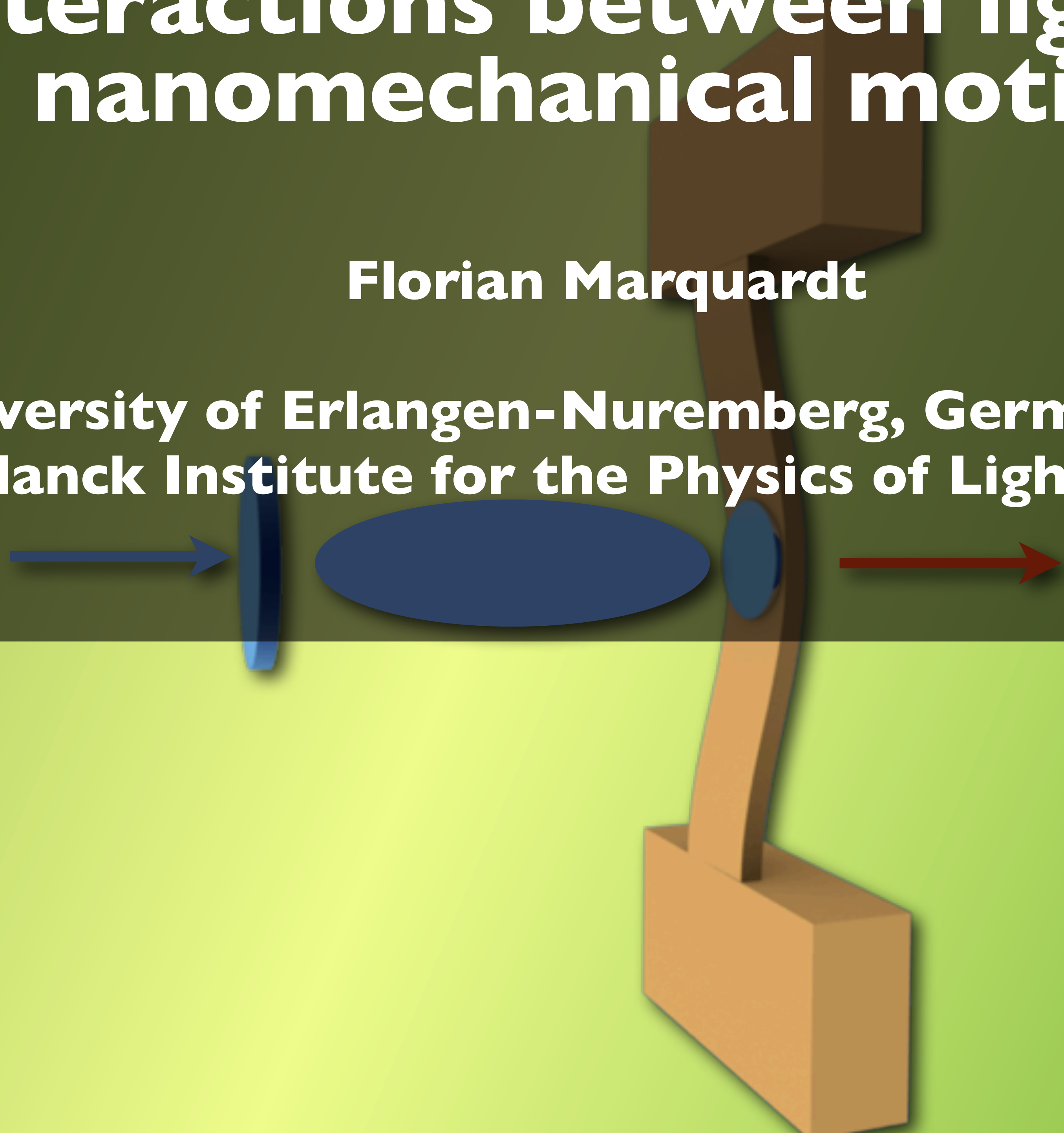
Cavity optomechanics: – interactions between light and nanomechanical motion

Florian Marquardt

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

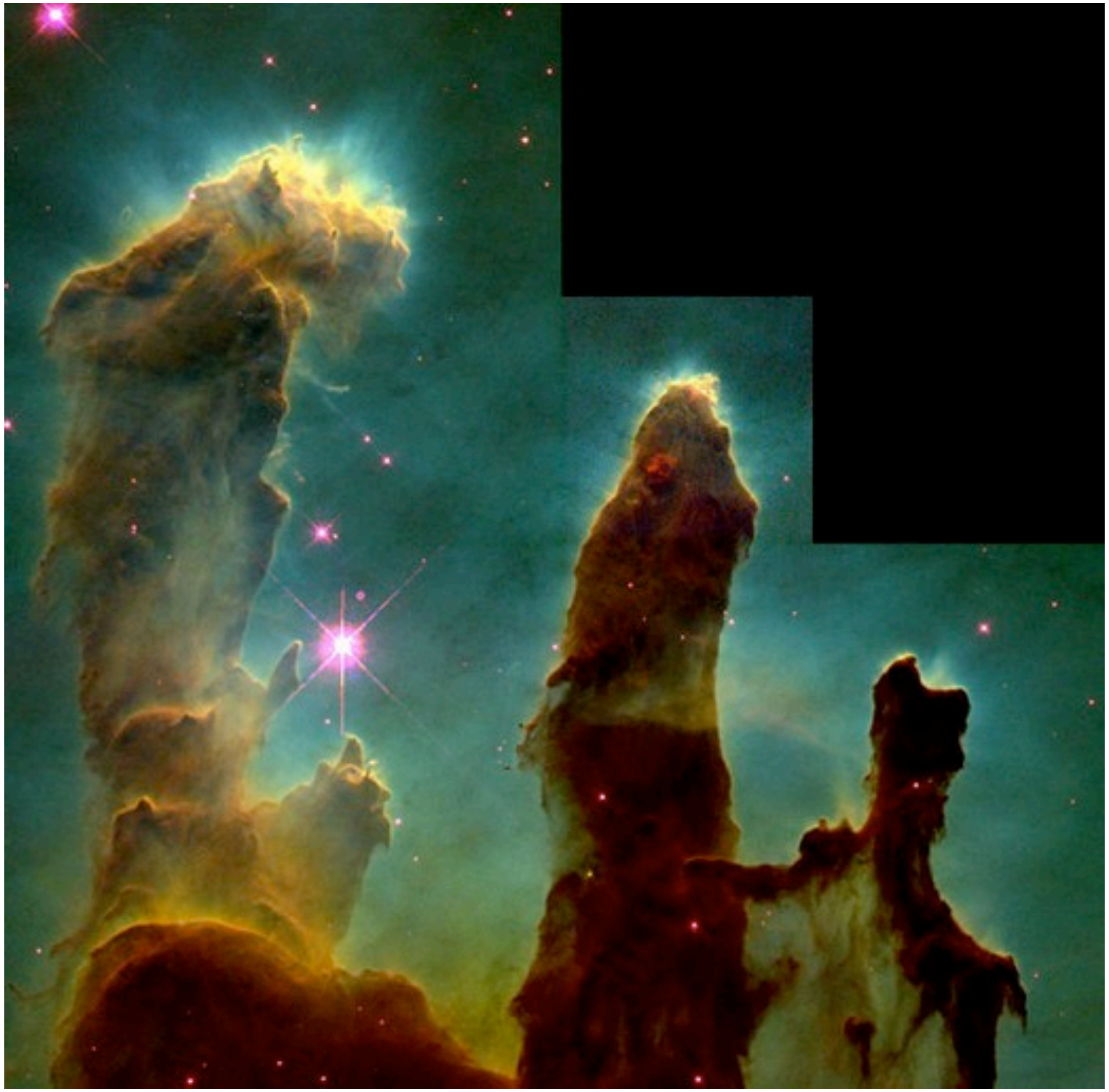


Radiation pressure

(Comet Hale-Bopp; by Robert Allevo)

Johannes Kepler
De Cometis, 1619

Radiation pressure



Johannes Kepler
De Cometis, 1619

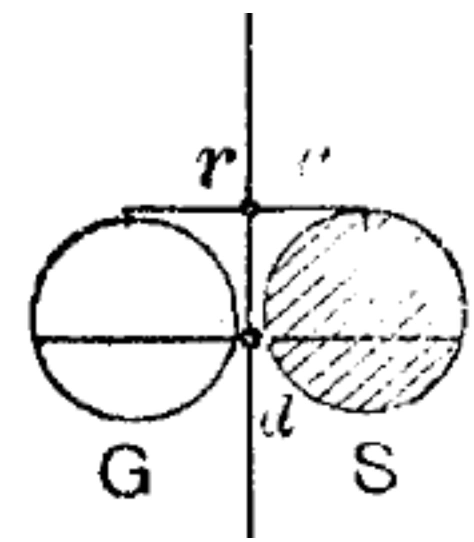
Radiation pressure

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.

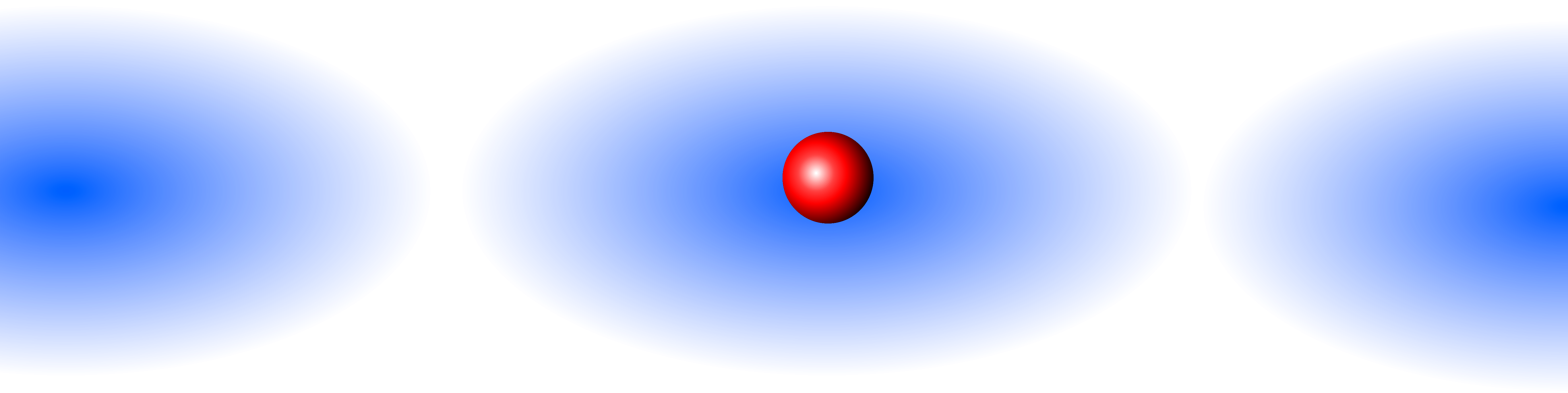
MAXWELL,[1] dealing mathematically with the stresses in an electro-magnetic field, reached the conclusion that "in a medium in which waves are propagated there is a pressure normal to the waves and numerically equal to the energy in unit volume."



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

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

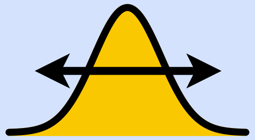
LIGO – Laser Interferometer Gravitational Wave Observatory

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

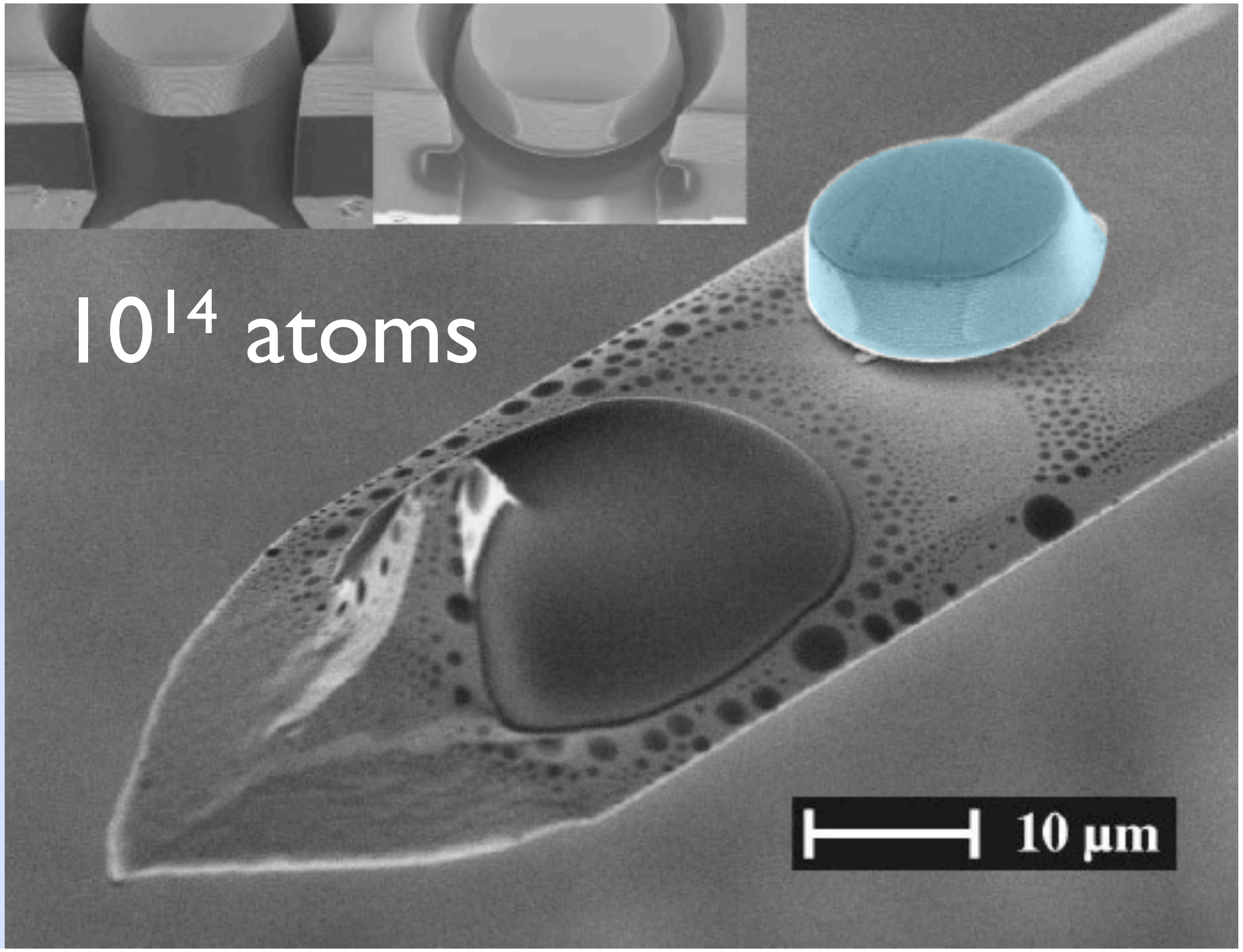
$$m \sim 10^{-12} - 10^{-10}\text{kg}$$

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

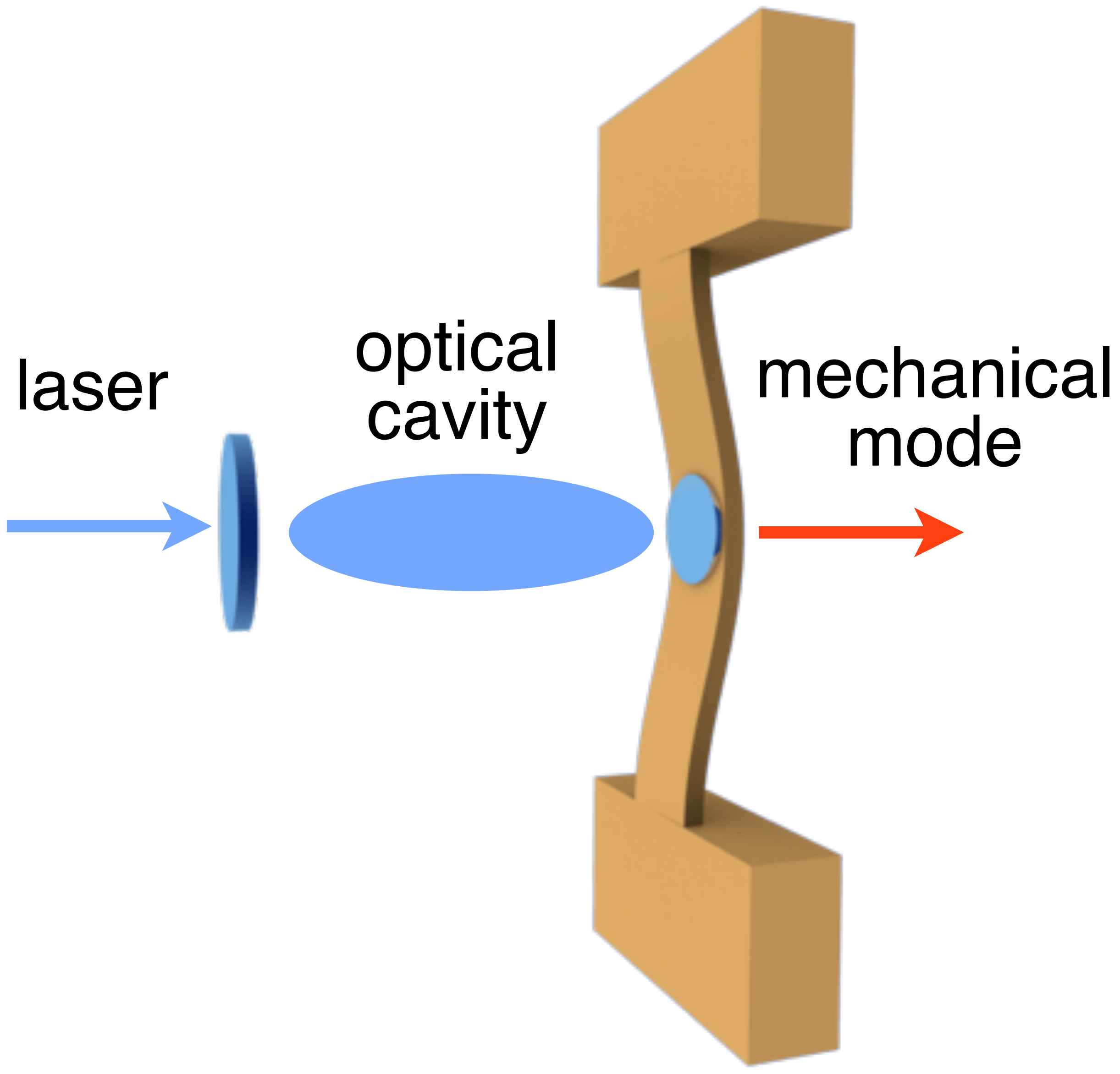
$$x_{\text{ZPF}} = \sqrt{\hbar/(2m\omega_M)}$$



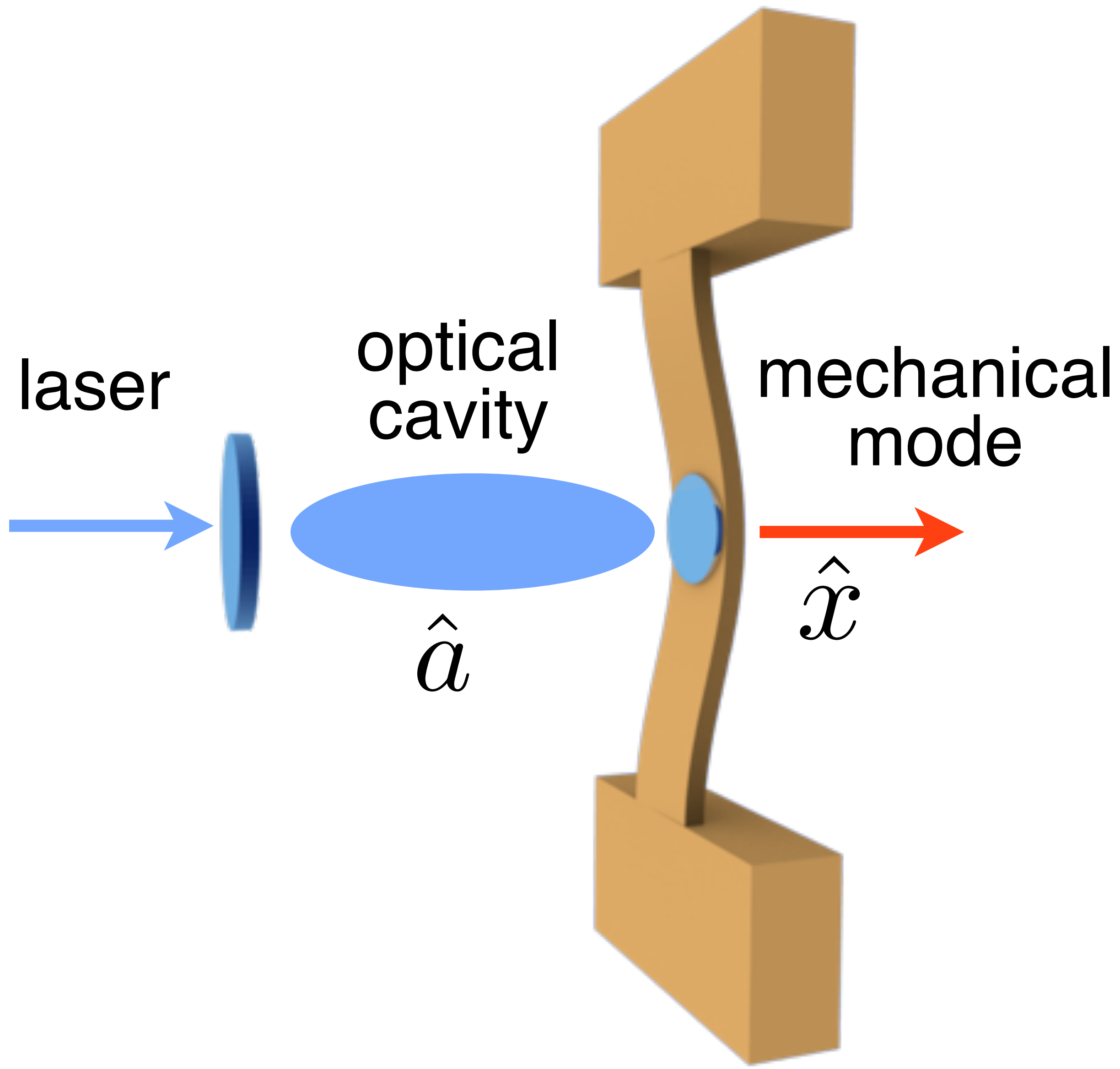
Mirror on cantilever – Bouwmeester lab, Santa Barbara (2006)



Optomechanical Hamiltonian



Optomechanical Hamiltonian

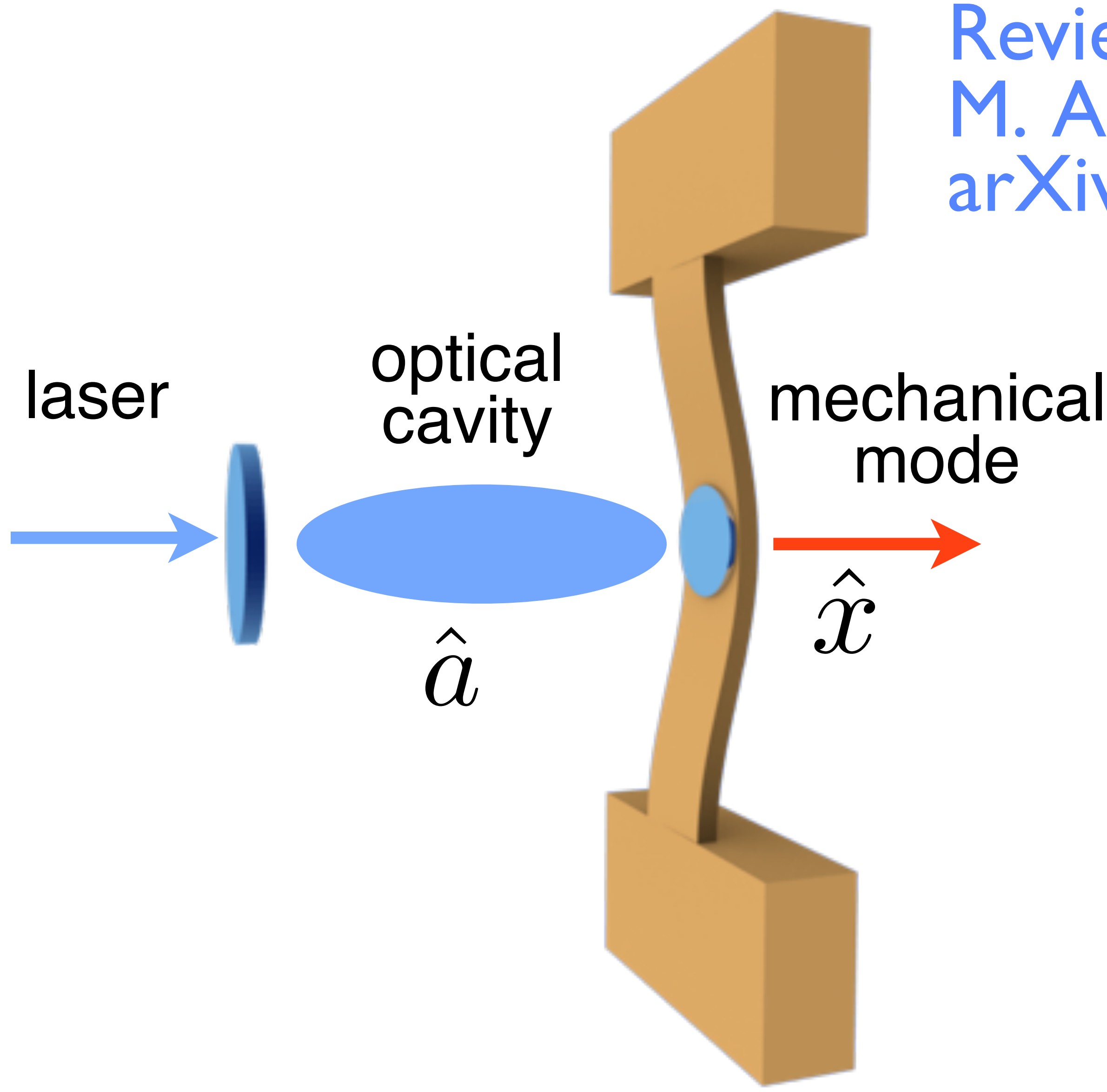


$$\hat{H} = \hbar\omega_{\mathrm{cav}} \cdot (1 - \hat{x}/L)\hat{a}^\dagger \hat{a} + \hbar\omega_M \hat{b}^\dagger \hat{b} + \ldots$$

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

Optomechanical Hamiltonian

Review "Cavity Optomechanics":
M. Aspelmeyer, T. Kippenberg, FM
arXiv:1303.0733



$$g_0 \sim \mathrm{Hz} - \mathrm{MHz}$$

$$\hat{H} = -(\Delta + g_0(\hat{b} + \hat{b}^\dagger))\hat{a}^\dagger\hat{a} + \Omega\hat{b}^\dagger\hat{b} + \ldots$$

laser detuning

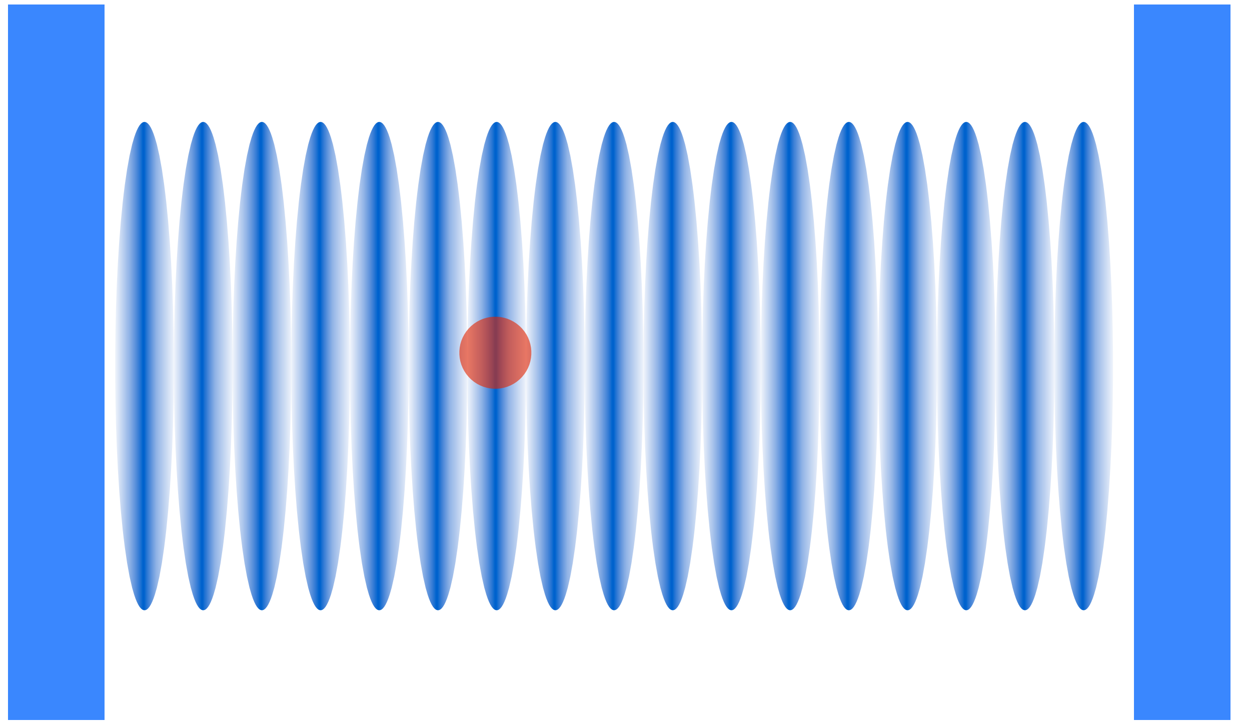
$$\Delta = \omega_L - \omega_{\mathrm{cav}}$$

optomech. coupling

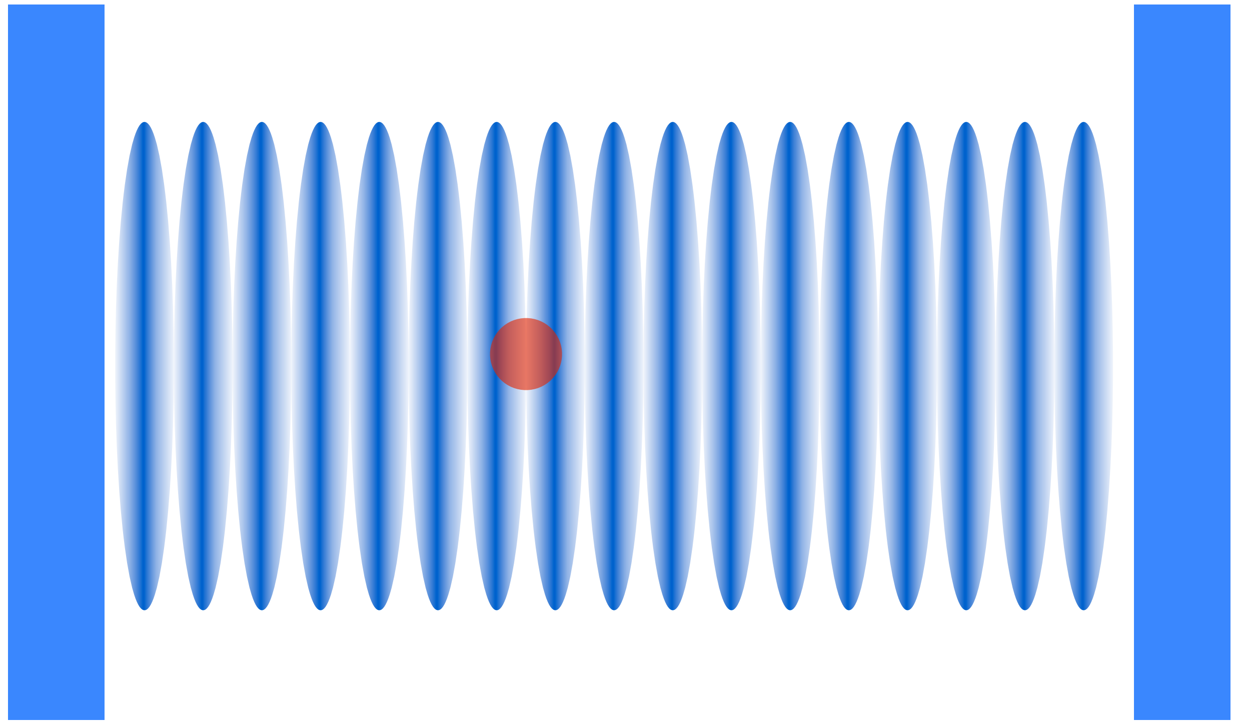
$$\hat{x} = x_{\mathrm{ZPF}}(\hat{b} + \hat{b}^\dagger)$$

$$x_{\mathrm{ZPF}} = \sqrt{\hbar/2m\Omega}$$

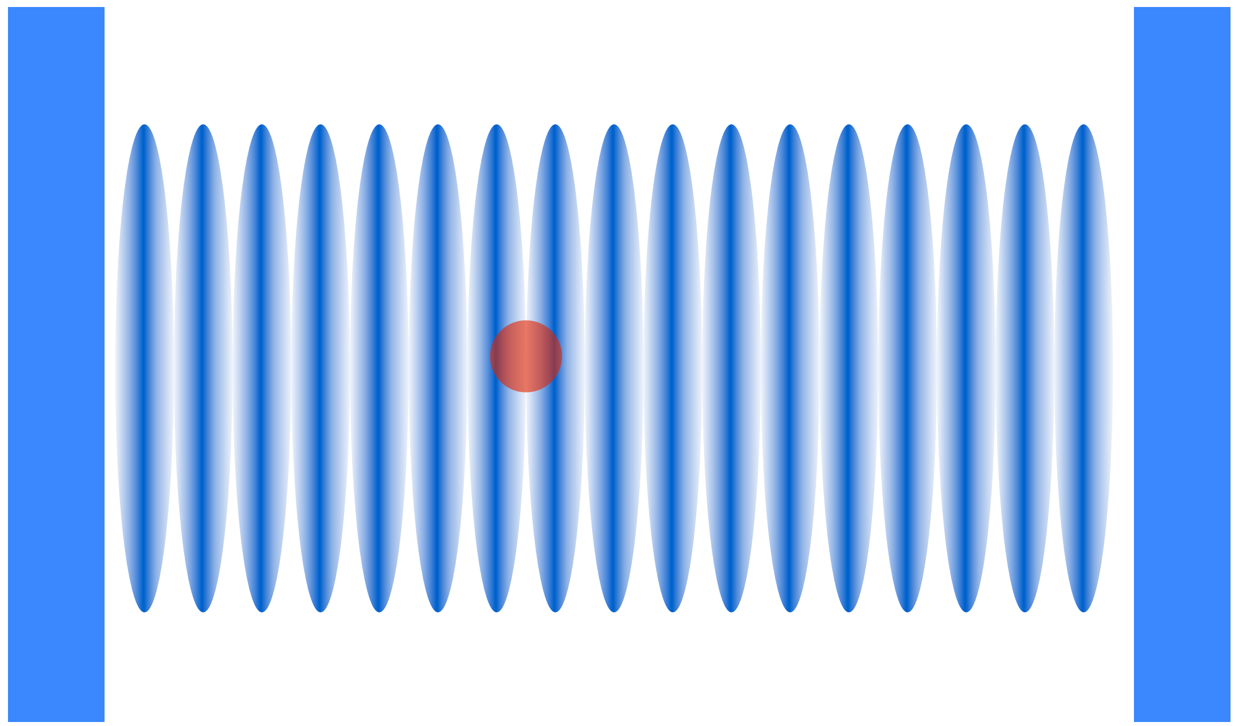
Optomechanical Hamiltonian



Optomechanical Hamiltonian



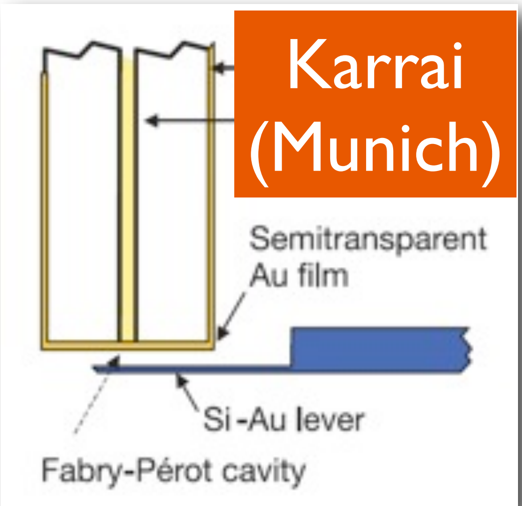
Optomechanical Hamiltonian



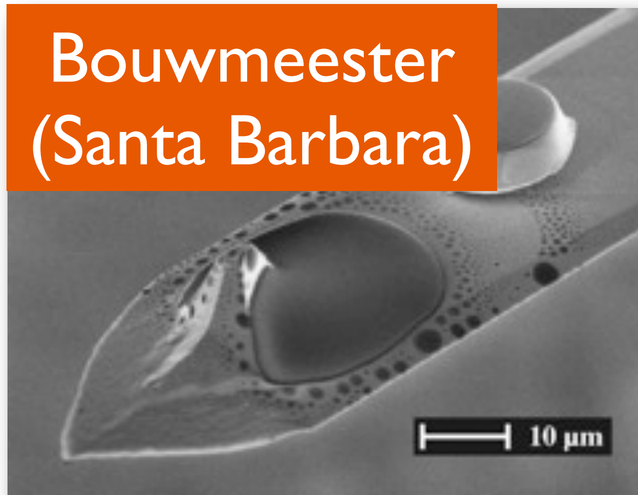
$$\hat{H} = \hbar\omega_{\text{cav}}(\hat{x})\hat{a}^\dagger\hat{a} + \hbar\omega_M\hat{b}^\dagger\hat{b} + \ldots$$

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

The zoo of optomechanical (and analogous) systems

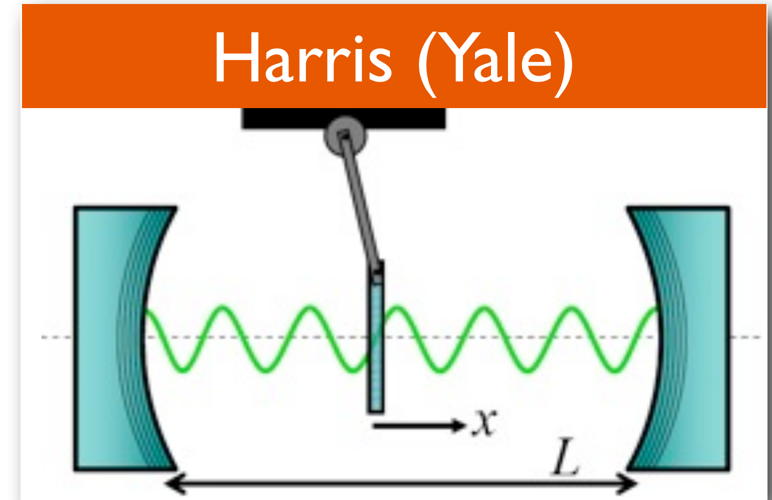


Karrai (Munich)

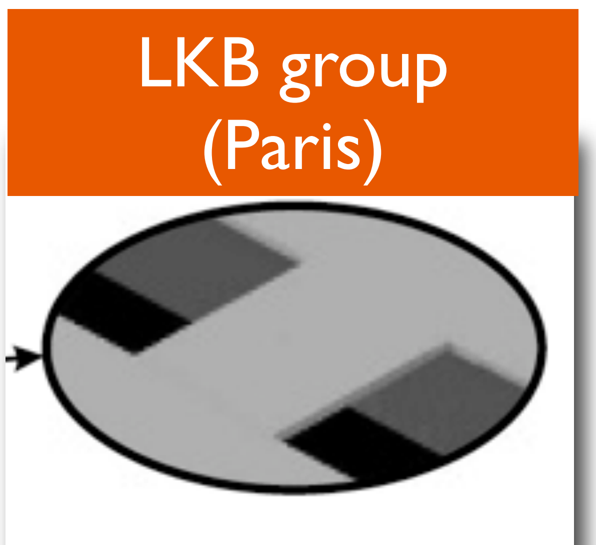


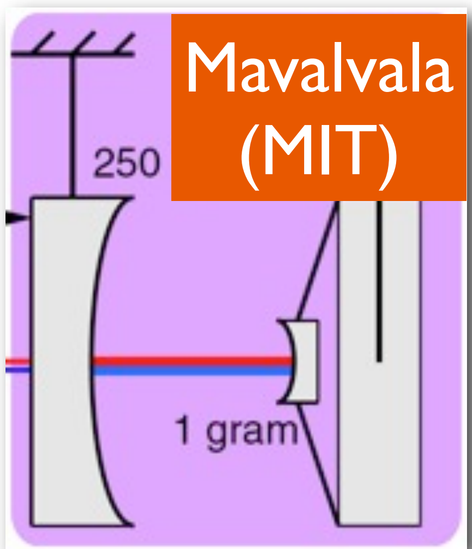
Bouwmeester (Santa Barbara)

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

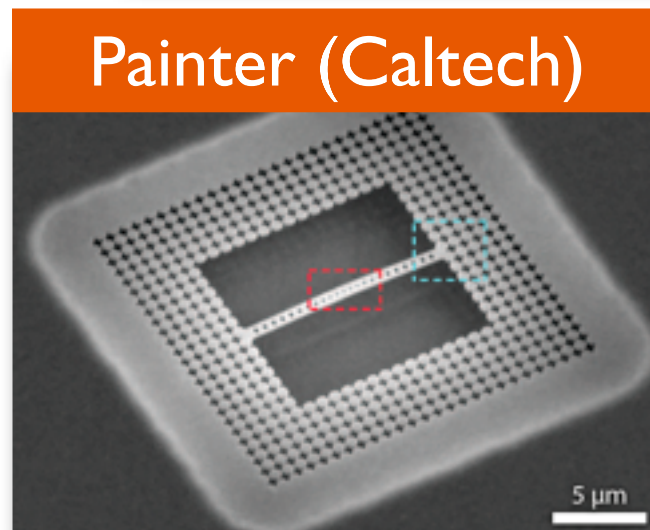


Harris (Yale)


LKB group (Paris)



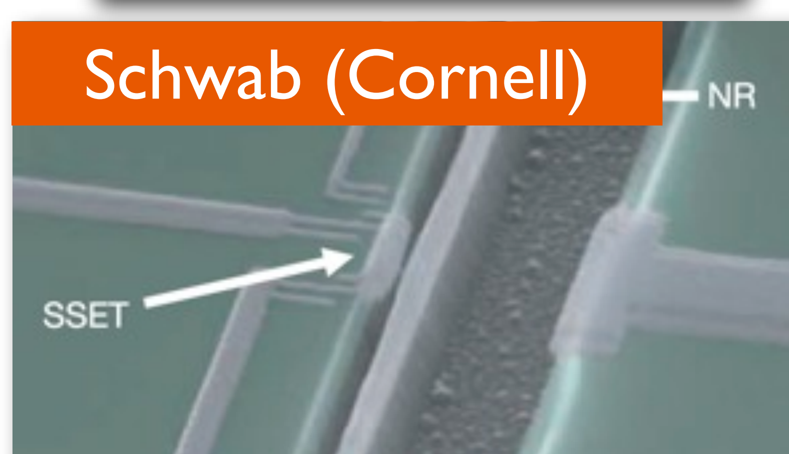
Mavalvala (MIT)



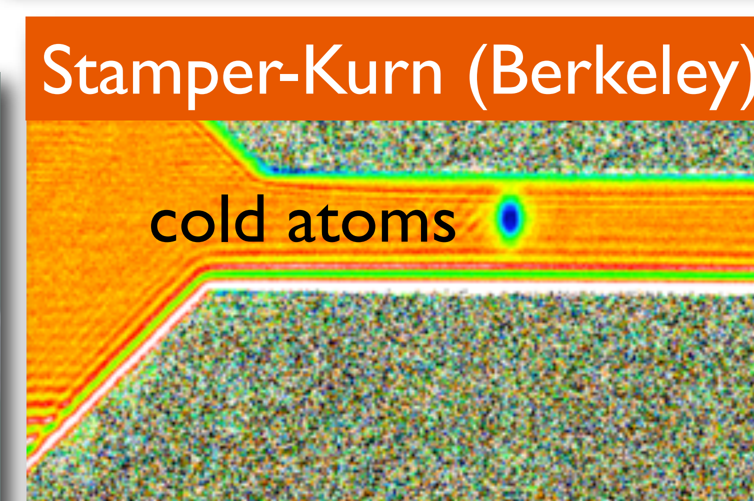
Painter (Caltech)

Teufel, Lehnert (Boulder)


Aspelmeyer (Vienna)

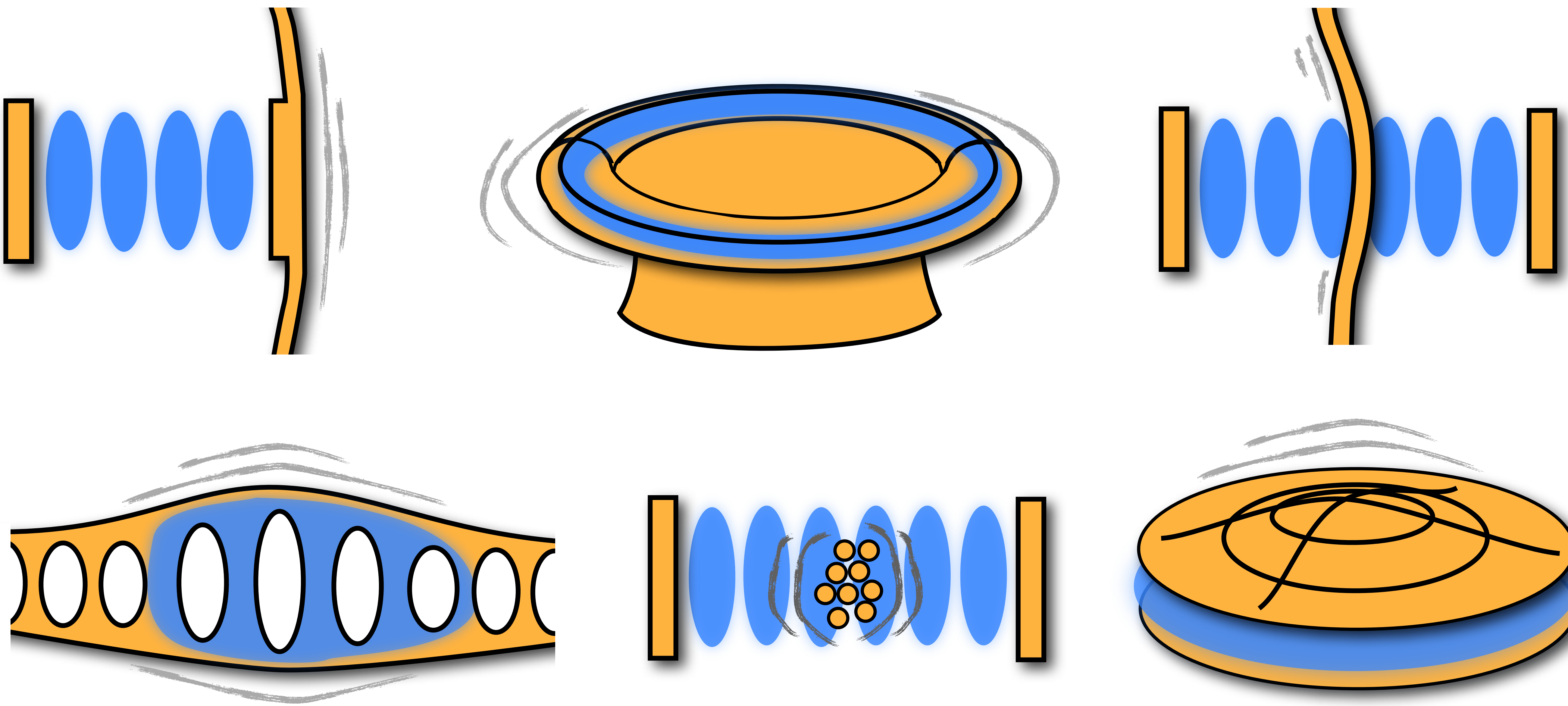


Schwab (Cornell)

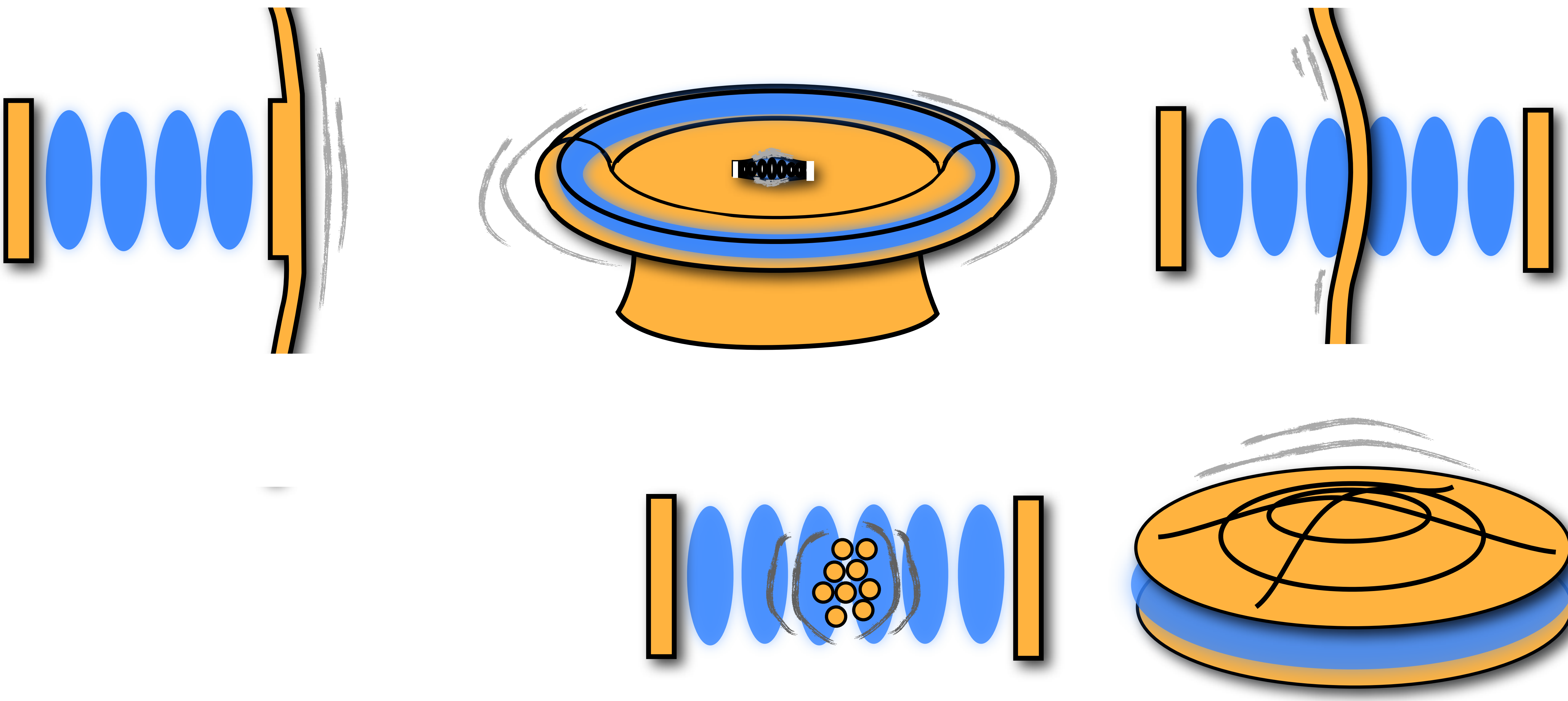


Stamper-Kurn (Berkeley)

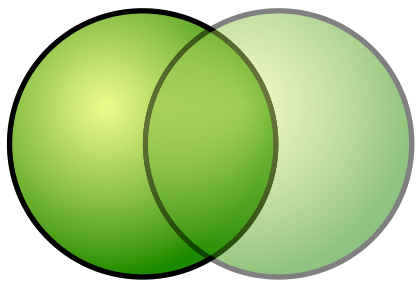
The zoo of optomechanical (and analogous) systems



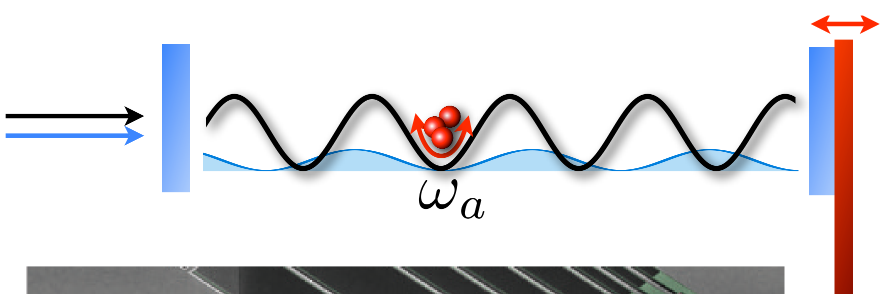
The zoo of optomechanical (and analogous) systems



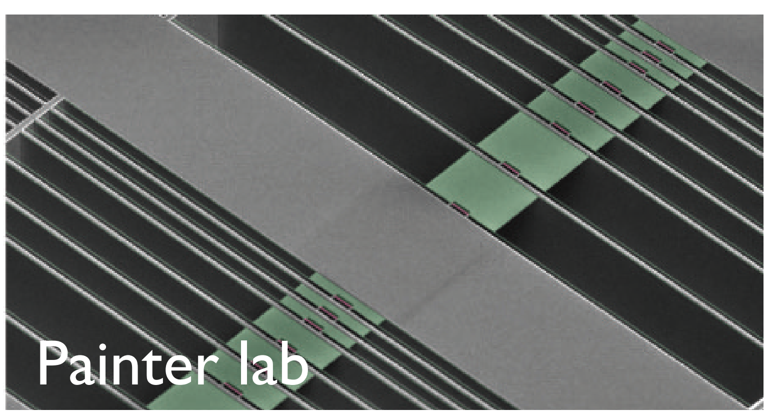
Optomechanics: general outlook



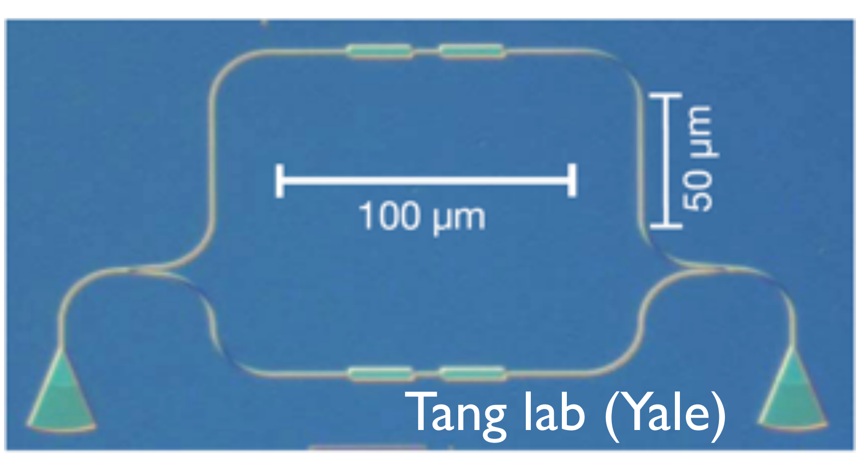
Fundamental tests of quantum mechanics in a new regime:
entanglement with 'macroscopic' objects, unconventional decoherence? [e.g.: gravitationally induced?]



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

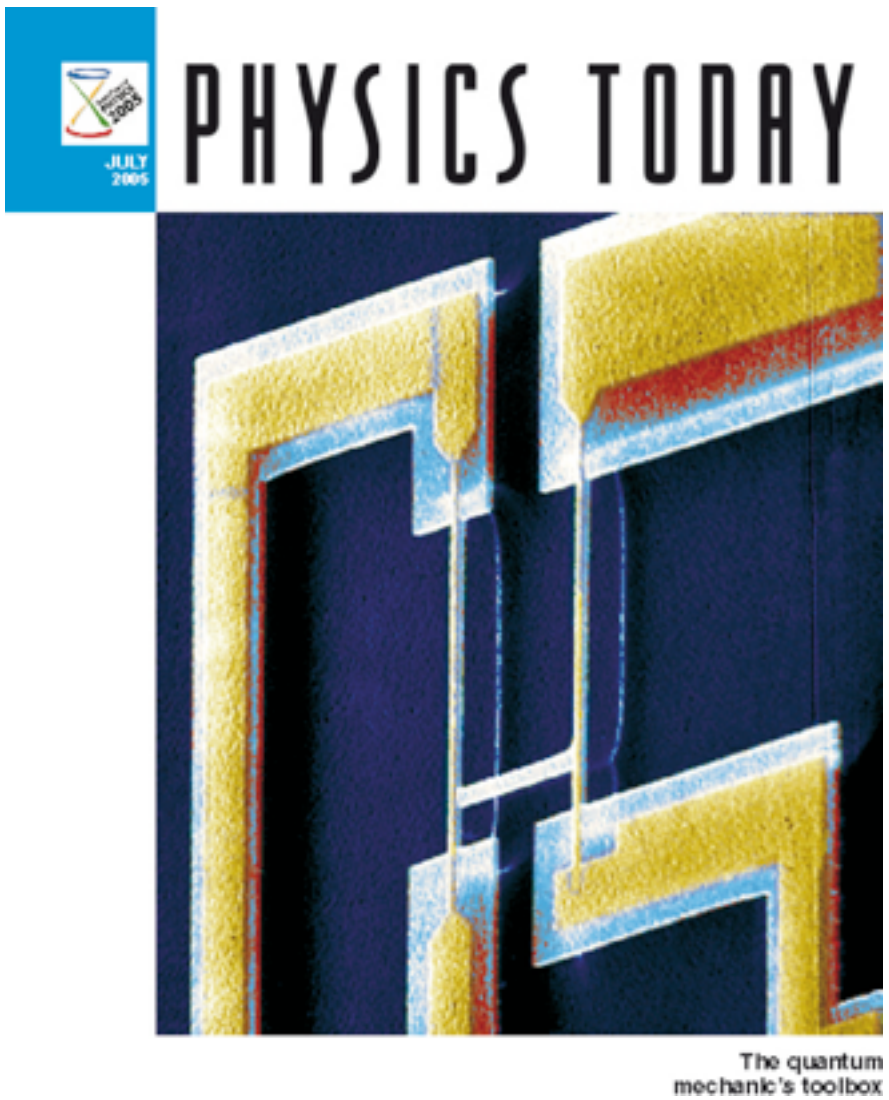


Precision measurements
small displacements, masses, forces, and accelerations



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

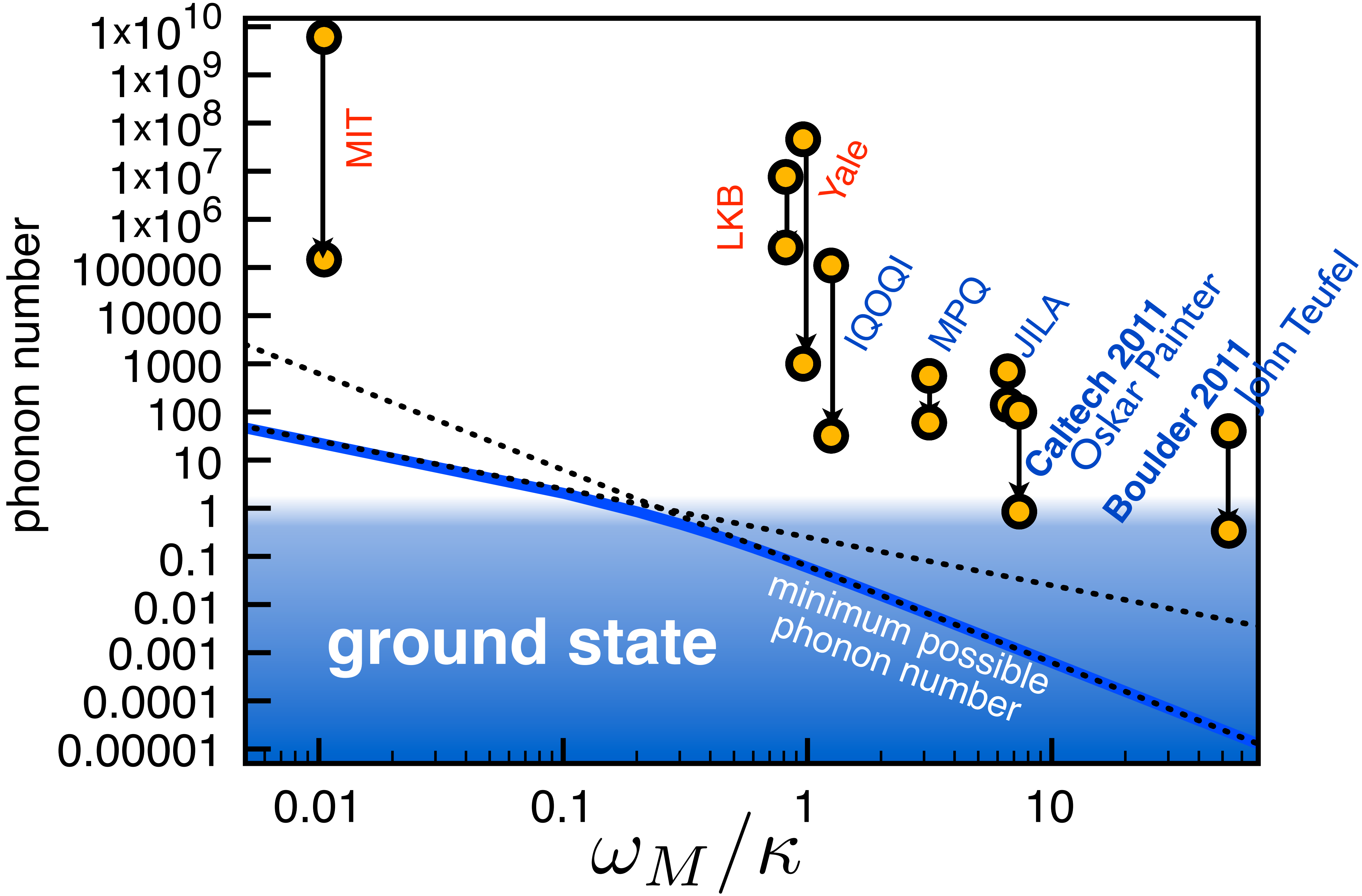
Schwab and Roukes, Physics Today 2005

- nano-electro-mechanical systems

Superconducting qubit coupled to nanoresonator: Cleland & Martinis 2010

- optomechanical systems

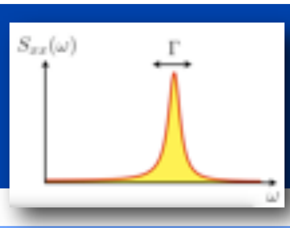
Laser-cooling towards the ground state



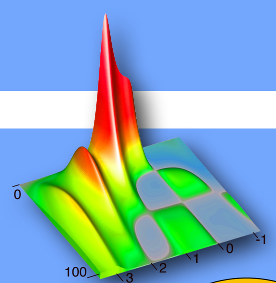
analogy to (cavity-assisted)
laser cooling of atoms

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

Optomechanics (Outline)

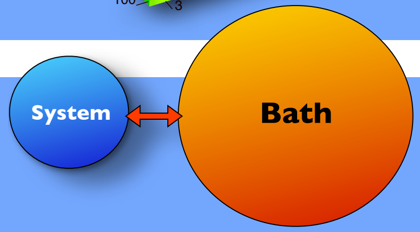


Displacement detection

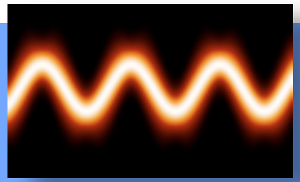


Linear optomechanics

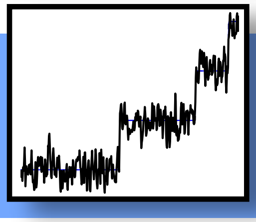
Nonlinear dynamics



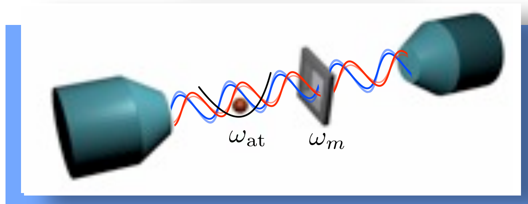
Quantum theory of cooling



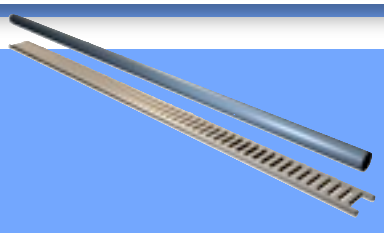
Interesting quantum states



Towards Fock state detection

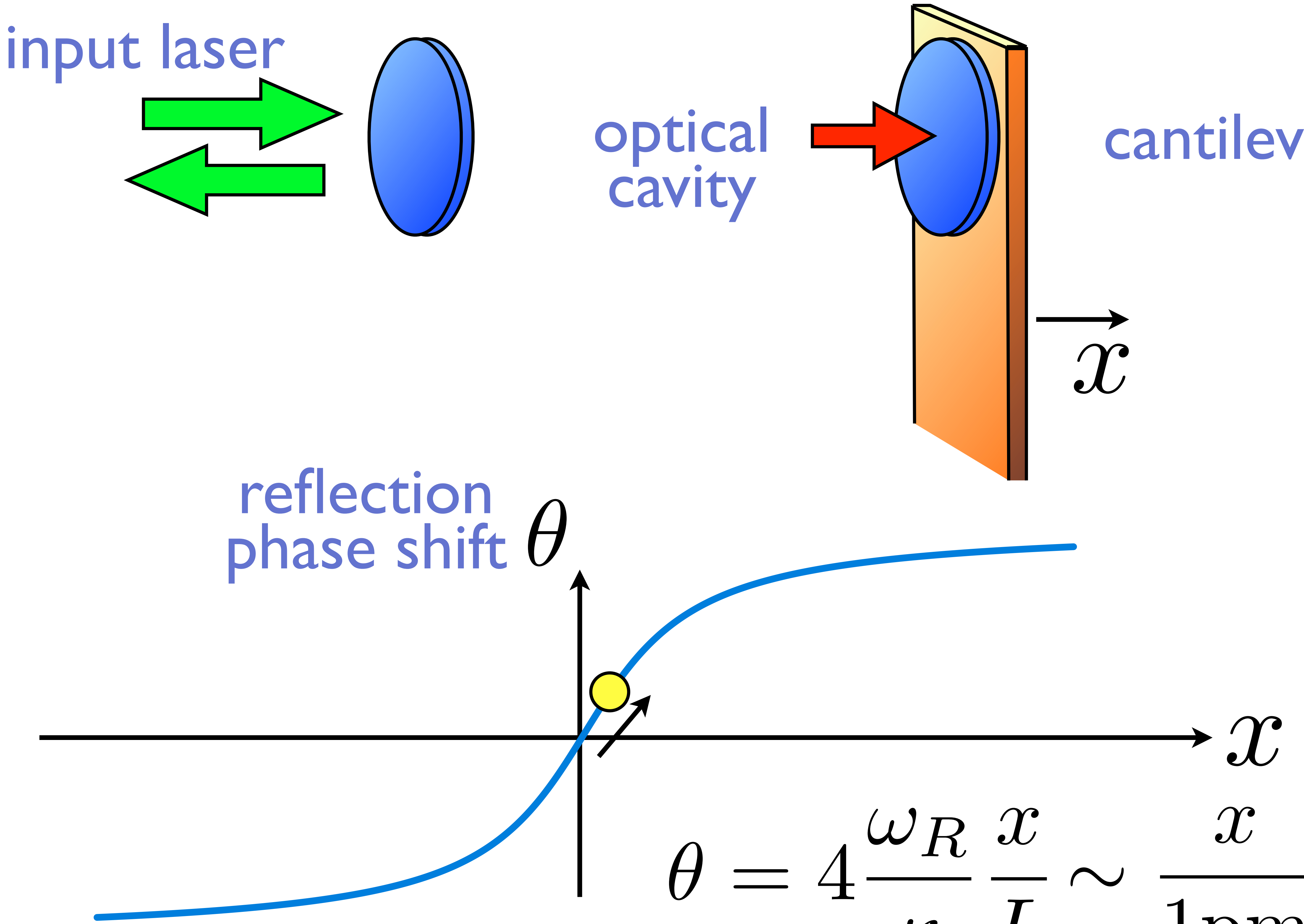


Hybrid systems: coupling to atoms



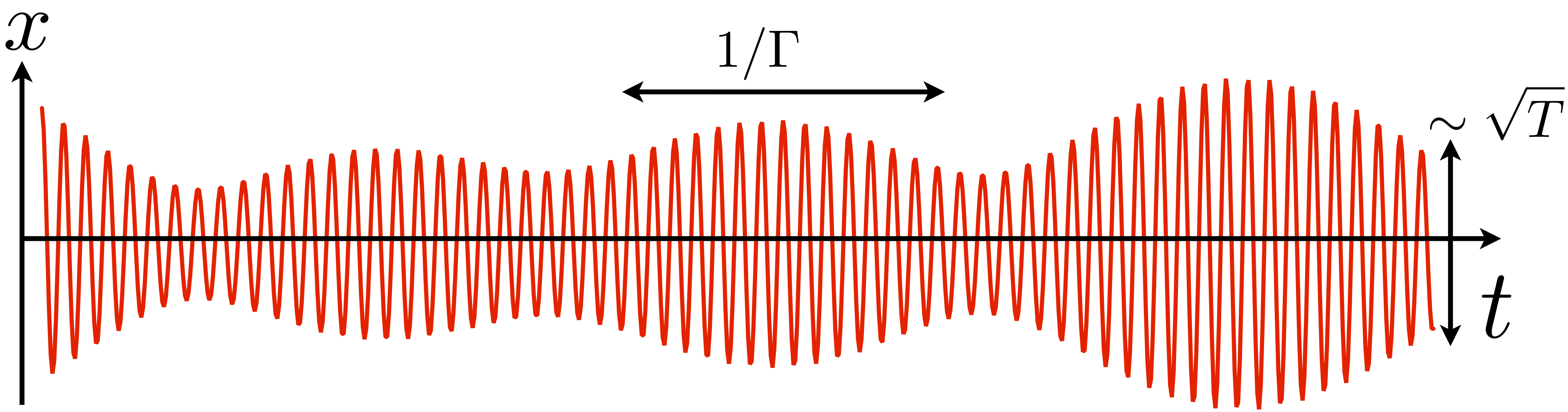
Optomechanical crystals & arrays

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:

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

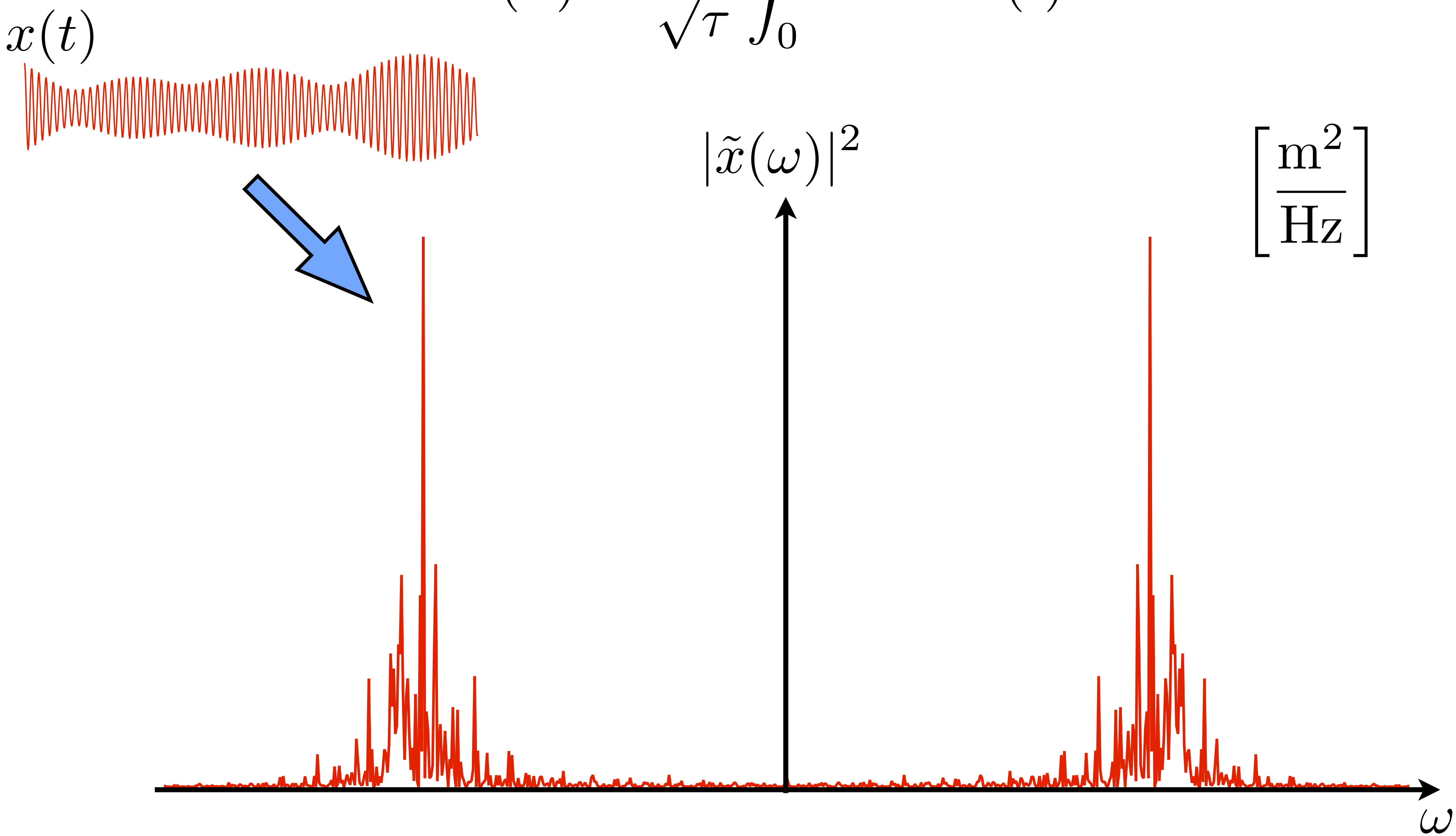
extract temperature!

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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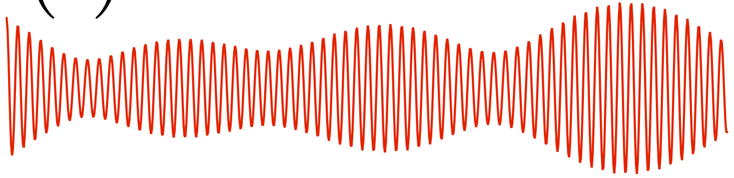
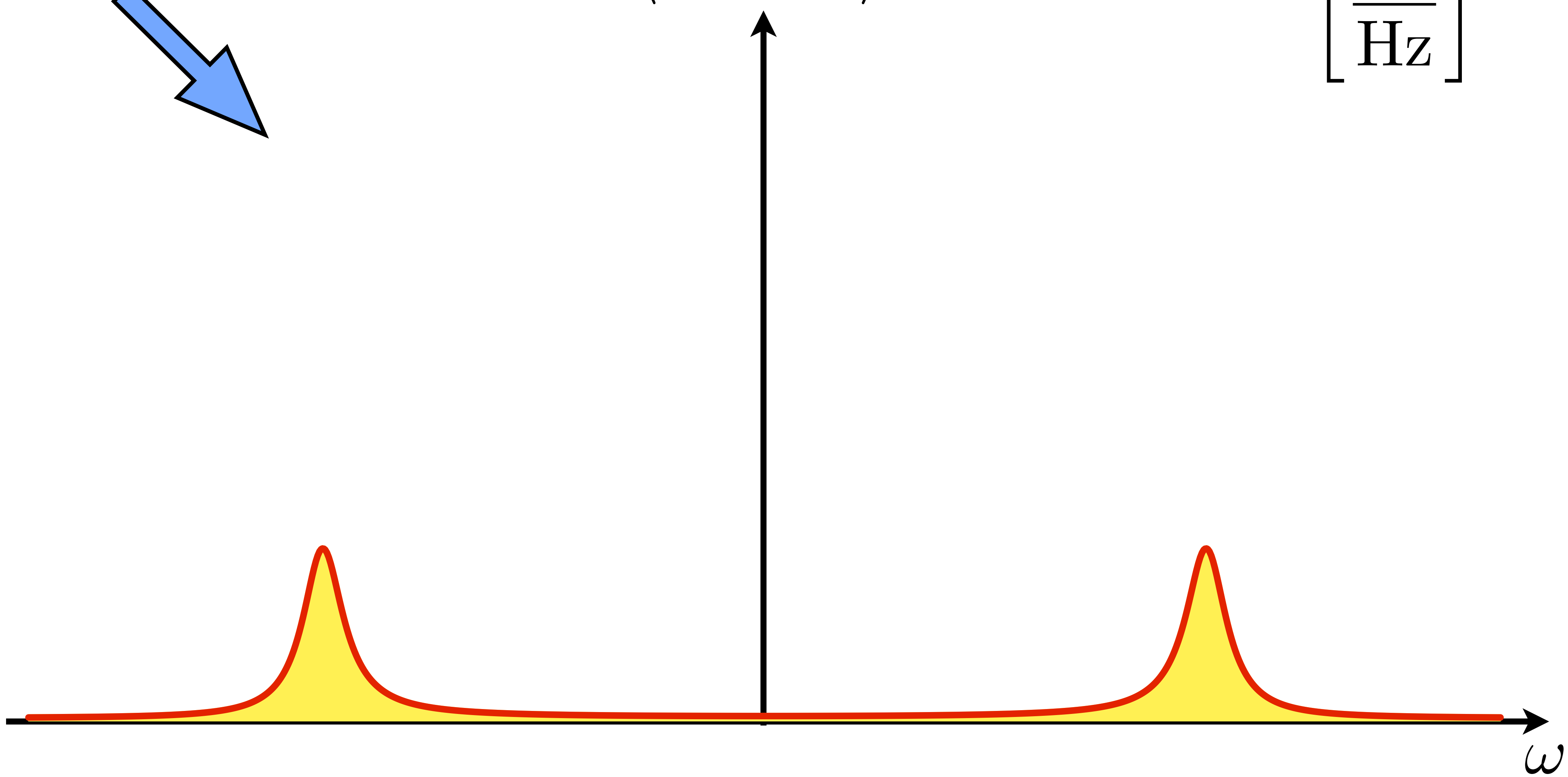
$x(t)$



$$\langle |\tilde{x}(\omega)|^2 \rangle \equiv S_{xx}(\omega)$$

$$\left[\frac{\mathrm{m}^2}{\mathrm{Hz}}\right]$$



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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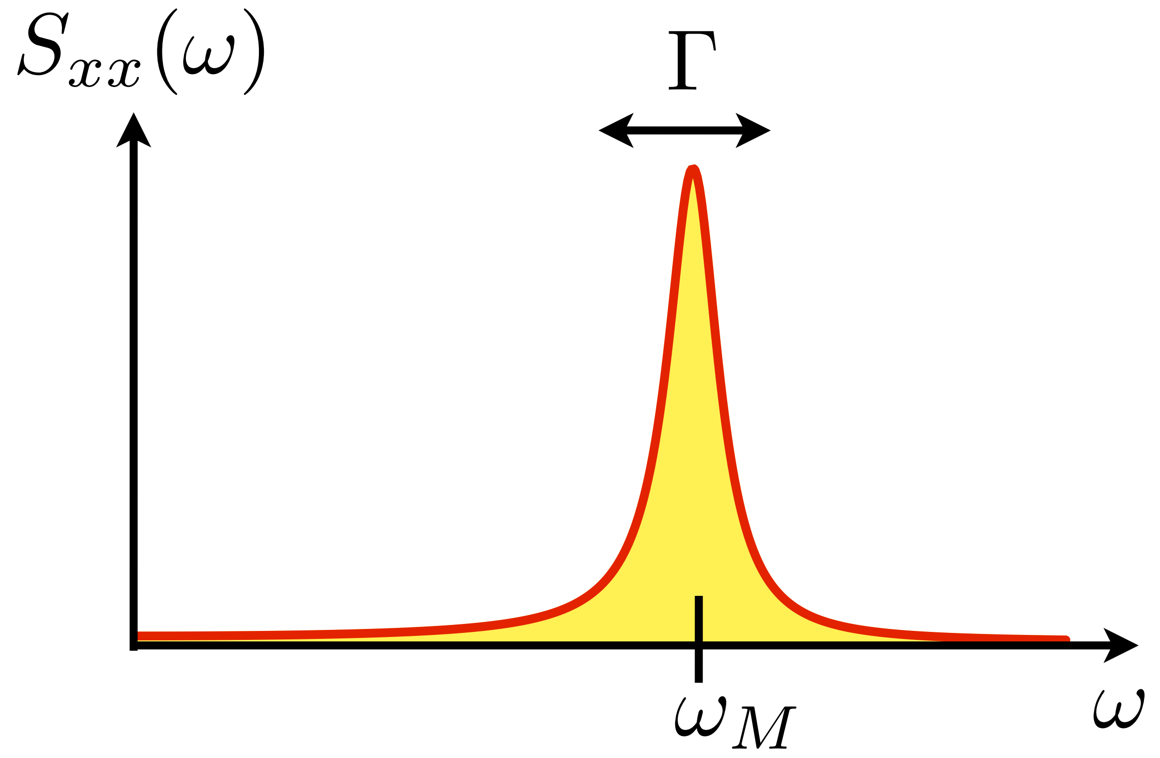
(classical limit)

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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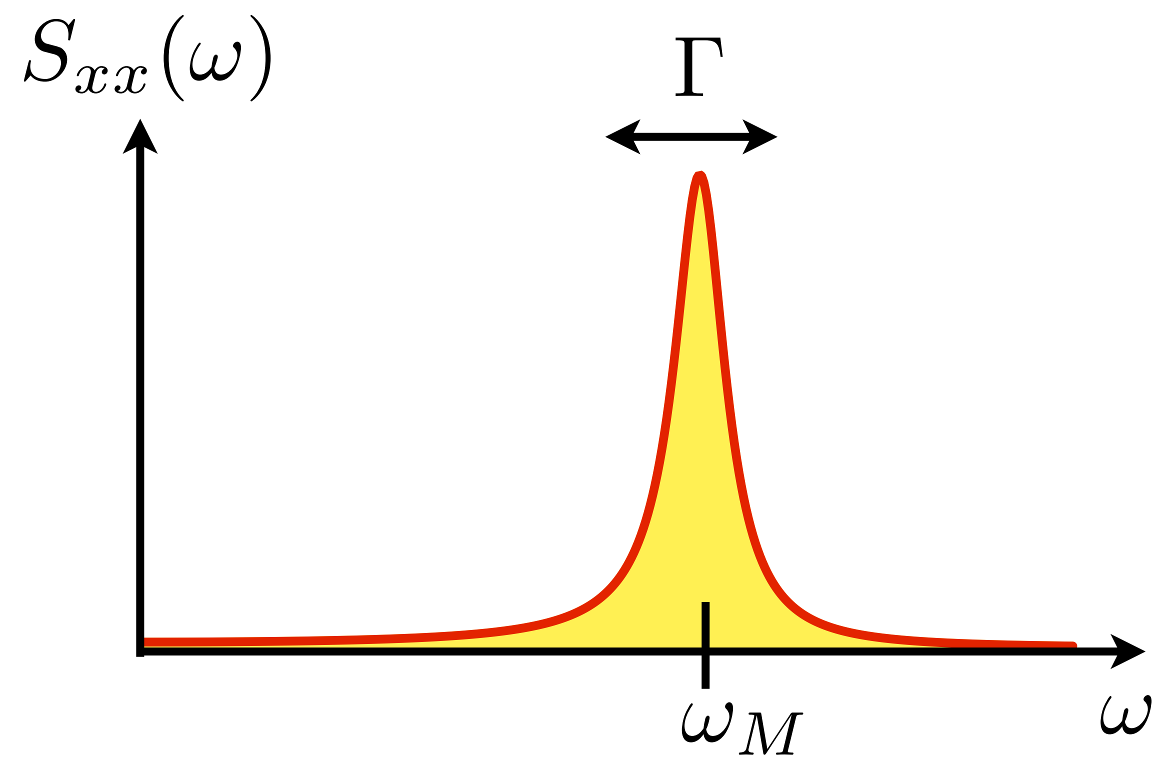
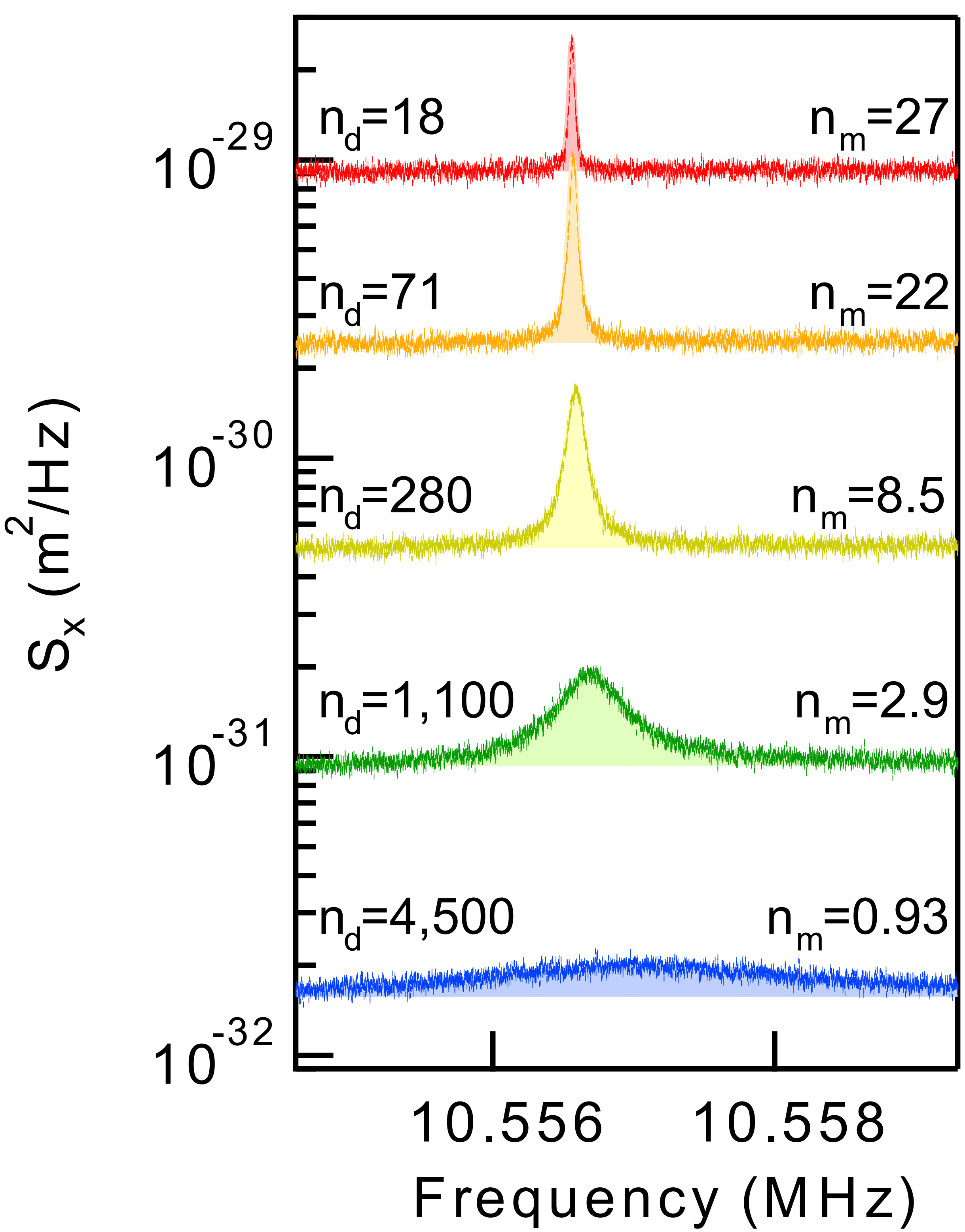


area yields variance of x:

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

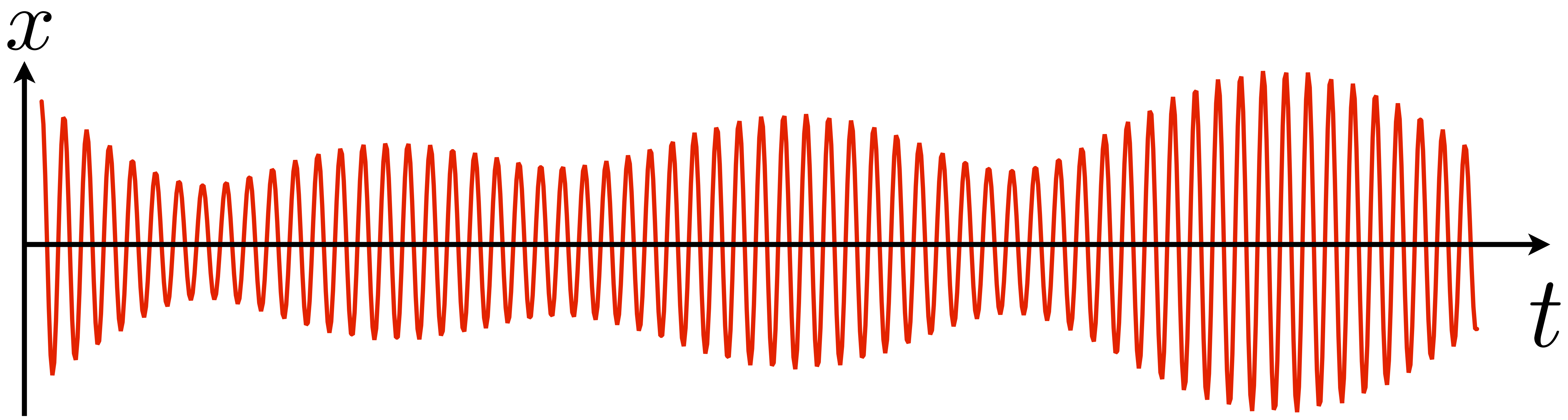
...yields temperature!

Displacement spectrum

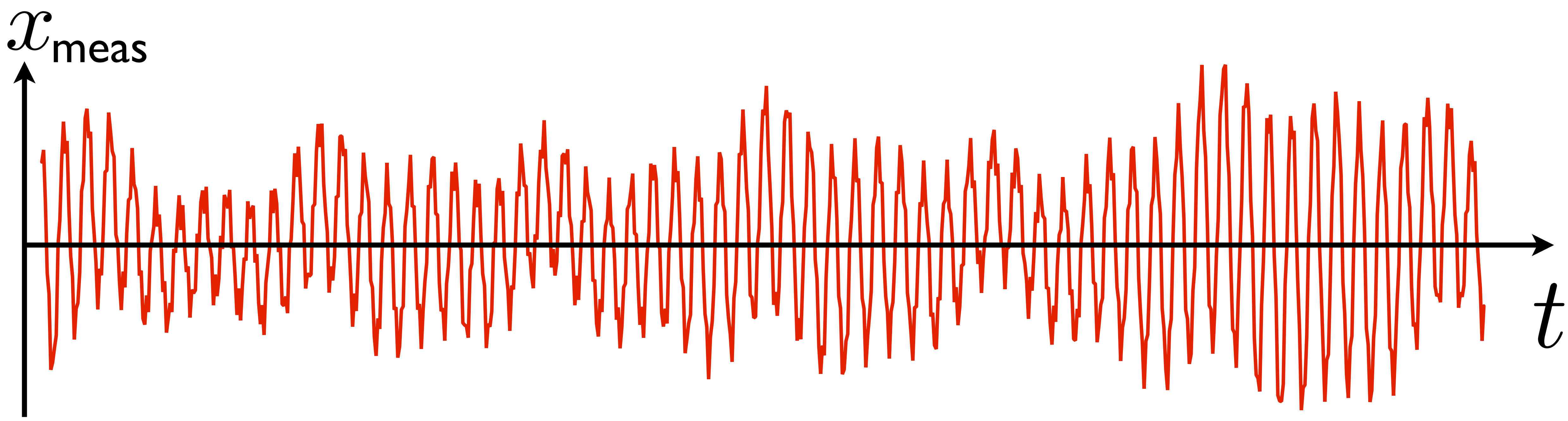


Teufel et al., Nature 2011

Measurement noise



Measurement noise



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

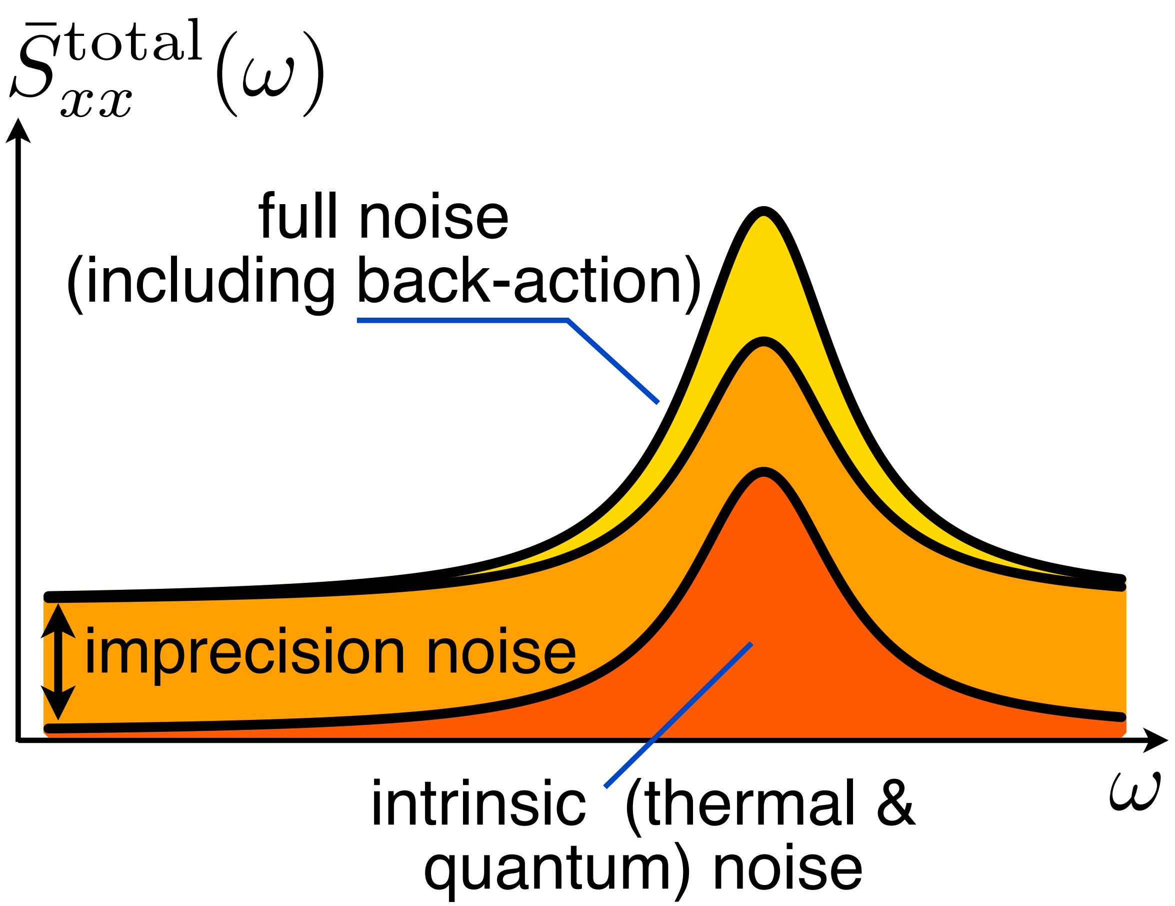
Two contributions to $x_{\text{noise}}(t)$

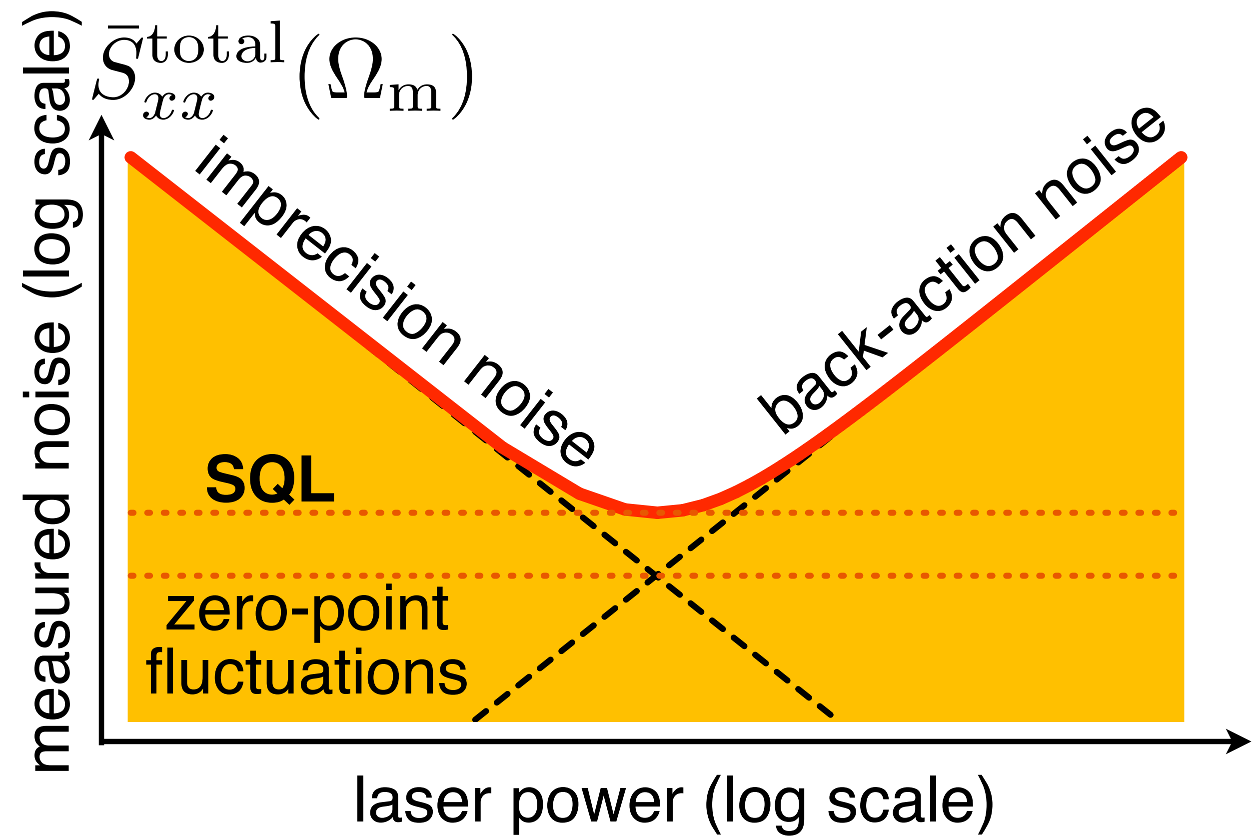
1. measurement imprecision
2. measurement back-action: fluctuating force on system

phase noise of laser beam (shot noise limit!)

noisy radiation pressure force

"Standard Quantum Limit"





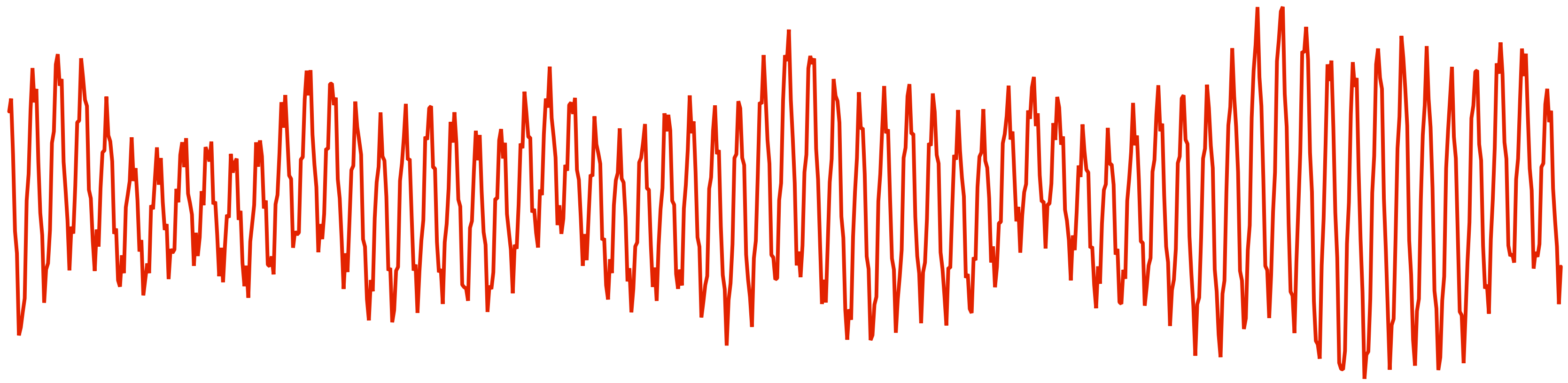
Best case allowed by quantum mechanics:

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

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

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

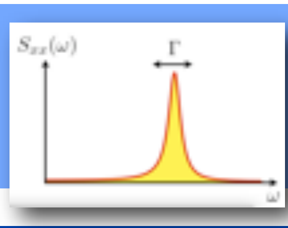
Heisenberg is the reason for SQL!

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

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

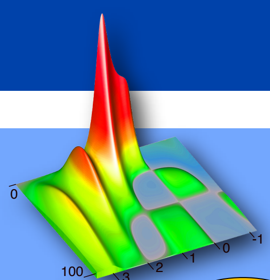
Impressive: $x_{\mathrm{ZPF}} \sim 10^{-15} m$!

Optomechanics (Outline)

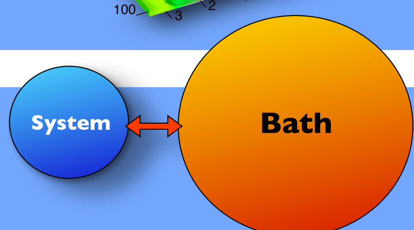


Displacement detection

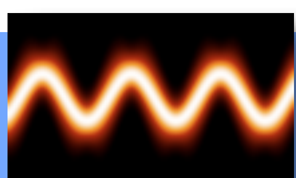
Linear optomechanics



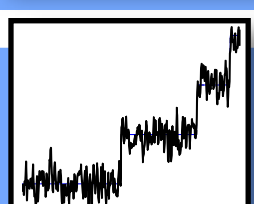
Nonlinear dynamics



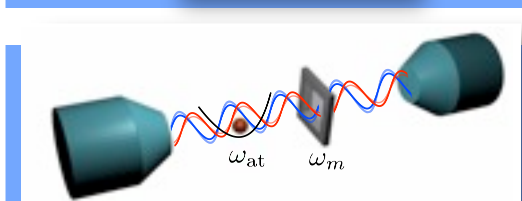
Quantum theory of cooling



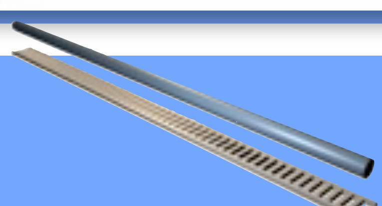
Interesting quantum states



Towards Fock state detection

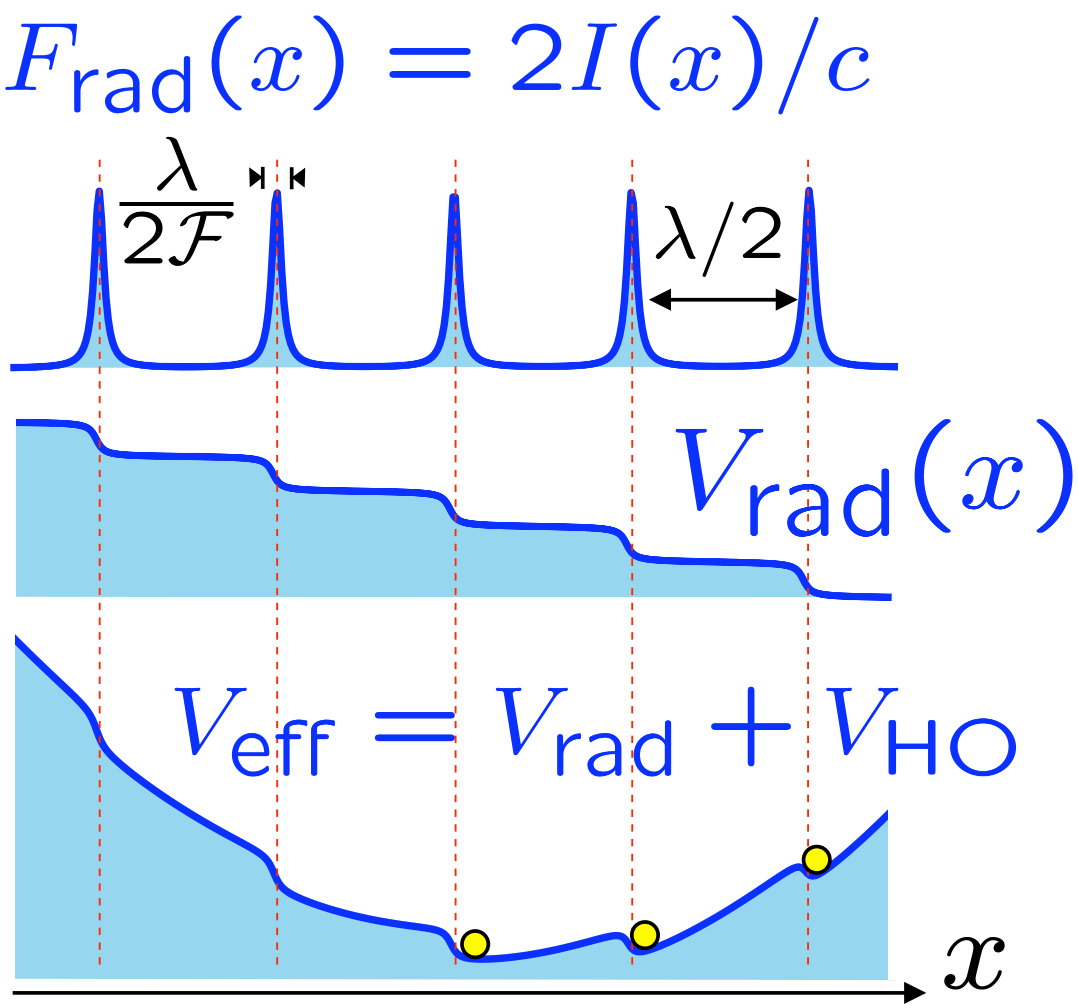


Hybrid systems: coupling to atoms



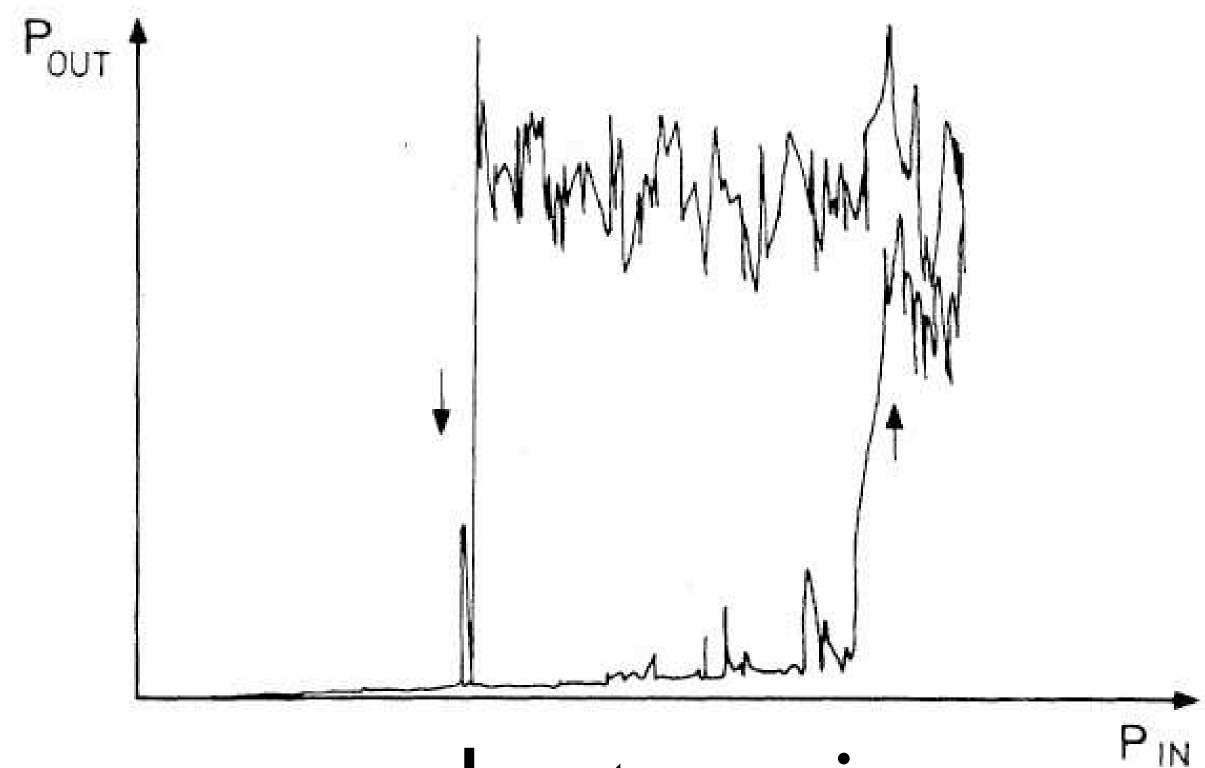
Optomechanical crystals & arrays

Basic physics: Statics



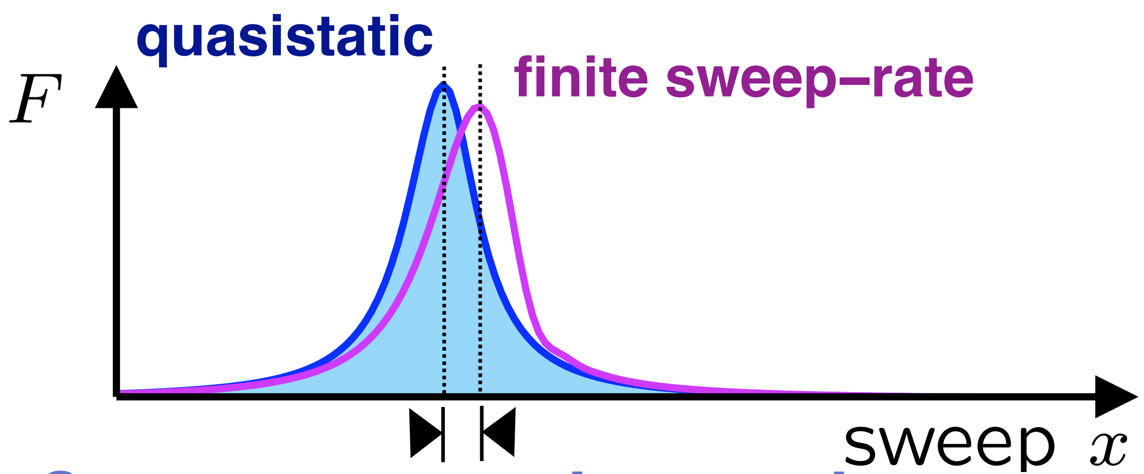
Experimental proof of static bistability:

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

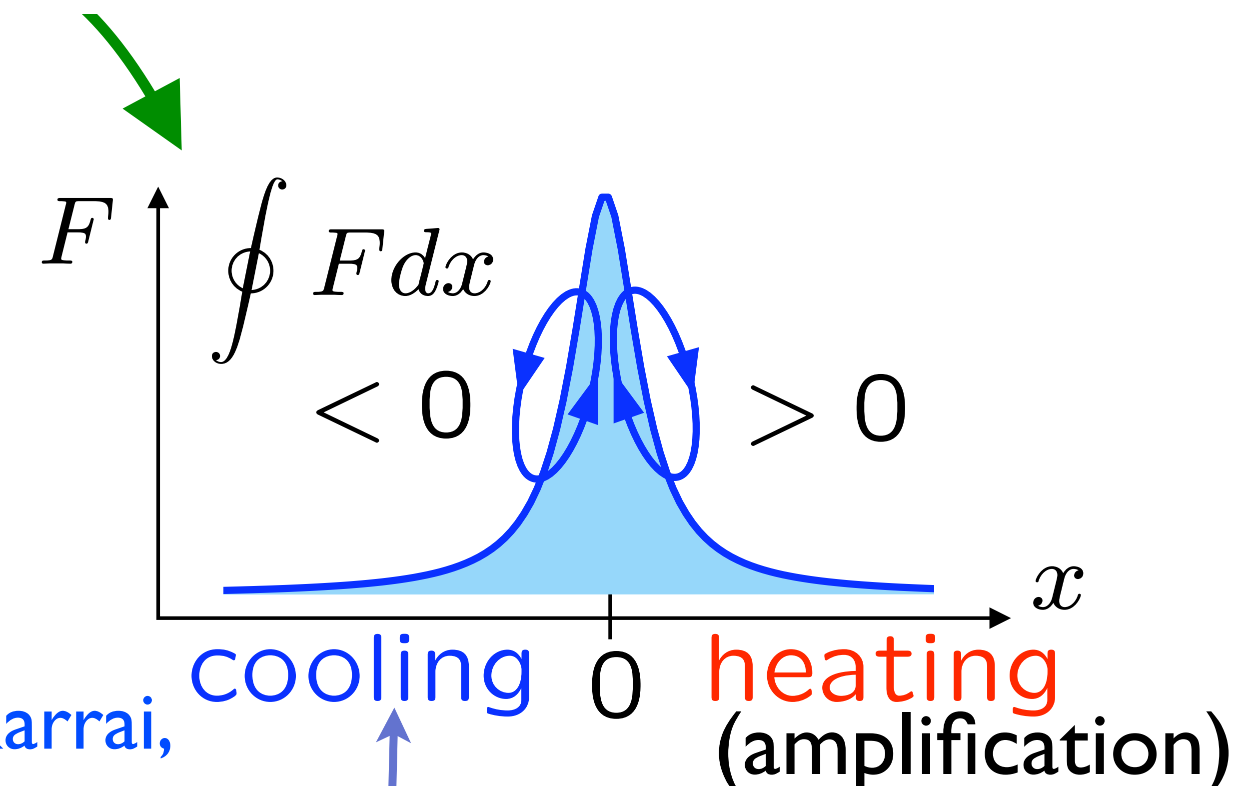


hysteresis

Basic physics: dynamics

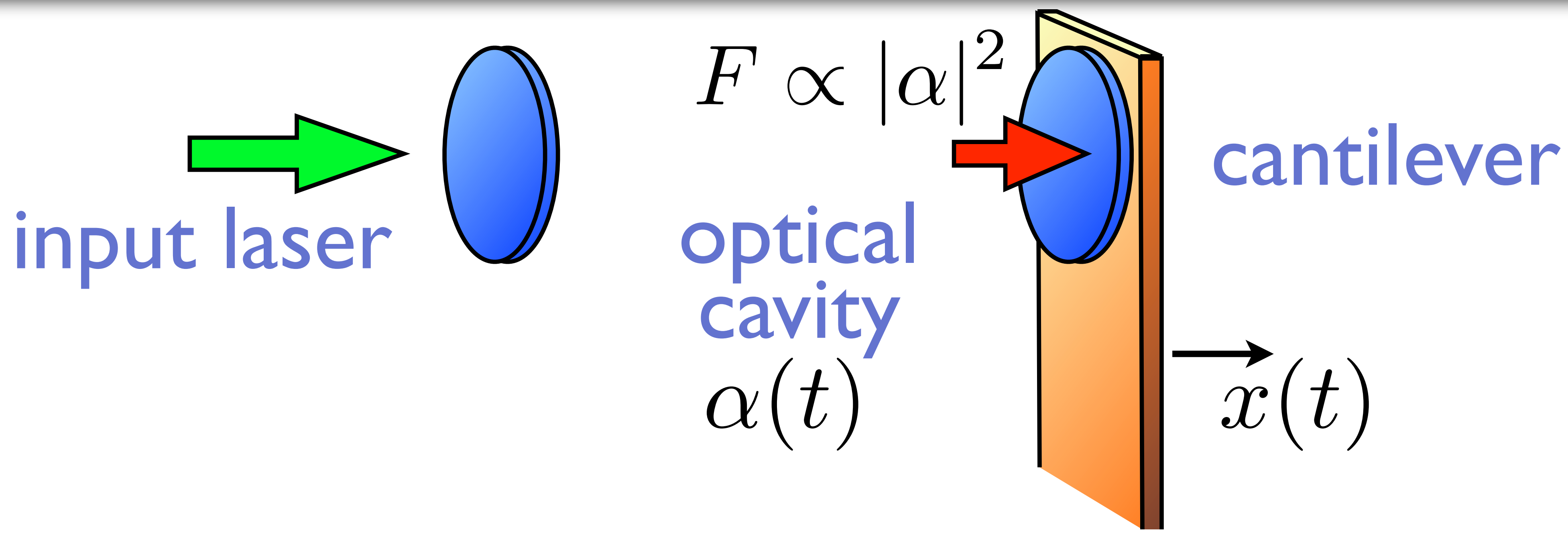


finite optical ringdown time κ^{-1} –
delayed response to cantilever motion

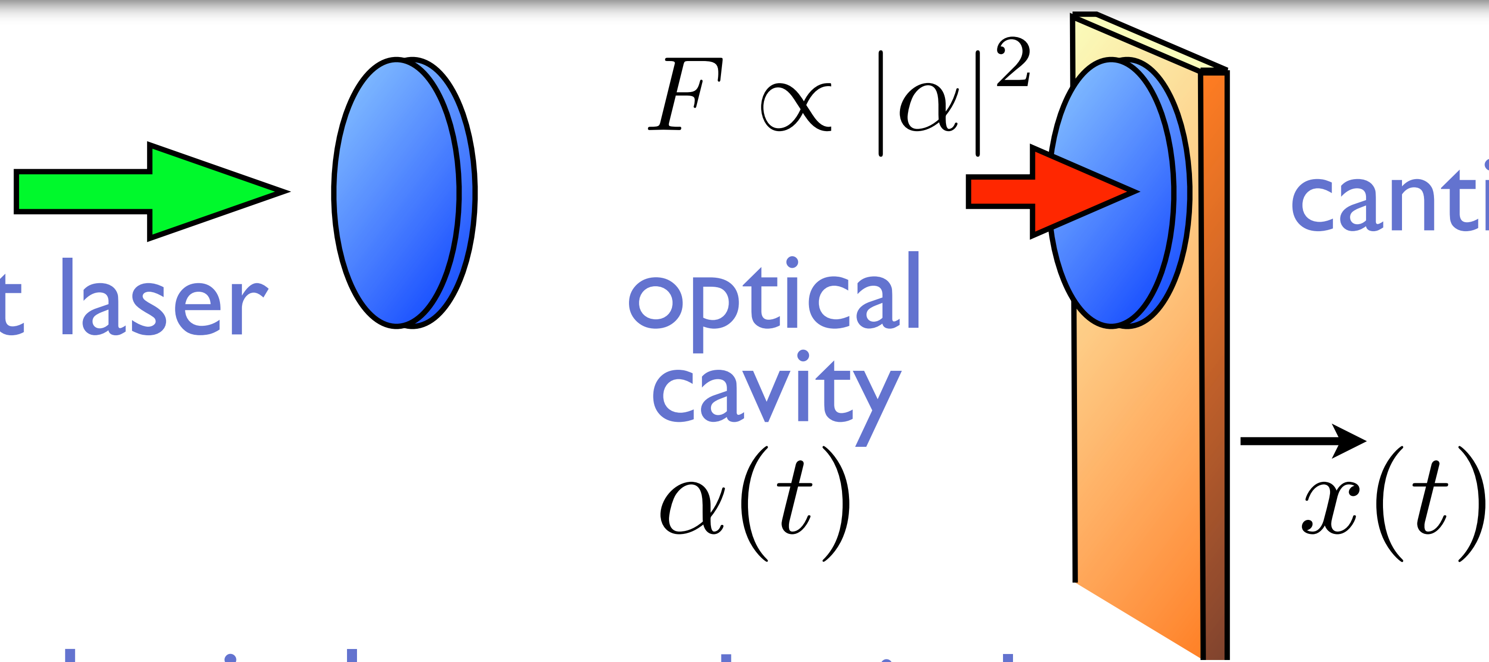


Höhberger-Metzger and Karrai,
Nature **432**, 1002 (2004):
300K to 17K [photothermal force]

Equations of motion



Equations of motion



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

mechanical frequency (ω_M^2); equilibrium position (x_0); mechanical damping (Γ); radiation pressure (F)

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

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

detuning from resonance ($\omega_R \frac{x}{L}$); cavity decay rate (κ); laser amplitude (α_{in})

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")

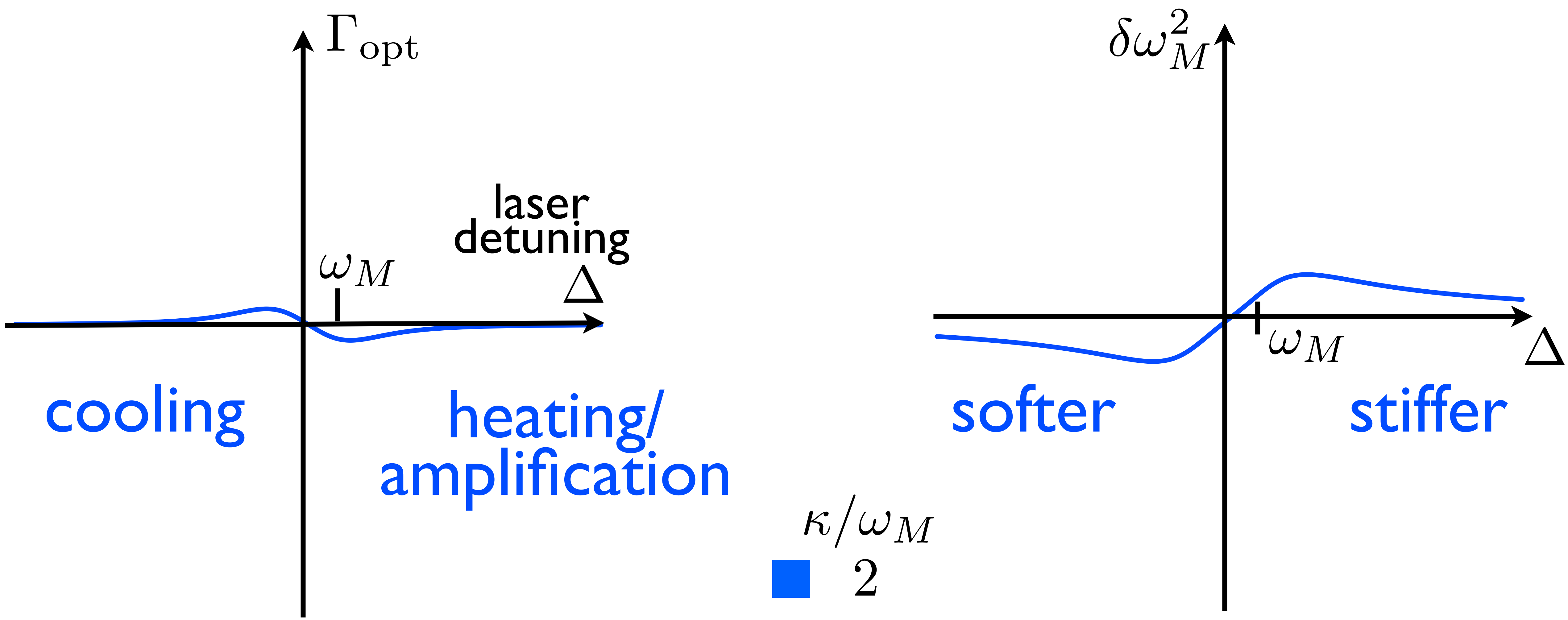
$$\Gamma_{\text{opt}} = -\frac{1}{m\omega_M}\text{Im}\Sigma(\omega_M)$$

Effective optomechanical damping rate

Linearized dynamics

Effective optomechanical damping rate

Optomechanical frequency shift ("optical spring")

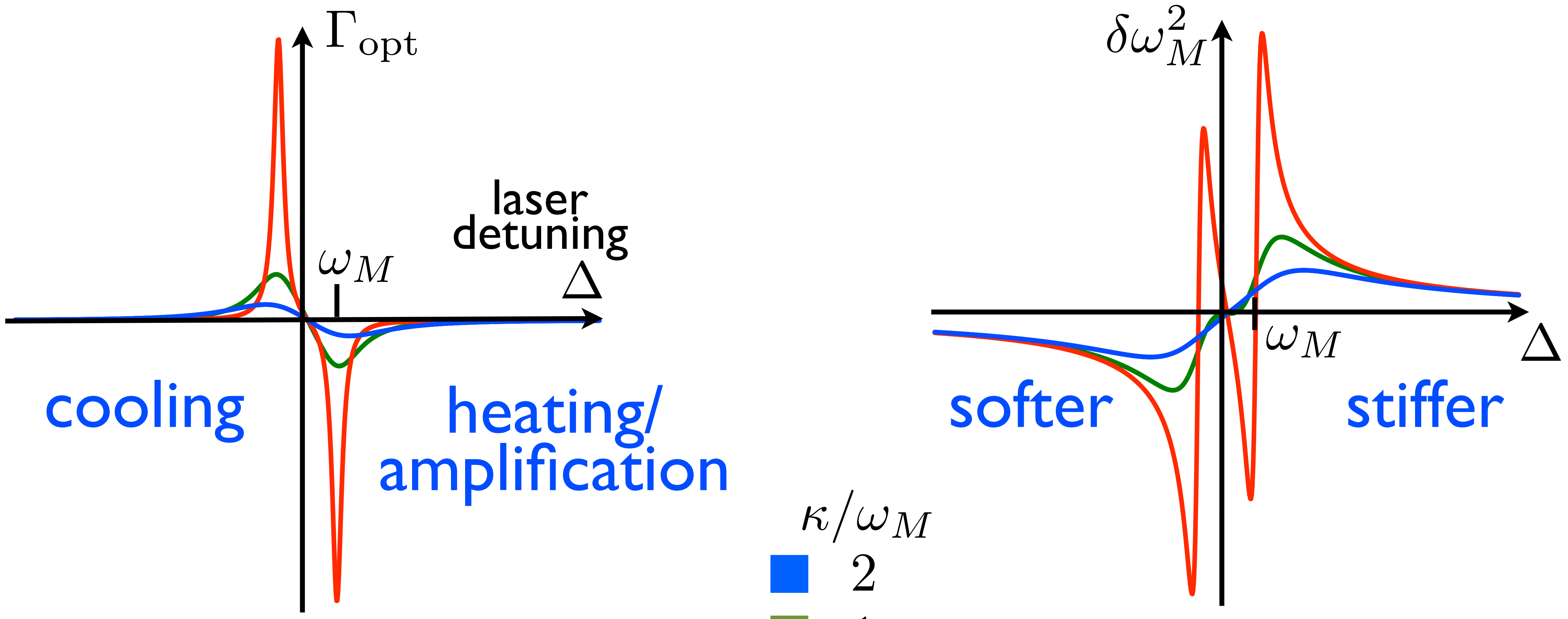


$(\Delta = \omega_R x_0 / L)$

Linearized dynamics

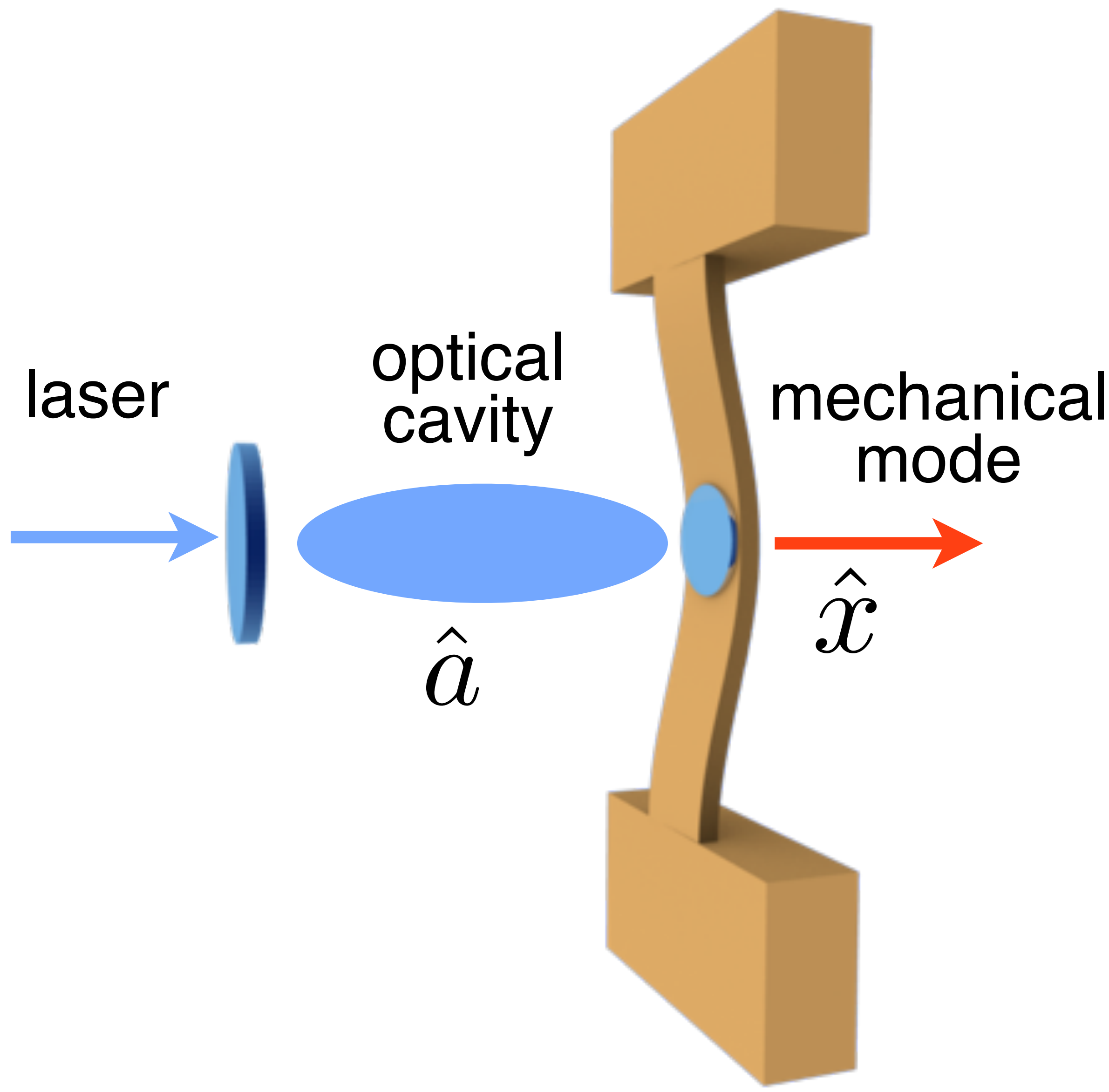
Effective optomechanical damping rate

Optomechanical frequency shift ("optical spring")



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

Optomechanical Hamiltonian



$$g_0 \sim \mathrm{Hz} - \mathrm{MHz}$$

$$\hat{H} = -(\Delta + g_0(\hat{b} + \hat{b}^\dagger))\hat{a}^\dagger \hat{a} + \Omega \hat{b}^\dagger \hat{b} + \ldots$$

laser detuning

$$\Delta = \omega_L - \omega_{\mathrm{cav}}$$

optomech. coupling

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

$$x_{\mathrm{ZPF}} = \sqrt{\hbar / 2m\Omega}$$

Quantum optomechanics: Linearized Hamiltonian

$$\hat{a} = \alpha + \delta\hat{a}$$

large amplitude (laser drive)

quantum fluctuations

$$g_0 \hat{a}^\dagger \hat{a}(\hat{b} + \hat{b}^\dagger) \mapsto \underline{g_0 \alpha}(\delta\hat{a} + \delta\hat{a}^\dagger)(\hat{b} + \hat{b}^\dagger)$$

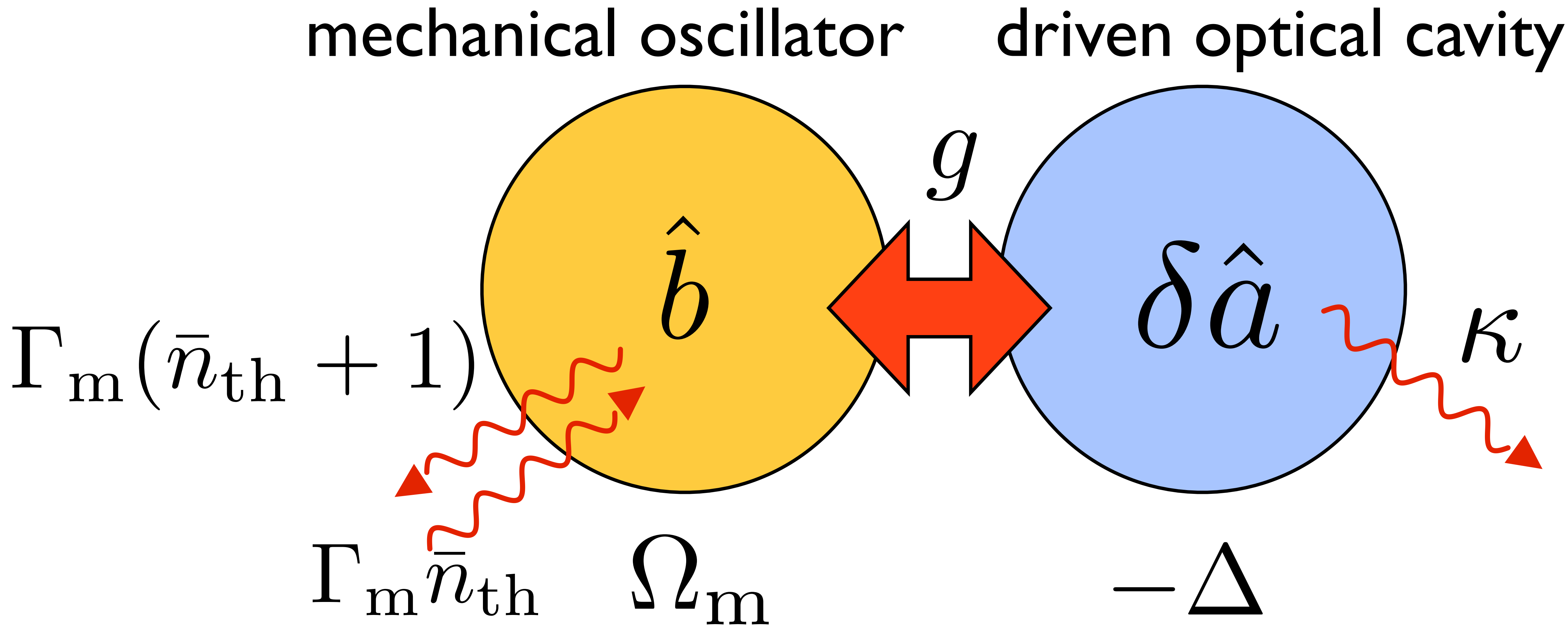
g

bilinear interaction
tunable coupling!

Sufficient to explain (almost) all current optomechanical experiments in the quantum regime

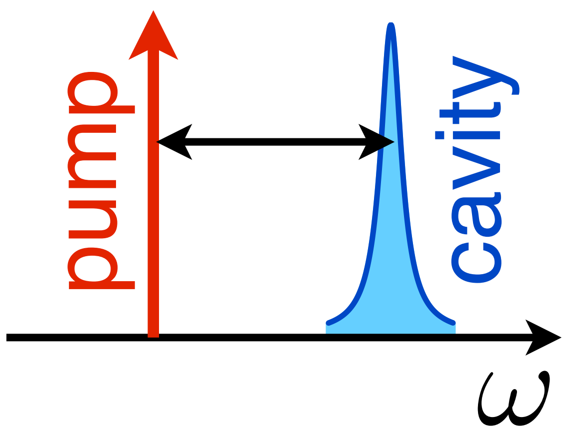
Mechanics & Optics

After linearization: two linearly coupled harmonic oscillators!



Different regimes

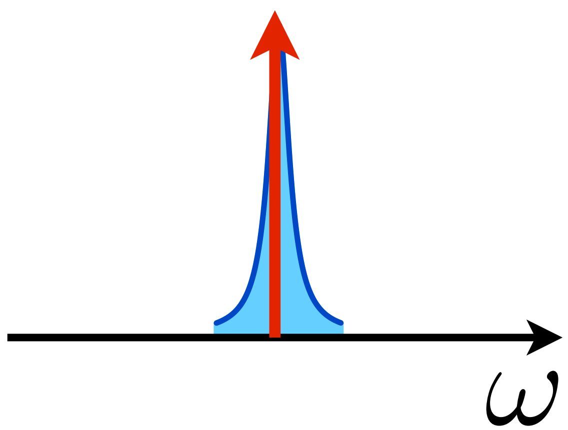
red-detuned



$$\Delta = -\Omega_{\mathrm{m}}$$

beam-splitter
(cooling)

$$\delta\hat{a}^\dagger\hat{b} + \hat{b}^\dagger\delta\hat{a}$$

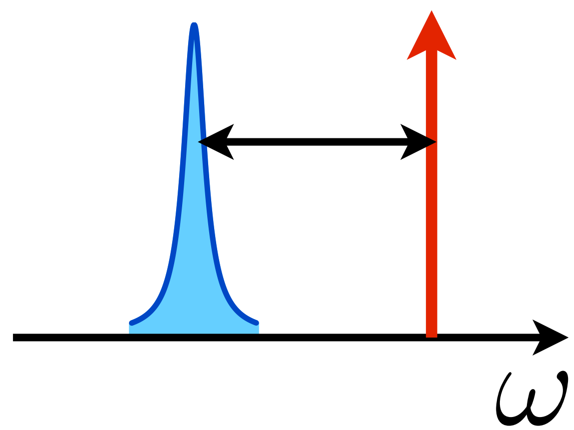


$$\Delta = 0$$

QND

$$\hat{x}_a\hat{x}_b$$

blue-detuned

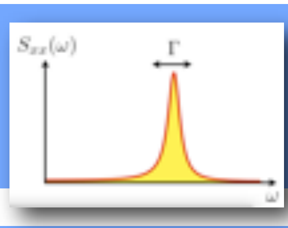


$$\Delta = +\Omega_{\mathrm{m}}$$

squeezer
(entanglement)

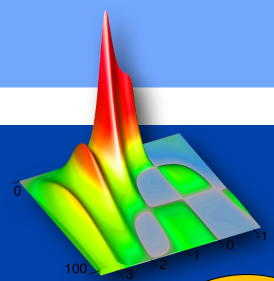
$$\delta\hat{a}^\dagger\hat{b}^\dagger + \hat{b}\delta\hat{a}$$

Optomechanics (Outline)

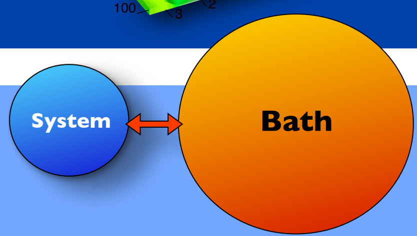


Displacement detection

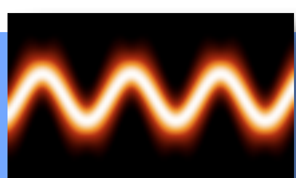
Linear optomechanics



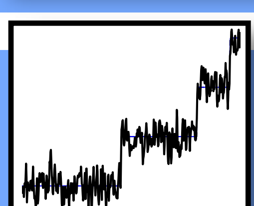
Nonlinear dynamics



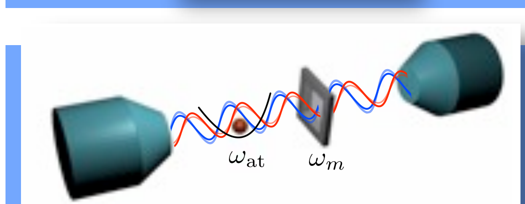
Quantum theory of cooling



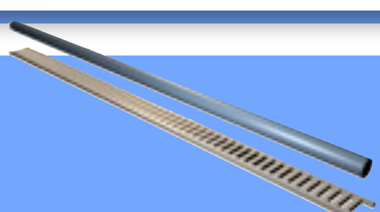
Interesting quantum states



Towards Fock state detection

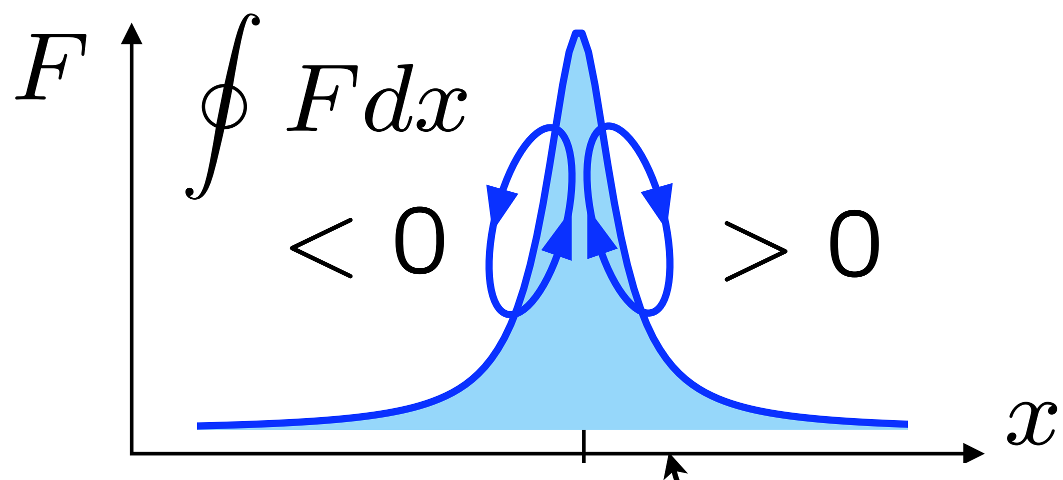


Hybrid systems: coupling to atoms



Optomechanical crystals & arrays

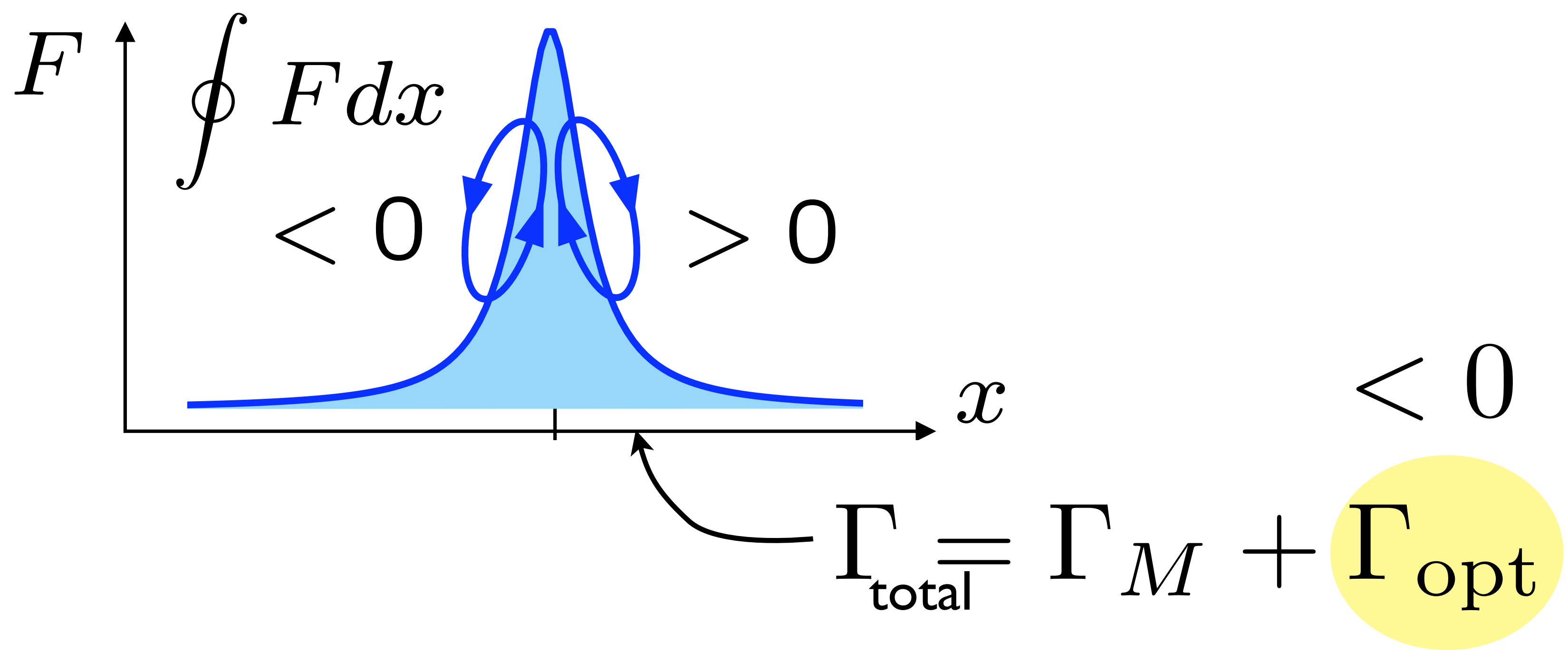
Self-induced oscillations



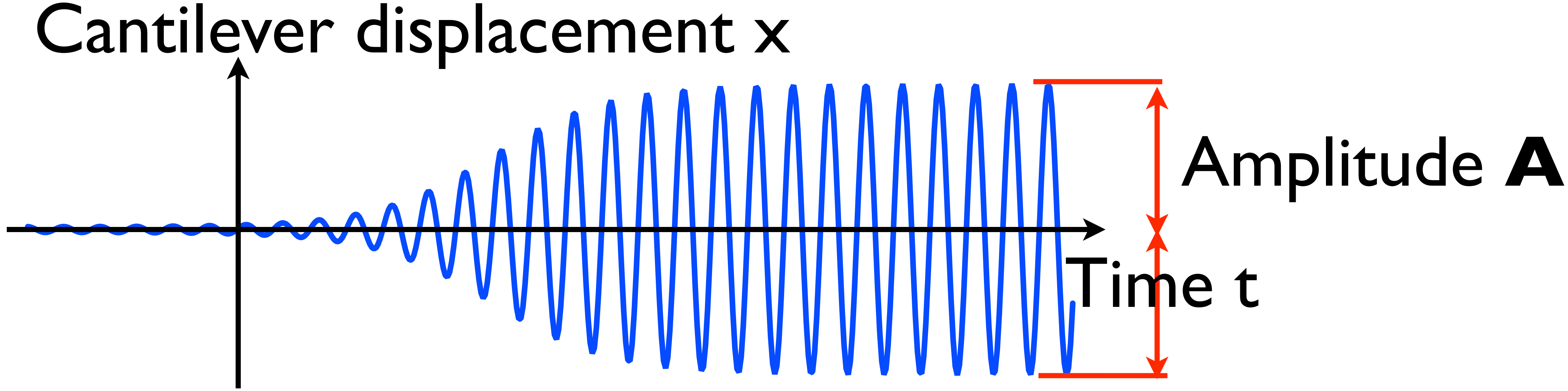
$$\Gamma_{\text{total}} = \Gamma_M + \Gamma_{\text{opt}}$$

< 0

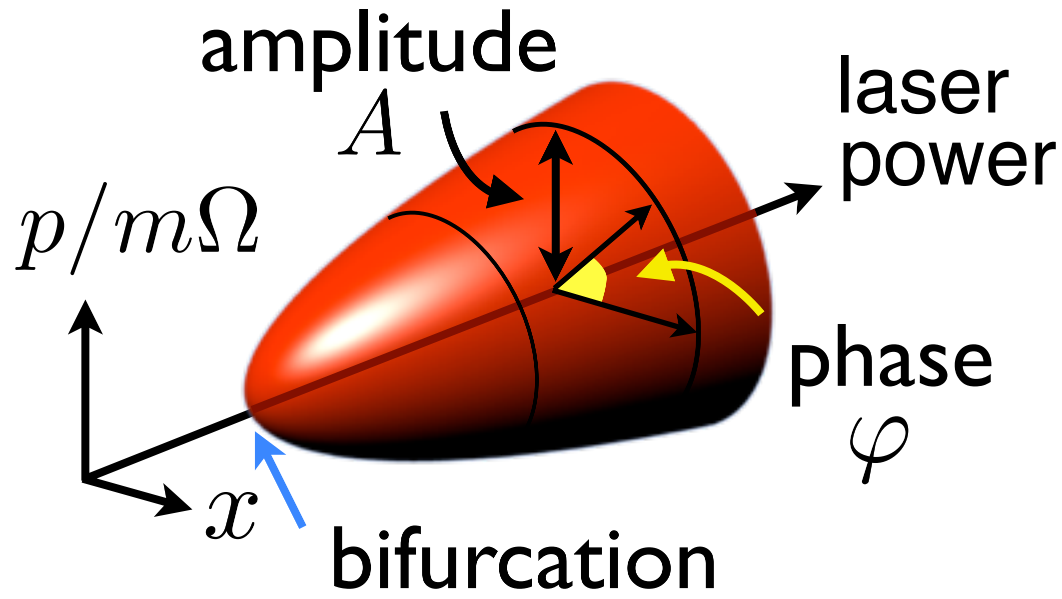
Self-induced oscillations



Beyond some laser input power threshold: instability

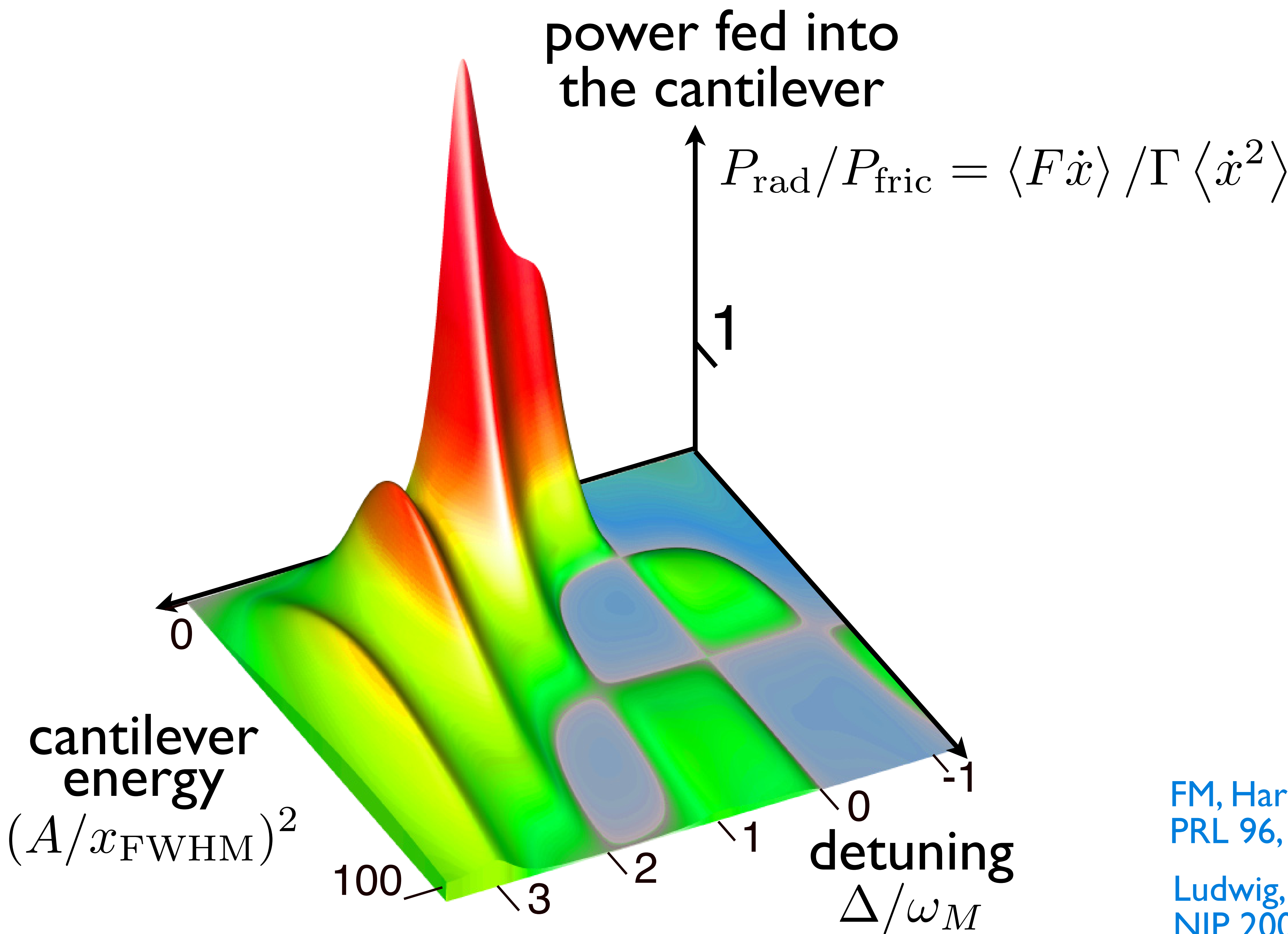


An optomechanical cell as a Hopf oscillator



Amplitude fixed, phase undetermined!

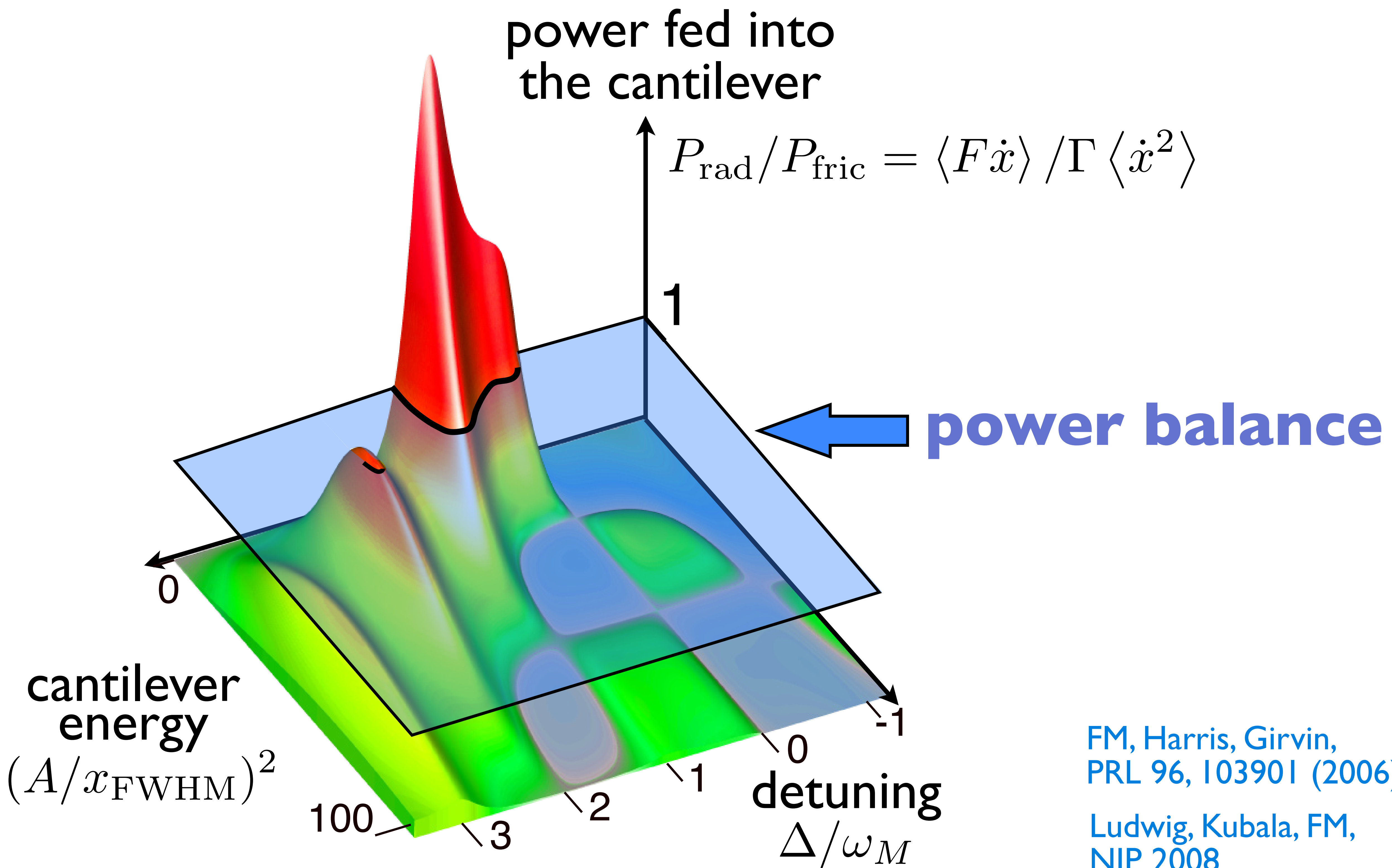
Attractor diagram



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

Ludwig, Kubala, FM,
NJP 2008

Attractor diagram



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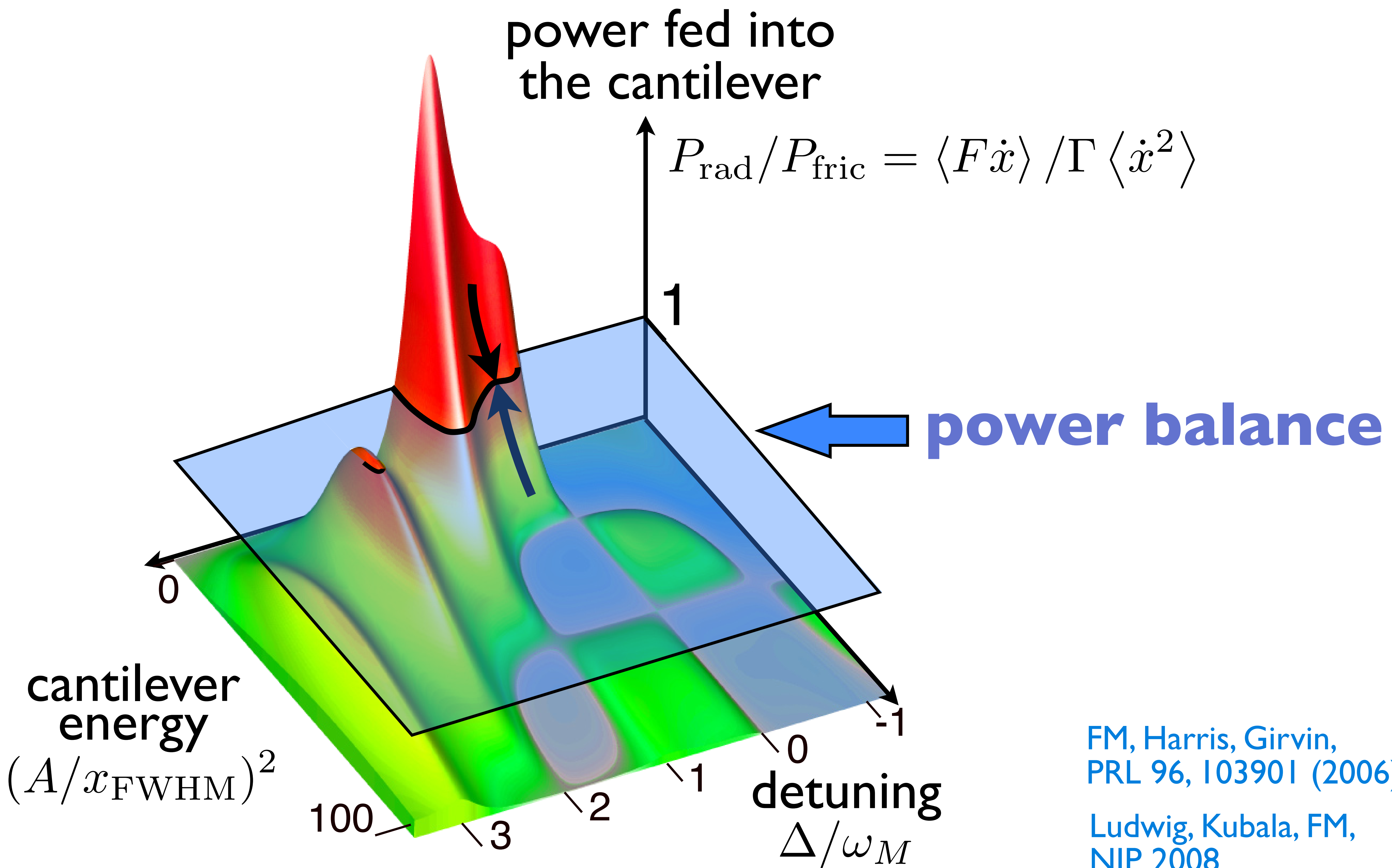

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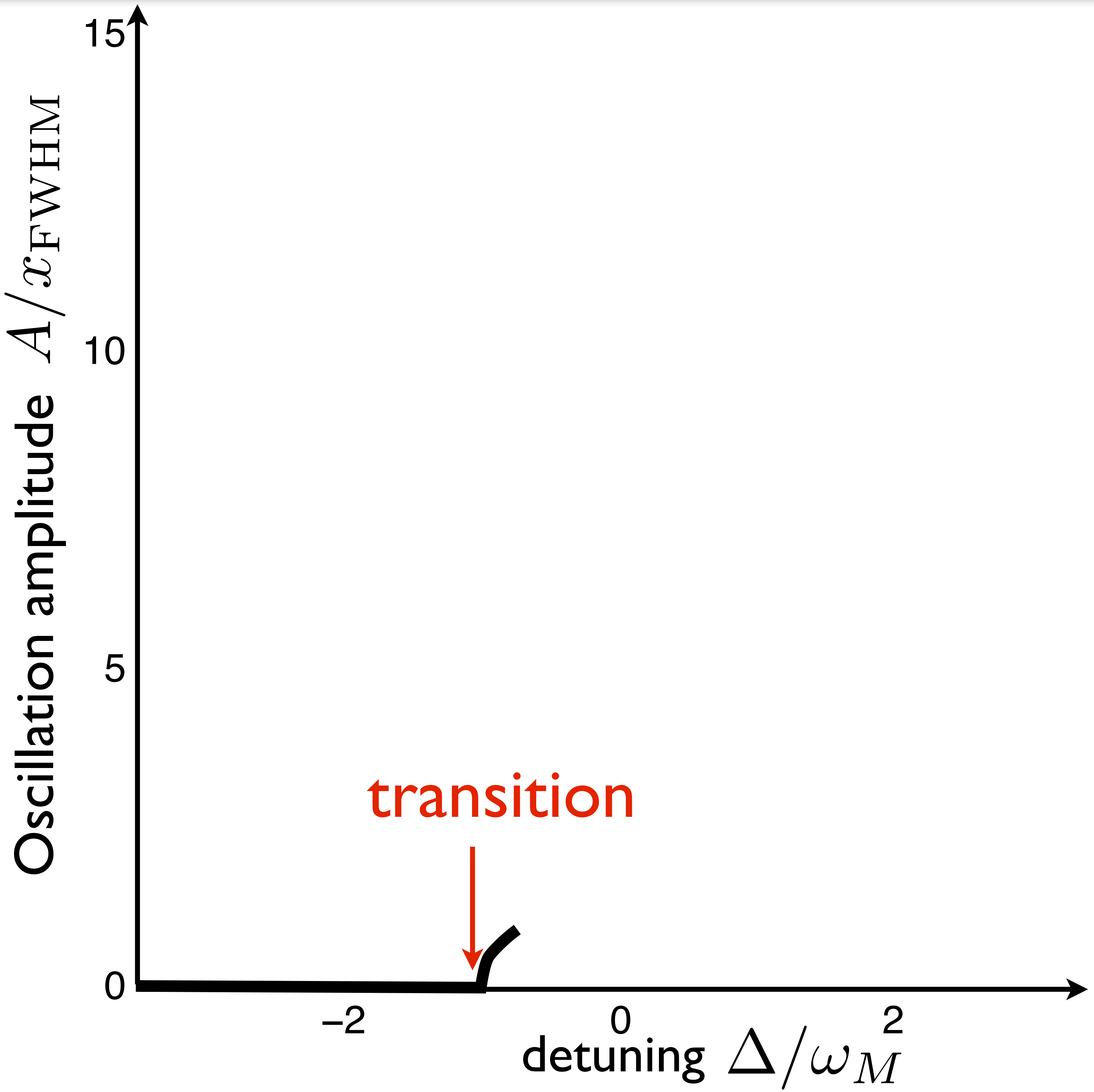

Höhberger, Karrai, IEEE proceedings 2004

Carmon, Rokhsari, Yang, Kippenberg, Vahala, PRL 2005

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Metzger et al., PRL 2008

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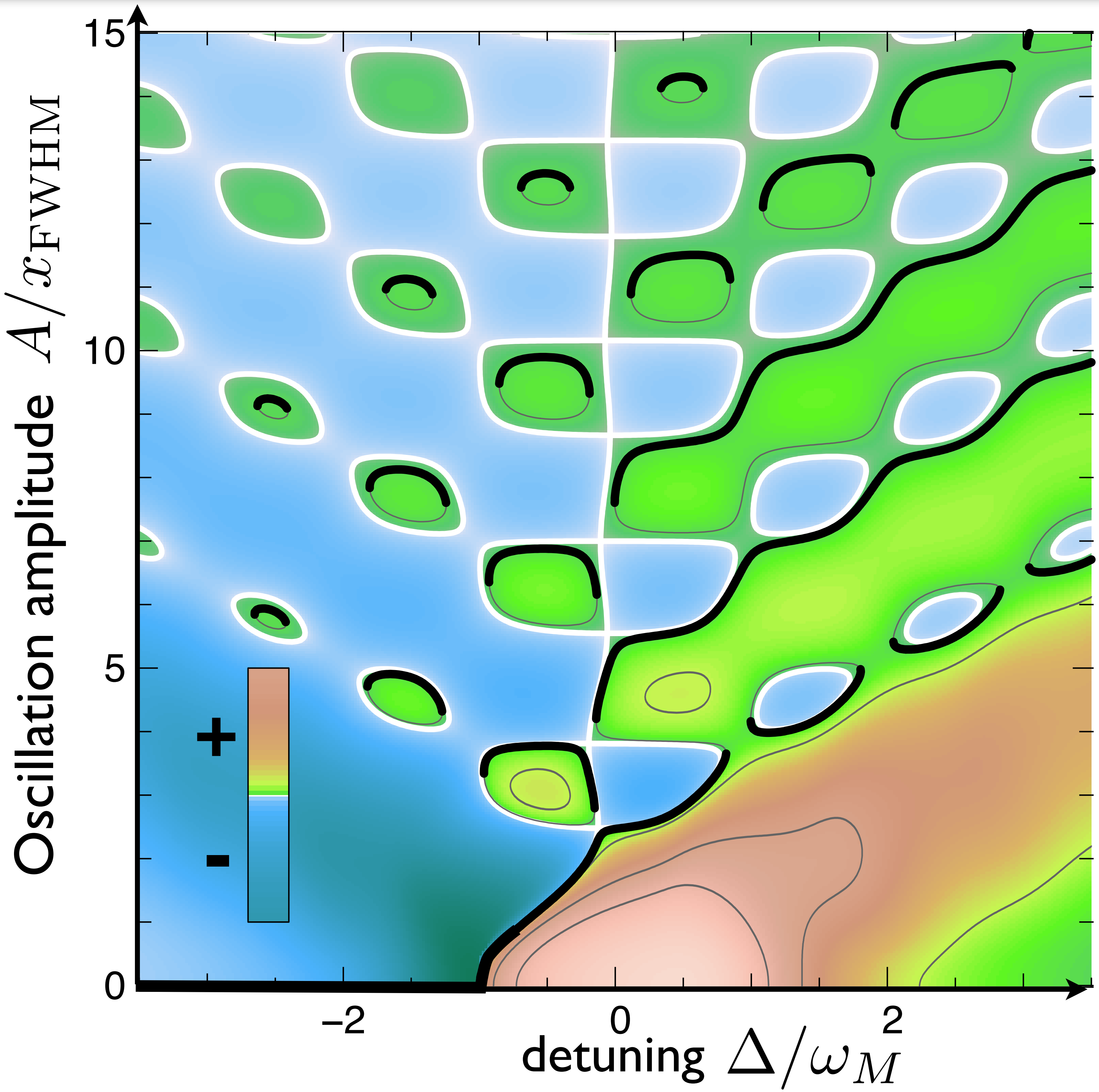

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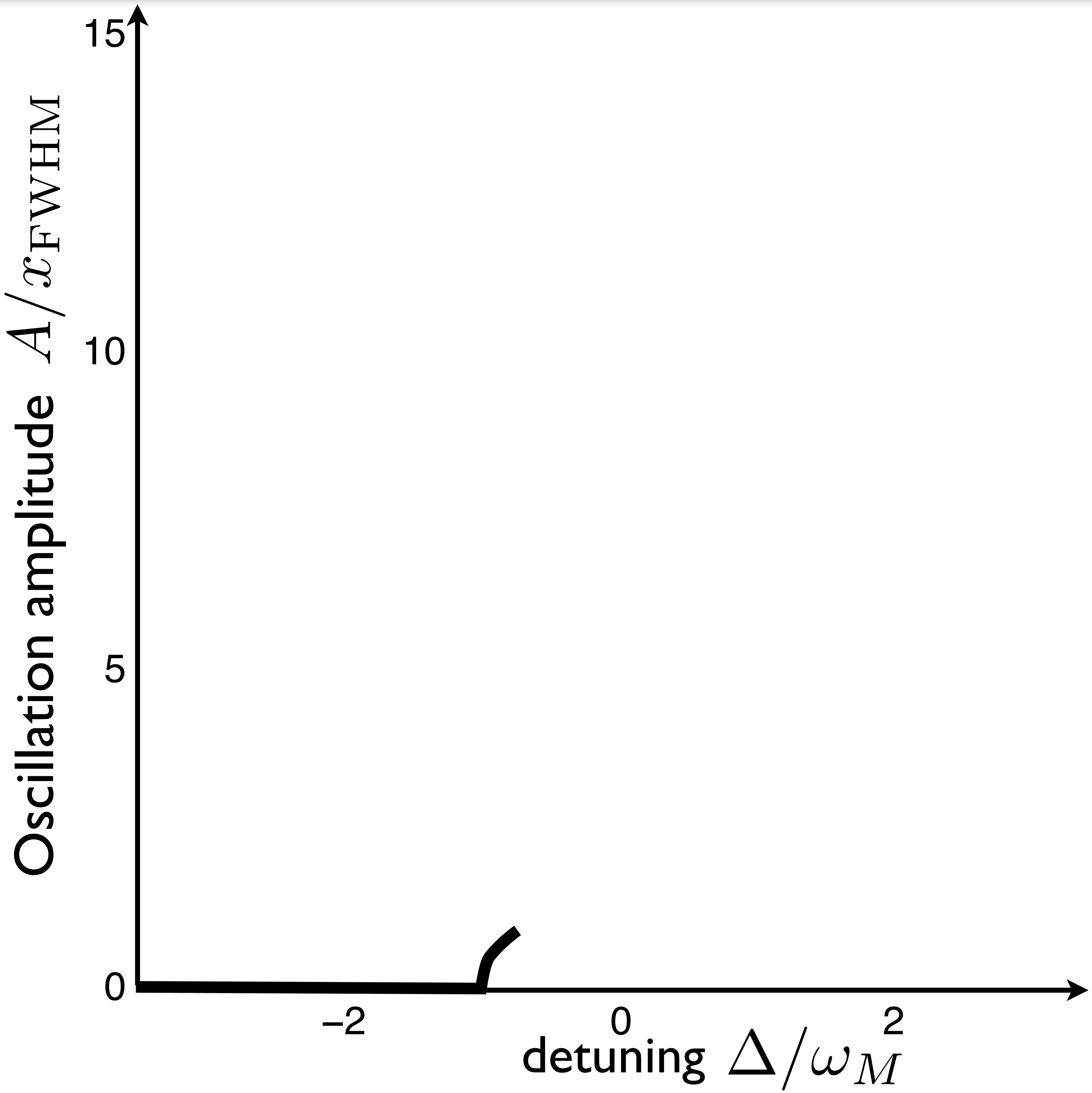


Höhberger, Karrai, IEEE proceedings 2004

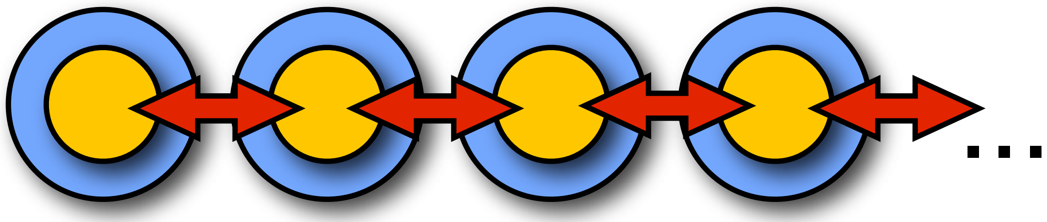
Carmon, Rokhsari, Yang, Kippenberg, Vahala, PRL 2005

FM, Harris, Girvin, PRL 2006

Metzger et al., PRL 2008

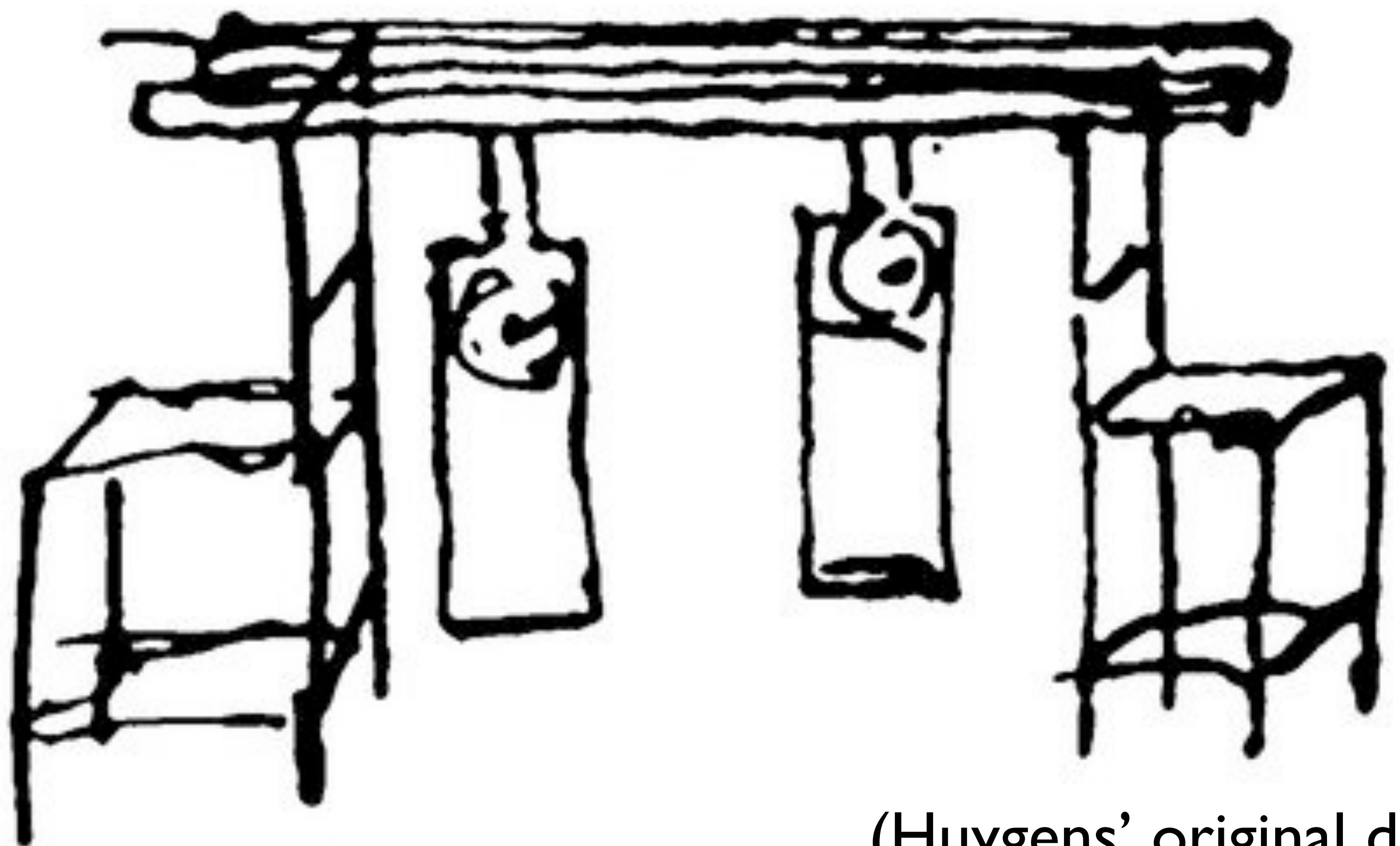
Coupled oscillators?

Coupled oscillators?



Collective dynamics in an array of coupled cells?
Phase-locking: **synchronization**!

Synchronization: Huygens' observation

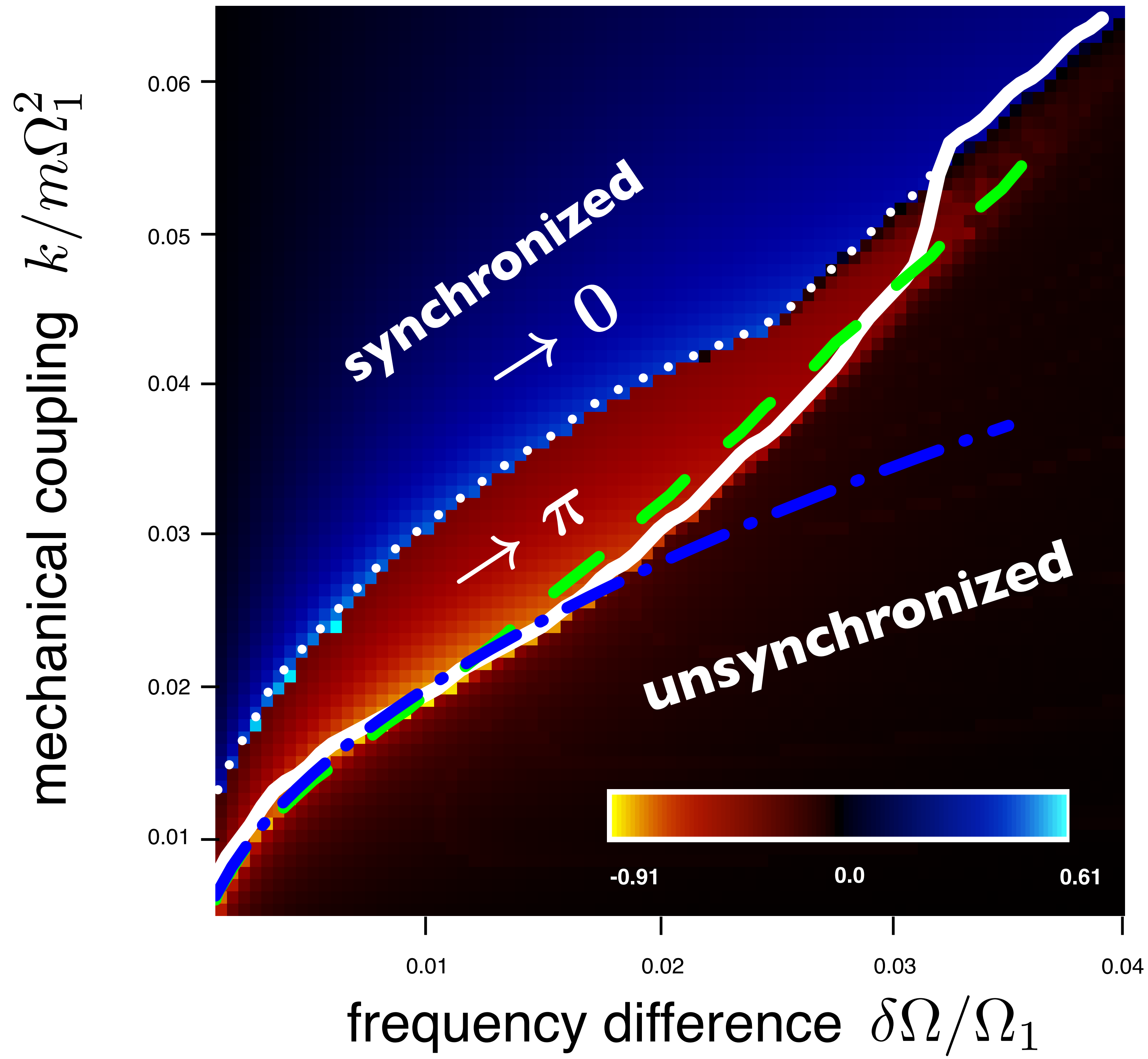


(Huygens' original drawing!)

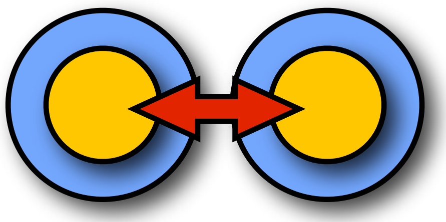
Coupled pendula synchronize...

...even though frequencies slightly different

Classical nonlinear collective dynamics: Synchronization in an optomechanical array



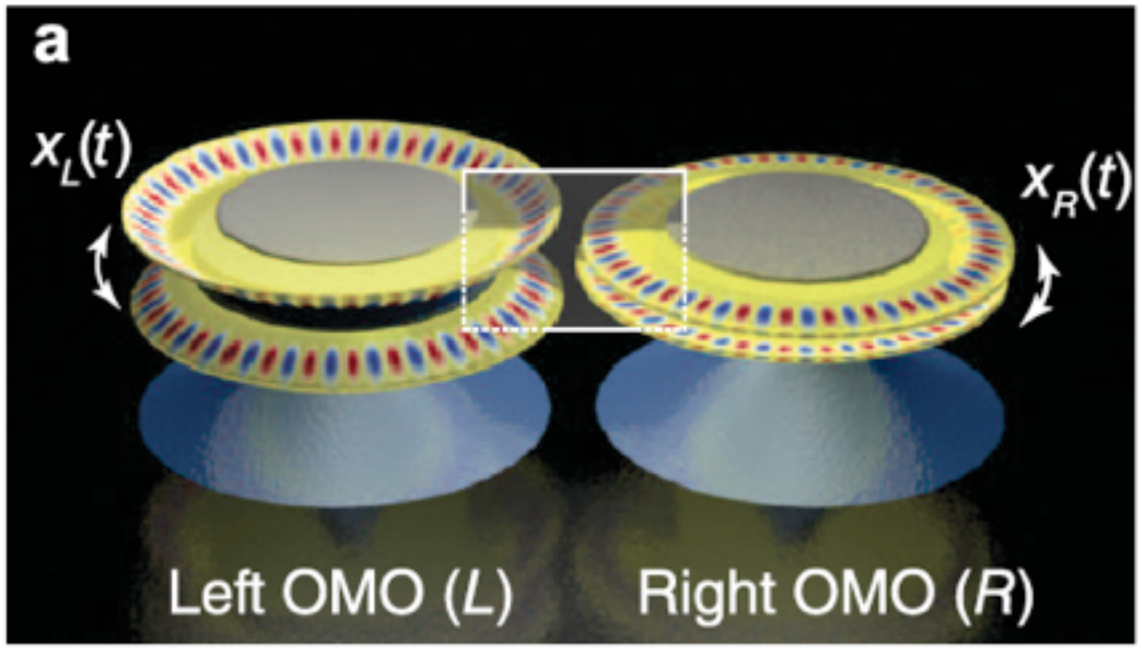
two coupled cells

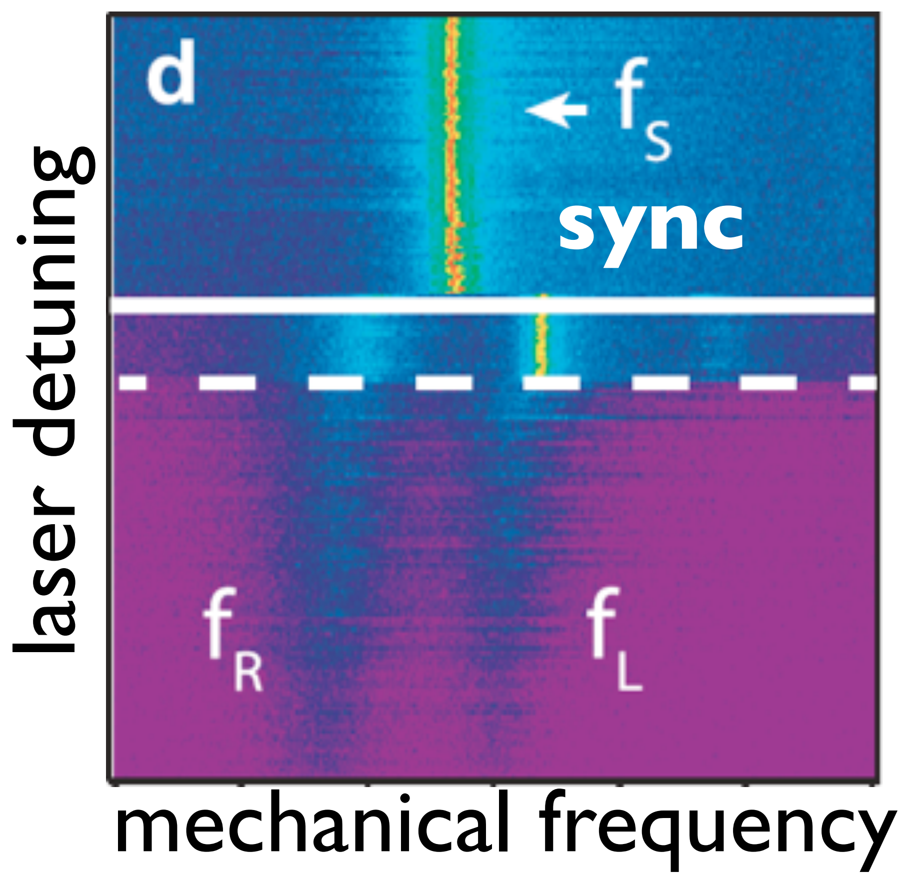


G. Heinrich et al., Phys. Rev. Lett. 107, 043603 (2011)

Experiments (two cells, joint optical mode)

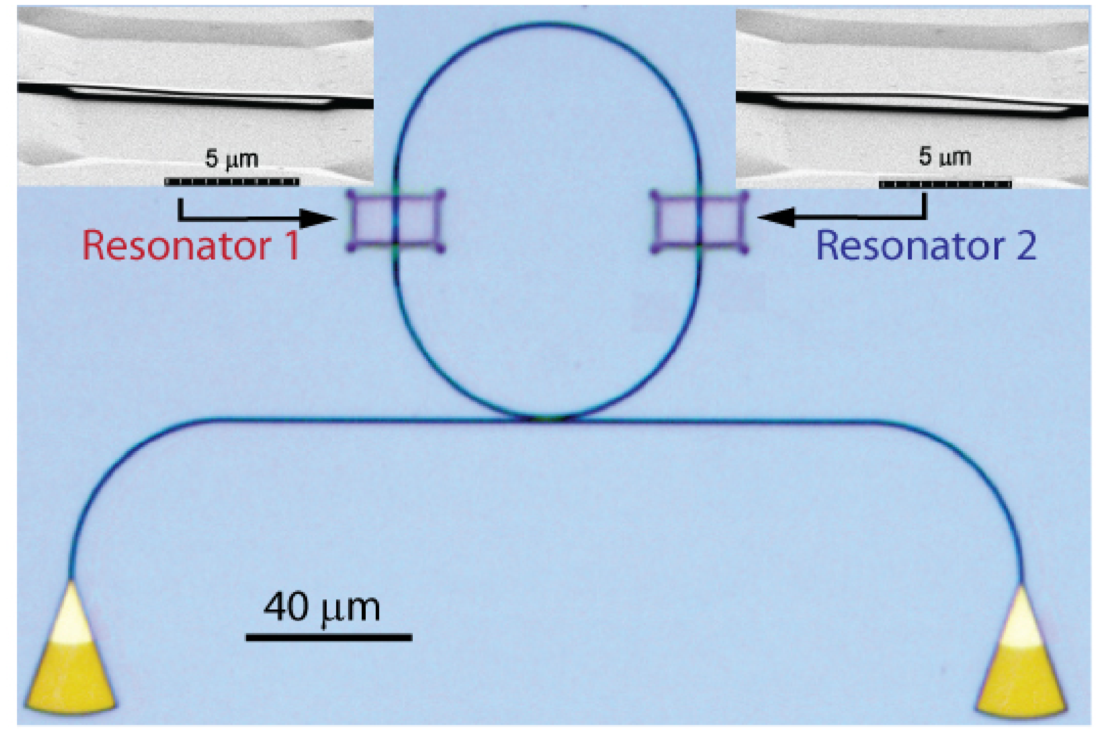
Michal Lipson lab, Cornell

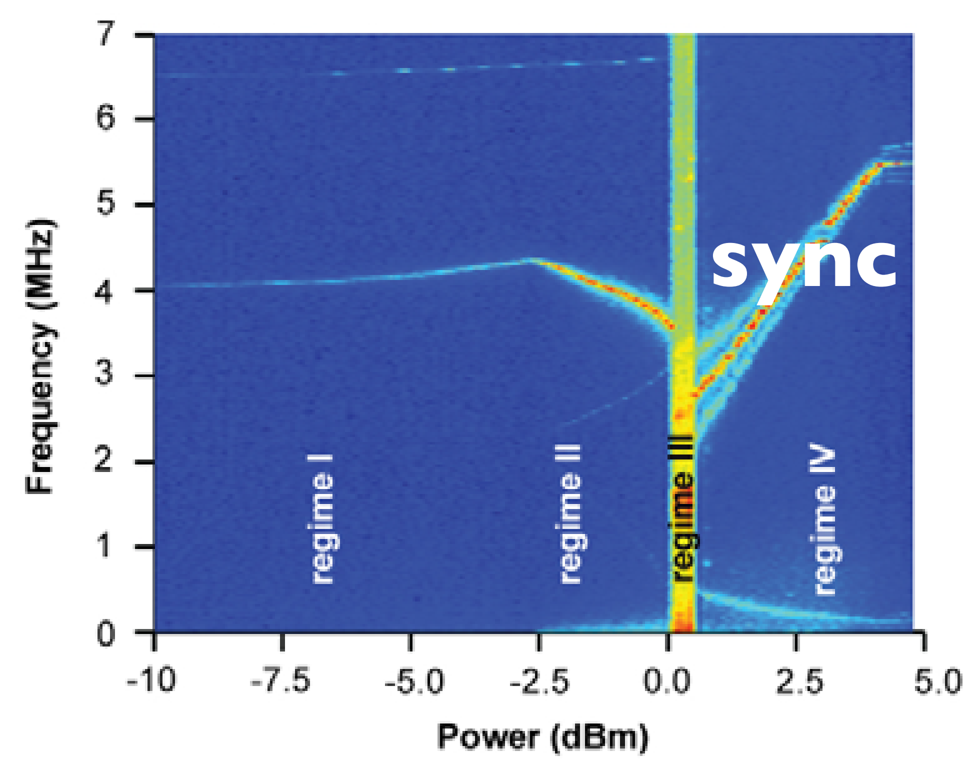




(Zhang et al., PRL 2012)

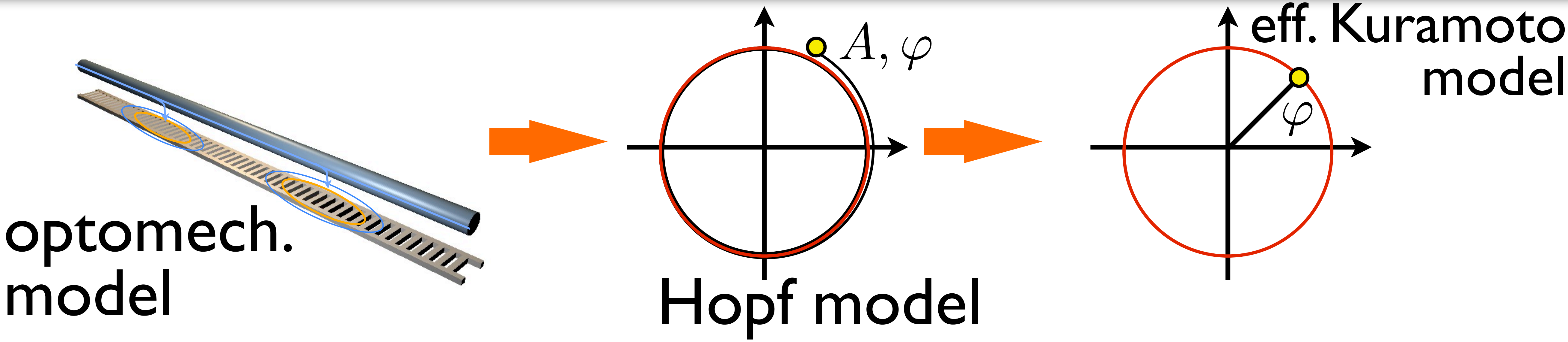
Hong Tang lab, Yale





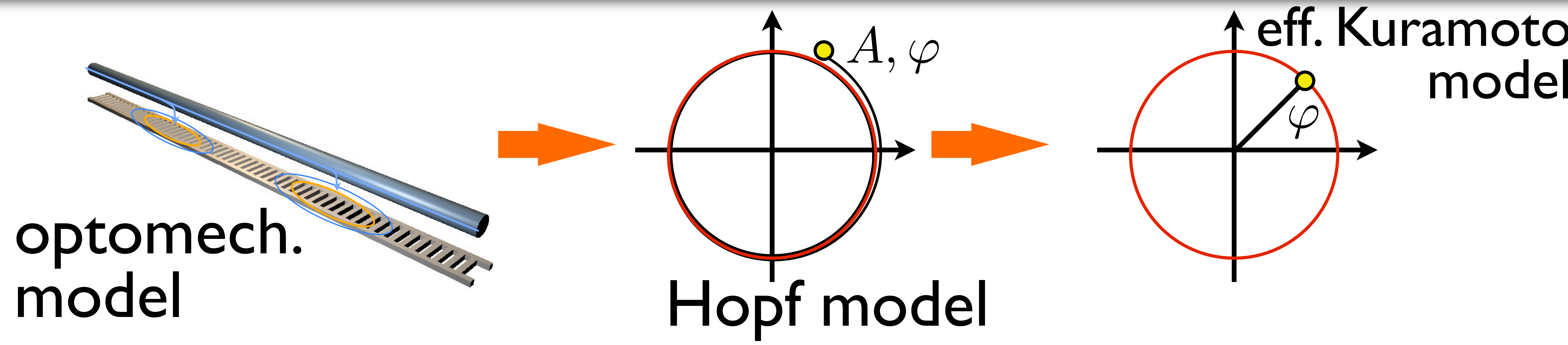
(Bagheri, Poot, FM, Tang; PRL 2013)

Effective Kuramoto model



G. Heinrich et al., Phys. Rev. Lett. 107, 043603 (2011)

Effective Kuramoto model

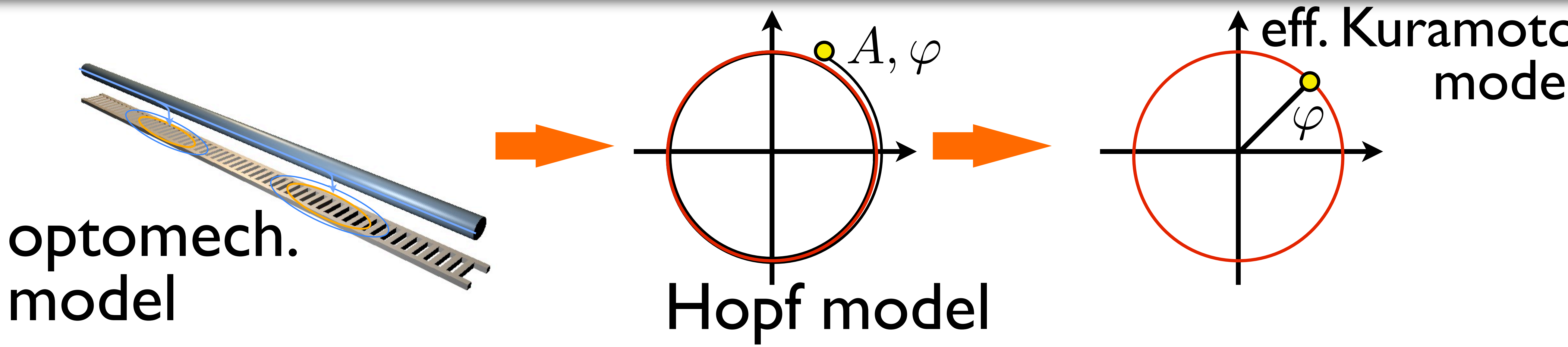


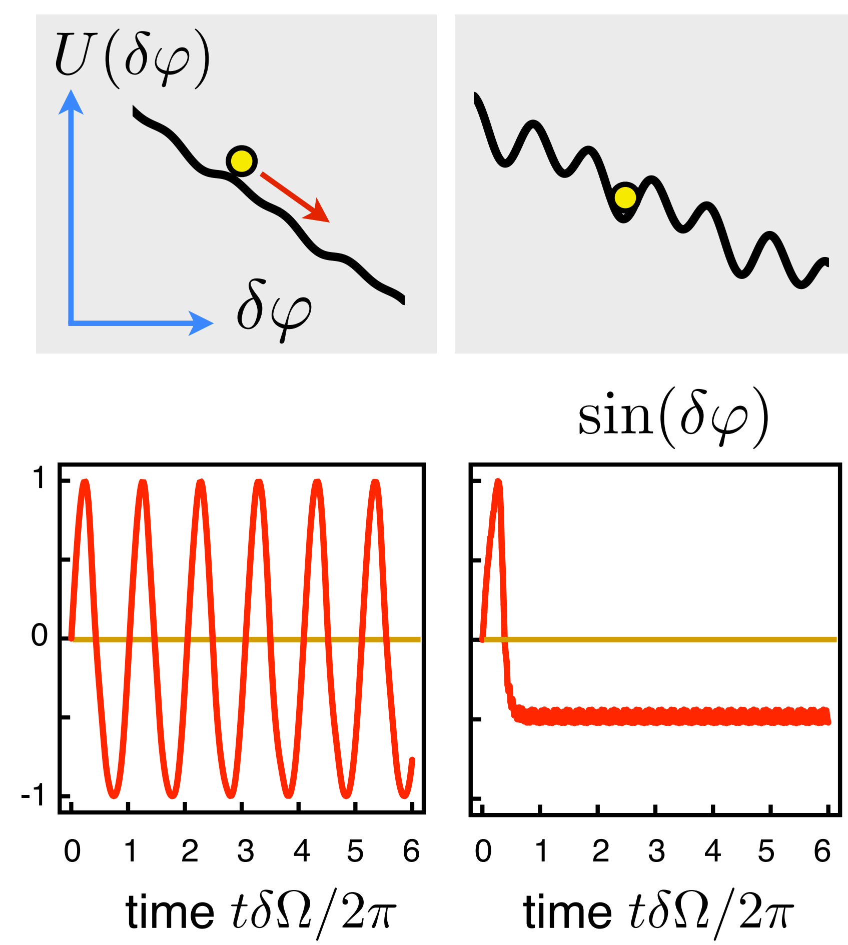
Effective Kuramoto-type model
for coupled Hopf oscillators:

$$\delta\dot{\varphi} = \delta\Omega - 2K_s \sin(2\delta\varphi) - 2K_c \cos(2\delta\varphi)$$

G. Heinrich et al., Phys. Rev. Lett. 107, 043603 (2011)

Effective Kuramoto model





Effective Kuramoto-type model for coupled Hopf oscillators:

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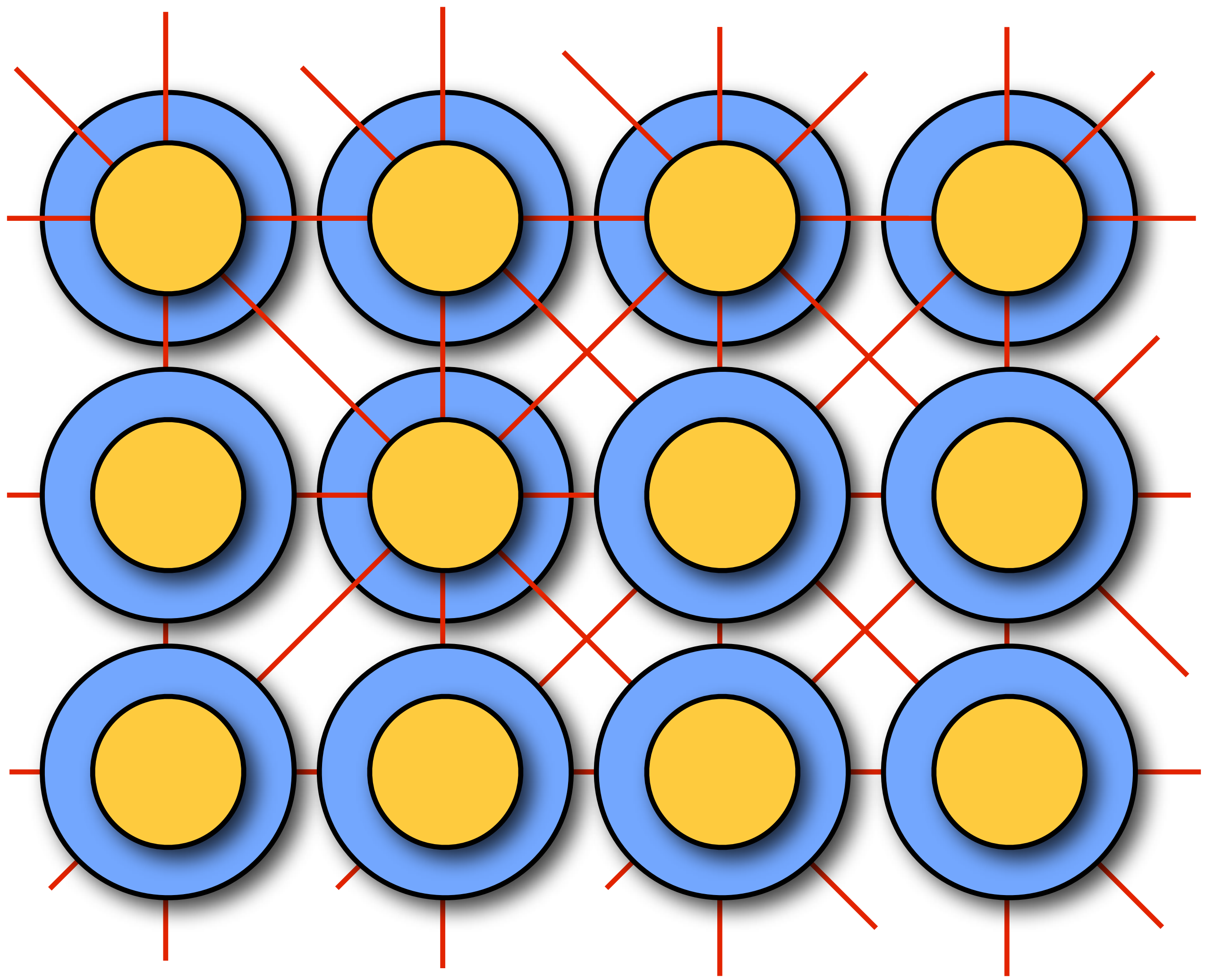
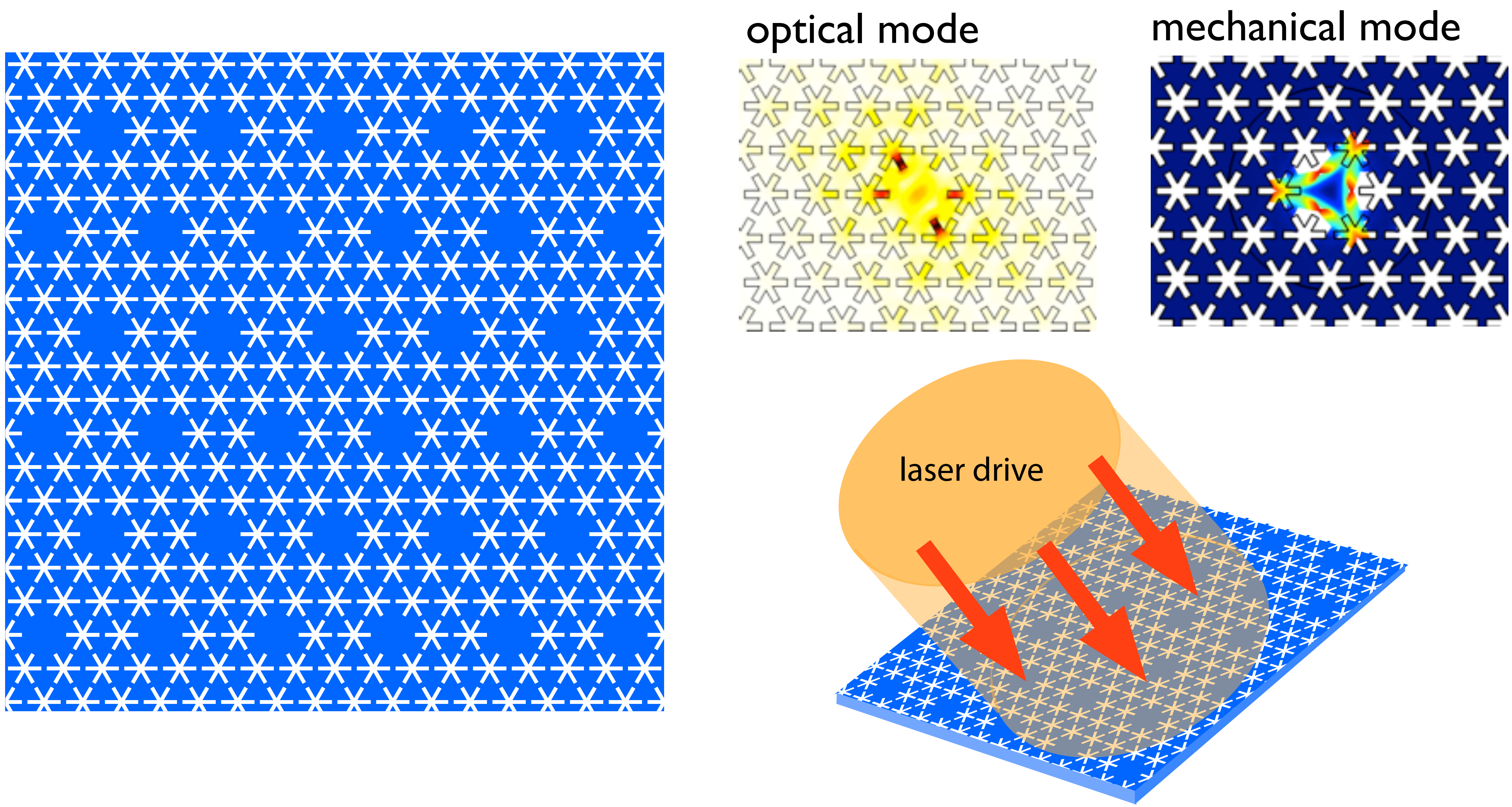
G. Heinrich et al., Phys. Rev. Lett. 107, 043603 (2011)

Synchronization in optomechanical arrays



Optomechanical arrays

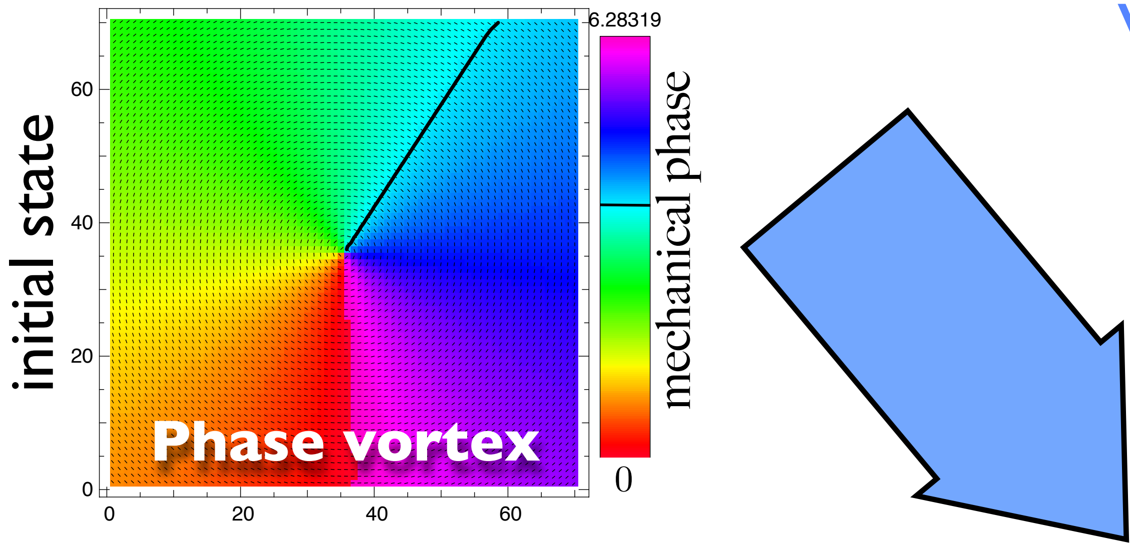
Optomechanical array: Many coupled optomechanical cells



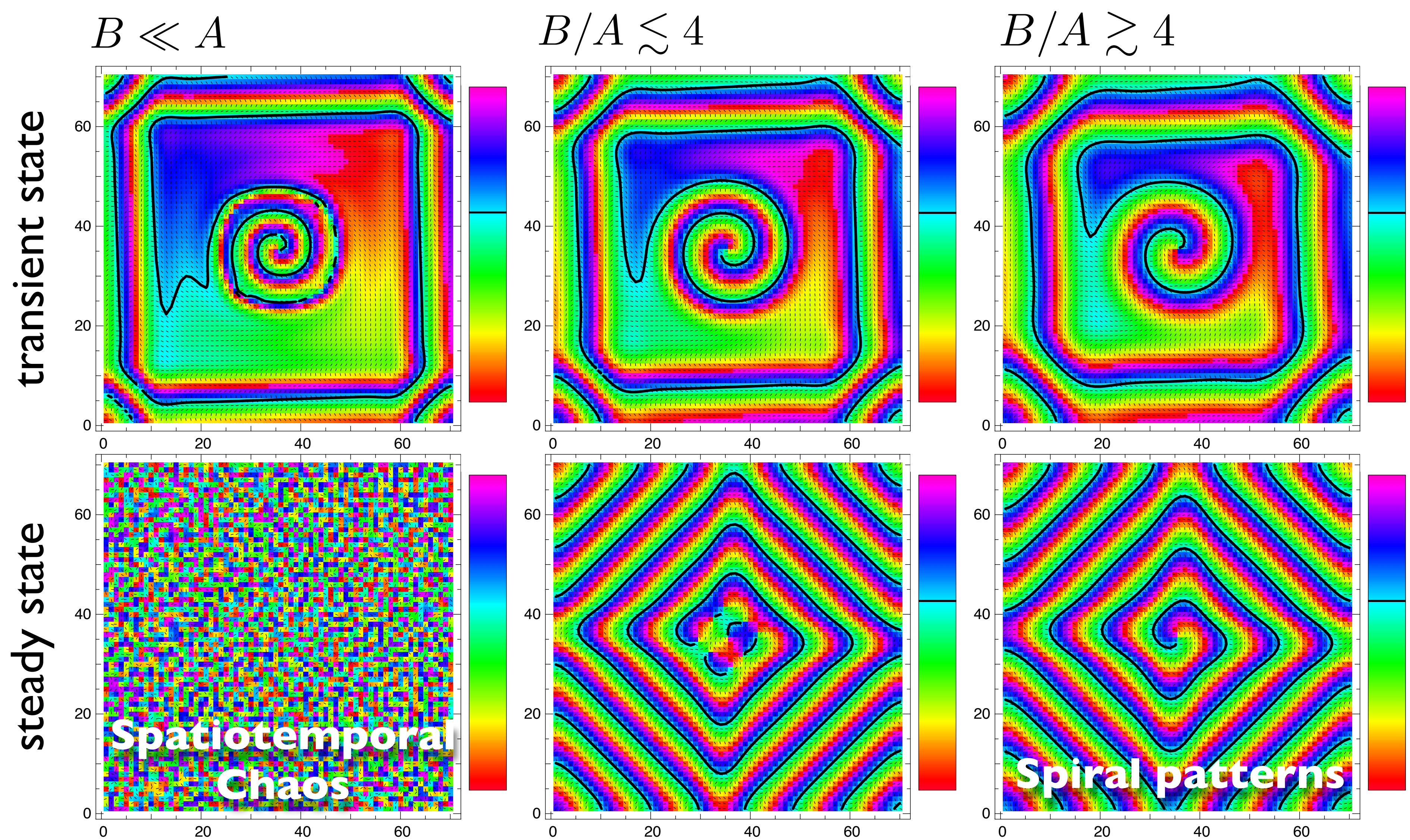
Possible design based on “snowflake” 2D optomechanical crystal (Painter group), here: with suitable defects forming a superlattice (array of cells)

Pattern formation in optomechanical arrays

work with Christian Brendel, Roland Lauter, Steve Habrake, Max Ludwig



(B,A can be calculated from microscopic parameters)

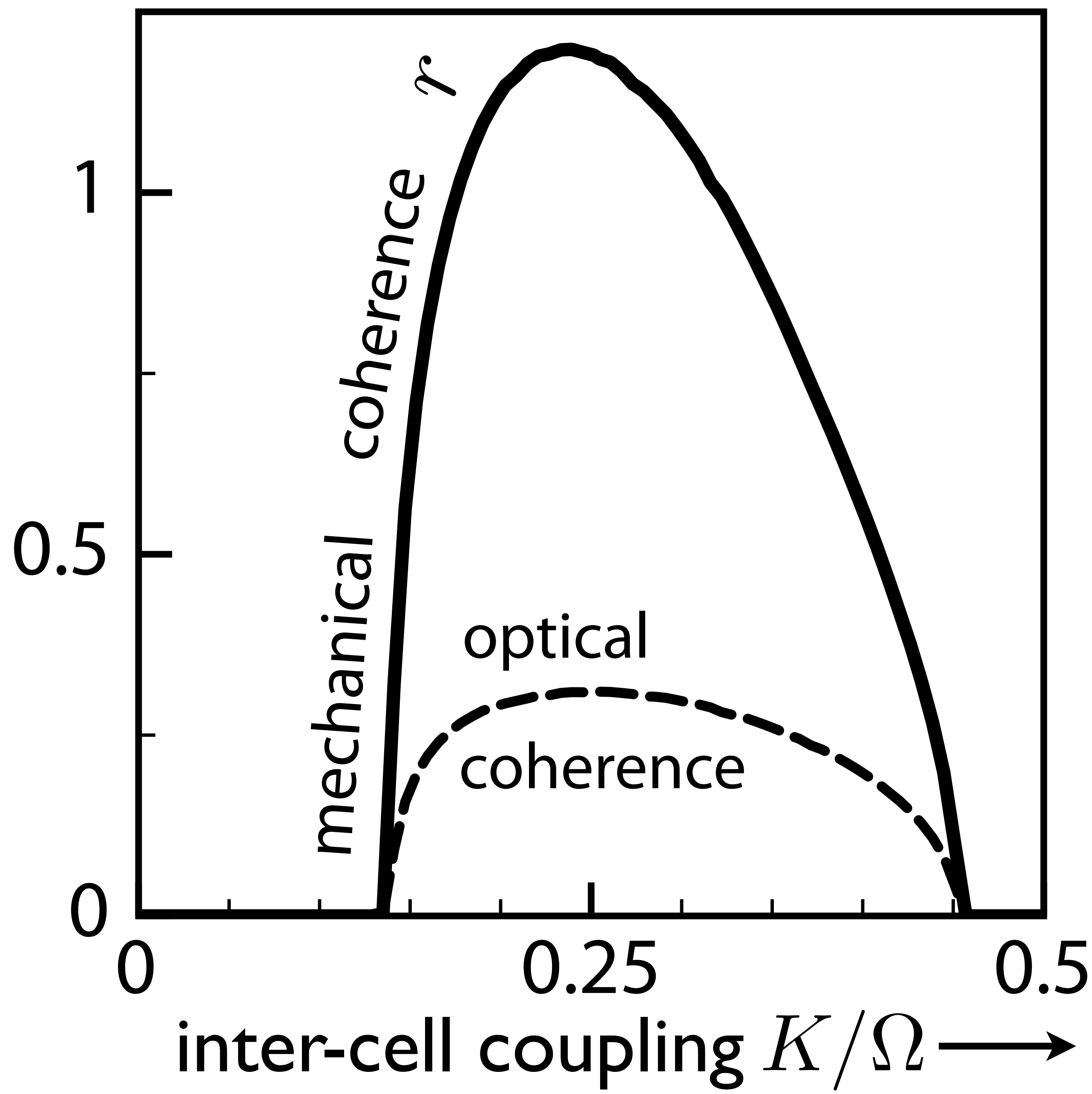


Transition towards coherent mechanical oscillations

Observation for strong inter-cell coupling:
spontaneous time-dependence of phonon field

"order parameter"
("mechanical coherence")

$$\langle\hat{b}\rangle(t) = \bar{b} + re^{-i\Omega_{\mathrm{eff}}t}$$

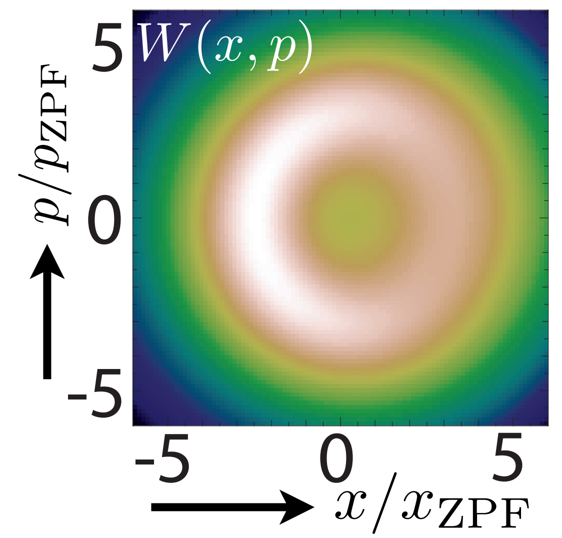


quantum mean-field result

Mechanical quantum states

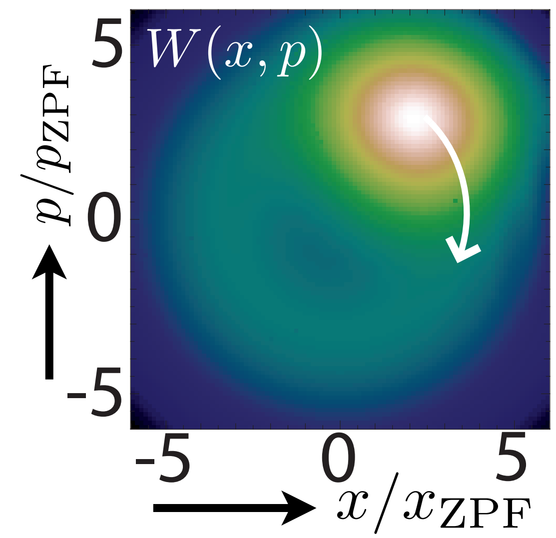
Incoherent mechan. oscillations (weak inter-cell coupling)

Mechanical Wigner density shows incoherent mixture of all possible oscillation phases



Coherent mechan. oscillations (strong inter-cell coupling)

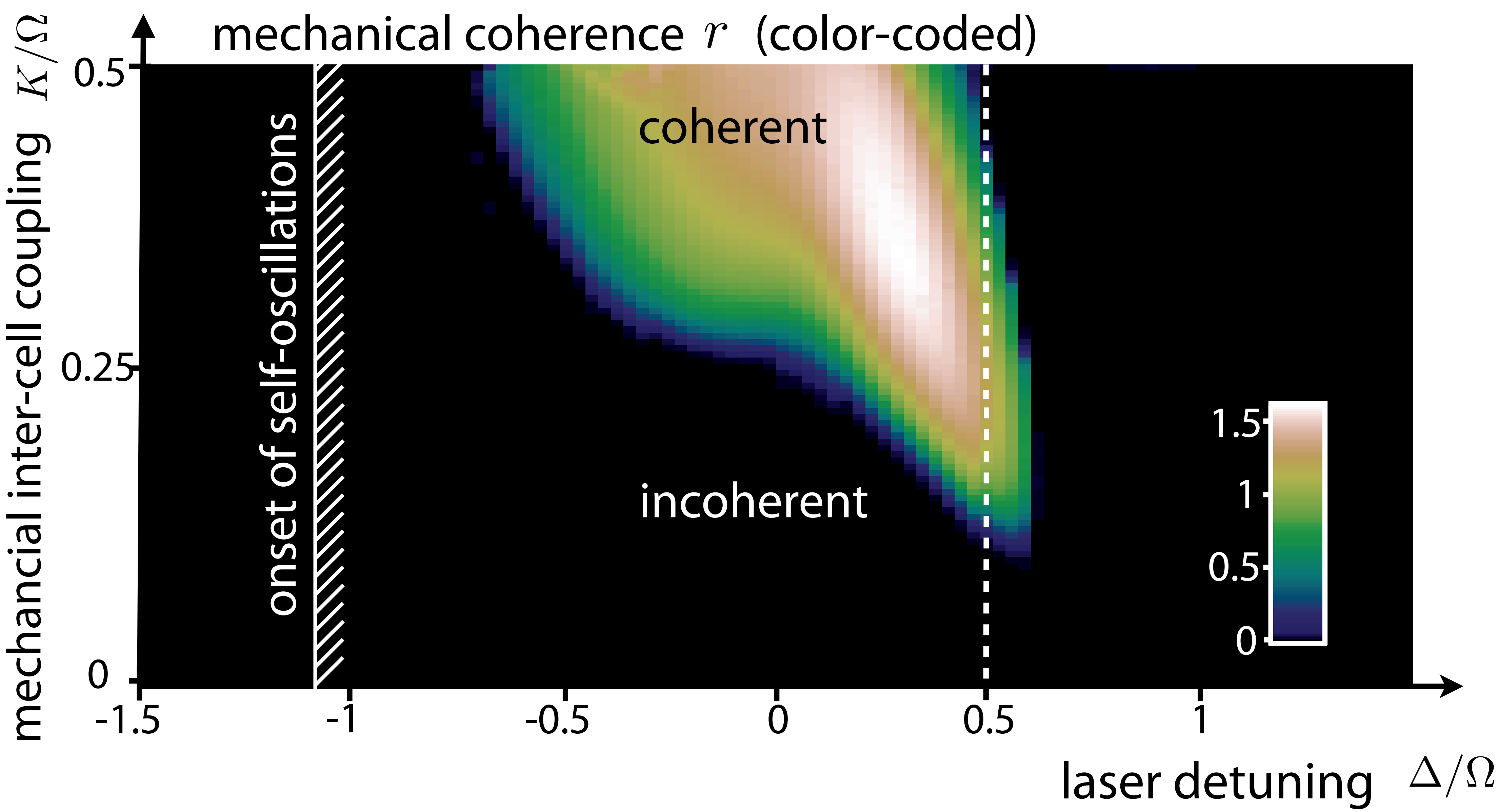
Mechanical Wigner density shows preferred phase (coherent state) – spontaneous symmetry breaking!



Transition towards coherent mechanical oscillations

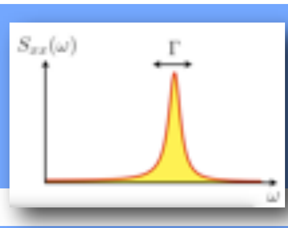
$$\langle\hat{b}\rangle(t) = \bar{b} + re^{-i\Omega_{\text{eff}}t}$$

"order parameter"
("mechanical coherence")



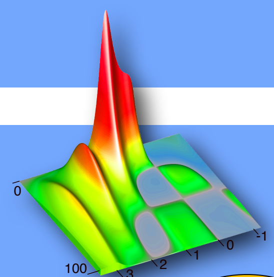
Max Ludwig, FM, PRL 111, 073603 (2013):Quantum many-body dynamics in optomechanical arrays

Optomechanics (Outline)

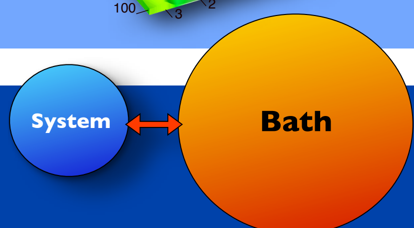


Displacement detection

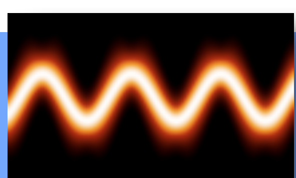
Linear optomechanics



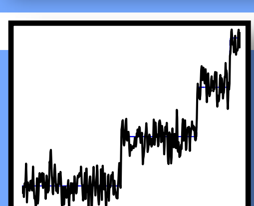
Nonlinear dynamics



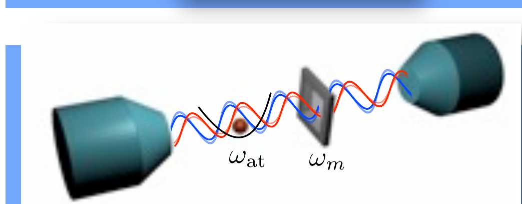
Quantum theory of cooling



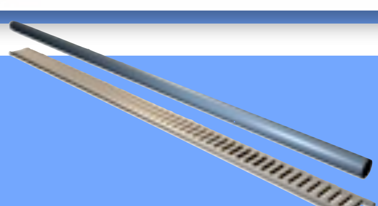
Interesting quantum states



Towards Fock state detection

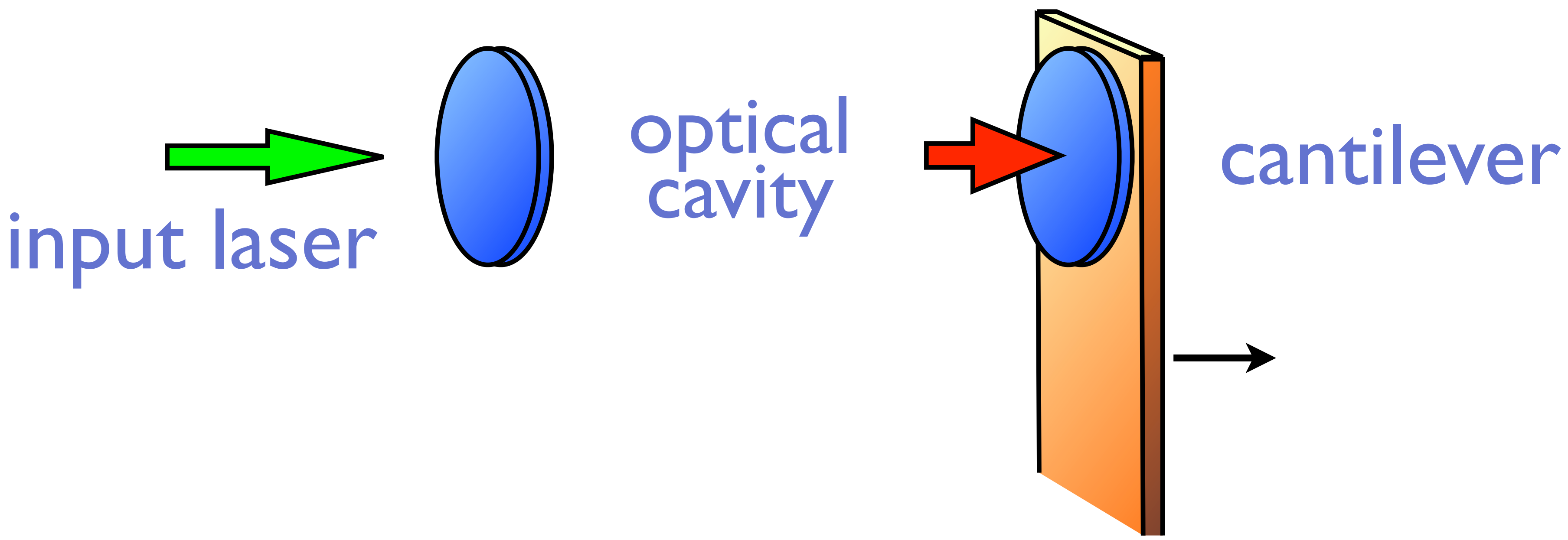


Hybrid systems: coupling to atoms



Optomechanical crystals & arrays

Cooling with light



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

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

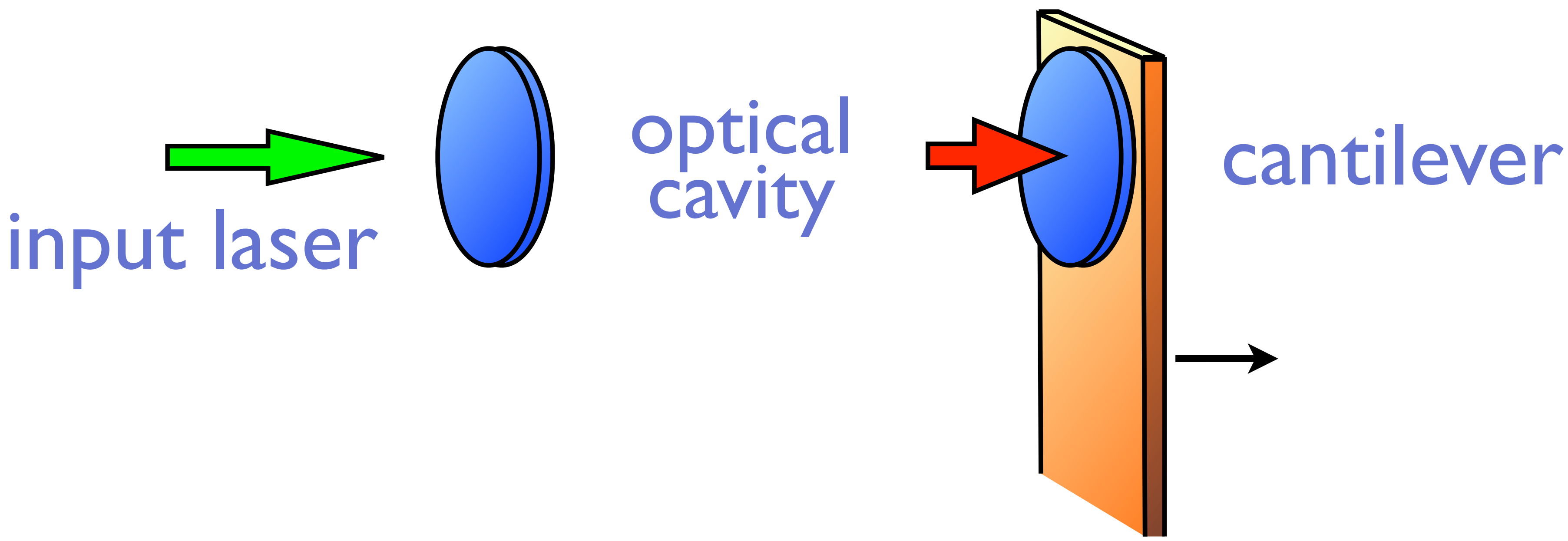
Classical theory:

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

optomechanical damping rate

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

Cooling with light



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quantum limit?

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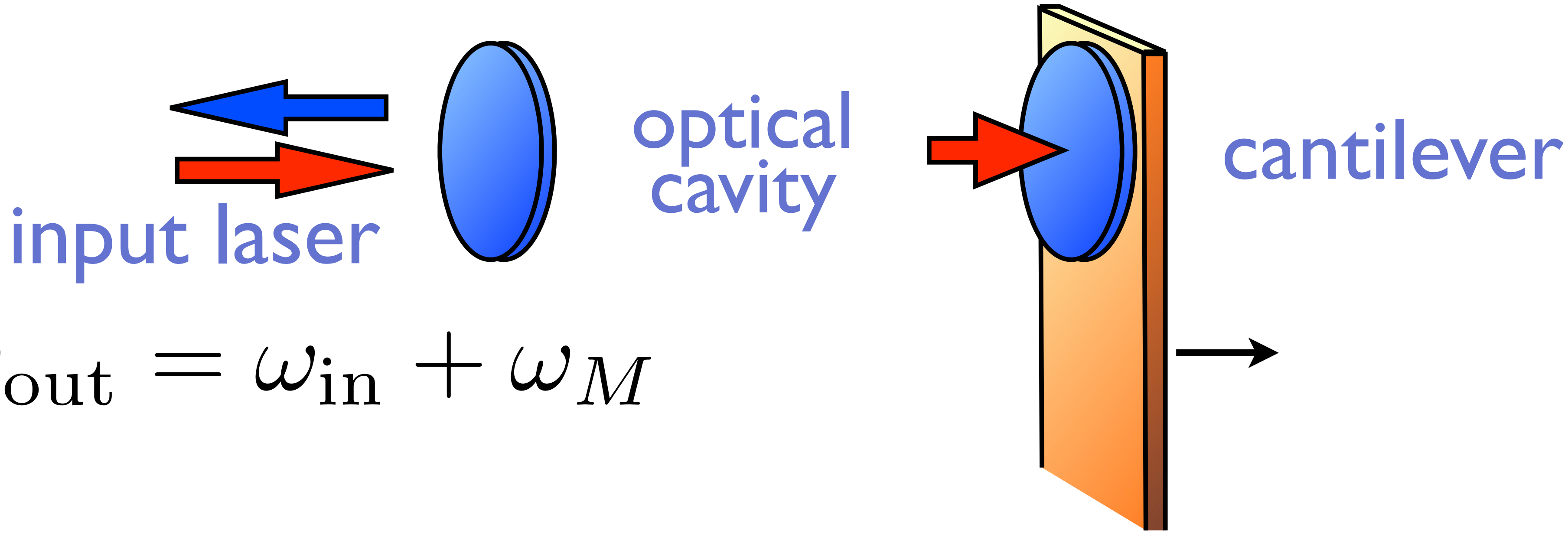
shot noise!

optomechanical damping rate

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

Cooling with light



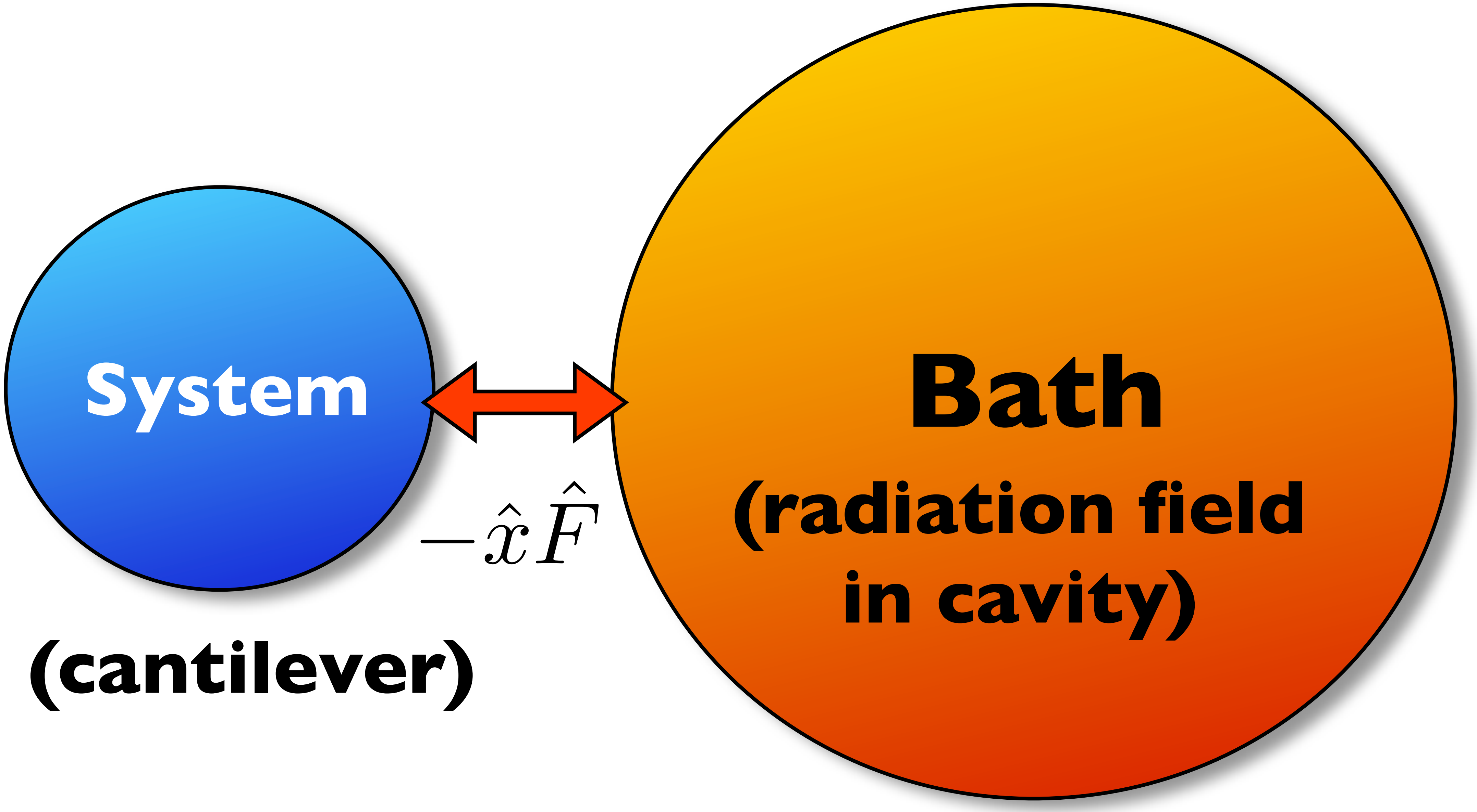
$$\omega_{\rm out} = \omega_{\rm in} + \omega_M$$

Quantum picture: Raman scattering – sideband cooling

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

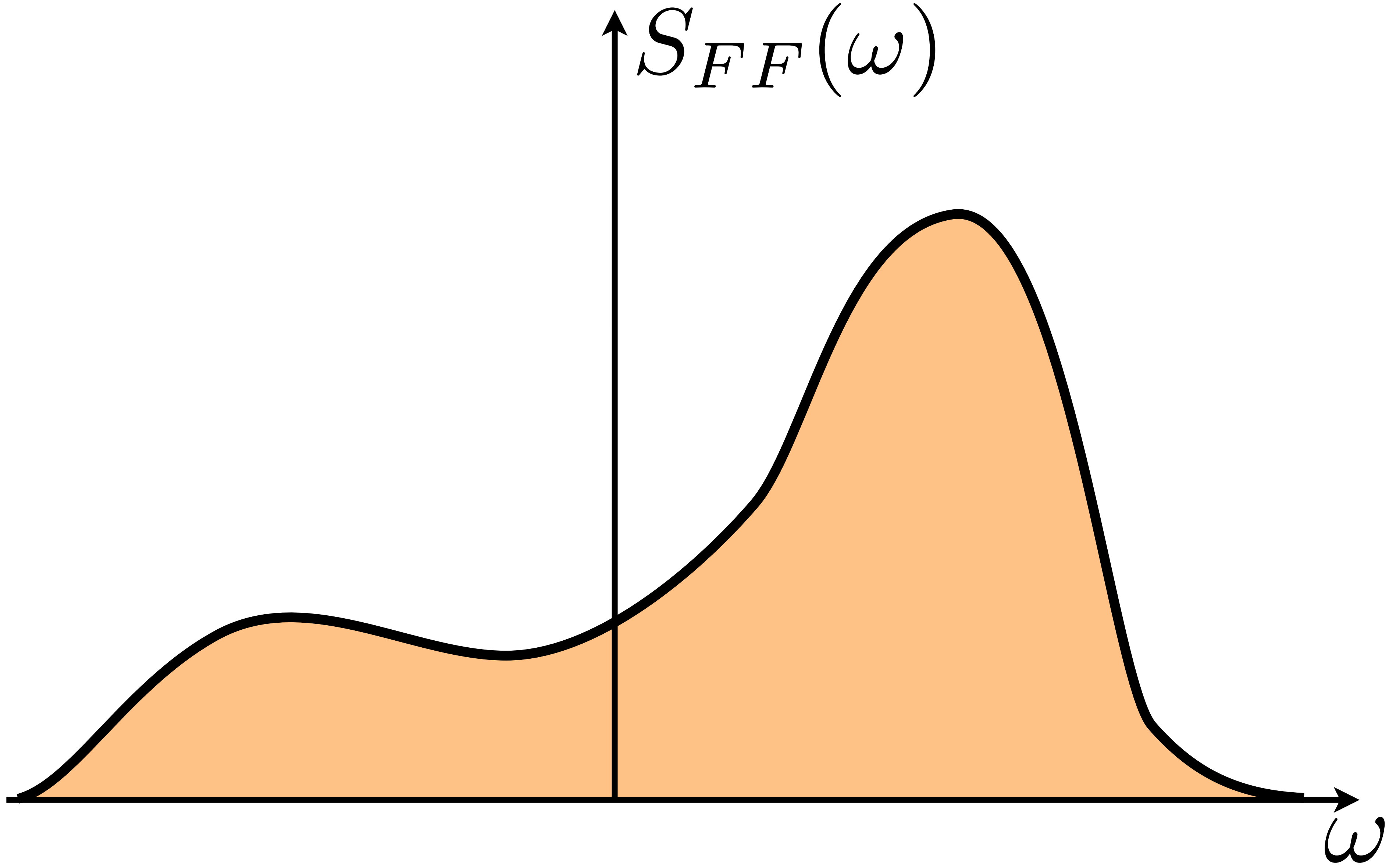
Similar ideas proposed for nanomechanics:
cantilever + quantum dot – Wilson-Rae, Zoller, Imamoglu 2004
cantilever + Cooper-pair box – Martin Shnirman, Tian, Zoller 2004
cantilever + ion – Tian, Zoller 2004
cantilever + supercond. SET – Clerk, Bennett / Blencowe, Imbers, Armour 2005, Naik et al. (Schwab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

Quantum noise approach



Quantum noise approach

spectrum $$S_{FF}(\omega) = \int e^{i\omega t} \left\langle \hat{F}(t)\hat{F}(0) \right\rangle dt$$



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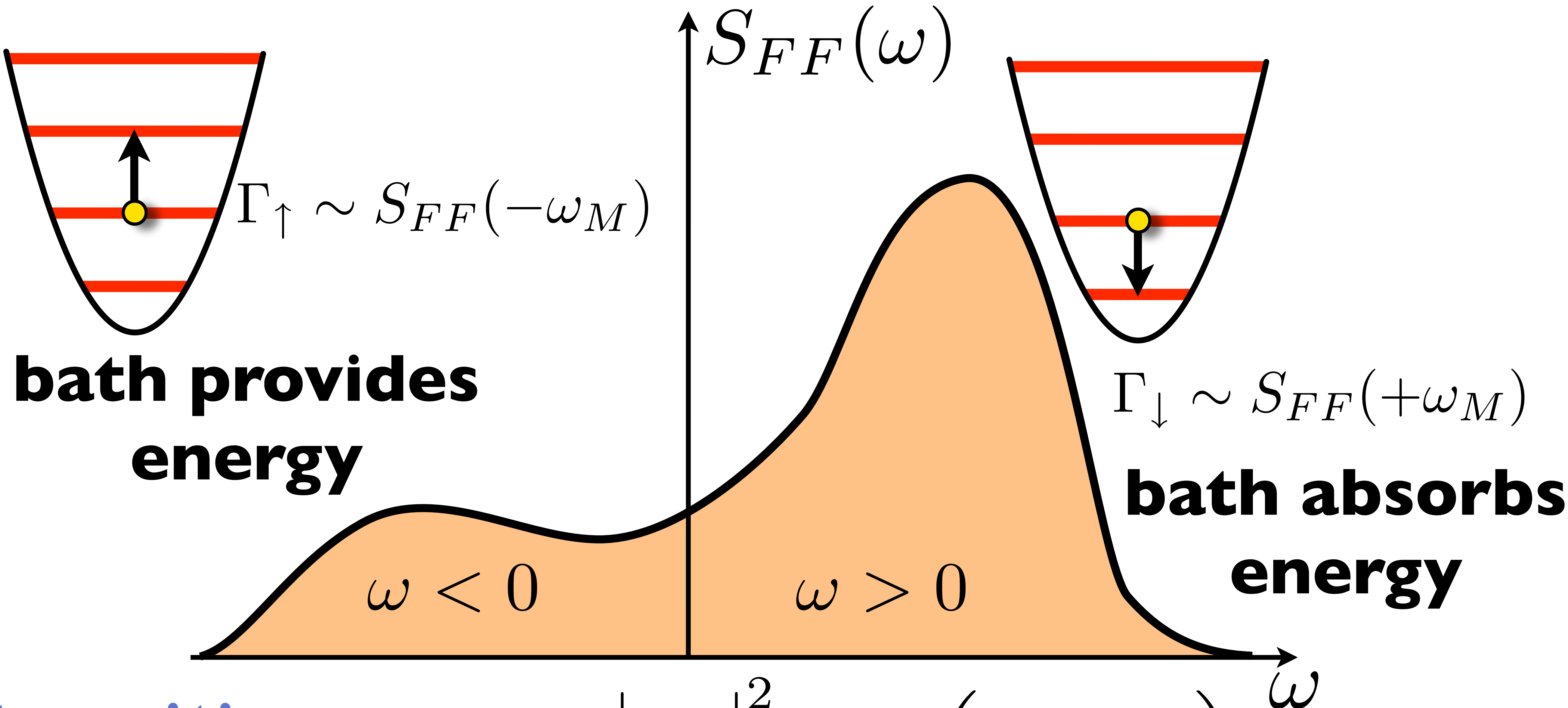

transition rate $$\Gamma_{f\leftarrow i} = \frac{|x_{fi}|^2}{\hbar^2} S_{FF}\left(\frac{\epsilon_i - \epsilon_f}{\hbar}\right)$$

Quantum theory of optomechanical cooling

Spectrum of radiation pressure fluctuations

$$S_{FF}(\omega) = \int e^{i\omega t} \left\langle \hat{F}(t)\hat{F}(0) \right\rangle dt$$

radiation pressure force

$$\hat{F} = \left(\frac{\hbar\omega_R}{L}\right) \hat{a}^\dagger \hat{a}$$

photon number

$$S_{FF}(\omega) = \left(\frac{\hbar\omega_R}{L}\right)^2 \bar{n}_p \frac{\kappa}{(\omega+\Delta)^2 + (\kappa/2)^2}$$

photon shot noise spectrum

Quantum theory of optomechanical cooling

Spectrum of radiation pressure fluctuations

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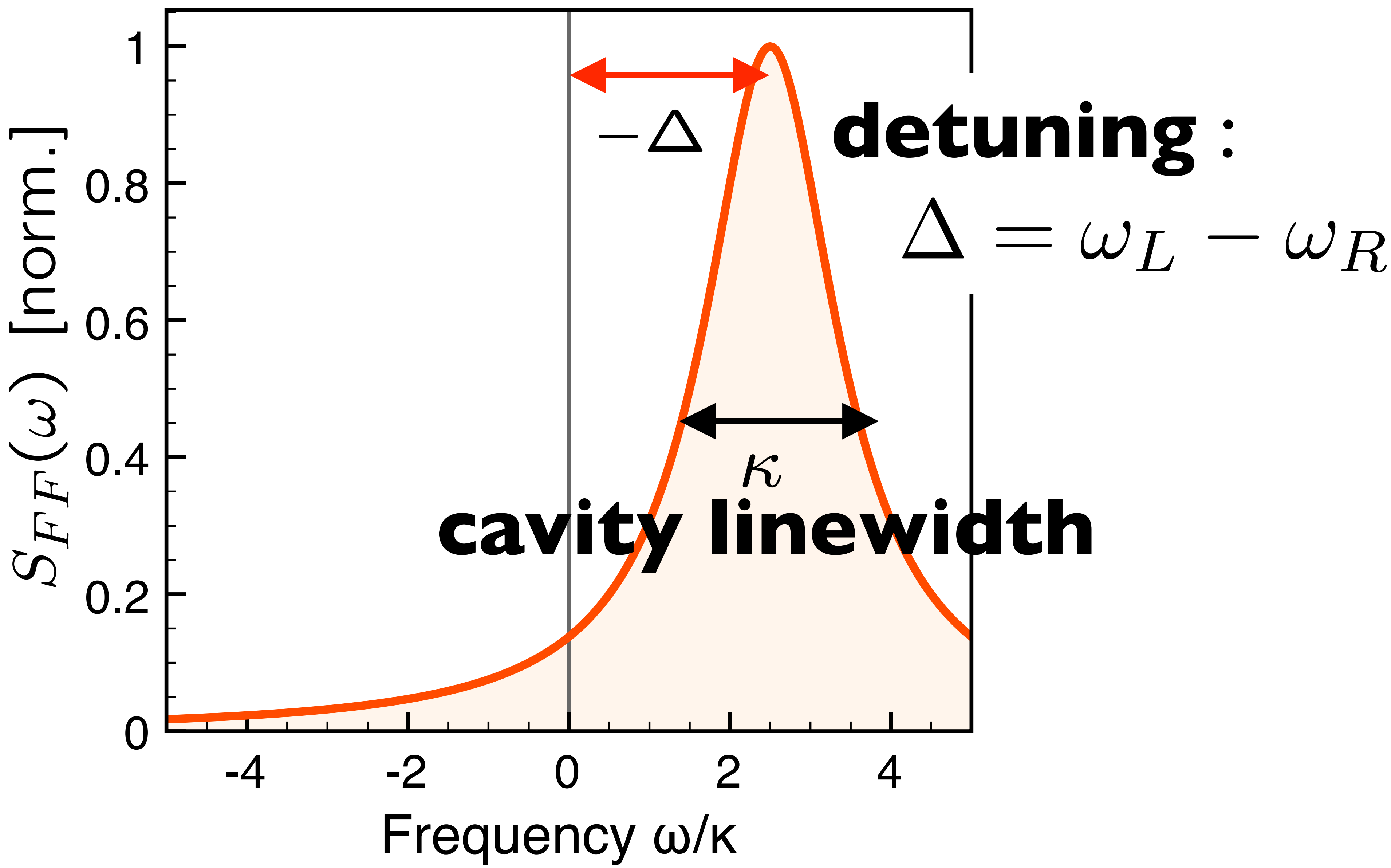
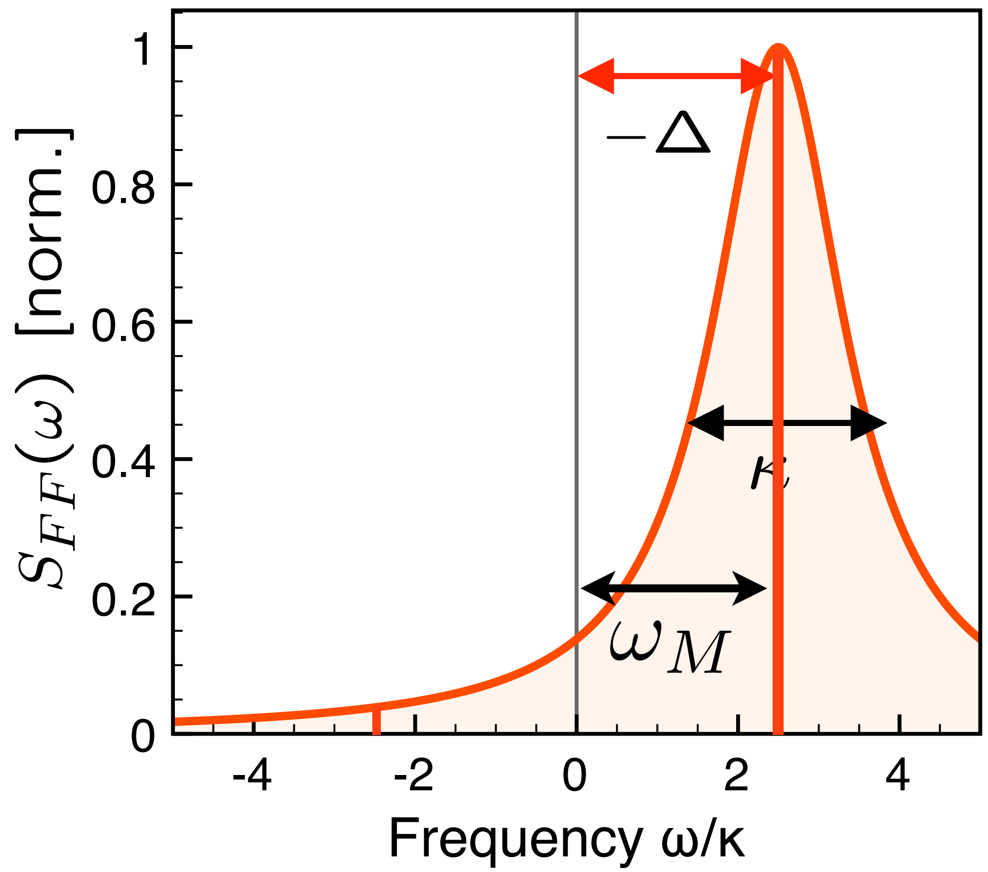


cavity emits energy / absorbs energy

Quantum theory of optomechanical cooling



cavity emits energy / absorbs energy

FM, Chen, Clerk, Girvin, PRL **93**, 093902 (2007)
also: Wilson-Rae, Nooshi, Zwerger, Kippenberg, PRL **99**, 093901 (2007); Genes et al, PRA 2008

experiment with $\kappa/\omega_M \approx 1/20$
Kippenberg group 2007

Cooling rate

$$\Gamma_{\rm opt} = \frac{{x_{\rm ZPF}}^2}{\hbar^2}\left[S_{FF}(+\omega_M) - S_{FF}(-\omega_M)\right]$$

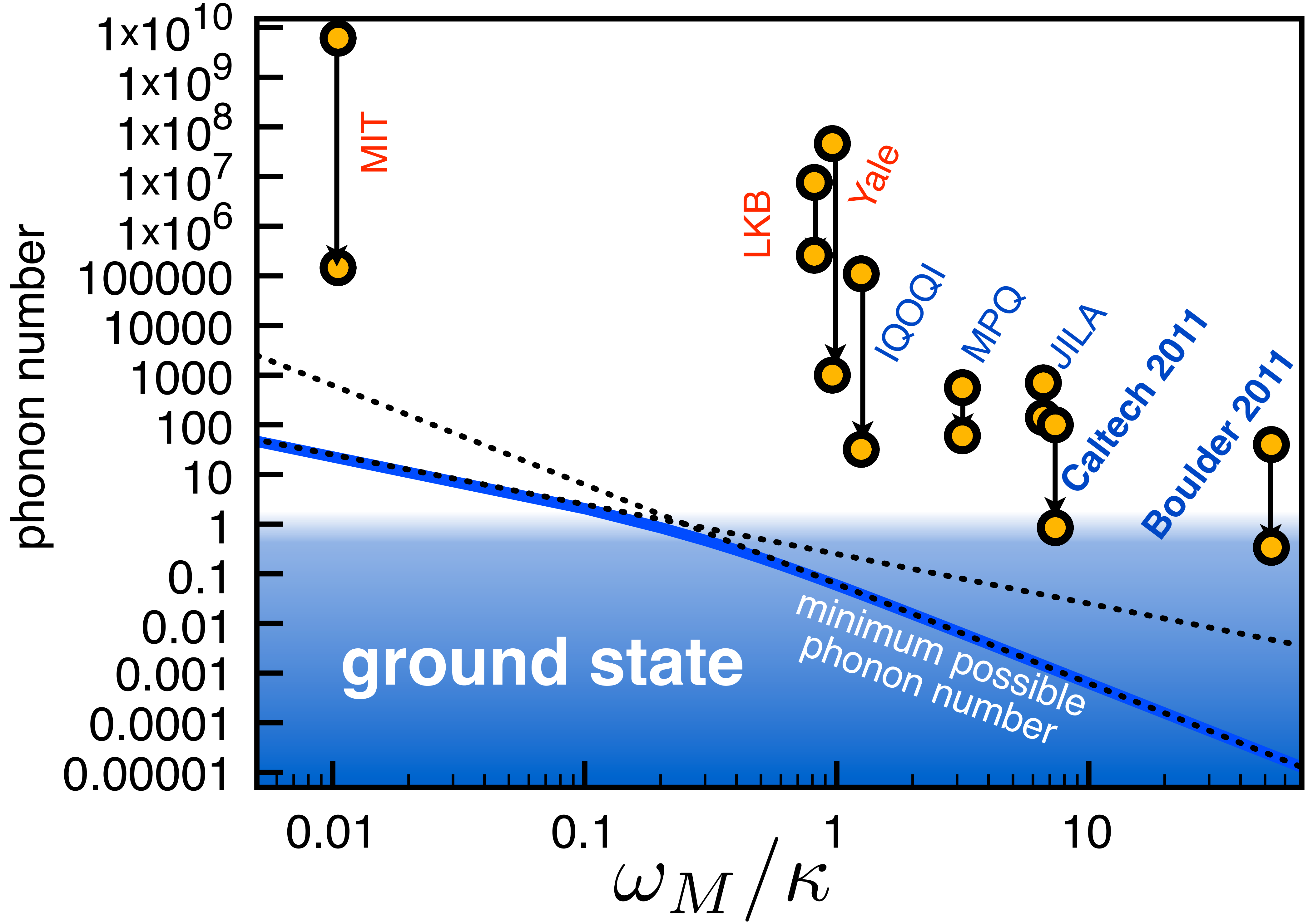
Quantum limit for cantilever phonon number

$$\frac{n_{\rm opt}+1}{n_{\rm opt}} = \frac{S_{FF}(+\omega_M)}{S_{FF}(-\omega_M)}$$

$$\Delta = -\omega_M \Rightarrow n_{\rm opt} = \left(\frac{\kappa}{4\omega_M}\right)^2$$

Ground-state cooling needs: high optical finesse / large mechanical frequency

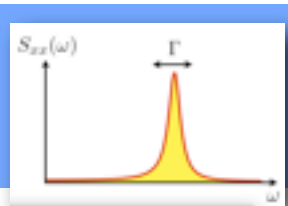
Laser-cooling towards the ground state



analogy to (cavity-assisted)
laser cooling of atoms

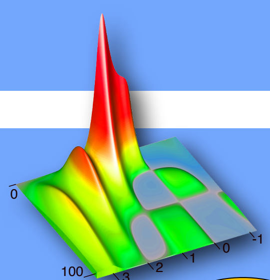
FM et al., PRL **93**, 093902 (2007)
Wilson-Rae et al., PRL **99**, 093901 (2007)

Optomechanics (Outline)



Displacement detection

Linear optomechanics



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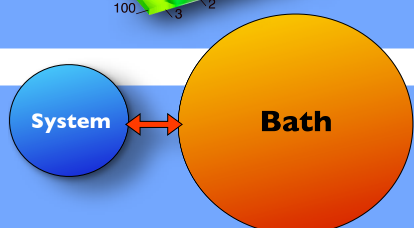

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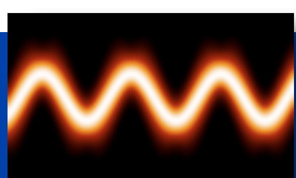

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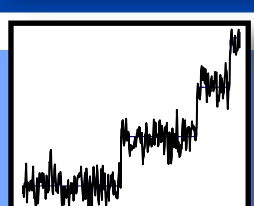

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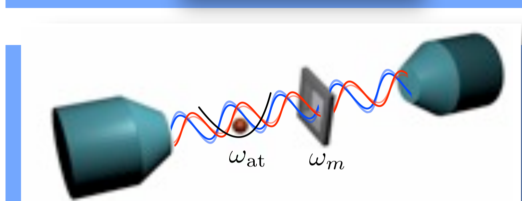

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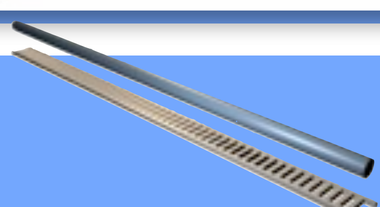
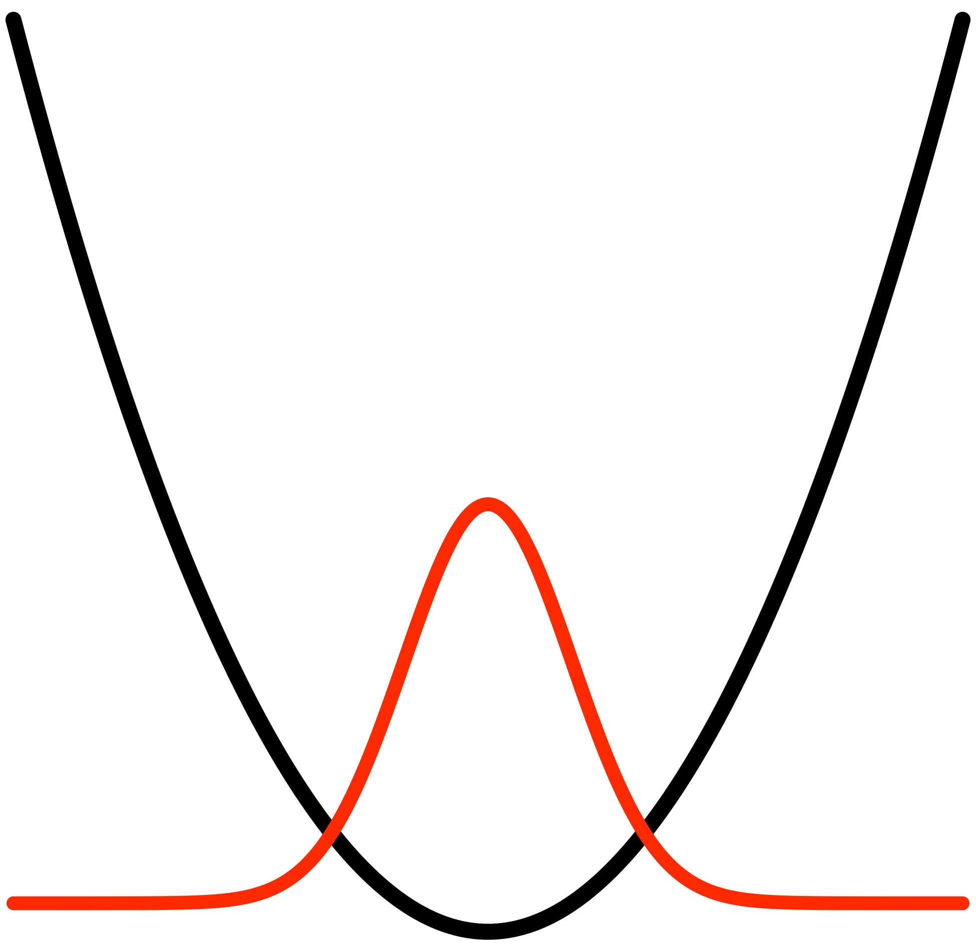


Optomechanical crystals & arrays

Squeezed states

Squeezing the mechanical oscillator state



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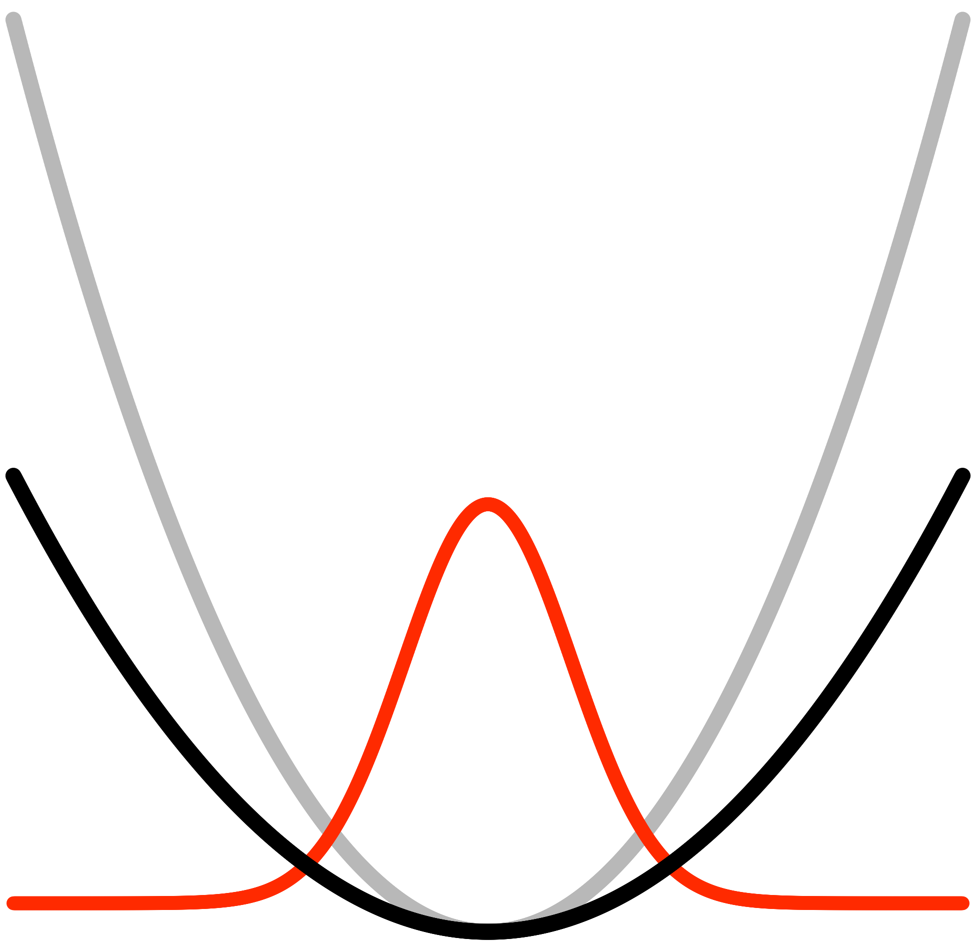
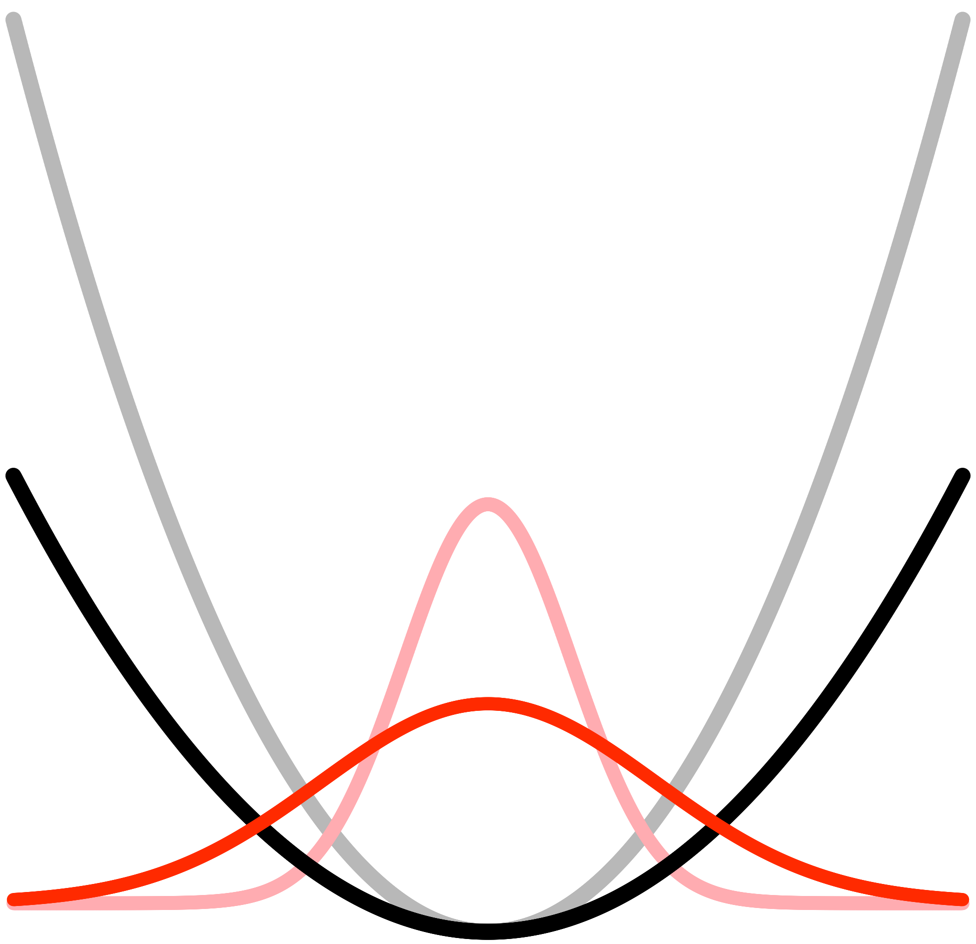


Squeezed states

Squeezing the mechanical oscillator state



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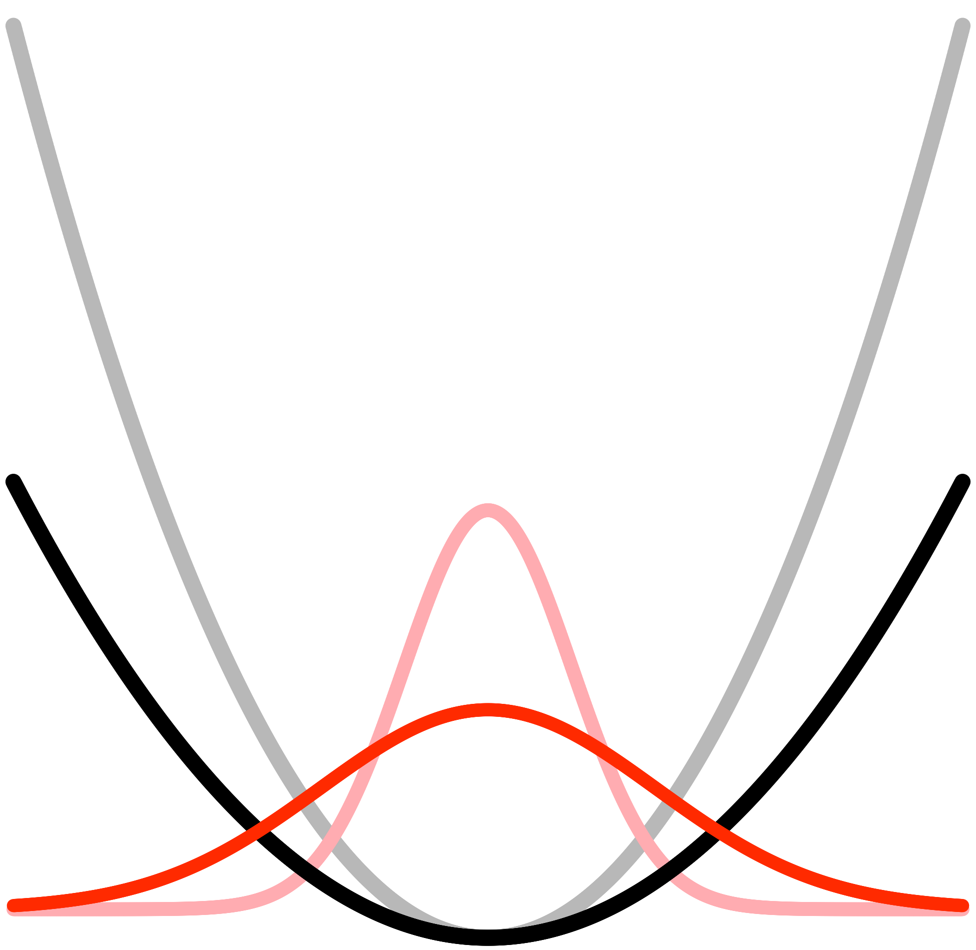

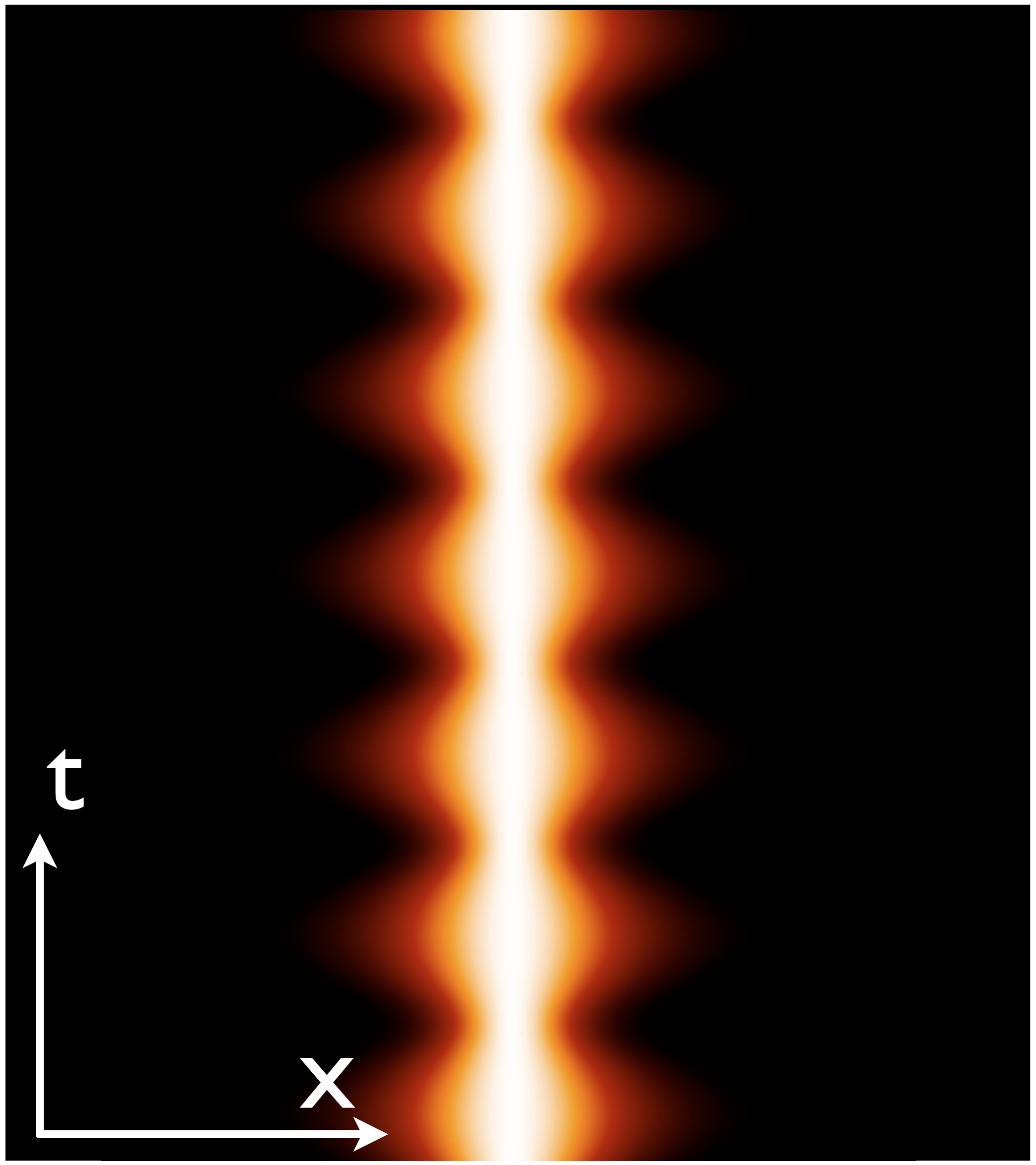

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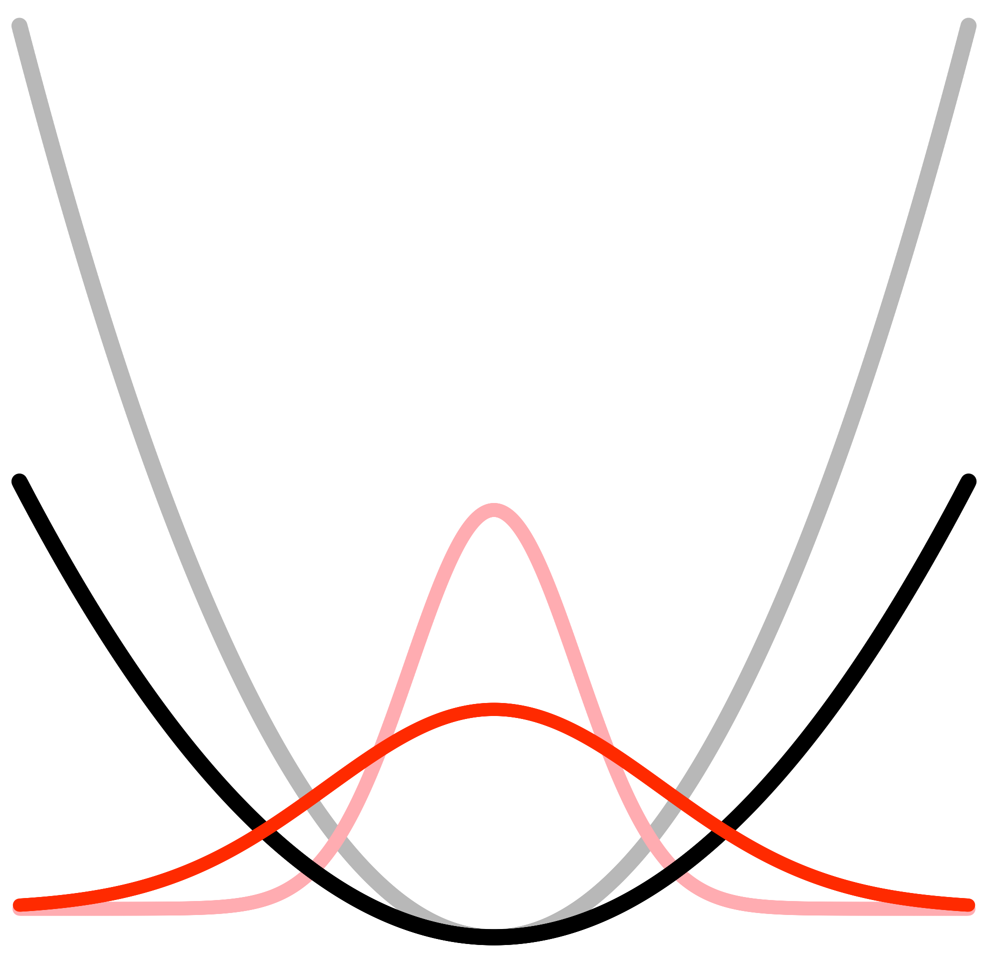
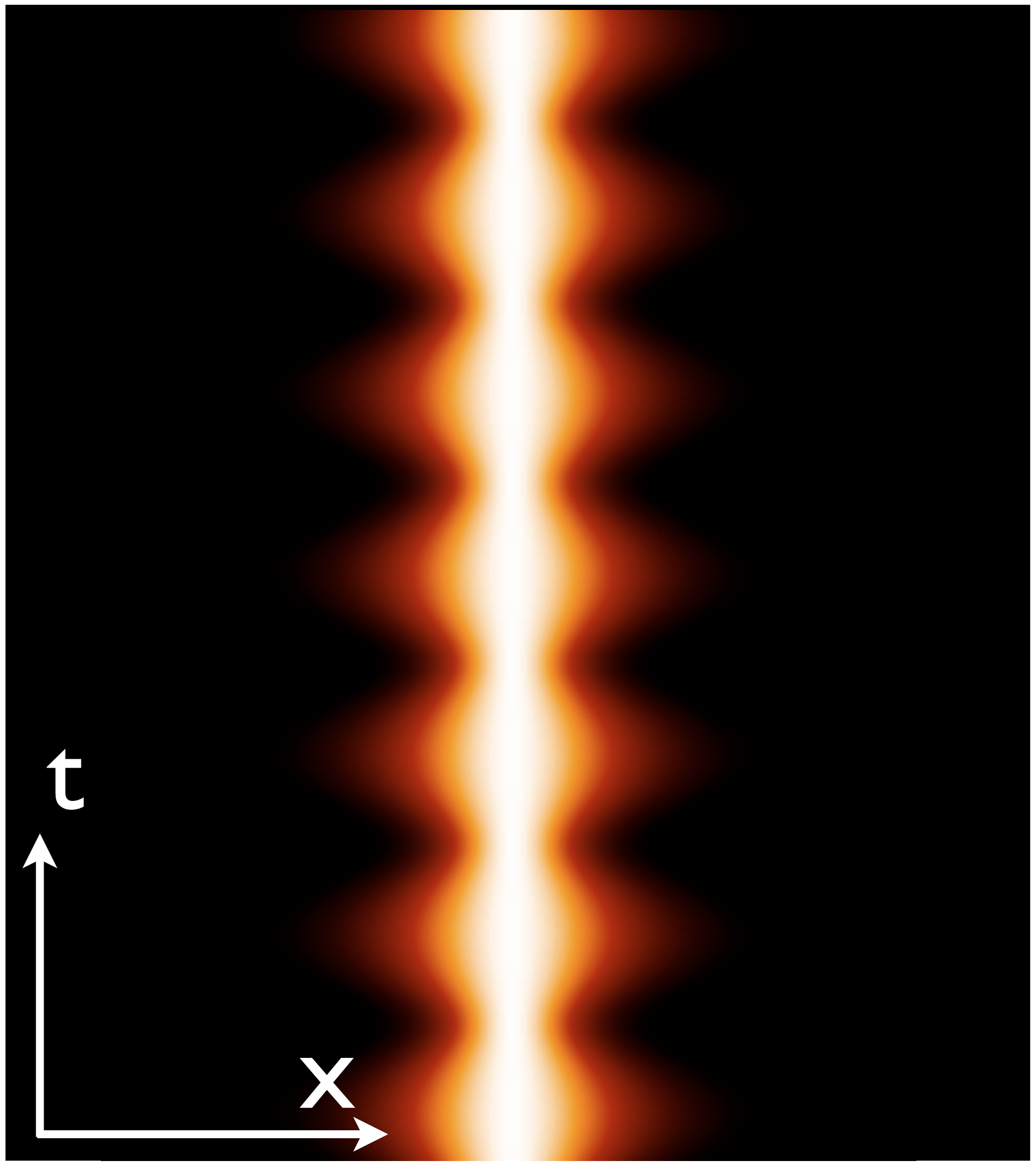
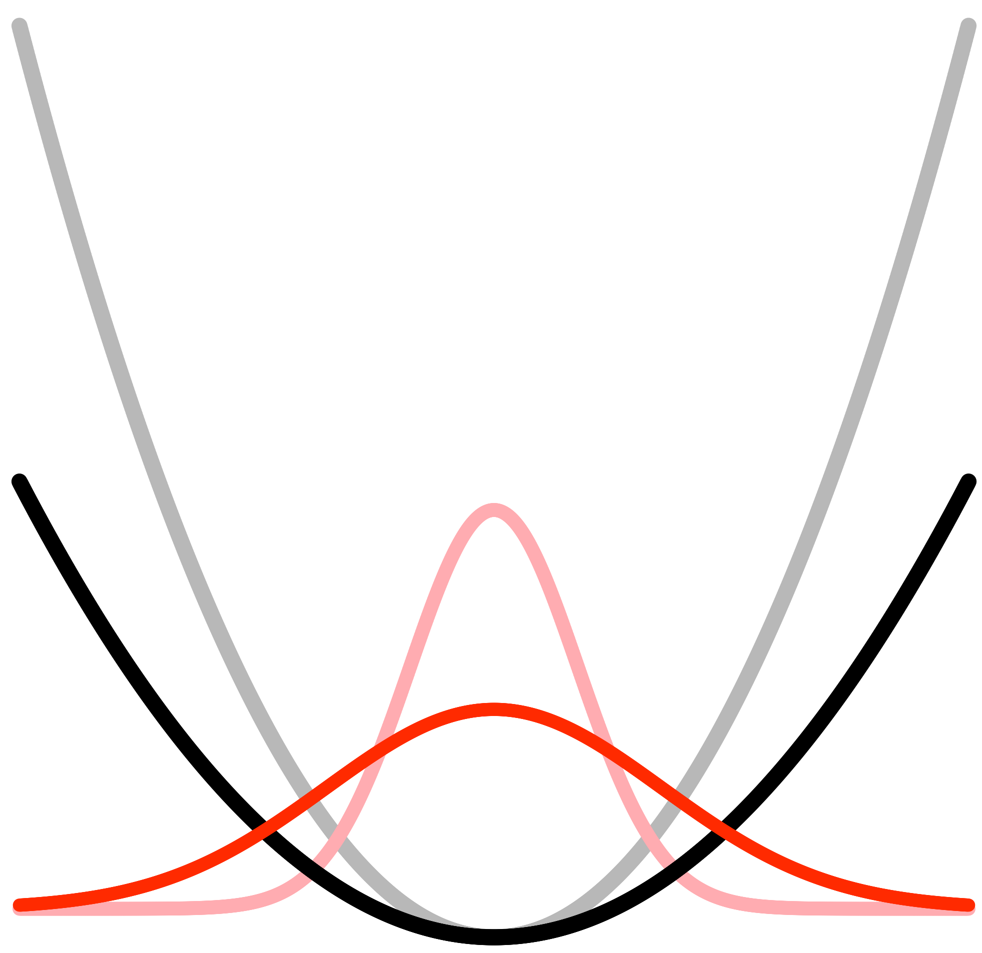


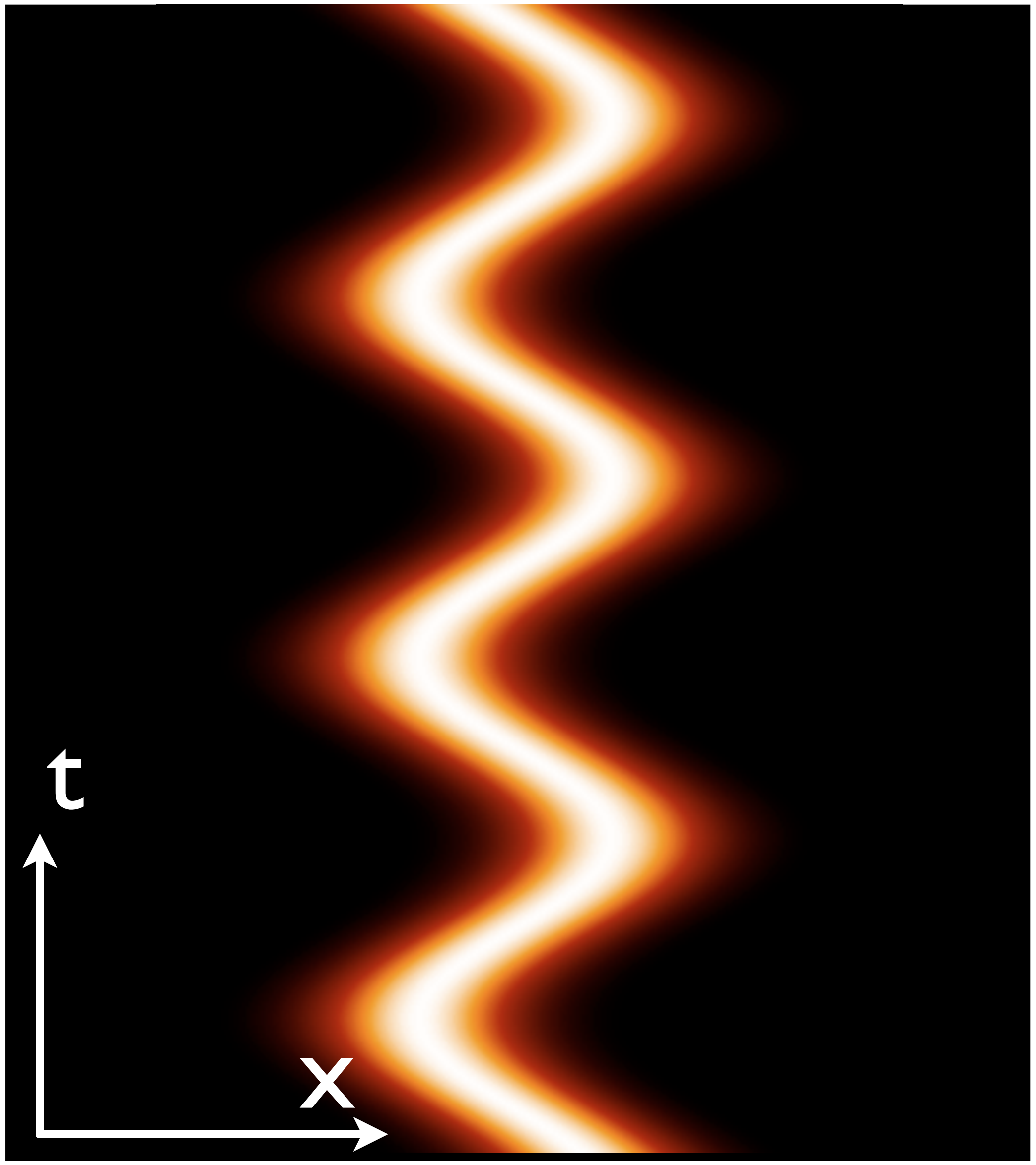


Periodic modulation of spring constant: $\delta\omega_M^2(t) \propto \cos(2\omega_M t)$
Parametric amplification

Squeezed states

Squeezing the mechanical oscillator state





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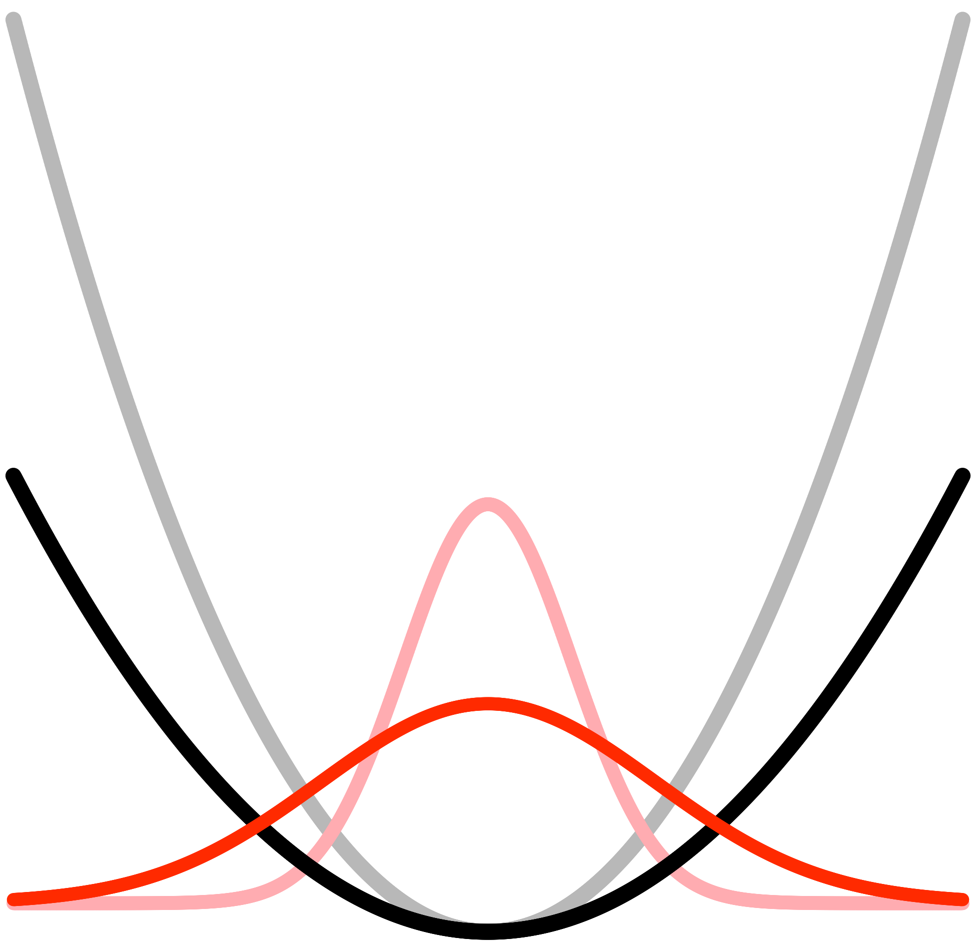

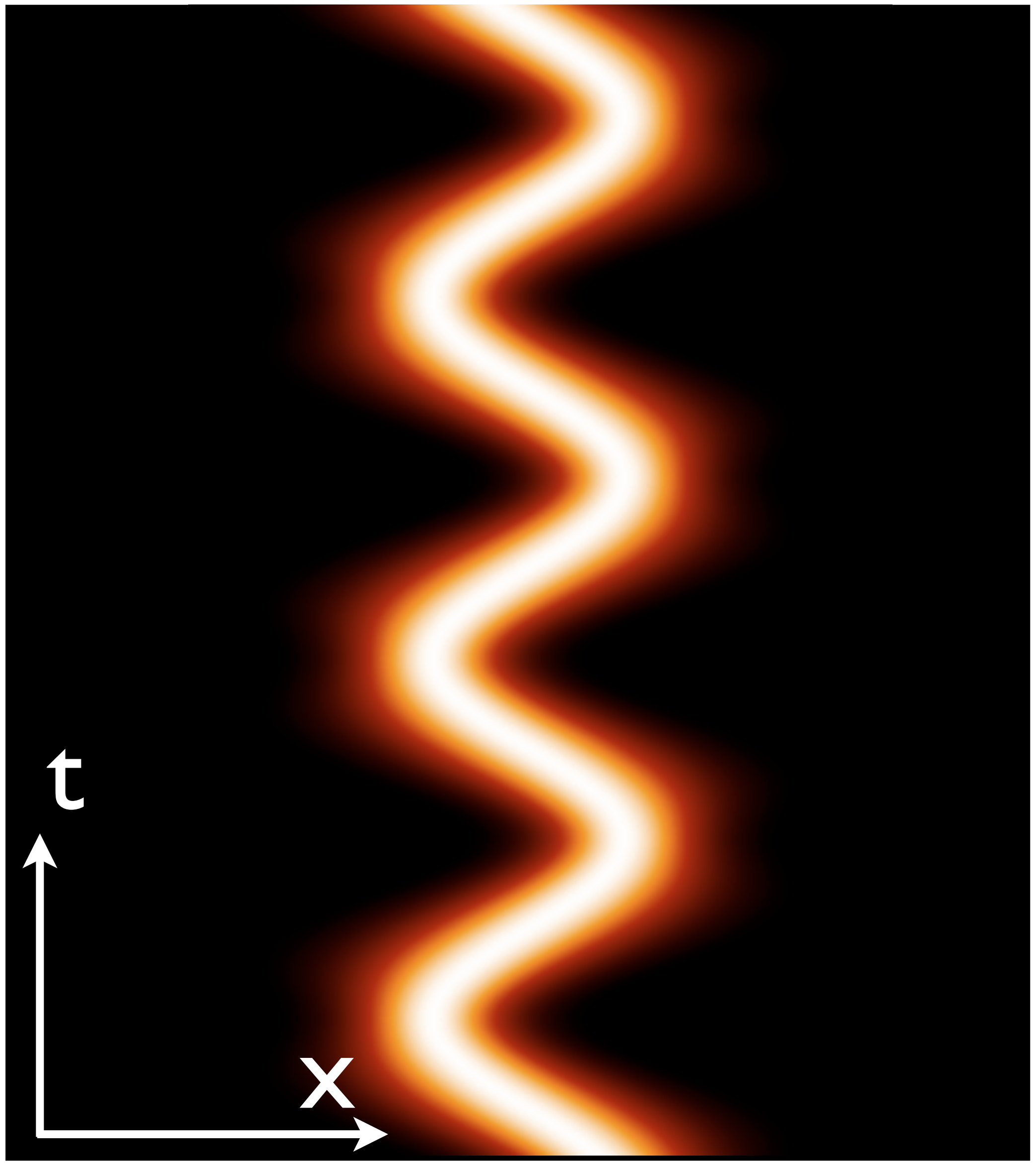

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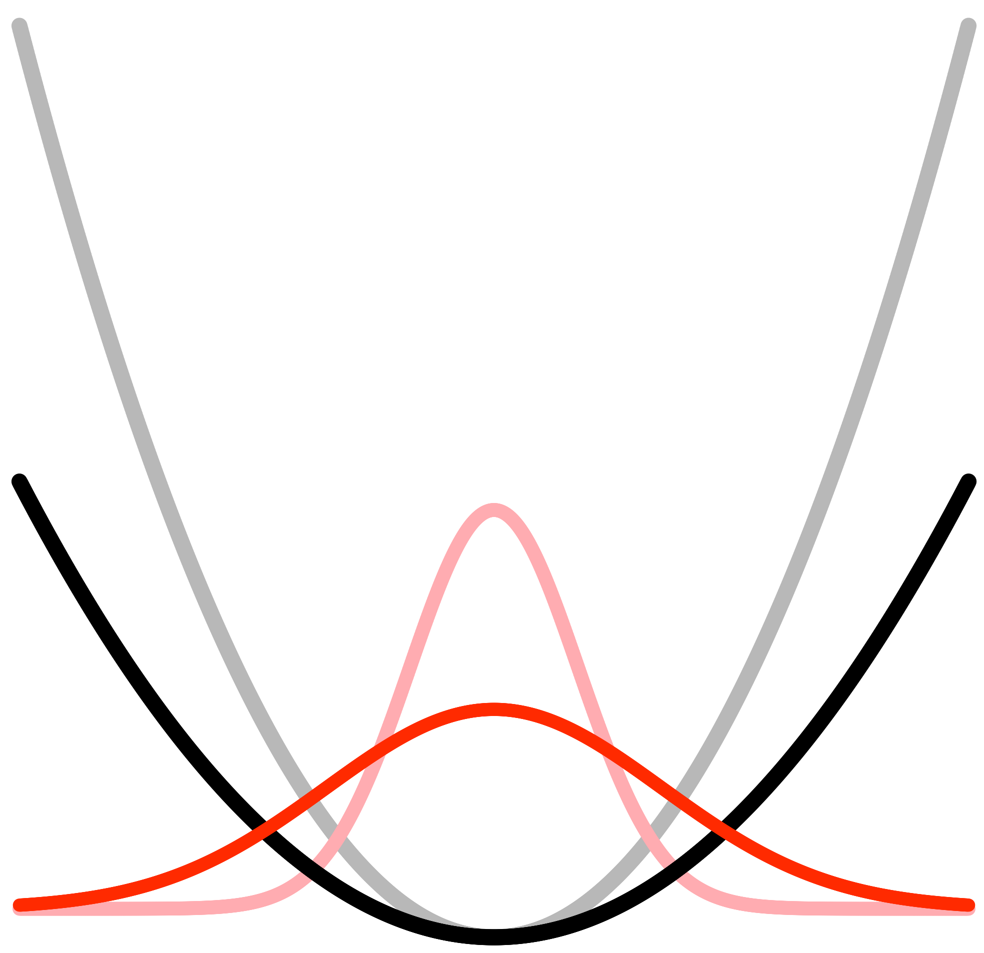

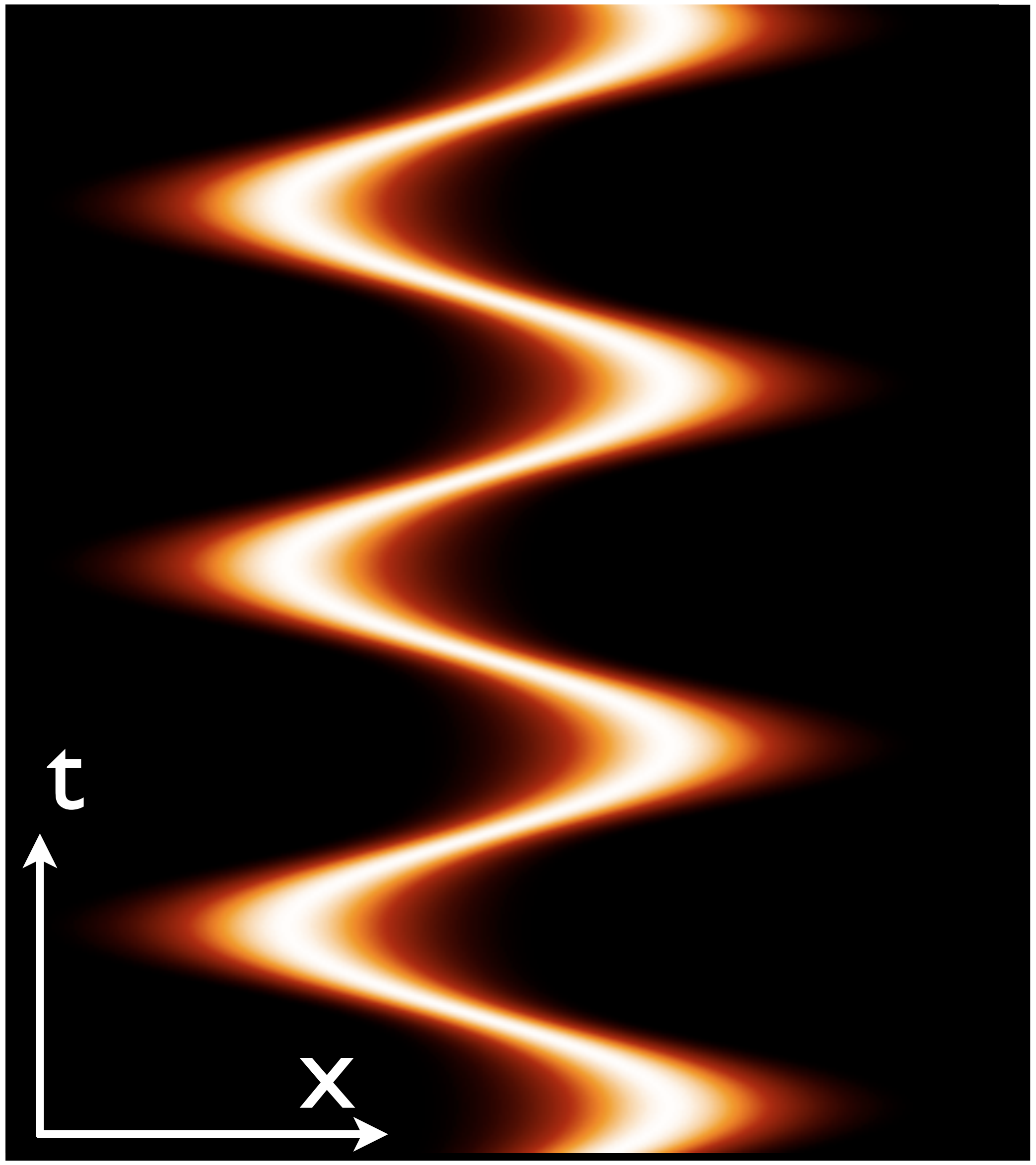

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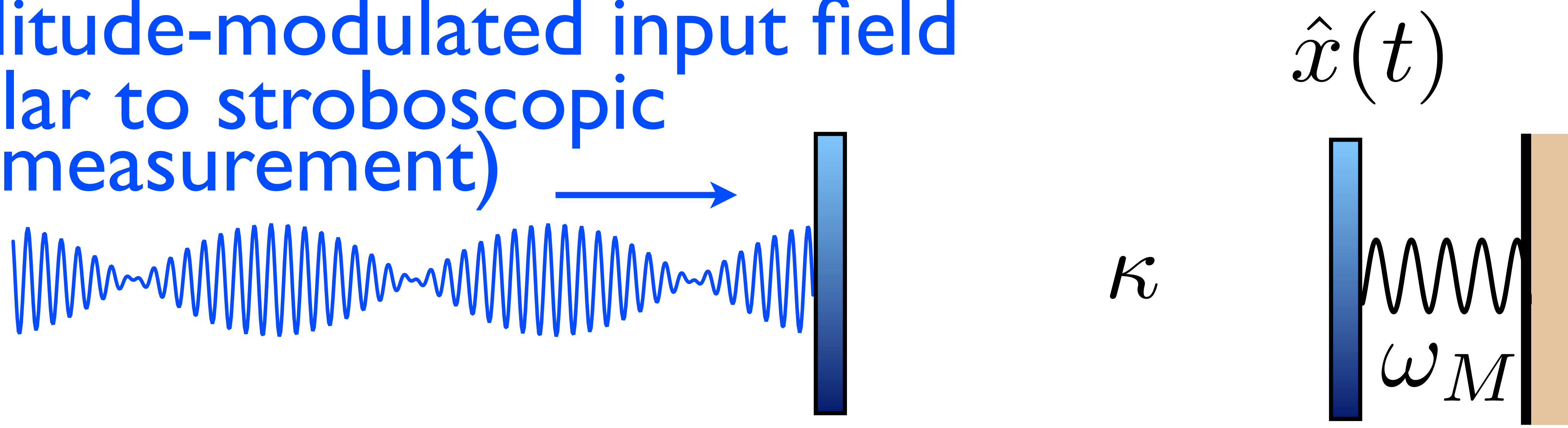
Parametric amplification

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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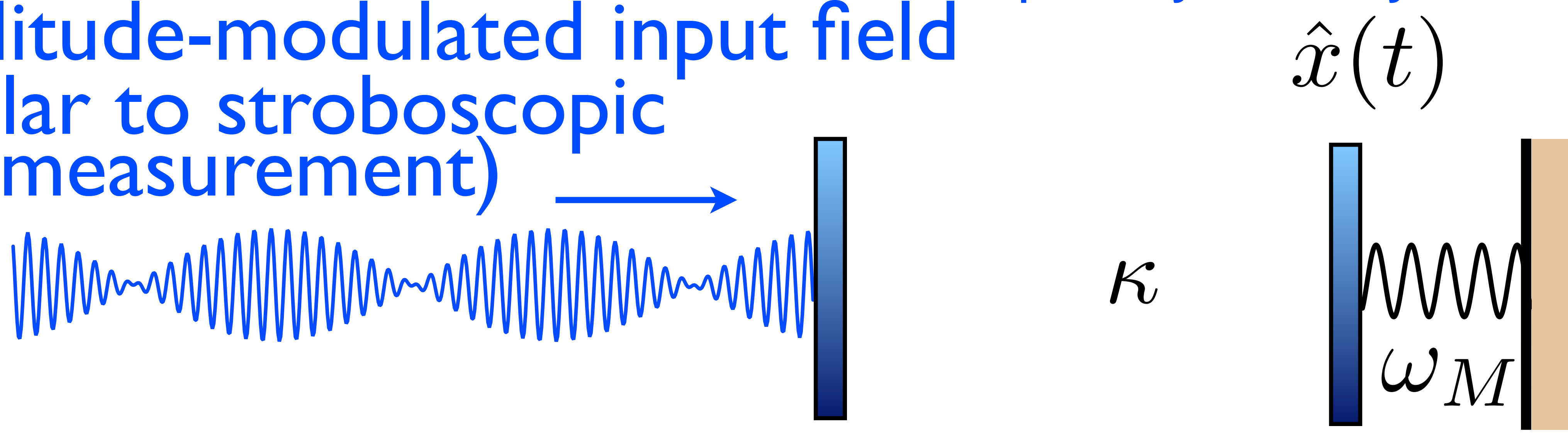

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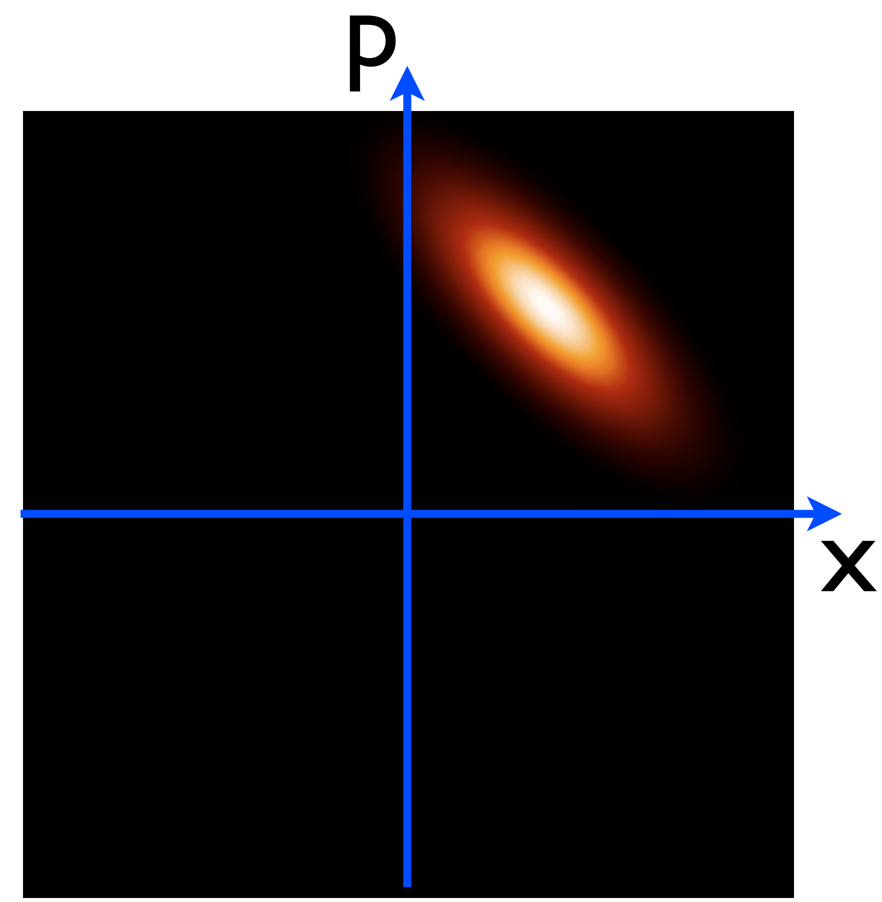
reconstruct mechanical Wigner density

(quantum state tomography)

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



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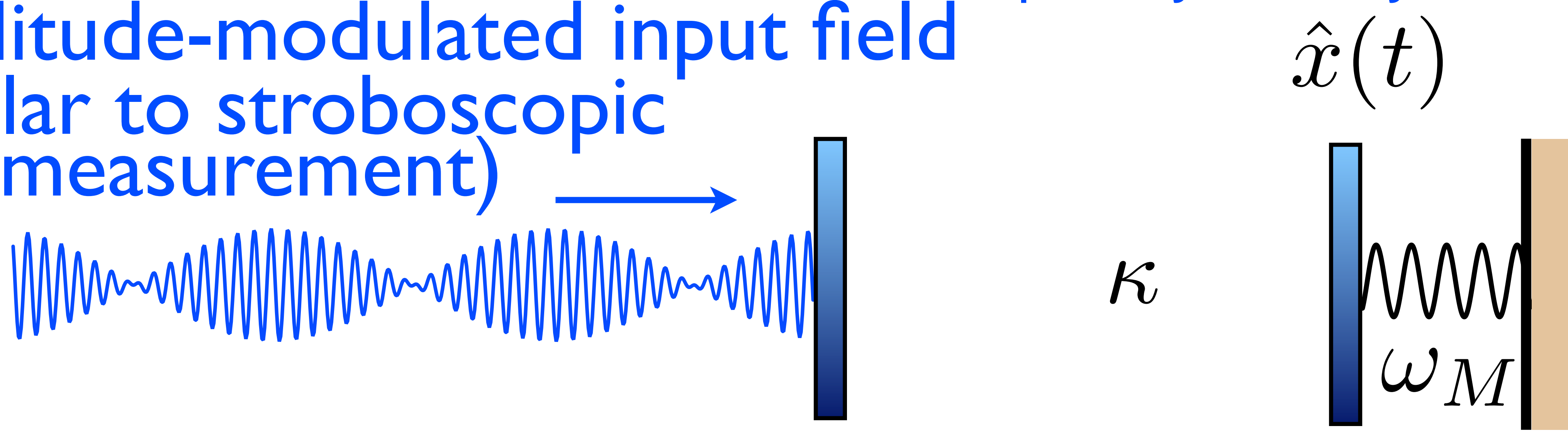

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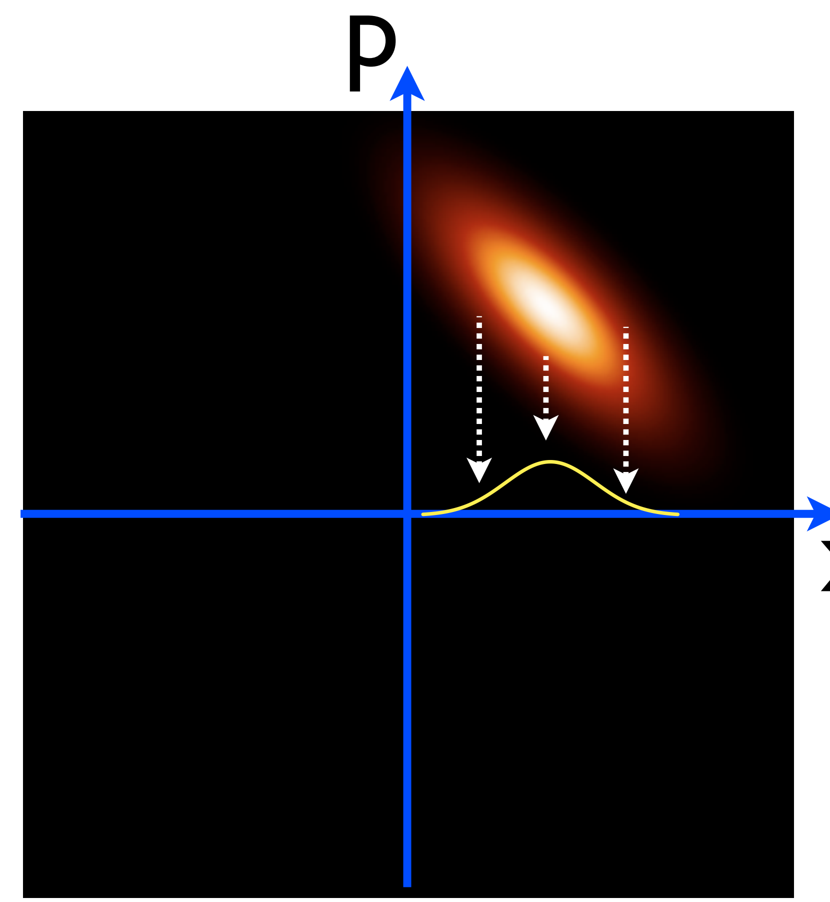

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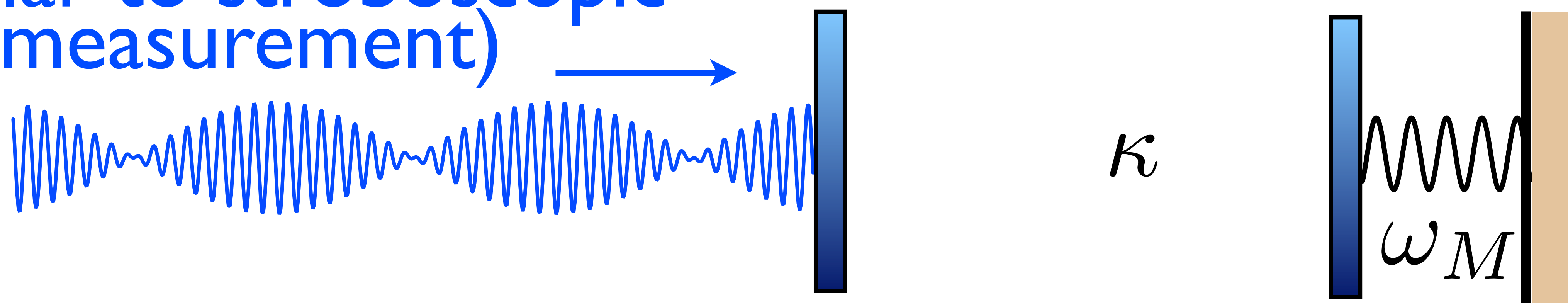

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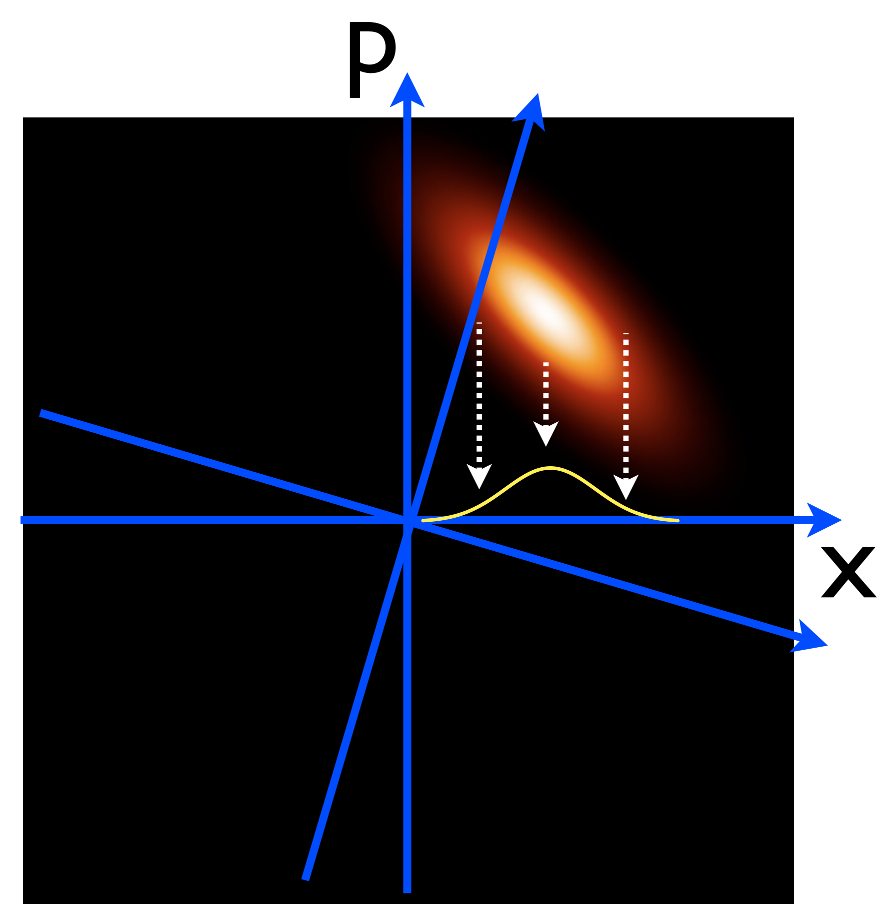
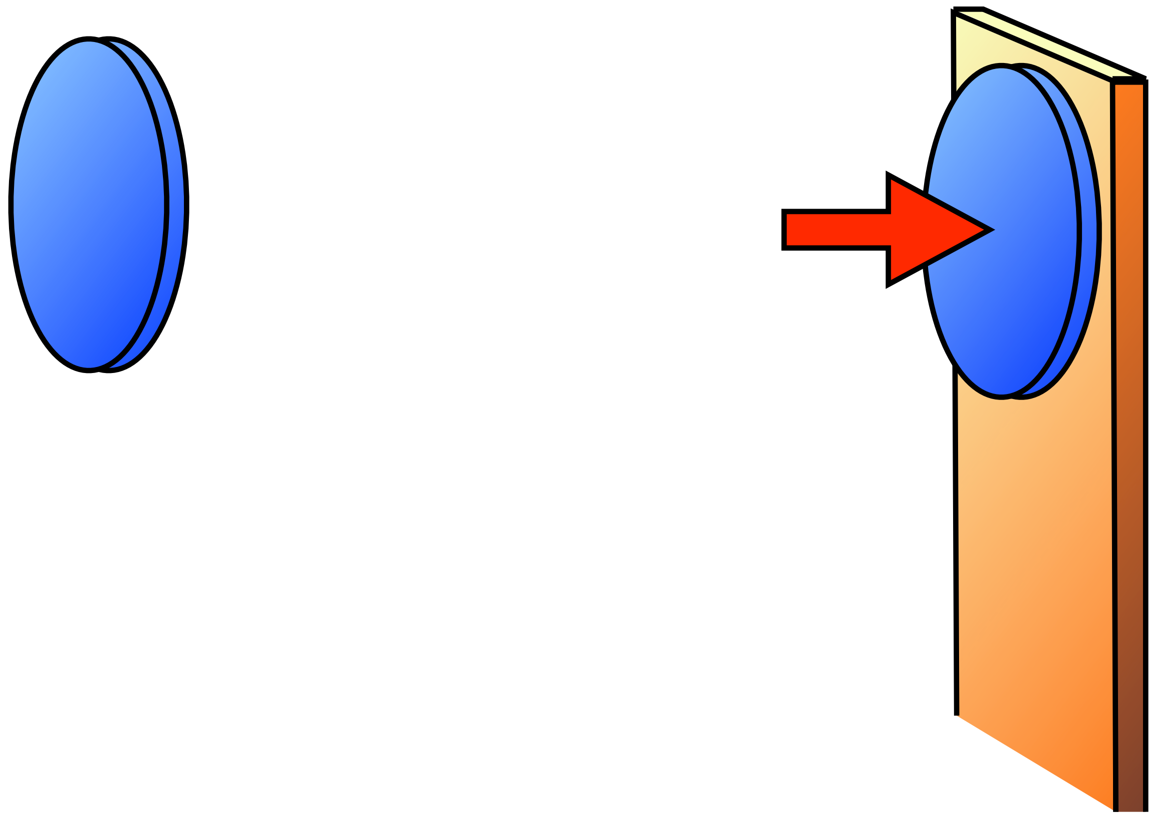
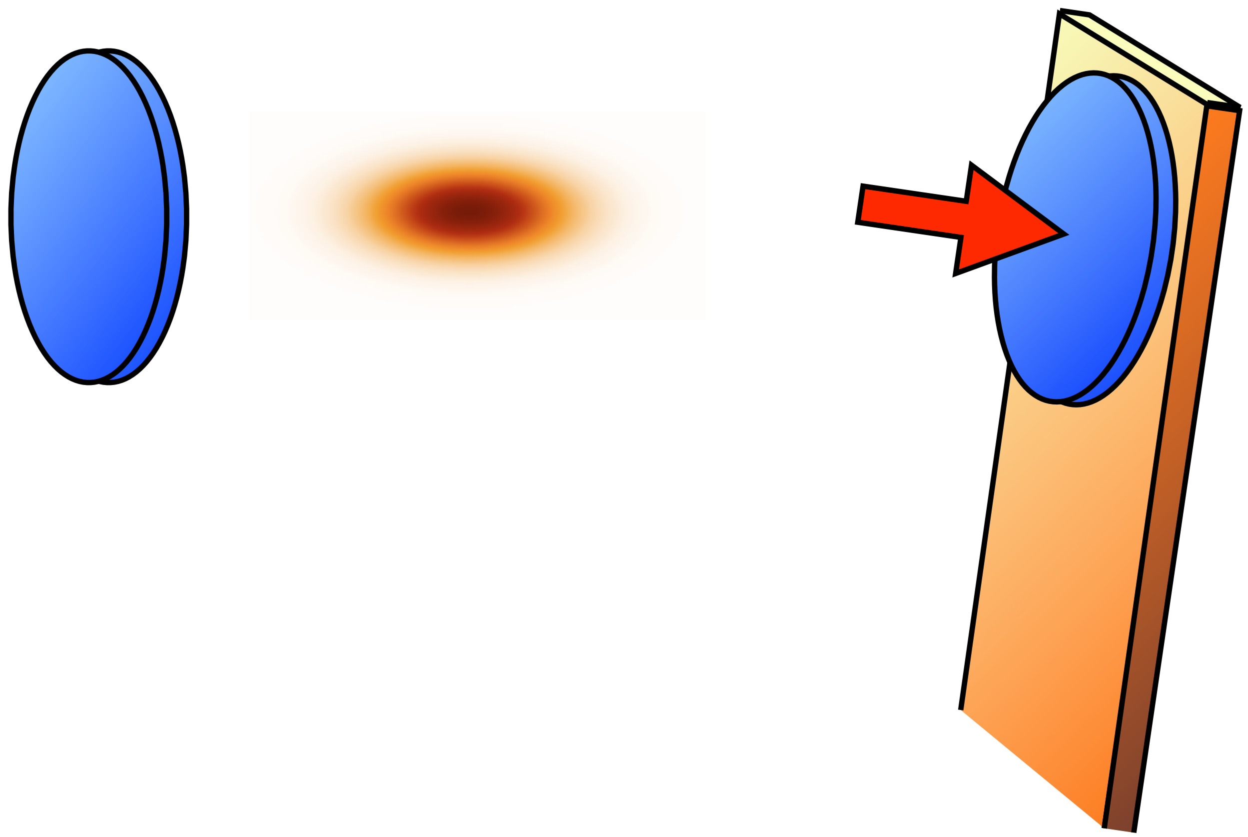


Optomechanical entanglement



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

Optomechanical entanglement



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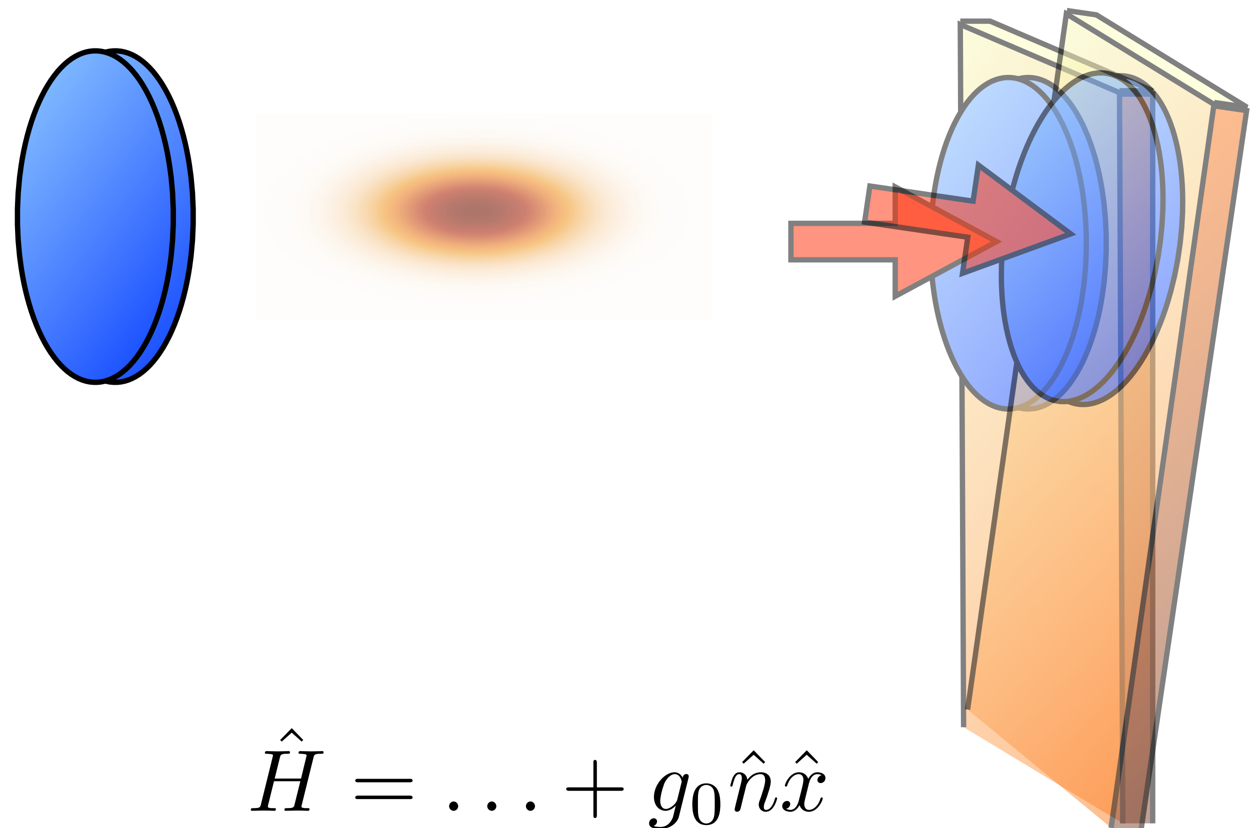
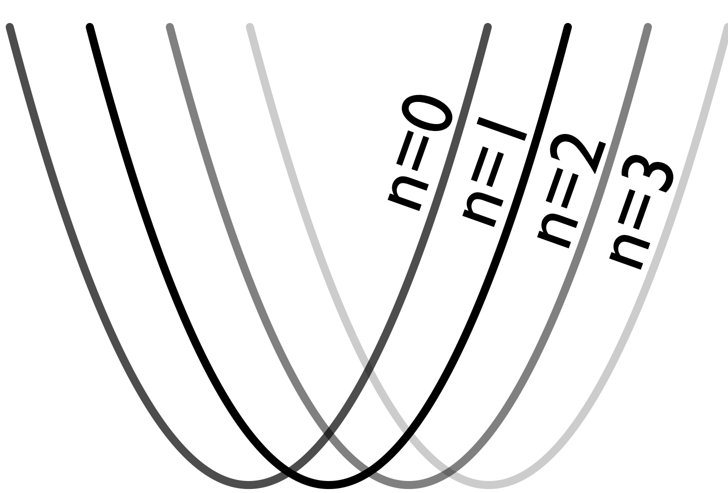


$$\hat{H} = \ldots + g_0 \hat{n} \hat{x}$$

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

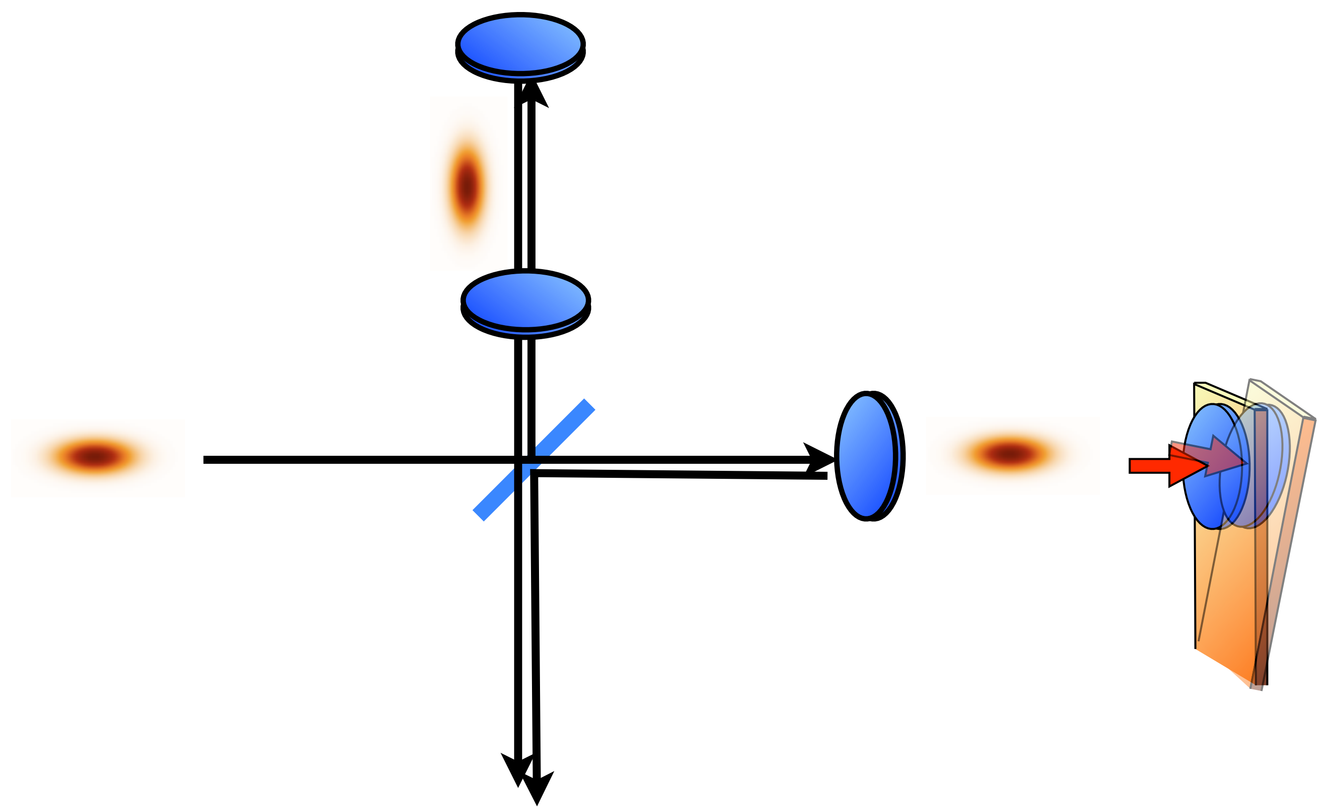
coherent mechanical state

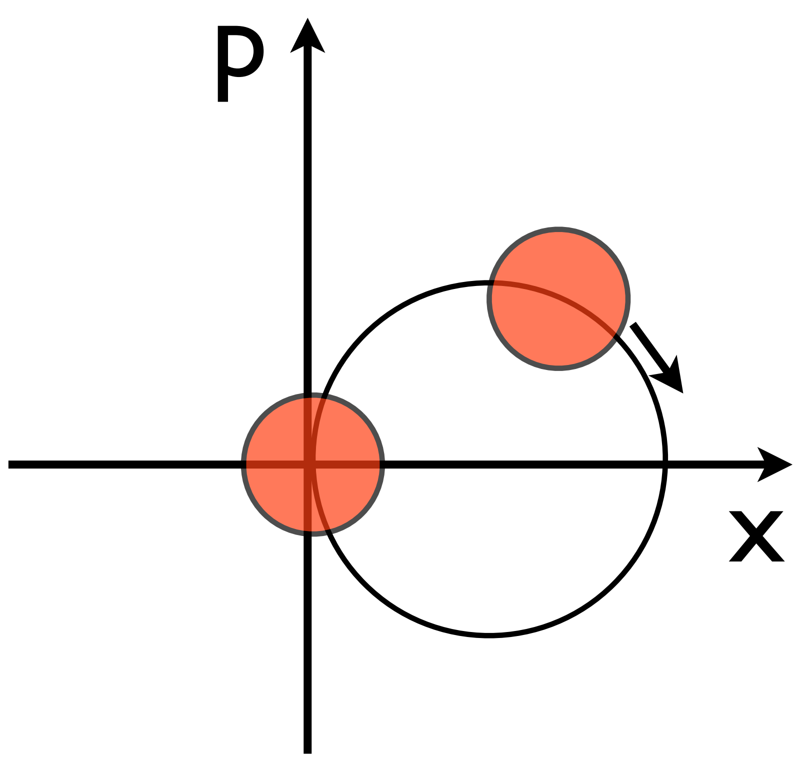
entangled state
(light field/mechanics)



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

Proposed optomechanical which-path experiment and quantum eraser



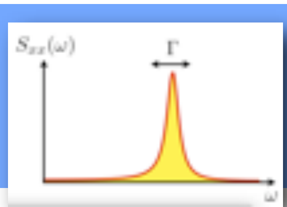


Recover photon coherence if interaction time equals a multiple of the mechanical period!

cf. Haroche experiments in 90s

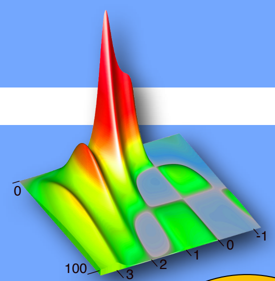
Marshall, Simon, Penrose, Bouwmeester, PRL **91**, 130401 (2003)

Optomechanics (Outline)

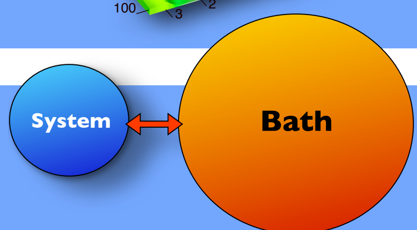


Displacement detection

Linear optomechanics



Nonlinear dynamics



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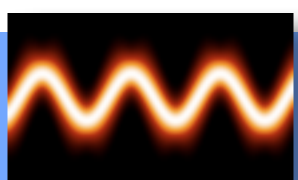
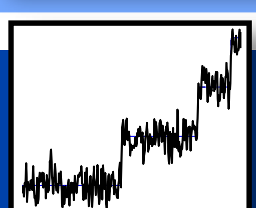


Interesting quantum states



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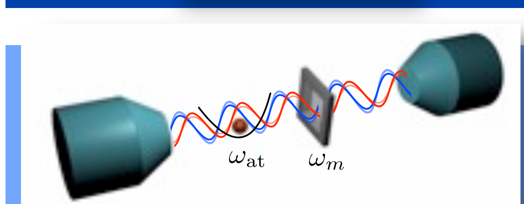
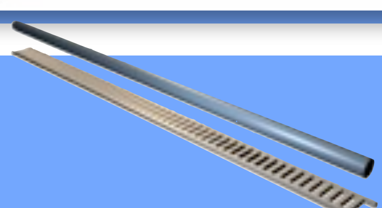


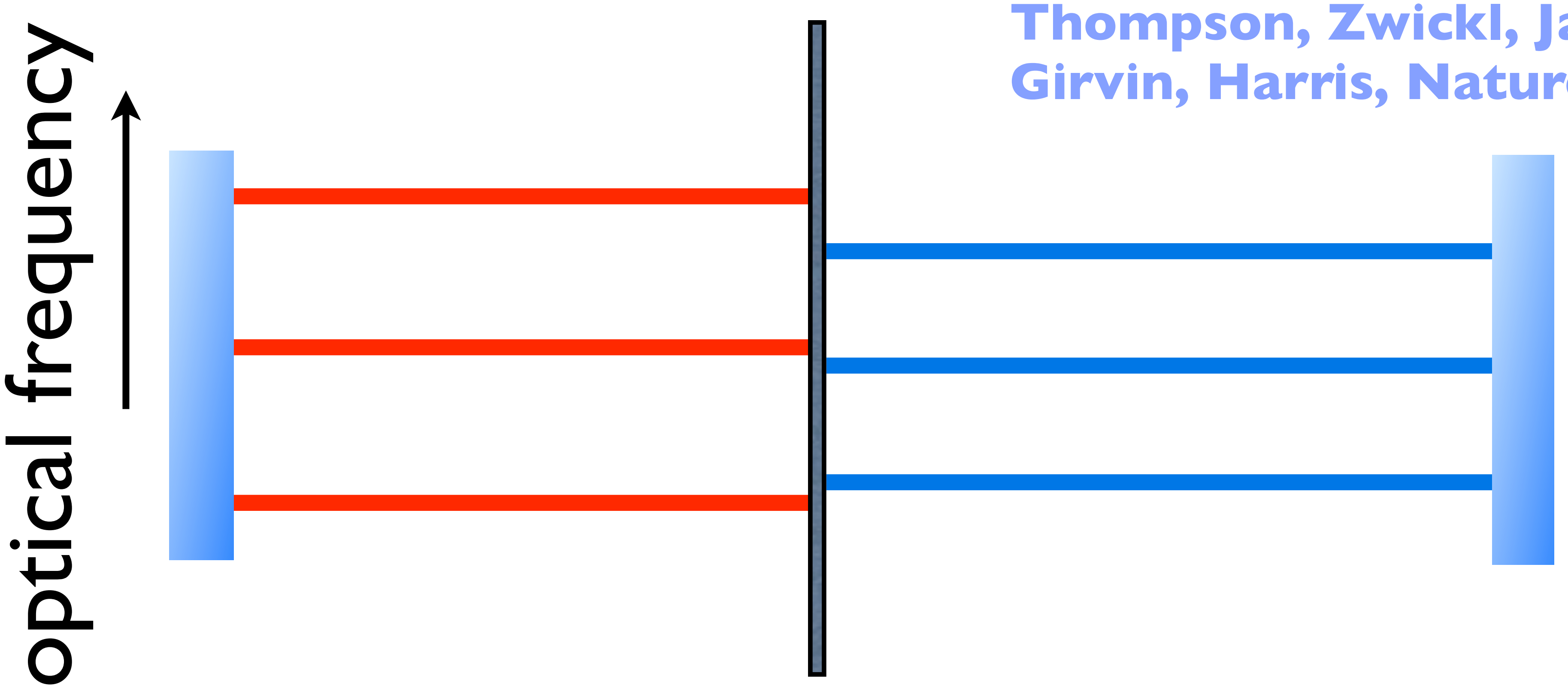
Hybrid systems: coupling to atoms



Optomechanical crystals & arrays

“Membrane in the middle” setup

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



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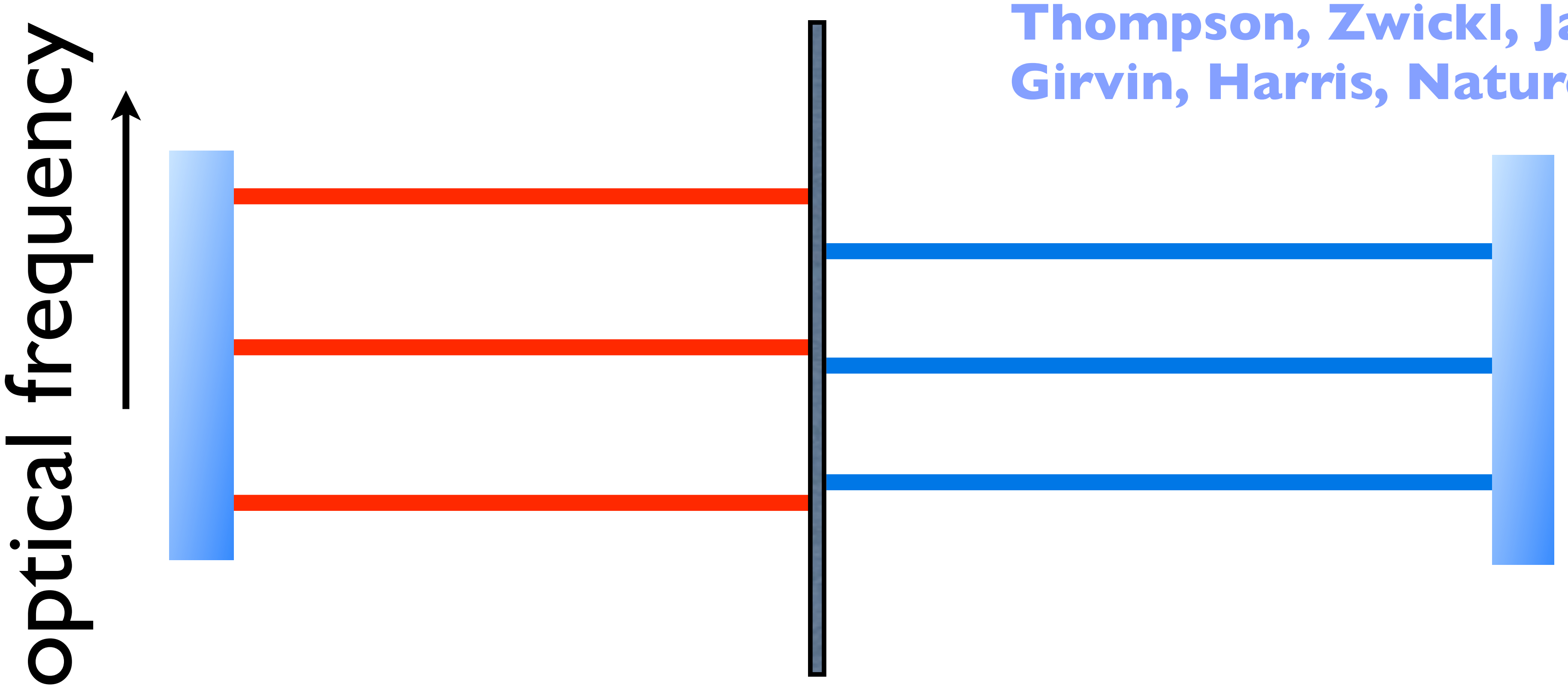
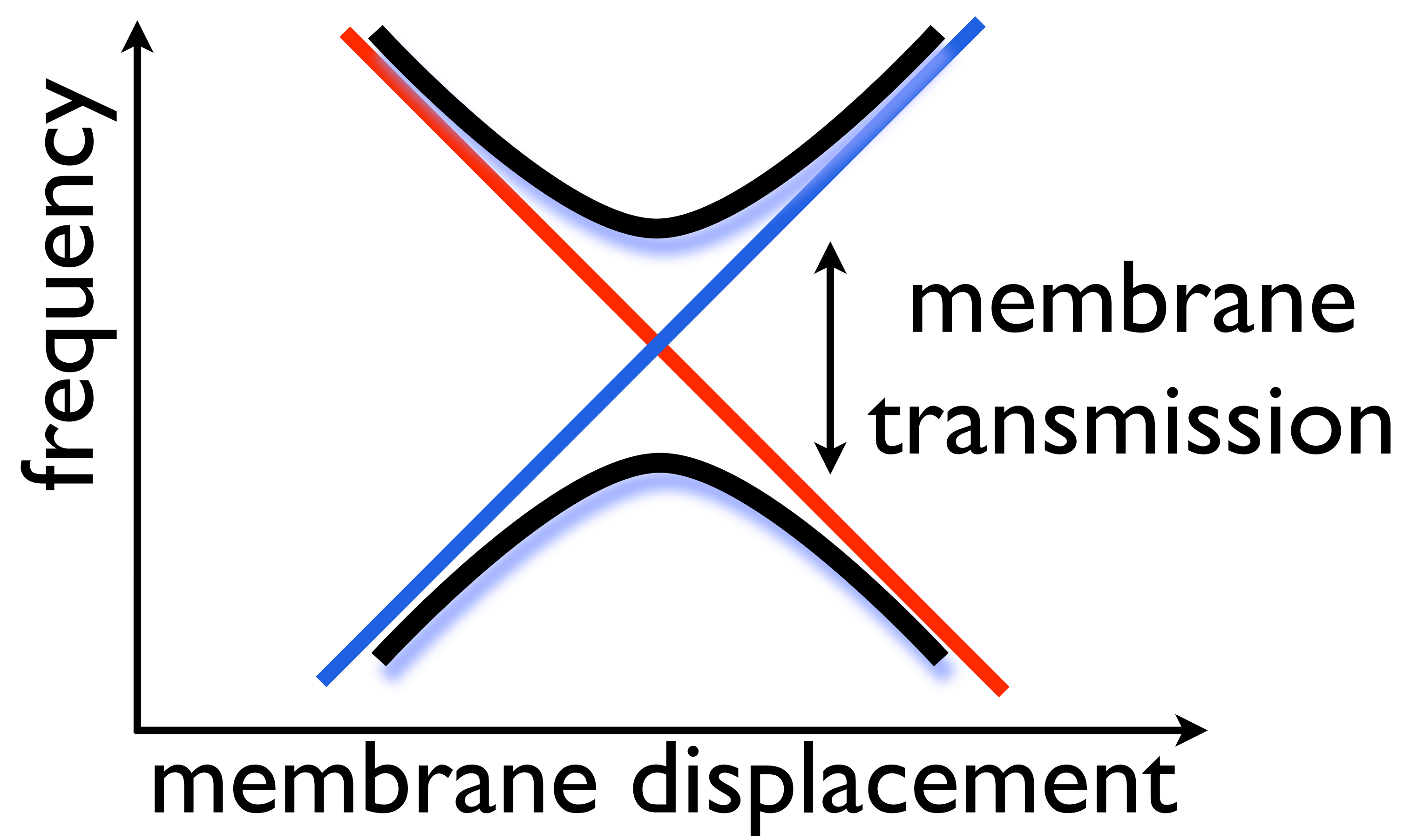
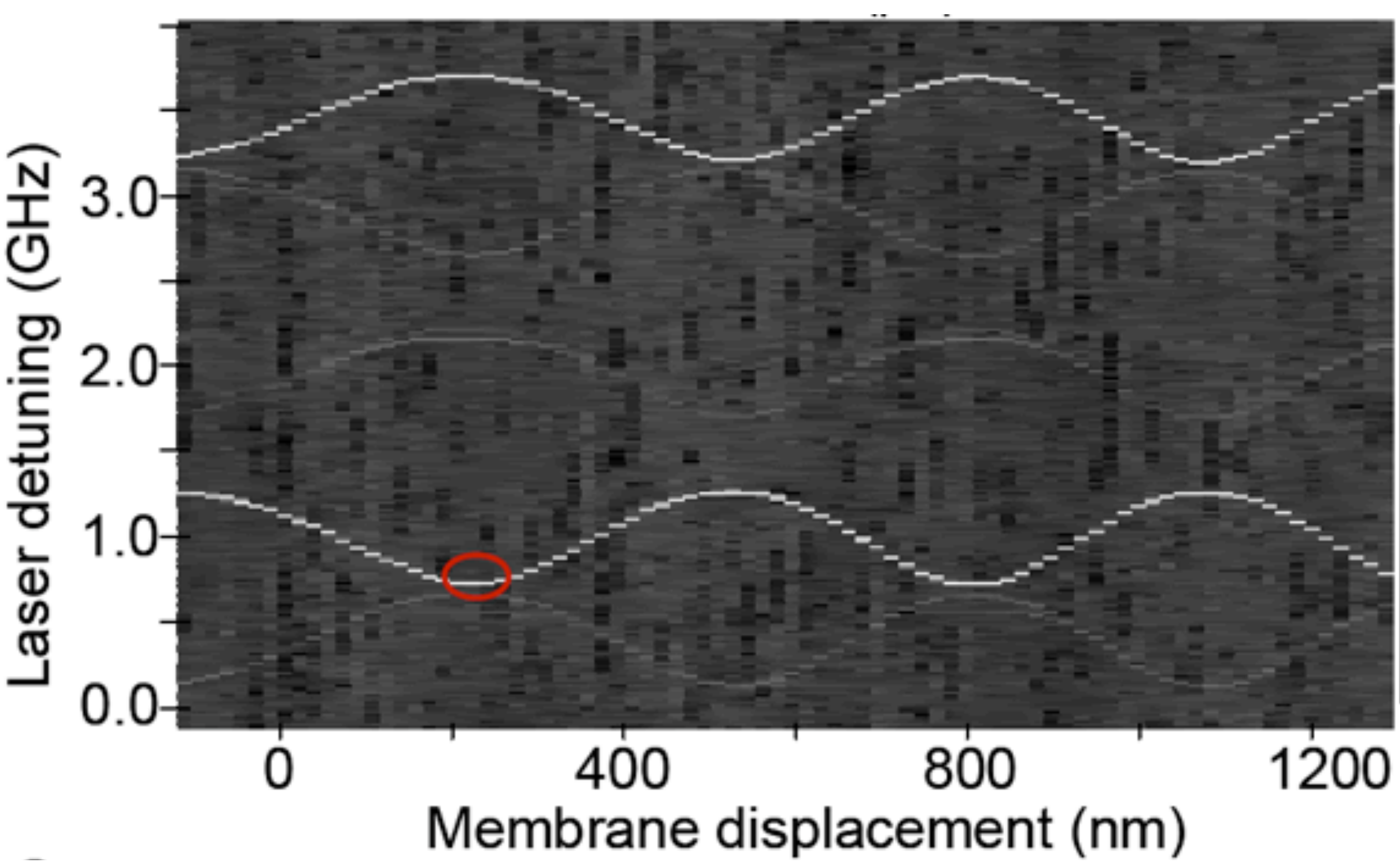




Experiment (Harris group, Yale)



Mechanical frequency:

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

Mechanical quality factor:

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

Optomechanical cooling from **300K** to **7mK**

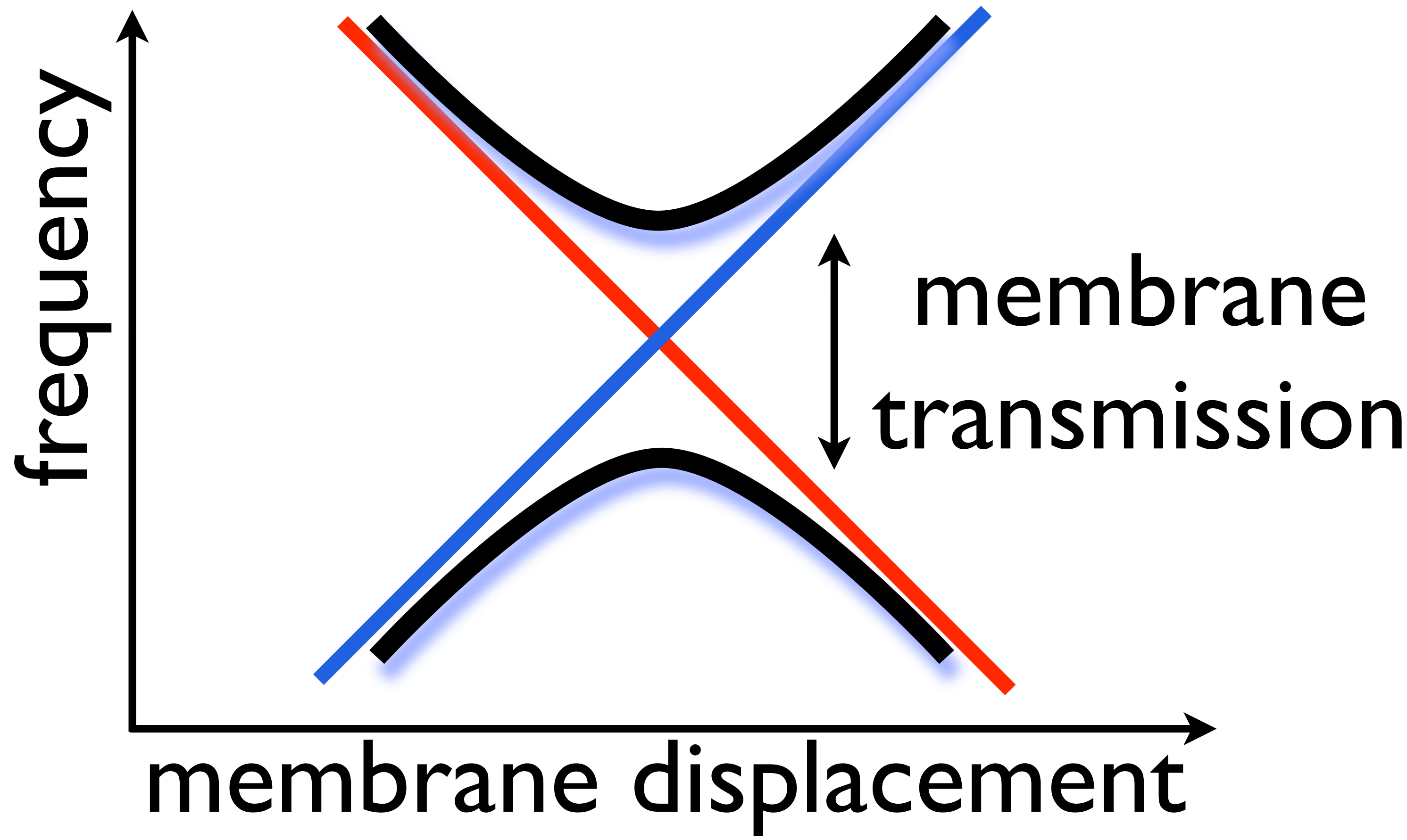
Thompson, Zwickl, Jayich, Marquardt, Girvin, Harris, Nature 72, 452 (2008)

Towards Fock state detection of a macroscopic object

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

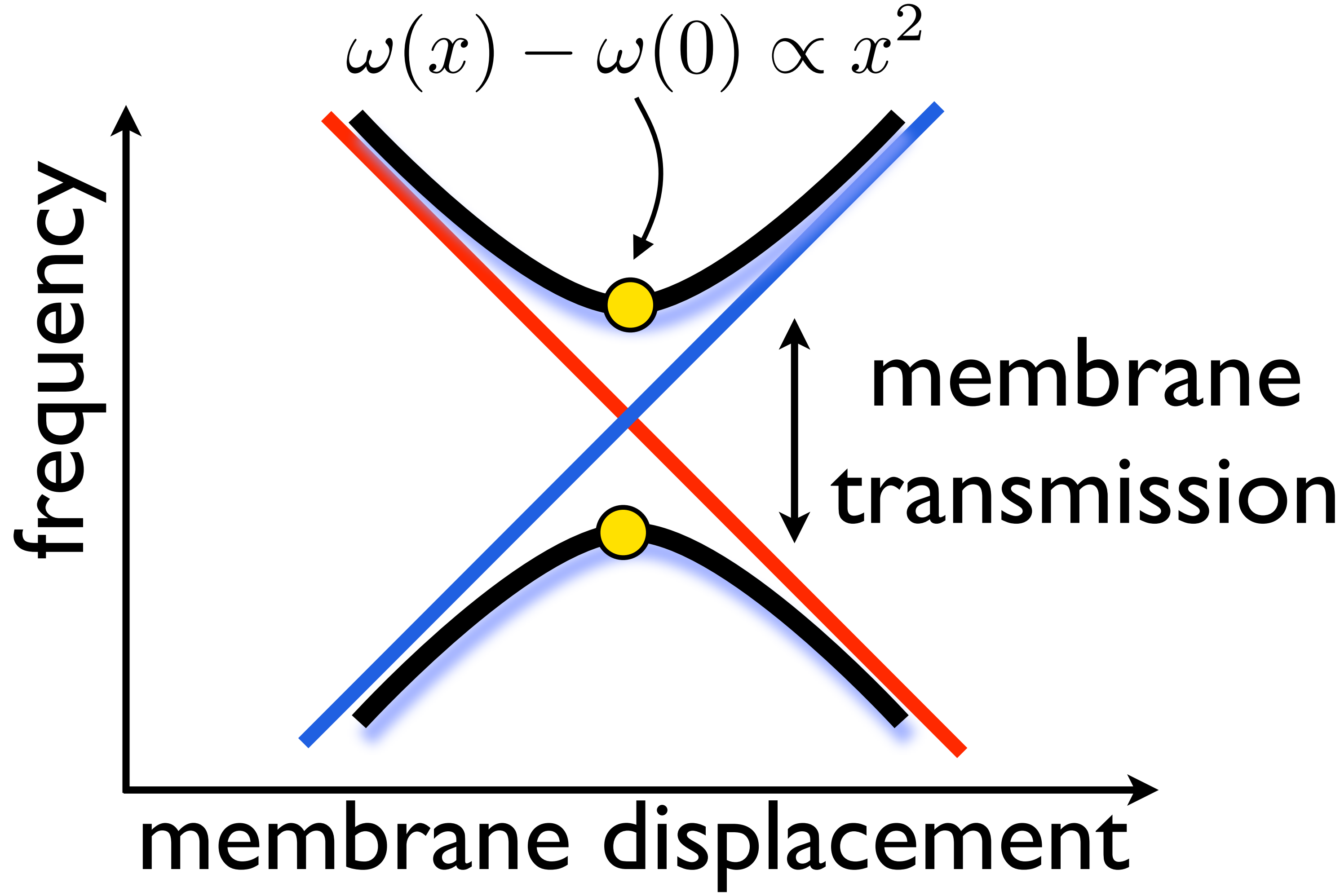
Towards Fock state detection of a macroscopic object

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

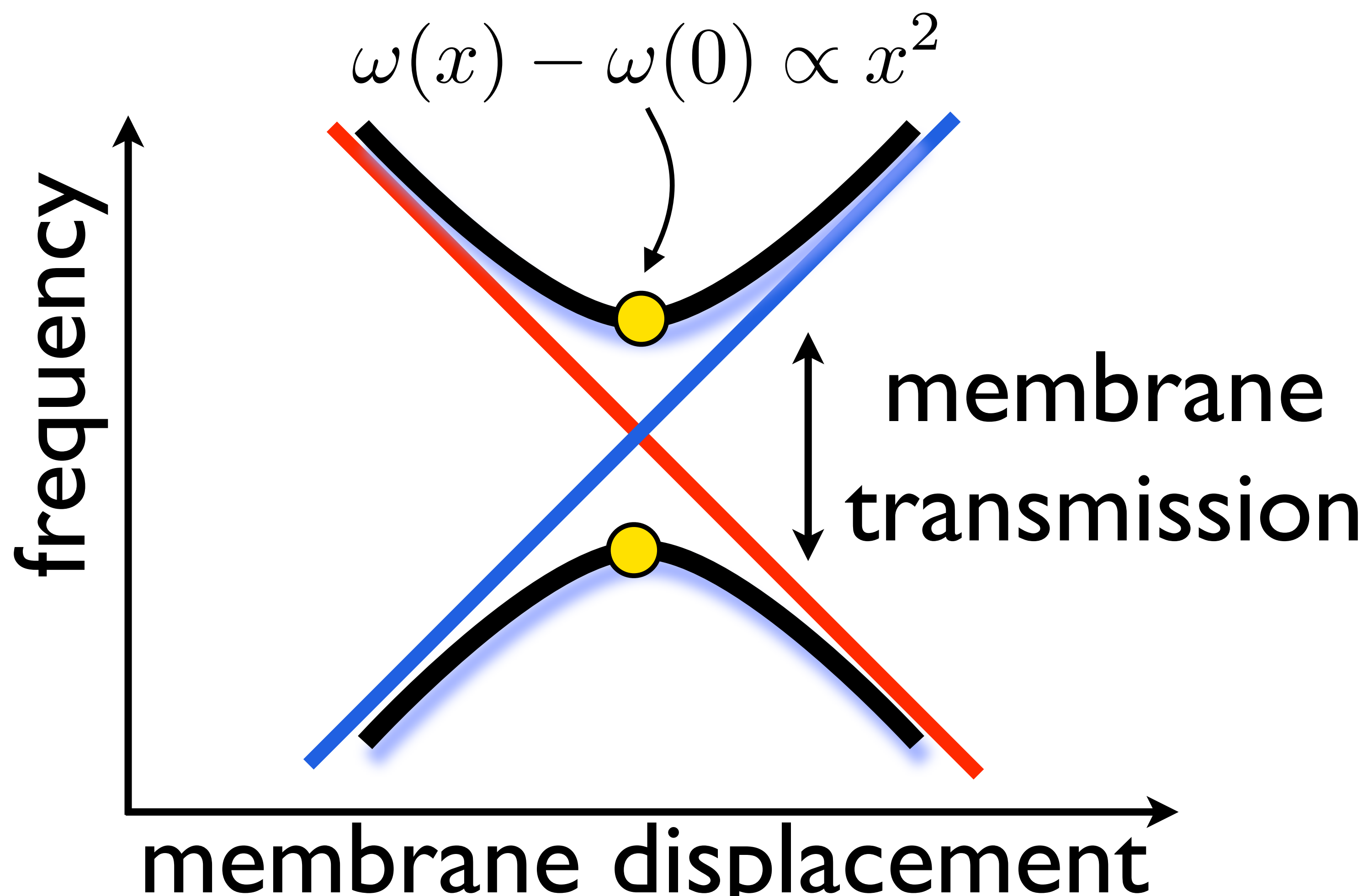


Towards Fock state detection of a macroscopic object

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



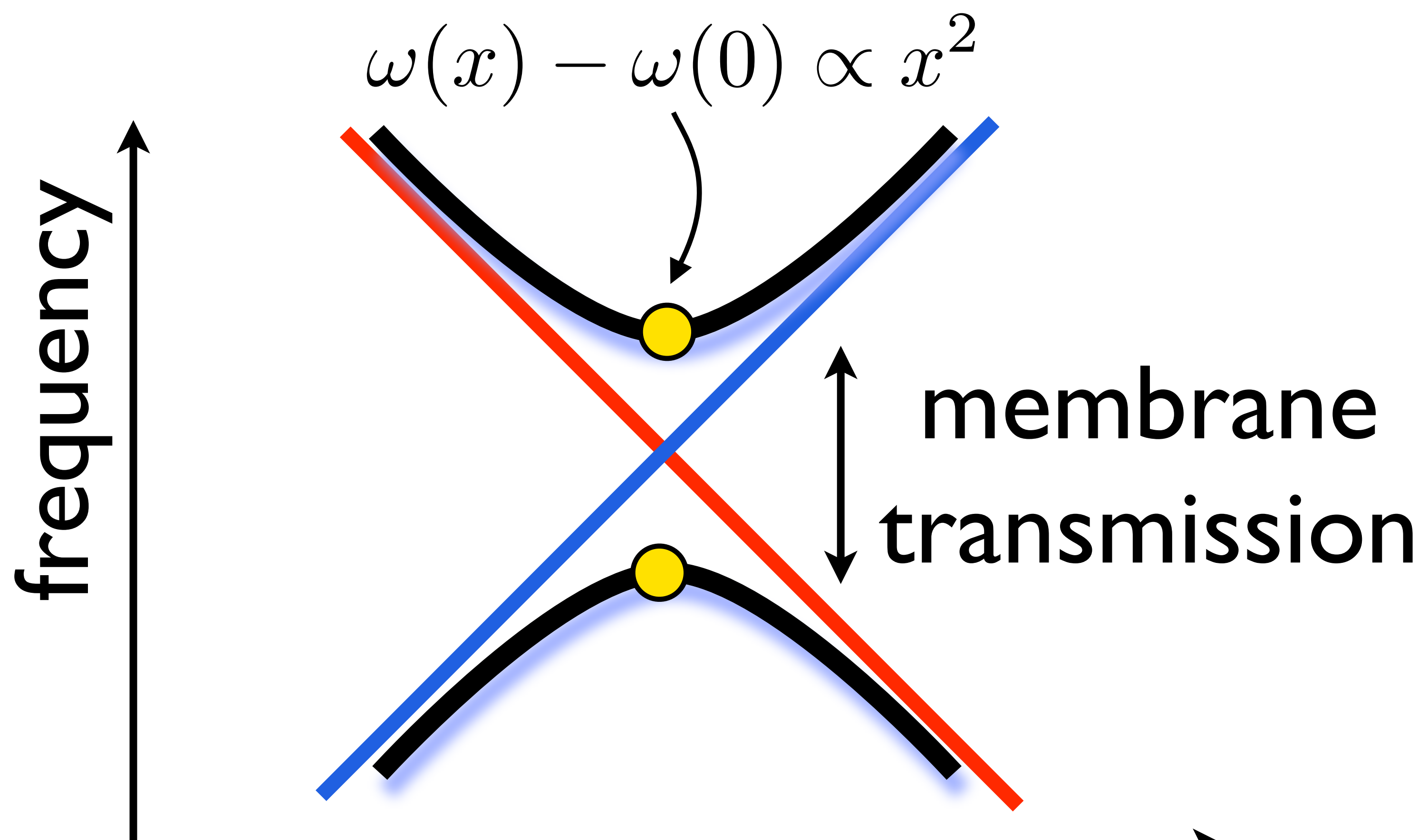
Towards Fock state detection of a macroscopic object



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



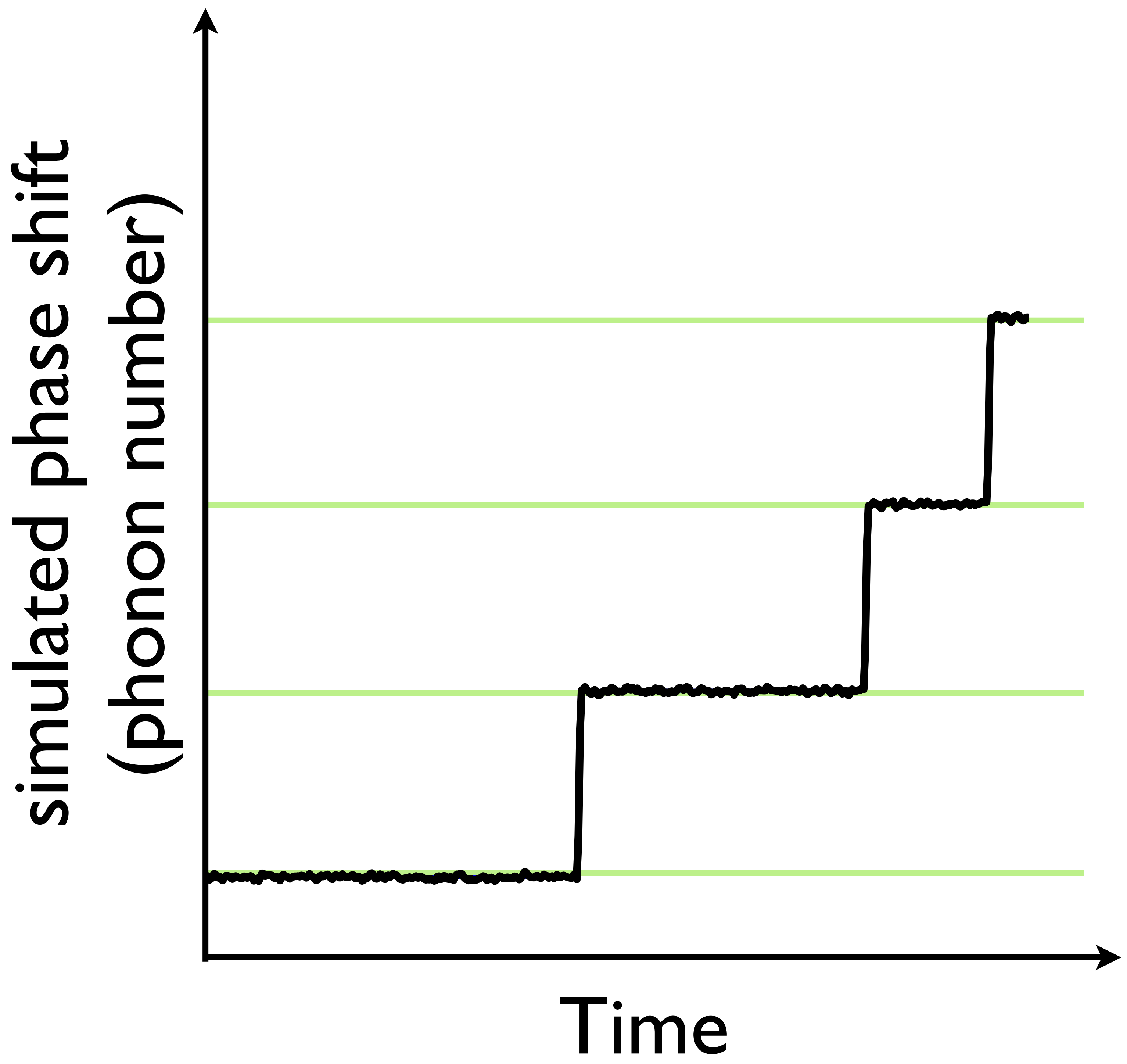
phase shift of measurement beam:

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

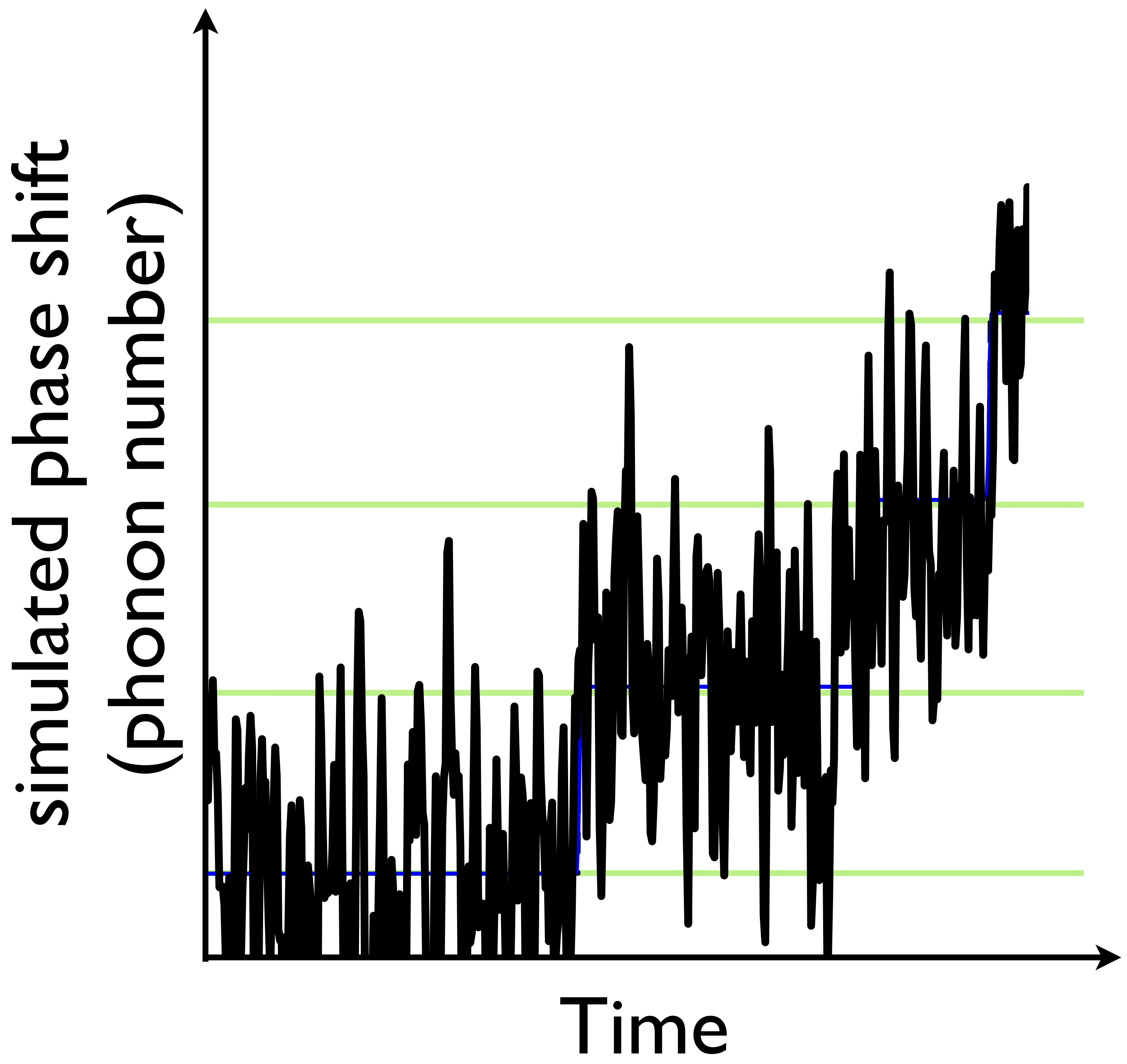
(Time-average over cavity ring-down time)

QND measurement of phonon number!

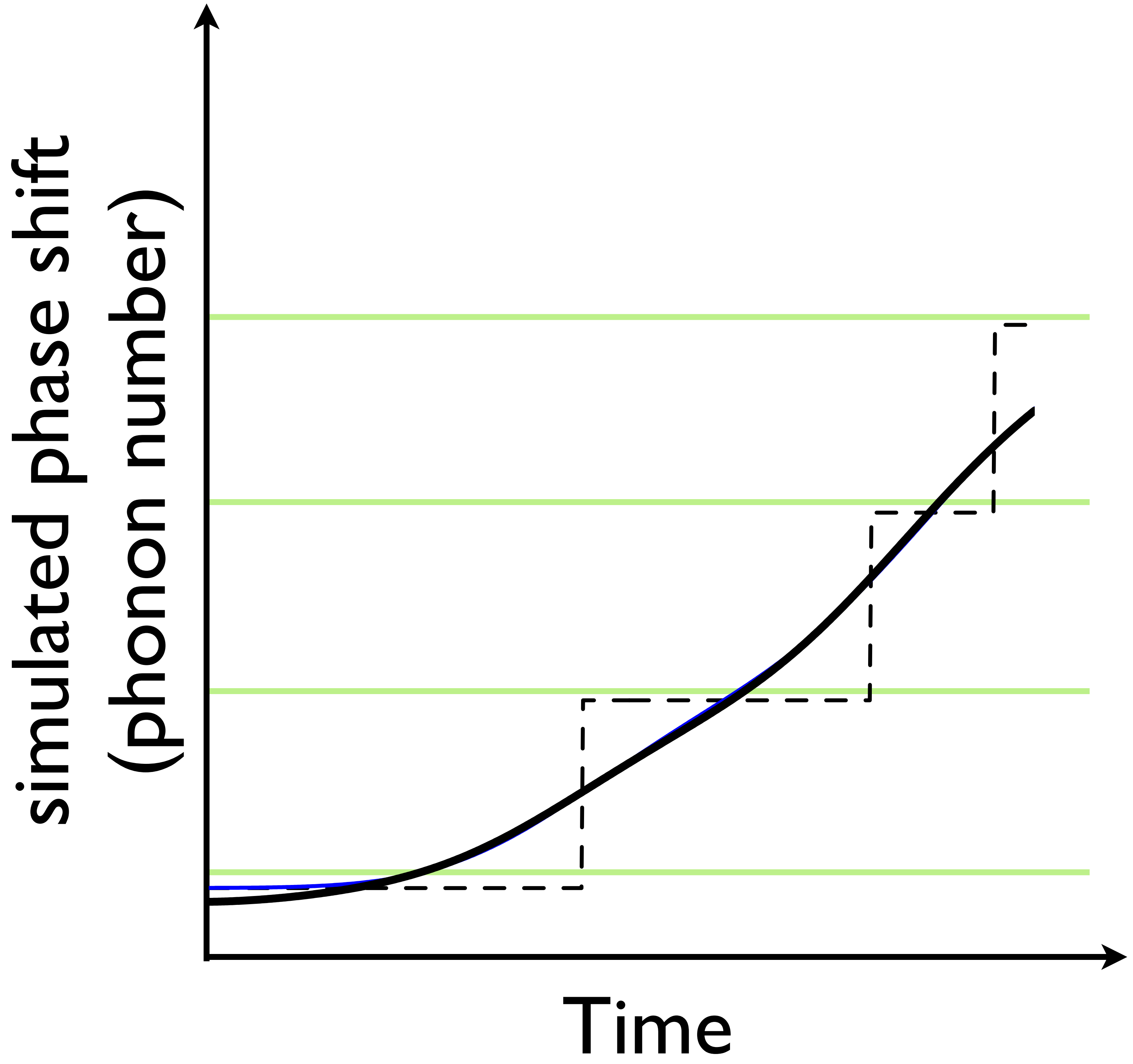
Towards Fock state detection of a macroscopic object



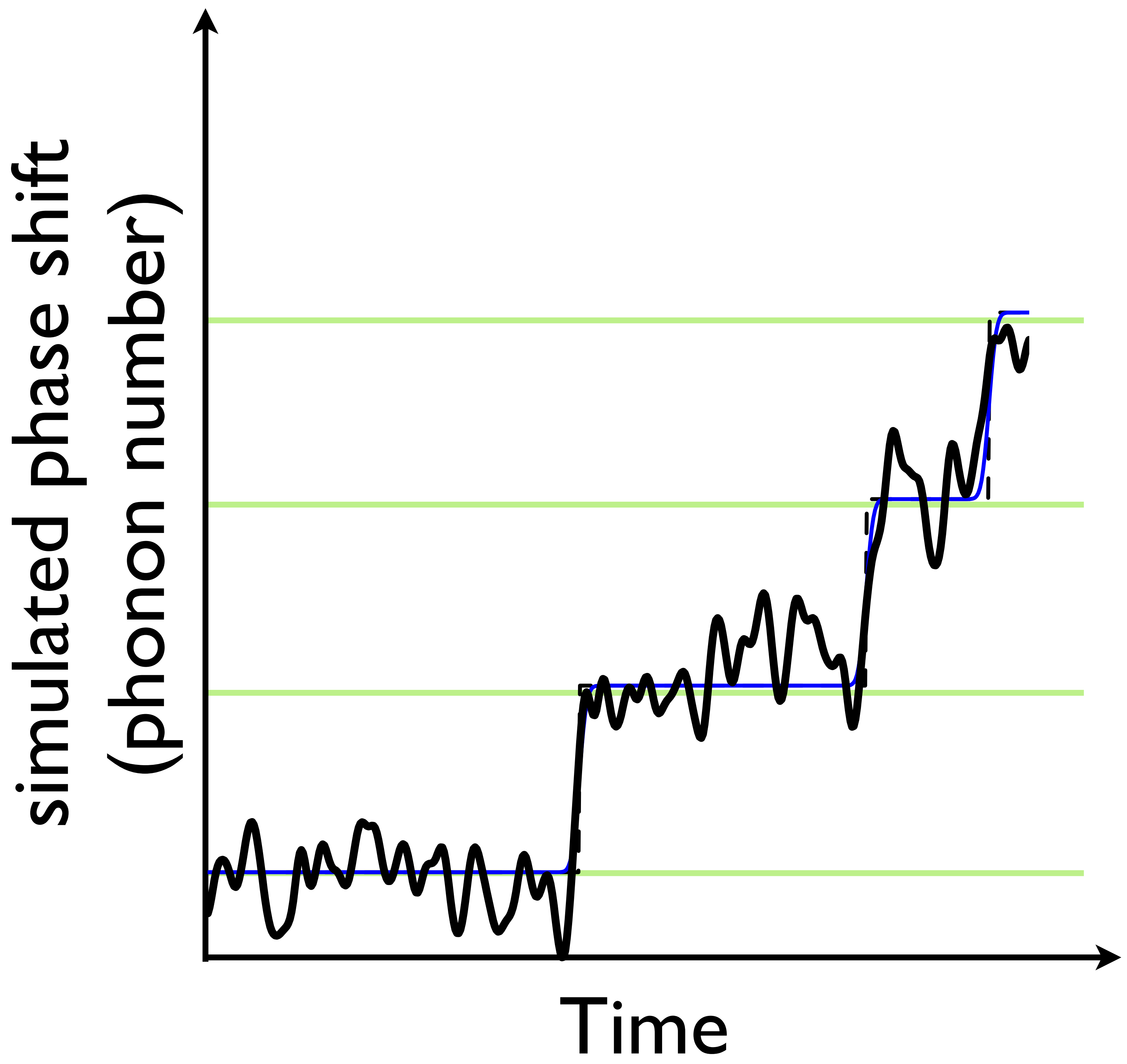
Towards Fock state detection of a macroscopic object



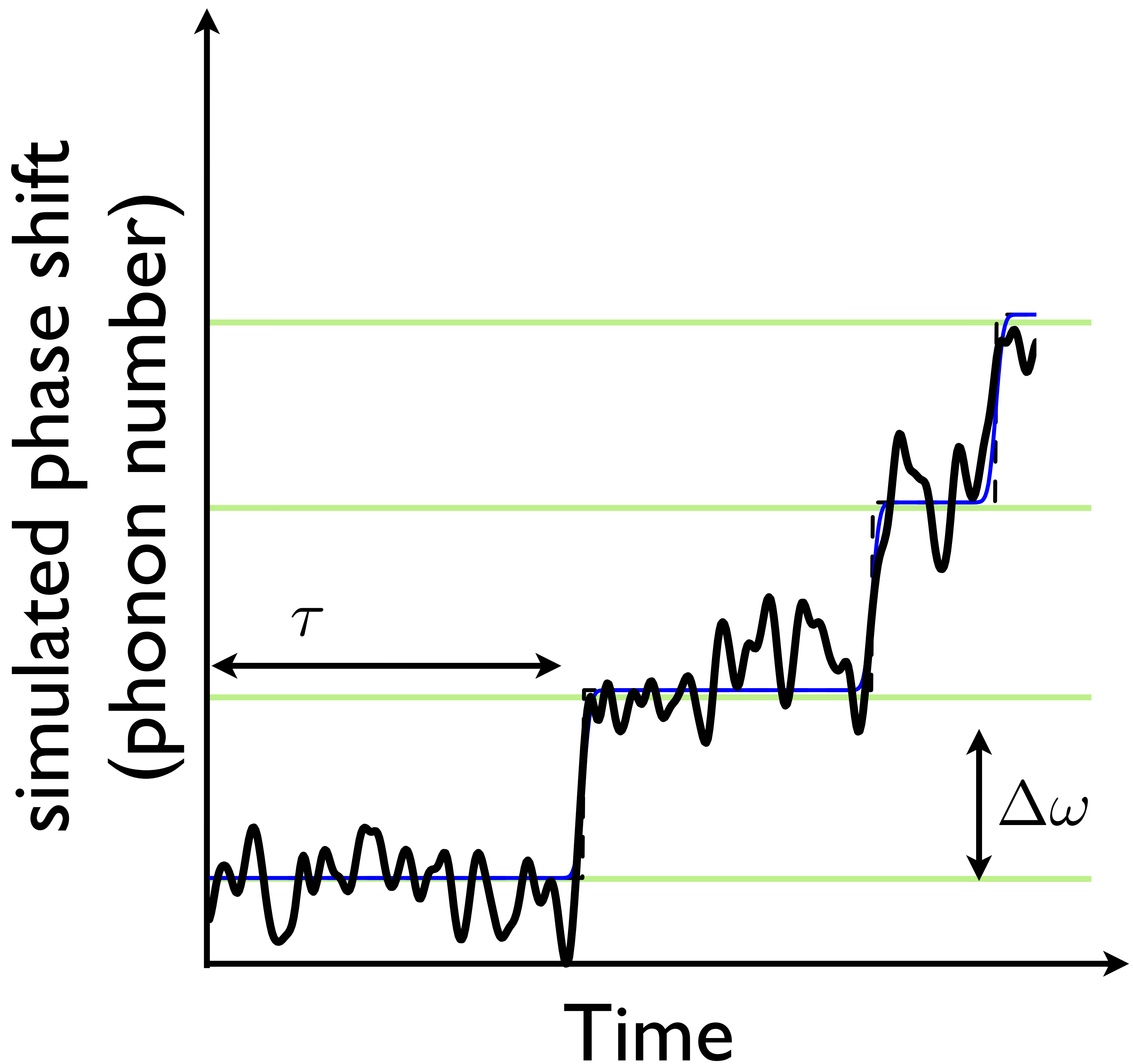
Towards Fock state detection of a macroscopic object



Towards Fock state detection of a macroscopic object



Towards Fock state detection of a macroscopic object



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

Optical freq. shift per phonon:

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

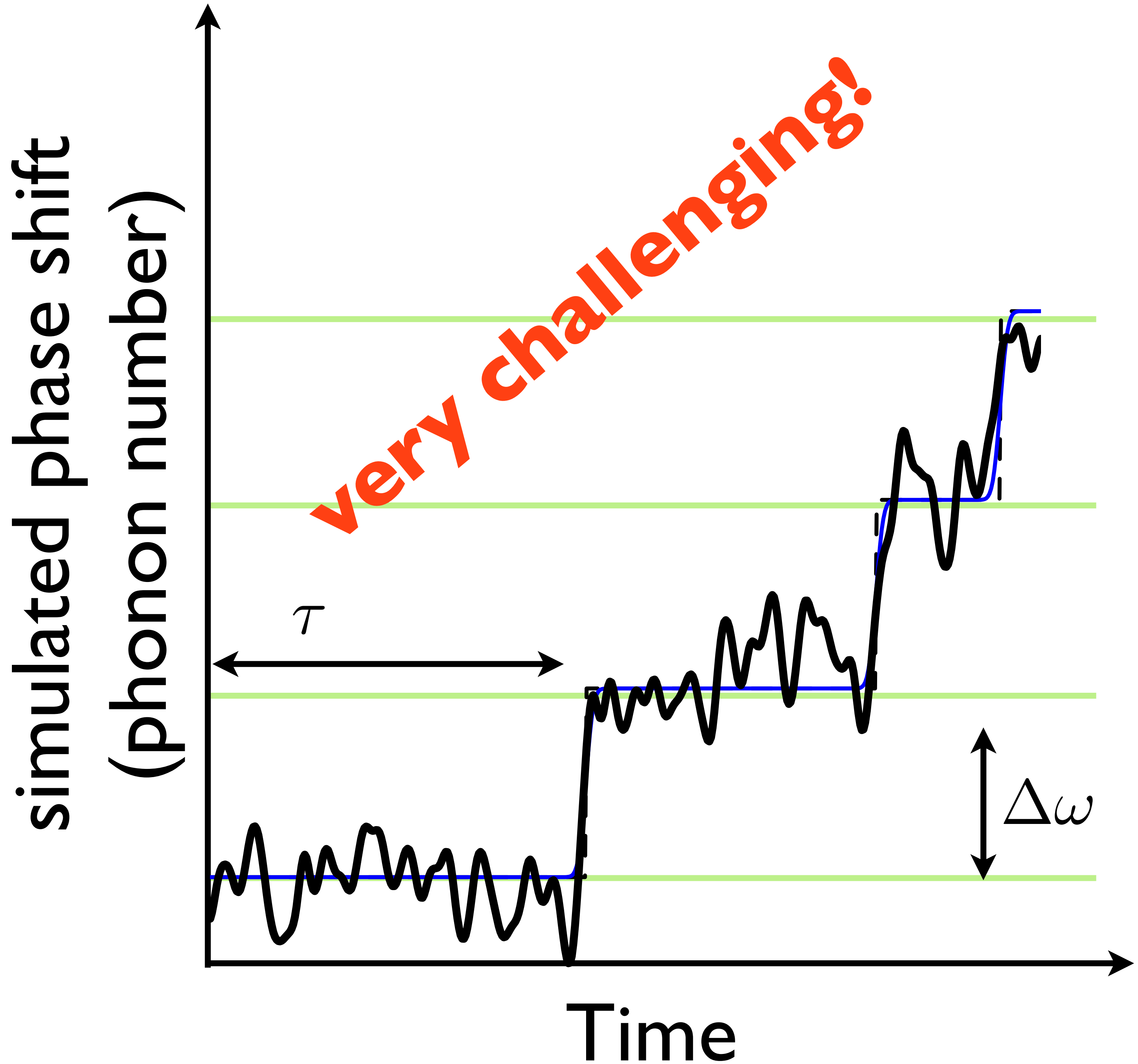
Noise power of freq. measurement:

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

Ground state lifetime:

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

Towards Fock state detection of a macroscopic object



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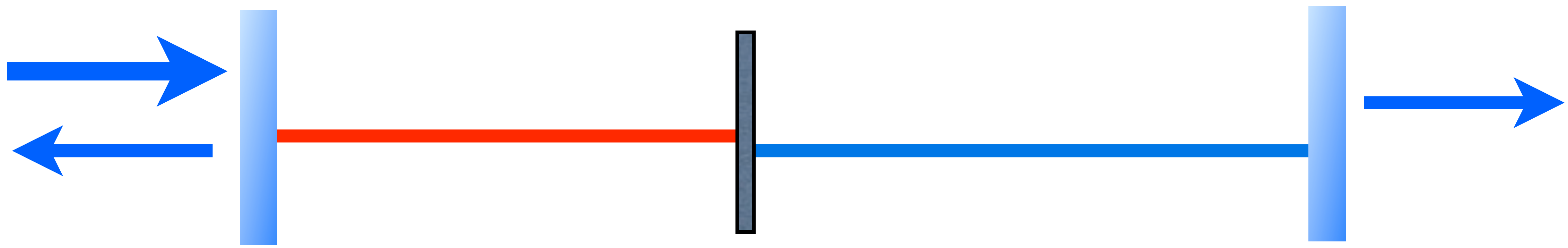
$$\frac{1}{\tau} = \Gamma \bar{n}_{\mathrm{thermal}}$$

Towards Fock state detection of a macroscopic object

Ideal single-sided cavity: Can observe **only** phase of reflected light, i.e. x^2: good

Two-sided cavity: Can **also** observe transmitted vs. reflected intensity: **linear** in x!



- need to go back to two-mode Hamiltonian!
- transitions between Fock states!

Single-sided cavity, but with losses: same story

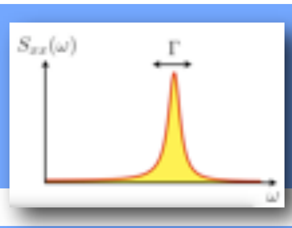
Detailed analysis (Yanbei Chen's group, PRL 2009) shows: need

$$g_0 > \kappa_{\mathrm{abs}}$$

absorptive part of photon decay (or 2nd mirror)

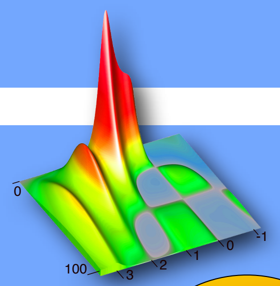
Miao, H., S. Danilishin, T. Corbitt, and Y. Chen, 2009, PRL 103, 100402

Optomechanics (Outline)

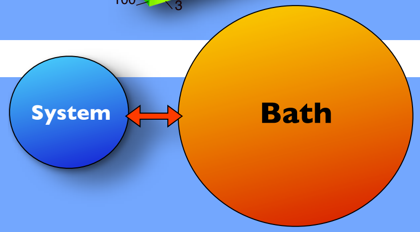


Displacement detection

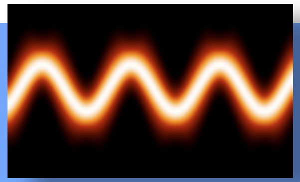
Linear optomechanics



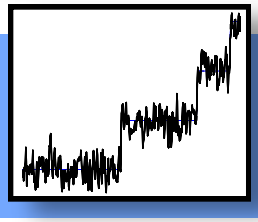
Nonlinear dynamics



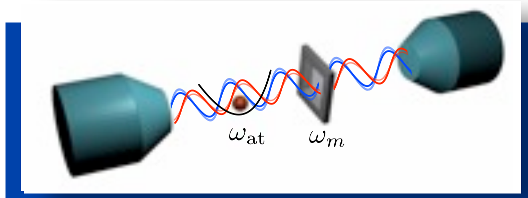
Quantum theory of cooling



Interesting quantum states



Towards Fock state detection



Hybrid systems: coupling to atoms

Optomechanical crystals & arrays

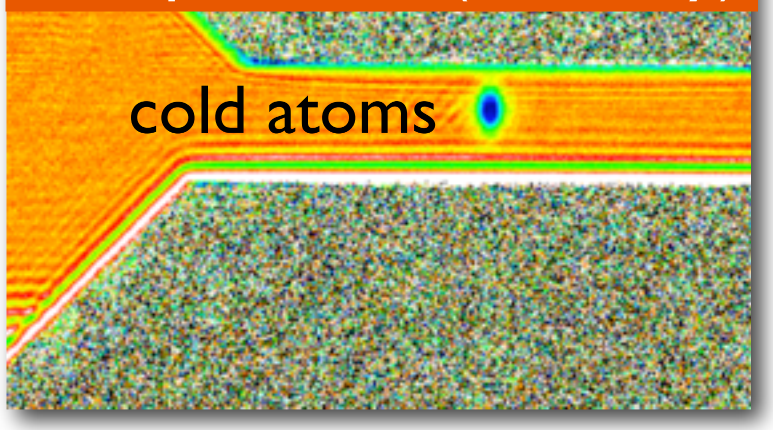
Atom-membrane coupling

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).

Stamper-Kurn (Berkeley)

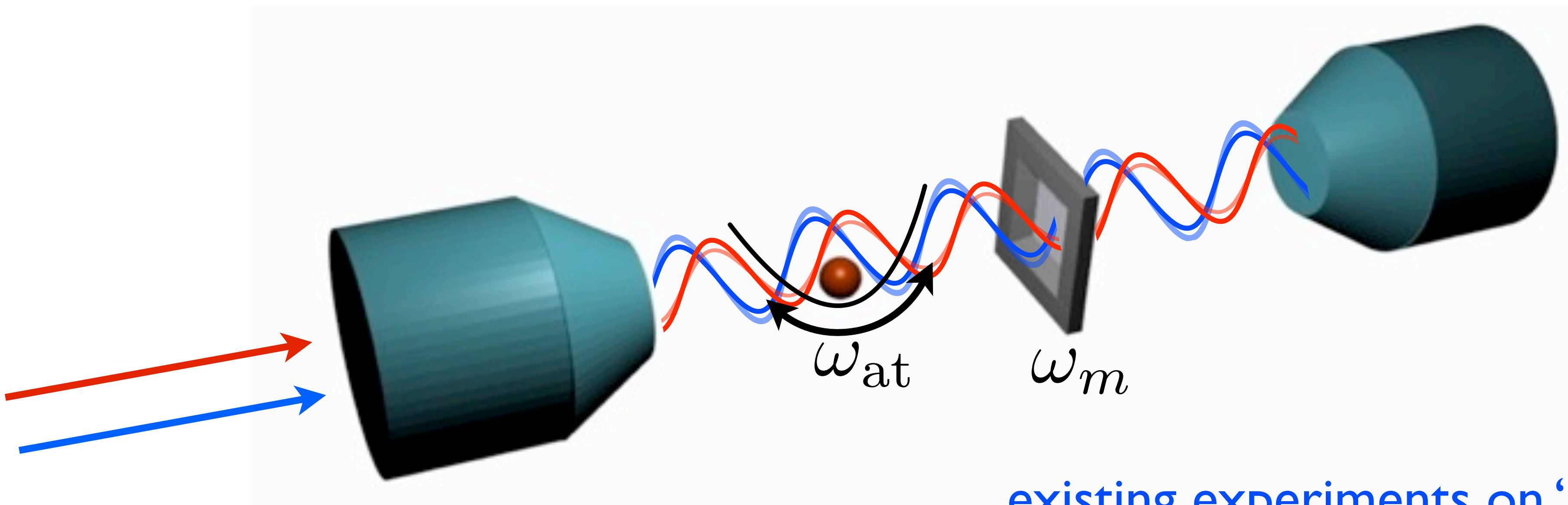


...profit from small mass of atomic cloud

Here: Coupling a single atom to a macroscopic mechanical object

Challenge: huge mass ratio

Strong atom-membrane coupling via the light field



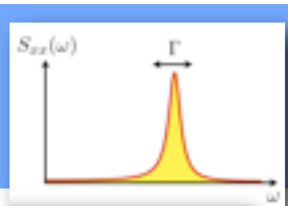
existing experiments on "optomechanics with cold atoms": labs of Dan-Stamper Kurn (Berkeley) and Tilman Esslinger (ETH)

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:

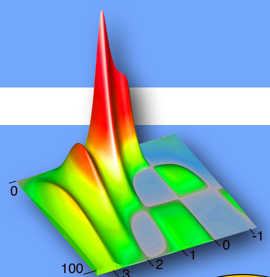
$$\hat{H} = \underbrace{\hbar\omega_{\rm at}\hat{a}^\dagger\hat{a}}_{\text{atom}} + \underbrace{\hbar\omega_m\hat{b}^\dagger\hat{b}}_{\text{membrane}} + \underbrace{\hbar G_{\rm eff}(\hat{a}^\dagger + \hat{a})(\hat{b}^\dagger + \hat{b})}_{\text{atom-membrane coupling}}$$

Optomechanics (Outline)

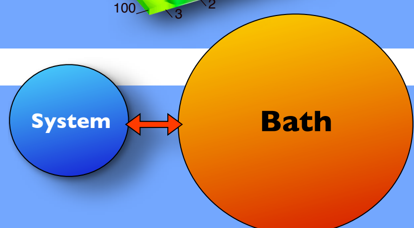


Displacement detection

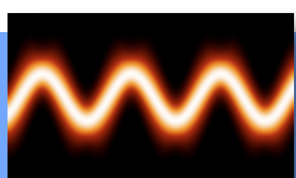
Linear optomechanics



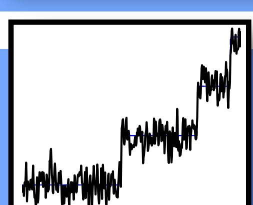
Nonlinear dynamics



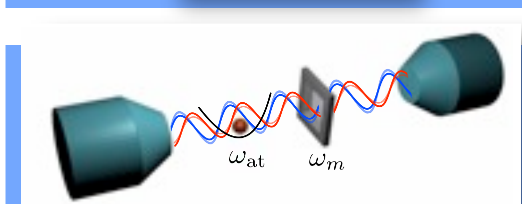
Quantum theory of cooling



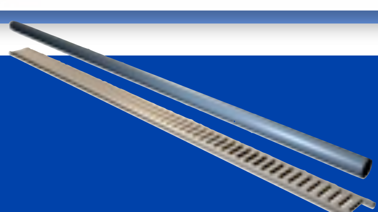
Interesting quantum states



Towards Fock state detection

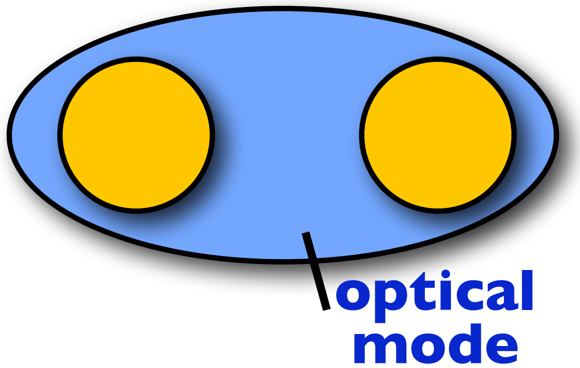


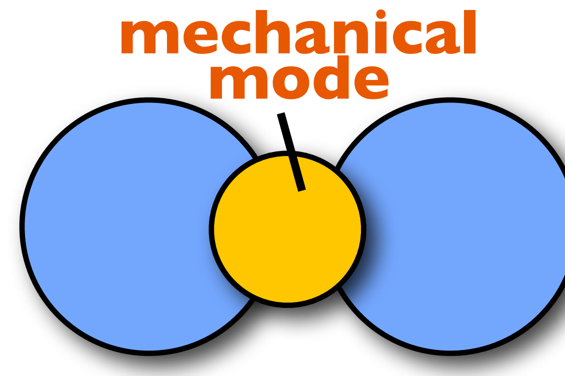
Hybrid systems: coupling to atoms

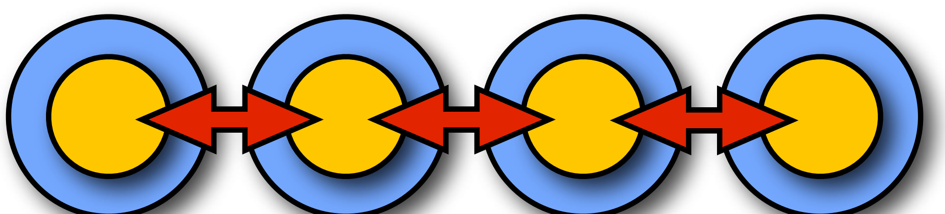


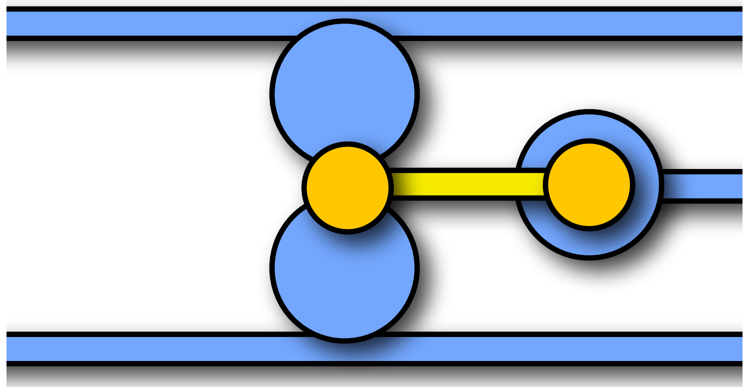
Optomechanical crystals & arrays

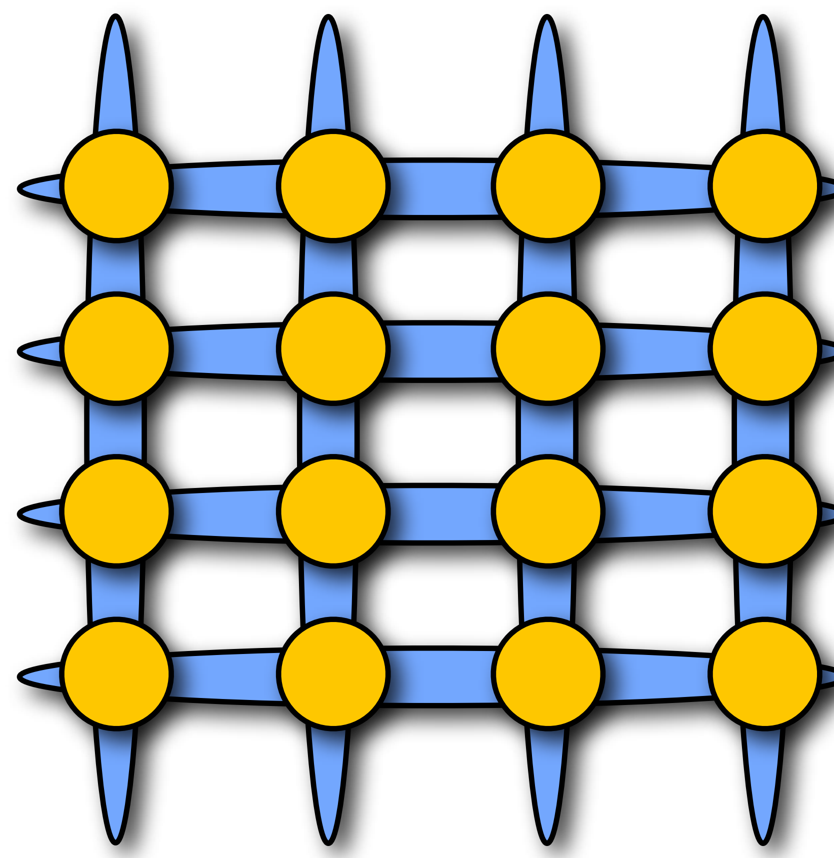
Many modes











Scaling down

cm

usual optical cavities

10 µm

LKB, Aspelmeyer, Harris, Bouwmeester, ...

Scaling down

cm

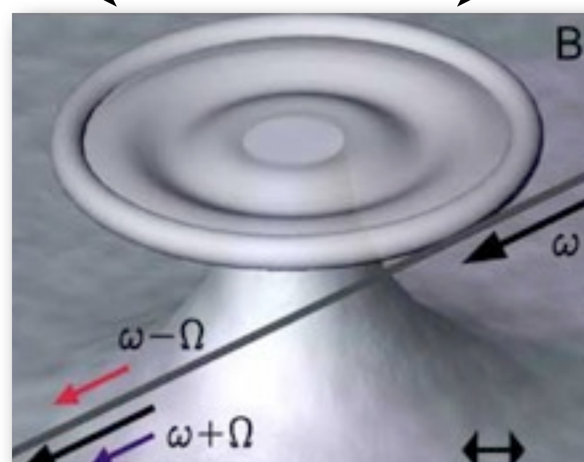
usual optical cavities

10 μm

LKB, Aspelmeyer, Harris, Bouwmeester, ...

50 μm

microtoroids



Vahala, Kippenberg, Carmon, ...

Scaling down

cm

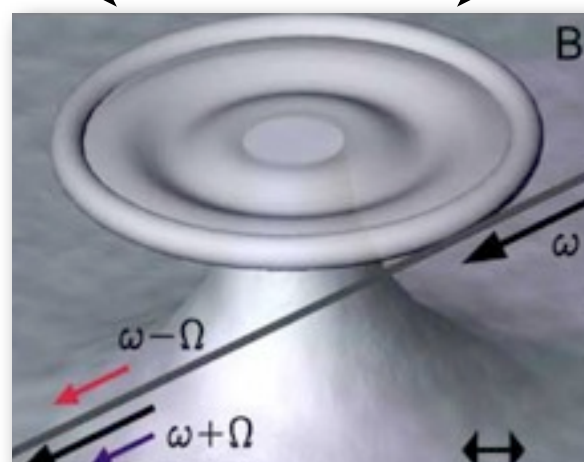
usual optical cavities

10 μm

LKB, Aspelmeyer, Harris, Bouwmeester, ...

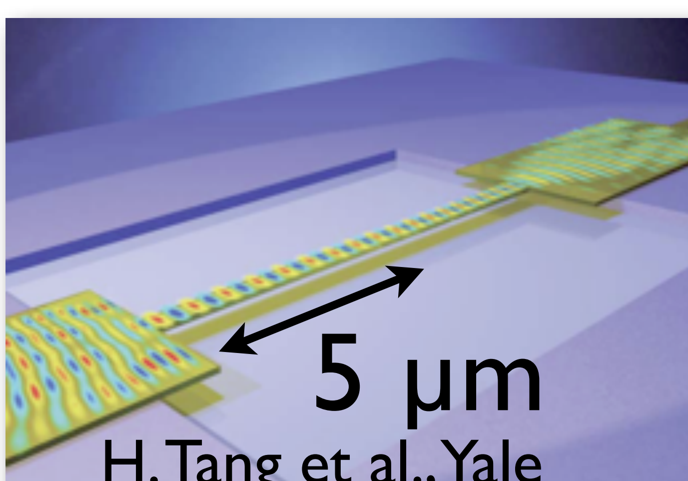
50 μm

microtoroids



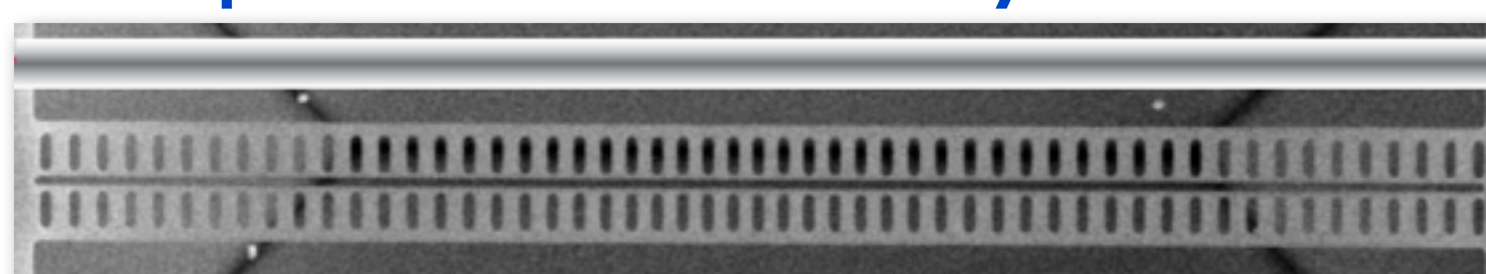
Vahala, Kippenberg, Carmon, ...

optomechanics in photonic circuits



H. Tang et al., Yale

optomechanical crystals



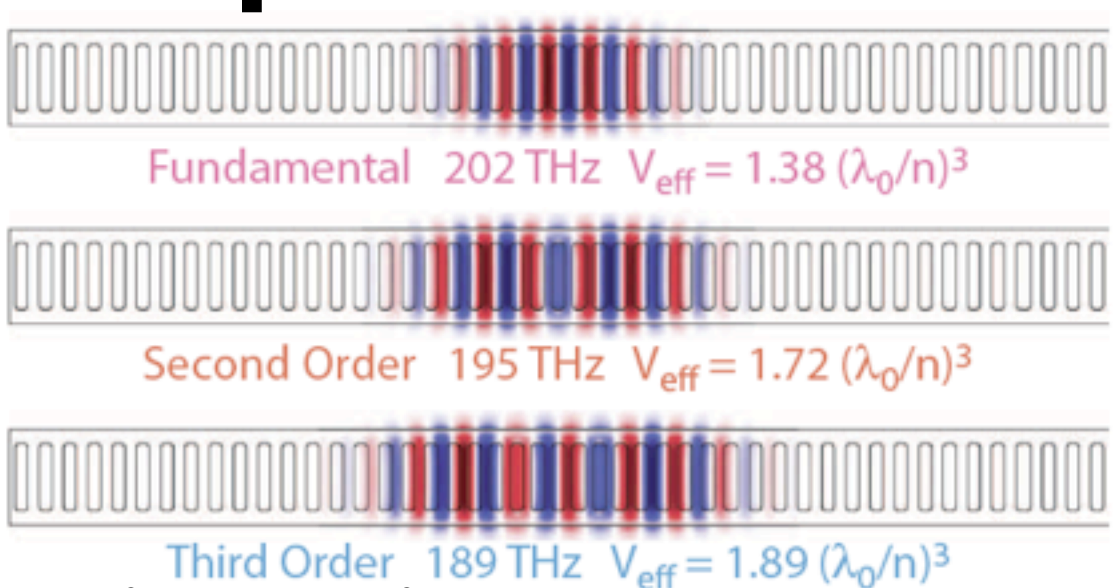
O. Painter et al., Caltech

10 μm

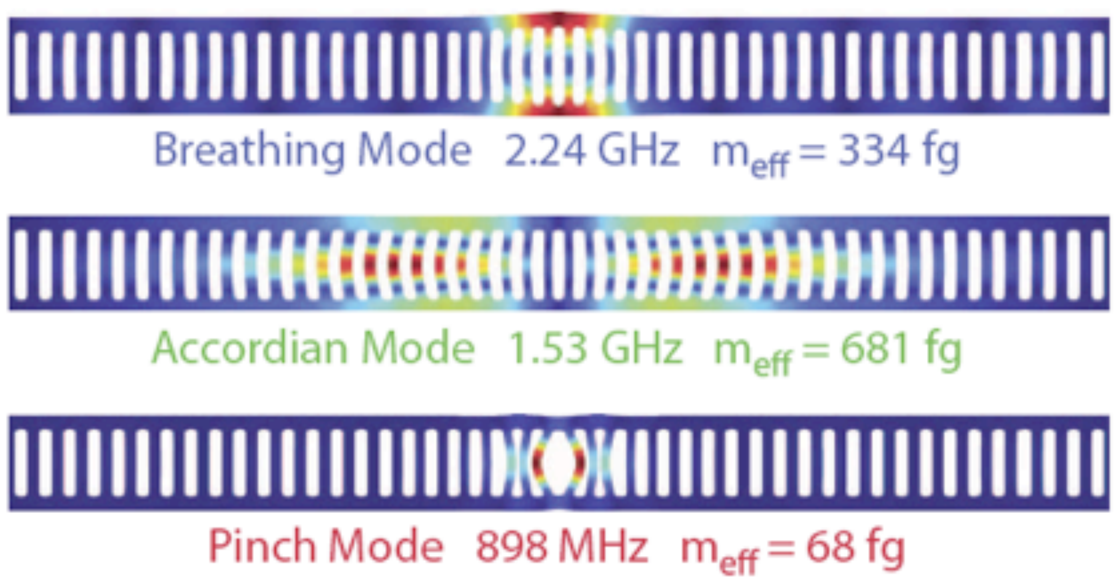
Optomechanical crystals

free-standing photonic crystal structures

optical modes



vibrational modes



advantages:

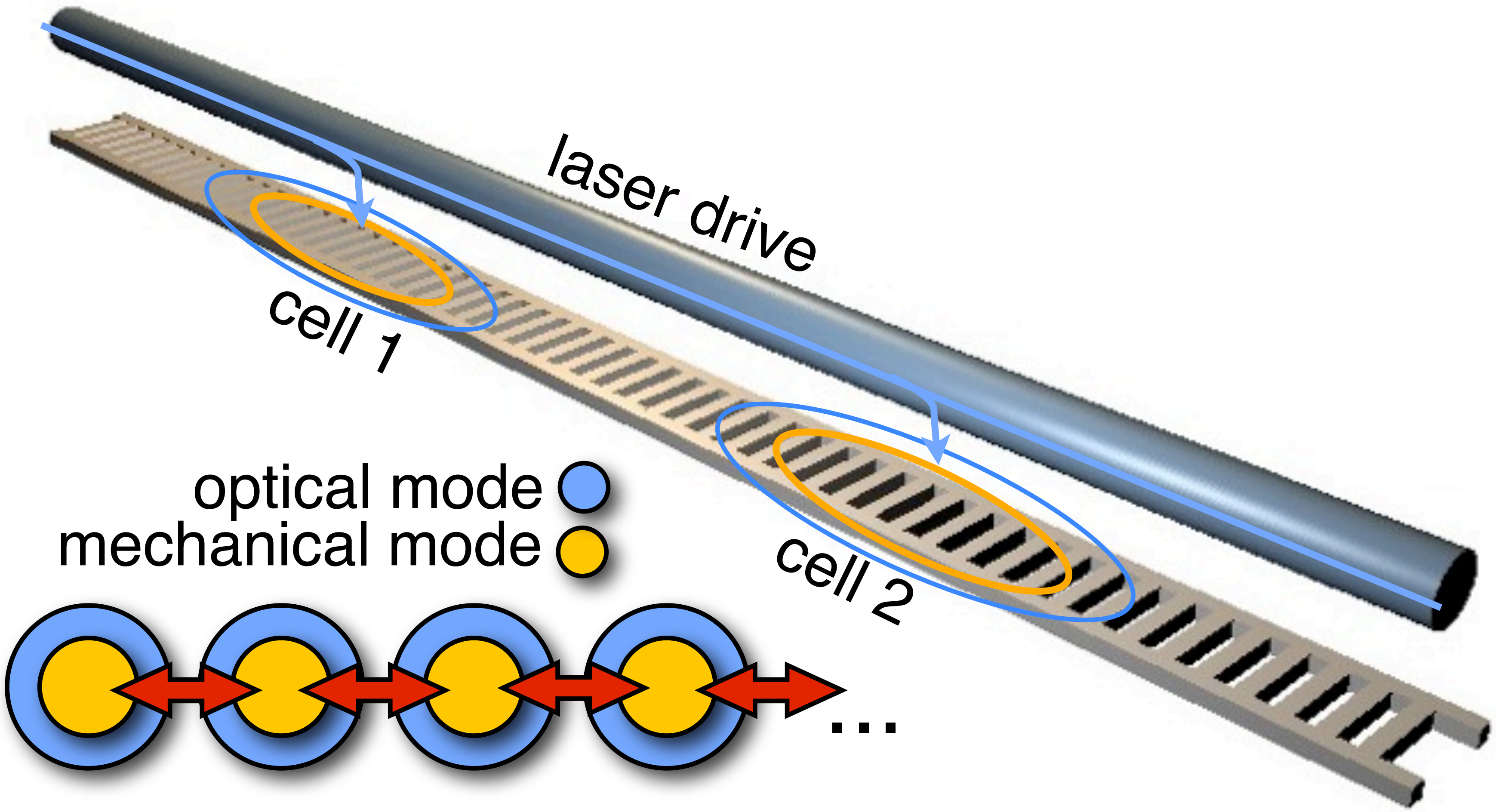
tight vibrational confinement:
high frequencies, small mass
(stronger quantum effects)

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

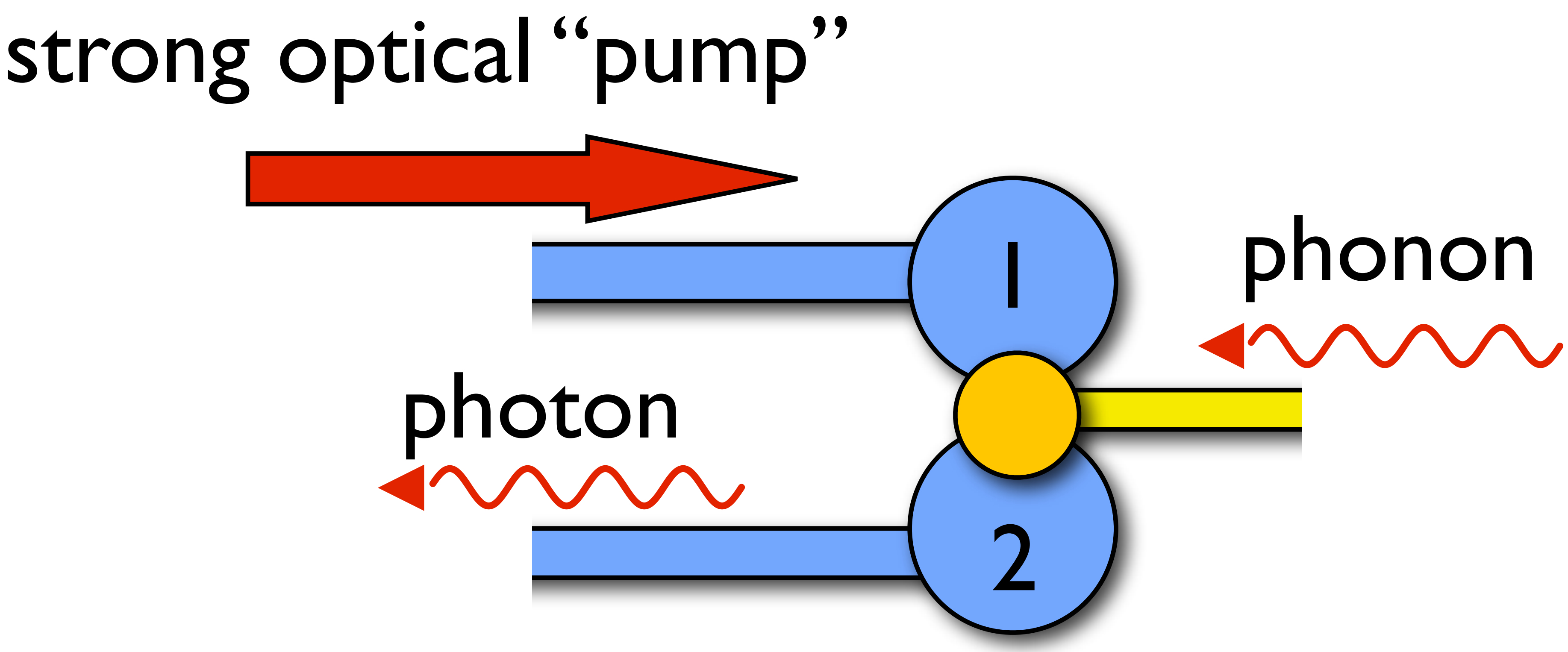
Dynamics in optomechanical arrays

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

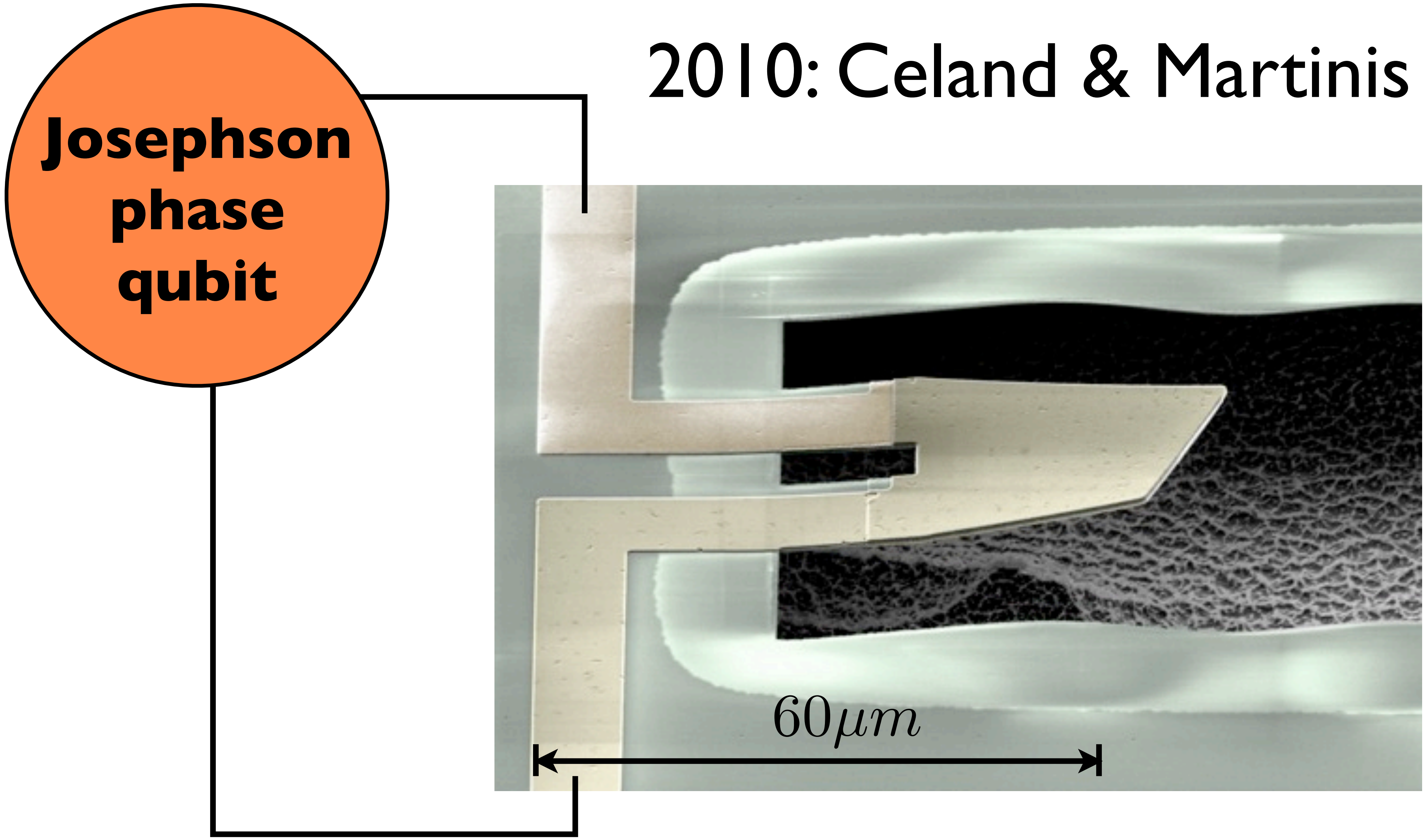
(concept: Painter group, Caltech)



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

Superconducting qubit coupled to nanomechanical resonator

2010: Celand & Martinis labs

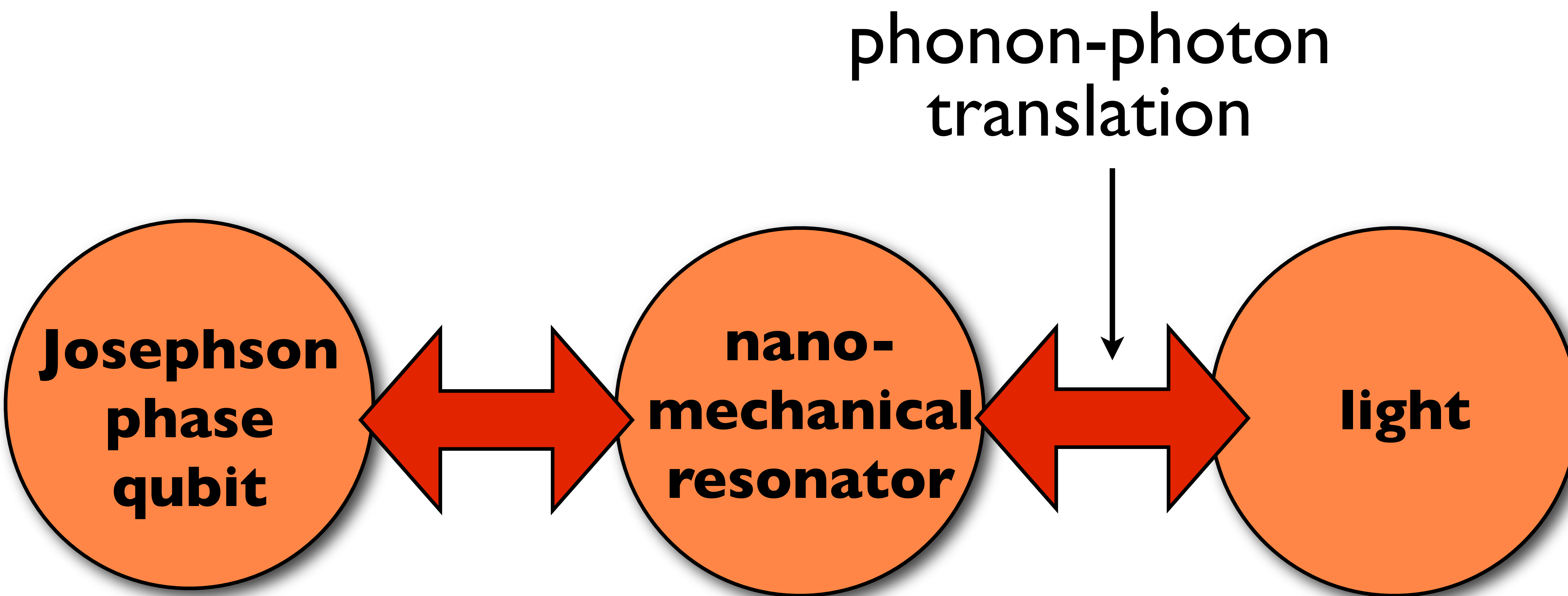


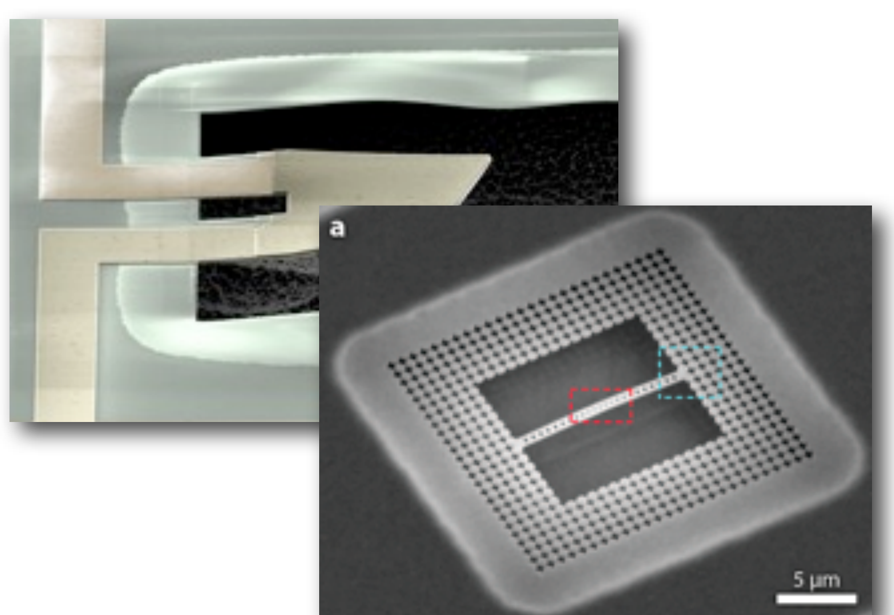
piezoelectric nanomechanical resonator

(GHz @ 20 mK: ground state!)

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

Conversion of quantum information

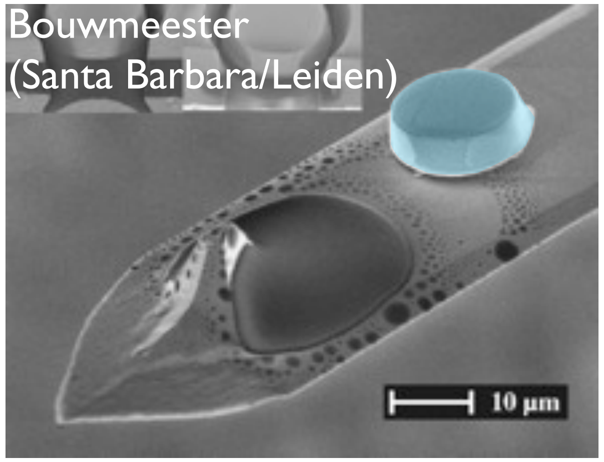




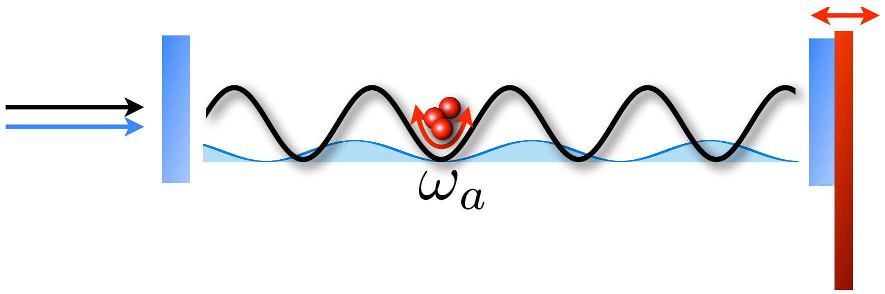
Recent trends

- 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.]

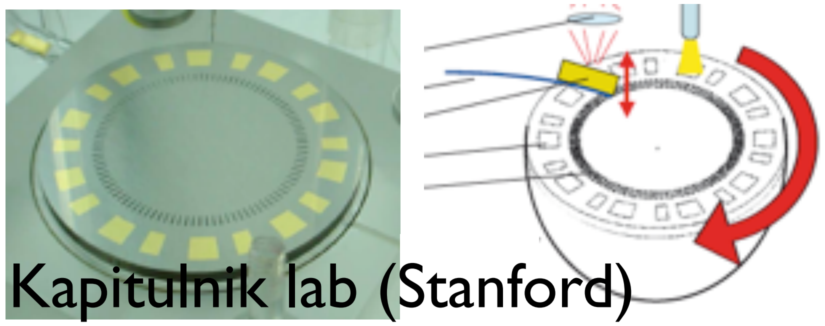
Optomechanics: general outlook



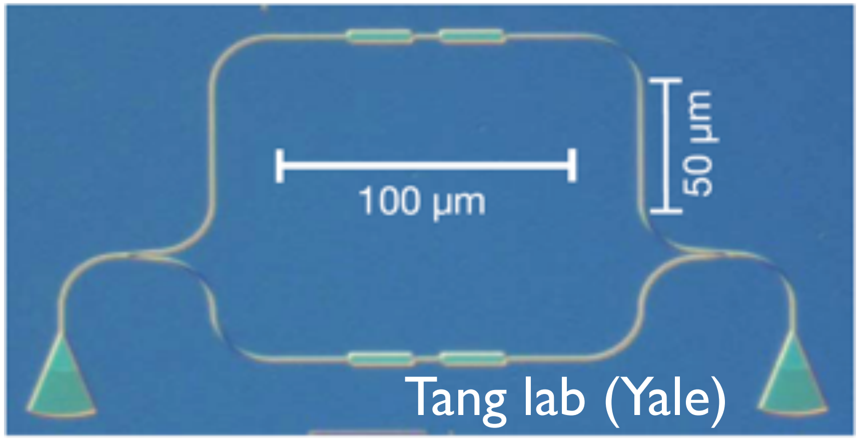
Fundamental tests of quantum mechanics in a new regime: entanglement with 'macroscopic' objects, unconventional decoherence? [e.g.: gravitationally induced?]



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

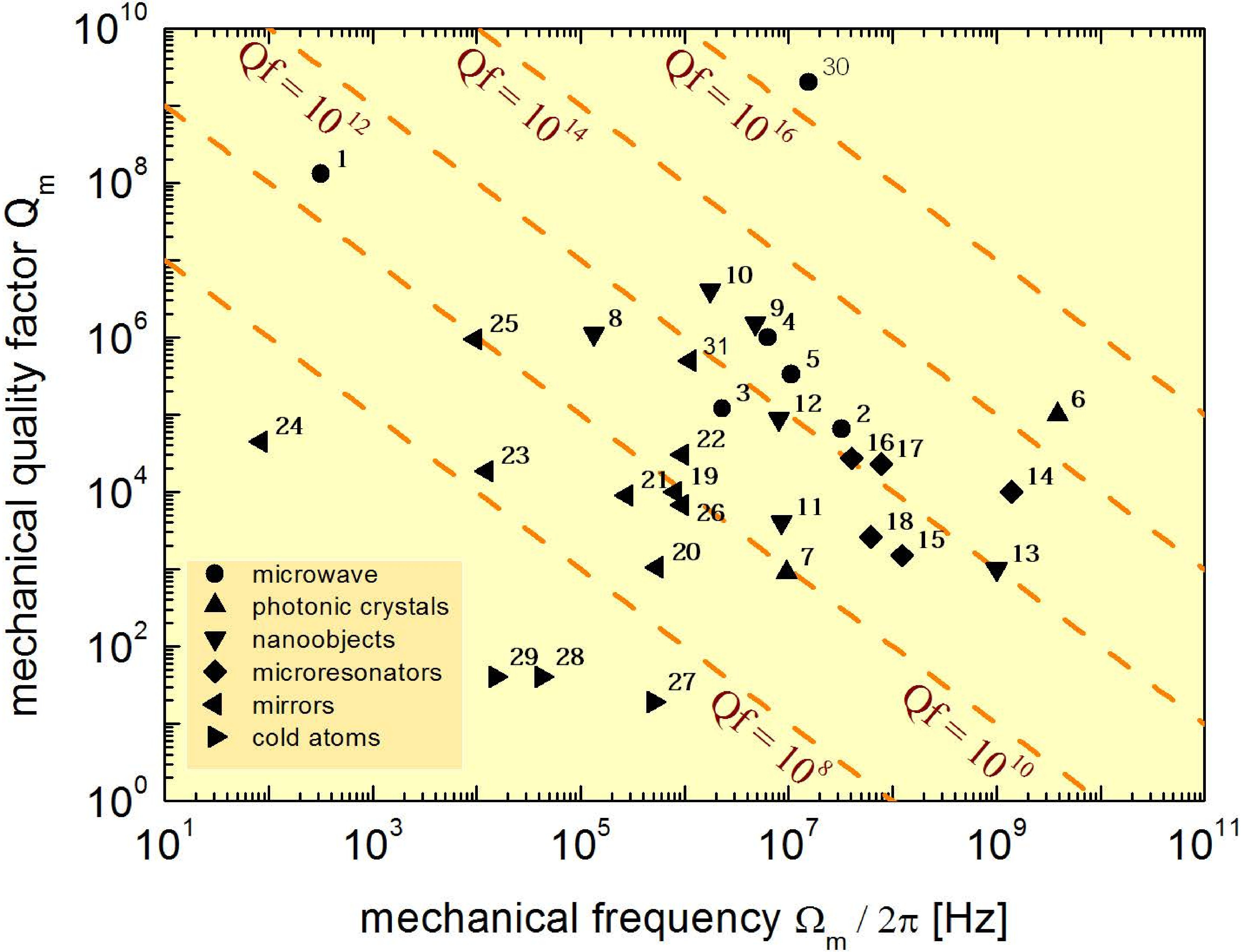
Parameters of Optomechanical Systems

Mechanical damping rate

Γ_{m} rate of energy loss,
linewidth in mechanical spectrum

$\Gamma_{\mathrm{m}}\bar{n}_{\mathrm{th}}$ rate of re-thermalization,
ground state decoherence rate

$Q = \frac{\Omega_{\mathrm{m}}}{\Gamma_{\mathrm{m}}}$ Mechanical quality factor,
number of oscillations during damping time



mechanical quality factor Q_m
mechanical frequency $\Omega_m / 2\pi$ [Hz]
$Qf = 10^{12}$
$Qf = 10^{14}$
$Qf = 10^{16}$
$Qf = 10^{8}$
$Qf = 10^{10}$
microwave
photonic crystals
nanoobjects
microresonators
mirrors
cold atoms

Optomechanical coupling strength

$$g_0 \hat{a}^\dagger \hat{a}(\hat{b} + \hat{b}^\dagger) \mapsto \underbrace{g_0 \alpha}_{g}(\delta\hat{a} + \delta\hat{a}^\dagger)(\hat{b} + \hat{b}^\dagger)$$

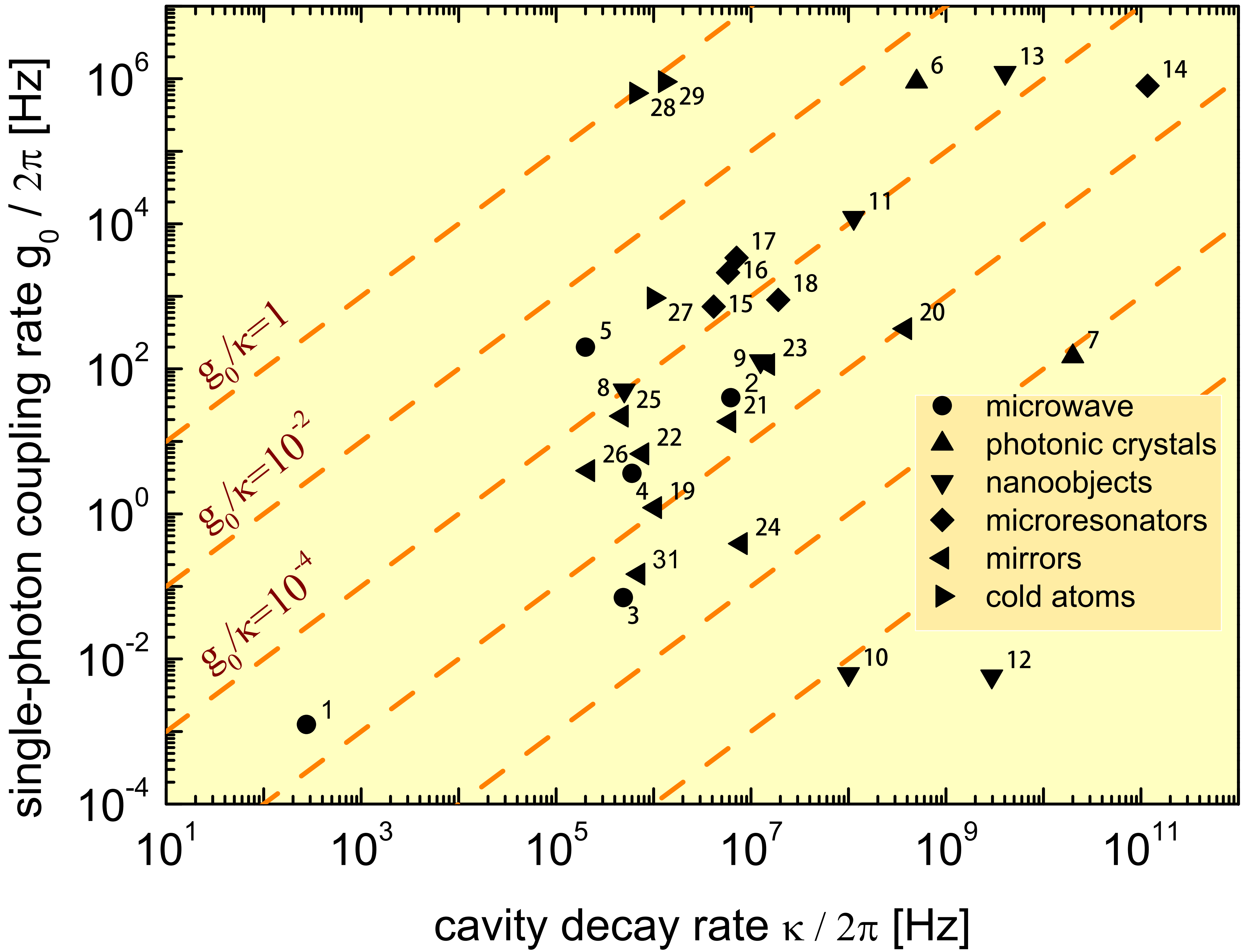
bilinear interaction
tunable coupling!

g_0 Single-photon optomechanical coupling rate

nonclassical mechanical quantum states, ...

g Linearized (driving-enhanced) optomechanical coupling rate

optomechanical damping rate, state transfer rate, ...



single-photon coupling rate g_0 / 2π [Hz]
cavity decay rate κ / 2π [Hz]
10^{-4}
10^{-2}
10^{0}
10^{2}
10^{4}
10^{6}
10^{1}
10^{3}
10^{5}
10^{7}
10^{9}
10^{11}
$g_0/\kappa=1$
$g_0/\kappa=10^{-2}$
$g_0/\kappa=10^{-4}$
microwave
photonic crystals
nanoobjects
microresonators
mirrors
cold atoms
1
2
3
4
5
6
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31

Cooperativities

Linearized (driving-enhanced) cooperativity

$$C = \frac{g_0^2 \bar{n}_{\rm cav}}{\Gamma_{\rm m} \kappa}$$

Optomechanically induced transparency, instability towards optomech. oscillations

Linearized (driving-enhanced) quantum cooperativity

$$C_{\rm th} = \mathcal{C} = \frac{g_0^2 \bar{n}_{\rm cav}}{\Gamma_{\rm m} \bar{n}_{\rm th} \kappa}$$

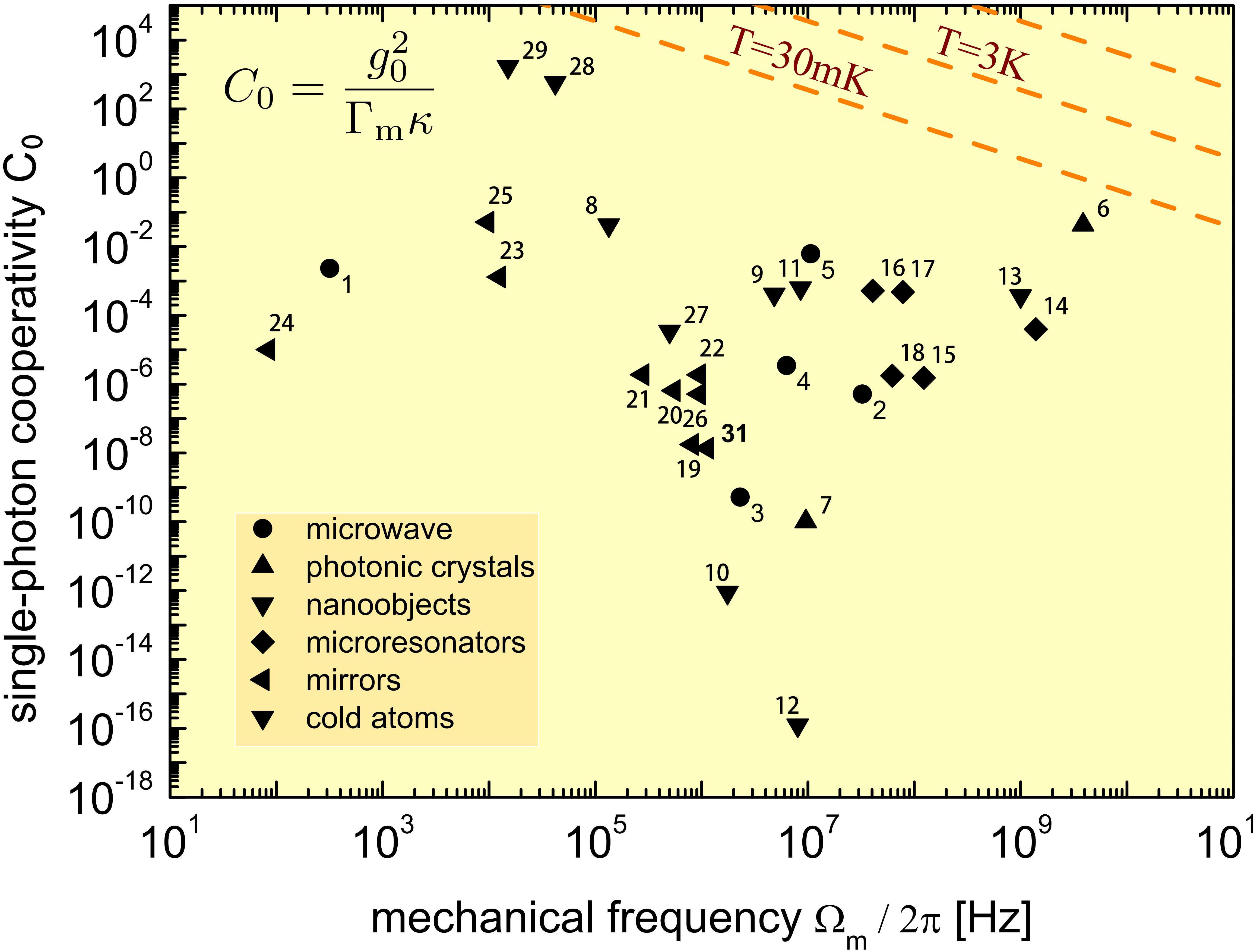
ground state cooling, state transfer, entanglement, squeezing of light, ...

Single-photon cooperativity

$$C_0 = \frac{g_0^2}{\Gamma_{\rm m} \kappa}$$

Single-photon “quantum” cooperativity

$$C_{0,\rm th} = \mathcal{C} = \frac{g_0^2}{\Gamma_{\rm m} \bar{n}_{\rm th} \kappa}$$

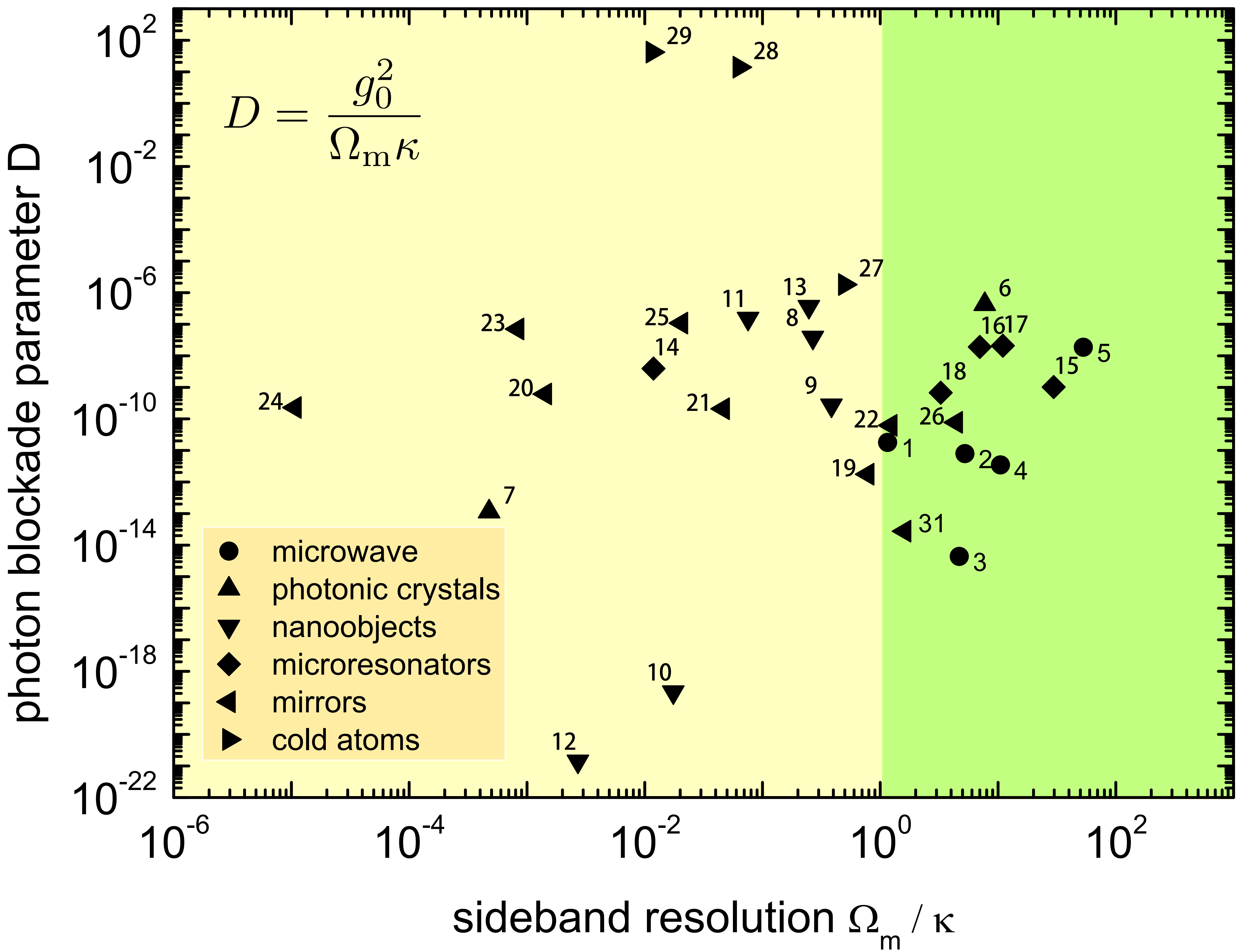


$C_0 = \frac{g_0^2}{\Gamma_m \kappa}$
T=30mK
T=3K
microwave
photonic crystals
nanoobjects
microresonators
mirrors
cold atoms
single-photon cooperativity C_0
mechanical frequency $\Omega_m / 2\pi$ [Hz]

Photon interaction

$$g_0 \hat{a}^\dagger \hat{a}(\hat{b} + \hat{b}^\dagger) \quad \mapsto -\frac{g_0^2}{\Omega_\mathrm{m}} (\hat{a}^\dagger \hat{a})^2$$

photon blockade, photon QND measurement, ...



$D = \frac{g_0^2}{\Omega_m \kappa}$
photon blockade parameter D
sideband resolution Ω_m / κ
microwave
photonic crystals
nanoobjects
microresonators
mirrors
cold atoms
10^{2}
10^{-2}
10^{-6}
10^{-10}
10^{-14}
10^{-18}
10^{-22}
10^{-6}
10^{-4}
10^{-2}
10^{0}
10^{2}
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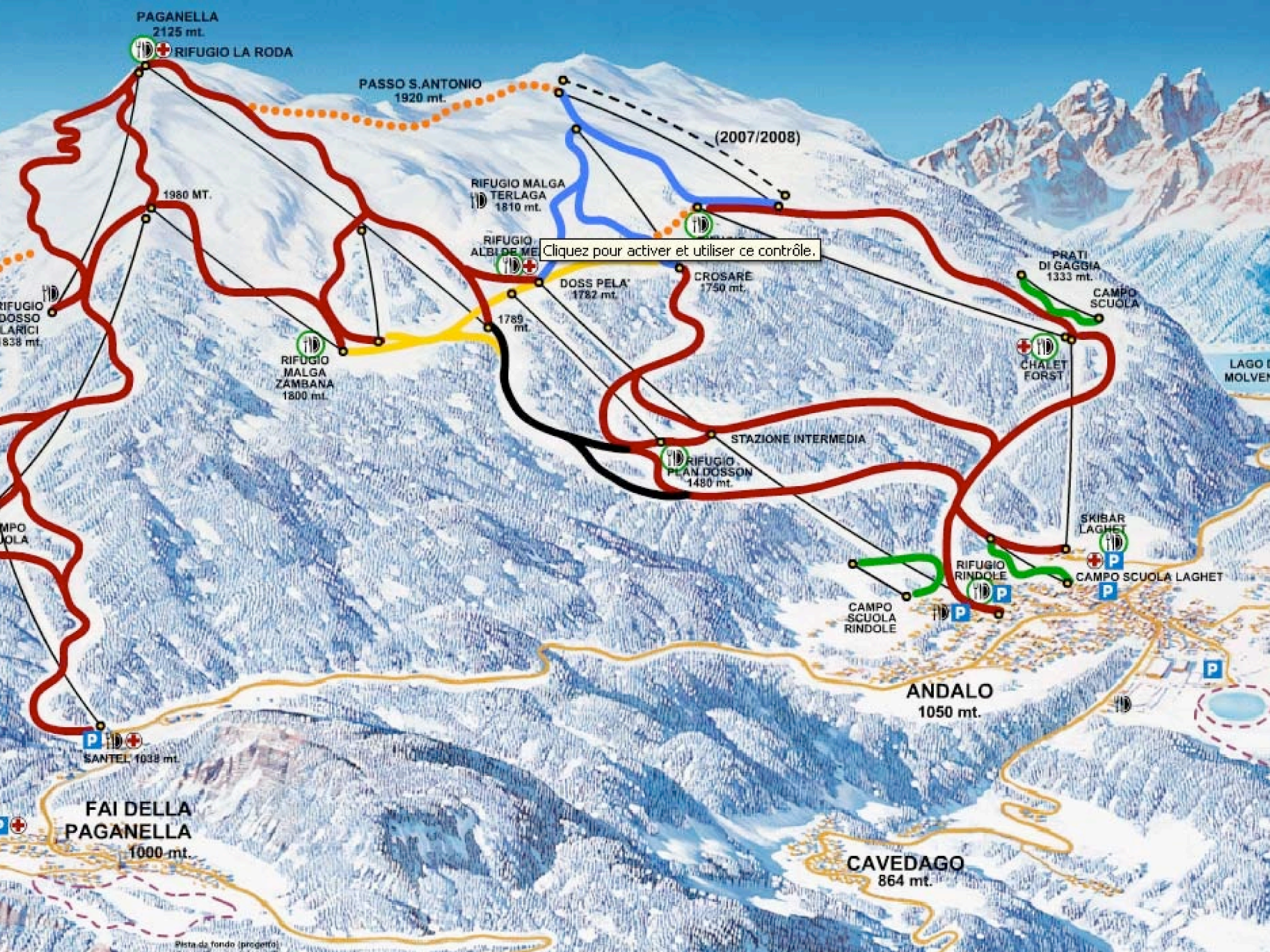
PAGANELLA
2125 mt.
RIFUGIO LA RODA
PASSO S.ANTONIO
1920 mt.
(2007/2008)
1980 MT.
RIFUGIO MALGA
TERLAGA
1810 mt.
RIFUGIO
ALBI DE ME
Cliquez pour activer et utiliser ce contrôle.
DOSS PELA'
1782 mt.
CROSARE
1750 mt.
PRATI
DI GAGGIA
1333 mt.
CAMPO
SCUOLA
RIFUGIO
DOSSO
LARICI
1838 mt.
RIFUGIO
MALGA
ZAMBANA
1800 mt.
1789
mt.
CHALET
FORST
LAGO D
MOLVEN
STAZIONE INTERMEDIA
RIFUGIO
PLAN DOSSON
1480 mt.
SKIBAR
LAGHET
RIFUGIO
RINDOLE
CAMPO SCUOLA LAGHET
CAMPO
SCUOLA
RINDOLE
ANDALO
1050 mt.
SANTEL 1038 mt.
FAI DELLA
PAGANELLA
1000 mt.
CAVEDAGO
864 mt.

Linear Optomechanics

- Displacement detection
- Optical Spring
- Cooling & Amplification
- Two-tone drive: "Optomechanically induced transparency"
- State transfer, pulsed operation
- Wavelength conversion
- Radiation Pressure Shot Noise
- Squeezing of Light
- Squeezing of Mechanics
- Entanglement
- Precision measurements

Optomechanical Circuits

- Bandstructure in arrays
- Synchronization/patterns in arrays
- Transport & pulses in arrays

Nonlinear Optomechanics

- Self-induced mechanical oscillations
- Synchronization of oscillations
- Chaos

Nonlinear Quantum Optomechanics

- Phonon number detection
- Phonon shot noise
- Photon blockade
- Optomechanical "which-way" experiment
- Nonclassical mechanical q. states
- Nonlinear OMIT
- Noncl. via Conditional Detection
- Single-photon sources
- Coupling to other two-level systems

Note:

Yesterday's red is today's green!

Linear Optomechanics

- Displacement detection
- Optical Spring
- Cooling & Amplification
- Two-tone drive: "Optomechanically induced transparency"
- Ground state cooling
- State transfer, pulsed operation
- Wavelength conversion
- Radiation Pressure Shot Noise
- Squeezing of Light
- Squeezing of Mechanics
- Light-Mechanics Entanglement
- Accelerometers
- Single-quadrature detection, Wigner density
- Optomechanics with an active medium
- Measure gravity or other small forces
- Mechanics-Mechanics entanglement
- Pulsed measurement
- Quantum Feedback
- Rotational Optomechanics

Multimode

- Mechanical information processing
- Bandstructure in arrays
- Synchronization/patterns in arrays
- Transport & pulses in arrays

Nonlinear Optomechanics

- Self-induced mechanical oscillations
- Attractor diagram?
- Synchronization of oscillations
- Chaos

○ White: yet unknown challenges/goals

Nonlinear Quantum Optomechanics

- QND Phonon number detection
- Phonon shot noise
- Photon blockade
- Optomechanical "which-way" experiment
- Nonclassical mechanical q. states
- Nonlinear OMIT
- Noncl. via Conditional Detection
- Single-photon sources
- Coupling to other two-level systems
- Optomechanical Matter-Wave Interferometry

Optomechanics

Review “Cavity Optomechanics”:
M. Aspelmeyer, T. Kippenberg, FM
arXiv:1303.0733