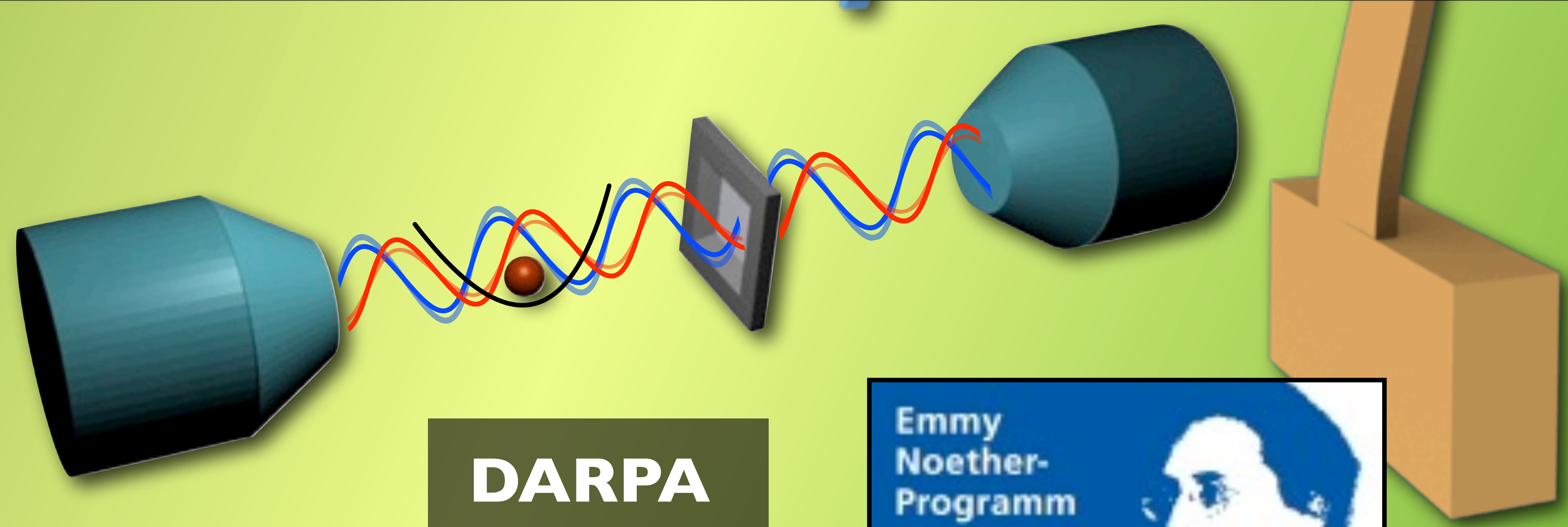
Cavity optomechanics: – interactions between light and nanomechanical motion

Florian Marquardt

University of Erlangen-Nuremberg, Germany, and Max-Planck Institute for the Physics of Light (Erlangen)



DARPA ORCHID

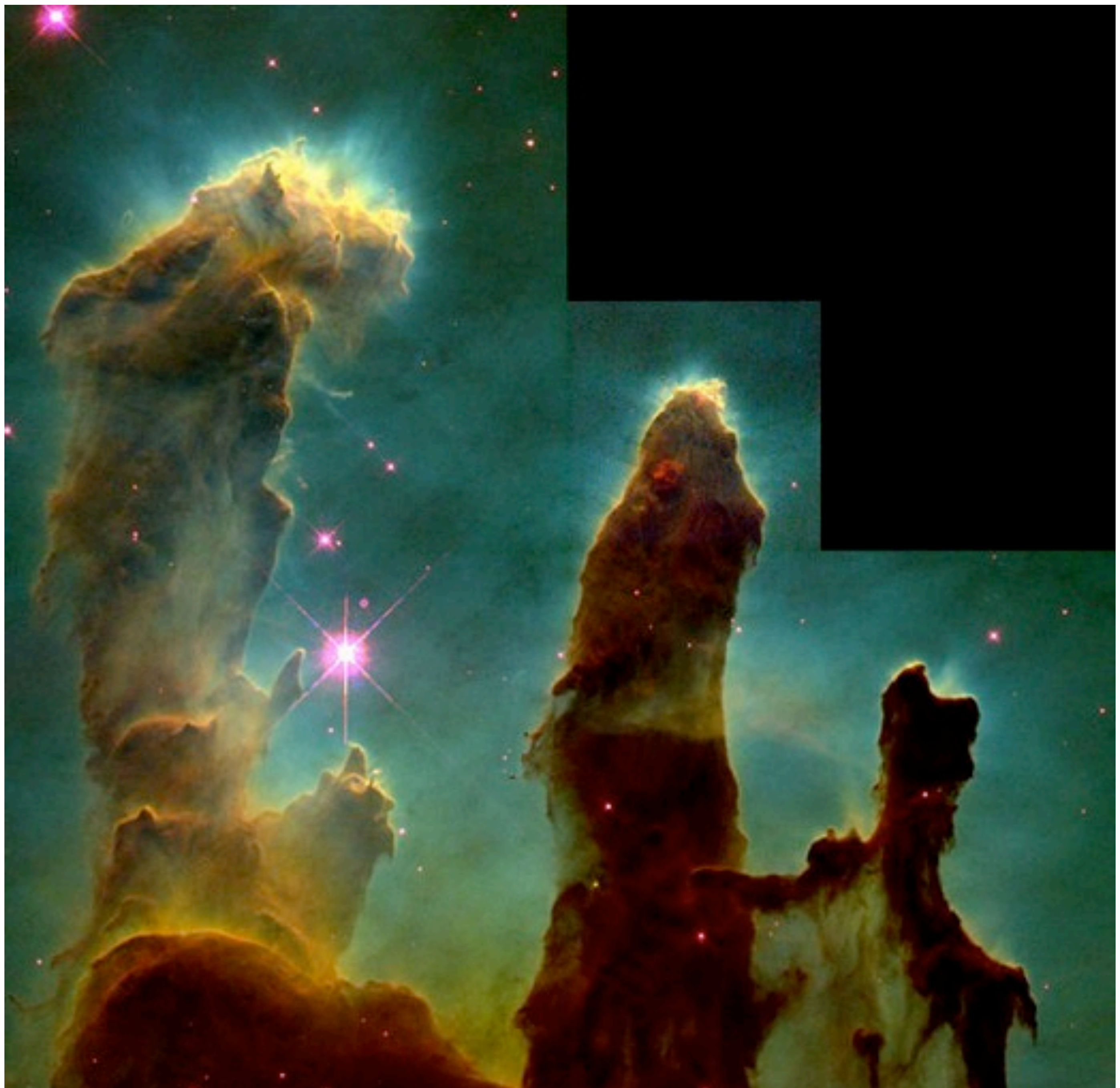
Emmy Noether-Programm
Deutsche Forschungsgemeinschaft
DFG

Radiation pressure

(Comet Hale-Bopp; by Robert Allevo)

Johannes Kepler
De Cometis, 1619

Radiation pressure



Johannes Kepler
De Cometis, 1619

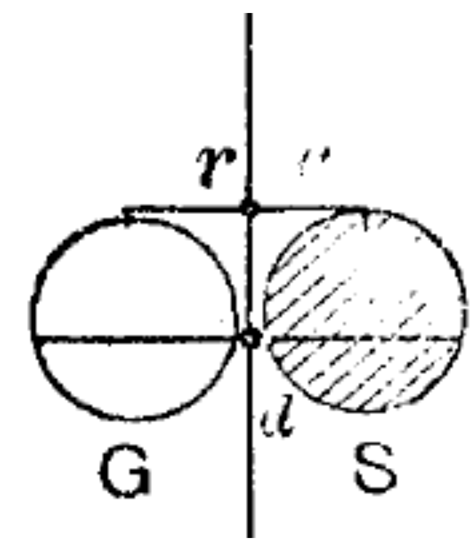
Radiation pressure

Nichols and Hull, 1901
Lebedev, 1901

A PRELIMINARY COMMUNICATION ON THE PRESSURE OF HEAT AND LIGHT RADIATION.

BY E. F. NICHOLS AND G. F. HULL.

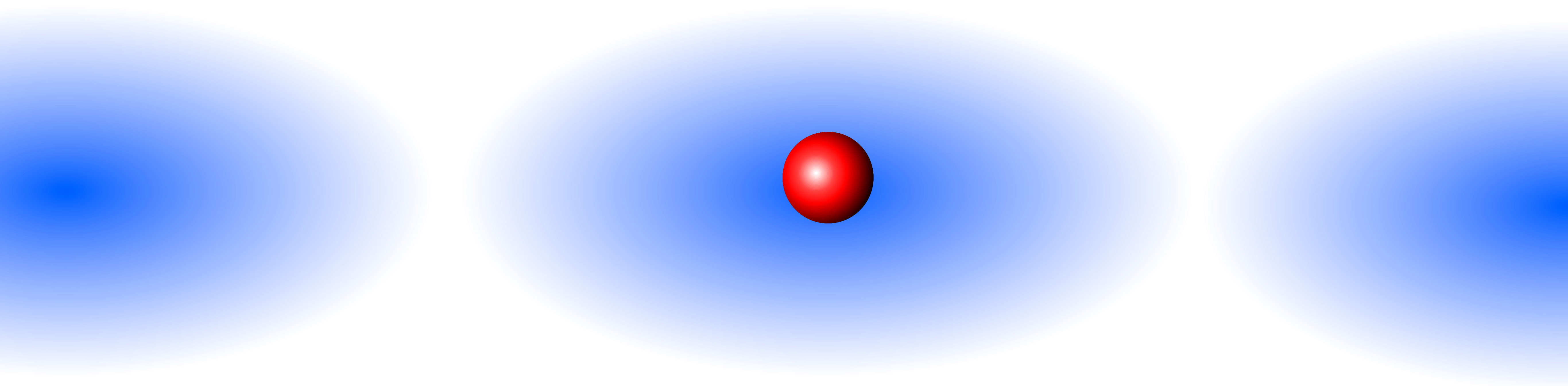
MAXWELL,[1] dealing mathematically with the stresses in an electro-magnetic field, reached the conclusion that "in a medium in which waves are propagated there is a pressure normal to the waves and numerically equal to the energy in unit volume."



$$F = \frac{2I}{c}$$

Nichols and Hull, Physical Review **13**, 307 (1901)

Radiation forces



Trapping and cooling

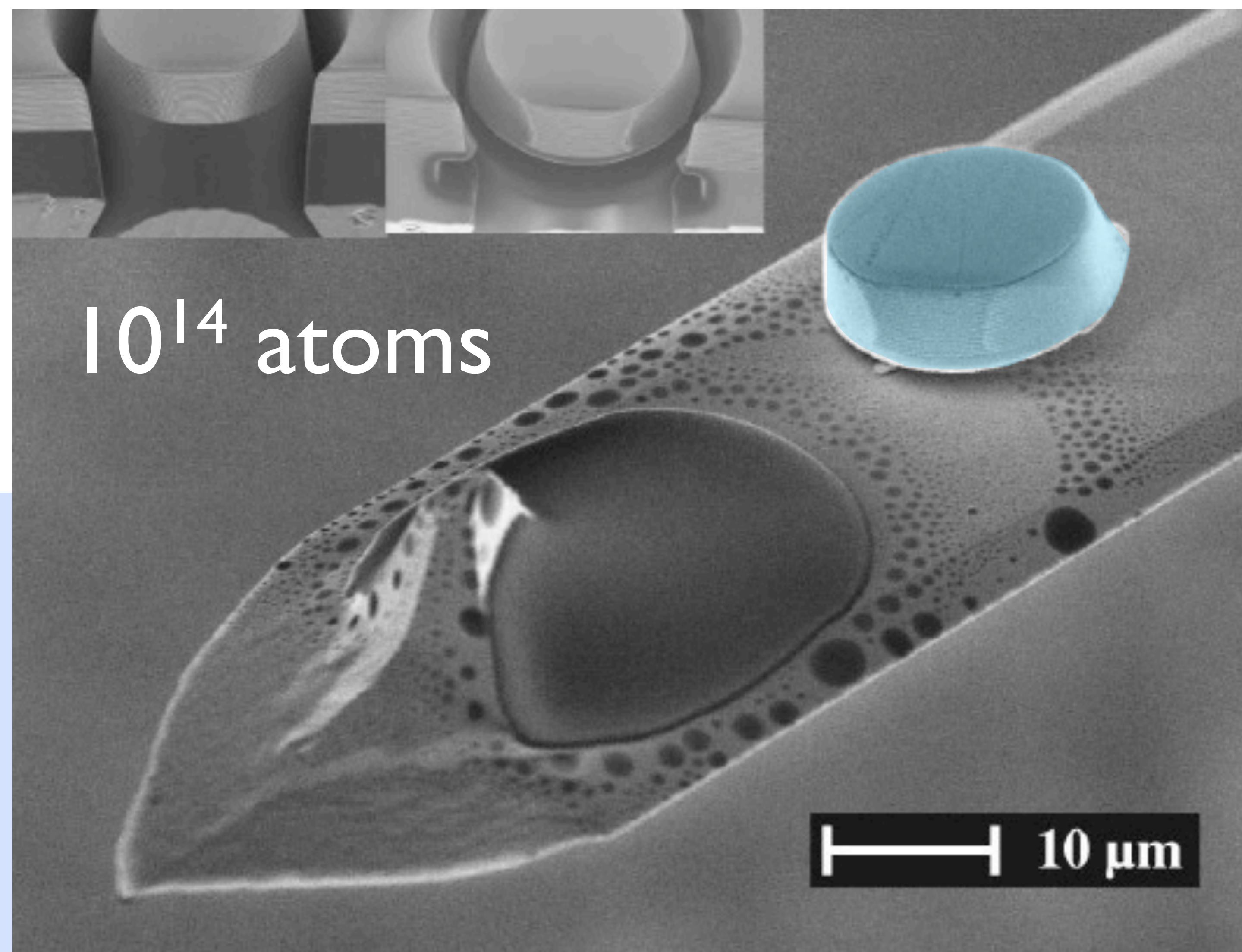
- Optical tweezers
- Optical lattices

...but usually no back-action from motion onto light!

Optomechanics on different length scales

LIGO – Laser Interferometer Gravitational Wave Observatory

Mirror on cantilever – Bouwmeester lab, Santa Barbara

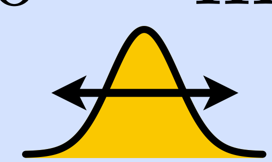


$$\omega_M \sim 1\text{kHz} - 1\text{GHz}$$

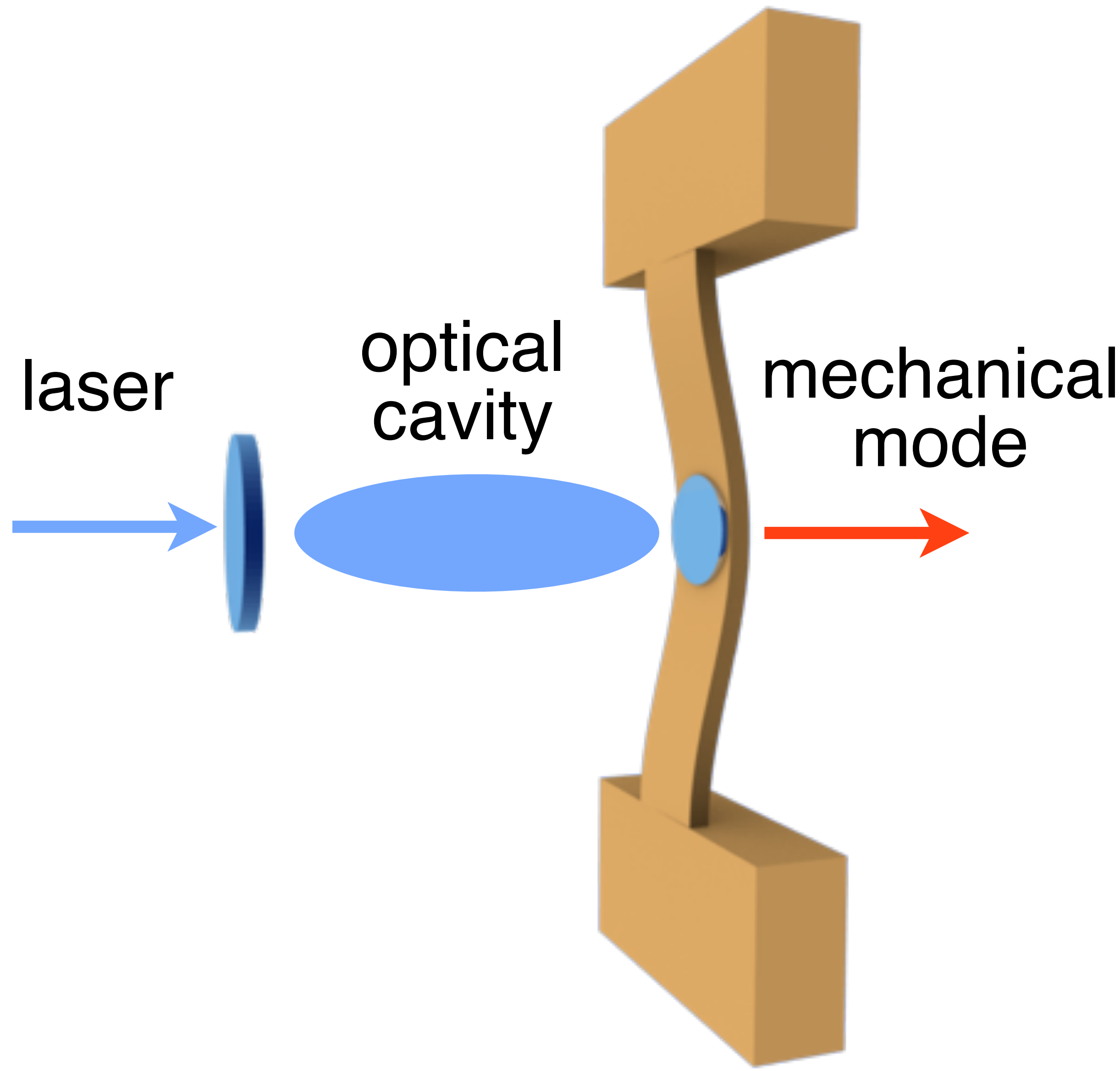
$$m \sim 10^{-12} - 10^{-10}\text{kg}$$

$$x_{\text{ZPF}} \sim 10^{-16} - 10^{-14}\text{m}$$

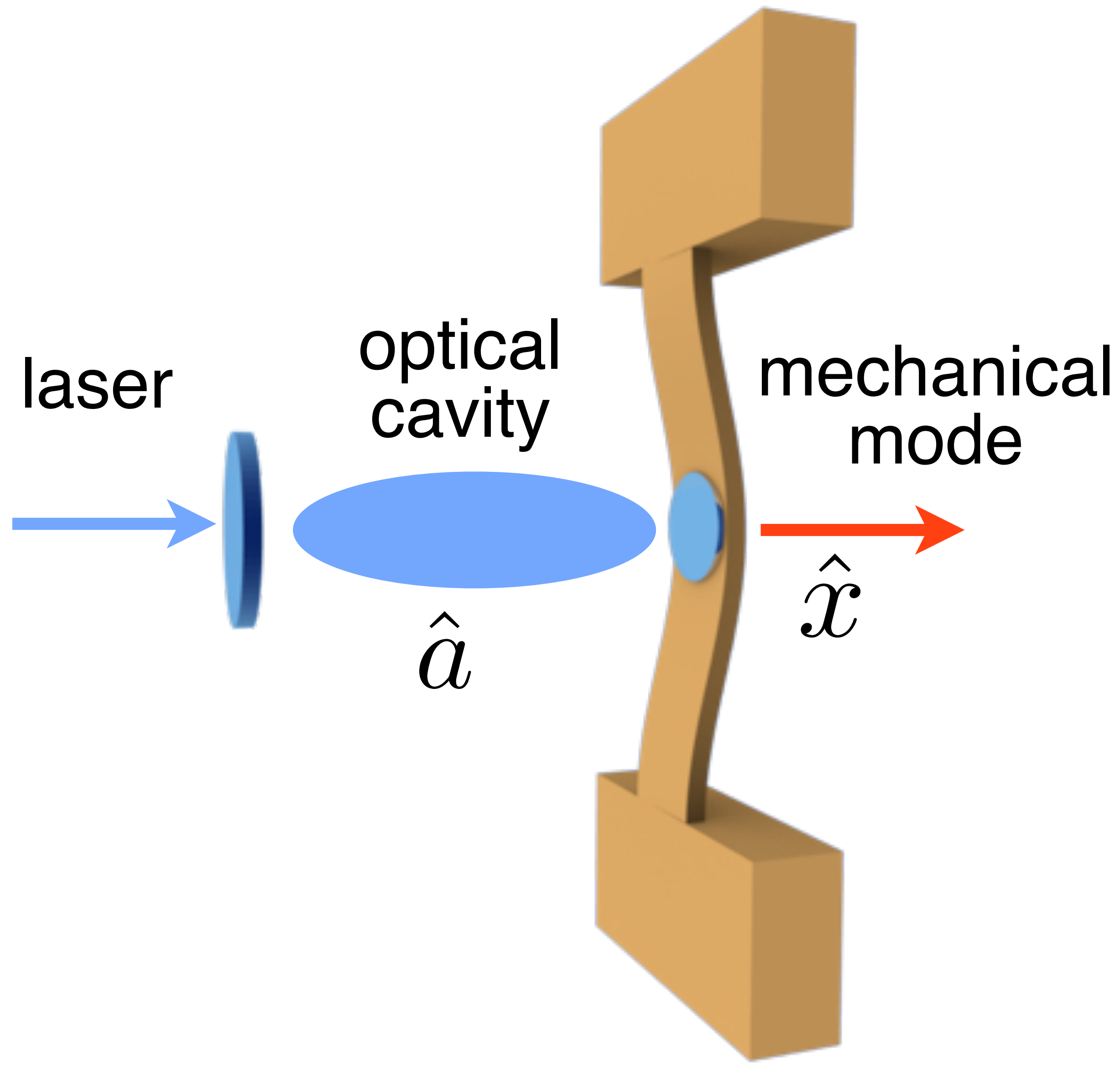
$$x_{\text{ZPF}} = \sqrt{\hbar/(2m\omega_M)}$$



Optomechanical Hamiltonian



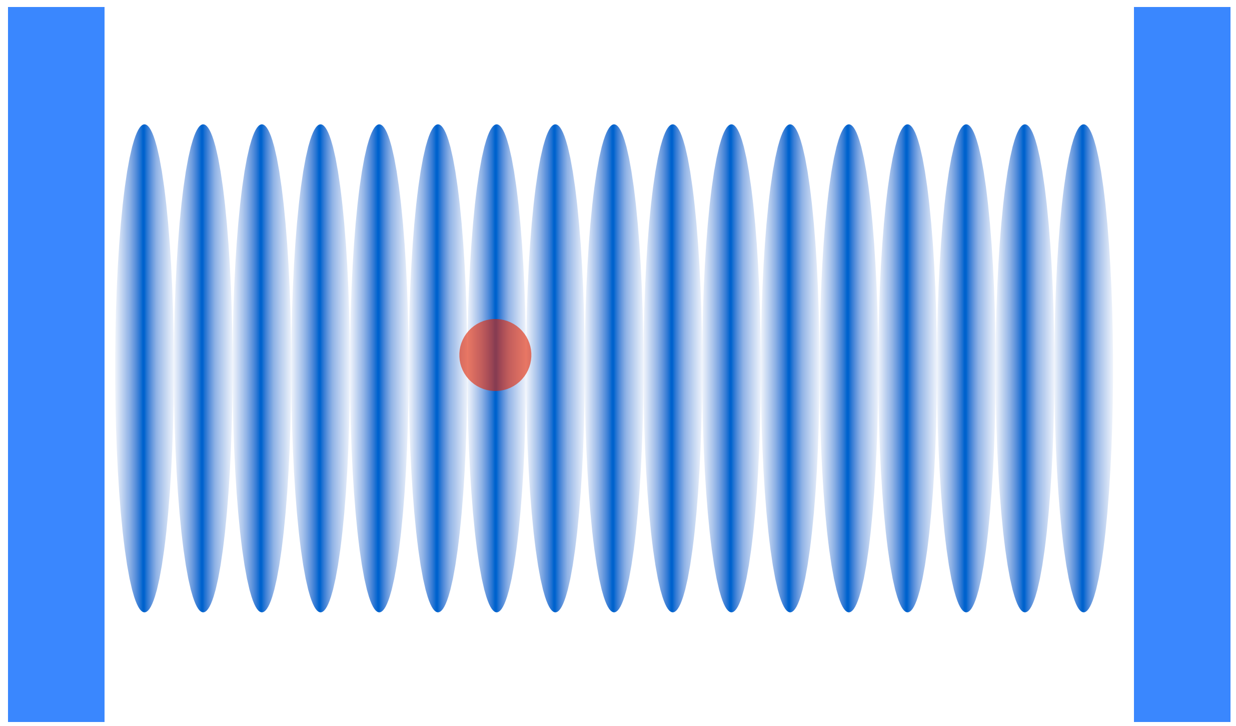
Optomechanical Hamiltonian



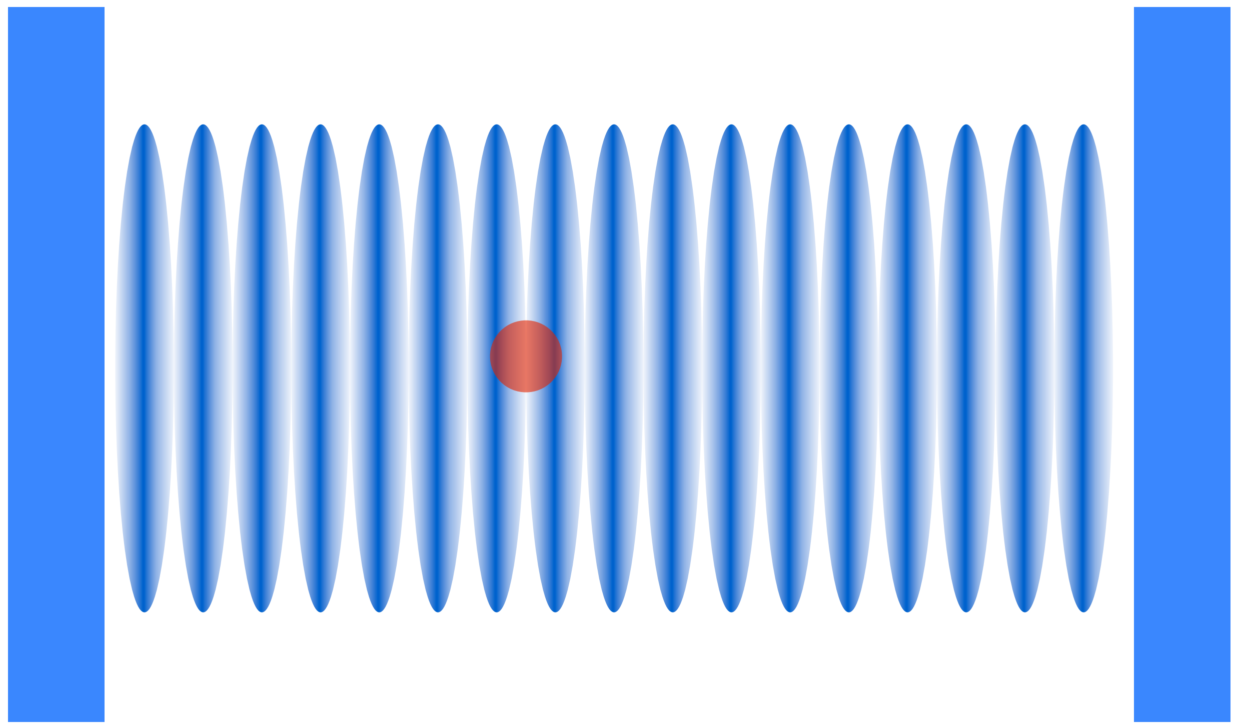
$$\hat{H} = \hbar\omega_{\mathrm{cav}} \cdot (1 - \hat{x}/L)\hat{a}^\dagger\hat{a} + \hbar\omega_M \hat{b}^\dagger\hat{b} + \ldots$$

$$\hat{x} = x_{\mathrm{ZPF}}(\hat{b} + \hat{b}^\dagger) \qquad x_{\mathrm{ZPF}} = \sqrt{\frac{\hbar}{2m\Omega}}$$

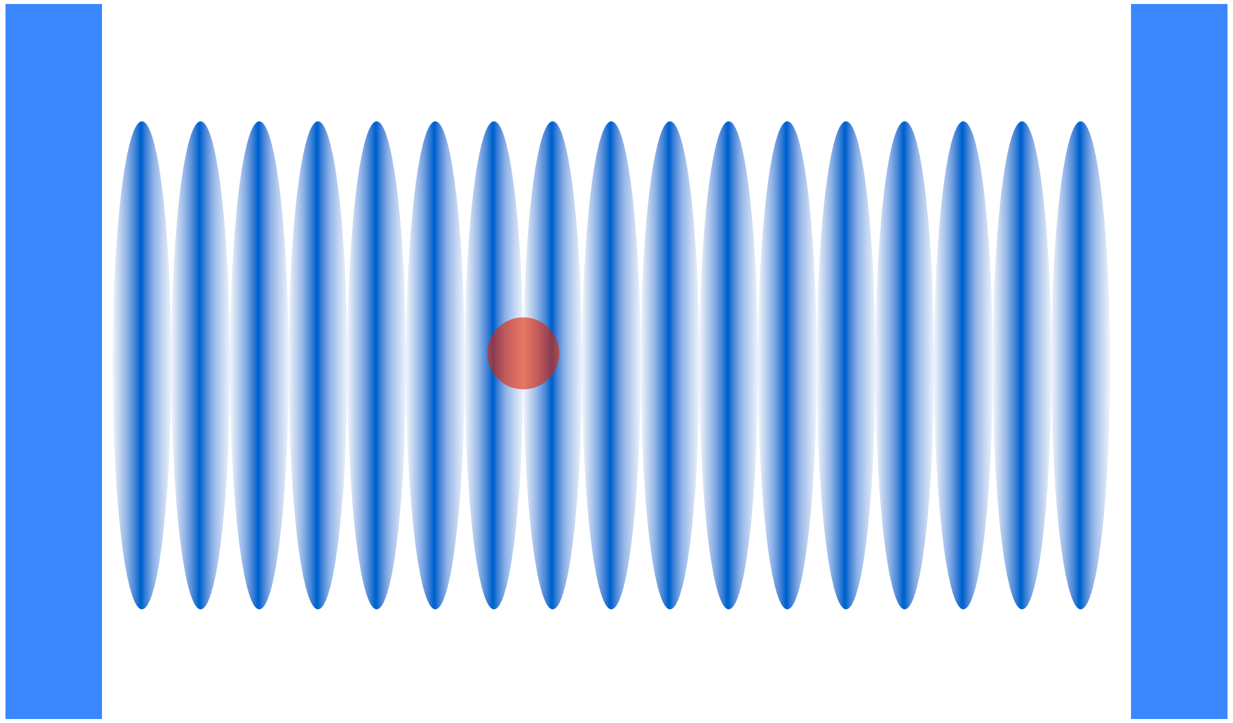
Optomechanical Hamiltonian



Optomechanical Hamiltonian



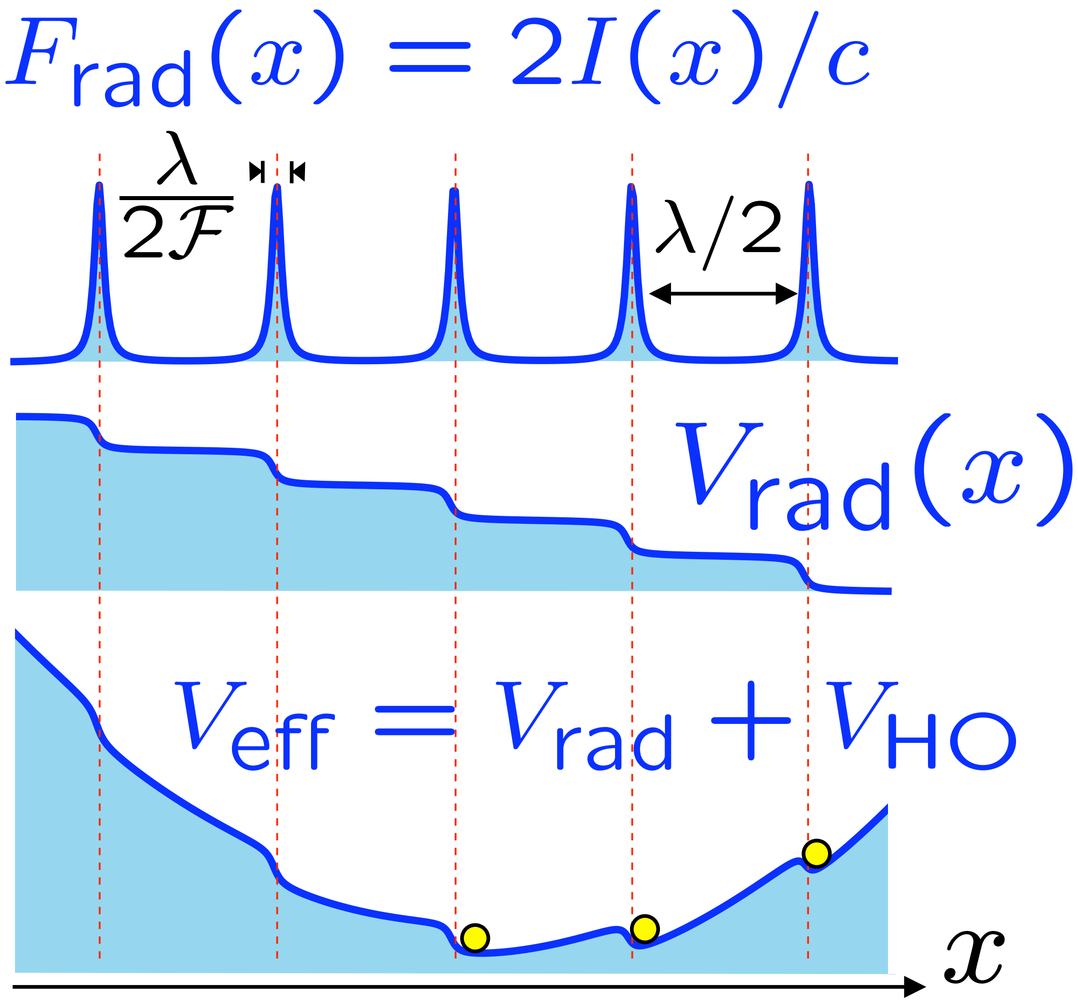
Optomechanical Hamiltonian



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

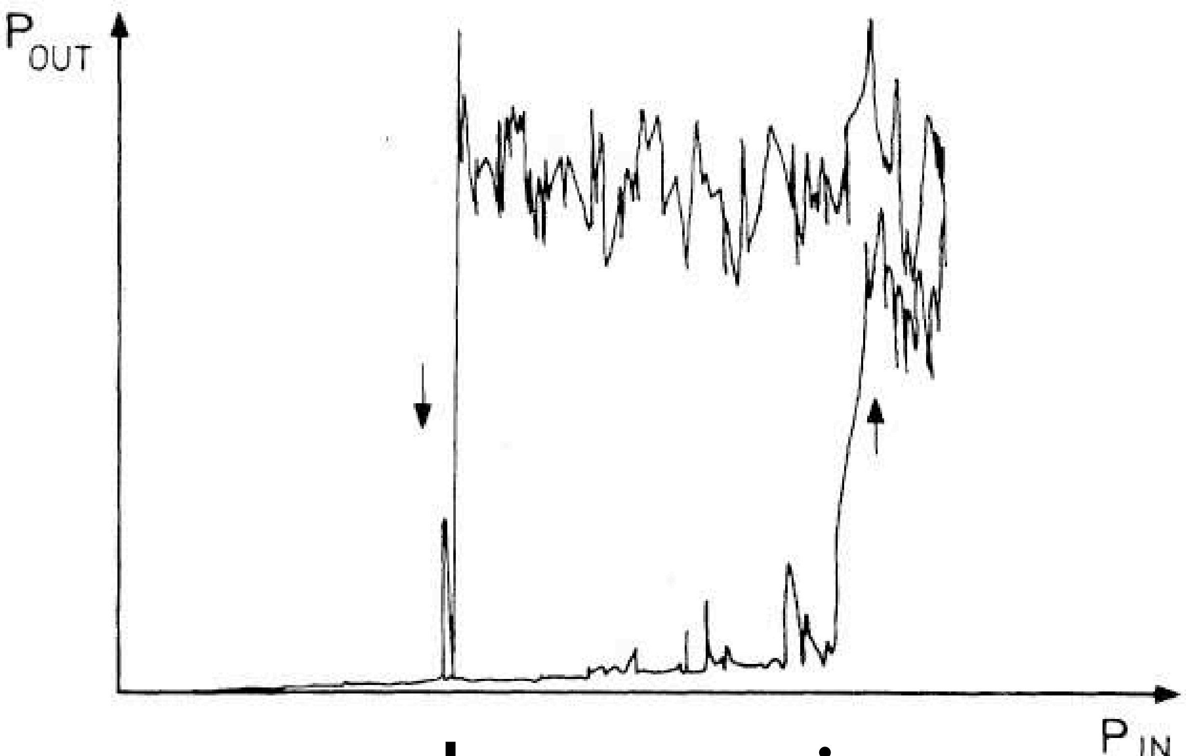
...any dielectric moving inside a cavity
generates an optomechanical interaction!

Basic physics: Statics



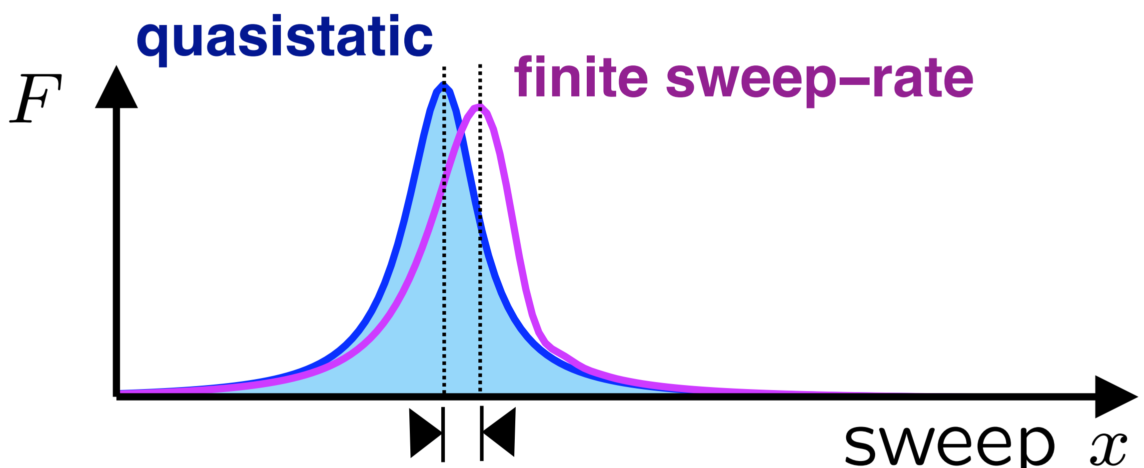
Experimental proof of static bistability:

A. Dorsel, J. D. McCullen, P. Meystre, E. Vignes and H. Walther: Phys. Rev. Lett. 51, 1550 (1983)

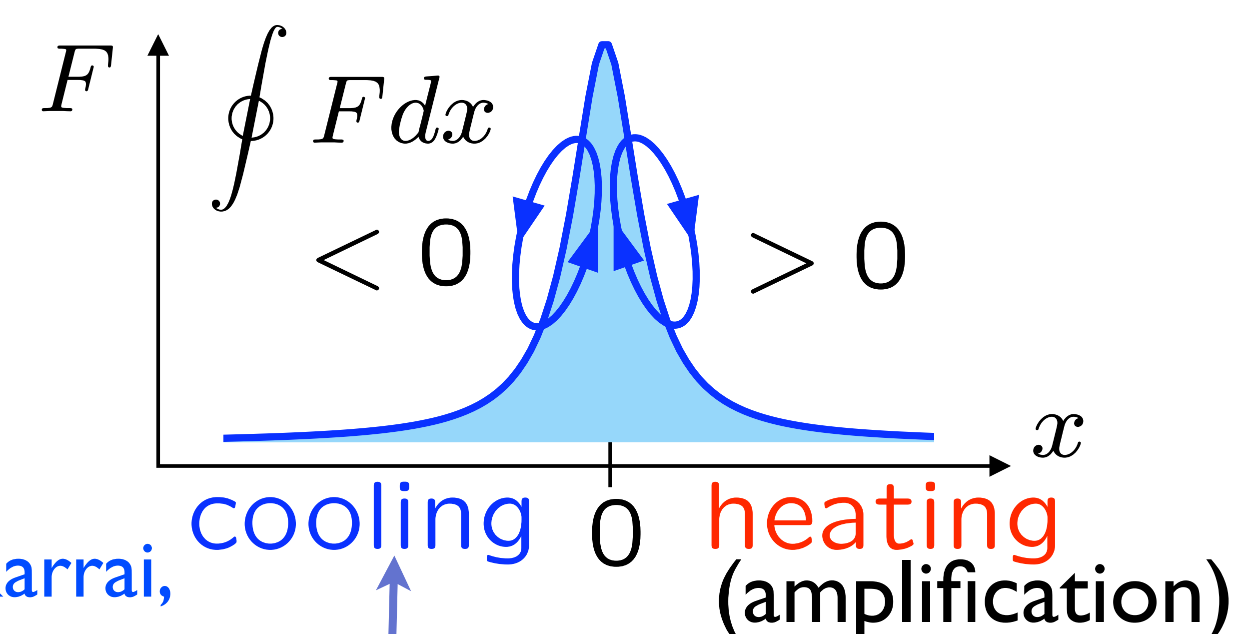


hysteresis

Basic physics: dynamics

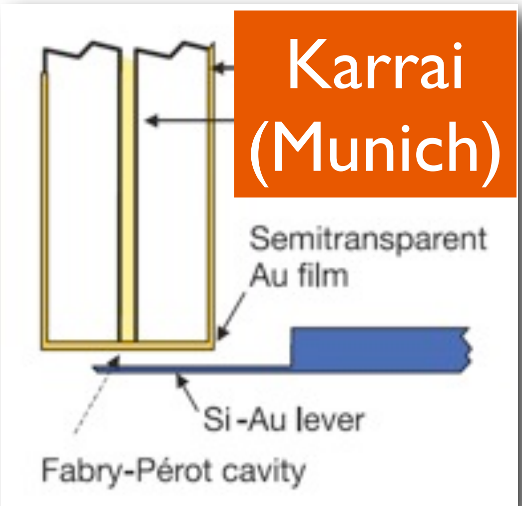


finite optical ringdown time κ^{-1} –
delayed response to cantilever motion

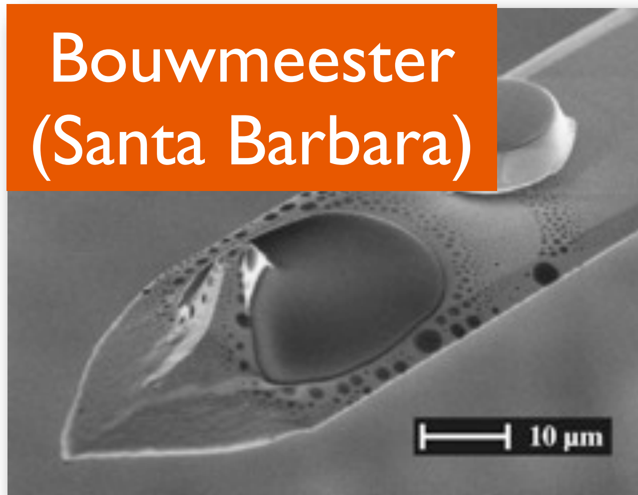


Höhberger-Metzger and Karrai,
Nature **432**, 1002 (2004):
300K to 17K [photothermal force]

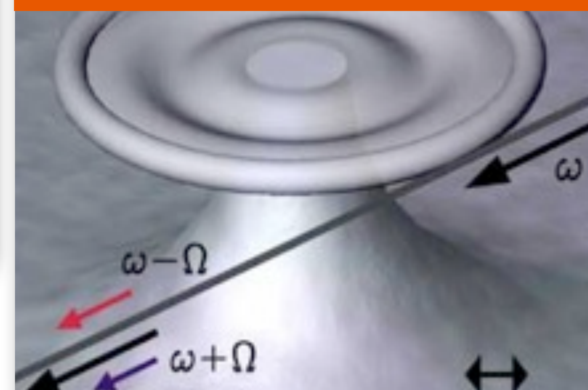
The zoo of optomechanical (and analogous) systems



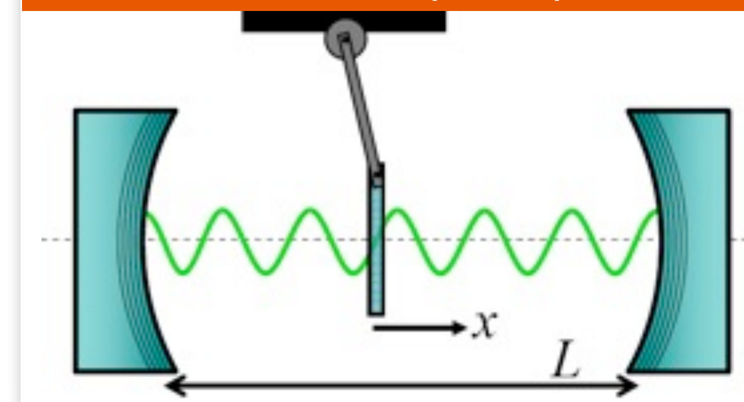
Karrai (Munich)



Bouwmeester (Santa Barbara)

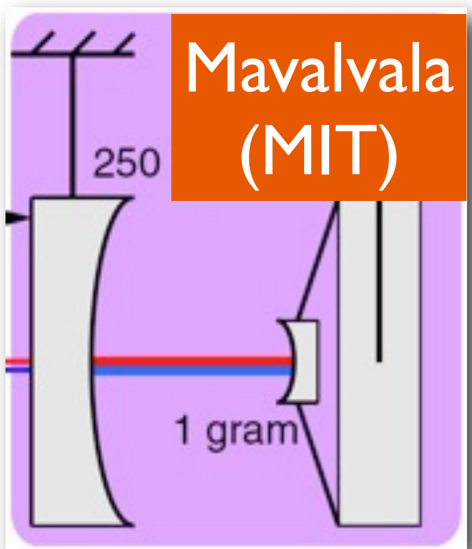


Vahala (Caltech) Kippenberg (EPFL), Carmon, ...

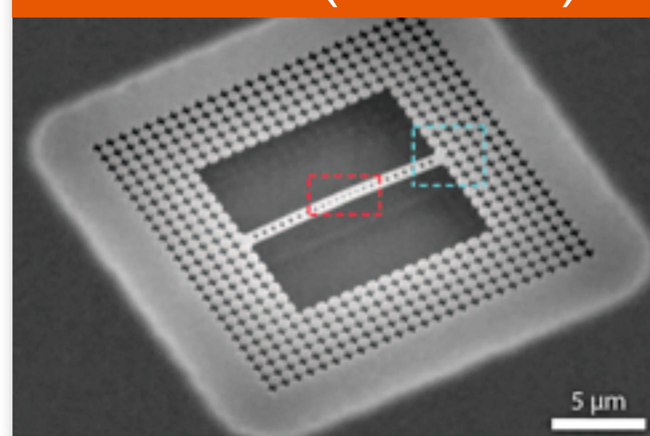


Harris (Yale)


LKB group (Paris)



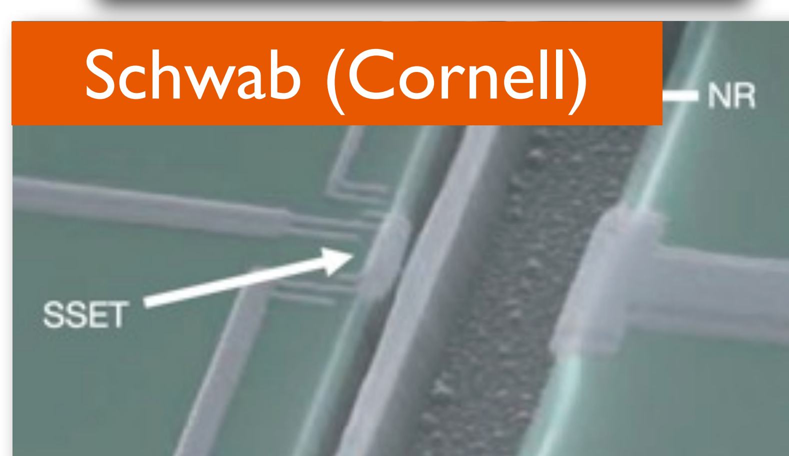
Mavalvala (MIT)



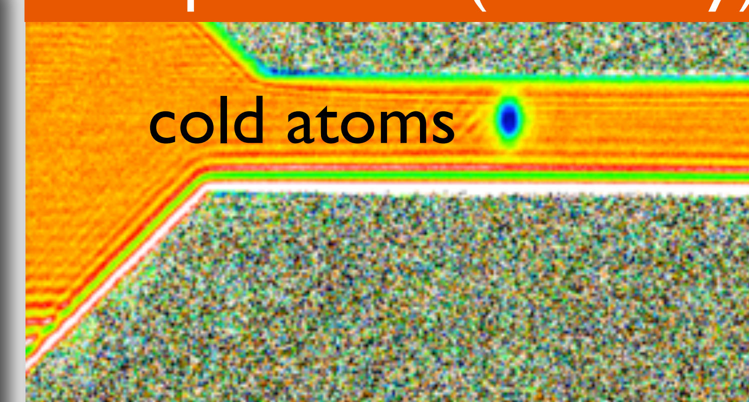
Painter (Caltech)

Teufel, Lehnert (Boulder)


Aspelmeyer (Vienna)

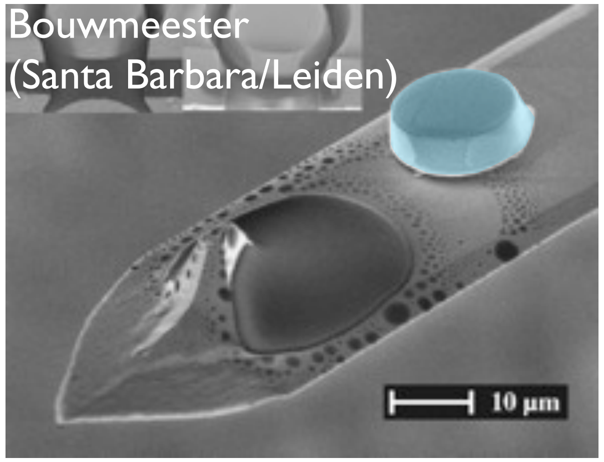


Schwab (Cornell)

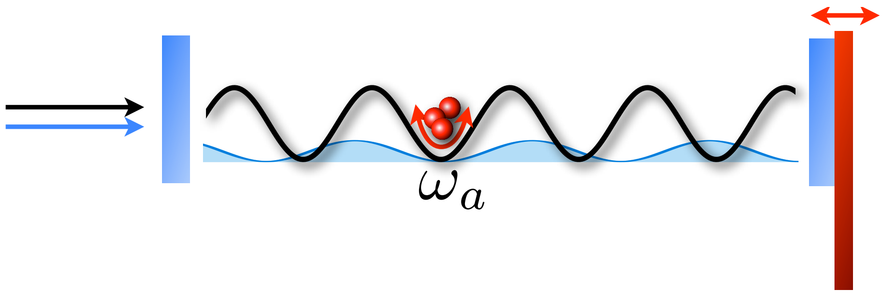


Stamper-Kurn (Berkeley)

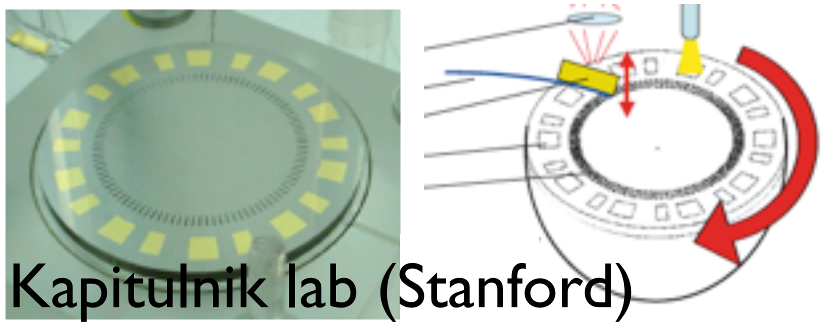
Optomechanics: general outlook



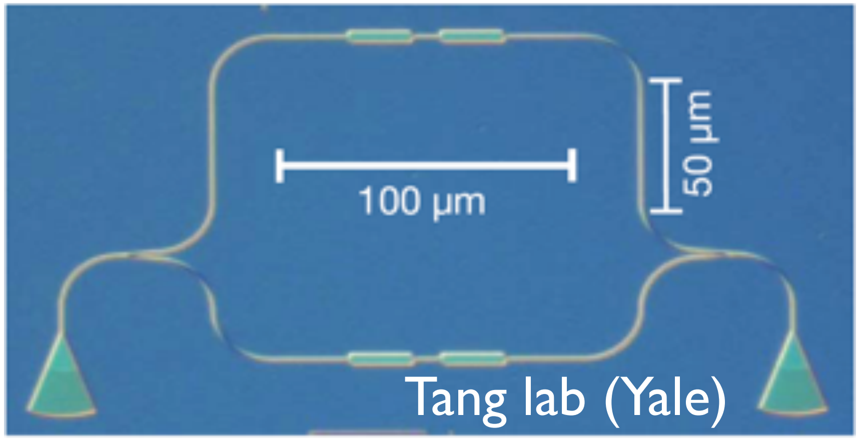
Fundamental tests of quantum mechanics in a new regime: entanglement with ‘macroscopic’ objects, unconventional decoherence? [e.g.: gravitationally induced?]



Mechanics as a ‘bus’ for connecting hybrid components: superconducting qubits, spins, photons, cold atoms, ...

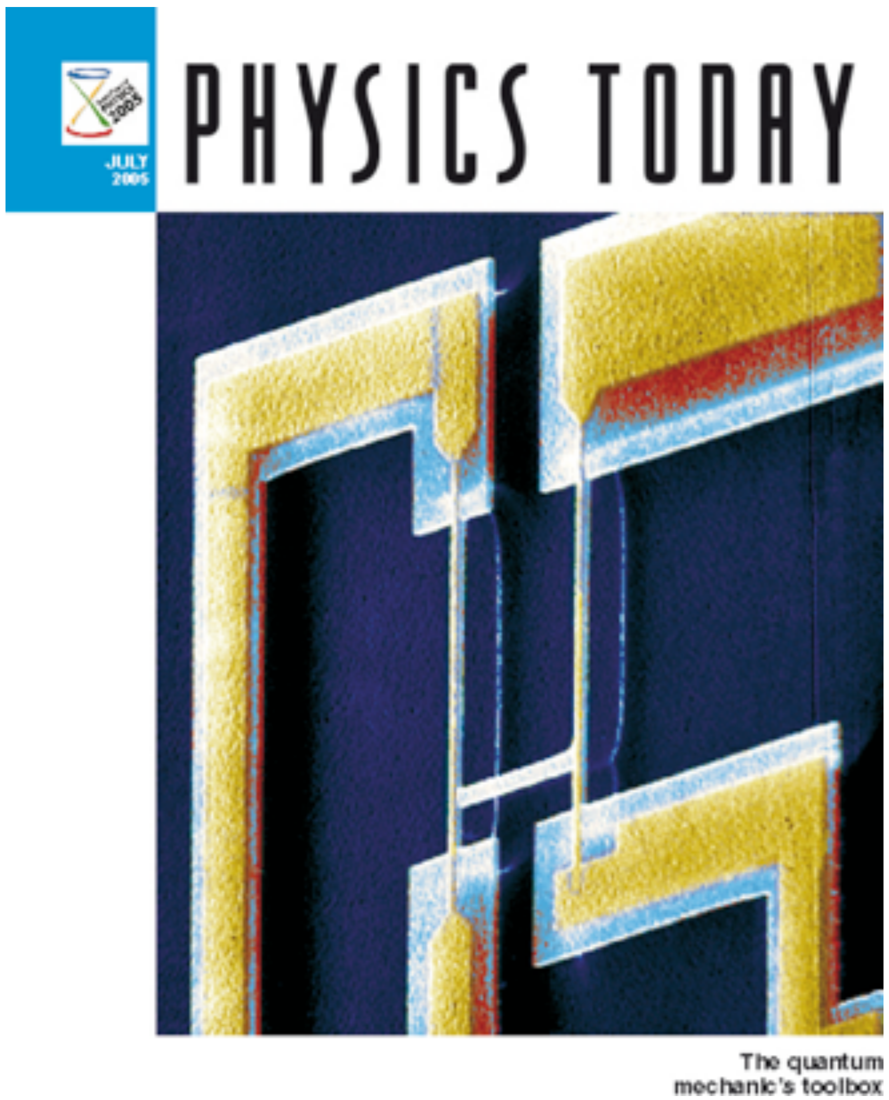


Precision measurements
[e.g. testing deviations from Newtonian gravity due to extra dimensions]



Optomechanical circuits & arrays
Exploit nonlinearities for classical and quantum information processing, storage, and amplification; study collective dynamics in arrays

Towards the quantum regime of mechanical motion



Putting Mechanics into Quantum Mechanics

Nanoelectromechanical structures are starting to approach the ultimate quantum mechanical limits for detecting and exciting motion at the nanoscale. Nonclassical states of a mechanical resonator are also on the horizon.

Keith C. Schwab and Michael L. Roukes

Everything moves! In a world dominated by electronic devices and instruments it is easy to forget that all measurements involve motion, whether it be the motion of electrons through a transistor, Cooper pairs or quasiparticles through a superconducting quantum interference device (SQUID), photons through an optical interferometer—or the simple displacement of a mechanical element.

achieved to read out those devices, now bring us to the realm of quantum mechanical systems.

The quantum realm

What conditions are required to observe the quantum properties of a mechanical structure, and what can we learn when we encounter them? Such questions have received

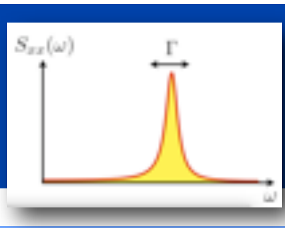
Schwab and Roukes, Physics Today 2005

- nano-electro-mechanical systems

Superconducting qubit coupled to nanoresonator: Cleland & Martinis 2010

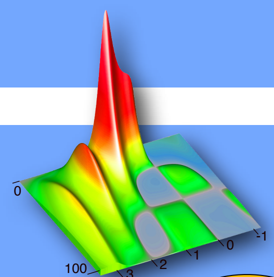
- optomechanical systems

Optomechanics (Outline)

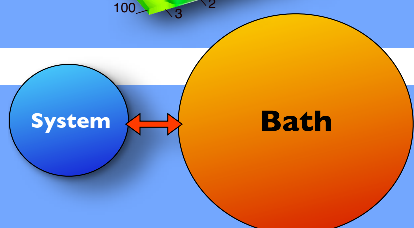


Displacement detection

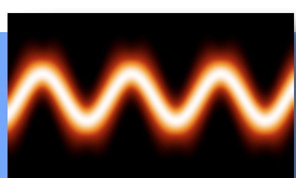
Linear optomechanics



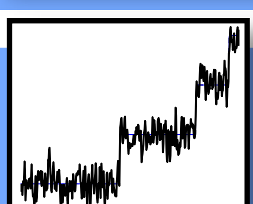
Nonlinear dynamics



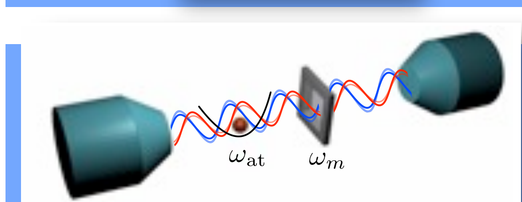
Quantum theory of cooling



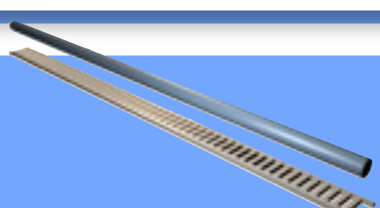
Interesting quantum states



Towards Fock state detection

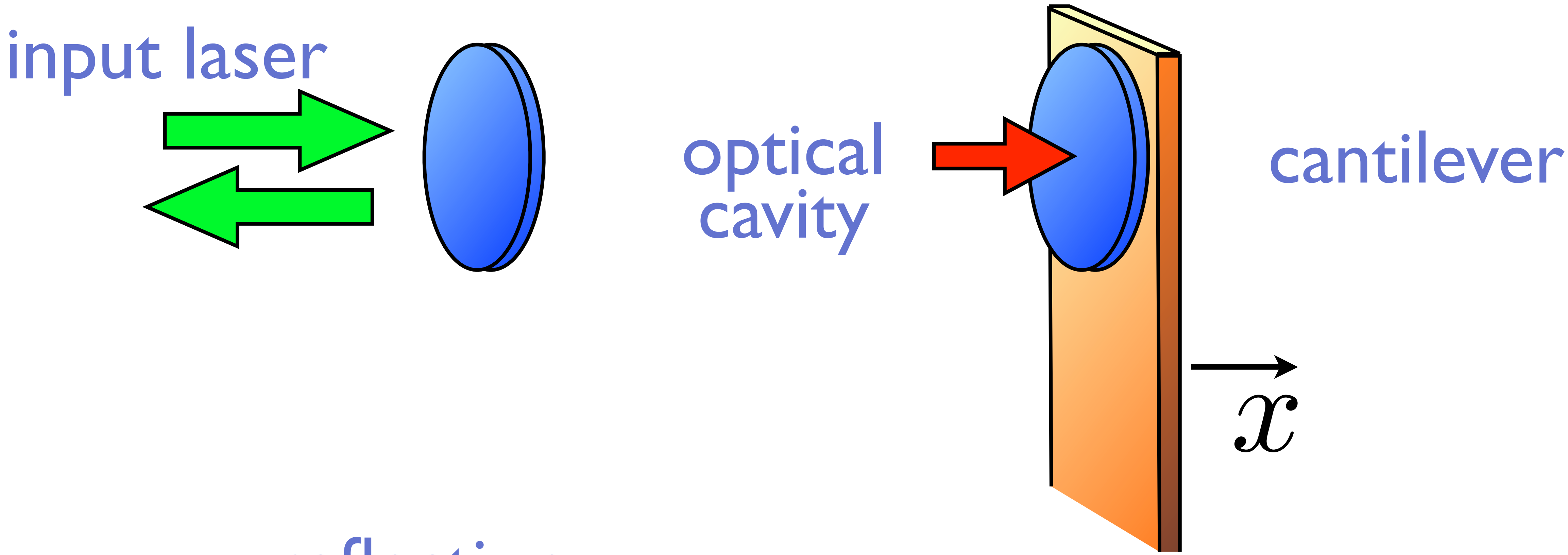


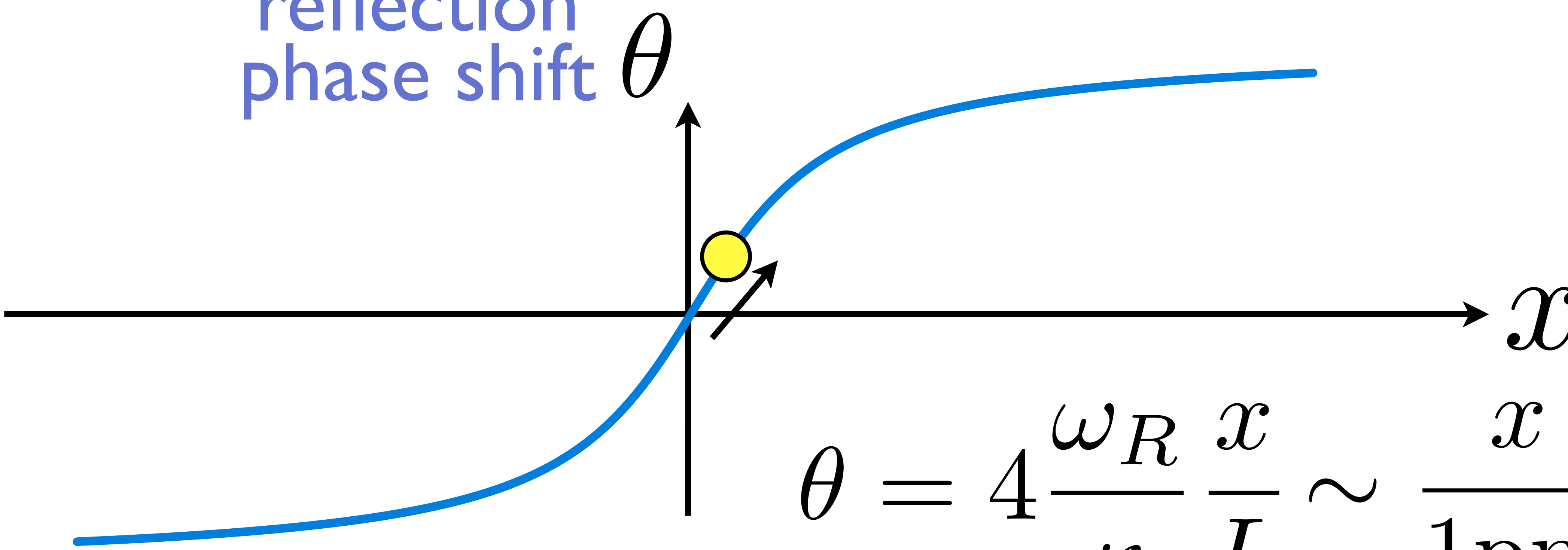
Hybrid systems: coupling to atoms



Optomechanical crystals & arrays

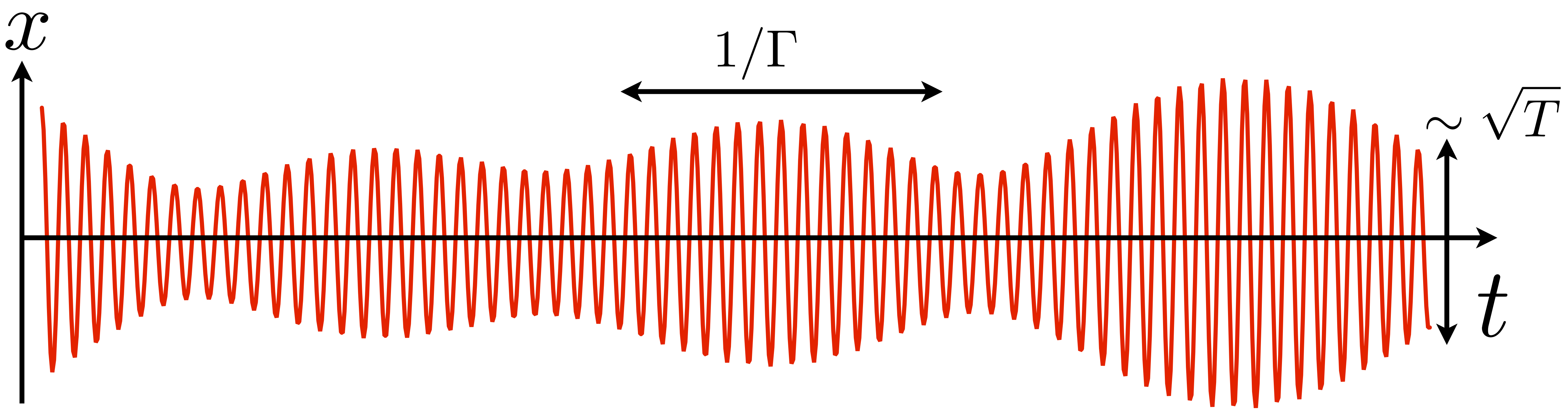
Optical displacement detection





$$\theta = 4\frac{\omega_R}{\kappa}\frac{x}{L} \sim \frac{x}{1\mathrm{pm}}$$

Thermal fluctuations of a harmonic oscillator



Classical equipartition theorem:

$$\frac{m\omega_M^2}{2}\left\langle x^2\right\rangle = \frac{k_B T}{2} \quad \Rightarrow \quad \left\langle x^2\right\rangle = \frac{k_B T}{m\omega_M^2}$$

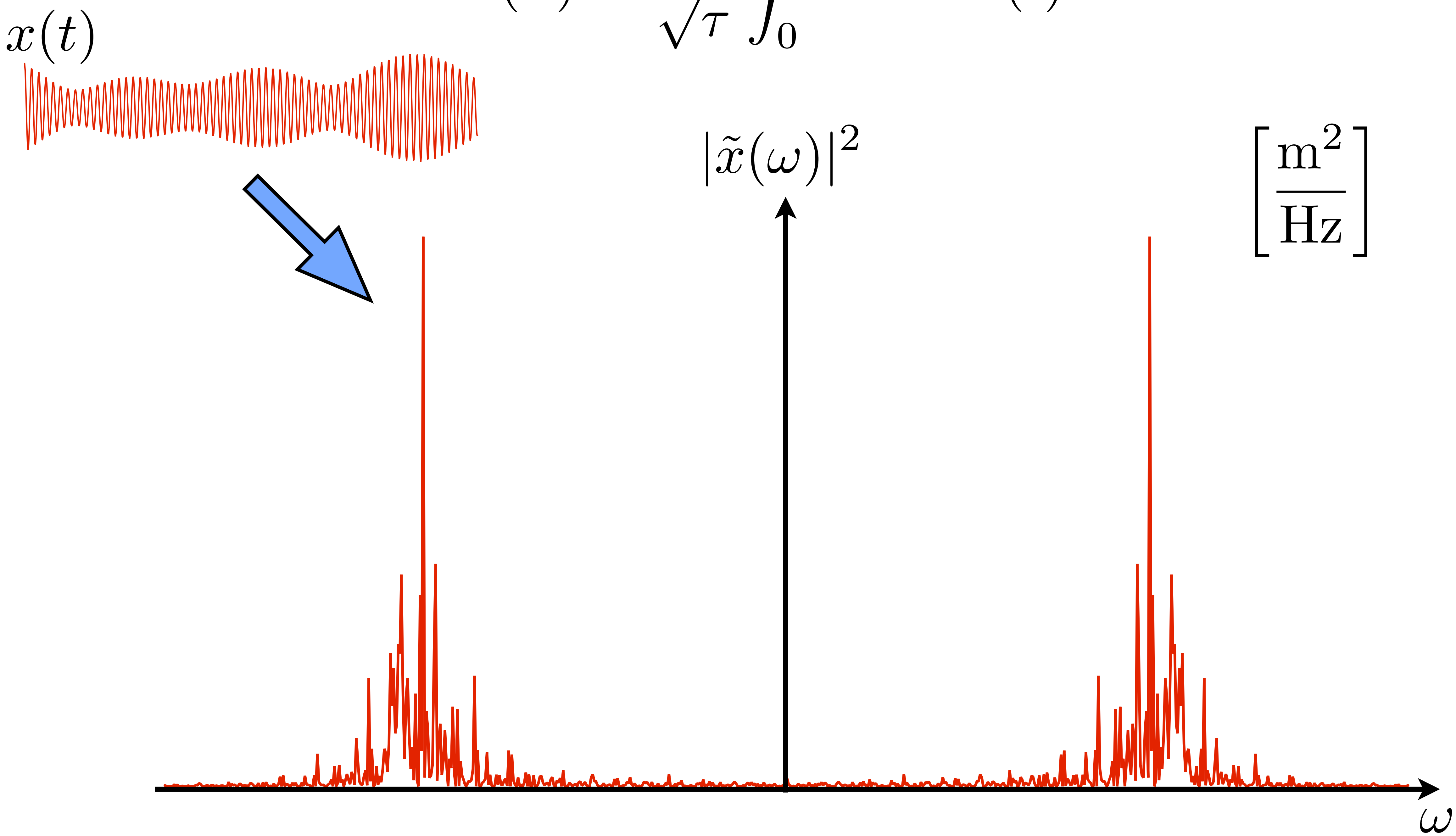
extract temperature!

Possibilities:

- Direct time-resolved detection
- Analyze **fluctuation spectrum of x**

Fluctuation spectrum

$$\tilde{x}(\omega) = \frac{1}{\sqrt{\tau}} \int_0^{\tau} dt e^{i\omega t} x(t)$$



Fluctuation spectrum

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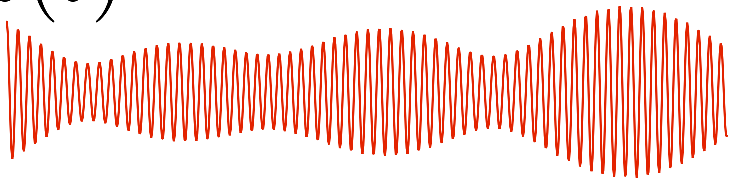
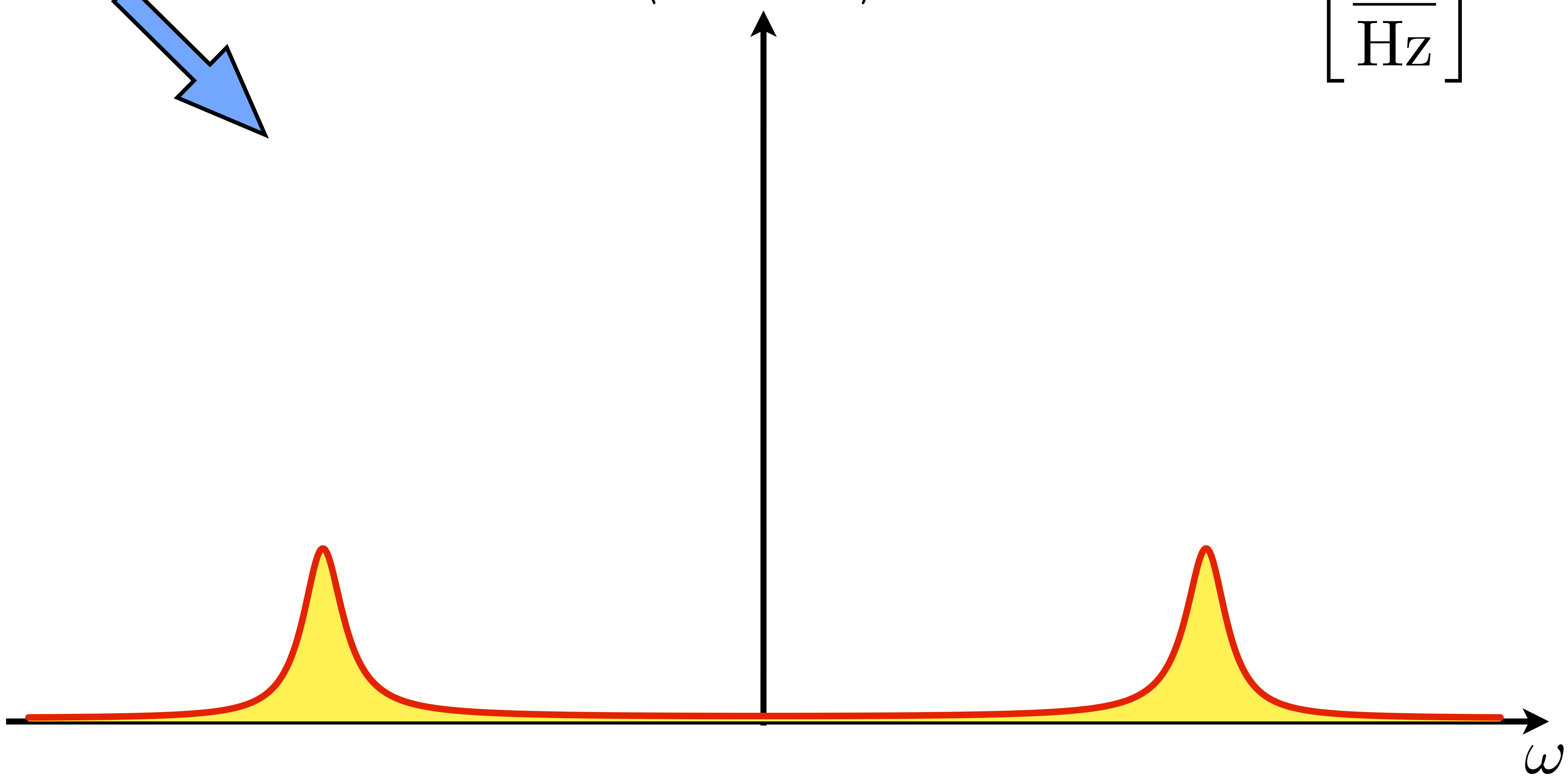
$x(t)$



$$\langle |\tilde{x}(\omega)|^2 \rangle \equiv S_{xx}(\omega) \qquad \left[\frac{\mathrm{m}^2}{\mathrm{Hz}} \right]$$



Fluctuation-dissipation theorem

General relation between noise spectrum and linear response susceptibility

$$\langle \delta x \rangle (\omega) = \chi_{xx}(\omega) F(\omega)$$

susceptibility

$$S_{xx}(\omega) = \frac{2k_B T}{\omega} \mathrm{Im} \chi_{xx}(\omega)$$

(classical limit)

Fluctuation-dissipation theorem

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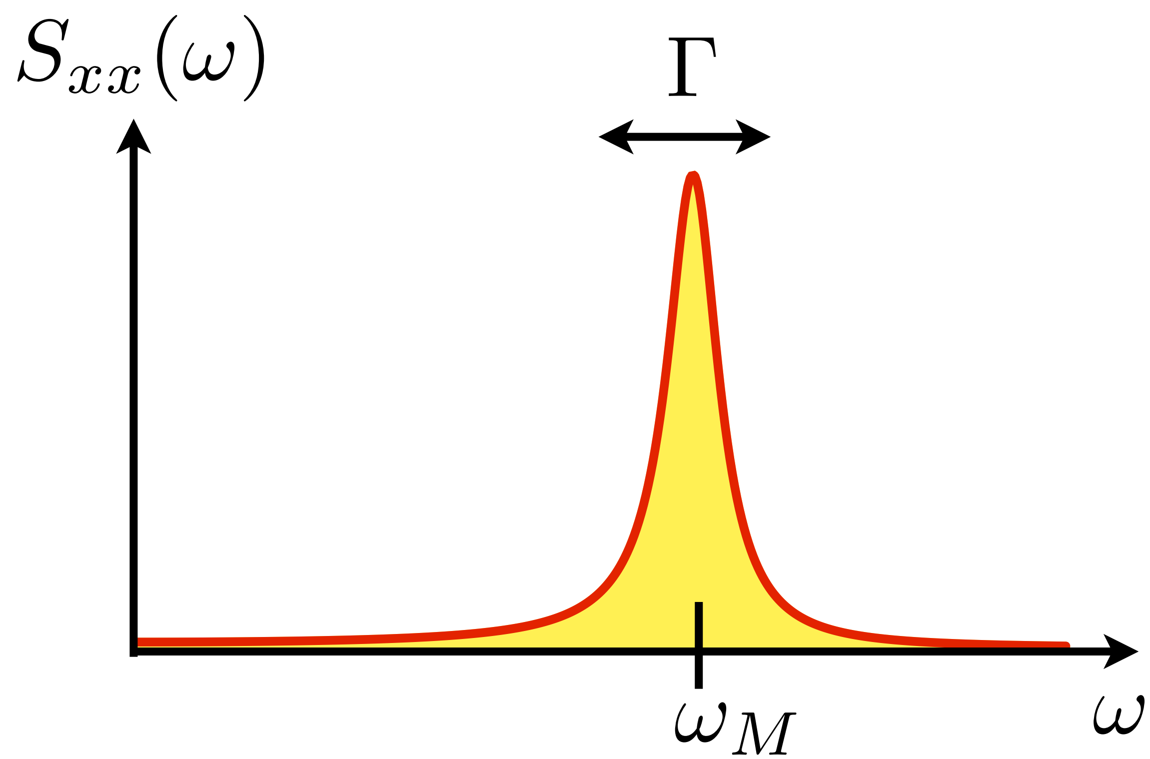
(classical limit)

for the damped oscillator:

$$m\ddot{x} + m\omega_M^2 x + m\Gamma\dot{x} = F$$

$$x(\omega) = \underbrace{\frac{1}{m(\omega_M^2 - \omega^2) - im\Gamma\omega}}_{\chi_{xx}(\omega)} F(\omega)$$



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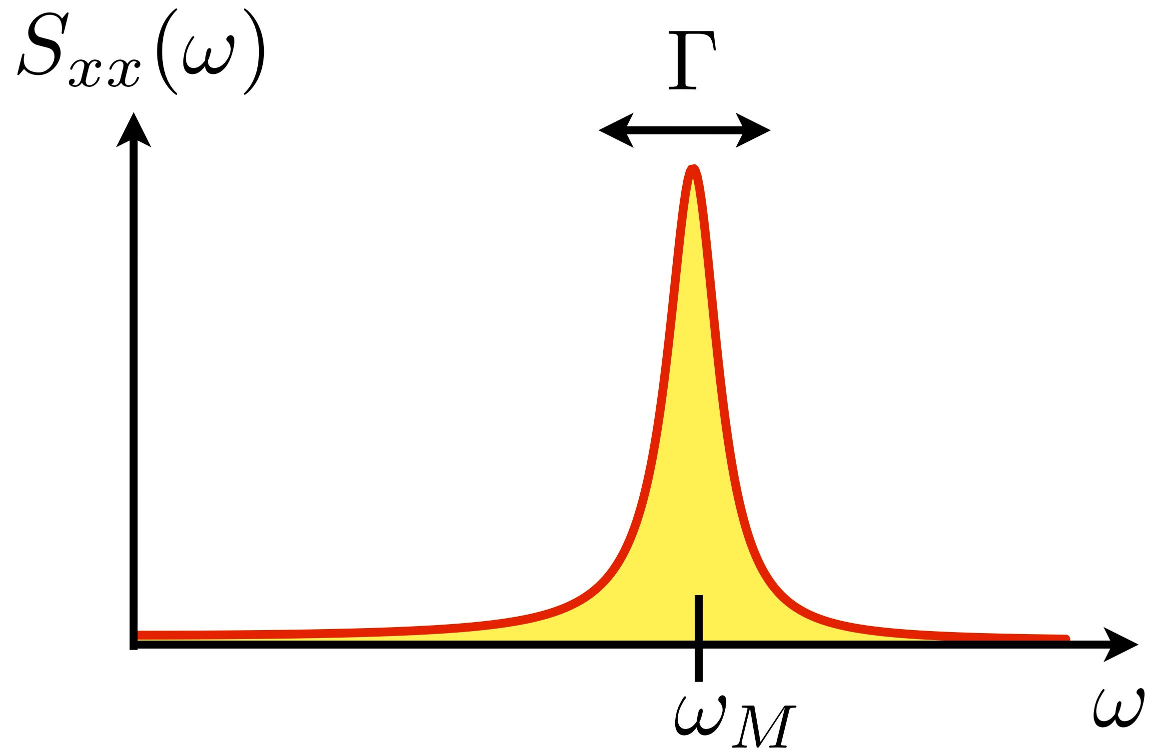
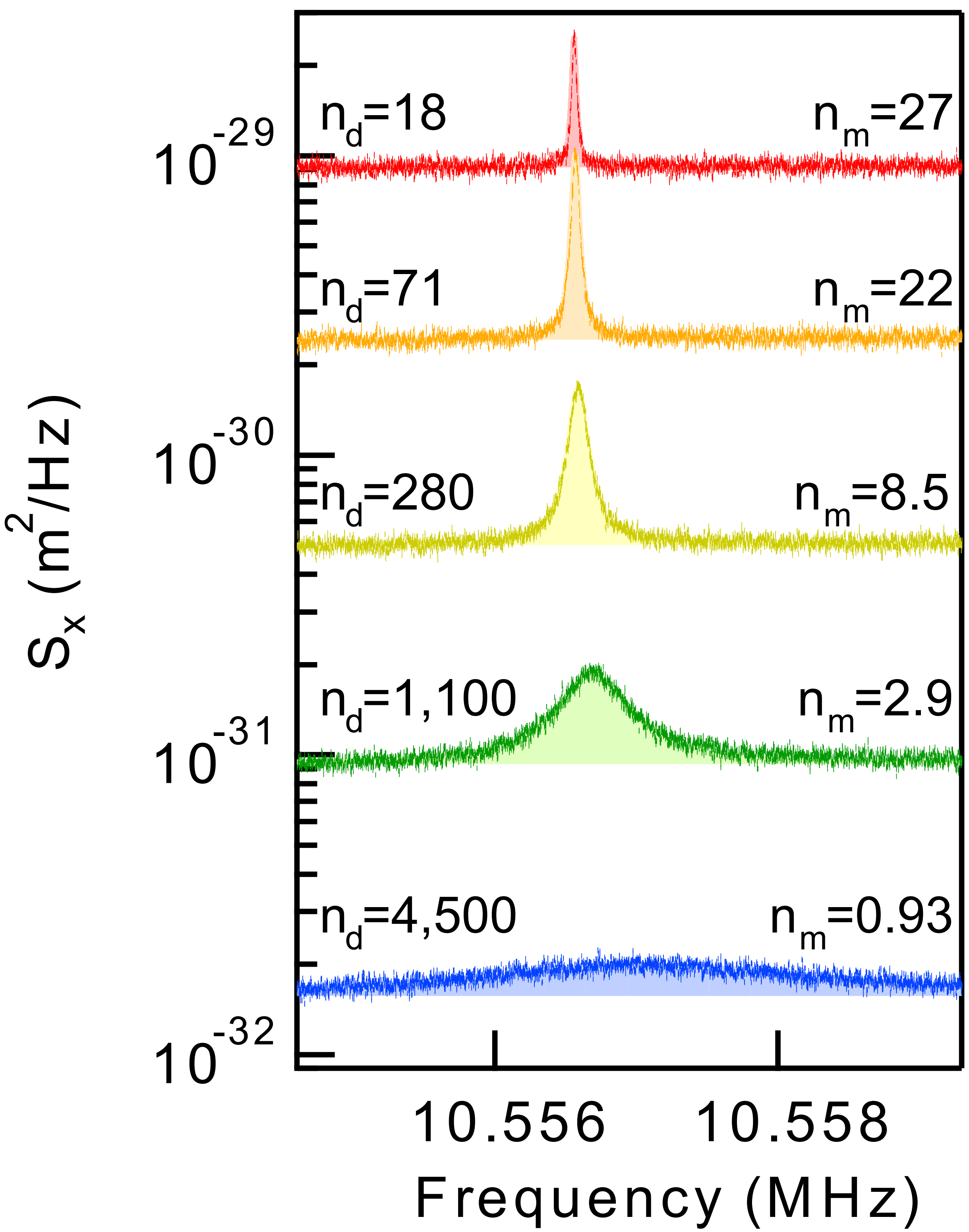


area yields variance of x:

$$\int_{-\infty}^{+\infty} \frac{d\omega}{2\pi} S_{xx}(\omega) = \langle x^2 \rangle$$

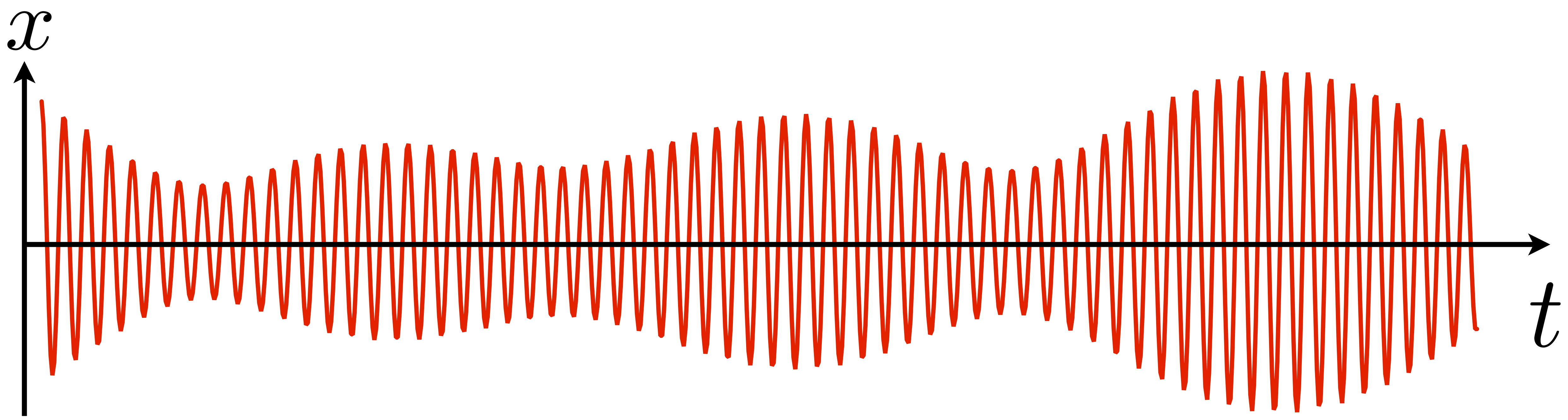
...yields temperature!

Displacement spectrum

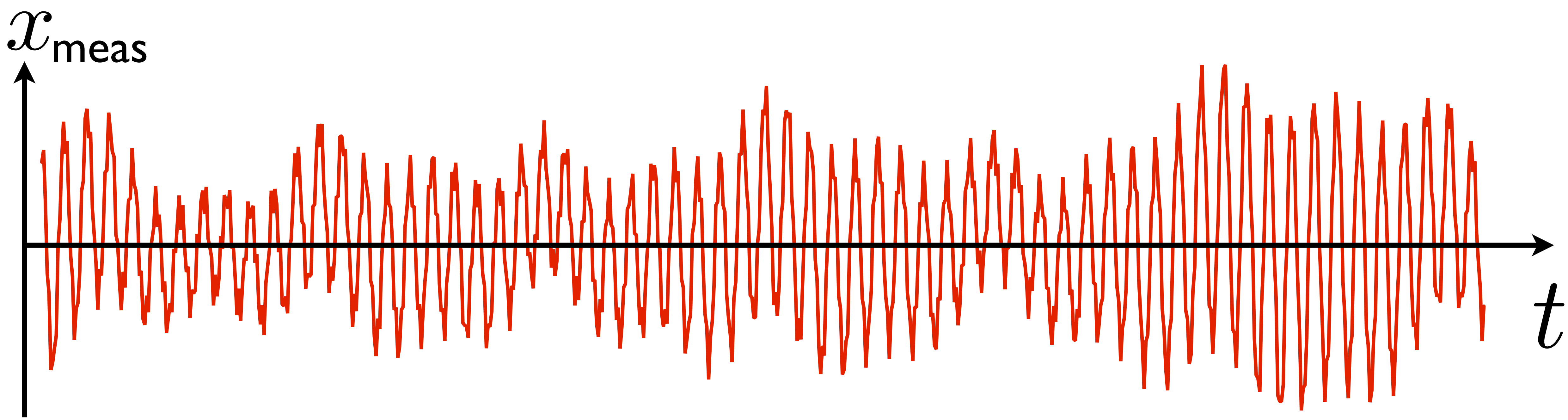


Teufel et al., Nature 2011

Measurement noise



Measurement noise



$$x_{\text{meas}}(t) = x(t) + x_{\text{noise}}(t)$$

Two contributions to $x_{\text{noise}}(t)$

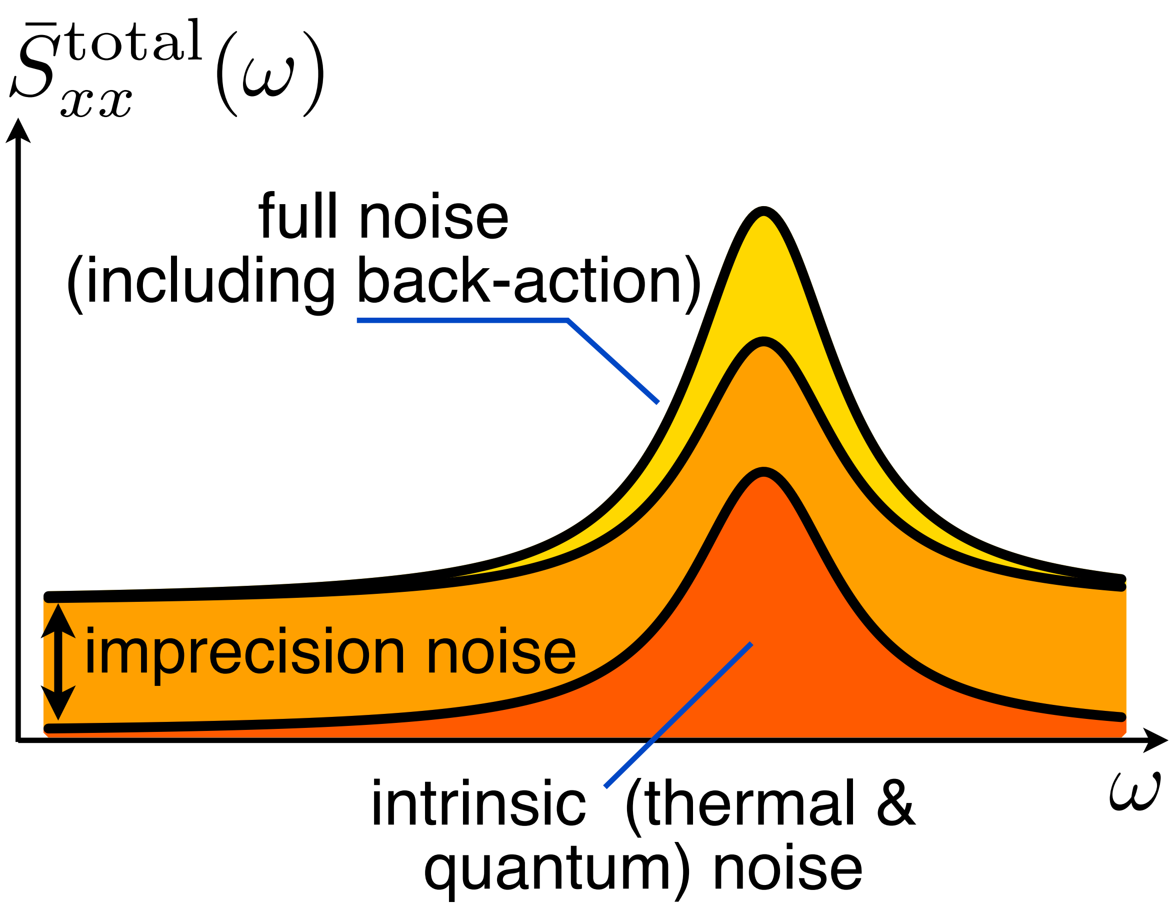
1. measurement imprecision

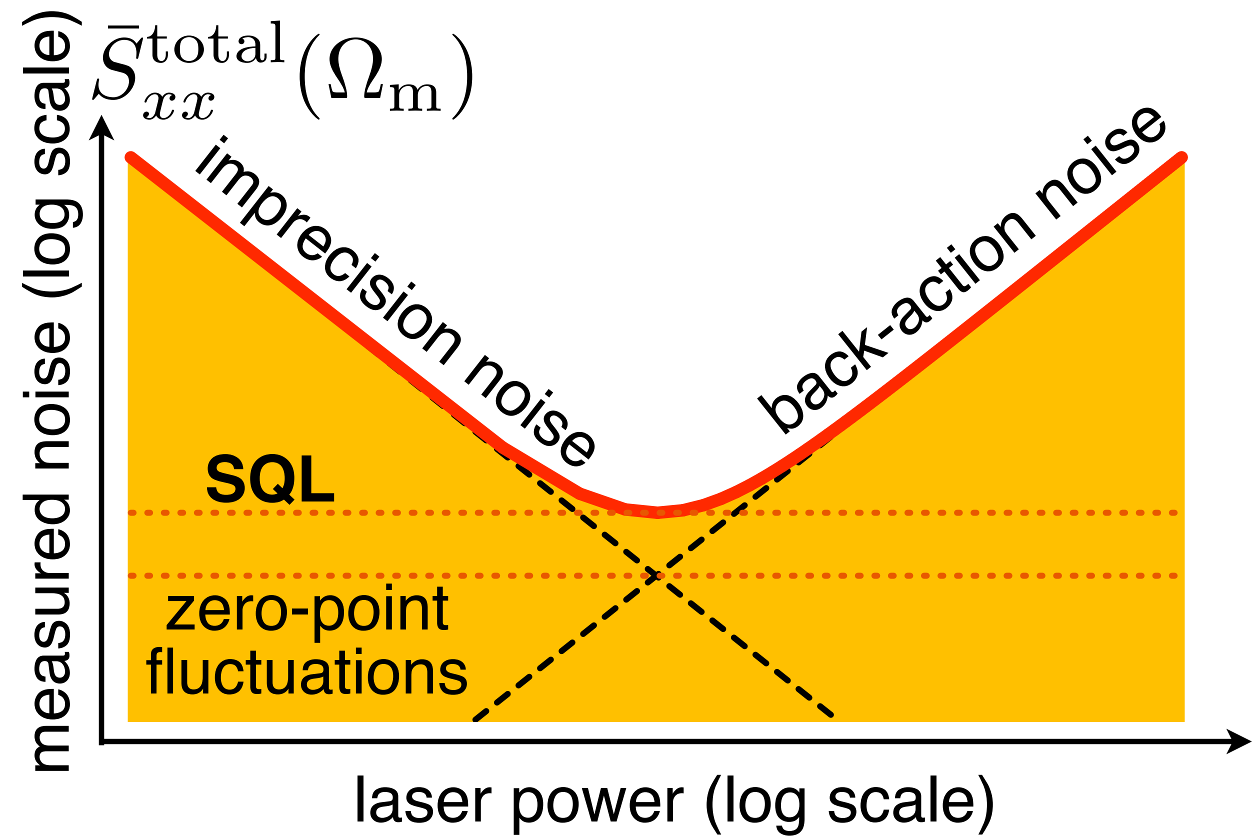
phase noise of laser beam (shot noise limit!)

2. measurement back-action: fluctuating force on system

noisy radiation pressure force

"Standard Quantum Limit"





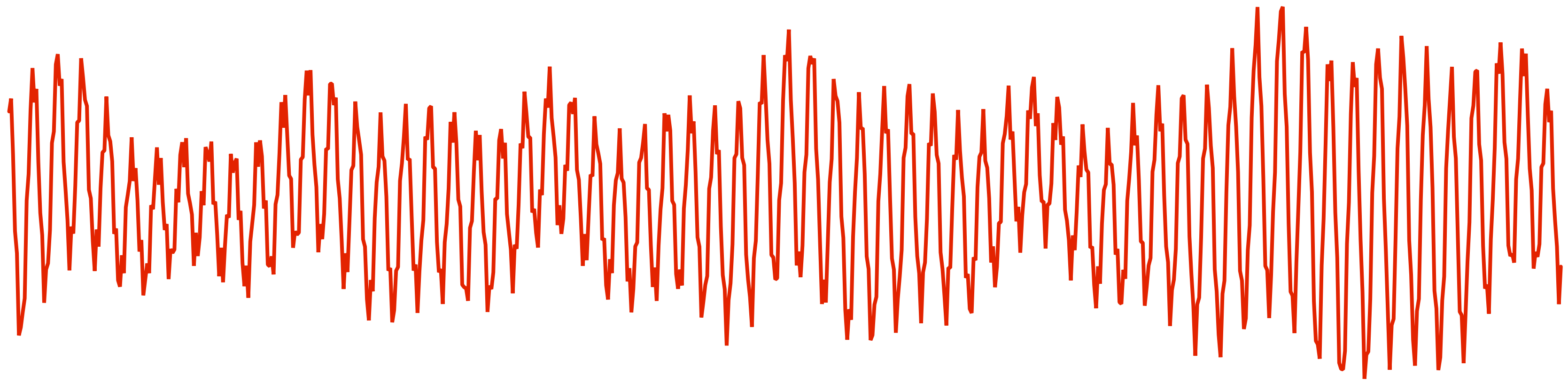
Best case allowed by quantum mechanics:

$$S_{xx}^{(\rm meas)}(\omega) \geq 2 \cdot S_{xx}^{T=0}(\omega)$$

"Standard quantum limit (SQL) of displacement detection"

...as if adding the zero-point fluctuations a second time: "adding half a photon"

Notes on the SQL



- "weak measurement": integrating the signal over time to suppress the noise
- trying to detect slowly varying "quadratures of motion": $\hat{x}(t) = \hat{X}_1 \cos(\omega_M t) + \hat{X}_2 \sin(\omega_M t)$

$$\left[\hat{X}_1, \hat{X}_2\right] = 2x_{\mathrm{ZPF}}^2$$

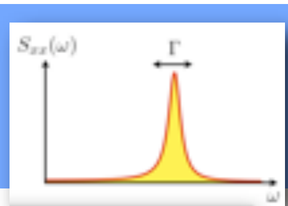
Heisenberg is the reason for SQL!

no limit for **instantaneous** measurement of x(t)!

- SQL means: detect $\hat{X}_{1,2}$ down to x_{ZPF} on a time scale $1/\Gamma$

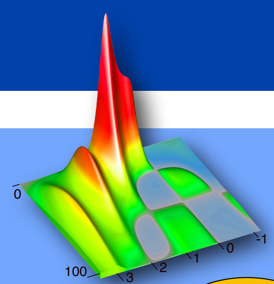
Impressive: $x_{\mathrm{ZPF}} \sim 10^{-15} m$!

Optomechanics (Outline)

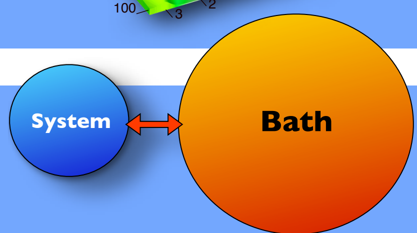


Displacement detection

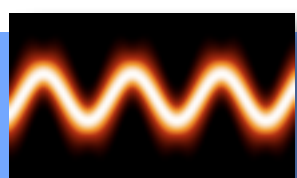
Linear optomechanics



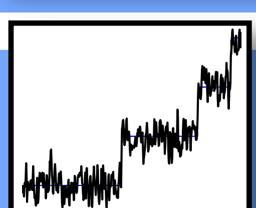
Nonlinear dynamics



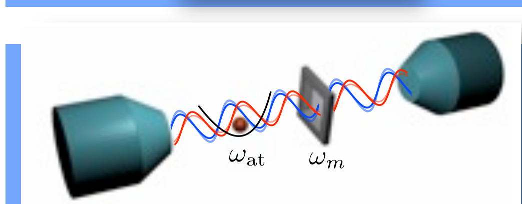
Quantum theory of cooling



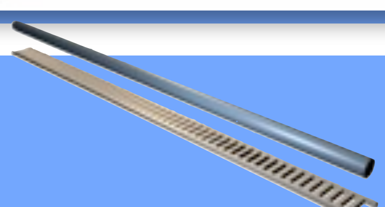
Interesting quantum states



Towards Fock state detection

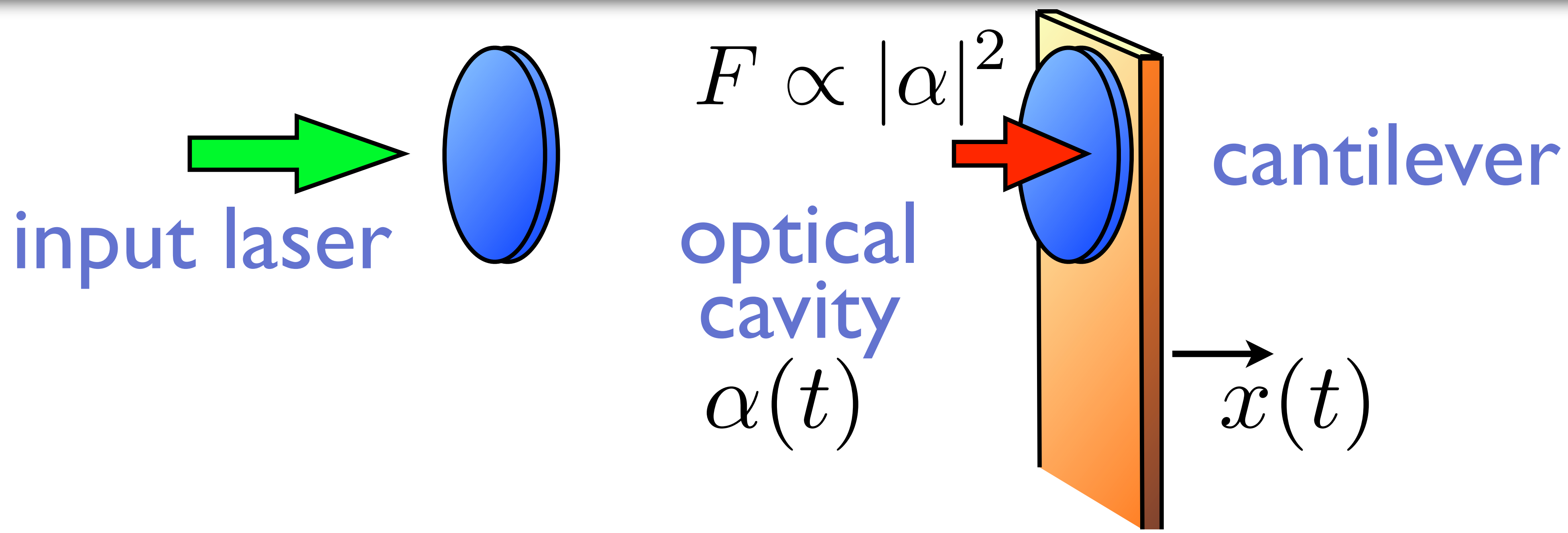


Hybrid systems: coupling to atoms

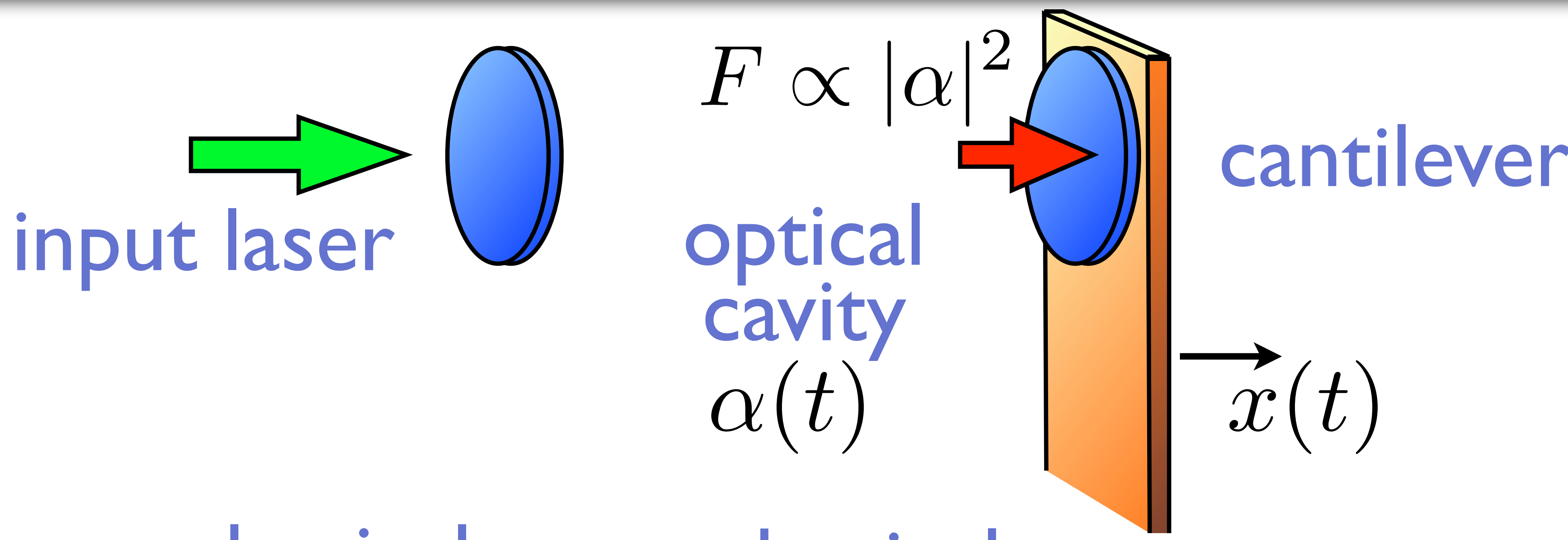


Optomechanical crystals & arrays

Equations of motion



Equations of motion



mechanical frequency, mechanical damping

$$\ddot{x} = -\omega_M^2 (x - x_0) - \Gamma \dot{x} + F/m$$

radiation pressure

equilibrium position

$$F = \frac{\hbar \omega_R}{L} |\alpha|^2$$

$$\dot{\alpha} = i\omega_R \frac{x}{L} \alpha - \frac{\kappa}{2} (\alpha - \alpha_{\text{in}})$$

laser amplitude

detuning from resonance, cavity decay rate

Linearized optomechanics

$$\alpha(t) = \bar{\alpha} + \delta\alpha(t)$$

$$x(t) = \bar{x} + \delta x(t)$$

$$\Rightarrow \ldots \Rightarrow$$

(solve for arbitrary $F_{\text{ext}}(\omega)$)

$$\delta x(\omega) = \underbrace{\frac{1}{m(\omega_M^2 - \omega^2) - im\omega\Gamma + \Sigma(\omega)}}_{\chi_{xx}^{\text{eff}}(\omega)} F_{\text{ext}}(\omega)$$

$$\delta\omega_M^2 = \frac{1}{m}\text{Re}\Sigma(\omega_M)$$

Optomechanical frequency shift ("optical spring")

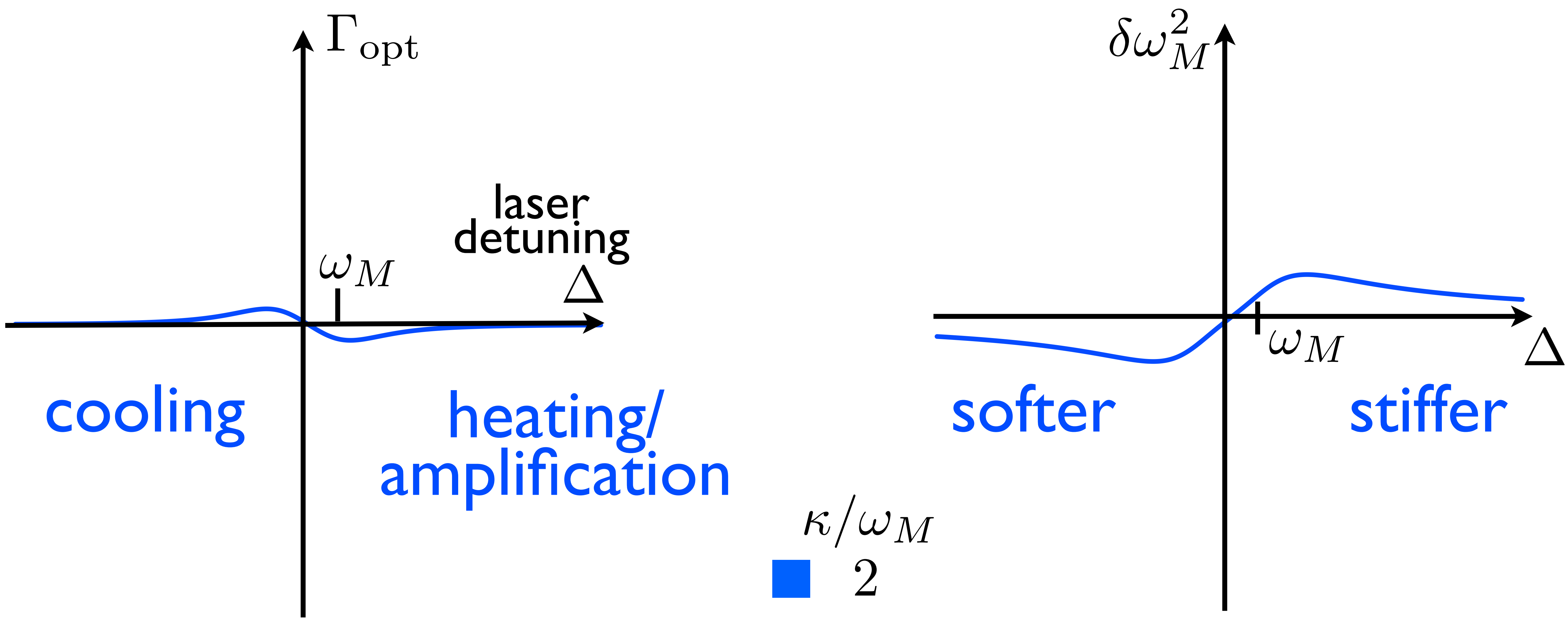
$$\Gamma_{\text{opt}} = -\frac{1}{m\omega_M}\text{Im}\Sigma(\omega_M)$$

Effective optomechanical damping rate

Linearized dynamics

Effective optomechanical damping rate

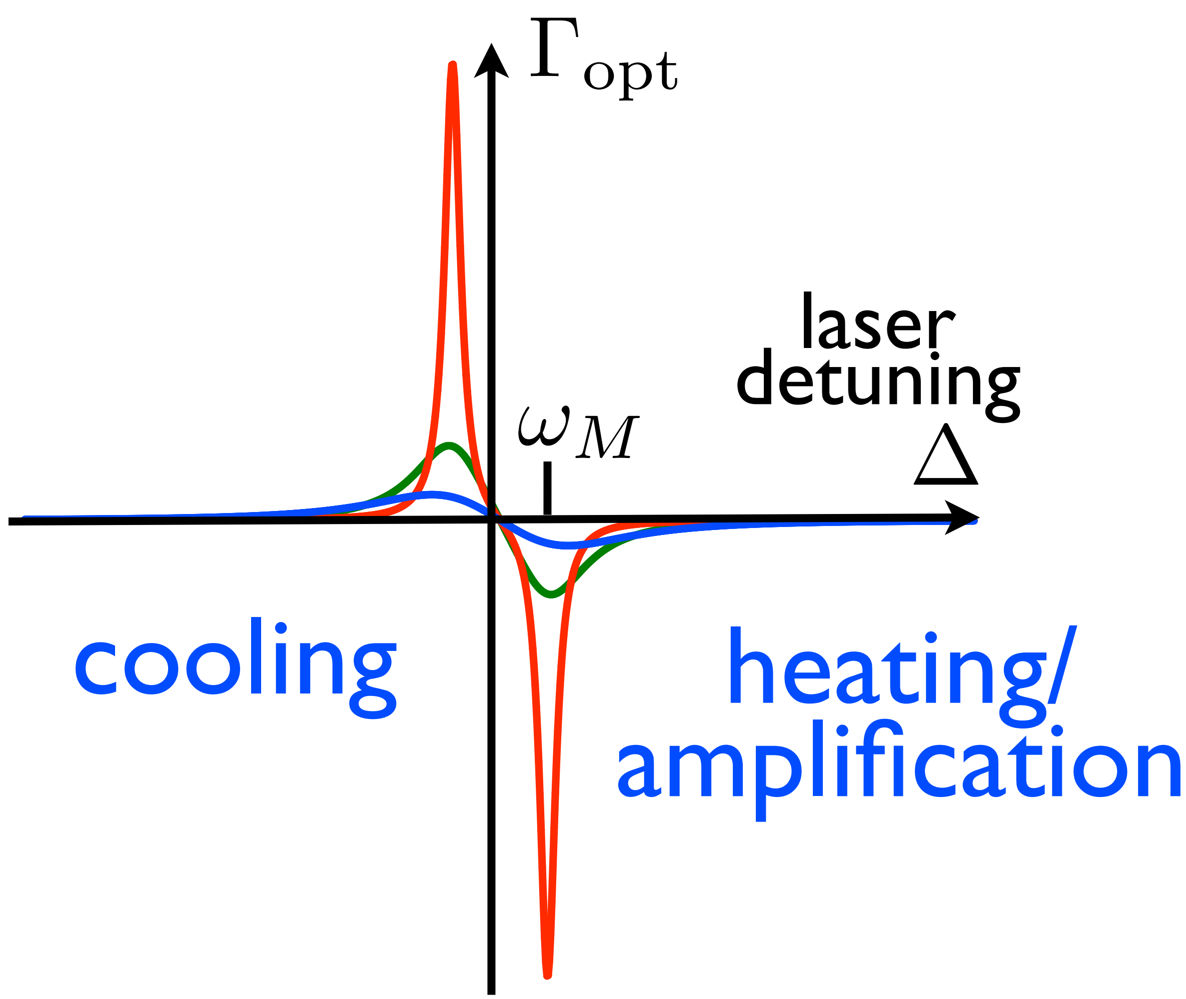
Optomechanical frequency shift ("optical spring")



$$(\Delta = \omega_R x_0 / L)$$

Linearized dynamics

Effective optomechanical damping rate



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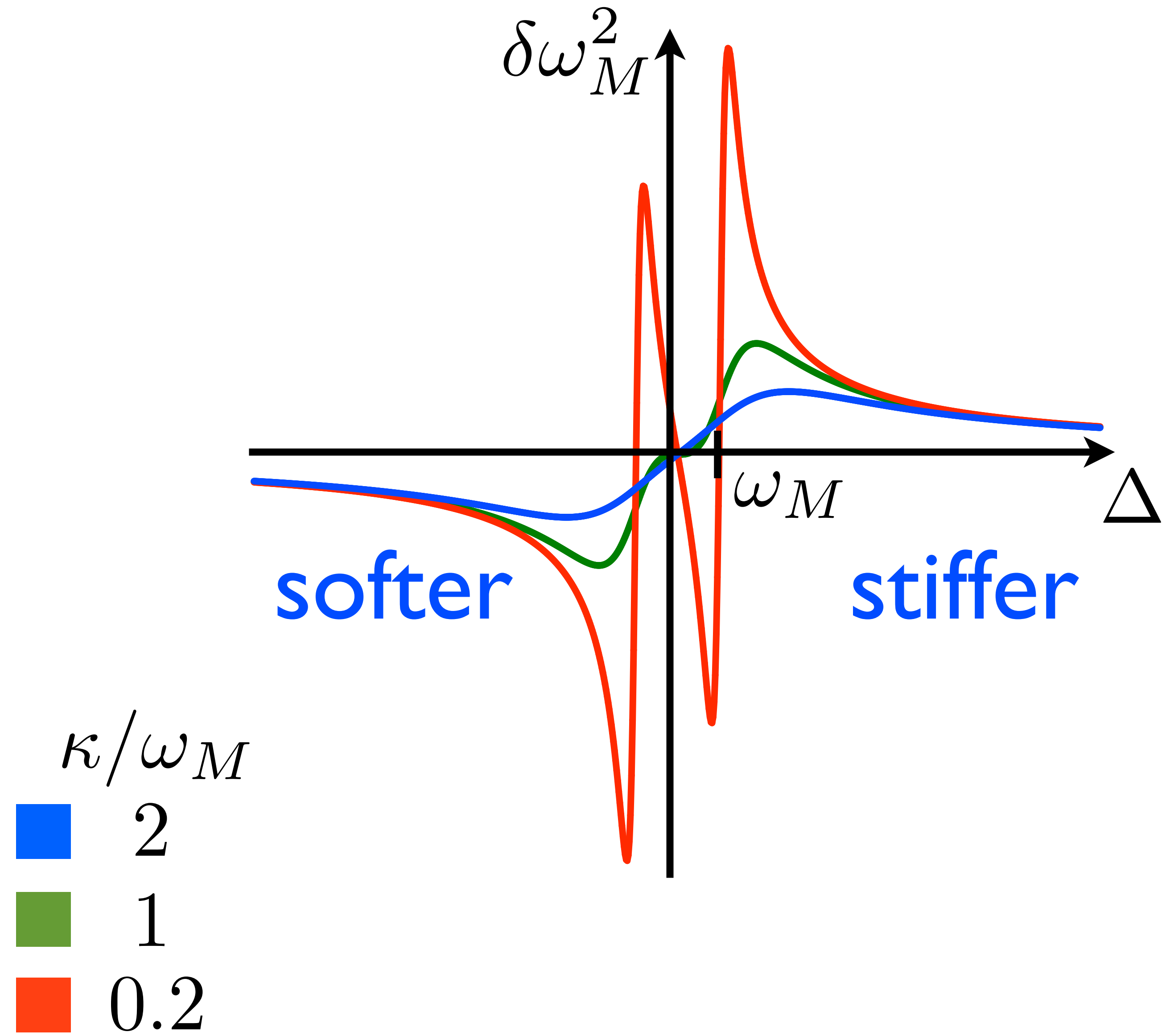
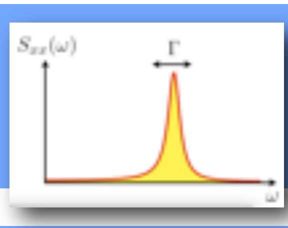
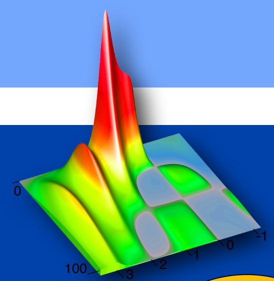


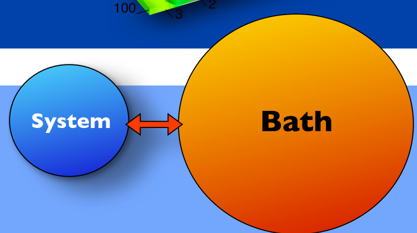
Optomechanics (Outline)



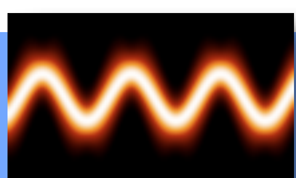
- Displacement detection
- Linear optomechanics



- **Nonlinear dynamics**



- Quantum theory of cooling



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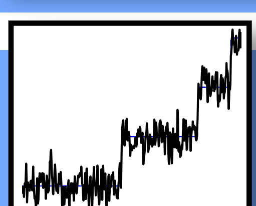

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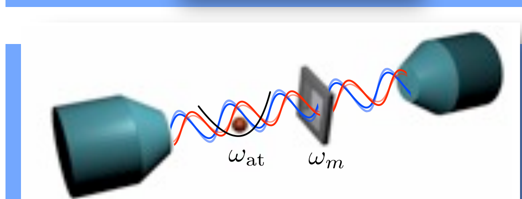

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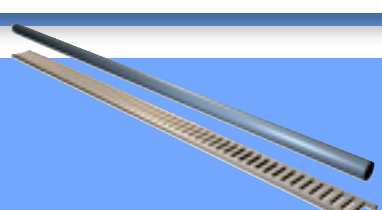
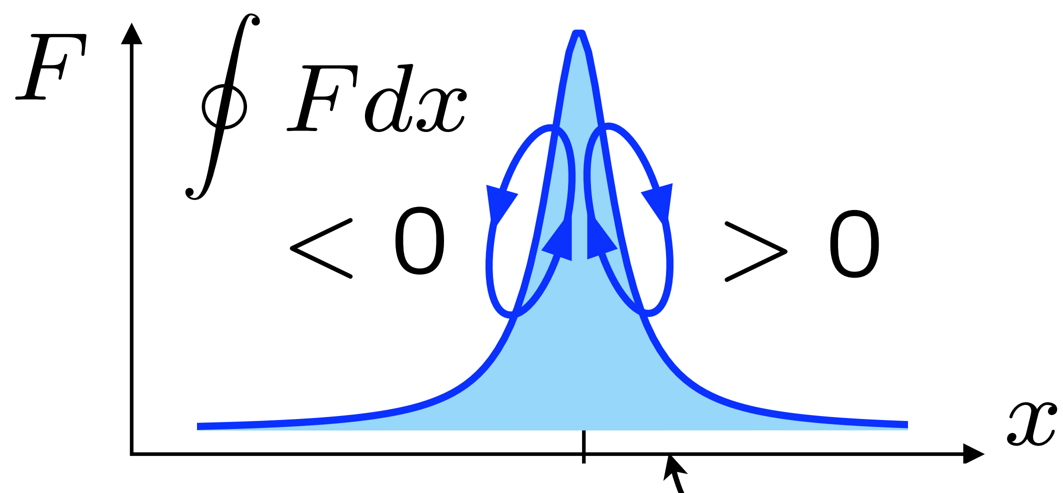


- Optomechanical crystals & arrays

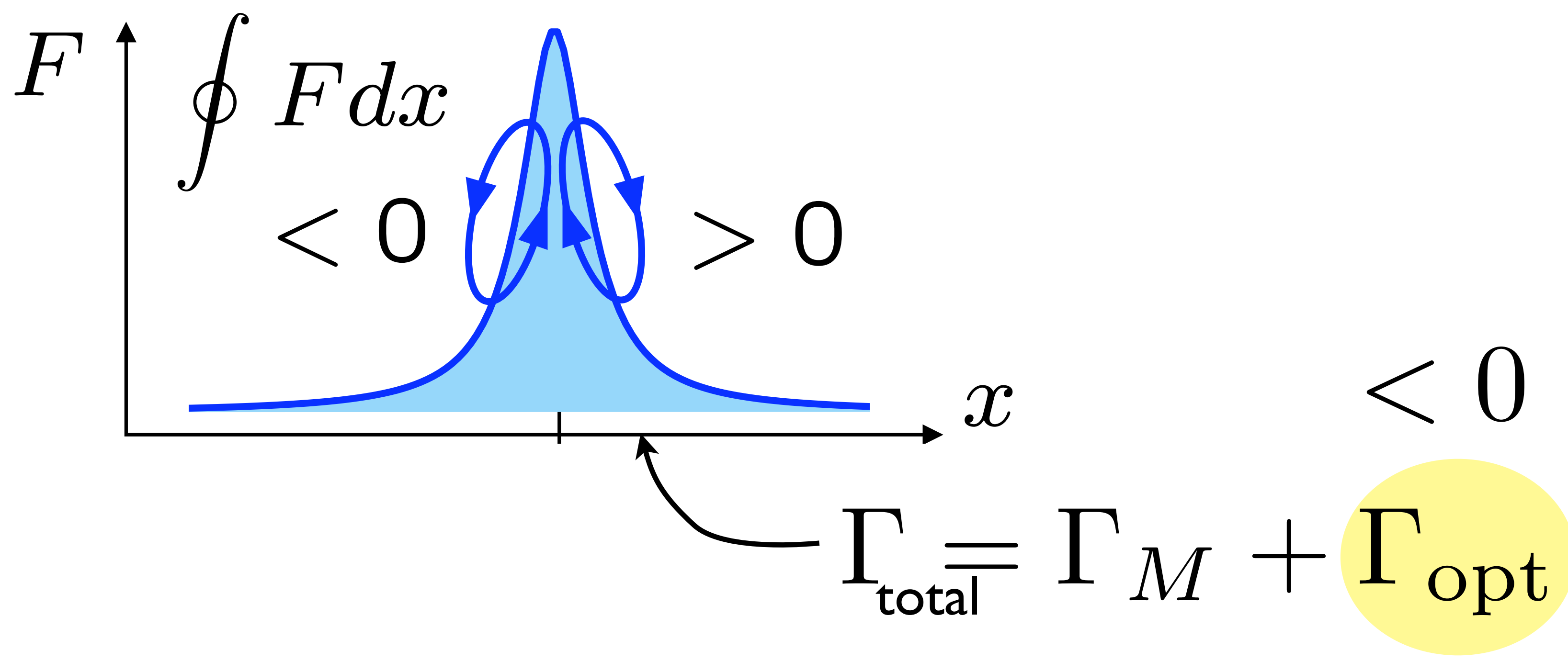
Self-induced oscillations



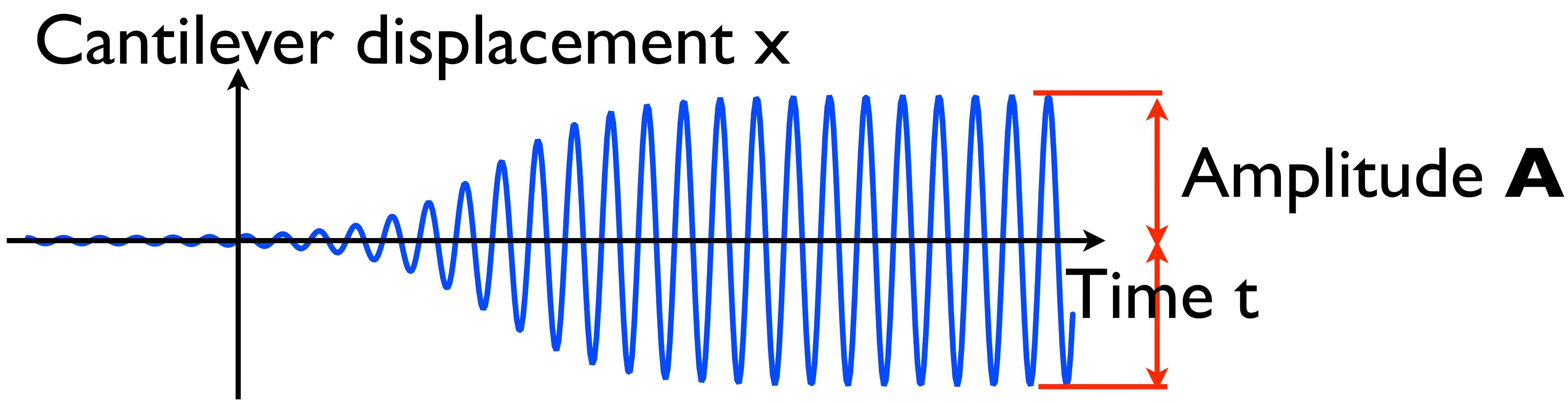
< 0

$$\Gamma_{\text{total}} = \Gamma_M + \Gamma_{\text{opt}}$$

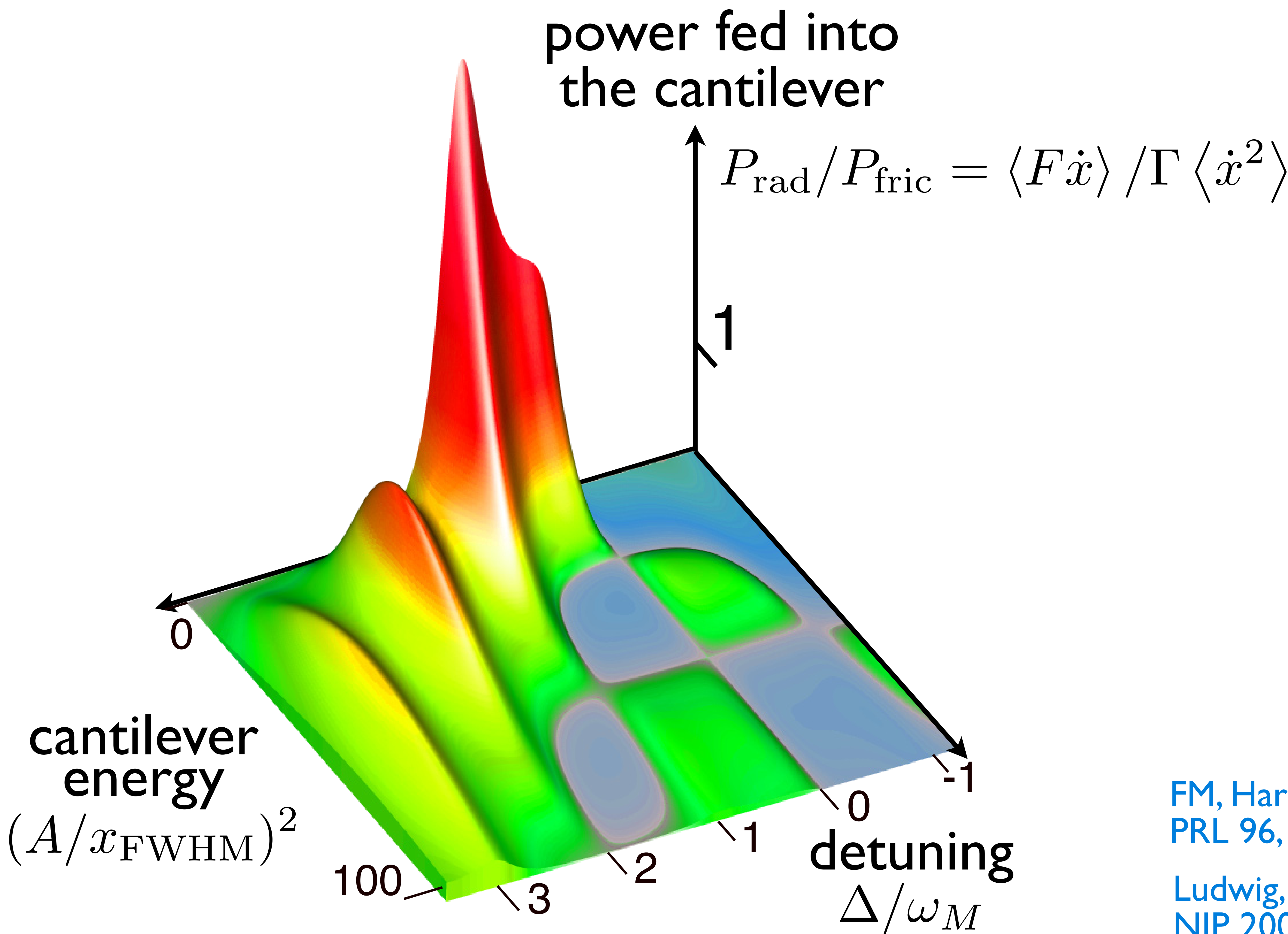
Self-induced oscillations



Beyond some laser input power threshold: instability



Attractor diagram



FM, Harris, Girvin,
PRL 96, 103901 (2006)

Ludwig, Kubala, FM,
NJP 2008

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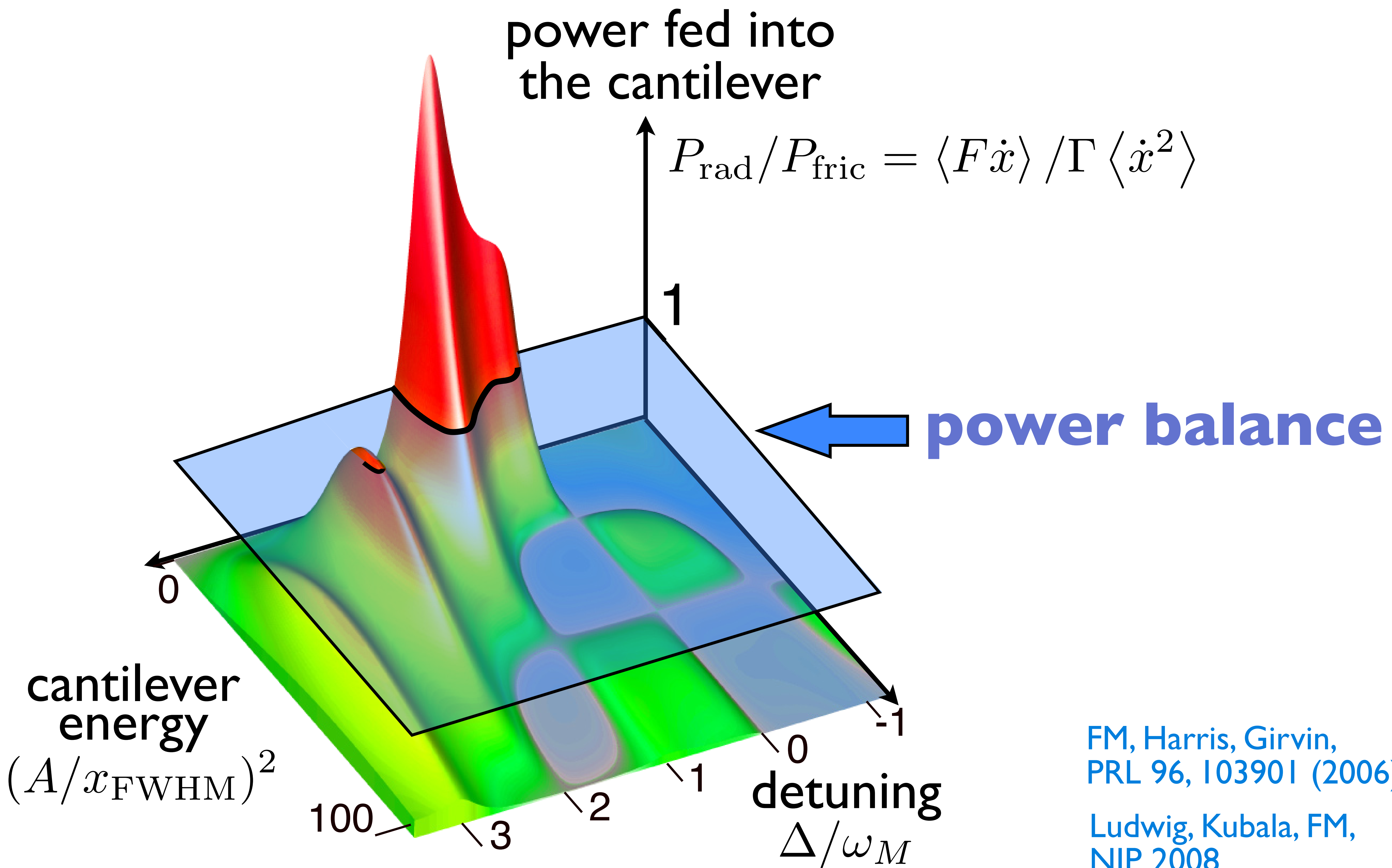

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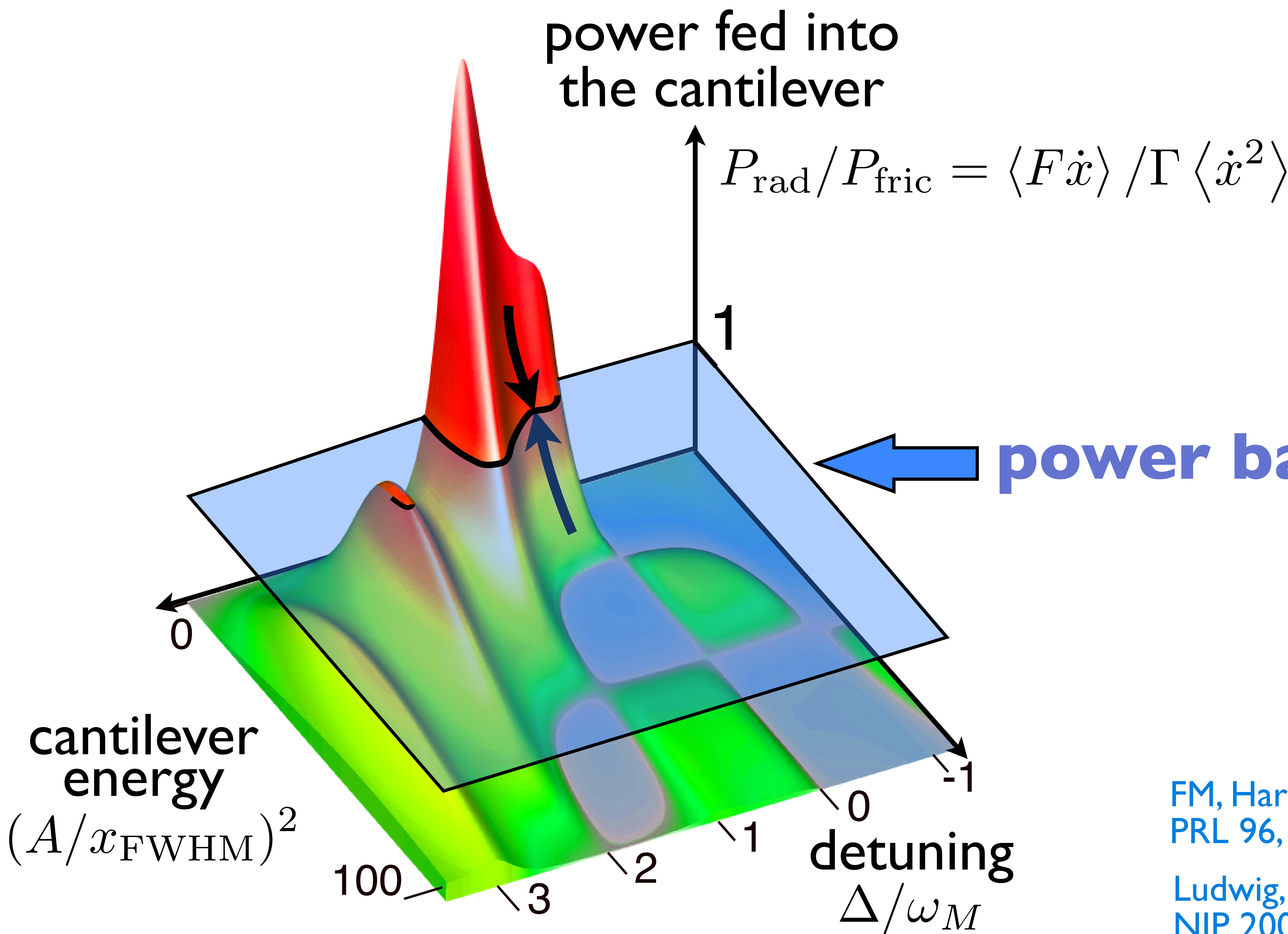

power balance

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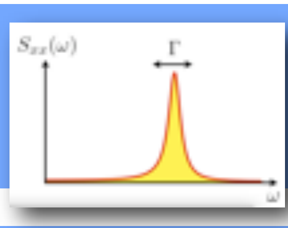
Optomechanics (Outline)



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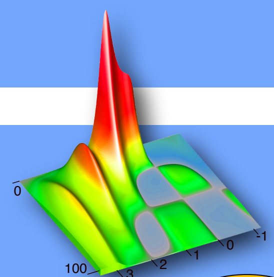
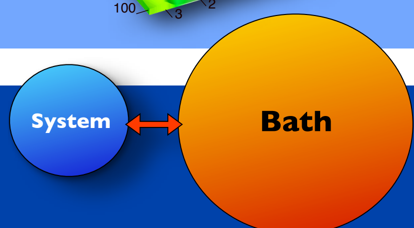
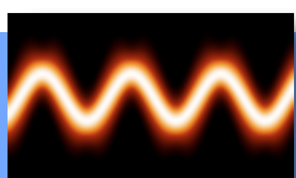


Linear optomechanics

Nonlinear dynamics



Quantum theory of cooling



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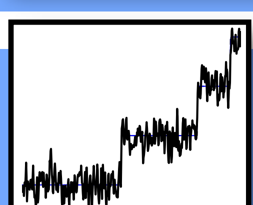

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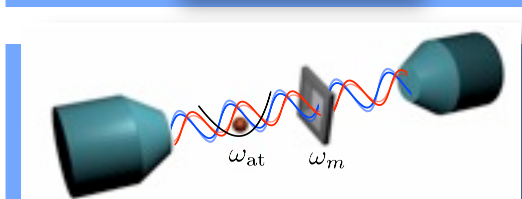
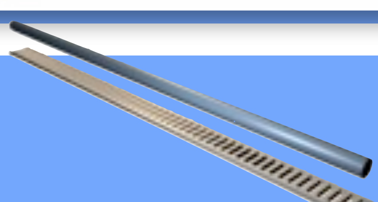
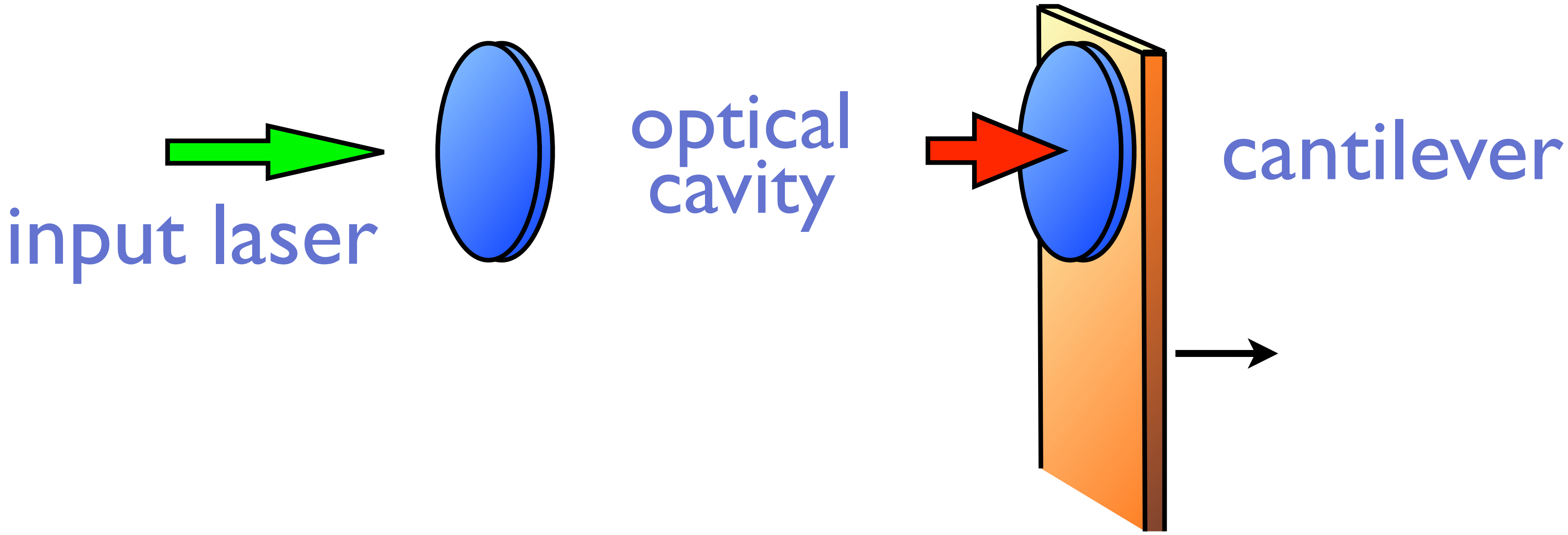


Hybrid systems: coupling to atoms



Optomechanical crystals & arrays

Cooling with light



Current goal in the field: *ground state* of mechanical motion of a macroscopic cantilever

$$k_B T_{\mathrm{eff}} \ll \hbar \omega_M$$

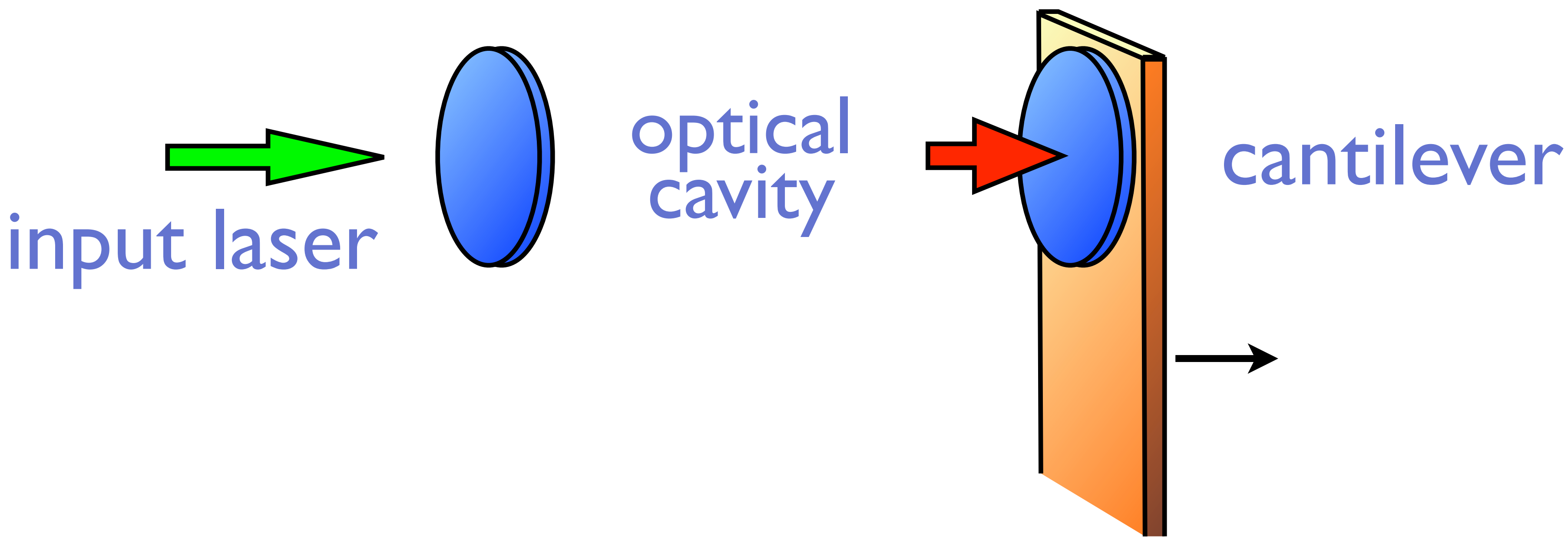
Classical theory:

$$T_{\mathrm{eff}} = T \cdot \frac{\Gamma_M}{\Gamma_{\mathrm{opt}} + \Gamma_M}$$

optomechanical damping rate

Pioneering theory and experiments: **Braginsky** (since 1960s)

Cooling with light



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Classical theory:

quantum limit?

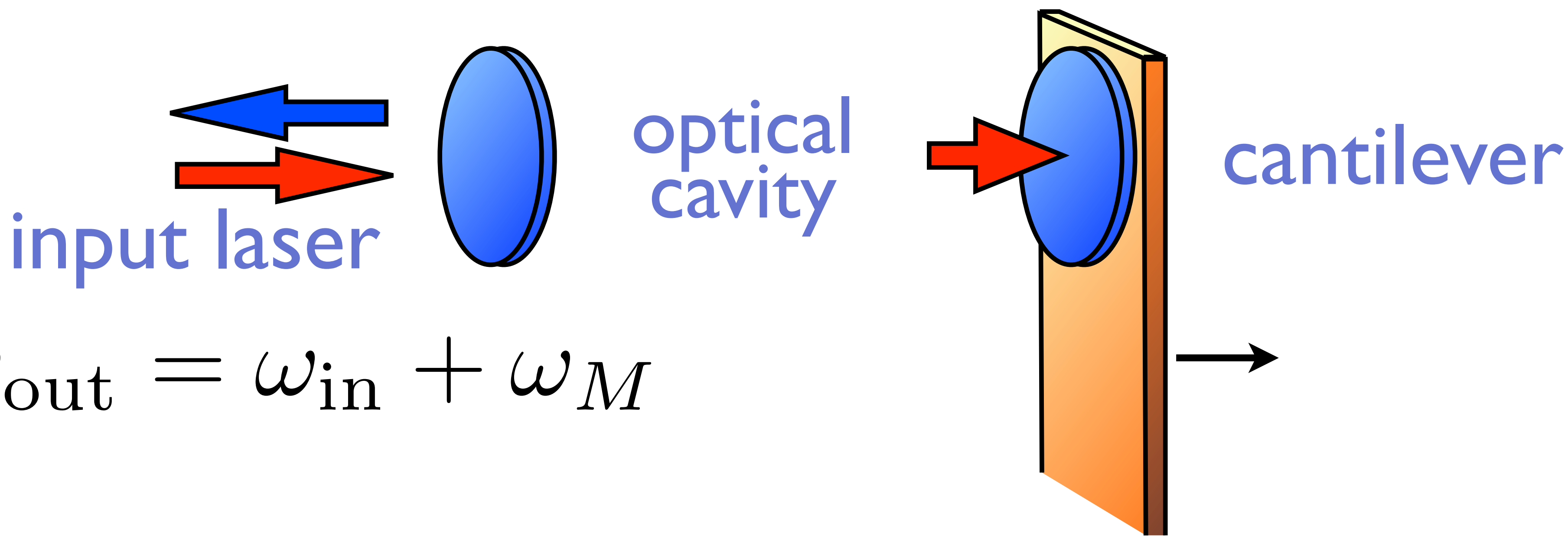
$$T_{\mathrm{eff}} = T \cdot \frac{\Gamma_M}{\Gamma_{\mathrm{opt}} + \Gamma_M} \rightarrow 0 \;?$$

shot noise!

optomechanical damping rate

Pioneering theory and experiments: **Braginsky** (since 1960s)

Cooling with light



$$\omega_{\mathrm{out}} = \omega_{\mathrm{in}} + \omega_M$$

Quantum picture: Raman scattering – sideband cooling

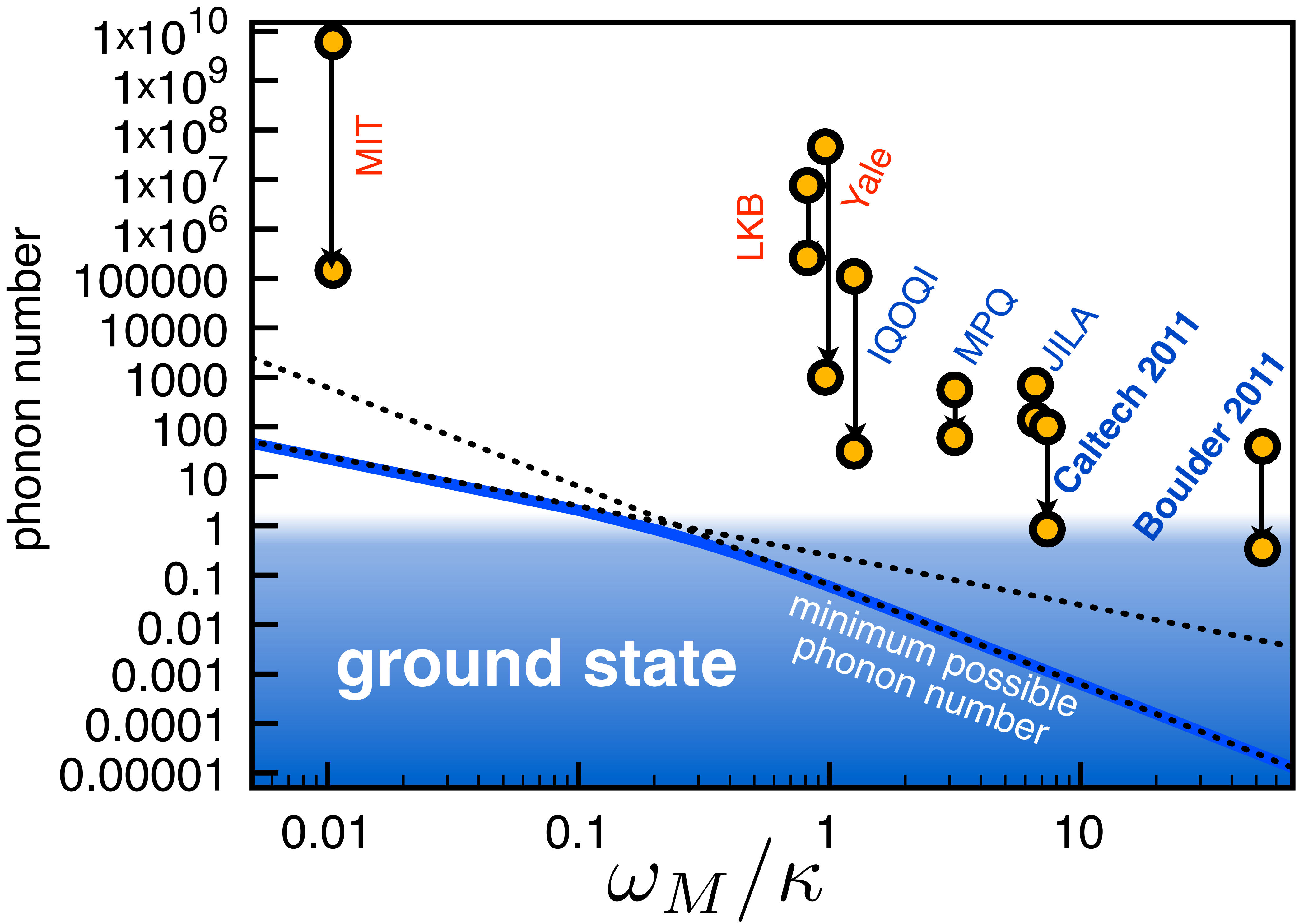
Original idea:

Sideband cooling in ion traps – Hänsch, Schawlow / Wineland, Dehmelt 1975

Similar ideas proposed for nanomechanics:

cantilever + quantum dot – Wilson-Rae, Zoller, Imamoglu 2004
cantilever + Cooper-pair box – Martin Shnirman, Tian, Zoller 2004
cantilever + ion – Tian, Zoller 2004
cantilever + supercond. SET – Clerk, Bennett / Blencowe, Imbers, Armour 2005,
Naik et al. (Schwab group) 2006

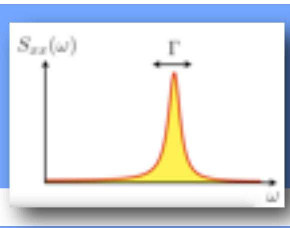
Laser-cooling towards the ground state



analogy to (cavity-assisted)
laser cooling of atoms

FM et al., PRL **93**, 093902 (2007)
Wilson-Rae et al., PRL **99**, 093901 (2007)

Optomechanics (Outline)



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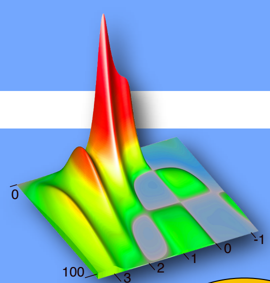

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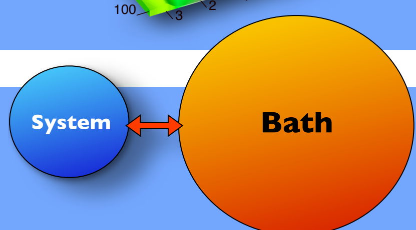

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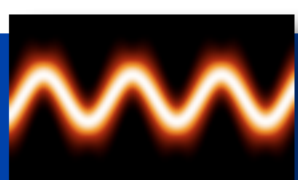

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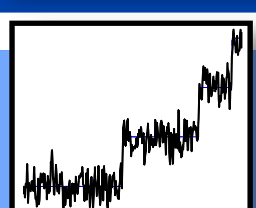

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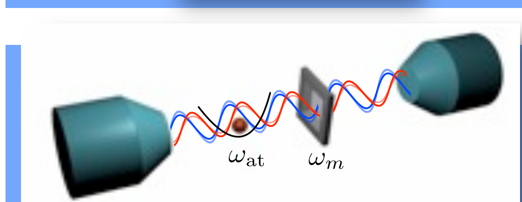

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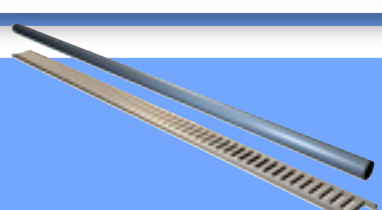
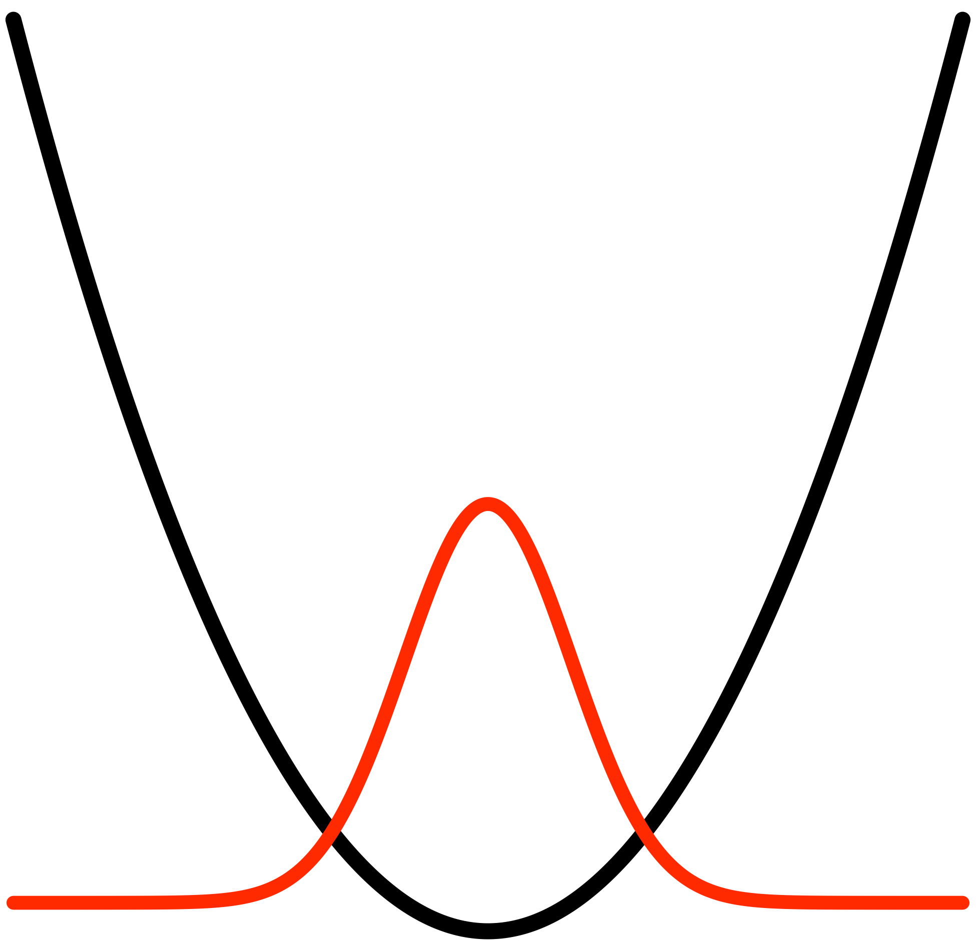


Optomechanical crystals & arrays

Squeezed states

Squeezing the mechanical oscillator state



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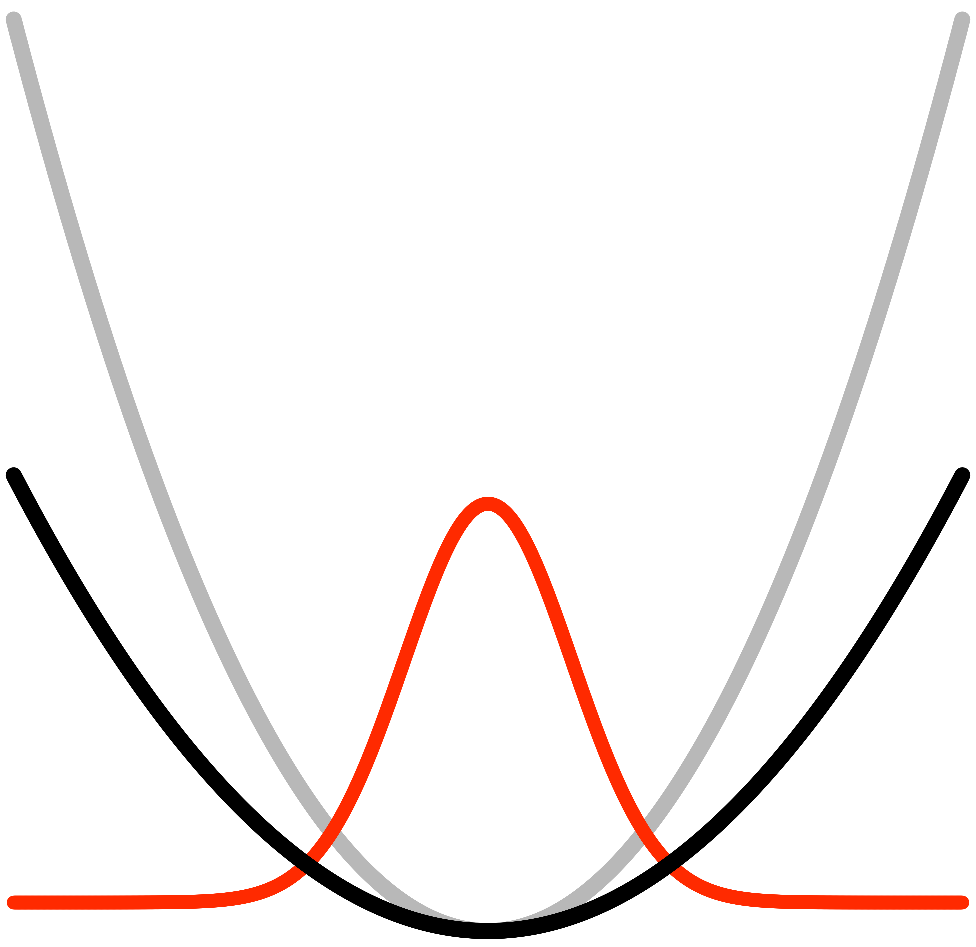

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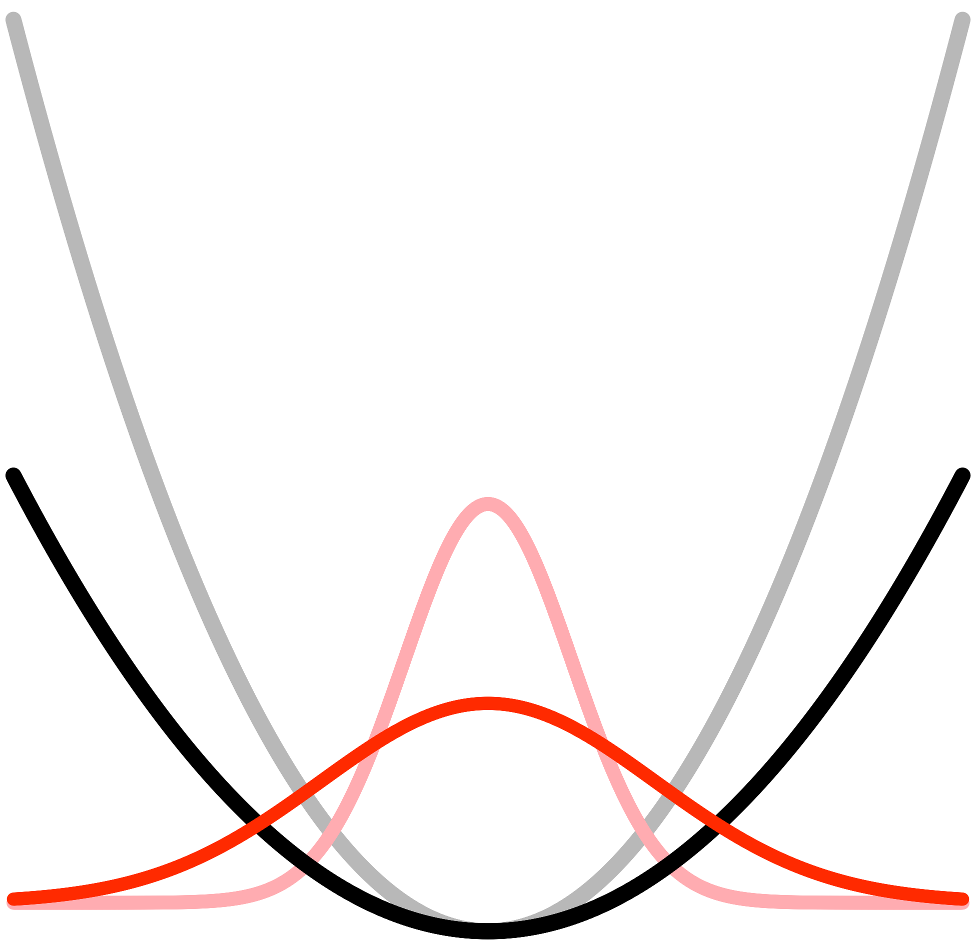

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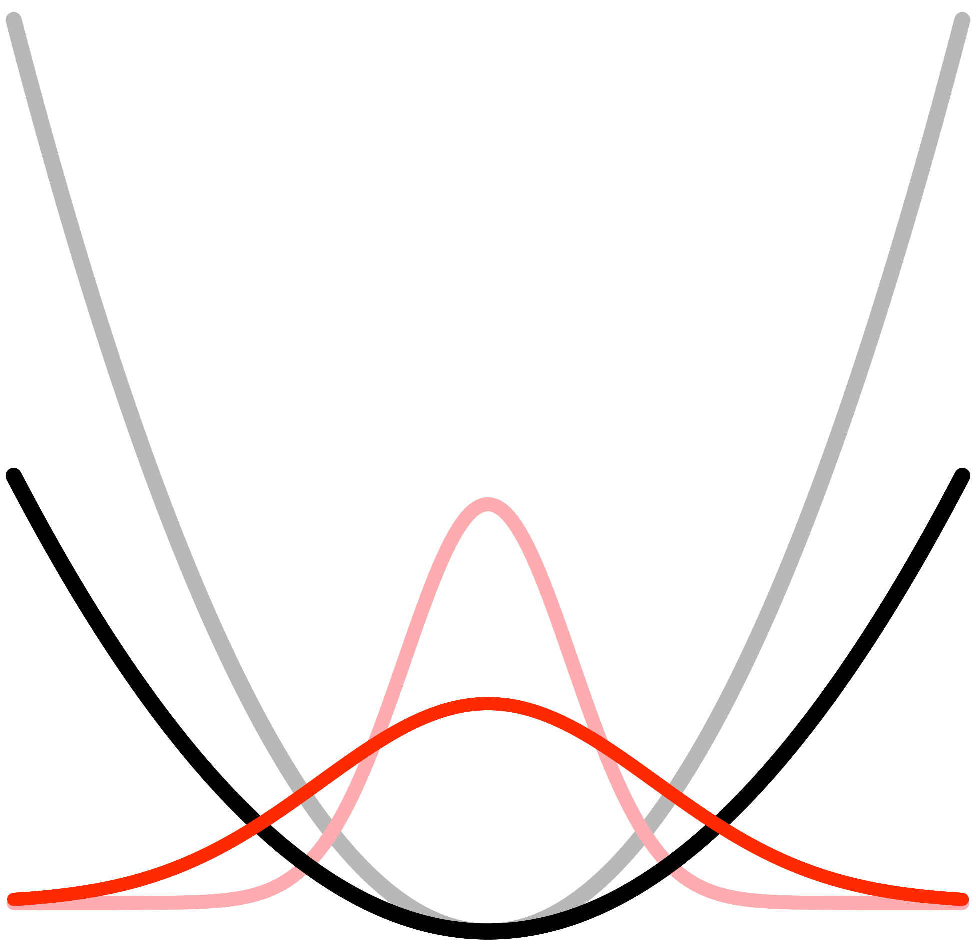

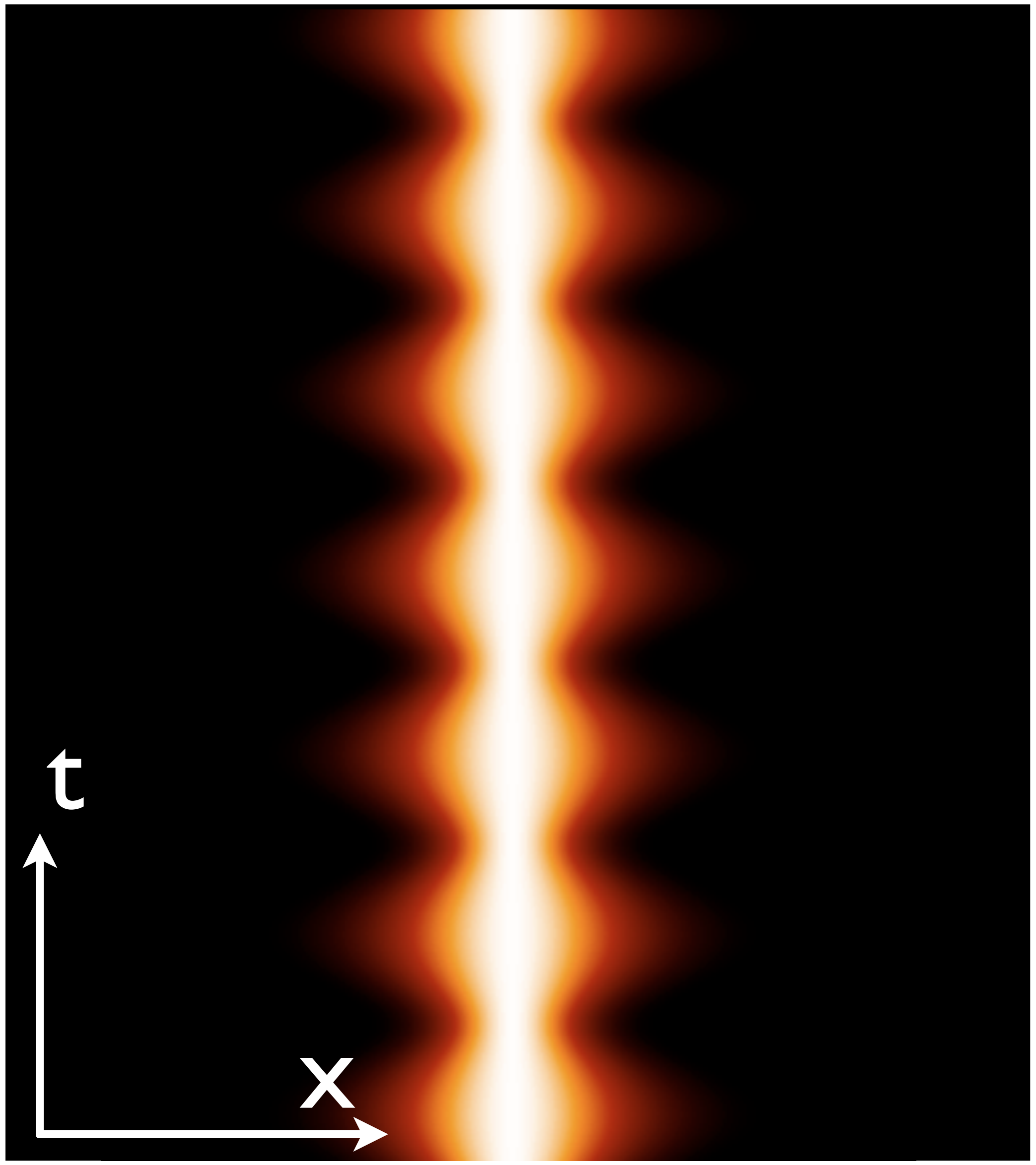

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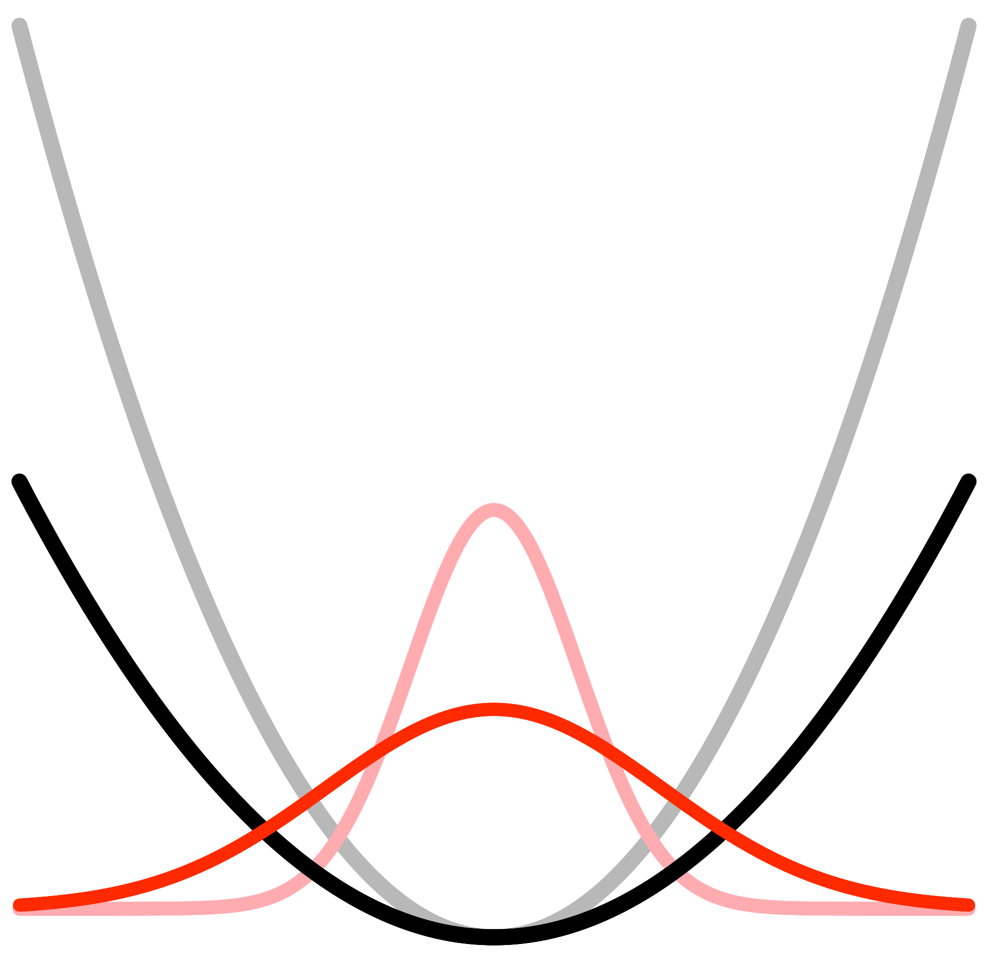
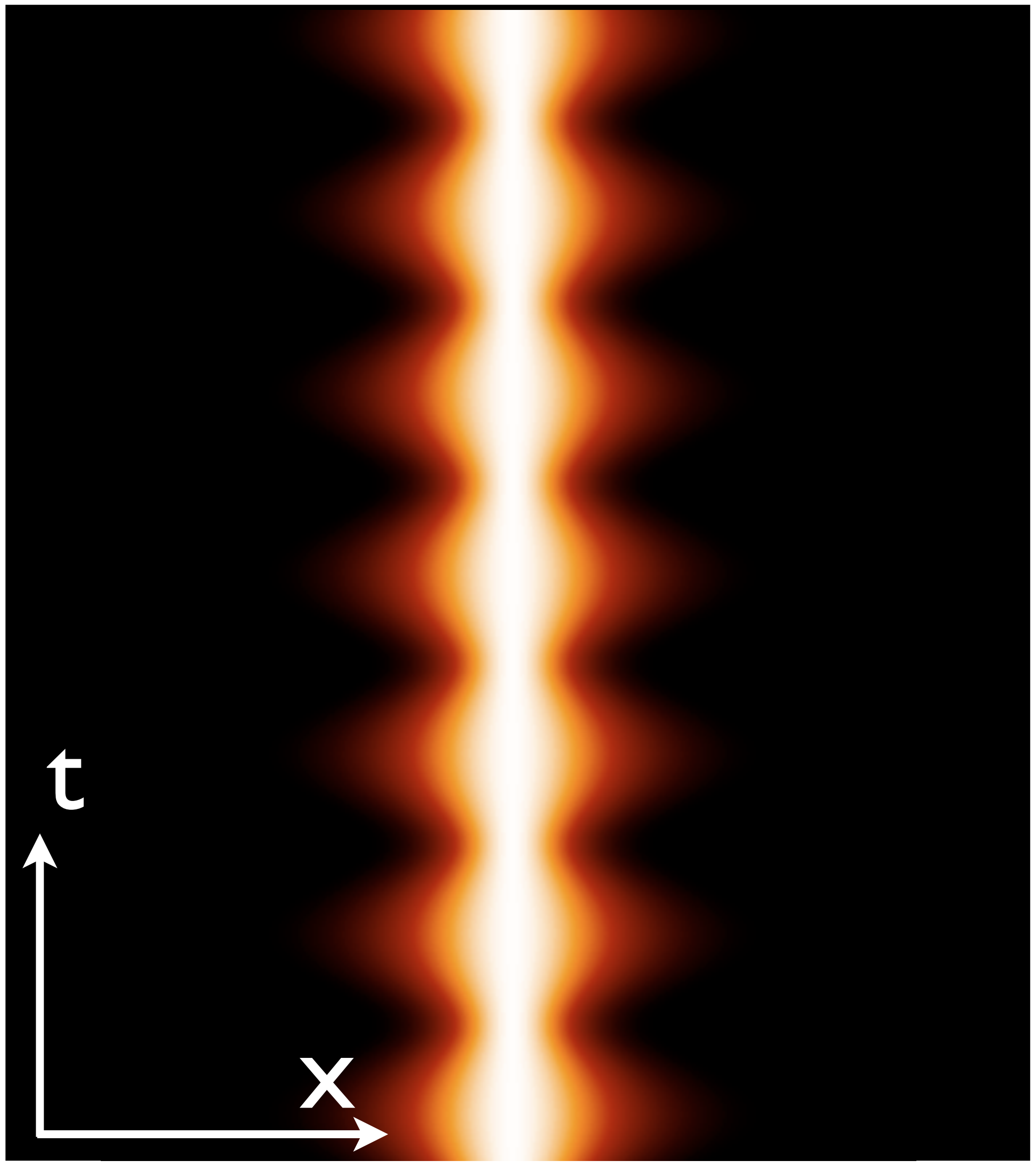
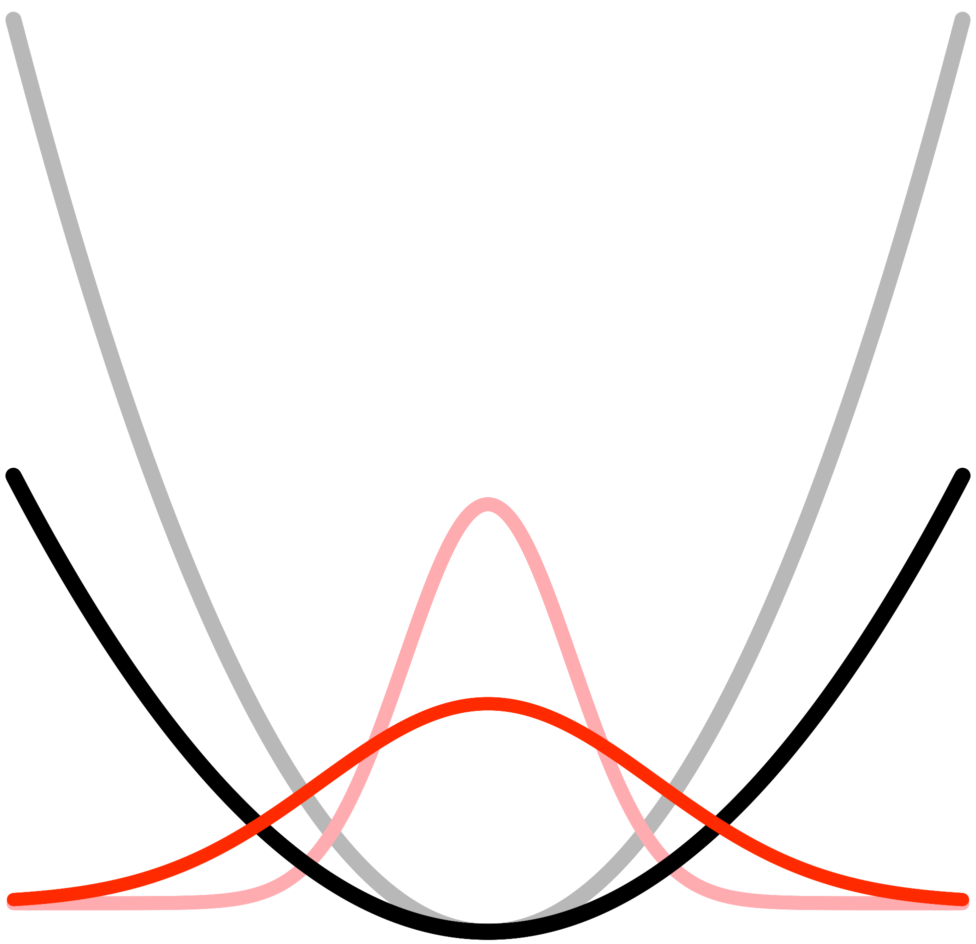


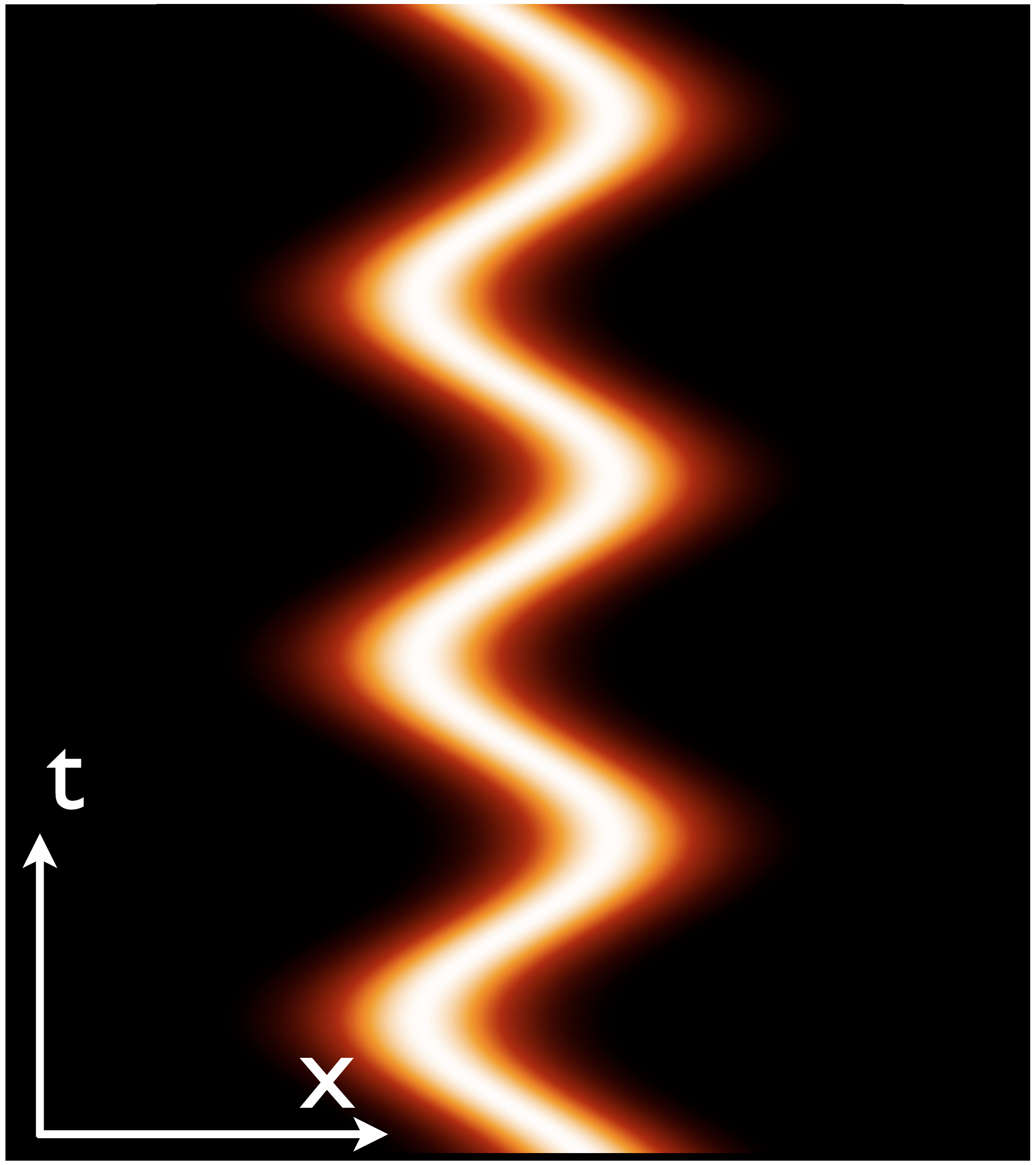


Periodic modulation of spring constant: $\delta\omega_M^2(t) \propto \cos(2\omega_M t)$
Parametric amplification

Squeezed states

Squeezing the mechanical oscillator state





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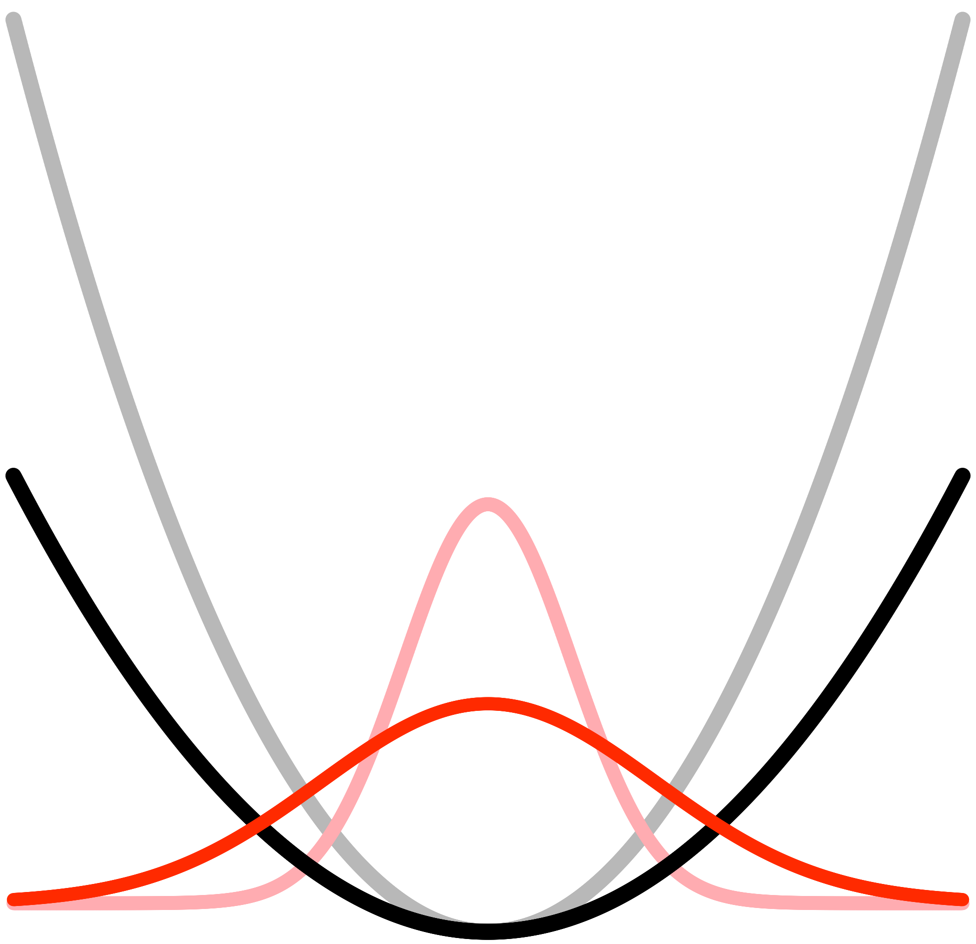

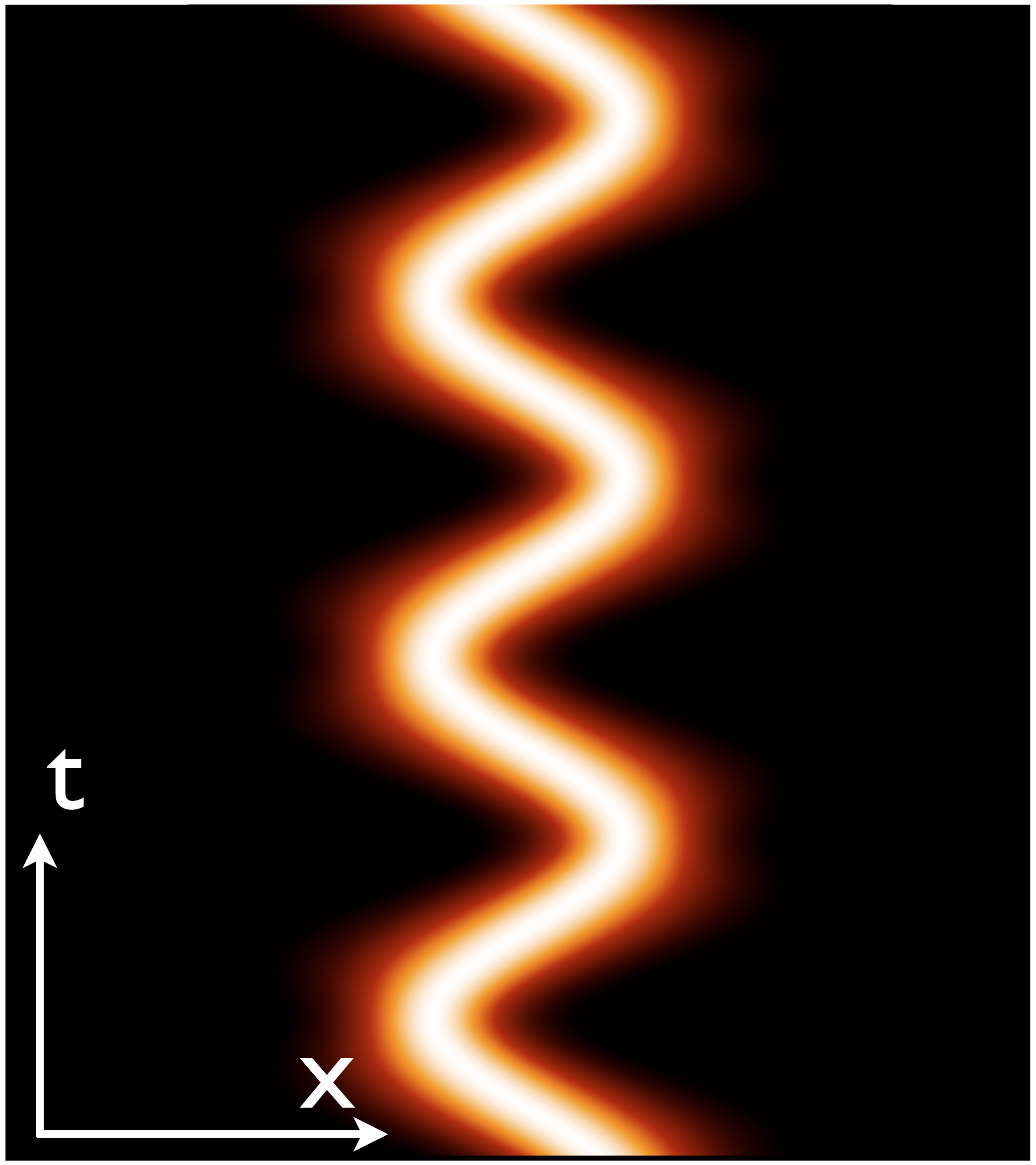

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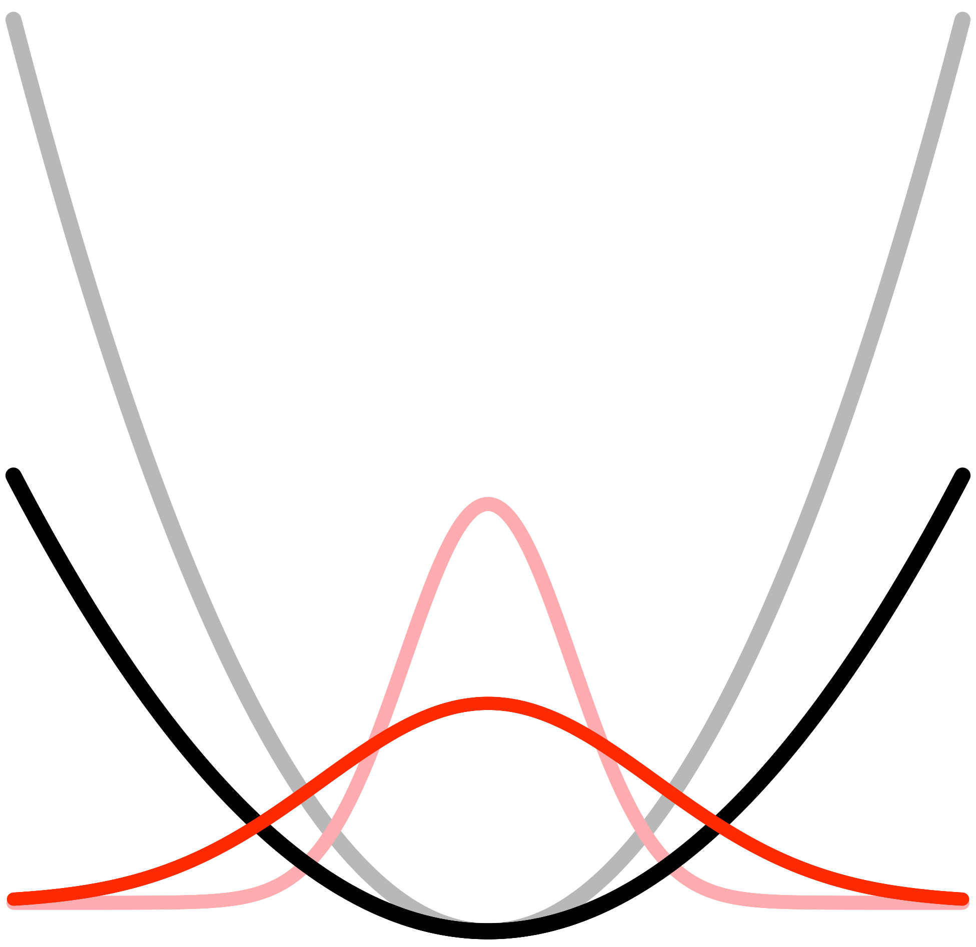

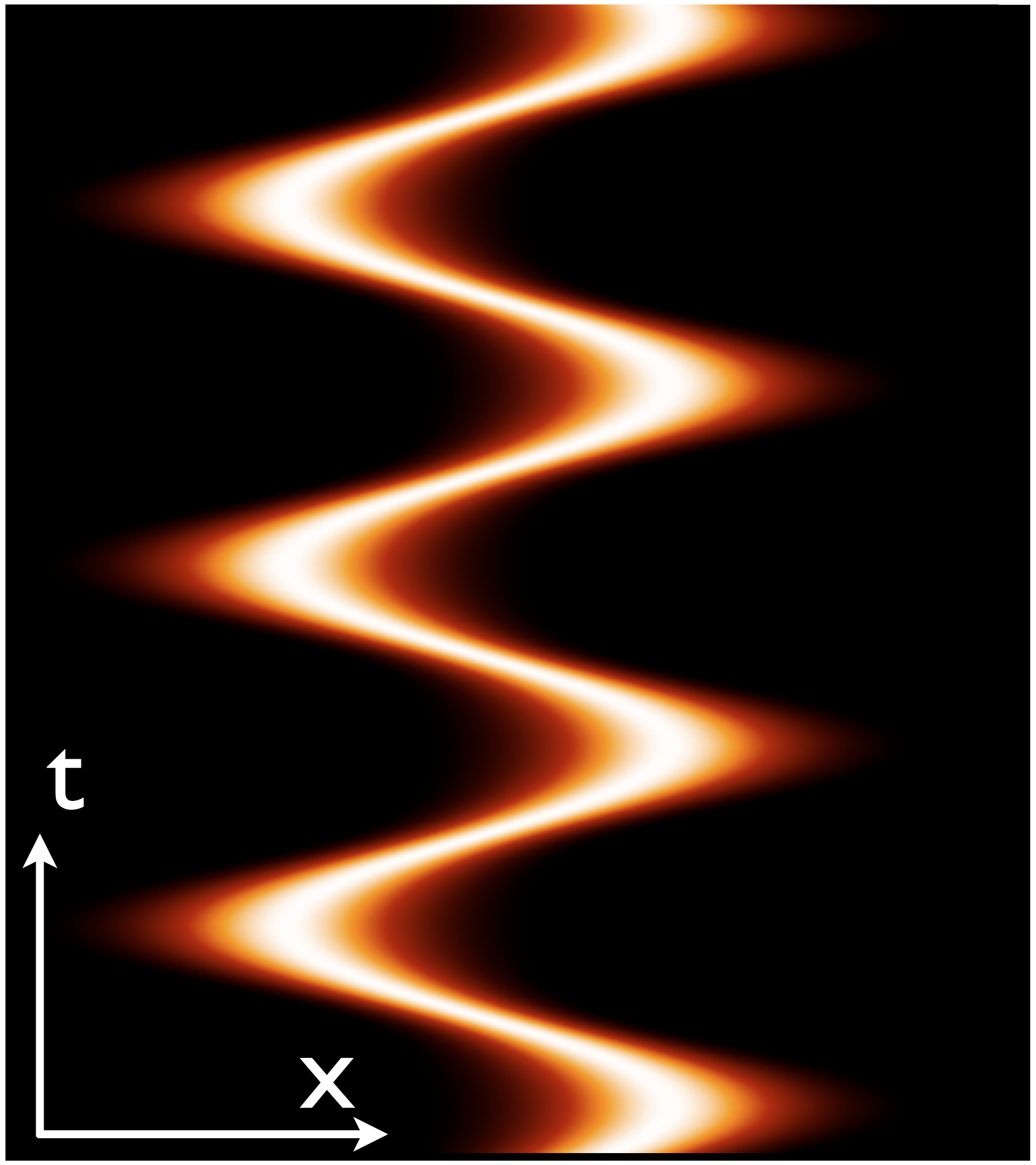

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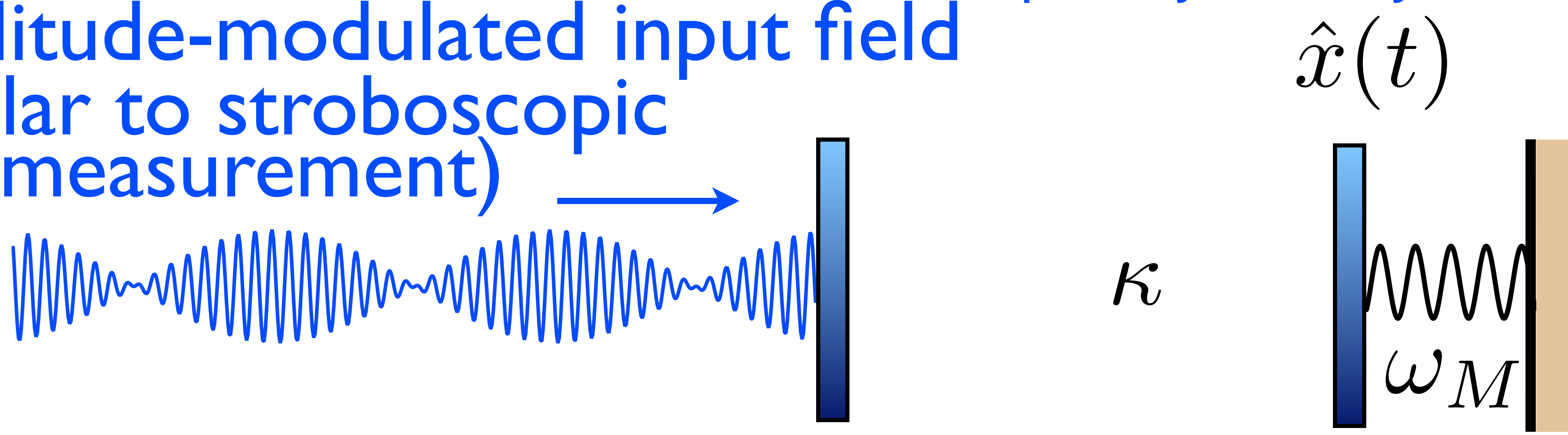
Measuring quadratures ("beating the SQL")

Clerk, Marquardt, Jacobs; NJP **10**, 095010 (2008)

amplitude-modulated input field (similar to stroboscopic measurement)



measure only one quadrature, back-action noise affects only the other one....need: $\kappa \ll \omega_M$

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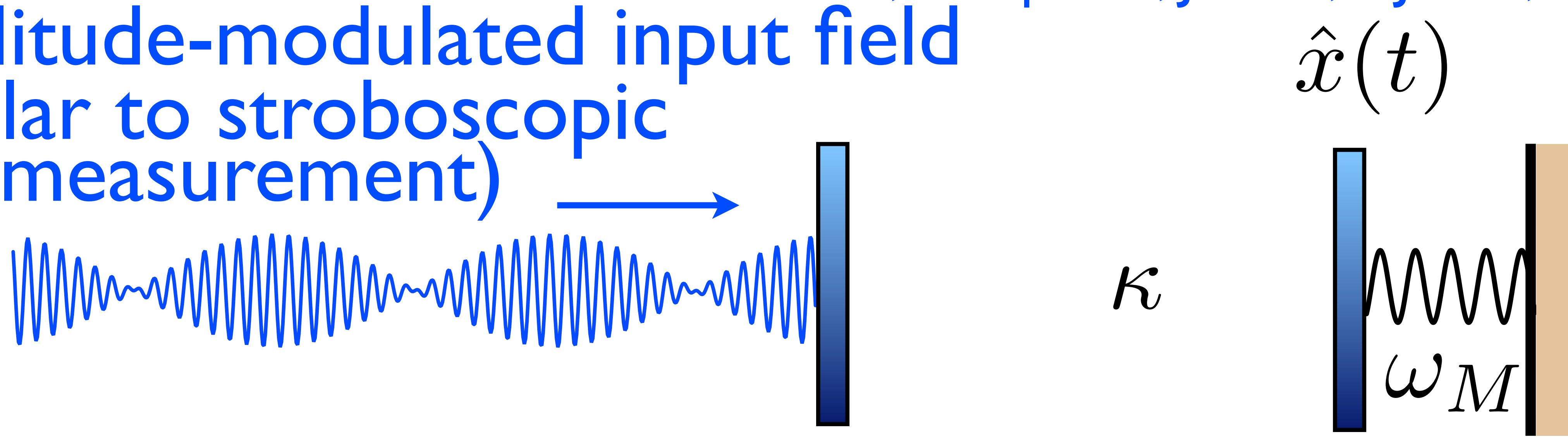

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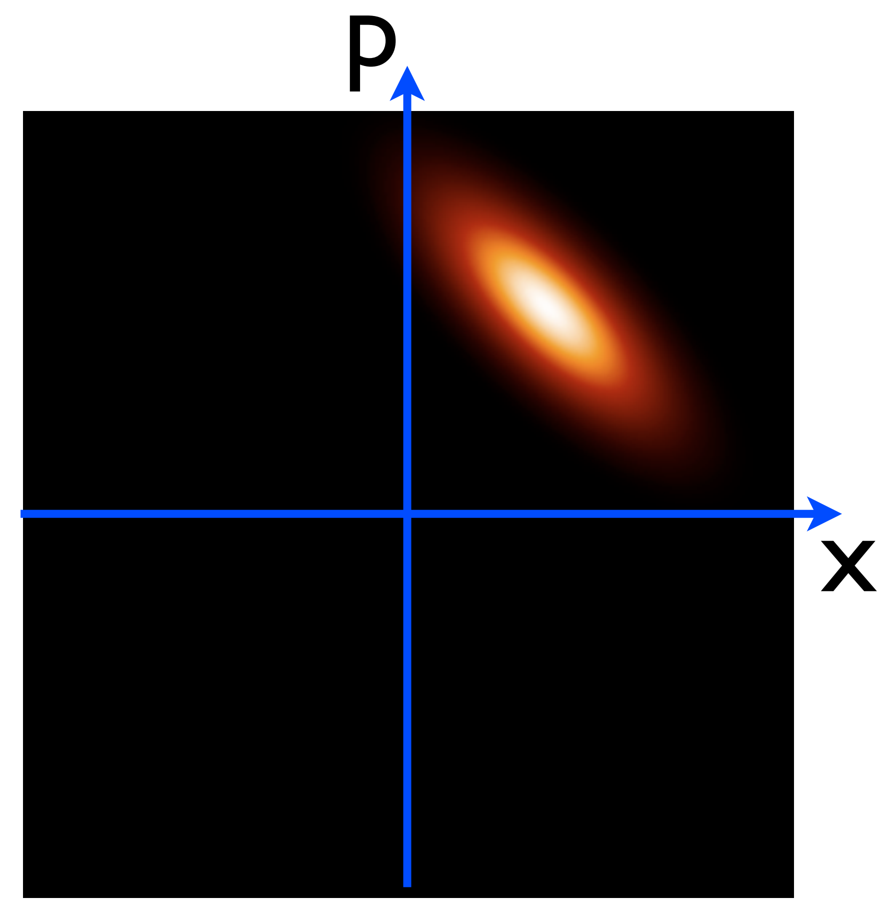
reconstruct mechanical Wigner density

(quantum state tomography)

$$W(x,p) \propto \int dy e^{ipy/\hbar} \rho(x - y/2, x + y/2)$$



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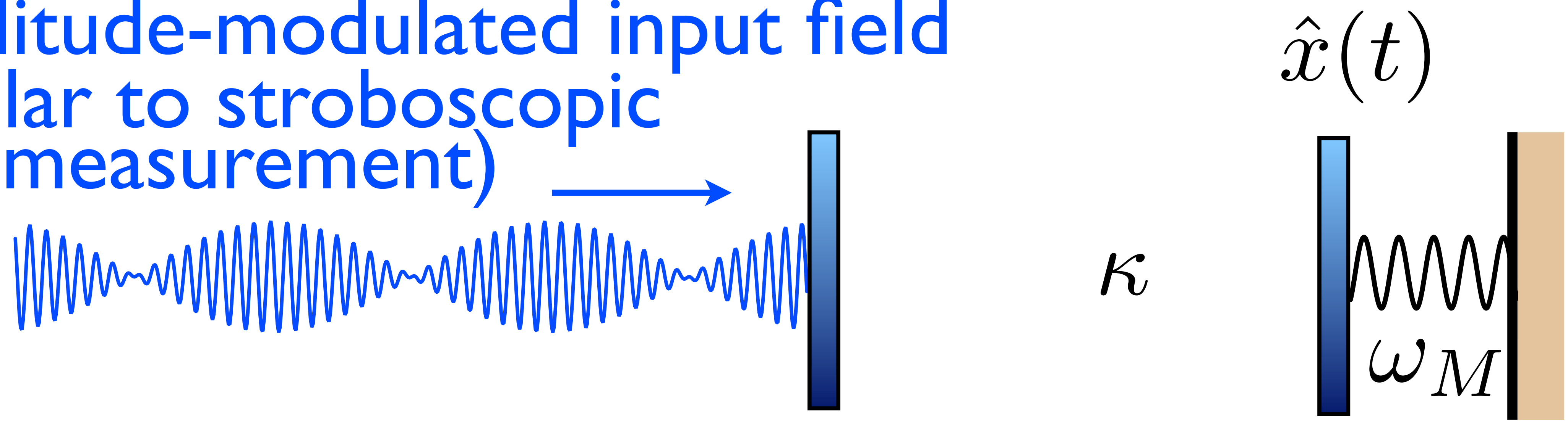

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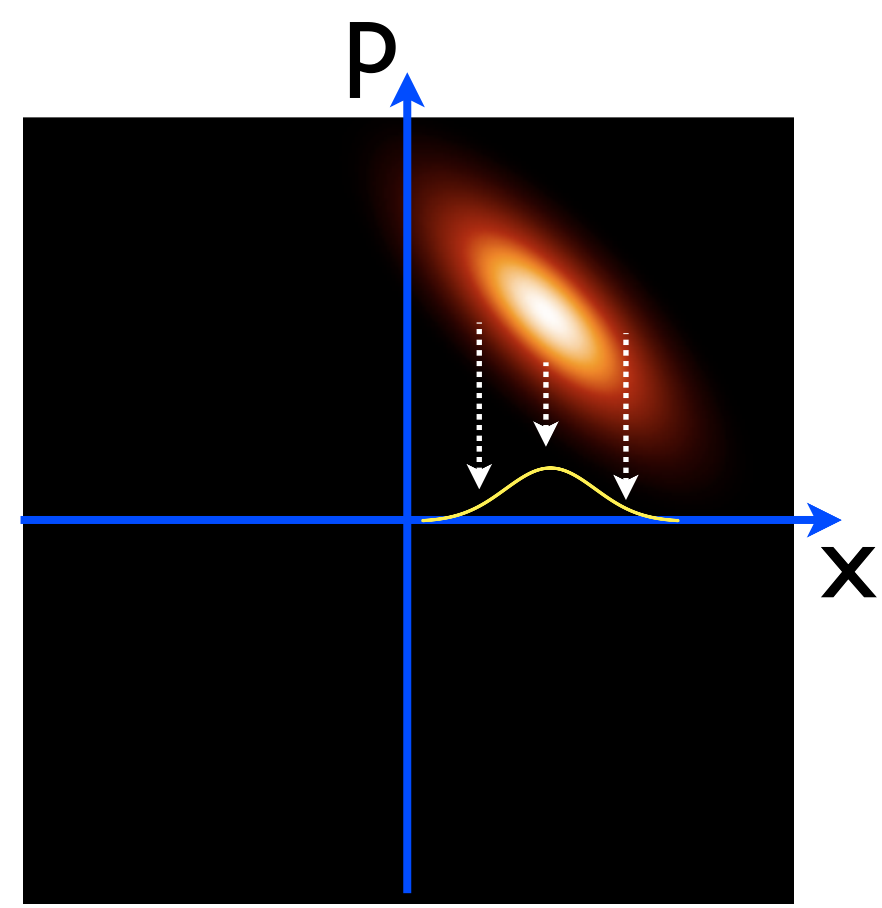

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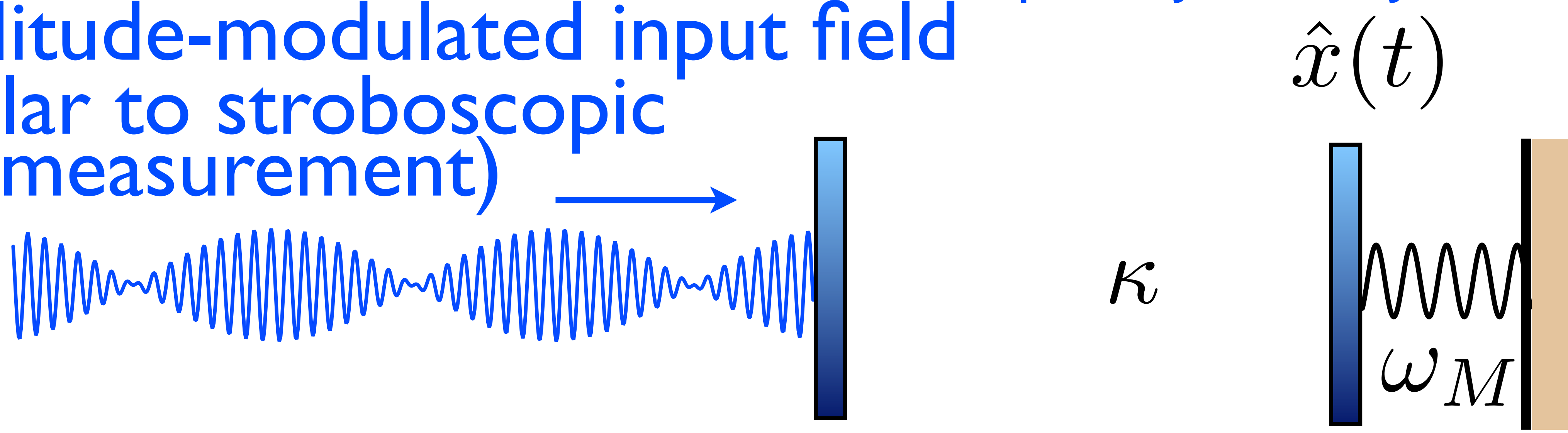

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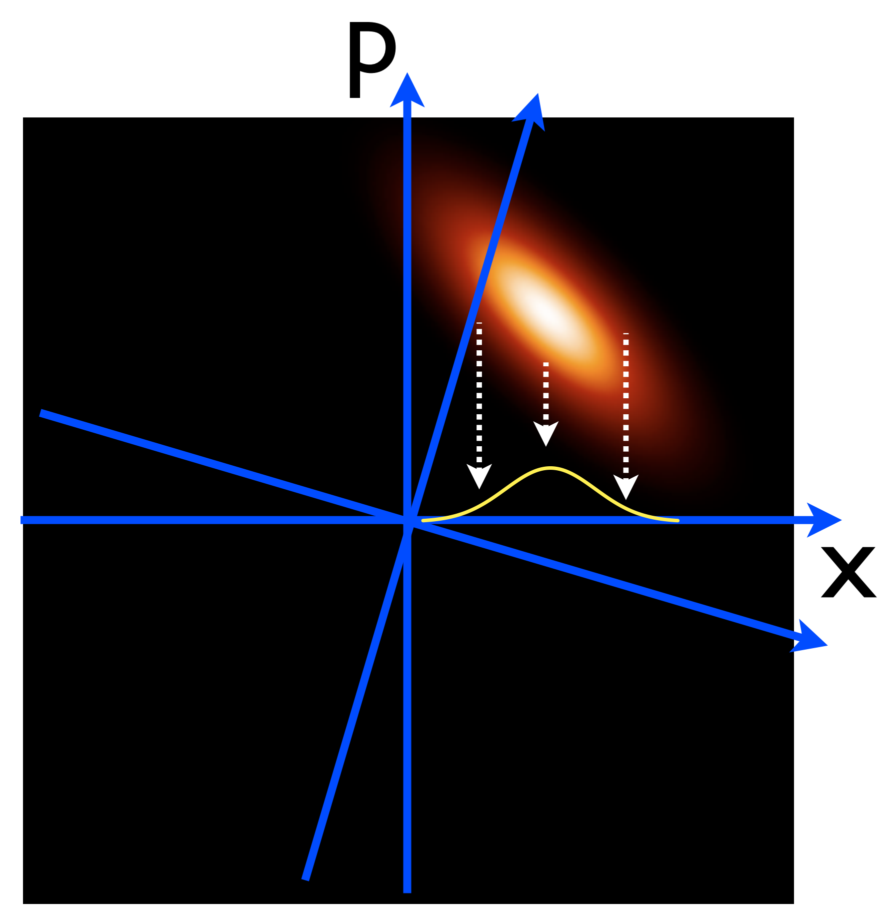
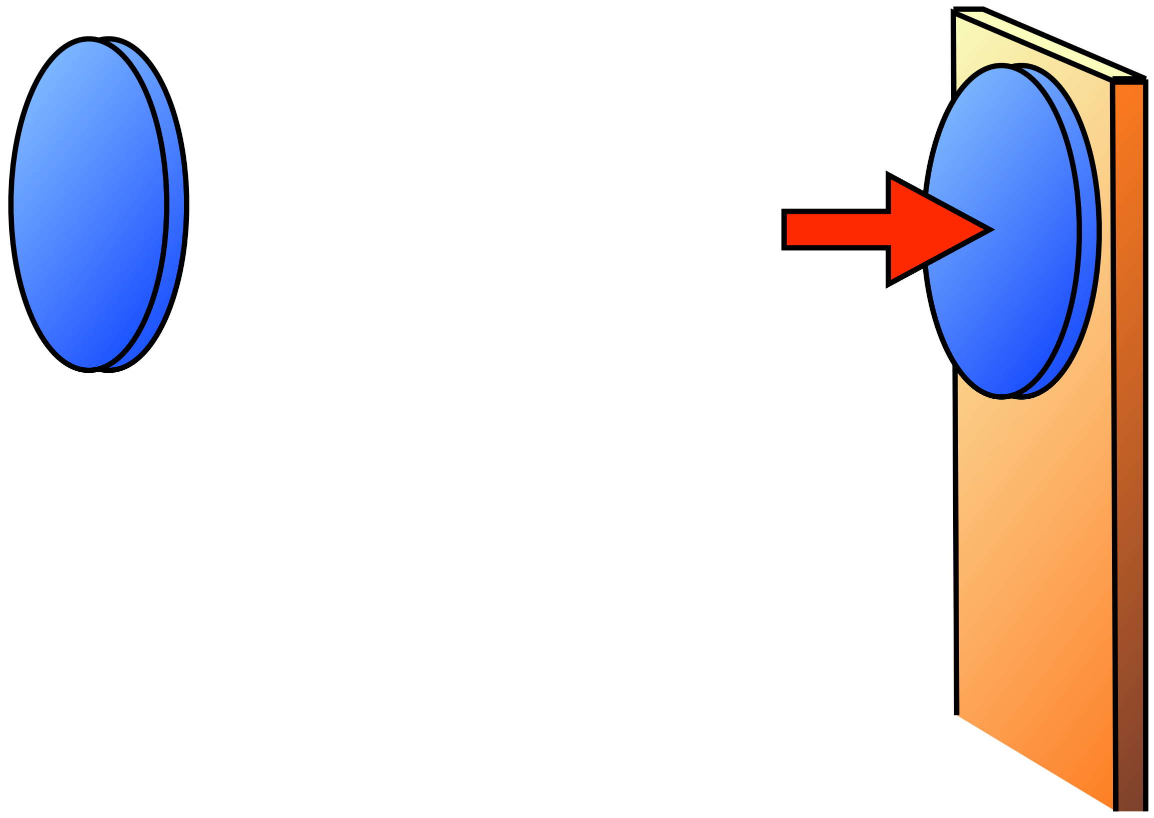
(quantum state tomography)

$$W(x,p) \propto \int dy e^{ipy/\hbar} \rho(x - y/2, x + y/2)$$

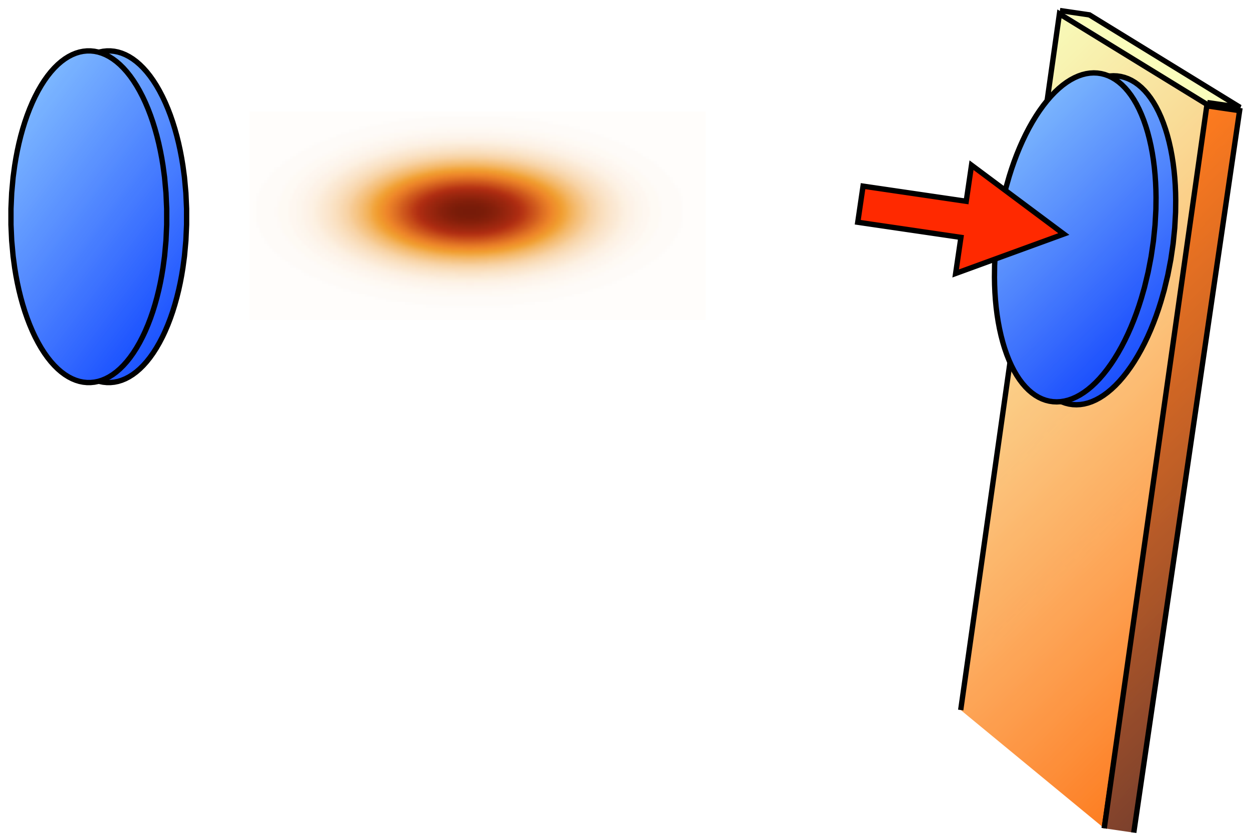


Optomechanical entanglement



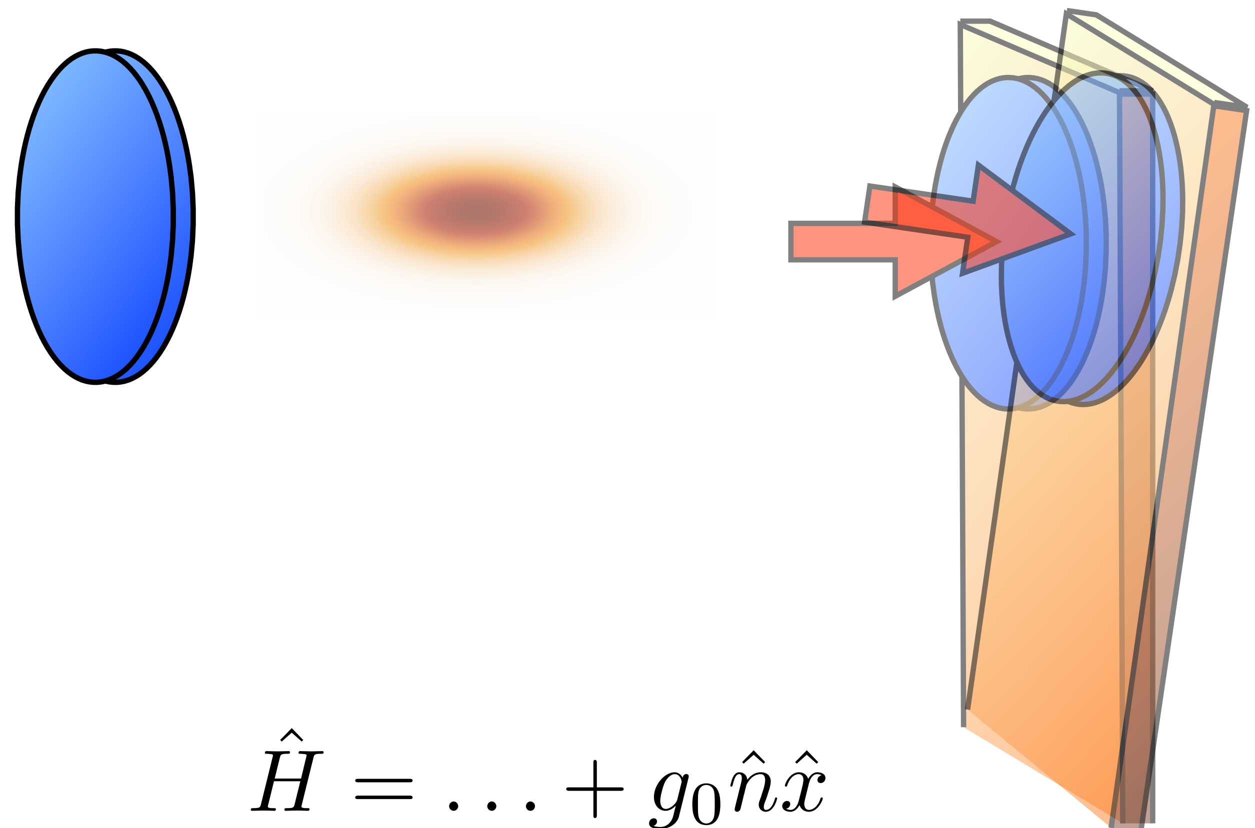
Bose, Jacobs, Knight 1997; Mancini et al. 1997

Optomechanical entanglement



Bose, Jacobs, Knight 1997; Mancini et al. 1997

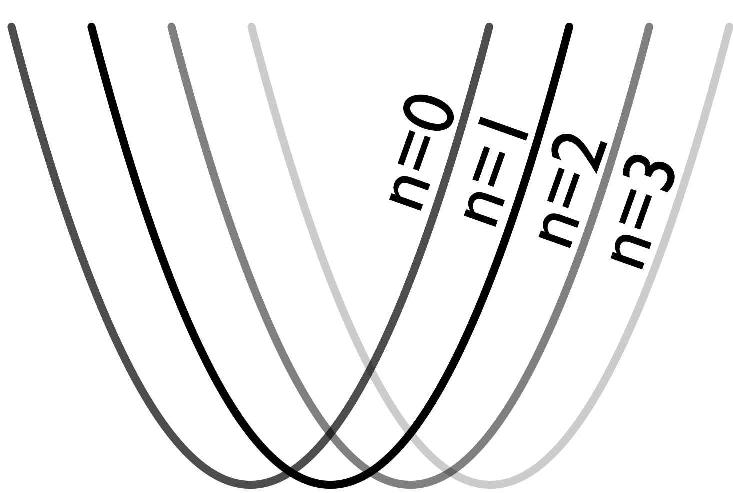
Optomechanical entanglement



$$\hat{H} = \ldots + g_0 \hat{n} \hat{x}$$

$$|\Psi\rangle = \sum_{n=0}^{\infty} c_n e^{-i\varphi_n(t)} |n\rangle \otimes |\alpha = \alpha_n(t)\rangle$$

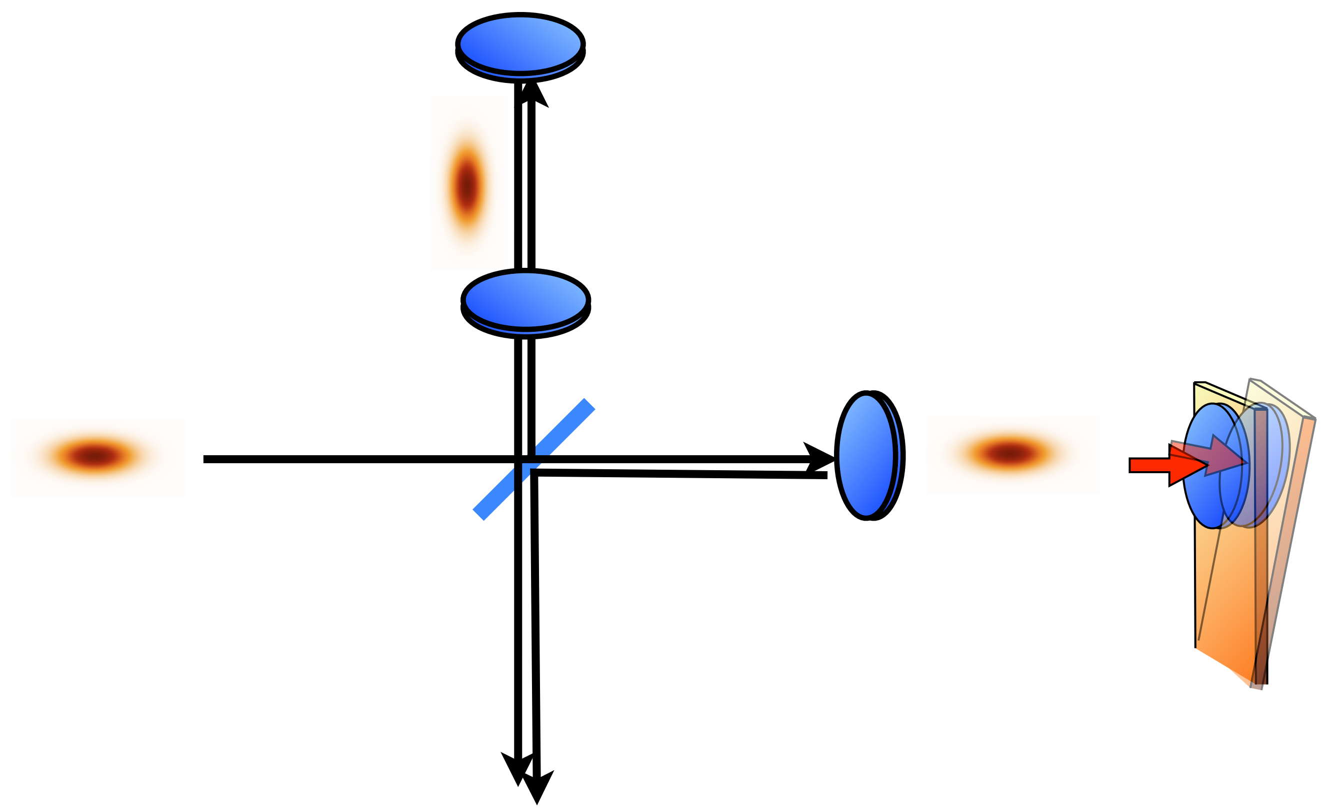
coherent mechanical state

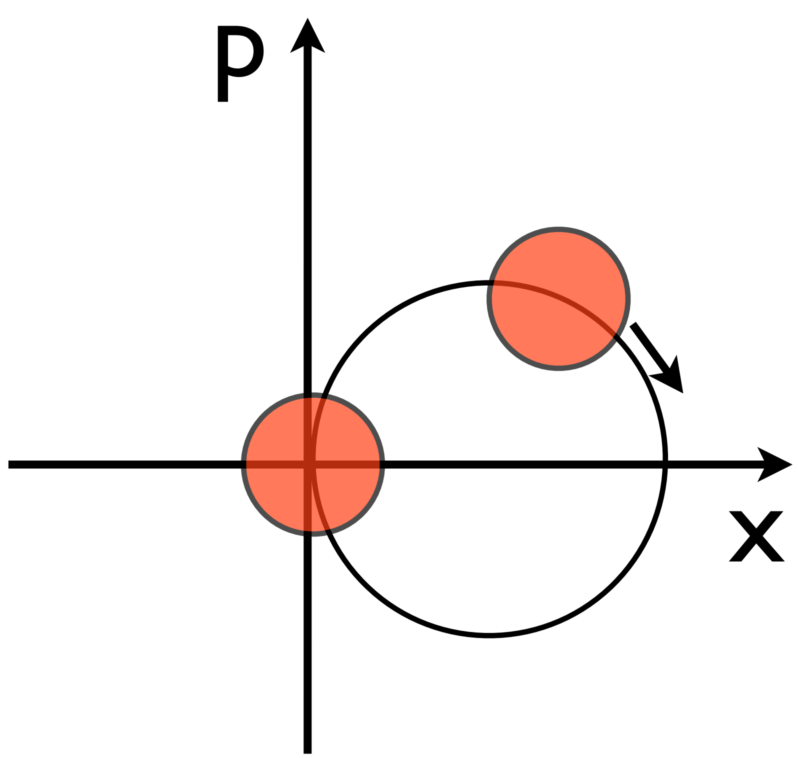


entangled state
(light field/mechanics)

Bose, Jacobs, Knight 1997; Mancini et al. 1997

Proposed optomechanical which-path experiment and quantum eraser



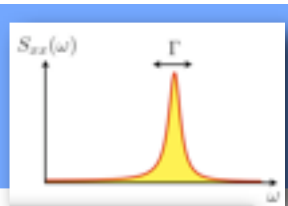


Recover photon coherence if interaction time equals a multiple of the mechanical period!

cf. Haroche experiments in 90s

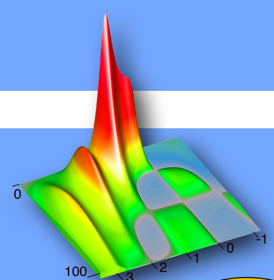
Marshall, Simon, Penrose, Bouwmeester, PRL **91**, 130401 (2003)

Optomechanics (Outline)

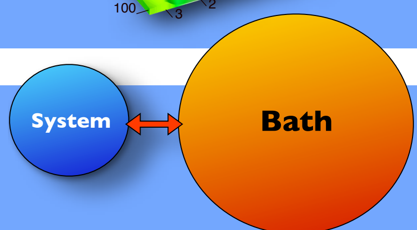


Displacement detection

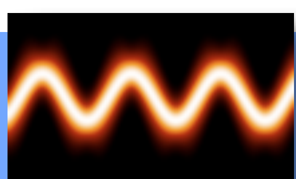
Linear optomechanics



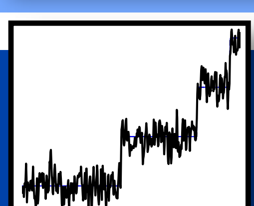
Nonlinear dynamics



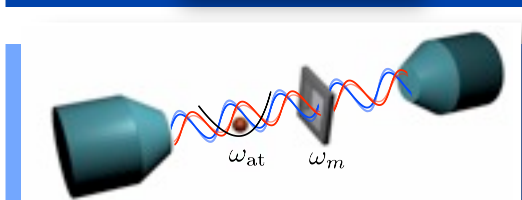
Quantum theory of cooling



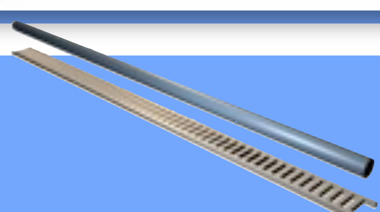
Interesting quantum states



Towards Fock state detection



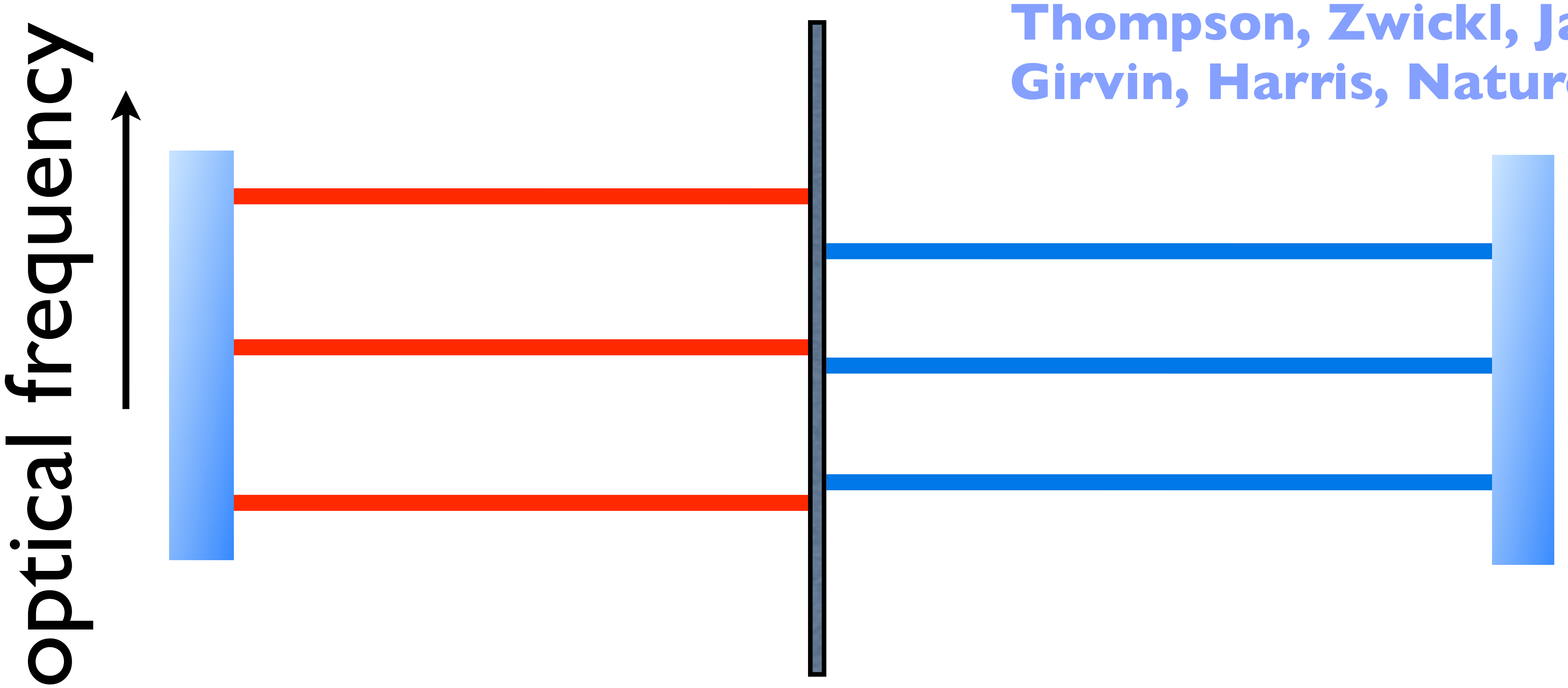
Hybrid systems: coupling to atoms



Optomechanical crystals & arrays

“Membrane in the middle” setup

Thompson, Zwickl, Jayich, Marquardt, Girvin, Harris, Nature 72, 452 (2008)



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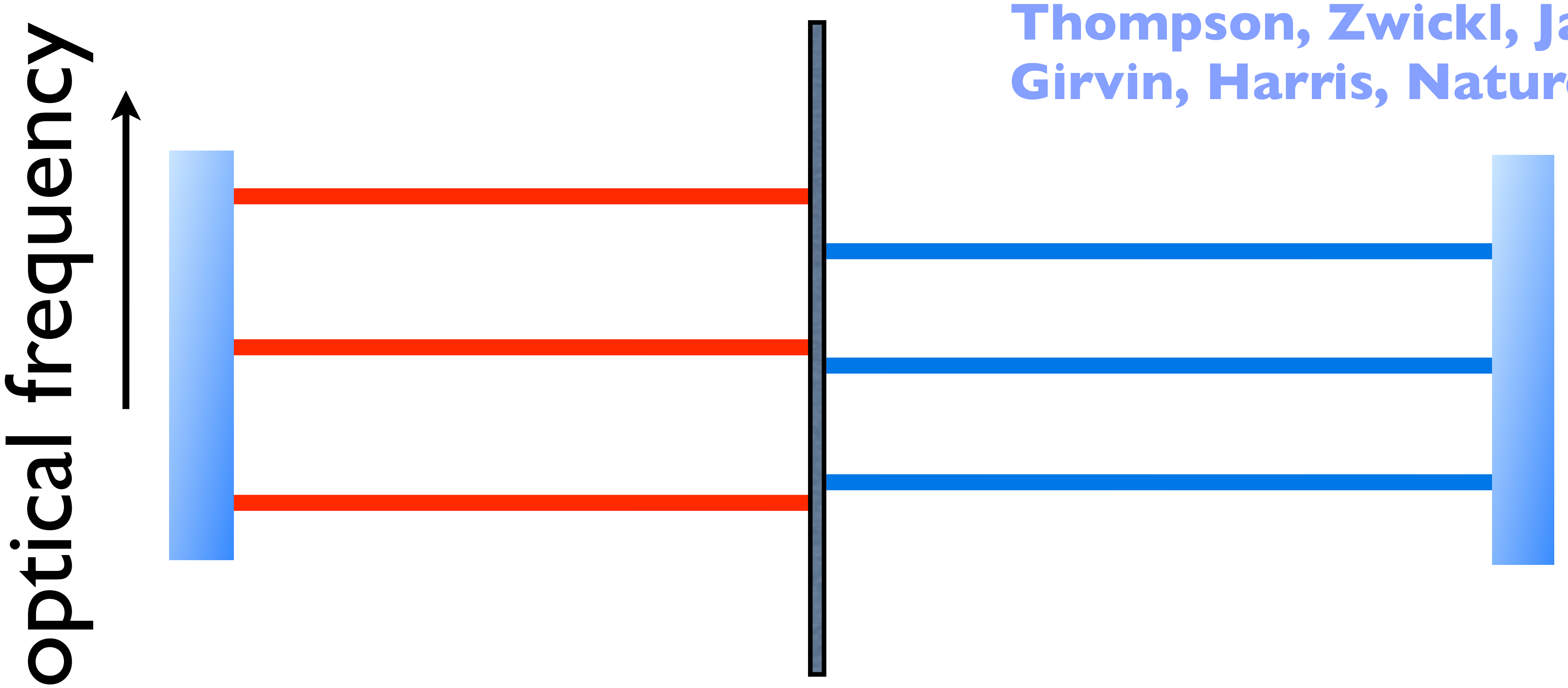
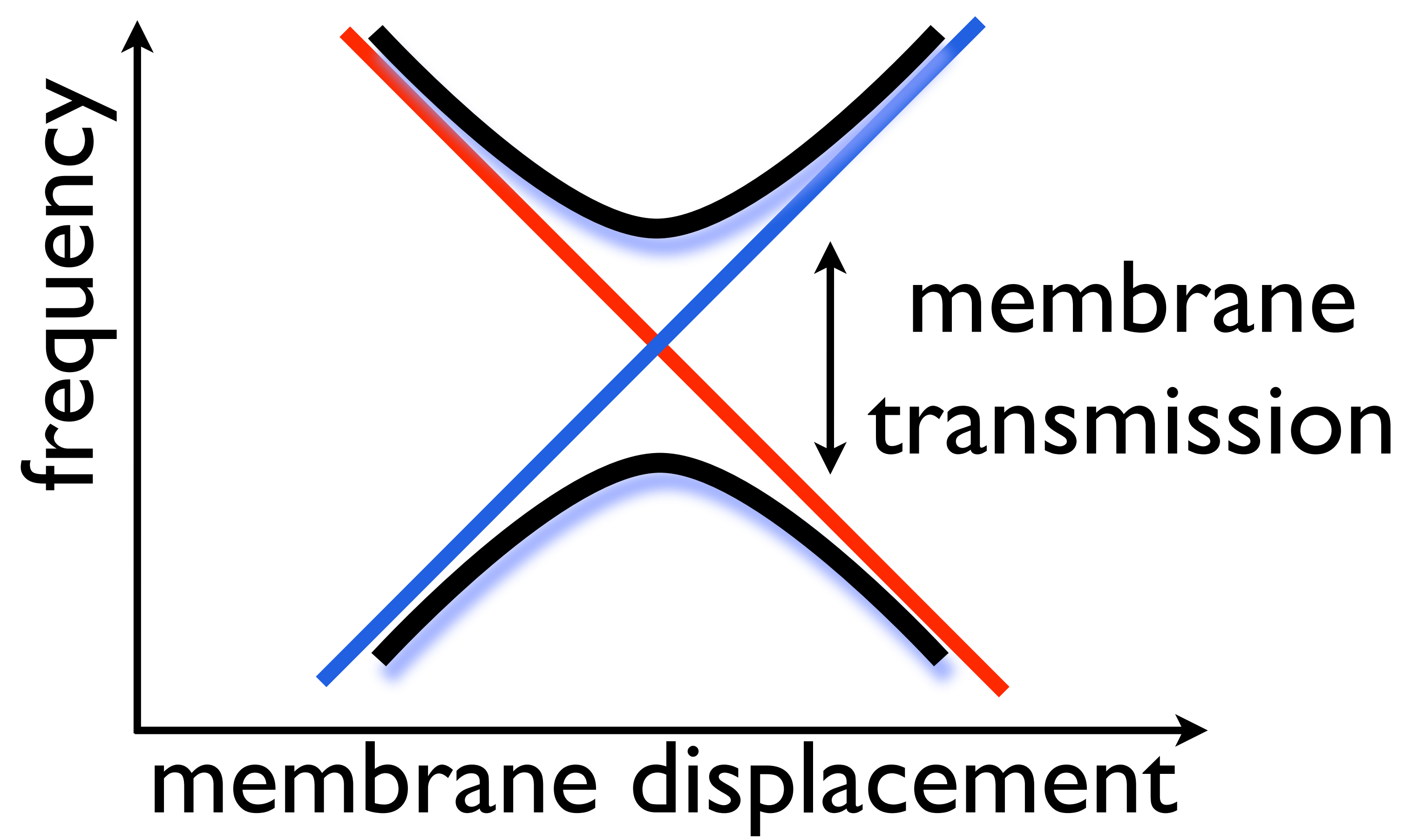
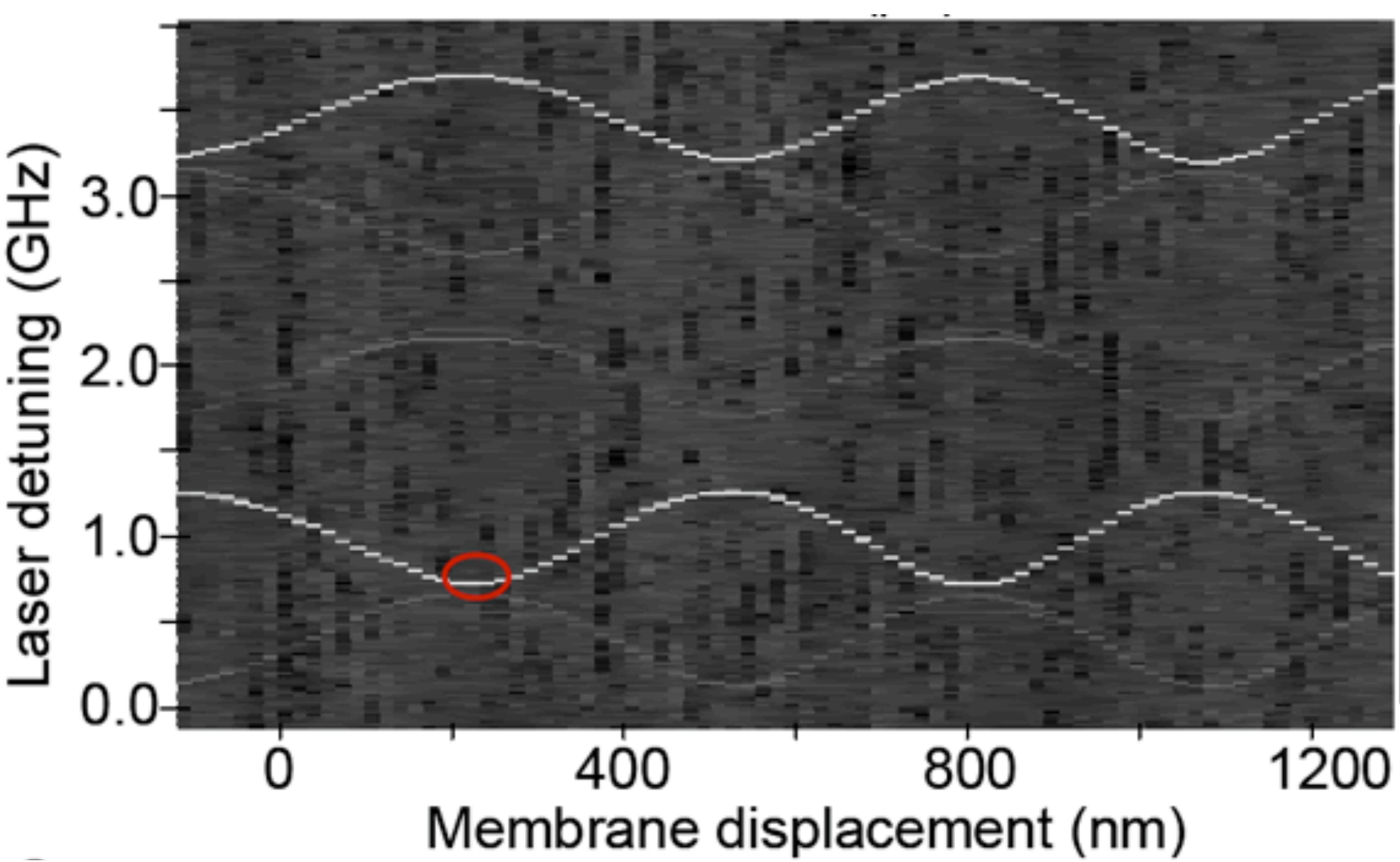




Experiment (Harris group, Yale)



Mechanical frequency:

$\omega_M = 2\pi \cdot 134$ kHz

Mechanical quality factor:

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

Current optical finesse:

$7000 \div 15000$ $(5 \cdot 10^5)$

[almost sideband regime]

Optomechanical cooling

from **300K** to **7mK**

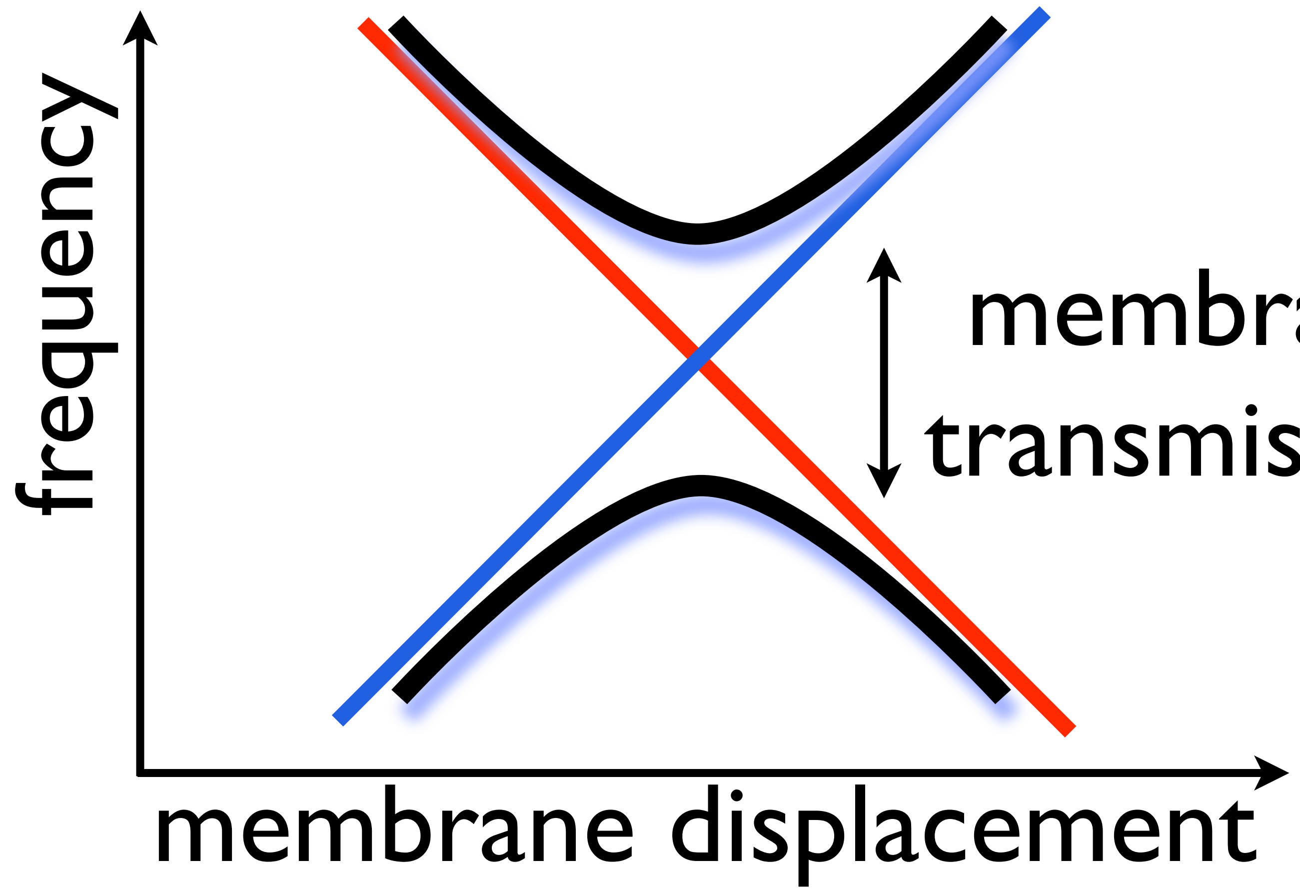
Thompson, Zwickl, Jayich, Marquardt, Girvin, Harris, Nature 72, 452 (2008)

Towards Fock state detection of a macroscopic object

Detection of displacement x: *not* what we need!

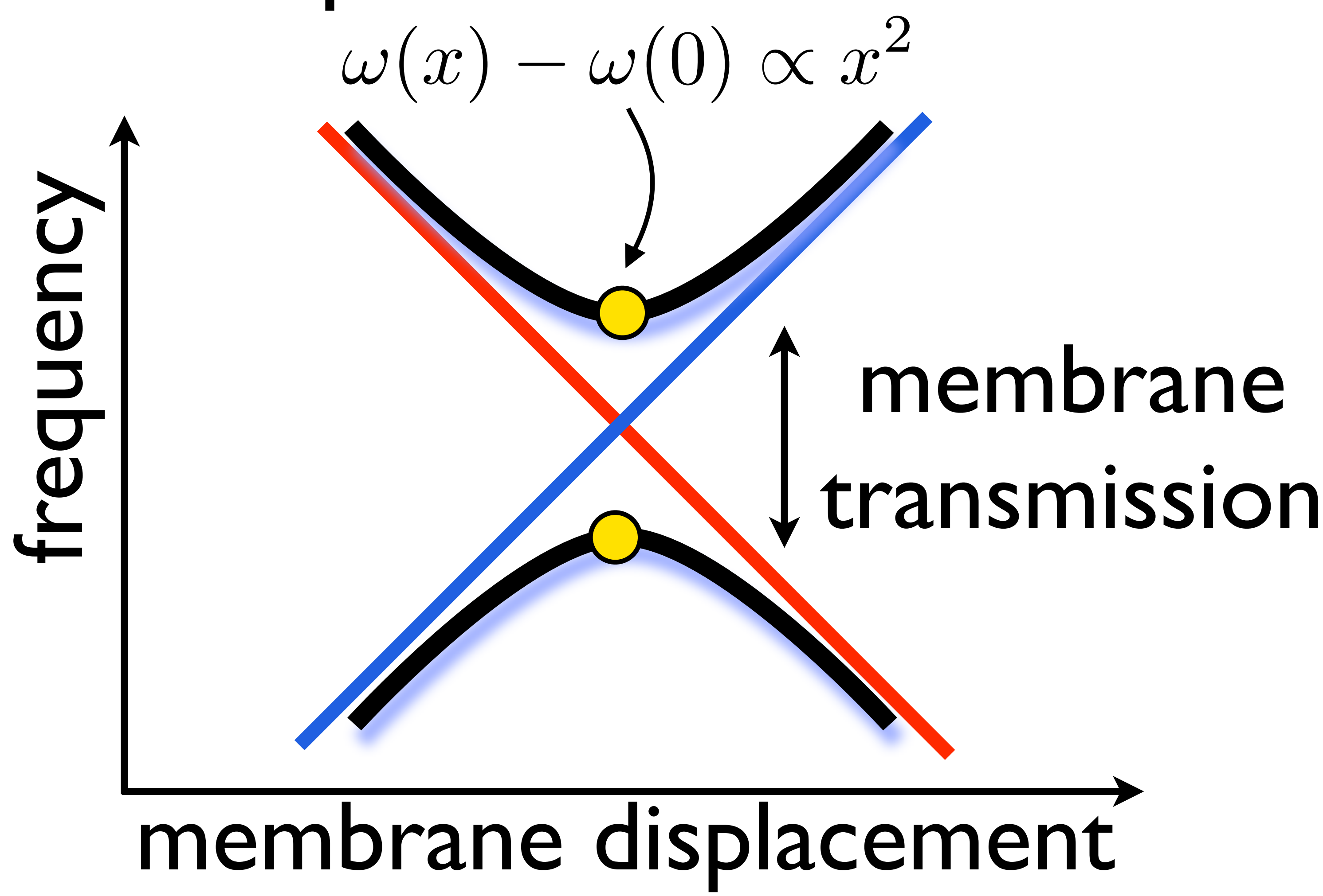
Towards Fock state detection of a macroscopic object

Detection of displacement x: *not* what we need!

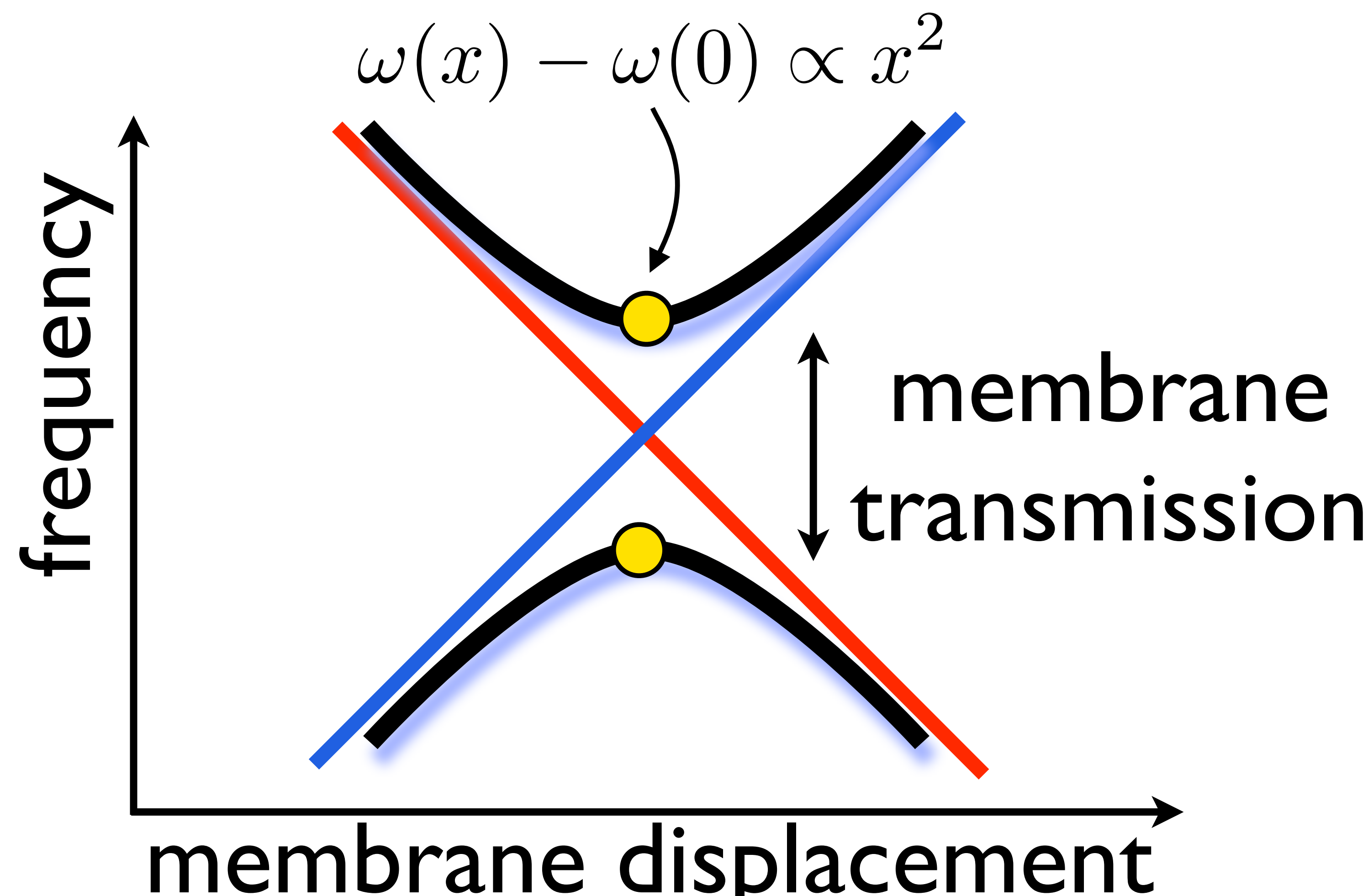


Towards Fock state detection of a macroscopic object

Detection of displacement x: *not* what we need!



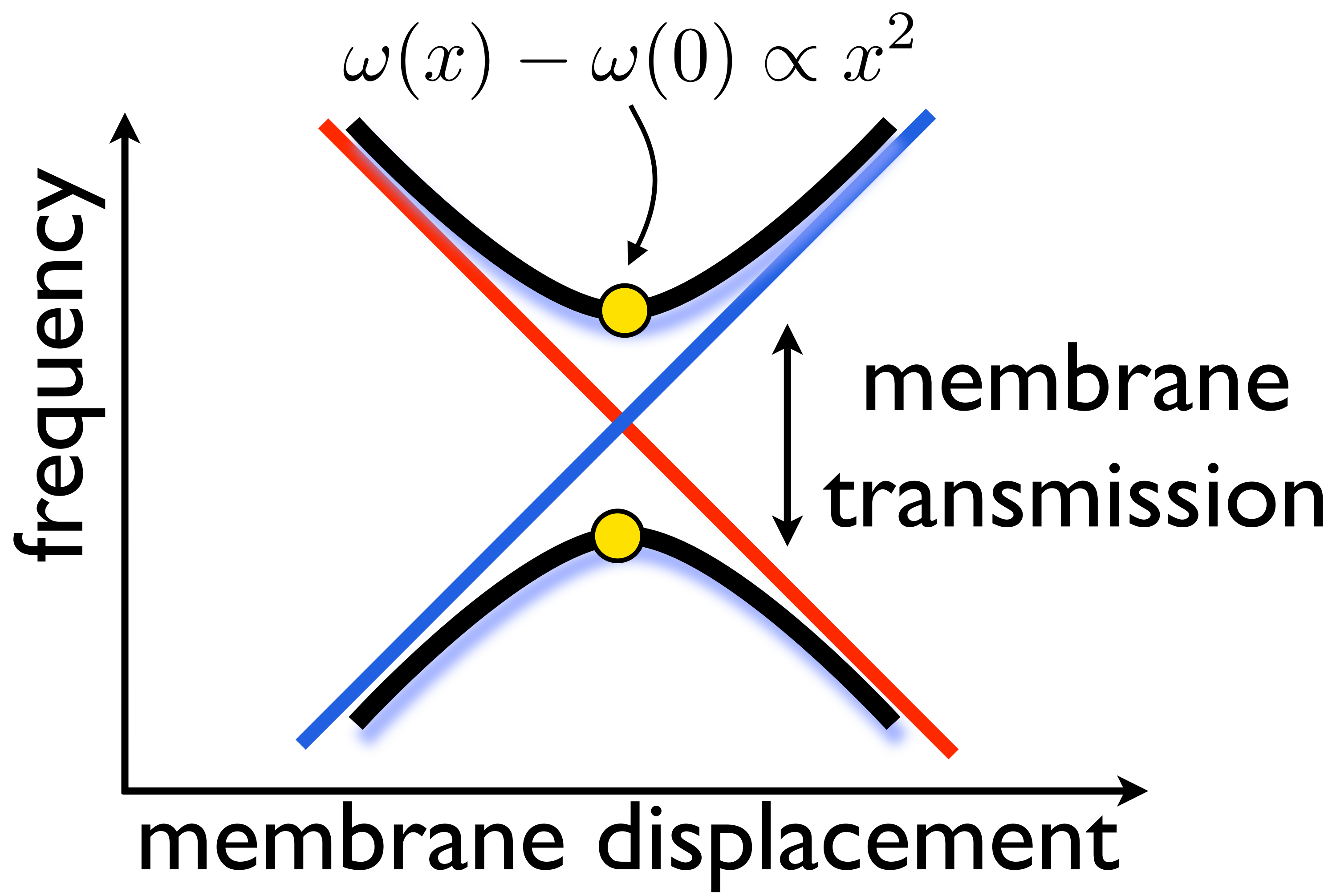
Towards Fock state detection of a macroscopic object



phase shift of measurement beam:

$$\hat{\theta} \propto \hat{x}(t)^2 \propto (\hat{b}(t) + \hat{b}^\dagger(t))^2 = \hat{b}^2 e^{-i2\omega_M t} + \hat{b}^{\dagger 2} e^{+i2\omega_M t} + \hat{b}^\dagger \hat{b} + \hat{b}\hat{b}^\dagger$$

Towards Fock state detection of a macroscopic object



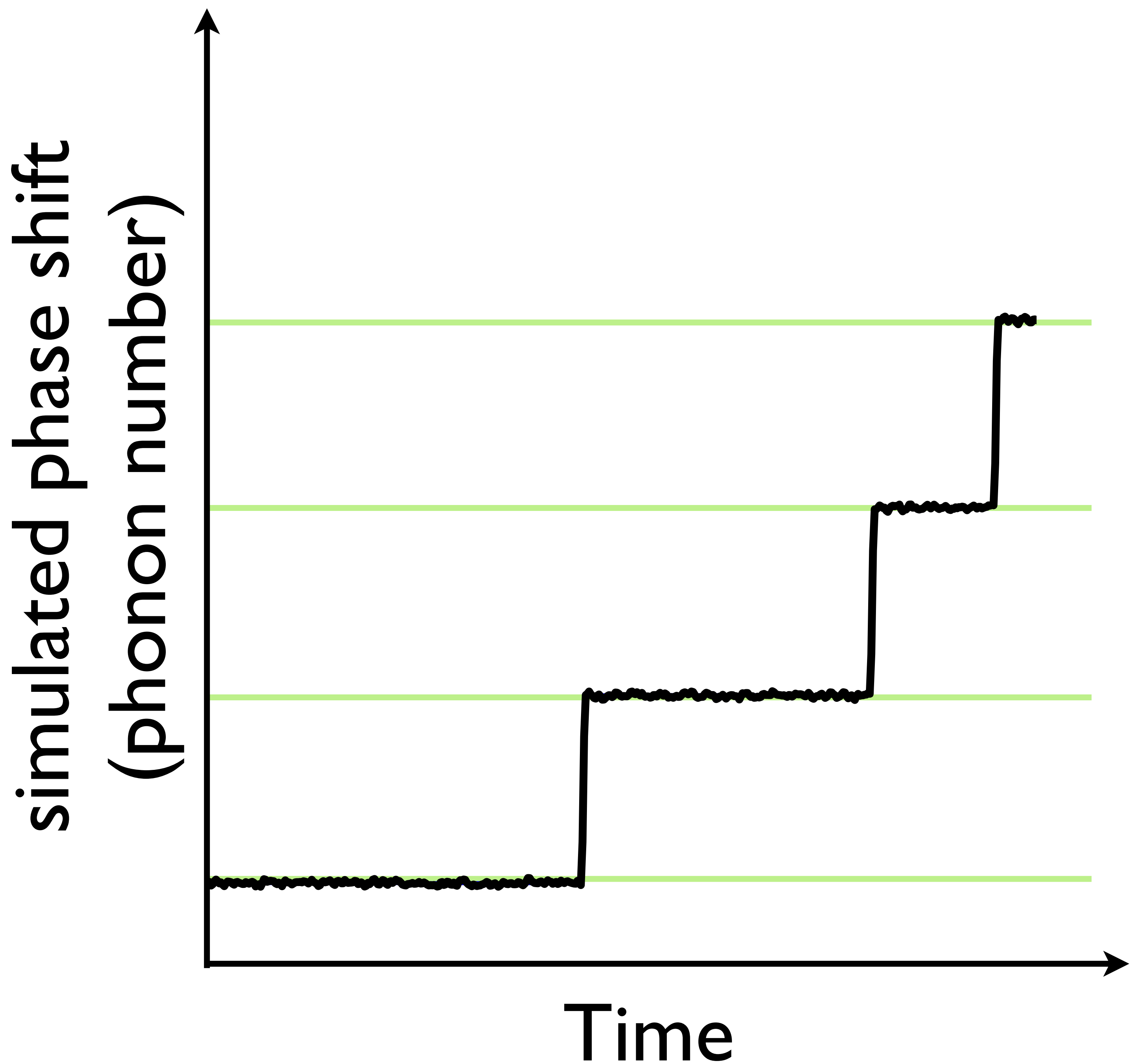
phase shift of measurement beam:

$$\overline{\hat{\theta}} \propto \overline{\hat{x}(t)^2} \propto \overline{(\hat{b}(t) + \hat{b}^\dagger(t))^2} \approx 2\hat{b}^\dagger\hat{b} + 1$$

(Time-average over cavity ring-down time)

QND measurement of phonon number!

Towards Fock state detection of a macroscopic object



Thompson, Zwickl, Jayich, FM, Girvin, Harris, Nature 72, 452 (2008)

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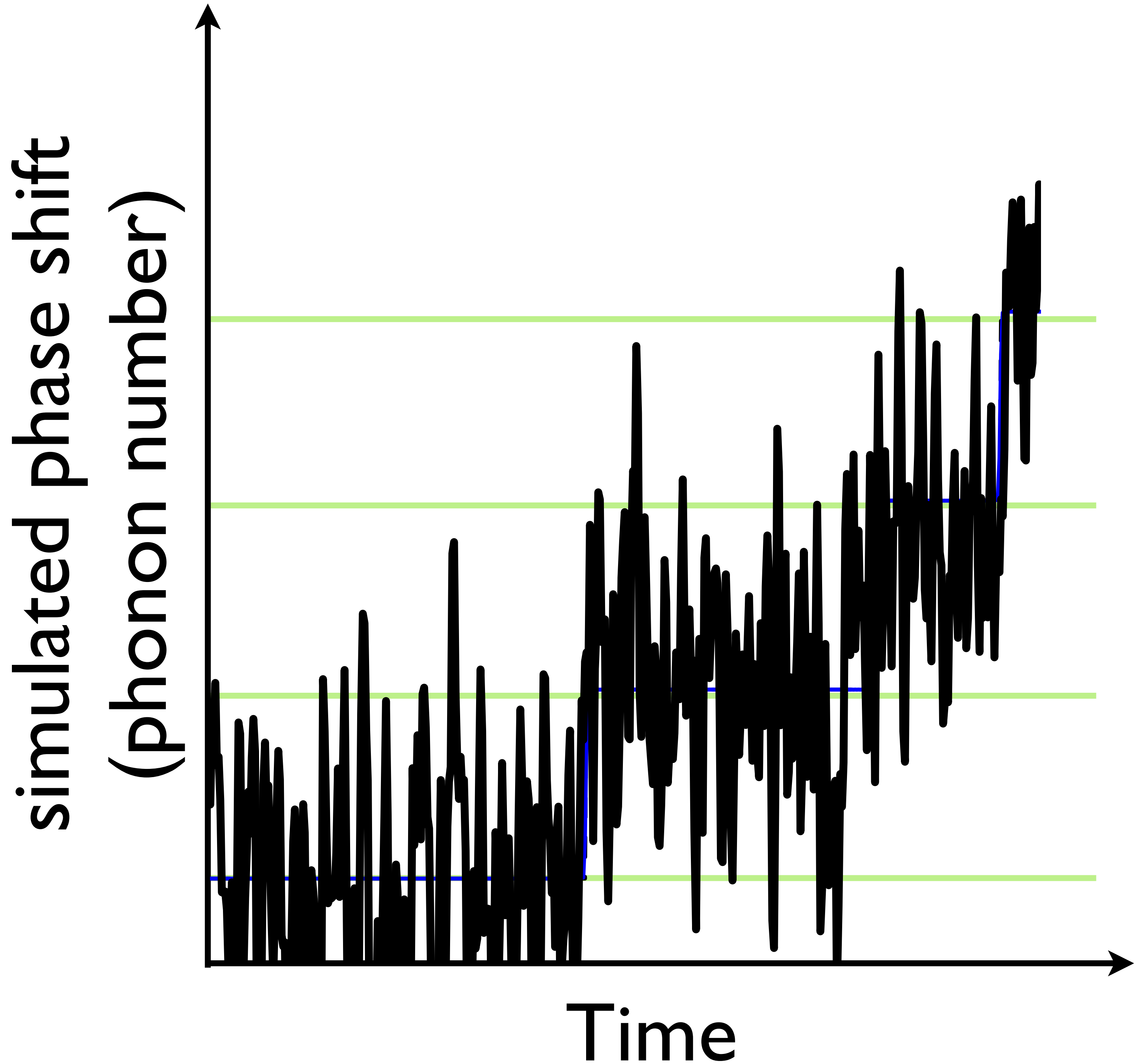

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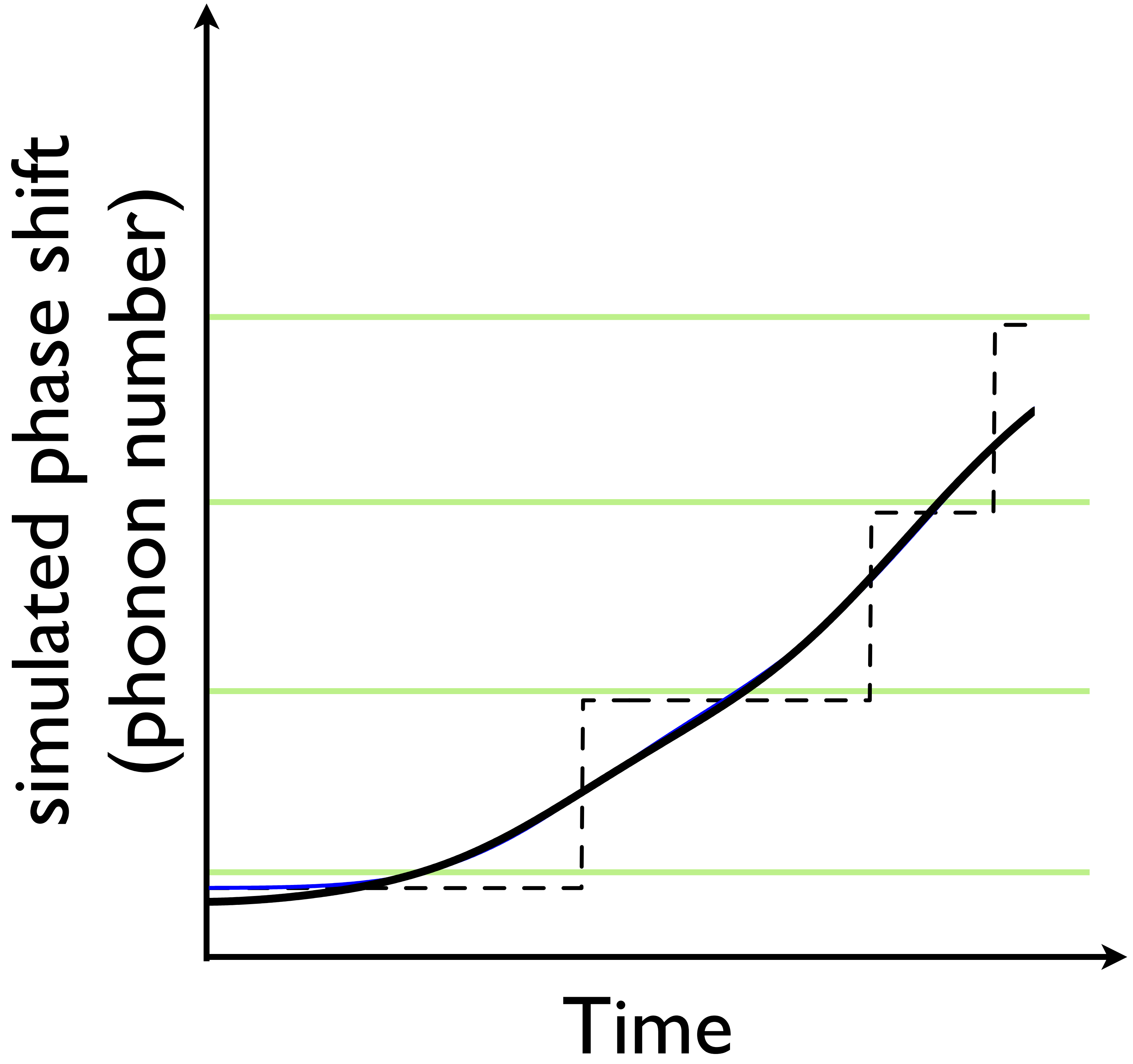

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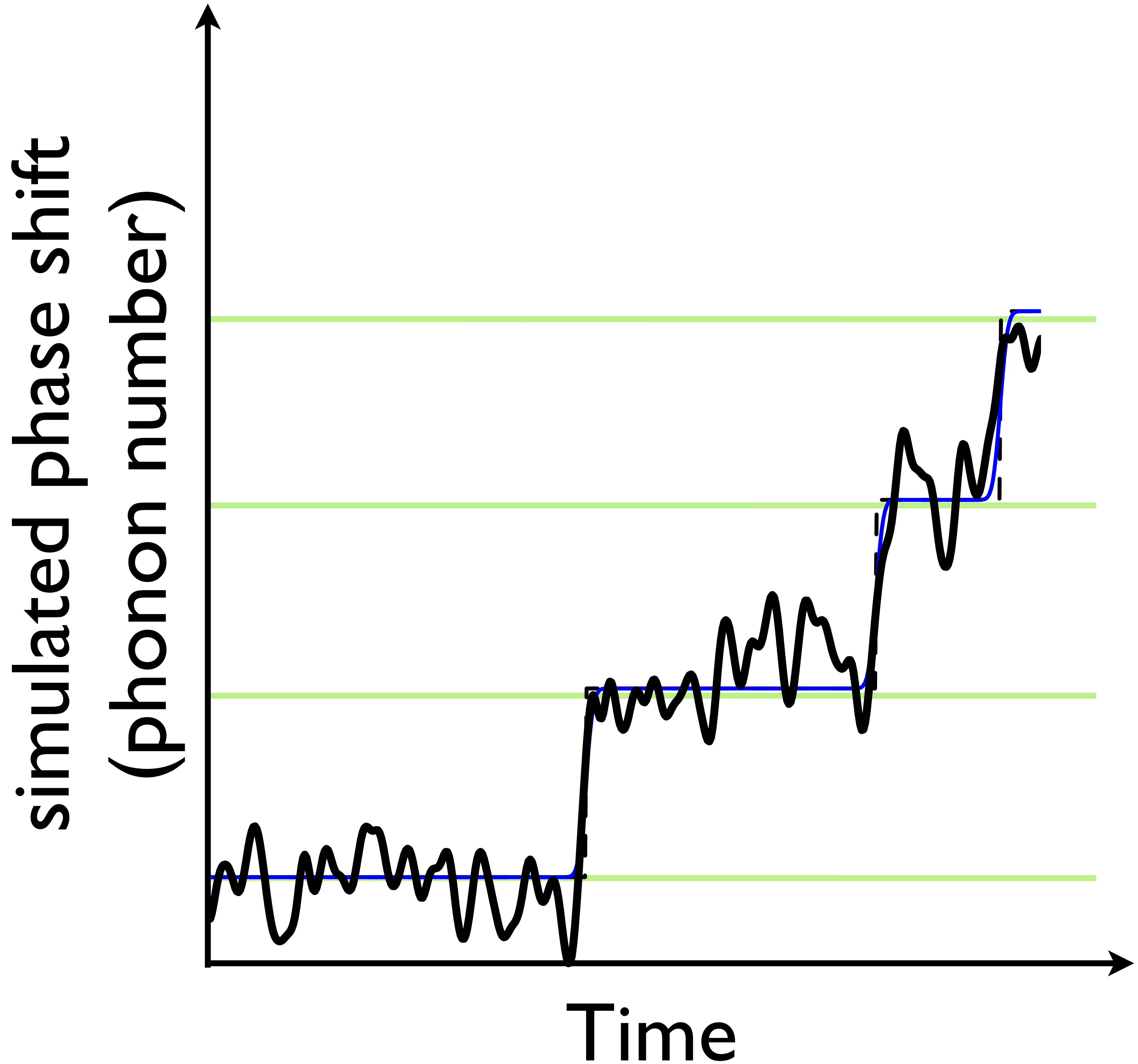

Thompson, Zwickl, Jayich, FM,
Girvin, Harris, Nature 72, 452 (2008)

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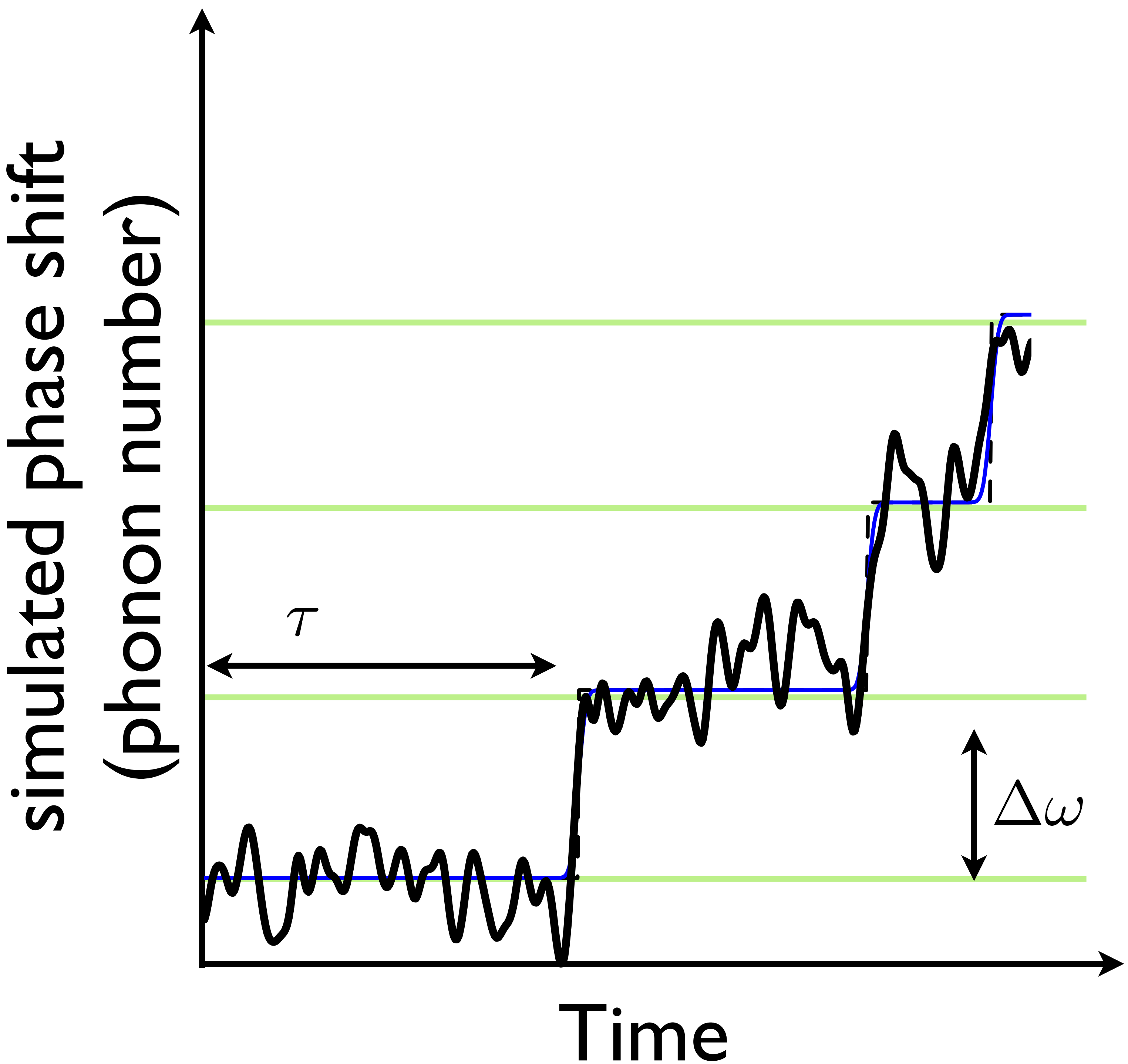


Signal-to-noise ratio: $\dfrac{\tau \Delta\omega^2}{S_\omega}$

Optical freq. shift per phonon:

$$\Delta\omega = x_{\mathrm{ZPF}}^2 \omega''$$

Noise power of freq. measurement:

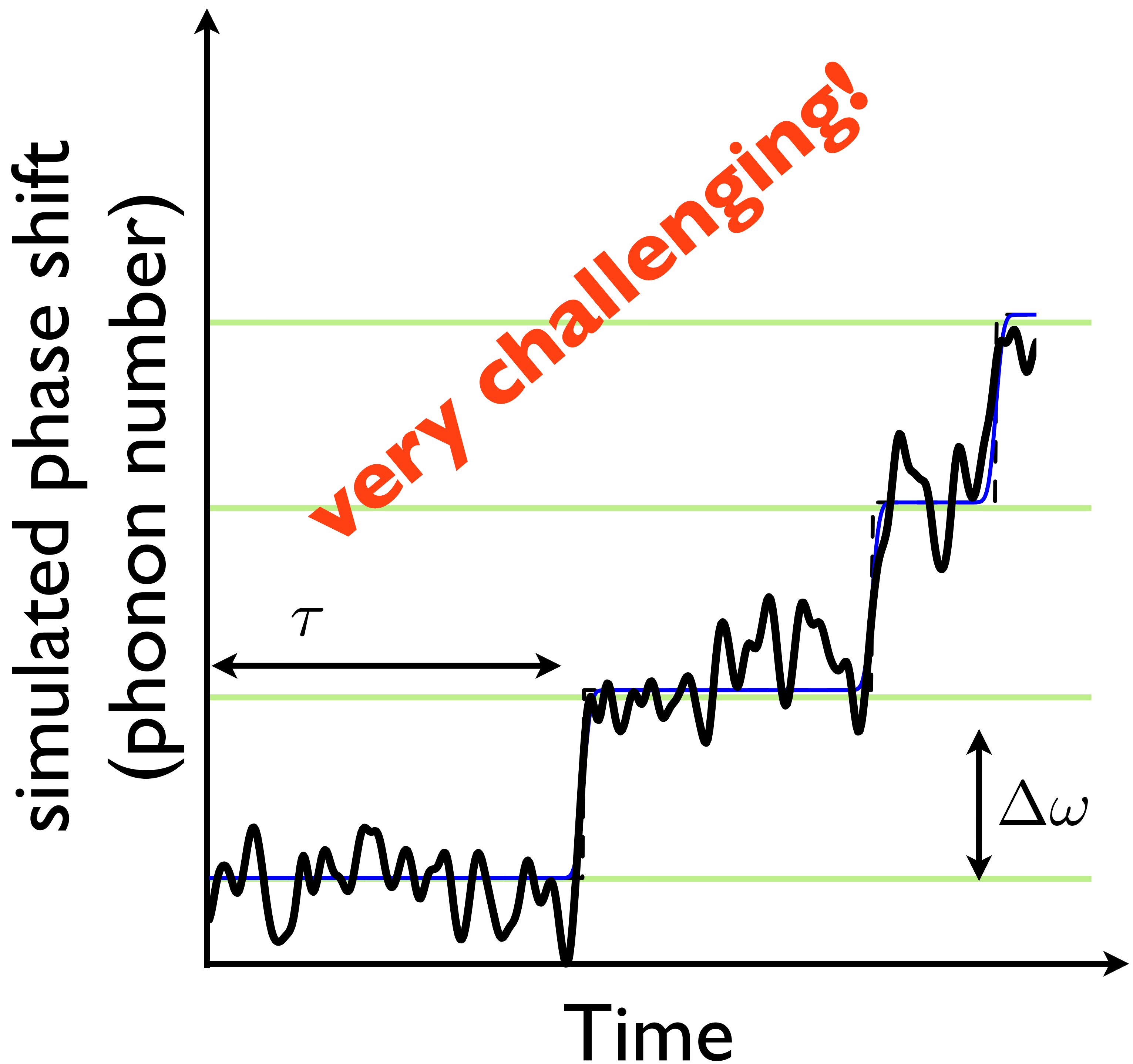
$$S_\omega = \frac{\kappa}{16\bar{n}_{\mathrm{cavity}}}$$

Ground state lifetime:

$$\frac{1}{\tau} = \Gamma \bar{n}_{\mathrm{thermal}}$$

Thompson, Zwickl, Jayich, FM, Girvin, Harris, Nature 72, 452 (2008)

Towards Fock state detection of a macroscopic object



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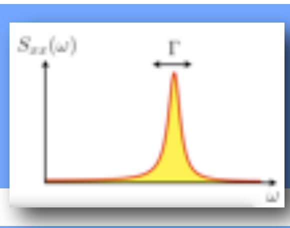
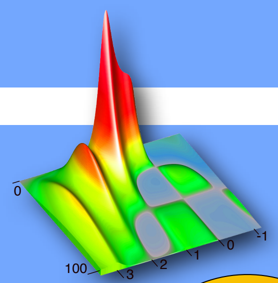
Optomechanics (Outline)

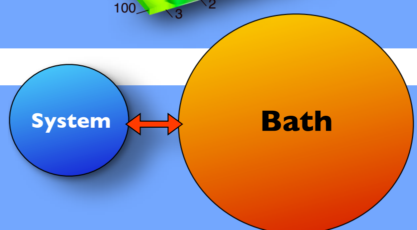


Displacement detection

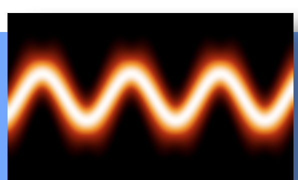


Linear optomechanics

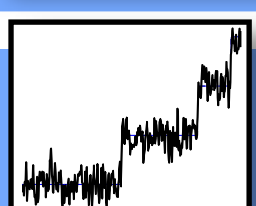
Nonlinear dynamics



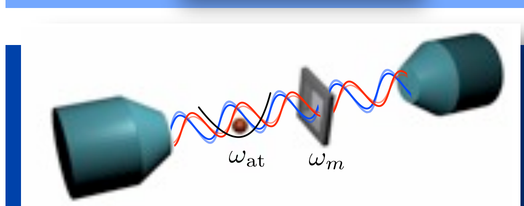
Quantum theory of cooling



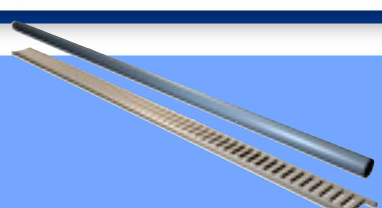
Interesting quantum states



Towards Fock state detection



Hybrid systems: coupling to atoms



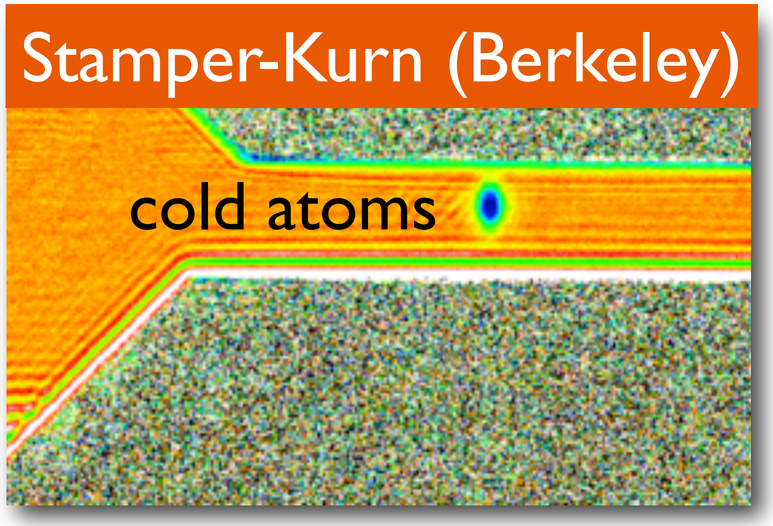
Optomechanical crystals & arrays

Atom-membrane coupling

Note: Existing works simulate optomechanical effects using cold atoms

K. W. Murch, K. L. Moore, S. Gupta, and D. M. Stamper-Kurn, Nature Phys. **4**, 561 (2008).

F. Brennecke, S. Ritter, T. Donner, and T. Esslinger, Science **322**, 235 (2008).

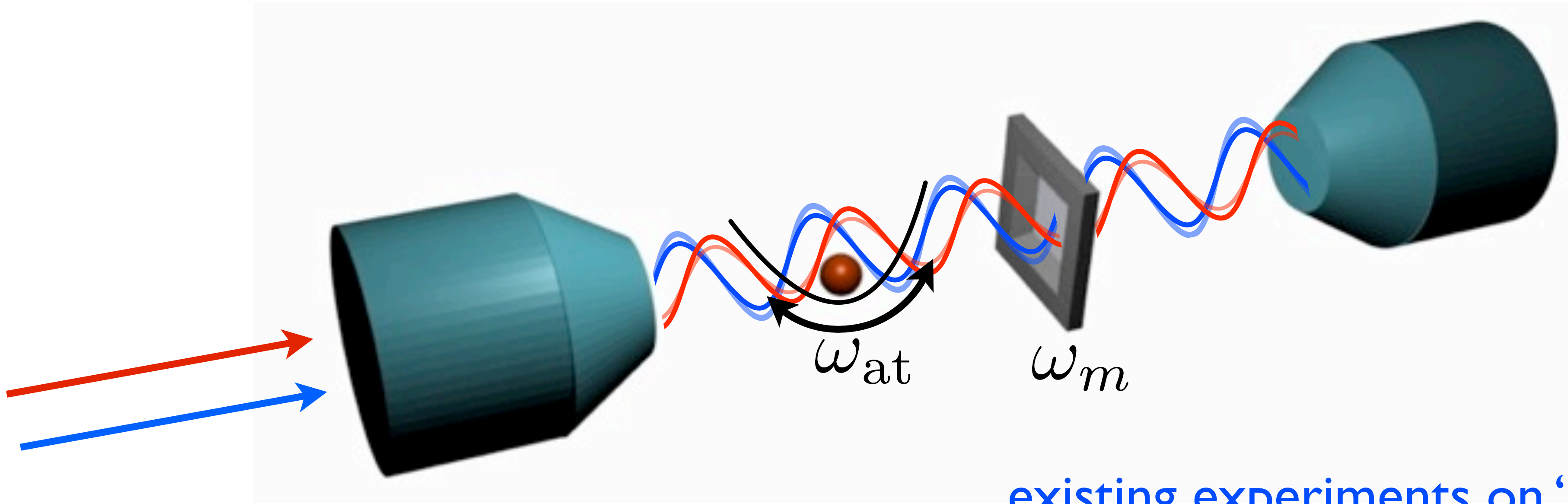


...profit from small mass of atomic cloud

Here: Coupling a single atom to a macroscopic mechanical object

Challenge: huge mass ratio

Strong atom-membrane coupling via the light field



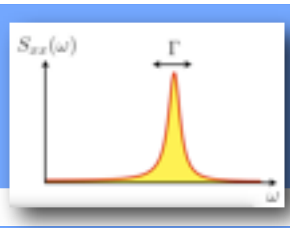
existing experiments on "optomechanics with cold atoms": labs of Dan-Stamper Kurn (Berkeley) and Tilman Esslinger (ETH)

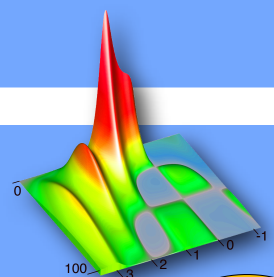
collaboration:
LMU (M. Ludwig, FM, P. Treutlein),
Innsbruck (K. Hammerer, C. Genes, M. Wallquist, P. Zoller),
Boulder (J. Ye), Caltech (H. J. Kimble)
Hammerer et al., PRL 2009

Goal:

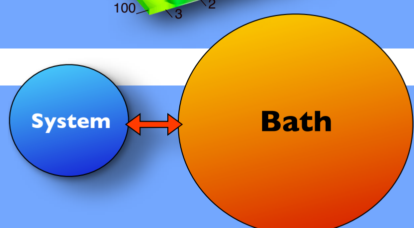
$$\hat{H} = \underbrace{\hbar\omega_{\mathrm{at}}\hat{a}^\dagger\hat{a}}_{\text{atom}} + \underbrace{\hbar\omega_m\hat{b}^\dagger\hat{b}}_{\text{membrane}} + \underbrace{\hbar G_{\mathrm{eff}}(\hat{a}^\dagger + \hat{a})(\hat{b}^\dagger + \hat{b})}_{\text{atom-membrane coupling}}$$

Optomechanics (Outline)

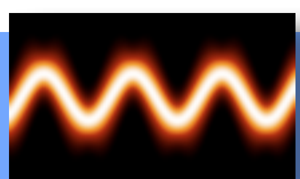

Displacement detection

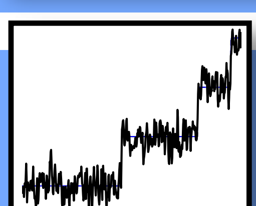

Linear optomechanics

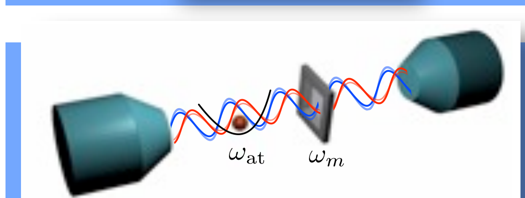
Nonlinear dynamics



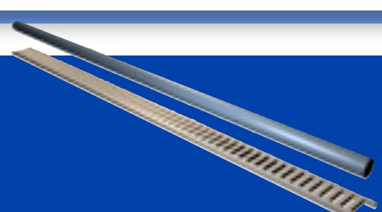
Quantum theory of cooling


Interesting quantum states

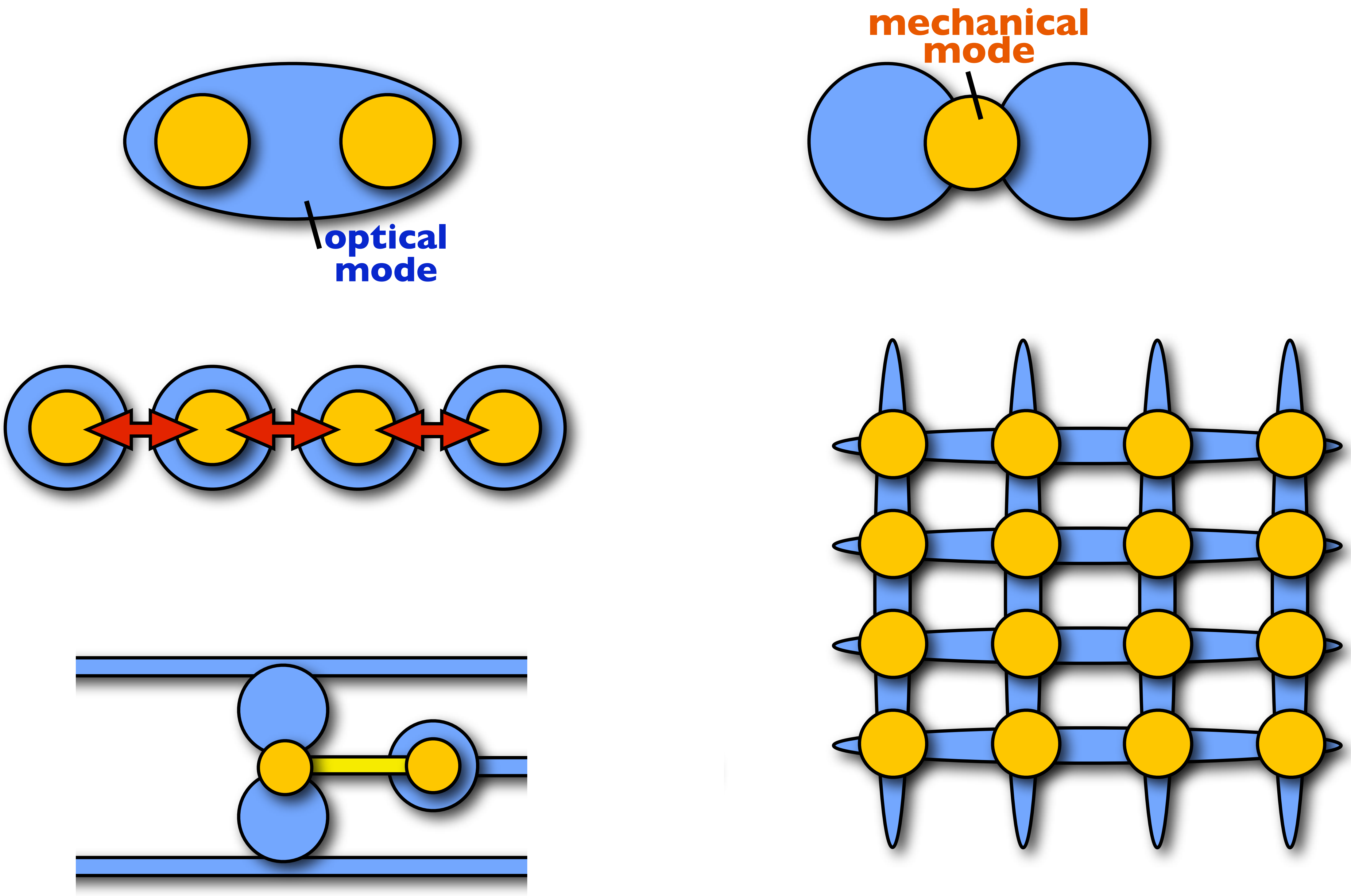

Towards Fock state detection



Hybrid systems: coupling to atoms


Optomechanical crystals & arrays

Many modes



Scaling down

cm

usual optical cavities

10 µm

LKB, Aspelmeyer, Harris, Bouwmeester, ...

Scaling down

cm

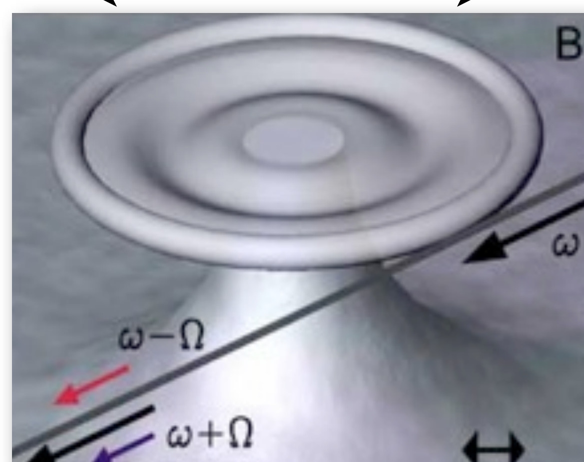
usual optical cavities

10 μm

LKB, Aspelmeyer, Harris, Bouwmeester, ...

50 μm

microtoroids



Vahala, Kippenberg, Carmon, ...

Scaling down

cm

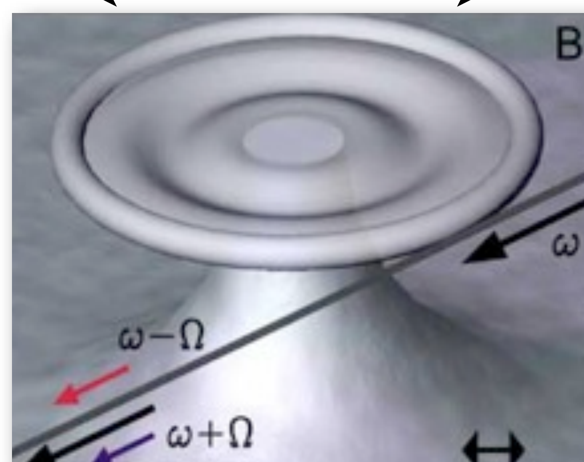
usual optical cavities

10 μm

LKB, Aspelmeyer, Harris, Bouwmeester, ...

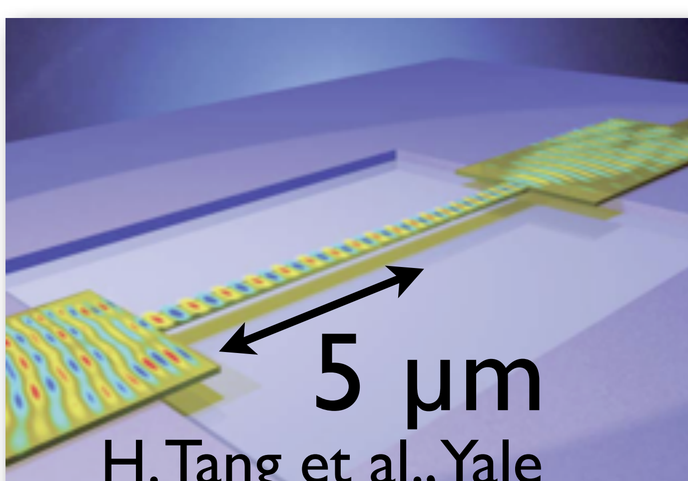
50 μm

microtoroids

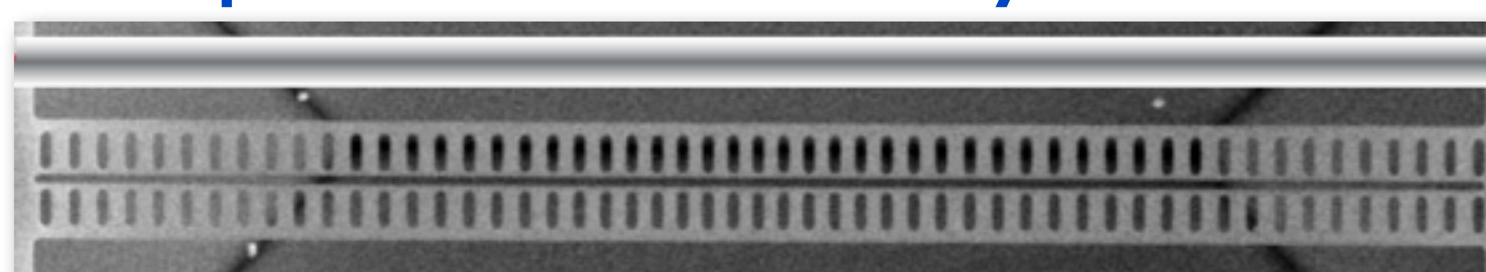


Vahala, Kippenberg, Carmon, ...

optomechanics in photonic circuits



optomechanical crystals



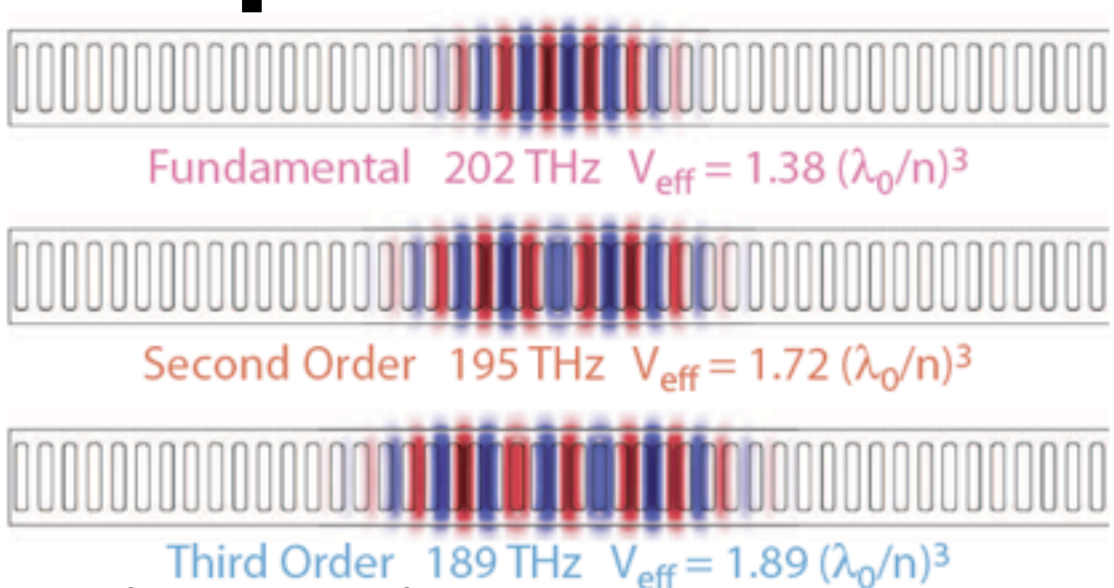
O. Painter et al., Caltech

10 μm

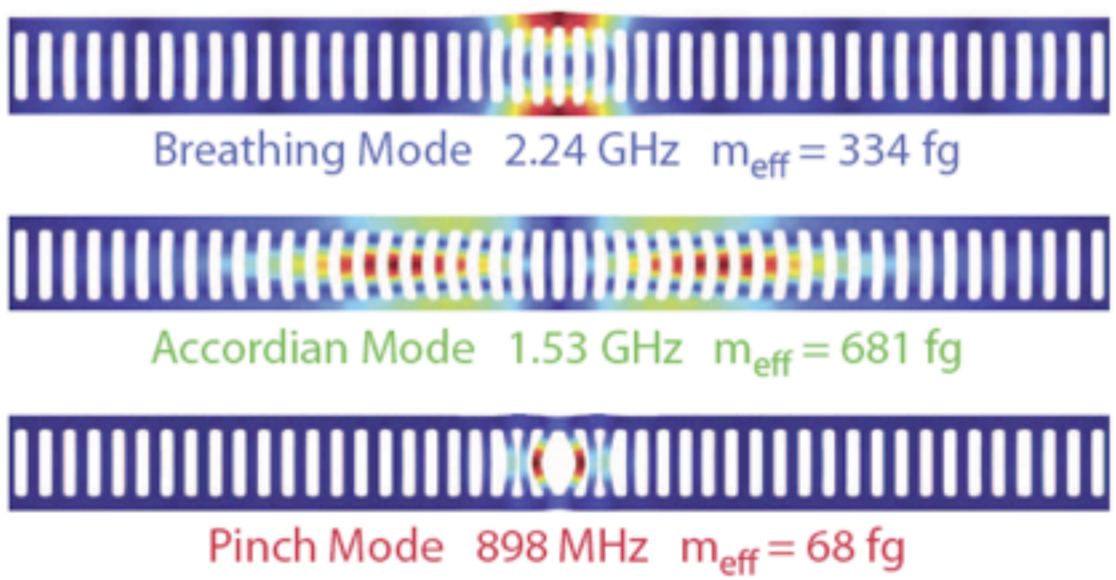
Optomechanical crystals

free-standing photonic crystal structures

optical modes



vibrational modes



advantages:

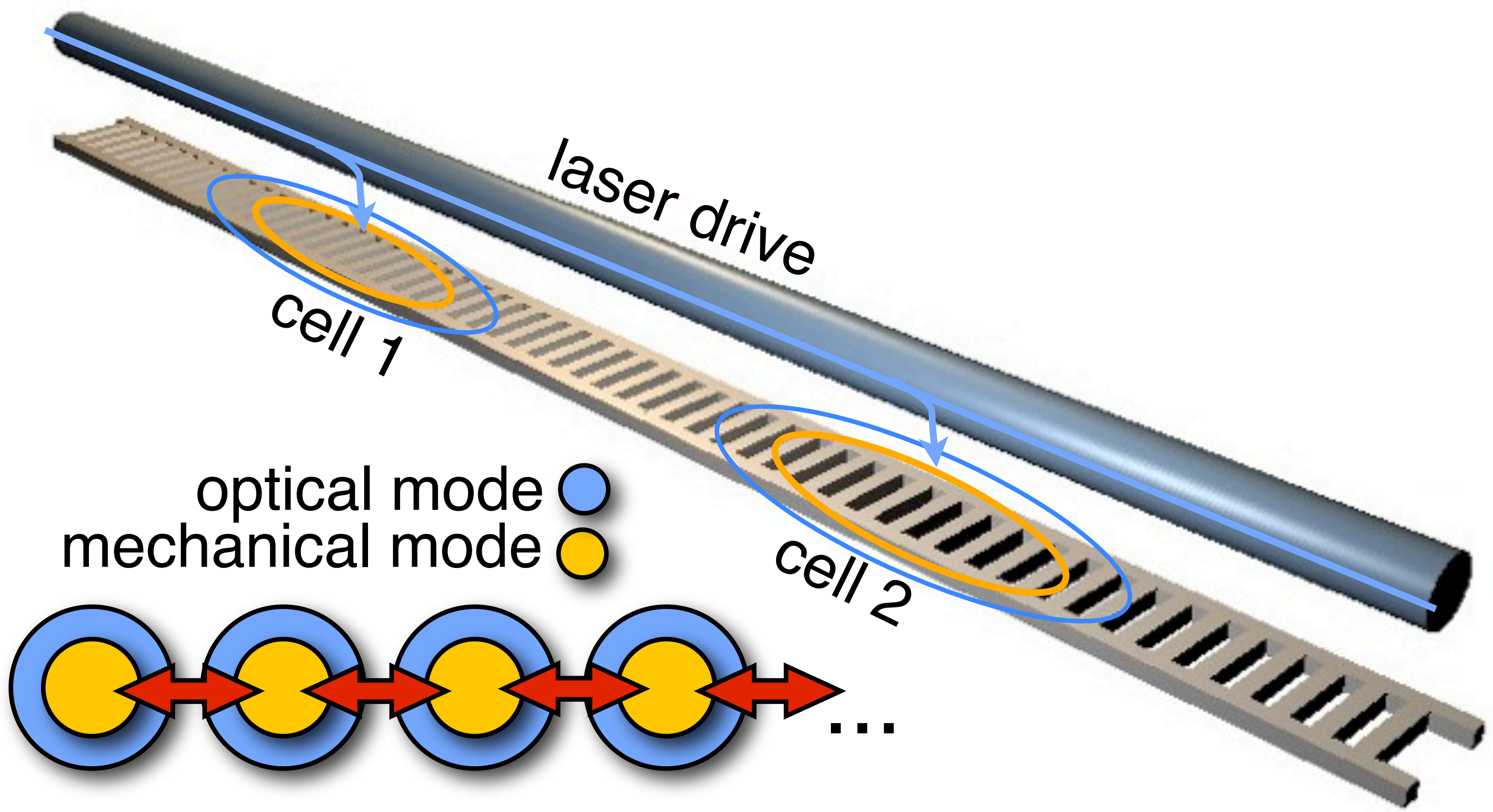
tight vibrational confinement:
high frequencies, small mass
(stronger quantum effects)

tight optical confinement:
large optomechanical coupling
(100 GHz/nm)

integrated on a chip

from: M. Eichenfield et al., Optics Express 17, 20078 (2009), Painter group, Caltech

Optomechanical arrays



collective nonlinear dynamics:
classical / quantum

cf. Josephson arrays

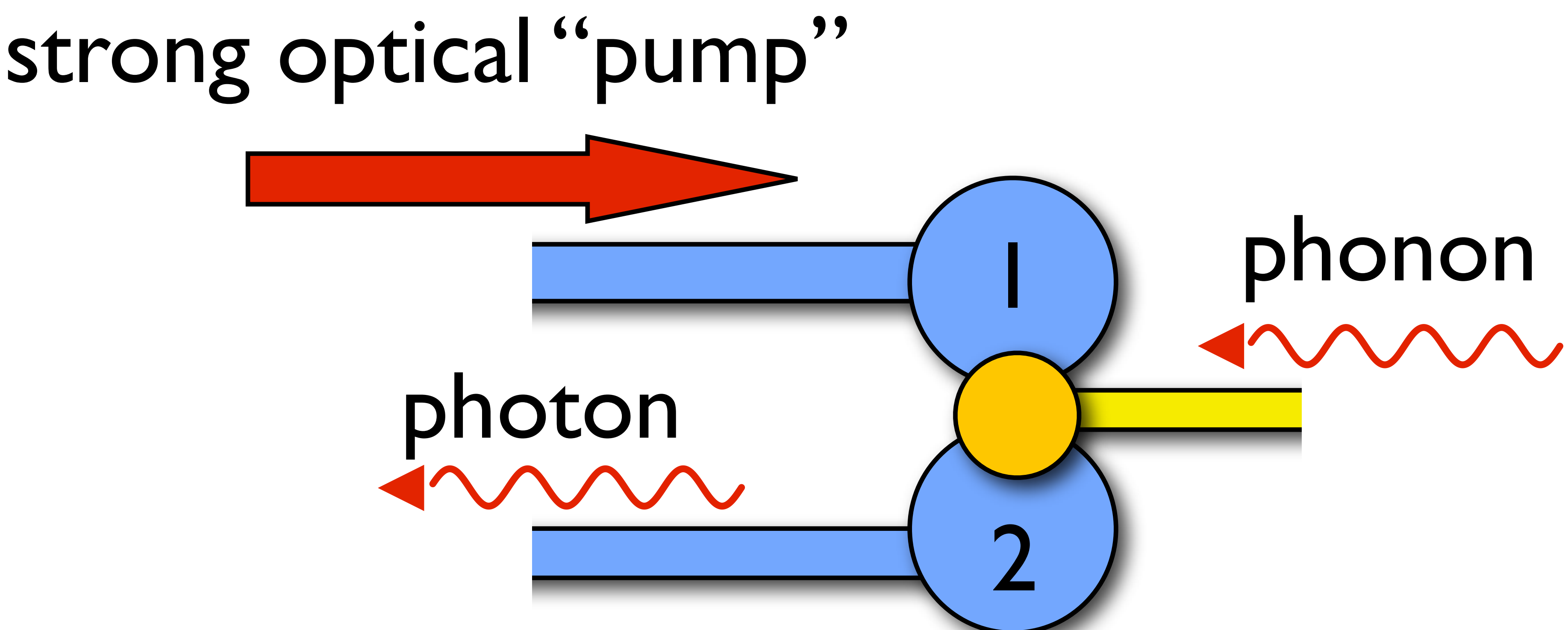
Dynamics in optomechanical arrays

Outlook

- 2D geometries
- Quantum or classical information processing and storage (continuous variables)
- Dissipative quantum many-body dynamics (quantum simulations)
- Hybrid devices: interfacing GHz qubits with light

Photon-phonon translator

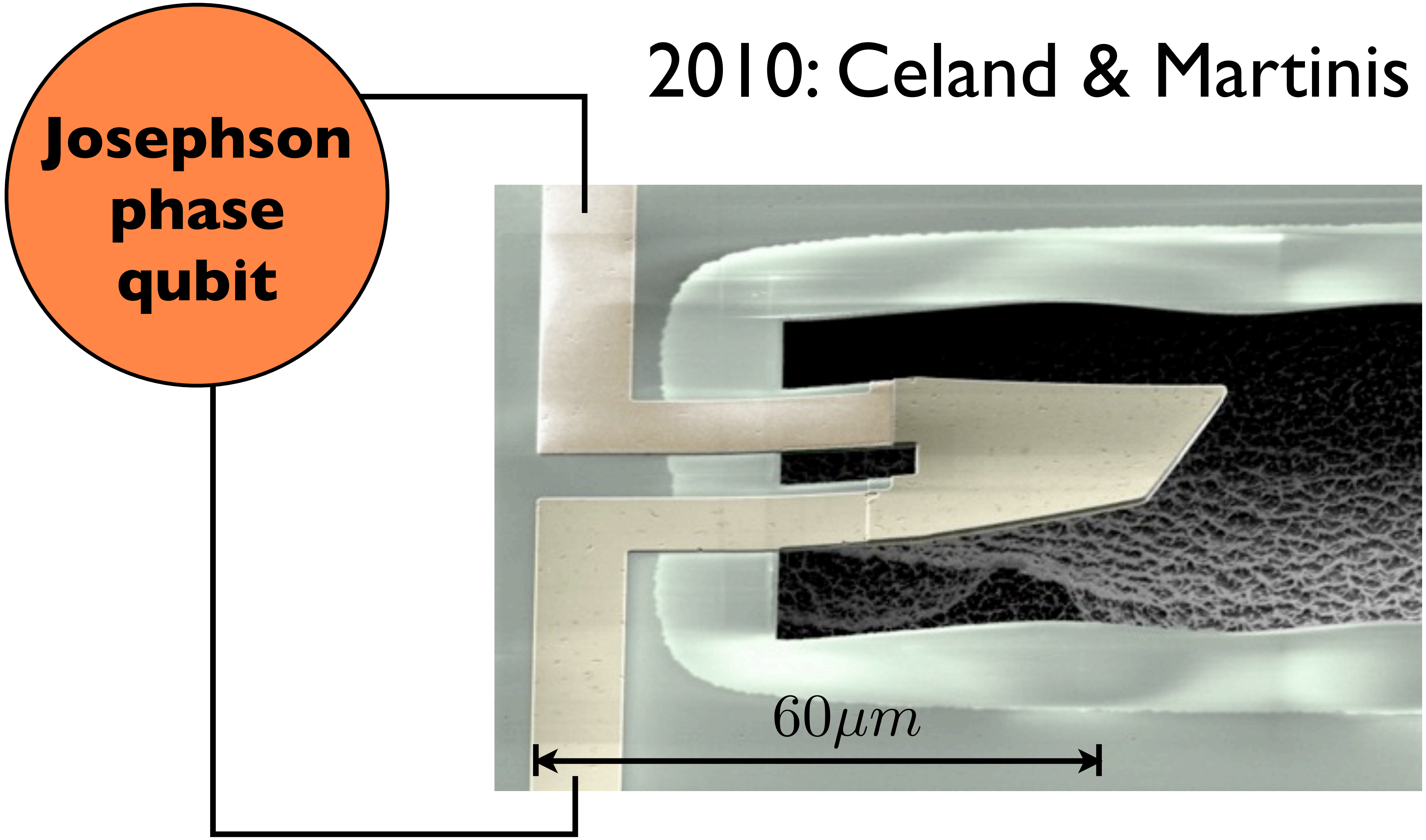
(concept: Painter group, Caltech)



$$\hat{H} = \ldots + \hbar g_0(\hat{a}_2^\dagger \hat{a}_1 + \hat{a}_1^\dagger \hat{a}_2)(\hat{b} + \hat{b}^\dagger)$$

Superconducting qubit coupled to nanomechanical resonator

2010: Celand & Martinis labs

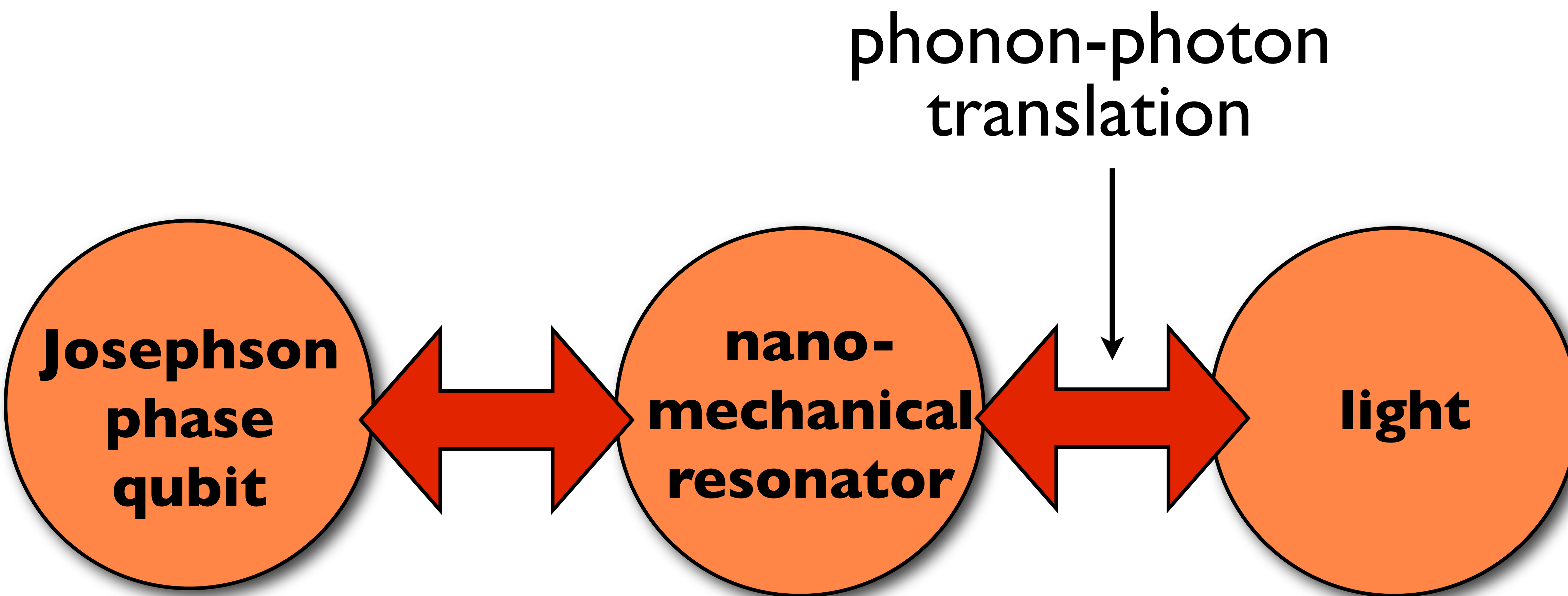


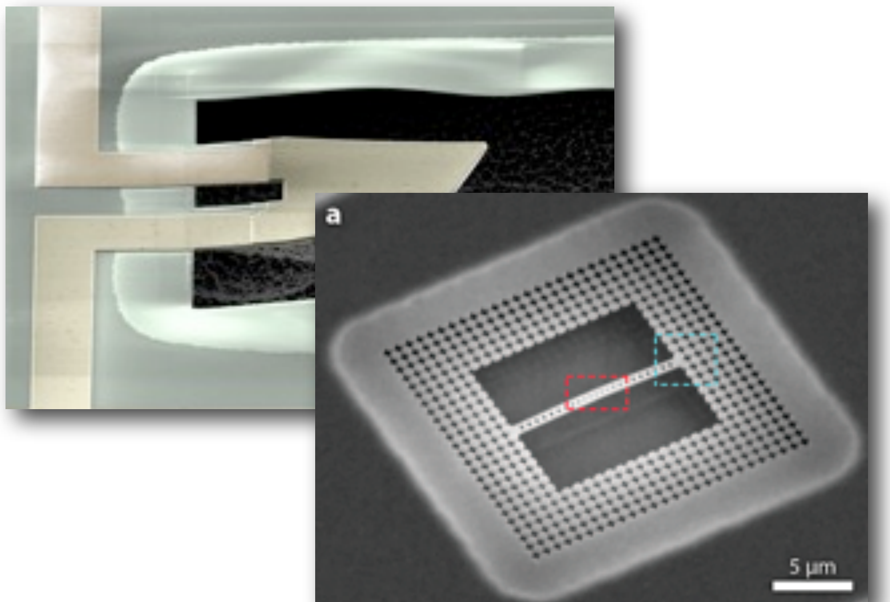
piezoelectric nanomechanical resonator

(GHz @ 20 mK: ground state!)

swap excitation between qubit and mechanical resonator in a few ns!

Conversion of quantum information

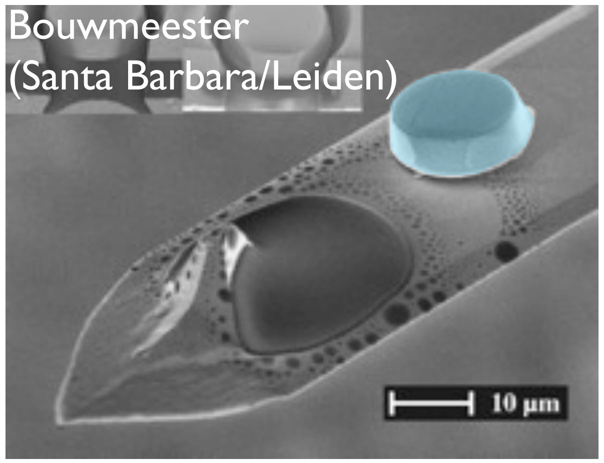




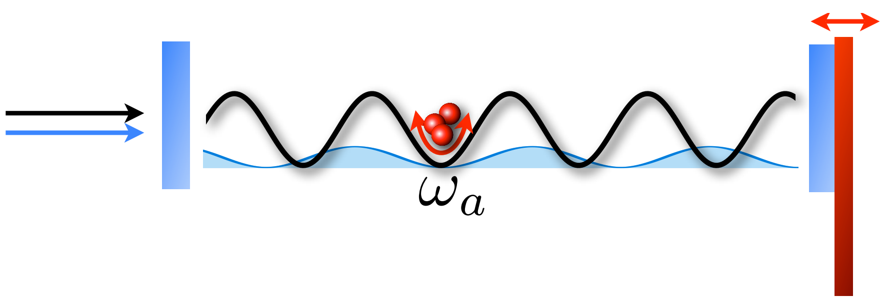
Recent trends

- Ground-state cooling: success! (spring 2011)
  [Teufel et al. in microwave circuit;
  Painter group in optical regime]
- Optomechanical (photonic) crystals
- Multiple mechanical/optical modes
- Option: build arrays or ‘optomechanical circuits’
- Strong improvements in coupling
- Possibly soon: ultrastrong coupling (resolve single photon-phonon coupling)
- Hybrid systems: Convert GHz quantum information (superconducting qubit) to photons
- Hybrid systems: atom/mechanics [e.g. Treutlein group]
- Levitating spheres: weak decoherence!
  [Barker/ Chang et al./ Romero-Isart et al.]

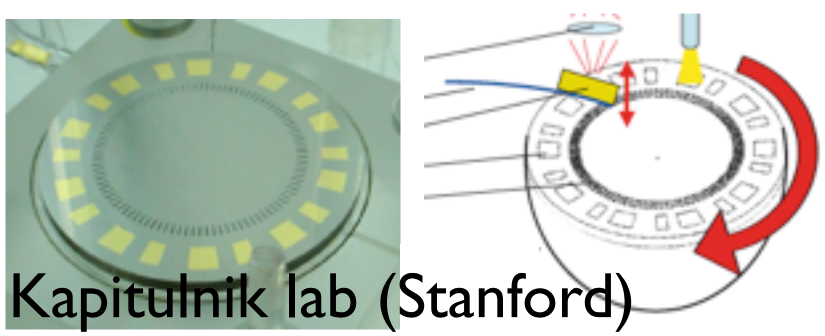
Optomechanics: general outlook



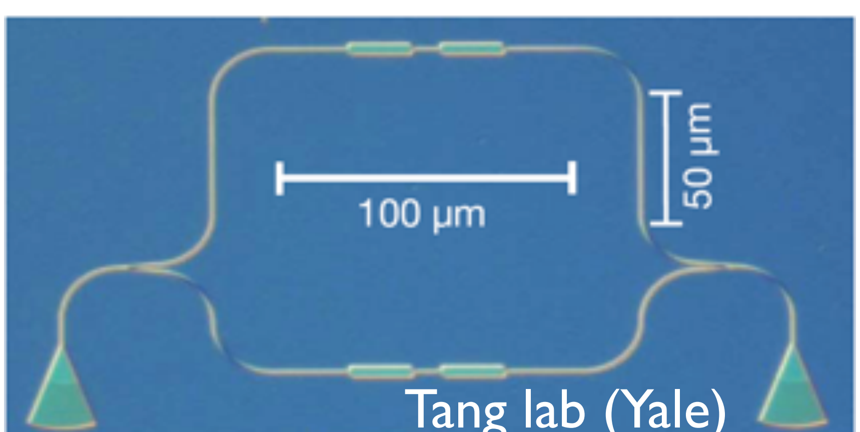
Fundamental tests of quantum mechanics in a new regime: entanglement with ‘macroscopic’ objects, unconventional decoherence? [e.g.: gravitationally induced?]



Mechanics as a ‘bus’ for connecting hybrid components: superconducting qubits, spins, photons, cold atoms, ...



Precision measurements
[e.g. testing deviations from Newtonian gravity due to extra dimensions]



Optomechanical circuits & arrays
Exploit nonlinearities for classical and quantum information processing, storage, and amplification; study collective dynamics in arrays

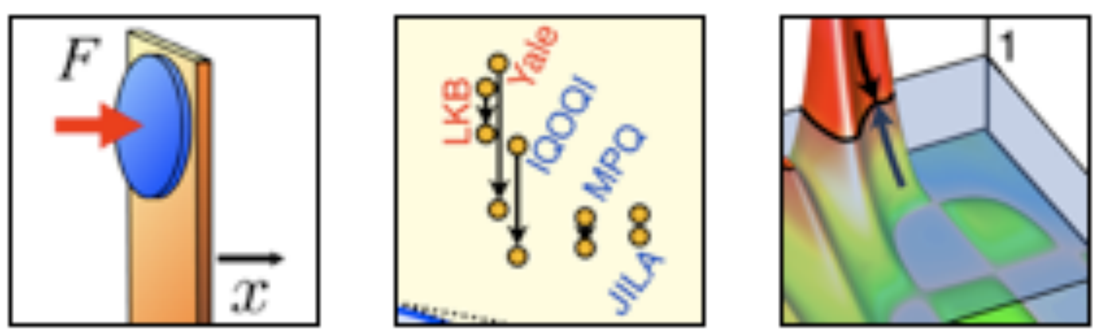
Optomechanics

Recent review on optomechanics:
APS Physics 2, 40 (2009)

Physics
spotlighting exceptional research

Trends

Optomechanics



Florian Marquardt and Steven M. Girvin, May 18, 2009

Recent review on quantum limits for detection and amplification:
Clerk, Devoret, Girvin, Marquardt, Schoelkopf; RMP 2010