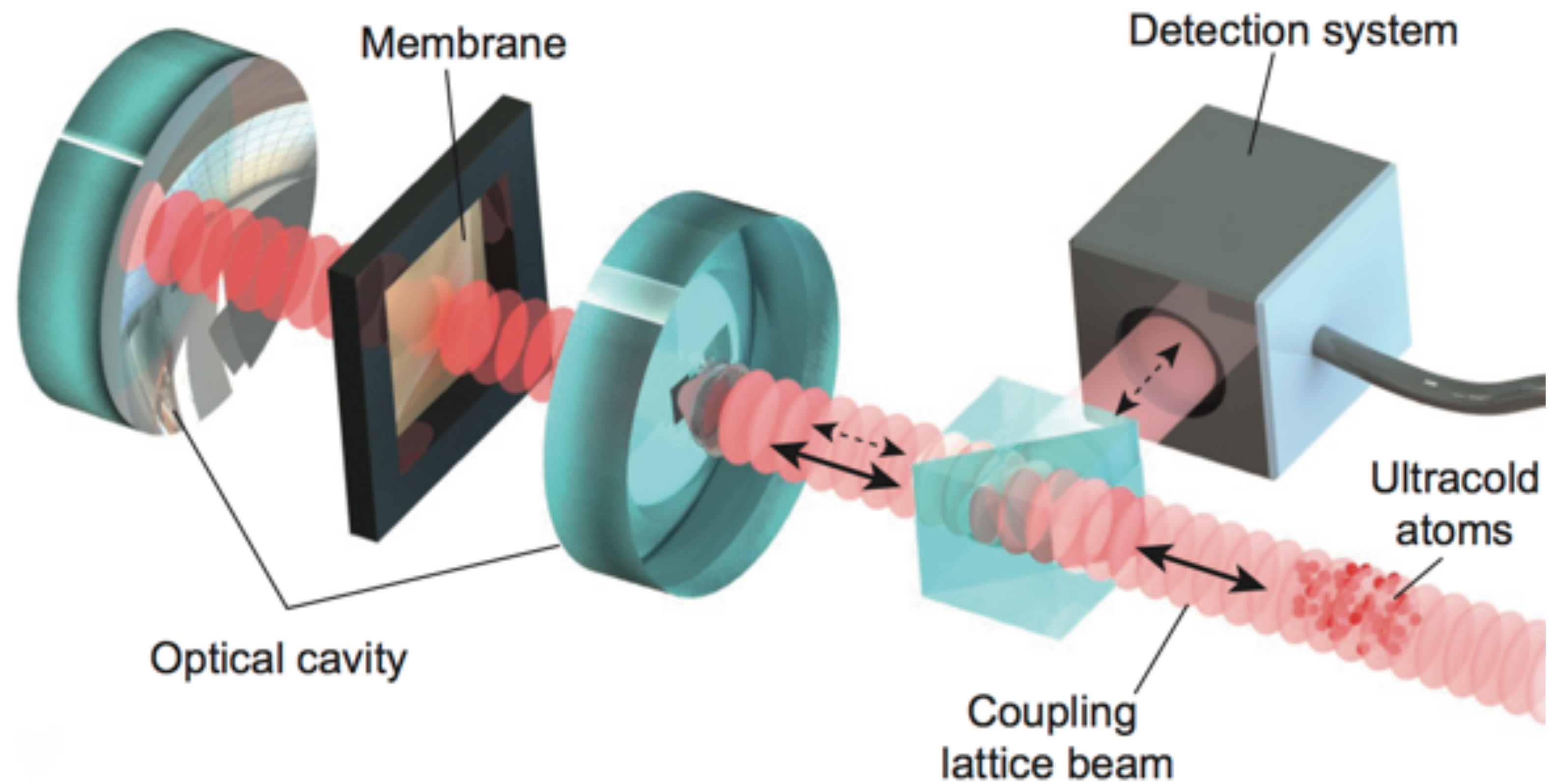
Hybrid atom-membrane optomechanics



Philipp Treutlein

A. Jöckel, A. Faber, T. Kampschulte, M. Korppi, M. T. Rakher

Department of Physics • University of Basel • Switzerland

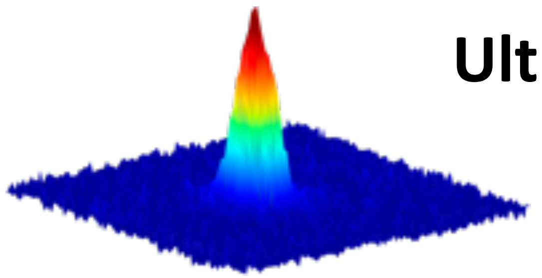
Theory: B. Vogell, K. Stannigel, P. Zoller (Innsbruck), K. Hammerer (Hannover)

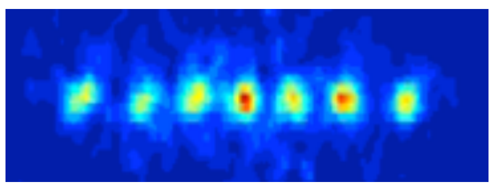
UNI BASEL

QSIT Quantum Science and Technology

SNI SWISS NANOSCIENCE INSTITUTE

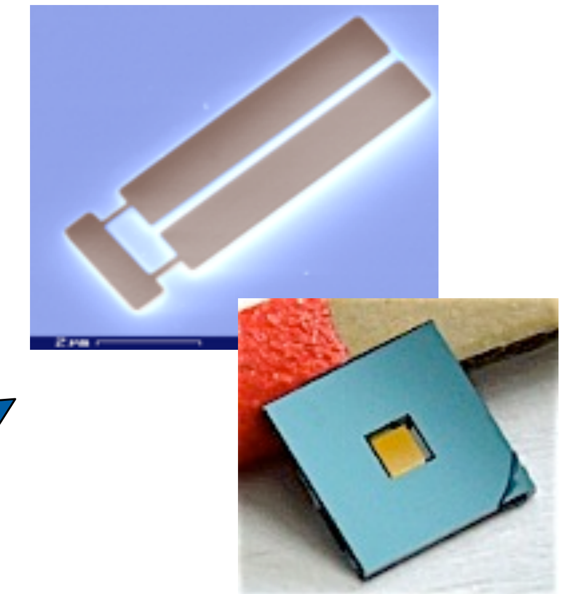
Hybrid quantum systems





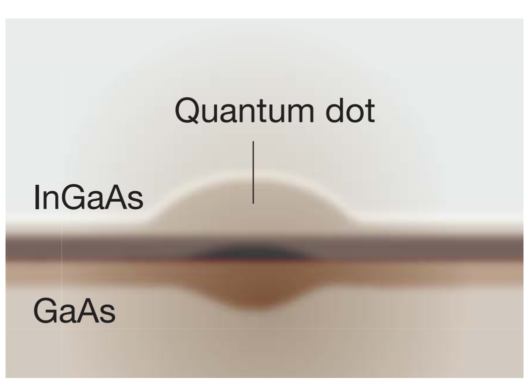
Ultracold atoms and ions

Mechanical oscillators

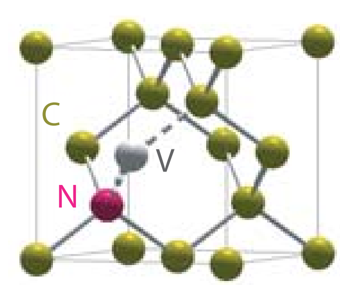


Hybrid quantum systems
for quantum computing, communication, metrology, fundamental physics

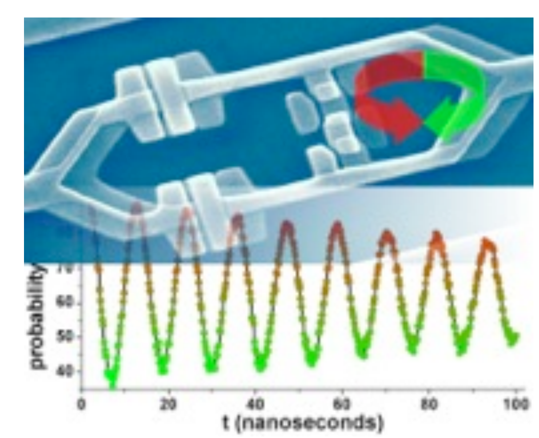
Semiconductor quantum dots



NV centers and other solid-state spin systems

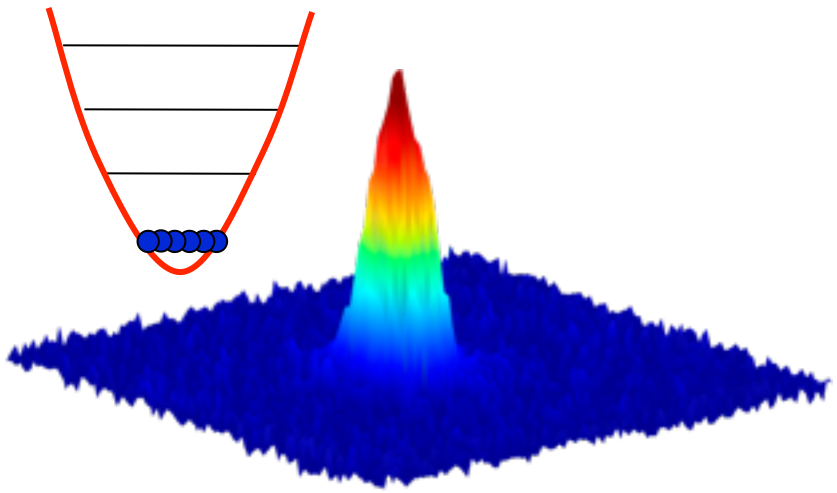


Superconducting devices

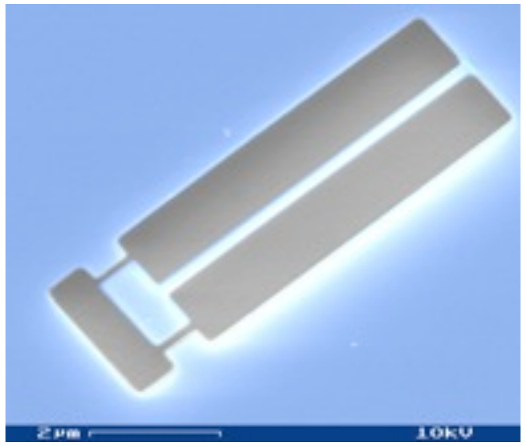


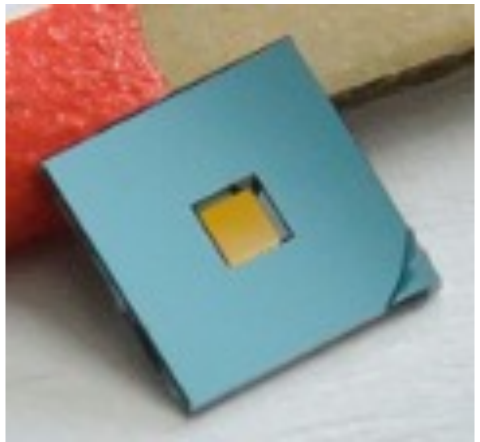
Atoms coupled to mechanical oscillators

Ultracold atoms in a trap



Micro- and nanofabricated mechanical oscillators





Sophisticated toolbox for

- ground state cooling
- coherent control of internal state + motion
- measurements on single quantum level

... developed since the 1980's

New player in the field of quantum science

- novel laser cooling and control methods
  → ***optomechanics***
- optomechanical analog of EIT, dressed states, Mollow triplet, ...
- sensitive force detection (AFM)
- quantum ***mechanics*** of massive objects

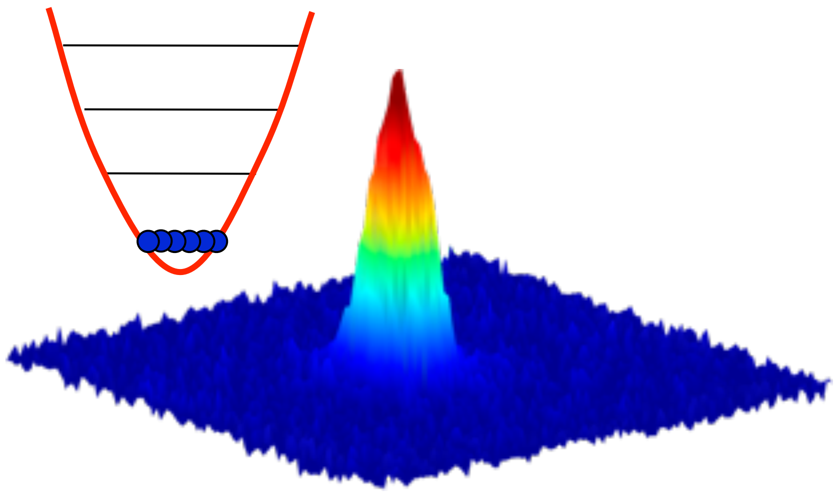
... developed over the past few years!

review: S. Chu, Nature 416, 206 (2002)

review: M. Aspelmeyer et al., arXiv:1303.0733

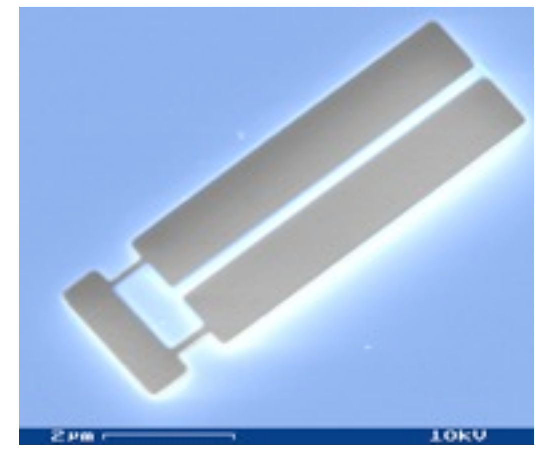
Atoms coupled to mechanical oscillators

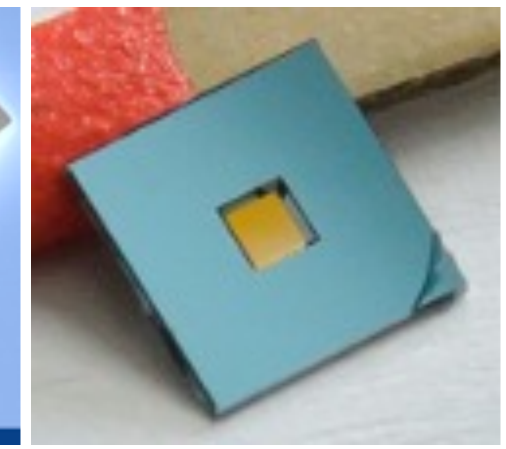
Ultracold atoms in a trap



optomechanical interface

Micro- and nanofabricated mechanical oscillators





Use atoms to prepare, detect, manipulate quantum states of mechanical oscillators

- make atomic physics toolbox available for control of mechanical devices

Mechanical oscillators as a new ingredient of atomic physics experiments

- on-chip RF source, optical lattice with micromechanical mirrors, ...

Mechanical oscillators as transducers

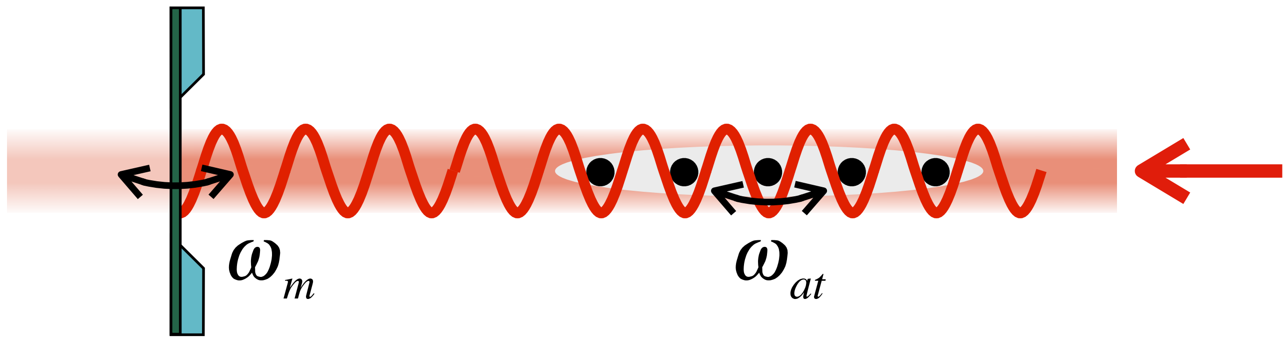
- interfacing atoms with solid-state spin systems, ...

Theory proposals: Hammerer, Zoller, Meystre, Genes, Vitali, Tombesi, Ritsch, Sun, Nori, Paternostro, Jonson, Bariani, Bienert, Rabl, Marquardt, ...

Review: P. Treutlein et al., arXiv:1210.4151 (2012)

First experiments

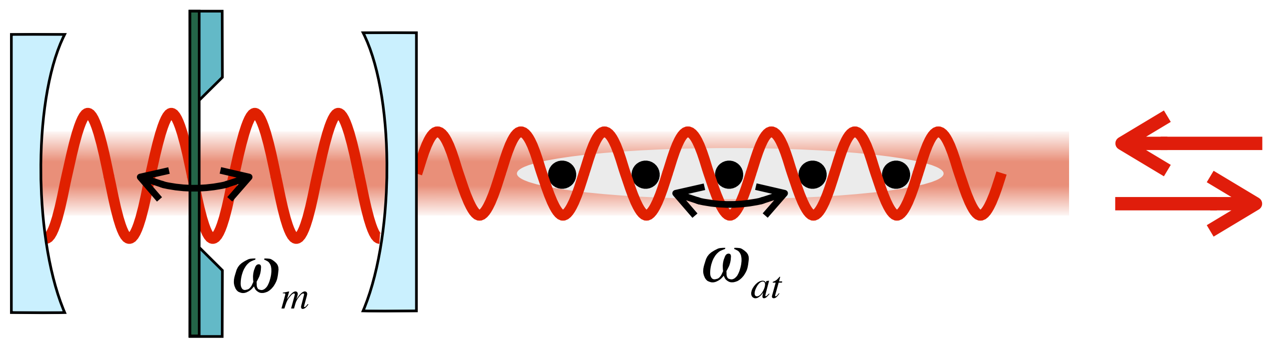
Optomechanical coupling of atoms and a membrane



Experiment: S. Camerer et al., PRL 107, 223001 (2011)

Theory: K. Hammerer et al. PRA 82, 021803 (2010)

Sympathetic cooling of a membrane with ultracold atoms



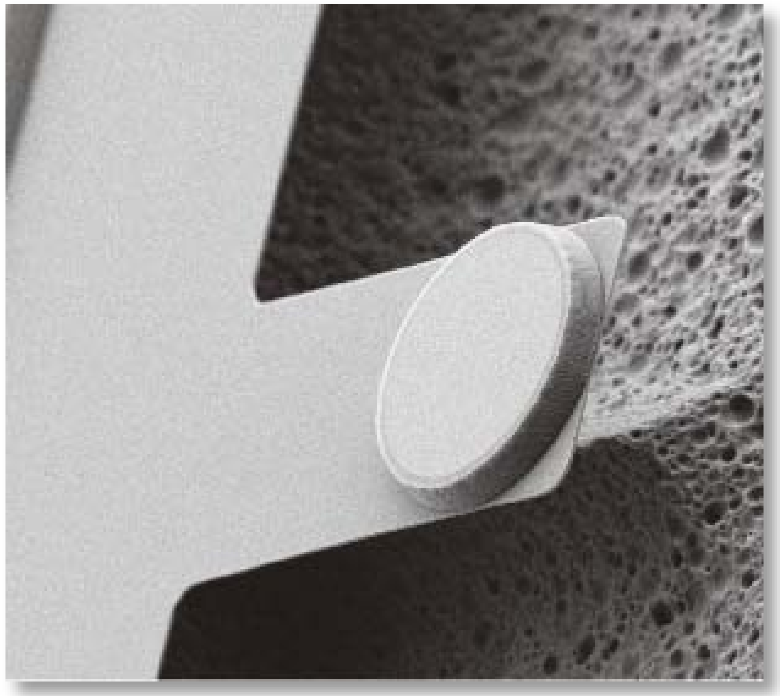
Experiment: A. Jöckel et al., arXiv:1407.6820 (2014)

Theory: B. Vogell et al., PRA 87, 023816 (2013)

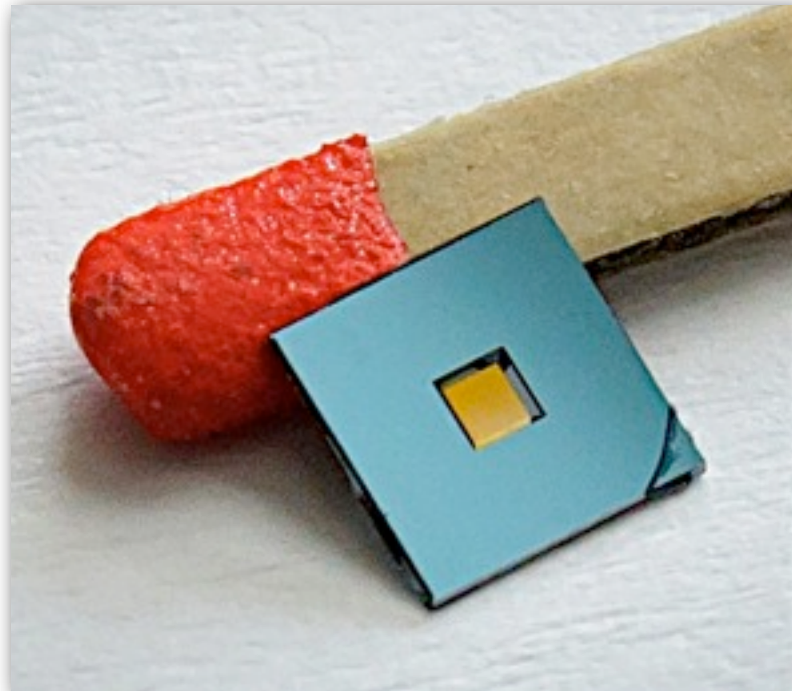
Other experiments (in preparation):
Polzik, Geraci, Vengalattore, Bowen, Kimble, Dantan, Sengstock, ...

Membrane optomechanics

Optomechanical systems

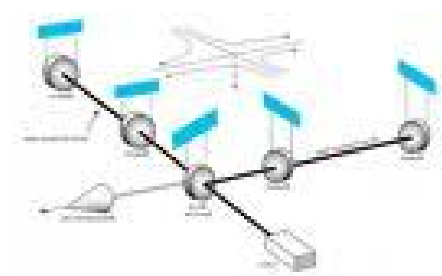


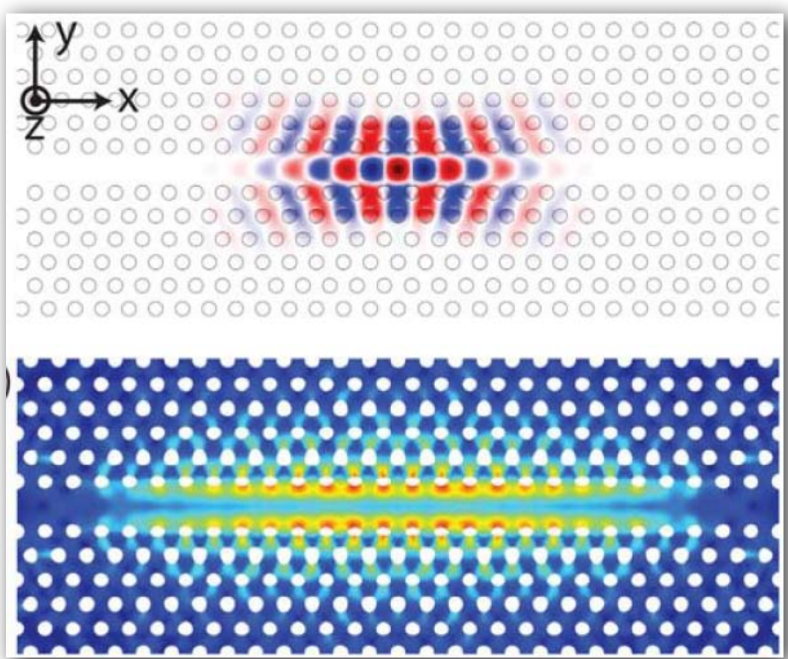
Mirror on cantilever



Membrane oscillator

LIGO – Laser Interferometer Gravitational Wave Observatory





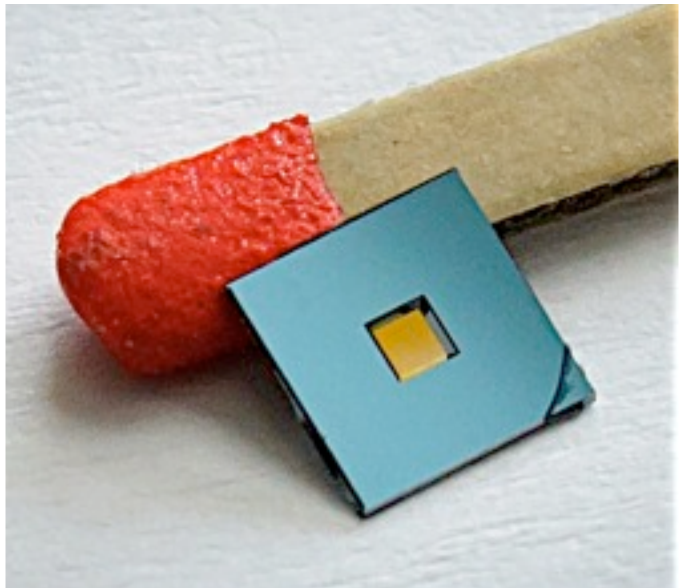
Optomechanical crystal

$$\Omega_m / 2\pi = \text{Hz} \ldots 10 \text{ GHz}$$

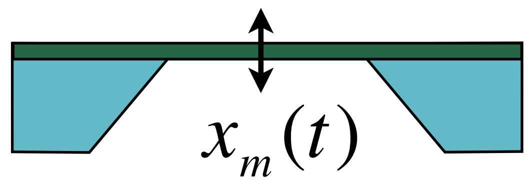
$$m_{eff} = \text{kg} \ldots \text{pg}$$

review: Aspelmeyer, Kippenberg, Marquardt, arXiv:1303.0733

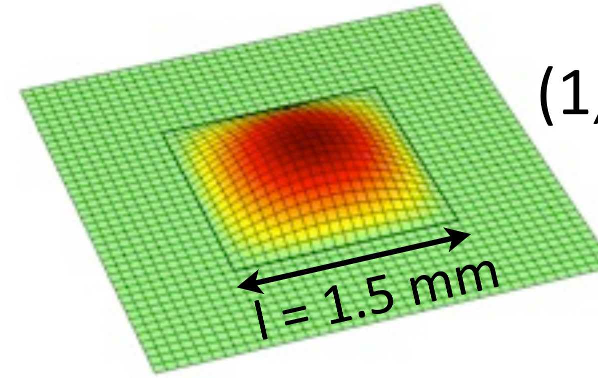
SiN membrane oscillators



SiN film (d = 40 nm)
tensile stress S = 0.9 GPa

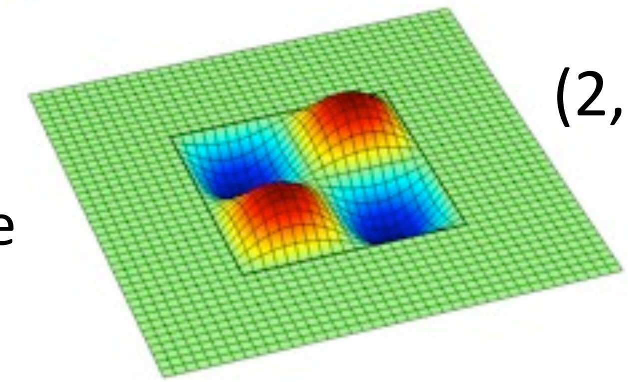


Si frame



(1,1) mode

“square drum”



(2,2)

fundamental mode
$\Omega_{1,1}/2\pi$ = 270 kHz
m_{eff} = 60 ng

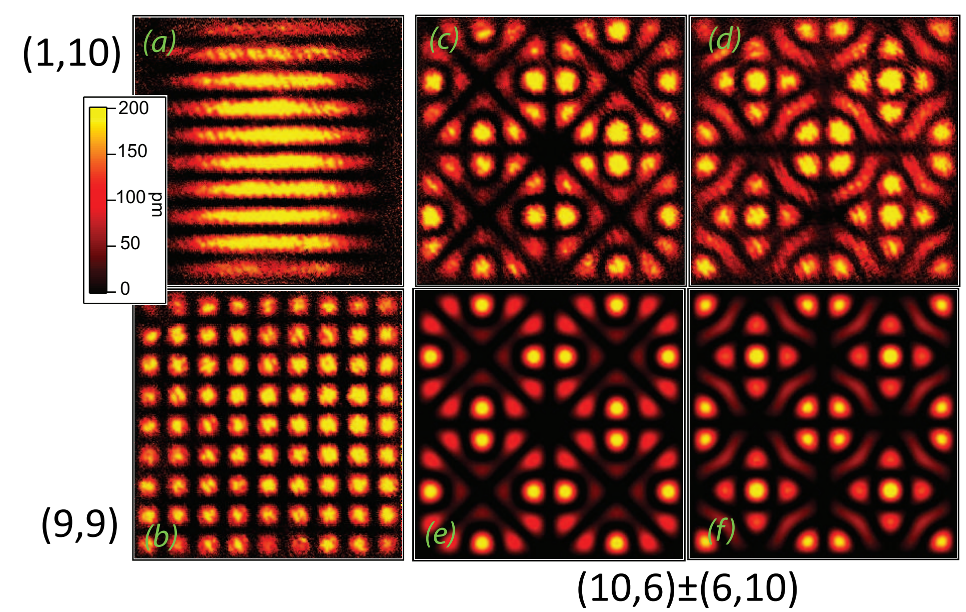
Extraordinary mechanical and optical properties!

Mechanical quality factor:
$Q_m = 3\times10^6$ (300 K, fundamental)
$Q_m = 5\times10^7$ (higher modes)

reflectivity: $r_m = 0.42$ @ 780 nm
absorption: $< 10^{-5}$

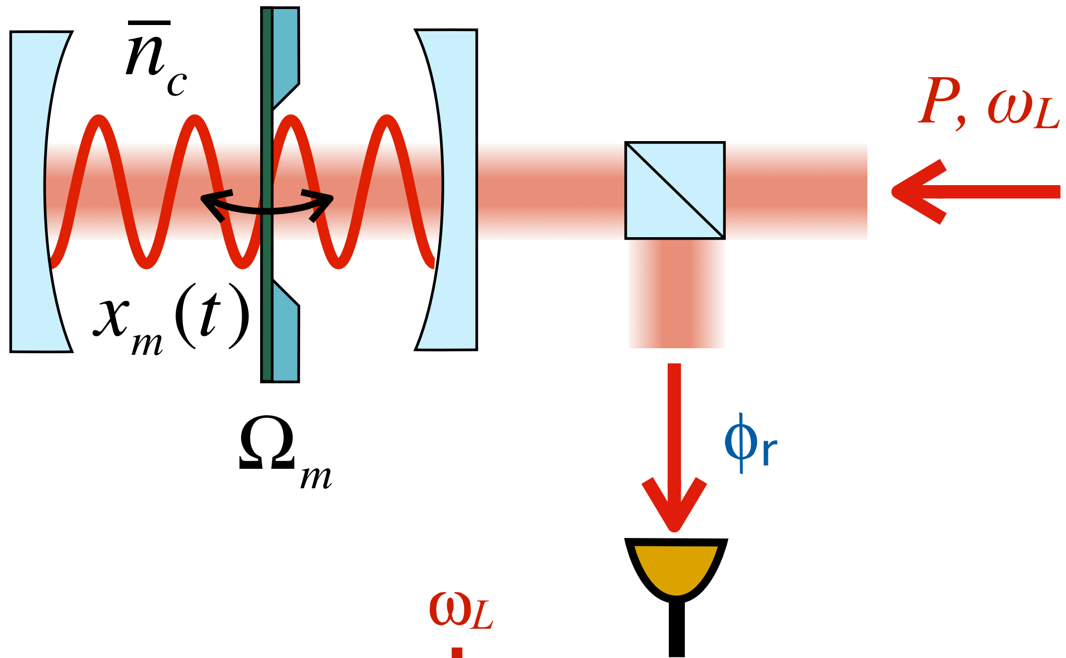
frequencies/time scales nicely matched to atoms

Interferometric imaging of modes
Chakram et al., PRL 112, 127201 (2014)

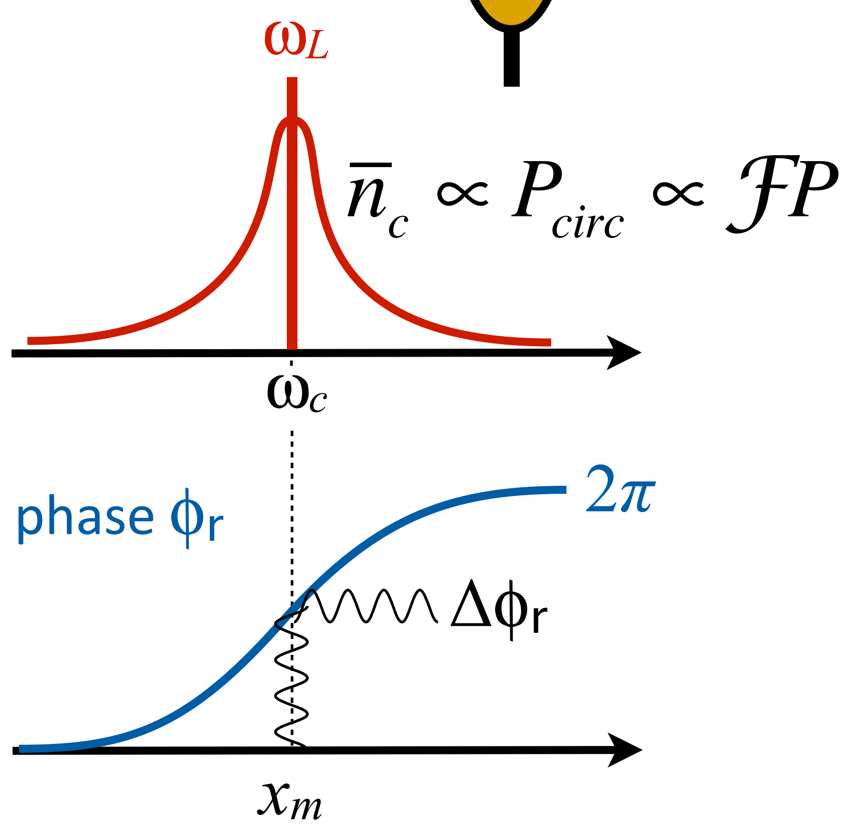


see also Harris, Kimble, Polzik, Regal, Vengalattore, ...

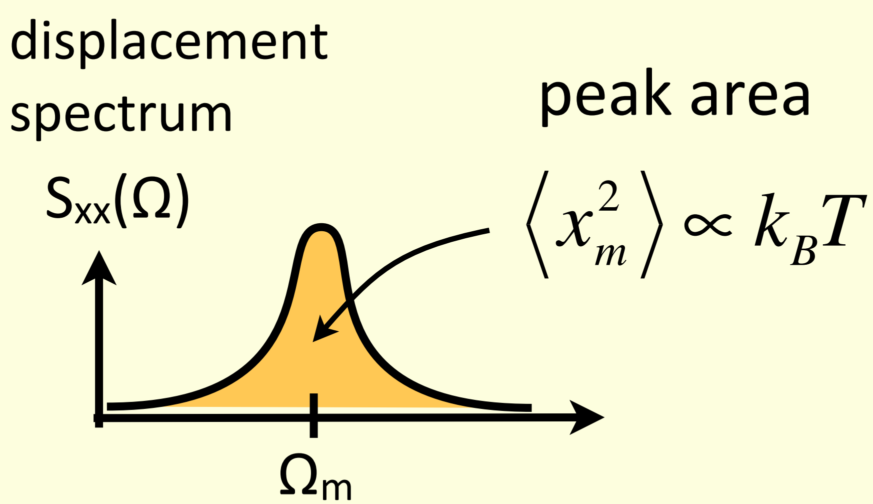
Membrane inside an optical cavity



Laser on resonance



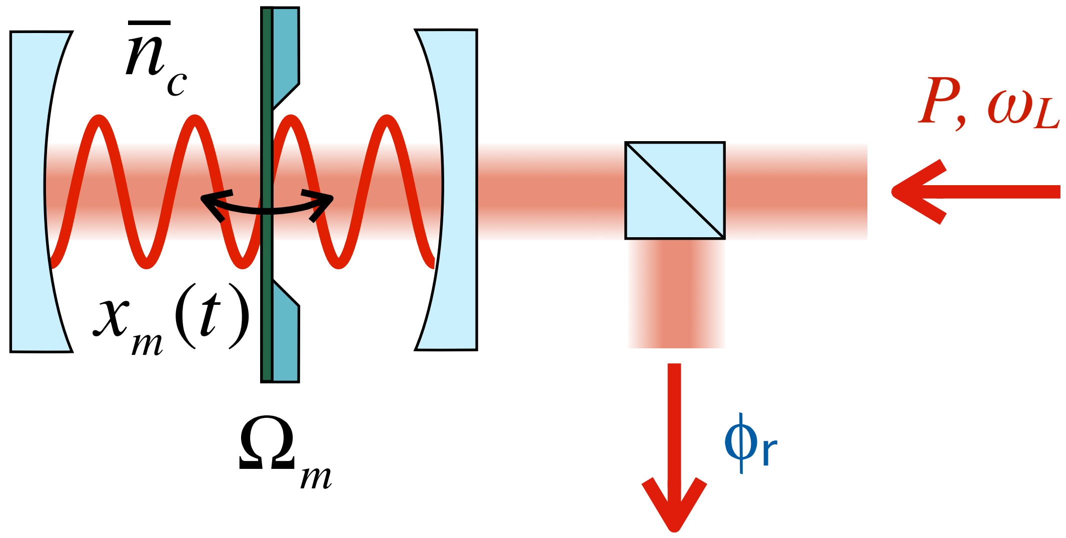
Measurement of mechanical displacement



Aspelmeyer, Kippenberg, Marquardt, arXiv:1303.0733
Kippenberg + Vahala, Science 321, 1172 (2008)

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

Membrane inside an optical cavity

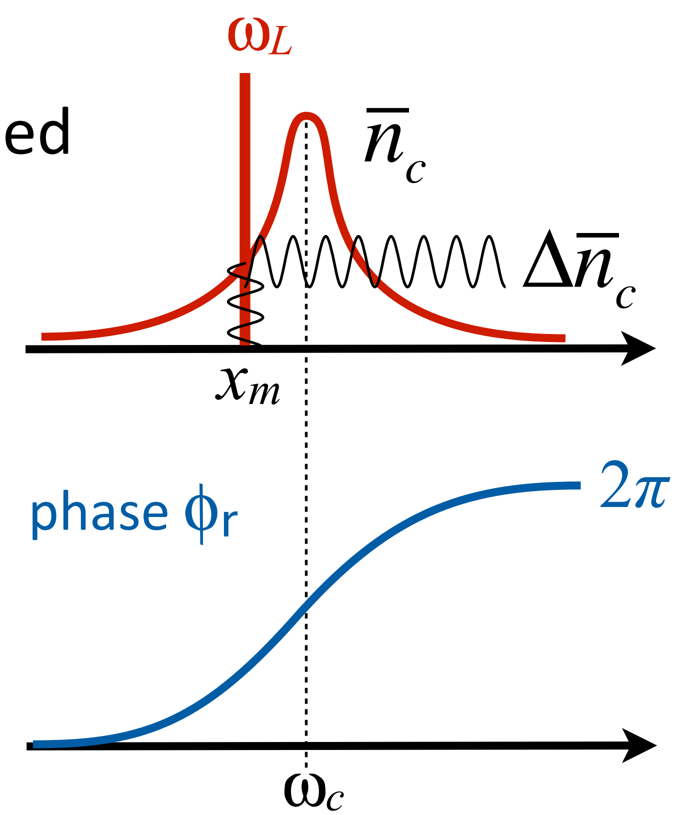


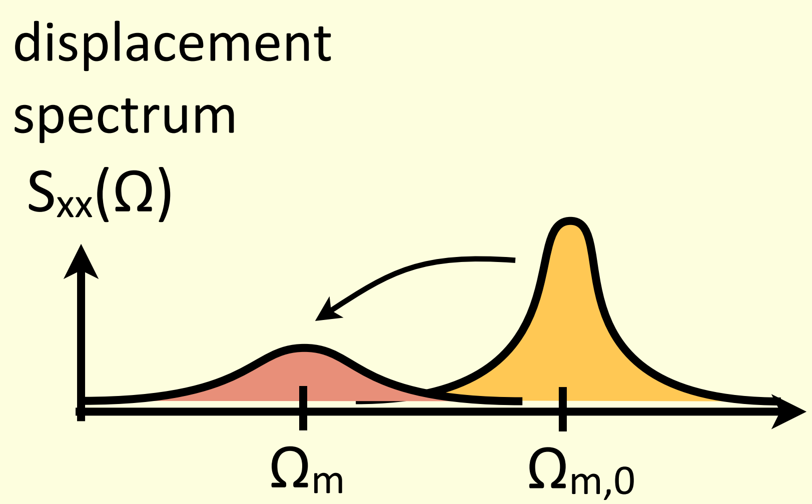
Radiation pressure force on membrane

$$\langle F_{rad} \rangle = 2 r_m 2\hbar k \frac{\bar{n}_c}{\tau_c}$$

$\tau_c = \dfrac{1}{\omega_{FSR}}$ cavity round trip time

Red-detuned laser





➡ **frequency shift** "optical spring"

➡ **damping** Γ_{opt}

➡ **cooling**

$$T \simeq \frac{\Gamma_m}{\Gamma_m + \Gamma_{opt}} T_{bath}$$

Aspelmeyer, Kippenberg, Marquardt, arXiv:1303.0733
Kippenberg + Vahala, Science 321, 1172 (2008)

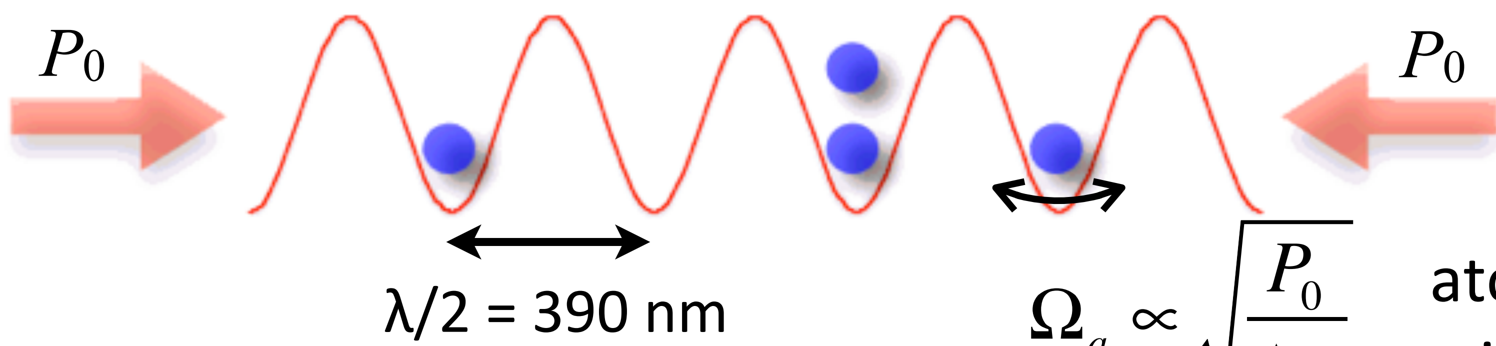
J. D. Thompson et al., Nature 452, 72 (2008)

Ultracold atoms in optical lattice

Optical lattices - perfect artificial crystals

Intensity variation of standing wave
→ optical dipole potential for atoms

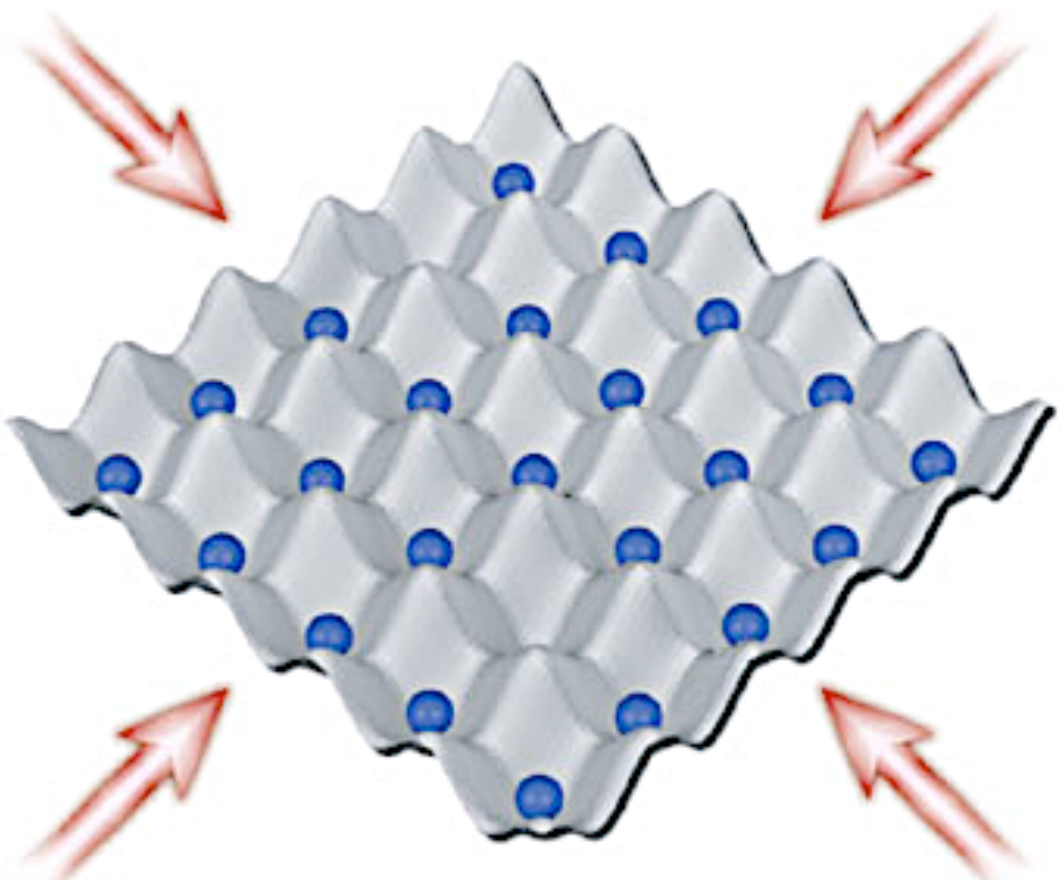
$$U_{dip}(r) \propto \frac{I(r)}{\Delta_{at}}$$



$$U_{dip}(z) = U_0 \sin^2(kz)$$

$$\Omega_a \propto \sqrt{\frac{P_0}{\Delta_{at}}}$$

atoms = mechanical oscillators with adjustable frequency



Periodic potential for ultracold atoms (1D, 2D, 3D)

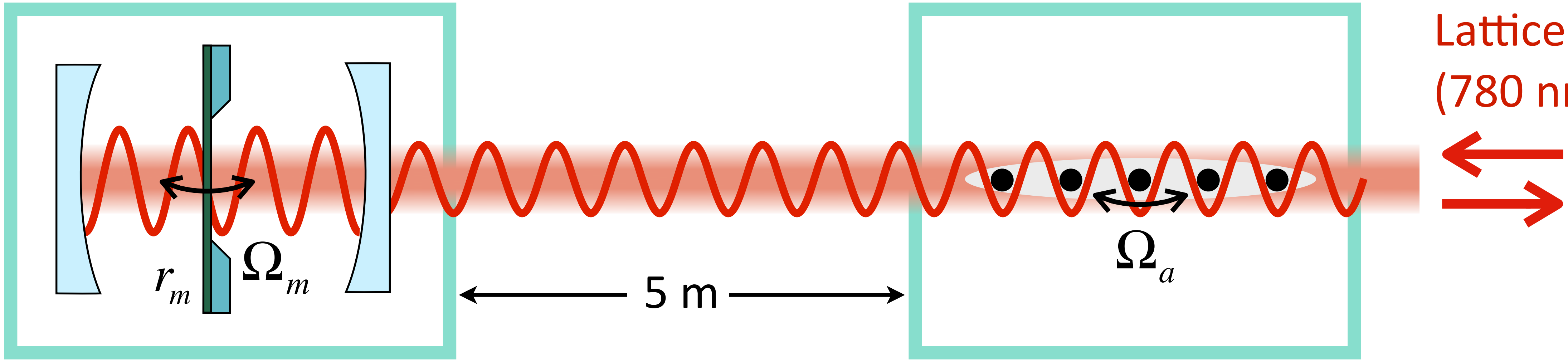
- model system for condensed matter physics
- quantum simulation
- quantum register

I. Bloch, Nature Phys. 1, 23 (2005)

Atom-membrane coupling

Optomechanical coupling of atoms and membrane

Experiment: A. Jöckel et al., arXiv:1407.6820 (2014)
Theory: B. Vogell et al., PRA 87, 023816 (2013)



SiN membrane in cavity
(single-sided, finesse $\mathcal{F}$, $\Omega_m \ll \kappa$)

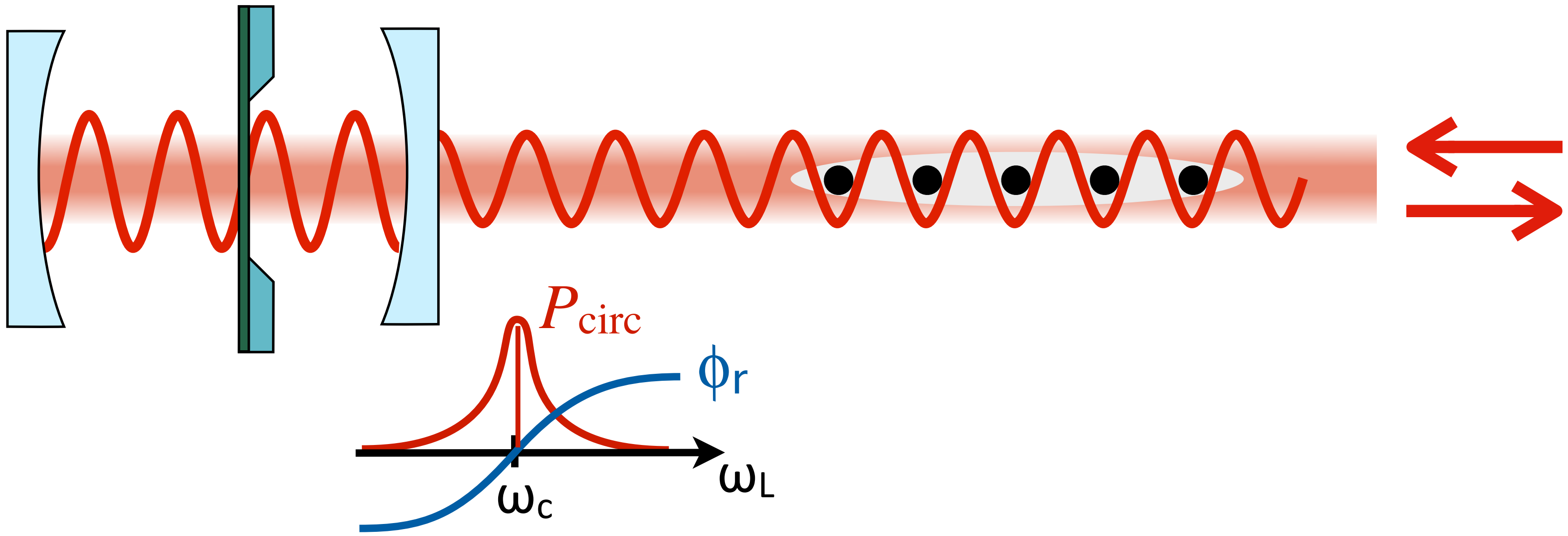
Laser-cooled ^{87}Rb atoms in optical lattice

Features:

- membrane vibrations couple to atomic c.o.m. vibrations
- long-distance coupling mediated by laser light
  → modular setup
- laser cooling of atoms on → sympathetic cooling of membrane
- laser cooling off → coherent dynamics

Coupling mechanism

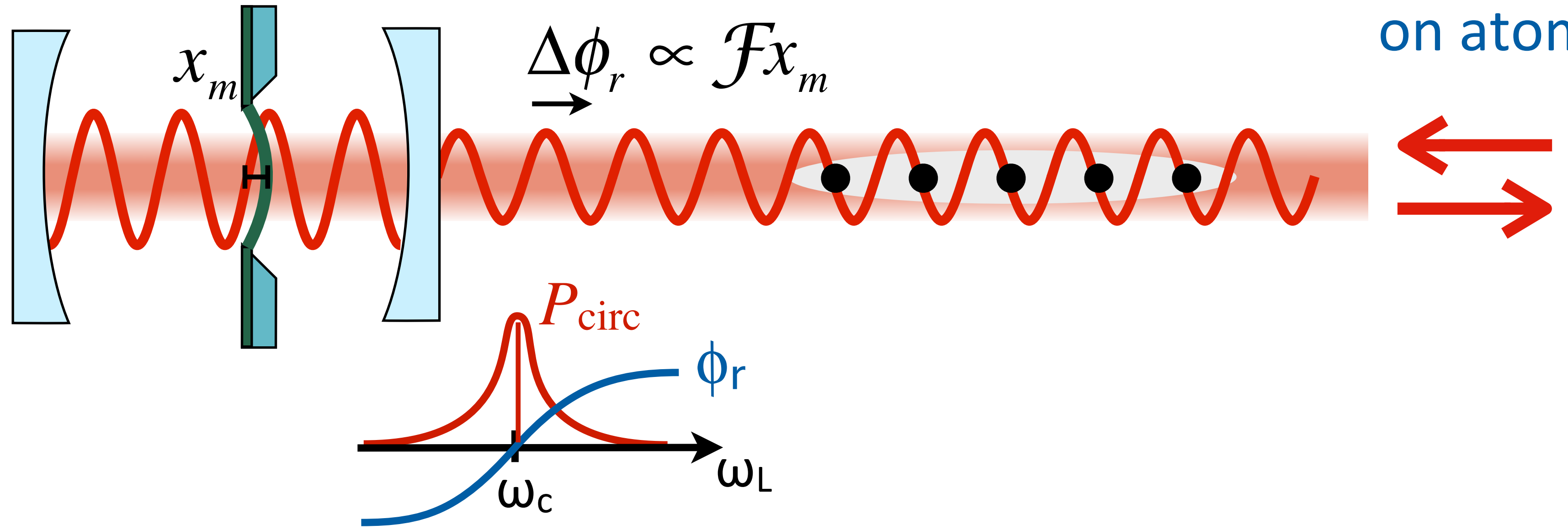
membrane → atoms



Coupling mechanism

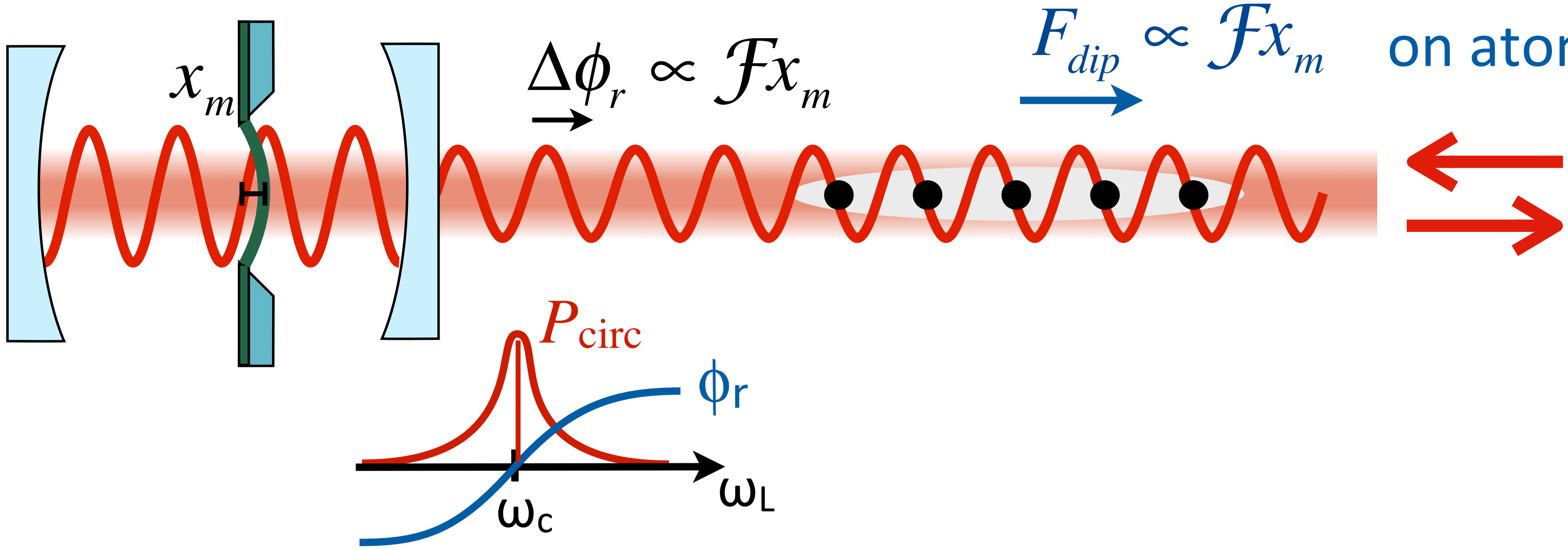
membrane → atoms

optical dipole force on atomic c.o.m.



Coupling mechanism

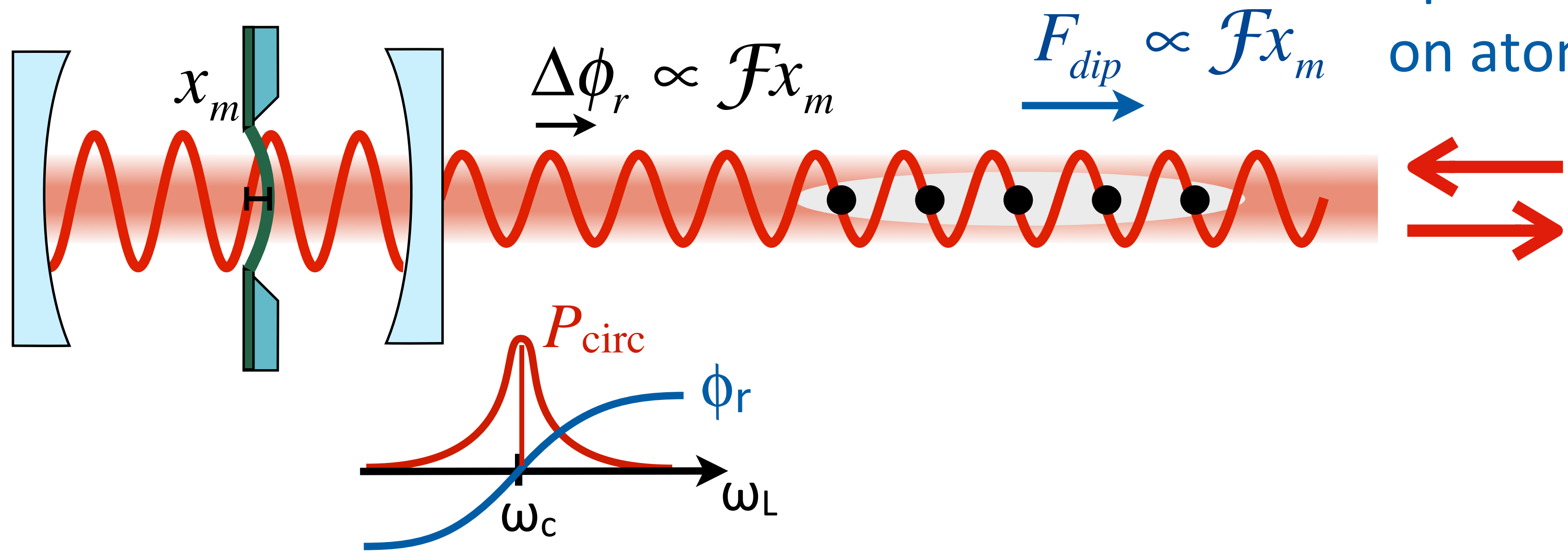
membrane → atoms



optical dipole force on atomic c.o.m.

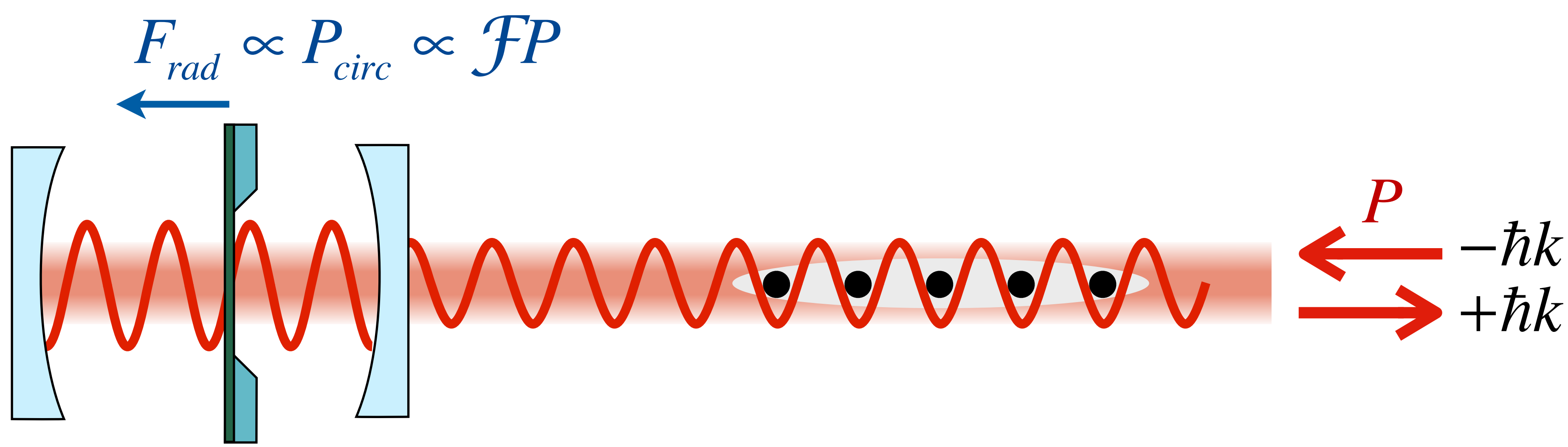
Coupling mechanism

membrane → atoms



optical dipole force on atomic c.o.m.

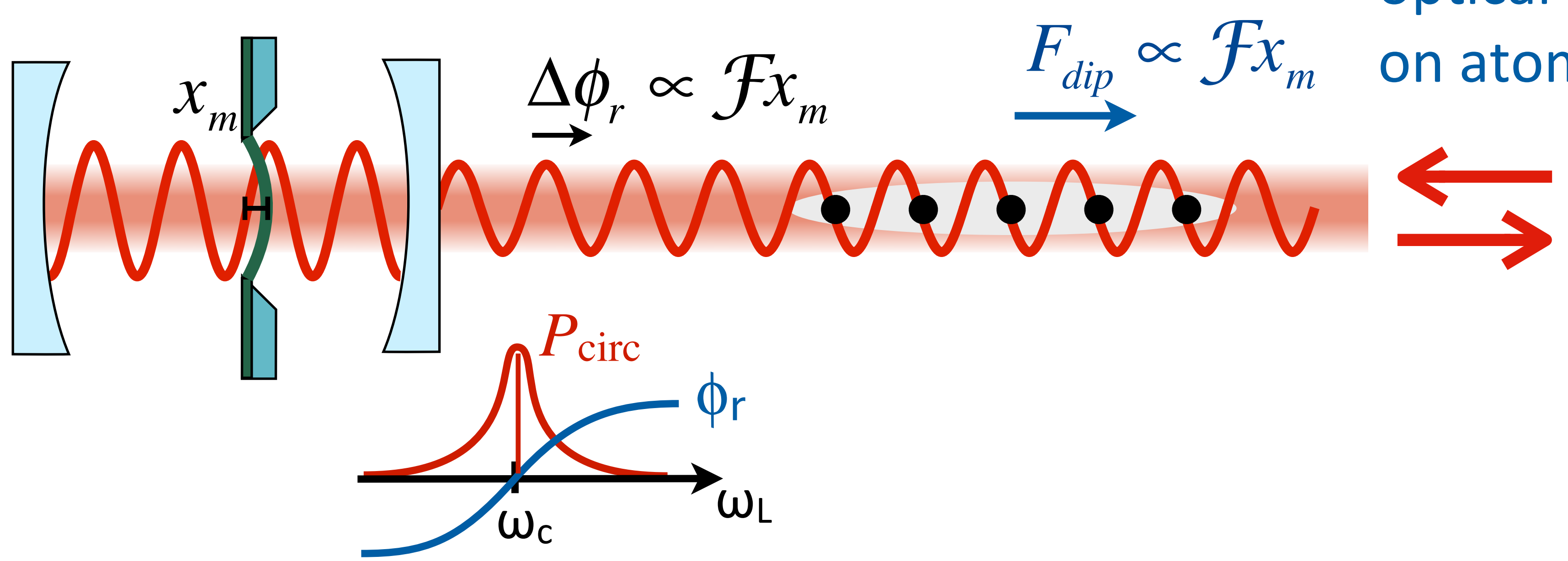
atoms → membrane (back-action)



radiation pressure force on membrane

Coupling mechanism

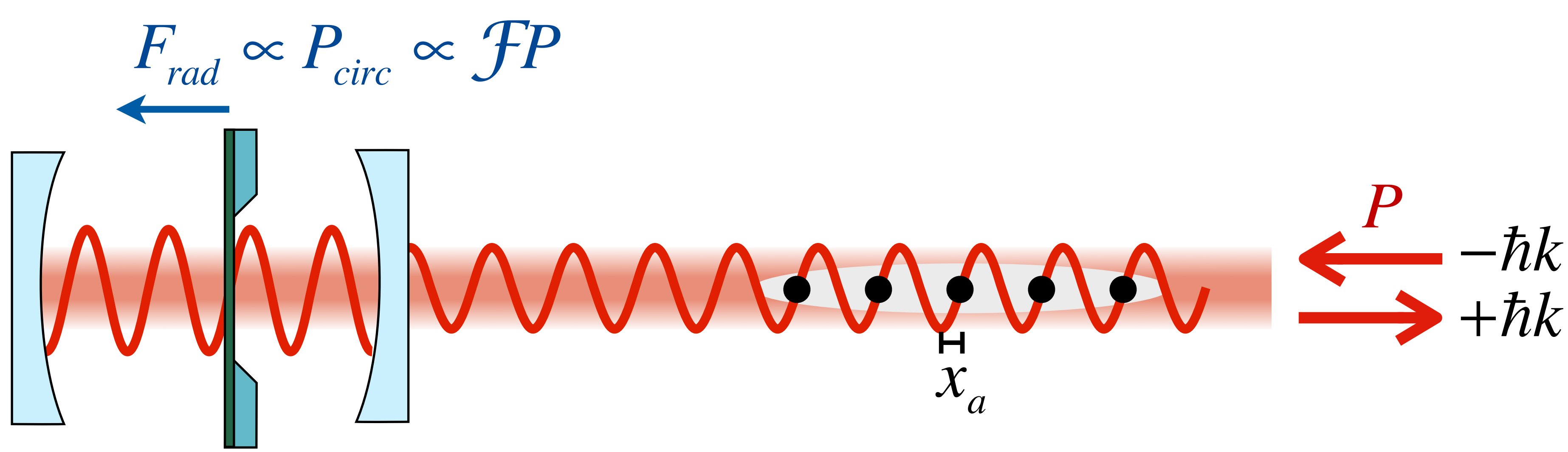
membrane → atoms



optical dipole force on atomic c.o.m.

atoms → membrane (back-action)

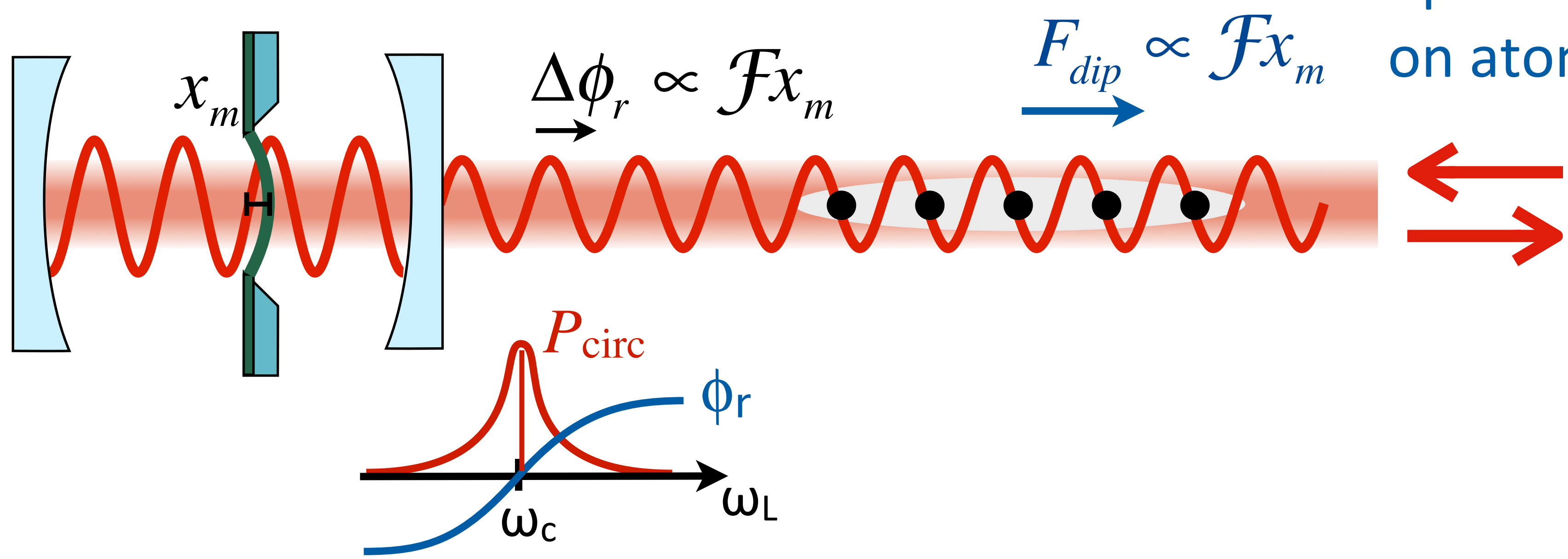
radiation pressure force on membrane



Coupling mechanism

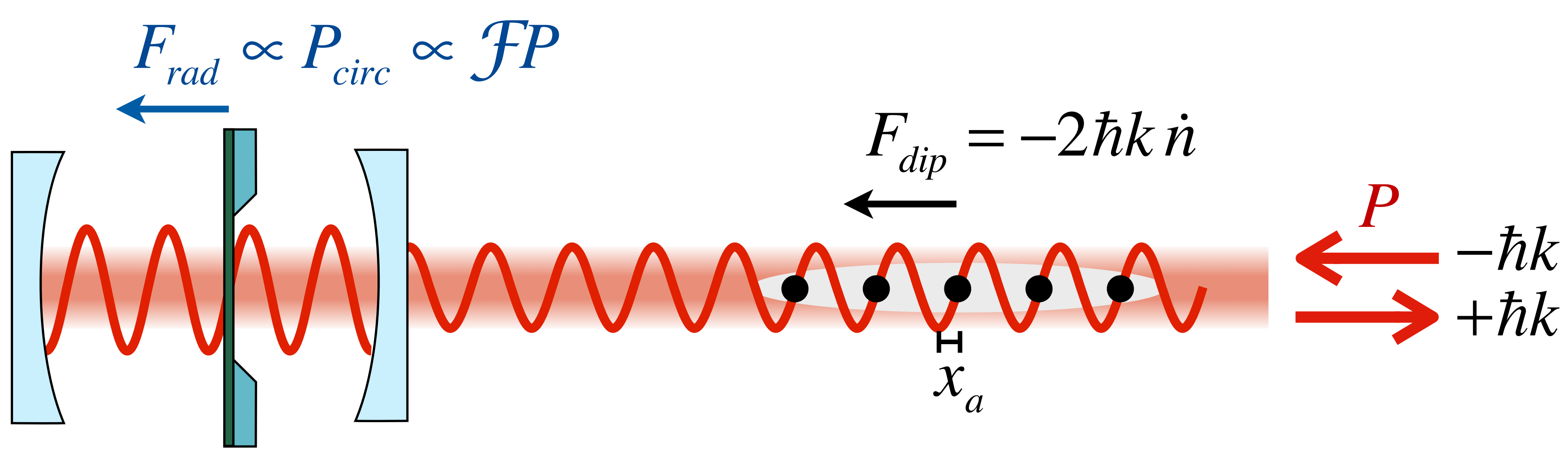
membrane → atoms

optical dipole force on atomic c.o.m.



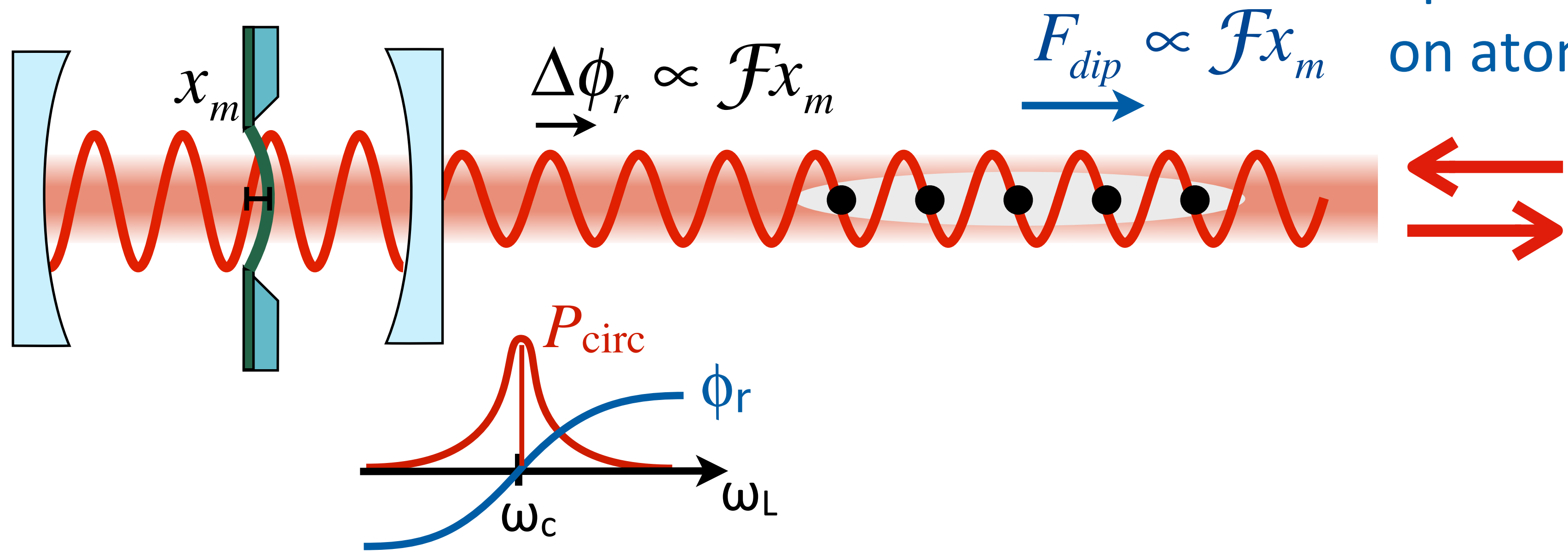
atoms → membrane (back-action)

radiation pressure force on membrane



Coupling mechanism

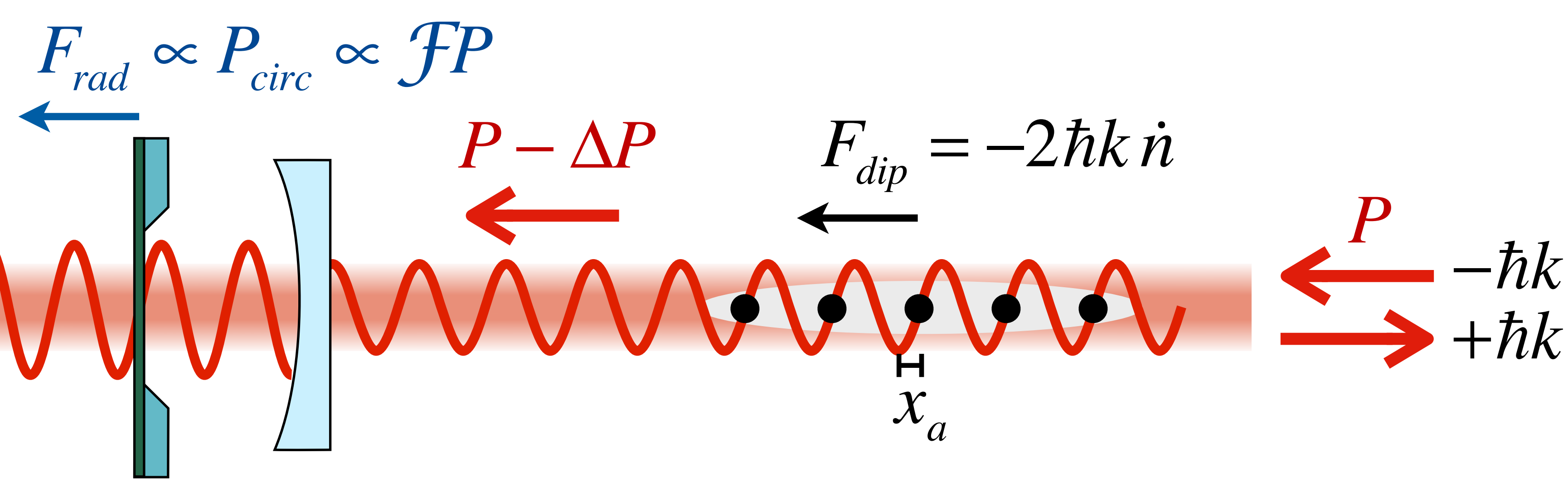
membrane → atoms



optical dipole force on atomic c.o.m.

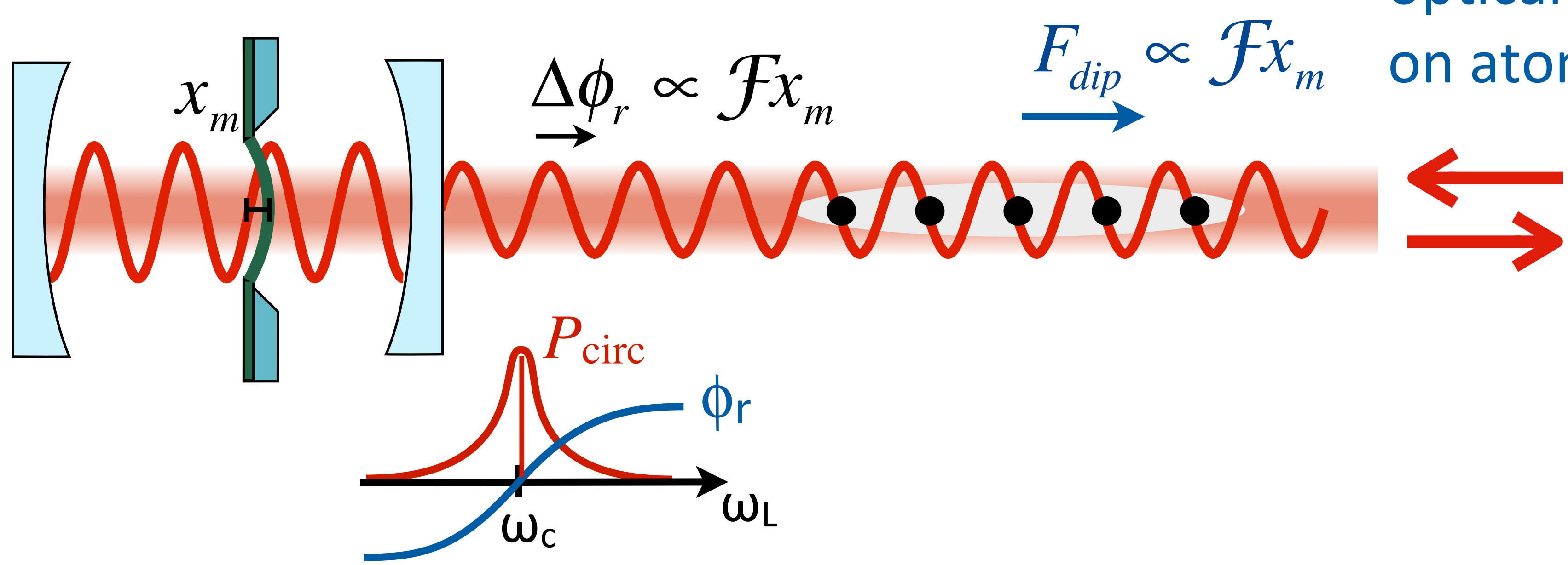
atoms → membrane (back-action)

radiation pressure force on membrane



Coupling mechanism

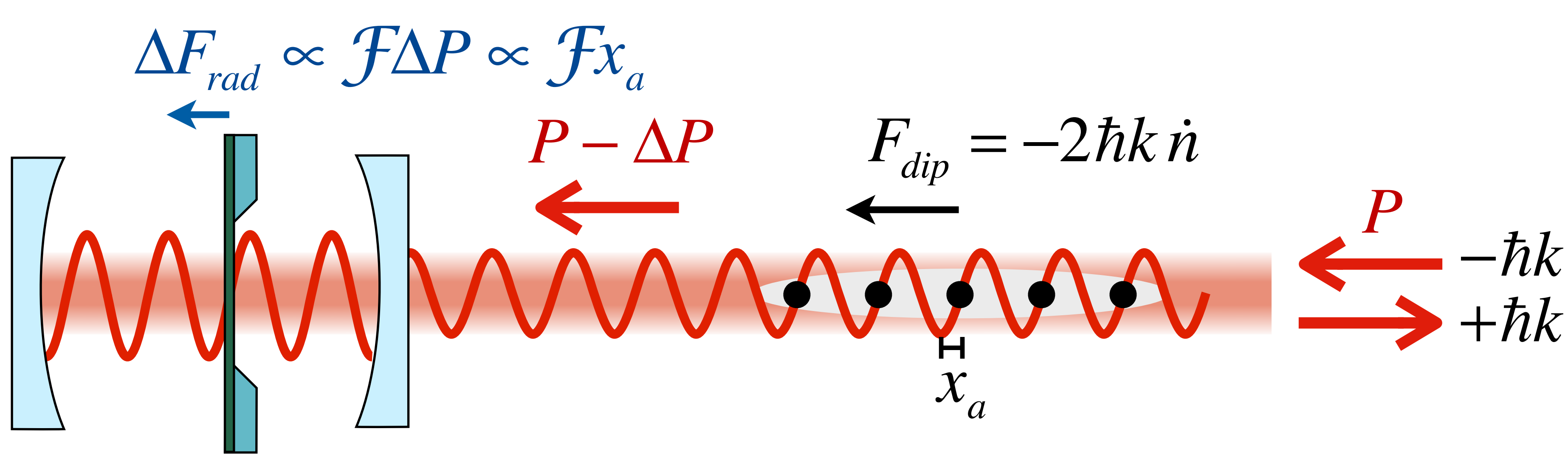
membrane → atoms



optical dipole force on atomic c.o.m.

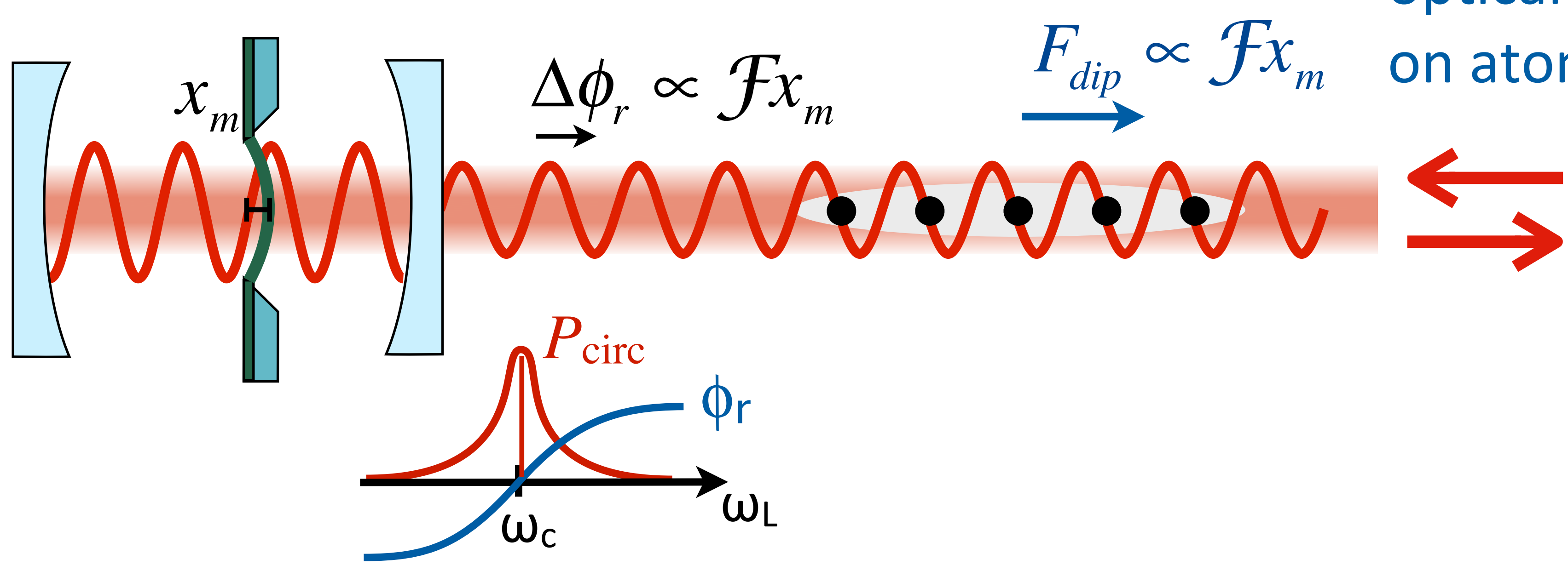
atoms → membrane (back-action)

radiation pressure force on membrane



Coupling mechanism

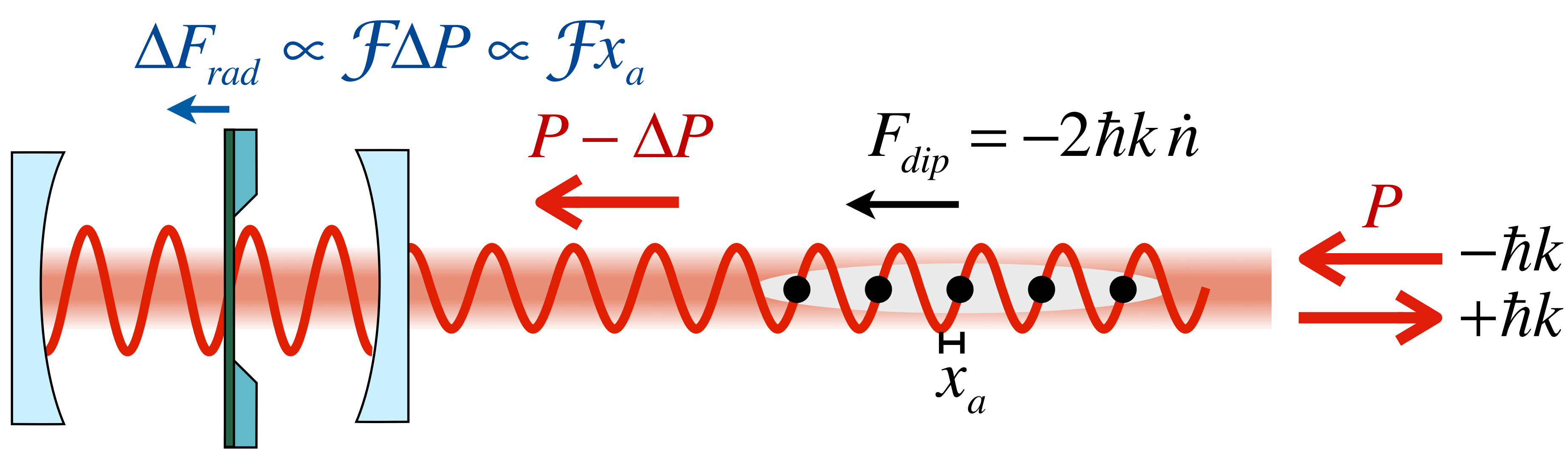
membrane → atoms



optical dipole force on atomic c.o.m.

atoms → membrane (back-action)

radiation pressure force on membrane



Vogell et al., PRA 87, 023816 (2013)

$$H_{\text{int}} = \hbar g x_a x_m$$

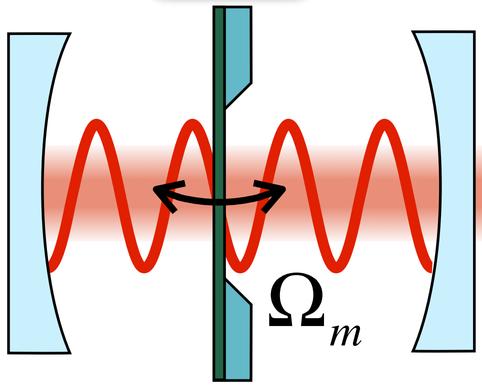
$$g = r_m \Omega_a \sqrt{\frac{N m_a}{m_{eff}} \frac{2F}{\pi}}$$

Cavity acts as a “lever” to impedance-match atoms and membrane

Sympathetic cooling
of a membrane
with ultracold atoms

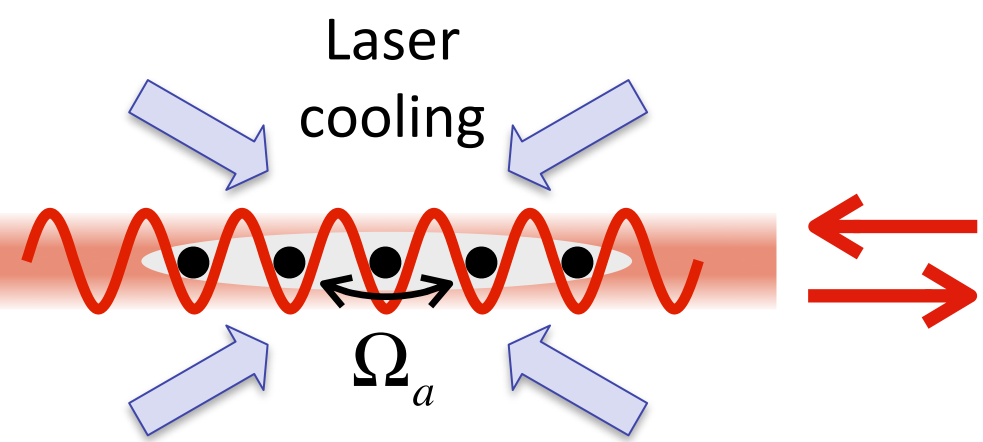
Sympathetic cooling of membrane with atoms

n_m membrane phonon number



$$g = r_m \Omega_a \sqrt{\frac{N m_a}{m_{eff}} \frac{2F}{\pi}}$$

$$(\Omega_a \approx \Omega_m)$$



$$\Gamma_m = \frac{\Omega_m}{Q_m}$$

Γ_a laser cooling rate

thermal bath

$$\bar{n}_{th} \simeq \frac{k_B T_{bath}}{\hbar \Omega_m} \gg 1$$

+ radiation pressure noise
+ technical laser noise

Strong coupling

$$g \gg \Gamma_a, \Gamma_m \bar{n}_{th}$$

$$\bar{n}_{th} \approx 0$$

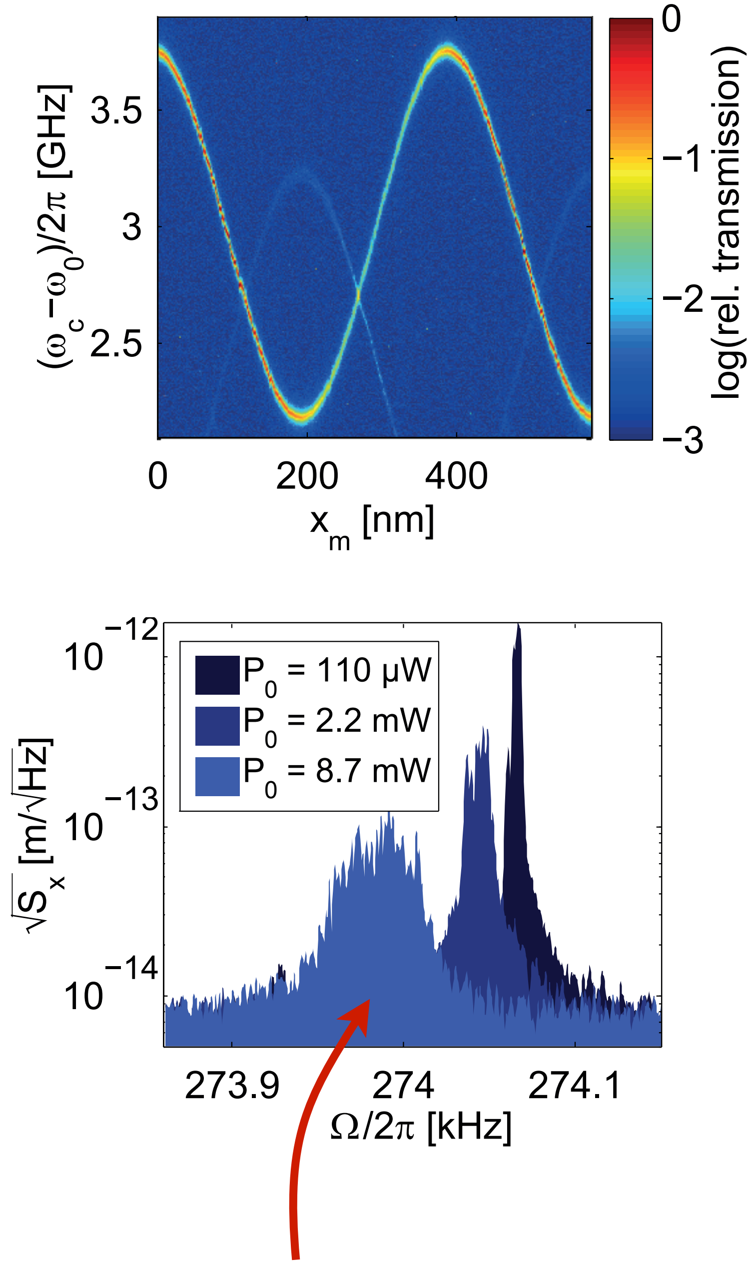
+ atomic momentum diffusion

Sympathetic cooling
$(\Gamma_a \gg g)$

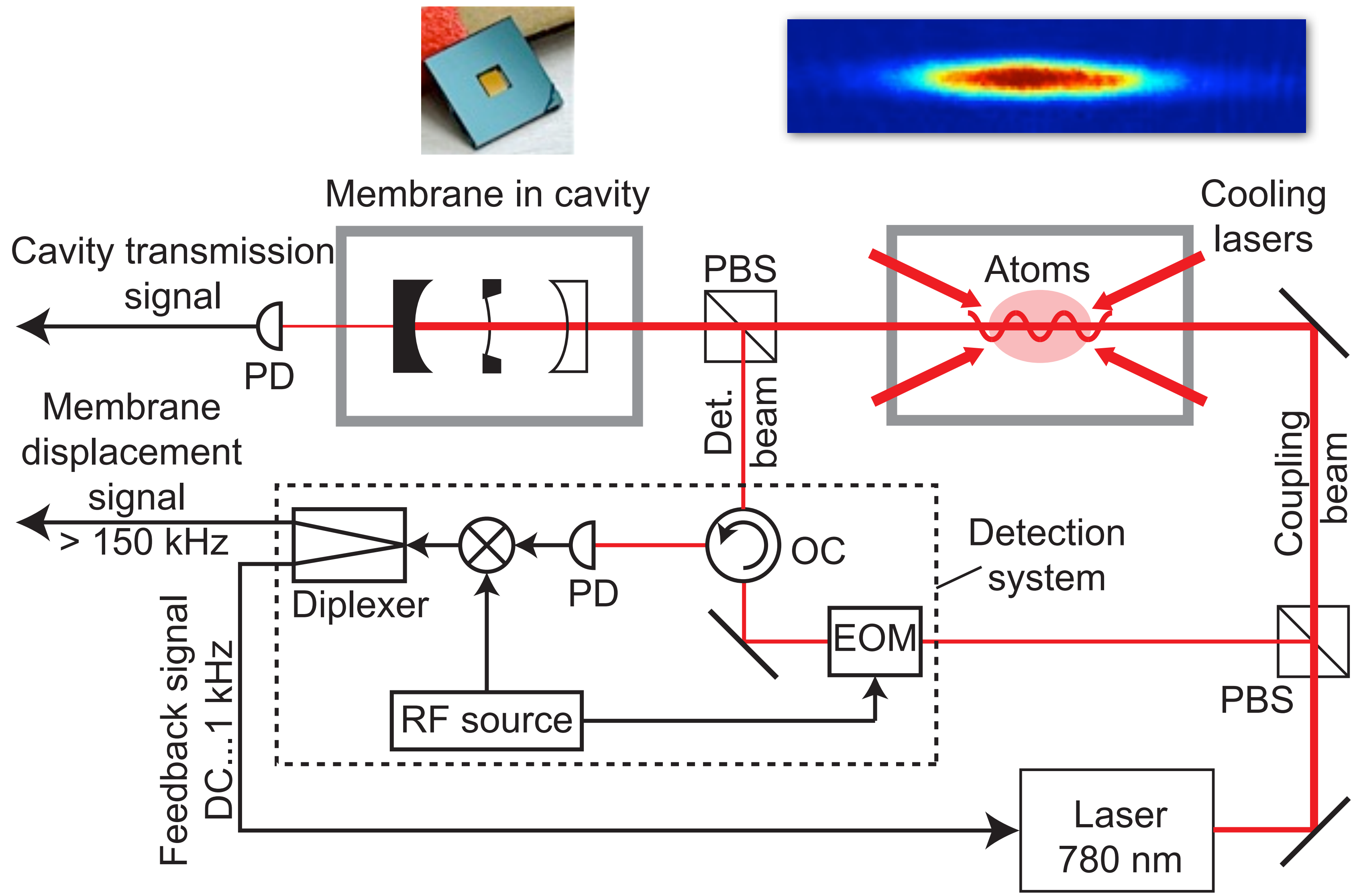
$$\Gamma_{sym} = \frac{4g^2}{\Gamma_a} \qquad n_m \simeq \frac{\Gamma_m}{\Gamma_{sym}} \bar{n}_{th}$$

Vogell et al., PRA 87, 023816 (2013)
Bennett et al., New J Phys 16, 083036 (2014)

Experimental setup



peak area
$\langle x_m^2 \rangle \sim T$



SiN membrane in cavity

$\Omega_m/2\pi$ = 274 kHz, Q = 3×10^6, a < 10^{-5}

$\Gamma_m = \Omega_m/Q$ = 0.6 s^{-1}

Single-sided cavity F = 140-300

Laser-cavity detuning Δ= -0.02 κ

Atoms in lattice:

N = 2×10^7, P_0 = 16.5 mW,

$\Delta_{at}/2\pi$ = -8 GHz

Γ_a = 2π×1.6 kHz

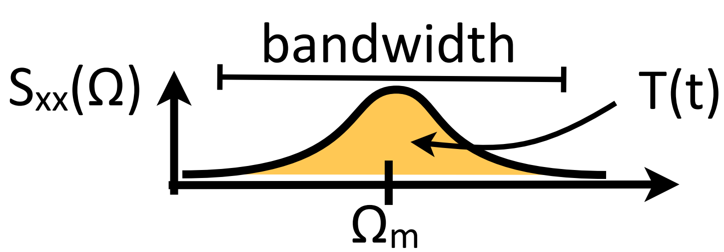
A. Jöckel et al., arXiv:1407.6820 (2014)

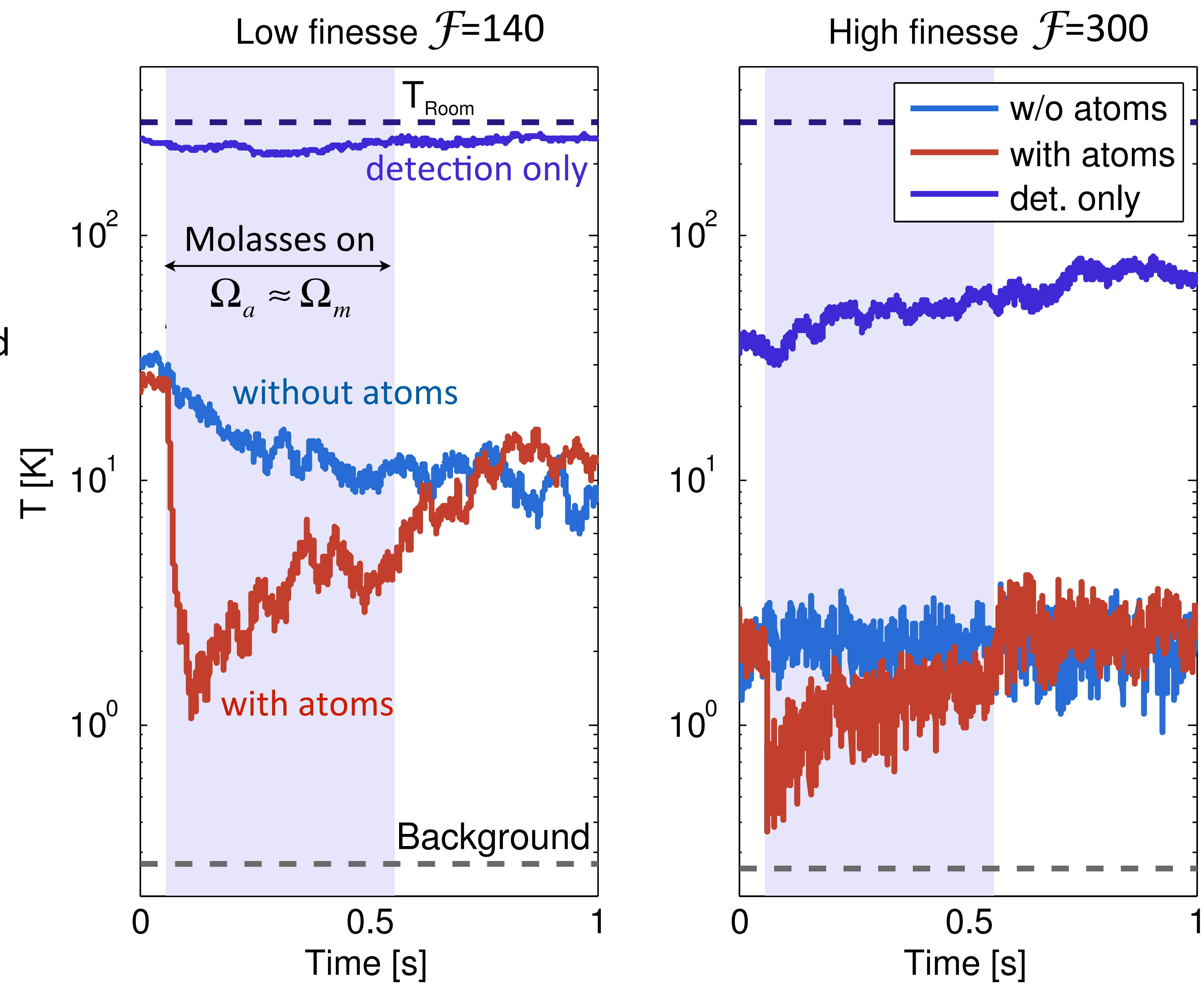
Sympathetic cooling of membrane with atoms

Three-step sequence:

1. atoms off-resonant $\Omega_a \ll \Omega_m$
2. atoms resonant $\Omega_a \approx \Omega_m$
3. Molasses cooling off

laser slightly red detuned to avoid parametric instability





A. Jöckel et al., arXiv:1407.6820 (2014)

Sympathetic cooling of membrane with atoms

Three-step sequence:

1. atoms off-resonant $\Omega_a \ll \Omega_m$
2. atoms resonant $\Omega_a \approx \Omega_m$
3. Molasses cooling off

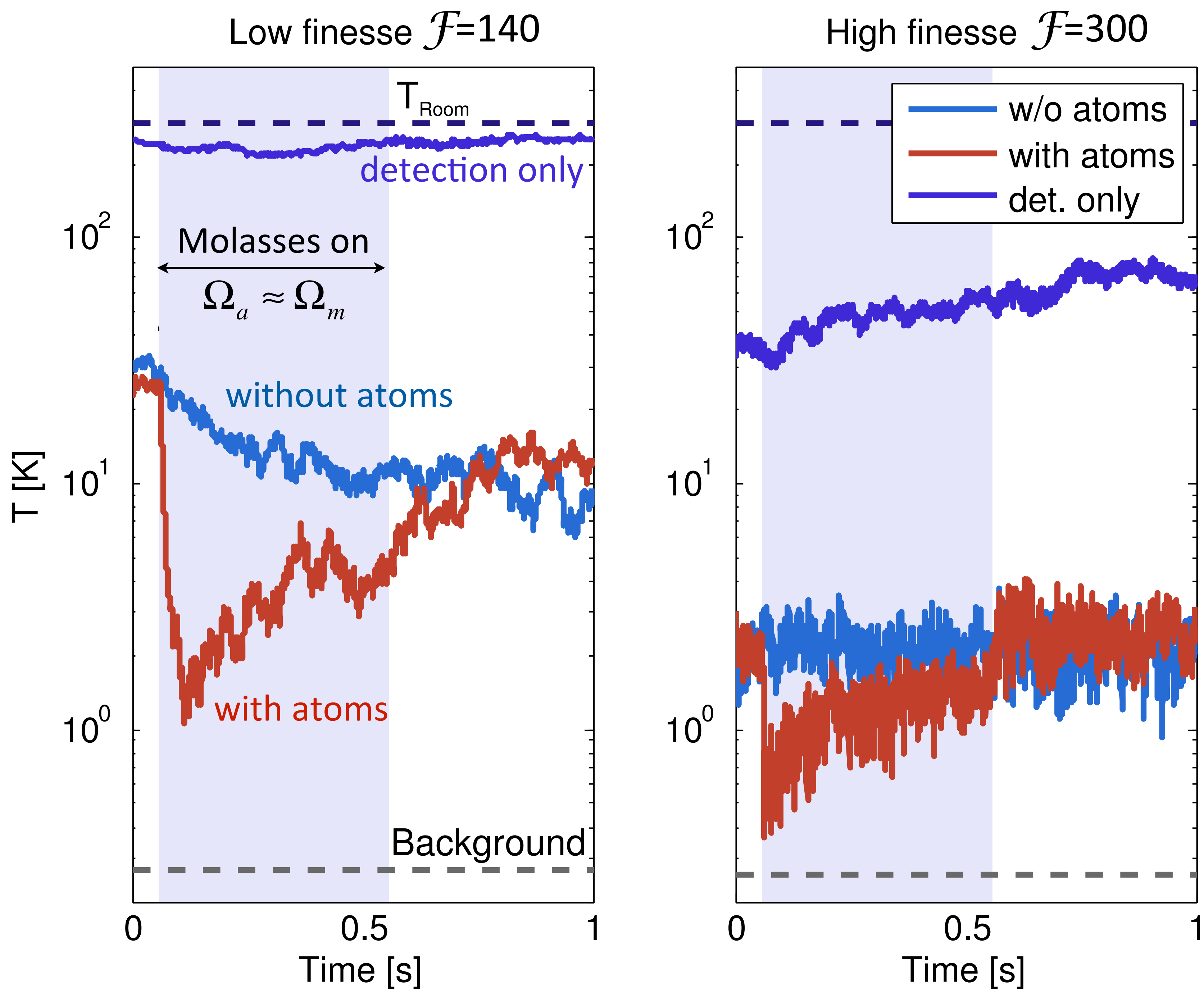
laser slightly red detuned to avoid parametric instability

Membrane cooled from **300 K** to **650 ± 230 mK** by coupling to atoms

Sympathetic cooling rate

$$\Gamma_{sym} = \eta^2 \frac{4g^2}{\Gamma_a} = 390\ \mathrm{s}^{-1}$$

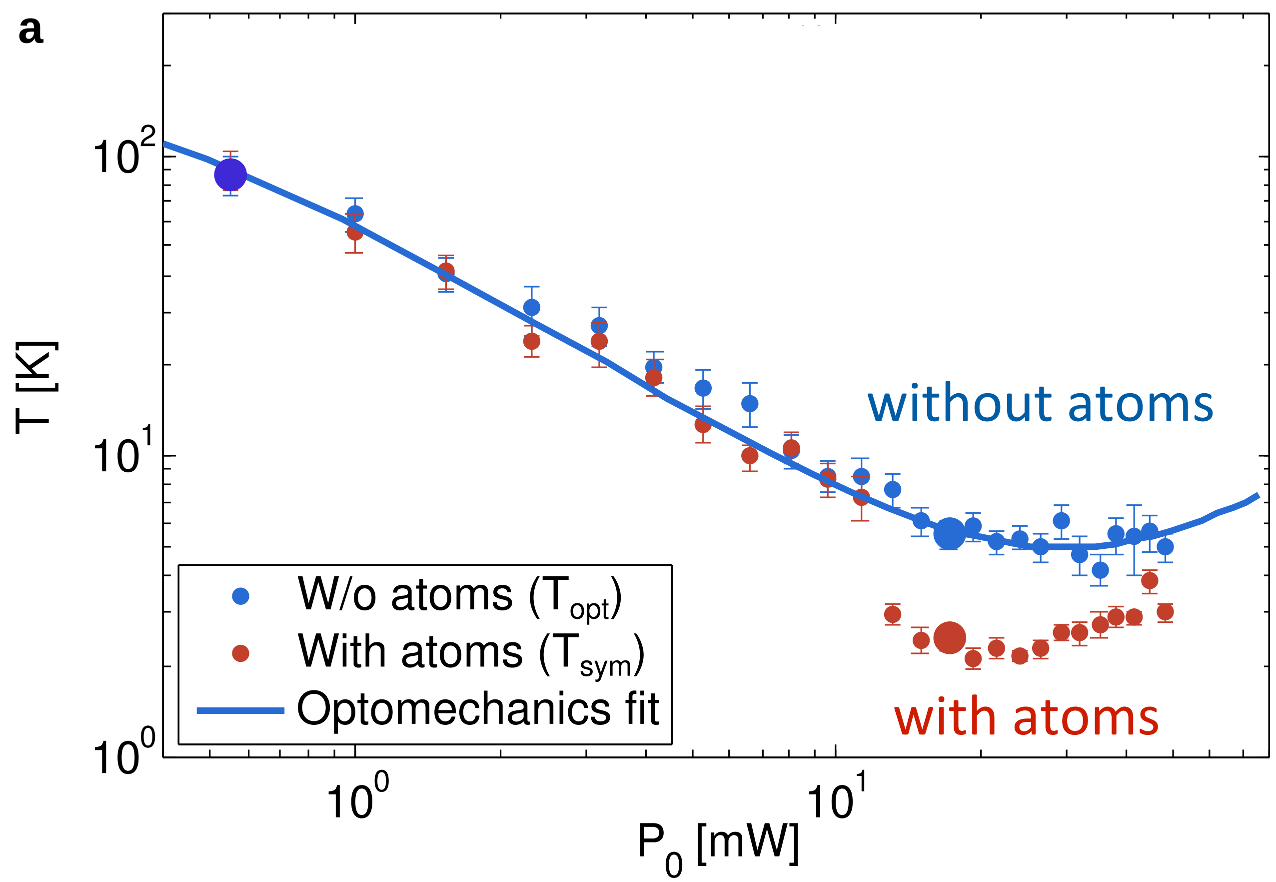
$$g = 1.3 \times 10^3\ \mathrm{s}^{-1}$$

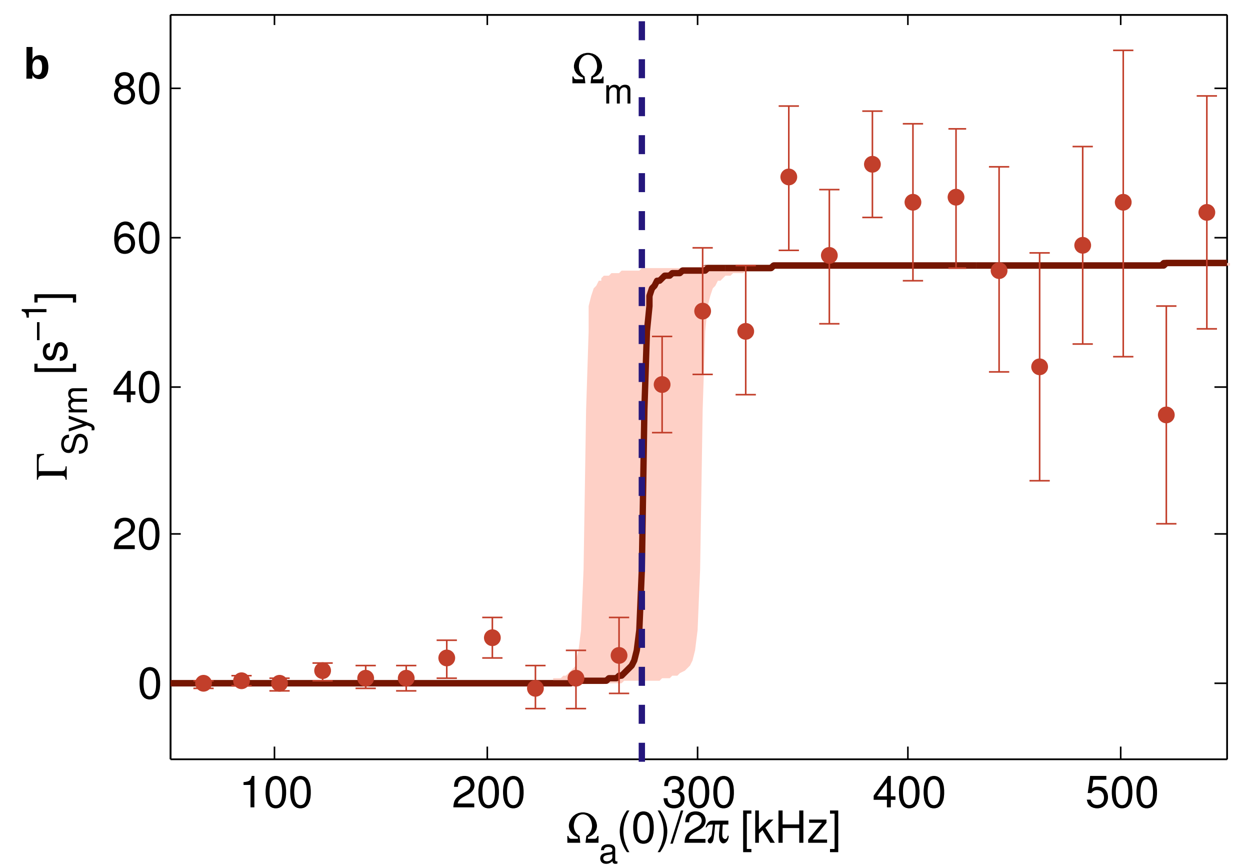


Atoms cool membrane even though $Nm_a/m_{eff} = 10^{-10}$!

A. Jöckel et al., arXiv:1407.6820 (2014)

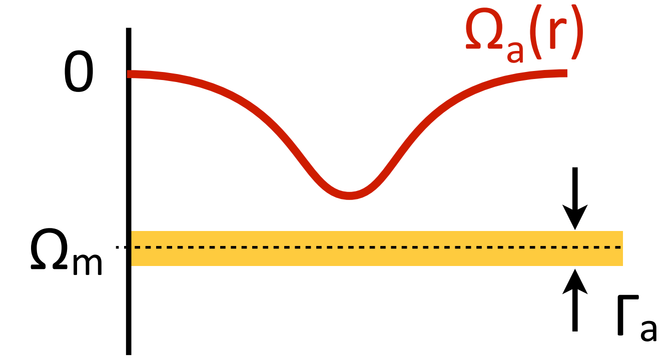
Resonant character of the interaction





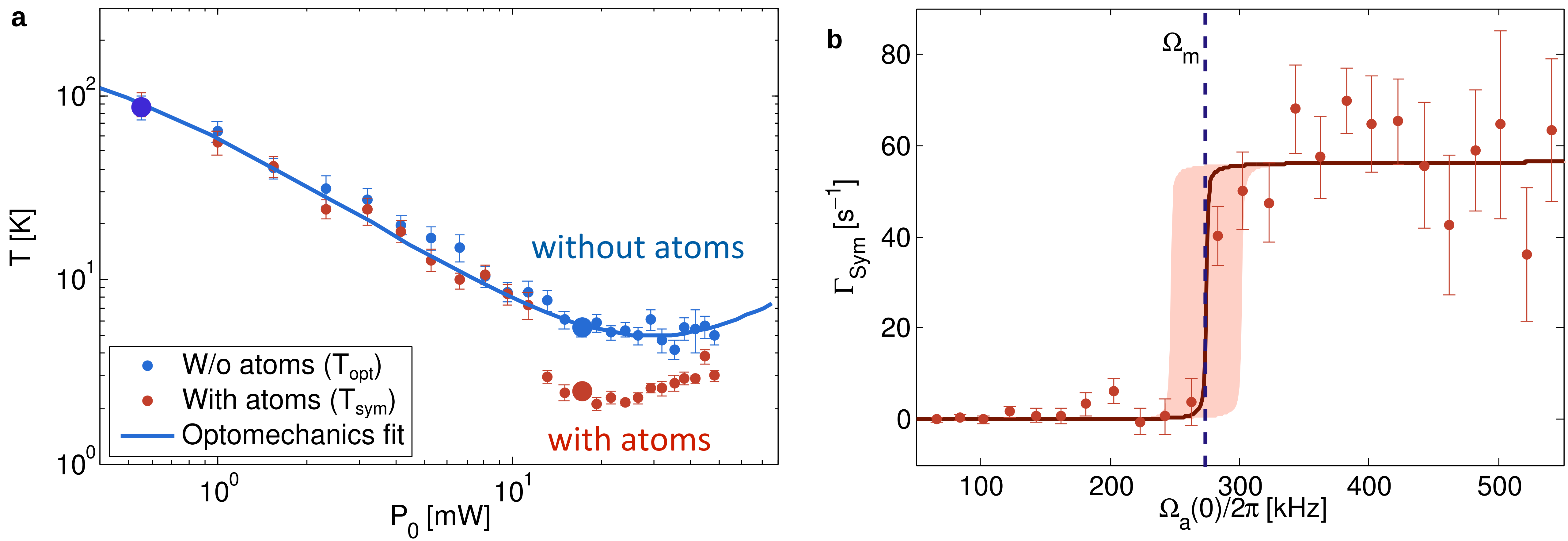
- Data *without* atoms well-described by cavity optomechanics theory
- Current limit: technical laser noise
- Sympathetic cooling stronger than cavity optomechanics cooling $\Gamma_{sym} > \Gamma_{opt}$

Atoms affect membrane only if $\Omega_a(0) \geq \Omega_m$



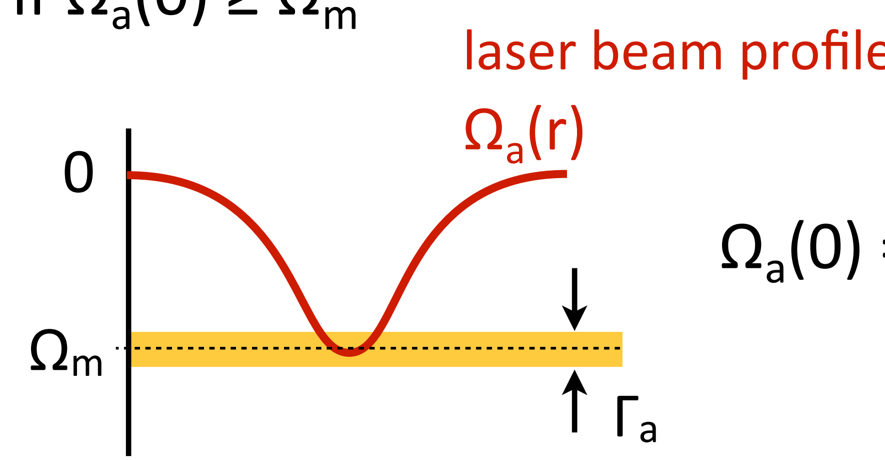
A. Jöckel et al., arXiv:1407.6820 (2014)

Resonant character of the interaction



- Data *without* atoms well-described by cavity optomechanics theory
- Current limit: technical laser noise
- Sympathetic cooling stronger than cavity optomechanics cooling $\Gamma_{sym} > \Gamma_{opt}$

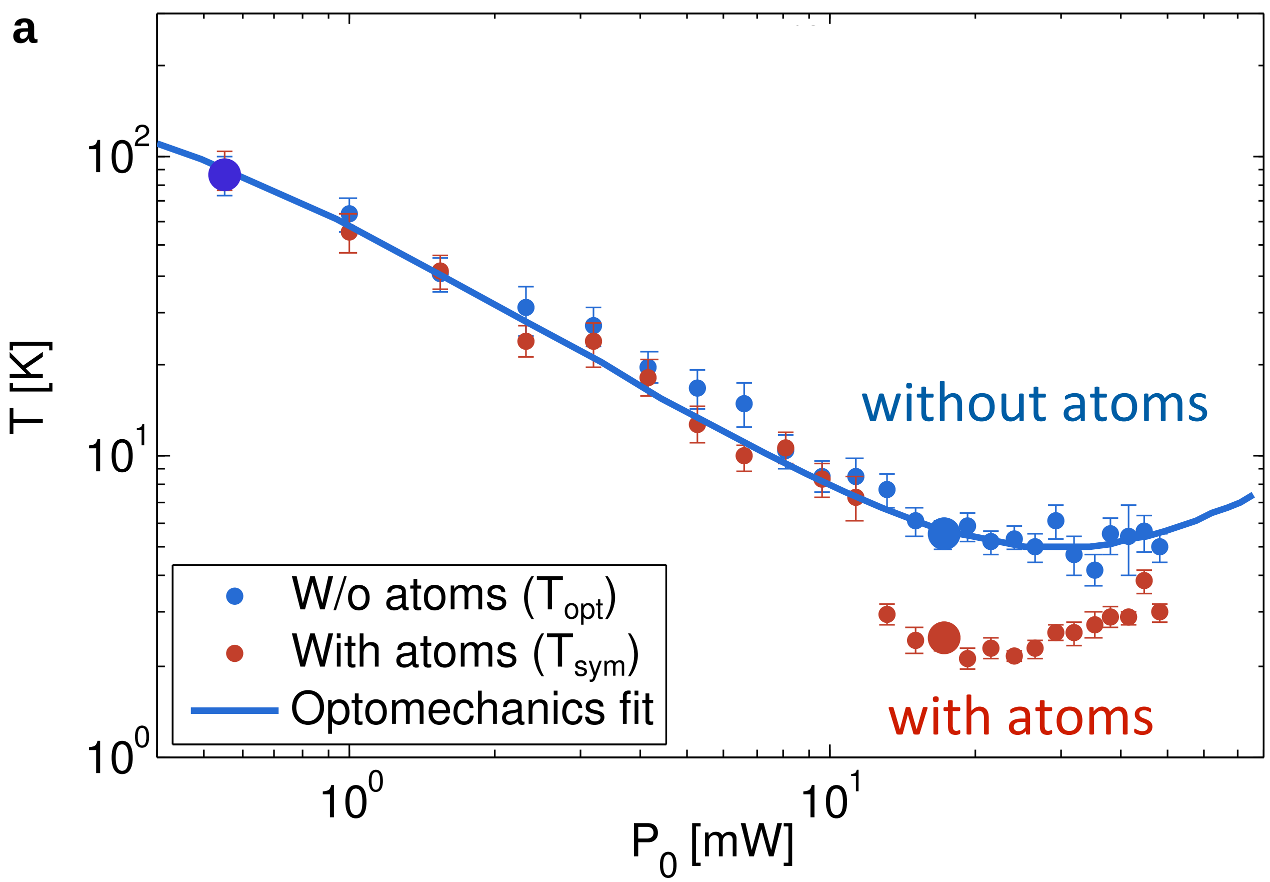
Atoms affect membrane only if $\Omega_a(0) \geq \Omega_m$

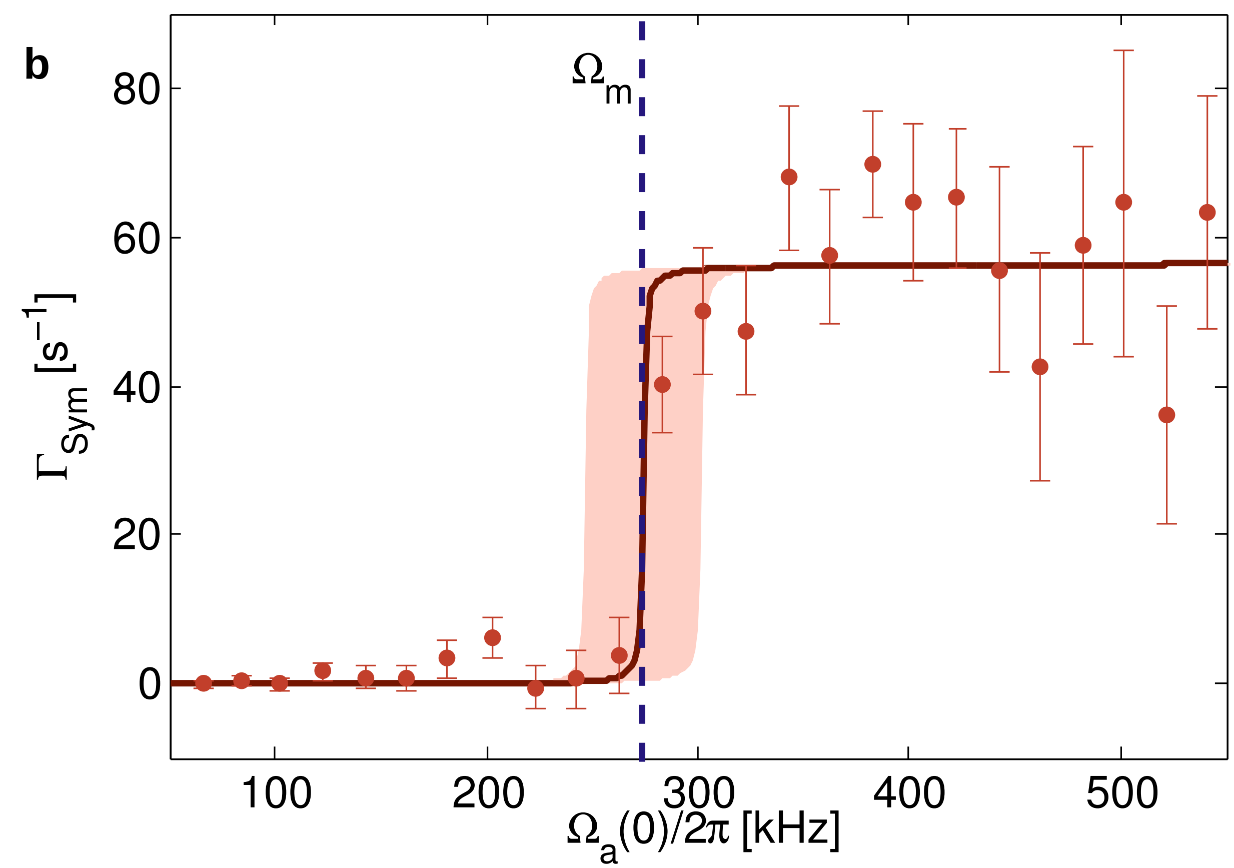


$\Omega_a(0) = \Omega_m$

A. Jöckel et al., arXiv:1407.6820 (2014)

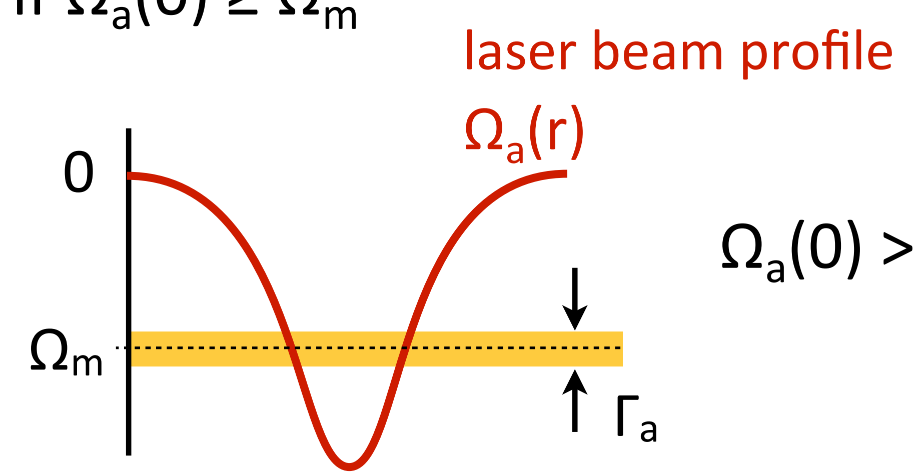
Resonant character of the interaction





- Data *without* atoms well-described by cavity optomechanics theory
- Current limit: technical laser noise
- Sympathetic cooling stronger than cavity optomechanics cooling $\Gamma_{sym} > \Gamma_{opt}$

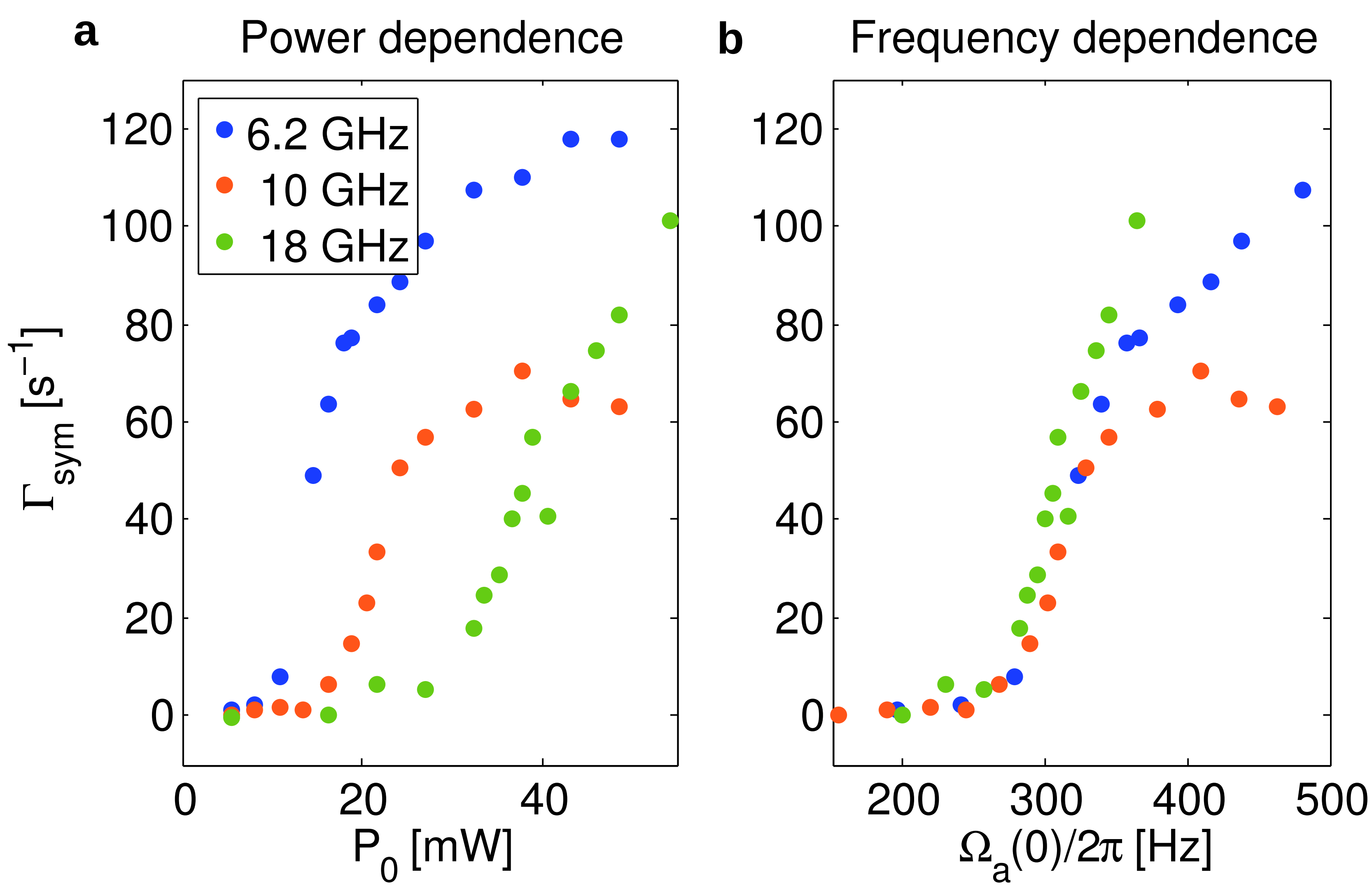
Atoms affect membrane only if $\Omega_a(0) \geq \Omega_m$



$\Omega_a(0) > \Omega_m$

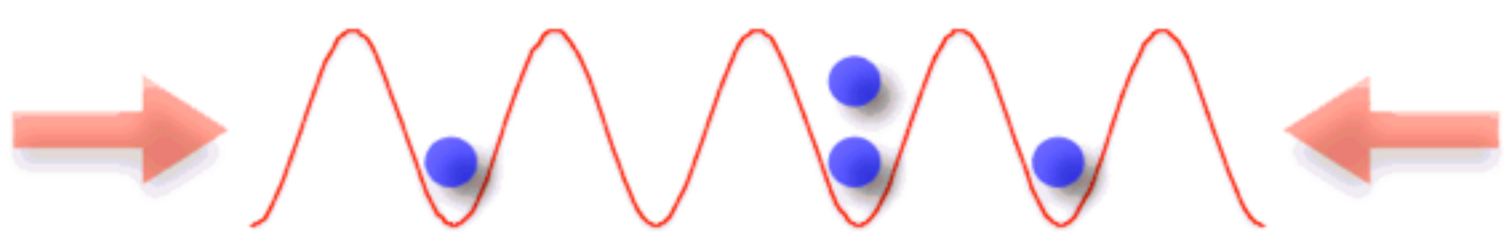
A. Jöckel et al., arXiv:1407.6820 (2014)

Dependence on lattice detuning and beam power



Measurements for different detunings from atomic resonance

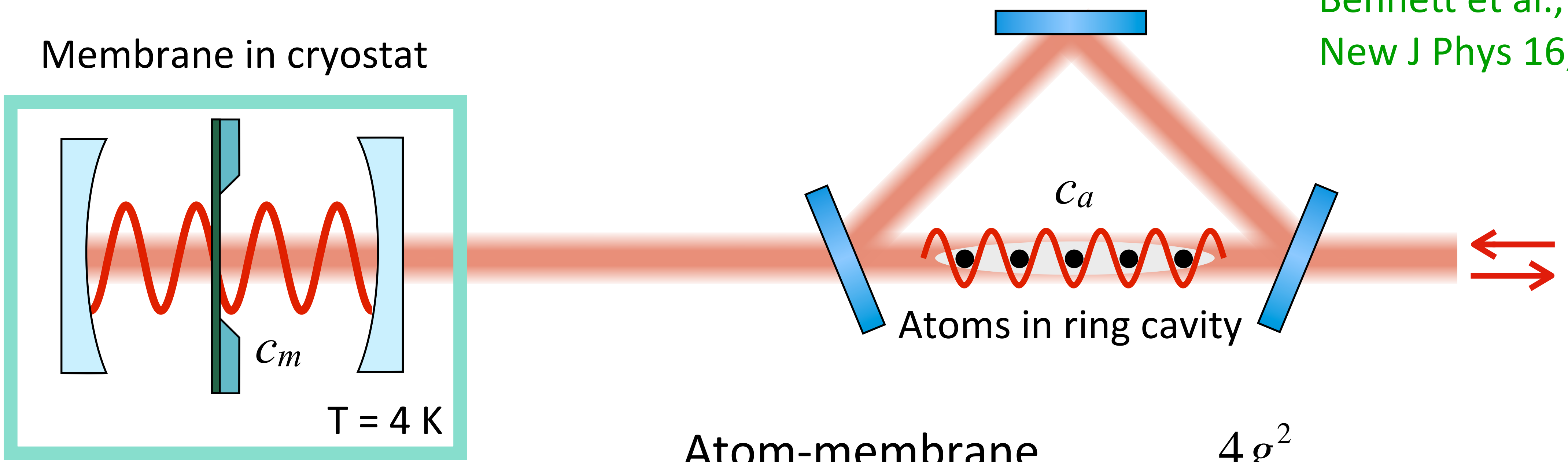
$$\Omega_a(0) \propto \sqrt{\frac{P_0}{\Delta_{at}}}$$



$$U_{dip}(r) \propto \frac{I(r)}{\Delta_{at}}$$

Perspectives: ground-state cooling and quantum control

Improvements of the system



Vogell et al., PRA 87, 023816 (2013)

Bennett et al.,
New J Phys 16, 083036 (2014)

N = 1×10[6], $\mathcal{F}_a = 80$
$Q_m = 10^7$, $\mathcal{F}_m = 360$

Atom-membrane cooperativity $$C = \frac{4g^2}{\Gamma_m \Gamma_a} = 16 c_m c_a$$

Ground-state cooling: $C > \bar{n}_{th}$ and $\Gamma_a > \Gamma_m \bar{n}_{th}$

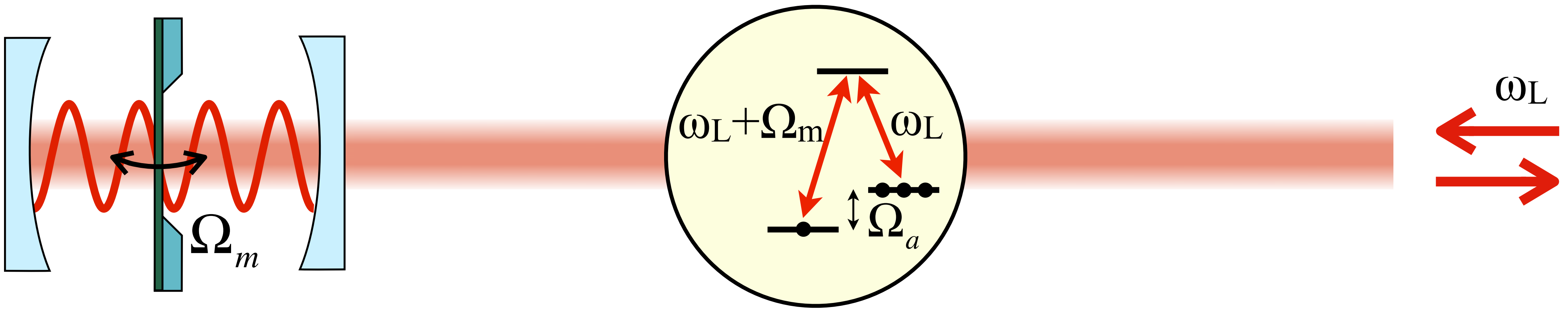
Current experiment: $C = 680 \Rightarrow$ atom-membrane EIT

- Atoms can provide ground-state cooling where optomechanical cavity cooling or feedback cooling cannot

$$C > \bar{n}_{th} \text{ but } c_m < \bar{n}_{th}/8$$

- resolved-sideband regime ***not*** required ($\Omega_m \ll \kappa$)
- Strong atom-membrane coupling ***without*** strong coupling to light

Coupling to internal state of the atoms



Internal state of atoms can be controlled with higher fidelity

- cooling = optical pumping
- tunable transition frequency: Ω_a = kHz - GHz
- inverted collective spin = oscillator with negative mass
  → EPR entanglement
  → "trajectories without quantum uncertainties"

Bariani et al.,
arXiv:1407.1073 (2014)

Hammerer, Polzik et al.,
PRL 102, 020501 (2009)
arXiv:1405.3067 (2014)

Use techniques developed for ensemble-based QIP

- Rydberg blockade → two-level system
- non-classical states of membrane, atom-membrane entanglement

Carmele et al.,
New J Phys 16, 063042 (2014)

Towards quantum interfaces of atoms, photons and phonons!

Basel ultracold atoms group

Theory collaboration:
K. Hammerer **(Hannover)**, B. Vogell, K. Stannigel, C. Genes, P. Zoller **(Innsbruck)**