The Abdus Salam International Centre for Theoretical Physics

2445-2

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Nonclassical states (and reservoir engineering) in cavity optomechanics

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ICTP Trieste, Sept 9 2013

Outline of the talk

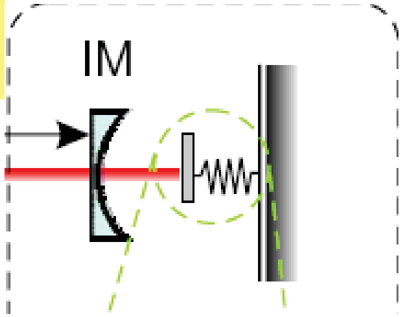
1. Cavity optomechanics with a **membrane-in-the-middle (MIM)** Fabry-Perot cavity: **linear** and **quadratic** interaction

2. Proposal for generating **nonclassical mechanical states in a quadratic MIM setup**

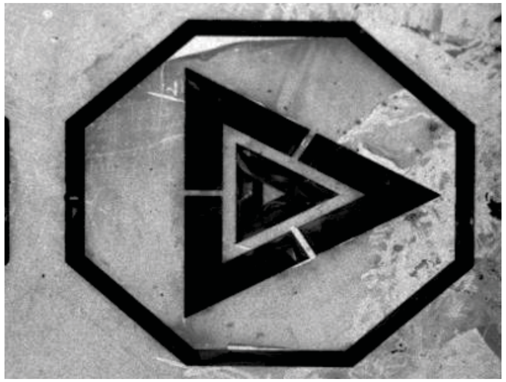
3. Controlling light with cavity optomechanics: Experiments on: i) **optomechanically induced transparency** (OMIT); ii) noise reduction for **ponderomotive squeezing**

4. Proposal for a quantum **optomechanical interface between microwave and optical signals**

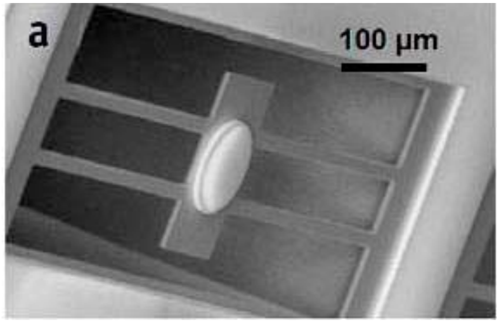
A large variety of cavity optomechanical devices: few examples



1. Fabry-Perot cavity with a moving micromirror



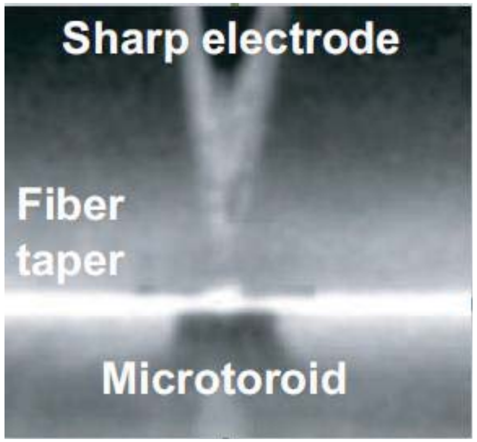
micropillar mirror (Heidmann, Paris)



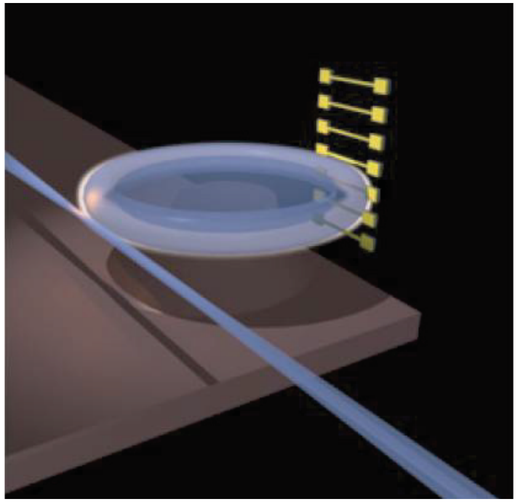
Monocrystalline Si cantilever, (Aspelmeyer, Vienna)

2. Silica toroidal optical microcavities

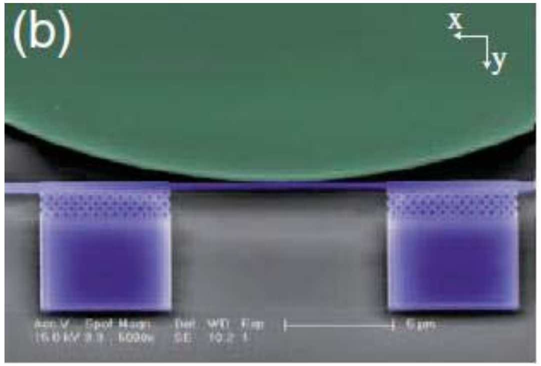
spoke-supported microresonator (Kippenberg, EPFL)



With electronic actuation, (Bowen, Brisbane)

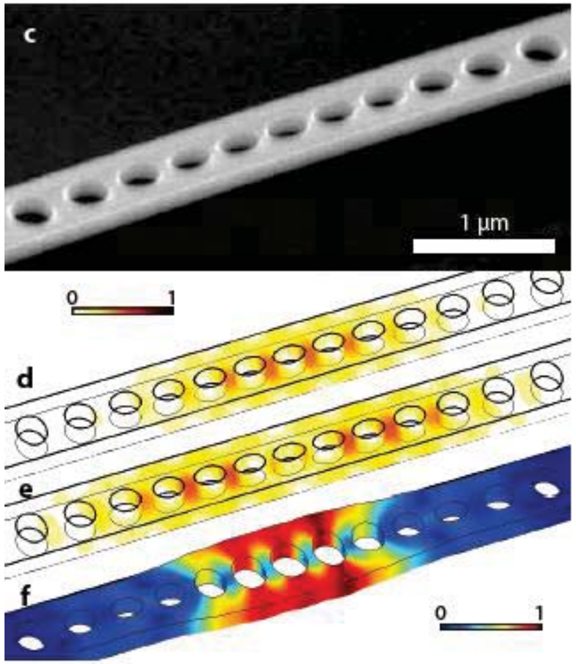


Evanescent coupling of a SiN nanowire to a toroidal microcavity (Kippenberg, EPFL)



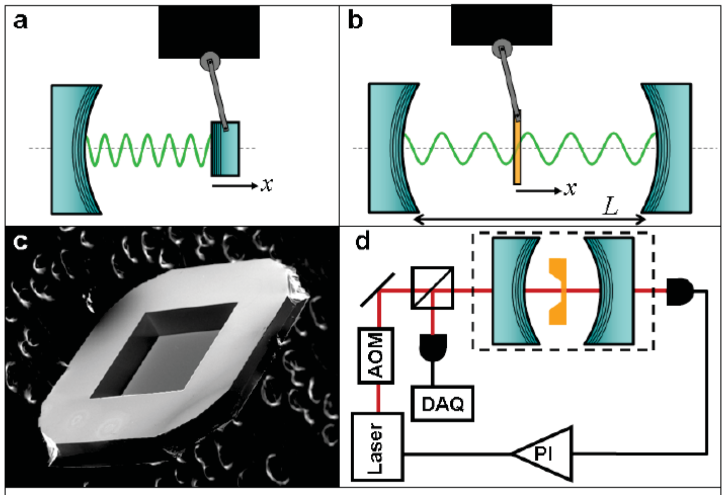
microdisk and a vibrating nanomechanical beam waveguide (Yale, H.Tang)

Radiation-pressure or dipole gradient coupling



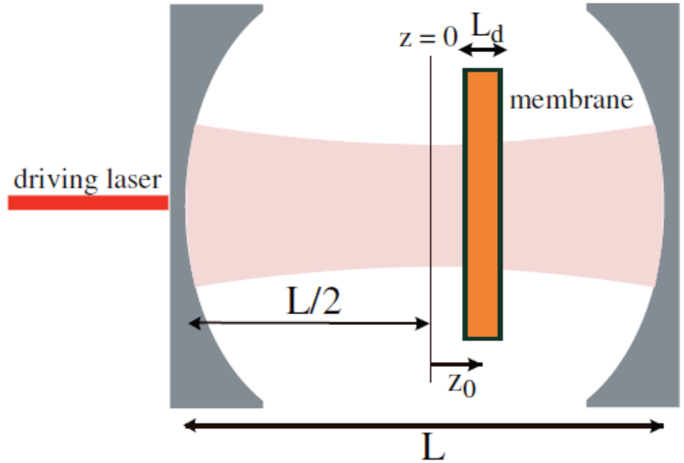
Silicon nanobeam photonic optomechanical cavity (Painter, Caltech)

"membrane in the middle" scheme: Fabry-Perot cavity with a thin SiN membrane inside (Yale, Caltech, JILA, Camerino)



The membrane-in-the-middle setup

(Thompson et al., Nature 2008)

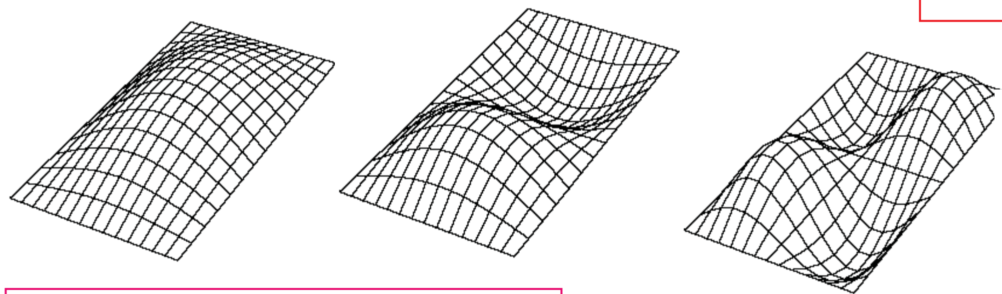


Many cavity modes (standard Gaussian TEM_{mn} if membrane aligned and close to the waist)

$$H_{cav} = \sum_k \hbar\omega_k(z_0)a_k^+ a_k$$

Many vibrational modes $u_{mn}(x,y)$ of the membrane

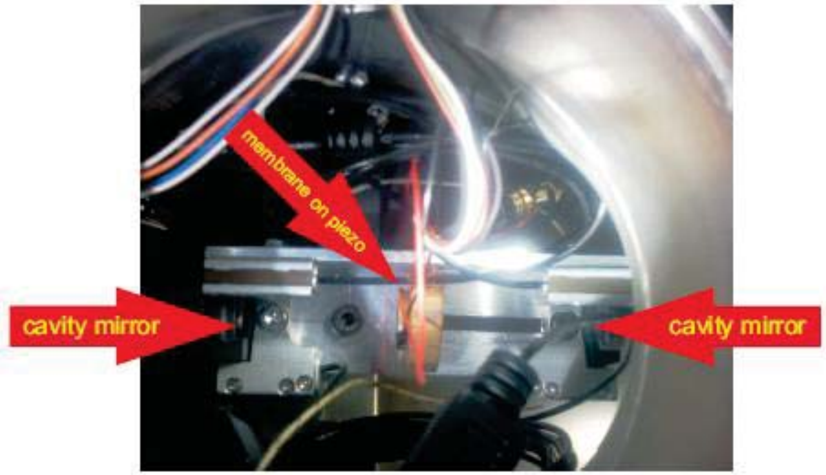
$$u_{mn}(x,y) = \sin\frac{n\pi x}{d}\sin\frac{m\pi y}{d}$$



$$\Omega_{nm} = \sqrt{\frac{\pi T}{\rho L_d d^2}(m^2+n^2)}$$

Vibrational frequencies

T = surface tension
ρ= SiN density,
L_d = membrane thickness
d = membrane side length
m,n = 1,2…



General multimode optomechanical interaction due to radiation pressure

$$H_{\text{int}} = -\int dxdy\, P_{rad}(x,y)\, z(x,y)$$

(at first order in z)

$$P_{rad}(x,y) = \varepsilon_0 \left(n_M^2 - 1\right) \int_{z_0 - L_d/2}^{z_0 + L_d/2} dz \left(\dot{\vec{E}}(x,y,z) \times \vec{B}(x,y,z)\right)_z$$

Radiation pressure field

$$z(x,y) = \sum_{n,m} \sqrt{\frac{\hbar}{M\Omega_{nm}}}\, q_{nm} u_{nm}(x,y)$$

Membrane axial deformation field

$$\hat{H}_{\text{int}} = -\frac{2\hbar}{L} \sum_{l,k,n,m} \sqrt{\frac{\hbar \omega_l \omega_k}{M\Omega_{nm}}}\, \Theta_{nmlk} \Lambda_{lk} q_{nm} a_l^{+} a_k$$

C. Biancofiore et al., Phys. Rev. A **84,** 033814 (2011)

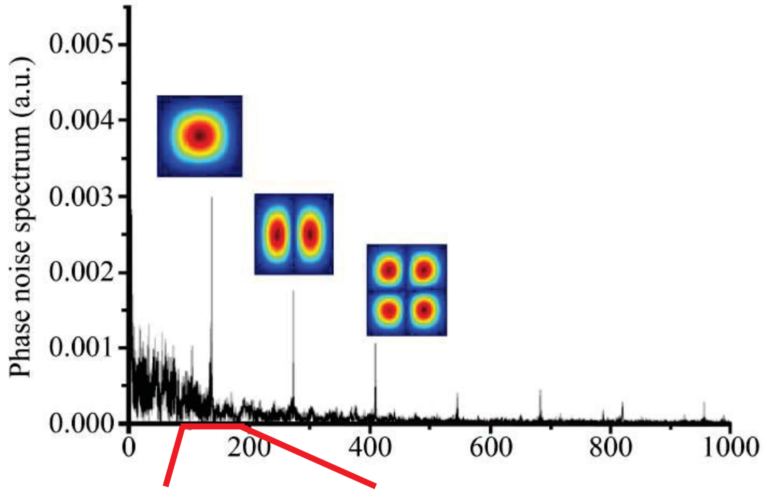
Multimode trilinear coupling describing photon scattering between cavity modes caused by the vibrating membrane

Simplified description: single mechanical oscillator, nonlinearly coupled to a single optical oscillator

Possible when:

• We **drive only a single cavity mode *a*** (and scattering into the other cavity modes is negligible , no frequency close mode)

• A **bandpass filter** in the detection scheme can be used, isolating a single mechanical resonance



$$\hat{H} = \frac{\hbar\omega_m}{2}\left(p^2 + q^2\right) + \hbar\omega(q)a^+a + H_{drive}$$

Cavity optomechanics Hamiltonian

$$\hat{H}_{drive} = i\hbar\left(Ee^{-i\omega_L t}a^+ - E^*e^{i\omega_L t}a\right)$$

$$E = \sqrt{\frac{2\kappa P_L}{\hbar\omega_L}}$$

amplitude of the driving laser with input power P_L

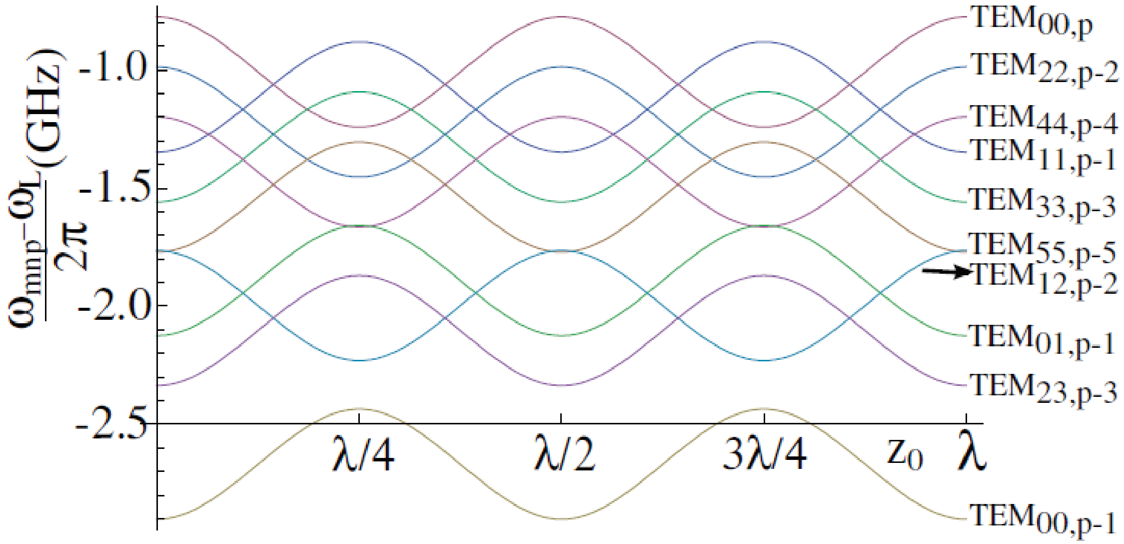
MIM setup: TUNABLE OPTOMECHANICAL INTERACTION by changing membrane position

Usual radiation pressure force interaction
⇔ first order expansion of $\omega(q)$

$$\omega(q) = \omega_c - G_0 q$$

Poor approximation at nodes and antinodes (where the dependence is quadratic) (Thompson et al., Nature 2008)

$$\omega(q) = \omega_0 + (-1)^p \arcsin\left\{\sqrt{R}\cos\left[2k_0 z_0(q)\right]\right\}$$



General periodic dependence for a **perfectly aligned membrane** with reflectivity R, **placed close to the waist**

Membrane misalignment (and shift from the waist) **couples the TEM_{mn} cavity modes**

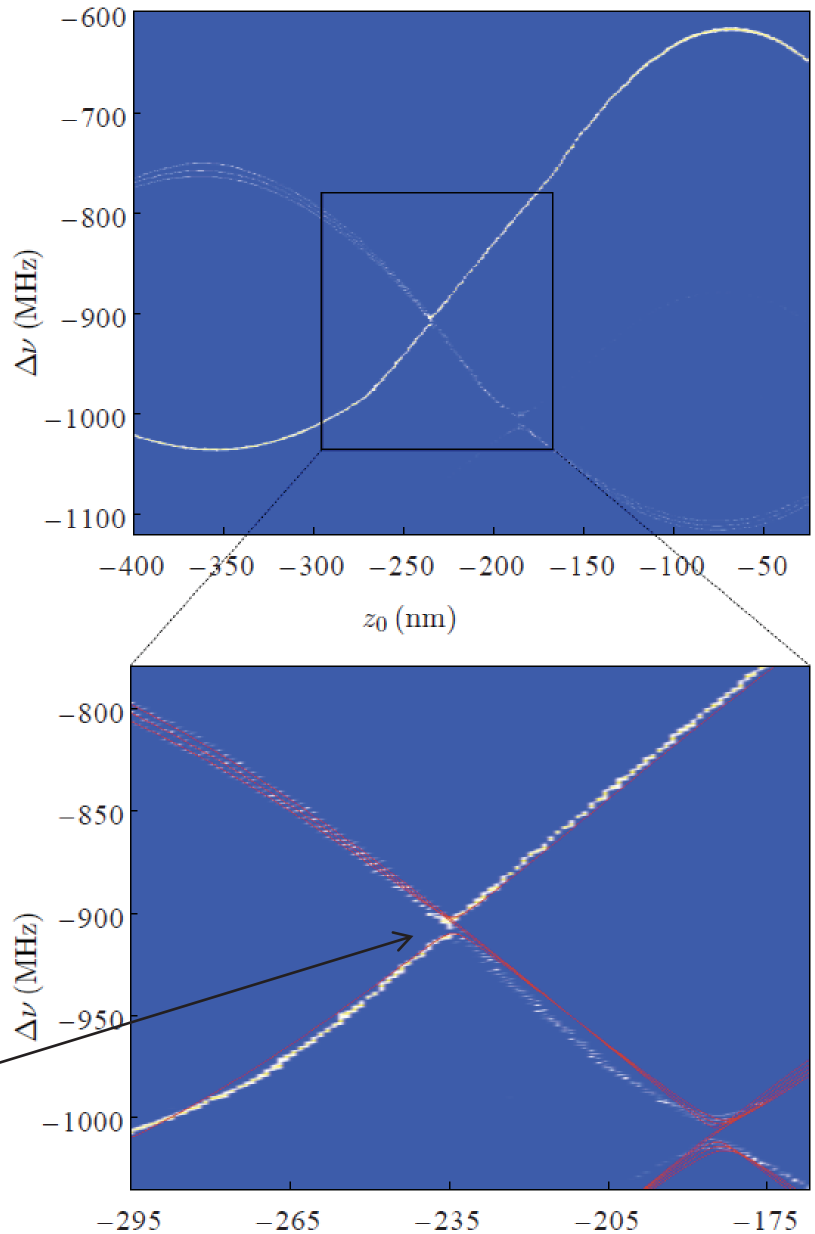
⇩

Splitting of degenerate modes and avoided crossings

linear combinations of nearby TEM_{mn} modes become the new cavity modes:
***ω(q)* is changed significantly: tunable optomechanical interaction**

(J.C. Sankey et al., Nat. Phys. 2010)

Crossing between the TEM_{00} singlet and the TEM_{20} triplet



Experimental cavity frequencies with 0.21 mrad misalignment
(M. Karuza et al., J. Opt. 15 (2013) 025704)

Enhanced quadratic interaction at an avoided crossing

(M. Karuza et al., J. Opt. 15 (2013) 025704)

Avoided crossing between

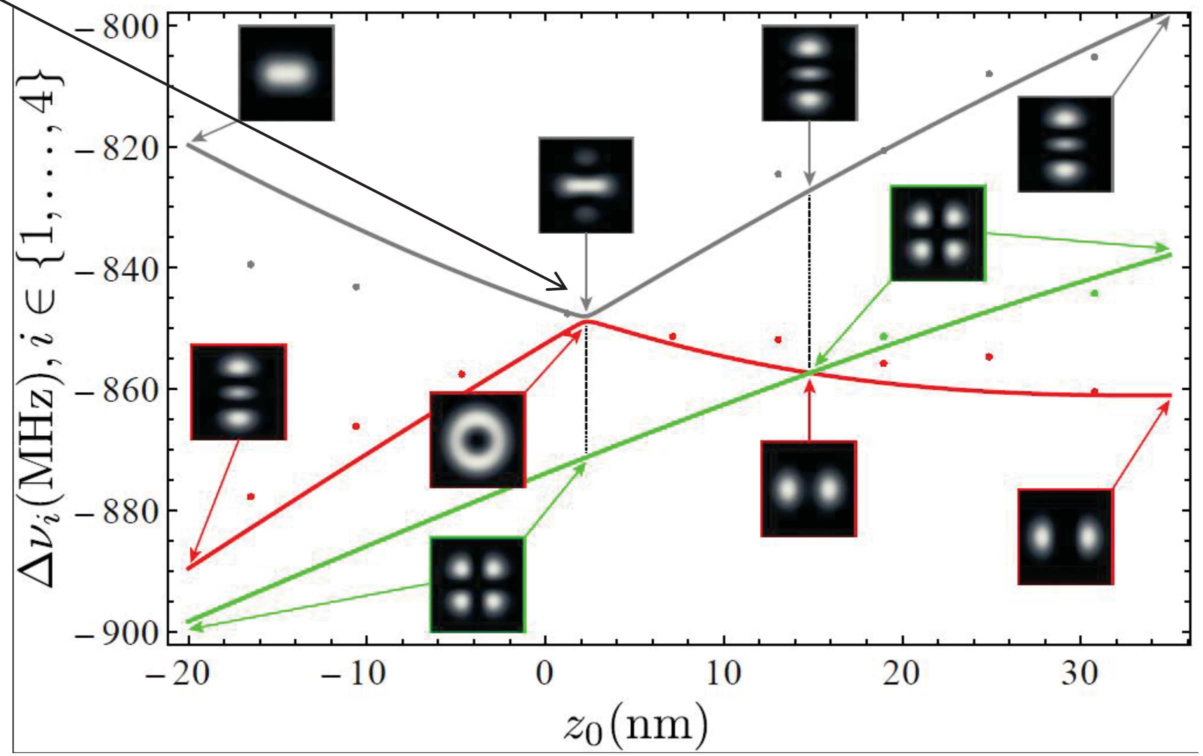
$[|\mathrm{TEM}_{20,p-1}\rangle + |\mathrm{TEM}_{02,p-1}\rangle - |\mathrm{TEM}_{00,p}\rangle]\,/\sqrt{3},$ and
$|\phi\rangle_{\mathrm{gray}} = [2|\mathrm{TEM}_{02,p-1}\rangle - |\mathrm{TEM}_{20,p-1}\rangle + |\mathrm{TEM}_{00,p}\rangle]\,/\sqrt{6}$

$$\frac{\omega''(q)}{2\pi} = 4.46 MHz/nm^2$$

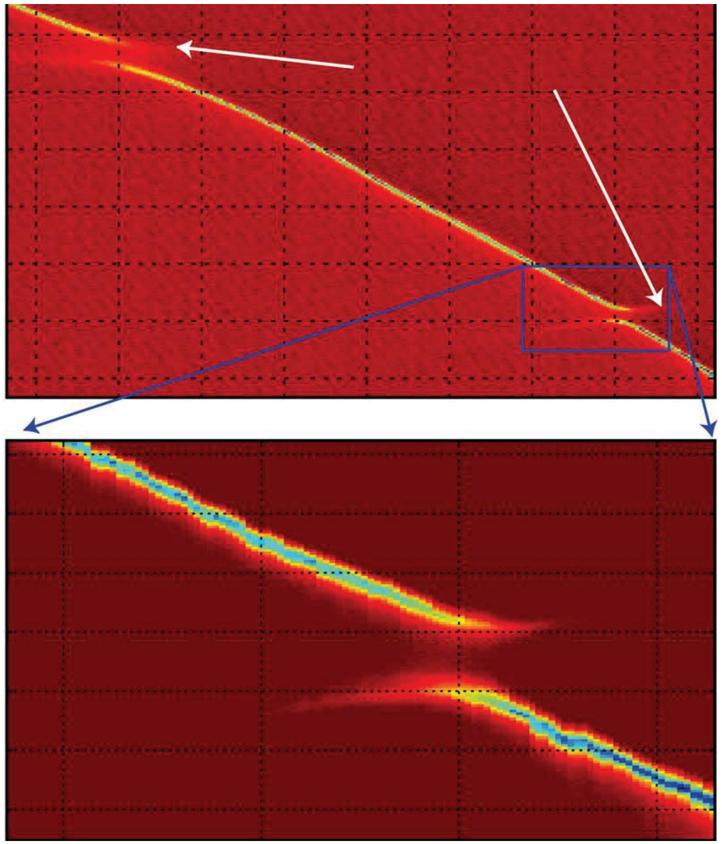
quadratic "dispersive" coupling

$$H_{\mathrm{int}} = \hbar\omega''(q)q^2 a^+ a$$

It allows the **nondemolition measurement** of mechanical energy: **possible detection of "phonon quantum jumps"**



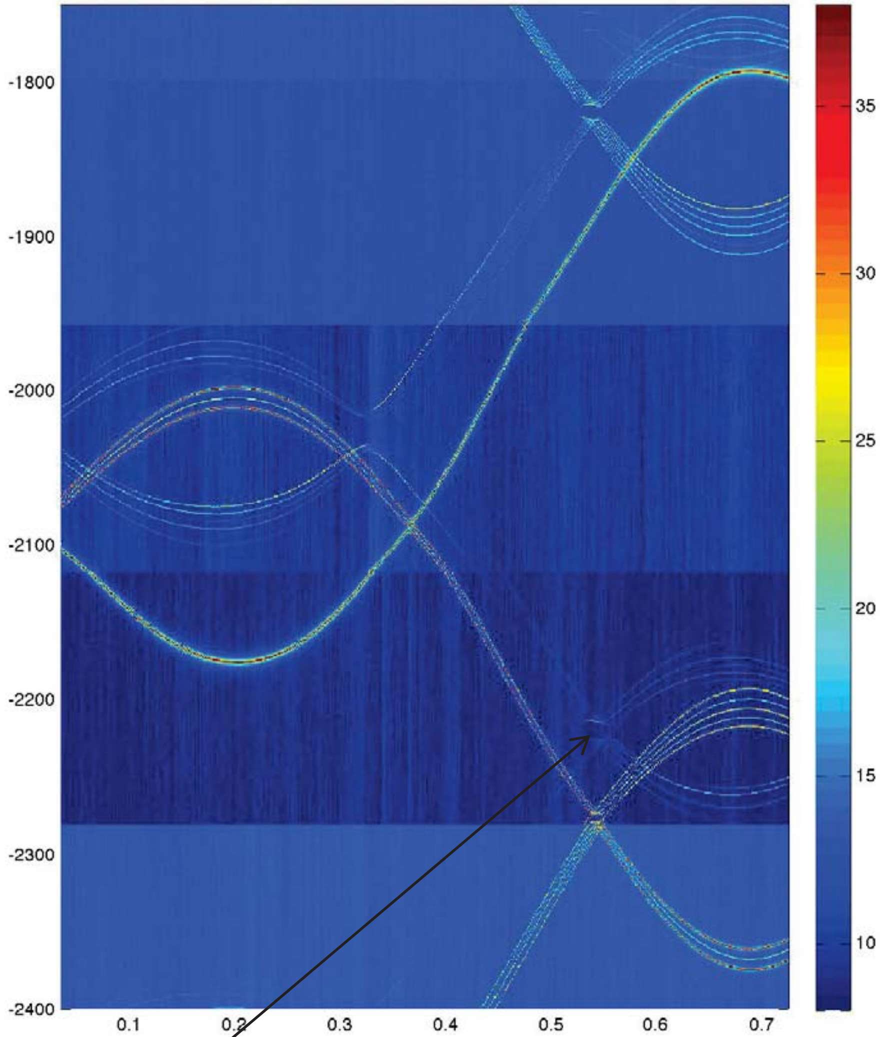
MORE RECENT RESULTS ON QUADRATIC COUPLING



Flowers-Jacobs et al. APL, 2012

Results in a very short fiber-based cavity setup at Yale.

$$\boxed{\frac{\omega''(q)}{2\pi} = 20GHz/nm^2}$$



More recent results in our setup

WHAT TO DO WITH A QUADRATIC HAMILTONIAN ?

Proposals for the generation of MECHANICAL NONCLASSICAL STATES

1. Schrodinger cat states through **reservoir engineering**

2. Stationary squeezed state with “bang-bang” open loop controls

(M. Asjad and D. Vitali, arXiv:1308.0259)

RESERVOIR ENGINEERING

Dynamics driven by an **effective dissipative generator**, with a **nonclassical steady state** ρ_∞ (target state) (Poyatos et al., 1993, generalization in Verstraete et al., 2009, Diehl et al., 2008)

$$\boxed{\frac{\partial}{\partial t}\rho = \mathcal{L}\rho} \quad \boxed{\mathcal{L}\rho_\infty = 0}$$

"Target state"

Typical solution = Lindblad generator

$$\boxed{\begin{aligned} \mathcal{L}\rho &= \Gamma\mathcal{D}(C)\rho \\ \mathcal{D}(C)\rho &= \left(2C\rho C^\dagger - C^\dagger C\rho - \rho C^\dagger C\right) \end{aligned}}$$

such that $\boxed{\rho_\infty = |\psi_\infty\rangle\langle\psi_\infty|}$

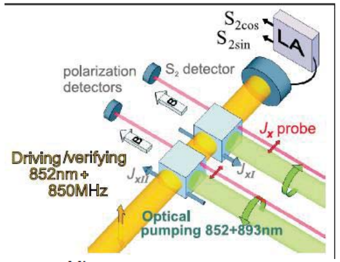
$$\boxed{C|\psi_\infty\rangle = 0}$$

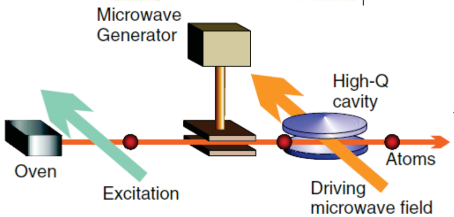
Engineered dynamics which must dominate over undesired ones

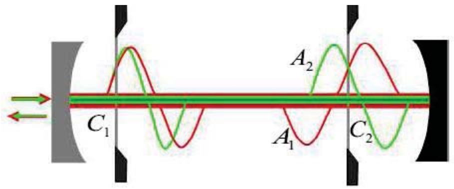
EXAMPLES

$$C = \mu \hat{b}_1 + \nu \hat{b}_2^+$$

Generation of **entangled two-mode squeezed state of two bosons** :







1. Entangled atomic ensembles through **engineered optical reservoir** (experiment by Krauter et al., PRL 2011)
2. Entangled cavity modes through **engineered atomic reservoir** (Pielawa et al., PRL 2007)
3. Entangled mechanical resonators in cavity optomechanics (Tan et al. PRA 2013)

$$C = \mu \hat{b} + \nu \hat{b}^+$$

Generation of **single-mode squeezed state**

1. Motion of Trapped ions (Carvalho, et al., PRL 2011)
2. Squeezed mechanical resonators in cavity optomechanics (Kronwald et al. , 2013)

$$C_1 = \hat{a}\hat{b} - \alpha^2$$
$$C_2 = \hat{a} - \hat{b}$$

Generation of **entangled cat states of two cavity modes with amplitude α**

$$|\alpha\rangle|\alpha\rangle + |-\alpha\rangle|-\alpha\rangle$$

(through engineered atomic reservoirs, Arenz et al., 2013)

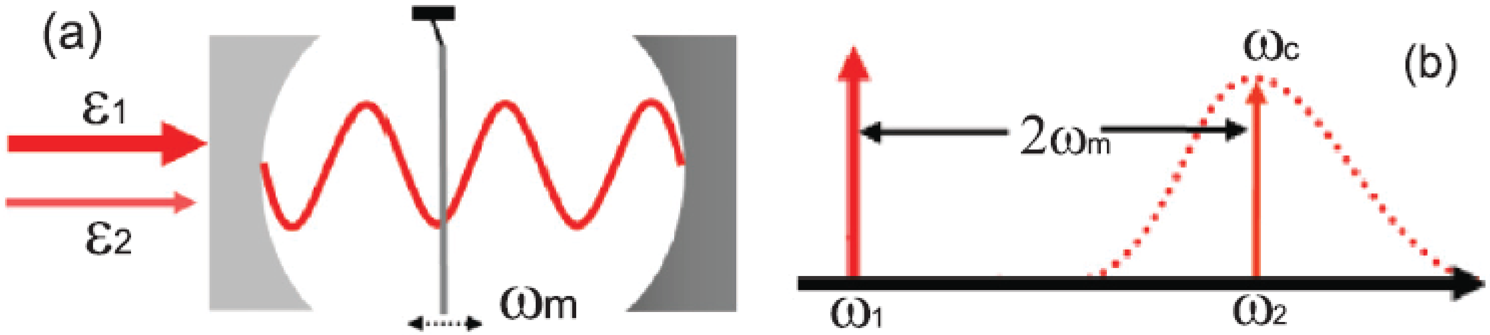
Here we engineer the "optical mode reservoir" in cavity optomechanics for robust generation of a mechanical Schrodinger cat states with amplitude β

$$|\psi_\infty\rangle \approx |\beta\rangle + |-\beta\rangle \quad \text{with} \quad C = \hat{b}^2 - \beta^2$$

(M. Asjad and D. Vitali, arXiv:1308.0259)

(see also in trapped ions motion (Carvalho et al. 2001) and also H. Tan et al., PRA 2013)

One needs **quadratic optomechanical coupling** and a **bichromatic driving** (pump on the second red sideband)



rotating wave approximation

$$\boxed{H_{\text{eff}} = \hbar g_2 \alpha_s^* \delta a \left(b^{\dagger\,2} - \mathrm{i} E_1 / g_2 \alpha_s^* \right) + \mathrm{H.C.},}$$

$$\boxed{\beta^2 = i \frac{E_1}{g_2 \alpha_s^*}}$$

Adiabatic elimination of cavity mode $\Rightarrow$ **effective dissipative dynamics for the mechanical resonator**

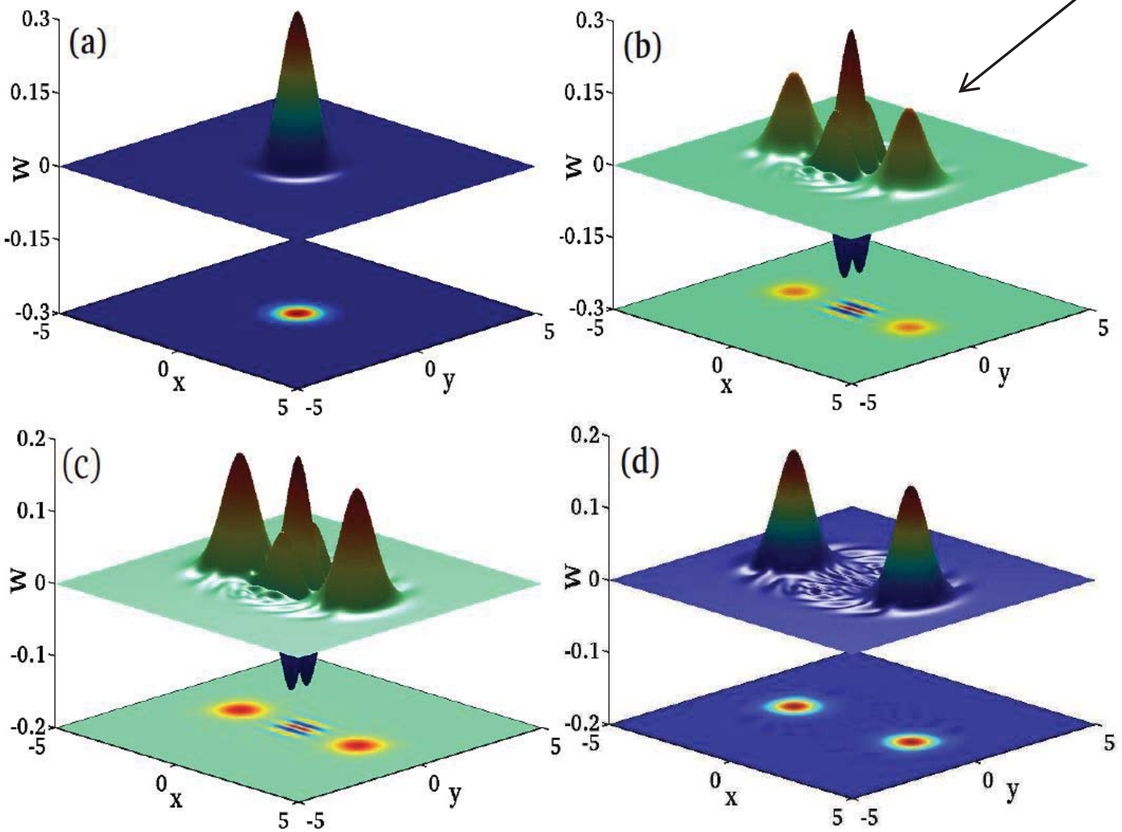
One has to **beat the undesired standard thermal reservoir** coupled with damping rate γ_m

$$\boxed{\frac{\partial}{\partial t}\rho = \Gamma\mathcal{D}(C)\rho + \frac{\gamma_m}{2}(\bar{n}+1)\mathcal{D}(b)\rho + \frac{\gamma_m}{2}\bar{n}\mathcal{D}(b^\dagger)\rho,}$$

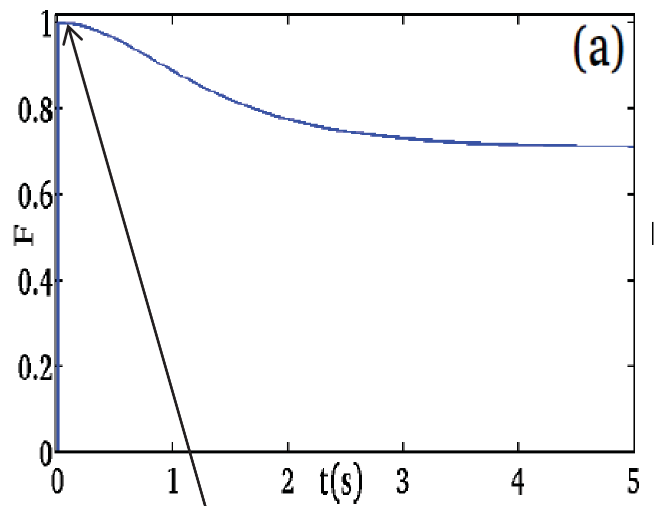
$$\boxed{\Gamma = g_2^2|\alpha_s|^2/\kappa_T}$$

$$\boxed{C = \hat{b}^2 - \beta^2}$$

The cat generation is possible at transient time ***t ≈ 1/Γ***, if $\boldsymbol{\Gamma \gg \gamma_m n}$

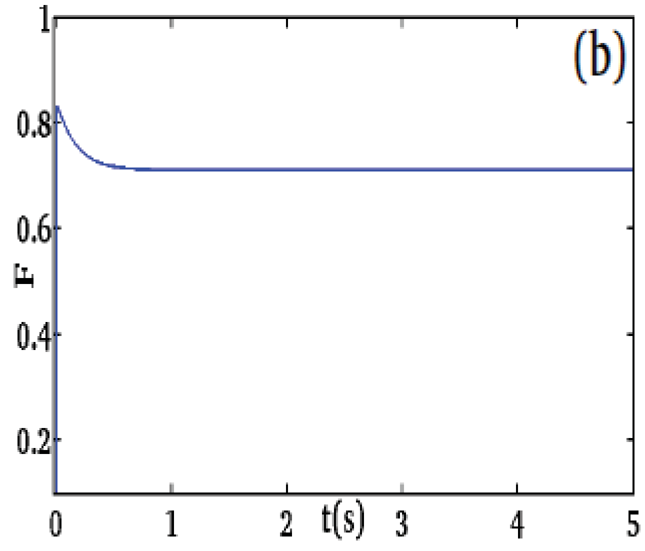


Cat state fidelity

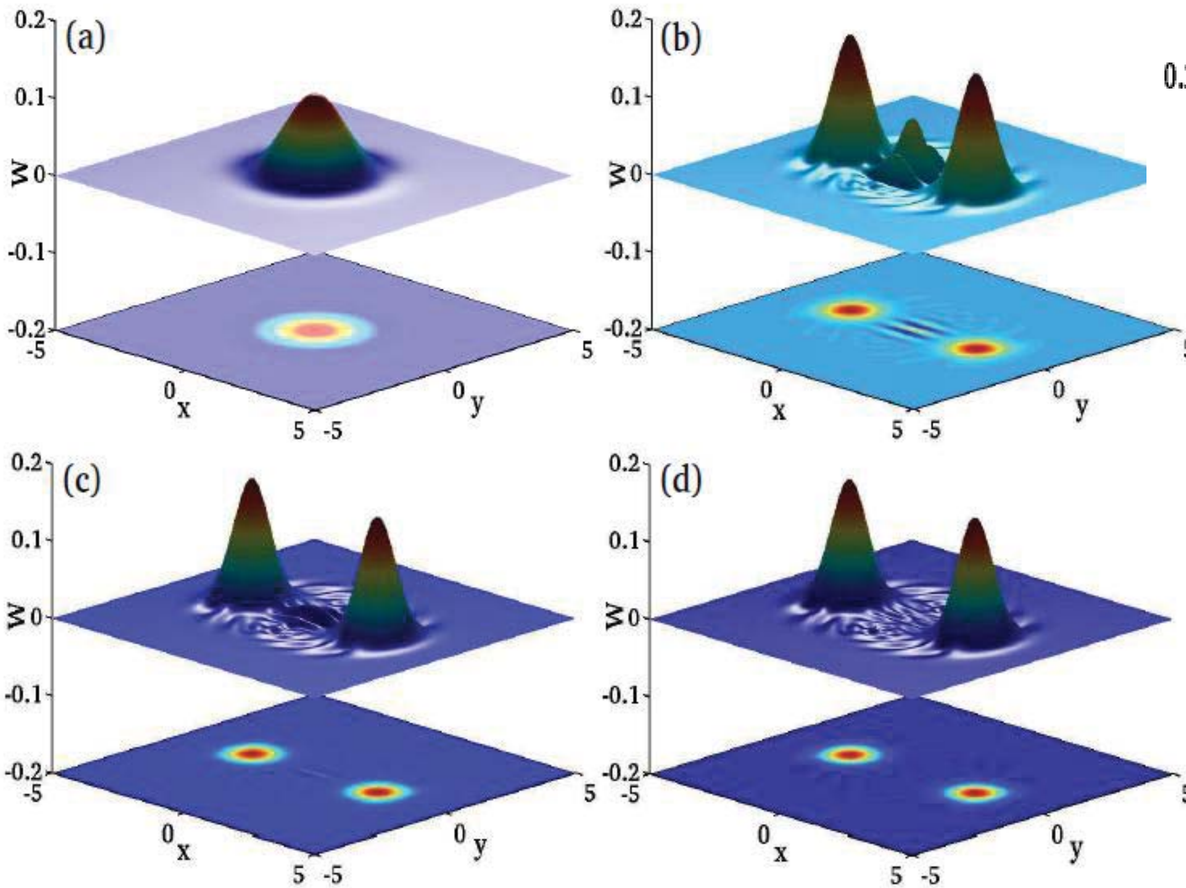


"Metastable" cat state
$Q_m = 10^7$

Worser performance if starting from a thermal state with n = 2, rather than from the ground state n = 0



fidelity



Time evolution very well approximated by a **"decohering cat" state**

$$\boxed{\rho_{\mathrm{app}}(t) = e^{-\Gamma t}\rho(0) + \left(1 - e^{-\Gamma t}\right)\rho_{\mathrm{dec}}^{\mathrm{cat}}(t)}$$

$$\boxed{\begin{aligned}\rho_{\mathrm{dec}}^{\mathrm{cat}}(t) &= \mathcal{N}(t)^{-1}\{|\beta\rangle\langle\beta| + |-\beta\rangle\langle-\beta| \\ &+ e^{-(1+2\bar{n})\gamma_m t}\left[|\beta\rangle\langle-\beta| + |-\beta\rangle\langle\beta|\right]\},\end{aligned}}$$

Such a state is ideal to test decoherence models (i.e., environmental decoherence versus collapse models….) on nanomechanical resonators

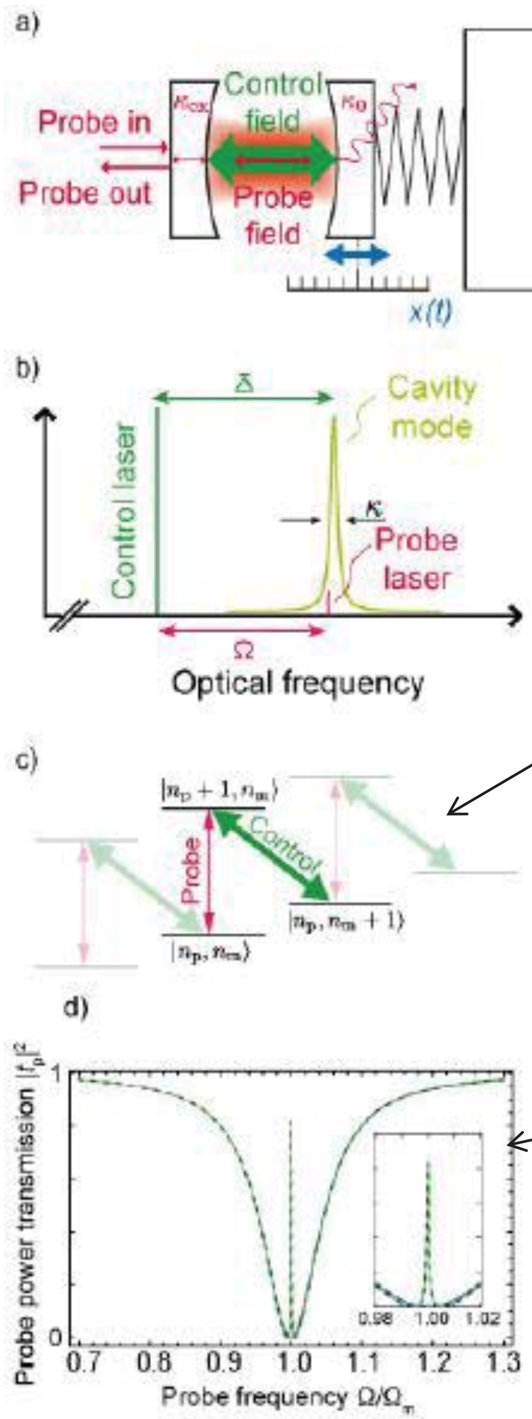
Macroscopic tests of quantum mechanics

(M. Asjad and D. Vitali, arXiv:1308.0259)

EFFECT OF THE MECHANICAL RESONATOR ON THE OPTICAL FIELD

I. EXPERIMENTS ON OPTOMECHANICALLY INDUCED TRANSPARENCY (OMIT)

The optomechanical analogue of electromagnetically-induced transparency (EIT)



The optomechanical analogue of EIT occurs when

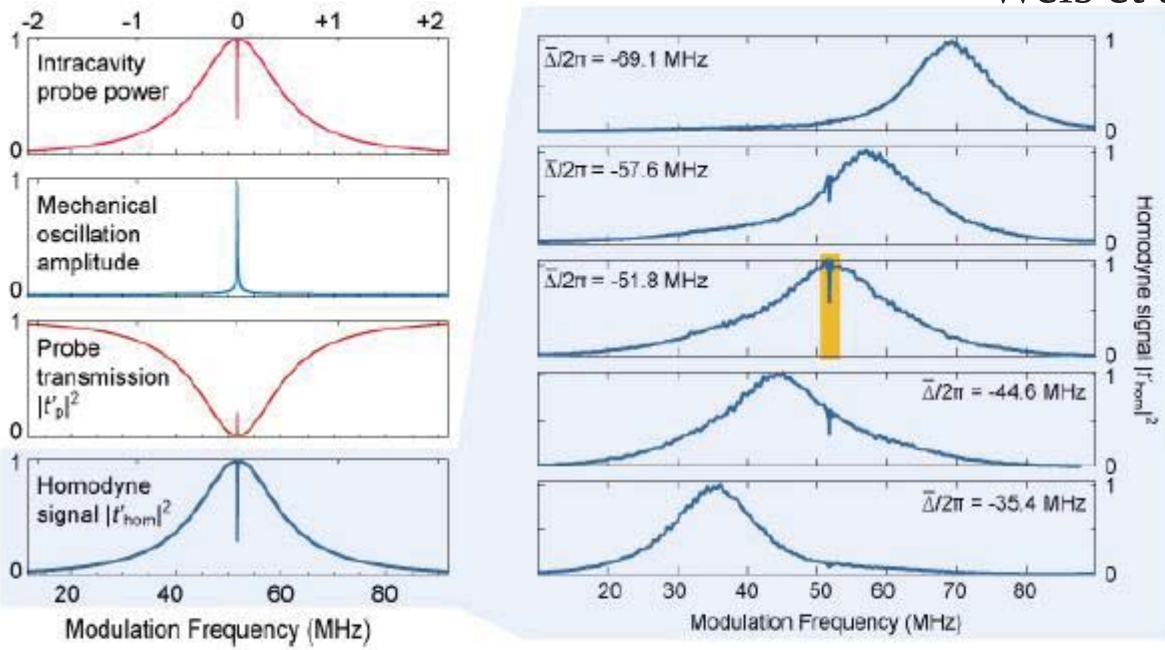
1. **an additional weak probe field is sent into the cavity**
2. **blue sideband of the laser is resonant with the cavity, $\Delta = \omega_m$**

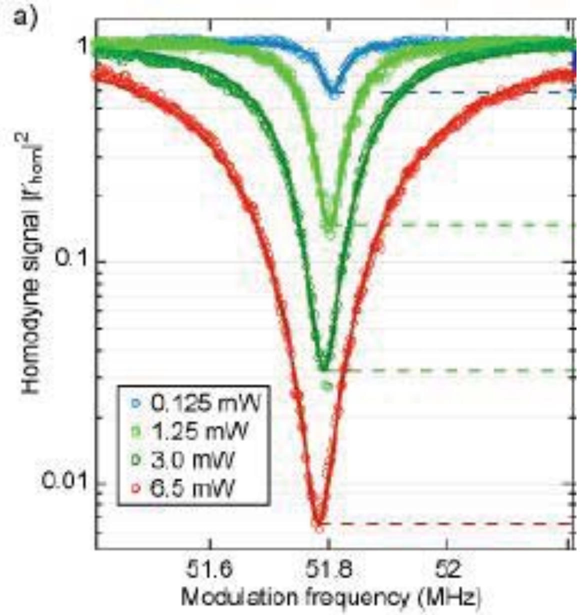
Agarwal & Huang, PRA 2010

Weis et al, *Science* ***330,*** 1520 (2010).

The probe at resonance is perfectly transmitted by the cavity instead of being fully absorbed: **destructive interference between the probe and the anti-Stokes sideband of the laser**

Weis et al, *Science* ***330,*** 1520 (2010).





Width of the transparency window

$$\boxed{\begin{aligned}\gamma_m^{eff} &= \gamma_m + \Gamma \\ \gamma_m^{eff} &= \gamma_m(1+C)\end{aligned}}$$

when $\boldsymbol{\Delta = \omega_m}$

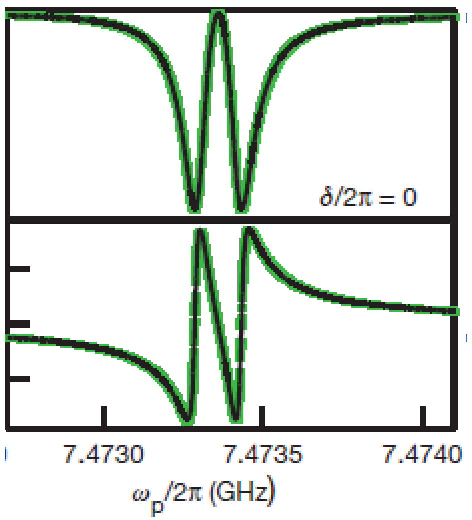
$$\boxed{C = G^2/2\kappa_{\mathrm{T}}\gamma_{\mathrm{m}}}$$

cooperativity

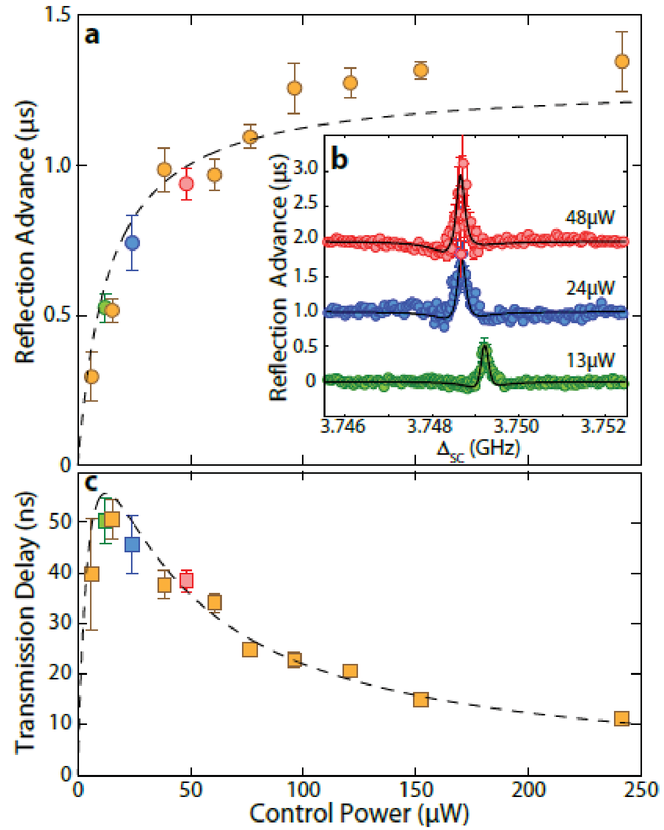
EIT is strongly reduced out of the resonant condition $\boldsymbol{\Delta = \omega_m}$

Concomitant with transparency, one has **strong group dispersion ⇔ slow light and superluminal effects**

⇒ EIT can be used for **tunable optical delays**, for stopping, storing and retrieving classical and quantum information



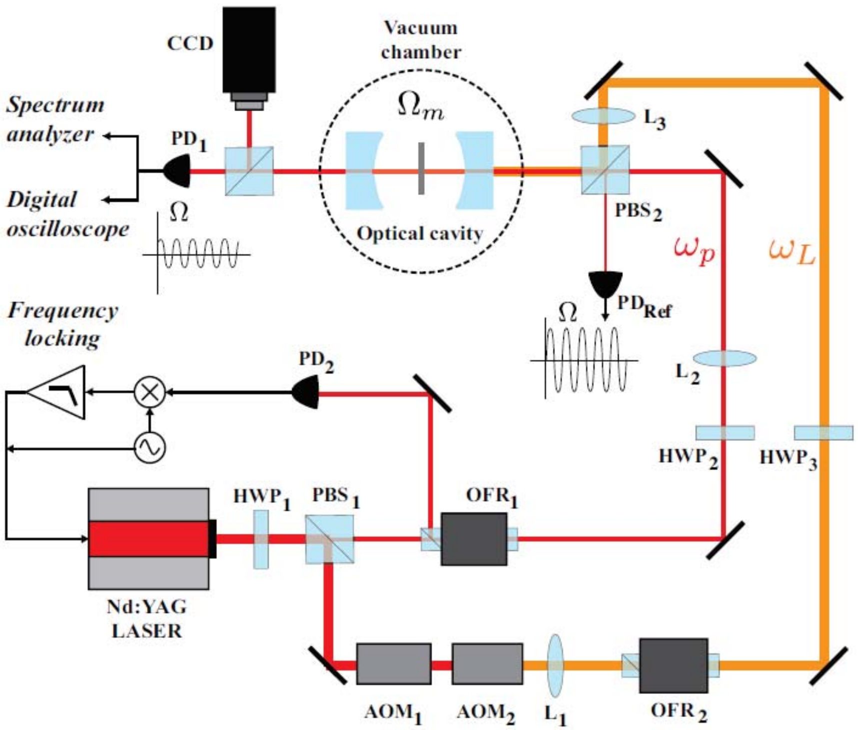
Teufel et al., Nature 471, 204 (2011) (OMIT with an electromechanical system)



A. H. Safavi-Naeini et al., Nature (London) 472, 69 (2011).

OUR OMIT EXPERIMENT WITH THE MEMBRANE

1. **Room temperature**
2. **Significantly lower frequencies (~ 350 kHz) rather than Ghz $\Rightarrow$ longer delay times**
3. **Free space (rather than guided) optics**

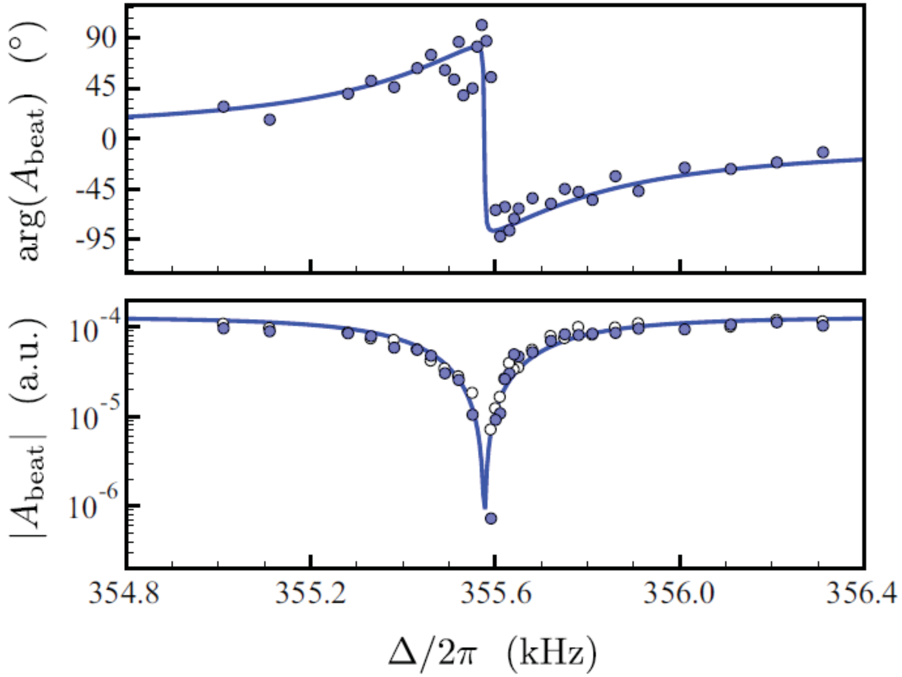


Karuza et al., PRA 88, 013804 (2013)

OMIT versus atomic EIT

1. it does not rely on naturally occurring resonances $\Rightarrow$ applicable to **inaccessible wavelengths;**
2. a single optomechanical element can already achieve unity contrast
3. **Long optical delay times achievable**, since they are limited only by the mechanical decay time

MEASURED PHASE AND AMPLITUDE OF THE TRANSMITTED BEAM



(we have induced "opacity" rather than transparency)

Estimated **group delay** **τ ≈ 670 ns** (from the derivative of the phase shift)

$$\tau^{R}_{\max} = \frac{2}{\gamma_m}\frac{\eta C}{(1+C)(1-\eta+C)}$$

$$A_{\text{beat}} =$$

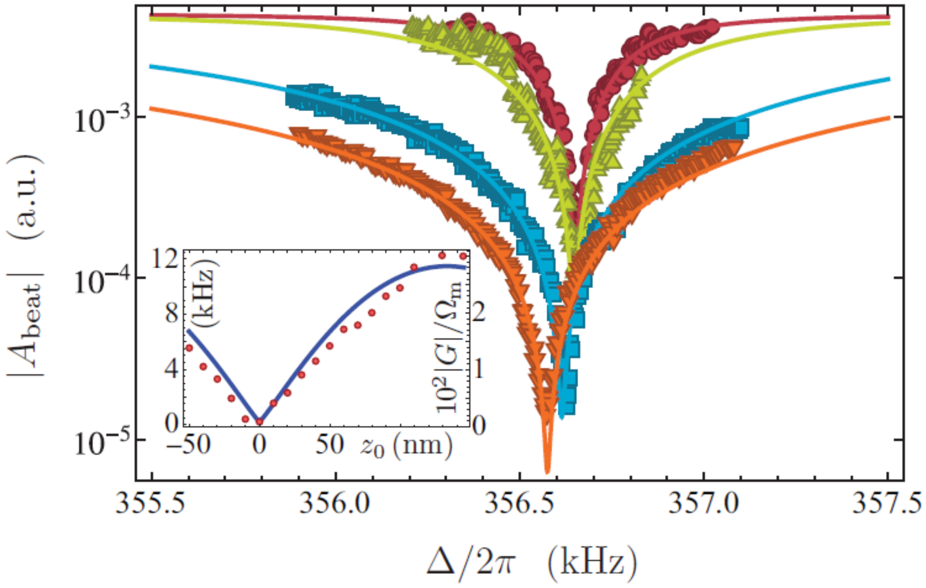
$$\frac{4\kappa_2\kappa_0|s_{\rm p}|}{\kappa_{\rm T}}\sqrt{\frac{\mathcal{P}}{\hbar\omega_{\rm L}\left(\kappa_{\rm T}^2+\Delta^2\right)}}\left[1+{\rm i}\frac{G^2\chi_{\rm eff}(\Delta)}{2\kappa_{\rm T}}\right]$$

$$C = G^2/2\kappa_{\rm T}\gamma_{\rm m}$$

Cooperativity (~160 here)

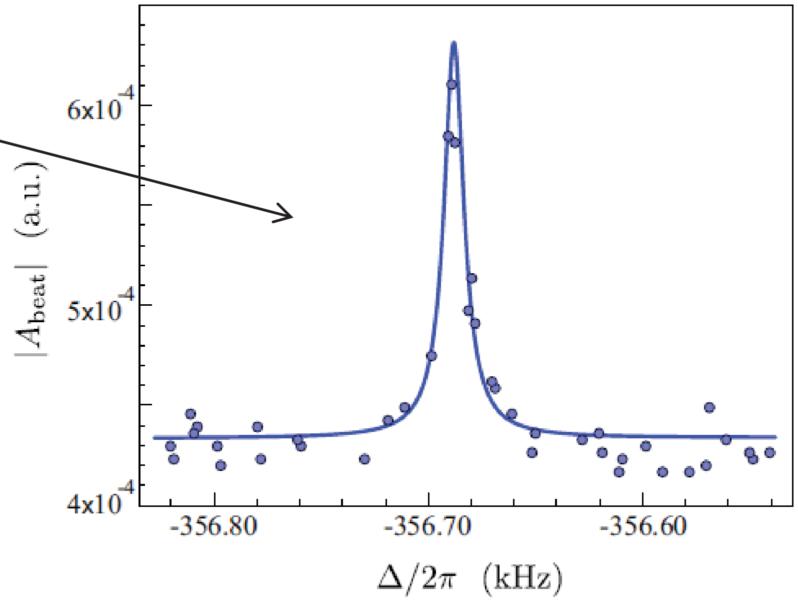
$$\eta = \frac{\kappa_{ex}}{\kappa_T}$$

Karuza et al., PRA 88, 013804 (2013)



The delay and the transparency window are here **tunable by shifting the membrane**, without varying power

When the **red** sideband of the laser is resonant with the cavity, $\Delta = -\omega_m$, one has instead **constructive interference** and "**optomechanically induced amplification**"



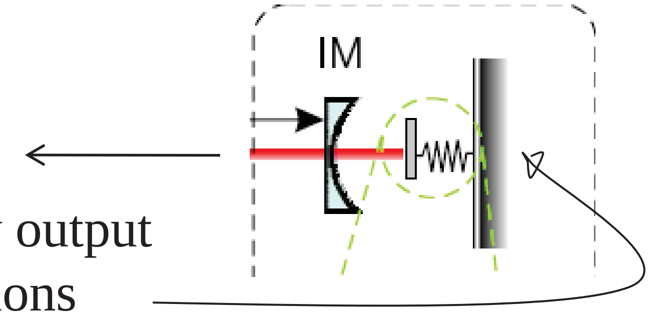
One has the **optomechanical analogue of a parametric oscillator below threshold**

Karuza et al., PRA 88, 013804 (2013)

EFFECT OF THE MECHANICAL RESONATOR ON THE OPTICAL FIELD

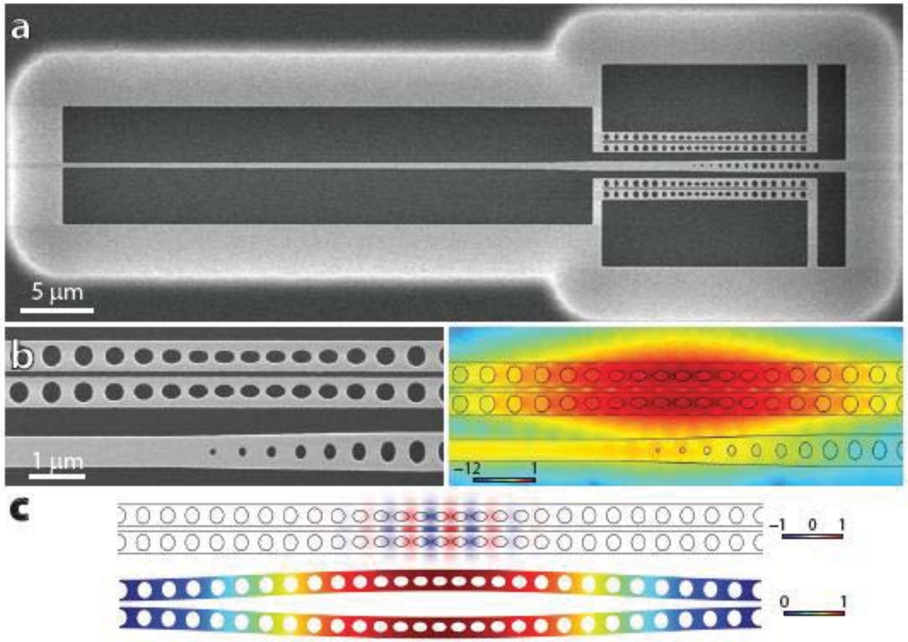
II. PONDEROMOTIVE SQUEEZING

Radiation pressure fluctuations
prevails over thermal fluctuations, $\Rightarrow$ correlations between the mechanical motion and the optical field $\Rightarrow$ **suppress fluctuations on an interferometer's output optical field below the shot-noise level**

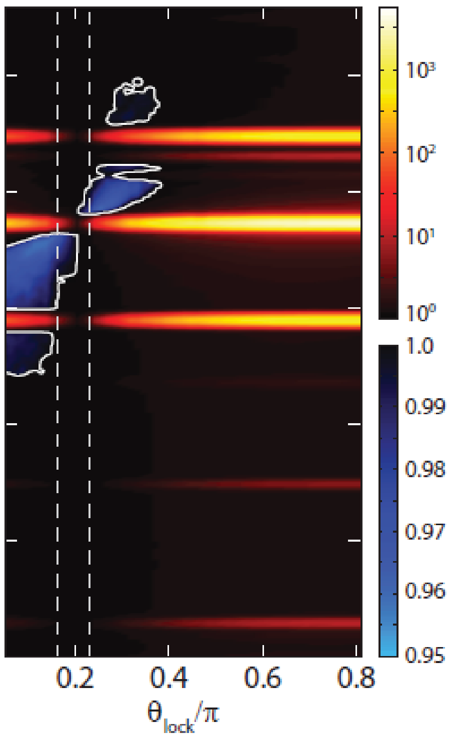


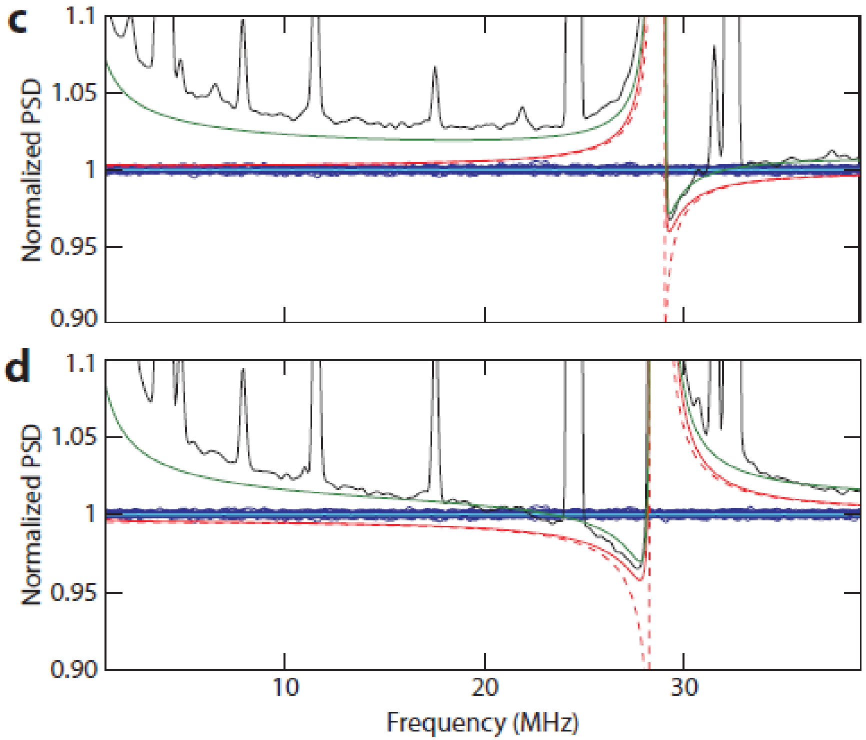
Squeezed amplitude of the cavity output correlated with resonator fluctuations

Ponderomotive squeezing of cavity output recently demonstrated **in the MHz range** (predicted by Tombesi, Fabre, PRA1994)



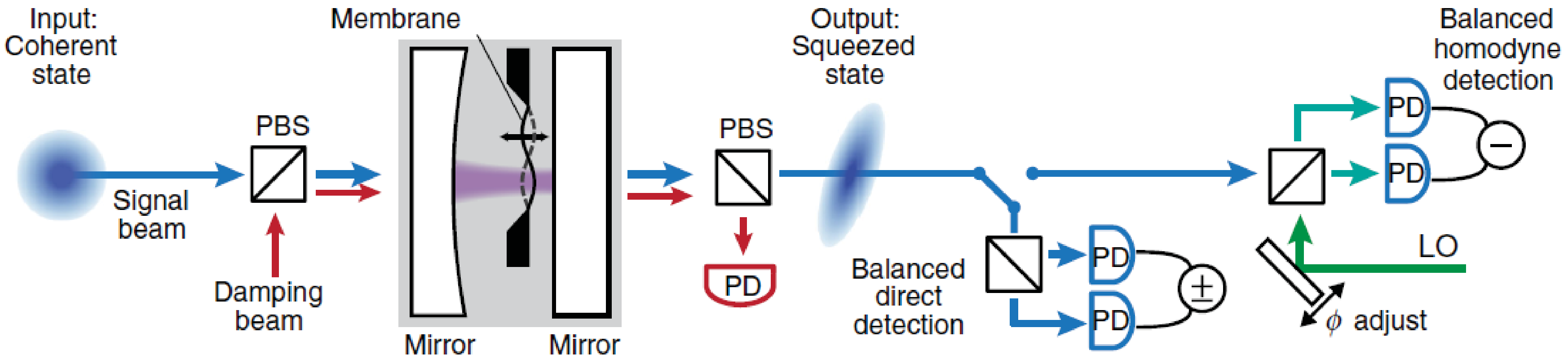
Waveguide-coupled zipper optomechanical cavity

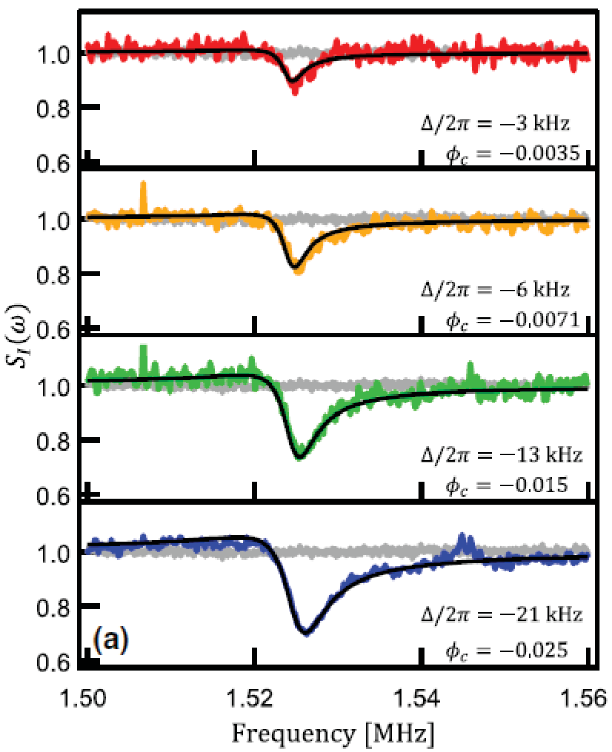


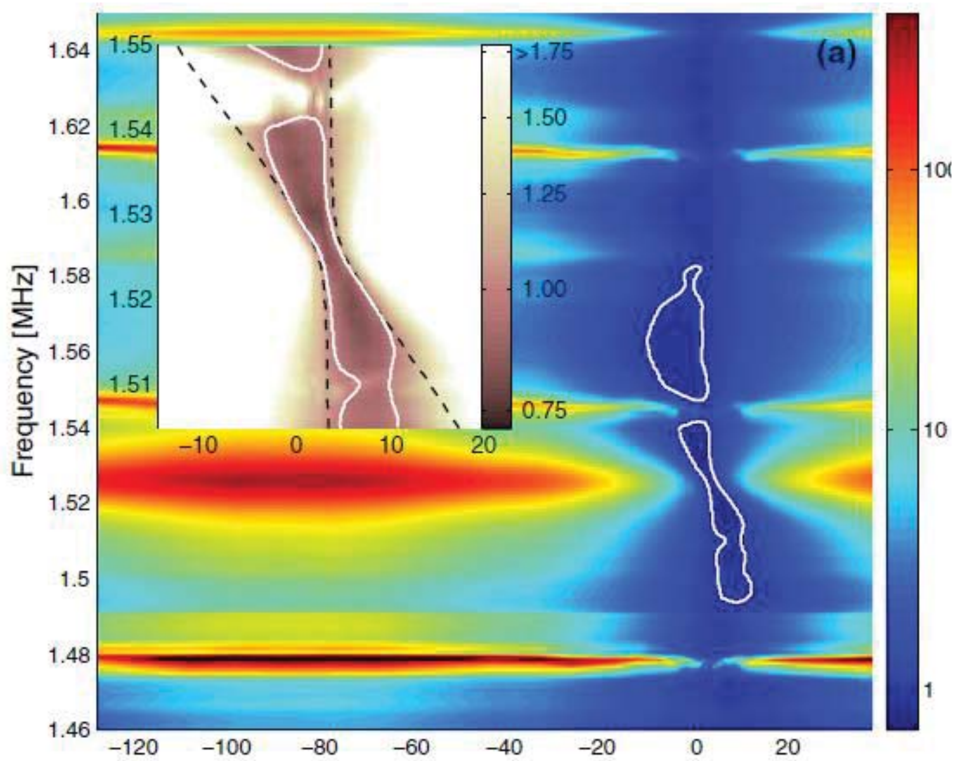


A, Safavi-Naeini et al., Nature 2013

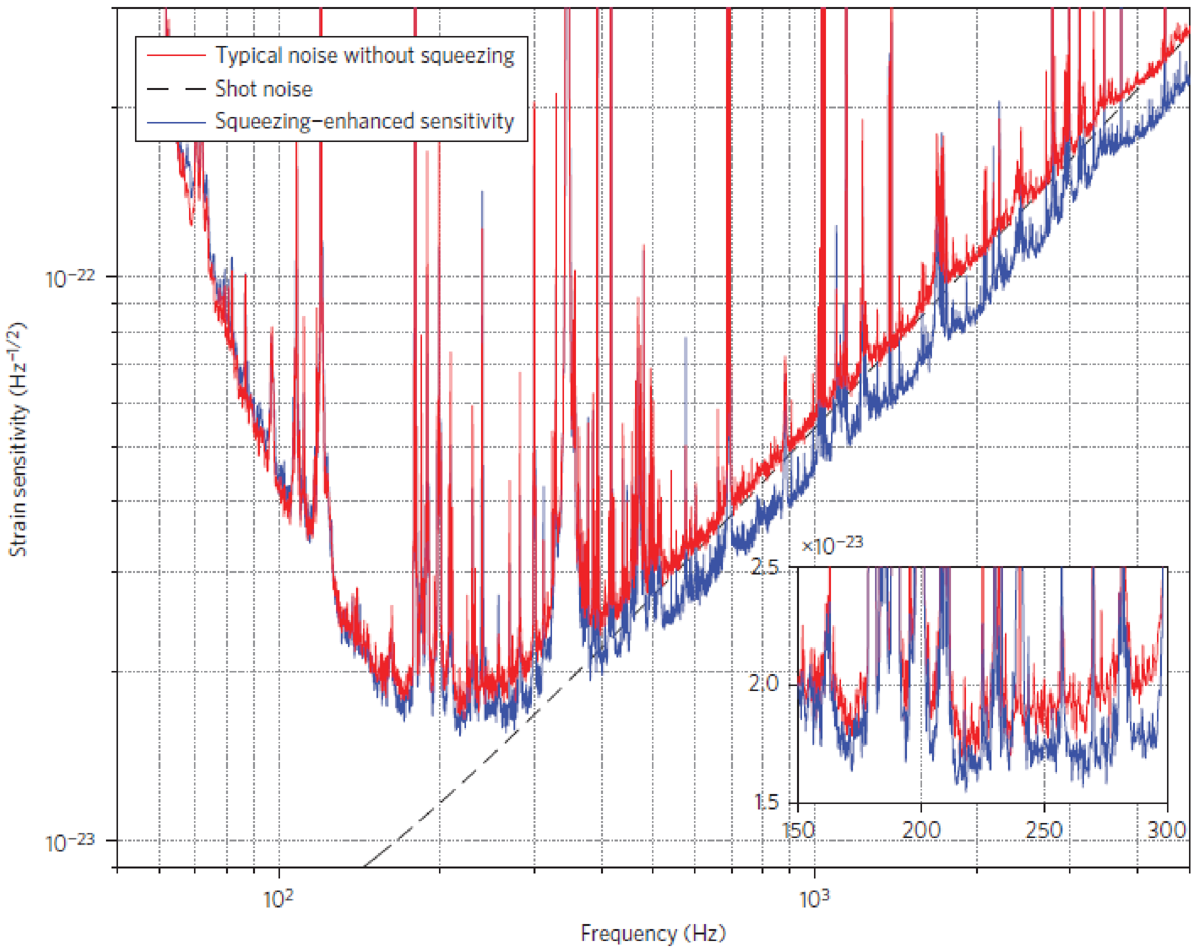
With a MIM setup, Purdy et al, PRX, August 2013, **1.7 dB of squeezing**







However, for gravitational wave detection, **squeezed light injection would be useful at lower frequencies, < kHz band**



Enhanced sensitivity of the LIGO gravitational wave detector by using squeezed states of light, Nat Phot. 2013

Injection of a low noise – low frequency OPO source of squeezed vacuum with nonlinear crystal (Valhbruch et al GEO600)

At lower frequencies, ponderomotive squeezing is more difficult, mainly due to **higher frequency noise** (from cavity and lasers)

We have recently experimentally demonstrated a **frequency noise cancelation in the kHZ band, in a Fabry-Perot cavity with a micromechanical mirror .** It can be useful for pond. squeezing.

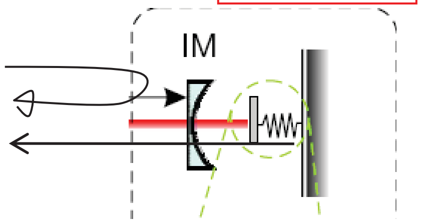
Camerino-Trento-Florence collaboration, A. Pontin et al., arXiv:1308.5176v1

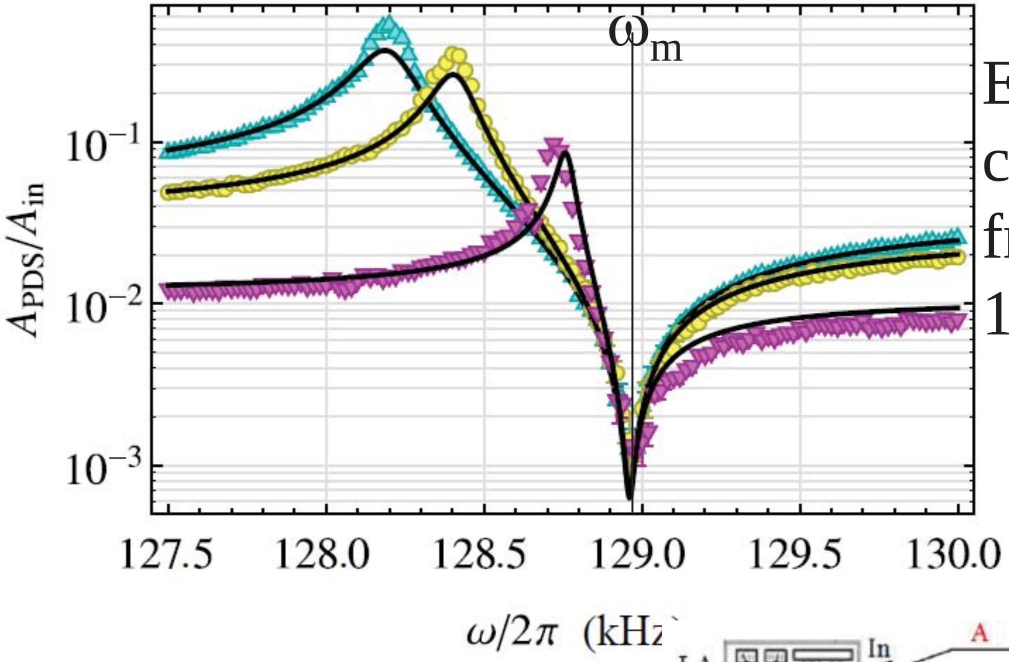
The cancelation is just around the **bare mechanical frequency, ω_m,** and is due to the **destructive interference** between the frequency noise directly affecting the cavity and the same frequency noise transduced by the resonator

$$\boxed{a_1^{\text{out}}(\omega)} \boxed{\propto \frac{\chi_{\text{eff}}(\omega)}{\chi_0(\omega)}\dot{\phi}(\omega)}$$

Cancelation when Q_m is large

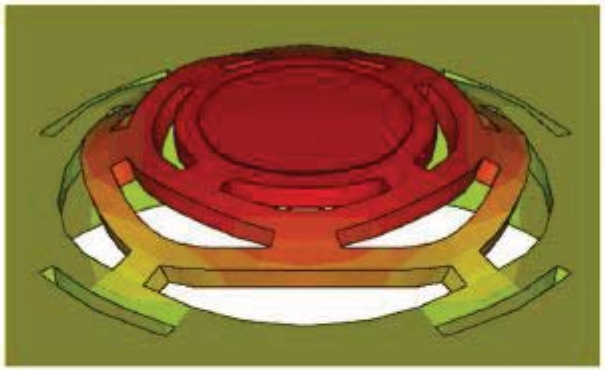
$$\boxed{\chi_0(\omega_m) \approx \infty}$$



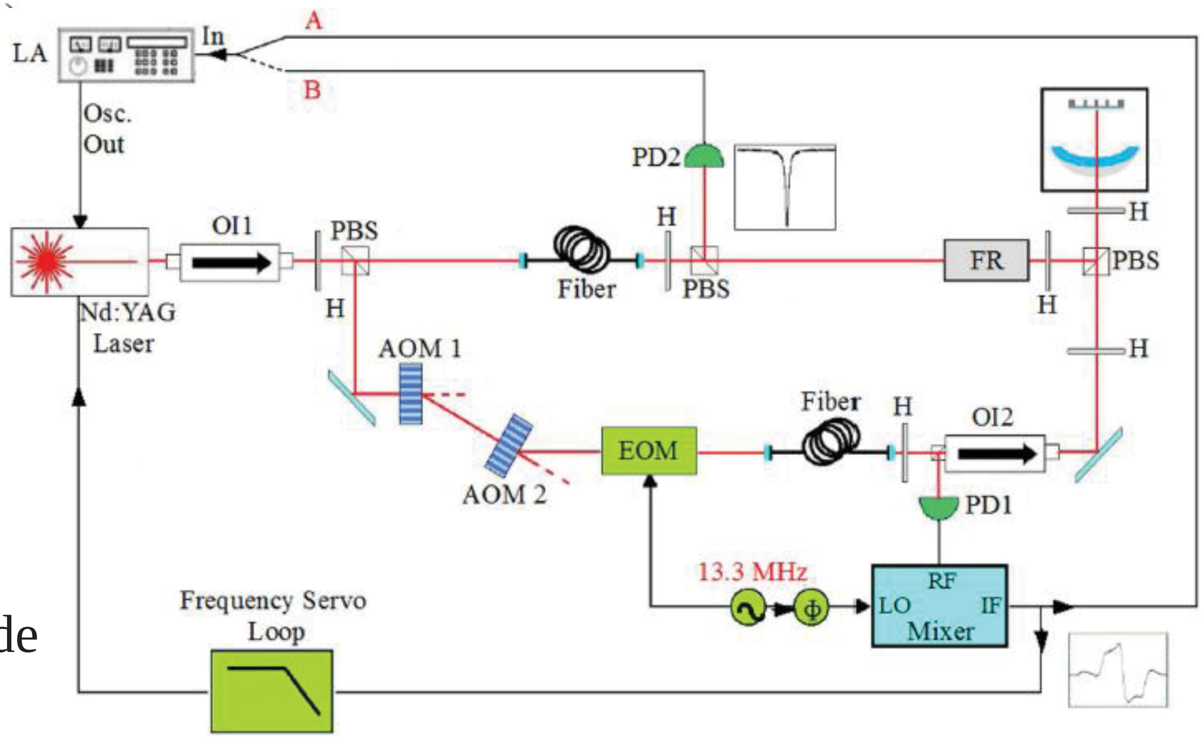


Experimental spectrum of the cavity output with added large frequency noise (room T, Q = 10^4)

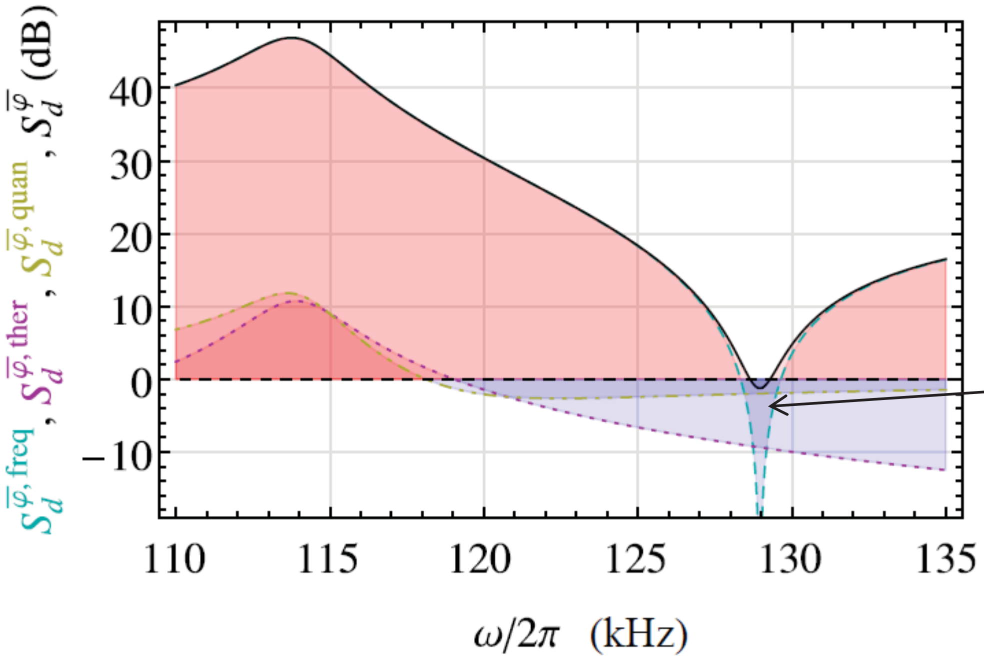
A. Pontin et al., arXiv:1308.5176v1



Micromechanical mirror mode



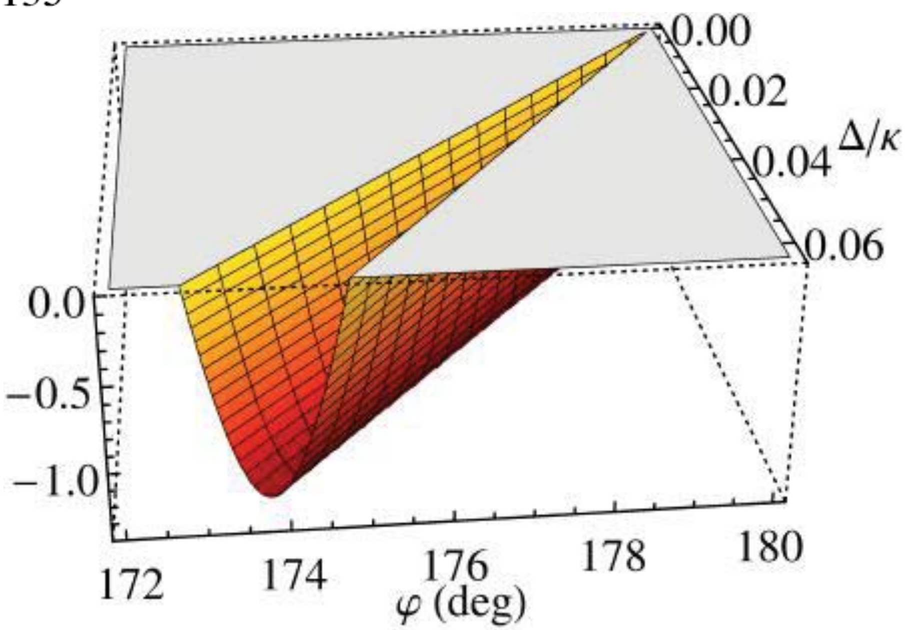
This frequency noise cancelation facilitates the detection of ponderomotive squeezing at low frequencies



Theory predictions at lower T, Q = 10^5, lower freq noise

Squeezing due to cancelation

Output spectrum at $\omega = \omega_m$ versus homodyne phase and detuning



How to use a nanomechanical resonator as a quantum interface between optics and microwaves

Based on:

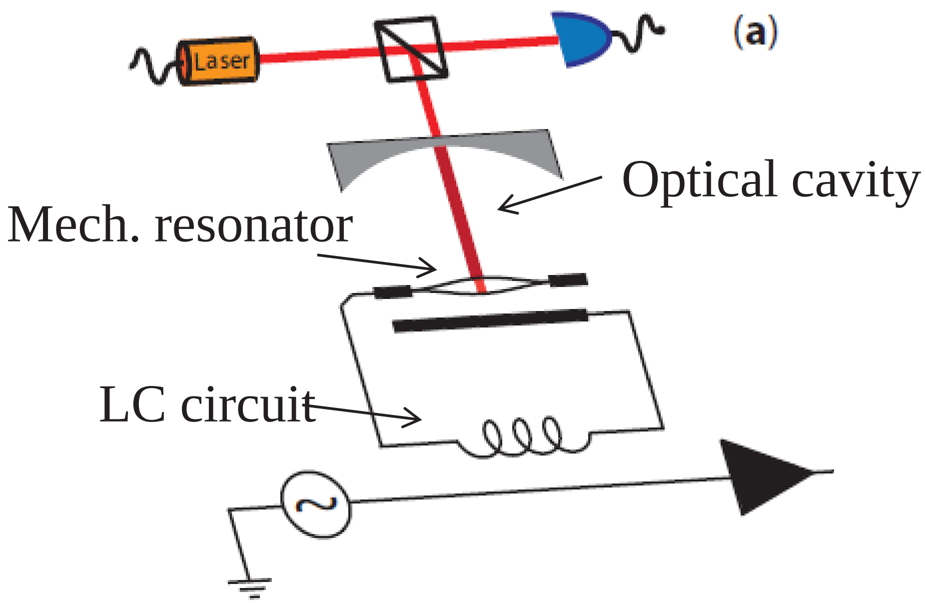
1. Establishing stationary, continuous wave, **strong continuous variable (CV) entanglement** between the optical and microwave output field
2. High-fidelity CV optical-to-microwave **teleportation** of nonclassical states

S. Barzanjeh, M. Abdi, G.J. Milburn, P. Tombesi, D. Vitali,
Phys. Rev. Lett. 109, 130503 (2012).

Why an optical-microwave transducer ?

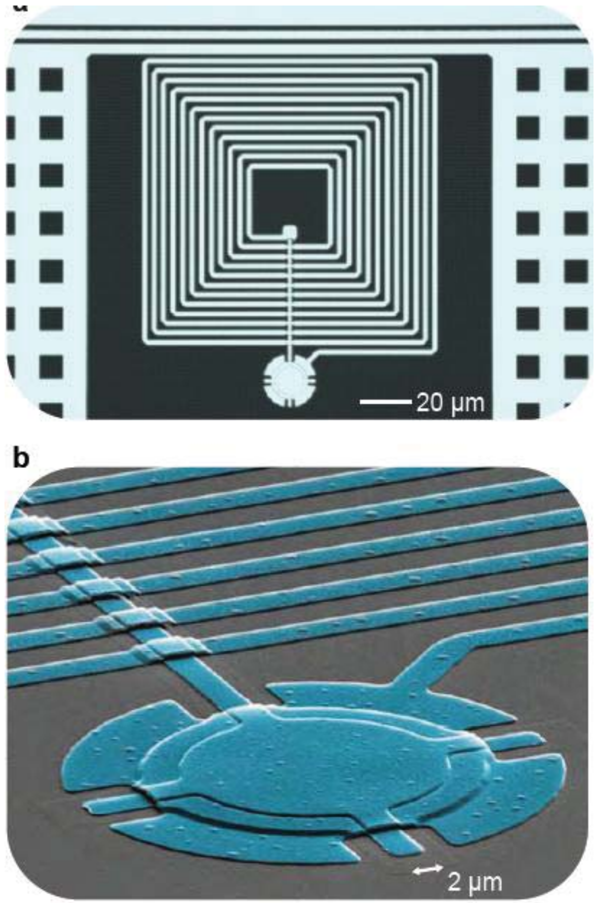
Light is optimal for quantum communications between nodes, while **microwaves** are used for manipulating solid state quantum processors

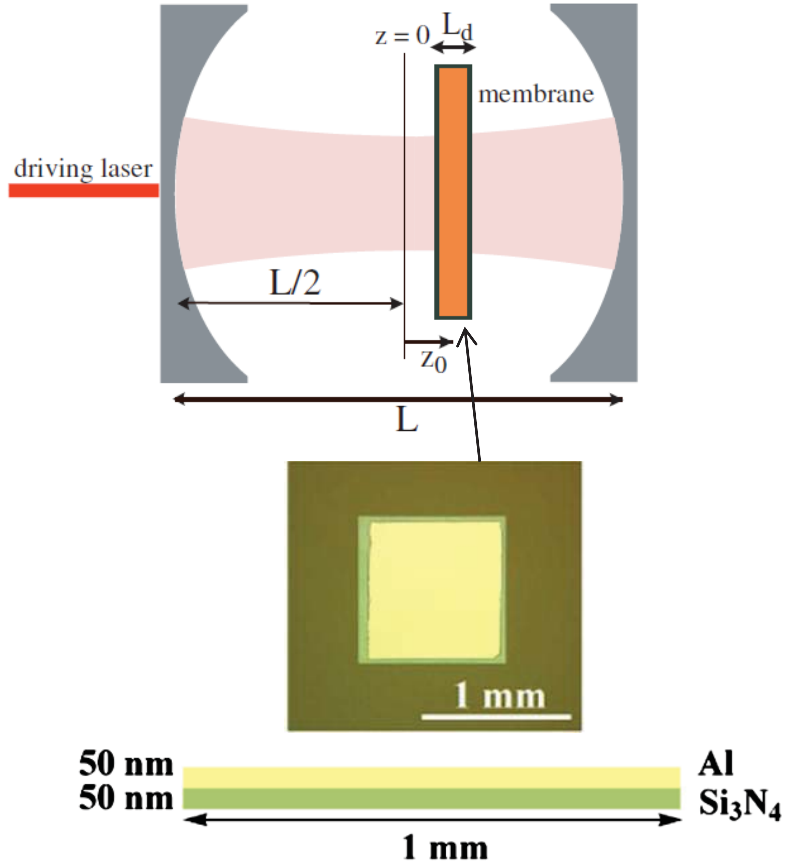
⇒ **a quantum interface between optical and microwave photons would be extremely useful**



Quantum interface between optical and microwave photons based on a **nanomechanical resonator in a superconducting circuit, simultaneously interacting with the two fields**

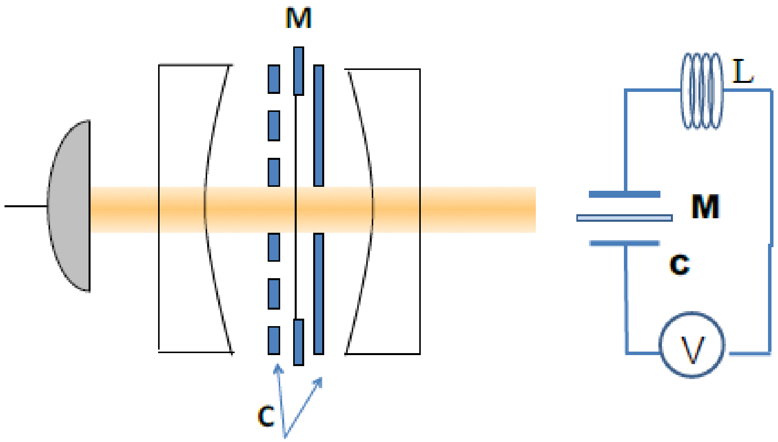
The **membrane resonator is coupled capacitively with the microwave cavity and by radiation pressure with the optical cavity. Possible implementations**:





Adding an optical cavity by coating the membrane capacitor of the superconducting LC circuit of Teufel et al., Nature (London), 471, 204 (2011).

Adding a LC circuit to the membrane-in-the-middle setup with a patterned Al film on top, Yu et al PRL 108, 083603 (2012)

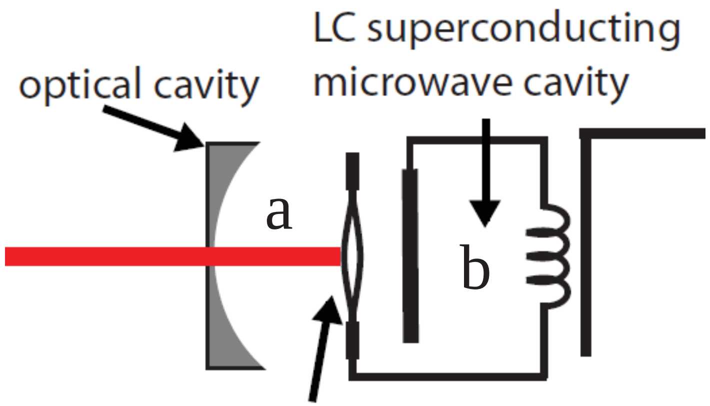


Similar proposal for radiofrequency-optical optomechanical transducer

J. Taylor, Sorensen, Marcus, Polzik, PRL 107, 273601 (2011), T. Bagci et al., 2013

Schematic of a **Fabry-Perot cavity with a nanomechanical membrane inserted in the waist of the cavity**; **the membrane, in turn, is part of a parametric capacitor**; (right) Equivalent circuit with a dc voltage bias describing the coupled electromechanical system.

See also A. Cleland talk, with electrically actuated AlN optomechanical crystal



Both cavities are driven coherently: $\Rightarrow$ the dynamics of the quantum fluctuations around the stable steady state **well described by Quantum Langevin Equations (QLE) for optical and microwave operators *a* and *b***

The nanomechanical resonator **mediates a retarded interaction between the two cavity fields (exact QLE), with a kernel** $\boxed{\chi_M(t) = e^{-\gamma_m t/2}\sin\omega_m t}$

$$
\begin{aligned}
\delta\dot{\hat{a}} &= -\kappa_c\delta\hat{a} + \sqrt{2\kappa_c}\hat{a}_{in}(t)e^{i\Delta_c t} + \frac{i}{2}\int_{-\infty}^{t} ds\chi_M(t-s)\left\{G_c\hat{\xi}(s)e^{i\Delta_c t}\right. \\
&\left. + G_c^2\left[\delta\hat{a}(s)e^{i\Delta_c(t-s)} + \delta\hat{a}^\dagger(s)e^{i\Delta_c(t+s)}\right] + G_cG_w\left[\delta\hat{b}(s)e^{i\Delta_c t - i\Delta_w s} + \delta\hat{b}^\dagger(s)e^{i\Delta_c t + i\Delta_w s}\right]\right\}, \\
\delta\dot{\hat{b}} &= -\kappa_w\delta\hat{b} + \sqrt{2\kappa_w}\hat{b}_{in}e^{i\Delta_w t} + \frac{i}{2}\int_{-\infty}^{t} ds\chi_M(t-s)\left\{G_w\hat{\xi}(s)e^{i\Delta_w t}\right. \\
&\left. + G_w^2\left[\delta\hat{b}(s)e^{i\Delta_w(t-s)} + \delta\hat{b}^\dagger(s)e^{i\Delta_w(t+s)}\right] + G_cG_w\left[\delta\hat{a}(s)e^{i\Delta_w t - i\Delta_c s} + \delta\hat{a}^\dagger(s)e^{i\Delta_w t + i\Delta_c s}\right]\right\}
\end{aligned}
$$

Beamsplitter-like optical-microwave interaction $\Rightarrow$ **state transfer term**

parametric optical-microwave interaction $\Rightarrow$ **entangling term**

One can resonantly select one of these processes by appropriately adjusting the two cavity detunings:

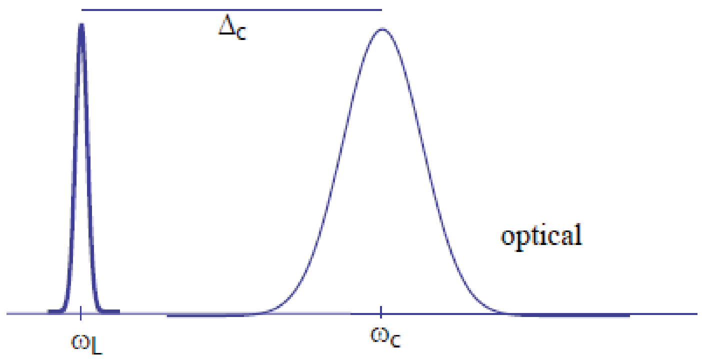
• Equal detunings: $\Delta_c = \Delta_w \Rightarrow$ **state transfer** between optics and microwave (see other proposals, Tian et al., 2010, Taylor et al., PRL 2011, Wang & Clerk, PRL 2011)

Opposite detunings: $\Delta_c = - \Delta_w \Rightarrow$ two-mode squeezing and entanglement

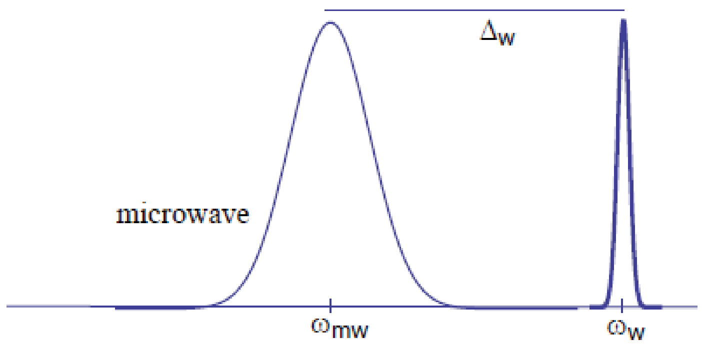
Interaction kernel = mechanical susceptibility

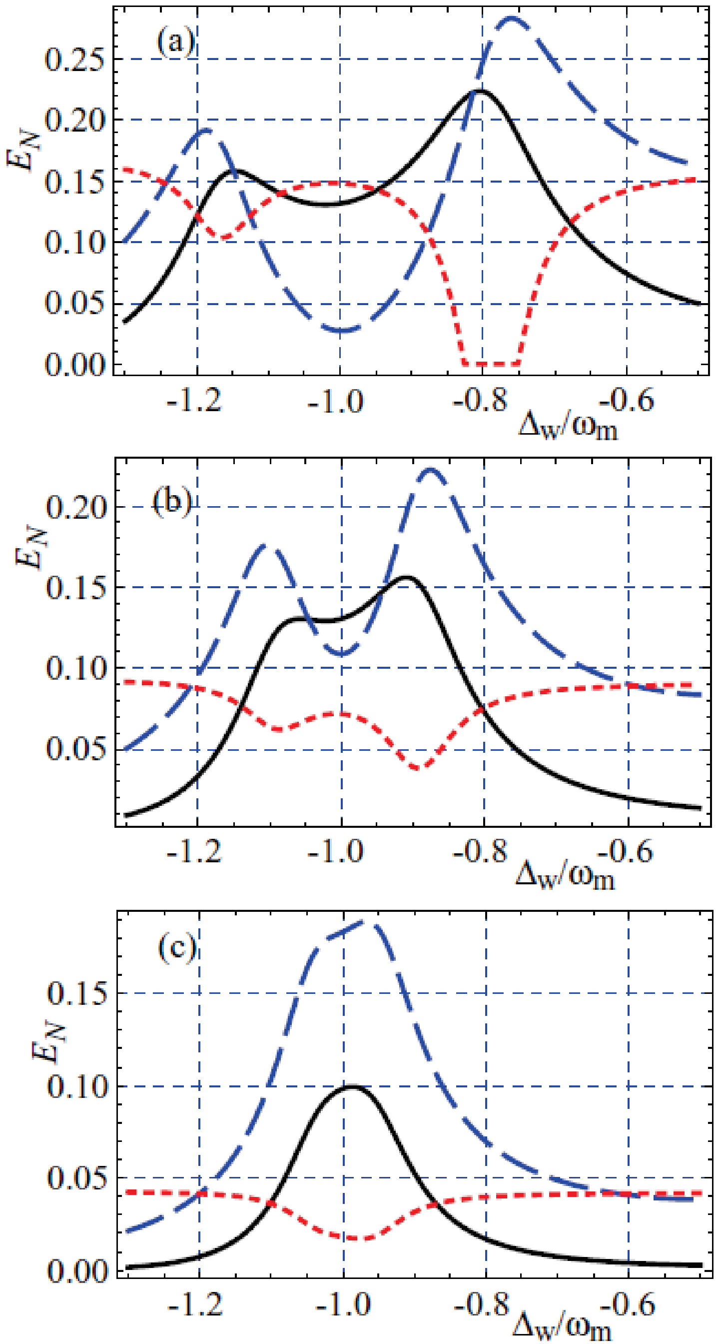
$$\boxed{\chi_M(t) = e^{-\gamma_m t/2} \sin \omega_m t}$$

Here we choose $\Delta_c = - \Delta_w = \pm\, \omega_m \Rightarrow$ two-mode squeezing is resonantly enhanced (because the interaction kernel does not average to zero)



The mechanical interface realizes an **effective parametric oscillator with an optical signal (idler) and microwave idler (signal)** $\Leftrightarrow$ microwave-optical two mode squeezing





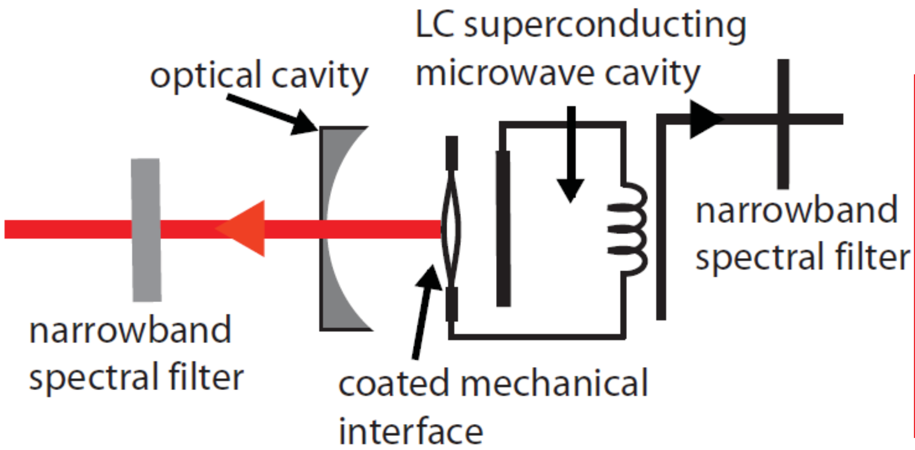
ENTANGLEMENT BETWEEN MECHANICS AND THE INTRACAVITY MODES IS NOT LARGE

E_N of the three bipartite subsystems (**OC-MC full black line**, **OC-MR dotted red line**, **MC-MR dashed blue line**) vs the normalized microwave cavity detuning at fixed temperature *T = 15 mK*, and **at three different MR masses**: *m = 10 ng (a), m = 30 ng (b), m = 100 ng*. The optical cavity detuning has been fixed at $\Delta_c = \omega_m$,

Sh. Barzanjeh et al., Phys. Rev. A **84,** 042342 (2011)

BUT, similarly to single-mode squeezing, **entanglement can be very strong for the OUTPUT cavity fields**

by properly choosing the central frequency Ω_j and the bandwidth $1/\tau$ of the output modes, one can optimally filter the entanglement between the two output modes



output cavity modes

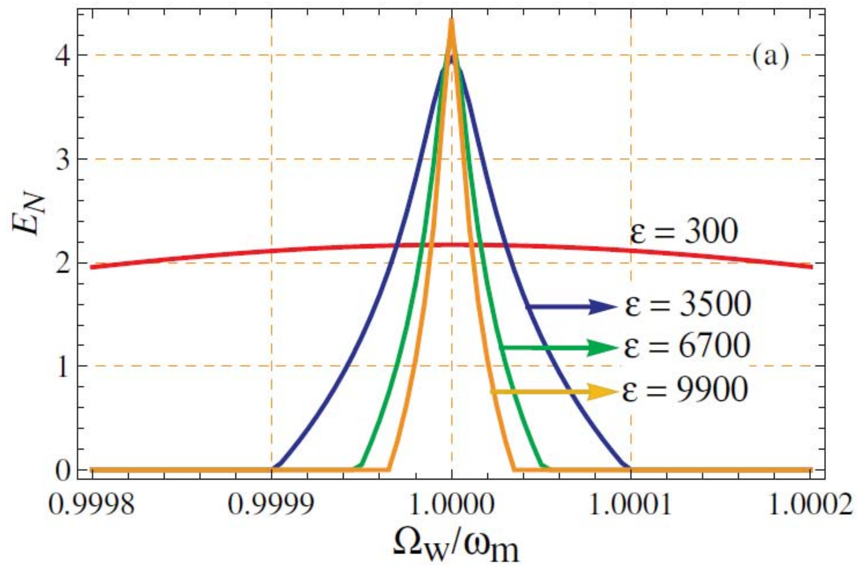
$$\hat{a}_c^{out}(t) = \int_{\infty}^{t} ds g_c(t-s)\hat{a}^{out}(s)$$

$$\hat{b}_w^{out}(t) = \int_{\infty}^{t} ds g_w(t-s)\hat{b}^{out}(s)$$

normalized causal filter function

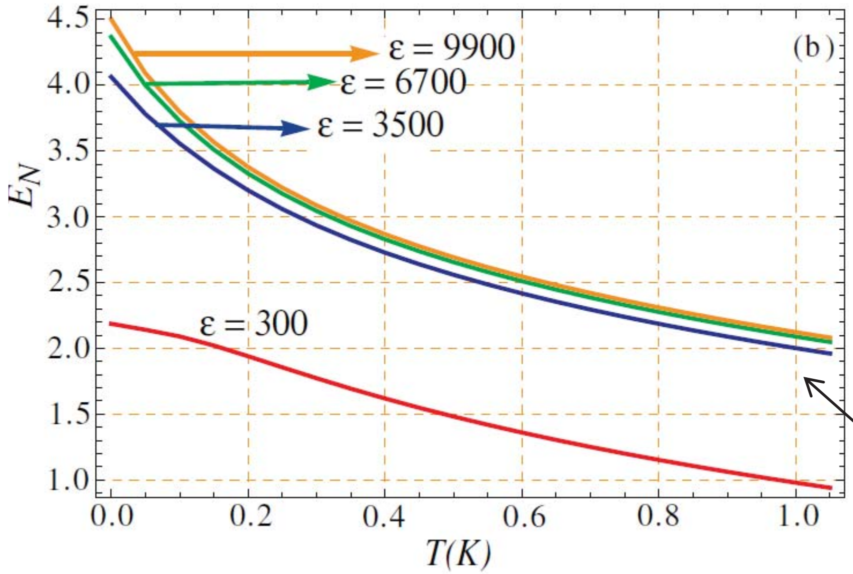
$$g_j(t) = \sqrt{\frac{2}{\tau}}\theta(t)e^{-(1/\tau+i\Omega_j)t} \quad j = c, w$$

OUTPUT MICROWAVE-OPTICAL ENTANGLEMENT



LARGE ENTANGLEMENT FOR **NARROW-BAND OUTPUTS**

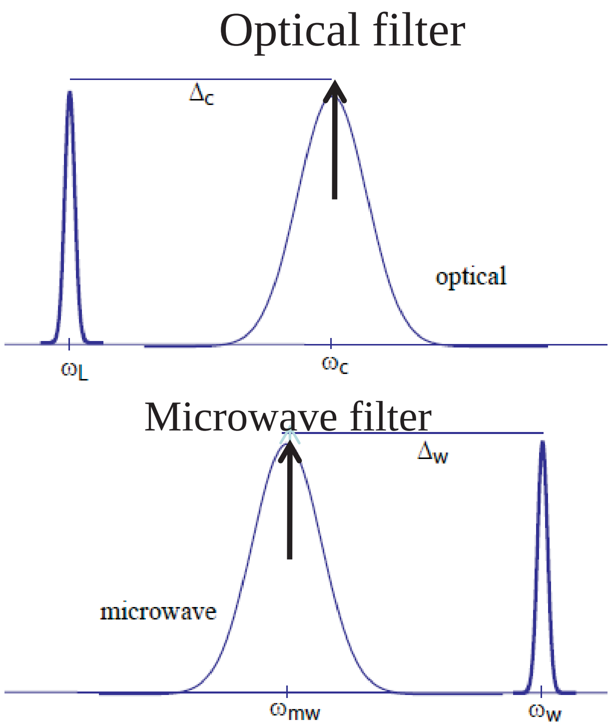
LogNeg at four different values of the normalized inverse bandwidth $\boldsymbol{\epsilon = \tau\omega_m}$ *vs* the normalized frequency Ω_w/ω_m, at fixed central frequency of the optical output mode $\Omega_c = -\omega_m$.

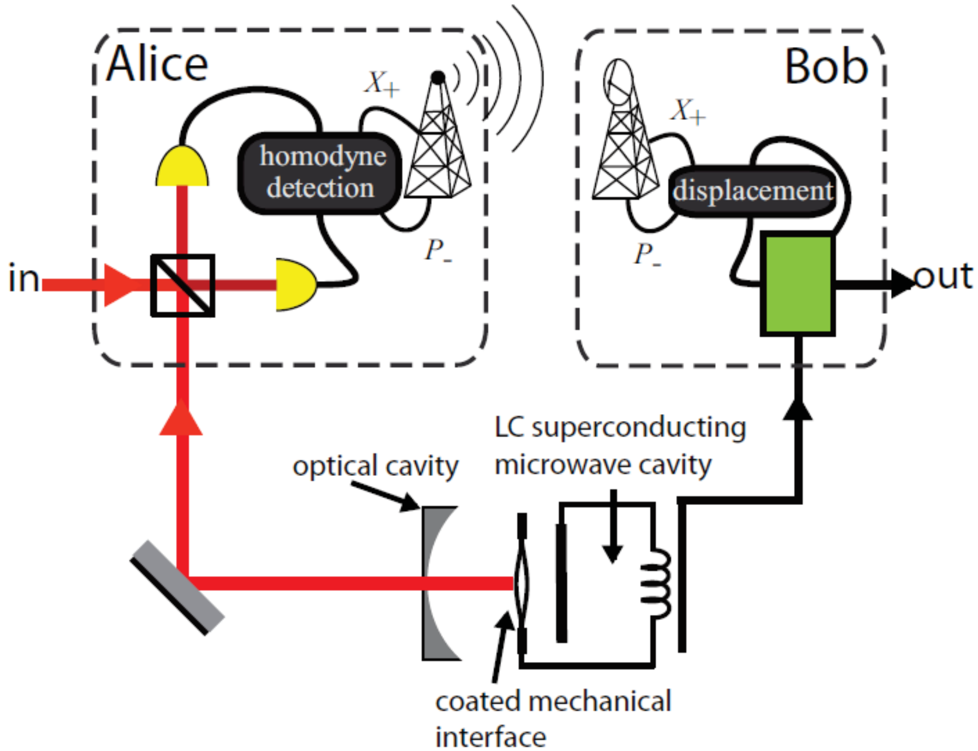


Optical and microwave cavity detunings fixed at $\Delta_c = -\Delta_w = -\omega_m$
Other parameters: $\omega_m/2\pi = 10$ MHz, $Q=1.5\text{x}10^5$, $\omega_w/2\pi = 10$ GHz, $\kappa_w = 0.04\omega_m$, $P_w = 42$ mW, $m = 10$ ng, $T = 15$ mK. This set of parameters is analogous to that of Teufel et al.
Optical cavity of length $L = 1$ mm and damping rate $\kappa_c = 0.04\omega_m$, driven by a laser with power $P_c = 3.4$ mW.

Entanglement is robust wrt to temperature

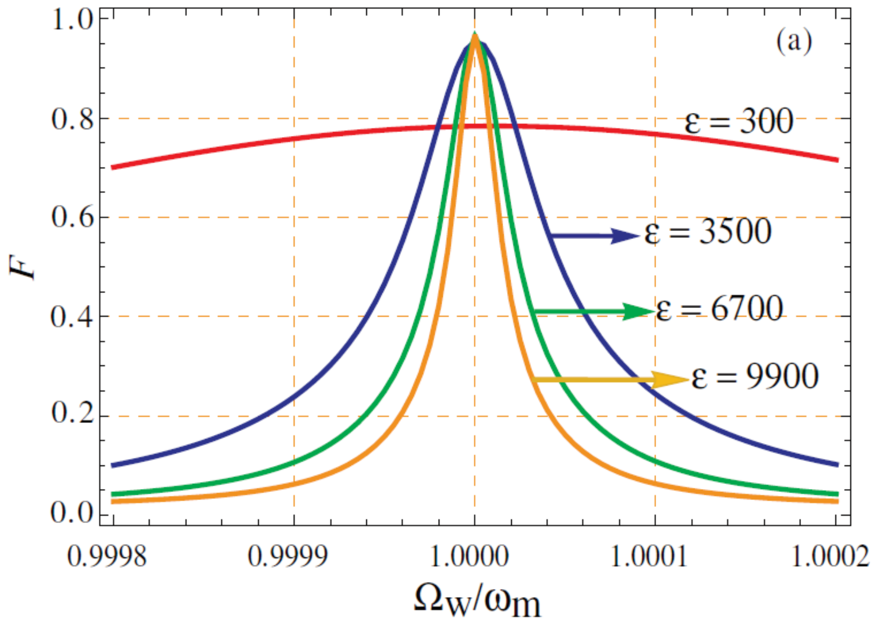
• The common interaction with the nanomechanical resonator establishes **quantum correlations which are strongest between the output Fourier components *exactly at resonance* with the respective cavity field**

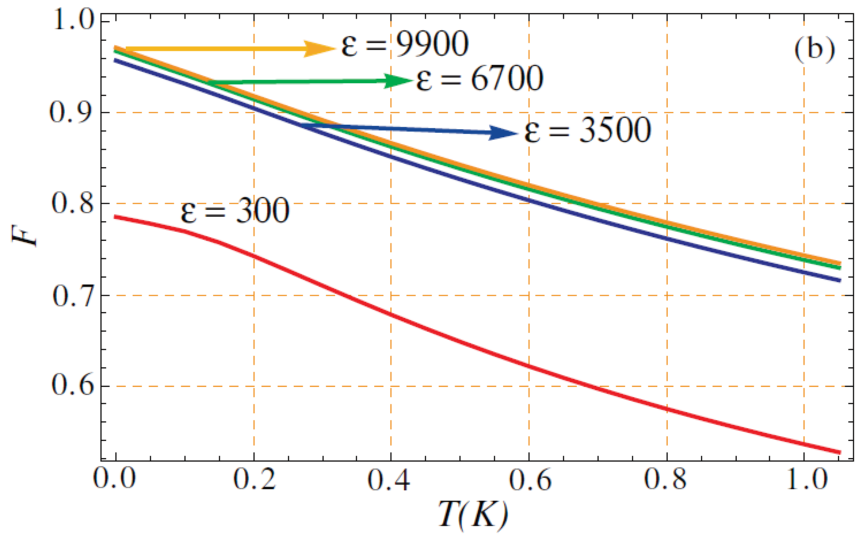




Such a large stationary entanglement can be exploited for continuous variable (CV) optical-to-microwave quantum teleportation:

TELEPORTATION FIDELITY OF A CAT STATE





Input cat state

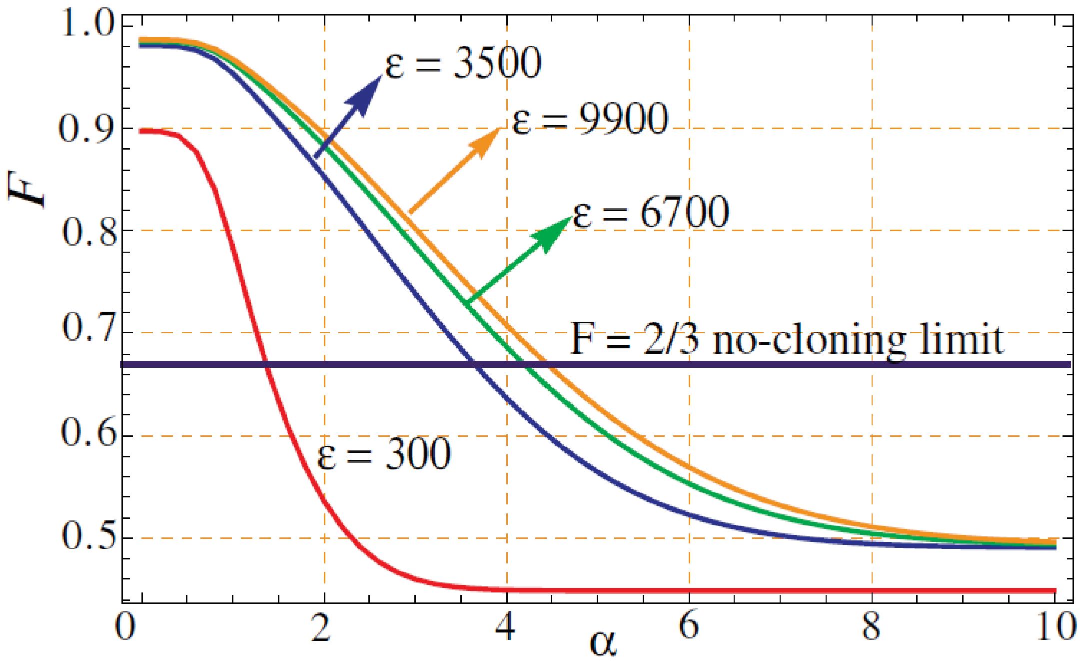
$$\boxed{|\psi\rangle = N(|\alpha\rangle + |-\alpha\rangle)}$$

(a) Plot of the teleportation fidelity F at four different values of $\epsilon = \tau\omega_m$ *versus* Ω_w/ω_m and for the Schrodinger cat-state amplitude $\alpha = 1$.

(b) Plot of F for the same values of ϵ *vs* temperature at a fixed central frequency of the microwave output mode $\Omega_w = \omega_m$.

The fidelity behaves as the logneg: **large and robust F for narrow output bandwidths**

TELEPORTATION FIDELITY OF NONCLASSICALITY



• the selected narrow-band microwave and optical output modes possess (EPR) correlations that can be optimally exploited for teleportation

F is not a local invariant, but here is very close to the optimal upper bound achievable for a given E_N

$$F_{opt} = \frac{1}{1+e^{-E_N}}$$

Through teleportation we realize a high-fidelity optical-to-microwave quantum state transfer assisted by measurement and classical communication

(see A. Mari, D. Vitali, PRA 78, 062340 (2008)).

CONCLUSIONS

1. Proposals for **generating mechanical Schrodinger cat and squeezed states in quadratically** coupled optomechanical system

2. Controlling light with cavity optomechanics:
   Experiments on: i) optomechanically induced transparency (OMIT); ii) noise reduction for ponderomotive squeezing

3. **CV optics-to-microwave interfaces** at the classical and quantum level realizable with opto-electro-mechanical systems