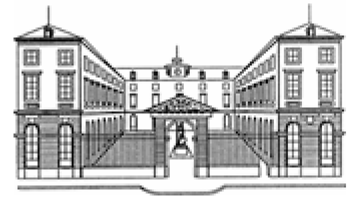


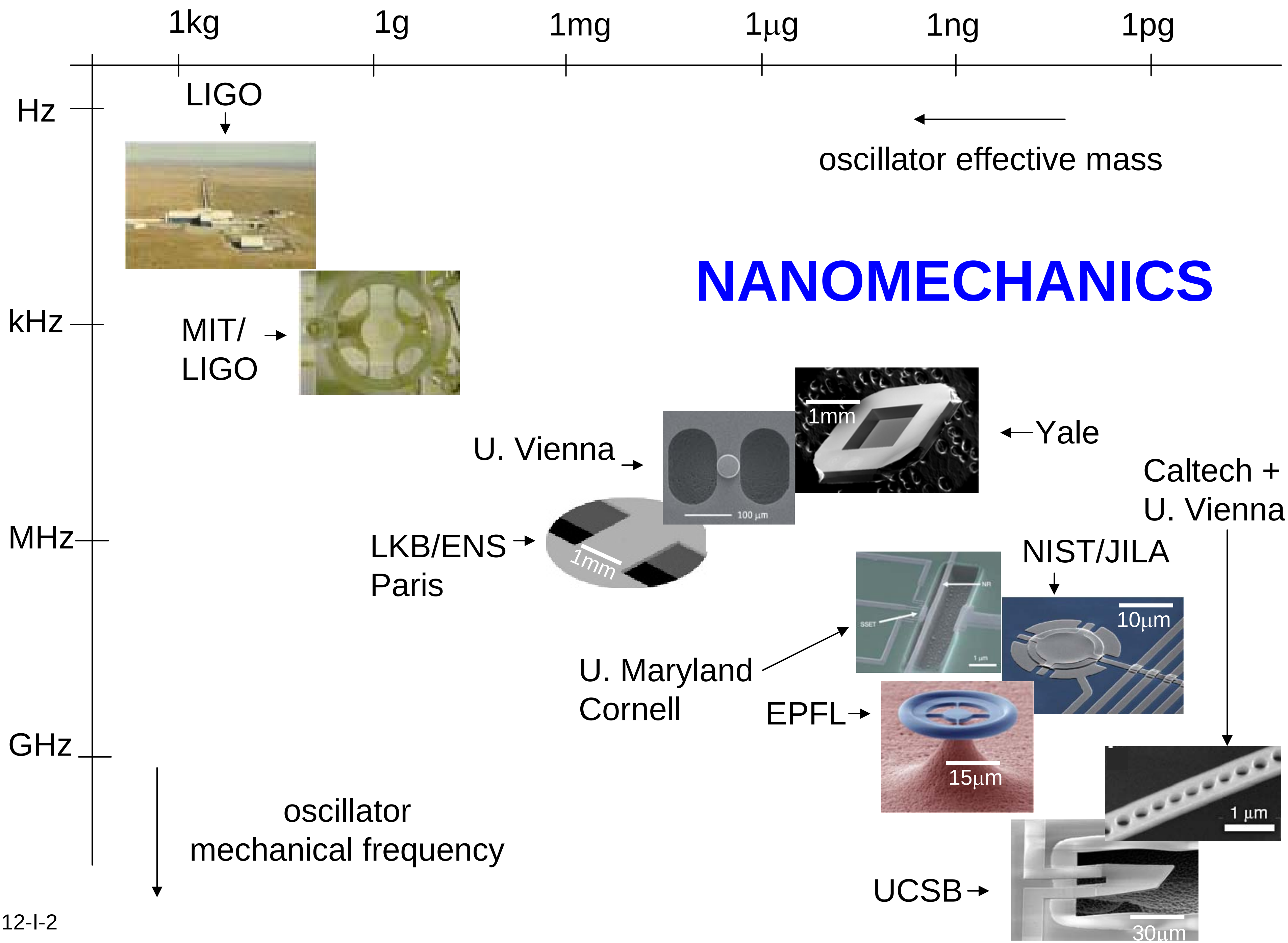
Chaire de Physique Mésoscopique
Michel Devoret
Année 2012, 15 mai -19 juin

RÉSONATEURS NANOMÉCANIQUES DANS LE RÉGIME QUANTIQUE

NANOMECHANICAL RESONATORS IN QUANTUM REGIME

Première leçon / *First lecture*

Last update: 120521


1kg
1g
1mg
1μg
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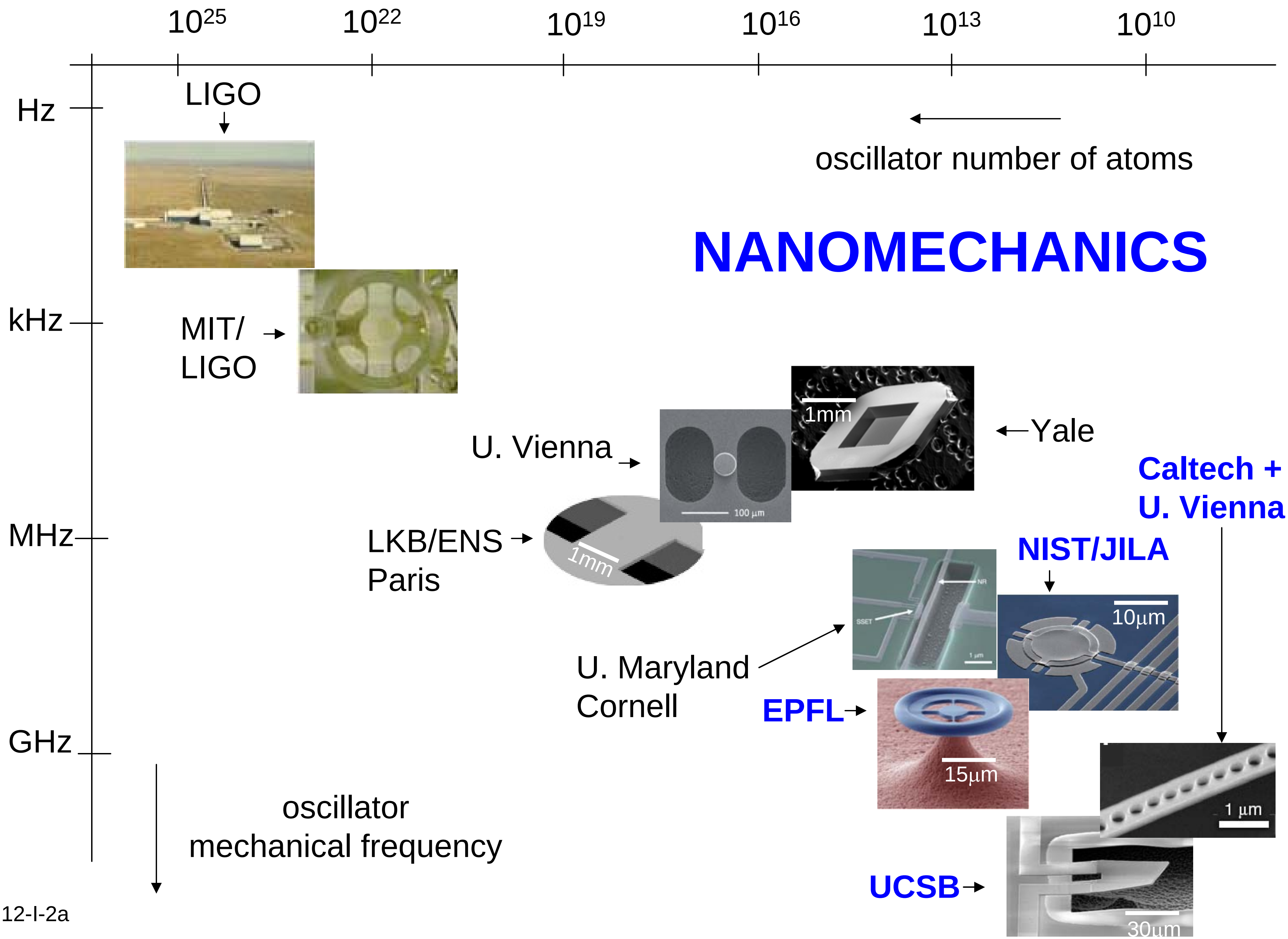
1pg
Hz
kHz
MHz
GHz
LIGO
oscillator effective mass
NANOMECHANICS
MIT/
LIGO
U. Vienna
100 μm
1mm
Yale
Caltech +
U. Vienna
LKB/ENS
Paris
1mm
NIST/JILA
10μm
U. Maryland
Cornell
EPFL
15μm
1 μm
UCSB
30μm
oscillator
mechanical frequency



10^25
10^22
10^19
10^16
10^13
10^10
Hz
kHz
MHz
GHz
LIGO
oscillator number of atoms
NANOMECHANICS
MIT/
LIGO
U. Vienna
100 µm
1mm
Yale
Caltech +
U. Vienna
LKB/ENS
Paris
1mm
NIST/JILA
10µm
U. Maryland
Cornell
EPFL
15µm
1 µm
UCSB
30µm
oscillator
mechanical frequency

12-I-2a

LECTURE I : INTRODUCTION TO QUANTUM ELECTROMECHANICAL AND OPTOMECHANICAL ENGINEERED SYSTEMS

CONTENTS

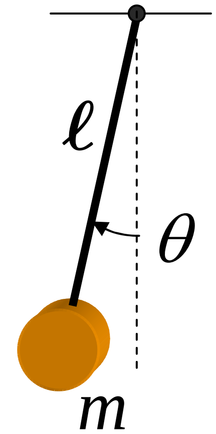
THE MACROSCOPIC MECHANICAL OSCILLATOR

Example: pendulum

$$E_K = \frac{1}{2} m \left(\ell \dot{\theta} \right)^2 ; \quad E_P = mg\ell \left(1 - \cos\theta \right)$$

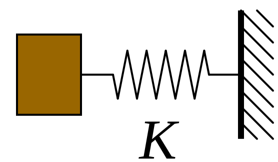
$$\mathcal{L}\left(\theta, \dot{\theta}\right) = E_K - E_P ; \quad M = m\ell^2 ; \quad K = mg\ell$$

$$p_\theta = \frac{\partial \mathcal{L}}{\partial \dot{\theta}} = M\dot{\theta} \quad \Rightarrow \quad H = \frac{p_\theta^2}{2M} + K\left(1 - \cos\theta\right)$$



$$\left.\begin{aligned} \dot{\theta} &= \frac{\partial H}{\partial p_\theta} = \frac{p_\theta}{M} \\ \dot{p}_\theta &= -\frac{\partial H}{\partial \theta} = -K \sin\theta \end{aligned}\right\} \quad \omega_0 = \sqrt{\frac{K}{M}} = \sqrt{\frac{g}{\ell}} ; \quad \overset{\text{mechanical impedance}}{\overset{\downarrow}{Z_0}} = M\omega_0 = \sqrt{KM}$$

Generic mass-spring: M

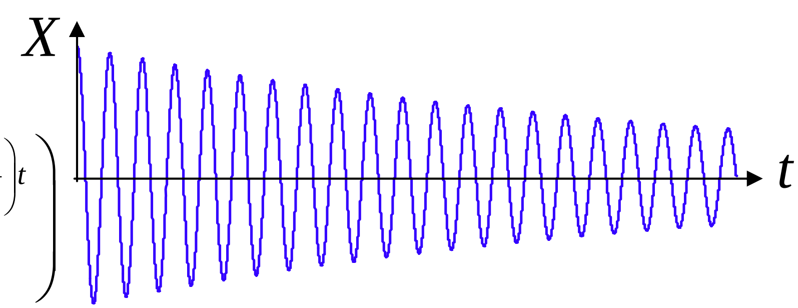


Equations of motion, including damping and drive: $M\ddot{X} + \overbrace{M\gamma}^{\eta}\dot{X} + KX = F\cos\Omega t$

Damping quality factor: $Q = \frac{\omega_0}{\gamma} = \frac{Z_0}{\eta}$

Underdamped regime: $Q \gg 1 \quad \Rightarrow \quad X = \mathrm{Re}\left(X_0 e^{-i\omega_0\left(1 - \frac{i}{2Q}\right)t} \right)$

(for F=0)



QUANTUM TREATMENT OF MECHANICAL HARMONIC OSCILLATOR

$$\hat{H} = \frac{\hat{P}^2}{2M} + \frac{1}{2}K\hat{X}^2; \quad \left[\hat{X},\hat{P}\right] = i\hbar$$

$$\omega_0 = \sqrt{K/M}; \quad Z_0 = \sqrt{KM}$$

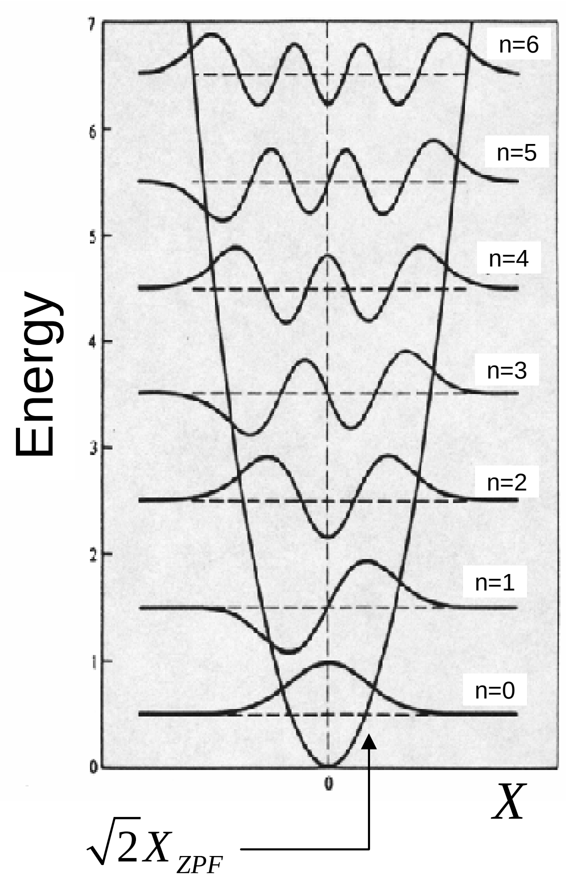
$$\hat{X} = X_{ZPF}\left(\hat{a}+\hat{a}^\dagger\right); \quad P = P_{ZPF}\left(\hat{a}-\hat{a}^\dagger\right)/i$$

$$\left[\hat{a},\hat{a}^\dagger\right] = 1; \quad X_{ZPF} = \sqrt{\frac{\hbar}{2Z_0}}; \quad X_{ZPF}P_{ZPF} = \frac{\hbar}{2}$$

$$\frac{\hat{H}}{\hbar} = \omega_0\left(\hat{n}+\frac{1}{2}\right); \quad \hat{n} = \hat{a}^\dagger\hat{a}; \quad \hat{n}\left|n\right\rangle = n\left|n\right\rangle$$

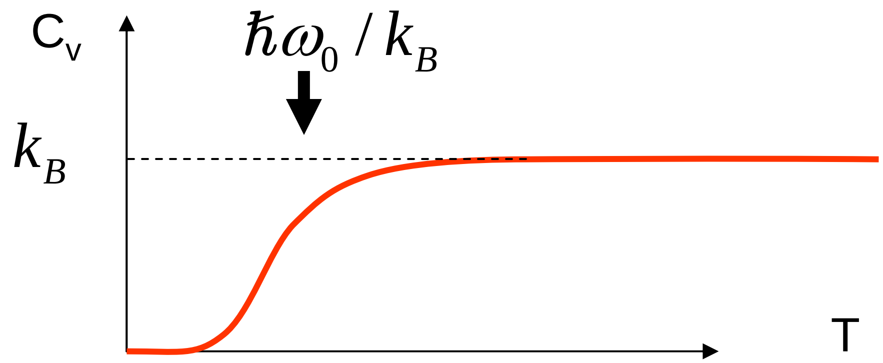
$$X_{ZPF} = \left\langle X^2\right\rangle_{n=0}; \quad \hat{a}\left|\alpha\right\rangle = \alpha\left|\alpha\right\rangle$$

$$\left|\alpha\right\rangle = \mathrm{e}^{-|\alpha|^2/2}\sum_n \frac{\alpha^n}{\sqrt{n!}}\left|n\right\rangle$$ "Coherent" state



Can we observe the quantum behavior of a macroscopic oscillator?

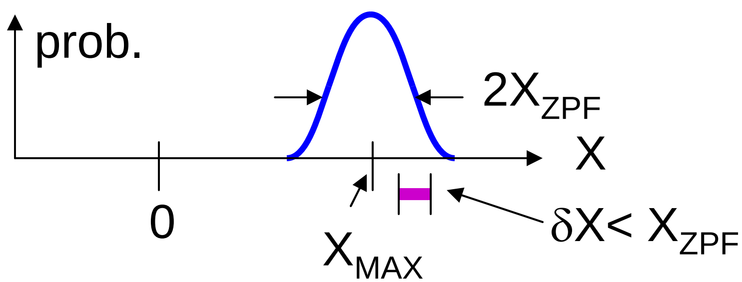
DIFFICULT REQUIREMENTS



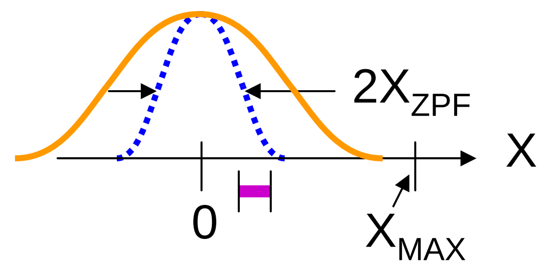
Discrete spectrum:
must reach low excitation number

Vanishing specific heat at low T:
need very sensitive calorimetry

Quantum back-action of position measurement on $|\alpha\rangle$ (Heisenberg uncertainty principle):



THEN



First, measure position X with imprecision δX when amplitude is maximum. Observe one of
$\sim X_{ZPF} / \delta X$
independent random outcomes

X is re-measured a quarter- period later, with same imprecision δX. Observe one of $\sim (X_{ZPF} / \delta X)^2$ random outcomes, instead of the $\sim X_{ZPF} / \delta X$. Need very precise X measurement!

WHY ARE MACROSCOPIC QUANTUM MECHANICS EXPERIMENTS EASIER WITH ELECTRICAL CIRCUITS THAN WITH MECHANICAL SYSTEMS?

Two crucial resources: long coherence times and short operation times.

Decoherence time: given a mechanism of coupling between bath and system, the decoherence time is proportional to $(h/kT)\times Q$.

Operation time: given a certain relative anharmonicity fixed by non-linear mechanism, the higher the frequency, the shorter the operation time.

The number of independent quantum operations is proportional to $f\times Q$.

For superconducting circuits this product is now in excess of 5×10^{15} Hz, with non-linearity of ~5%. *Will be shown in Rob Schoelkopf's seminar*

Mechanical systems tend to have at present lesser $f\times Q$ (*) and smaller non-linearity.

* A very recent unpublished work finds values > 10^{16} for this product in quartz resonators (arXiv: 1202.4556v2)

THE PRECIOUS RESOURCE OF FREQUENCY × QUALITY FACTOR

Resonant structure	Material	Frequency	Q factor	$f \times Q$ (Hz)
Free–free beam	Poly-Si	92MHz	7,450	6.85×10^{11}
Double ended tuning fork	Single crystal Si	154 kHz	80,000	1.23×10^{10}
Clamped-clamped beam	Single crystal Si	80 kHz	74,000	5.92×10^{9}
Clamped-clamped beam	Poly-Si	9.34MHz	3,100	2.90×10^{10}
Wine glass disk	Poly-Si	60MHz	145,780	8.75×10^{12}
Wine glass disk	Single crystal Si	149.3MHz	45,742	6.83×10^{12}
Radial-contour disk	Poly-Si	193MHz	23,000	4.44×10^{12}
“Hollow-disk” ring	Poly-Si	1.2GHz	14,603	1.75×10^{13}
Impedance-mismatched disk	Poly-diamond	498MHz	55,300	$\boxed{2.75\times10^{13}}$
Square extensional	Single crystal Si	2.18MHz	1,160,000	2.53×10^{12}
Square Lame	Single crystal Si	6.3MHz	1,600,000	1.01×10^{13}
Length extensional	Single crystal Si	12MHz	180,000	2.16×10^{12}
Convex quartz	Quartz	10MHz	1,300,000	1.3×10^{13}
Wine glass disk	Single crystal Si	5.43MHz	1,900,000	1.02×10^{13}

from Lee and Seshia, Sensors and Actuators A 156 (2009) 28–35

MICROSCOPIC MECHANICAL HARMONIC OSCILLATOR

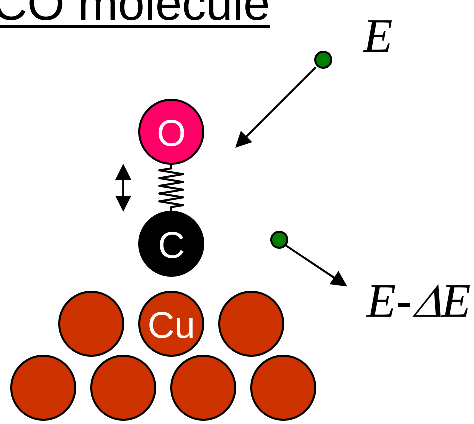
Example of CO molecule

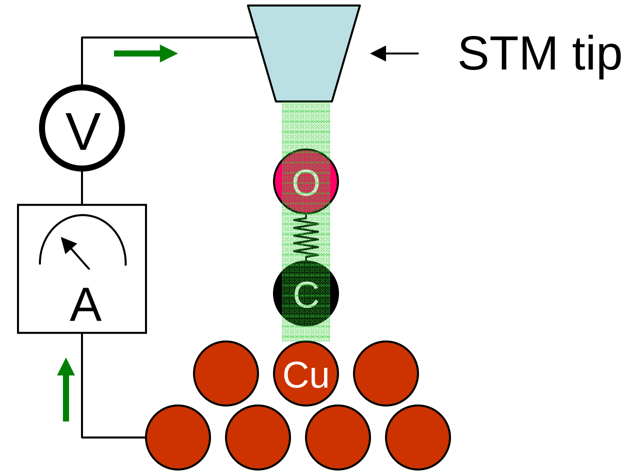
$$\frac{\omega_m}{2\pi} \simeq 60\text{THz}$$

$$M_{eff} \simeq 10^{-26}\text{kg}$$

$$K_{eff} \simeq 100 \text{ N/m}$$

$$X_{ZPF} \simeq 4\text{pm}$$





HREELS

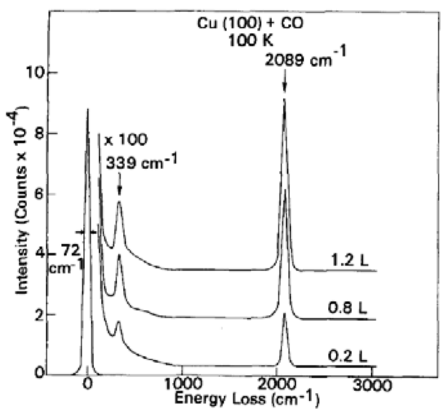


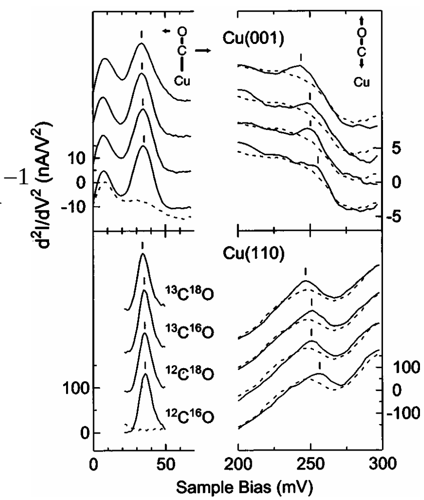
Fig. 7. Energy loss spectrum of CO adsorbed on Cu(100) at 100 K, at different coverages. The 1.2L spectrum is approximately 0.6 monolayers. The beam energy was 5 eV

B. A. Sexton, Chem. Phys. Lett. 63, 451 (1979)

Appl. Phys. A 26, 1–18 (1981)

STM-IETS

$$h \times 60\text{THz} \simeq h \times c \times 2000\text{cm}^{-1} \simeq e \times 250\text{mV} \simeq k_B \times 3000\text{K}$$



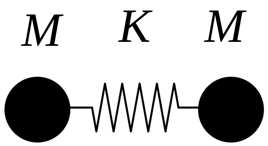
PHYSICAL REVIEW B VOLUME 60, NUMBER 12 15 SEPTEMBER 1999-II

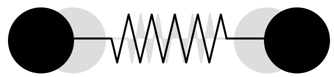
Single-molecule vibrational spectroscopy and microscopy: CO on Cu(001) and Cu(110)

L. J. Lauhon and W. Ho
Laboratory of Atomic and Solid State Physics and Cornell Center for Materials Research, Cornell University, Ithaca, New York 14853
(Received 6 May 1999)

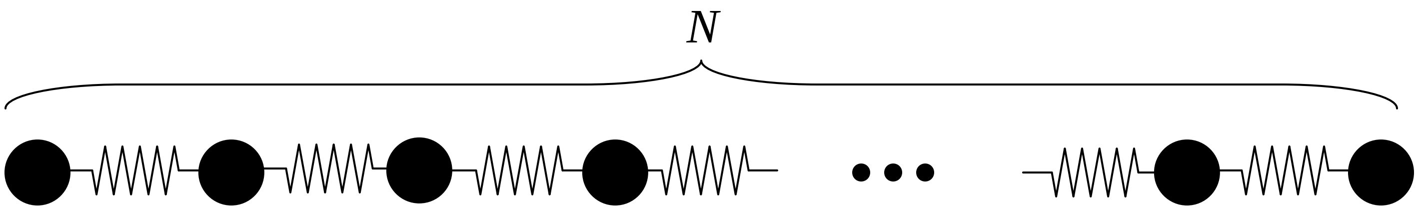
Single-molecule vibrations of four isotopes of CO on Cu(001) and Cu(110) at 8 K have been measured by inelastic electron tunneling spectroscopy with the scanning tunneling microscope (STM-IETS). While the low energy hindered rotation exhibits strong intensity, the C-O stretch approaches the present detection limit of

FROM MOLECULES TO SOLIDS





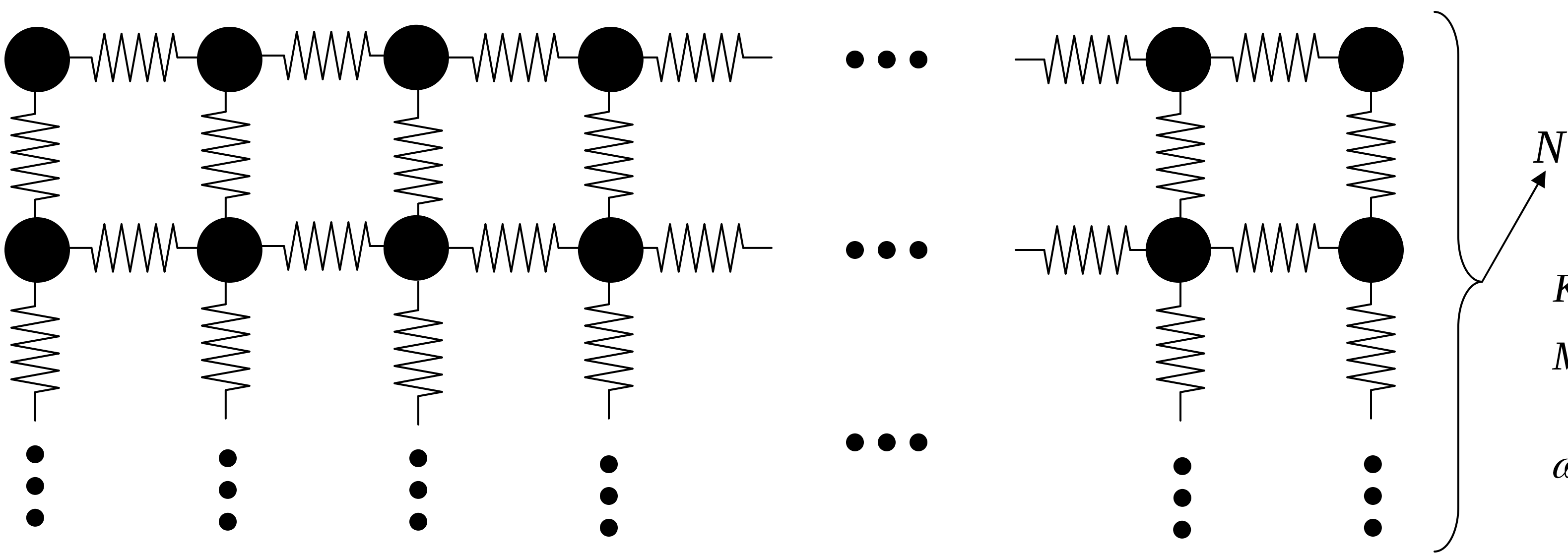
$$\omega_m = \sqrt{\frac{2K}{M}} = \sqrt{2}\omega_0$$



$$K_{eff} \approx K / N$$

$$M_{eff} \approx NM$$

$$\omega_m = \sqrt{\frac{K_{eff}}{M_{eff}}} = \frac{1}{N}\omega_0$$



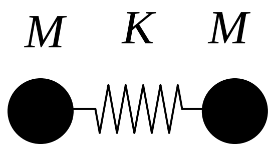
$$K_{eff} \approx N'K / N$$

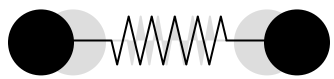
$$M_{eff} \approx NN'M$$

$$\omega_m = \sqrt{\frac{K_{eff}}{M_{eff}}}$$

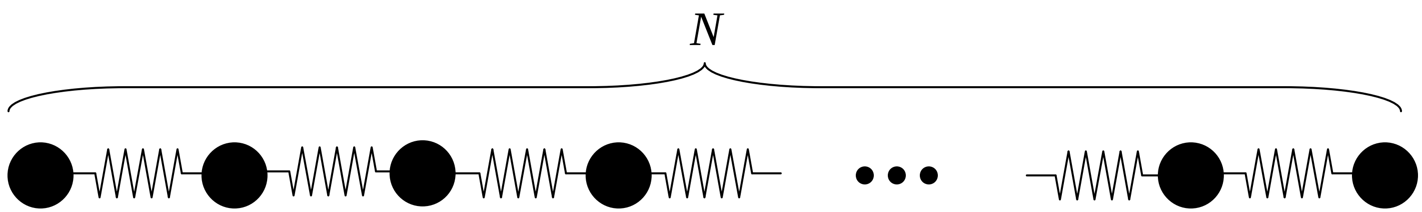
$$= \frac{1}{N}\omega_0$$

FROM MOLECULES TO SOLIDS





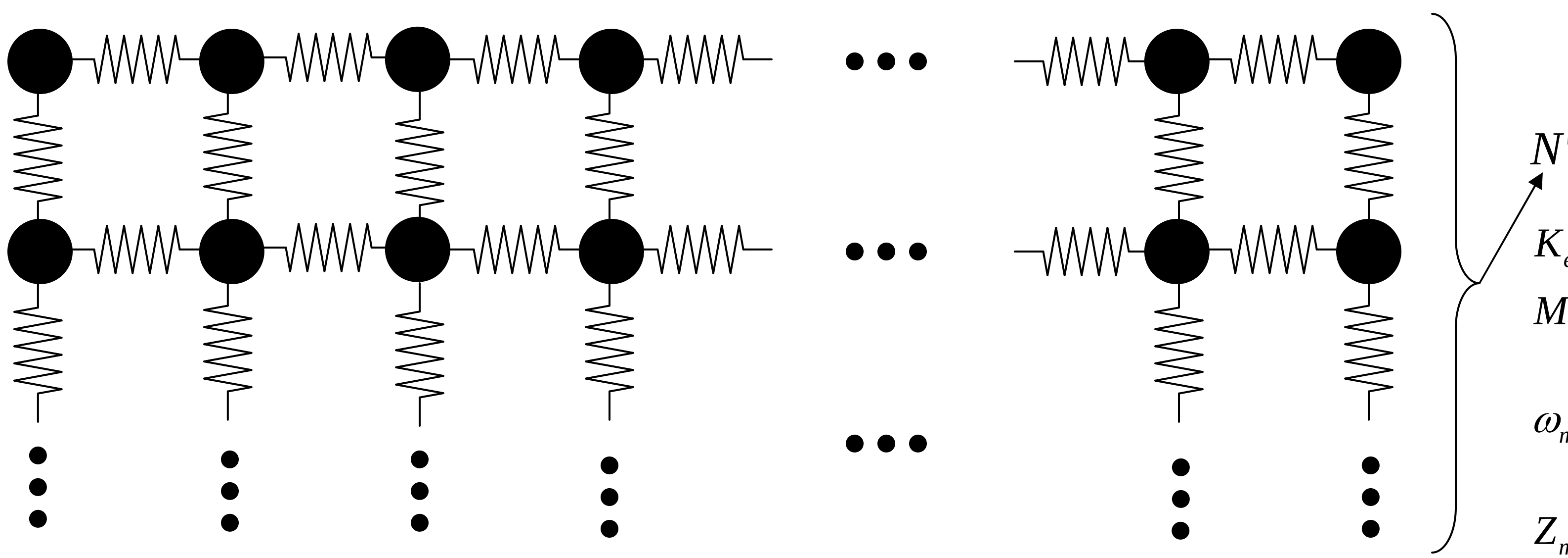
$$\omega_m = \sqrt{\frac{2K}{M}} = \sqrt{2}\omega_0$$



$$K_{eff} \approx K / N$$

$$M_{eff} \approx NM$$

$$\omega_m = \sqrt{\frac{K_{eff}}{M_{eff}}} = \frac{\omega_0}{N}$$



$$K_{eff} \approx N'K / N$$

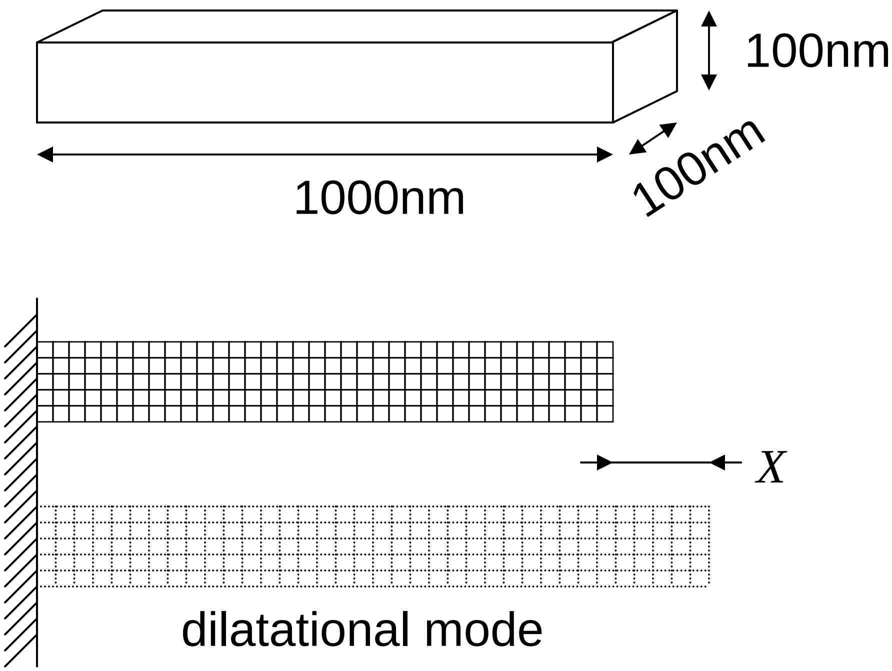
$$M_{eff} \approx NN'M$$

$$\omega_m = \sqrt{\frac{K_{eff}}{M_{eff}}} = \frac{\omega_0}{N}$$

$$Z_m = \sqrt{K_{eff} M_{eff}}$$

$$= N'Z_0$$

MOTION OF A NANOMECHANICAL BEAM



Flexural modes have lower frequencies and smaller mechanical impedances.

$$K_{eff} \approx N'K / N$$

$$M_{eff} \approx NN'M$$

$$N \simeq 10^4; \quad N' \simeq 10^6$$

$$\omega_m = \sqrt{\frac{K_{eff}}{M_{eff}}} = \frac{1}{N}\sqrt{\frac{K}{M}} = \frac{\omega_0}{N}$$

$$Z_m = \sqrt{K_{eff} M_{eff}} = N'\sqrt{KM} = N'Z_0$$

$$X_{ZPF} = \sqrt{\frac{\hbar}{2Z_m}} = \frac{1}{\sqrt{N'}}\sqrt{\frac{\hbar}{2Z_0}}$$

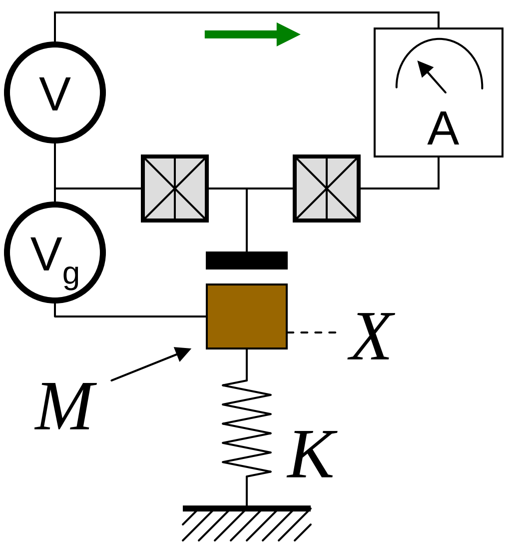
$$\frac{\omega_m}{2\pi} = 10^{-4}\frac{\omega_0}{2\pi} \approx \mathrm{GHz}$$

$$X_{ZPF} = 10^{-3} X_{ZPF,0} \approx \mathrm{fm!}$$

HOW CAN WE MEASURE OSCILLATOR POSITION?

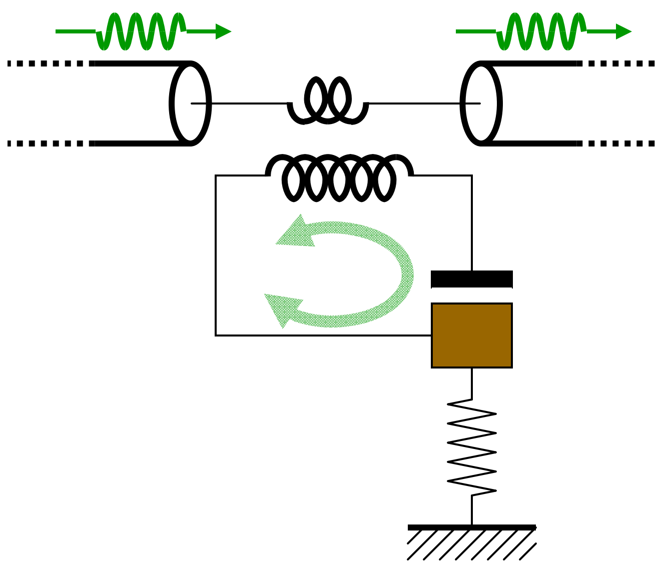
3 main strategies

Single Charge Transistor (or DC SQUID):
Charge induced on island gate capacitance by oscillator mass placed at elevated potential modulates current thru the device (in SQUID, flux modulates voltage)



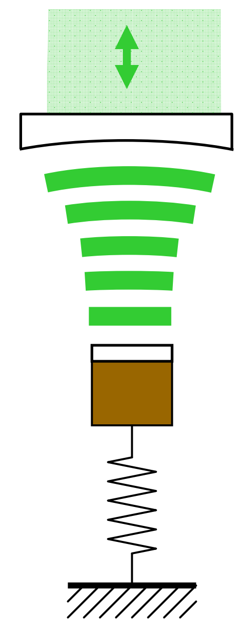
NIST, U. Maryland, UCSB, Cornell

Microwave resonator:
Resonator frequency modulated by displacement of oscillator mass. Phase shift of microwave signal coupled to the resonator carries information about mass position



NIST/JILA

Optical cavity:
Cavity frequency modulated by displacement of oscillator mass. Phase shift of light bouncing off the resonator carries information about mass position



LKB-Paris,
U. Vienna,
Yale,
EPFL
Caltech

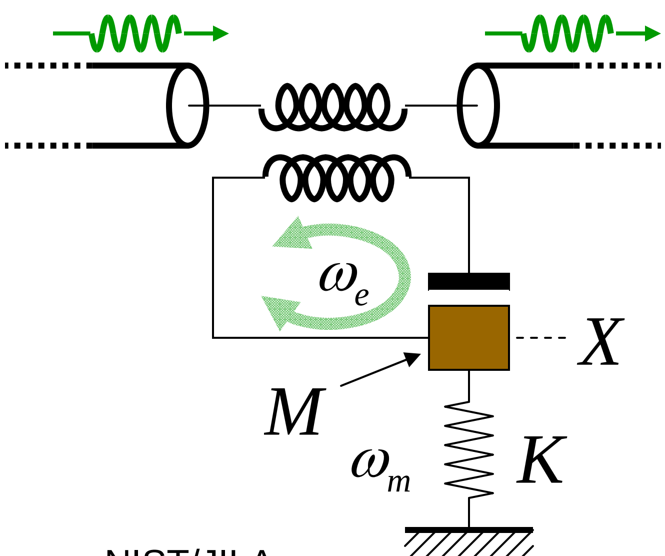
QUANTUM ELECTRO/OPTO-MECHANICS HAMILTONIAN

$$\frac{\hat{H}}{\hbar} = \left(\omega_e + \frac{i}{2}\kappa\right)\hat{a}^\dagger\hat{a} + \left(\omega_m + \frac{i}{2}\gamma\right)\hat{b}^\dagger\hat{b} + g_3\left(\hat{b} + \hat{b}^\dagger\right)\hat{a}^\dagger\hat{a}$$

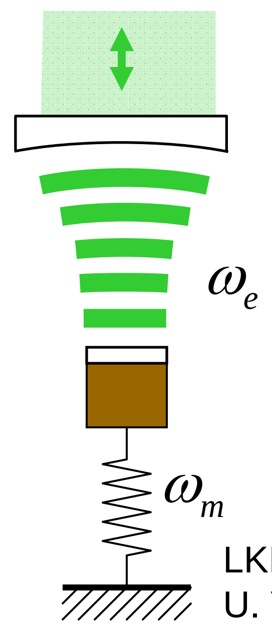
mostly external

internal

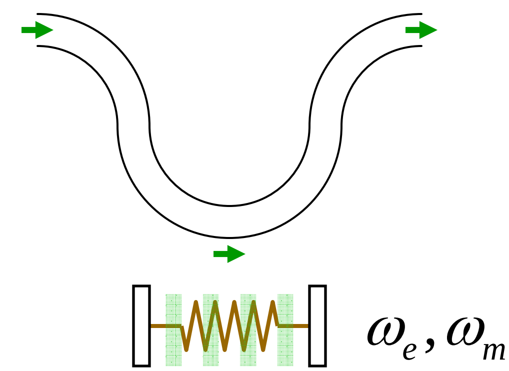
$$g_3 = X_{ZPF}\frac{\partial \omega_e}{\partial X}$$



NIST/JILA



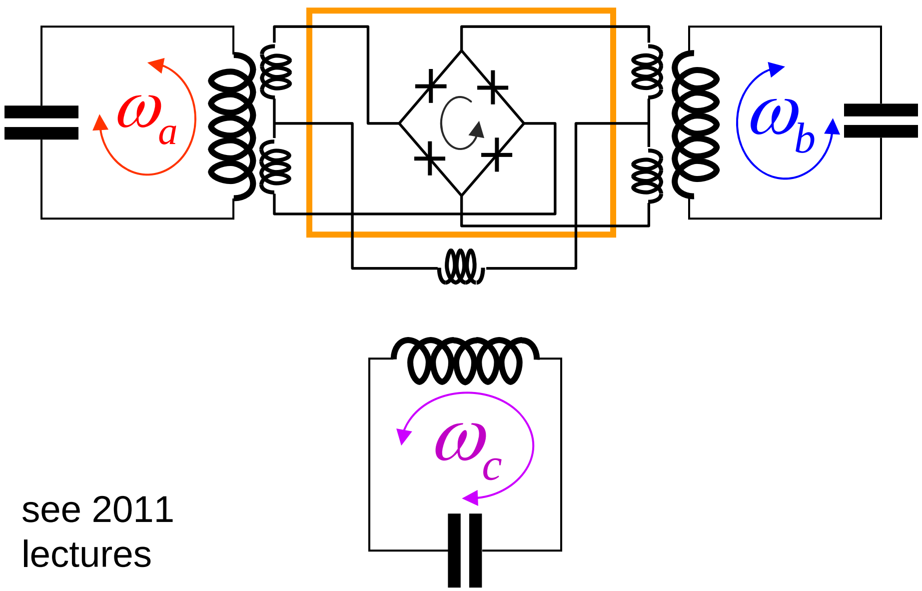
LKB-Paris,
U. Vienna



EPFL, Caltech
U. Vienna

THREE-WAVE COUPLING HAMILTONIAN

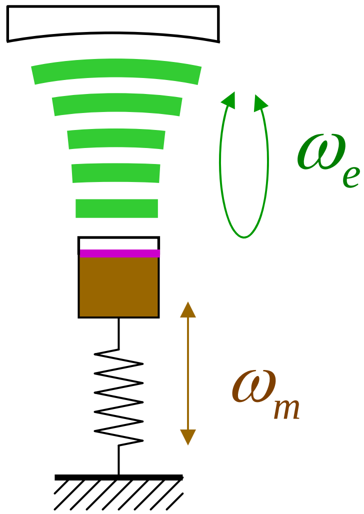
Josephson circuits: 3 non-linearly coupled oscillators



see 2011 lectures

$$\frac{\hat{H}_{sys}}{\hbar} = \omega_a \hat{a}^\dagger \hat{a} + \omega_b \hat{b}^\dagger \hat{b} + \omega_c \hat{c}^\dagger \hat{c} + \left[g_3 \hat{a}^\dagger \hat{b}^\dagger \hat{c} + \text{h.c.} \right]$$

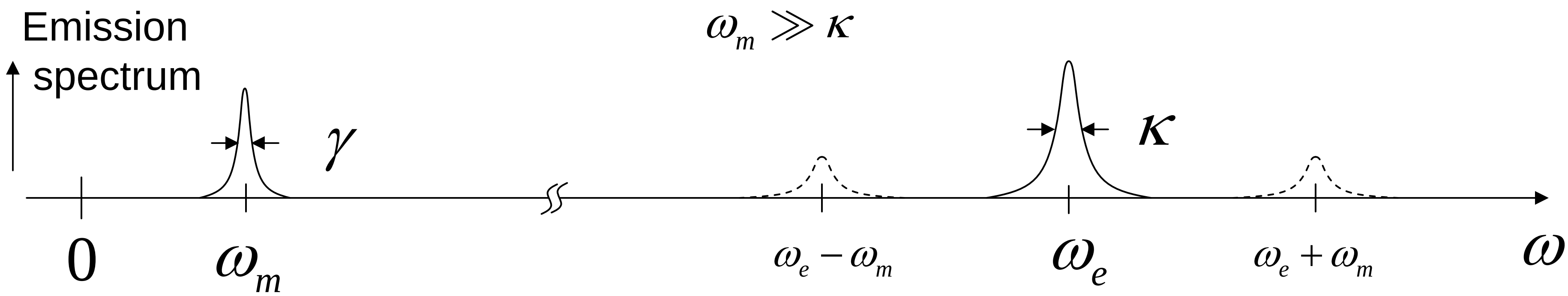
Optomechanics: 2 non-linearly coupled oscillators



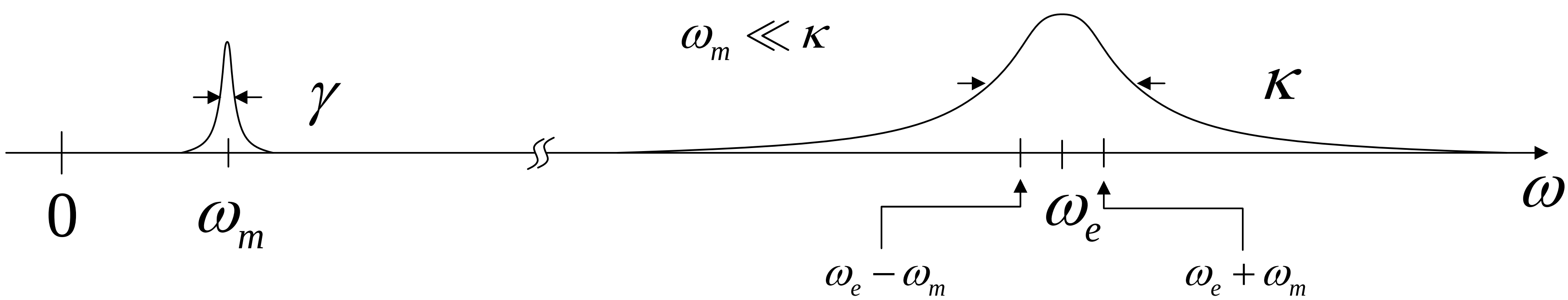
$$\frac{\hat{H}_{sys}}{\hbar} = \omega_e \hat{a}^\dagger \hat{a} + \omega_m \hat{b}^\dagger \hat{b} + g_3 \left(\hat{b} + \hat{b}^\dagger \right) \hat{a}^\dagger \hat{a}$$

FREQUENCY LANDSCAPE

Resolved sideband regime:



Un-resolved sideband regime:



PHONON HEATING RATE

$$\gamma_{eff} = n_{b,T}\gamma$$

Heating rate of mechanical oscillator

Phonon occupancy

Damping rate of mechanical oscillator

FEEDBACK COOLING

THE REDUCTION IN THE BROWNIAN MOTION OF ELECTROMETERS

by J. M. W. MILATZ, J. J. VAN ZOLINGEN *) and B. B. VAN IPEREN **)

Publication from the Physisch Laboratorium der Universiteit van Utrecht, Nederland

Physica XIX, 195-207 (1953)

Synopsis

A method is described to reduce the Brownian deflections of electrometer systems. This is achieved by replacing the air damping by a special type of artificial damping. The latter is realised by means of a photoelectric amplifier containing a differentiating circuit, comp. fig. 1. The amount of light entering the photocell is made proportional to the deflection of the electrometer system and the output of the amplifier is fed back to the electrometer.

The motion of the electrometer is studied with a photoelectric relay and a recording galvanometer allowing a magnification up to 14300×. The application of this method of damping has already resulted in a hundred fold reduction of the Brownian energy and an increase in precision of a factor of ten.

In order to reach the same accuracy with normal air-damping it should be necessary to cool the instrument to 3°K.

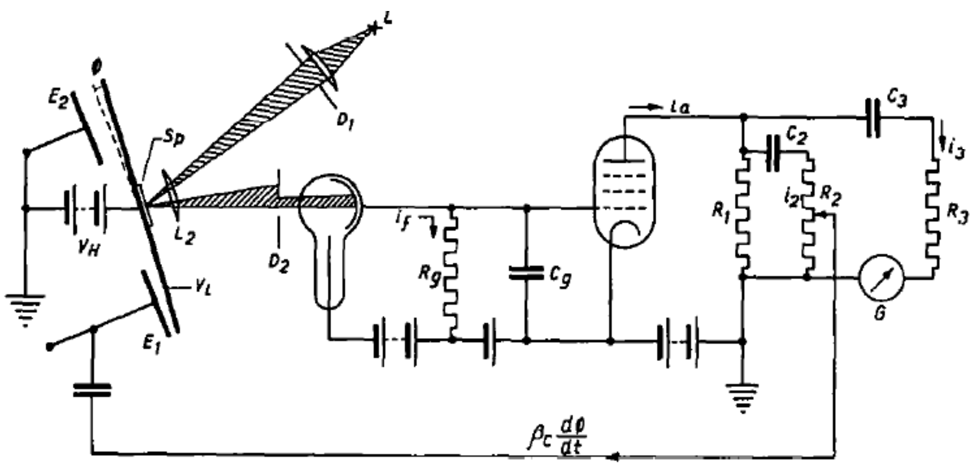
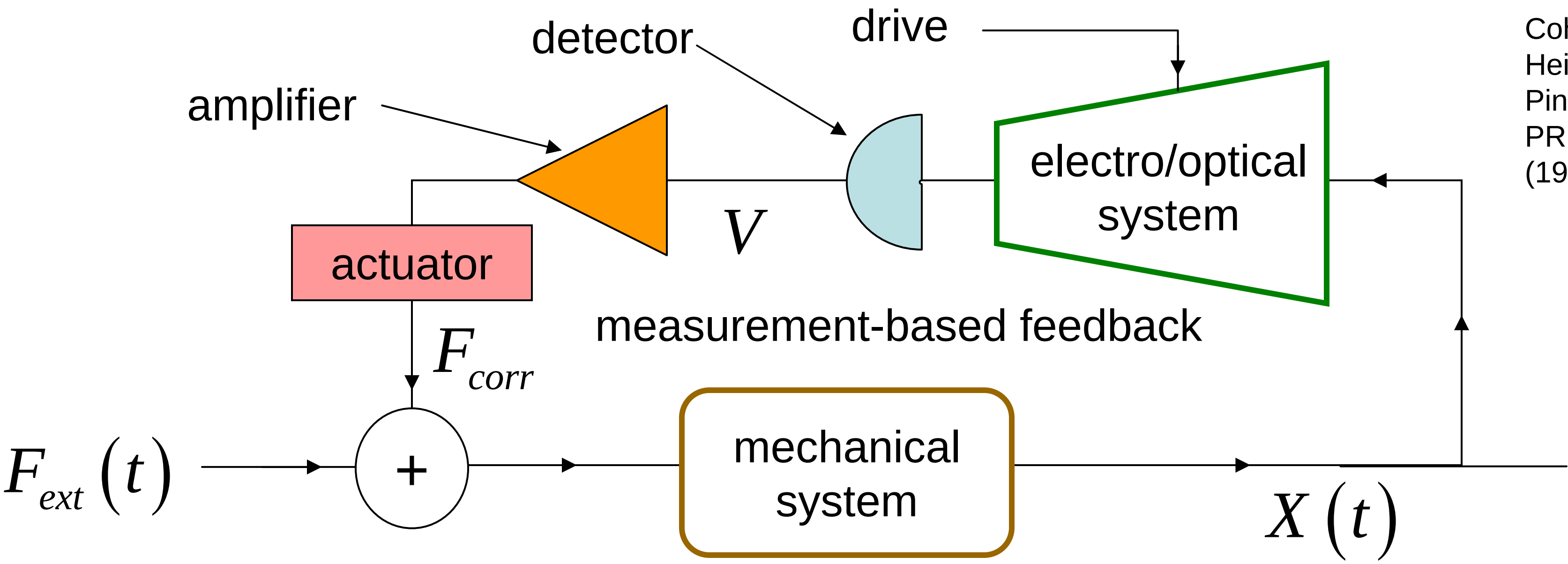
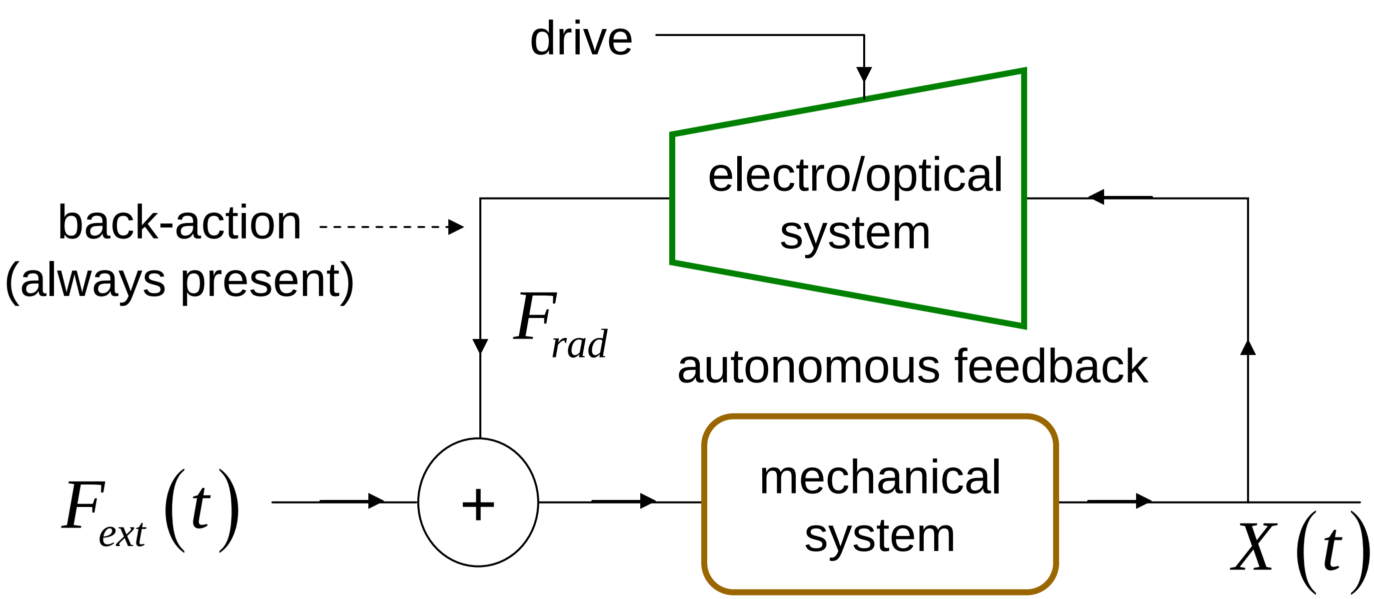


Fig. 1. Schematic arrangement of the electrometer, the damping circuit and the recording galvanometer.

2 TYPES OF FEEDBACK COOLING



Cohadon
Heidmann
Pinard
PRL **83**, 3174 (1999)



IS IT POSSIBLE TO REACH THE GROUND STATE?

Problem similar to that of cooling of atoms (or ions) confined in a potential.

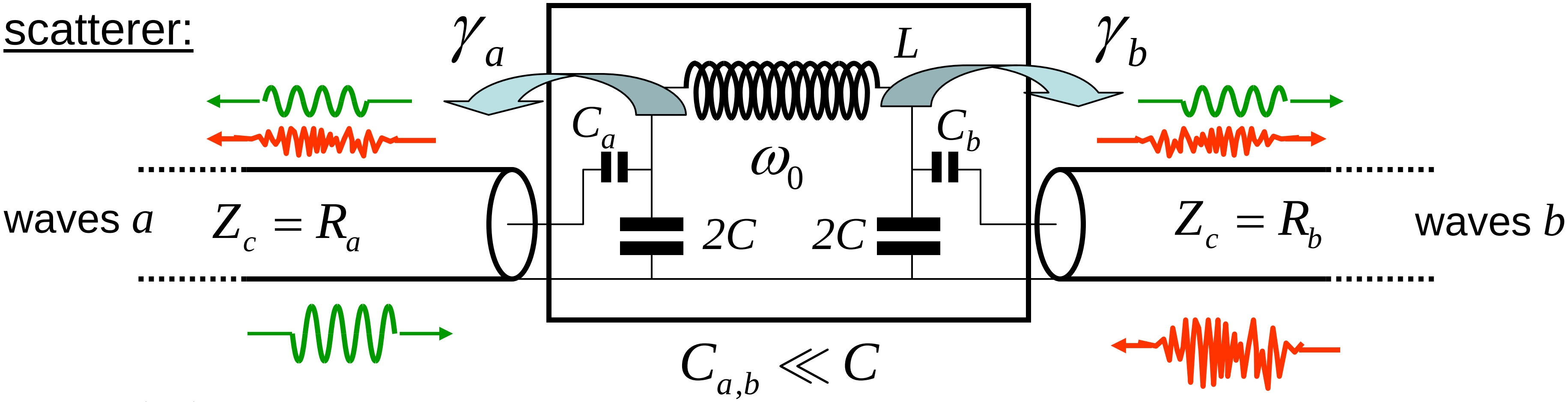
Measurement-based feedback will cool down to noise temperature of amplifier in feedback loop. Problem is that ground state is not an eigenstate of position X and amplifier usually adds noise.

Autonomous feedback has not such limitation. In the resolved sideband regime, it can measure $X+iP$, which the ground state is an eigenstate of, without adding noise.

Three approaches: - Classical feedback
- Semi-classical input-output theory
- Fully quantum theory of active/dynamical cooling

INPUT-OUTPUT APPROACH

Electromagnetic scatterer:



$s_{aa}(\omega)$ attenuation of reflected signal

$$S = \left[\begin{array}{c:c} \dfrac{\Gamma_a - \Gamma_b - i\Delta\omega}{\Gamma_a + \Gamma_b + i\Delta\omega} & -\dfrac{2\Gamma_a^{1/2}\Gamma_b^{1/2}}{\Gamma_a + \Gamma_b + i\Delta\omega} \\ \hdashline -\dfrac{2\Gamma_a^{1/2}\Gamma_b^{1/2}}{\Gamma_a + \Gamma_b + i\Delta\omega} & \dfrac{\Gamma_b - \Gamma_a - i\Delta\omega}{\Gamma_a + \Gamma_b + i\Delta\omega} \end{array}\right]$$

$$\Gamma_{a,b} = \frac{\gamma_{a,b}}{2} \cong \frac{R_{a,b} C_{a,b}^2}{4LC^2}$$

$$\Delta\omega = \omega - \omega_0$$

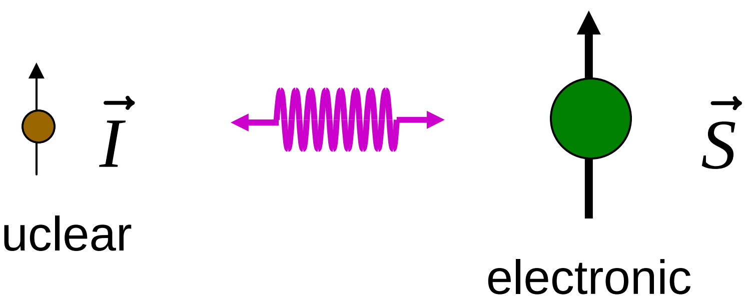
Interference: when $\Delta\omega = 0$ & $\gamma_a = \gamma_b$, reflection vanishes! Waves are perfectly transmitted.

Electro/opto mechanics:

When driven by pump, system has analogous scattering matrix for small fluctuations. Difference: waves *a* and *b* do not have at the same frequency.

AUTONOMOUS FEEDBACK COOLING OF OSCILLATOR BELONGS TO THE CLASS OF DYNAMICAL COOLING EFFECTS*

Two spins:

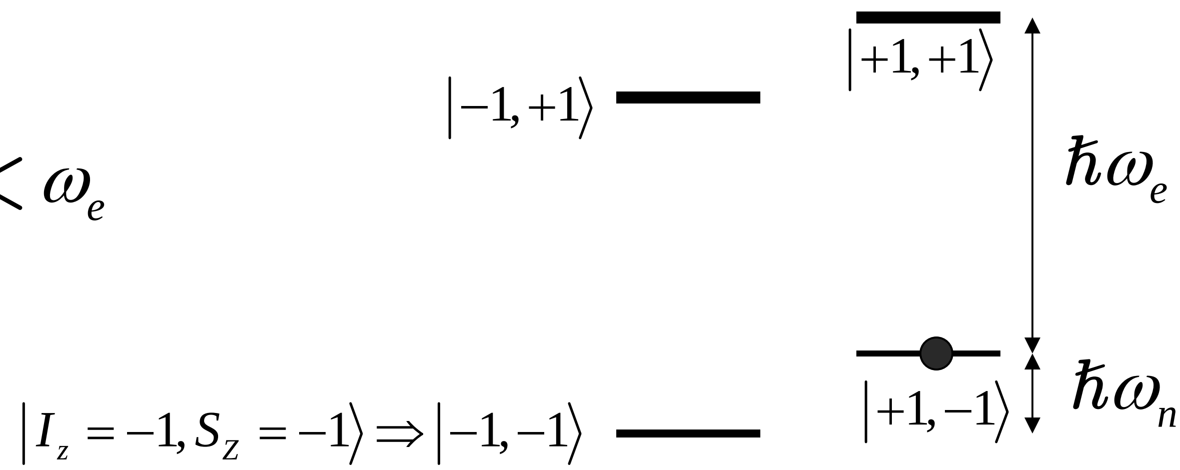


Hamiltonian contains electron-spin coupling:

$$\frac{H}{\hbar} = \omega_n I_Z + \omega_e S_Z + g\,\vec{I}\cdot\vec{S} \text{ + spin relaxation}$$

Levels:

$$g \ll \omega_n \ll \omega_e$$



* A. Abragam and M. Goldman, "Principles of dynamic nuclear polarisation", Rep. Prog. Phys., Vol 41, 1978

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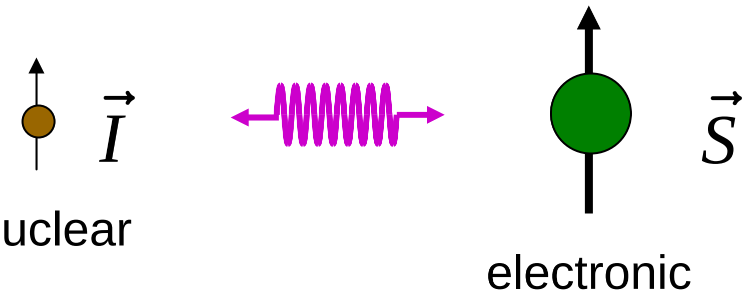

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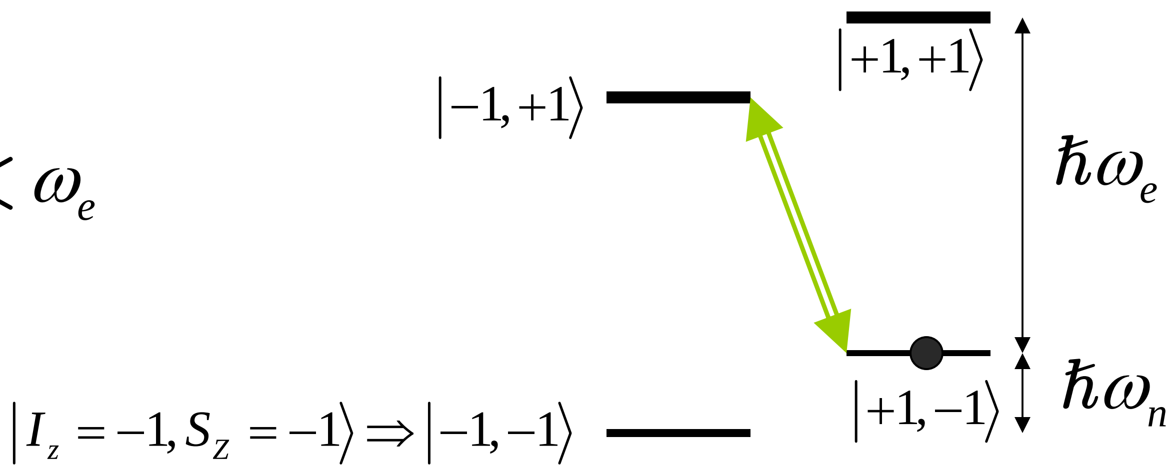

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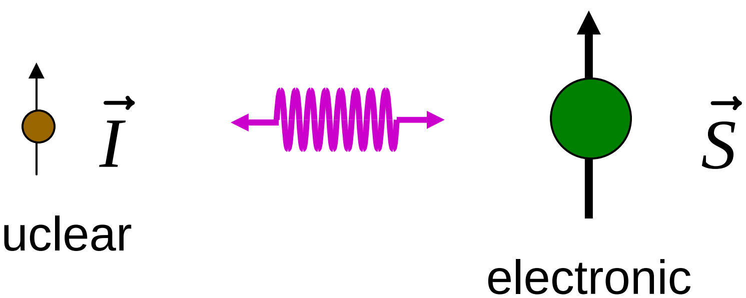

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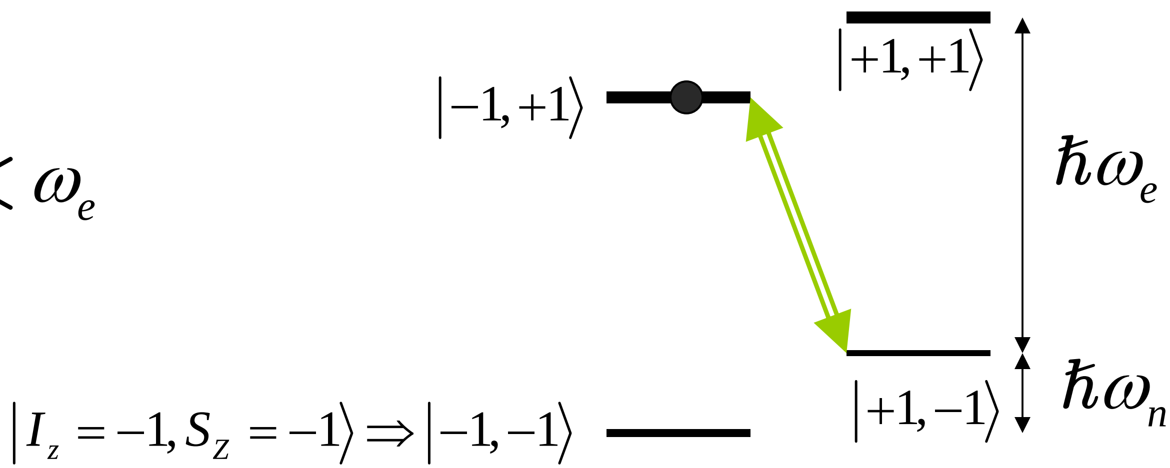

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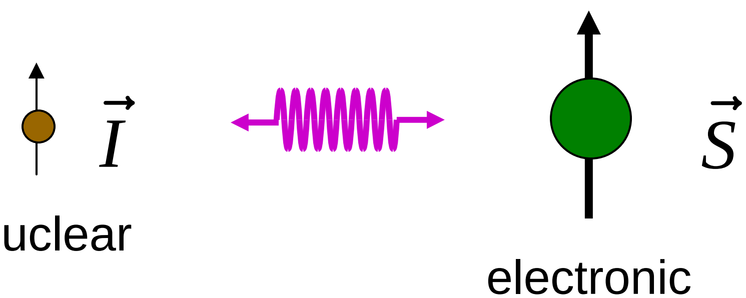

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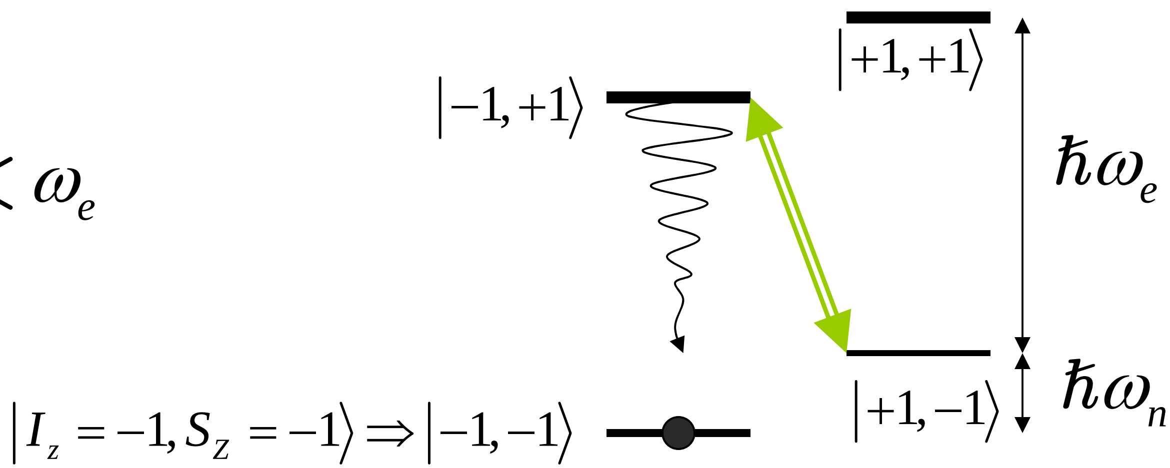

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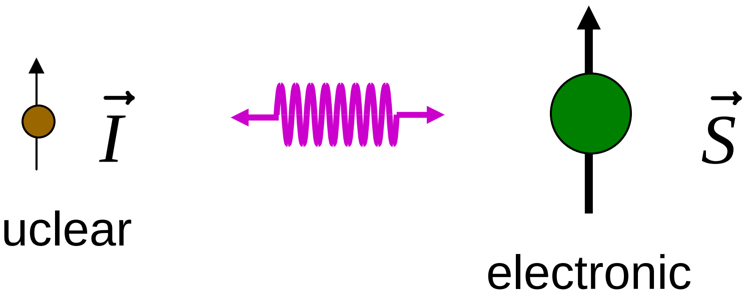

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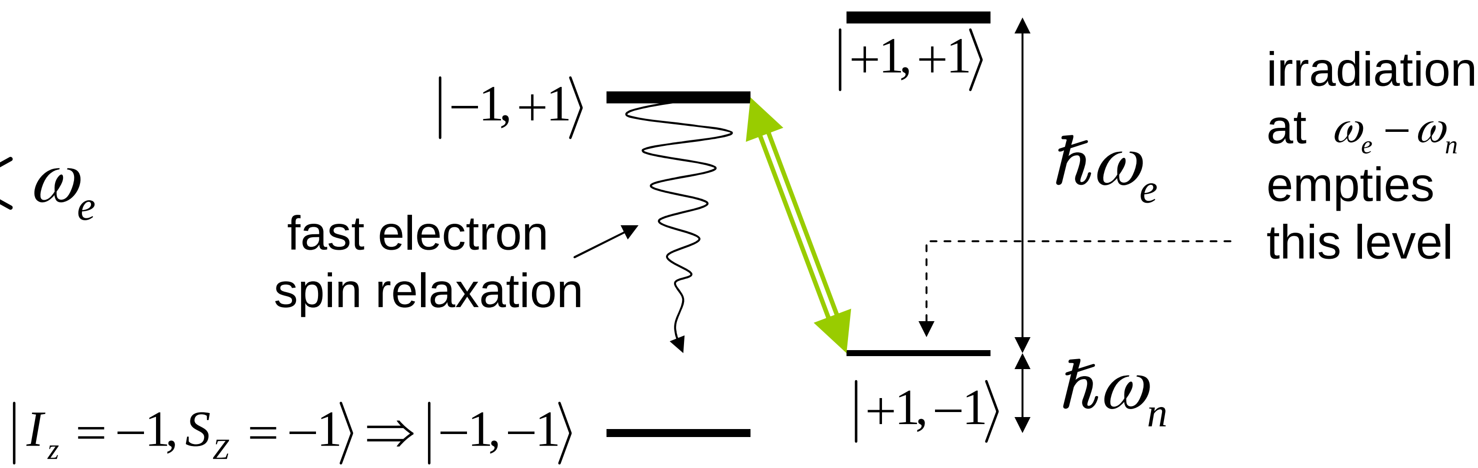

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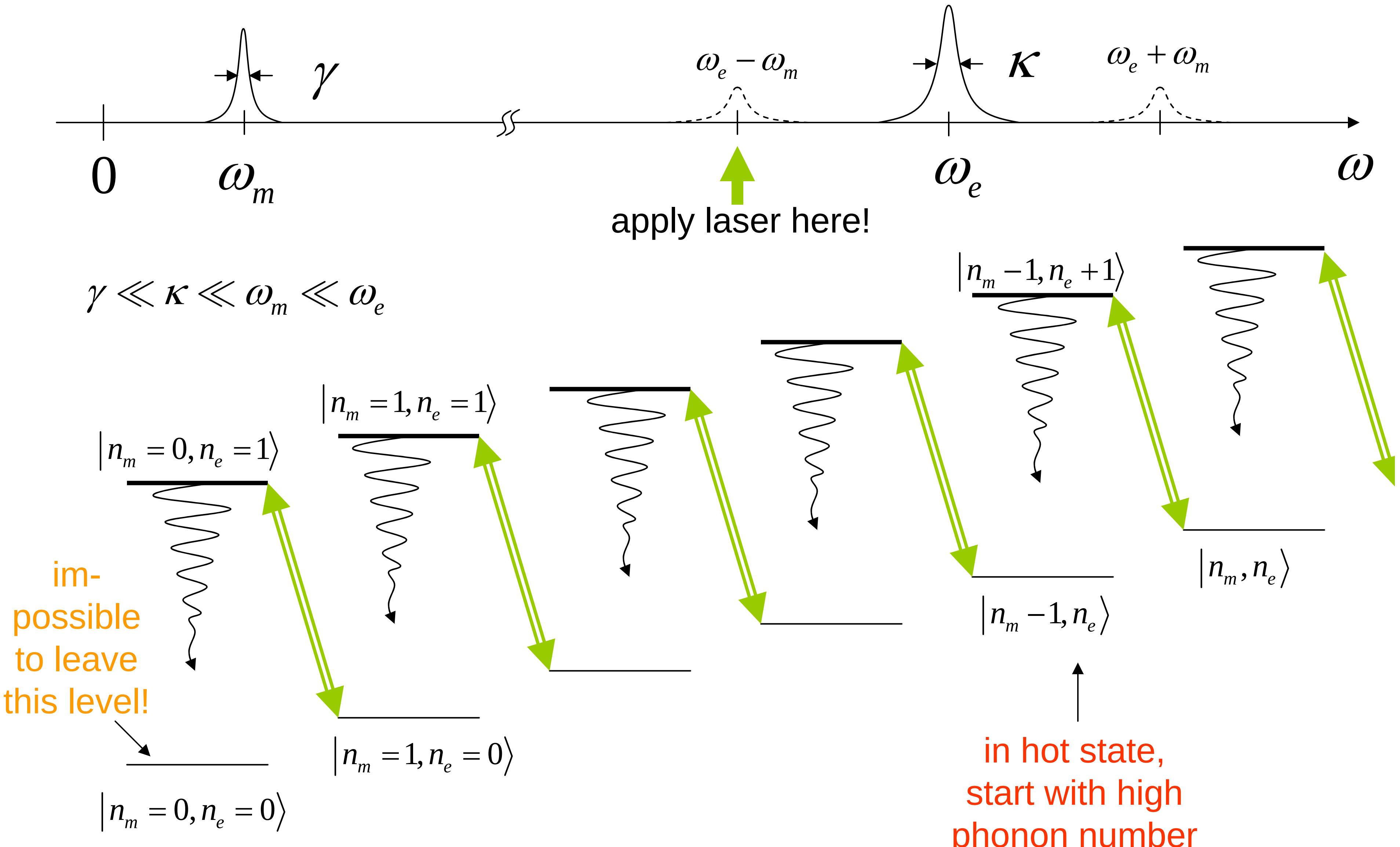
DYNAMICAL COOLING OF OSCILLATOR MOTION IN THE RESOLVED SIDEBAND REGIME



PROGRAM OF THIS YEAR'S LECTURES

Lecture I: Introduction to nanomechanical systems

Lecture II: How is the coupling between electromagnetic radiation and mechanical motion modeled?

Lecture III: Is it possible to measure the position of a mechanical oscillator without being affected by zero-point motion of the detector?

Lecture IV: In the active cooling of a nanomechanical resonator, is measurement based feedback inferior to autonomous feedback?

Lecture V: How close to the ground state can we bring a nano-resonator?

Lecture VI: What oscillators do we need to convert quantum information from the microwave domain to the optical domain?

SELECTED BIBLIOGRAPHY FOR THE COURSE

Books

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Clarke, J. and Braginsky, A. I., eds., "The SQUID Handbook" (Wiley-VCH, Weinheim, Germany, 2006).

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Articles

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Chan J., *et al.*, "Laser cooling of a nanomechanical oscillator into its quantum ground state", Nature **478**, 89 (2011)

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Teufel J.D. *et al.*, "Sideband cooling of micromechanical motion to the quantum ground state", Nature **475**, 359 (2011)

CALENDAR OF 2012 SEMINARS

May 15: **Rob Schoelkopf (Yale University, USA)**
Quantum optics and quantum computation with superconducting circuits.

May 22: **Konrad Lehnert (JILA, Boulder, USA)**
Micro-electromechanics: a new quantum technology.

May 29: **Olivier Arcizet (Institut Néel, Grenoble)**
A single NV defect coupled to a nanomechanical oscillator: hybrid nanomechanics.

June 5: **Ivan Favero (MPQ, Université Paris Diderot)**
From micro to nano-optomechanical systems: photons interacting with mechanical resonators.

June 12: **A. Douglas Stone (Yale University, USA)**
Lasers and anti-lasers: a mesoscopic physicist's perspective on scattering from active and passive media.

June 19: **Tobias J. Kippenberg (EPFL, Lausanne, Suisse)**
Cavity optomechanics: exploring the coupling of light and micro- and nanomechanical oscillators.

END OF LECTURE