iQUOEMS
Interfacing quantum optical electrical and mechanical systems

Final Review Meeting

Period: 10/2015 –12/2016

Brussels, March 14 2017

http://d7.unicam.it/iquoems/

CONSORTIUM

Aalto-Korkeakoulusaatio

Aalto University

Ecole Polytechnique Federale de Lausanne

ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

Gottfried Wilhelm Leibniz Universitaet Hannover

Leibniz Universität Hannover

Københavns Universitet

KØBENHAVNS UNIVERSITET

Università degli Studi di Camerino

UNICAM Università di Camerino 1336

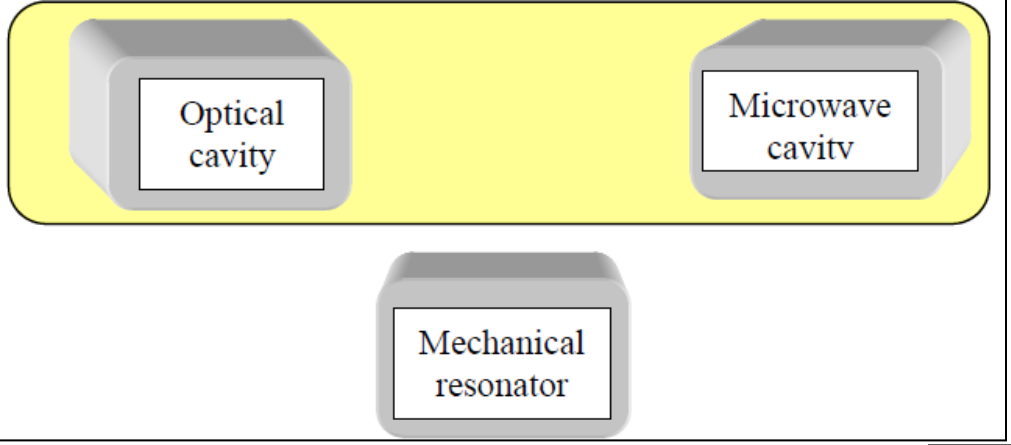
Universitaet Wien

universität wien

Project objectives

- development of **interfaces** for the coherent **conversion of radio and microwave frequencies to the optical domain**; more specifically:

1) realization of a coherent microwave-to-optical link, based on a **cavity-electro-optical** setup;
2) implementation of coherent interconversion between microwave/optical photons and MHz/GHz phonons;
3) implementation of a **nanomechanical interface for microwave-optical interconversion**.

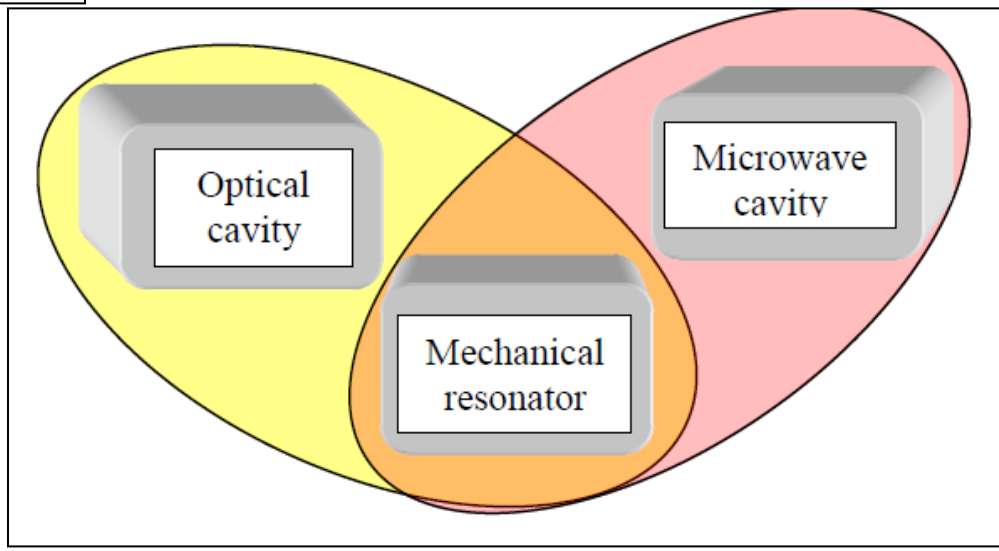


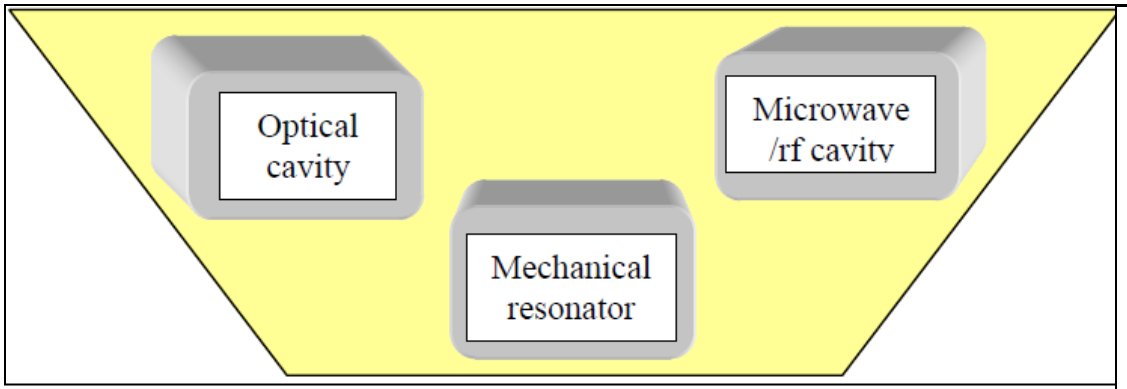
WP2: Photon-phonon interfaces

Main objective: implementation of coherent interconversion between microwave/optical photons and MHz/GHz phonons

WP1: Photon conversion at vastly different wavelengths

Main objective: realization of a direct coherent microwave-to-optical link

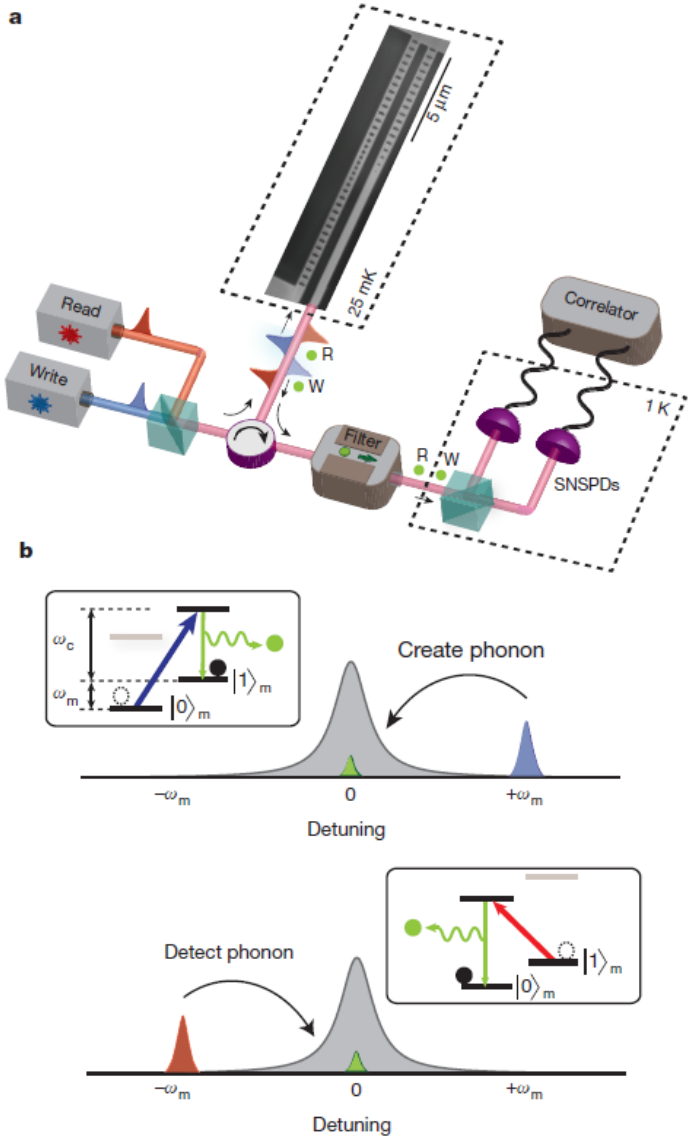




WP3: Photon-phonon-photon interfaces

Main objective: implementation of a nanomechanical interface for microwave-optical interconversion

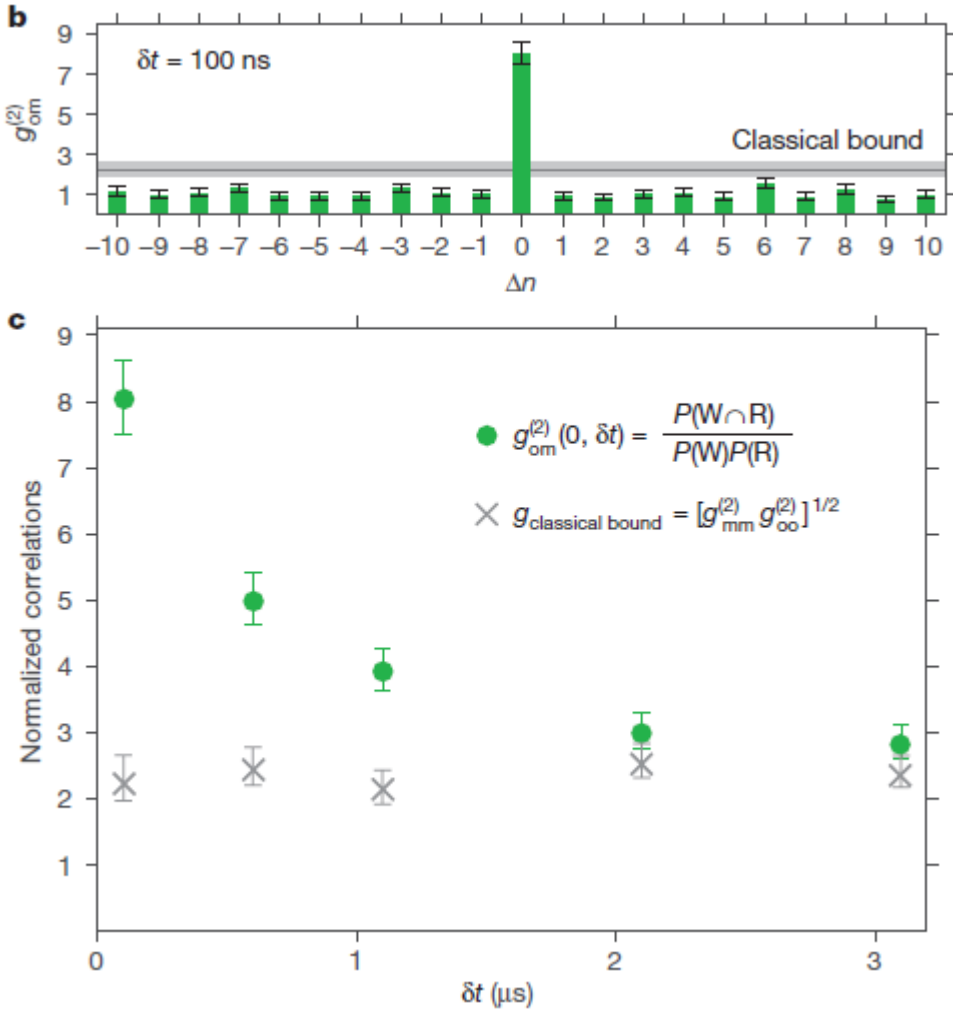
Relevant results of the project



First demonstration of photon-phonon correlations at the quantum level with an integrated nanomechanical device (WP2)

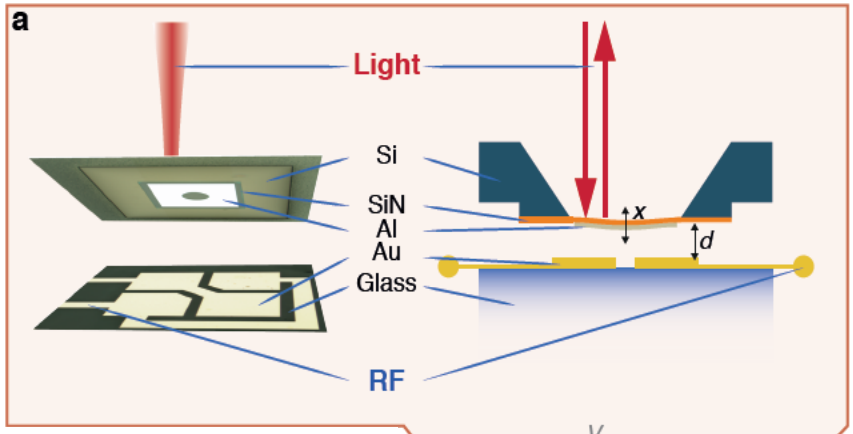
(R. Riedinger e al., Nature (London), 530, 313-316 (2016)).

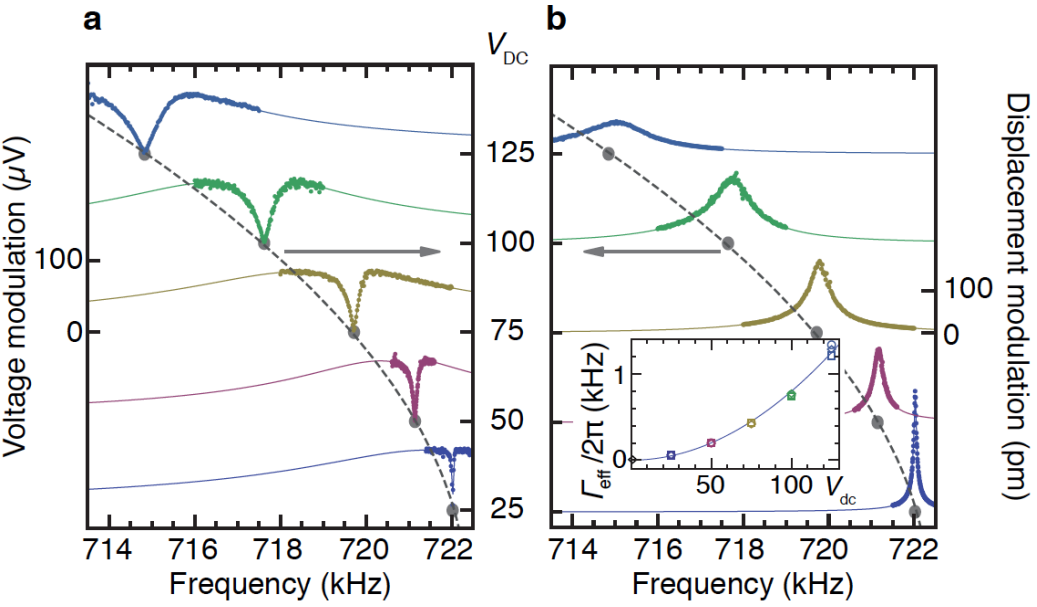
This demonstrates the availability of on-chip solid-state mechanical resonators as light–matter quantum interfaces, quantum memories, and quantum transducers



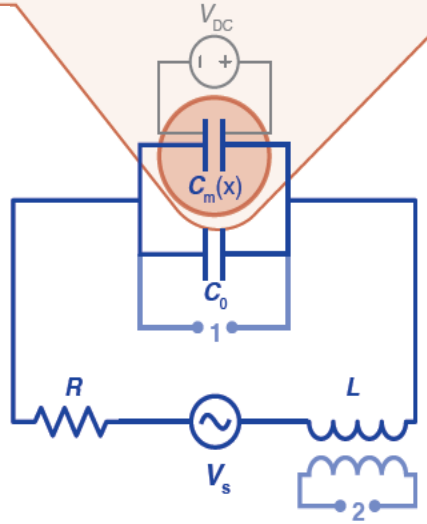
the output light from both pulses has been used to measure the cross-correlation function $g^{(2)}$. **The observed violation of a Cauchy–Schwarz inequality obeyed by $g^{(2)}$ for classical light, is clear evidence for the non-classical nature** of the mechanical state generated

Opto-electro-mechanical transducer: high-sensitive optical detection of radio waves (80 pV/√Hz) (WP3)

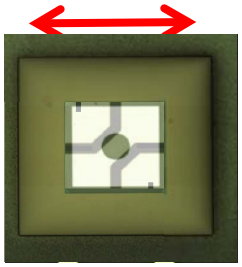




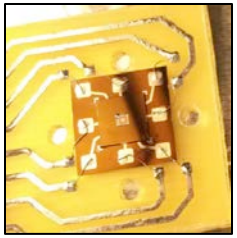
Strong electro-mechanical coupling



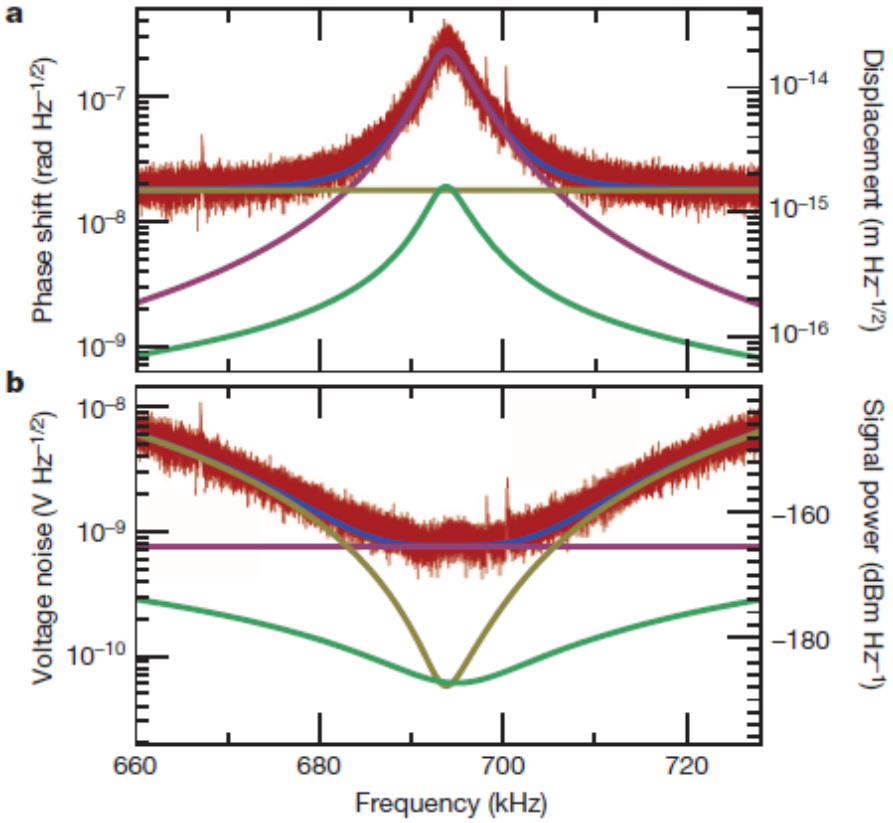
Bagci, Simonsen, Schmid, Villanueva, Zeuthen, Appel, Taylor, Sørensen, Usami, Schliesser, Polzik, Nature **507**, 81 (2014)



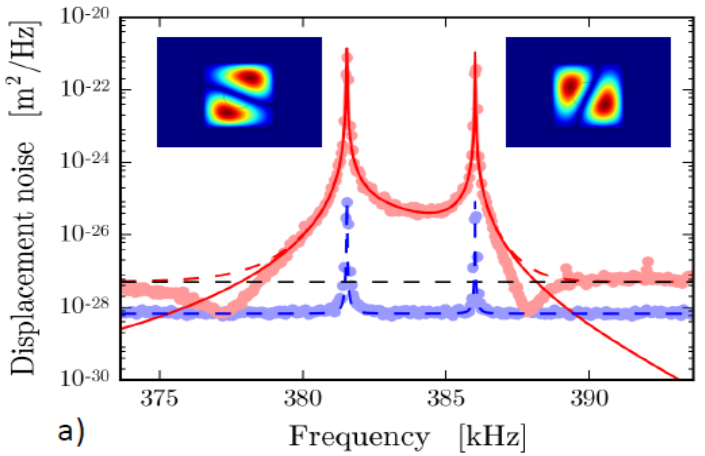
Al-metallized SiN membrane,
d = 5,5 μm, G = 10^4 V/m

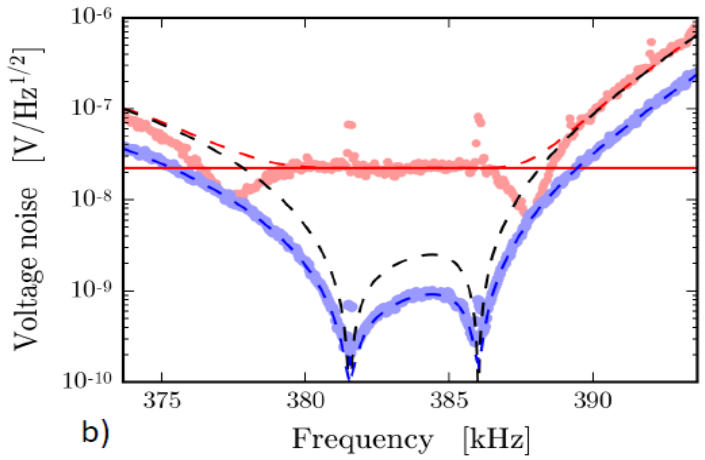


Nb-metallized SiN membrane,
d = 22 μm, G = 230 V/m



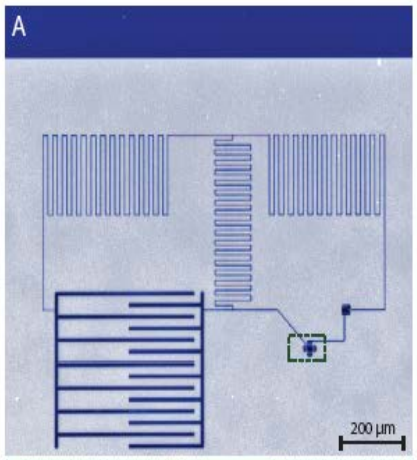
Strong coupling, high sensitivity

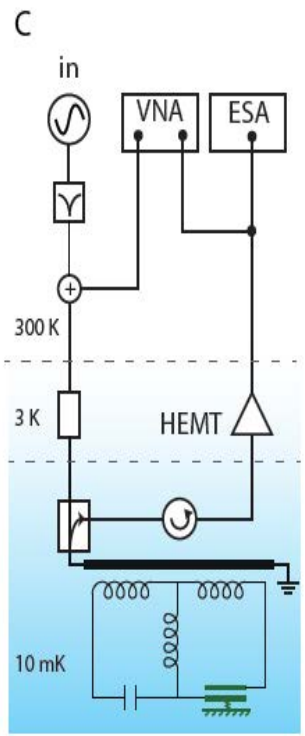


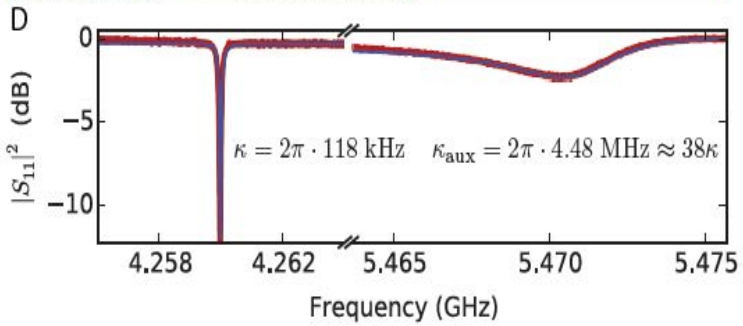


Mechanical doublet

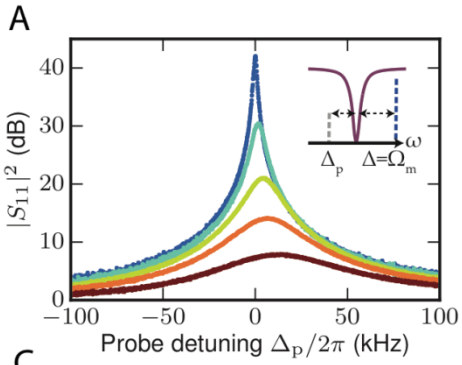
Low-noise, near quantum-limited microwave amplifier of novel design: a) via mechanical reservoir engineering (WP1 & WP2)

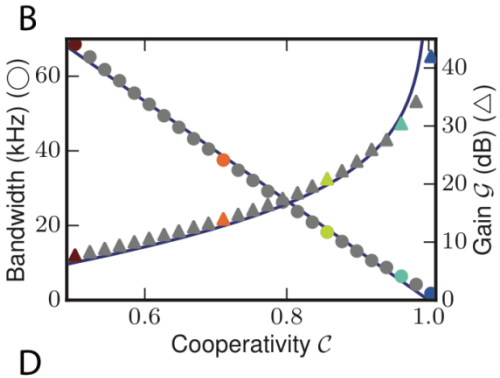


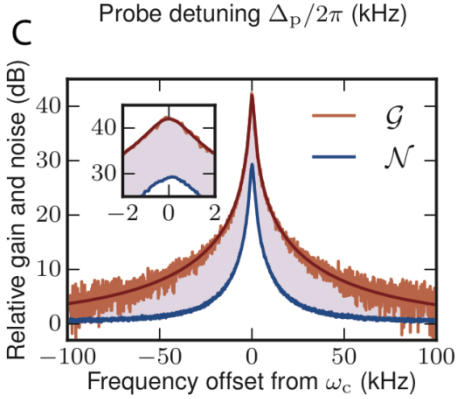


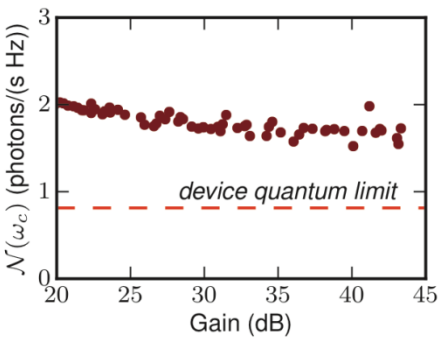


above 40 dB gain phase preserving microwave amplifier that operates 0.87 quanta above the quantum limit



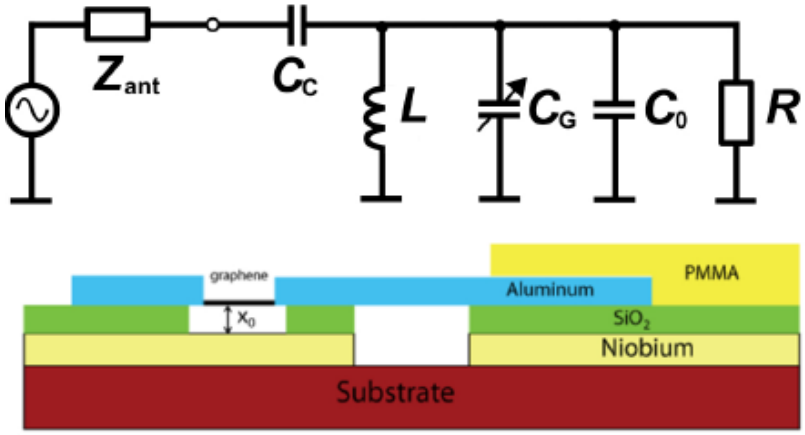






Graphene-based optomechanical amplifier with single phonon resolution(WP3)

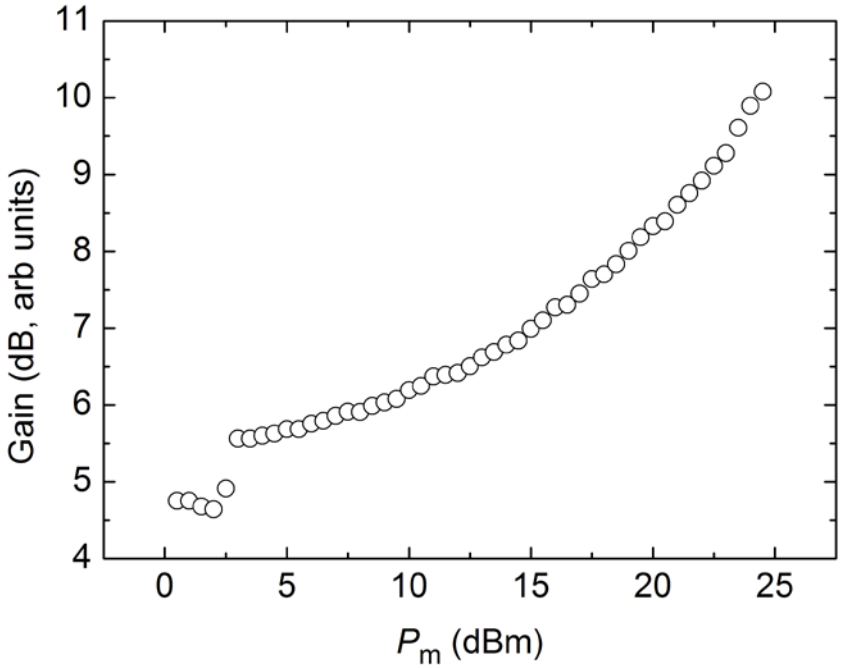
- strong pump to cavity at **blue** mechanical sideband
- weak signal tone α_{in} near cavity frequency



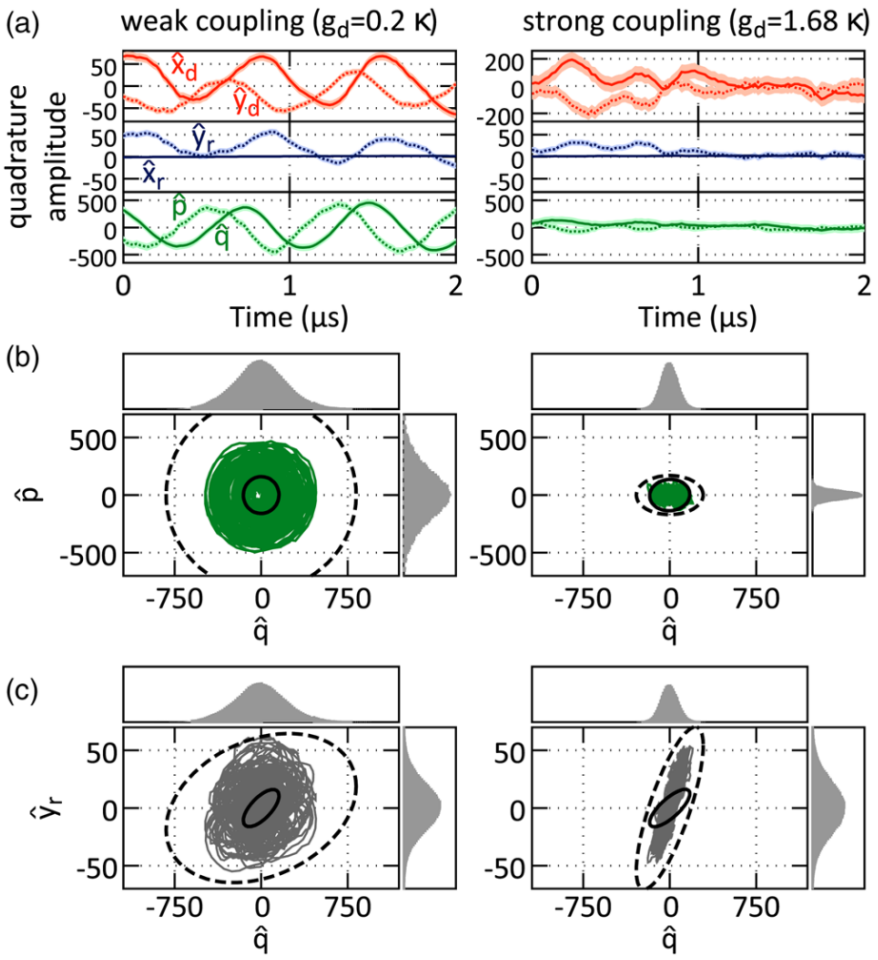
Thermal number of mechanical quanta: $\delta N \approx 50$

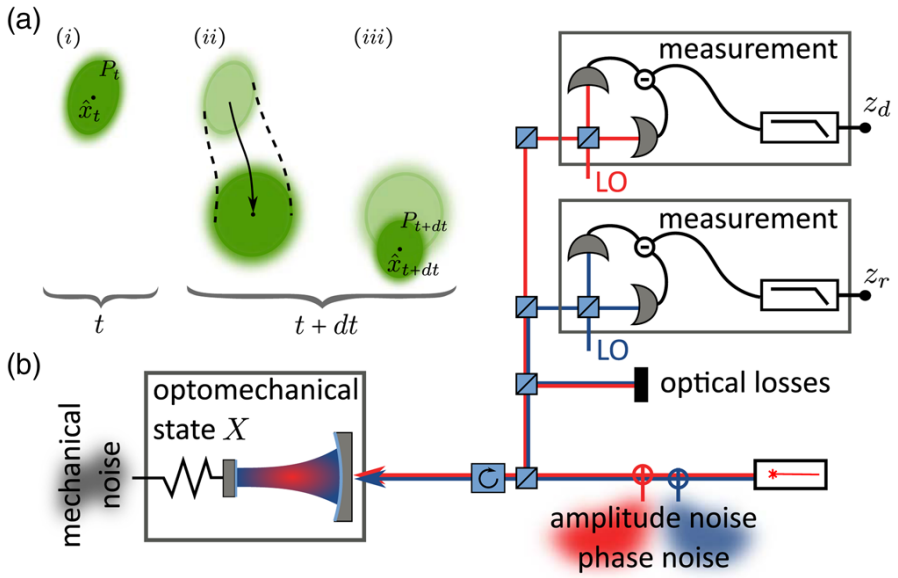
$$\sqrt{N} \approx 300 \Rightarrow \delta N / 2\sqrt{N} \approx 1$$

Gain with double pumping



The first optimal state estimation of an optomechanical setup and detection of strong optomechanical correlations (WP2)

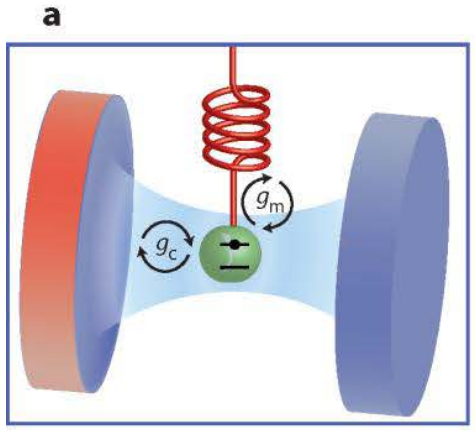


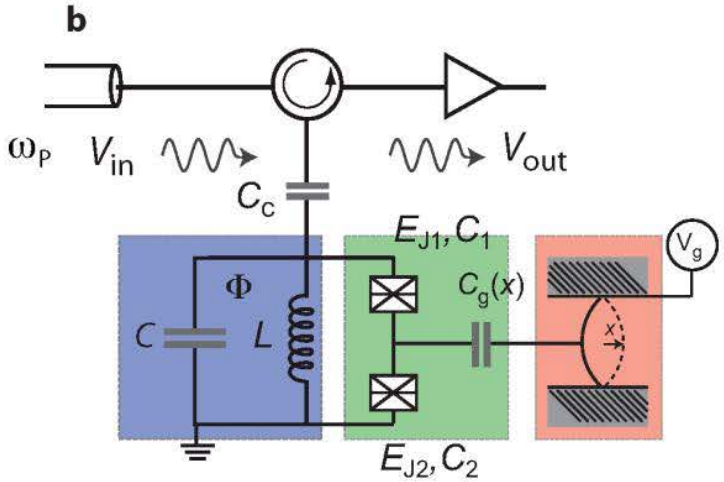


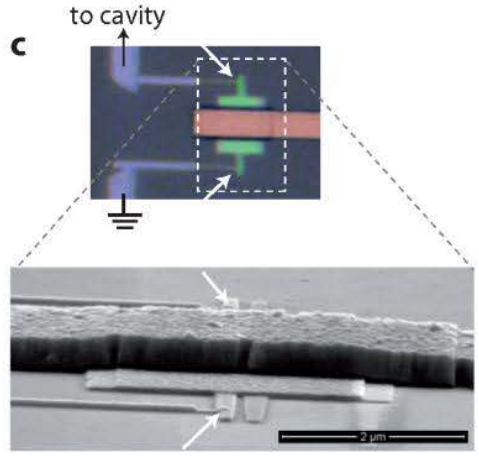
Kalman filter for optomechanics

W. Wieczorek, S. G. Hofer, J. Hoelscher-Obermaier, R. Riedinger, K. Hammerer, M. Aspelmeyer "Optimal state estimation for cavity optomechanical systems", Phys. Rev. Lett. 114, 223601 (2015)

Demonstration of strong single-photon coupling cavity optomechanics mediated by a quantum two-level system (WP2)

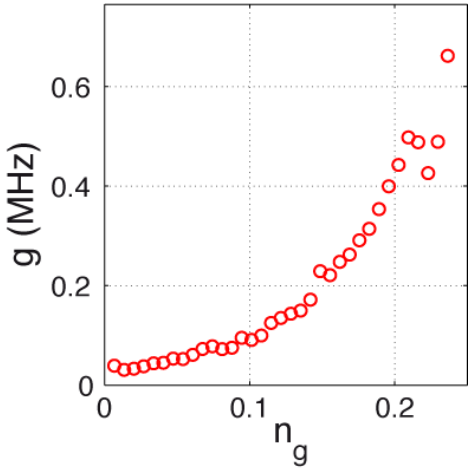






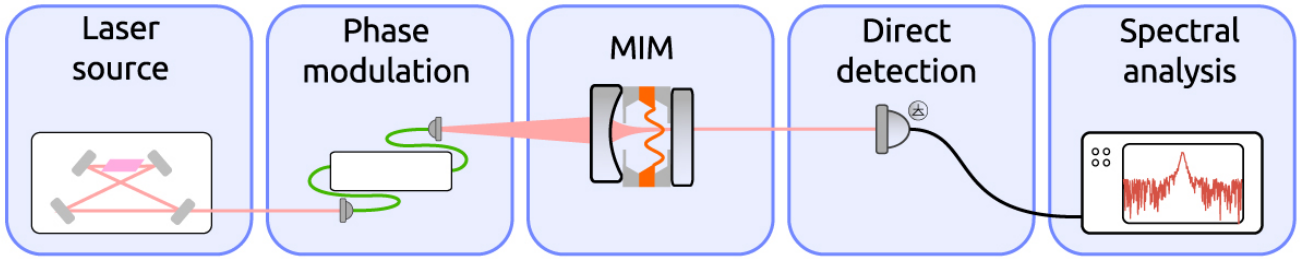
Microwave optomechanical system with a Josephson charge qubit

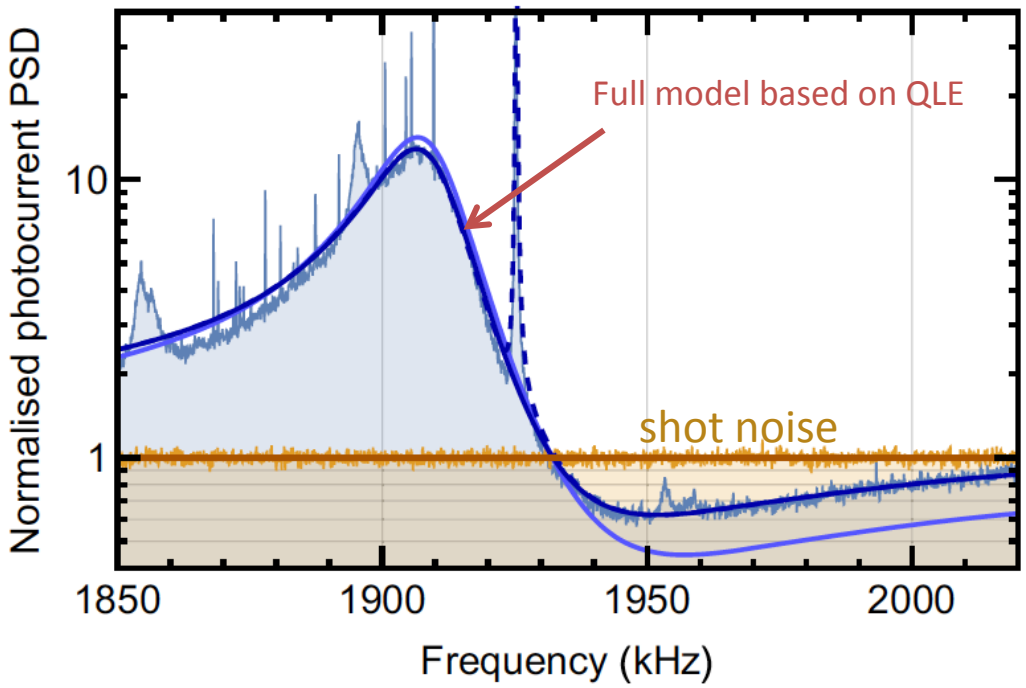
J.-M. Pirkkalainen, S.U. Cho, F. Massel, J. Tuorila, T.T. Heikkilä, P.J. Hakonen, and M.A. Sillanpää, "Cavity optomechanics mediated by a quantum two-level system", Nature Communications 6, 6981 (2015)



1 Hz ⇒ 0.5 MHz

Large cooperativity and optomechanical squeezing





Coherent optomechanical interaction generates
a non-classical state of light

Squeezing by 42% (2.4dB) observed
3.6 dB if corrected for loss

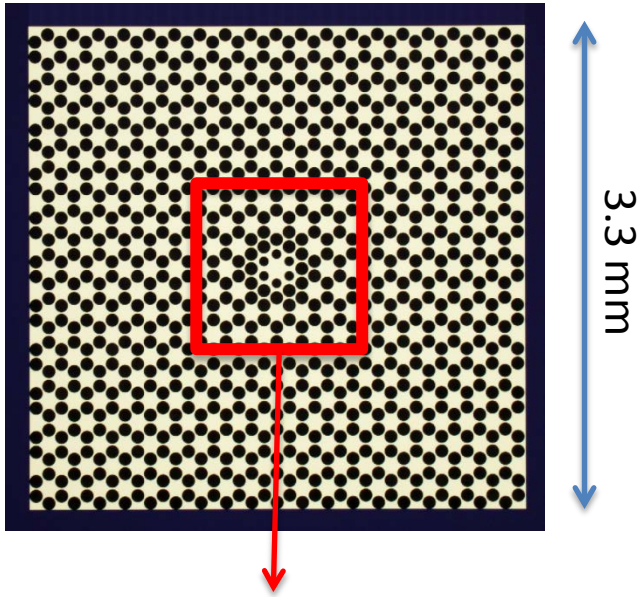
Cooperativity C=560,000
Quantum cooperativity C_q=4.7

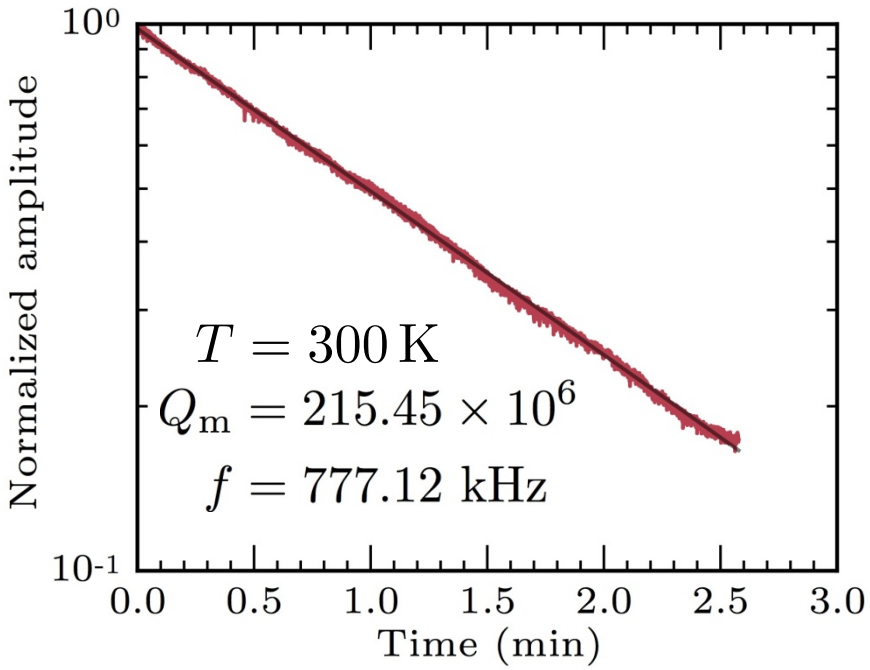
Nielsen, Tsaturyan, Møller, Polzik, Schliesser, PNAS 144, 62 (2017)

See also: Regal & Painter groups

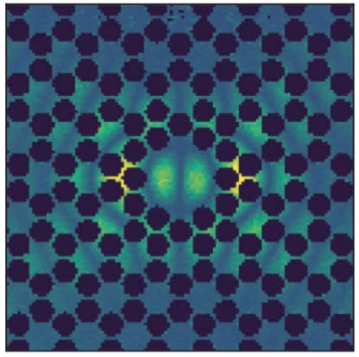
Ultrahigh Q at room temperature

Including the phononic pattern directly into membrane also provides shielding from frame modes





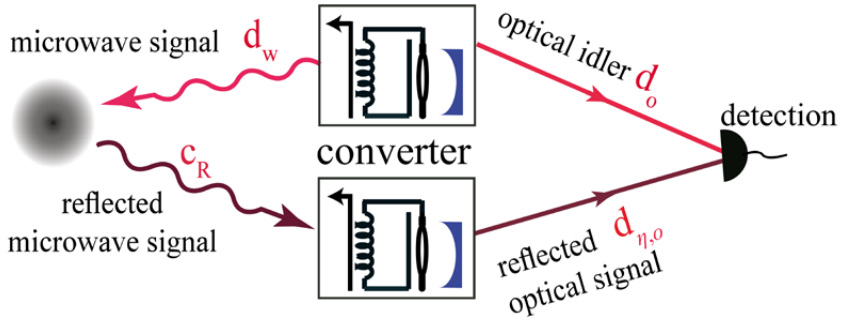
Localized defect mode



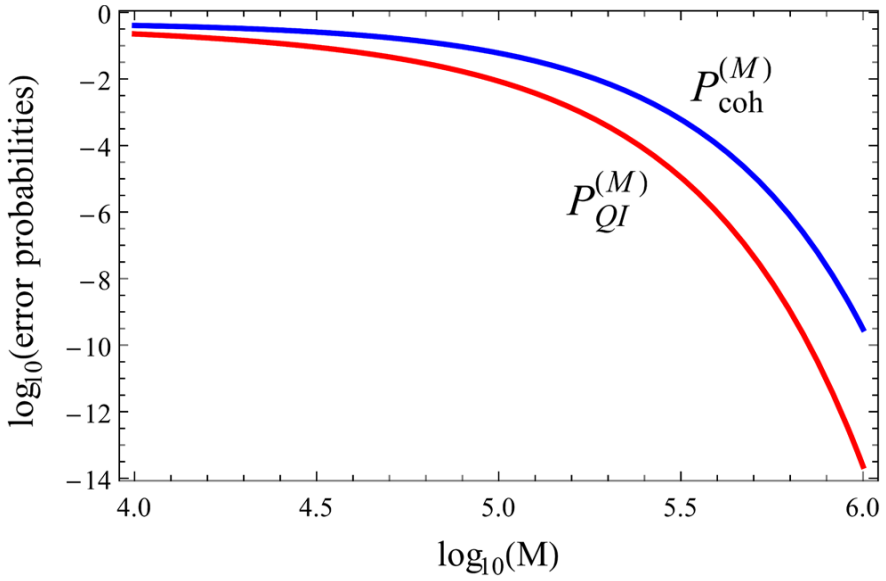
Measured spatial displacement pattern

Tsaturyan, Barg, Polzik, Schliesser, *arXiv:1608.00937*

"Quantum radar": quantum illumination for target detection at microwave wavelengths based on opto-electro-mechanical transduction (WP3)



The transmitter entangles microwave and optical fields. The receiver transforms the returning microwave field to the optical domain while performing a phase-conjugate operation.



Quantum vs classical error probability

S. Barzanjeh, S. Guha, C. Weedbrook, D. Vitali, J. H. Shapiro, S. Pirandola, "Microwave quantum illumination", Phys. Rev. Lett. 114, 080503 (2015)

LAST YEAR DELIVERABLES

Deliverable number	Deliverable name	Status
D1.2	Demonstration of optical readout of the electric field	Partially achieved
D1.3	Microwave cooling and amplification	Achieved
D1.4	*Q*uantum limited microwave amplifier	Achieved
D2.4	Coherent photon-phonon conversion	Achieved
D2.5	Demonstration of large single-photon optomechanical coupling	Partially achieved
D2.6	Strong charge qubit-graphene-resonator coupling	Achieved
D3.4	Radio-frequency field readout with close-to-unity quantum efficiency	Readdressed/Partially achieved
D3.5	Mechanical-microwave amplifier with single phonon resolution	Achieved
D3.6	Graphene-based photon-phonon-photon THz detector in the Microwave regime	Achieved

iQUOEMS activities

- **59 iQUOEMS publications** (**17** in high-impact journals)
- **153 invited lectures** and seminars at international conferences, workshops and colloquia.
- iQUOEMS researchers have been awarded 10 prestigious national and international Prizes and Awards
- **Joint activities with the Marie Curie ITN project "cQOM – Cavity Quantum Optomechanics"**

Two joint iQUOEMS-cQOM meetings

- 1-5 February 2015, Diavolezza (CH)

- 31 January – 4 February 2016, Diavolezza (CH)

iQUOEMS Conference

http://d7.unicam.it/iquoems/ericeconference

Erice, Sicily, Italy
July 31 – August 5 2016

ETTORE MAJORANA FOUNDATION AND CENTRE FOR SCIENTIFIC CULTURE

Quantum Interfaces with Nano-opto-electro-mechanical devices: Applications and Fundamental Physics

Directors:
Konrad Lehnert (JILA, Boulder)
Francesco Marin (Univ Firenze)
David Vitali (Univ Camerino)

iquoems

POTENTIAL IMPACT

- iQUOEMS has provided demonstrations of opto-electro-mechanical systems operating in the quantum regime, **providing further evidence of the key role that these hybrid platforms will play within the incoming Quantum Technology Flagship.**

- Novel rf and microwave high-sensitive detectors with optical readout (improved radioastronomy, MRI) (Patent by UCPH)

POTENTIAL IMPACT

- nanomechanically-based microwave-optical interfaces operating at the quantum level and quantum limited microwave amplifiers and isolators **for superconducting quantum computers (IBM, Google)**

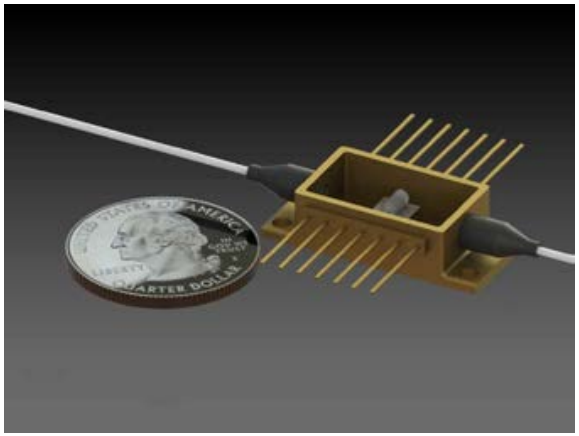
- better quality nanomechanical resonators (**record Q = 10^8 at room T**, patent application by UCPH) for other applications (classical sensors, AFM, MEMS…)

First technology transfer attempt

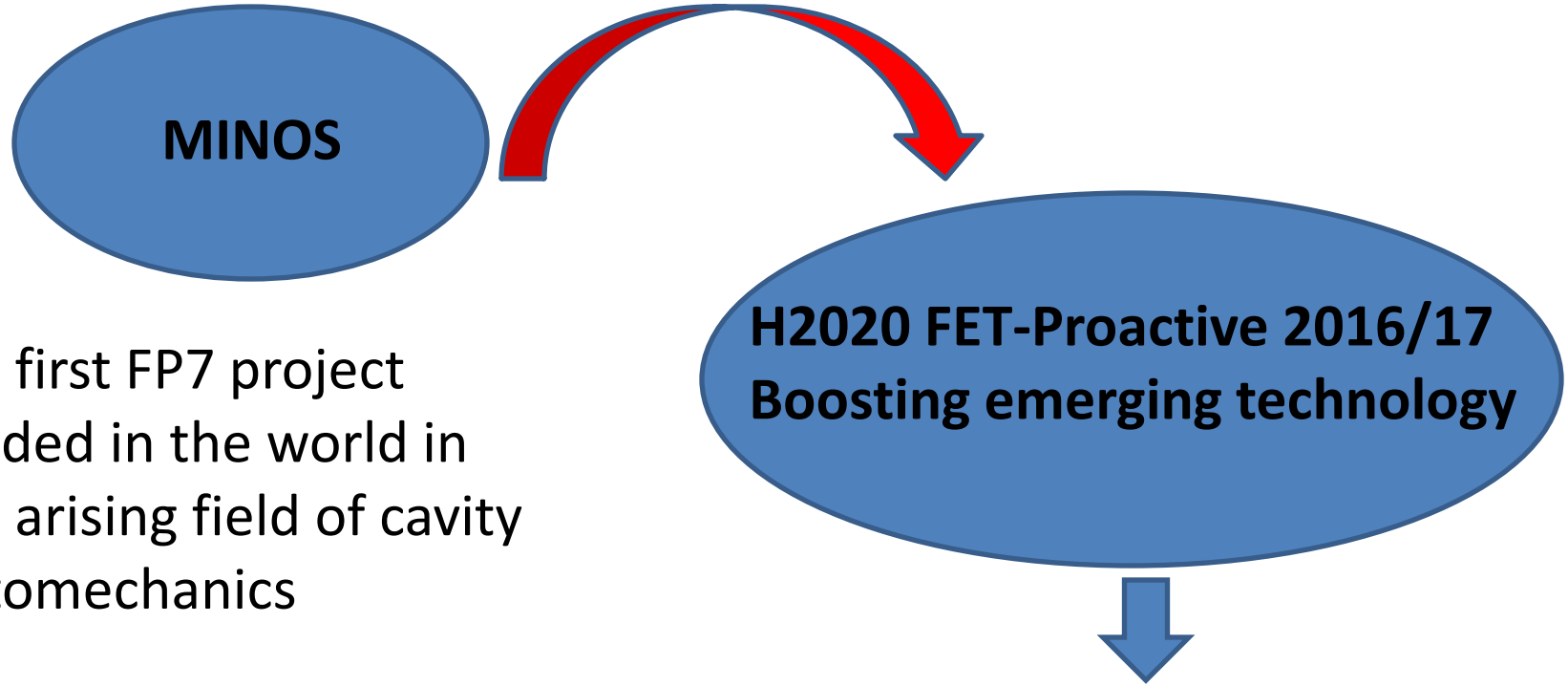
- **FET-Innovation Launchpad project "Rugged Optical Microresonators (ROM) – Merging Microfabricated Waveguides and Optical Microresonators"**

- The proposal combines optical microresonators with microfabricated optical waveguide technology developed during iQUOEMS to create a robustly packaged system that is resistant to strong temperature and vibrational perturbations.

The end result would have been a successfully-demonstrated prototype that would open up new markets for a start-up company being developed at EPFL.



iQUOEMS as a bridge



the first FP7 project funded in the world in the arising field of cavity optomechanics

two funded projects on activities related to optomechanics and to iQUOEMS activities in particular