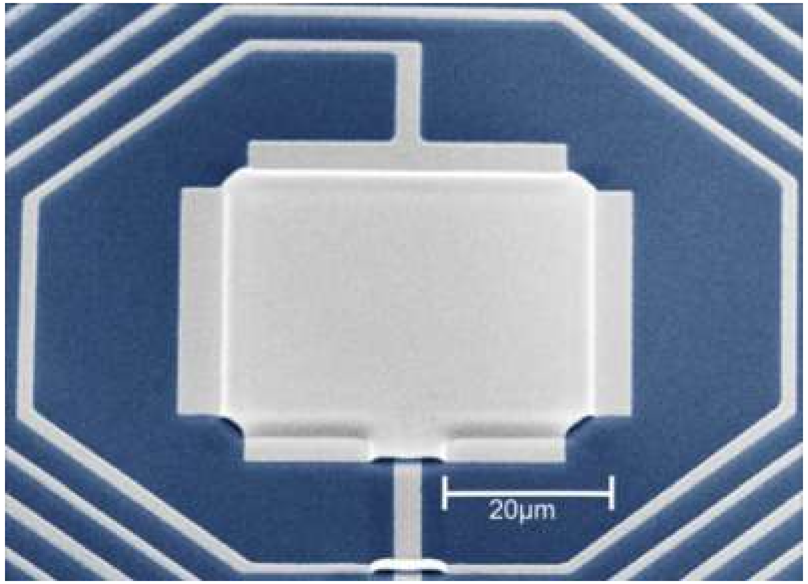
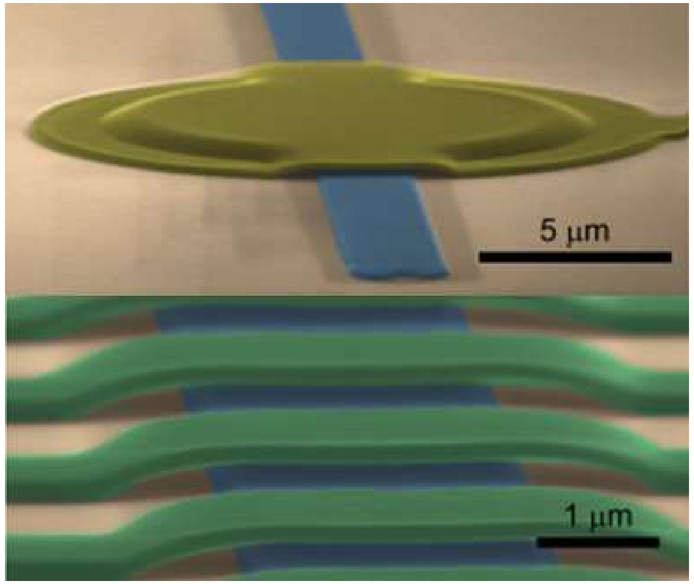
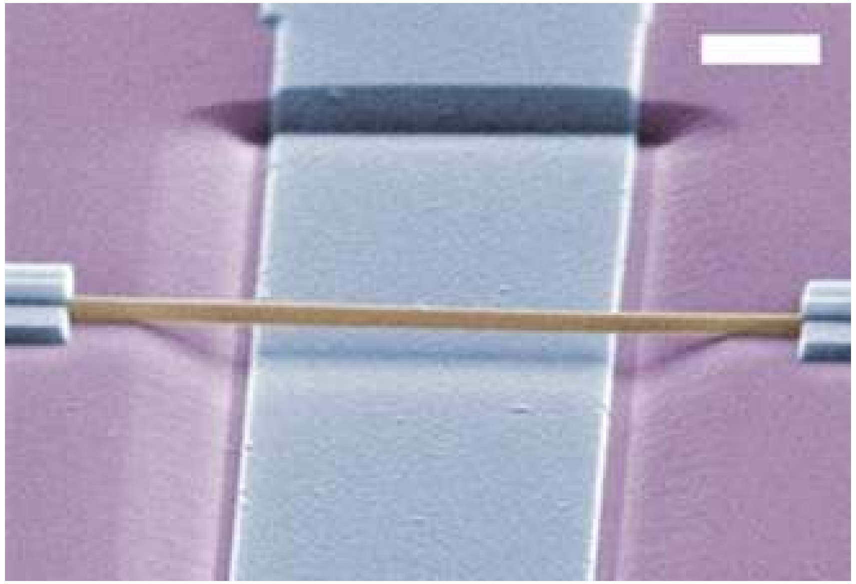






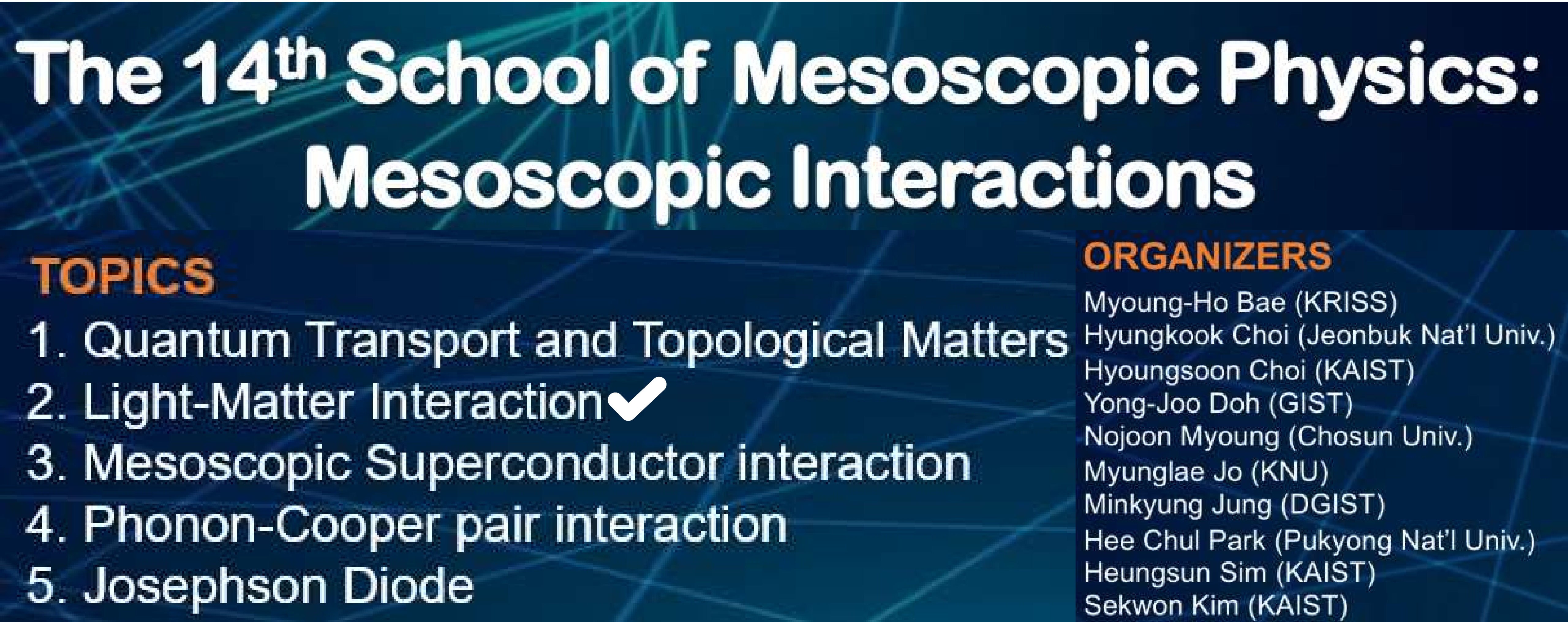
중시계 진동자의 광역학적 상호작용
Optomechanical interactions in mesoscopic oscillators

HQL
hybrid quantum device lab

Junho Suh

Pohang University of Science and Technology

1986



The 14th School of Mesoscopic Physics: Mesoscopic Interactions

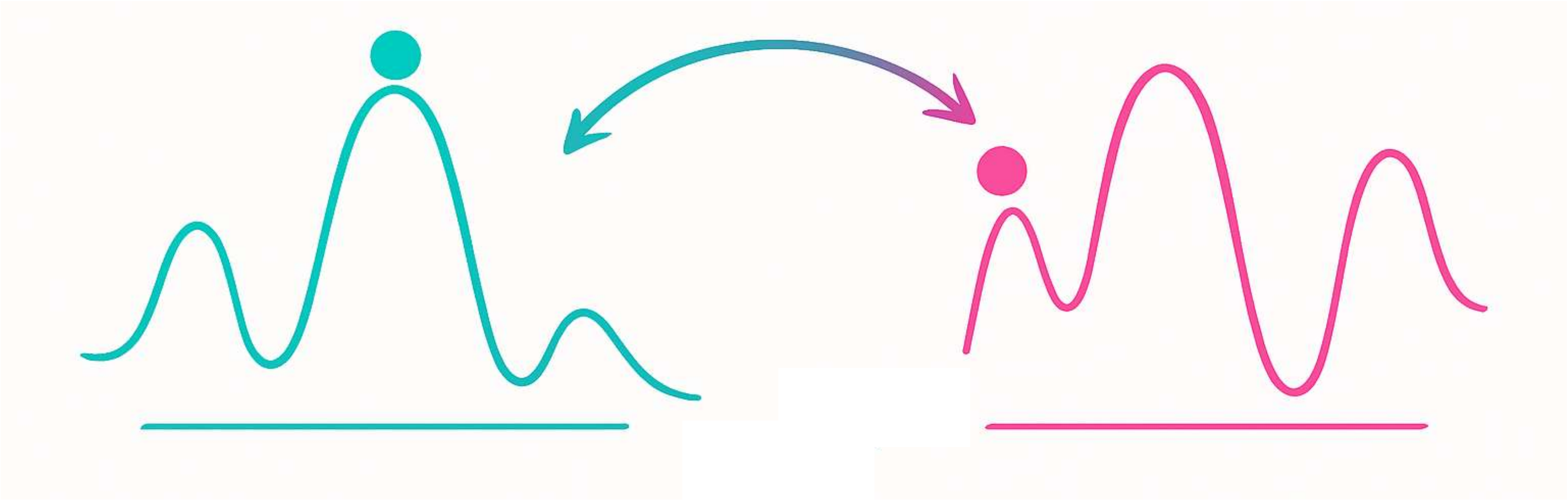
TOPICS

1. Quantum Transport and Topological Matters
2. Light-Matter Interaction ✓
3. Mesoscopic Superconductor interaction
4. Phonon-Cooper pair interaction
5. Josephson Diode

ORGANIZERS

Myoung-Ho Bae (KRISS)
Hyungkook Choi (Jeonbuk Nat'l Univ.)
Hyoungsoon Choi (KAIST)
Yong-Joo Doh (GIST)
Nojoon Myoung (Chosun Univ.)
Myunglae Jo (KNU)
Minkyung Jung (DGIST)
Hee Chul Park (Pukyong Nat'l Univ.)
Heungsun Sim (KAIST)
Sekwon Kim (KAIST)

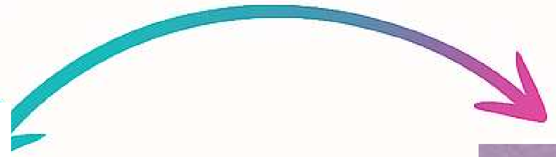
상호(相互) 작용 - (Mutual) Interaction



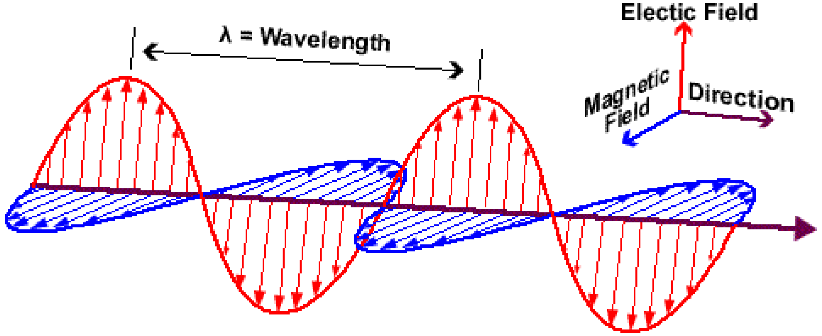
* “interacting quantum states” image generated by chatGPT

광역학적 상호작용

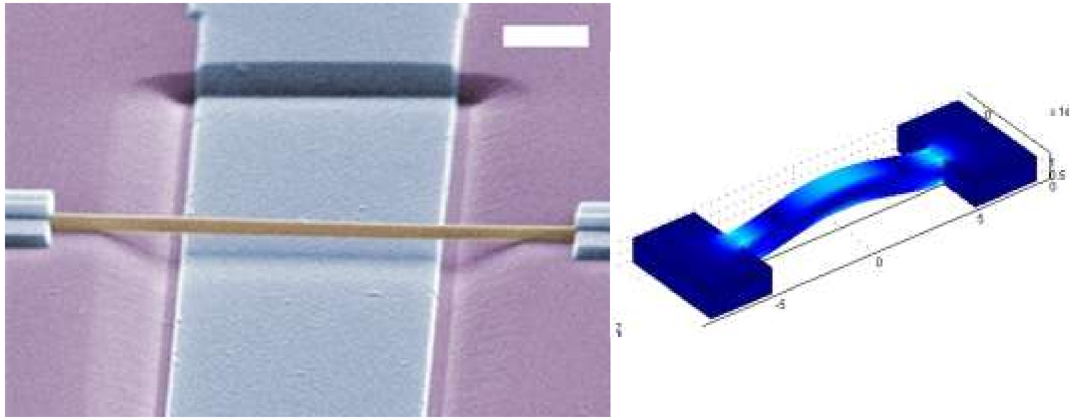
빛



중시계 (역학적) 진동자

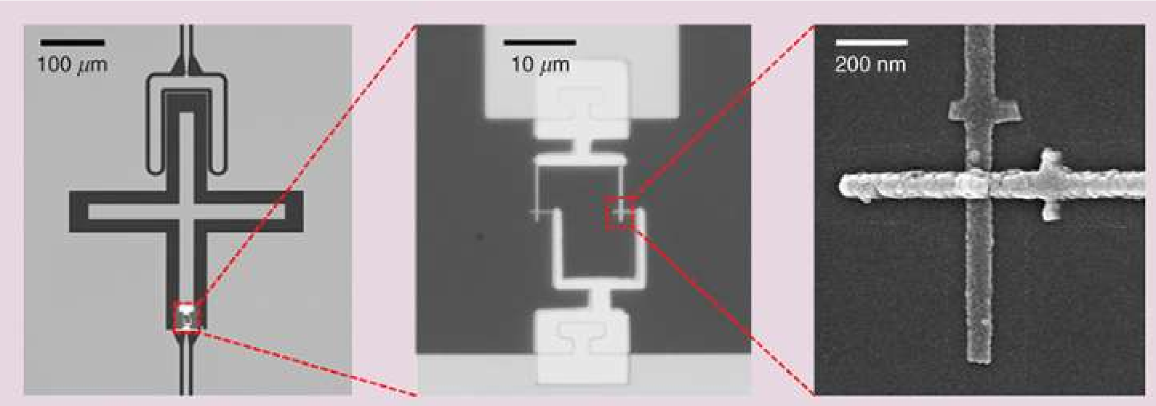


마이크로파 대역 전자기파
(0.3~30 GHz)

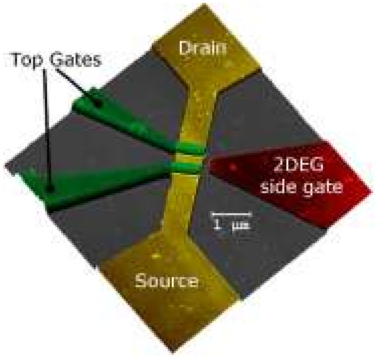


마이크로/나노 역학적 진동자
(MHz~GHz)

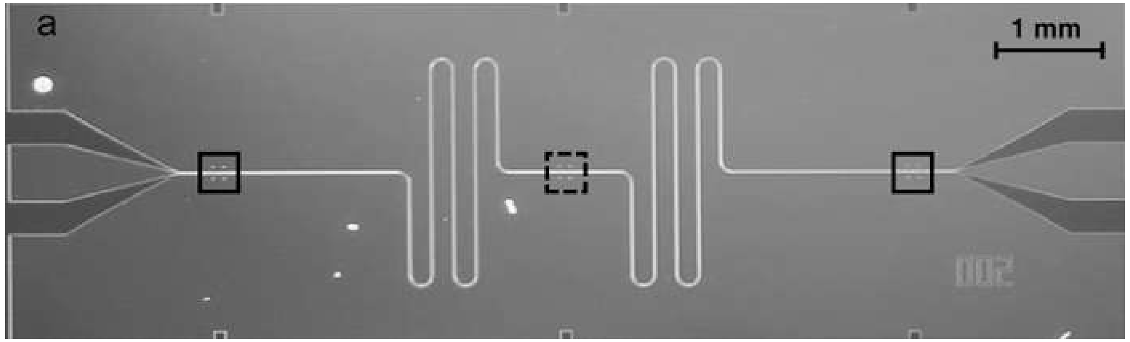
마이크로파 중시계 소자의 예



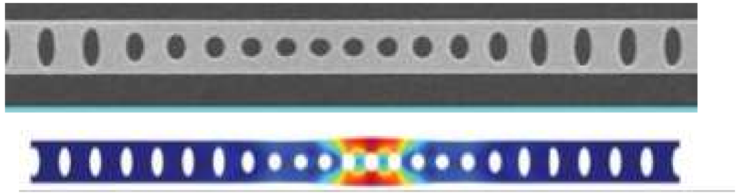
Superconducting qubit



Electron quantum dot qubit



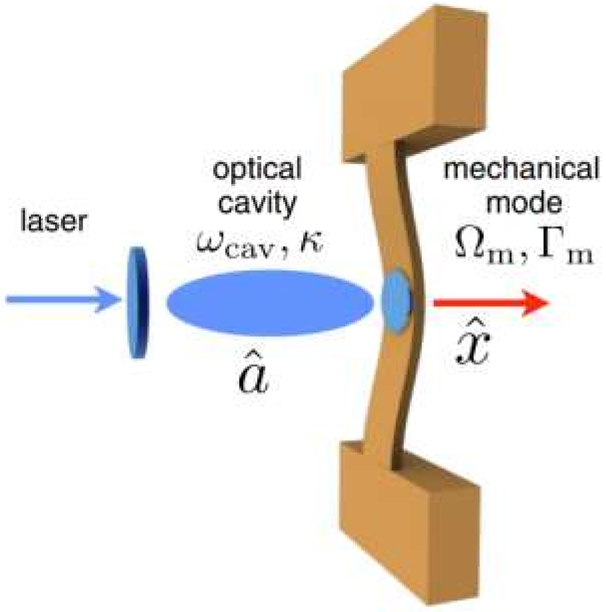
Superconducting CPW resonator

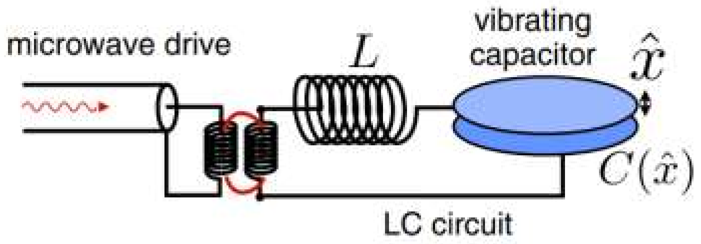


Nano-acoustic resonator

*** Low temperature necessary:
Why? Microwave photon energy > thermal energy
e.g.) 1 GHz microwave photon ~ 50 mK thermal energy

Cavity optomechanical system (광역학계)





[Cavity Hamiltonian]

$$= \hbar\omega_{cav}\hat{a}^{\dagger}\hat{a}$$

↓

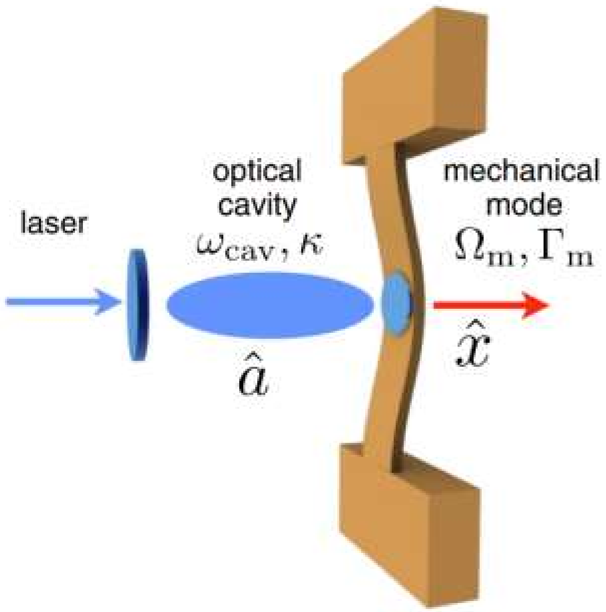
[Optomechanical interaction Hamiltonian]

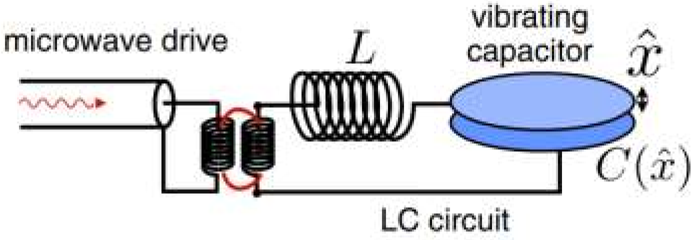
$$= \hbar\frac{\partial\omega_{cav}}{\partial x}\hat{x}\hat{a}^{\dagger}\hat{a}$$

"radiation pressure"

* Aspelmeyer *et al.*, *Rev. Mod. Phys.* **86**, 29 (2014).

Cavity optomechanical system (광역학계)





[Cavity Hamiltonian]

$$= \hbar\omega_{cav}\hat{a}^{\dagger}\hat{a}$$

$$\downarrow$$

[Optomechanical interaction Hamiltonian]

$$= \hbar\frac{\partial\omega_{cav}}{\partial x}\hat{x}\hat{a}^{\dagger}\hat{a}$$

"radiation pressure"

$$L_{cav} = n\lambda = n\frac{2\pi c}{\omega_{cav}} \rightarrow \delta x = \delta L_{cav} \approx -n\frac{2\pi c}{{\omega_{cav}}^2}\delta\omega_{cav}$$

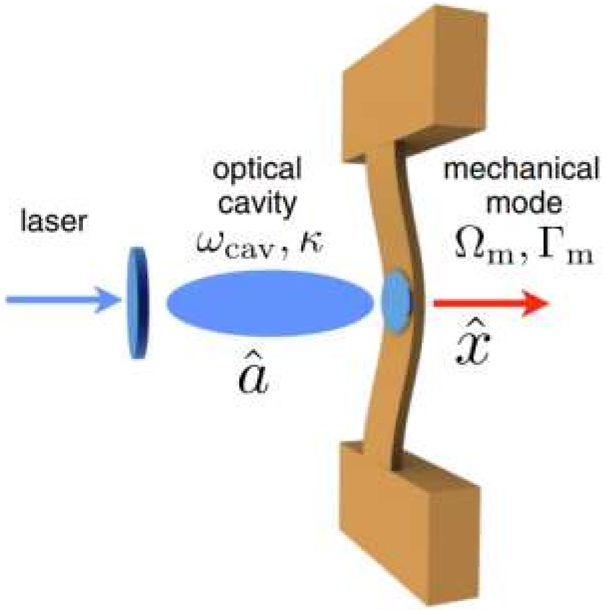
$$\frac{\partial\omega_{cav}}{\partial x} = \approx -\frac{{\omega_{cav}}^2}{2\pi cn}$$

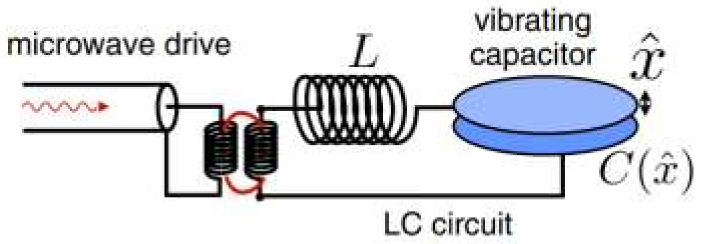
$$\omega_{cav} = \frac{1}{\sqrt{LC}}; C = \frac{\varepsilon_0 A_{cap}}{d_{cap}} \rightarrow \delta x = \delta d_{cap} \approx \frac{2d_{cap}}{\omega_{cav}}\delta\omega_{cav}$$

$$\frac{\partial\omega_{cav}}{\partial x} = \approx \frac{\omega_{cav}}{2d_{cap}}$$

* Aspelmeyer *et al.*, *Rev. Mod. Phys.* **86**, 29 (2014); Devoret *et.al., lecture notes of les houches summer school* (2011).

Cavity optomechanical system (광역학계)





Mechanical oscillator couples to photons

$$\hat{H} = \hbar\omega_{cav}\hat{a}^{\dagger}\hat{a} + \hbar\Omega\hat{b}^{\dagger}\hat{b} + \hbar g_0\hat{a}^{\dagger}\hat{a}\overbrace{(\hat{b}^{\dagger} + \hat{b})}$$

photon

phonon

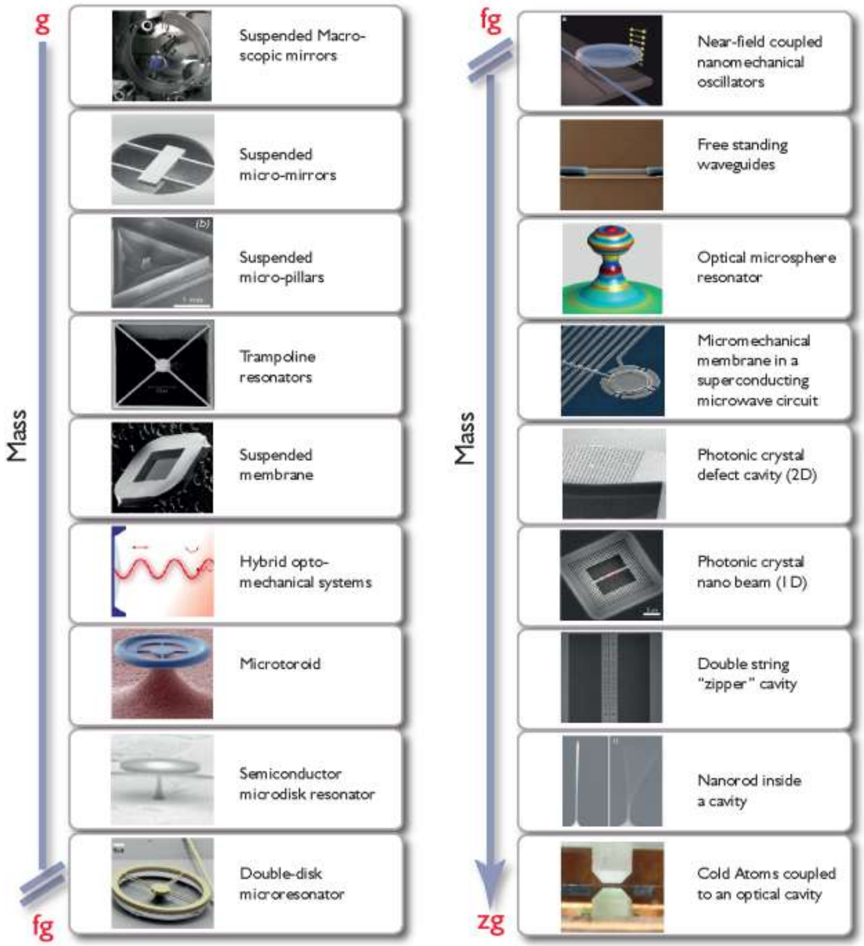
interaction

* Optomechanical "single-photon" coupling strength

$$g_0 = \frac{\partial\omega_{cav}}{\partial x}x_{zpf}$$

* Aspelmeyer *et al.*, *Rev. Mod. Phys.* **86**, 29 (2014); Devoret *et.al., lecture notes of les houches summer school* (2011).

Cavity optomechanical system (광역학계)



Mechanical oscillator couples to photons

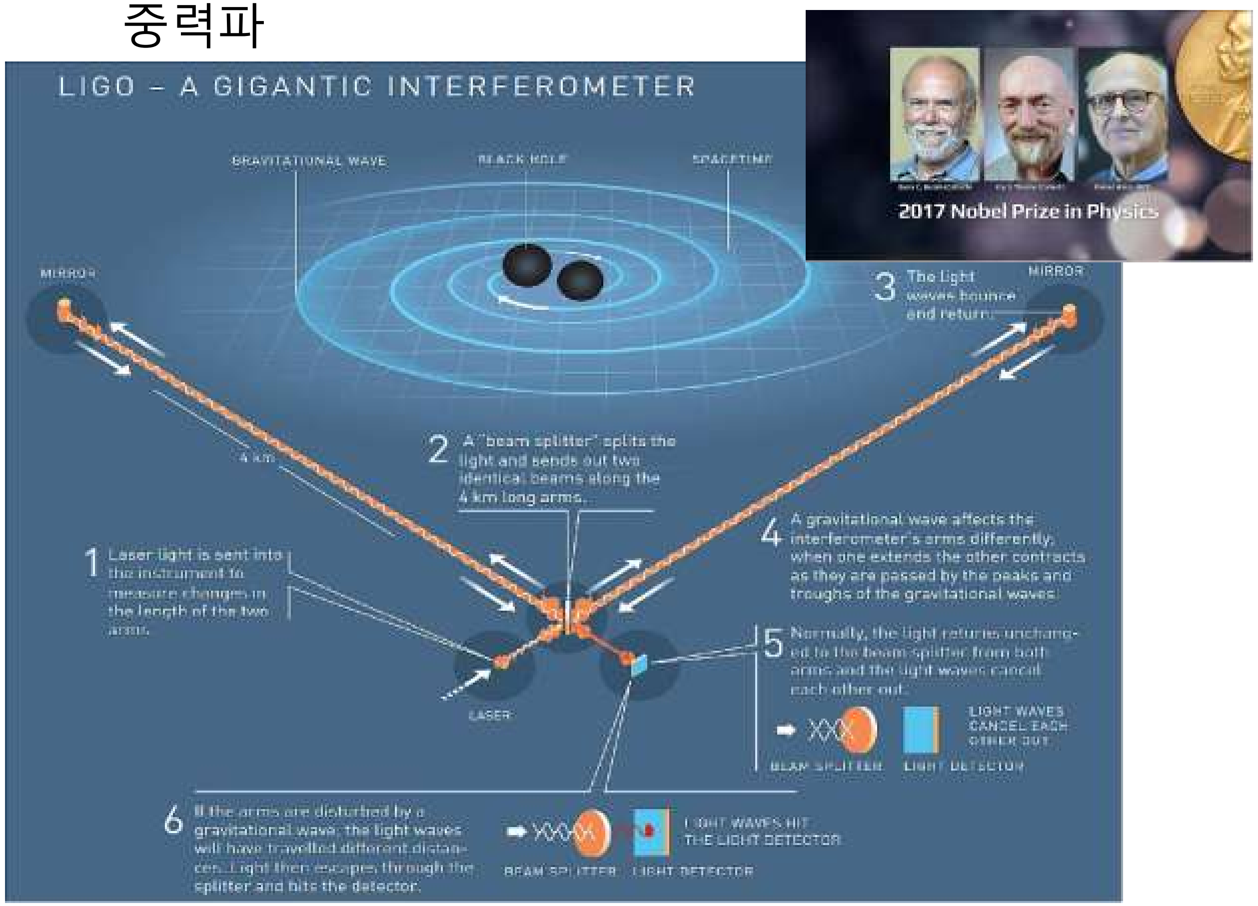
$$\hat{H} = \underset{\substack{\uparrow \\ \text{photon}}}{\hbar\omega_c\hat{a}^\dagger\hat{a}} + \underset{\substack{\uparrow \\ \text{phonon}}}{\hbar\omega_m\hat{b}^\dagger\hat{b}} + \underset{\substack{\uparrow \\ \text{interaction}}}{\hbar g\hat{a}^\dagger\hat{a}}\overbrace{(\hat{b}^\dagger + \hat{b})}^{=\hat{x}/x_{zp}}$$

- Ultrasensitive measurements
- Quantum hybrid systems
- Fundamental tests of quantum mechanics with gravity
- Classical/Quantum information processing …

* Aspelmeyer *et al.*, *Rev. Mod. Phys.* **86**, 29 (2014).

Cavity optomechanical system (광역학계)

중력파



1 Laser light is sent into the instrument to measure changes in the length of the two arms.

2 A "beam splitter" splits the light and sends out two identical beams along the 4 km long arms.

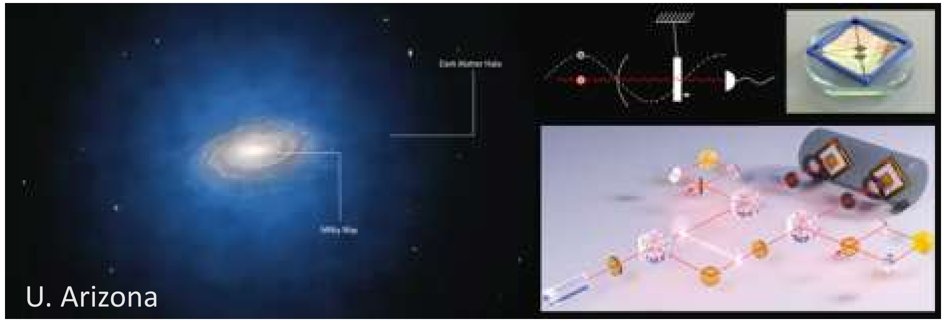
3 The light waves bounce and return.

4 A gravitational wave affects the interferometer's arms differently, when one extends the other contracts as they are passed by the peaks and troughs of the gravitational waves.

5 Normally, the light returns unchanged to the beam splitter from both arms and the light waves cancel each other out.

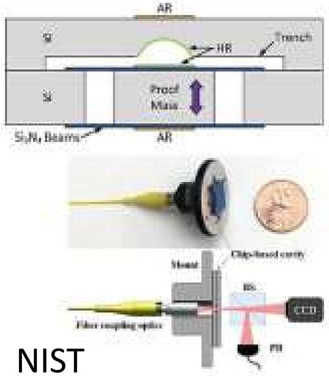
6 If the arms are disturbed by a gravitational wave, the light waves will have travelled different distances. Light then escapes through the splitter and hits the detector.

암흑물질



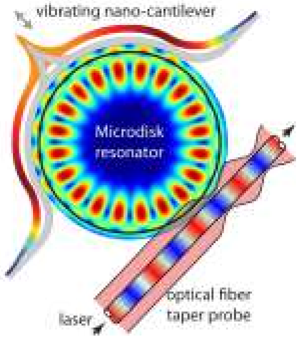
U. Arizona

가속도



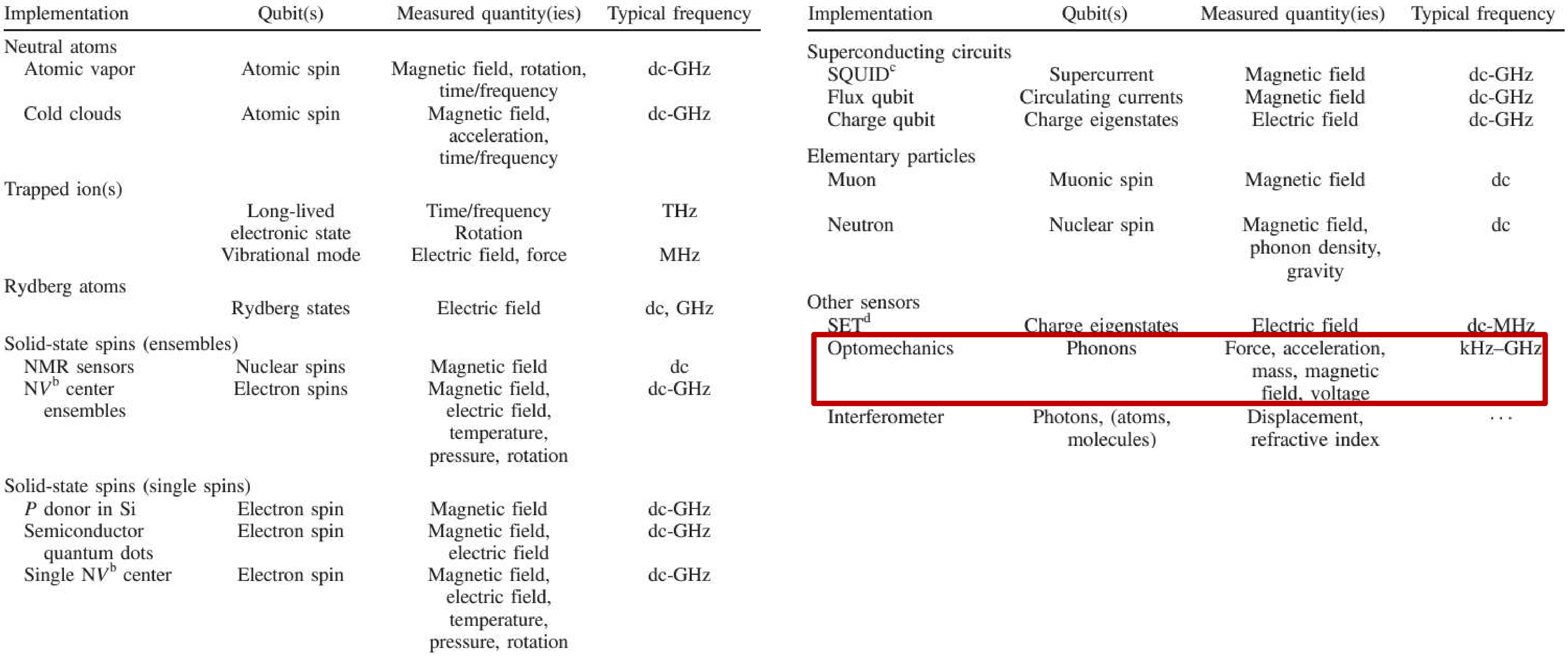
NIST

Atomic force



NIST

Mechanical quantum sensing

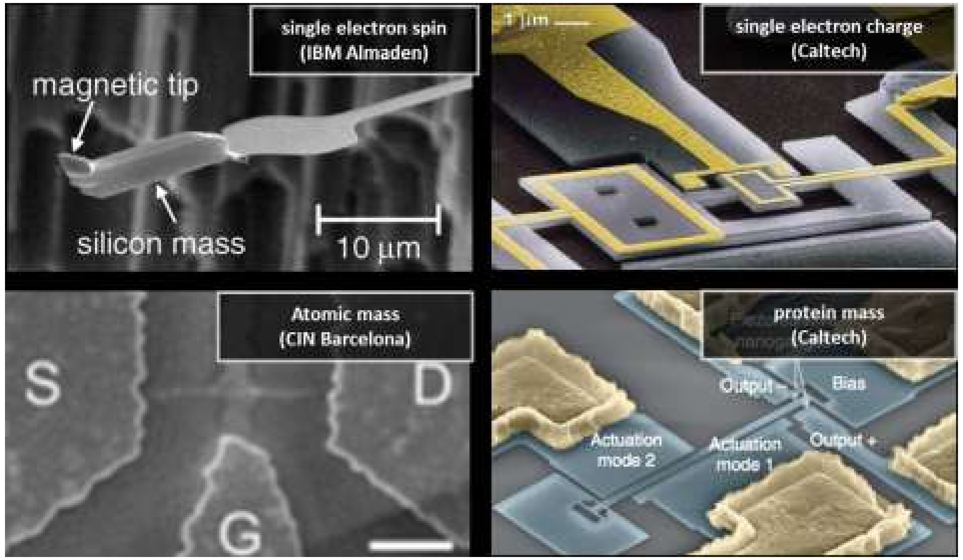


Implementation	Qubit(s)	Measured quantity(ies)	Typical frequency
Neutral atoms			
Atomic vapor	Atomic spin	Magnetic field, rotation, time/frequency	dc-GHz
Cold clouds	Atomic spin	Magnetic field, acceleration, time/frequency	dc-GHz
Trapped ion(s)			
	Long-lived electronic state	Time/frequency	THz
		Rotation	
	Vibrational mode	Electric field, force	MHz
Rydberg atoms			
	Rydberg states	Electric field	dc, GHz
Solid-state spins (ensembles)			
NMR sensors	Nuclear spins	Magnetic field	dc
NV[b] center ensembles	Electron spins	Magnetic field, electric field, temperature, pressure, rotation	dc-GHz
Solid-state spins (single spins)			
P donor in Si	Electron spin	Magnetic field	dc-GHz
Semiconductor quantum dots	Electron spin	Magnetic field, electric field	dc-GHz
Single NV[b] center	Electron spin	Magnetic field, electric field, temperature, pressure, rotation	dc-GHz
Superconducting circuits			
SQUID[c]	Supercurrent	Magnetic field	dc-GHz
Flux qubit	Circulating currents	Magnetic field	dc-GHz
Charge qubit	Charge eigenstates	Electric field	dc-GHz
Elementary particles			
Muon	Muonic spin	Magnetic field	dc
Neutron	Nuclear spin	Magnetic field, phonon density, gravity	dc
Other sensors			
SET[d]	Charge eigenstates	Electric field	dc-MHz
Optomechanics	Phonons	Force, acceleration, mass, magnetic field, voltage	kHz–GHz
Interferometer	Photons, (atoms, molecules)	Displacement, refractive index	···

* C. L. Degen *et.al*, *“Quantum sensing”*, *Rev. Mod. Phys.* **89**, 035002 (2017).

Mechanical oscillators as force sensors

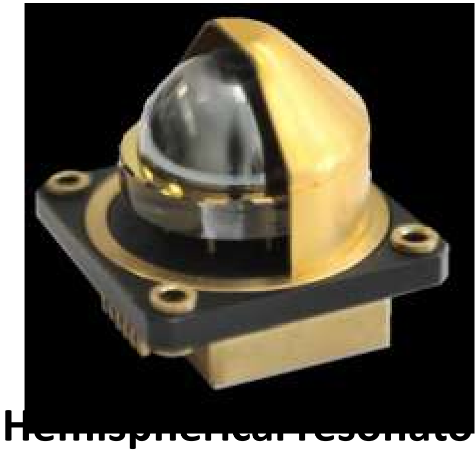
Scientific



MEMS/NEMS sensors

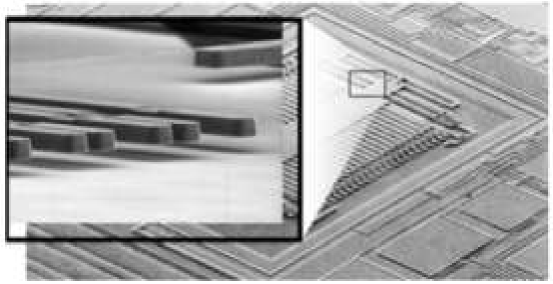
- Force from single quanta
- Mass of single atom/molecule

Industrial



Hemispherical resonator gyroscope

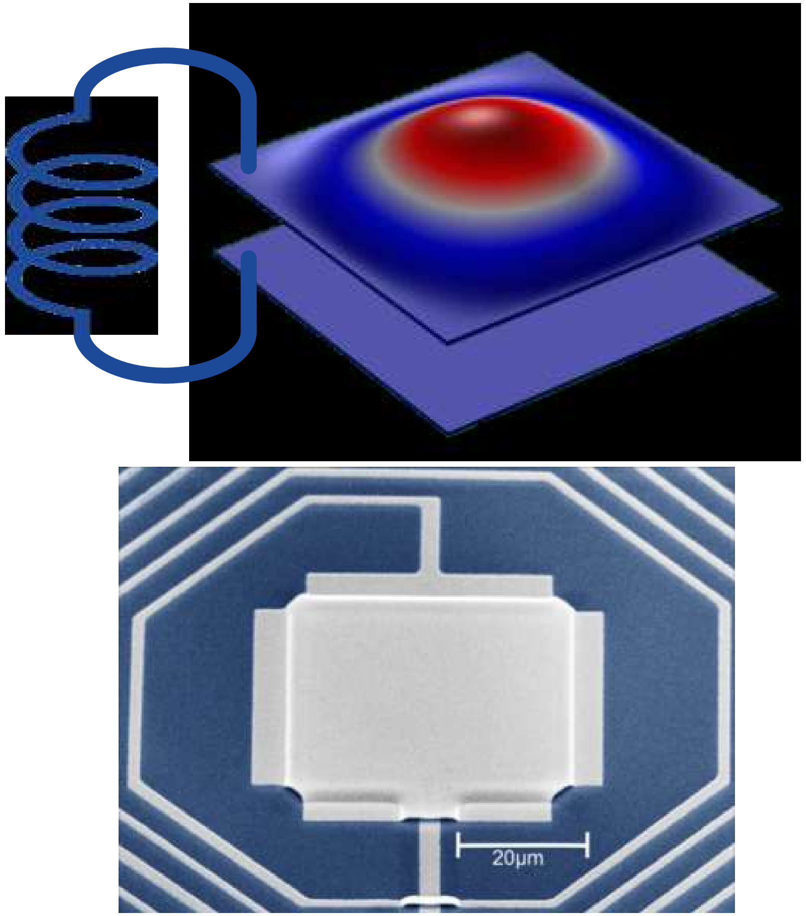
- Coriolis force



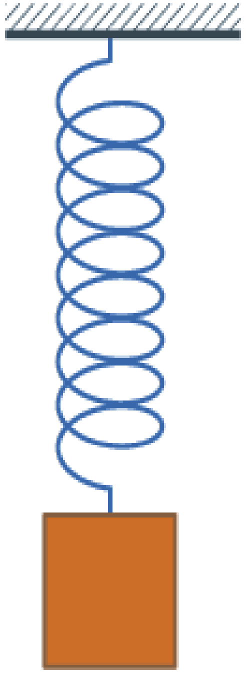
MEMS accelerometer

- inertial force from acceleration

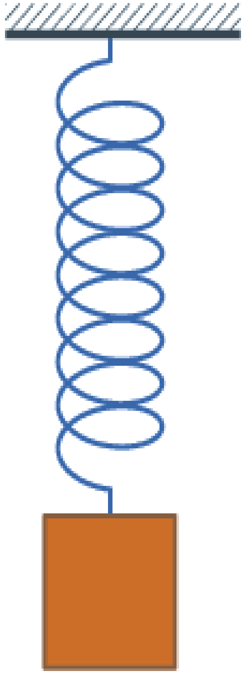
역학적 진동자



* Suh *et al.*, *Science* **344**, 1262 (2014)

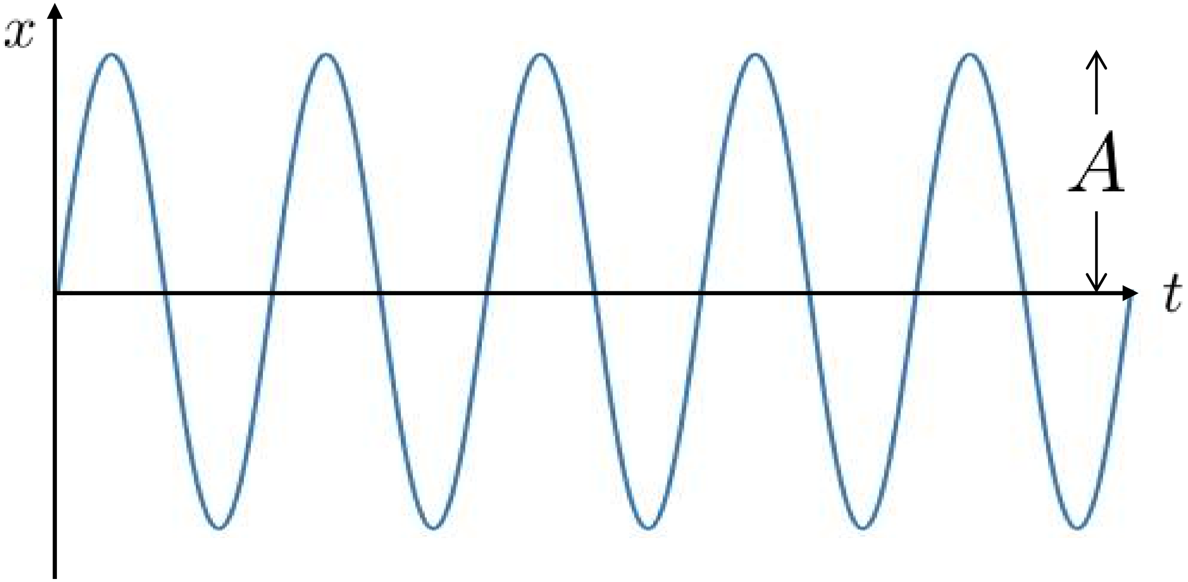


조화 진동자

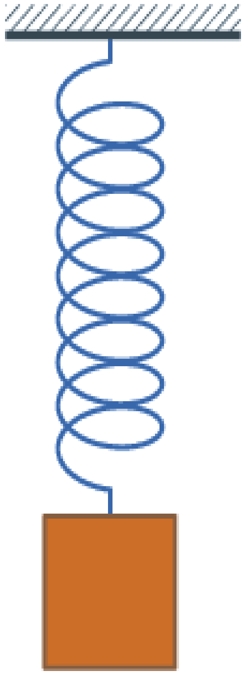


for external force $F\cos\omega t$,

$$m\frac{d^2x}{dt^2}+\frac{m\omega_0}{Q}\frac{dx}{dt}+m\omega_0^2x=F\cos\omega t$$



Amplitude measurement



[redacted]

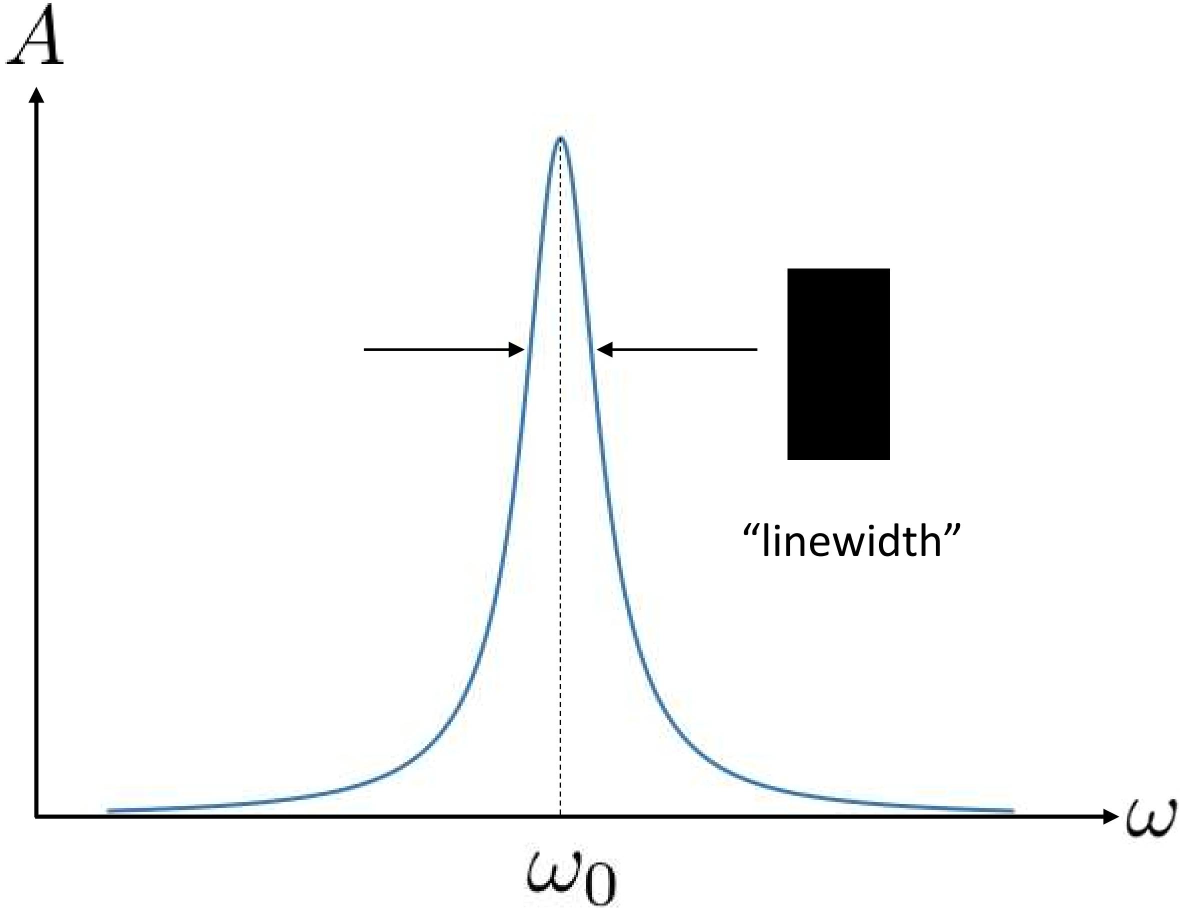
[redacted]

Q-값 (품질값); $10 \sim 10^{9}$

측정량

스프링계수; $10^{-4} \sim 10^{2}$ N/m

Near-resonant Force



[redacted]

“linewidth”

Frequency measurement

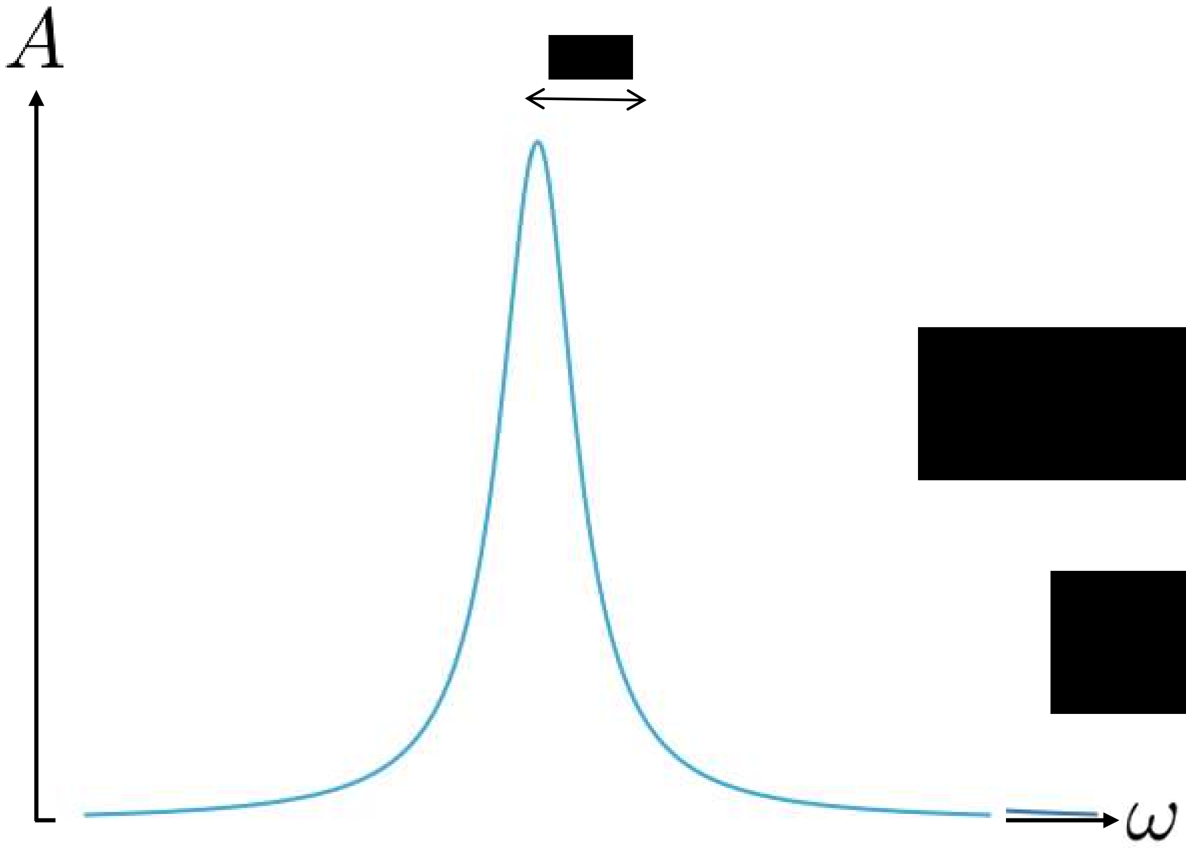
스프링계수; 10^{-4} ~ 10^{2} N/m

$$\omega_0 = \sqrt{\frac{k}{m}}$$

질량; pg ~ ng

측정량

Frequency measurement



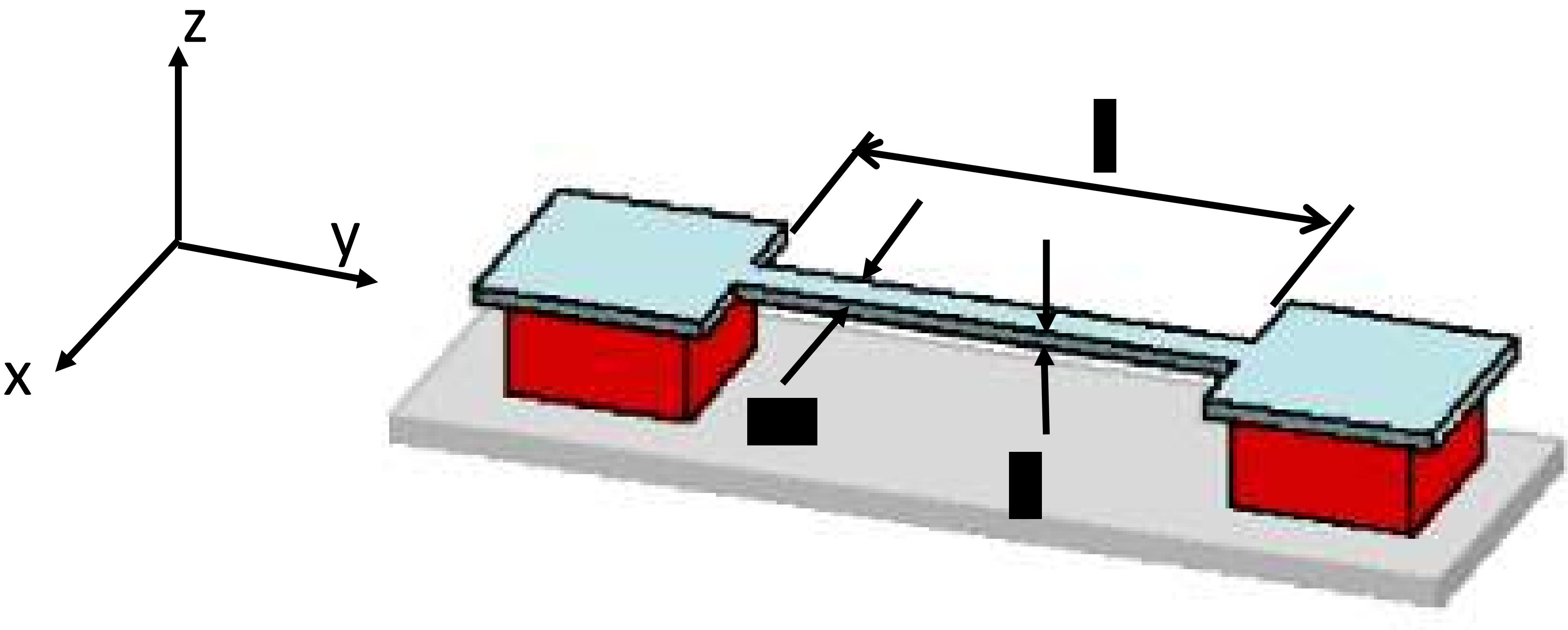
[redacted]

스프링계수 or
force gradient
([redacted])의 변화

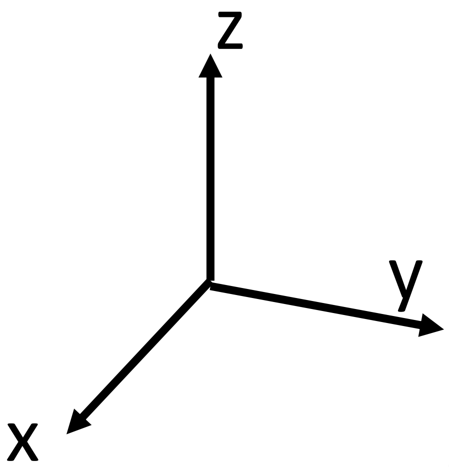
[redacted]

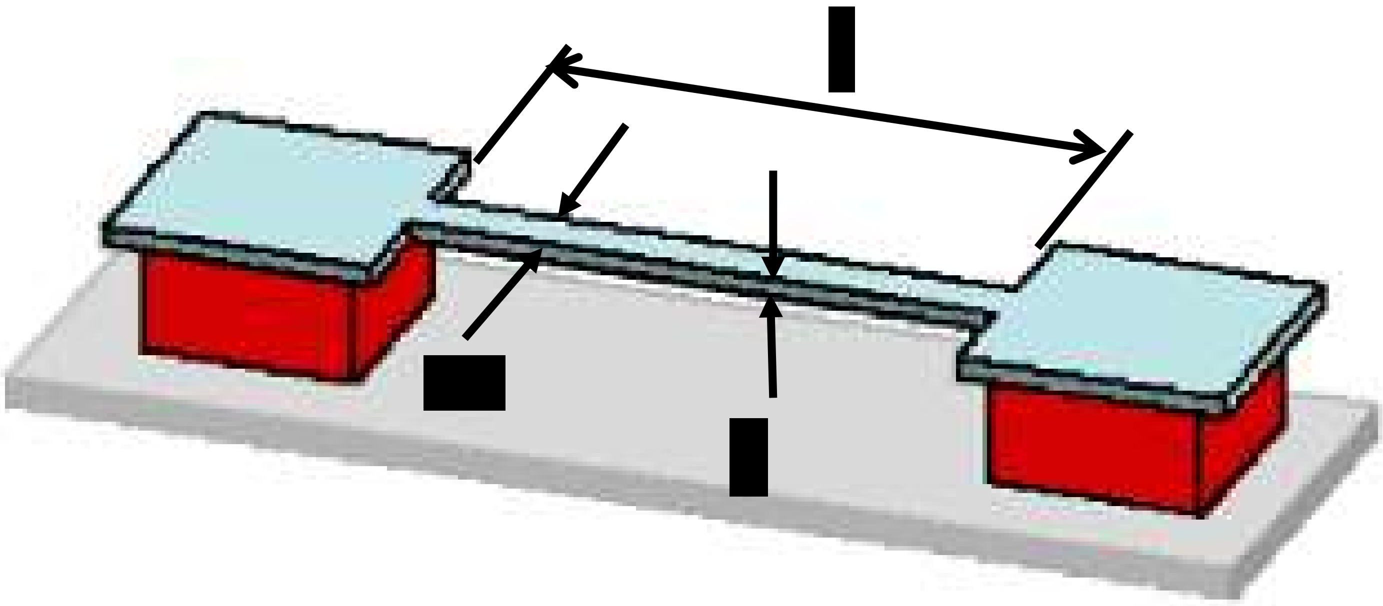
질량의 변화

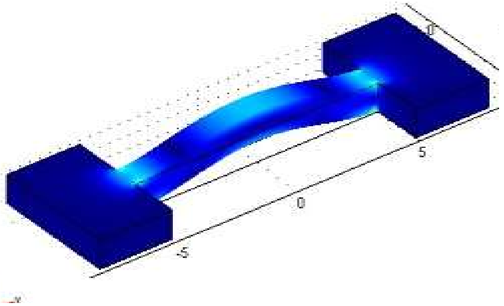
Example of doubly clamped beam



Eigenmode = harmonic oscillator







Equation of motion

- Euler-Bernulli equation

[redacted]

Young's modulus

Moment of inertia
(=$t^3w/12$)

density

Cross-section
(=wt)

- seperation of variables; normal modes

[redacted]

* Foundations of nanomechanics, A. N. Cleland

Equation of motion

- damping can be included by adding a dissipation term [redacted]

[redacted]

- In frequency domain (quality factor [redacted]),

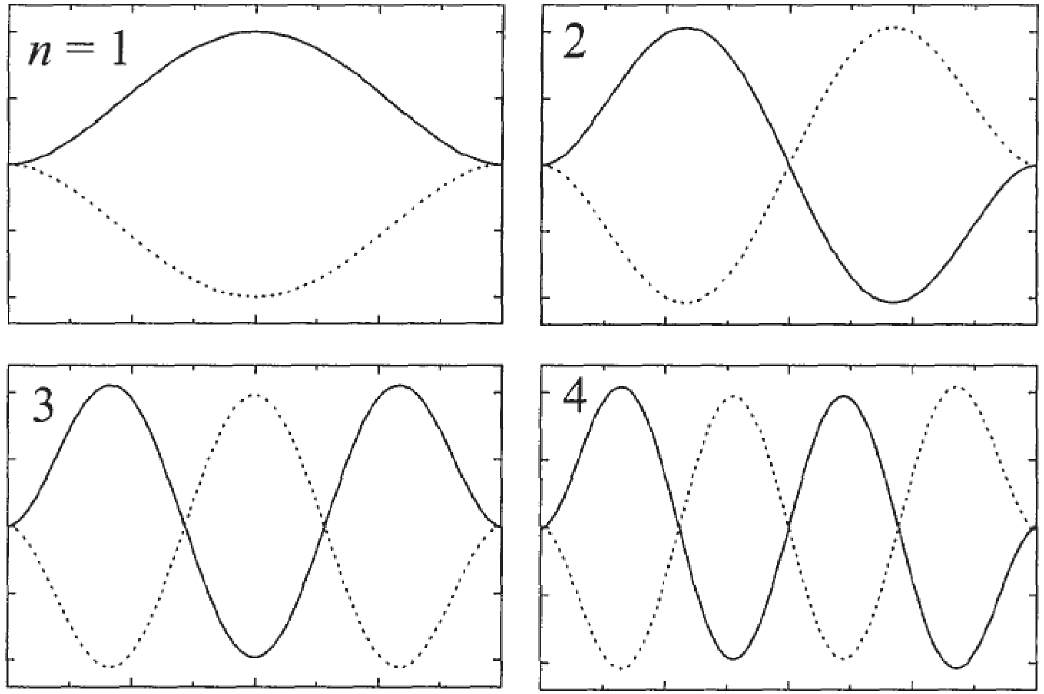
[redacted]

- At resonance, [redacted]

* Foundations of nanomechanics, A. N. Cleland

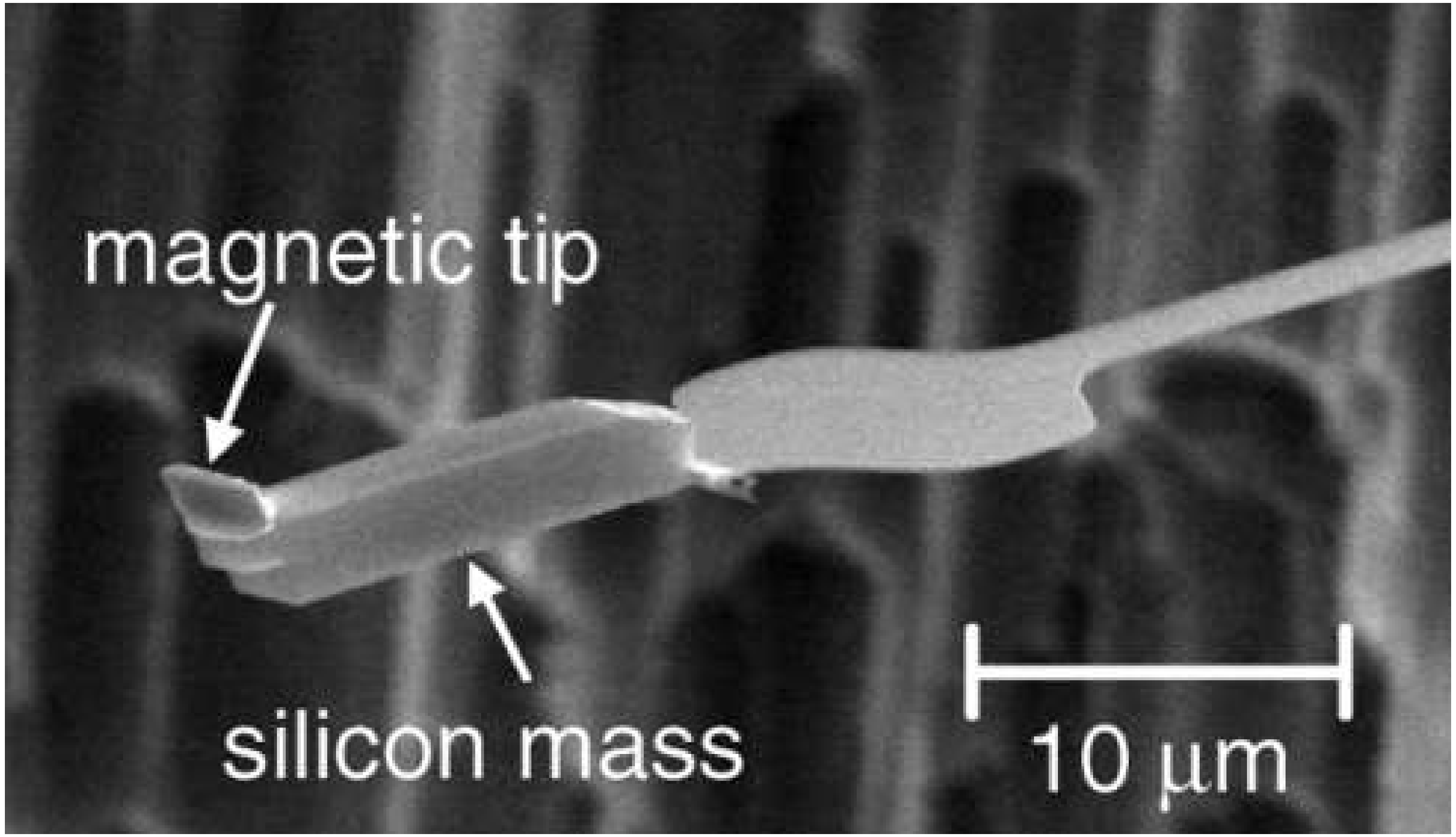
Example of doubly-clamped beam

- boundary condition: fixed ends, zero-slopes
- First four mode shapes



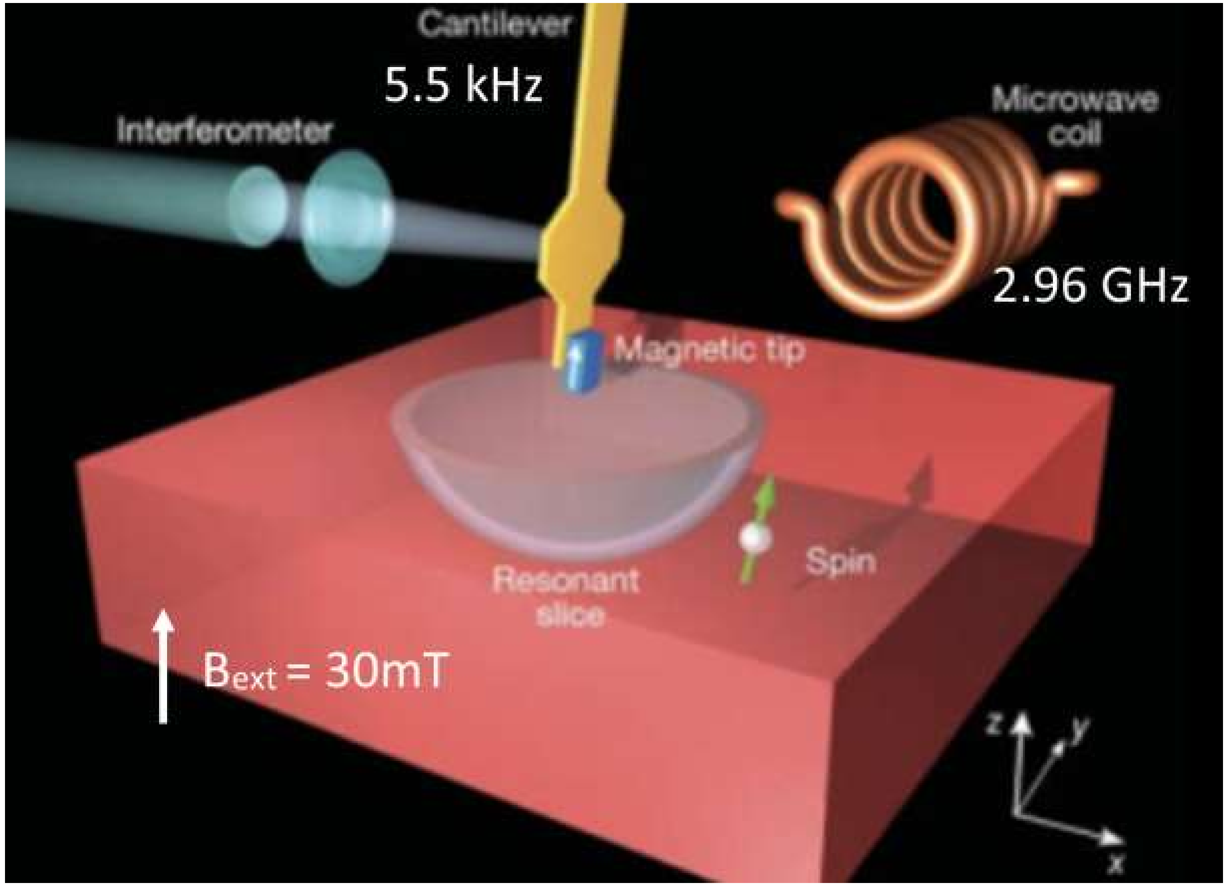
* Foundations of nanomechanics, A. N. Cleland

예제: magnetic resonance force microscopy



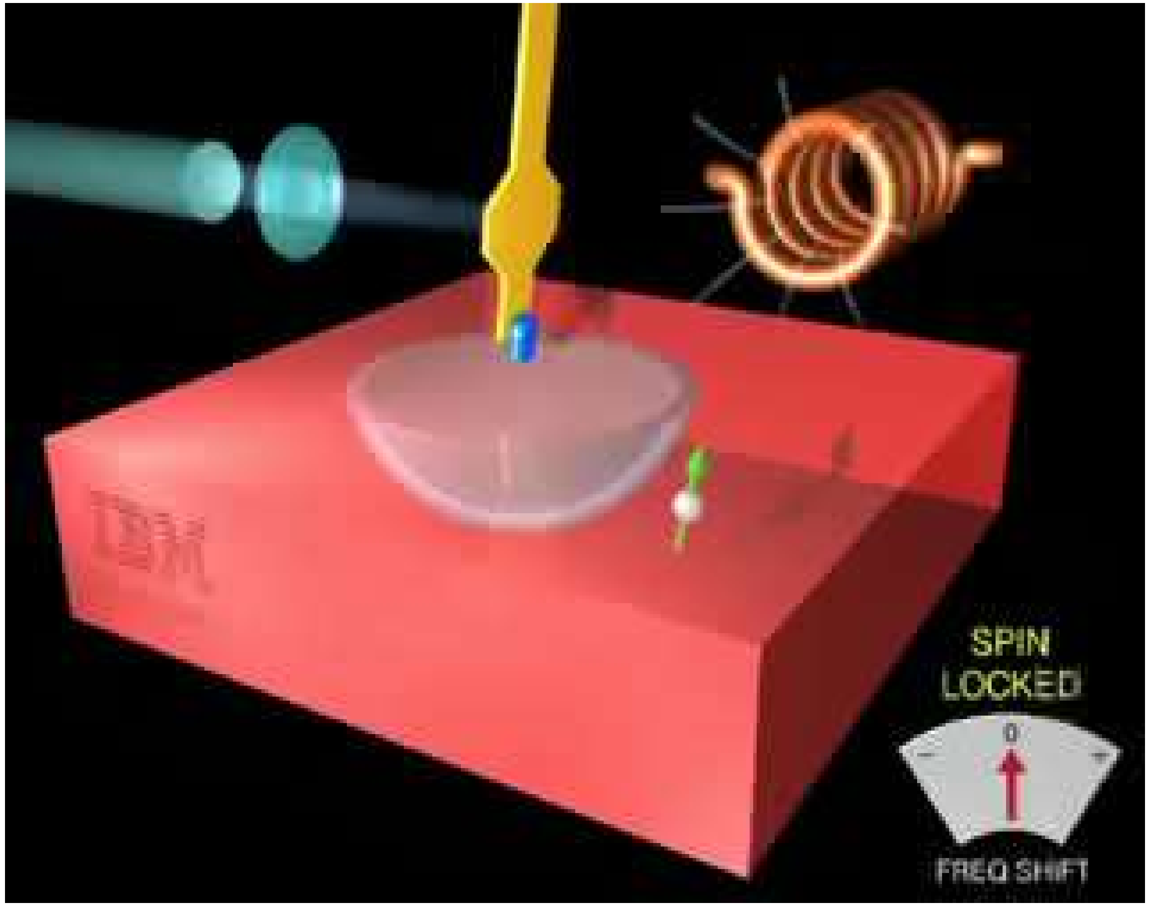
* D. Rugar *et.al.*, Single spin detection by magnetic resonance force microscopy, *Nature* **430**, 329 (2004).

Mechanical detection of single electron spin flip



* D. Rugar *et.al.*, Single spin detection by magnetic resonance force microscopy, *Nature* **430**, 329 (2004).

Mechanical detection of single electron spin flip

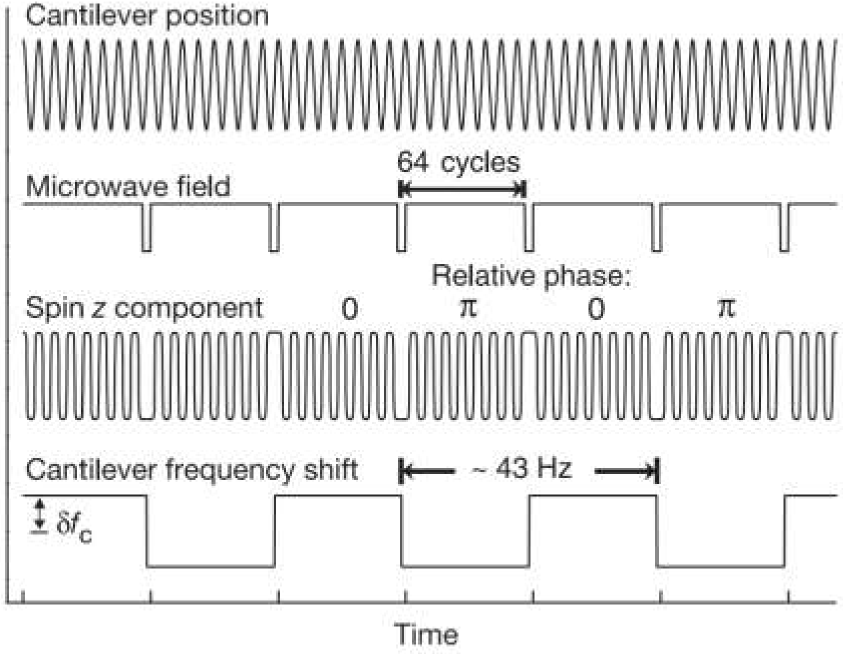


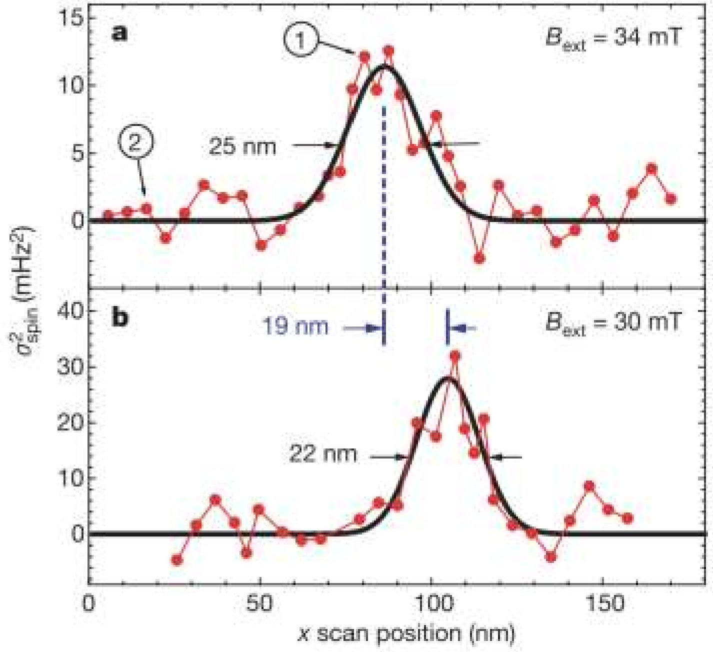
* D. Rugar *et.al.*, Single spin detection by magnetic resonance force microscopy, *Nature* **430**, 329 (2004).

Frequency measurement

$$\delta f_{\mathrm{c}} = \pm \frac{2 f_{\mathrm{c}} G \mu_{\mathrm{B}}}{\pi k x_{\mathrm{peak}}}$$

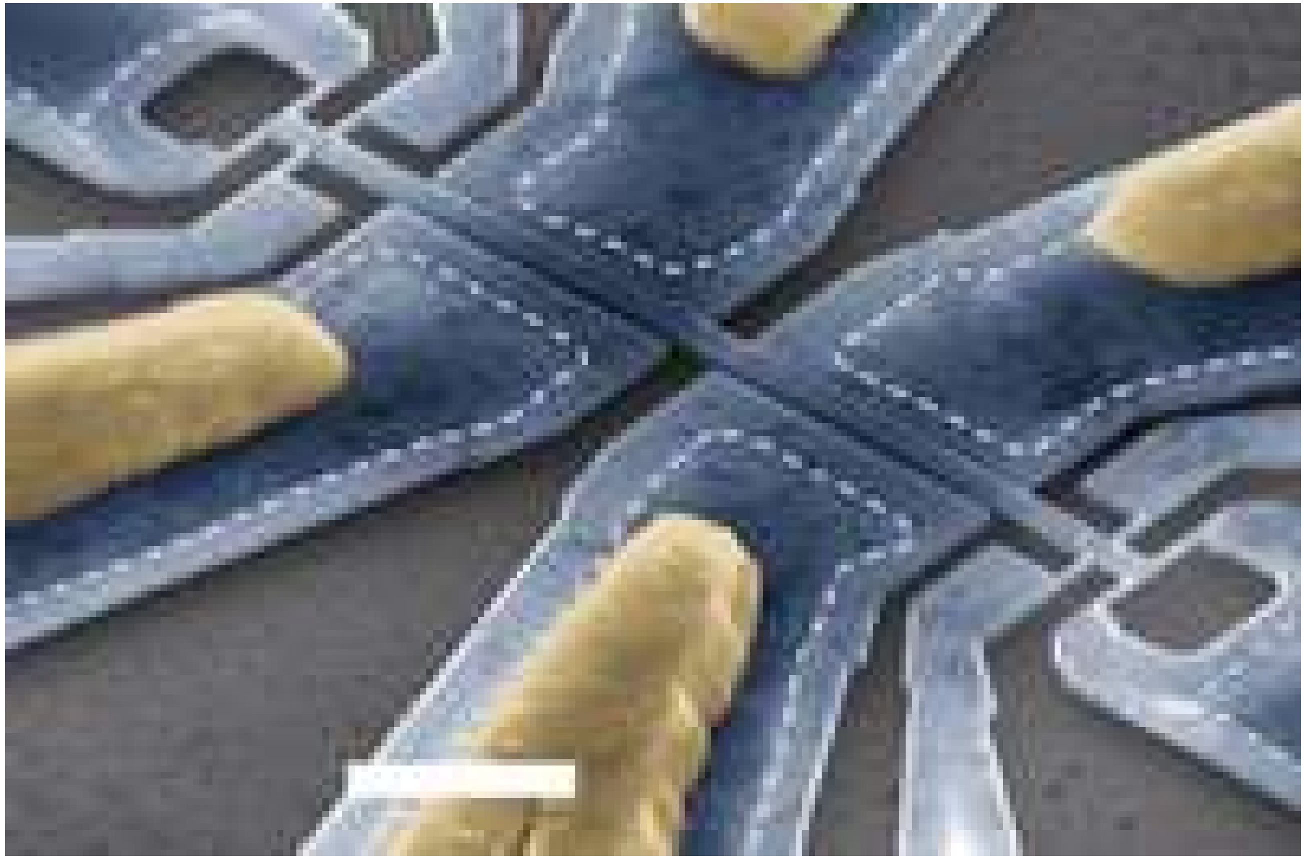
$$G \equiv \partial B_0 / \partial x$$





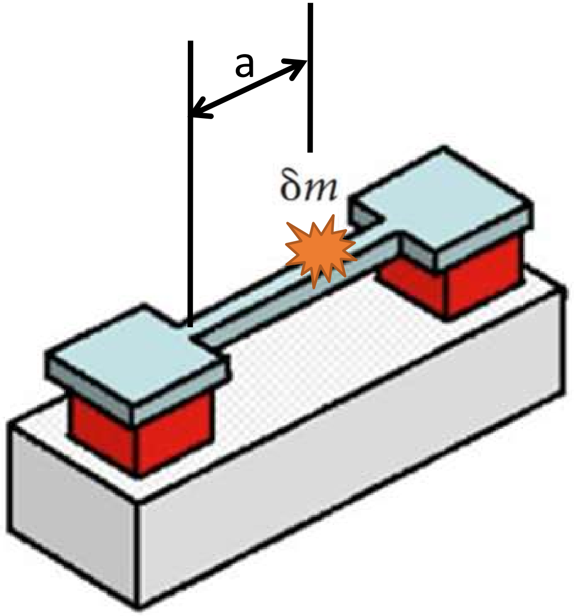
* D. Rugar *et.al.*, Single spin detection by magnetic resonance force microscopy, *Nature* **430**, 329 (2004).

예제: protein mass spectrometry

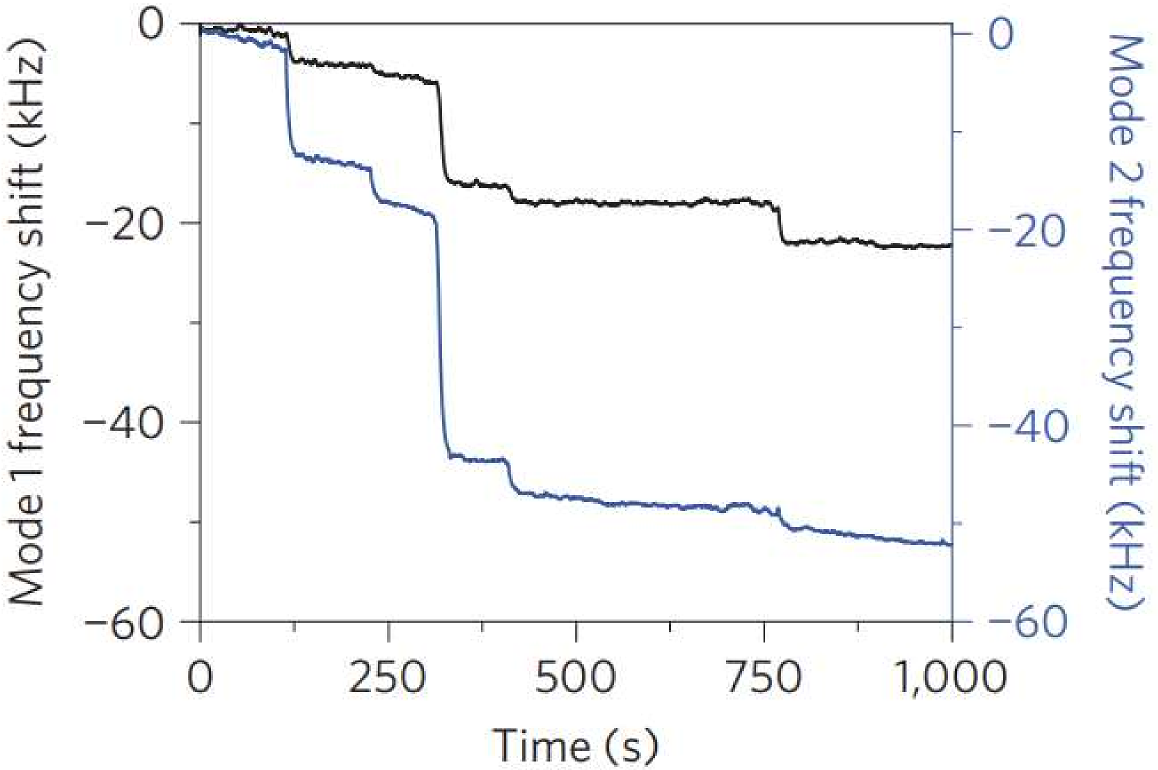


* M. S. Hanay *et.al.*, Single-protein nanomechanical mass spectrometry in real time, *Nat. Nano.* **7**, 602 (2012).

Mechanical mass sensing

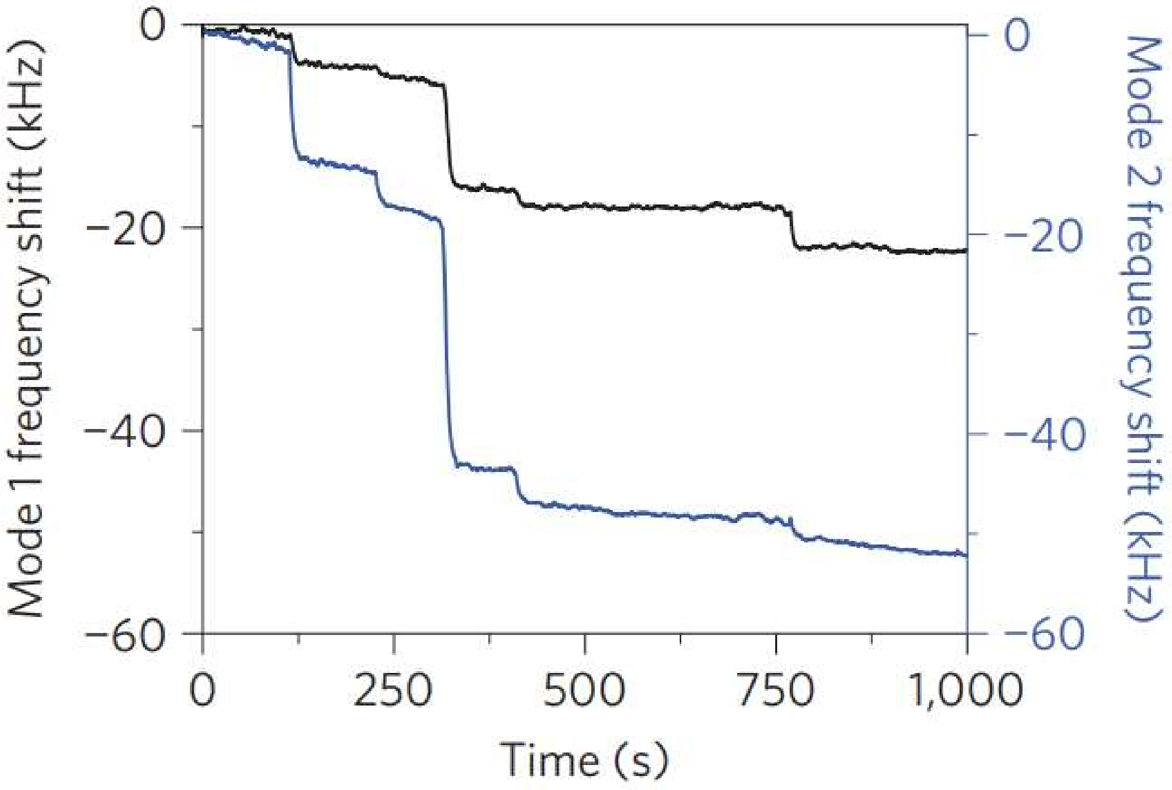


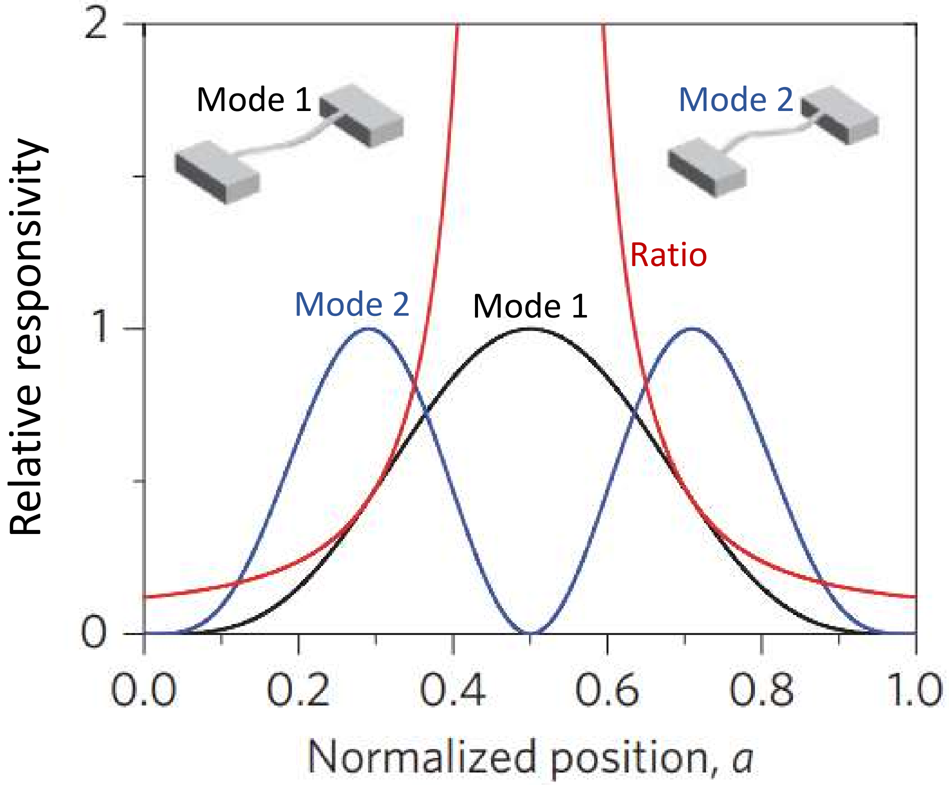
$$\frac{\delta f_n}{f_n} = -\frac{\delta m}{M}\frac{\varphi_n(a)^2}{\alpha_n}$$



* M. S. Hanay *et.al.*, Single-protein nanomechanical mass spectrometry in real time, *Nat. Nano.* **7**, 602 (2012).

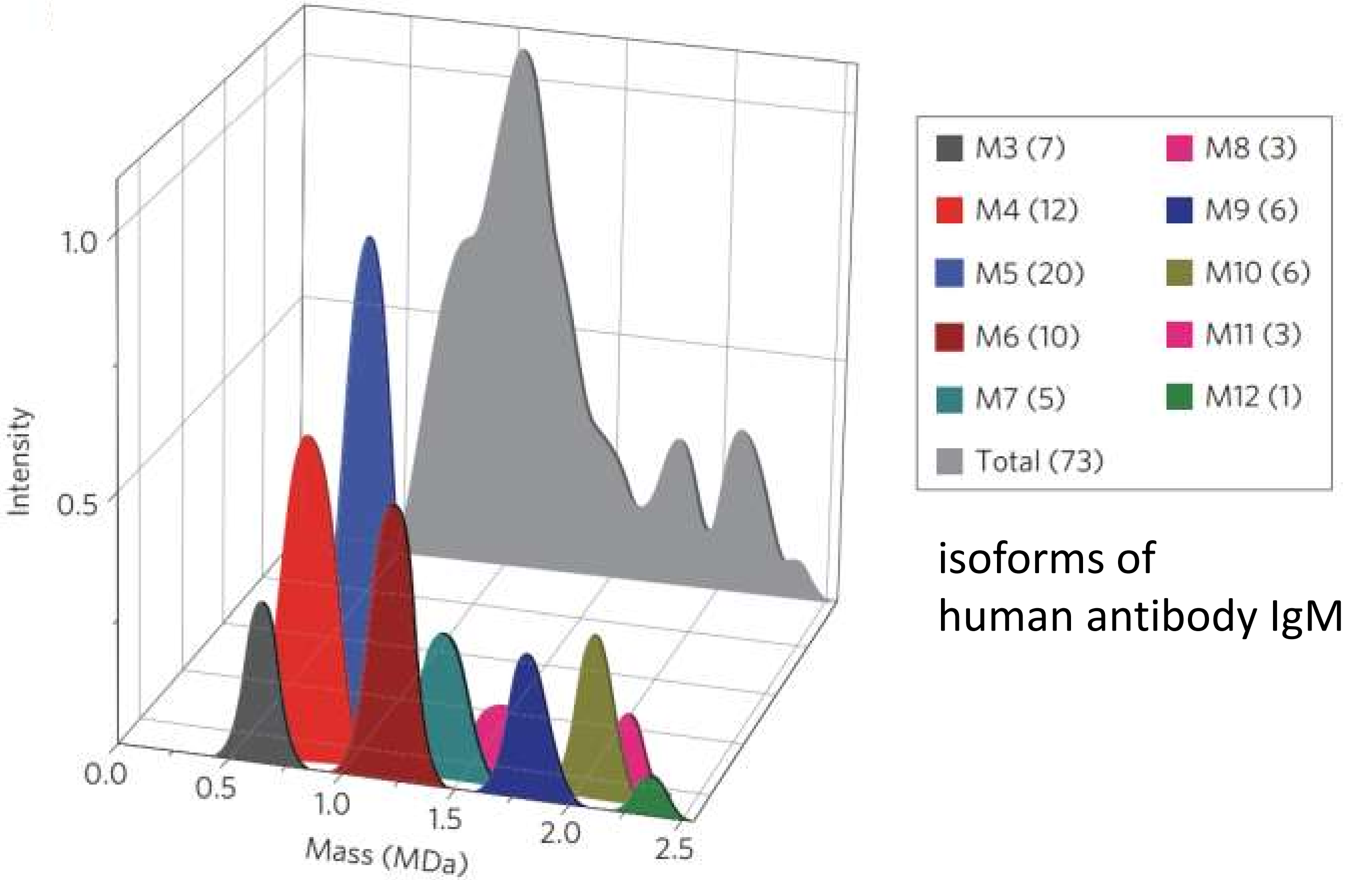
Multi-mode frequency measurement





* M. S. Hanay *et.al.*, Single-protein nanomechanical mass spectrometry in real time, *Nat. Nano.* **7**, 602 (2012).

Protein mass spectrometry



isoforms of
human antibody IgM

* M. S. Hanay *et.al.*, Single-protein nanomechanical mass spectrometry in real time, *Nat. Nano.* **7**, 602 (2012).

Quantum mechanics defines minimum uncertainty in position measurement

[redacted]

“standard quantum limit”

* C. M. Caves *et.al.*, *Rev. Mod. Phys.* **52**, 341 (1980).

Quantum mechanics defines minimum uncertainty in position measurement

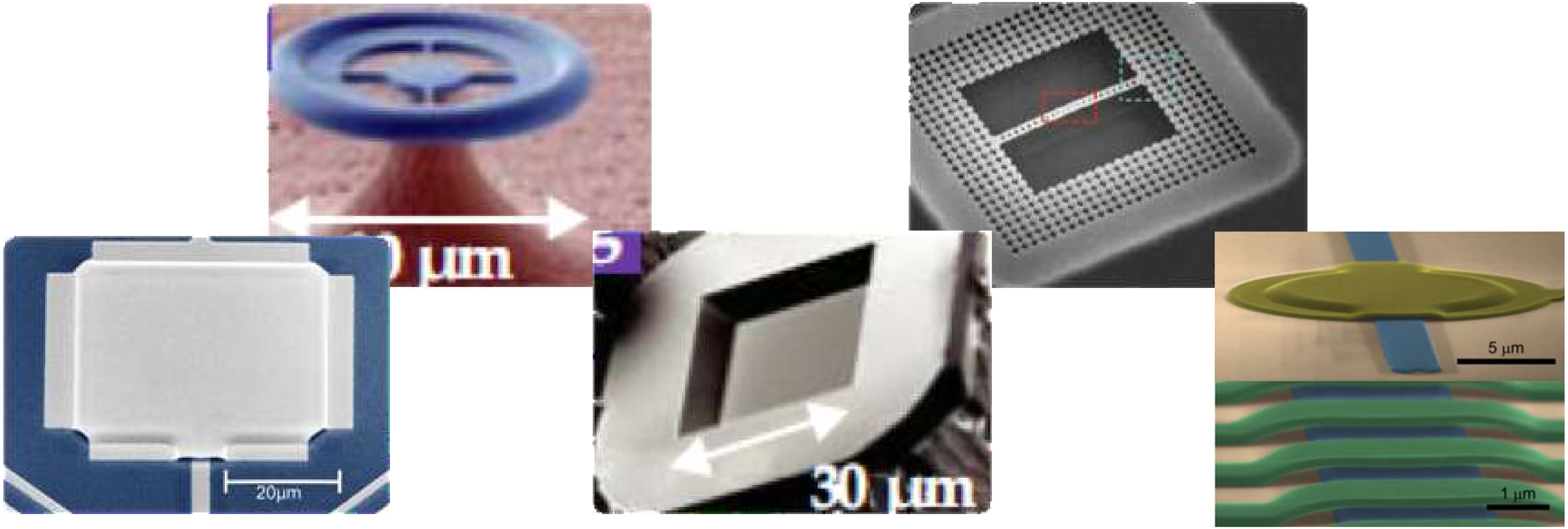
Quantum measurement of mechanical oscillators

||

Ultimate-precision force sensing

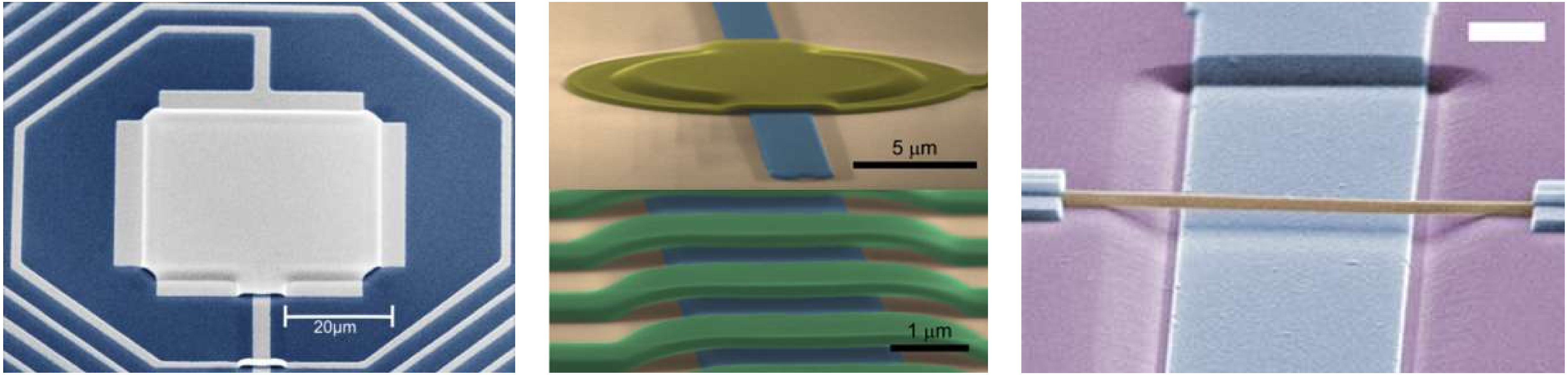
* C. M. Caves *et.al.*, *Rev. Mod. Phys.* **52**, 341 (1980).

Cavity optomechanical system (광역학계)



Strong coupling between phonons and photons

⇒ *hybrid quantum devices for quantum information science*



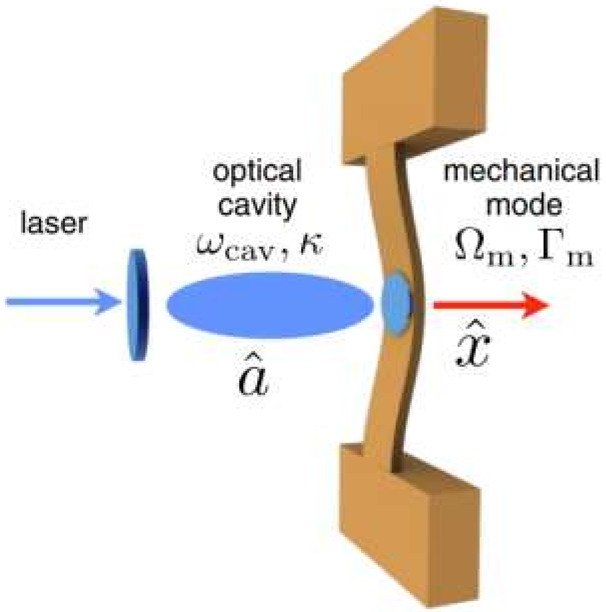
중시계 진동자의 광역학적 상호작용
Optomechanical interactions in mesoscopic oscillators

HQL
hybrid quantum device lab

Junho Suh

Pohang University of Science and Technology

Cavity optomechanical system (광역학계)



[Cavity Hamiltonian]

$$= \hbar \omega_{cav} \hat{a}^{\dagger} \hat{a}$$

↓

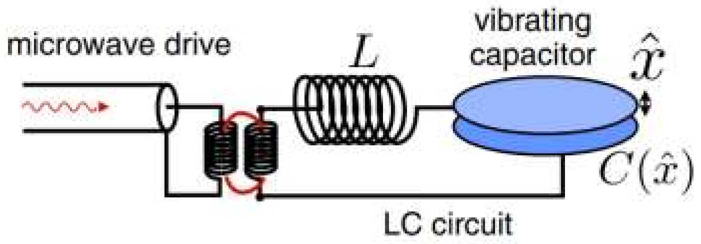
[Optomechanical interaction Hamiltonian]

$$= \hbar \frac{\partial \omega_{cav}}{\partial x} \hat{x} \hat{a}^{\dagger} \hat{a}$$

“radiation pressure”

$$L_{cav} = n\lambda = n\frac{2\pi c}{\omega_{cav}} \rightarrow \delta x = \delta L_{cav} \approx -n\frac{2\pi c}{{\omega_{cav}}^{2}}\delta\omega_{cav}$$

$$\frac{\partial \omega_{cav}}{\partial x} = \approx -\frac{{\omega_{cav}}^{2}}{2\pi c n}$$



$$\omega_{cav} = \frac{1}{\sqrt{LC}}; C = \frac{\varepsilon_0 A_{cap}}{d_{cap}} \rightarrow \delta x = \delta d_{cap} \approx \frac{2d_{cap}}{\omega_{cav}}\delta\omega_{cav}$$

$$\frac{\partial \omega_{cav}}{\partial x} = \approx \frac{\omega_{cav}}{2d_{cap}}$$

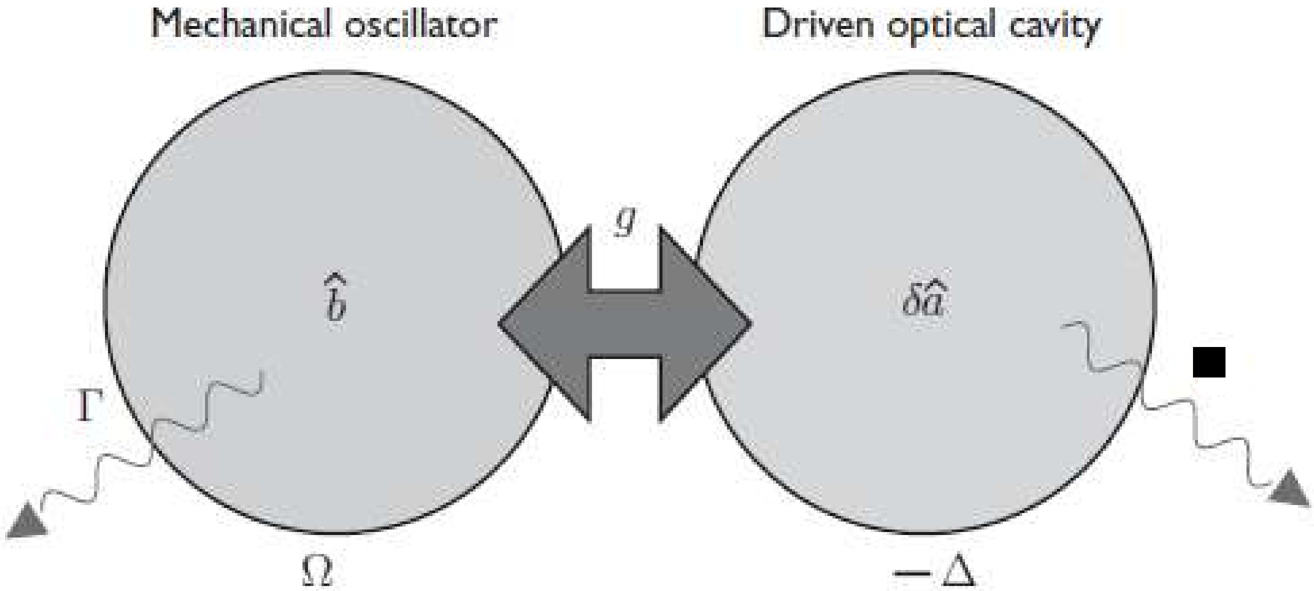
* Aspelmeyer *et al.*, *Rev. Mod. Phys.* **86**, 29 (2014).

Optomechanical interaction

* Devoret *et.al.*, *lecture notes of les houches summer school* (2011).

Optomechanical interaction

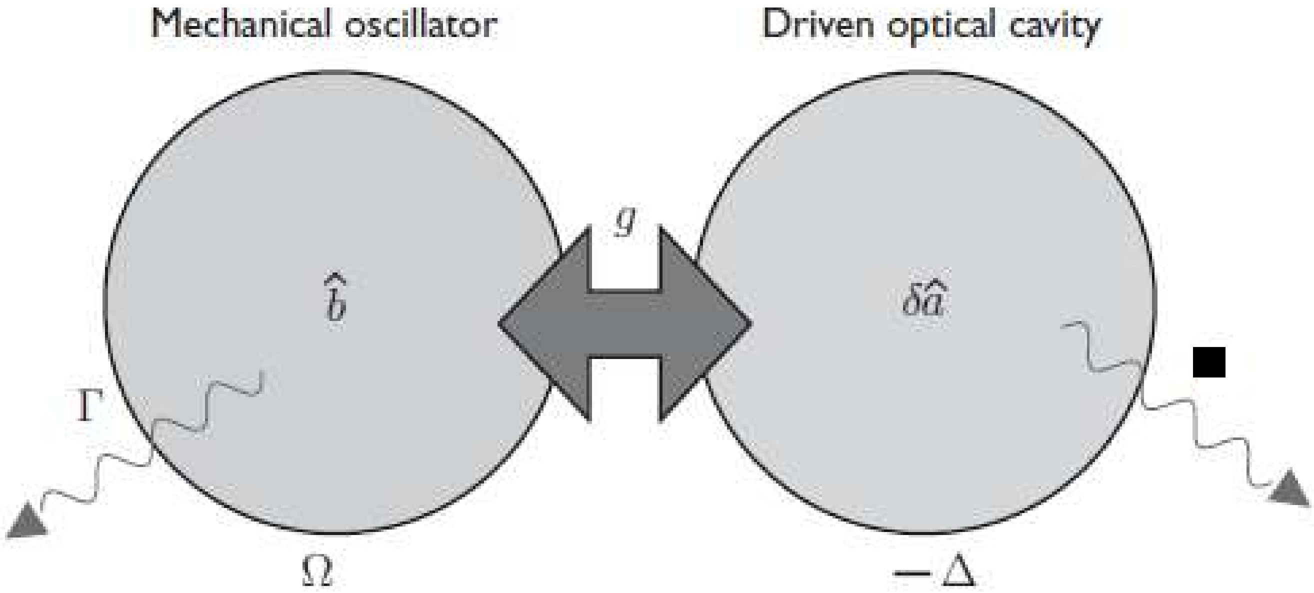
[redacted]



* Devoret *et.al., lecture notes of les houches summer school* (2011).

Optomechanical interaction

[redacted]



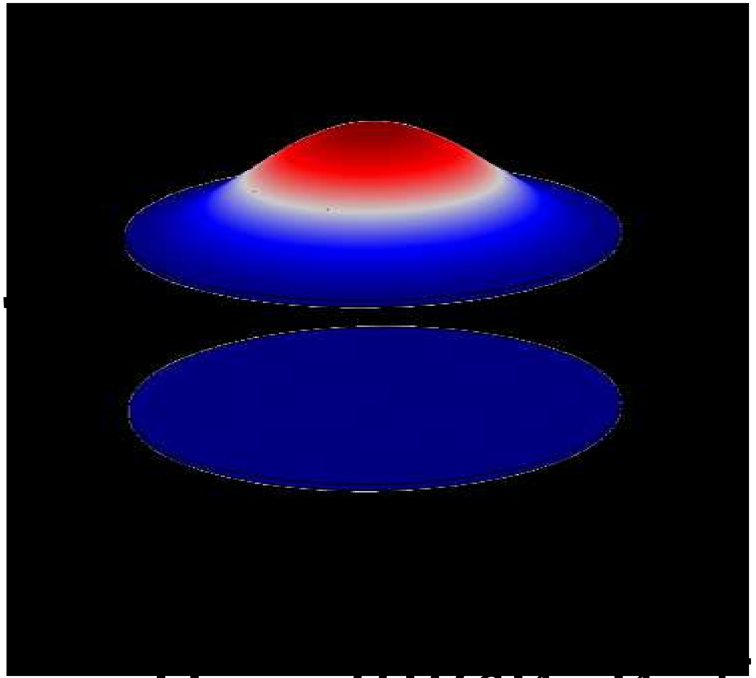
* Devoret *et.al., lecture notes of les houches summer school* (2011).

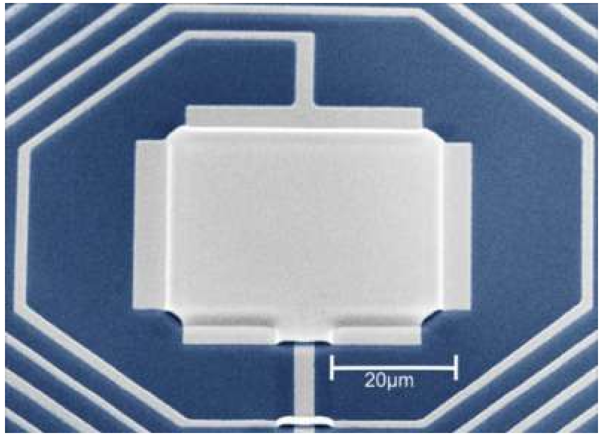
Optomechanical interaction

* Devoret *et.al., lecture notes of les houches summer school* (2011).

Microwave cavity optomechanical system

"L"



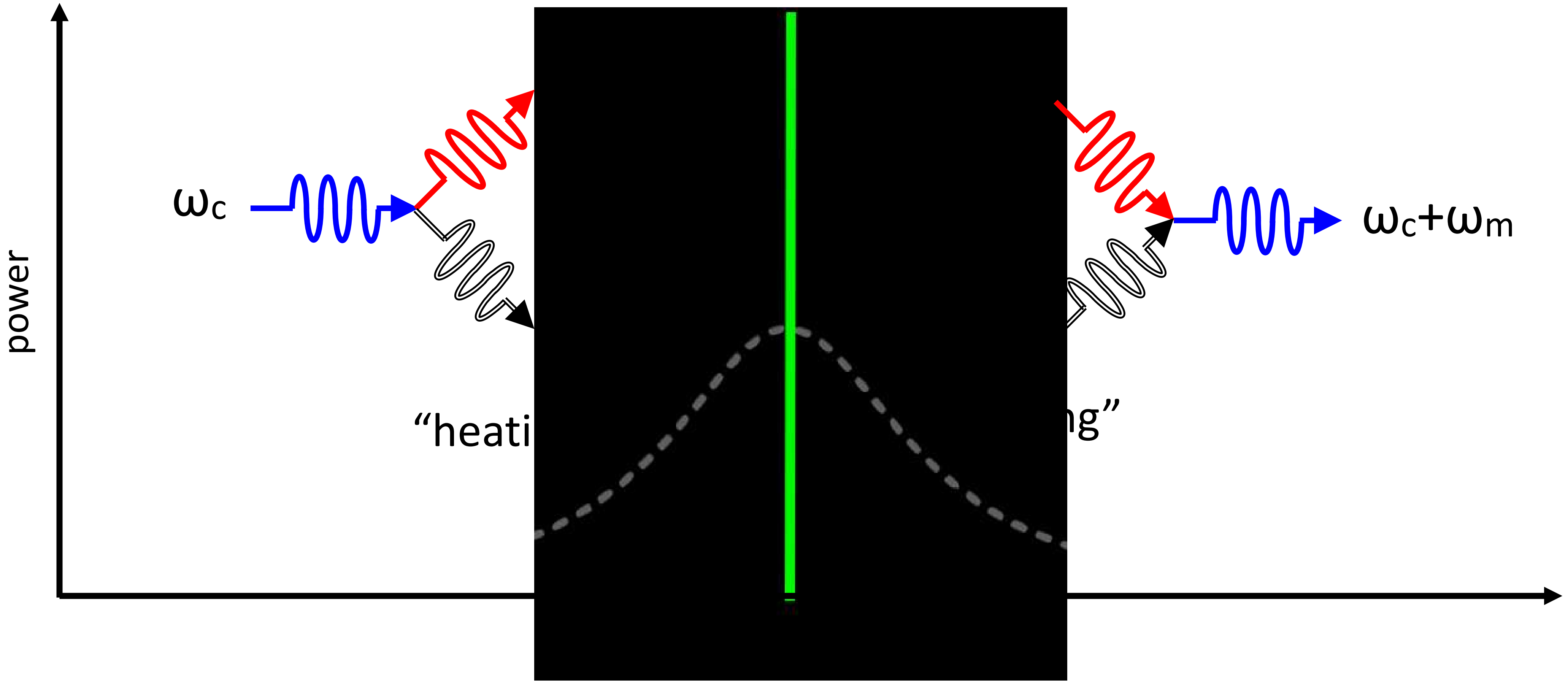


* **JS** et.al., *Science* **344,** 1262 (2014).

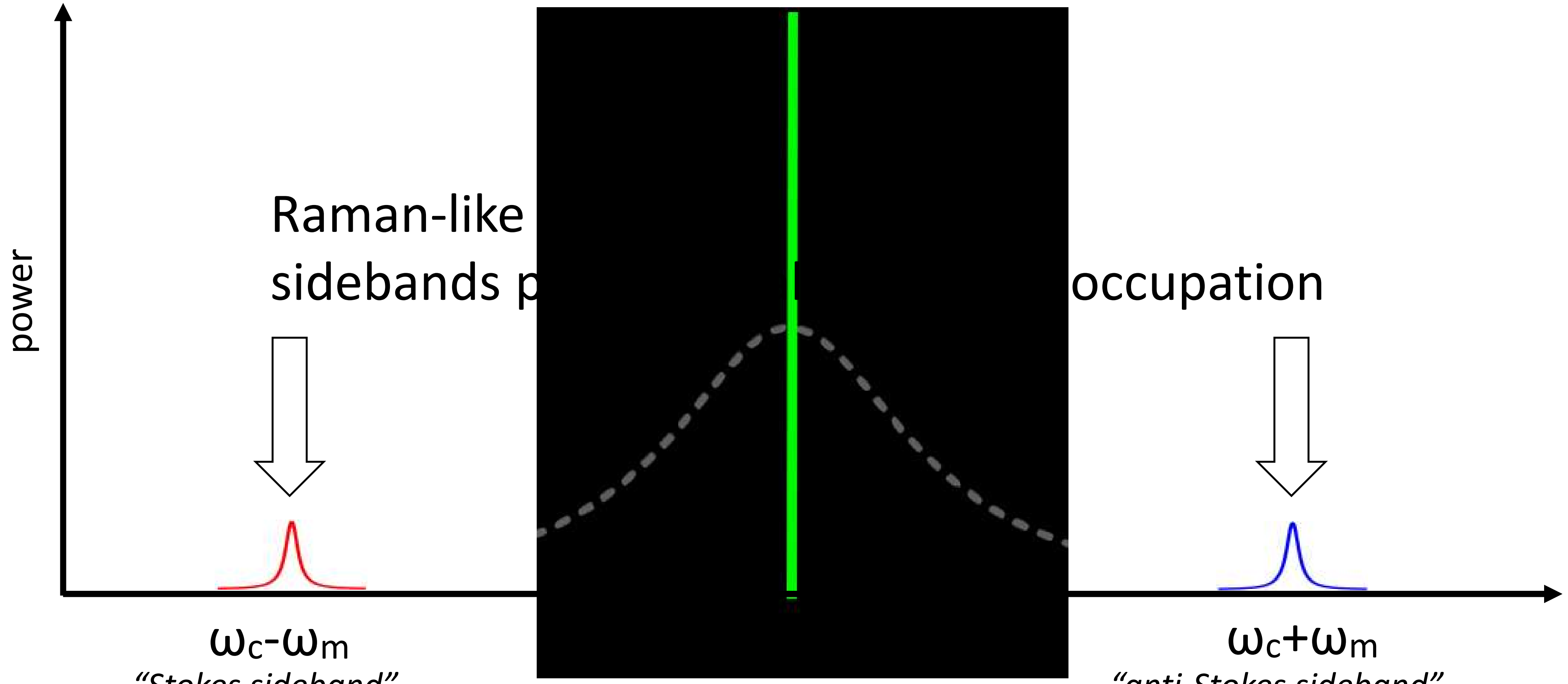
$$H = \hbar\omega_c\hat{a}^\dagger\hat{a} + \hbar\omega_m\hat{b}^\dagger\hat{b} + \hbar g\hat{a}^\dagger\hat{a}(\hat{b}^\dagger+\hat{b})$$

Photon	Phonon	Interaction
ω_c = 5.4 GHz	ω_m = 4 MHz	g = 14 Hz
κ = 0.9 MHz	Γ_m = 10 Hz	
	x_{zp} = 2 fm	

Photon-phonon coupling



Quantum-limited detection of motion



Raman-like

sidebands p occupation

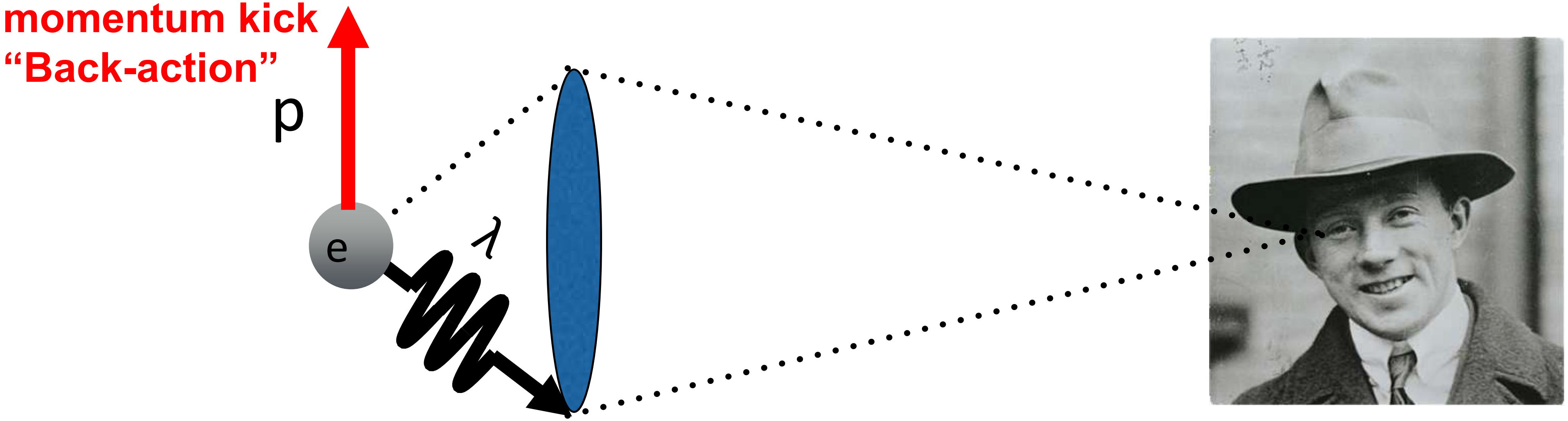
$\omega_c - \omega_m$

“Stokes sideband”

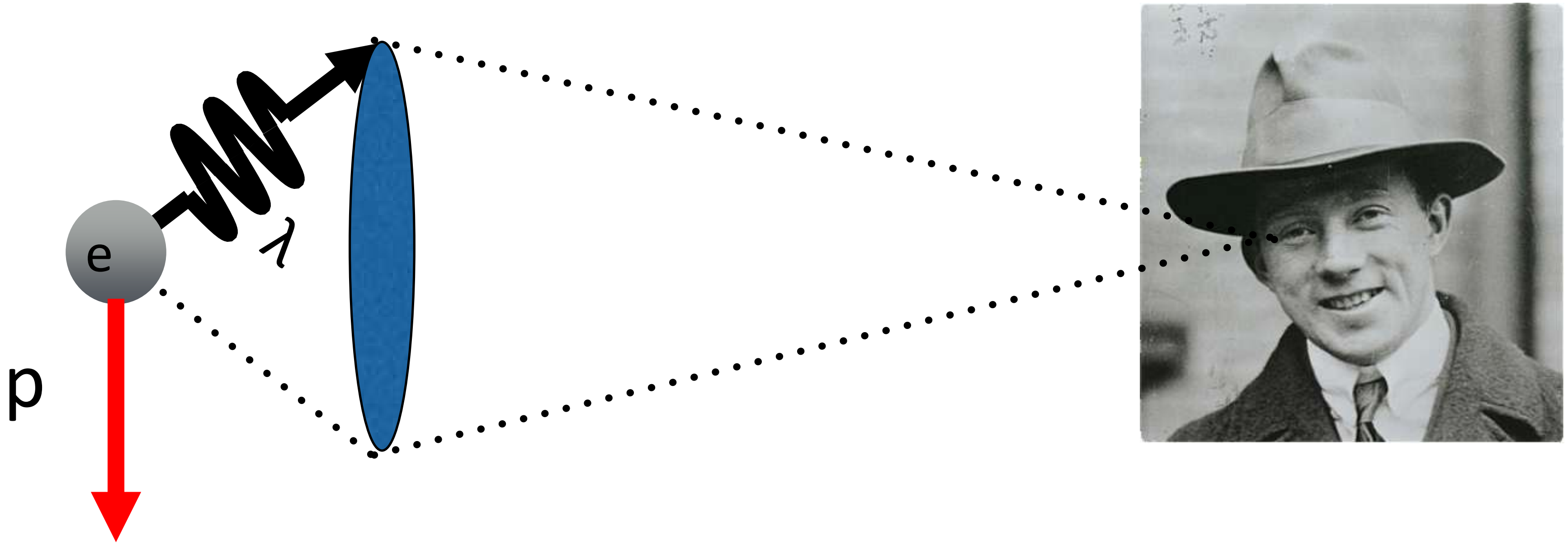
$\omega_c + \omega_m$

“anti-Stokes sideband”

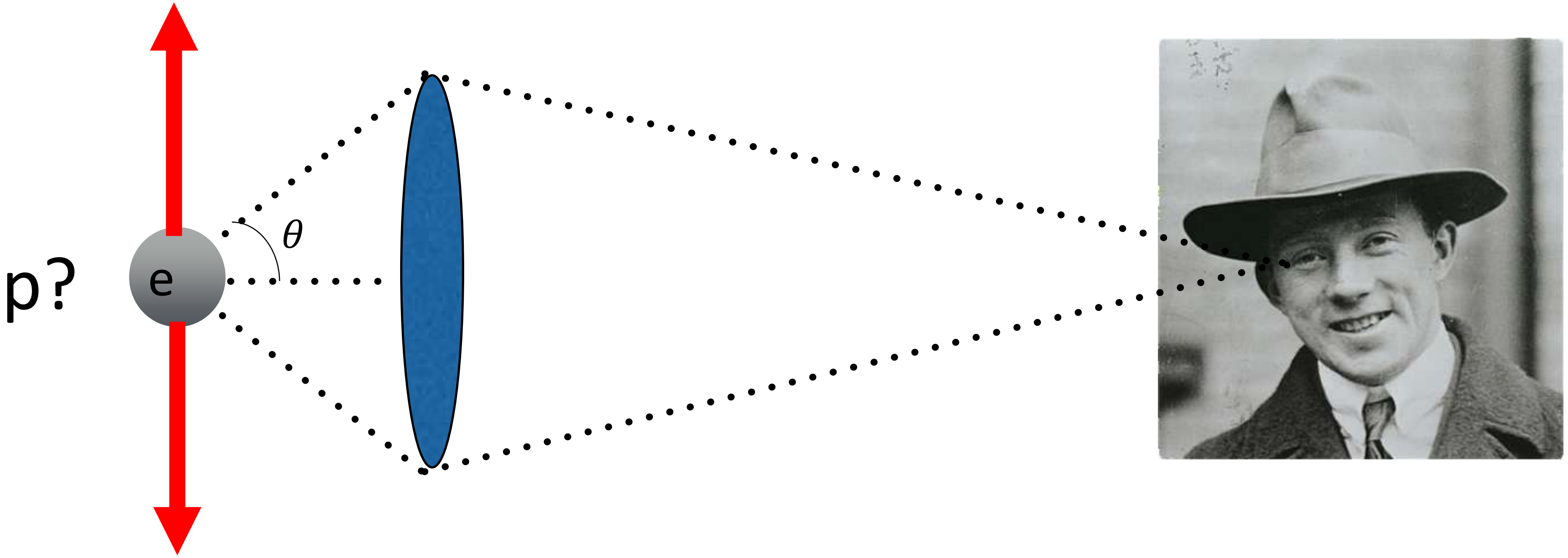
Measurement back-action in Heisenberg's microscope



Measurement back-action in Heisenberg’s microscope

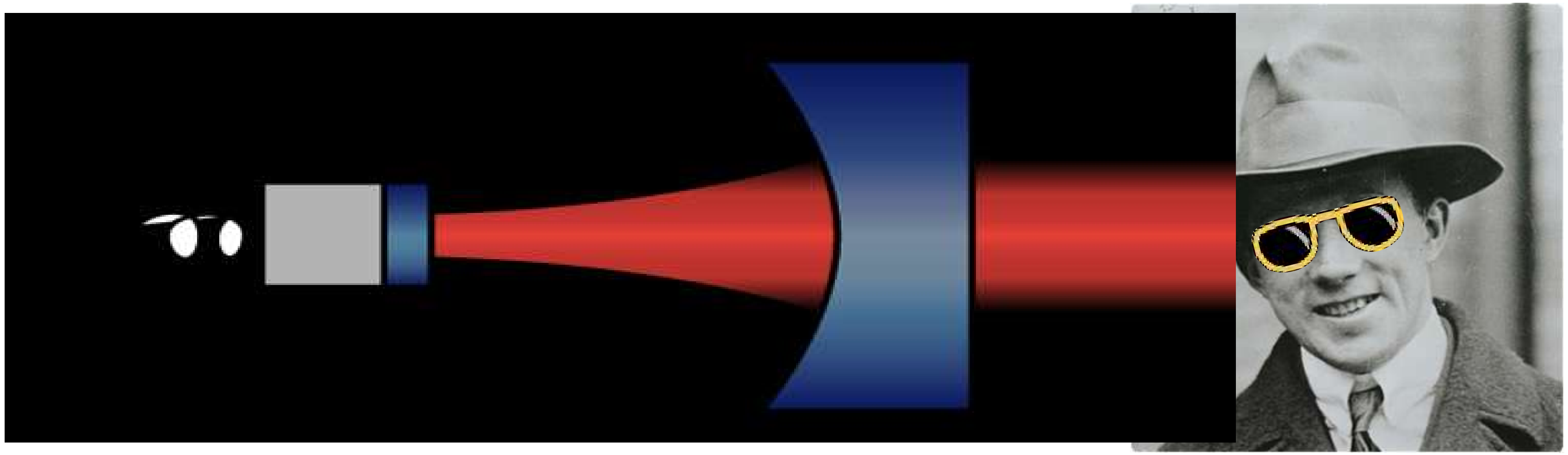


Measurement back-action in Heisenberg's microscope



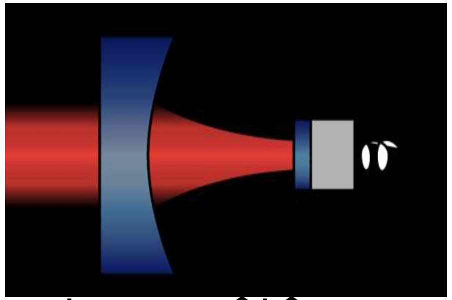
$$\Delta x \sim \frac{\lambda}{2\sin\theta} \quad \& \; \Delta p \sim \frac{h\sin\theta}{\lambda} \quad \rightarrow \Delta x \cdot \Delta p \sim \frac{h}{2}$$

How about mechanical oscillator?



Standard quantum limit

an *ideal* measurement of mechanical motion

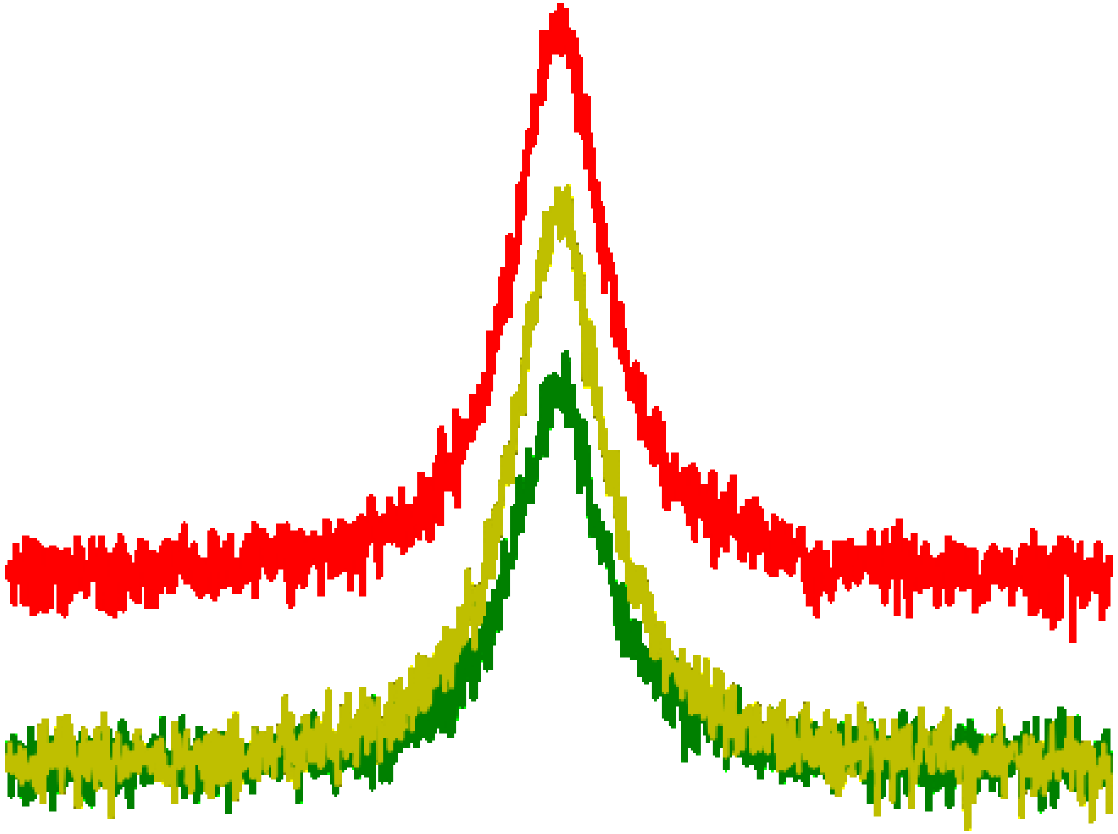


$$\hat{H} = \hbar\omega_c\hat{a}^\dagger\hat{a}+\hbar\omega_m\hat{b}^\dagger\hat{b} + \hbar g\hat{a}^\dagger\hat{a}(\hat{b}^\dagger + \hat{b})$$

photon

mechanics or “phonon”

interaction



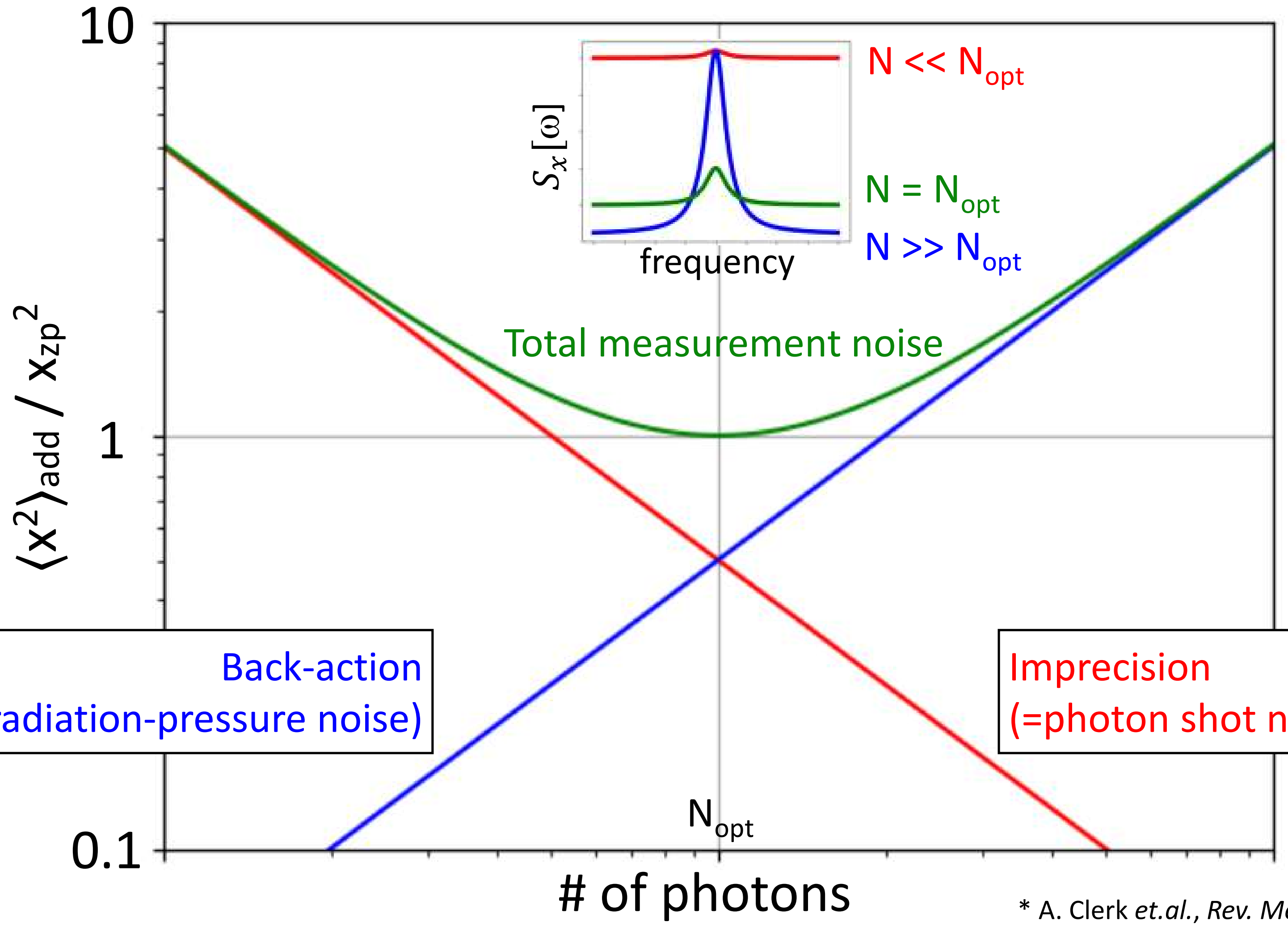
ation pressure noise
k-action”

on shot noise
recision”

(=

* A. Clerk *et.al.*, *Rev. Mod. Phys.* **82**, 1155 (2010).

Standard quantum limit

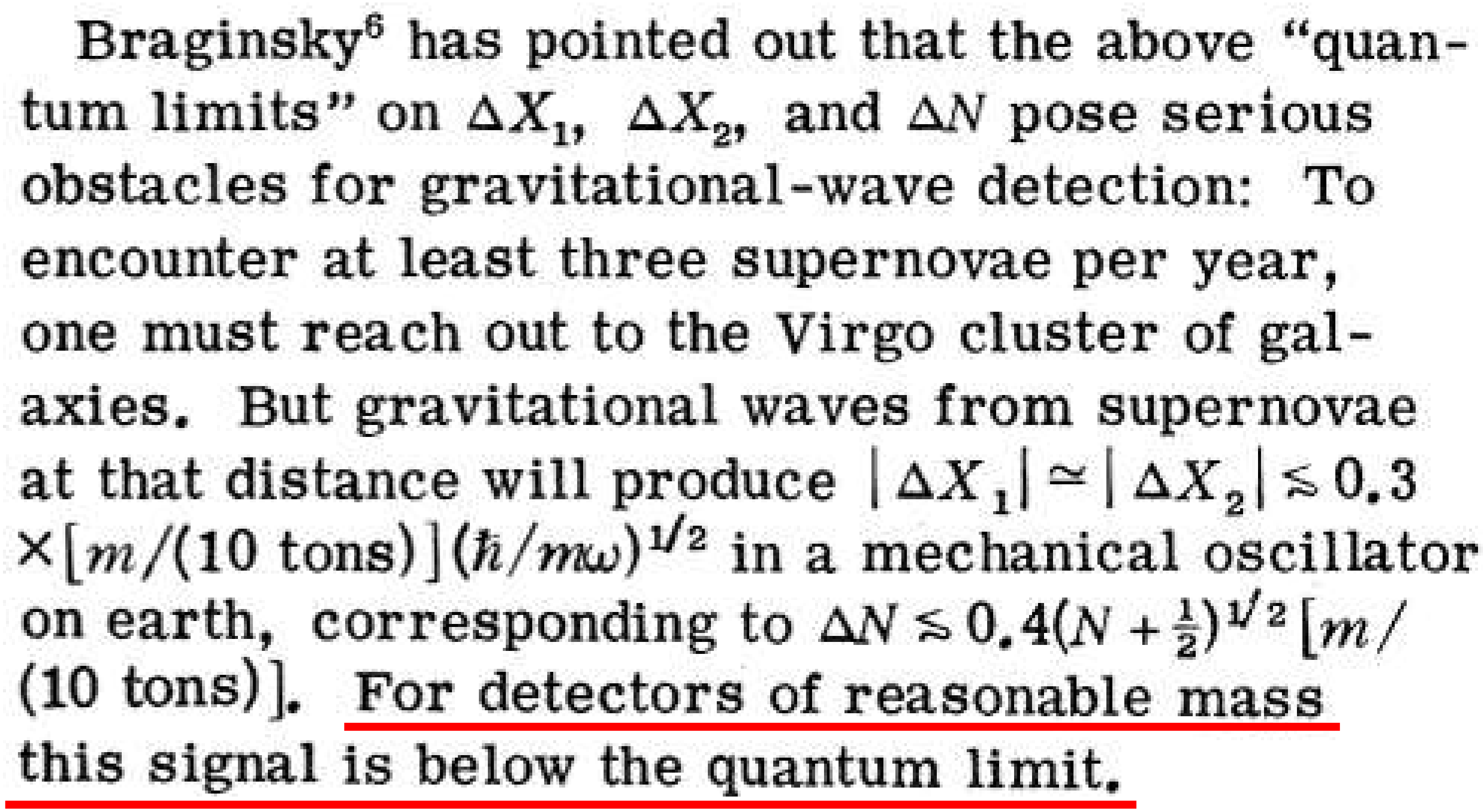


Back-action
(=radiation-pressure noise)

Imprecision
(=photon shot noise)

* A. Clerk *et.al.*, *Rev. Mod. Phys.* **82**, 1155 (2010).

Quantum limit in gravitational-wave detectors



Braginsky[6] has pointed out that the above "quantum limits" on ΔX_1, ΔX_2, and ΔN pose serious obstacles for gravitational-wave detection: To encounter at least three supernovae per year, one must reach out to the Virgo cluster of galaxies. But gravitational waves from supernovae at that distance will produce $|\Delta X_1| \simeq |\Delta X_2| \lesssim 0.3 \times [m/(10 \text{ tons})](\hbar/m\omega)^{1/2}$ in a mechanical oscillator on earth, corresponding to $\Delta N \lesssim 0.4(N+\frac{1}{2})^{1/2}[m/(10 \text{ tons})]$. For detectors of reasonable mass this signal is below the quantum limit.

* K. S. Thorne *et.al.*, *Phys. Rev. Lett.* **40**, 667 (1978).

Evading quantum back-action

[redacted]

“Quadratures” of motion

[redacted]

[redacted]

[redacted]

[redacted]

[redacted]

No back-action

Evading quantum back-action

$$\hat{x}(t) = \hat{X}_1 \cos\omega_m t + \hat{X}_2 \sin\omega_m t$$

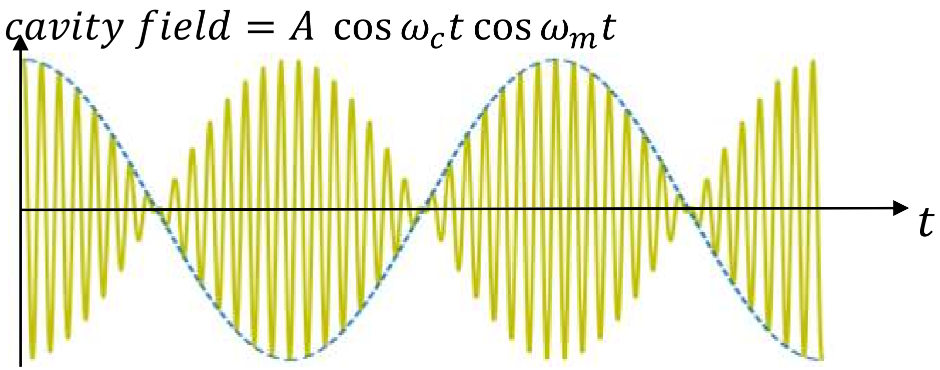
"Quadratures" of motion

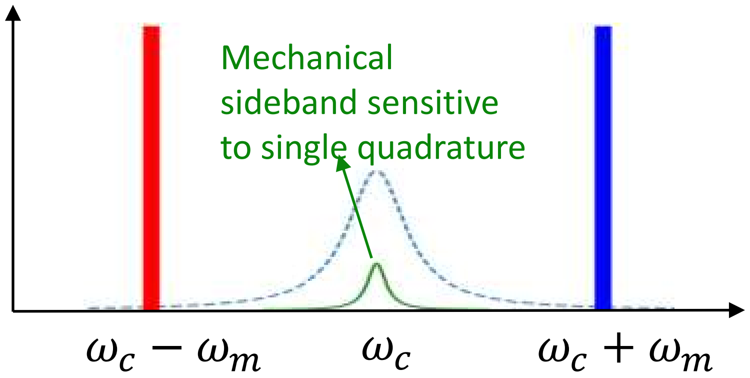
$\hat{X}_1, \hat{X}_2$: constants of motion of harmonic oscillator

⇒ can be measured with no back-action

⇒ back-action into the "unseen" quadrature

* Braginskii *et.al.*, *Sov. Phys. Usp.* **17**,644 (1975);
Thorne *et.al.*, *Phys. Rev. Lett.* **40**, 667 (1978).

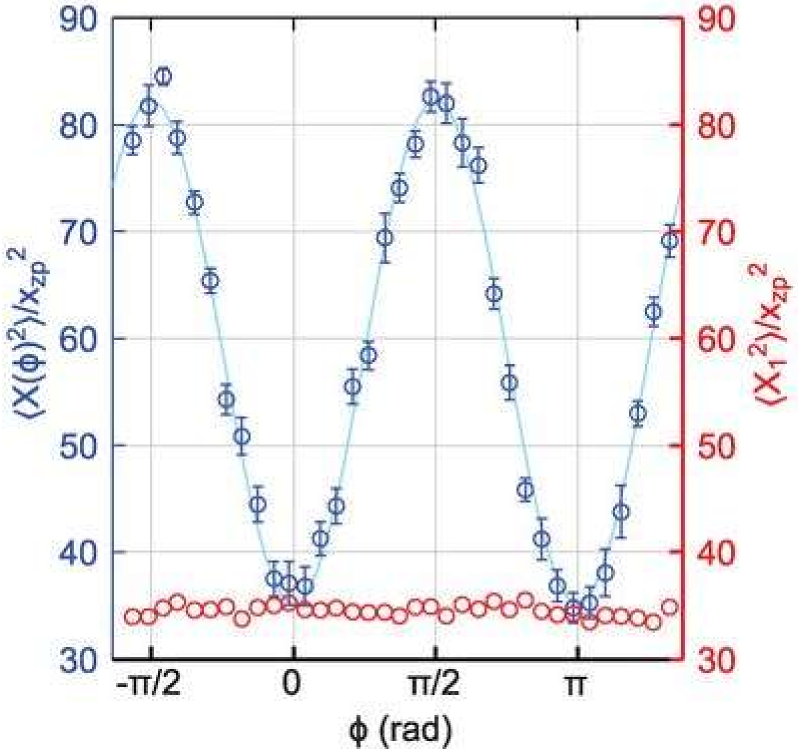




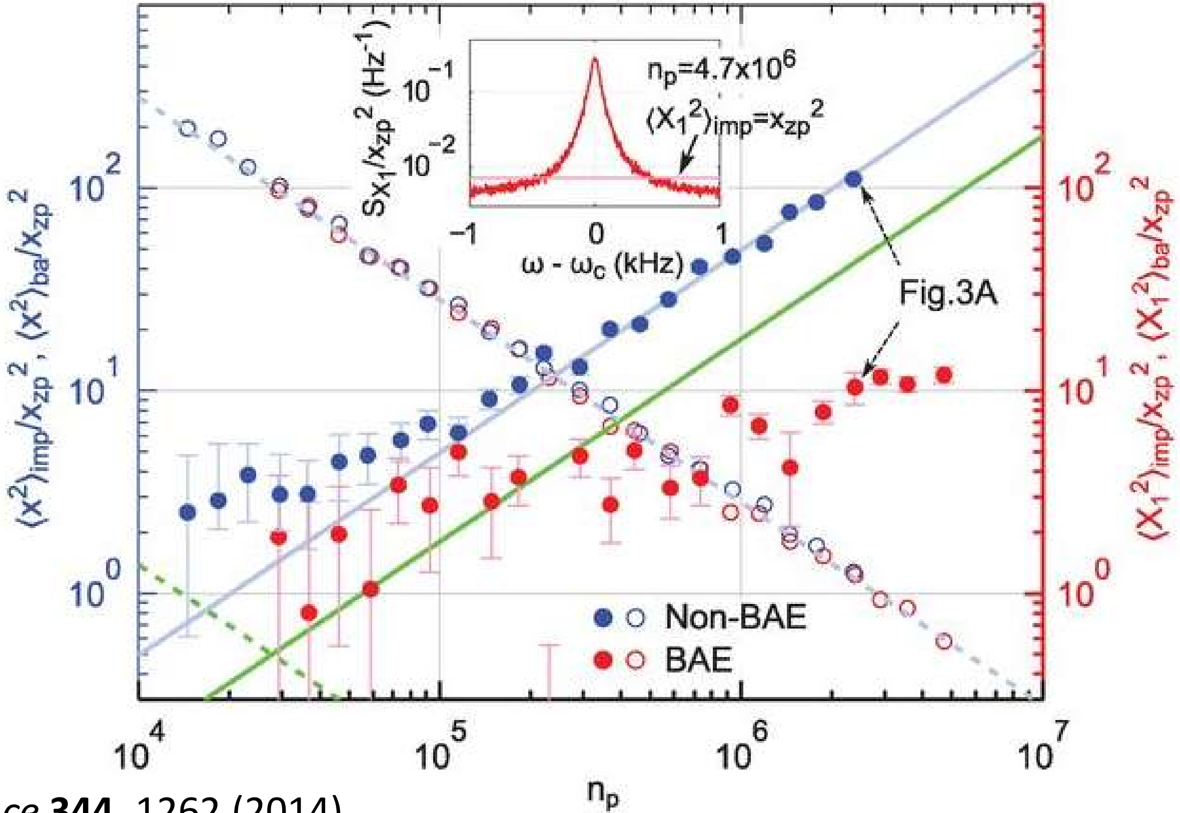
$$\hat{H}_{int} \propto \hat{X}_1(1 + \cos 2\omega_m t) + \hat{X}_2 \sin 2\omega_m t$$

Experiments

back-action on ONE quadrature

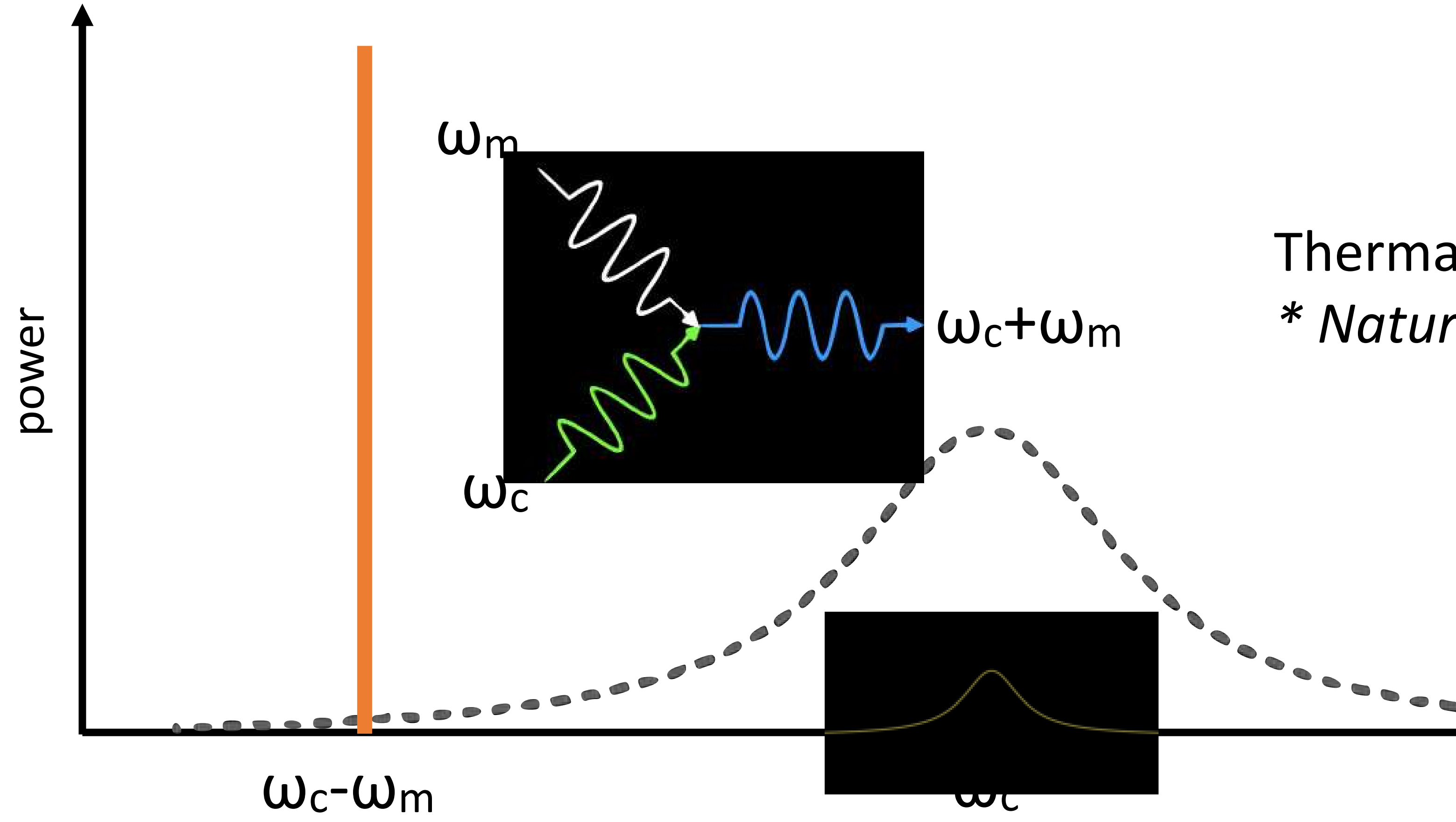


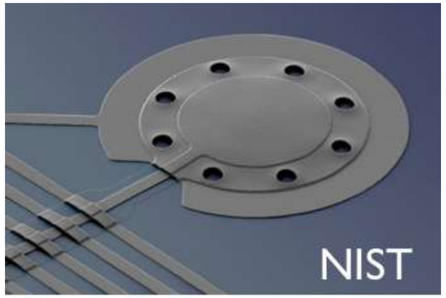
Evade quantum back-action by 8.5 dB



* **JS** et.al., *Science* **344,** 1262 (2014).

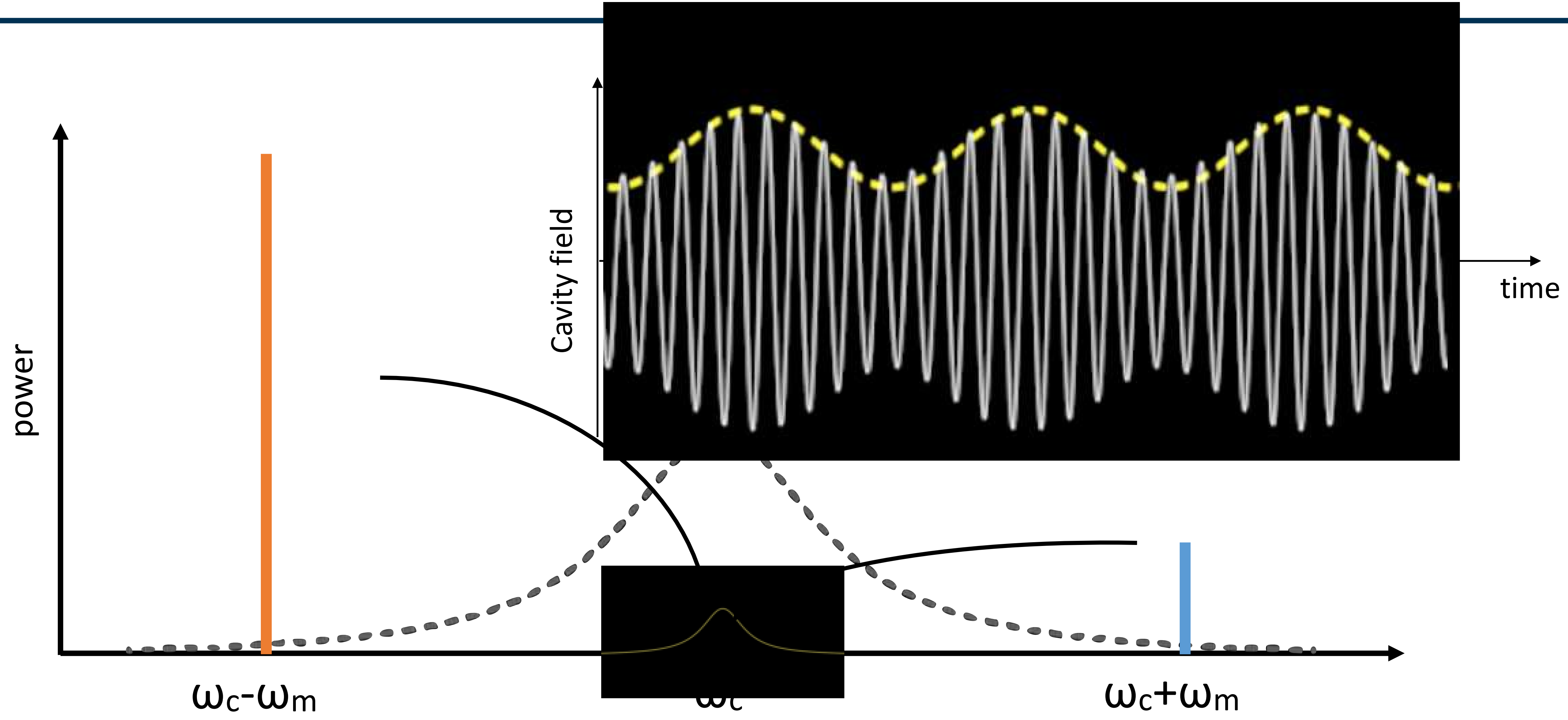
Ground state cooling of mechanical motion





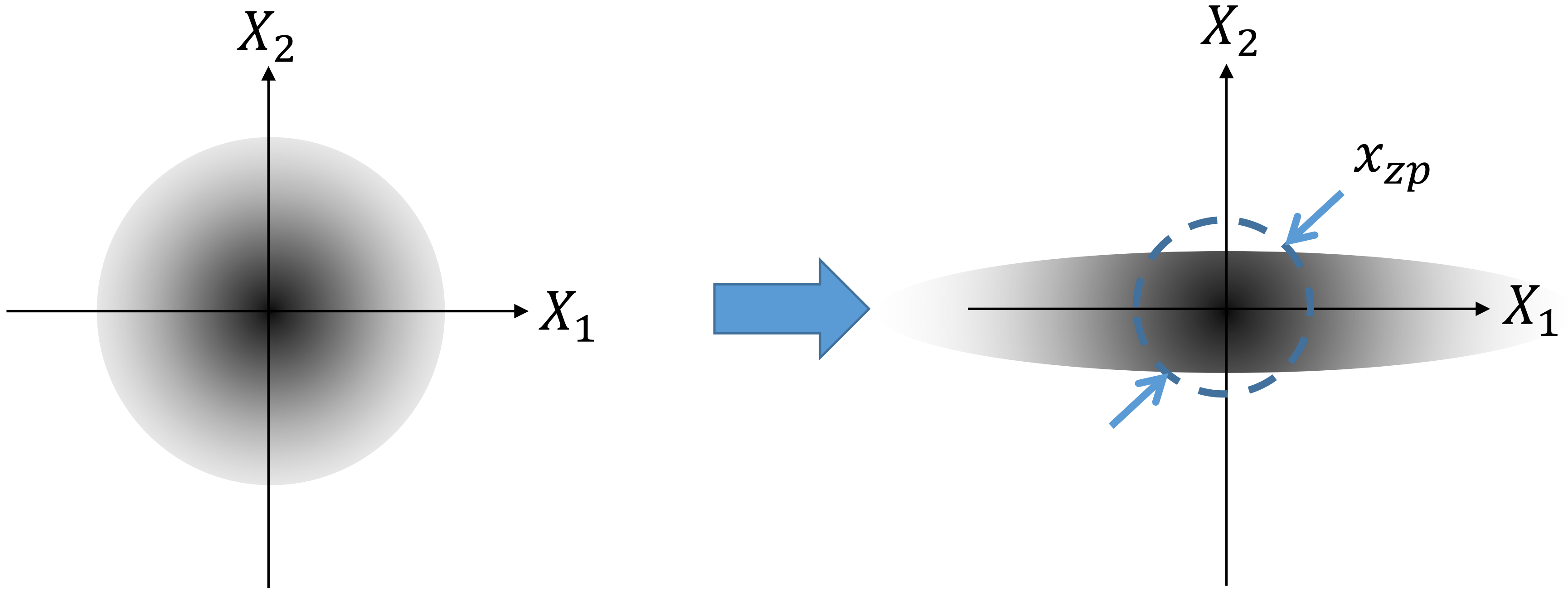
Thermal occupation factor ~ 0.2
* *Nature* **541**,191 (2017).

Phase-dependent cooling

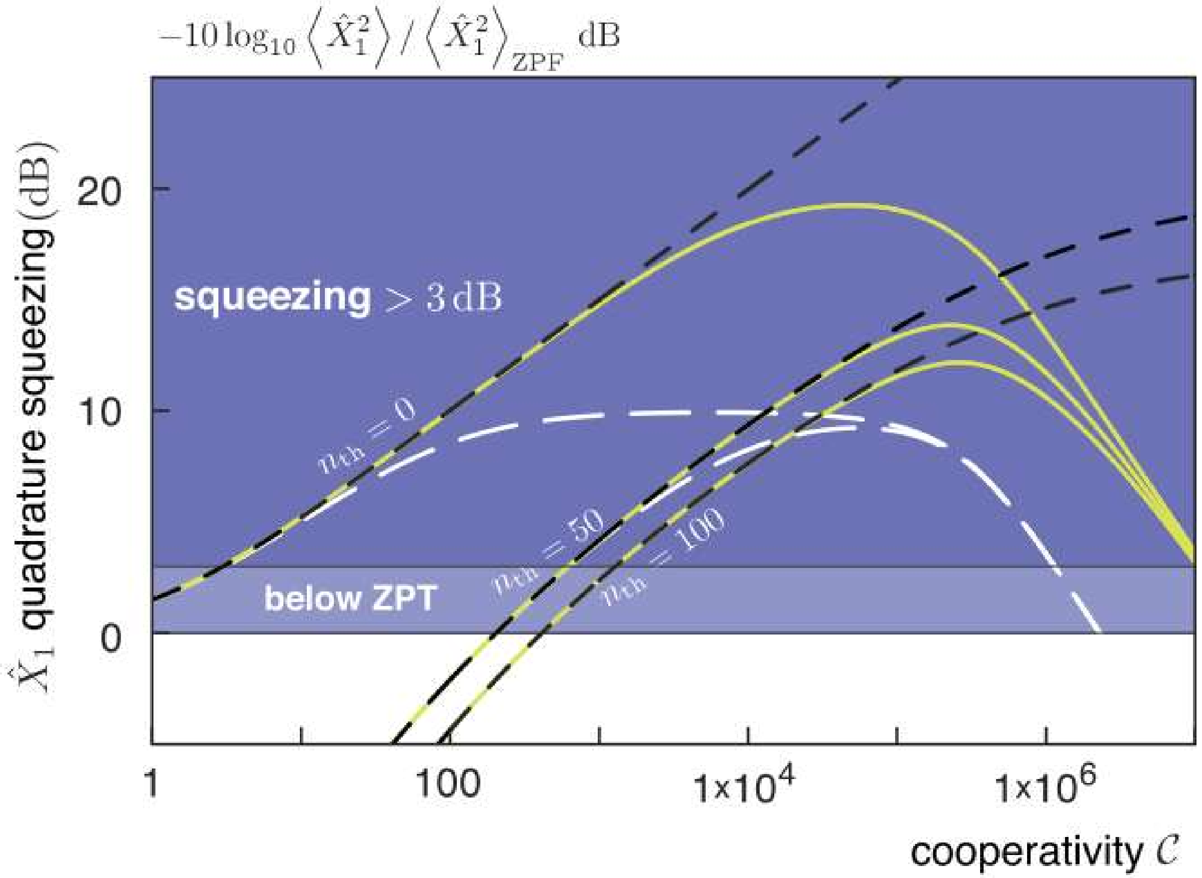


"Phase-dependent" reduction of mechanical motion (i.e. Squeezing)

$$\hat{x}(t) = \widehat{X_1}(t)\cos\omega_m t + \widehat{X_2}(t)\sin\omega_m t$$



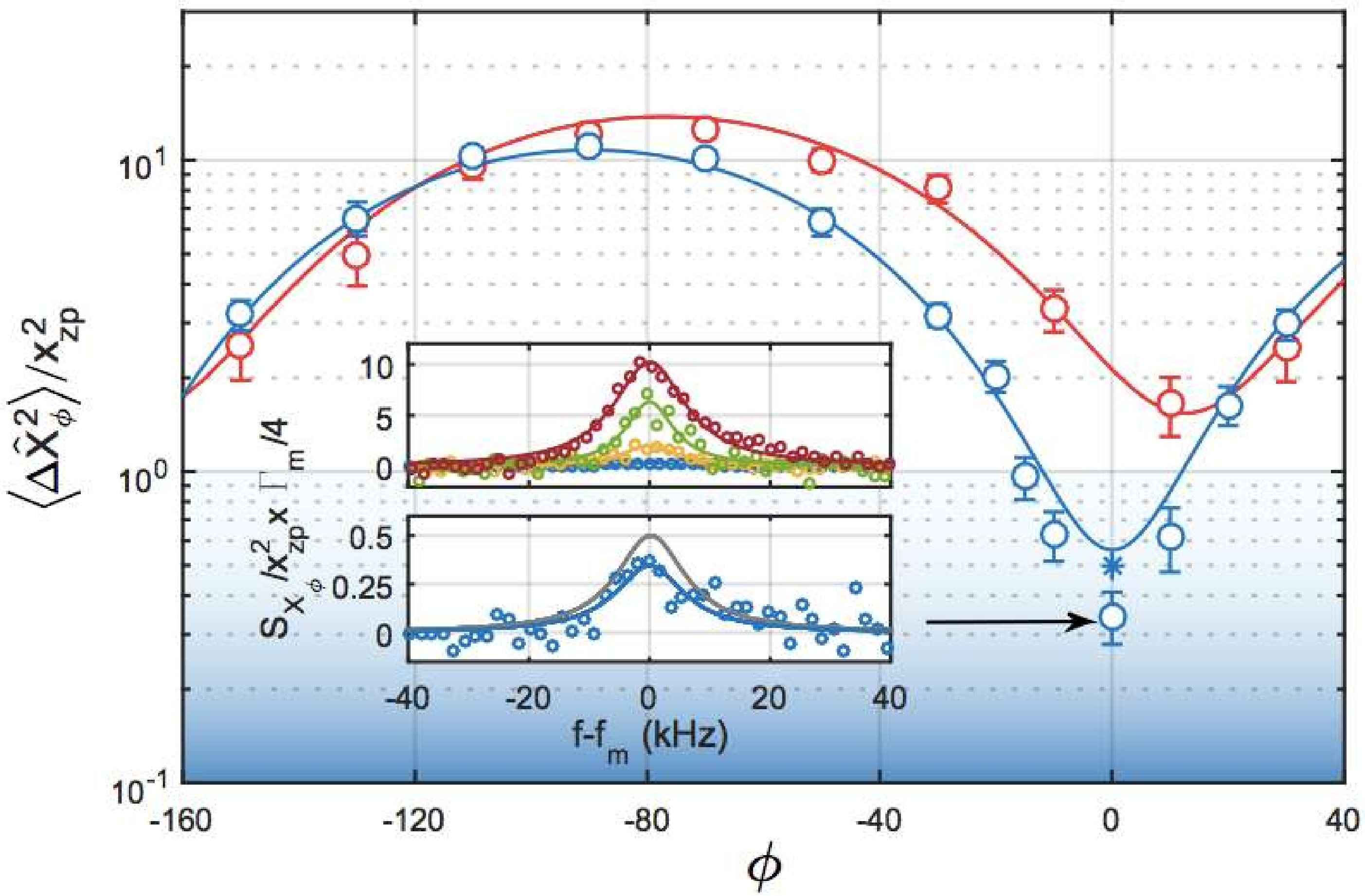
Arbitrarily large steady-state bosonic squeezing via dissipation



- Optimal ratio between red and blue power
- Squeezing beyond 3dB possible
- Steady state is squeezed thermal state
- State purity vs. squeezing

* Kronwald *et.al. Phys. Rev. A* **88**, 063833 (2014).

Squeezing more than 3 dB below zero-point

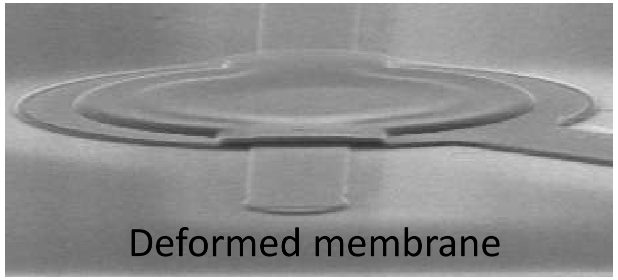


* Lei, Weinstein, **JS**, Wollman, Kronwald, Marquardt, Clerk, Schwab, *PRL* **117**, 100801 (2016).

Niobium for cavity optomechanical sensing under magnetic field

Niobium superconducts at higher temperatures and magnetic fields.

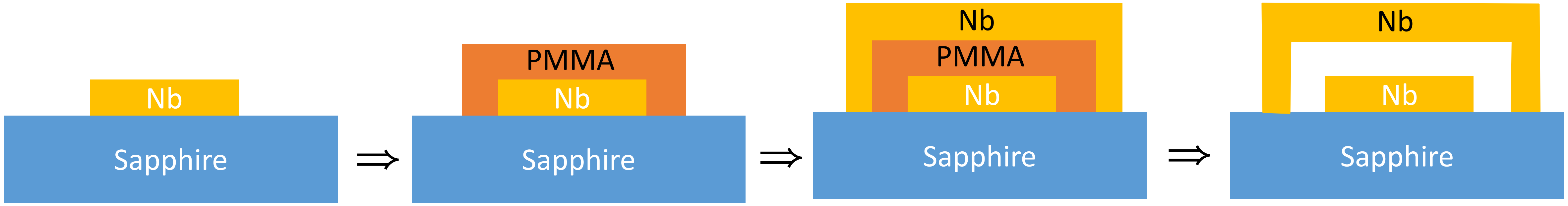
	Aluminum	Niobium
Critical Temperature (Tc)	1.2K	9.26K
Critical Magnetic Field(Hc)	0.01 T	0.82 T
Density	2700 kg/m^3	8570 kg/m^3
Young's modulus	70 Gpa	105 GPa
Poisson ratio	0.35	0.4
Advantages	• Easy to control the film stress • Large zero point motion due to the small mass	• Good mechanical properties • High critical temperature and magnetic field
Disadvantages	• Low critical temperature	• Difficult to control the film stress



Jinwoong Cha (KRISS)

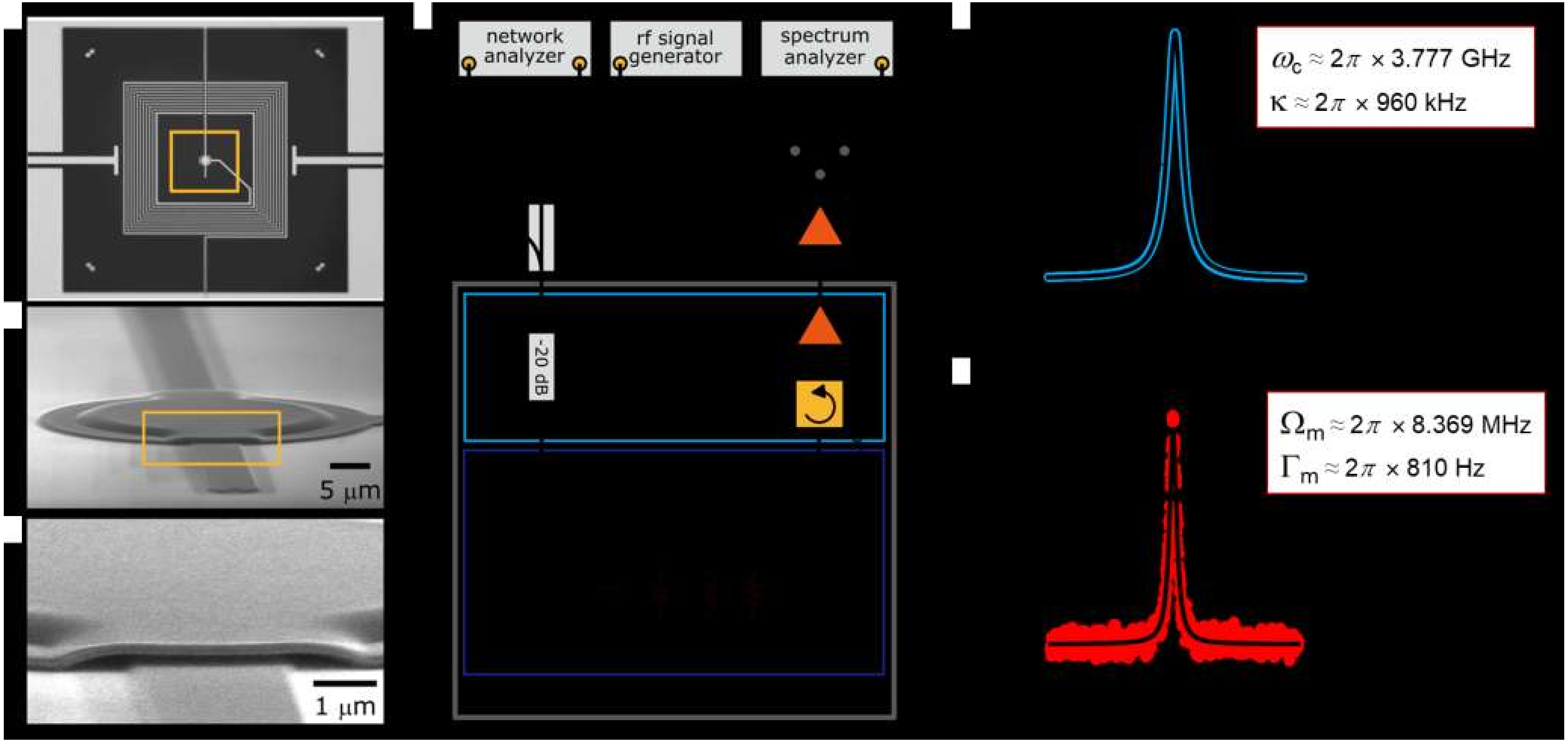
* J. Cha *et.al.*, *"Superconducting Nanoelectromechanical Transducer Resilient to Magnetic Fields"*, *Nano Letters* **21**, 1800 (2021).

Fabrication



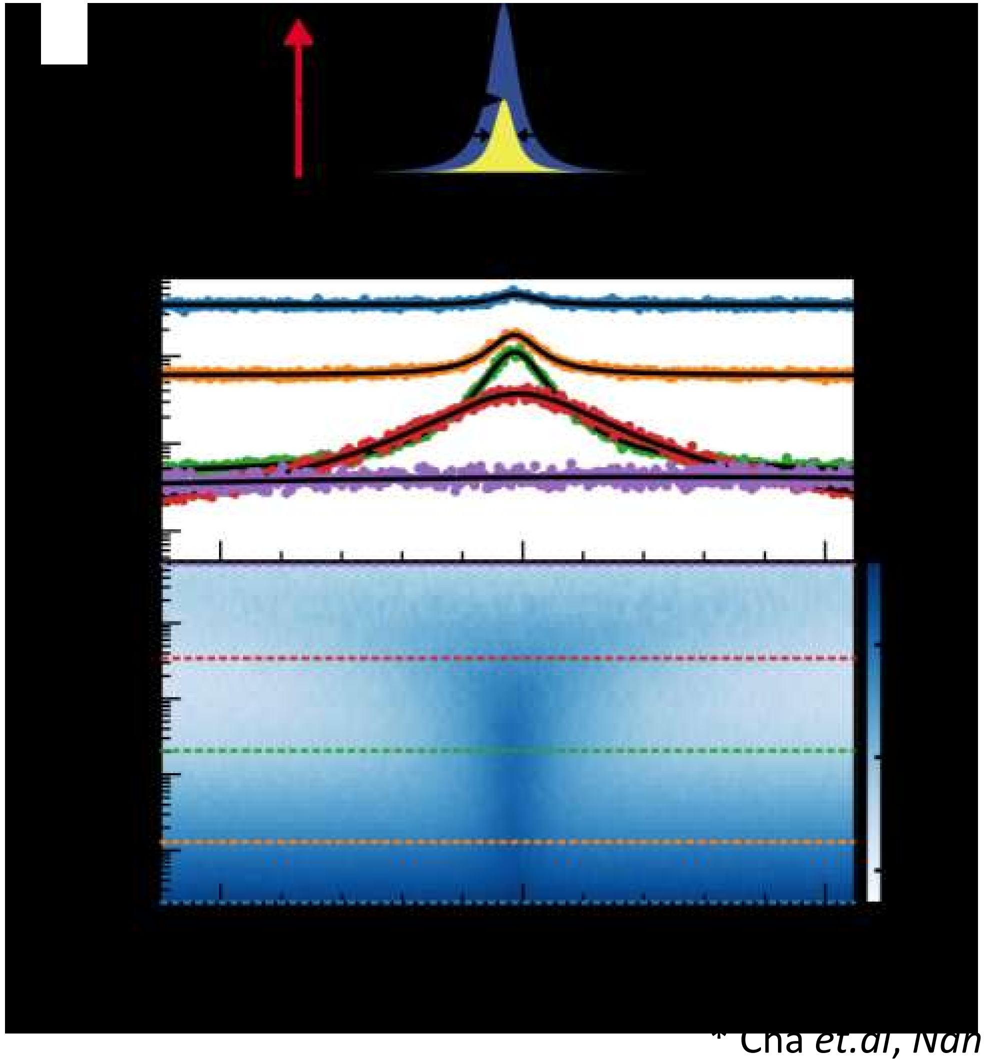
《Bottom Nb》 《Sacrificial PMMA》 《Top Nb》 《Release》

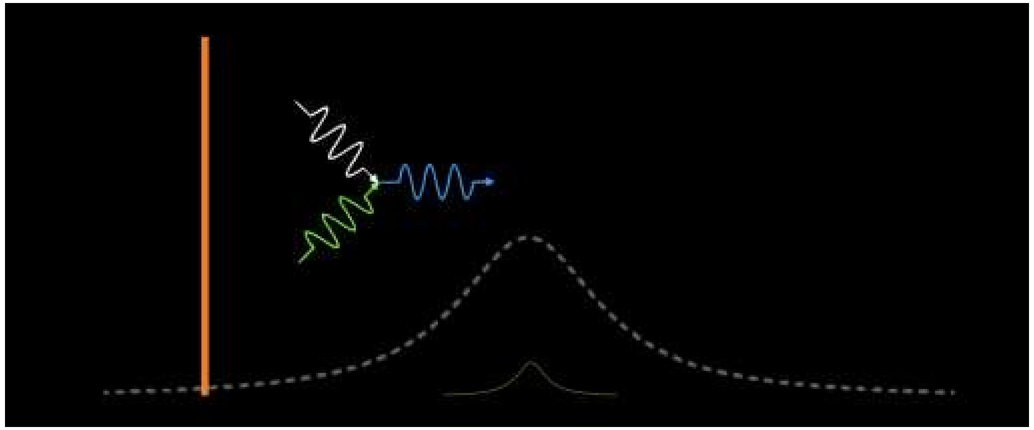
Microwave cavity optomechanics at 4.2 K



* Cha *et.al*, *Nano Letters* **21**, 1800 (2021).

Back-action cooling at 4.2 K

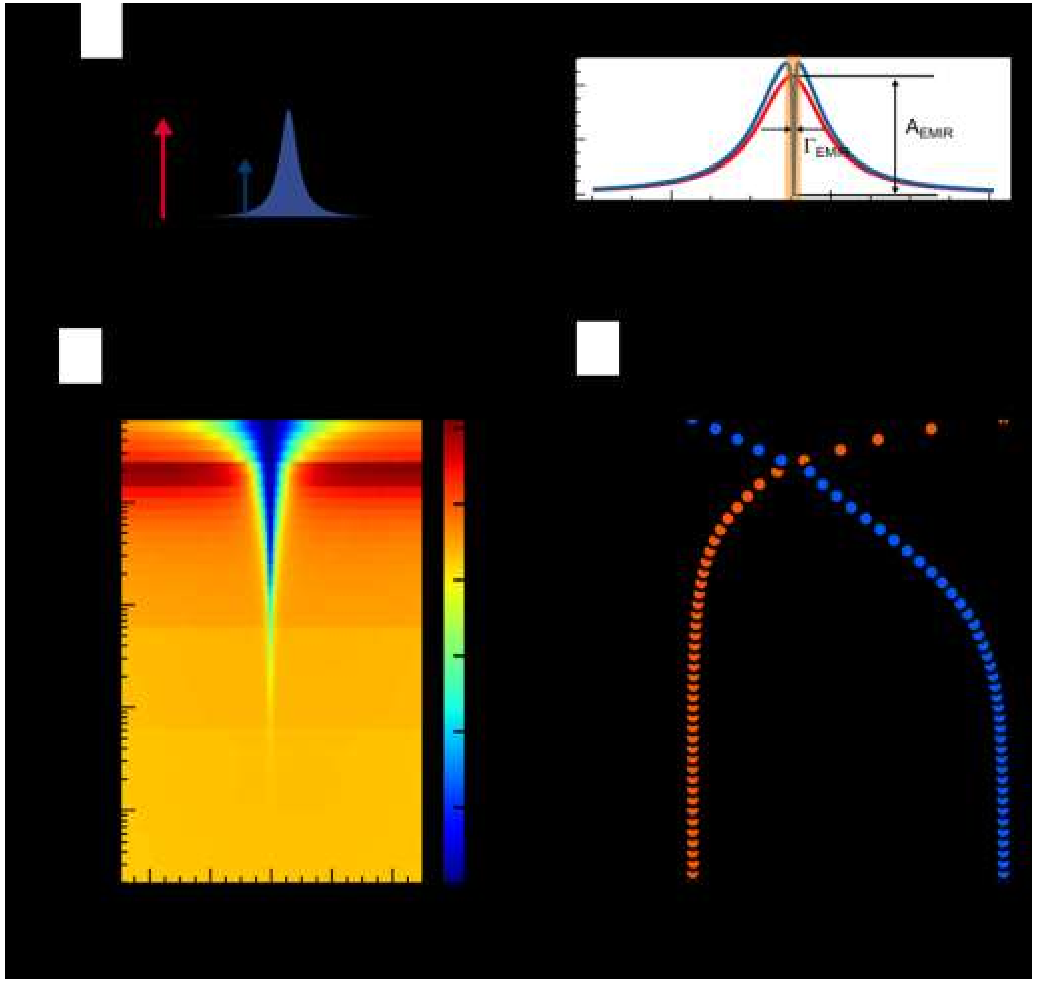




- Cooling process accompanies with mechanical linewidth broadening
- Efficient cooling of mechanical mode temperature from 4.2 K to 76 mK

* Cha *et.al*, *Nano Letters* **21**, 1800 (2021).

Electromechanical induced reflection of microwave



- Probe microwave interferes destructively with mechanical sideband from pump

- Reflection window

$$\Gamma_{\mathrm{EMIR}} = \Gamma_{\mathrm{m}}\left(1 + \frac{4g_0^2 n_d}{\kappa \mathit{\Gamma}_m}\right) = \Gamma_{\mathrm{m}}(1 + C)$$

- Single photon coupling

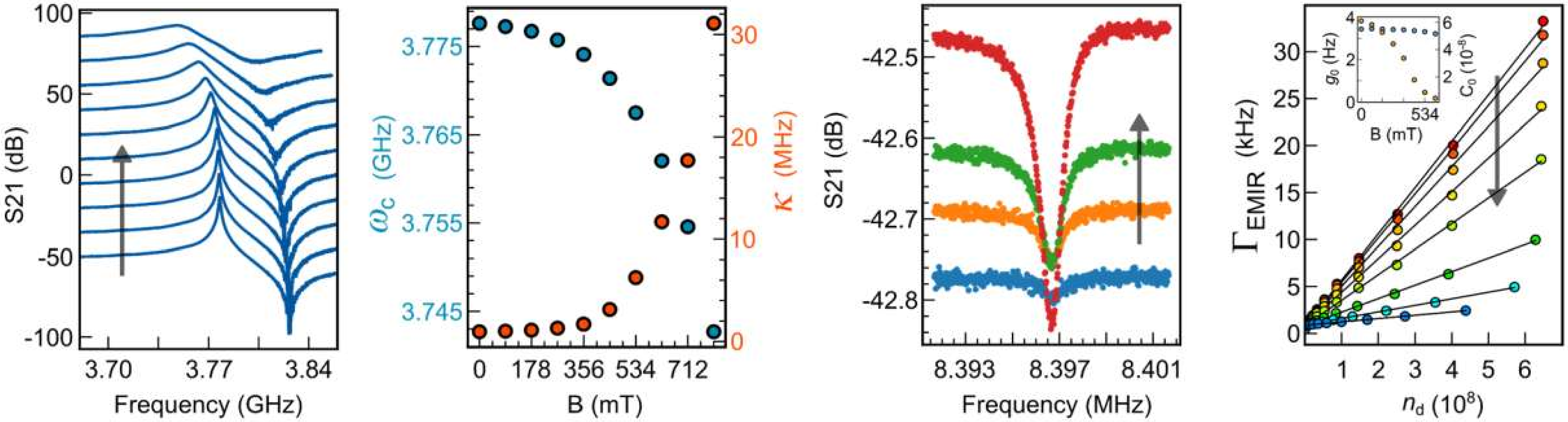
$$g_0 \approx 3.3\ \mathrm{Hz}$$

- Cooperativity

$$C \approx 40$$

* Cha *et.al*, *Nano Letters* **21**, 1800 (2021).

Operation in magnetic field



- Magnetic field B affects the microwave resonance frequency and linewidth.
- Mechanical sideband signal persists even at 0.8 T.
- Cooperativity decreases as *B* increases due to the increasing cavity decay rate.
- Single-photon coupling rate is independent of magnetic field.

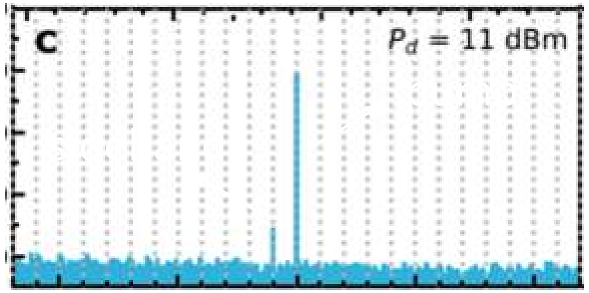
* Cha *et.al*, *Nano Letters* **21**, 1800 (2021).

Niobium optomechanics for non-linear optomechanics

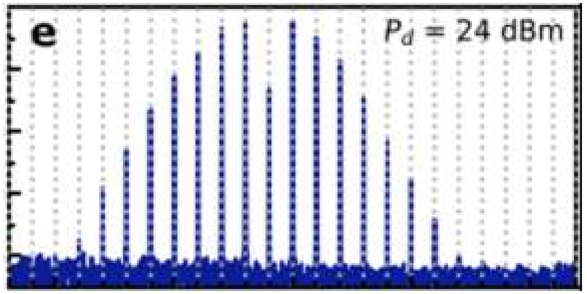
Nb handles more RF current (~6x10^3 more RF photons)

	Aluminum	**Niobium**
Critical Temperature (Tc)	1.2K	9.26K
Critical Magnetic Field(Hc)	0.01 T	0.82 T
Density	2700 kg/m^3	8570 kg/m^3
Young's modulus	70 Gpa	105 GPa
Poisson ratio	0.35	0.4
Advantages	• Easy to control the film stress • Large zero point motion due to the small mass	• Good mechanical properties • High critical temperature and magnetic field
Disadvantages	• Low critical temperature	• Difficult to control the film stress

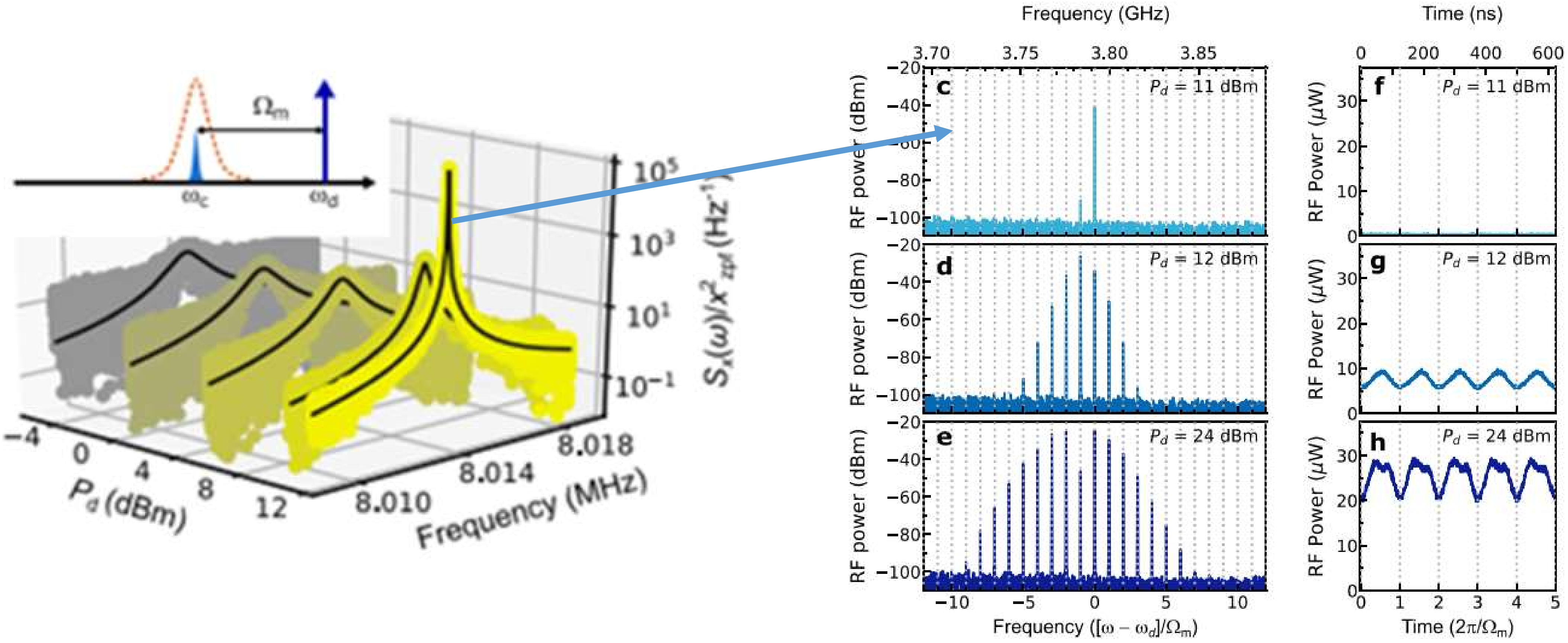
Linear photon-phonon conversion



Multiple non-linear sidebands

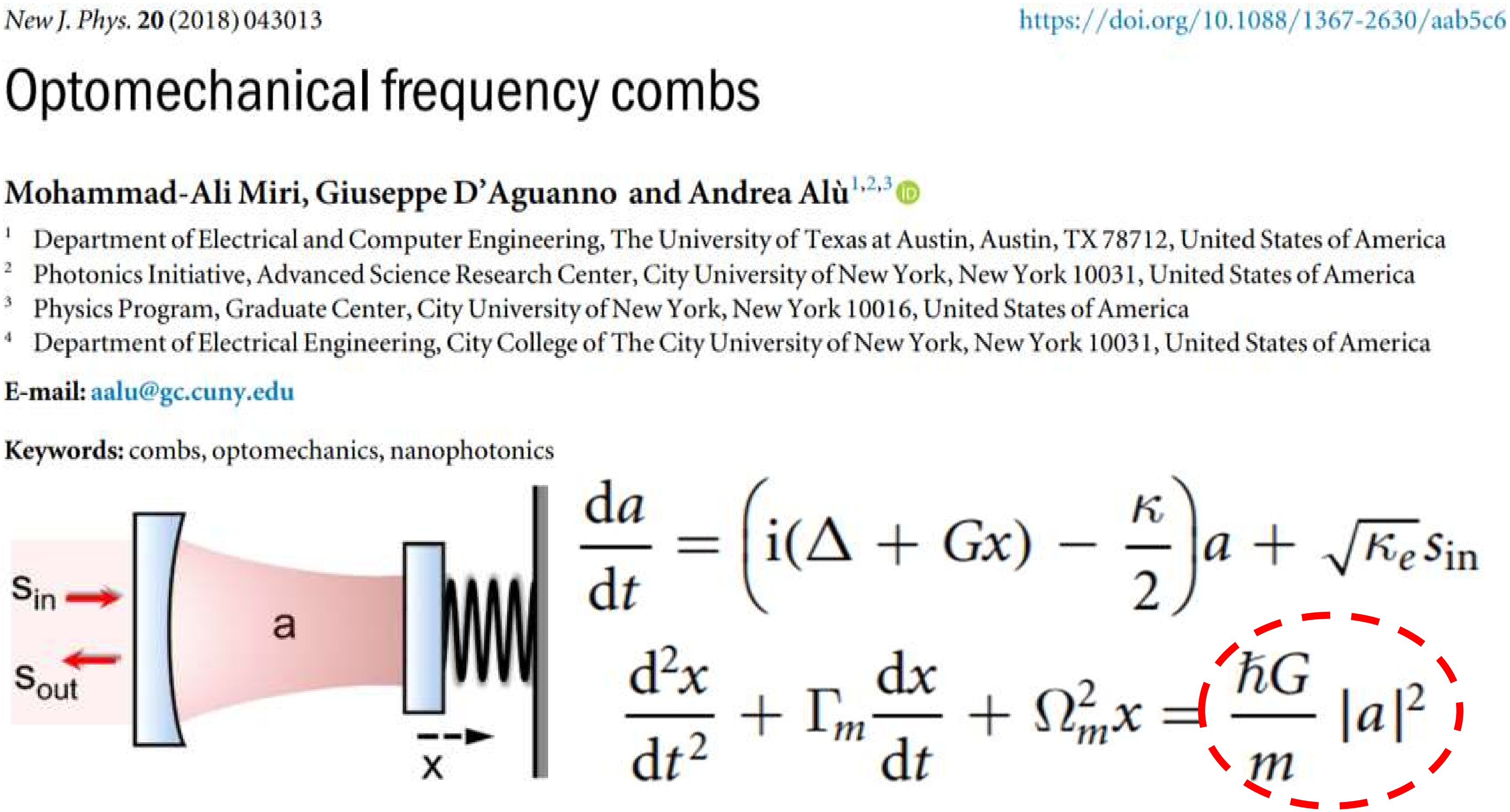


Nonlinear responses above instability



* J. Shin *et.al.*, *Nano Letters* **22**, 5459 (2022).

Optomechanical frequency comb



New J. Phys. **20** (2018) 043013 https://doi.org/10.1088/1367-2630/aab5c6

Optomechanical frequency combs

Mohammad-Ali Miri, Giuseppe D'Aguanno and Andrea Alù[1,2,3]

[1] Department of Electrical and Computer Engineering, The University of Texas at Austin, Austin, TX 78712, United States of America
[2] Photonics Initiative, Advanced Science Research Center, City University of New York, New York 10031, United States of America
[3] Physics Program, Graduate Center, City University of New York, New York 10016, United States of America
[4] Department of Electrical Engineering, City College of The City University of New York, New York 10031, United States of America

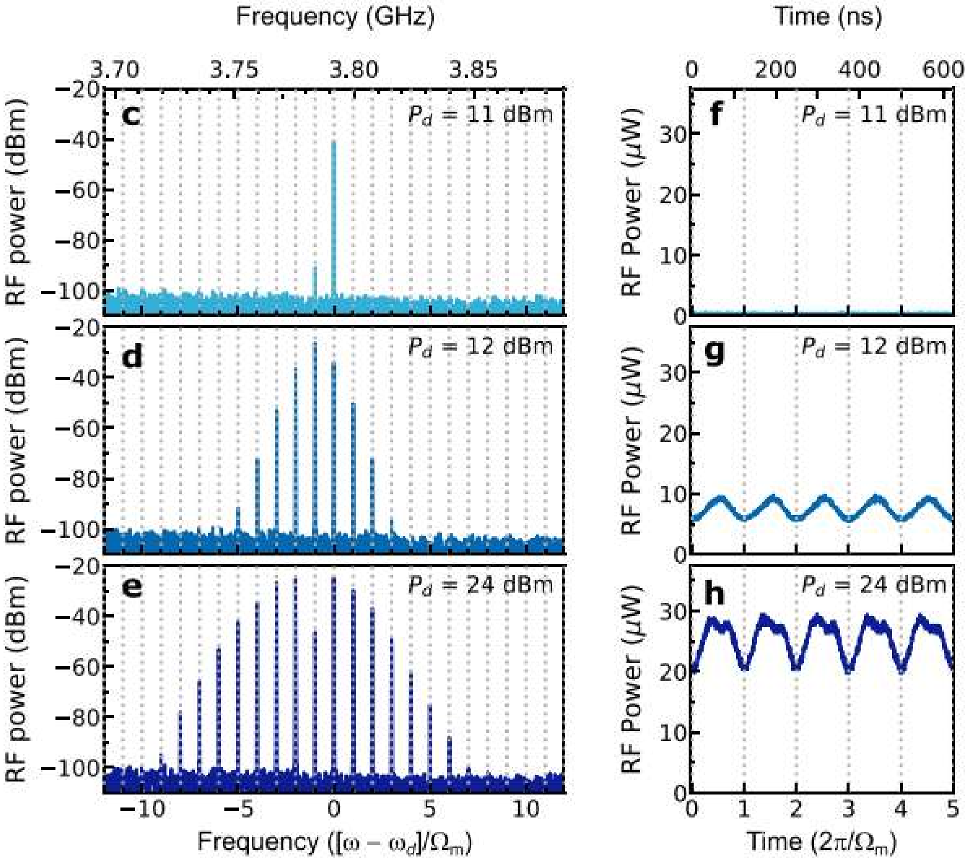
E-mail: aalu@gc.cuny.edu

Keywords: combs, optomechanics, nanophotonics

$$\frac{da}{dt} = \left(i(\Delta + Gx) - \frac{\kappa}{2}\right)a + \sqrt{\kappa_e}\,s_{in}$$

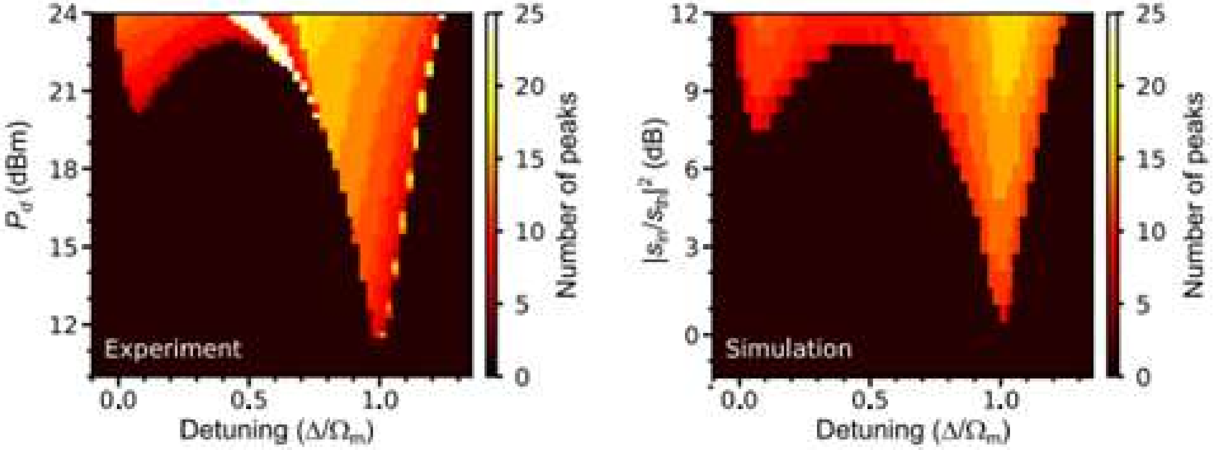
$$\frac{d^2x}{dt^2} + \Gamma_m \frac{dx}{dt} + \Omega_m^2 x = \frac{\hbar G}{m}|a|^2$$

Optomechanical frequency comb

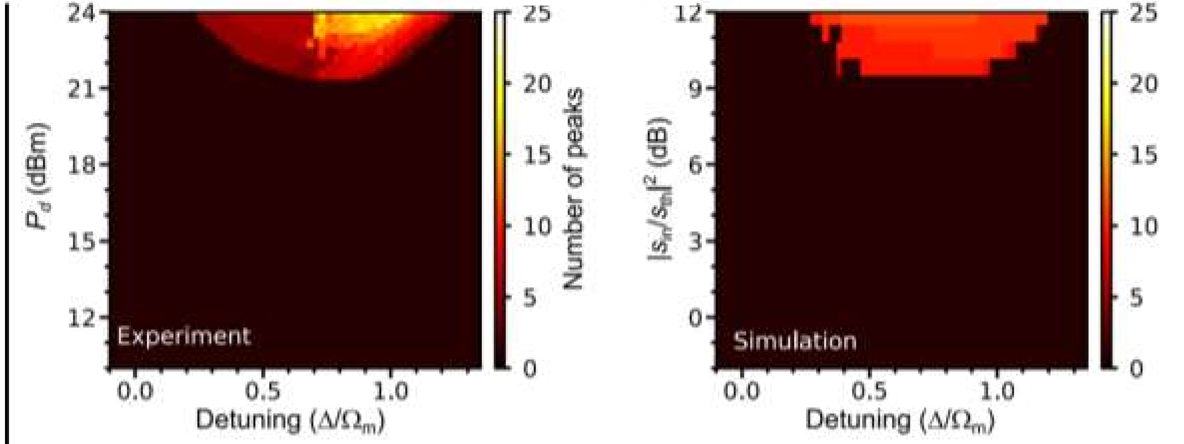


* J. Shin *et.al.*, *Nano Letters* **22**, 5459 (2022).

$\kappa \sim 0.14\Omega_\mathrm{m}$

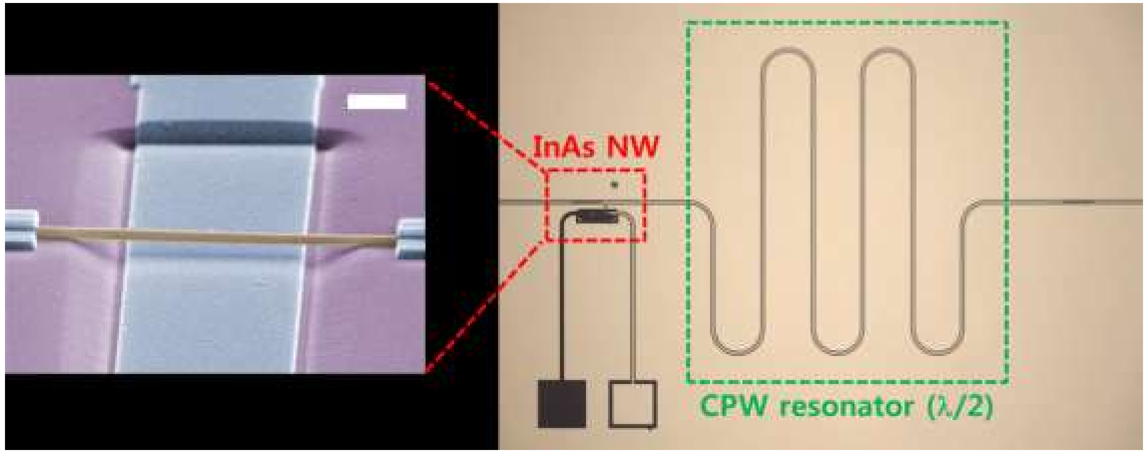


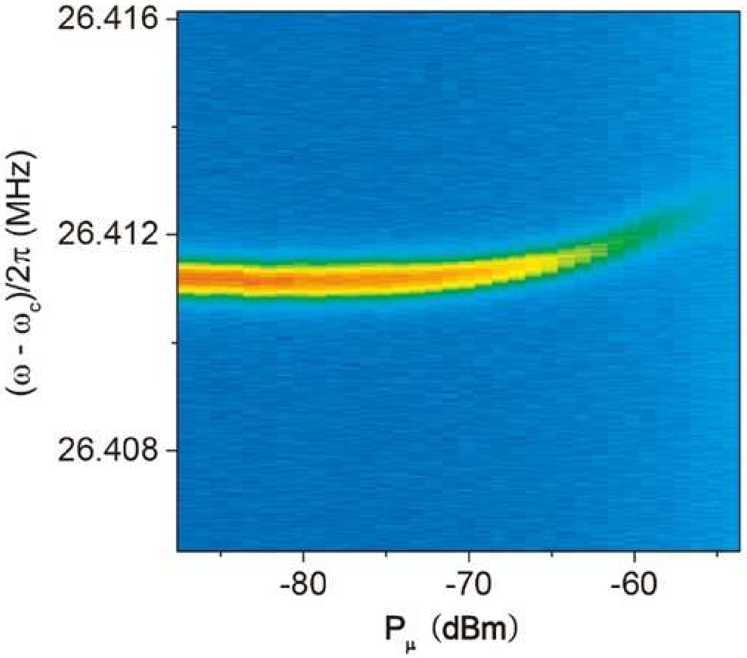
$\kappa \sim \Omega_\mathrm{m}$

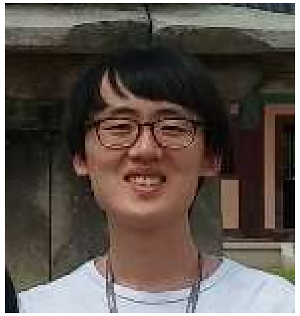


Utilizing Dissipation: Nanomechanical microwave bolometer

Nanomechanical sensor detects heat from microwave photons





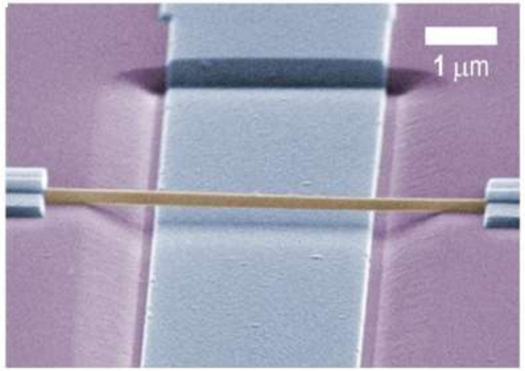


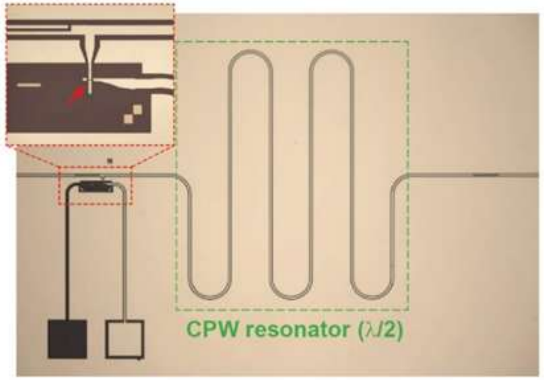
Jihwan Kim
(now at ADD)

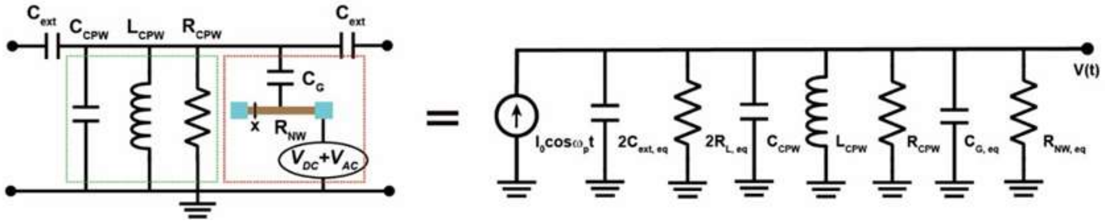
* J. Kim *et.al.*, *"Nanomechanical Microwave Bolometry with Semiconducting Nanowires"*, *Physical Review Applied* **15**, 034075 (2021).

InAs nanowire based cavity optomechanics

Resistive nanowire dissipates microwave power

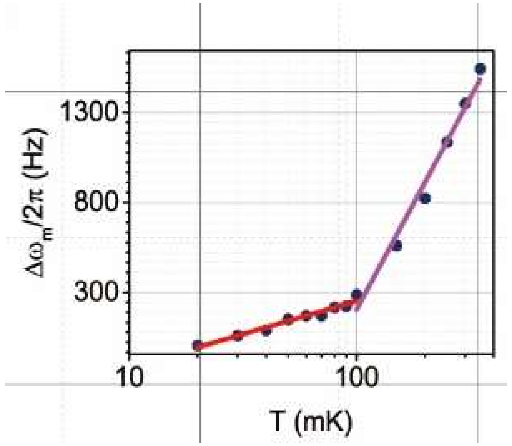




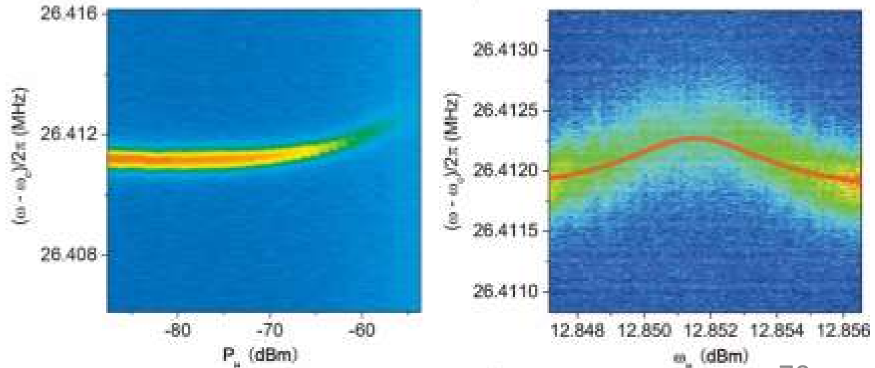


* J. Kim *et.al.*, *Physical Review Applied* **15**, 034075 (2021).

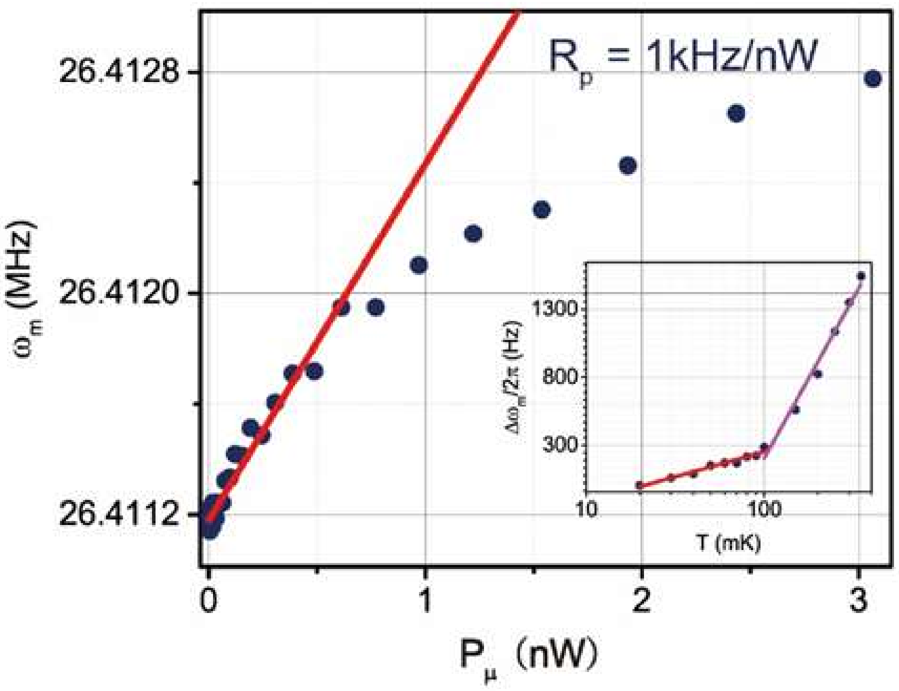
Nanomechanical thermometer

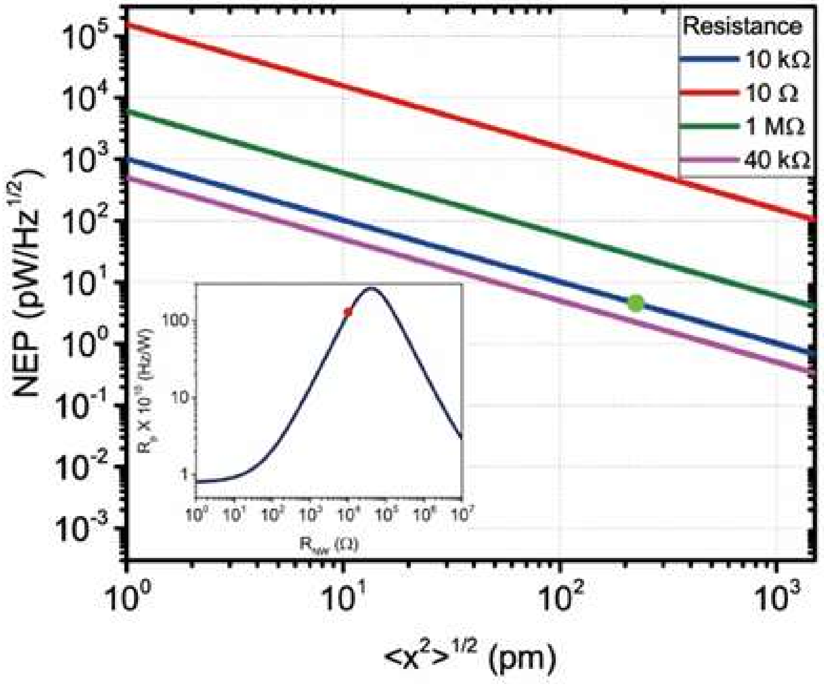


Mechanical resonance senses microwave power



Nanomechanical microwave bolometry

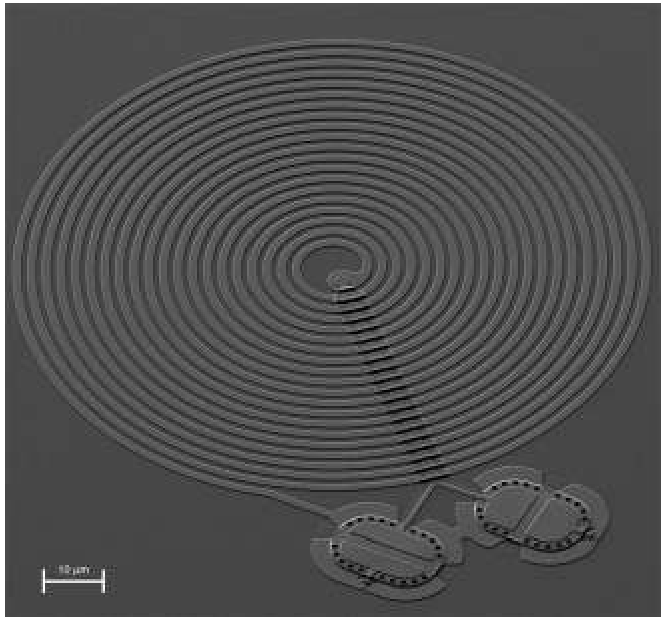




- "Noise equivalent power" NEP = 4.5 pW/Hz$^{1/2}$
- Maximum detectable power ~ nW
- c.f. Josephson bolometer has NEP ~ aW/Hz$^{1/2}$ and maximum power ~ fW (ref. *Nature* **586**, 42 (2020))

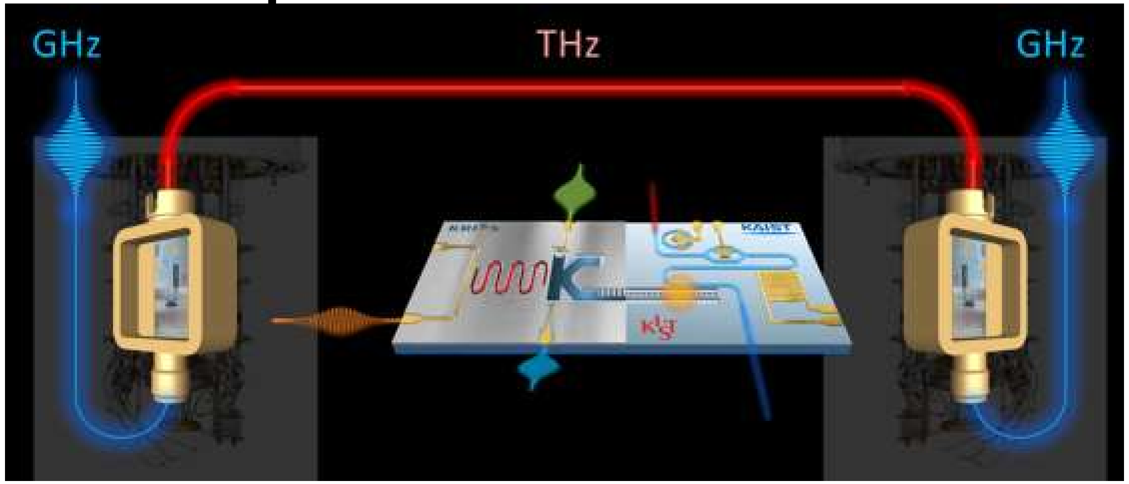
Outlook: quantum transducer and sensors

entangled force sensors



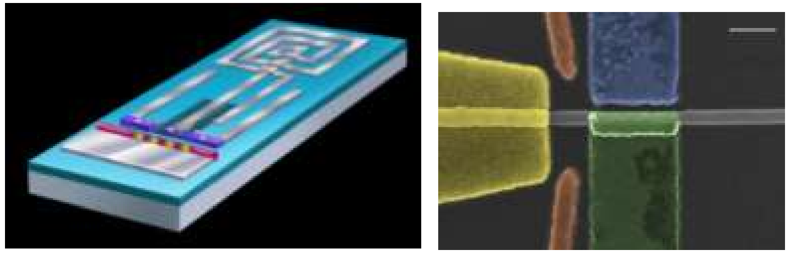
*Kotler *et al.*, *Science* **372**, 622 (2021).

quantum transduction



* “Integrated quantum interconnects for long-distance quantum networks” funded by NST

sensors for new physics



* “Quantum electromechanical interface for Majorana qubits” funded by Samsung foundation

Hybrid Quatum Device Lab

hql.postech.ac.kr

NRF 한국연구재단 Center for Quantum Coherence in Condensed Matter IITP