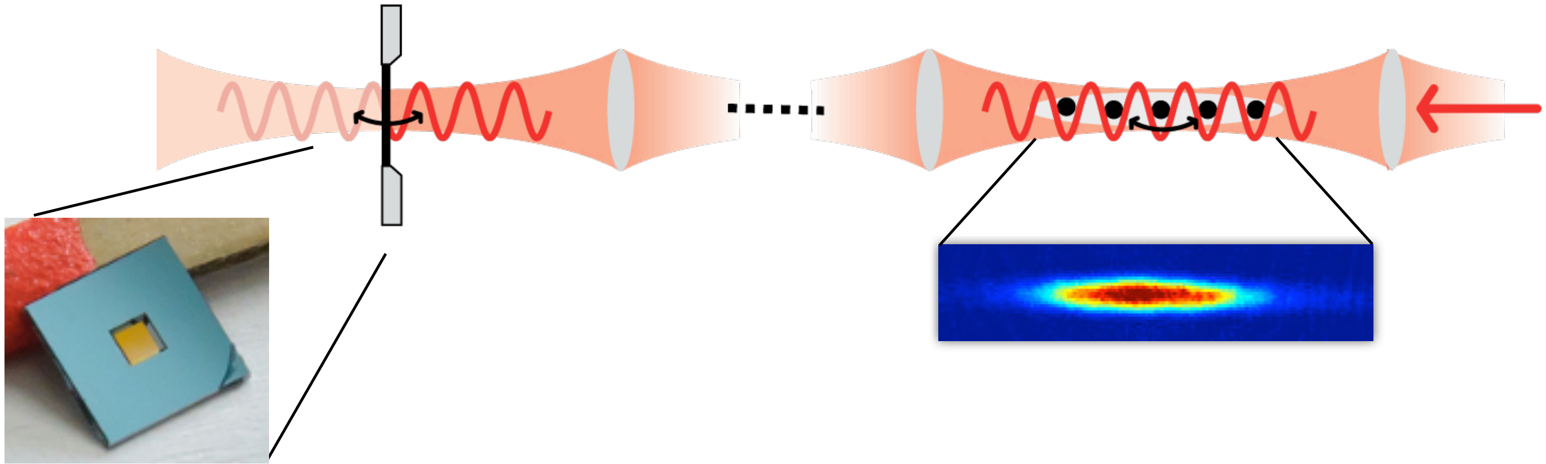
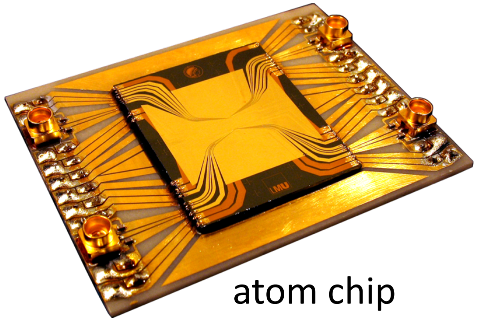
Hybrid atom-optomechanics



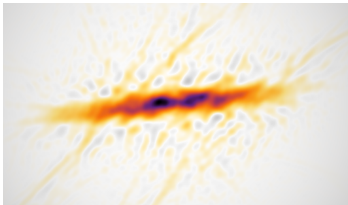
Philipp Treutlein
Maria Korppi, Andreas Jöckel, Matthew T. Rakher
Department of Physics • University of Basel • Switzerland

Former co-workers: David Hunger, Stephan Camerer
Theory collaboration: K. Hammerer, K. Stannigel, C. Genes, P. Zoller

Projects in our group



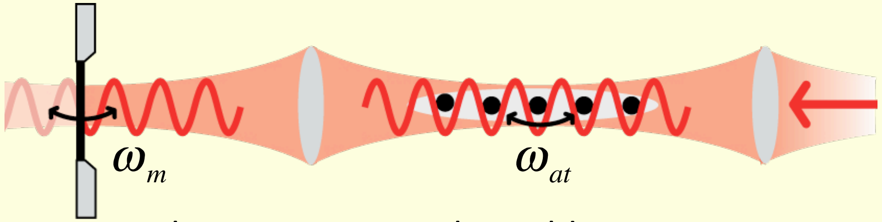
atom chip



spin-squeezed BEC

Quantum metrology with chip-based atom interferometers

Nature 464, 1170 (2010).
New J. Phys. 13, 065019 (2011).

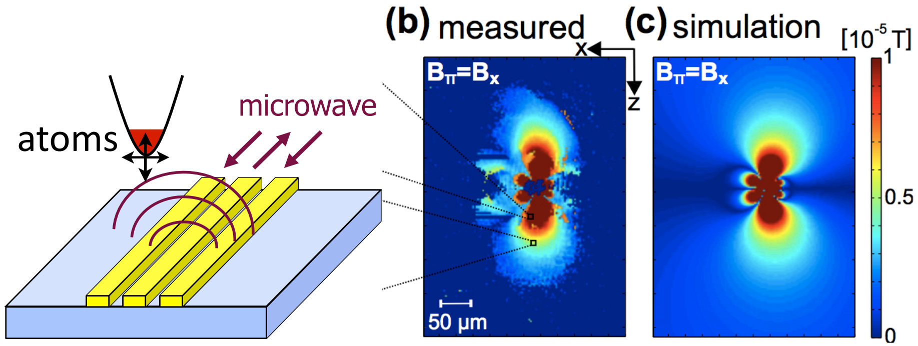


SiN membrane

ultracold atoms

Quantum interfaces of ultracold atoms and mechanical oscillators

Phys. Rev. Lett. 107, 223001 (2011).



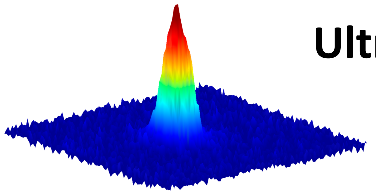
coplanar waveguide

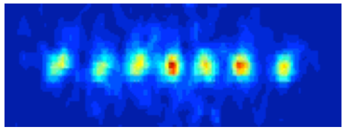
mw field of coplanar waveguide

Microwave field imaging using ultracold atoms

Appl. Phys. Lett. 97, 051101 (2010).

Hybrid quantum systems



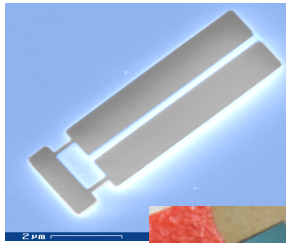


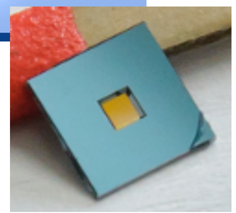
Ultracold atoms and ions

Memory
Clocks
Simulators

Mechanical oscillators

Sensors
Transducers

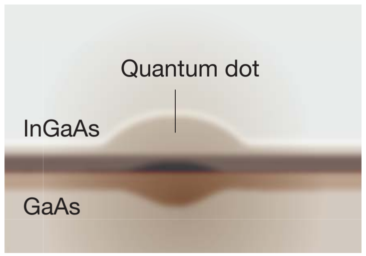




Hybrid quantum systems
quantum computing
quantum communication
quantum metrology

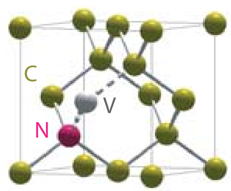
Single-photon sources

Semiconductor quantum dots "artificial atoms"



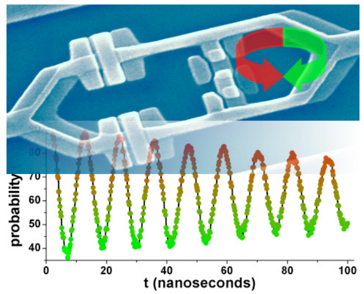
Memory
Sensors

Solid-state spin systems (NV centers, ...)



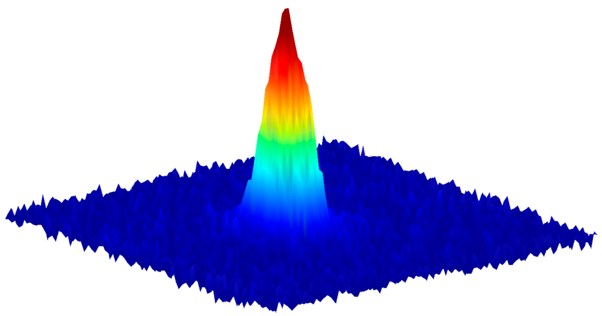
Processors

Superconducting devices

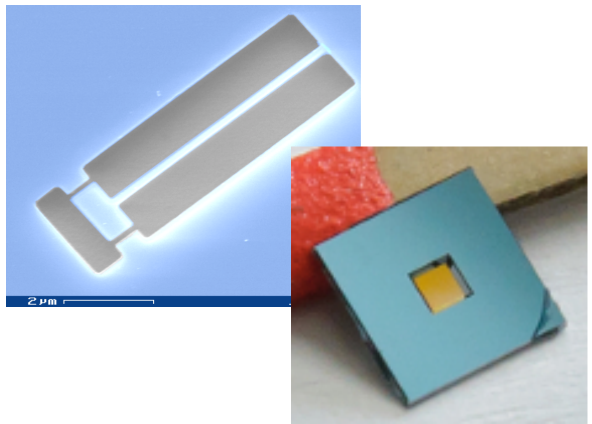


Big question...

How can we coherently couple ultracold atoms to solid-state quantum systems?



quantum interface

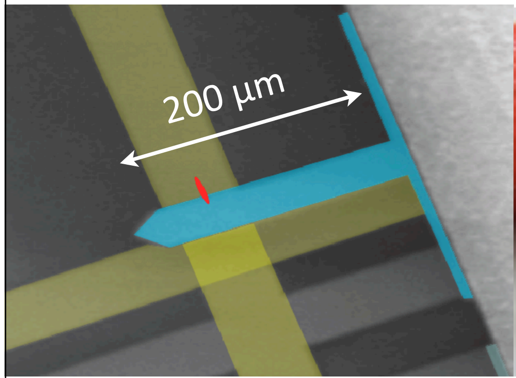


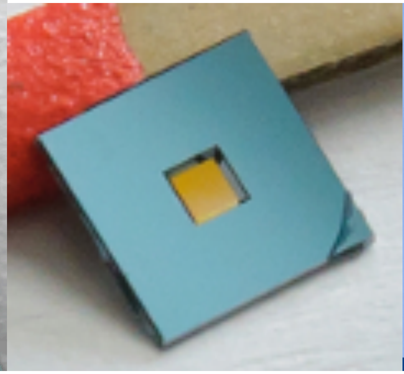
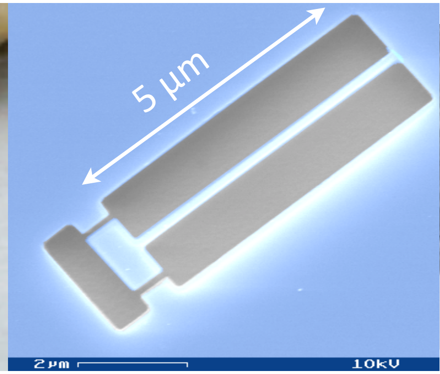
Ultracold atoms

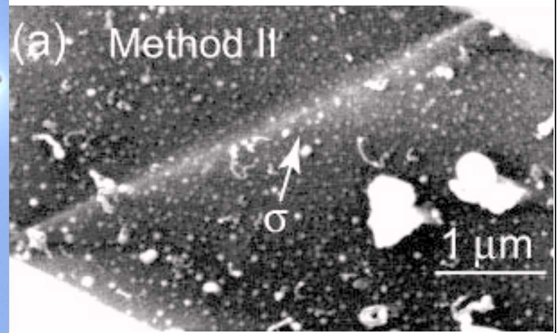
Solid-state quantum systems
(e.g. mechanical oscillators)

Micro- and nanomechanical oscillators

kHz **frequency** GHz





AFM cantilever | SiN membrane | Si nanocantilever | C-nanotube

ng **(effective) mass** ag

Sensitive detectors of force, mass, ...

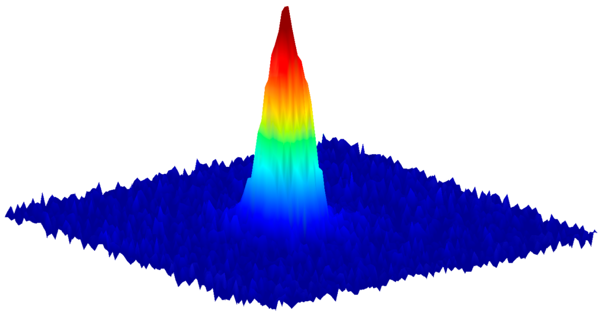
Mechanical oscillators in the quantum regime

- cryogenic or novel laser cooling methods (optomechanics)
- quantum *mechanics* on a "macroscopic" scale
- applications in sensitive force detection

A. D. O'Connell et al., Nature 464, 697 (2010).
J. D. Teufel et al., arXiv:1103.2144 (2011).

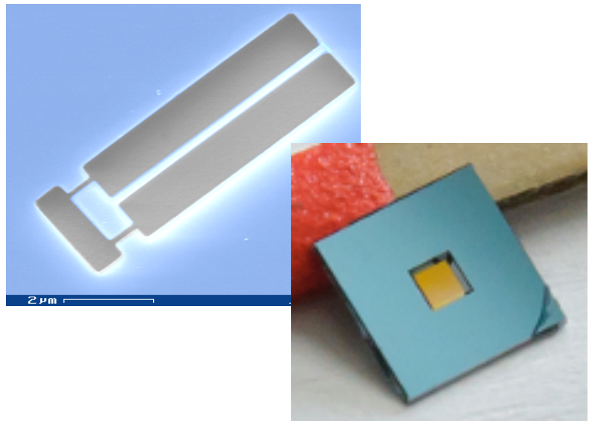
Atoms coupled to mechanical oscillators

Ultracold atoms



quantum interface

Micro- and nanofabricated mechanical oscillators



Prepare, detect, manipulate quantum states of mechanical oscillators by coupling to other (microscopic) quantum systems

- atoms, ions, NV centers, Cooper-pair box,...

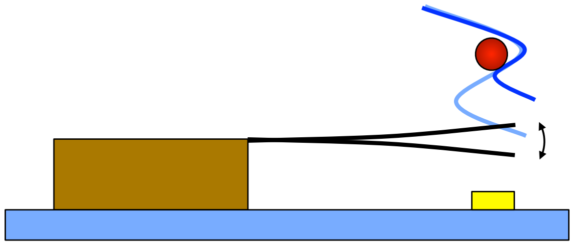
Mechanical oscillators as a new tool for AMO experiments

- local probe (sub-wavelength) for manipulation on atomic systems
- optical lattice with micromechanical mirrors (phonons?)

Mechanical oscillators as transducers

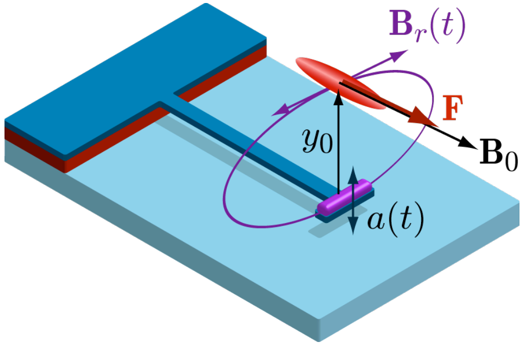
- interfacing e.g. atoms with solid-state spin systems

Coupling mechanisms



coupling via atom-surface forces

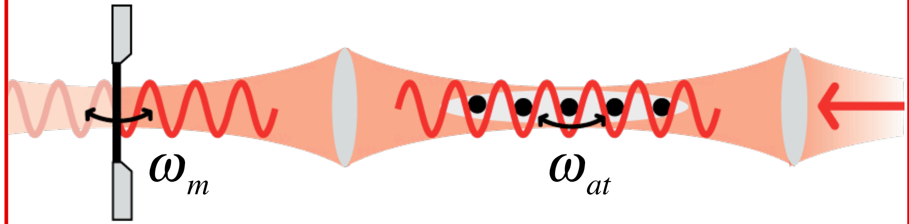
experiment:
D. Hunger et al., PRL 104, 143002 (2010).



magnetic coupling to atomic spin

theory:
P. Treutlein et al., PRL 99, 140403 (2007).

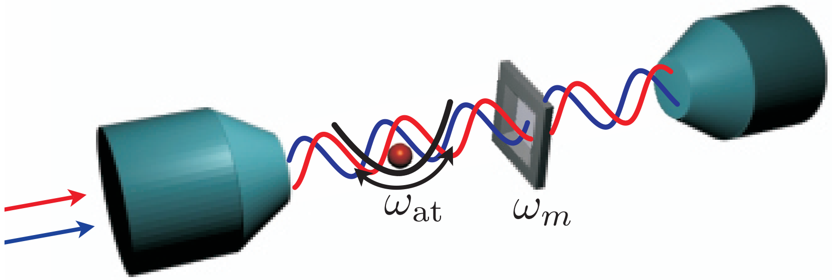
related experiment (room-temperature atoms):
Y.-J. Wang et al., PRL 97, 227602 (2006).



coupling via optical lattice

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

experiment: S. Camerer, M. Korppi et al., PRL 107, 223001 (2011).



cavity-mediated coupling

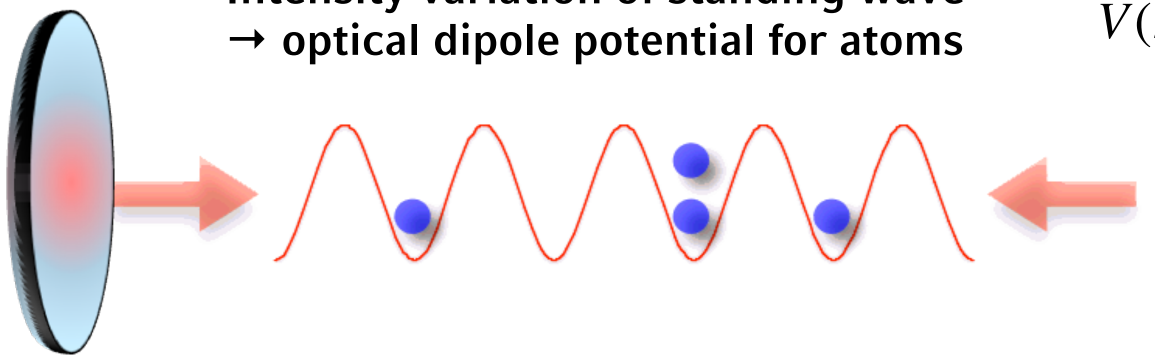
theory:
K. Hammerer et al., PRL 103, 063005 (2009).

related theory: Meystre, Ritsch, Sun, Nori, ...

Optical lattices

Intensity variation of standing wave
→ optical dipole potential for atoms

$$V(r) \propto \frac{I(r)}{\Delta}$$

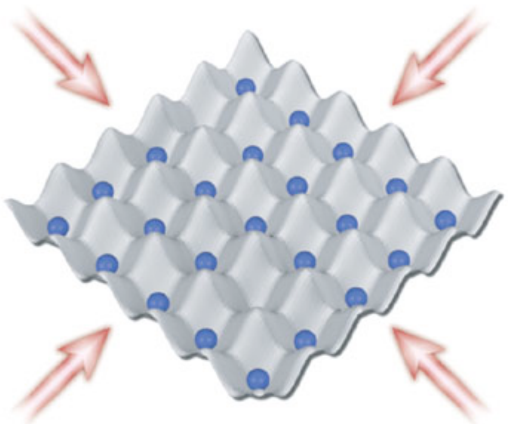


$$V(z) = V_0 \sin^2(kz)$$

Usual optical lattice experiments:

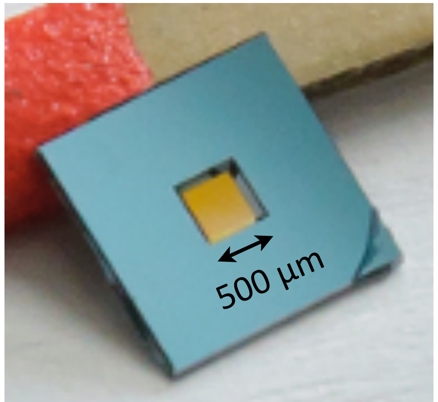
- motion and (thermal) vibrations of the mirrors negligible
- backaction of atomic motion onto light field minimized

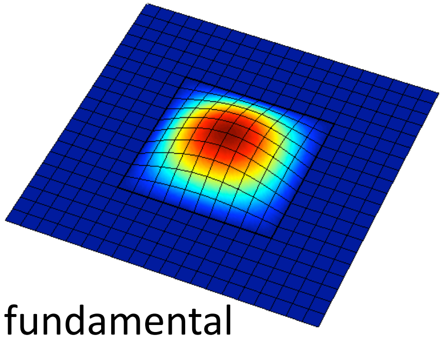
Optical lattice acts as a static container for atoms.



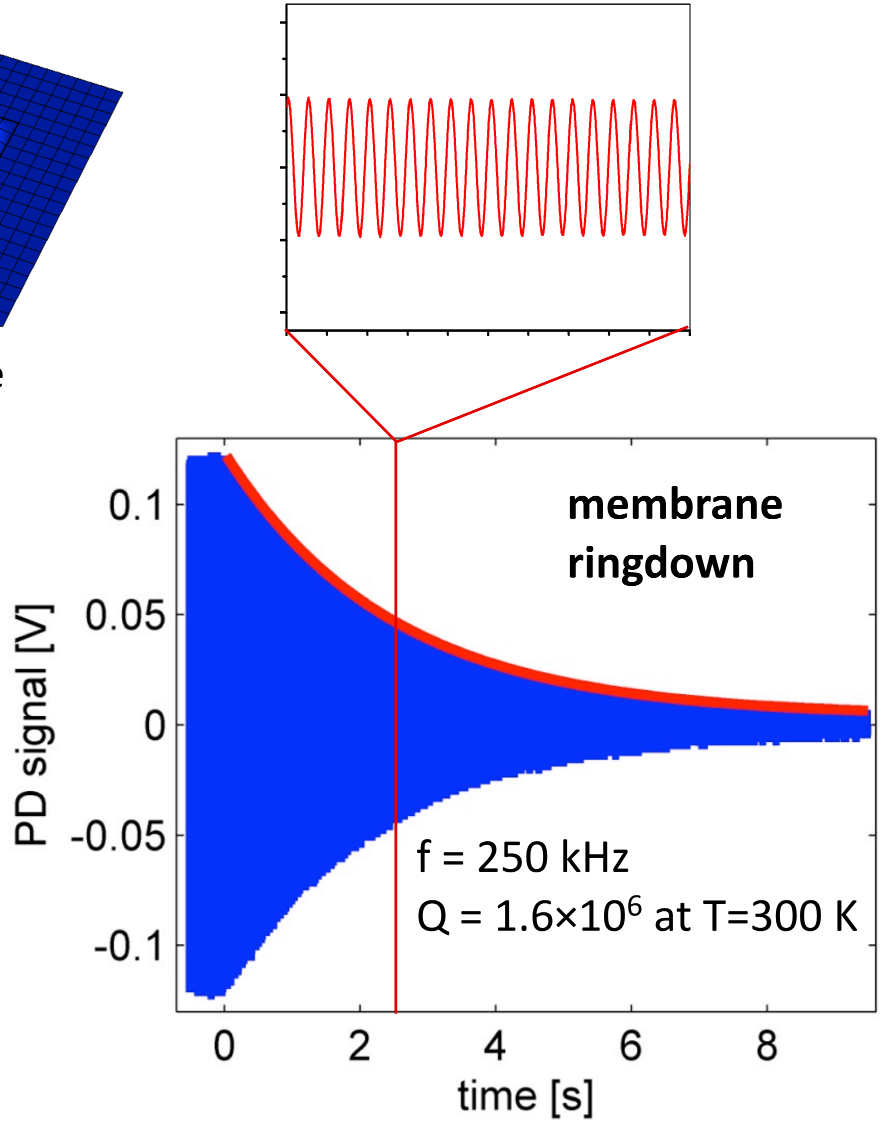
- model system for condensed matter physics
- quantum register

SiN membrane oscillators





fundamental mechanical mode



dimensions

$l \times w = 0.5$ mm $\times$ 0.5 mm

$t = 50$ nm

tensile stress: 100 MPa

mechanical properties

$\omega_m/2\pi = 250$ kHz

$m_{eff} = 1 \times 10^{-11}$ kg

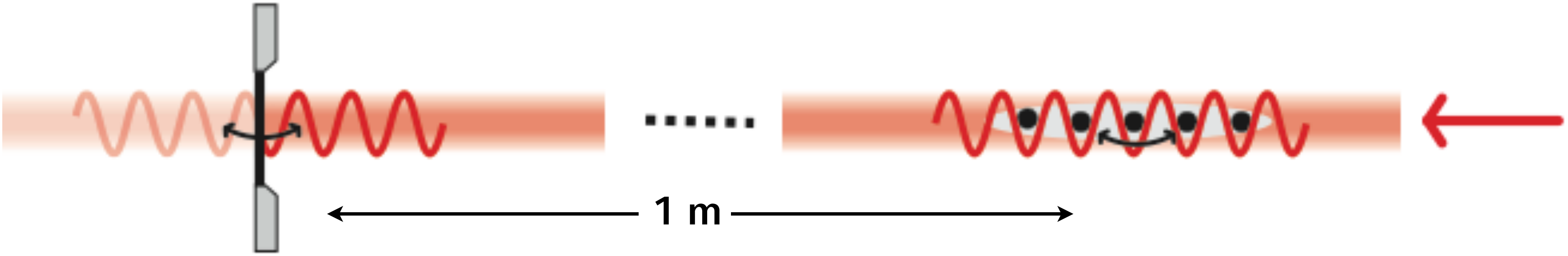
$Q = \omega_m/\gamma_m = 1.5 \times 10^6$ @ 300 K

optical properties

reflectivity: R = 0.5 @ 780 nm

Optical lattice with micromechanical mirror

K. Hammerer, K. Stannigel, C. Genes, and P. Zoller,
P. Treutlein, S. Camerer, D. Hunger, and T. W. Hänsch, PRA 82, 021803 (2010).



SiN membrane

Laser-cooled atoms in optical lattice

Loading from magneto-optical trap (MOT)

Ground state cooling possible
(Raman sideband cooling)

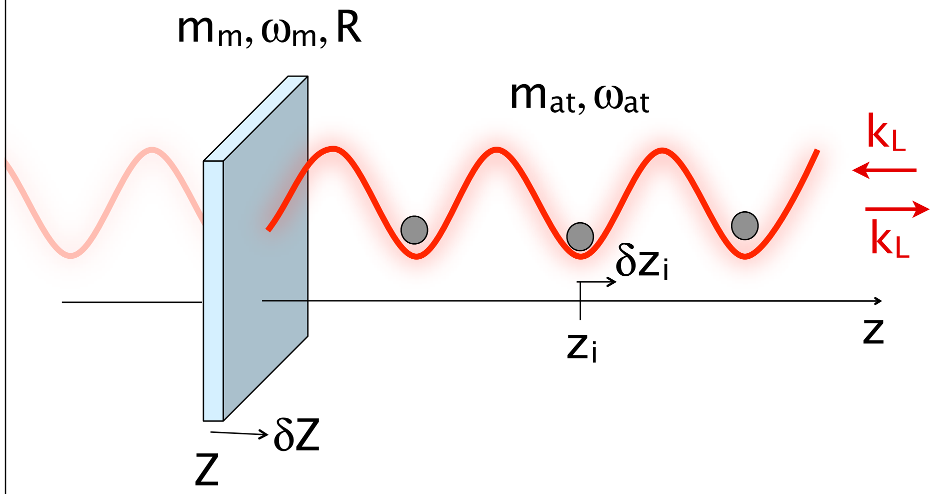
Lattice couples membrane vibrations
to c.o.m. motion of the atoms

⇒ sympathetic cooling of membrane

⇒ coherent dynamics if laser cooling turned off

Membrane motion couples to atoms

Membrane = (slowly) moving boundary condition



lattice potential

$$V(z) = \sum_i V_0 \sin^2\left[k_L(z_i - Z)\right] + \text{const.}$$

expand around equilibrium

$$V_{at} = \sum_i V_0 k_L^2 \delta z_i^2 = \sum_i \tfrac{1}{2} m_{at} \omega_{at}^2 \delta z_i^2$$

$$H_i = 2V_0 k_L^2 \sum_i \delta z_i \delta Z = 2\hbar g x_{at} x_m$$

trap frequency $\omega_{at} = \sqrt{2V_0 k_L^2 / m_{at}}$ **coupling constant** $\boxed{g = \dfrac{\omega_{at}}{2}\sqrt{N}\sqrt{\dfrac{m_{at}}{m_m}}}$

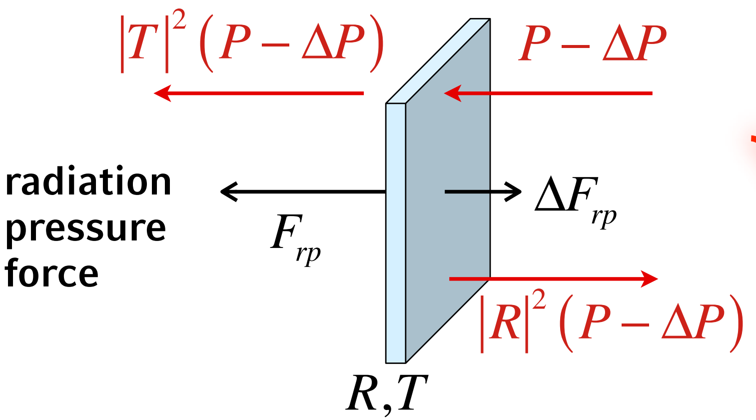
$(\omega_{at} \approx \omega_m)$

$$\boxed{H = \hbar\omega_{at} a_{at}^\dagger a_{at} + \hbar\omega_m a_m^\dagger a_m + \hbar g (a_{at} + a_{at}^\dagger)(a_m + a_m^\dagger)}$$ **(for R=1)**

atomic c.o.m. coordinate $x_{at} = (a_{at} + a_{at}^\dagger)/\sqrt{2} = \sum_i \delta z_i / l_{at}\sqrt{N}$

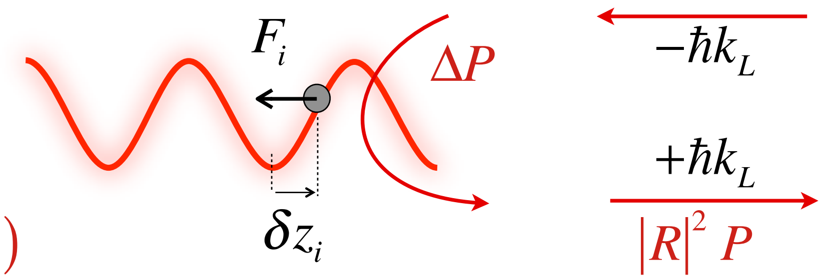
membrane coordinate $x_m = (a_m + a_m^\dagger)/\sqrt{2} = \delta Z / l_m$

Back-action of atoms onto membrane



force on atom

$$F_i = -2\hbar k_L \dot{n}_i$$



Atomic motion ⇒ redistribution of photons between running waves

laser power modulation $\quad \Delta P = \hbar\omega \sum_i \dot{n}_i = -\dfrac{c}{2}\sum_i F_i$

Radiation pressure force on membrane $\quad F_{rp} = -2\hbar k_L \dfrac{|R|^2 (P-\Delta P)}{\hbar\omega}$

modulation due to atoms: $\quad \Delta F_{rp} = \dfrac{2}{c}|R|^2 \Delta P = -|R|^2 \sum_i F_i$

asymmetric coupling

$$g_{at\to m} = |R|^2 g_{m\to at}$$

Dynamics of coupled system

equations of motion for expectation values:

$$x_{at,m} \equiv \langle x_{at,m} \rangle$$

$$\ddot{x}_{at} + \gamma_{at}\dot{x}_{at} + \omega_{at}^2 x_{at} = 2g\omega_{at}x_m$$

$$\ddot{x}_m + \gamma_m \dot{x}_m + \omega_m^2 x_m = 2g|R|^2 \omega_m x_{at}$$

$$g = \frac{\omega_{at}}{2}\sqrt{N}\sqrt{\frac{m_{at}}{m_m}}$$

apply strong laser cooling to the atoms

$\gamma_{at} \gg g, \gamma_m$ atomic dissipation dominates

$$\boxed{\Gamma_m = \gamma_m + \frac{4|R|^2 g^2}{\gamma_{at}}}$$

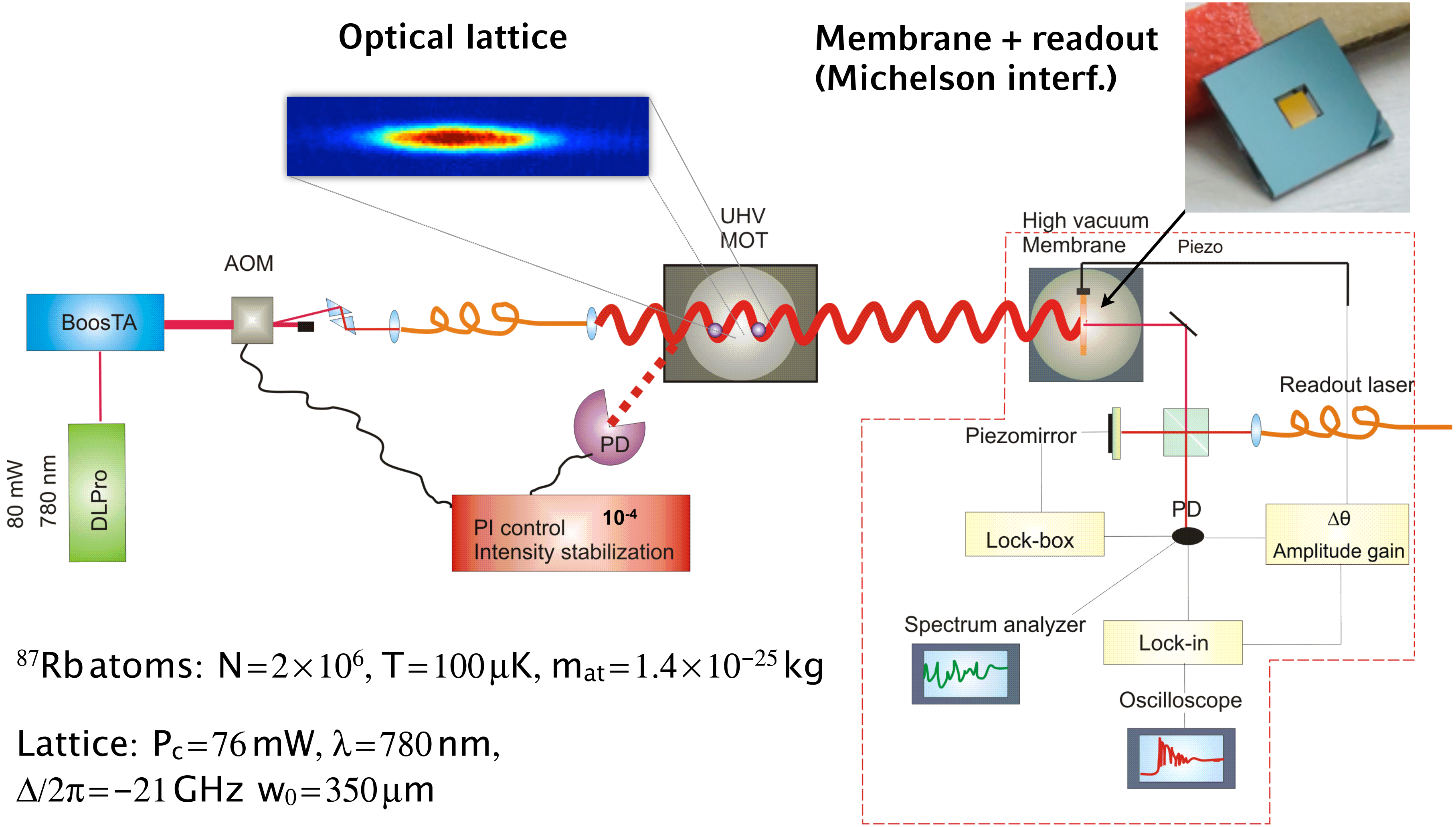
effective membrane dissipation rate

damping/cooling of membrane with atoms!

rigorous derivation (full quantum theory): K. Hammerer et al., PRA 82, 021803 (2010).

asymmetric coupling: characteristic feature of cascaded quantum system

Experimental setup

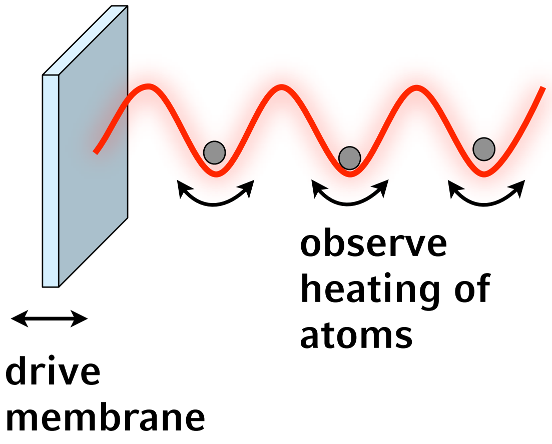


^{87}Rb atoms: $N=2\times10^{6}$, $T=100\,\mu K$, $m_{at}=1.4\times10^{-25}$ kg

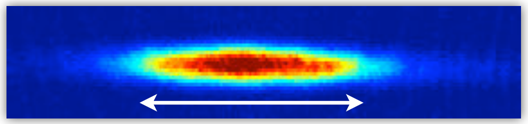
Lattice: $P_c=76$ mW, $\lambda=780$ nm,
$\Delta/2\pi=-21$ GHz $w_0=350\,\mu m$

SiN membrane: $l=0.5$ mm, $t=50$ nm, $\omega_m/2\pi=250$ kHz,
$m_m=1\times10^{-11}$ kg, $Q=1.5\times10^{6}$@300 K, $R=0.5$

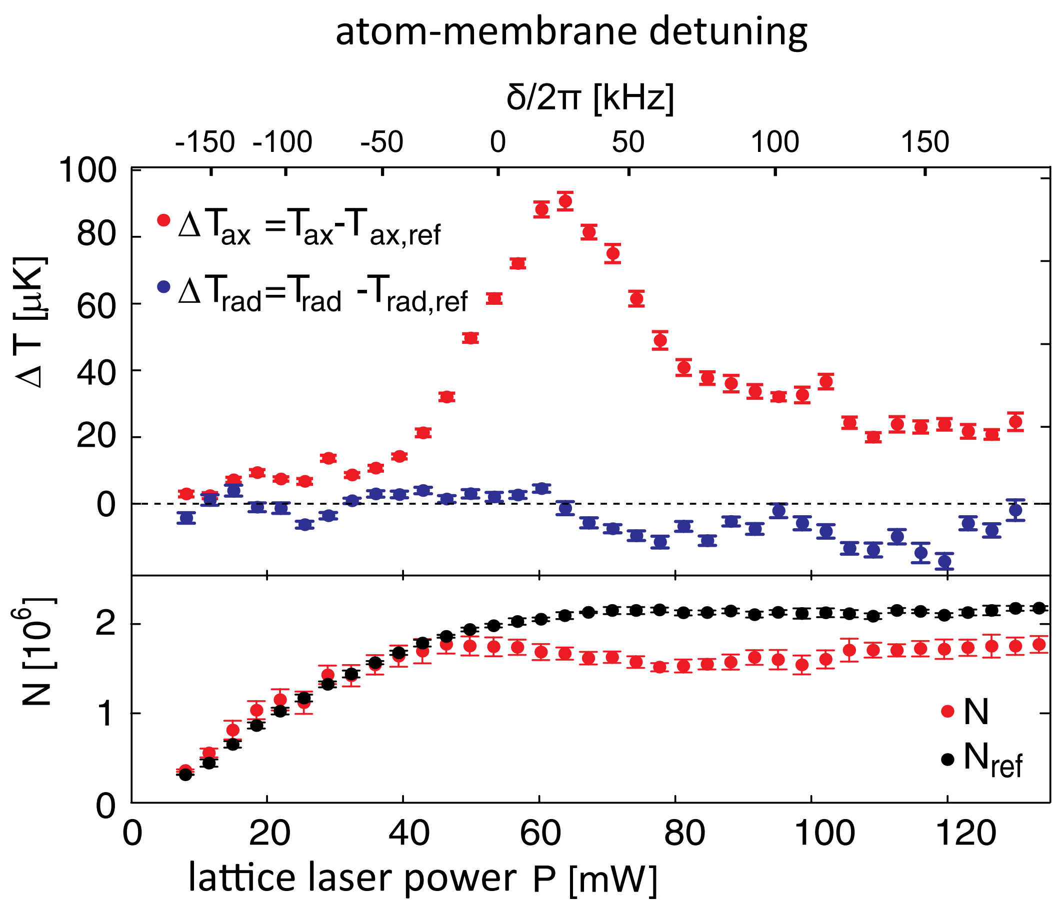
Effect of membrane vibrations on atoms



(amplitude 330 pm)

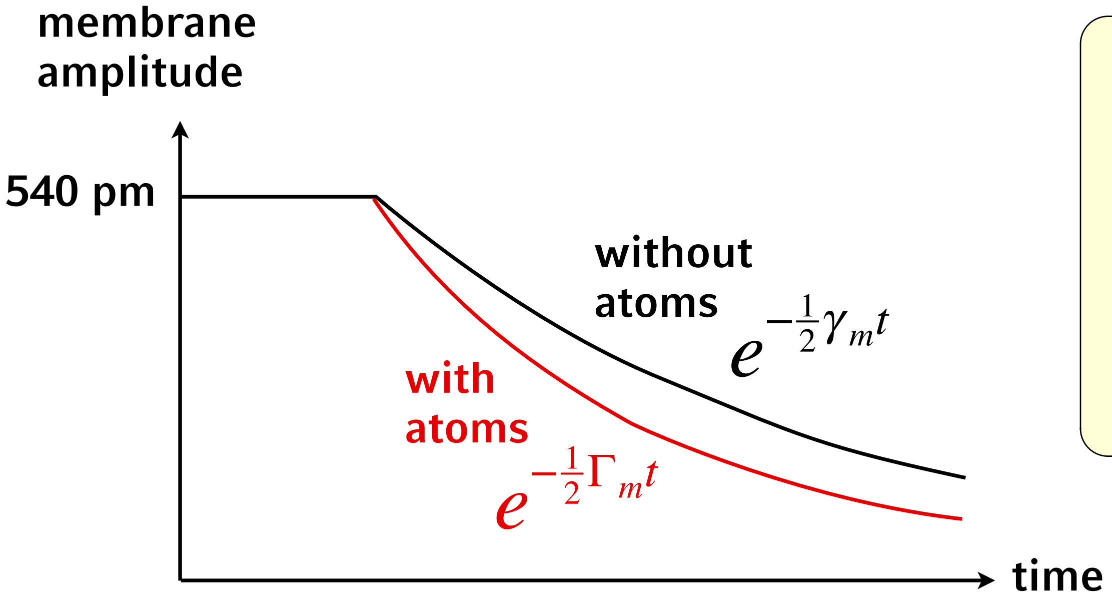


measure cloud width
after time-of-flight
→ temperature increase ΔT



shift and shape of resonance due to
- finite temperature of atoms
- evaporation

Back-action of atoms onto membrane



Membrane ringdown measurements

identical sequence with/without atoms (except MOT detuning)

decay rate without atoms: $\gamma_m = \dfrac{\omega_m}{Q}$

decay rate with atoms in lattice: $\Gamma_m = \gamma_m + \dfrac{4|R|^2 g^2}{\gamma_{at}}$

(atoms laser cooled with rate $\gamma_{at} \gg g$)

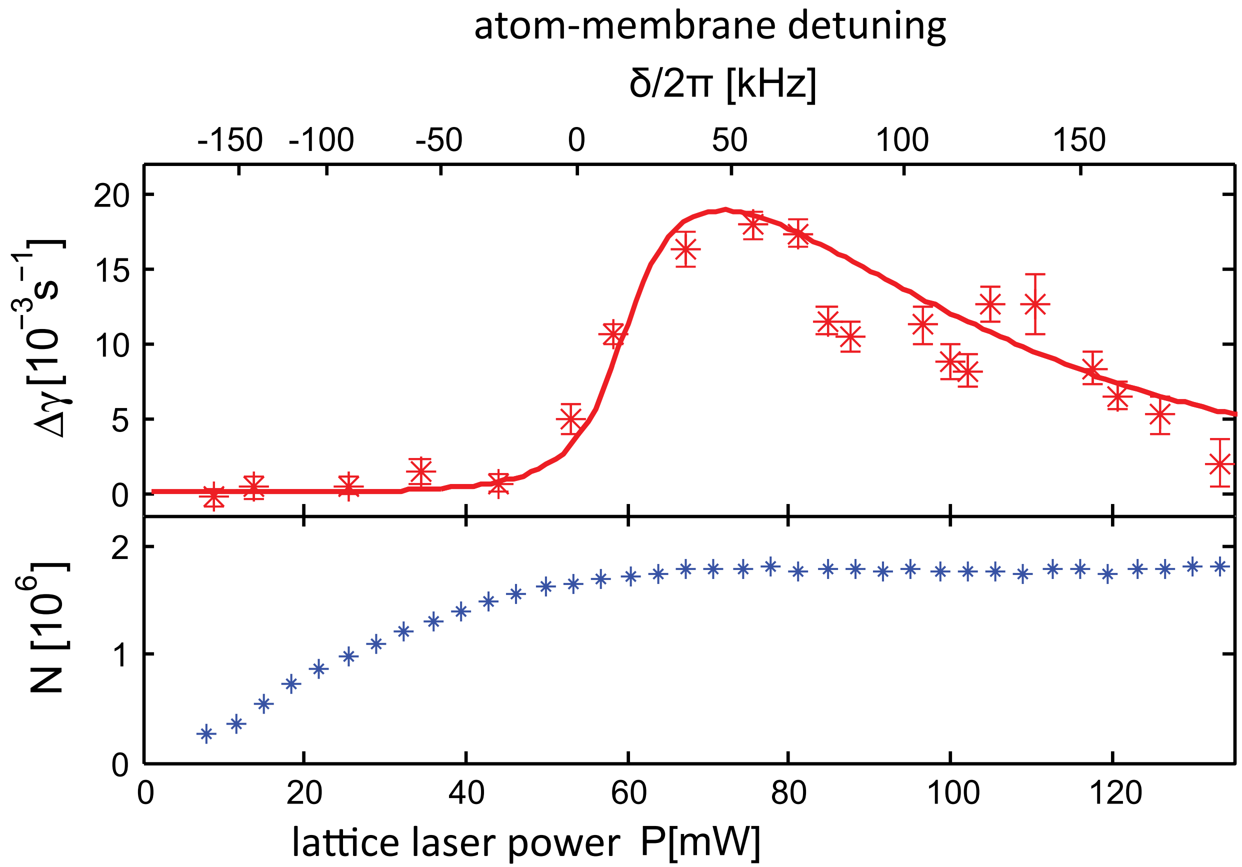
Back-action of atoms onto membrane

$$\Delta\gamma = \Gamma_m - \gamma_m$$

difference in measured membrane decay rates with/without atoms

measured on resonance:
$\Delta\gamma = 0.018\,s^{-1}$

predicted by simple theory:
$\Delta\gamma = 0.023\,s^{-1}$



Resonance shape explained by theory for thermal ensemble of atoms in lattice

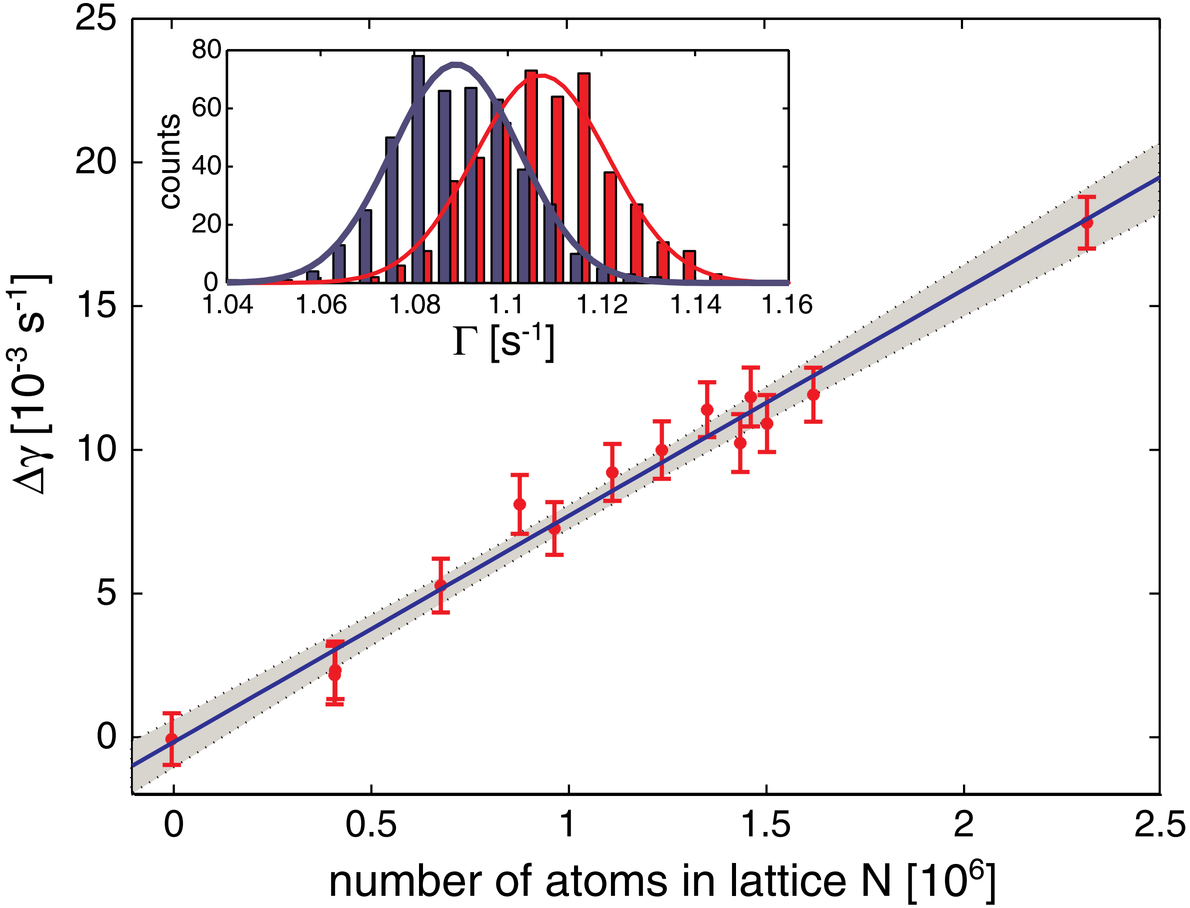
S. Camerer, M. Korppi et al., Phys. Rev. Lett. **107**, 223001 (2011).

Scaling of back-action with atom number

measurement
on resonance:
$\omega_{at} = \omega_m$

expect linear dependence on N:

$$\Delta\gamma = \frac{4|R|^2 g_0^2 N}{\gamma_{at}}$$



Atoms influence membrane, even though $m_{eff}/Nm_{at} = 3\times10^7$!

S. Camerer, M. Korppi et al., Phys. Rev. Lett. **107**, 223001 (2011).

Possible technical improvements

transverse 2D lattice → suppress heating + loss due to spont. emission

blue-detuned coupling lattice → suppress heating and loss

larger beam waist → more atoms, smaller $\Delta\omega_{at}$

Raman sideband cooling → colder atoms

Raman sideband ground state cooling of $N=3\times10^8$ atoms in near-resonant lattice has been demonstrated: A. Kerman et al., PRL 84, 439 (2000).

Cryogenic, optimized setup (2 K):

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

$g=40\,\text{kHz}$, $\gamma_{at}=20\,\text{kHz}$, $\Gamma_{th}=24\,\text{kHz}$,
$\Gamma_{rp}=52\,\text{Hz}$, $\gamma_h=16\,\text{kHz}$, $\Delta\omega_{at}/2\pi=24\,\text{kHz}$

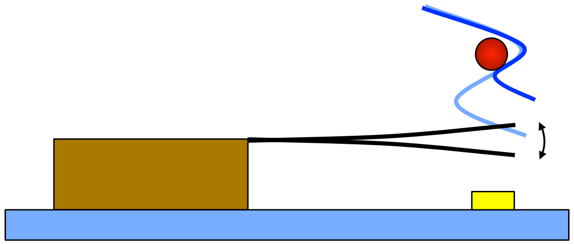
$\to g \geq \gamma_{at}, \Gamma_{th}, \Gamma_{rp}, \gamma_h$

cooling factor:
$$\Gamma_c/\gamma_m \simeq 2\times10^4$$

smaller membrane: $l=150\,\mu\text{m}$, $t=50\,\text{nm}$,
$\omega_m/2\pi=0.9\,\text{MHz}$, $M=8\times10^{-13}\,\text{kg}$, $Q=10^7$

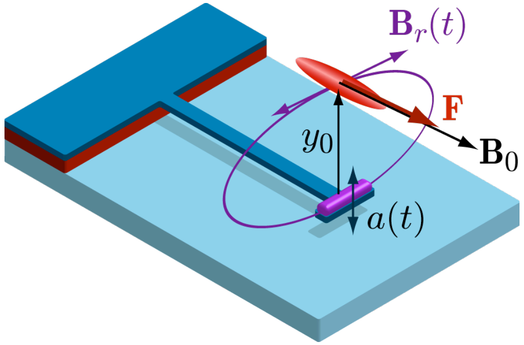
atoms and lattice: $N=3\times10^8$, $P=7\,\text{mW}$,
$\Delta/2\pi=1.0\,\text{GHz}$, $w_0=230\,\mu\text{m}$, $\gamma_h=16\,\text{kHz}$

Coupling mechanisms



coupling via atom-surface forces

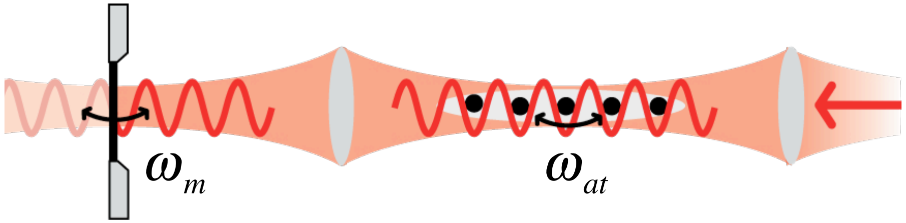
experiment:
D. Hunger et al., PRL 104, 143002 (2010).



magnetic coupling to atomic spin

theory:
P. Treutlein et al., PRL 99, 140403 (2007).

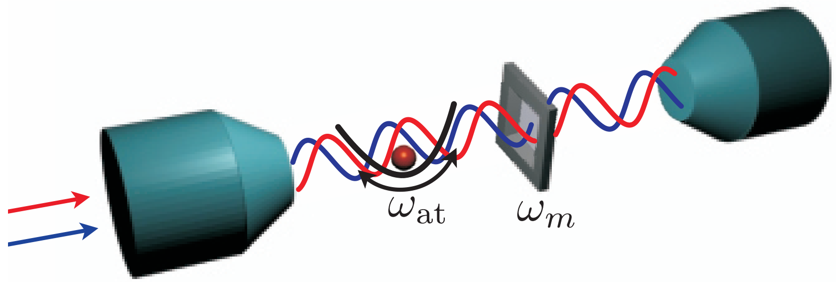
related experiment (room-temperature atoms):
Y.-J. Wang et al., PRL 97, 227602 (2006).



coupling via optical lattice

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

experiment: S. Camerer, M. Korppi et al.,
PRL 107, 223001 (2011).



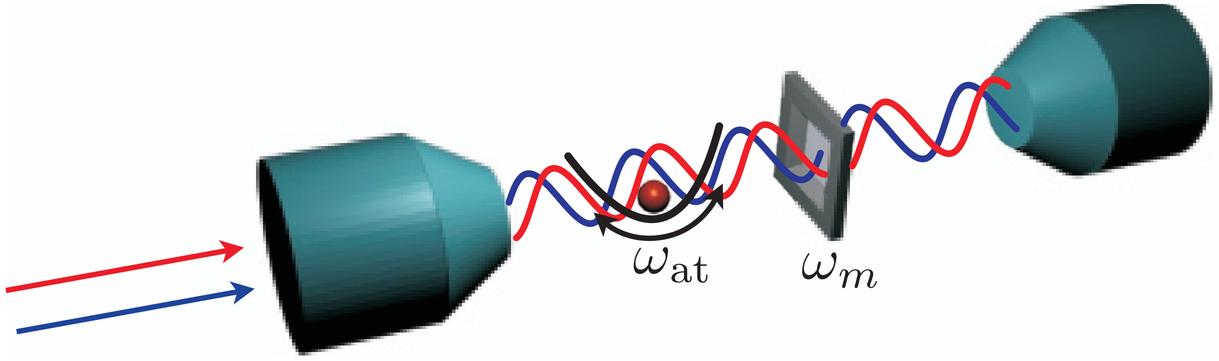
cavity-mediated coupling

theory:
K. Hammerer et al., PRL 103, 063005 (2009).

related theory: Meystre, Ritsch, Sun, Nori, ...

Cavity-mediated coupling

K. Hammerer et al., PRL 103, 063005 (2009). Innsbruck/Basel/Boulder/Caltech



motion of single atom **micromechanical membrane**

AC Stark shift g_{at} g_m optomechanical coupling
(Harris group/Yale)

quantized light field in cavity

- cavity mediates effective interaction (after adiab. elimination):

$$H = \omega_m a_m^\dagger a_m + \omega_{at} a_{at}^\dagger a_{at} - G(a_{at} + a_{at}^\dagger)(a_m + a_m^\dagger) \qquad G \simeq \frac{g_{at} g_m}{\Delta}$$

- high finesse - strong enhancement
- strong atom-membrane coupling for realistic experimental parameters

Parameters for strong coupling

K. Hammerer et al., PRL 103, 063005 (2009).

Effective atom-membrane coupling

$$G = 2\pi \times 45 \text{ kHz} \approx 10 \times \Gamma_{at}, \Gamma_c, \Gamma_m$$

Decoherence mechanisms

- spontaneous emission of atom, Γ_{at}
- cavity decay, Γ_c
- membrane heating due to thermal bath, absorption of lasers, Γ_m

System parameters

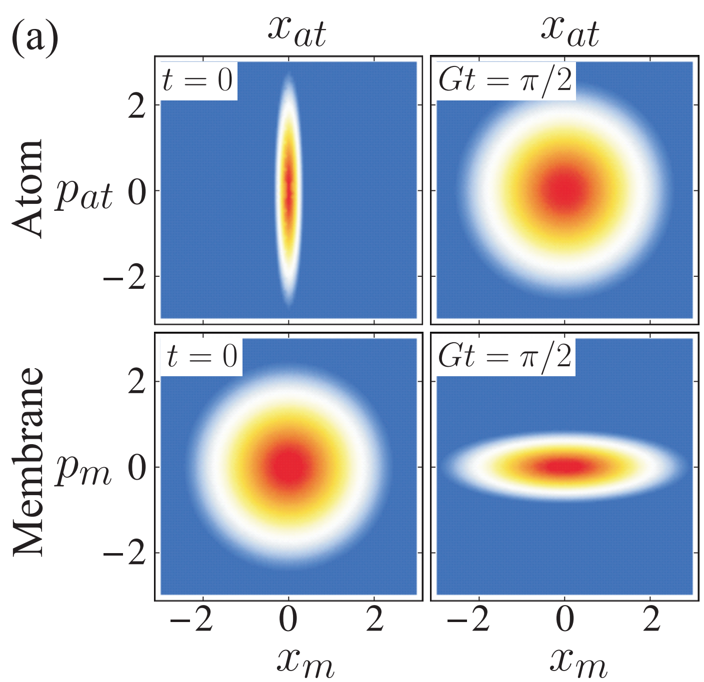
Cs atom: $\lambda = 852\,\text{nm} / 895\,\text{nm}$

Membrane: $l = 100\,\mu\text{m}$, $t = 50\,\text{nm}$,
$\omega_m/2\pi = 1.3\,\text{MHz}$, $m_{eff} = 4\times10^{-13}\,\text{kg}$, $Q = 10^7$,
$T = 2.5\,\text{K}$, $r = 0.45$, $\text{Im}(n) = 1.5\times10^{-5}$

Cavity: $F = 2\times10^5$, $L = 50\,\mu\text{m}$,
$w_0 = 10\,\mu\text{m}$, $P_c = 850\,\mu\text{W}$, $C = 140$

$$\frac{m}{M} = 6\times10^{-13}$$

Transfer of squeezed state from atom to membrane



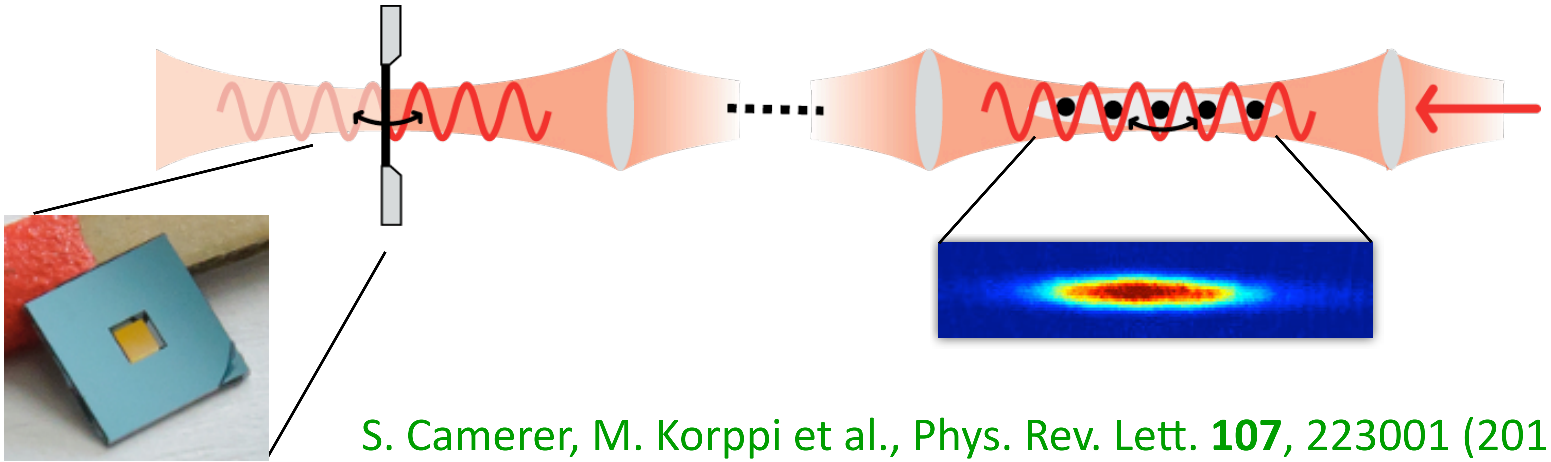
(membrane mode precooled to $n_{th} = 5$)

Summary and Outlook

- realized optomechanical interface between atoms and membrane
- observed back-action of atomic motion onto membrane
- sympathetic damping of membrane vibrations with laser-cooled atoms

With future improvements (new setup):

- strong sympathetic cooling of membrane with atoms
- normal mode splitting
- coherent dynamics



S. Camerer, M. Korppi et al., Phys. Rev. Lett. **107**, 223001 (2011).

The Basel ultracold atoms team

Post-doc and PhD positions available!

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