Cavity Optomechanics: a playground for fundamental tests of physics

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INTRODUCTION

Micro- and nano-(opto)-electro-mechanical devices, i.e., MEMS, MOEMS and NEMS are extensively used in many technological applications :

- **high-sensitive sensors** (accelerometers, atomic force microscopes, mass sensors….)
- **actuators** (in printers, electronic devices…)

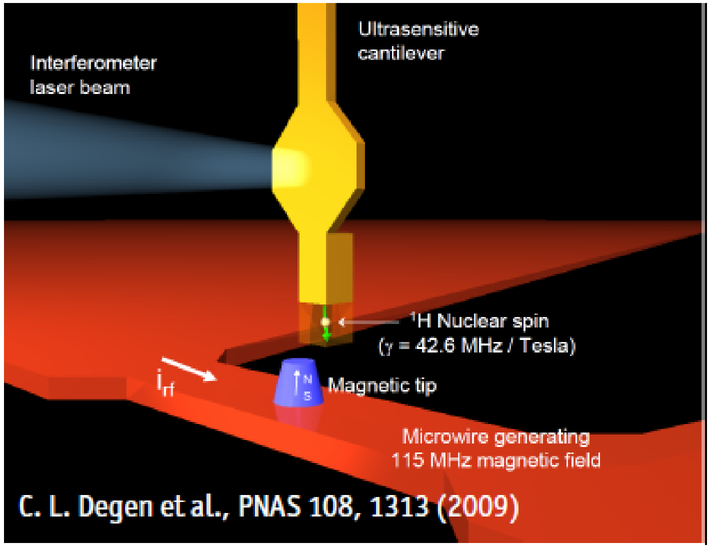
- These devices operate in the **classical regime** for both the electromagnetic field and the motional degree of freedom

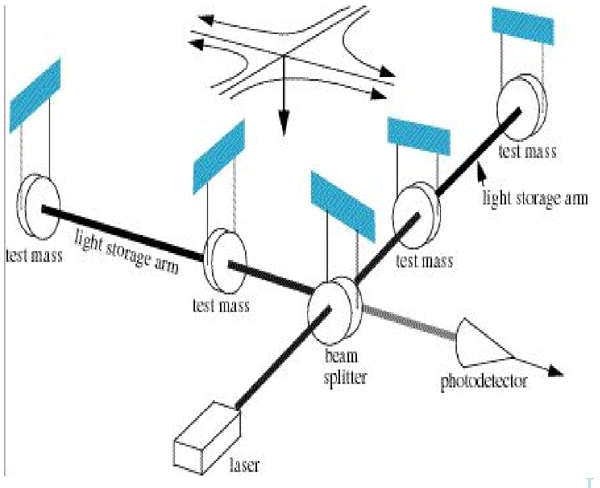
However very recently **cavity optomechanics** has emerged as a new field with **two elements of originality**:

1. the opportunities offered by **entering the quantum regime for these devices**
2. The crucial role played by an **optical (microwave) cavity**

Why entering the quantum regime for opto- and electro-mechanical systems ?

1. **quantum-limited sensing**, i.e., working at the sensitivity limits imposed by Heisenberg uncertainty principle: in a very broad range of scales





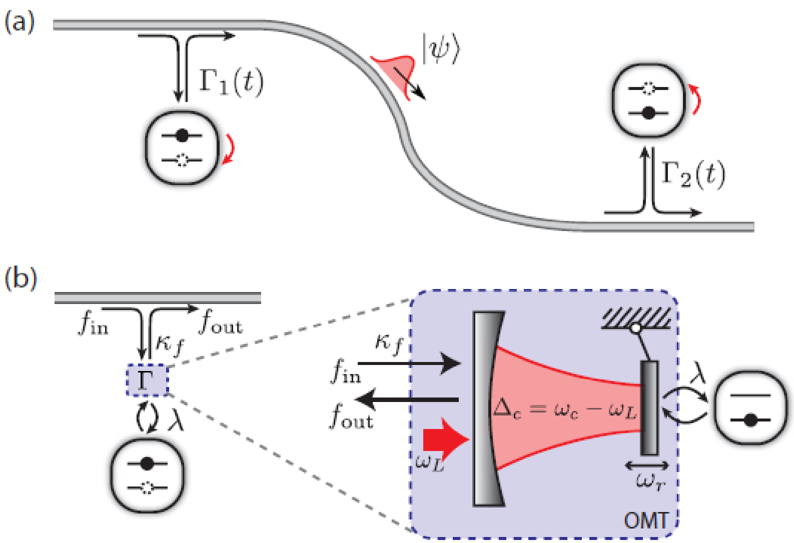
VIRGO (Pisa)

Nano-scale: **Single-spin MRFM**
D. Rugar group, IBM Almaden

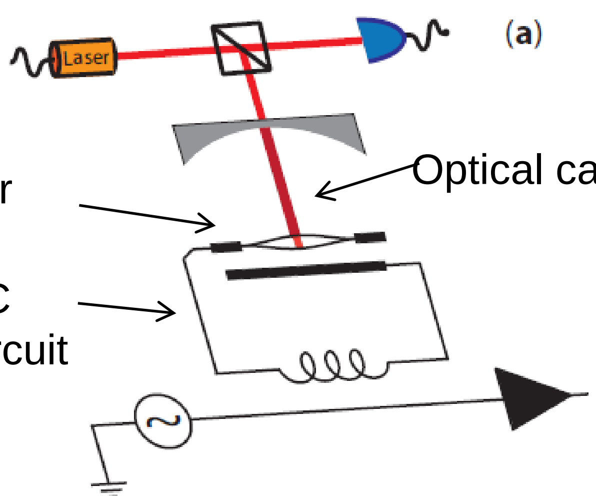
Macro-scale: **gravitational wave interferometers** (VIRGO, LIGO) close to be limited by quantum noise of light in some bandwidth

2. TRANSDUCTION OF QUANTUM INFORMATION

as **light-matter interfaces** and **transducers for quantum computing architectures, or long-distance quantum communication**

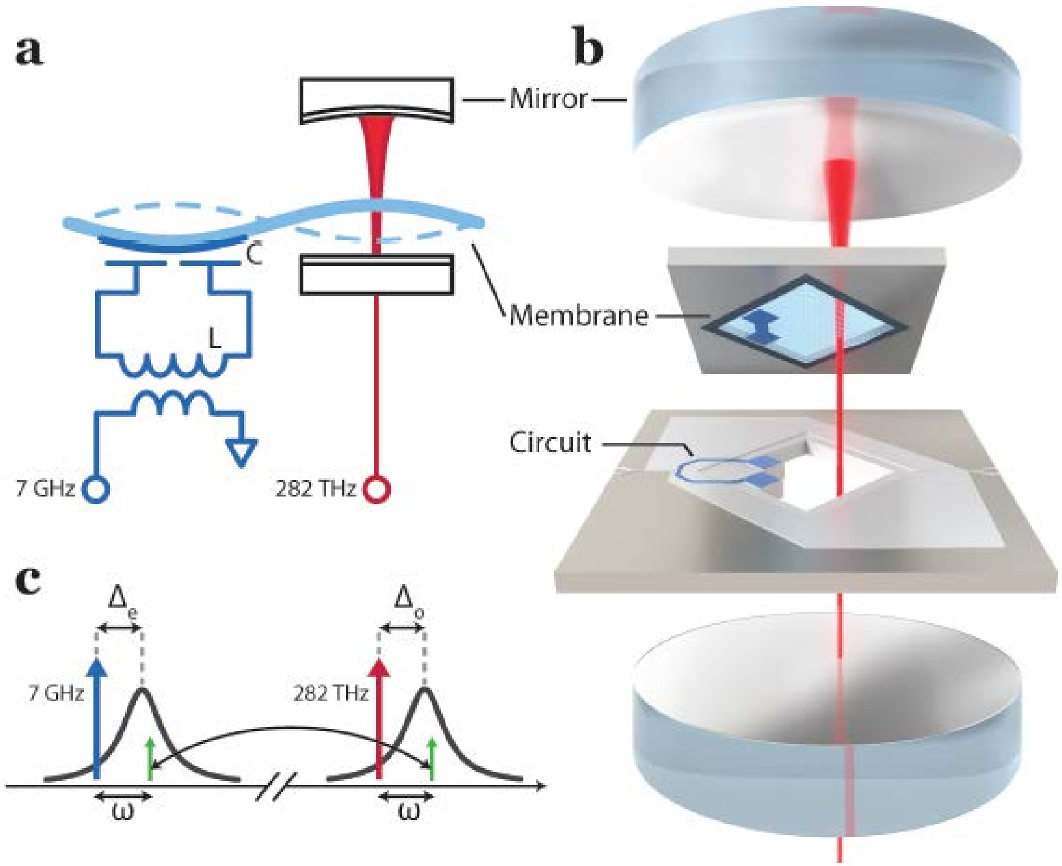


a) optimal solid state/superconducting qubits – optical photon transducer (Stannigel et al. 2012)



b) Microwave-to-optical nanomechanical transduction based on a **nanomechanical resonator in a superconducting circuit, simultaneously interacting with the two fields (Barzanjeh et al, 2012)**

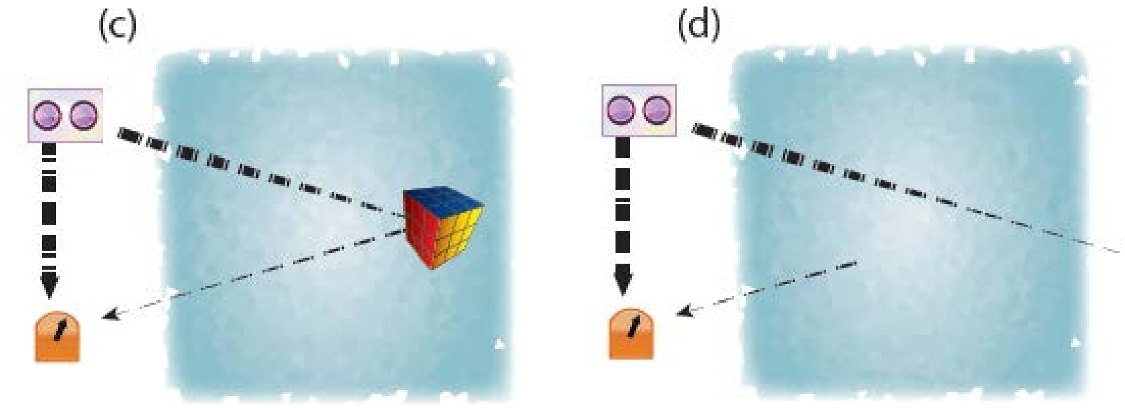
FIRST EXPERIMENTAL DEMONSTRATIONS OF A MICROWAVE-OPTICAL CONVERTER (STILL WITH CLASSICAL SIGNALS)



Adding a LC circuit to the membrane-in-the-middle setup, Andrews et al., Nat. Phys. 2014 (Lehnert-Regal group)

Such transduction can be used for microwave quantum illumination

- It exploits nonclassicality (**entanglement**) for a **target detection**
- two **maximally-entangled systems**, one is kept (idler) and the other one sent for target detection (signal).
- The reflected signal and idler are finally detected by a **joint measurement**.
- the use of an entangled source yields better performance, even though entanglement fails to survive the return trip.

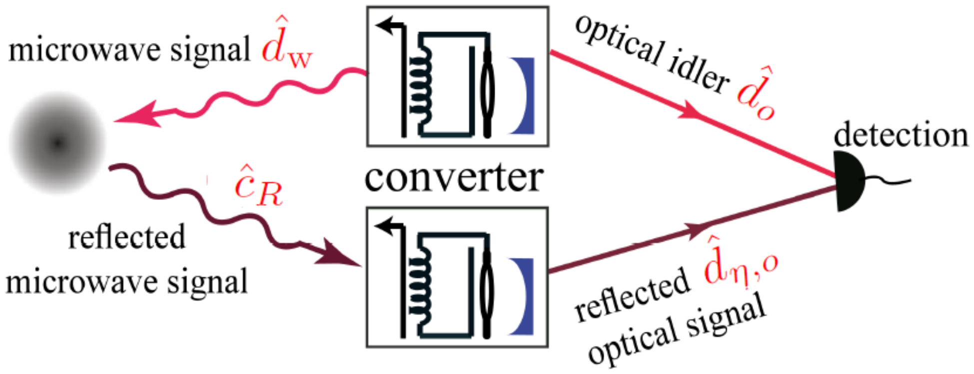


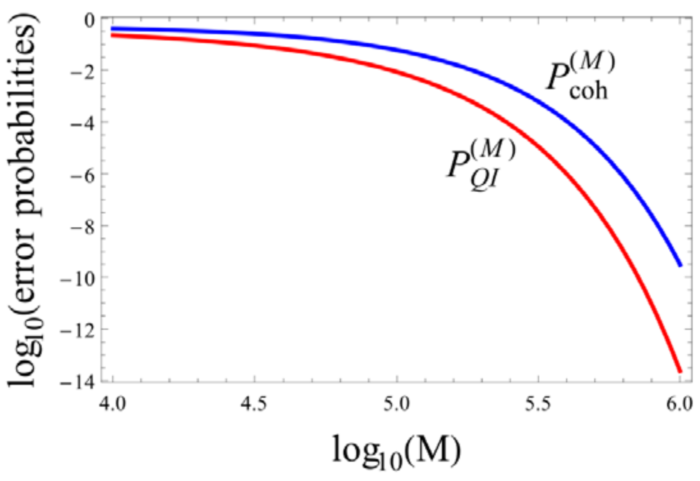
Opto-electro-mechanical scheme for quantum illumination at microwave wavelengths

It is used either for microwave-optical entanglement generation and for upconversion to optical for optimal photodetection

Entangled source

QI advantage in the error probability

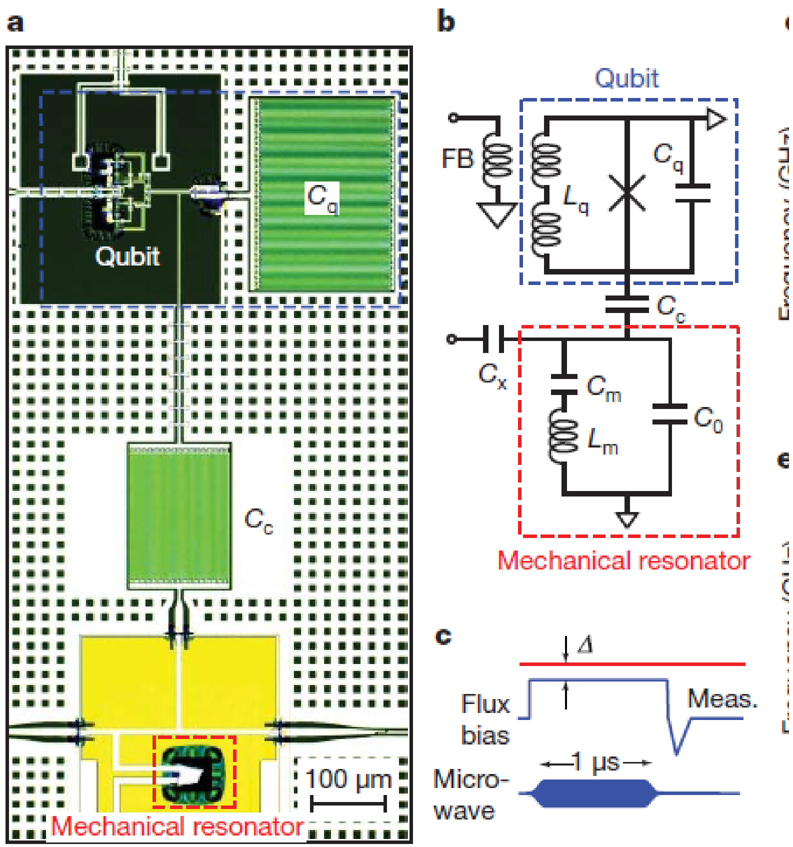


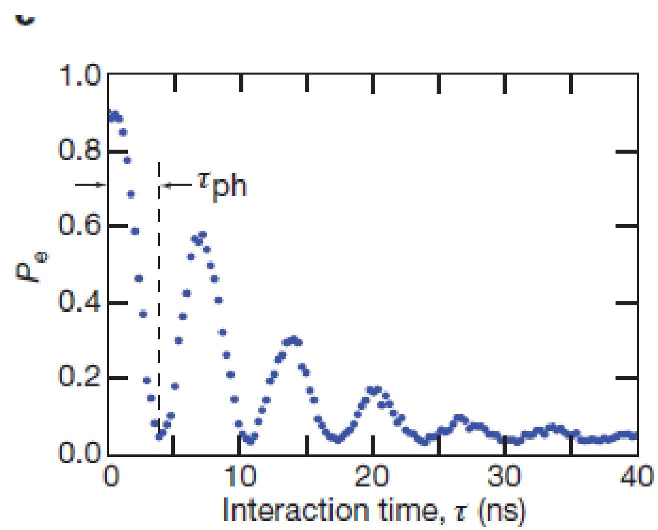


[Sh. Barzanjeh et al., “Microwave Quantum Illumination”, Phys. Rev. Lett. 114, 080503 (2015)]

NANO-OPTOMECHANICAL AND ELECTROMECHANICAL SYSTEMS HAVE ALREADY REACHED THE QUANTUM REGIME, WITH DIFFERENT DEVICES

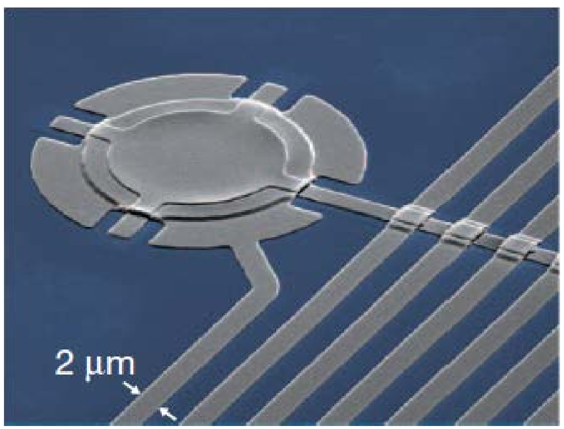
Quantum ground state of nanomechanical resonator and single-phonon control (Cleland group 2010) (via coupling with a superconducting-phase-qubit)

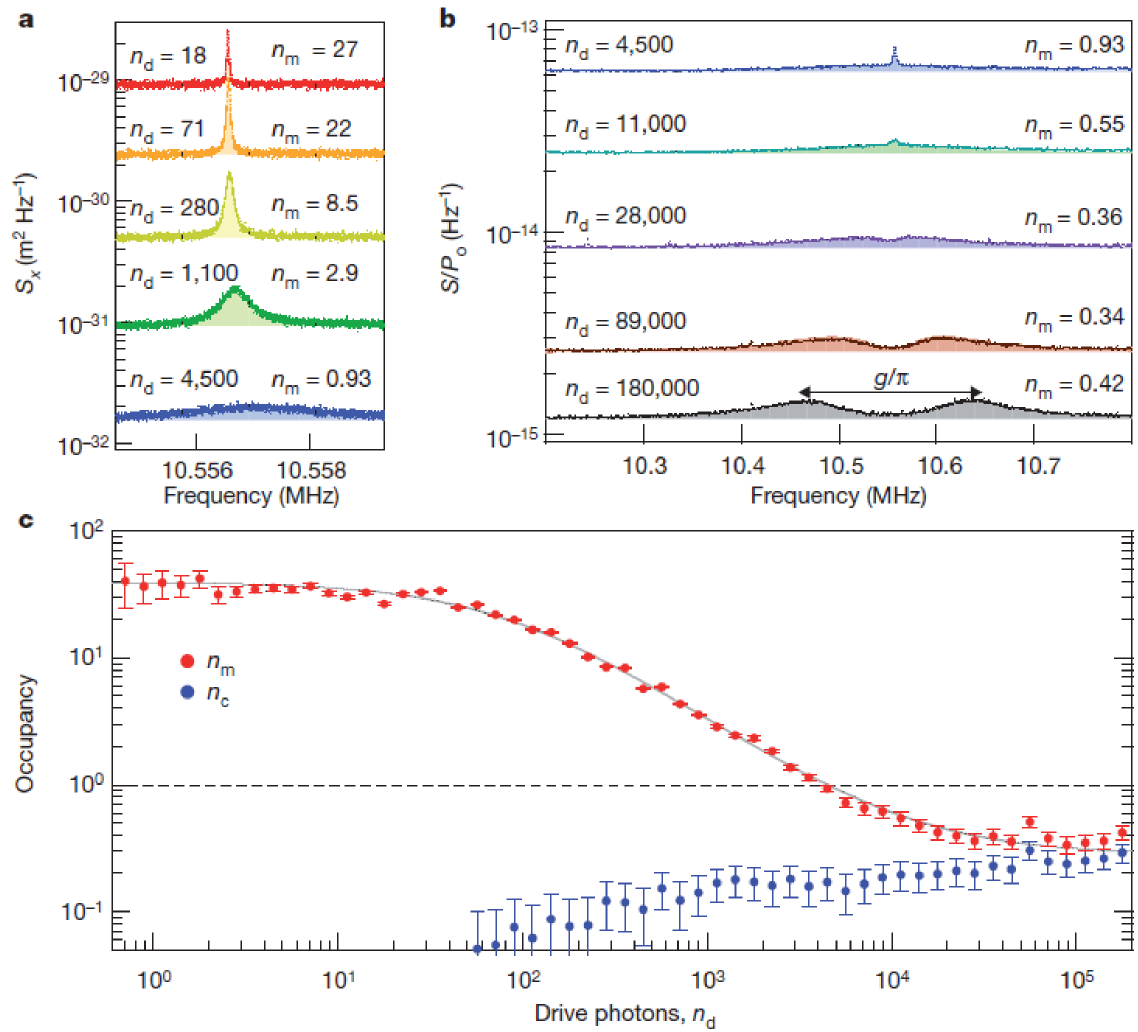




RESOLVED SIDEBAND GROUND STATE COOLING VIA COUPLING WITH A MICROWAVE CAVITY

micromechanical membrane embedded into a superconducting microwave resonant LC circuit

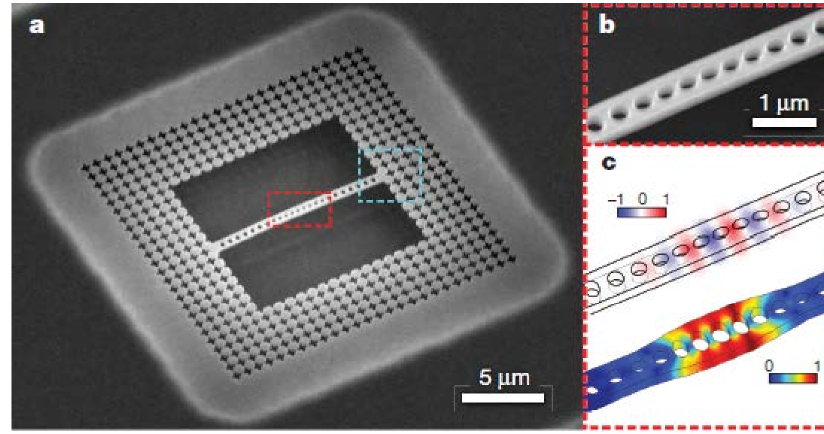


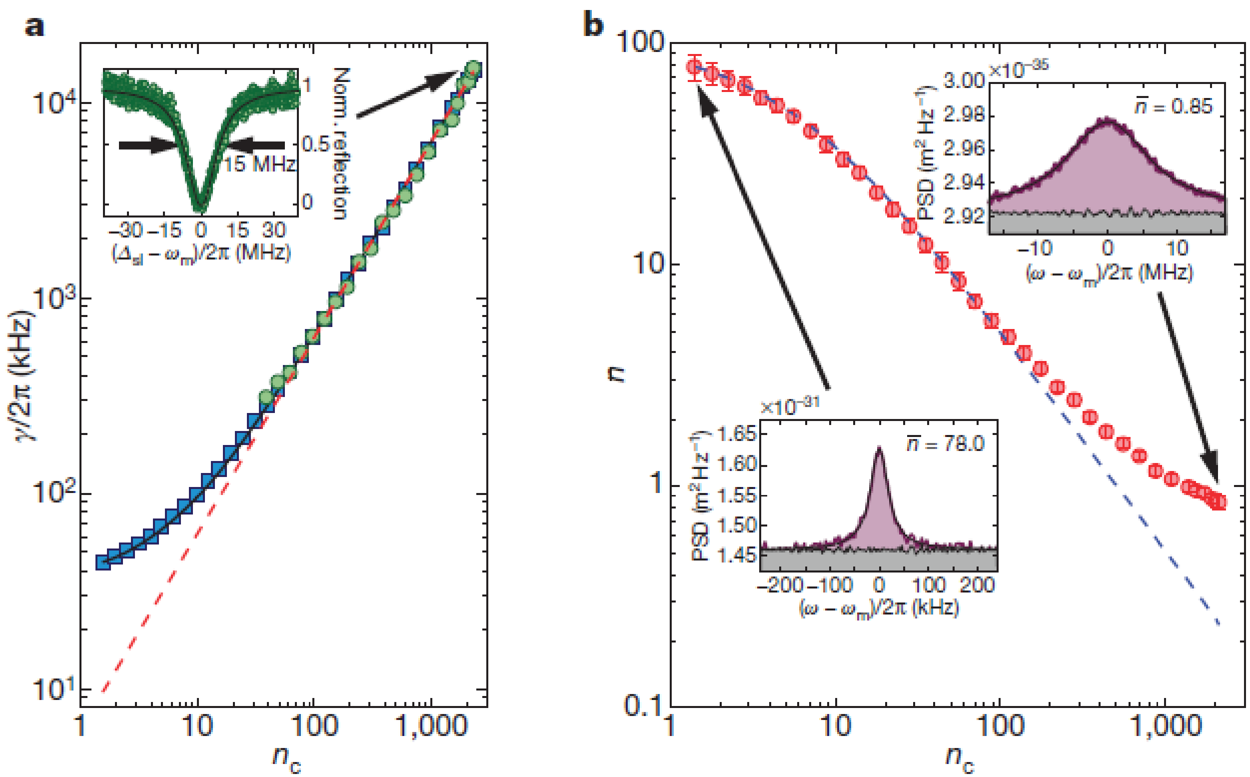


J.D. Teufel et al. Nature 475, 359 (2011)

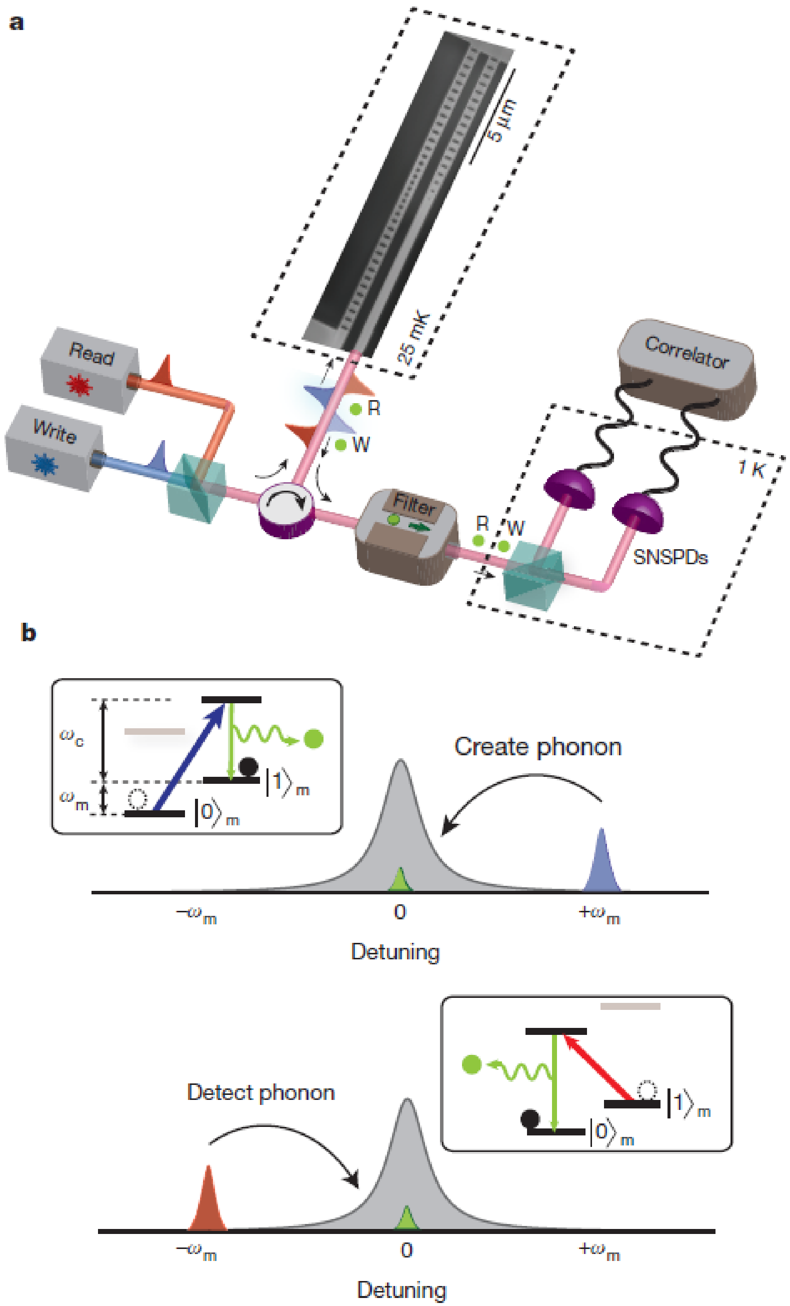
GROUND STATE COOLING ALSO WITH AN OPTICAL CAVITY

Patterned silicon nanobeam with an acoustic resonance (**breathing mode**), which is **coupled by radiation pressure to the co-localized optical resonance** (**photonic crystal optomechanical cavity)**



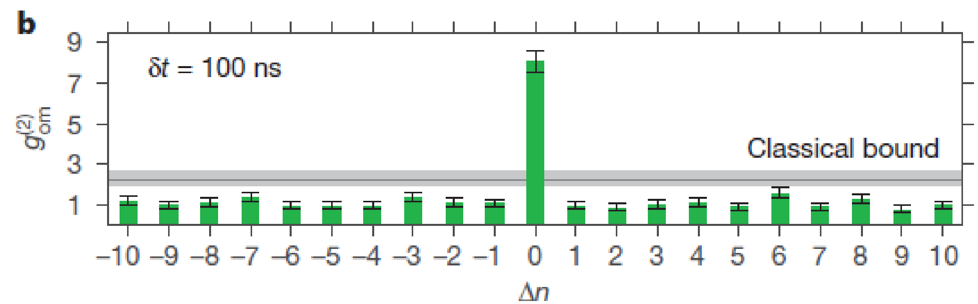


J. Chan et al., Nature 478, 89 (2011)



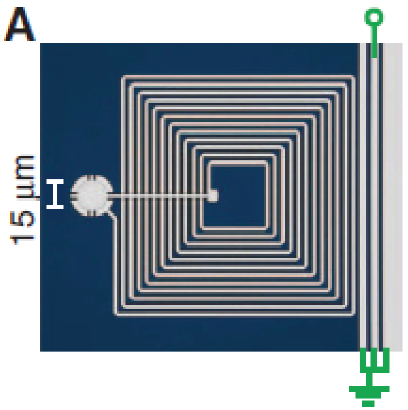
photon-phonon correlations at the quantum level with an integrated nanomechanical device

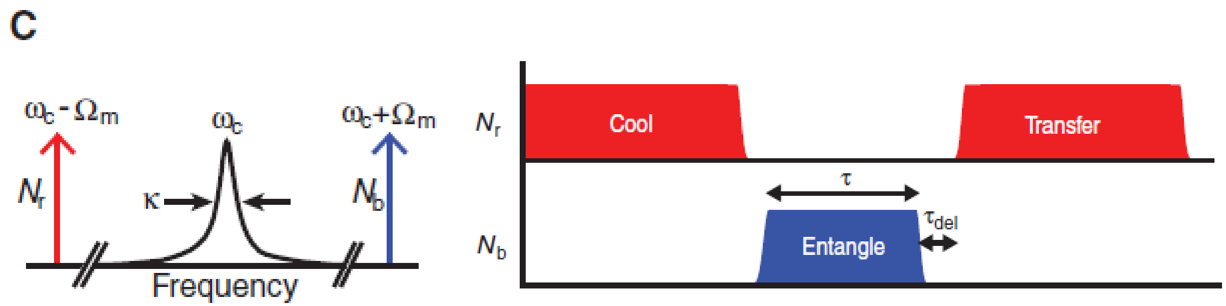
R. Riedinger e al., Nature (London), 530, 313-316 (2016)).

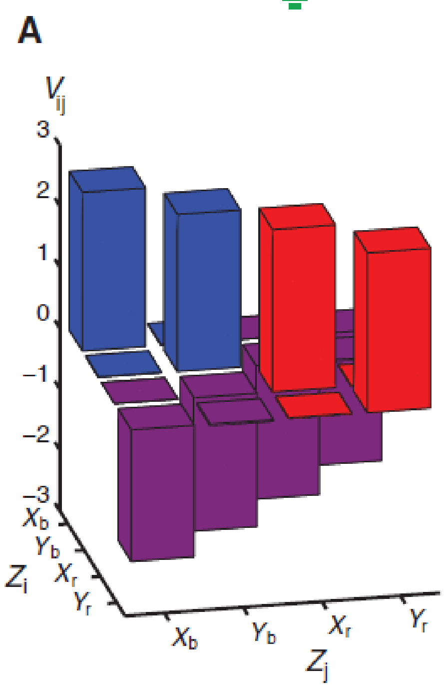


The observed violation of a Cauchy–Schwarz inequality obeyed by $g^{(2)}$ for classical light, is clear evidence for the non-classical nature of the mechanical state generated

CONTINUOUS VARIABLE ENTANGLEMENT BETWEEN A MICROWAVE CAVITY AND A MECHANICAL RESONATOR

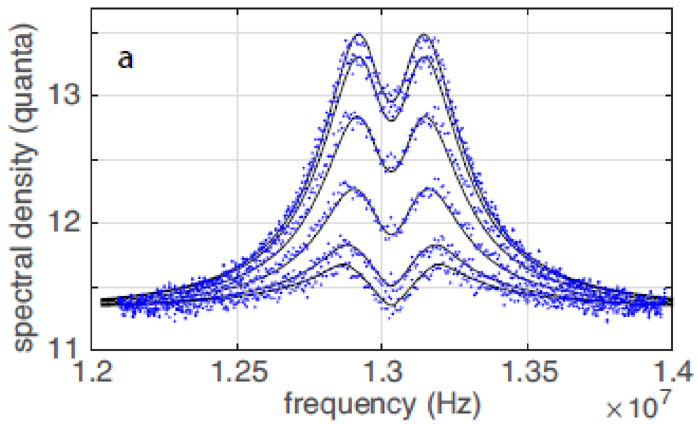


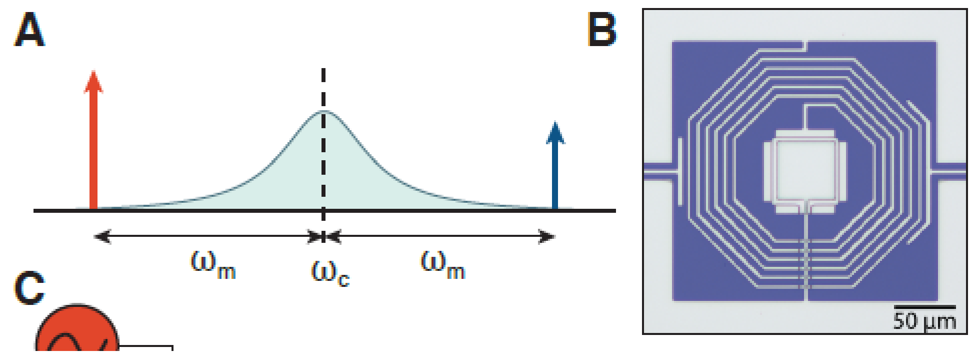


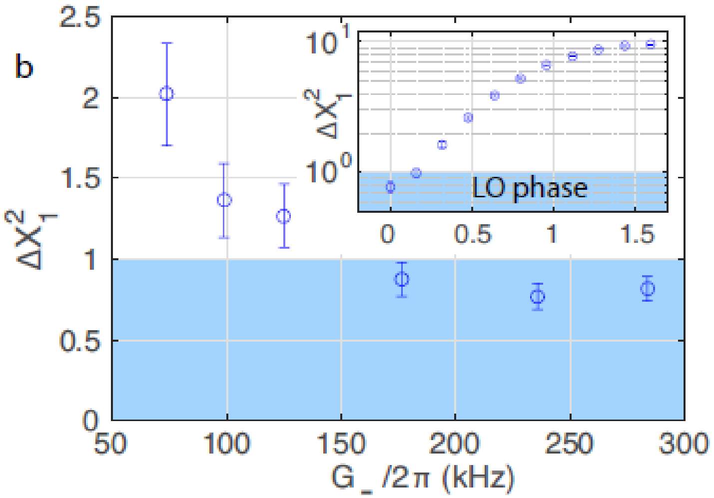


Covariance matrix and corresponding **log-negativity measured** (measured $E_N = 0.16$, inferred $E_N = 1.1$) , Palomaki et al, Science, 2013, JILA

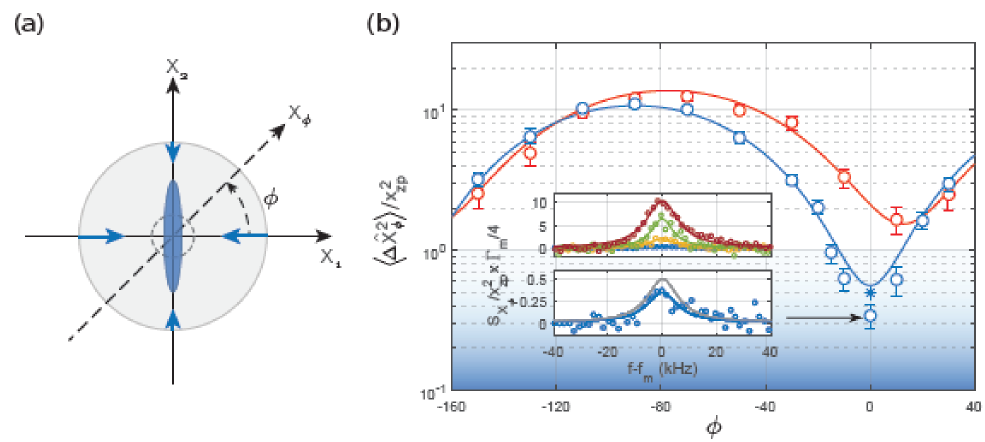
GENERATION AND DETECTION OF SQUEEZED STATES OF A NANOMECHANICAL RESONATOR





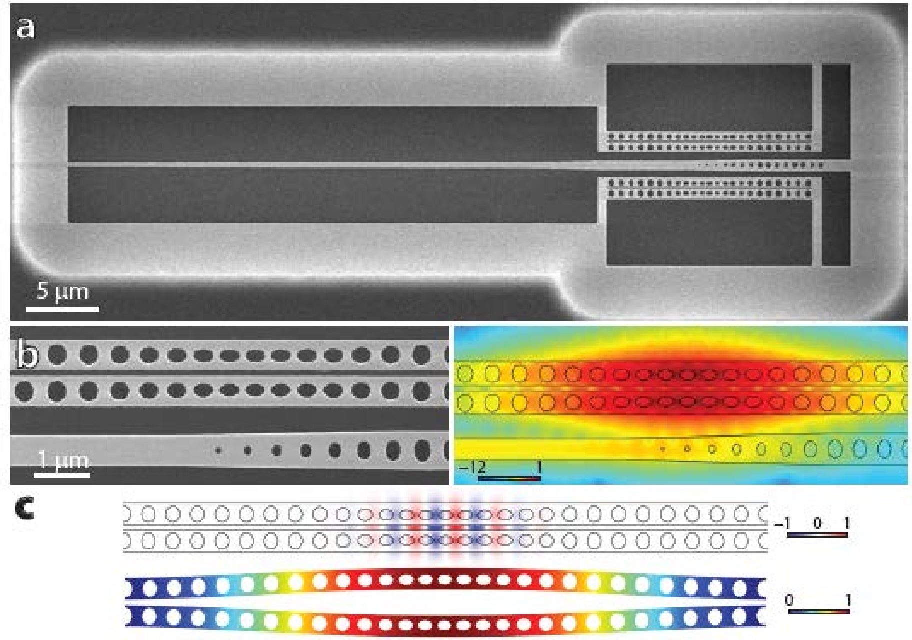


K, Schwab group (Caltech) 2015,
Sillanpaa group (Helsinki 2016)

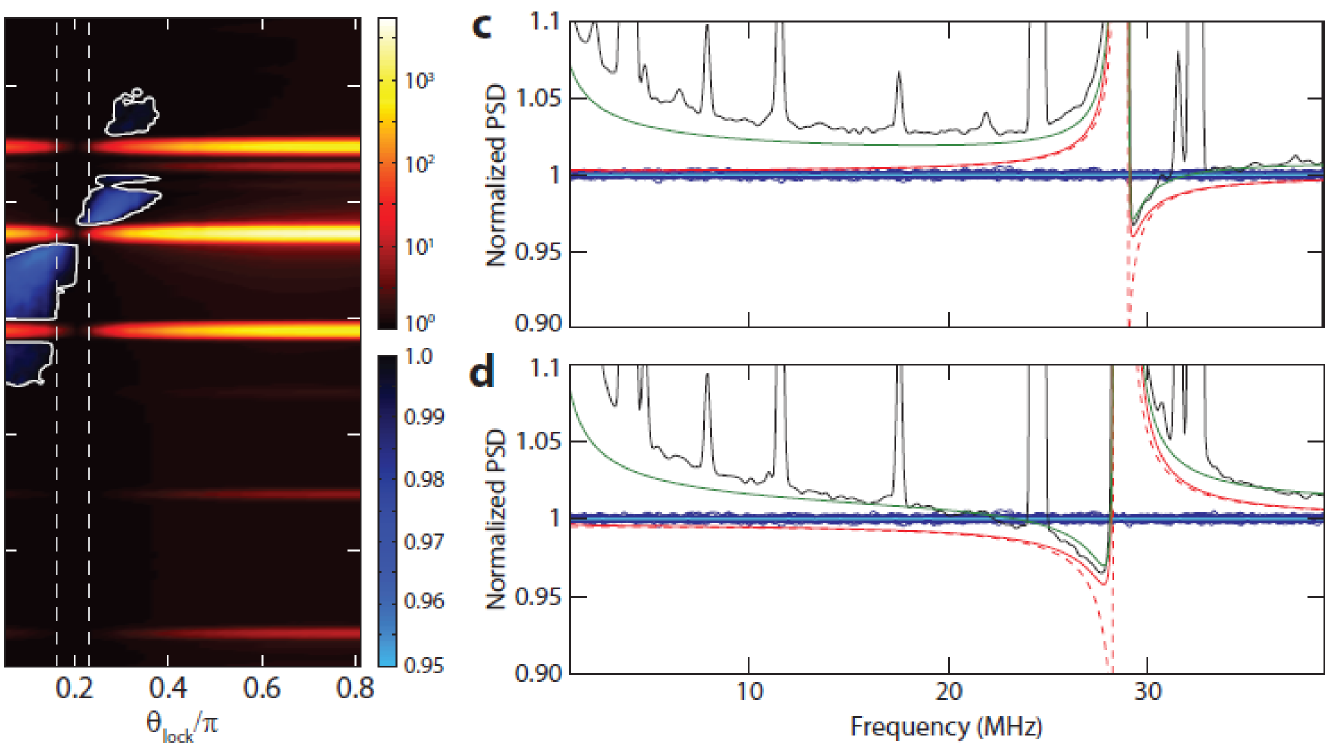


QUANTUM-NONDEMOLITION (back-action evading) measurement of the squeeezed quadrature

Ponderomotive squeezing of an optical cavity output

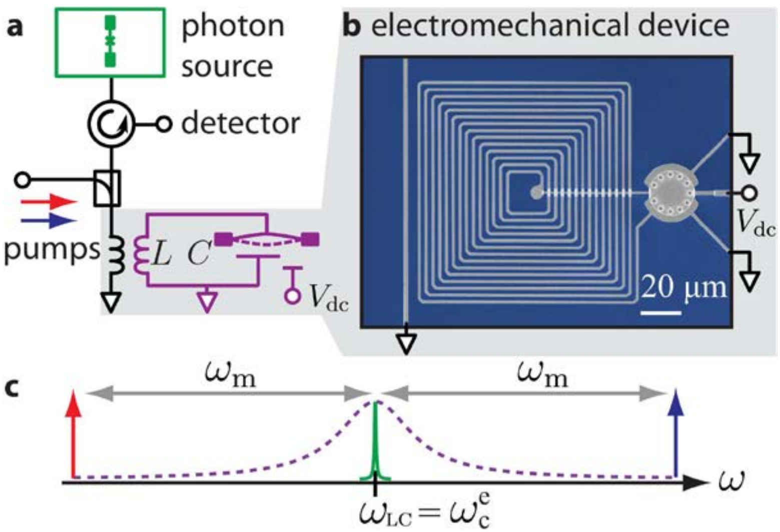


Waveguide-coupled zipper optomechanical cavity, T = 16 K, Q = 10^5

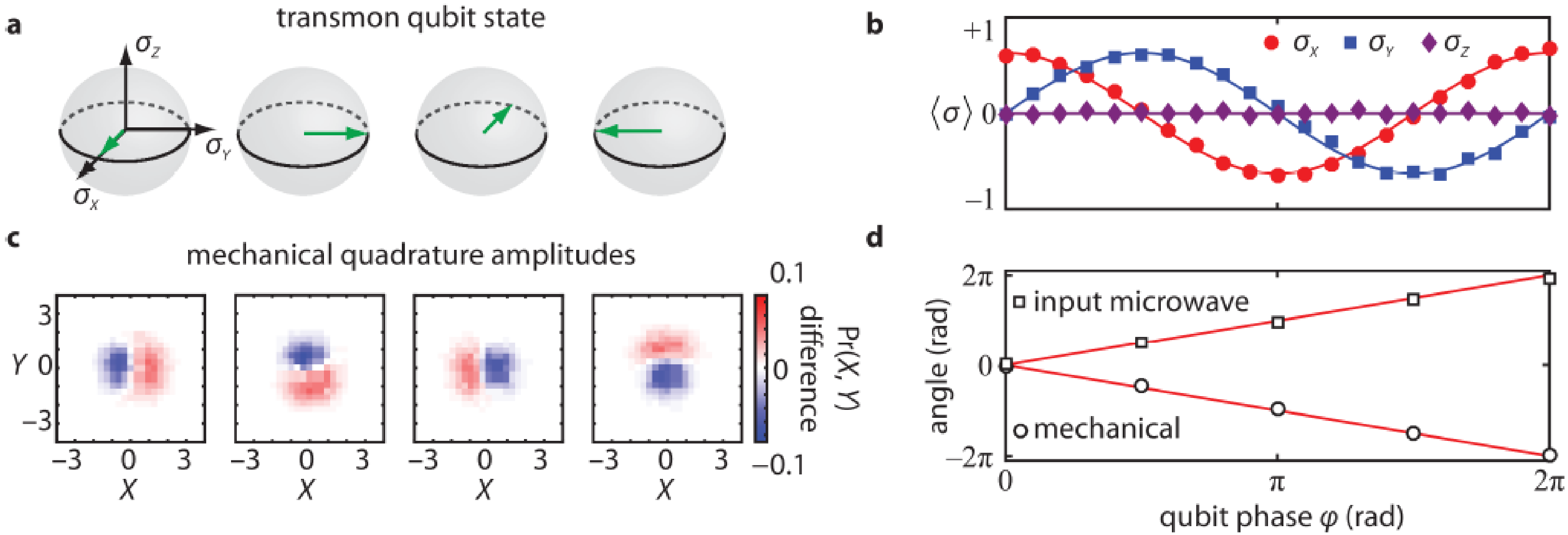


A, Safavi-Naeini et al., Nature 2013 (O. Painter group, Caltech)

Quantum state transfer from a qubit to nanomechanical resonator



Very recent demonstration of conversion of propagating qubits encoded as superpositions of zero and one photons to the motion of a micrometer-sized mechanical resonator (Jila, NIST, Yale, Reed et al 2017) (fidelity F = 0.83)

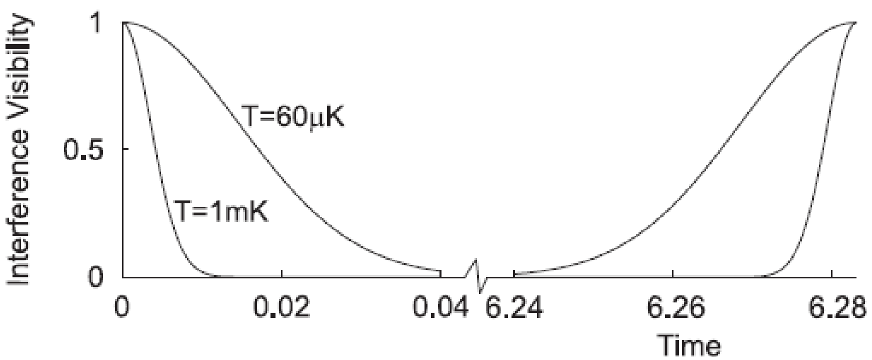


THIRD FURTHER MOTIVATION FOR REALIZING QUANTUM OPTOMECHANICAL SYSTEMS: THEY ARE AN IDEAL PLAYGROUND FOR FUNDAMENTAL TESTS

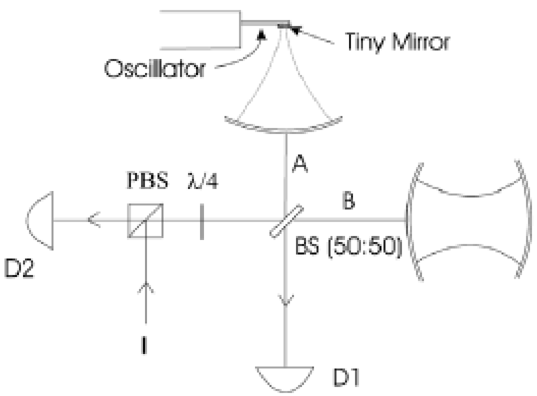
1. **Wide range of masses**, devices, configurations

2. Possibility to have **quantum-limited detection** of optical fields (and more recently also of microwaves)

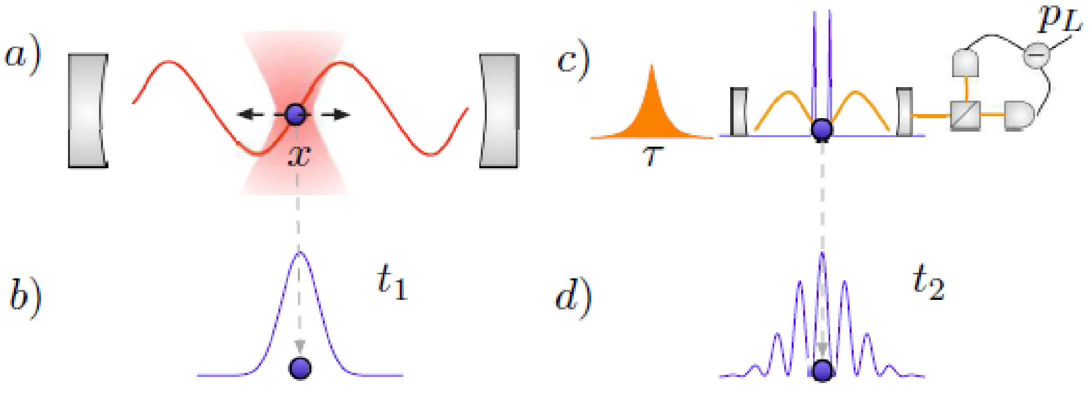
First relevant proposal: optical **interferometric** detection of **Schrodinger cat states of a cantilever**



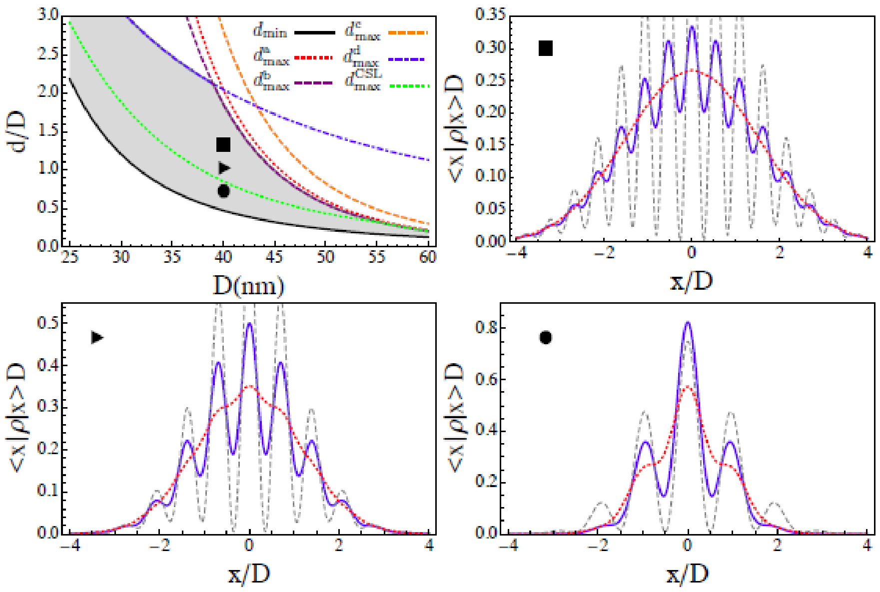
Marshall, Simon, Penrose, Bouwmeester, PRL 91, 130401 (2003)



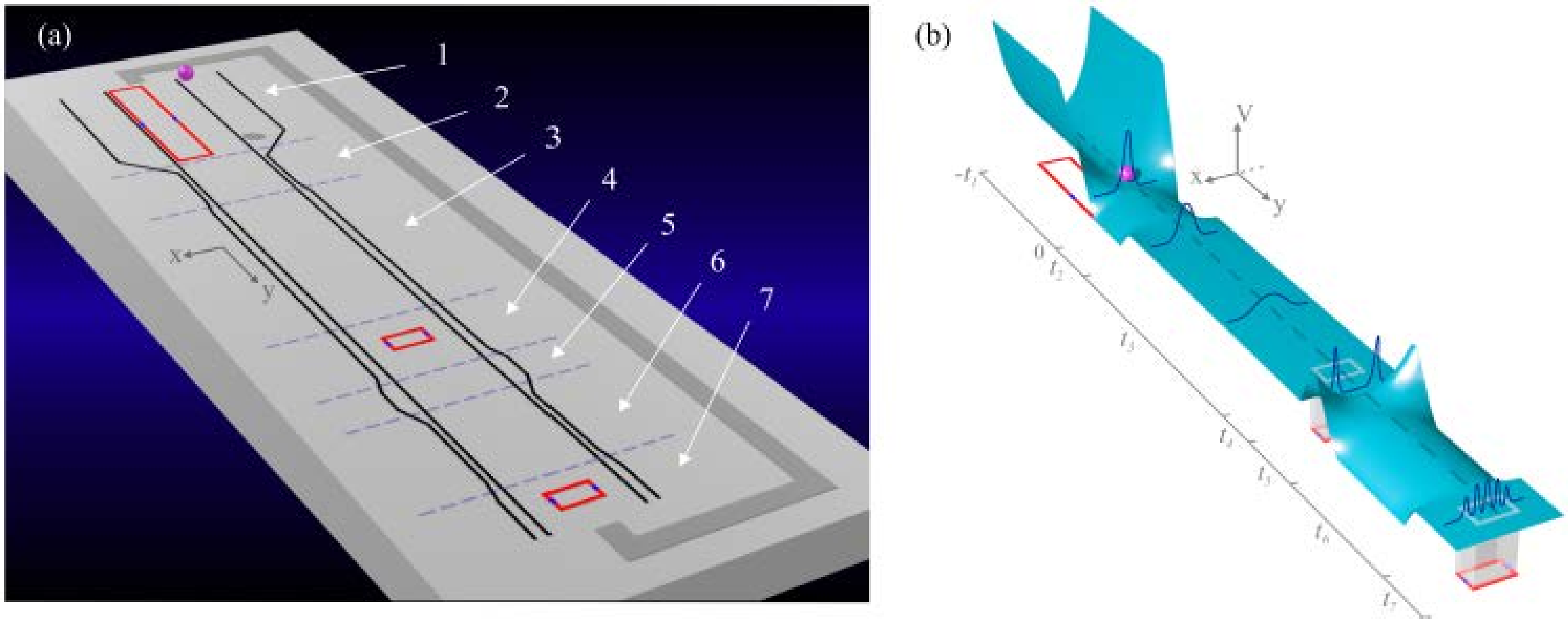
More promising: OPTICALLY LEVITATED NANOSPHERES : tunable masses and potentially weakly affected by environmental decoherence



Generation of a cat state and **test of collapse models** through monitorning of decoherence (O. Romero-Isart, et al., Phys. Rev. Lett. 107, 020405 (2011).

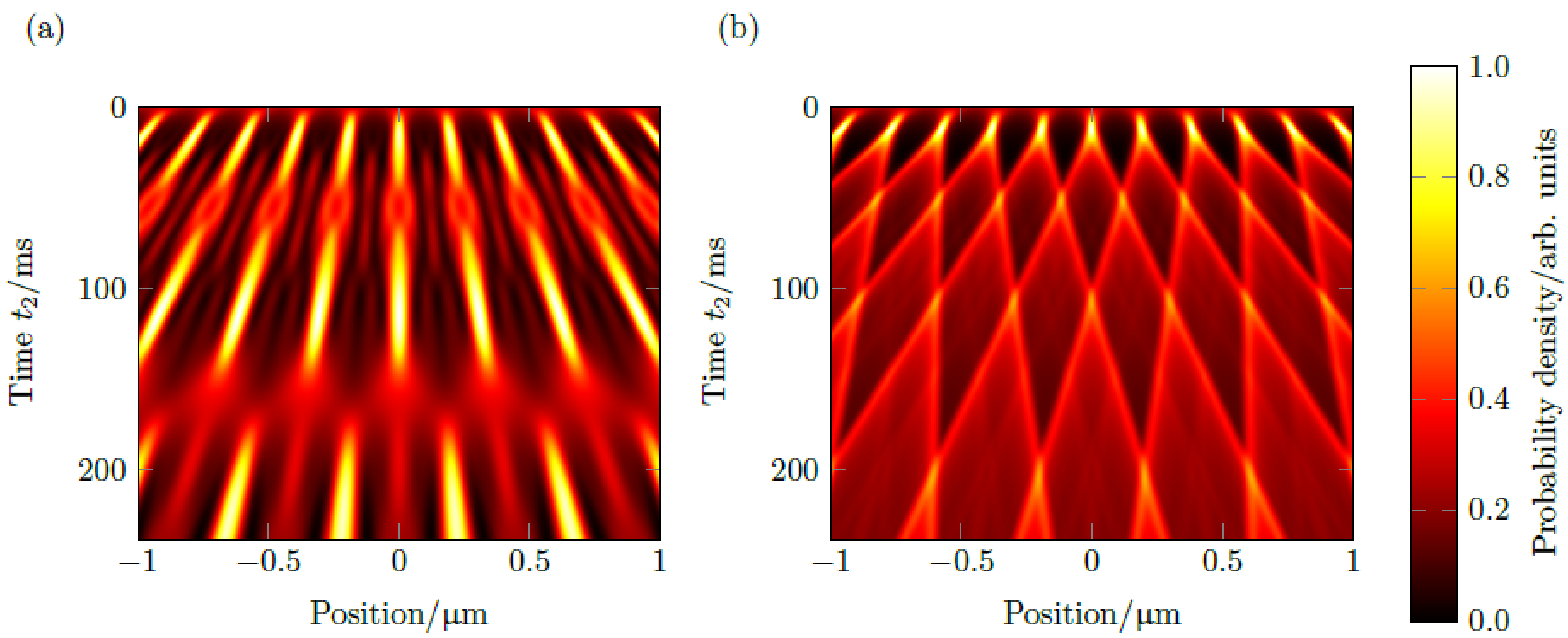


Recent evolution: MAGNETICALLY LEVITATED PARTICLES; they can be scaled to larger radii (R > 1 μm) (Romero-Isart, 2016)

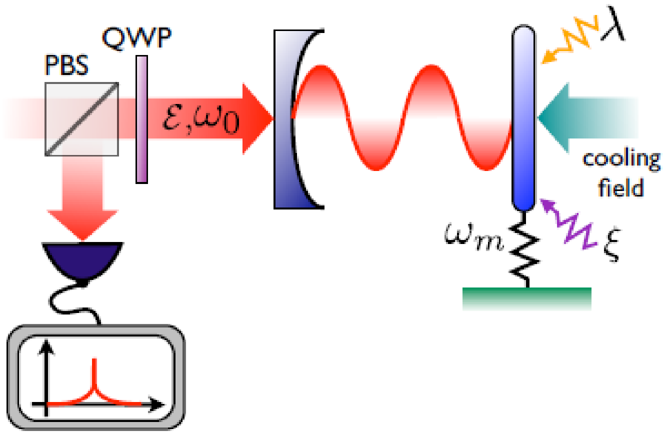


“magnetic skatepark implementation”
In a cryogenic superconducting circuit

See also the near-field Talbot interferometer generation of superpositions for a levitated nanospheres by Bateman et al., Nat Comm 2014



NON-INTERFEROMETRIC TESTS OF COLLAPSE THEORIES



Bahrami et al., PRL 2014

The effect of collapses an nanosphere is equivalent to an effective diffusion process, i.e., an additional stochastic force f(t)

$$\langle f(t) f(t') \rangle = \lambda_{eff} \delta(t - t')$$

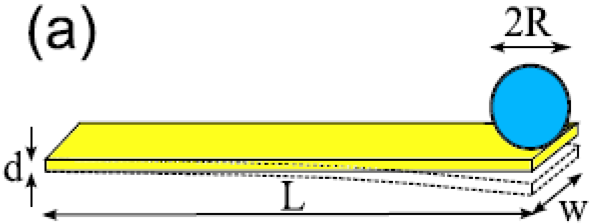
One can detect collapses through the additional heating rate (or temperature increase) due to spontanous localization (see also Diosi)

However this requires an **extremely careful calibration of noises and of system temperature** (how one can distinguish collapses from an unknown noise source ?)

RECENT EXPERIMENTAL BOUND DERIVED

Collapses yield a weak violation of energy conservation and one has a temperature increase

$$\Delta T_{CSL} = \frac{\hbar^2 Q}{2k_B m\omega}\lambda_{eff}$$



Cantilever (3 kHz), with a ferromagnetic sphere detected by a SQUID current sensor.

From careful measurement and calibration of thermal noise in the range 0.03 – 1 K
(other noise were negligible)

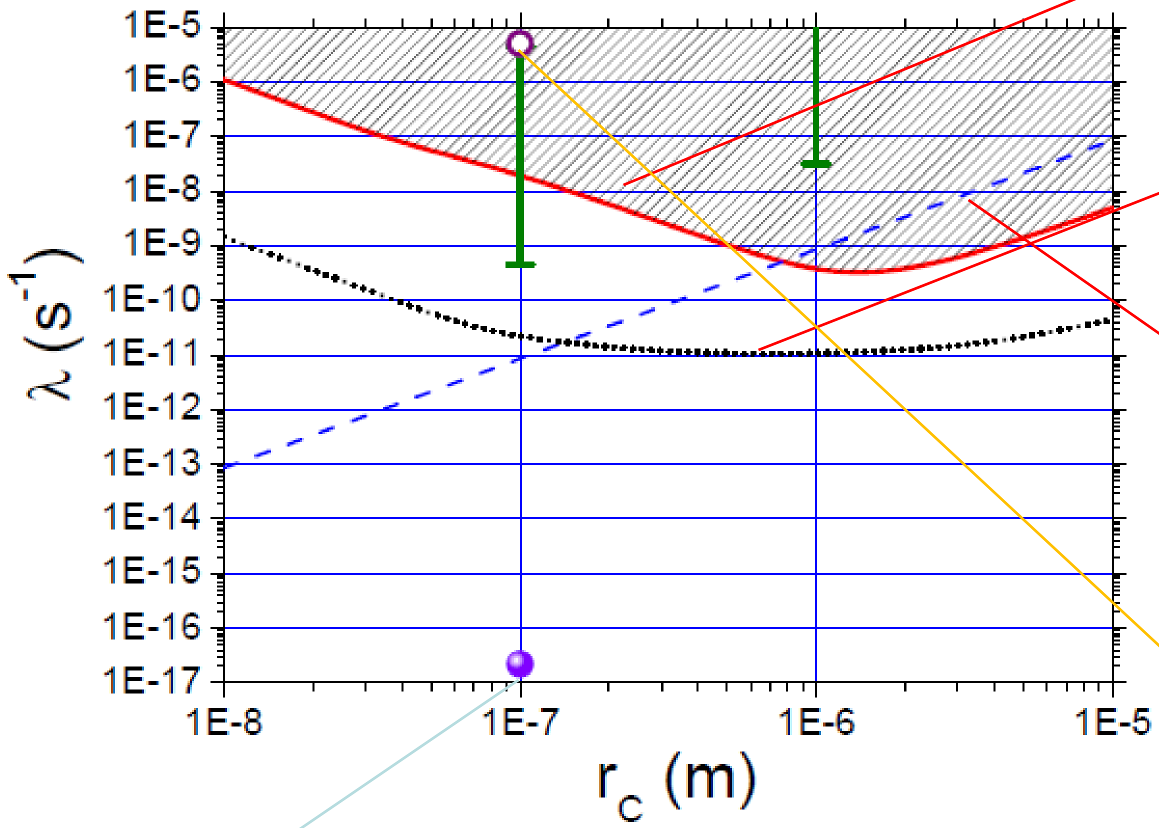
$$\Delta T_{CSL} < 2.5 \quad mK$$

A. Vinante et al, Phys. Rev. Lett. 116, 090402 (2016)

Derived bounds

More recent bound

Estimated improved bound



X-ray spontaneous emission (high energy tests)

GRW

Matter wave interferometry

A. Vinante et al, Phys. Rev. Lett. 116, 090402 (2016)

ALTERNATIVE IDEA: Different scaling of collapse noise in optically trapped particles

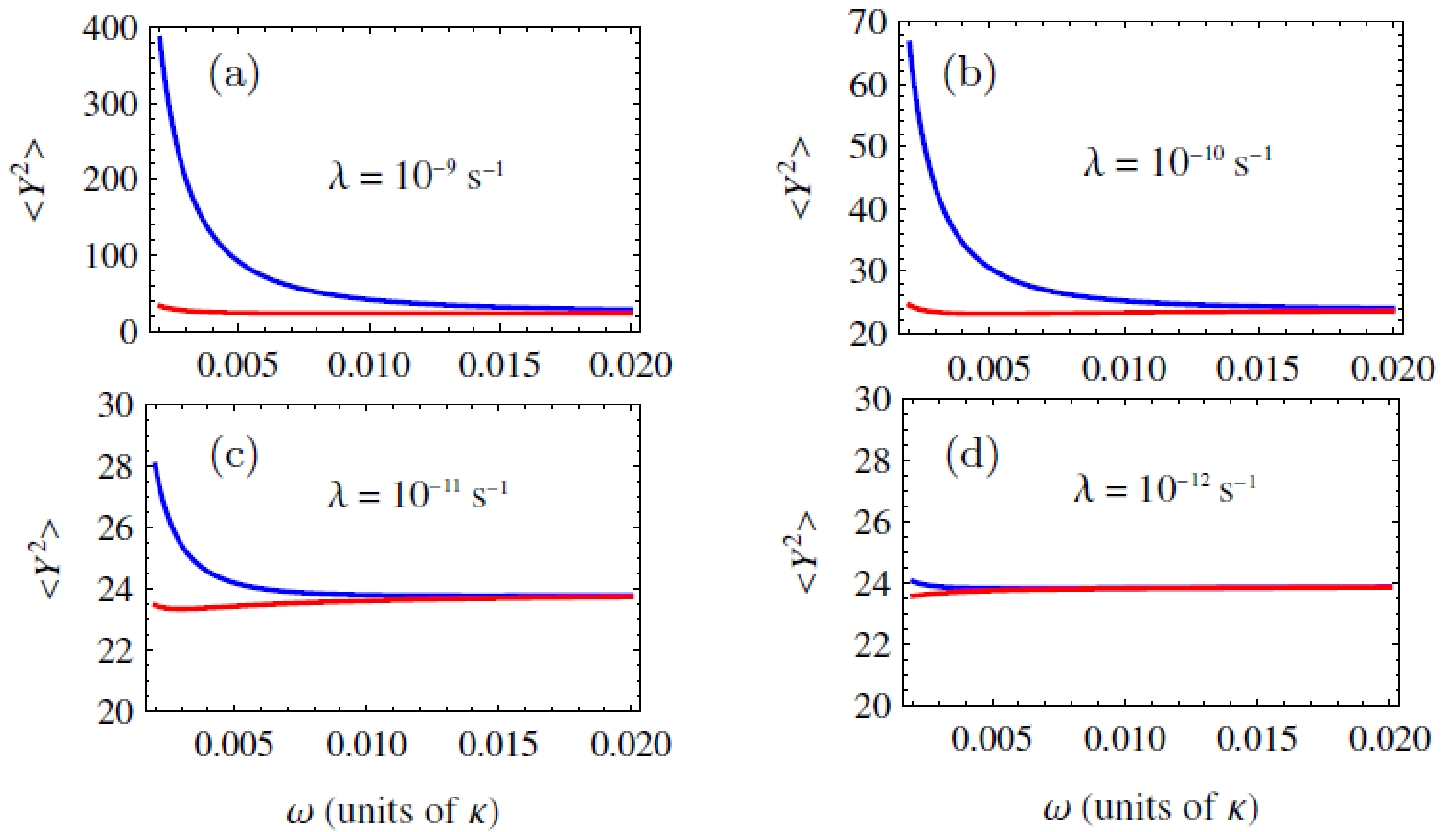
different sources of noise exhibit **different scalings** with the system parameters, and hence **distinguishable scalings** of measurable quantities are expected to be observed

In particular, the validity of the CSL model can be actually probed by the study of the nanoparticle dynamics **as a function of the trapping frequency *ω* and the cavity length *L*.**

Measured quantity $\langle Y^2 \rangle$ = integrated homodyne phase noise spectrum

J. Li et al., PHYS. REV. A 93, 050102(R) (2016), see also B. Goldwater et al., Phys. Rev. A **94**, 010104(R) (2016).

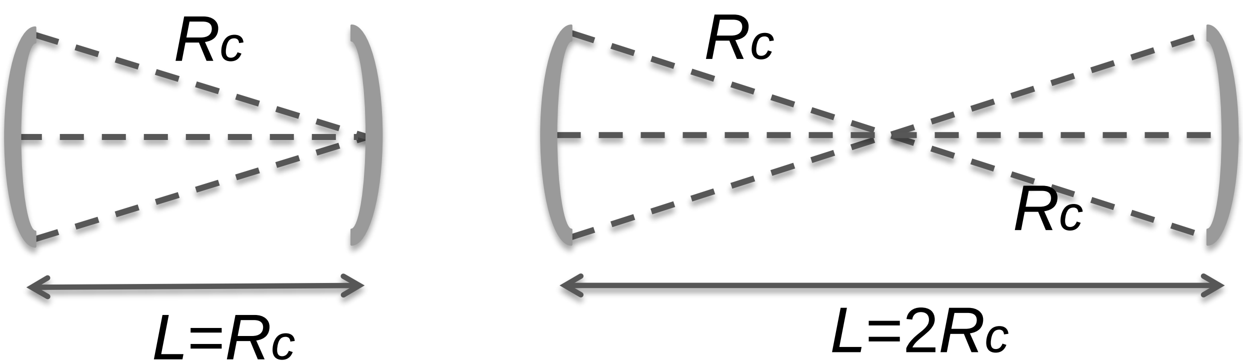
If we do not see any visible effect of CSL, we can put an upper bound to the collapse rate $\lambda < 10^{-12}\ s^{-1}$



J. Li et al., PHYS. REV. A 93, 050102(R) (2016)

Another peculiar and different scaling between the two noises is that on CAVITY LENGTH L, at fixed Δ/κ, ω/κ and G/κ

At fixed radius of curvature R_c, and finesse F, we consider different cavity lengths L



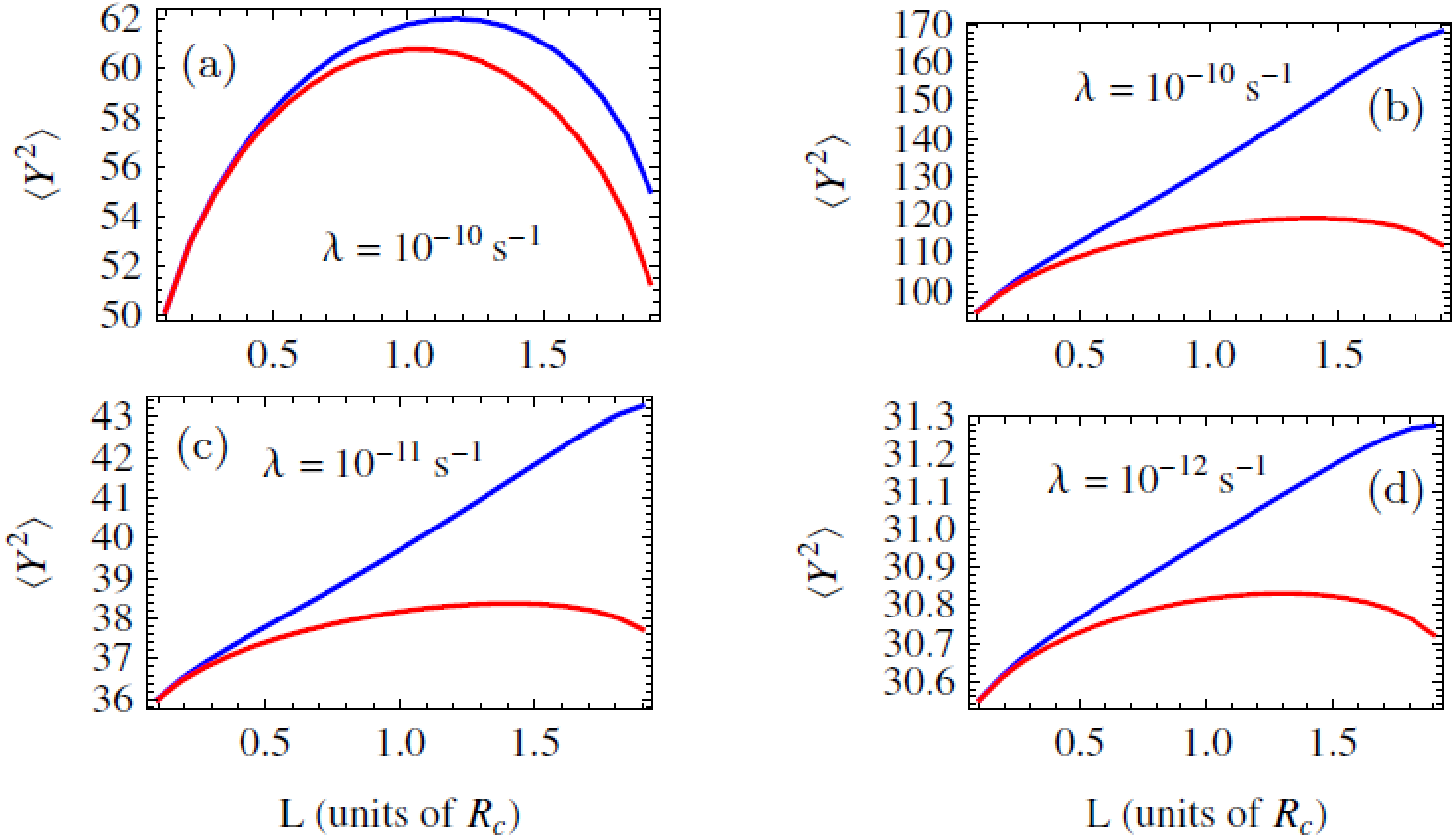
Confocal cavity

Concentric cavity

$D_t \propto 1/L$ $\quad D_c \propto \sqrt{2R_c/L-1}$

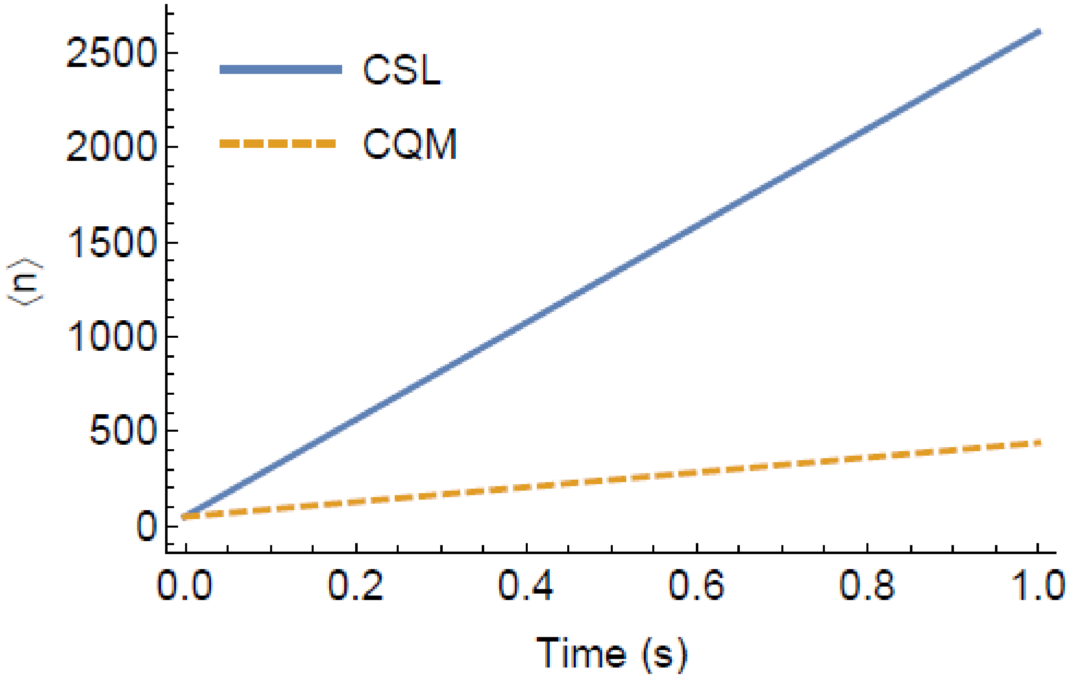
$D_a \propto L$ $\quad \lambda_{sph} \propto L$

Different **(positive/negative) slopes** of the curves for L > R_c



More difficult: **repeating the experiment with different cavity lengths and calibration of all the other values (at 2% level)**

Alternative approach: **turn off cooling laser field and detect the heating**: Under certain conditions, the heating should be detectably higher due to CSL

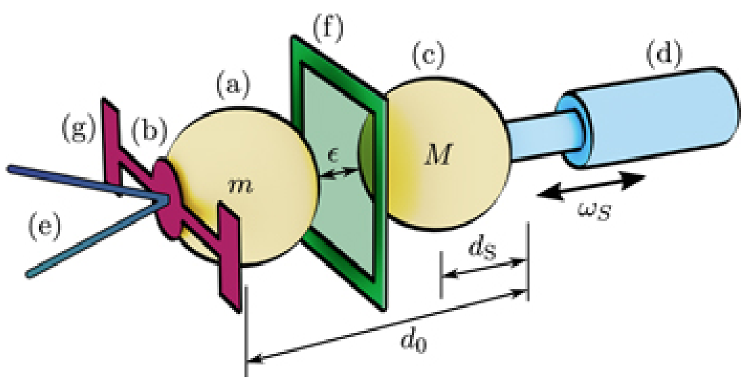


D. Goldwater, M. Paternostro, P. Barker, B. Goldwater et al., Phys. Rev. A **94**, 010104(R) (2016).

FURTHER PROMISING PLAYGROUND:

TESTING THE LARGELY UNKNOWN TERRITORY OF THE INTERPLAY BETWEEN GRAVITY AND QUANTUM MECHANICS

From the purely classical regime of Newton force…..



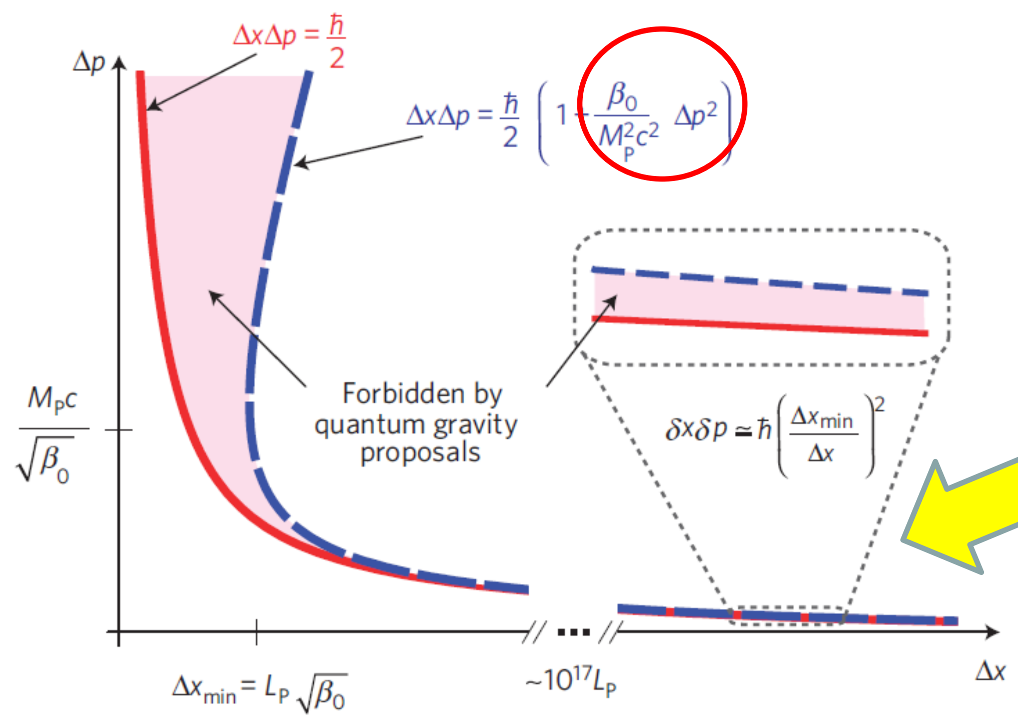
A micromechanical proof-of-principle experiment for **measuring the gravitational force of milligram masses**, J. Schmole et al, Class. Quant. Grav. 2016, Aspelmeyer group

….down to phenomenological quantum gravity theories…

Phenomenological quantum gravity

- One cannot determine a position with an accuracy better than the Planck length **$L_P = \sqrt{hG/c^3} = 1.6\ 10^{-35}$ m**
- Generalized Heisenberg uncertainty relations (GUP)
- Generalized commutators between *p* e *q*
- Modified quantum physics

Detecting signatures of Planck scale-physics in highly-sensitive metrological systems



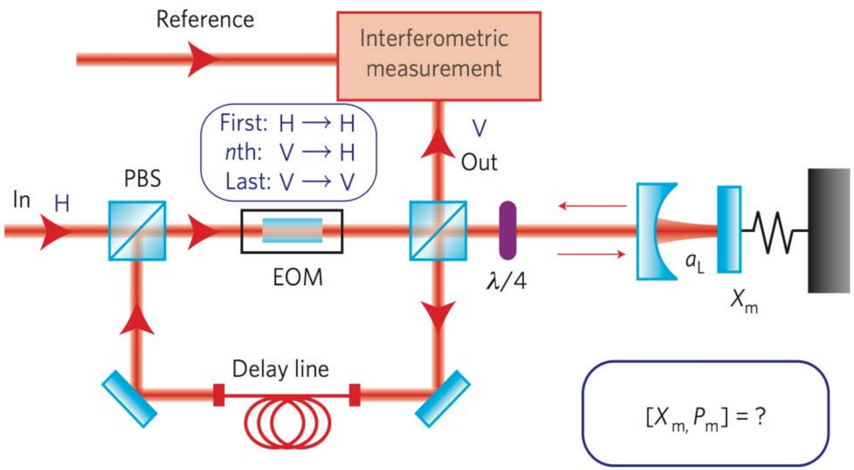
Pikovsky et al. Nat. Phys. 2012

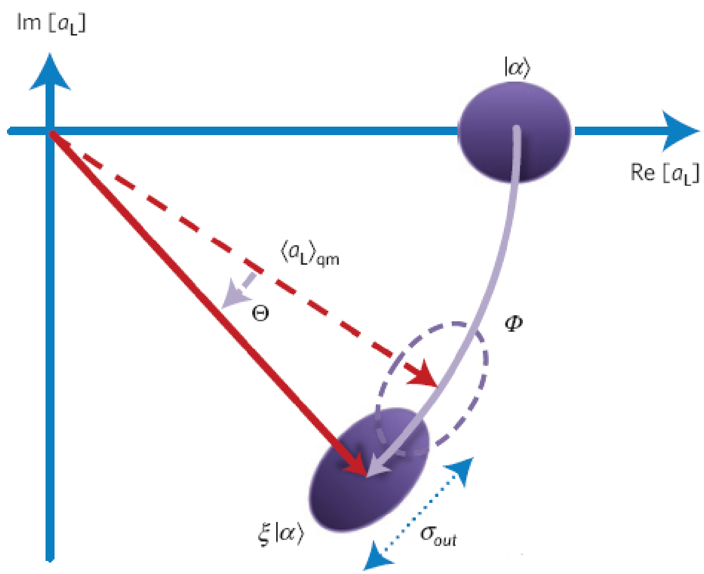
nature physics ARTICLES
PUBLISHED ONLINE: 18 MARCH 2012 | DOI: 10.1038/NPHYS2262

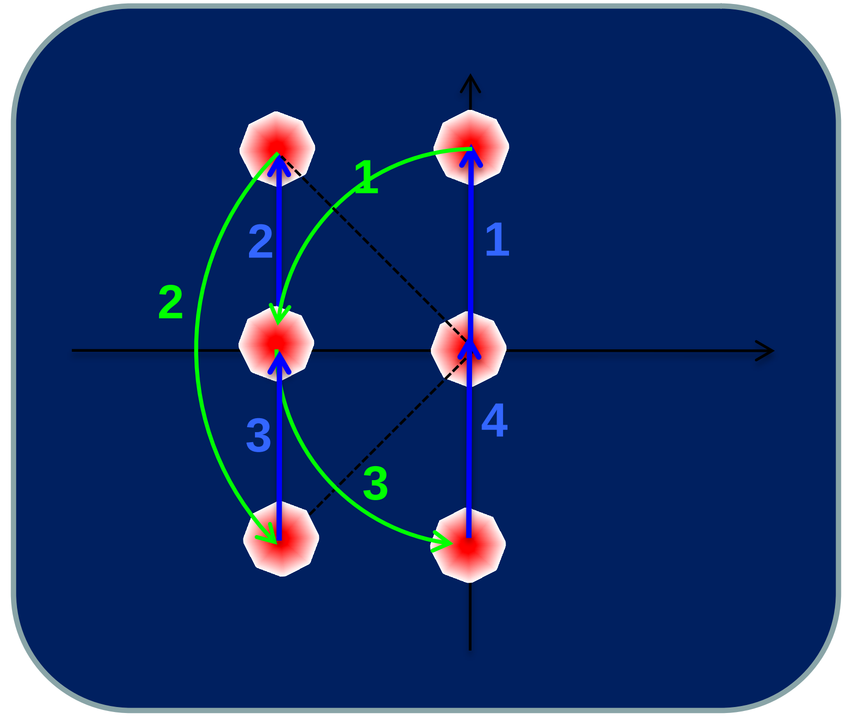
Probing Planck-scale physics with quantum optics

Igor Pikovski[1,2]*, Michael R. Vanner[1,2], Markus Aspelmeyer[1,2], M. S. Kim[3]* and Časlav Brukner[2,4]

Test of quantum gravity: **optical interferometric measurement of the q-p commutator modified by quantum gravity**







Involved four-pulse scheme

We followed a simpler approach: deformed commutator = effective nonlinear dynamics

$$\frac{\mathrm{d}\hat{O}}{\mathrm{d}t} = \frac{1}{i\hbar}[\hat{O}, H]$$

Heisenberg dynamics

$$[x, p] = i\hbar\left(1 + \beta_0\left(\frac{p}{M_p c}\right)^2\right)$$

Deformed commutation relations

$$\Delta x \Delta p \geq \frac{\hbar}{2}\left(1 + \beta_0\left(\frac{\Delta p}{M_p c}\right)^2\right)$$

$$H = \frac{\hbar\omega_0}{2}\left(X^2 + P^2\right)$$

Solution for an harmonic oscillator:

$$\beta = \beta_0 \frac{\hbar m \omega_0}{M_p^2 c^2}$$

$$X = X_0\left[\sin(\tilde{\omega}t) + \frac{\beta}{8} X_0^2 \sin(3\,\tilde{\omega}t)\right]$$

$$\tilde{\omega} = \left(1 + \frac{\beta}{2} X_0^2\right)\omega_0$$

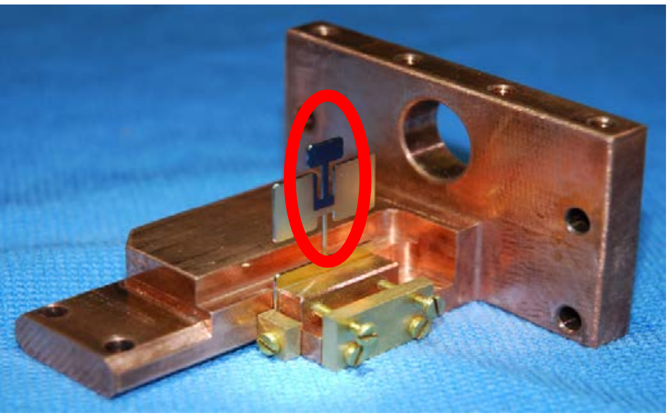
(First order in βX_0^2)

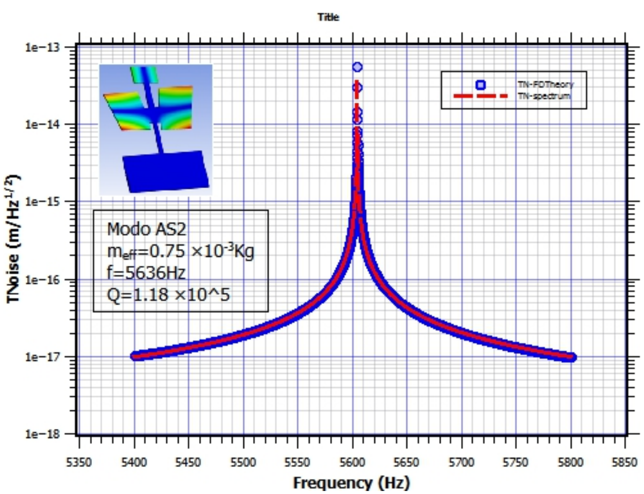
3° harmonic

Freq. shift

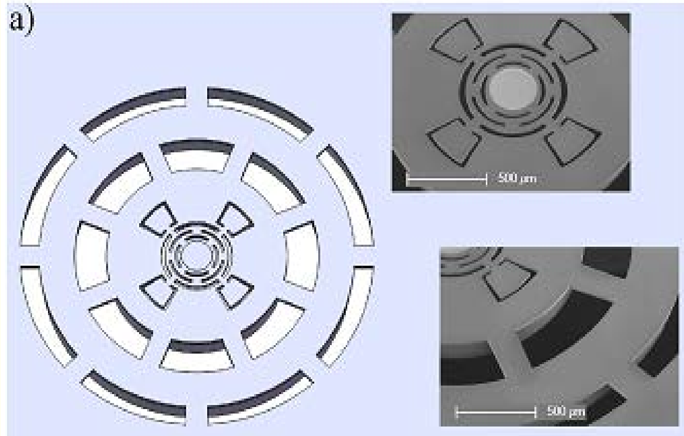
Experimental upper bounds on β

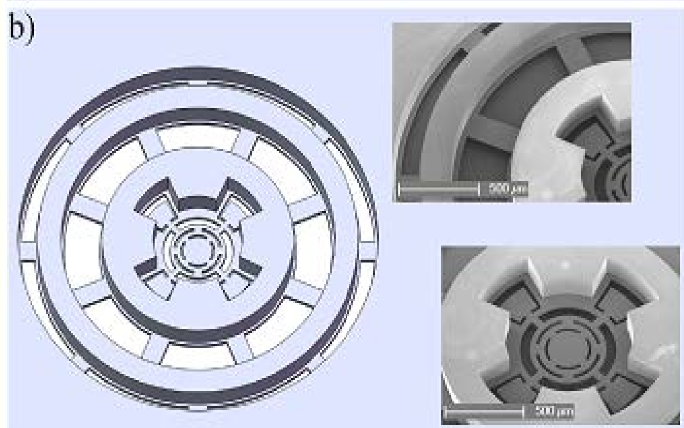
1° oscillator: $m \cong 1$ g





2° oscillator: $m \cong 100\ \mu g$





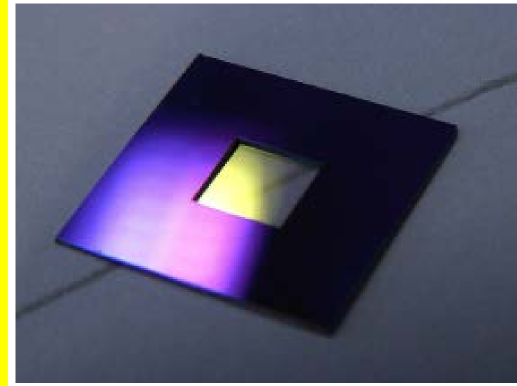
$m = 20\ \mu g$

$f_m = 141$ KHz

$Q = 1.2 \times 10^6$

$T = 4.3$ K

3° oscillator: $m \cong 100$ ng

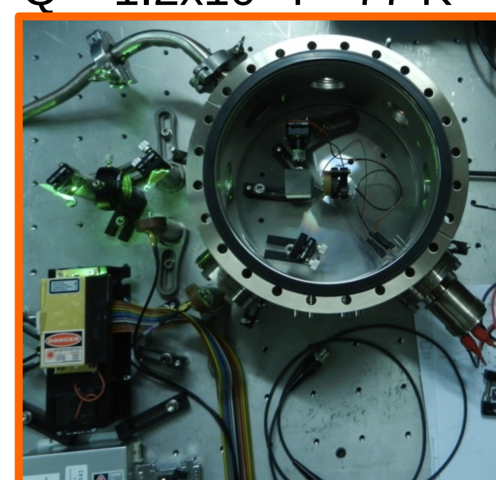


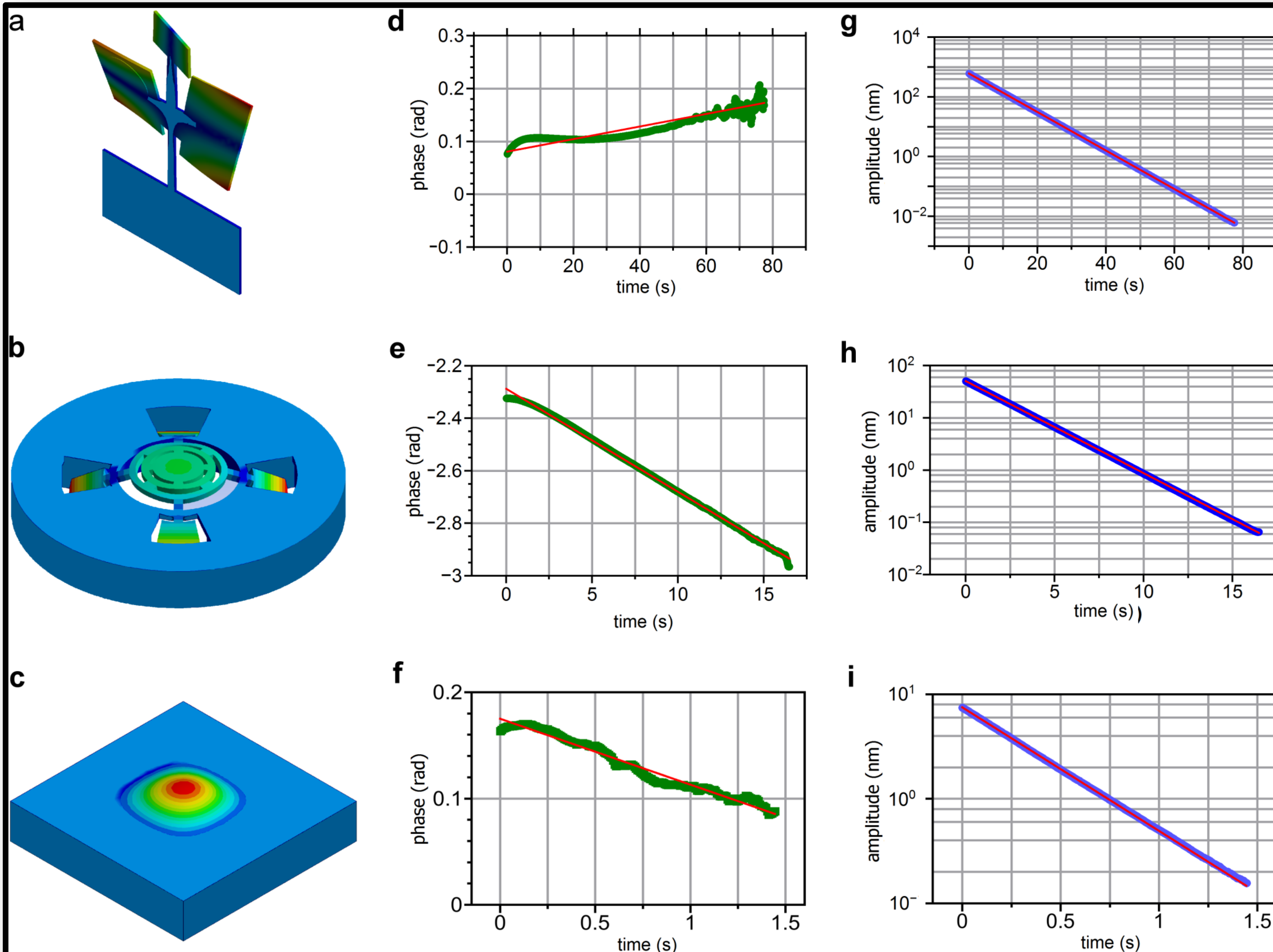
SiN membrane

$0.5 \times 0.5\ mm^2 \times 50 nm$

mass = 135 ng

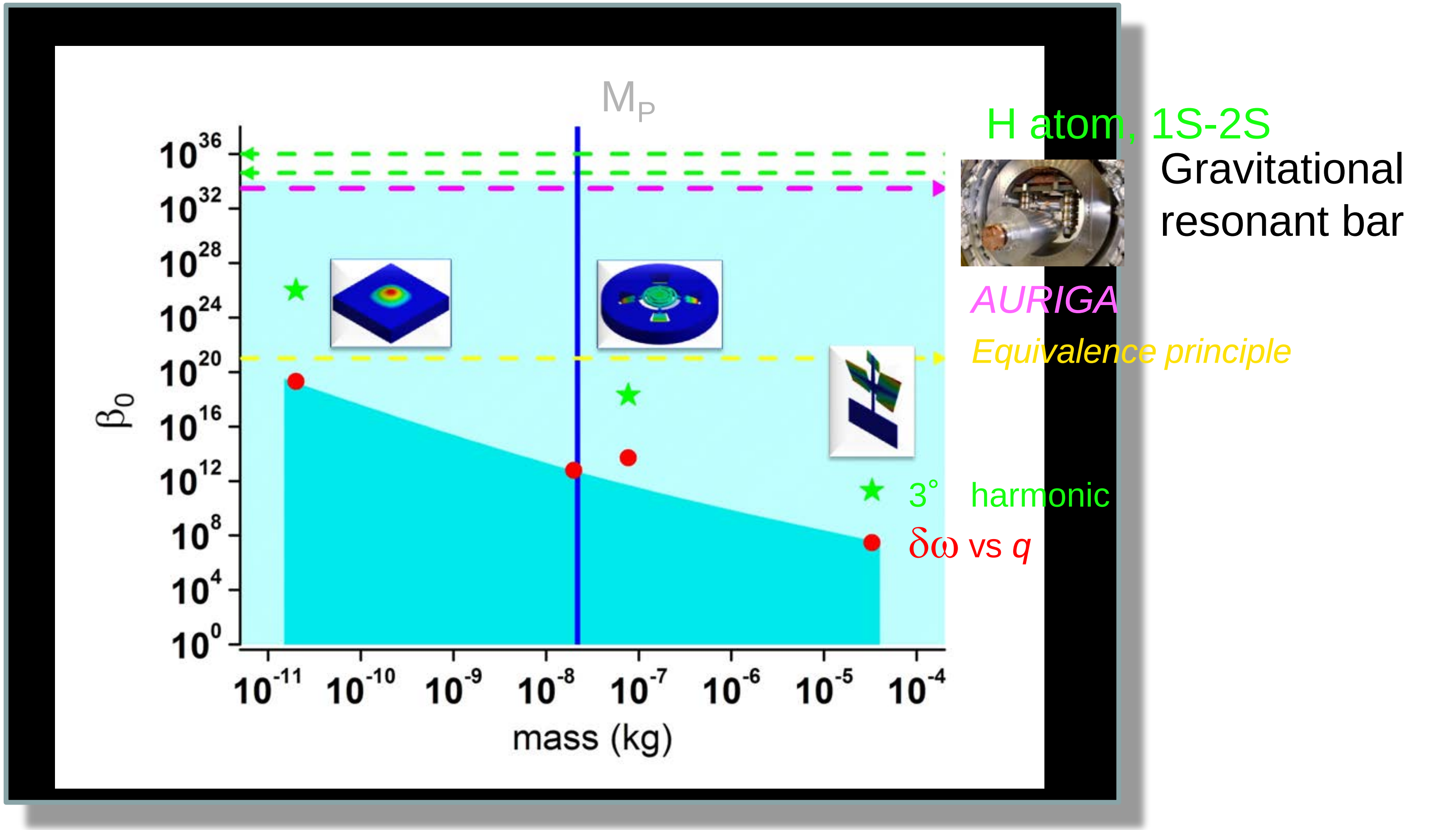
$Q = 1.2 \times 10^6$ T= 77 K





a
b
c
d
phase (rad)
time (s)
e
phase (rad)
time (s)
f
phase (rad)
time (s)
g
amplitude (nm)
time (s)
h
amplitude (nm)
time (s)
i
amplitude (nm)
time (s)

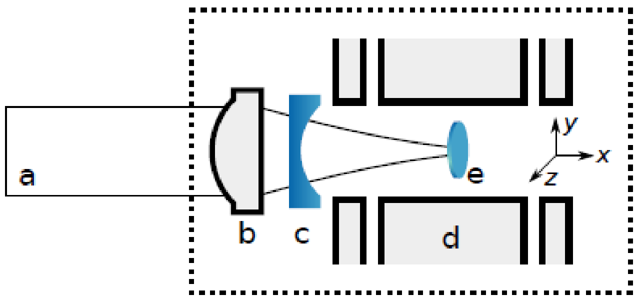
We substantially lower existing bounds on deformation parameter β

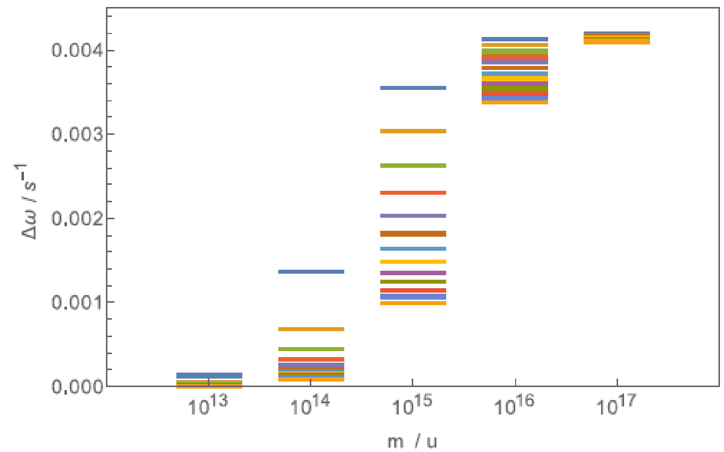


M. Bawaj, et al., Nat. Commun. 6, 7503 (2015).

Camerino-Firenze-Trento INFN Collaboration

Optomechanical systems have been proposed also for testing the Schrodinger-Newton equation:

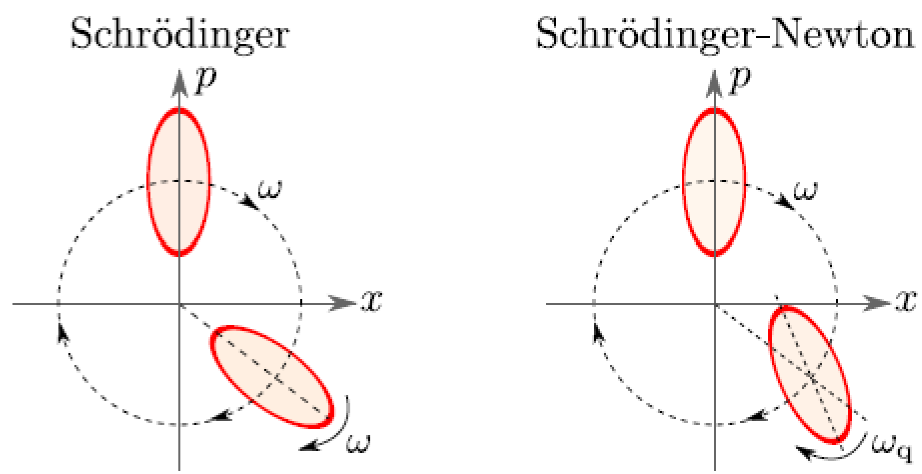




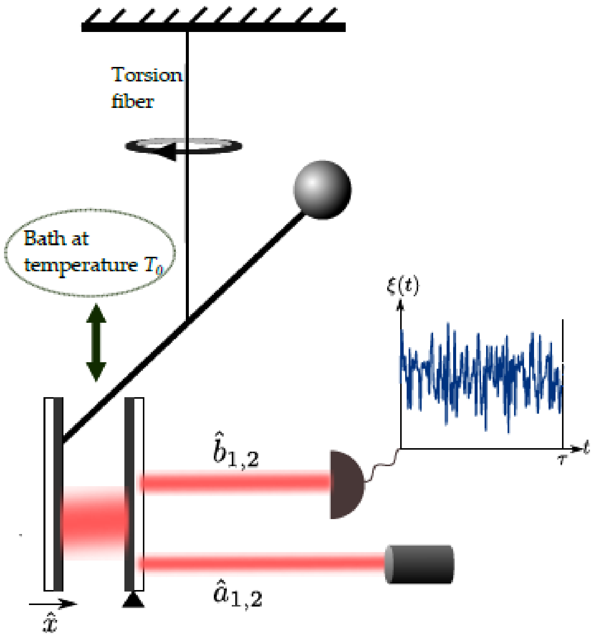
Measurement of the frequency spectrum of a levitated mirror (Grossardt et al., PRD 2016)

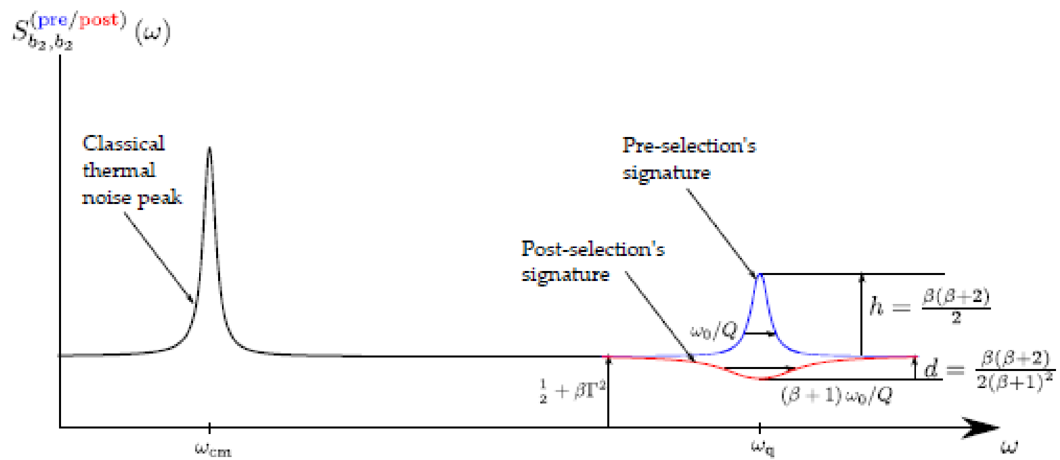
For a harmonically trapped mass, SN equation yields a very small frequency shift < 1 Hz

$$\Delta\omega = \omega_g - \omega_0 = \sqrt{\omega_0^2 + \omega_{\rm SN}^2} - \omega_0 \simeq \frac{\omega_{\rm SN}^2}{2\omega_0}.$$



Proposal with an **optically detected low-freq torsion pendulum**





Possible to be detected with spectral noise measurements

B. Helou et al., arXiv:1612.06310v1