Quantum Optomechanics, Quantum Sensing, and Quantum Information in UNICAM

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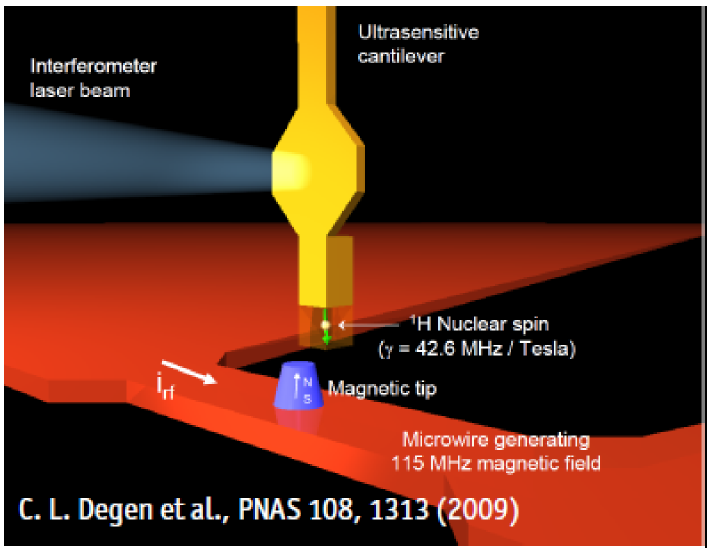
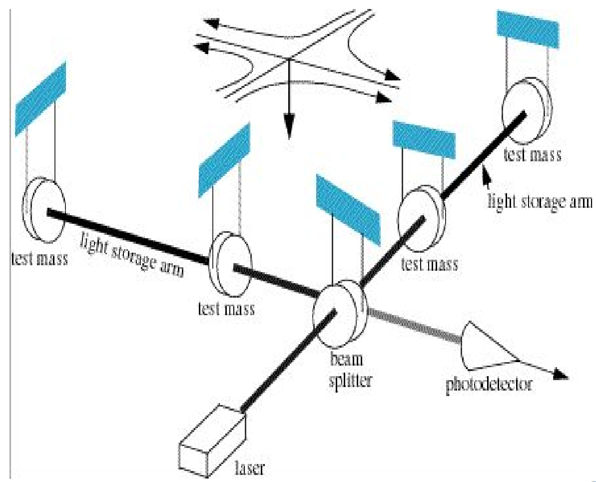
+ Stefano Mancini's group on Quantum and Geometrical aspects of Information

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



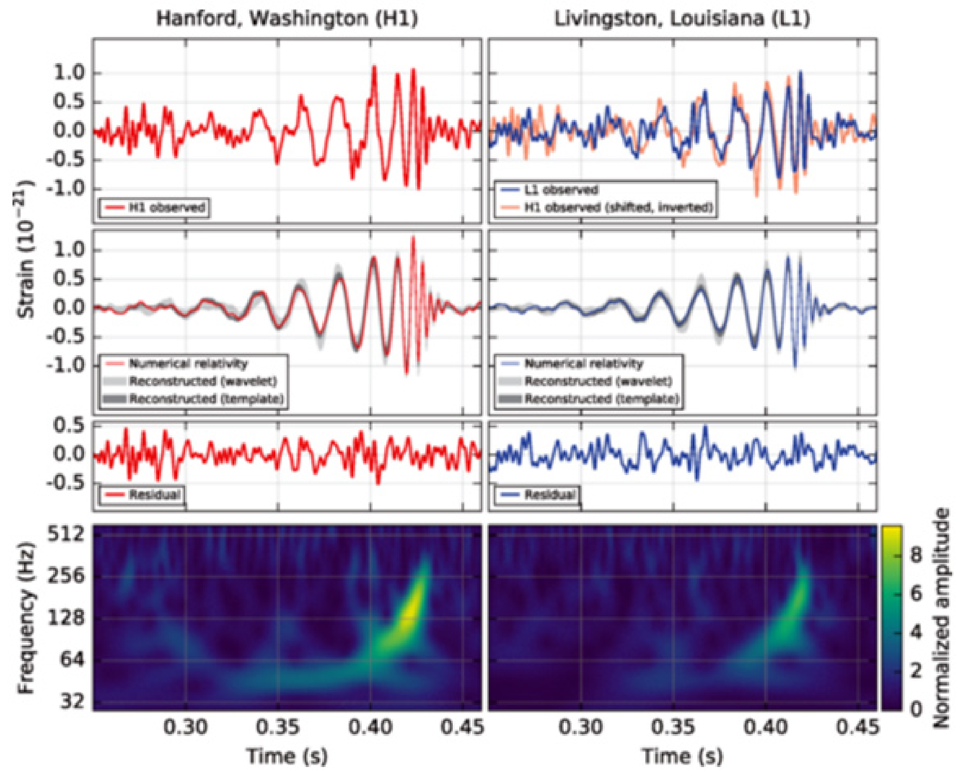


VIRGO

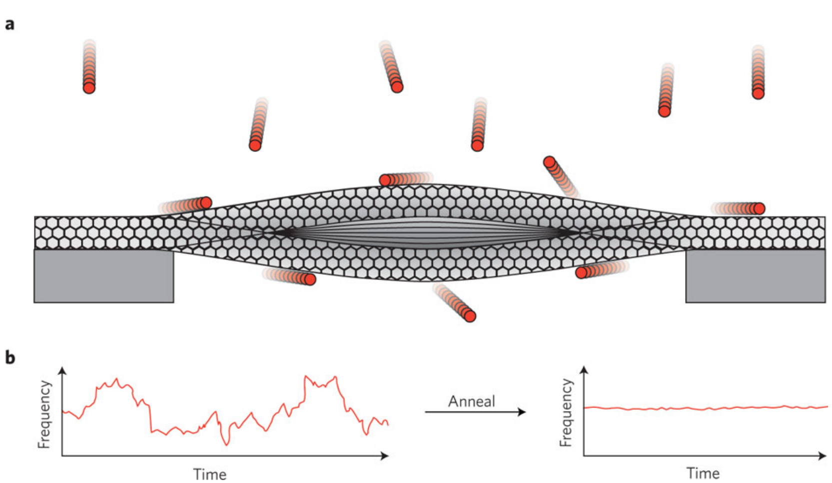
Nano-scale: **Single-spin MRFM**
D. Rugar group, IBM Almaden

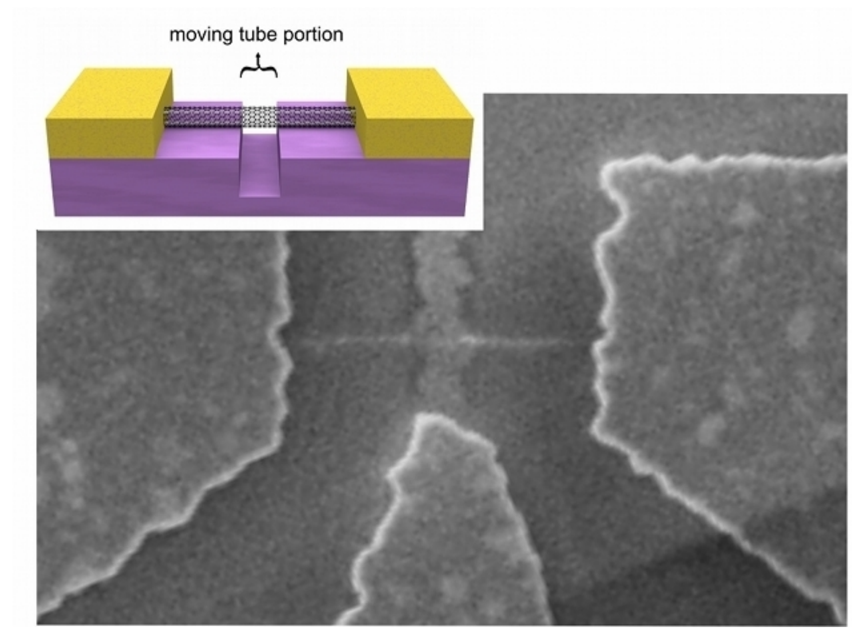
Macro-scale: **gravitational wave interferometers** (VIRGO, LIGO) limited by quantum noise of light in some bandwidth

⇒ **High-sensitive detection of** **displacements and forces (LIGO-VIRGO)**



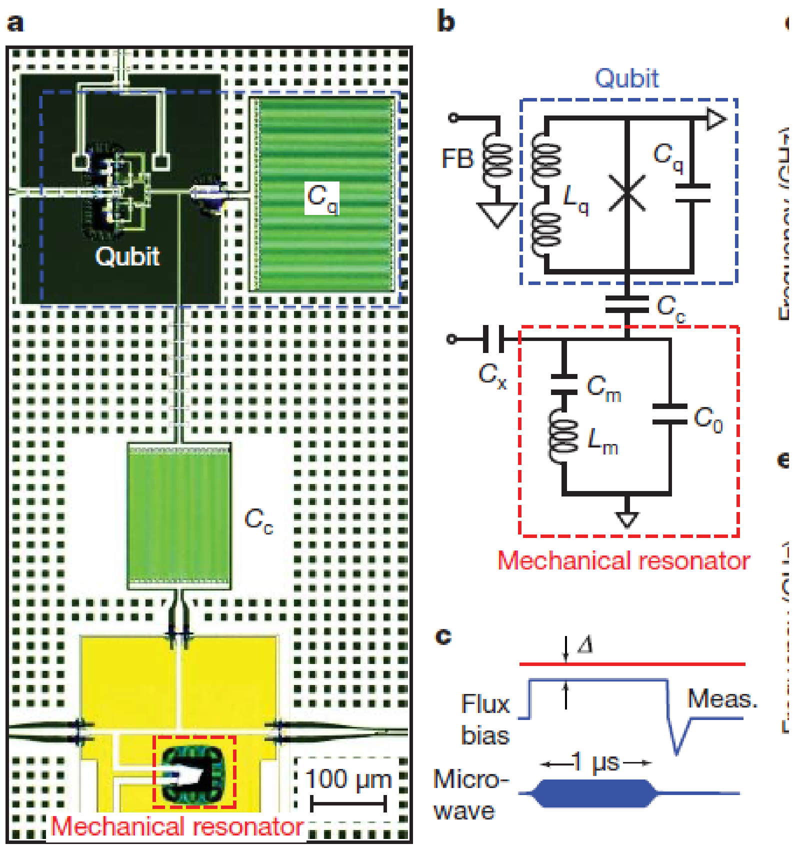
Proton-mass resolution mass sensing with carbon nanotubes (Bachtold group, ICFO)

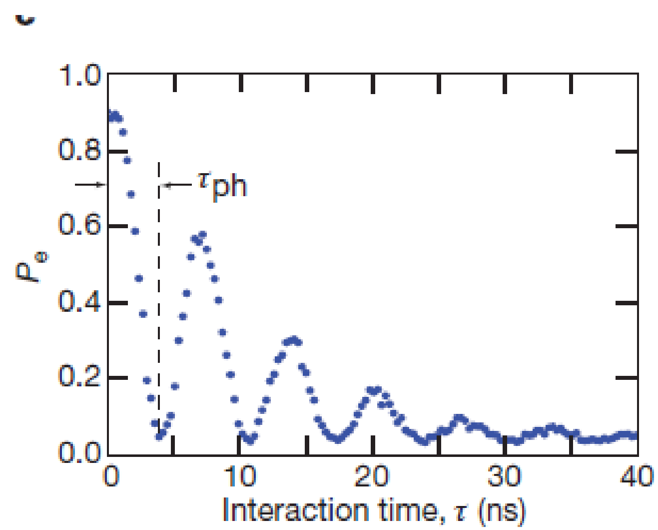




NANO-OPTOMECHANICAL AND ELECTROMECHANICAL SYSTEMS HAVE ALREADY REACHED THE QUANTUM REGIME

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

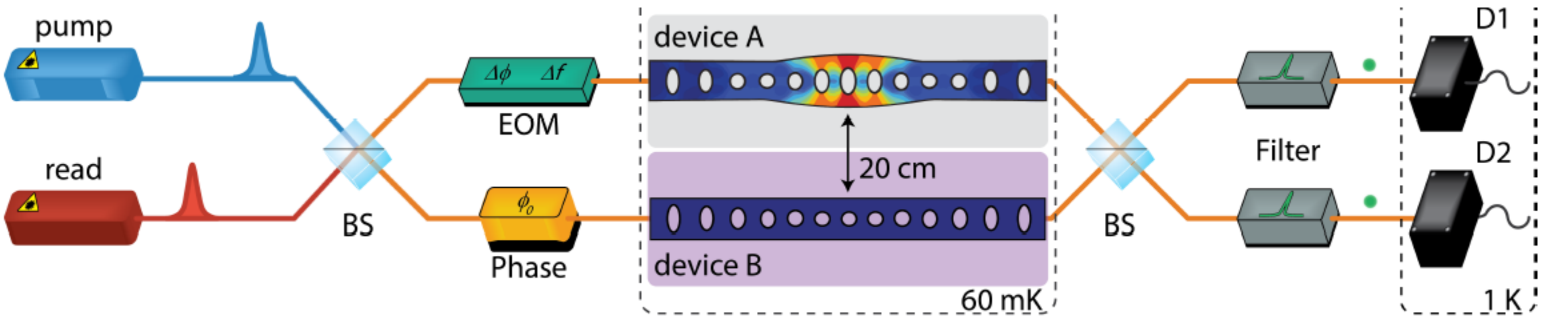


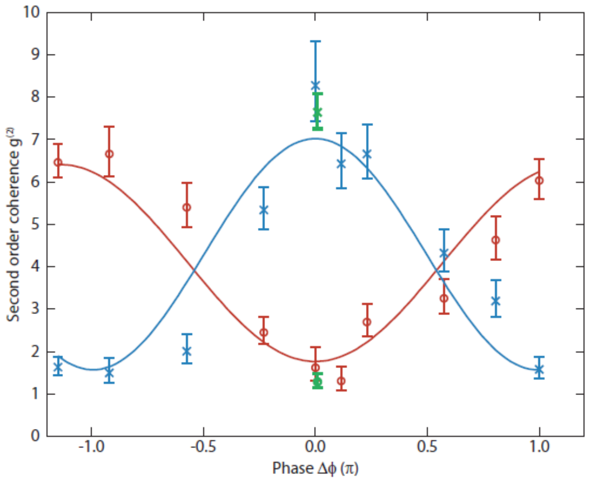


$$|\Psi\rangle = \frac{1}{\sqrt{2}}\left(|1\rangle_{\mathrm{A}}|0\rangle_{\mathrm{B}} \pm e^{i\theta_{\mathrm{m}}(0)}|0\rangle_{\mathrm{A}}|1\rangle_{\mathrm{B}}\right),$$

Remote single-phonon quantum entanglement between two micromechanical oscillators

R. Riedinger e al., Nature 2018, Delft & Vienna

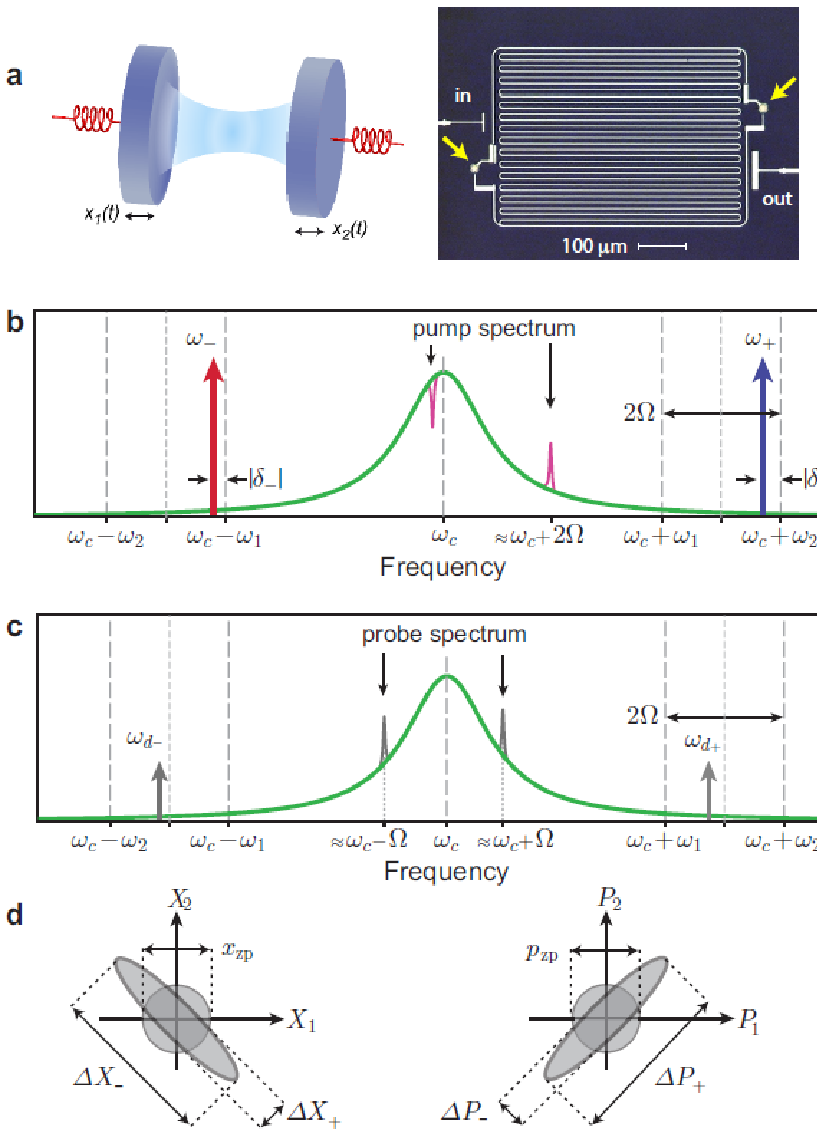




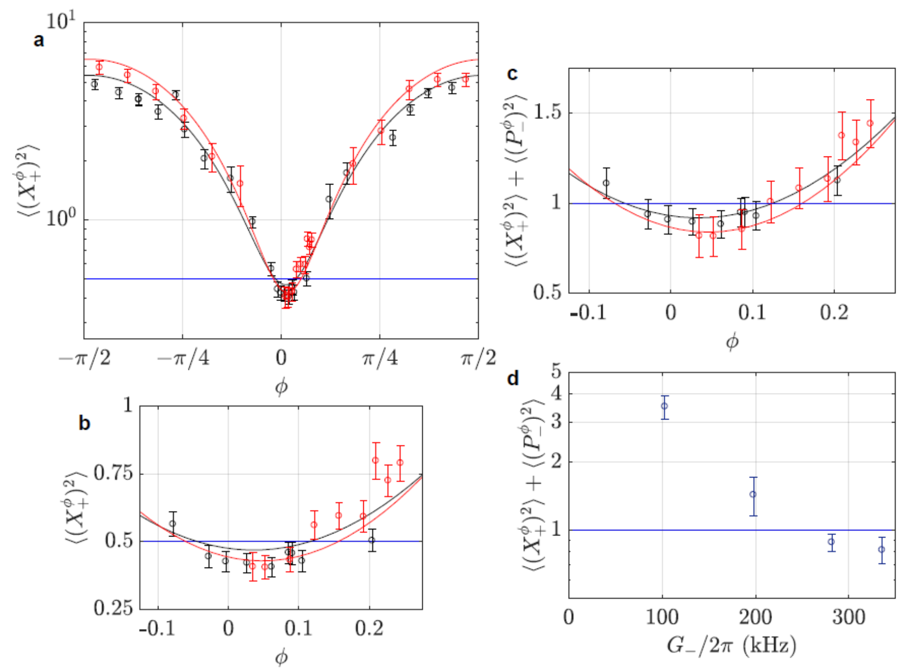
Using read & write pulses, as with atomic ensembles

Pros: integrable device
Cons: dilution fridge T

CONTINUOUS VARIABLE ENTANGLEMENT BETWEEN TWO MECHANICAL RESONATORS



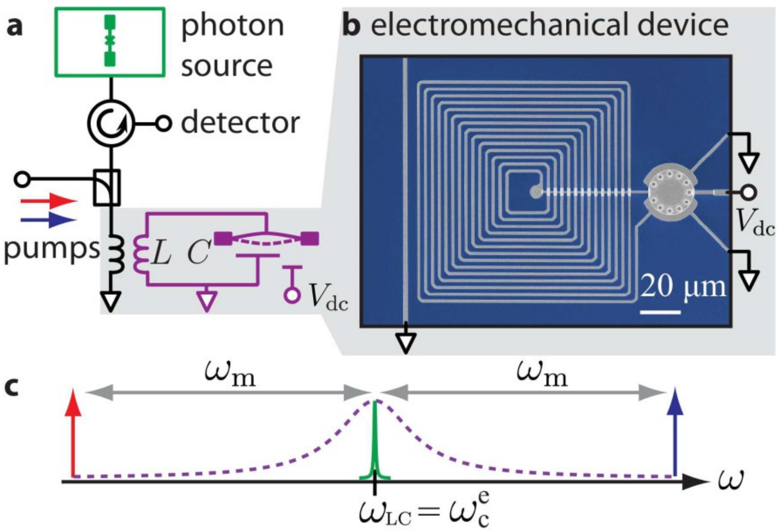
C.F. Ockeloen-Korppi et al.,
Nature 2018 (Aalto)



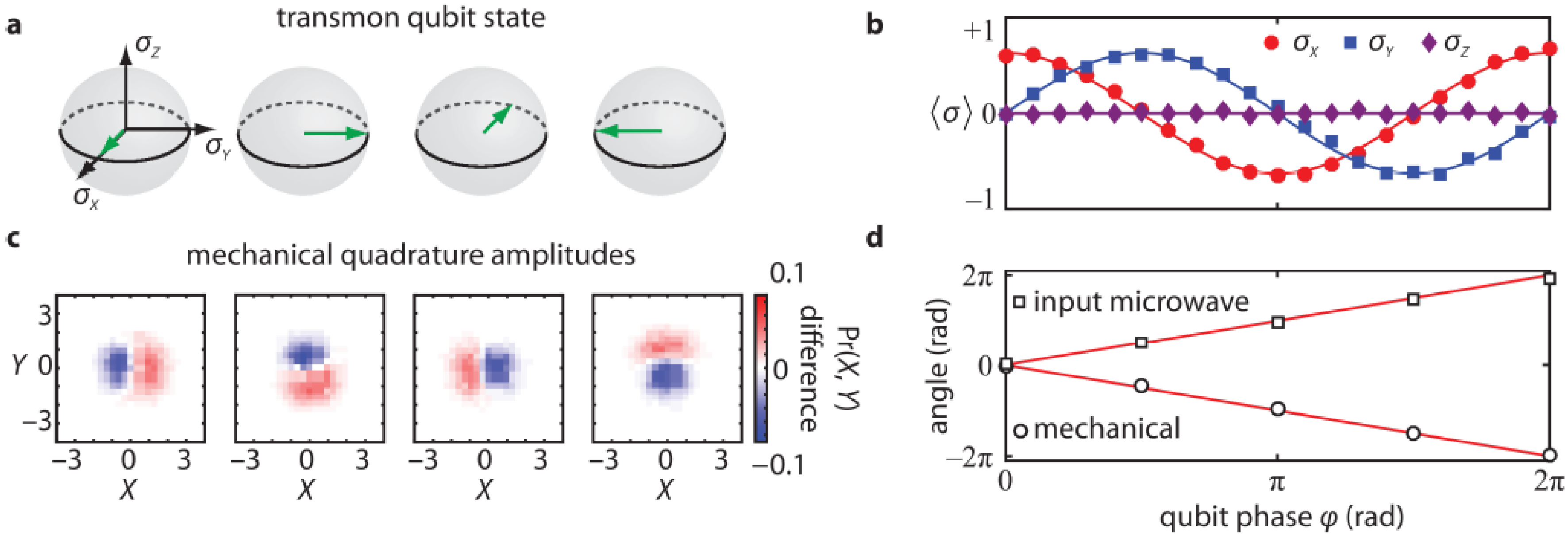
$$\langle X_+^2 \rangle + \langle P_-^2 \rangle < 1,$$

EPR-like entanglement criterion satisfied

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)



However all these quantum manifestations have been realised in cryogenic environments (< 10 K)

The key condition to achieve quantum behavior is to have a LARGE OPTOMECHANICAL COOPERATIVITY C (similar to that in cavity QED)

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

Linearized optomechanical coupling $\mathbf{G = g_0\, n_{ph}}$

κ_T = cavity decay rate

γ_m = mechanical damping rate

n_{ph} = intracavity photon number

single-photon optomechanical coupling

$$g_0 = \frac{d\omega_c}{dx} x_{zpf} \qquad x_{zpf} = \sqrt{\frac{\hbar}{2m\omega_m}}$$

The key condition is

$$C > \bar{n}_{th} \approx \frac{k_B T}{\hbar\omega_m}$$

= mean thermal phonon number

Typically achieved by going at low temperatures

A practically useful quantum sensor should operate at room T

We need optomechanical devices with very large single photon cooperativities

$$C_0 = \frac{g_0^2}{\kappa \gamma_m} >> 1$$

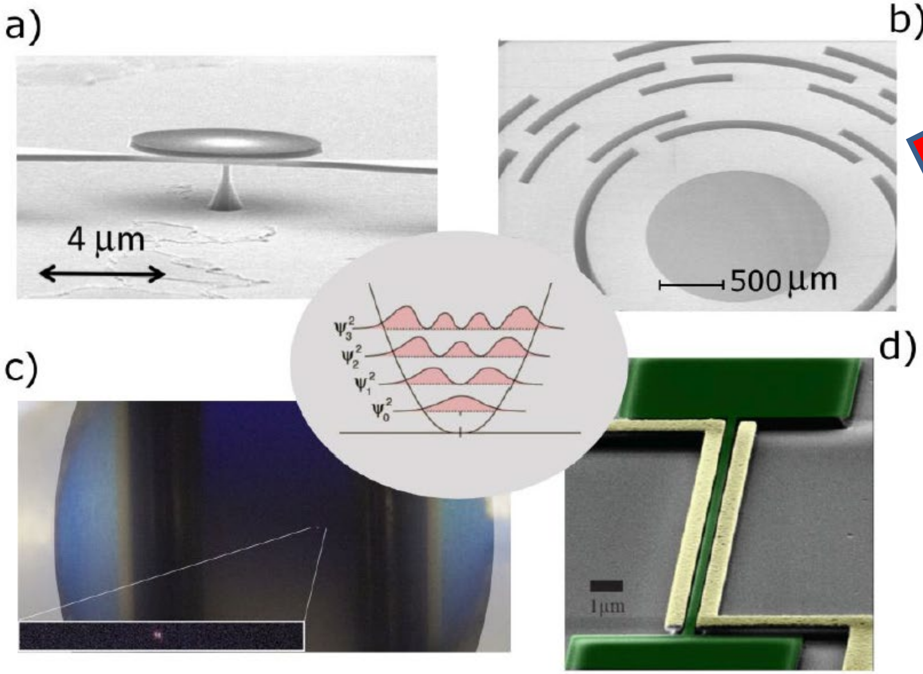
(it could be useful to avoid too large intracavity photon number n_{ph}, for possible absorption, photorefractive effects,…)

We are investigating this route in the Quantera project QUASERT (Optomechanical quantum sensors at room T)

300K

QuaSeRT

Chosen optomechanical platforms

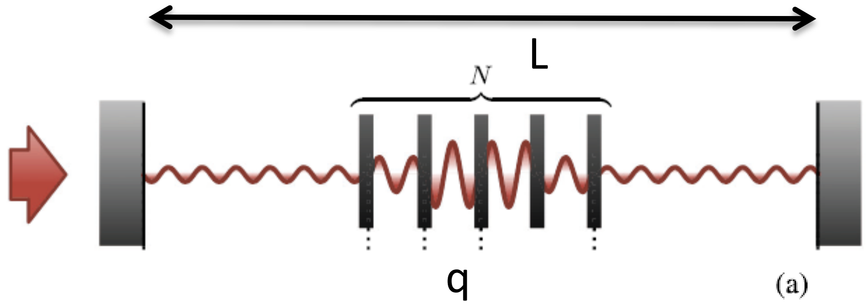


Our SiN membrane resonator

Fig. 1. a) GaAs waveguide/disk integrated optomechanical device [25]. b) High-stress silicon nitride membrane (100 nm thick) with on-chip mechanical filtering system [16]. c) Silica nanoparticle trapped in an optical cavity [21]. d) High-stress silicon nitride nanobeam with electrodes used to polarize and resonantly excite the beam [28-30].

•At UNICAM (in collaboration with CNR-INO and Delft) we will develop a **two-membrane setup, able to increase by orders of magnitude g_0.**

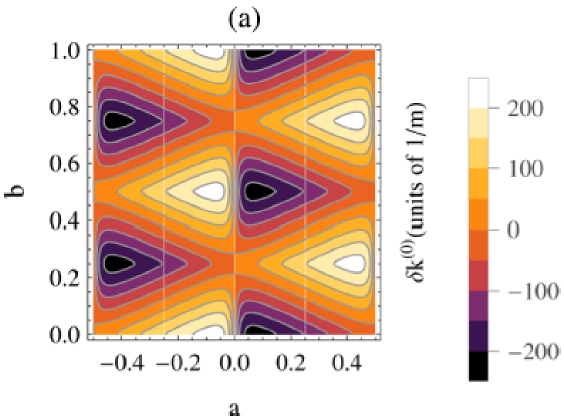
• In fact we showed that **due to optical interference, a two membrane system in a cavity can achieve the strong coupling condition $g_0/\kappa > 1$**

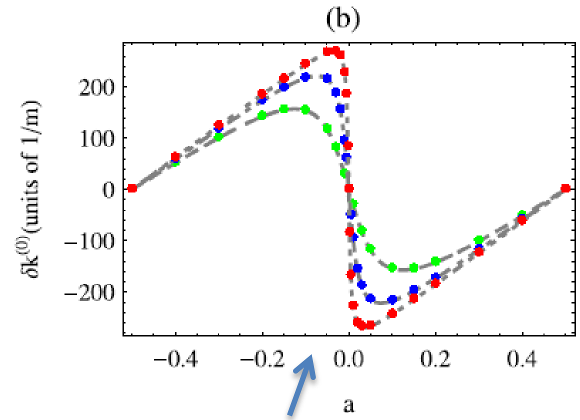


First proposal, with many membranes, by A. Xuereb et al,, PRL 109, 223601 (2012)

$$\frac{(g_0/\kappa)_{double}}{(g_0/\kappa)_{single}} = \frac{L}{2q} >> 1$$

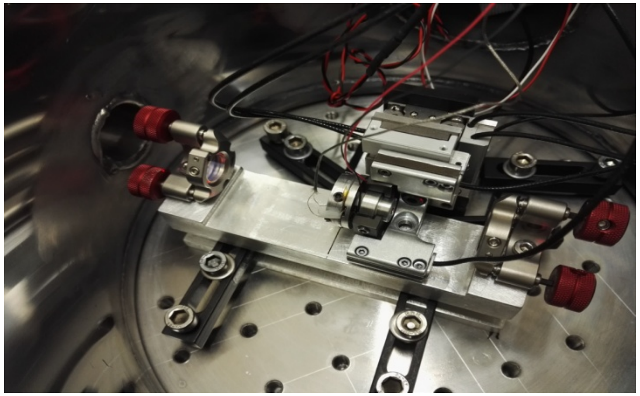
In the R ->1 limit

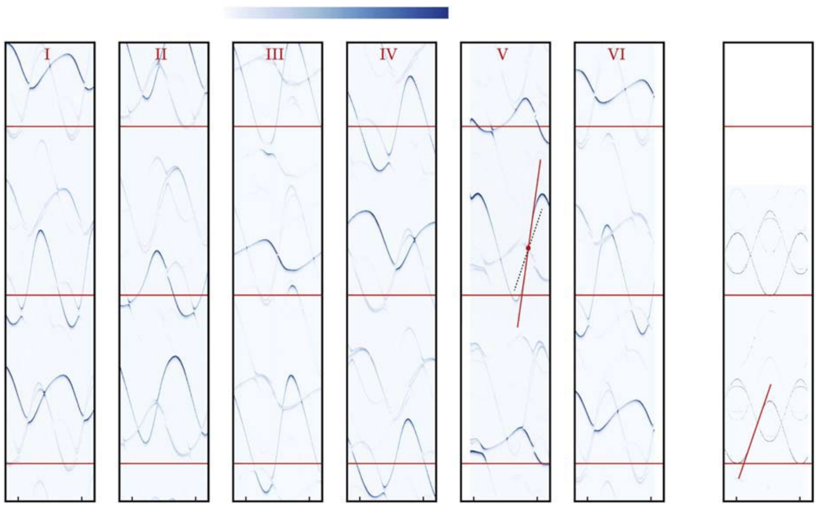




Large dω/dx

We provided the first exp. demonstration in P. Piergentili et al., 2018, New J. Phys. 20 083024.

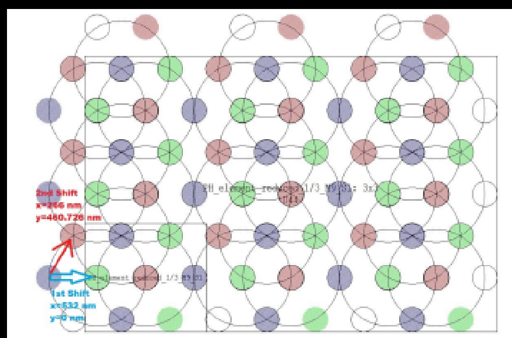




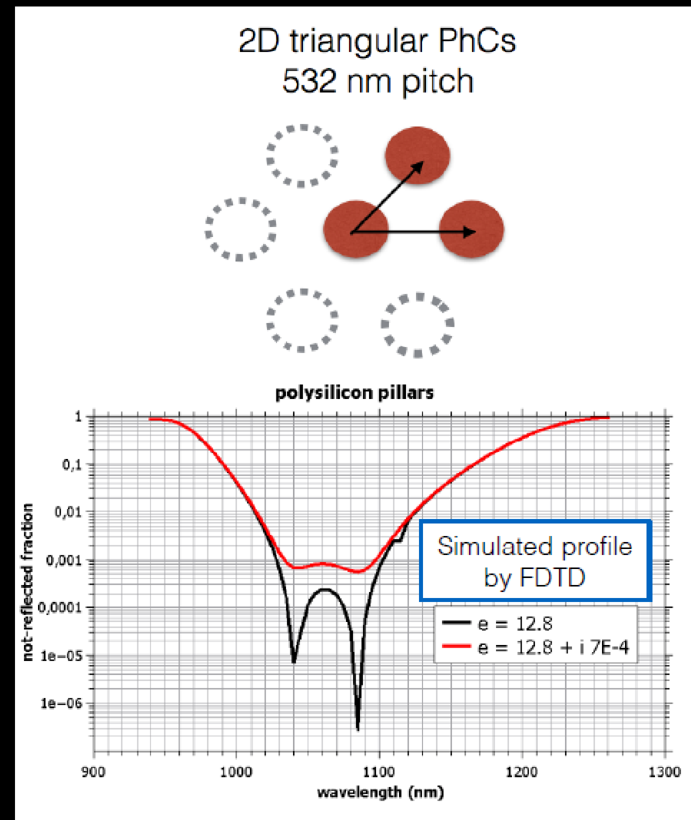
Developing META-REFLECTORS on a SiN membrane

All-dielectric meta-materials based on **Lorentz-MIE resonances** for increasing the optomechanical interaction (99.9% reflectivity).

Pushing the limit of i-line stepper
Critical Dimension is 260 nm



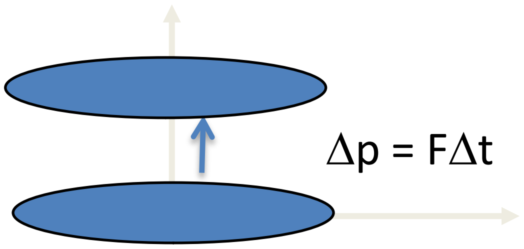
Top-down approach based on optical lithography Multiple patterning based on 3 exposures **and 2 accurate displacements of the wafer stage.**



E. Serra, M. Bonaldi, FBK, CNR-Trento

Which kind of protocols for quantum sensing we aim at ?

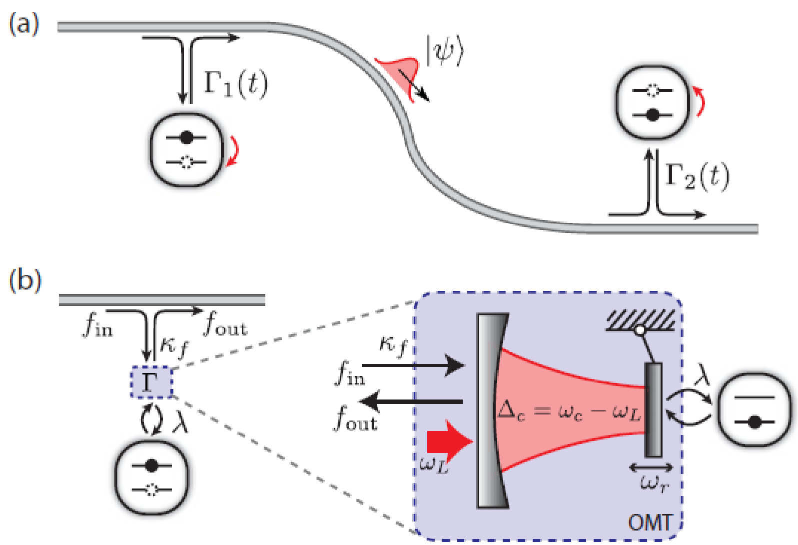
1. **Optimal quantum force sensing with a mechanical resonator in a squeezed state (it maximizes the Fisher information for estimating a classical force** (C.L. Latune et al, PRA 88, 042112 (2013))



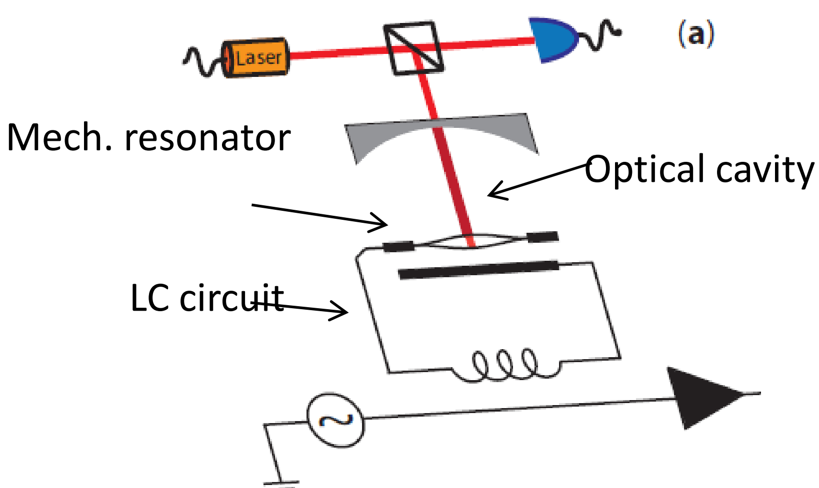
2. Measurement of **cross-phase-amplitude correlations in optomechanical systems** due to radiation pressure and visible even at room temperature (T. Purdy et al, *Science* Vol. 356, pp. 1265-1268 (2017), V. Sudhir et al., Phys. Rev. X **7**, 031055 (2017).

2. NANOMECHANICAL RESONATORS AS QUANTUM TRANSDUCERS

light-matter interfaces and <u>transducers</u> for quantum computing architectures, or long-distance quantum communication

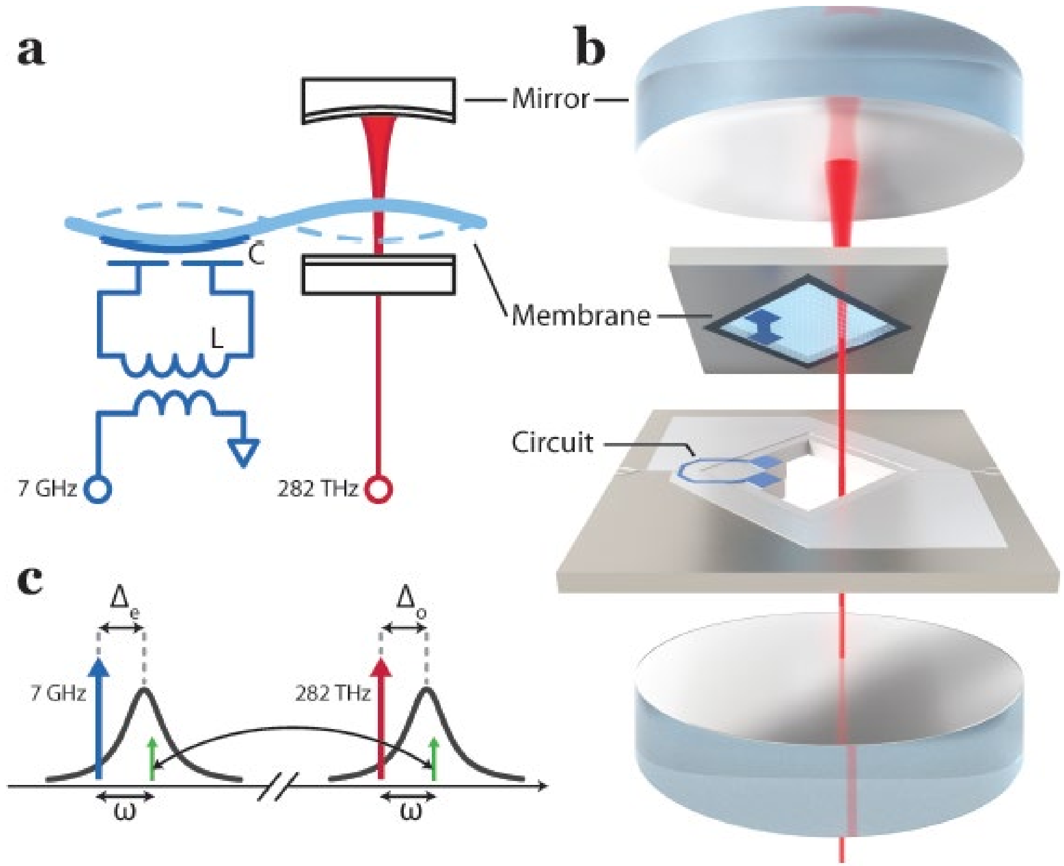


a) optimal solid state/superconducting qubits – optical photon transducer (Stannigel et al. 2012)



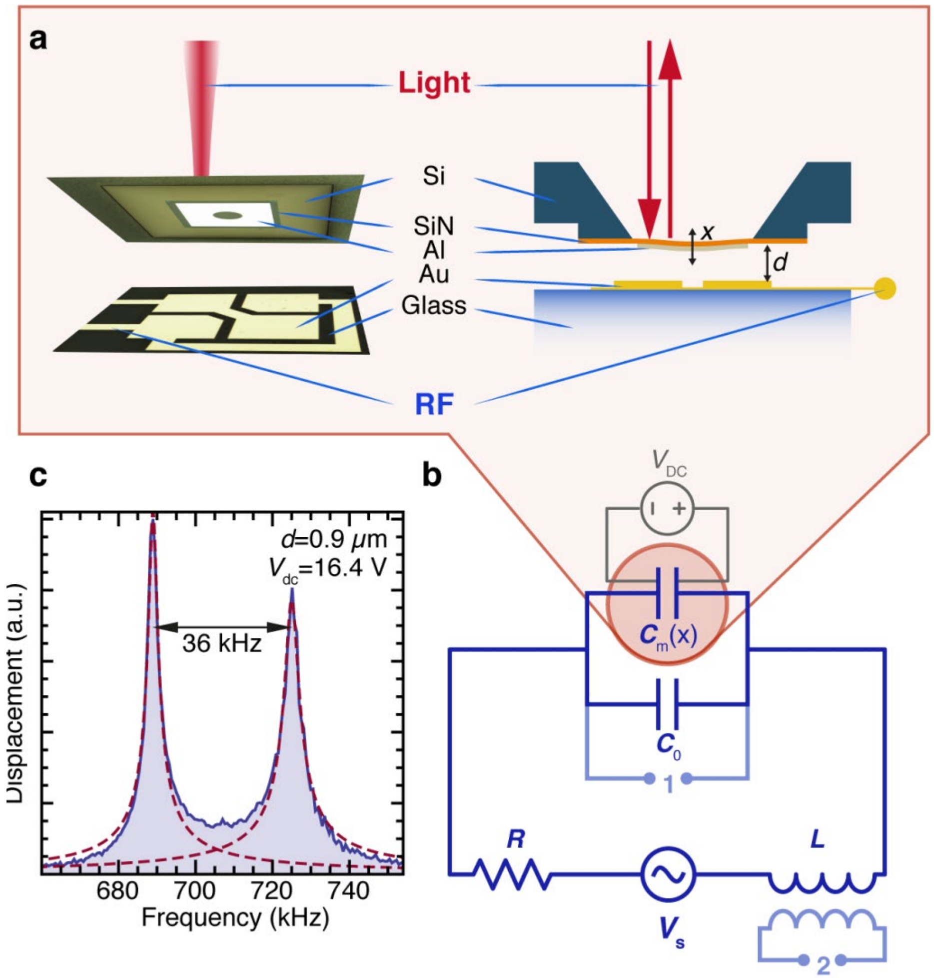
b) Microwave-to-optical nanomechanical transduction based on a **nanomechanical resonator in a superconducting circuit, simultaneously interacting with the two fields (Barzanjeh et al, 2012)**

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



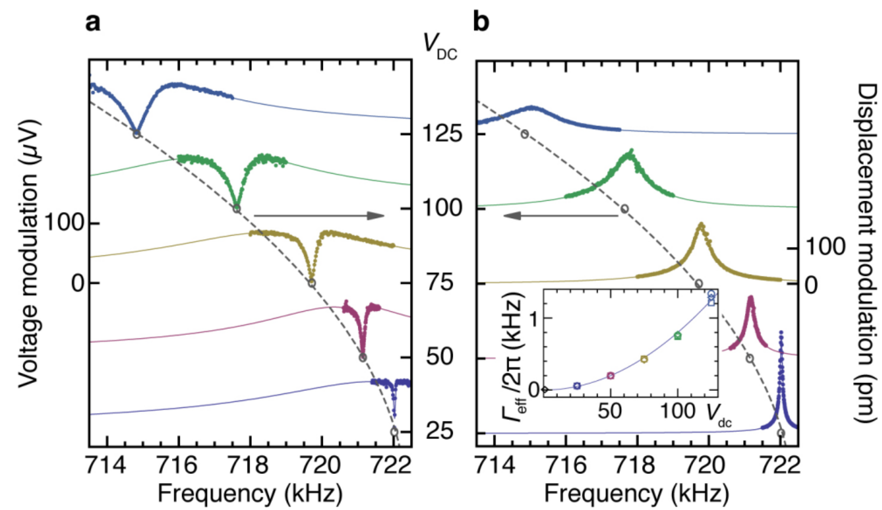
Adding an LC circuit to the membrane-in-the-middle setup, Andrews et al., Nat. Phys. 2014 (Lehnert-Regal group)

OPTICAL READOUT OF RADIOWAVES

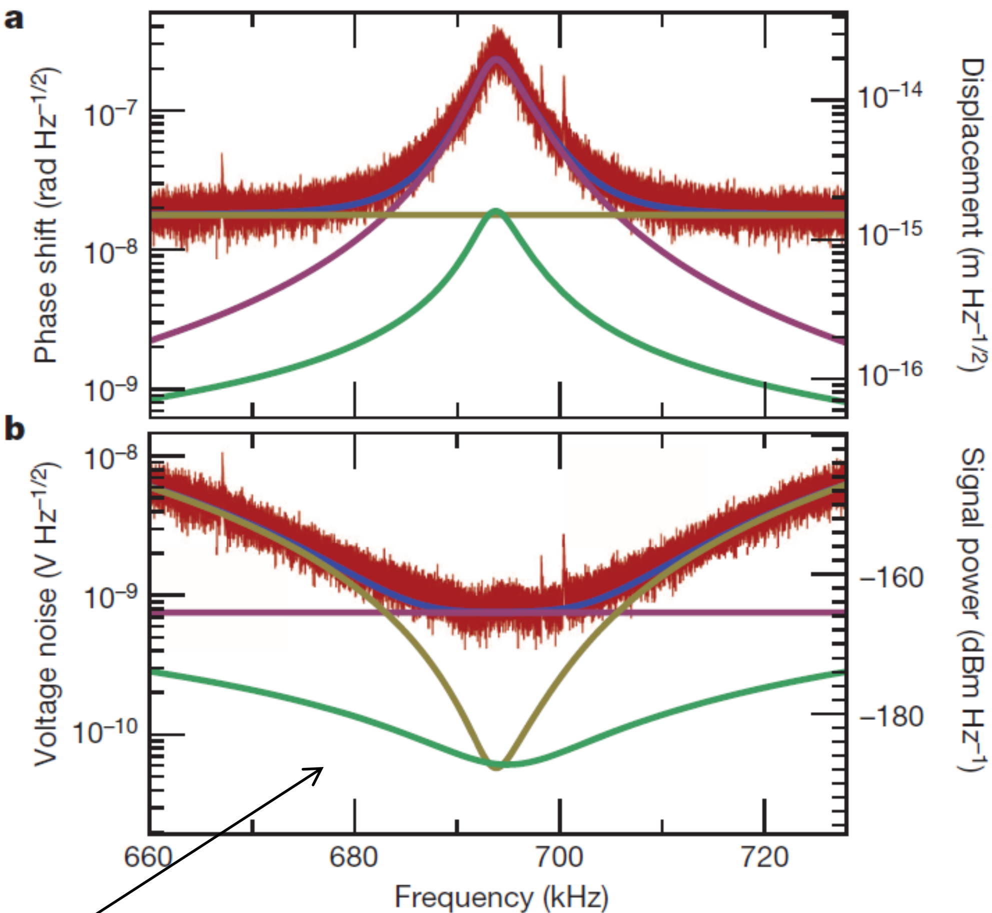


Bagci et al., Nature 507, 81–85 (2014)

Resonant interaction between RF circuit and membrane resonator



Output spectrum



Recalibrated as voltage noise detector

High-sensitive optical detection of an rf signal: sensitivity =

800 pV/√Hz , 60 pV/√Hz achievable

Transduction bandwidth determined by the effective resonance width of the nanomechanical membrane transducer (broadened by strong electromechanical cooling

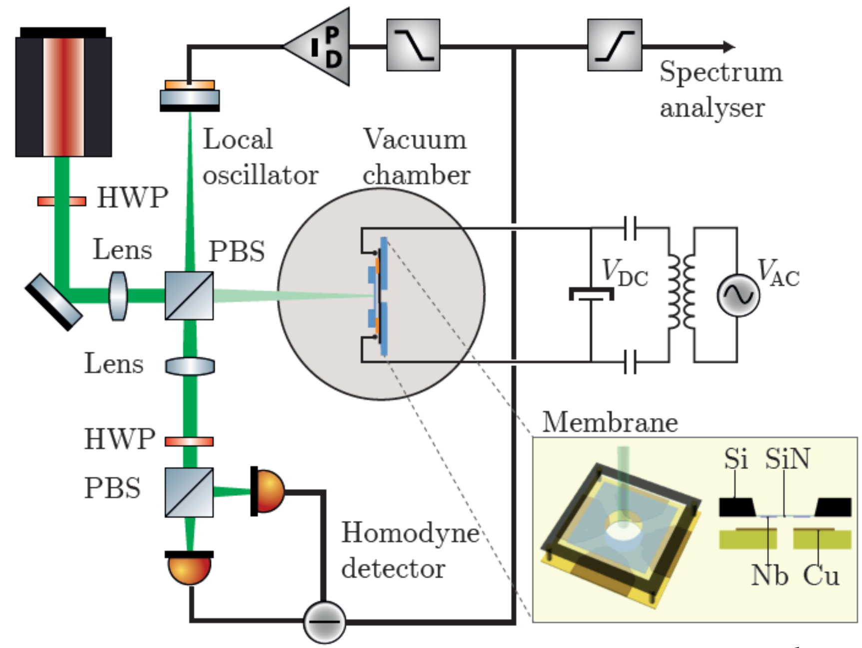
Bagci et al., Nature 507, 81–85 (2014)

OUR MEMBRANE-OPTICAL-TO-RADIOFREQUENCY CONVERTER

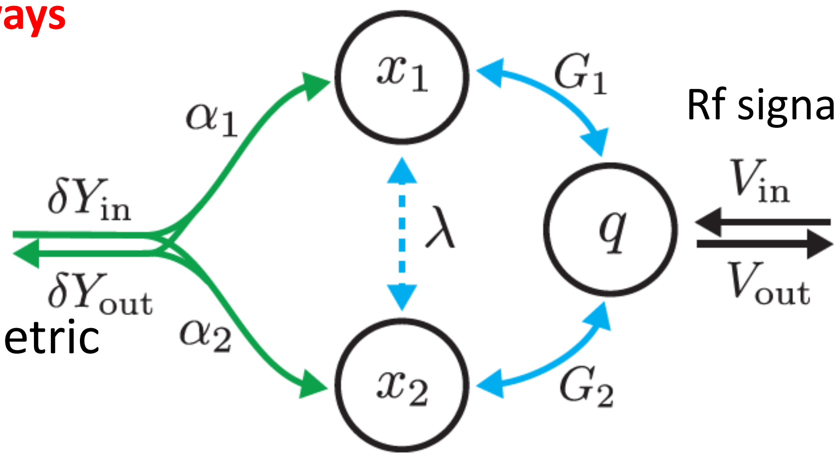
HOW TO INCREASE AND SCALE-UP BANDWIDTH ?

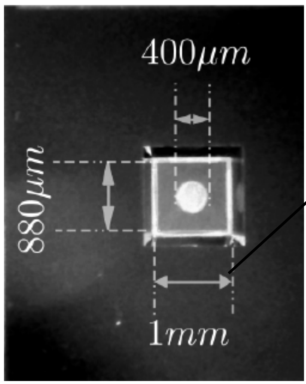
Consider **more nearby nanomechanical resonances** and design the interaction **so that they all cooperate to increase the bandwidth**

This require **control of the interference between electromechanical transduction pathways**

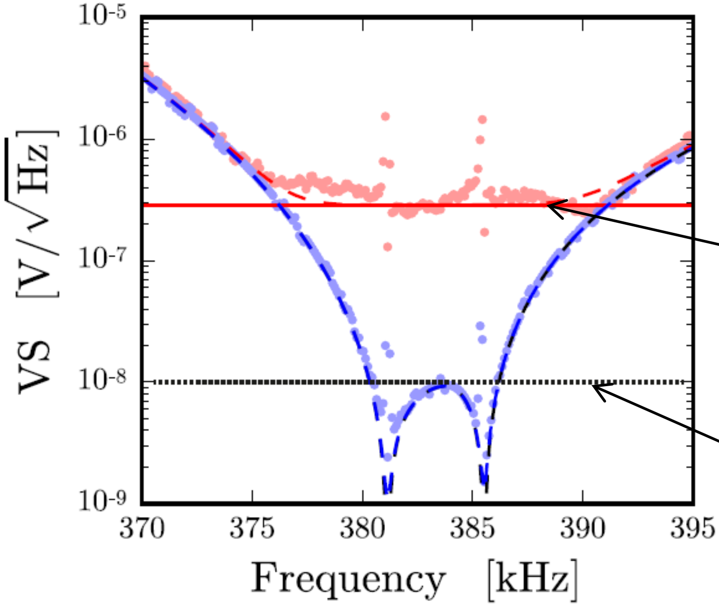


Optical interferometric readout





Nb-metalised SiN membrane



Voltage sensitivity = 300 nV/√Hz over a 15 kHz bandwidth with rf-noise added

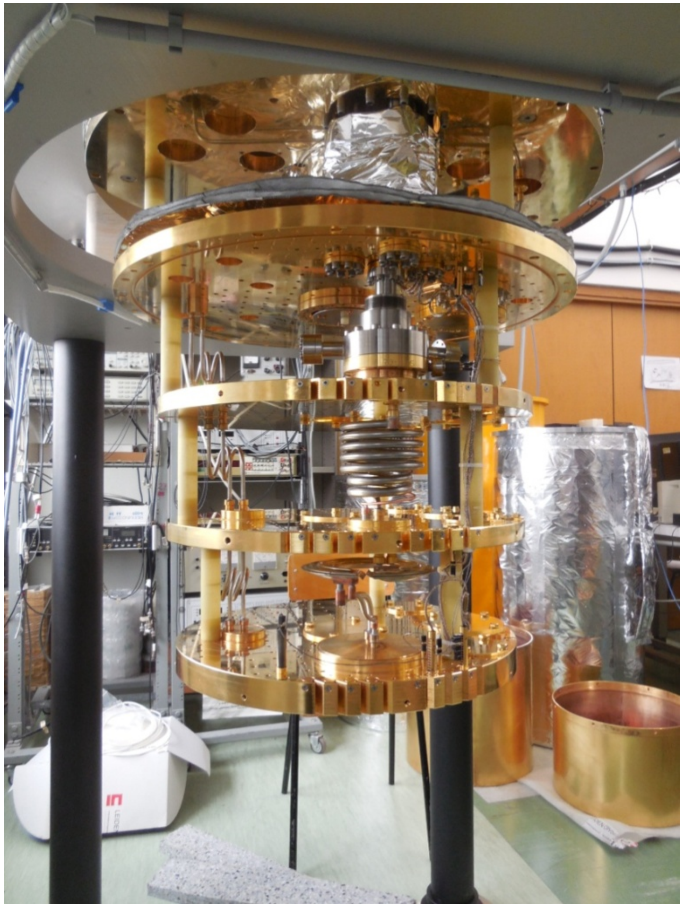
Optimal shot-noise limited sensitivity = 10 nV/√Hz over a 5 kHz bandwidth (negligible rf noise)

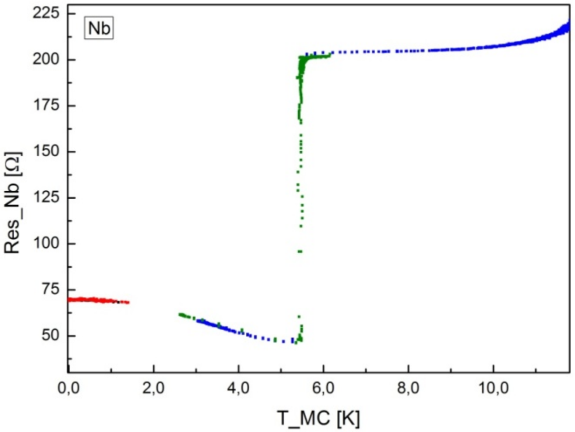
I. Moaddel Haghighi, N. Malossi, R. Natali, G. Di Giuseppe, and D. Vitali
Phys. Rev. Applied **9**, 034031 (2018)

UNICAM has also coordinated iQUOEMS, an FP7 FET-OPEN project on mechanical resonators as quantum interface between optical and microwave/rf signals

iquoems
interfacing quantum optical electrical mechanical systems

Aiming at operating these devices in the **quantum regime**. This is possible in an **ultracryogenic environment (dilution-fridge, T = 10–300 mK)** where thermal noise is limited





Measurement of a Nb thin film superconducting transition

Quantum and geometrical aspects of information

- **Stefano Mancini's** group (http://qmit.phys.unicam.it)

- **Quantum channels** (Capacities and their application to Quantum Cryptography (Two-way protocols)

- **Quantum control and error correction** (for entanglement preservation)

Quantum and geometrical aspects of information - II

- **Entanglement characterization** (ent typicality, entanglement in a relativistic scenariom flat and curved spacetime)
- **Information Geometry** (in classical and quantum contexts)

- Funding from FQxI, COST, FP7, INFN

- International collaborations: G. Amosov (Steklov Inst., Moscow); S. Braunstein (Univ. York); A. Ekert (QCT Singapore); S. Lloyd (MIT); M. Pettini (Aix-Marseille Univ.); R. Renner (ETH Zurich); M. Wilde (Louisiana Univ.); A. Winter (Univ. Autonoma Barcelona); H. Wiseman (Univ. Brisbane)