Optomechanics

Dan Stamper-Kurn
UC Berkeley

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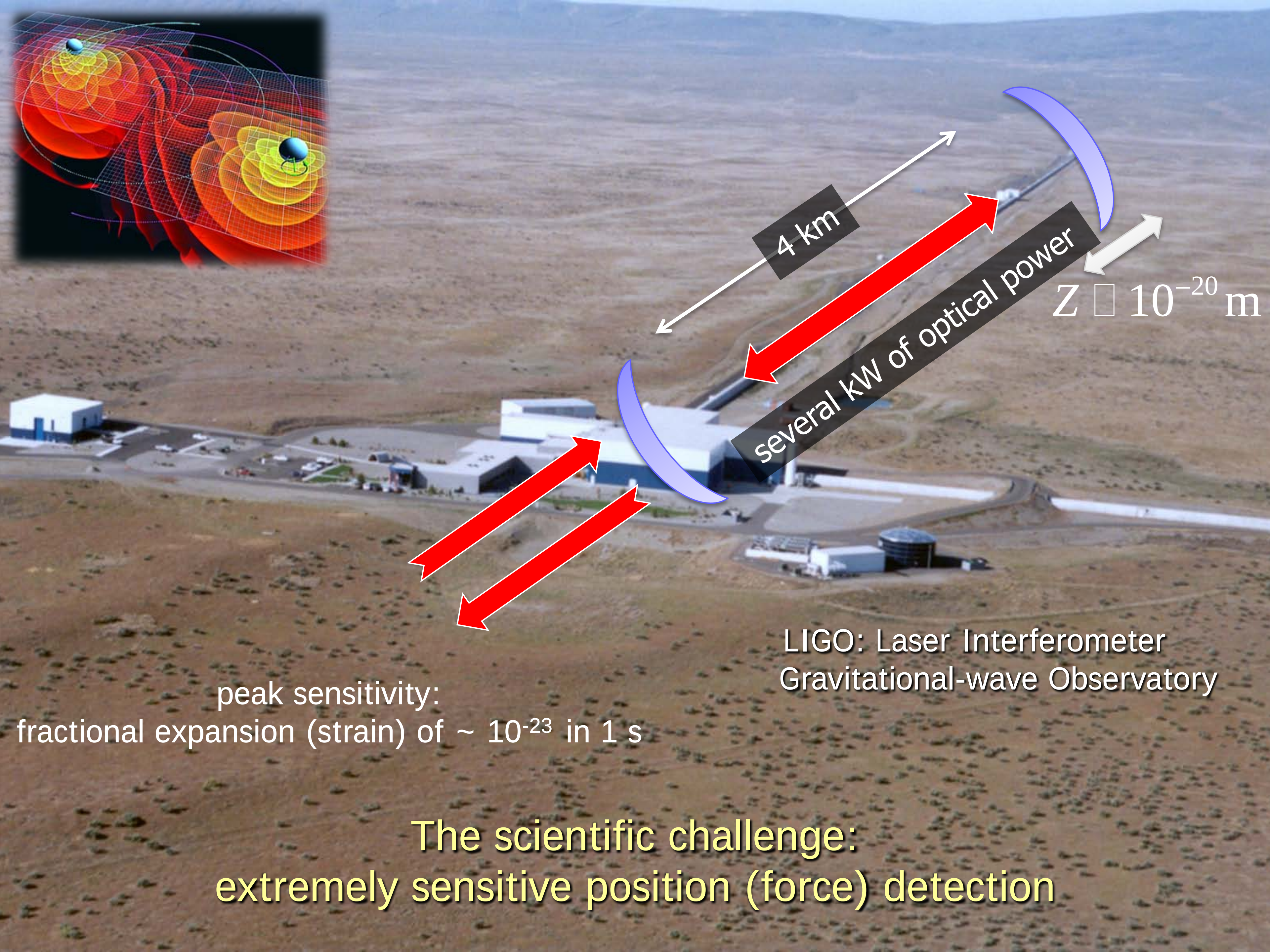
2. **Influence of light (measurement) on the mechanics:** Optomechanical potential, optomechanical spring effect; cavity cooling and amplification; measurement backaction
3. **Feedback model for optomechanics:** optomechanical gain spectrum; ponderomotive squeezing
4. **Future directions**



4 km
several kW of optical power
Z □ 10^{-20} m
LIGO: Laser Interferometer
Gravitational-wave Observatory
peak sensitivity:
fractional expansion (strain) of ~ 10^{-23} in 1 s
The scientific challenge:
extremely sensitive position (force) detection

PHYSICAL REVIEW
LETTERS

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Quantum-Mechanical Radiation-Pressure Fluctuations in an Interferometer

Carlton M. Caves
W. K. Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California 91125
(Received 29 January 1980)

The interferometers now being developed to detect gravitational vaves work by measuring small changes in the positions of free masses. There has been a controversy whether quantum-mechanical radiation-pressure fluctuations disturb this measurement. This Letter resolves the controversy: They do.

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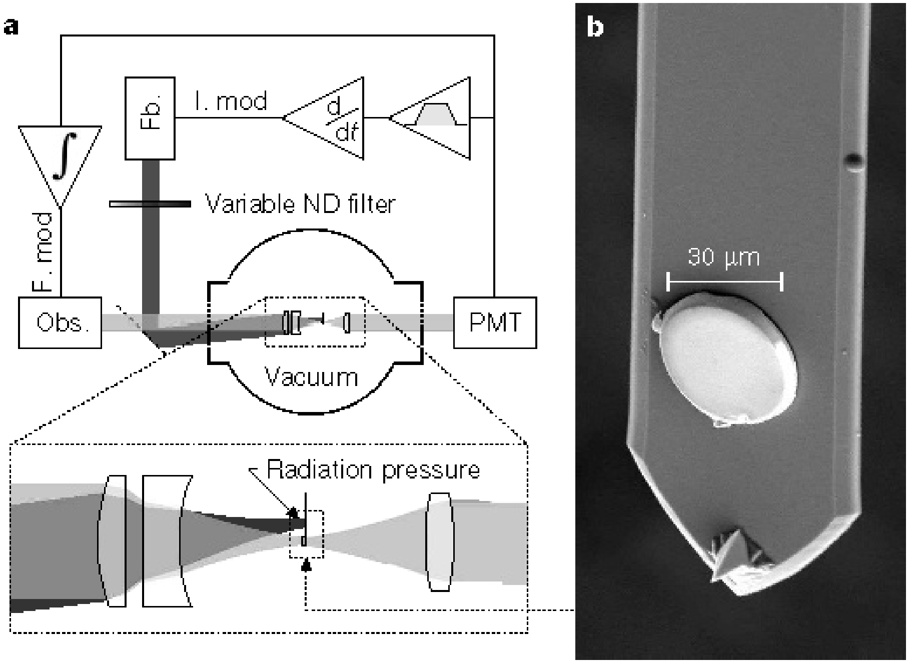
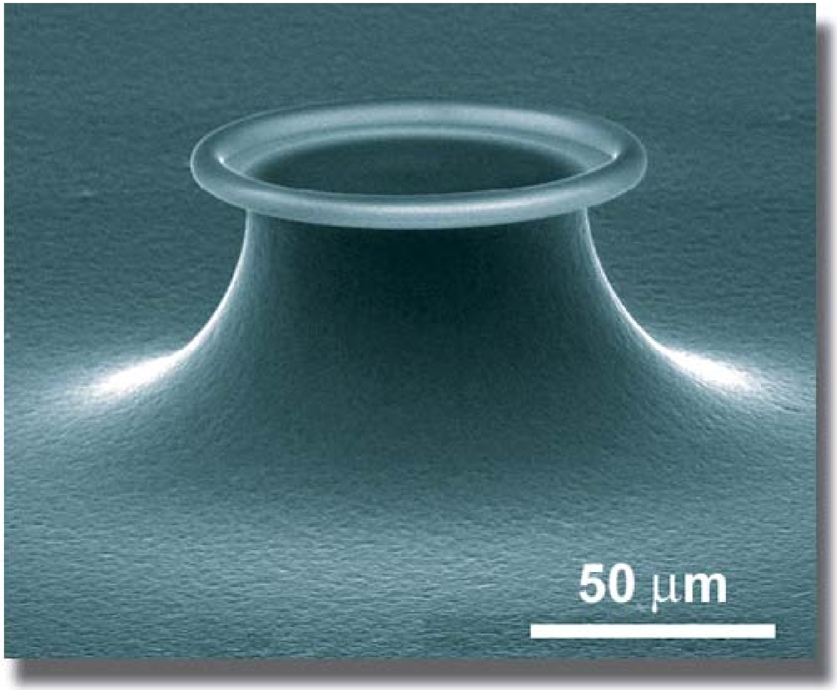
Gallery of cavity optomechanical systems

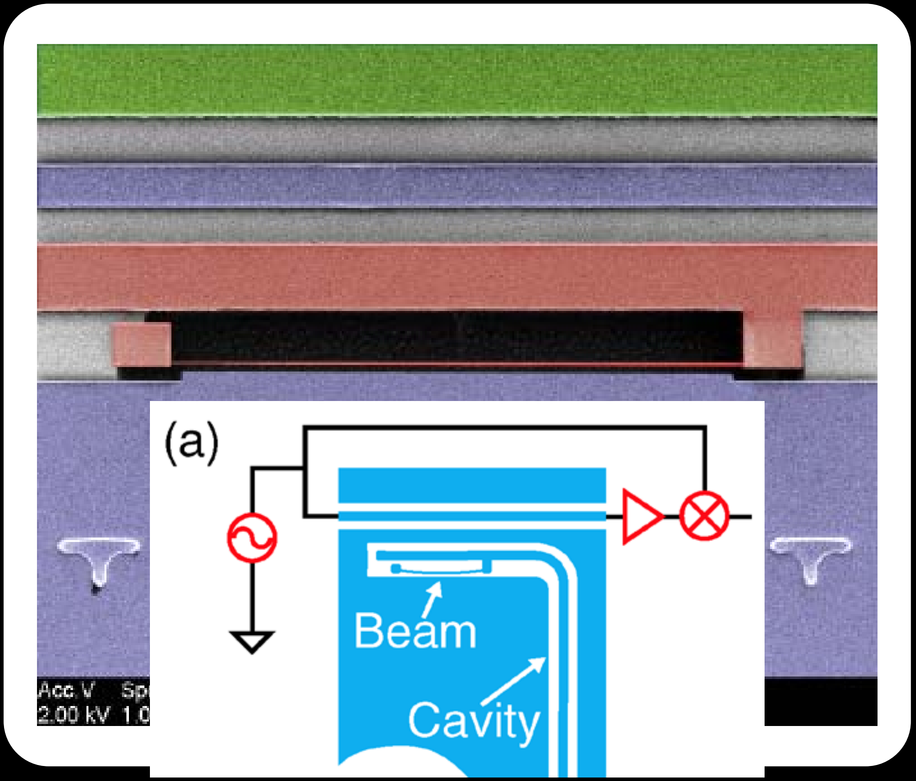


Bouwmeester [(Nature 444, 75 (2006)]



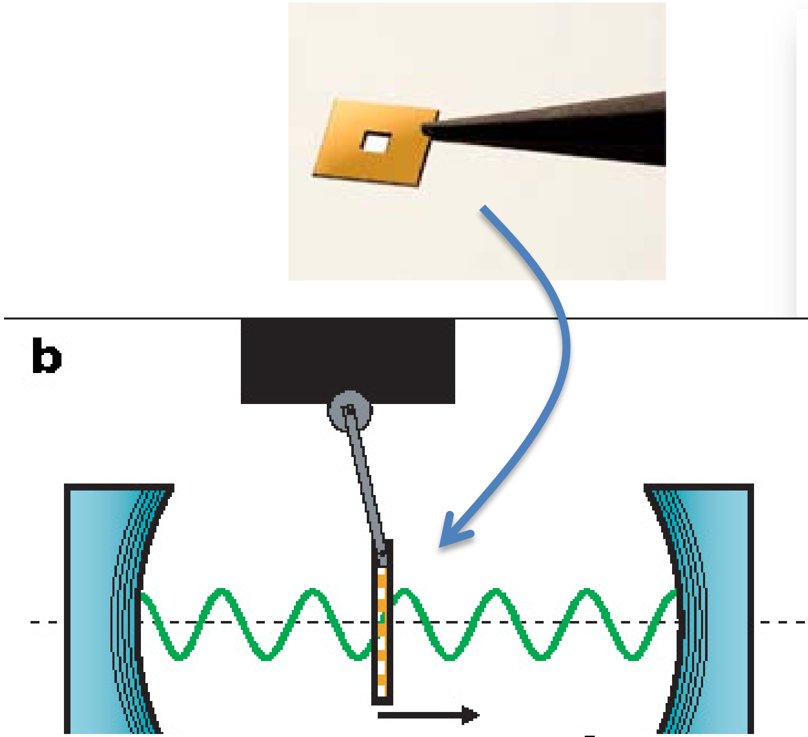
Kippenberg

Gallery of cavity optomechanical systems

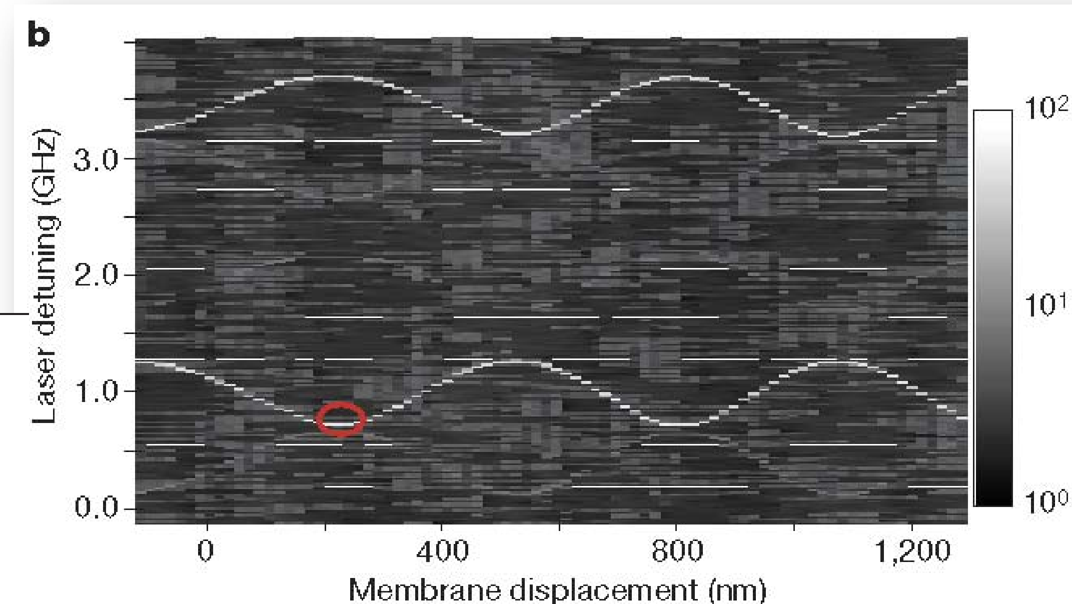


Lehnert group

“Membrane in the middle” (Harris, Yale; others)



$$\varphi = 2kZ_0$$

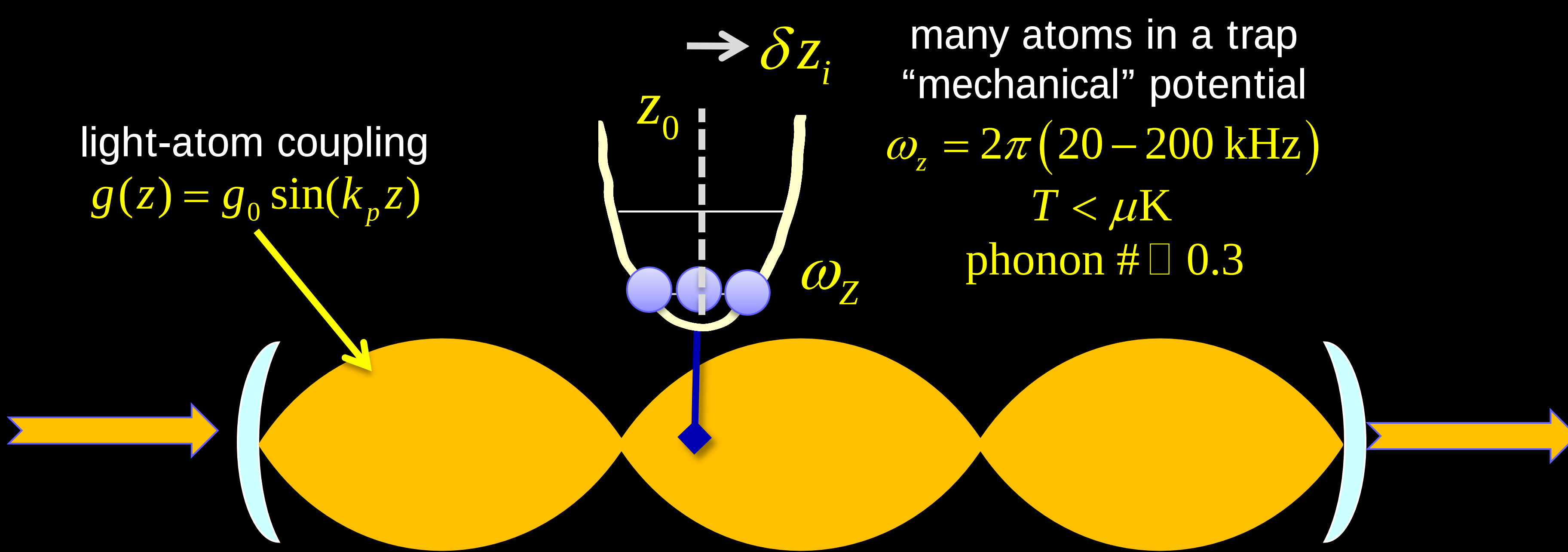


Nature **452**, 72 (2008)

$$H_{om} = E(2\varphi)\hat{n} - F\sin(2\varphi)\hat{Z}_{CoM}\hat{n} - Fk\cos(2\varphi)\hat{Z}_{CoM}^2\hat{n} + \ldots$$

linear coupling:
optical spring, bistability,
ponderomotive squeezing…

quadratic coupling:
phonon QND,…



$$H_{om} = \sum_{atoms} \frac{\hbar g^2(\hat{z}_i)}{\Delta_{ca}} \hat{n} \simeq \hbar \Delta_N^{(0)} \hat{n} - F \sin(2\varphi) \hat{Z}_{CoM}\, \hat{n} - F k \cos(2\varphi)\left[\hat{Z}_{CoM}^2 + \sigma^2\right]\hat{n}$$

- Tunability of optomechanical coupling (strength, type)
- Immediately in the quantum regime (ultracold)
- Dominated by quantum radiation pressure fluctuations (thermally isolated)
- Connected directly to basic theory (quantum optics, atomic physics)

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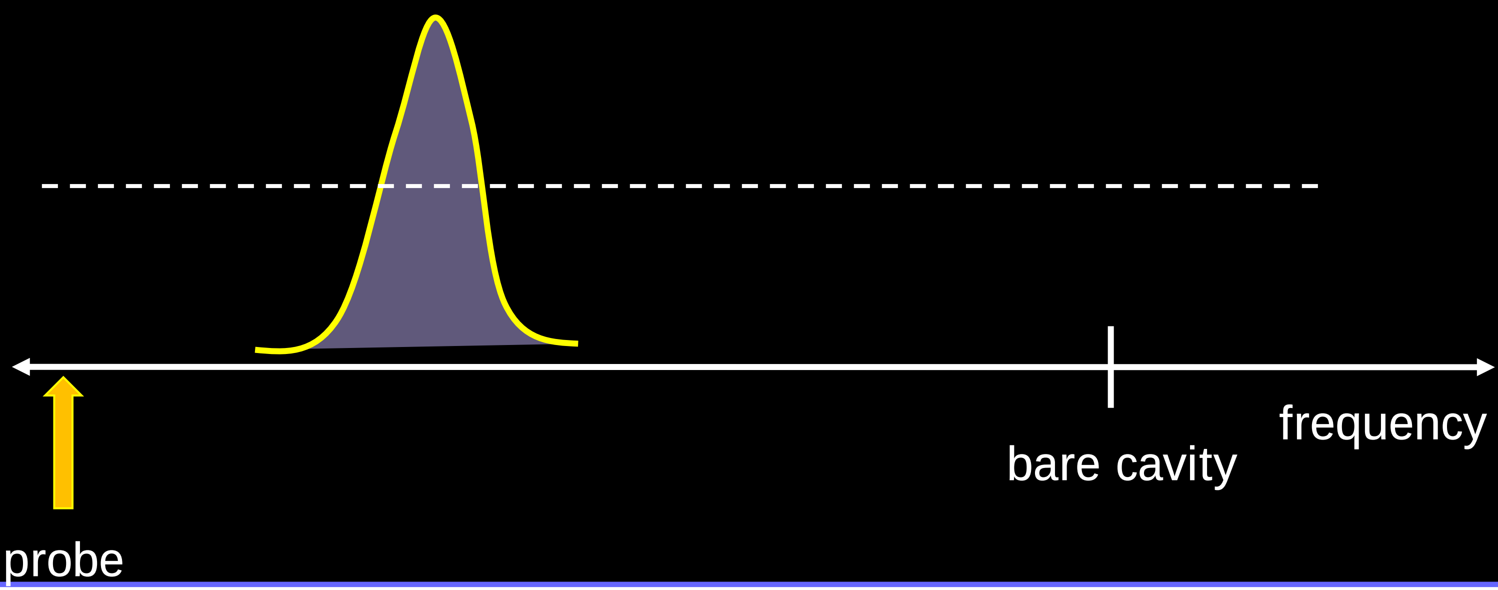
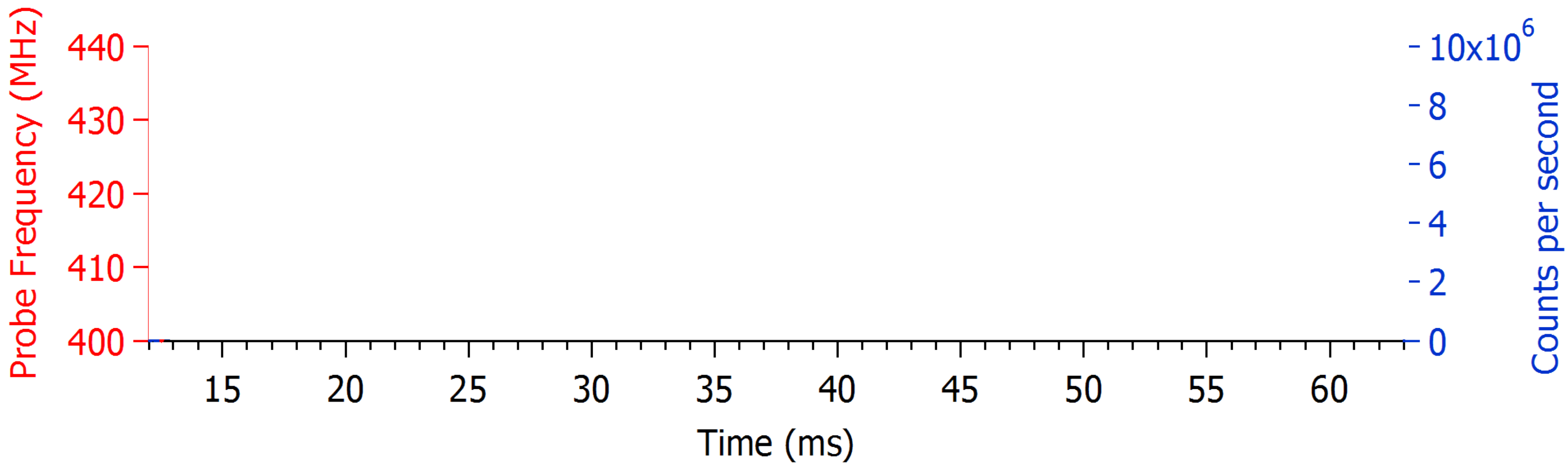
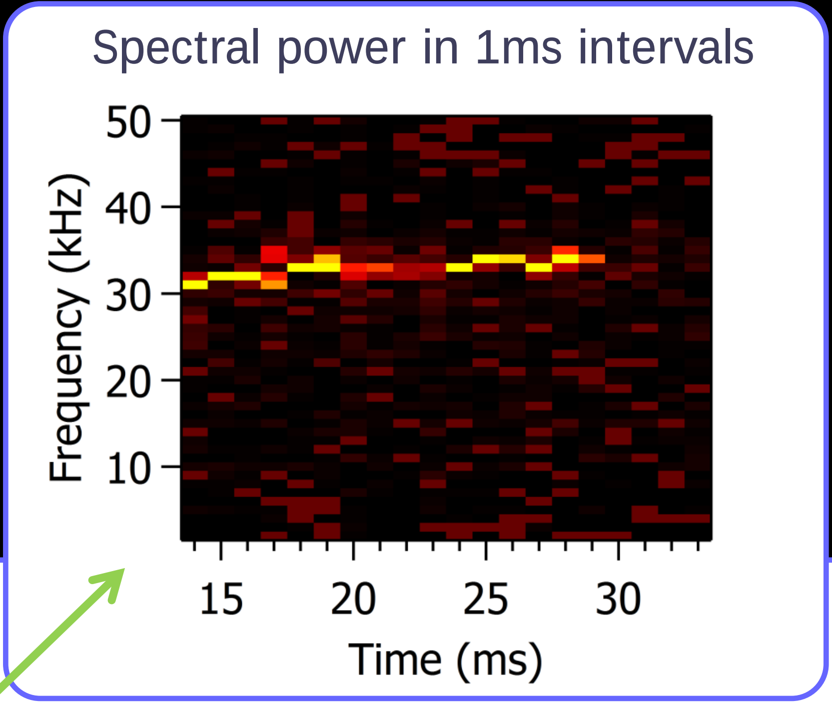
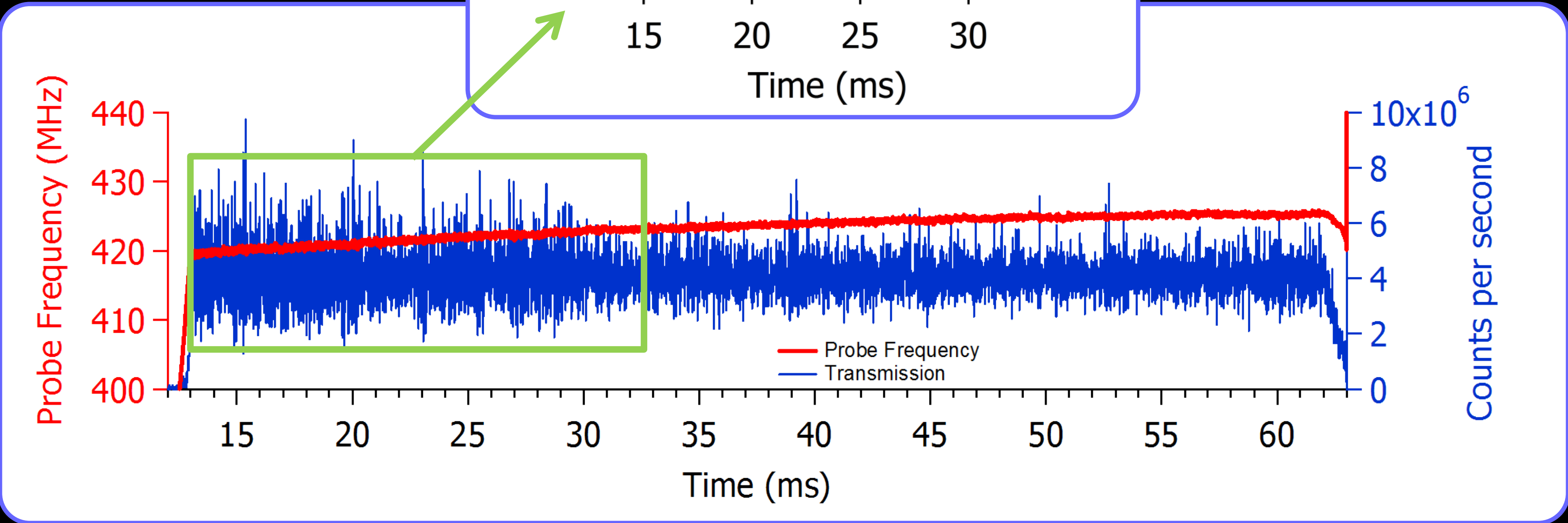
Direct observation of collective atomic motion: probe side-lock





Direct observation of collective atomic motion: probe side-lock

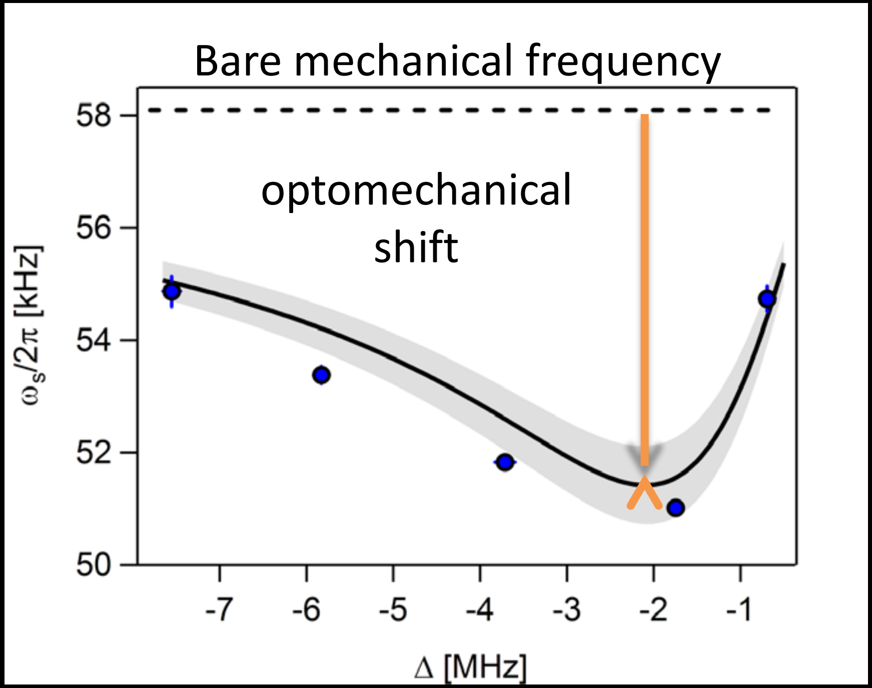




The optical spring effect

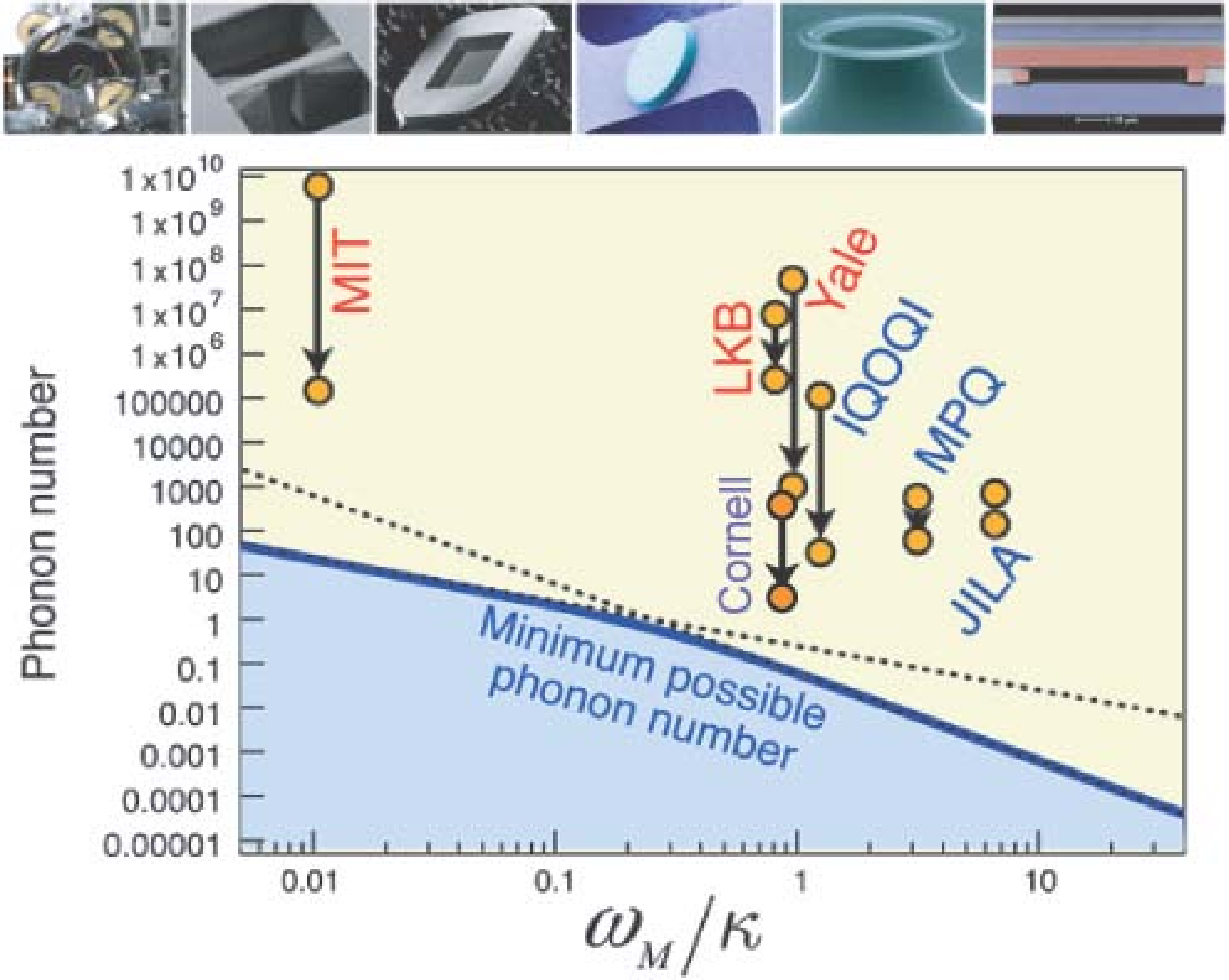
force on collective variable:

$$F_Z = Fn(Z) - M\omega_z^2 Z$$



Purdy et al., arXiv:1005.4085

- Q: Why is cantilever moving?
  A: Radiation pressure fluctuations



Phonon number
1x10^10
1x10^9
1x10^8
1x10^7
1x10^6
100000
10000
1000
100
10
1
0.1
0.01
0.001
0.0001
0.00001
0.01
0.1
1
10
ω_M / κ
MIT
LKB
Yale
IQOQI
MPQ
Cornell
JILA
Minimum possible phonon number

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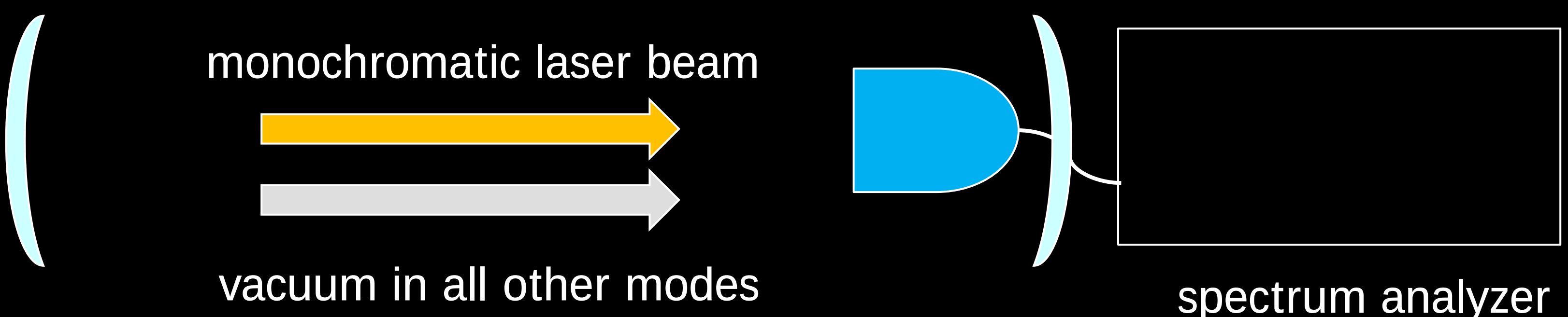
Quantum fluctuations of light within a cavity

- For our system (non-granular, low temperature):

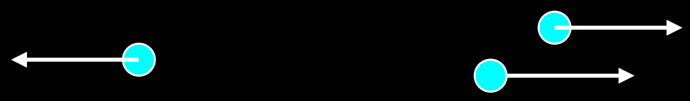
$$S_{nn}(\omega) \propto \frac{2\bar{n}}{\kappa} \frac{1}{1+(\Delta-\omega)^2/\kappa^2}$$

↑ Proportional to intensity

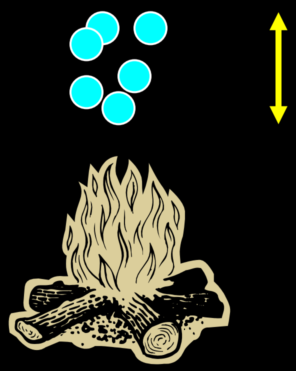
Note: At constant intensity, shot noise fluctuations of photon number in a resonant cavity are enhanced w.r.t. those in free space!



Cavity-induced heating: measured by atom loss



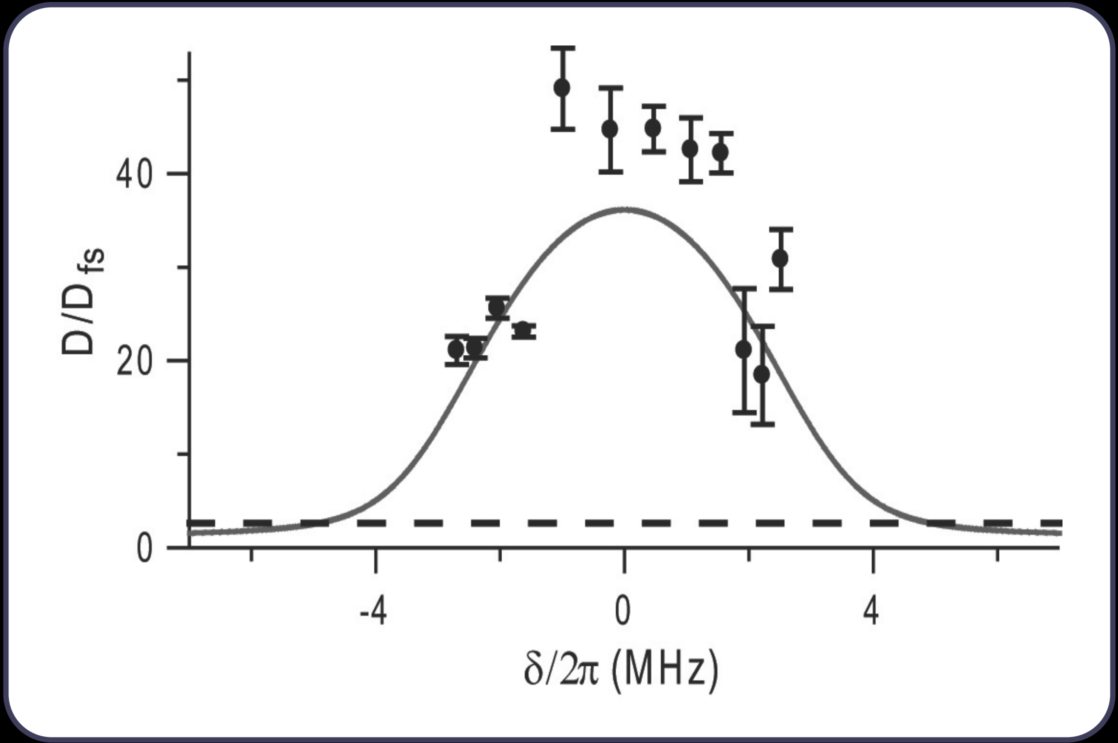
$$N\frac{dE}{dt} = (U - k_B T)\frac{-dN}{dt}$$



$$k_B T \approx \frac{1}{10} U$$

Cavity-induced heating: measured by atom loss

Heating rate per cavity photon compared to free space value



What this means:

- Quantum fluctuations of radiation pressure dominate over other heating sources
- Quantum metrology: back-action heating of macroscopic object at level prescribed by quantum measurement limits

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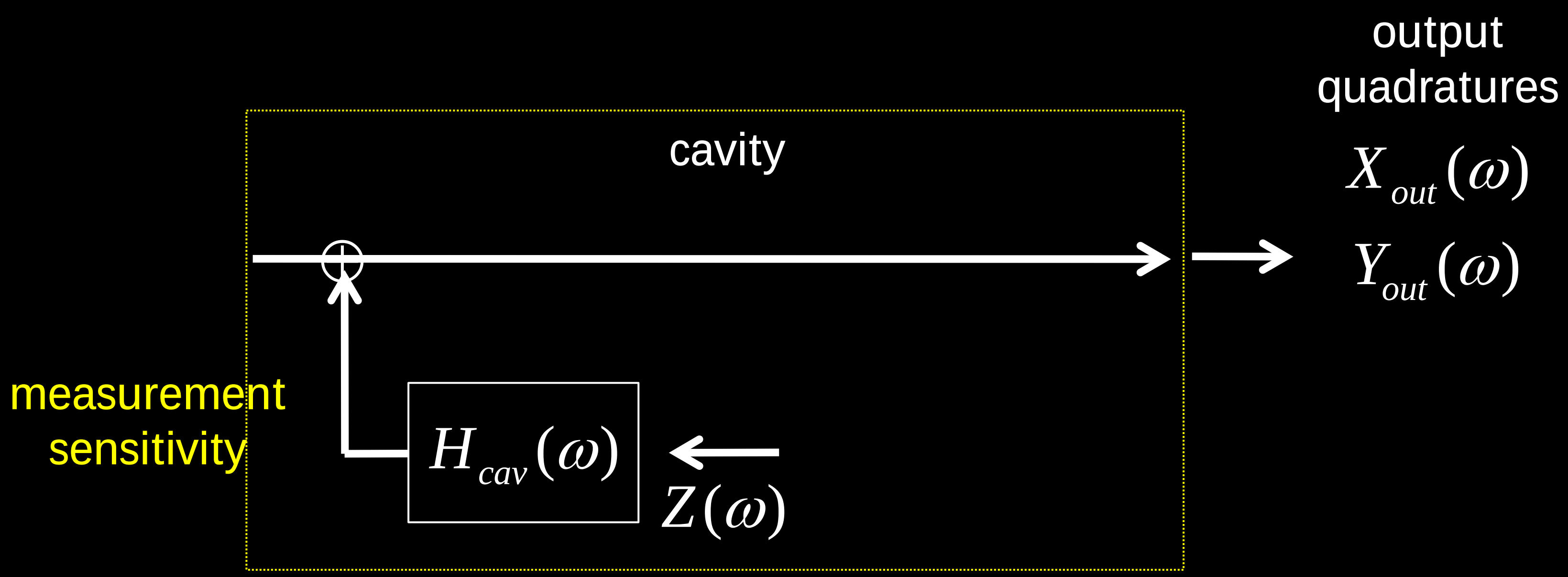
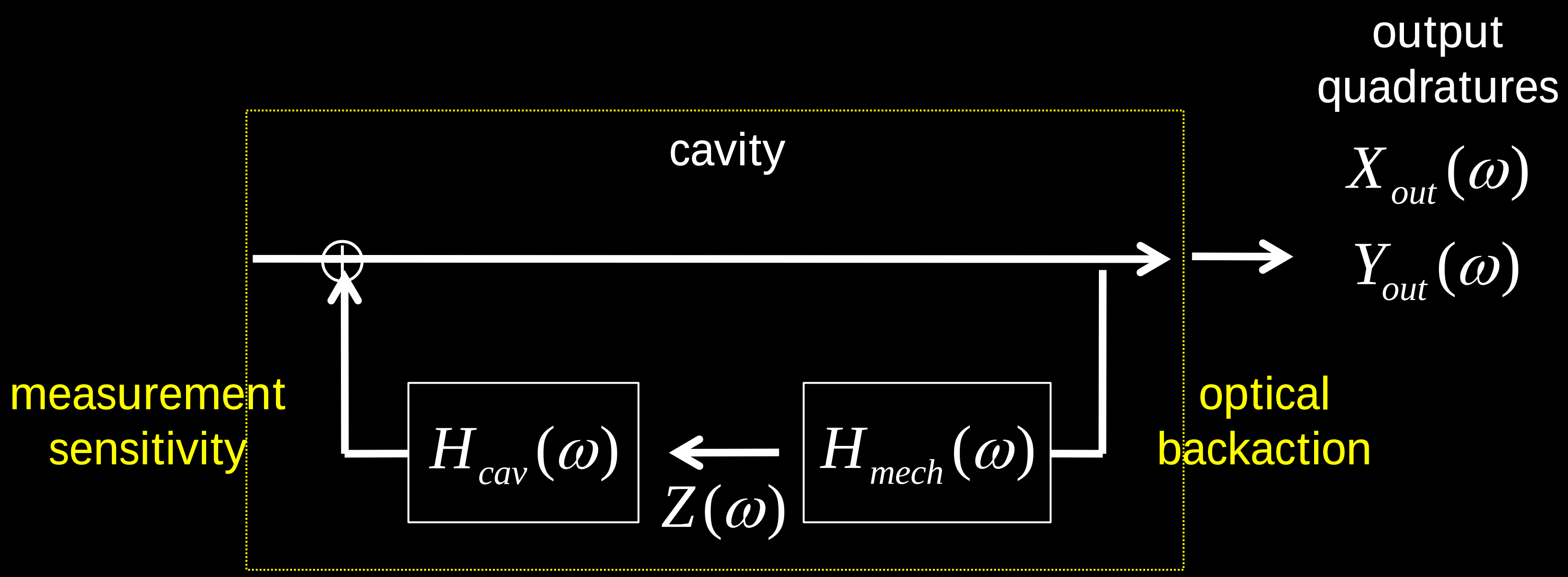
Measurement and feedback in cavity optomechanics

- Measurement scenario



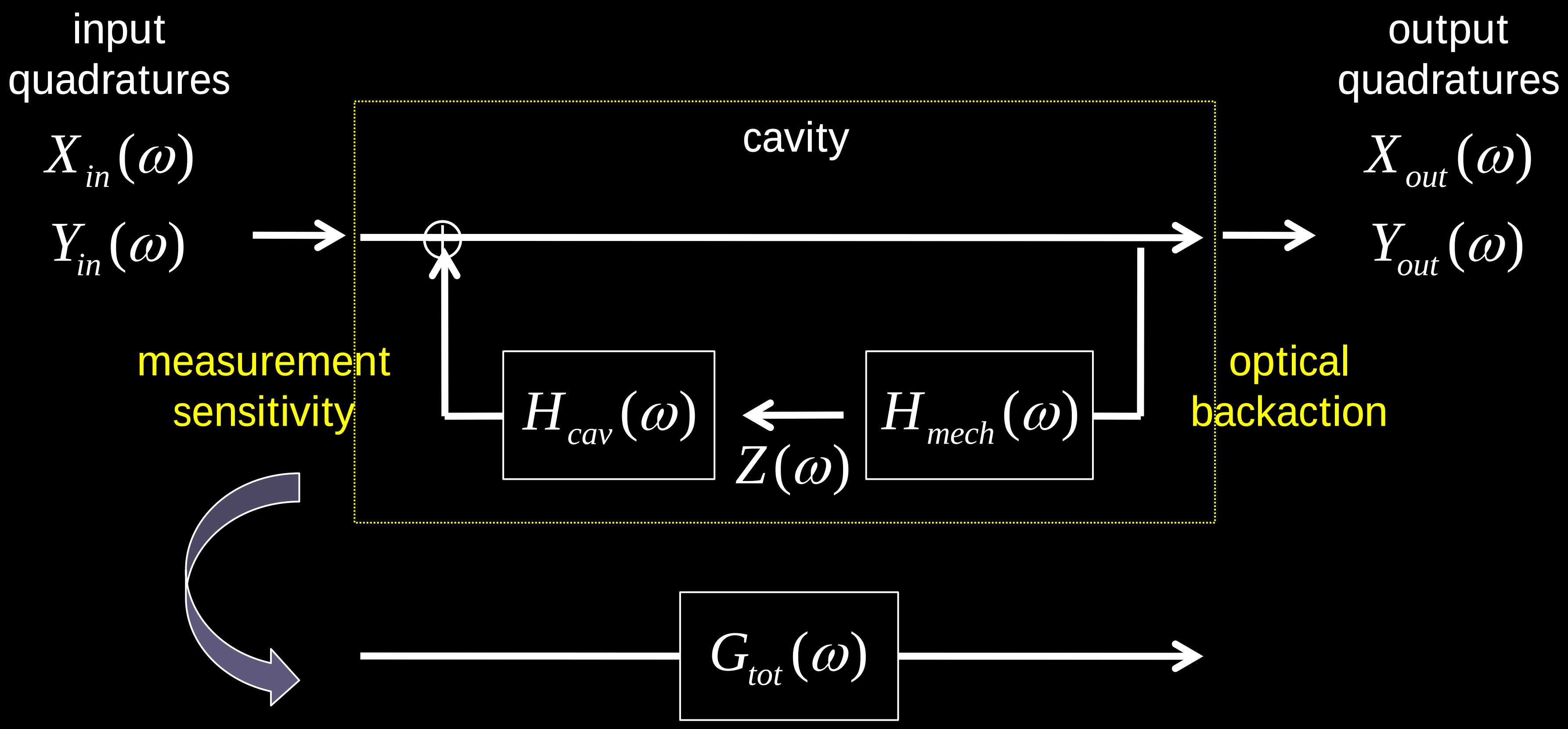
Measurement and feedback in cavity optomechanics

- Coherent backaction scenario
  - optomechanical frequency shift
  - cavity nonlinearity and bistability



Measurement and feedback in cavity optomechanics

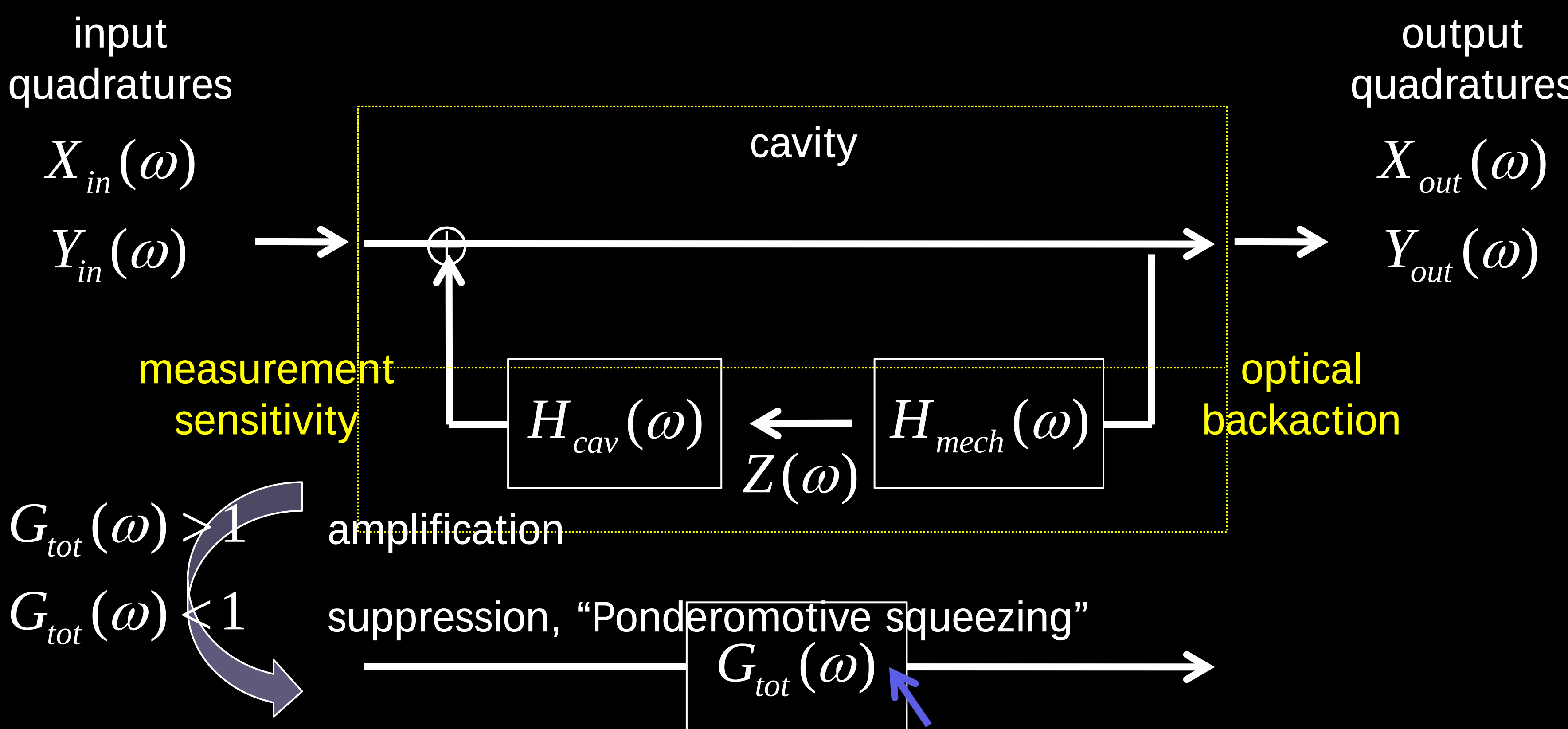
- Optomechanical amplification/squeezing of light



Optomechanical gain spectrum

Measurement and feedback in cavity optomechanics

- Optomechanical amplification/squeezing of light



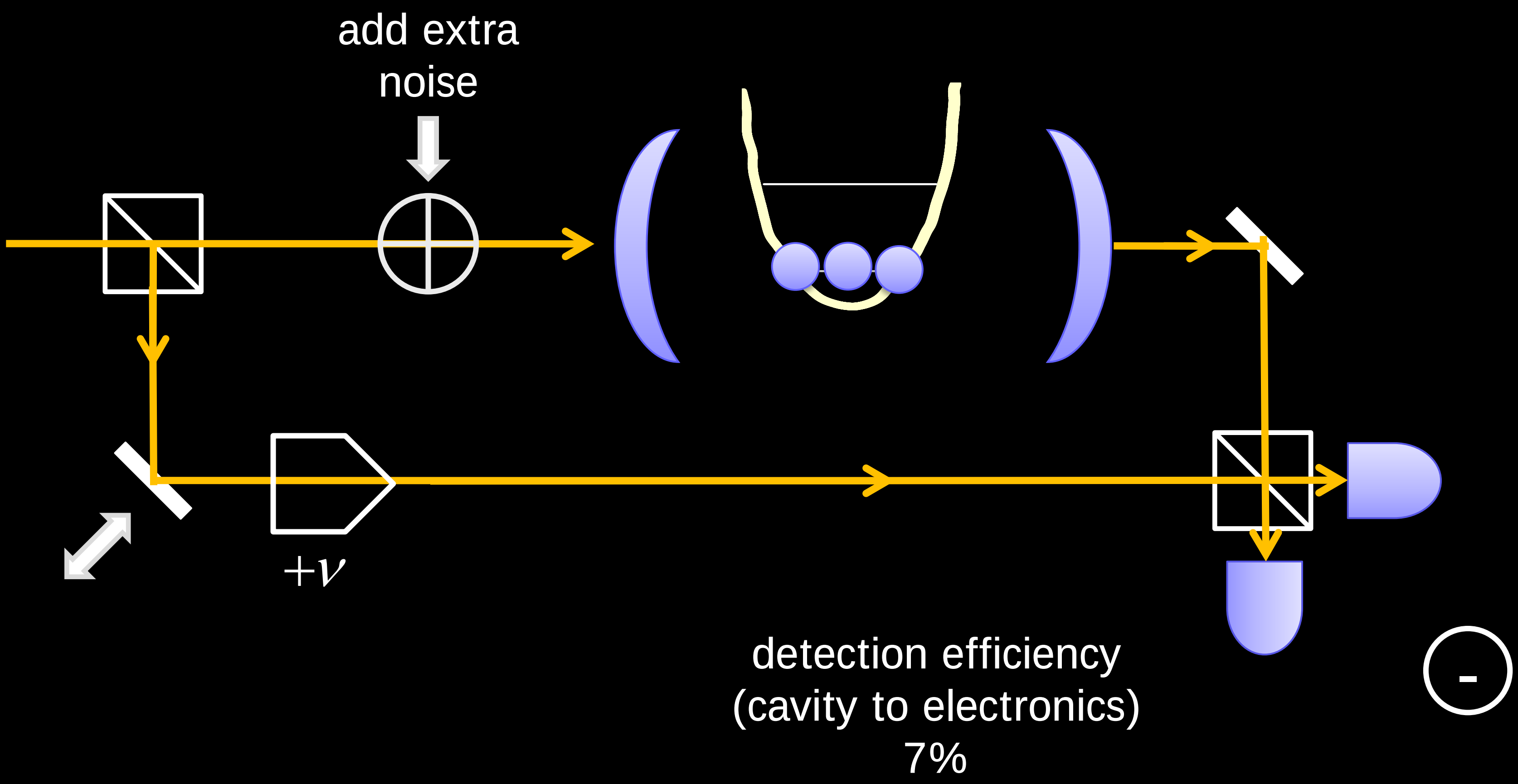
Key component in future of LIGO: from detector to observatory

Optomechanical gain spectrum

see Kimble et al., PRD **62**, 022002 (2001).

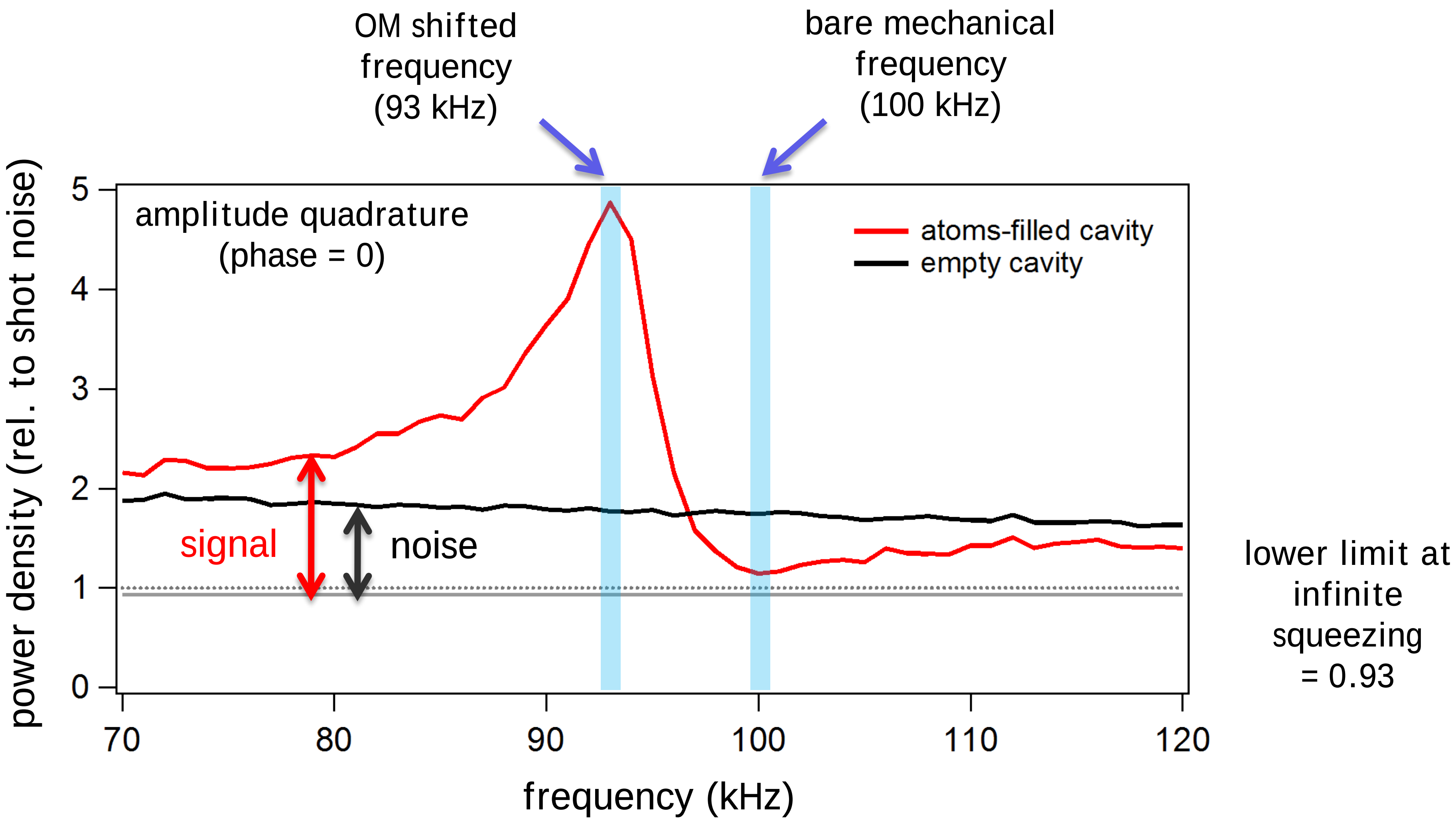
Measurements of optomechanical gain spectrum

see Marino et al., PRL **104**, 073601 (2010); Verlot et al.,ibid, 133602.



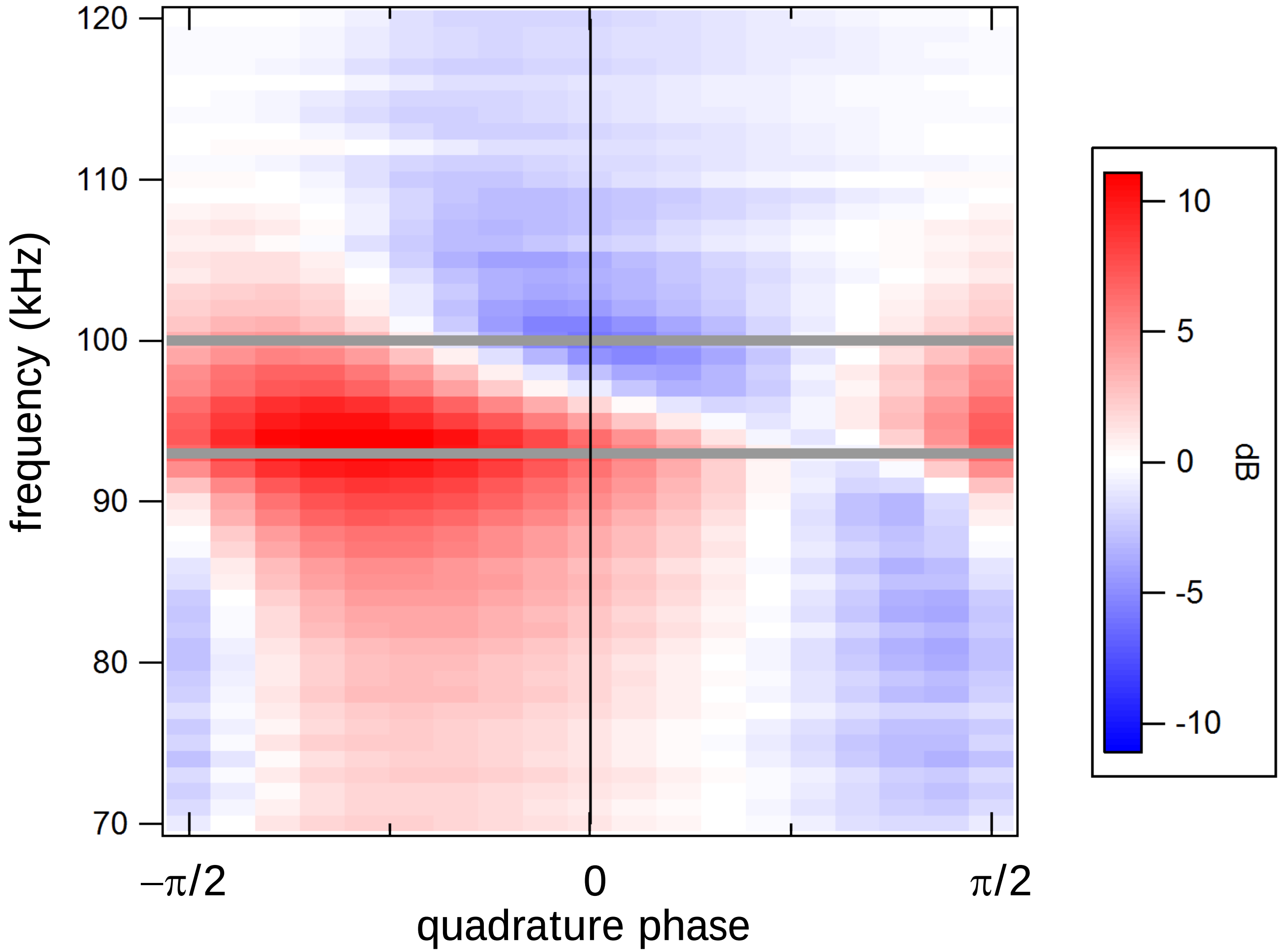
Spectral record of noise-driven atomic motion

- added noise ~ 10x shot noise



Measurements of optomechanical gain spectrum

- adjusted for detector efficiency



settings:
Δ_{ca} = -2 GHz
5000 atoms
<n> = 2

Measurements of optomechanical gain spectrum

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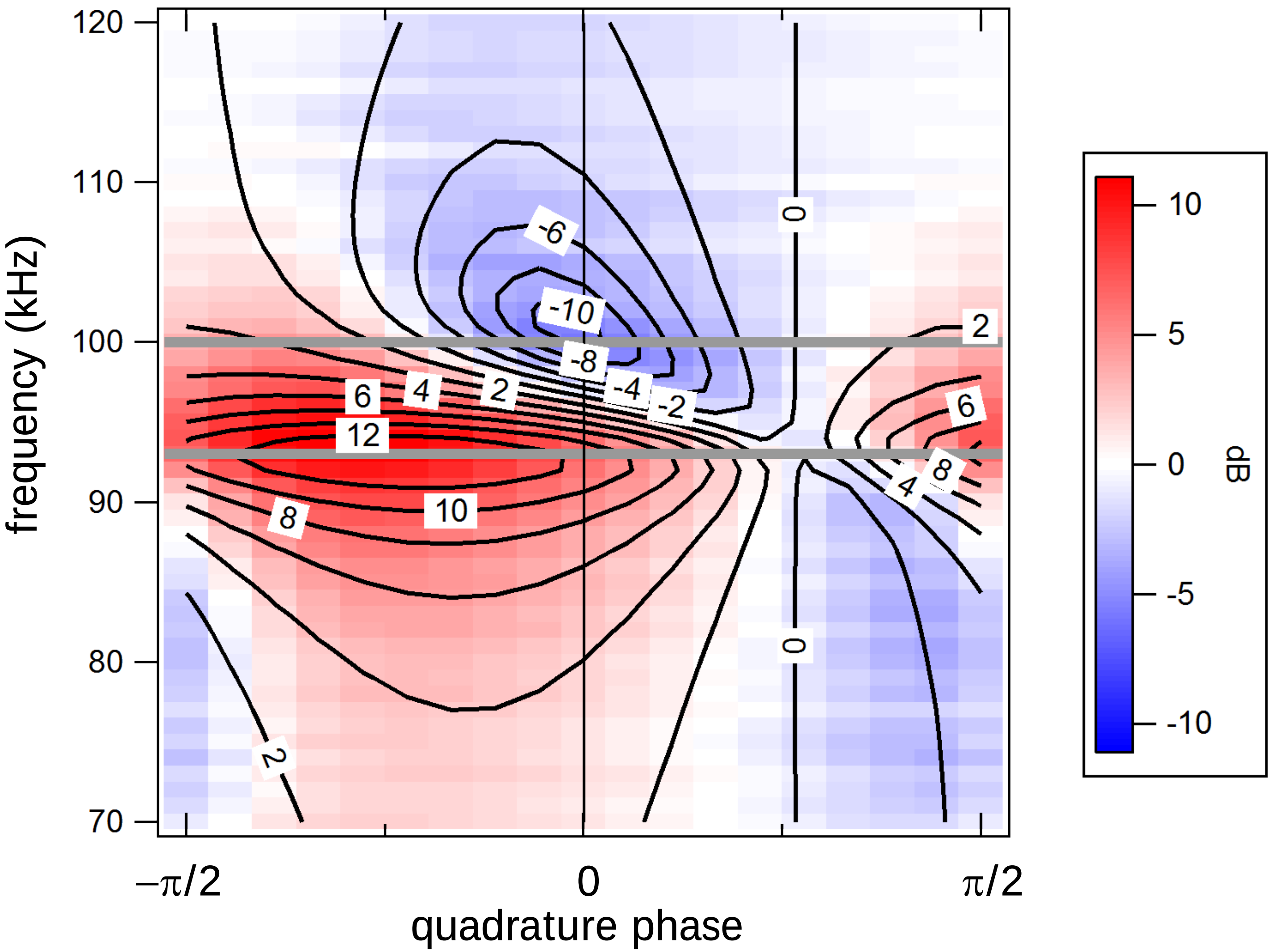

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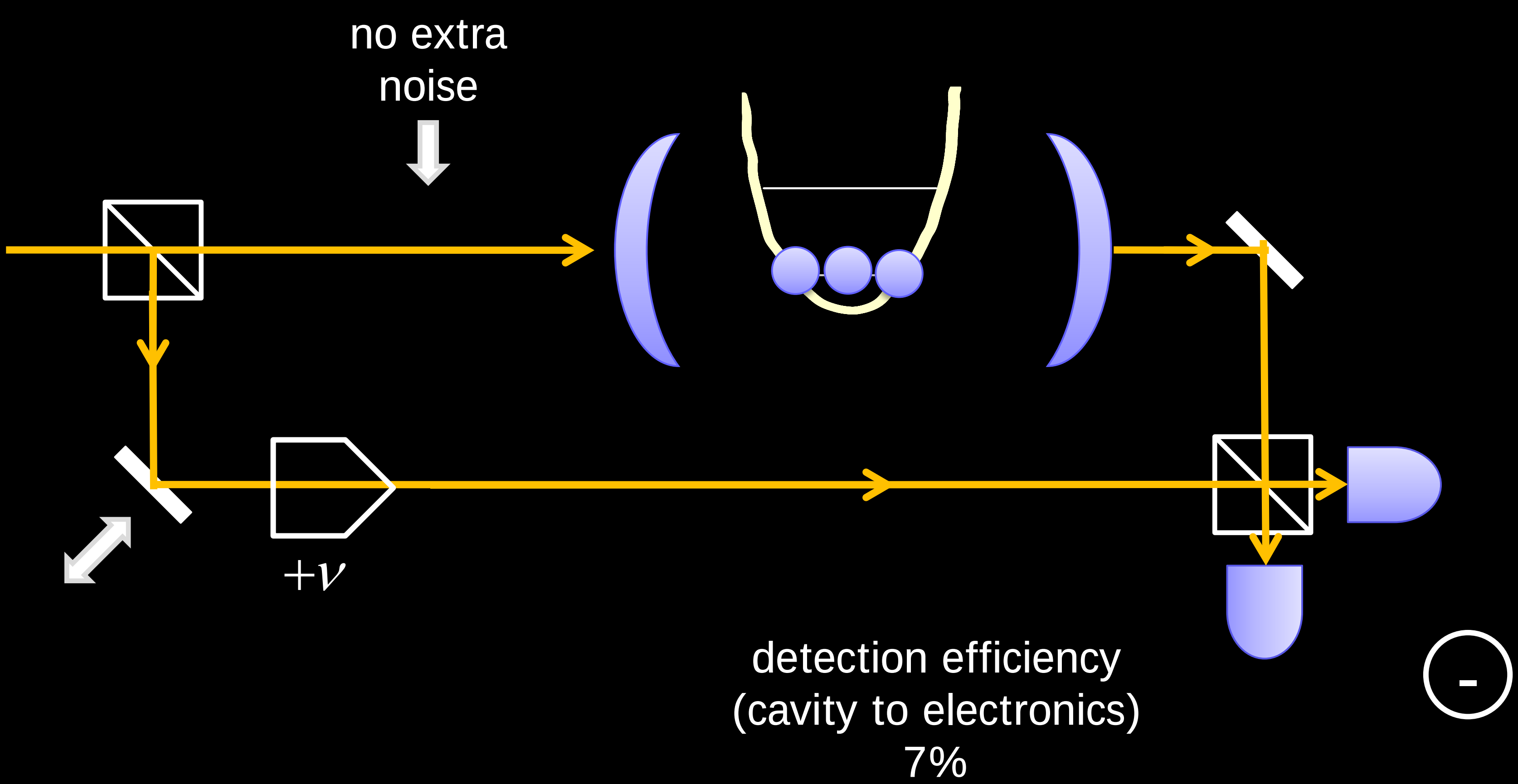
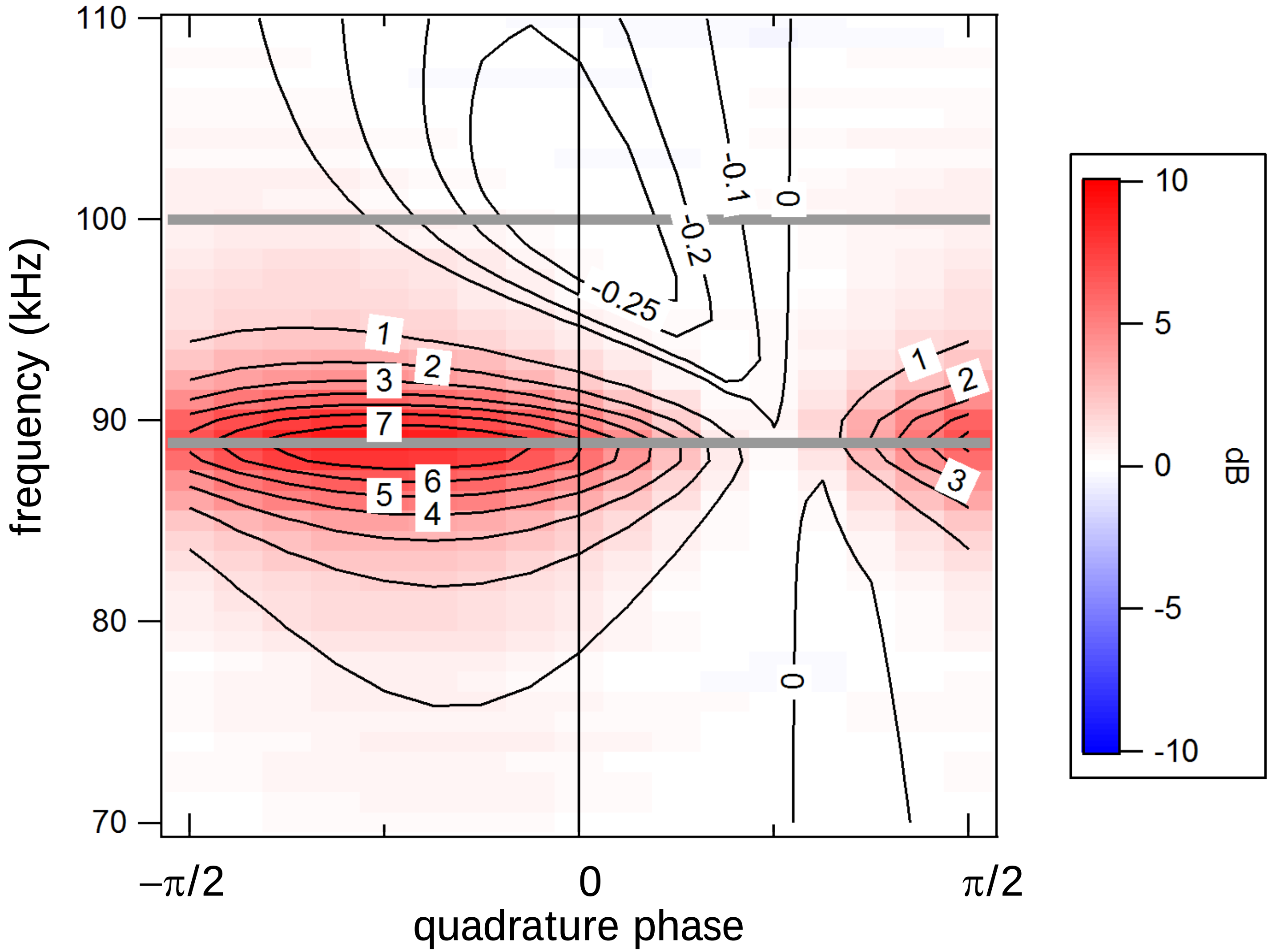
- Theory: semiclassical Langevin equations, one free parameter
  Fabre et al., PRA **49**, 1337 (1994); Mancini and Tombesi, ibid., 4055.

Ponderomotive squeezing?



Optomechanical amplification of vacuum noise

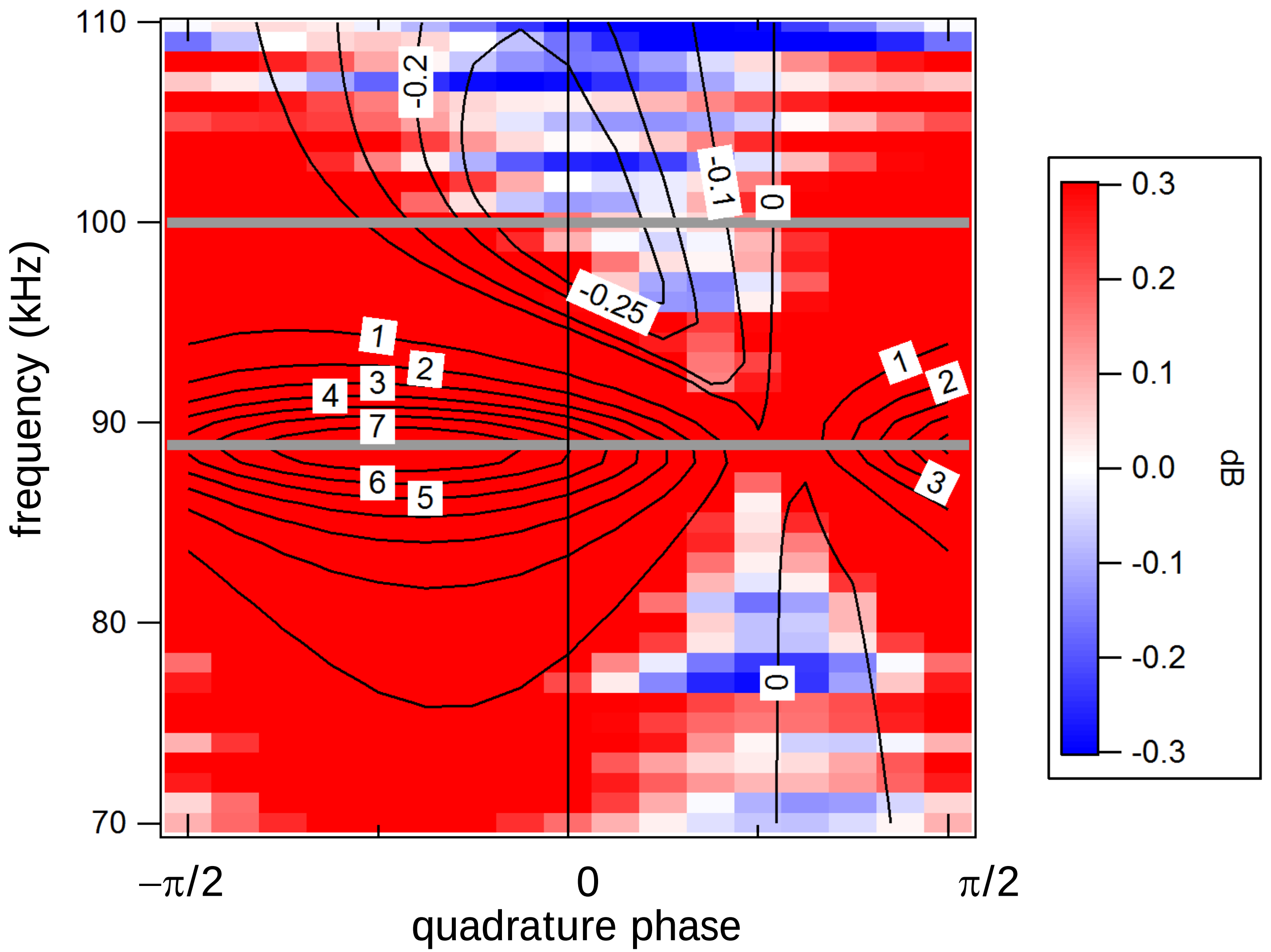
- NOT adjusted for detector efficiency (max reduction to 0.93 = - 0.3 dB)



settings:
Δ_{ca} = -2 GHz
3700 atoms
<n> = 2.5

Ponderomotive squeezing? (not clear yet)

- NOT adjusted for detector efficiency (max reduction to 0.93 = - 0.3 dB)



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More to do

- Granularity: strong coupling bewteen single phonons/photons
  - what happens to canonical phenomena of cavity optomechanics?
  - quantum optics, quantum information
- Cavity spin optodynamics in analogy with cavity optomechanics
- Many-body atomic physics inside a driven cavity
  - Dicke model and superradiance
  - lots more unrealistic ideas out there
- Quantum metrology (cf Thompson)