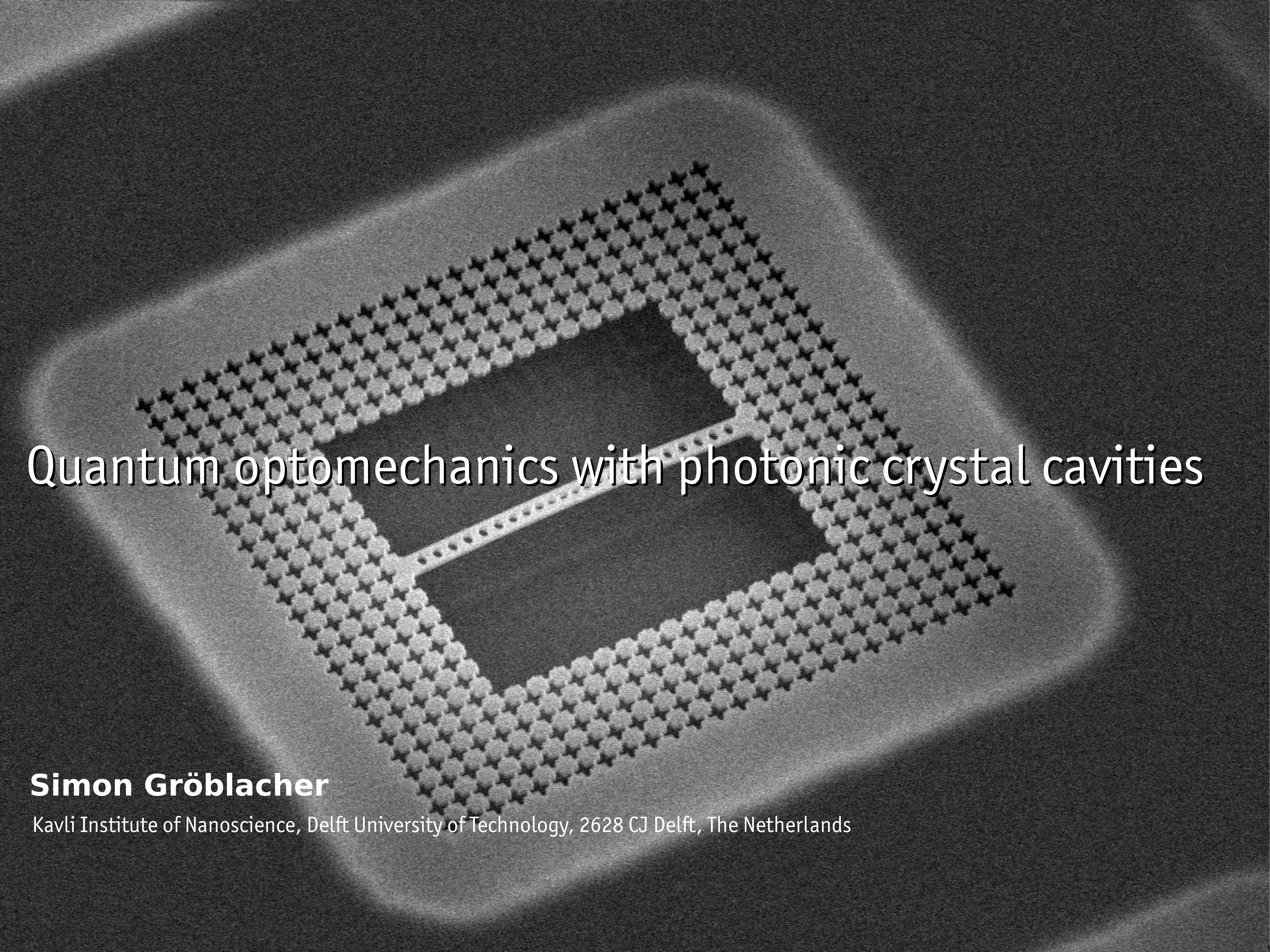


# Quantum optomechanics with photonic crystal cavities

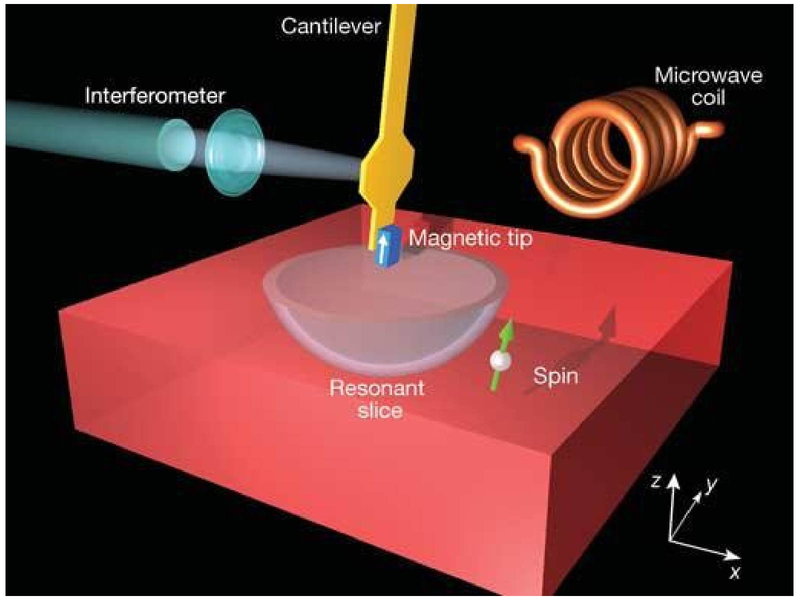
**Simon Gröblacher**

Kavli Institute of Nanoscience, Delft University of Technology, 2628 CJ Delft, The Netherlands

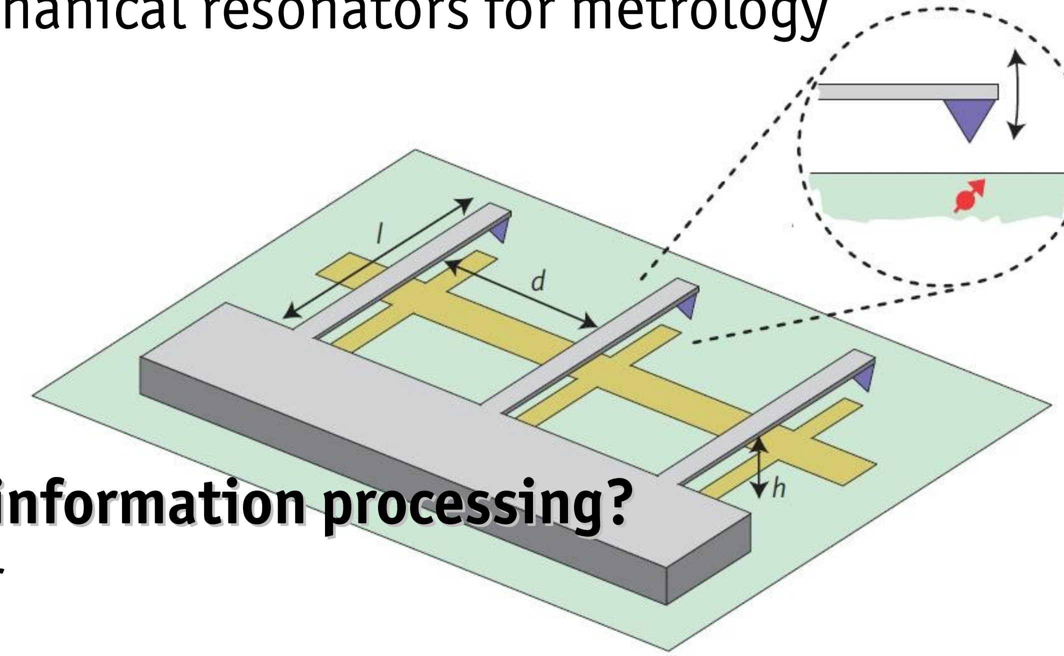
# Macroscopic quantum physics

**Quantum behaviour of macroscopic systems**

- **Is there a size- / mass-limit in quantum physics?**
  quantum physics in a new parameter regime of massive, macroscopic systems




- **What are the quantum limits in (mechanical) sensing?**
  quantum states of nanomechanical resonators for metrology

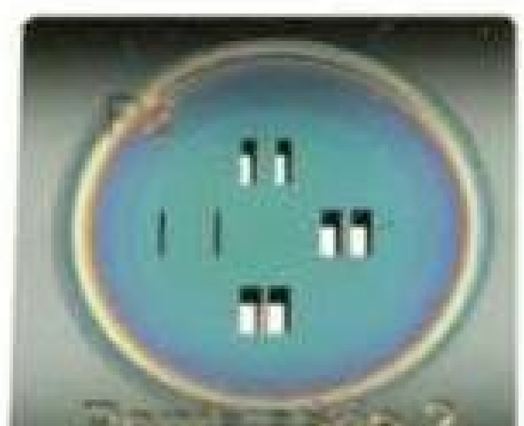



- **Can mechanical systems serve as platforms for quantum information processing?**
  functionalized mechanical systems as quantum transducer

# Opto-mechanical systems

**cm** → **mm**

MIT

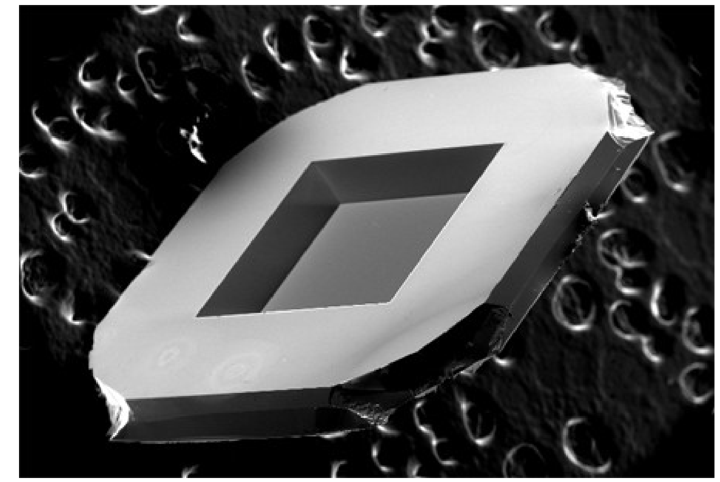


$\omega_m$ … mechanical frequency

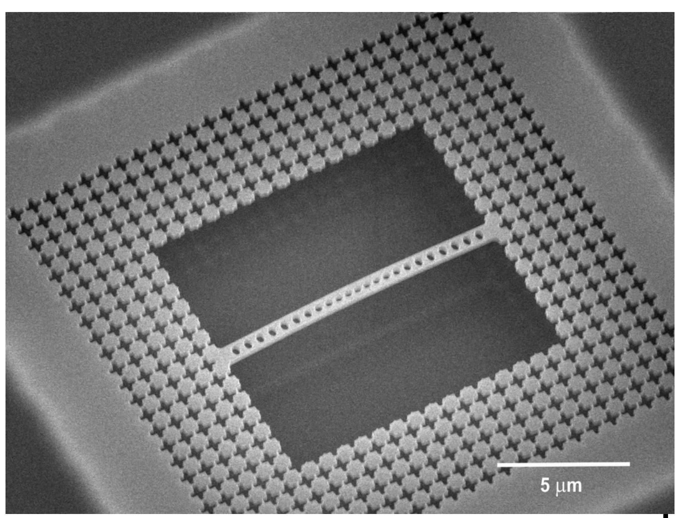
R … optical reflectivity

Q … mechanical quality

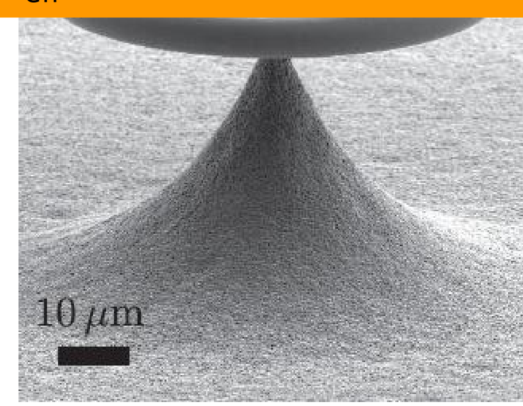
$m_{eff}$ … (effective) mass



Yale




Caltech

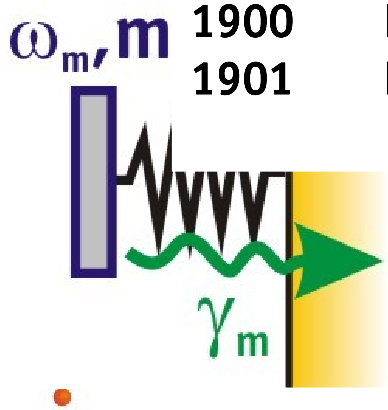



Lausanne / Caltech / Brisbane

Vienna

**μm** ← **mm**

# Radiation pressure

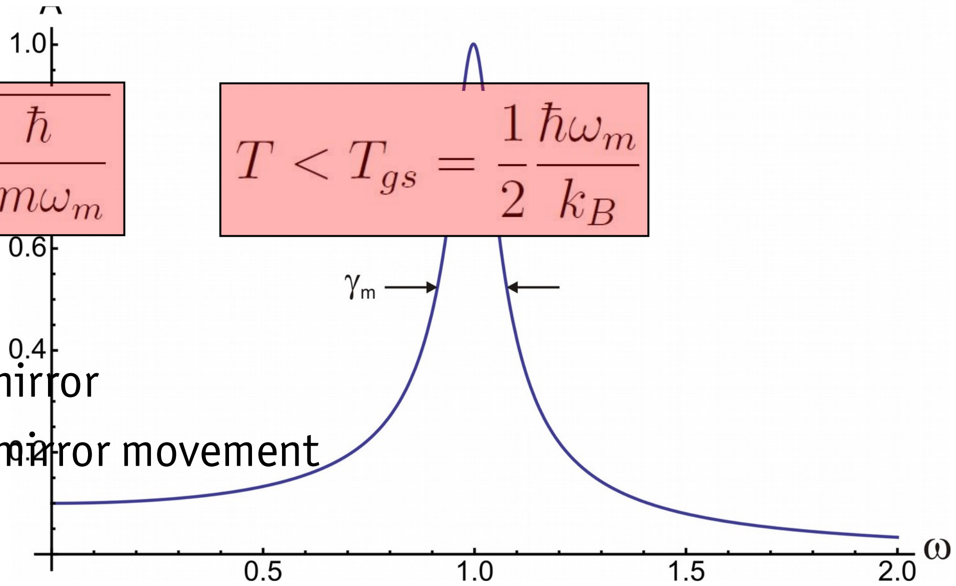


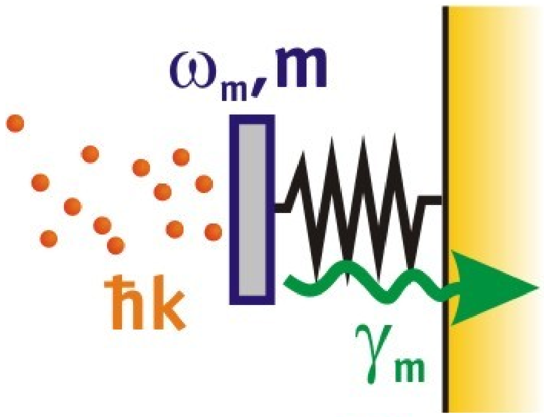

**1900** Lebedev, „Untersuchungen über die Druckkraft des Lichts," Ann. Phys. (1900)

**1901** Nichols, Hull: „A preliminary communication on the pressure of heat and light radiation" Phys. Rev. 13, 307 (1901)

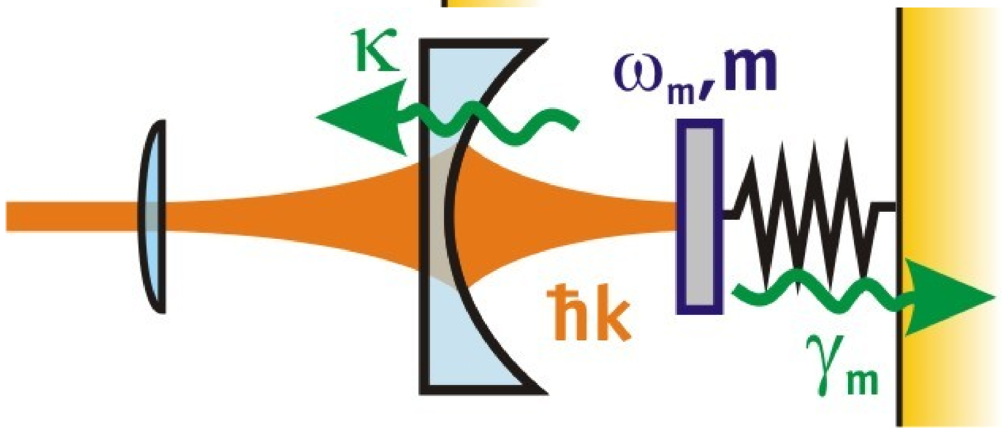
$$x_{zp} = \sqrt{\frac{\hbar}{2m\omega_m}}$$

$$T < T_{gs} = \frac{1}{2}\frac{\hbar\omega_m}{k_B}$$



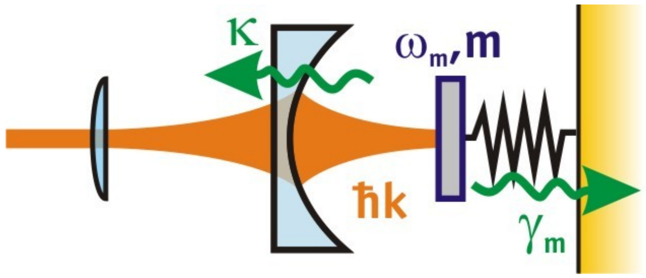




- intensity dependent displacement of mirror
- Doppler-shift of reflected light due to mirror movement




… Kerr-like interaction

# Radiation pressure




$$\tilde{H} = \hbar\omega_c g_0 \left(b + b^\dagger\right) a^\dagger a$$

with coupling rate $$g_0 = x_{zpf}\frac{\partial\omega_c}{\partial x}$$

for FP cavity $$g_0 = \frac{\omega_c}{L}x_{zpf}$$

$$g = g_0 \cdot \alpha_s = g_0\sqrt{n_c} \gg g_0$$

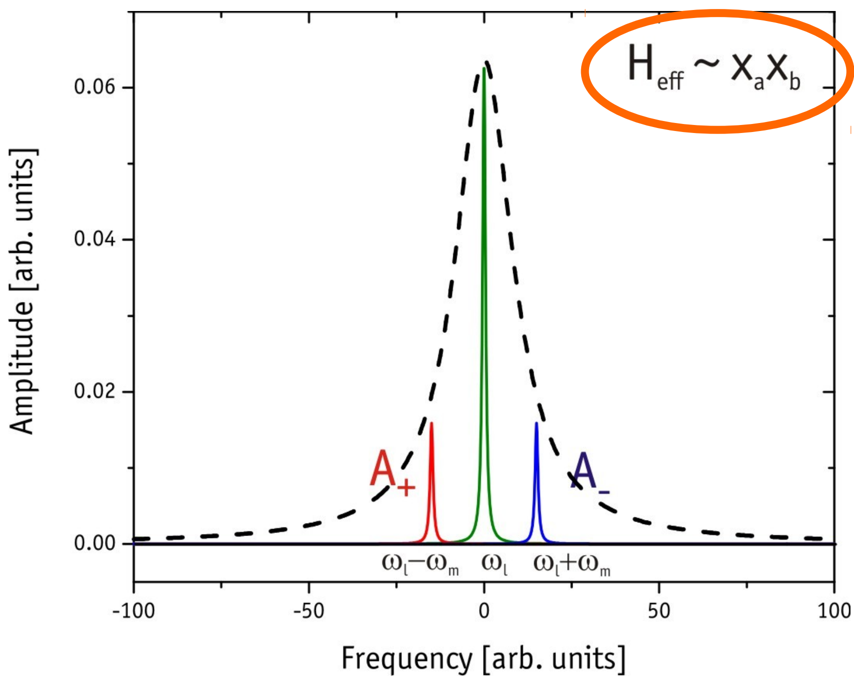
rotating wave approximation:

$$H_{RP} = \hbar g \left(\underline{abe^{-i(\Delta+\omega_m)t} + a^\dagger b^\dagger e^{i(\Delta+\omega_m)t}}\right) + \hbar g \left(\underline{ab^\dagger e^{-i(\Delta-\omega_m)t} + a^\dagger b e^{i(\Delta-\omega_m)t}}\right)$$

$$\propto ab + a^\dagger b^\dagger \qquad \boxed{\Delta = -\omega_m}$$

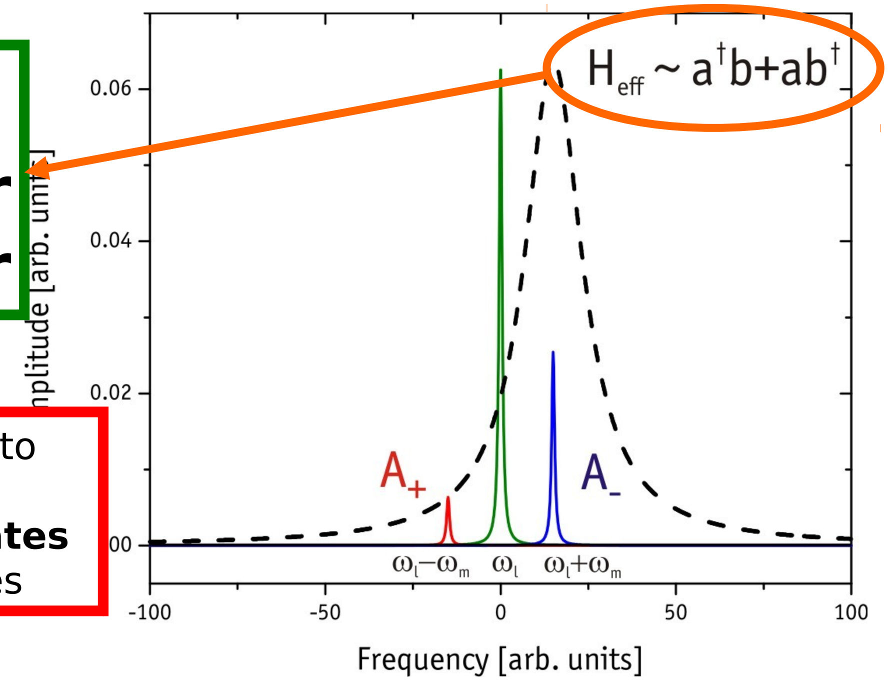
$$\propto ab^\dagger + a^\dagger b \qquad \boxed{\Delta = +\omega_m}$$

# Quantum opto-mechanics toolbox




- **QND / Kerr**
- **Beamsplitter**
- **TM Squeezer**

**quantum optics toolbox** to prepare and control **mechanical quantum states** via photonic quantum states




* Strongly coupled optomechanics
* Optomechanical entanglement / teleportation
* Ground-state cooling
* Non-classical mechanical states (fock, cat, squeezed, ...)
* Squeezing of light
* Wavelength conversion
* Radiation pressure backaction
* Standard quantum limit

Frequency [arb. units]

# Macro opto- / electro-mechanics

**Radiation pressure cooling...**

S. Gigan et al., Nature **444**, 67-70 (2006)
O. Arcizet et al., Nature **444**, 71-74 (2006)
Schliesser et al., Phys. Rev. Lett. **97**, 243905 (2006)
Corbitt et al., Phys. Rev. Lett. **98**, 150892 (2007)

A. Naik et al., Nature **443**, 193-196 (2006)
T. Rocheleau et al., Nature **463**, 72-75 (2010)

**...into the quantum ground state (n < 1):**

J. Chan et al., Nature **478**, 89-92 (2011)

J. D. Teufel et al., Nature **475**, 359-363 (2011)

**Strong coupling:**

S. Gröblacher et al., Nature **460**, 724-727 (2009)
E. Verhagen et al., Nature **482**, 63-67 (2012)

J. D. Teufel et al., Nature **471**, 204-208 (2011)

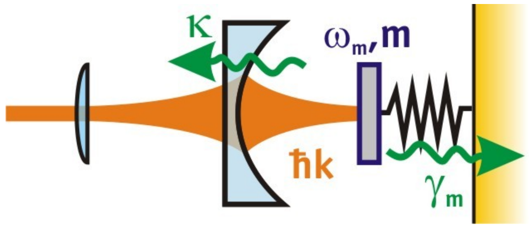
**Radiation pressure back-action:**

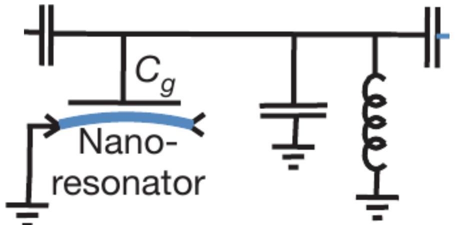
T. P. Purdy et al., Science **339**, 801-804 (2013)
A. H. Safavi-Naeini et al., Nature **500**, 185-189 (2013)

**Mechanical quantum effects:**

A. H. Safavi-Naeini et al., Phys. Rev. Lett. **108**, 033602 (2012)

A. D. O'Connell et al., Nature **464**, 697-703 (2010)
T. A. Palomaki et al., Science **342**, 710-713 (2013)

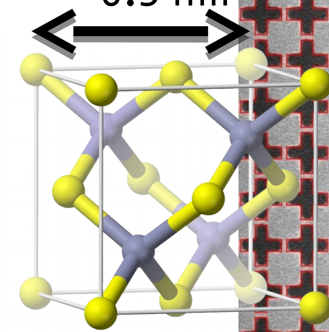


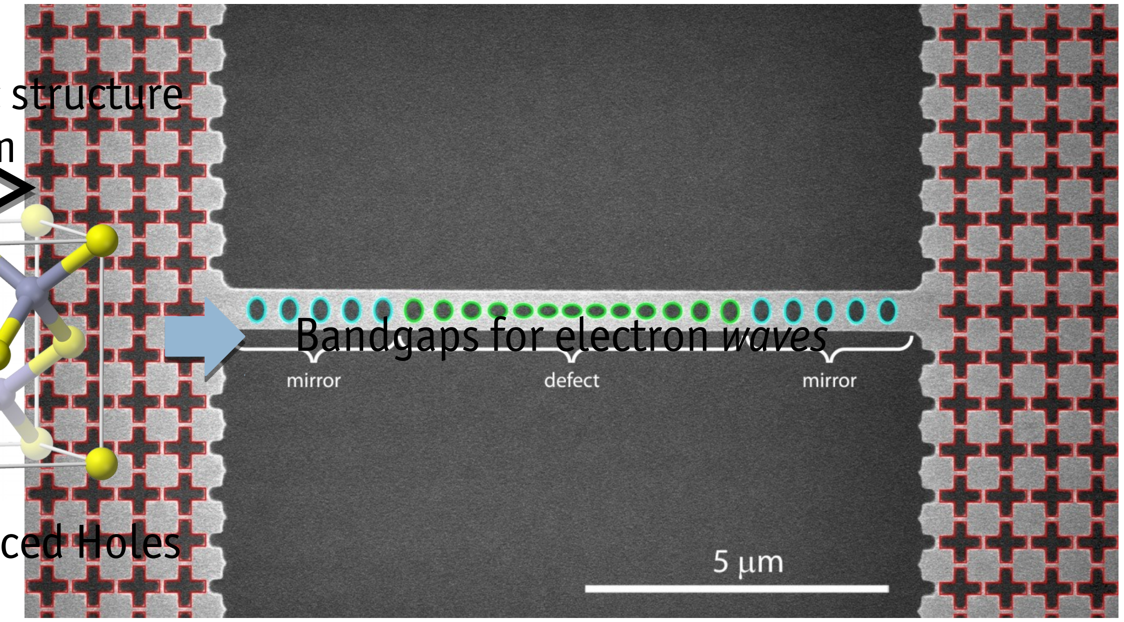



# Photonic crystals

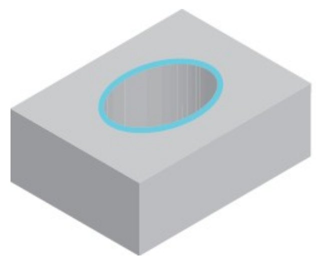
Periodic atomic structure

0.5 nm






Bandgaps for electron *waves*

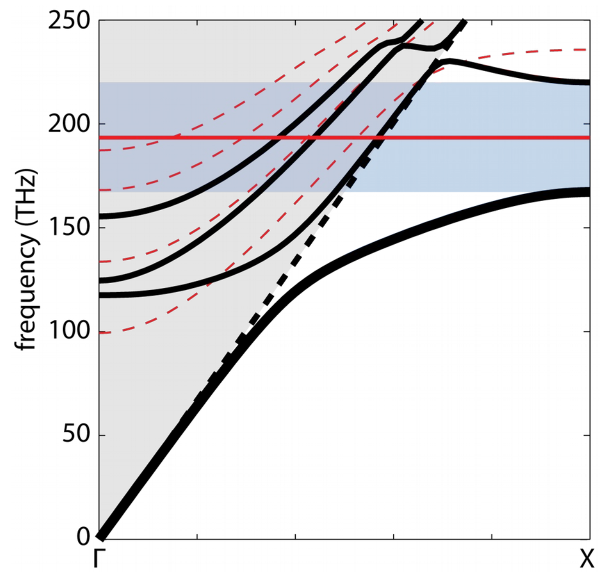


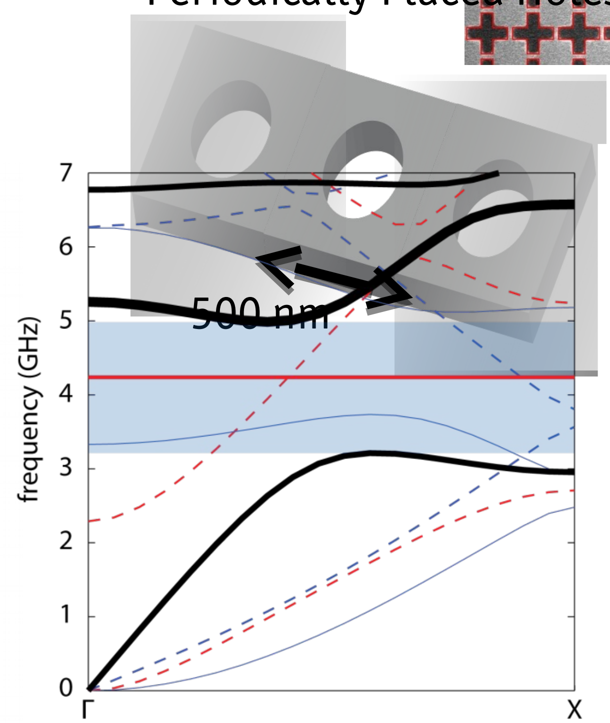
nominal unit cell

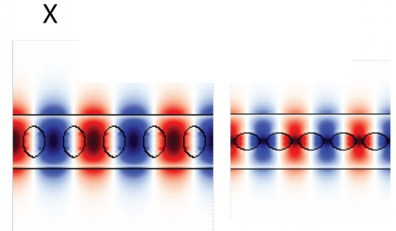
Periodically Placed Holes

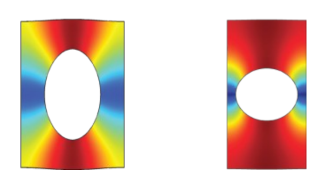
500 nm

aps for light and sound *waves*

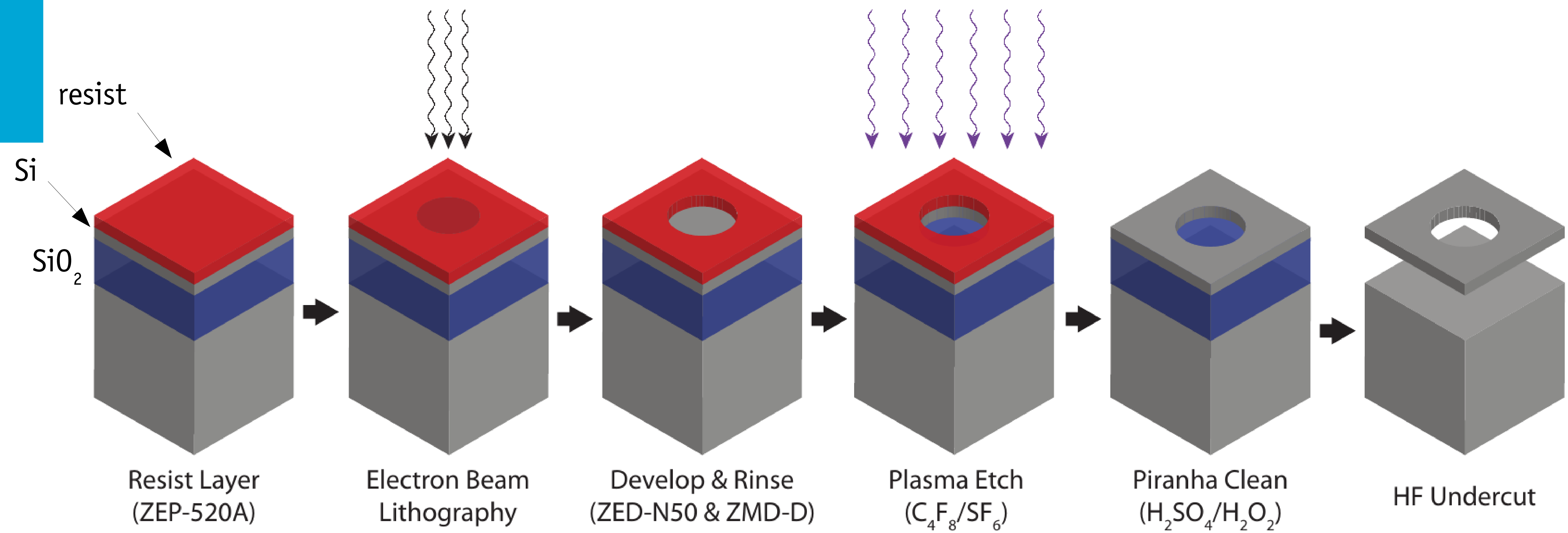


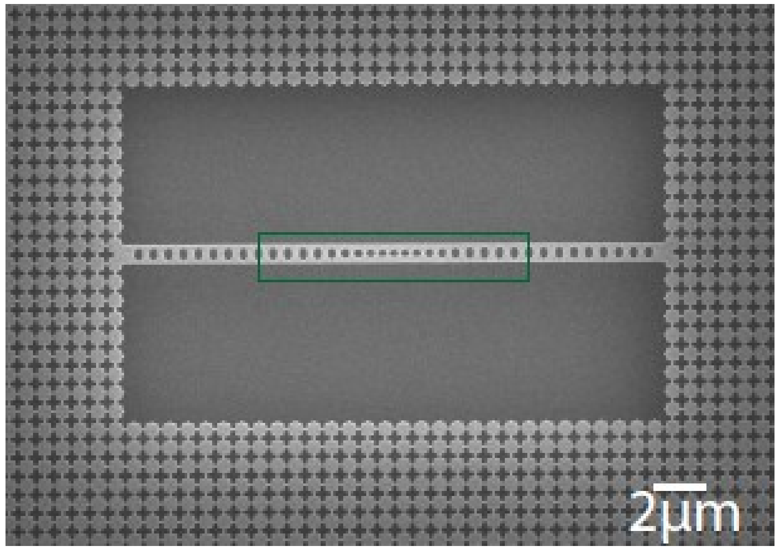





# Photonic crystal nanobeams

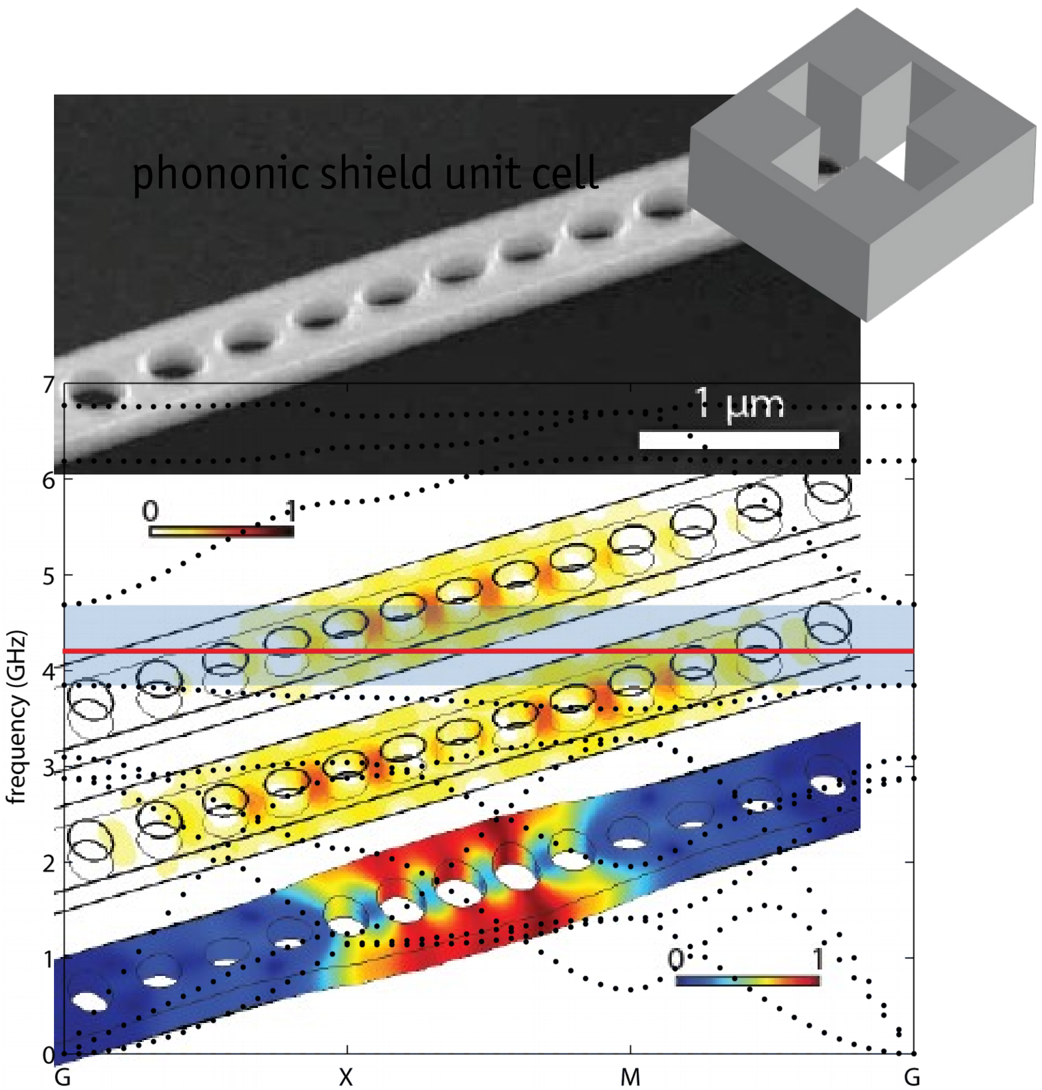


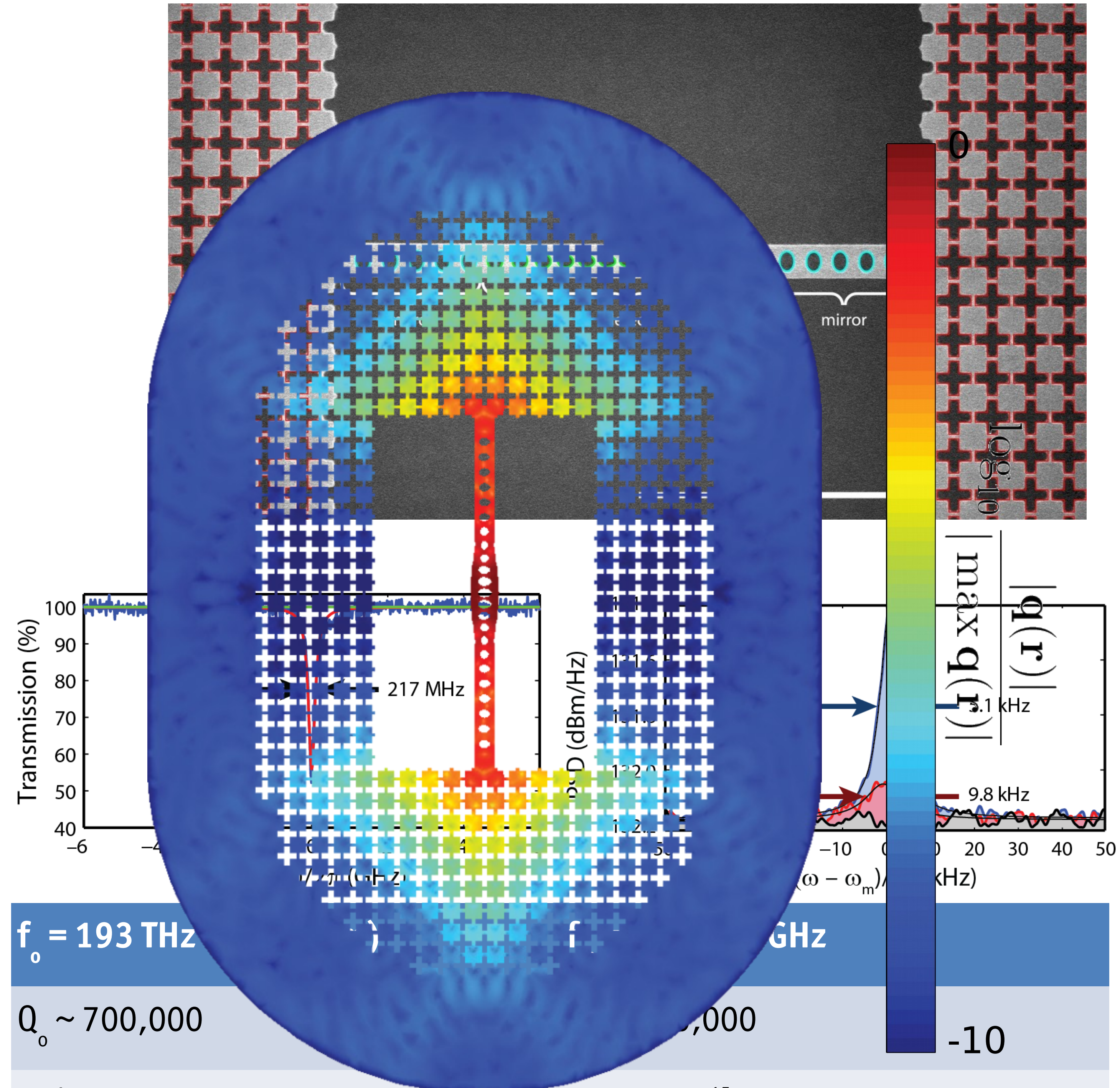



# Device design

‘Cross’ structure around the OMC acts as a phononic shield

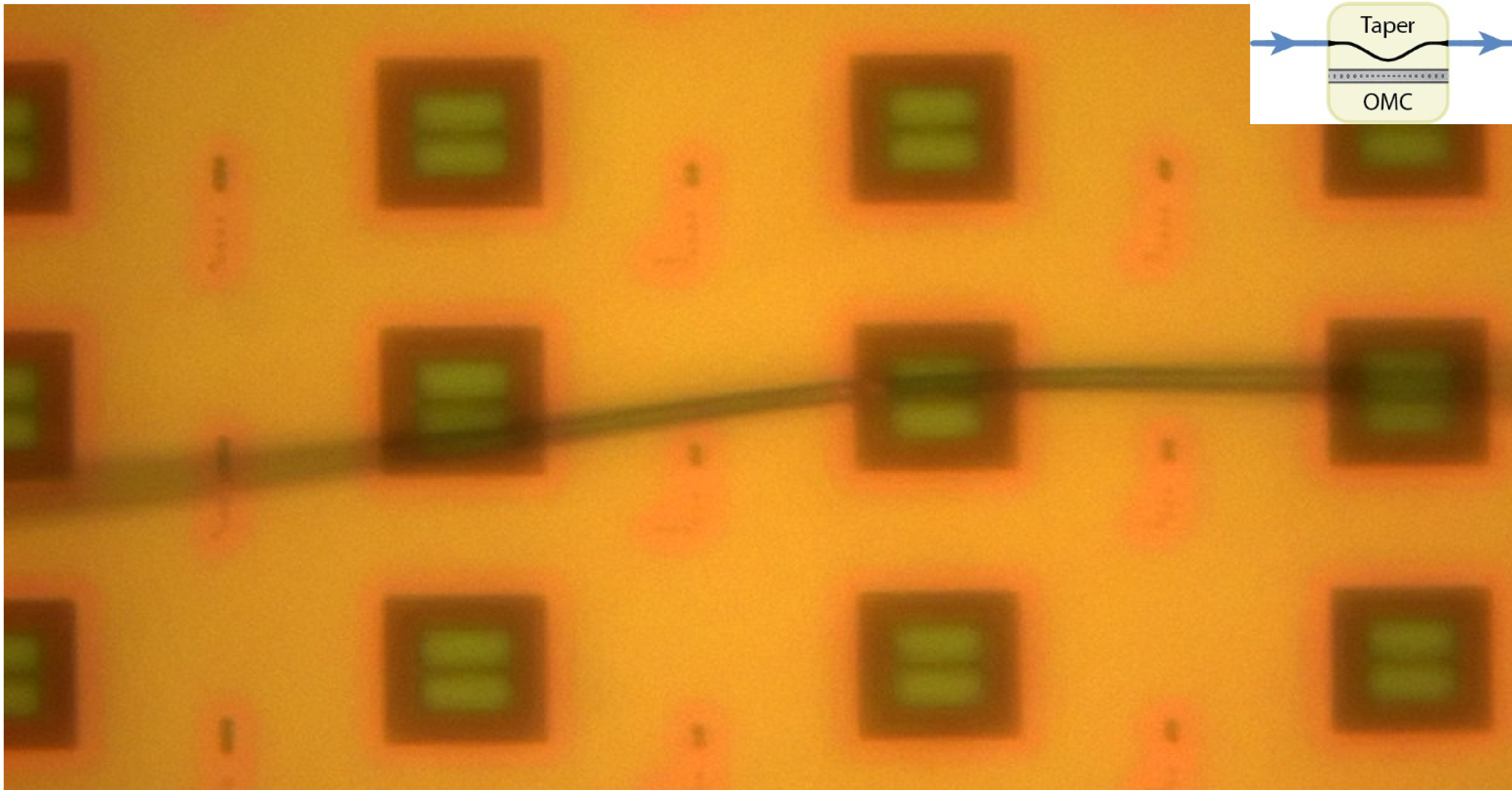
- full mechanical bandgap
- decreases mechanical losses

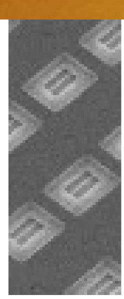


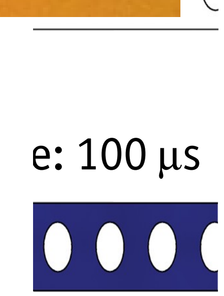

| | |
|---|---|
| $f_o$ = 193 THz | [illegible] |
| $Q_o$ ~ 700,000 | [illegible] |
| $g_0/2\pi$ = 1 MHz | $f_m \cdot Q_m = 10^{15}$ |

# Photonic crystal nanobeams

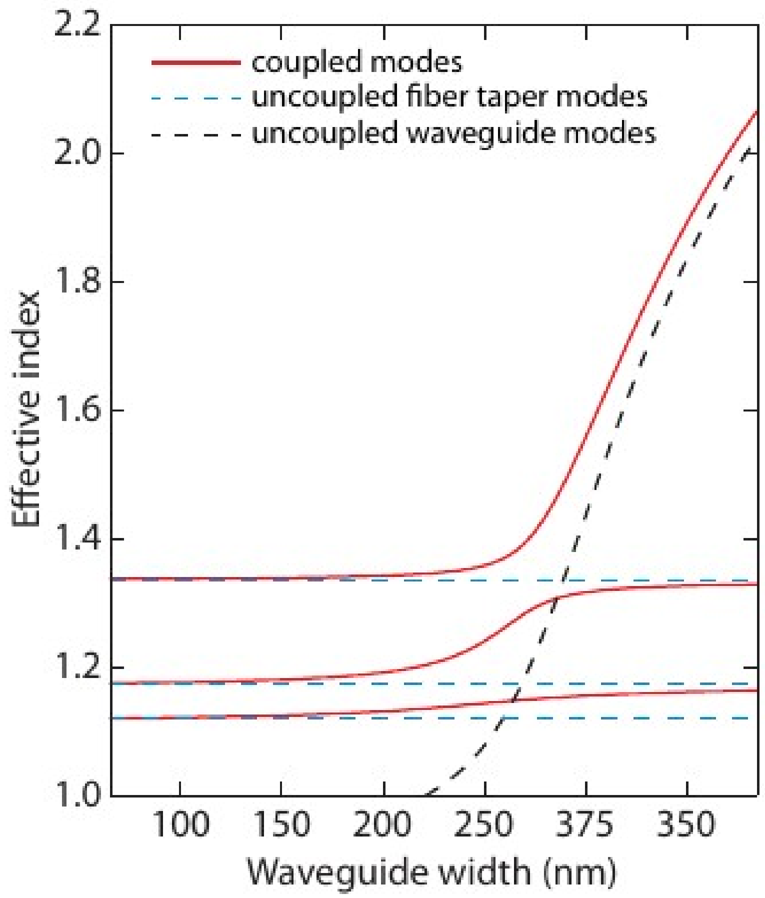


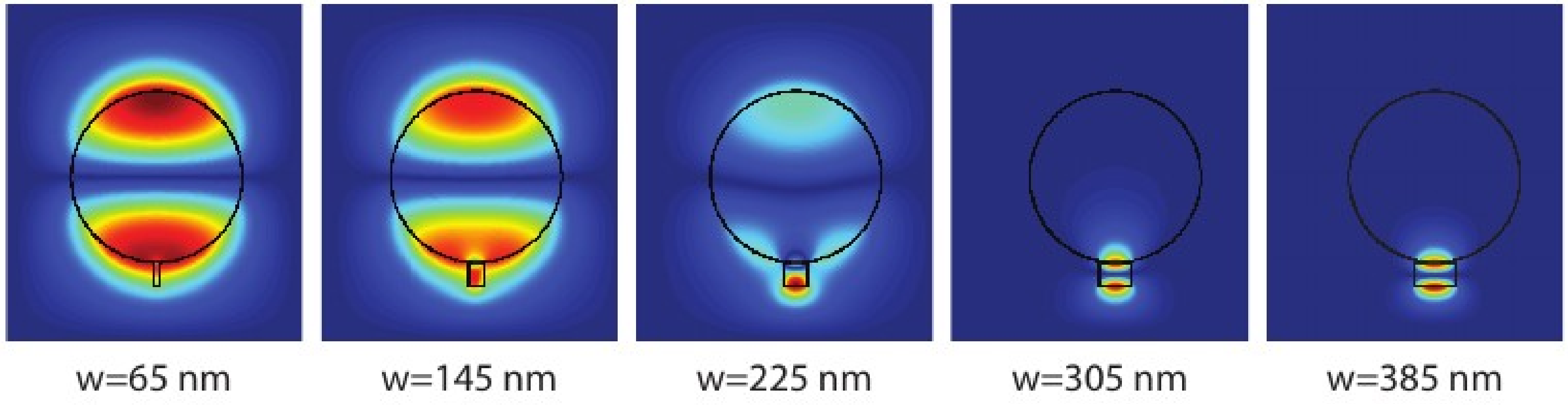



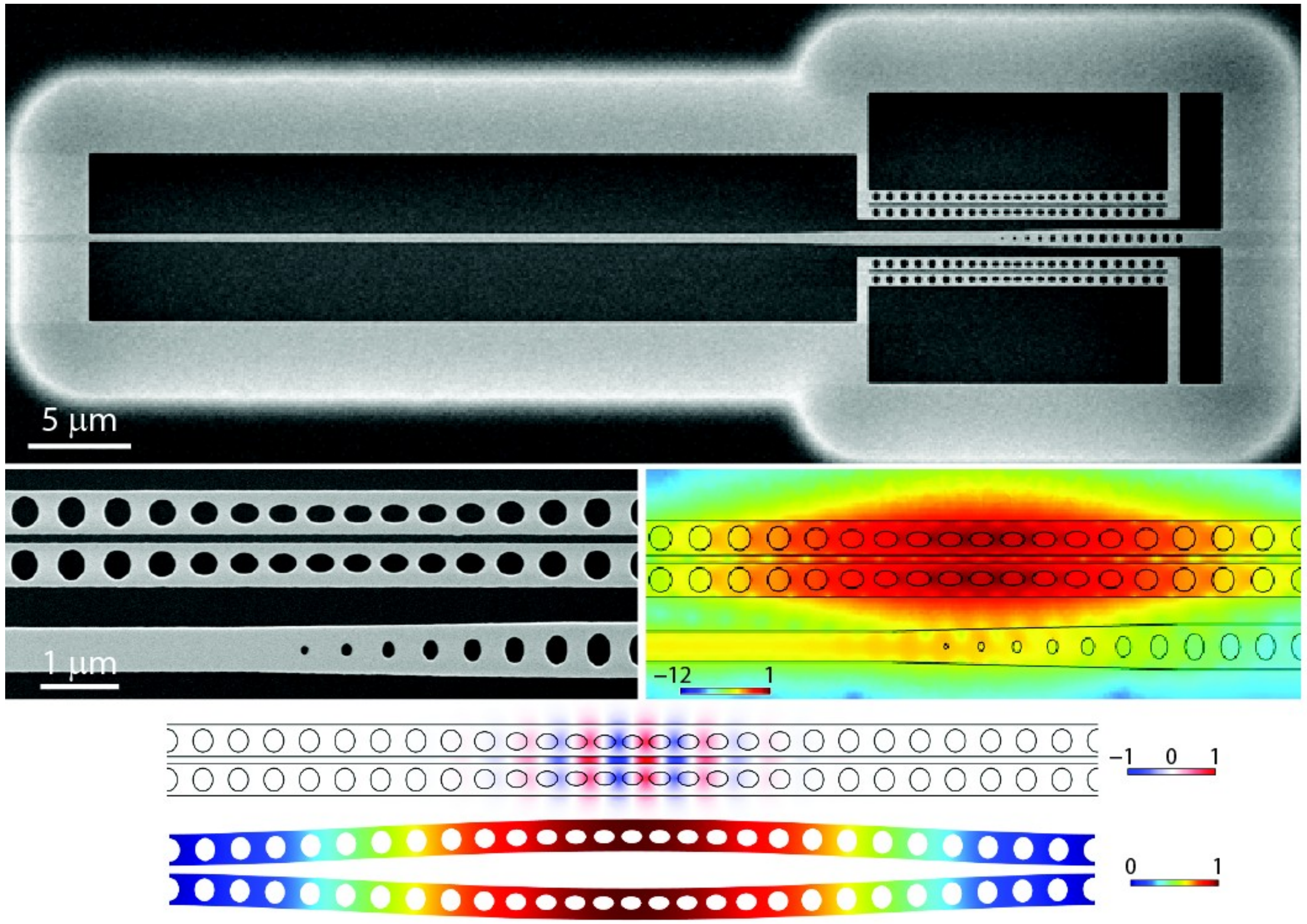
* EIT: A. H. Safavi-Naeini et al., Nature **472**, 69-73 (2011)
* ground-state cooling: J. Chan et al., Nature **478**, 89-92 (2011)
* sideband asymmetry: A. H. Safavi-Naeini et al., Phys. Rev. Lett. **108**, 033602 (2012)
* wavelength conversion: J. T. Hill et al., Nature Comm. **3**, 1196 (2012)



# Efficient coupling



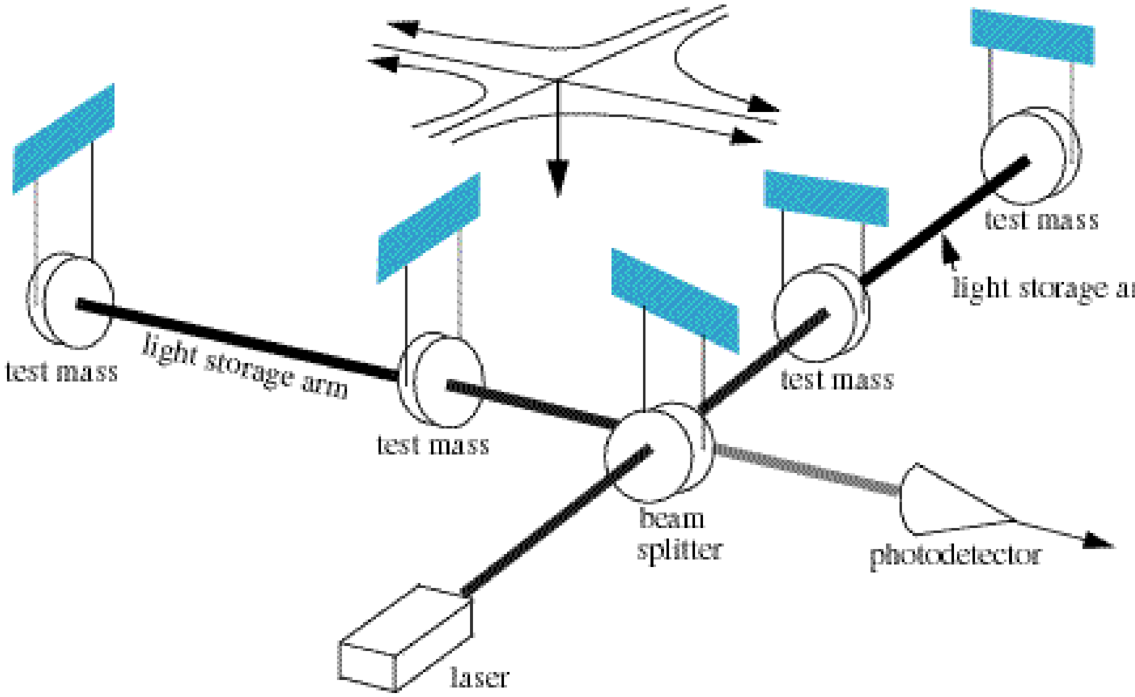



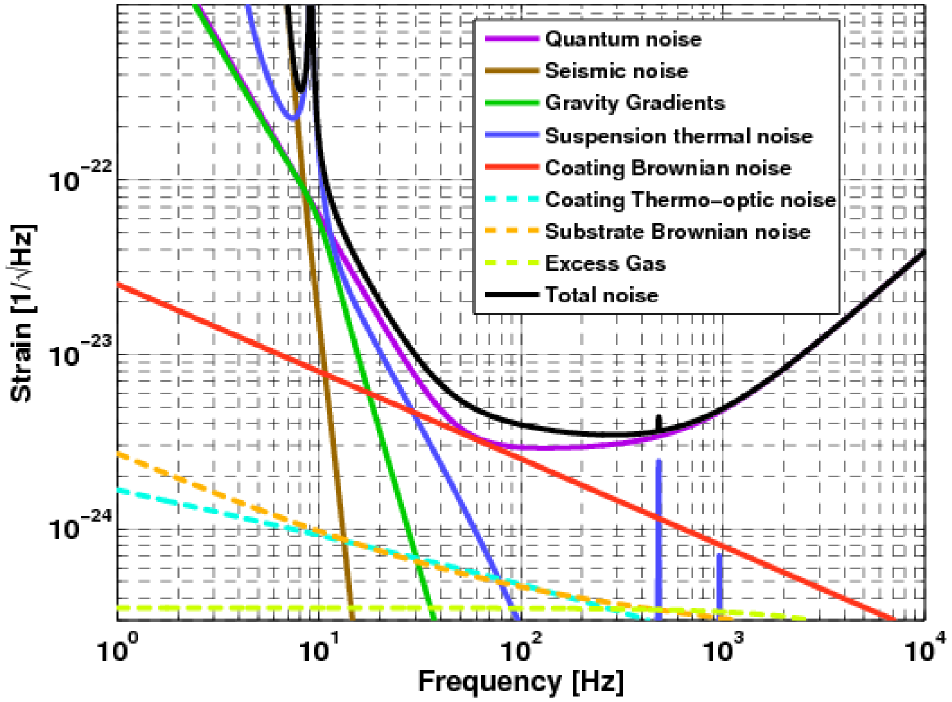




* taper to waveguide coupling efficiency >90%
* waveguide to cavity coupling adjustable

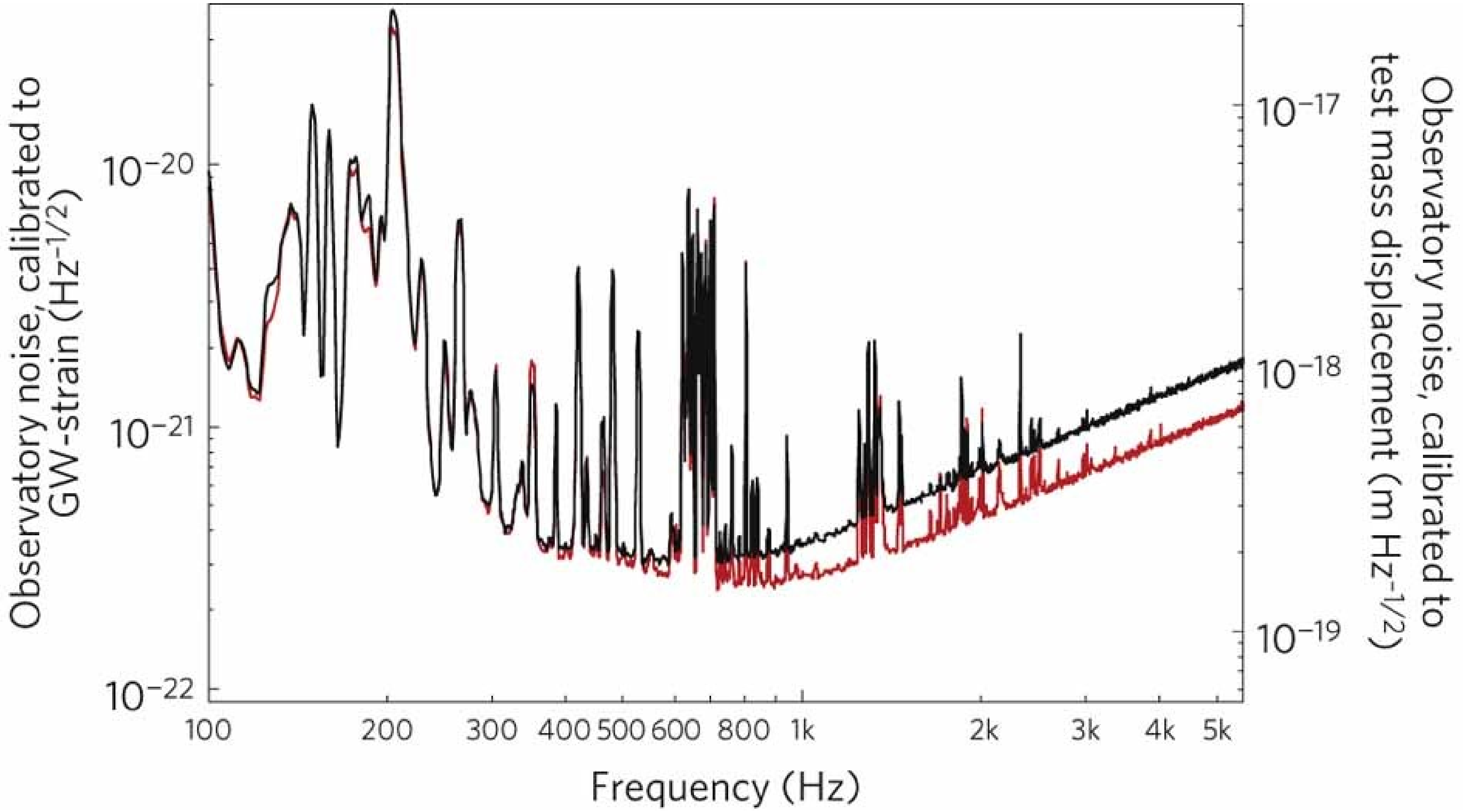
SG et al., Appl. Phys. Lett. **103**, 181104 (2013)

# Gravitational waves


# Squeezed light for GW

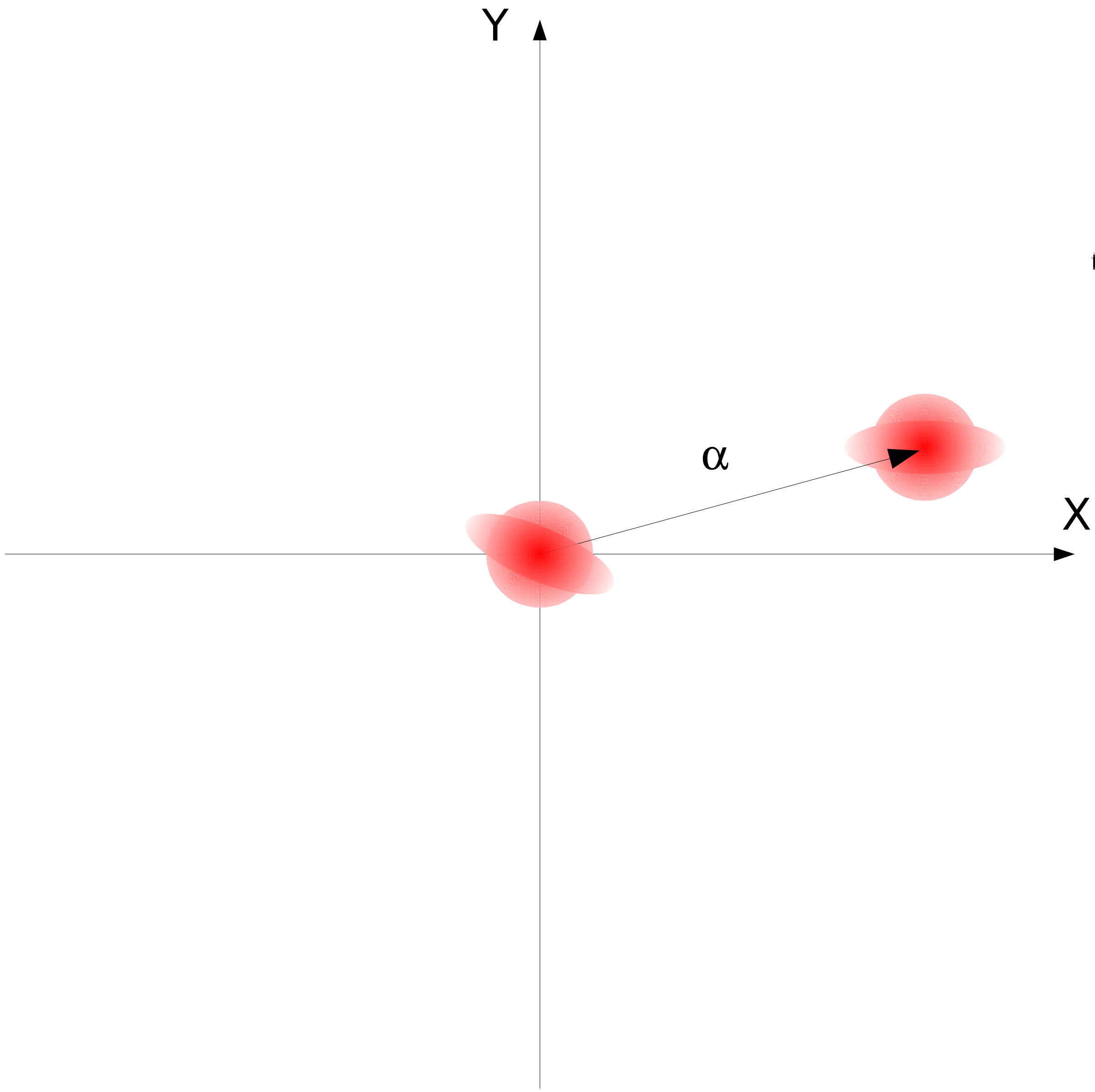


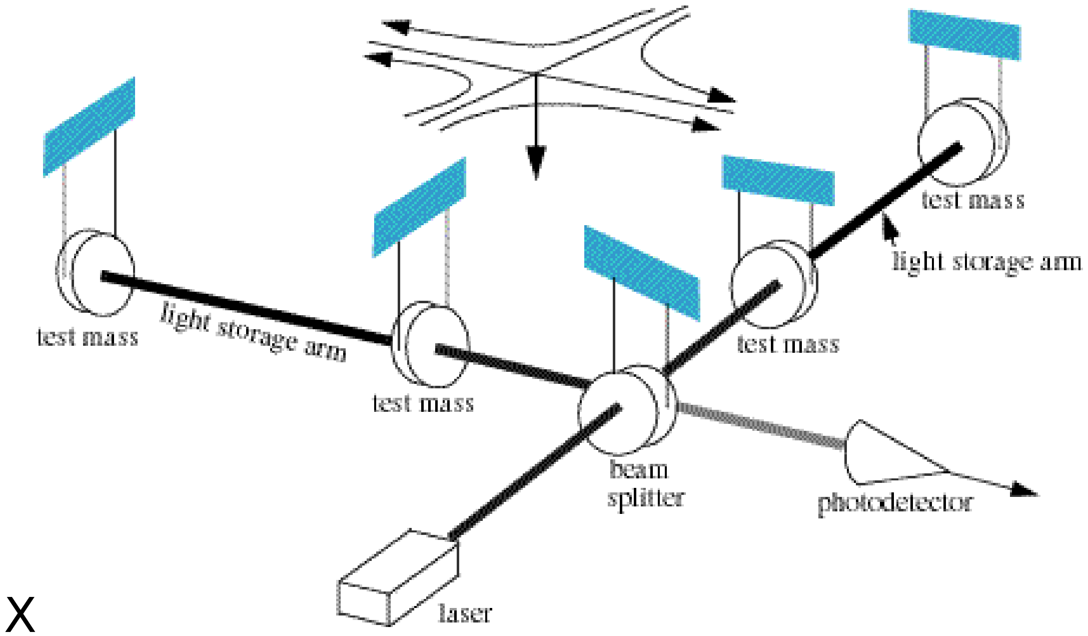


C. M. Caves, Phys. Rev. D **23**, 1693-1708 (1981)
The LIGO Scientific Collaboration, Nature Phys. **7**, 962-965 (2011)

R. E. Slusher et al., PRL **55**, 2409 (1985)
R. M. Shelby et al., PRL **57**,619 (1986)
L. A. Wu et al., PRL **57**, 2520 (1986)
S. Machida et al., PRL **58**, 1000 (1987)

# Squeezed light



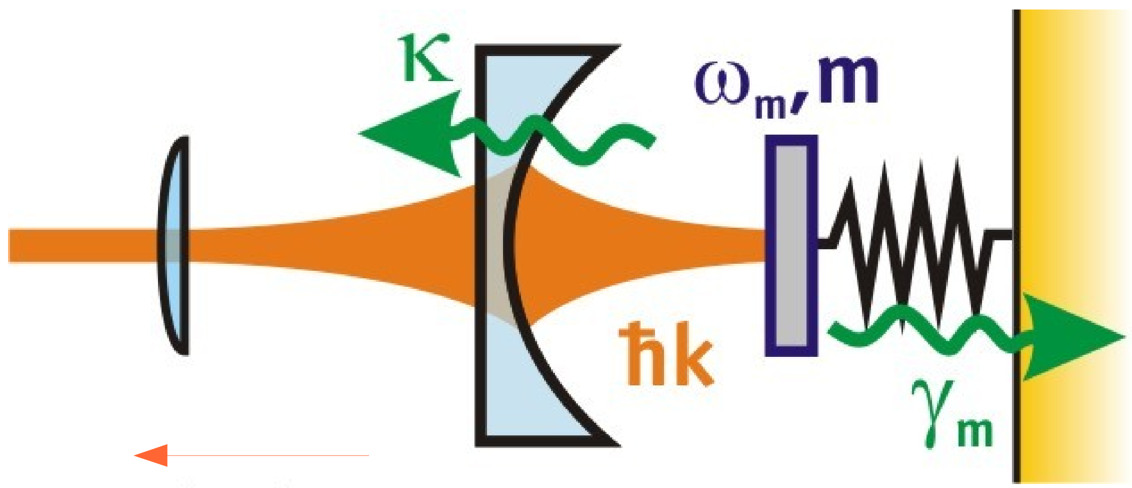

C. Fabre et al., Phys. Rev. A **49**, 1337 (1994)
S. Mancini and P. Tombesi, Phys. Rev. A **49**, 4055 (1994)

vacuum: $\Delta X \Delta Y = \hbar/2$
displaced vacuum = coherent state $\sqrt{n} = |\alpha|$
squeezed coherent
squeezed vacuum $\Delta X \neq \Delta Y$

12.3dB squeezing!

R. E. Slusher et al., PRL **55**, 2409 (1985)
R. M. Shelby et al., PRL **57**,619 (1986)
L. A. Wu et al., PRL **57**, 2520 (1986)
S. Machida et al., PRL **58**, 1000 (1987)
M. Mehmet et al., Opt. Express **19**, 25763 (2011)

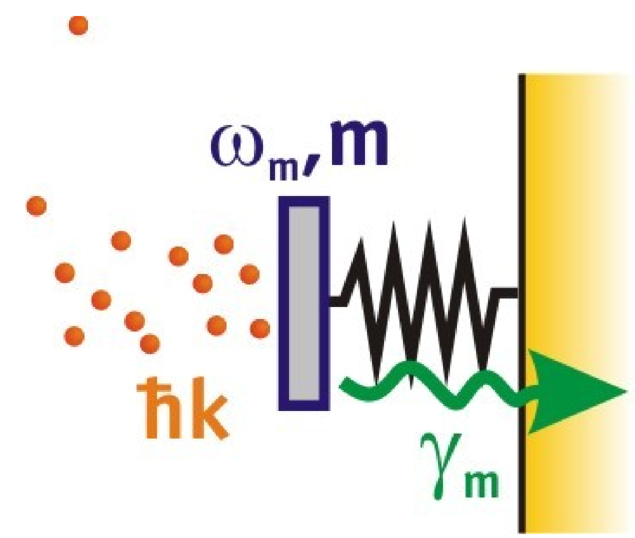
# Light squeezing with optomechanics




$$\hat{X}_\theta^{(j)} = \hat{a}_j e^{-i\theta} + \hat{a}_j^\dagger e^{i\theta}$$

$$\hat{X}_\theta^{(out)}(t)$$

$$\hat{X}_\theta^{(in)}(t) \rightarrow \hat{x}(t)$$

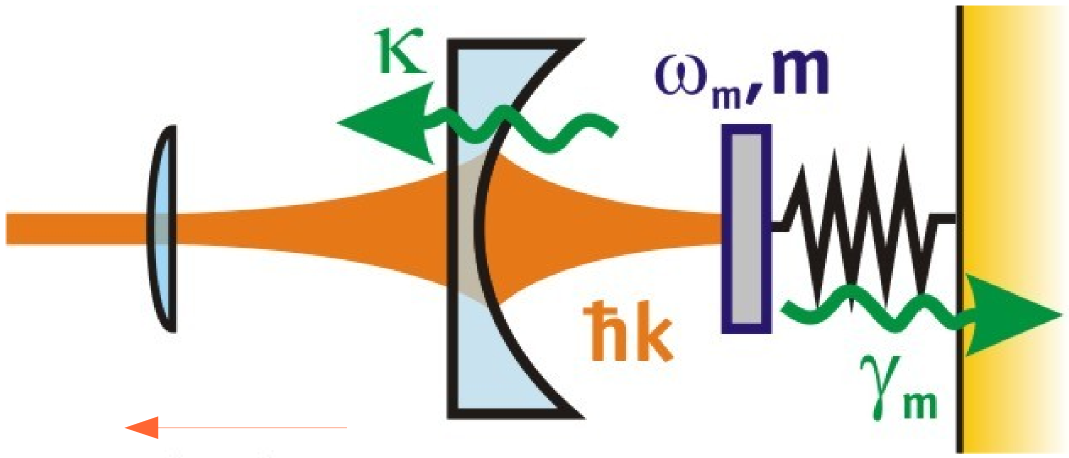



$$\hat{X}_\theta^{(out)}(t) = -\hat{X}_\theta^{(in)}(t) - 2\frac{\sqrt{\Gamma_{meas}}}{x_{zpf}}\hat{x}(t)\cdot\sin(\theta)$$

$$\Gamma_{meas} = \frac{4g^2 n_c}{\kappa}$$

T. Purdy et al., Science **339**, 801 (2013)

# Light squeezing with optomechanics



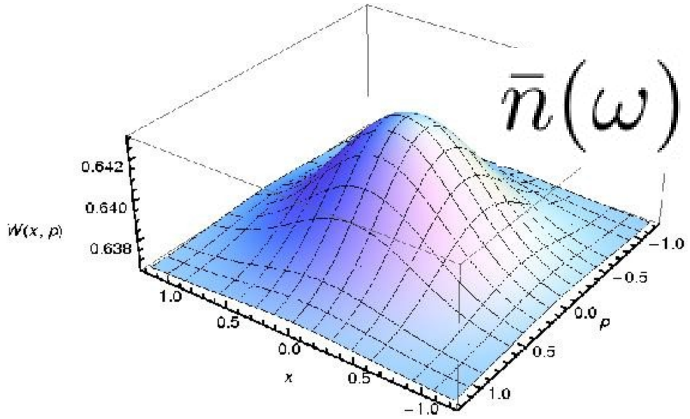

$$\hat{X}_\theta^{(\mathrm{j})} = \hat{a}_\mathrm{j} e^{-i\theta} + \hat{a}_\mathrm{j}^\dagger e^{i\theta}$$

measure... $\langle \hat{X}_\theta^{(\mathrm{out})}(t) \hat{X}_\theta^{(\mathrm{out})}(t') \rangle$

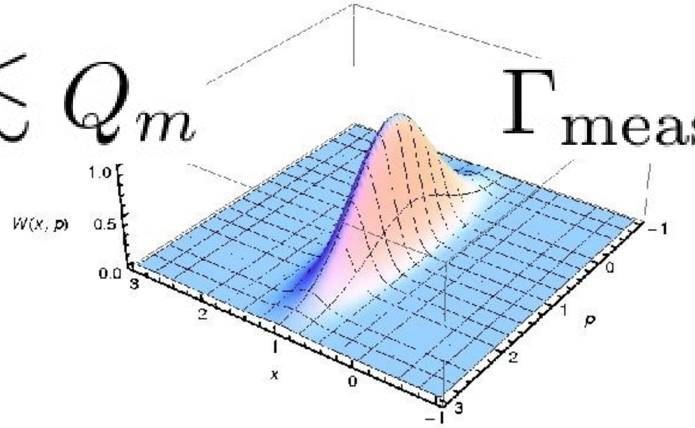
$\hat{X}_\theta^{(\mathrm{out})}(t)$

$$\bar{S}_{II}^{\mathrm{out}}(\omega) = 1 + \frac{4\Gamma_\mathrm{meas}}{x_\mathrm{zpf}^2}\left[\bar{S}_{xx}\sin^2(\theta) + \frac{\hbar}{2}\mathrm{Re}\{\chi_\mathrm{m}\}\sin(2\theta)\right]$$

shot-noise | thermal, BA heating, technical | squeezing



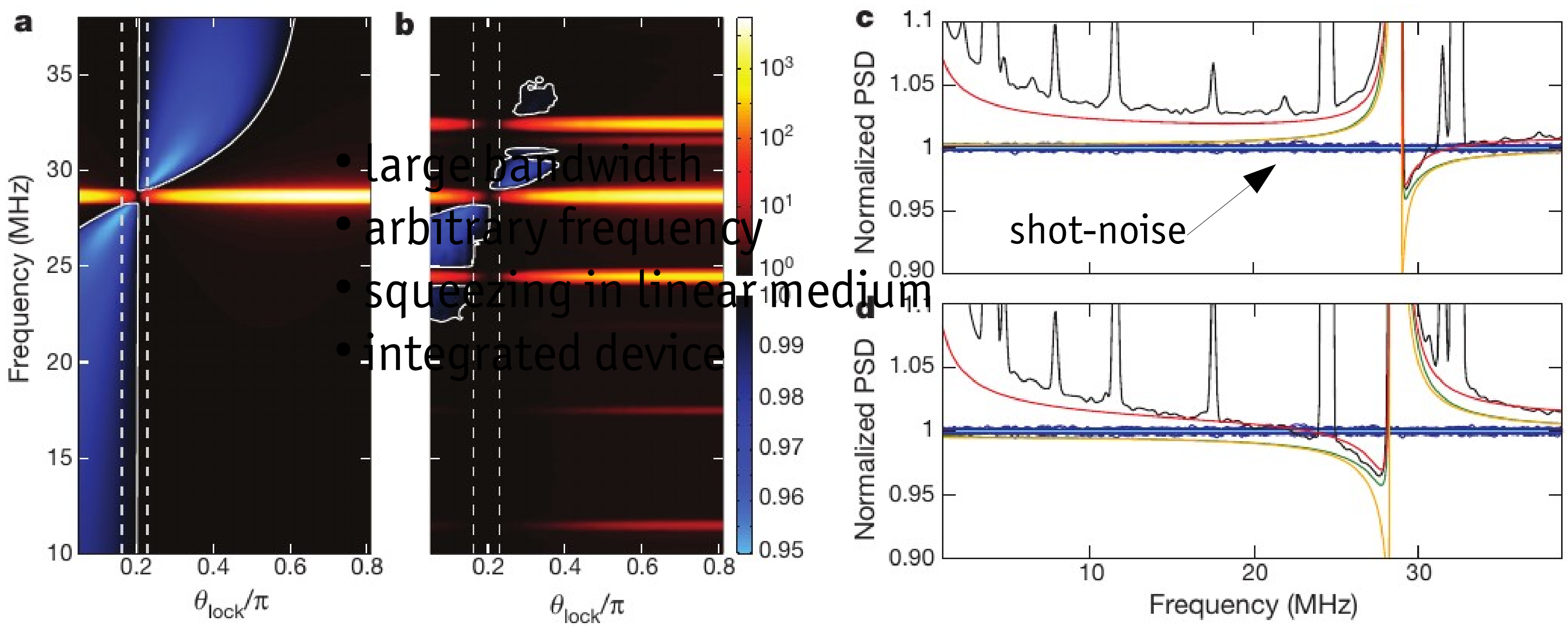

$\bar{n}(\omega) \lesssim Q_m$



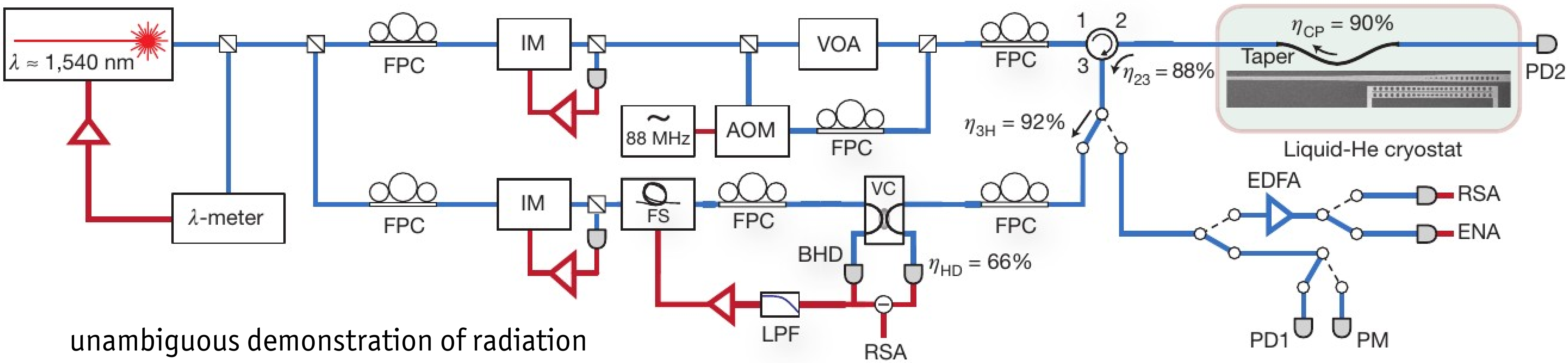

$\Gamma_\mathrm{meas}$ large!

# Sub shot-noise squeezing

$T_0$ = 16 K
$\omega_m = 2\pi$ x 28 MHz
$Q_{opt}$ = 57,000
$Q_m$ = 166,000
$g_0 = 2\pi$ x 750 kHz




- large bandwidth
- arbitrary frequency
- squeezing in linear medium
- integrated device




unambiguous demonstration of radiation pressure back action

A. H. Safavi-Naeini*, S. Gröblacher*, J. T. Hill*, J. Chan, M. Aspelmeyer, and O. Painter, Nature **500**, 185-189 (2013)

D. W. C. Brooks et al., Nature **488**, 476-480 (2012)
T. P. Purdy et al., PRX **3**, 031012 (2013)

# The Marquardt challenges

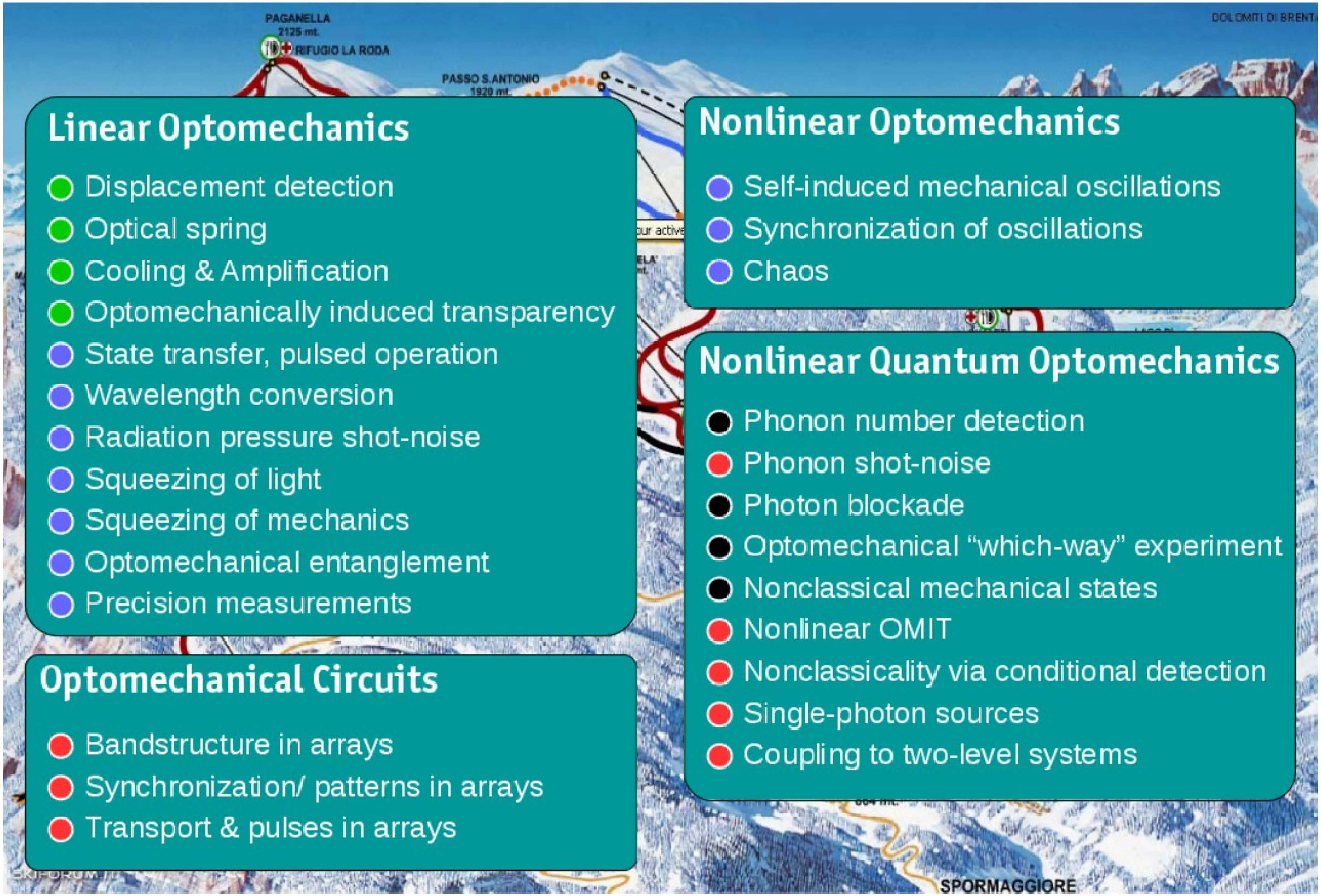



*Image courtesy of Florian Marquardt*

# Future quantum optomechanics

$$H_{rp} = \hbar\omega_c g_0 \left(b + b^\dagger\right) a^\dagger a$$

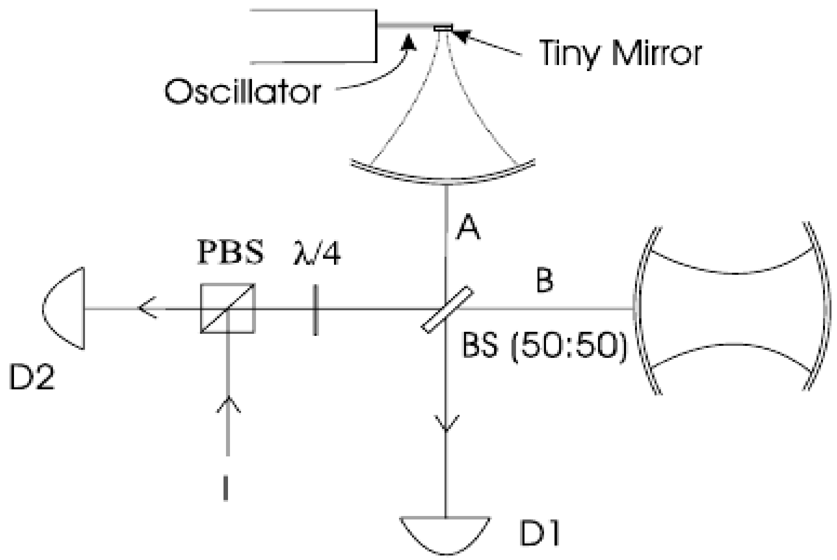
... need full access to non-linear interaction!

| # | Publication | κ/2π [Hz] | $g_0$/2π [Hz] | $g_0$/κ |
|---|---|---|---|---|
| 1 | Gigan et al., Nature **444**, 67 – 70 (2006) | 7.5 x $10^{6}$ | 3.09 | 4.1 x $10^{-7}$ |
| 2 | Arcizet et al., Nature **444**, 71 – 74 (2006) | 1.0 x $10^{6}$ | 0.86 | 8.3 x $10^{-7}$ |
| 3 | Corbitt et al., Phys. Rev. Lett. **99**, 160801 (2007) | 1 x $10^{3}$ | 8.2 x $10^{-3}$ | 8.6 x $10^{-8}$ |
| 4 | Thompson et al., Nature **452**, 72 – 75 (2008) | 1.6 x $10^{5}$ | 4.7 | 2.9 x $10^{-5}$ |
| 5 | Schliesser et al., Nature Phys. **4**, 415 – 419 (2008) | 1.6 x $10^{6}$ | 149 | 9.3 x $10^{-5}$ |
| 6 | Anetsberger et al., Nature Phys. **5**, 909 – 914 (2009) | 4.9 x $10^{6}$ | 589 | 1.2 x $10^{-4}$ |
| 7 | Gröblacher et al., Nature Phys. **5**, 485 – 488 (2009) | 7.7 x $10^{5}$ | 5.1 | 6.6 x $10^{-6}$ |
| 8 | Gröblacher et al., Nature **460**, 724 – 727 (2009) | 2.1 x $10^{5}$ | 2.8 | 1.3 x $10^{-5}$ |
| 9 | Wilson et al., Phys. Rev. Lett. **103**, 207204 (2009) | 1.3 x $10^{7}$ | 6.1 | 4.9 x $10^{-7}$ |
| 10 | Li et al. Phys. Rev. Lett. **103**, 223901 (2009) | 8 x $10^{8}$ | 37.8 | 4.7 x $10^{-8}$ |
| 11 | Ding et al., Phys. Rev. Lett. **105**, 263903 (2010) | 1.7 x $10^{9}$ | 1.7 x $10^{5}$ | 1.0 x $10^{-4}$ |
| 12 | Safavi-Naeini et al., Appl. Phys. Lett. **97**, 181106 (2010) | 8.1 x $10^{7}$ | 8.0 x $10^{5}$ | 1.0 x $10^{-2}$ |
| 13 | Chan et al., Nature **478**, 89 – 92 (2011) | 5.0 x $10^{8}$ | 9.1 x $10^{5}$ | 1.8 x $10^{-3}$ |
| 14 | Verhagen et al., Nature **482**, 63 – 67 (2012) | 6.0 x $10^{6}$ | 3.4 x $10^{3}$ | 5.7 x $10^{-4}$ |
| 15 | Purdy et al., Phys. Rev. X **3**, 031012 (2013) | 1.7 x $10^{6}$ | 33 | 1.9 x $10^{-5}$ |

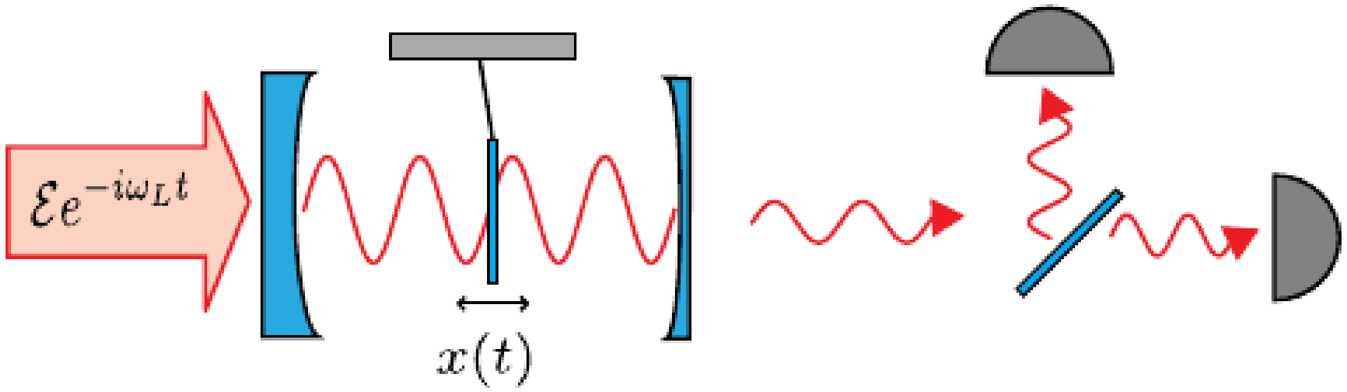
# … but what if…

e.g. F. Khalili et al., PRL 105, 070403 (2010)

… could realize for example vacuum Rabi oscillations, quantum state preparation, etc. and:




W. Marshall et al., PRL 91, 130401 (2003)

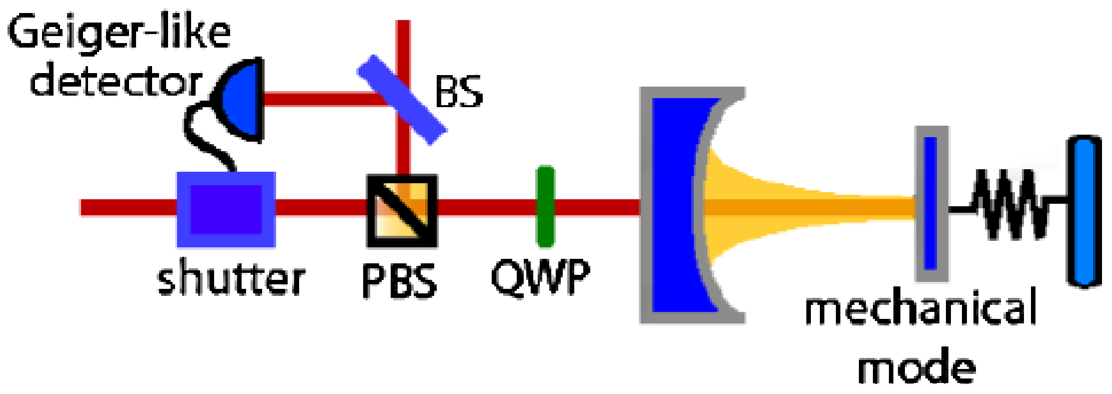



P. Rabl, PRL 107, 063601 (2011)
see also: A. Nunnenkamp et al., PRL 107, 063602 (2011)

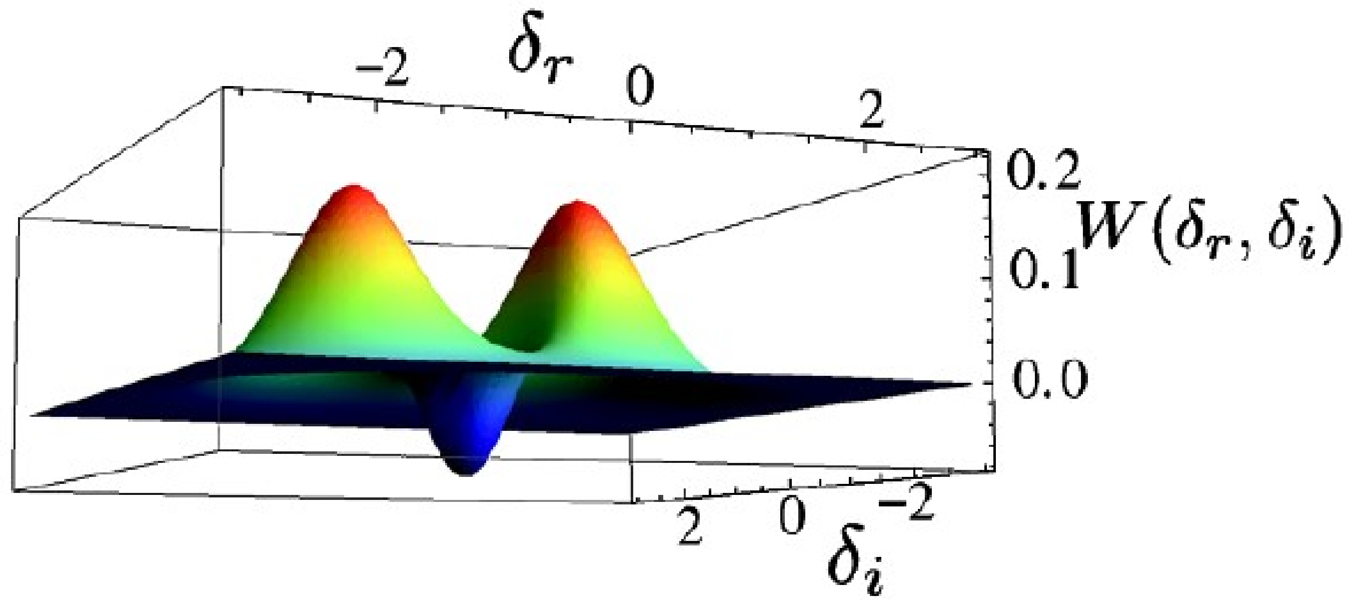
# Quantum optomechanics

and other types of non-linearities?

for example post-selection:

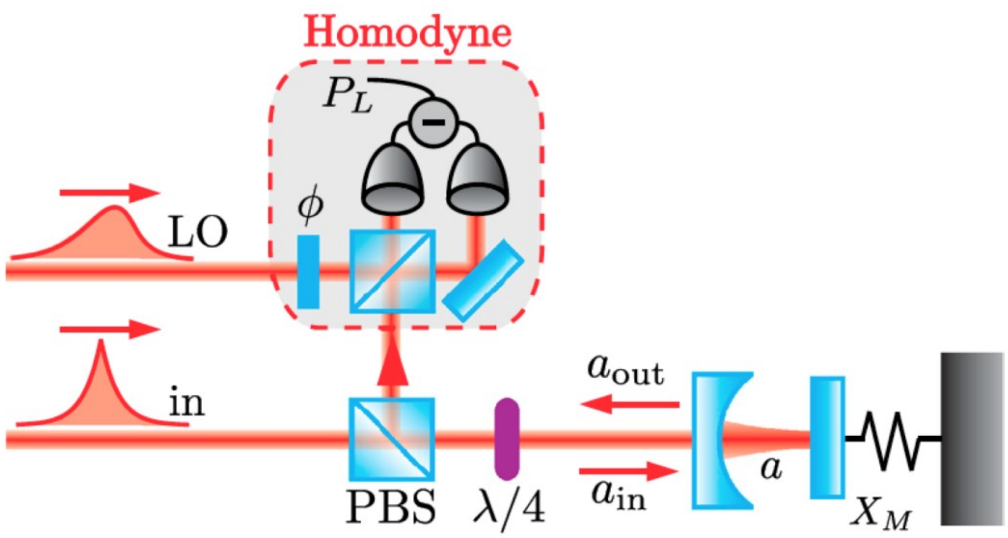



$20\ \mathrm{mW}$
$L = 1\,\mathrm{mm}$
finesse $10^4$
$\mu = 5 \times 10^{-12}\,\mathrm{kg}$
$\Delta/\omega_m = 0.05,\ T = 0.4\ \mathrm{K},$

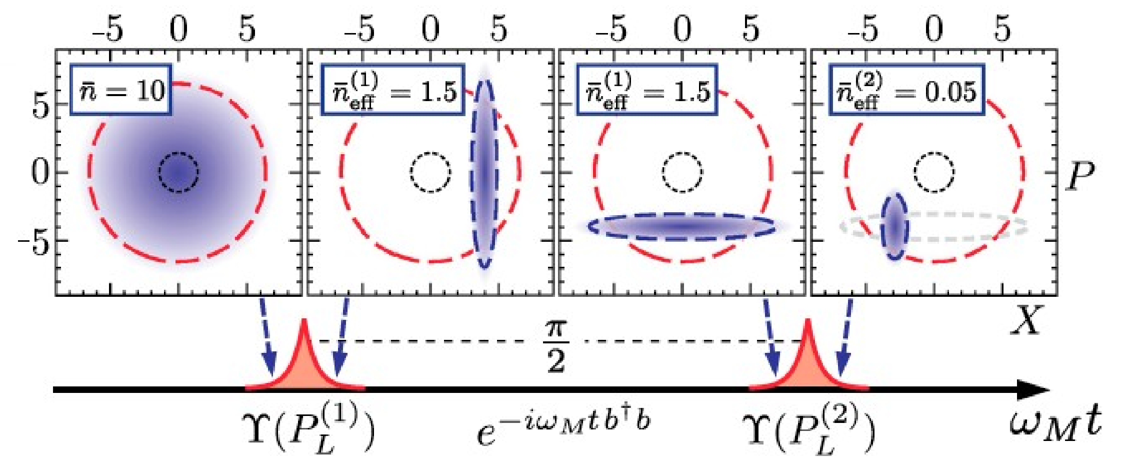



M. Paternostro, PRL 106, 183601 (2011)

# Pulsed optomechanics

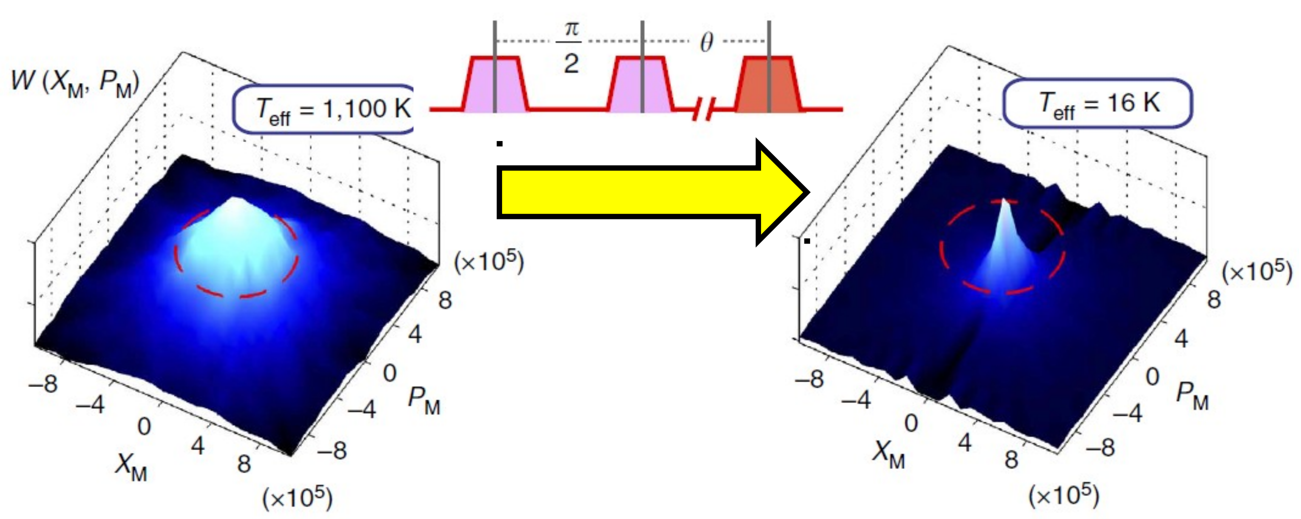



M. Vanner et al., PNAS **108**, 16182 (2011)




$$\chi = 2\sqrt{5}\frac{g_0}{\kappa}\sqrt{N_p}$$ ... measurement strength

measurements bound by SQL
→ back action evasion




$\chi \sim 10^{-4}$

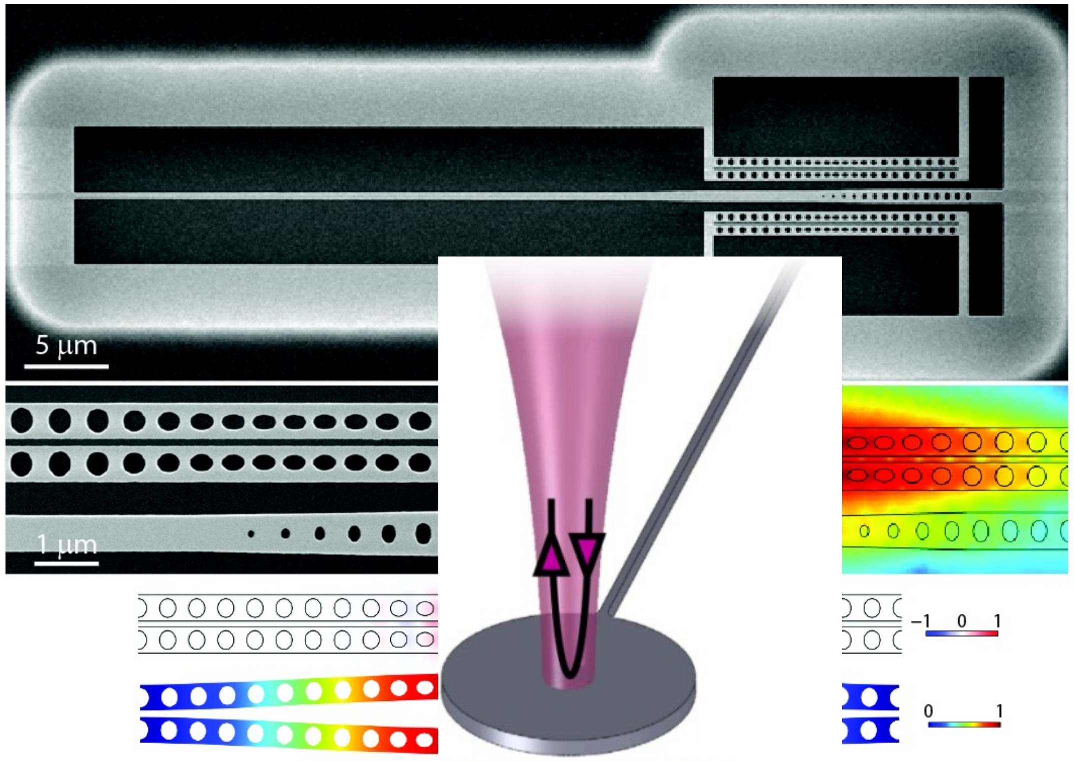
Purely classical so far, but:

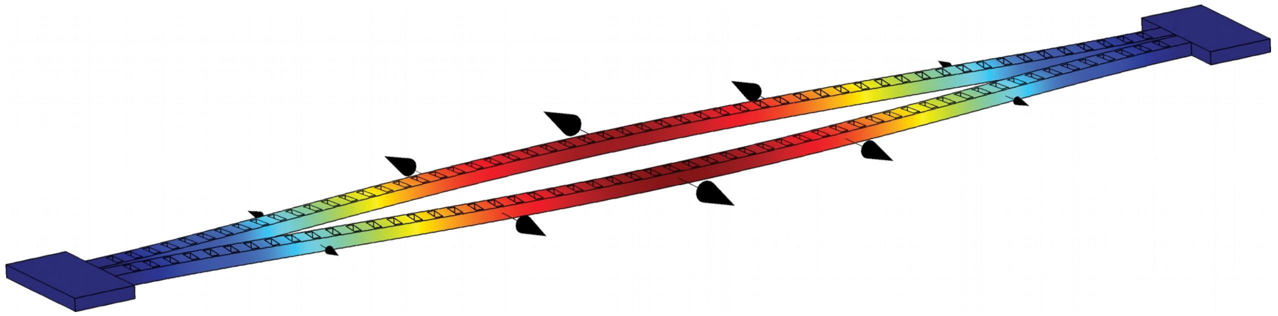
- Ground-state cooling (from arbitrary T)
- Mechanical squeezing
- Non-classical states of mechanics

→ increase $\chi$

M. Vanner et al., Nature Commun. **4**, 2295 (2013)

# Pulsed optomechanics with PhC

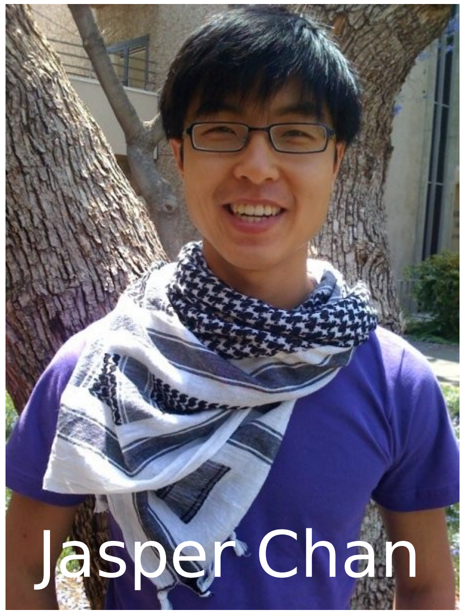


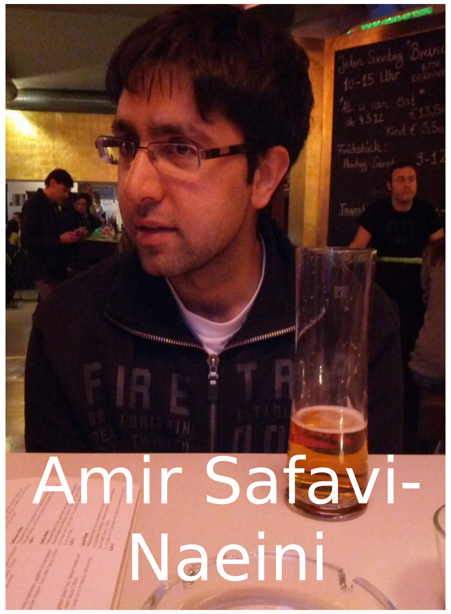



| | Vanner et al. | Photonic crystal |
|---|---|---|
| $\omega_m/2\pi$ | 984 Hz | 1 MHz |
| $\kappa/2\pi$ | - | 2 GHz |
| $Q_m$ | $3.1\times10^4$ | $10^6$ |
| $g_0$ | - | .5 MHz |
| $N_P$ | $10^8$ | $10^8$ |
| $\chi$ | $10^{-4}$ | >1 |

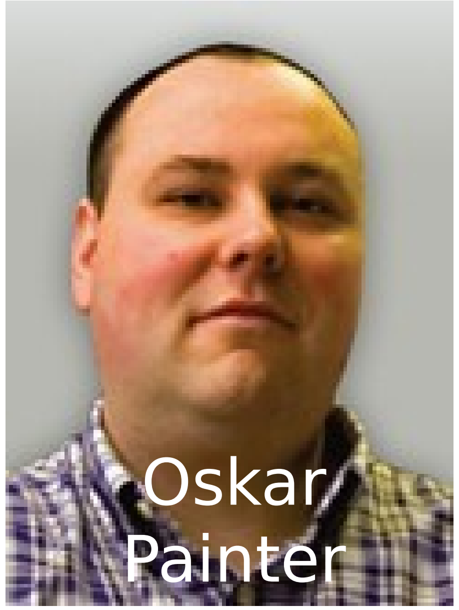
# Current status


# Acknowledgements



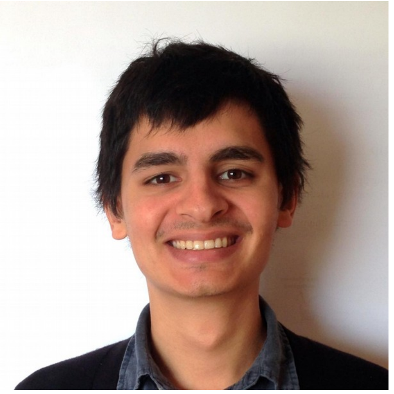


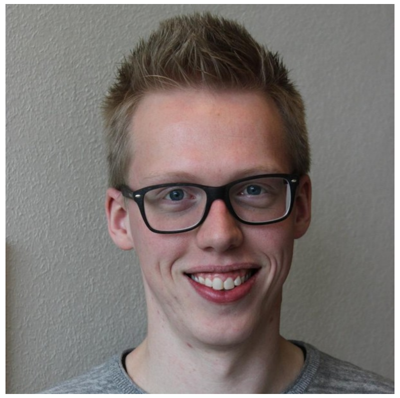
# Gröblacher Lab

**Richard**

**Alex**



**João**



**Gregory**

**Simon**

http://groeblacherlab.tudelft.nl

collaborators:

**Sungkun**

**Ralf**

**Markus**