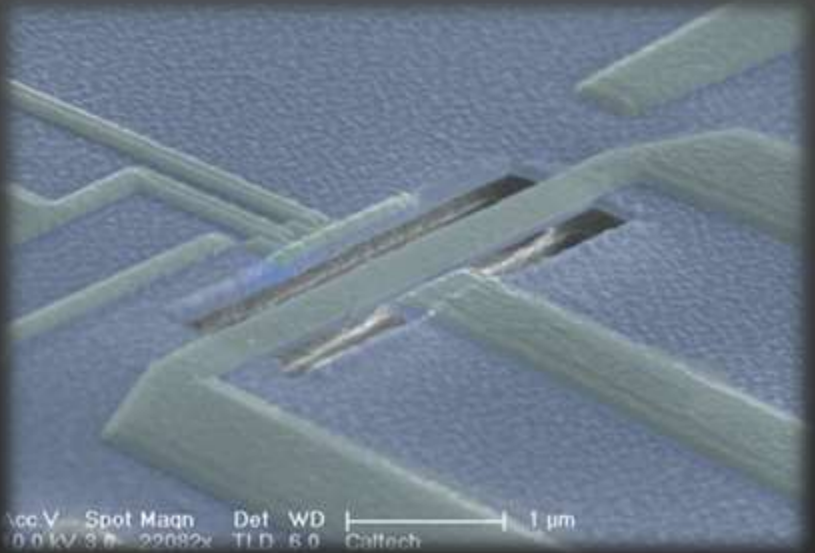
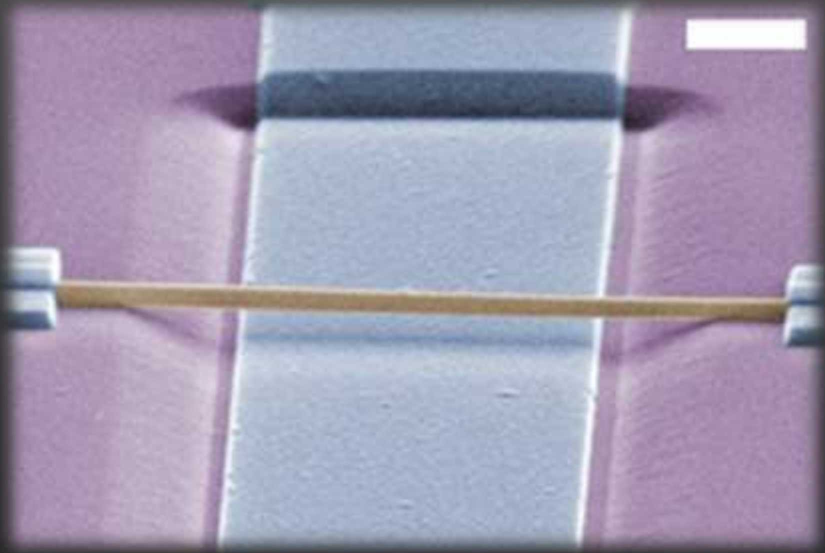
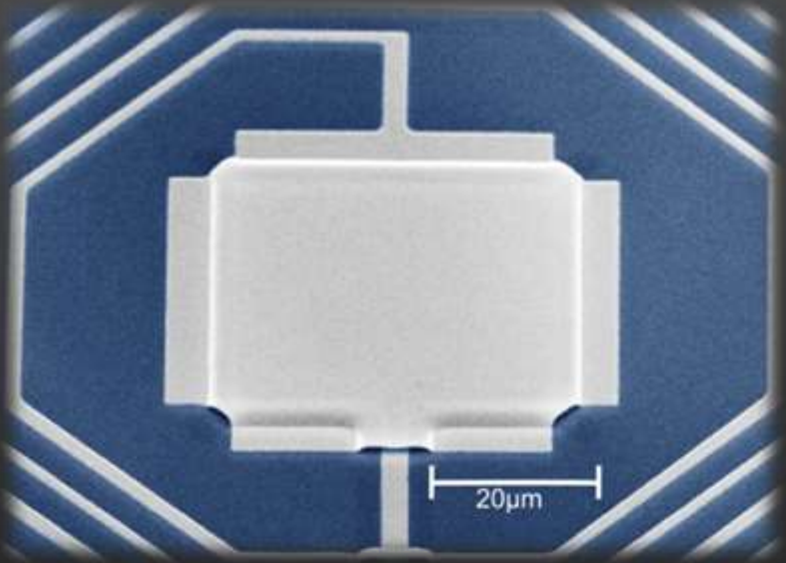






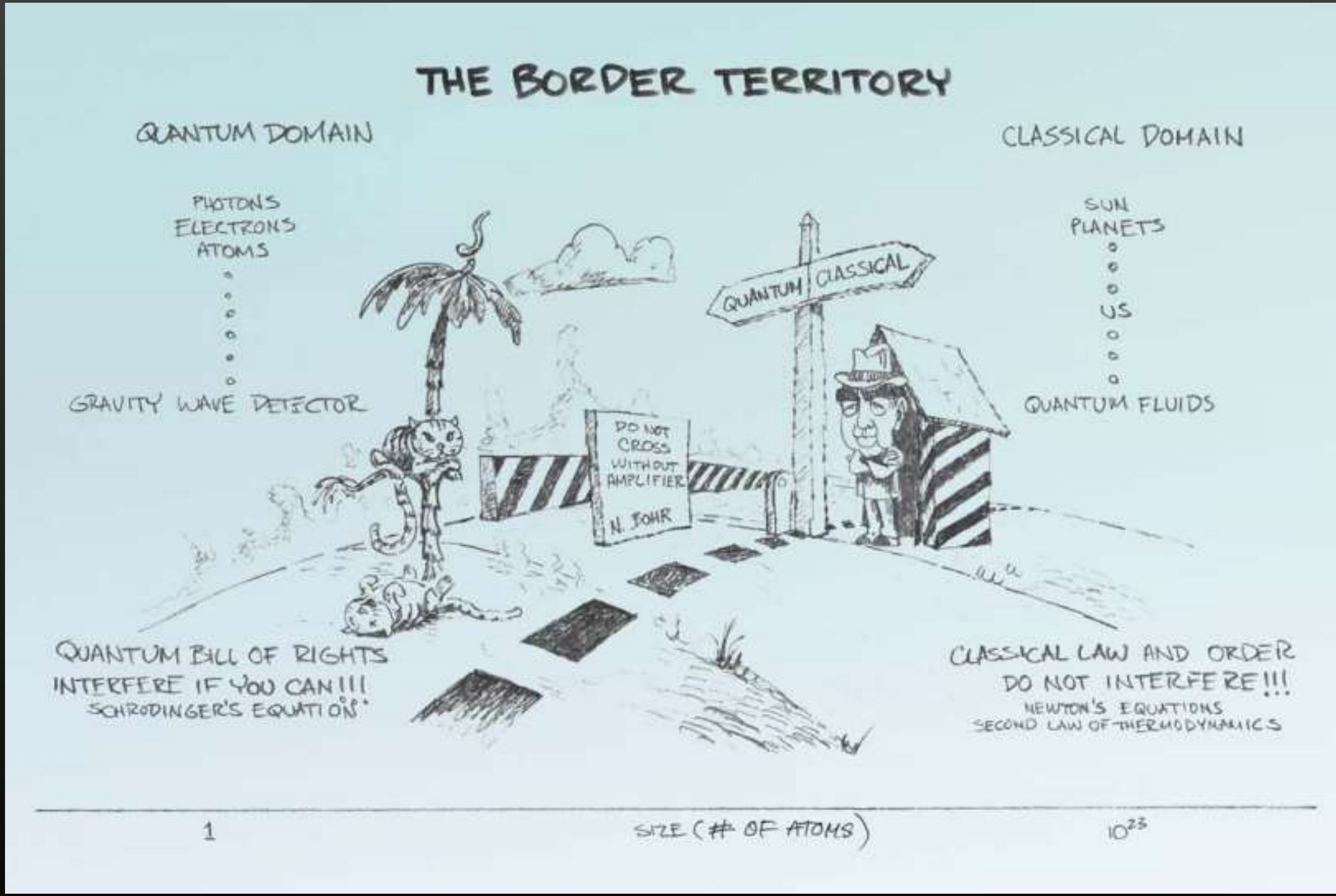
Nanomechanical Quantum Sensors

Junho Suh

Korea Research Institute of Standards and Science

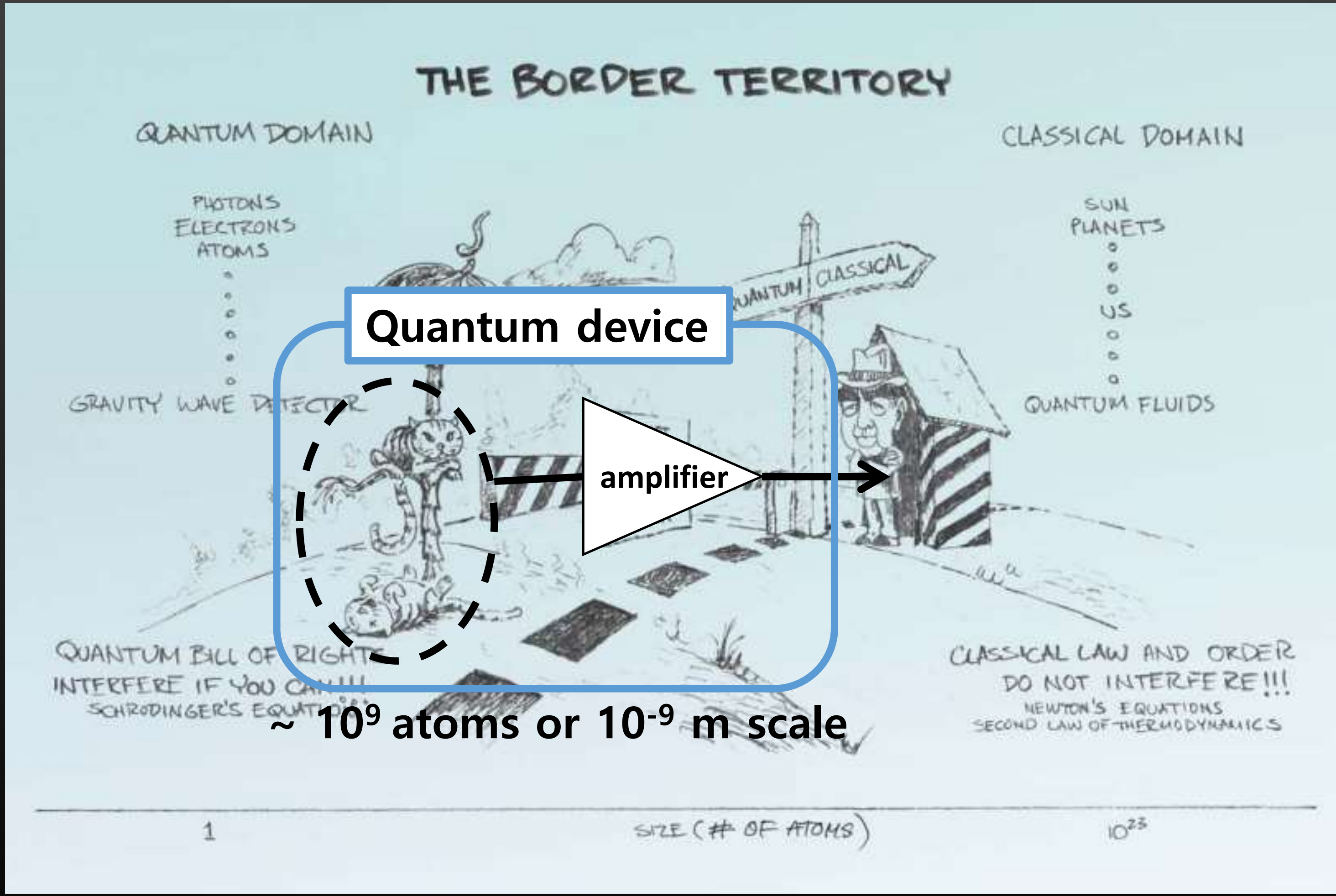
KRISS
한국표준과학연구원
Korea Research Institute of Standards and Science

Quantum vs. Classical



* "Decoherence and the Transition from Quantum to Classical" by Wojciech H. Zurek

How to **Use** Quantum Mechanics?



* "Decoherence and the Transition from Quantum to Classical" by Wojciech H. Zurek

Quantum technology: the second quantum revolution

Jonathan P. Dowling and Gerard J. Milburn

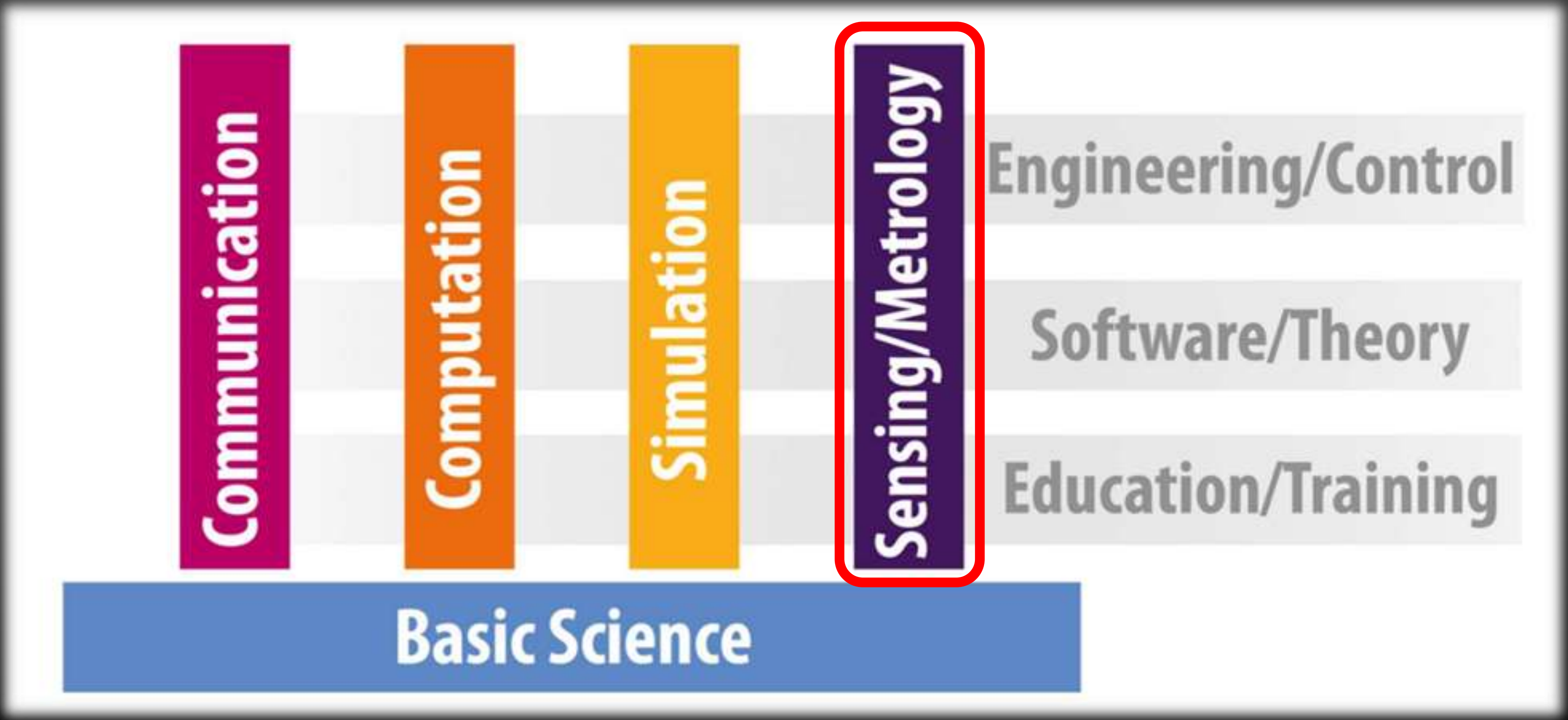
Published: 20 June 2003 | https://doi.org/10.1098/rsta.2003.1227

Abstract

We are currently in the midst of a *second quantum revolution* The first quantum revolution gave us new rules that govern physical reality. The second quantum revolution will take these rules and use them to develop new technologies. In this review we discuss the principles upon which quantum technology is based and the tools required to develop it. We discuss a number of examples of research programs that could deliver quantum technologies in coming decades including: quantum information technology, quantum electromechanical systems, coherent quantum electronics, quantum optics and coherent matter technology.

"superposition" and "entanglement"

Quantum Technologies



* *Quantum Technologies Flagship Intermediate Report* (2017).

Quantum sensing

C. L. Degen*

Department of Physics, ETH Zurich, Otto Stern Weg 1, 8093 Zurich, Switzerland

F. Reinhard†

Walter Schottky Institut and Physik-Department, Technische Universität München, Am Coulombwall 4, 85748 Garching, Germany

P. Cappellaro‡

Research Laboratory of Electronics and Department of Nuclear Science & Engineering, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, Massachusetts 02139, USA

(published 25 July 2017)

"Quantum sensing" describes the use of a quantum system, quantum properties, or quantum phenomena to perform a measurement of a physical quantity. Historical examples of quantum sensors

Quantum Sensing

(I) Use of a quantum object to measure a physical quantity (classical or quantum). The quantum object is characterized by quantized energy levels. Specific examples include electronic, magnetic or vibrational states of superconducting or spin qubits, neutral atoms, or trapped ions.

(II) Use of quantum coherence (i.e., wavelike spatial or temporal superposition states) to measure a physical quantity.

(III) Use of quantum entanglement to improve the sensitivity or precision of a measurement, beyond what is possible classically.

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

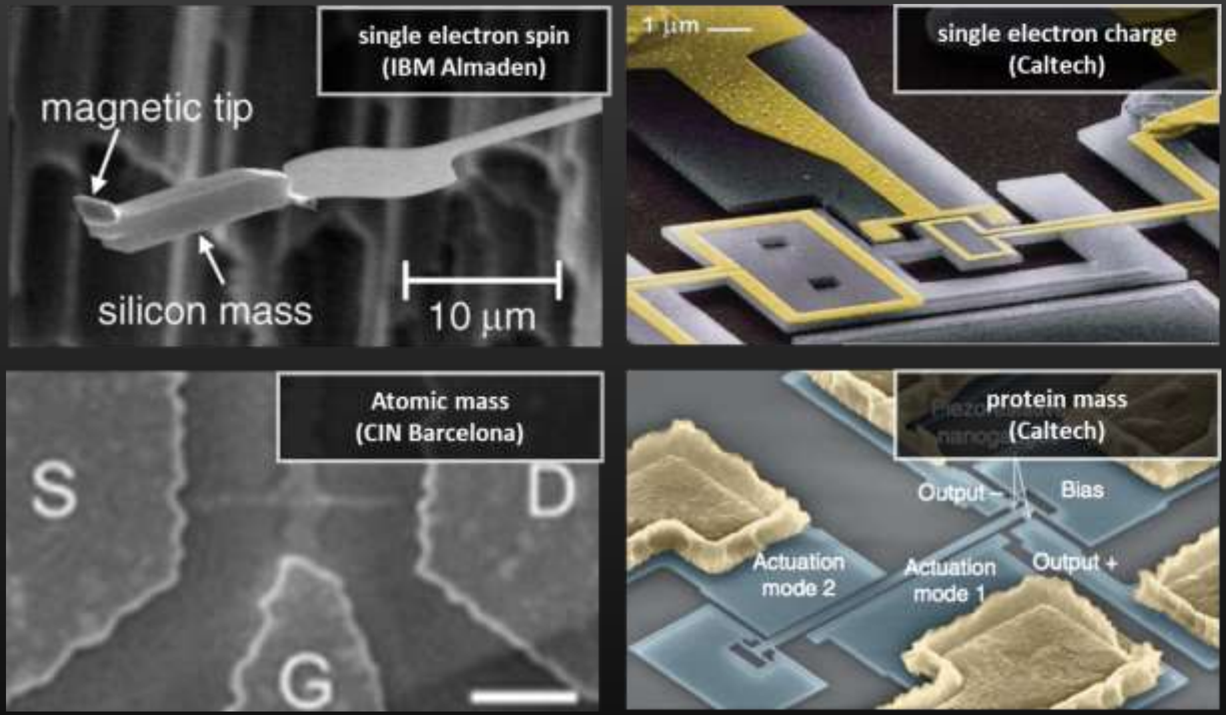
Quautum Sensing

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 Rotation	THz
	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

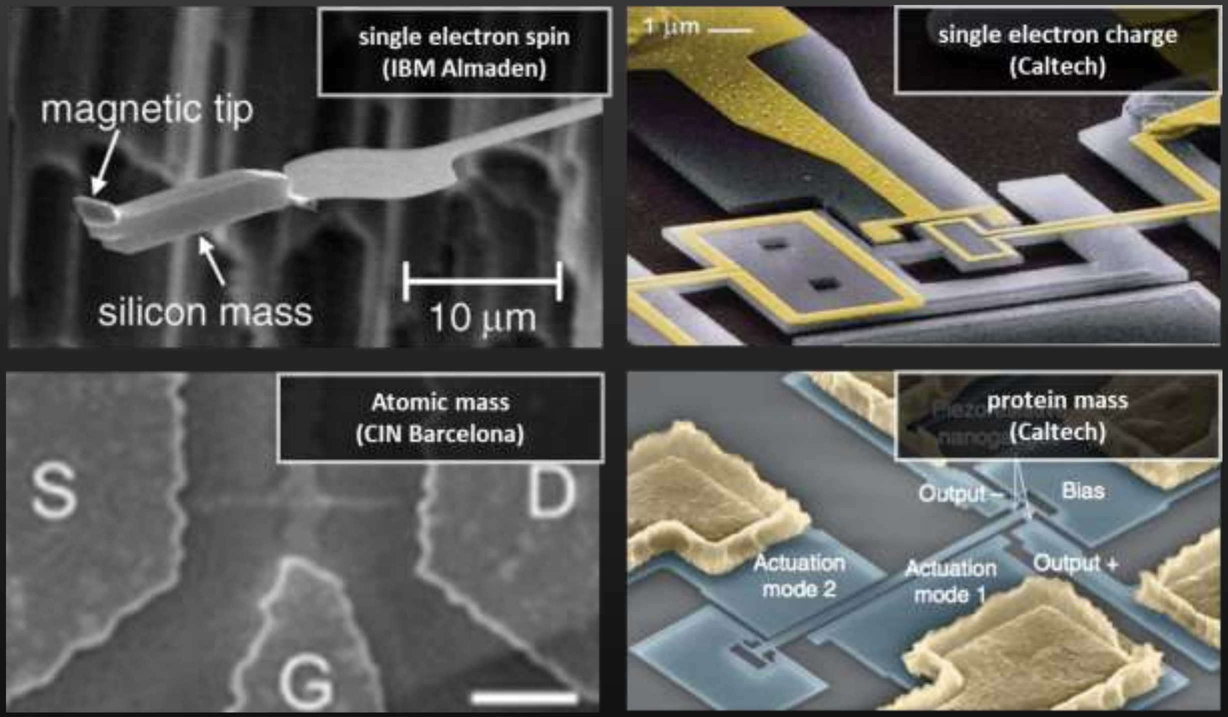
Implementation	Qubit(s)	Measured quantity(ies)	Typical frequency
Superconducting circuits			
SQUID[c]	Supercurrent	Magnetic field	dc-GHz
Flux qubit	Circulating currents	Magnetic field	dc-GHz
Charge qubit	Charge eigenstates	Electric field	dc-GHz
Elementary particles			
Muon	Muonic spin	Magnetic field	dc
Neutron	Nuclear spin	Magnetic field, phonon density, gravity	dc
Other sensors			
SET[d]	Charge eigenstates	Electric field	dc-MHz
Optomechanics Electromechanics	Phonons	Force, acceleration, mass, magnetic field, voltage	kHz–GHz
Interferometer	Photons, (atoms, molecules)	Displacement, refractive index	...

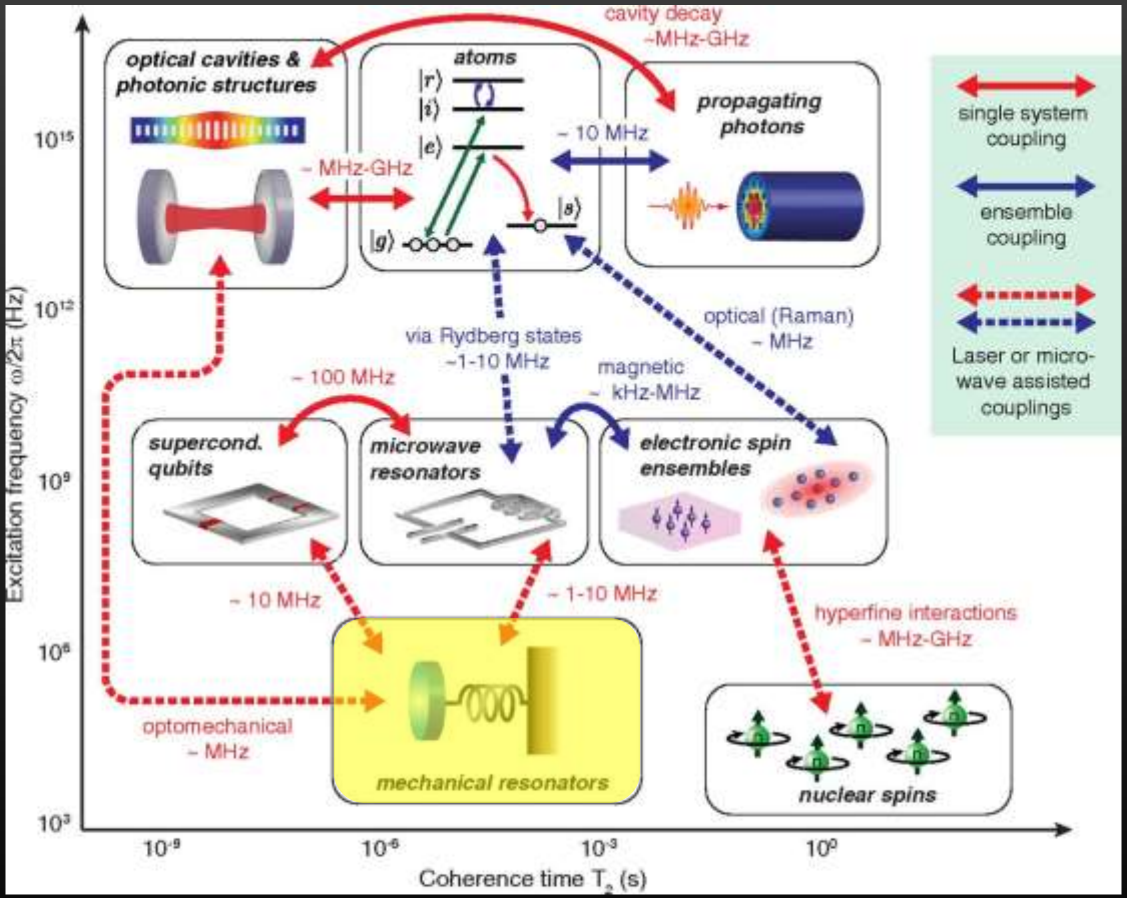
* C. L. Degen *et.al*, *“Quantum sensing”*, *Rev. Mod. Phys.* **89**, 035002 (2017).

(Nano) Mechanical Sensors



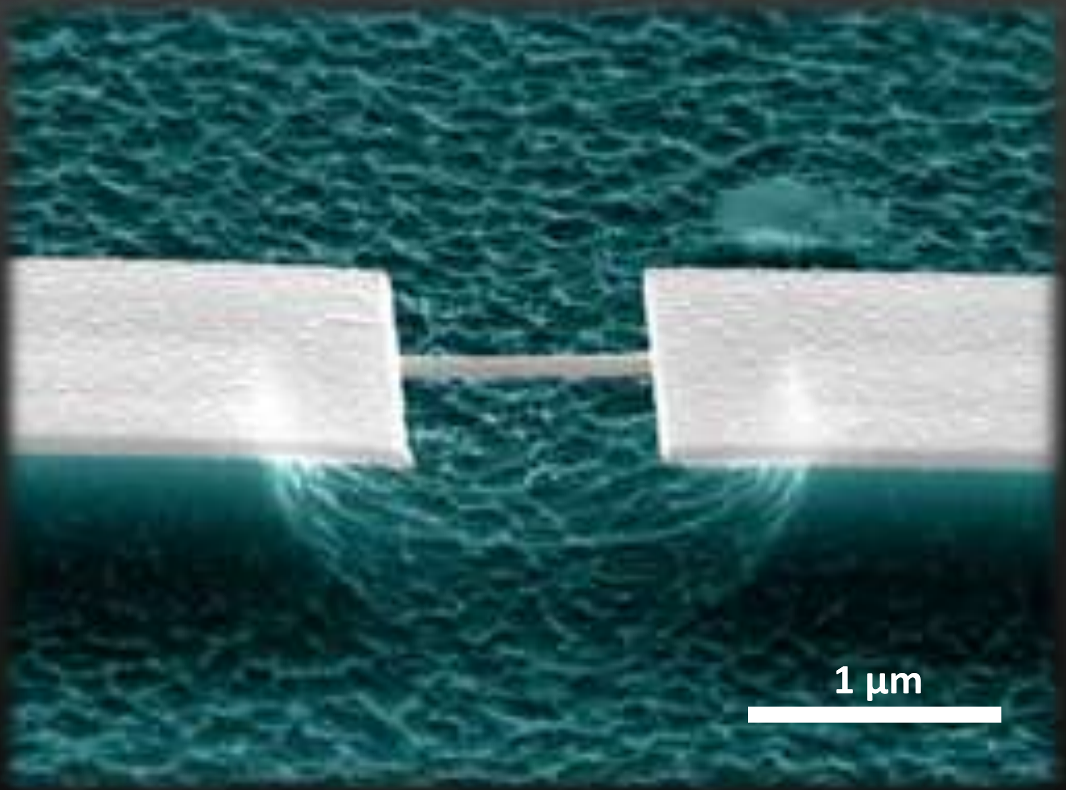
(Nano) Mechanical Sensors

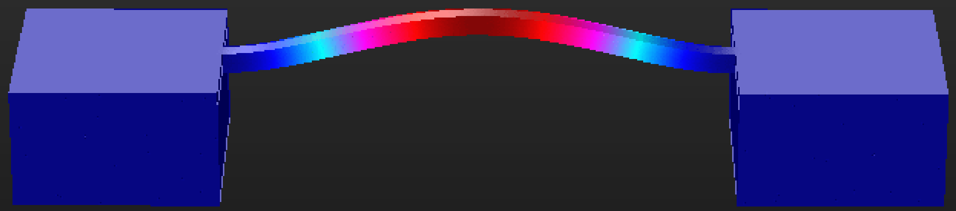




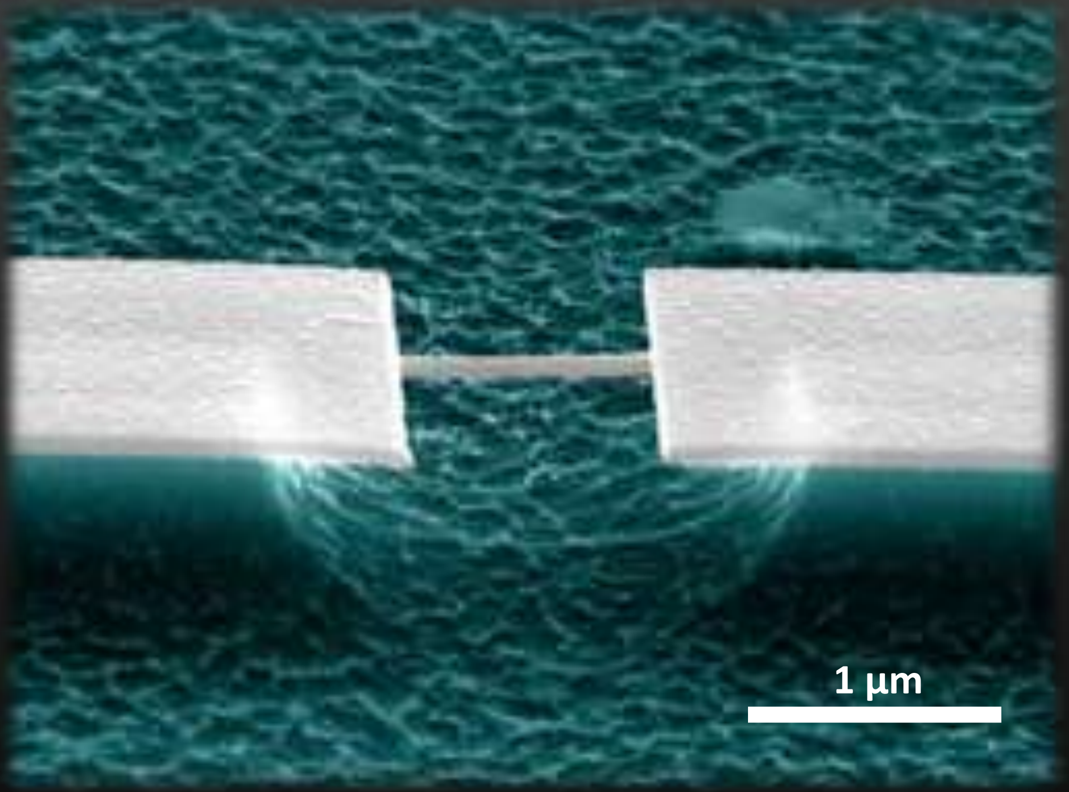
* Kurizki *et.al*, *PNAS* **112**, 3866 (2015).

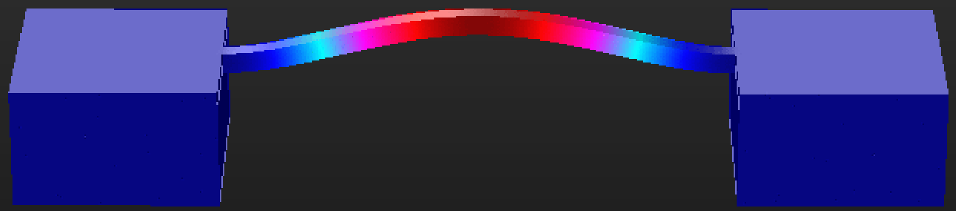
Example: Nano-Beam Resonators





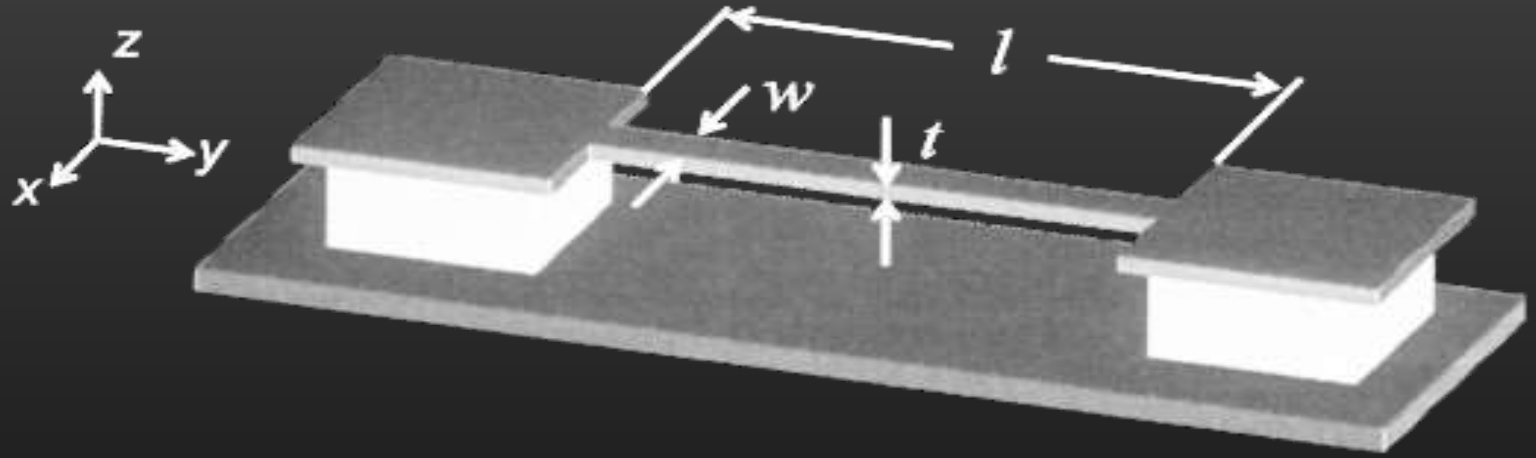
Eigenmode of vibration = Harmonic oscillator





MHz ~ GHz

Euler-Bernulli Equation



$$EI\frac{\partial^4 U(y,t)}{\partial y^4} + \rho A \frac{\partial^2 U(y,t)}{\partial t^2} = f(y,t)$$

Young's modulus

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

Density

Cross-section (=tw)

External force

* Foundations of nanomechanics, A. N. Cleland

Equation of Motion

$$EI\frac{\partial^4 U(y,t)}{\partial y^4} + \rho A\frac{\partial^2 U(y,t)}{\partial t^2} = f(y,t)$$

- Separation of variables; normal modes $\varphi_n(y)$

$$U(y,t) = \sum \varphi_n(y) q_n(t)$$

- Consider homogeneous case, i.e. $f(y,t) = 0$

$$\frac{\partial^4 \varphi_n(y)}{\partial y^4} - \beta_n^4 \varphi_n(y) = 0;\ \frac{\partial^2 q_n(t)}{\partial t^2} + \omega_n^2 q_n(t) = 0; \beta_n^4 = \frac{\rho A}{EI}\omega_n^2$$

- Integrate Euler-Bernulli equation

$$m_n \ddot{q_n} + k_n q_n = \int_0^l f(y,t)\,\varphi_n(y)dy;\ m_n = \rho A l \int_0^l (\varphi_n(y))^2 dy\,; k_n = \frac{EI}{l^3}\int_0^l (\partial^2 \varphi_n(y)/\partial y^2)^2 dy$$

* Foundations of nanomechanics, A. N. Cleland

Equation of Motion

- For the fundamental mode shape $\varphi_0(y)$, the displacement $u(t)$ at $y = y_0$ under uniformly distributed force $f(t)$ satisfies, ($F(t)$ = total force)

$$m_{eff}\ddot{u} + k_{eff}u = F(t)$$

$$m_{eff} = \frac{\rho A l \int_0^l (\varphi_0(y))^2 dy}{\varphi_0(y_0)\int_0^l \varphi_0(y)dy}; k_{eff} = \frac{\frac{EI}{l^3}\int_0^l (\partial^2\varphi_n(y)/\partial y^2)^2 dy}{\varphi_0(y_0)\int_0^l \varphi_0(y)dy}$$

- Damping can be included:

$$m_{eff}\ddot{u} + m_{eff}\gamma\dot{u} + k_{eff}u = F(t)$$

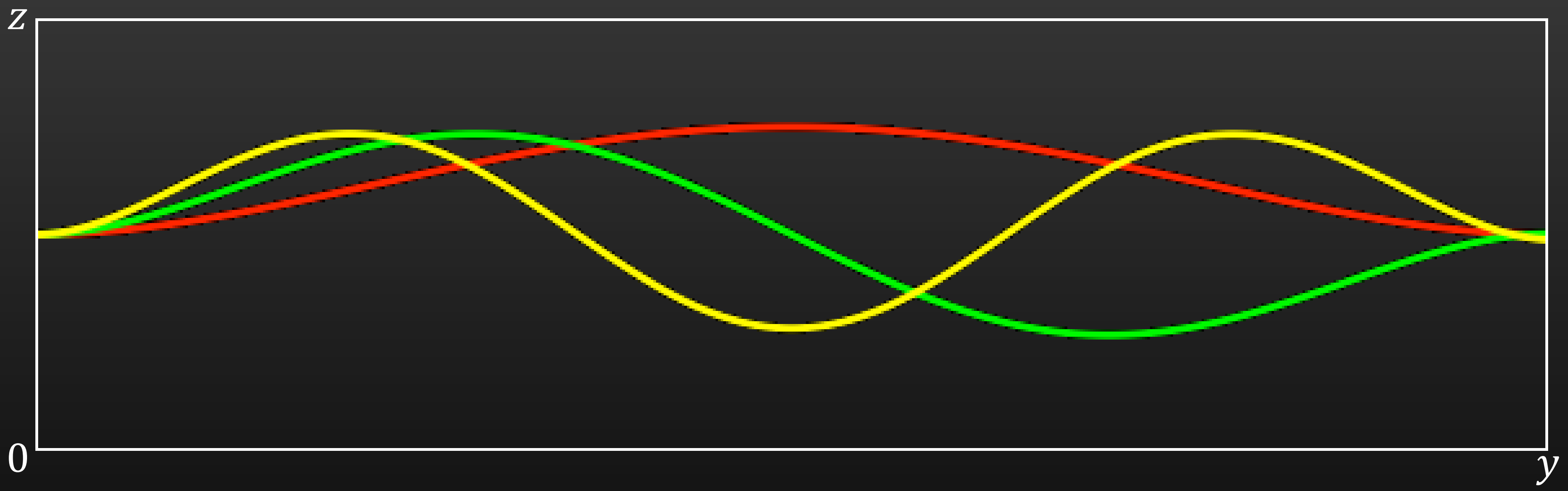
- In frequency domain:

$$u(\omega) = \frac{F(\omega)/m_{eff}}{(\omega_0^2 - \omega^2) + i\frac{\omega\omega_0}{Q}}; Q = \frac{\omega_0}{\gamma}$$

* Foundations of nanomechanics, A. N. Cleland

Example of Nano-Beam

- Fixed ends + zero-slope at the ends



$$\omega_n = a_n \sqrt{\frac{E}{\rho}} \frac{t}{l^2} (a_n = 6.47, 17.9, 35.0, \ldots)$$

* Foundations of nanomechanics, A. N. Cleland

Nanomechanical Sensing

Center of mass displacement: $x(t)$

$$m_{eff}\ddot{x} + m_{eff}\gamma\dot{x} + k_{eff}x = f(t)$$

with $f(t) = F(\omega)e^{i\omega t}$, $x(t) = X(\omega)e^{i\omega t}$:

$$X(\omega) \cong \frac{F(\omega)/\left(m_{eff}\omega_0\right)}{2(\omega_0 - \omega) + i\gamma}$$

$$\left(\omega \approx \omega_0 = \sqrt{\frac{k_{eff}}{m_{eff}}} \gg \gamma\right)$$

$\Rightarrow$ Maximum amplitude ("resonance") when $f(t) = F\cos\omega_0 t$

$$x(t) = X\sin\omega_0 t = \frac{F\cdot\frac{\omega_0}{\gamma}}{k_{eff}}\sin\omega_0 t = \frac{F\cdot Q}{k_{eff}}\sin\omega_0 t$$

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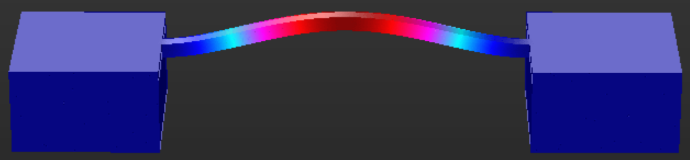

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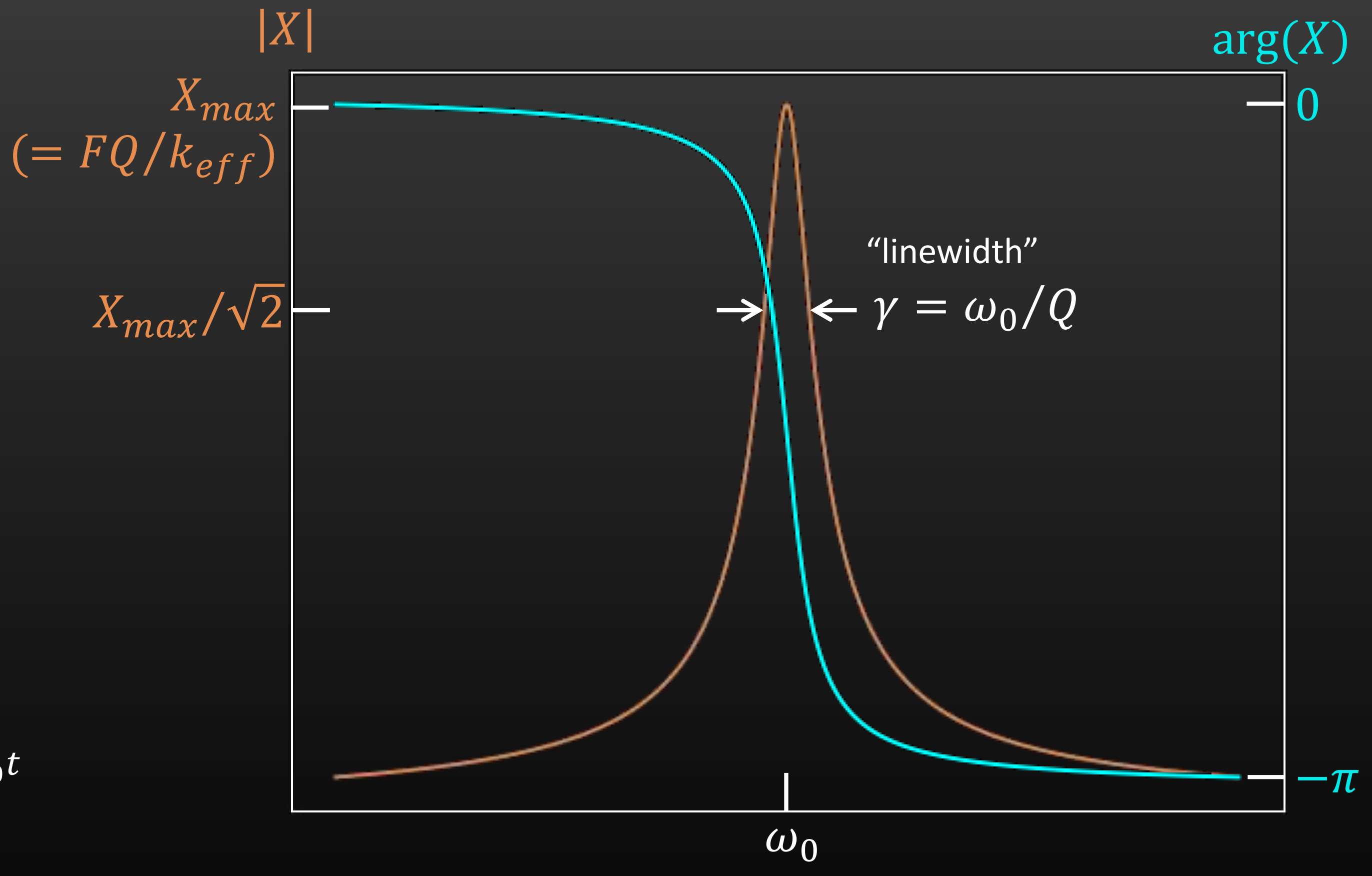

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1) Force vs displacement

$$\delta X = \delta F\frac{\omega_0/\gamma}{k_{eff}} = \delta F\frac{Q}{k_{eff}}$$

2) Resonance vs mass/spring constant

$$\delta\omega_0 = \delta m_{eff}\frac{\omega_0}{2m_{eff}} \text{ or } \delta k_{eff}\frac{\omega_0}{2k_{eff}}$$

Nanomechanical Sensing

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⇒ Maximum amplitude (“resonance”):

$$f(t) = F\cos\omega_0 t\,;\; x(t) = X\sin\omega_0 t = \frac{F_0\cdot\frac{\omega_0}{\gamma}}{k_{eff}}\sin\omega_0 t$$

$$\delta X = \delta F\,\frac{Q}{k_{eff}}$$

⇒ Maximum sensitivity in force measurement requires:

1) High Q (i.e. low dissipation)

2) High compliance (i.e. small mass)

3) Low measurement noise in δX (i.e. quantum-limited)

Quantum limit

"zero-point motion" "thermal motion"

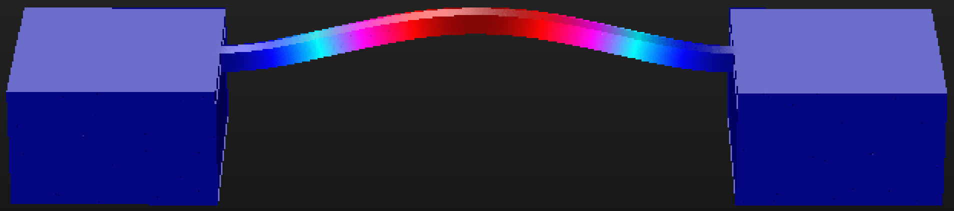
$$\delta X_{quantum} = \sqrt{\frac{\hbar}{2m\omega}} > \delta X_{thermal} = \sqrt{\frac{k_B T}{2m\omega^2}}$$

or $$\hbar\omega > k_B T$$

(zero-point energy overcomes thermal energy)

Quantum limit

$$\hbar\omega > k_B T$$



- Speed of sound ~ 10^4 m/s
- Device temperature ~ 50 mK
- $k_B T$ ~ 4 µeV or 1 GHz

∴ device length scale

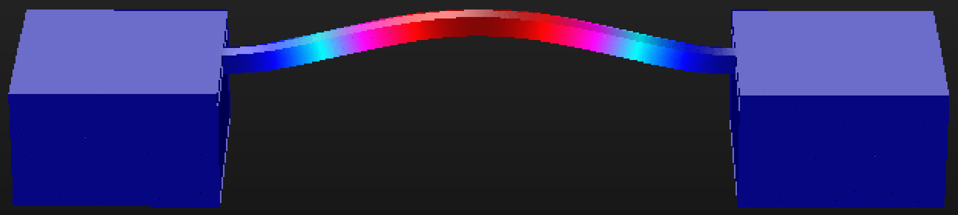
~ (10^4 m/s) / (1 GHz) = ***100 nm***

Single phonon vs single photon

	phonon	photon
medium	solid	vacuum
nonlinearity	high	low
mass	m_{eff}	zero
wavelength	Sub-micron	Micron or centimeter
Electric charge/dipole	possible	no
Magnetic dipole	possible	no

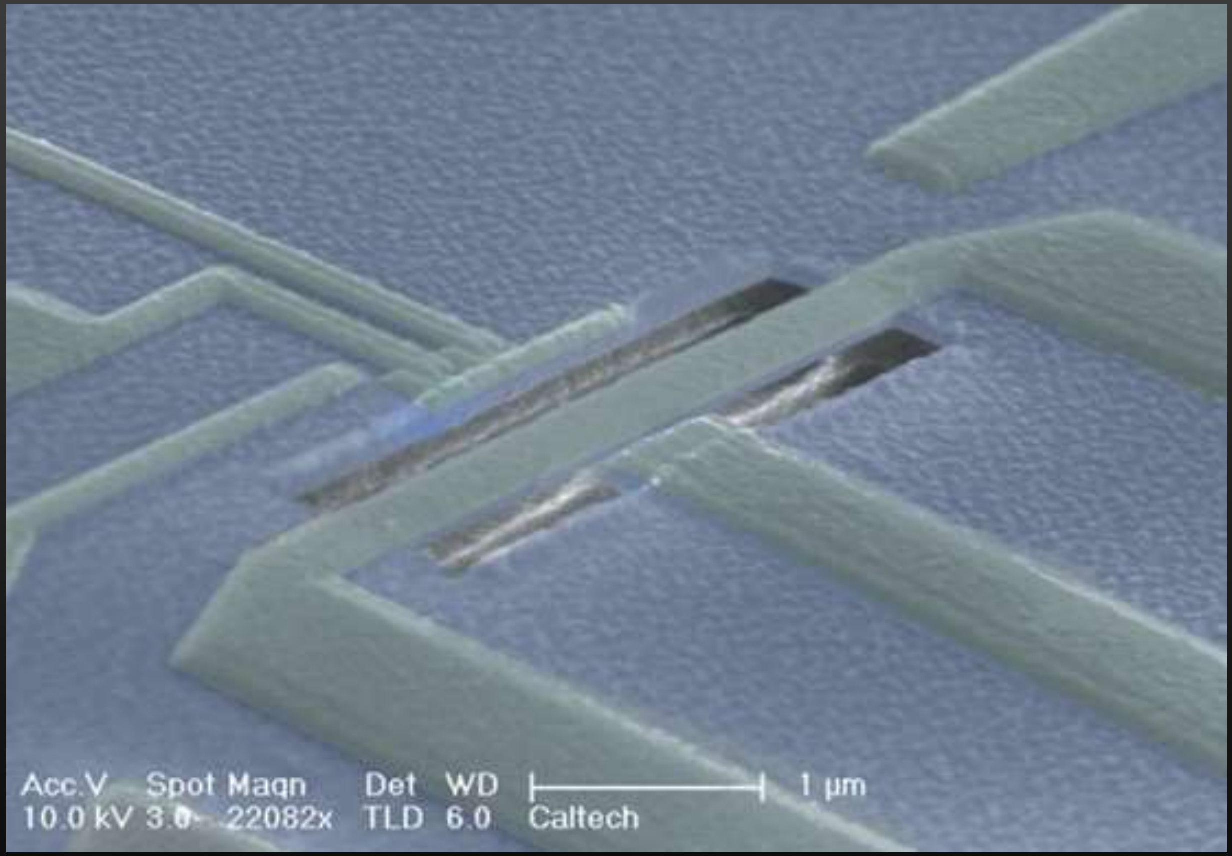
Mechanical quantum sensor

$$\hbar\omega > k_B T$$



- How to generate?
- How to apply them in sensing?
- How to hybrid with other quantum system?

Example1: Quantum electromechanical system



* LaHaye, **JS** *et.al*, *"Nanomechanical measurements of a superconducting qubit"*, *Nature* **459**, 960 (2009).

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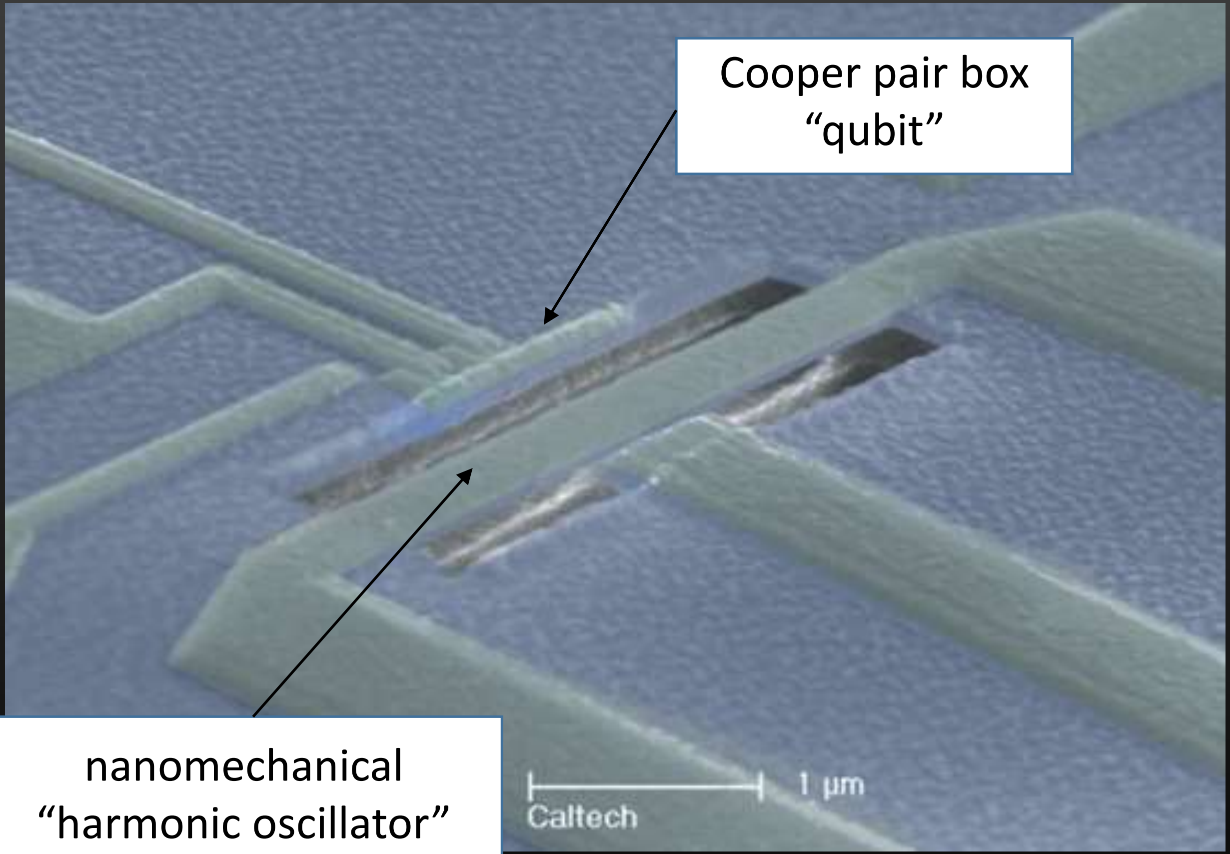

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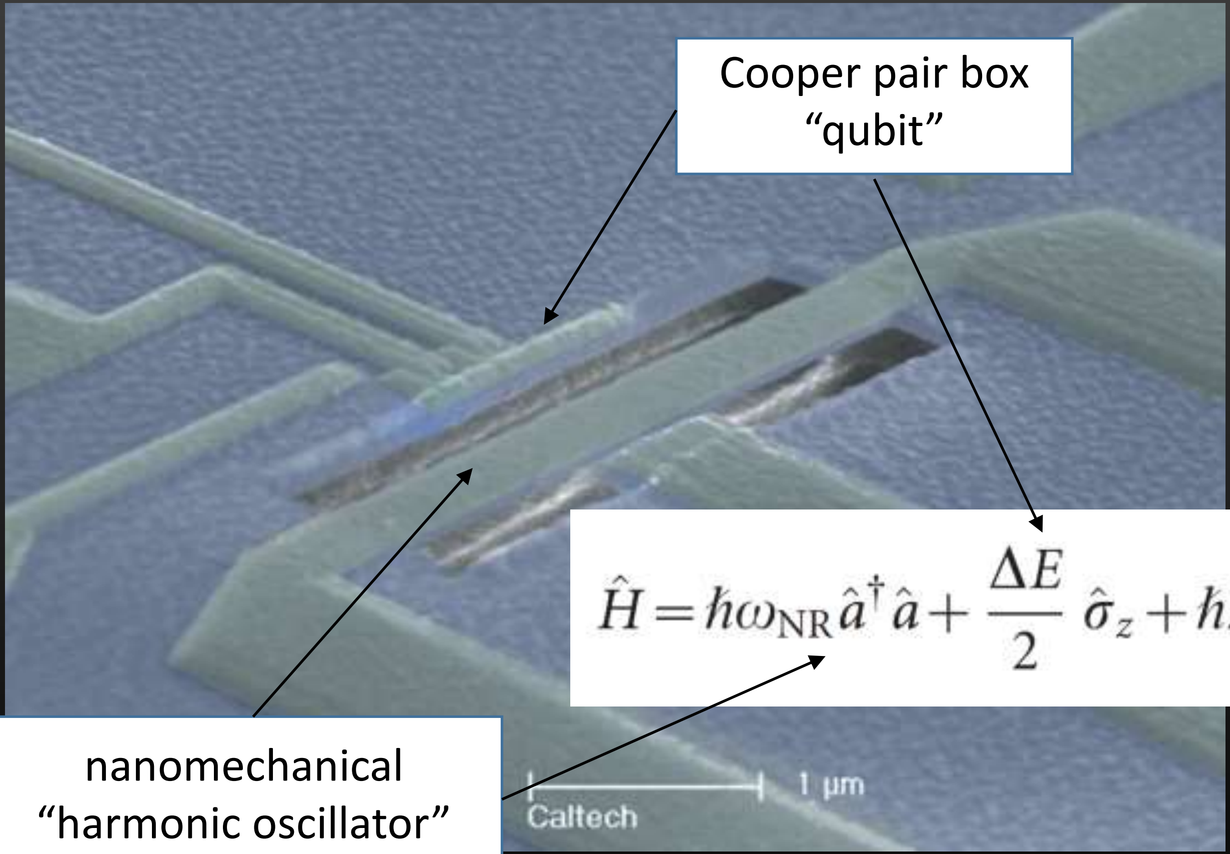

$$\hat{H} = \hbar\omega_{\mathrm{NR}}\hat{a}^{\dagger}\hat{a} + \frac{\Delta E}{2}\hat{\sigma}_z + \hbar\lambda(\hat{a}+\hat{a}^{\dagger})\left(\frac{E_{\mathrm{el}}}{\Delta E}\hat{\sigma}_z - \frac{E_{\mathrm{J}}}{\Delta E}\hat{\sigma}_x\right)$$

nanomechanical
"harmonic oscillator"

* LaHaye, **JS** *et.al*, *"Nanomechanical measurements of a superconducting qubit"*, *Nature* **459**, 960 (2009).

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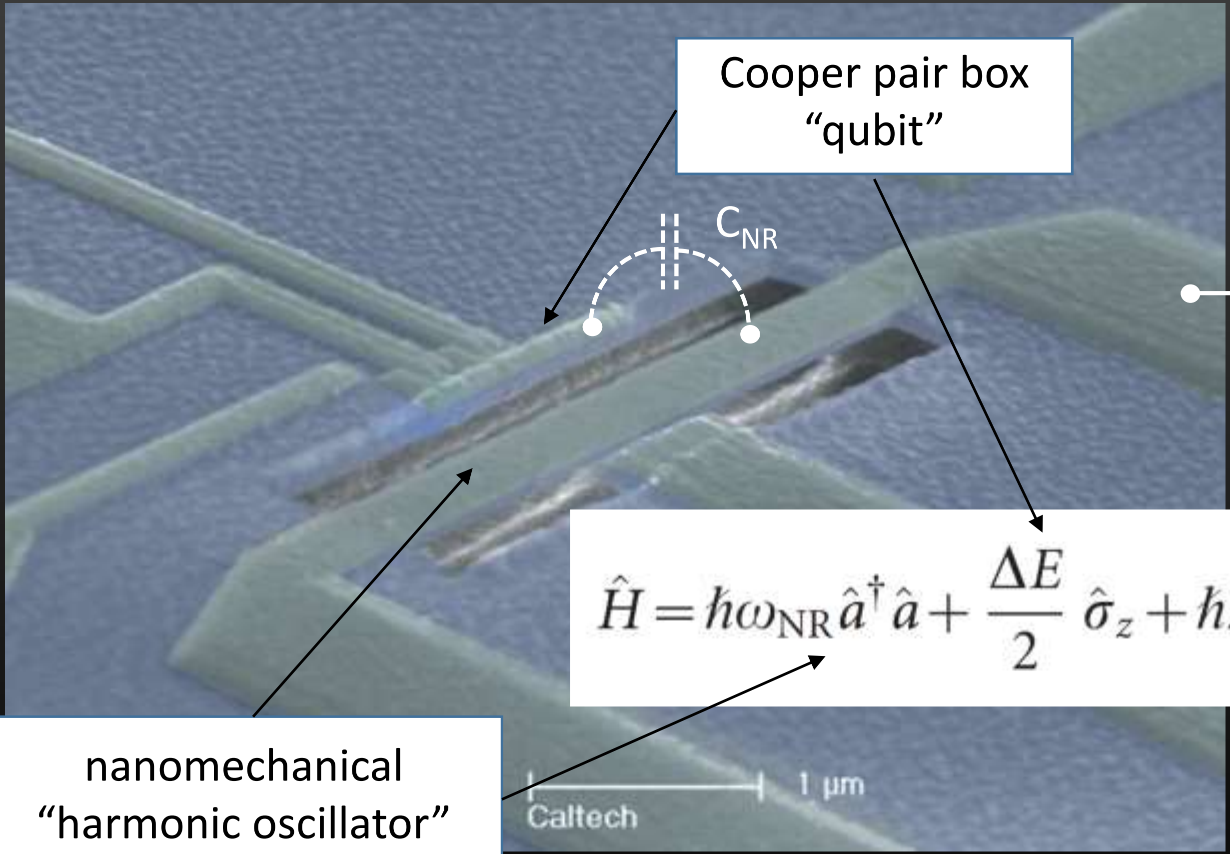

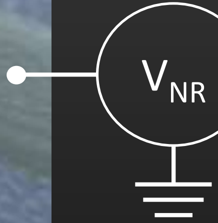

“coupling”

$$\hat{H} = \hbar\omega_{NR}\hat{a}^{\dagger}\hat{a} + \frac{\Delta E}{2}\hat{\sigma}_z + \hbar\lambda(\hat{a}+\hat{a}^{\dagger})\left(\frac{E_{el}}{\Delta E}\hat{\sigma}_z - \frac{E_J}{\Delta E}\hat{\sigma}_x\right)$$

$$\lambda \approx \frac{4n_{NR}E_C}{\hbar}\frac{1}{C_{NR}}\frac{\partial C_{NR}}{\partial x}x_{zp}$$

$$n_{NR} = C_{NR}V_{NR}/2e$$

nanomechanical
“harmonic oscillator”

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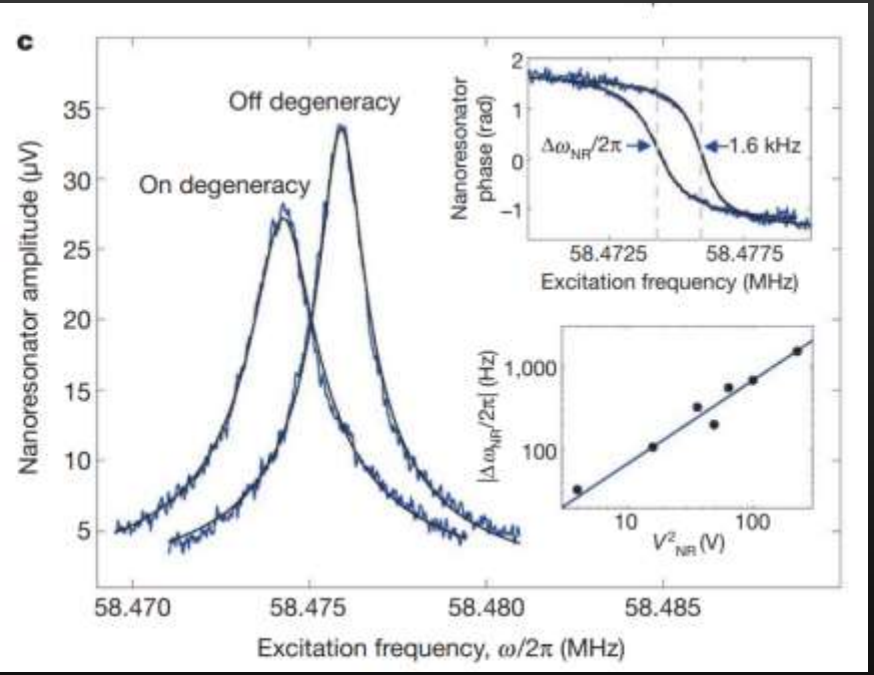
Example1: Quantum electromechanical system

$$\hat{H} = \hbar\omega_{\mathrm{NR}}\hat{a}^\dagger\hat{a} + \frac{\Delta E}{2}\hat{\sigma}_z + \hbar\lambda(\hat{a}+\hat{a}^\dagger)\left(\frac{E_{\mathrm{el}}}{\Delta E}\hat{\sigma}_z - \frac{E_{\mathrm{J}}}{\Delta E}\hat{\sigma}_x\right)$$

$\hbar|\lambda|\langle\hat{a}^\dagger\hat{a}\rangle \ll |\Delta E - \hbar\omega_{\mathrm{NR}}|$ (dispersive coupling limit)

"qubit-state dependent mechanical resonance shift"

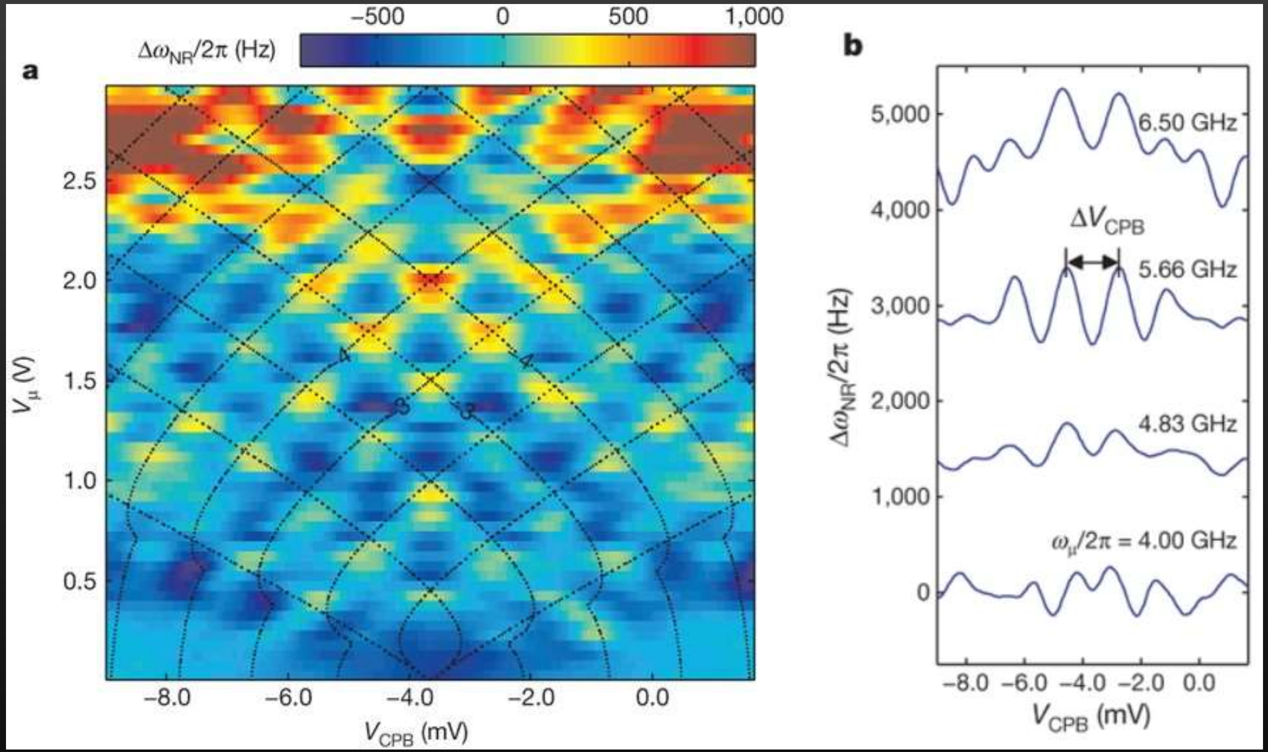
$$\frac{\Delta\omega_{\mathrm{NR}}}{2\pi} = \frac{\hbar\lambda^2}{\pi}\frac{E_{\mathrm{J}}^2}{\Delta E(\Delta E^2 - (\hbar\omega_{\mathrm{NR}})^2)}\langle\hat{\sigma}_z\rangle$$

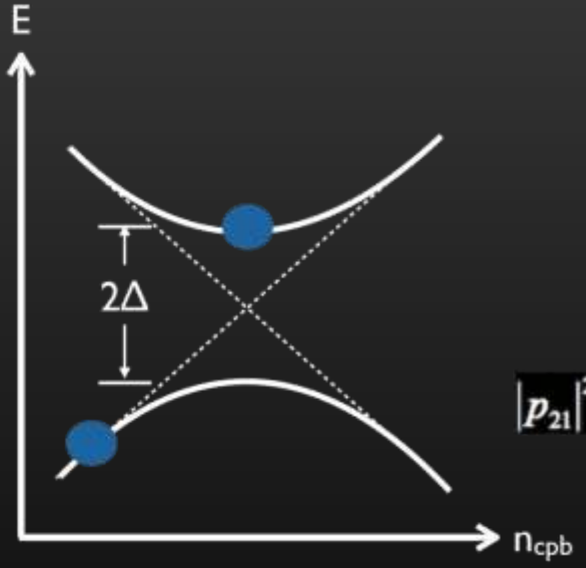


* LaHaye, **JS** *et.al*, *"Nanomechanical measurements of a superconducting qubit"*, *Nature* **459**, 960 (2009).

Nanomechanical probe of quantum coherence

"Landau-Zener Interference"





$$P_{LZ} = \exp(-2\pi\delta)$$

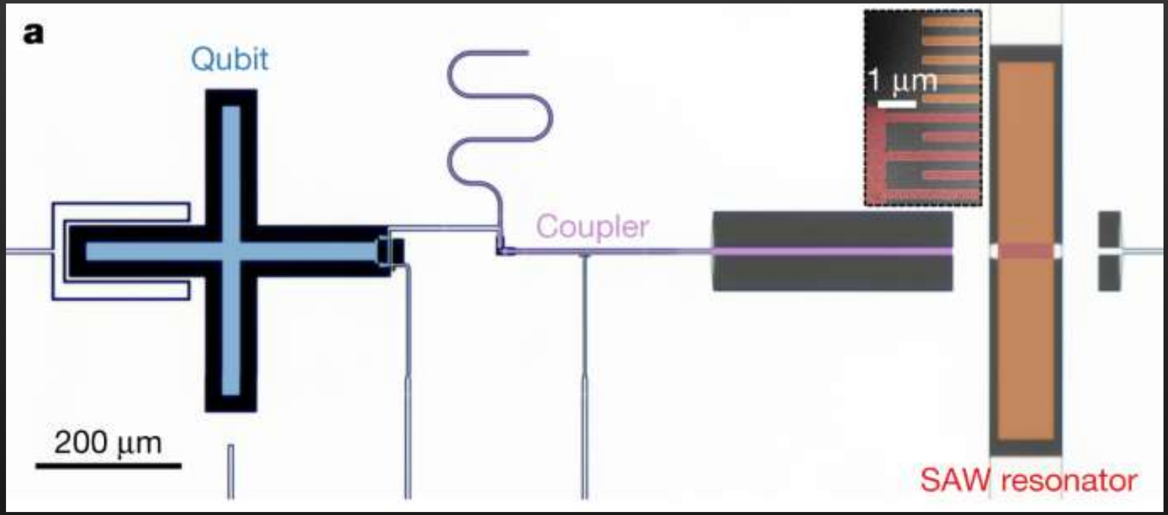
$$\varphi_{LZ} = -\frac{\pi}{4} + \arg[\Gamma(1 - i\delta)] + \delta(\log\delta - 1)$$

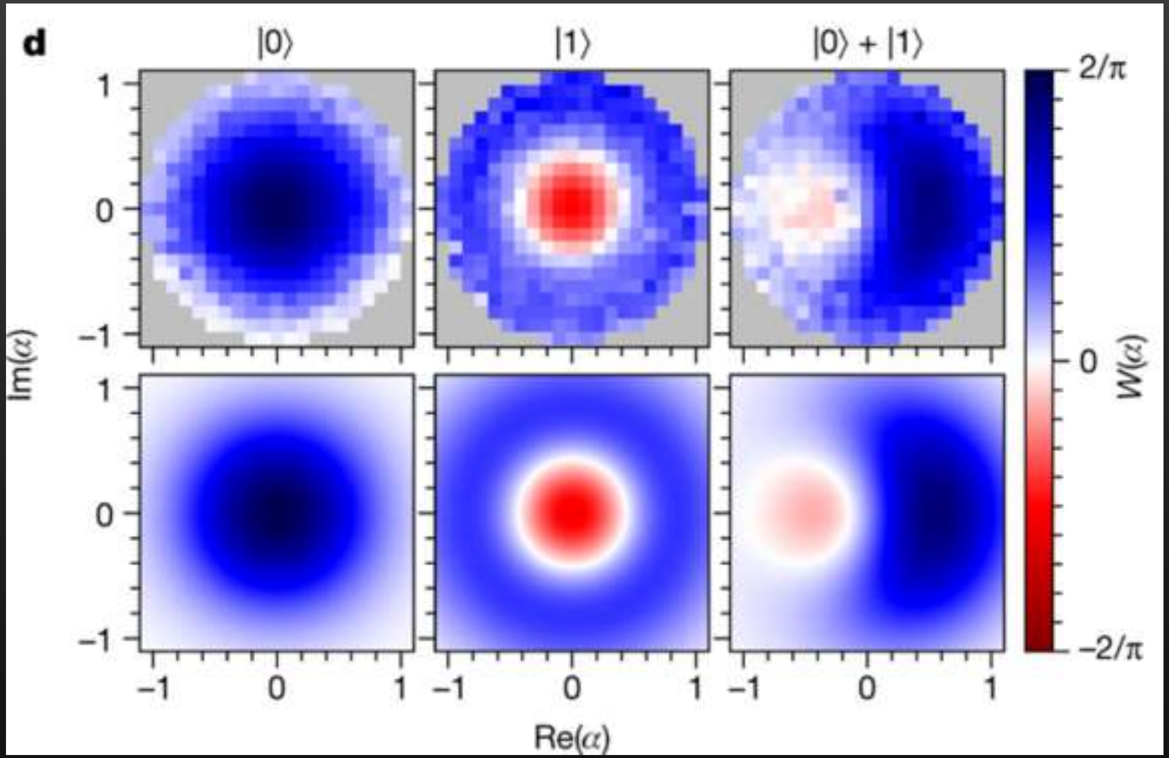
$$\delta = \frac{\Delta^2}{\hbar \frac{dE}{dt}}$$

$$|p_{21}|^2 = 2P_{LZ}(1 - P_{LZ})[1 + \cos(\varphi - 2\varphi_{LZ})]$$

* LaHaye, **JS** *et.al*, *"Nanomechanical measurements of a superconducting qubit"*, *Nature* **459**, 960 (2009).

Quantum tomography of mechanical phonon

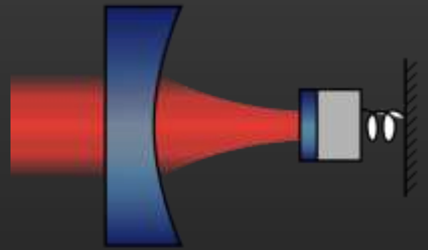




* Satzinger *et.al*, *"Quantum control of surface acoustic-wave phonons"*, *Nature* **563**, 661 (2018).

Example 2: Quantum optomechanical system

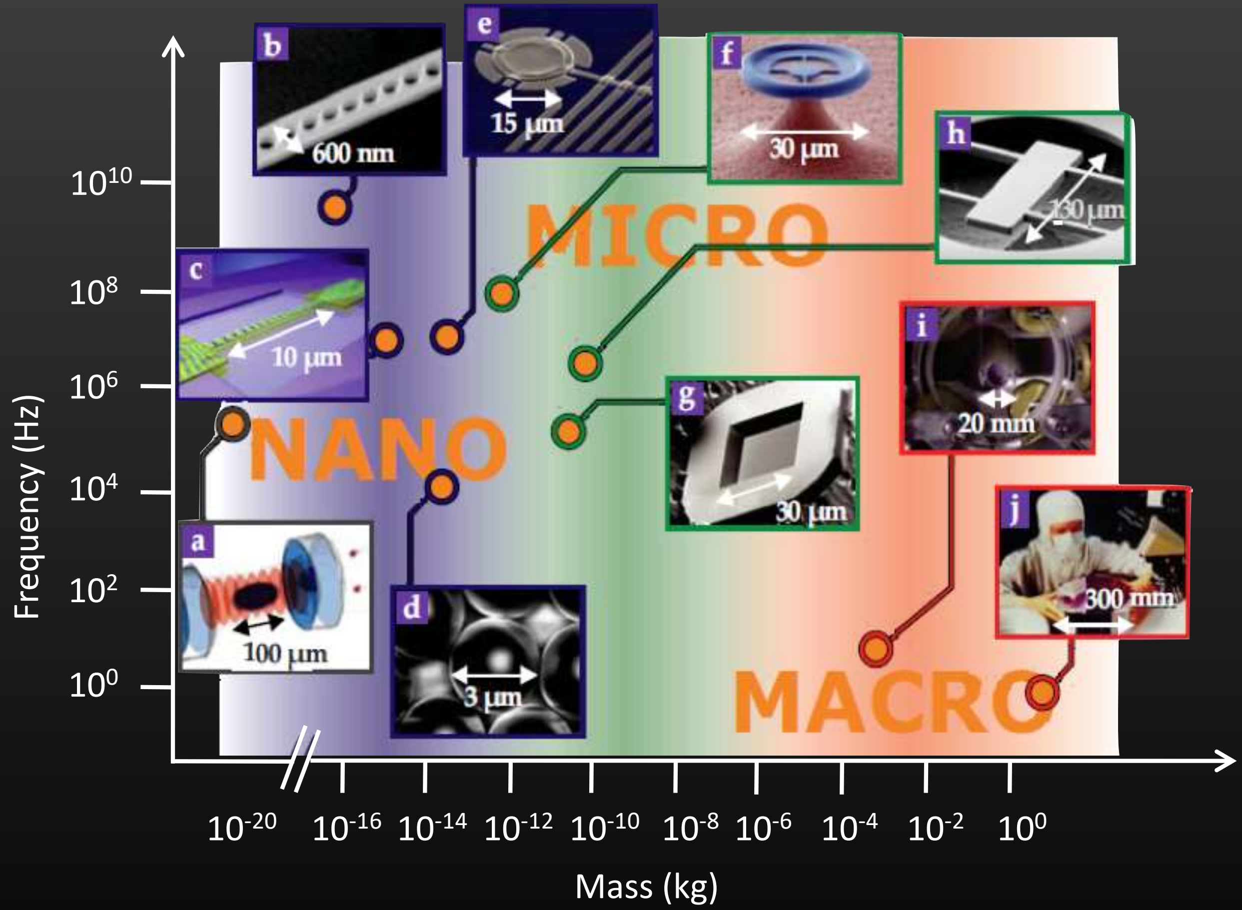
<u>Mechanical oscillator coupled to *photons*</u>



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

photon — mechanics or "phonon" — interaction

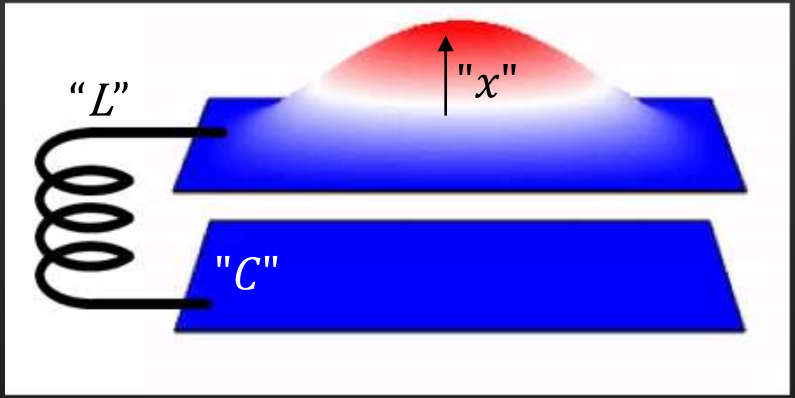
- Quantum non-demolition measurement
- Quantum squeezing
- Ground state cooling
- Microwave-optical photon conversion
- Zero-point fluctuation of motion …



* Aspelmeyer *et al.*, *Phys. Today* **65**, 29 (2012).

Cavity quantum electro-mechanics

= *microwave resonator*



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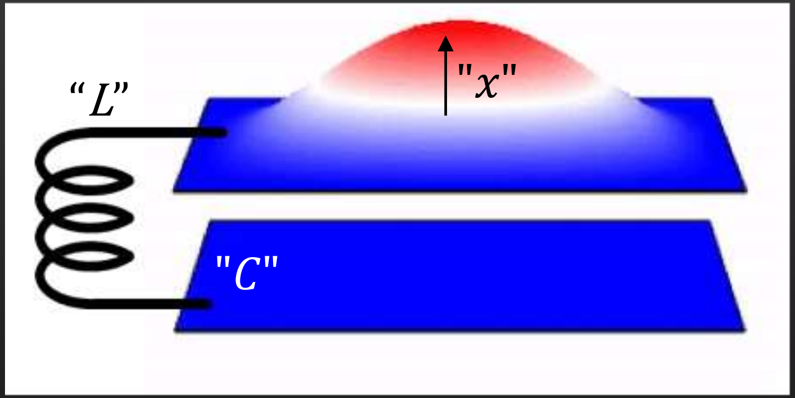


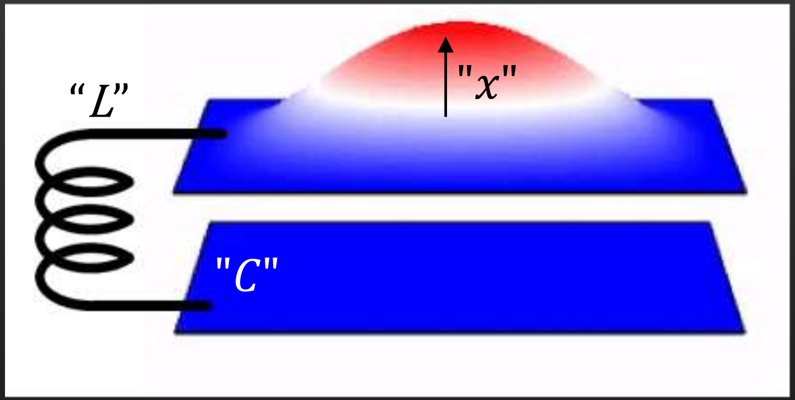
$$\omega_c = \sqrt{\frac{1}{LC(x)}} \approx \omega_c(x=0) + \left(\frac{\partial \omega_c}{\partial x}\right) x$$

"cavity frequency shift per zero-point motion"

$$g \equiv \left(\frac{\partial \omega_c}{\partial x}\right) x_{zp}$$

Cavity quantum electro-mechanics

= *microwave resonator*



$$\omega_c = \sqrt{\frac{1}{LC(x)}} \approx \omega_c(x=0) + \left(\frac{\partial \omega_c}{\partial x}\right) x$$

"cavity frequency shift per zero-point motion"

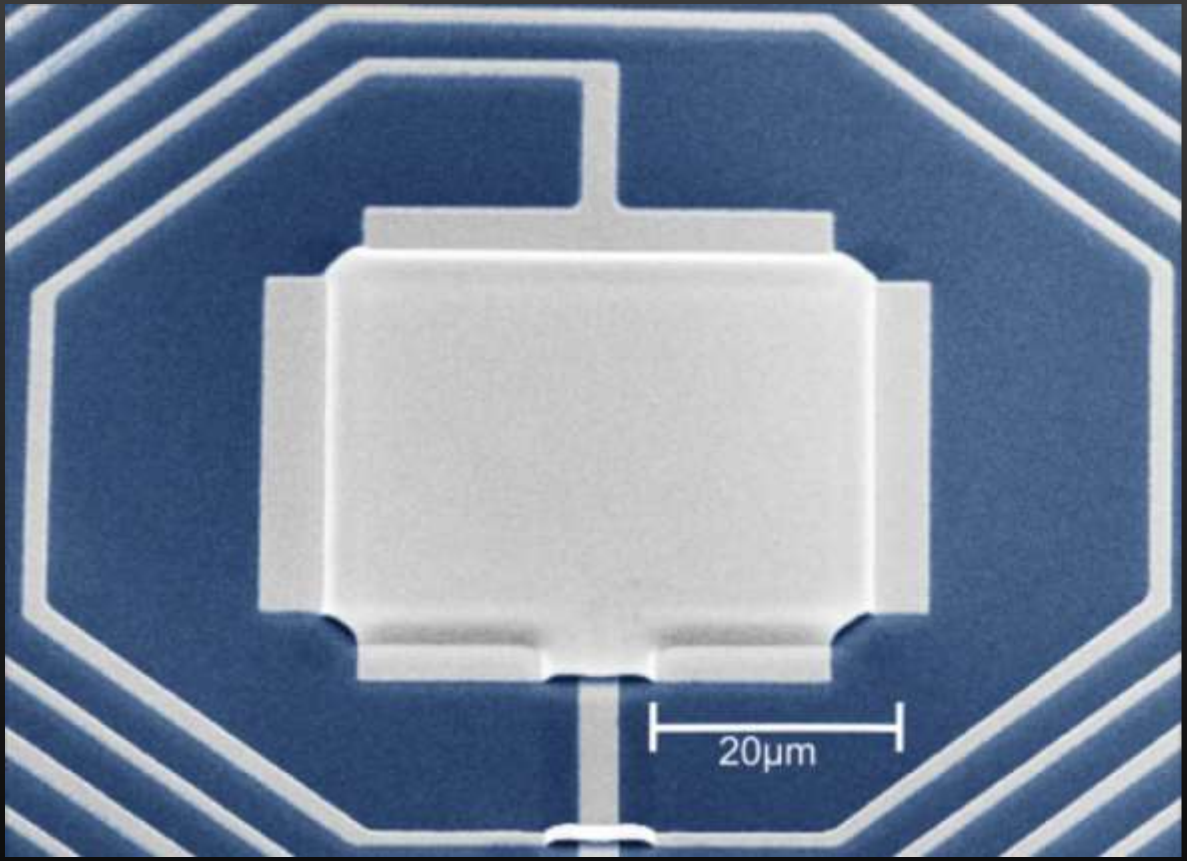
$$g \equiv \left(\frac{\partial \omega_c}{\partial x}\right) x_{zp}$$

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

Photon	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	

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

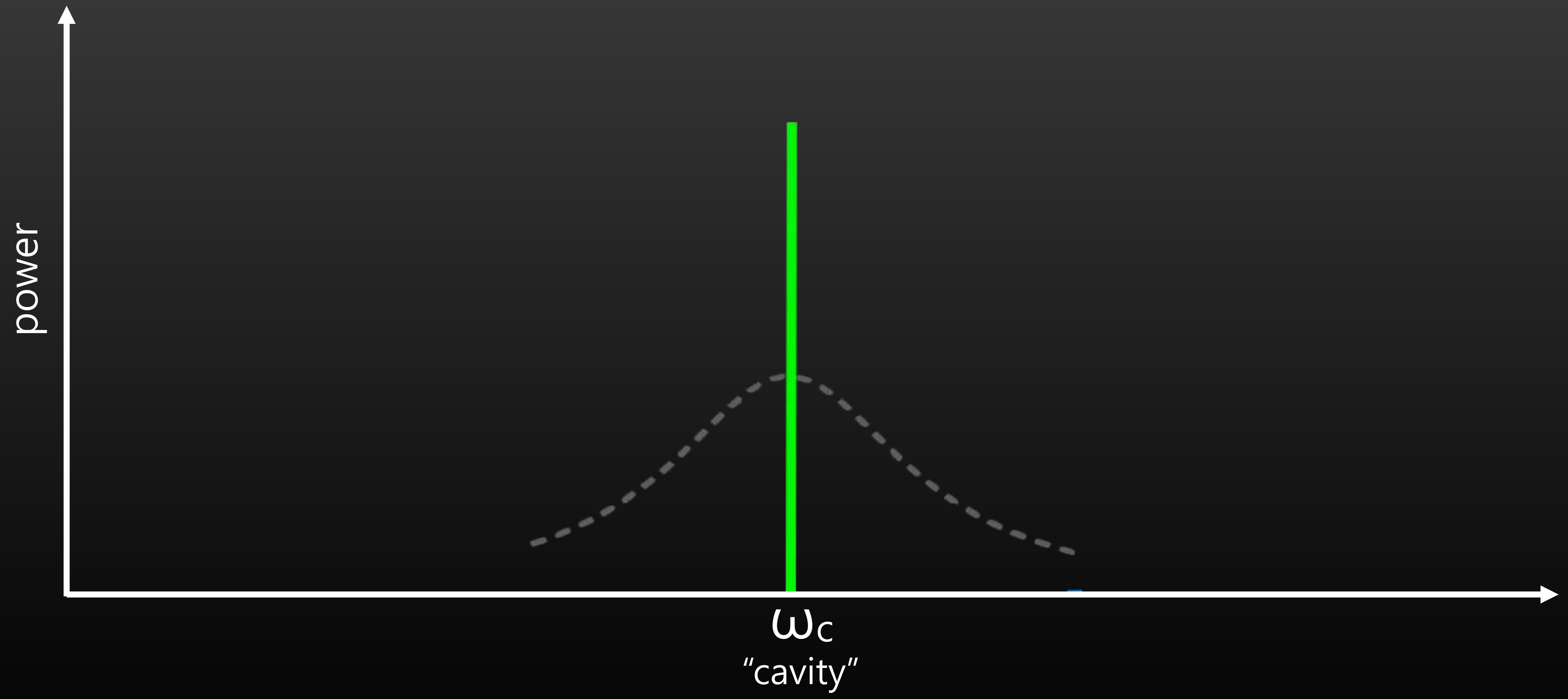
Cavity quantum electro-mechanics



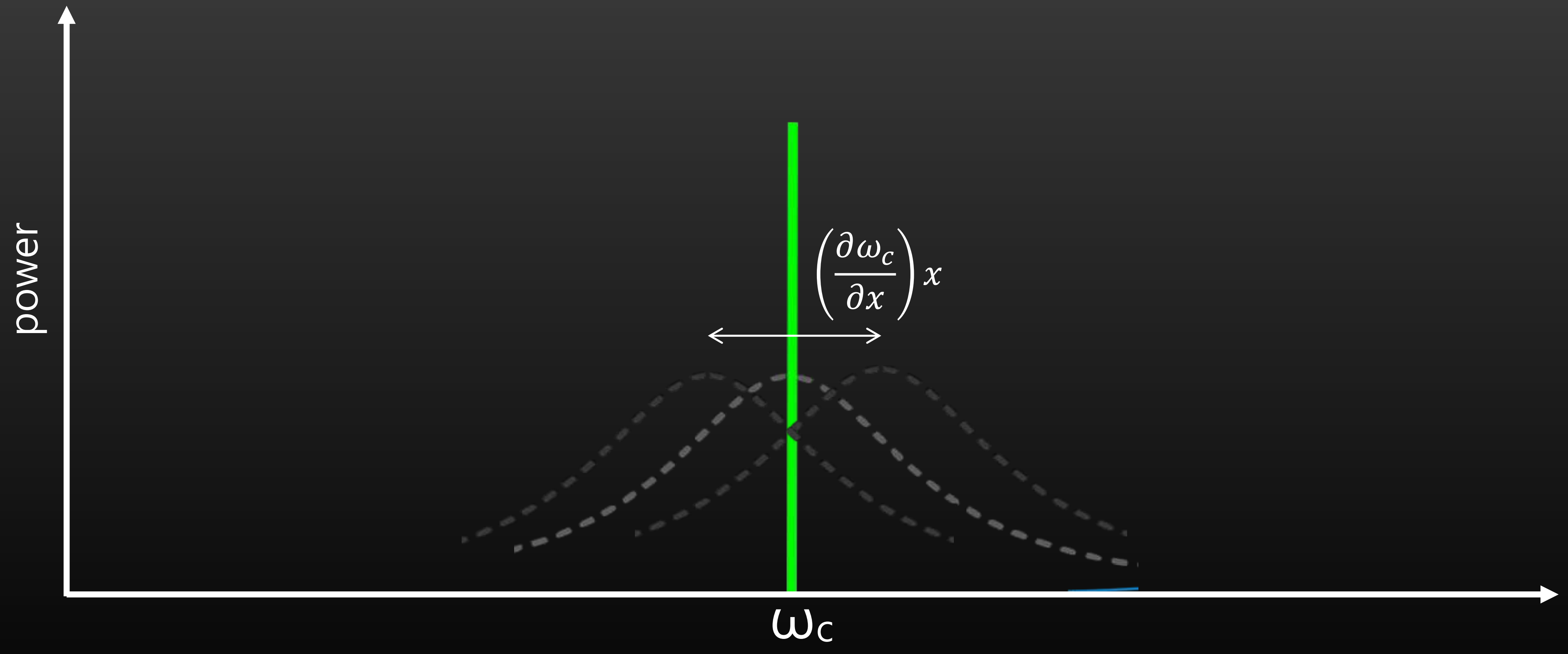
- Quantum non-demolition measurements
  - **JS** *et.al.*, *Science* **344**, 1262 (2014).

- Quantum squeezing of motion
  - Wollman, Lei, Weinstein, **JS** *et.al.*, *Science* **349**, 952 (2015).
  - Lei, Weinstein, **JS** *et.al.*, *Phys. Rev. Lett.* **117**, 100801 (2016).

Microwave resonance

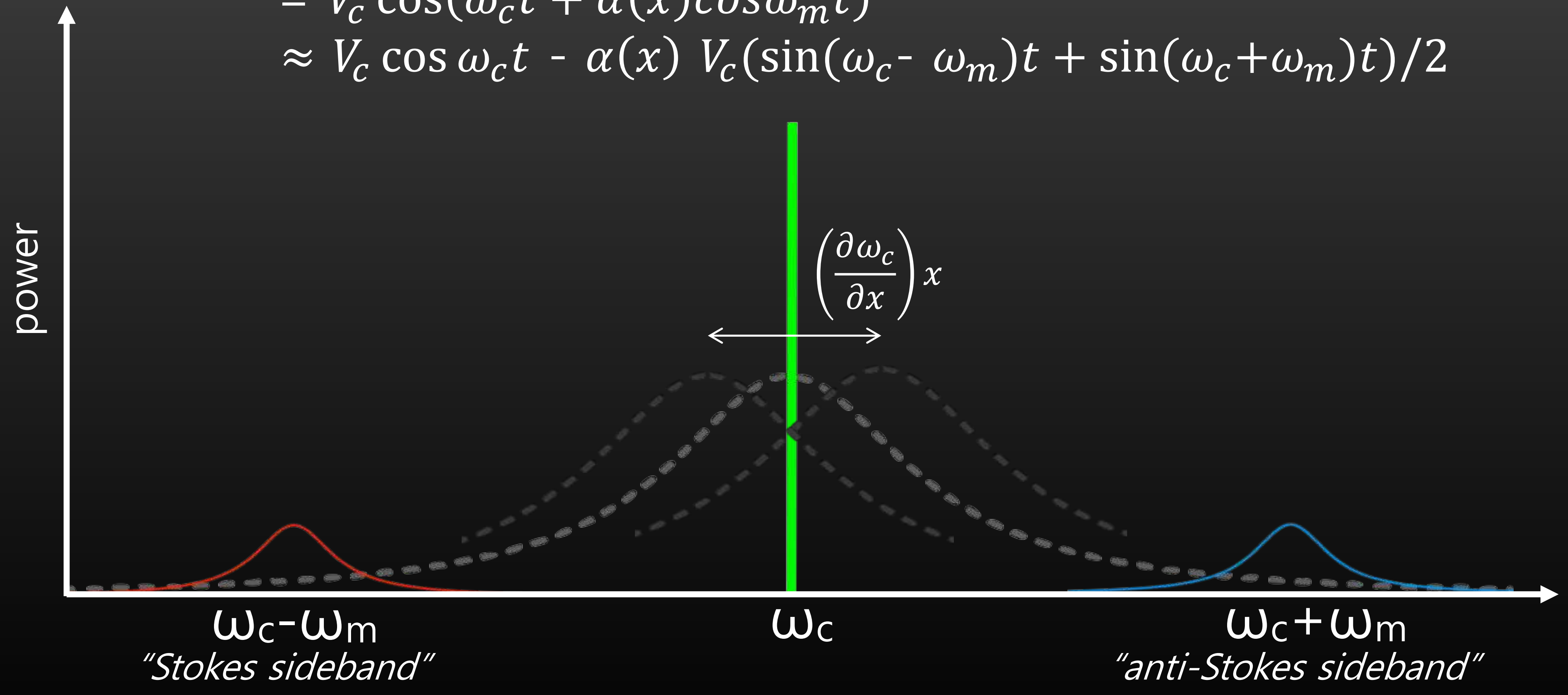


Motion moves cavity resonance

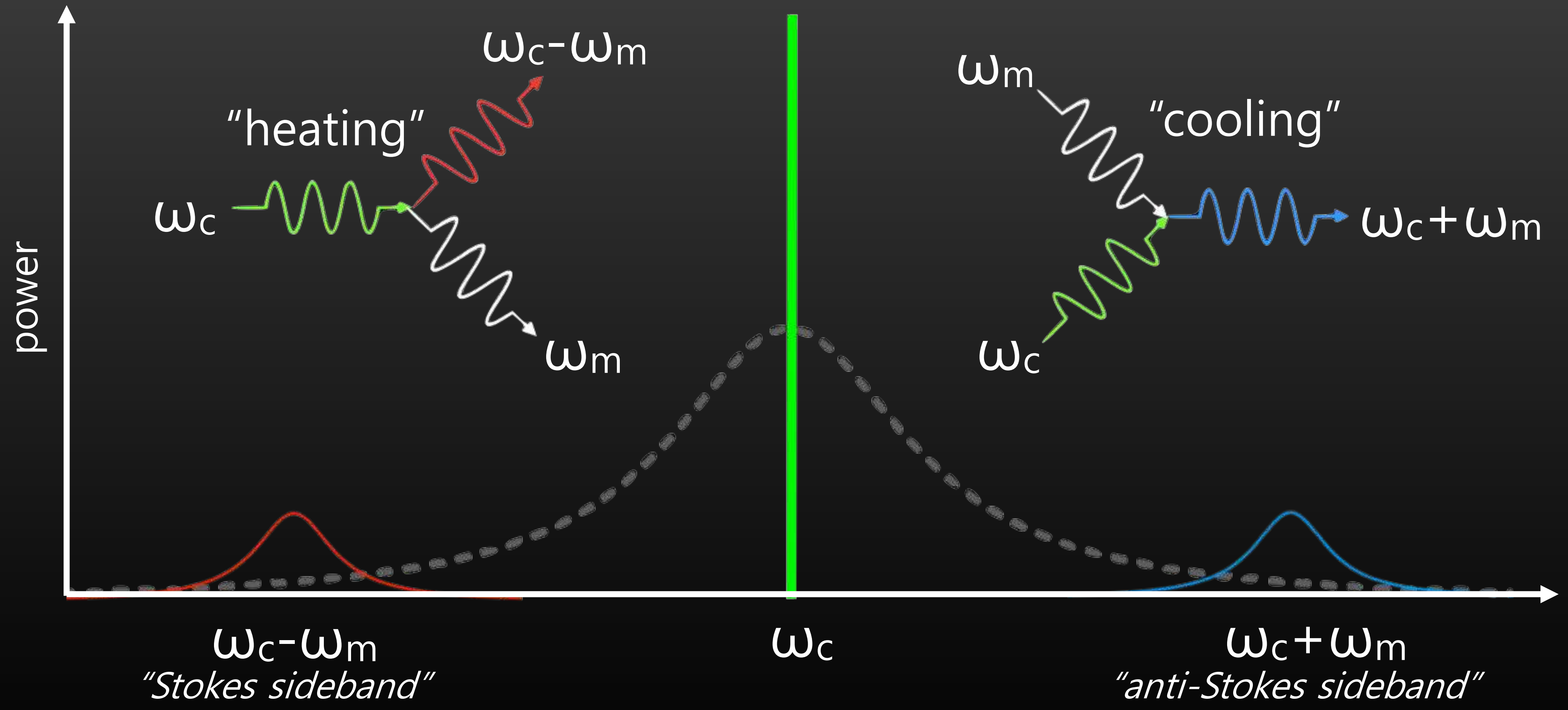


Motion converts photons

$$V_{out} \propto V_c \cos\left(\omega_c t + \varphi_m(t)\right)$$
$$= V_c \cos(\omega_c t + \alpha(x) cos\omega_m t)$$
$$\approx V_c \cos \omega_c t \text{ - } \alpha(x)\ V_c(\sin(\omega_c \text{- } \omega_m)t + \sin(\omega_c + \omega_m)t)/2$$

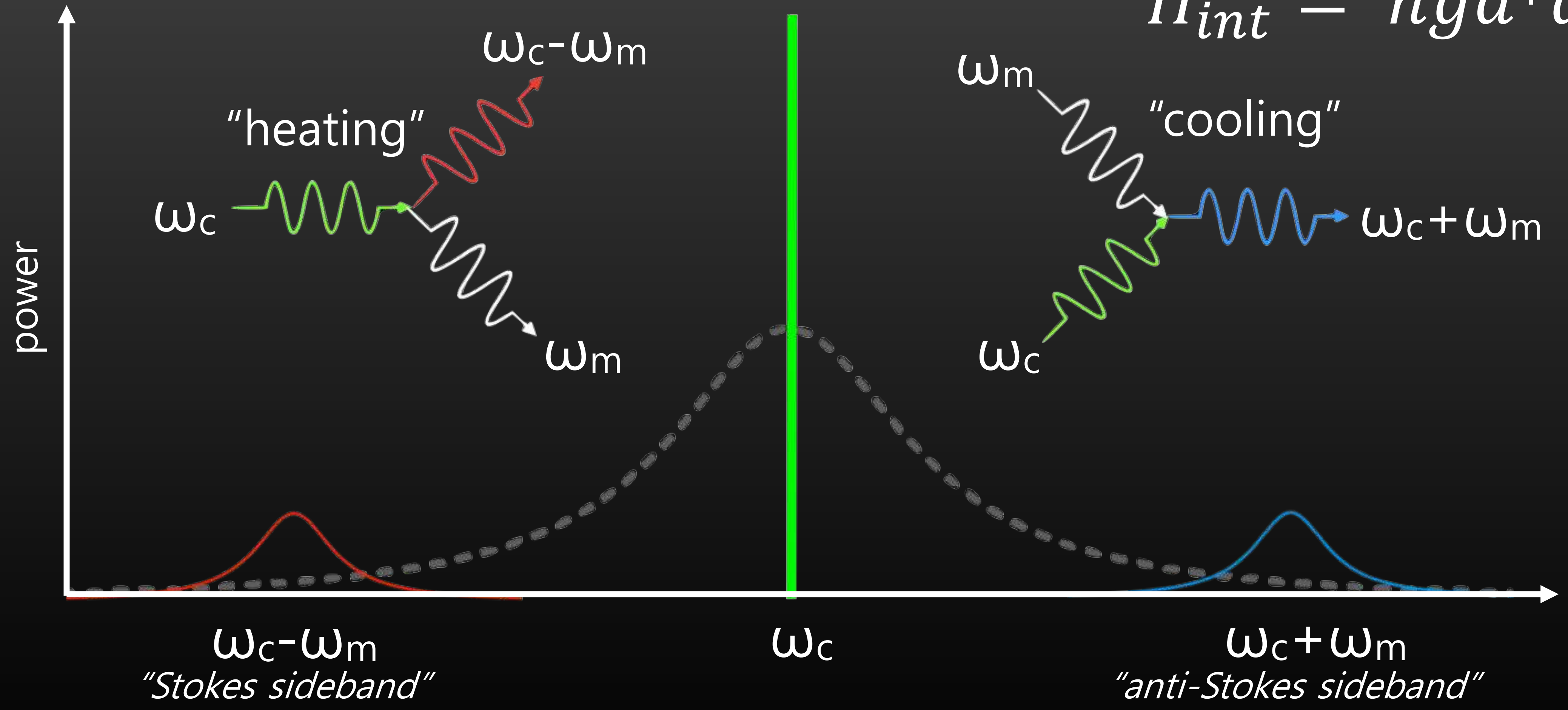


Photon-phonon coupling

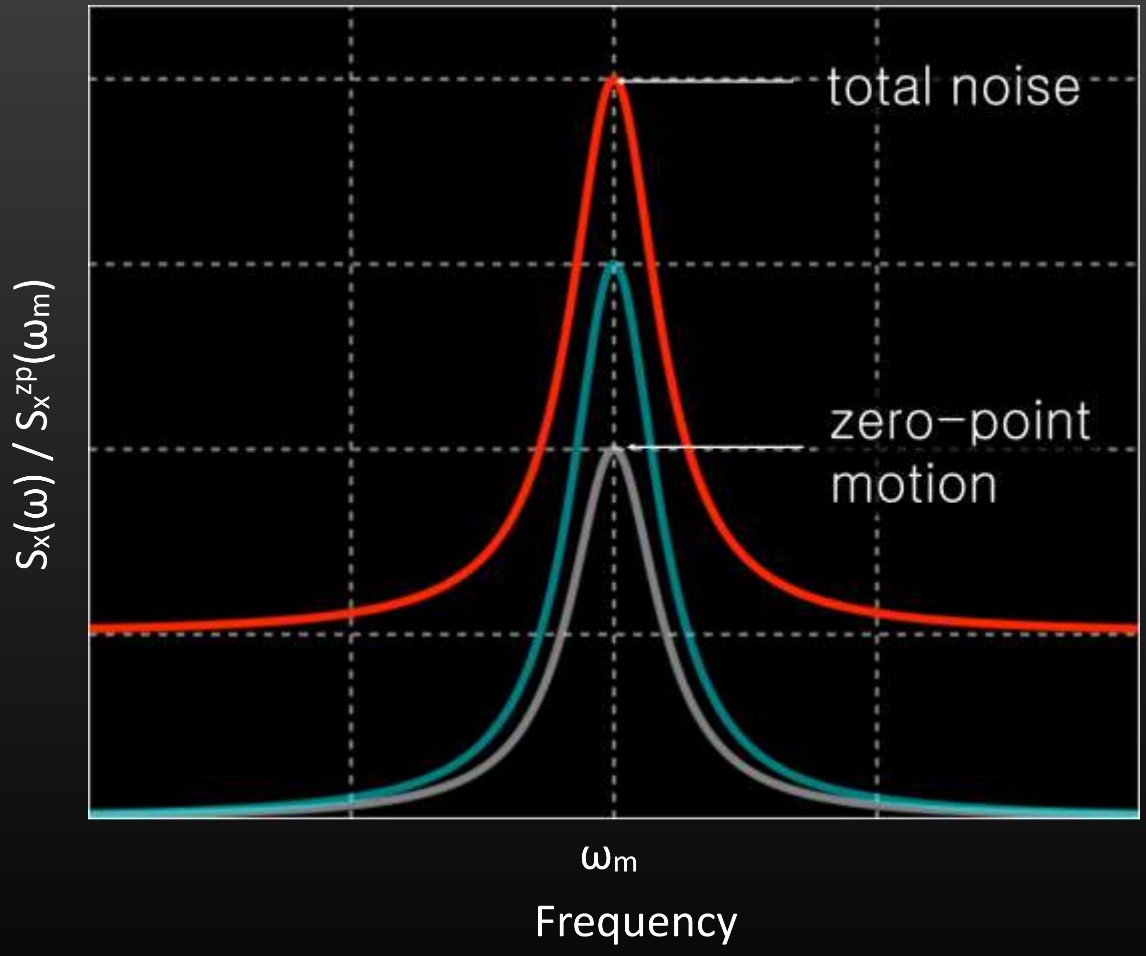


(Ideal) Detection of motion

$$\hat{H}_{int} = \hbar g \hat{a}^{\dagger}\hat{a}\hat{x}$$



Continuous position detection of harmonic oscillator

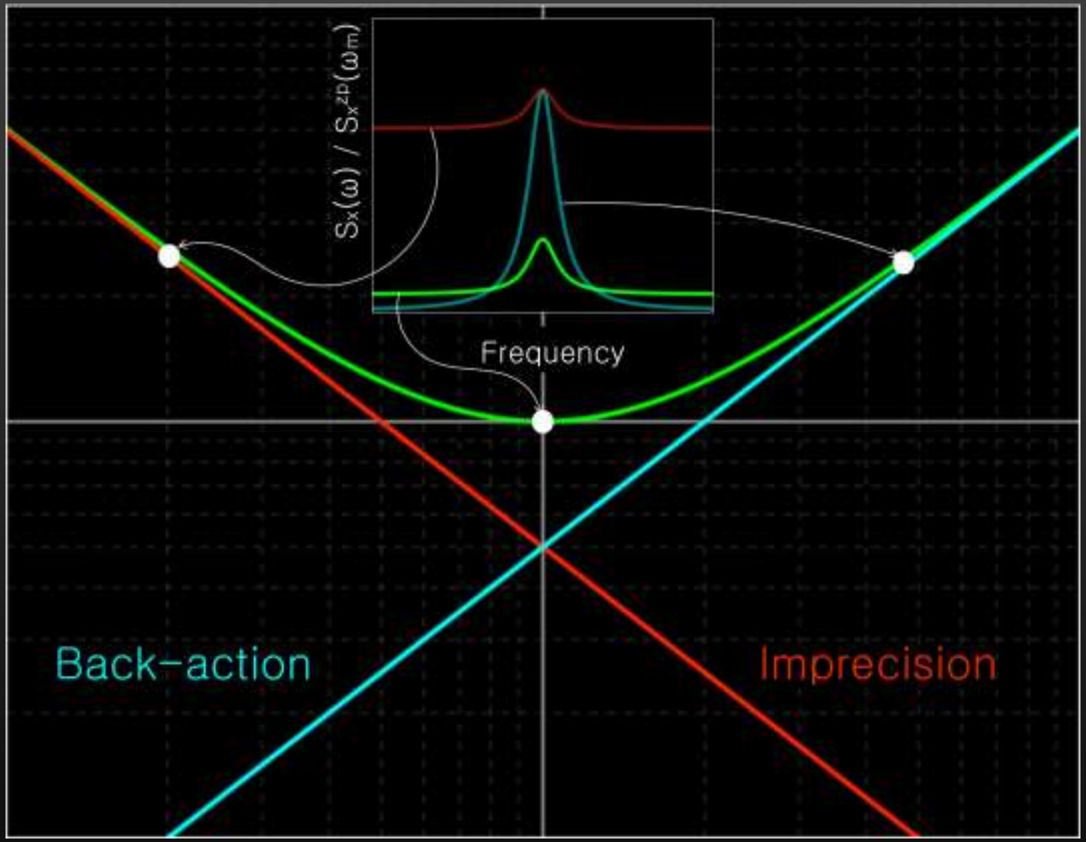


Back-action
(i.e. radiation pressure noise)

Imprecision
(i.e. photon shot noise)

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

Standard quantum limit



$\langle x^2 \rangle_{add} / x_{zp}^2$

# of photons

* 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 (i.e. quantum non-demolition measurement)

"quadrature operators"

$$\widehat{X_1}(t) = \hat{x}(t)\cos\omega t - \frac{\hat{p}(t)}{m\omega}\sin\omega t\,;\ \widehat{X_2}(t) = \hat{x}(t)\sin\omega t + \frac{\hat{p}(t)}{m\omega}\cos\omega t$$

i.e. $\hat{x}(t) = \widehat{X_1}(t)\cos\omega t + \widehat{X_2}(t)\sin\omega t$

$$[\widehat{X_1}, \widehat{X_2}] = \frac{i\hbar}{m\omega}$$

$$\Delta X_1 \cdot \Delta X_2 \geq \frac{\hbar}{2m\omega}$$

$\widehat{X_1}$ $\widehat{X_2}$

$$\frac{d\widehat{X_1}}{dt} = \frac{\partial\widehat{X_1}}{\partial t} - \frac{i}{\hbar}\left[\widehat{X_1}, \widehat{H_{osc}}\right] = 0$$

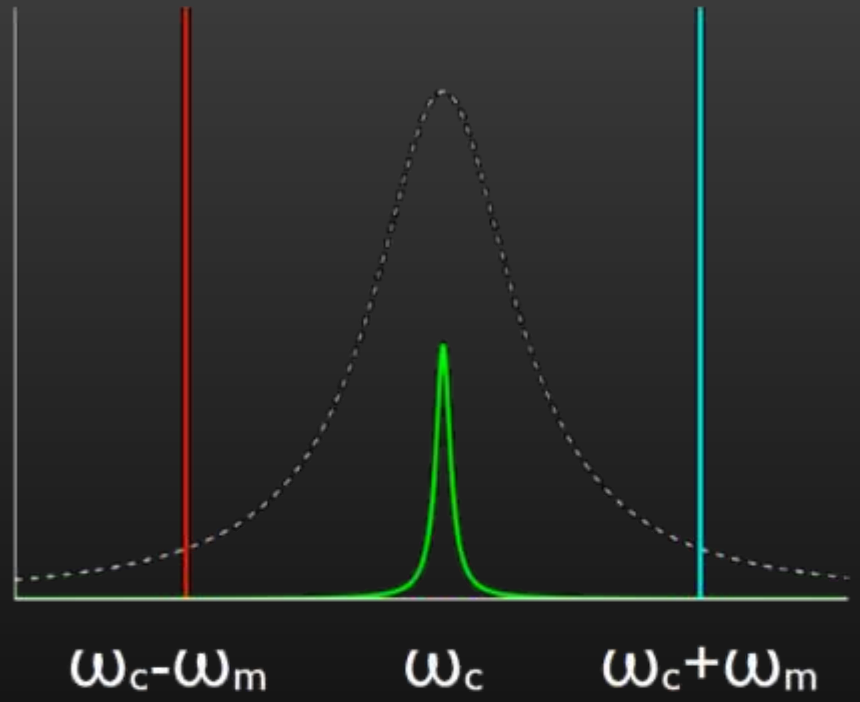
Quadrature conserves; no measurement back-action!

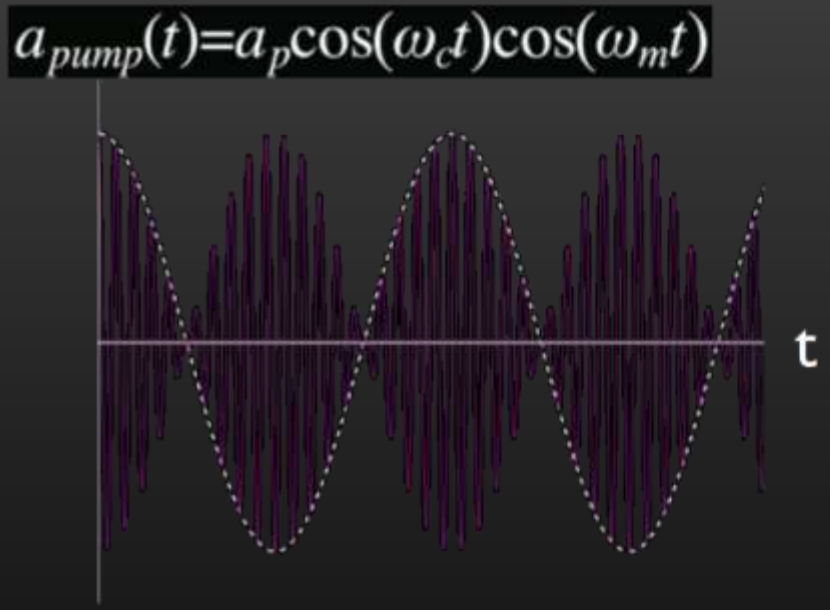
* Braginskii *et.al.*, *Sov. Phys. Usp.* **17**,644 (1975); Thorne *et.al.*, *Phys. Rev. Lett.* **40**, 667 (1978).

Evading quantum back-action

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

Evading quantum back-action

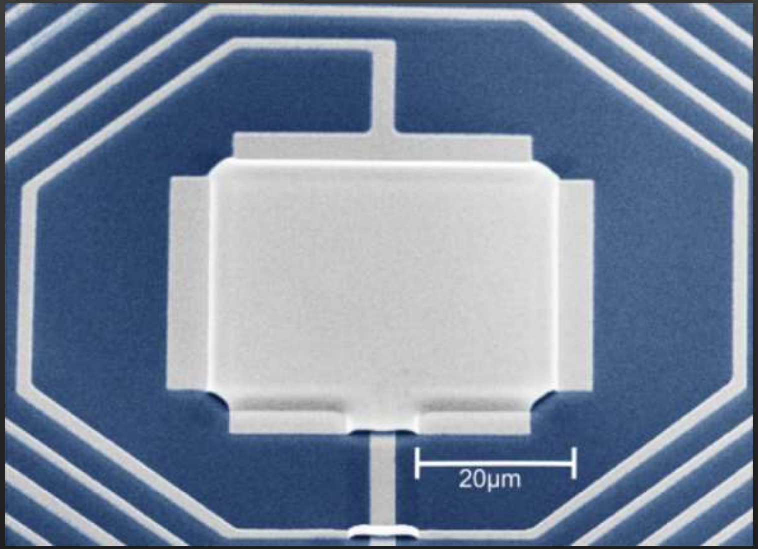


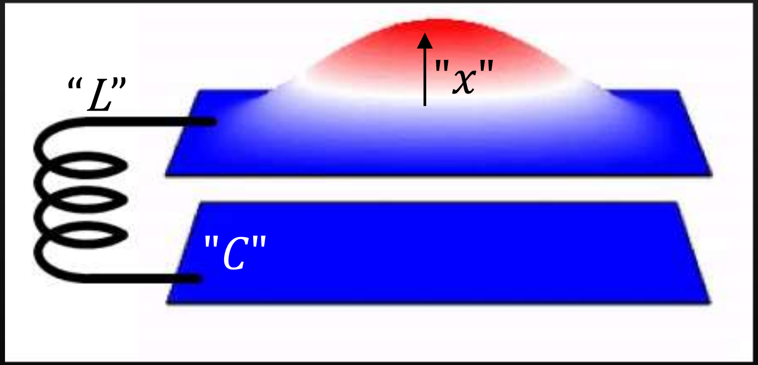


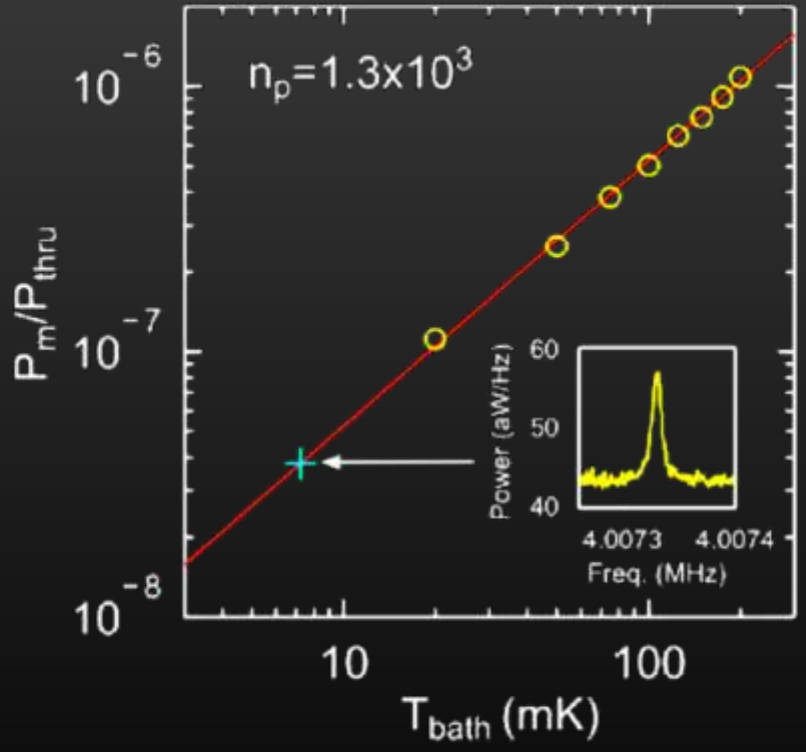
$$\hat{H}_{\text{int}} \propto \hat{X}_1(1+\cos 2\omega_m t)+\hat{X}_2 \sin 2\omega_m t$$

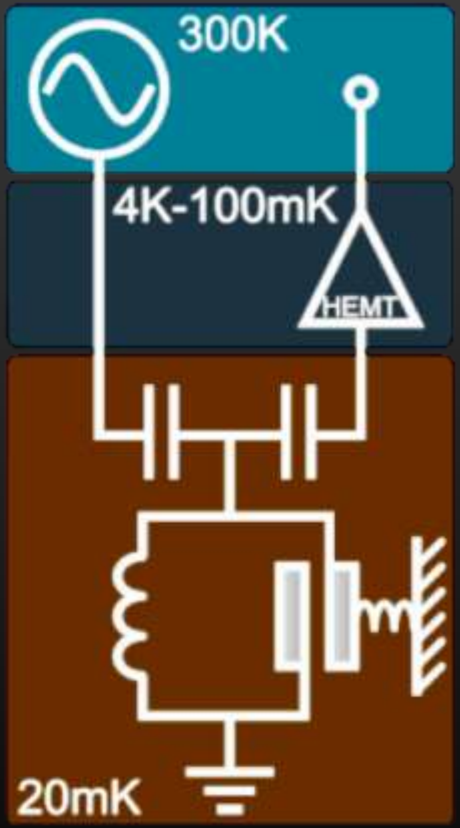
* Braginskii *et.al.*, *Sov. Phys. Usp.* **17**,644 (1975); Thorne *et.al.*, *Phys. Rev. Lett.* **40**, 667 (1978).

Experiments





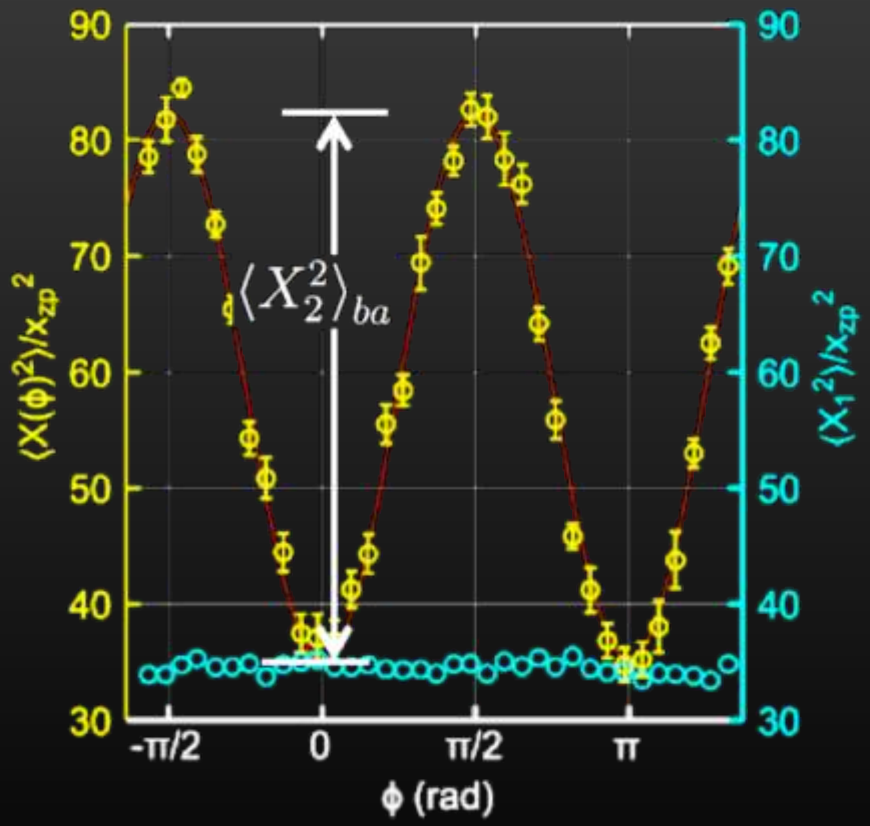




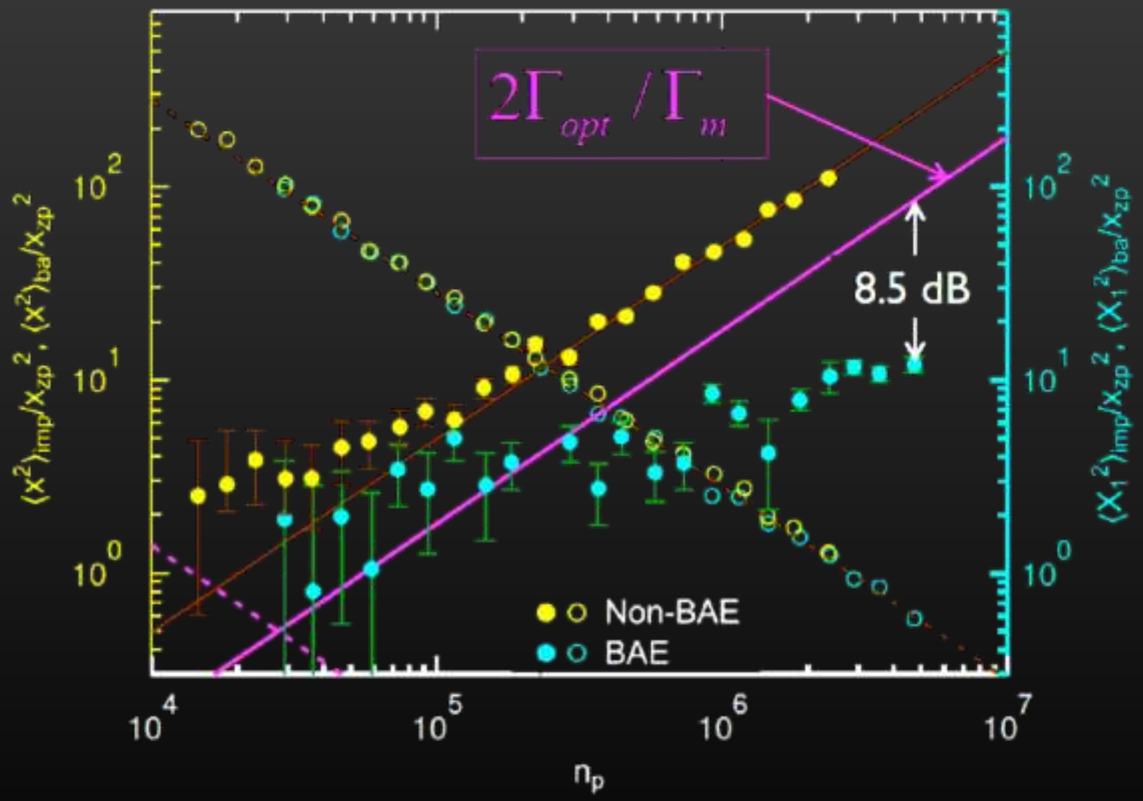
* **JS** et.al., *Science* **344,** 1262 (2014).

Experiments

"back-action on ONE quadrature"



"Evade quantum back-action by 8.5 dB"

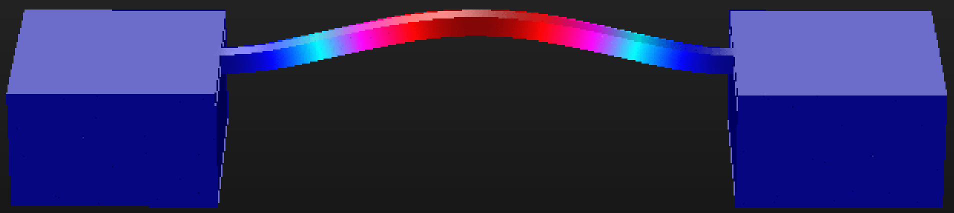


* **JS** et.al., *Science* **344,** 1262 (2014).

10 min break

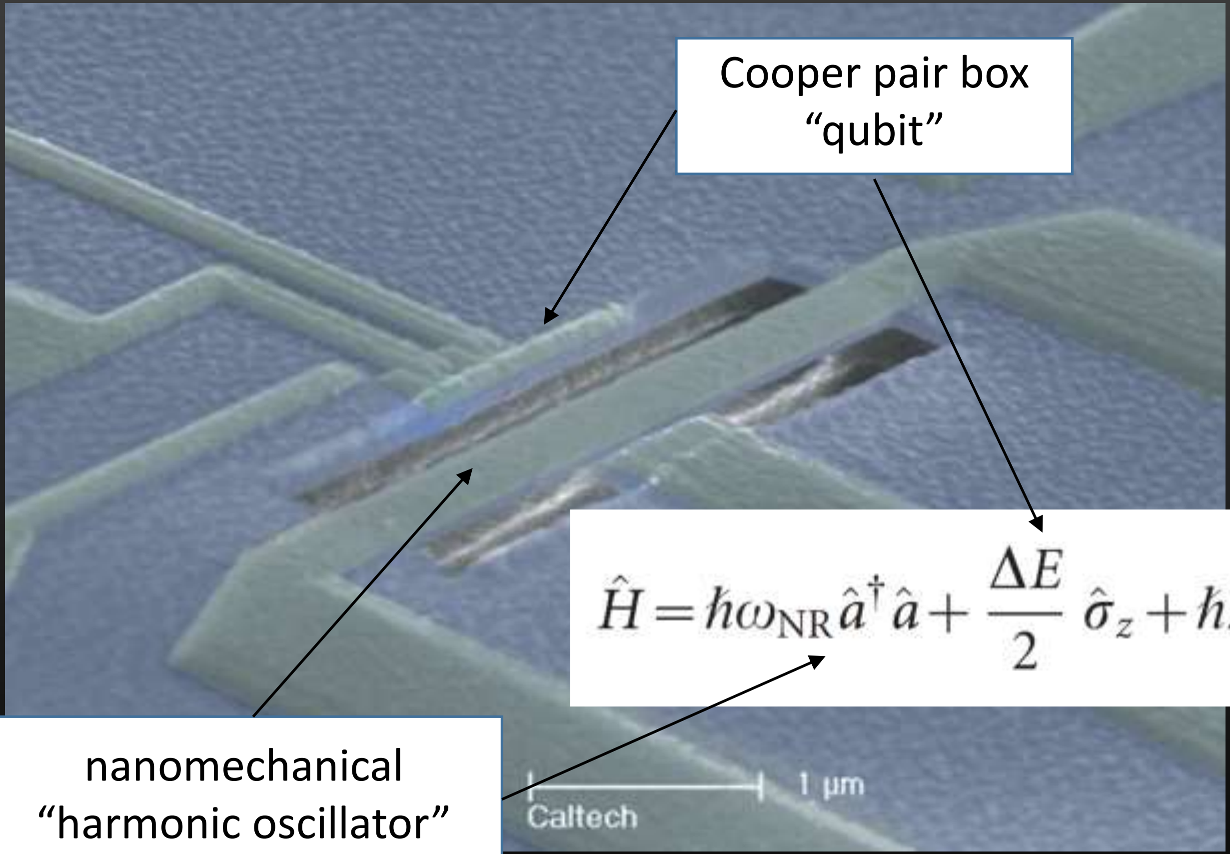
Mechanical quantum sensor

$$\hbar\omega > k_B T$$



- How to generate?
- How to apply them in sensing?
- How to hybrid with other quantum system?

Example1: Quantum electromechanical system



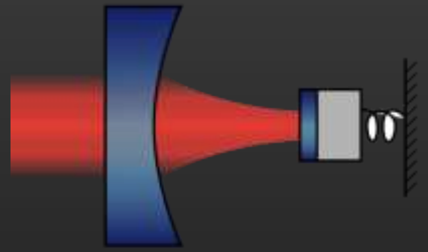
$$\hat{H} = \hbar\omega_{\mathrm{NR}}\hat{a}^{\dagger}\hat{a} + \frac{\Delta E}{2}\hat{\sigma}_z + \hbar\lambda(\hat{a}+\hat{a}^{\dagger})\left(\frac{E_{\mathrm{el}}}{\Delta E}\hat{\sigma}_z - \frac{E_{\mathrm{J}}}{\Delta E}\hat{\sigma}_x\right)$$

nanomechanical
“harmonic oscillator”

* LaHaye, **JS** *et.al*, *“Nanomechanical measurements of a superconducting qubit”*, *Nature* **459**, 960 (2009).

Example 2: Quantum optomechanical system

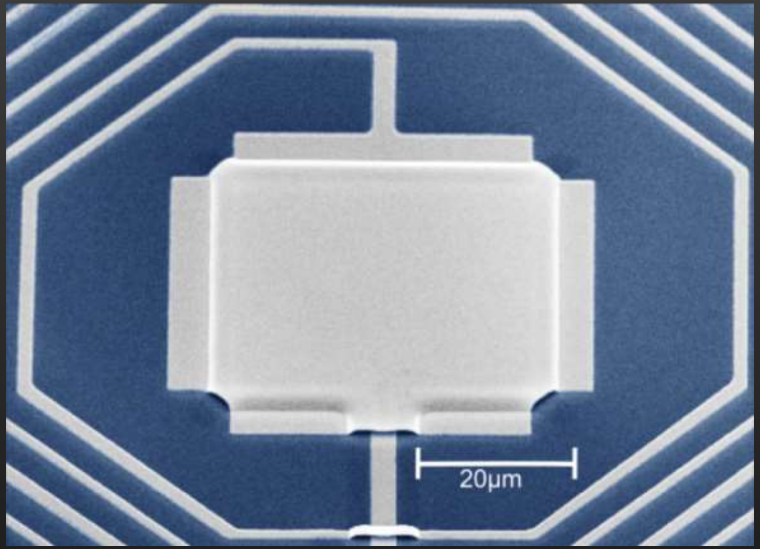
Mechanical oscillator coupled to *photons*

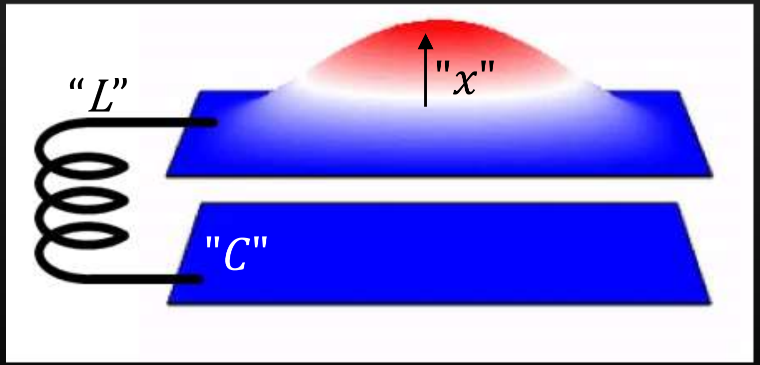


$$\hat{H} = \hbar\omega_c \hat{a}^\dagger \hat{a} + \hbar\omega_m \hat{b}^\dagger \hat{b} + \hbar g \hat{a}^\dagger \hat{a}(\hat{b}^\dagger + \hat{b})$$

photon — mechanics or "phonon" — interaction

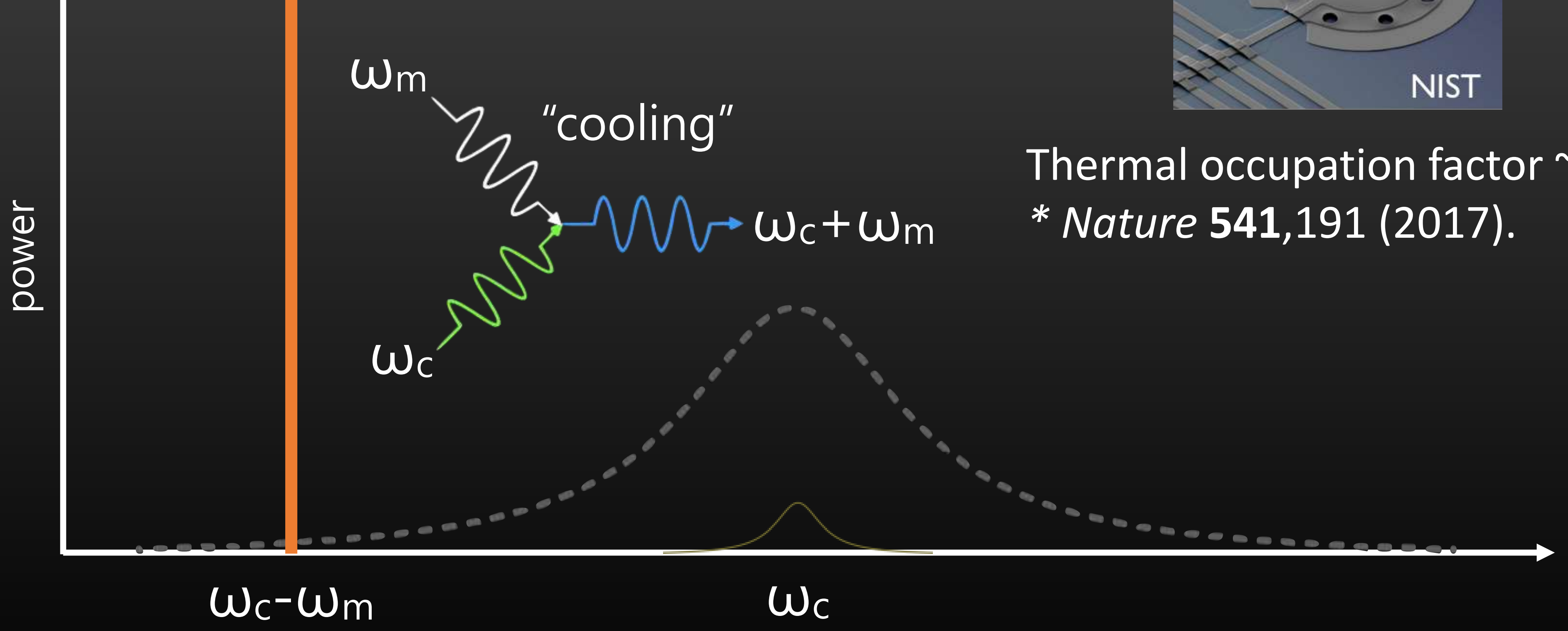
- Quantum non-demolition measurement
- Quantum squeezing
- Ground state cooling
- Microwave-optical photon conversion
- Zero-point fluctuation of motion …

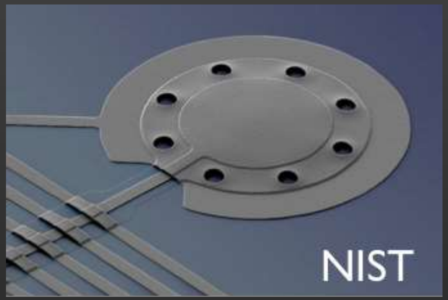




* **JS** et.al., *Science* **344,** 1262 (2014).

Ground state cooling of mechanical motion



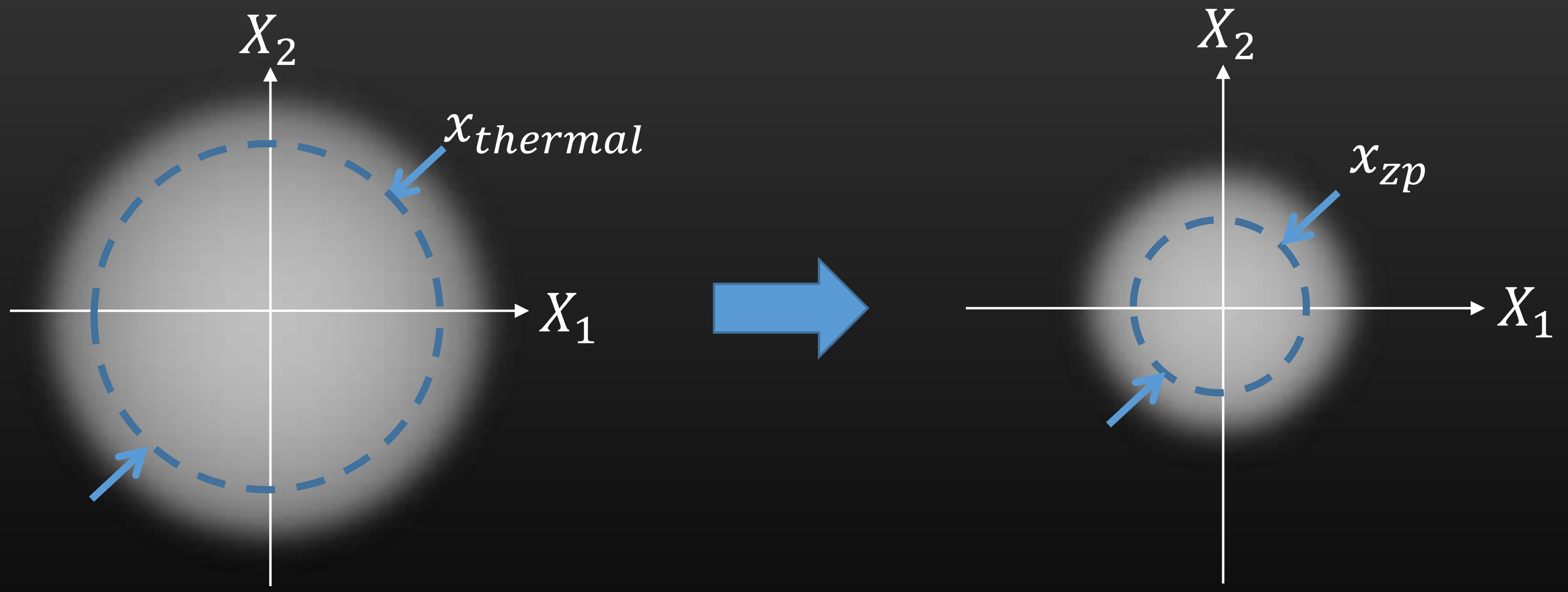


Thermal occupation factor ~ 0.2

* *Nature* **541**,191 (2017).

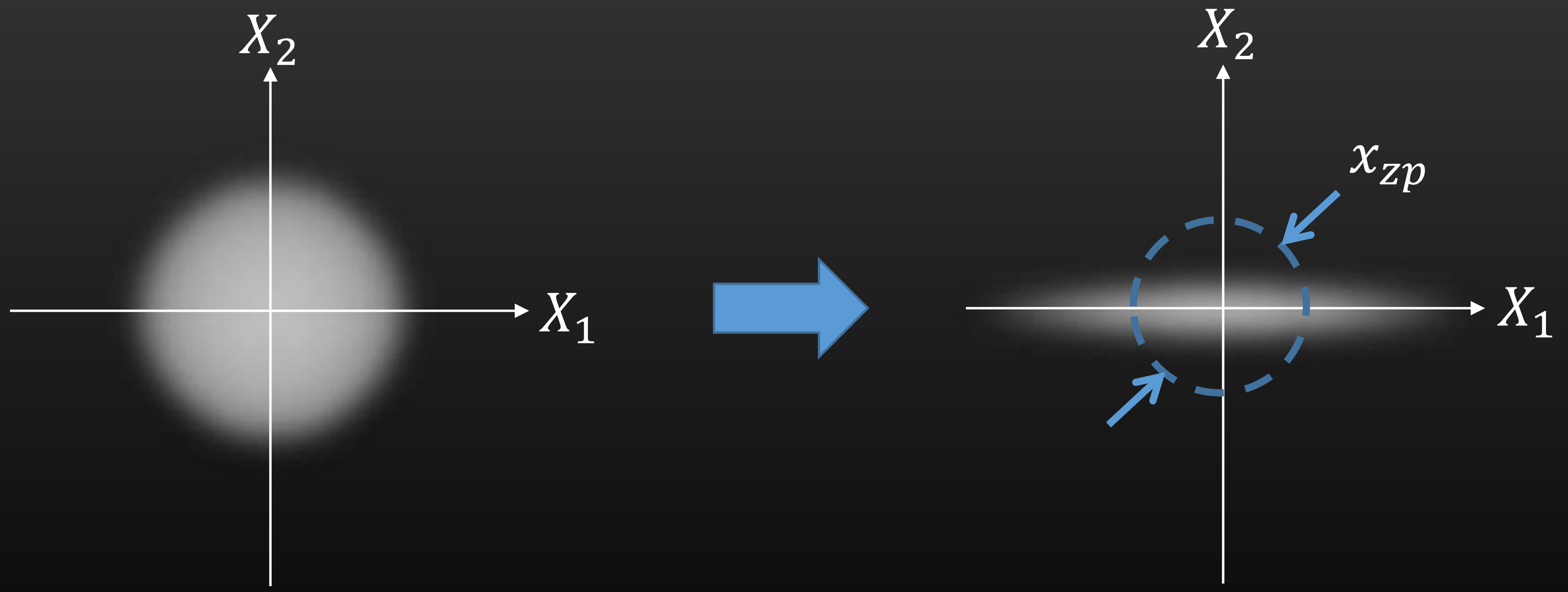
Reduction of mechanical motion (i.e. Cooling)

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

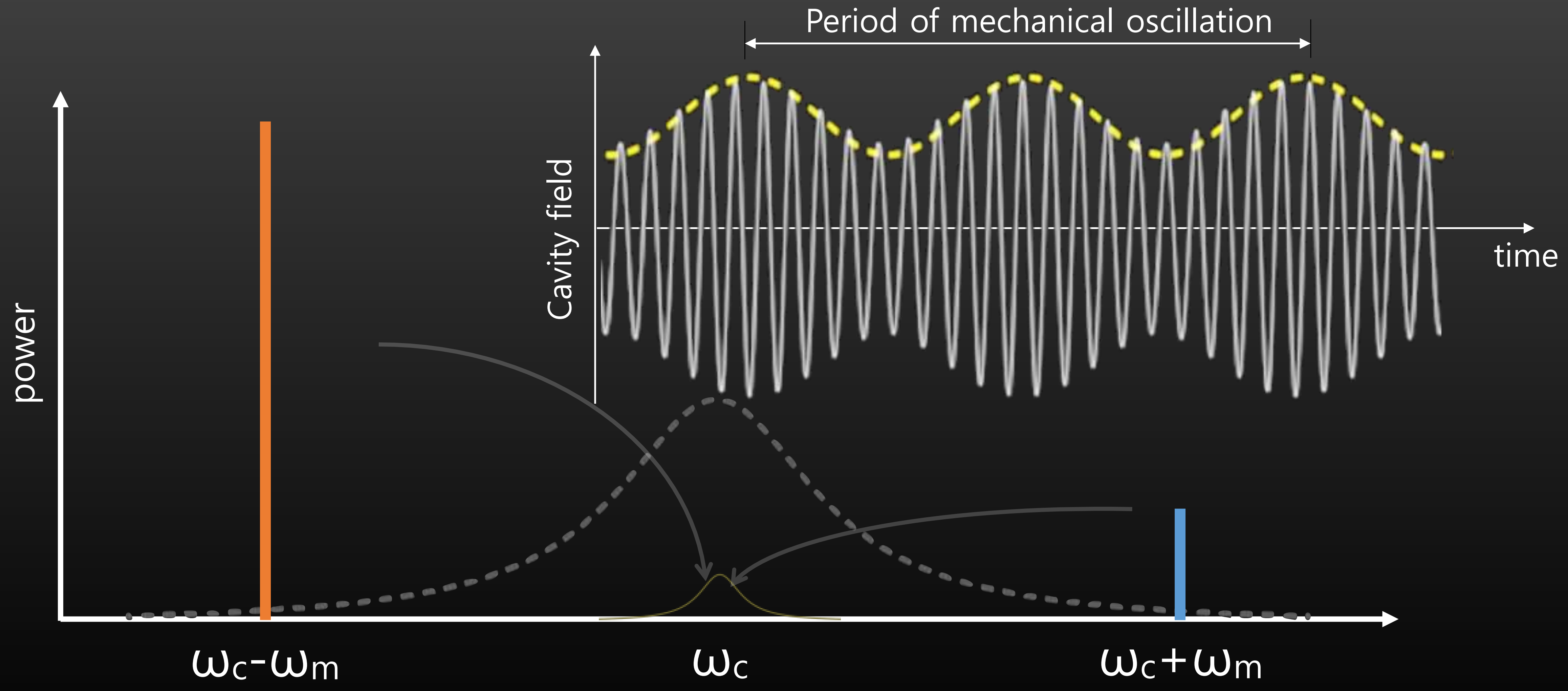


Squeezing "phonons"

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

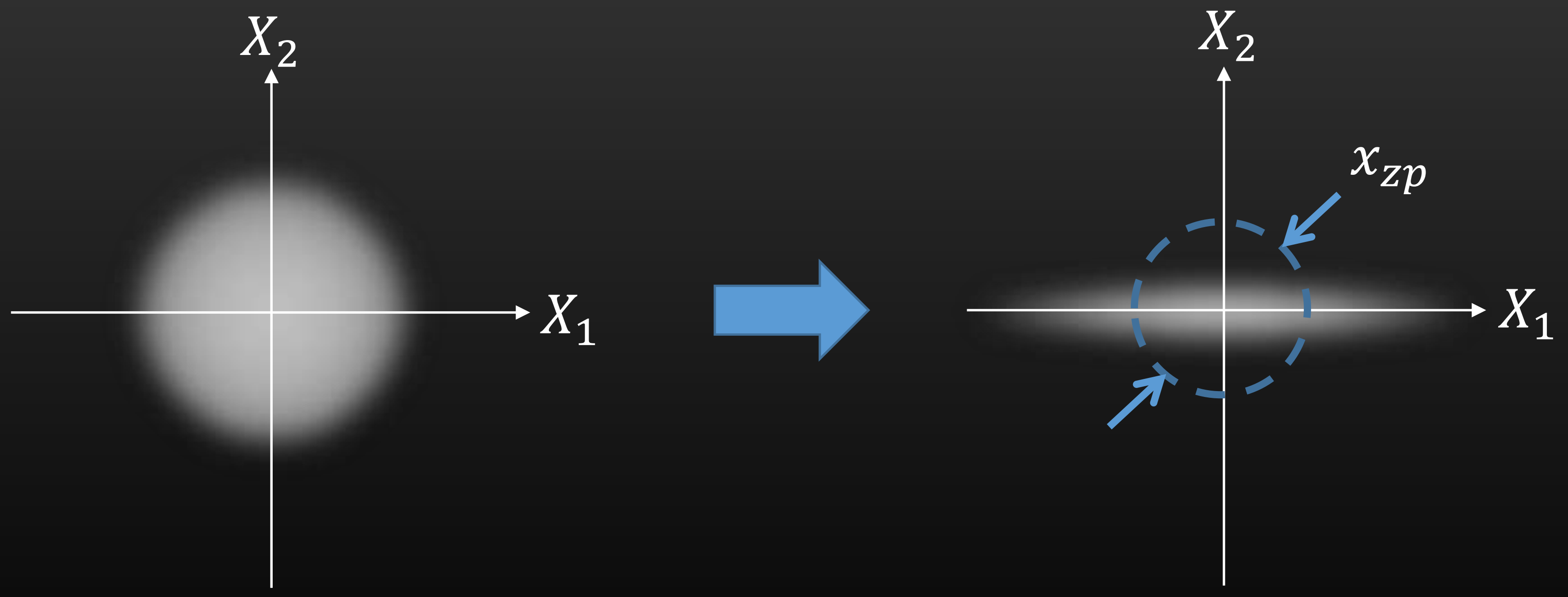


Phase-dependent cooling

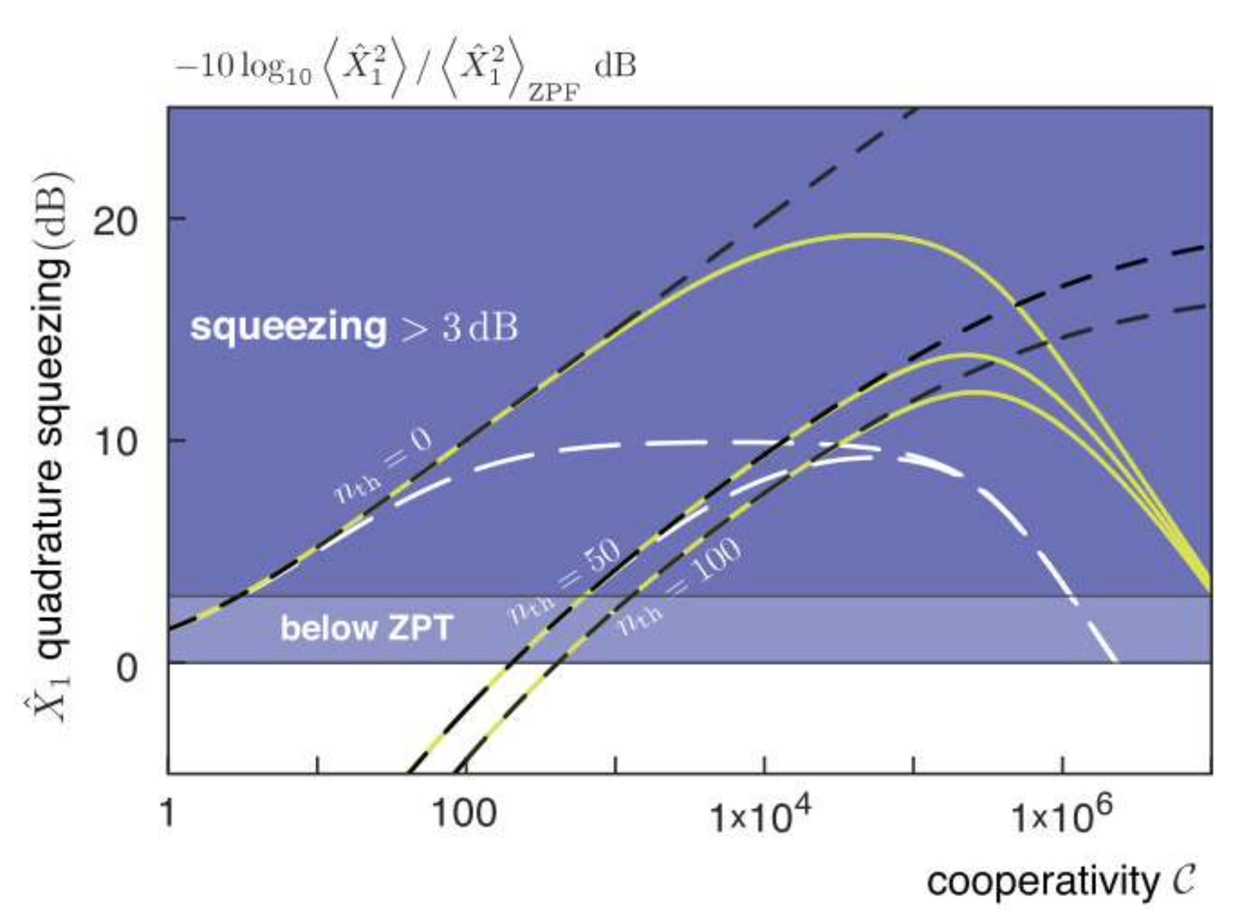


"Phase-dependent" reduction of mechanical motion (i.e. Squeezing)

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



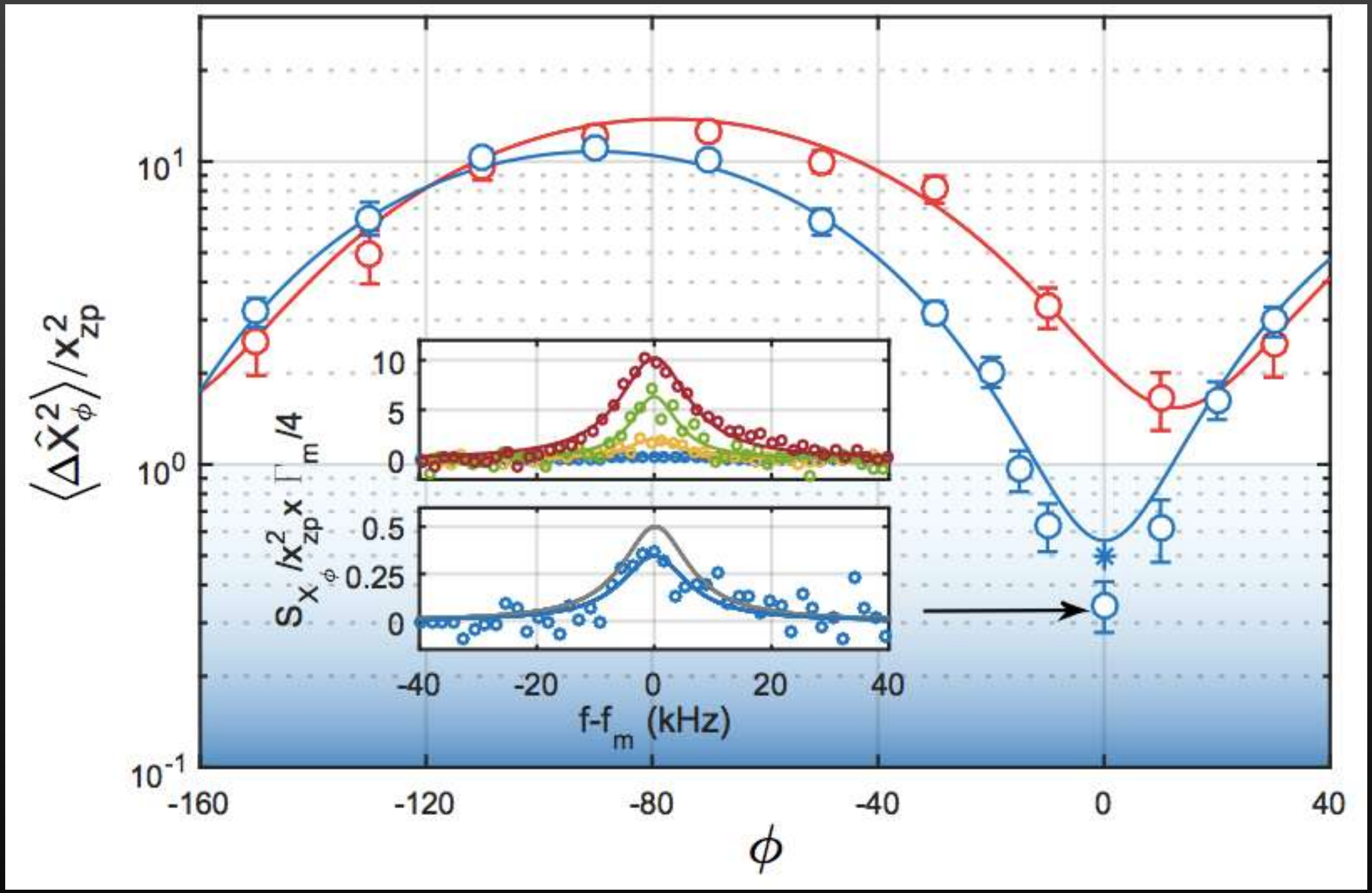
Arbitrarily large steady-state bosonic squeezing via dissipation



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

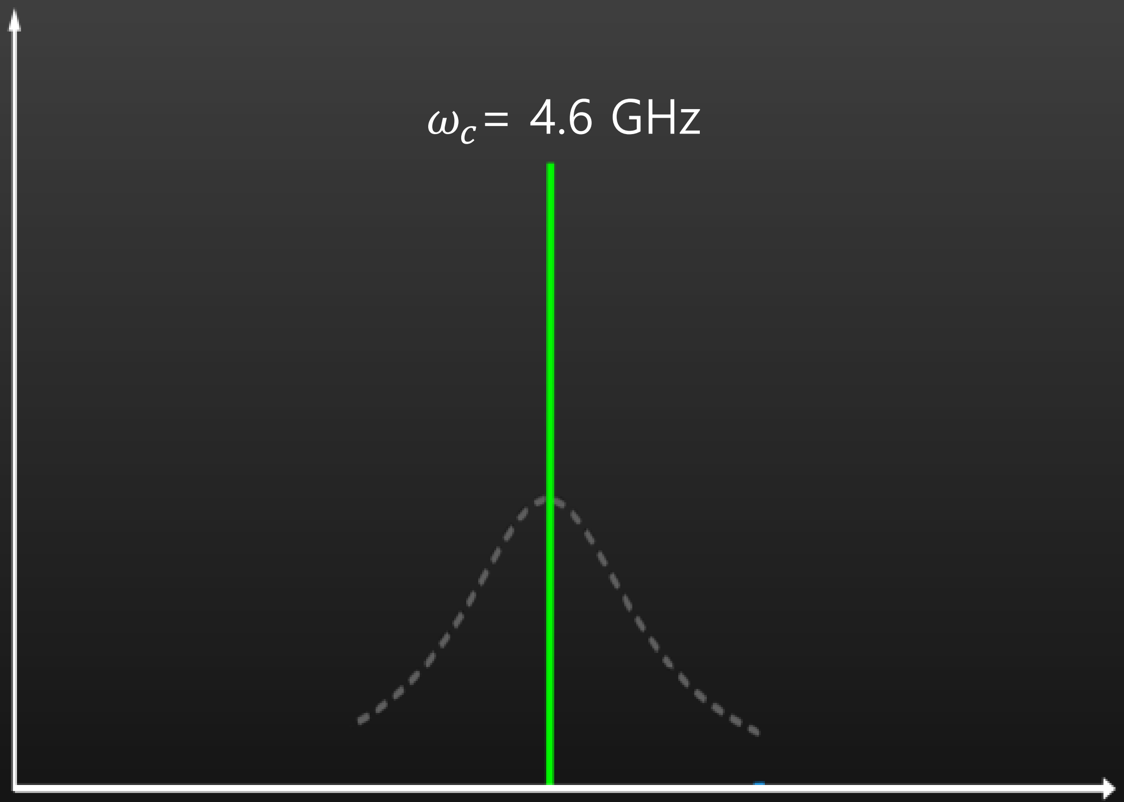
* Kronwald *et.al. Phys. Rev. A* **88**, 063833 (2014).

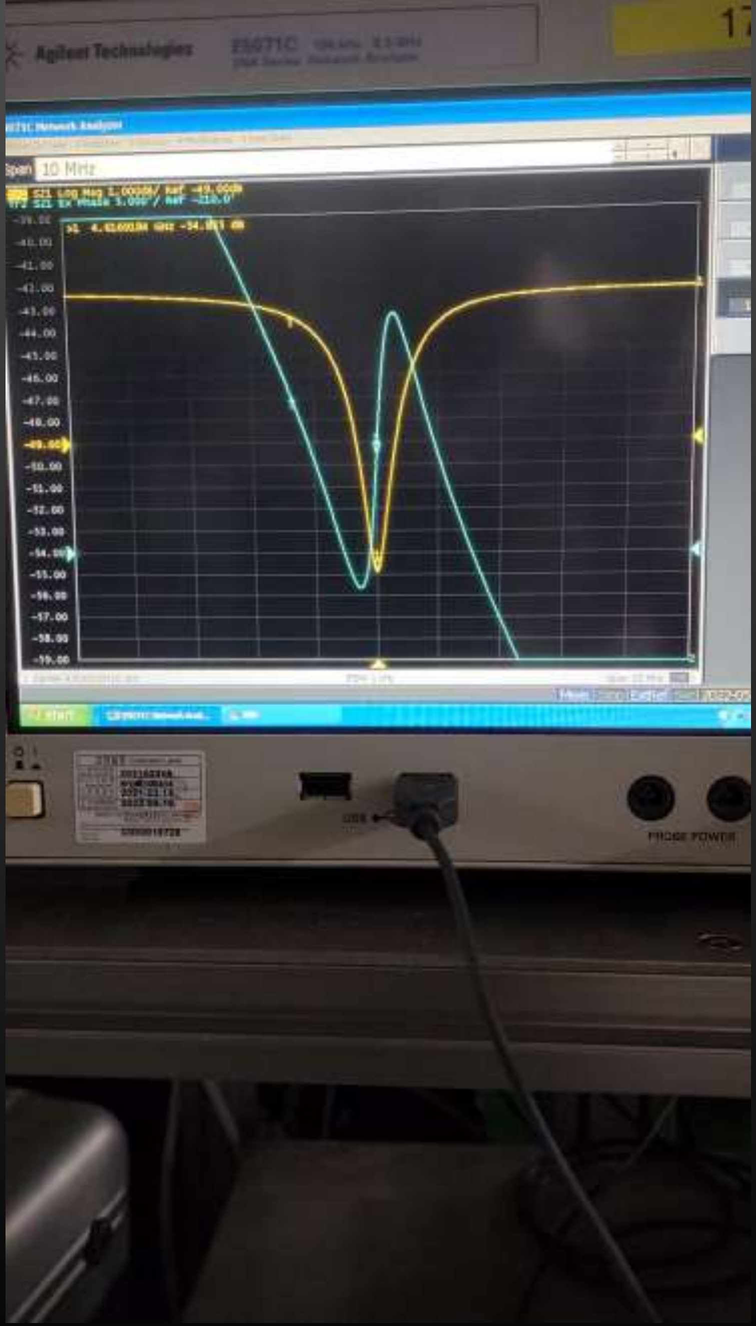
Squeezing more than 3 dB

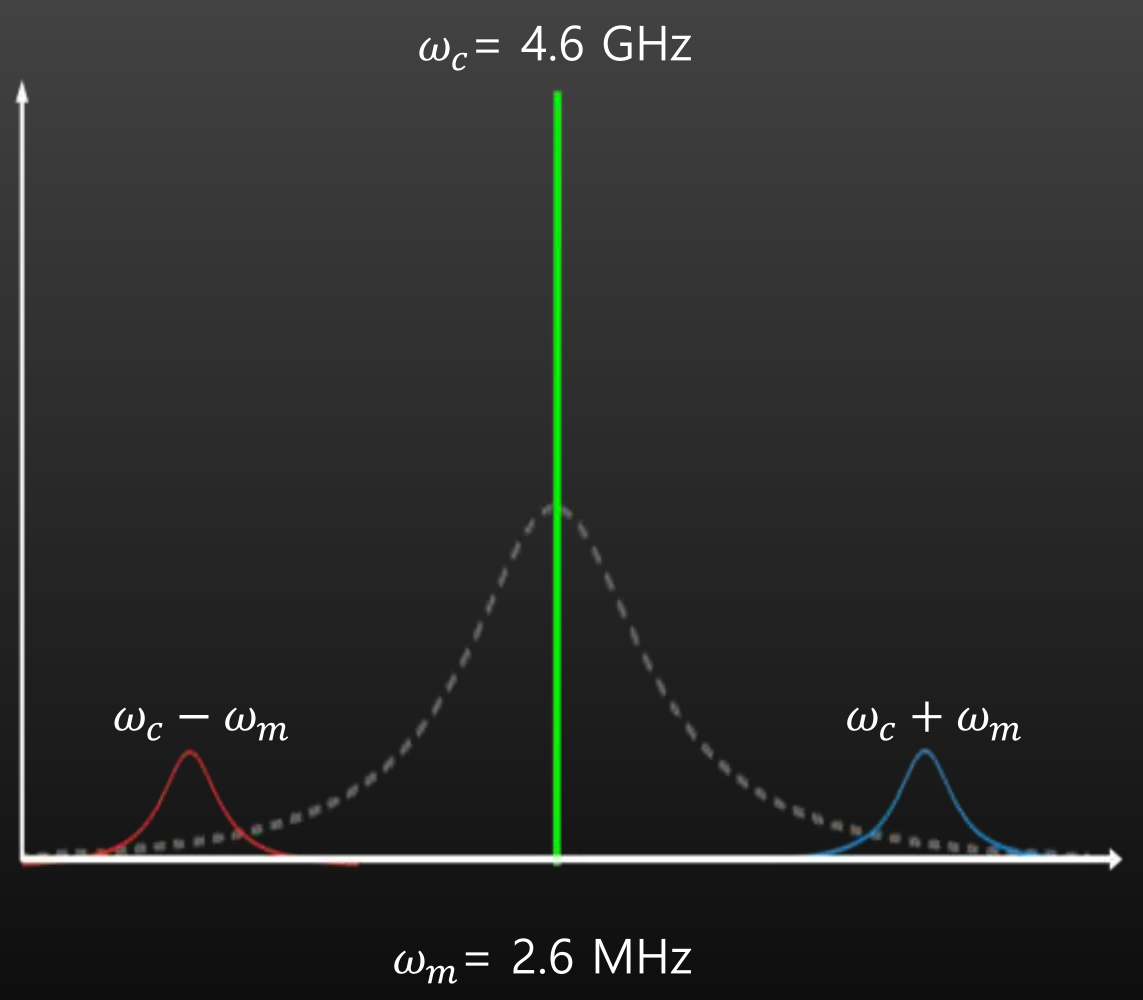


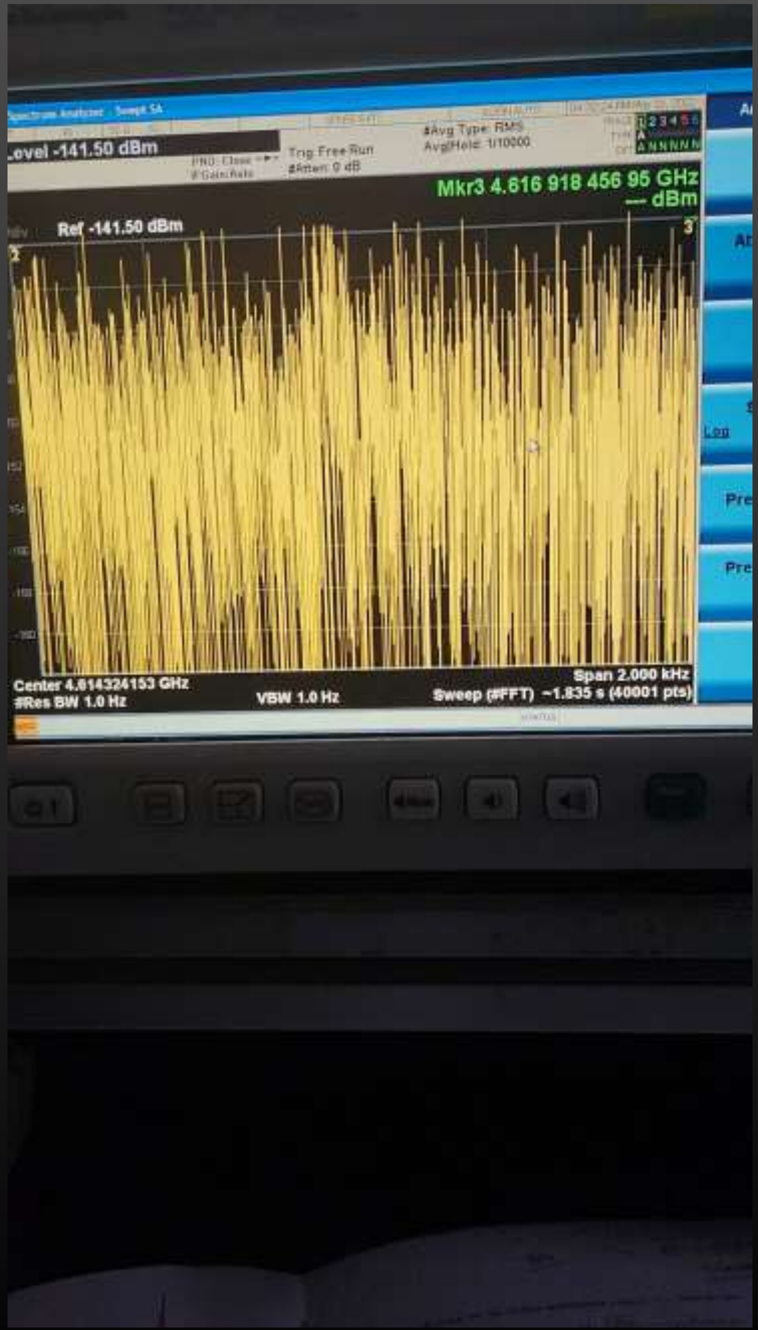
* Lei, Weinstein, **JS**, Wollman, Kronwald, Marquardt, Clerk, Schwab, *PRL* **117**, 100801 (2016).

KRISS QEM Lab


ω_c = 4.6 GHz


Agilent Technologies
E5071C
Span 10 MHz

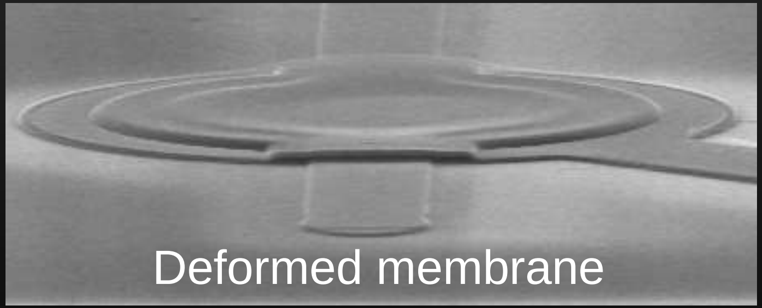

$\omega_c = 4.6$ GHz
$\omega_c - \omega_m$
$\omega_c + \omega_m$
$\omega_m = 2.6$ MHz


Trig Free Run
#Avg Type: RMS
Mkr3 4.616 918 456 95 GHz
— dBm
Ref -141.50 dBm
Center 4.614324153 GHz
#Res BW 1.0 Hz
VBW 1.0 Hz
Span 2.000 kHz
Sweep (#FFT) ~1.835 s (40001 pts)

Niobium for better Cavity QEM sensor

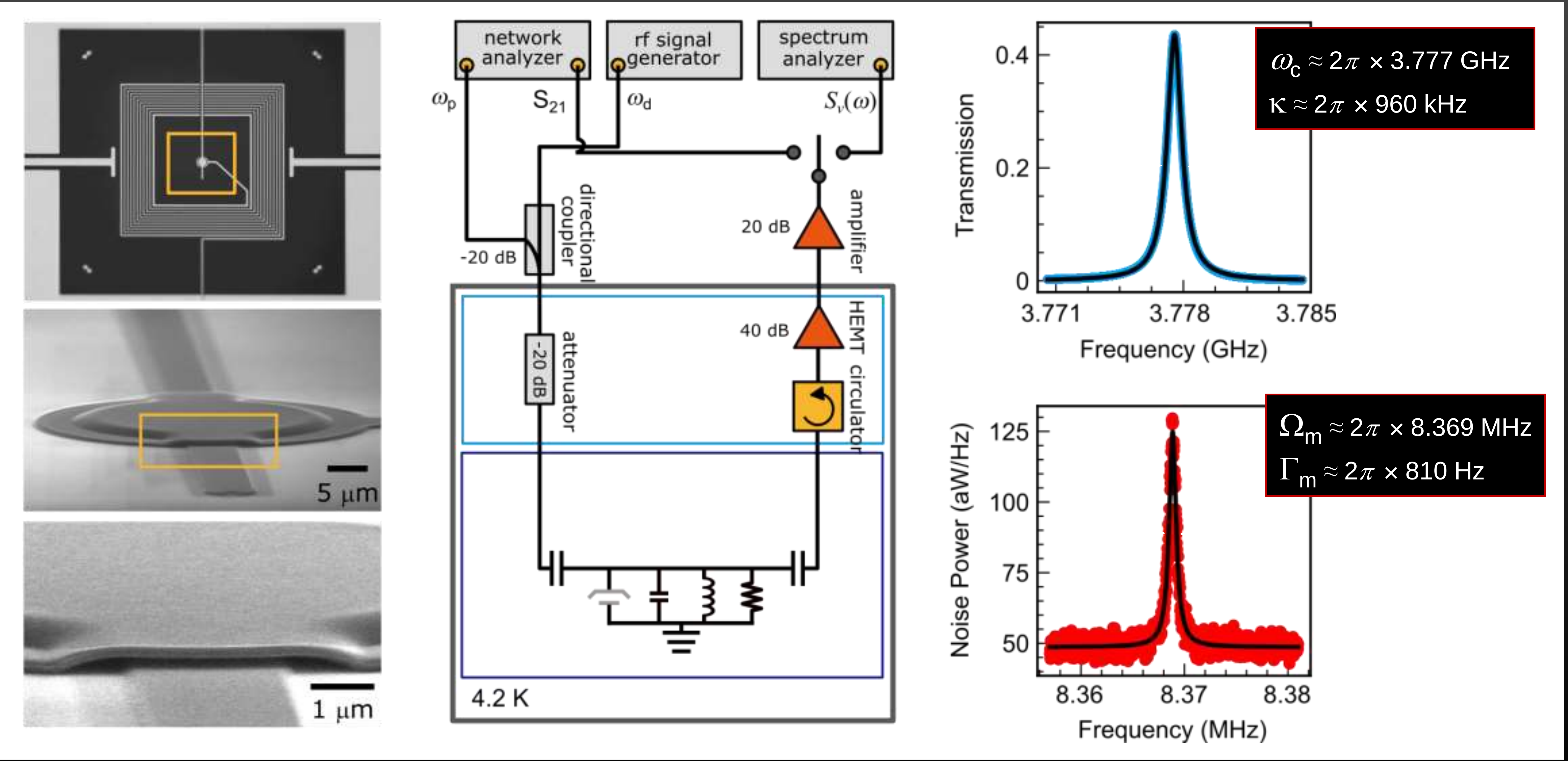
<u>Niobium cavity QEM works at higher temperatures magnetic fields.</u>

	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



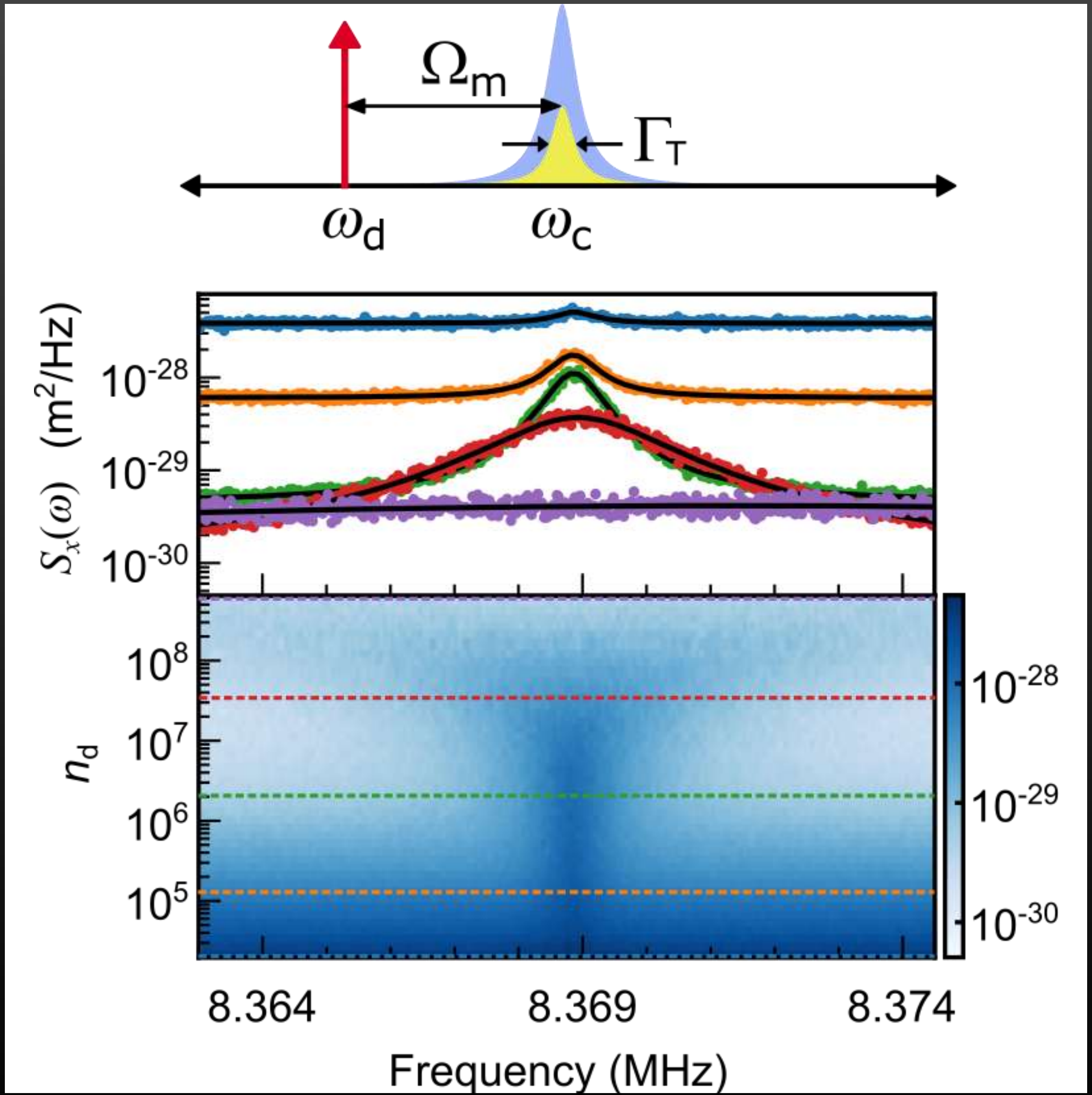
* J. Cha *et.al.*, *"Superconducting Nanoelectromechanical Transducer Resilient to Magnetic Fields"*, *Nano Letters* **21**, 1800 (2021).

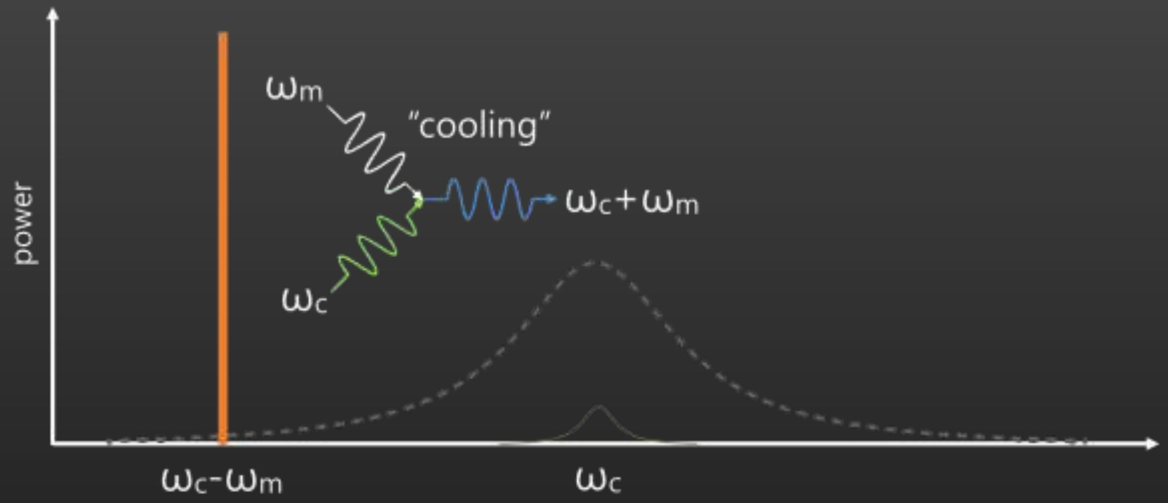
Niobium QEM at 4 K



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

Back-action cooling at 4 K

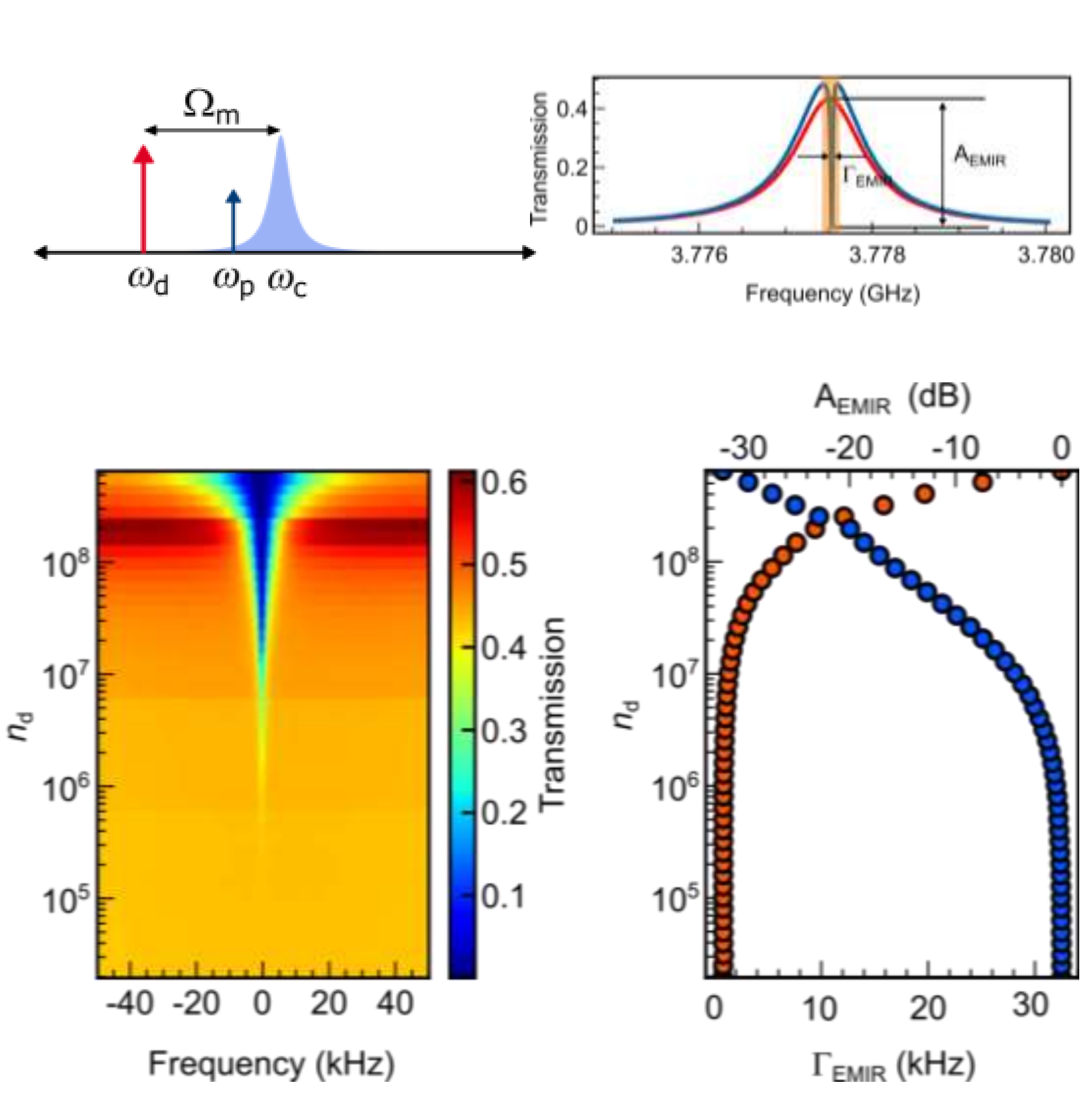




- Cooling process accompanies with mechanical linewidth broadening
- Efficient cooling of mechanical mode temperature from 4.2 K to 76 mK

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

Electromechanical induced reflection of microwave at 4 K



- Probe microwave interferes destructively with mechanical sideband from pump

- Reflection window

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

- Single photon coupling

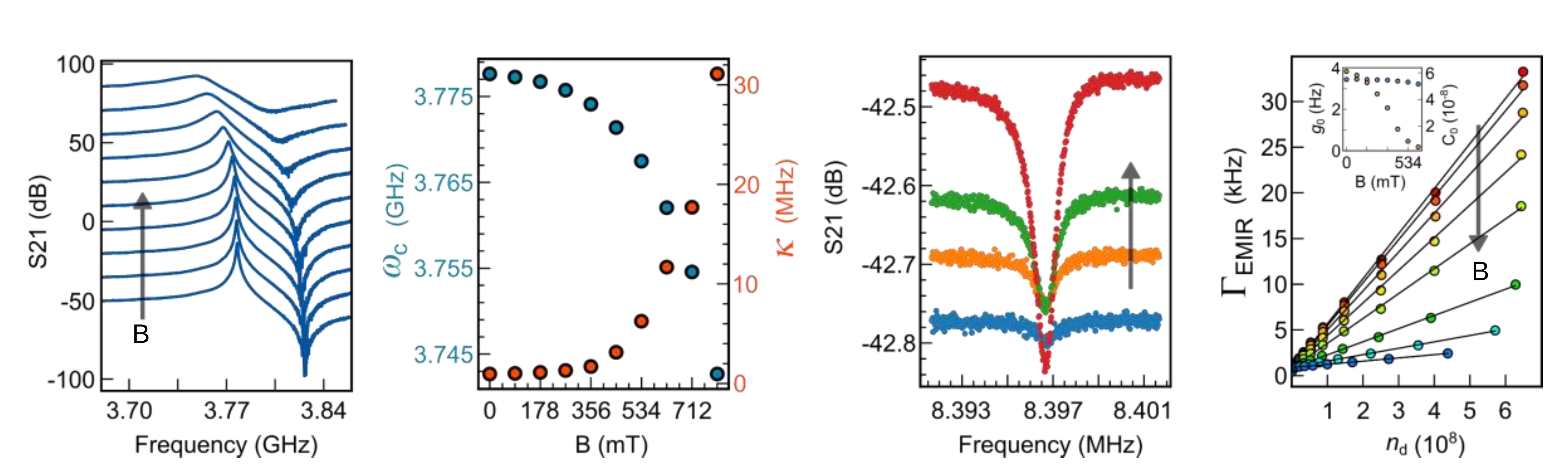
$$g_0 \approx 3.3\ \mathrm{Hz}$$

- Cooperativity

$$C \approx 40$$

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

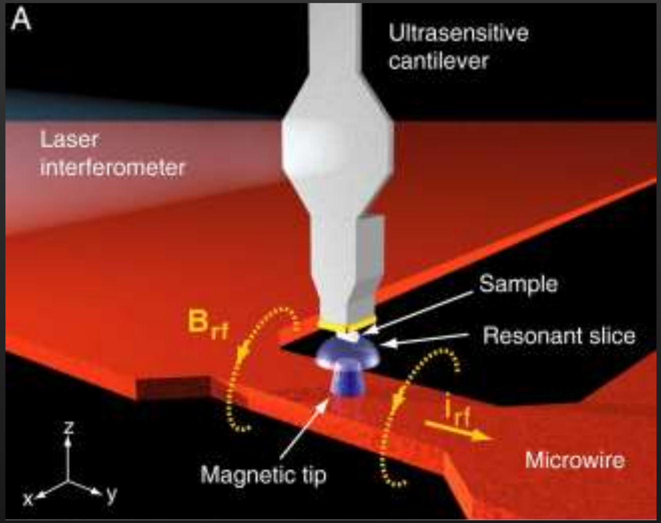
Niobium QEM under magnetic field



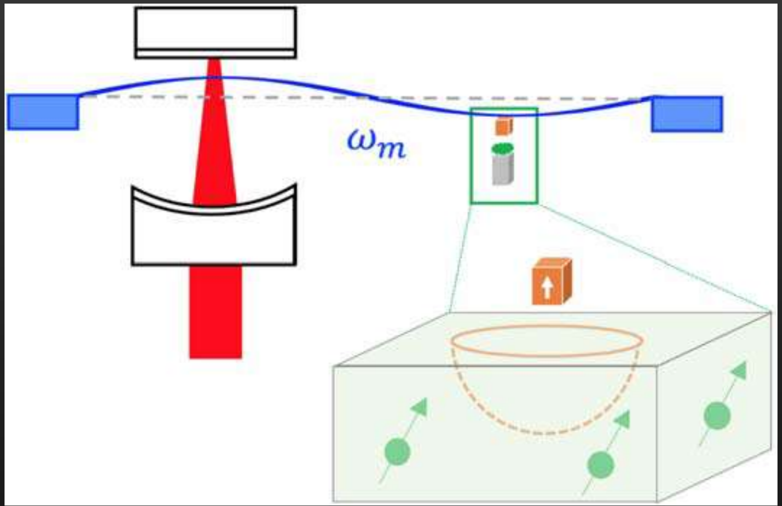
- Magnetic field B affects the microwave resonance frequency and linewidth.
- EMIR persists even at 0.8 T.
- Cooperativity decreases as *B* increases due to the increasing cavity decay rate.
- Single-photon coupling rate is independent of magnetic field.

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

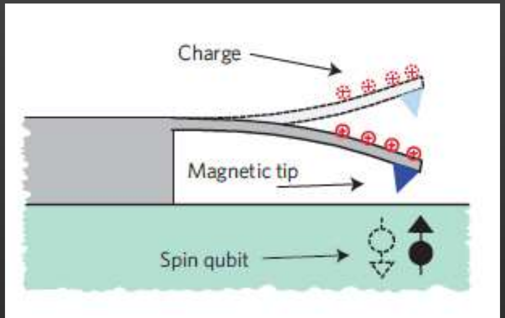
Outlook: Niobium QEM for single spin control

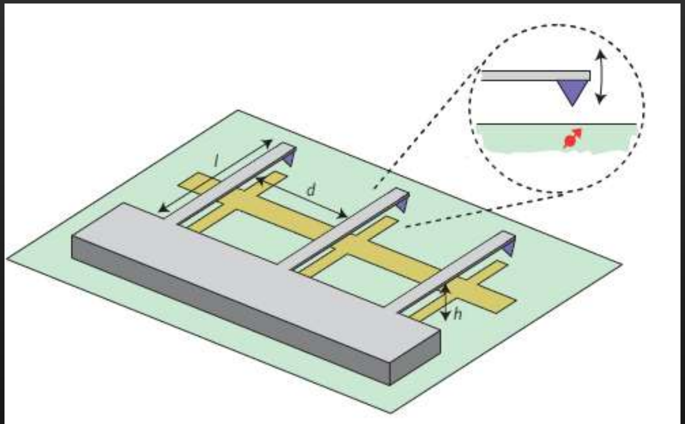


PNAS *106*, 1313-1317 (2009)



New J. Phys *21*, 043049 (2019)



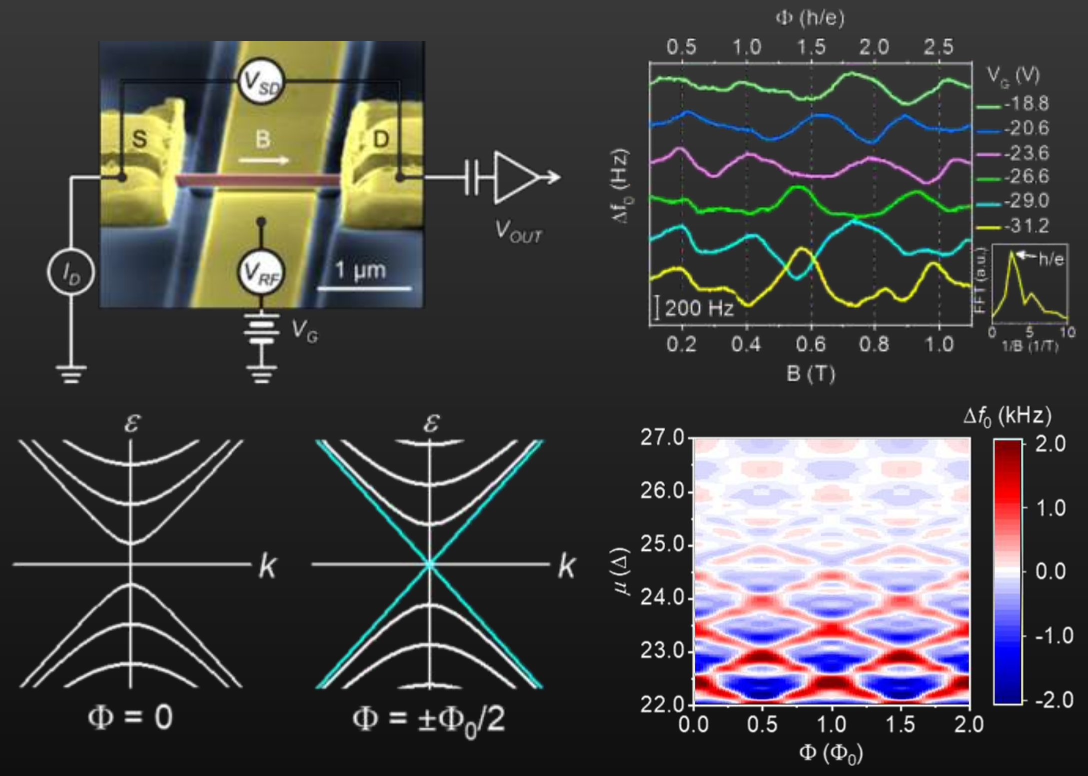


Nature Physics *6*, 602-608 (2010)

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

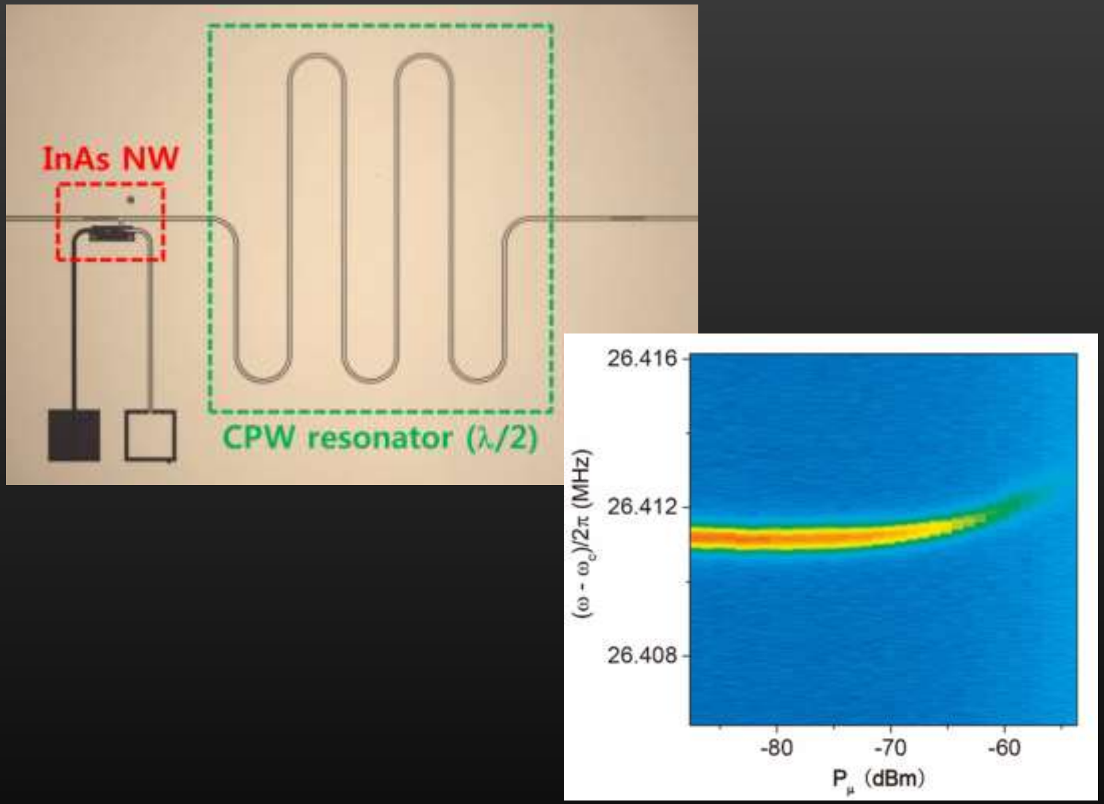
Nanowire for wider QEM sensing applications

Nanomechanical probe for TI surface states



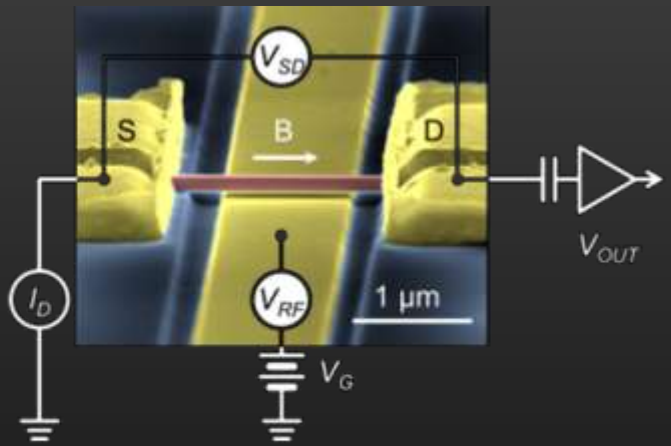
* M. Kim *et al.*, *Nature Comm.* **10**, 4522 (2019).

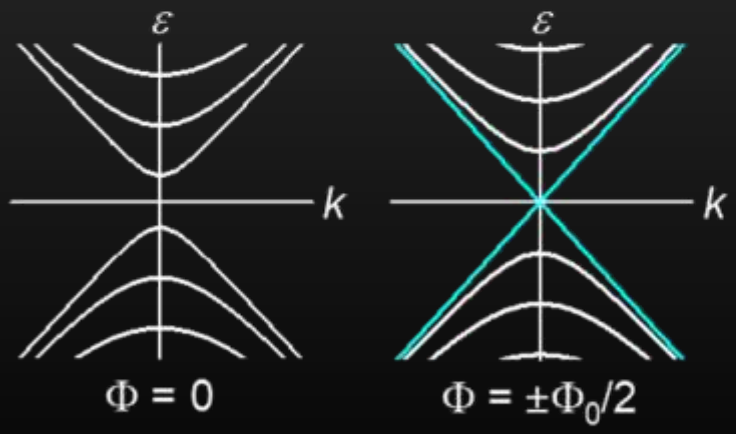
Microwave bolometer at millikelvin

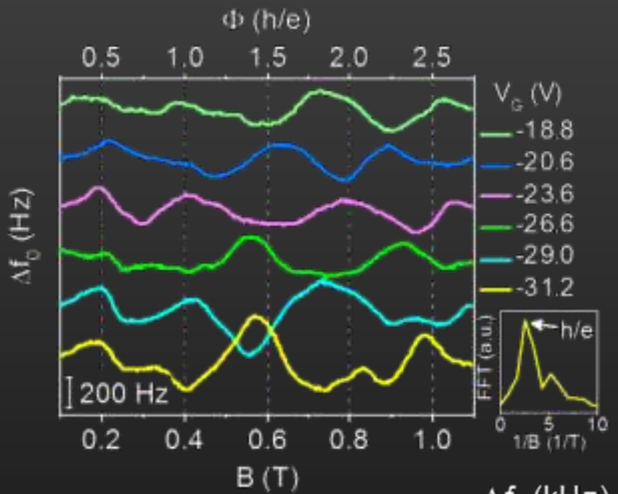


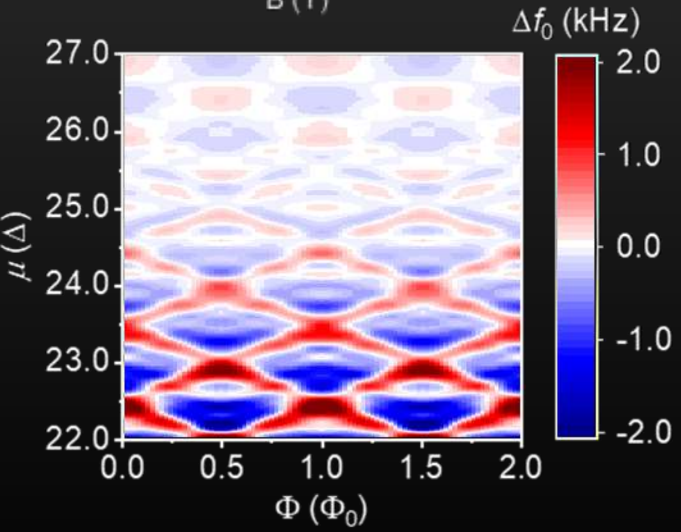
* J. Kim *et al.*, *Phys. Rev. Appl.* **15**, 034075 (2021).

Nanomechanical characterization of quantum interference in a topological insulator nanowire







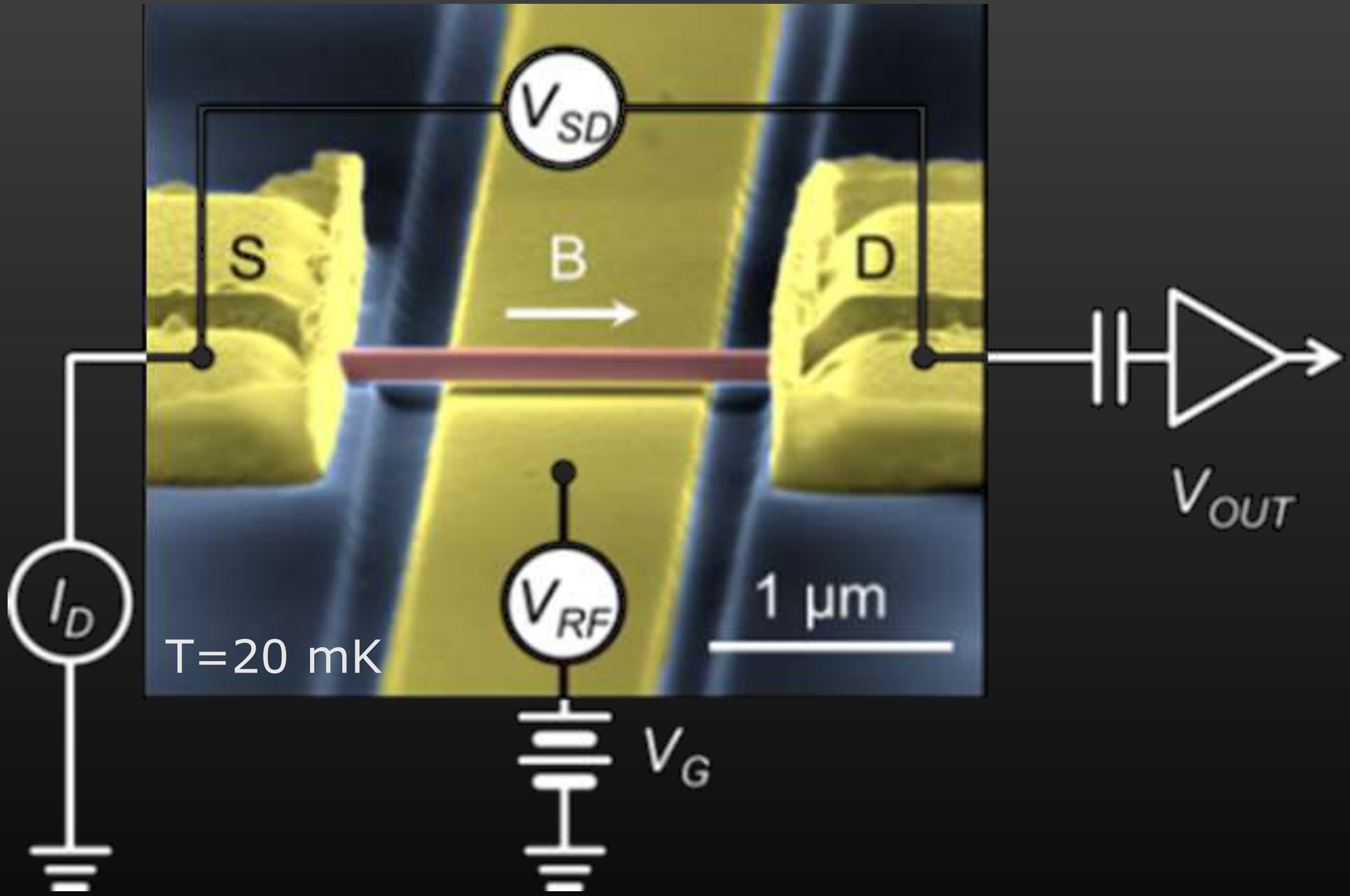


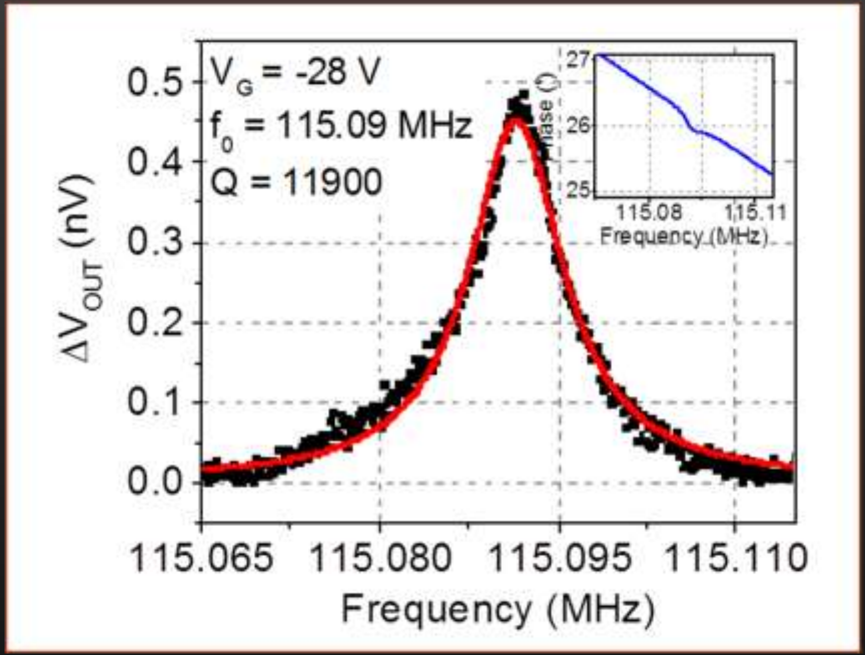
Minjin Kim

Kunwoo Kim

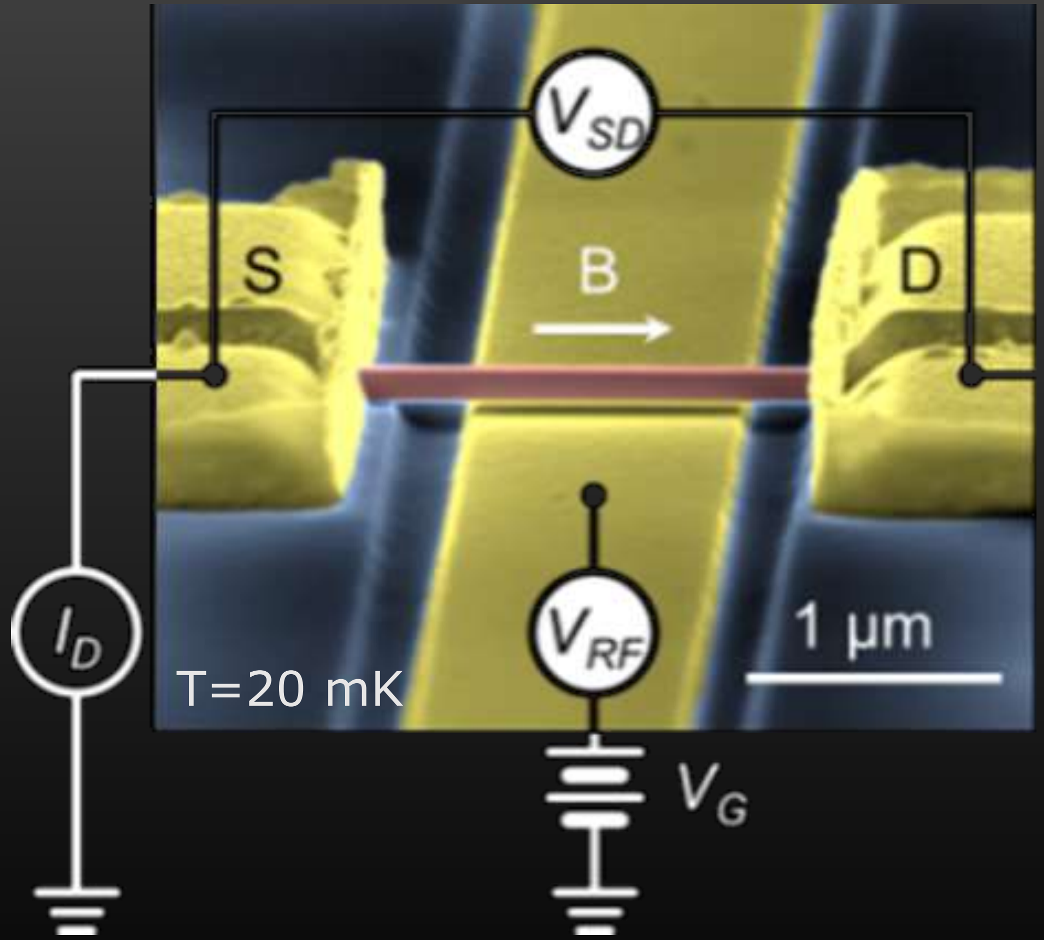
Nature Comm.* **10, 4522 (2019)

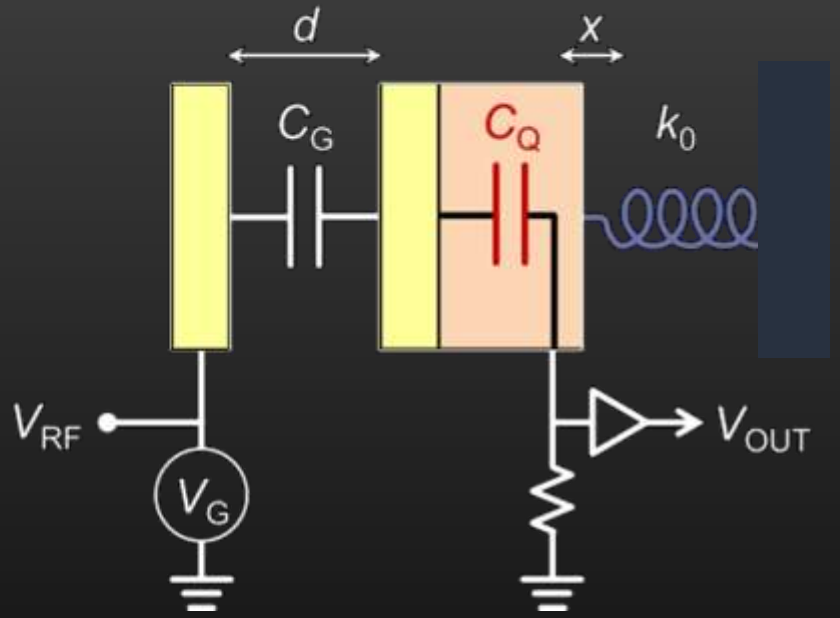
Bi_2Se_3 nanowire electromechanical resonator





Bi_2Se_3 nanowire electromechanical resonator



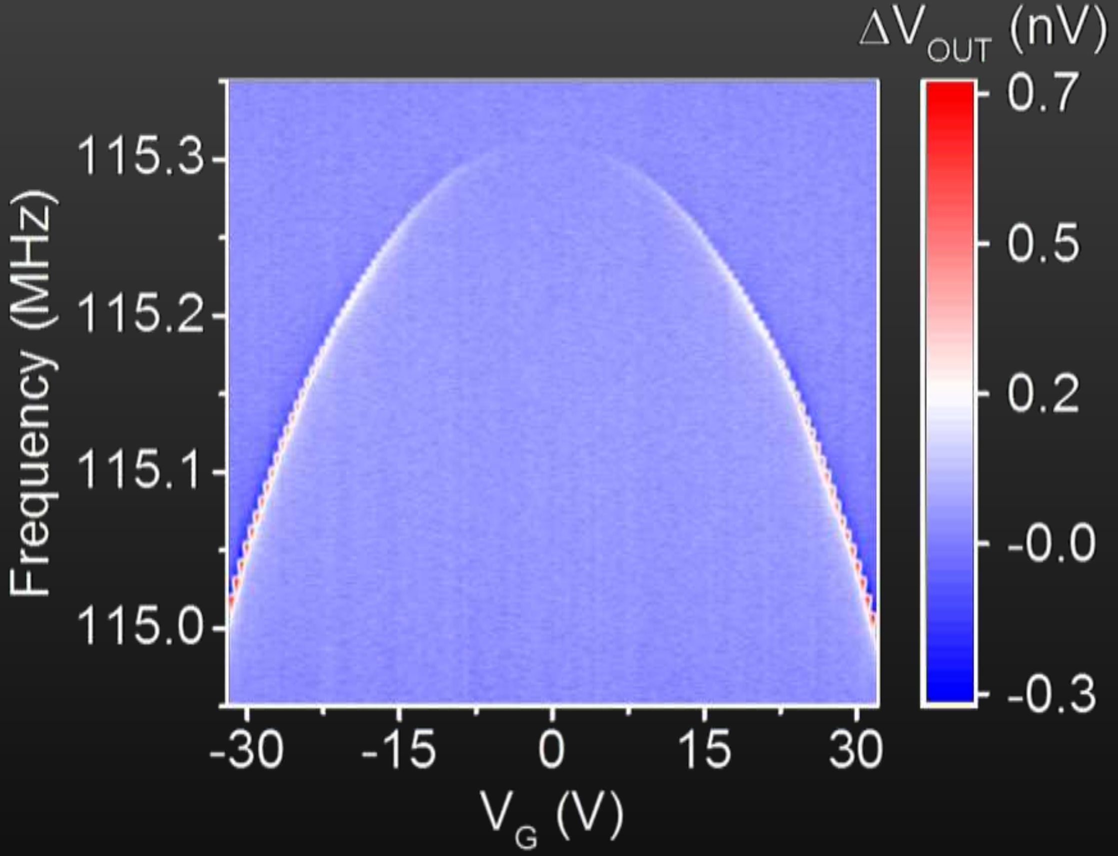


"quantum capacitance"

$C_Q = e^2 \cdot$ (Density of States)

* Luryi, *Appl. Phys. Lett.*. **52**, 501 (1988).

Capacitive tuning of mechanical resonance



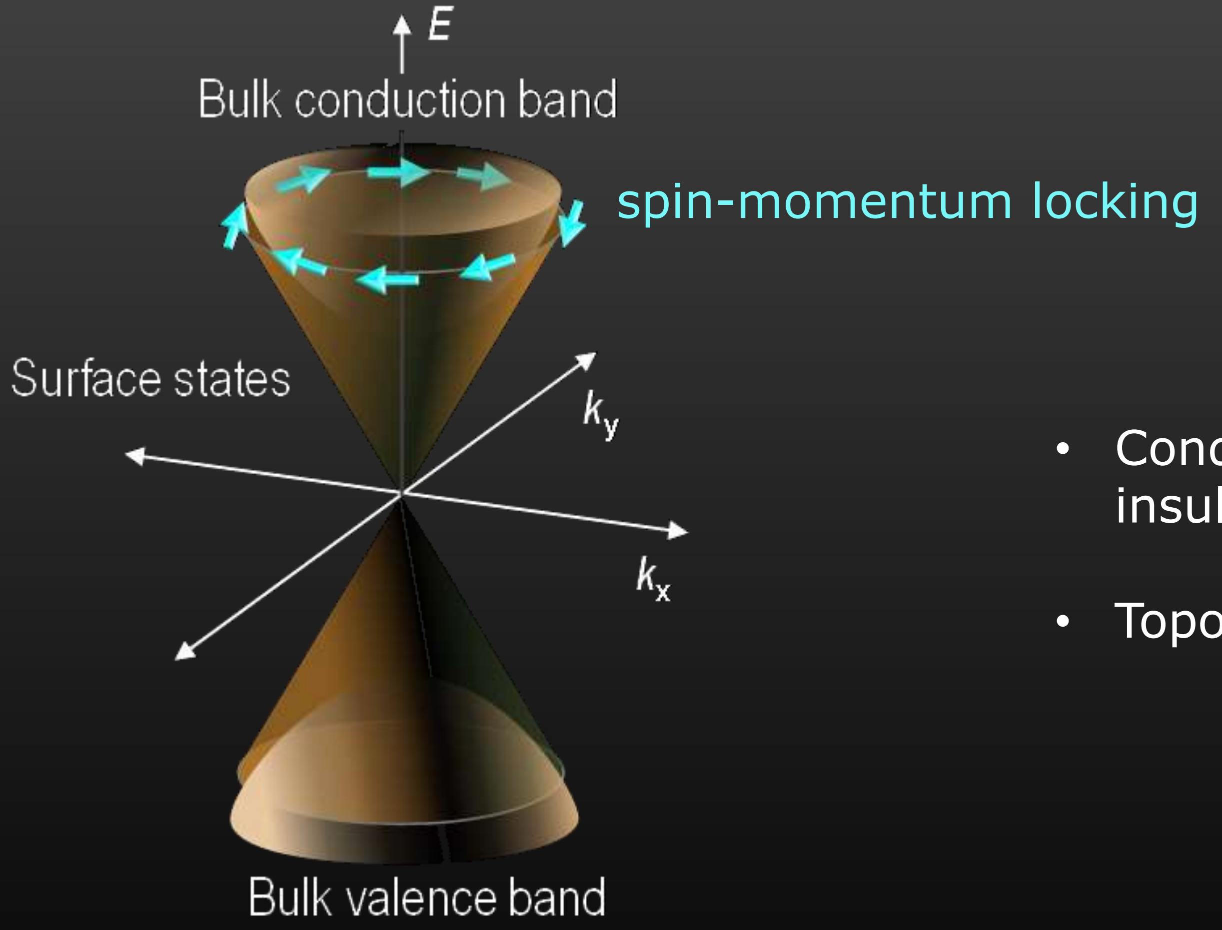
"capacitive softening"

$$\delta k_{eff} \approx -\frac{1}{2}\frac{\partial^2 C}{\partial x^2}{V_g}^2$$

- Total capacitance $C = \frac{C_g C_Q}{C_g + C_Q}$
- $C_Q \gg C_g$; C_g dominates softening
- C_Q, $\partial C_Q/\partial x, \partial^2 C_Q/\partial x^2$ modify δk_{eff}

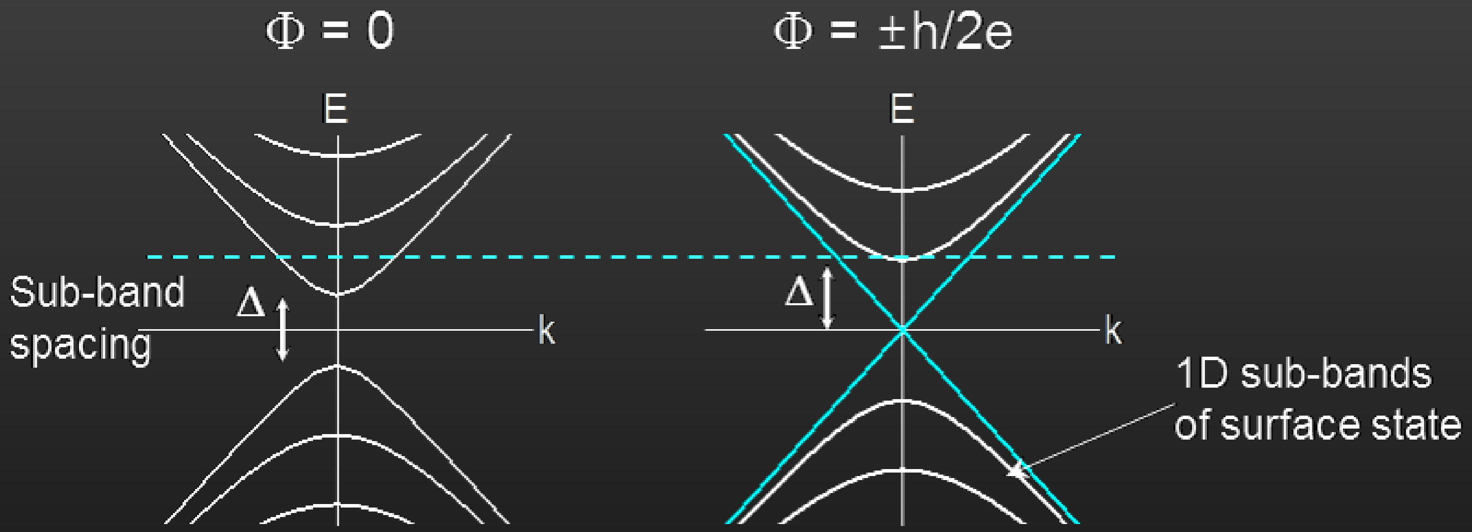
⇒ Surface state C_Q modulates mechanical resonance

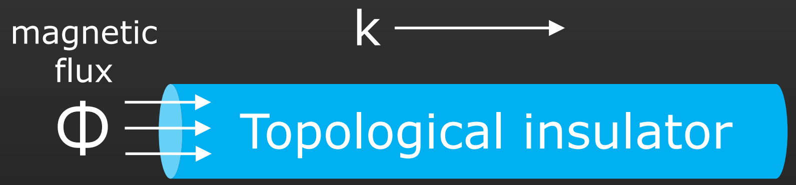
Surface states of topological insulator



- Conducting surface states with insulating bulk
- Topologically protected

1D subband of TI nanowire surface

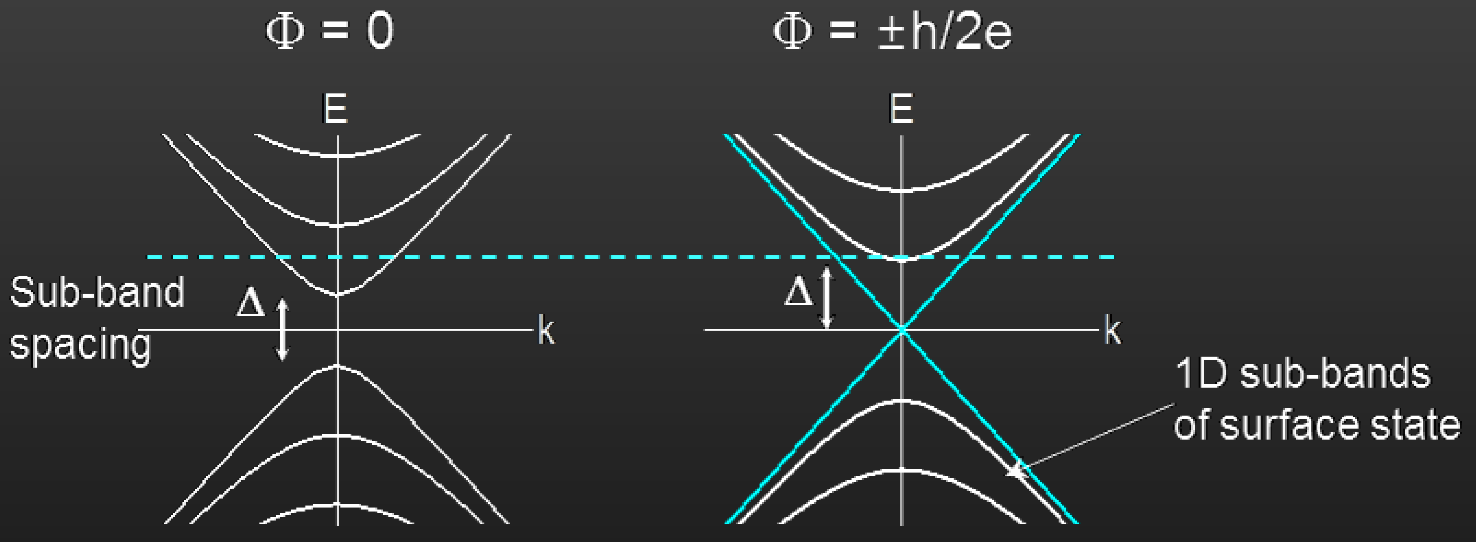




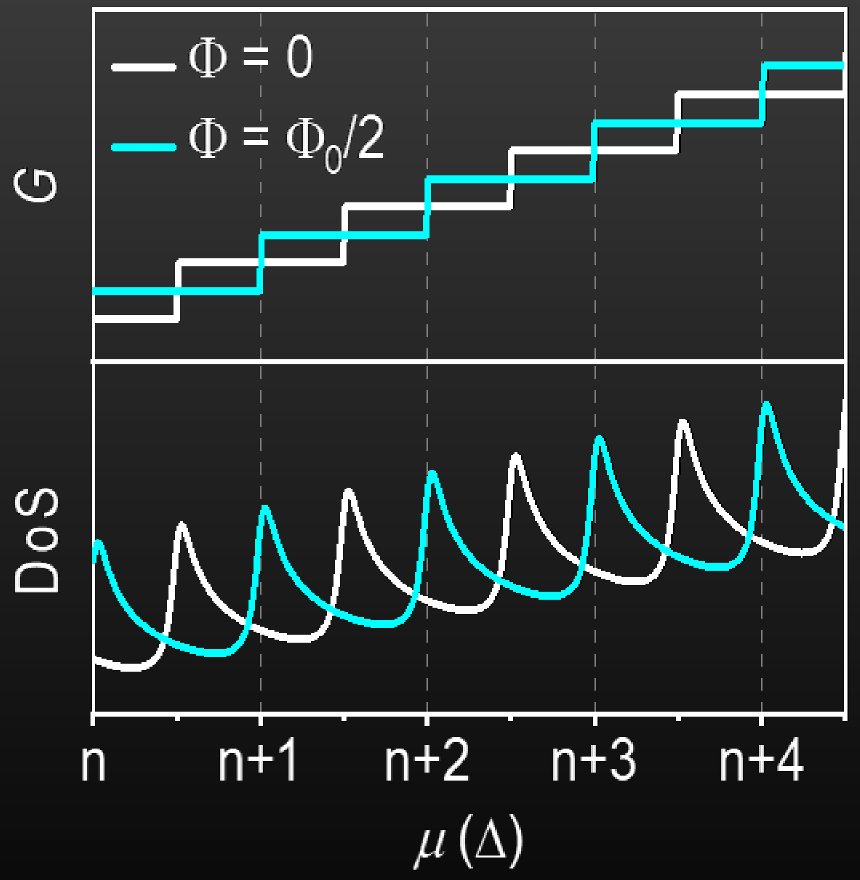
$$\varepsilon(n,k,\Phi) = \pm\hbar v_{\mathrm{F}}\sqrt{k^2 + \frac{(n + 1/2 - \Phi/\Phi_0)^2}{R^2}}$$

* Bardarson *et al.*, *Phys. Rev. Lett.* **105**, 156803 (2010).

1D subband of TI nanowire surface

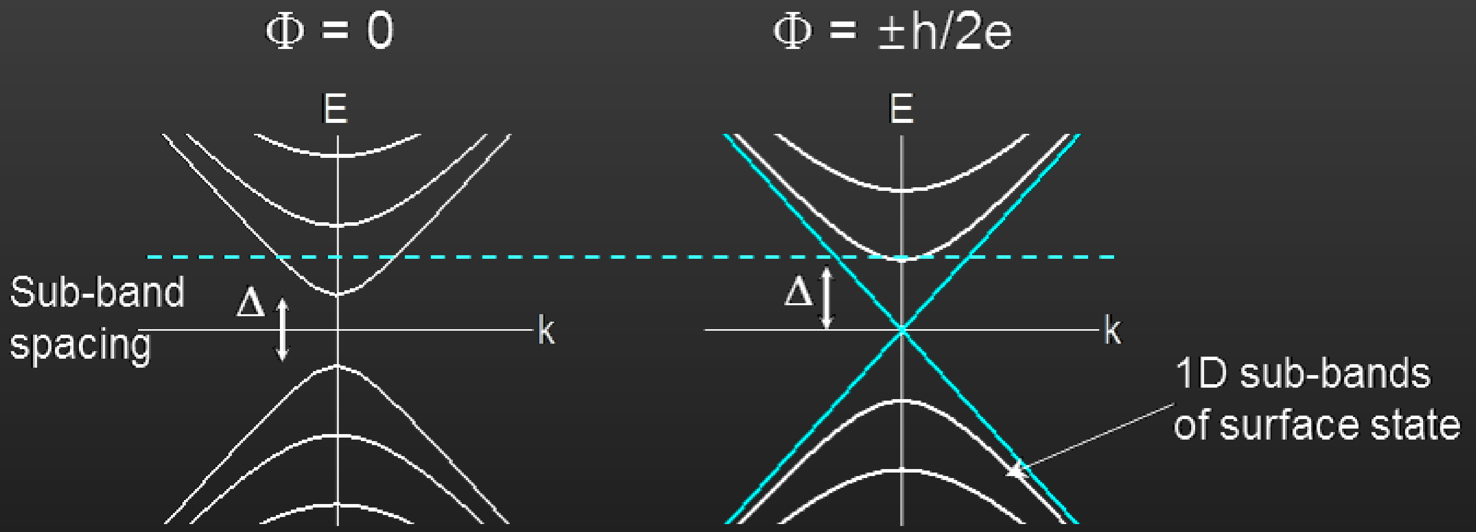


$$\varepsilon(n,k,\Phi) = \pm\hbar v_F \sqrt{k^2 + \frac{(n+1/2-\Phi/\Phi_0)^2}{R^2}}$$



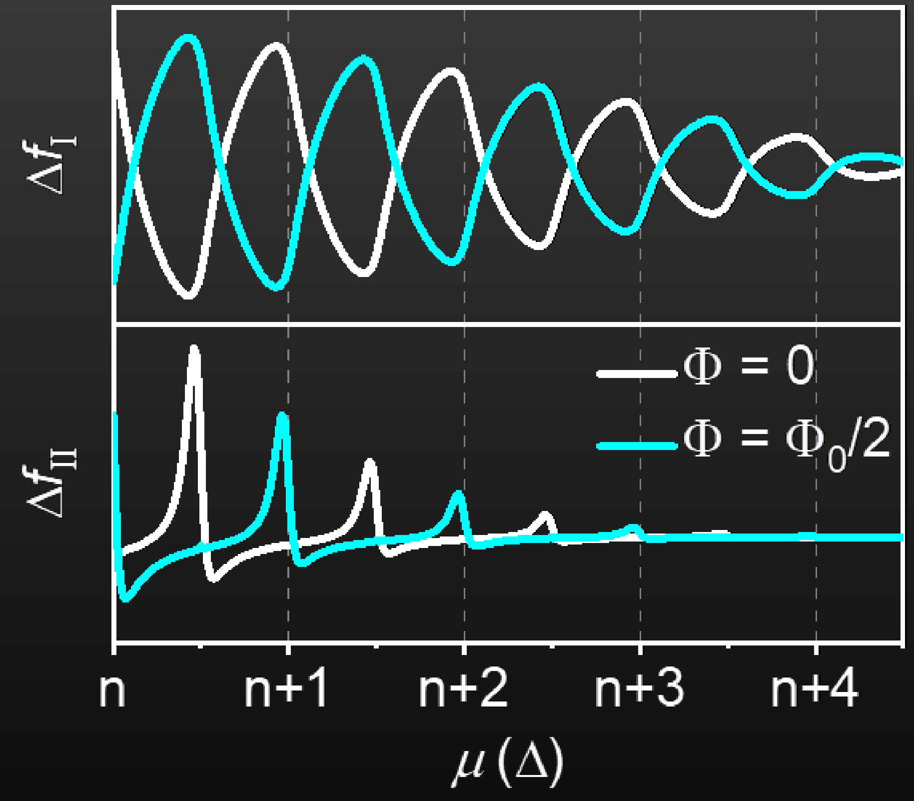
* Bardarson *et al.*, *Phys. Rev. Lett.* **105**, 156803 (2010).

1D subband of TI nanowire surface



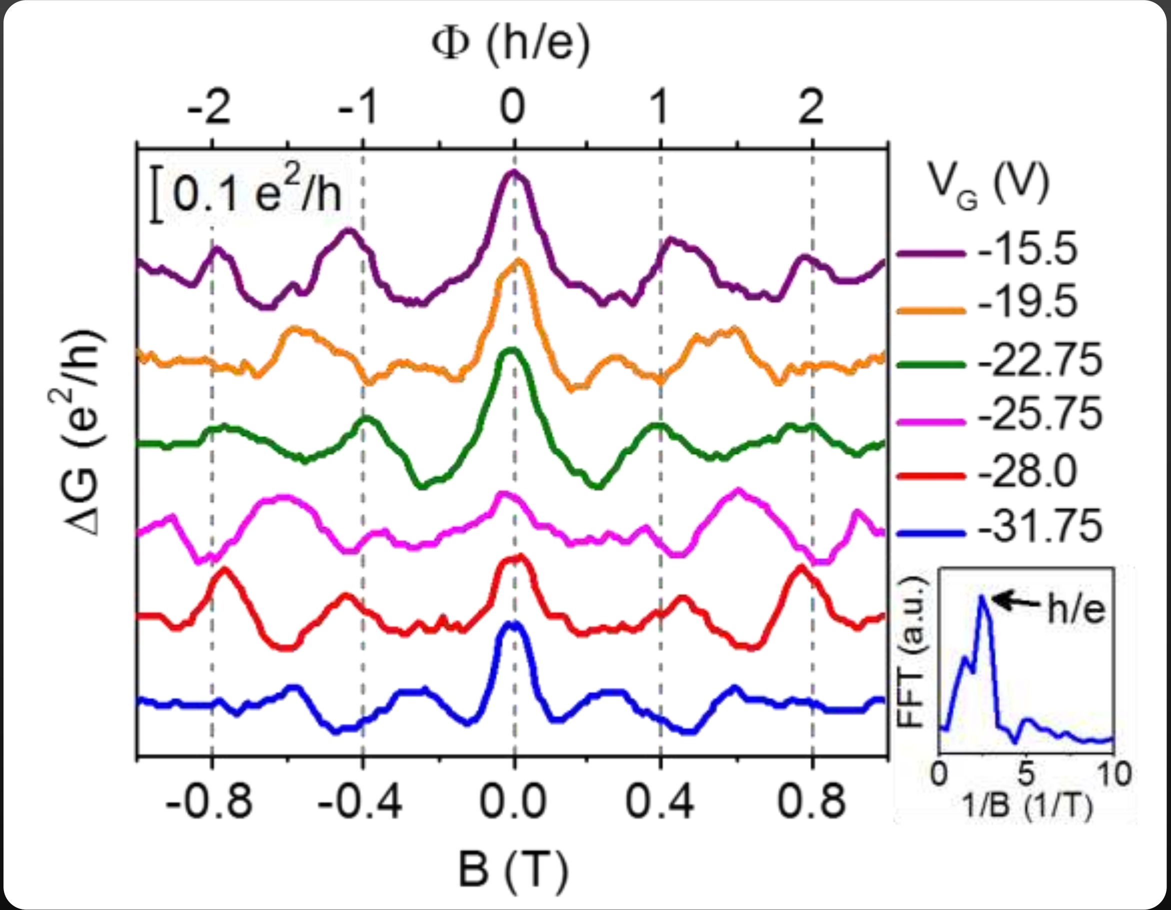
$$\varepsilon(n,k,\Phi) = \pm\hbar v_{\mathrm{F}}\sqrt{k^2 + \frac{(n + 1/2 - \Phi/\Phi_0)^2}{R^2}}$$

* Bardarson *et al.*, *Phys. Rev. Lett.* **105**, 156803 (2010).

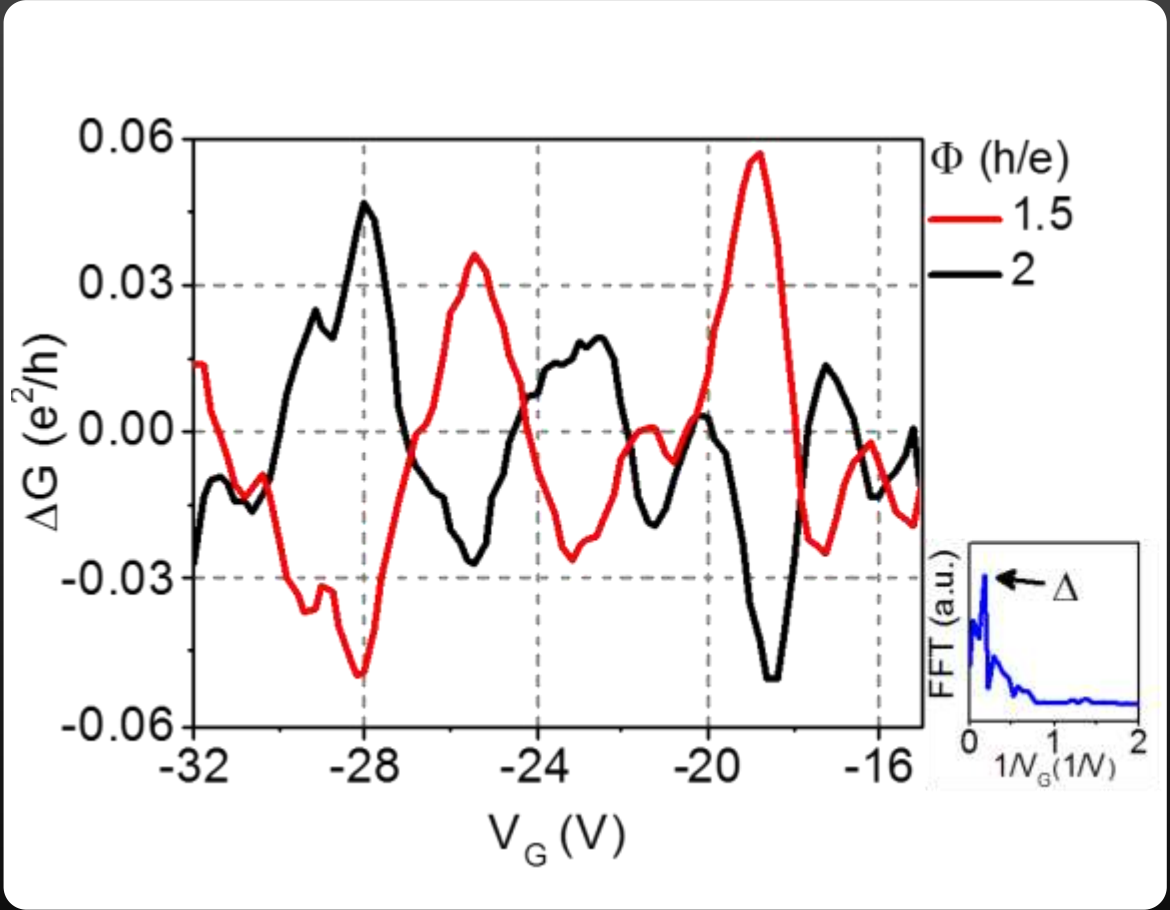


* $\Delta f_0 = \Delta f_I + \Delta f_{II}$

Aharonov-Bohm conductance oscillation

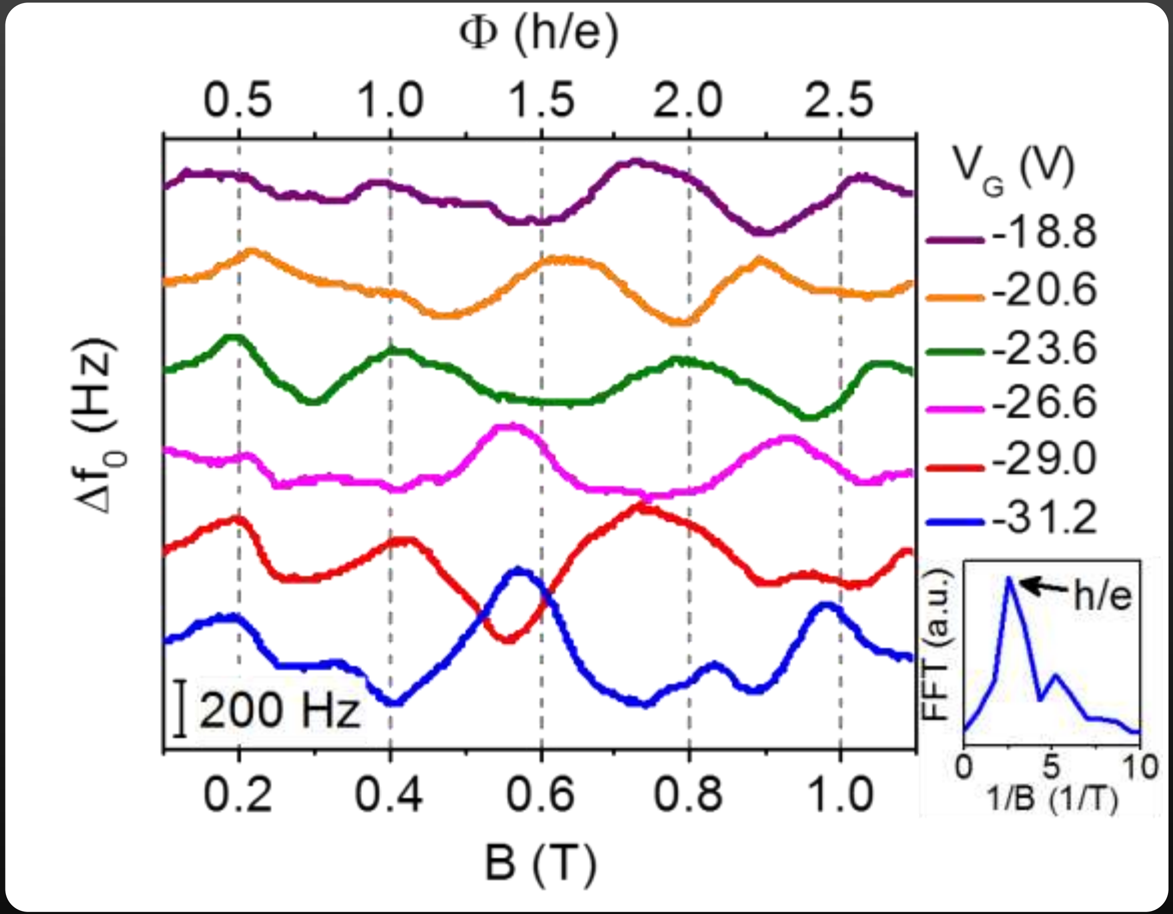


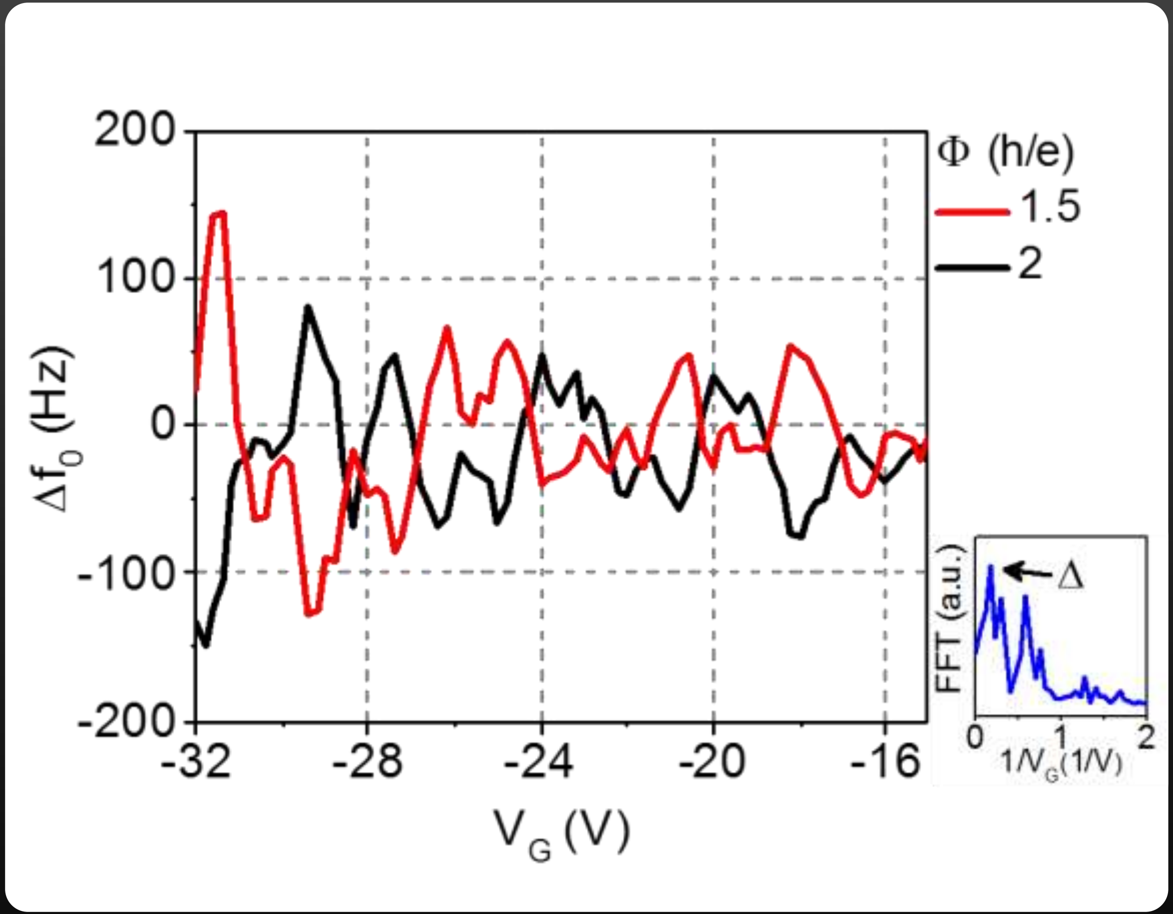
Period = Φ_0/(cross-section)



Period = Δ

AB oscillation of mechanical resonance frequency



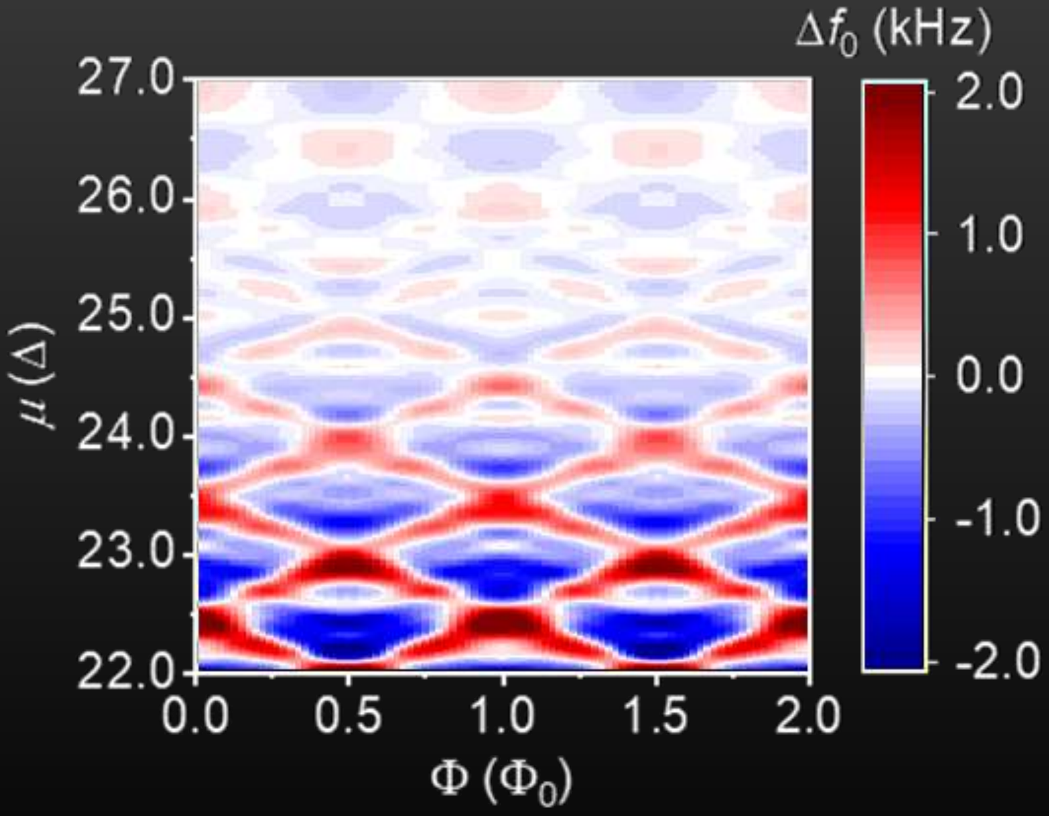


Period = Φ_0/(cross-section)

Period = Δ

Nanomechanical resonance shift

$$\Delta k_{eff} \approx -\frac{1}{2}\left(\frac{\ddot{C}_G}{C_G^2}\right)Q^2 + \frac{e}{2}\left(\frac{\dot{C}_G}{C_G}\right)^2 \frac{\partial}{\partial\mu}\left(\frac{1}{C_Q^2}\right)Q^3$$

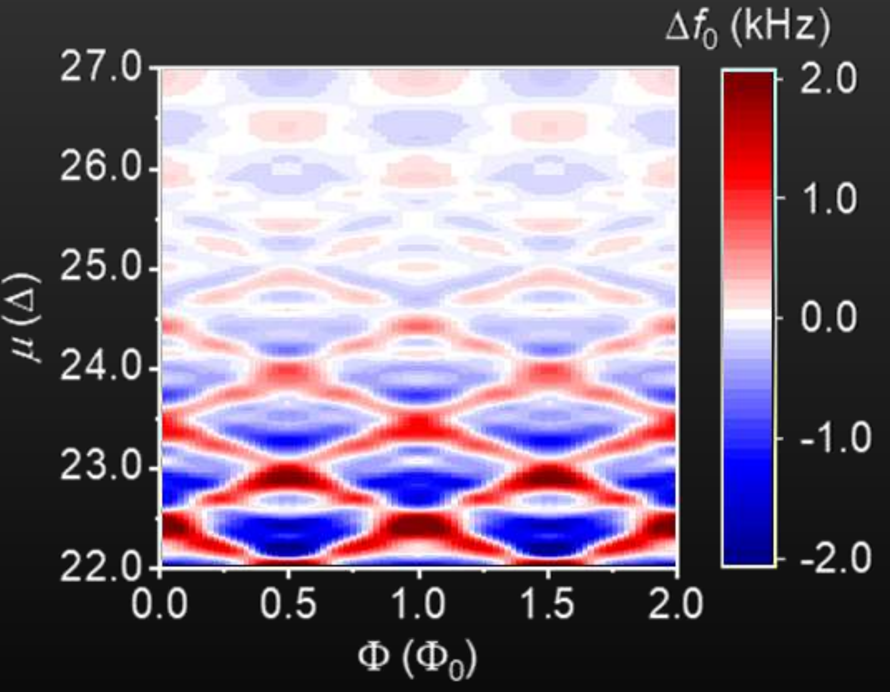


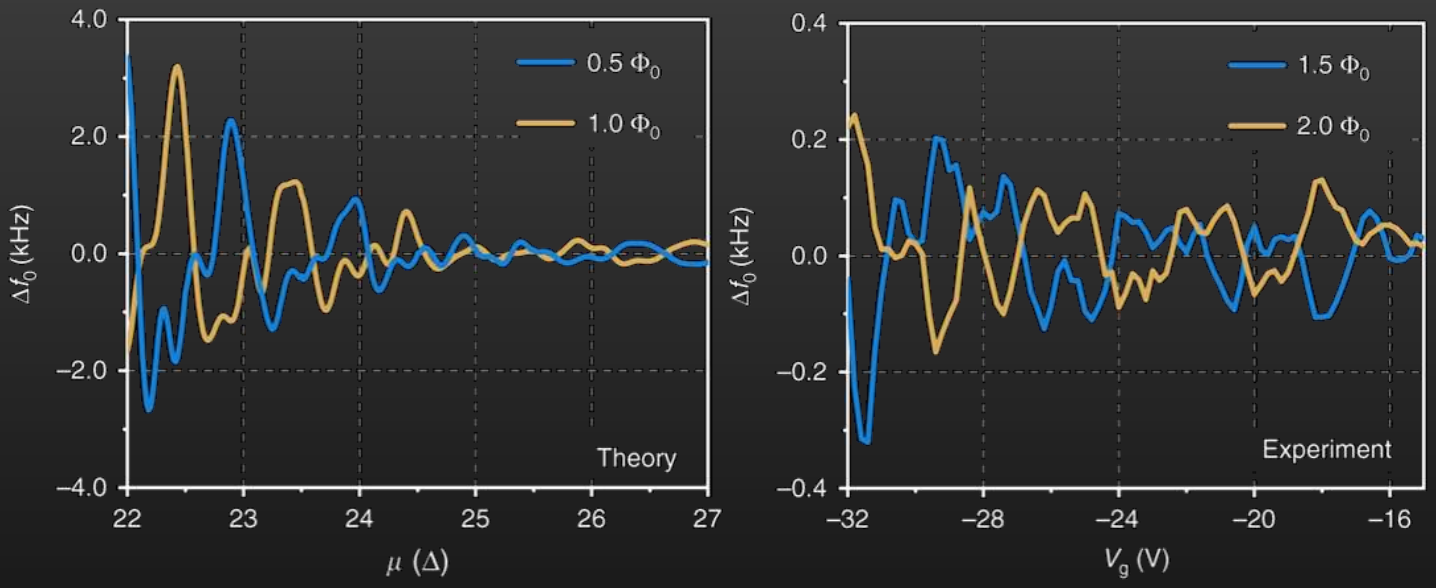
Kunwoo Kim* (CAU)

* previously at IBS

Nanomechanical resonance shift

$$\Delta k_{eff} \approx -\frac{1}{2}\left(\frac{\ddot{C}_G}{C_G^2}\right)Q^2 + \frac{e}{2}\left(\frac{\dot{C}_G}{C_G}\right)^2 \frac{\partial}{\partial\mu}\left(\frac{1}{C_Q^2}\right)Q^3$$



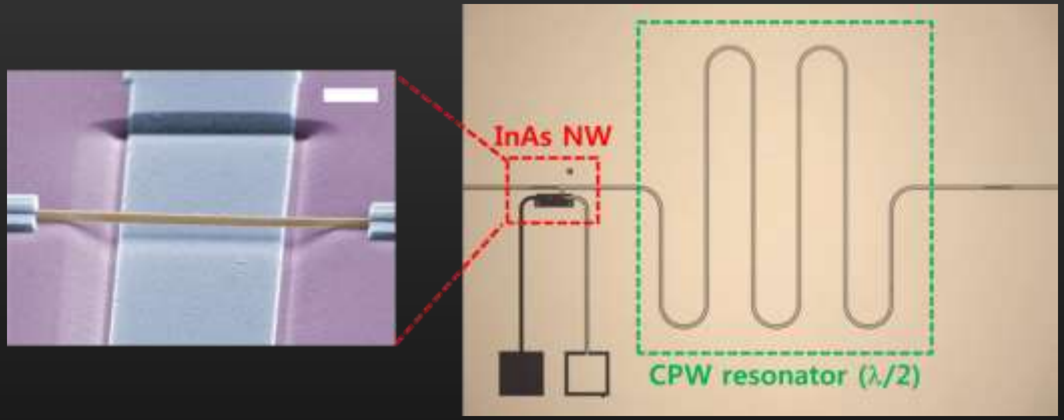


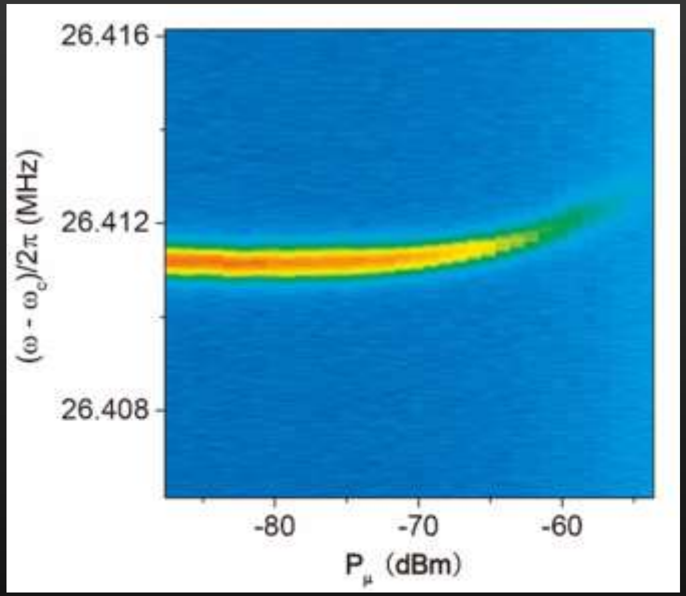
- Stronger mechanical effect closer to Dirac point
- Applicable to other Dirac systems*

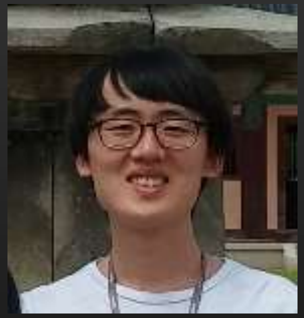
* Chen *et al. Nat. Phys.* **12**, 240–244 (2016).

Nanomechanical microwave bolometer

Nanomechanical QEM detects heat from microwave photons.



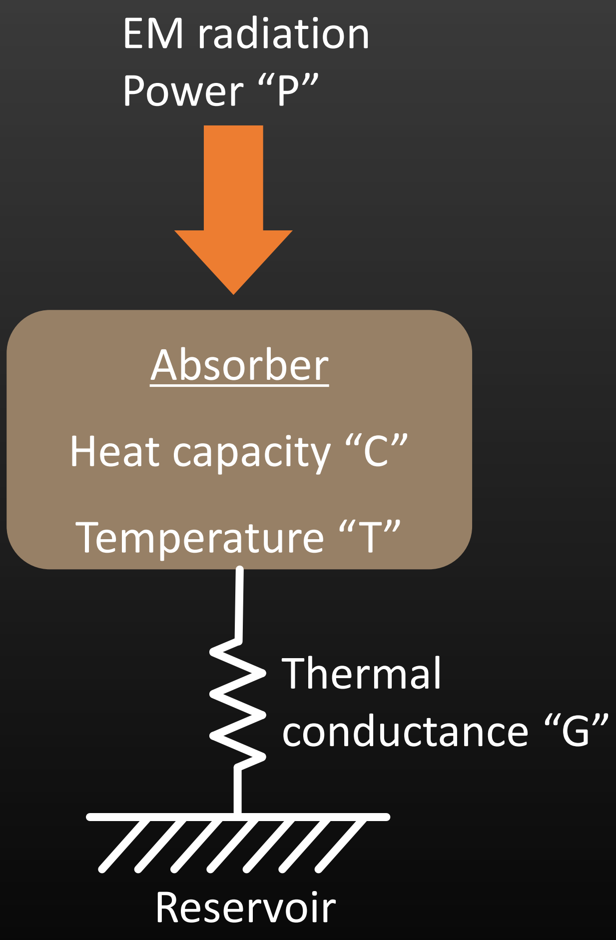




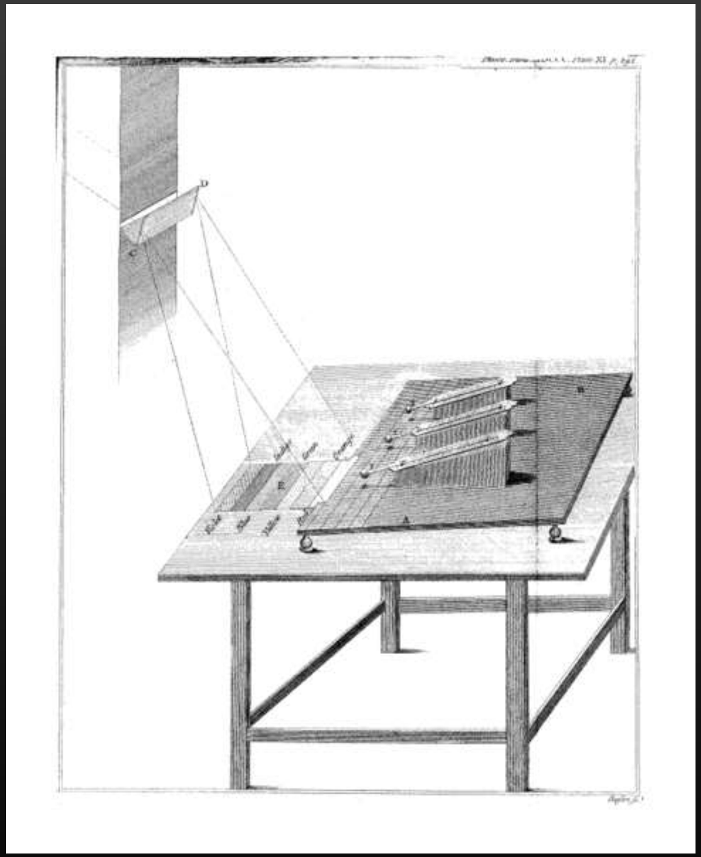
Jihwan Kim (KAIST)

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

Bolometer = thermal radiation detector

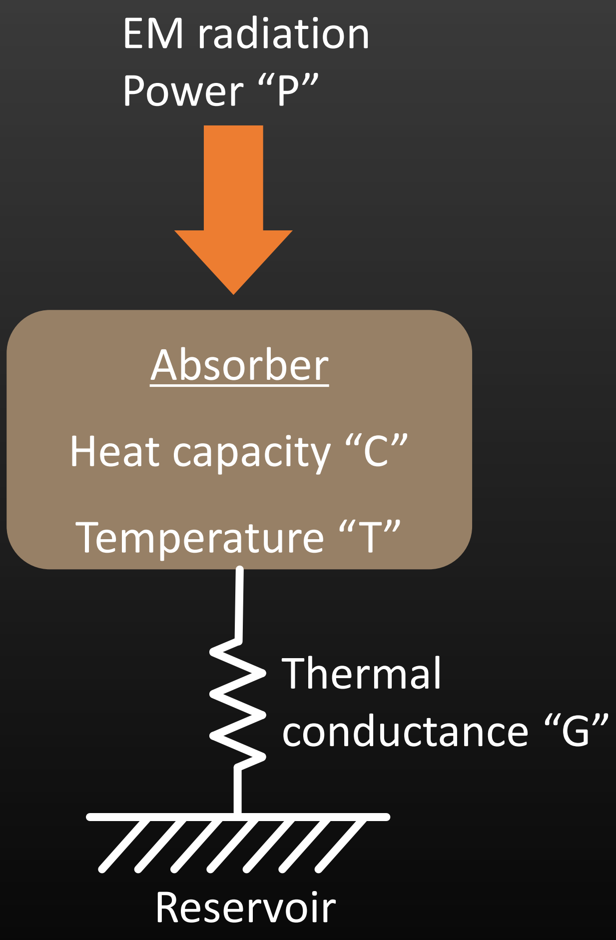


$$P = G \cdot \Delta T$$
$$\tau = C/G$$



Sir William Herschel (1800)

Bolometer = thermal radiation detector



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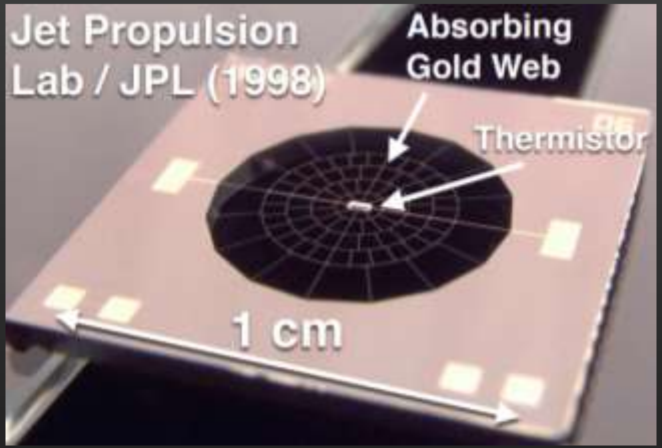
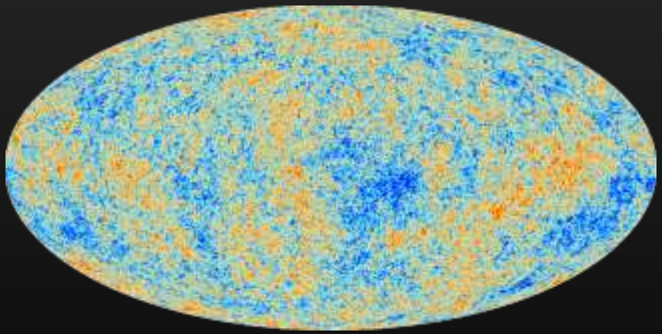
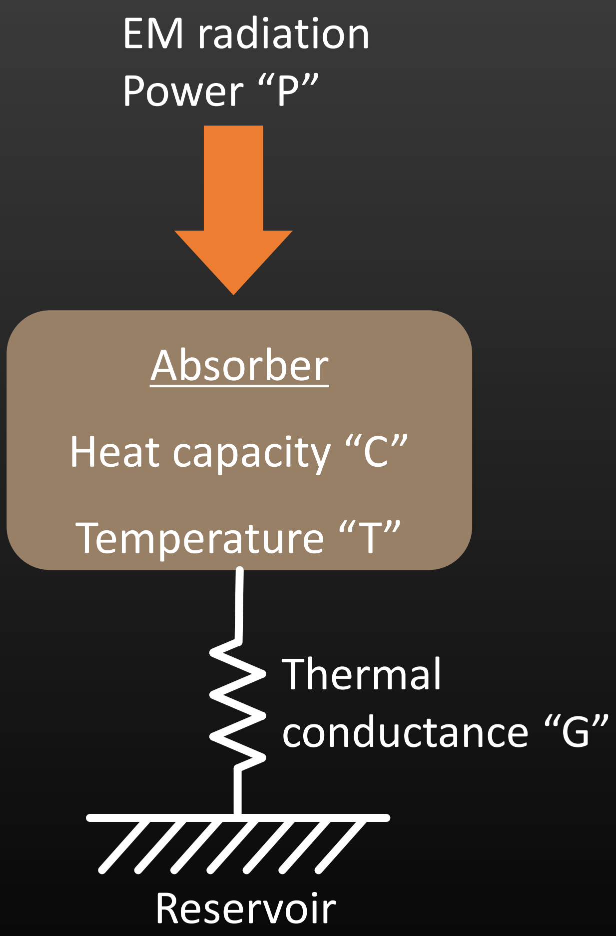


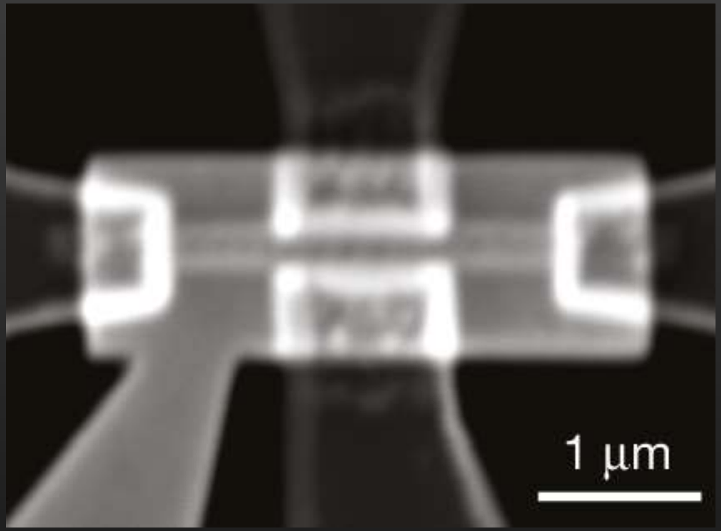


- Cosmic microwave background map from Plank mission (2009)
- 100 ~ 857 GHz

Bolometer = thermal radiation detector



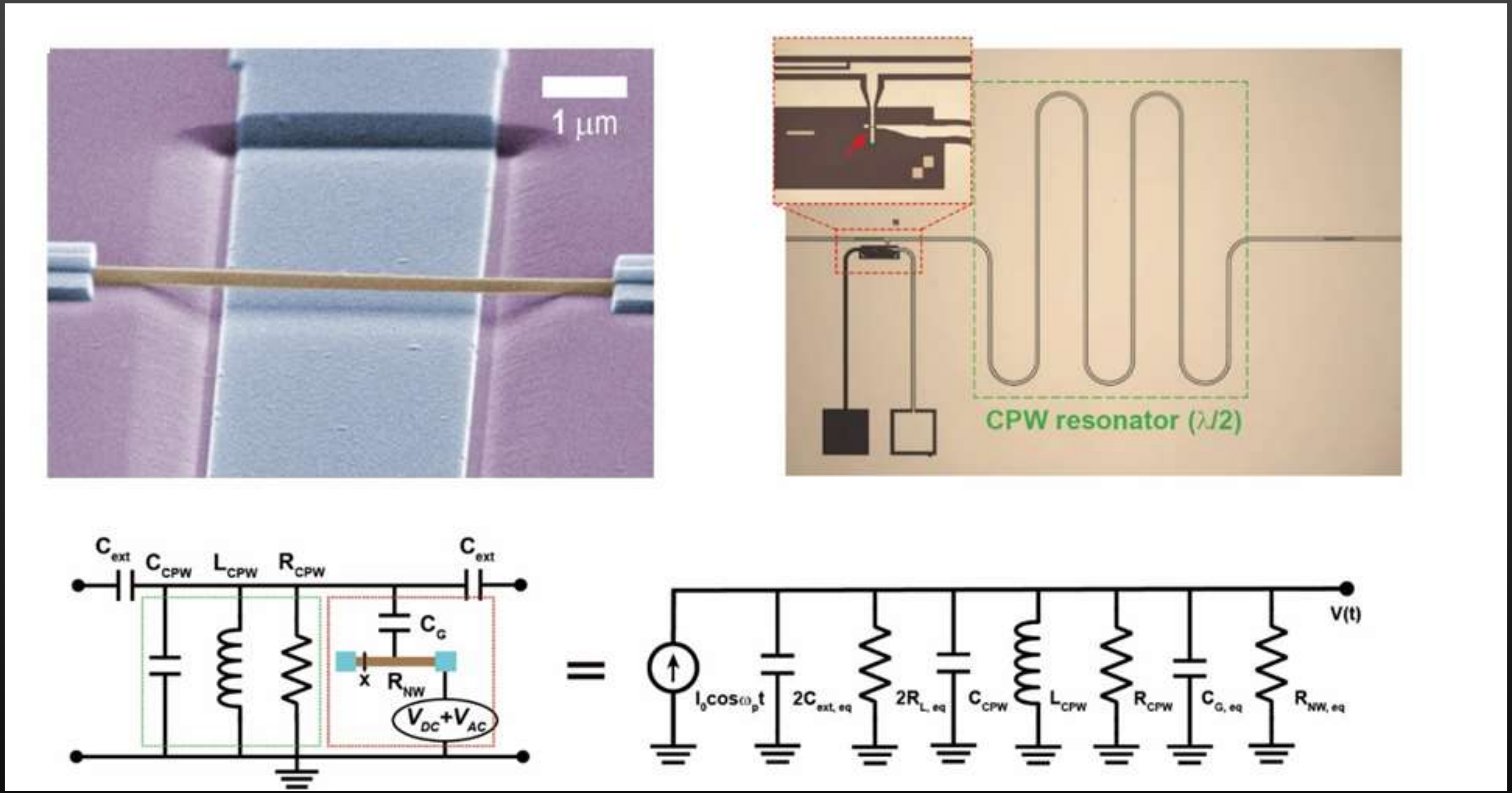
$$P = G\cdot\Delta T$$
$$\tau = C/G$$



- 8 GHz
- Sensitivity ~ 32 GHz single photon

* G. Lee *et.al.*, *Nature* **586**, 42–46 (2020).

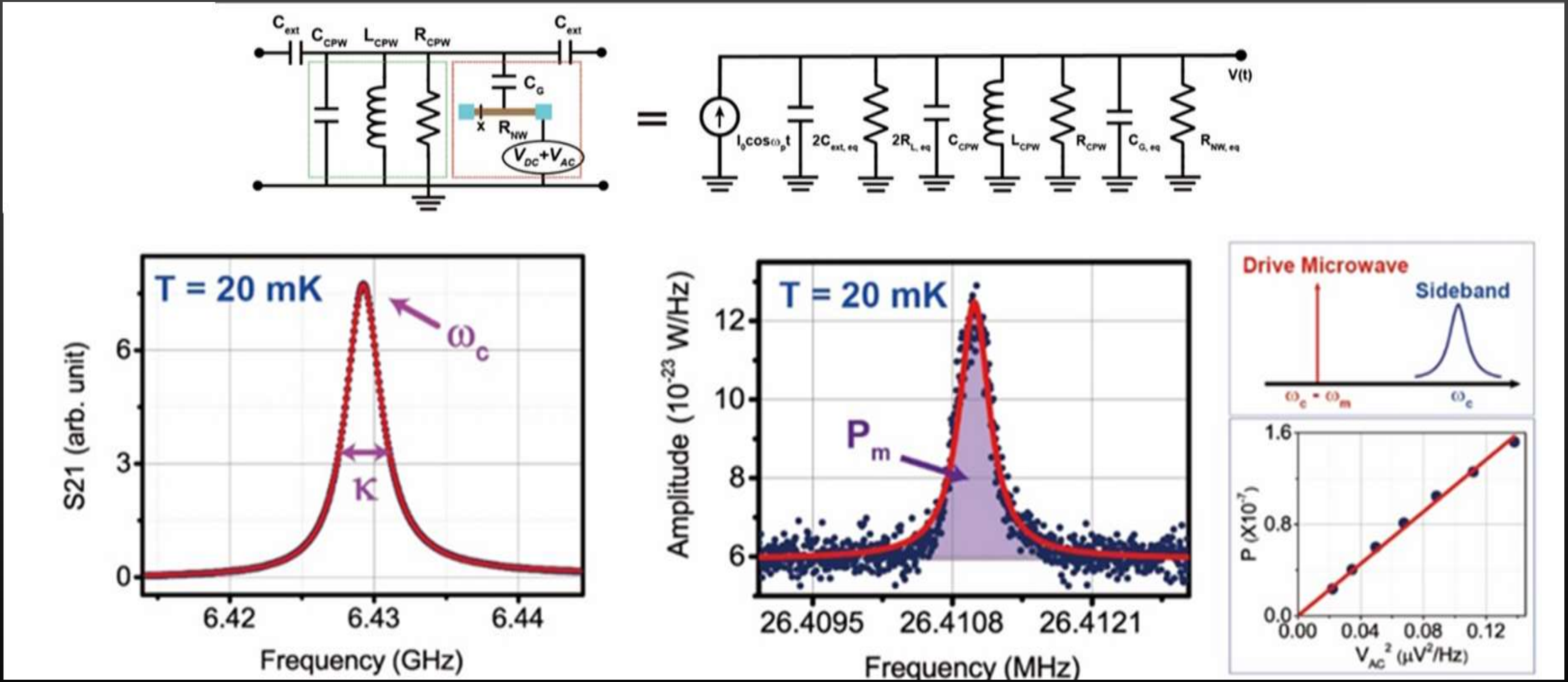
InAs nanowire based cavity electromechanics



Resistive nanowire dissipates microwave power

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

InAs nanowire based cavity electromechanics

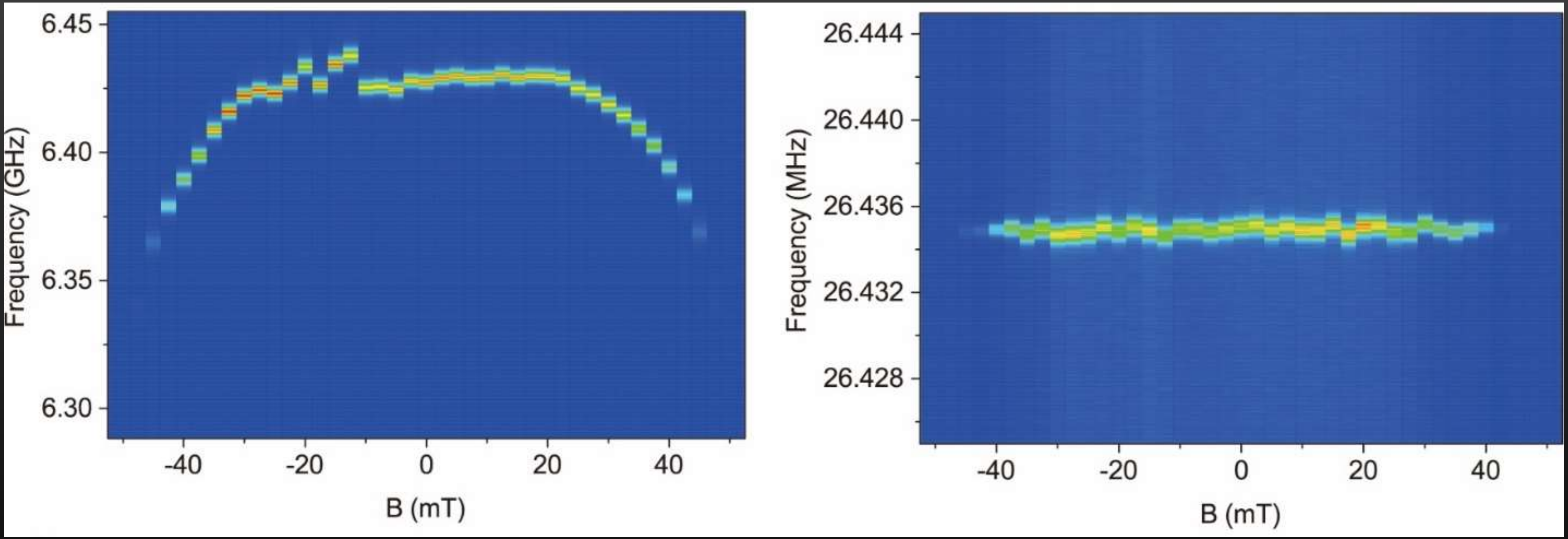


* J. Kim *et.al.*, *Physical Review Applied* **15**, 034075 (2021).

InAs nanowire based cavity electromechanics

Microwave cavity resonance

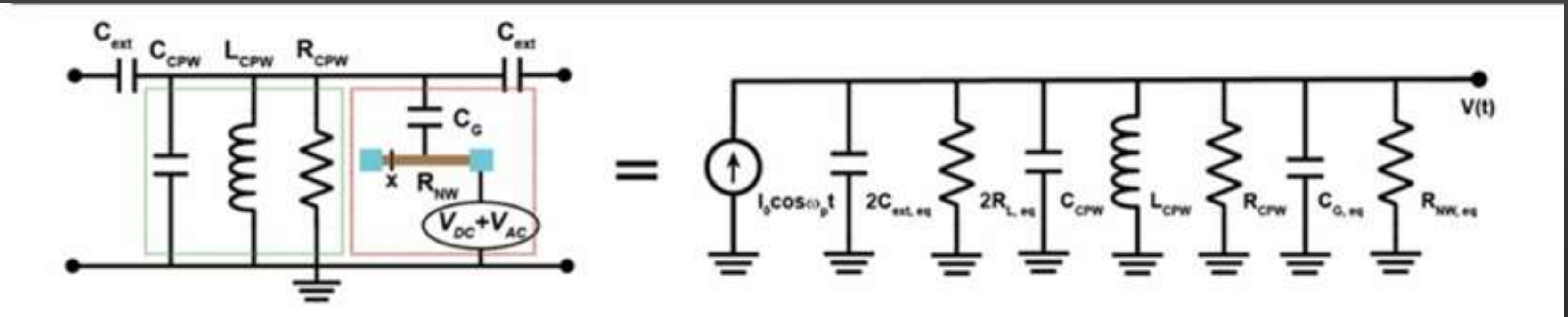
Mechanical resonance



<u>Mechanical resonance signal comes from superconducting cavity</u>

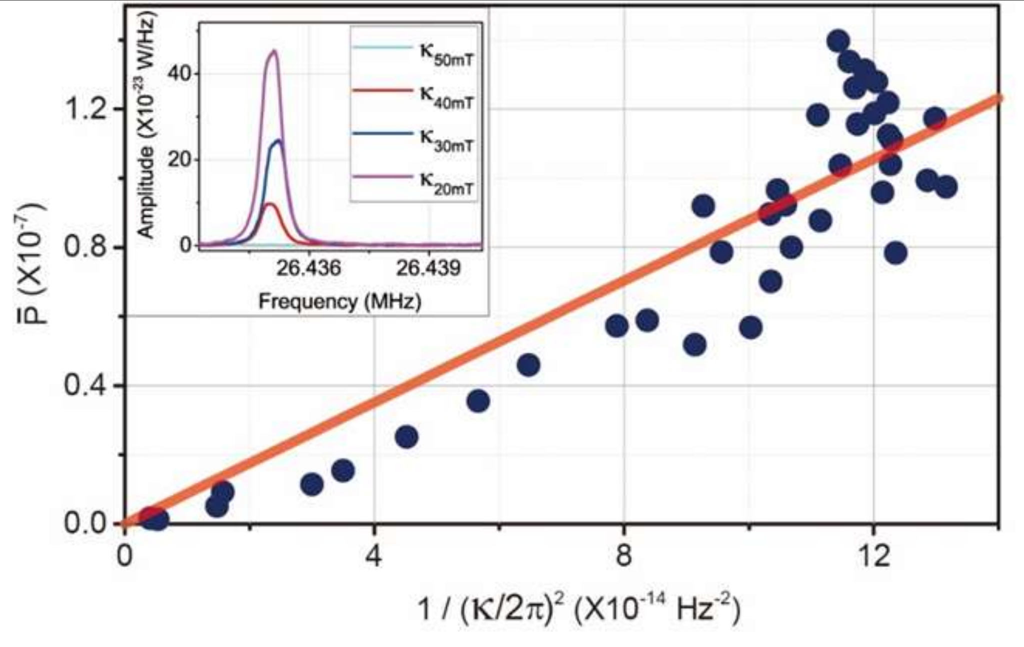
* J. Kim *et.al.*, *Physical Review Applied* **15**, 034075 (2021).

InAs nanowire based cavity electromechanics



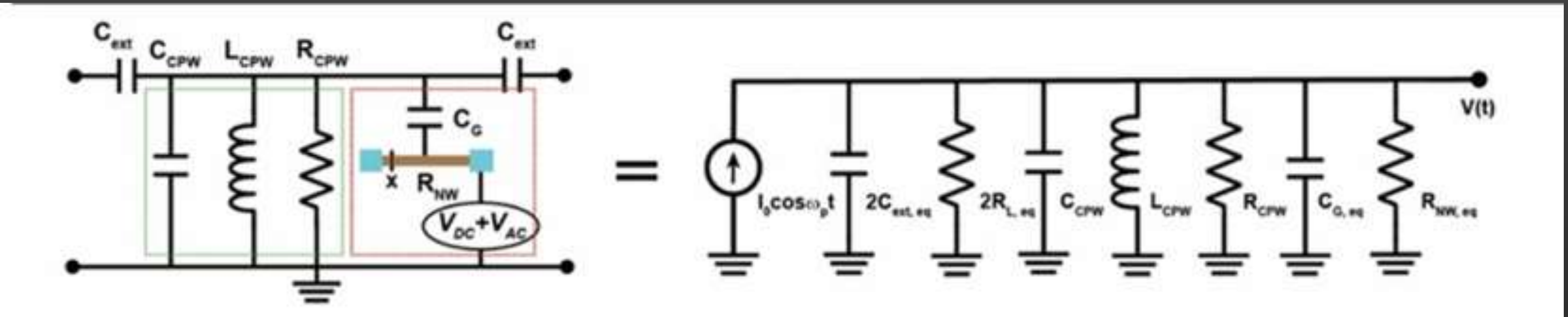
$$\bar{P} = \frac{P_m}{P_{pump}} = \frac{2(g_I^2 + g_{II}^2/4)}{\kappa^2}\langle x^2\rangle$$

where $g_I = \partial\omega_c/\partial x$ and $g_{II} = \partial\kappa/\partial x$



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

InAs nanowire based cavity electromechanics



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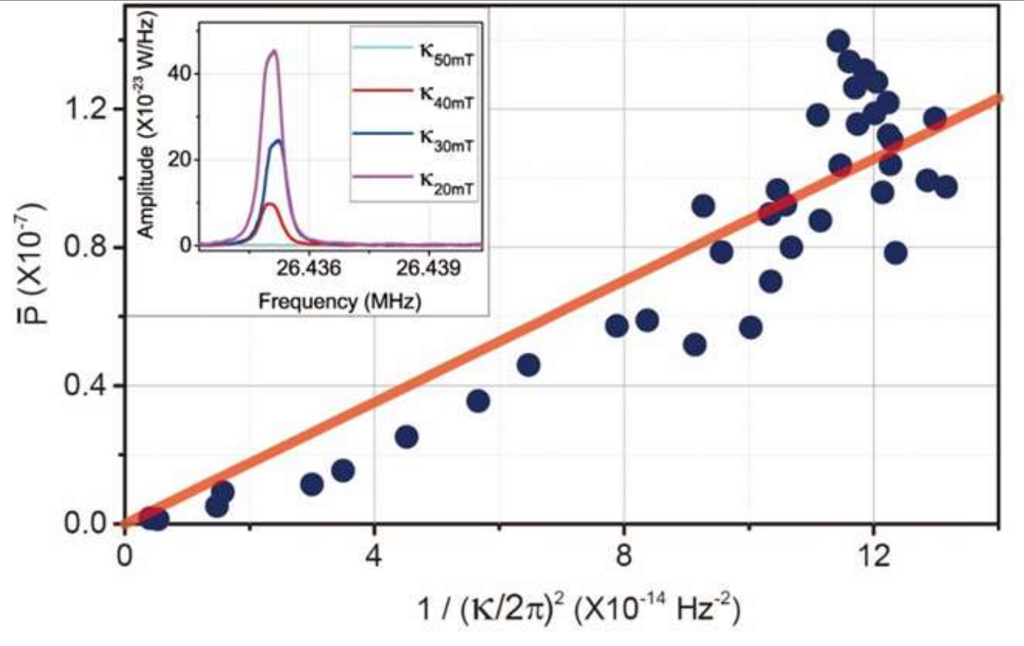
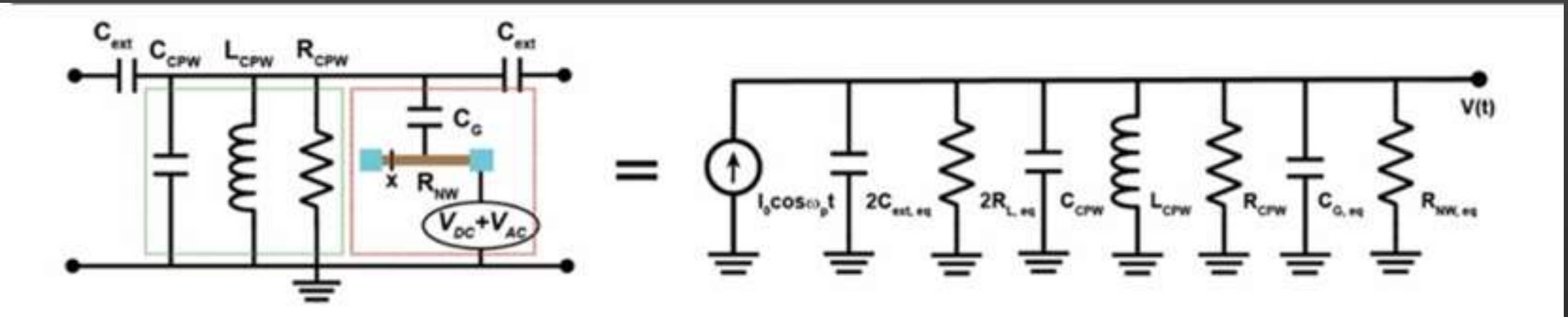
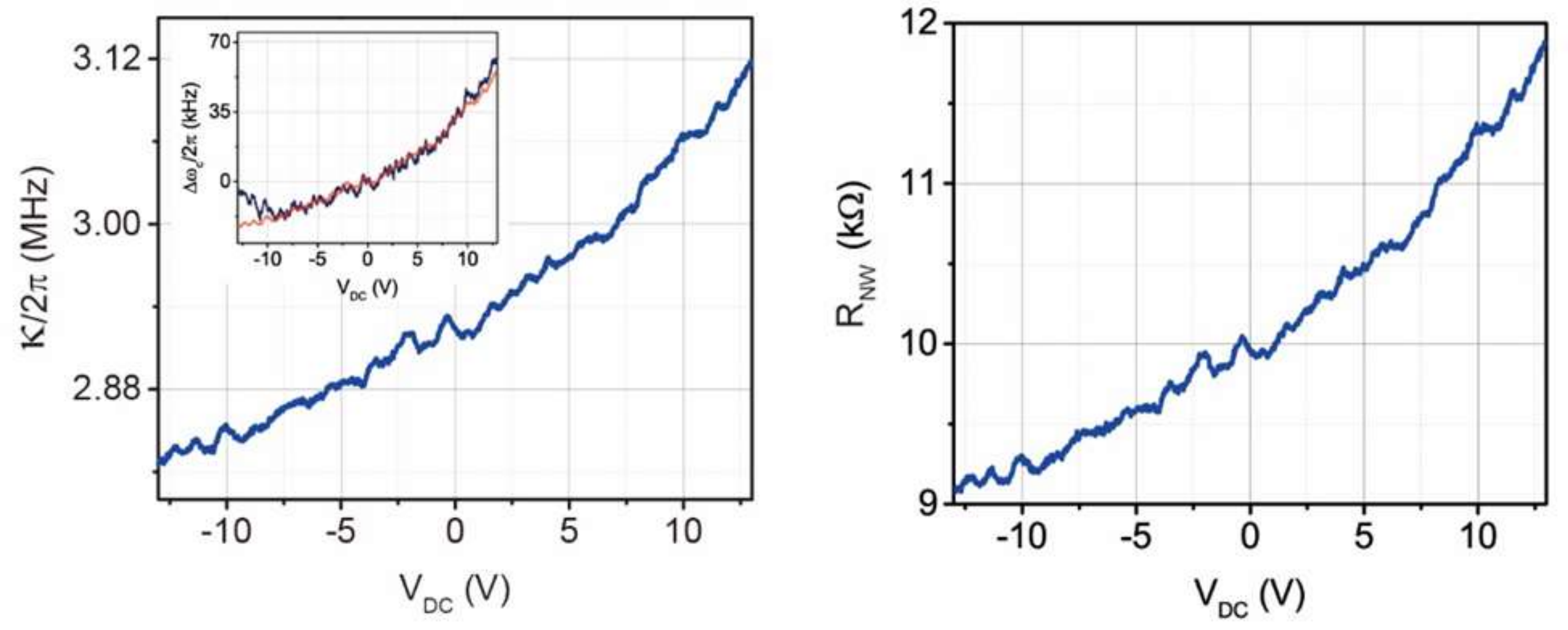
where $g_I = \partial\omega_c/\partial x$ and $g_{II} = \partial\kappa/\partial x$



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

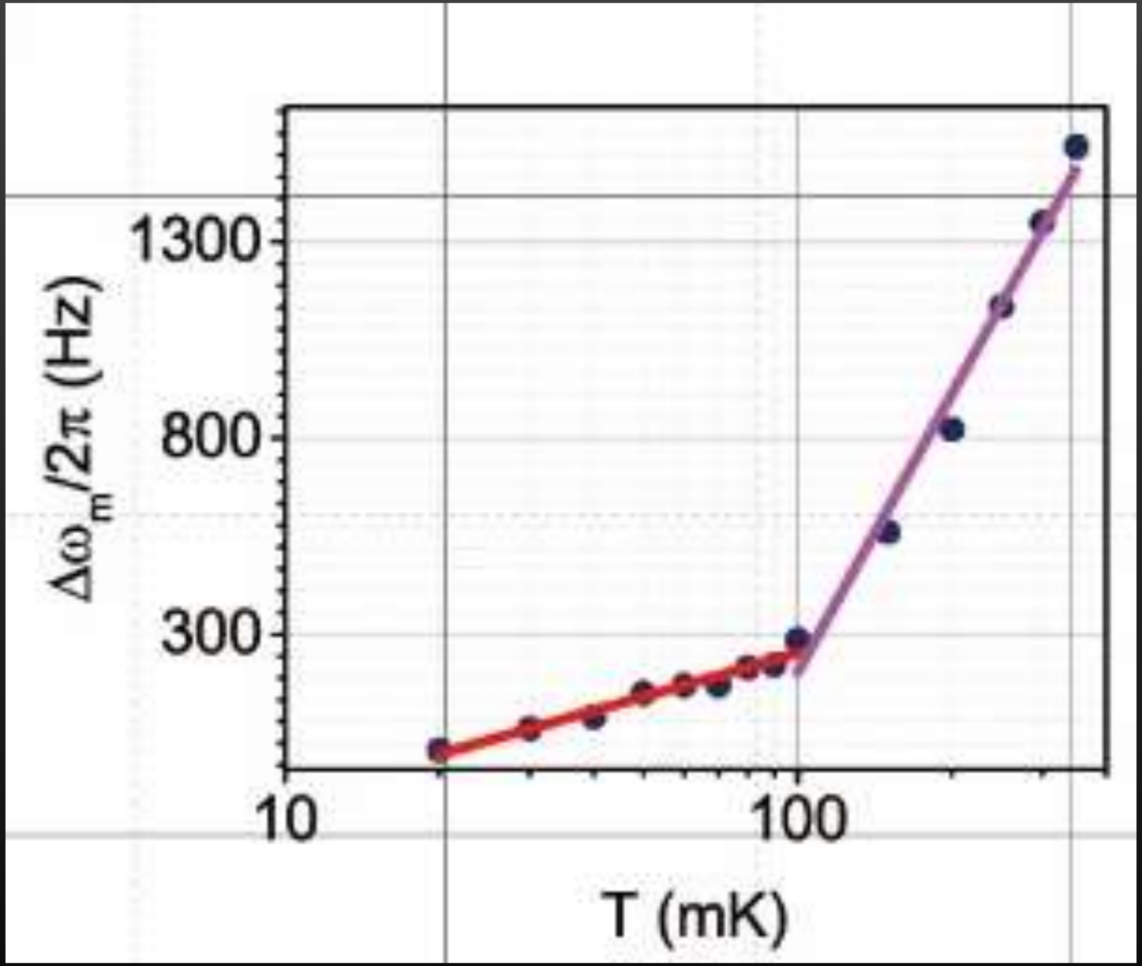
Nanowire controls cavity dissipation





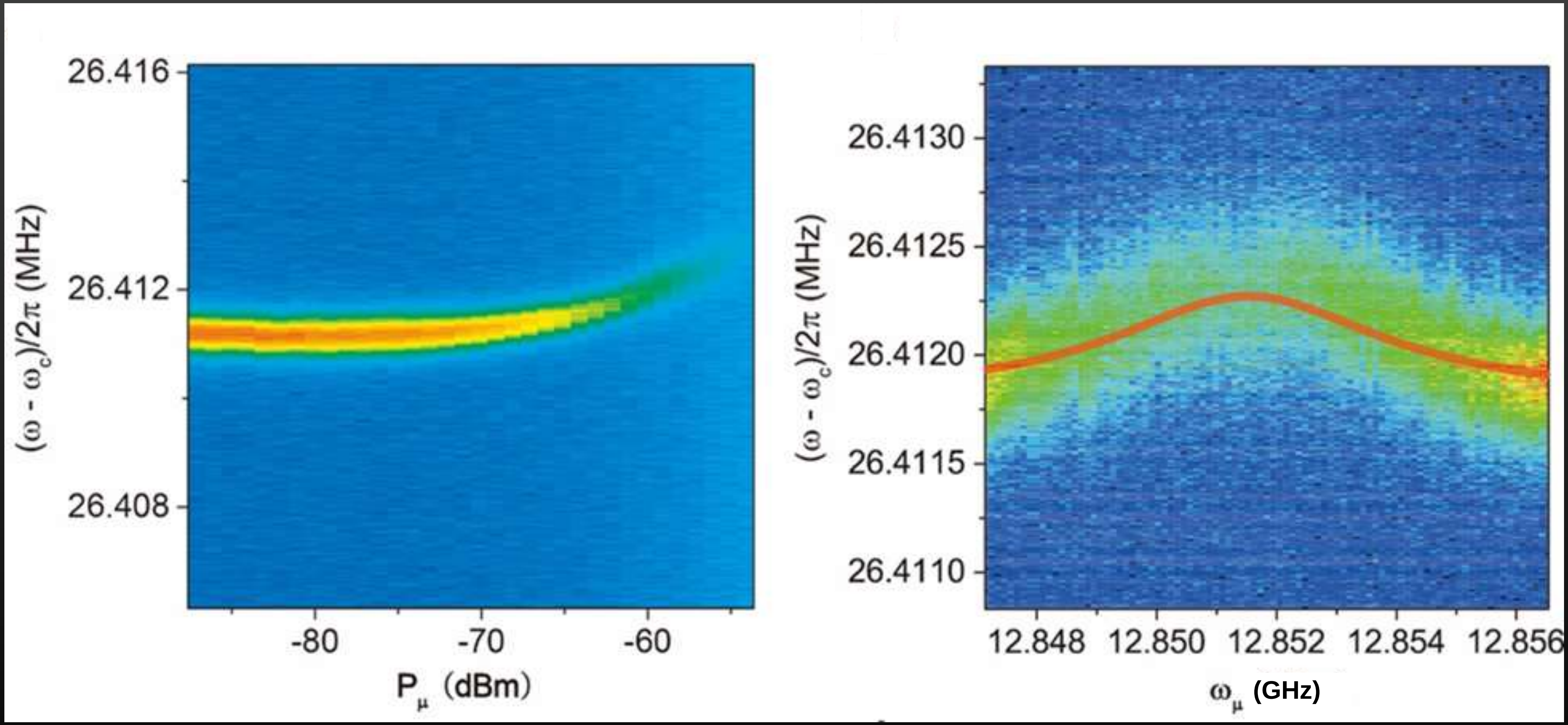
* J. Kim *et.al.*, *Physical Review Applied* **15**, 034075 (2021).

Nanomechanical resonance thermometer



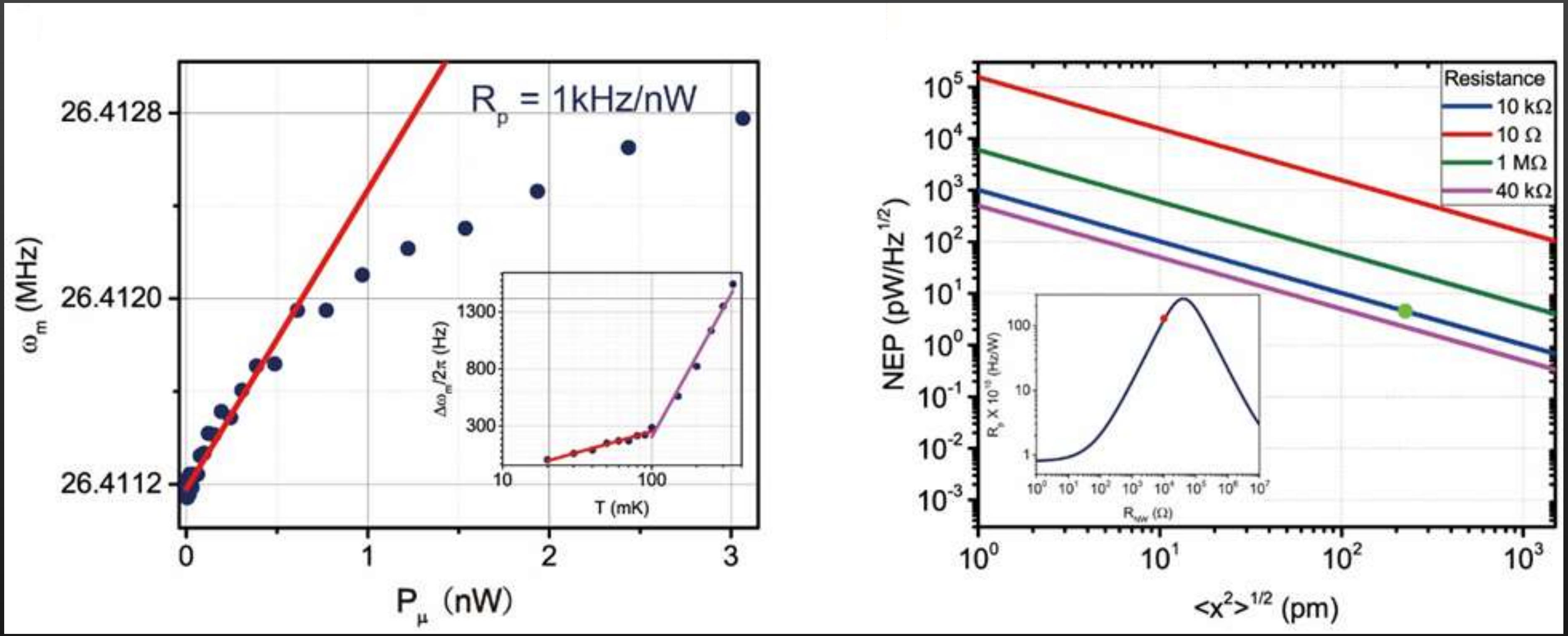
* J. Kim *et.al.*, *Physical Review Applied* **15**, 034075 (2021).

Microwave-power-dependent nanomechanical resonance



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

Nanomechanical microwave bolometry

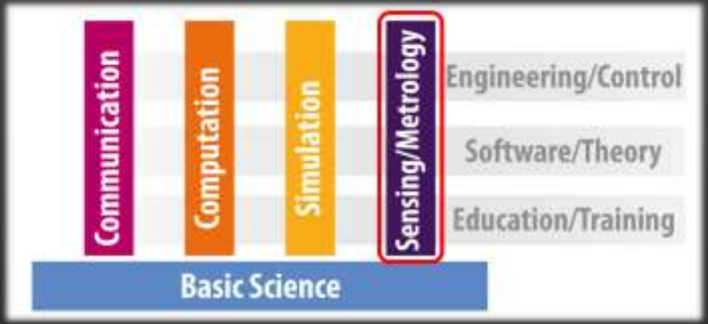


- “Noise equivalent power” NEP = 4.5 pW/Hz$^{1/2}$
- Maximum detectable power ~ nW
- c.f. Josephson bolometer has NEP ~ aW/Hz$^{1/2}$ and maximum power ~ fW (ref. *Nature* **586**, 42 (2020))

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

Summary

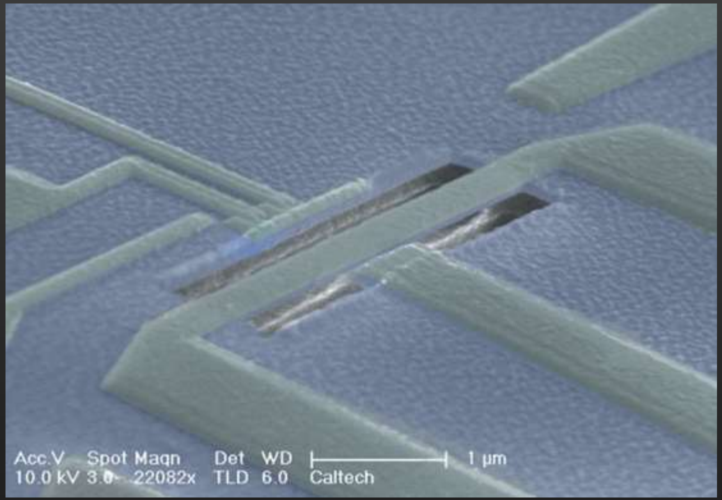
"Quantum Technology"



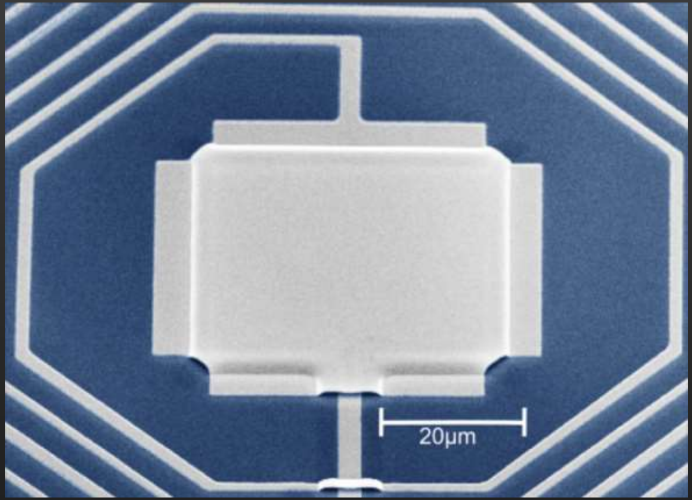
"Quantum Sensing"
: the use of a quantum system, quantum properties, or quantum phenomena to perform a measurement of a physical quantity

Implementation	Qubit(s)	Measured quantity(ies)	Typical frequency
Optomechanics Electromechanics	Phonons	Force, acceleration, mass, magnetic field, voltage	kHz–GHz

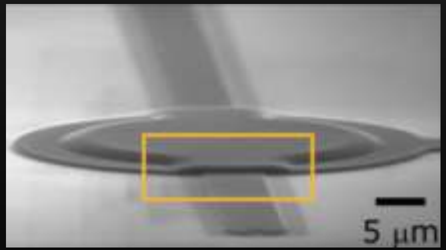
nanomechanical resonator for superconducting qubit measurement



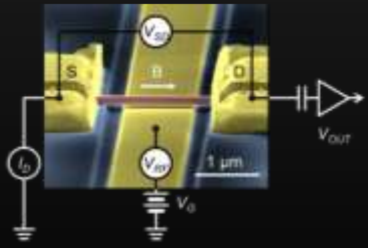
cavity electromechanics for quantum non-demolition measurement of motion

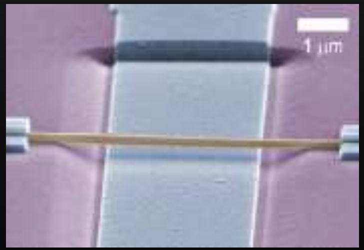


Nb cavity QEM



nanowire mechanics for quantum sensing

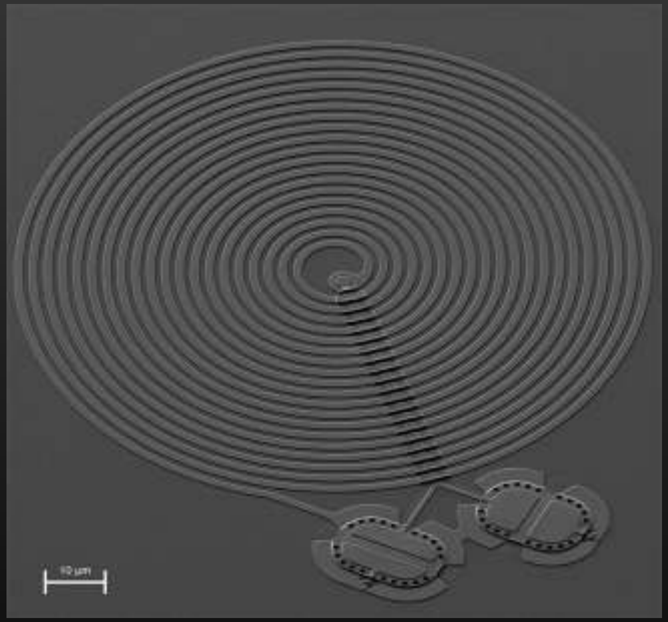




Outlook

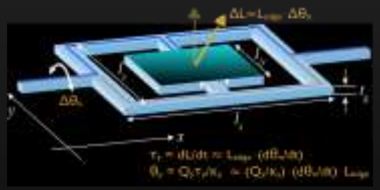
quantum transduction

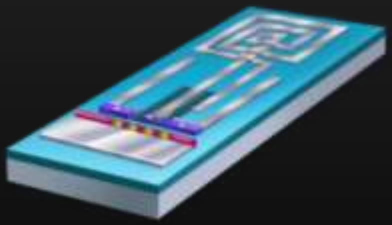
entangled force sensors

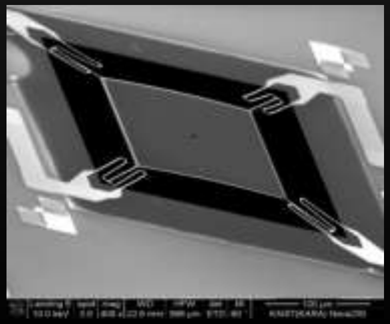


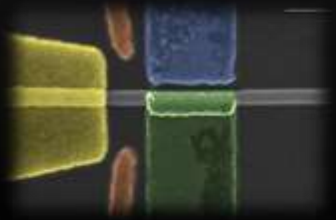
*Kotler *et al.*, *Science* **372**, 622 (2021).

sensors for new physics









Hybrid Quantum Systems Team

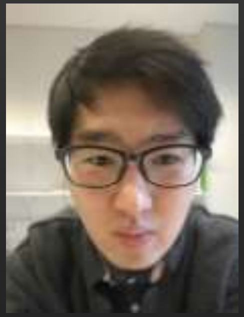
KRISS
한국표준과학연구원
Korea Research Institute of Standards and Science

developing nano electro-mechanical and hybrid quantum devices


Junho Suh

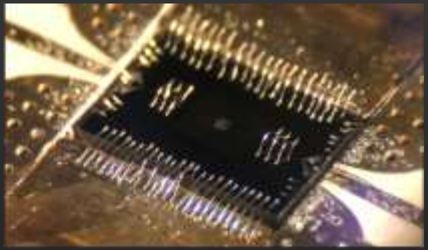

Jinwoong Cha

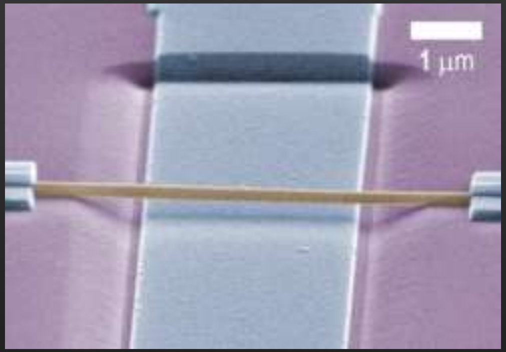

Seung-Bo Shim

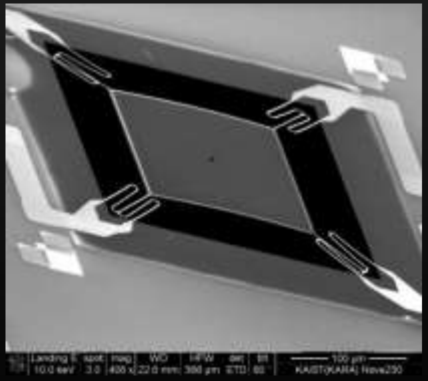

Byoung-moo Ann

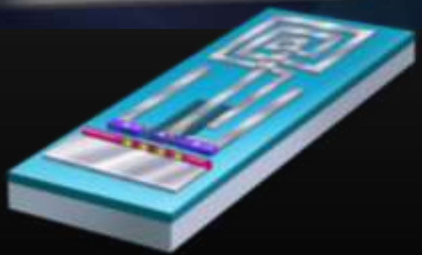

Minkyu Lee

Post-doc : Junghyun Shin, Jihwan Kim (KAIST SRC)
Ph.D. student : Younghoon Ryu (KAIST SRC)









Hybrid Quantum Systems Team

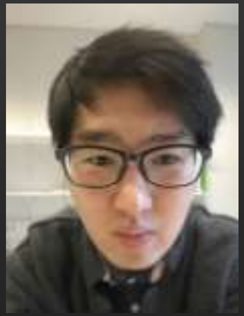
KRISS
한국표준과학연구원
Korea Research Institute of Standards and Science

developing nano electro-mechanical and hybrid quantum devices


Junho Suh


Jinwoong Cha


Seung-Bo Shim


Byoung-moo Ann


Minkyu Lee

Post-doc : Junghyun Shin, Jihwan Kim (KAIST SRC)
Ph.D. student : Younghoon Ryu (KAIST SRC)

Hiring post-docs!

contact: junho.suh@kriss.re.kr

Collaboration

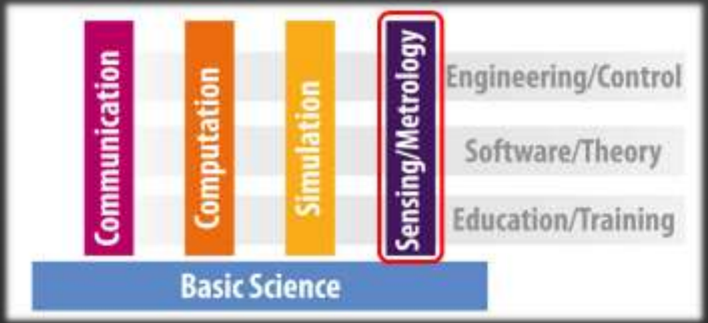
- Chulki Kim, Jin Dong Song (KIST)
- Kunwoo Kim (IBS), Heechul Park (IBS), Heung-Sun Sim (KAIST)
- Jinhoon Jeong, Hyungsoon Choi (KAIST)
- Yong-Joo Doh (GIST), Dong Yu (UC Davis)
- Joon Sue Lee (U. Tennessee)
- Mann-Ho Cho (YU)

** Lei, Weinstein, Schwab, Roukes for the works at Caltech (2009,2014)

NRF 한국연구재단 National Research Foundation of Korea
Center for Quantum Coherence in Condensed Matter
SAMSUNG 삼성미래기술육성재단
nst 국가과학기술연구회

Summary

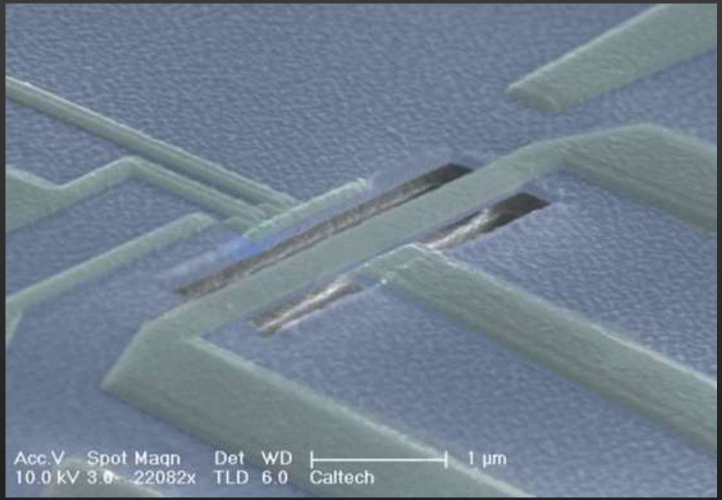
"Quantum Technology"



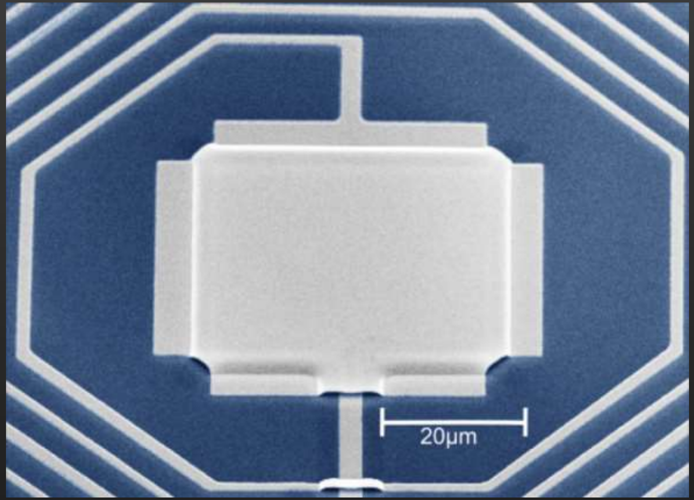
"Quantum Sensing"
: the use of a quantum system, quantum properties, or quantum phenomena to perform a measurement of a physical quantity

Implementation	Qubit(s)	Measured quantity(ies)	Typical frequency
Optomechanics Electromechanics	Phonons	Force, acceleration, mass, magnetic field, voltage	kHz–GHz

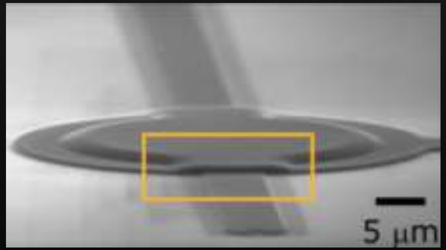
nanomechanical resonator for superconducting qubit measurement



cavity electromechanics for quantum non-demolition measurement of motion



Nb cavity QEM



nanowire mechanics for quantum sensing