Cavity Optomechanics

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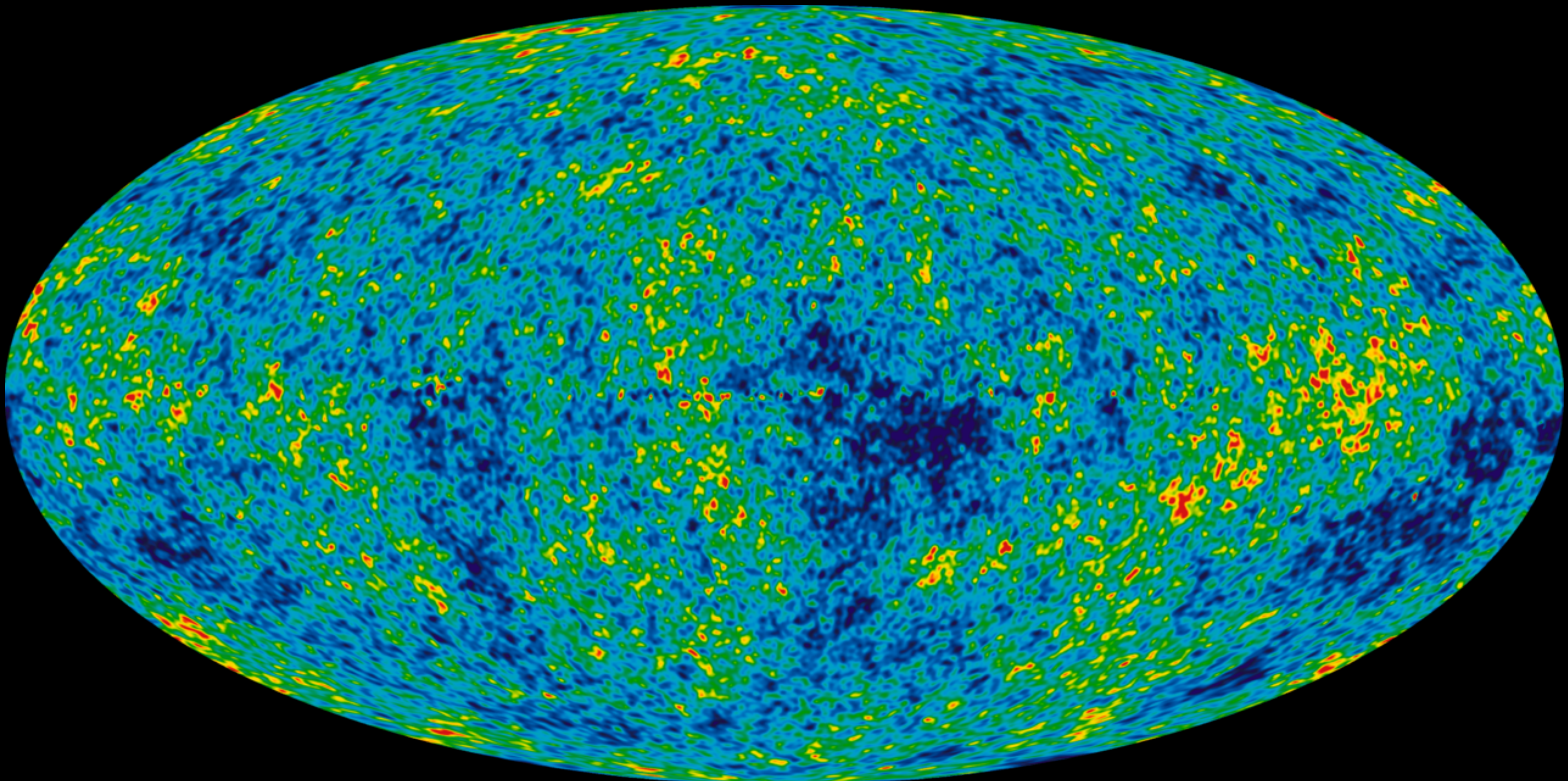
Radiation forces

baryon-photon fluid: sound speed $c/\sqrt{3}$



Radiation pressure

Johannes Kepler
De Cometis, 1619

(Comet Hale-Bopp; by Robert Allevo)

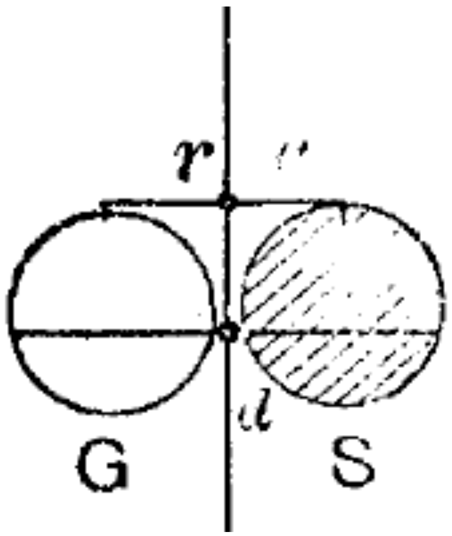
Radiation pressure

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."



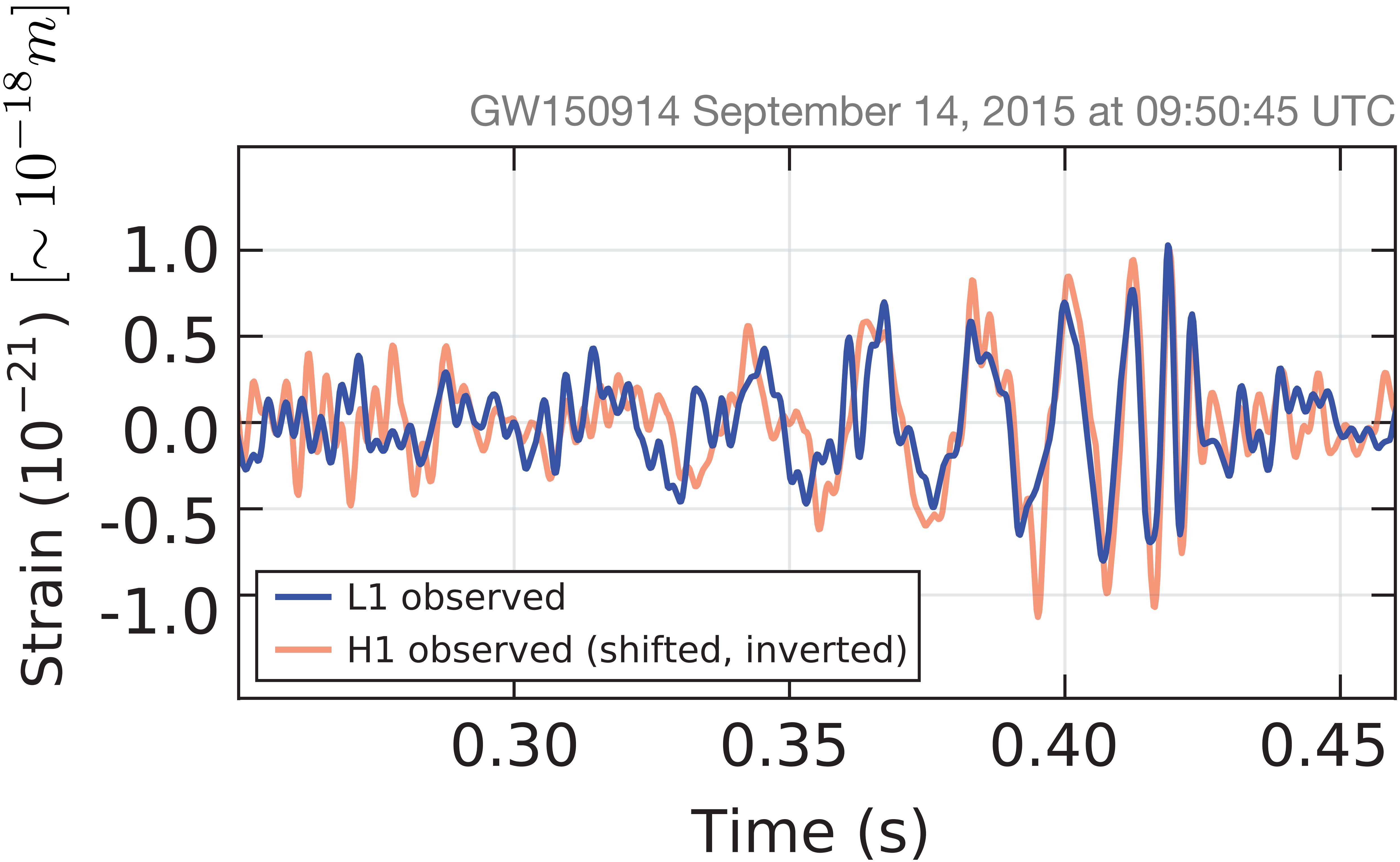
$$F = \frac{2P}{c}$$

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

Laser Interferometer for
Gravitational Wave Detection (LIGO Livingston)


Image: SXS project

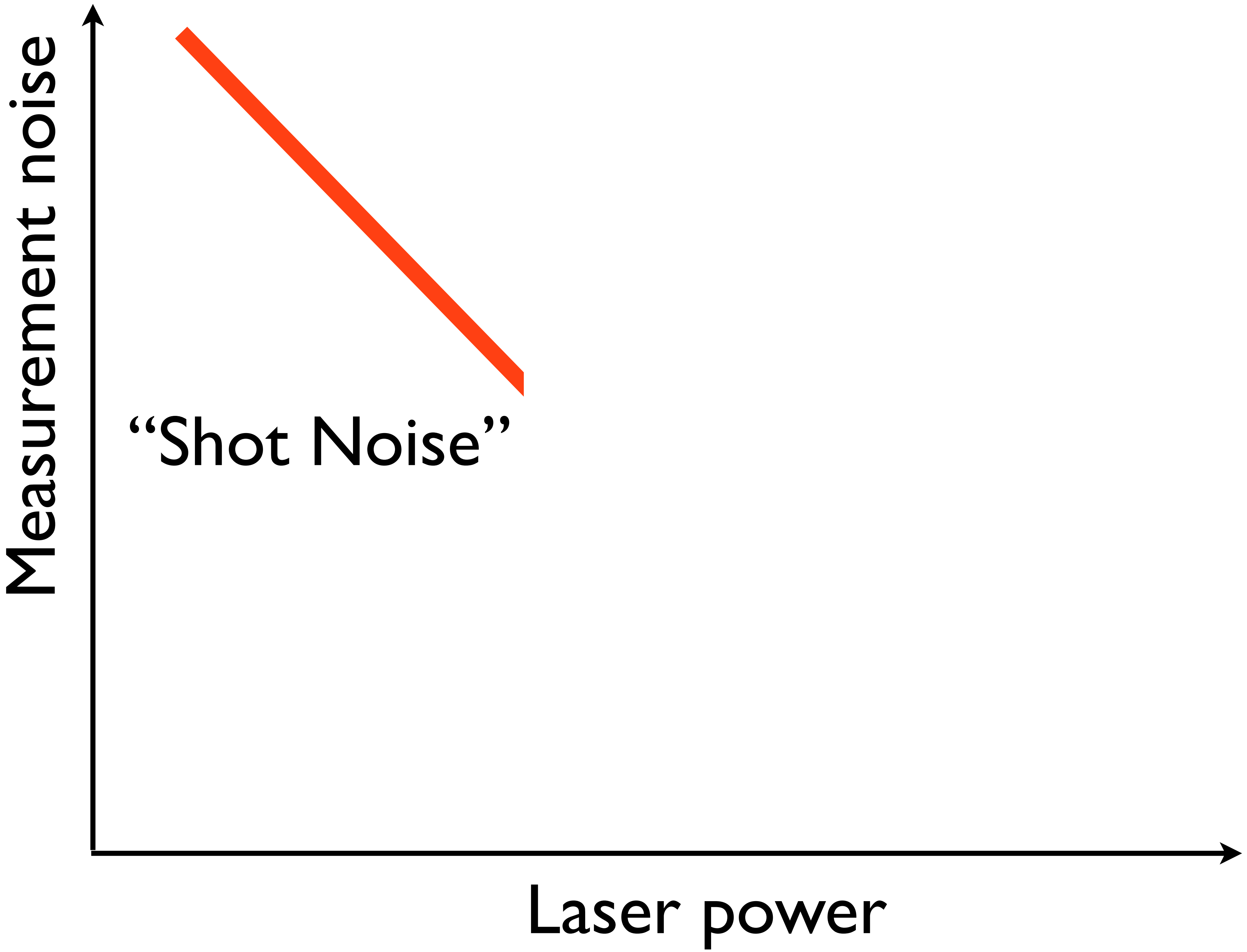
Observation of Gravitational Waves



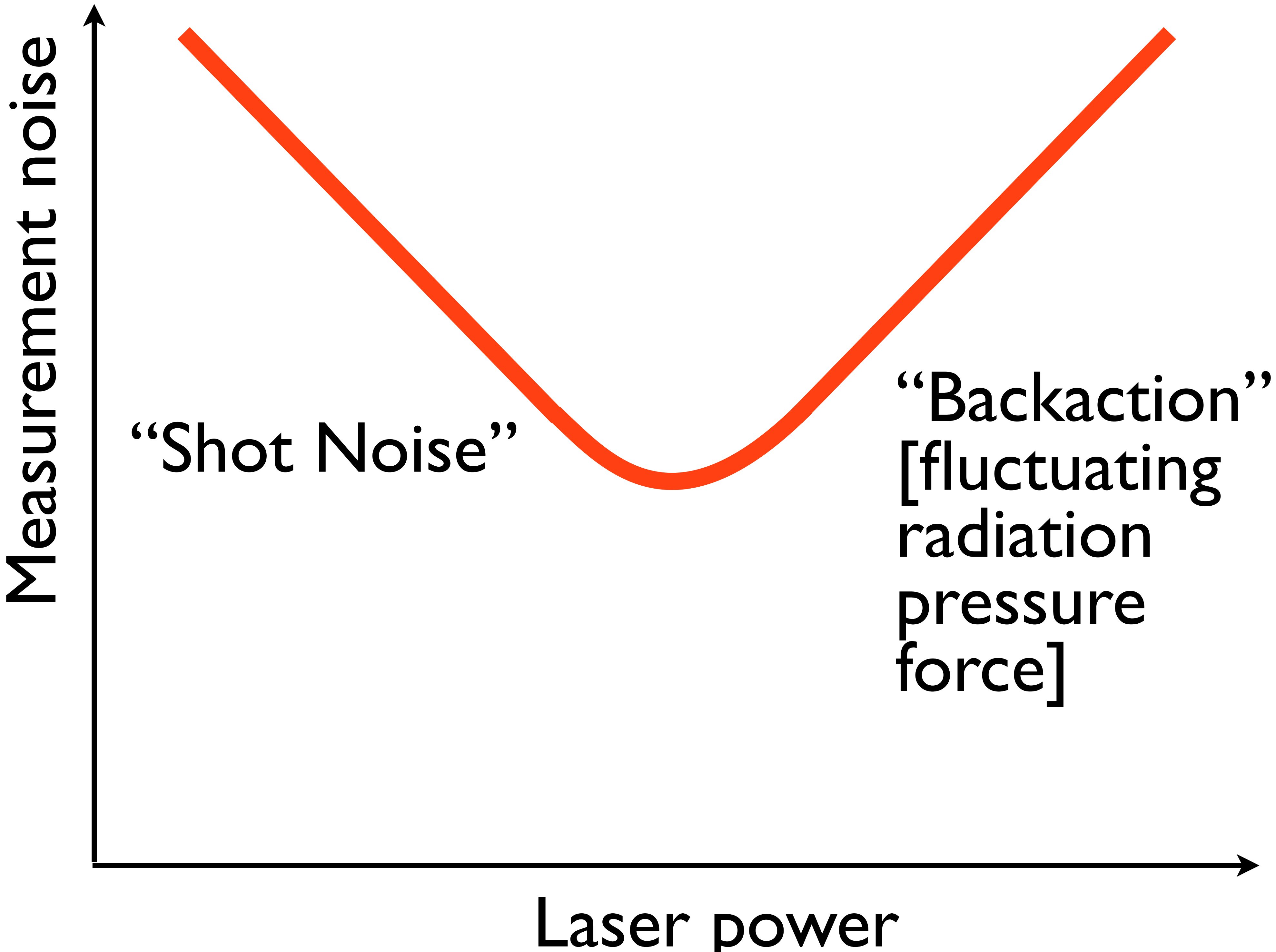
LIGO collaboration, Phys. Rev. Lett. **116**, 061102 (2016)

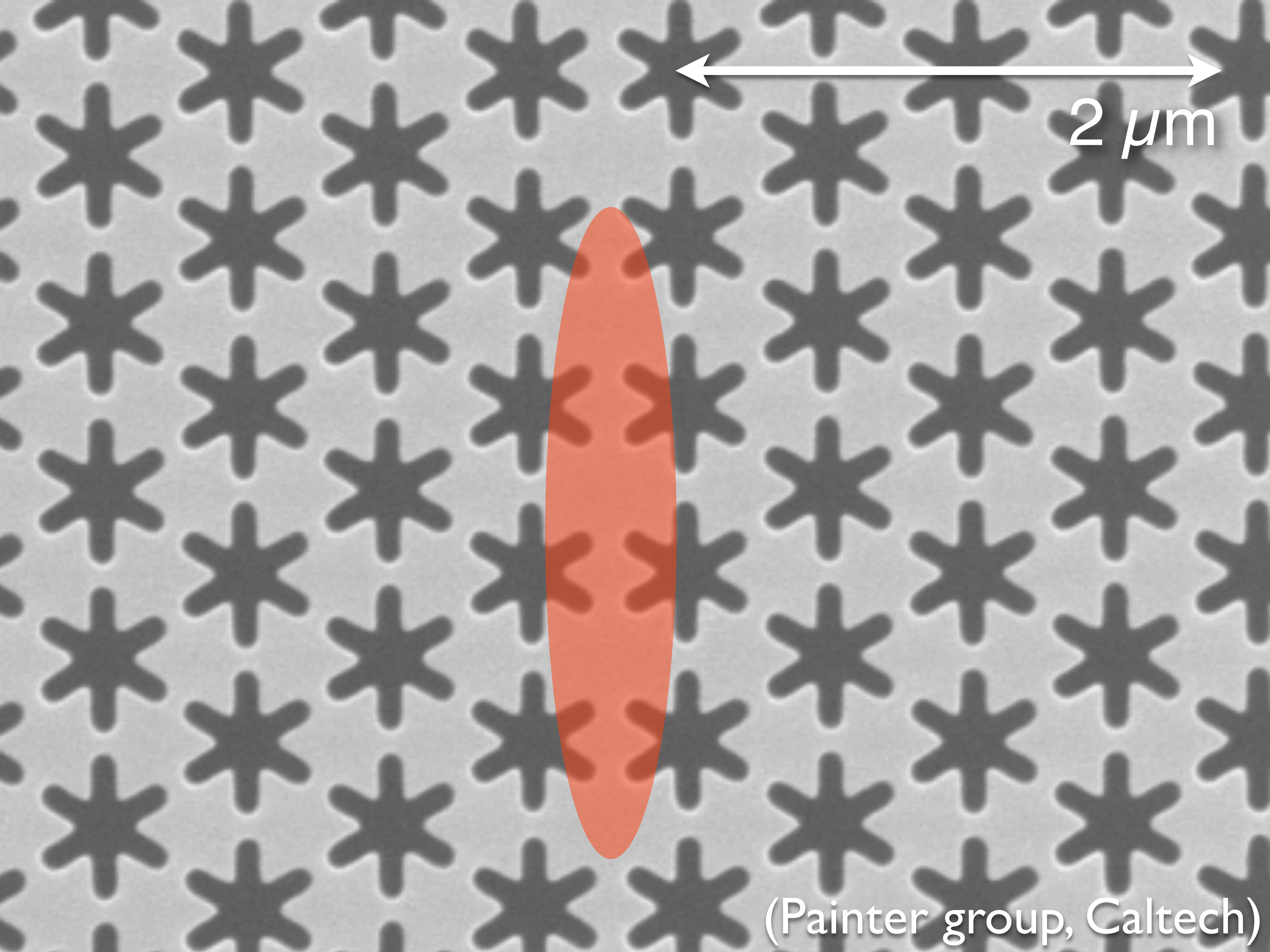

4 km
Laser Interferometer for
Gravitational Wave Detection
(LIGO Livingston)

How precise can one measure?



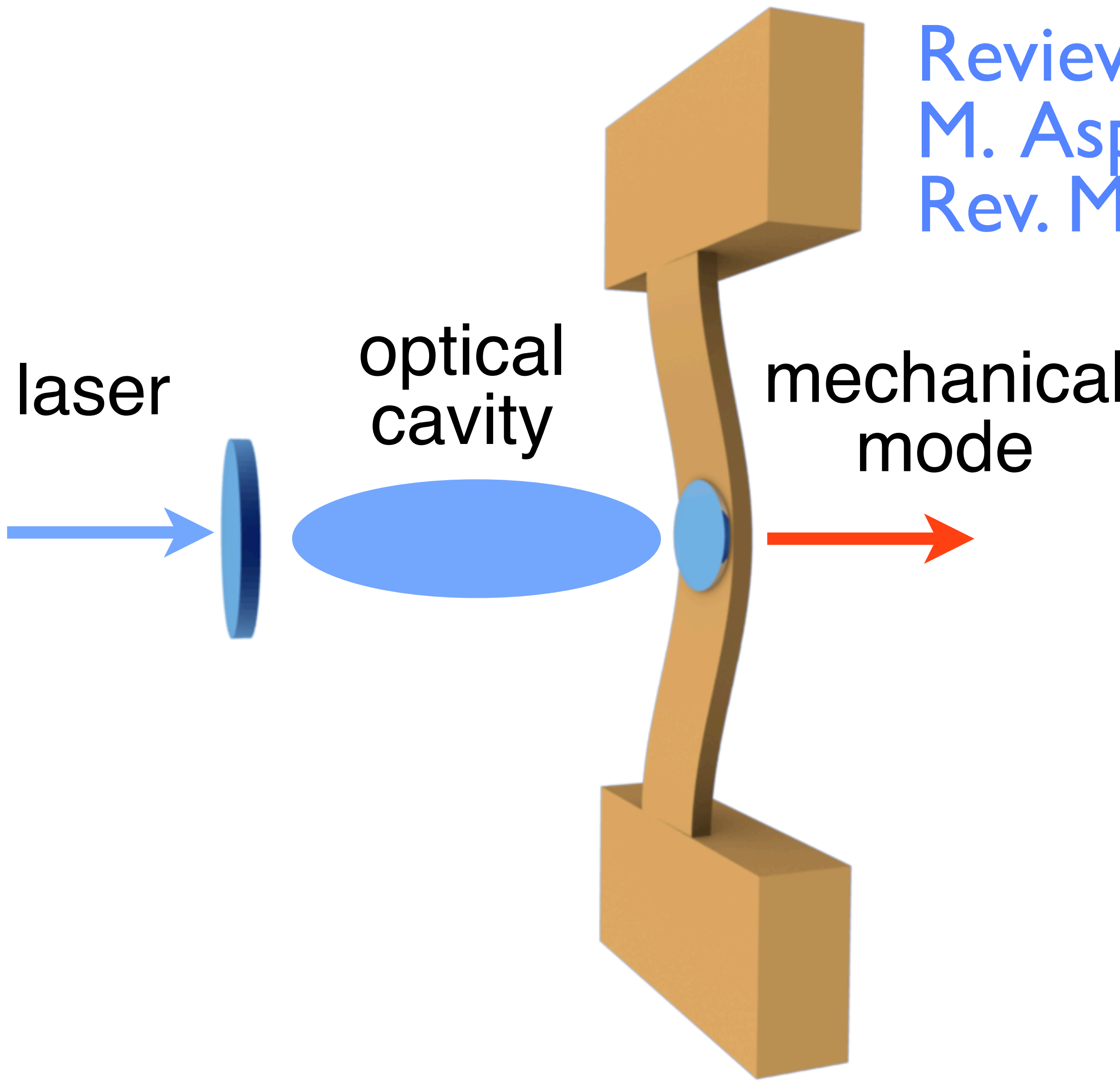
How precise can one measure?




2 μm
(Painter group, Caltech)

Optomechanical Hamiltonian

Optomechanical Hamiltonian



Review "Cavity Optomechanics":
M. Aspelmeyer, T. Kippenberg, FM
Rev. Mod. Phys. 2014

Optomechanical Hamiltonian

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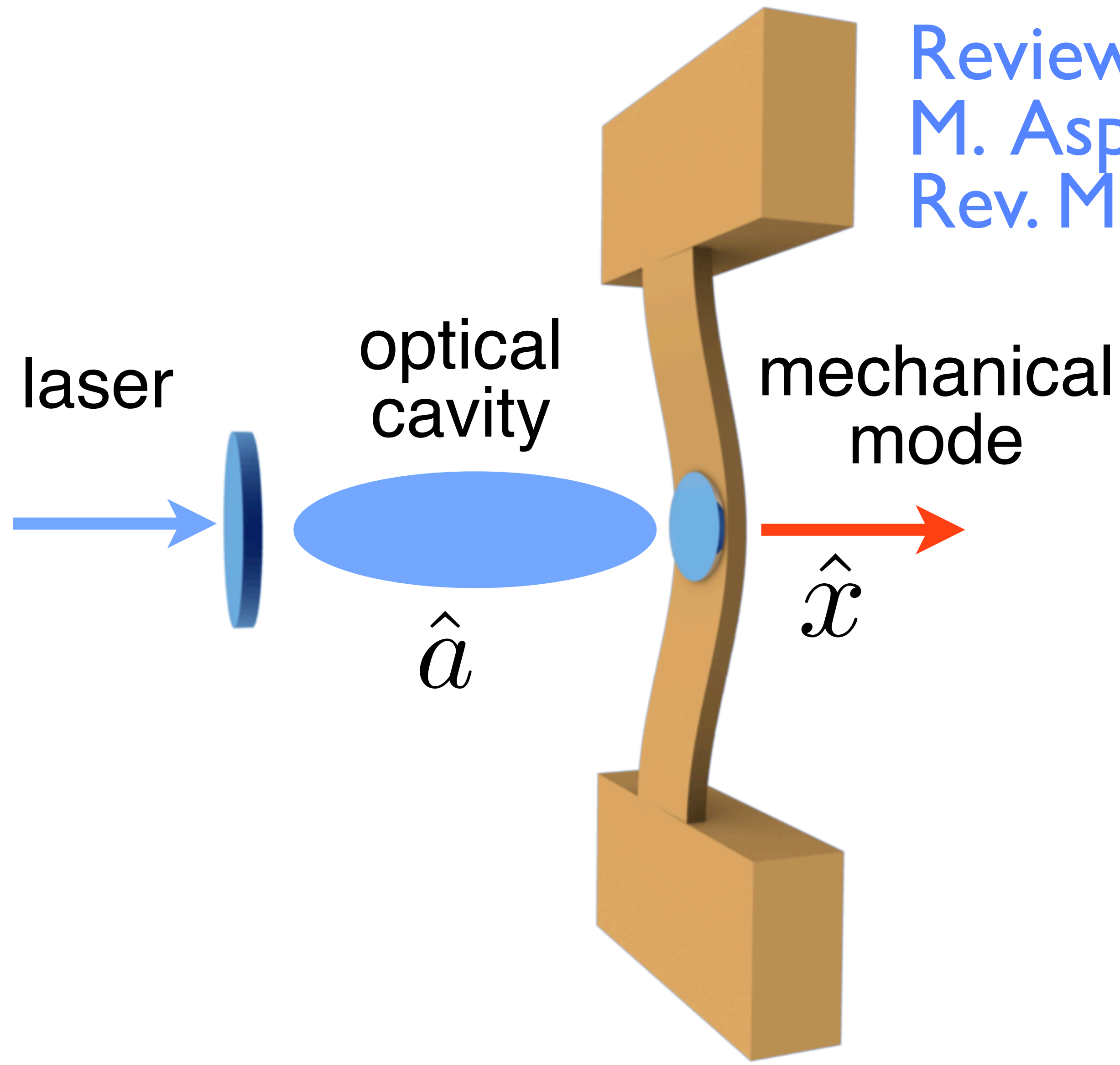
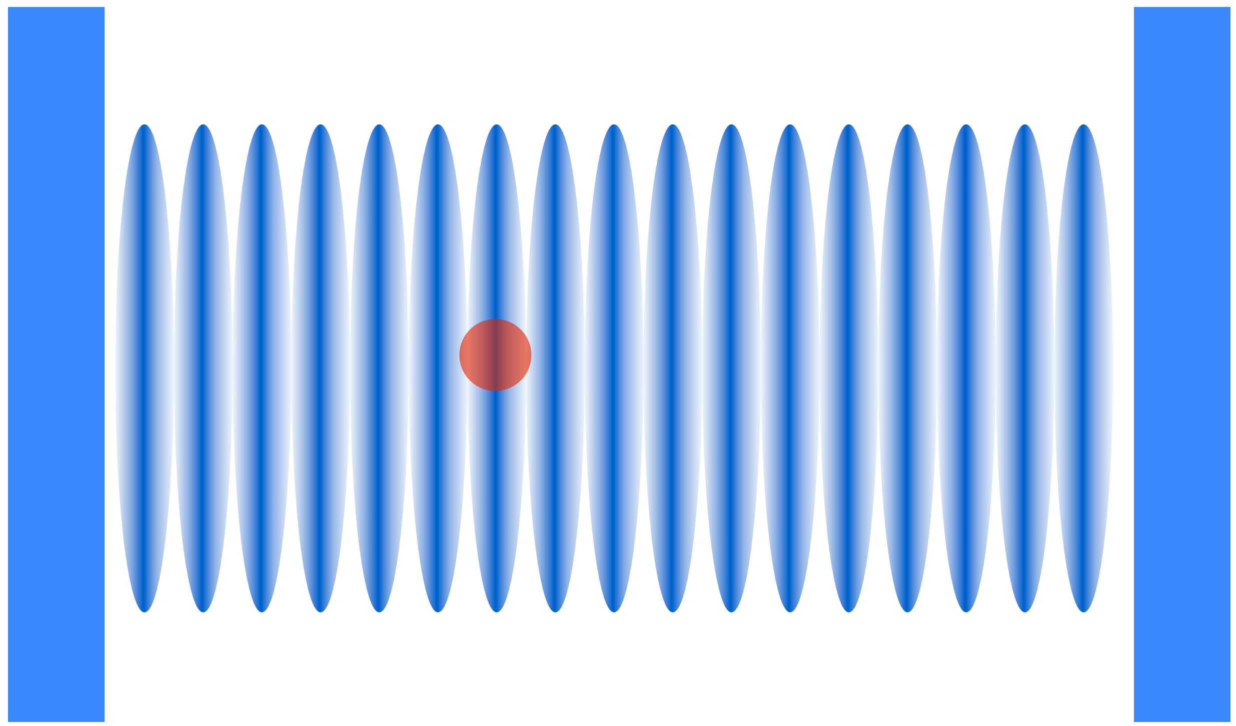


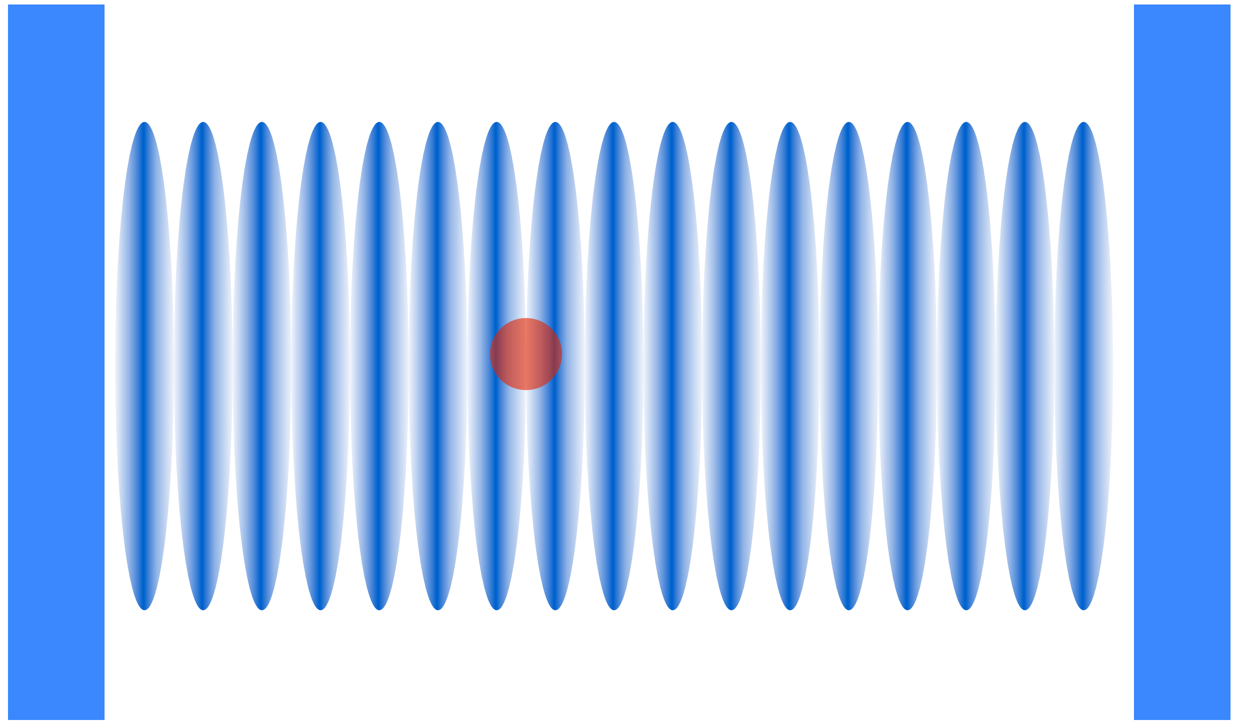
$$\hat{H} = \hbar\omega_{\mathrm{cav}} \cdot (1 - \hat{x}/L)\hat{a}^\dagger\hat{a} + \hbar\omega_M \hat{b}^\dagger\hat{b} + \ldots$$

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

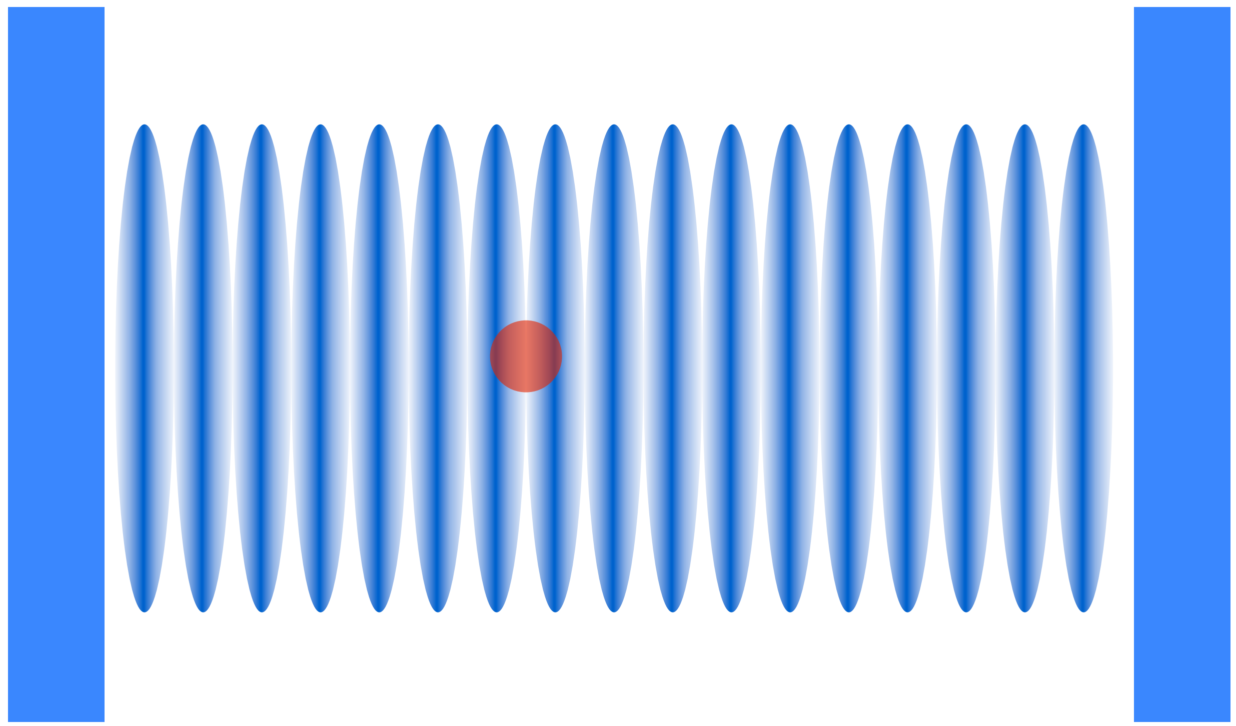
Optomechanical Hamiltonian



Optomechanical Hamiltonian



Optomechanical Hamiltonian



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

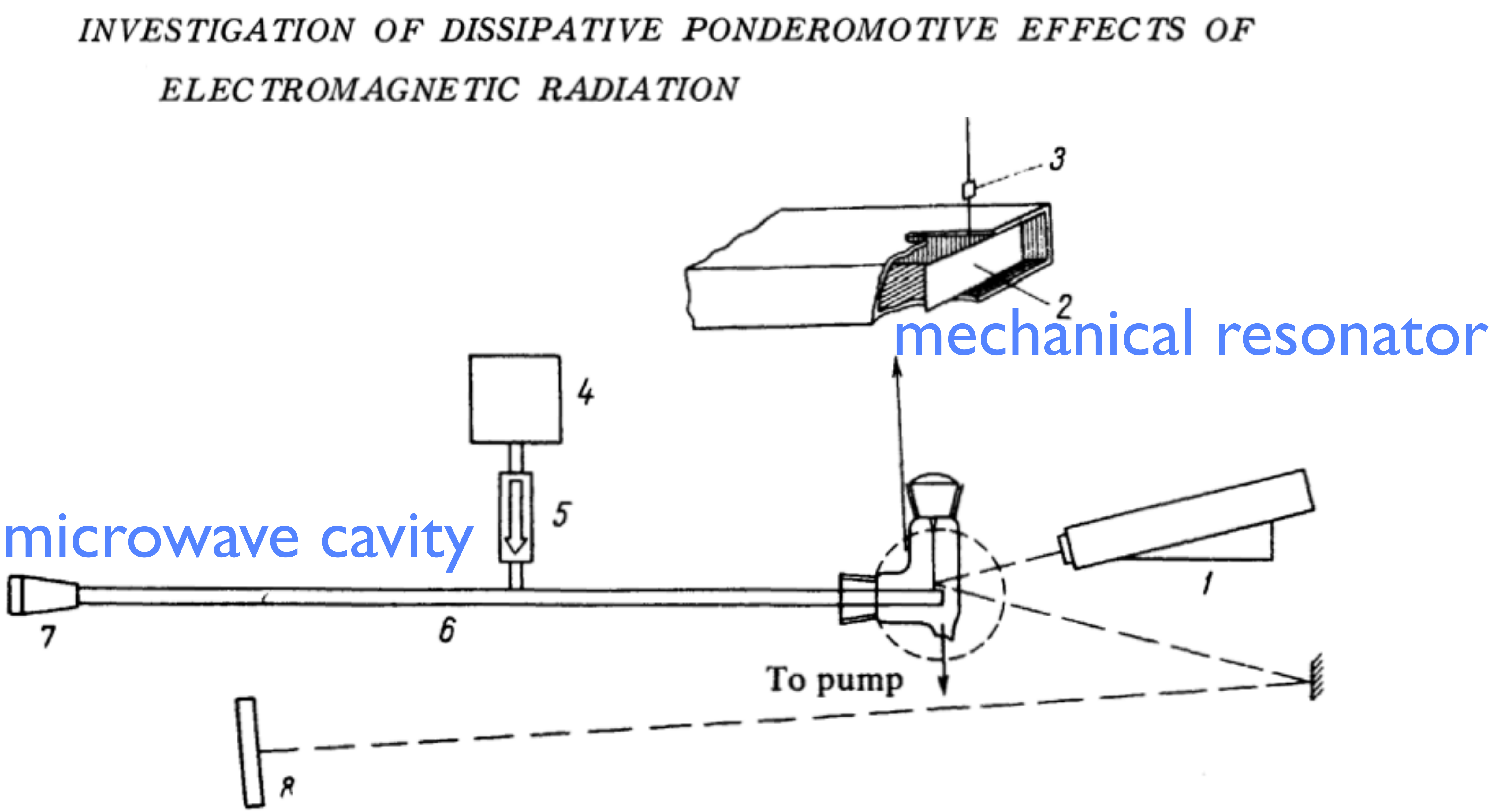
...any dielectric moving inside a cavity generates an optomechanical interaction!

A bit of history

First cavity optomechanics experiments

optomechanical change of mechanical damping rate

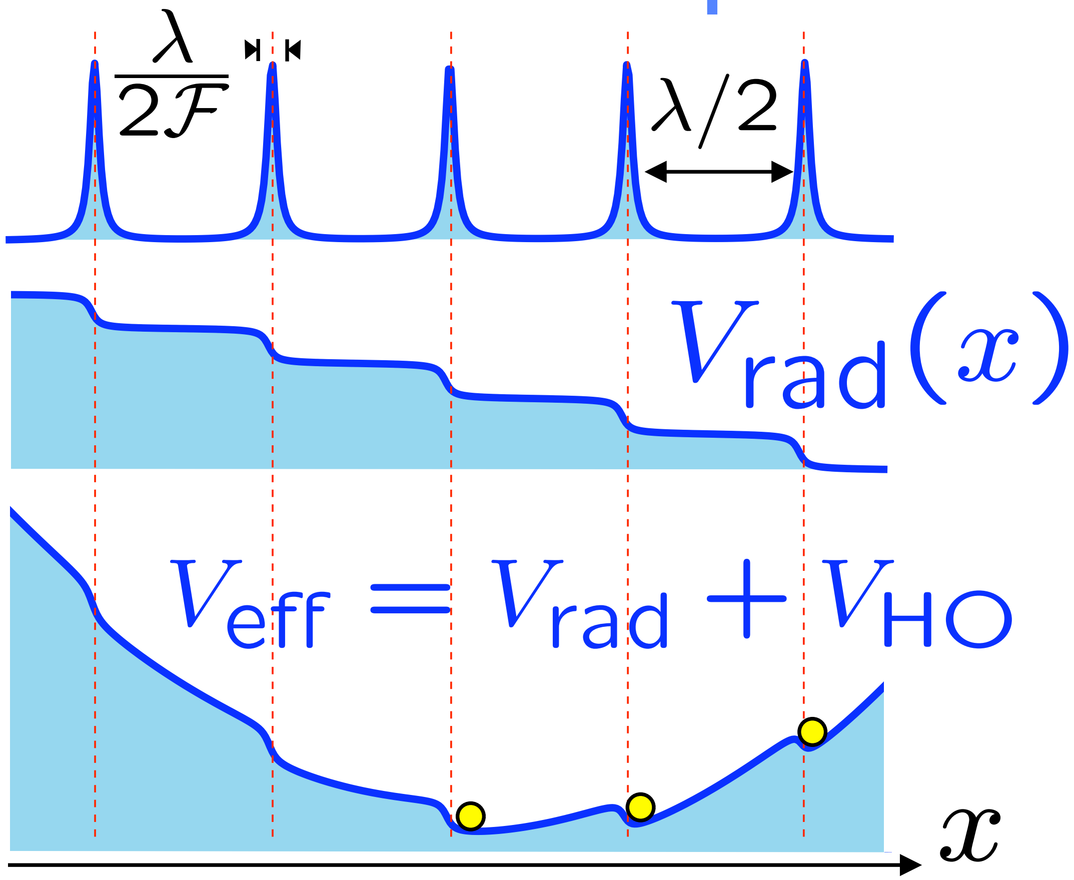
Braginsky, Manukin, Tikhonov JETP 1970

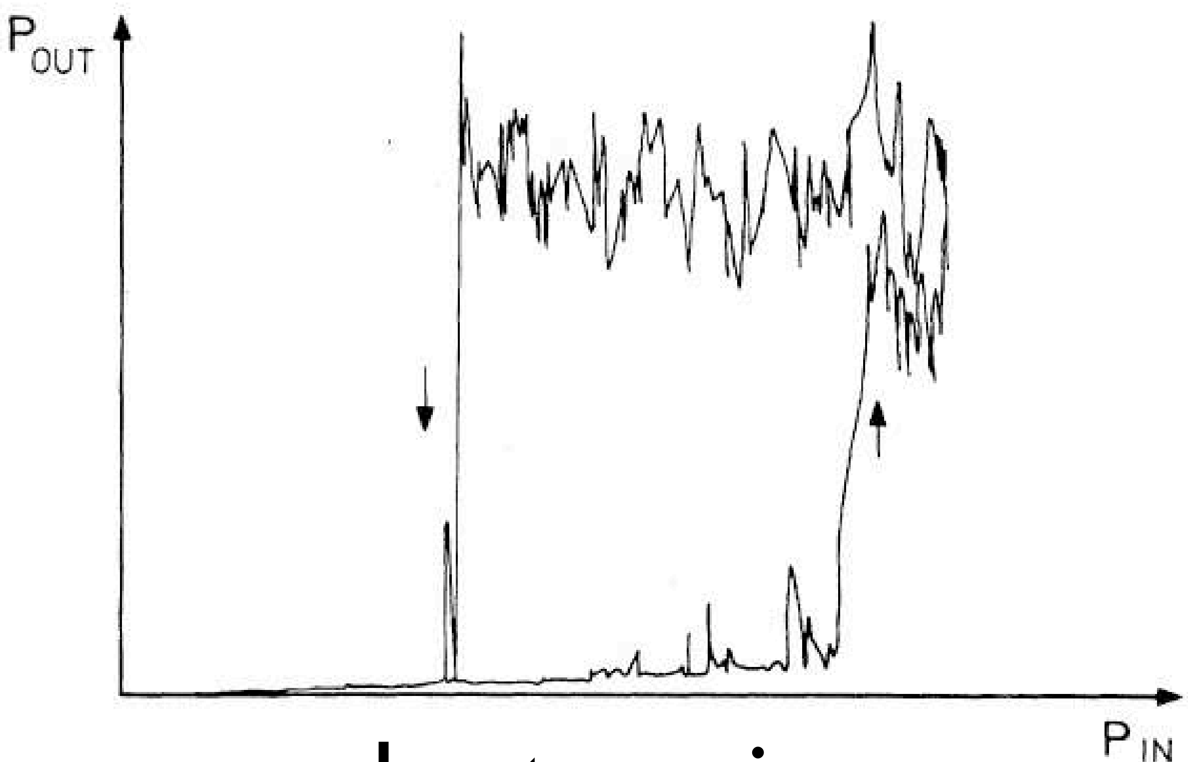


First cavity optomechanics experiments

Static bistability in an optical cavity experiment
Dorsel, McCullen, Meystre, Vignes, Walther PRL 1983

force vs. mirror position

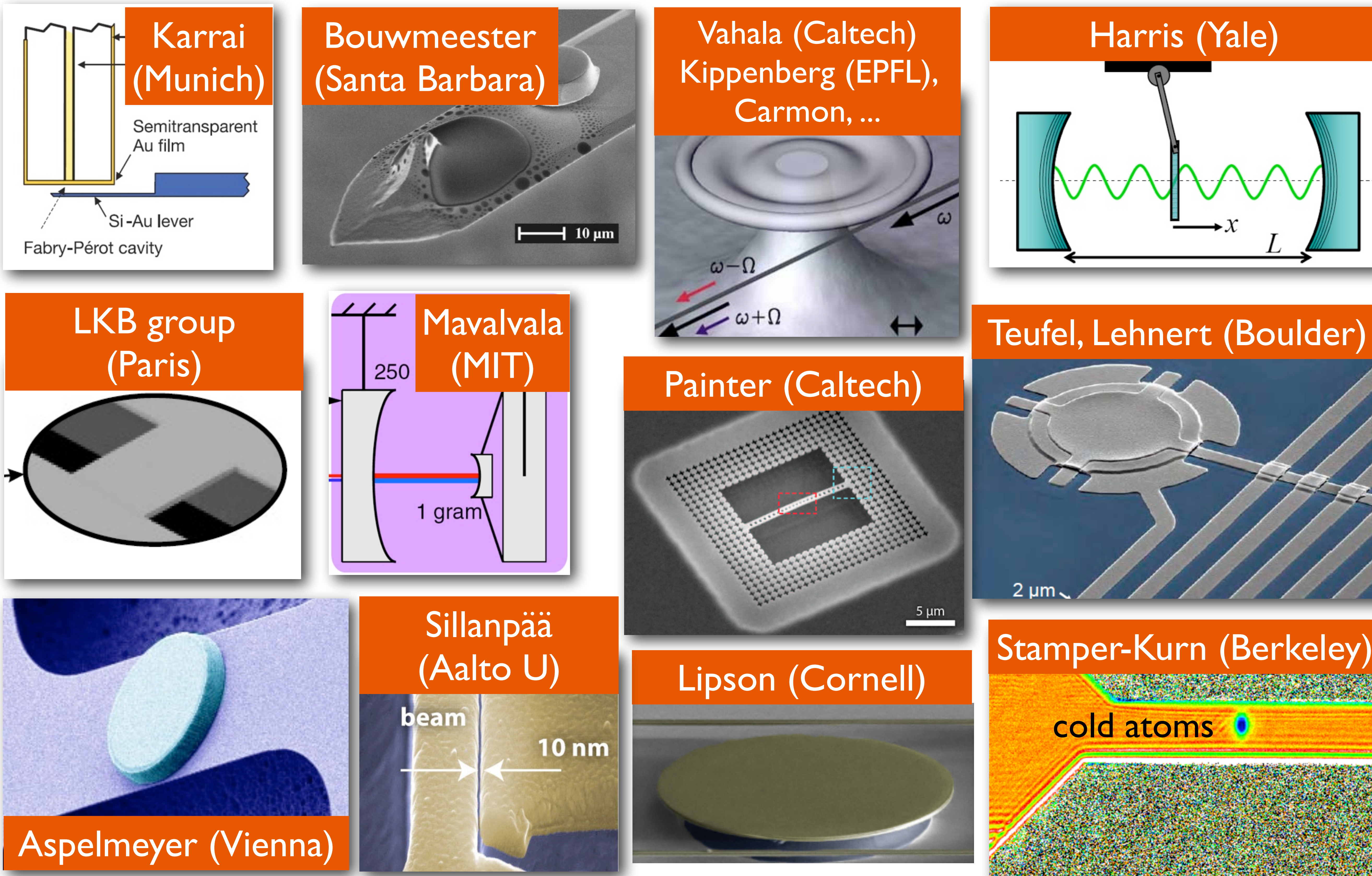




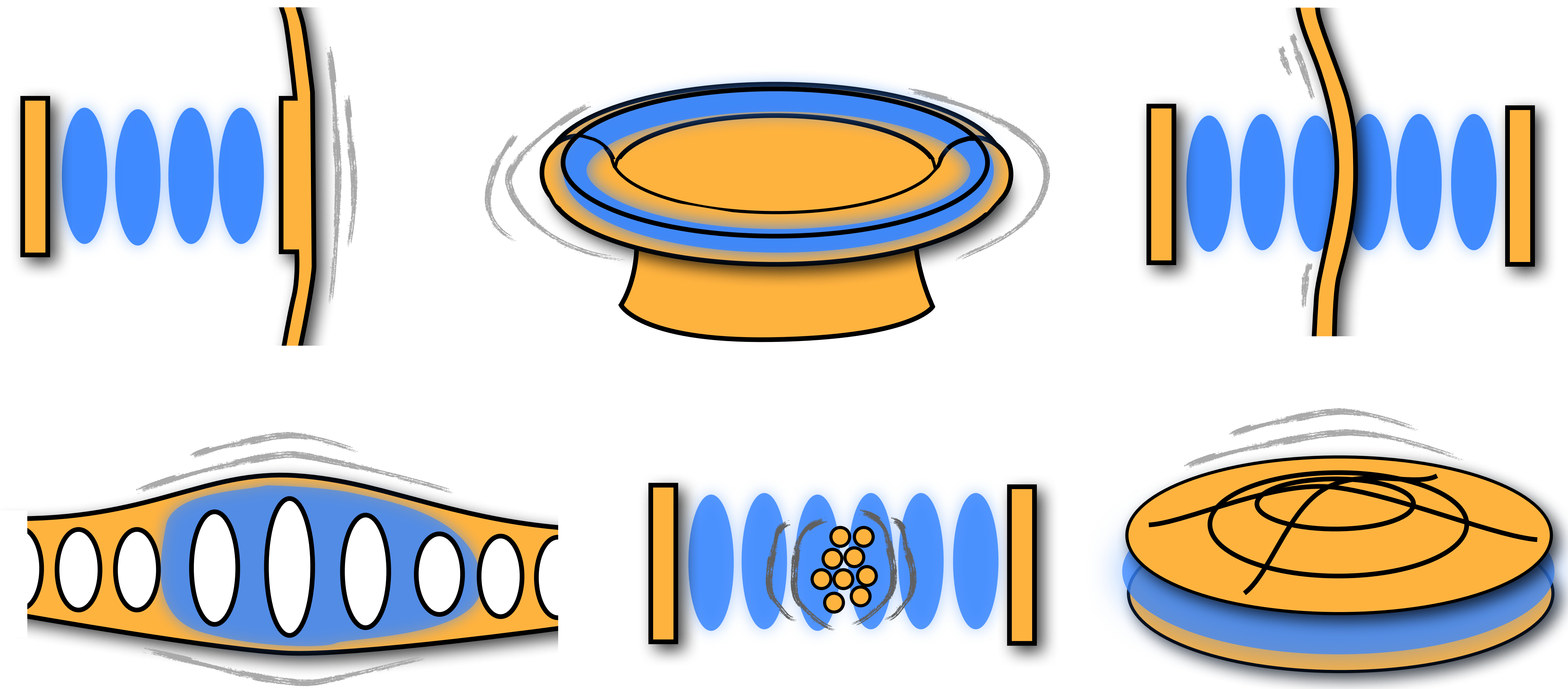
hysteresis

A zoo of devices

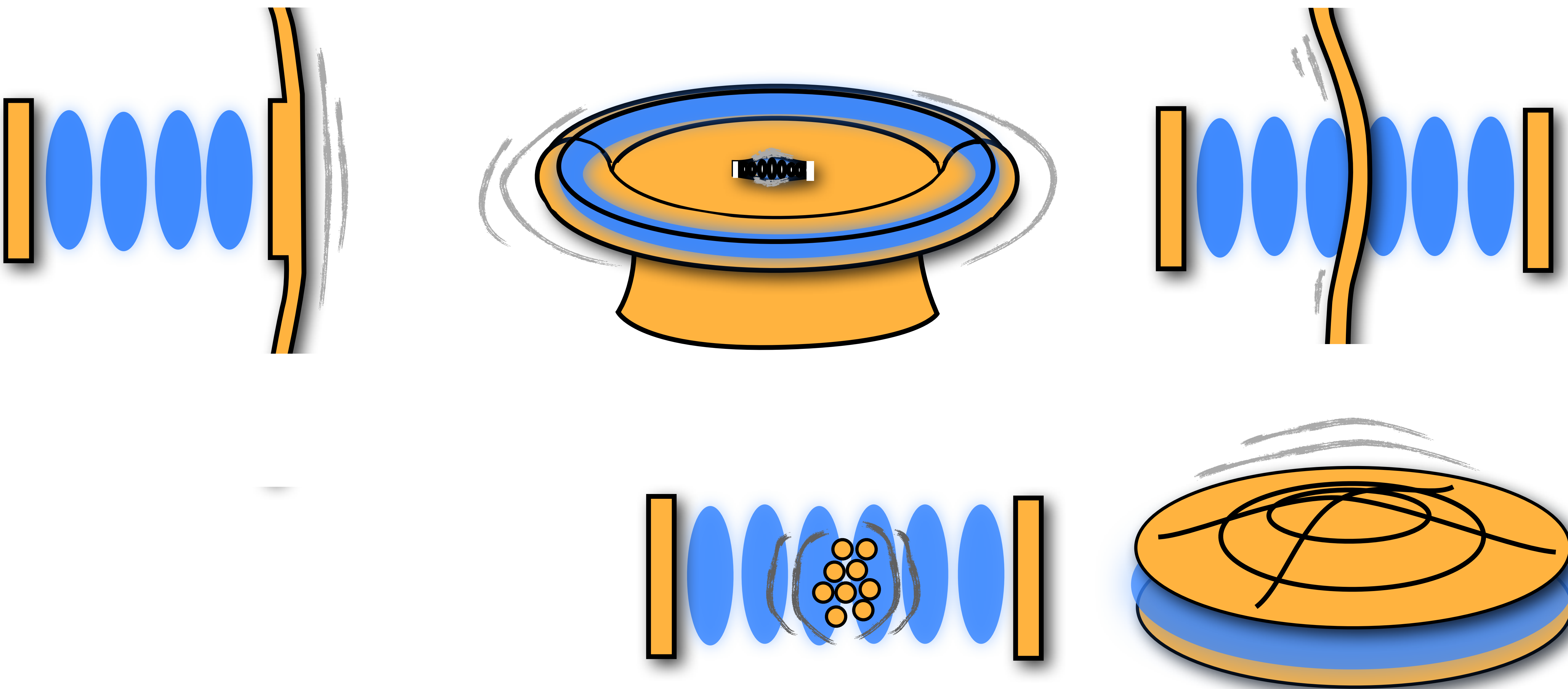
The zoo of optomechanical systems (2005-now)



The zoo of optomechanical systems

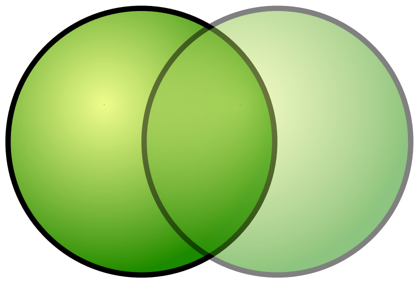


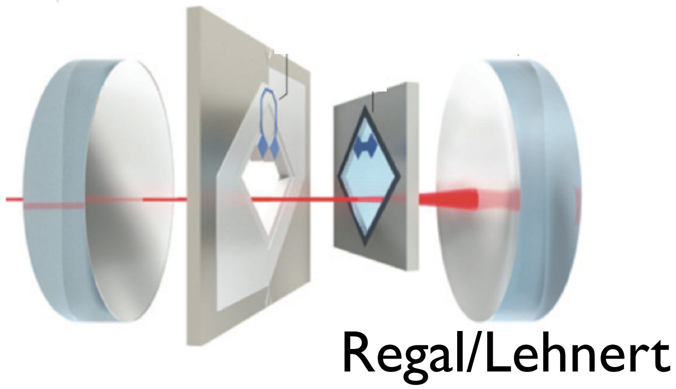
The zoo of optomechanical systems

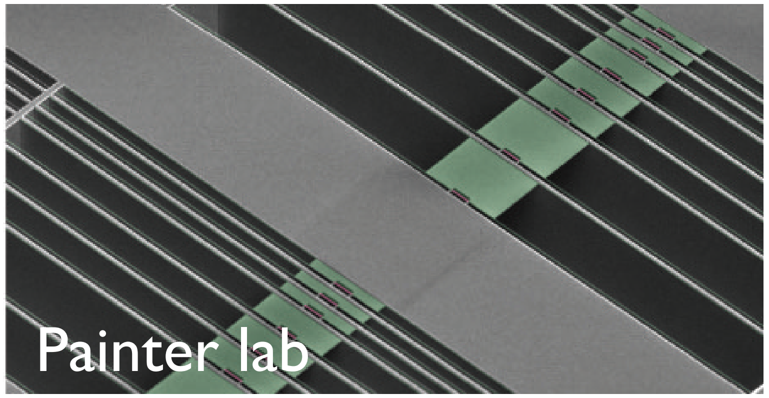


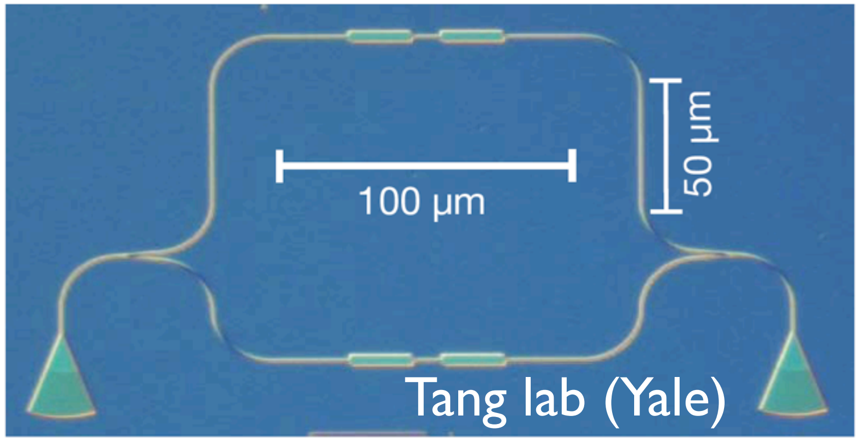
Why?

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, ...

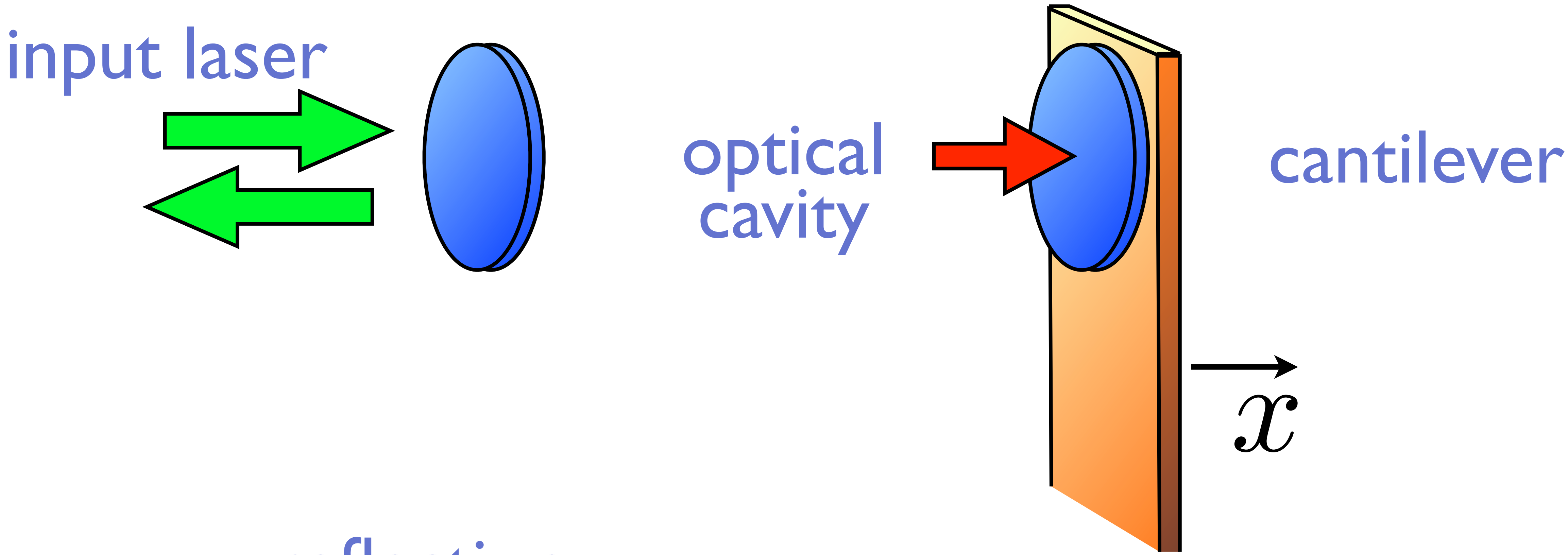
Precision measurements
small displacements, masses, forces, and accelerations

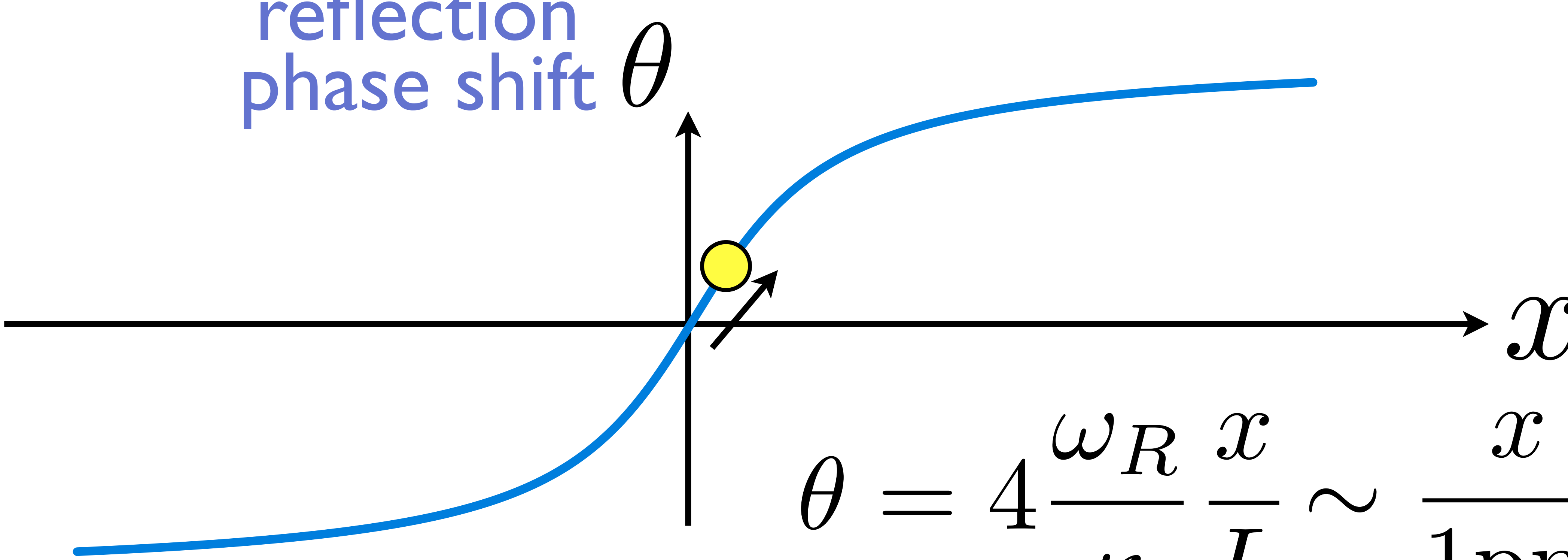
Optomechanical circuits & arrays
Exploit nonlinearities for classical and quantum information processing, storage, and amplification; study collective dynamics in arrays

Sensing mechanical motion at the quantum limit


Laser Interferometer for
Gravitational Wave Detection
LIGO Livingston

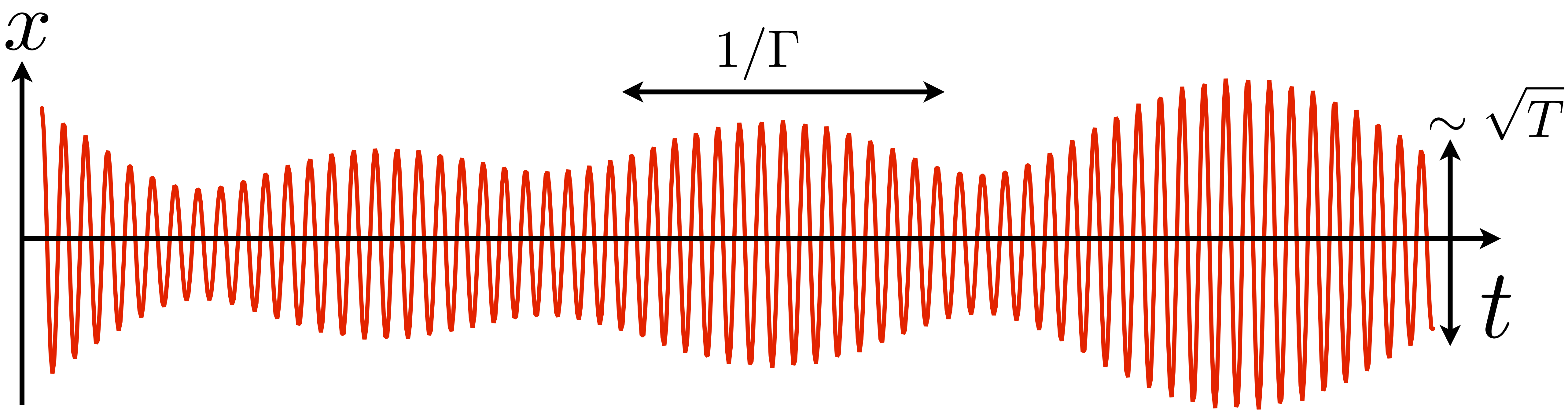
Optical displacement detection





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

Thermal fluctuations of a harmonic oscillator



Classical equipartition theorem:

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

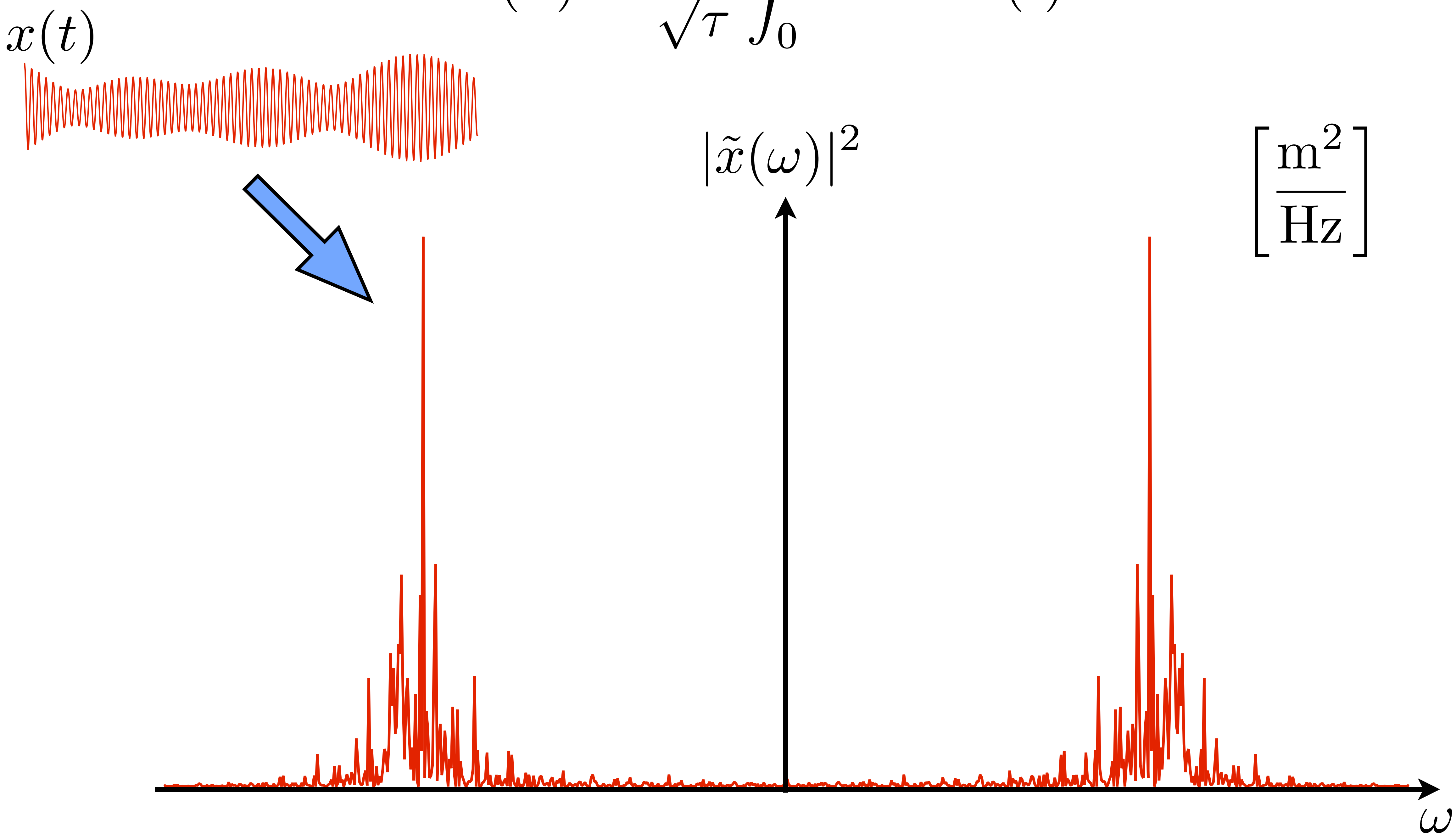
extract temperature!

Possibilities:

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

Fluctuation spectrum

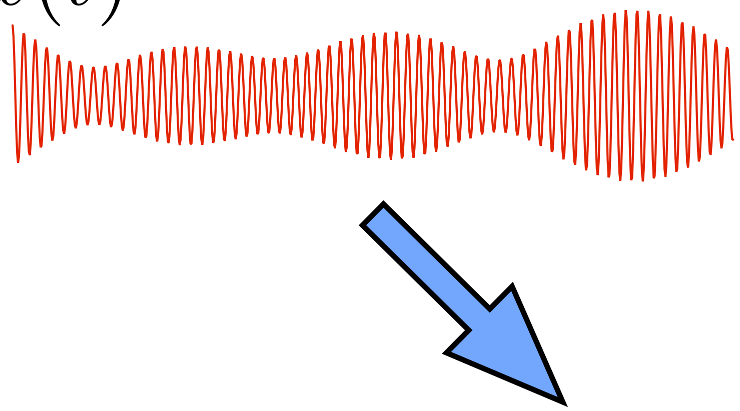
$$\tilde{x}(\omega) = \frac{1}{\sqrt{\tau}} \int_0^{\tau} dt e^{i\omega t} x(t)$$



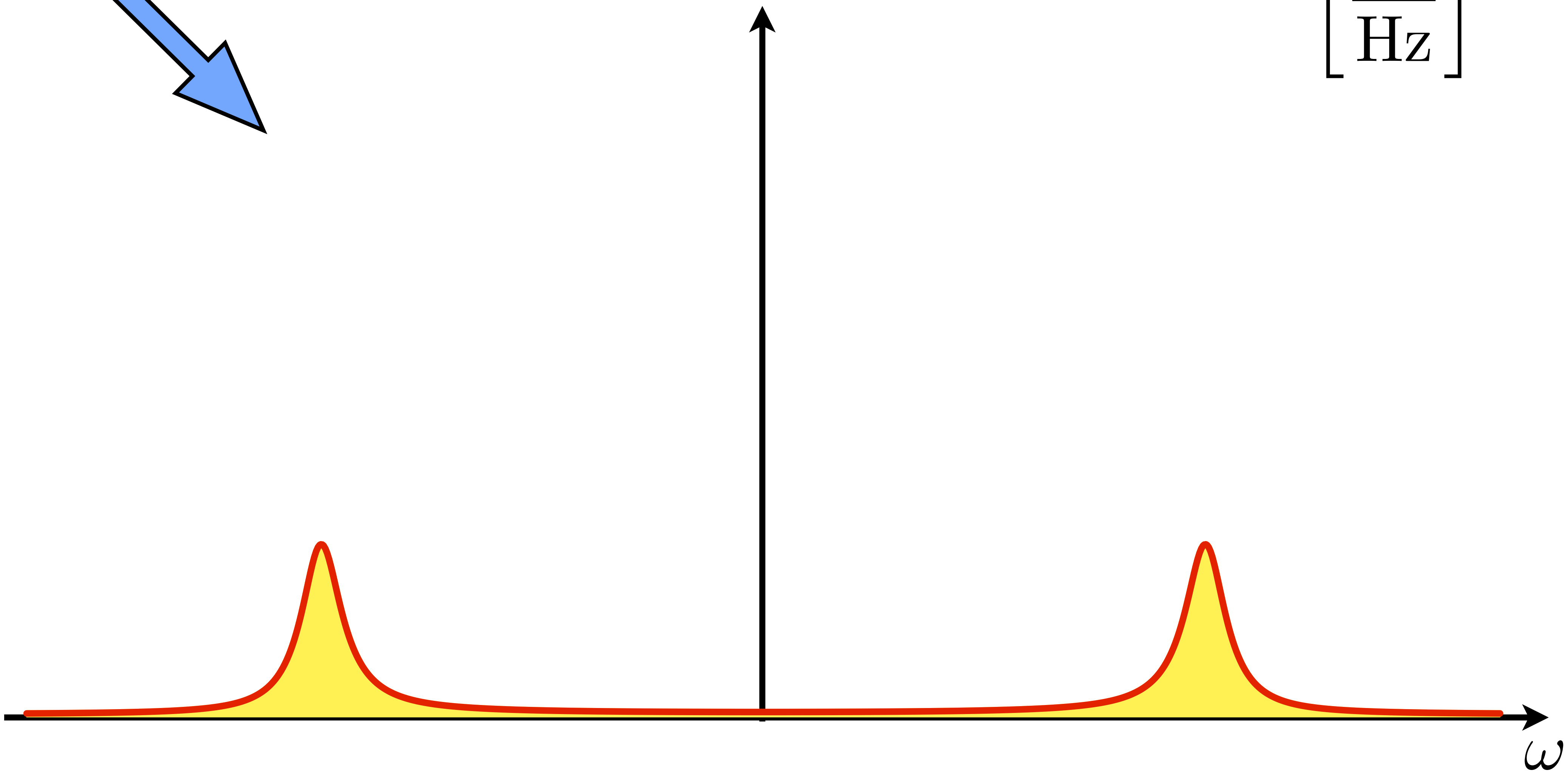
Fluctuation spectrum

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

$x(t)$



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



Fluctuation spectrum

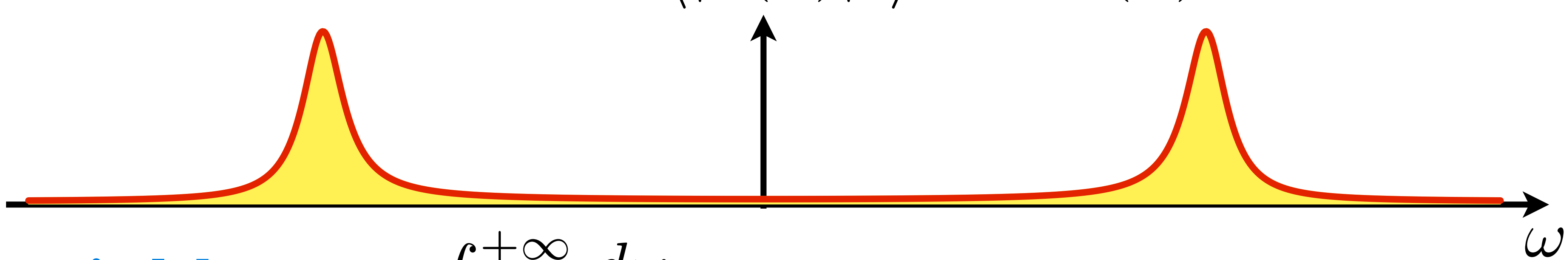
$$\tilde{x}(\omega) = \frac{1}{\sqrt{\tau}} \int_0^{\tau} dt e^{i\omega t} x(t)$$

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

$$\approx \quad \int_{-\infty}^{+\infty} dt e^{i\omega t} \left\langle x(t) x(0) \right\rangle$$

“Wiener-Khinchin theorem”

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



area yields variance of x:

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

Fluctuation-dissipation theorem

General relation between noise spectrum and linear response susceptibility

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

susceptibility

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

(classical limit)

Fluctuation-dissipation theorem

General relation between noise spectrum and linear response susceptibility

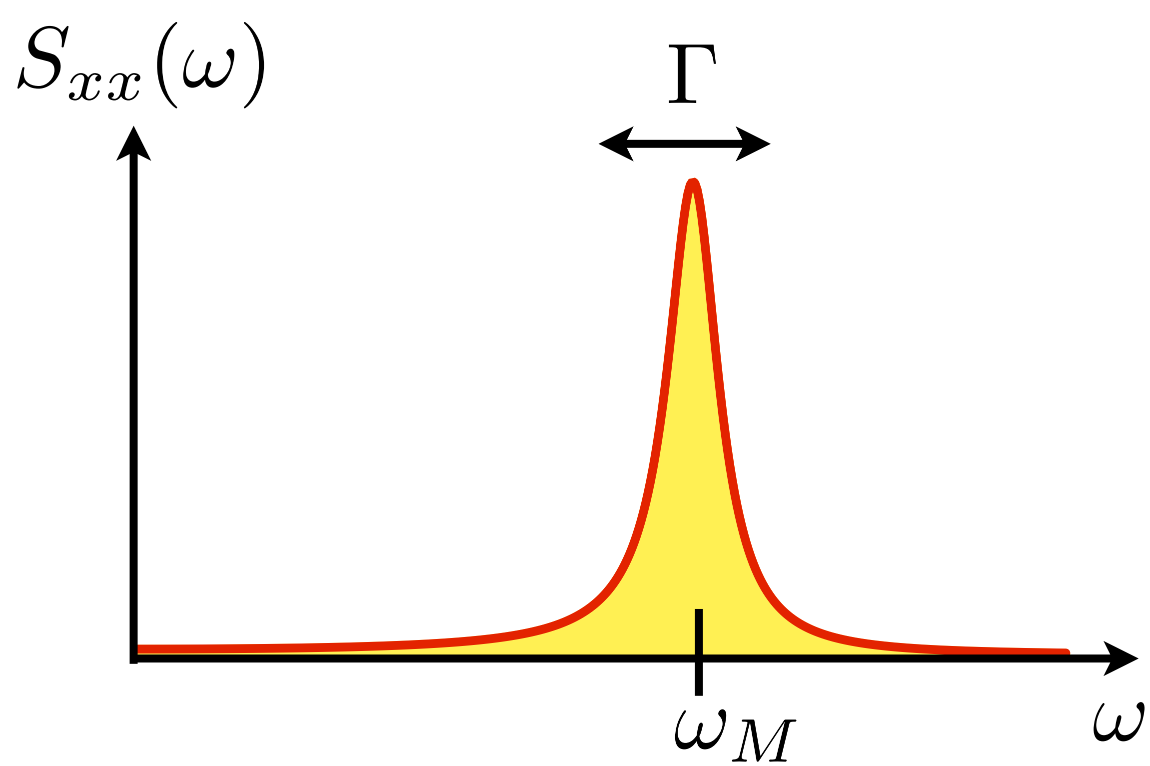
$$\langle \delta x \rangle (\omega) = \underbrace{\chi_{xx}(\omega)}_{\text{susceptibility}} F(\omega)$$

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

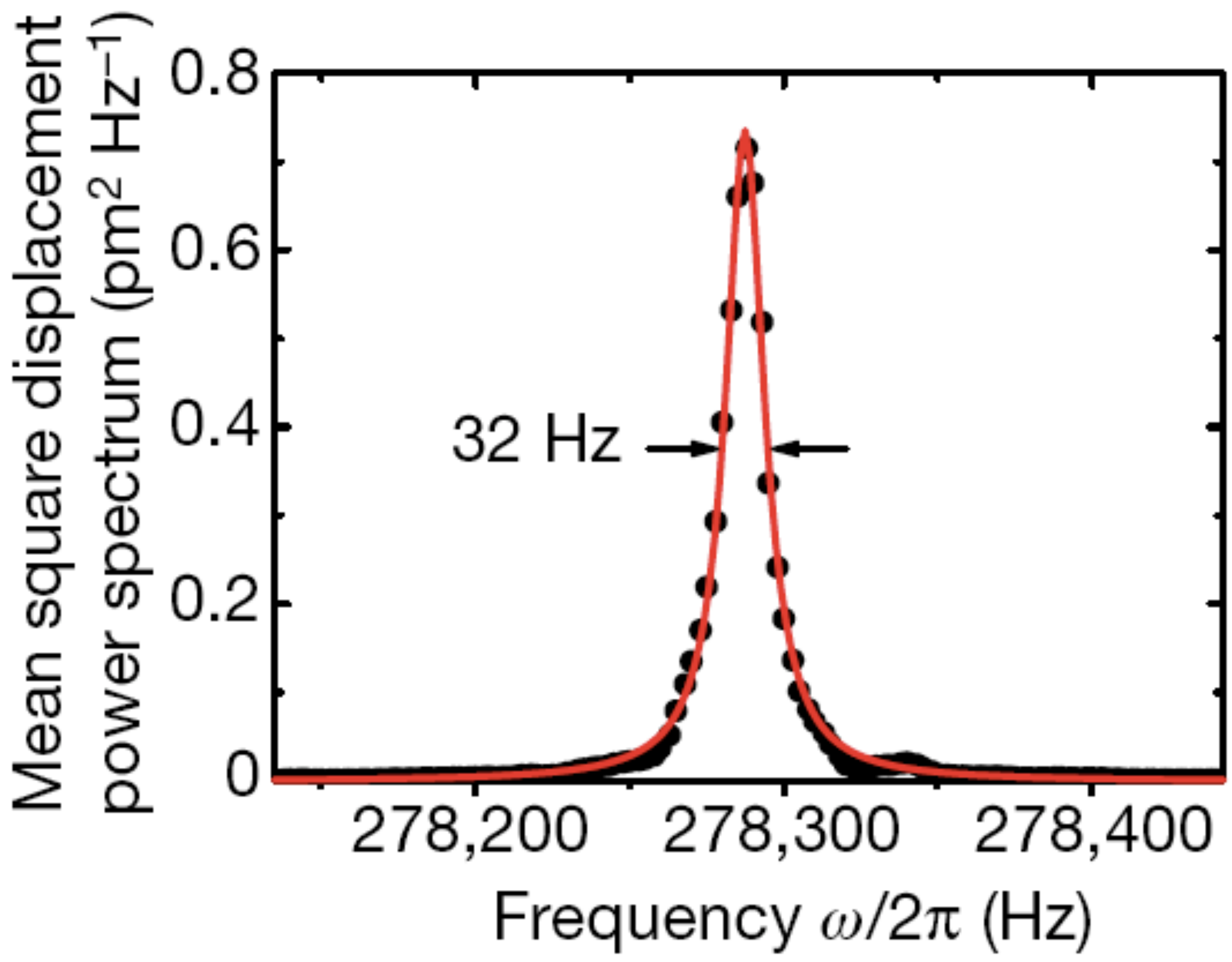
for the damped oscillator:

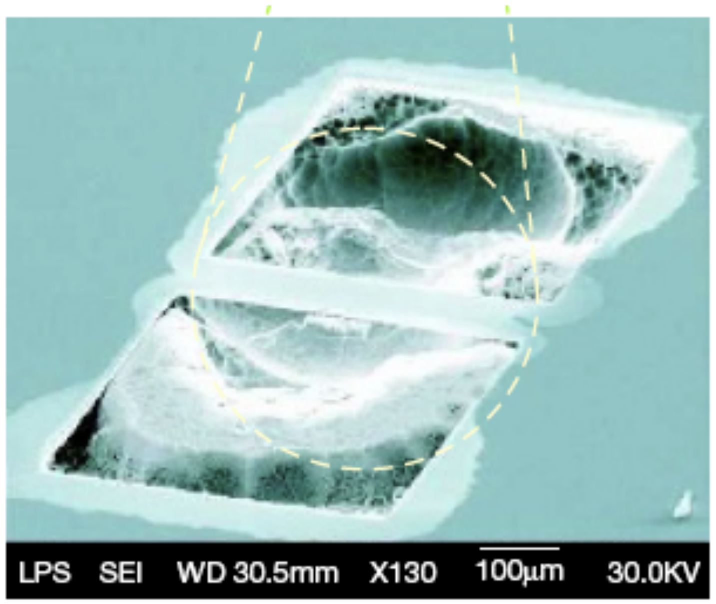
$$m\ddot{x} + m\omega_M^2 x + m\Gamma\dot{x} = F$$

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



Displacement spectrum

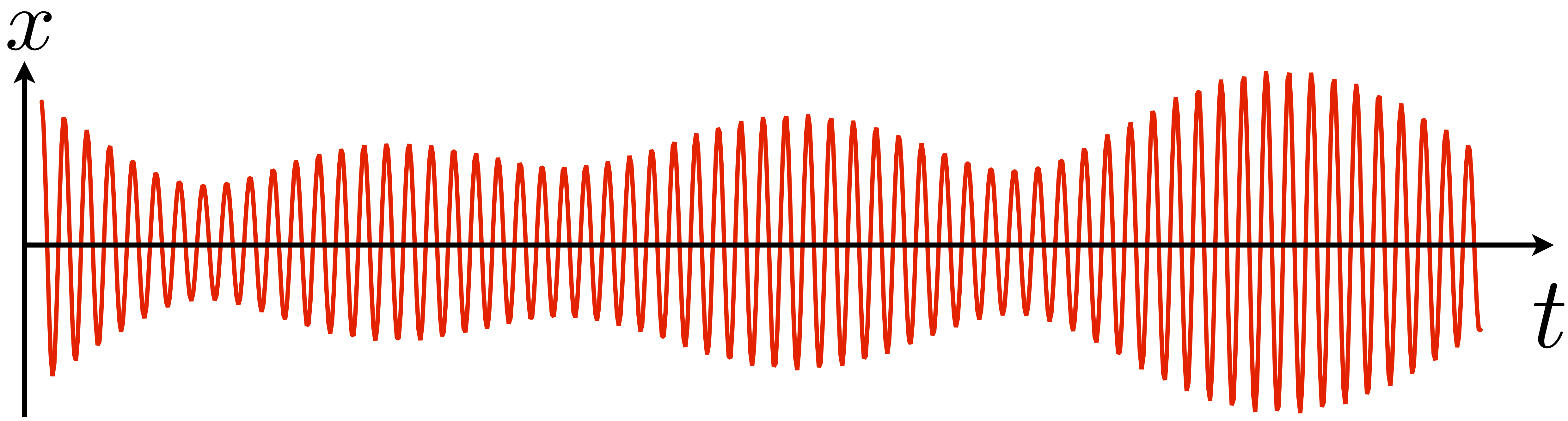




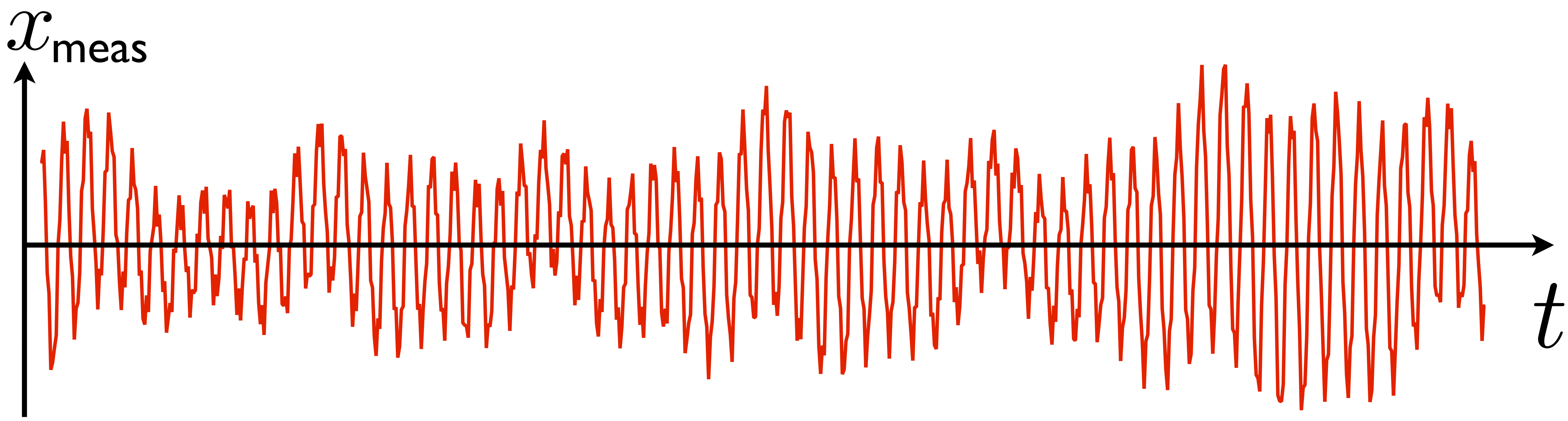
T=300 K

Experimental curve:
Gigan et al., Nature 2006

Measurement noise



Measurement noise



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

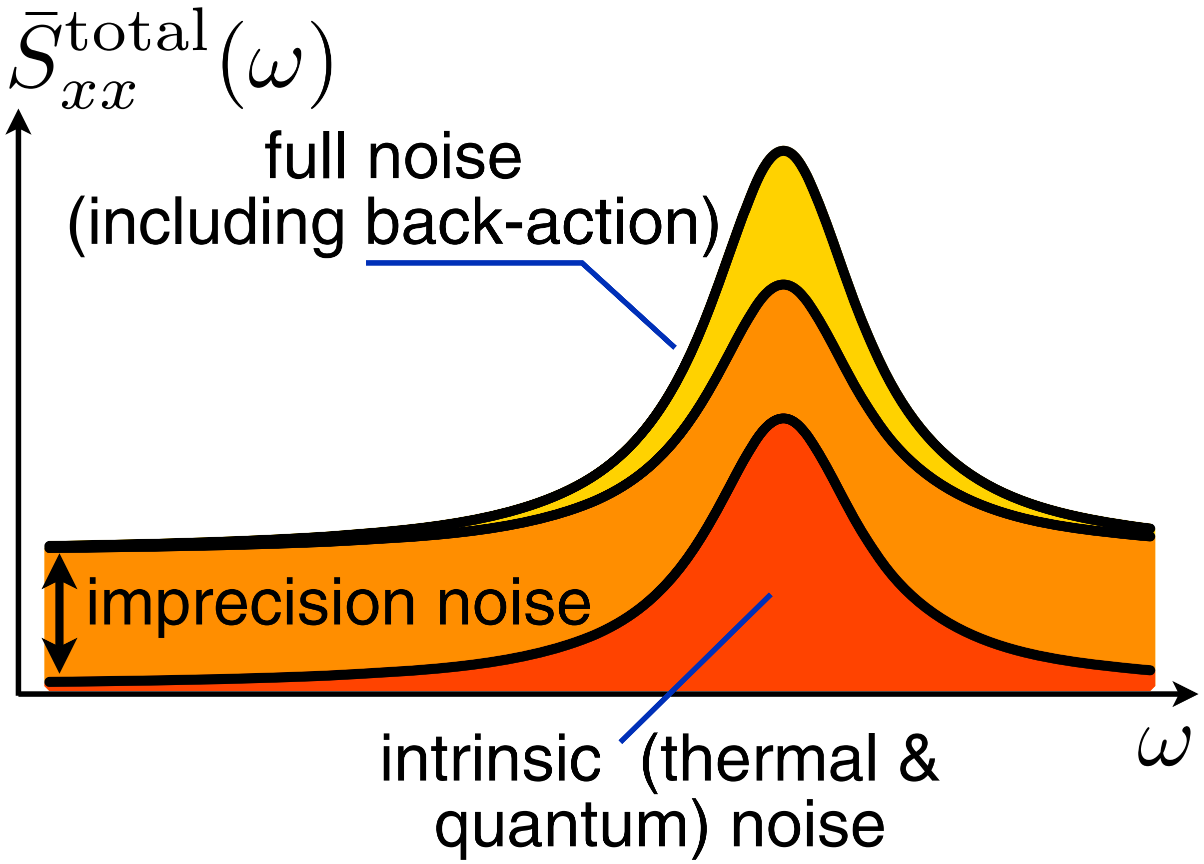
Two contributions to $x_{\text{noise}}(t)$

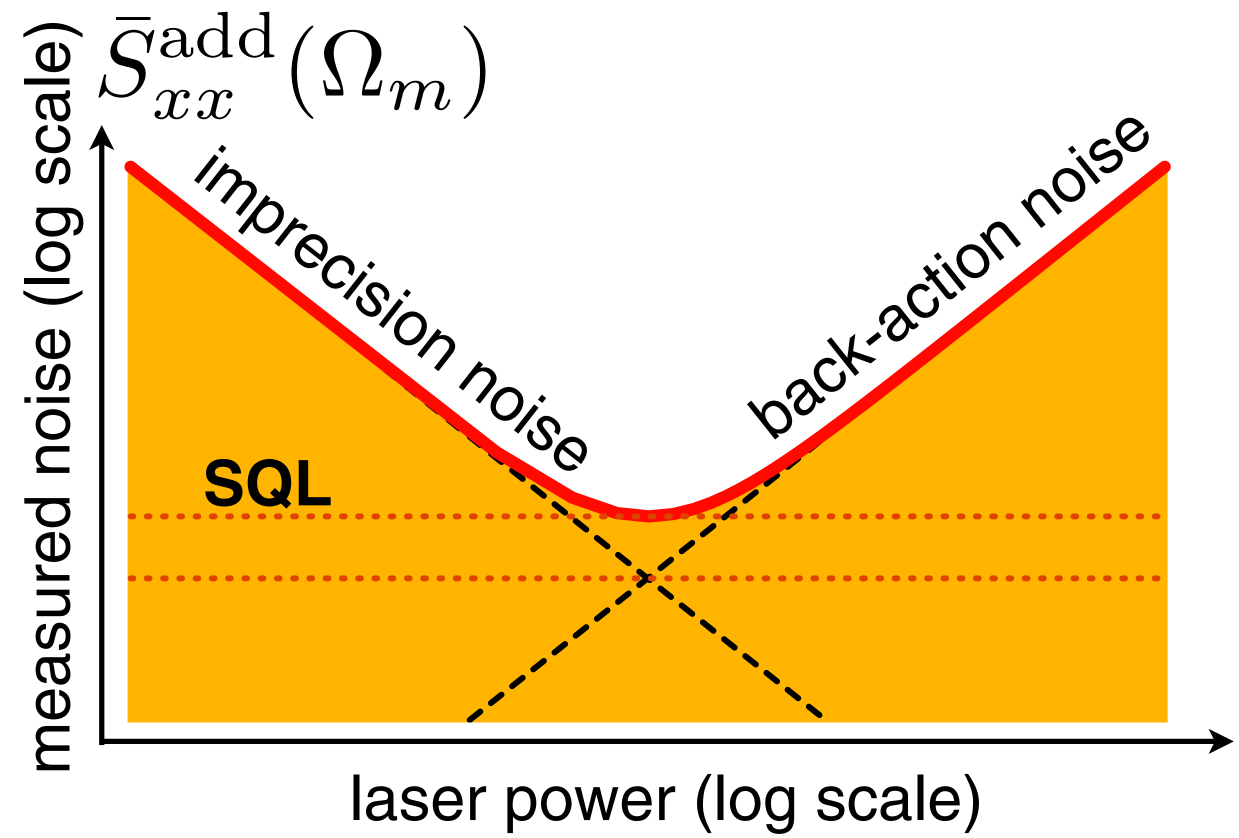
1. measurement imprecision
2. measurement back-action: fluctuating force on system

phase noise of laser beam (shot noise limit!)

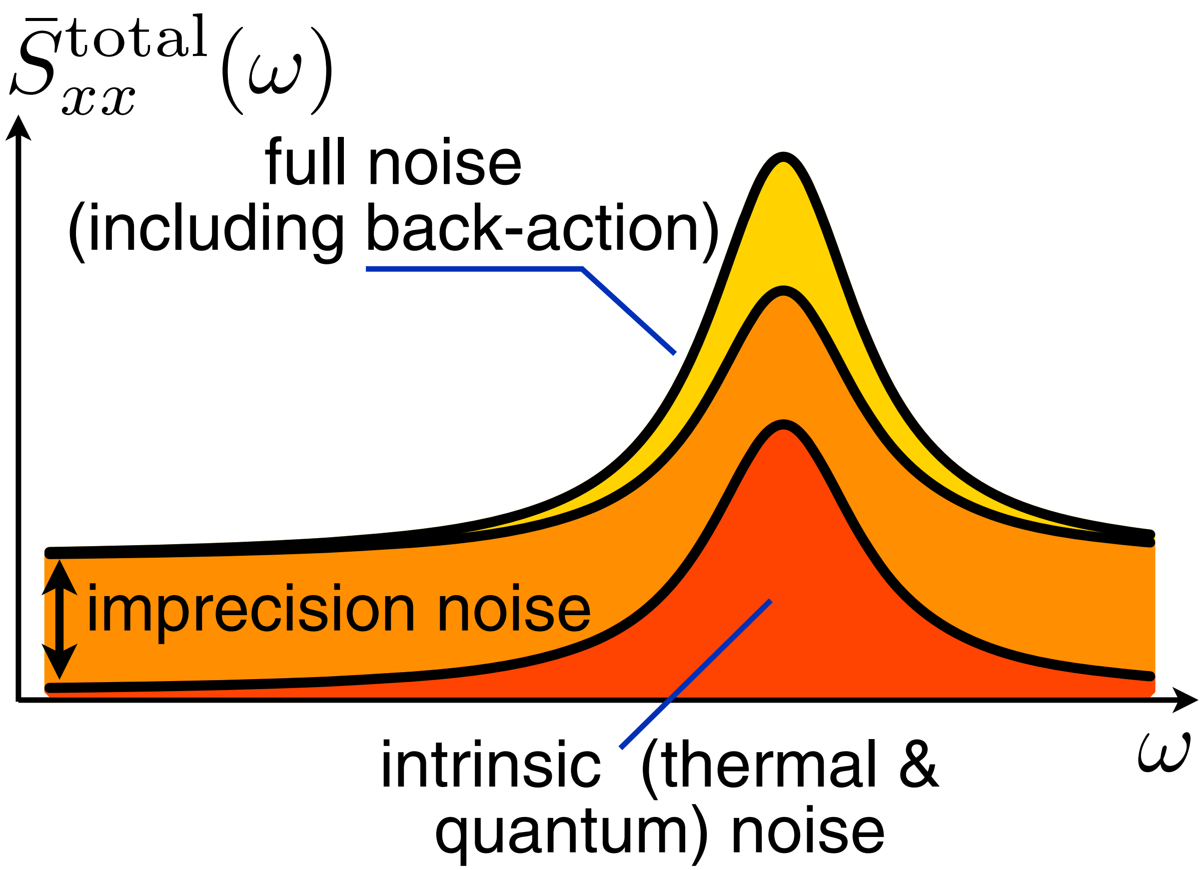
noisy radiation pressure force

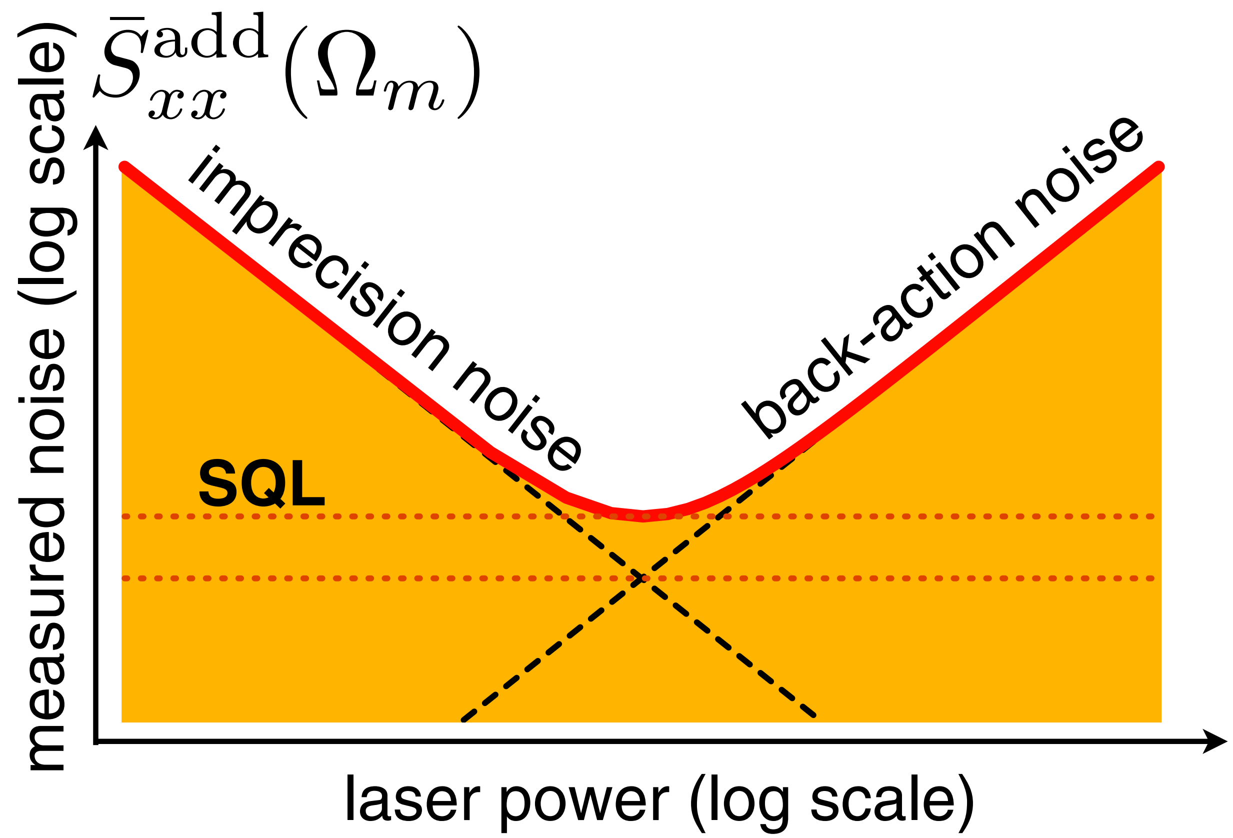
"Standard Quantum Limit"





“Standard Quantum Limit”





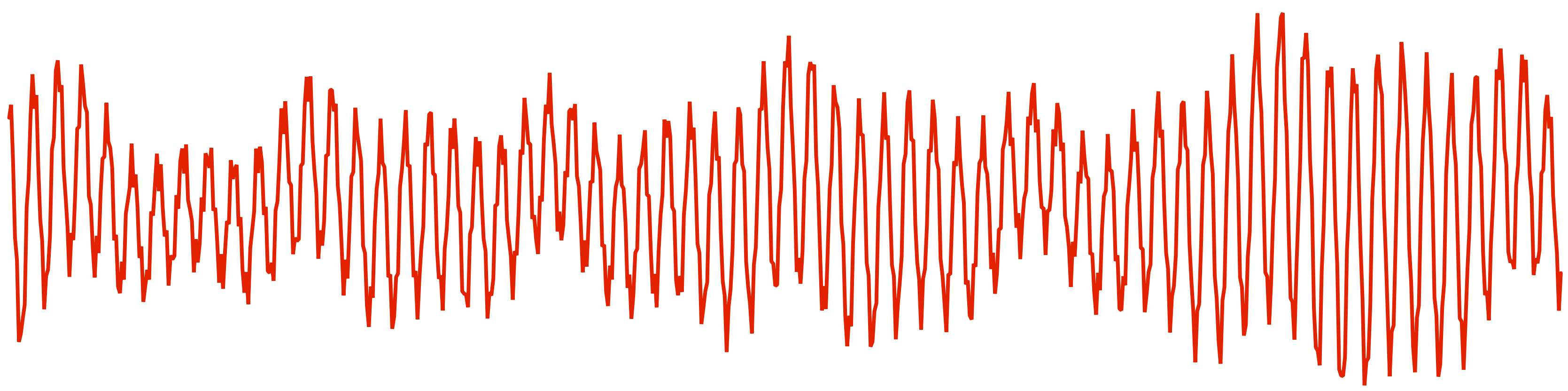
Best case allowed by quantum mechanics:

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

“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



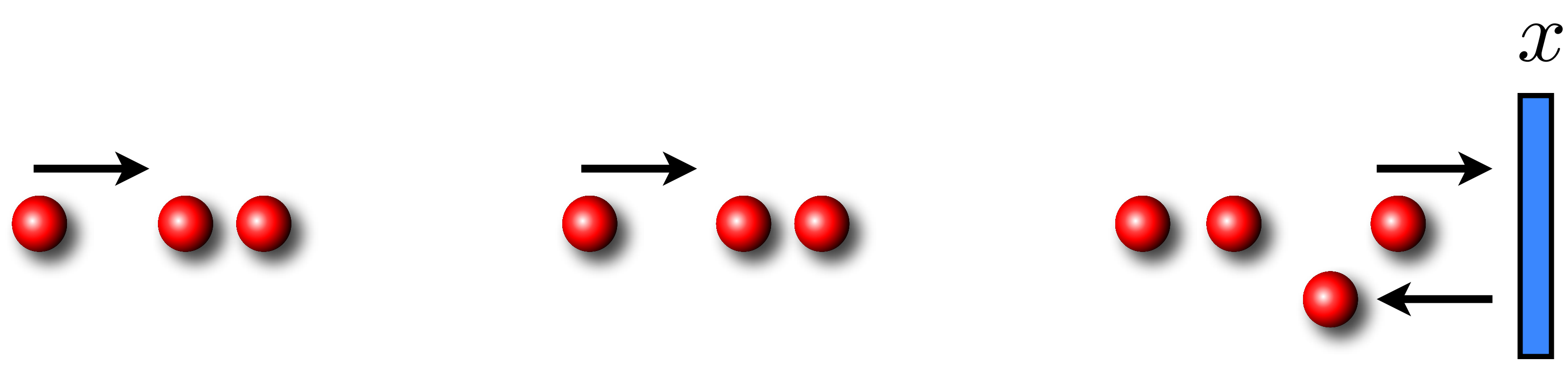
- "weak measurement": integrating the signal over time to suppress the noise
- trying to detect slowly varying "quadratures of motion": $\hat{x}(t) = \hat{X}_1 \cos(\omega_M t) + \hat{X}_2 \sin(\omega_M t)$

  $\left[\hat{X}_1, \hat{X}_2\right] = 2x_{\mathrm{ZPF}}^2$ 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: $x_{\mathrm{ZPF}} \sim 10^{-15} m$!

Enforcing the SQL (Heisenberg) in a weak optical measurement



reflection phase shift: $\theta = 2kx$
(here: free space)

N photons arrive in time t

fluctuations: $\delta N = \sqrt{\mathrm{Var} N} = \sqrt{\bar{N}}$

Poisson distribution for a coherent laser beam

1. Uncertainty in phase estimation:

$$\delta N \cdot \delta\theta \geq \frac{1}{2} \quad \Rightarrow \quad \delta\theta \geq \frac{1}{2\sqrt{\bar{N}}} \quad \Rightarrow \quad \delta x = \frac{\delta\theta}{2k} \sim \frac{1}{2\sqrt{\bar{N}}2k}$$

2. Fluctuating force: momentum transfer $\Delta p = 2\hbar k \cdot N$

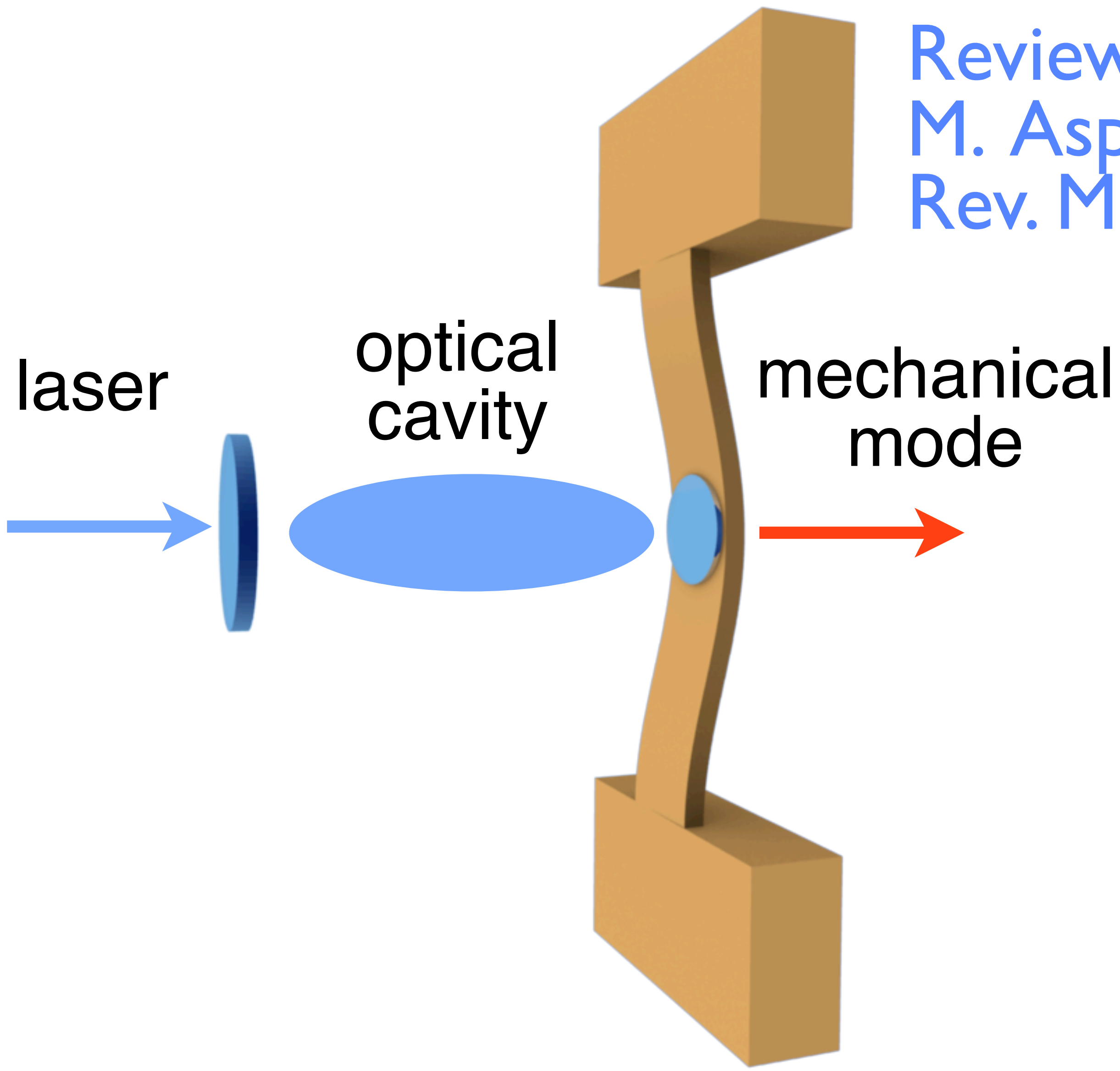
$$\delta p = \sqrt{\mathrm{Var}\Delta p} = 2\hbar k\sqrt{\bar{N}}$$

Uncertainty product: $\delta x \delta p \geq \frac{\hbar}{2}$ Heisenberg

Quantum dynamics

Optomechanical Hamiltonian

Review "Cavity Optomechanics":
M. Aspelmeyer, T. Kippenberg, FM
Rev. Mod. Phys. 2014



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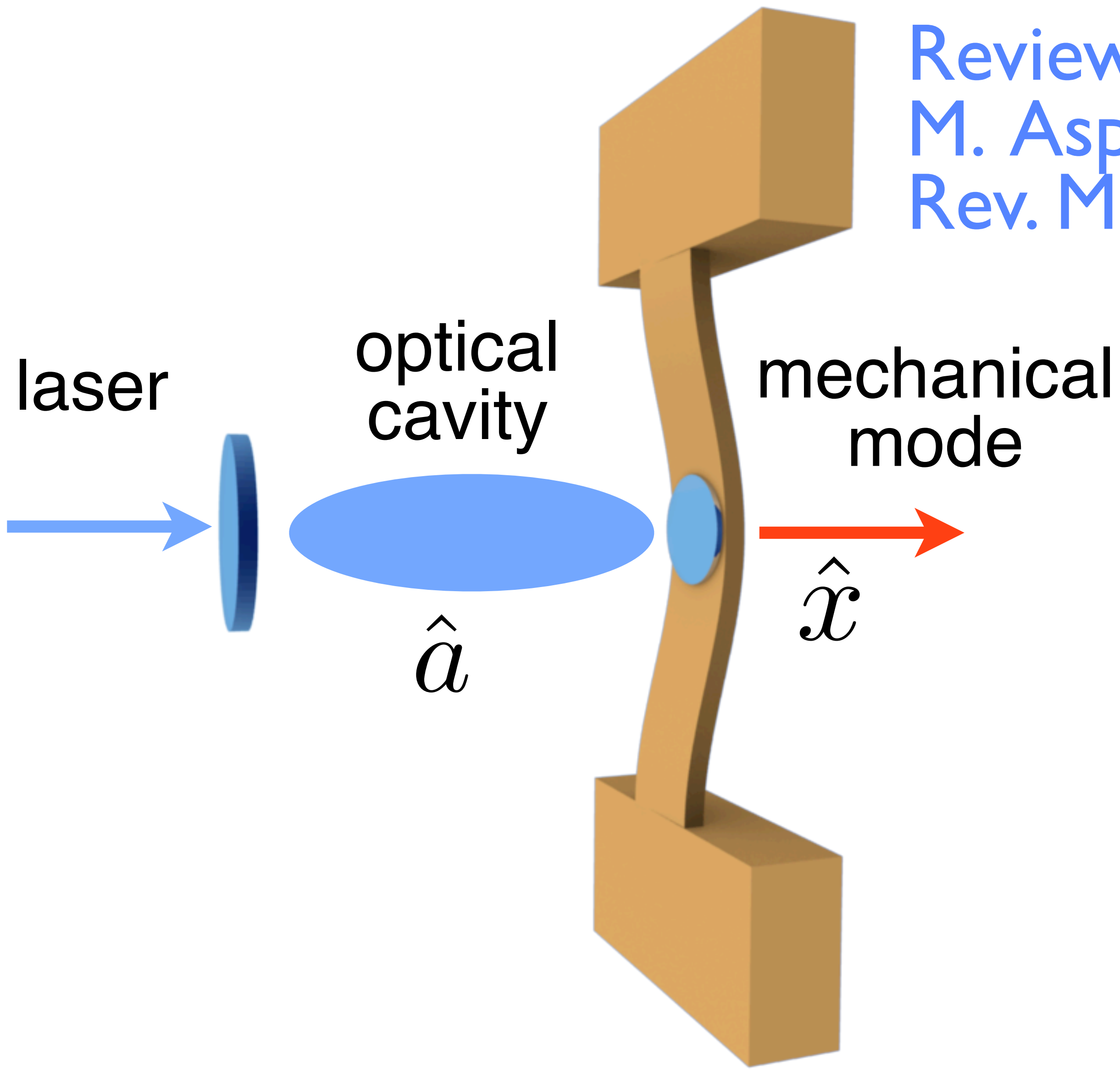

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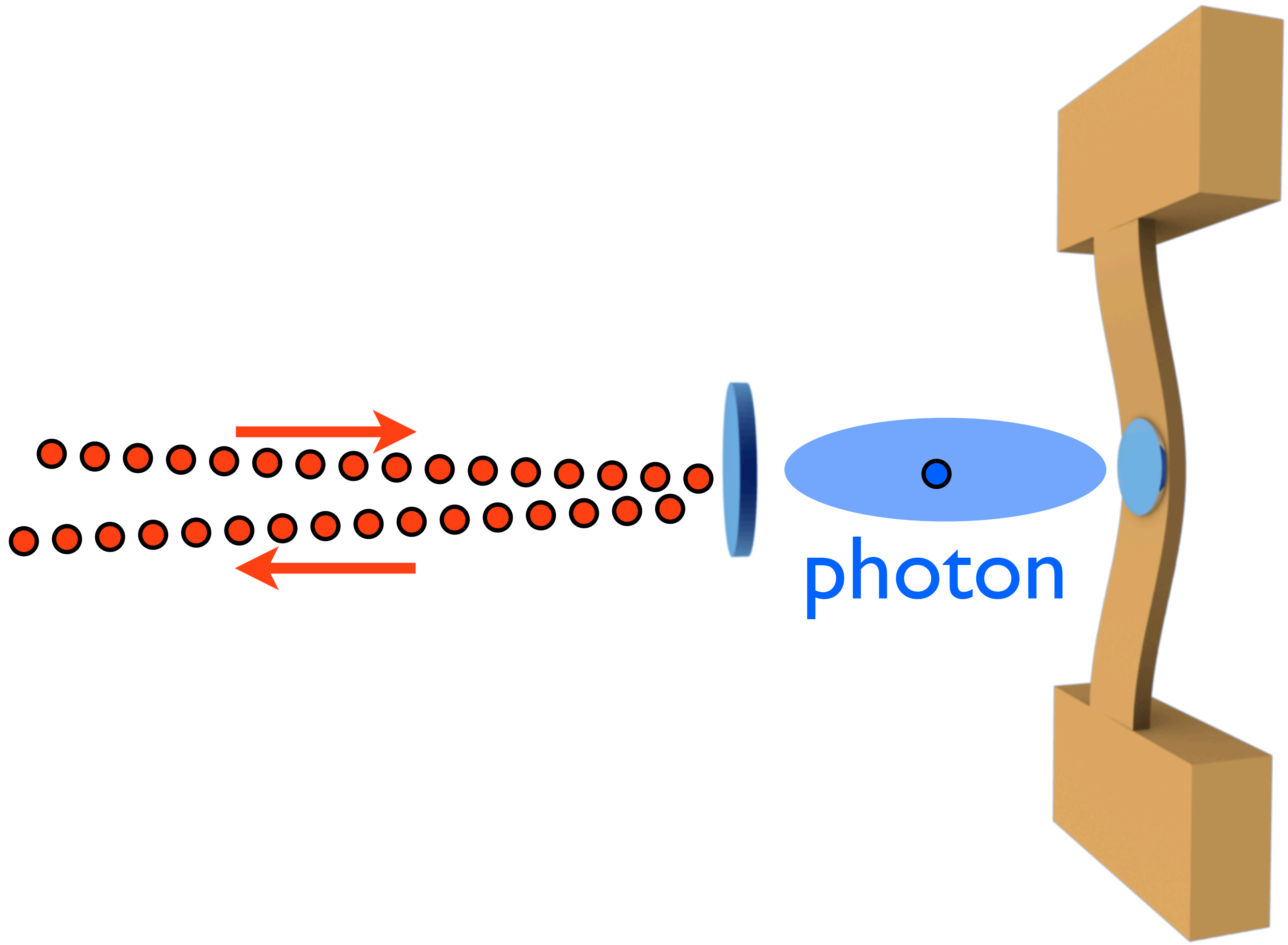
Converting photons into phonons



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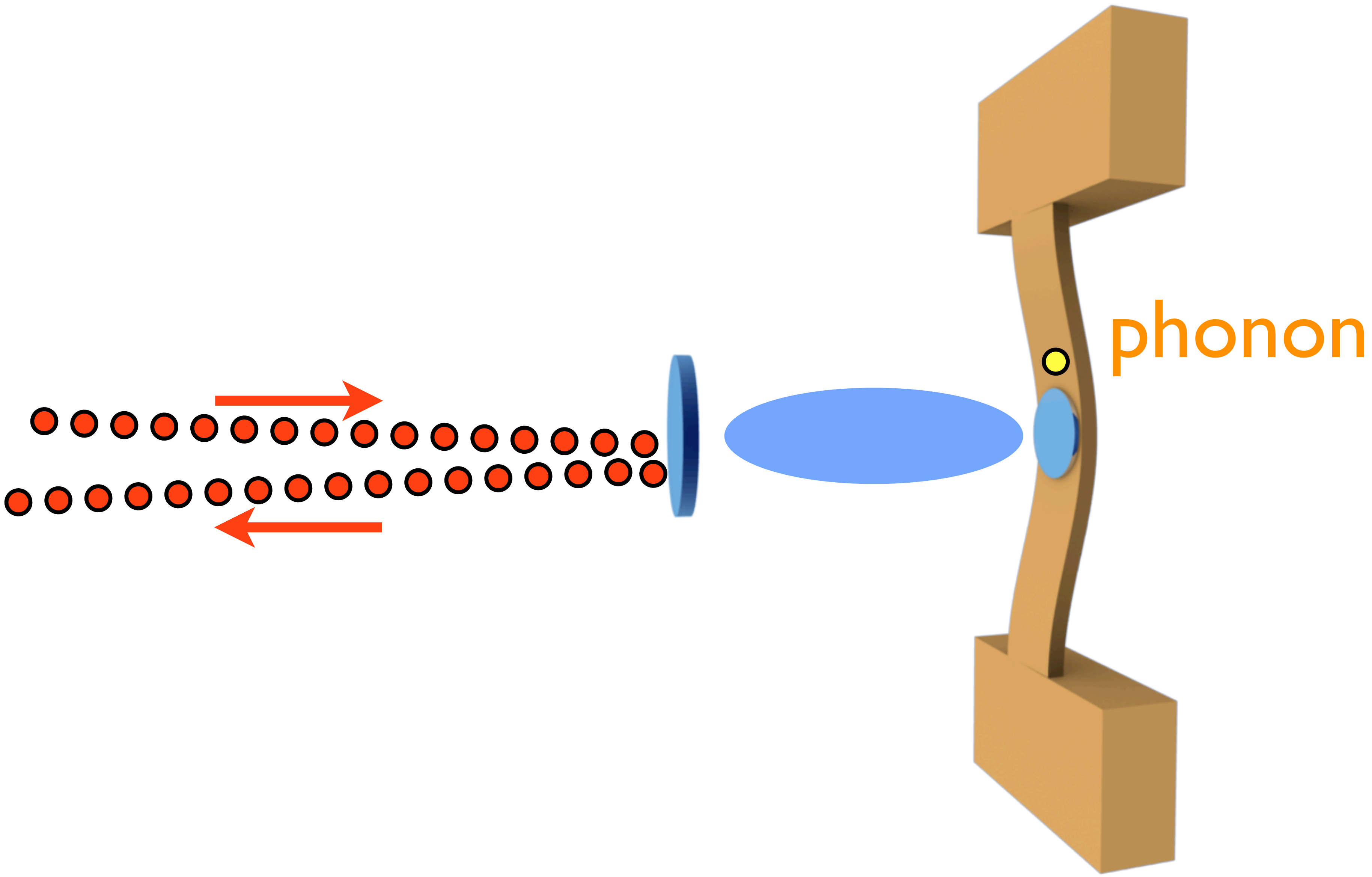

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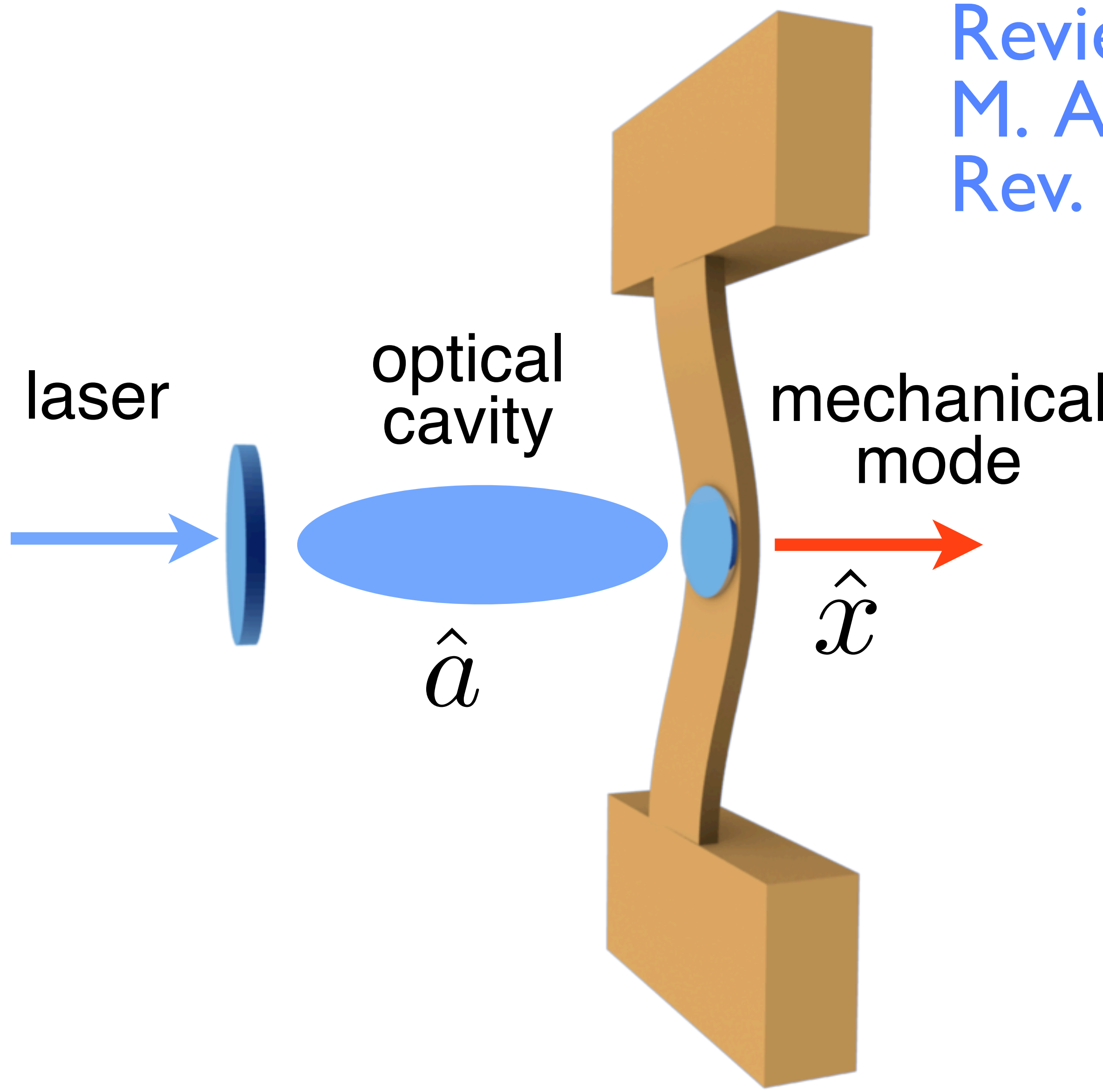


$$g_0 \sim \mathrm{Hz} - \mathrm{MHz}$$

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

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 Interaction: Nonlinear

$$\hat{a}^\dagger \hat{a}(\hat{b}^\dagger + \hat{b})$$

"Linearized" Optomechanical Hamiltonian

$$\hbar g_0 \hat{a}^\dagger \hat{a} (\hat{b} + \hat{b}^\dagger)$$

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

$$\hbar g_0 (\alpha \delta\hat{a}^\dagger + \alpha^* \delta\hat{a})(\hat{b} + \hat{b}^\dagger)$$

"laser-enhanced optomechanical coupling": $g = g_0 \alpha$

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

bare optomechanical coupling
(geometry, etc.: fixed!)

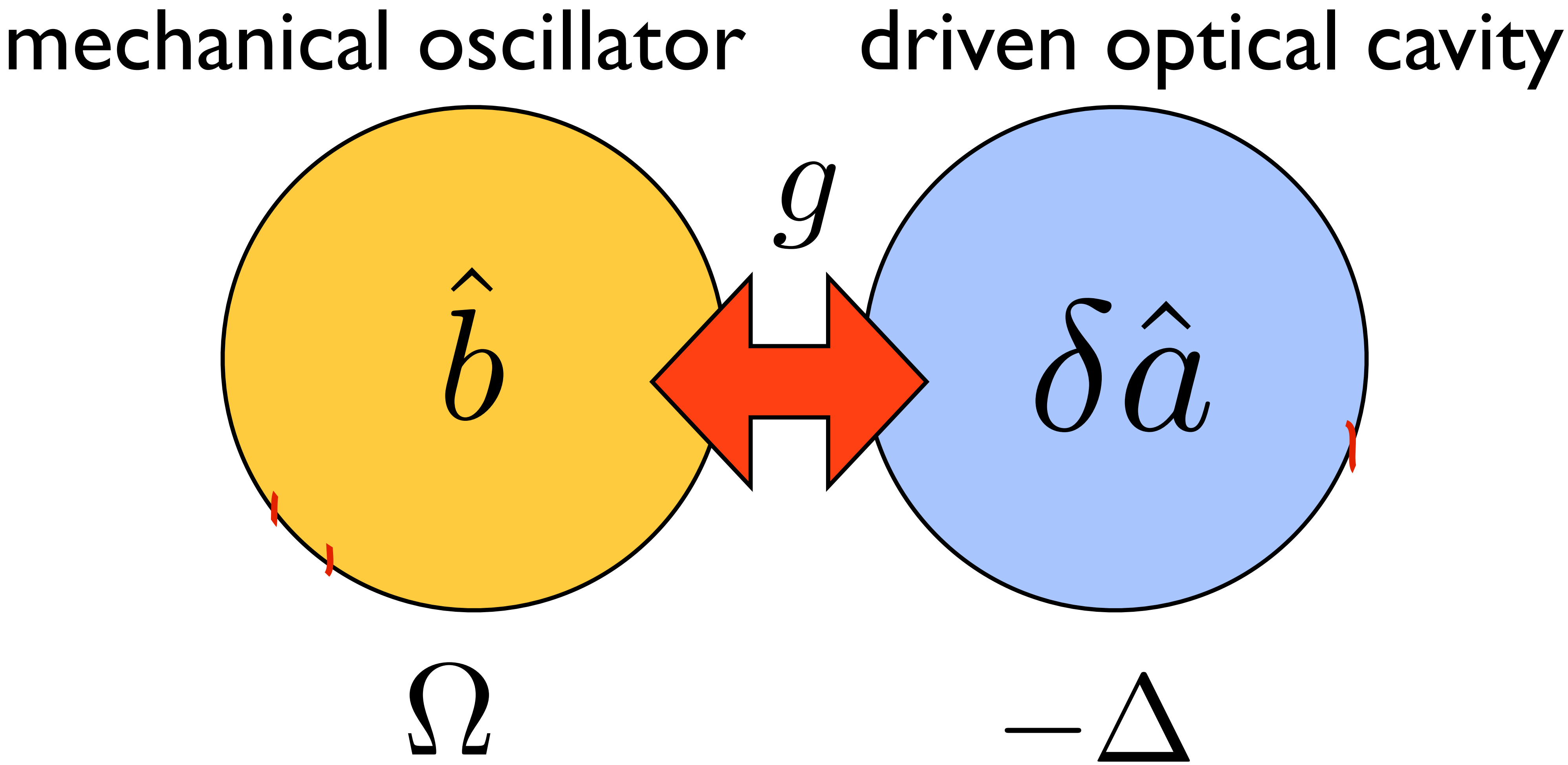
$$\alpha$$

laser-driven
cavity amplitude

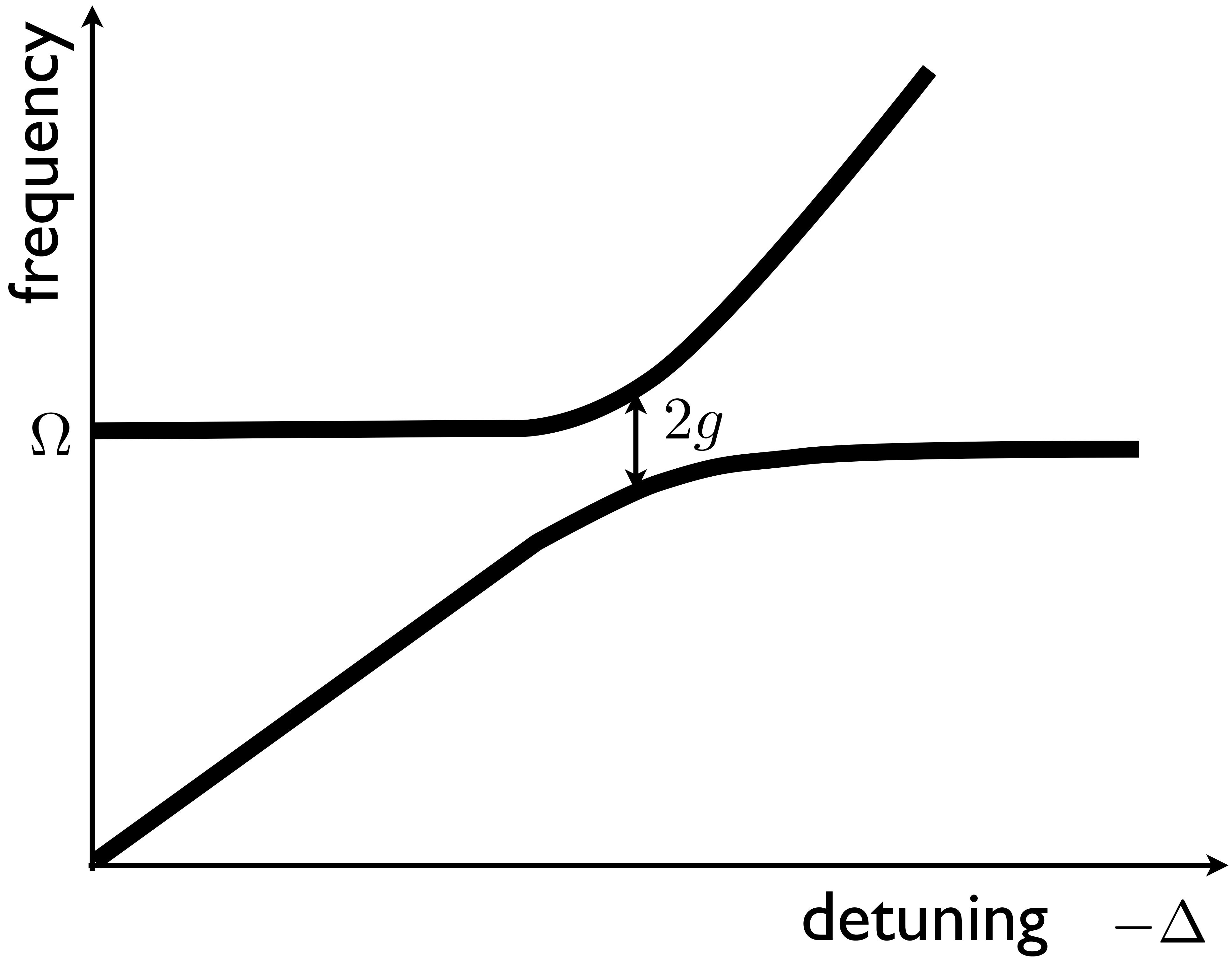
tuneable! **phase**!

Phonons & Photons

After linearization: two linearly coupled harmonic oscillators!



Photon-phonon polaritons



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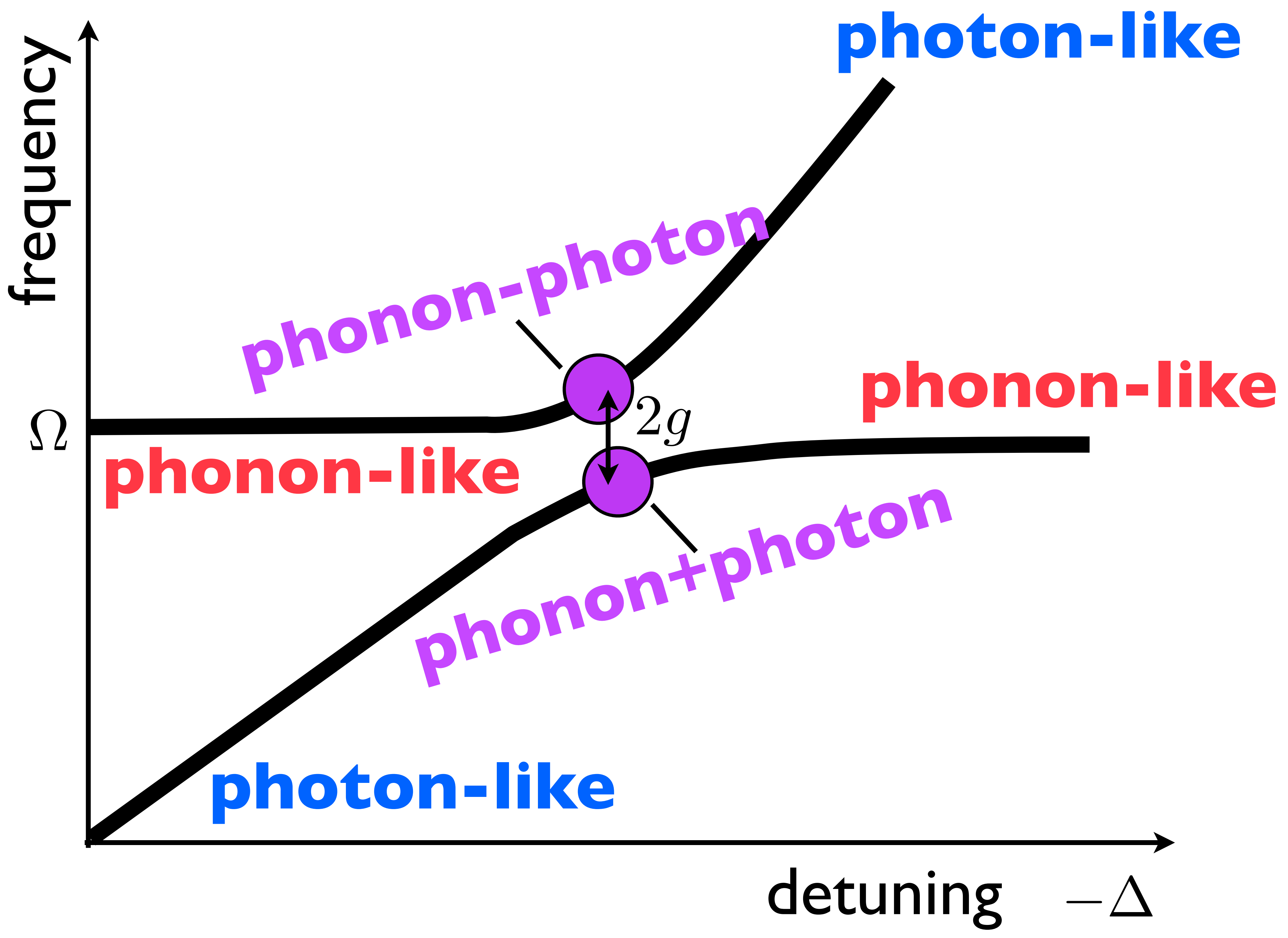

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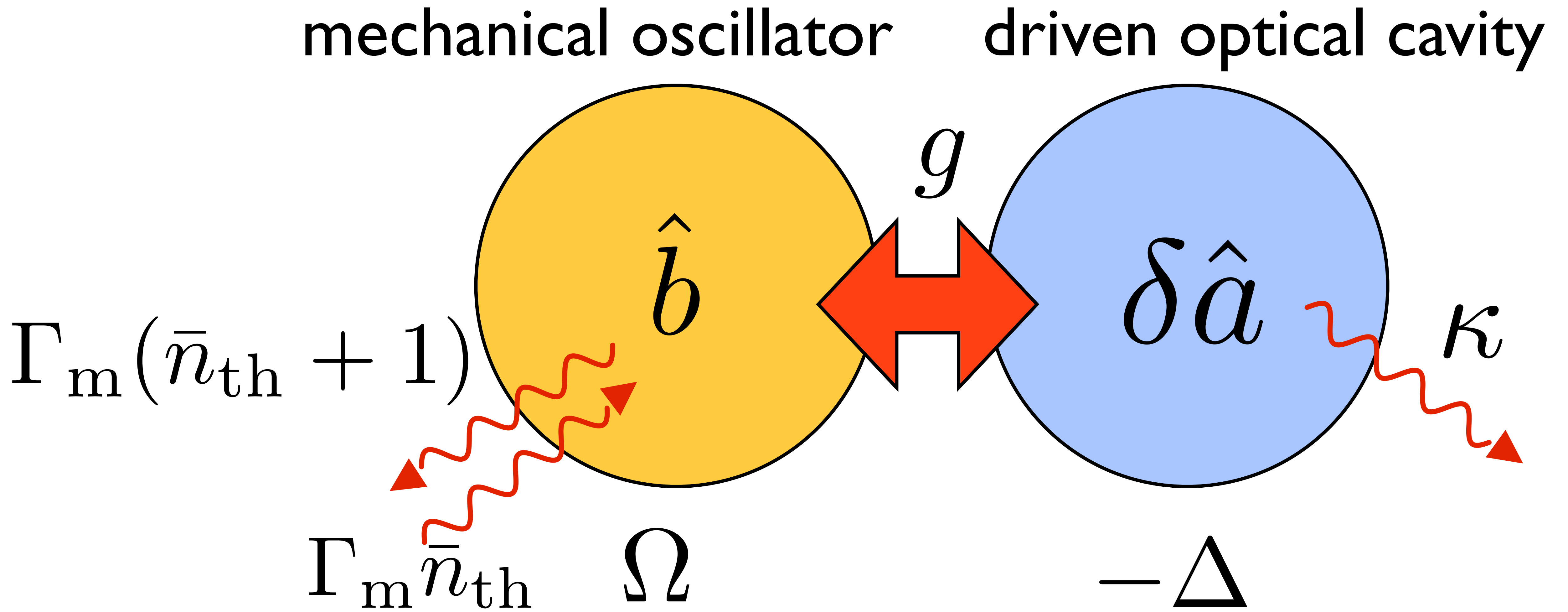

Phonons & Photons

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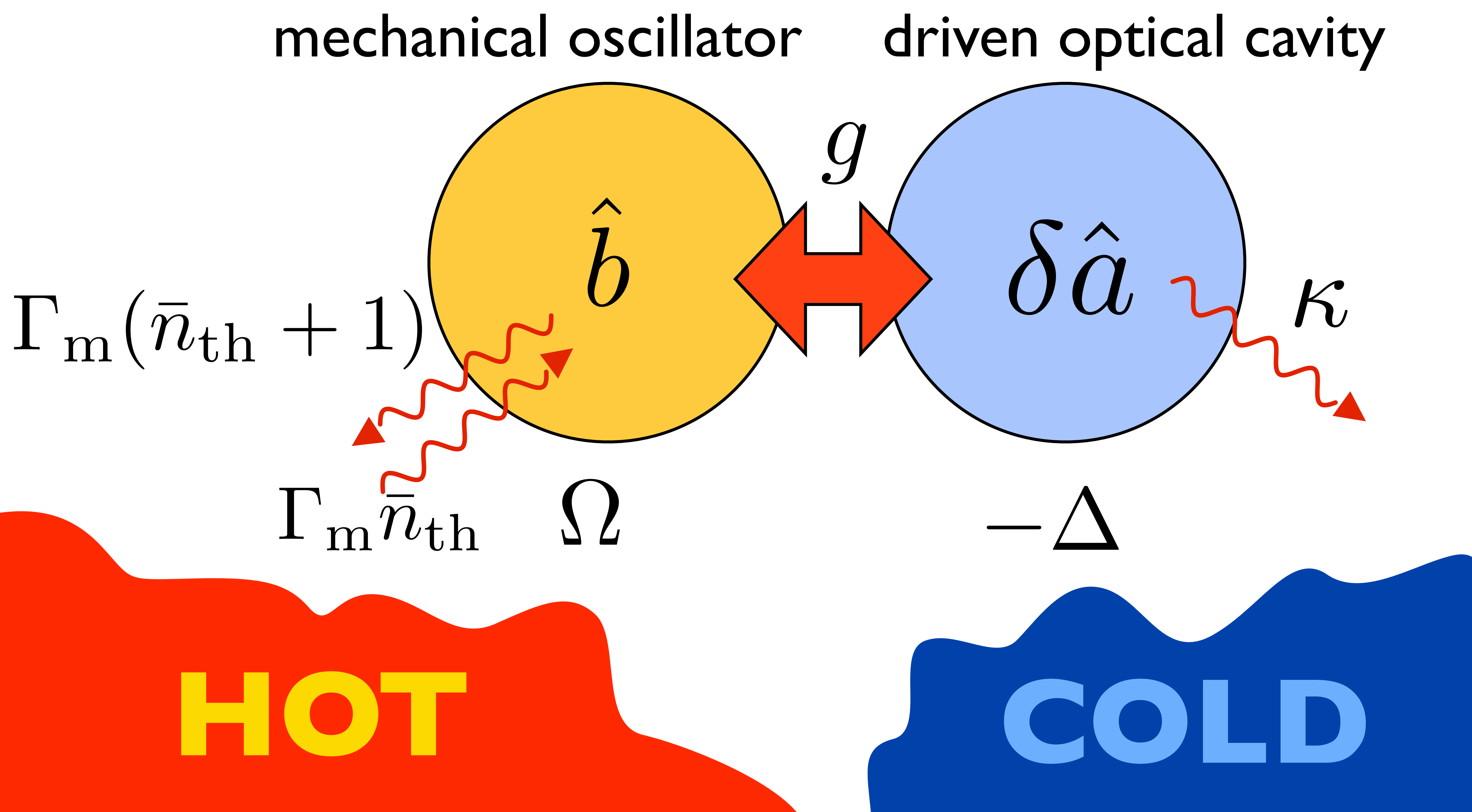
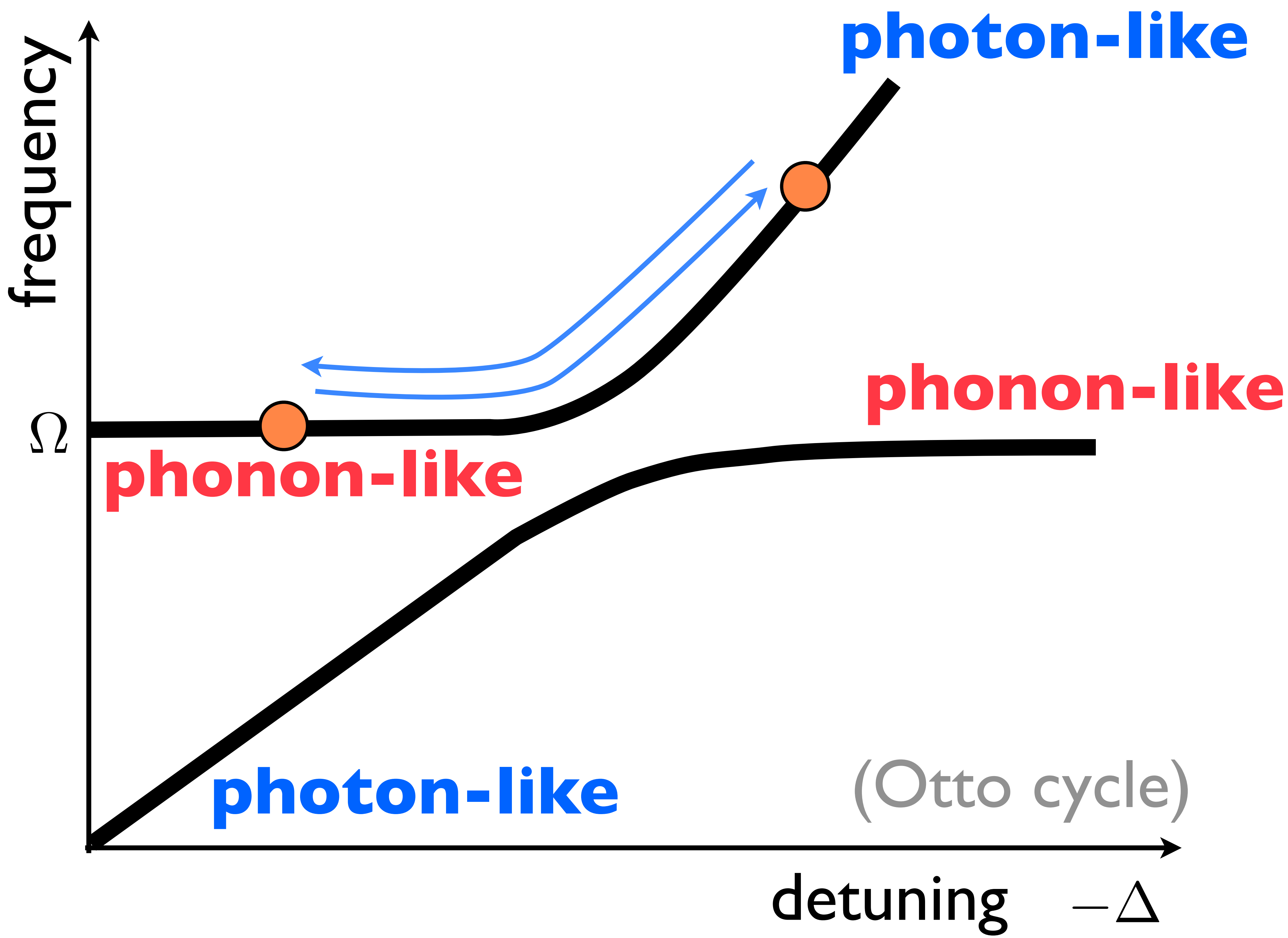
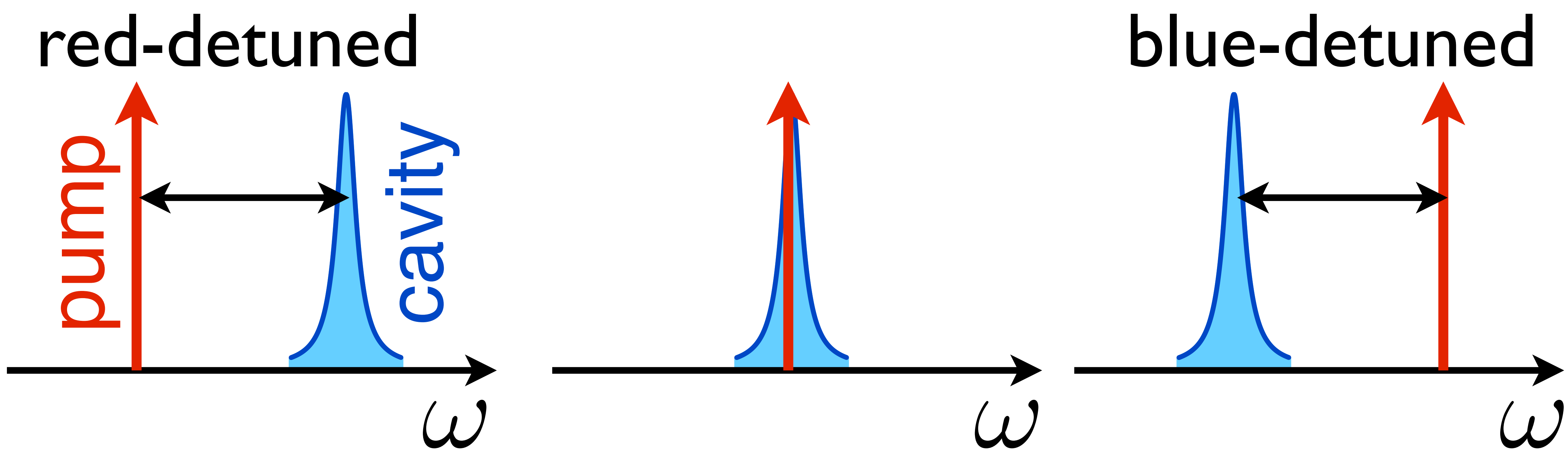


Aside: Quantum Heat Engine in Optomechanics



Keye Zhang, Francesco Bariani, Pierre Meystre; Phys. Rev. Lett. 2014

Different regimes



$$\Delta = -\Omega \qquad \Delta = 0 \qquad \Delta = +\Omega$$

beam-splitter
(cooling)

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

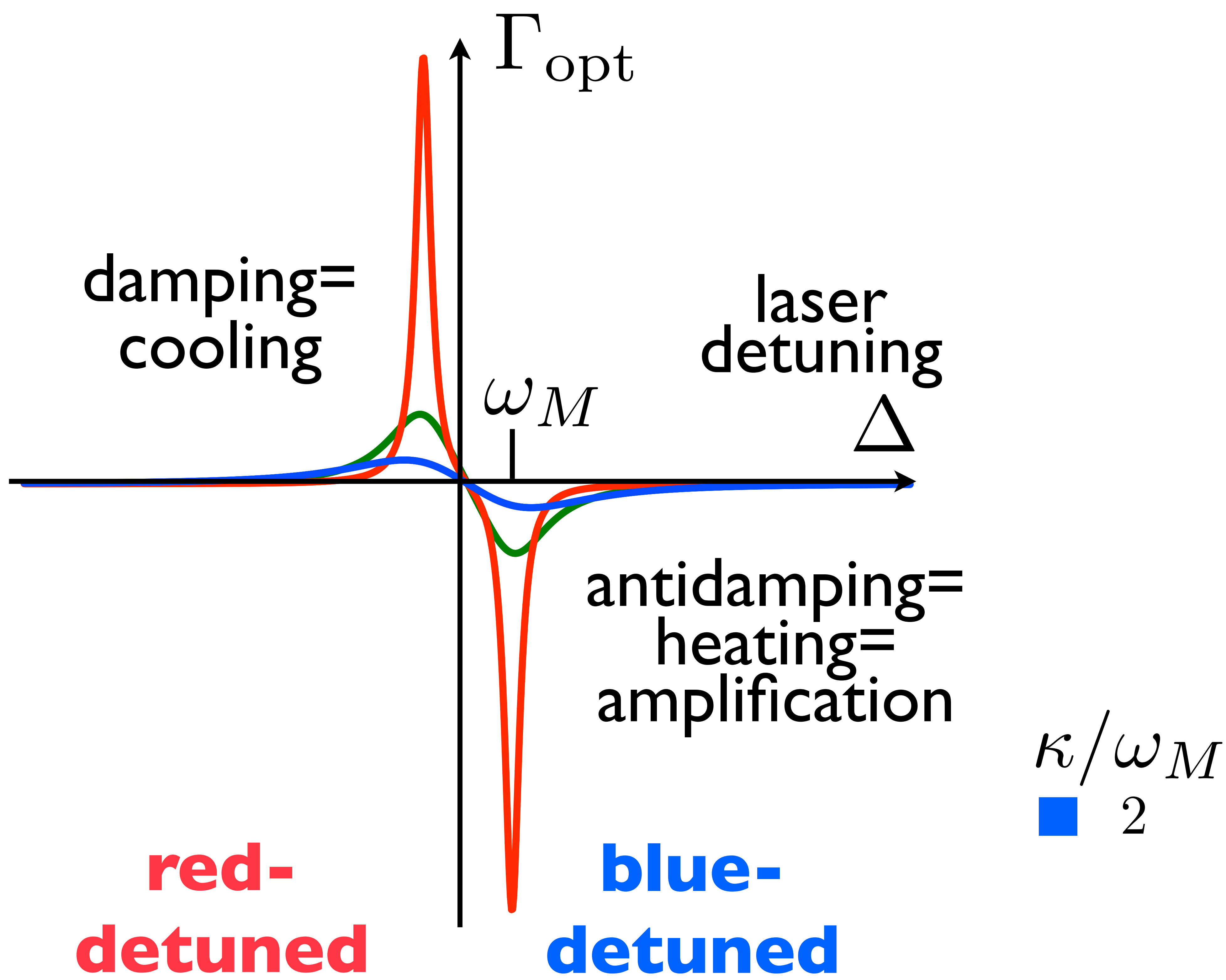
QND

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

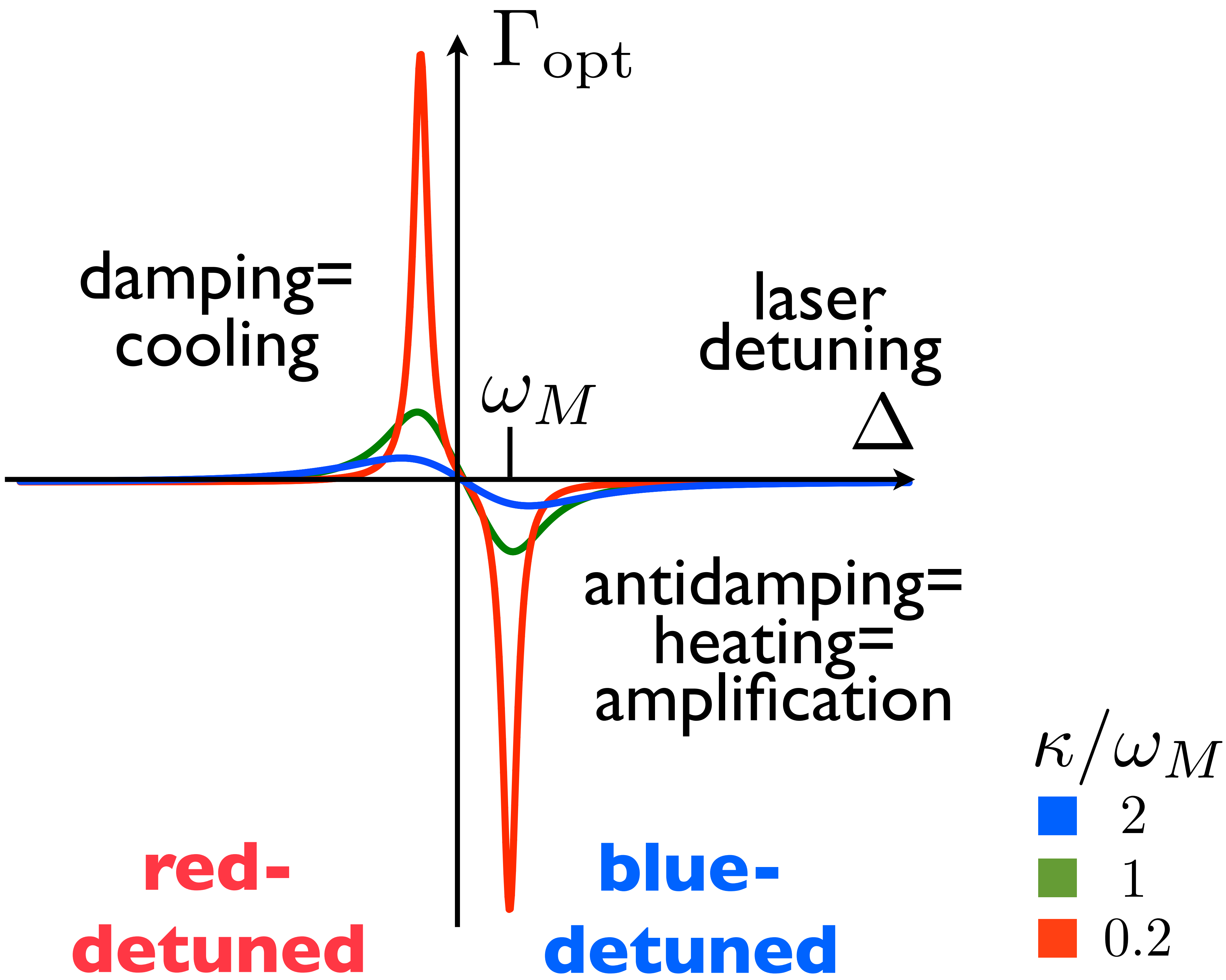
squeezer
(entanglement)

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

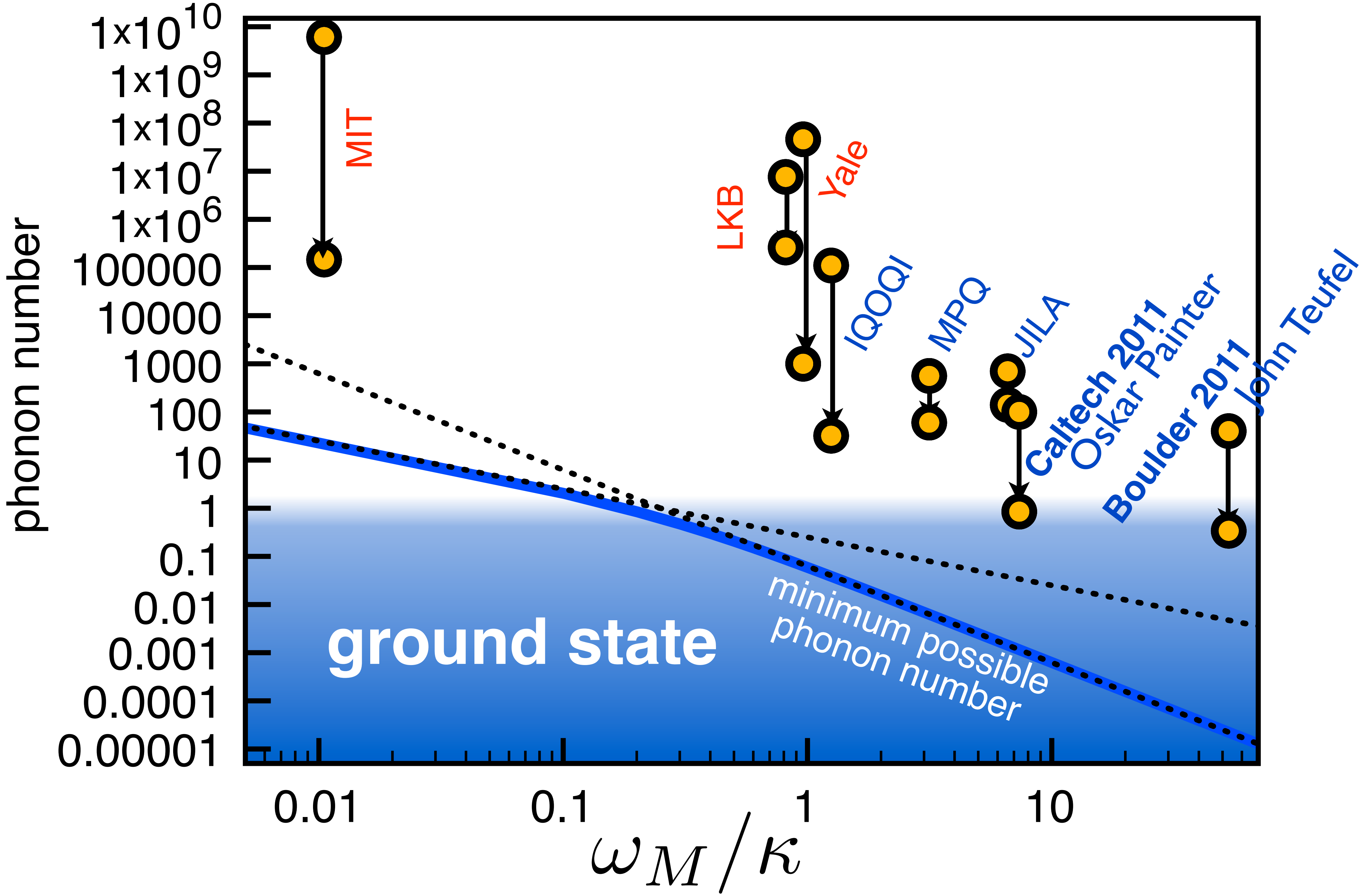
Effective Optomechanical Damping Rate



Effective Optomechanical Damping Rate



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)

“The slopes of Optomechanics”

HAFNERGRUPPE
NATIONALPARK HOHE TAUERN
RADSTÄDTER TAUERN
KATSCHBERG
GROSSECK - SPEIERECK
SPEIERECK
2.411 m
GROSSECK
2.066 m
SCHWANDHÖHE
2.050 m
ST. MICHAEL
1.075 m
ST. MARTIN
MAUTERNDORF
1.122 m
ST. MARGARETHEN
1.066 m
FANNINGBERG
MARIAPFARR
1.121 m
UNTERNBERG
GÖRIACH
ST. ANDRÄ
LESSACH
TAMSWEG
RAMINGSTEIN

Linear Optomechanics

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

Optomechanical Arrays

- Bandstructure in arrays
- Synchronization in arrays
- Transport of photons & phonons
- Topological phases

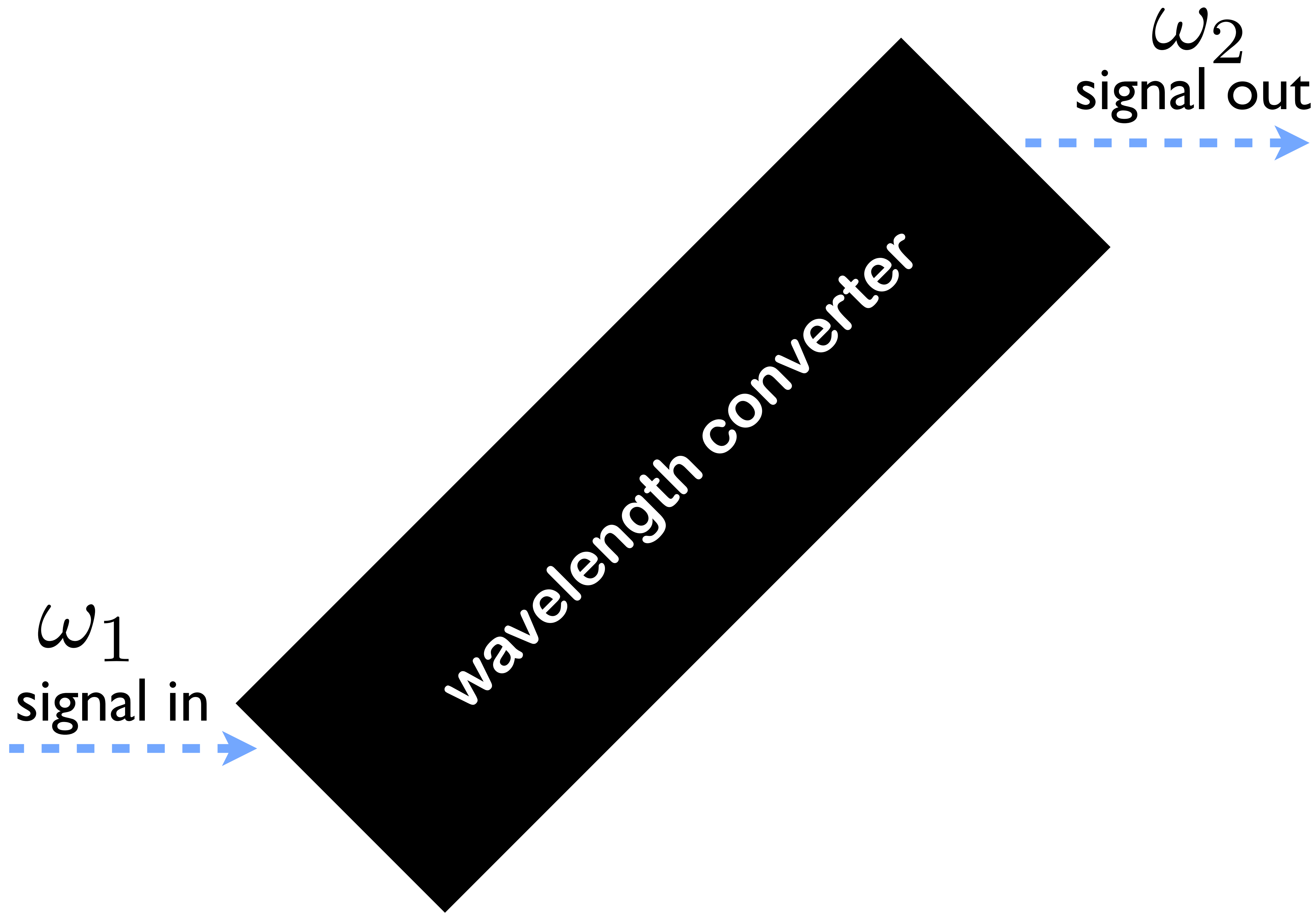
Nonlinear Classical Optomechanics

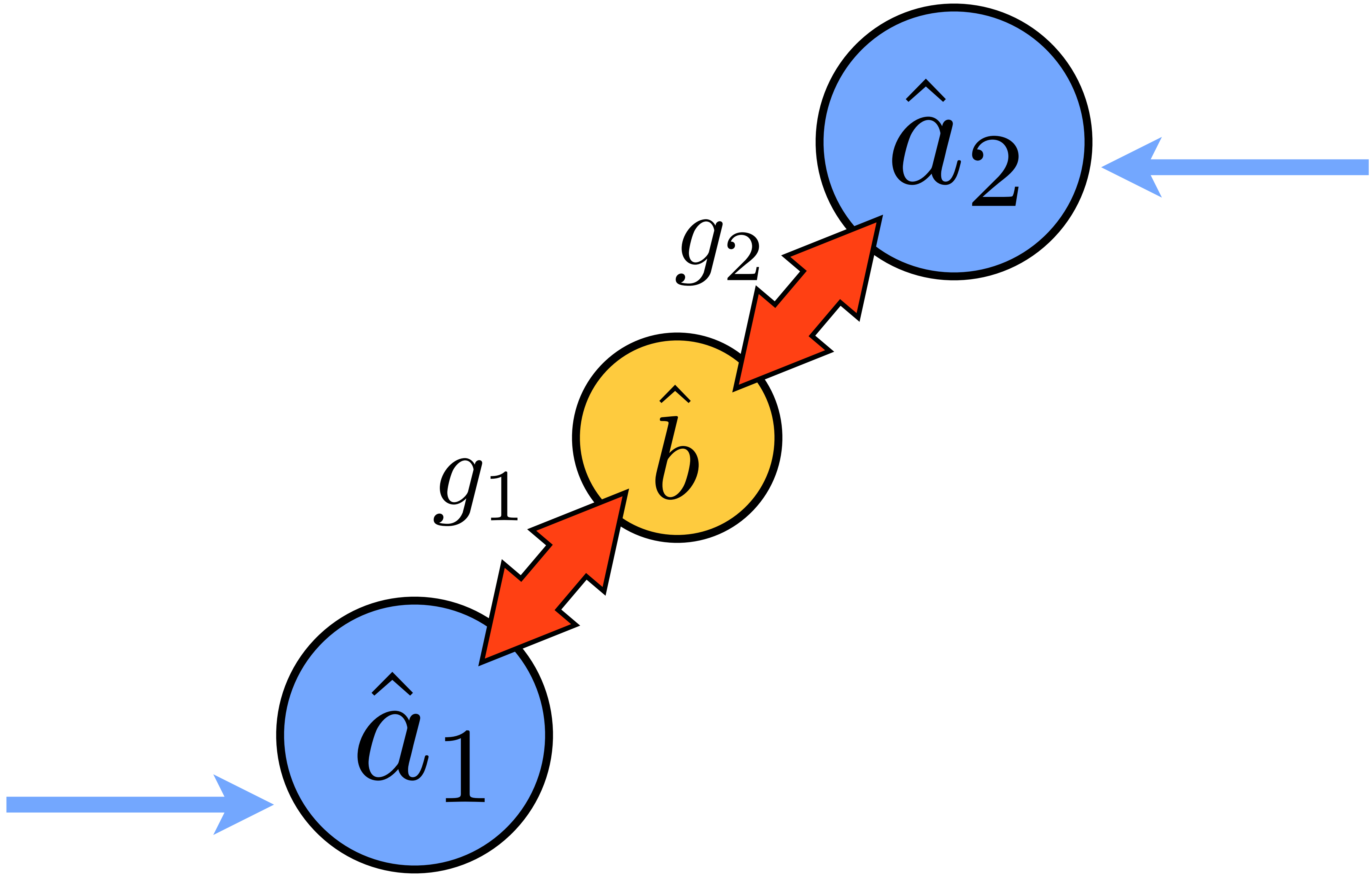
- Self-induced mechanical oscillations
- Synchronization of oscillations
- Chaos

Nonlinear Quantum Optomechanics

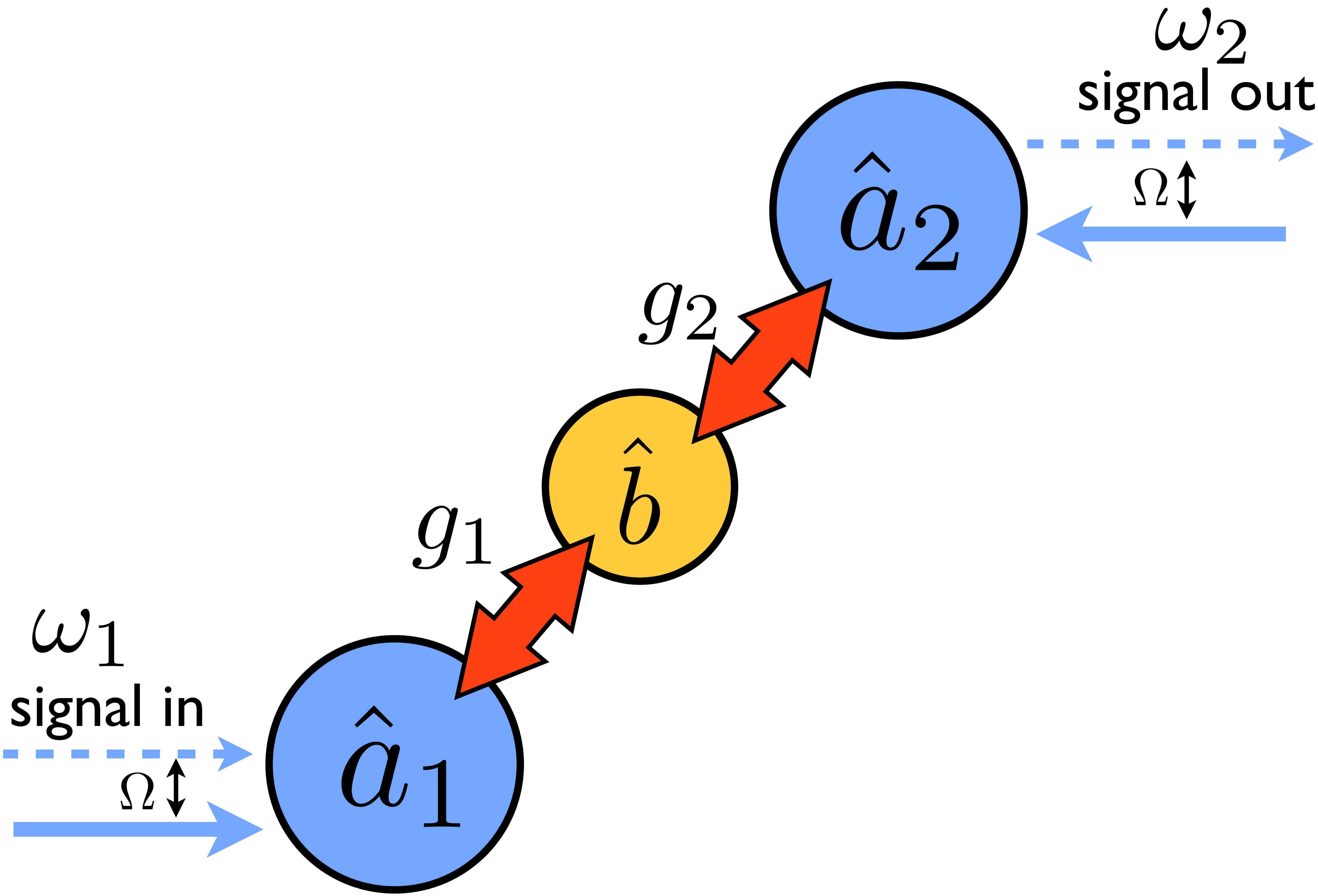
- Phonon number detection
- Phonon shot noise
- Photon blockade
- Optomechanical "which-way" expt.
- Nonclassical mechanical q. states
- Optomechanical matter-wave interference
- Nonlinear OMIT
- Noncl. via Conditional Detection
- Single-photon sources
- Coupling to two-level systems

Optomechanical wavelength conversion

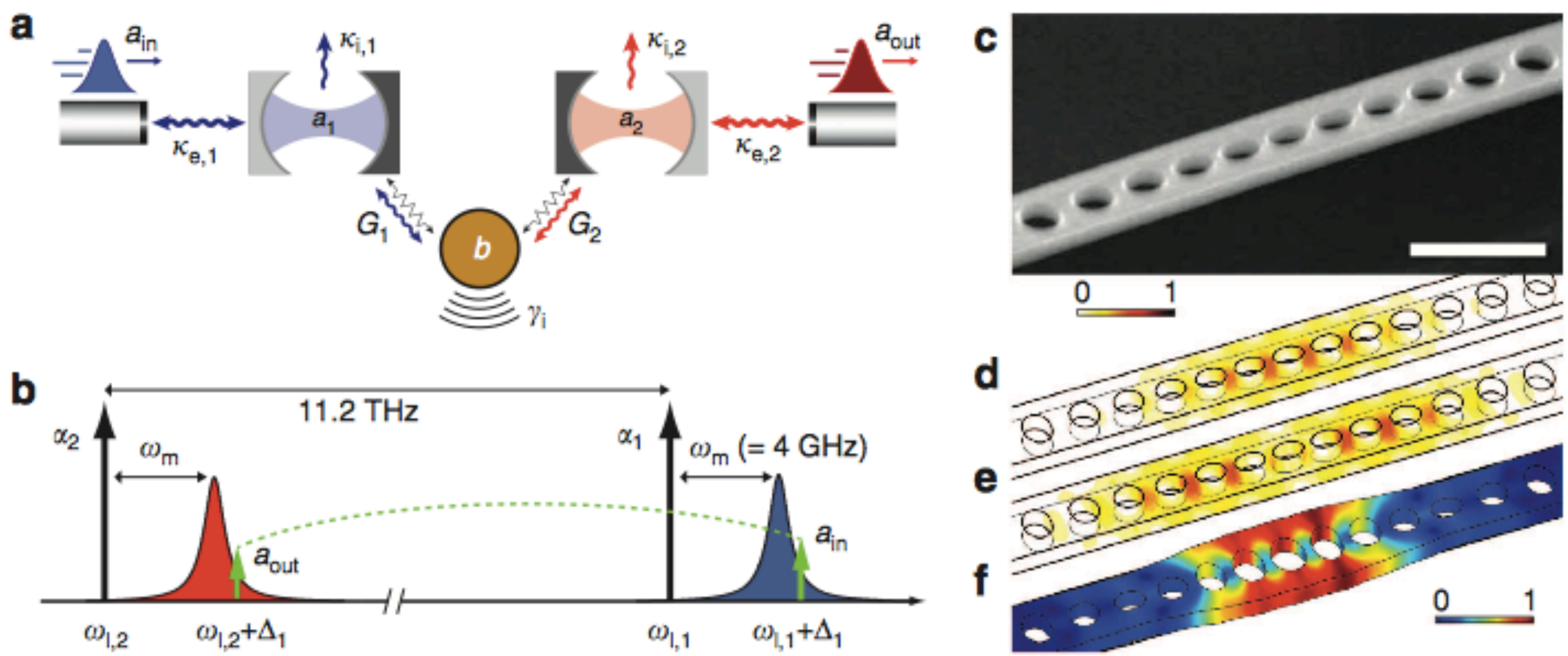

ω_2
signal out
wavelength converter
ω_1
signal in



$\hat{a}_2$
g_2
$\hat{b}$
g_1
$\hat{a}_1$

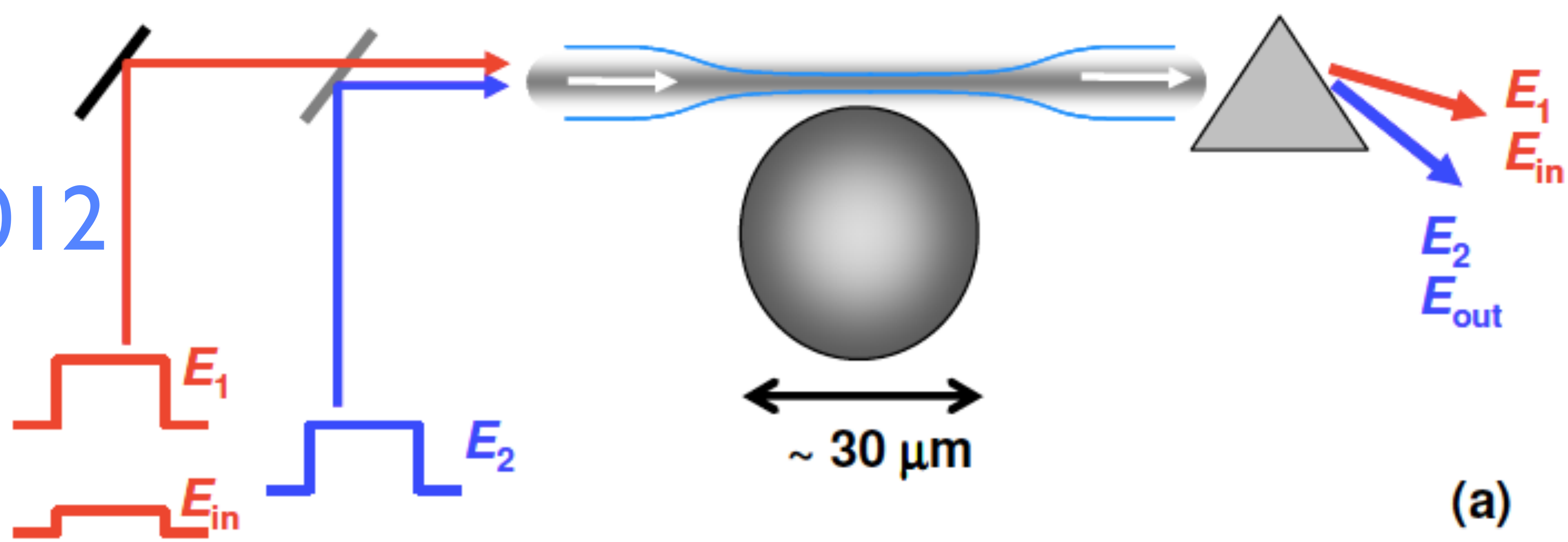

ω_2
signal out
Ω
$\hat{a}_2$
g_2
$\hat{b}$
g_1
ω_1
signal in
Ω
$\hat{a}_1$

optics to optics:

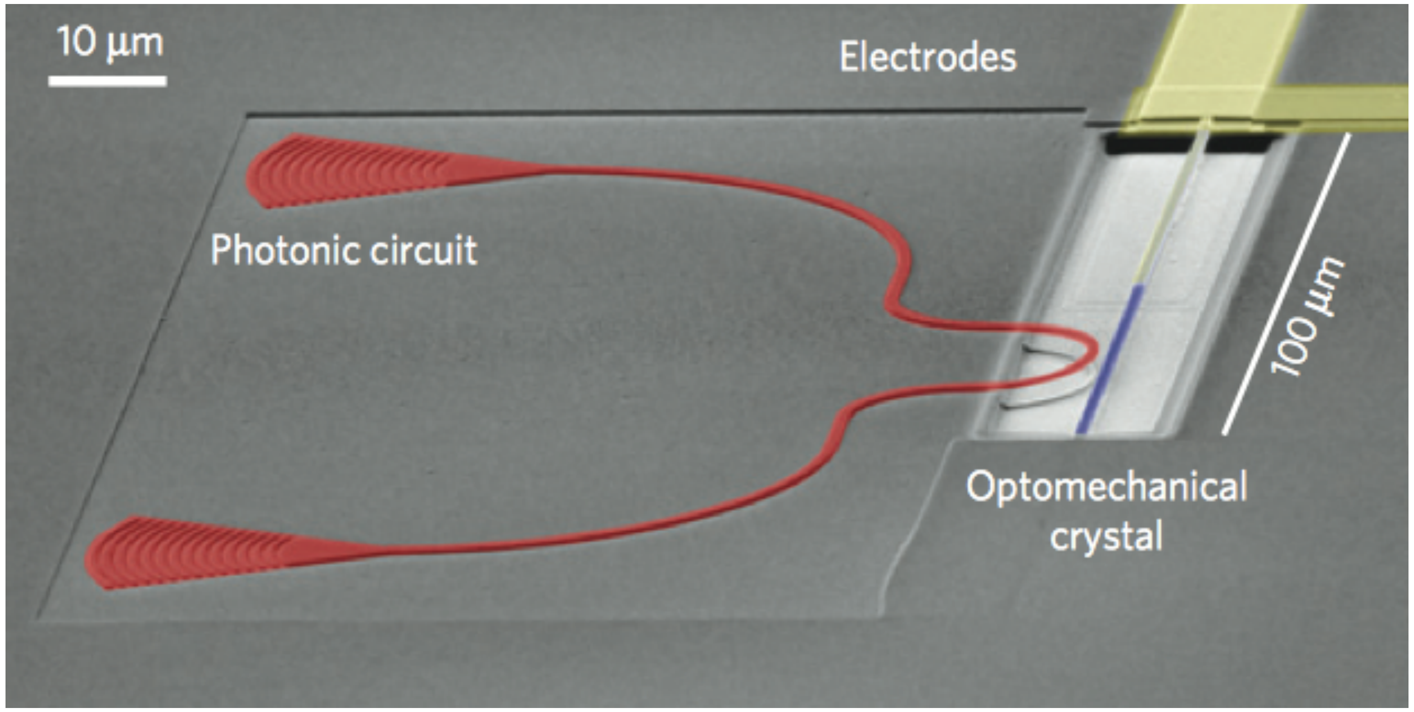


Painter 2012

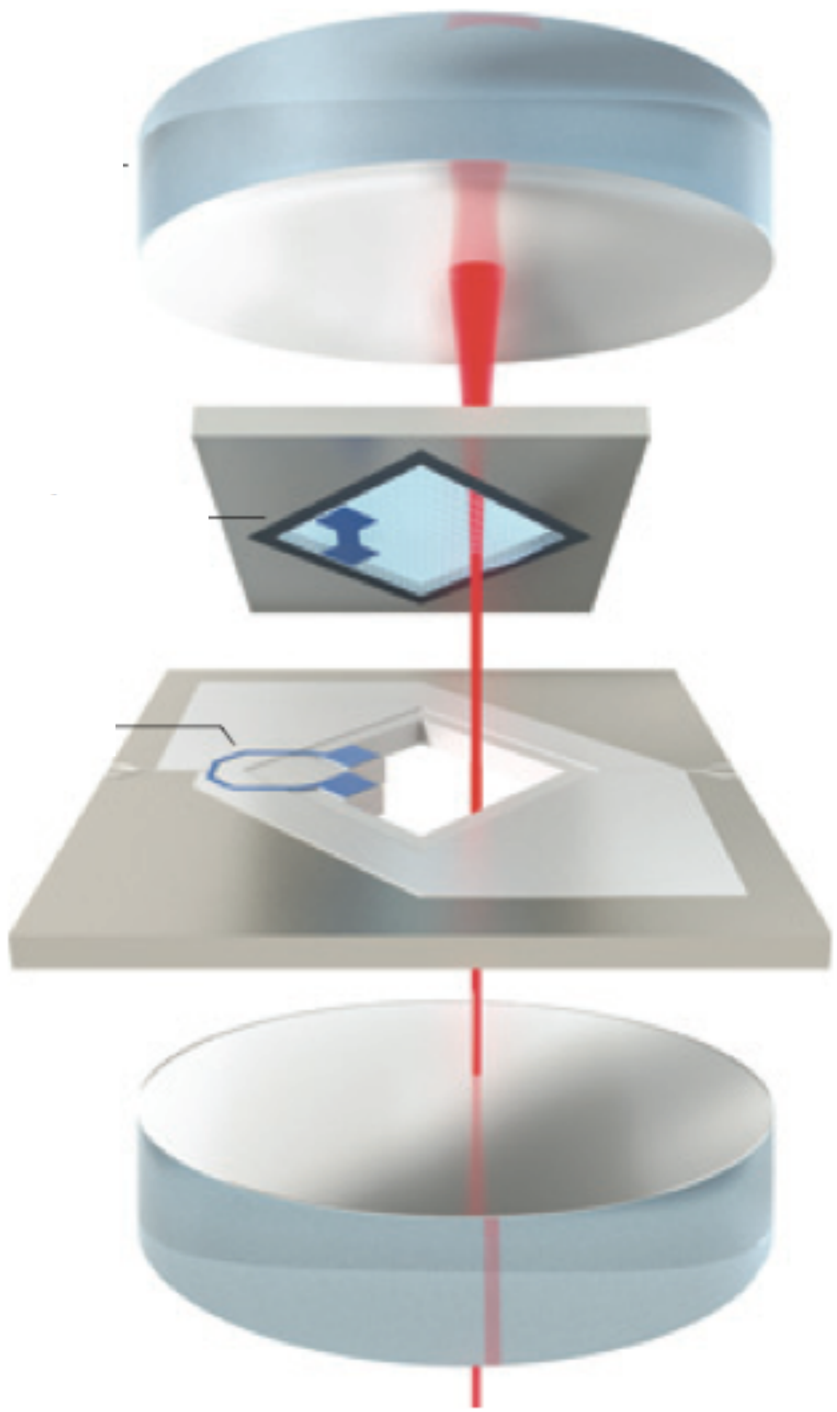
Wang 2012



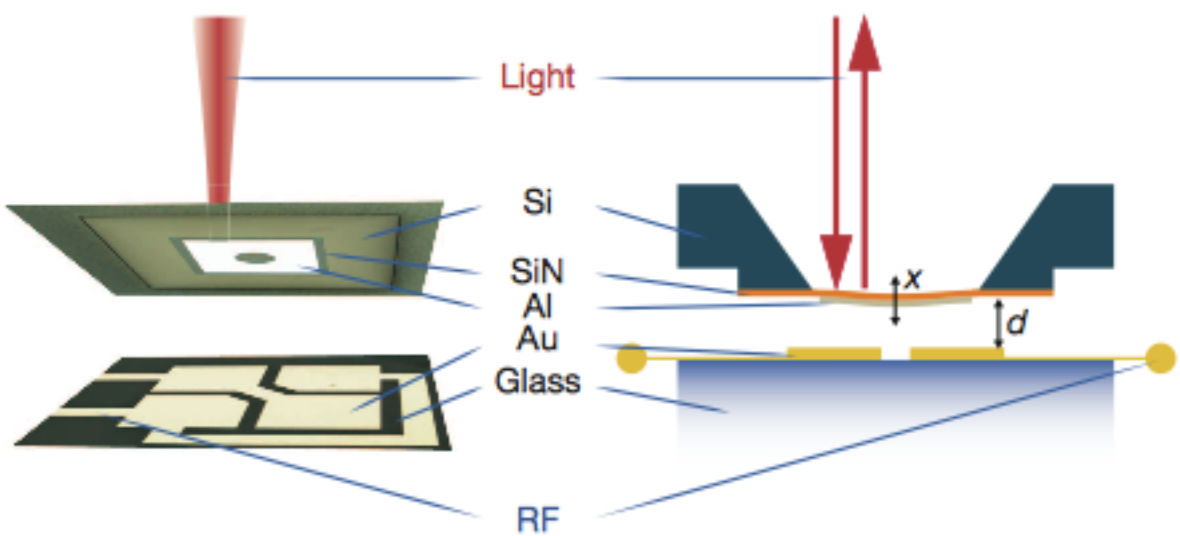
microwave/RF to optics:



Cleland 2013



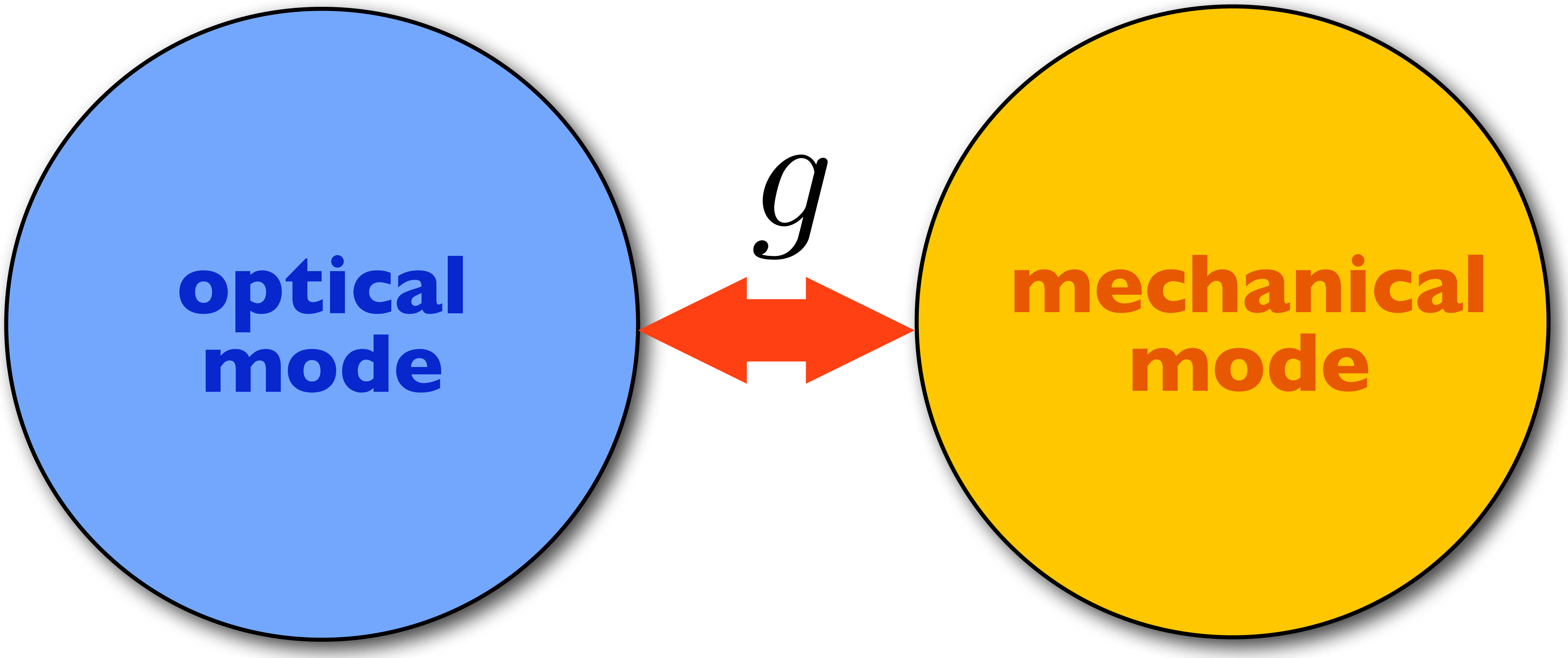
Lehnert, Regal 2014



Schliesser, Polzik 2014

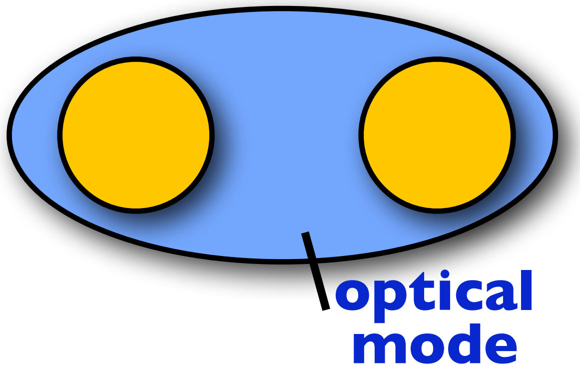
Optomechanical Arrays

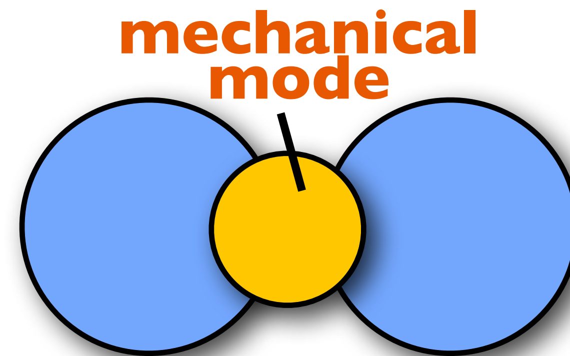
Single-mode optomechanics

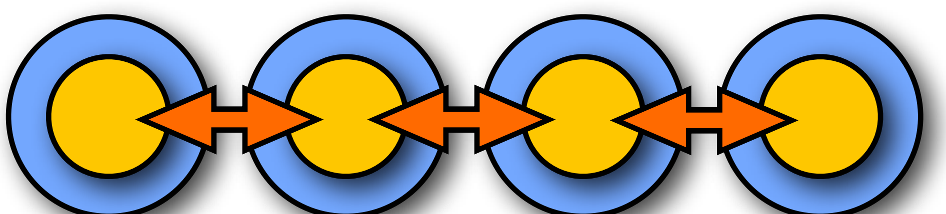


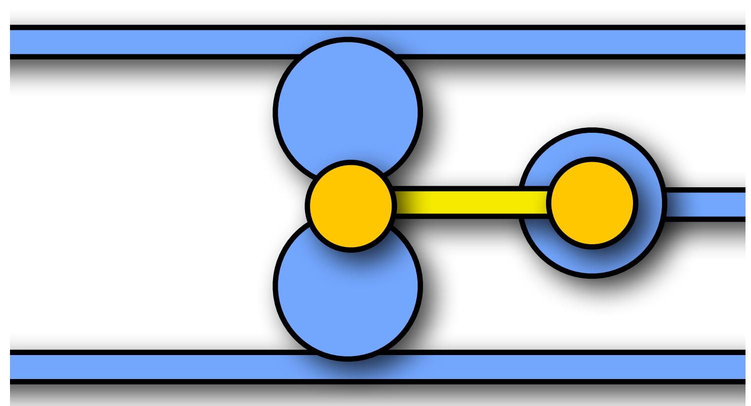
✓ displacement sensing
✓ cooling
✓ strong coupling
✓ self-oscillations (limit cycles)

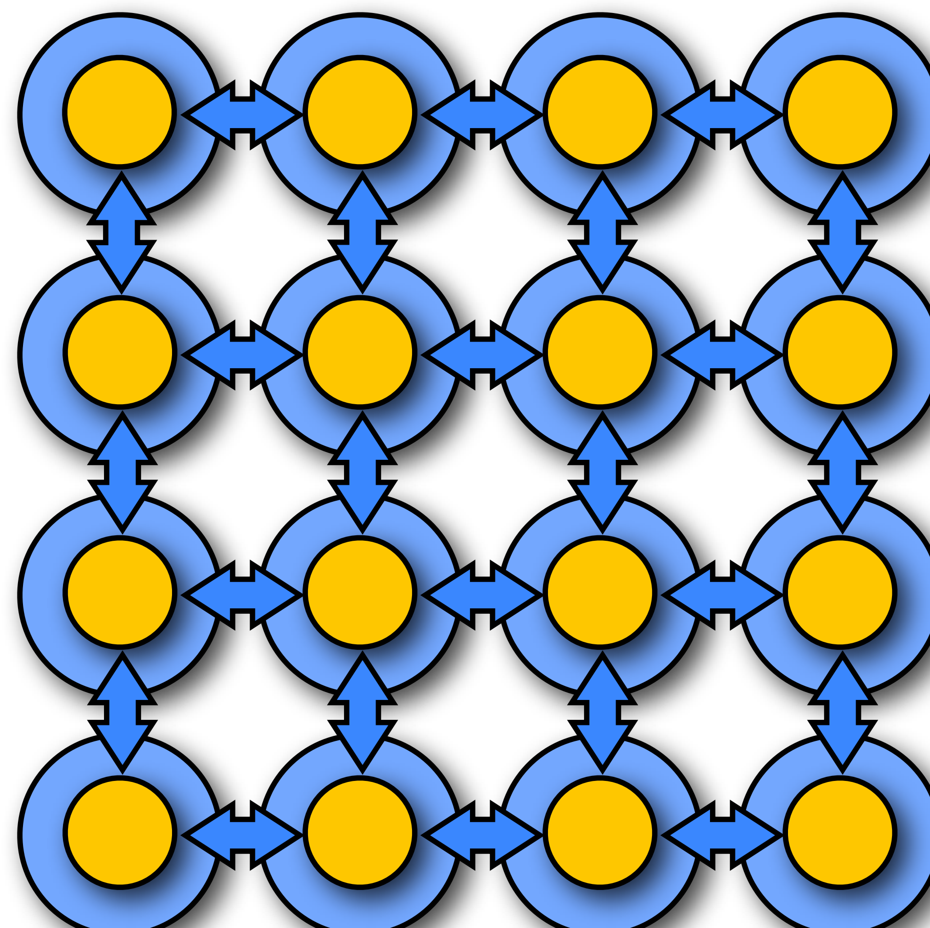
Many modes



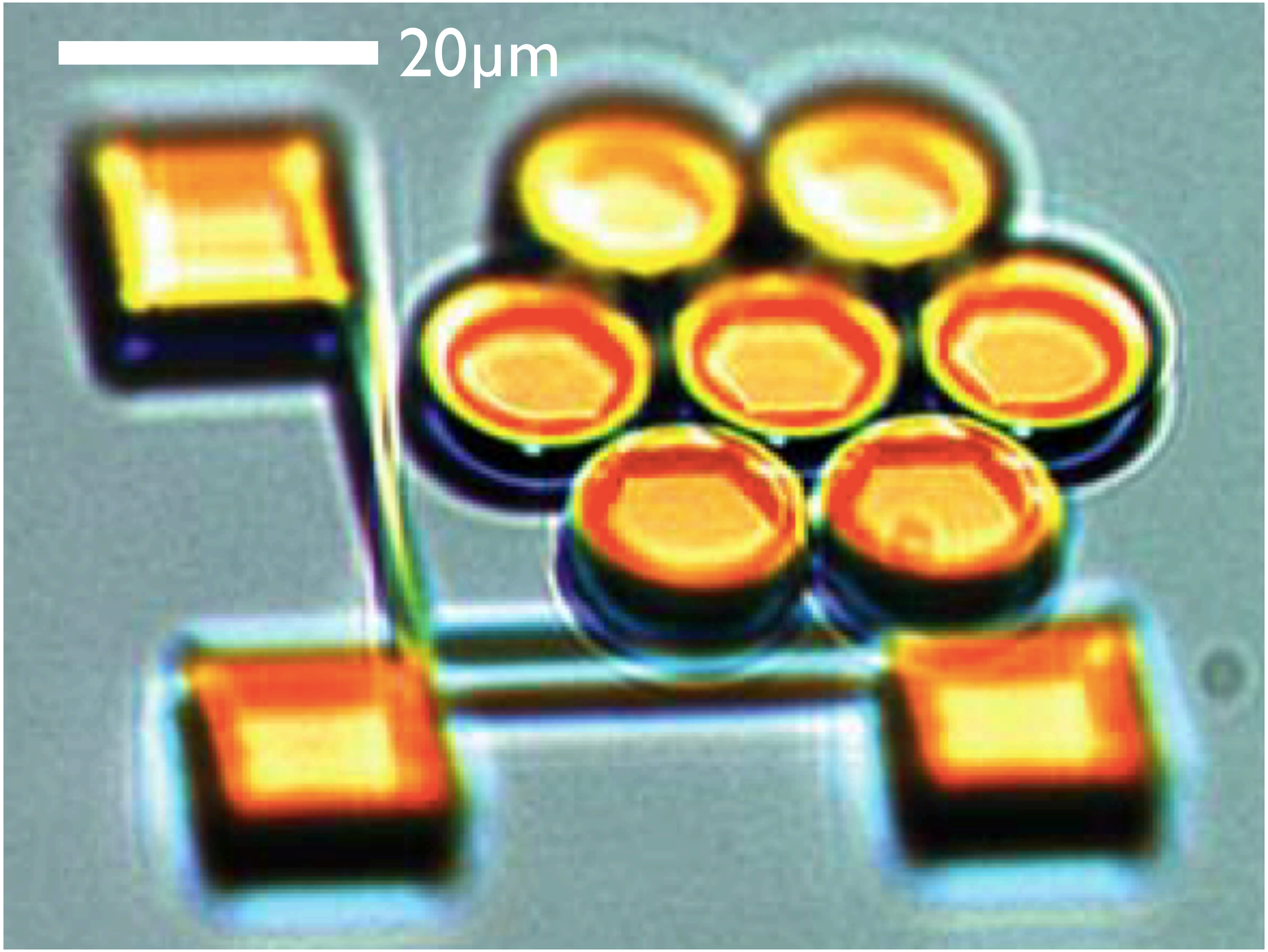








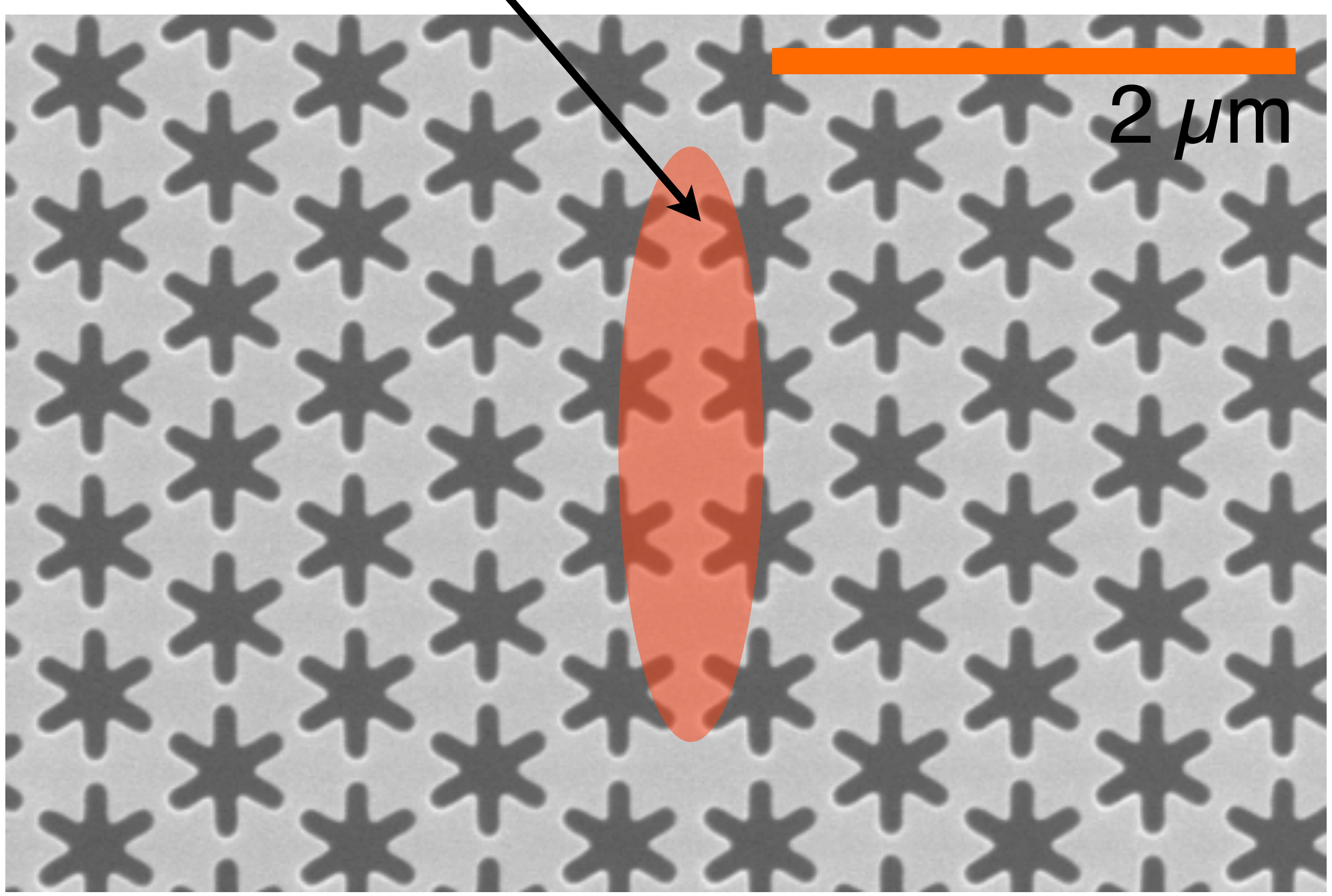
First realizations



Lipson group, Cornell arXiv:1505.02009 (synchronization)

Optomechanical crystals

= free-standing photonic crystal structures (Painter group)



advantages:

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

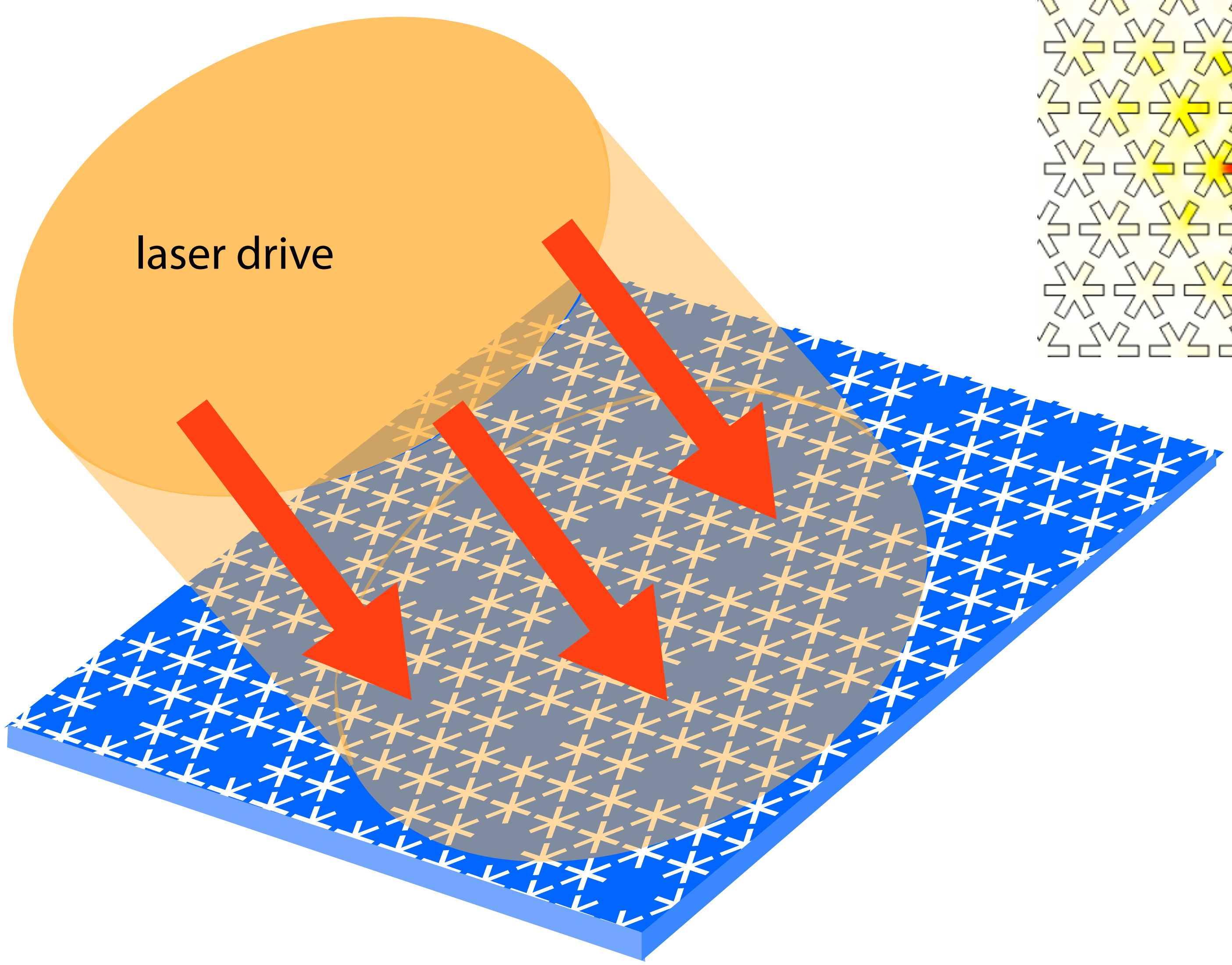
tight optical confinement:
large optomechanical coupling
(100 GHz/nm)

integrated on a chip

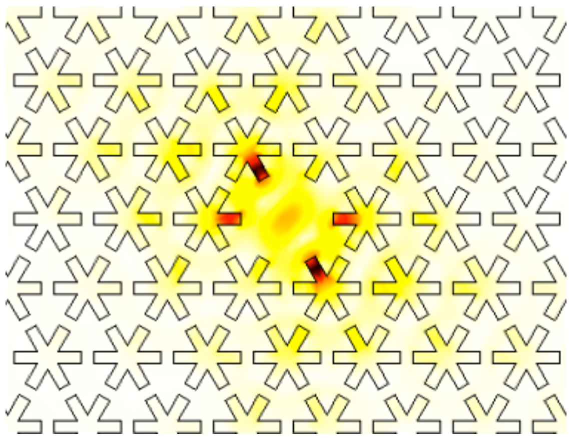
Safavi-Naeini et al PRL 2014
Eichenfield et al Nature 2009

Optomechanical arrays

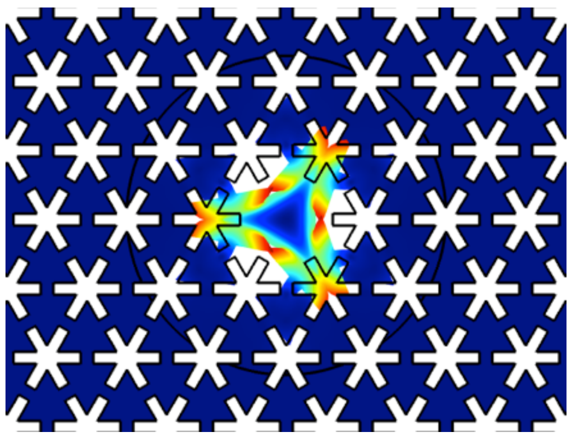
Optomechanical array: Many coupled optomechanical cells



optical mode



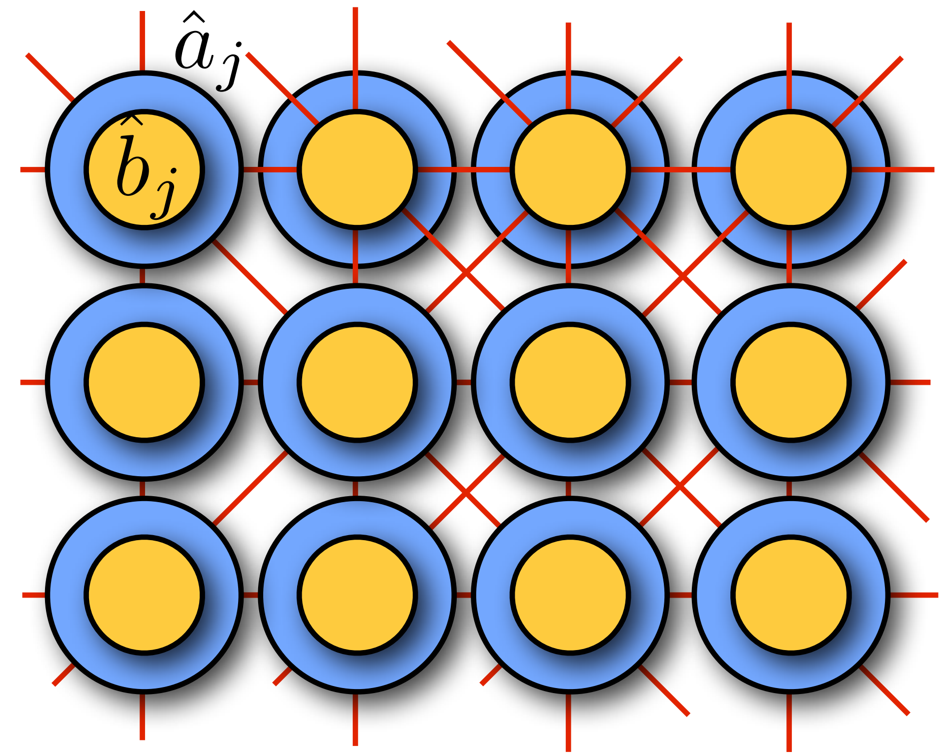
mechanical mode



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

Modeling an optomechanical array

Tight-binding model for photons & phonons hopping and interacting on a lattice



laser detuning

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

each cell: optomech. interaction laser drive

$$\hat{H}_{\mathrm{om},j} = -\Delta \hat{a}_j^\dagger \hat{a}_j + \Omega \hat{b}_j^\dagger \hat{b}_j - g_0 (\hat{b}_j^\dagger + \hat{b}_j) \hat{a}_j^\dagger \hat{a}_j + \alpha_L (\hat{a}_j^\dagger + \hat{a}_j)$$

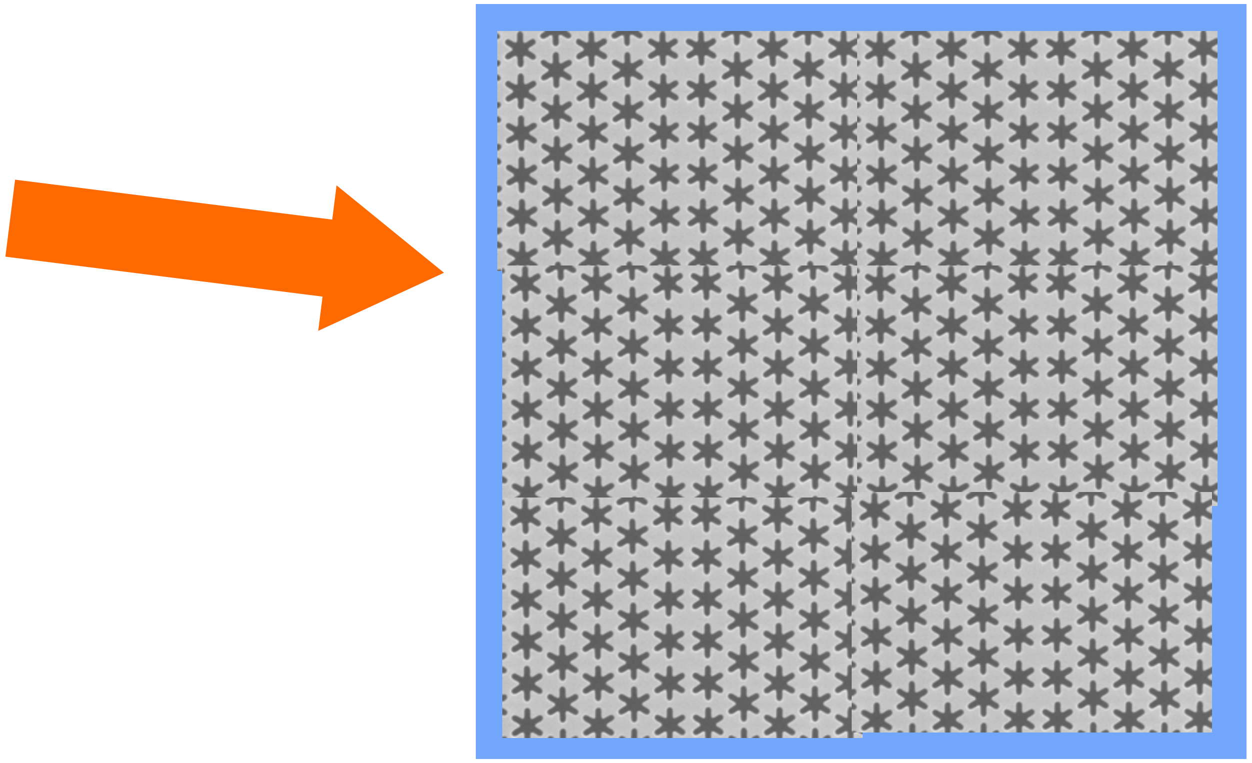
$$\hat{H}_{\mathrm{int}} = - \mathrm{J} \sum_{\langle i,j \rangle} (\hat{a}_i^\dagger \hat{a}_j + \hat{a}_i \hat{a}_j^\dagger) - \mathrm{K} \sum_{\langle i,j \rangle} (\hat{b}_i^\dagger \hat{b}_j + \hat{b}_i \hat{b}_j^\dagger)$$

optical coupling (photon tunneling) mechanical coupling (phonon tunneling)

Max Ludwig, FM, Phys. Rev. Lett. 111, 073602 (2013)

Optomechanical Arrays

global view:
light-tunable metamaterial for photons & phonons



similar in spirit:
optical lattices
nonlinear optical materials

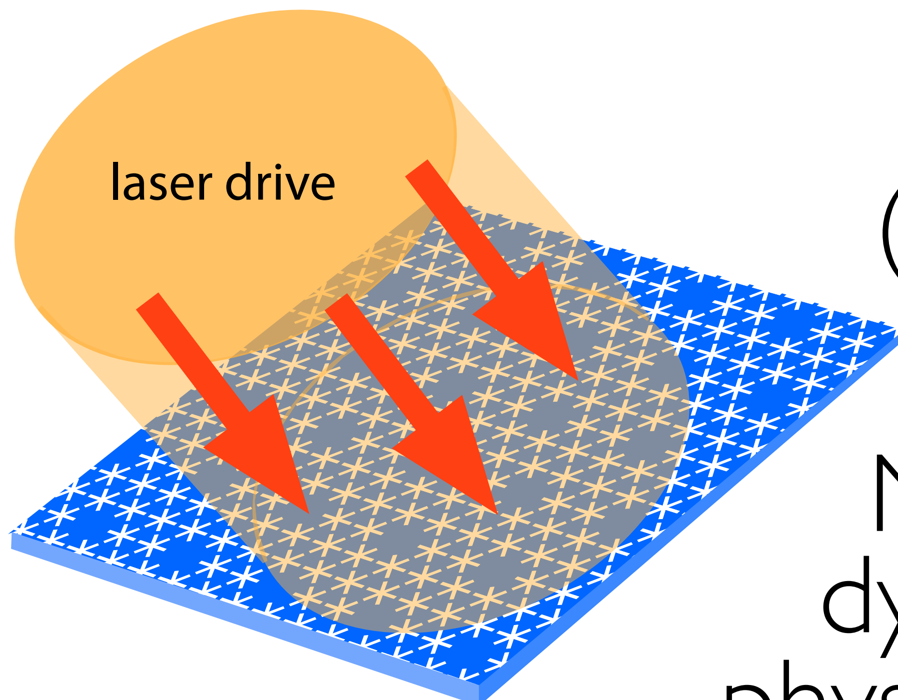
conceptually simple: one material, with holes

Optomechanical Arrays: The Future

Synthetic magnetic fields for photons/phonons

Topological Phases

Dirac Physics



Transport (edge states/wires)

Synchronization and Pattern Formation

Nonequilibrium dynamics/Quench physics/Thermalization

Quantum Information Processing

Strongly Correlated Quantum Physics?

Tuneable/re-configurable in-situ

All-optical control/readout

Nonlinear Optomechanics (Classical Regime)

Nonlinear dynamics

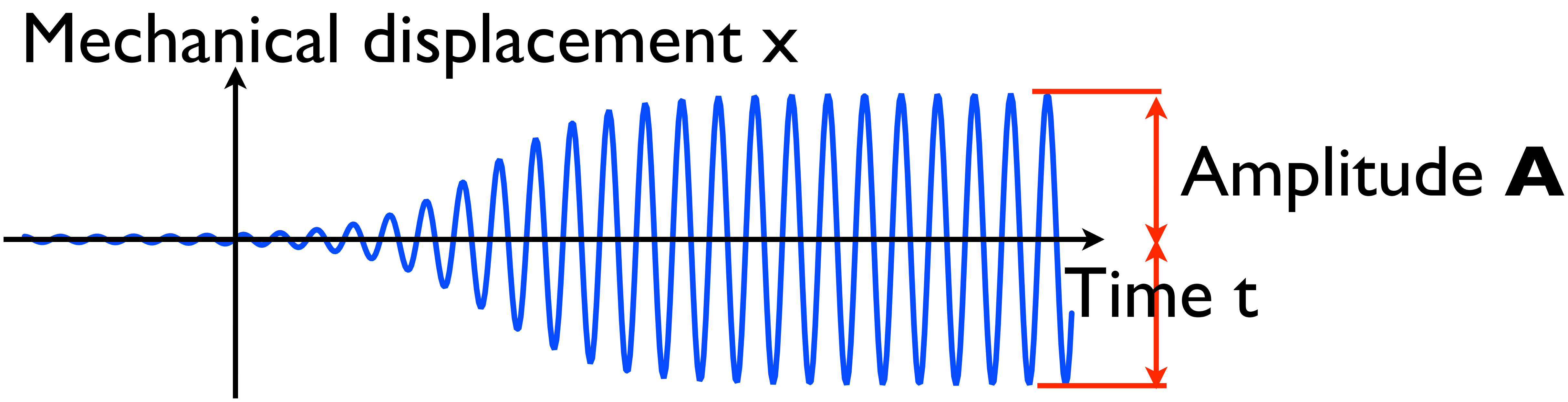
blue-detuned laser:
anti-damping!

$$\Gamma = \Gamma_M + \underbrace{\Gamma_{\mathrm{opt}}}^{< 0}$$

Nonlinear Dynamics

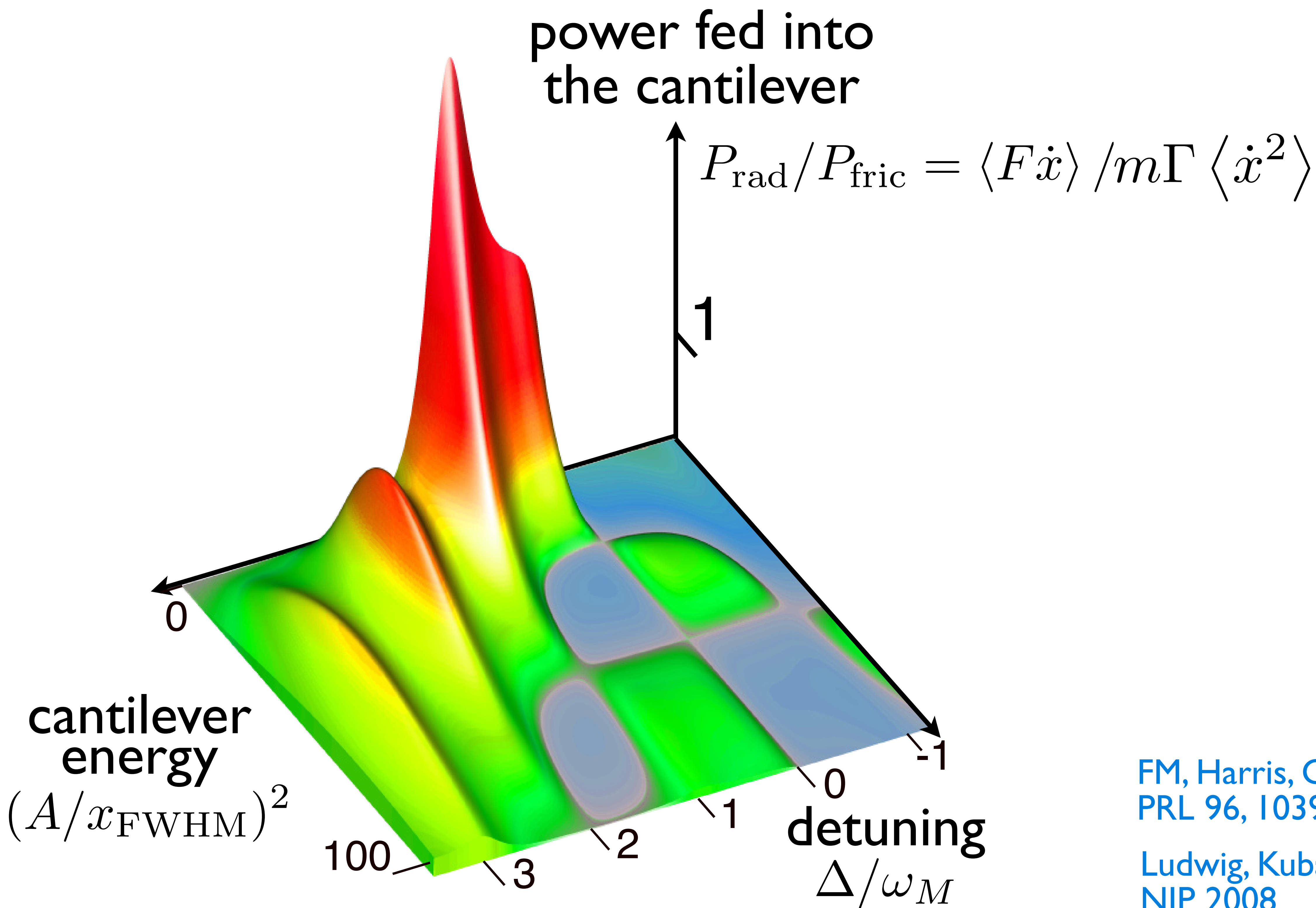
Nonlinear Dynamics

Beyond some laser input power threshold: instability



Self-sustained mechanical oscillations!

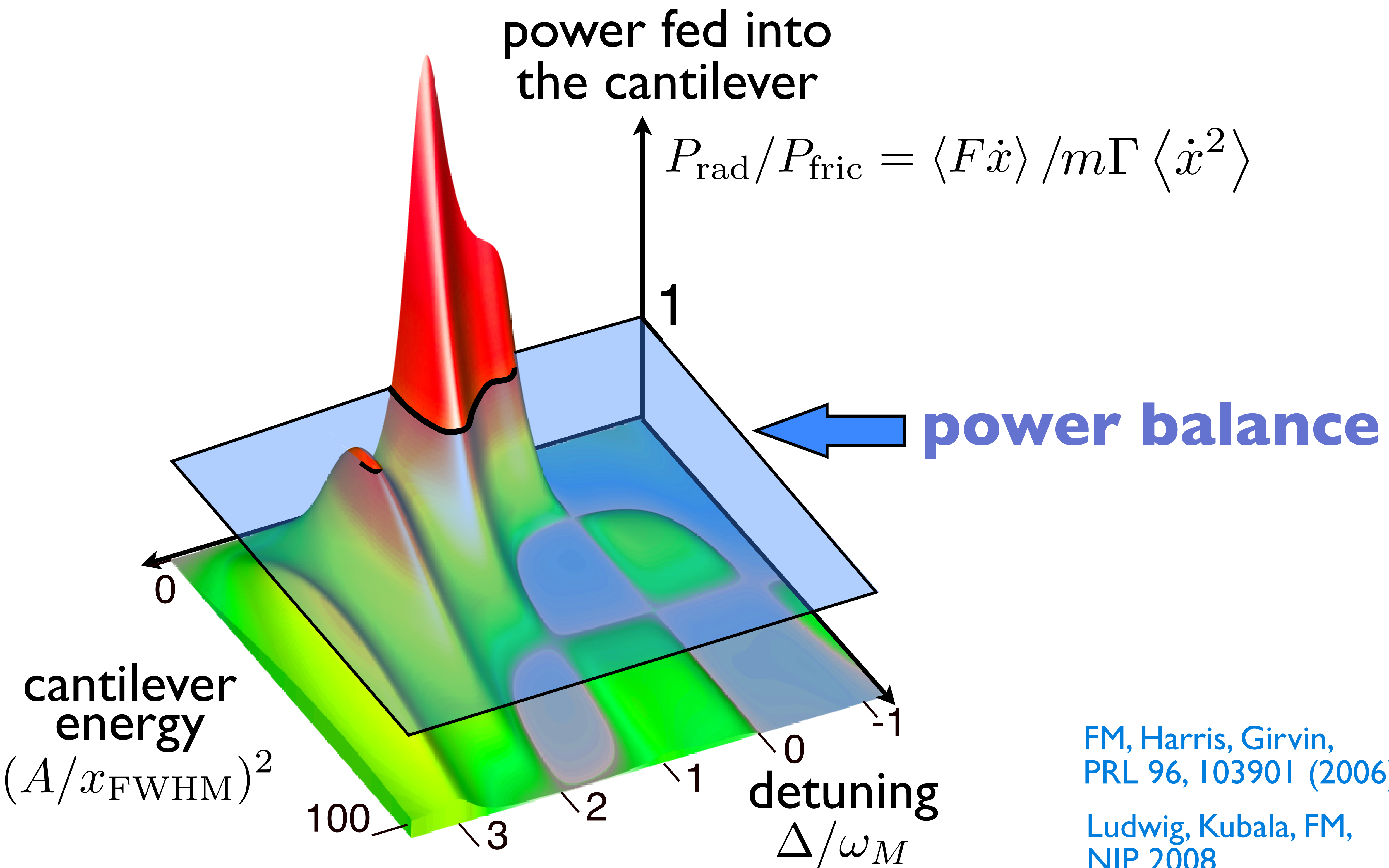
Attractor diagram



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

Ludwig, Kubala, FM,
NJP 2008

Attractor diagram



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PRL 96, 103901 (2006)

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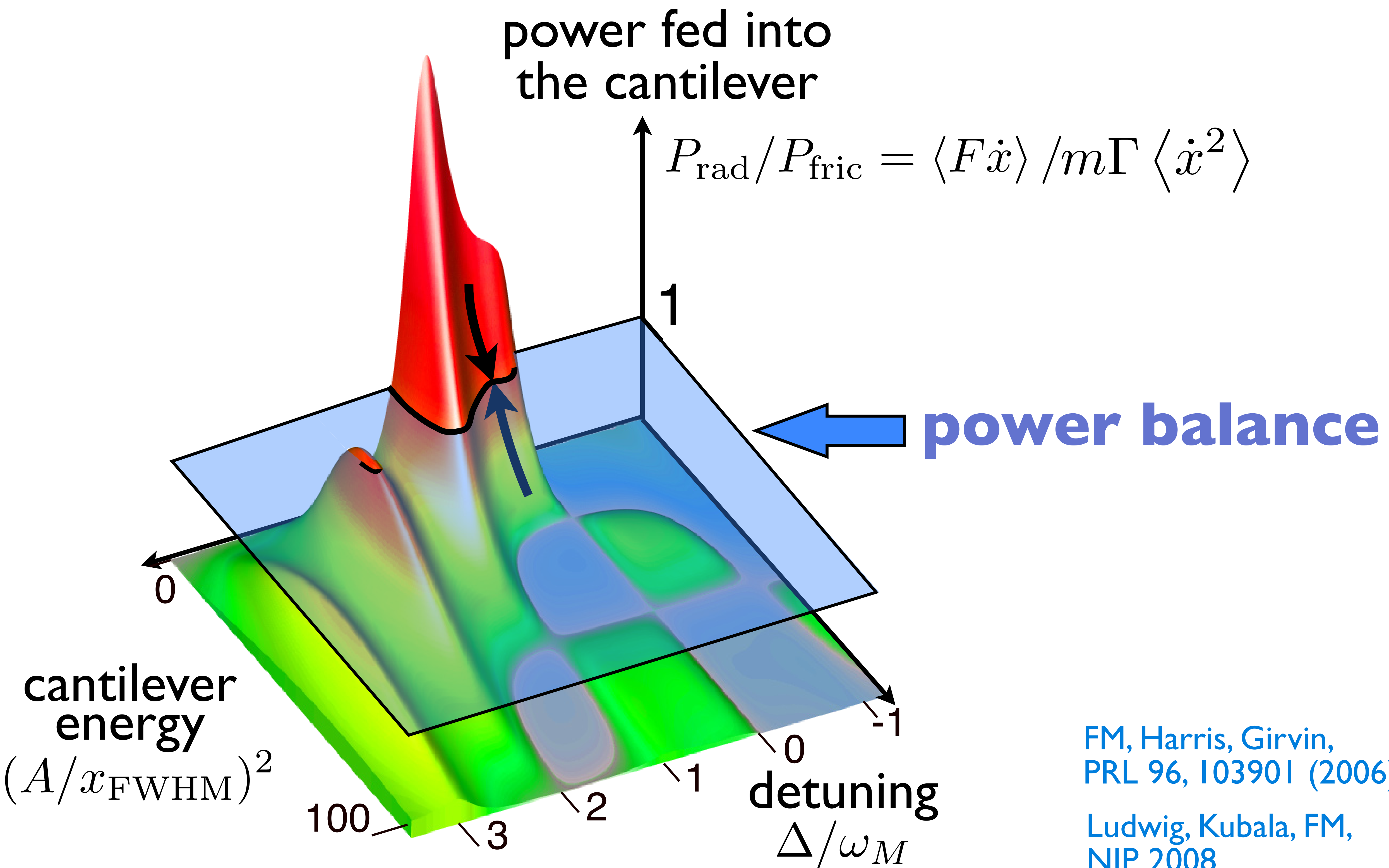
NJP 2008

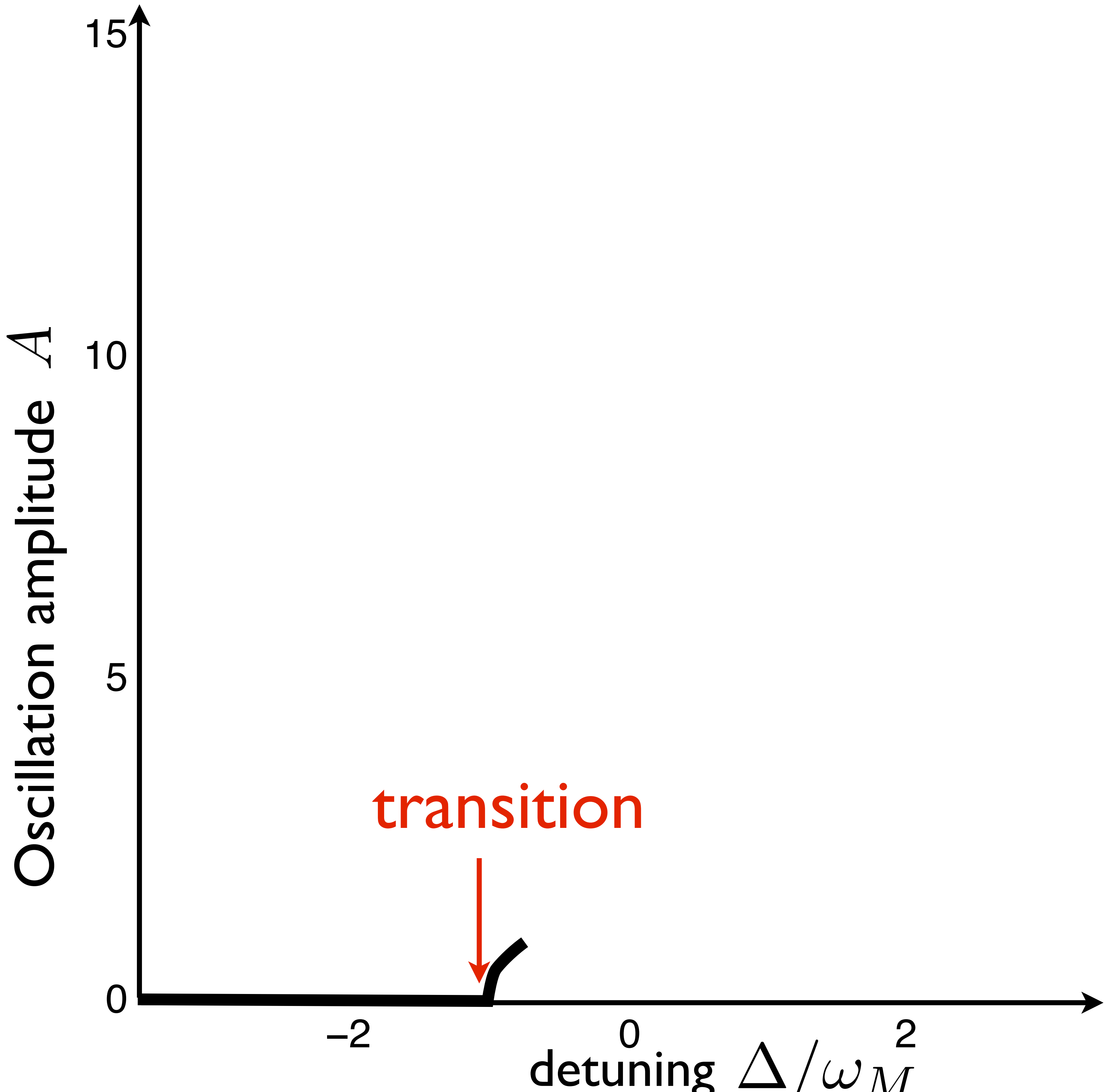
Attractor diagram



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

Ludwig, Kubala, FM,
NJP 2008

Attractor diagram



experiments:

Höhberger, Karrai, IEEE proceedings 2004

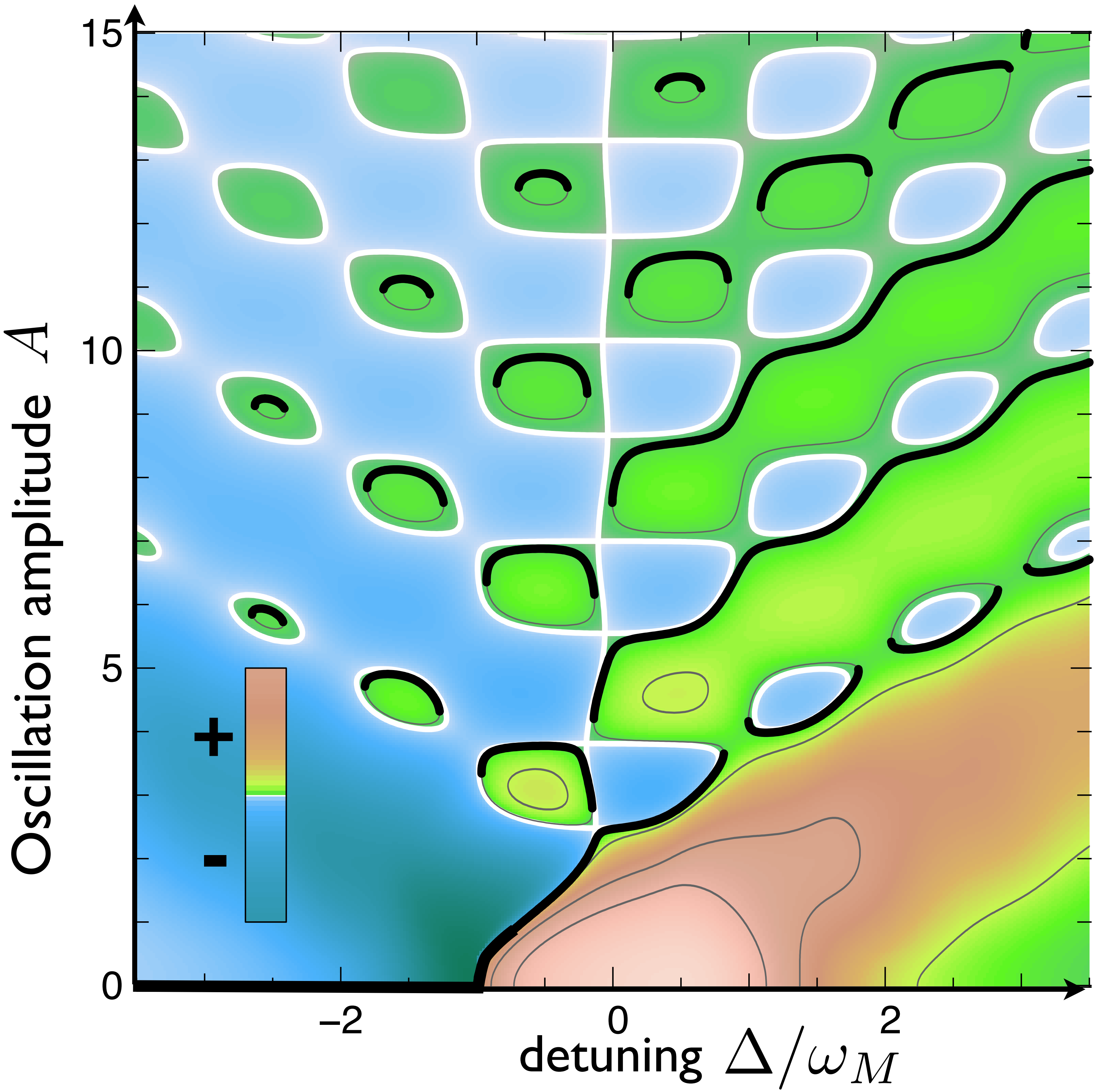
Carmon, Rokhsari, Yang, Kippenberg, Vahala, PRL 2005

Metzger et al., PRL 2008

theory:

FM, Harris, Girvin, PRL 2006

Attractor diagram



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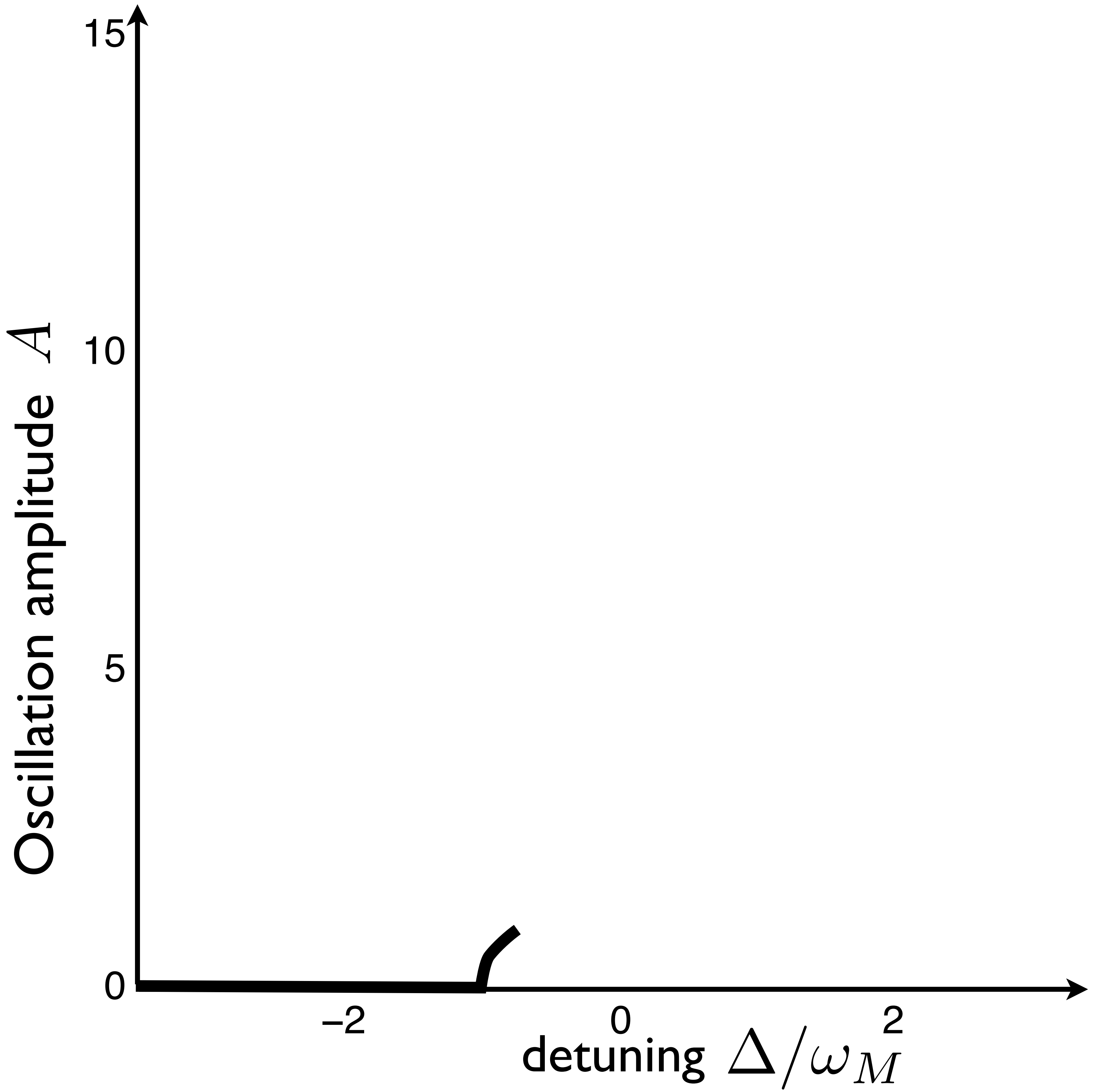
Attractor diagram



experiments:

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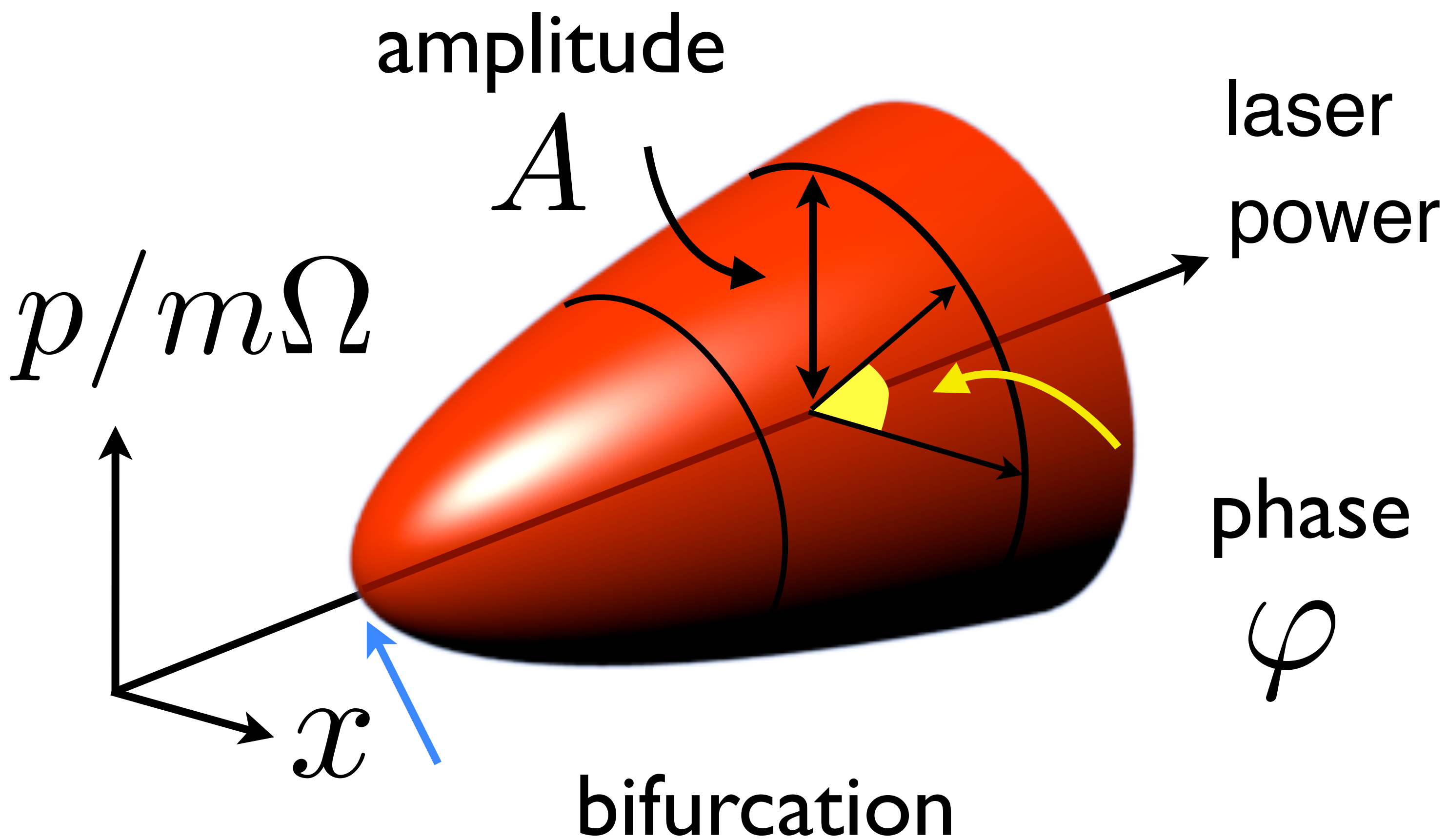
Metzger et al., PRL 2008

theory:

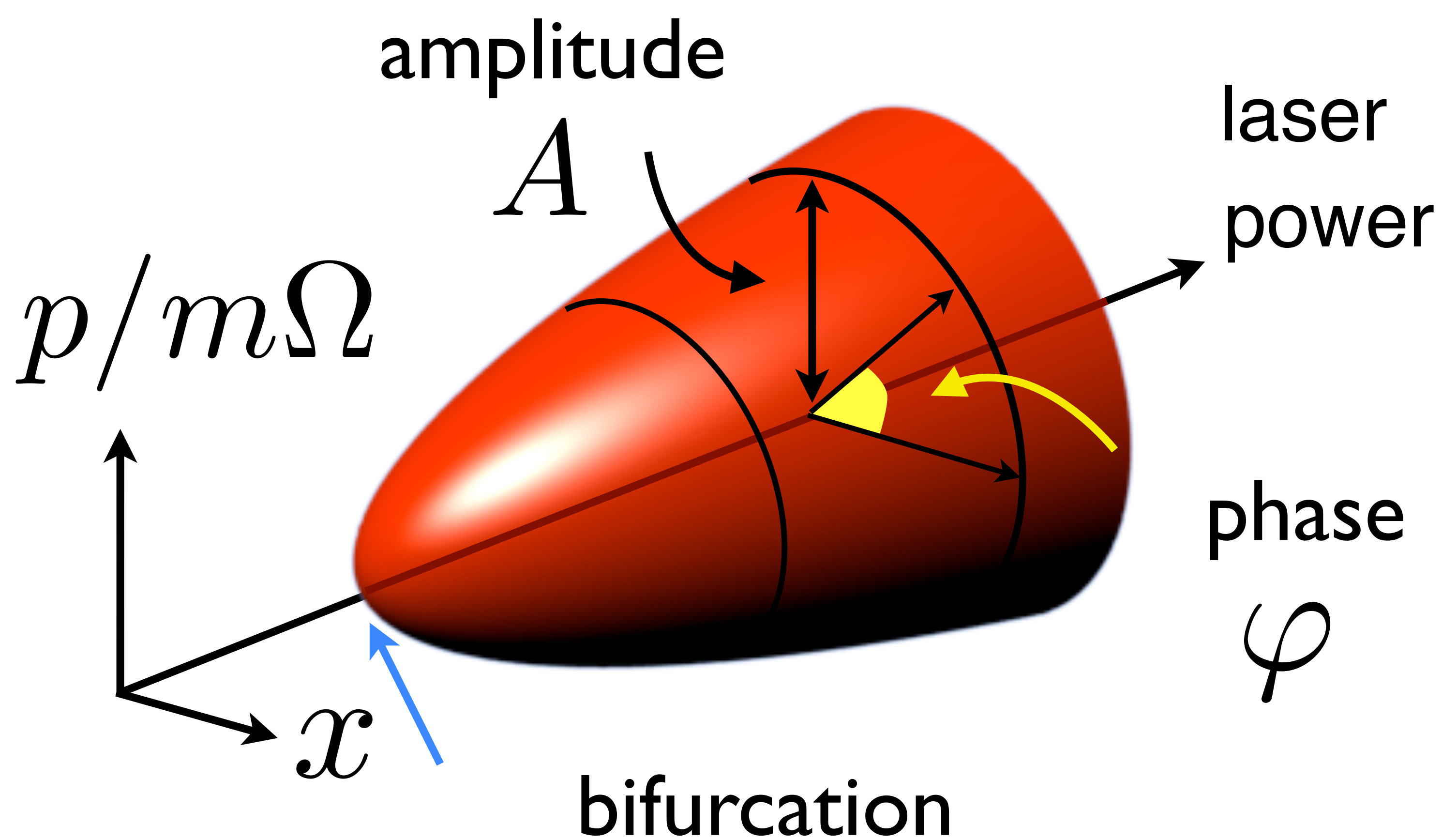
FM, Harris, Girvin, PRL 2006

An optomechanical cell as a Hopf oscillator

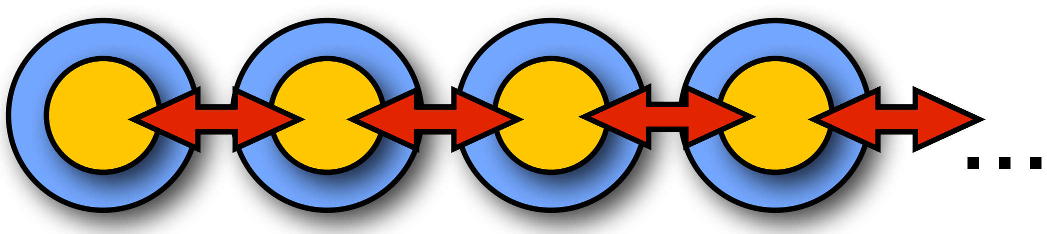


Amplitude fixed, phase undetermined!

An optomechanical cell as a Hopf oscillator

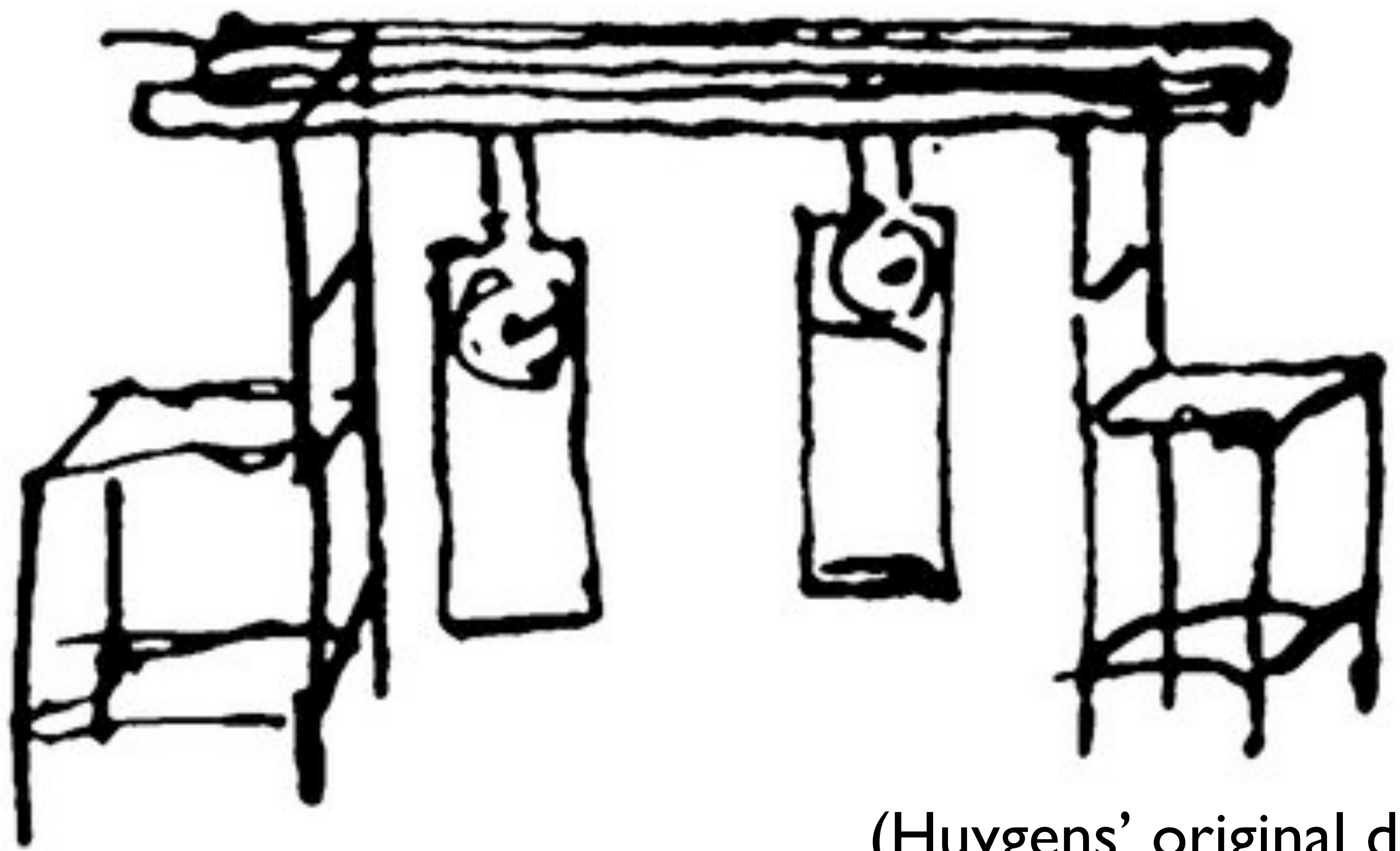


Amplitude fixed, phase undetermined!



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

Synchronization: Huygens' observation

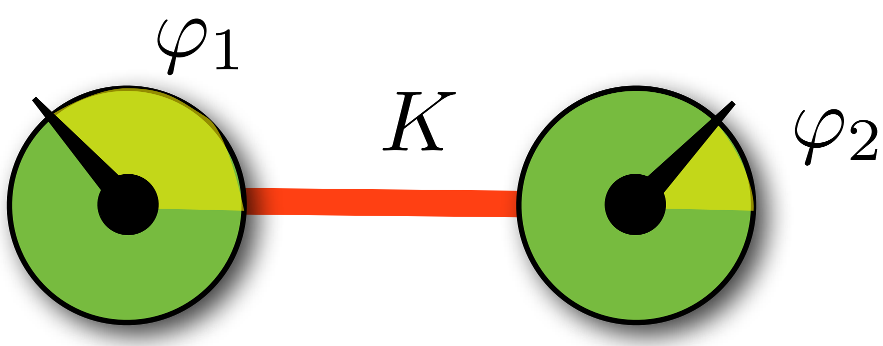


(Huygens' original drawing!)

Coupled pendula synchronize...
...even though intrinsic frequencies slightly different

important in physics, chemistry, biology, ...
Josephson arrays, laser arrays, ...

The Kuramoto model



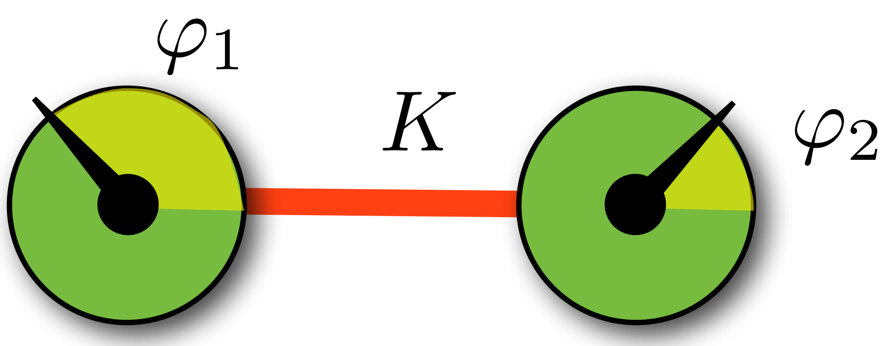
Kuramoto model:

$$\dot{\varphi}_1 = \Omega_1 + K \sin(\varphi_2 - \varphi_1)$$
$$\dot{\varphi}_2 = \Omega_2 + K \sin(\varphi_1 - \varphi_2)$$

- captures essential features
- often found as limiting model

Kuramoto 1975, 1984
Acebron et al. , Rev. Mod. Phys. 77, 137 (2005)

The Kuramoto model



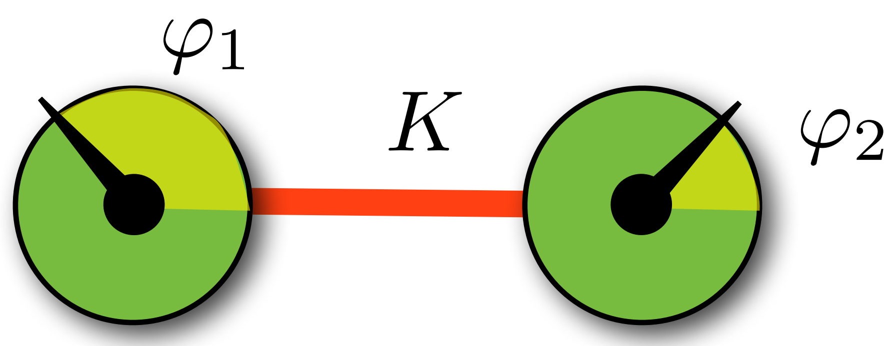
$$\dot{\varphi}_1 = \Omega_1 + K\sin(\varphi_2 - \varphi_1)$$
$$\dot{\varphi}_2 = \Omega_2 + K\sin(\varphi_1 - \varphi_2)$$

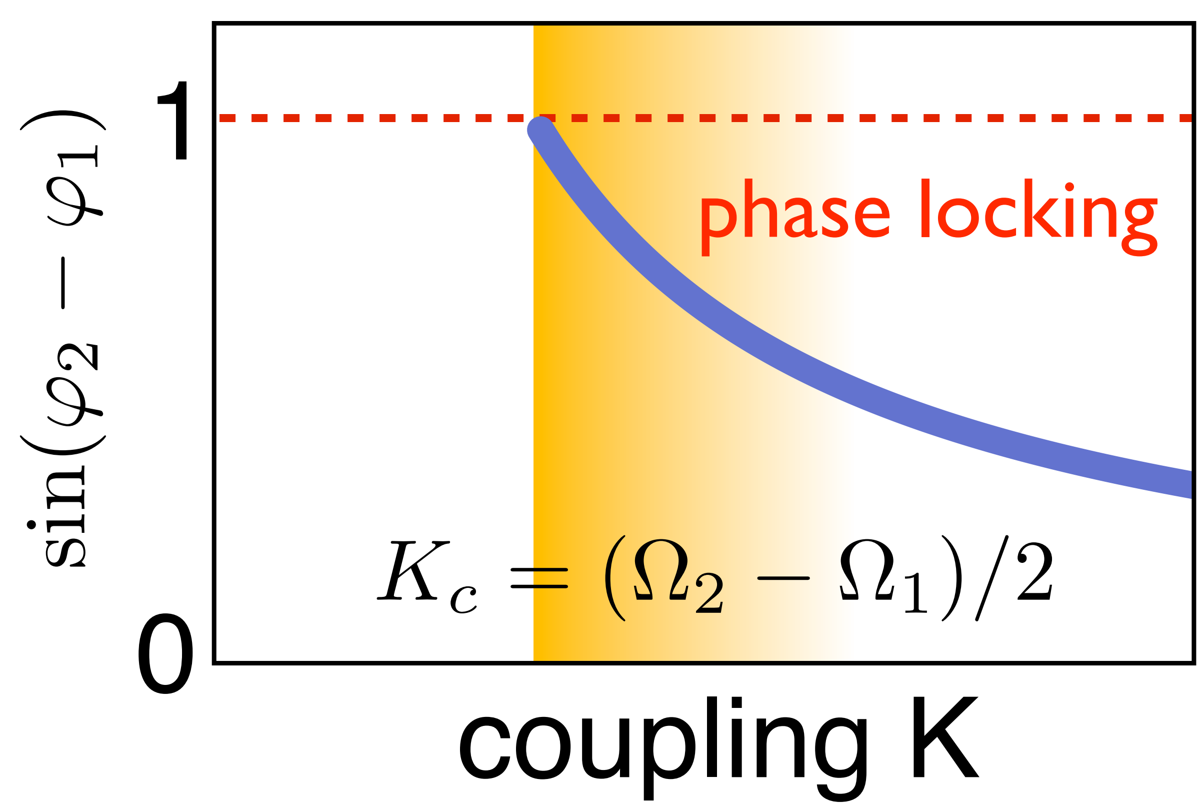
Synchronization:

$$\dot{\varphi}_1 = \dot{\varphi}_2 \quad \Rightarrow \quad \sin(\varphi_2 - \varphi_1) = \frac{\Omega_2 - \Omega_1}{2K}$$

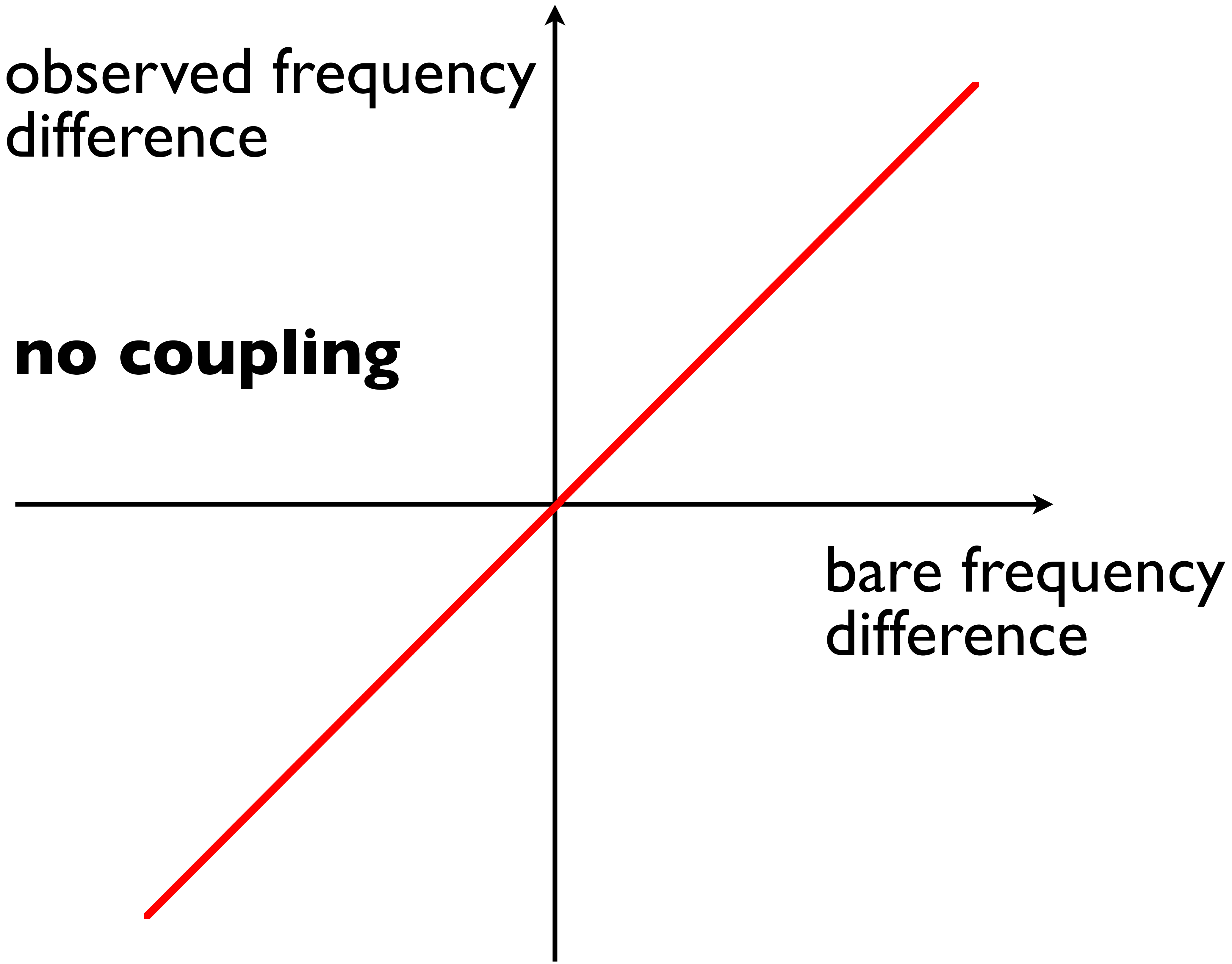
phase lag

The Kuramoto model

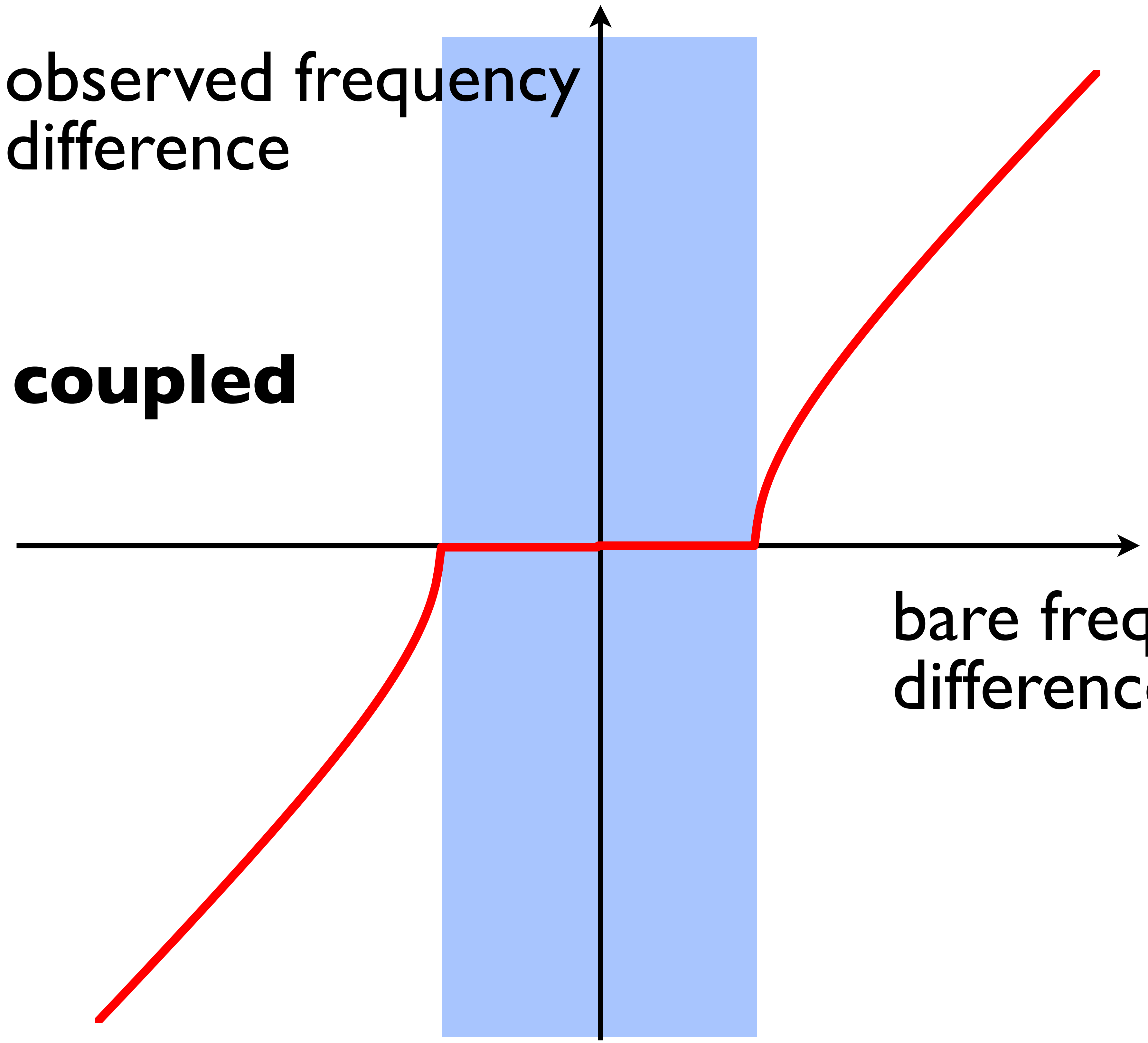




Frequency Locking



Frequency Locking



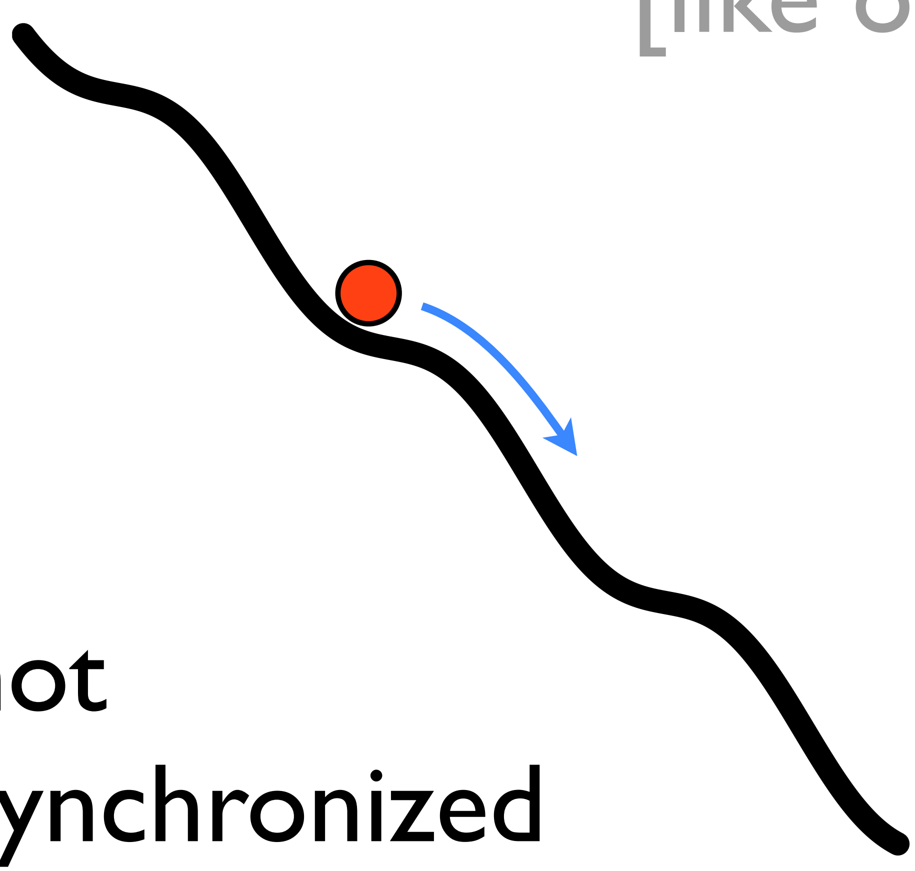
The washboard potential

$$\delta\dot{\phi} = \delta\Omega - 2K\sin(\delta\phi)$$

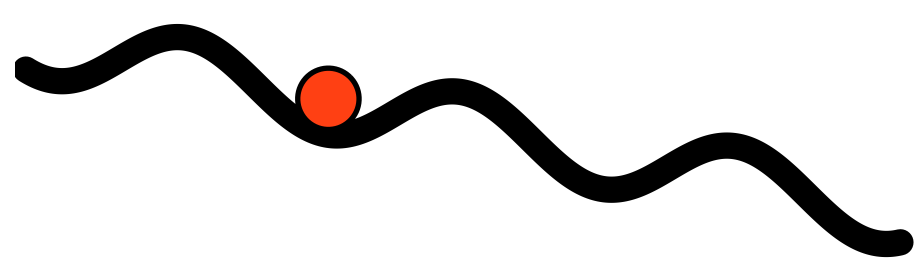
rewrite as: $\delta\dot{\phi} = -\dfrac{\partial U}{\partial \delta\phi}$

with $U = -\delta\Omega\delta\phi - 2K\cos(\delta\phi)$

[like overdamped Josephson junction!]



not synchronized

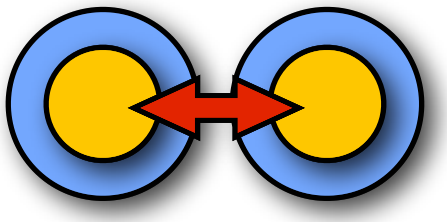


synchronized

Synchronization of two optomechanical oscillators?

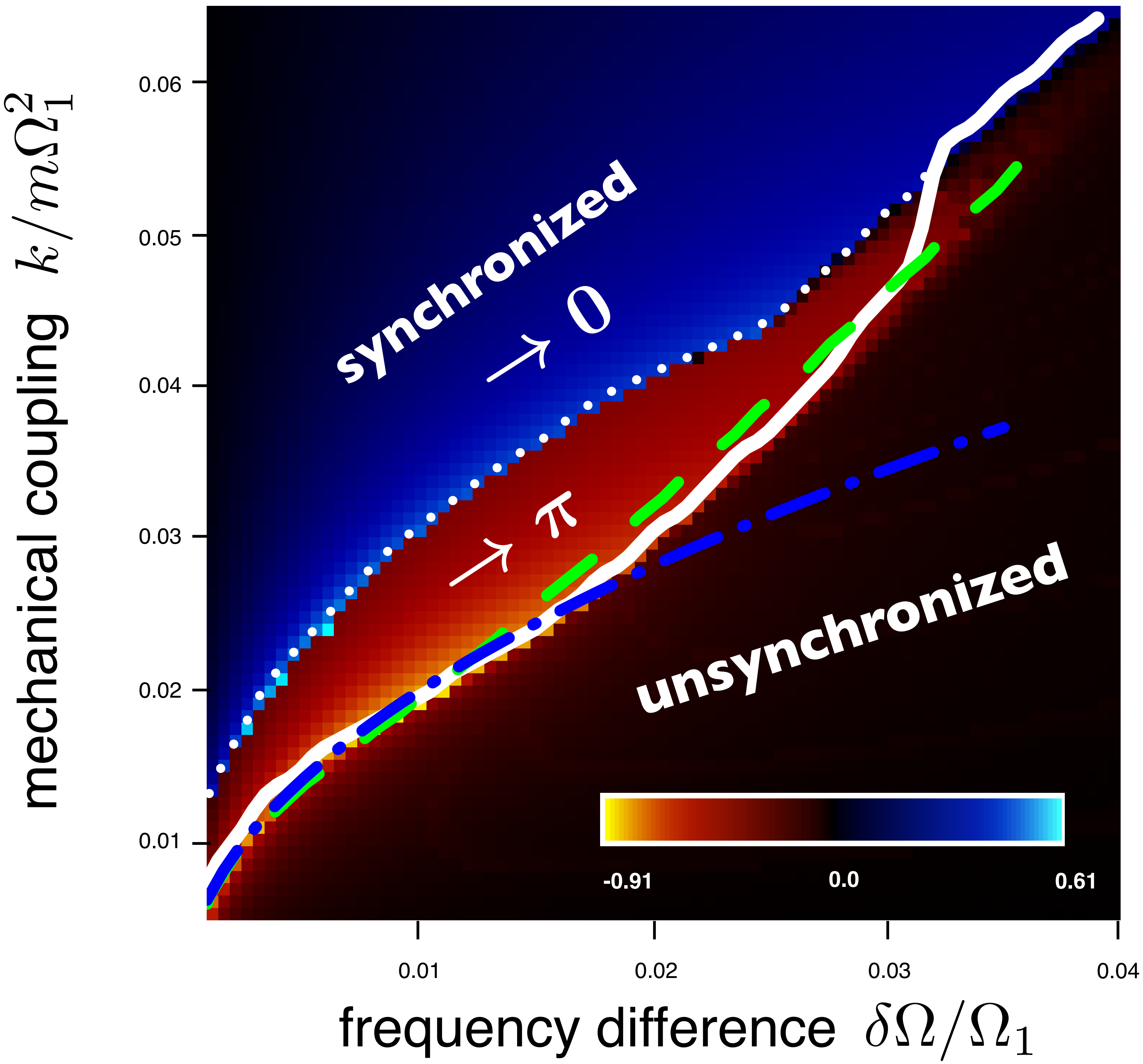
limit cycle
(blue-detuned drive)

two coupled
cells



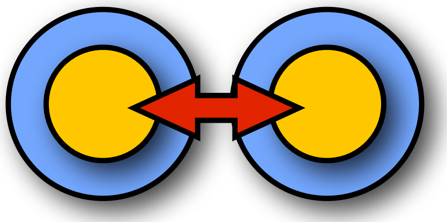
different
intrisic
frequencies

Synchronization of two optomechanical oscillators!



limit cycle
(blue-detuned drive)

two coupled
cells

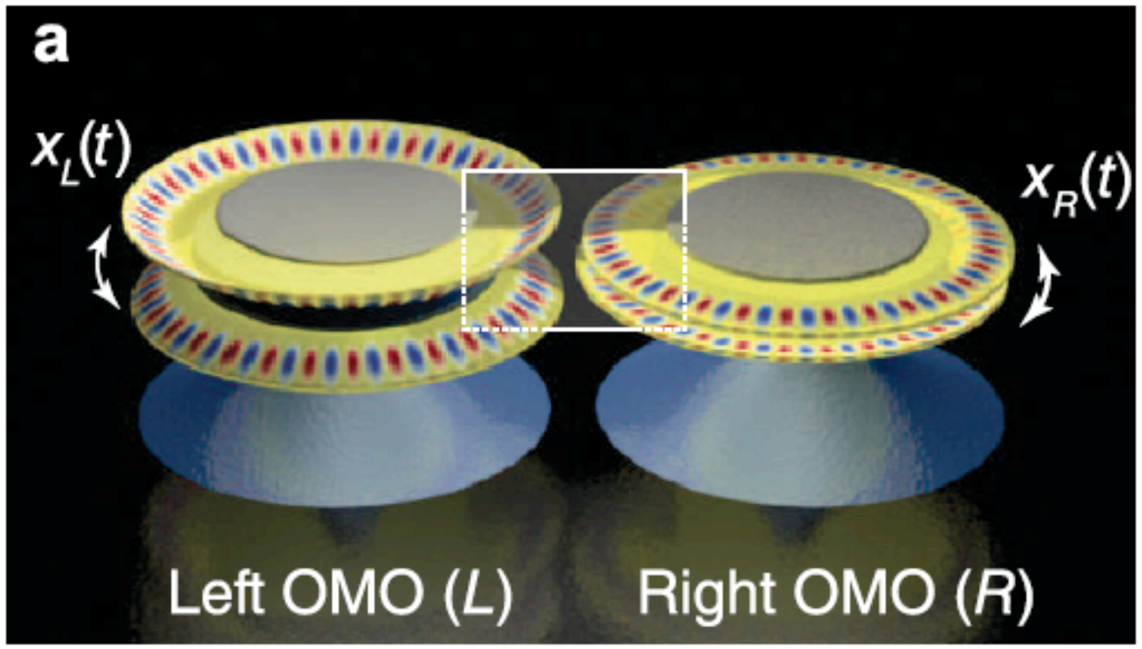


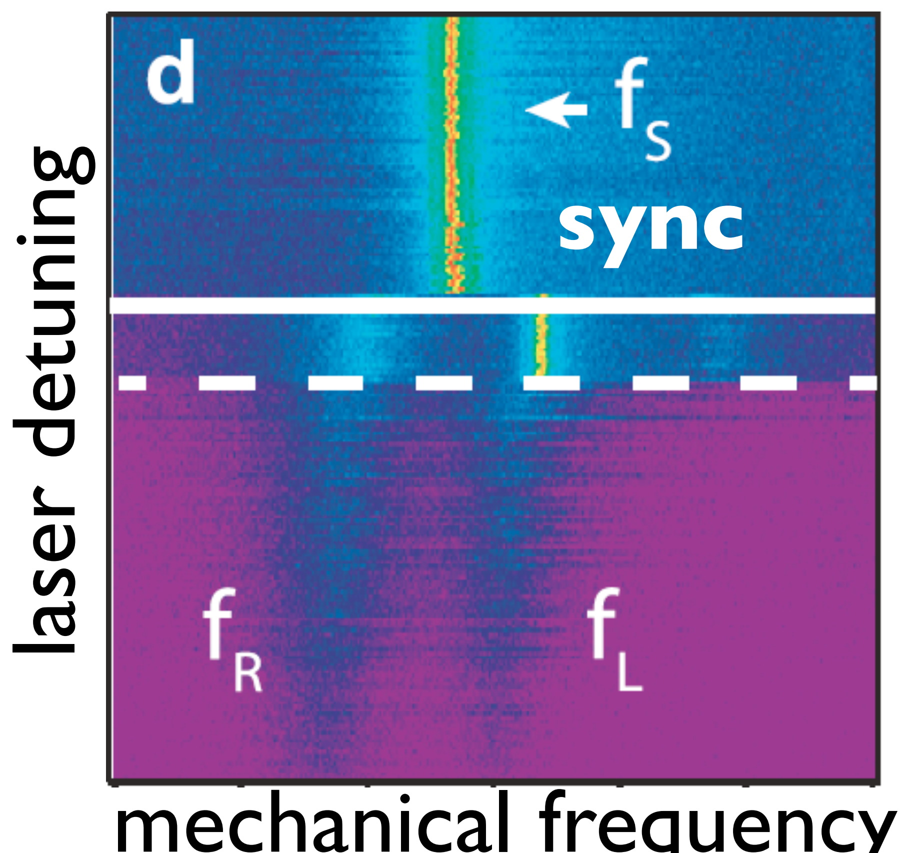
different
intrisic
frequencies

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

Experiments (two cells, joint optical mode)

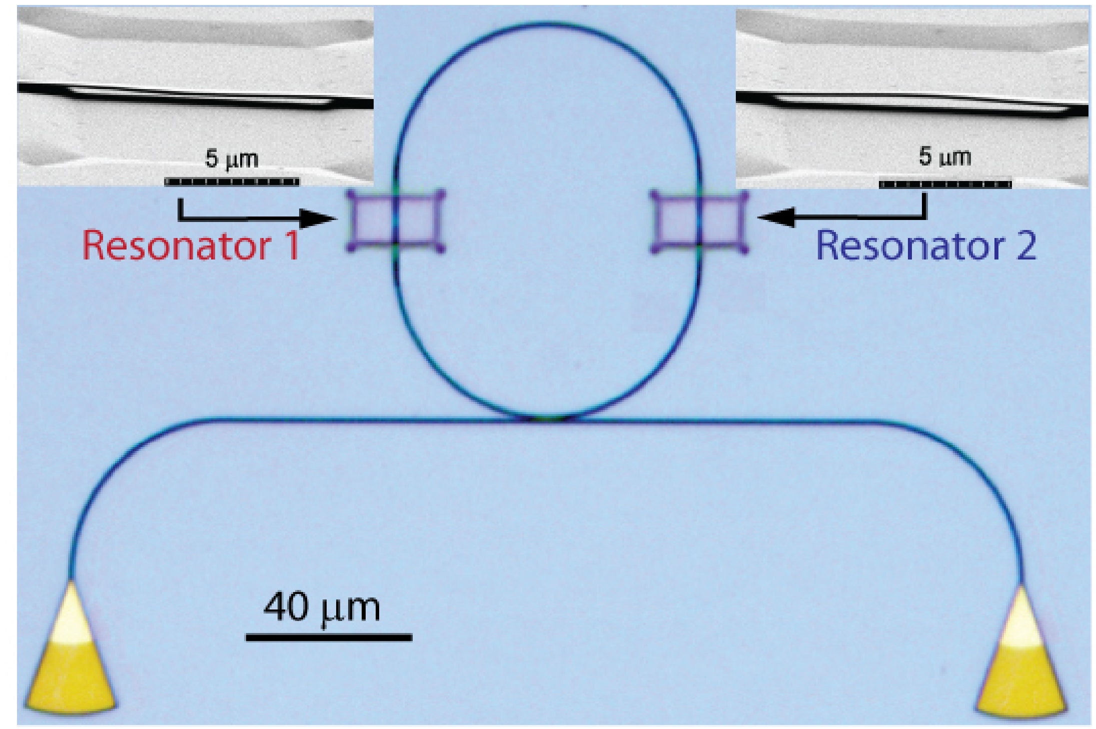
Michal Lipson lab, Cornell

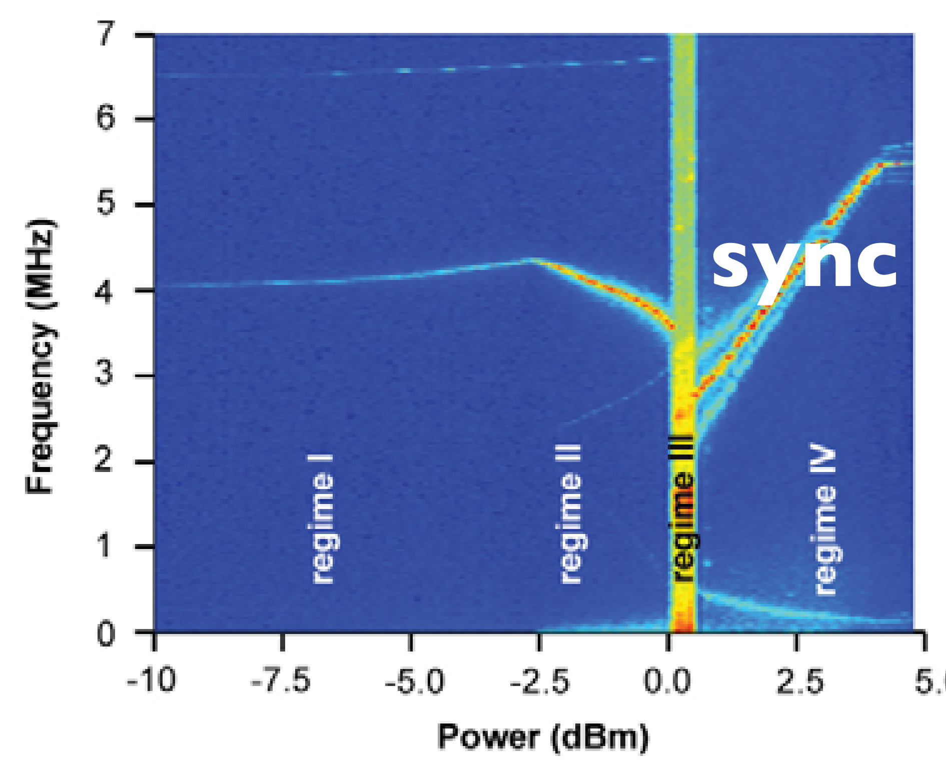




(Zhang et al., PRL 2012)

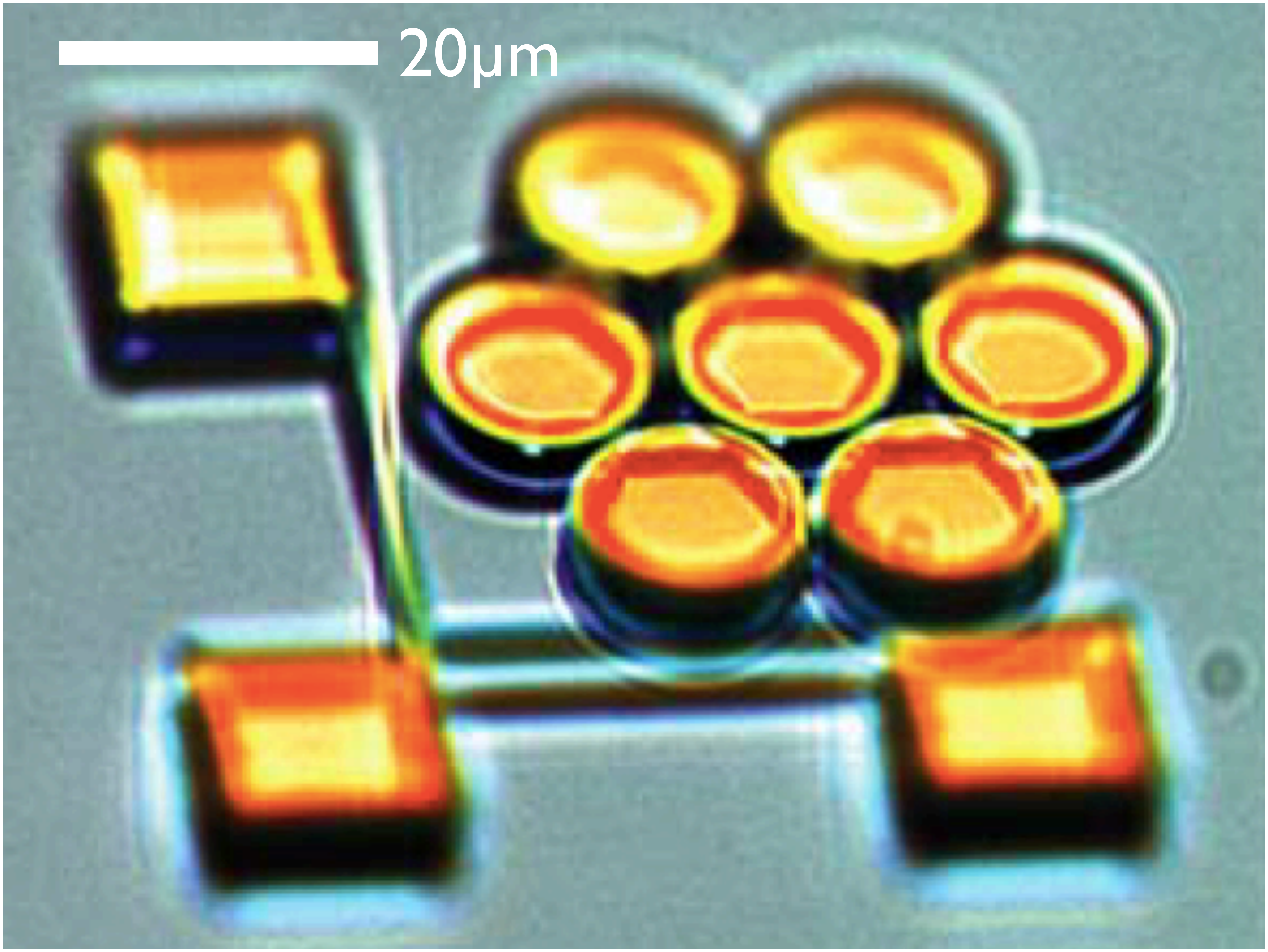
Hong Tang lab, Yale





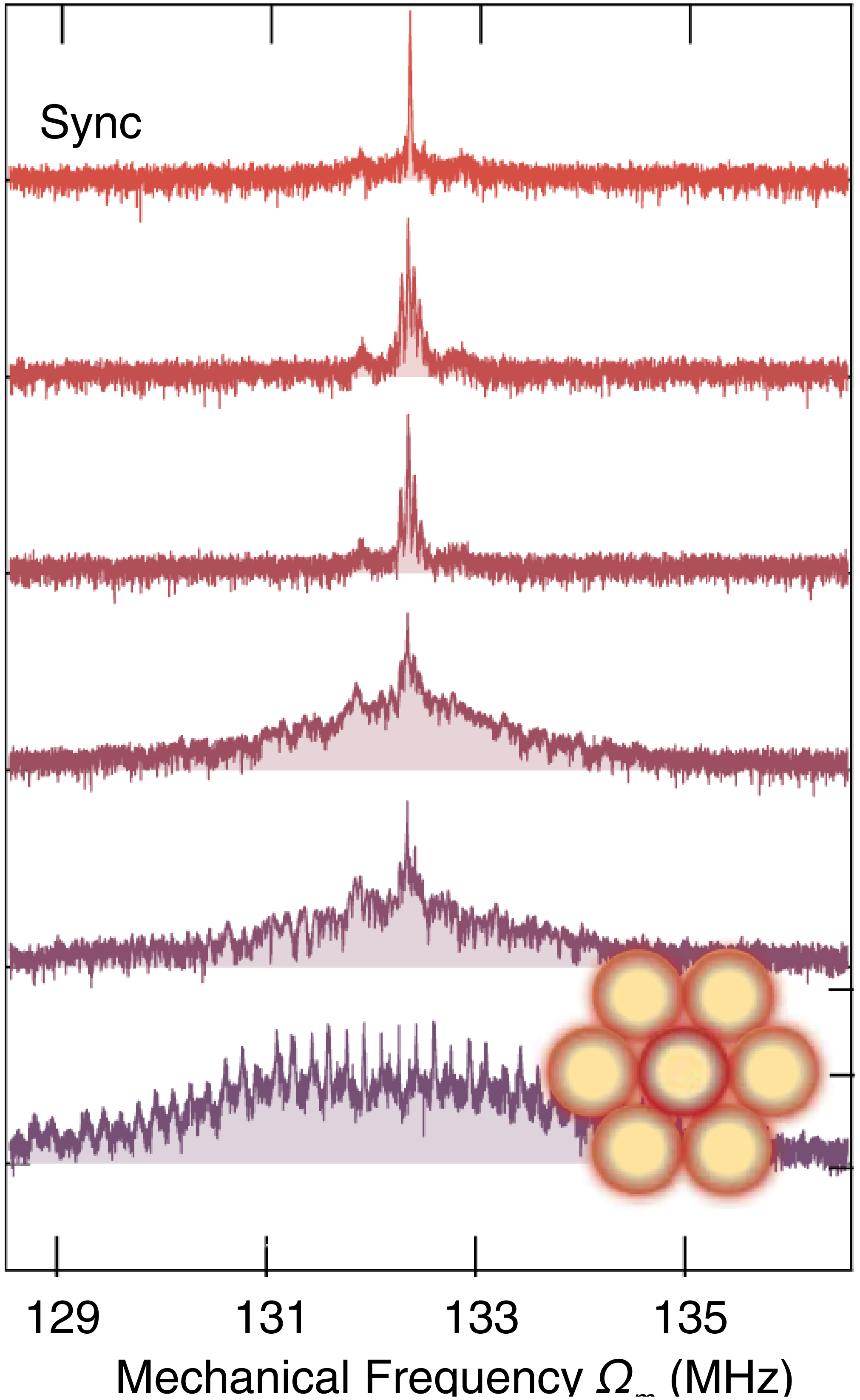
(Bagheri, Poot, FM, Tang; PRL 2013)

7-disk array



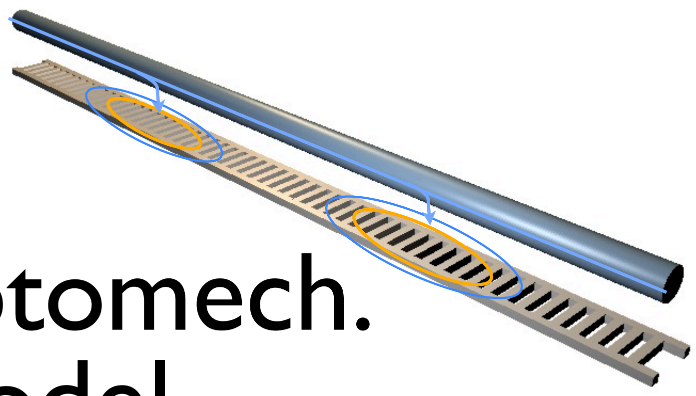
Lipson group PRL 2015 (synchronization)

7-disk array

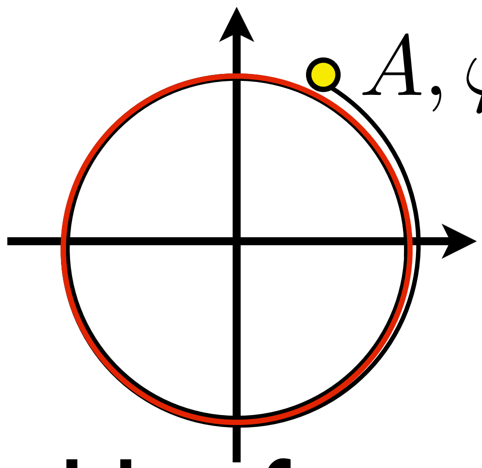


Lipson group PRL 2015 (synchronization)

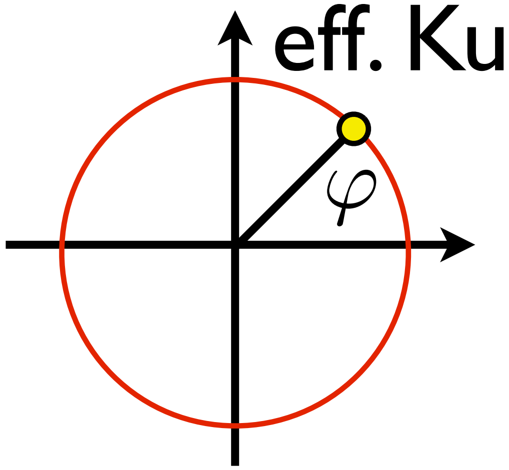
Optomechanical Kuramoto model



optomech.
model



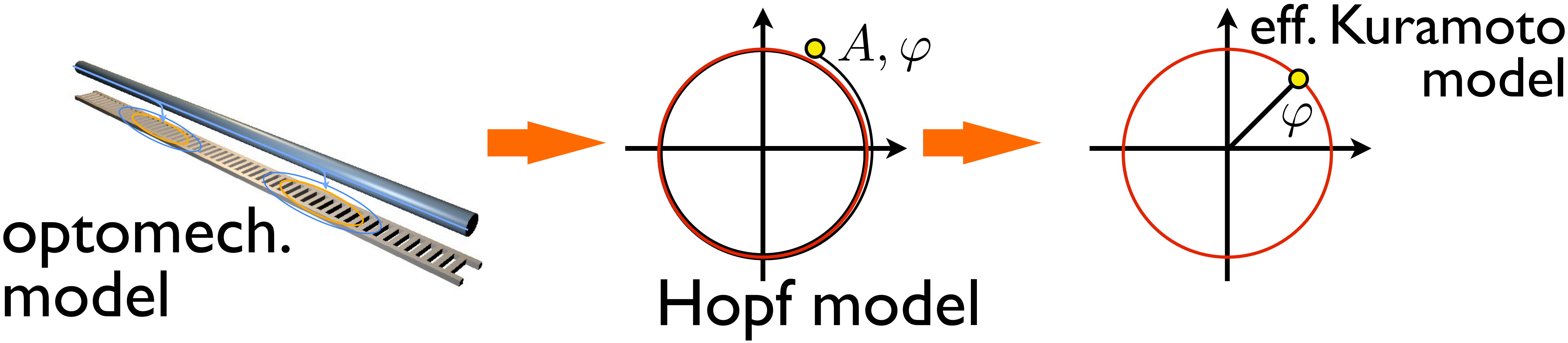
Hopf model



eff. Kuramoto
model

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

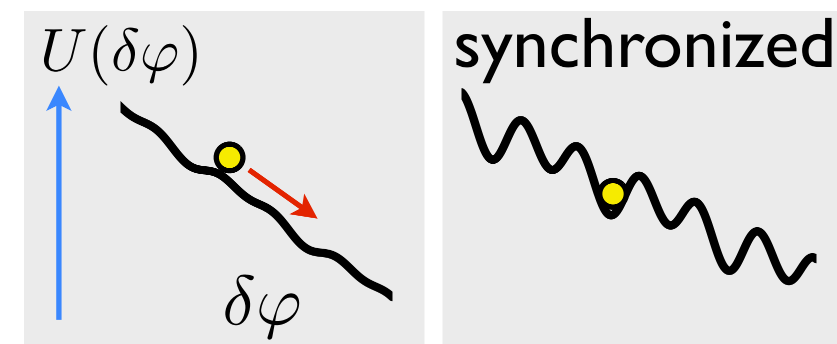
Optomechanical Kuramoto model



Standard Kuramoto model:

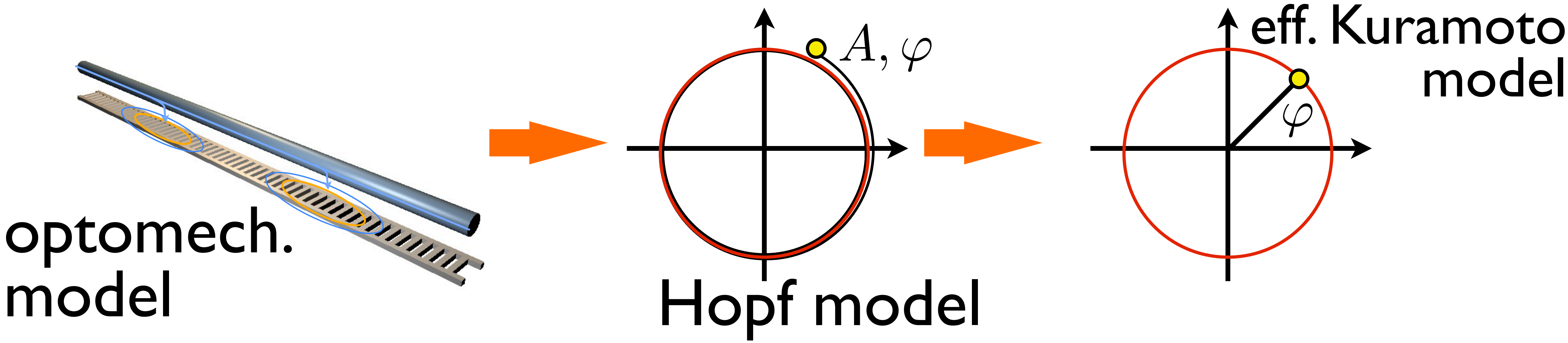
$$\delta\dot{\varphi} = \delta\Omega - 2K\sin(\delta\varphi)$$

(here: for two oscillators)



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

Optomechanical Kuramoto model



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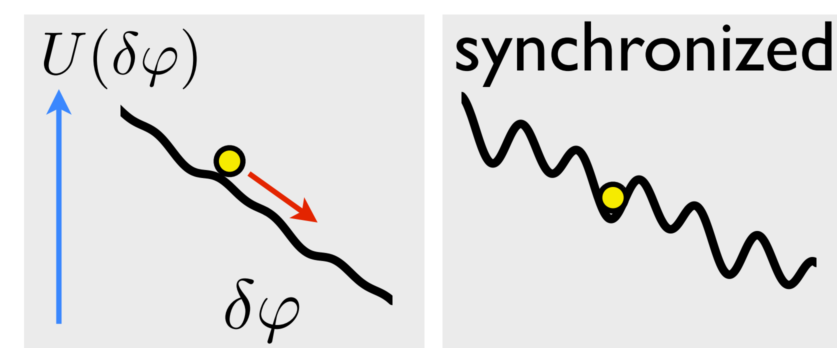

Effective Kuramoto model for optomechanical array:

$$\dot{\varphi}_i = -\Omega + A\sum_{\langle ij\rangle}\cos(\varphi_j - \varphi_i) + B\sum_{\langle ij\rangle}\sum_{\langle ik\rangle}\sin(\varphi_j + \varphi_k - 2\varphi_i)$$
$$+ B\sum_{\langle ij\rangle}\sum_{\langle jk\rangle}\left(\sin(2\varphi_j - \varphi_k - \varphi_i) - \sin(\varphi_k - \varphi_i)\right) - C\sum_{\langle ij\rangle}\sin(\varphi_j - \varphi_i)$$

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

Pattern formation in optomechanical arrays

Phase field

Questions...

“Phase Diagram” of this stochastic field theory?

What about the quantum regime?

Can the phase evolution show quantum coherence?

Can one couple this to topological transport?

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