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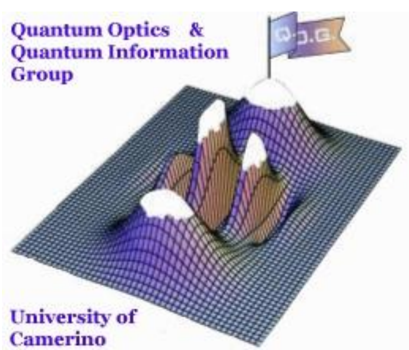
iquoems
interfacing quantum optical electrical mechanical systems

Cavity Optomechanics at the Quantum Optics and Quantum Information group in Camerino

School of Science and Technology, Physics Division, University of Camerino, Italy,



iQUOEMS kick-off Meeting January 11 2014, Camerino

THE GROUP AND COLLABORATIONS

both theory and experiments

Gianni Di Giuseppe
Nicola Malossi
Riccardo Natali
Paolo Tombesi
David Vitali

PhDs:

Muhammad Asjad
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Iman Moaddel-Haghighi
Norshamsuri Bin Ali

Master students

Paolo Piergentili
Alessandro Seri
Federica Bonfigli

Strong collaborations with

- **Irene Marzoli** (theory)
- **Javad Revzani, Nicola Pinto (and also INRIM Torino)** for nanodepositions

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Further collaborations:

• **Francesco Marin group (Florence**) for ponderomotive squeezing

• **Michele Bonaldi and Giovanni Prodi (Trento and FBK**) for nanofabrication of micromirrors and nanomembranes

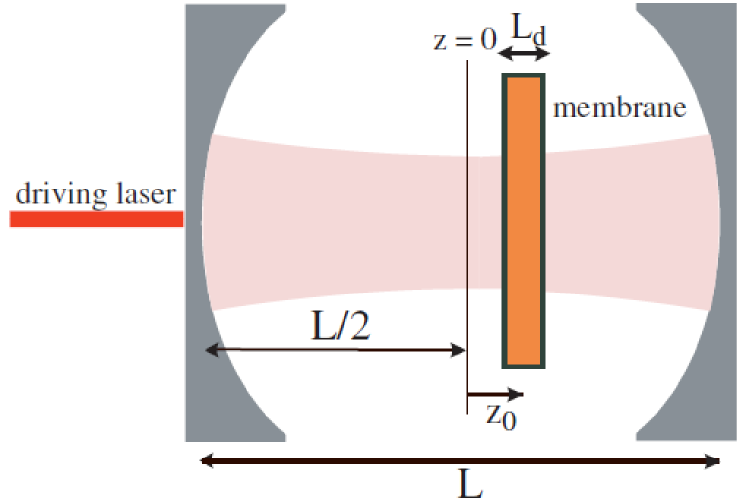
• Theory collaborations with Gerard Milburn, Myungshik Kim, G. Agarwal

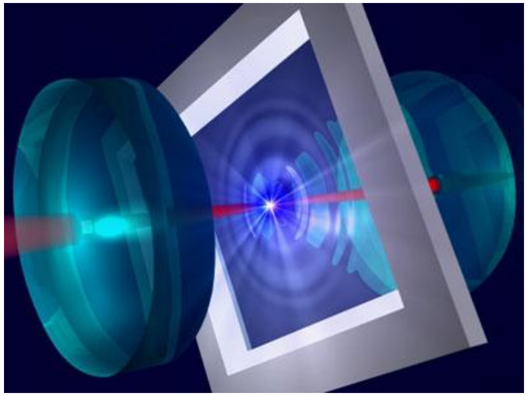
Previous members:

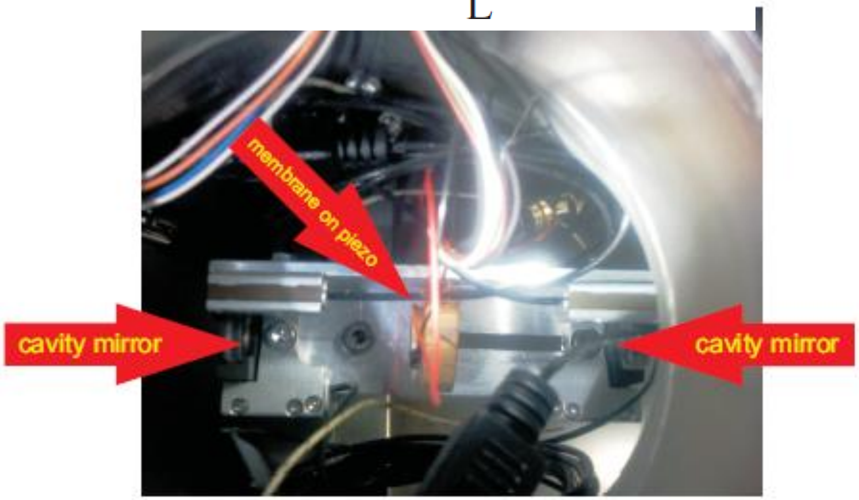
Marin Karuza, Chiara Molinelli, Marco Galassi, Mehdi Abdi, Shabir Barzanjeh

RECENT EXPERIMENTS IN CAVITY OPTOMECHANICS

"membrane in the middle" scheme: Fabry-Perot cavity with a thin SiN membrane inside (J. Harris-Yale, C. Regal-JILA…)







Recent experimental results

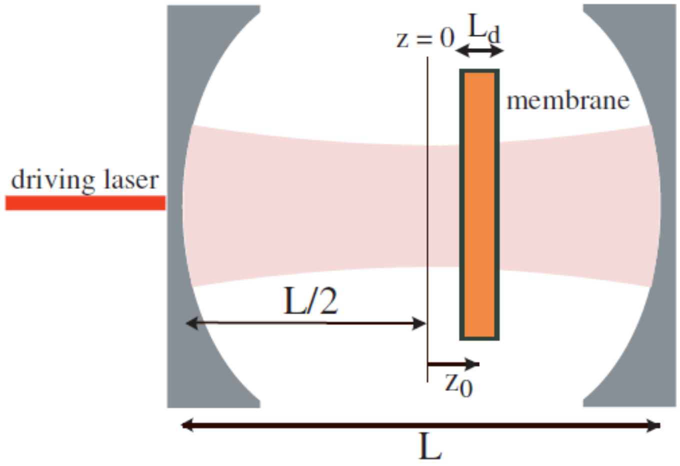
• **Enhanced quadratic optomechanical interaction** at avoided crossing between higher-order TEM cavity modes (M. Karuza et al., J. Opt. 15 (2013) 025704)

• **Resolved sideband cooling** and quadratic optical spring effect, Karuza et al., New J. Phys. 14, 095015 (2012)

• **Optomechanical induced transparency (OMIT) and amplification**, Karuza et al., PRA 88, 013804 (2013)

(Experimental activity also on single photon-quantum key distribution, parametric down conversion…..)

The membrane-in-the-middle setup

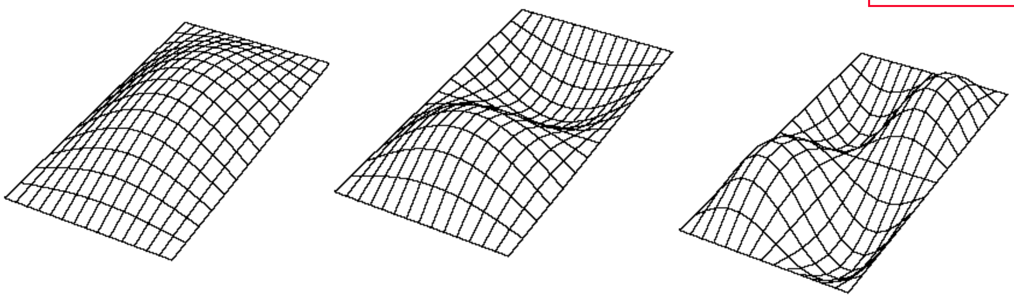


Many cavity modes (still Gaussian TEM_{mn} for an aligned membrane close to the waist)

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

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

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



Vibrational modes

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

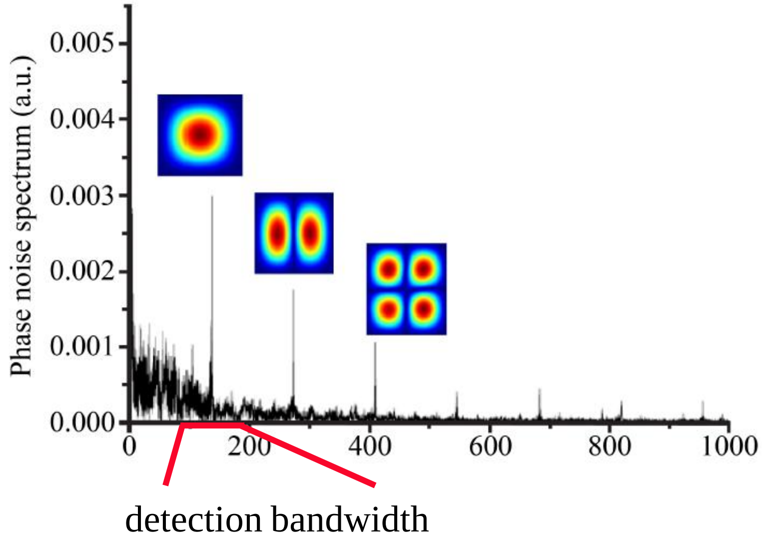
T = surface tension
ρ= SiN density,
L_d = membrane thickness
d = membrane side length
m,n = 1,2…

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

When:

• The external laser (with frequency $\omega_L \approx \omega_c$) **drives 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
valid for a wide variety of systems

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

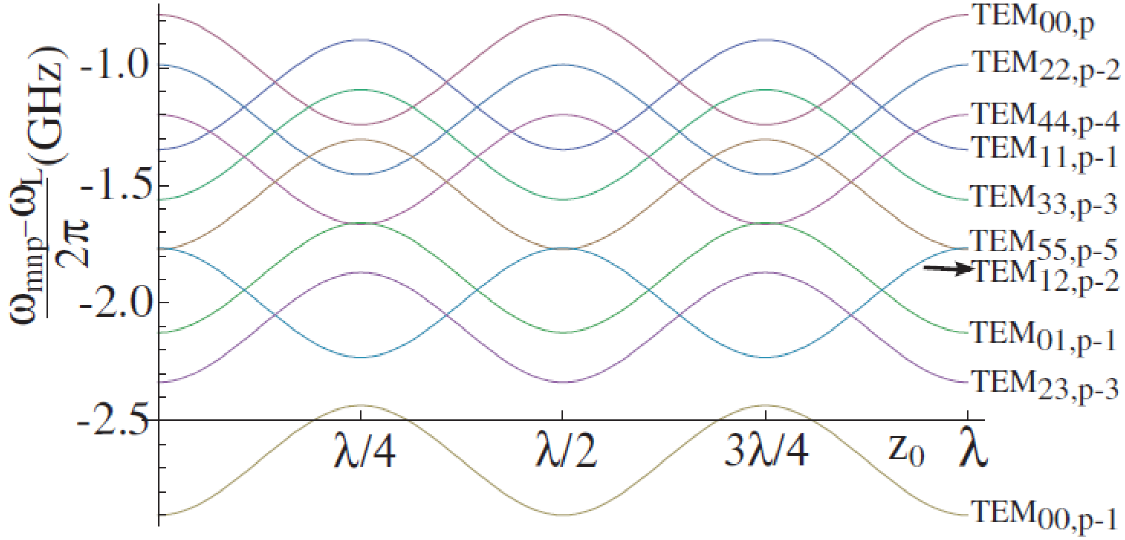
TUNABLE OPTOMECHANICAL INTERACTION by changing membrane position and orientation

Radiation pressure 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)

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



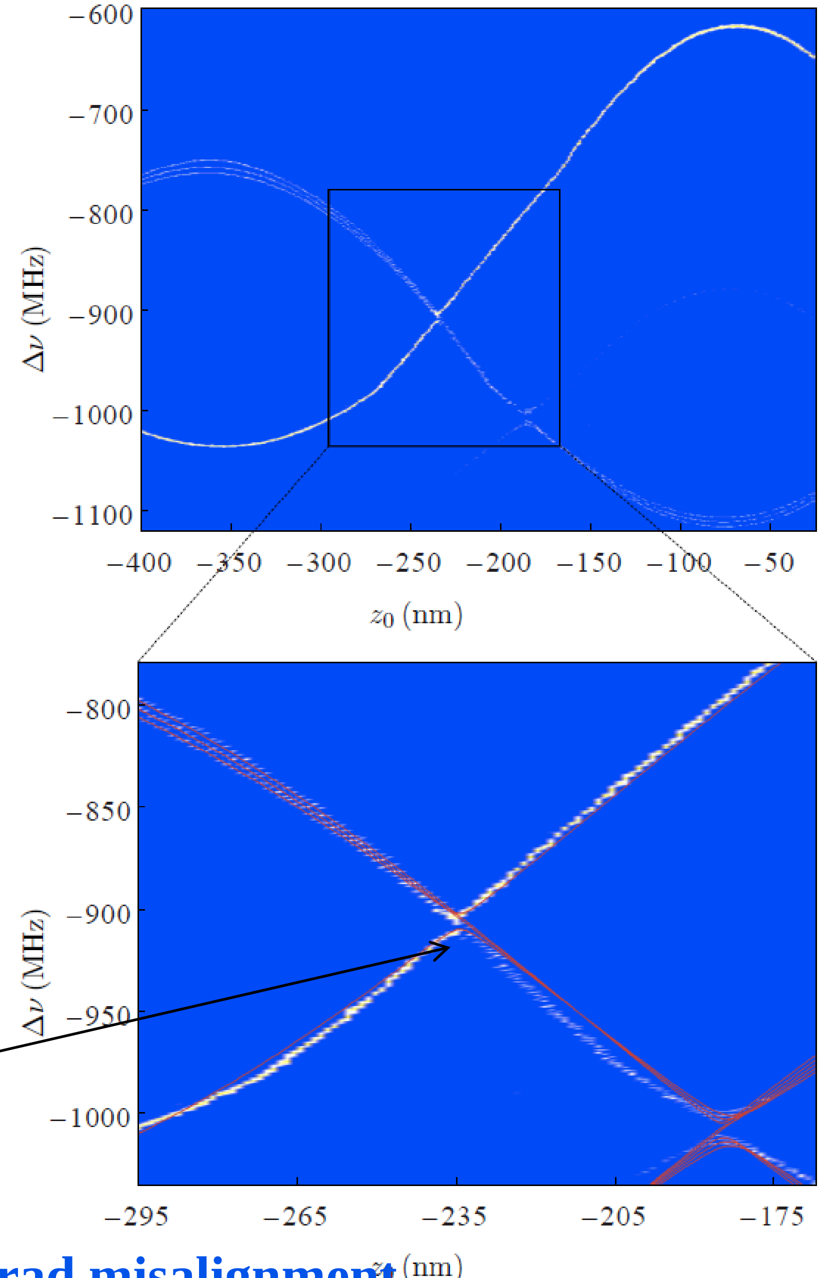
OPTICAL MODE SPECTROSCOPY for a perfectly aligned membrane with reflectivity R=0.2, **placed close to the waist**

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

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**

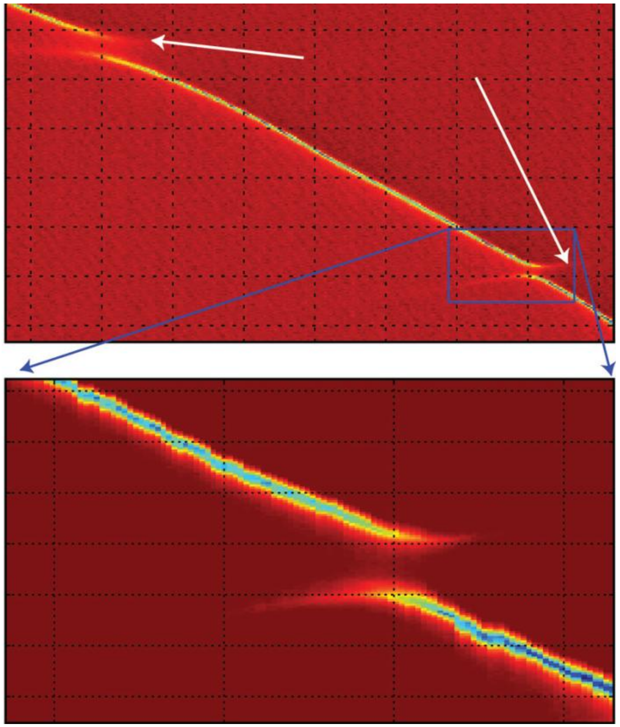
Crossing between the TEM_{00} singlet and the TEM_{20} triplet



Experimental cavity frequencies with 0.21 mrad misalignment

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

Enhanced quadratic interaction at an avoided crossing



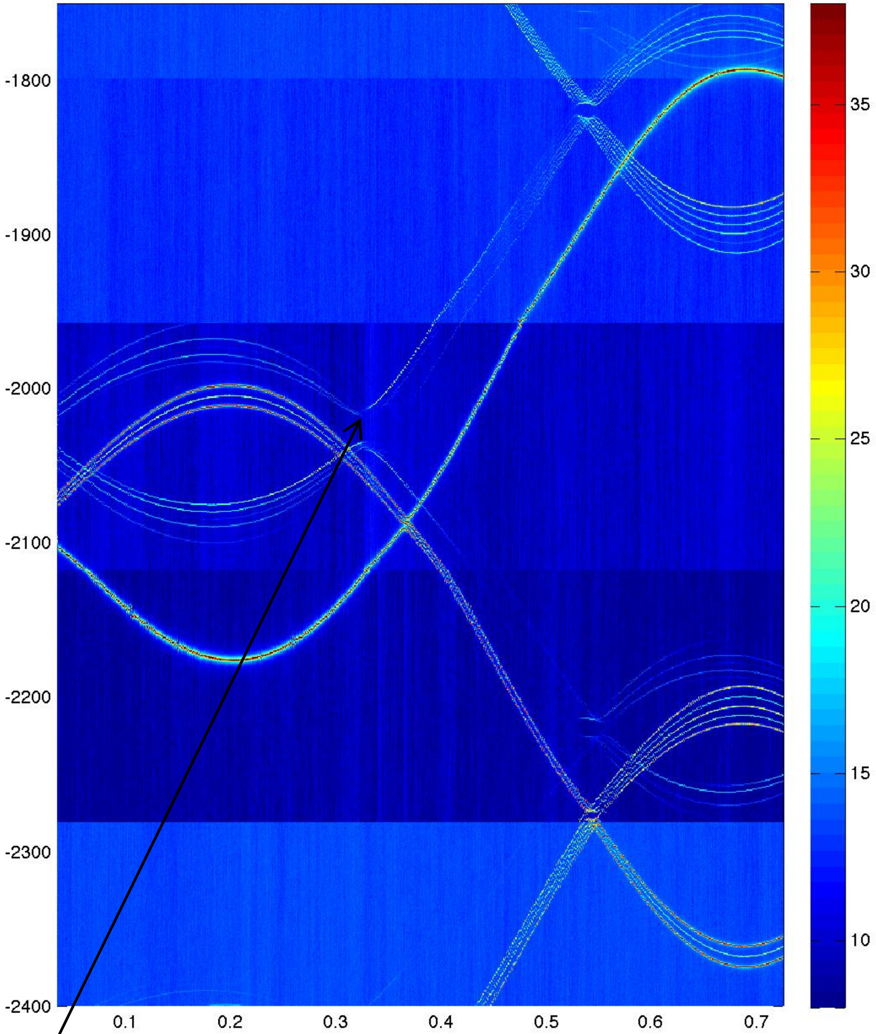
Flowers-Jacobs et al. APL, 2012

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

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

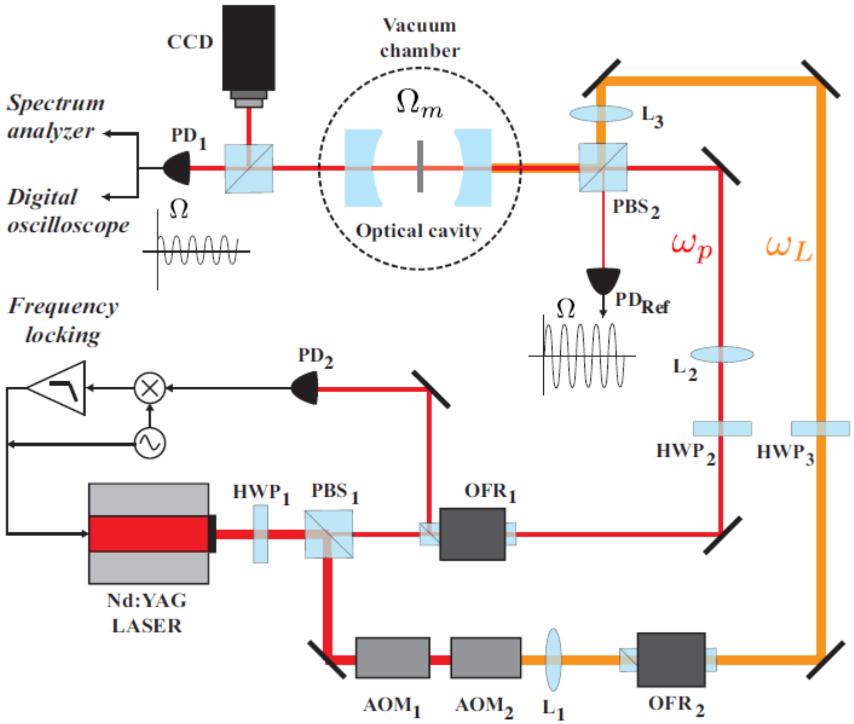
$$H_{\text{int}} = \hbar\omega''(q)q^2a^+a$$

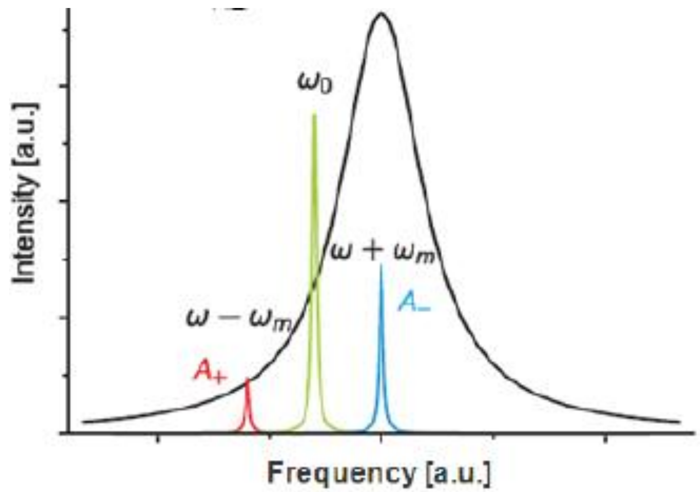
quadratic "dispersive" coupling



Recent results in our setup

RESOLVED SIDEBAND COOLING





$$\Gamma = A_- - A_+$$

net laser cooling rate

$$\gamma_m^{eff}(\omega_m) = \gamma_m + \frac{2G^2\Delta\omega_m\kappa}{|(\kappa - i\omega_m)^2 + \Delta^2|^2} \equiv \gamma_m + \Gamma$$

Stokes, A_+ or anti-Stokes, A_- = rates at which photons are scattered by the moving oscillator,

EFFECT OF RADIATION PRESSURE ON THE MECHANICAL RESONATOR

Modified mechanical susceptibility

$$\chi_{\mathrm{eff}}(\omega) = \frac{\Omega_{\mathrm{m}}}{\tilde{\Omega}_{\mathrm{m}}^2 - \omega^2 - \mathrm{i}\omega\gamma_{\mathrm{m}} - \frac{G^2 \Delta \Omega_{\mathrm{m}}}{(\kappa_{\mathrm{T}} - \mathrm{i}\omega)^2 + \Delta^2}}$$

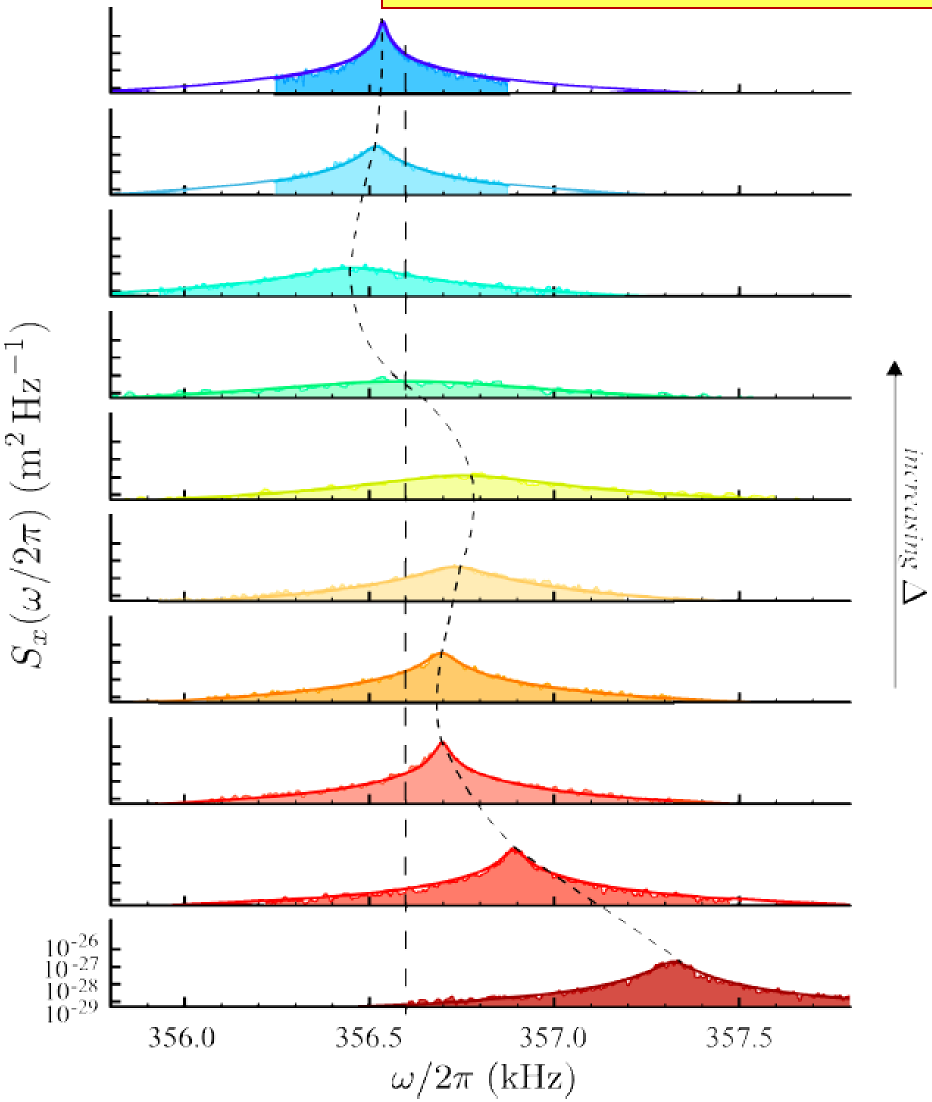
$$\gamma_m^{eff}(\omega) = \gamma_m + \frac{2G^2 \Delta \omega_m \kappa}{|(\kappa - i\omega)^2 + \Delta^2|^2}$$

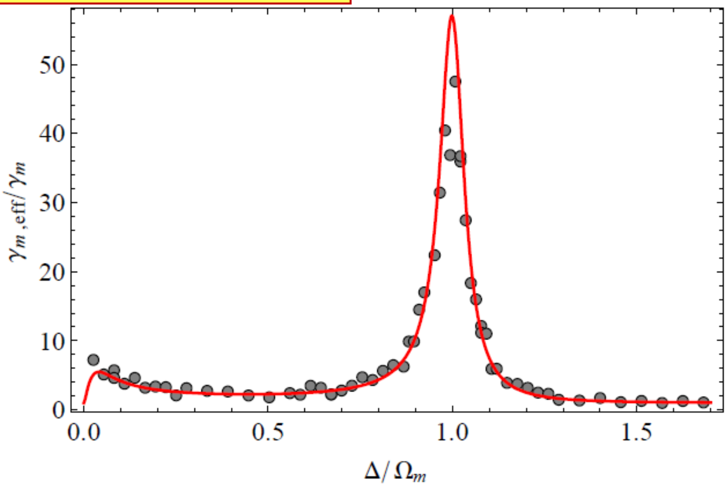
effective damping

- **shift of the mechanical resonance**

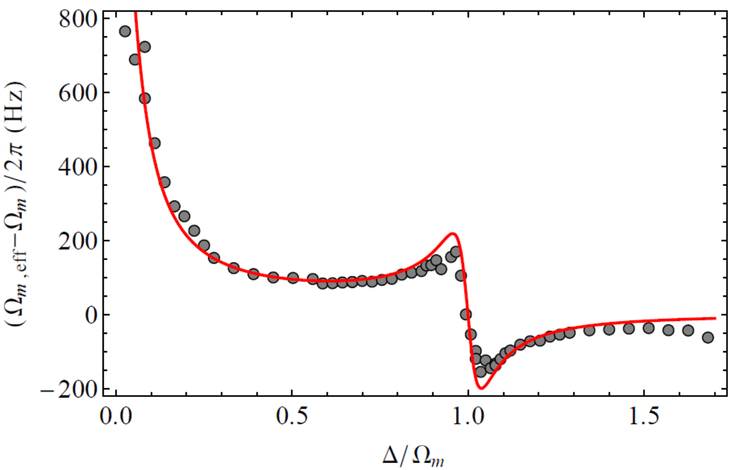
- **increased damping (**for $\Delta > 0$, red-detuned driving):

Detected position noise spectrum





Effective damping



Mechanical frequency shift

Karuza et al., New J. Phys. 14, 095015 (2012).

Optical spring effect due to quadratic interaction (nonzero mechanical shift also at cavity resonance $\Delta = 0$)

Driving laser about resonant with the cavity ($\Delta \approx 0$):

- the effective susceptibility becomes

$$\chi_{\text{eff}}(\omega) = \frac{1}{[\chi_{\text{mech}}(\omega)]^{-1} + h},$$

where only $h := \tilde{\omega}_c''(q_s)\alpha_s^2$ depends on z_0;

- the dependence $\partial_{z_0}\chi_{\text{eff}} \not\equiv 0 \Rightarrow \partial_{z_0}\Omega_m^{\text{eff}} \not\equiv 0$ is peculiar for the MIM system.

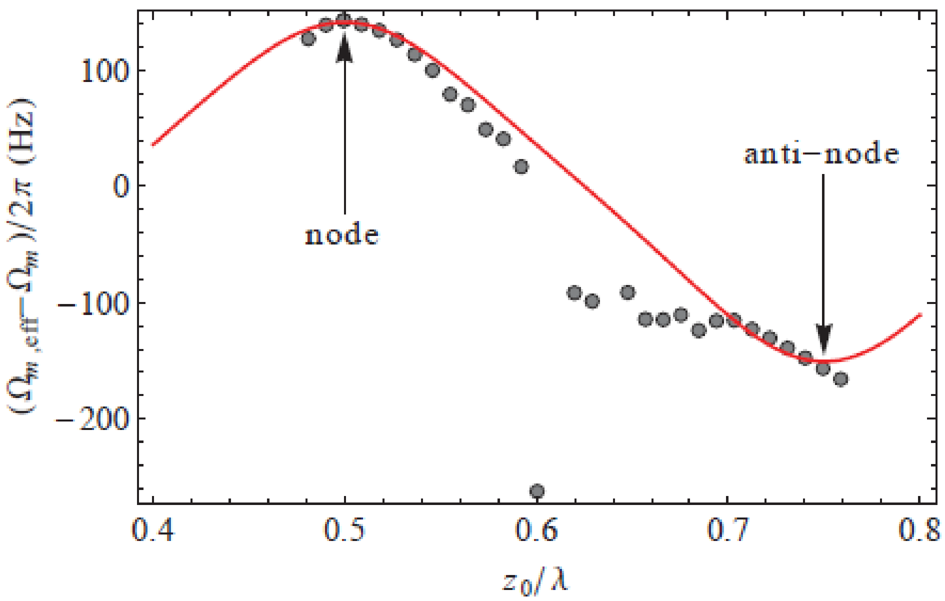


Figure: Mechanical frequency shift vs z_0 at $\Delta \approx 0$.

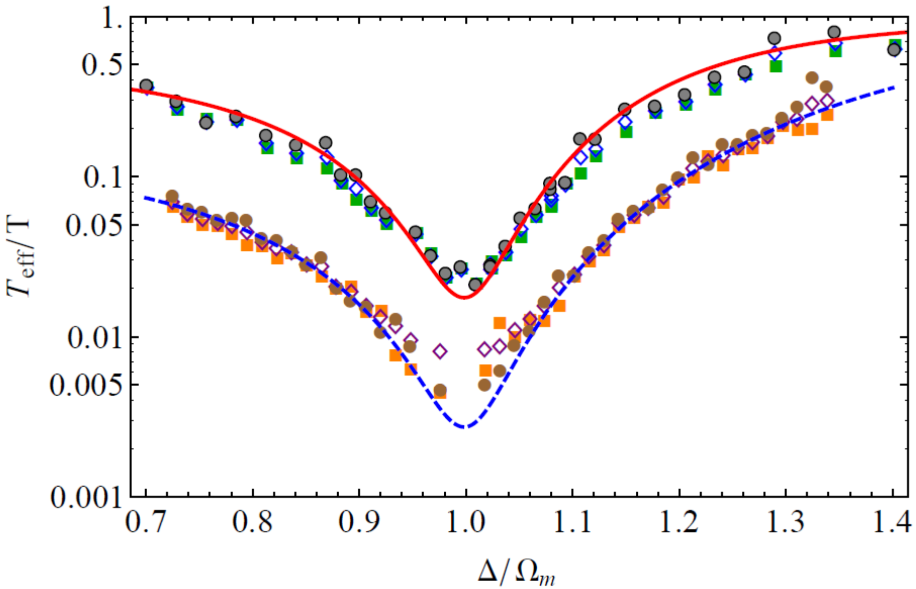
[M. Karuza, C. Molinelli, M. Galassi, C. Biancofiore, *et al.*, *New J. Phys.* **14**, 095015 (2012)]

2. Significant cooling when $\Delta = \omega_m$

$$\left\langle \delta x^2 \right\rangle = \int \frac{d\omega}{2\pi} S_x(\omega) = \frac{kT_{eff}}{m\Omega_m^2}$$

Effective temperature ∝ area of the resonance peak

Overdamping ⇔ cooling



Karuza et al., New J. Phys. 14, 095015 (2012).

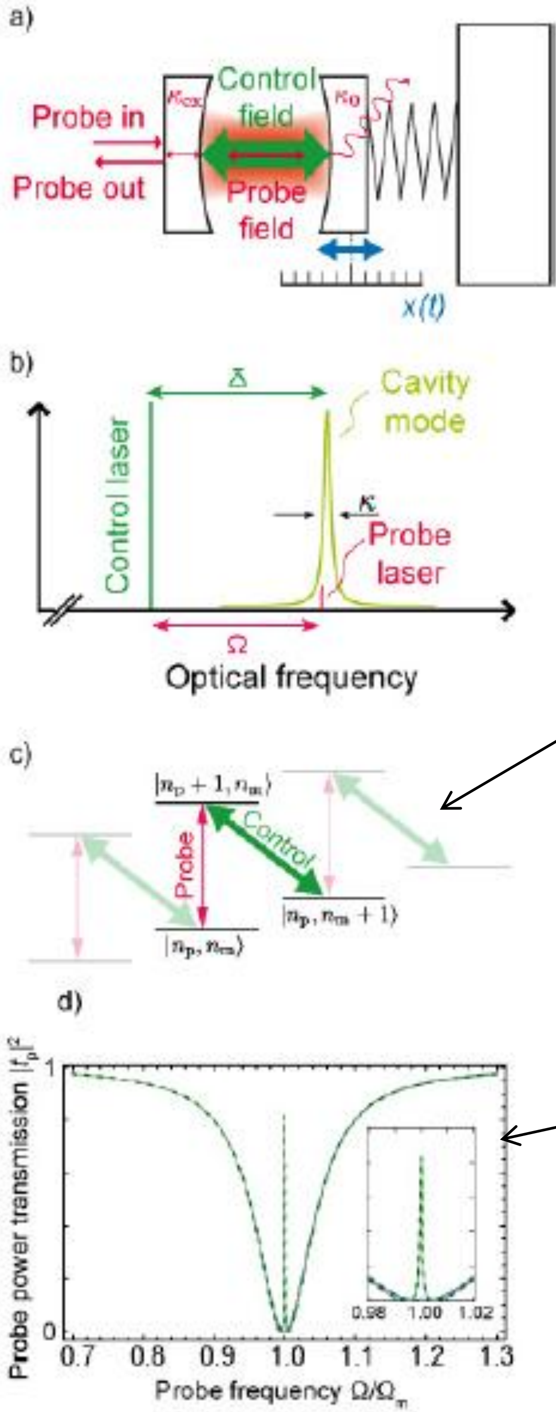
Effective resonator temperature

⇒ **membrane mode laser-cooled down to ~ 1 K from room T**

The resonator is cooled by the cavity mode = **effective additional zero-temperature reservoir**, optimally coupled when $\Delta = \omega_m$.

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, $\Delta = \omega_m$**

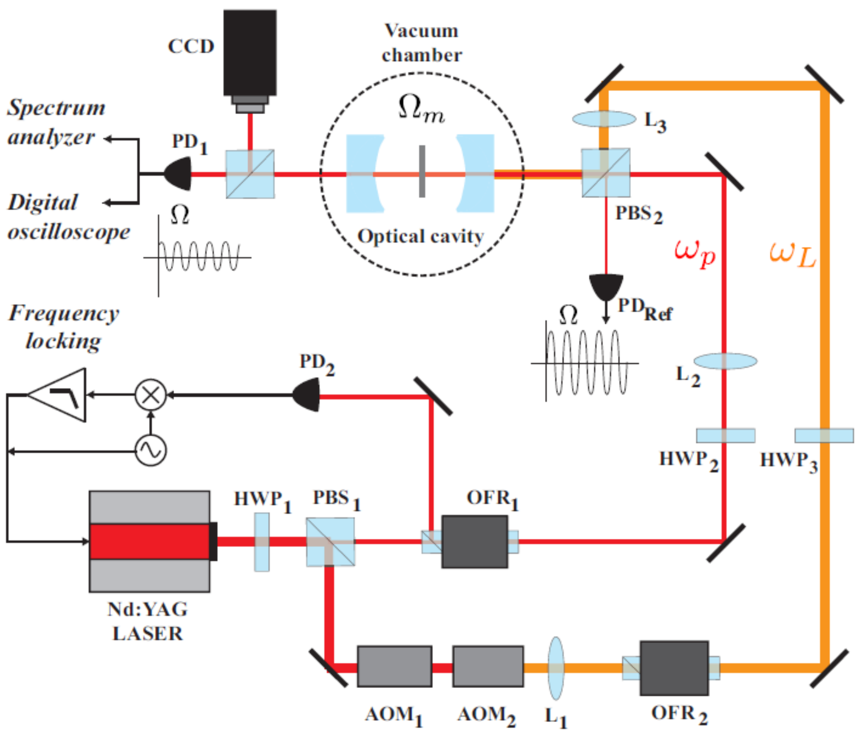
Agarwal & Huang, PRA 2010

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**

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**

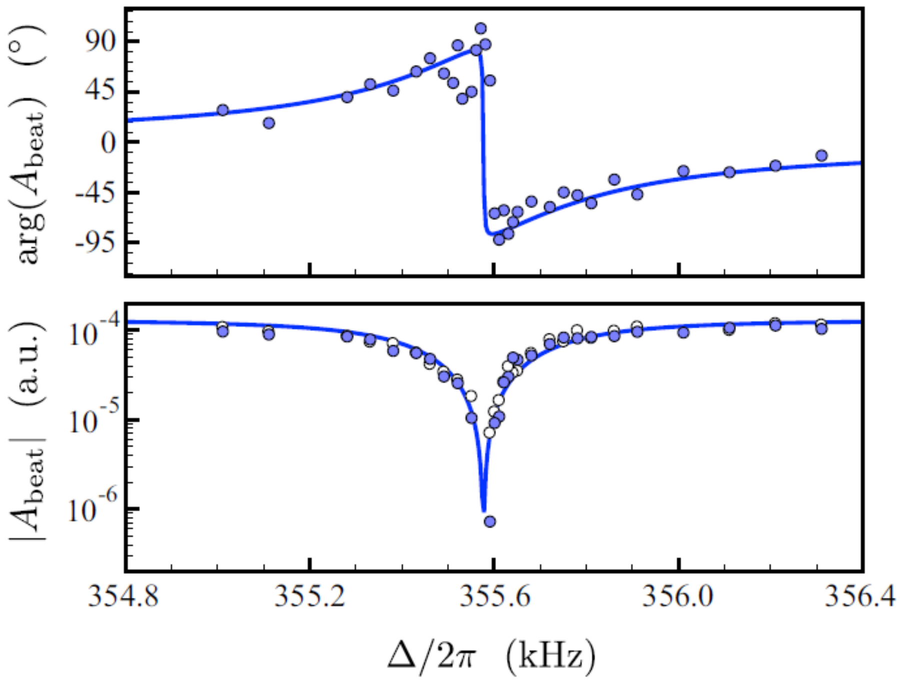


Karuza et al., PRA 88, 013804 (2013)

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 in the case of a symmetric FP cavity)

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

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

$$A_{\mathrm{beat}} =$$

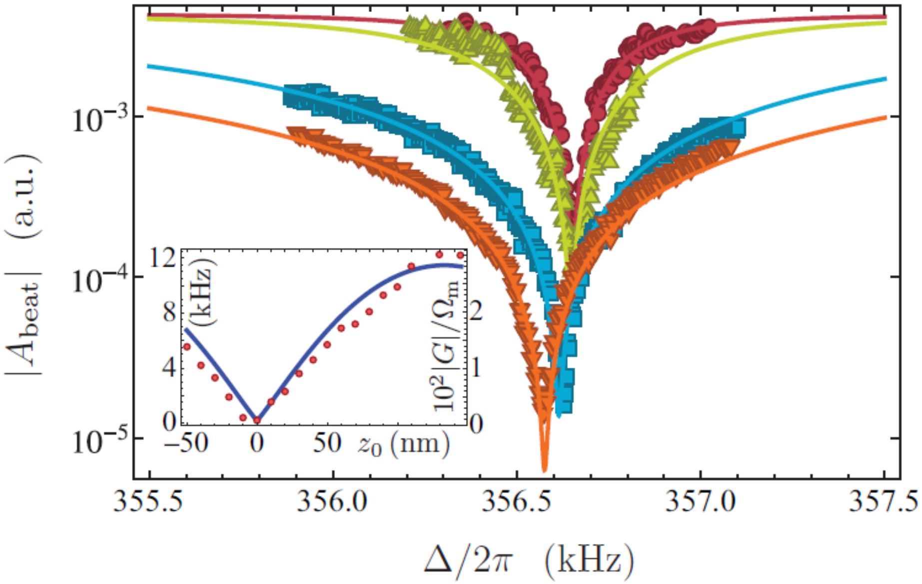
$$\frac{4\kappa_2\kappa_0|s_{\mathrm{p}}|}{\kappa_{\mathrm{T}}}\sqrt{\frac{\mathcal{P}}{\hbar\omega_{\mathrm{L}}\left(\kappa_{\mathrm{T}}^2+\Delta^2\right)}}\left[1+\mathrm{i}\frac{G^2\chi_{\mathrm{eff}}(\Delta)}{2\kappa_{\mathrm{T}}}\right]$$

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

Cooperativity (~160 here)

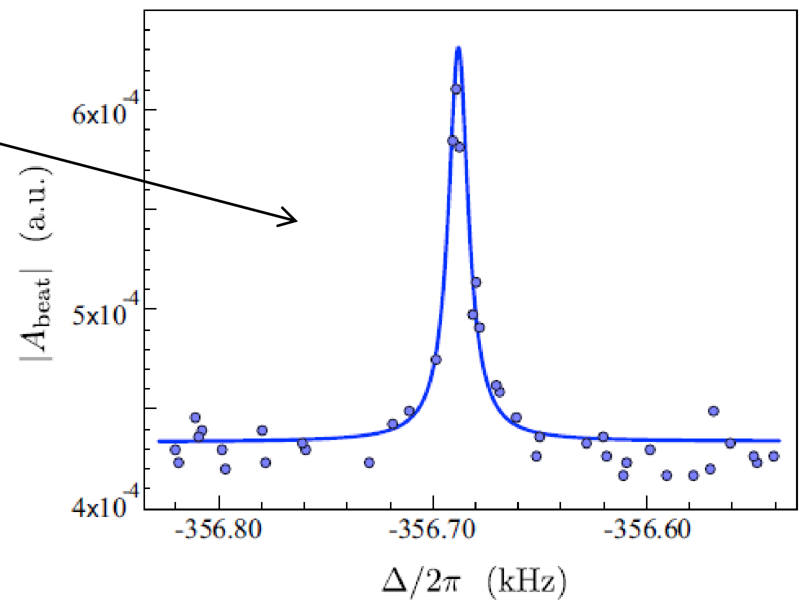
$$\eta = \frac{\kappa_{ex}}{\kappa_T}$$

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**"

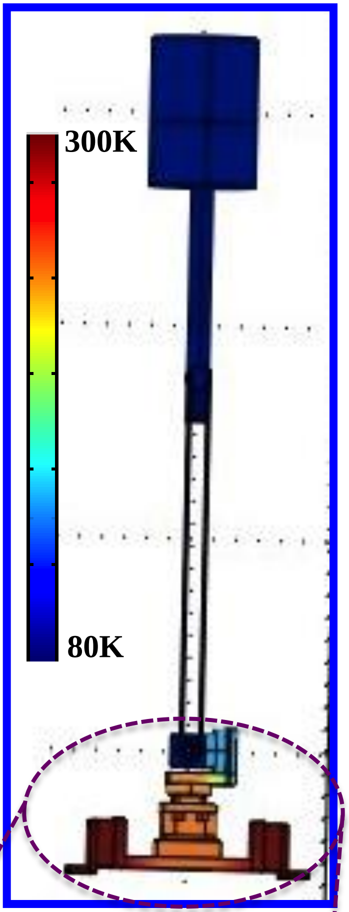


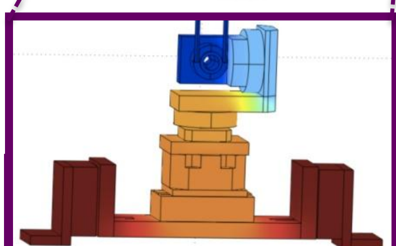
One has the **optomechanical analogue of a parametric oscillator below threshold**

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

CURRENT IMPROVEMENTS ON THE EXPERIMENTAL SETUPS

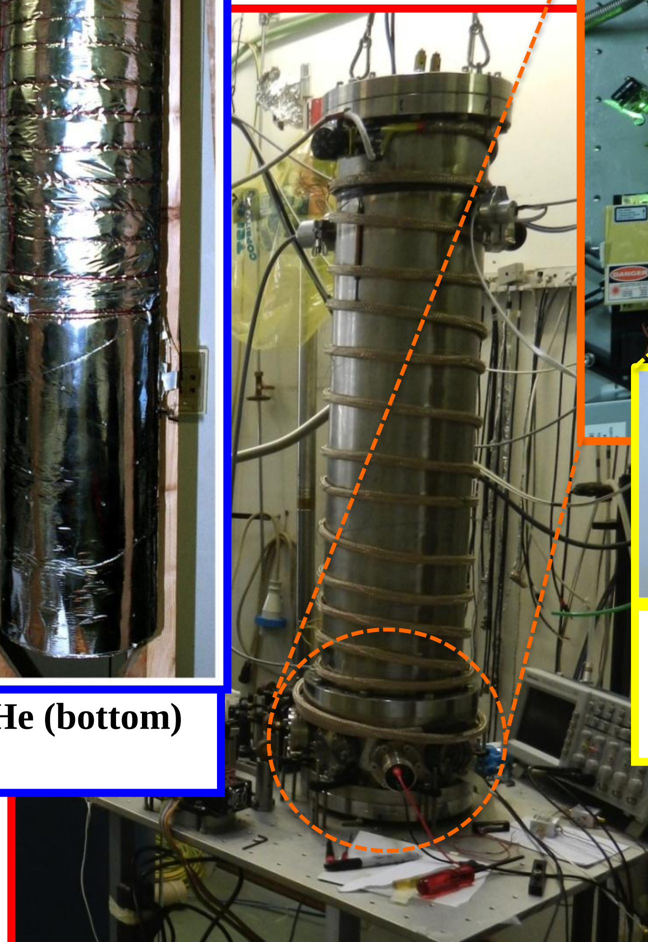
Towards liquid He temperatures





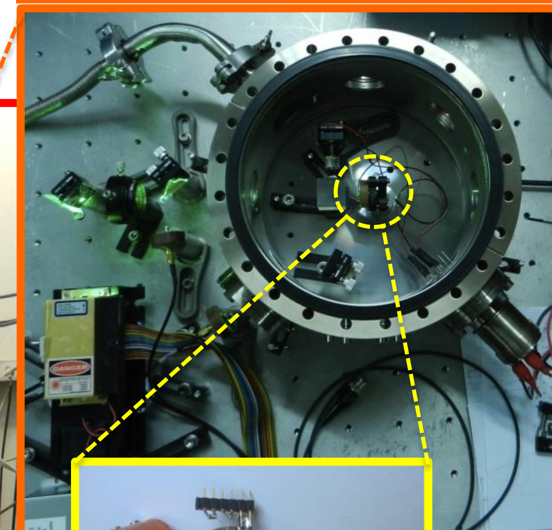
Design of the new membrane holder and simulation of the temperature using LN_2 in the bottom chamber.

LN_2 (top) and LHe (bottom) chambers



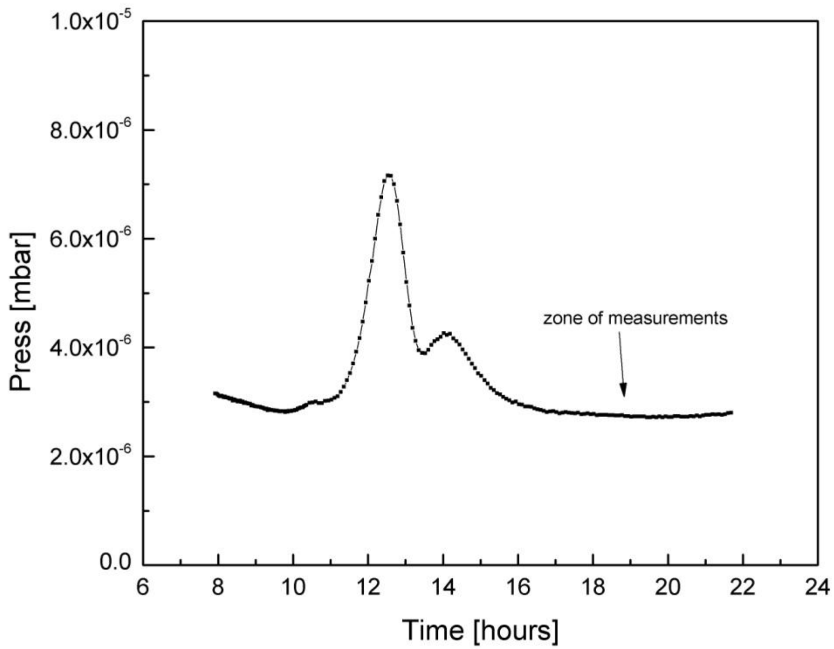
Optical table with the experimental setup assambled for first test

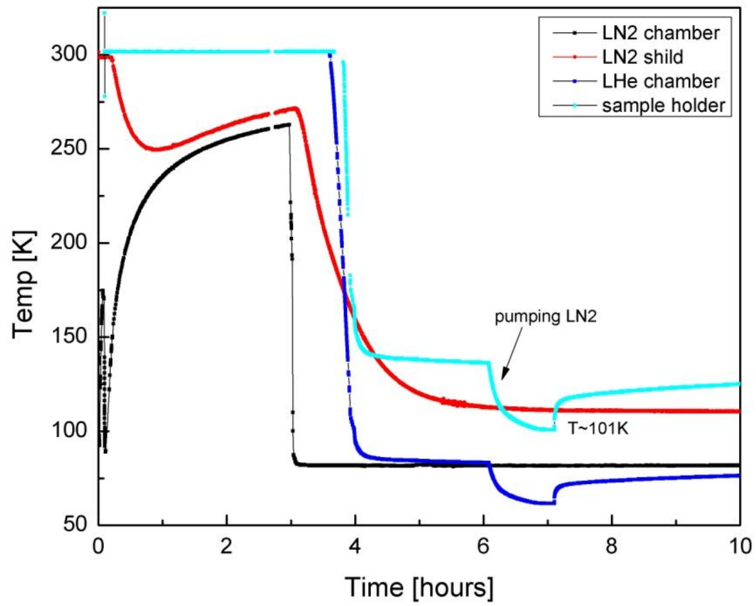
Vacuum chamber for the cavity



Membrane holder with termal contact to cold finger

Cryostat test at LN

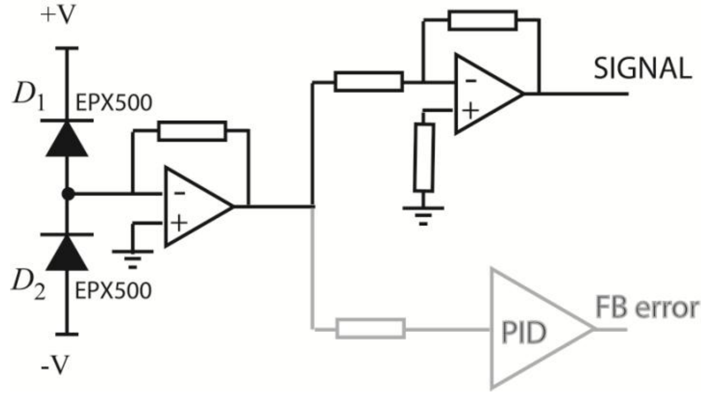


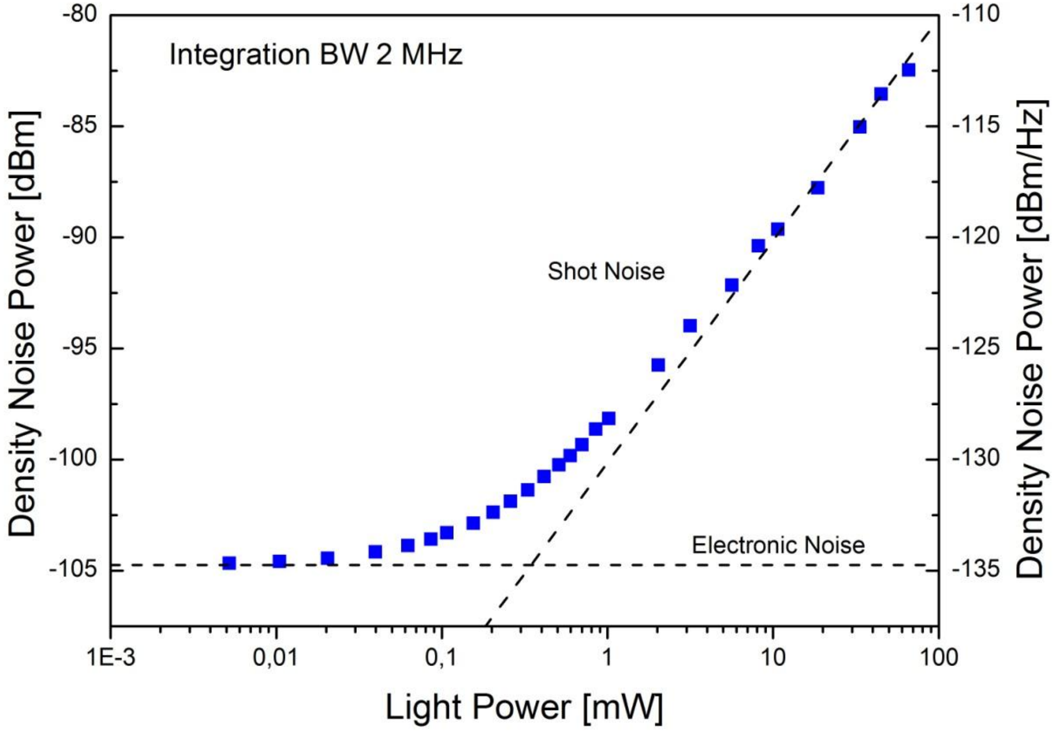


Homodyne detection

Preliminary tests and results

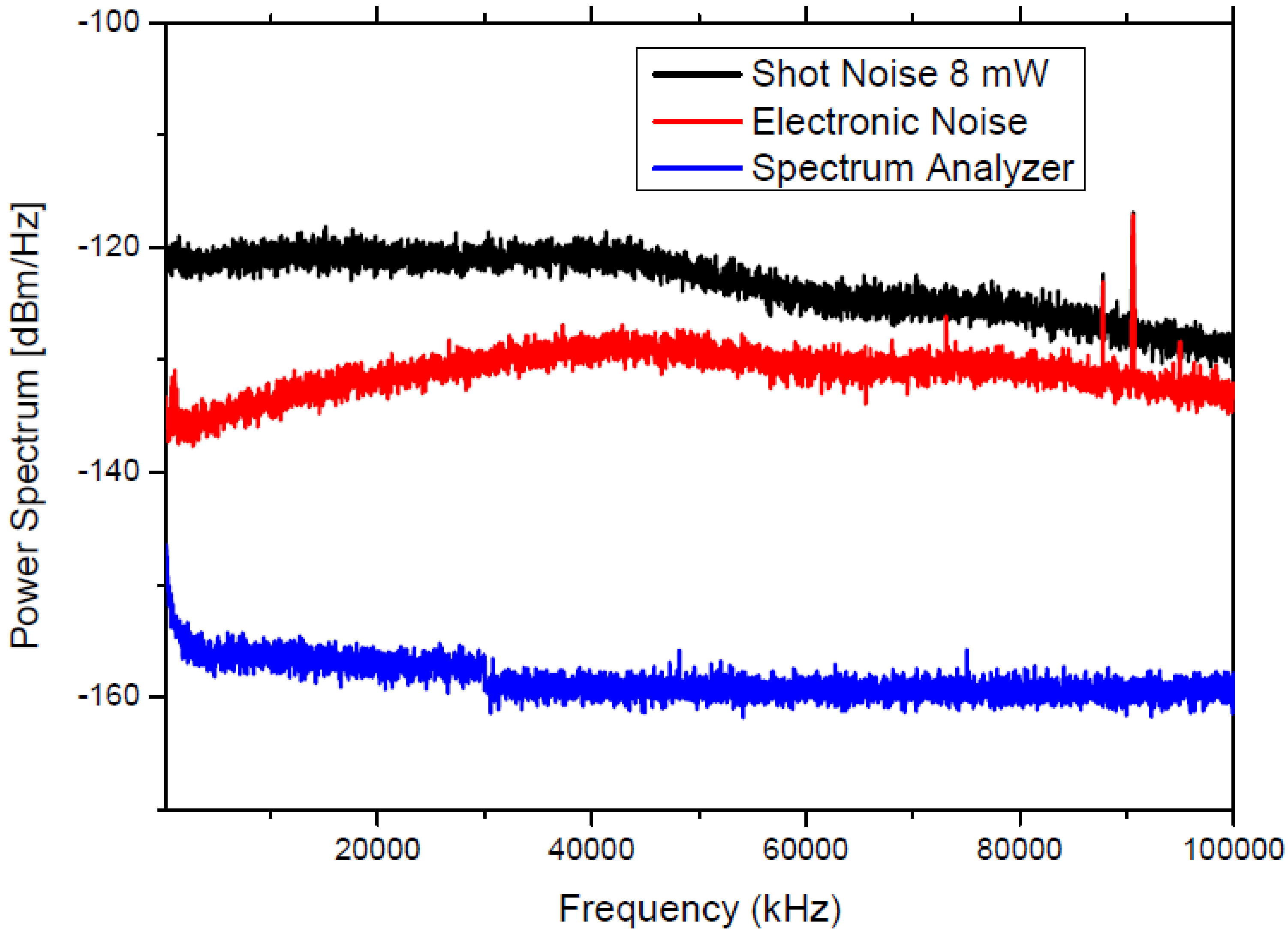
Electronic





Tech. Infos	**OPA847**	**JDSU ETX500/1000 (InGaAs)**
	– GBW = 3.9 GHz	– R(@850nm) = 0.2 A/W
	– Noise = 0.85 nV/Hz$^{-1/2}$ / 3.5pA/Hz$^{-1/2}$	– R(@1330nm) = 0.9 A/W
		– Noise current density = 60 fA/Hz$^{-1/2}$

Homodyne detection
Bandwidth



RECENT THEORY ACTIVITY

•**Proposal for a nanomechanical quantum interface** between optics and microwaves (iQUOEMS related !) and **continuous variable quantum communication protocol** (teleportation, swapping)

• **Quantum states with optomechanical quadratic interaction:**

1. **Reservoir engineering** for generating mechanical cat states
2. Mechanical squeezing via “optical spring kicks”

Nanomechanical quantum interface between optics and microwaves

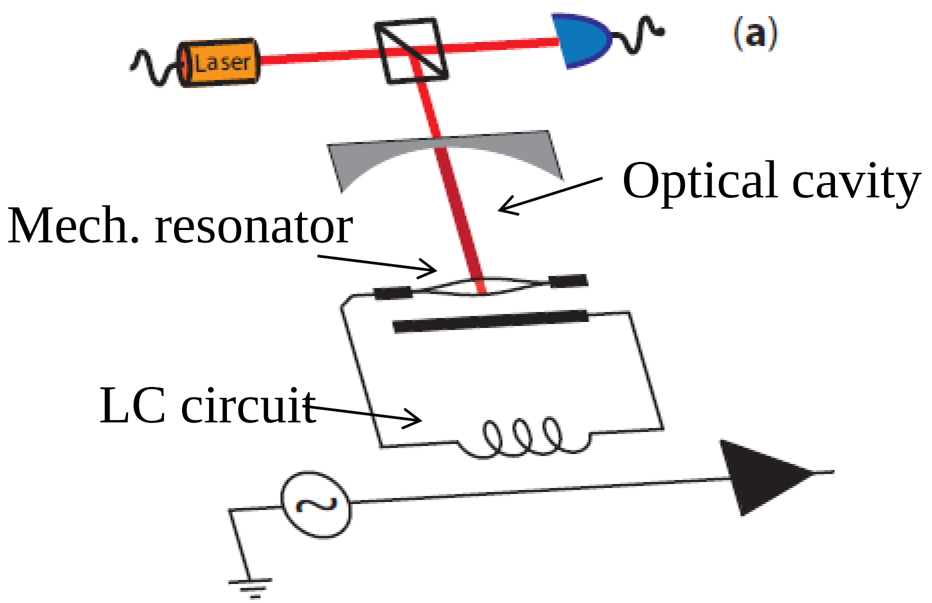
1. **Recent experiments based on (classical) excitation transfer** mediated by mechanics
2. We proposed an alternative based on stationary, continuous wave, **strong CV entanglement** between the optical and microwave output field
3. High-fidelity CV optical-to-microwave **teleportation** of nonclassical states

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

Why an optical-microwave transducer ?

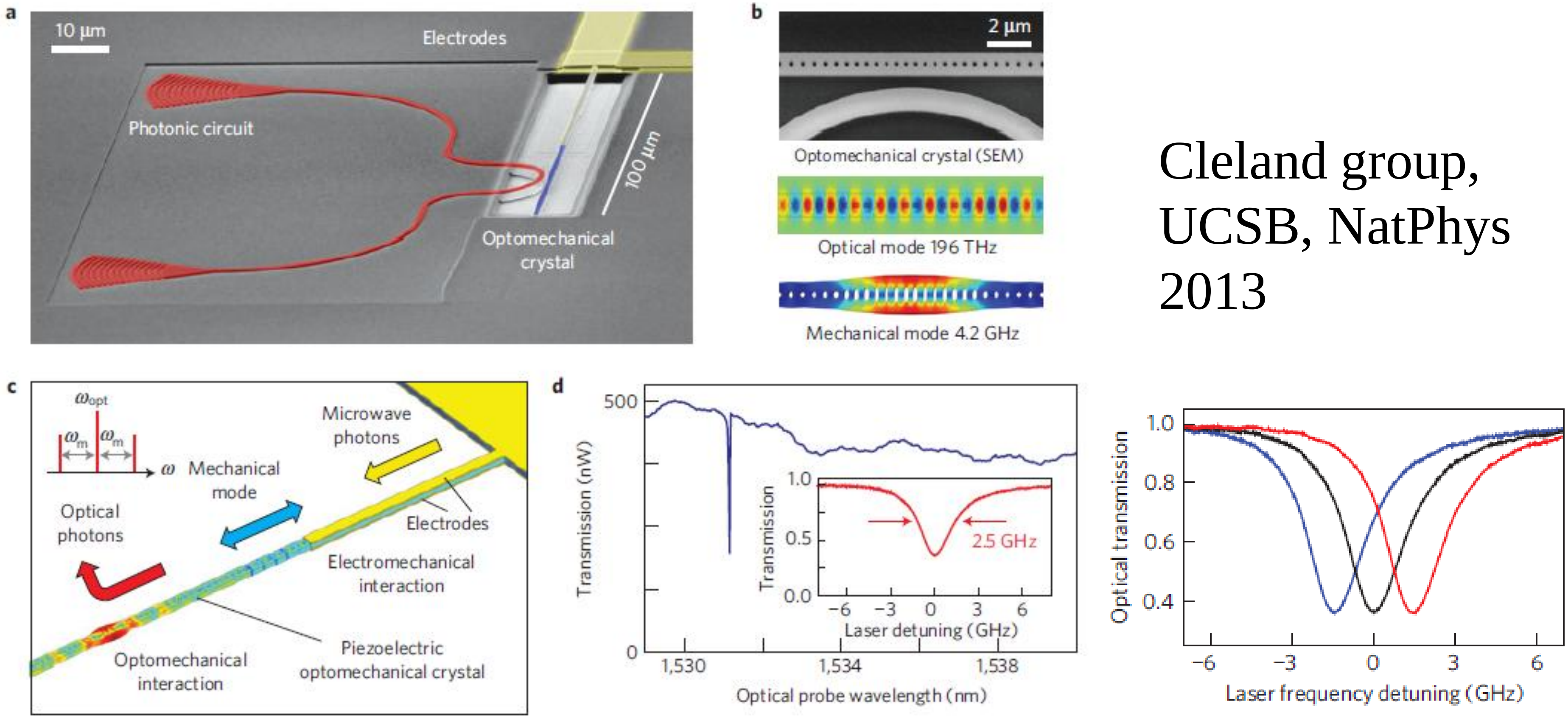
Light is optimal for quantum communications between nodes, while **microwaves** are used for manipulating solid state quantum processors

⇒ **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 super-conducting circuit, simultaneously interacting with the two fields**

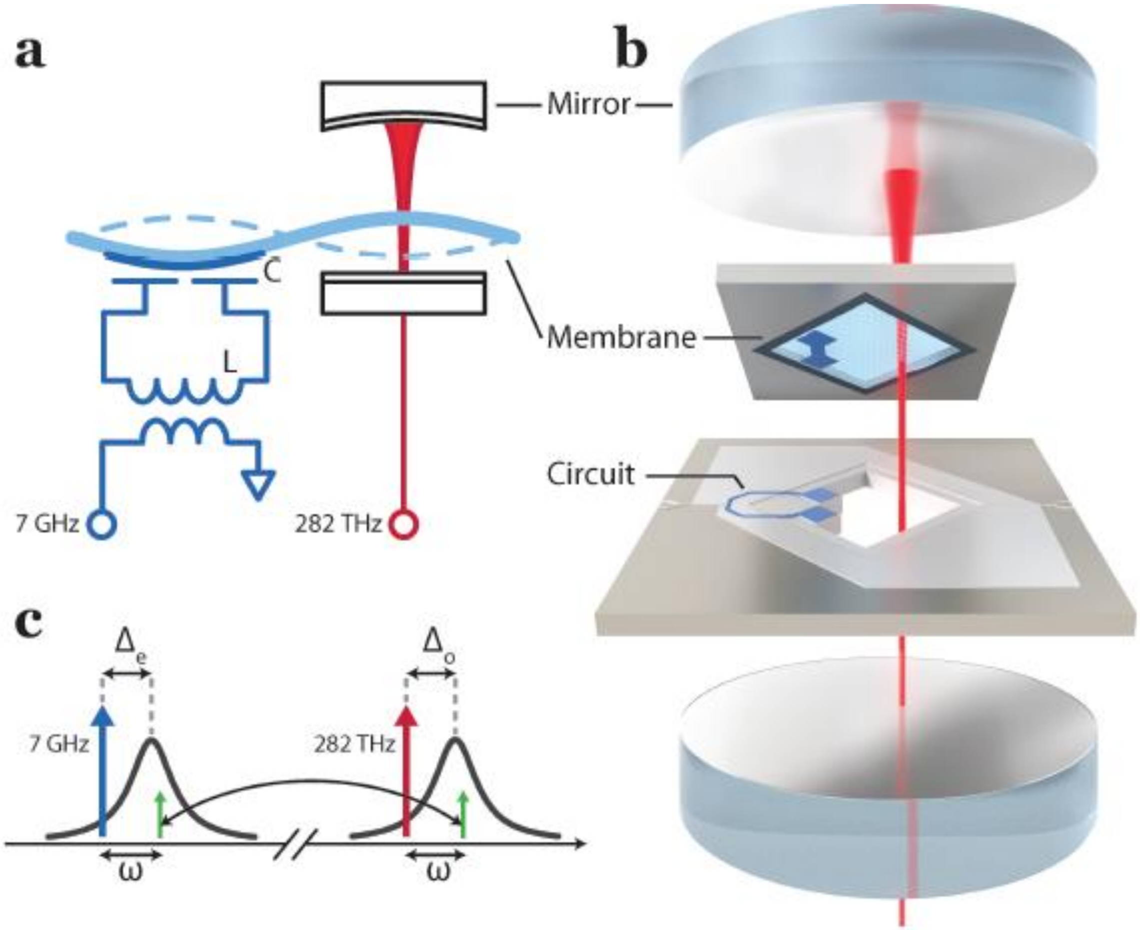
VERY RECENT EXPERIMENTAL RESULTS (STILL IN THE CLASSICAL DOMAIN)



Cleland group, UCSB, NatPhys 2013

Piezoelectrically controlled optomechanical crystal

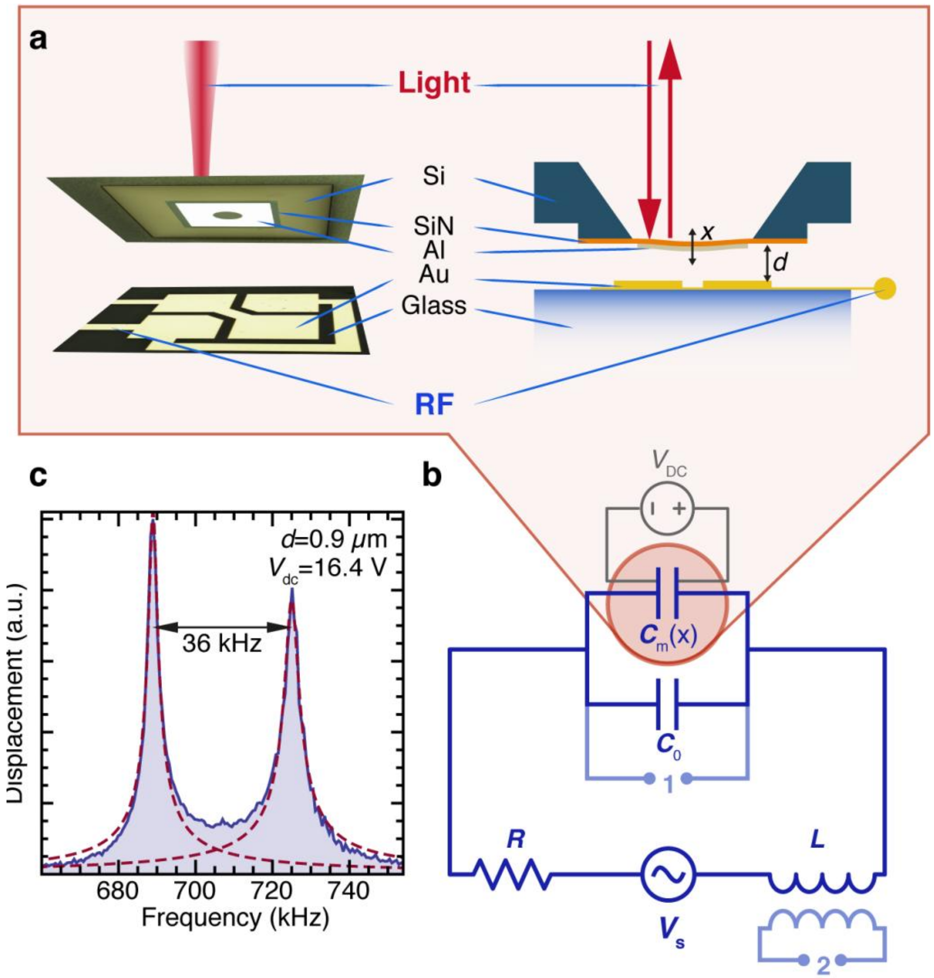
MEMBRANE-OPTICAL-TO-MICROWAVE CONVERTER



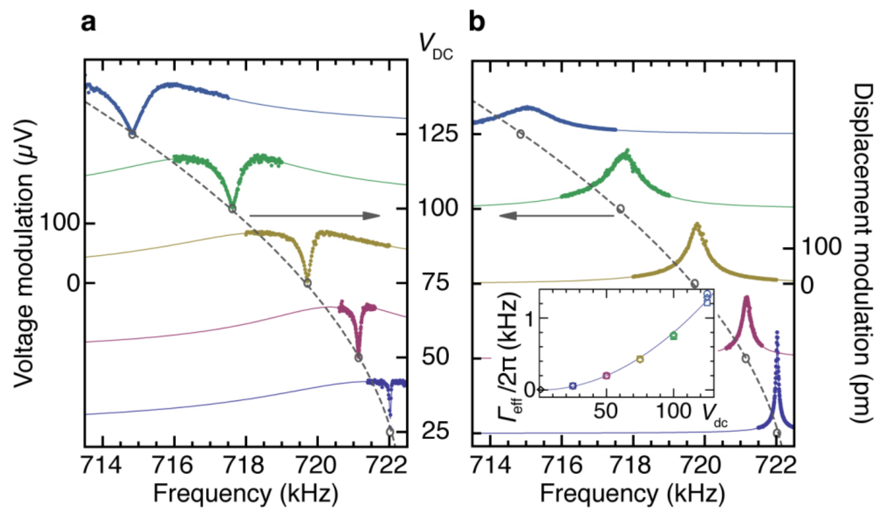
Adding a LC circuit to the membrane-in-the-middle setup, Andrews et al., arXiv13105276.v1 (Lehnert-Regal group)

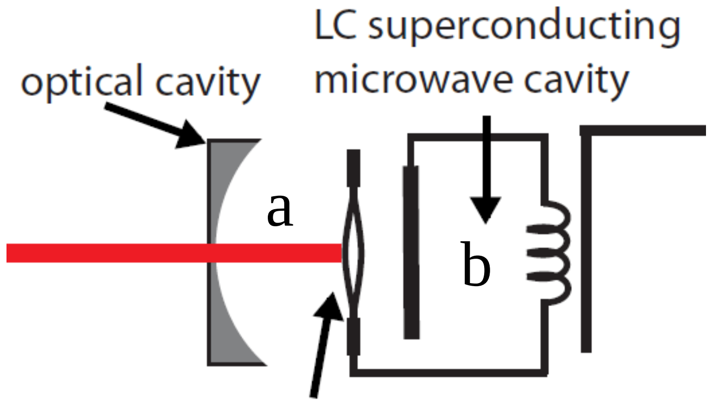
OPTICAL READOUT OF A RADIOFREQUENCY CAVITY

Polzik group, Bagci et al., arXiv:1307.3467v2



Resonant interaction between RF circuit and membrane resonator





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

$$\delta\dot{\hat{a}} = -\kappa_c\delta\hat{a} + \sqrt{2\kappa_c}\hat{a}_{in}(t)e^{i\Delta_c t} + \frac{i}{2}\int_{-\infty}^{t} ds\,\chi_M(t-s)\left\{G_c\hat{\xi}(s)e^{i\Delta_c t}\right.$$

$$\left.+G_c^2\left[\delta\hat{a}(s)e^{i\Delta_c(t-s)} + \delta\hat{a}^\dagger(s)e^{i\Delta_c(t+s)}\right] + G_cG_w\left[\delta\hat{b}(s)e^{i\Delta_c t - i\Delta_w s} + \delta\hat{b}^\dagger(s)e^{i\Delta_c t + i\Delta_w s}\right]\right\},$$

$$\delta\dot{\hat{b}} = -\kappa_w\delta\hat{b} + \sqrt{2\kappa_w}\hat{b}_{in}e^{i\Delta_w t} + \frac{i}{2}\int_{-\infty}^{t} ds\,\chi_M(t-s)\left\{G_w\hat{\xi}(s)e^{i\Delta_w t}\right.$$

$$\left.+G_w^2\left[\delta\hat{b}(s)e^{i\Delta_w(t-s)} + \delta\hat{b}^\dagger(s)e^{i\Delta_w(t+s)}\right] + G_cG_w\left[\delta\hat{a}(s)e^{i\Delta_w t - i\Delta_c s} + \delta\hat{a}^\dagger(s)e^{i\Delta_w t + i\Delta_c s}\right]\right\}$$

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:

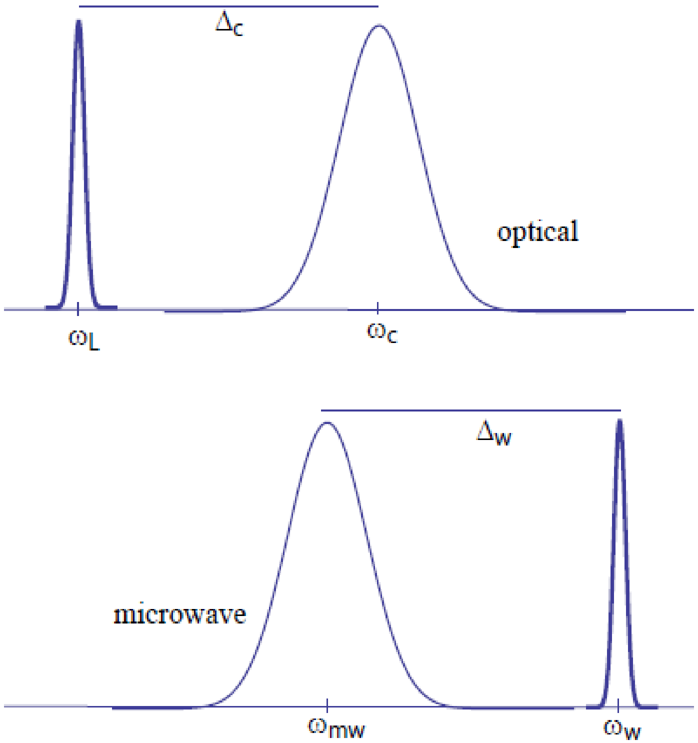
• Equal detunings: $\Delta_c = \Delta_w \Rightarrow$ **state transfer** between optics and microwave (see other proposals, Tian et al., 2010, Taylor et al., PRL 2011, Wang & Clerk, PRL 2011)

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

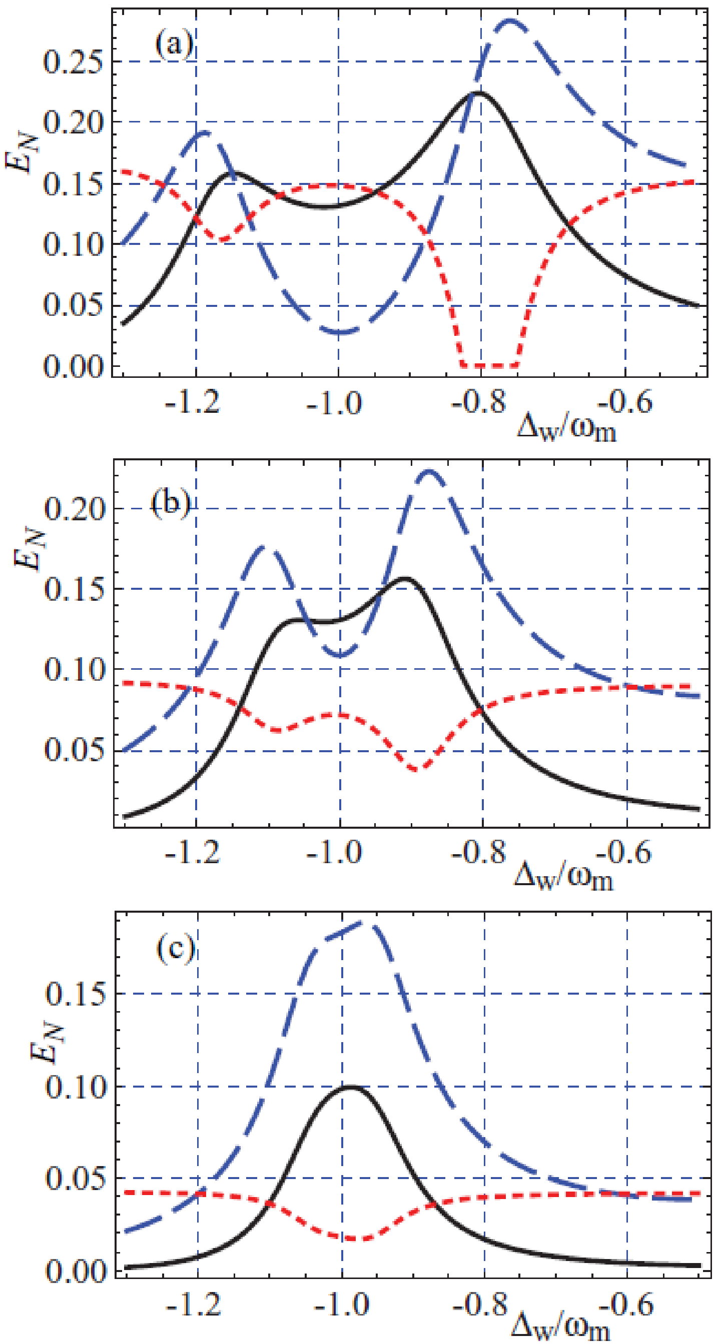
Interaction kernel = mechanical susceptibility

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

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



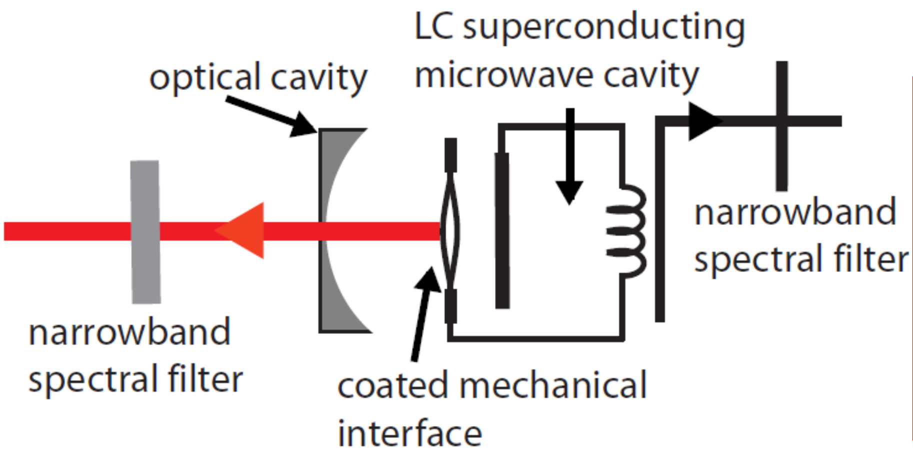
ENTANGLEMENT BETWEEN MECHANICS AND THE INTRACAVITY MODES IS NOT LARGE

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

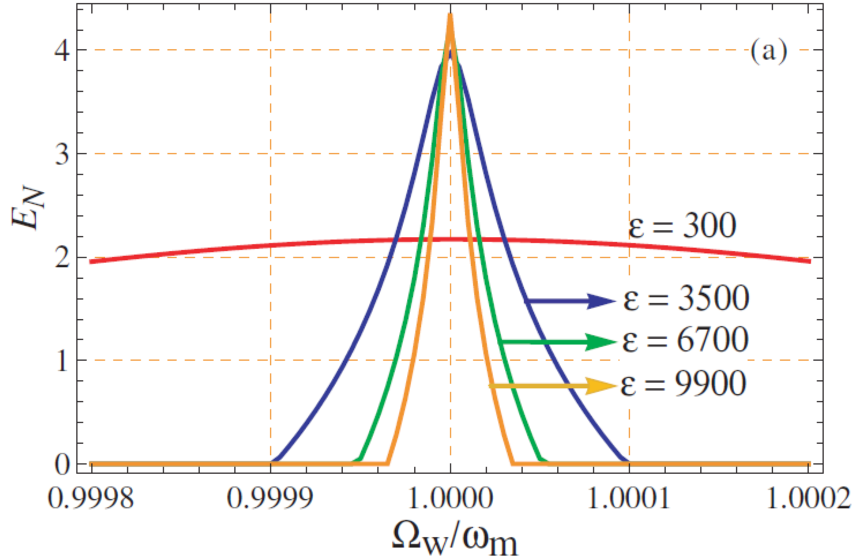
$$\hat{a}_c^{out}(t) = \int_{\infty}^{t} ds g_c(t-s)\hat{a}^{out}(s)$$

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

normalized causal filter function

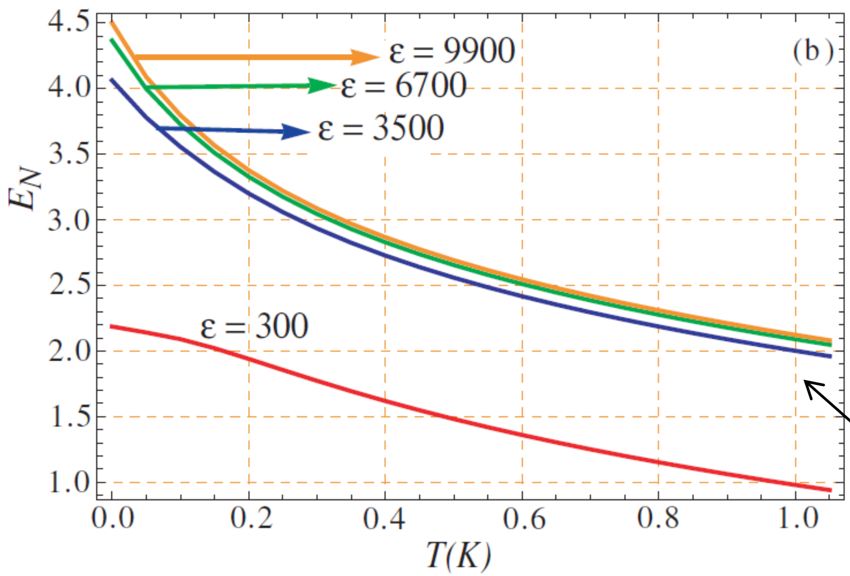
$$g_j(t) = \sqrt{\frac{2}{\tau}}\theta(t)e^{-(1/\tau+i\Omega_j)t} \quad j=c,w$$

OUTPUT MICROWAVE-OPTICAL ENTANGLEMENT



LARGE ENTANGLEMENT FOR **NARROW-BAND OUTPUTS**

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



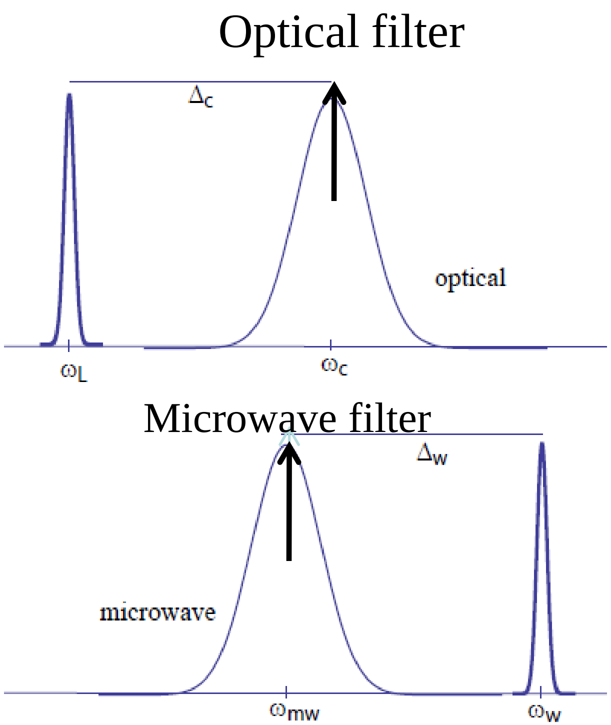
Optical and microwave cavity detunings fixed at $\Delta_c = -\Delta_w = -\omega_m$

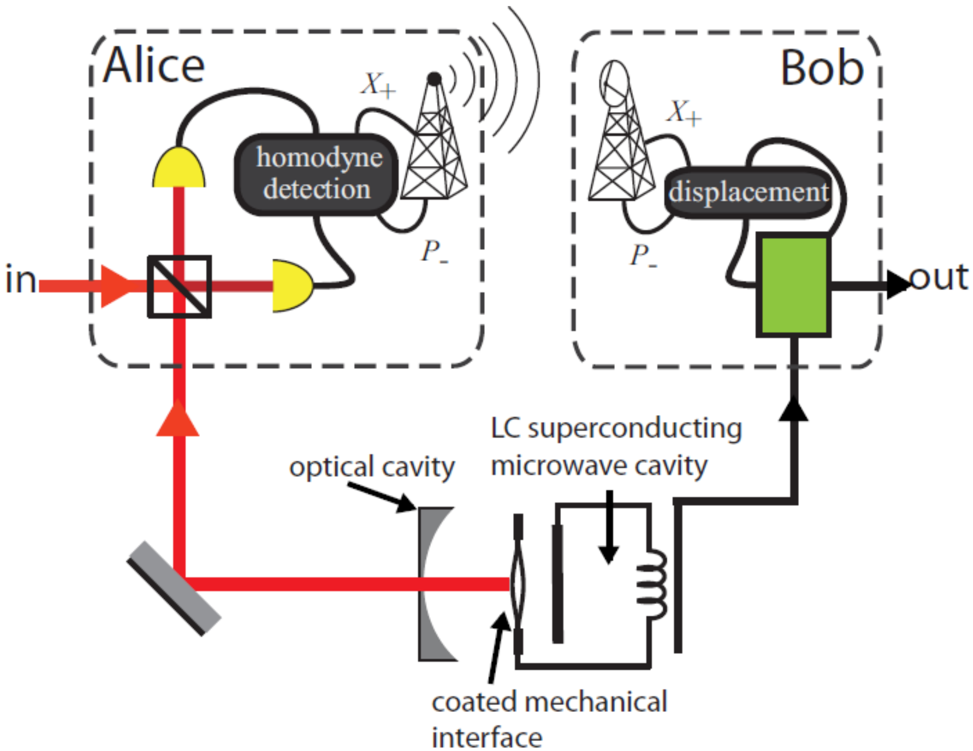
Other parameters: $\omega_m/2\pi = 10$ MHz, $Q=1.5\times10^5$, $\omega_w/2\pi = 10$ GHz, $\kappa_w = 0.04\omega_m$, $P_w = 42$ mW, $m = 10$ ng, $T = 15$ mK. This set of parameters is analogous to that of Teufel et al.

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

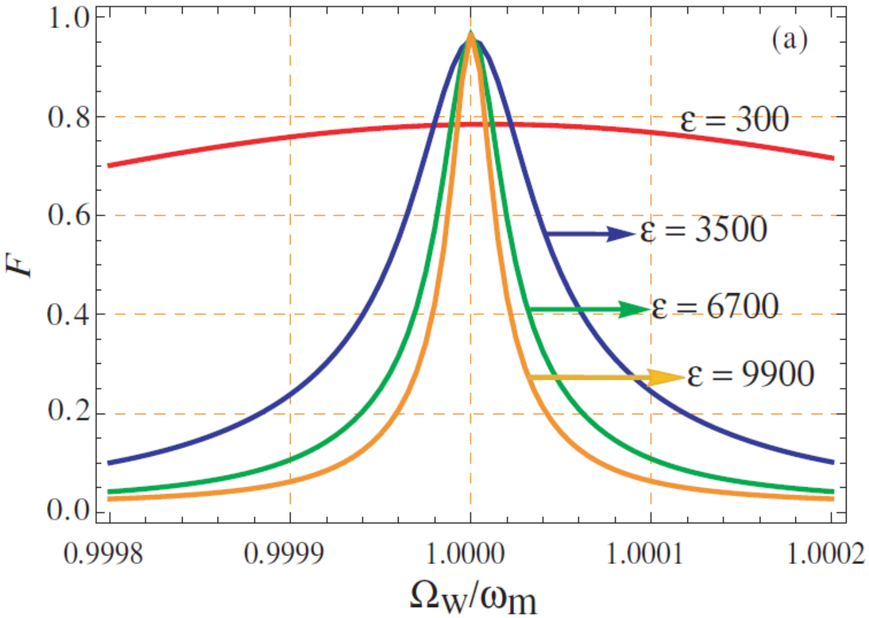
• The common interaction with the nanomechanical resonator establishes **quantum correlations which are strongest between the output Fourier components *exactly at resonance* with the respective cavity field**

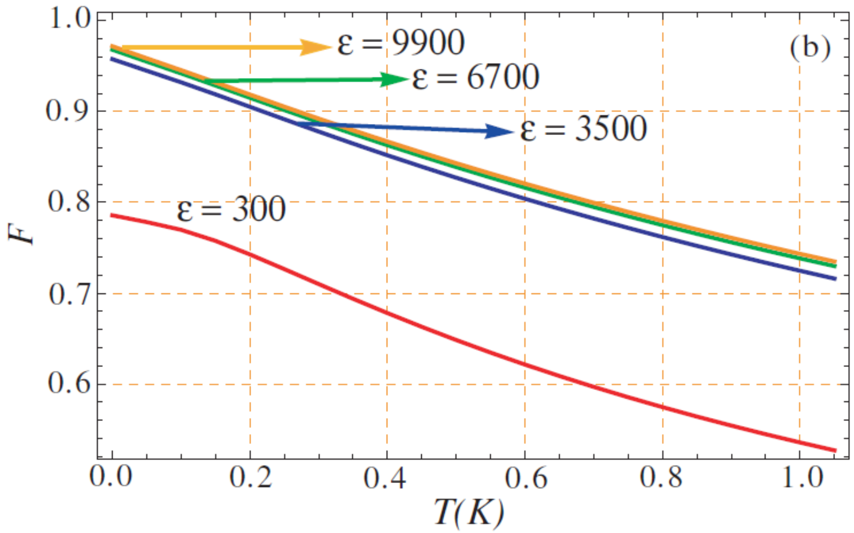




Such a large stationary entanglement can be exploited for continuous variable (CV) optical-to-microwave quantum teleportation:

TELEPORTATION FIDELITY OF A CAT STATE





Input cat state

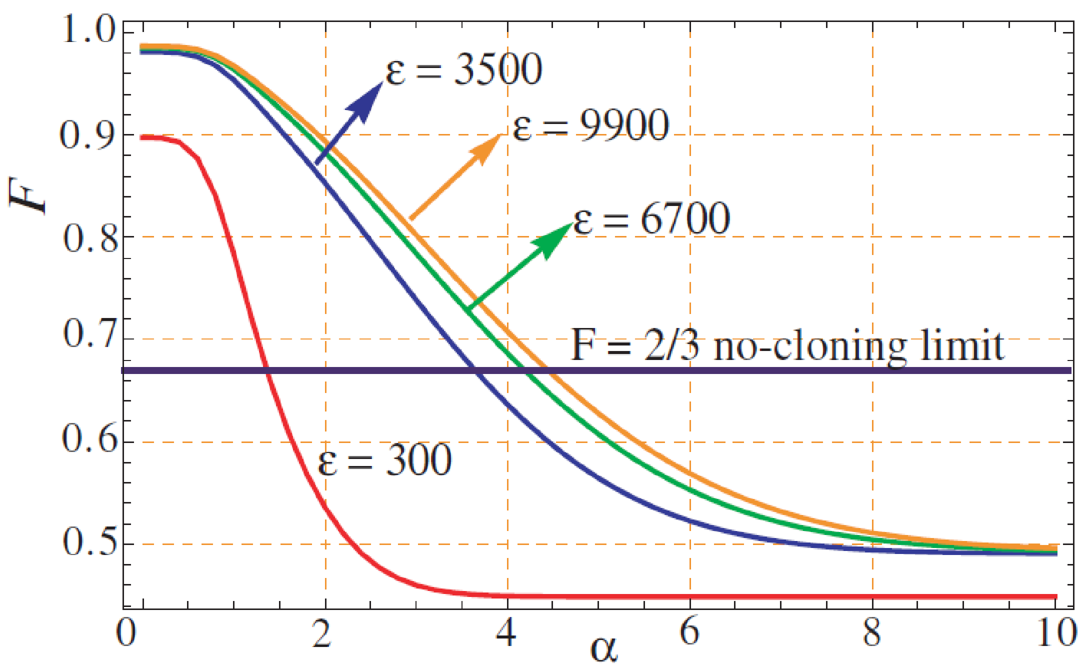
$$|\psi\rangle = N(|\alpha\rangle + |-\alpha\rangle)$$

(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

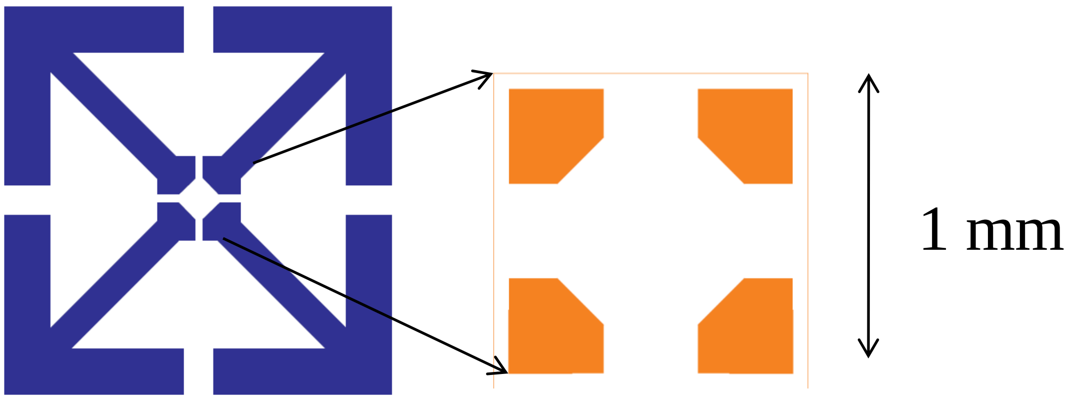
F is not a local invariant, but here is very close to the optimal upper bound achievable for a given E_N

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

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

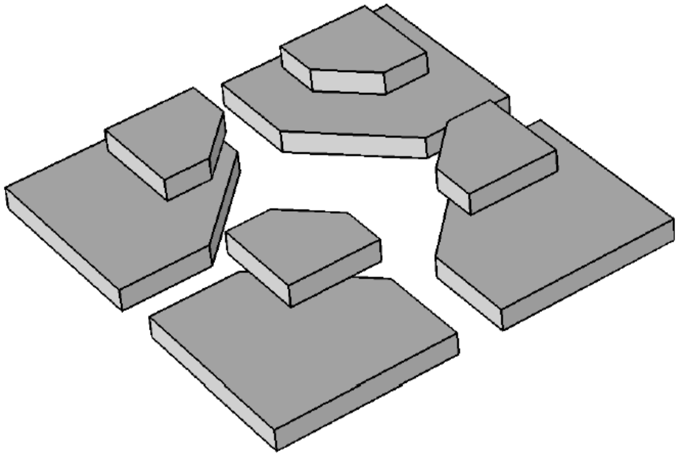
(see A. Mari, D. Vitali, PRA 78, 062340 (2008)).

FIRST SAMPLES OF THE MEMBRANE CAPACITOR



Larger electrode

Membrane with Al coating



Contacts

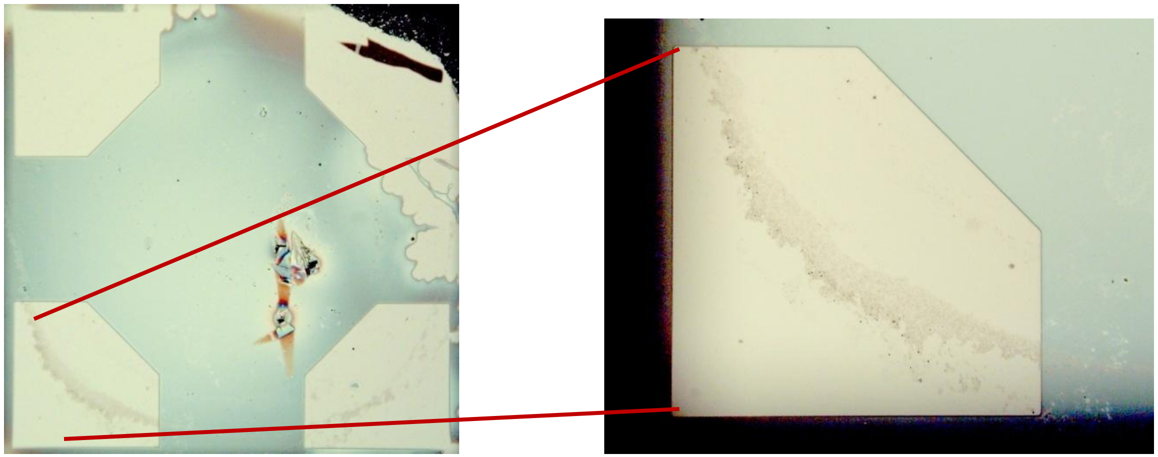


Image of the membrane Al coating

WHAT TO DO WITH A QUADRATIC INTERACTION HAMILTONIAN ?

i) **Generation of mechanical** Schrodinger cat states through **reservoir engineering** (M. Asjad and D. Vitali, arXiv:1308.0259)

ii) **Generation of mechanical squeezing via optical spring kicks** (M. Asjad et al., arXiv:1309.5485)

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)

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

"Target state"

Typical solution = Lindblad generator

$$\mathcal{L}\rho = \Gamma\mathcal{D}(C)\rho$$
$$\mathcal{D}(C)\rho = \left(2C\rho C^\dagger - C^\dagger C\rho - \rho C^\dagger C\right)$$

such that

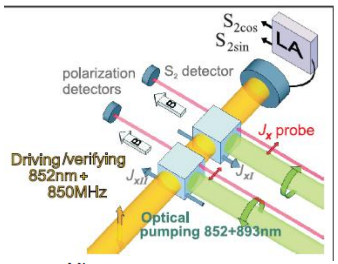
$$\rho_\infty = |\psi_\infty\rangle\langle\psi_\infty|$$
$$C|\psi_\infty\rangle = 0$$

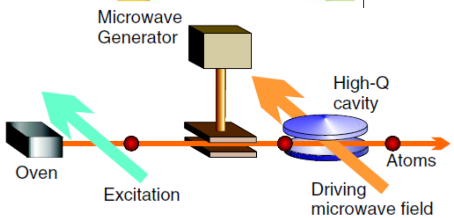
Engineered dynamics which must dominate over undesired ones

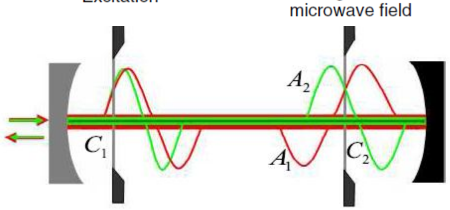
EXAMPLES

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

Generation of **entangled two-mode squeezed state of two continuous variable (CV) systems** :







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 2001)
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)

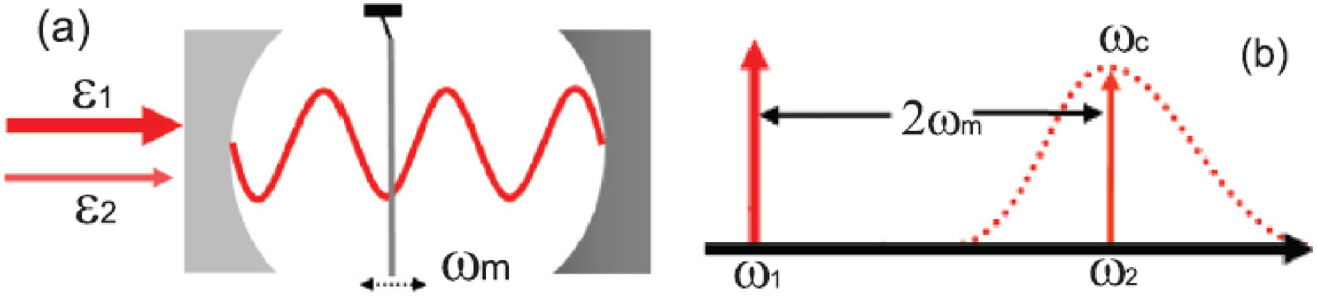
Here we engineer the "optical mode reservoir" in cavity optomechanics for robust generation of a mechanical Schrodinger cat states with amplitude β

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

(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)



Linearization around steady state $a \rightarrow \alpha_s + \delta a$
+ rotating wave approximation $\Rightarrow$

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

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

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

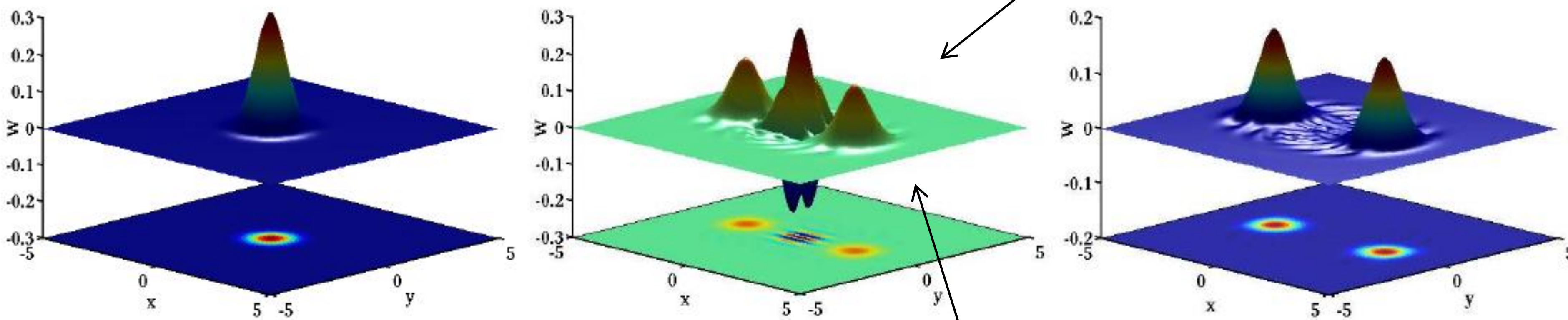
One has to **beat the undesired standard thermal reservoir** coupled with damping rate γ_m

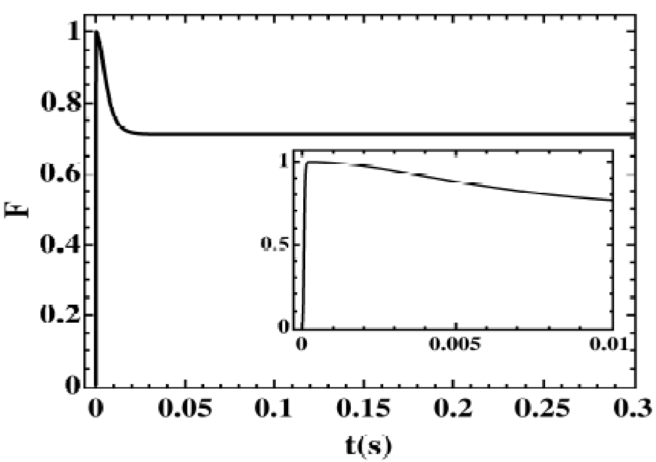
$$\frac{\partial}{\partial t}\rho = \Gamma\mathcal{D}(C)\rho + \frac{\gamma_m}{2}(\bar{n}+1)\mathcal{D}(b)\rho + \frac{\gamma_m}{2}\bar{n}\mathcal{D}(b^\dagger)\rho,$$

$$\Gamma = g_2^2|\alpha_s|^2/\kappa_T$$

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

The cat generation is possible at transient time $t \approx 1/\Gamma$, if $\Gamma \gg \gamma_m n$

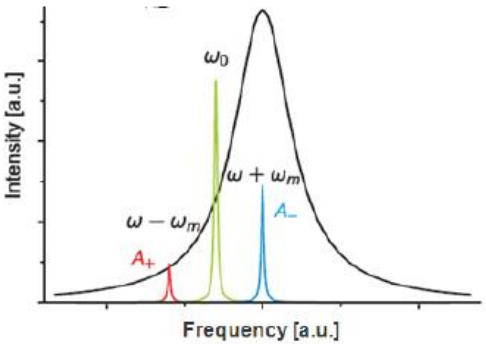




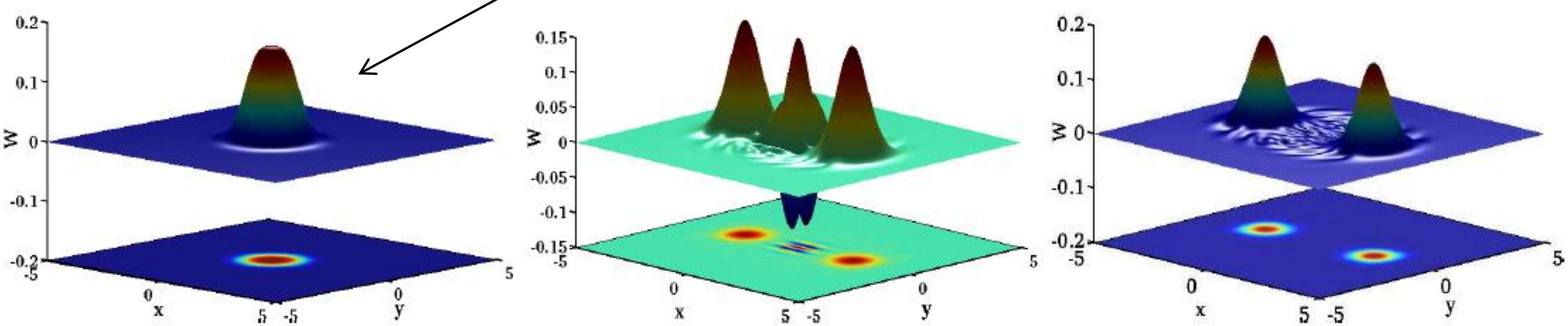
Fidelity $F_{max} = 0.999$ starting from precooled ground state $\rho_m \approx |0\rangle\langle 0|$

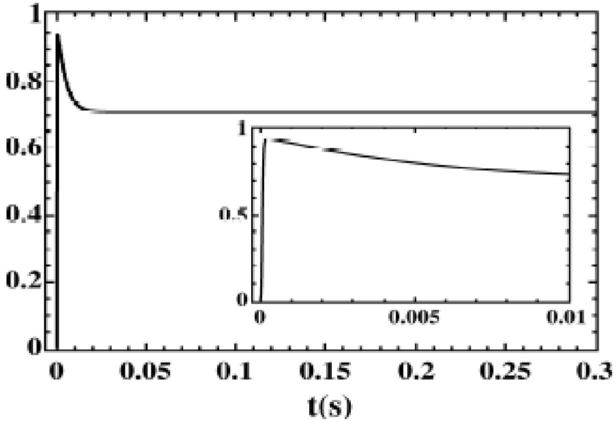
$\omega_m = 10\ MHz,\ T = 10\ mK \Rightarrow n_T = 100,\ Q_m = 10^7$

Ground state pre-cooling requires **linear coupling** and driving at the **first red sideband** $\Rightarrow$ **fast switching from linear to quadratic interaction**



Using only quadratic coupling: we first cool with **two-phonon cooling** ($E_1 = \beta = 0$) and then switch on the resonant pump E_1.
When $\Gamma \gg \gamma_m n$, one cools down to $\rho_m \approx 0.75\,|0\rangle\langle 0| + 0.25\,|1\rangle\langle 1|$ (Nunnenkamp et al. PRA 2010) and cat state generation is good also in this case.





Fidelity F_{max} = *0.94* starting from two-photon cooled state $\rho_m \approx 0.75\ |0\rangle\langle 0| + 0.25\ |1\rangle\langle 1|$

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

$$\rho_{\rm app}(t > t_0) = \mathcal{N}(t-t_0)^{-1}\left\{|\beta\rangle\langle\beta| + |-\beta\rangle\langle-\beta| + e^{-(1+2\bar{n})\gamma_m(t-t_0)}\left[|\beta\rangle\langle-\beta| + |-\beta\rangle\langle\beta|\right]\right\},$$

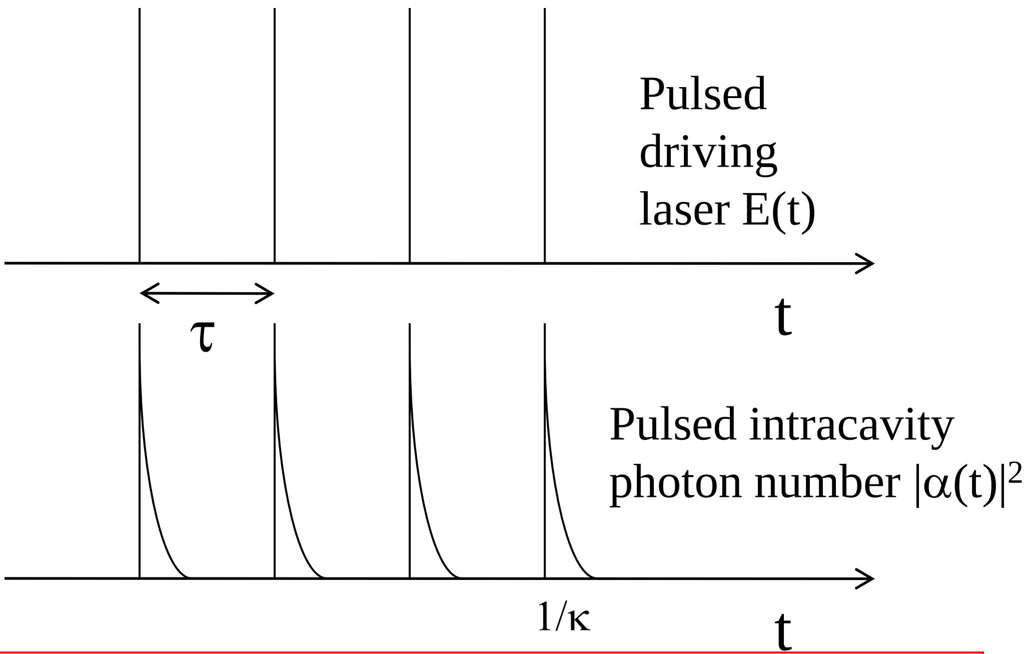
Decoherence rate

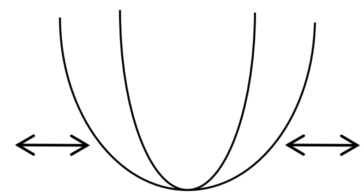
$$2\gamma_m|\beta|^2\,(2\bar{n}+1)$$

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

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

Open loop controls: “Optical spring kicks” for stationary mechanical squeezing





kicking the potential stiffness

$$U_K = e^{i\theta q^2}$$

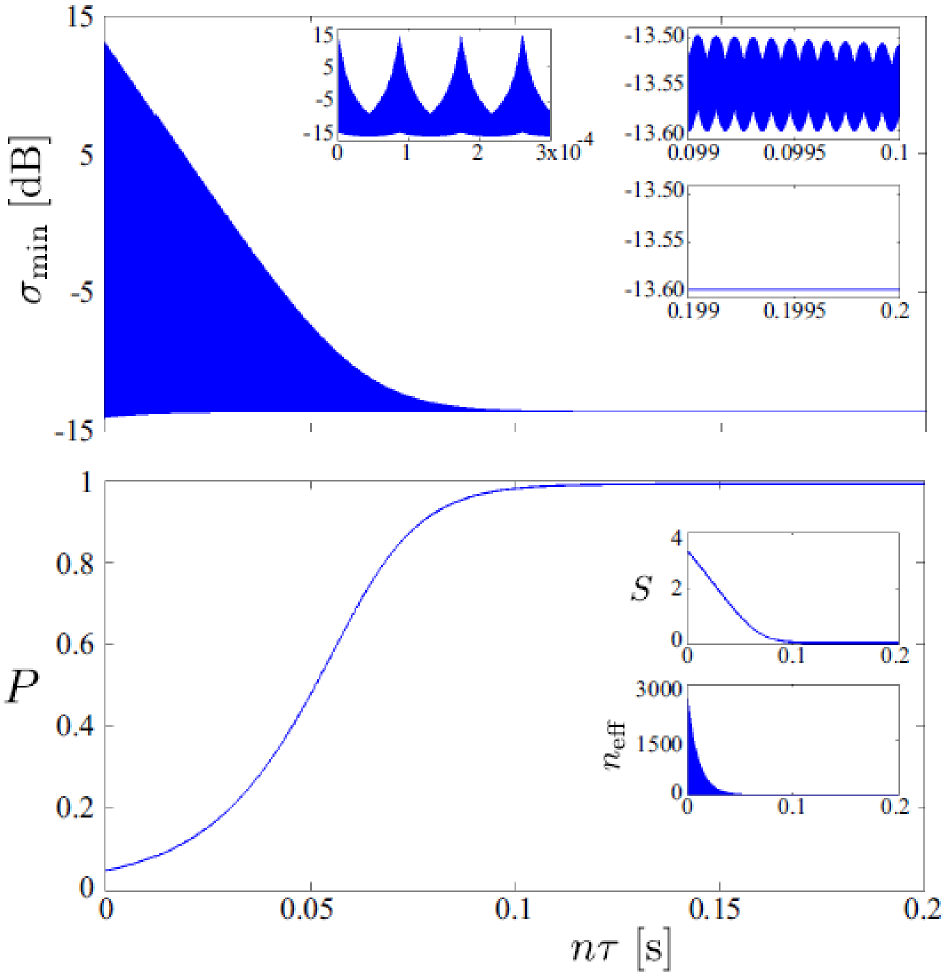
$$H = \frac{\hbar\omega_m}{2}p^2 + \frac{\hbar}{2}\left[\omega_m + 2g_2|\alpha(t)|^2\right]q^2$$

$$\theta = 2g_2 \int_{\Delta t} dt|\alpha(t)|^2$$

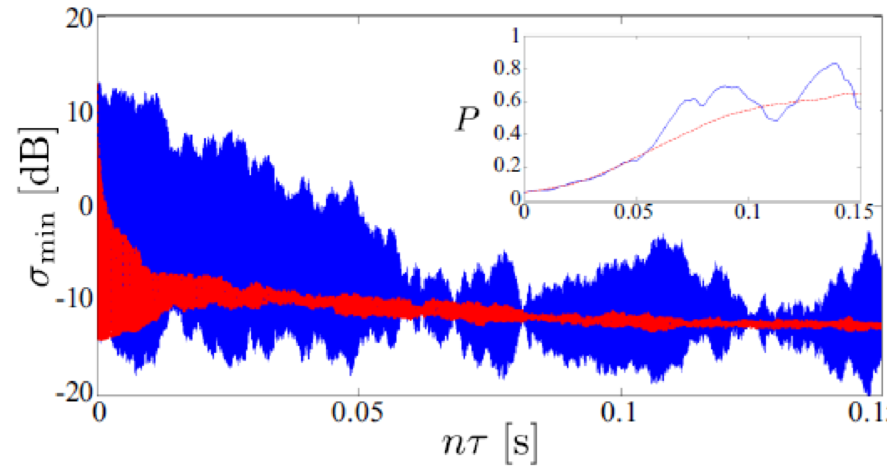
Short “bad” cavity ⇒ fast kicks

$$c/2L > \tau_p^{-1} \gg \kappa \gg \tau^{-1}$$

Taking into account thermal noise and damping, one gets a **stationary purified mechanical squeezed state (~13 dB) ,** even if starting from the equilibrium thermal state $\mathbf{n_{th} = 10}$

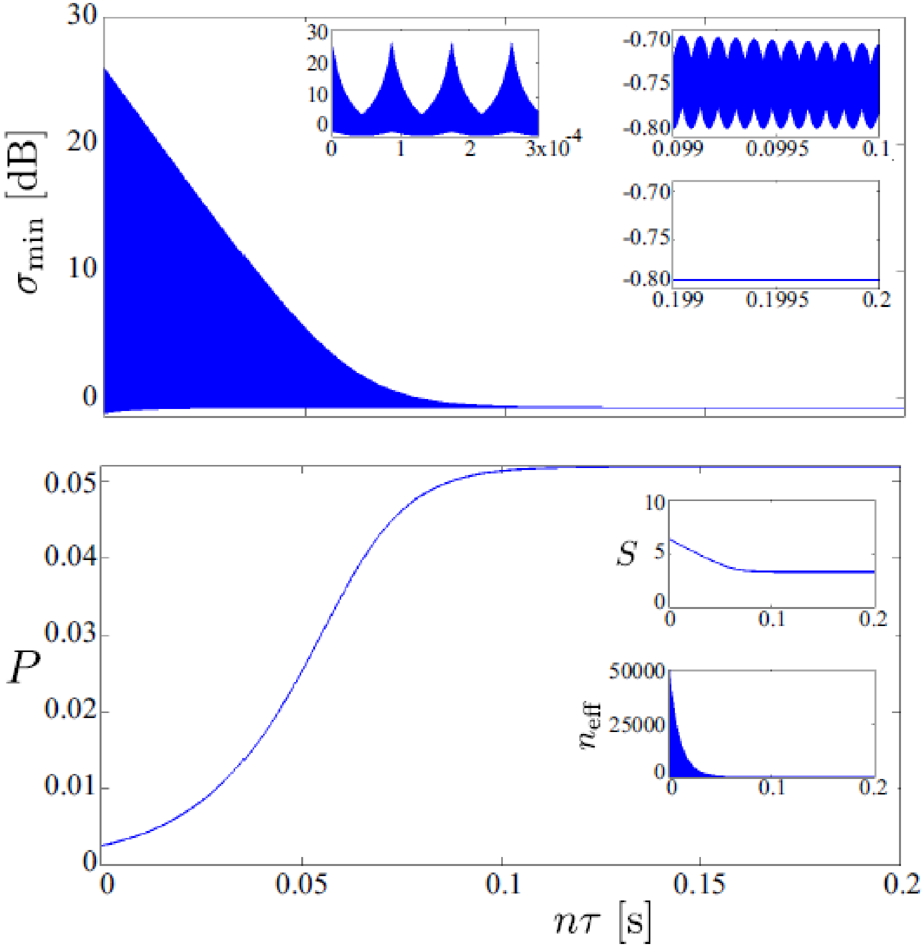


Time evolution of purity, entropy and occupancy



minimum variance, in the case when the pulse area fluctuates randomly from kick to kick (0.3% level)

M. Asjad et al., arXiv:1309.5485



The **stationary state is much less pure, when starting from the equilibrium thermal state n_{th} = 200, even though still 0.8 dB of squeezing**

M. Asjad et al., arXiv:1309.5485