Realization of an optomechanical interface between ultracold atoms and a membrane

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Realization of an optomechanical interface between ultracold atoms and a membrane

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We have realized a hybrid optomechanical system by coupling ultracold atoms to a micromechanical membrane. The atoms are trapped in an optical lattice, which is formed by retro-reflection of a laser beam from the membrane surface. In this setup, the lattice laser light mediates an optomechanical coupling between membrane vibrations and atomic center-of-mass motion. We observe both the effect of the membrane vibrations onto the atoms as well as the backaction of the atomic motion onto the membrane. By coupling the membrane to laser-cooled atoms, we engineer the dissipation rate of the membrane. Our observations agree quantitatively with a simple model.

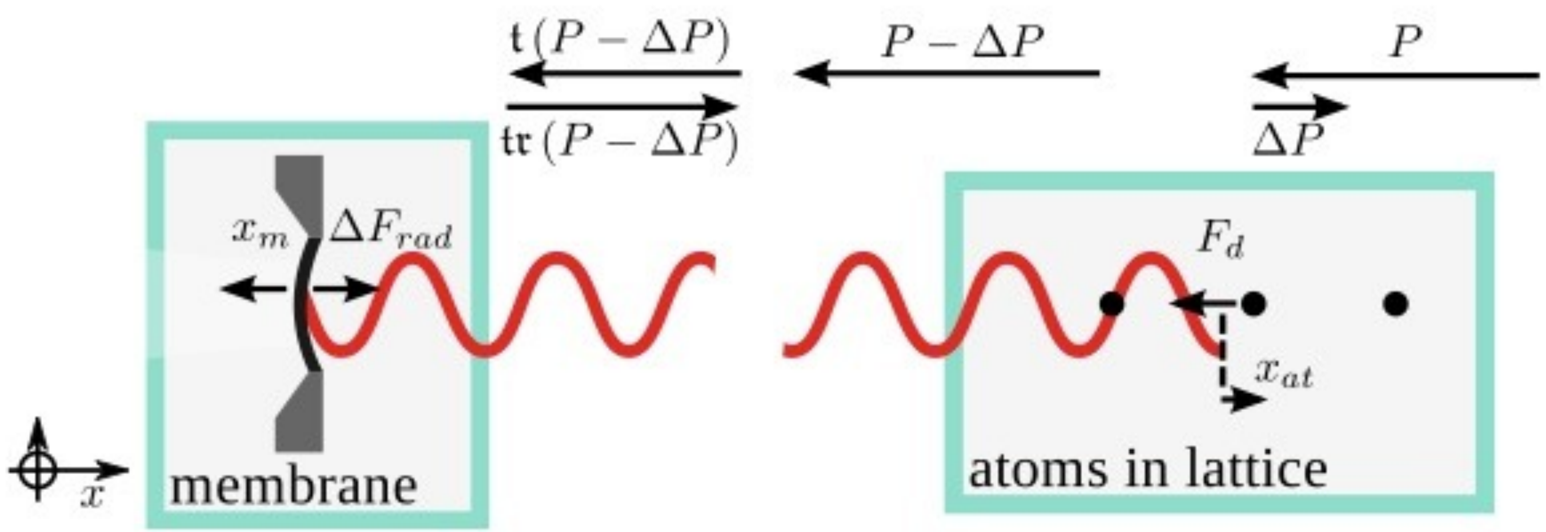
Outline

- Introduction
- Theory Model
- Experimental Setup
- Results
- Conclusion

Introduction

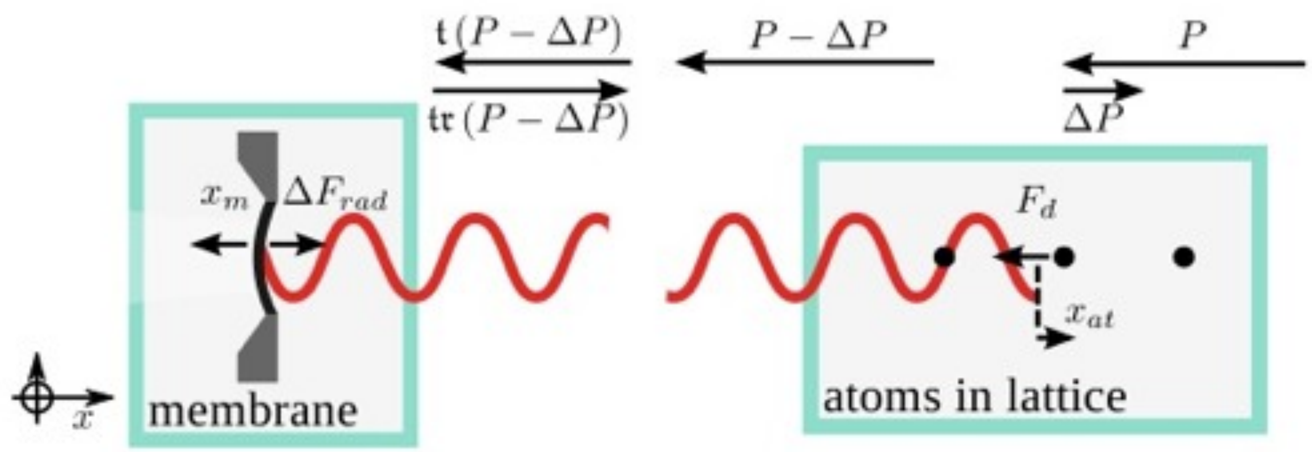
- Optomechanics:
  light forces (radiation pressure,dipole force) are exploited for cooling and control of the vibrations of a mechanical oscillator
- Applications:
  precise force sensing, studies of Quantum Physics at macroscopic scales

Theory



$\mathfrak{t}(P - \Delta P)$
$\mathfrak{tr}(P - \Delta P)$
$P - \Delta P$
P
ΔP
x_m
ΔF_{rad}
F_d
x_{at}
x
membrane
atoms in lattice

Effect of Membrane on Atoms

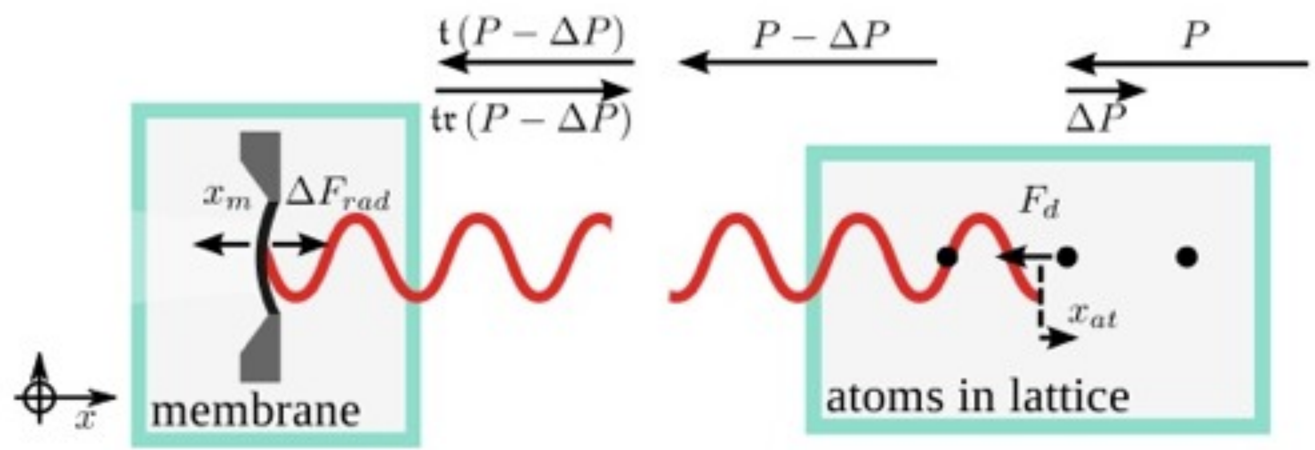


- Displacement of Membrane: x_m

$$F = m\omega_{at}^2 x_m$$

$$F_{com} = NF$$

Effects of COM motion on Membrane



- an atom displaced by: x_{at}

$$F_d = -m\omega_{at}^2 x_{at}$$

momentum kick : $\pm 2\hbar k$

$\rightarrow$ force $= \pm 2\hbar k\Gamma = F_d$

power modulation : $\Delta P = \hbar\omega n$

$(\partial_t \rightarrow \Gamma)$

$\rightarrow \Delta P = \hbar c k N\Gamma = cN(\hbar k\Gamma)$

$= \frac{cN}{2} F_d$

(Since reflectivity : r

and $P_{ower} = F . v$!)

$\Rightarrow \Delta F_d = r \frac{2}{c} \Delta P$

$\Rightarrow \Delta F_d = N F_d$

Equations of Motion

$$\begin{aligned}
\dot{p}_{at} &= -\gamma_{at} p_{at} - N m \omega_{at}^2 x_{at} + N m \omega_{at}^2 x_m \\
\dot{x}_{at} &= p_{at}/Nm \\
\dot{p}_m &= -\gamma_m p_m - M \omega_m^2 x_m + \mathfrak{rt} N m \omega_{at}^2 x_{at} \\
\dot{x}_m &= p_m/M
\end{aligned}$$

$$a = e^{i\omega_m t}\sqrt{Nm\omega_{at}/2\hbar}\,(x_{at} + i p_{at}/Nm\omega_{at})$$

$$b = e^{i\omega_m t}\sqrt{M\omega_m/2\hbar}\,(x_m + i p_m/M\omega_m)$$

Equations of Motion

$$\dot{a} \;=\; -i\delta a - (\gamma_{at}/2)a + igb,$$
$$\dot{b} \;=\; -(\gamma_m/2)b + i\mathfrak{r}\mathfrak{t}ga.$$

$$g \;=\; \frac{\omega_{at}}{2}\sqrt{\frac{Nm\omega_{at}}{M\omega_m}}$$

$$\delta = \omega_{at} - \omega_m$$

$$\gamma_{at} \;=\; \gamma_c + \gamma_\phi$$

Solution

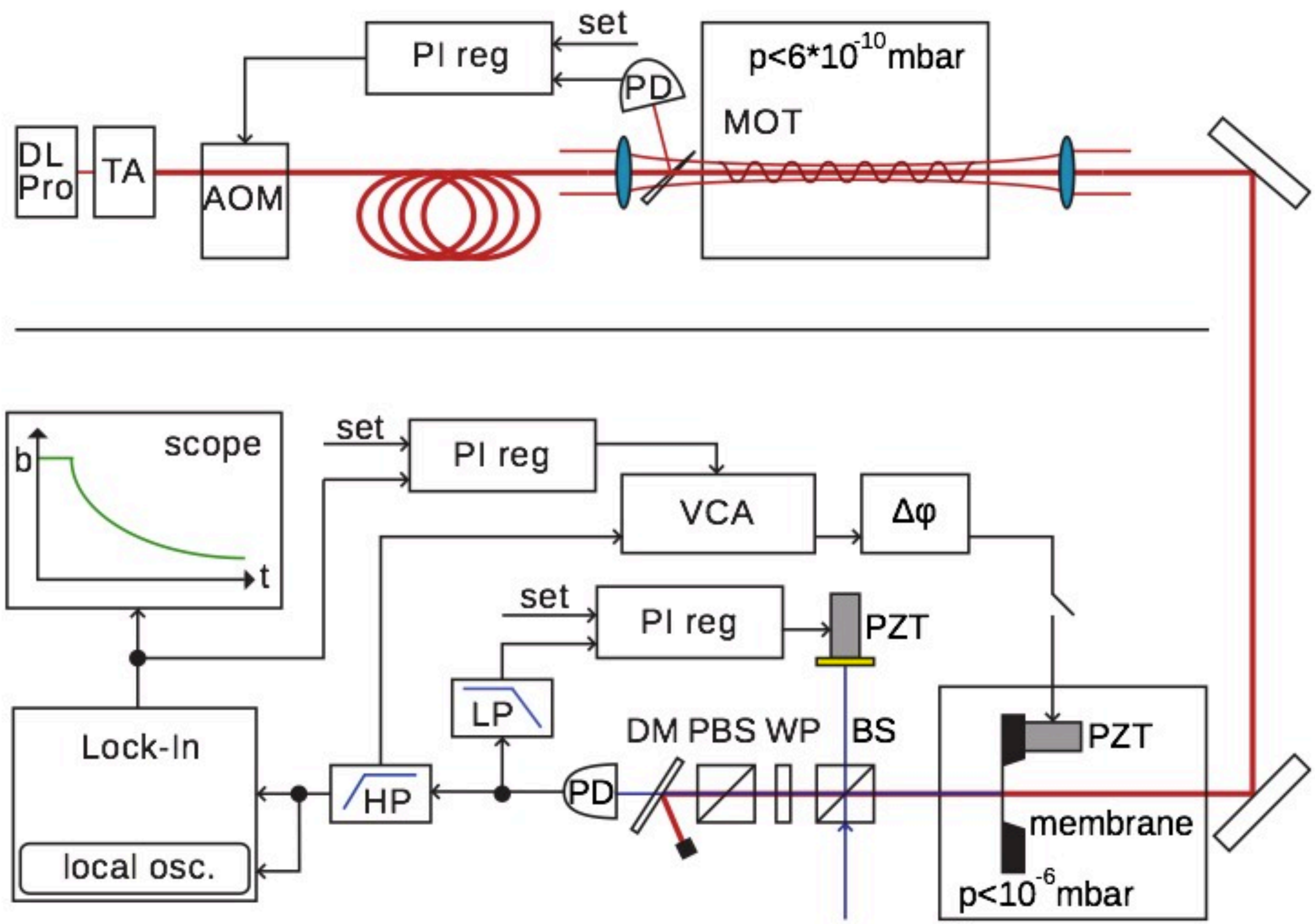
$$\gamma_{at} \gg g, \gamma_m$$

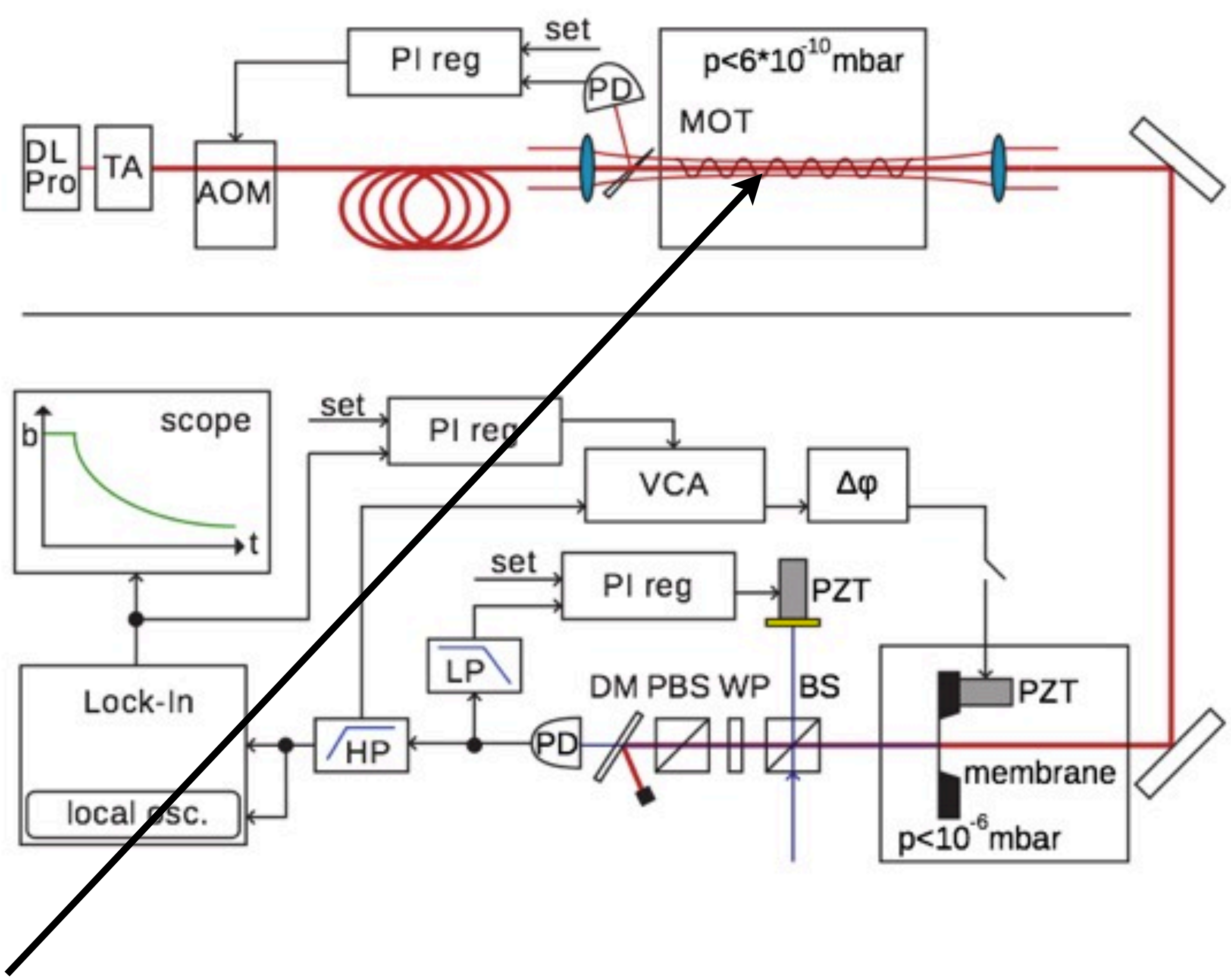
$$(\dot{a} \simeq 0)$$

$$|b(t)|^2 = |b(0)|^2 \exp(-\Gamma t)$$

$$\Gamma = \gamma_m + \gamma_{at} \frac{g^2 \mathfrak{rt}}{\delta^2 + (\gamma_{at}/2)^2}$$

Experimental Setup





$$\Delta = 2\pi \times 21GHz$$

$$D2\,{}^{87}Rb(F=2 \longleftrightarrow F'=3)$$

$$P = 0...140mW$$

$$w_0 = 350 \pm 30\mu m$$
$$for P = 76mW$$

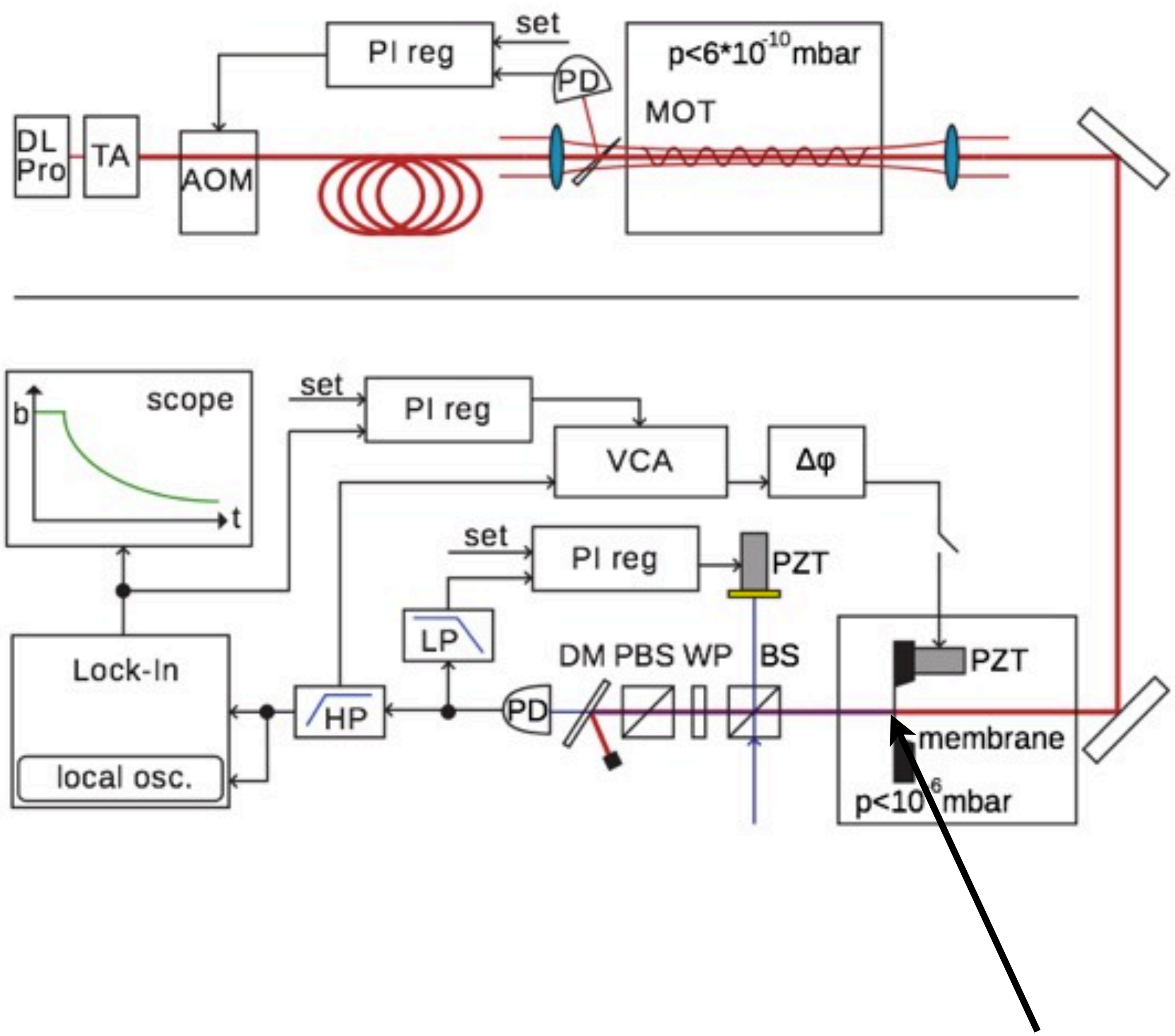
$$U = k_B \times 290\mu K$$

$$\omega_{at} = 2\pi \times 305KHz$$

$$MOT$$

$$N = 2 \times 10^6$$

$$T = 100\mu K$$



SiN

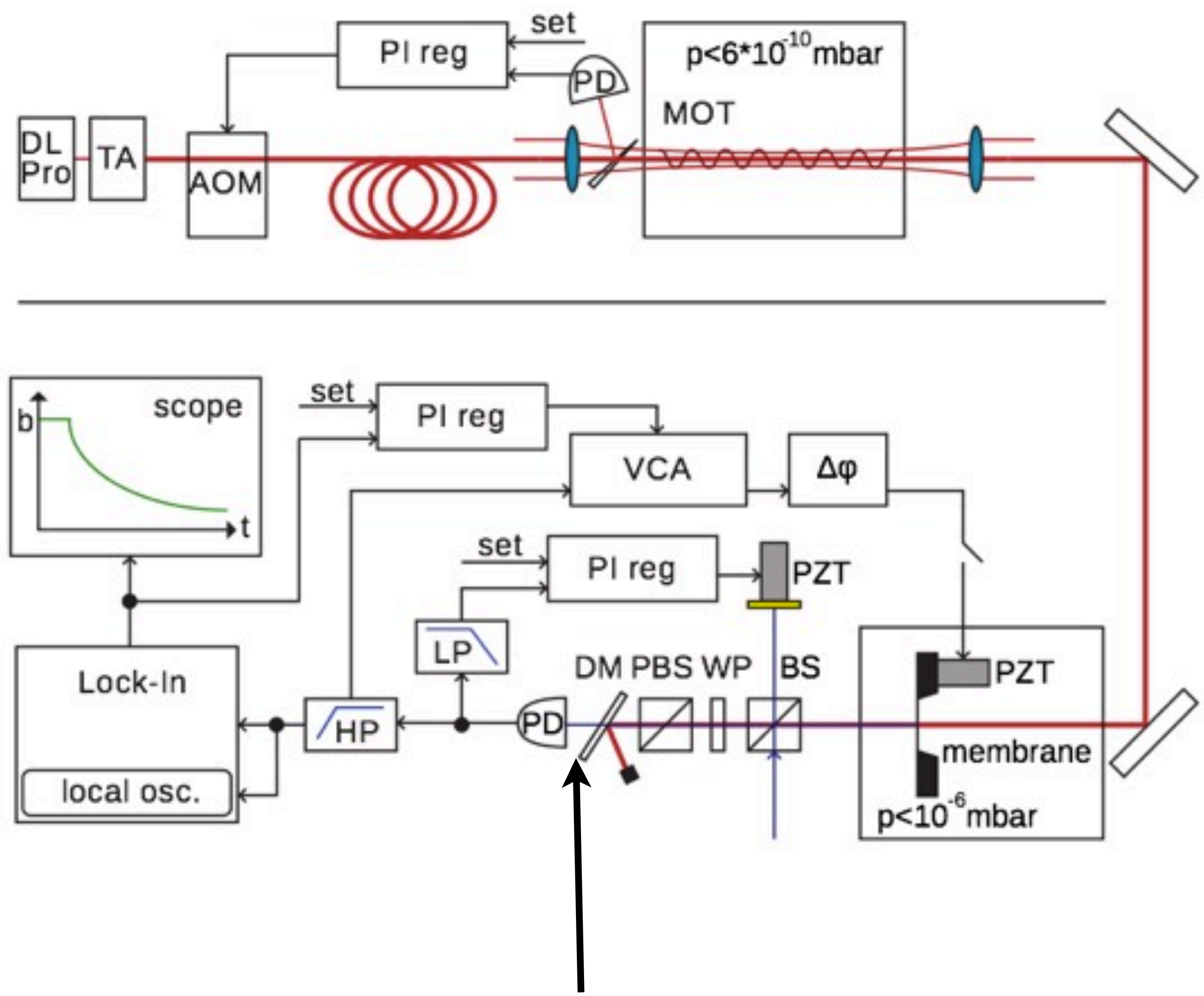
$tensile \quad Stress: 120 MPa$

$0.5mm \times 0.5mm \times 50nm$

$r = 0.28 @ \lambda = 780nm$

$\omega_m = 2\pi \times 272 kHz$

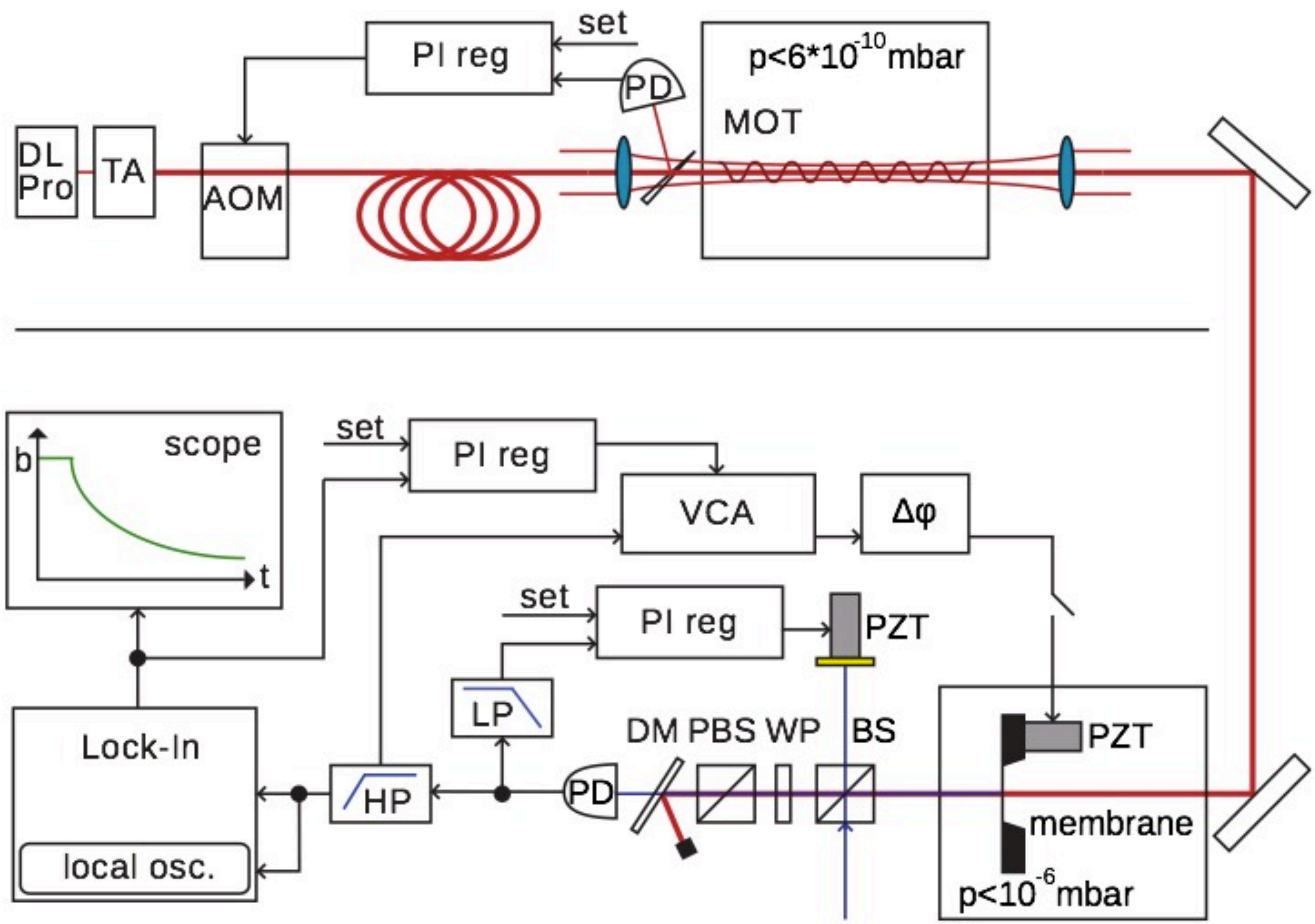
$M = 10^{-11} kg$



$$Michelson \quad interferometer$$

$$Position \quad sensitivity: 3\times10^{-14}\, m/\sqrt{Hz}$$

Measurements!



Results

Backaction of atoms on membrane

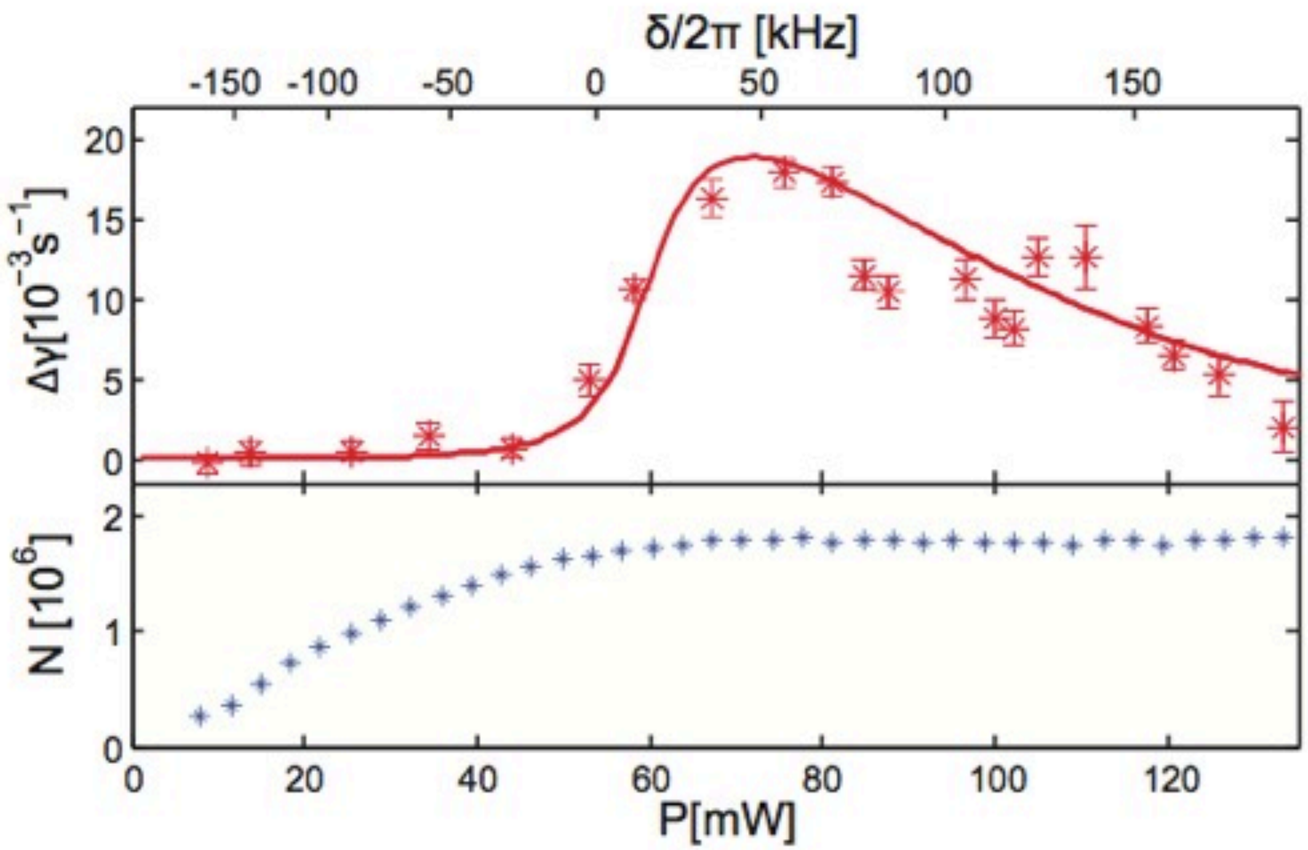


FIG. 3: Backaction of laser-cooled atoms onto the membrane. Top: measured additional membrane dissipation rate $\Delta\gamma = \Gamma - \gamma_m$ due to coupling to atoms as a function of P. The rates Γ and γ_m are extracted from exponential fits to averaged decay curves (2×455 experimental runs per datapoint). Solid line: theory for a thermal ensemble in the lattice (see text). Bottom: lattice atom number in the experiment.

dependance on number of atoms

$$g = \frac{\omega_{at}}{2}\sqrt{\frac{N m \omega_{at}}{M \omega_m}}$$

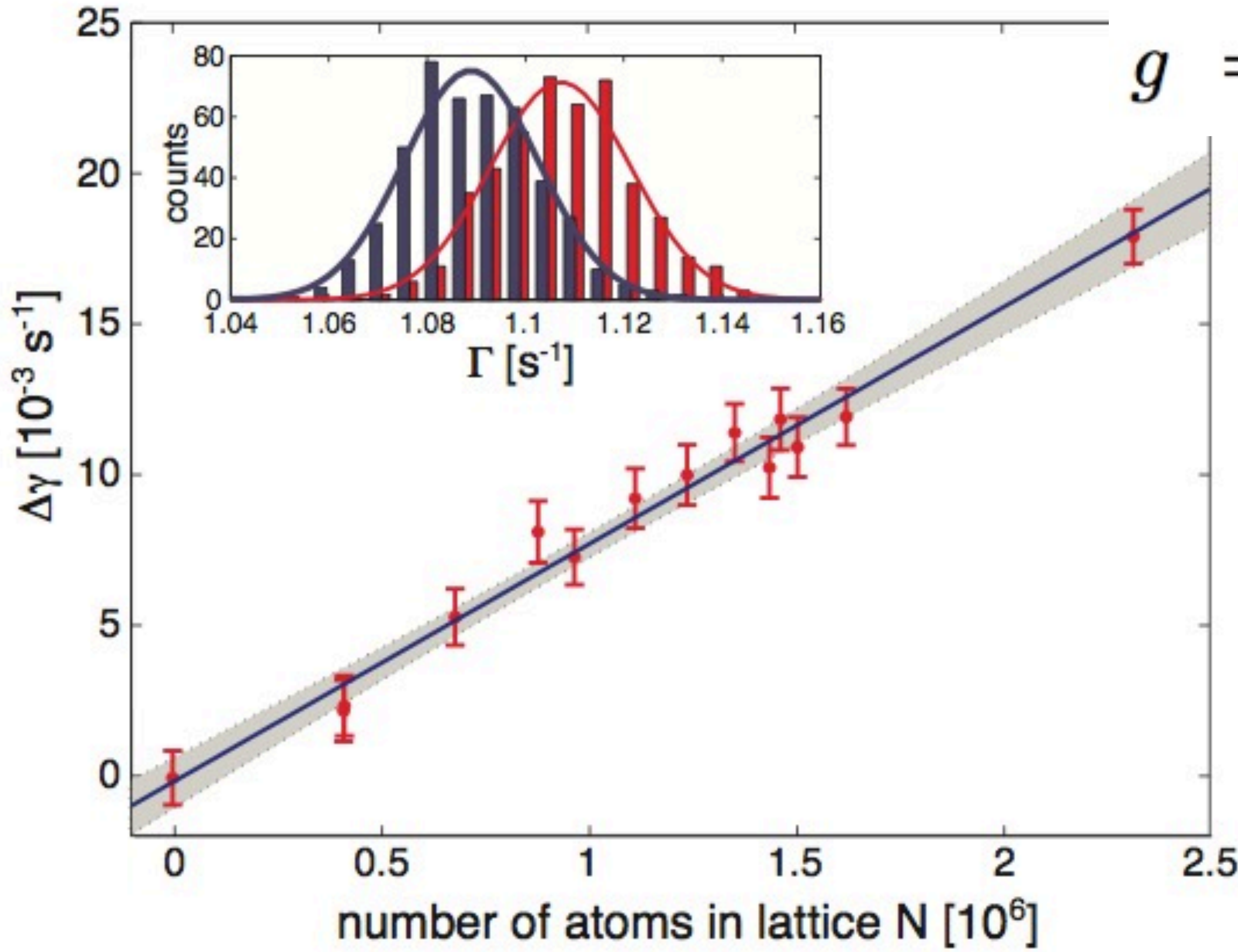


FIG. 4: Measured additional membrane dissipation $\Delta\gamma$ as a function of atom number for resonant coupling ($P = 76$ mW). The blue line is a linear fit. The observed dependence agrees well with theory. Inset: histogram of measurements of Γ for $N = 2.3 \times 10^6$ (red) and $N = 0$ (blue).

$$\gamma_{at}\frac{g^2 \mathfrak{rt}}{\delta^2 + (\gamma_{at}/2)^2}$$

Effect of Membrane on atoms

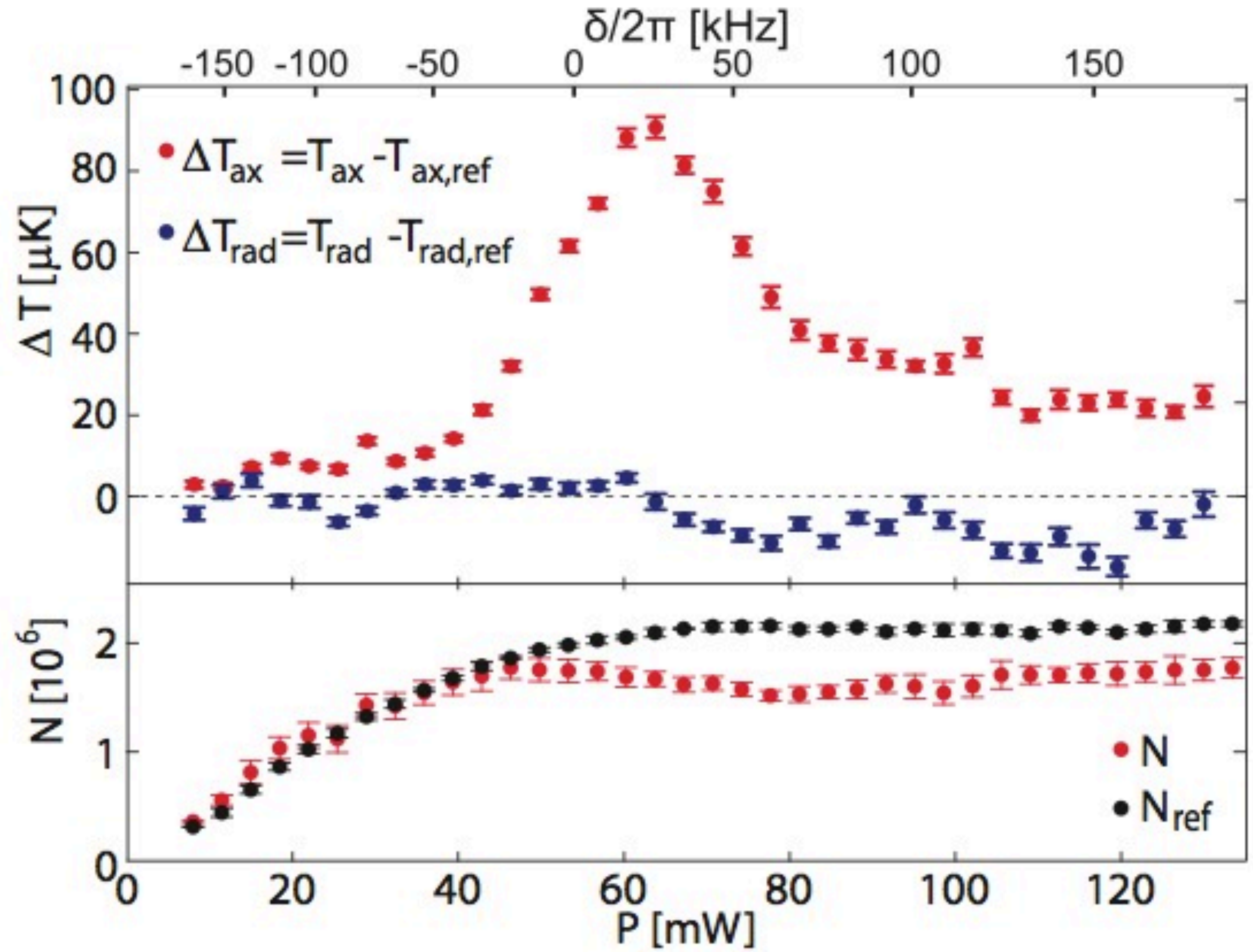


FIG. 5: Effect of membrane vibrations on the atoms when laser cooling is off. Top: temperature increase of the atoms along the lattice ΔT_{ax} and in the radial direction ΔT_{rad} for a driven membrane with respect to reference measurements for an undriven membrane. Bottom: dependence of lattice atom number on P, for driven and undriven membrane.

Conclusion

- Effect of the Membrane on Atom and Atoms on Membrane is Observed
- By using a more sophisticated model the broadening and shift on resonance is studied
- Further investigations:
  Sideband cooling
  3D Lattice

Thanks!

(Special thanks to Connor for not sleeping!)