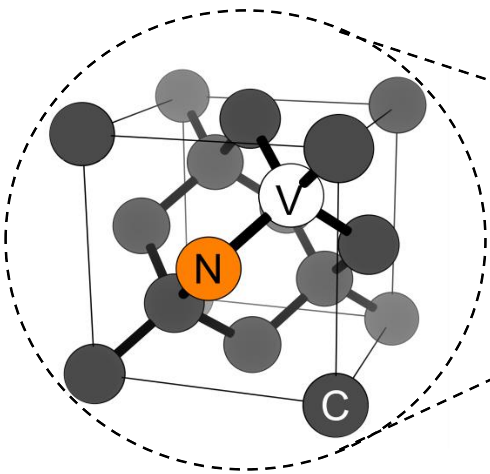
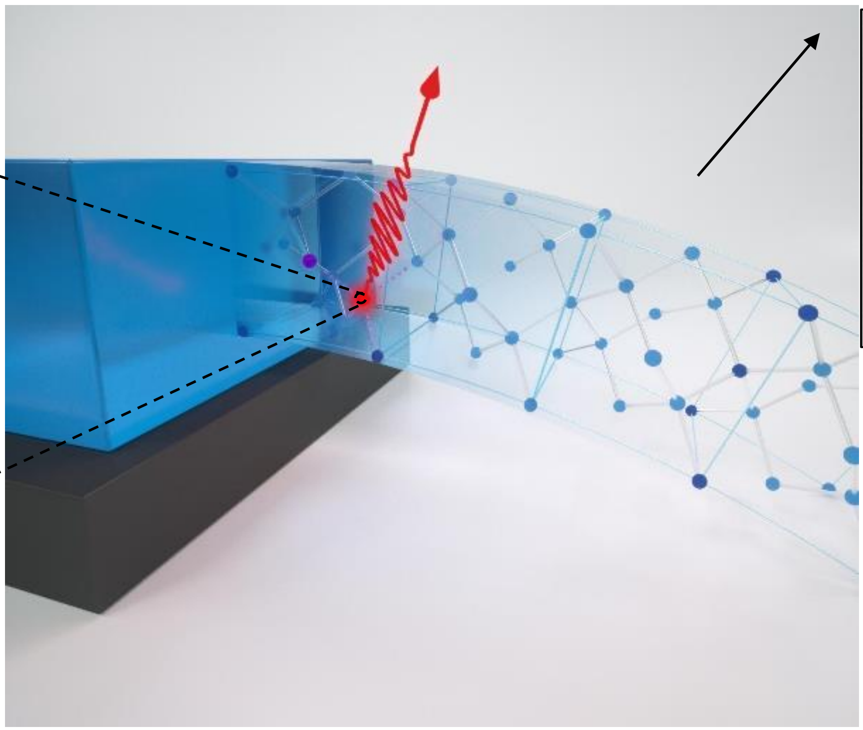
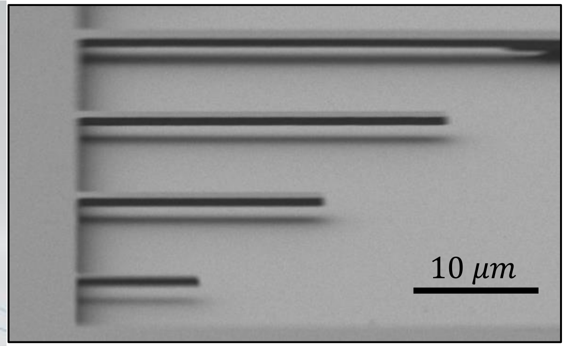


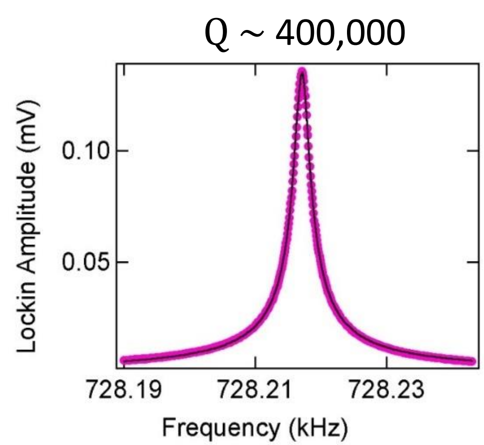
Spin qubits
(e.g. NV centers)

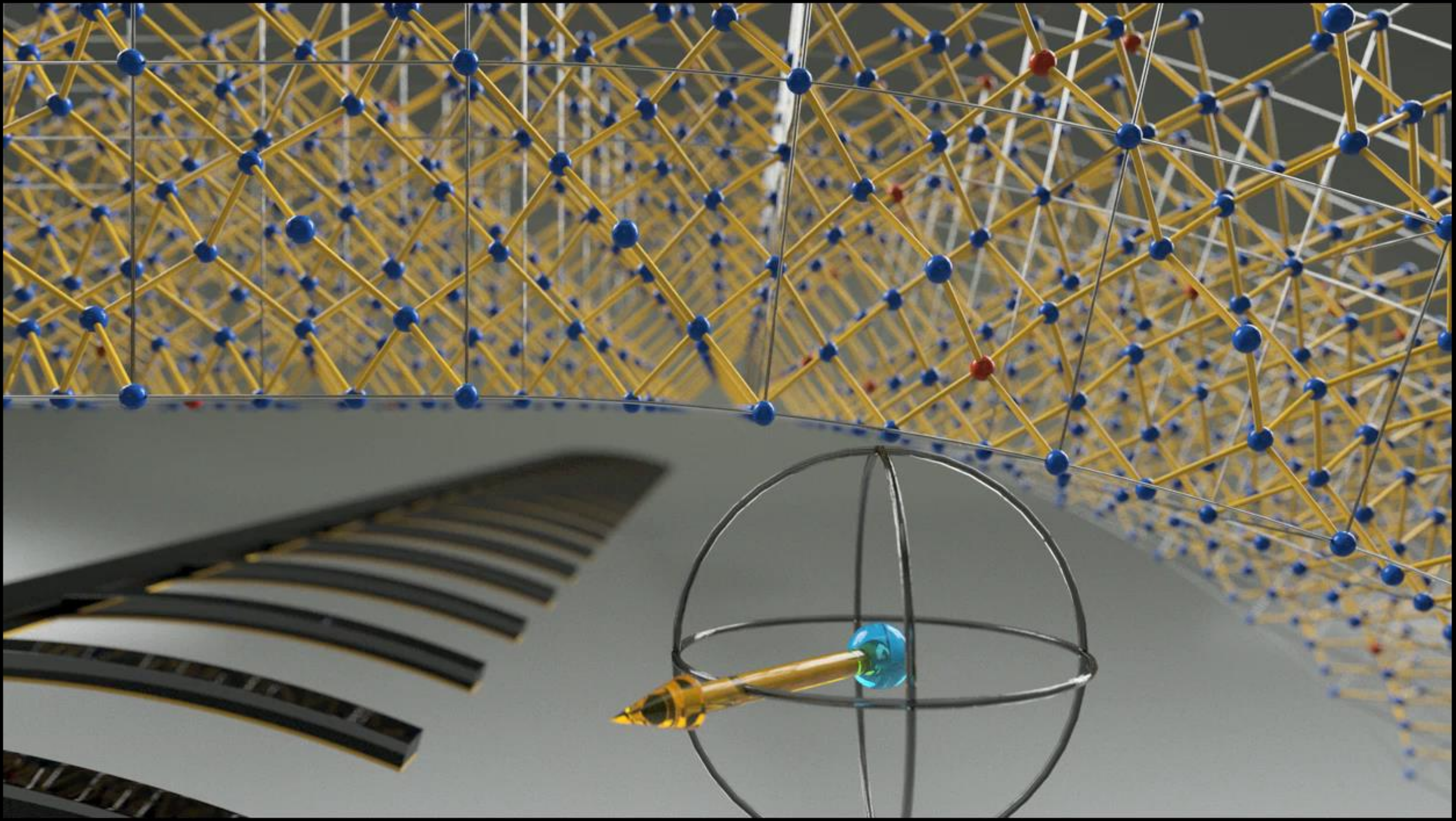
<u>Diamond hybrid quantum system</u>



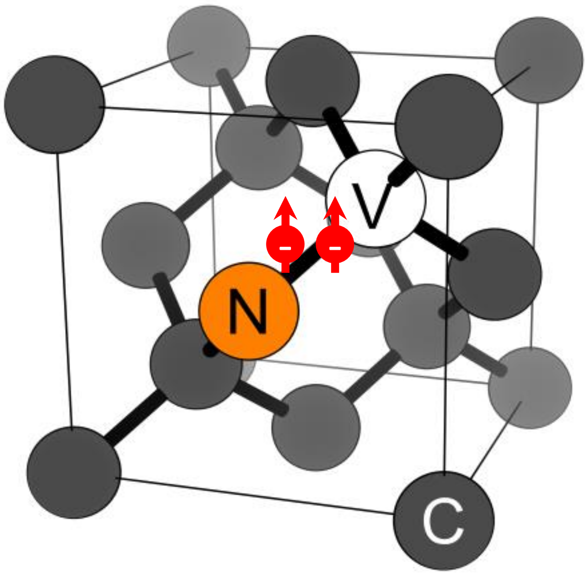
Diamond mechanical oscillator





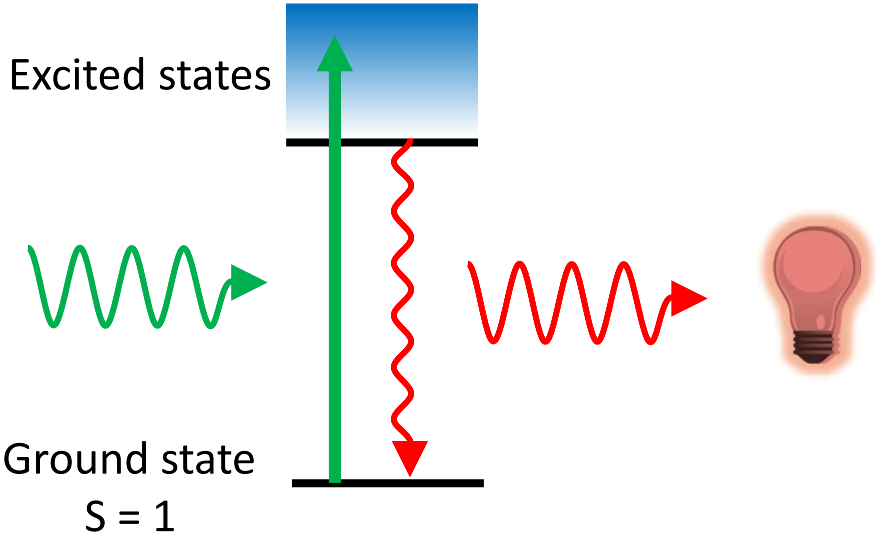


Nitrogen-vacancy defects in diamond



NV defects in diamond

- Spin qubits in solid state material
- Optical preparation and readout of spin state
- Long coherence time even at RT (e.g. $T_2 \sim$ ms)
- High field sensitivity e.g. magnetic, electric, **strain field**



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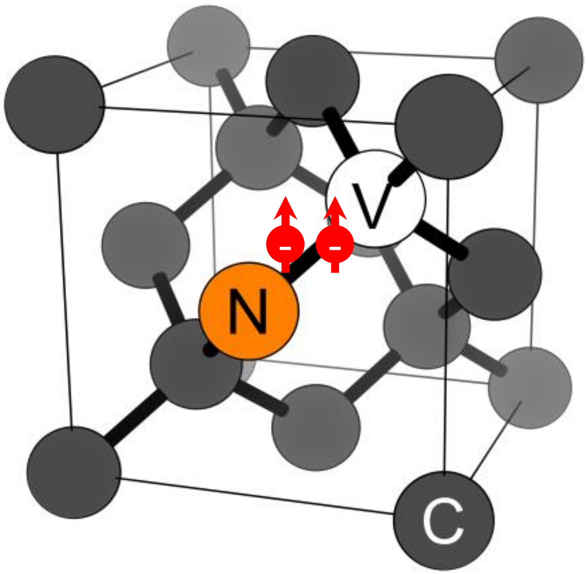

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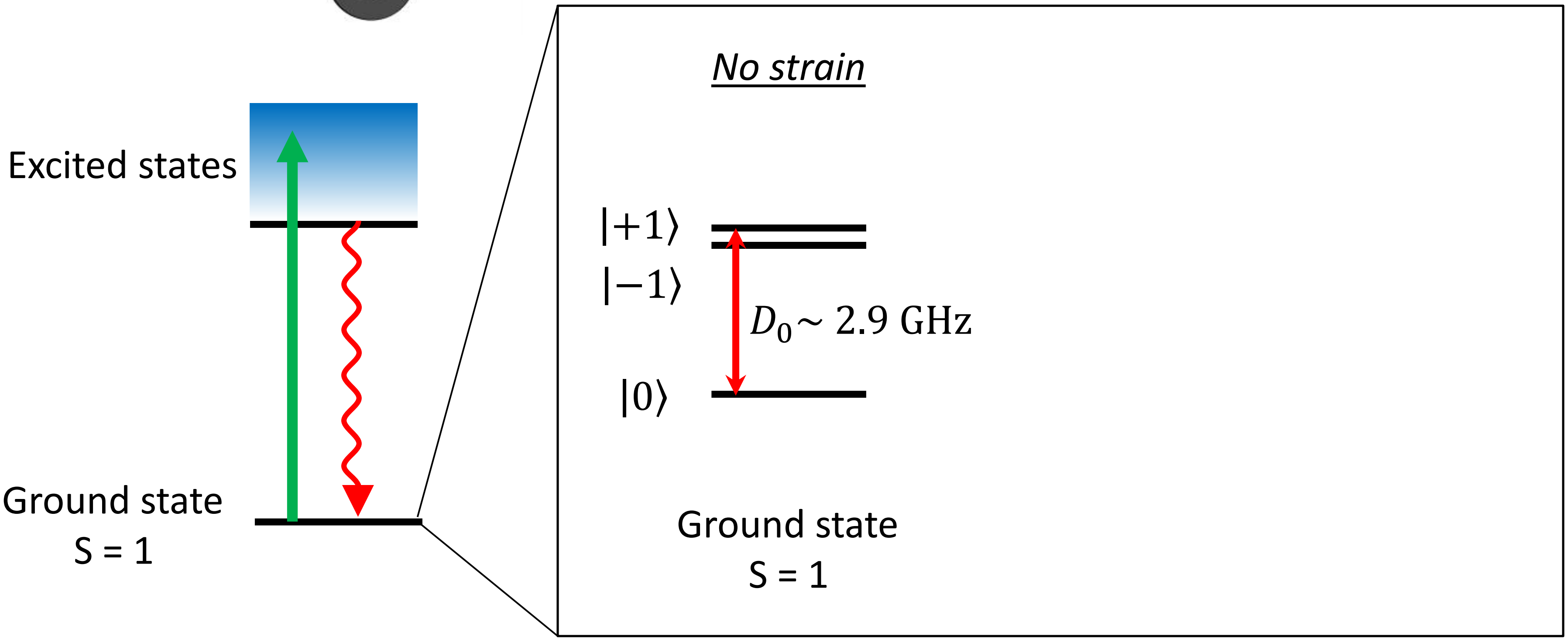

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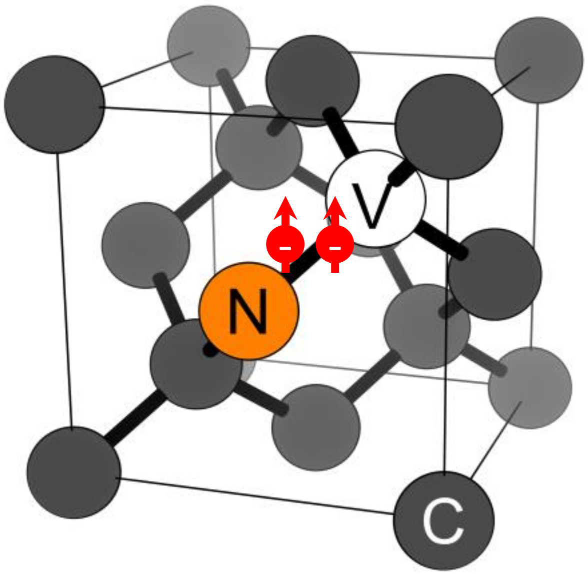

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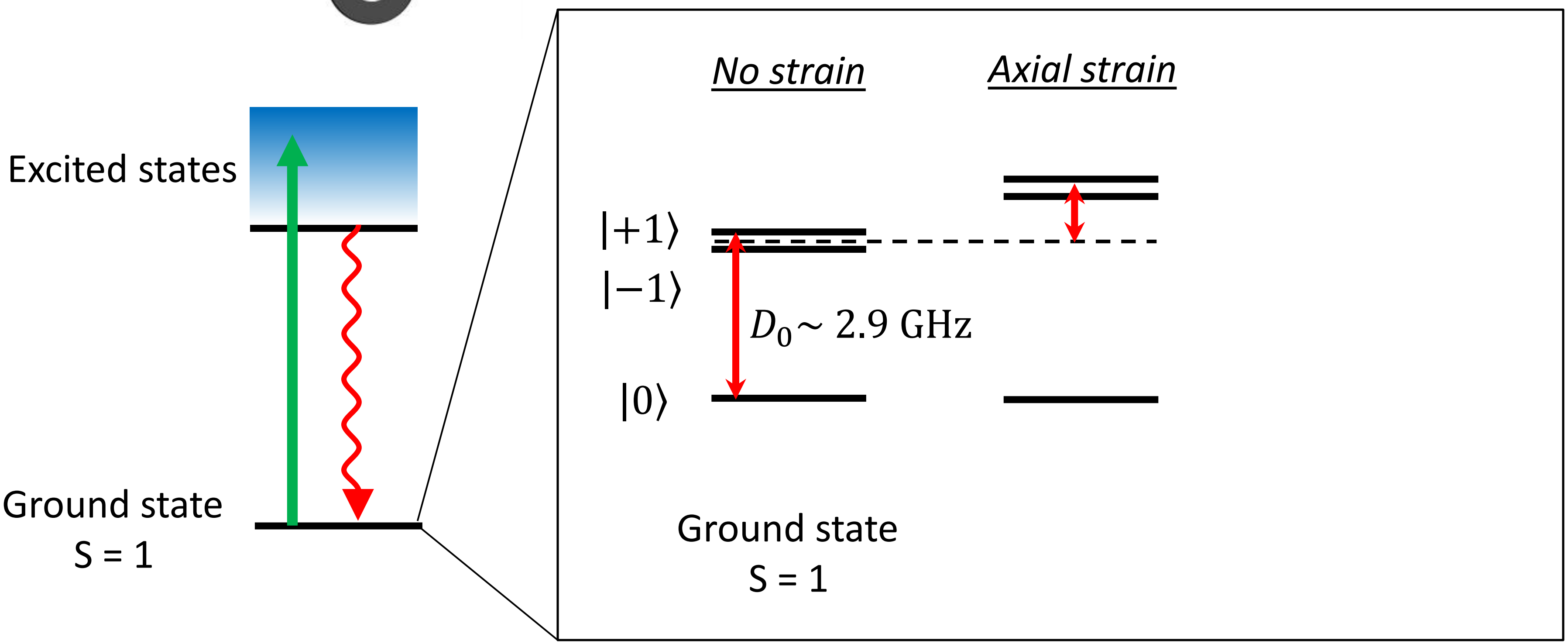

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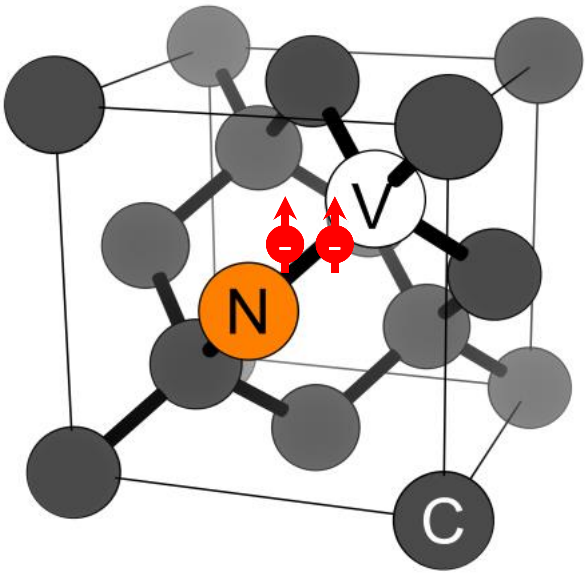

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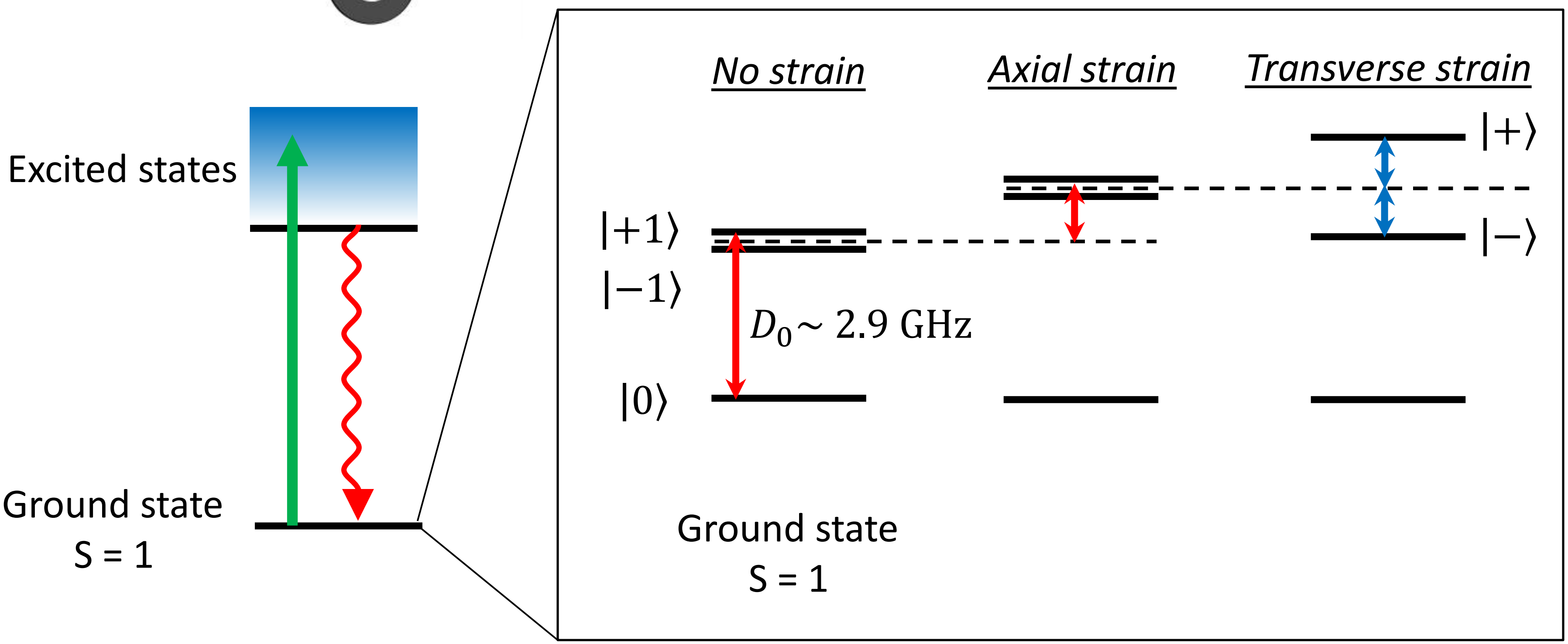
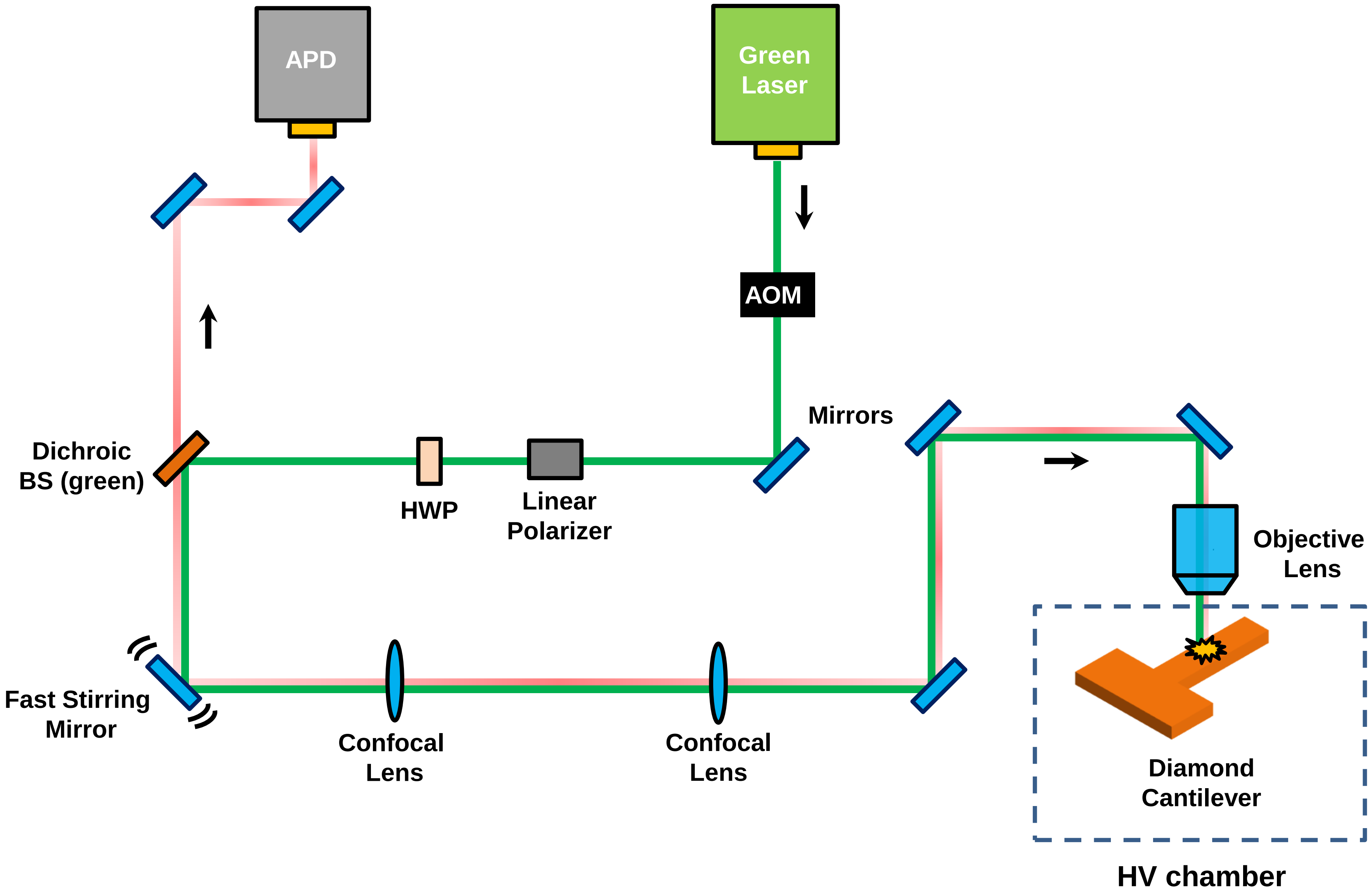
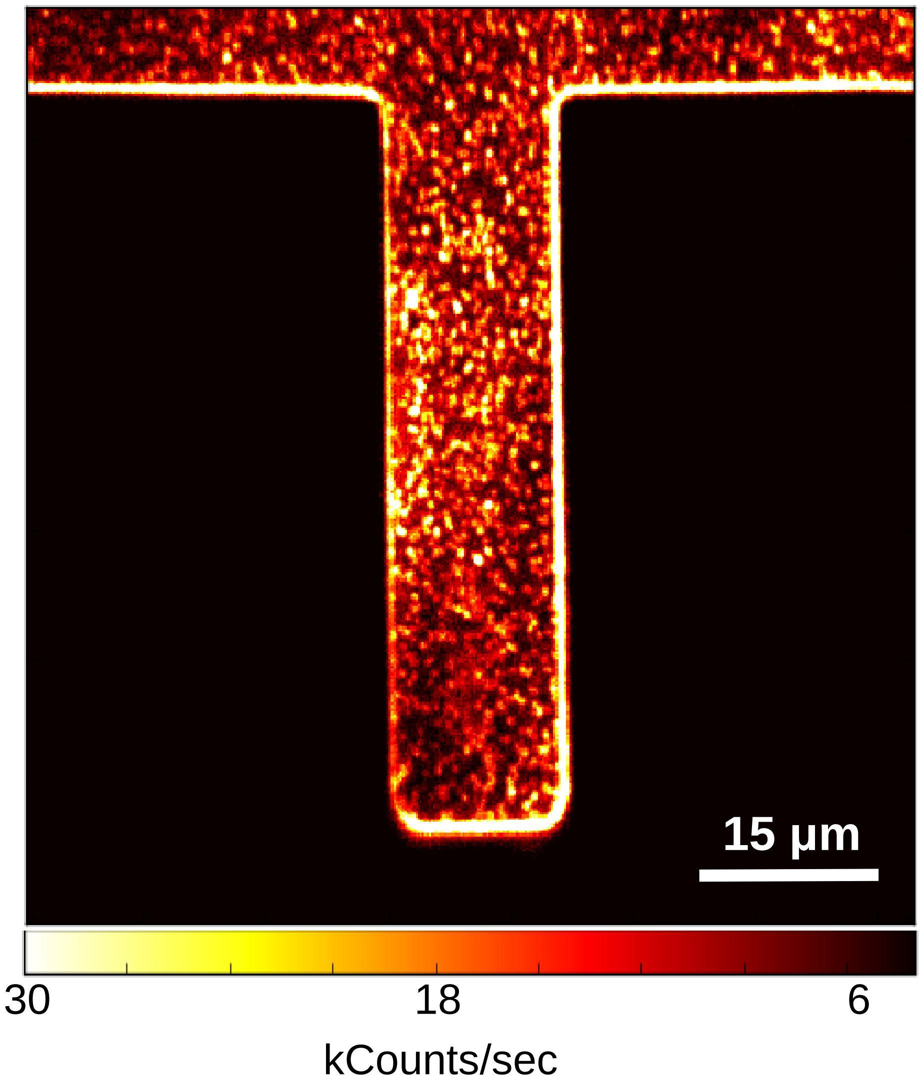


Confocal optics setup for ground state measurement



Confocal image of mechanical oscillator and NV centers

Confocal image of cantilever



Confocal image of mechanical oscillator and NV centers

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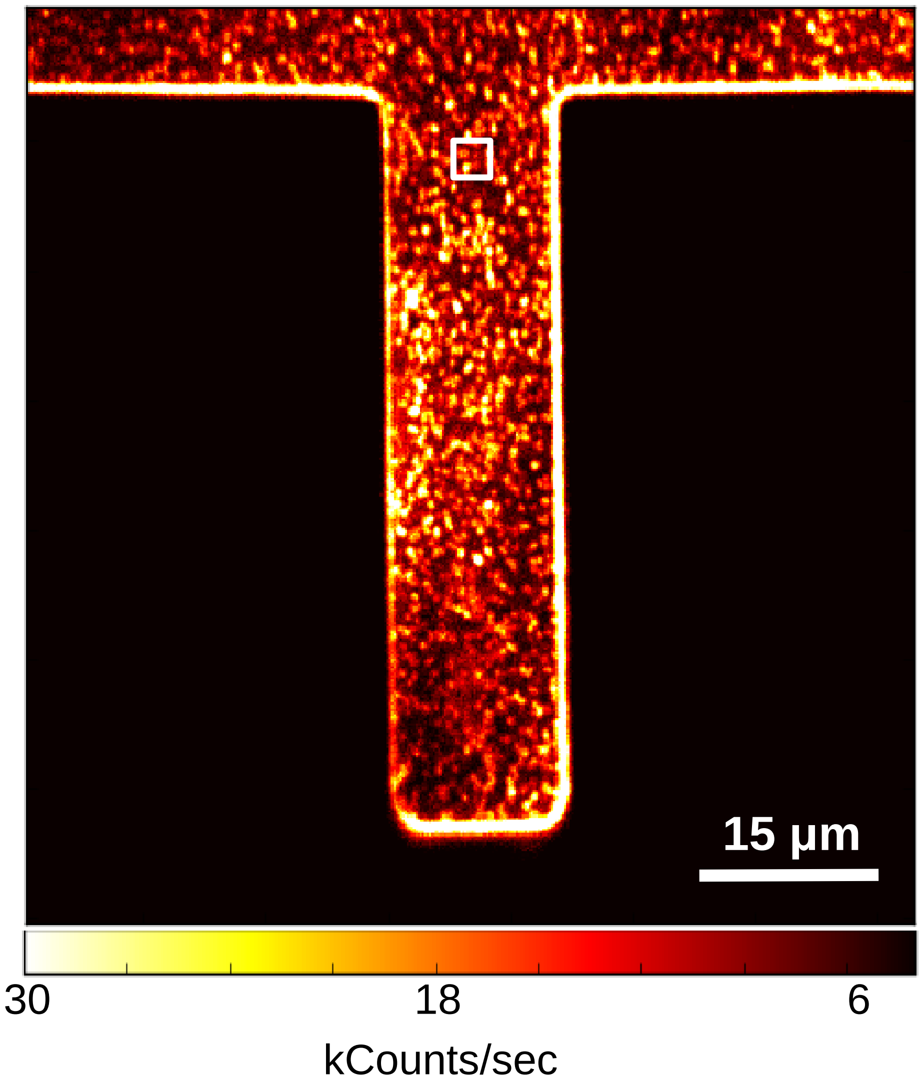
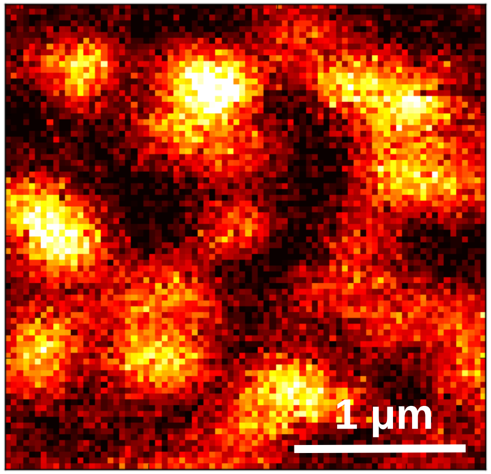
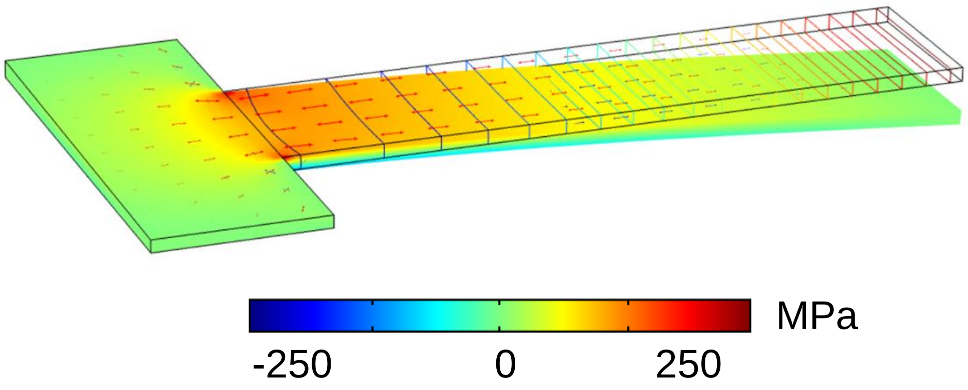


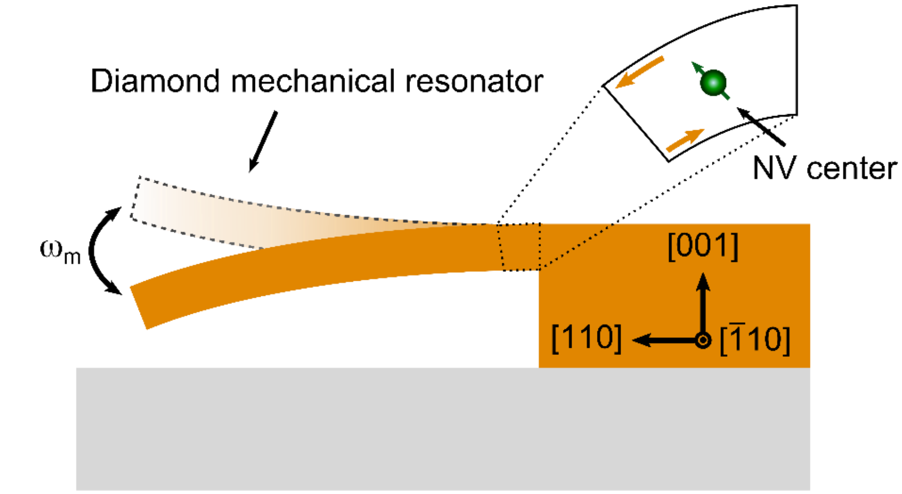
Confocal image of NV centers

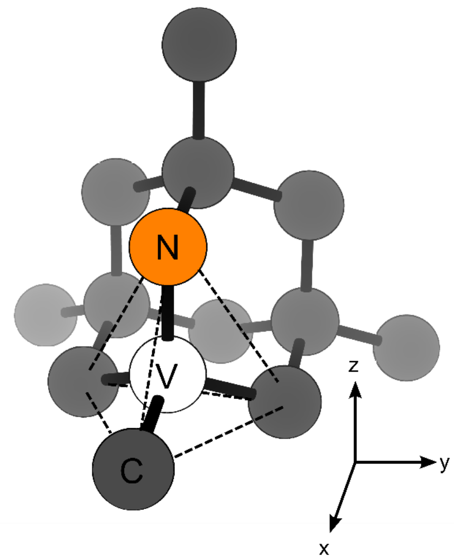




- Stress/strain simulation (COMSOL)
- Fundamental flexural mode (e.g. $f_m \sim 900$ kHz)
- Drive motion with a piezo actuator

Spin state coupled to mechanical motion

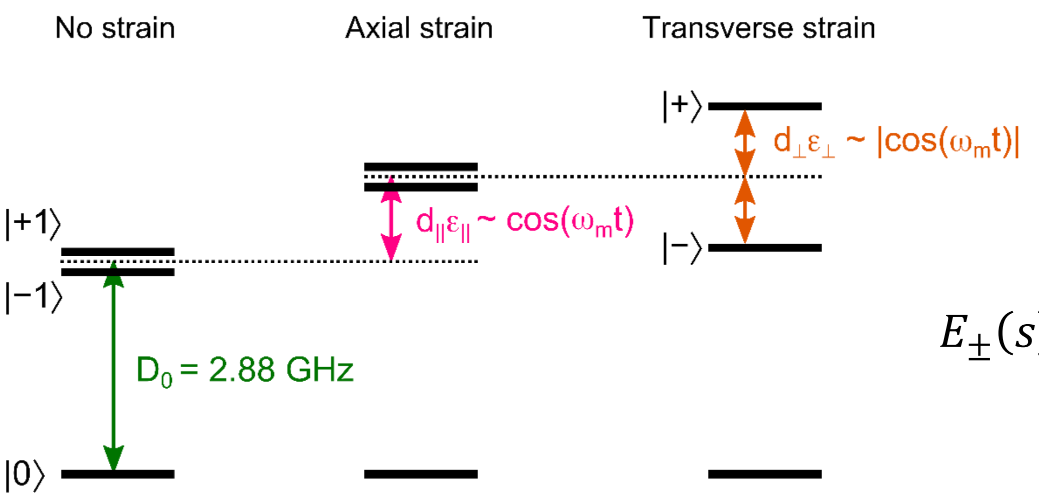




C_{3v} symmetry group

Three mirror planes

$120^{o}, 240^{o}$ rotation



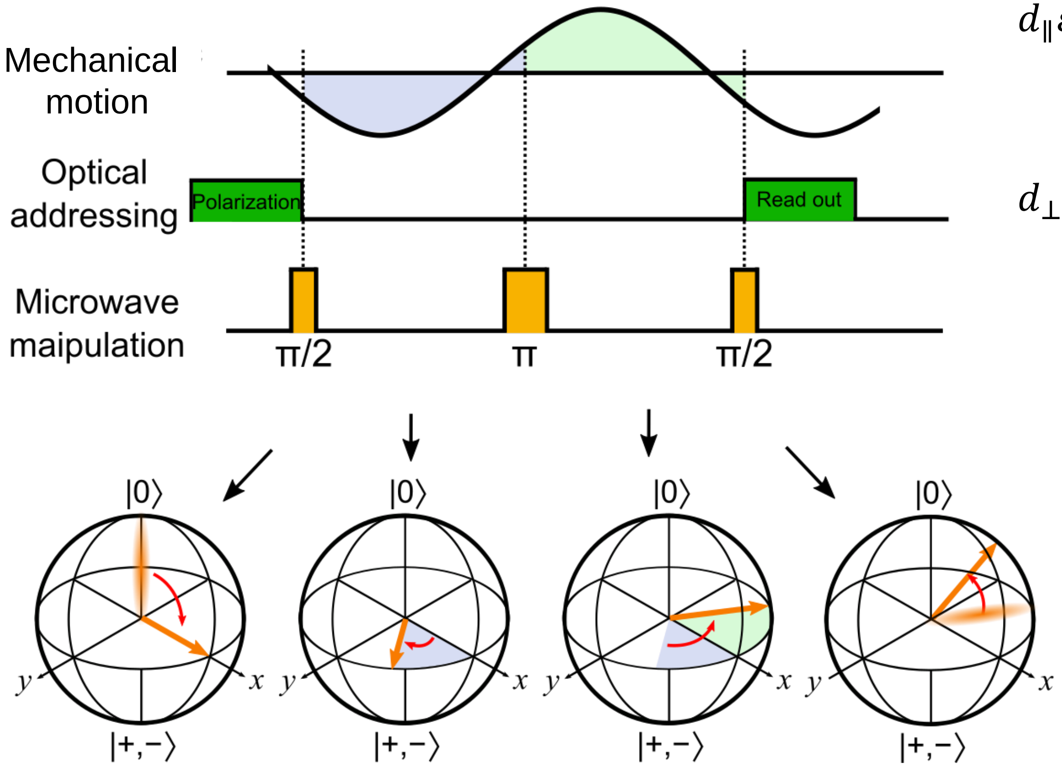
$$E_{\pm}(s) = D_0 + \boldsymbol{d_{\parallel}\varepsilon_{\parallel}} \pm \sqrt{(\boldsymbol{\gamma_{NV}B_z})^2 + (\boldsymbol{d_{\perp}\varepsilon_{\perp}})^2}$$

- AC parallel strain modulates at mechanical frequency
- AC perpendicular strain modulates at twice mechanical frequency

Spin state coupled to mechanical motion

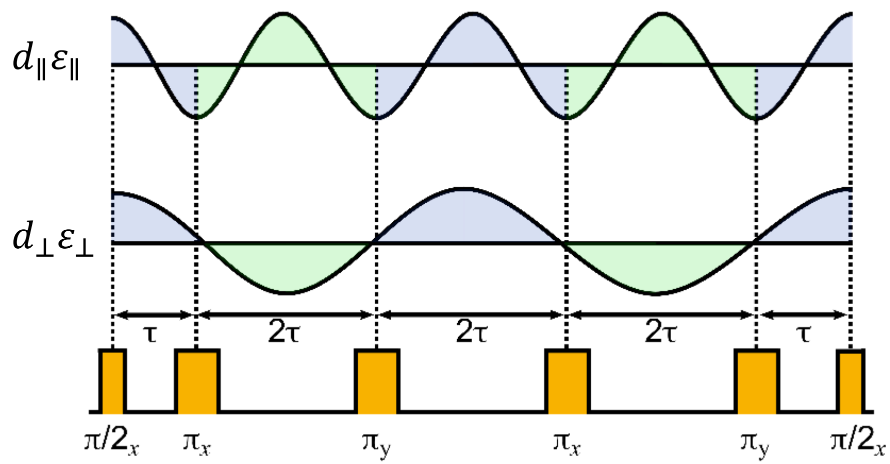
Axial strain measurement

e.g. Hahn echo pulse sequence



Transverse strain measurement

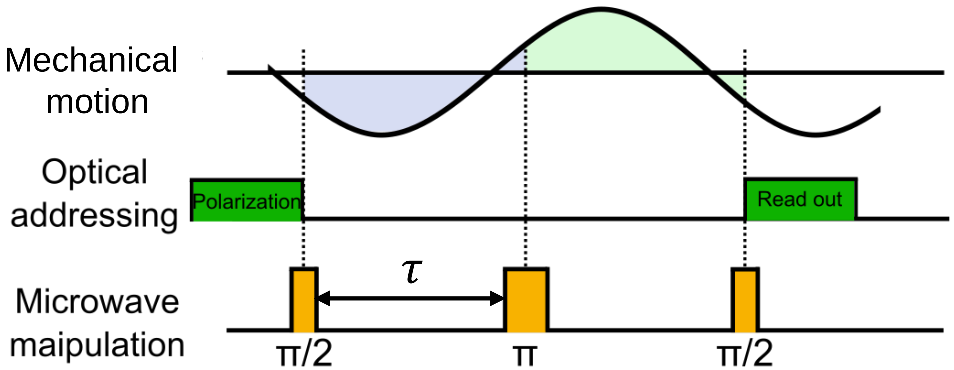
e.g. XY4 pulse sequence



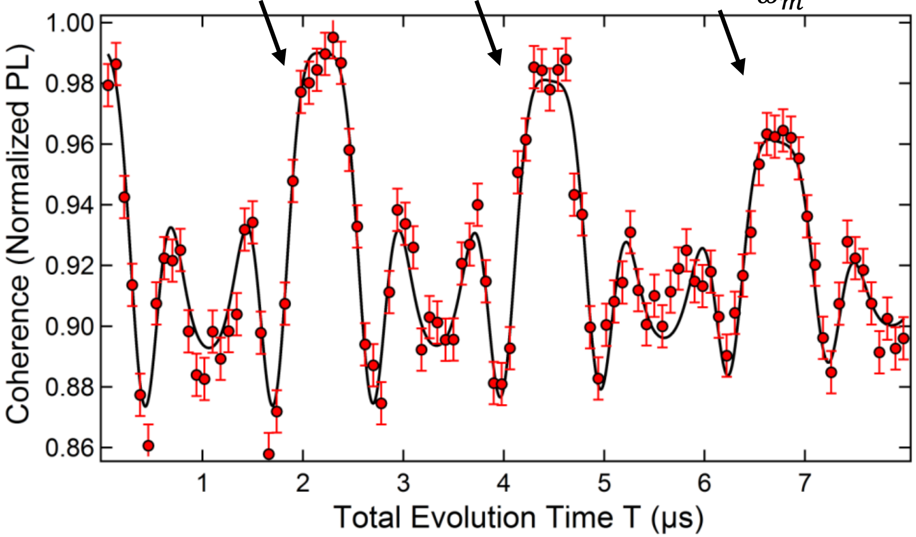
Spin state coupled to mechanical motion

Axial strain measurement

e.g. Hahn echo pulse sequence



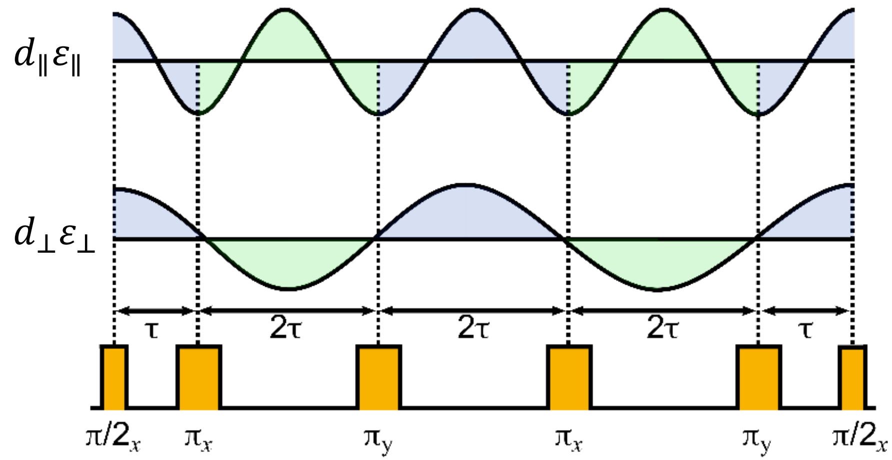
Revival of spin coherence when $\tau = \frac{2n\pi}{\omega_m}$

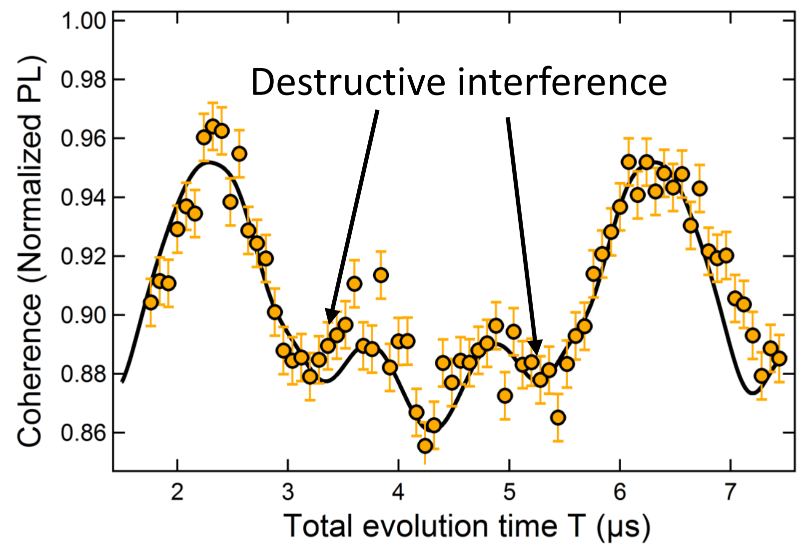


$d_{\parallel} = 13.4 \pm 0.8$ GHz/strain

Transverse strain measurement

e.g. XY4 pulse sequence

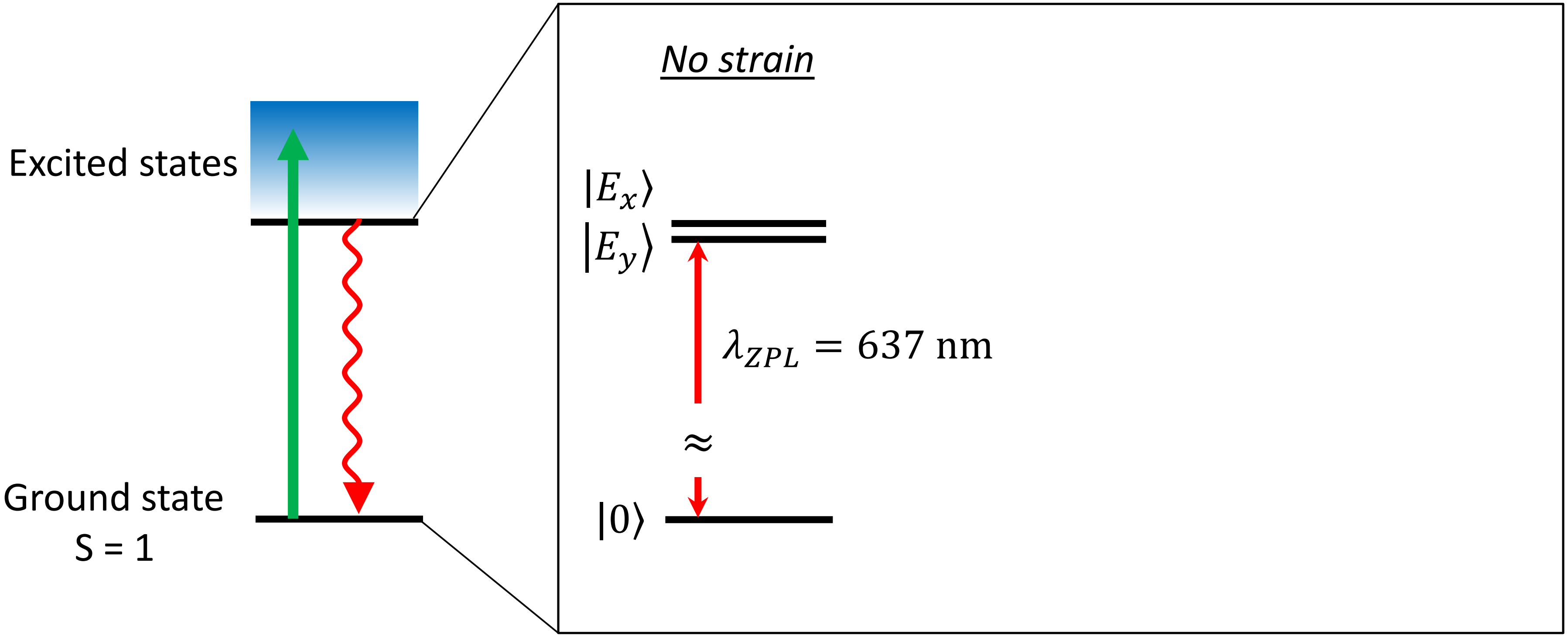


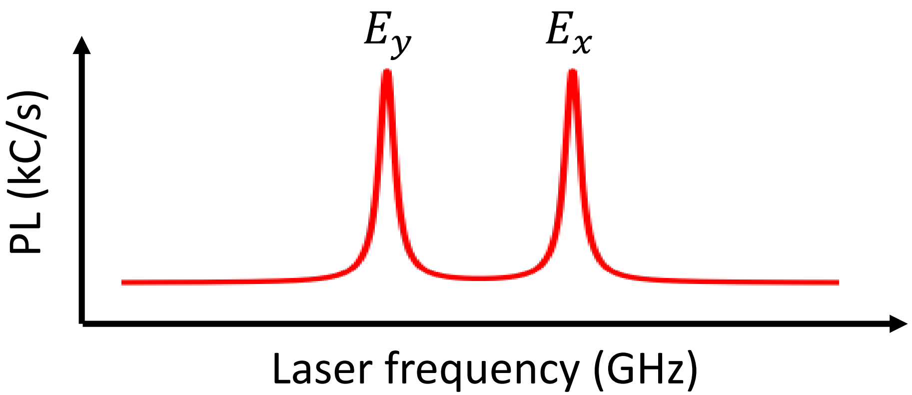


$d_{\perp} = 21.5 \pm 0.8$ GHz/strain

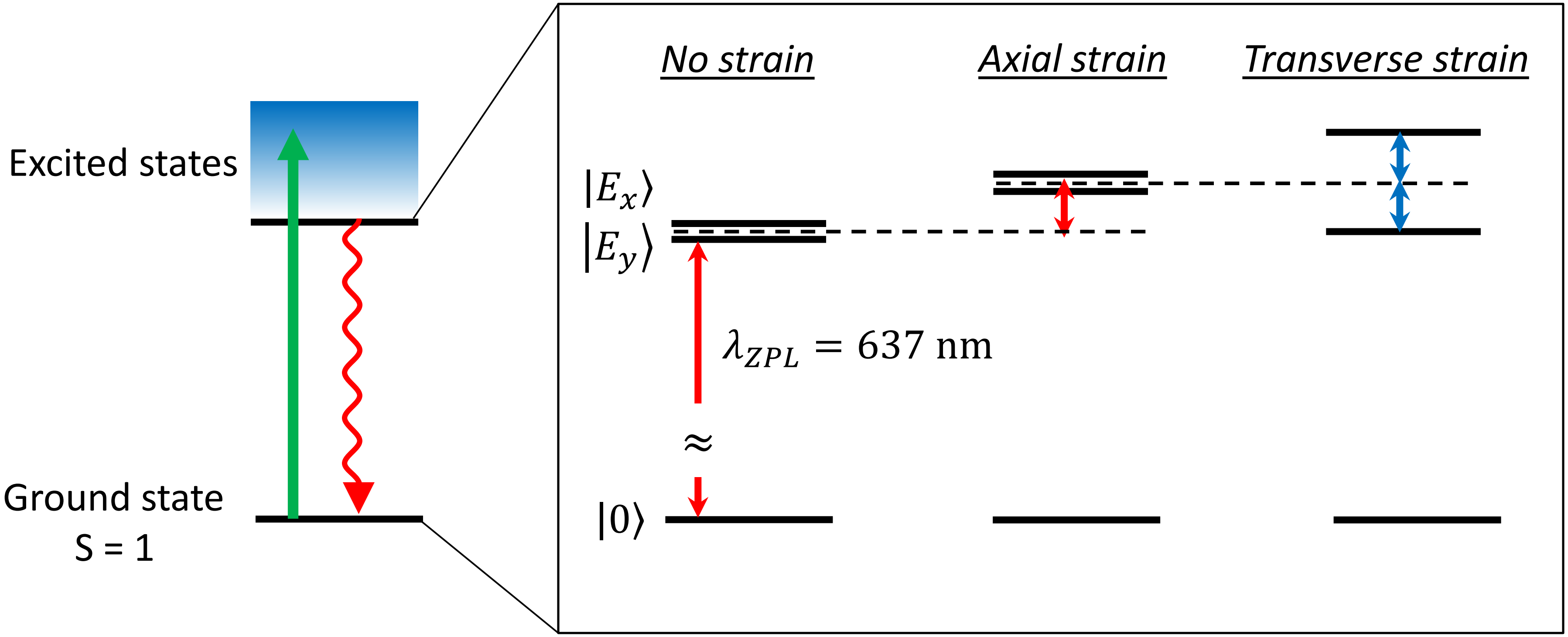
P. Ovartchaiyapong *et al.*, Nat. Comm. (2014)

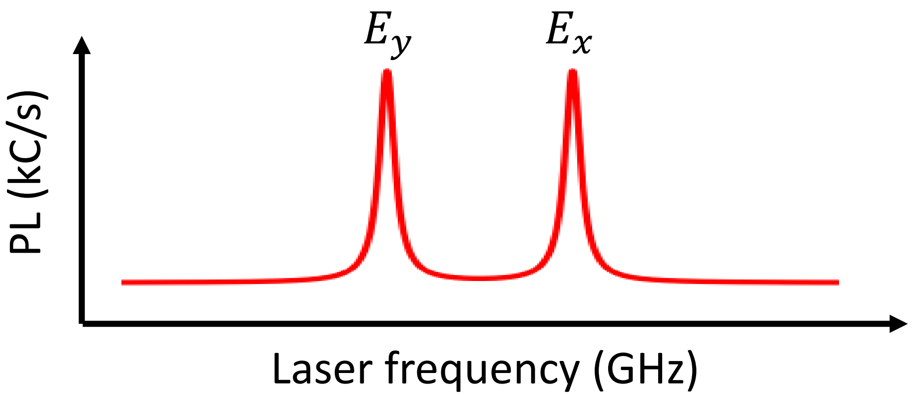
Orbital state coupled to mechanical motion



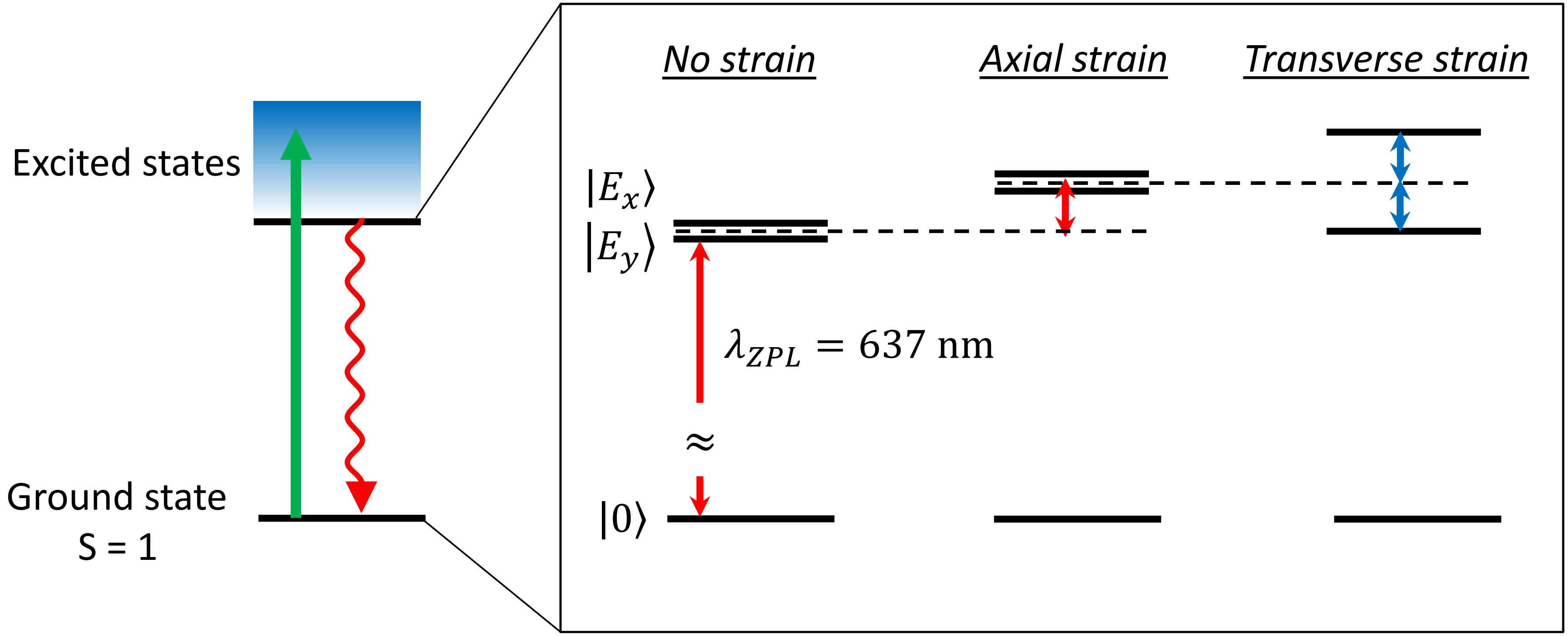


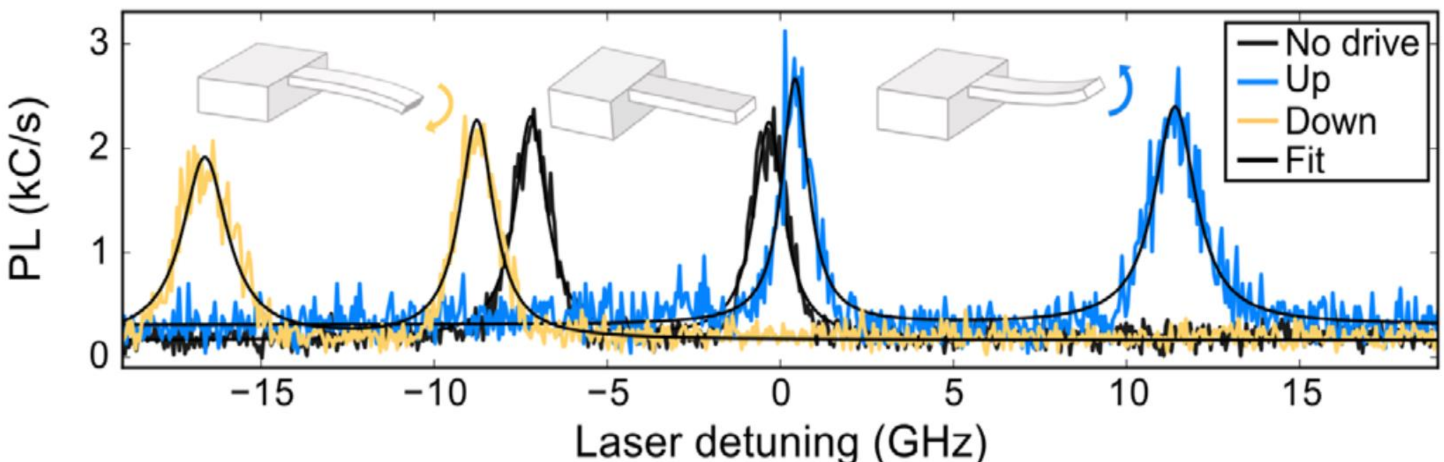
Orbital state coupled to mechanical motion





Orbital state coupled to mechanical motion





K. Lee *et al.*, PR Applied (2016)

NV center + mechanical oscillators

Orbital-strain coupling constants

$$\lambda_{\parallel 1} = -1.95 \pm 0.29 \text{ PHz/strain}$$

$$\lambda_{\parallel 2} = 2.16 \pm 0.32 \text{ PHz/strain}$$

$$\lambda_{\perp 1} = -0.85 \pm 0.13 \text{ PHz/strain}$$

$$\lambda_{\perp 2} = 0.02 \pm 0.01 \text{ PHz/strain}$$

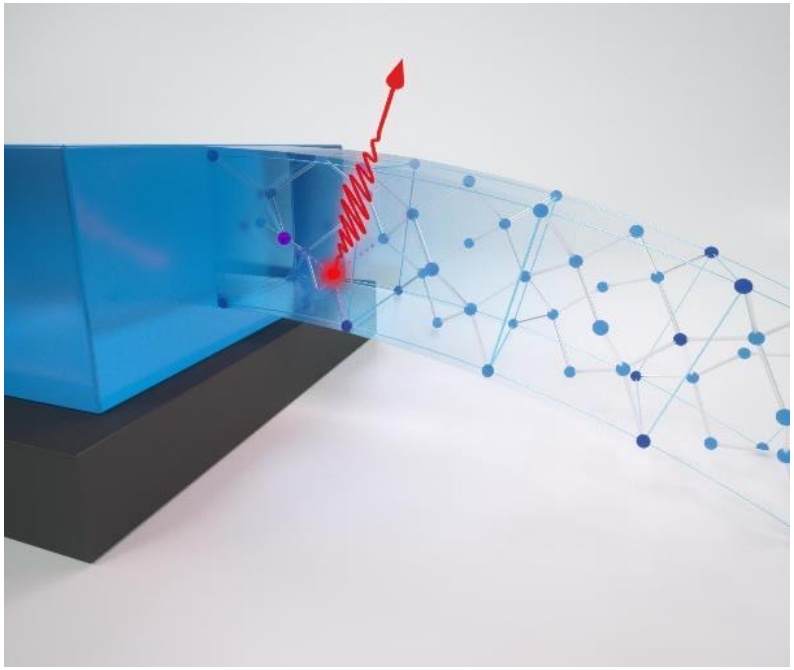
K. Lee *et al.*, PR Applied (2016)

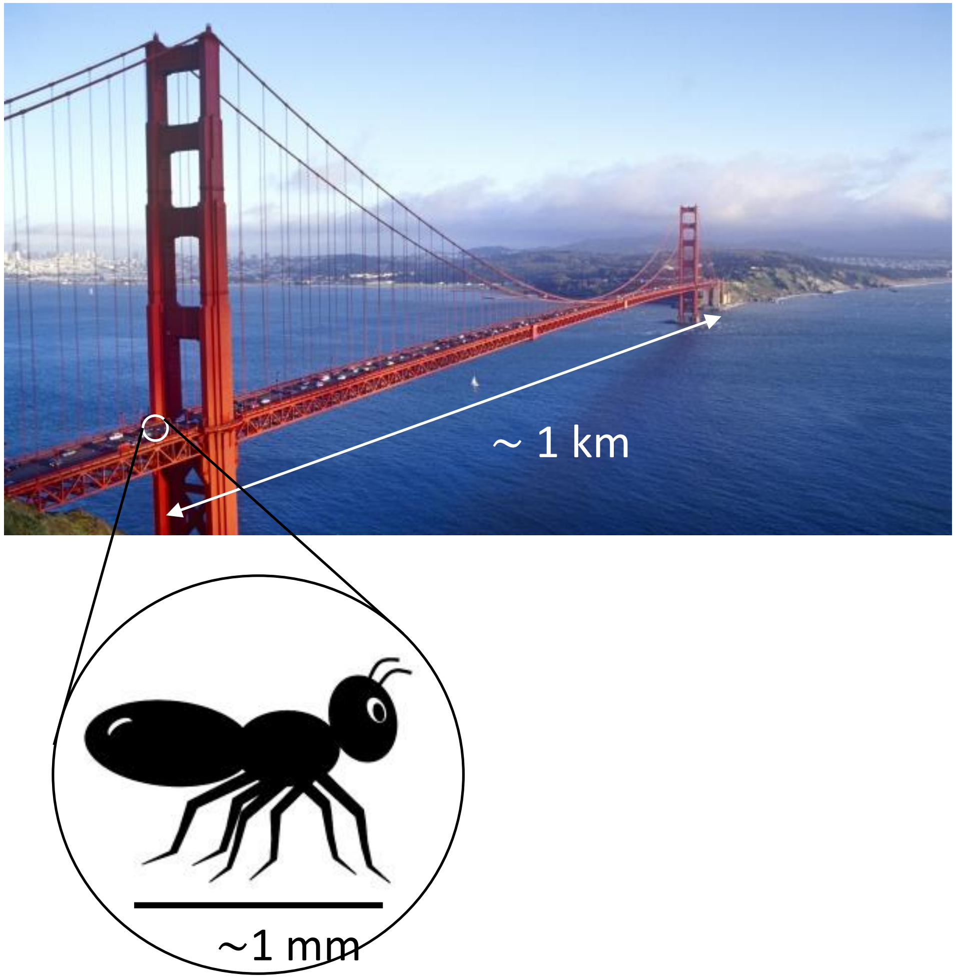
Spin-strain coupling constants

$$d_{\parallel} = 13.4 \pm 0.8 \text{ GHz/strain}$$

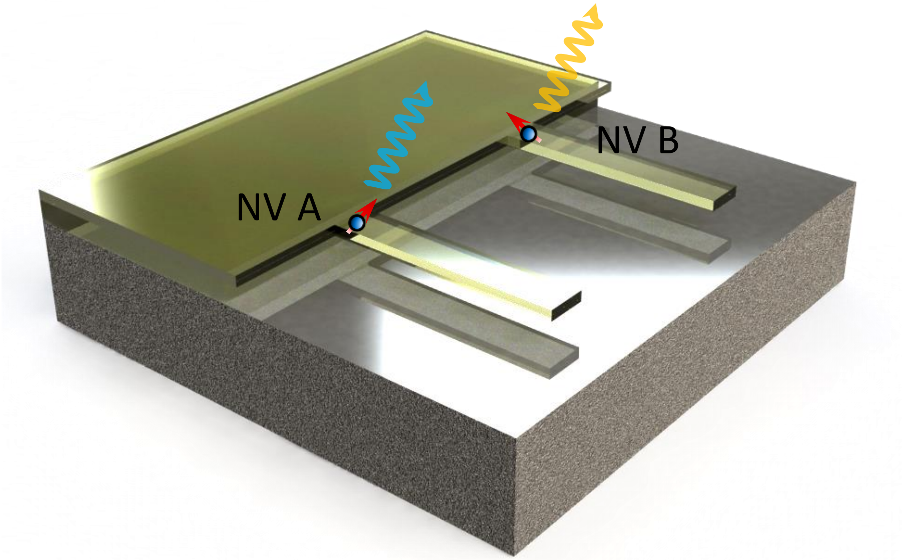
$$d_{\perp} = 21.5 \pm 0.8 \text{ GHz/strain}$$

P. Ovartchaiyapong *et al.*, Nat. Comm. (2014)



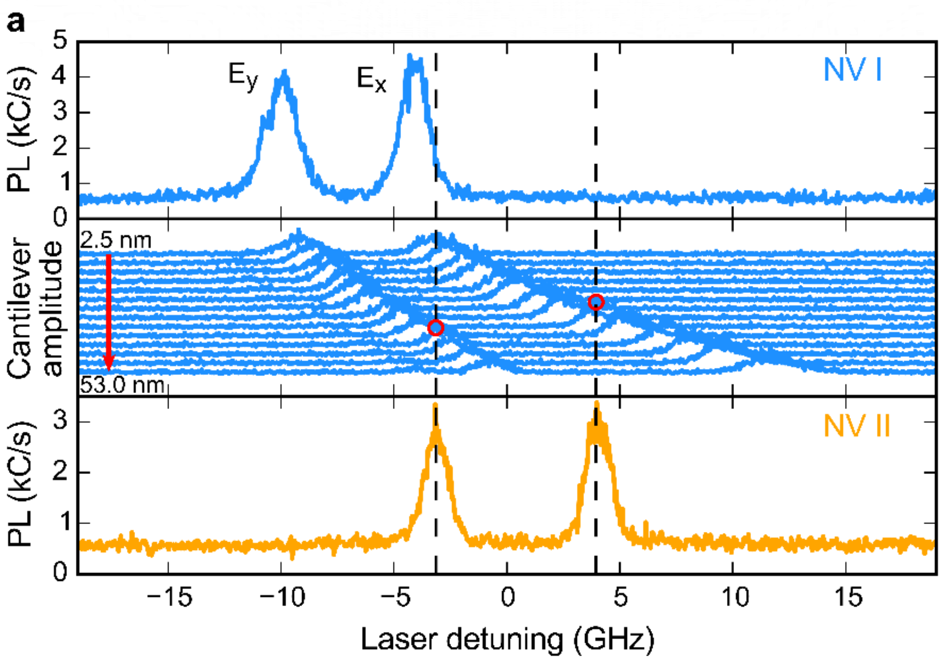


Application #1: strain-controlled of NV's spin and optical states

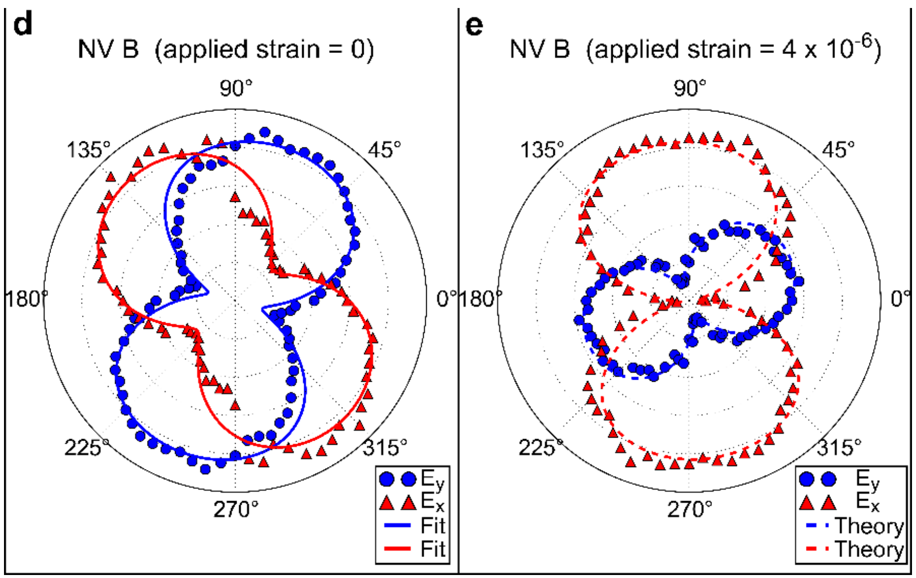


- Indistinguishable single photon source
- Energy and polarization matching

<u>Energy matching</u>

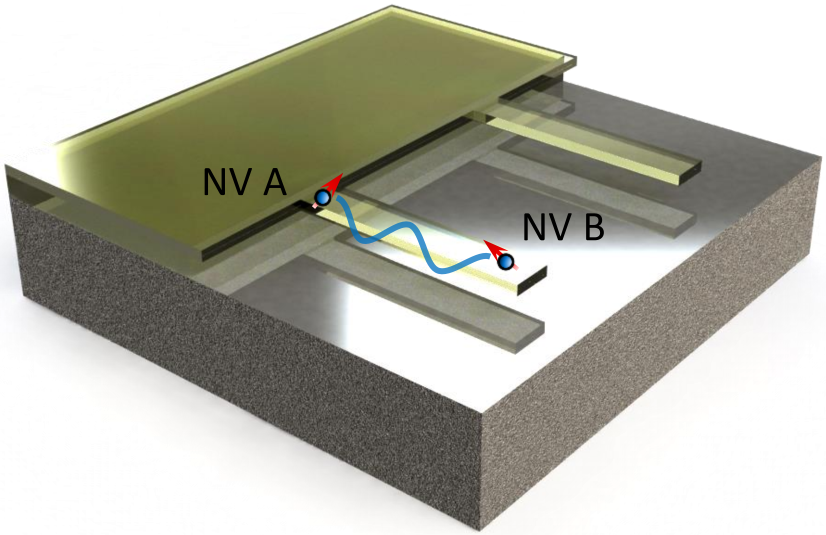


<u>Polarization matching</u>



K. Lee *et al.*, PR Applied (2016)

Application #2: strain-mediated spin-spin interactions

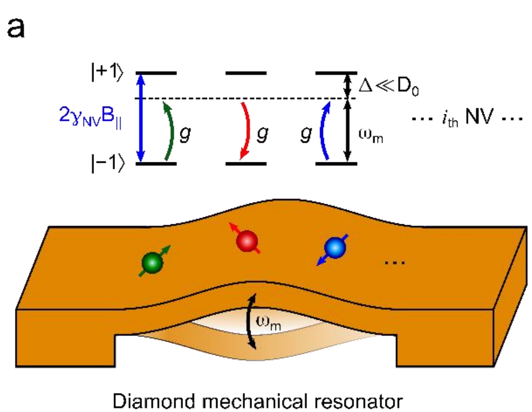


Strain-mediated long range interactions

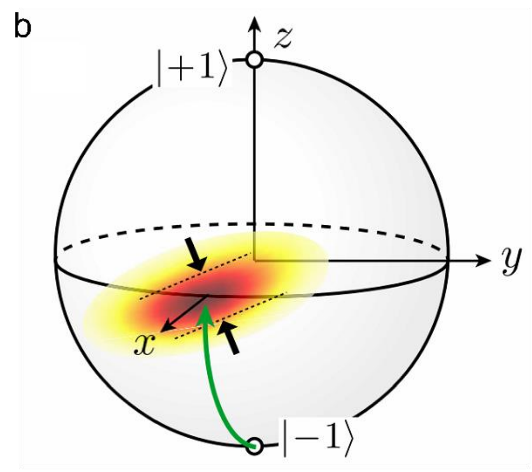
$$H_{int} = \lambda(\sigma_A{}^{+}\sigma_B{}^{-} + \sigma_A{}^{-}\sigma_B{}^{+})$$
$$\lambda = 2{g_\perp}^2/\Delta$$

For quantum regime, require high cooperativity:

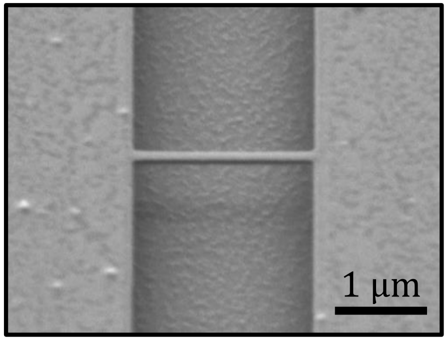
$$\eta = 2\pi \frac{{g_\perp}^2 T_2 Q}{\omega_m \bar{n}} > 1$$



D. Lee *et al.*, JOP (2017)



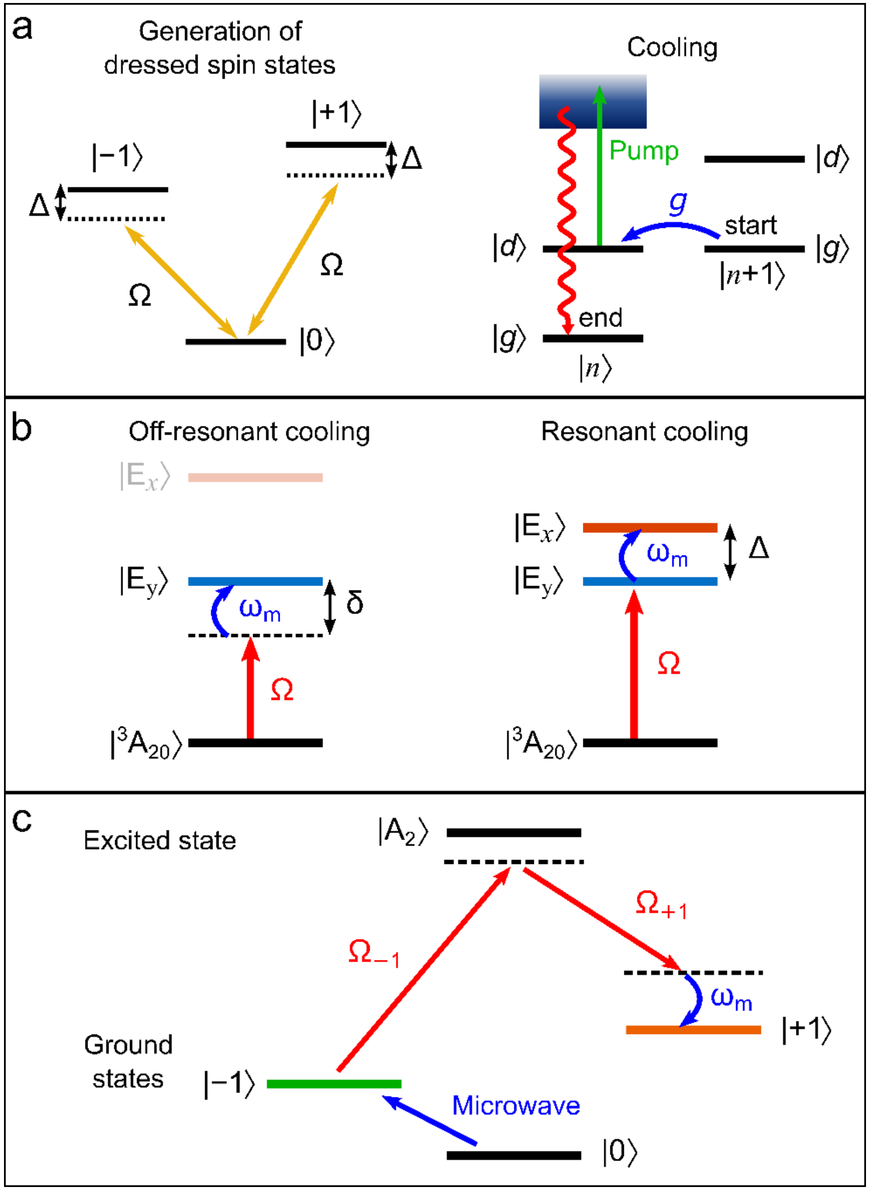
S. Bennett *et al.*, PRL (2013)



System parameters:
- 2 μm × 100 nm × 50 nm
- $\omega_m \approx$ 240 MHz
- Q = 10^6
- T = 100 mK
- T_2 = 100 ms

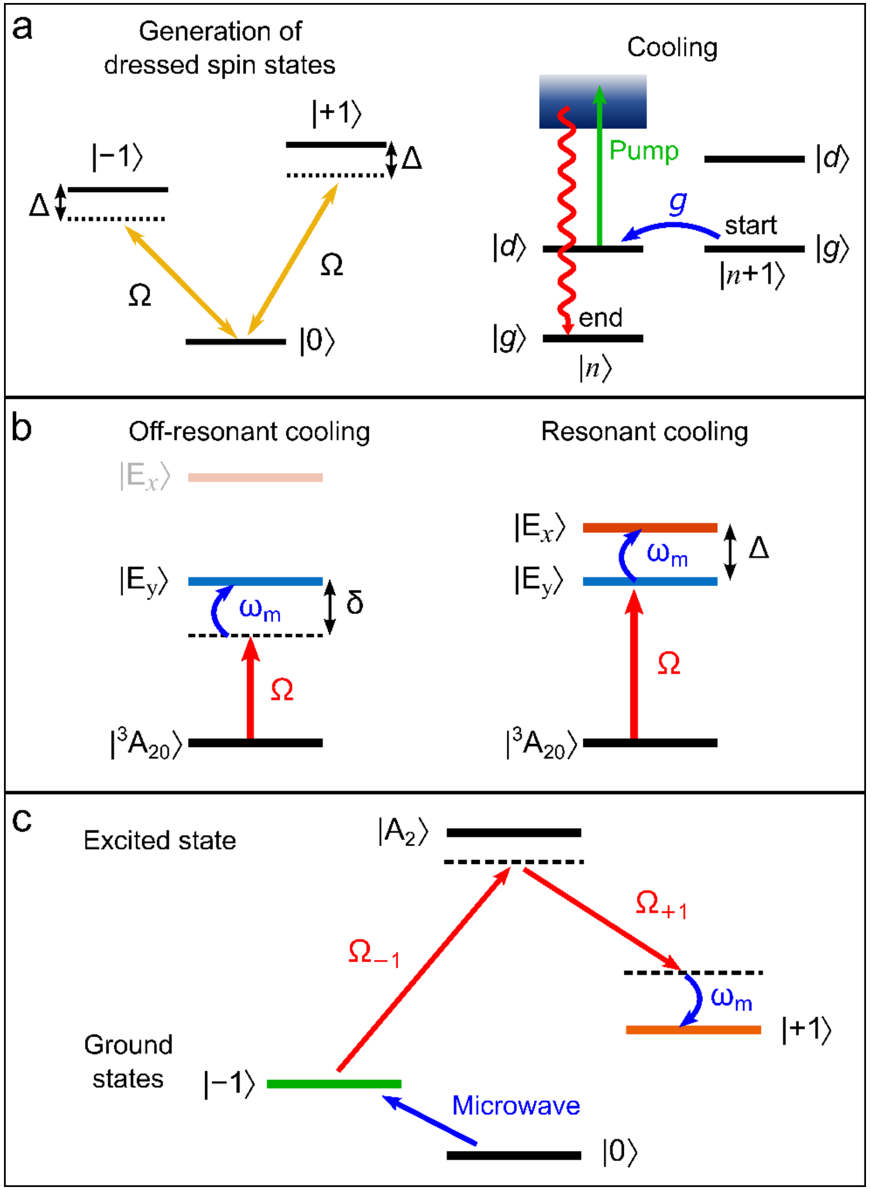
$\boxed{\eta = 1.9}$

Application #3: strain-controlled phonon cooling and lasing



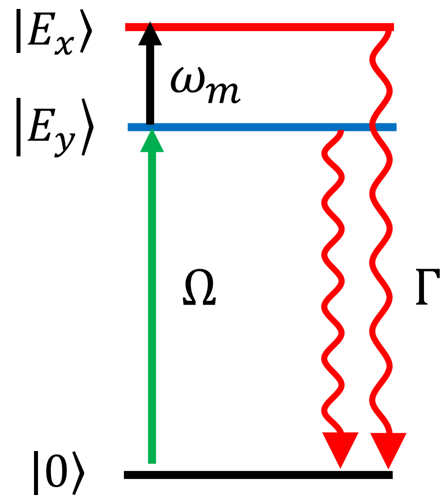
D. Lee *et al.*, JOP (2017)

Application #3: strain-controlled phonon cooling and lasing



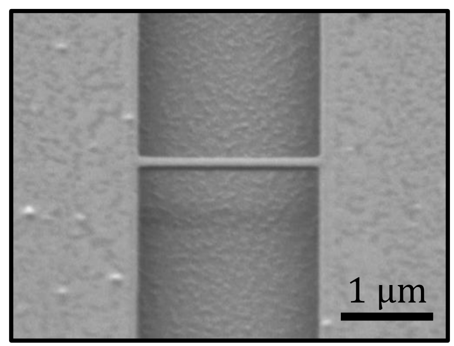
D. Lee *et al.*, JOP (2017)

Resonant cooling



$$\tilde{\Gamma}_{cooling} \approx \frac{\lambda_{\perp}^{2}}{\Gamma}\frac{4\Omega^2}{\Gamma^2}$$

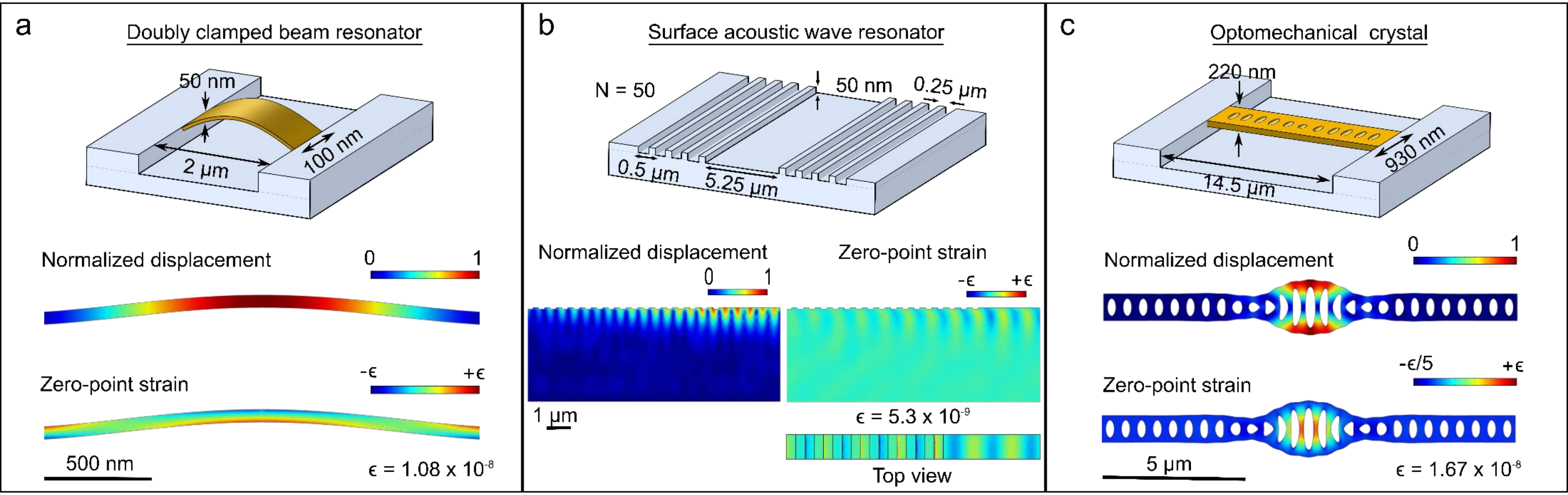
K. Kepesidis *et al.*, PRB (2013)



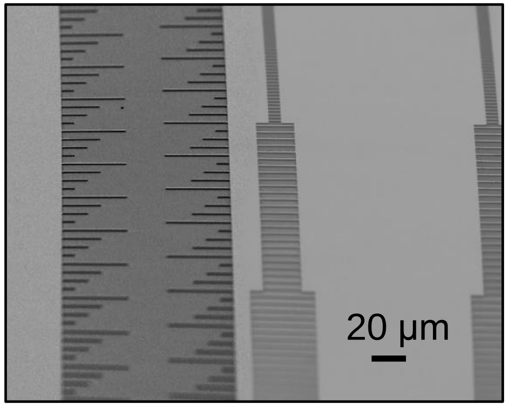
- 2 µm × 100 nm × 50 nm
- $\omega_m \approx$ 1 GHz
- Q = 10^5
- T = 4 K
- Ω = 100 MHz
- Γ = 100 MHz

$\boxed{\bar{n} = 0.4}$

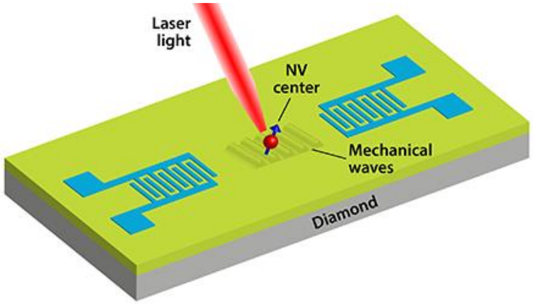
Application #3: strain-controlled phonon cooling and lasing



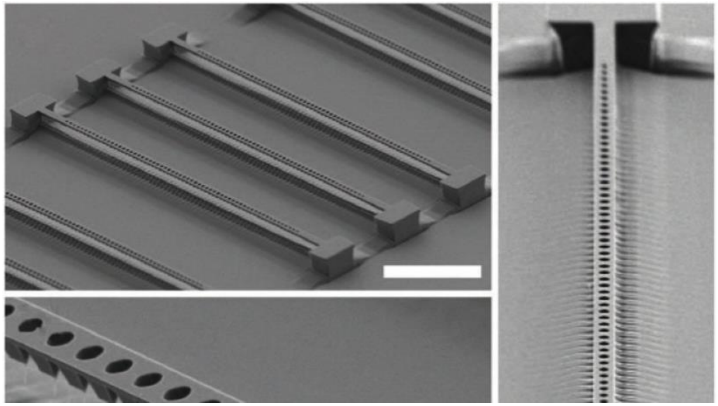
D. Lee *et al.*, JOP (2017)



UCSB (unpublished)



D. Golter *et al.*, PRL (2016)



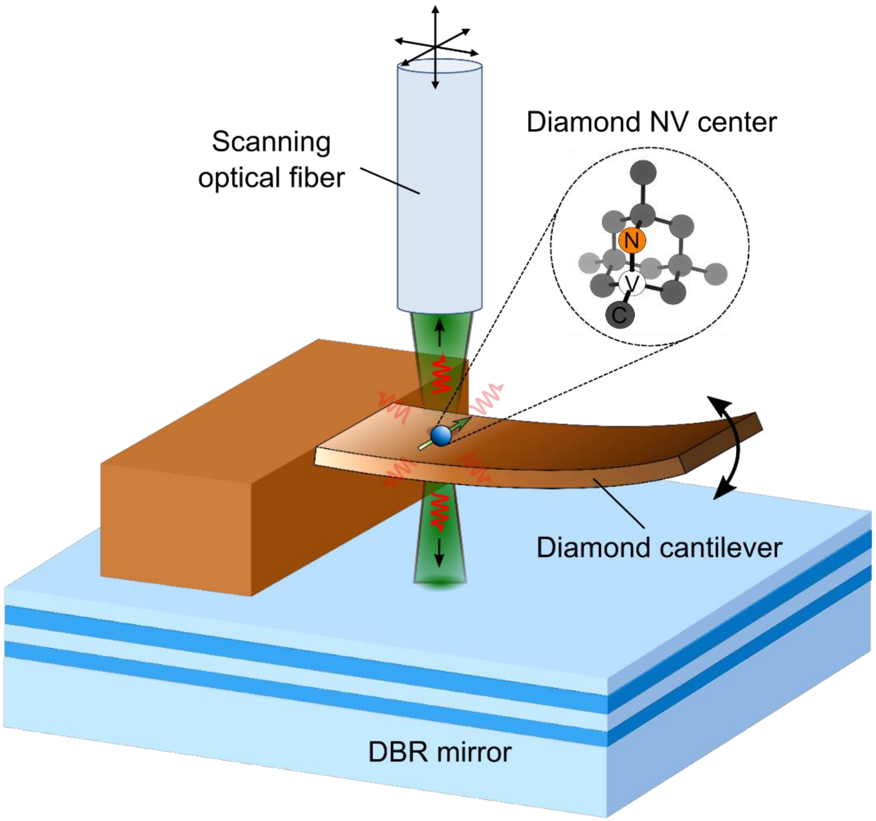
M. Burek *et al.*, Optica (2016)

Summary

- Phonon met photon : cavity optomechanics
- Phonon met spin : diamond hybrid quantum systems

<u>Research at KU</u>

Phonon met photon and spin



Acknowledgement

Cavity optomechanics work

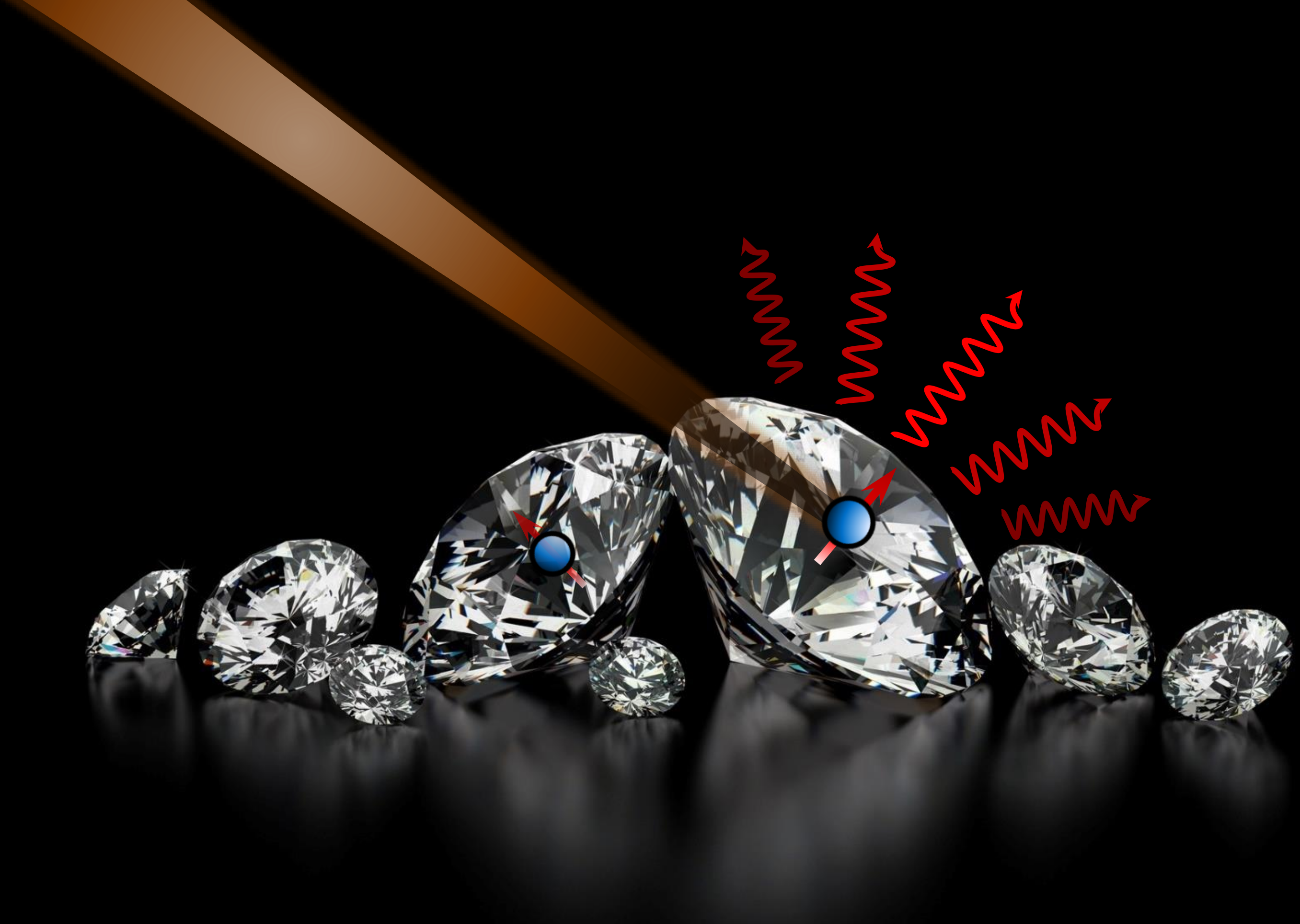
Prof. Jack Harris group at Yale Univ.

Diamond work

Prof. Ania Jayich group at UCSB

Team at Korea Univ.

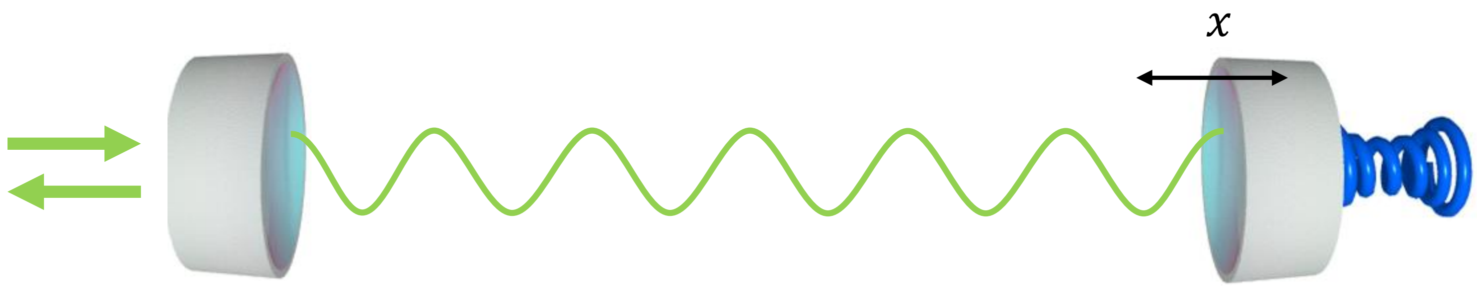
오주언, Mohan Mathpal, 최순욱,
이명원, 윤정배, 박윤석, 변남혁



Thank you!

Extra slides

Single mode cavity optomechanics



Cavity mode
$\hat{a}, \omega_c$

Mechanical mode
$\hat{b}, \omega_m$

Single mode Hamiltonian

$$\hat{H} = \underbrace{\hbar\omega_c(x)\hat{a}^\dagger\hat{a}}_{\textit{Cavity mode}} + \underbrace{\hbar\omega_m\hat{b}^\dagger\hat{b}}_{\textit{Mechanical mode}} + \cdots$$

$$\hat{x} = x_{zpf}(\hat{b} + \hat{b}^\dagger)$$

linear Interaction
$\omega_c(x) \propto \hat{x}$

$$\approx \hbar\omega_c\hat{a}^\dagger\hat{a} + \hbar\omega_m\hat{b}^\dagger\hat{b} + \hbar g\hat{a}^\dagger\hat{a}(\hat{b} + \hat{b}^\dagger) + \cdots$$

Recent progress based on single mode optomechanics:

- Mechanical ground state (UCSB, JILA/NIST, Caltech, Yale)
- Entangled with qubits, photons (UCSB, JILA/NIST)
- Radiation pressure shot noise, squeezed light (Caltech, Berkeley, JILA, Yale)
- Back action evasion measurement (Caltech, JILA/NIST)

Multi-mode optomechanics

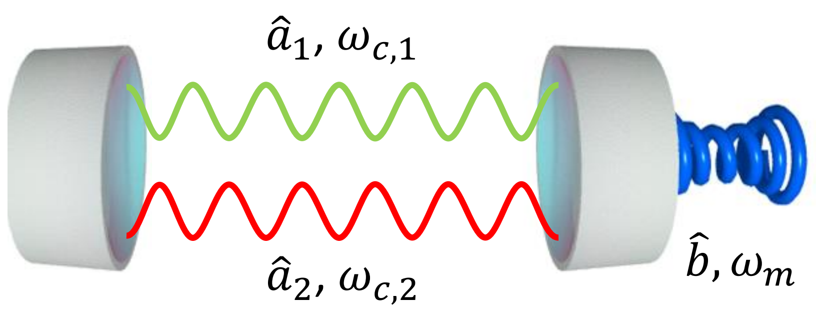
Multi-mode Hamiltonian

$$\hat{H} = \sum_k \hbar\omega_{c,k}\hat{a}_k{}^{\dagger}\hat{a}_k + \sum_j \hbar\omega_{m,j}\hat{b}_j{}^{\dagger}\hat{b}_j + \hbar\sum_{j,k,l} g^j_{kl}\hat{a}_k{}^{\dagger}\hat{a}_l\left(\hat{b}_j + \hat{b}_j{}^{\dagger}\right) + \cdots$$

Why multi-mode ?

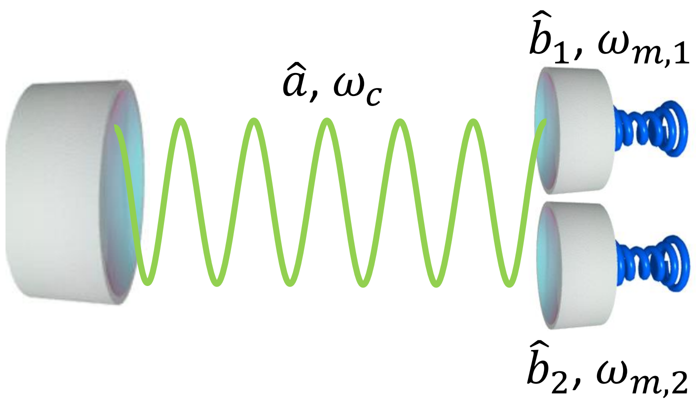
- Enhanced displacement sensitivity
- Energy transfer between modes
- Non-linear dynamics, hybridization, synchronization
- QND (quantum non-demolition) measurement
- Optomechanical arrays, circuits

Two cavity modes + a mechanical mode



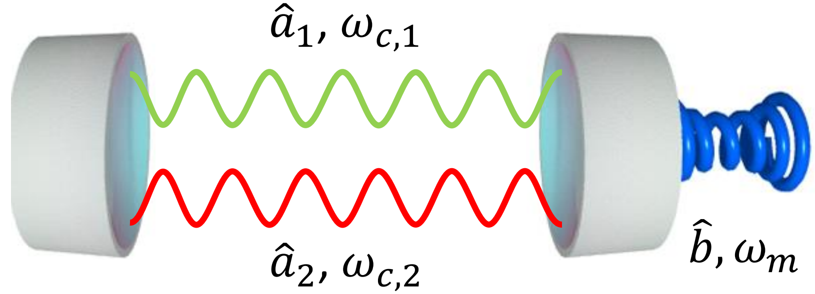
- QND measurement of phonons, photons

Two mechanical modes + a cavity mode



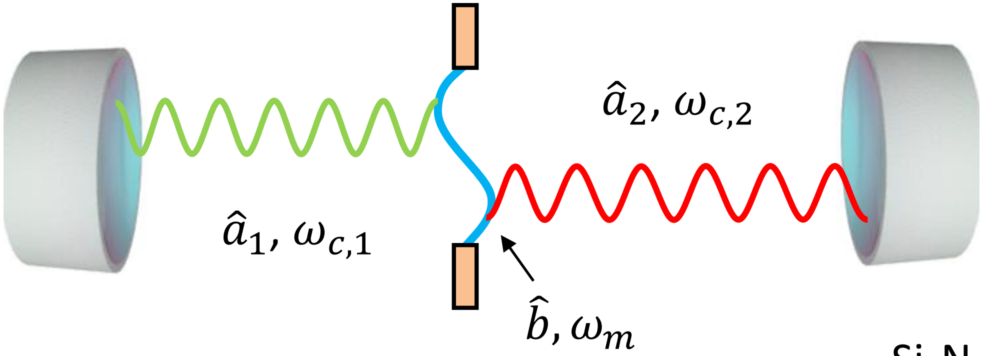
- Topological energy transfer via EPs

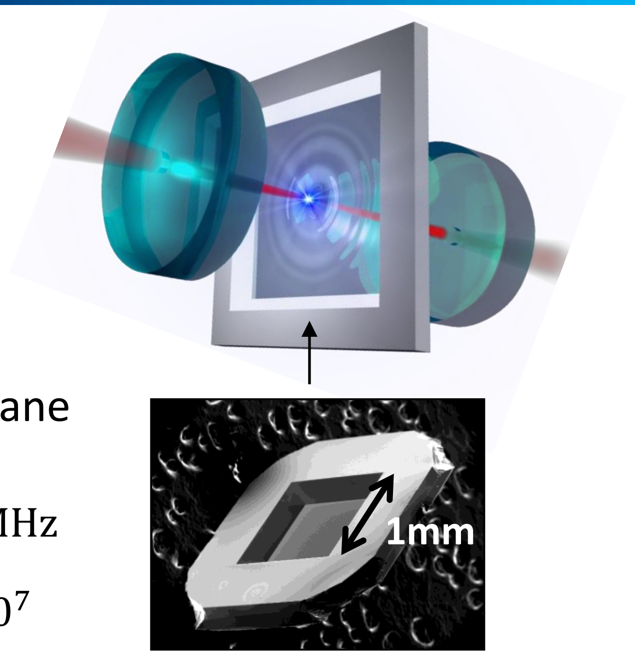
Two cavity modes + a mechanical mode



- QND measurement of phonons, photons

Two cavity modes + a mechanical mode



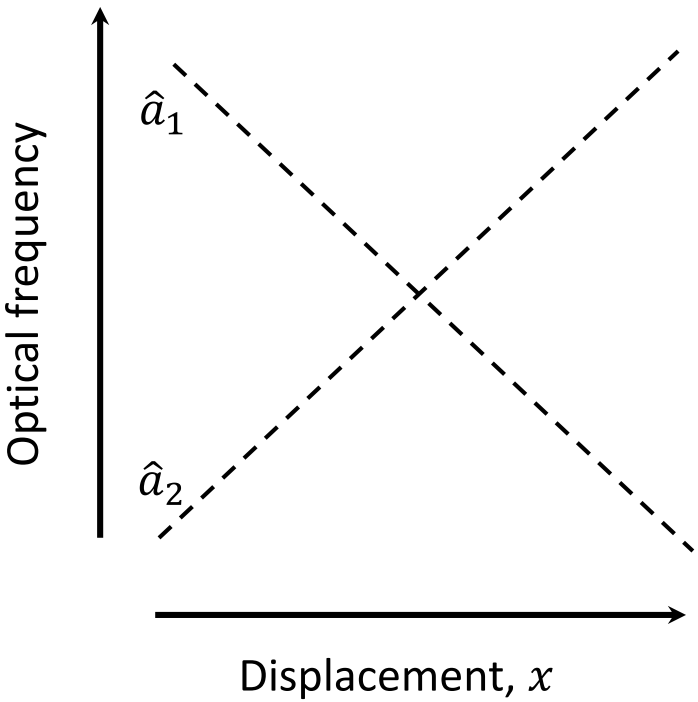


$\mathrm{Si_3N_4}$ membrane

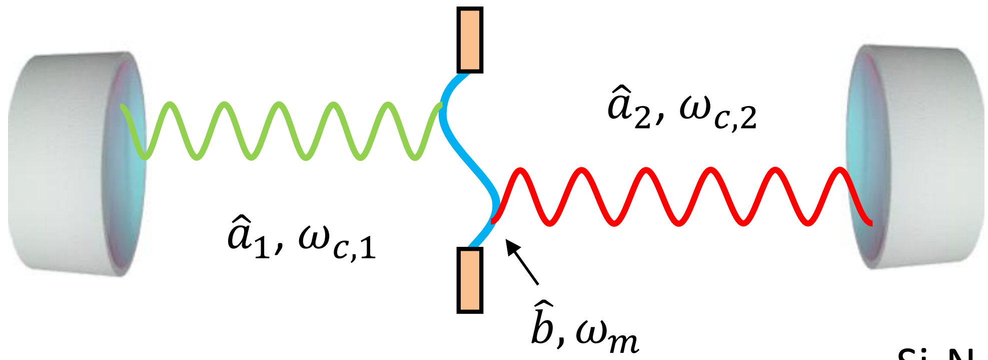
$\omega_m/2\pi =$
$100s$ kHz ~ MHz

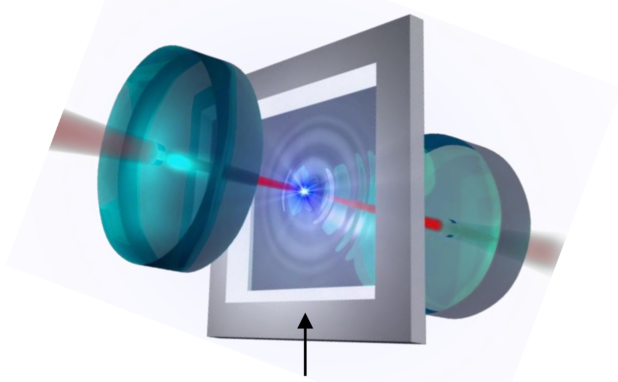
$Q = 10^6 \sim 10^7$

J. D. Thompson *et al.*, *Nature* (2008)



Two cavity modes + a mechanical mode

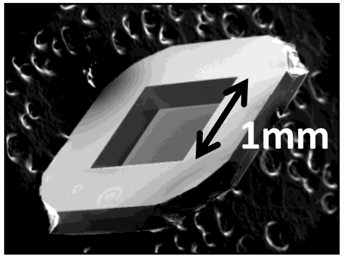




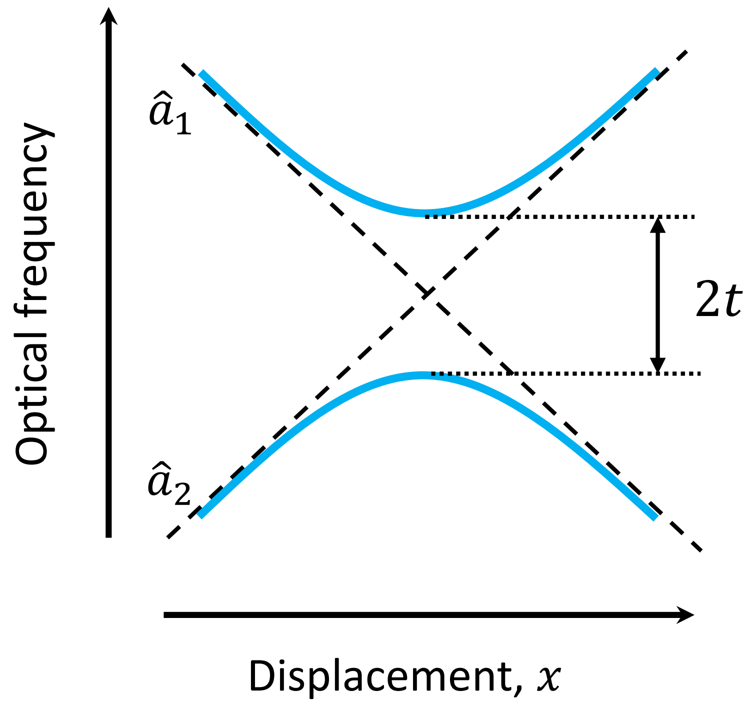
Si$_3$N$_4$ membrane

$\omega_m/2\pi =$
$100s$ kHz $\sim$ MHz

$Q = 10^6 \sim 10^7$



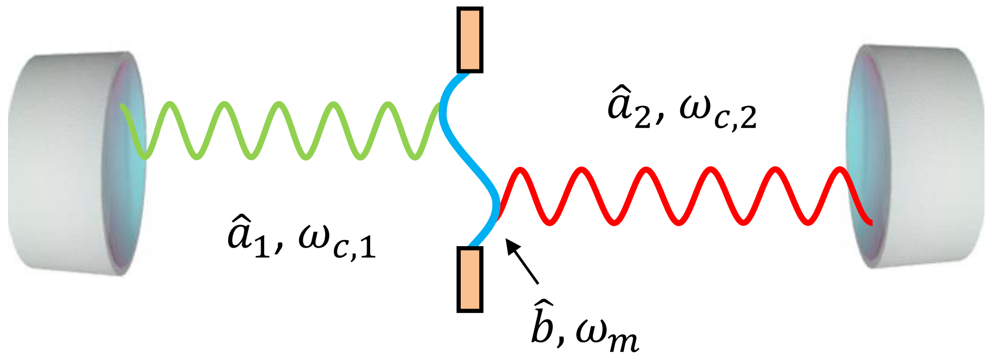
J. D. Thompson *et al.*, *Nature* (2008)

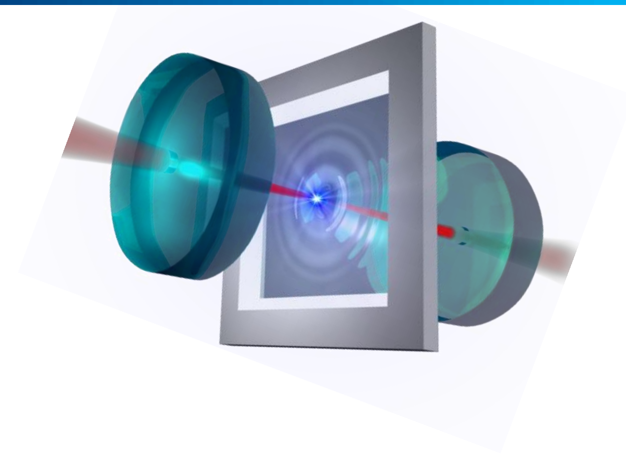


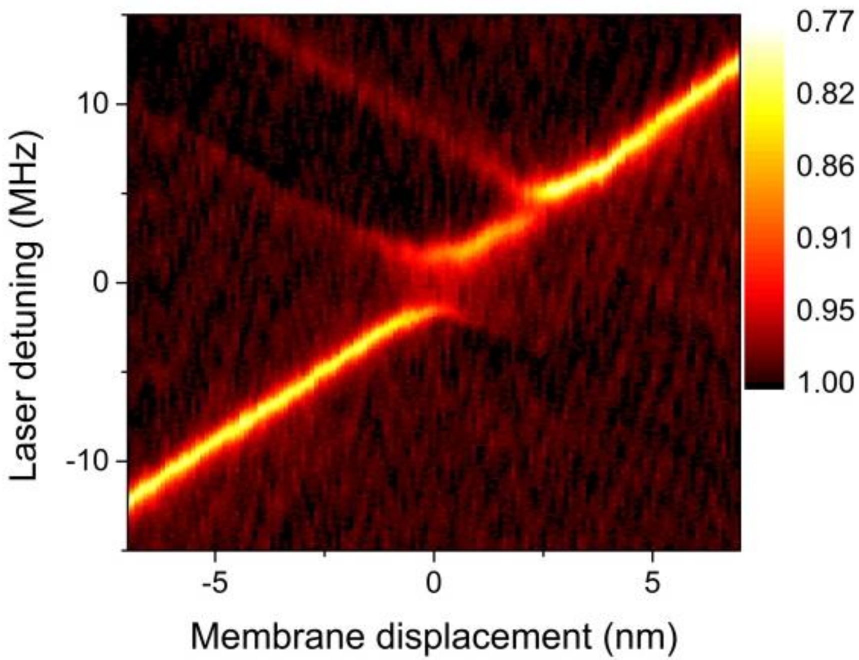
$$\hat{H} = \vec{a}^\dagger \boldsymbol{M} \vec{a} + \hbar\omega_m \hat{b}^\dagger \hat{b} + \cdots$$

$$\boldsymbol{M} = \begin{pmatrix} \omega_{c,1} + g_1 x & t e^{i\phi} \\ t e^{-i\phi} & \omega_{c,2} + g_2 x \end{pmatrix}, \vec{a} = \begin{pmatrix} \hat{a}_1 \\ \hat{a}_2 \end{pmatrix}$$

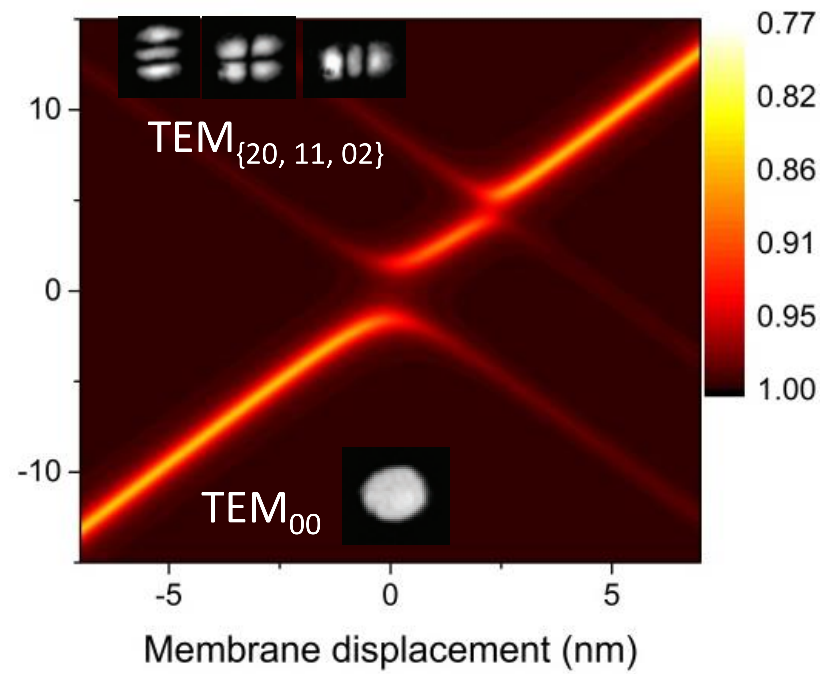
Two cavity modes + a mechanical mode





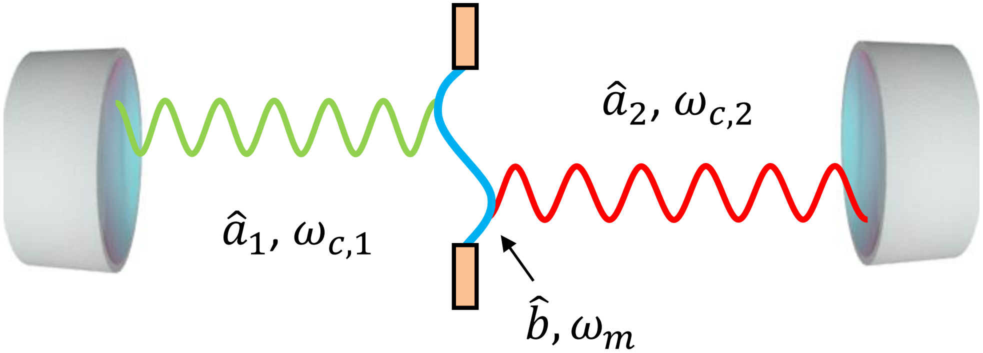


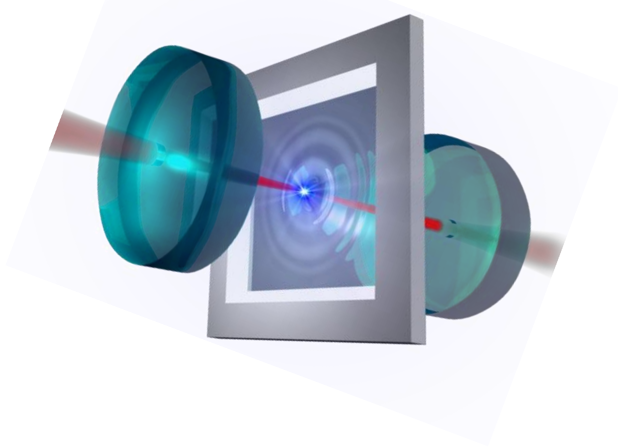
Theory plot

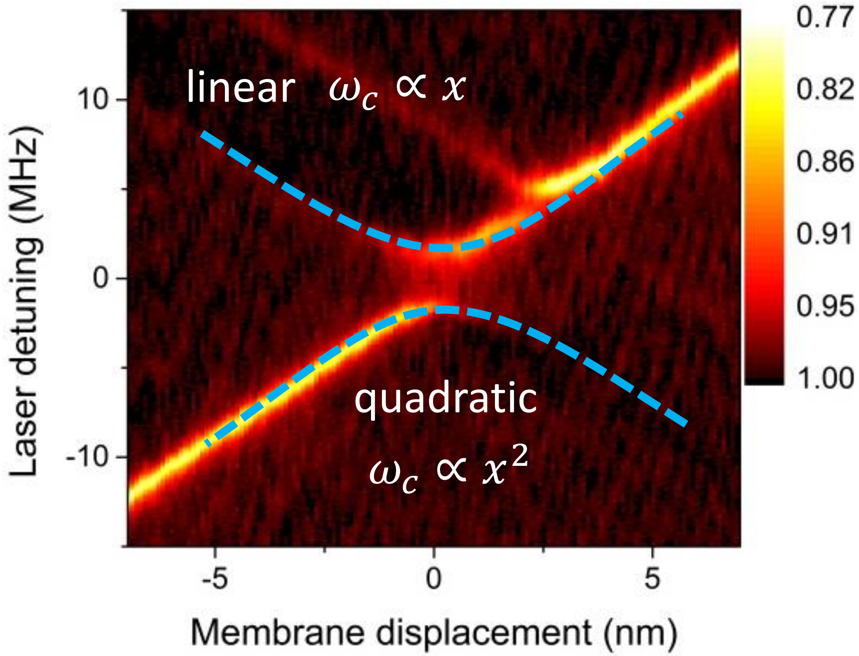


D. Lee et al., Nature Comm. 6, 6232 (2015)

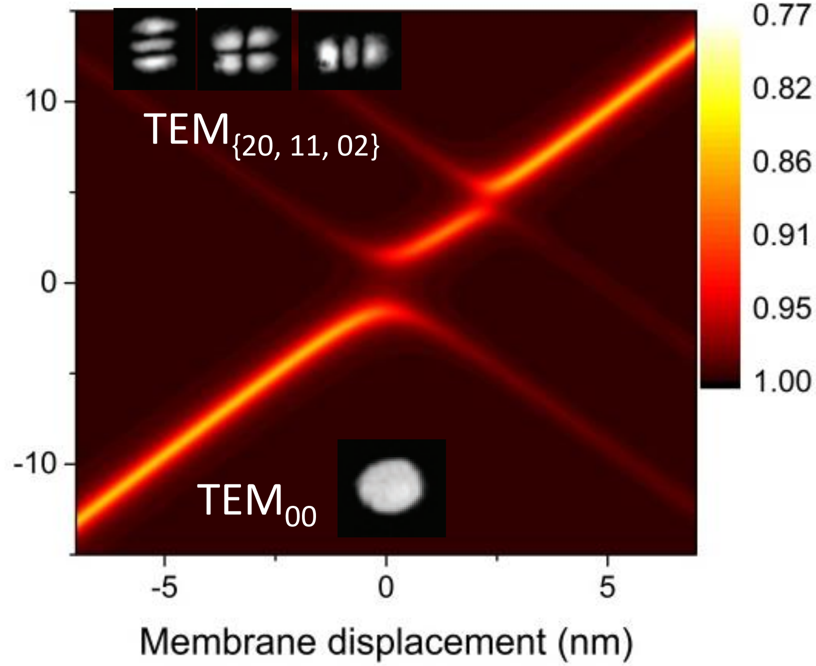
Two cavity modes + a mechanical mode





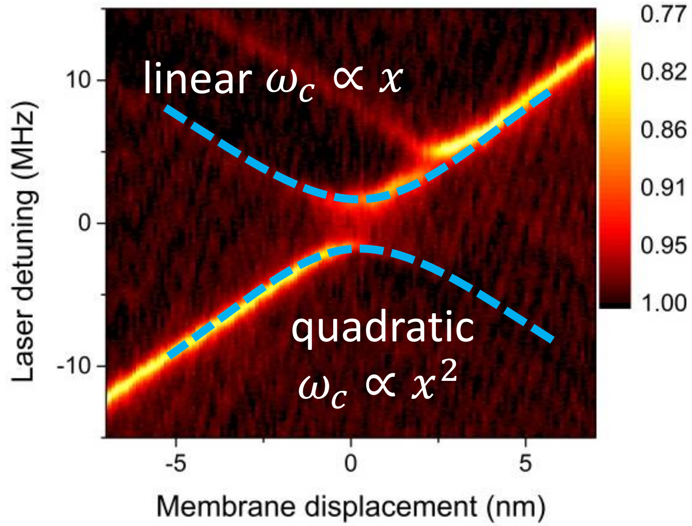


Theory plot



D. Lee et al., Nature Comm. 6, 6232 (2015)

Linear vs quadratic coupling



<u>Linear regime</u>

$$\hat{H} = \hbar\omega_c(x)\hat{a}^\dagger\hat{a} + \hbar\omega_m\hat{b}^\dagger\hat{b} + \cdots$$

$$\omega_c(x) \approx \omega_c + \frac{\partial\omega_c}{\partial x}\hat{x}$$

$$\hat{H} \approx \hbar\omega_c\hat{a}^\dagger\hat{a} + \hbar\omega_m\hat{b}^\dagger\hat{b}$$
$$+\hbar g\hat{a}^\dagger\hat{a}(\hat{b} + \hat{b}^\dagger) + \cdots$$

$[\hat{H}, \hat{b}^\dagger\hat{b}] \neq 0$ Backaction

<u>Quadratic regime</u>

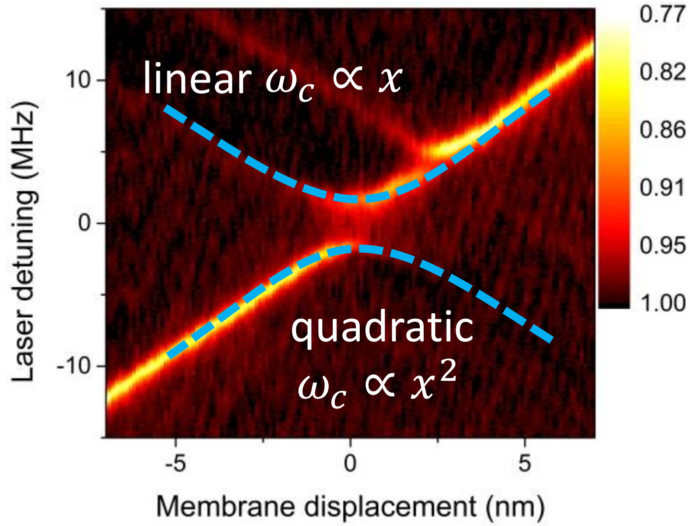
$$\hat{H} = \hbar\omega_c(x)\hat{a}^\dagger\hat{a} + \hbar\omega_m\hat{b}^\dagger\hat{b} + \cdots$$

$$\omega_c(x) \approx \omega_c + \frac{1}{2}\frac{\partial^2\omega_c}{\partial x^2}\hat{x}^2$$

$$\hat{H} \approx \hbar\omega_c\hat{a}^\dagger\hat{a} + \hbar\omega_m\hat{b}^\dagger\hat{b}$$
$$+\hbar g\hat{a}^\dagger\hat{a}\hat{b}^\dagger\hat{b} + \cdots$$

$[\hat{H}, \hat{b}^\dagger\hat{b}] = 0$ QND measurement

Linear vs quadratic coupling



$$\hat{H} = \hbar(\underline{\omega_c + g_2\hat{b}^\dagger\hat{b}})\hat{a}^\dagger\hat{a} + \hbar\omega_m\hat{b}^\dagger\hat{b} + \cdots$$

- Shift-per-phonon
- Quantum jumps of phonon

$$\hat{H} = \hbar\omega_c\hat{a}^\dagger\hat{a} + \hbar(\underline{\omega_m + g_2\hat{a}^\dagger\hat{a}})\hat{b}^\dagger\hat{b} + \cdots$$

- Shift-per-photon
- Quantum jumps of photon

<u>Quadratic regime</u>

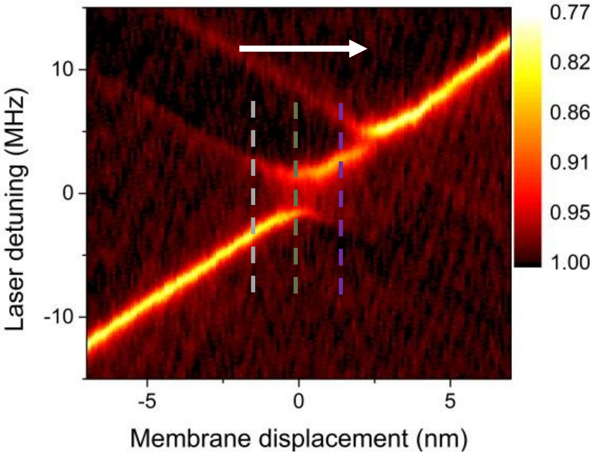
$$\hat{H} = \hbar\omega_c(x)\hat{a}^\dagger\hat{a} + \hbar\omega_m\hat{b}^\dagger\hat{b} + \cdots$$

$$\omega_c(x) \approx \omega_c + \frac{1}{2}\frac{\partial^2\omega_c}{\partial x^2}\hat{x}^2$$

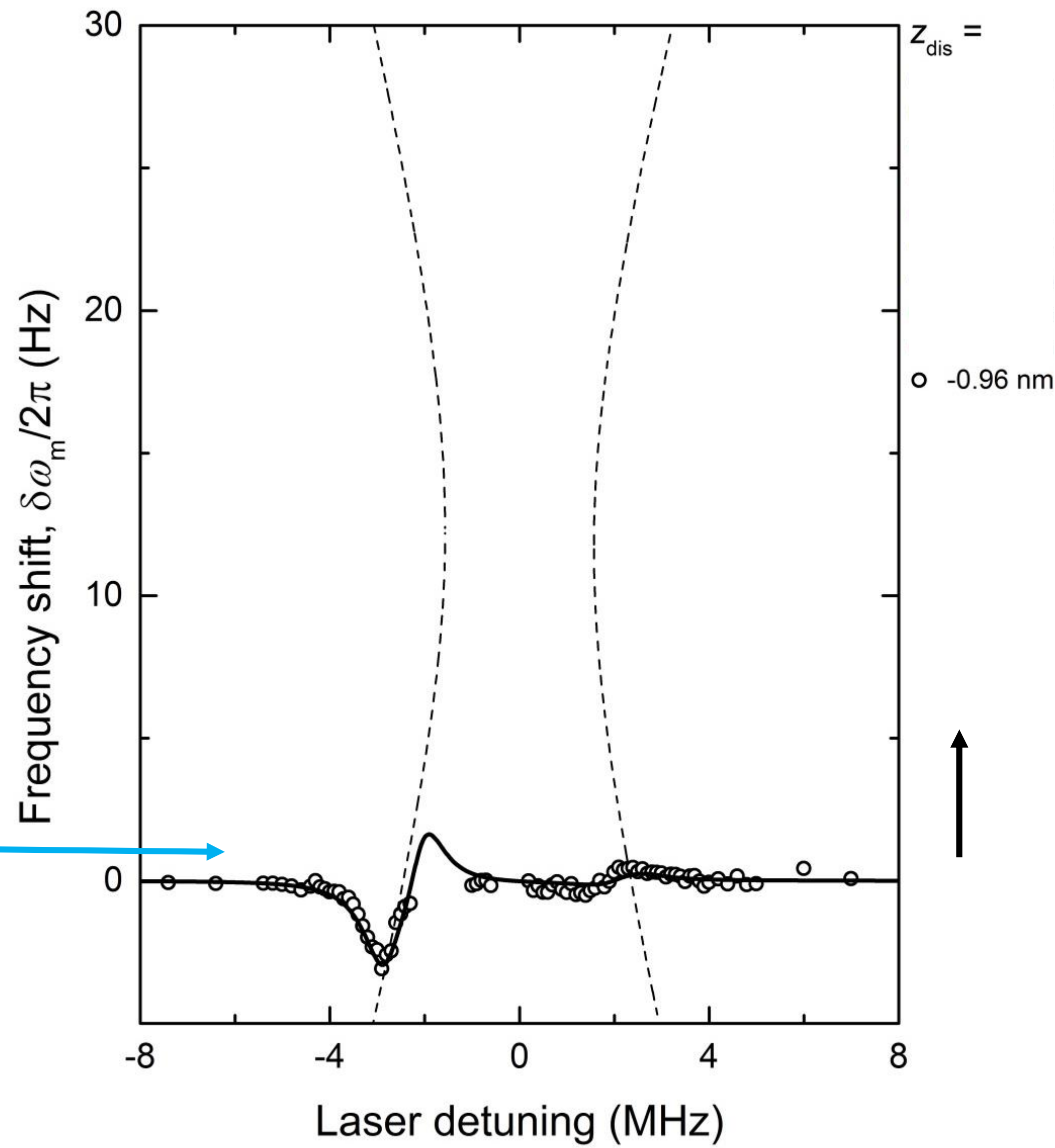
$$\hat{H} \approx \hbar\omega_c\hat{a}^\dagger\hat{a} + \hbar\omega_m\hat{b}^\dagger\hat{b}$$
$$+\hbar g\hat{a}^\dagger\hat{a}\hat{b}^\dagger\hat{b} + \cdots$$

$$\boxed{[\hat{H}, \hat{b}^\dagger\hat{b}] = 0 \qquad \text{QND measurement}}$$

Dynamics of linear vs quadratic coupling



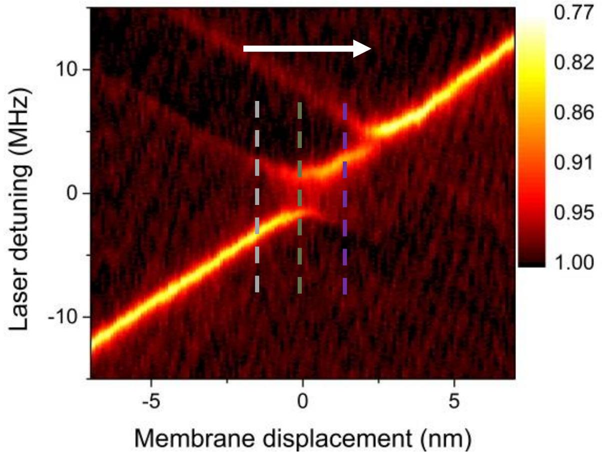
Optical spring effect



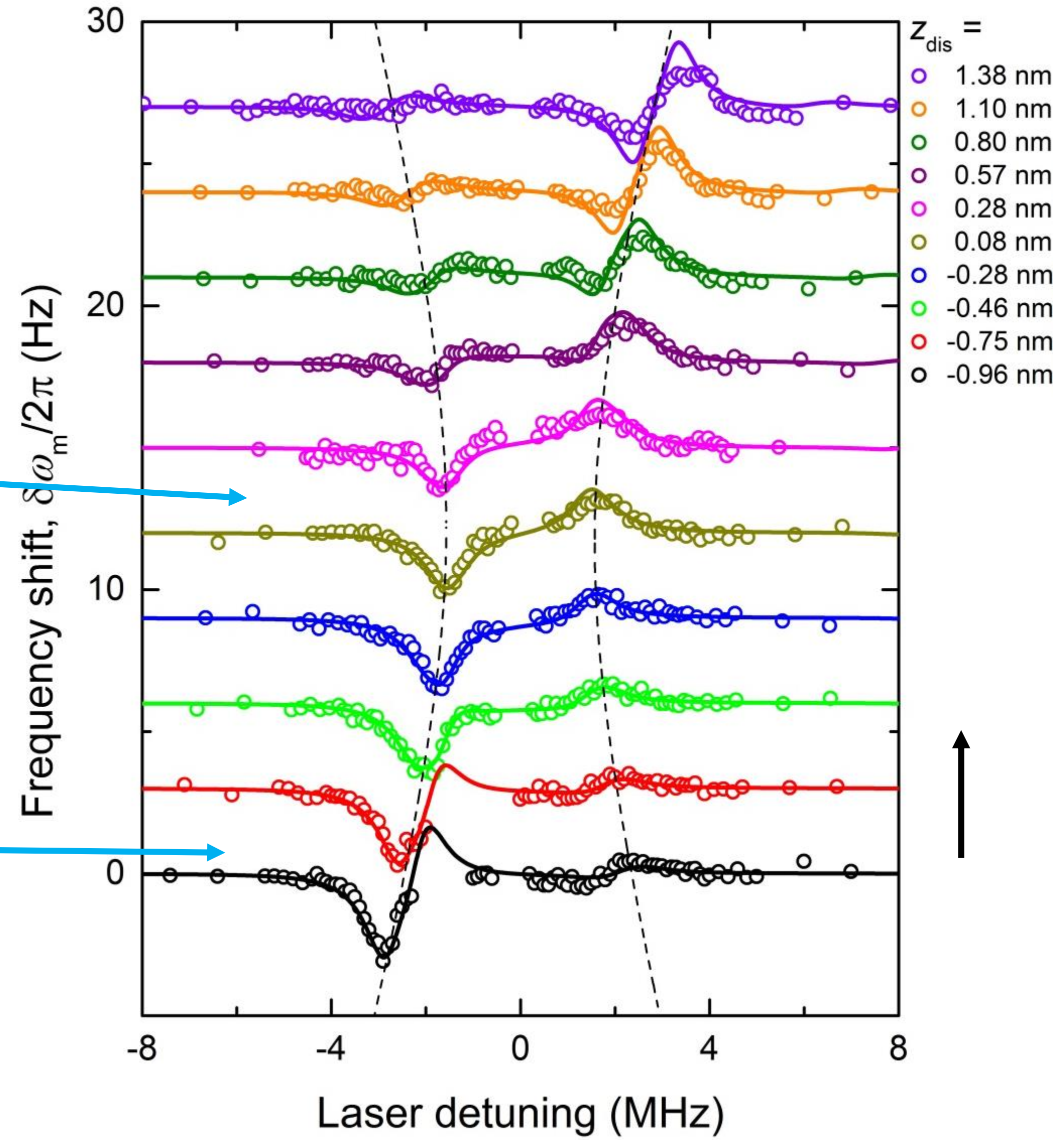
Linear regime

- Shape: derivative of Lorentzian
- Odd symmetry about the cavity resonance

Dynamics of linear vs quadratic coupling



Optical spring effect



Quadratic regime

- Shape: Lorentzian
- Even symmetry about the cavity resonance

$$\hat{H} = \hbar(\underline{\omega_c + g_2\hat{b}^\dagger\hat{b}})\hat{a}^\dagger\,\hat{a} + \hbar\omega_m\hat{b}^\dagger\hat{b} + \cdots$$

Linear regime

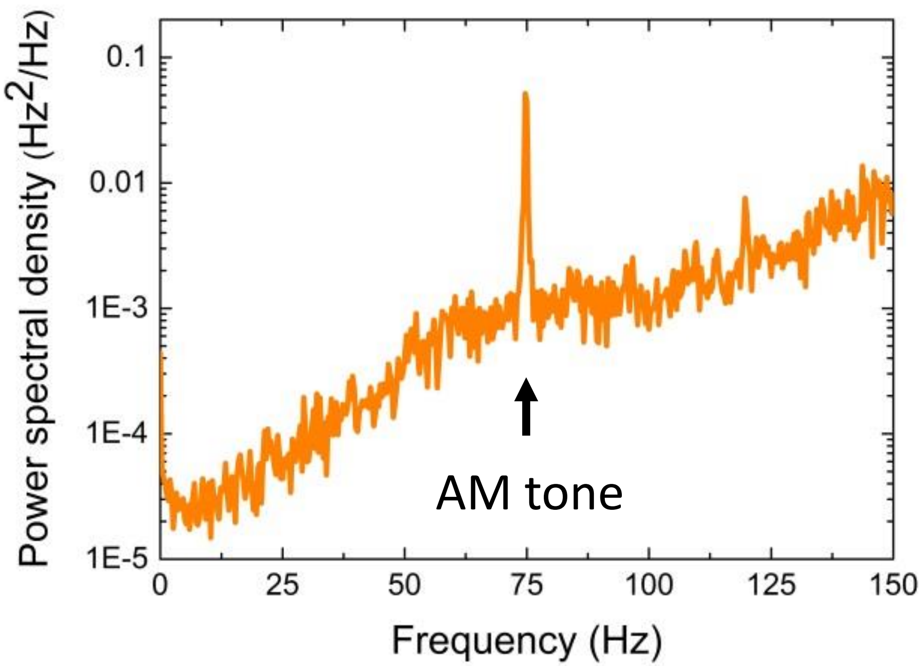
- Shape: derivative of Lorentzian
- Odd symmetry about the cavity resonance

Classical version of QND of photons

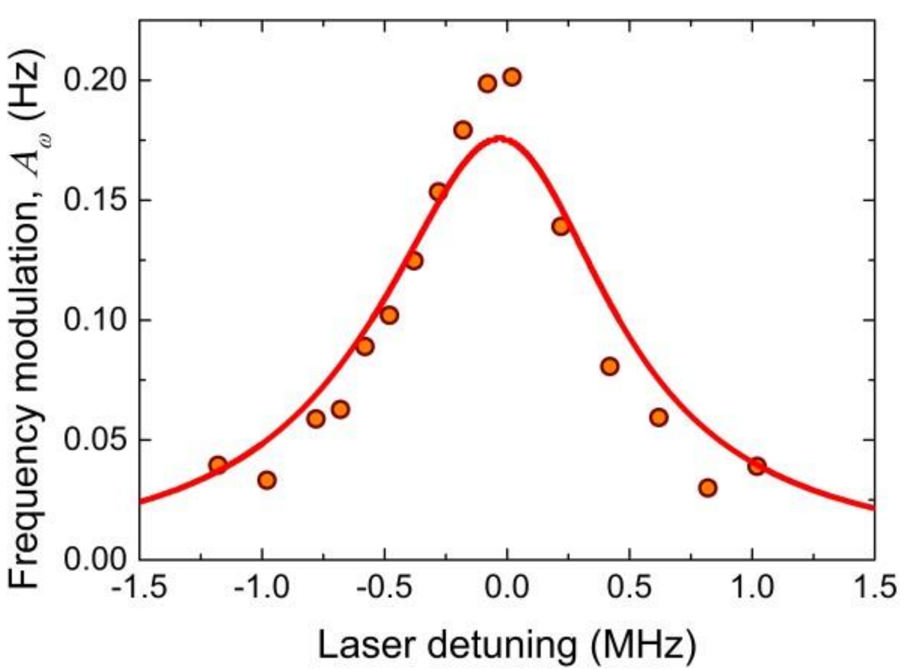
$$\hat{H} = \hbar\omega_c \hat{a}^\dagger \hat{a} + \hbar(\omega_m + g_2 \underbrace{\hat{a}^\dagger \hat{a}}_{= \bar{a} + \underline{\hat{d}}})\hat{b}^\dagger \hat{b}$$

- *Real time measurement of photon fluctuations via quadratic optical spring*
- *Quantum version: QND of photons*

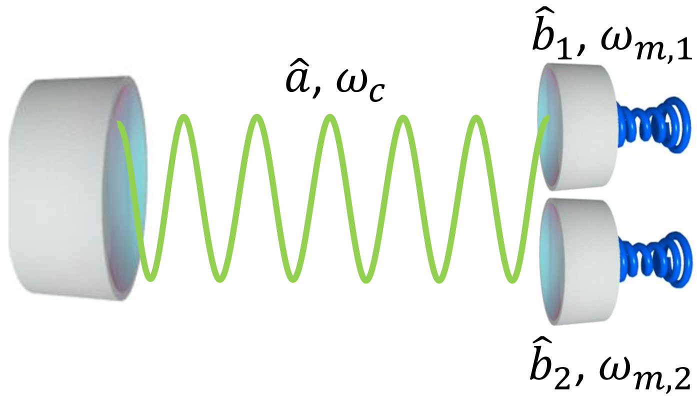
<u>*PSD of mechanical frequency*</u>



<u>*Quadratic coupling regime*</u>

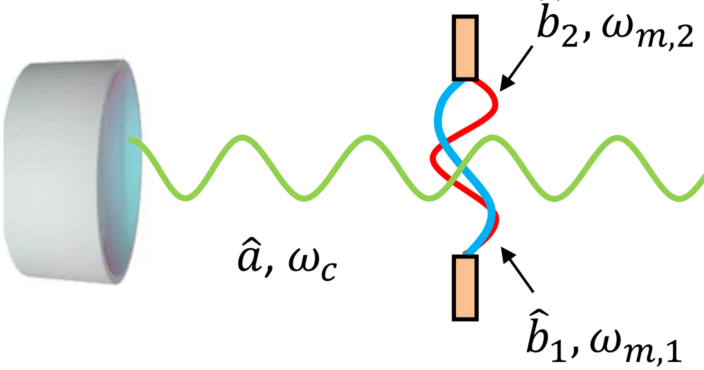


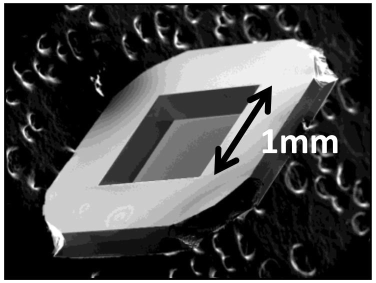
Two mechanical modes + a cavity mode



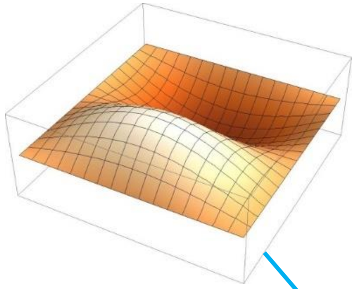
- Topological energy transfer via EPs

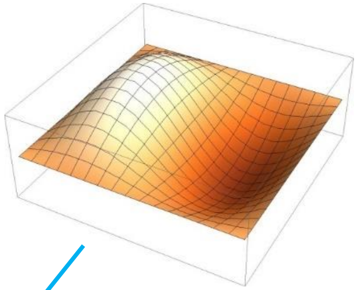
Two mechanical modes + a cavity mode



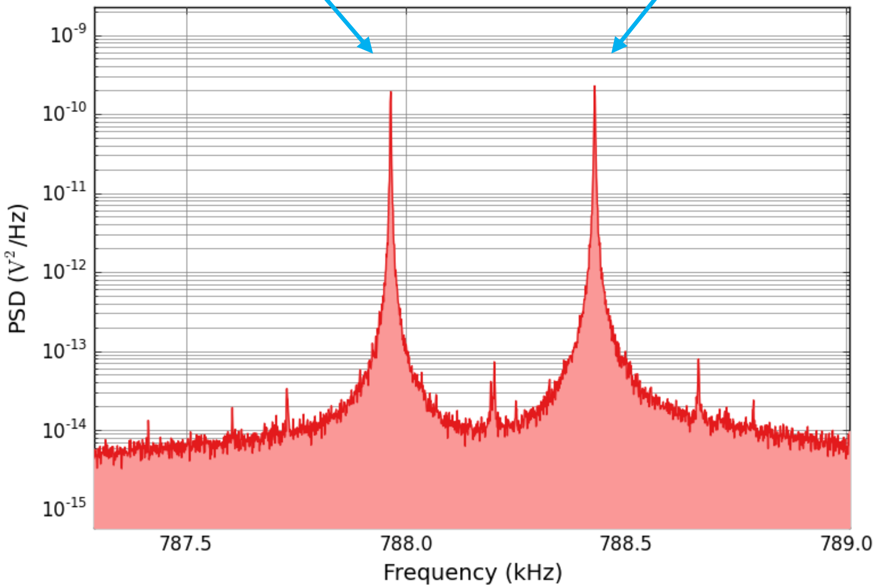


Nearly degenerate mechanical modes





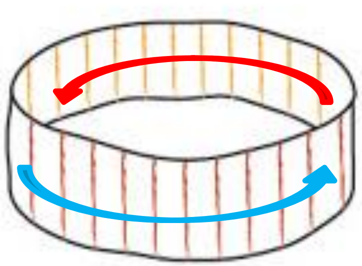
$\omega_{m,1}/2\pi = 788.024 \text{ kHz}$



$\omega_{m,2}/2\pi = 788.487 \text{ kHz}$

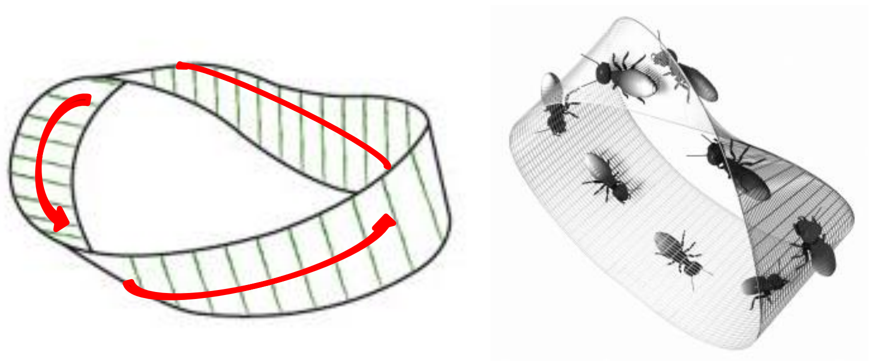
Topological energy transfer via exceptional points

<u>Two topological states without EPs</u>



- Adiabatic passage leads to original state

<u>Two topological states with EPs</u>



- Adiabatic passage leads to other state
- Topological energy transfer is possible between two states via EPs

<u>Multi-mode optomechanics with exceptional points</u>

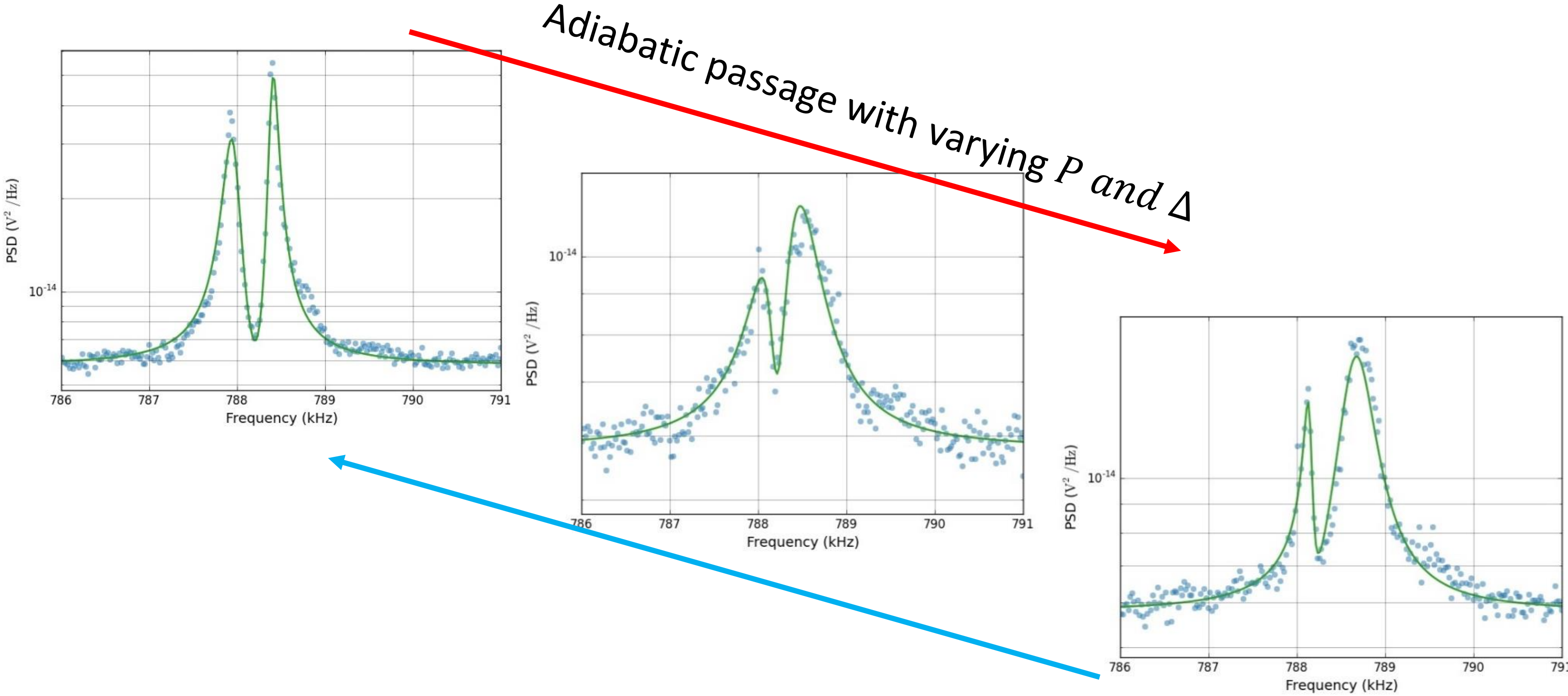
- Novel means of topological energy transfer between normal modes
- Novel dynamics with exceptional points e.g. thermal and quantum fluctuations

Adiabatic passage with varying P and Δ

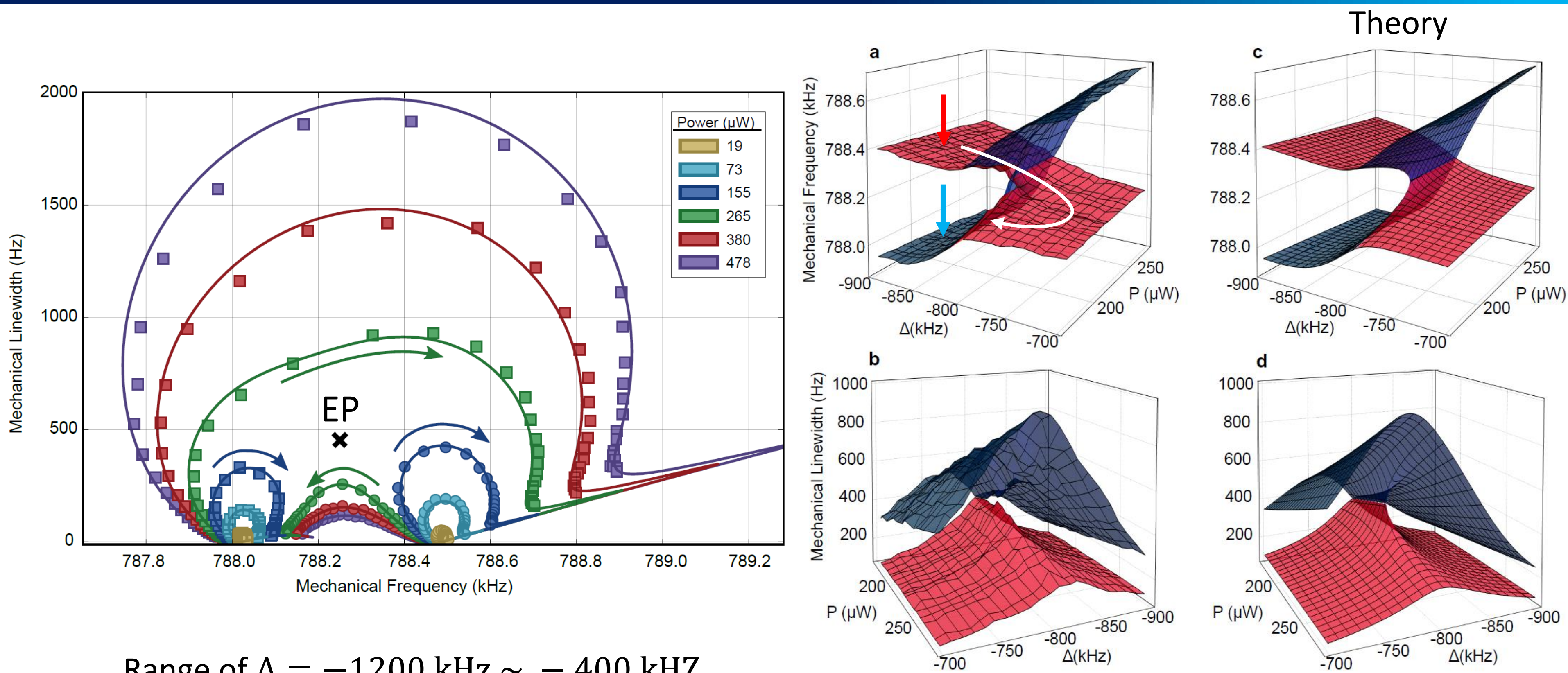
Equation of motion: $i\dot{\boldsymbol{B}}(t) = H\boldsymbol{B}(t)$ $\boldsymbol{B}(t) = \begin{pmatrix} b_1(t) \\ b_2(t) \end{pmatrix}$

$$H = \begin{pmatrix} \omega_{m,1} - \frac{i\gamma_1}{2} - ig_1^2\sigma & -ig_1g_2\sigma \\ -ig_1g_2\sigma & \omega_{m,2} - \frac{i\gamma_2}{2} - ig_2^2\sigma \end{pmatrix}$$

$\sigma(P,\Delta)$: complex mechanical susceptibility



Topological energy transfer via exceptional points

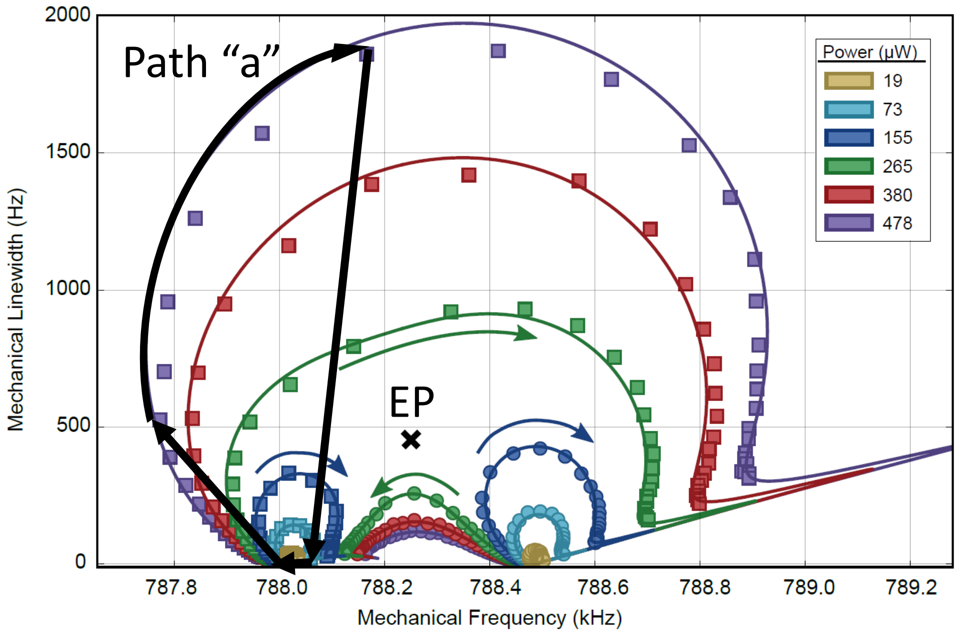


Range of $\Delta = -1200\ \mathrm{kHz} \sim -400\ \mathrm{kHZ}$

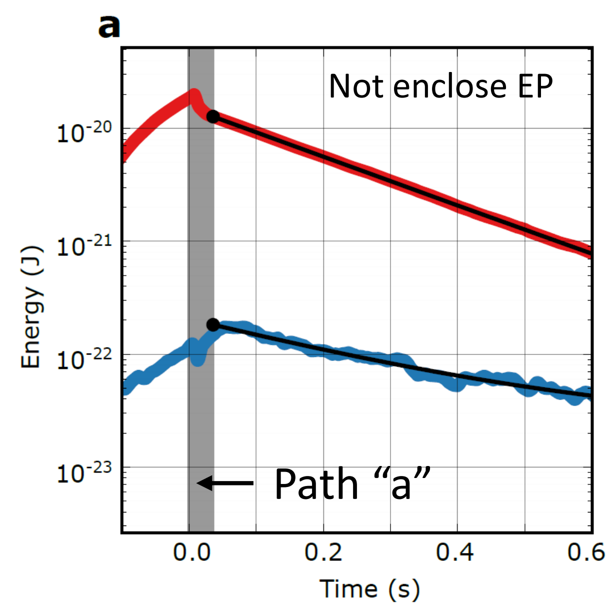
- At small power, back to original modes
- At high power, move to other modes (enclosing EP)

H. Xu et al., Nature 537, 80 (2016)

Topological energy transfer via exceptional points



Topological energy transfer



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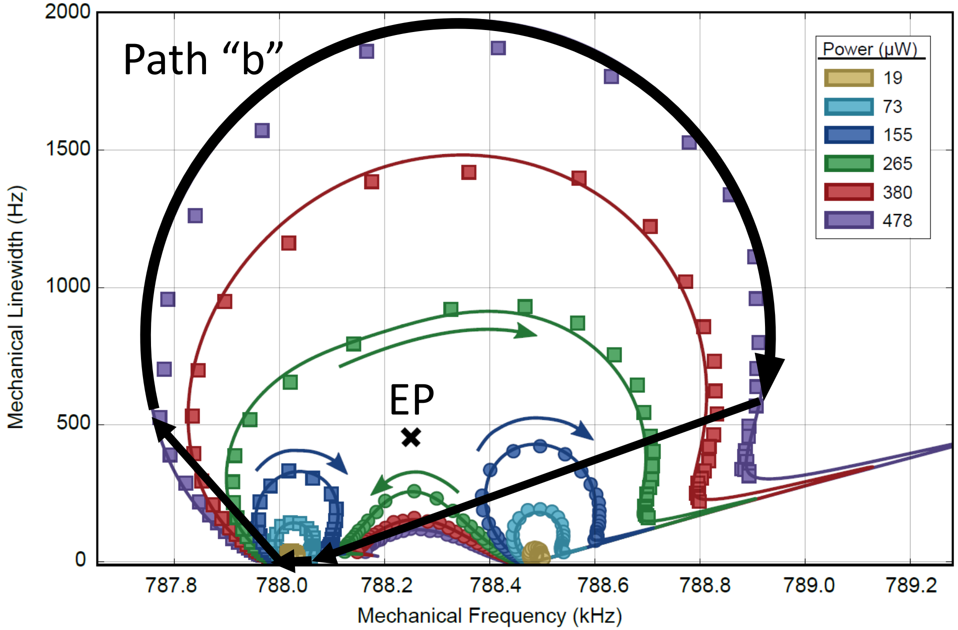
Topological energy transfer via exceptional points



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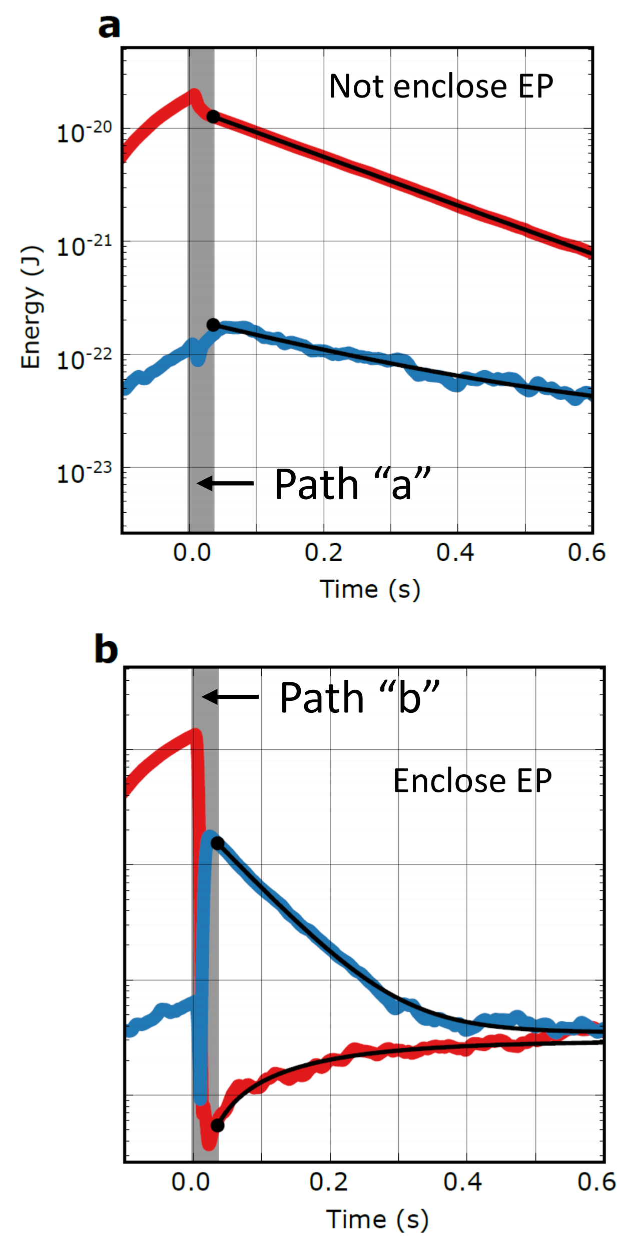
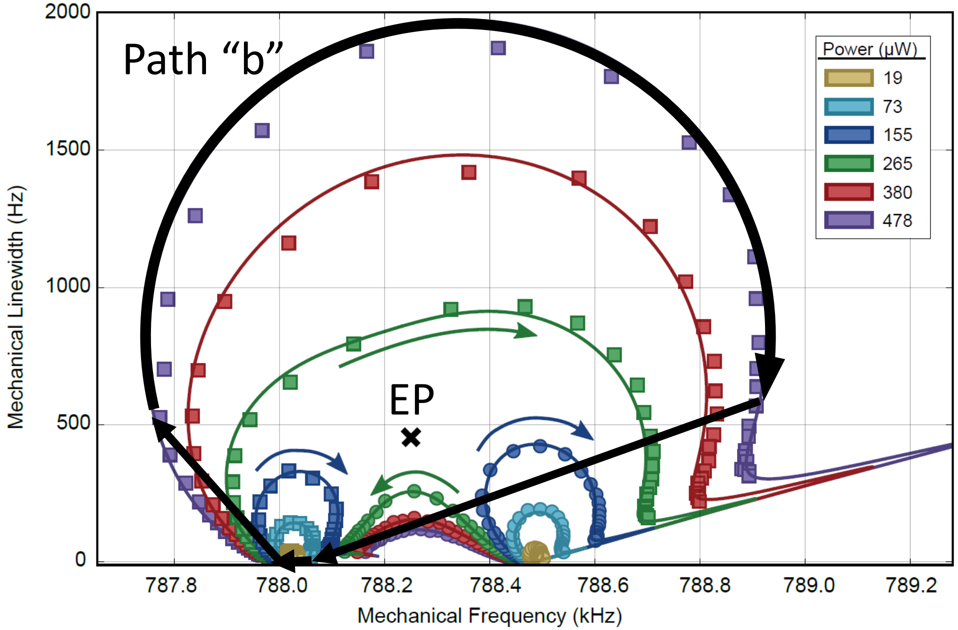
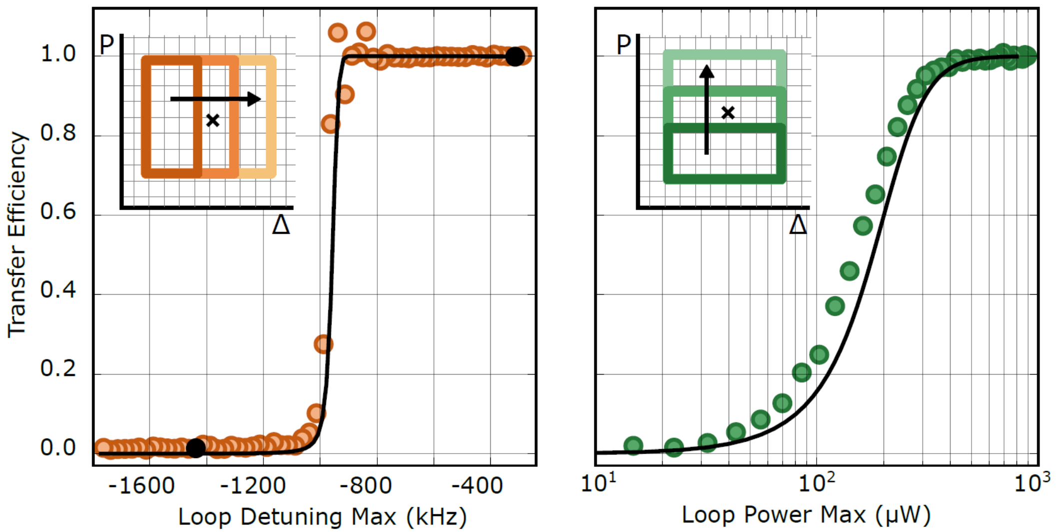
Topological energy transfer

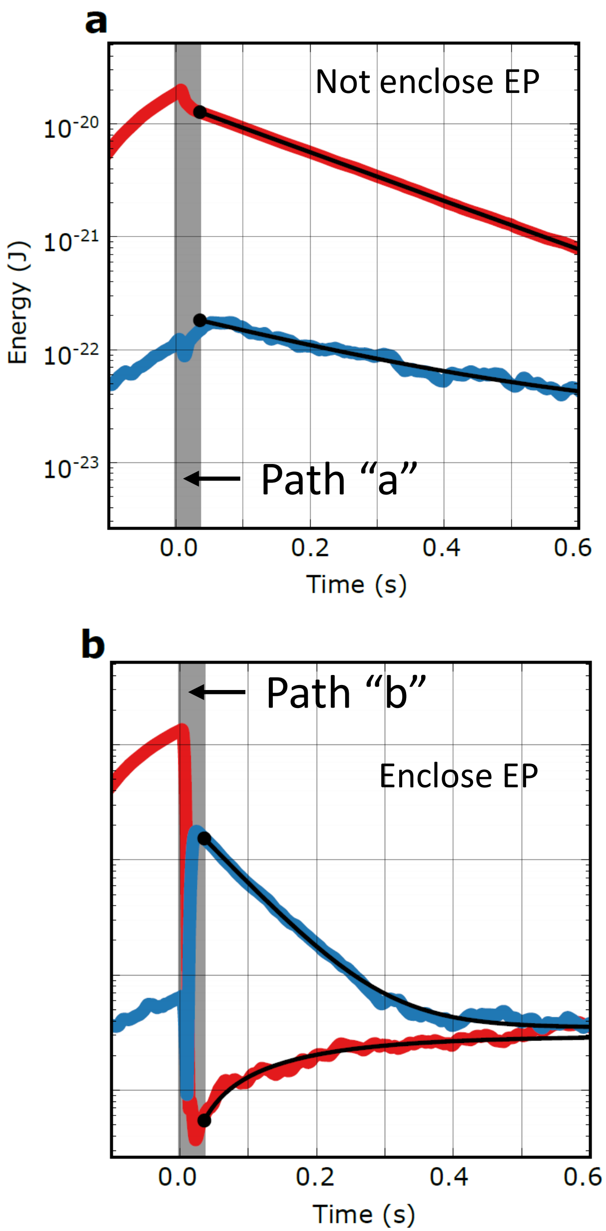


Topological energy transfer via exceptional points

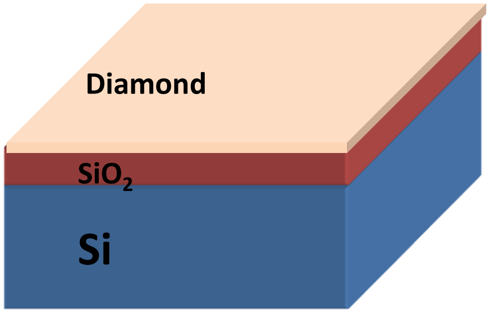


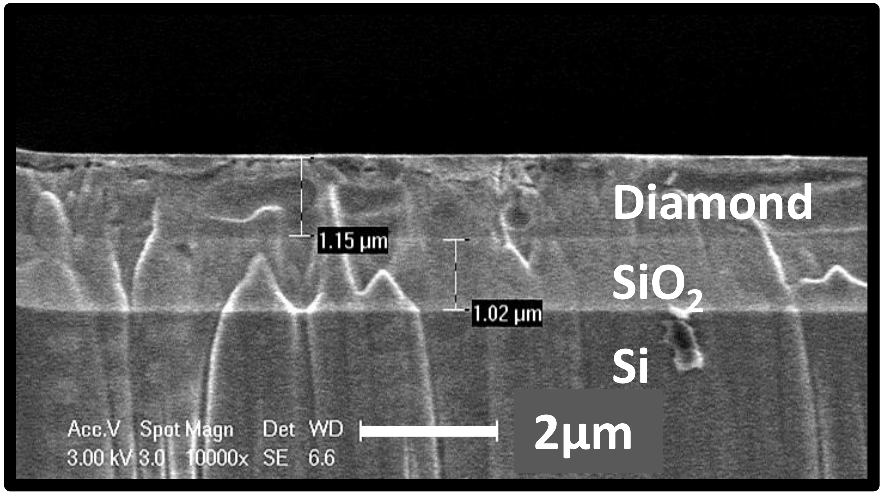


Topological energy transfer



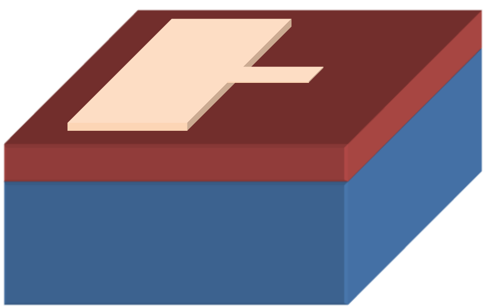
Fabrication of diamond mechanical resonators

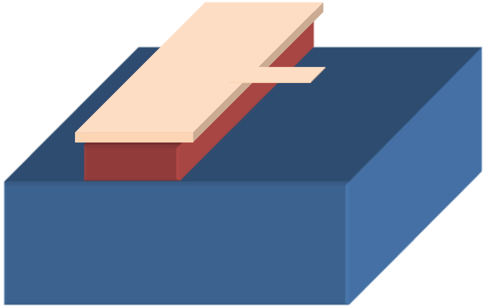




Define resonators lithographically and Oxygen ICP etching

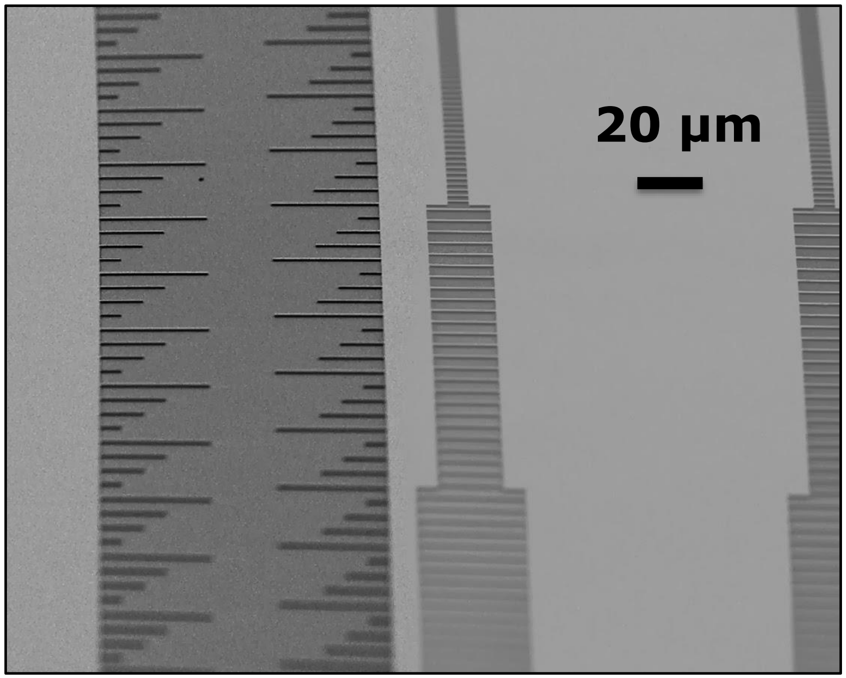
Release sacrificial layer BHF

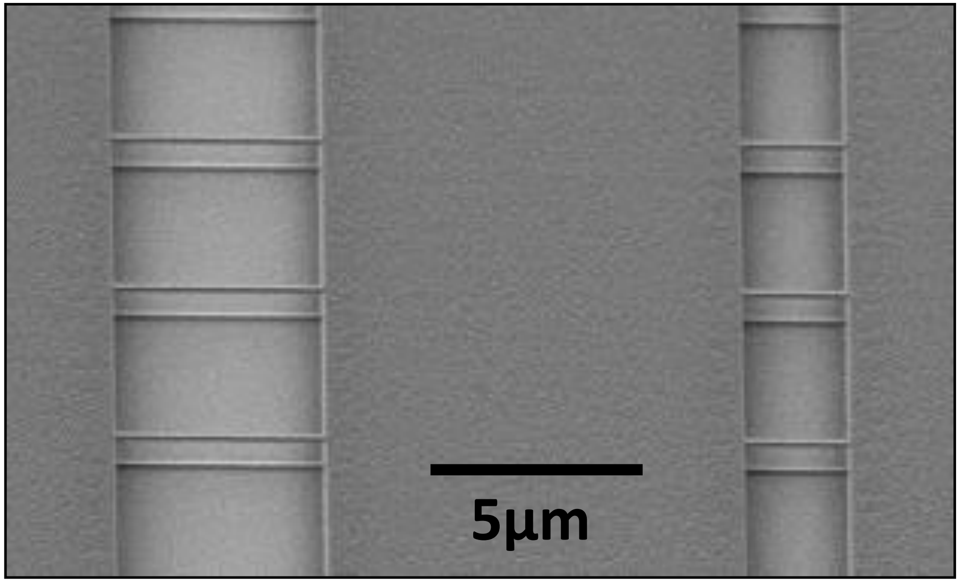


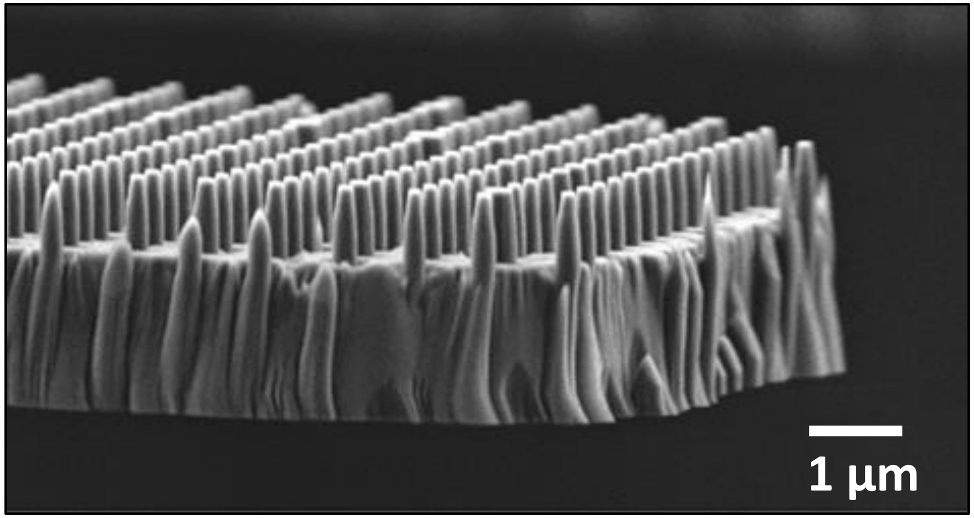


P. Ovartchaiyapong *et al.*, **APL** (2012)

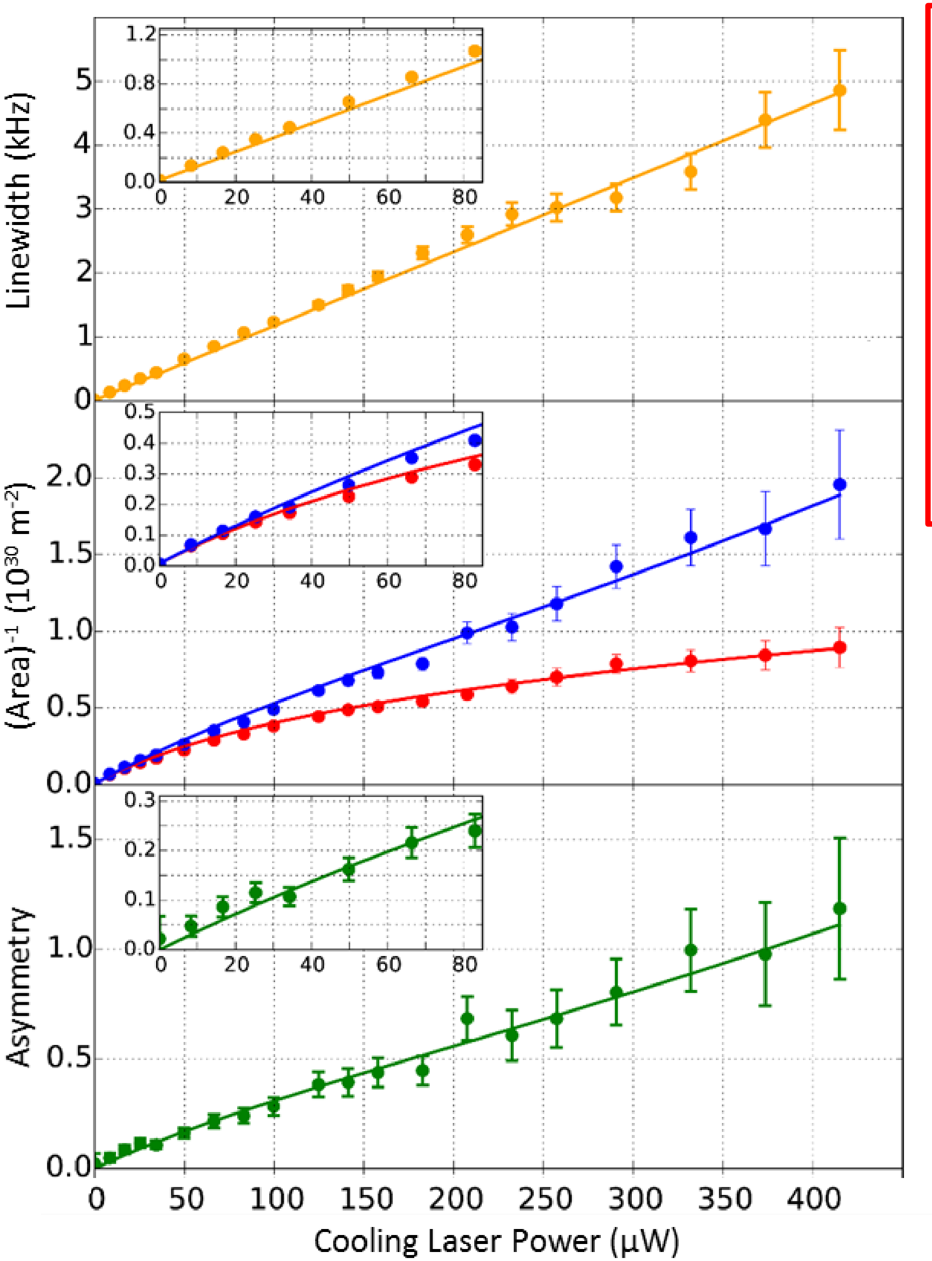
Gallery of diamond nanostructures

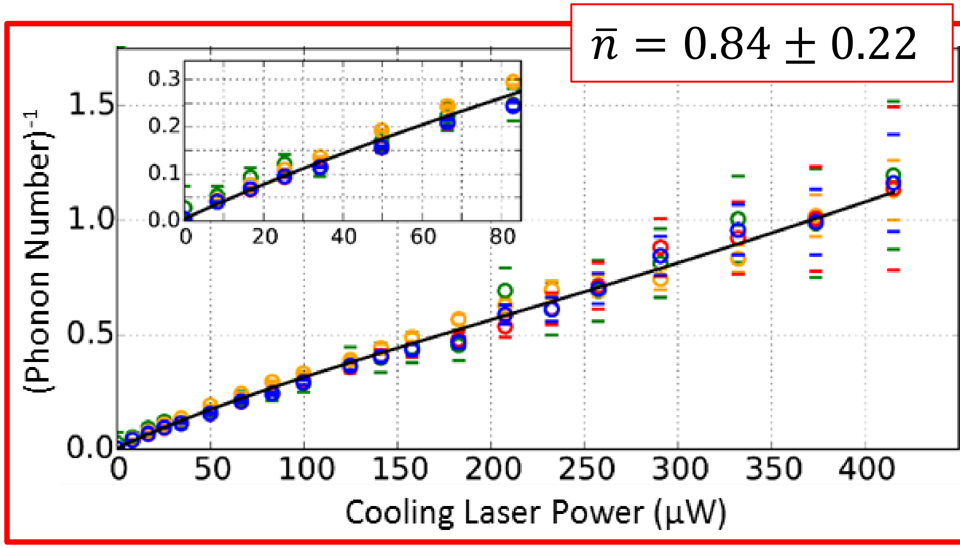






Laser-assisted cooling of mechanical motion





Mean phonon number obtained from:

- **Blue sideband area:** $m\omega_m \langle x^2 \rangle = \hbar\omega_m \bar{n}$
- **Red sideband area:** $m\omega_m \langle x^2 \rangle = \hbar\omega_m (\bar{n}+1)$
- **Sideband asymmetry:**

$$\xi = \left(\frac{A^{(r)}}{A^{(b)}} - 1\right) = \left(\frac{\bar{n}+1}{\bar{n}} - 1\right) = \frac{1}{\bar{n}}$$

- **Mechanical linewidth:** $\dfrac{T}{T_{bath}} = \dfrac{\gamma_0}{\gamma_{tot}}$

M. Underwood *et al.*, PRA (2015)