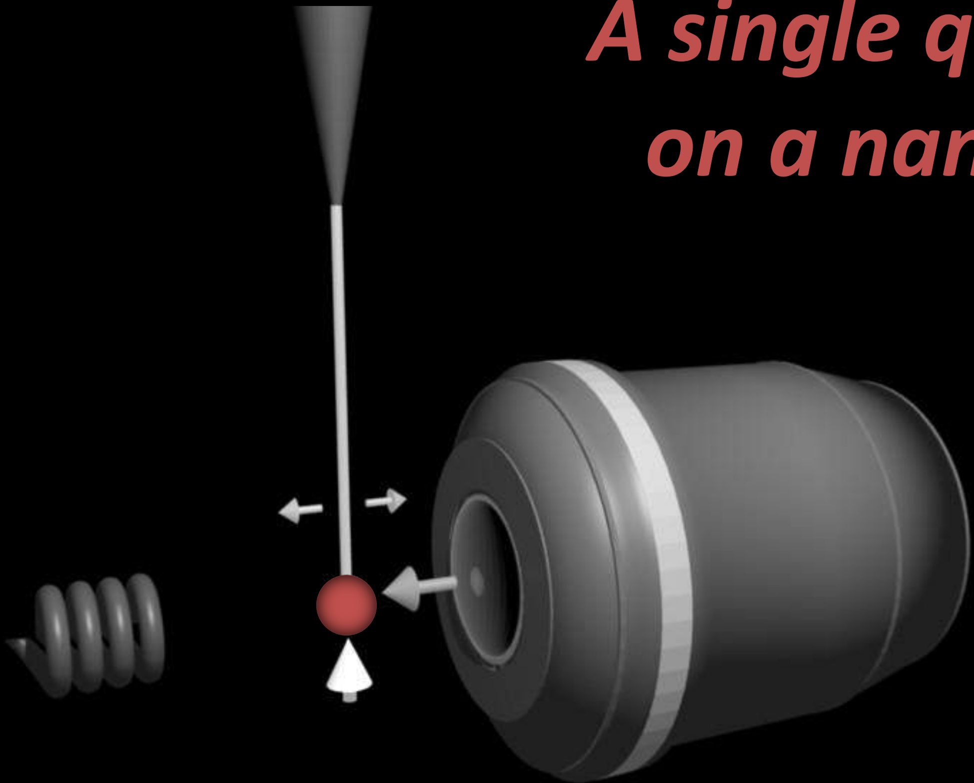
A single quantum emitter on a nanomechanical oscillator



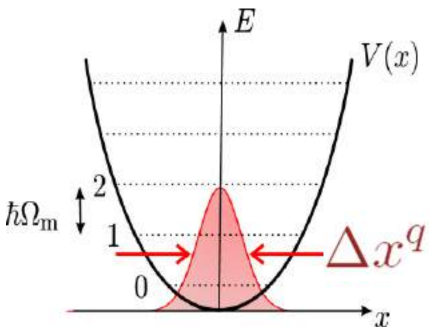
Hybrid nanomechanics

Arnaud Gloppe Sven Rohr
Eva. Dupont-Ferrier
Signe Seidelin Olivier Arcizet
@Néel

Vincent Jacques J.F. Roch
@LPQM

Alessandro Siria Philippe Poncharal
Pascal Vincent
@LPMCN

Context - Ultracold Mechanical Oscillators



$$\Delta x^q = \sqrt{\frac{\hbar}{2M\Omega_m}}$$

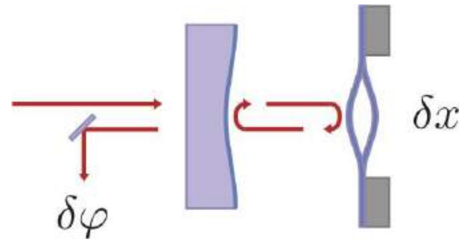
Δx^q = 10 fm

$$k_B T \leq \hbar\Omega_m$$

T < 500 µK @ 10 MHz

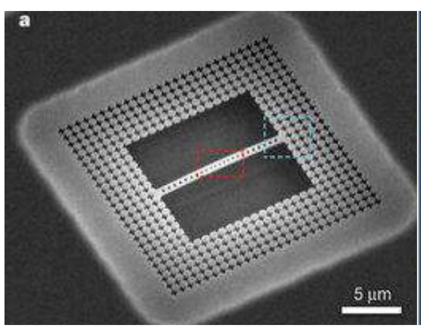
Cooling and observing mechanical oscillators down to their *ground state of motion*

Tool: Optomechanical coupling

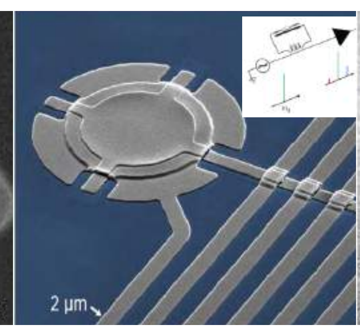


Ultrasensitive displacement sensors

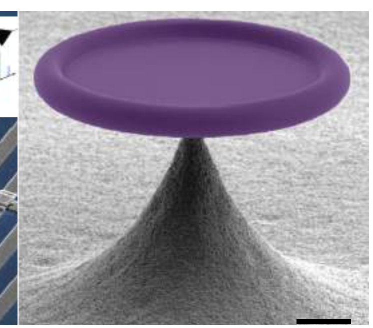
Laser cooling of mechanical oscillators



Caltech



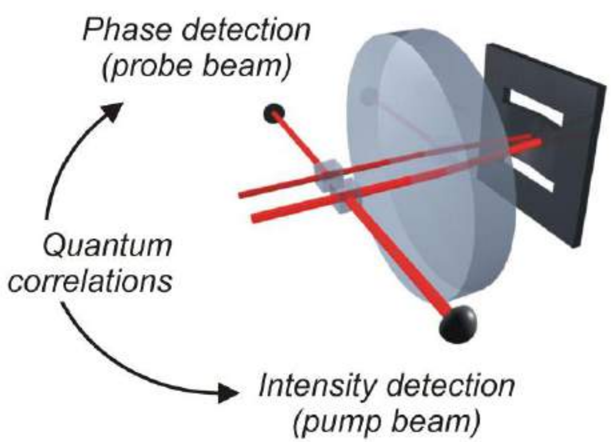
NIST



Garching - EPFL

Ground state cooling achieved in 2010-11

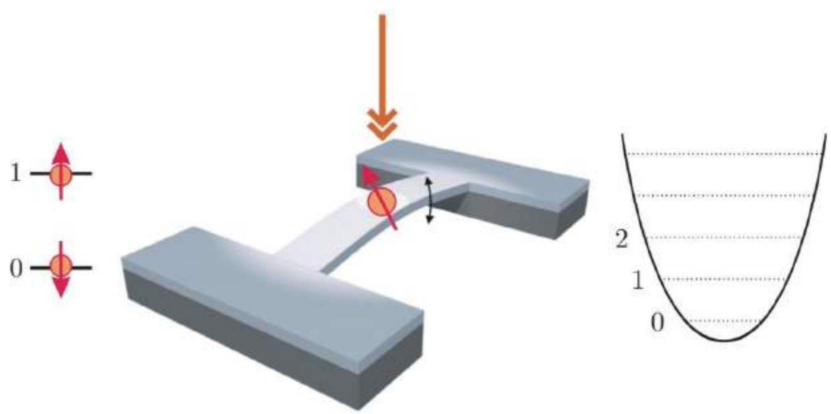
Context - Ultracold Mechanical Oscillators



(LKB experiments, A. Heidmann)

Quantum regime of the optomechanical interaction

- QND measurement of laser intensity
- Beating the standard quantum limit
- Increased force sensitivity

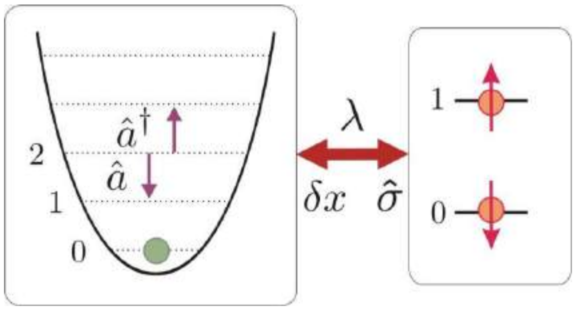


Hybrid mechanical systems

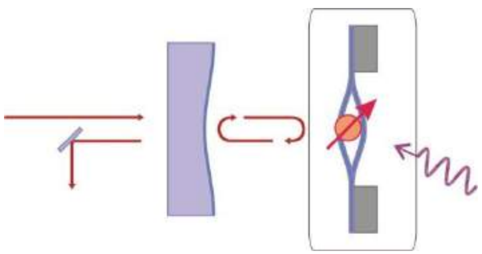
Objectives

beyond ground-state cooling :

Generate and Observe non-classical states of motion of a macroscopic oscillator



$$H_{\text{int}} = \hbar\lambda_i(\hat{a} + \hat{a}^\dagger)\hat{\sigma}_i$$



Generate

- Coupling to an external quantum system
- Quantum state transfer

⇒ Hybrid mechanical systems

Observe

- Monitoring both hybrid components

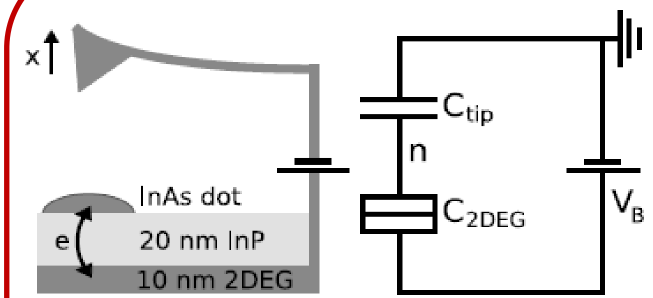
⇒ Optomechanics of hybrid systems

Motivations

- Quantum signatures with macroscopic oscillators
- Quantum information processing
- Ultrasensitive force sensing
- CQED with phonons and spins
- Physics at low phonon number

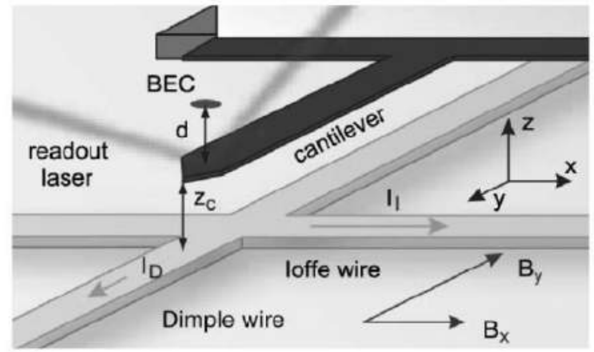
Other hybrid mechanical systems

T> Tq



Quantum dots - Electrical coupling

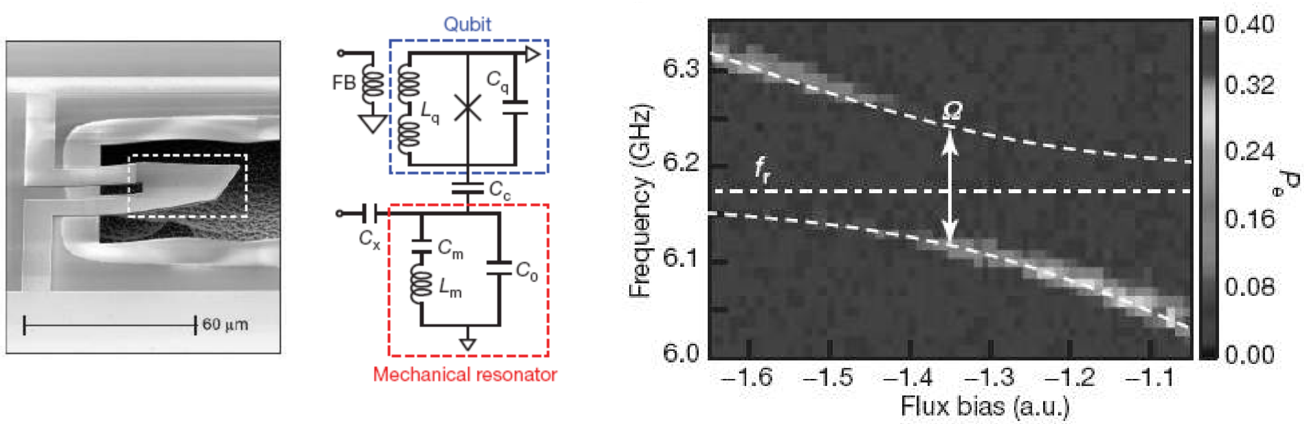
Mc Gill 2010



BEC – Magnetic coupling

LMU 2009 - Basel 2011

T < Tq

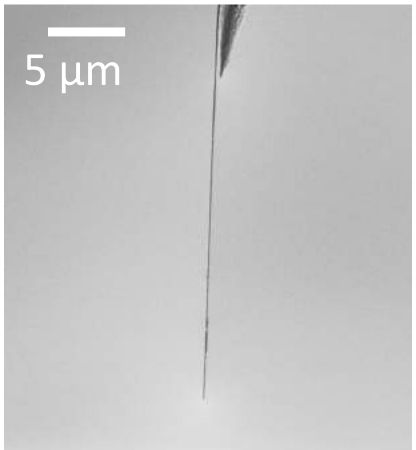


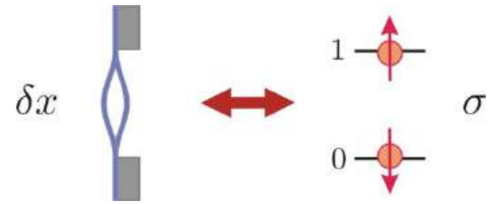
Phase qubits - Capacitive coupling

UCSB 2010, Aalto 2012

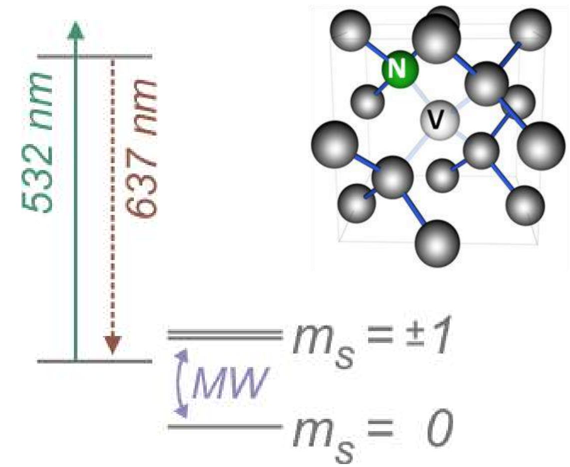
Hybrid spin-nanomechanics

Nanomechanical oscillators





NV defect in diamond



Ultrasensitive force sensors (aN)
Large zero point fluctuations (pm)
High oscillation frequencies (MHz)

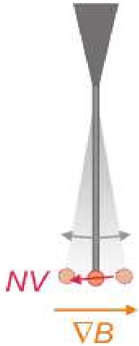
Single photon source @ 300 K
Ultralong spin coherence (2 ms)
Readout and manipulation
with optical and µ-wave fields

$$H_{\rm int} = \hbar \lambda_i (\hat{a} + \hat{a}^\dagger) \hat{\sigma}_i$$

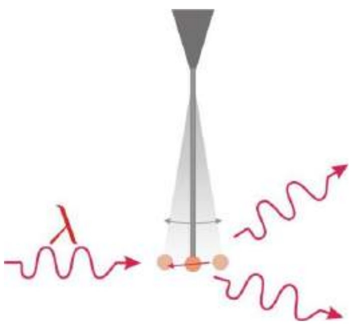
Magnetic or Strain coupling

Rabl et al. PRB 2009

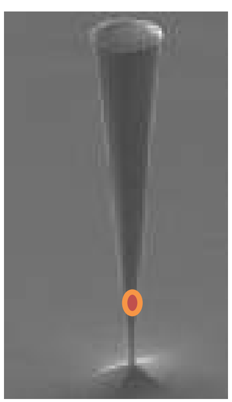
Outline



Magnetic coupling between a NV electronic spin and a nanomechanical oscillator

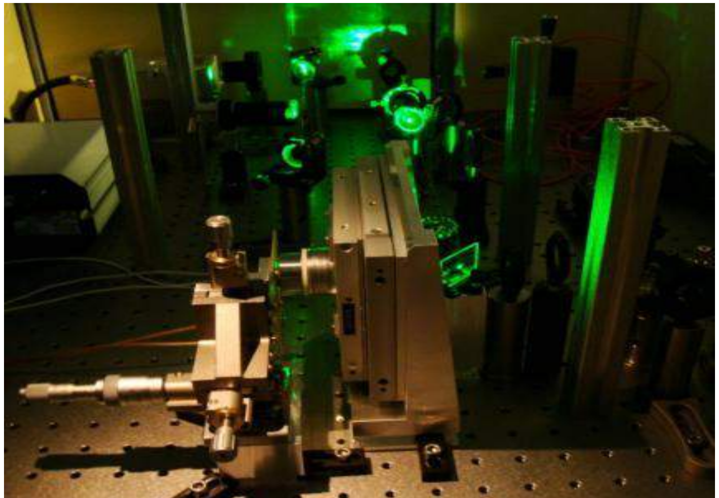


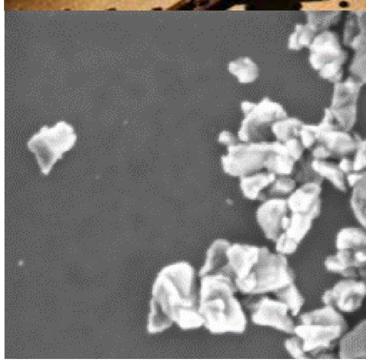
Optical readout of nanomechanical oscillators

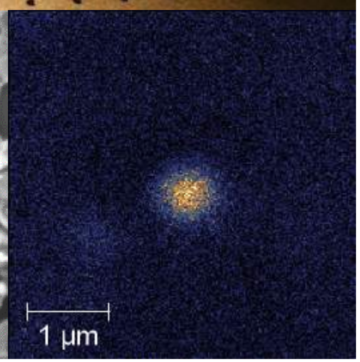


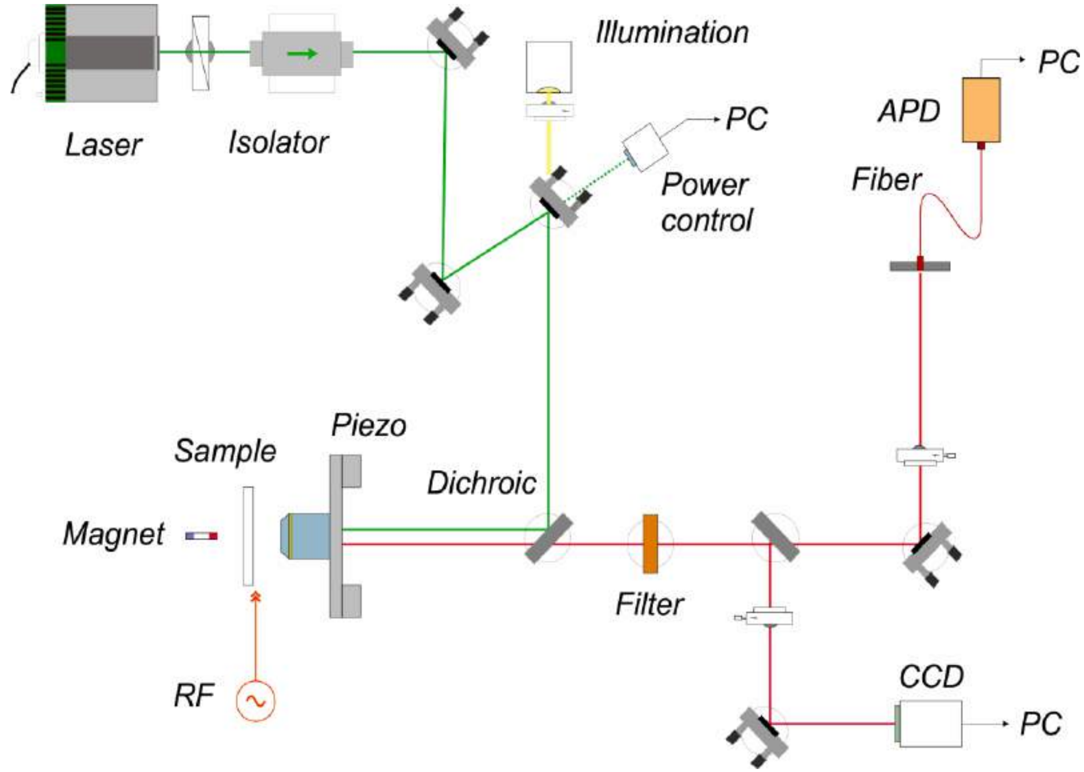
Strain coupling

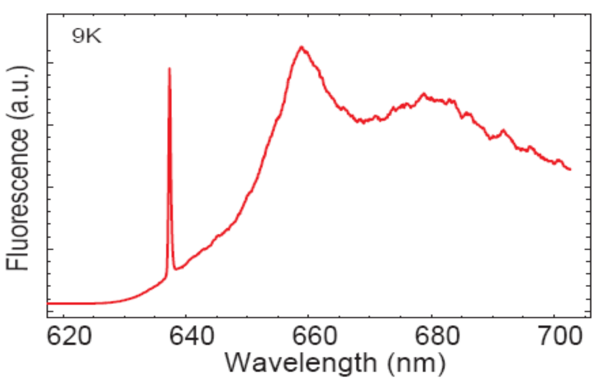
Observing NV defects

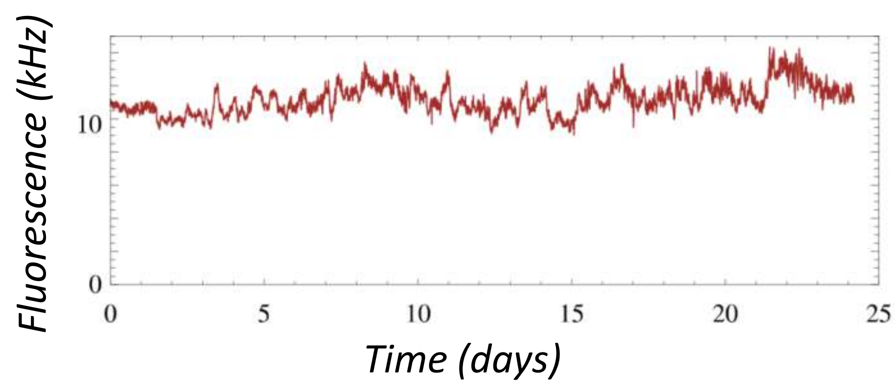




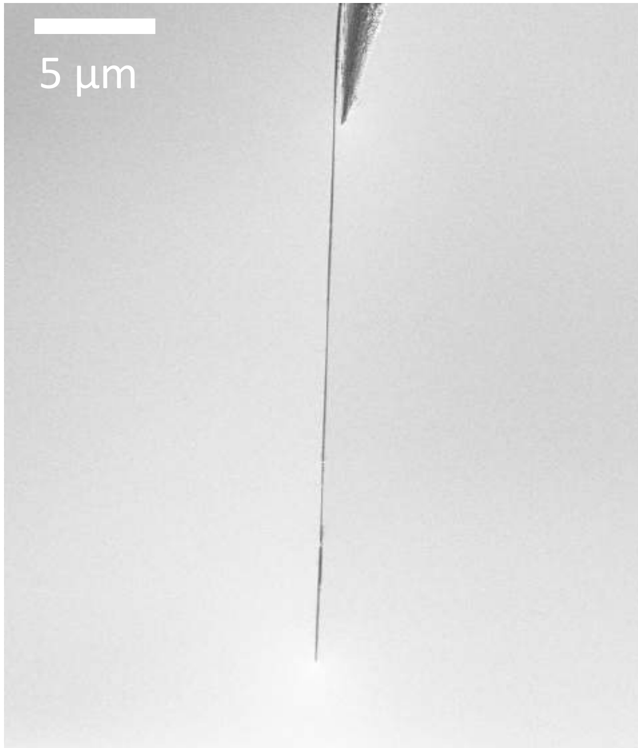


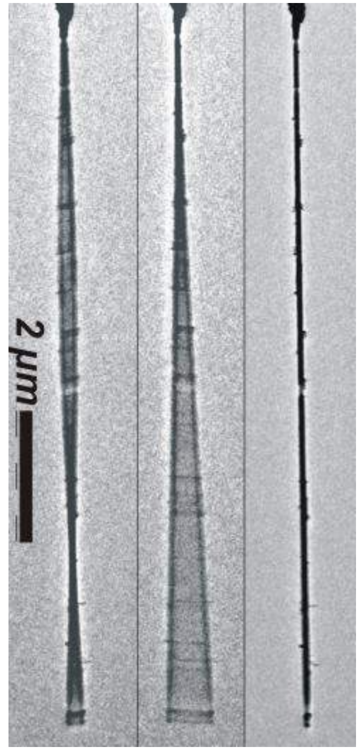






SiC nanomechanical oscillators





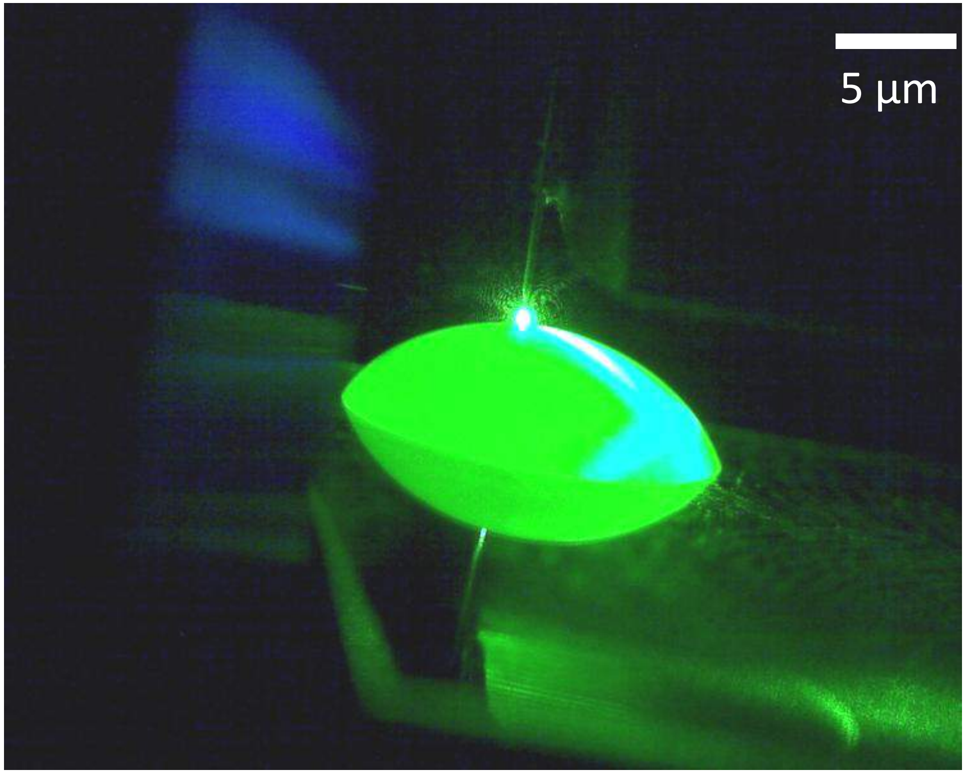
A. Siria, P. Poncharal, P. Vincent
LPMCN, Lyon

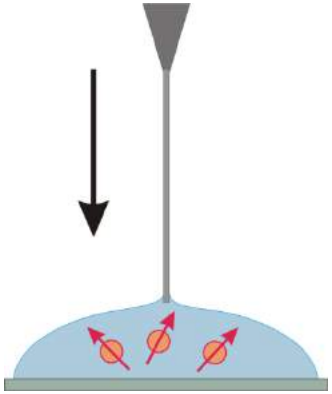
Ultralow mass (10 fg)
High frequency (10 kHz-20 MHz)
Large oscillating amplitudes (µm)
Good mechanical Q factors (>10 000)

10 µm x 100 nm

Silicon Carbide:
-low light absorption
-high stiffness (Young modulus: 450 GPa)
-large aspect ratio

Functionalization





Piezo controlled immersion in a solution of diamond nanocrystals

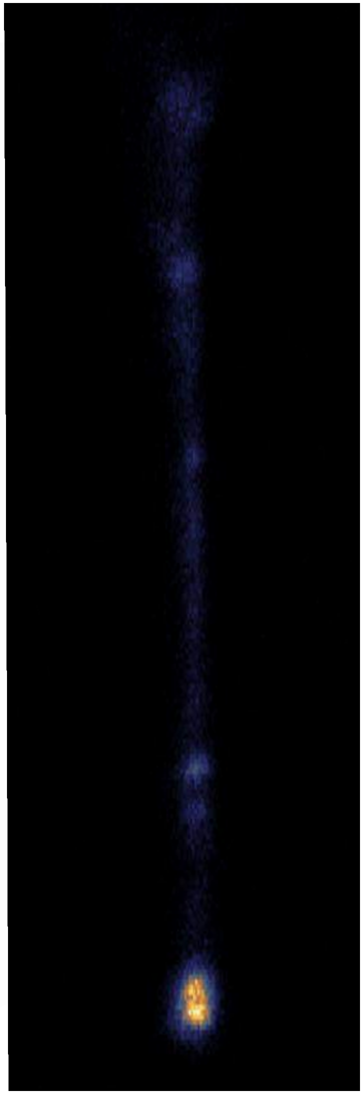
Efficiency increased under laser illumination
(larger agitation and optical trapping)

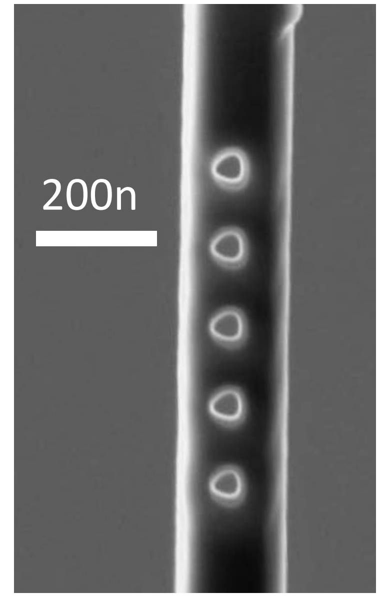
Works with SiC nanowires, C and BN nanotubes

Functionalization and preparation

SEM

Fluorescence



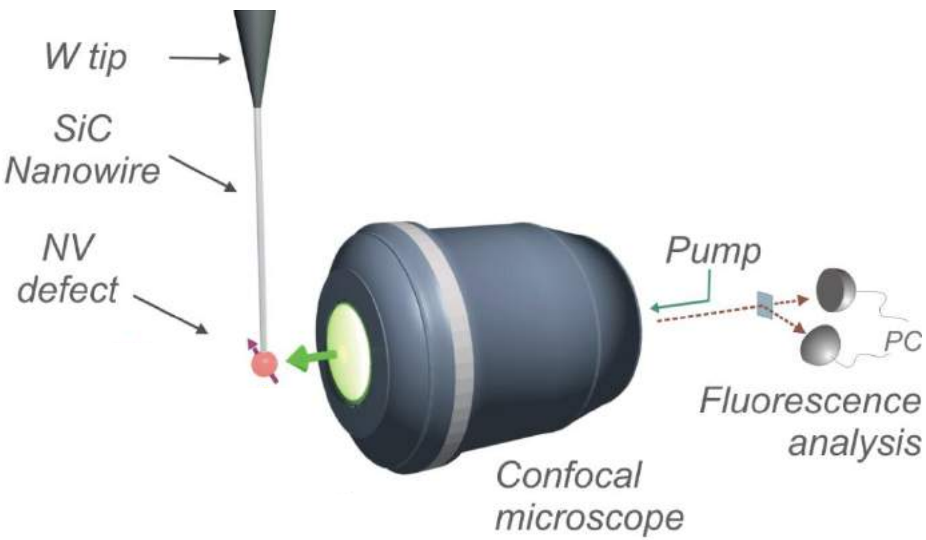


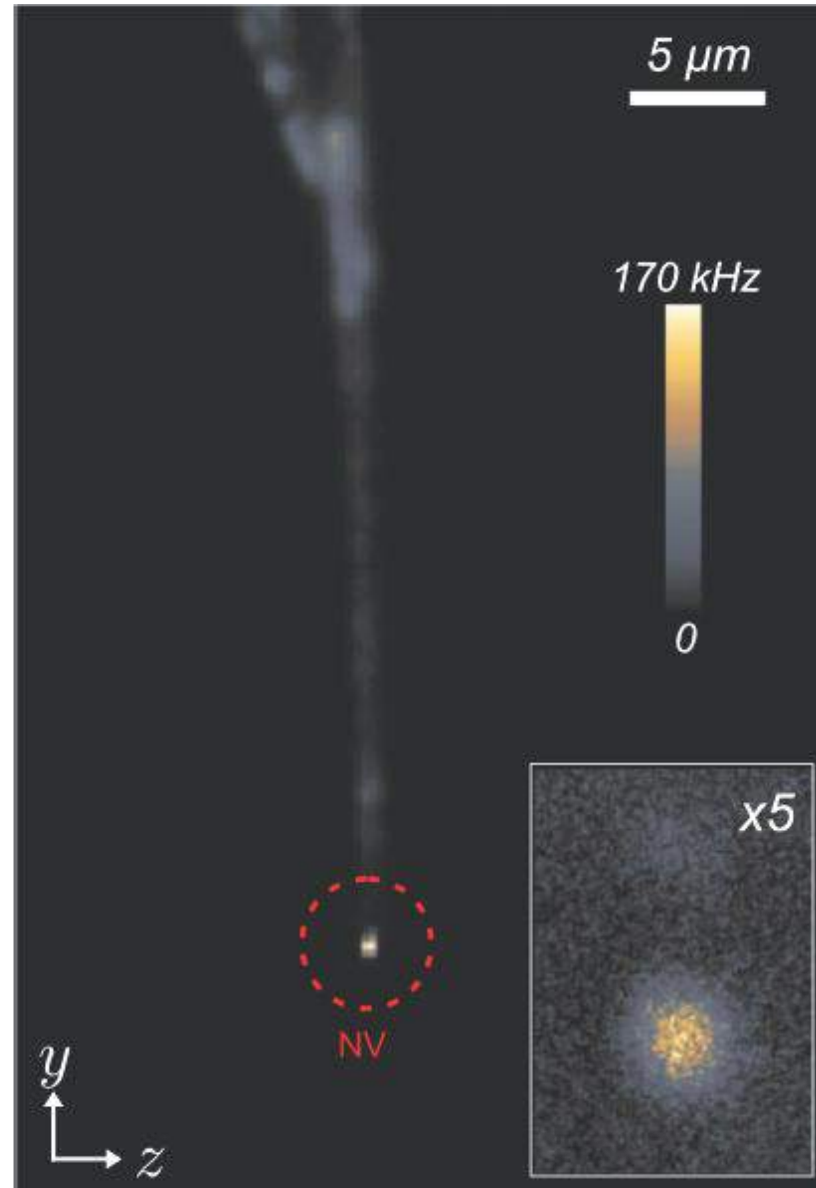
FIB cut of the nanowires

J.F. Motte @Nanofab

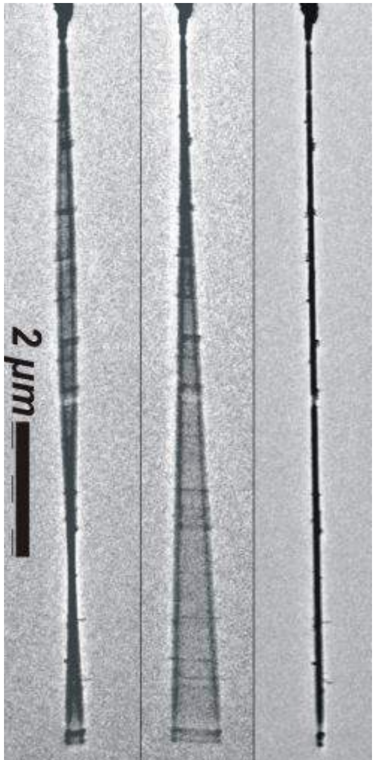
Optical and mechanical optimisations

A single NV center on a nano-mechanical oscillator





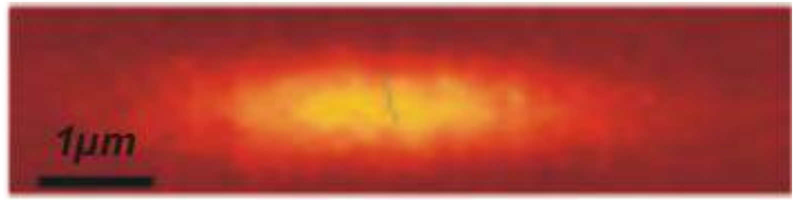
A NV center with a mechanical degree of freedom



4887 kHz

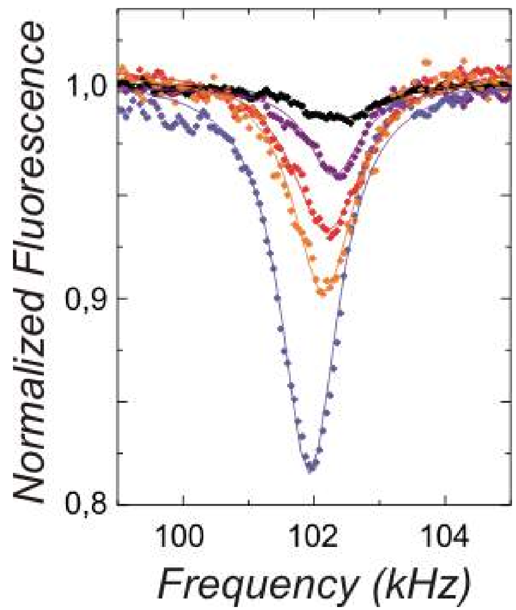
654 kHz

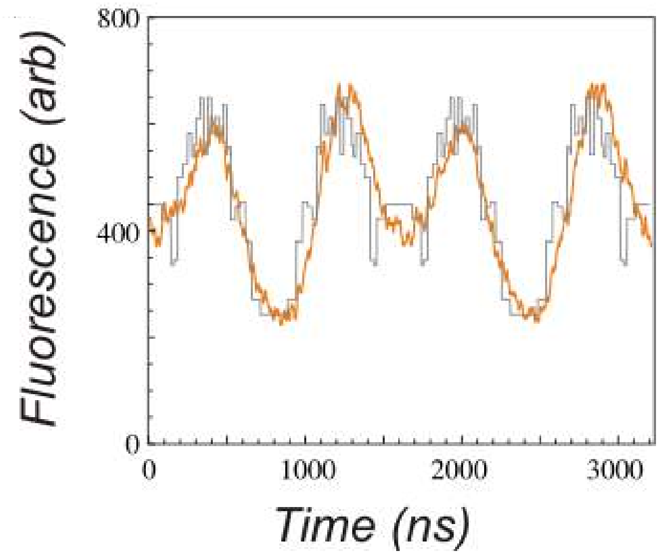
Rest



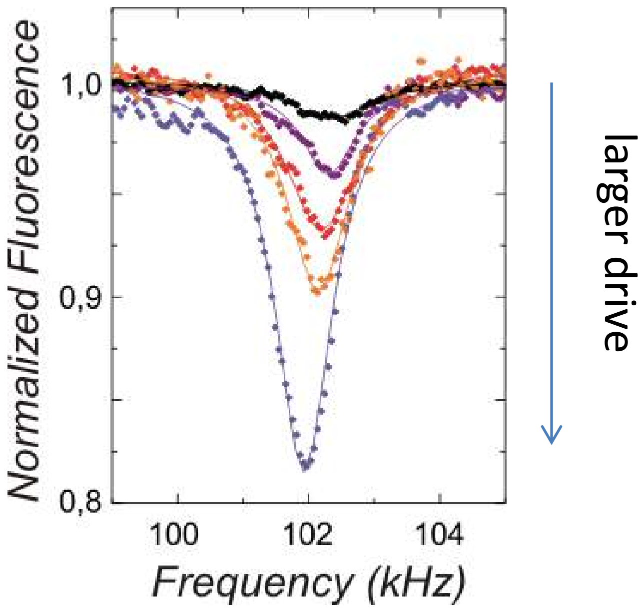
Fluorescence map

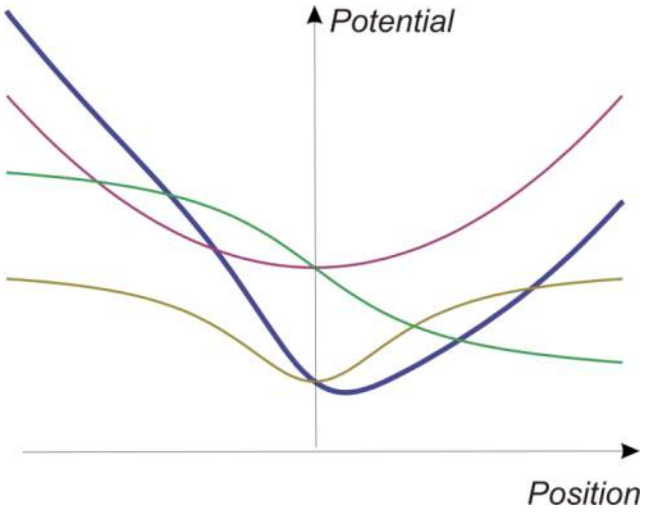
Laser



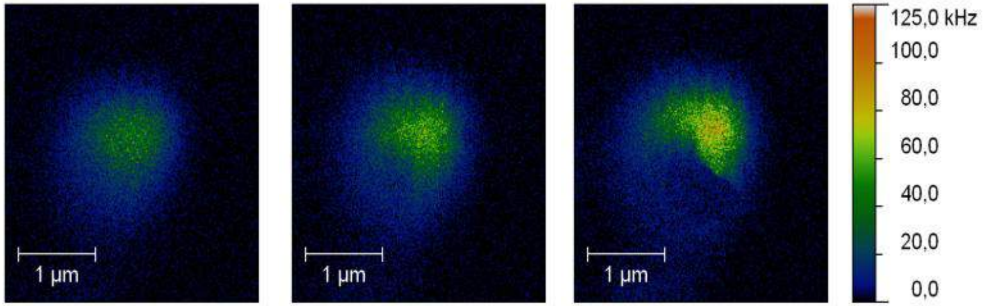


Optical forces acting on the nanoresonator



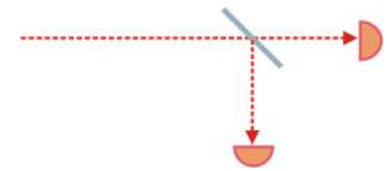


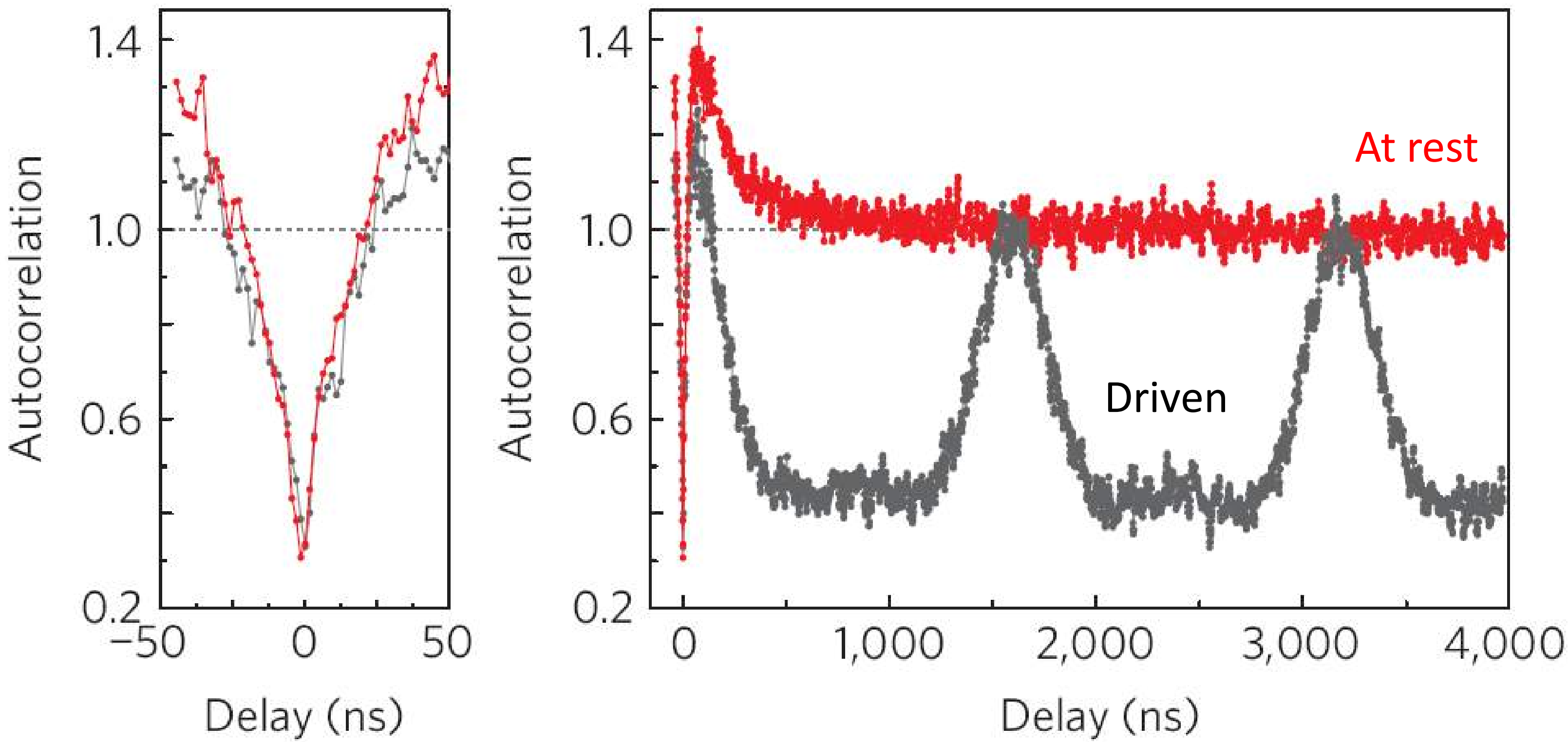
Static signatures of optical tweezers



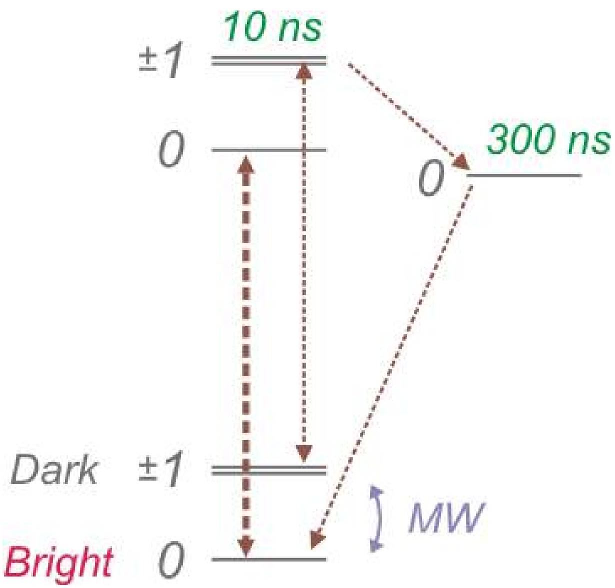
Oscillating signatures in the autocorrelation trace

Hanbury Brown Twiss setup





Electronic spin resonances (ESR)



The electronic spin state can be read out by pure optical means (photon counting)

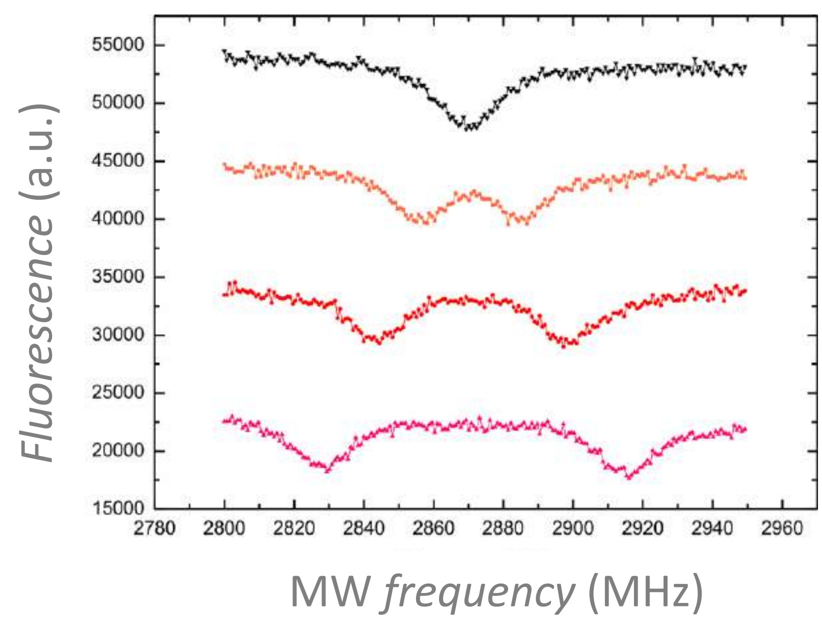
Manipulation with microwave fields (2.88 GHz)

Spin polarization through optical pumping

Optically detected electron spin resonance (ESR).

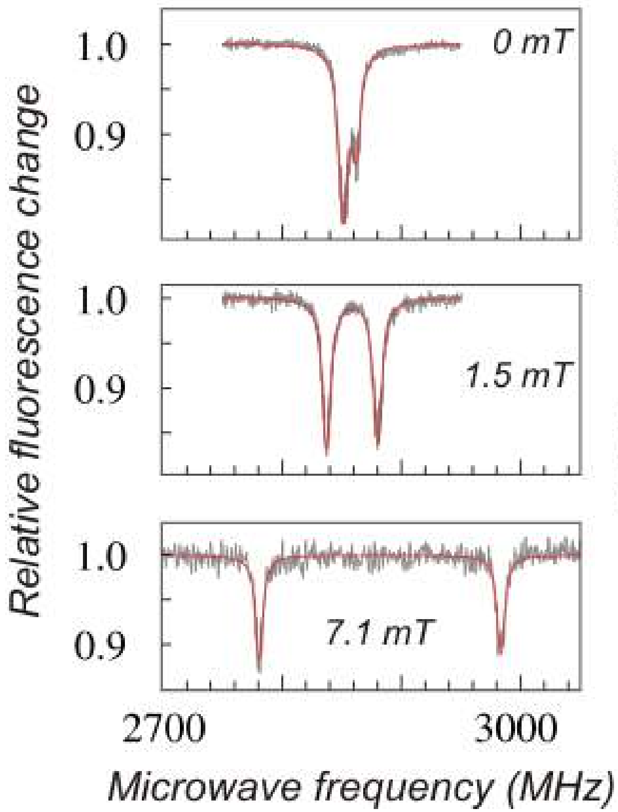
Magnetic sensitivity (Zeeman effect).
(28 MHz/mT)

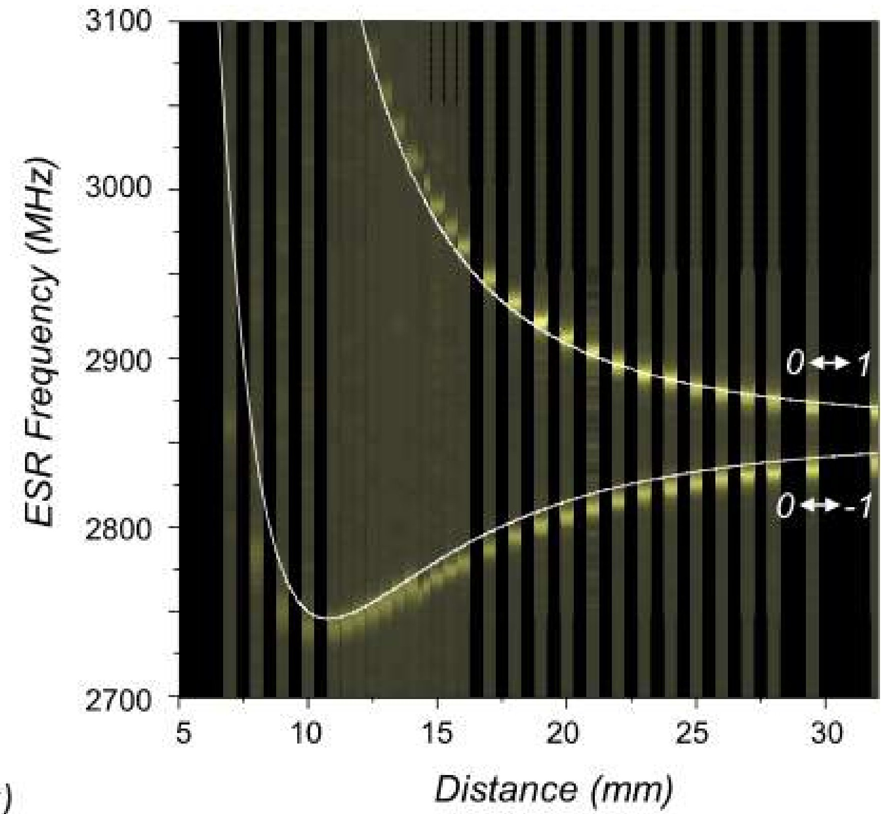
Nanosized magnetic field sensors
(µT dc-sensitivity with 50 nm nanocrystals)



ESR - A suspended magnetic field sensor

NV orientation determined with a calibrated NdFeB magnet





$$H_{\mathrm{spin}} = DS_Z^2 + E(S_X^2 - S_Y^2) + g\mu_B \mathbf{B} \cdot \mathbf{S}$$

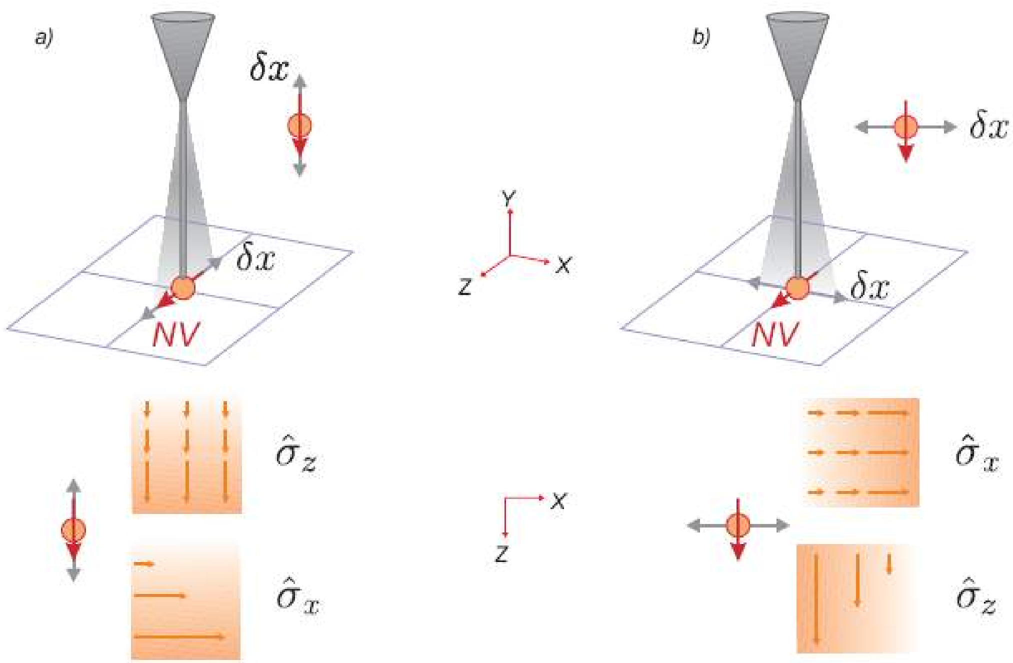
Slope: 28 MHz/mT
Linewidth: MHz range

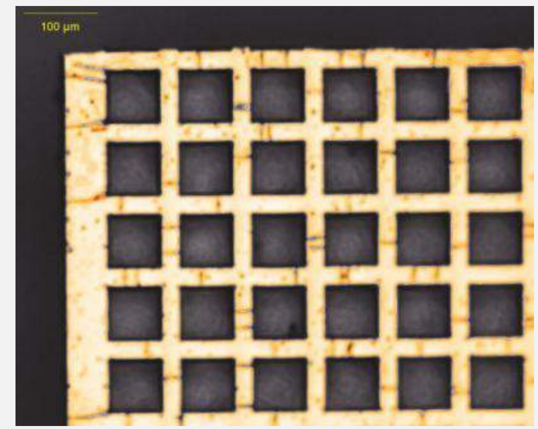
NV spin magnetically coupled to the nanomotion

Spin-position coupling achieved in **a strong magnetic field gradient**

$$H_{\text{int}} = g\mu_B \hat{\sigma} \cdot \mathbf{B}(\hat{\mathbf{r}}) \qquad \hat{\mathbf{r}} = \mathbf{r_0} + \hat{x}\,\mathbf{u}$$

$$H_{\text{int}} = g\mu_B \hat{\sigma} \cdot \mathbf{B}(\mathbf{r_0}) + g\mu_B \hat{x}\,\hat{\sigma} \cdot (\mathbf{u} \cdot \nabla)\mathbf{B}$$





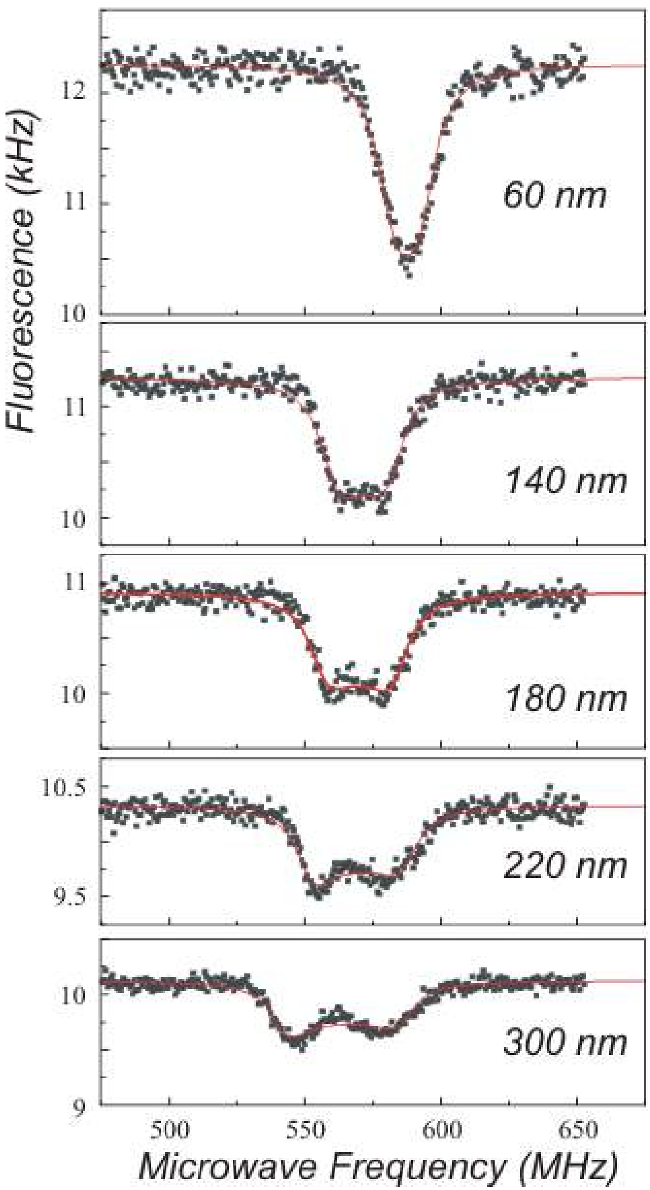
NdFeB on Silicon

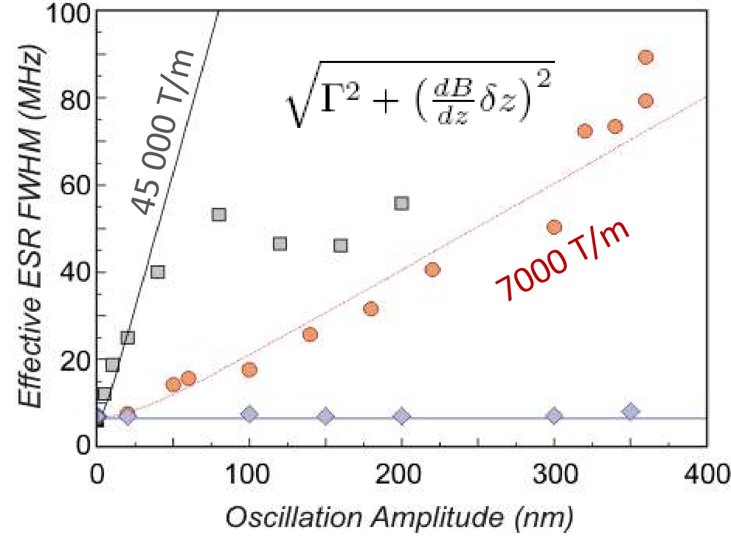
N. Dempsey, F. Dumas-Bouchiat, O. Fruchart, D. Givord,…

up to 10^6 T/m=1 T/µm

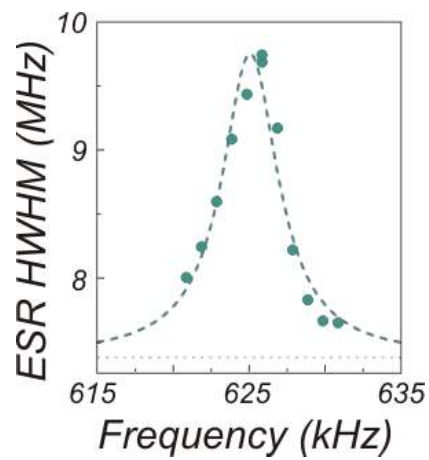
A single-spin-based nanomotion transducer

625 kHz driving





$$\Xi(f, \delta z) = \frac{1}{T}\int_0^T \mathfrak{L}\left(f, f_0 - \frac{g\mu_B}{h}B(\delta z \cos\Omega_m t)\right) dt$$

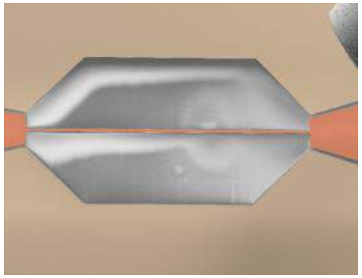


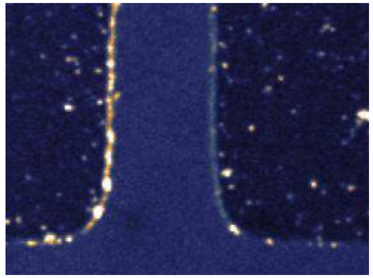
Coupling strength up to
100 mT/µm
(100 000 T/s)

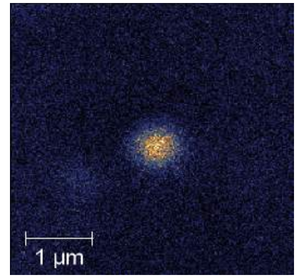
Adiabatic regime
625 kHz vs 7 MHz
$\Omega_m < \Gamma_{spin}$

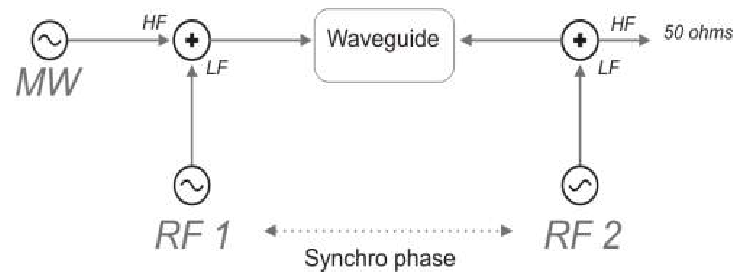
Nature Physics, 2011

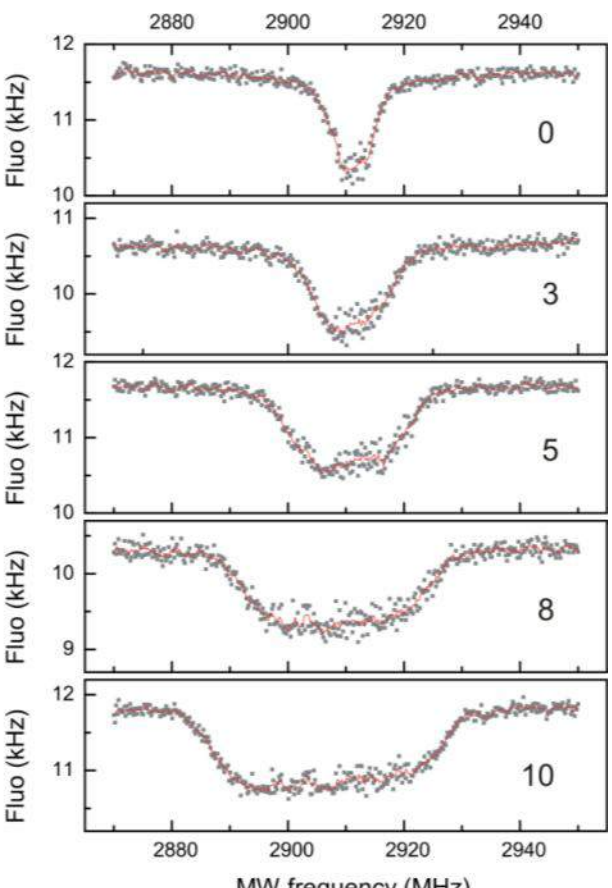
Experimental simulation of the RSB regime $\Omega_m > \Gamma_{spin}$











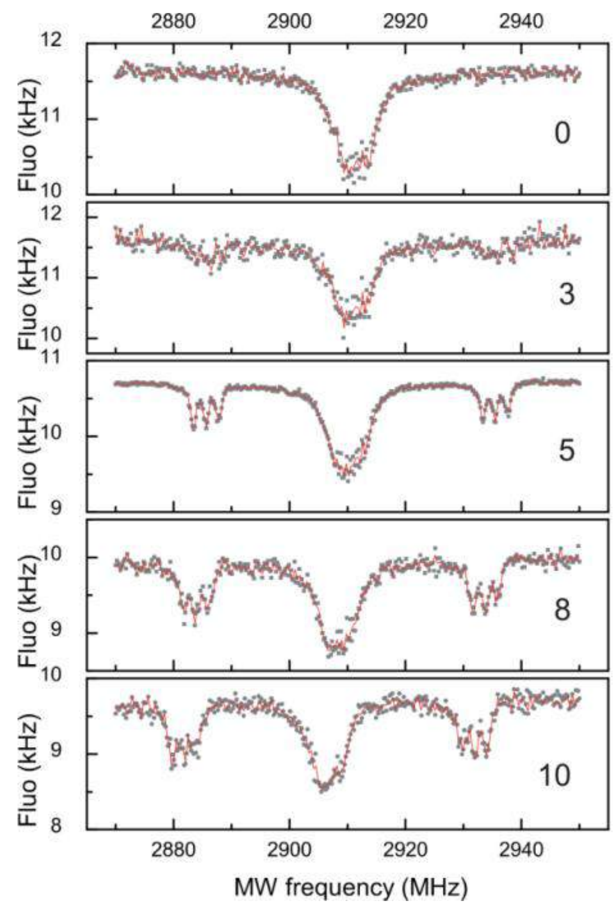
RF @100 kHz

A RF field simulates the oscillating magnetic field seen by the NV defect

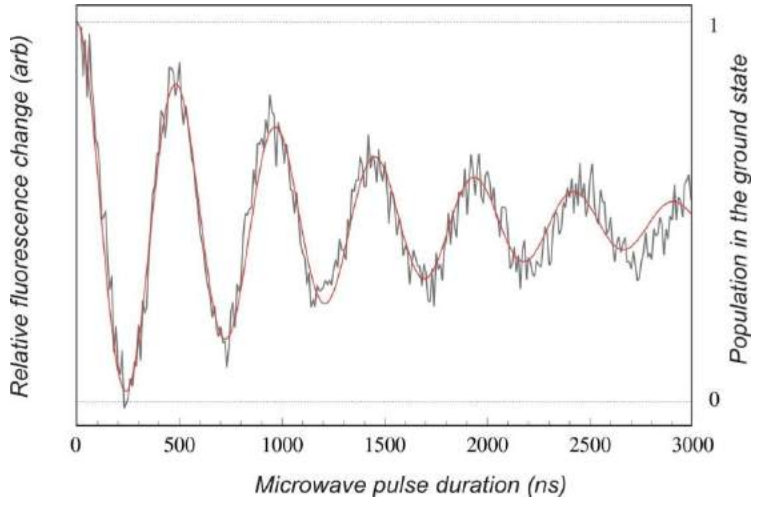
Sven Rohr PhD Thesis & Eva Dupont Ferrier

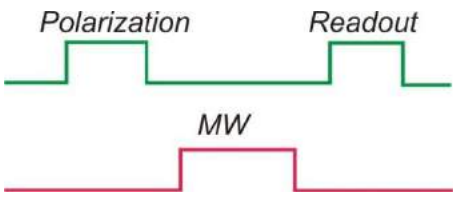
+Matthieu Dartiailh

RF @25 MHz

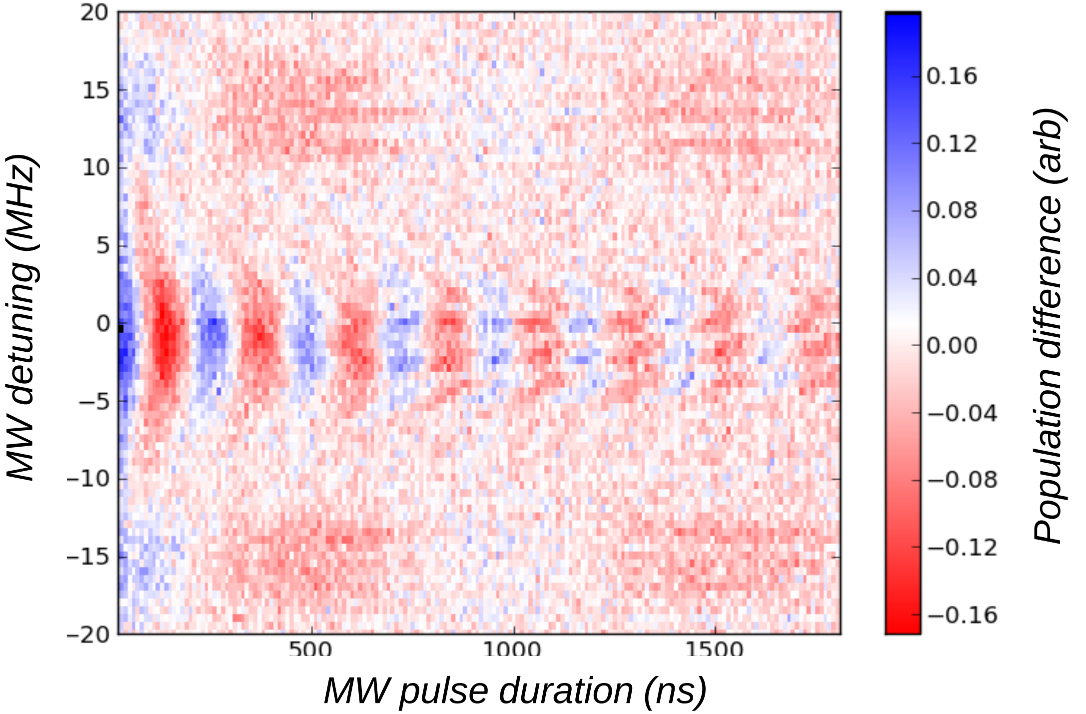


Spin dynamics in the RSB regime (dispersive coupling)





Rabi oscillations for varying MW detuning



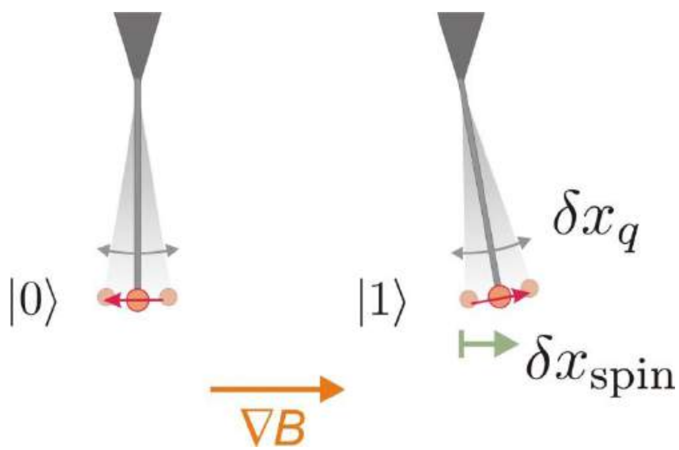
Phonon number estimation through sideband thermometry (asymetry appearing close to the ground state)

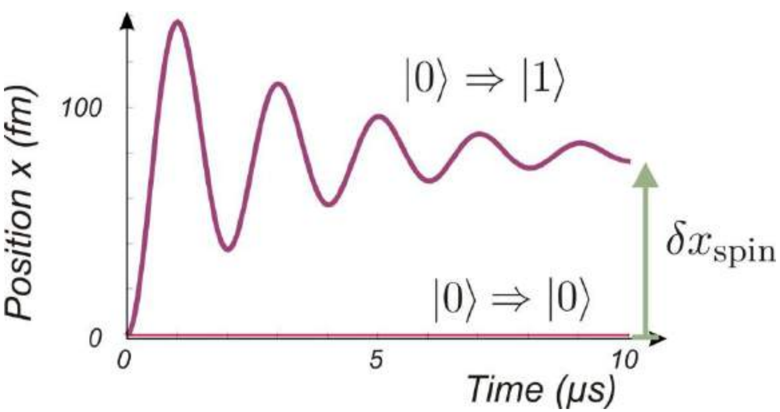
S. Rohr et al, in preparation

Next step: Spin dependent forces

$$H_{\rm int} = \hbar\lambda(\hat{a} + \hat{a}^\dagger)\hat{\sigma}_z$$

$$F(m_S) = g\mu_B \nabla B m_S$$





Magnitude

20 aN @10^6 T/m $\delta x_{\rm spin} = 80\ {\rm fm}$

Force sensitivity (300K) = 9 aN/$\text{Hz}^{1/2}$

⇨ Spin state encoding on the oscillator dynamics (Stern - Gerlach effect) 25 s @300K

Mechanical QND readout of spin state

⇨ Observing spin quantum jumps with ultracold oscillators

Other directions

Spin cooling of the resonator

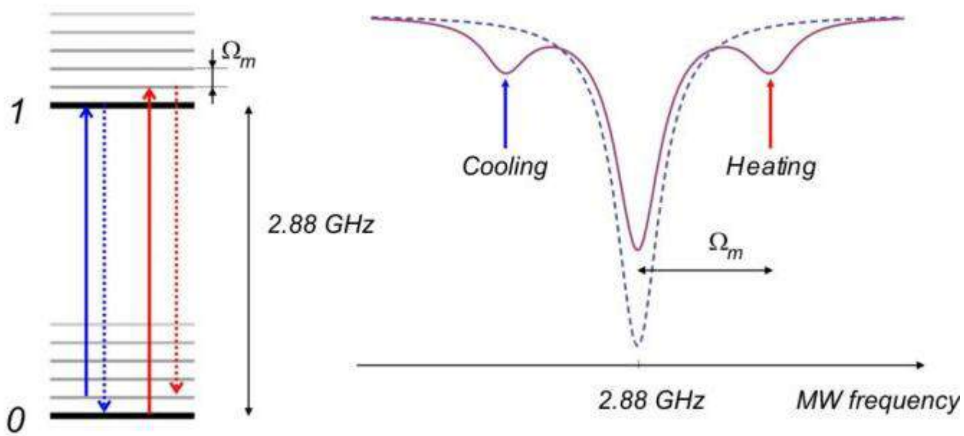
Strong & Ultrastrong coupling regimes

Future: Spin cooling of mechanical motion

PHYSICAL REVIEW B 82, 165320 (2010)

Cooling of mechanical motion with a two-level system: The high-temperature regime

P. Rabl



Resolved sideband regime
and active cooling protocols

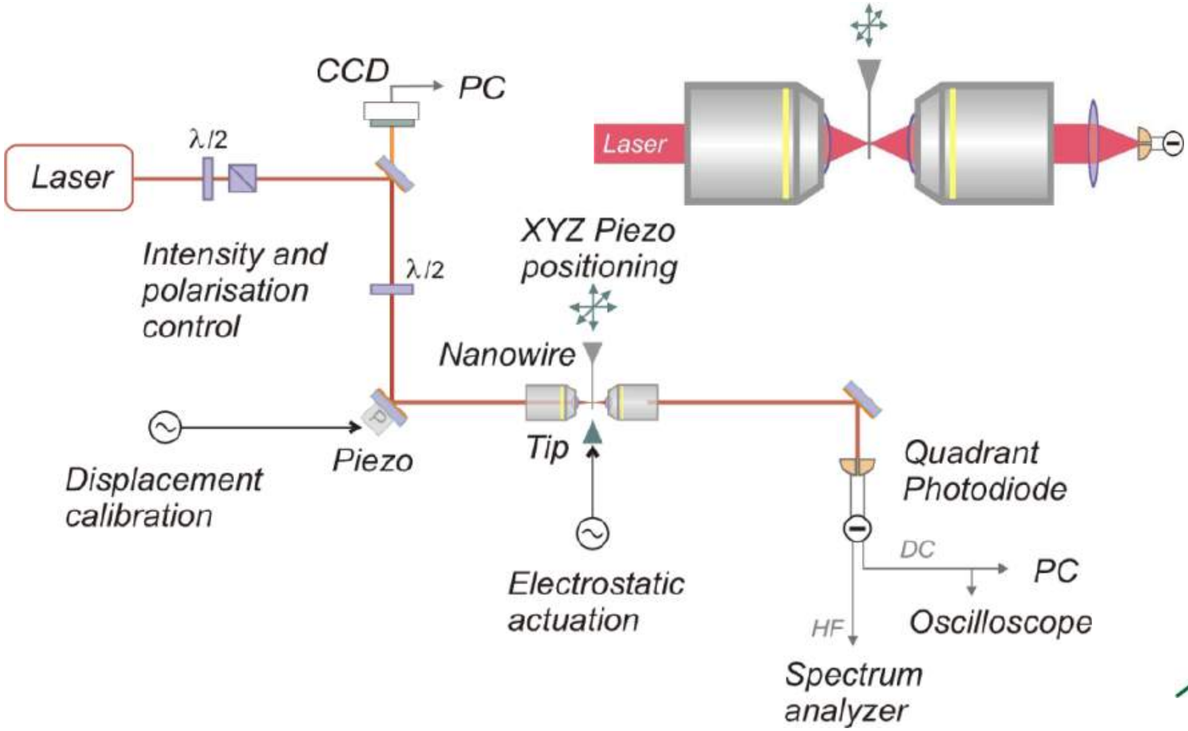
$$\Omega_\mathrm{m} \gg \Gamma_\mathrm{spin}$$

Resolved motionnal sidebands

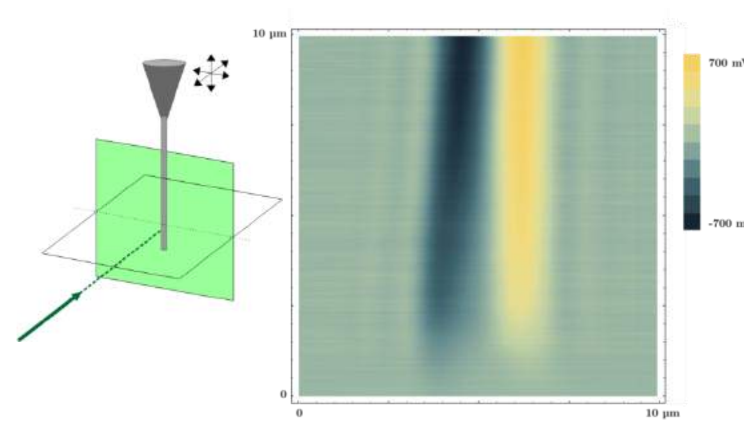
New cooling protocols

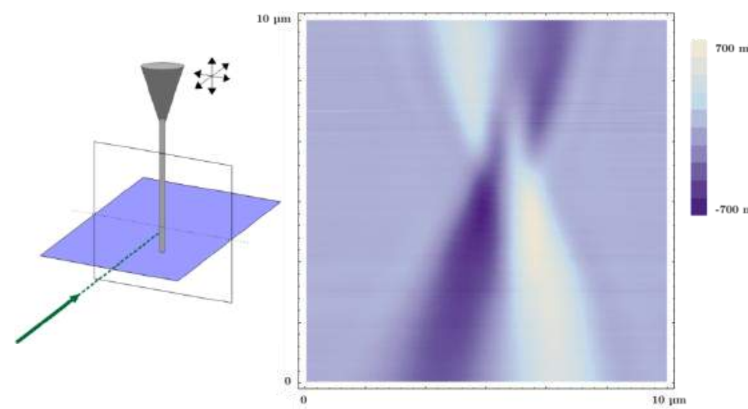
Rabl & Lukin PRB 2009, PRB 2010

Optical readout of the nanomotion



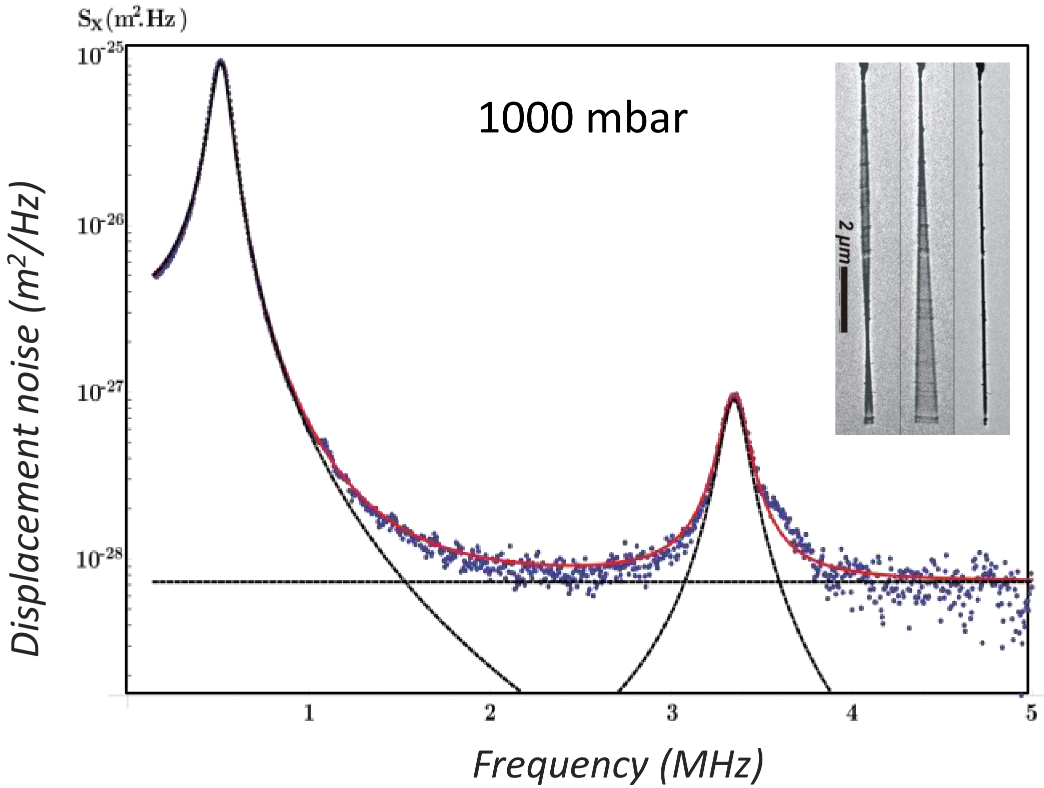
Arnaud Gloppe PhD Thesis
& Eva Dupont Ferrier





Vacuum operation (1e-4 mbar)
Low noise photodiode amplifier
Electrostatic actuation

Brownian motion of SiC nanoresonators

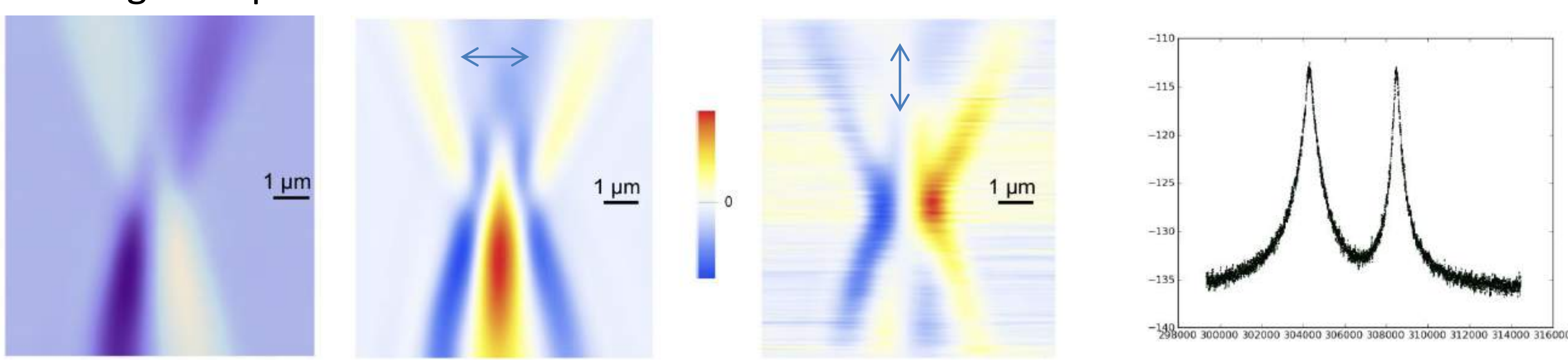


Shot-noise limited detection sensitivity (approx1 fm/Hz$^{1/2}$ for 10 mW)

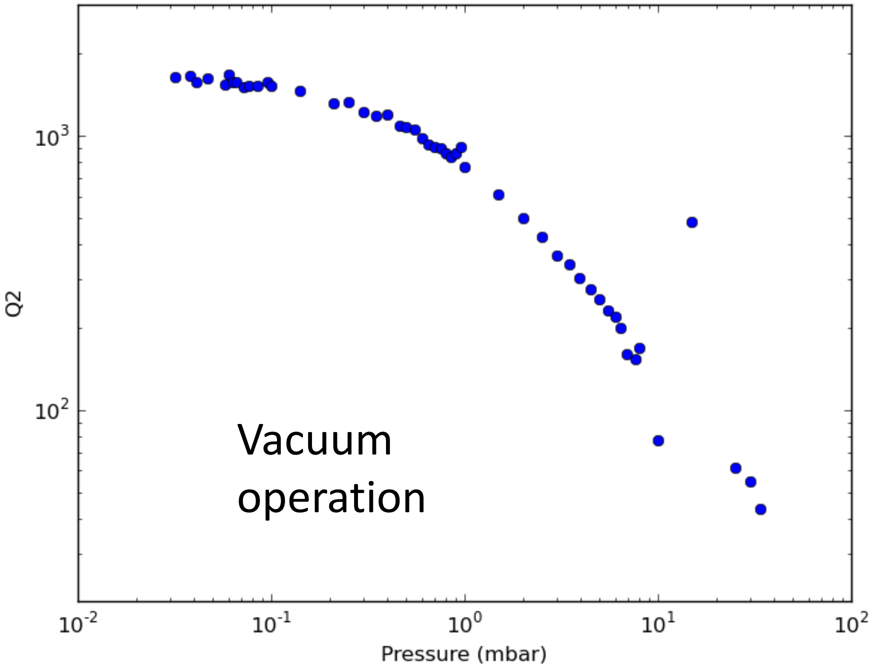
Approaching the standard quantum limit in a cavity-free experiment.

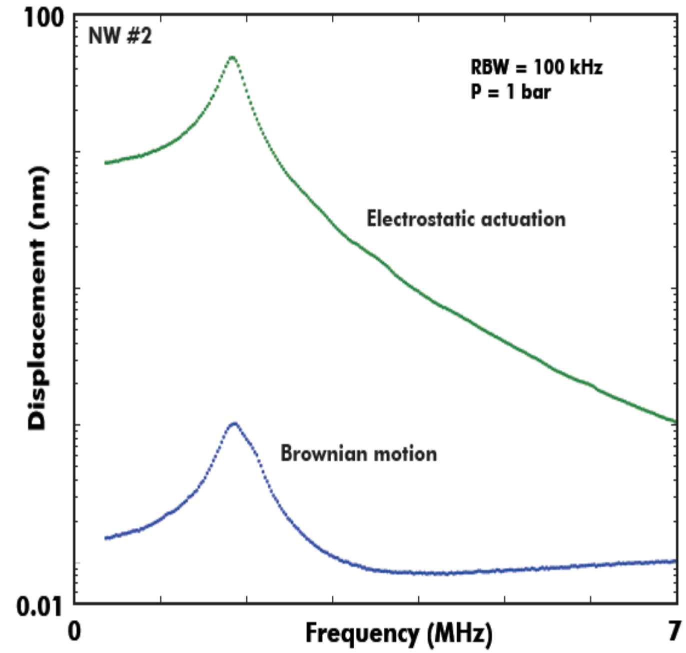
Ultrasensitive force sensors: aN/Hz$^{1/2}$ at room temperature

Probing both polarisations of vibration : vectorial force sensor

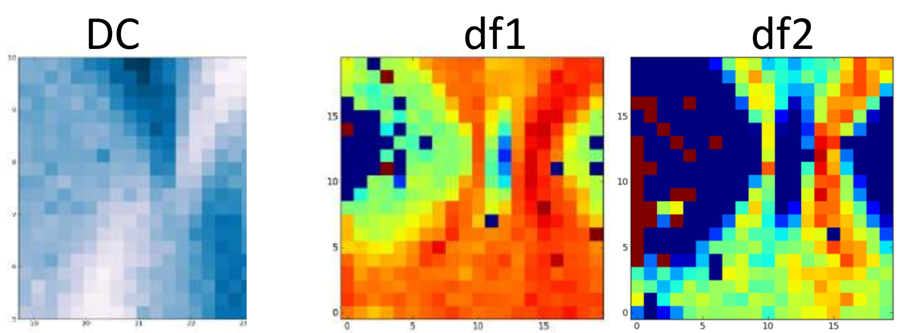


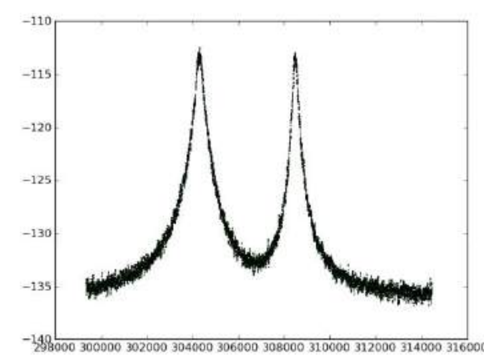
Towards ultrasensitive force sensitivity





Optical forces: radiation pressure and gradient force

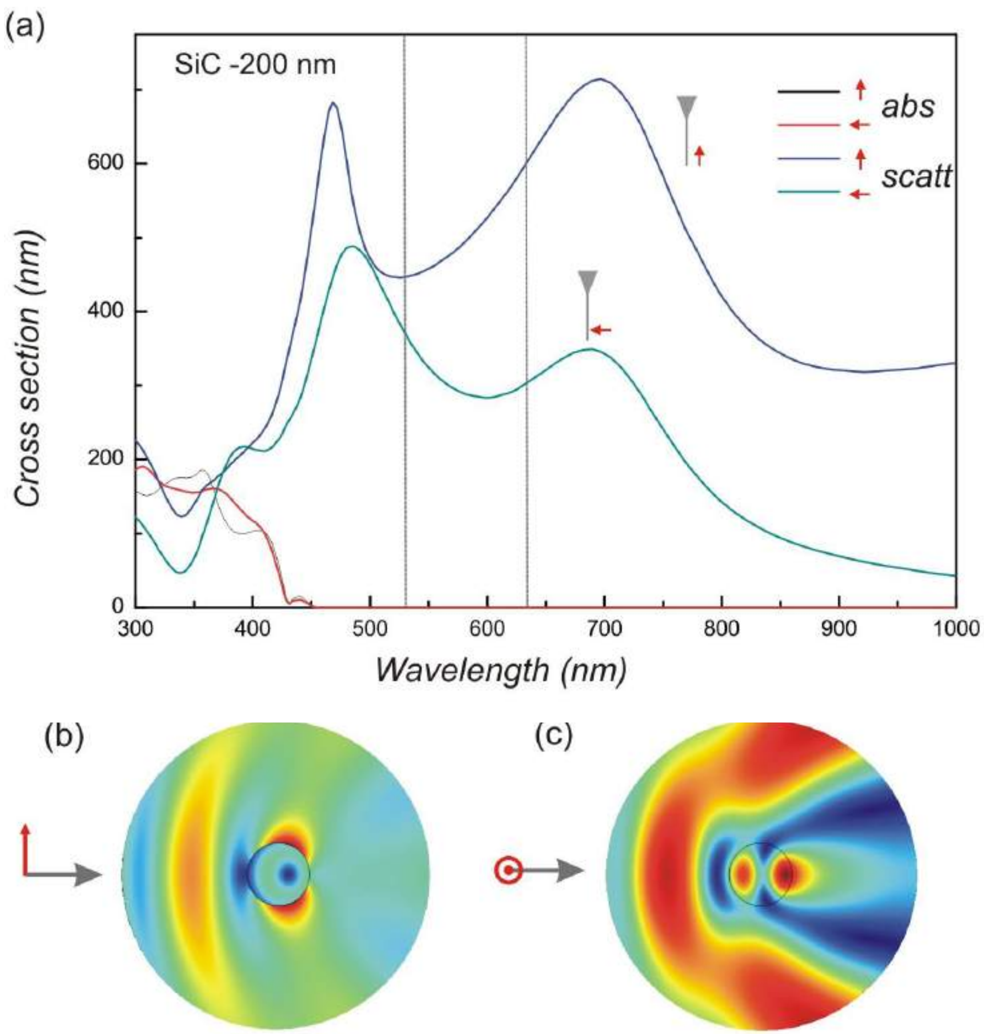




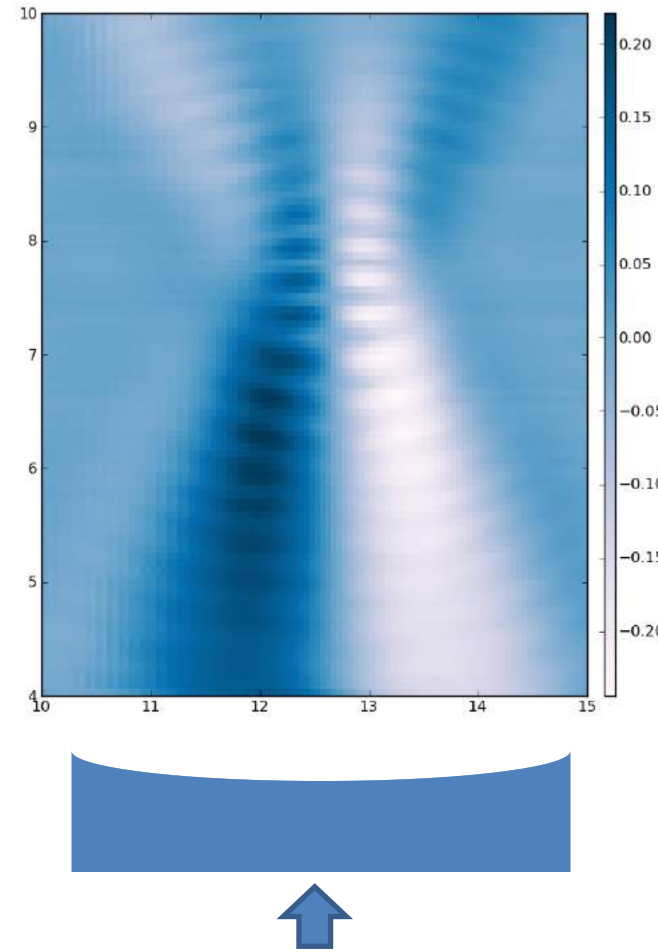
Measured on the Brownian motion

Optical resonances of the nanowires

FEM Simulation (G. Bachelier)

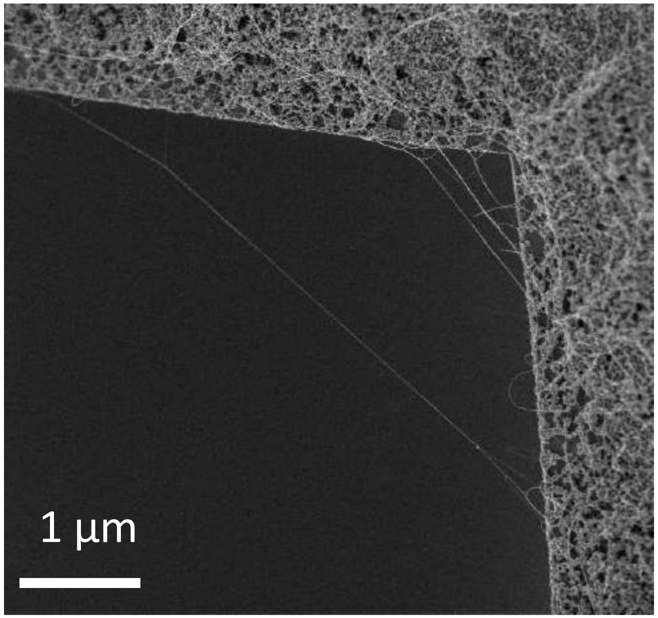


Wave fronts at the optical waist

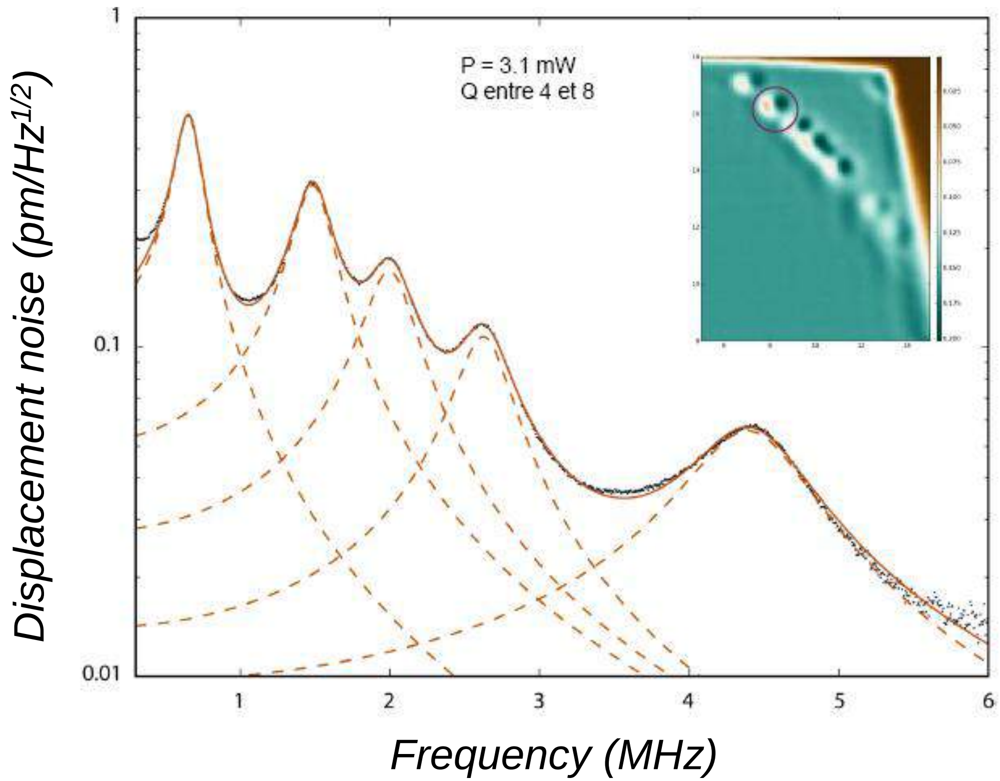


laser

Brownian motion of carbon nanotubes

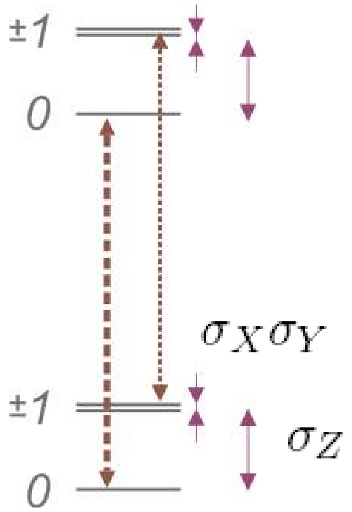


Optically resonant nanotubes



In collaboration with A. Reserbat, V. Bouchiat, L. Marty, N. Bendiab

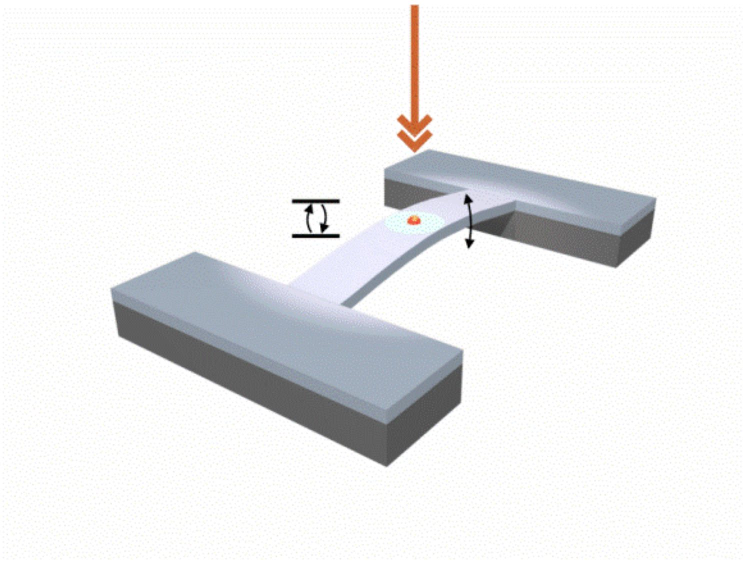
Strain coupling in diamond nanoresonators



a 2 Gpa strain increase induces a 10 meV shift of the 1.945 eV ZPL

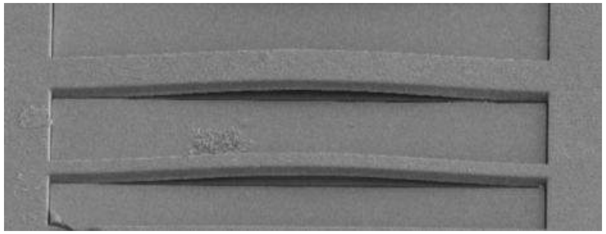
$$H_{\text{int}} = \frac{Y}{L}\frac{dE}{dP} S_Z \, z \qquad H_{\text{int}} = g\mu_B \nabla B \, S_Z \, z$$

4 orders of magnitude larger than the magnetic coupling



Development of diamond nanoresonators
Cryogenic operation

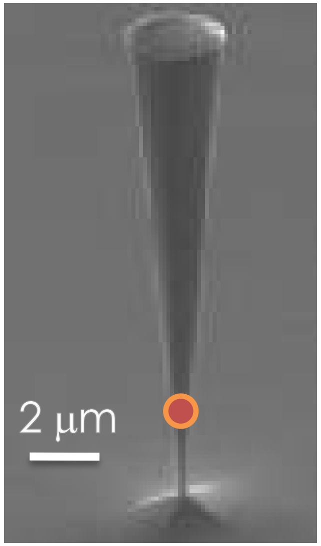
SCGG and CQ groups and P. Olivero (Turin)
NV implantation : J. Meier (Bochum)

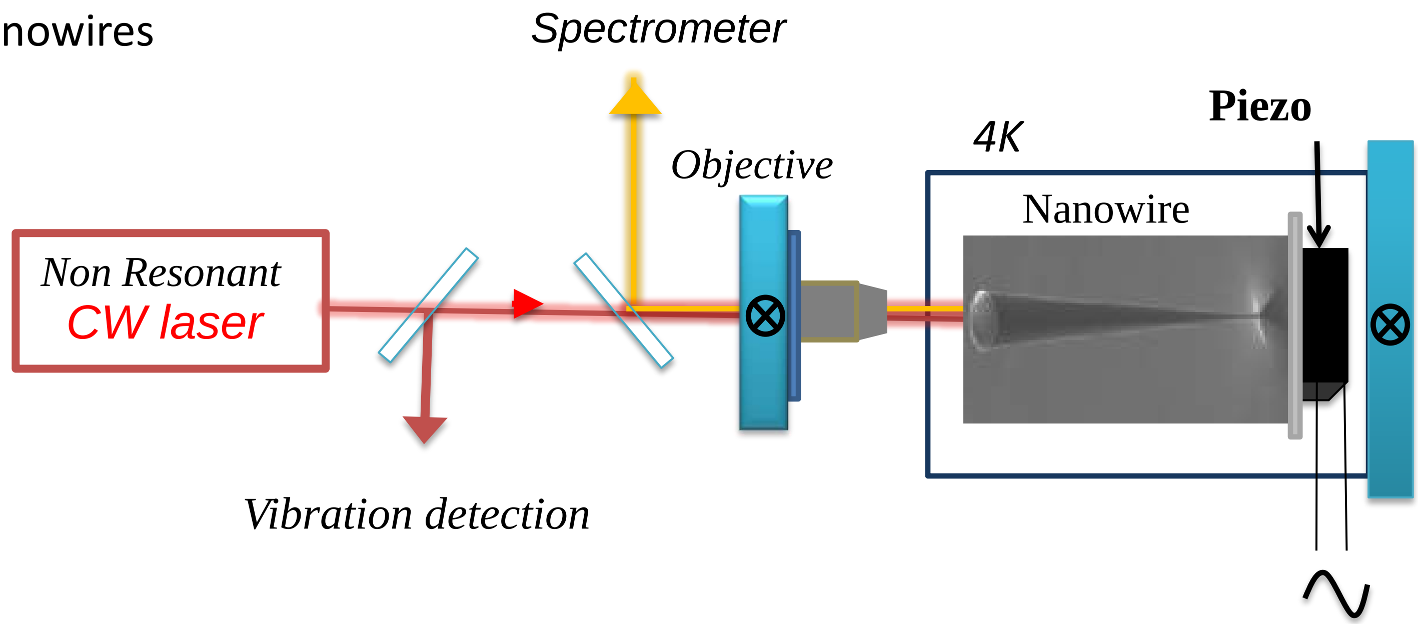


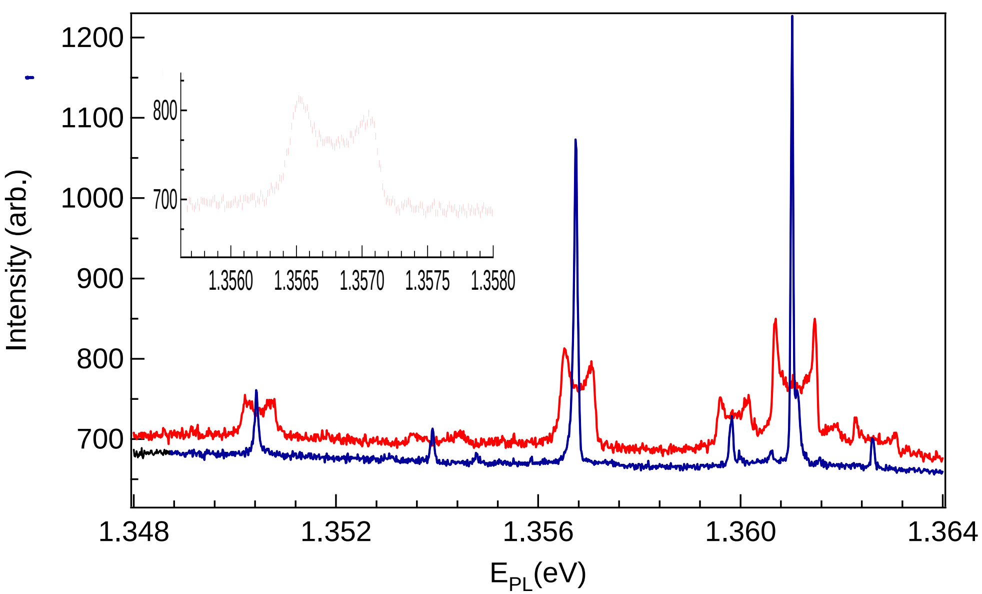
Monocrystaline resonators

Strain coupling to QD in photonic microwires

InAs QD in GaAs nanowires





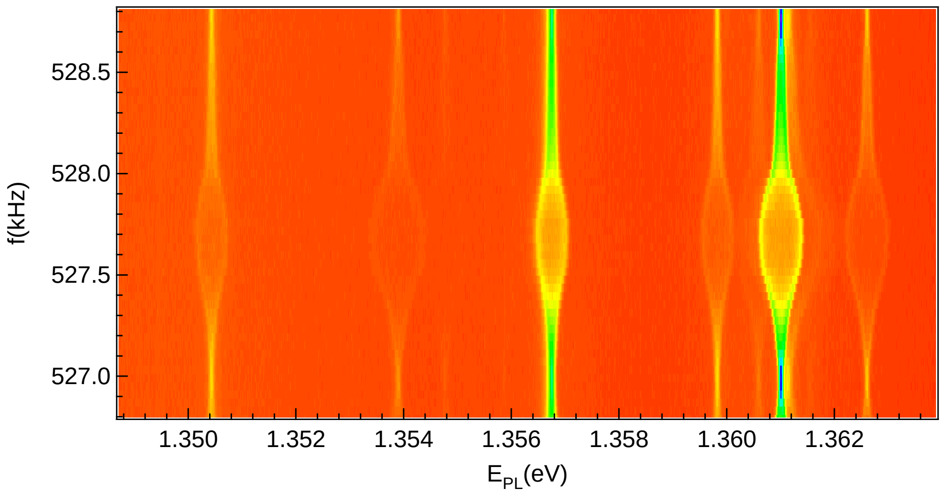


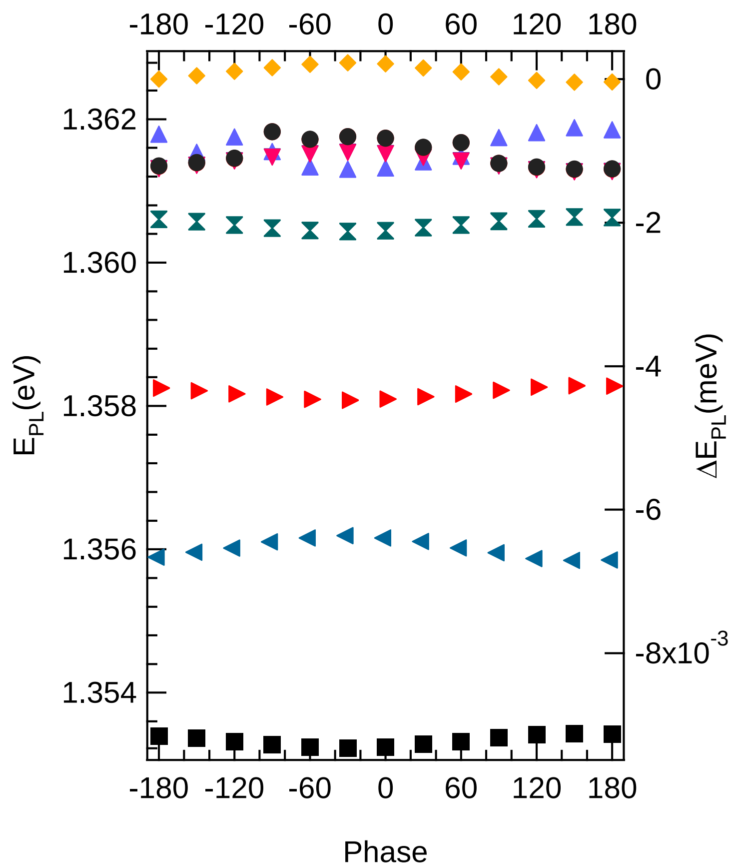
Integrated hybrid structures

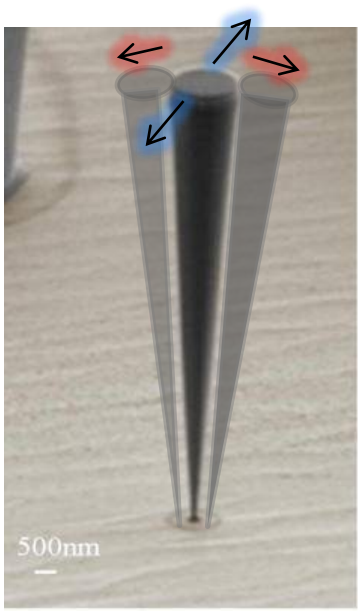
Larger coupling strength
QD localization

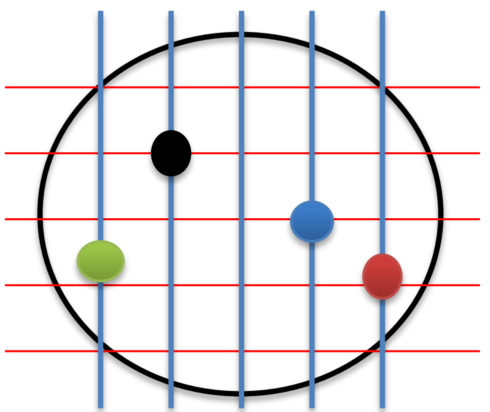
PhD Inah Yeo, PL de Assis
J.P. Poizat, M. Richard, A. Auffeves.
G. Nogues
fab.@ CEA: J. Claudon J.M. Gerrard

Strain coupling with QD in GaAs photonic microwires

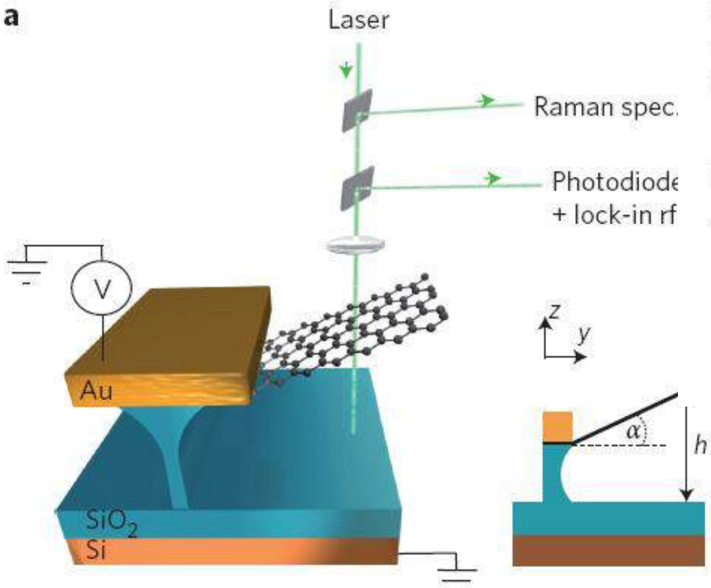


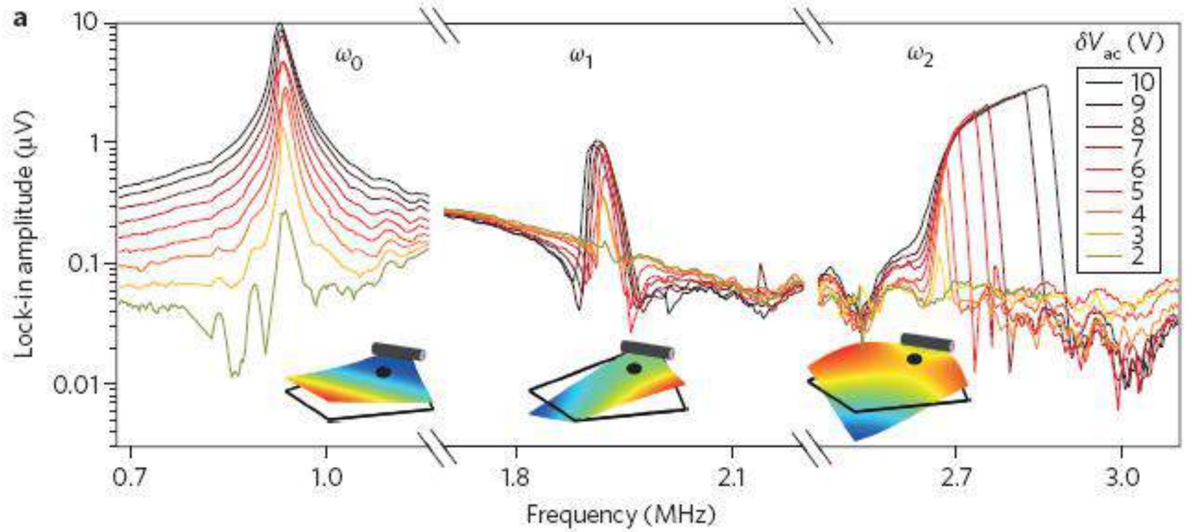




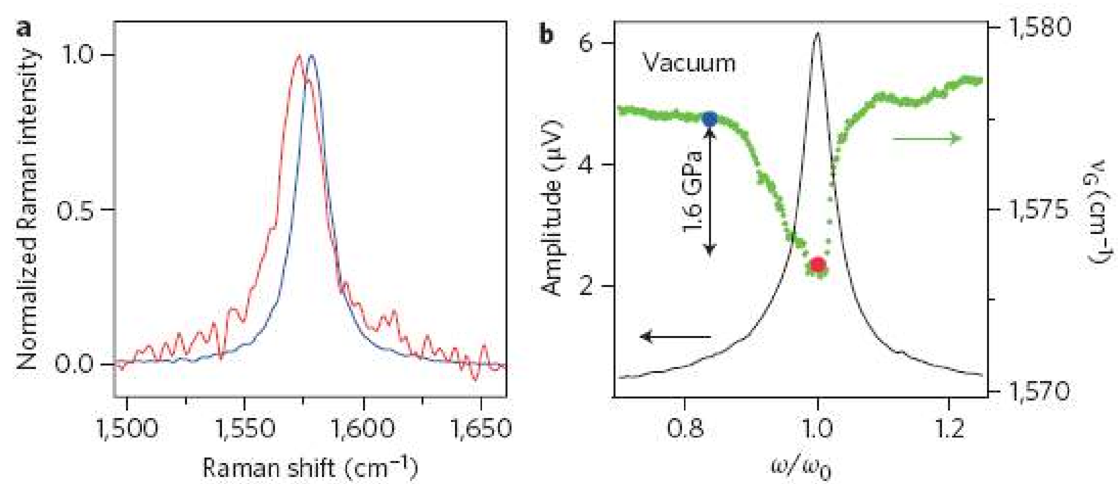


Dynamical strain measurement with Raman spectroscopy





G band

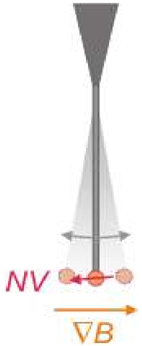


Access to both stress and strain with an optical resolution

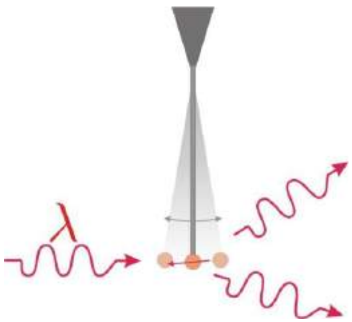
A. Reserbat, V. Bouchiat,
B. L. Marty, N. Bendiab

A. Reserbat-Plantey et al, Nature Nanotechnology, 2012

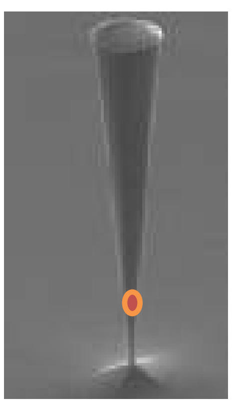
Conclusion



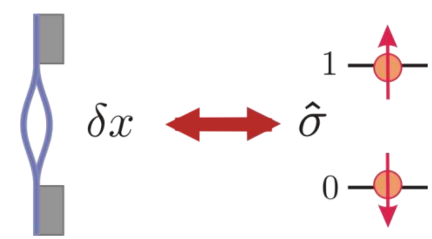
Magnetic coupling between a NV electronic spin and a nanomechanical oscillator



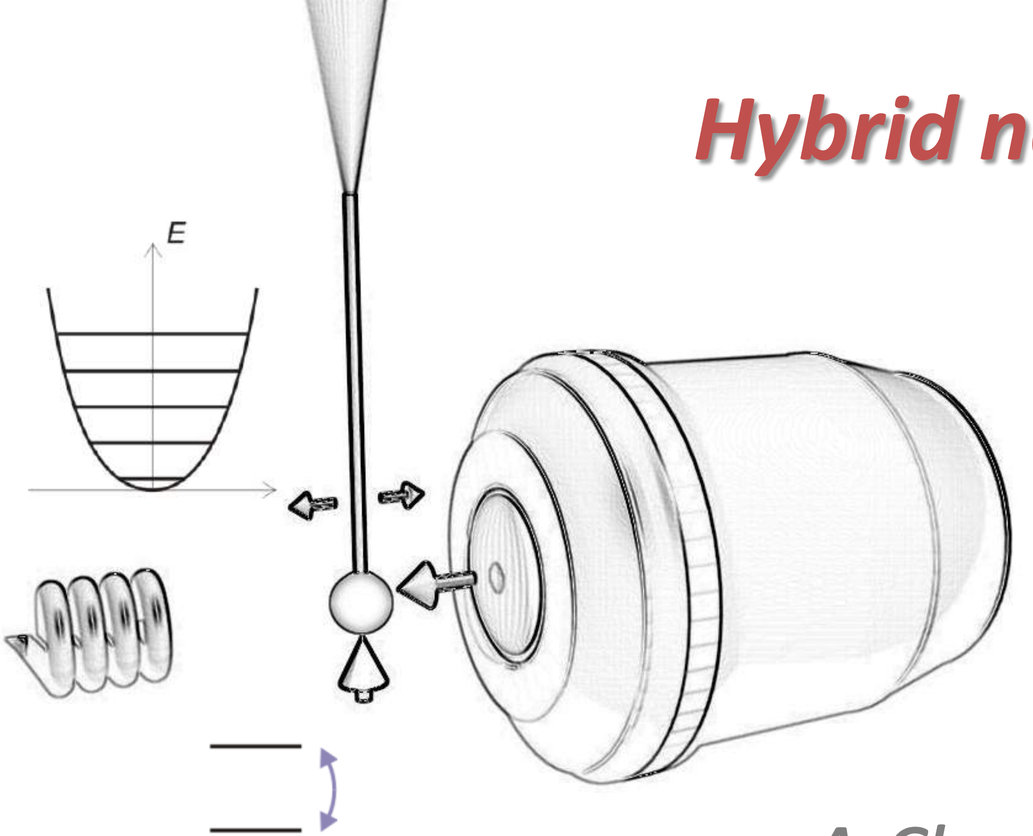
Optical readout of nanomechanical oscillators



Strain coupling



Hybrid nano-optomechanics



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