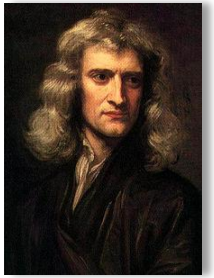
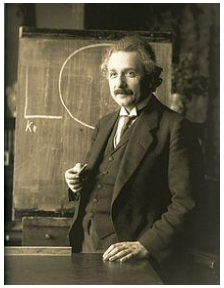
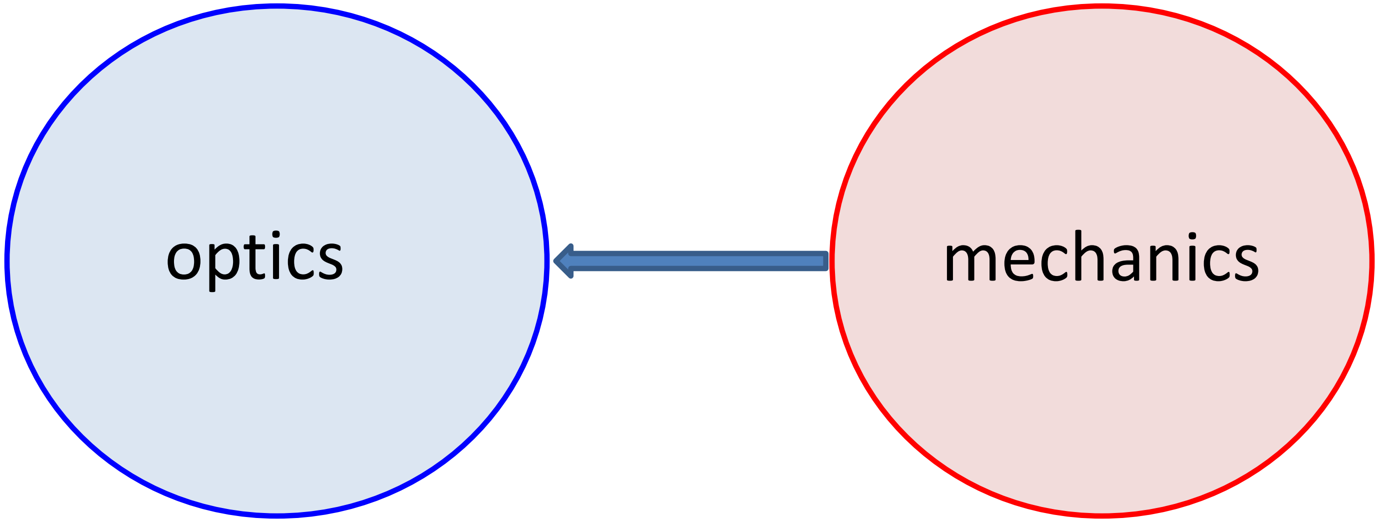
Opto-mechanics

RCAST - **R**esearch **C**enter for **A**dvanced **S**cience and **T**echnology
The University of Tokyo
Koji Usami

Optics & mechanics

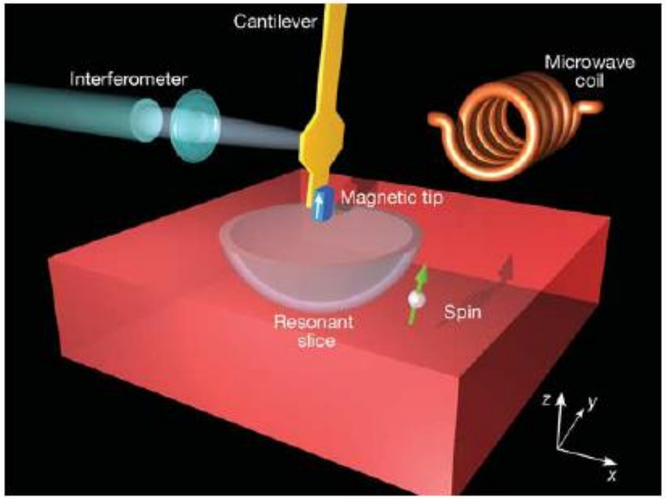
	Optics	Mechanics
 **Isaac Newton**	Newton’s prism Newton’s rings Newtonian telescope	Newton’s laws
Christiaan Huygens	Huygens' principle	Moment of inertia
Thomas Young	Young’s interference experiment	Young’s modulus
Lord Rayleigh	Rayleigh scattering	Rayleigh waves
 **Albert Einstein**	Photo-electric effect Einstein’s A, B coefficients Bose-Einstein statistics	Special relativity General relativity

Optics & mechanics



<u>Measuring</u> mechanics optically

Optics & mechanics

Gravitational wave	 **LIGO** Laser Interferometer Gravitational Wave Observatory
Single spin	 **MRFM** Magnetic Resonance Force Microscope

Optics & mechanics

Optics

High sensitivity
(Shot-noise-limited)

- ✓Laser is available
- ✓Good photo-detectors
- ✓Higher energy quanta

Mechanics

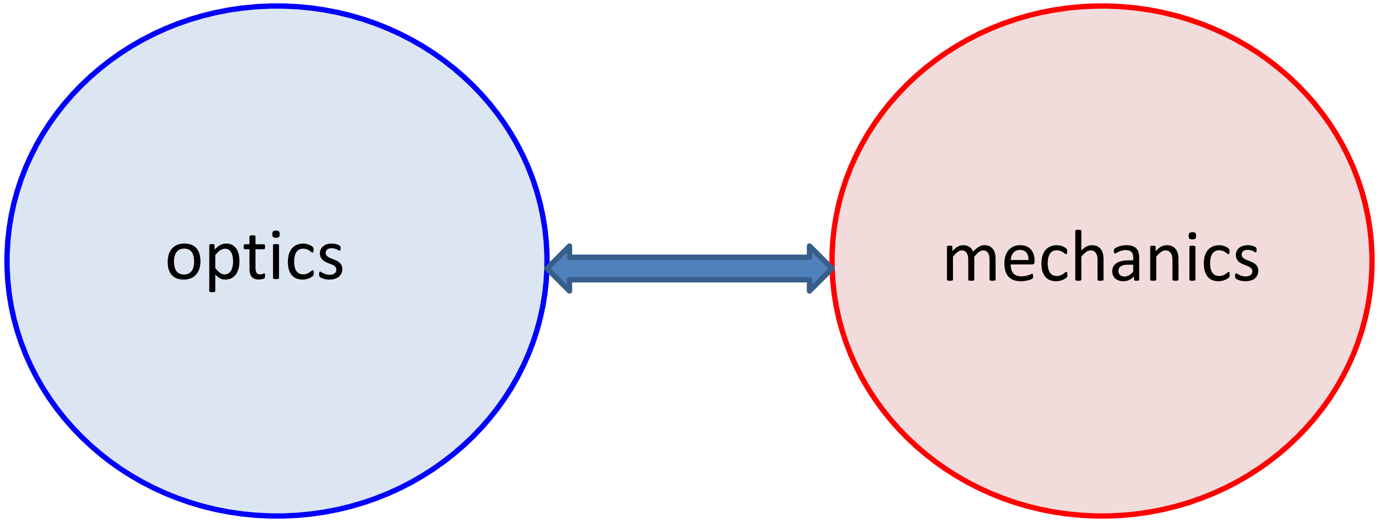
High sensitivity
(High mechanical Q)

- ✓Well-isolated from the other D.O.F.
- ✓Easy to design/machine
- ✓Collective modes

Opto-mechanics

Optics & Mechanics

Opto-mechanics

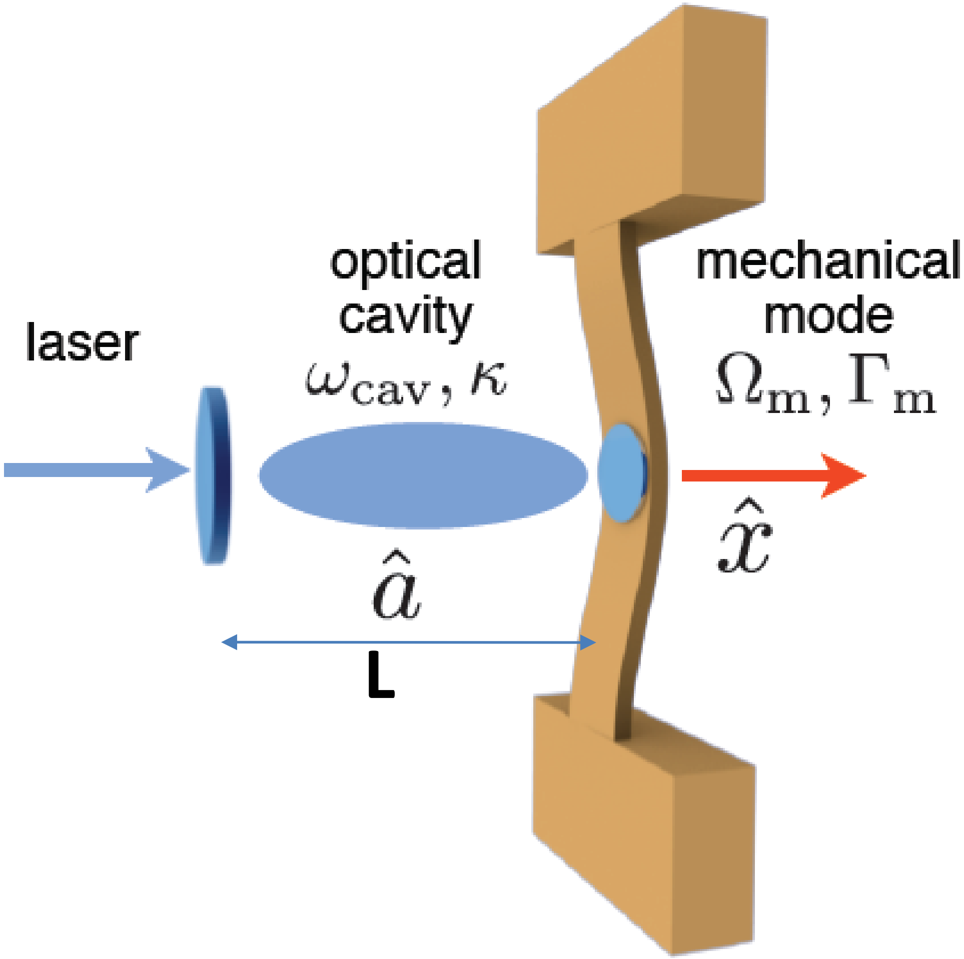


<u>Controlling</u> mechanics optically
(Dynamical back-action)

Cavity opto-mechanics

- **Position sensing**
  - Tiny displacement of mechanical object can be measured
- **Mechanical effect of light**
  - Radiation pressure can be boosted

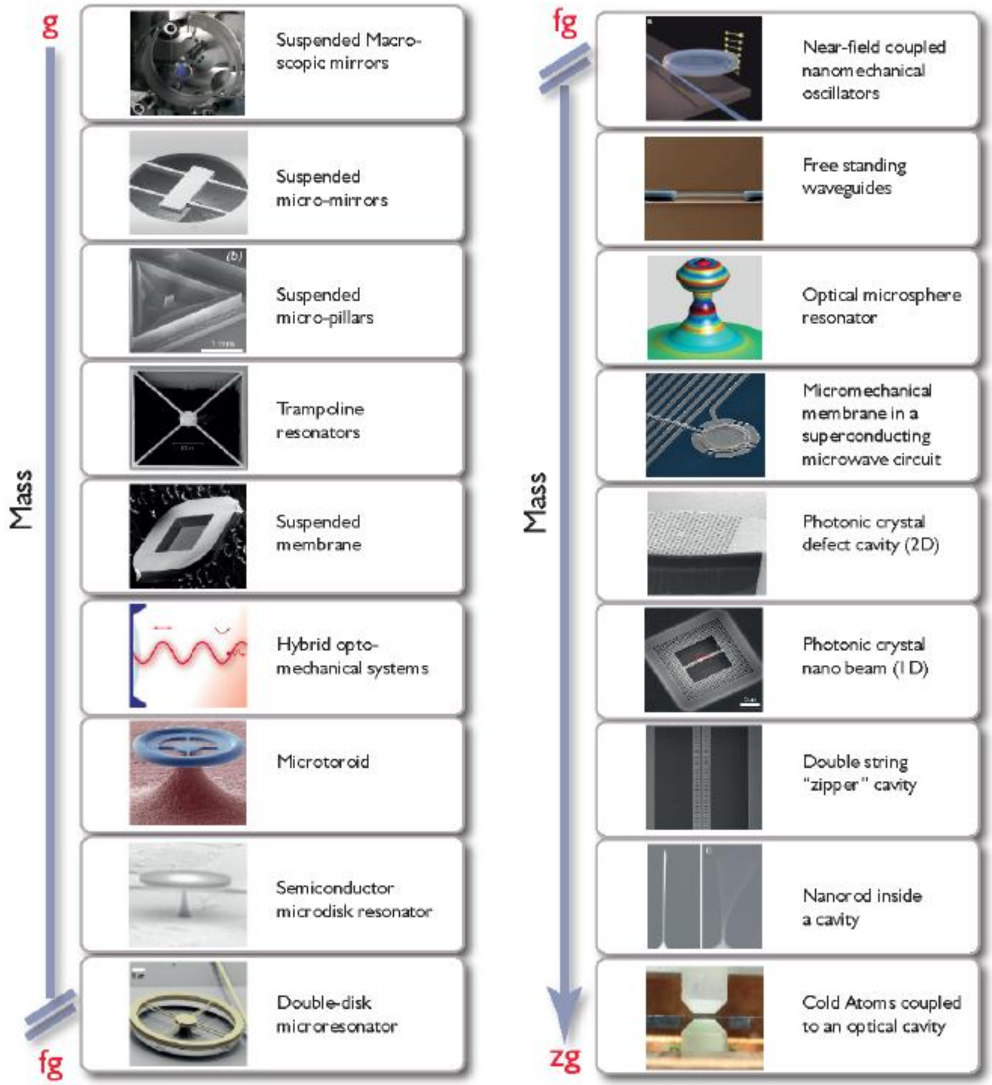
Cavity opto-mechanics



M. Aspelmeyer, T. J. Kippenberg, and F. Marquardt, arXiv:1303.0733v1

Showcase of opto-mechanical systems

Gram



Zepto-gram (10^{-21} gram)

M. Aspelmeyer, T. J. Kippenberg, and F. Marquardt, arXiv:1303.0733v1

References

Review articles

- **T. J. Kippenberg** and **K. J. Vahala**, Science **321**, 1172 (2008).
- **F. Marquardt** and **S. M. Girvin**, Physics **2**, 40 (2009).
- **I. Favero** and **K. Karrai**, Nature Photonics **3,** 201 (2009).
- **M. Aspelmeyer**, **T. J. Kippenberg**, and **F. Marquardt**, arXiv:1303.0733v1 (2013).

etc.

Ph.D theses

- **Albert Schliesser**, Ludwig-Maximilians-University (Germany) 2011.
- **Dalziel Wilson**, Caltech (US) 2012.

etc.

Theme:

What makes **laser (cavity) cooling** conceptually different from conventional **cryogenics**?

Contents

- Optics & mechanics
  - Fabry-Perot cavity
  - Ornstein-Uhlenbeck process
  - Dissipation-fluctuation theorem
- Opto-mechanics
  - Carnot cycle for black-body radiation
  - Sideband cooling
  - Detailed balance
  - Cold damping (cavity cooling)

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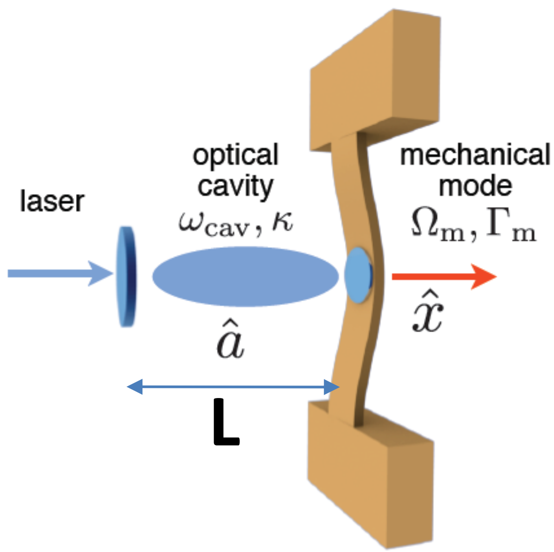
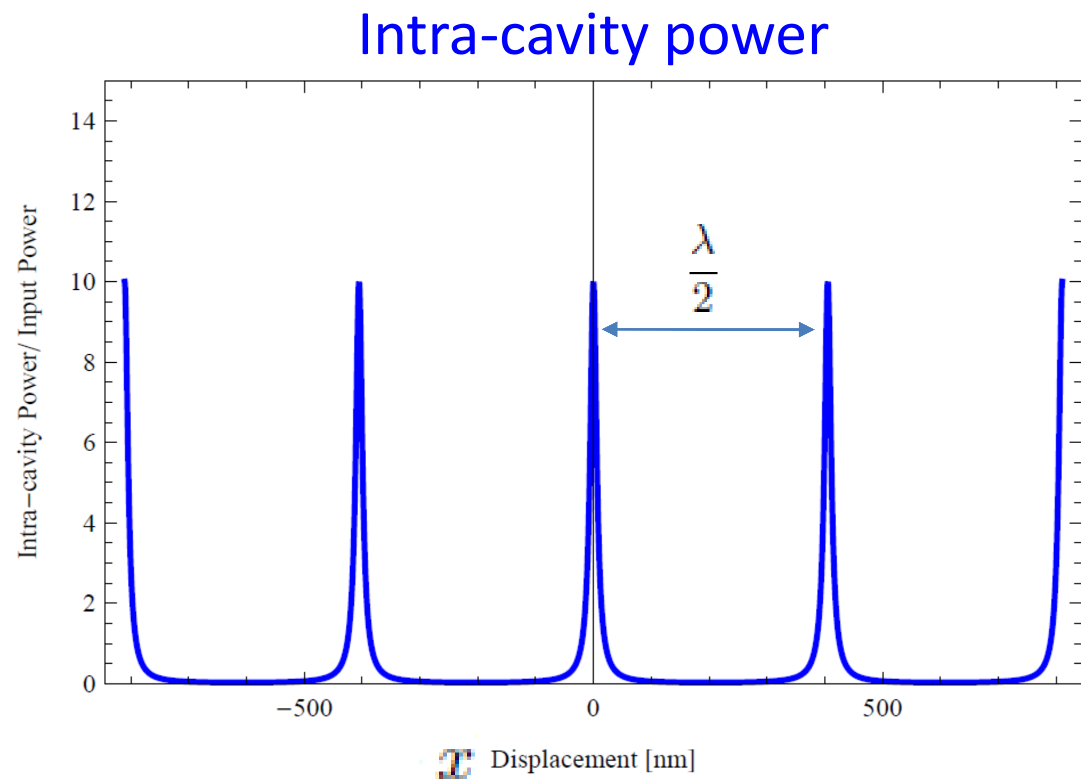
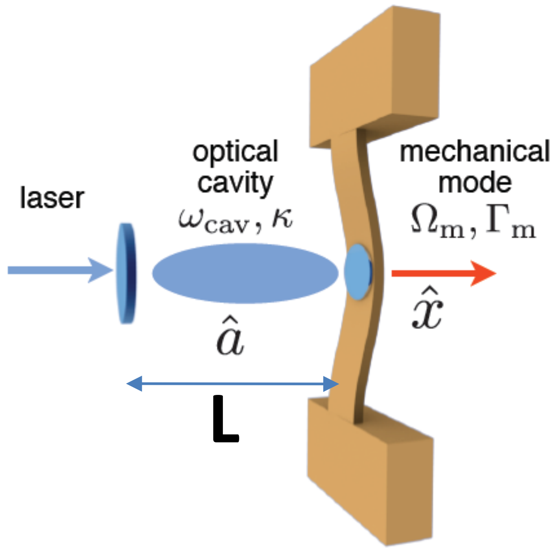
Fabry-Perot Cavity



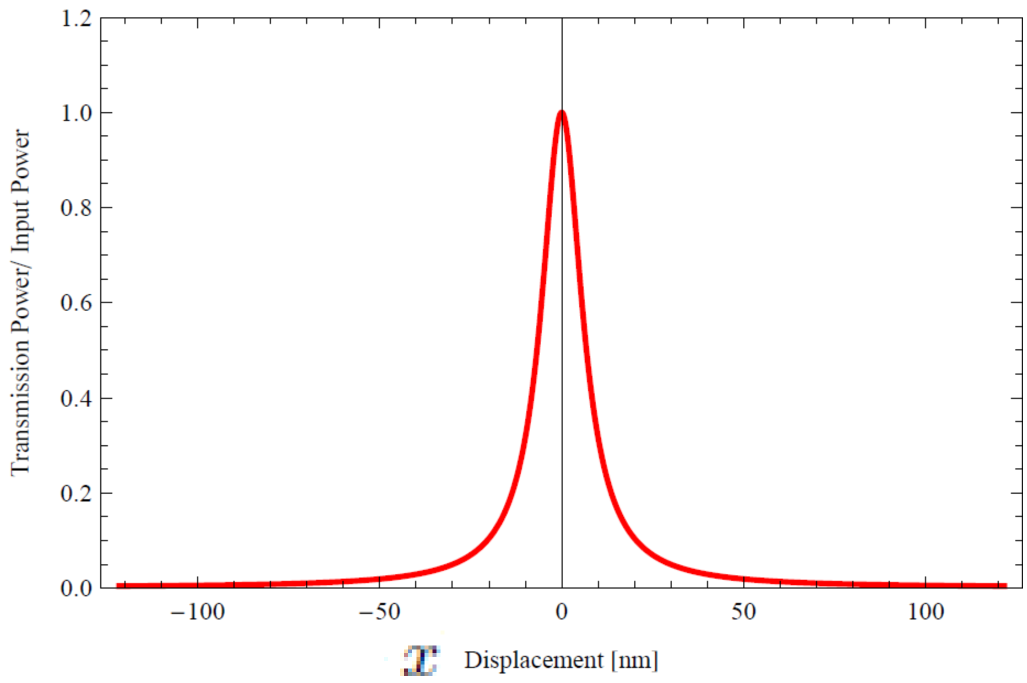


Resonance condition : $2(L+x) = \lambda n$

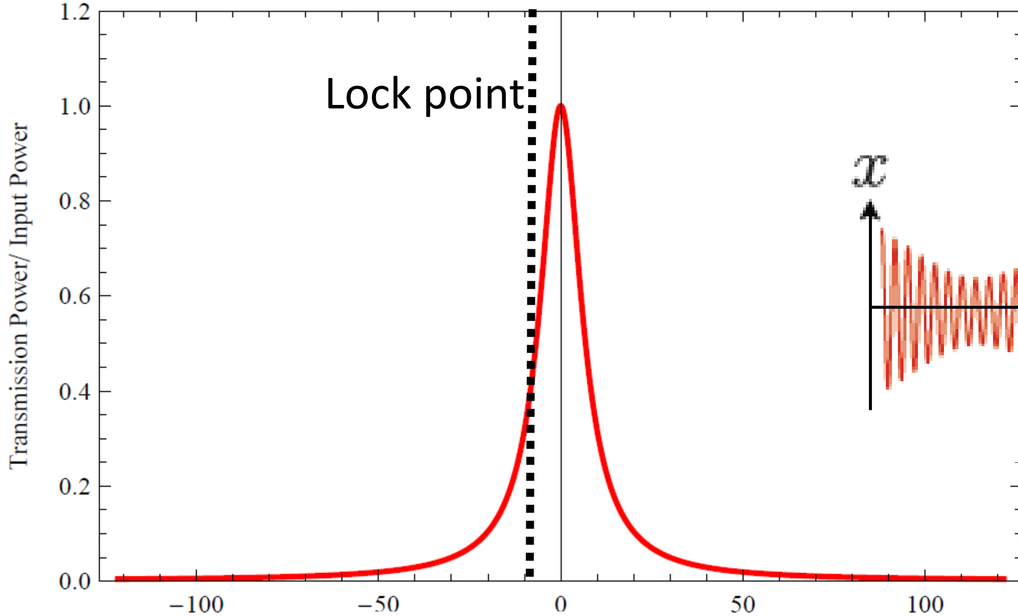
Zooming up one resonance

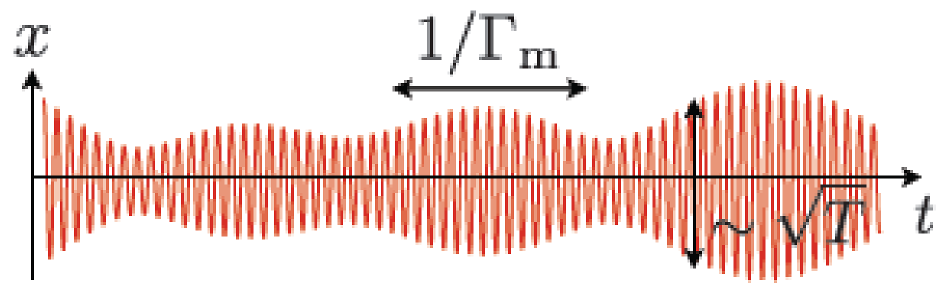


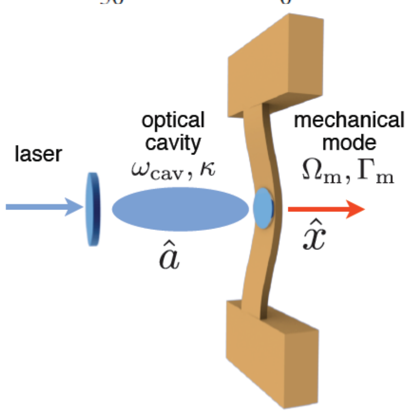
Transmission



Fabry-Perot cavity = displacement sensor







M. Aspelmeyer, T. J. Kippenberg, and F. Marquardt, arXiv:1303.0733v1

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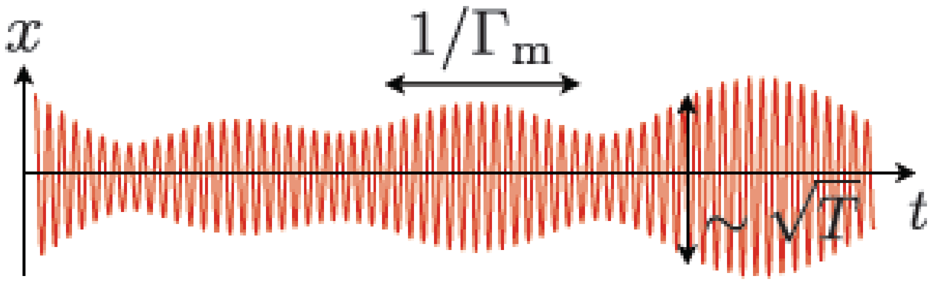
Mechanics = Damped harmonic oscillator



Langevin equation

$$\ddot{x} + \Gamma_m \dot{x} + \Omega_m^2 x = \frac{F_{\mathrm{B}}(t)}{m}$$

$F_{\mathrm{B}}(t)$: Langevin force

Γ_m : energy decay rate

Langevin force = **Gaussian white noise**

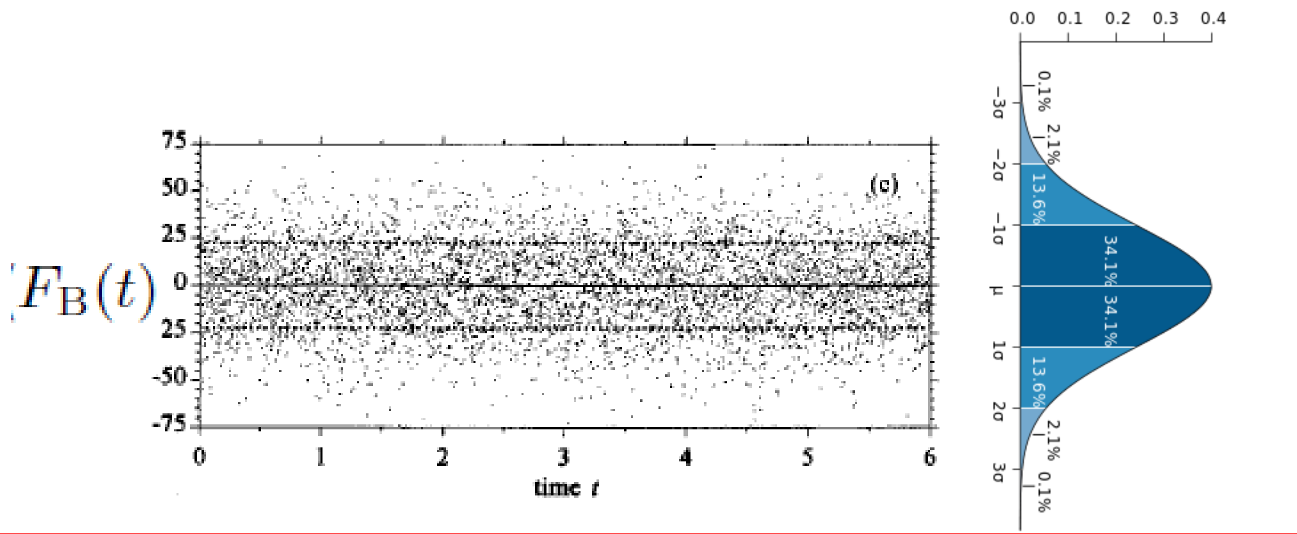
$$\begin{aligned} \langle F_{\mathrm{B}}(t) \rangle &= 0 \\ \langle F_{\mathrm{B}}(t) F_{\mathrm{B}}(t+\tau) \rangle &= 2D\delta(\tau) \end{aligned}$$

~ variance

M. C. Wang and G. E. Uhlenbeck, Rev. Mod. Phys. **17, 323** (1945)

$F_{\rm B}(t)$: Gaussian white noise

Distribution = Gaussian



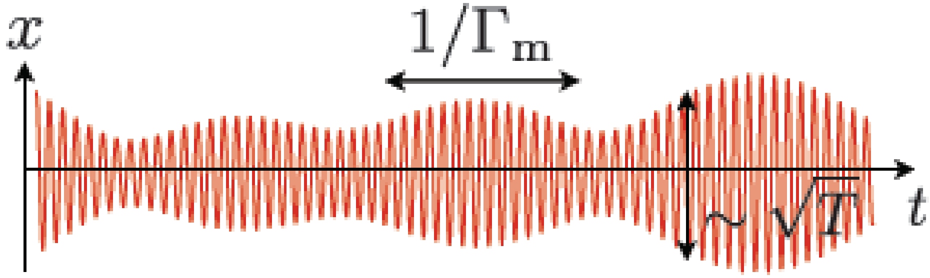
Power spectrum = White

$$
\begin{aligned}
S_F(f) &= 4\int_0^\infty \underbrace{\langle F_{\rm B}(t)F_{\rm B}(t+\tau)\rangle}_{2D\delta(\tau)} \cos(2\pi f\tau)d\tau \\
&= 4D
\end{aligned}
$$

Wiener-Khinchin Theorem

D. T. Gillespie, Am. J. Phys. **64,** 255 (1996)

Damped Harmonic Oscillator



Gaussian white noise

Langevin equation

$$\ddot{x} + \Gamma_m \dot{x} + \Omega_m^2 x = \frac{F_\mathrm{B}(t)}{m}$$

Solution

$x(t)$: Stochastic process (Ornstein-Uhlenbeck process)

M. C. Wang and G. E. Uhlenbeck, Rev. Mod. Phys. **17, 323** (1945)

From force noise to displacement noise

Langevin equation

Gaussian white noise

$$\ddot{x} + \Gamma_m \dot{x} + \Omega_m^2 x = \frac{F_{\mathrm{B}}(t)}{m}$$

Formally Fourier-transforming

$$\tilde{x}(f) = \frac{1/m}{\Omega_m^2 - (2\pi f)^2 + 2\pi i f \Gamma_m} \tilde{F}_{\mathrm{B}}(f)$$

Squaring

Power spectrum of displacement

$$\begin{aligned} S_x(f) &= \left| \frac{1/m}{\Omega_m^2 - (2\pi f)^2 + 2\pi i \Gamma_m f} \right|^2 S_F(f) \\ &= \frac{4D/m^2}{(\Omega_m^2 - (2\pi f)^2)^2 + (2\pi f)^2 \Gamma_m^2} \end{aligned}$$

$x(t)$: Ornstein-Uhlenbeck process

Auto-correlation of displacement

Power spectrum of displacement

$$\langle x(t)x(t+\tau)\rangle = \int_0^\infty S_x(f)\cos(2\pi f\tau)df$$

(Wiener-Khinchin Theorem)

$$= \int_0^\infty \frac{4D/m^2}{(\Omega_m^2-(2\pi f)^2)^2+(2\pi f)^2\Gamma_m^2}\cos(2\pi f\tau)df$$

$$= \frac{D}{m\Gamma_m}\frac{1}{m\Omega_m^2}e^{-\frac{\Gamma_m}{2}\tau}\left(\cos(\Omega_1\tau)+\frac{\Gamma_m}{2\Omega_1}\sin(\Omega_1\tau)\right)$$

(where $\Omega_1 = \sqrt{\Omega_m^2 - \frac{\Gamma_m^2}{4}}$)

M. C. Wang and G. E. Uhlenbeck, Rev. Mod. Phys. **17, 323** (1945)

Auto-correlation of displacement

$$\langle x(t)x(t+\tau)\rangle = \frac{D}{m\Gamma_m}\frac{1}{m\Omega_m^2}e^{-\frac{\Gamma_m}{2}\tau}\left(\cos(\Omega_1\tau)+\frac{\Gamma_m}{2\Omega_1}\sin(\Omega_1\tau)\right)$$

$$\tau \rightarrow 0$$

$$\langle x(t)^2\rangle = \int_0^\infty S_x(f)df = \frac{D}{m\Gamma_m}\frac{1}{m\Omega_m^2} = \frac{D}{m\Gamma_m}\frac{1}{k}$$

Spring constant

Equipartition theorem

$$\frac{1}{2}k\langle x(t)^2\rangle = \frac{1}{2}k_B T$$

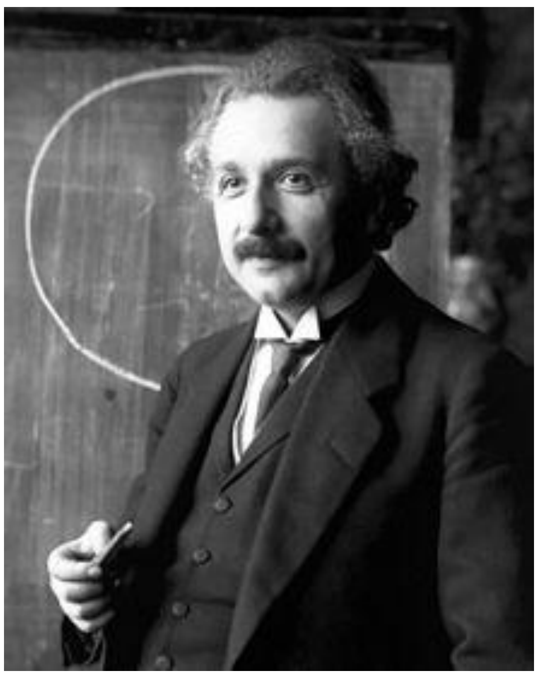
$$\Rightarrow D = k_B T(m\Gamma_m)$$

Contents

Dissipation-fluctuation theorem

$$D = k_{\mathrm{B}} T (m \Gamma_m)$$

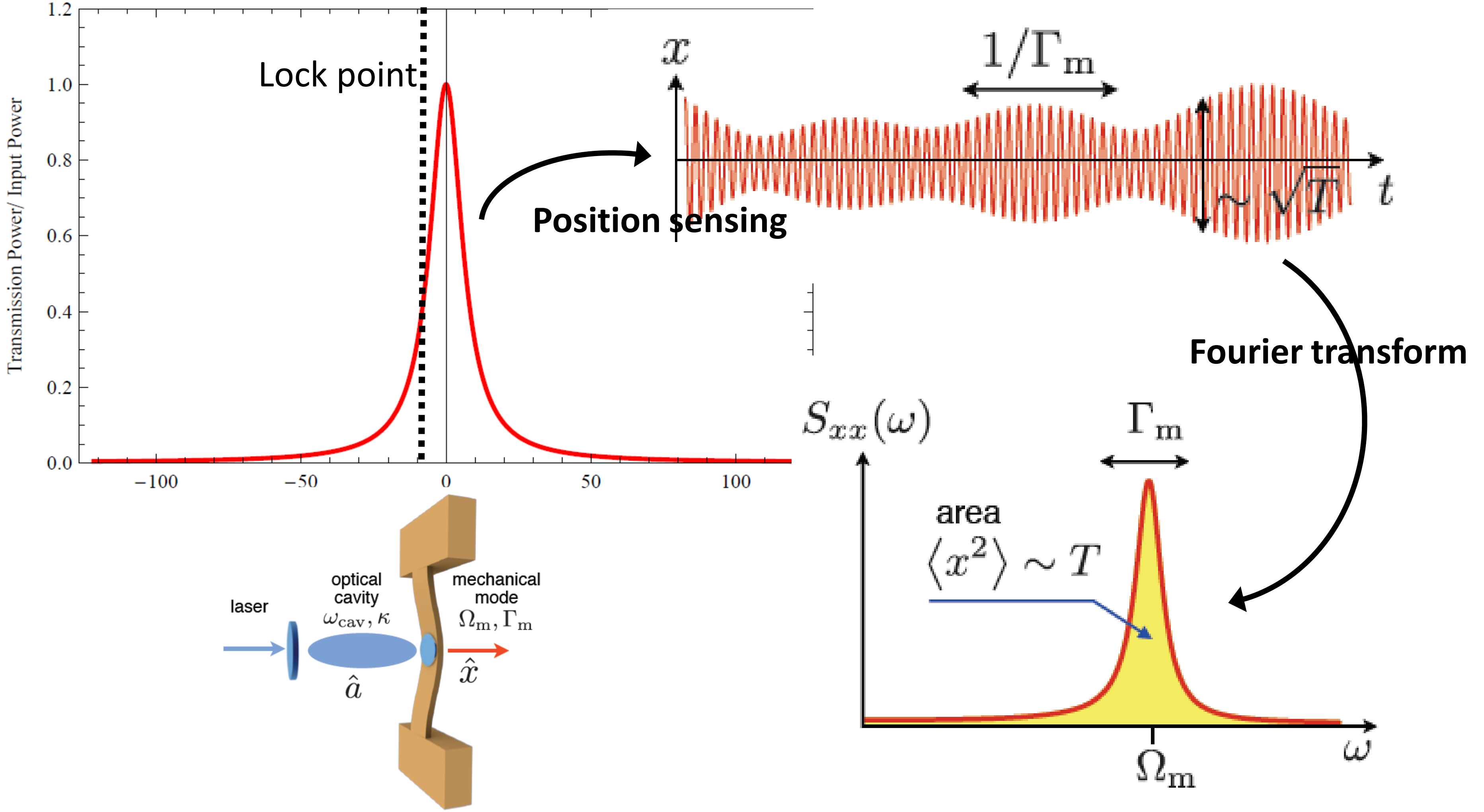
- Albert Einstein



$$\ddot{x} + \Gamma_m \dot{x} + \Omega_m^2 x = \frac{F_{\mathrm{B}}(t)}{m}$$

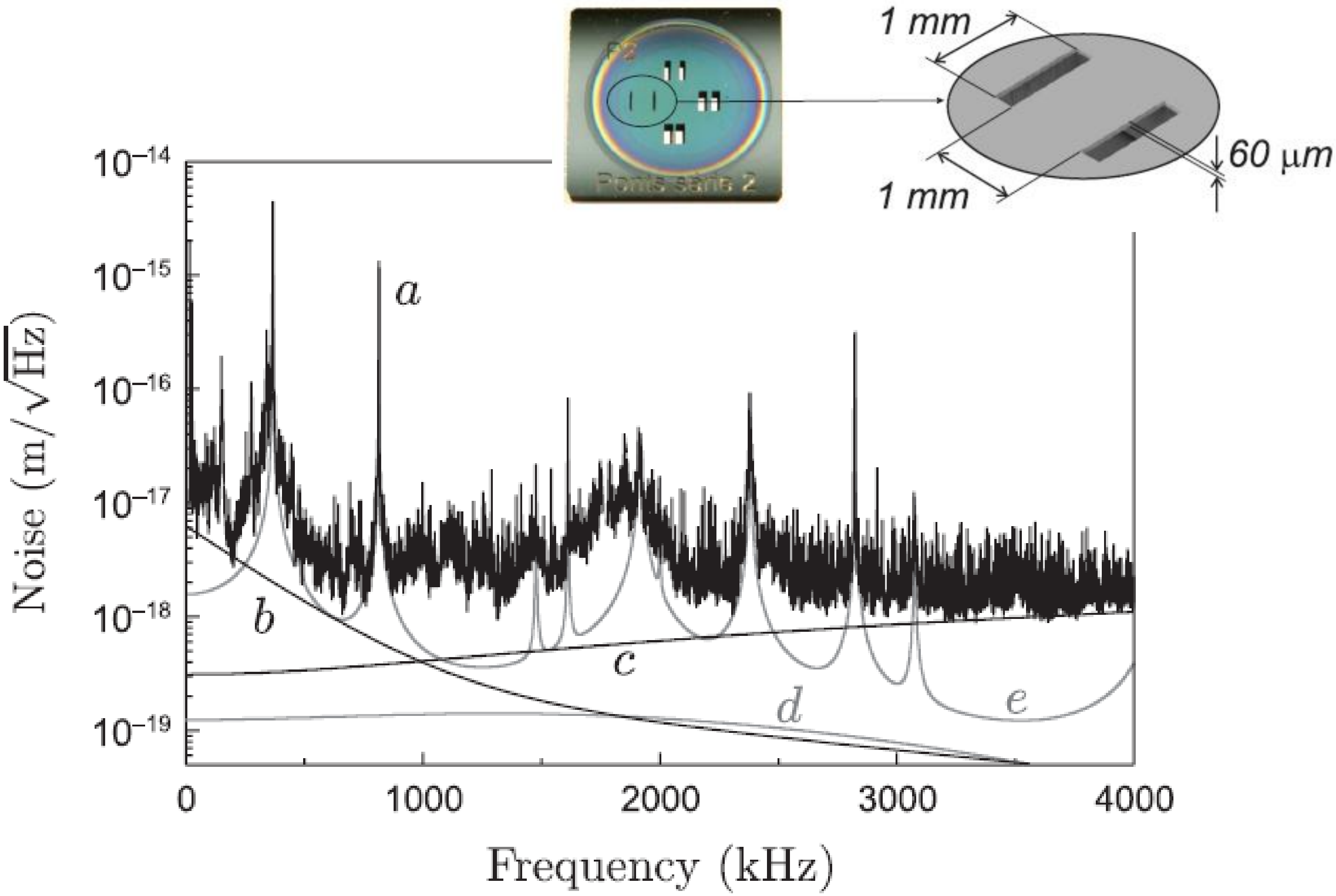
$$\begin{aligned} \langle F_{\mathrm{B}}(t) \rangle &= 0 \\ \langle F_{\mathrm{B}}(t) F_{\mathrm{B}}(t+\tau) \rangle &= 2D\delta(\tau) \end{aligned}$$

Cavity opto-mechanics



M. Aspelmeyer, T. J. Kippenberg, and F. Marquardt, arXiv:1303.0733v1

Real power spectrum of displacement @ 300K



O. Arcizet et al., Phys. Rev. Lett., **97,** 133601 (2006)

Thermal motion estimates

Equilibrium thermally-driven displacement: $\sqrt{\langle x(t)^2 \rangle} = \sqrt{\frac{k_B T}{m \Omega_m^2}}$ [m]

- dimension: $1[\mathrm{mm}] \times 1[\mathrm{mm}] \times 50[\mathrm{nm}]$
- motional mass: $m = 34$ [ng]
- resonance frequency: $\Omega_m / 2\pi = 1.0$ [MHz]

J. D. Thompson et al., Nature, **452,** 72 (2008)

Temperature	displacement $\sqrt{\langle x(t)^2 \rangle}$
300 K	1.8×10^{-12} m
77 K	8.9×10^{-13} m
4 K	2.0×10^{-13} m
300 mK	5.6×10^{-14} m
3 mK	5.6×10^{-15} m
0 K	**5.0×10^{-16} m** (zero point fluctuation)

Cf) Proton radius : 8.8×10^{-16} m

Shot-noise-limited sensitivity estimates

Displacement sensitivity
(with Pound-Drever-Hall method)

$$S_L = \frac{\lambda}{8\mathcal{F}\sqrt{n}} = \frac{\sqrt{hc\lambda}}{8\mathcal{F}\sqrt{P_c}}$$ [m Hz$^{-1/2}$]

$$S_L = \left(8.1\times 10^{-21}\frac{m}{\sqrt{\mathrm{Hz}}}\right)\frac{10^4}{\mathcal{F}}\sqrt{\frac{\lambda}{1064\ \mathrm{nm}}\frac{500\ \mathrm{mW}}{P_c}}.$$

Eric D. Black, Am. J. Phys., **69,** 79 (2001)

Power	1s-measurement sensitivity
500 mW	8.1×10^{-21} m
5 mW	8.1×10^{-20} m
0.05mW	8.1×10^{-19} m

Measuring  **'s zero point fluctuation (5.0×10^{-16} m) is feasible!**

Is it?

State-of-the-art
dilution refrigerator
(down to ~**a few mK**)

Temperature	displacement $\sqrt{\langle x(t)^2 \rangle}$
300 K	1.8×10^{-12} m
77 K	8.9×10^{-13} m
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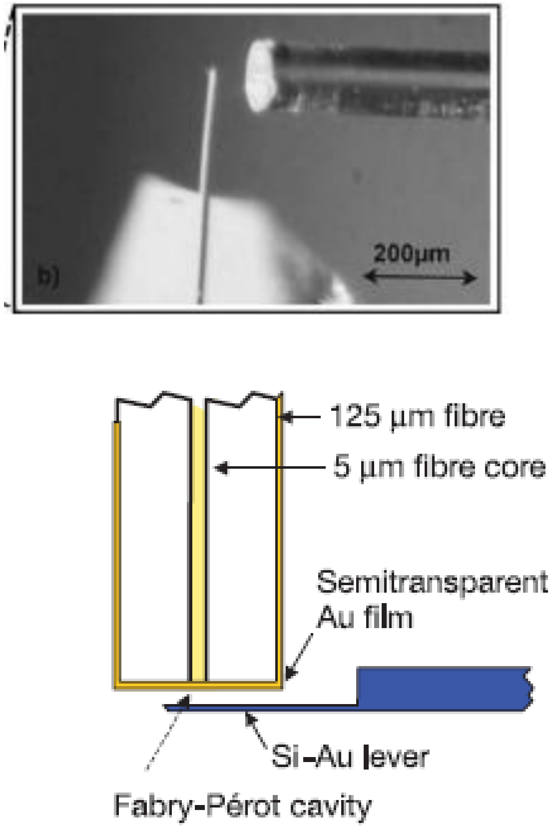
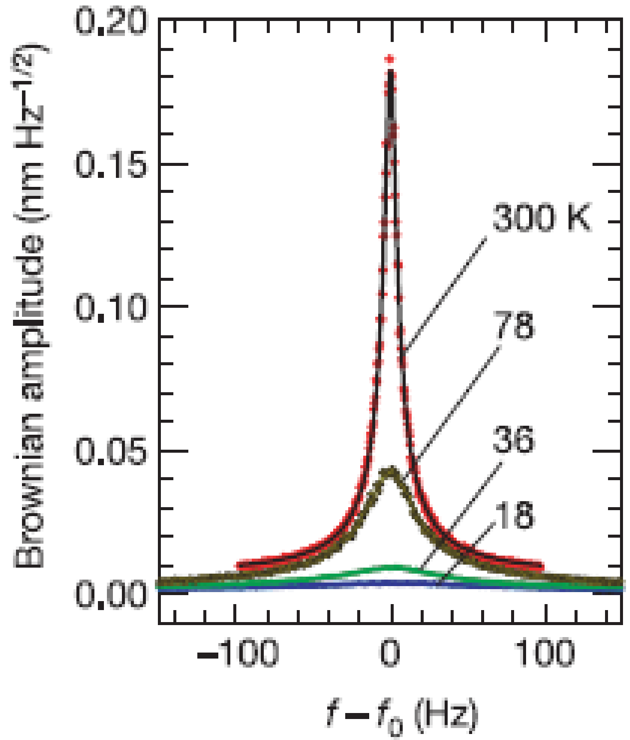
First <u>dynamical back-action cooling</u> experiment with photo-thermal effect (2004)





C. Metzger and K. Karrai, Nature, **432,** 1002 (2004)

First dynamical back-action cooling experiments with radiation pressue (2006)

A cooling light breeze

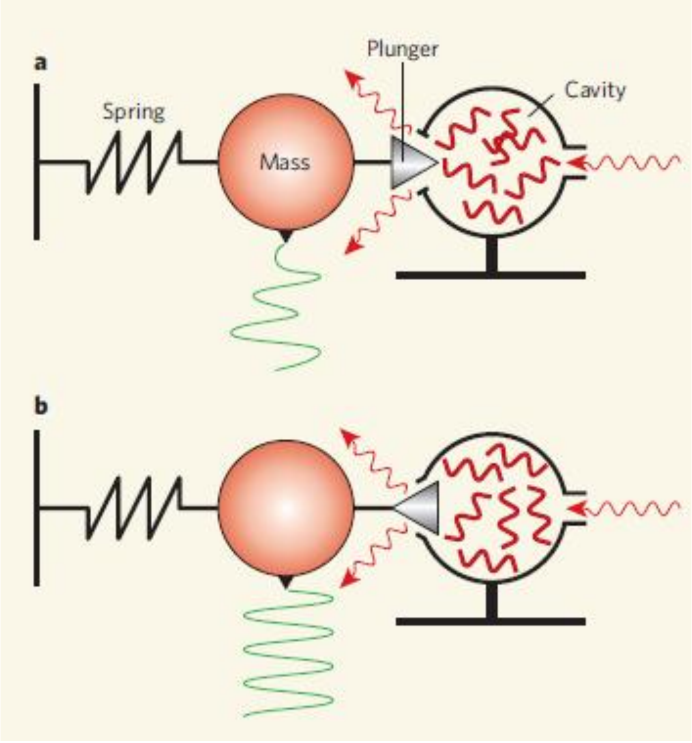
Khaled Karrai

Mirrors confine light, and light exerts pressure on mirrors. The combination of these effects can be exploited to cool tiny, flexible mirrors to low temperatures purely through the influence of incident light.

NEWS & VIEWS

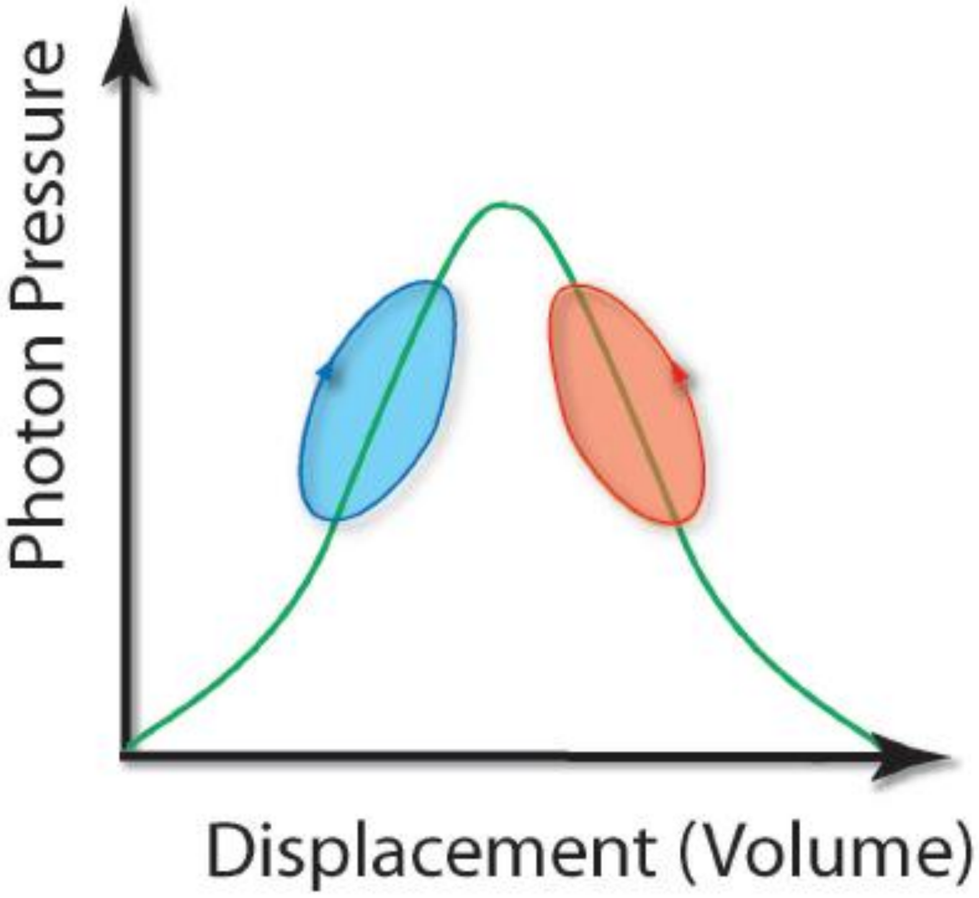
For

- S. Gigan et al., Nature, **444,** 67 (2006)
- O. Arcizet et al., Nature, **444,** 71 (2006)



K. Karrai, Nature, **444,** 41 (2006)

Photon gas performs work on mechanics (heating)
Mechanics performs work on photon gas (cooling)



T. J. Kippenberg and K. J. Vahala, Opt. Express, **15,** 17172 (2007)

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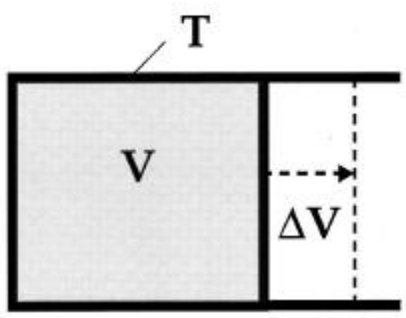
Cavity cooling = Carnot cycle of photon gas?



R. E. Kelly, Am. J. Phys., **49,** 714 (1981)
M. Howard Lee, Am. J. Phys., **69,** 874 (2001)
H. S. Leff, Am. J. Phys., **70,** 792 (2002)

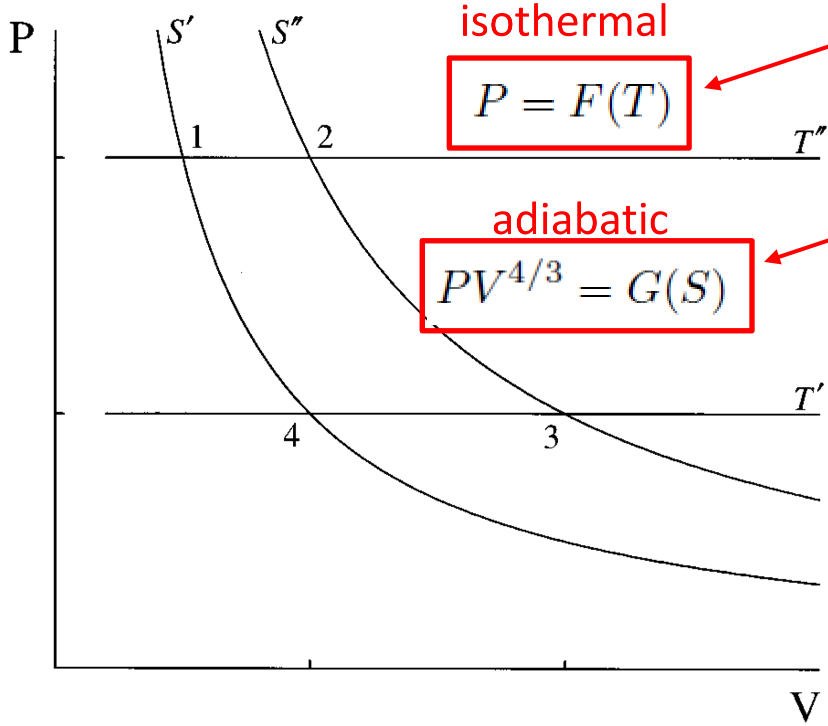
Classical ideal gas	Photon gas
N is specified and fixed	$N = rVT^3$
$U = \frac{3}{2}NkT$	$U = bVT^4 = 2.7NkT$
$P = NkT/V$	$P = \frac{1}{3}bT^4 = 0.9NkT/V$
$S = Nk[\ln(T^{3/2}V/N) + \ln(2\pi mk/h)^{3/2} + \frac{5}{2}]$	$S = \frac{4}{3}bVT^3 = 3.6Nk$

Bose gas with μ=0

$$b = \frac{4\sigma}{c} = \frac{\pi^2 k_B^4}{15\hbar^3 c^3}$$

thermodynamics
relativity
quantum mechanics

Cavity cooling = Carnot cycle of photon gas?



isothermal

$$P = F(T)$$

$$PV = f(T) \quad \text{(Ideal gas)}$$

adiabatic

$$PV^{4/3} = G(S)$$

$$PV^{\gamma} = PV^{5/3} = g(S) \quad \text{(Ideal gas)}$$

efficiency

$$\eta \equiv \frac{Q(12) - Q(34)}{Q(12)} = \frac{T'' - T'}{T''} < 1.$$

Same as ideal gas Carnot cycle!

R. E. Kelly, Am. J. Phys., **49,** 714 (1981)
M. Howard Lee, Am. J. Phys., **69,** 874 (2001)
H. S. Leff, Am. J. Phys., **70,** 792 (2002)

No!

1) Too small

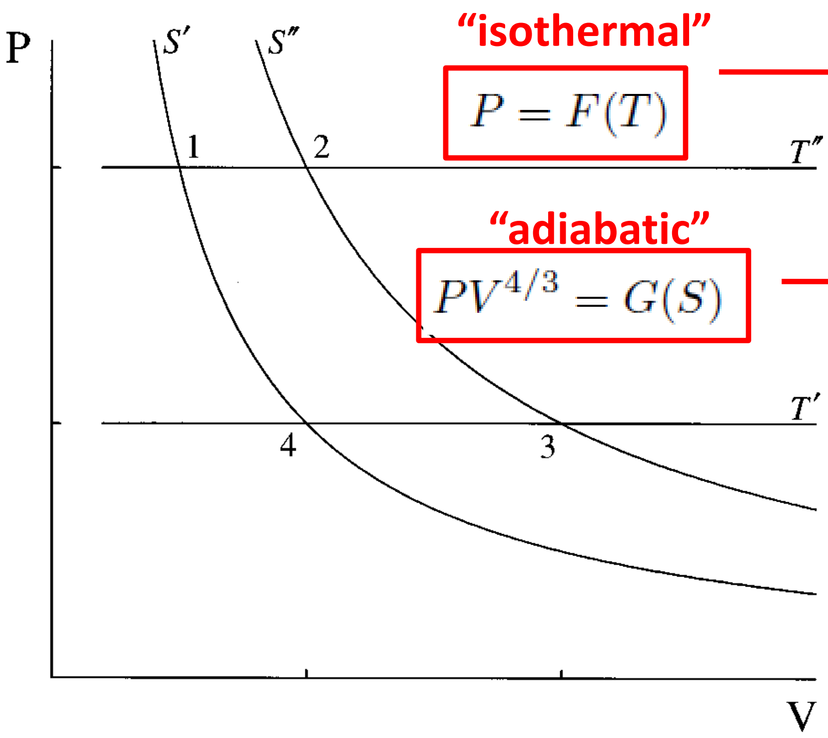
Table III. Numerical comparison of classical ideal and photon gas functions. Here the ideal gas is 1.00 mol of monatomic argon at $P = 1.01 \times 10^5$ Pa, $V = 2.47 \times 10^{-2}$ m^3, and $T = 300$ K.

Function	Classical ideal gas	Photon gas
N	6.02×10^{23} atoms	1.35×10^{13} photons
U	3.74×10^3 J	1.51×10^{-7} J
P	1.01×10^5 Pa	2.04×10^{-6} Pa
S	155 J/K	6.71×10^{-10} J/K

H. S. Leff, Am. J. Phys., **70,** 792 (2002)

No!

2) Not a quasi-static process



Always thermal equilibrium

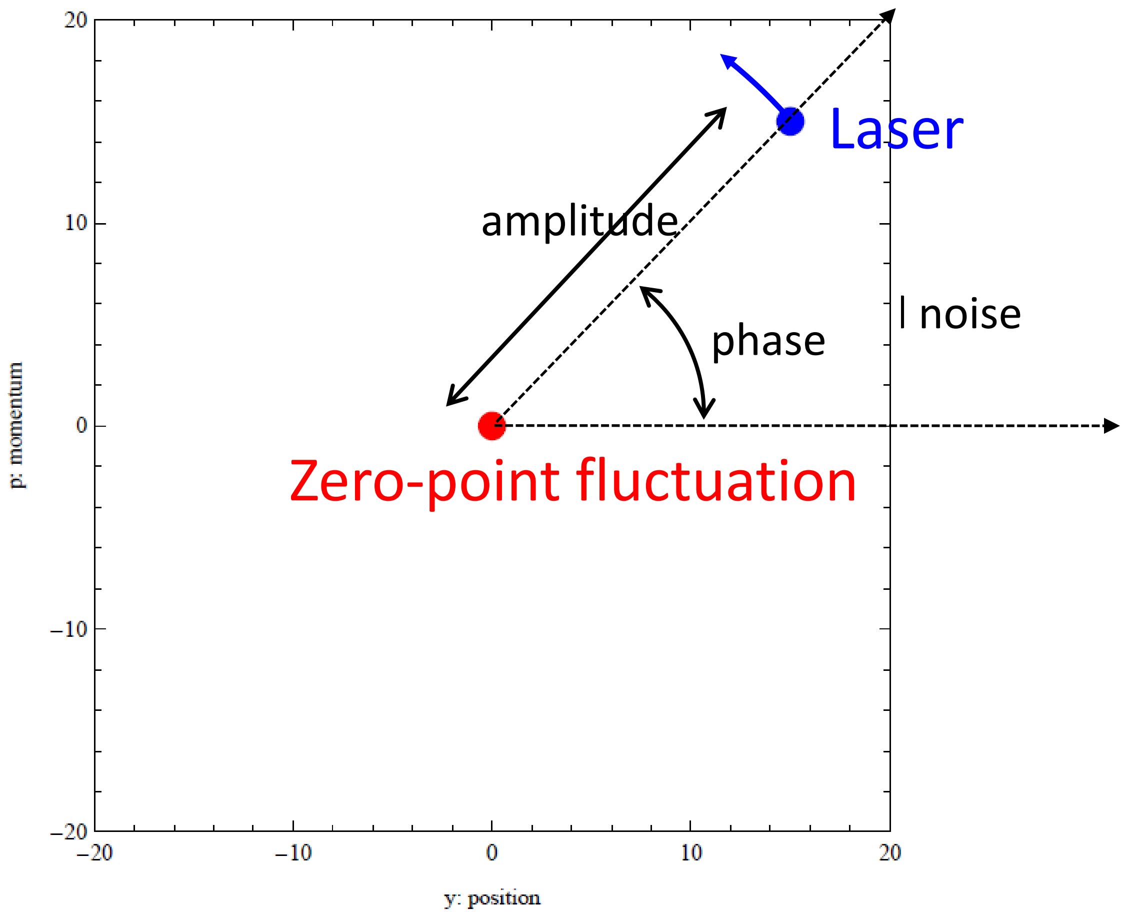
- slow process than thermal relaxation time
- finite response time

Thermally isolated

- dissipation rate: $\Gamma_m \to 0$
- instantaneous response time

No!

3) Not a black-body radiation but laser!



Cavity cooling = Carnot cycle of photon gas? No!

1) Too small

- Compared with classical ideal gas

2) Not a quasi-static process

-**Beyond the equilibrium thermodynamics**

3) Not a black-body radiation but laser!

- **Cavity is driven by coherent radiation**

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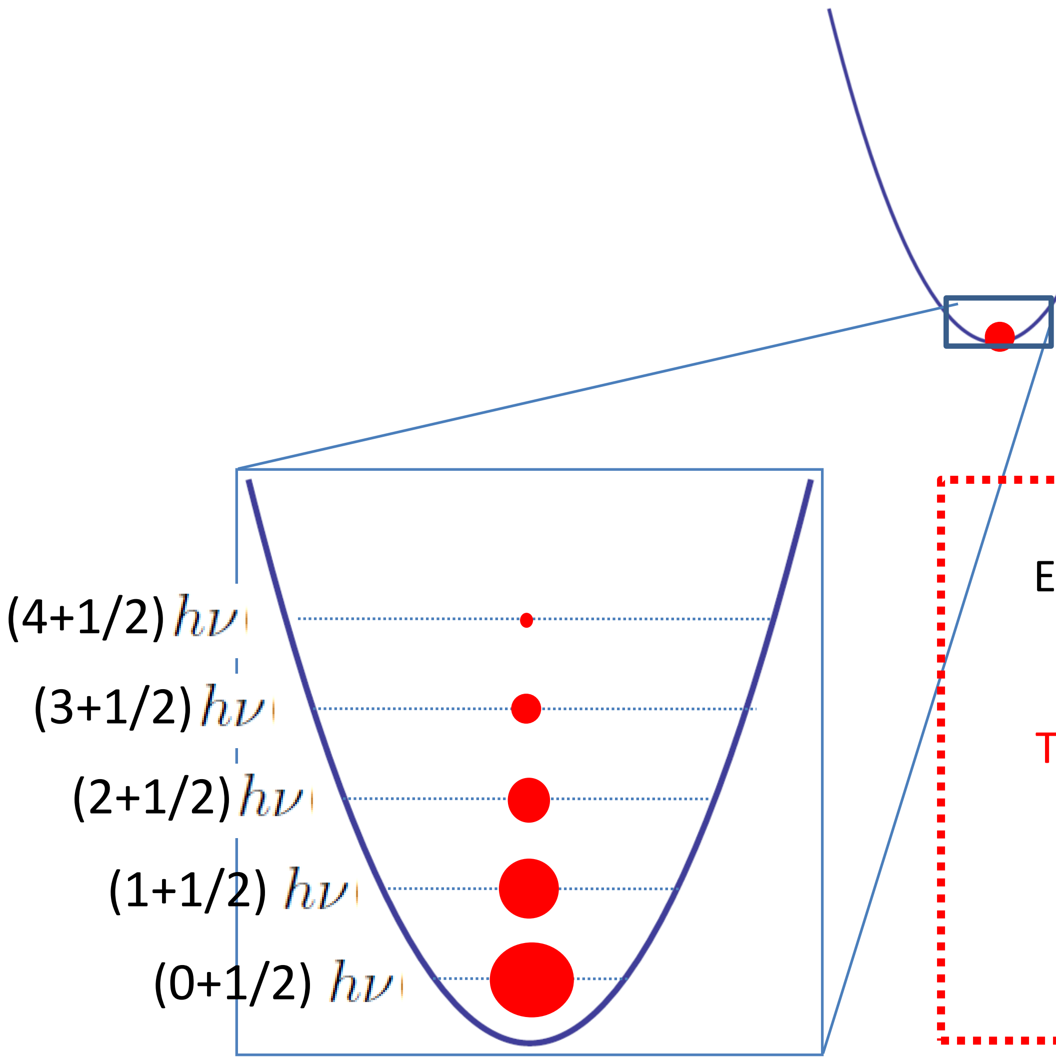
Quantization of a harmonic oscillator



Energy: $k_{\mathrm{B}}T$

Energy: $h\nu(\langle n\rangle + \frac{1}{2})$

h : Planck's constant

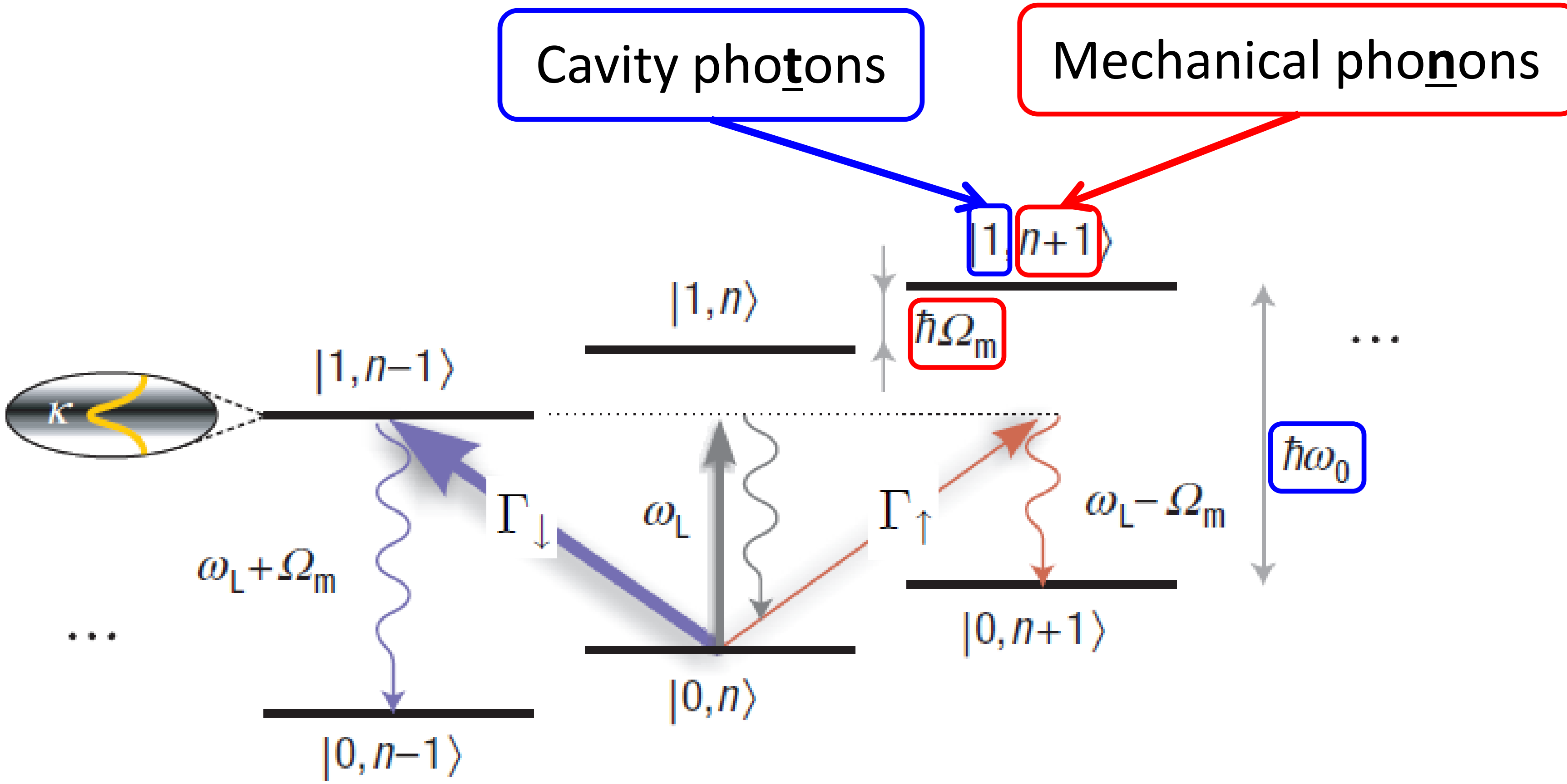
Thermal occupation number

$$\langle n\rangle = \frac{1}{\exp[\frac{h\nu}{k_{\mathrm{B}}T}] - 1}$$

$$\rightarrow \frac{k_{\mathrm{B}}T}{h\nu}$$

Reducing temperature = reducing phonons

Sideband cooling



Phonon absorption rate: $\Gamma_\downarrow$ **Phonon emission rate:** $\Gamma_\uparrow$

A. Schliesser *et al*. Nature Phys. **4**, 415–419 (2008).

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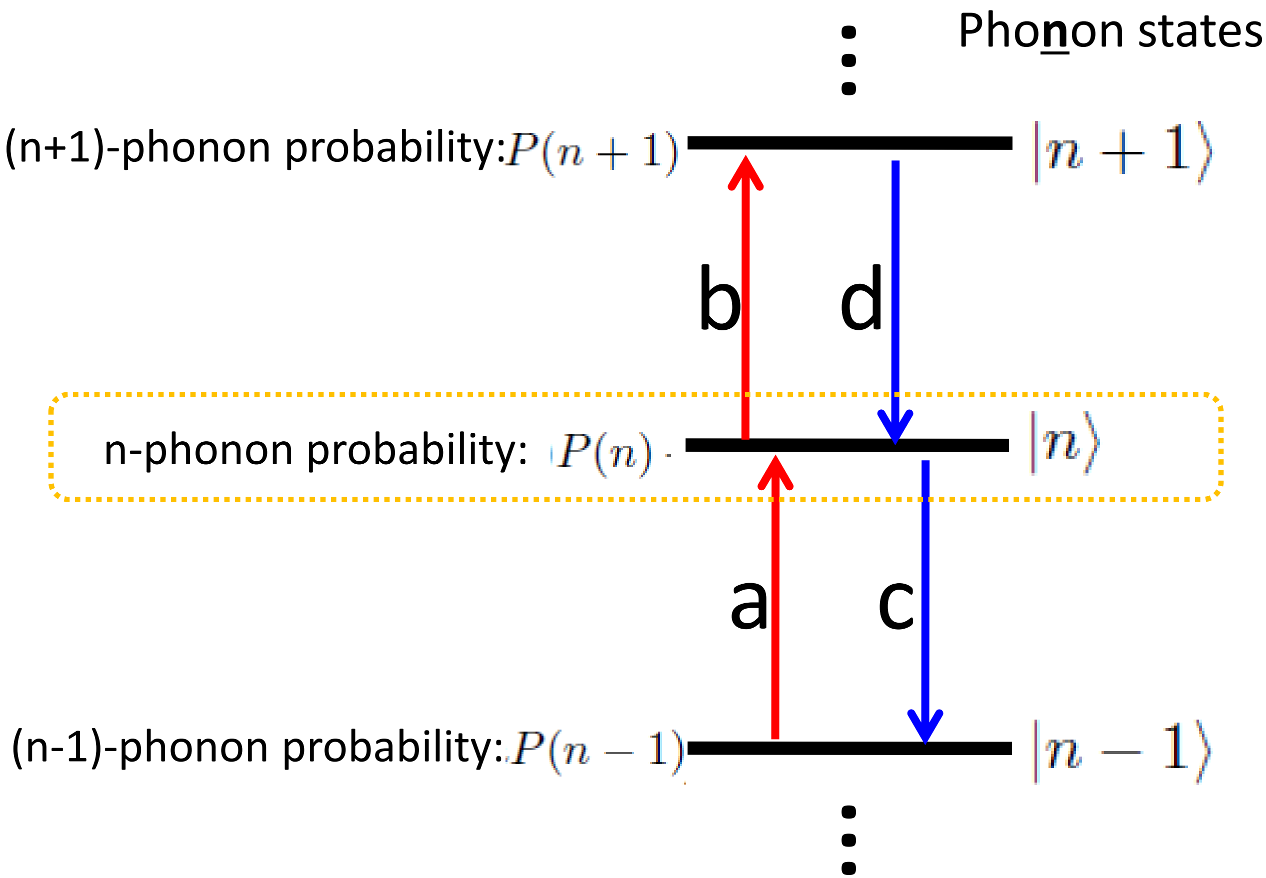
Pho**n**on-occupation probability



Phonon emission rate: $\Gamma_\uparrow$ **Phonon absorption rate:** $\Gamma_\downarrow$

$$\frac{dP(n)}{dt} = \underbrace{\Gamma_\uparrow n P(n-1)}_{a} - \underbrace{\Gamma_\uparrow (n+1) P(n)}_{b} - \underbrace{\Gamma_\downarrow n P(n)}_{c} + \underbrace{\Gamma_\downarrow (n+1) P(n+1)}_{d}$$

Detailed balance

$$\frac{dP(n)}{dt} = \underbrace{\Gamma_\uparrow nP(n-1)}_{a} - \underbrace{\Gamma_\uparrow (n+1)P(n)}_{b} - \underbrace{\Gamma_\downarrow nP(n)}_{c} + \underbrace{\Gamma_\downarrow (n+1)P(n+1)}_{d}$$

Rate equation

$$\begin{aligned} \frac{d\langle n\rangle}{dt} &= \sum_n n\frac{dP(n)}{dt} \\ &= \Gamma_\uparrow \sum_n (n+1)P(n) - \Gamma_\downarrow \sum_n nP(n) \\ &= \Gamma_\uparrow \langle n+1\rangle - \Gamma_\downarrow \langle n\rangle \end{aligned}$$

Steady state :

$$\Gamma_\uparrow \langle n+1\rangle = \Gamma_\downarrow \langle n\rangle$$

Detailed balance

Effective temperature in non-equilibrium environment

Detailed balance :

$$\Gamma_{\uparrow} \langle n+1 \rangle = \Gamma_{\downarrow} \langle n \rangle$$

Final phonon number :

$$\begin{aligned} \langle n_{\mathrm{opt}} \rangle &= \frac{\Gamma_{\uparrow}}{\Gamma_{\downarrow} - \Gamma_{\uparrow}} \\ &= \frac{1}{\exp\left(\frac{\hbar\Omega_m}{k_{\mathrm{B}} T_{\mathrm{eff}}}\right) - 1} \end{aligned}$$

Effective temperature of driven cavity !

Contents

- Optics & mechanics
  - Fabry-Perot cavity
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  - Dissipation-fluctuation theorem
- Opto-mechanics
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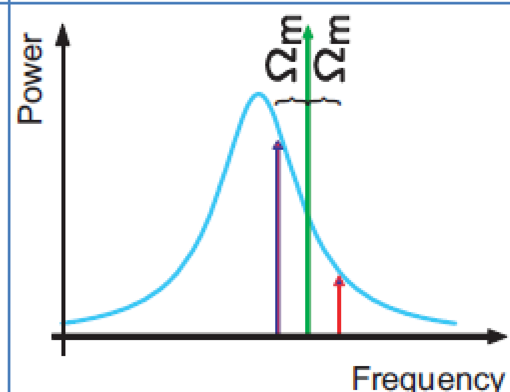
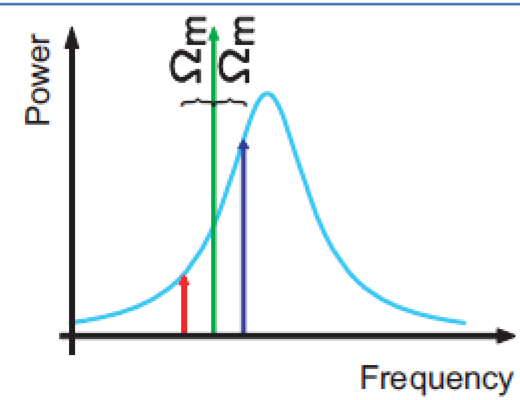
  - Sideband cooling
  - Detailed balance
  - Cold damping (cavity cooling)

Cavity cooling/heating

Final phonon number :

$$\langle n_{\mathrm{opt}} \rangle = \frac{\Gamma_{\uparrow}}{\Gamma_{\downarrow} - \Gamma_{\uparrow}} = \frac{1}{\exp\left(\frac{\hbar\Omega_m}{k_B T_{\mathrm{eff}}}\right) - 1}$$

	Heating	**Cooling**
	$\Gamma_{\downarrow} < \Gamma_{\uparrow}$	$\Gamma_{\downarrow} > \Gamma_{\uparrow}$
Detuning		
Effective temp.	$T_{\mathrm{eff}} < 0$	$T_{\mathrm{eff}} > 0$

Cold damping

Cold damping:

Rate equation

$$\frac{d\langle n\rangle}{dt} = \Gamma_\uparrow \langle n+1\rangle - \Gamma_\downarrow \langle n\rangle$$
$$= -(\Gamma_\downarrow - \Gamma_\uparrow)\langle n\rangle + \Gamma_\uparrow$$
$$= -\Gamma_{\mathrm{opt}}\langle n\rangle + \Gamma_{\mathrm{opt}}\langle n_{\mathrm{opt}}\rangle$$

$$\langle n_{\mathrm{opt}}\rangle = \frac{\Gamma_\uparrow}{\Gamma_{\mathrm{opt}}} = \frac{1}{\exp\left(\frac{\hbar\Omega_m}{k_B T_{\mathrm{eff}}}\right) - 1}$$

Detailed balance

Cold damping

Intrinsic damping:

Rate equation

$$\frac{d\langle n\rangle}{dt} = -\Gamma_m \langle n\rangle + \Gamma_m \langle n_{\rm th}\rangle$$

$$\langle n_{\rm th}\rangle = \frac{1}{\exp\left(\frac{\hbar\Omega_m}{k_B T}\right) - 1}$$

Thermal equilibrium

Cold damping:

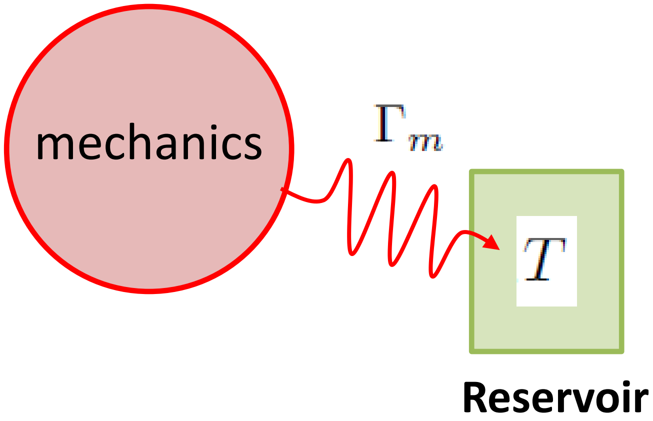
Rate equation

$$\begin{aligned}\frac{d\langle n\rangle}{dt} &= \Gamma_\uparrow \langle n+1\rangle - \Gamma_\downarrow \langle n\rangle \\ &= -(\Gamma_\downarrow - \Gamma_\uparrow)\langle n\rangle + \Gamma_\uparrow \\ &= -\Gamma_{\rm opt}\langle n\rangle + \Gamma_{\rm opt}\langle n_{\rm opt}\rangle\end{aligned}$$

$$\langle n_{\rm opt}\rangle = \frac{\Gamma_\uparrow}{\Gamma_{\rm opt}} = \frac{1}{\exp\left(\frac{\hbar\Omega_m}{k_B T_{\rm eff}}\right) - 1}$$

Detailed balance

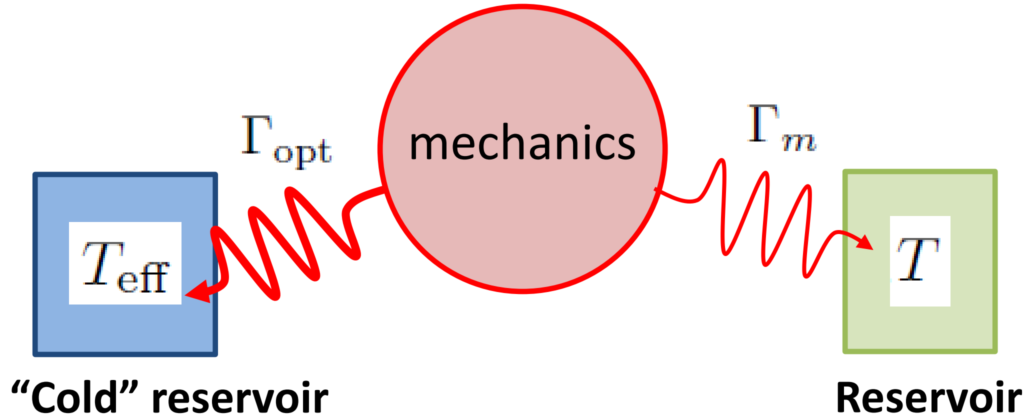
Intrinsic damping



Langevin equation

$$\ddot{x} + \Gamma_m \dot{x} + \Omega_m^2 x = \frac{F_{\mathrm{B}}(t)}{m}$$

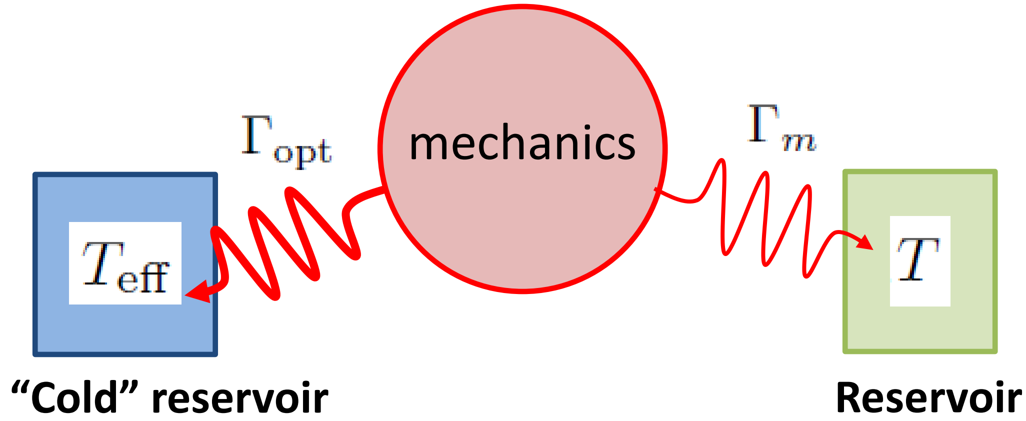
(Intrinsic + cold) damping



Langevin equation

$$\ddot{x} + \Gamma_m \dot{x} + \Omega_m^2 x = \frac{F_{\rm B}(t)}{m}$$

(Intrinsic + cold) damping



Langevin equation

$$\ddot{x} + \Gamma_m \dot{x} + \Omega_m^2 x = \frac{F_B(t)}{m}$$

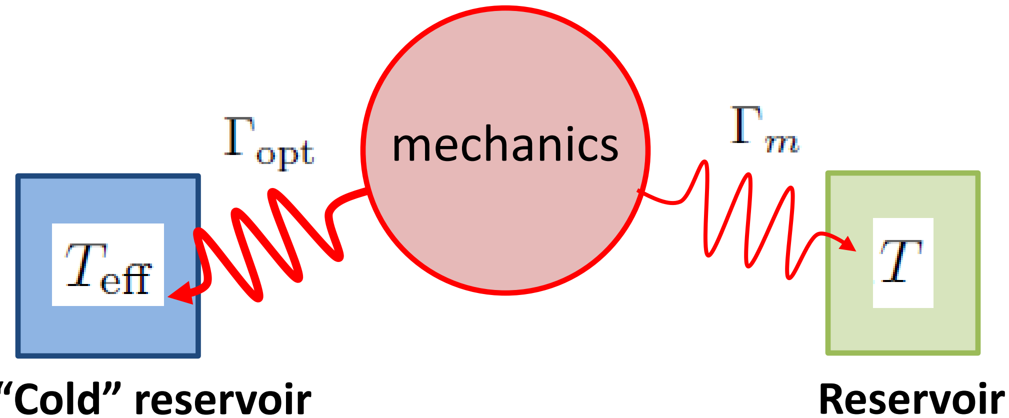
$$\ddot{x} + (\Gamma_m + \Gamma_{opt})\dot{x} + \Omega_m^2 (1 + \delta_{opt}) x = \frac{F_B(t)}{m} + \frac{F_{opt}(t)}{m}$$

Dissipation-fluctuation theorem: $F_B \sim \sqrt{2m\Gamma_m k_B T}$ $F_{opt} \sim \sqrt{2m\Gamma_{opt} k_B T_{eff}}$

Final phonon number

Rate equation

$$\frac{d\langle n\rangle}{dt} = -(\Gamma_m + \Gamma_{opt})\langle n\rangle + \Gamma_m\langle n_{th}\rangle + \Gamma_{opt}\langle n_{opt}\rangle$$

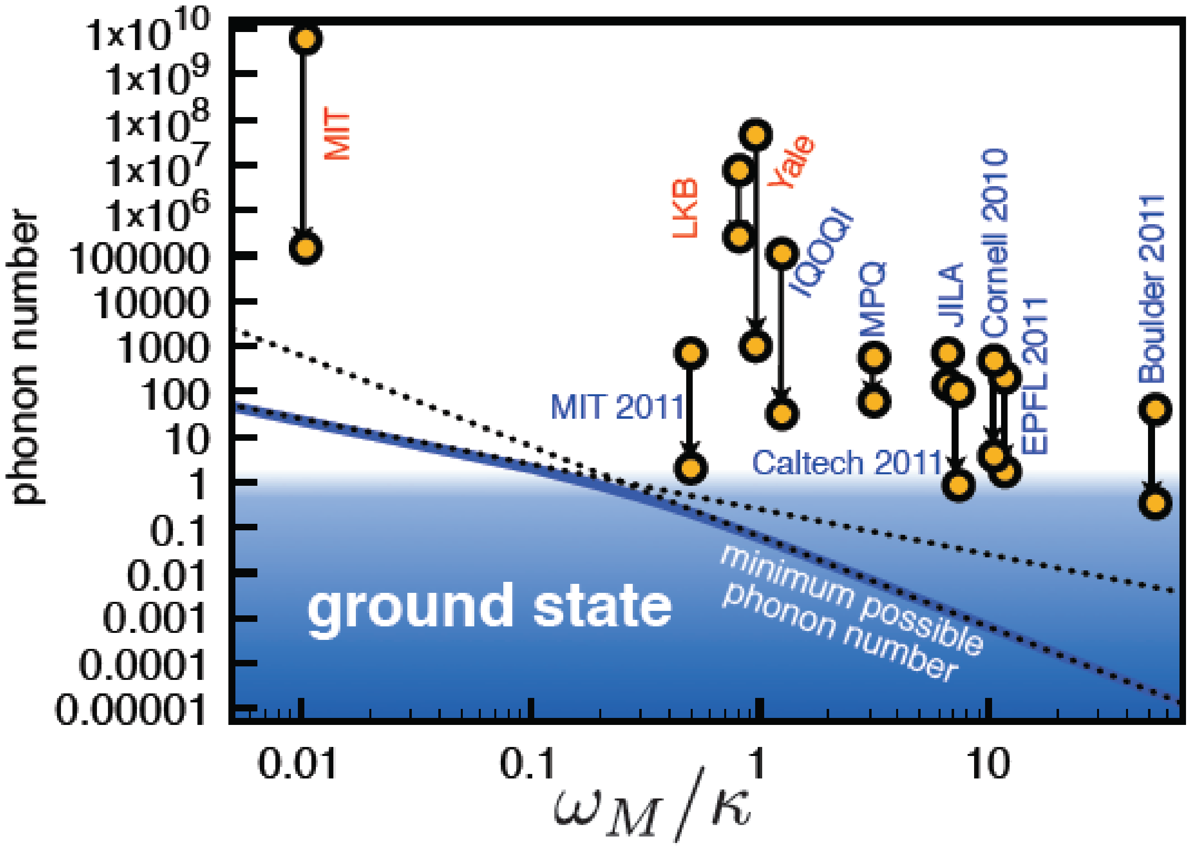


Final phonon number :

$$\langle n_{fin}\rangle = \frac{\Gamma_m\langle n_{th}\rangle + \Gamma_{opt}\langle n_{opt}\rangle}{\Gamma_m + \Gamma_{opt}} \sim \frac{\Gamma_m\langle n_{th}\rangle}{\Gamma_{opt}}$$

I. Wilson-Rae *et al.*, Phys. Rev. Lett., **99**, 093901 (2007).
F. Marquardt *et al.*, Phys. Rev. Lett., **99**, 093902 (2007).

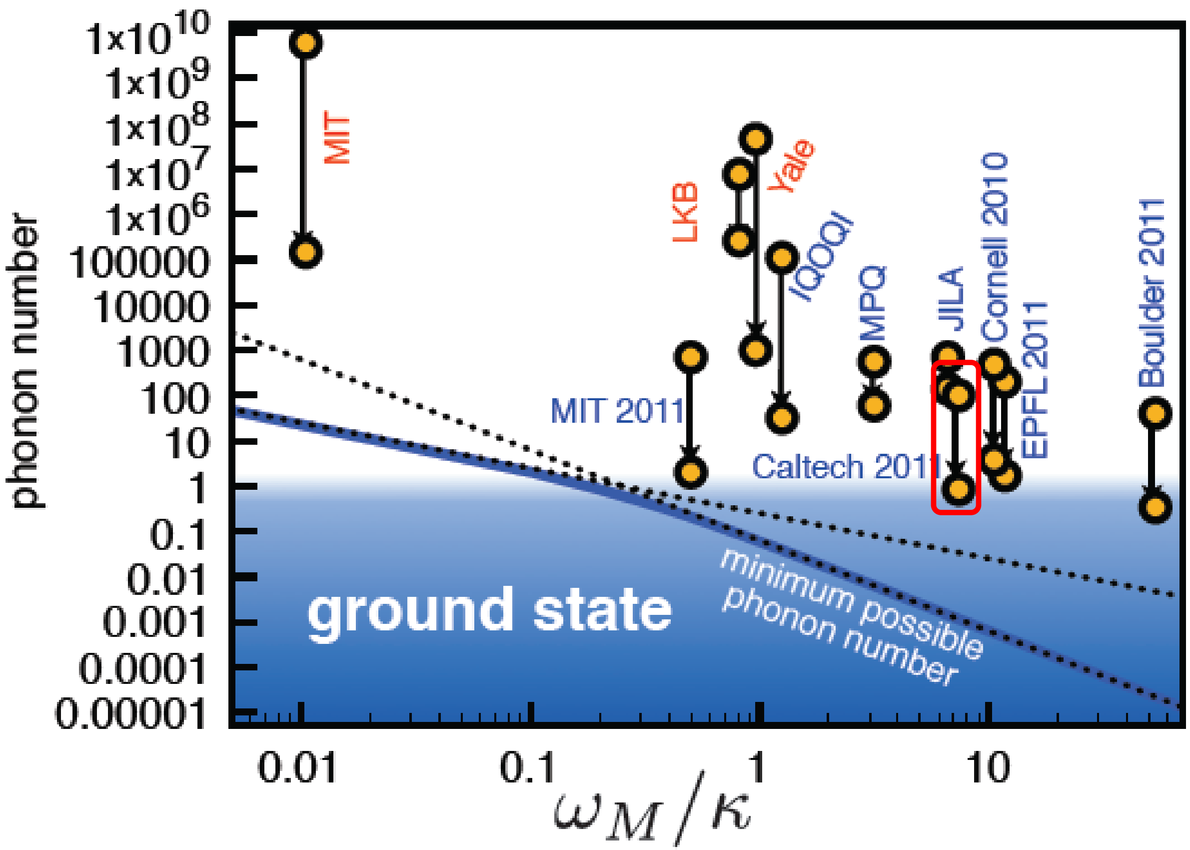
Final phonon number



is plotted as well. MIT: (Corbitt *et al.*, 2007a), LKB: (Arcizet *et al.*, 2006a), Yale: (Thompson *et al.*, 2008), Vienna: (Gröblacher *et al.*, 2009b), MPQ: (Schliesser *et al.*, 2009), JILA: (Teufel *et al.*, 2008), Cornell 2010: (Rocheleau *et al.*, 2010), Caltech 2011: (Chan *et al.*, 2011), EPFL 2011: (Riviere *et al.*, 2011), Boulder 2011: (Teufel *et al.*, 2011a), MIT 2011: (Schleier-Smith *et al.*, 2011)

M. Aspelmeyer, T. J. Kippenberg, and F. Marquardt, arXiv:1303.0733v1

Final phonon number



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M. Aspelmeyer, T. J. Kippenberg, and F. Marquardt, arXiv:1303.0733v1

Nature **478,** 89 (2011).

LETTER

doi:10.1038/nature10461

Laser cooling of a nanomechanical oscillator into its quantum ground state

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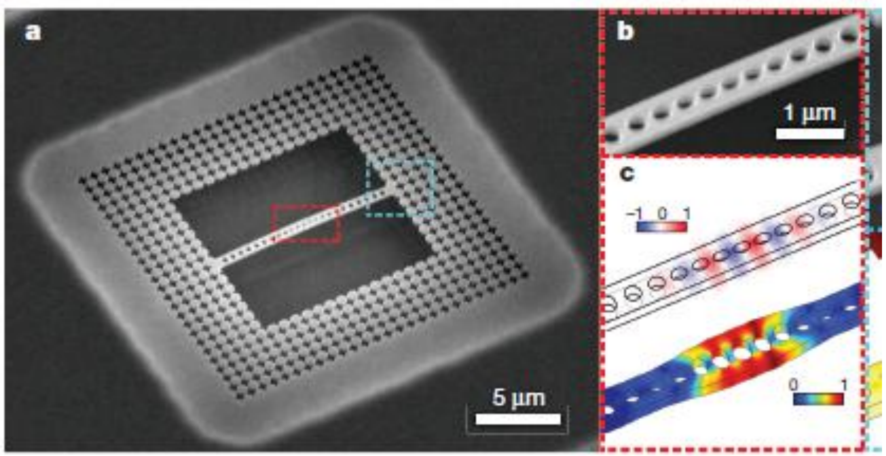

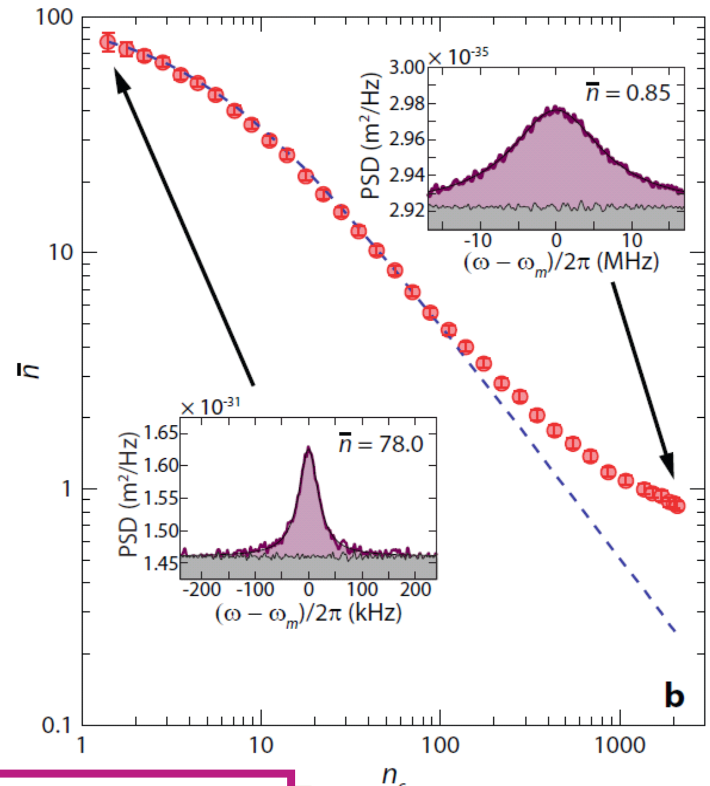

- photonic & phononic bandgap structure
- **3.5 GHz mechanical mode** at 20 K (<n> ~ 100)
- m ~ O(pg), N ~ O(10^{10} atoms)

<n> ~ 0.85 (200mK)

Summary

- Optics & mechanics
  - Fabry-Perot cavity
  - Ornstein-Uhlenbeck process
  - **Dissipation-fluctuation theorem**
- Opto-mechanics
  - Carnot cycle for black-body radiation
  - Sideband cooling
  - **Detailed balance**
  - **Cold damping (cavity cooling)**

Summary

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  - **Cold damping (cavity cooling)**

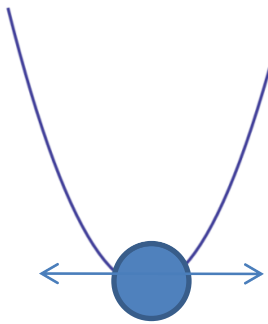
Theme:

What makes **laser (cavity) cooling** conceptually different from conventional **cryogenics**?

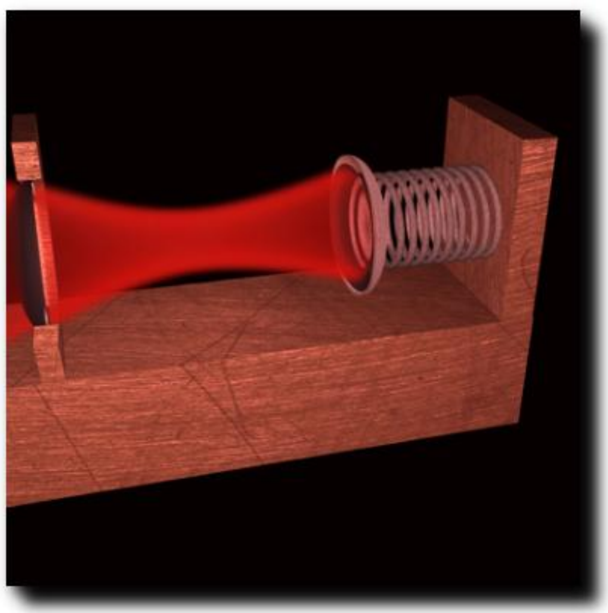
Open questions (for me)

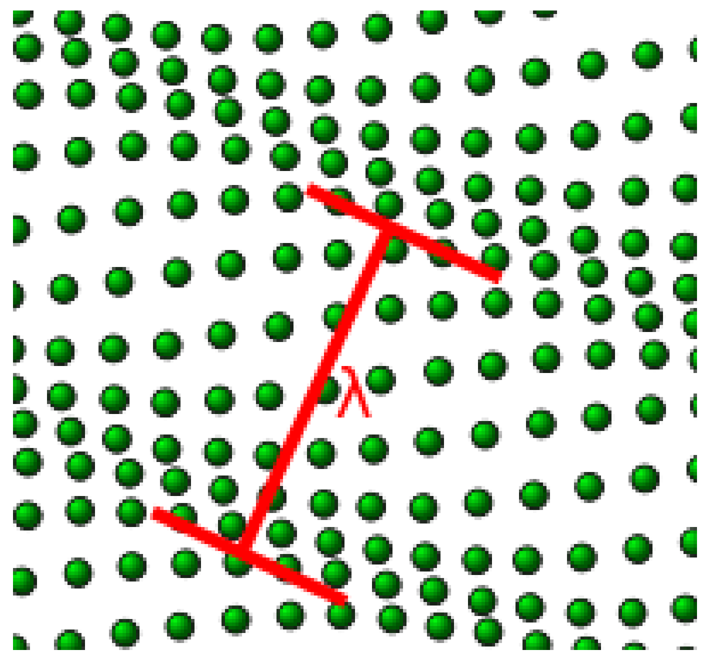
- Can we laser-cool solid?
  - Can the laser cooling be a real cryogenics technique?

Laser cooling addressing only a 1D harmonic oscillator…



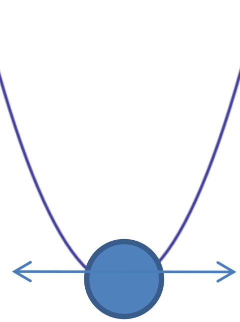
Heat capacity: $$C = \frac{\partial E}{\partial T} = k_{\mathrm{B}}$$

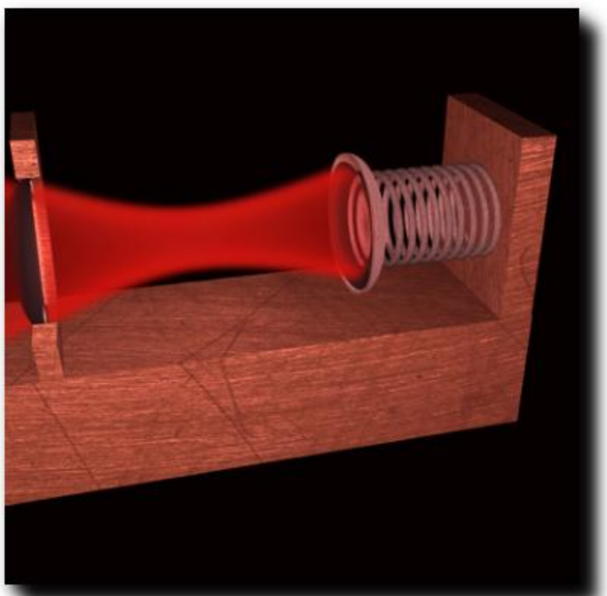




http://en.wikipedia.org/wiki/Phonon

Laser cooling addressing only a 1D harmonic oscillator…





Heat capacity: $C = \frac{\partial E}{\partial T} = k_{\mathrm{B}}$

Heat capacity: $C = \frac{\partial E}{\partial T} = 3N k_{\mathrm{B}}$

Number of atoms >> 1

Not real cryogenics…

Open questions (for me)

- Can we laser-cool solid?
  - Can the laser cooling be a real cryogenics technique?
- Can we induce phase transition of solid state system by laser cooling?
  - Like BEC in atomic physics