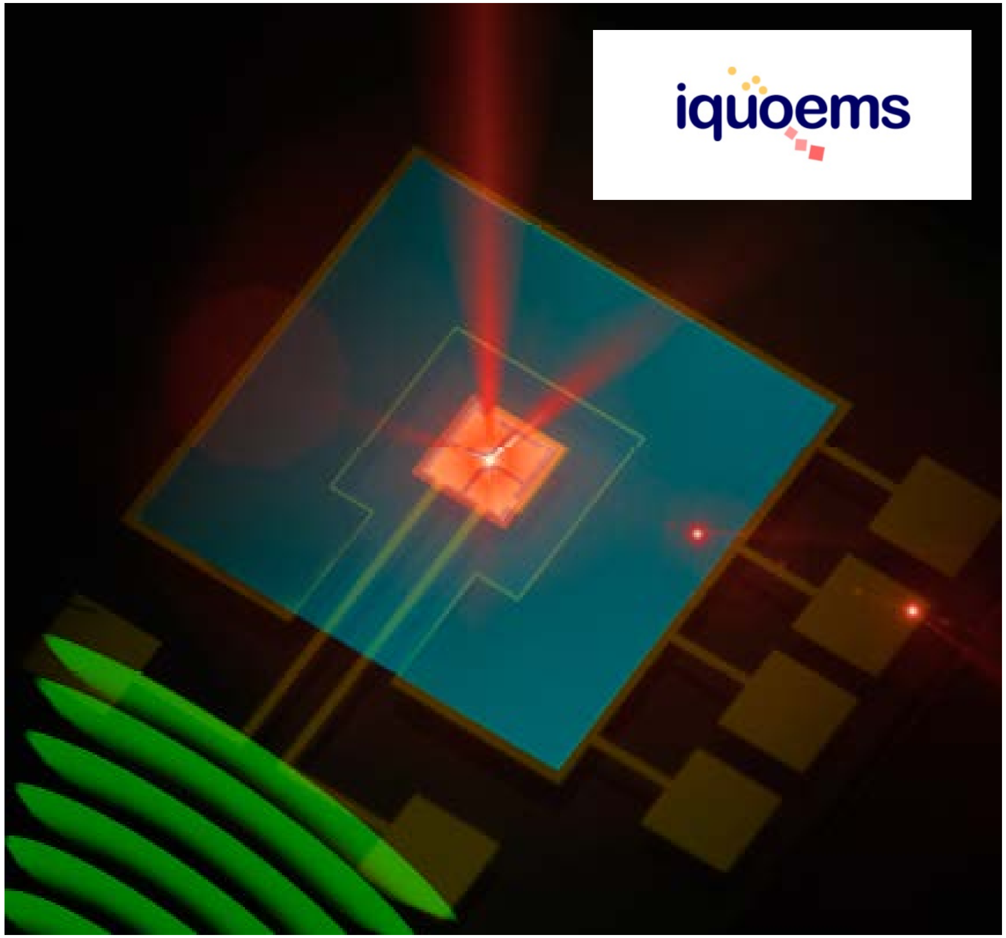



Danish Quantum Optics Center

QUANTOP

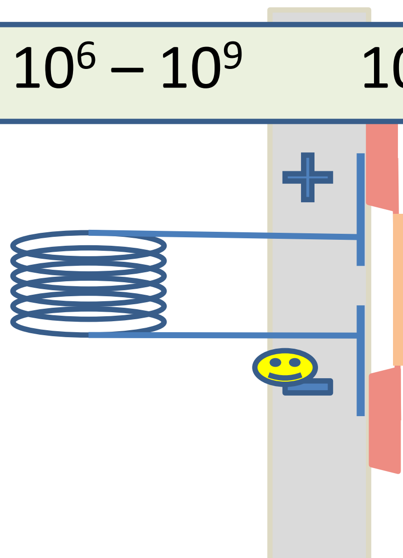
Niels Bohr Institute

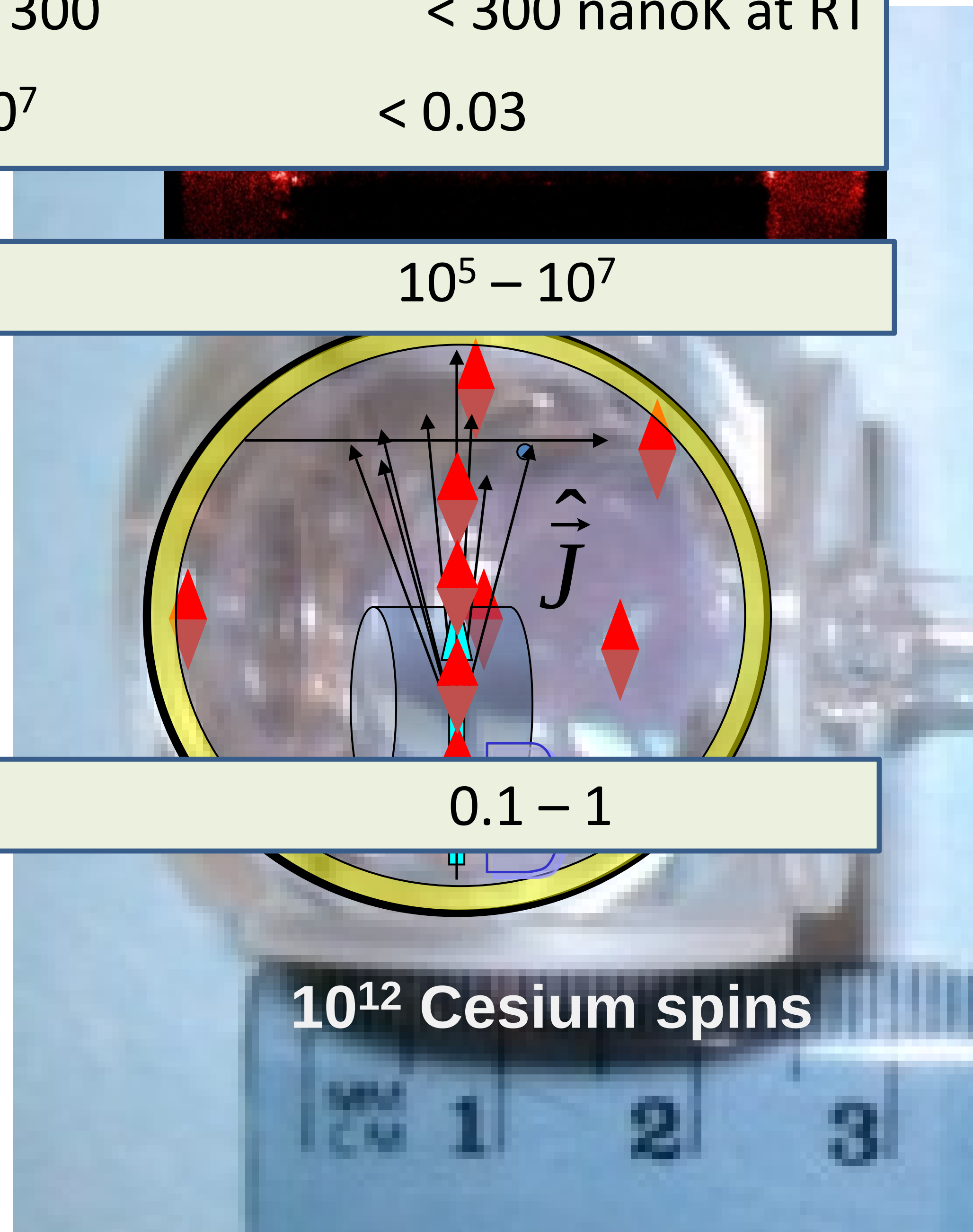
Copenhagen

KØBENHAVNS UNIVERSITET

# Quantum oscillators in the lab

| | | | |
|---|---|---|---|
| Temperature | 0.04 - 300 | 0.04 - 300 | < 300 nanoK at RT |
| $N_{thermal}$ | $1 - 10^7$ | $10^2 - 10^7$ | < 0.03 |
| Frequency(Hz) | $10^6 – 10^9$ | $10^6$ | $10^5 – 10^7$ |
| $T_2$ (sec) | $10^{-5} - 10^{-8}$ | 1 | 0.1 – 1 |





Task 3.1. Interconversion of microwaves and optical fields by means of a nanomechanical quantum interface.

**D3.1: Strong electro-mechanical coupling at room temperature [month 12]**

D3.2: Theoretical analysis of the microwave to optical interface using mechanical transduction [month 12]

**D3.3: Development of composite graphene-insulator, metal-insulator and semiconductor membrane actuators [month 24]**

D3.4: Theoretical analysis of quantum limits on sensitivity and bandwidth [month 24]

**D3.5: Demonstration of radio-frequency field readout with close-to-unity quantum efficiency [month 36]**

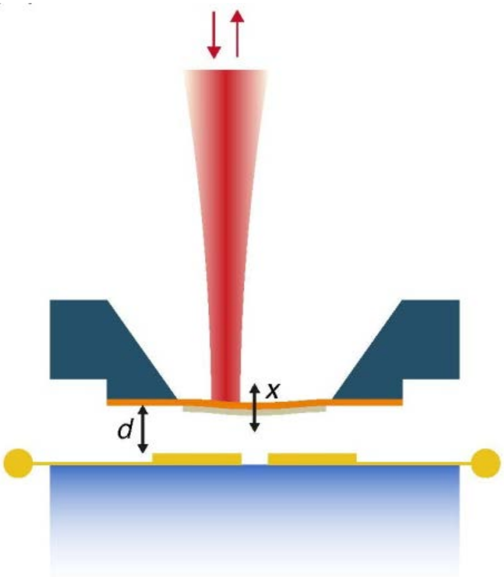
**D3.6: Demonstration of strong electro-mechanical coupling with superconducting LC circuit [month 36]**

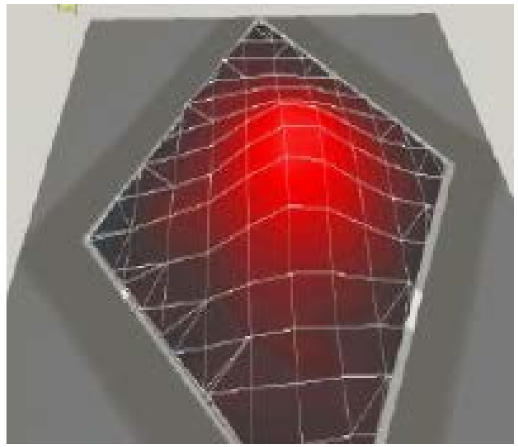
D3.7: Demonstration of a mechanical microwave amplifier with single phonon resolution [month 36]

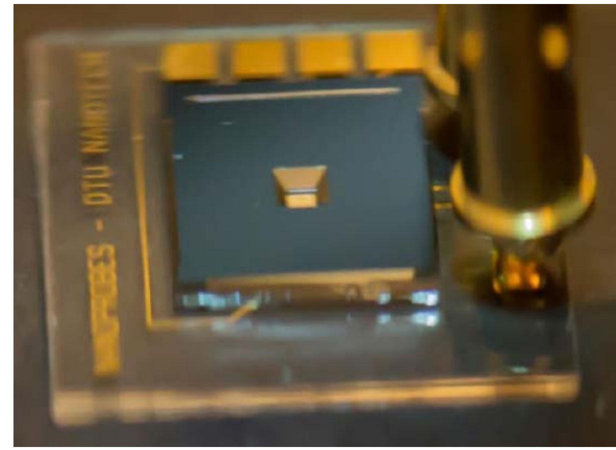
D3.8: Proof of principle demonstration of graphene-based photon-phonon-photon THz detector in the microwave regime [month 36]

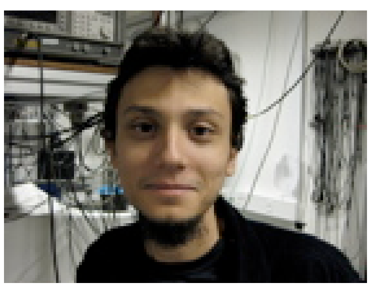
# Optical readout of radio waves through a nanomechanical transducer.

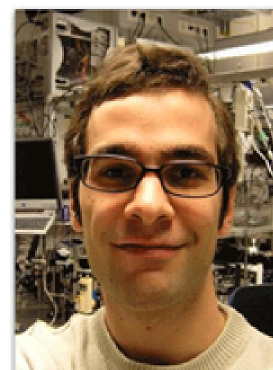
(in principle) accepted to Nature.









**T. Bagci, A. Simonsen, E. Zeuthen, A. Sørensen, K. Usami, A. Schliesser and ESP.**
*Niels Bohr Institute, Copenhagen*

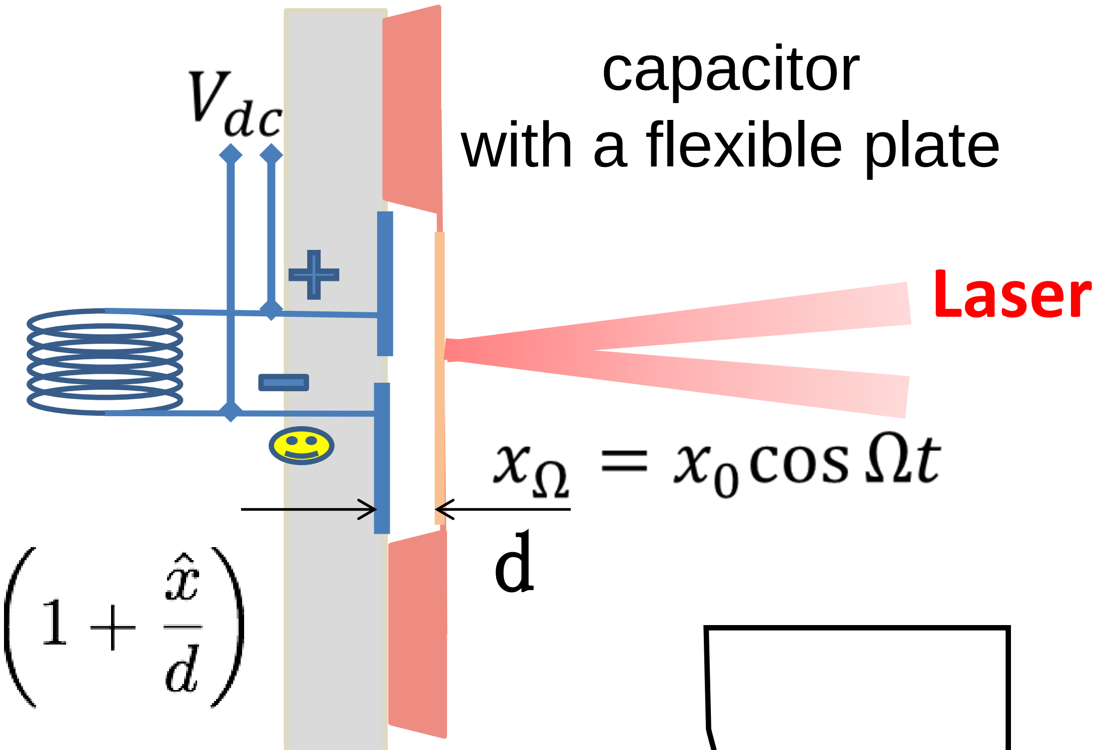
**J. M. Taylor** *Joint Quantum Institute, USA*

**L. G. Villanueva, S. Schmid** *Technical University of Denmark*

# Mechanically oscillating capacitor

$$C = \frac{\epsilon_0 A}{d}$$

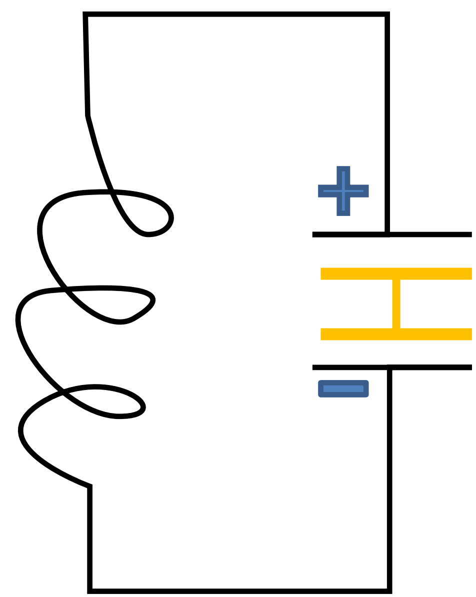
$$Q \propto V_\Omega = V_0 \cos \Omega t$$



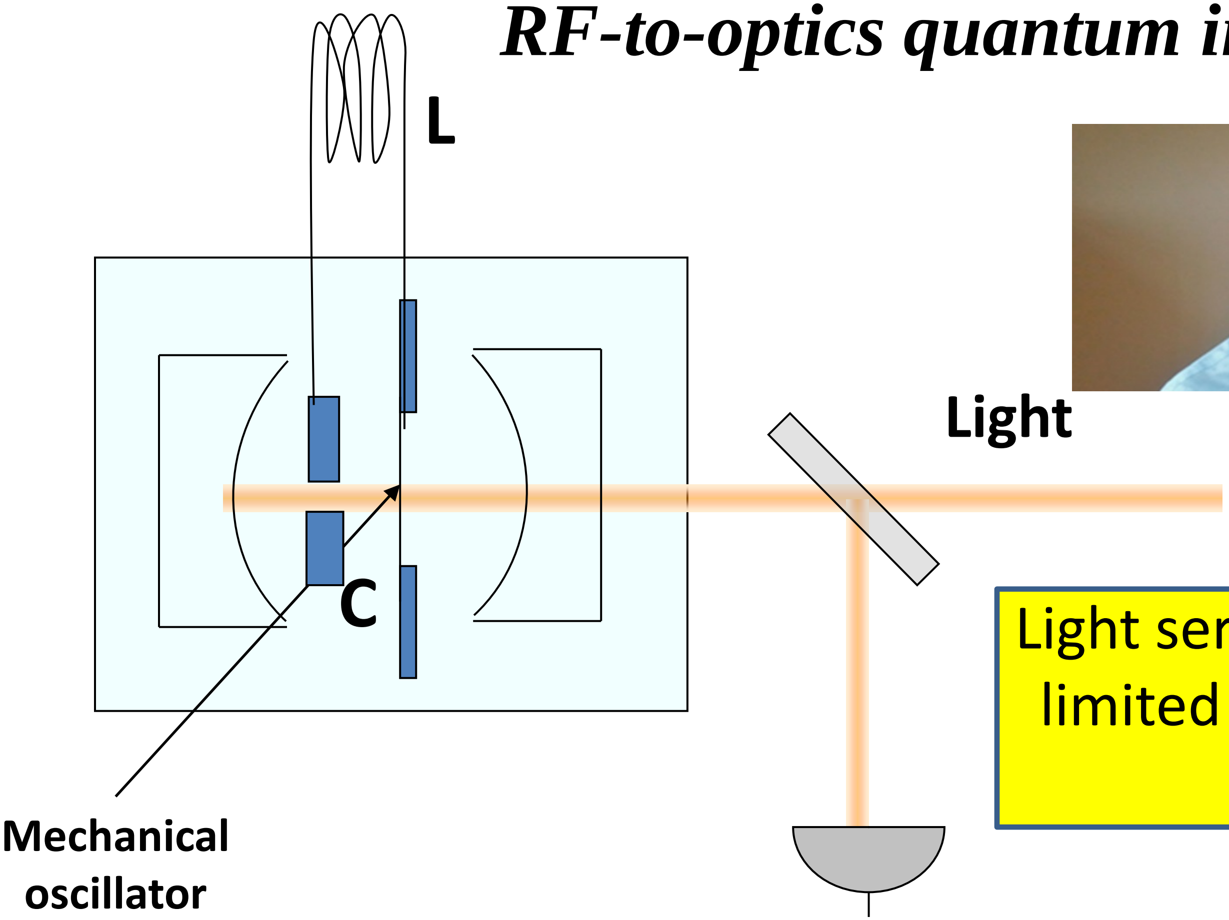

LC circuit : $H = \frac{\phi^2}{2L} + \frac{Q^2}{2C}\left(1 + \frac{\hat{x}}{d}\right)$

Linear electro-mechanical coupling
enhanced by dc voltage:

$$\tfrac{1}{2}CV^2 = C_0\left(1 + \frac{x_\Omega}{d}\right)(V_{dc} + V_\Omega)^2 \propto V_{dc}x_\Omega V_\Omega$$



# *RF-to-optics quantum interface*




Light serves as a (sub)-shot noise limited amplifier/readout of LC signals

PRL 107, 273601 (2011) PHYSICAL REVIEW LETTERS week ending 30 DECEMBER 2011

**Laser Cooling and Optical Detection of Excitations in a *LC* Electrical Circuit**

J. M. Taylor,[1] A. S. Sørensen,[2] C. M. Marcus,[3] and E. S. Polzik[2]

**Theory**

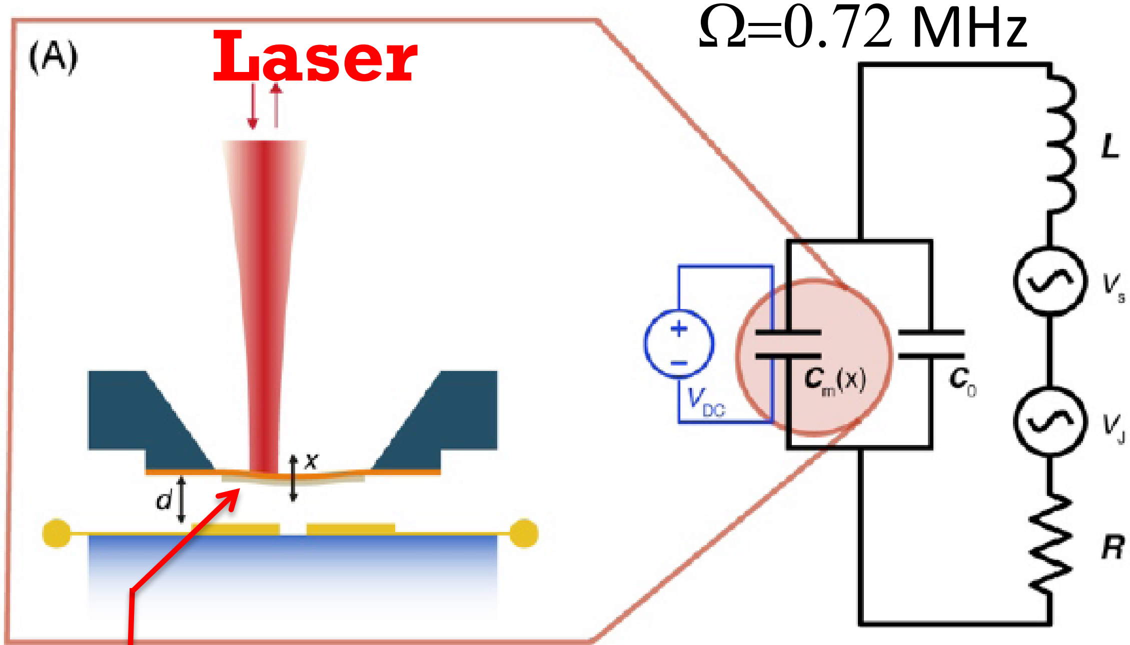
Highlight: March 2012 issue of Nature Photonics

# Opto-electro-mechanical hybrid

Antenna Q = 110

$\Gamma_{LC}$ = 7 kHz

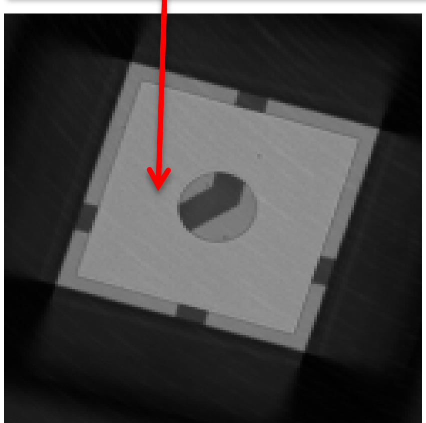
$\Omega$=0.72 MHz



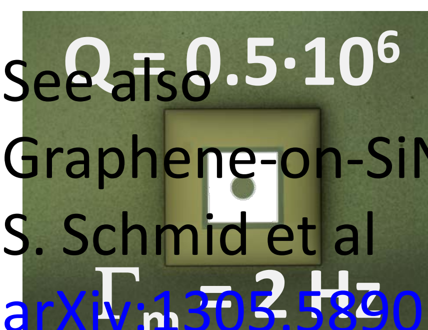

Cooperativity and coupling rate

$$C = \frac{g^2}{\gamma_m \Gamma_{LC}} \propto (V_{dc})^2$$

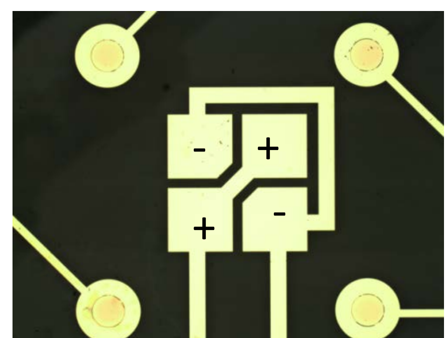
Electro-mechanical coupling: $\frac{1}{2}CV^2 = C_0\left(1+\frac{x_\Omega}{d}\right)(V_{dc}+V_\Omega)^2 \propto V_{dc}x_\Omega V_\Omega$



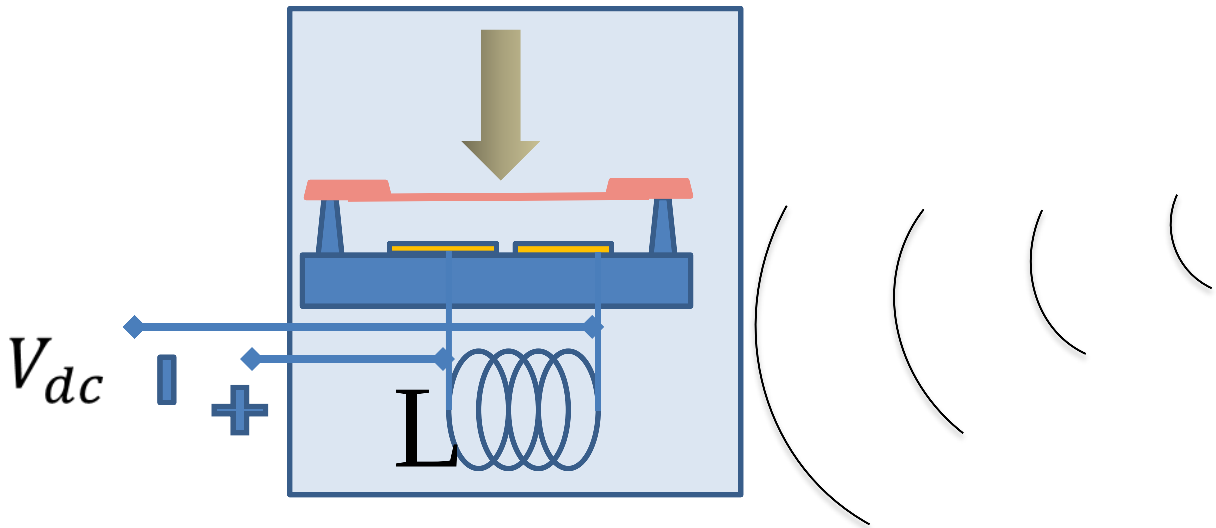
SiN – 100 nm + Al – 50 nm




See also
Graphene-on-SiN
S. Schmid et al
arXiv:1305.5890



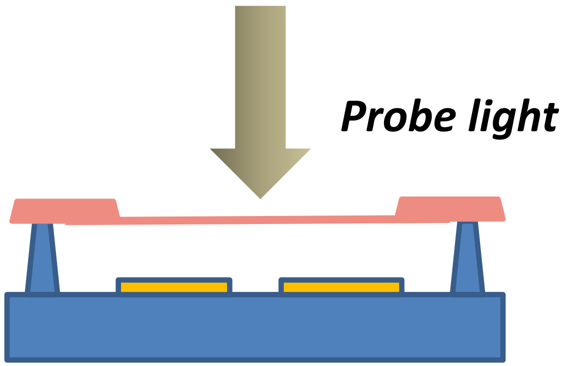
# Optical detection of electro-mechanical coupling: from Mechanically-Induced Transparency to Strong Coupling

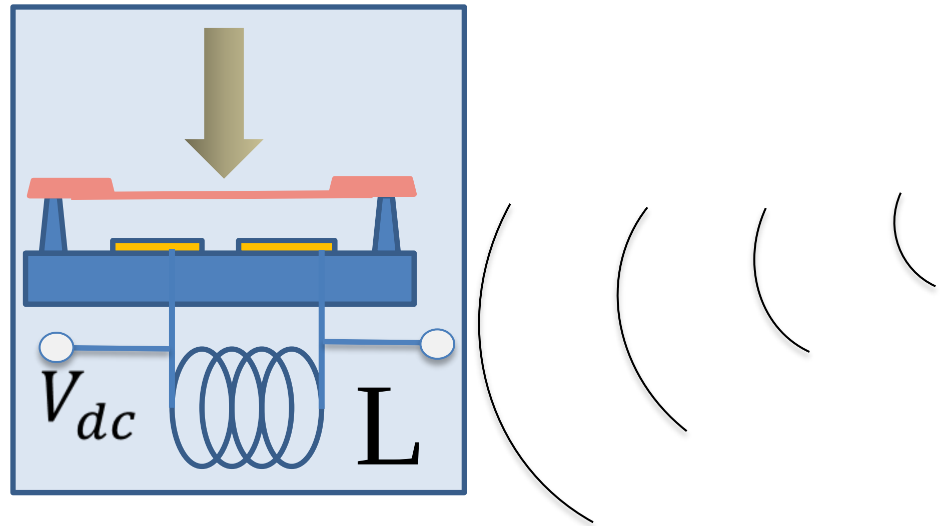



$$\frac{g^2}{\Omega^2} = \frac{C}{Q_{LC} Q_m} = \frac{\delta C}{C}$$

Strong coupling: $\frac{g}{\Omega} Q_{LC} = Q_{LC}\sqrt{\frac{\delta C}{C}} > 1$

# Optical and electrical readout of coupled electro-mechanical oscillators



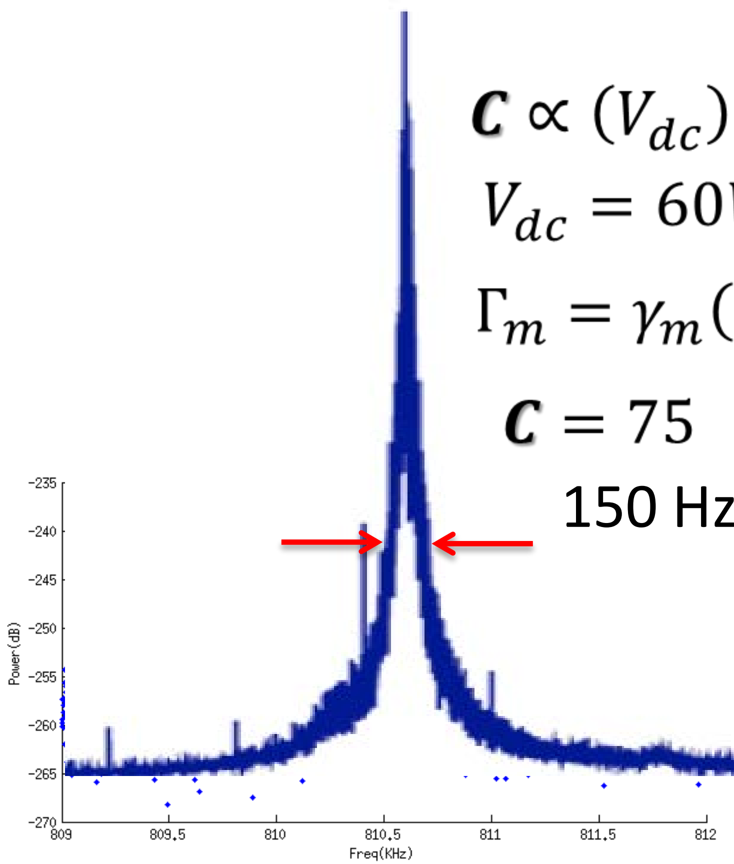




$$\mathcal{C} \propto (V_{dc})^2$$

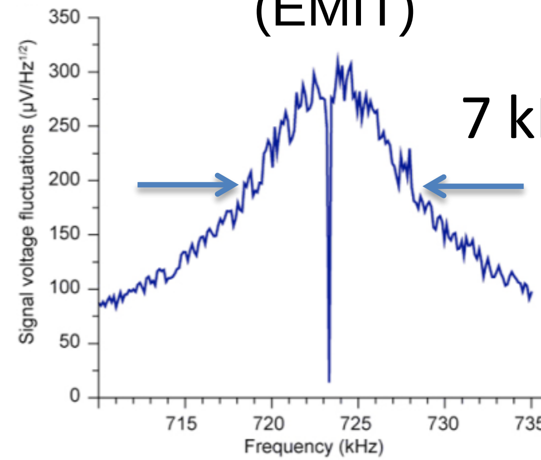
$$V_{dc} = 60V$$

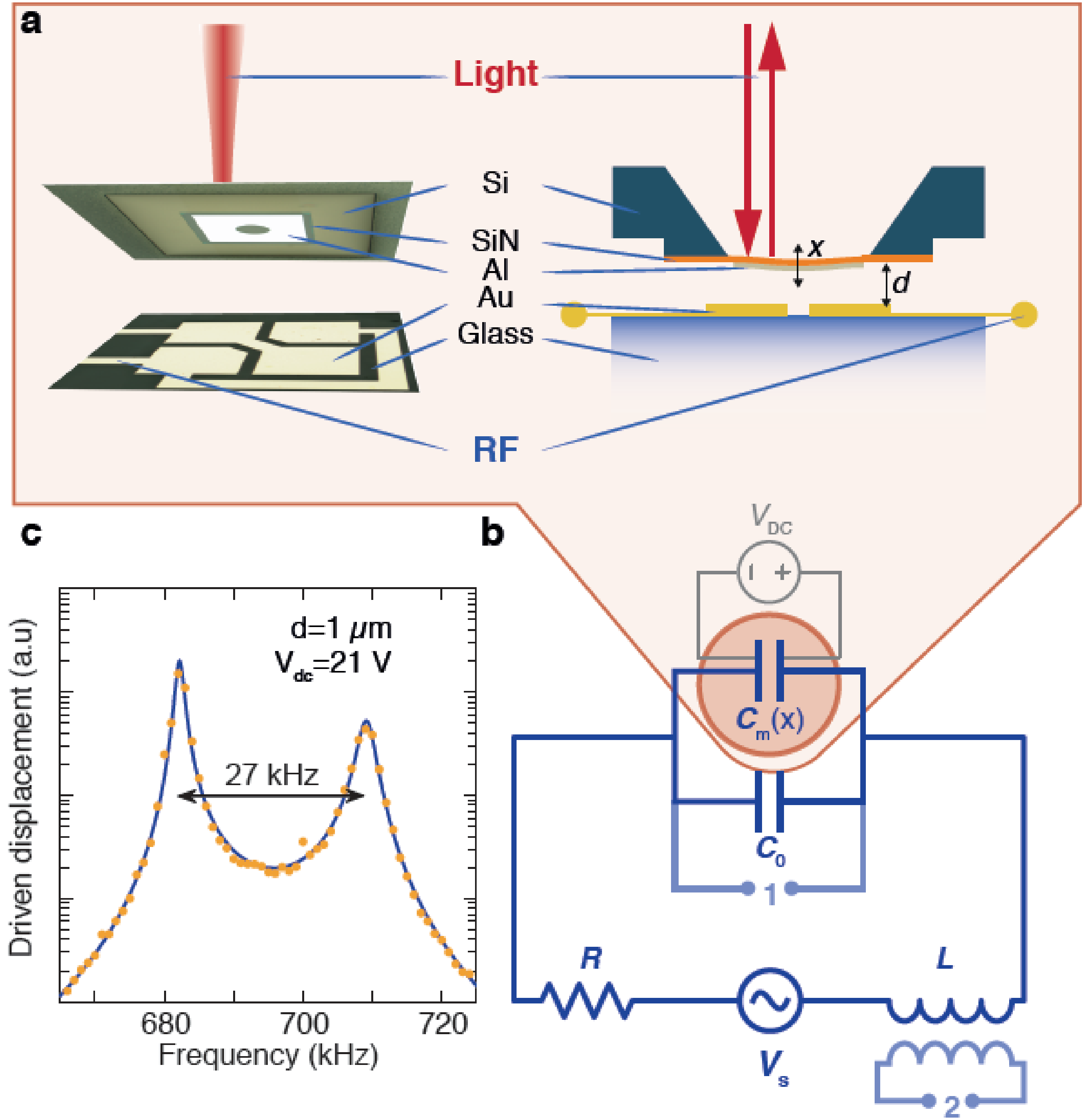
$$\Gamma_m = \gamma_m(1 + \mathcal{C})$$

$$\mathcal{C} = 75$$



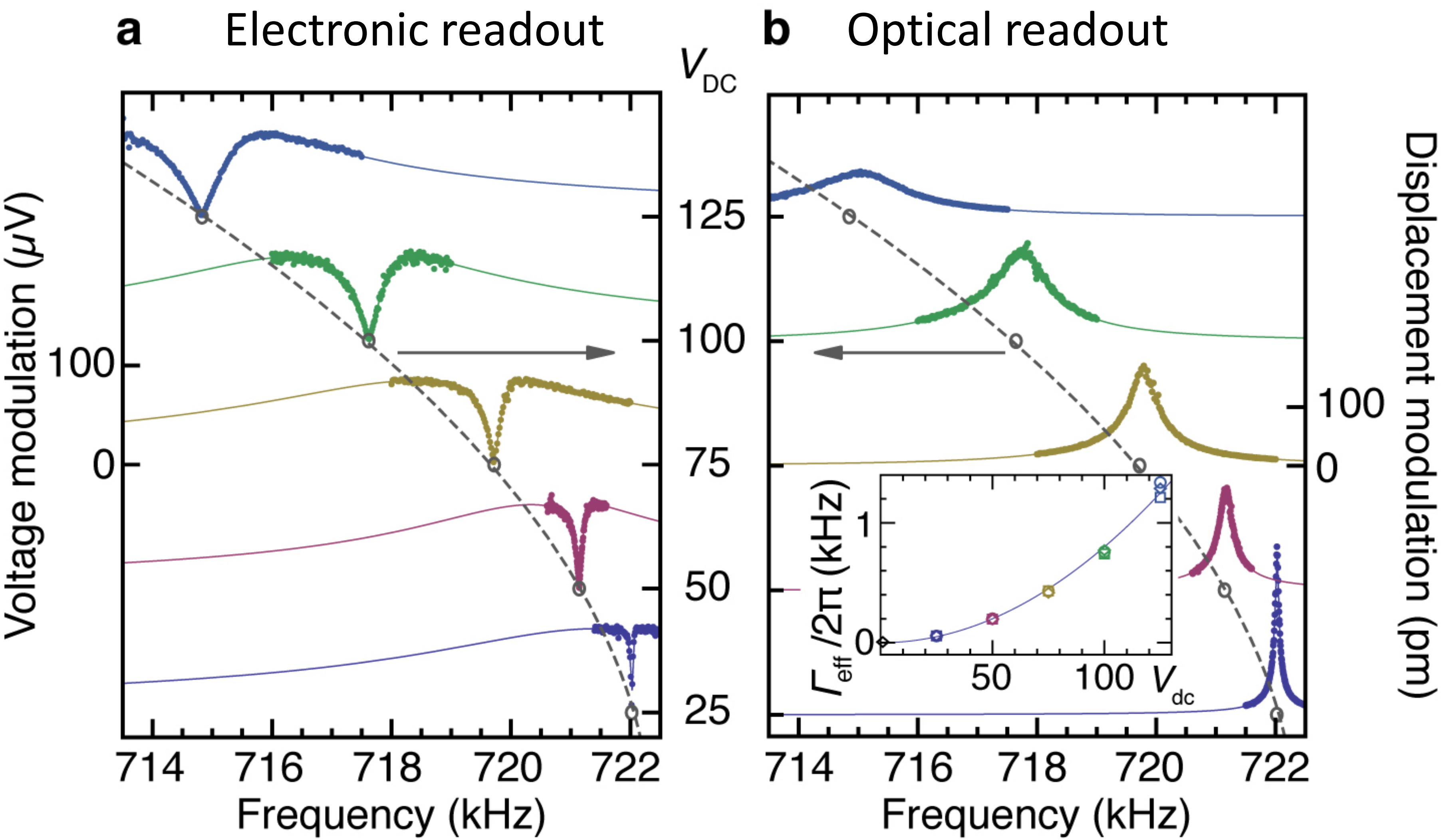

LC resonance coupled to mechanics
Electrical Mechanically-induced transparency
(EMIT)





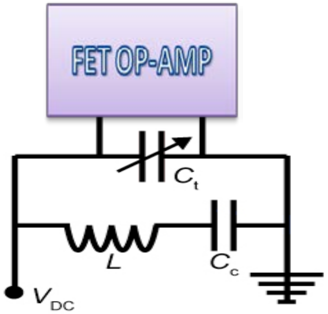
a
Light
Si
SiN
Al
Au
Glass
x
d
RF
b
$V_{DC}$
$C_m(x)$
$C_0$
1
R
L
$V_s$
2
c
d=1 μm
$V_{dc}$=21 V
27 kHz
Driven displacement (a.u)
680
700
720
Frequency (kHz)

# Electrical Mechanically-induced transparency (EMIT)

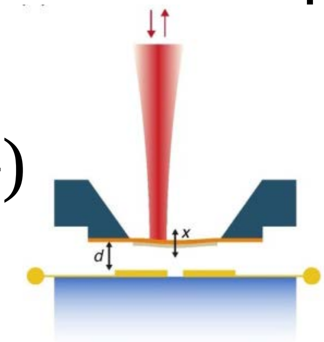


# Optical readout of strong electro-mechanical coupling

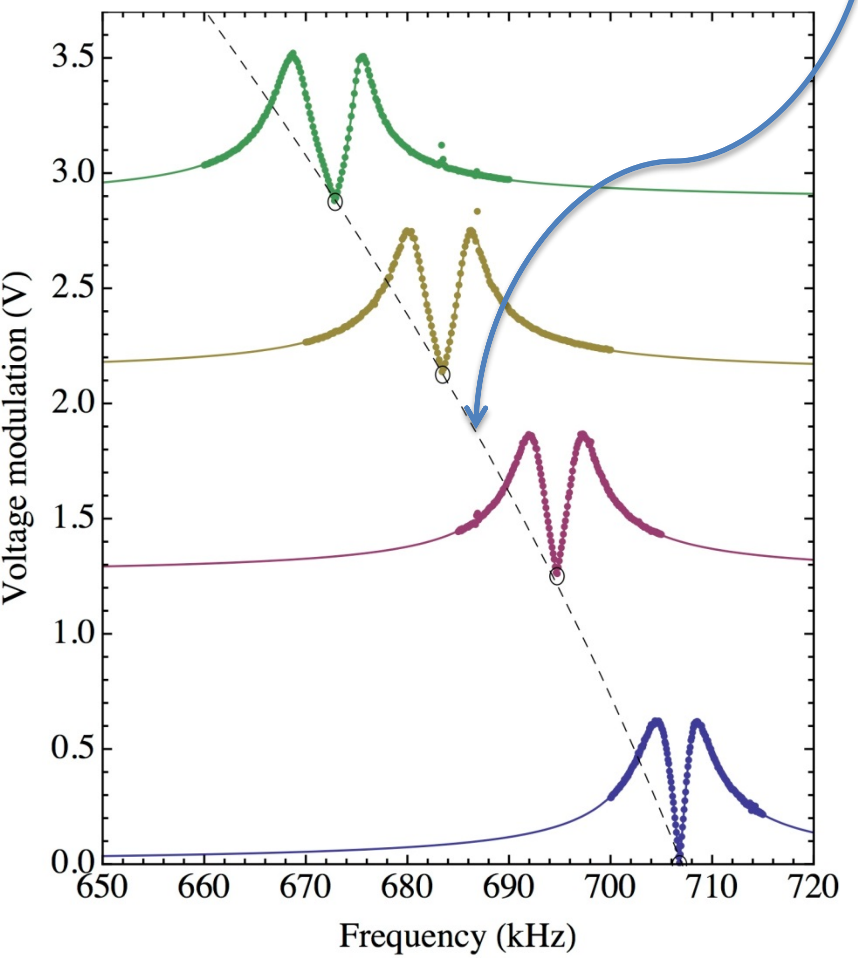
Electrically measured LC response




$$f = f_0\left(1 - \frac{d^2C}{dx^2}\frac{V_{DC}^{\ 2}}{2k_0}\right)$$




Optically observed membrane resonance



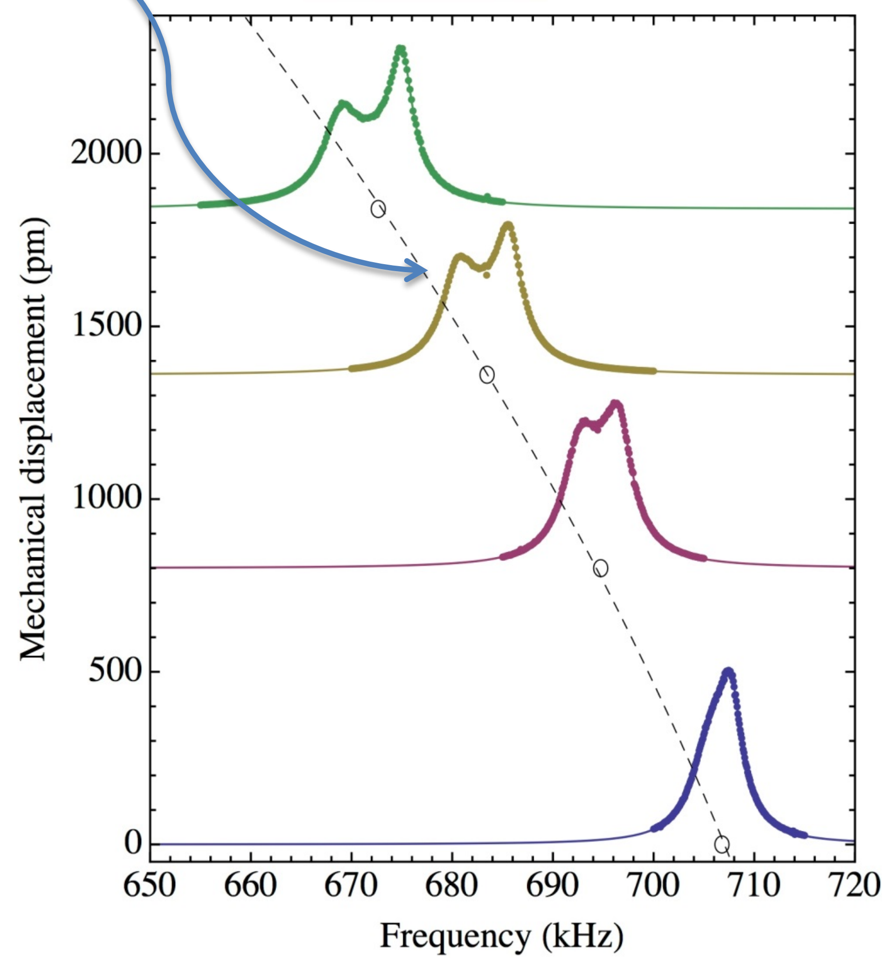

DC

290V

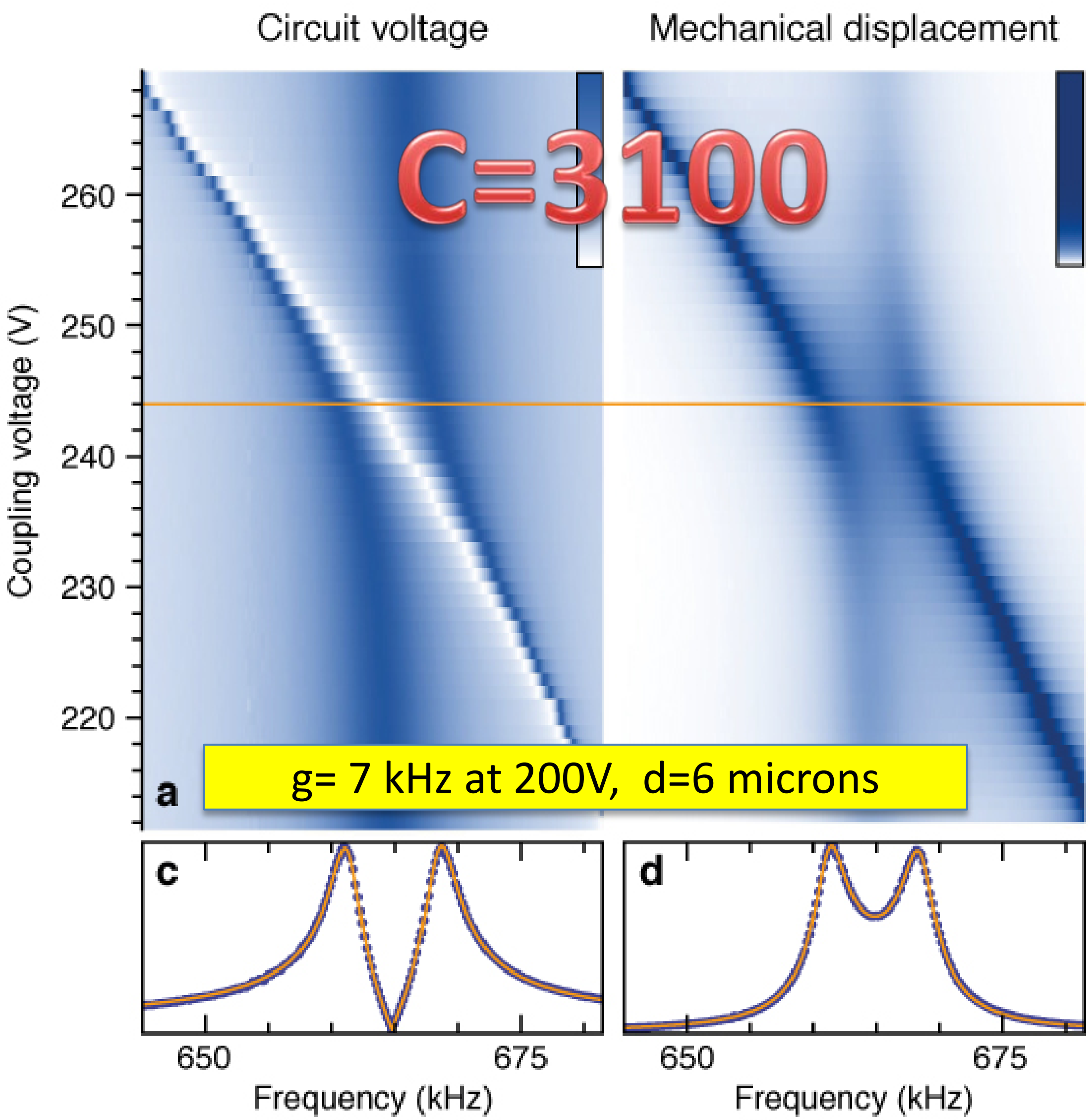
260V

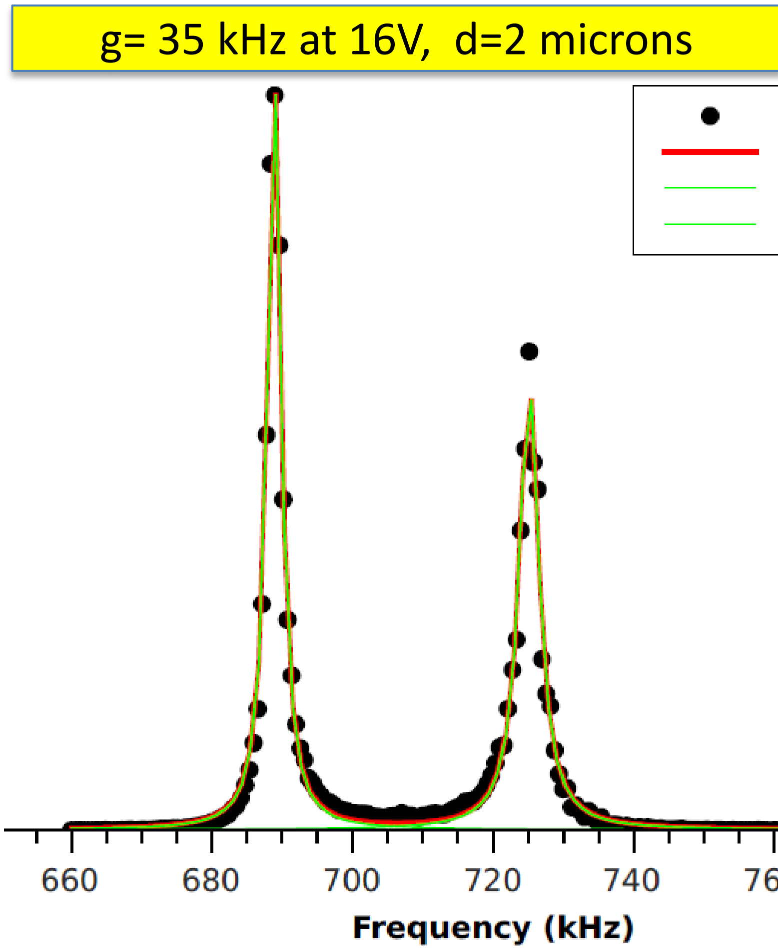
225V

175V

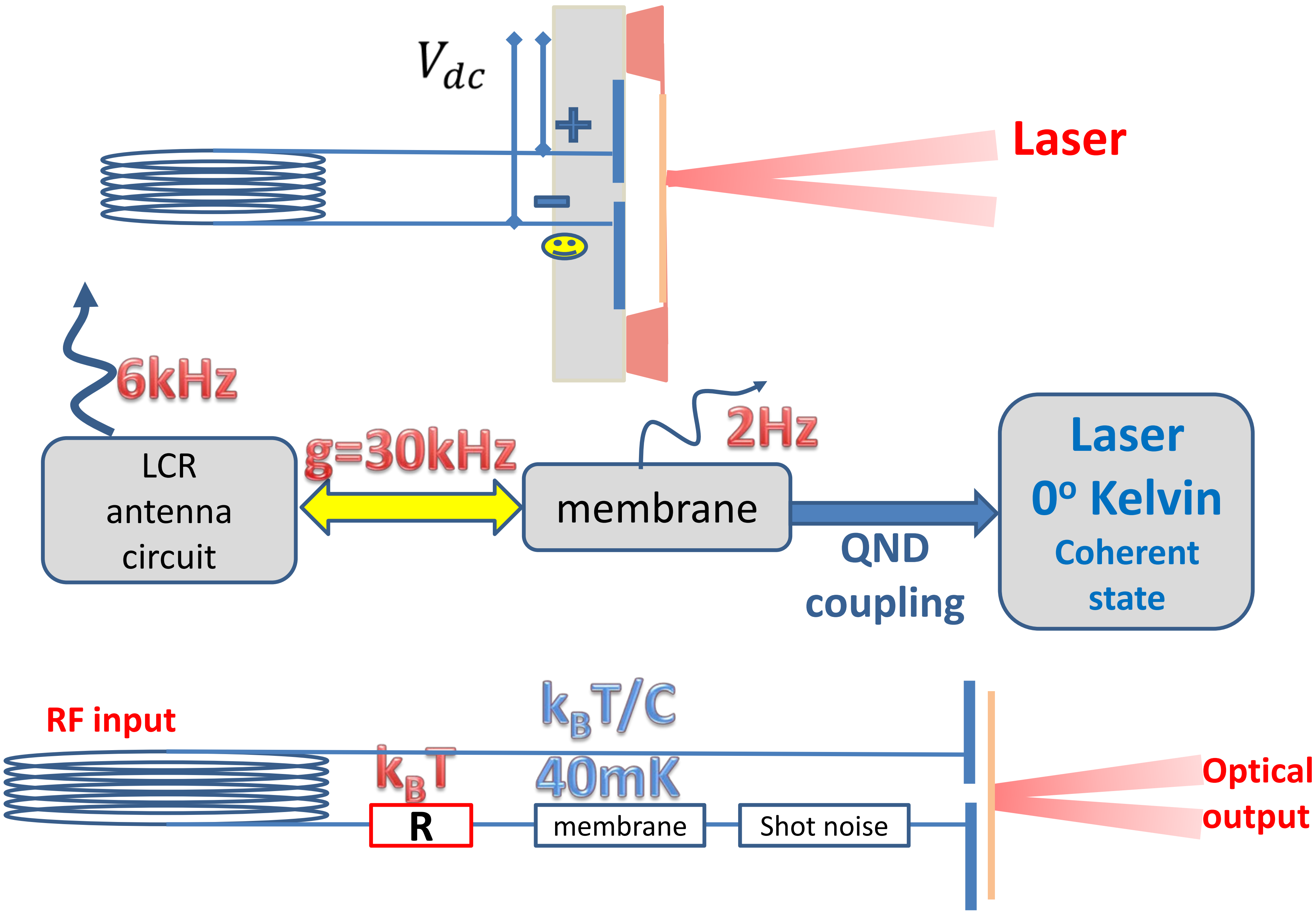


# Optical observation of electro-mechanical normal mode splitting and anti-crossing

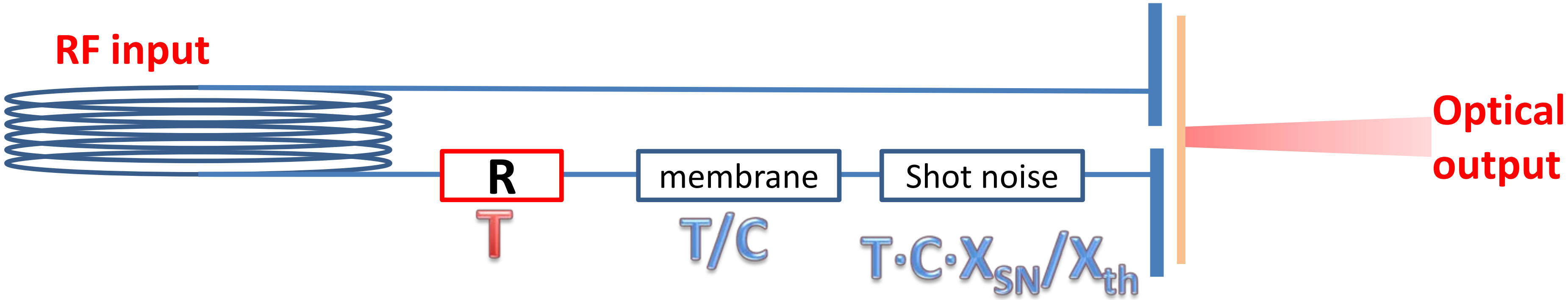


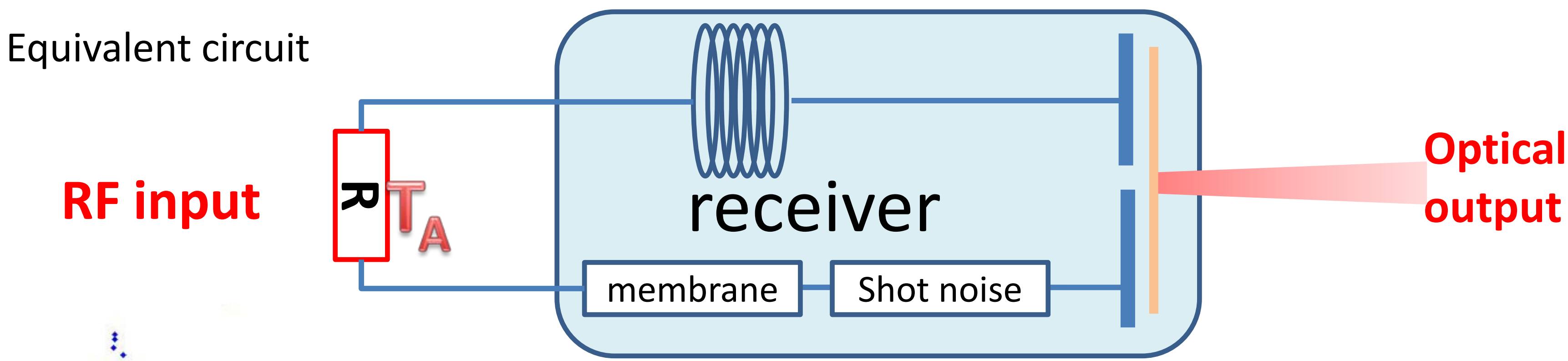



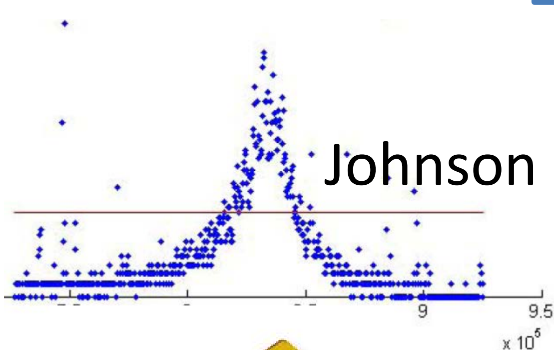
# Noise sources of the rf-to-optical transducer



# Sensitivity and added noise of the rf-to-optical transducer



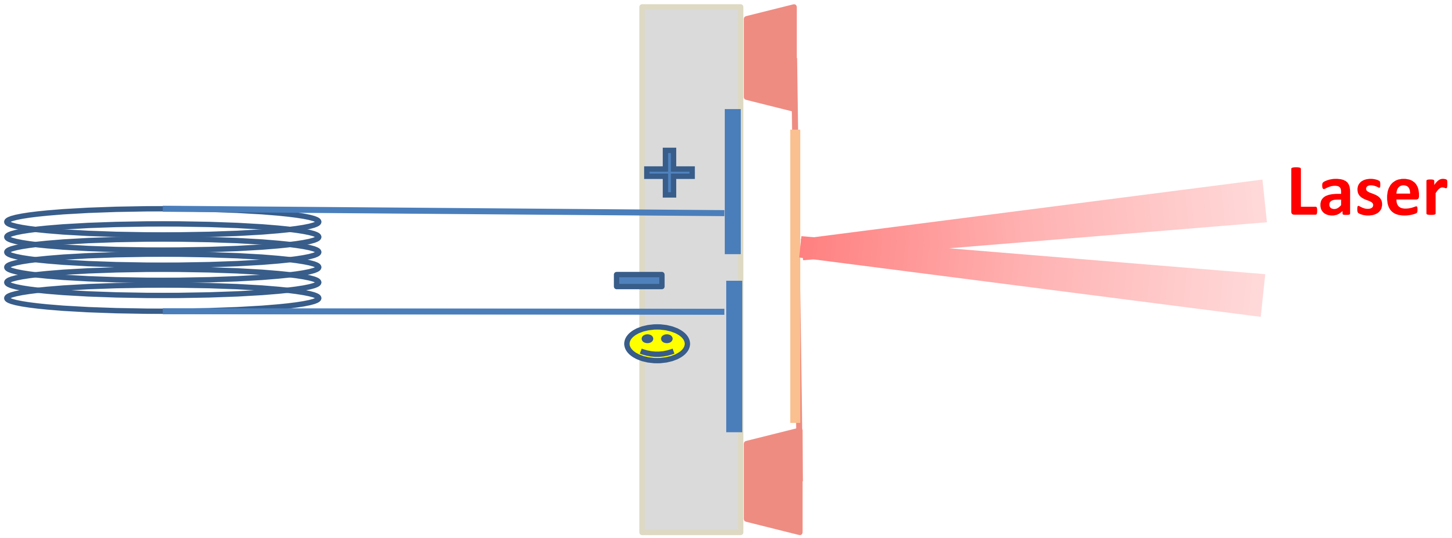

Johnson noise

$T/C + T \cdot C \cdot X_{SN}/X_{th}$


$$T_{min} = 2T\frac{X_{SN}}{X_{th}} = 600mK$$ achieved

$$= 80\text{mK}$$ feasible

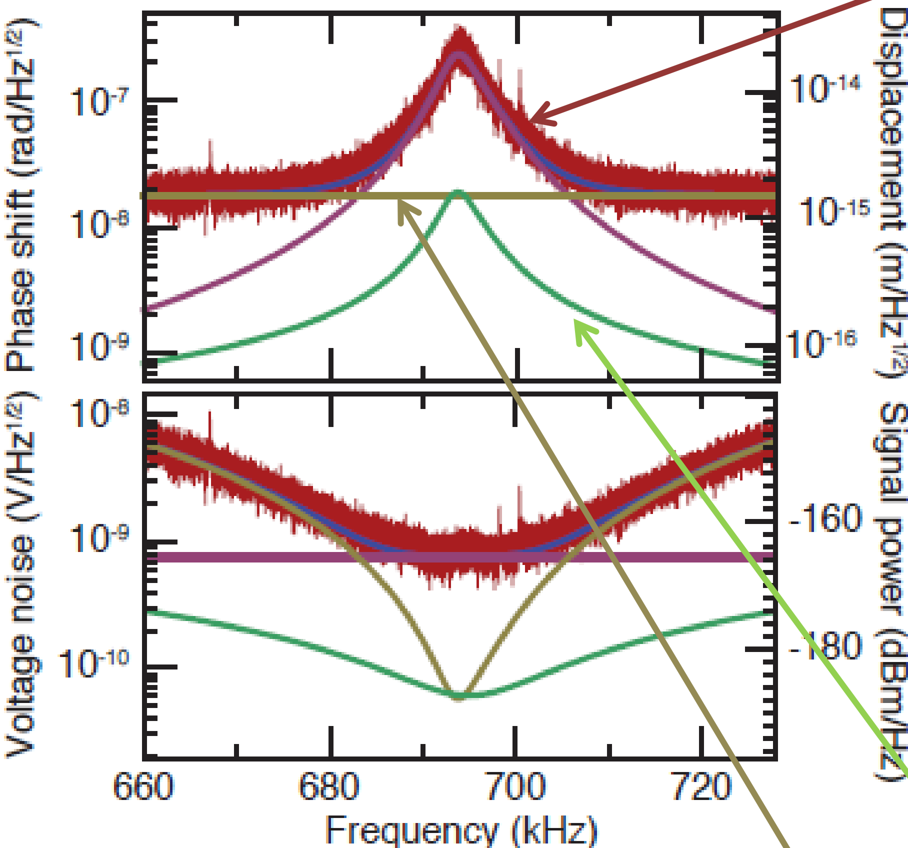
# Used as light modulator – half wave V = 140 microVolts

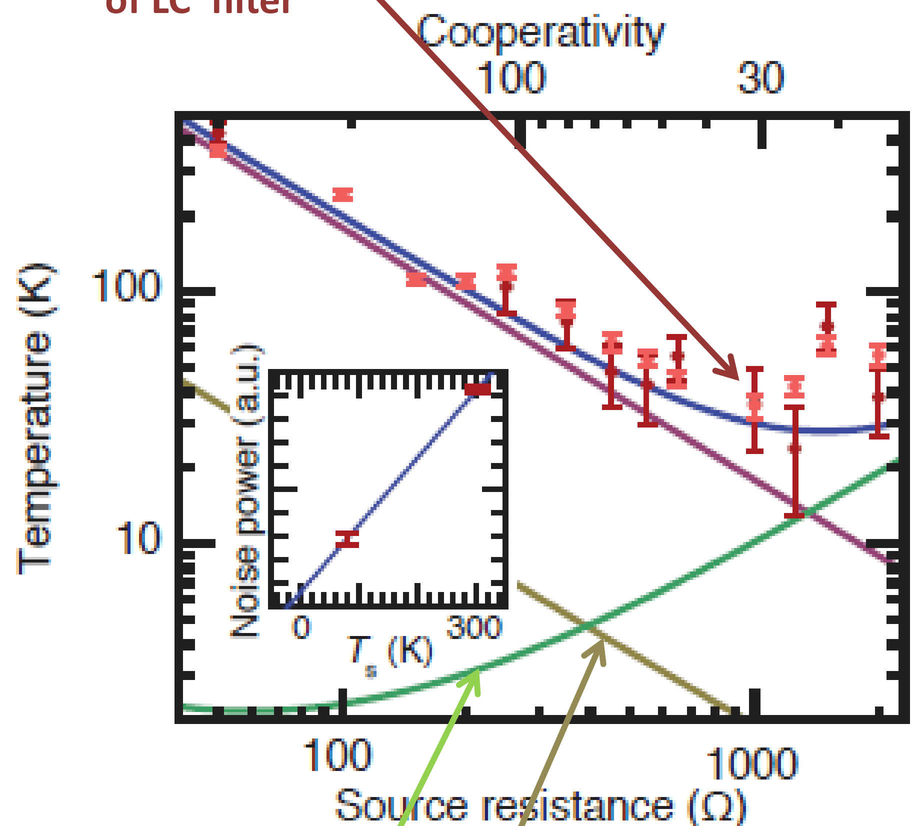



**RF to optical quantum efficiency**
**10% observed**
**>100% feasible (it is an amplifier)**

$$\eta_{eo} = 4(kx_{zpf})^2 \frac{\Phi_{car}}{\Gamma_m}.$$

# Sensitivity and added noise of the rf-to-optical transducer



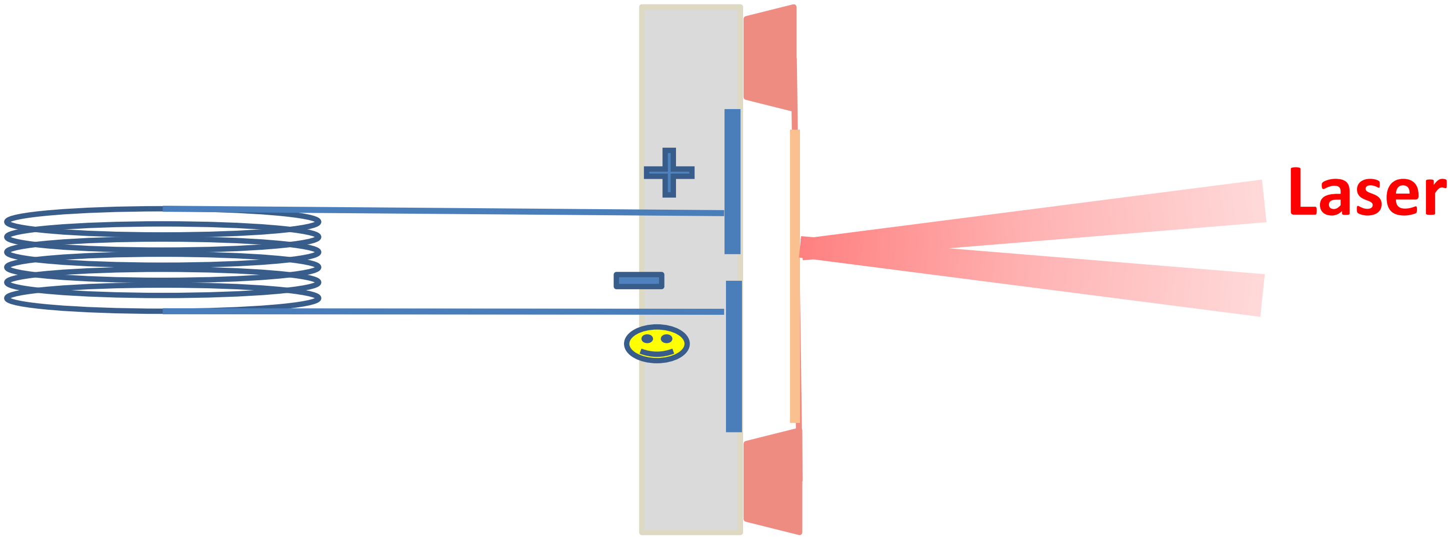




Johnson noise of LC filter

Membrane thermal noise 60pV/√Hz

Laser quantum noise 60pV/√Hz

# Used as light modulator – half wave V = 140 microVolts



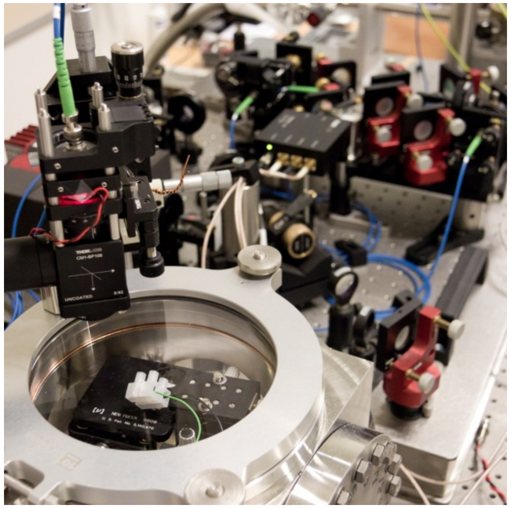

**RF to optical quantum efficiency**
**≈10% observed**
**>100% feasible (it is an amplifier)**

$$\eta_{eo} = 4(k x_{zpf})^2 \frac{\Phi_{car}}{\Gamma_m}.$$

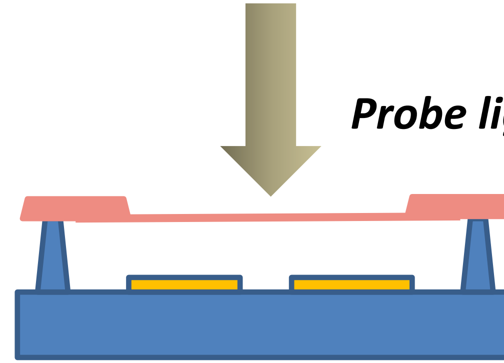
# Summary

- Strong electro-mechanical coupling at room temperature
- Optical read-out and amplification of electronic signals
- Added noise floor of 40 milliKelvin
- Nanomechanical transduction from RF to optics
- All-optical processing of electronic signals
- Extension to microwave-to-optics

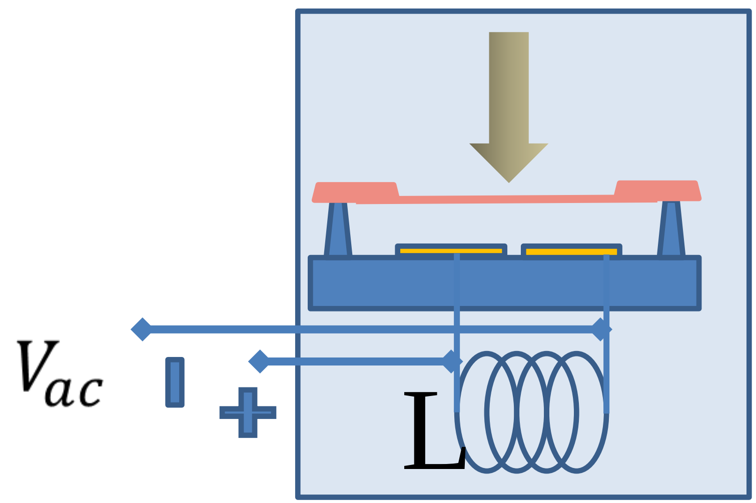
# Outlook



Integrated interferometer




Medium F cavity formed by membrane + chip

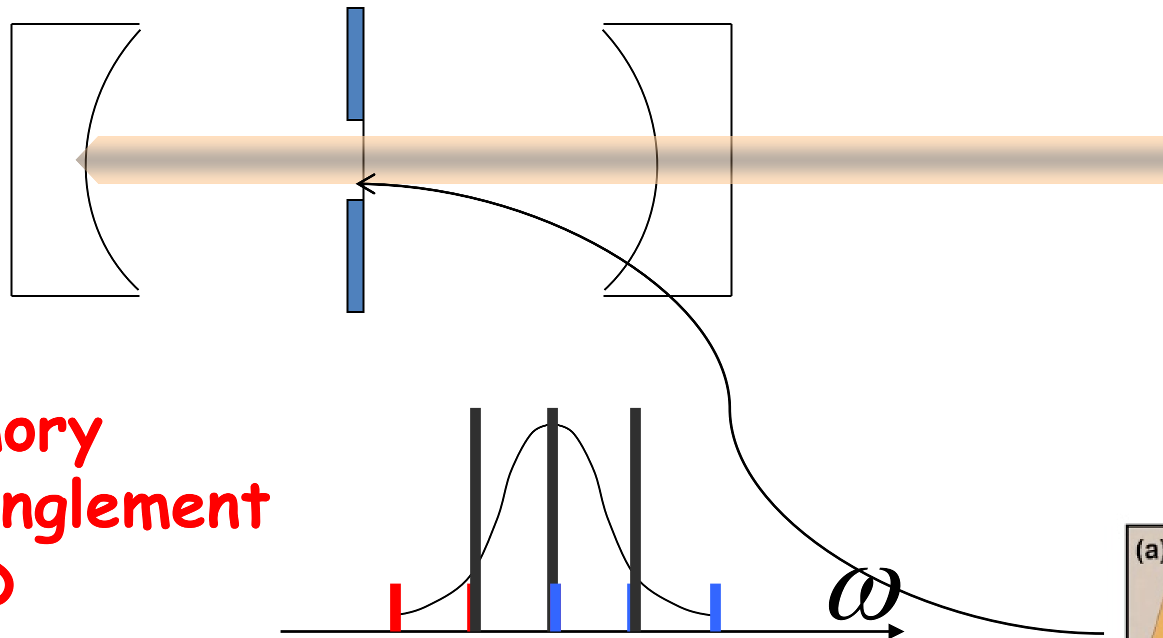


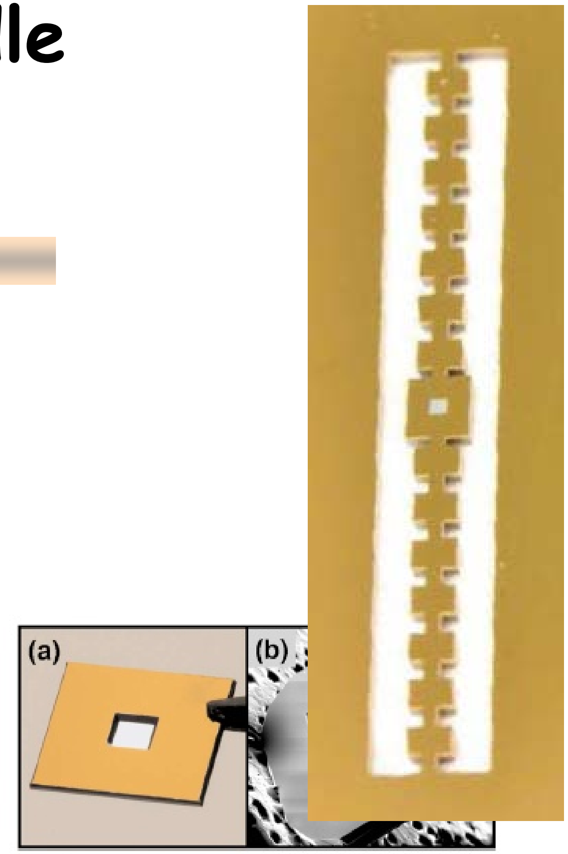

From dc to ac drive

GHz

SUPERCONDUCTING LC

# Membrane in the middle




**Memory**
**Entanglement**
**QND**
**…**

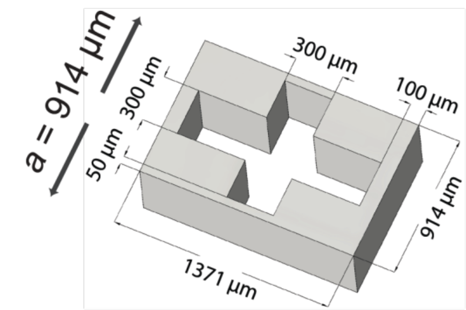
$$H=\chi_{Par}\hat{a}^{\dagger}\hat{b}^{\dagger}+\chi_{BS}\hat{a}^{\dagger}\hat{b}+h.c.\Rightarrow\sqrt{2}\chi\hat{P}_{L}\hat{P}_{A},\ if\ \chi_{Par}=\chi_{BS}$$

phoTon phoNon

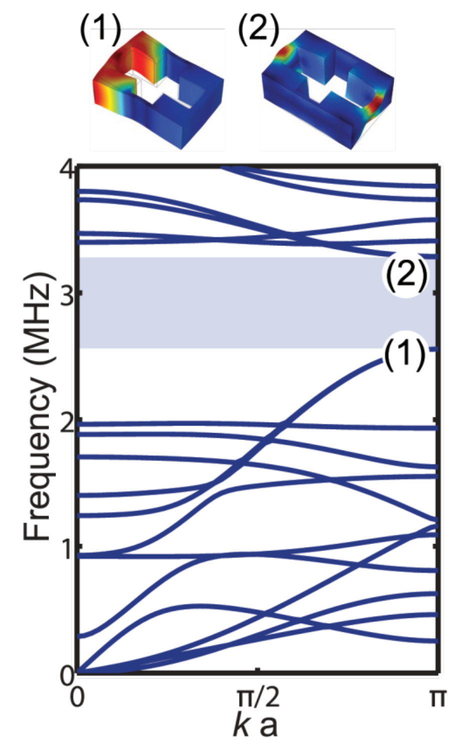
# Suppression of phonon tunneling losses in membrane resonators

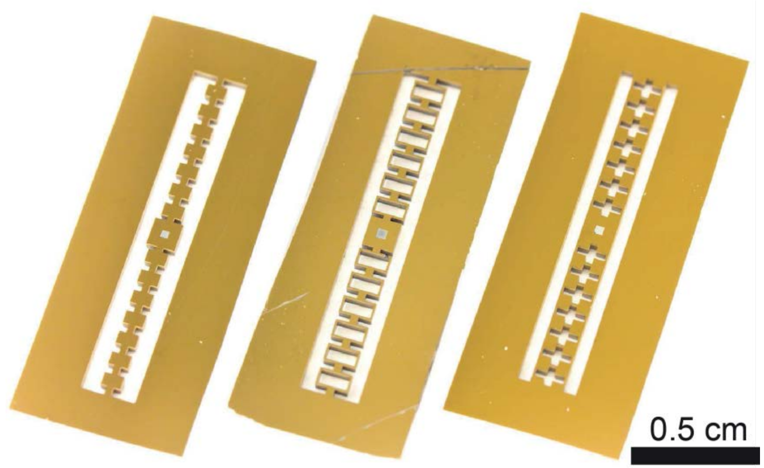
**Yeghishe Tsaturyan[1], Andreas Barg[1], Anders Simonsen[1], Luis Guillermo Villanueva[2], Silvan Schmid[2], Albert Schliesser[1] and Eugene S. Polzik[1]**

[1] *Niels Bohr Institute, Copenhagen University, Blegdamsvej 17, 2100 Copenhagen, Denmark*
[2] *Department of Micro- and Nanotechnology, Technical University of Denmark, 2800 Kongens Lyngby, Denmark*



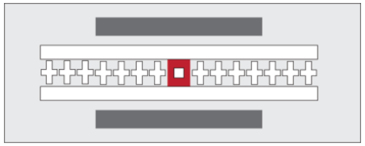

- Clamping losses set an upper limit to mechanical *Q*-factor
- Tailor the phononic state density in the membrane frame with a phononic structure
- Membrane modes of interest - inside the phononic bandgap, thus decoupling from the environment

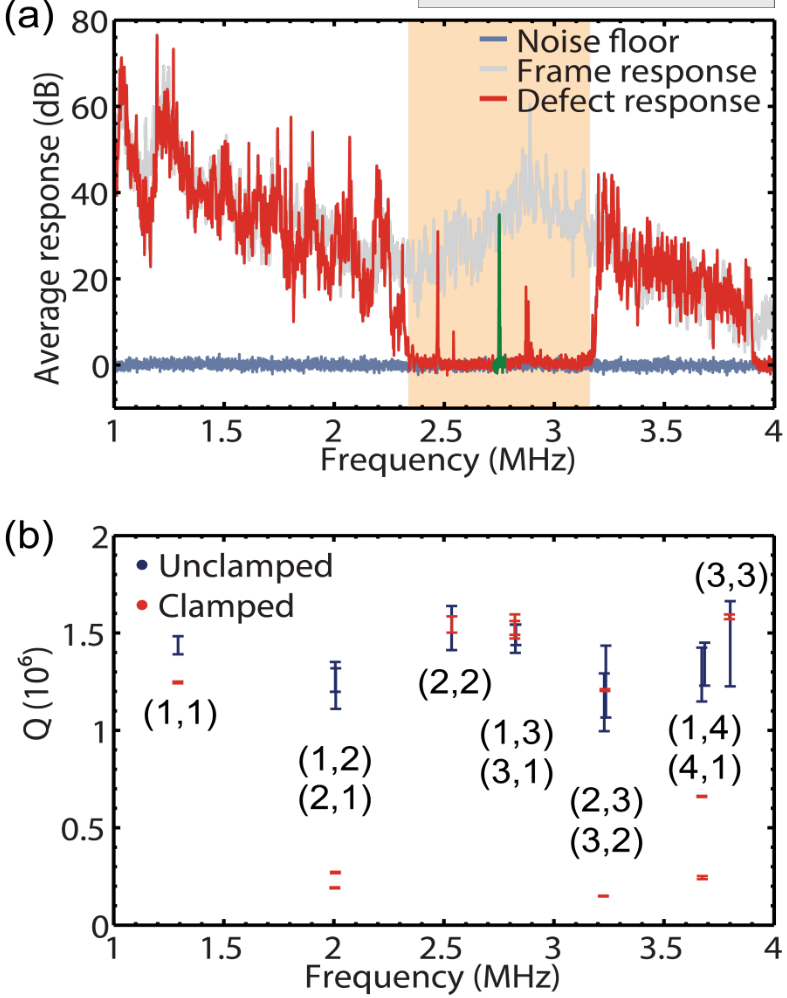


# Suppression of phonon tunneling losses in membrane resonators

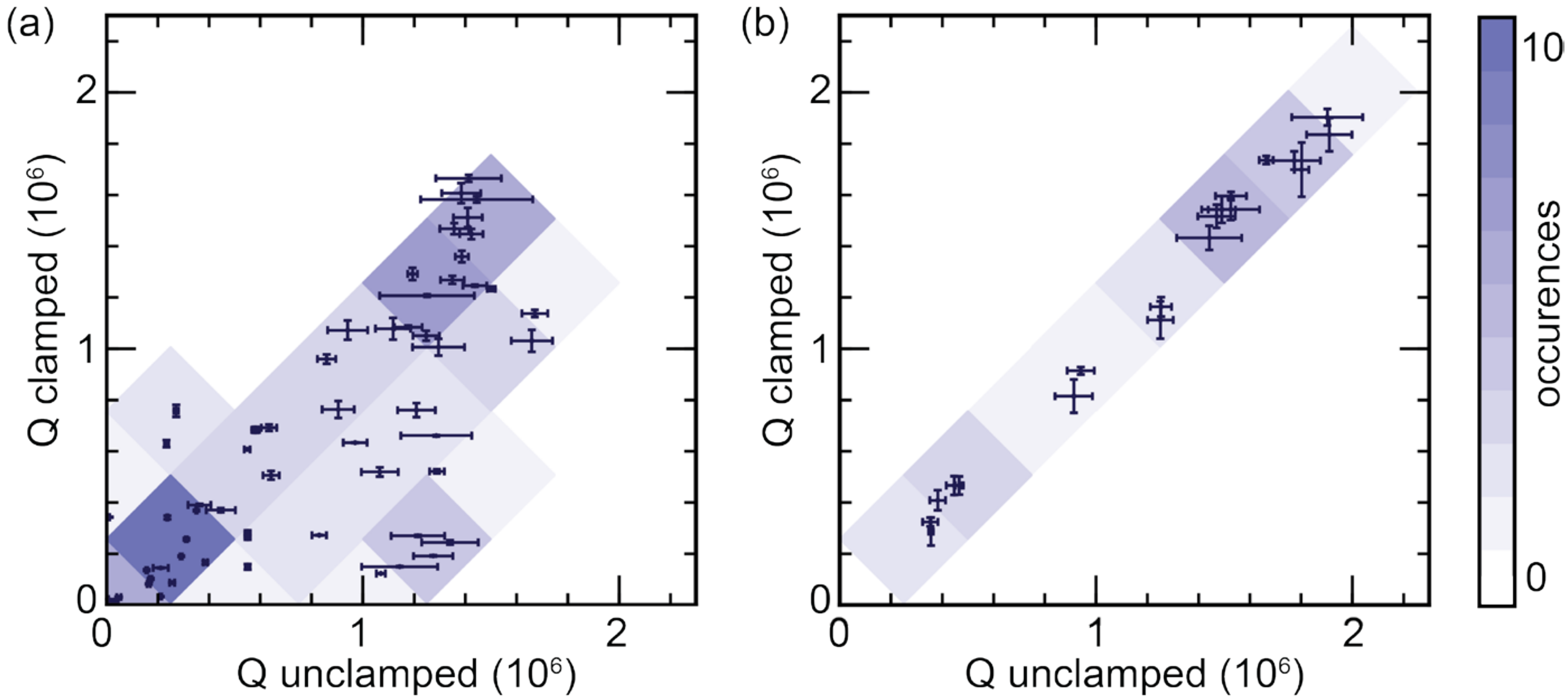
- Driven response measurements of the displacement, measured on the defect and the frame
- Up to 40 dB suppression inside the phononic bandgap
- Ringdown measurements, with free-standing and bolted down samples
- Modes inside the bandgap are unaffected by clamping





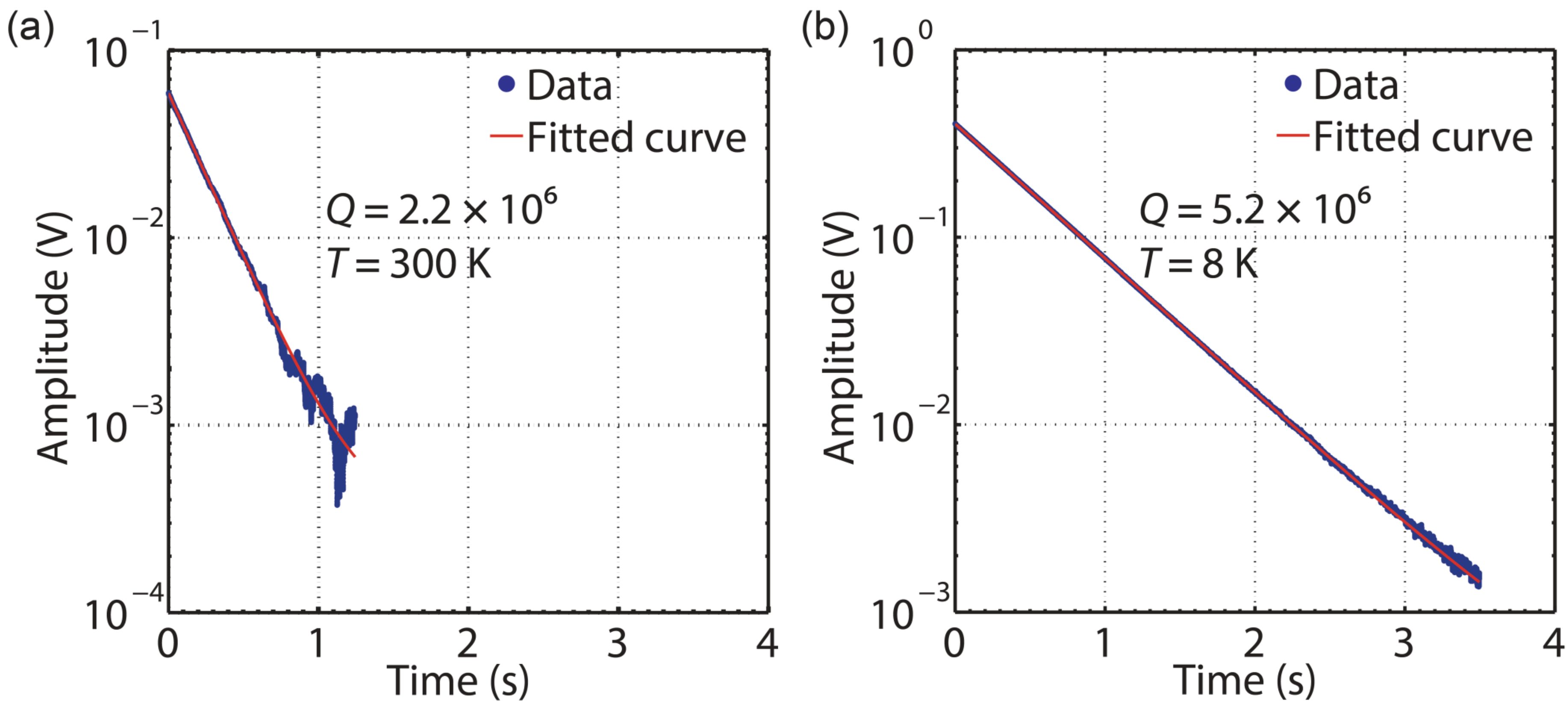
# Suppression of phonon tunneling losses in membrane resonators

- Compilation of clamped/unclamped ringdown measurements (7 samples, 11 membrane modes on each)
- Data sorted into modes outside (a) and inside (b) a bandgap.

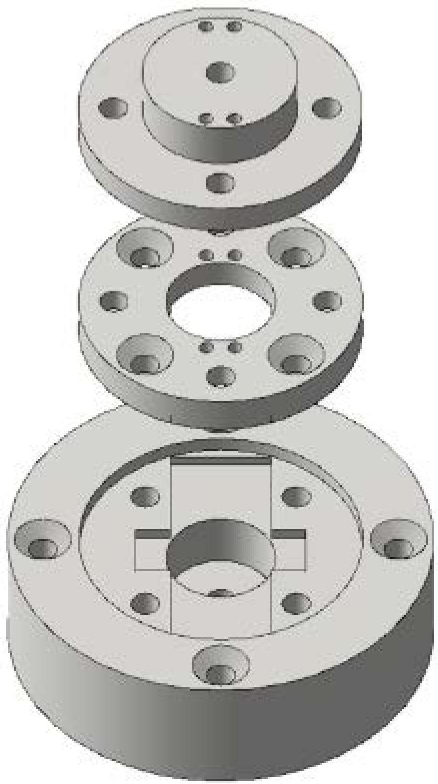


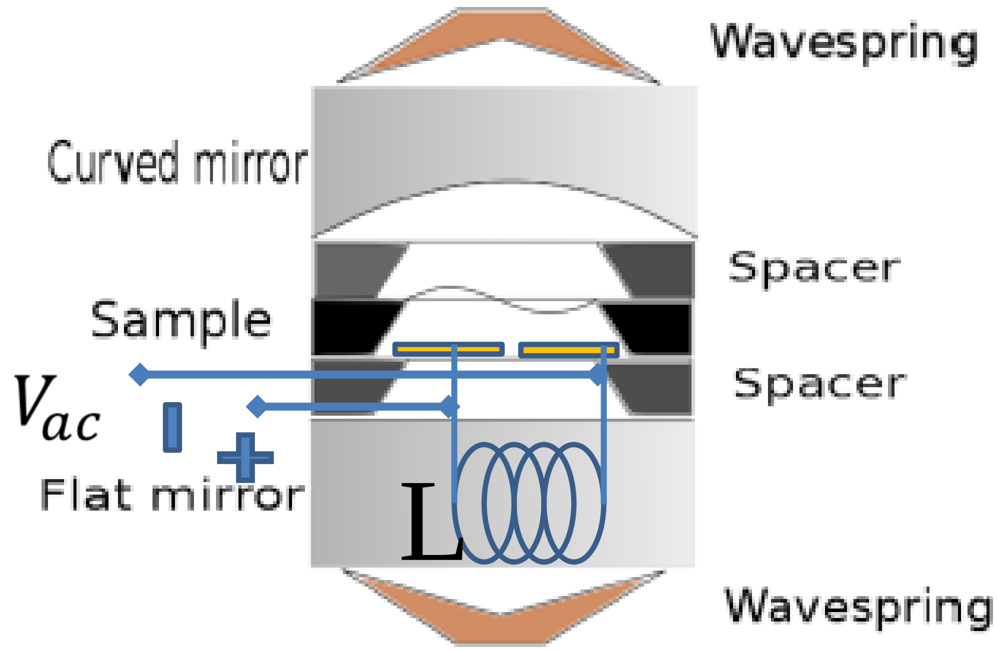
# Suppression of phonon tunneling losses in membrane resonators

- Cryogenic measurements with the sample bolted to the cold finger
- Q × *f* – products of 6 × $10^{12}$ Hz at 300 K and 14 × $10^{12}$ Hz at 8 K



# Solid cryogenic cavity design

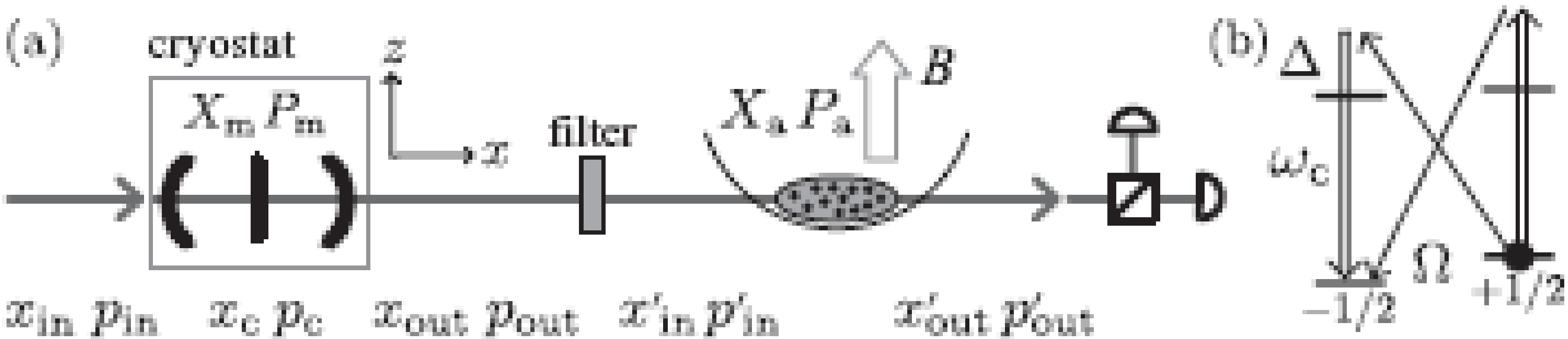





Towards photon-phonon-photon strong coupling

# Towards probing mechanical oscillator beyond SQL

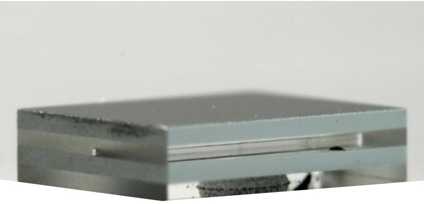
Entanglement of a mechanical oscillator (positive mass) with an atomic ensemble (”negative mass”)

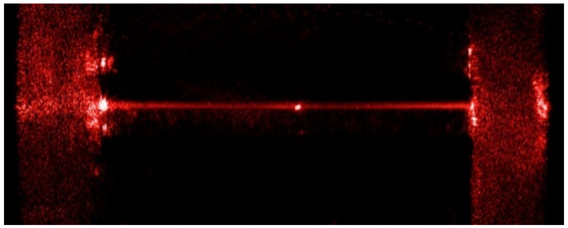



**mechanical oscillator**

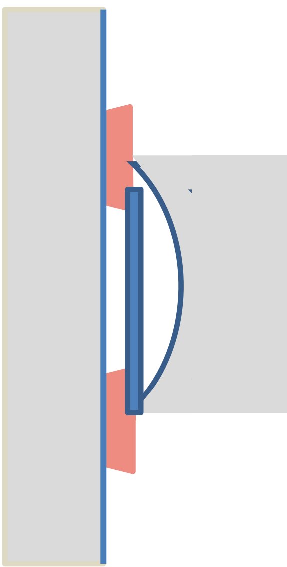
**”Negative mass” oscillator**

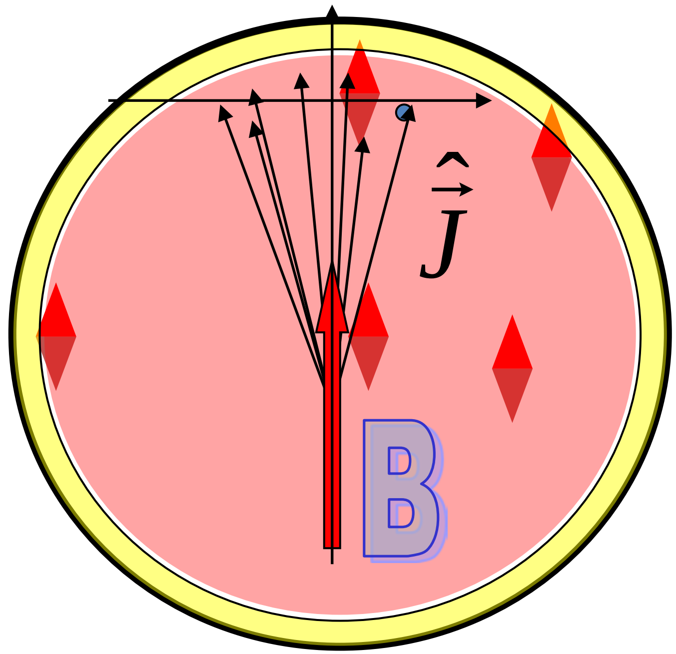
Establishing Einstein-Podolsky-Rosen channels between nanomechanics and atomic ensembles. K. Hammerer, M. Aspelmeyer, E.S. Polzik, P. Zoller. **Phys. Rev. Lett.** 102, 020501 (2009).





# Quantum optical interface for disparate oscillators



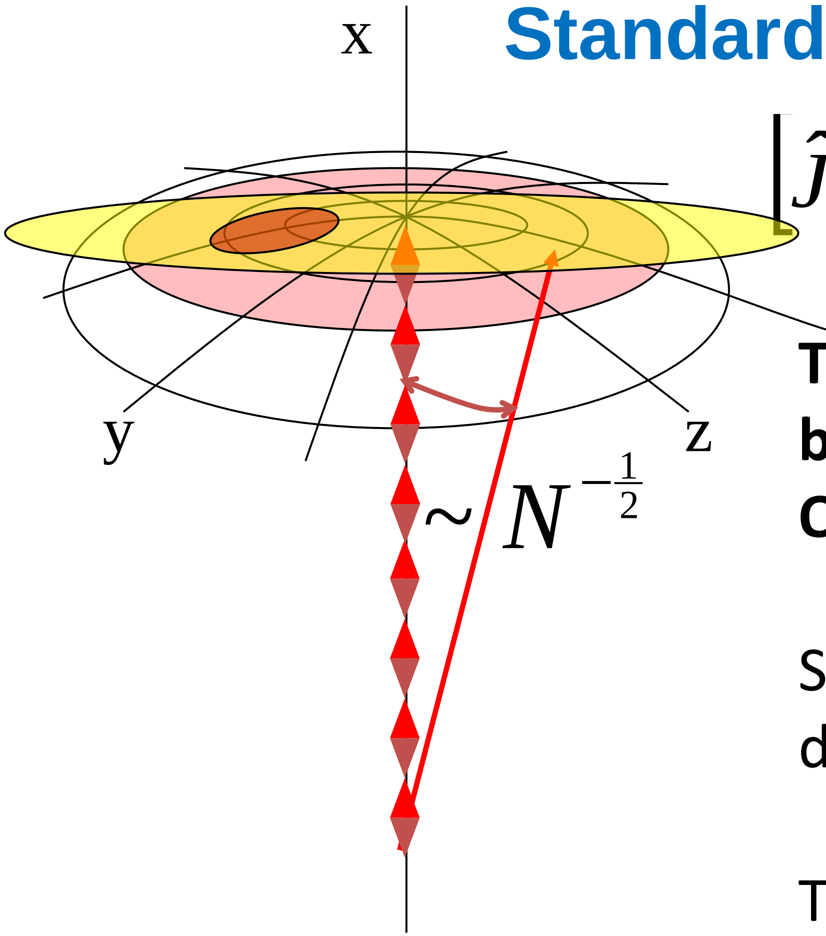



**$10^8$ spins at room temperature**

Theory collaboration with: Denis Vasyliev and Klemmens Hammerer

# Processing Quantum States below the Heisenberg Uncertainty Bound

## Standard (?) Quantum Limit (SQL)




$$\left[\hat{J}_z, \hat{J}_y\right] = iJ_x \qquad \delta J_z \cdot \delta J_y \geq \frac{F}{4} N$$

**Tracing the spin direction with precision better than SQL – Trajectories without Quantum Uncertainties**

Steady state entanglement generated by dissipation

Transfer of spin states from one location to another – quantum teleportation

# 3 steps to noiseless quantum trajectories

1. Trajectory is defined relative to an origin system which is treated quantum mechanically

2. The origin system has an effective negative mass or negative frequency (for oscillator)

3. Entangled state of the origin system and the system of interest is generated

# From free particles to oscillators

$$\left[\hat{X}, \hat{P}\right] = i$$

Oscillator in classical coordinate frame:

$$X(t) = X(0)\cos(\omega t) + P(0)\sin(\omega t)/m$$

Oscillator in quantum reference frame with respect to a negative mass ($m = -m_0 = 1$) or negative frequency system:

$$X(t) - X_0(t) = [X(0) - X_0(0)]\cos(\omega t) + [P(0) + P_0(0)]\sin(\omega t)$$

*Simon* (2000); *Duan, Giedke, Cirac, Zoller* (2000)

<u>Entanglement condition</u>

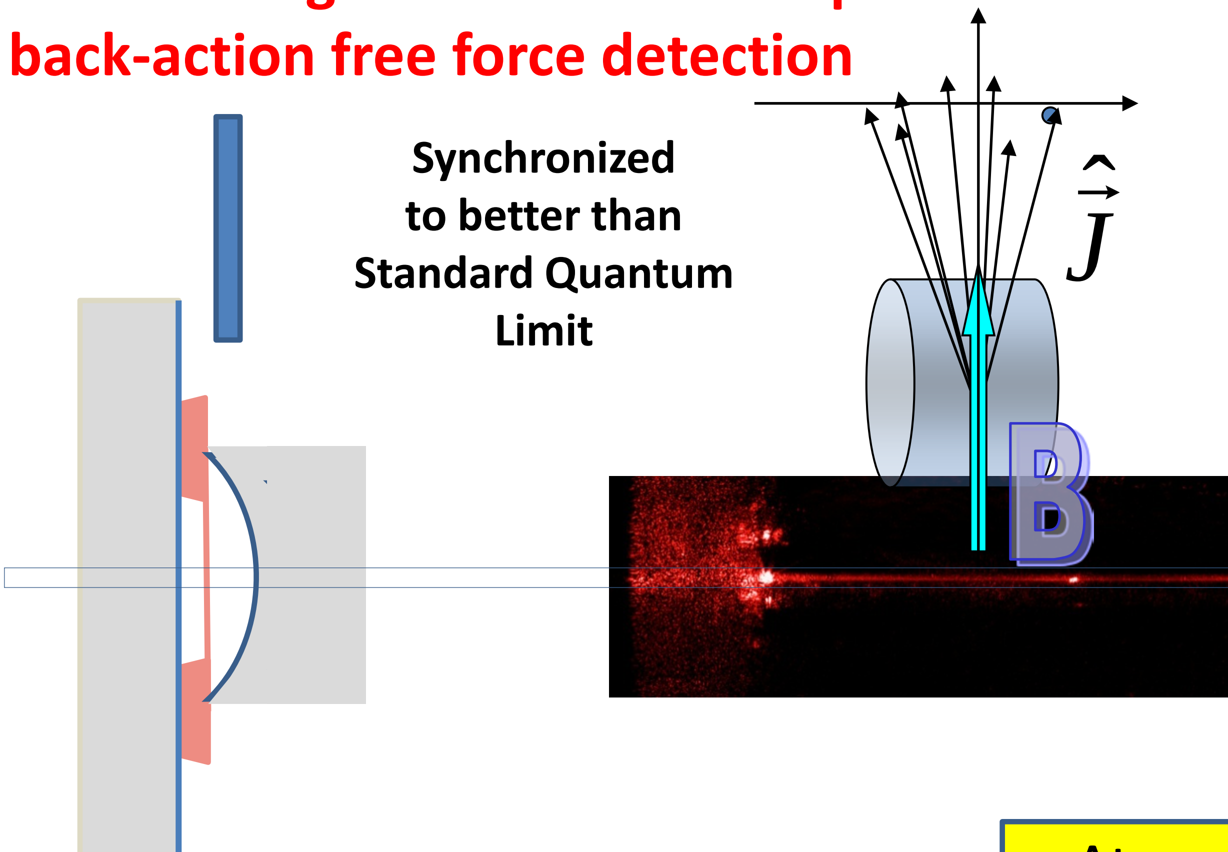
$$Var(X - X_0) + Var(P + P_0) < 2$$

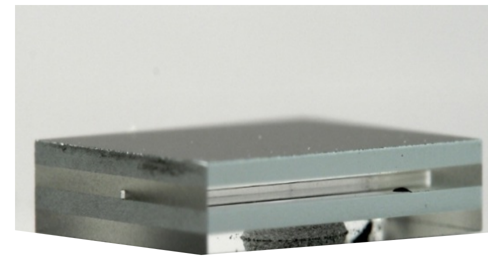
$\Leftrightarrow$ $Var[X(t) - X_0(t)] < 1$

standard quantum limit

# Towards entanglement of atomic spins and mechanical oscillator for back-action free force detection

**Synchronized to better than Standard Quantum Limit**



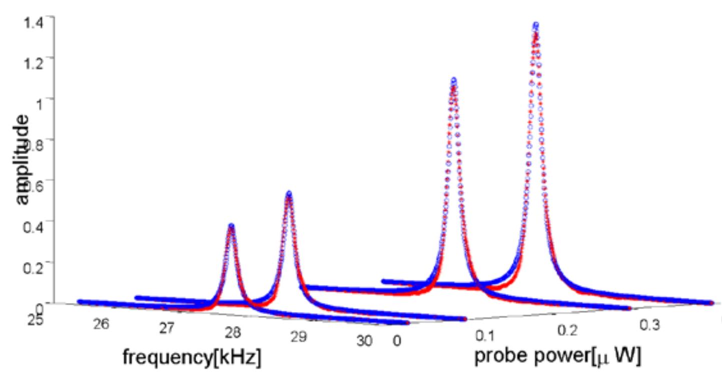



**Atoms $T_2$ = 5 ms**

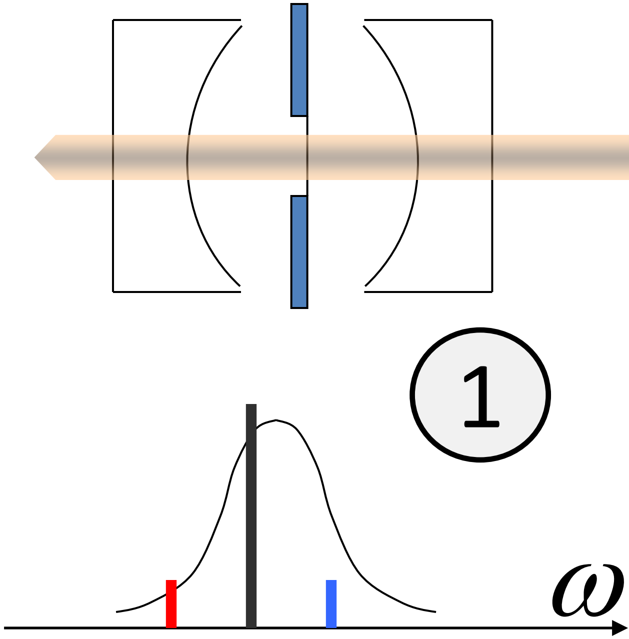
***Membrane- 3 seconds***

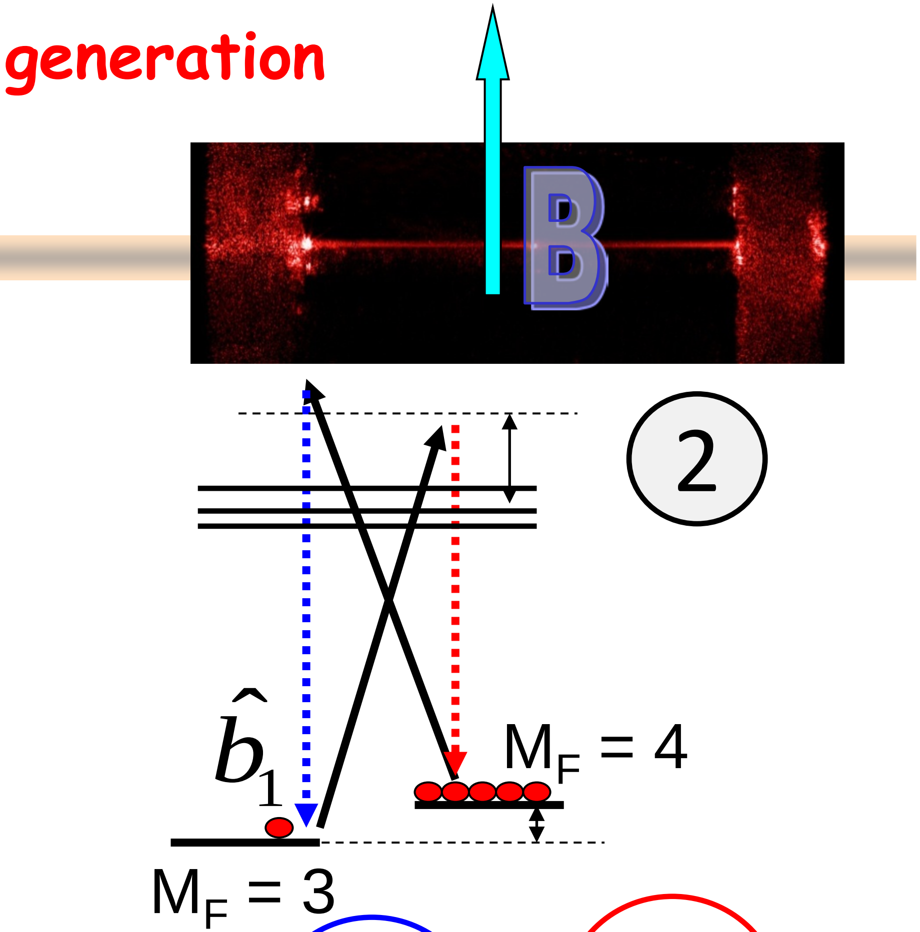
Time it takes to get 1 MHz thermal phonon from the environment:

| | |
|---|---|
| 300K | 3K |
| $10^7$ Phonons | $10^5$ phonons |
| 300 nsec | 30 microsec |



# Steady state entanglement generation




$$H = \chi_{Par}\hat{a}^{\dagger}_{-}\hat{b}^{\dagger}_{1} + \chi_{BS}\hat{a}^{\dagger}_{+}\hat{b}_{1} + h.c.$$

phoTon phoNon

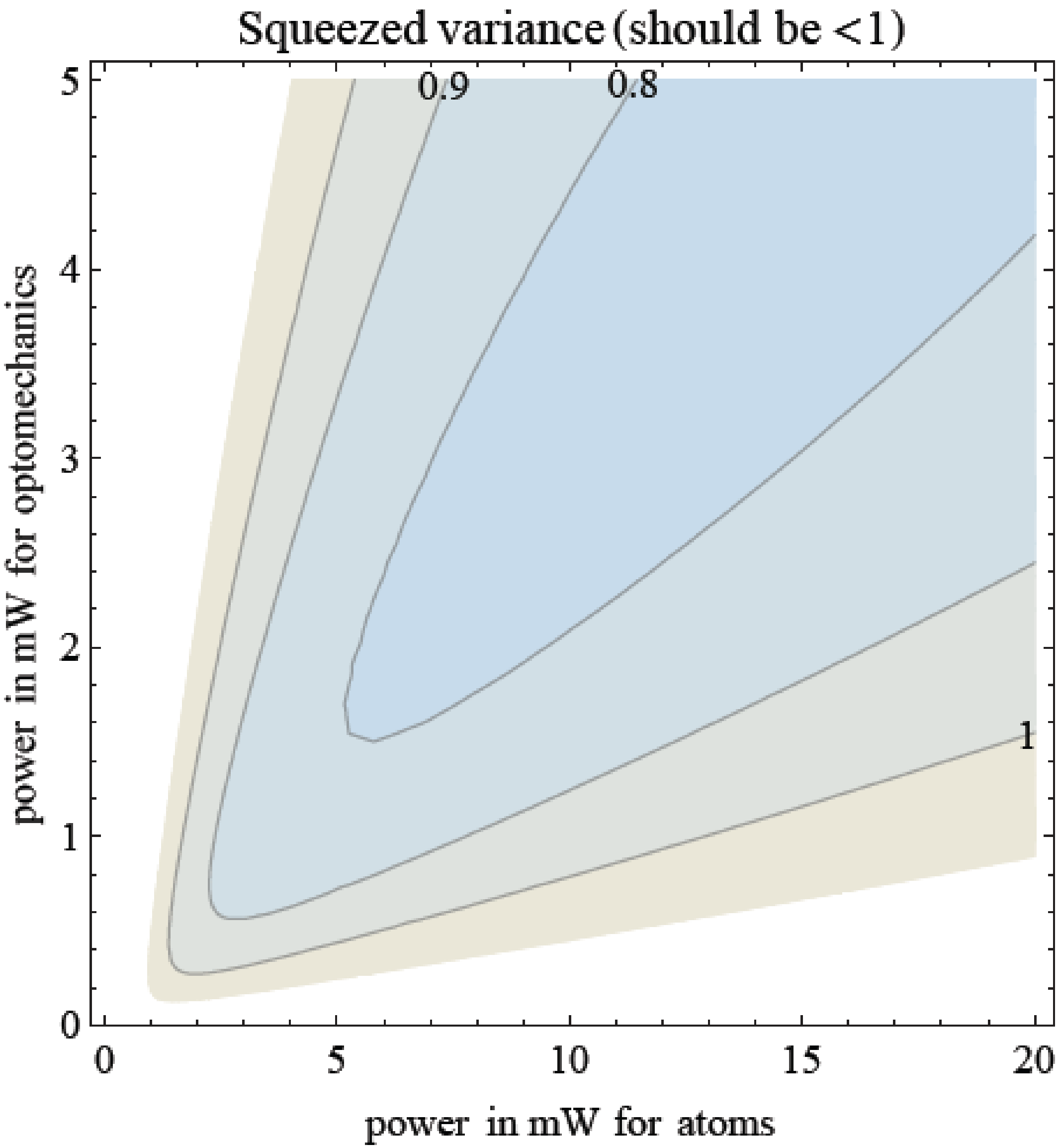
$$H = \chi_{Par}\hat{a}^{\dagger}_{+}\hat{b}^{\dagger}_{2} + \chi_{BS}\hat{a}^{\dagger}_{-}\hat{b}_{2} + h.c.$$

phoTon spin

EPR entanglement

$$Var(X_1 - X_2) + Var(P_1 + P_2) < 2$$


H. Krauter, C. Muschik, K. Jensen, W. Wasilewski, J. Pedersen, I. Cirac, E. S. Polzik, Phys.Rev.Lett. 107, 080503 (2011)




Denis Vasyliev and Klemmens Hammerer