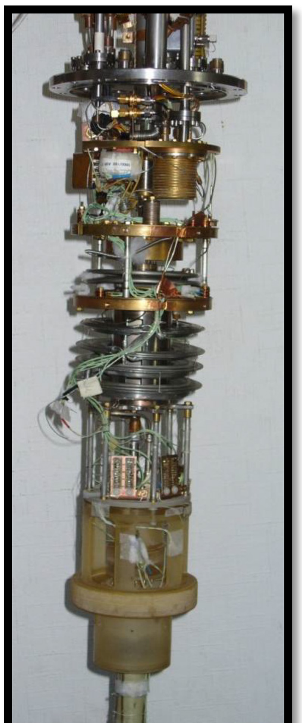
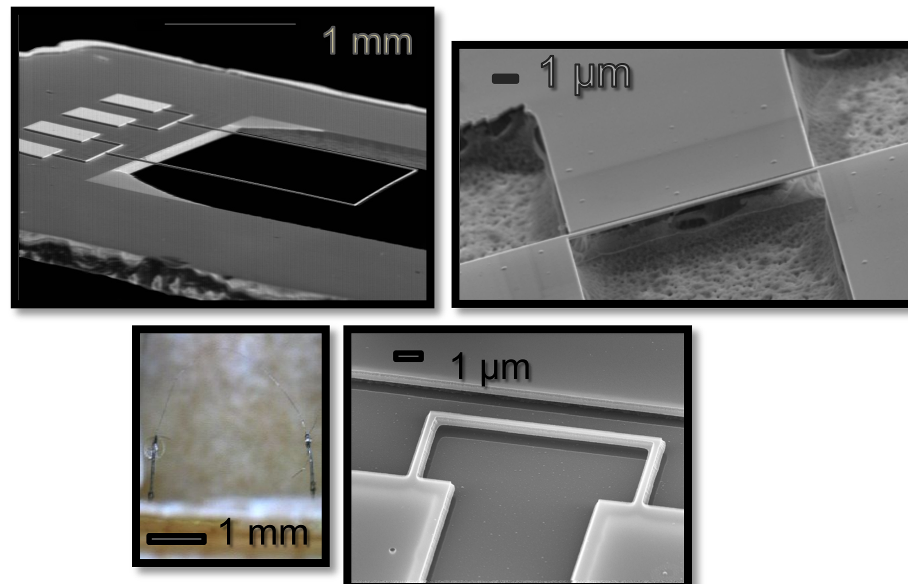
Low temperature micro/nano mechanics



Demag fridge ULT Group, I. NEEL



Low temp. devices, ULT Group, I. NEEL

E. Collin, ULT group Grenoble - Néel institute, CNRS

OIST 04/2012

Outline

Why micro and nano mechanical systems?

Brief history
& key remarks

Micro-electo-mechanical : **MEMS** Micro-opto-mechanical : **MOMS**

Nano-electo-mechanical : **NEMS** Nano-opto-mechanical : **NOMS**

Introduction to experimental techniques

How to actuate a micro/nano mechanical device?
How to detect a micro/nano mechanical device's motion?
What type of micro/nano mechanical devices?
Why is "small" different?

Why micro and nano mechanics at low temperatures?

Review of published works ; how our works gets inserted in that
& key aspects of low temperature micro/nano mechanics

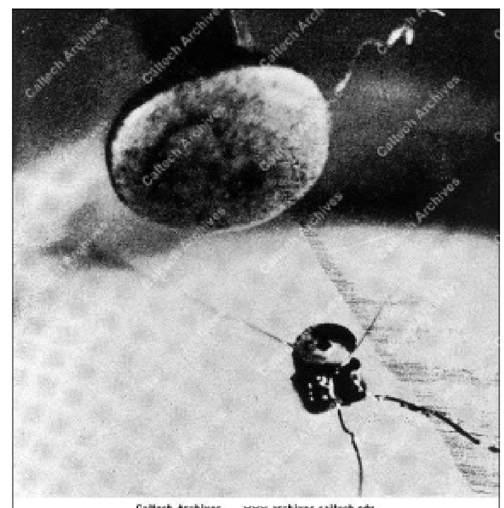
Why micro and nano mechanical systems?

A bit of History:

1948: Transistor (Bardeen, Brattain, Shockley)
1958: Integrated Circuit (Kilby, Noyce)
1959: Feynman's famous conference
"There is plenty of room at the bottom"

Feynman's competition:
$1000 to create an electrical motor "smaller than 1/64th of an inch"
(i.e. less than 0.4 mm)

CalTech



Winner William McLellan, using tweezers and a microscope!

Source:
J.A. Pelesko & D.H. Bernstein, Chapman & Hall/CRC 2003
R. Feynman, Journal of microelectromechanical systems **2**, 1993
And… the Web!

Why micro and nano mechanical systems?

A bit of History:

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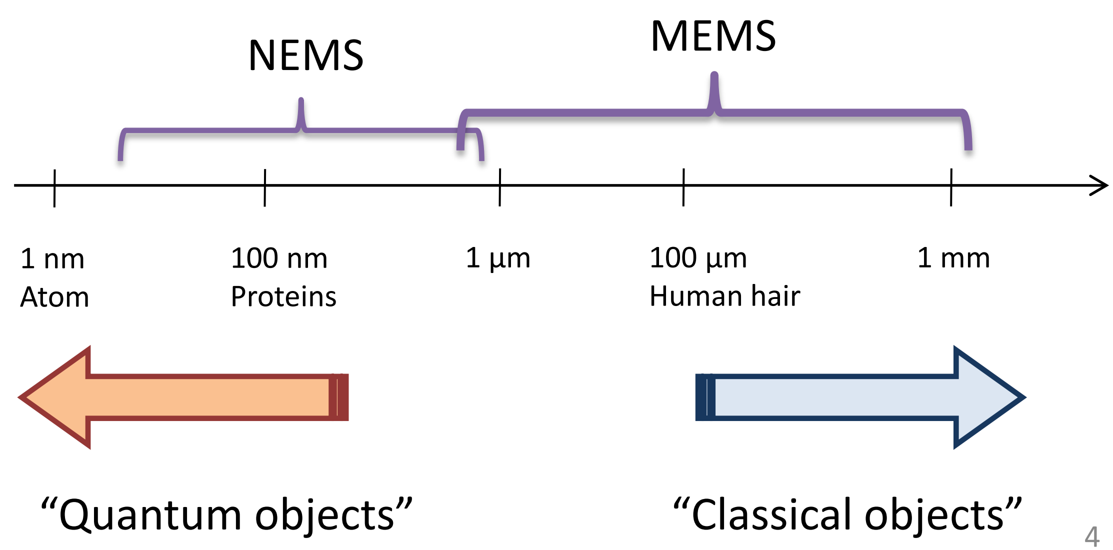
1959: Feynman’s famous conference
“There is plenty of room at the bottom”
1964: First batch fabricated micromechanical device
(H.C. Nathanson et al.)

Feynman’s point:
Trying to imagine all what could be done by “micro-machines”!



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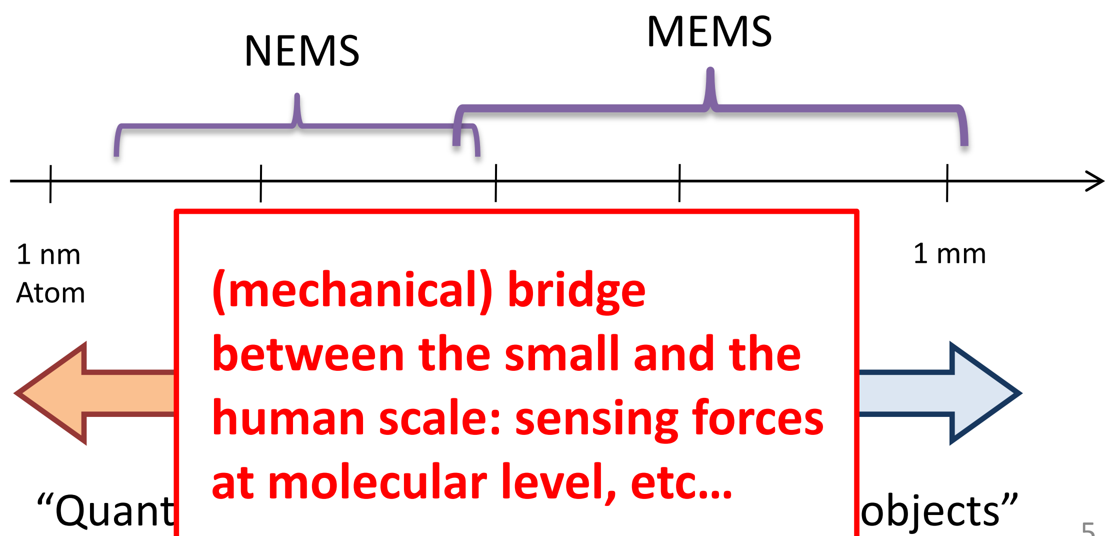
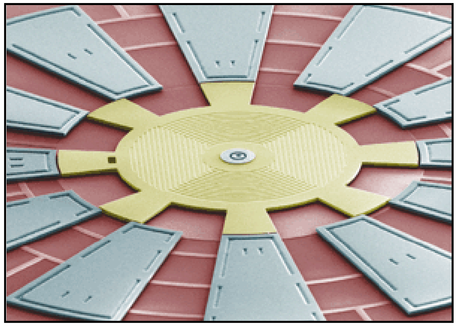


(mechanical) bridge between the small and the human scale: sensing forces at molecular level, etc...

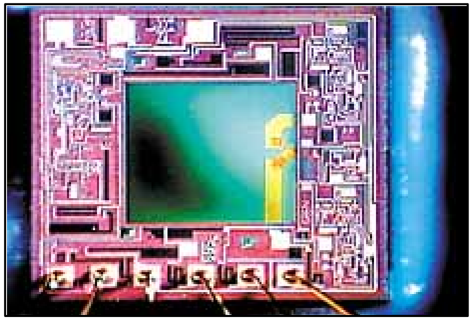
Why micro and nano mechanical systems?

A bit of History:

Since then: **explosion** of proposals, applications and research on MEMS/NEMS



(Texas Instrument M. Mehregany)
SEM (false colors) image of a motor a few microns in diameter



(X-ducer, Motorola)
Manometer, membrane 3 x 3 mm, two op-amps on-chip, measures pressures from 10 bar to 40 mbar, differential

Why micro and nano mechanical systems?

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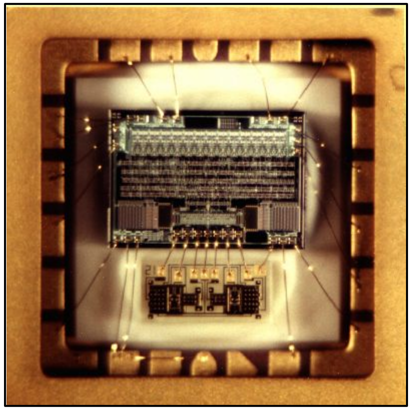
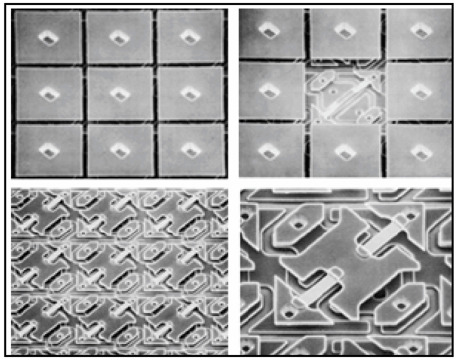


(Silicon Designs, Inc.)
Accelerometer, from 1 g to 20 000 g, one to three axes.
1 mm plane supported by 100 µm x 100 µm x 5 µm pillar; air bag launcher



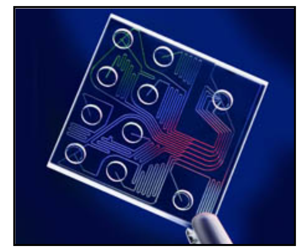
(Texas Instruments, DID)
Digital projector (Deformable Mirror Device).
Micro mirrors. Each mirror can be switched on/off to modulate the light, creating the image

Why micro and nano mechanical systems?

A bit of History:

Since then: **explosion** of proposals, applications and research on MEMS/NEMS

… and many more (microfluidics – lab on chip, etc…)

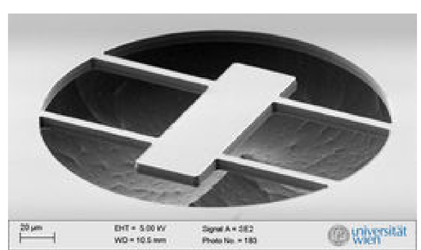


Agilent Technologies

Introductory papers on on-going research:

K. Schwab and M. Roukes, Physics today 2005: claimed **“everything moves!”**
This is back to Feynman’s argument, but introducing explicitly **quantum mechanics**

F. Marquardt and S. Girvin, Physics 2009: on **“Optomechanics”**
Considering the quantum nature of photons interacting with mechanical objects



M. Aspelmeyer
Quantum Optics Group

Why micro and nano mechanical systems?

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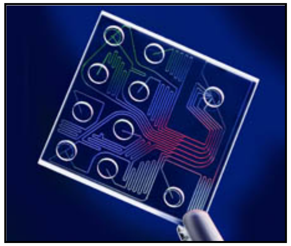


Agilent Technologies

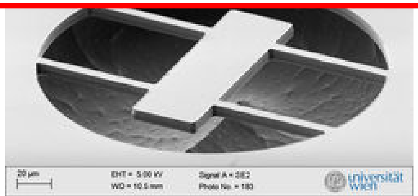
Introductory papers on on-going research:

K. Schv ,
This is **:hanics**

F. Marc
Consid ects

Both fundamental issues and potential applications!

- ❑ **Main difficulty: accurate detection of NEMS motion**
- ❑ **Reaching the quantum regime of a macroscopic collective mechanical degree of freedom**

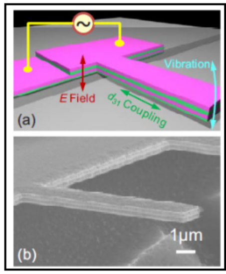


M. Aspelmeyer
Quantum Optics Group

An introduction to experimental techniques

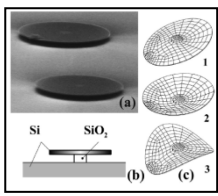
How to actuate a micro/nano mechanical device?

M. Roukes



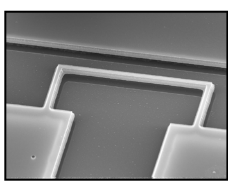
- Piezoelectric: a voltage applied on a piezoelectric material generates a displacement of its surface that couples to the device R. B. Karabalin *et al.*, APL 95, 103111 (2009)

J. Parpia



- Optical: a laser heats the material, it dilates and creates thus the motion M. Zalalutdinov *et al.*, APL 78, 3142 (2001)

E. Collin & O. Bourgeois



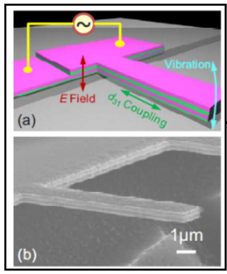
- Magnetomotive: a current is fed through the device which lies in a magnetic field, $\vec{F} = I\vec{l} \wedge \vec{B}$
  Very simple, used a lot at low temperatures E. Collin *et al.*, JLTP 158, 678 (2010)

- Capacitive: a voltage applied between metallic electrodes generates a displacement of (at least) one of the electrodes
  Dustin W. Carr *et al.*, APL 77, 1545 (2000)

An introduction to experimental techniques

How to actuate a micro/nano mechanical device? At the quantum limit?

M. Roukes



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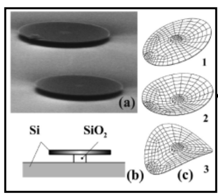
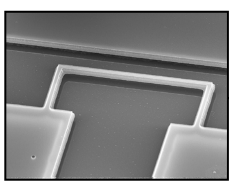


- Optical: a laser heats the material, it dilates and creates thus the motion M. Zalalutdinov *et al.*, APL 78, 3142 (2001)
- Optical, quantum: a laser is coupled to a moving mirror through radiation pressure Jing Zhang *et al.*, Phys. Rev. A 68, 013808 (2003)

E. Collin & O. Bourgeois



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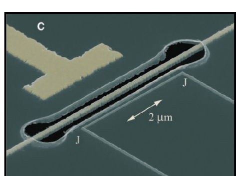
K. Schwab

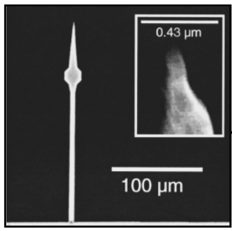


- Capacitive: a voltage applied between metallic electrodes generates a displacement of (at least) one of the electrodes
  Dustin W. Carr *et al.*, APL 77, 1545 (2000)
- Capacitive or inductive, quantum: the device is capacitively coupled to a quantum bit
  M. D. LaHaye, O. Buu, B. Camarota, K. C. Schwab, Nature **304** 2004

An introduction to experimental techniques

How to detect a micro/nano mechanical device's motion?

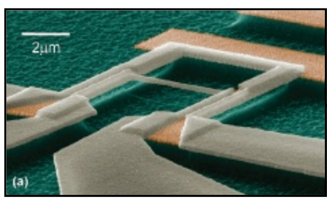
D. Rugar



- Transport property, e.g. piezoresistivity: the distortion induces a change in the electric resistance of the device
  A. Dâna, F. Ho, Y. Yamamoto, Appl. Phys. Lett. 72(10), 1152 (1998)

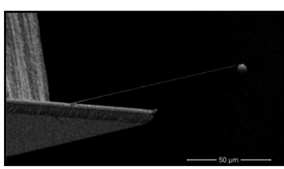
- Optical: a laser is reflected by the device and detected by means of an interferometric setup T.D. Stowe *et al.*, APL 71, 288 (1997)

M. Roukes



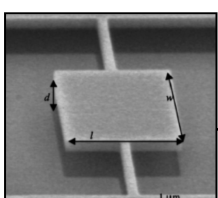
- Magnetomotive: the motion in a magnetic field induces a voltage (flux time variation), $V = d\phi / dt$, $(\phi = \iint_{motion} \vec{B} d\vec{S})$
  Very simple and used a lot at low temperatures, even on complex designs R. B. Karabalin *et al.*, Nano Letters 9, 3116 (2009)

T. H. Oosterkamp



- Magnetic: the moving part has a magnetic particle on it that couples to a SQUID O. Usenko *et al.*, APL 98, 133105 (2011)

J. Parpia

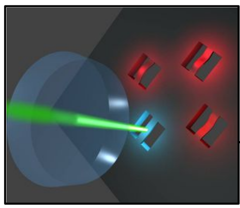


- Capacitive: the moving part modulates a capacitance which is measured by an electronic setup (bridge, lock-in, resonant cavity)
  Dustin W. Carr *et al.*, APL 77, 1545 (2000)

An introduction to experimental techniques

How to detect a micro/nano mechanical device's motion? At the quantum limit?

A. Heidmann



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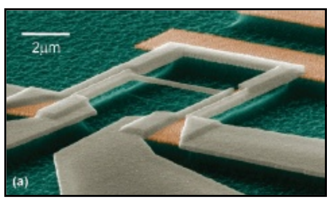
M. Roukes



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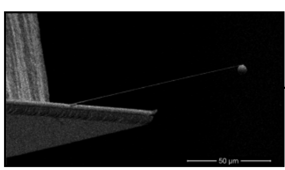
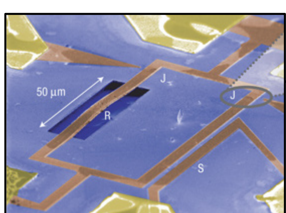


- Magnetic: the moving part has a magnetic particle on it that couples to a SQUID   O. Usenko *et al.*, APL 98, 133105 (2011)

H. Van der Zant

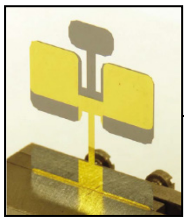


- Capacitive or inductive, quantum: the moving part is coupled to a quantum limited detector (SET, SQUID, microwave cavity)
  S. Etaki *et al.*, Nature Physics 4, 785, (2008)

An introduction to experimental techniques

What type of micro/nano mechanical devices?

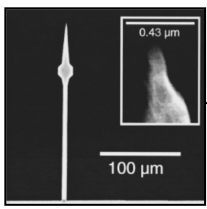
J. Parpia



- Torsional oscillators: two wings coupled to electrodes which exert a torsion on the central rod, clamped on one side

  A. D. Fefferman, R. O. Pohl, and J. M. Parpia, Phys. Rev. B 82, 064302 (2010)

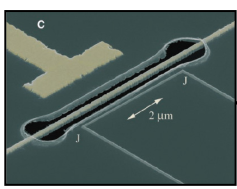
D. Rugar



- Cantilevers: a simply clamped beam with one end moving

  T.D. Stowe *et al.*, APL 71, 288 (1997)

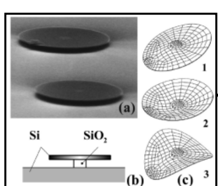
K. Schwab



- Doubly clamped beams: a beam clamped on both side with its middle part moving

  M. D. LaHaye, O. Buu, B. Camarota, K. C. Schwab, Nature **304** 2004

J. Parpia



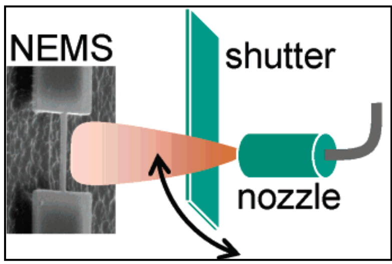
- Drums: a moving membrane

  M. Zalalutdinov *et al.*, APL 78, 3142 (2001)

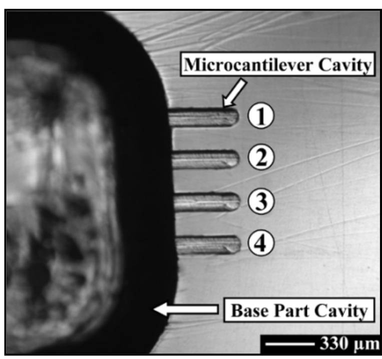
Plus some others (dilatational, shuttle, traveling waves…) and all sorts of "mixtures"! And different **materials**: silica, silicon, GaAs, diamond, nanotubes, graphene…

Why is "small" different?

Volumic effects become small compared to **surface effects**:
New possibilities!

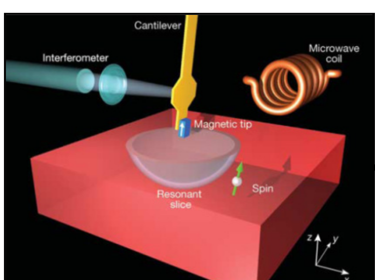


Zeptogram balance: detecting very small quantities of matter.
Change in resonance frequency when mass is added,
Y. T. Yang, C. Callegari, X. L. Feng, K. L. Ekinci, and M. L. Roukes,
Nano Letters **6** 2006



Measuring forces at the molecular scale: Adsorbing molecules creates stress, which also changes the resonance frequency,
A. W. McFarland and J. S. Colton, J. of MEMS **14** 2005

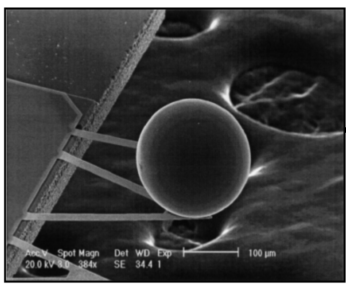
Biological sensing: these two properties, with a functionalized object can be used for biological detection,
J. Dorignac, A. Kalinowski, S. Erramilli, and P. Mohanty, Phys. Rev. Lett. **96** 2006



Single electron spin detection: using optics and a magnetic tip,
D. Rugar, R. Budakian, H. J. Mamin & B. W. Chui, Nature **430** 2009

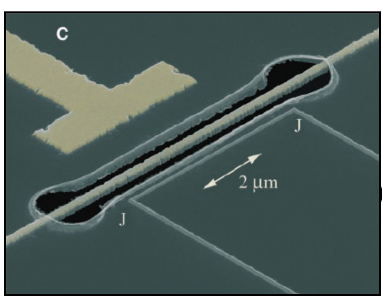
Why is “small” different?

small means also getting closer to the domain where **quantum mechanics prevails**:
New possibilities!



Casimir force: force due to virtual photons between two metallic surfaces; depends on $F \propto Area/d^4$
U. Mohideen and A. Roy , Phys. Rev. Lett. **81** 1998

Quantum sensors sensing classical forces: example of gravitational wave detectors (thought of for large objects in the first place)
C.M. Caves, K.S. Thorne, R.W.P. Drever, V.D. Sandberg and M. Zimmermann, Reviews of modern physics **52** 1980 ;
A.A. Clerk, Phys. Rev. B **70** 2004



Mechanical objects in their quantum ground state: small means high frequency , thus possible to reach $k_B T << \hbar\omega$, and large zero point motion $\Delta x = \sqrt{\hbar/(2m\omega)}$; quantum signatures and quantum control!
M. D. LaHaye, O. Buu, B. Camarota, K. C. Schwab, Nature **304** 2004

Why micro and nano mechanics at low temperatures?

Benefit from low temperatures:

Low noise, only low energy states populated, high magnetic fields, cryogenic vacuum, superconducting materials, no thermal expansion for T< 30 K, …

Low temperature standardized sensors:

Better oscillators, well defined and reproducible, new scales and geometries. Replacing "vibrating wires" in quantum fluids ; cryogenic pressure gauges, …

Reaching the regime $\frac{k_B T}{\hbar\omega} << 1$:

Ability to measure ground state properties, and manipulate quantum states of quantum mechanical harmonic oscillator ; create non-classical states, study their decoherence, …

Benefit from low temperatures: fundamental (classical) mechanics

Low noise, only low energy states populated, high magnetic fields, cryogenic vacuum, superconducting materials, no thermal expansion for T< 30 K, …

Micro and nano mechanical devices at low temperatures are model systems!

Address materials study: the temperature is a control parameter!

Understanding silicon, silica glass, GaAs, SiN, carbon, …

Address fundamental issues of Classical Physics: mimicking complex mechanical dynamics!

Nonlinear dynamics, chaos, coupled dynamics, …

Benefit from low temperatures: fundamental (classical) mechanics

Use of low temperature techniques: essential for some experiments!

Magnetomotive drive of beams: $\vec{F} = I\vec{l} \wedge \vec{B}$ and $V = d\phi / dt$ $\quad (\phi = \iint_{motion} \vec{B} d\vec{S})$

P. Mohanty, D. A. Harrington, K. L. Ekinci, Y. T. Yang, M. J. Murphy, and M. L. Roukes, PRB 66, 085416 (2002)

$\vec{B}$

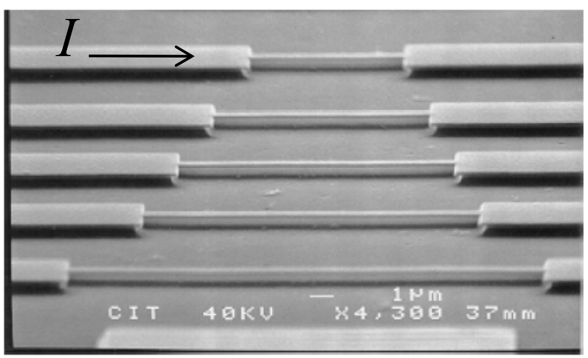


FIG. 2. A series of silicon beams with transverse dimensions in the submicron scale.

In 8 T at 4.2 K, with 10^{-2} mTorr

$I = I_0 \cos(\omega t)$, *B* static

V

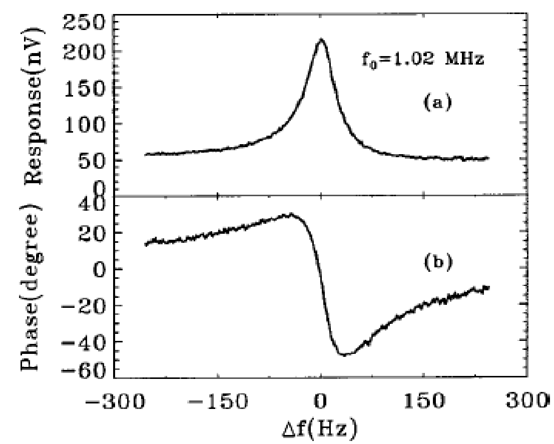


FIG. 5. Measured response to an applied ac drive: (a) the induced emf generated in the gold electrode due to the motion, and (b) the corresponding phase.

Induced voltage measured by a lock-in

Benefit from low temperatures: fundamental (classical) mechanics

Address materials study: the temperature is a control parameter!

Magnetomotive drive of beams: $\vec{F} = I\vec{l} \wedge \vec{B}$ and $V = d\phi / dt$ $\quad (\phi = \iint\limits_{motion} \vec{B} d\vec{S})$

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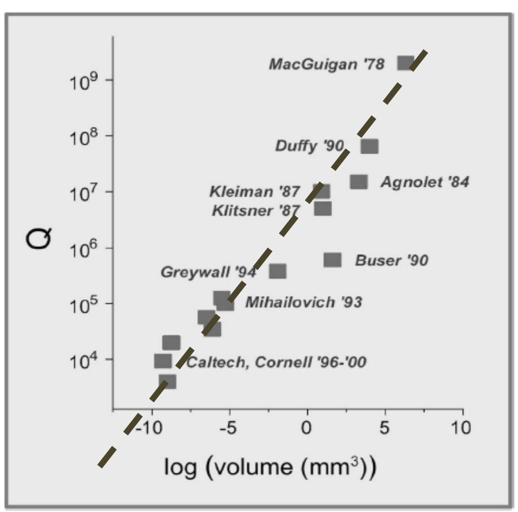


FIG. 1. The overall trend of the size dependence of quality factor in mechanical resonators.

Monocrystalline silicon devices

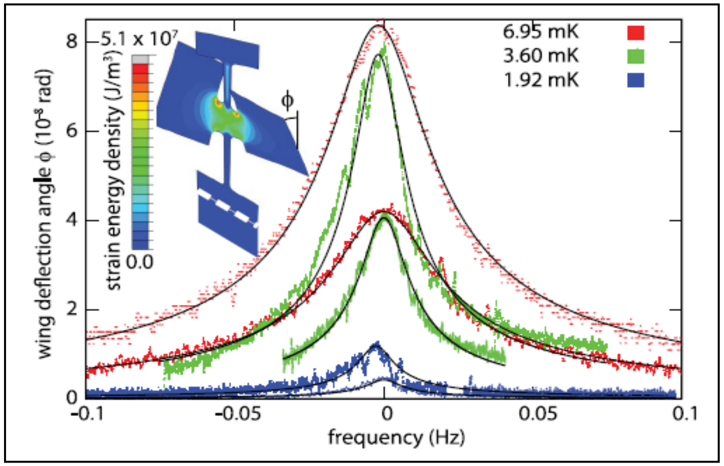
The Quality factor becomes worse for small devices!

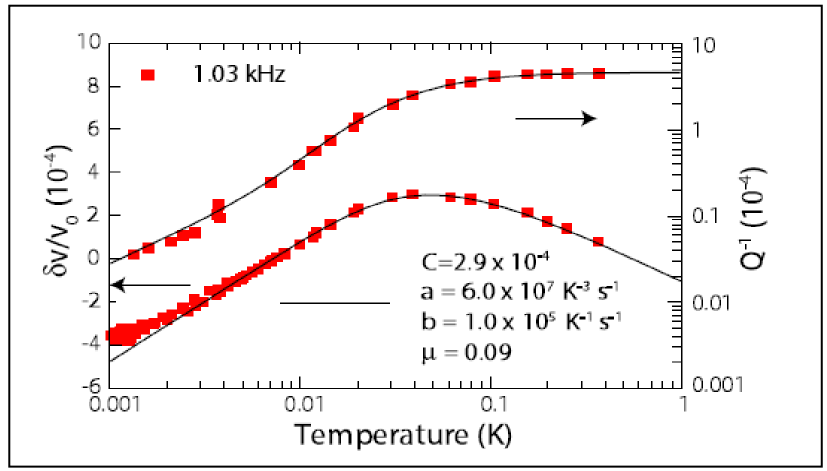
Both **fundamental issue** (understand why) and a **technical issue** (make better oscillators)

Benefit from low temperatures: fundamental (classical) mechanics

Address materials study: the temperature is a control parameter!

A. D. Fefferman, *et al.*





The study of glasses, through mechanical systems: various materials & shapes

R.N. Kleiman, G. Agnolet, D.J. Bishop, PRL 59, 2079 (1987); torsional oscillator

P. Strehlow, C. Enss, S. Hunklinger, PRL 80, 5361 (1998) ; dielectric measurements

E. Gaganidze, R. König, P. Esquinazi, K. Zimmer, A. Burin, PRL 79, 5038 (1997) ; vibrating reed

A. D. Fefferman, R. O. Pohl, A. T. Zehnder, and J. M. Parpia, PRL 100, 195501 (2008) ; torsional oscillator silica

D. R. Southworth, R. A. Barton, S. S. Verbridge, B. Ilic, A. D. Fefferman, H. G. Craighead, and J. M. Parpia, PRL 102, 225503 (2009); Si_3N_4 membranes

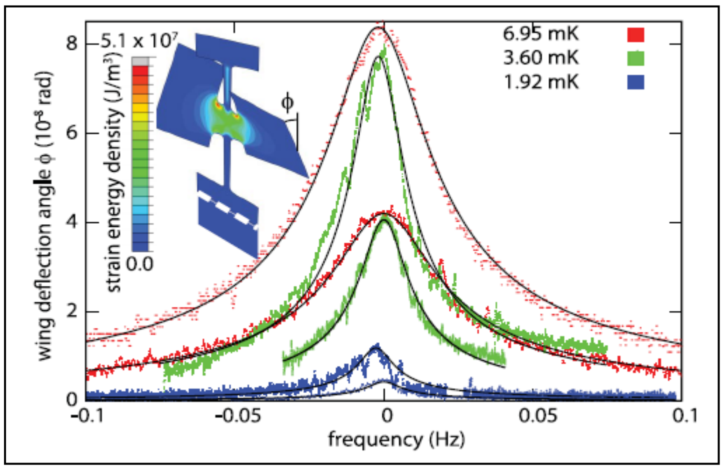
A. Venkatesan, K.J. Lulla, M.J. Patton, A.D. Armour, C.J. Mellor, J.R. Owers-Bradley, JLTP 158, 685 (2010); gold wires

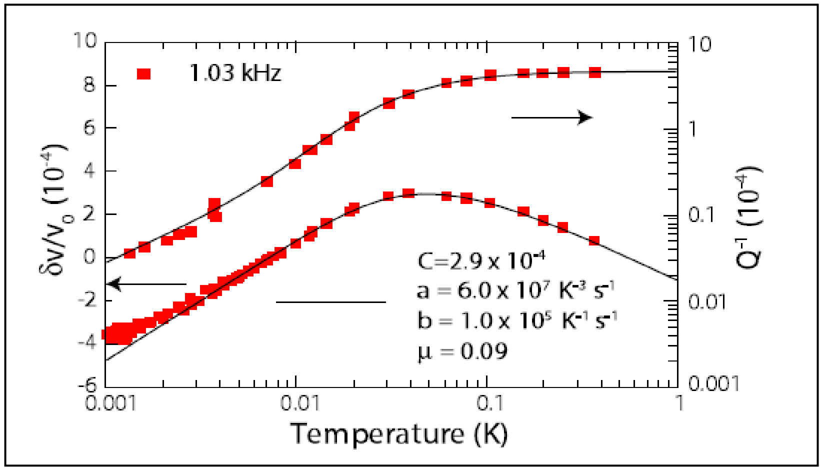
Many others…

Benefit from low temperatures: fundamental (classical) mechanics

Address materials study: the temperature is a control parameter!

A. D. Fefferman, *et al.*



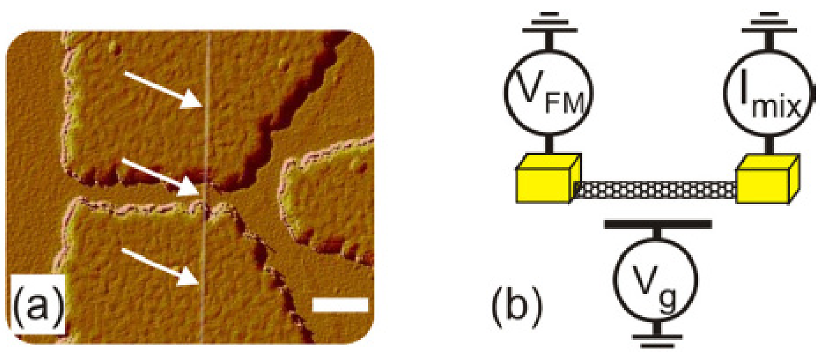


Glassy properties, **extensions of the Standard Tunneling Model**:
Resolving the interactions between Two Level Systems in glasses. Linked to many topical questions:
damping in MEMS/NEMS, supersolidity, noise in qu-bits…

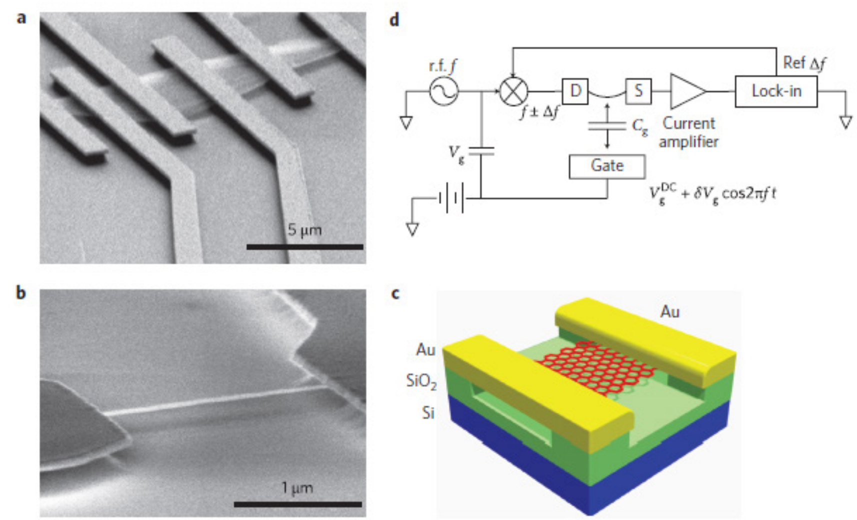
Benefit from low temperatures: fundamental (classical) mechanics

Address materials study: the temperature is a control parameter!

Reaching very-high frequencies
with carbon, **graphene and nanotubes (up to GHz)!** **With about Q ≈ 10^4 around 4 K**



J. Chaste, M. Sledzinska, M. Zdrojek, J. Moser, and A. Bachtold, APL **99**, 213502 (2011)



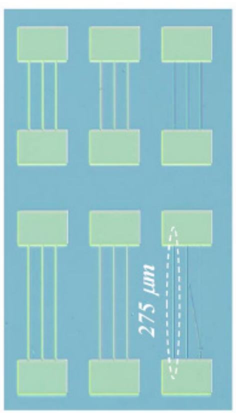
Changyao Chen *et al.*, Nature nanotech. **4**, 861 (2009)

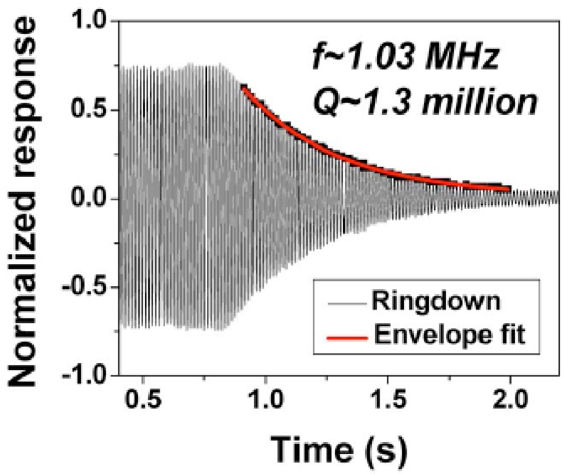
Making use of a clever electromechanical **down-mixing scheme** for GHz detection

Benefit from low temperatures: fundamental (classical) mechanics

Address materials study: the temperature is a control parameter!

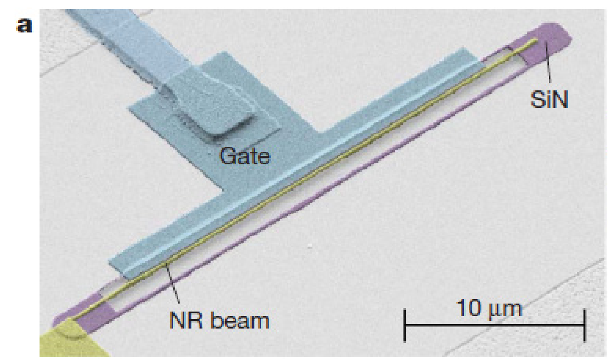
Reaching very-high frequencies
with high-stress silicon nitride, **up to 100 MHz devices, and Q up to a million!**





Room Temperature MHz device!

S.S. Verbridge, H.G. Craighead, J.M. Paria, APL **92**, 013112 (2008)



10 MHz, 100 mK device, Q ≈ 10^6

T. Rocheleau *et al.*, Nature **463**, 72 (2010)

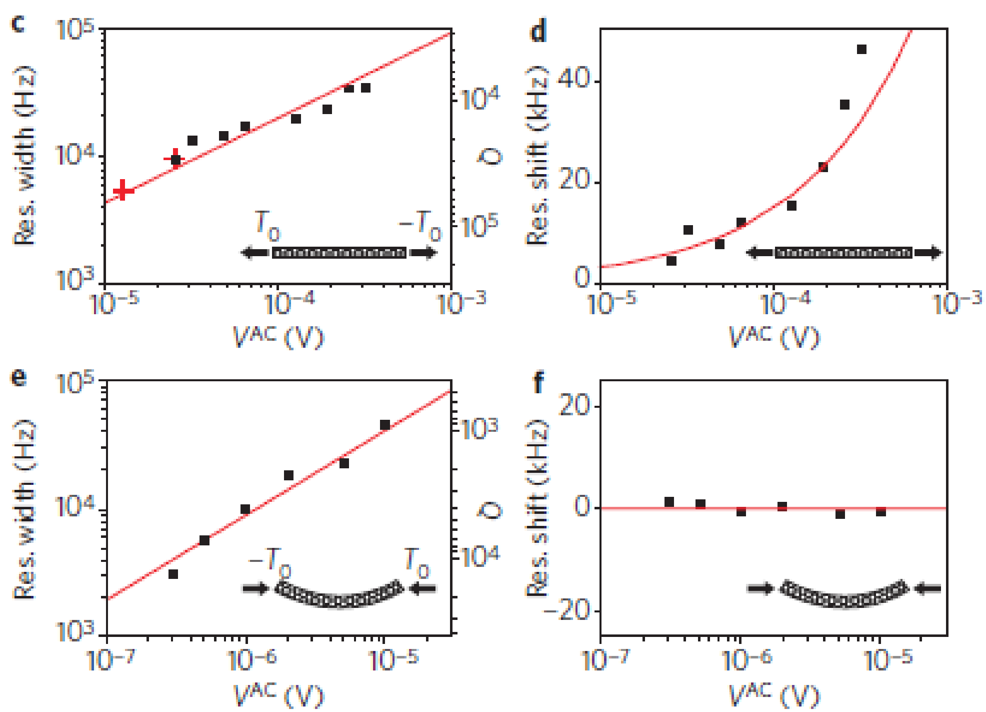
Benefit from low temperatures: fundamental (classical) mechanics

Address materials study: the temperature is a control parameter!

Non-linear damping in materials

Metallic coatings on monocrystalline silicon

E. Collin, J. Kofler, S. Lakhloufi, S. Pairis, Yu. M. Bunkov, and H. Godfrin, JAP **107**, 114905 (2010)



Intrinsic in nanotube and graphene devices

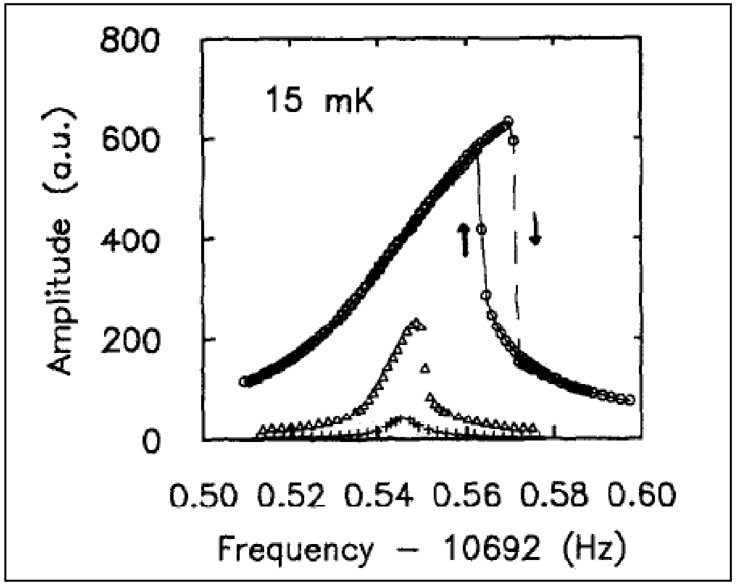
A. Eichler, J.Moser, J. Chaste, M. Zdrojek, I. Wilson-Rae and A. Bachtold, Nature Nanotech. **6**, 339 (2011)

Benefit from low temperatures: fundamental (classical) mechanics

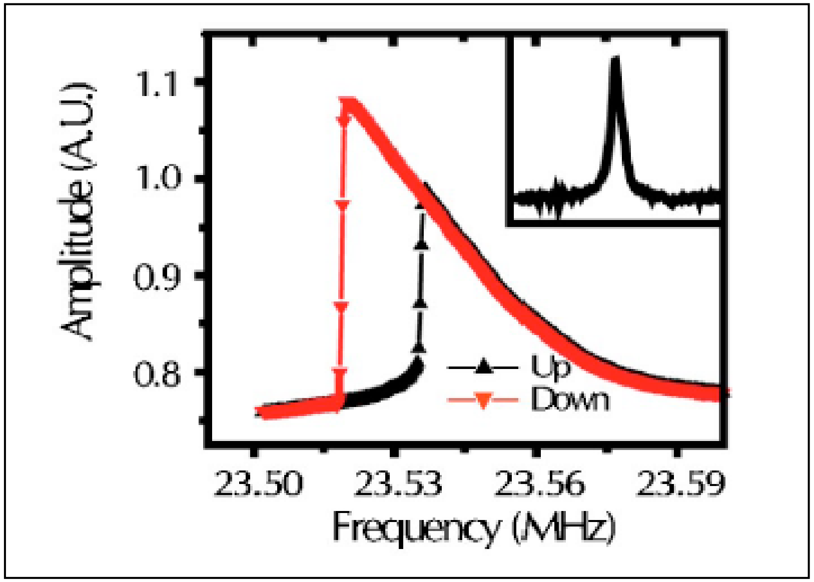
Address fundamental issues of Classical Physics: nonlinear dynamics, chaos, …

Nonlinear dynamics: frequency pulling and hysteresis

R.E. Mihailovich & J.M Parpia



R.L. Badzey *et al.*



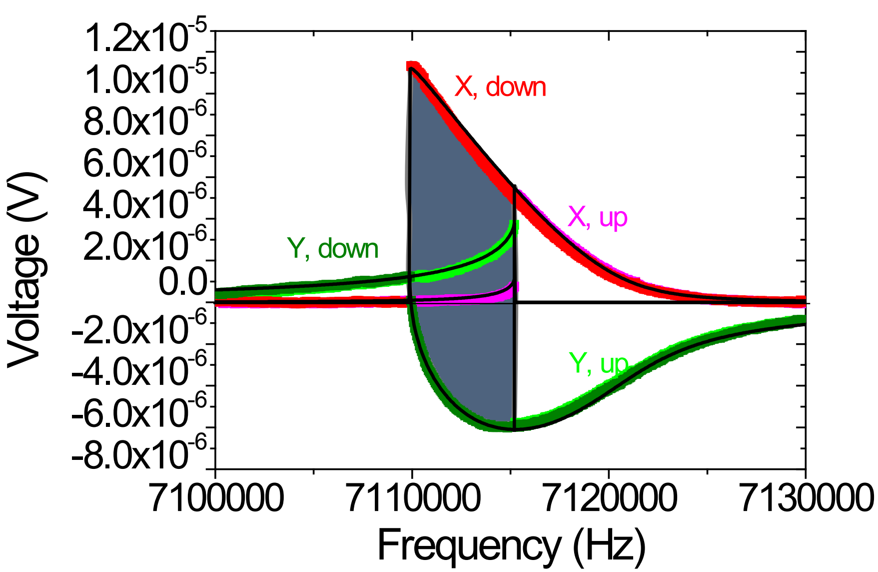
R.E. Mihailovich, J.M. Parpia, Physica B, 165&166, 125 (1990); torsional oscillator
R.L. Badzey, G. Zolfagharkhani, A. Gaidarzhy, P. Mohanty, APL 85, 3587 (2004); beam
E. Collin, Yu. M. Bunkov, and H. Godfrin, PRB **82**, 235416 (2010); cantilevers
Many others…

Benefit from low temperatures: fundamental (classical) mechanics

Address fundamental issues of Classical Physics: nonlinear dynamics, chaos, …

Dynamic bifurcation

$$F(t) = F_0 \cos(\omega t)$$



D. Ryvkine, M. I. Dykman, and B. Golding, PRE 69, 061102 (2004):
In the hysteretic region, two states coexist.

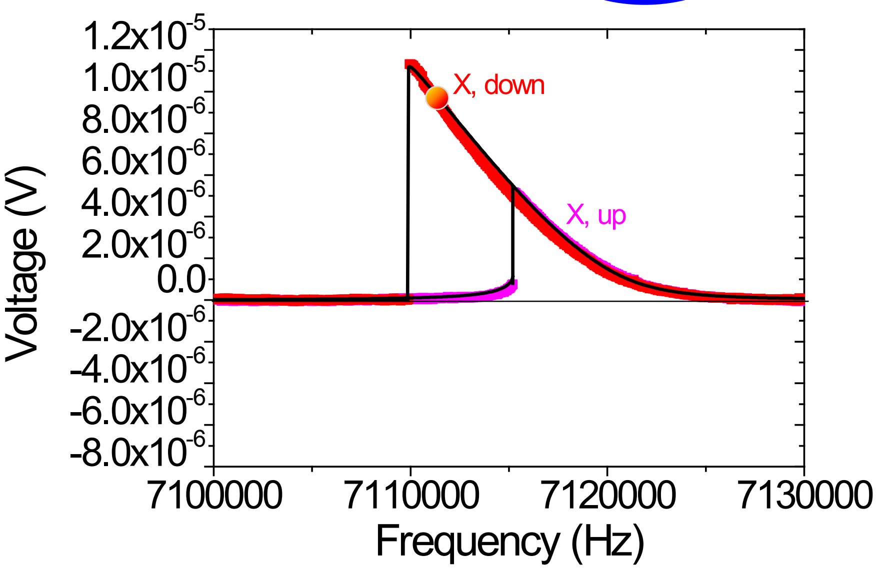
Benefit from low temperatures: fundamental (classical) mechanics

Address fundamental issues of Classical Physics: nonlinear dynamics, chaos, ...

Dynamic bifurcation

Controlled white noise, $I_N \propto f_{noise}(\omega)$

$$F(t) = F_0 \cos(\omega t) + f_{noise}(t)$$



D. Ryvkine, M. I. Dykman, and B. Golding, PRE 69, 061102 (2004):

In the hysteretic region, two states coexist. Here, upper state is metastable and relaxes on the lower one.

By adding a controlled amount of noise, the system can relax down faster:

exponential activation

I_N noise intensity

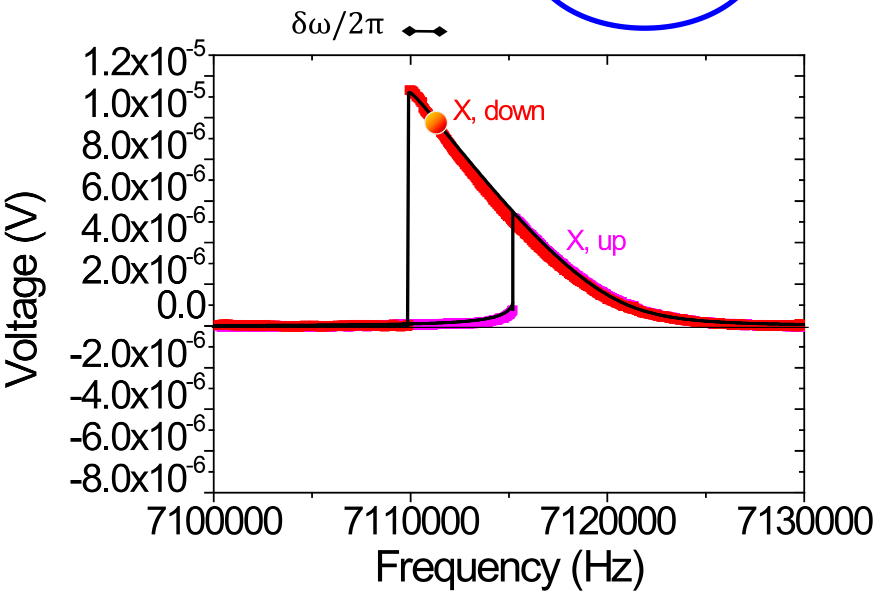
Benefit from low temperatures: fundamental (classical) mechanics

Address fundamental issues of Classical Physics: nonlinear dynamics, chaos, …

Dynamic bifurcation

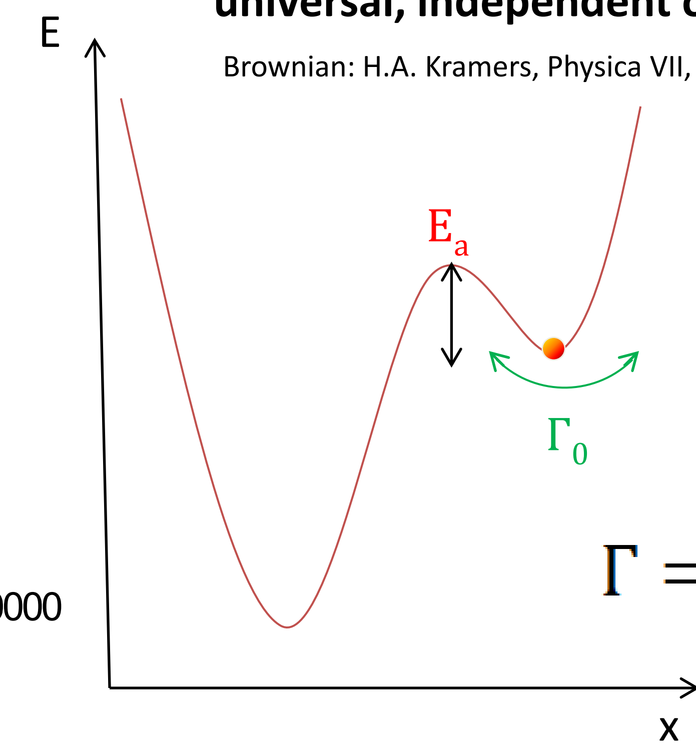
$I_N \propto f_{noise}(\omega)$

$$F(t) = F_0 \cos(\omega t) + f_{noise}(t)$$



Probabilistic process, universal, independent of system!

Brownian: H.A. Kramers, Physica VII, 284 (1940)



$\Gamma_0 = \lambda\, \delta\omega^{\zeta}$

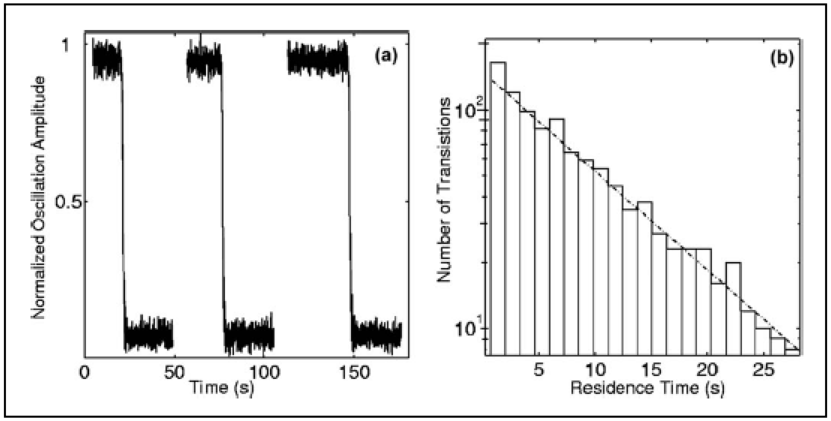
$E_a = \eta\, \delta\omega^{\xi}$

$$\Gamma = \Gamma_0\, e^{-\frac{E_a}{I_N}}$$

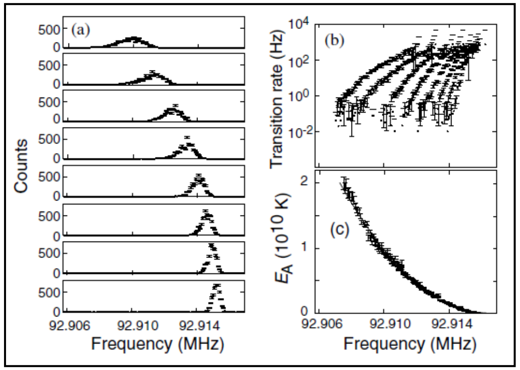
Benefit from low temperatures: fundamental (classical) mechanics

Address fundamental issues of Classical Physics: nonlinear dynamics, chaos, …

Dynamic bifurcation



C. Stambaugh and H. B. Chan, PRB 73, 172302 (2006):
The most direct park,-wait-and-see experiment on a MEMS torsional oscillator.



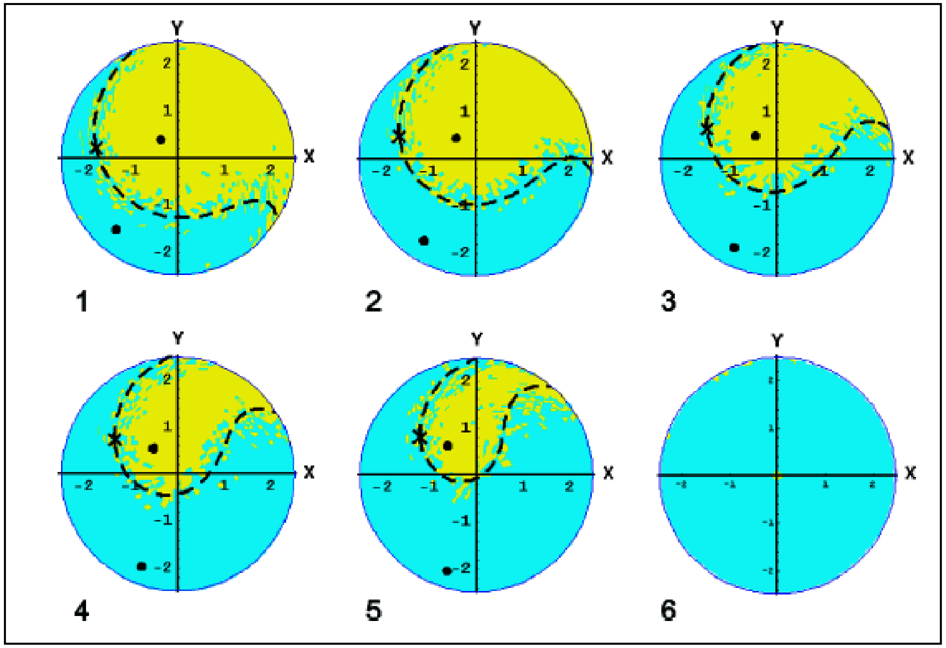
J. S. Aldridge and A. N. Cleland, PRL 94, 156403 (2005):
The switching experiment is this time performed on a **NEMS** while ramping the drive frequency at a slow rate through the bifurcation point.

M. Defoort *et al.*, in preparation. Residence-time on a **NEMS** device.

Benefit from low temperatures: fundamental (classical) mechanics

Address fundamental issues of Classical Physics: nonlinear dynamics, chaos, …

Dynamic bifurcation

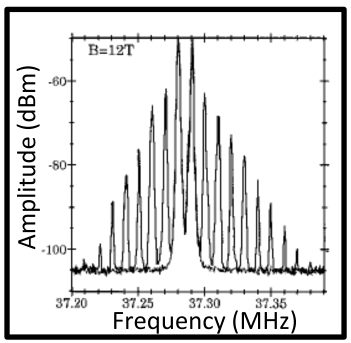


I. Kozinsky, H.W. Ch. Postma, O. Kogan, A. Husain, and M. L. Roukes, PRL 99, 207201 (2007):
Reconstructing the “basins of attraction” of the two stable states of the oscillator in the parameter space by following the dynamical state as a function of the initial position.

Benefit from low temperatures: fundamental (classical) mechanics

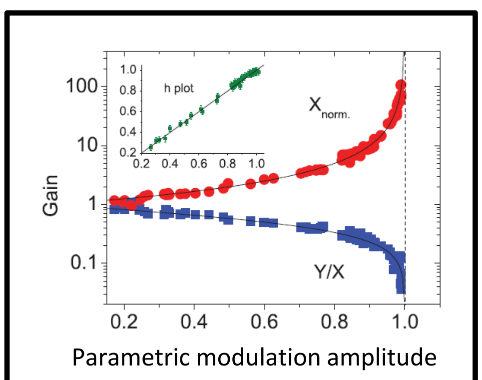
Address fundamental issues of Classical Physics: nonlinear dynamics, chaos, …

➡ Many other effects that can be addressed at low temperatures…



A. Erbe, H. Krömmer, A. Kraus, R. H. Blick, G. Corso and K. Richter, APL 77, 3102 (2000):
Nanomechanical mixing between a low frequency signal and the NEMS mechanical drive.

M. Defoort *et al.*, Appl. Phys. Lett. **99**, 233107 (2011).



E. Collin, T. Moutonet, J.-S. Heron, O. Bourgeois, Yu. M. Bunkov, and H. Godfrin, PRB **84**, 054108 (2011):
Parametric amplification (modulation of the spring constant at 2ω) of a weak signal and its application.

R. B. Karabalin, S. C. Masmanidis, and M. L. Roukes, APL **97**, 183101 (2010); **highest gain** reported 1000.

Benefit from low temperatures: fundamental (classical) mechanics

Address fundamental issues of Classical Physics: nonlinear dynamics, chaos, …

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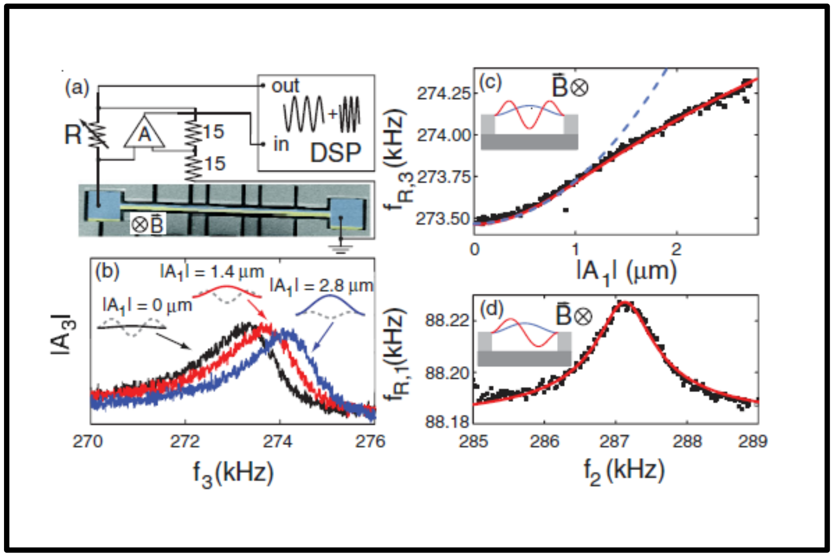


H. J. R. Westra, M. Poot, H. S. J. van der Zant, and W. J. Venstra, PRL **105**, 117205(2000): **Nonlinear coupling** between two modes of the same nanomechanical device.

Between two different flexural modes (in and out of plane); anticrossings
E.M. Weig and co-workers, arXiv:1201.4083v1

➡ **See Kunal Lulla's talk; mode coupling at low temperature in SiN beams**

Low temperature standardized sensors

Better oscillators, well defined and reproducible, new scales and geometries.
Replacing “vibrating wires” in quantum fluids ; cryogenic pressure gauges, …

Micro and nano mechanical devices at low temperatures are excellent probes!

Replace existing technology: Better devices.
Address new possibilities opened by MEMS/NEMS: New quantum fluid physics…

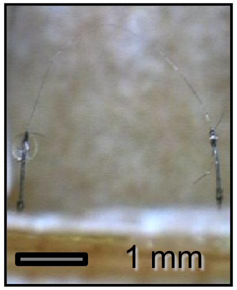
Quantum fluid means ^{3}He and ^{4}He liquids below 4.2 K

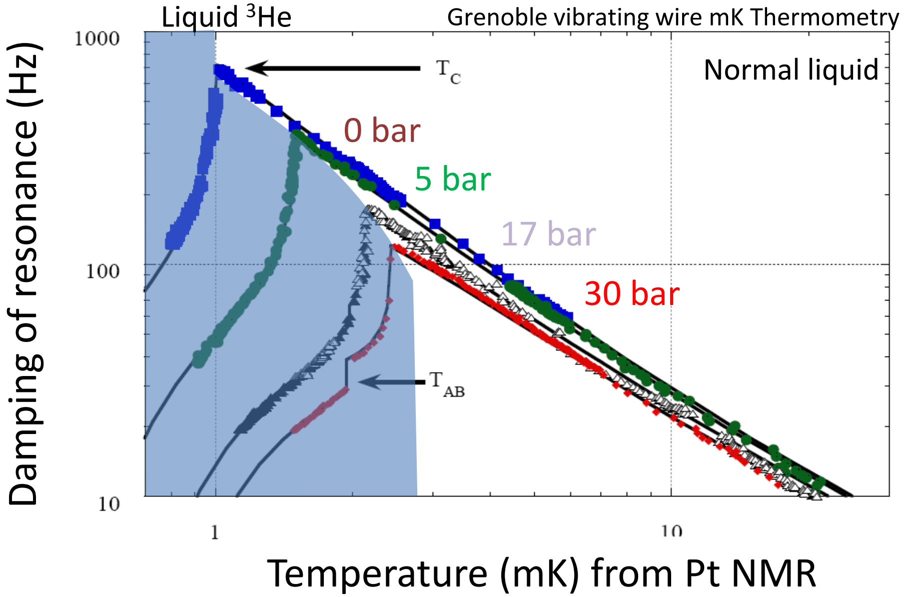
Low temperature standardized sensors

Replace existing technology: Better devices.

"Vibrating wire"

5 µm diam. NbTi wire





Well known technique
for probing Quantum Fluids.
Measure friction with fluid in resonant mode.

J. Tough, W. McCormick, J. Dash, Phys. Rev. 132, 2373 (1963)
M. Black, H. Hall, K. Thompson, J. Phys. C: Solid St. Phys. 4, 129 (1971)
D. Carless, H. Hall, J. Hook, JLTP 50, 583 (1983)
A. Guénault, V. Keith, C. Kennedy, S. Mussett, G. Pickett, JLTP 62, 511 (1986)

Low temperature standardized sensors

Replace existing technology: Better devices.

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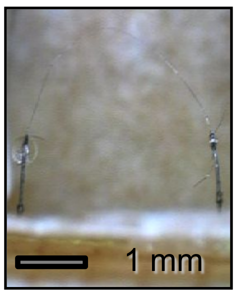

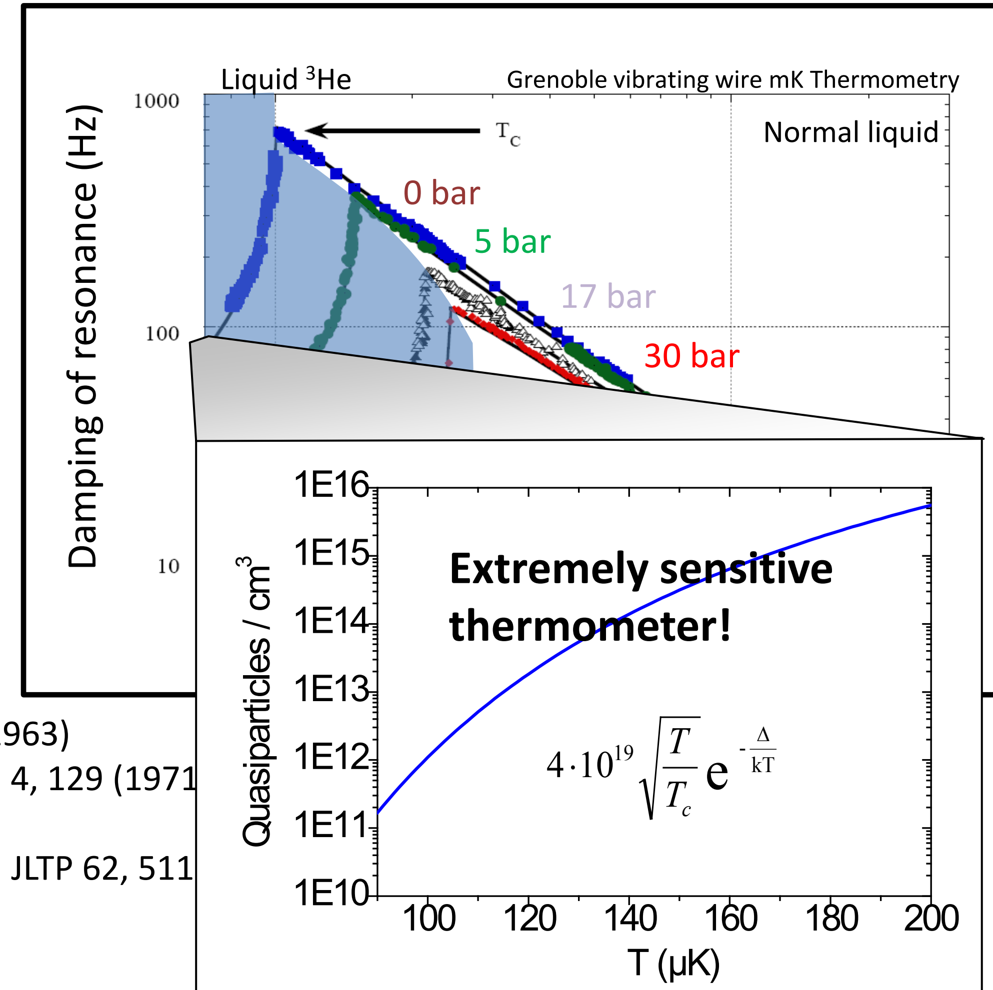

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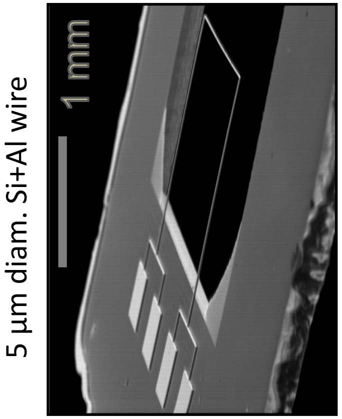
D. Carless, H. Hall, J. Hook, JLTP 50, 583 (1983)
A. Guénault, V. Keith, C. Kennedy, S. Mussett, G. Pickett, JLTP 62, 511

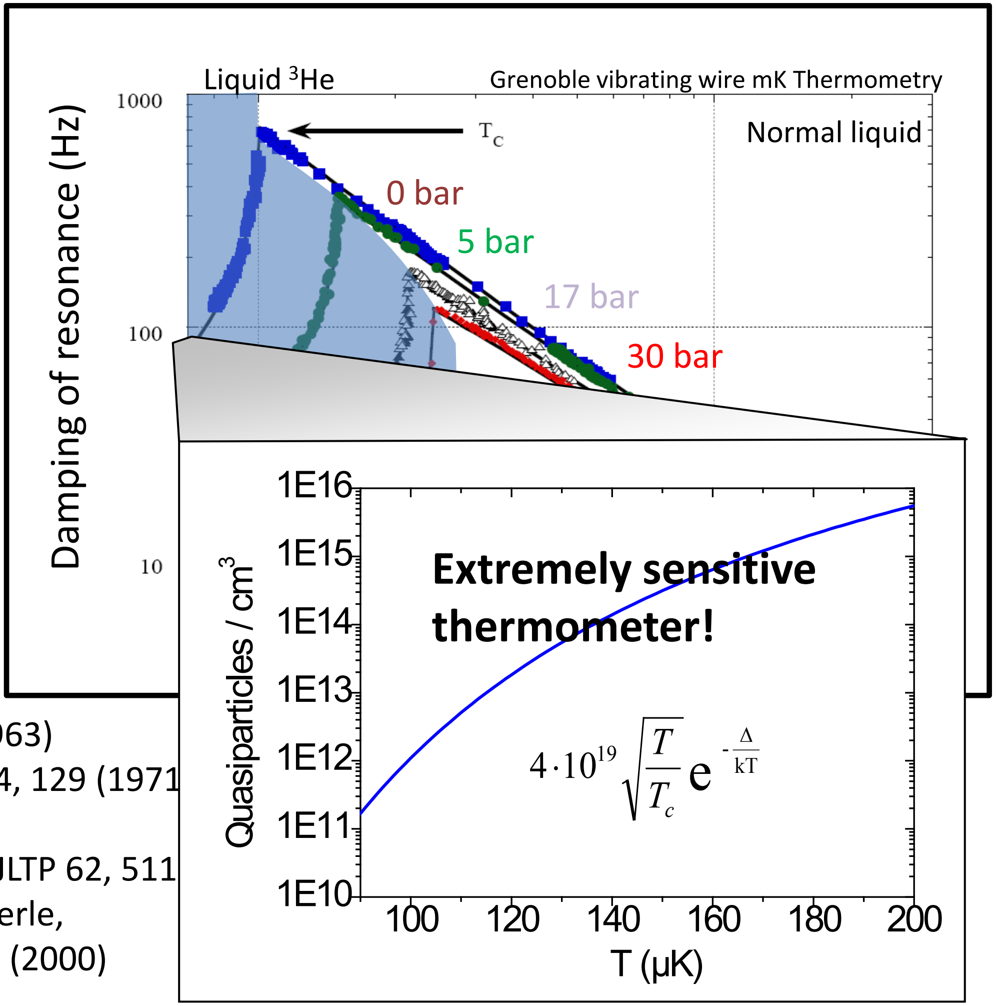
Low temperature standardized sensors

Replace existing technology: Better devices.

Silicon “Vibrating wire”



f_0 = 5 kHz
Q= 0.5 10^6
Thickness/width
1 µm – 30 µm



Mimicking vibrating wire with silicon,
for probing Quantum Fluids.
Measure friction with fluid in resonant mode.

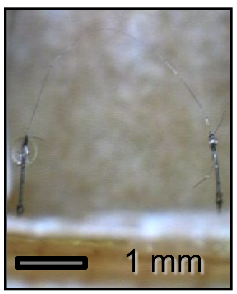
J. Tough, W. McCormick, J. Dash, Phys. Rev. 132, 2373 (1963)
M. Black, H. Hall, K. Thompson, J. Phys. C: Solid St. Phys. 4, 129 (1971
D. Carless, H. Hall, J. Hook, JLTP 50, 583 (1983)
A. Guénault, V. Keith, C. Kennedy, S. Mussett, G. Pickett, JLTP 62, 511
S. Triqueneaux, E. Collin, D. J. Cousins, T. Fournier, C. Bäuerle,
Yu. M. Bunkov and H. Godfrin, Physica B **284**, 2141-2142 (2000)

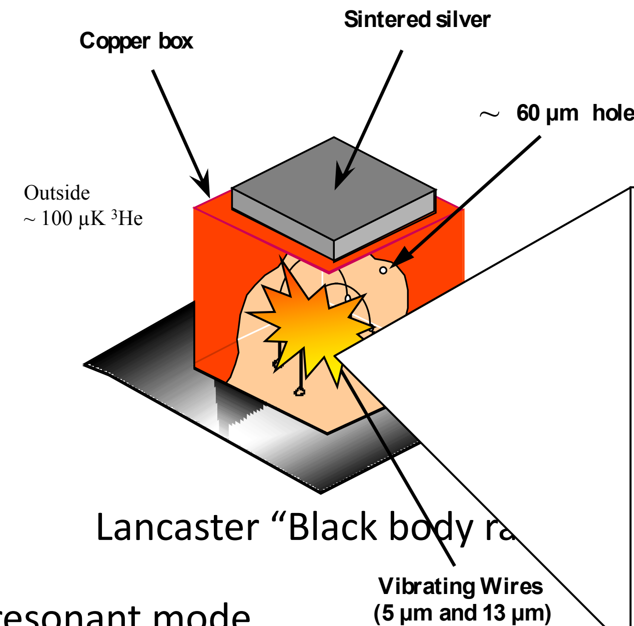
Low temperature standardized sensors

Replace existing technology: Better devices.

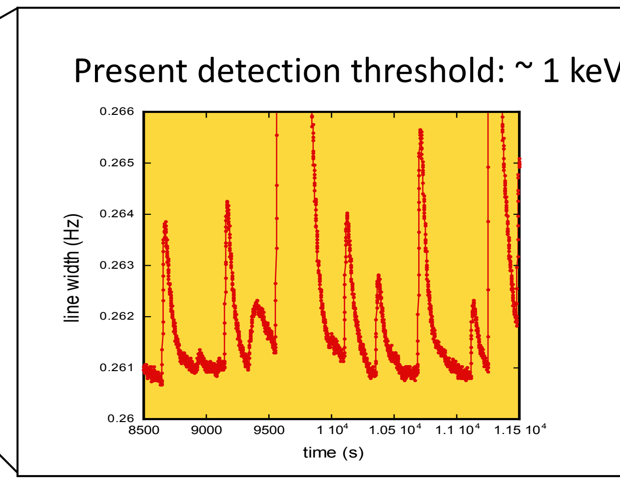
"Vibrating wire"

5 μm diam. NbTi wire





Extremely sensitive bolometer!



Well known technique
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Measure friction with fluid in resonant mode.

Lancaster "Black body ra

J. Tough, W. McCormick, J. Dash, Phys. Rev. 132, 2373 (1963)
M. Black, H. Hall, K. Thompson, J. Phys. C: Solid St. Phys. 4, 129 (1971)
D. Carless, H. Hall, J. Hook, JLTP 50, 583 (1983)
A. Guénault, V. Keith, C. Kennedy, S. Mussett, G. Pickett, JLTP 62, 511 (1986)
C. Bäuerle, Yu. M. Bunkov, S. N. Fisher, and H. Godfrin, Phys. Rev. B 57, 14381 (1998).

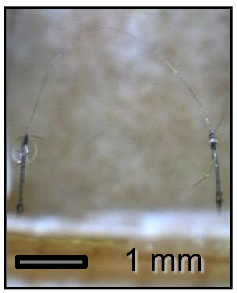
Low temperature standardized sensors

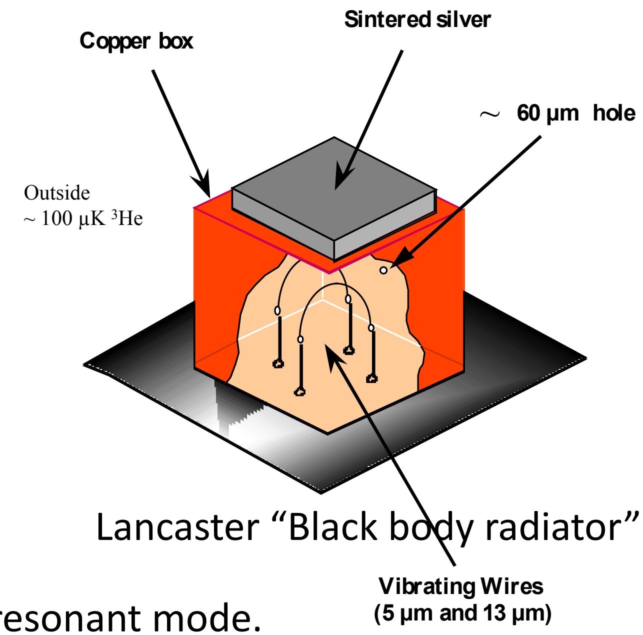
Replace existing technology: Better devices.

Quantum turbulence devices

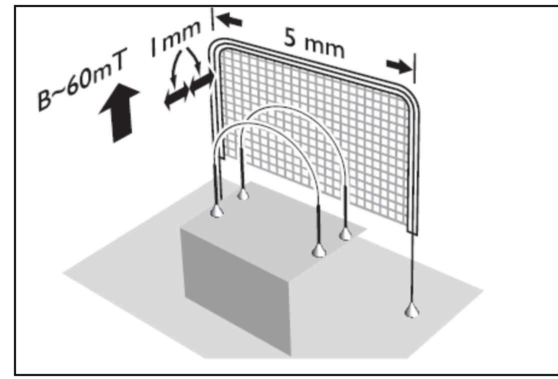
“Vibrating wire”

5 µm diam. NbTi wire

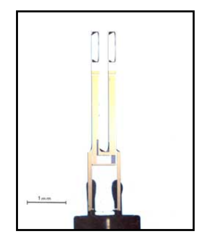




Lancaster “Black body radiator”



“Vortex grid”



“Fork”

Well known technique
for probing Quantum Fluids.
Measure friction with fluid in resonant mode.

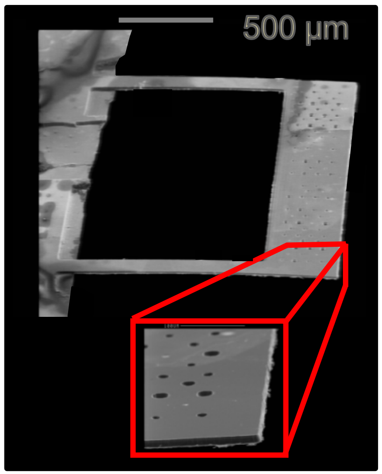
J. Tough, W. McCormick, J. Dash, Phys. Rev. 132, 2373 (1963)
M. Black, H. Hall, K. Thompson, J. Phys. C: Solid St. Phys. 4, 129 (1971)
D. Carless, H. Hall, J. Hook, JLTP 50, 583 (1983)
A. Guénault, V. Keith, C. Kennedy, S. Mussett, G. Pickett, JLTP 62, 511 (1986)
C. Bäuerle, Yu. M. Bunkov, S. N. Fisher, and H. Godfrin, Phys. Rev. B 57, 14381 (1998).
D. I. Bradley, D.O. Clubb, S. N. Fisher, A. M. Guénault, R. P. Haley, C. J. Matthews, G. R. Pickett, V. Tsepelin, and K. Zaki, PRL 96, 035301 (2006) ; M. Blažková, D. Schmoranzer, L. Skrbek, and W. F. Vinen, Phys. Rev. B 79, 054522 (2009)

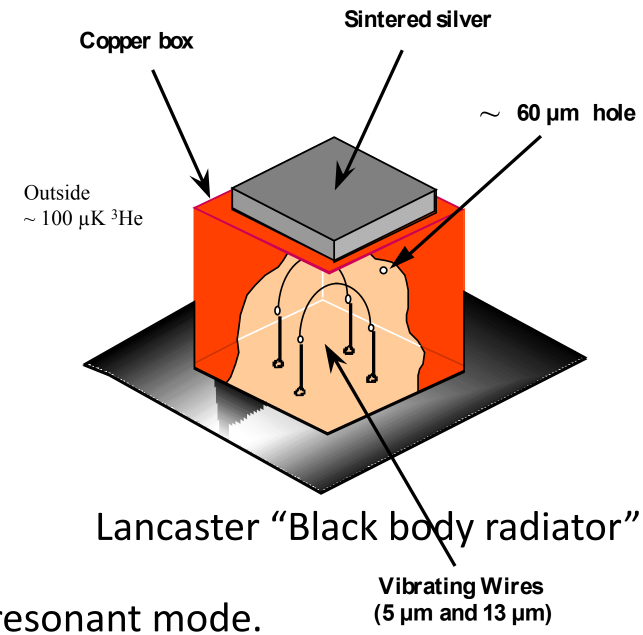
Low temperature standardized sensors

Replace existing technology: Better devices.

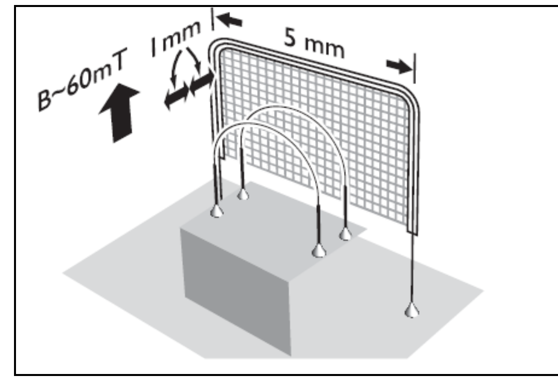
Quantum turbulence devices

Silicon "grid"

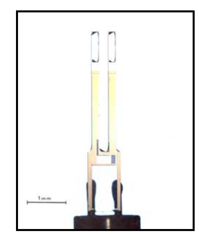




Lancaster "Black body radiator"



"Vortex grid"



"Fork"

Adapting **shapes**,
for probing Quantum Fluids.
Measure friction with fluid in resonant mode.

J. Tough, W. McCormick, J. Dash, Phys. Rev. 132, 2373 (1963)
M. Black, H. Hall, K. Thompson, J. Phys. C: Solid St. Phys. 4, 129 (1971)
D. Carless, H. Hall, J. Hook, JLTP 50, 583 (1983)
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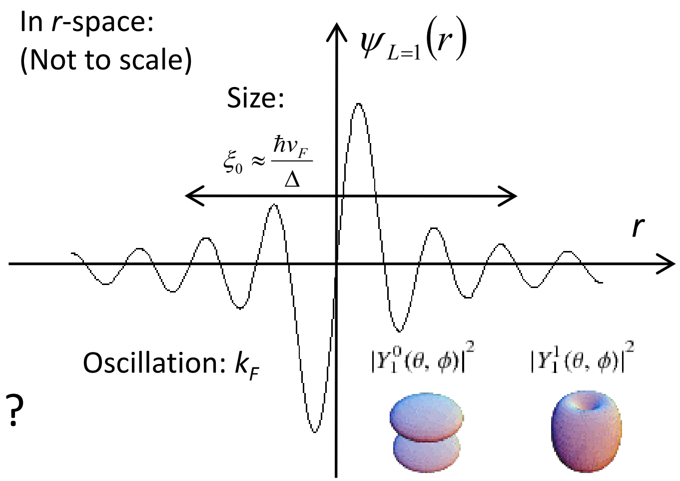
C. Bäuerle, Yu. M. Bunkov, S. N. Fisher, and H. Godfrin, Phys. Rev. B 57, 14381 (1998).
D. I. Bradley, D.O. Clubb, S. N. Fisher, A. M. Guénault, R. P. Haley, C. J. Matthews, G. R. Pickett, V. Tsepelin, and K. Zaki, PRL 96, 035301 (2006) ; M. Blažková, D. Schmoranzer, L. Skrbek, and W. F. Vinen, Phys. Rev. B 79, 054522 (2009)

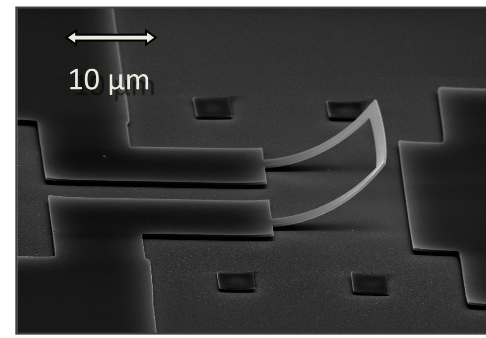
Low temperature standardized sensors

Address new possibilities opened by MEMS/NEMS: New quantum fluid physics…

➢Interaction with quasi-particles **in the bulk**, at the scale of $\xi_0 \approx 100$ nm

Resolving elementary excitations of BCS *p*-paired superfluid?

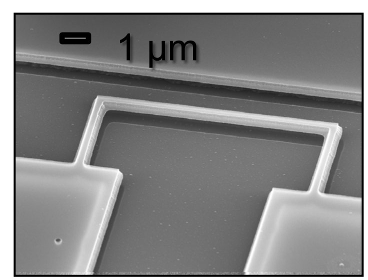




Grenoble NEMS goalposts

➢Probing **surface states**
(Andreev bound states)
a 100 nm from a wall

H. Choi, J. P. Davis, J. Pollanen, and W. P. Halperin, PRL 96, 125301 (2006),
S. Murakawa *et al.,* PRL 103, 155301 (2009).



Probing Majorana's?

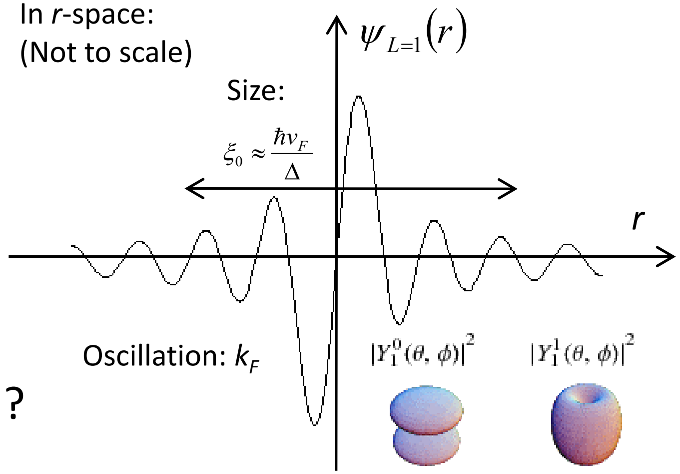
Andreev bound states in ^{3}He-B are **Majorana Fermions**!
Xiao-Liang Qi, Taylor L. Hughes, S. Raghu, and Shou-Cheng Zhang, PRL 102, 187001 (2009)

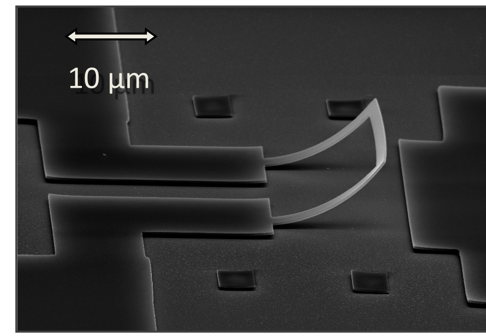
Low temperature standardized sensors

Address new possibilities opened by MEMS/NEMS: New quantum fluid physics…

- Interaction with quasi-particles **in the bulk**, at the scale of $\xi_0 \approx 100$ nm

Resolving elementary excitations of BCS *p*-paired superfluid?





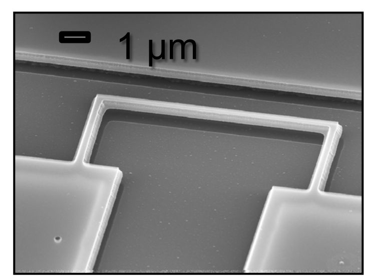
Grenoble NEMS goalposts

- Probing **slab states**

In confined 3He experiments,
Peculiar interplay between bulk and boundary relaxation

P. Sharma, A. Corcoles, R. G. Bennett, J. M. Parpia, B. Cowan, A. Casey, and J. Saunders, PRL **107**, 196805 (2011).

In the superfluid case: new phases/distorted order parameter!
The density of quasi particles (QP) gives a signature of the order parameter



Probed through QP?

L. Levitin, A. Casey, J. Saunders NMR works in London (unpublished)

Reaching the Quantum regime of a macroscopic mechanical object

Ability to measure ground state properties, and manipulate quantum states of quantum mechanical harmonic oscillator

Quantum NEMS

Fundamental physics: quantum mechanics of a macroscopic collective single degree of freedom, here… the center-of-mass!

Probing basic quantum mechanics…

New type of devices: New engineering possibilities: mechanical quantum control, new quantum devices for quantum computing, …

Reaching the Quantum regime of a macroscopic mechanical object

Fundamental physics: quantum mechanics of a macroscopic collective single degree of freedom , here… the center-of-mass!

How do microscopic quantum object transform into classical macroscopic ensembles?
Measurement theory, see e.g. W. Zurek, *Physics Today* 44, 36 (1991)
A. Leggett, *Suppl. of the Progr. of Theor. Phys.* 69, 80 (1980)

But: absence of proof is not proof of absence.
No idea about any fundamental decoherence mechanisms of macroscopic mechanical objects…

A. Leggett, *J. Phys.: Condens. Matter* 14, R415-R451 (2002)

For instance, possibility of position-state decoherence due to gravitons

$$\Gamma = \frac{Gm^2}{2\hbar L^3} x^2$$

R. Penrose, *General Relativity and Gravitation* 28, 581 (1996)

For instance, proposal to "test" Quantum Gravity

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

Igor Pikovski, Michael R. Vanner, Markus Aspelmeyer, M. S. Kim, Časlav Brukner, *Nature Physics* 2:262 (2012)

Reaching the Quantum regime of a macroscopic mechanical object

Fundamental physics: quantum mechanics of a macroscopic collective single degree of freedom , here… the center-of-mass!

Note: macroscopic current in a SQUID loop in a superposed state has no center-of-mass motion! A superconducting current state in a long wire involves only pair correlations!

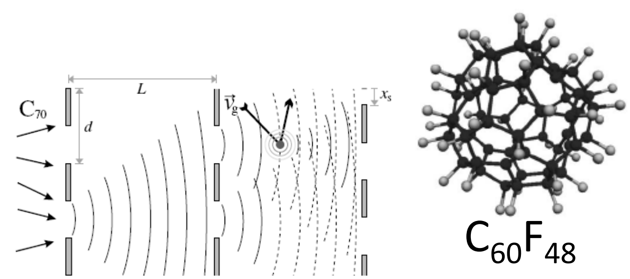
A. Leggett, *J. Phys.: Condens. Matter* 14, R415-R451 (2002)

Matter waves interferometry: “macroscopic”?

Klaus Hornberger et al., *Phys. Rev. Lett.* 90, 160401 (2003)

Stefan Gerlich et al., *Nature Comm.* 2:263 (2011)

Up to 6 910 amu!



$C_{60}F_{48}$

1632 amu

Nanofabricated devices:

truly macroscopic, but… quantum control very difficult!

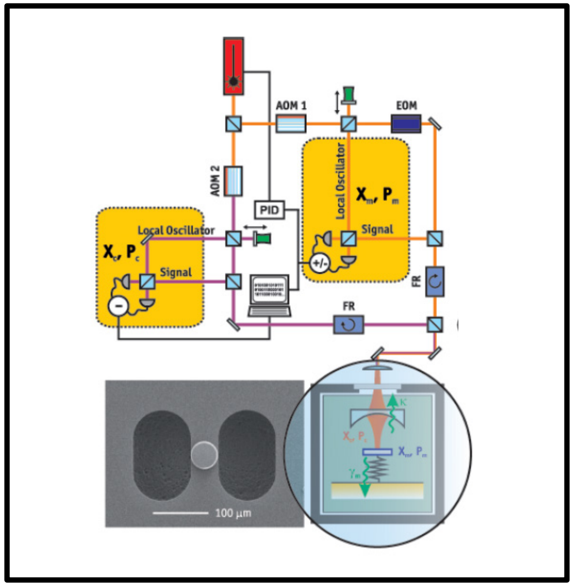
Reaching the Quantum regime of a macroscopic mechanical object

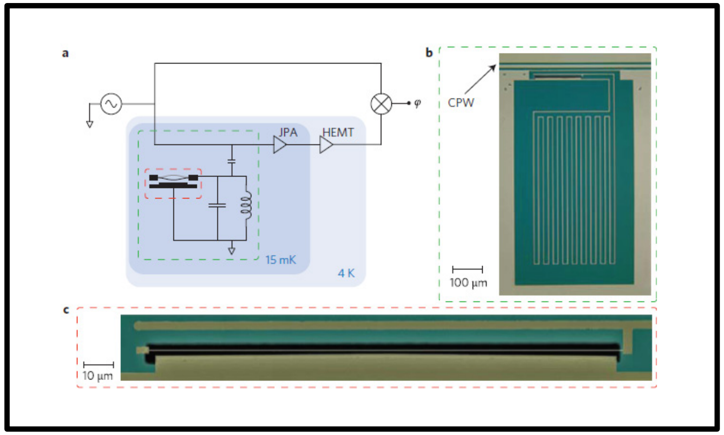
Fundamental physics: quantum mechanics of a macroscopic collective single degree of freedom , here… the center-of-mass!

Typically 2 classes of experiments:

Nanofabricated devices: NOMS version

Simon Gröblacher, Klemens Hammerer, Michael R. Vanner, Markus Aspelmeyer, Nature 460, 724 (2009)





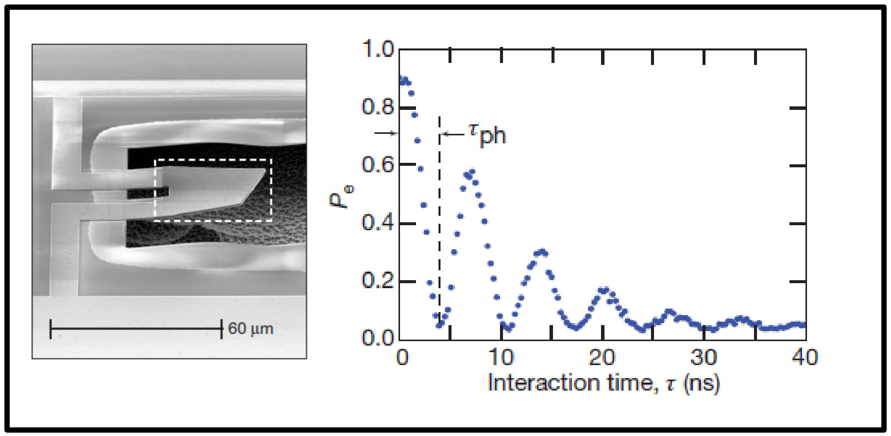
Nanofabricated devices: NEMS version… moving towards microwave photons!

J. D. Teufel, T. Donner, M. A. Castellanos-Beltran, J. W. Harlow and K. W. Lehnert, Nature nanotechnology 4, 820 (2009)

Reaching the Quantum regime of a macroscopic mechanical object

Fundamental physics: quantum mechanics of a macroscopic collective single degree of freedom , here… the center-of-mass!

Quite a few groups along these lines…



Coupling a mechanical mode to a quantum bit: transferring energy coherently to the NEMS, at the **single phonon level**!

A.D. O'Connell, M. Hofheinz, M. Ansmann, R.C. Bialczak1, M. Lenander, E. Lucero, M. Neeley, D. Sank, H. Wang, M. Weides, J. Wenner, J.M. Martinis, A.N. Cleland, Nature 464, 697 (2010)

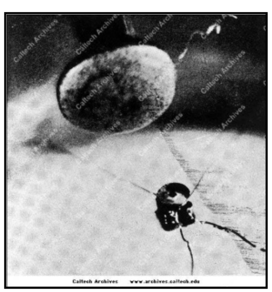
Reaching the Quantum regime of a macroscopic mechanical object

New type of devices: New engineering possibilities…

Quantum sensors sensing classical forces: this reaches **the absolute limit** of sensitivity (i.e. Heisenberg's principle)
C.M. Caves, K.S. Thorne, R.W.P. Drever, V.D. Sandberg and M. Zimmermann, Reviews of modern physics **52** 1980

Quantum sensors entangled to other quantum objects:
Opens up completely new possibilities of control!
For mechanics, for hybrid devices with qubits…

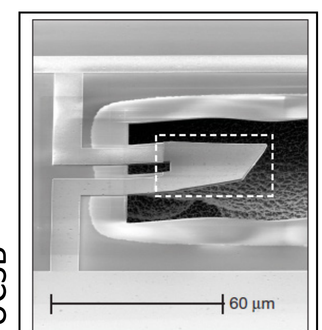
1960



CalTech

End of the story… In 2012

2010



UCSB